Higgs Physics – Lecture 1

Higgs Physics at the LHC – Introduction

Ricardo Gonçalo – UC/LIP

IDPASC Course on Physics at the LHC – LIP, 5 April 2023

1290 UNIVERSIDADE D COIMBRA
LIP
CERN
ATLAS EXPERIMENT
FCT Fundação para a Ciência e a Tecnologia

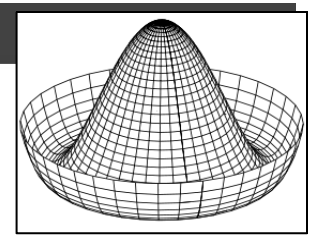
Higgs Lectures

Monday, 4 April

17:00 → 18:30 **Higgs Physics 1**

Introduction
Reminder of some shortcomings of the SM: masses, WW scattering.
The Higgs mechanism. Production and decay of the Higgs boson at colliders: LEP, Tevatron and LHC.
Previous searches at LEP and the Tevatron.

Speakers: Ricardo Goncalo, Ricardo Gonçalo (U. Coimbra/LIP)

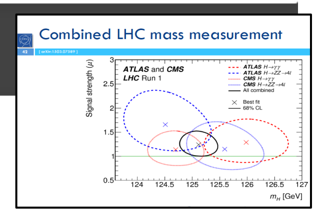


Wednesday, 6 April

17:00 → 18:30 **Higgs Physics 2**

Discovery of the Higgs boson in the different final states:
Algorithms, challenges, tools,
combination of results

Speakers: Pedro Silva (LIP) , Pedro Vieira De Castro Ferreira Da Silva (CERN)

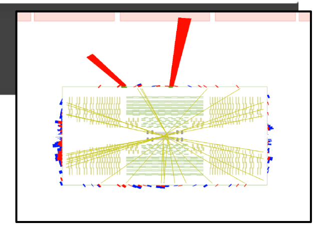


Monday, 11 April

17:00 → 18:30 **Higgs Physics 3**

Case-study of the H->bb search, H->bb observation
Algorithms, challenges, tools
Higgs measurements with H->bb

Speakers: Rute Costa Batalha Pedro (LIP Laboratorio de Instrumentacao e Fisica Experimental de Particulas (PT)) , Rute Pedro (LIP)



Wednesday, 13 April

17:00 → 18:30 **Higgs Physics 4**

- Search for new physics in the Higgs sector.
- The Higgs boson and processes beyond the SM.
- Extensions of the SM, minimal and non-minimal extensions.
- High mass searches.
- MSSM Higgs searches: neutral, charged.
- Light pseudoscalar, resonant and non-resonant Higgs pair production.

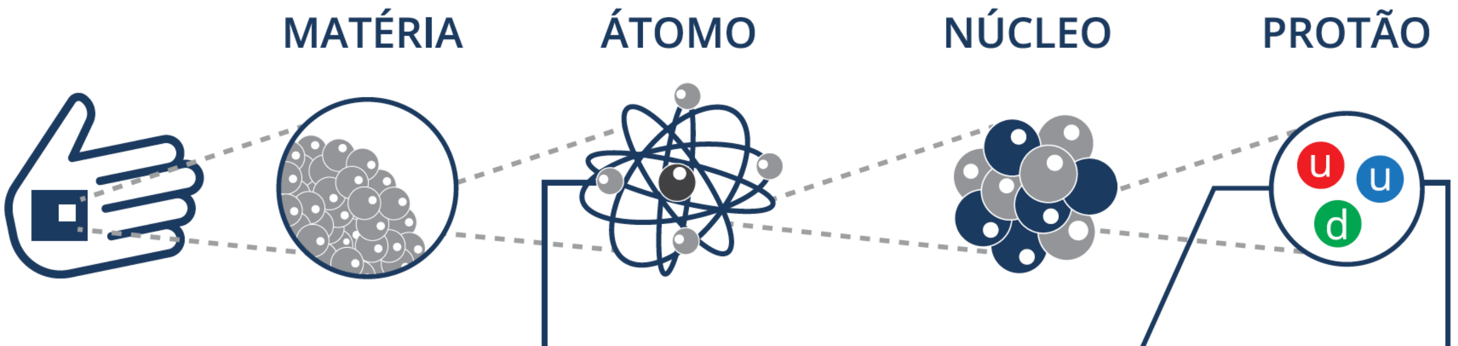
Speaker: Michele Gallinaro (LIP)

Outlook

- What is the Higgs boson and what is it good for?
- How did we find it?
- Why do we care?
- And what comes next?

Introduction

The Standard Model particles and interactions, and some theory to set the scene…



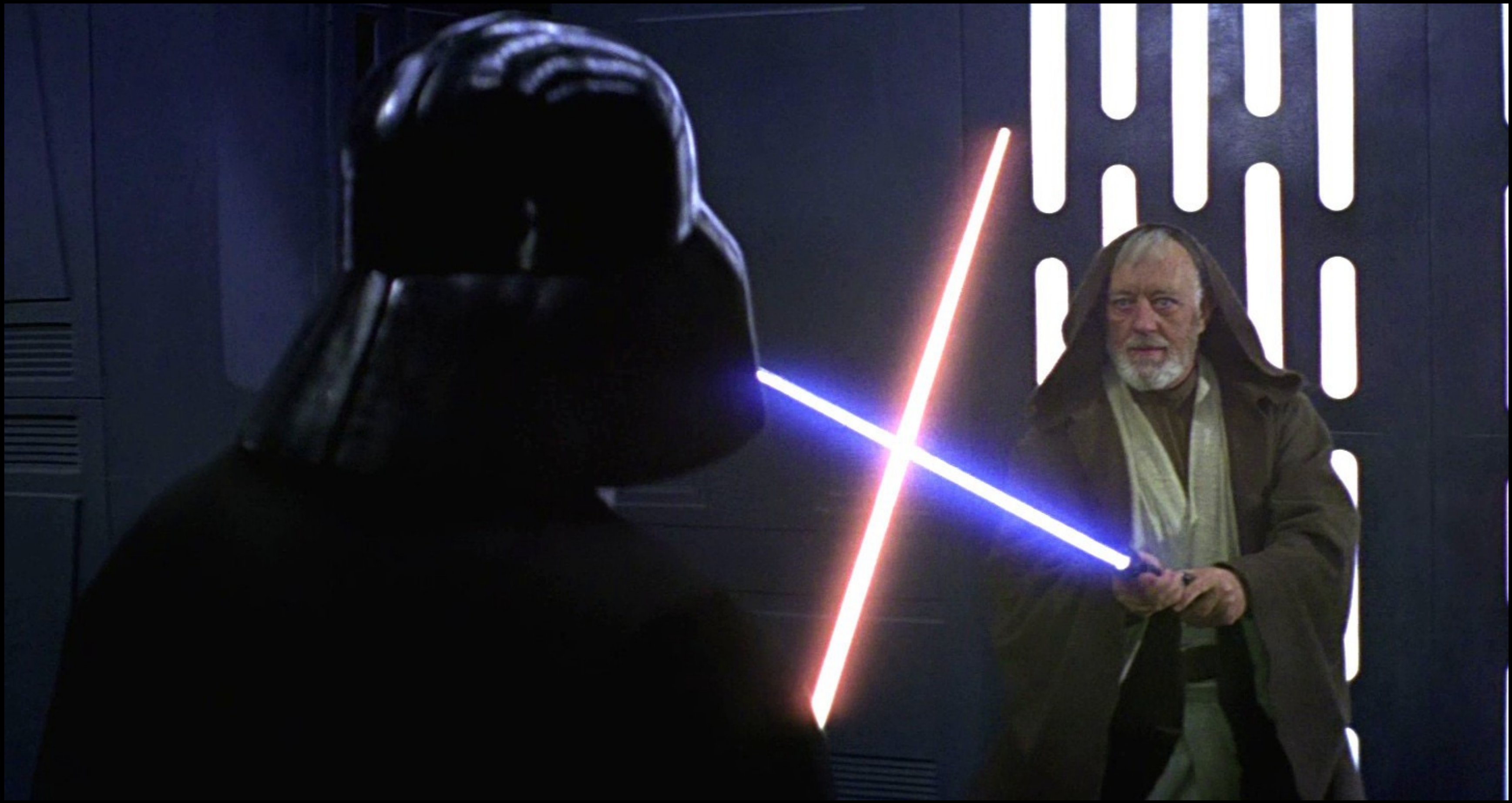
LEPTÕES

ν_e NEUTRINO DO ELETRÃO 0 ½	e ELETRÃO -1 ½
ν_μ NEUTRINO DO MUÃO 0 ½	μ MUÃO -1 ½
ν_τ NEUTRINO DO TAU 0 ½	τ TAU -1 ½

QUARKS

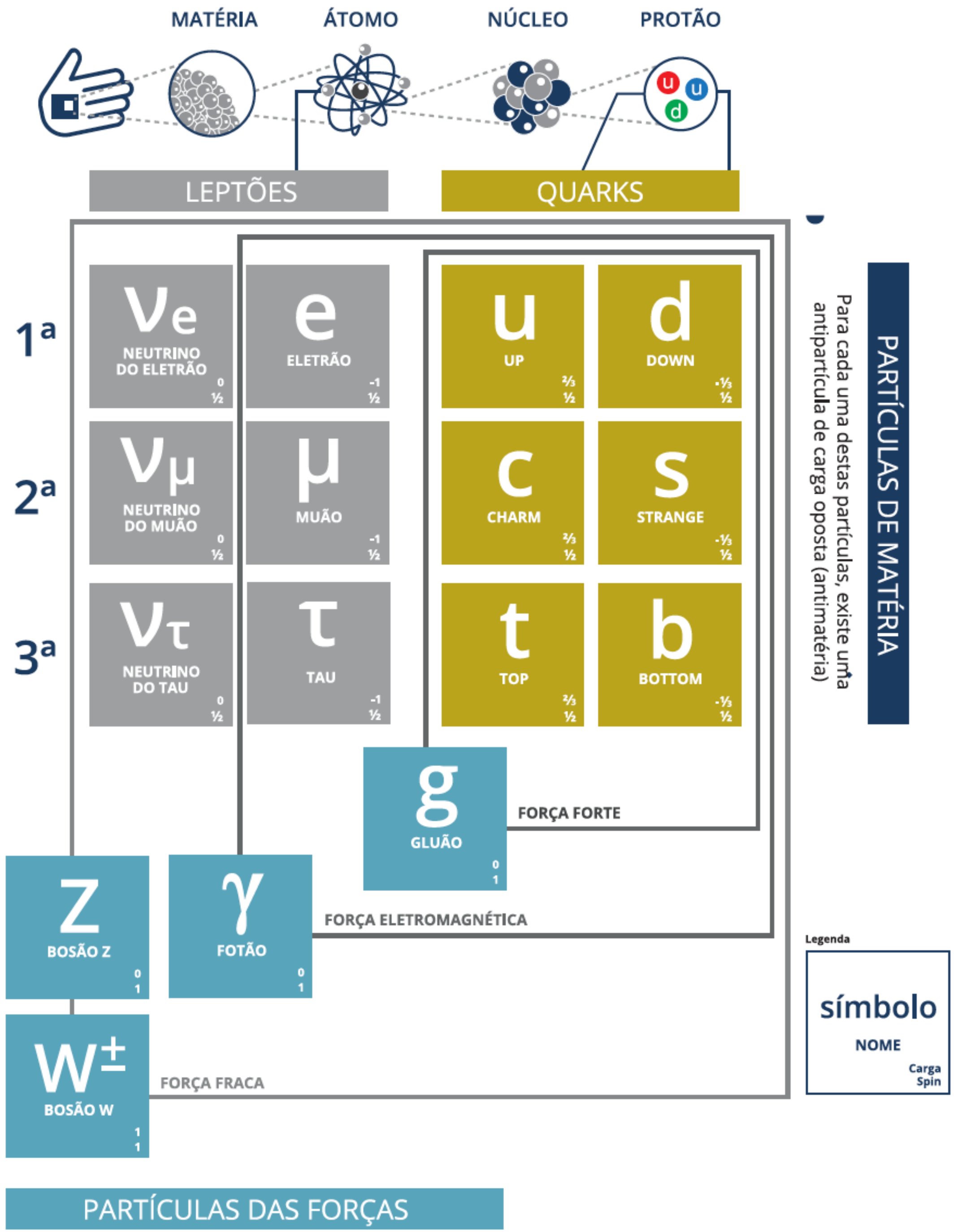
u UP ⅔ ½	d DOWN -⅓ ½
c CHARM ⅔ ½	s STRANGE -⅓ ½
t TOP ⅔ ½	b BOTTOM -⅓ ½

Fundamental Forces



Fundamental forces

- Electromagnetic:
  - Carried by photons
  - Acts on electrical charge
- Weak:
  - Carried by:
    - $W^{\pm}$ (charged current)
    - Z^0 (neutral current)
  - Acts on weak isospin
- Strong:
  - Carried by 8 gluons
  - Acts on colour



Lagrangians, symmetries and all that

Leonhard Euler(1707–1783)

Emmy Noether (1882 – 1935)

Joseph-Louis Lagrange (1736–1813)

Lagrangians in classical mechanics

The equations of motion of a system are derived from a scalar **Lagrangian** function of **generalized coordinates** and **velocities** (time derivatives of the coordinates)

$$L(q, \dot{q}) = T - V$$

From minimizing the action S, get the **Euler-Lagrange equations**:

$$S = \int dt L(q_i, \dot{q}_i) \qquad \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = 0$$

For a point particle in a potential U, with $q_i = x, y, z$

$$L = \frac{1}{2}m\dot{q}_i^2 - U(q_i) \qquad \frac{d}{dt}(m\dot{q}_i) + \frac{\partial U}{\partial q_i} = 0 \qquad m\ddot{q}_i = -\frac{\partial U}{\partial q_i}$$

Symmetries and conservation laws

Noether's theorem:

> If a system has a continuous symmetry property, then there are corresponding quantities whose values are conserved in time.

Simplest case:

> Coordinates not explicitly appearing in the Lagrangian => Lagrangian invariant over a transformation of these coordinates

Example: point mass m orbiting in the field of a fixed mass M

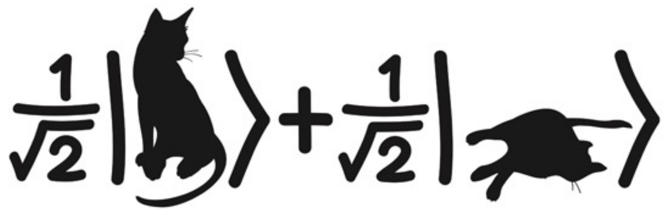
$$L(r, \phi, \dot{r}, \dot{\phi}) = T - V = \frac{1}{2}m\dot{r}^2 + \frac{1}{2}mr^2\dot{\phi}^2 + \frac{GMm}{r}$$

Since the lagrangian doesn't depend explicitly on φ (symmetry with respect to rotations in space), the Euler-Lagrange equation gives

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\phi}}\right) = 0 \Leftrightarrow \frac{\partial L}{\partial \dot{\phi}} = mr^2\dot{\phi} = J$$

Where the angular momentum J is a constant of motion!

Let’s go to quantum fields...



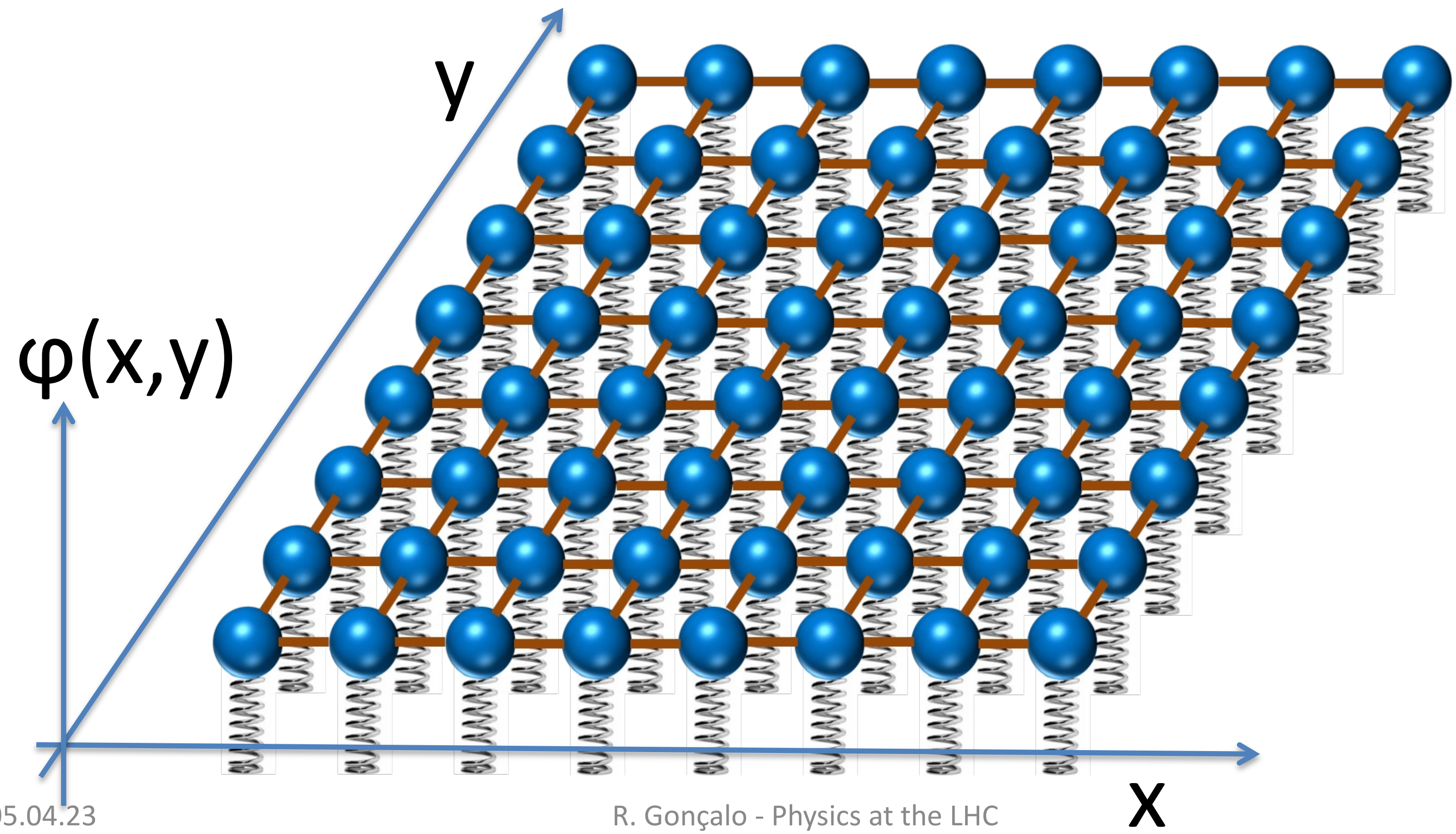
Richard Feynman
(1918 - 1988)

Fluffy (?-?)

Erwin
Schrödinger
(1887 - 1961)

Now in quantum field theory…

Imagine space as an infinite continuum of balls and springs, where each ball is connected to its neighbours by elastic bands. **Particles are perturbations of this field**



Generalized coordinates are now **fields** (dislocation of each spring)

$$q_i \to \phi_i(x^\mu)$$

In a relativistic theory we must treat space and time coordinates on an equal footing, so the derivatives in the classical equations are now

$$\frac{d}{dt}, \nabla \to \partial_\mu = (\frac{\partial}{\partial t}, \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z})$$

In place of a Lagrangian we have a **Lagrangian density** (we call it Lagrangian anyway, just to be confusing)

$$L(q_i, \frac{dq_i}{dt}) \to \mathcal{L}(\phi_i, \partial_\mu \phi_i) \quad \text{with:} \quad L = \int \mathcal{L} d^3\boldsymbol{x}$$

The new Euler-Lagrange equation now becomes

$$\partial_\mu(\frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi_i)}) - \frac{\partial \mathcal{L}}{\partial \phi_i} = 0$$

- Example Lagrangians and equations of motion:
- Klein-Gordon Lagrangian for spin 0 particles (scalars):

$$\mathcal{L}_{KG} = \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2} m^2 \phi^2$$

$$\boxed{\partial_\mu \partial^\mu \phi + m^2 \phi = 0}$$

- Dirac Lagrangian for spin ½ particles (fermions):

$$\mathcal{L}_D = i\bar{\psi}\gamma^\mu \partial_\mu \psi - m\bar{\psi}\psi$$

$$\boxed{i\gamma^\mu \partial_\mu \psi - m\psi = 0}$$

- Proca Lagrangian for spin 1 (vector) particles:

$$\mathcal{L}_P = \frac{-1}{16\pi}(\partial^\mu A^\nu - \partial^\nu A^\mu)(\partial_\mu A_\nu - \partial_\nu A_\mu) + \frac{1}{8\pi} m^2 A^\nu A_\nu$$

$$\boxed{\partial_\mu(\partial^\mu A^\nu - \partial^\nu A^\mu) + m^2 A^\nu = 0}$$

- Important:

Mass terms in Lagrangian are quadratic in the fields

Global gauge invariance

Take the Dirac Lagrangian for a spinor field ψ representing a spin-½ particle, for example an electron:

$$\mathcal{L} = i\hbar\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi$$

It is invariant under a global U(1) phase transformation like:

$$\psi(x) \to \psi'(x) = e^{iq\chi}\psi(x)$$

Where χ is a constant

$$\mathcal{L}' = e^{-iq\chi}e^{iq\chi}(i\hbar\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi) = \mathcal{L}$$

Note: gauge invariance of the Dirac equation can be demonstrated to lead to conservation of probability current j^{μ}

$$j^{\mu} = (\rho, \mathbf{J}) = \overline{\psi}\gamma^{\mu}\psi$$

Local gauge invariance and interactions

If $\chi = \chi\,(x)$ then we get extra terms in the Lagrangian:

$$\begin{aligned}\mathcal{L}' &= ie^{-iq\chi}\bar{\psi}\gamma^\mu[e^{iq\chi}\partial_\mu\psi + iq(\partial_\mu\chi)e^{iq\chi}\psi] - me^{-iq\chi}e^{iq\chi}\bar{\psi}\psi \\ &= \mathcal{L} - q\bar{\psi}\gamma^\mu(\partial_\mu\chi)\psi\end{aligned}$$

But we can now make the Lagrangian invariant by adding an ***interaction term*** with a new **gauge** field $\boldsymbol{A_\mu}$ which transforms as:

$$A_\mu \to A'_\mu = A_\mu - \partial_\mu\chi$$

We get:

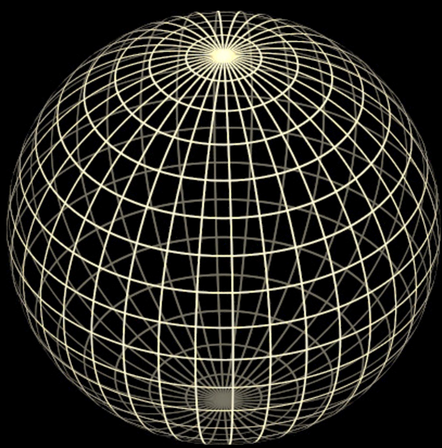
$$\mathcal{L} = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi - q\bar{\psi}\gamma^\mu A_\mu\psi$$

Note:

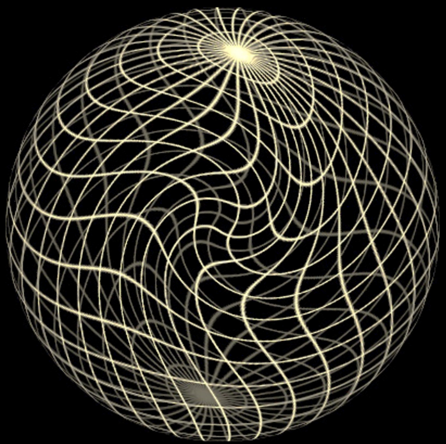
1. The new gauge field $\boldsymbol{A_\mu}$ is the photon in QED
2. The mass of the fermion is the coefficient of the term on $\overline{\psi}\psi$
3. There is no term in $\boldsymbol{A_\mu A^\mu}$ (the photon has zero mass)

$$\psi(x) \rightarrow \psi'(x) = e^{iq\chi}\psi(x)$$

Original sphere



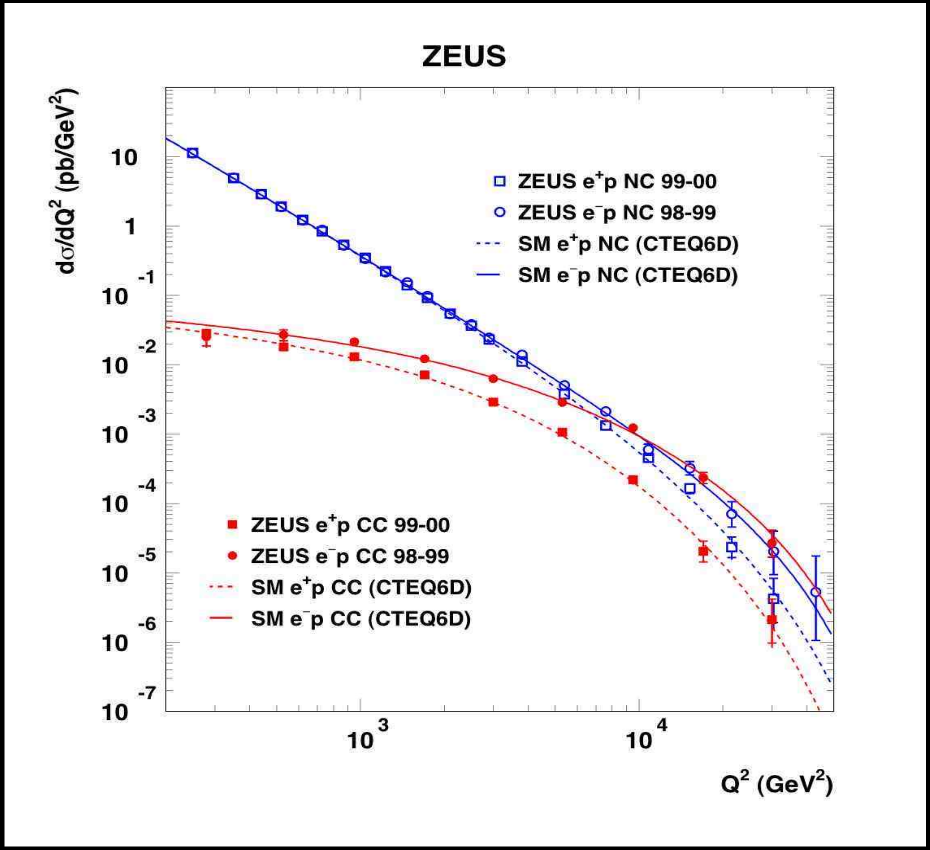
Local transformação



χ = **constant**

$\chi = \chi\,(x)$

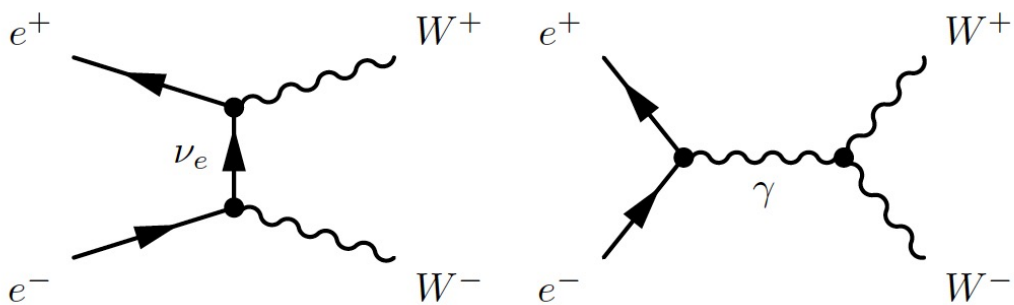
Weak Neutral Currents and Electroweak Unification

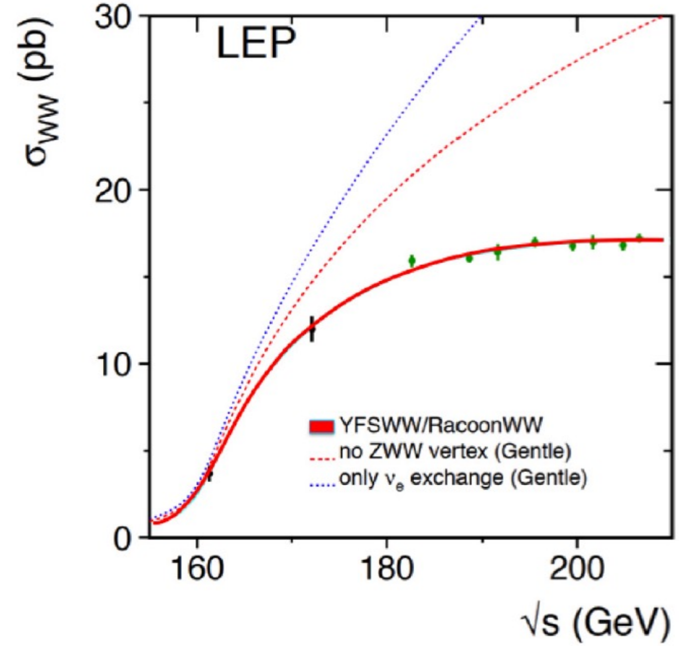


Weak Charged and Neutral Currents

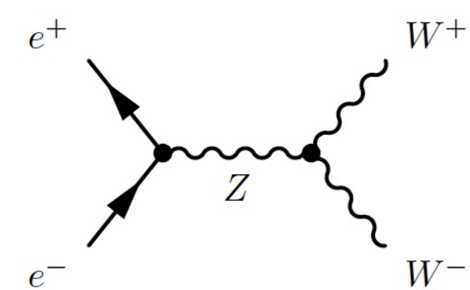
- Weak CC interactions explained by $W^{\pm}$ boson exchange
- $W^{\pm}$ bosons are charged, thus they couple to the γ

Consider $e^-e^+ \to W^+W^-$: 2 diagrams (+interference)





- Cross-section diverges at high energy
- Divergence cured by introducing Z boson
- Extra diagram for $e^-e^+ \to W^+W^-$
- Idea only works if γ, $W^{\pm}$, Z couplings are related



Weak Gauge Theory

- Postulate invariance under a gauge transformation like:
$$\psi \to \psi' = e^{ig\vec{\sigma}.\vec{\Lambda}(\vec{r},t)}\psi$$
an "SU(2)" transformation (σ are 2x2 matrices).
- Operates on the state of "weak isospin" – a "rotation" of the isospin state.
- Invariance under SU(2) transformations $\Rightarrow$ three massless gauge bosons (W_1, W_2, W_3) whose couplings are well specified.
- They also have self-couplings.

But this doesn't quite work...
Predicts W and Z have the same couplings – not seen experimentally!

Sheldon Glashow's "stumbling block"

- There are hints that EM and weak interactions have a common origin
  - Similar gauge structure
  - $W^{\pm}$ couples to charge
- But there are obvious differences:
  - Different masses of $W^{\pm}$, Z and photon
  - Structure of the vertex is different

PARTIAL-SYMMETRIES OF WEAK INTERACTIONS

SHELDON L. GLASHOW †
Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark

Received 9 September 1960

Abstract: Weak and electromagnetic interactions of the leptons are examined under the hypothesis that the weak interactions are mediated by vector bosons. With only an isotopic triplet of leptons coupled to a triplet of vector bosons (two charged decay-intermediaries and the photon) the theory possesses no partial-symmetries. Such symmetries may be established if additional vector bosons or additional leptons are introduced. Since the latter possibility yields a theory disagreeing with experiment, the simplest partially-symmetric model reproducing the observed electromagnetic and weak interactions of leptons requires the existence of at least four vector-boson fields (including the photon). Corresponding partially-conserved quantities suggest leptonic analogues to the conserved quantities associated with strong interactions: strangeness and isobaric spin.

1. Introduction

At first sight there may be little or no similarity between electromagnetic effects and the phenomena associated with weak interactions. Yet certain remarkable parallels emerge with the supposition that the weak interactions are mediated by unstable bosons. Both interactions are universal, for only a single coupling constant suffices to describe a wide class of phenomena: both interactions are generated by vectorial Yukawa couplings of spin-one fields [††]. Schwinger first suggested the existence of an "isotopic" triplet of vector fields whose universal couplings would generate both the weak interactions and electromagnetism — the two oppositely charged fields mediate weak interactions and the neutral field is light [2]). A certain ambiguity beclouds the self-interactions among the three vector bosons; these can equivalently be interpreted as weak or electromagnetic couplings. The more recent accumulation of experimental evidence supporting the $\Delta I = \frac{1}{2}$ rule characterizing the non-leptonic decay modes of strange particles indicates a need for at least one additional neutral intermediary [3]).

The mass of the charged intermediaries must be greater than the K-meson mass, but the photon mass is zero — surely this is the principal stumbling block in any pursuit of the analogy between hypothetical vector mesons and photons. It is a stumbling block we must overlook. To say that the decay intermediaries

The GWS Model

The Glashow, Weinberg and Salam model treats EM and weak interactions as different manifestations of a single unified electroweak force (Nobel Prize 1979)

Start with 4 massless bosons W^+, W_3, W^- and B. The neutral bosons mix to give physical bosons (the particles we see), i.e. the $W^{\pm}$, Z, and γ.

$$\begin{pmatrix} W^+ \\ W_3 \\ W^- \end{pmatrix} ; \quad B \quad \rightarrow \quad \begin{pmatrix} W^+ \\ Z \\ W^- \end{pmatrix} ; \quad \gamma$$

Physical fields: W^+, Z, W^- and A (photon).

$$Z = W_3 \cos\theta_W - B \sin\theta_W$$

$$A = W_3 \sin\theta_W + B \cos\theta_W$$

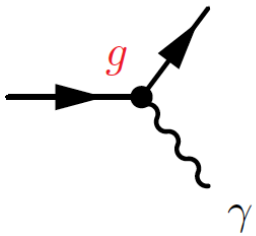
θ_W Weak Mixing Angle

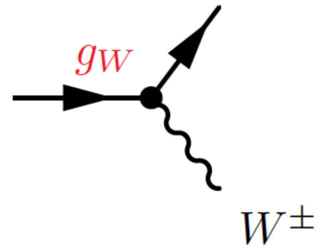
$W^{\pm}$, Z "acquire" mass via the Higgs mechanism.

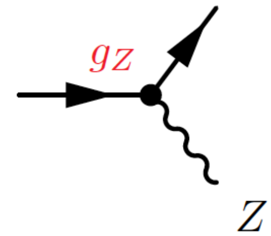
The GWS Model

The beauty of the GWS model is that it makes exact predictions of the $W^{\pm}$ and Z masses and of their couplings with only 3 free parameters.

Couplings given by α_{EM} and θ_W







$$\alpha_{EM} = \frac{e^2}{4\pi} \quad g \sim e \qquad g_W = \frac{e}{\sin\theta_W} \qquad g_Z = \frac{e}{\sin\theta_W \cos\theta_W} = \frac{g_W}{\cos\theta_W}$$

Masses also given by G_F and θ_W

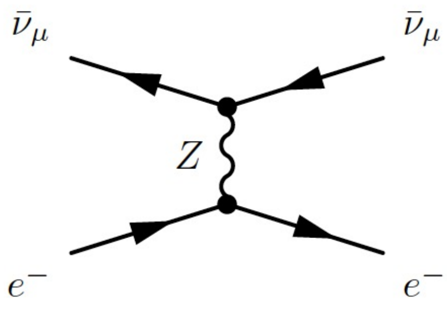
From Fermi theory

$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8m_W^2} = \frac{e^2}{8m_W^2 \sin^2\theta_W} \qquad m_{W^{\pm}} = \left(\frac{\sqrt{2}e^2}{8G_F \sin^2\theta_W}\right)^{1/2} \qquad m_Z = \frac{m_W}{\cos\theta_W}$$

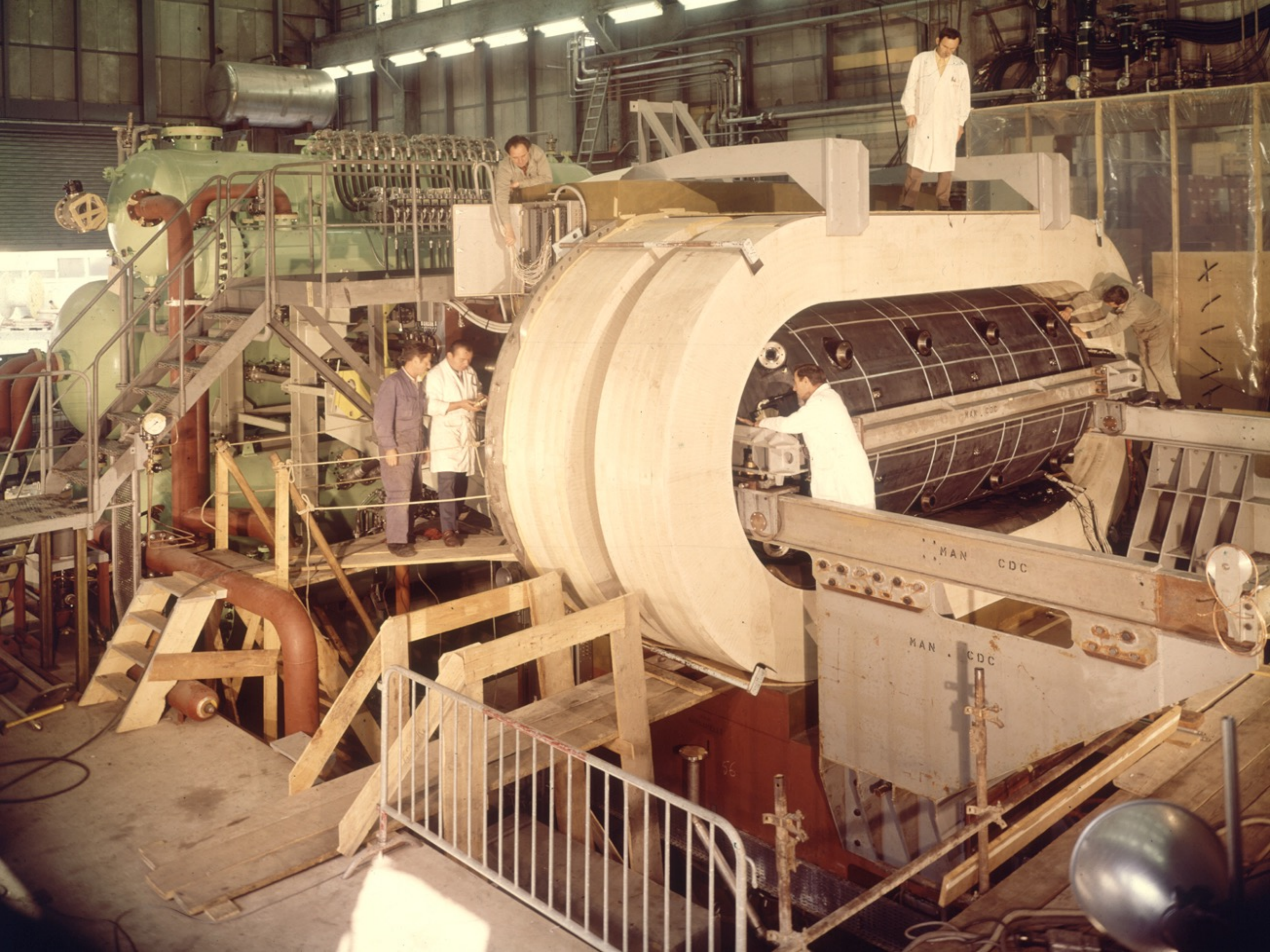
If we know α_{EM}, G_F, $\sin\theta_W$ (from experiment), everything else is defined.

Evidence for the GWS model

- **Discovery of Neutral Currents (1973)**
  The process $\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^-$ was observed.
  Only possible Feynman diagram (no $W^\pm$ diagram).
  Indirect evidence for Z.



Gargamelle Bubble Chamber at CERN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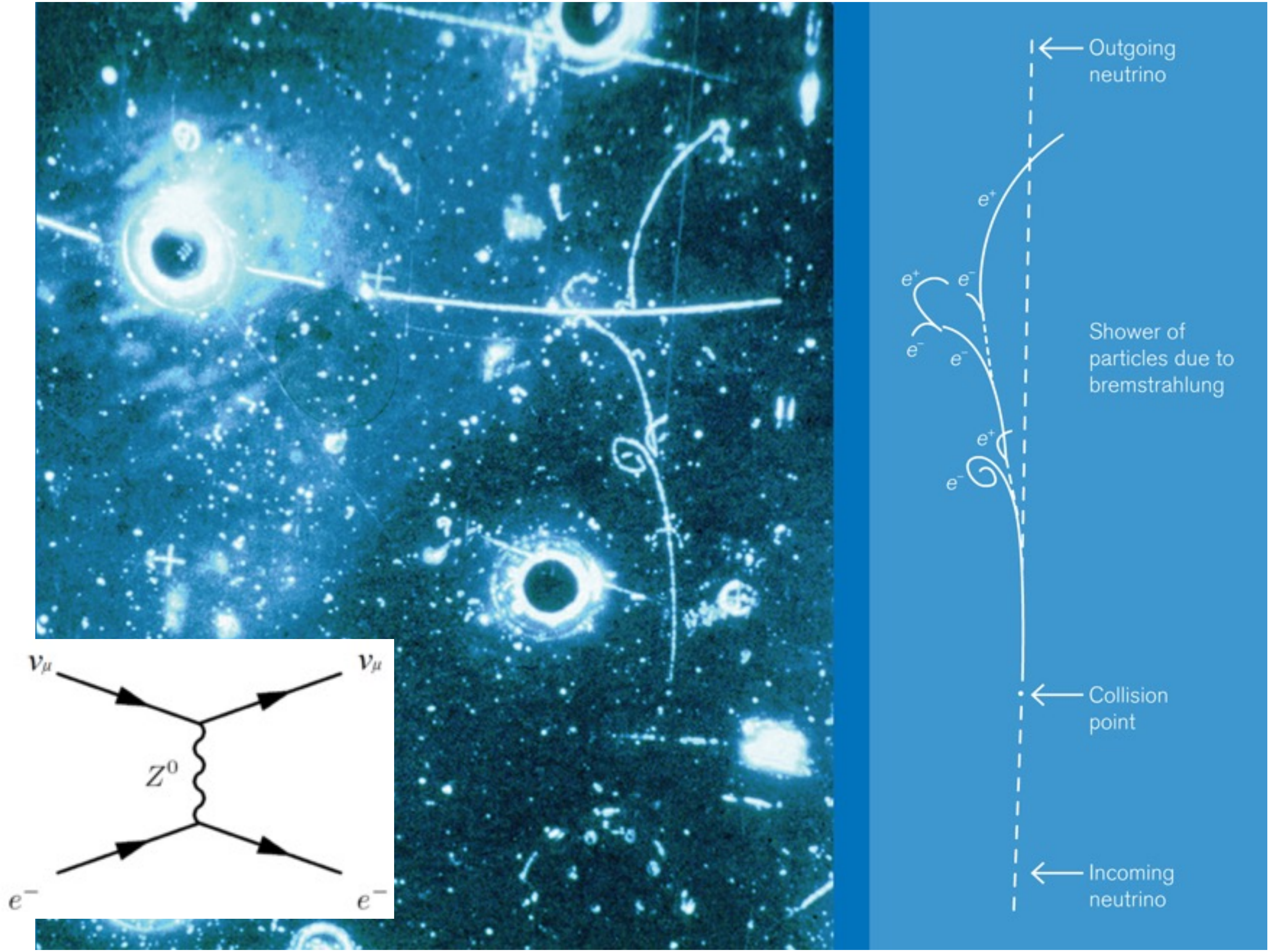
MAN CDC
MAN . CDC



ν_μ
ν_μ
Z^0
e^-
e^-
Outgoing neutrino
e^+
e^+
e^-
e^-
e^-
e^+
e^-
Shower of particles due to bremstrahlung
Collision point
Incoming neutrino

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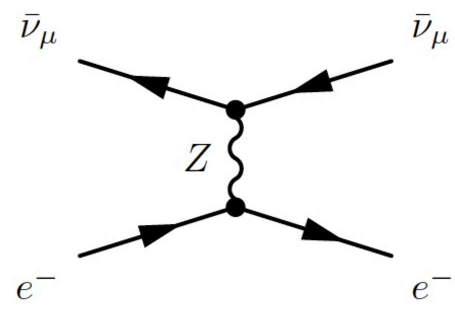
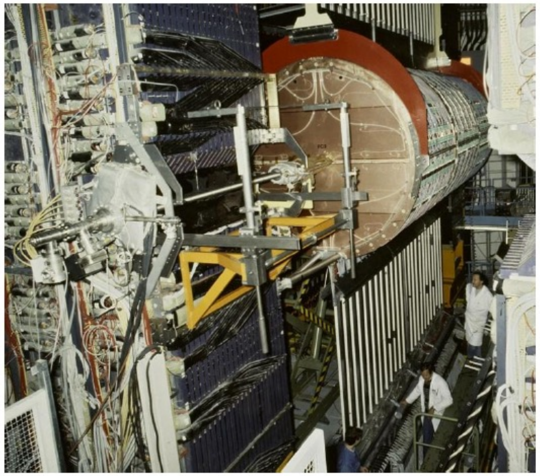
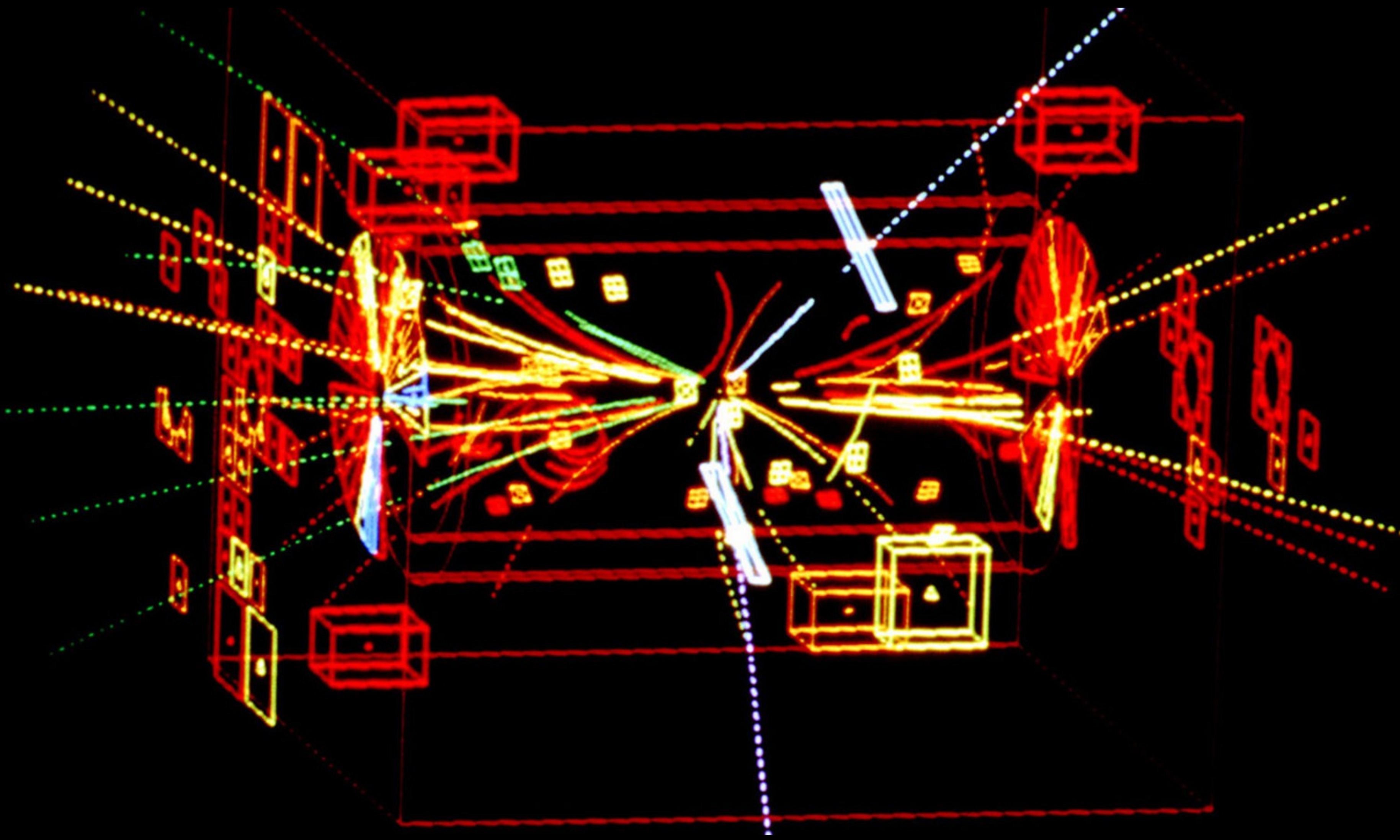


- **Direct Observation of $W^\pm$ and Z (1983)**
  First direct observation in $p\bar{p}$ collisions at $\sqrt{s} = 540\ \mathrm{GeV}$ via decays into leptons

$$p\bar{p} \to W^\pm + X \quad \hookrightarrow e^\pm \nu_e, \mu^\pm \nu_\mu \qquad p\bar{p} \to Z + X \quad \hookrightarrow e^+ e^-, \mu^+ \mu^-$$

UA1 Experiment at CERN
Used Super Proton Synchrotron
(now part of LHC!)





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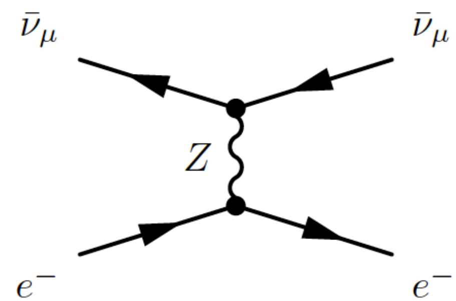

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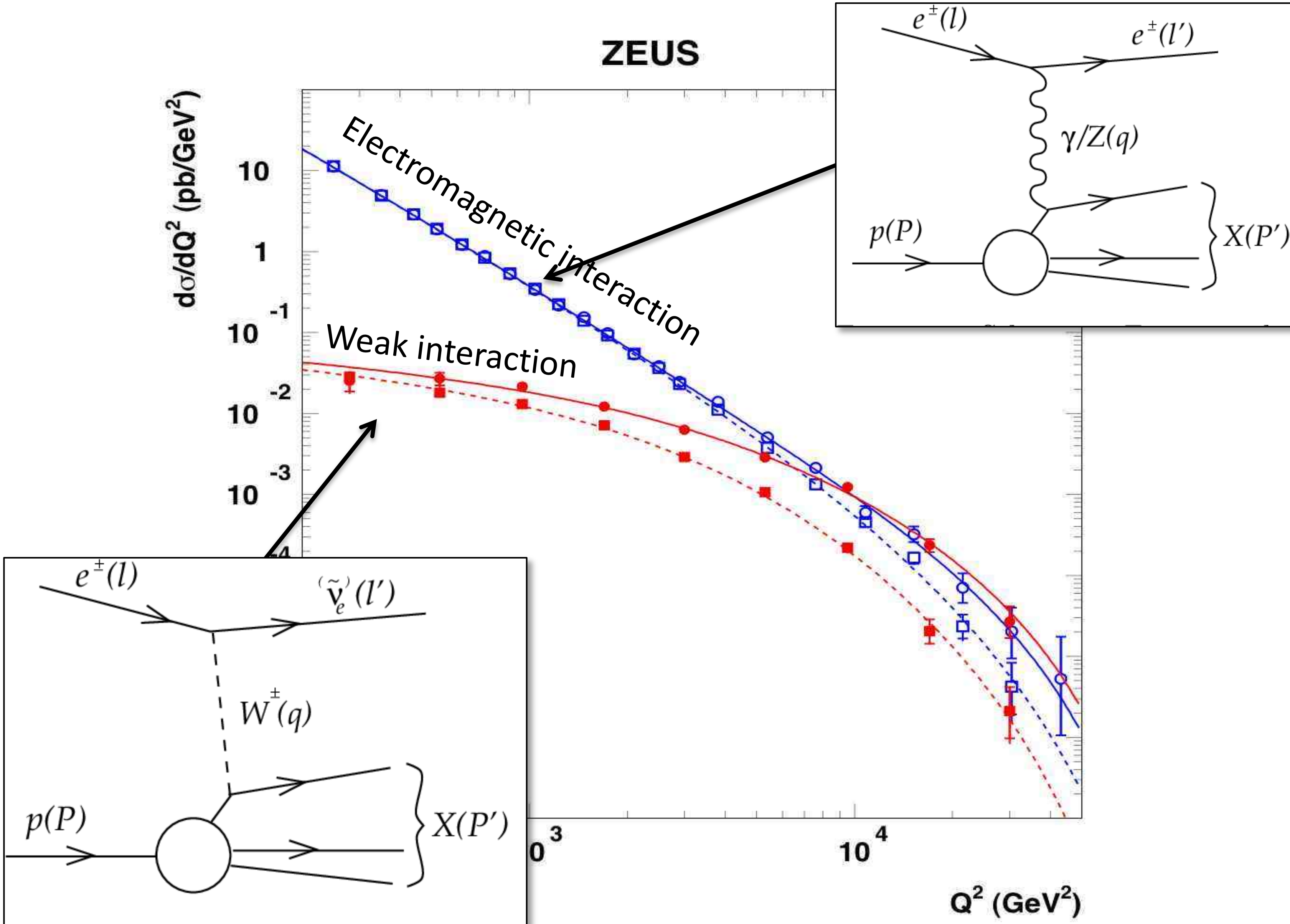
$$p\bar{p} \to W^\pm + X \qquad\qquad p\bar{p} \to Z + X$$
$$\hookrightarrow e^\pm \nu_e, \mu^\pm \nu_\mu \qquad\qquad \hookrightarrow e^+e^-, \mu^+\mu^-$$

- **Precision Measurements of the Standard Model (1989-2000)**
  LEP e^+e^- collider provided many precision measurements of the Standard Model.

- Wide variety of different processes consistent with GWS model predictions and measure same value of

$$\sin^2\theta_W = 0.23113 \pm 0.00015 \qquad\qquad \theta_W \sim 29^\circ$$


ZEUS
dσ/dQ² (pb/GeV²)
10
1
10⁻¹
10⁻²
10⁻³
Electromagnetic interaction
Weak interaction
Q² (GeV²)
10⁴
e±(l)
e±(l′)
γ/Z(q)
p(P)
X(P′)
W±(q)

Now for the problems...

Problem 1: Mass of elementary particles and gauge bosons

What if we add a photon mass term to the QED Lagrangian?

$$\mathcal{L}_{QED} = \bar{\psi}(i\gamma^\mu\partial_\mu - m_e)\psi - e\bar{\psi}\gamma^\mu\psi A_\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_\gamma A_\mu A^\mu$$

To keep the Lagrangian gauge invariant (against a local $\mathrm{U}(1)$ local phase transformation) the photon field transforms as:

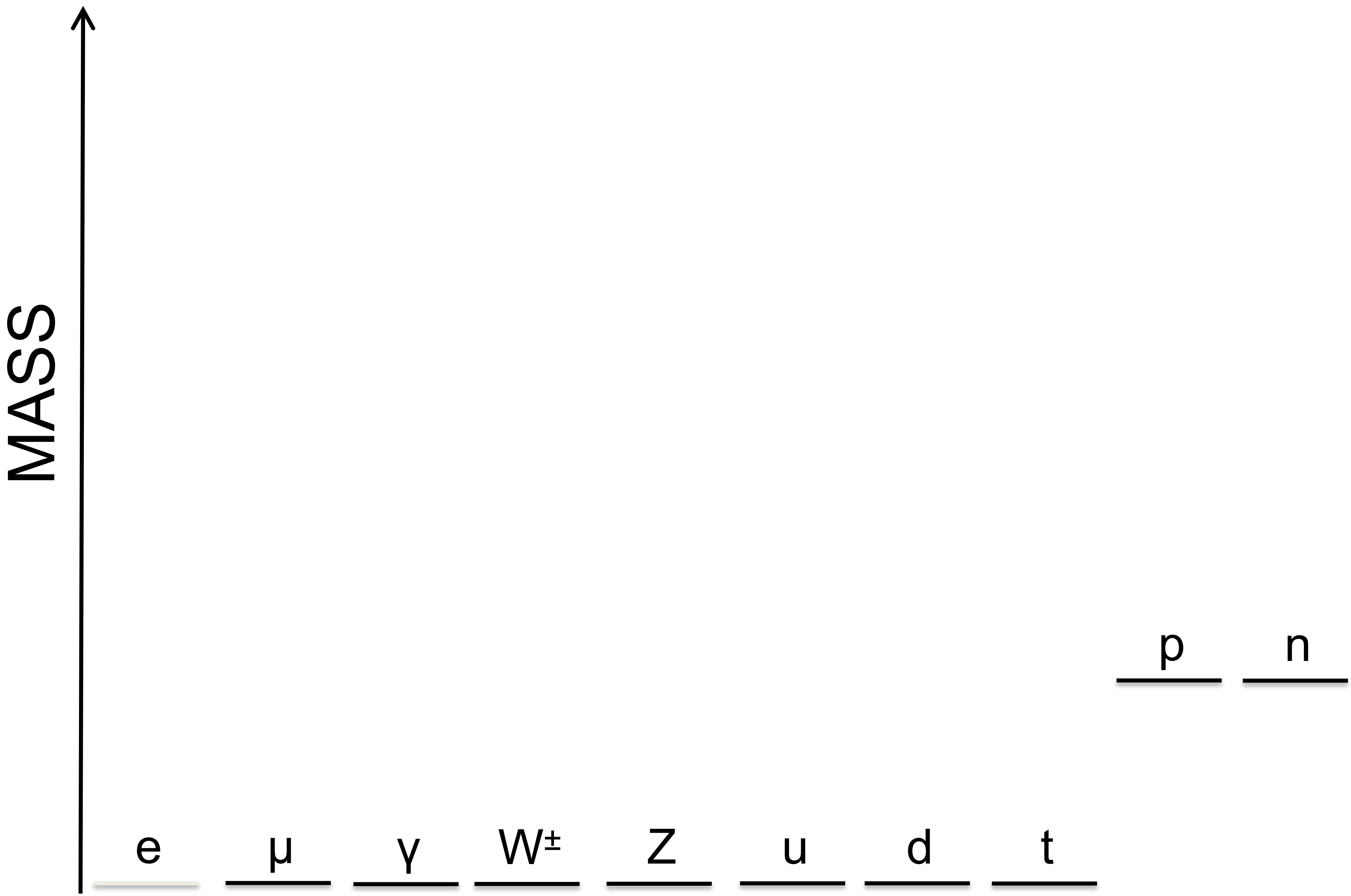
$$A_\mu \to A'_\mu = A_\mu - \partial_\mu\chi$$

But the A^μ mass term breaks the Lagrangian invariance:

$$\frac{1}{2}m_\gamma A_\mu A^\mu \to \frac{1}{2}m_\gamma(A_\mu - \partial_\mu\chi)(A^\mu - \partial^\mu\chi) \neq \frac{1}{2}m_\gamma A_\mu A^\mu$$

For the $\mathrm{SU}(2)_L$ gauge symmetry transformations of the **weak interaction** the fermion mass term $m_e\overline{\psi}\psi$ also breaks invariance!

It should not work…



Problem 2:

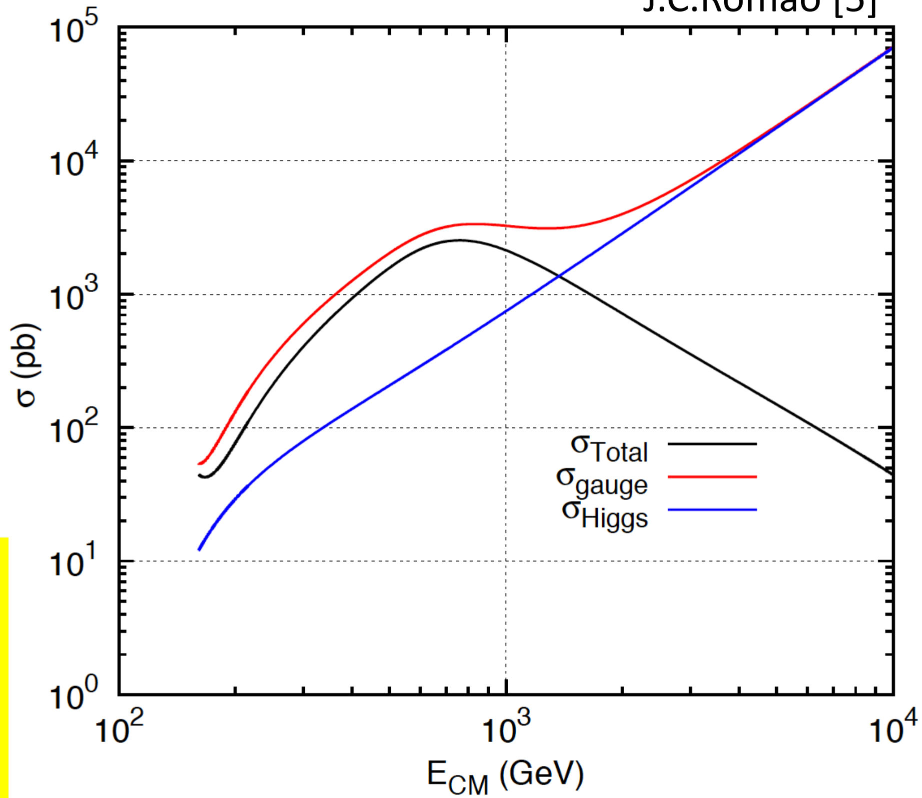
Longitudinal gauge-boson scattering

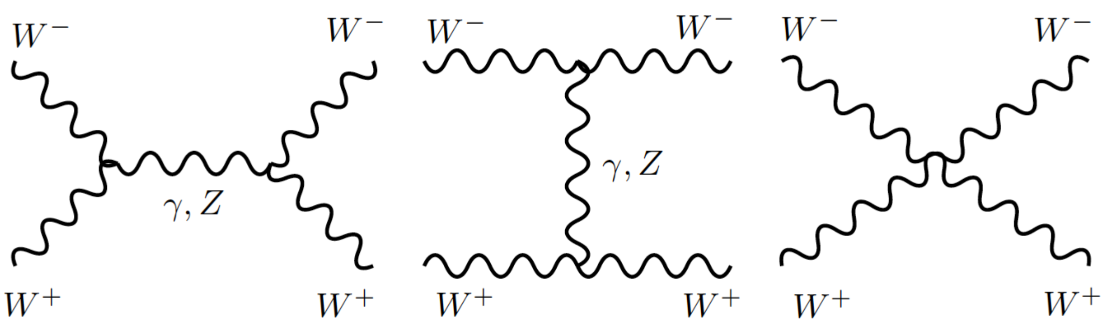
In the absence of the Higgs, some processes have cross sections that grow with the centre of mass energy of the collision… i.e. breaks unitarity!

The Higgs regulates the cross section through negative interference

Bottom line: **the SM (without the Higgs mechanism) results in wrong calculations and breaks down for massive particles**

J.C.Romão [5]





Feynman diagrams contributing to longitudinal WW scattering

The Higgs Mechanism

Robert Brout (1928 – 2011)

Peter Higgs (b. 1929)

François Englert
(b. 1932)

- Introduce a SU(2) doublet of spin-0 complex fields

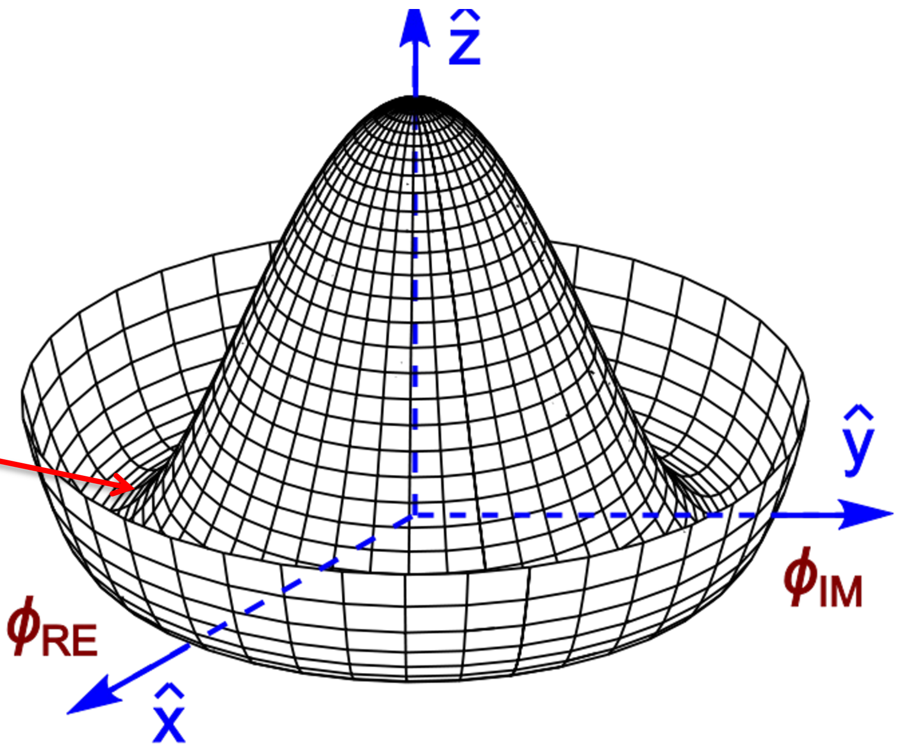
$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi 4 \end{pmatrix}$$

- New Lagrangian term: $\mathcal{L} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi)$

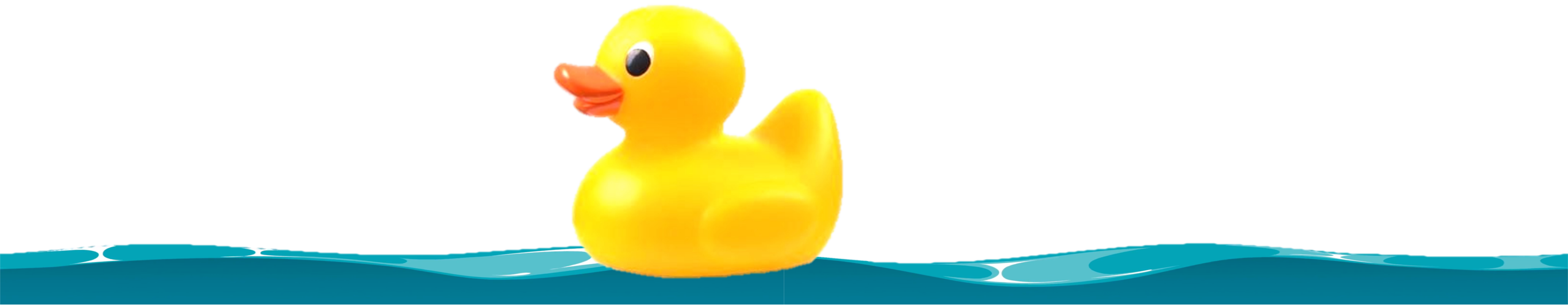
- With a potential $V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$

- For $\lambda>0$, $\mu^2>0$ the potential has a minimum at the origin
- For $\lambda>0$, $\mu^2<0$ the potential has an infinite number of minima at:

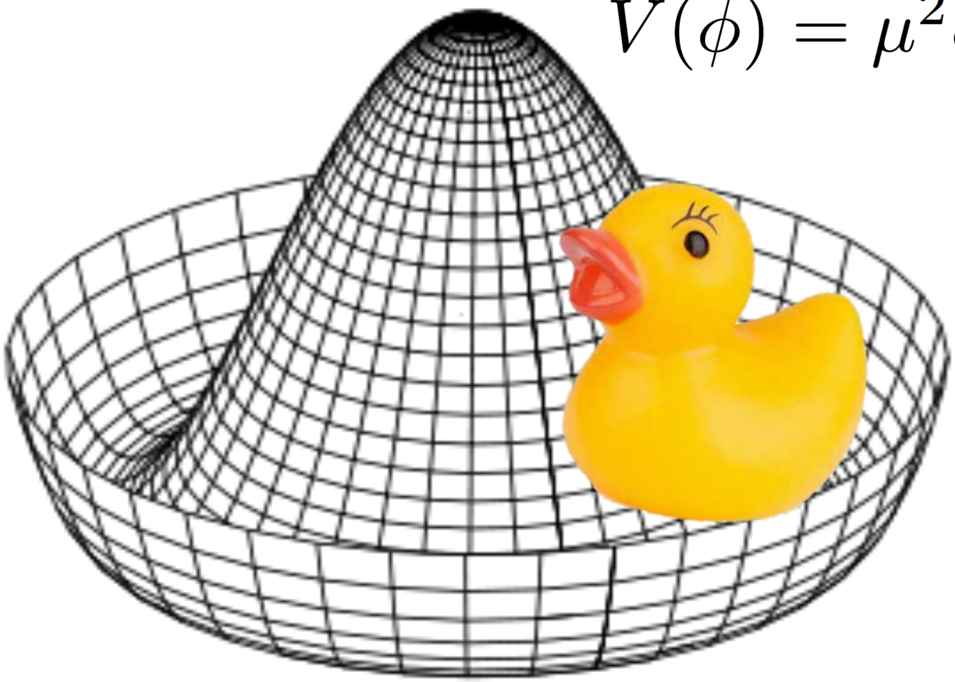
$$|\phi| = \frac{v}{\sqrt{2}} = \sqrt{-\frac{\mu^2}{2\lambda}}$$



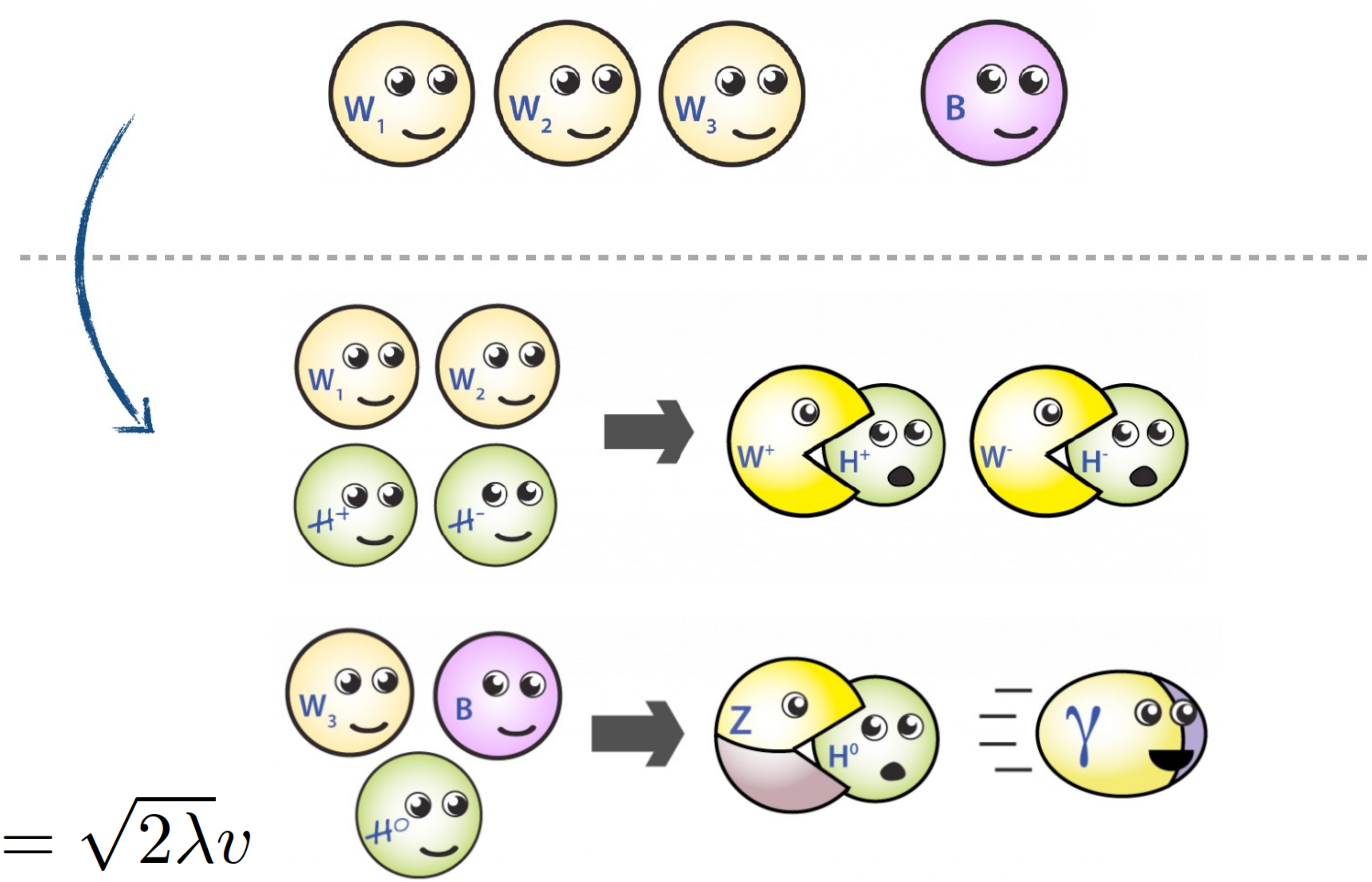
The choice of vacuum (lowest energy state of the field) breaks the symmetry of the Lagrangian



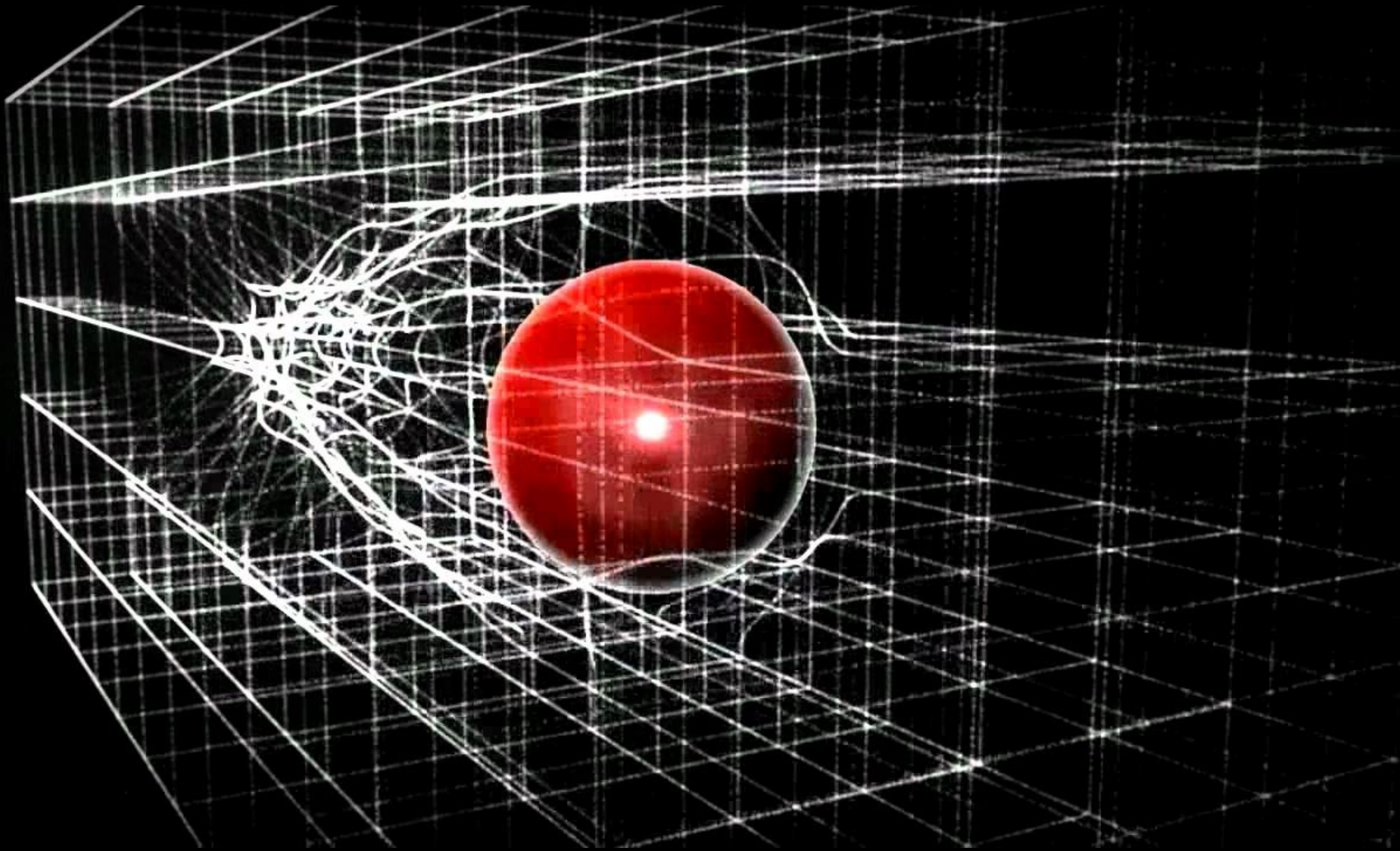
$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$



EWK Symmetry Breaking in Pictures



$$m_h = \sqrt{2\lambda}v$$



Higgs Properties

- Mass $m_h = \sqrt{2\lambda}v$
- Spin: 1 degree of freedom => 0
- Couplings:
- To gauge bosons

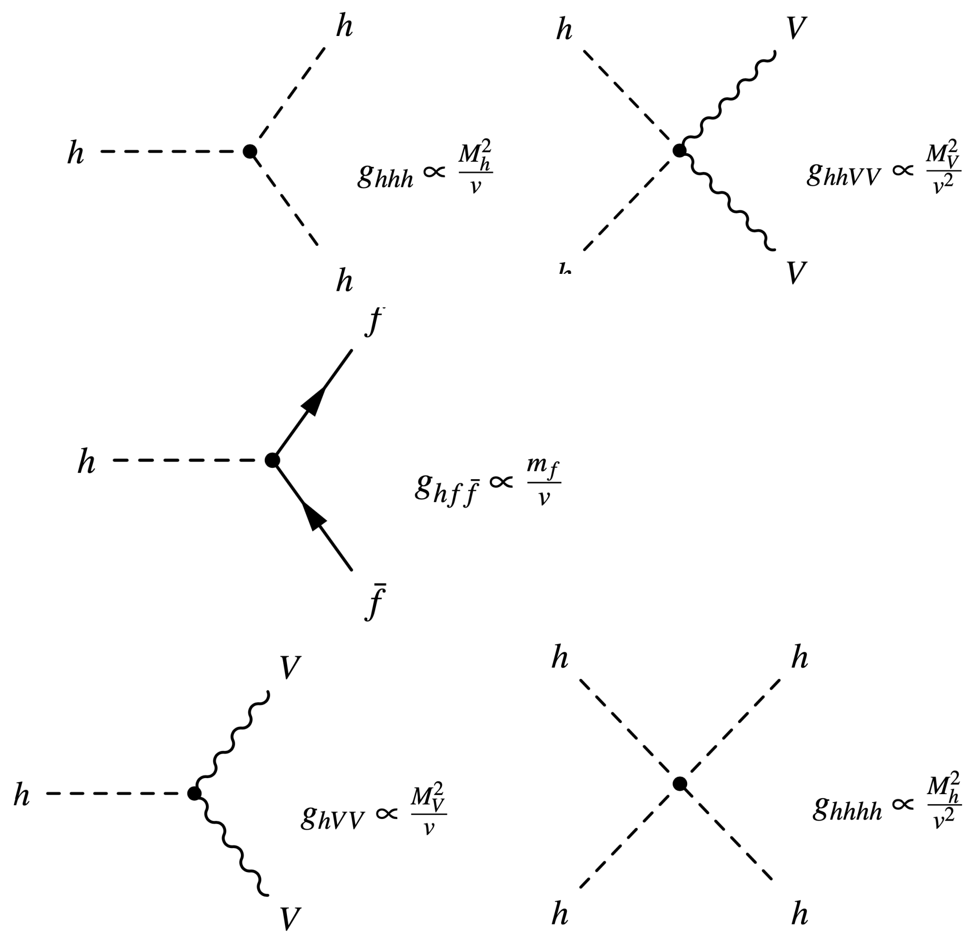
$$g_{hVV} \propto \frac{M_V^2}{v} \quad g_{hhVV} \propto \frac{M_V^2}{v^2}$$

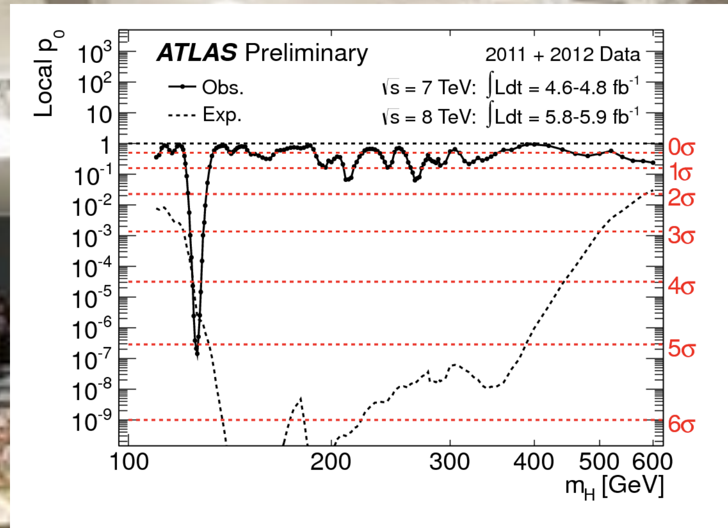
- Yukawa couplings to fermions

$$g_{hf\bar{f}} \propto \frac{m_f}{v}$$

- Self-couplings

$$g_{hhh} \propto \frac{M_h^2}{v} \quad g_{hhhh} \propto \frac{M_h^2}{v^2}$$





The Long Way to Discovery

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

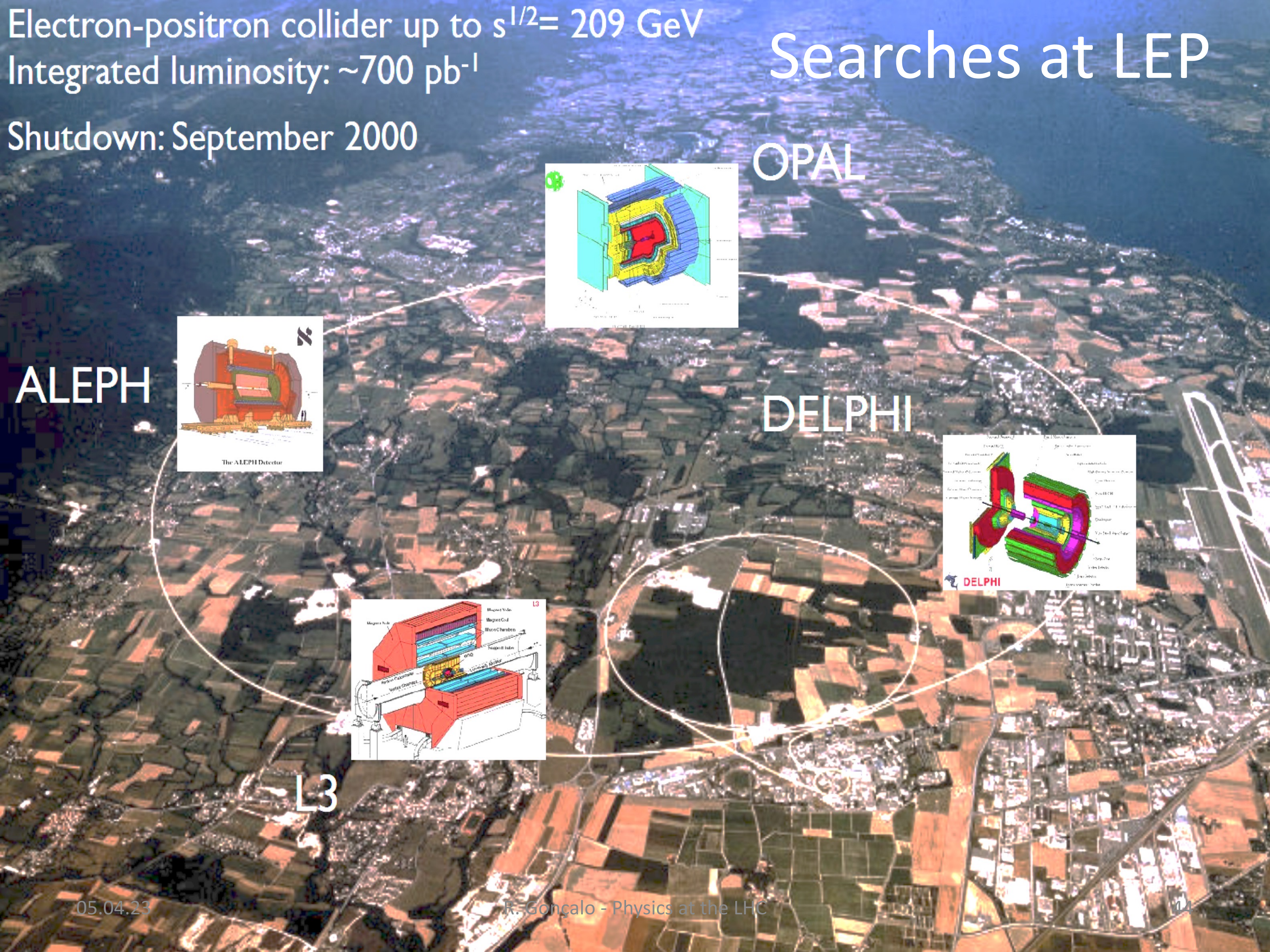
Received 7 November 1975

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3),4)] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Searches at LEP

Electron-positron collider up to $s^{1/2}$= 209 GeV
Integrated luminosity: ~700 pb^{-1}

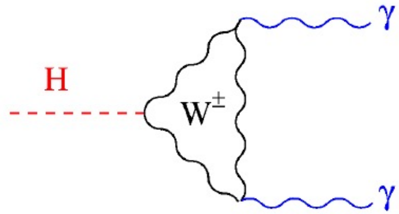
Shutdown: September 2000



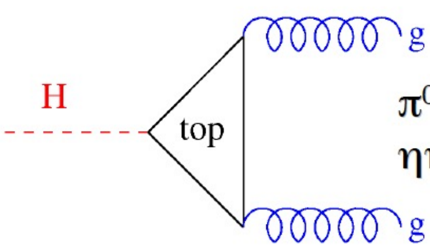
Low-mass searches at LEP

The decay branching ratios depend only on m_H:

- ❑ $m_H < 2m_e$: $H \to \gamma\gamma$ + large lifetime;



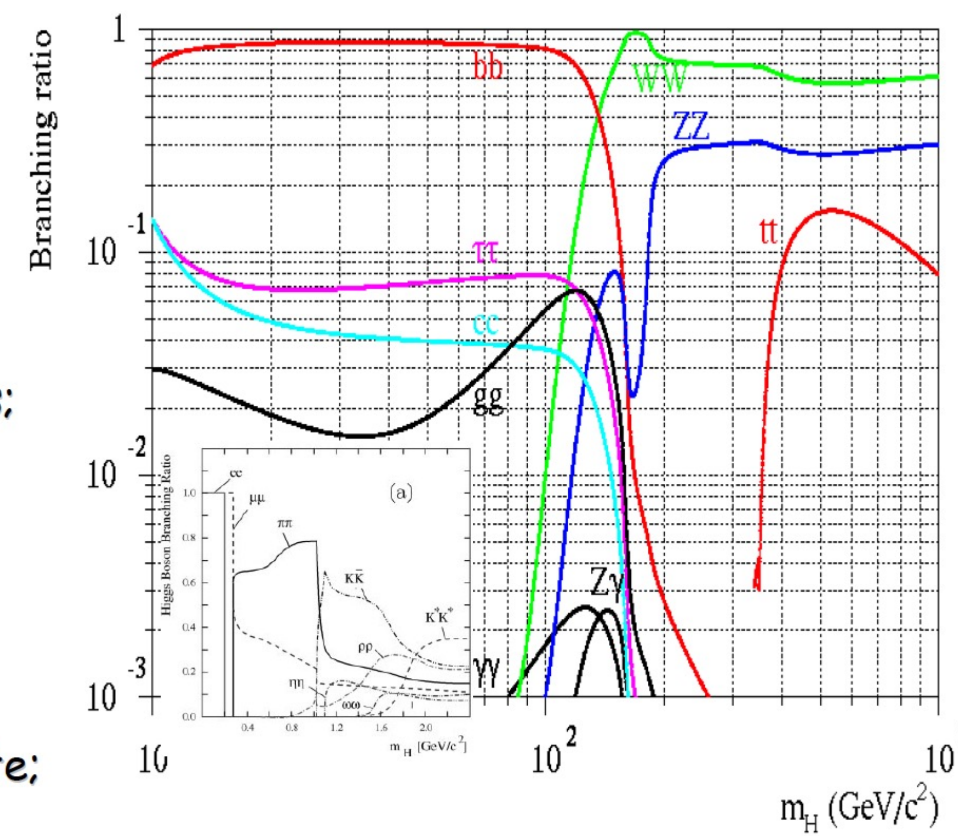
- ❑ $m_H < 2m_\mu$: $H \to e^+e^-$ dominates;
- ❑ $m_H < 2m_\pi$: $H \to \mu^+\mu^-$ dominates;
- ❑ $m_H < 3$ - 4 GeV: $H \to gg$ dominates;



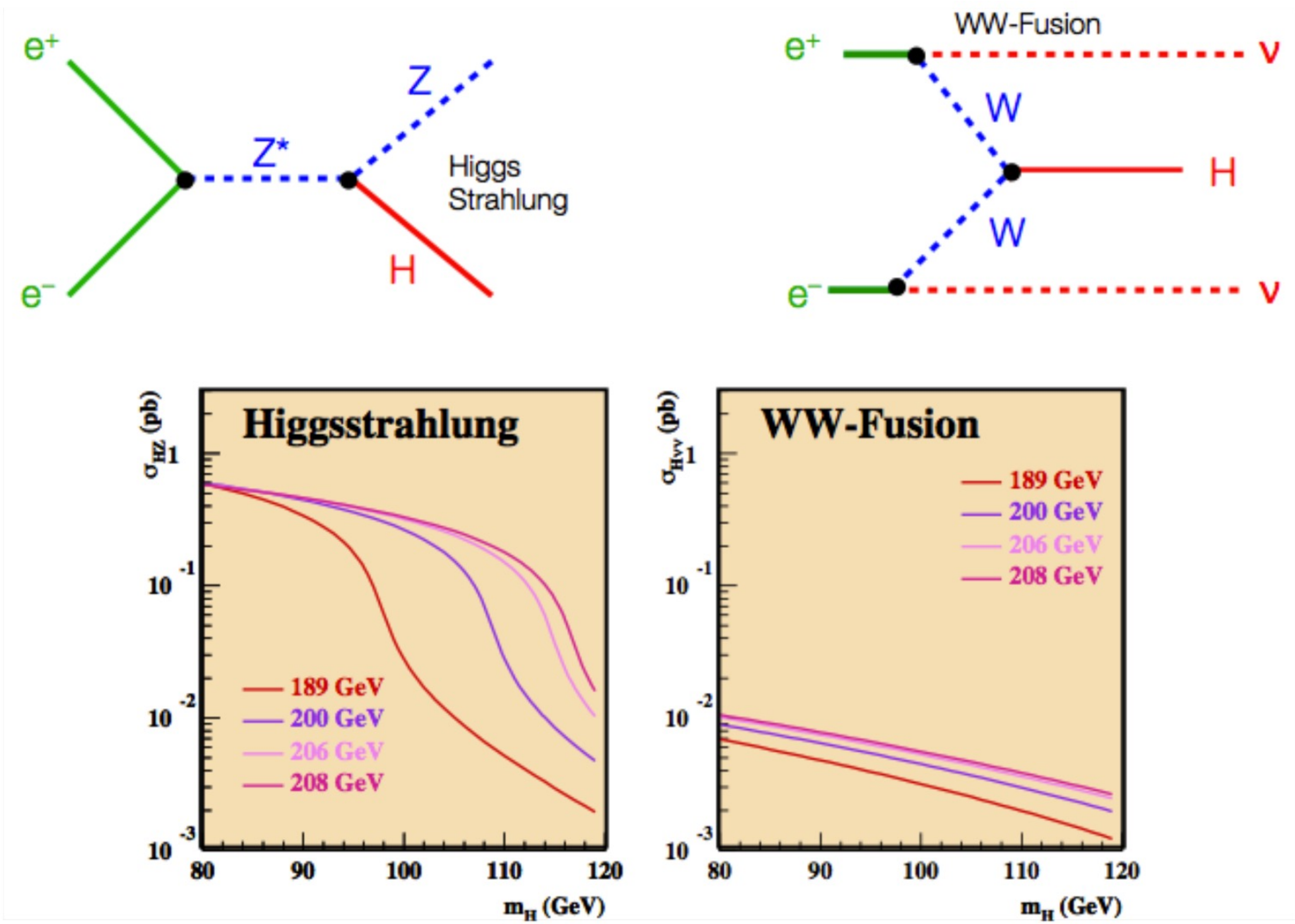
$\pi^0\pi^0$, $\pi^+\pi^-$, KK, $\eta\eta$, ... etc

- ❑ $m_H < 2m_b$: $H \to \tau^+\tau^-$ and $c\bar{c}$ dominate;

- ❑ $m_H > 2m_b$ up to 1000 GeV/c^2:



Higher-mass Higgs production at LEP



Summary of all Higgs candidates found at LEP

Invariant mass of all candidates

In total 17 candidates selected

- 15.8 background events expected

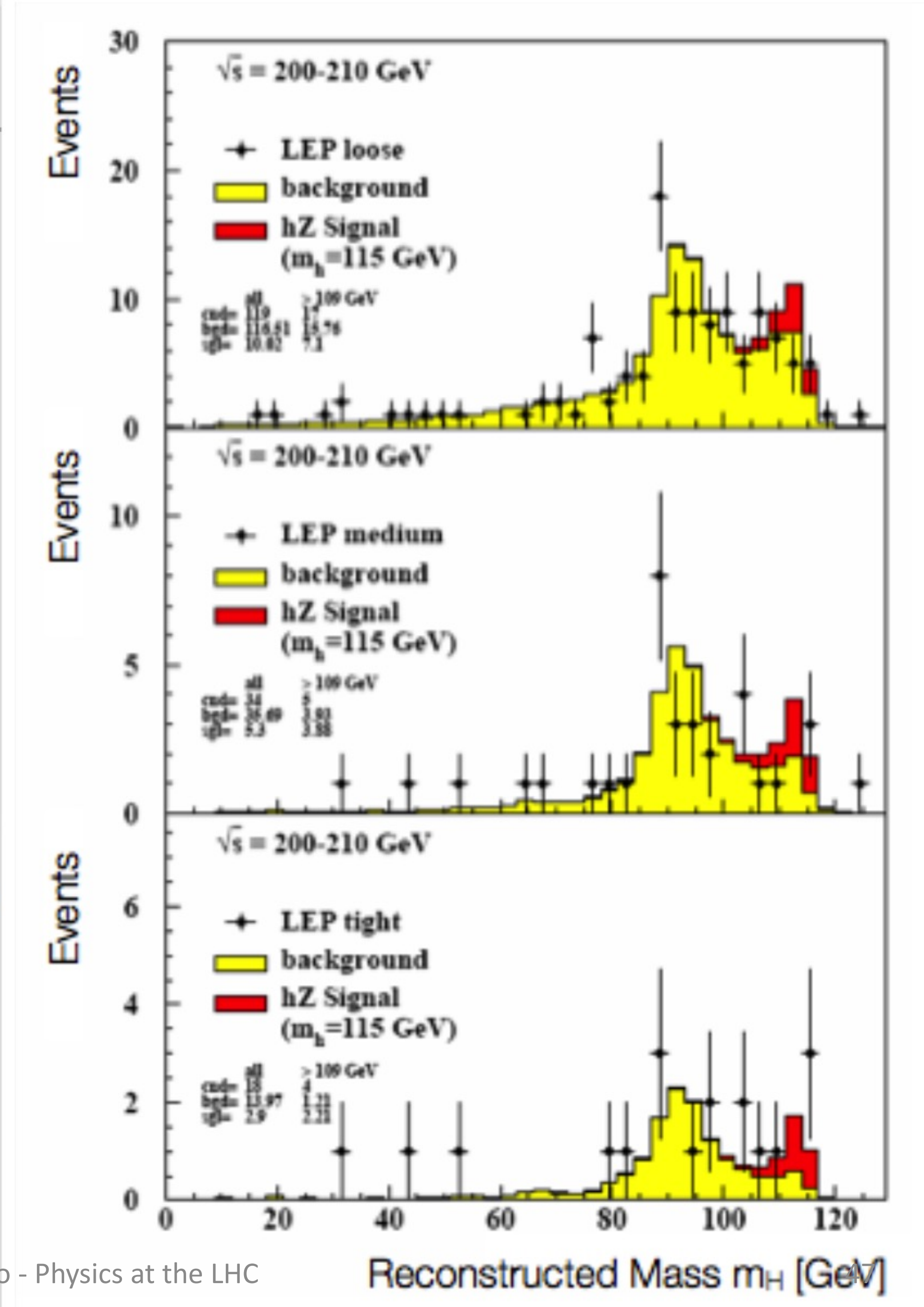
Expectation for m_H=115 GeV

- 8.4 events

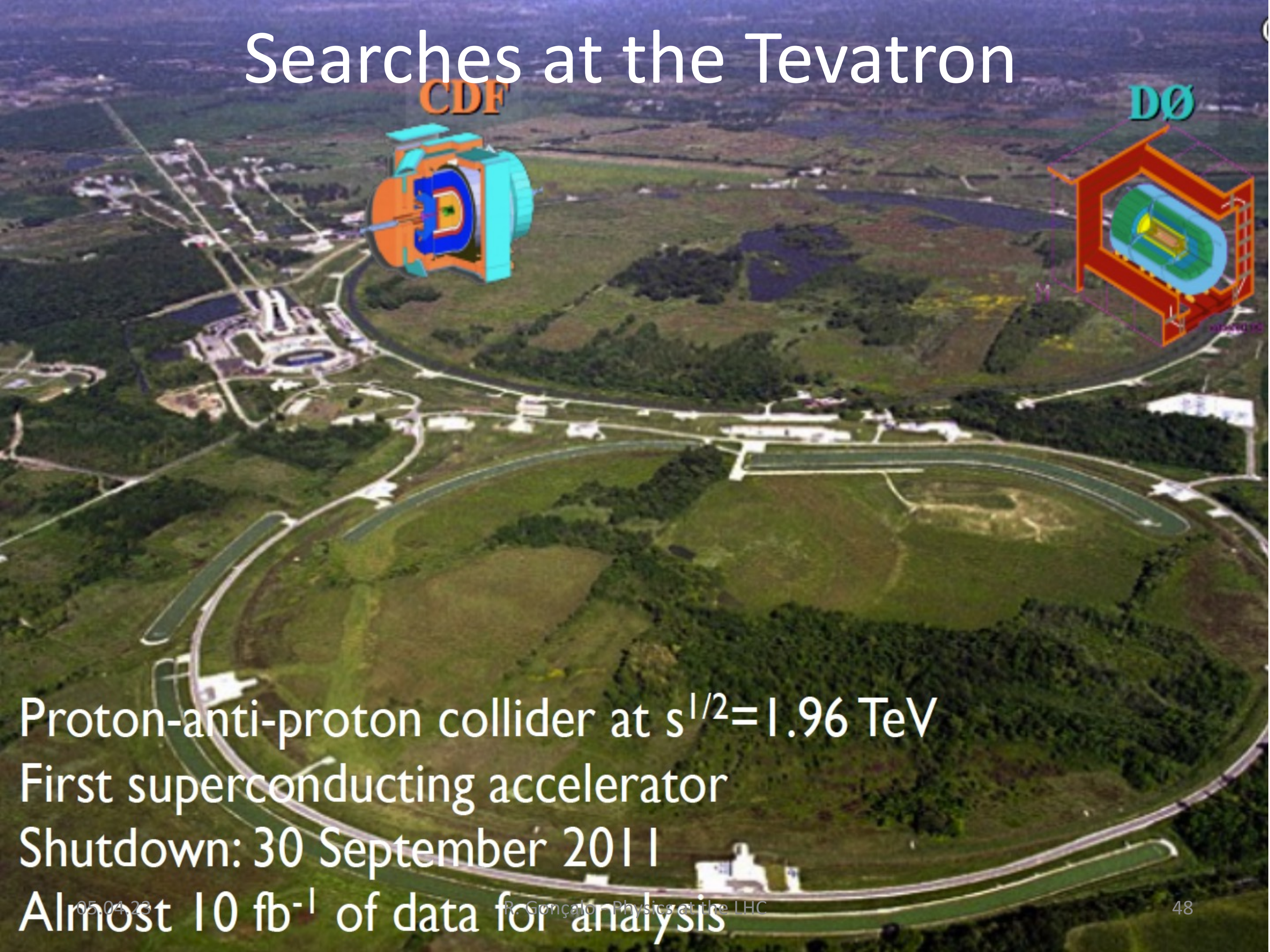
Corresponding excess was not observed

Final verdict from LEP

m_H>114.4 GeV @ 95% CL

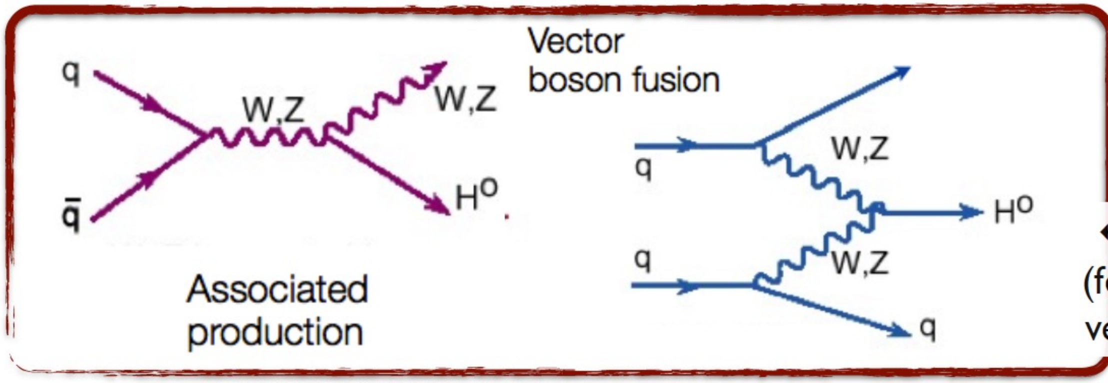


Searches at the Tevatron

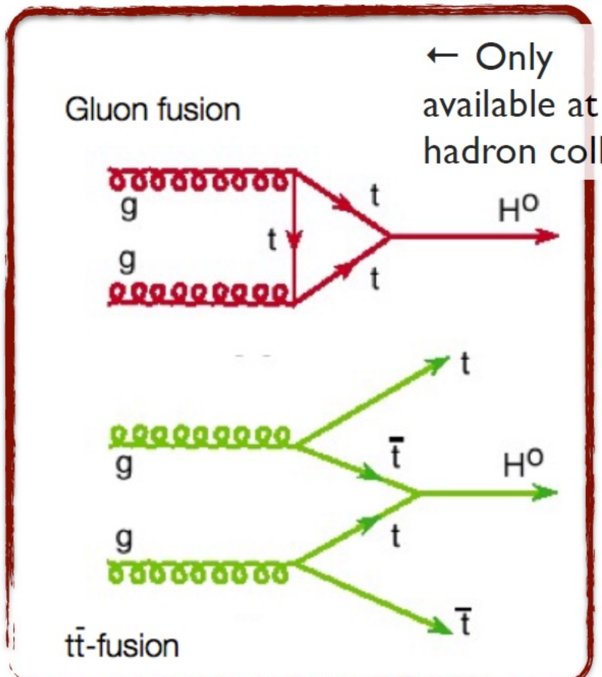


Proton-anti-proton collider at $s^{1/2}$=1.96 TeV
First superconducting accelerator
Shutdown: 30 September 2011
Almost 10 fb^{-1} of data for analysis

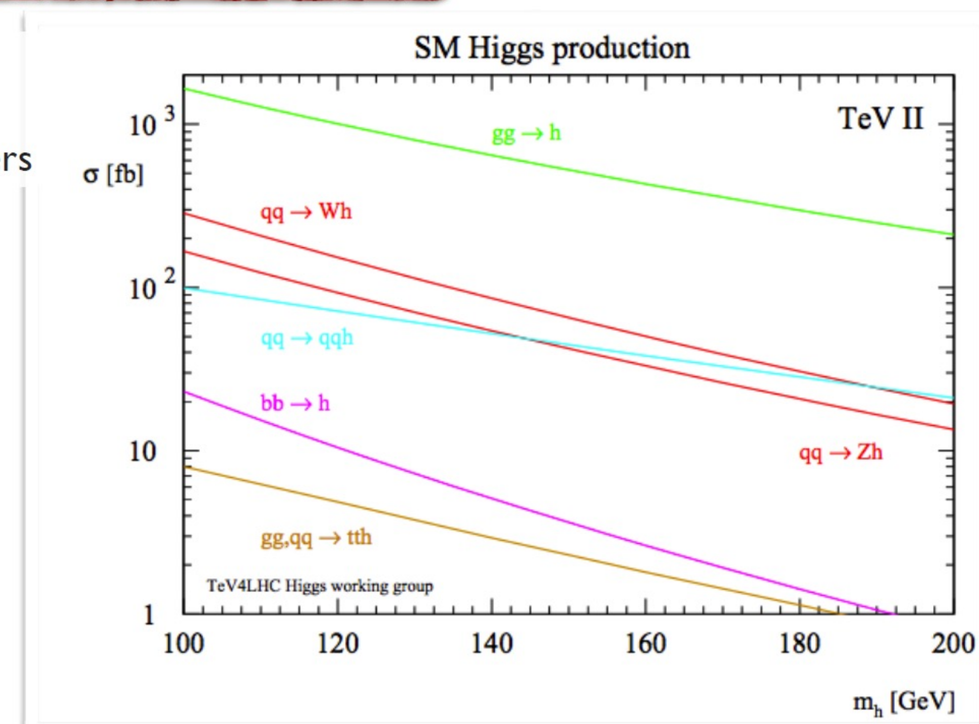
Higgs production at the Tevatron



← (fermion annihilation and vector boson scattering)

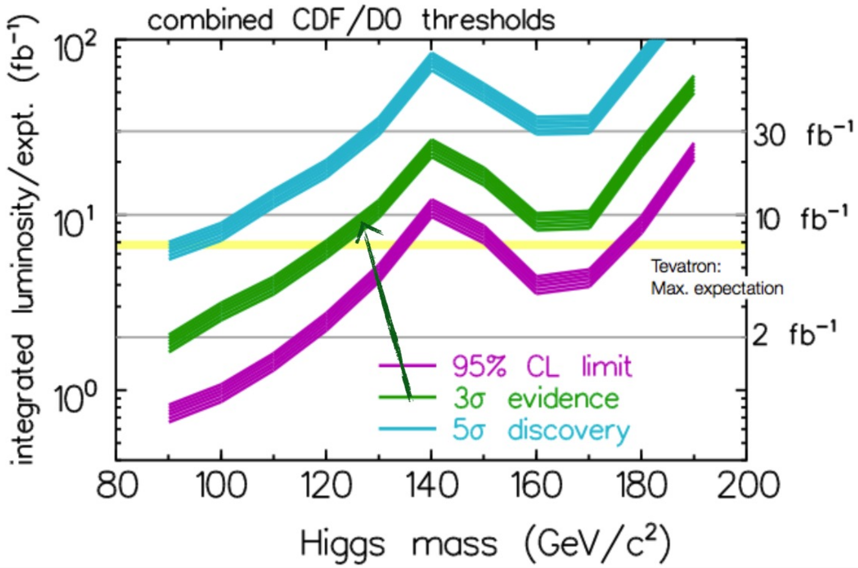


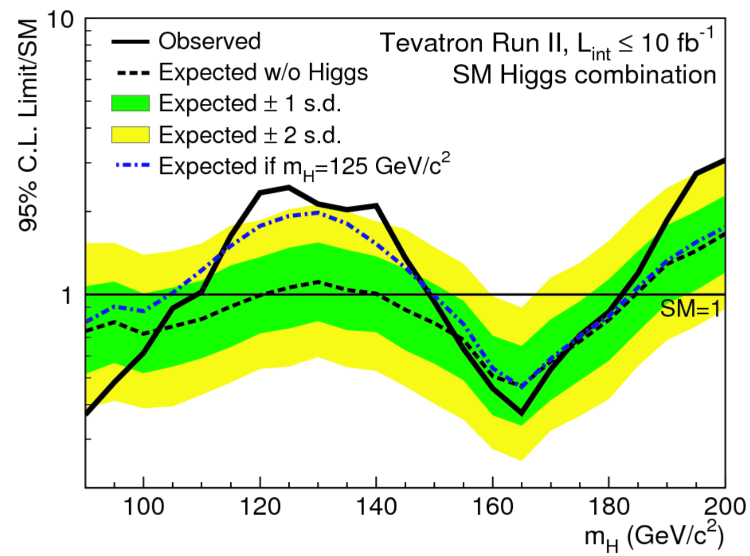
← Only available at hadron colliders



The final stand of the Tevatron

- By the end of its lifetime, the Tevatron had very sophisticated analyses of a huge number of channels
- By that time the LHC was collecting data and analysing it very fast
- The CDF and D0 experiments obtained an excess of around 3 standard deviations in the mass range $115<M_H<140$ GeV
- Not enough to claim discovery, but consistent with the LHC results

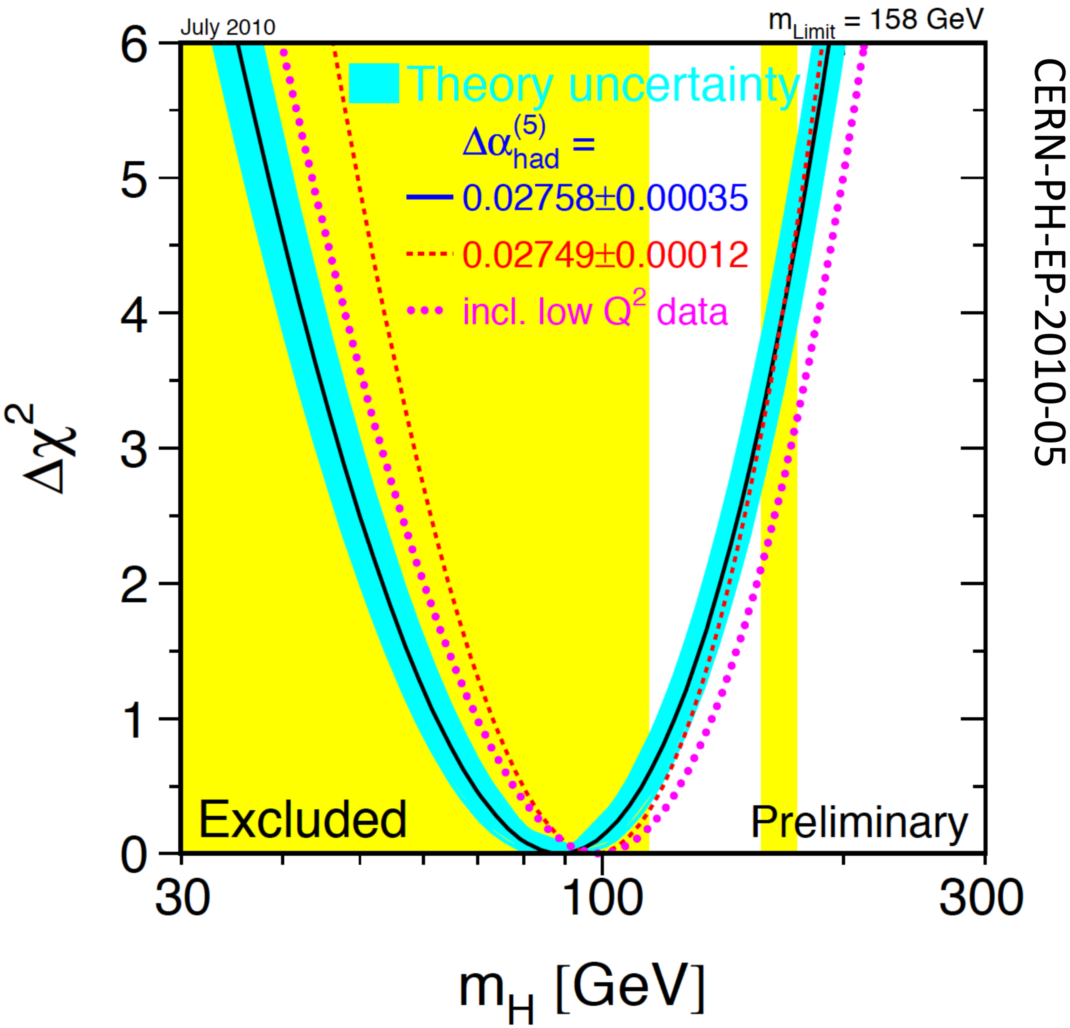




LEP and Tevatron: the Blue Band Plot

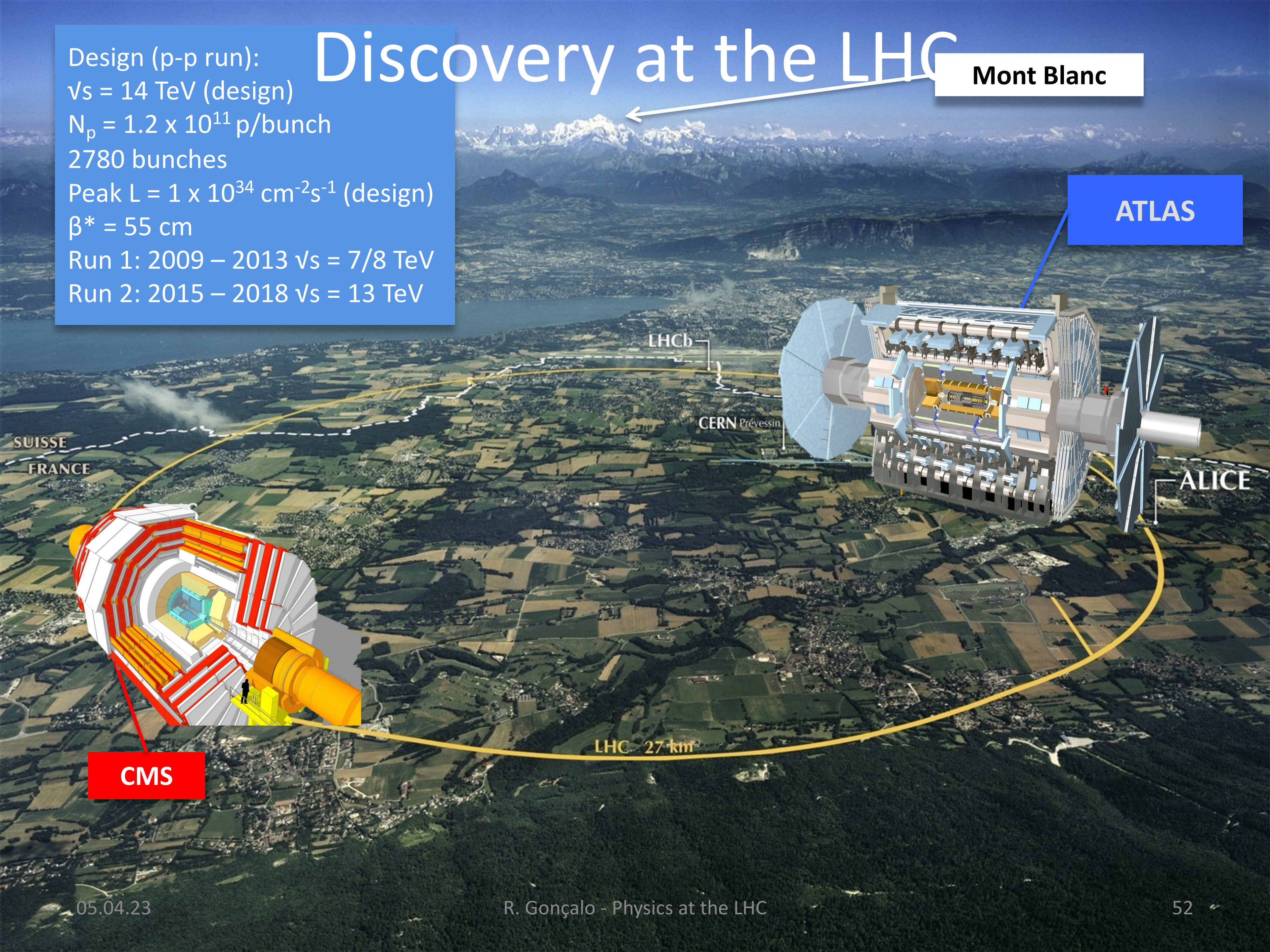
- Decades of searches in several experiments...

- By July 2010:
  - LEP+Tevatron+SLD limits
  - Higgs excluded for m_h<114.4 GeV at 95% CL
  - Plus between 158 and 175 GeV

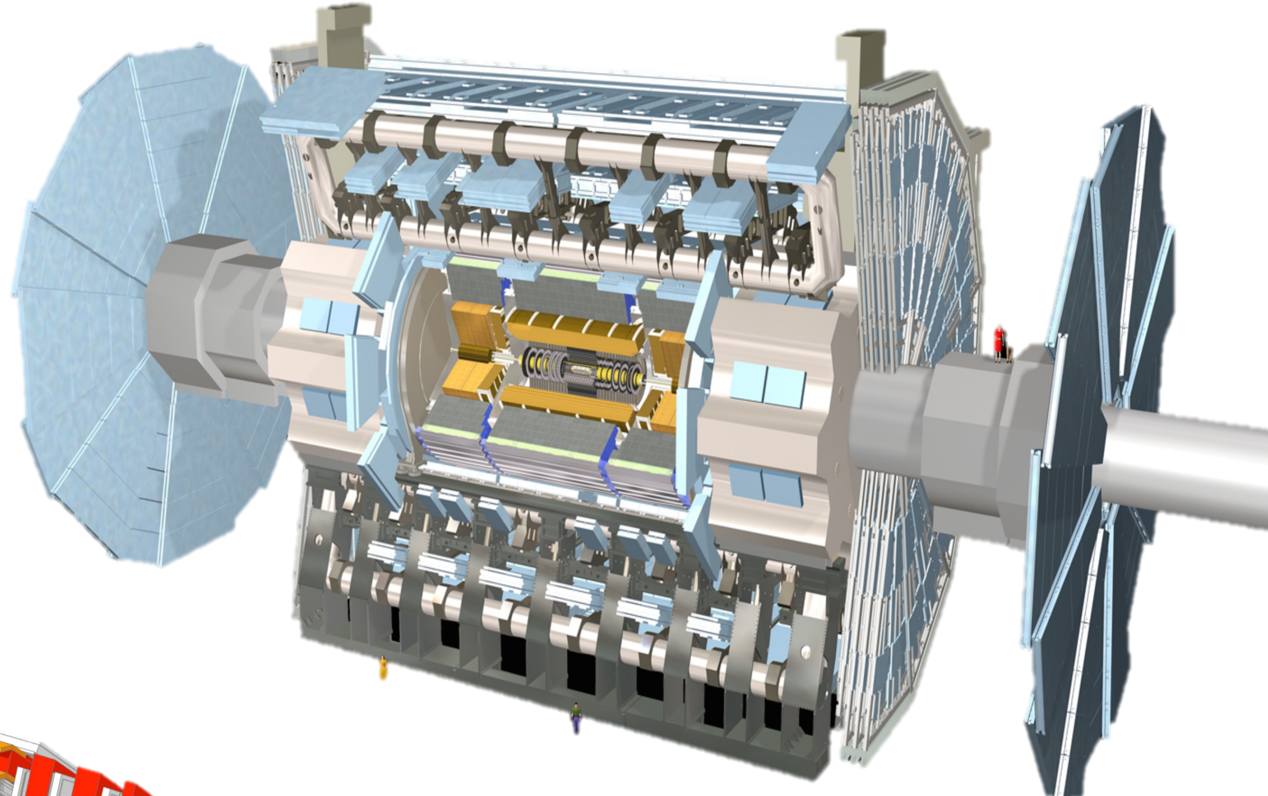


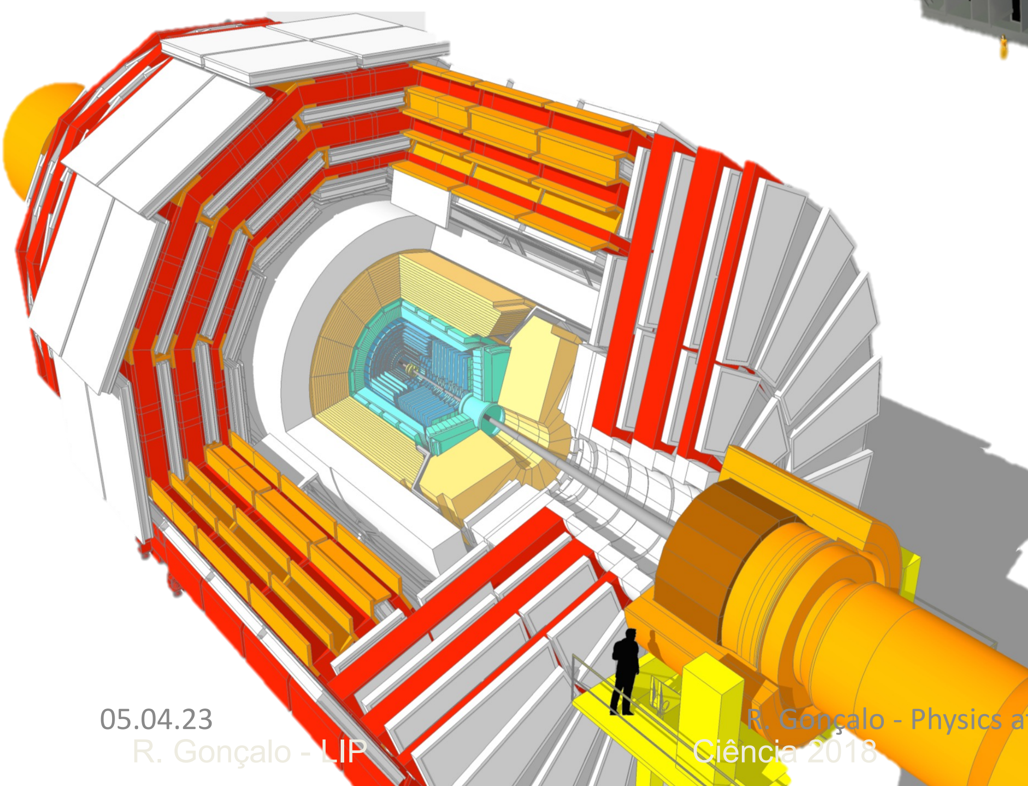
Discovery at the LHC

Design (p-p run):
$\sqrt{s}$ = 14 TeV (design)
$N_p = 1.2 \times 10^{11}$ p/bunch
2780 bunches
Peak $L = 1 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ (design)
$\beta^* = 55$ cm
Run 1: 2009 – 2013 $\sqrt{s}$ = 7/8 TeV
Run 2: 2015 – 2018 $\sqrt{s}$ = 13 TeV

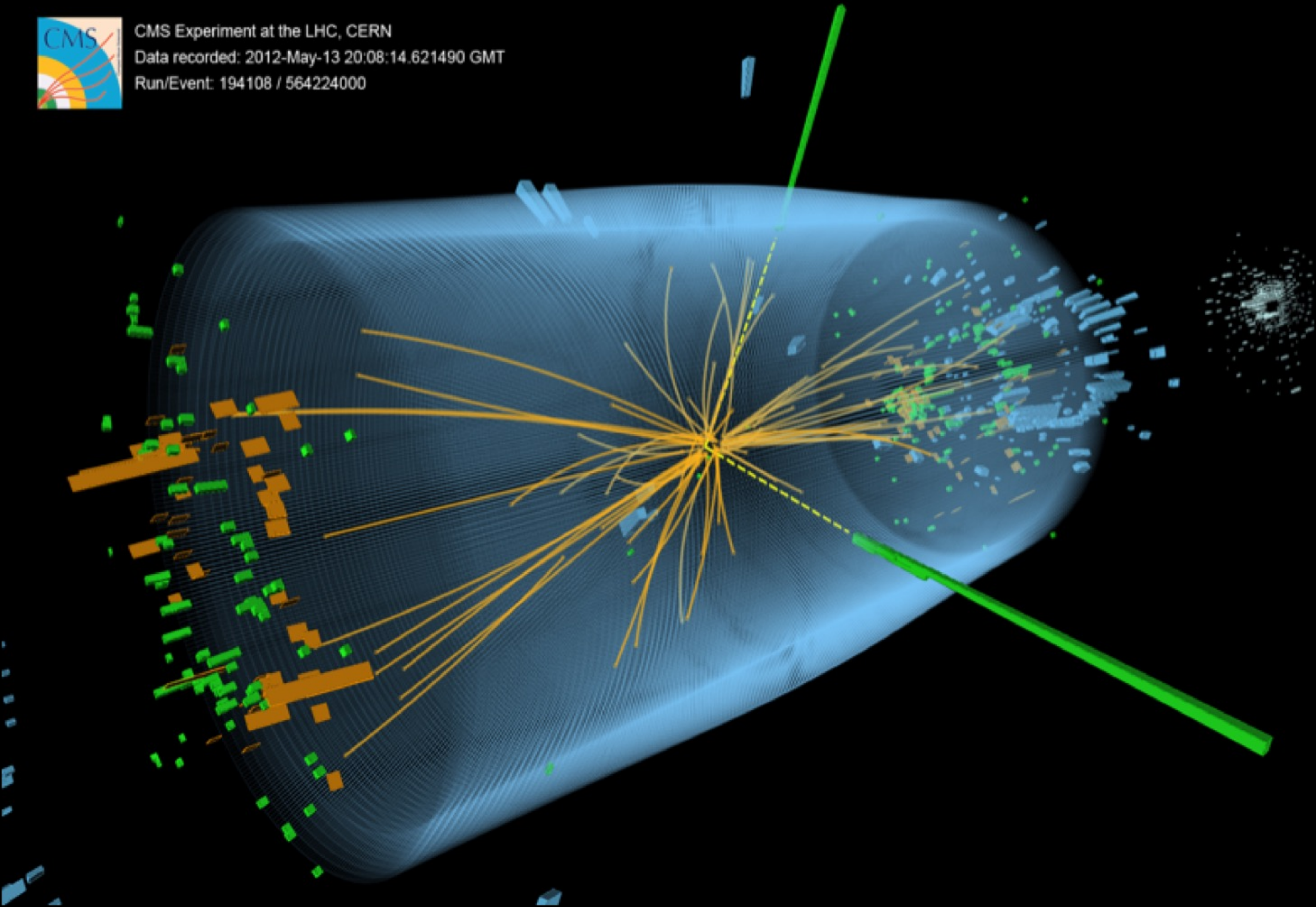


ATLAS
3000 colaboradores
175 institutos de 38 países
L = 44 m, ∅ ≈ 25 m, 7 000 t



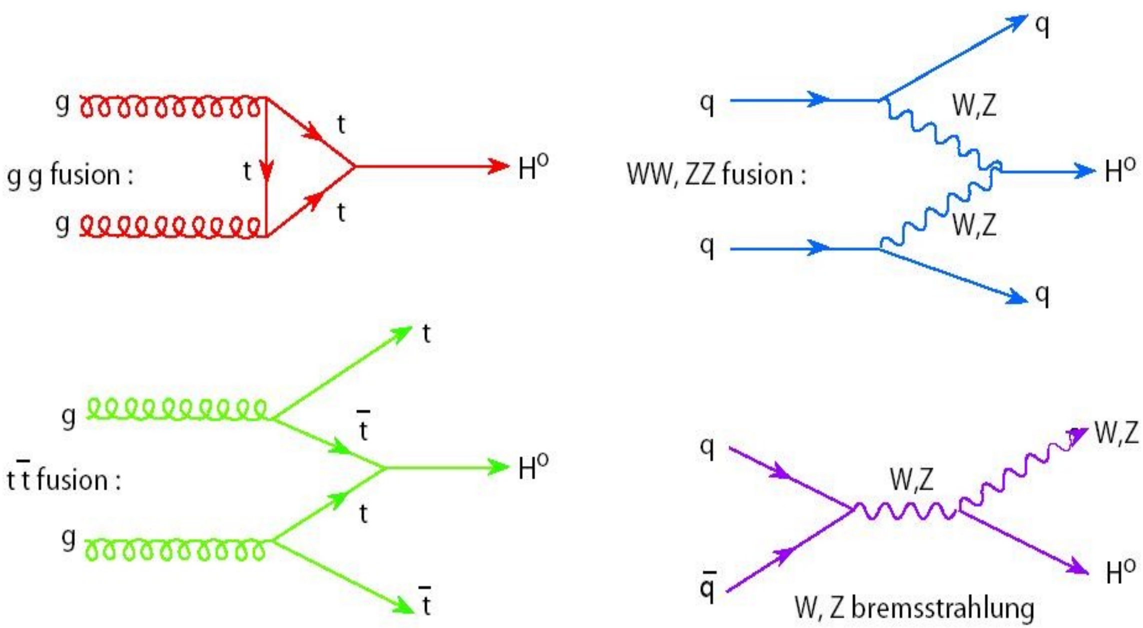


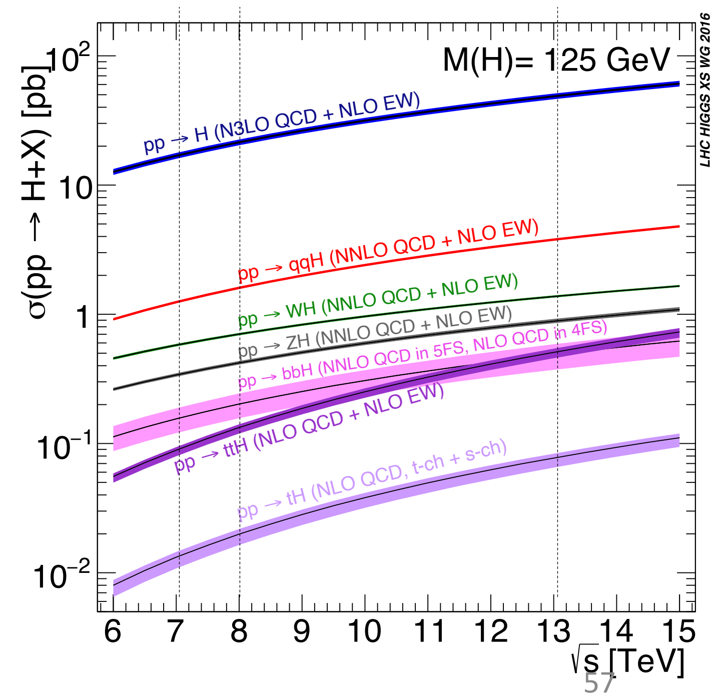
CMS
3800 colaboradores
199 institutos de 43 países
L = 22 m, ∅ ≈ 15 m, 14 000 t


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

Higgs @ the LHC

- Many different production and decay mechanisms
  - Span 3 orders of magnitude in cross section and branching ratio
  - Some very clean decays with low BR (γγ, 4l)
  - Other very difficult with higher rates (bb, WW, ττ,...)
- Access Higgs properties through combination of different channels





Higgs @ the LHC

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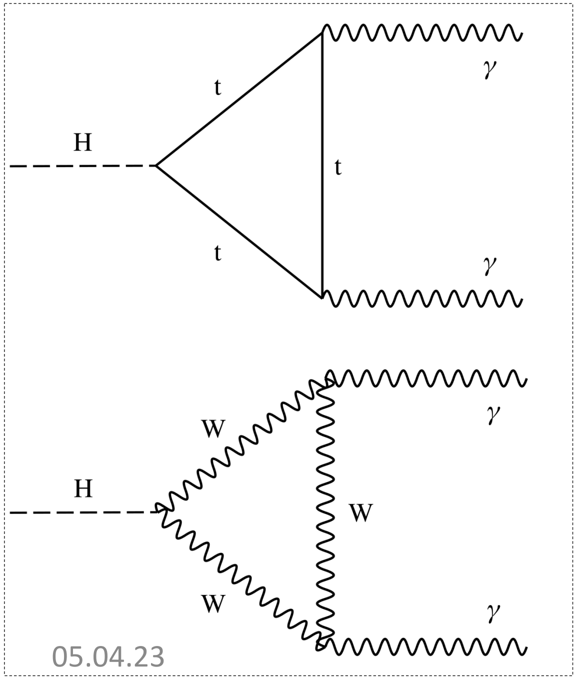
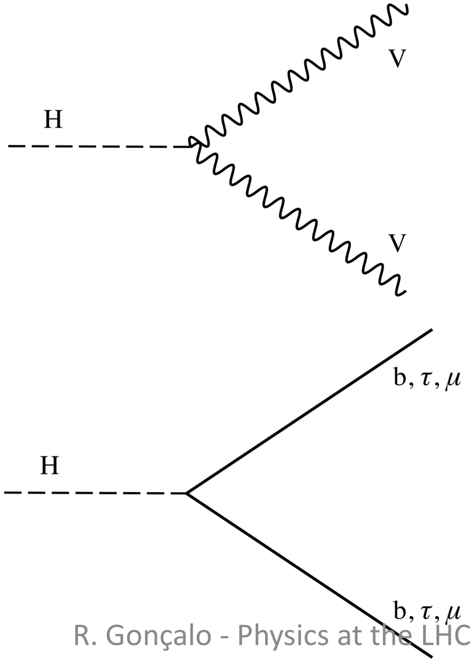
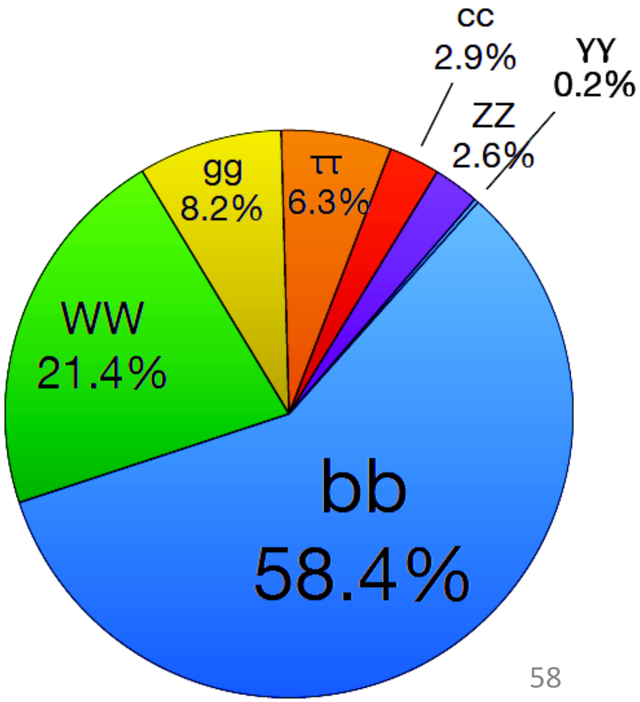
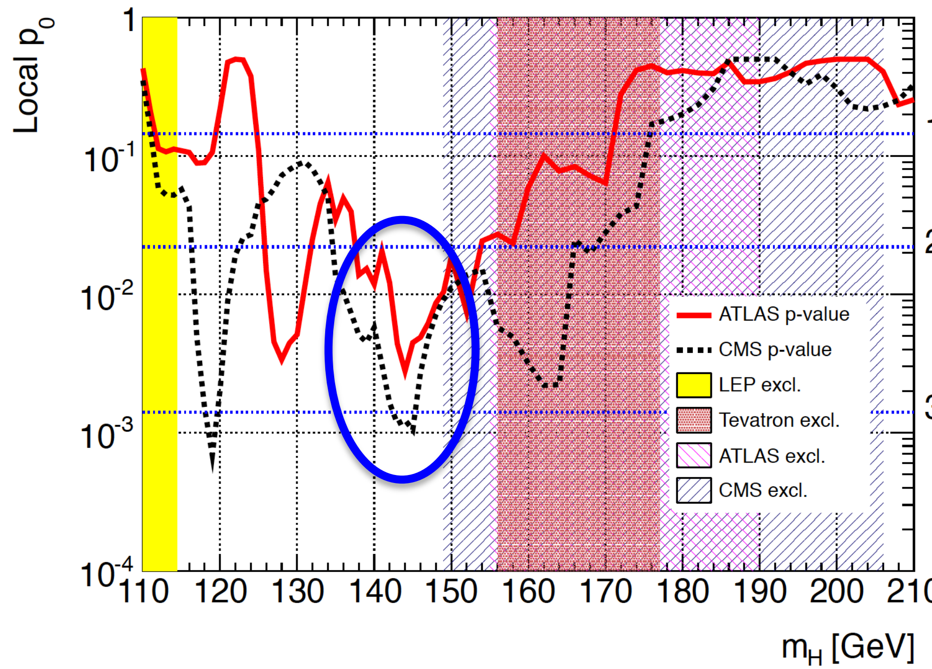




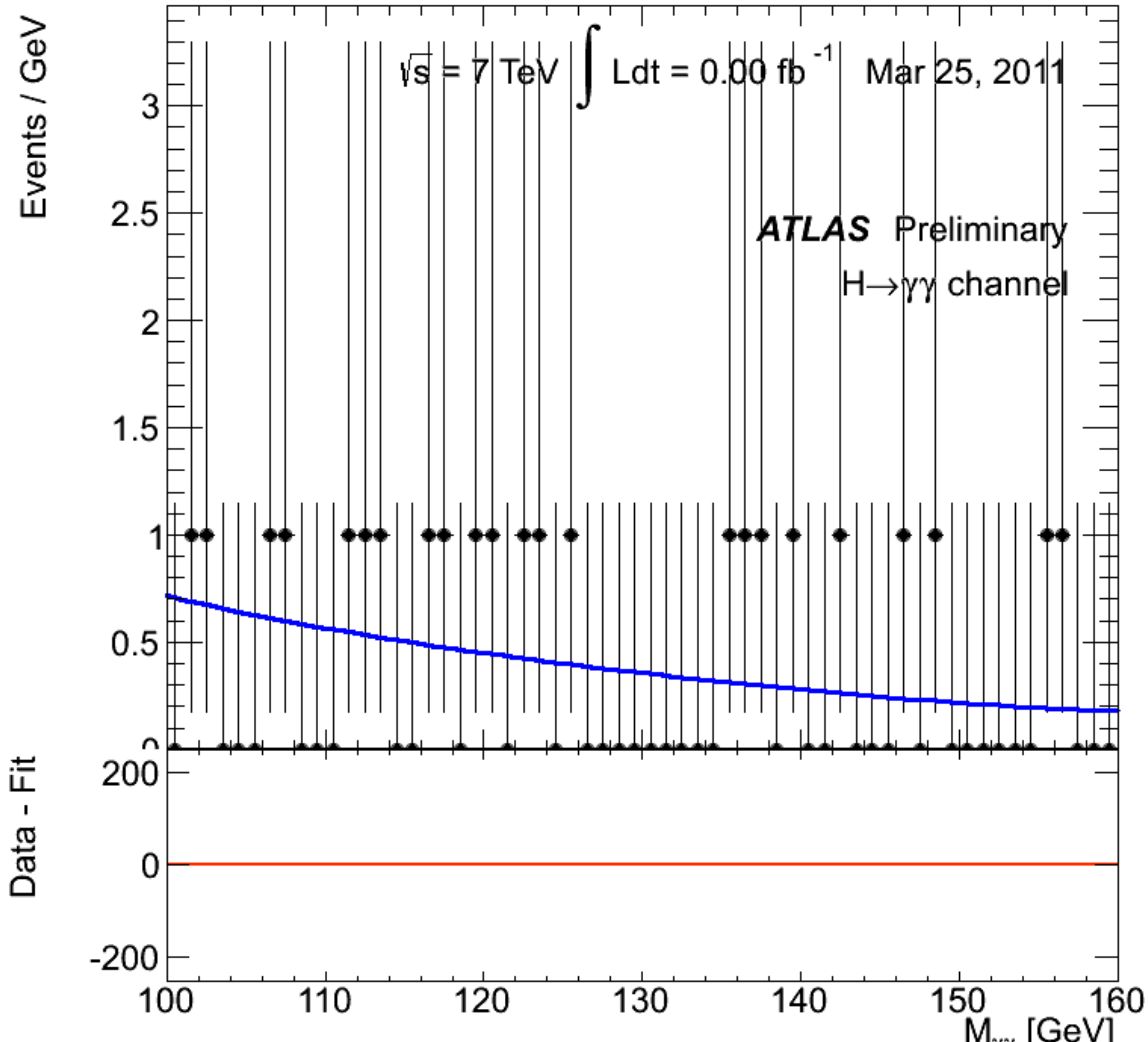


It takes time to get it right

EPS-HEP 2011 conference [6]



2012: Descoberta do bosão de Higgs: H->$\gamma\gamma$

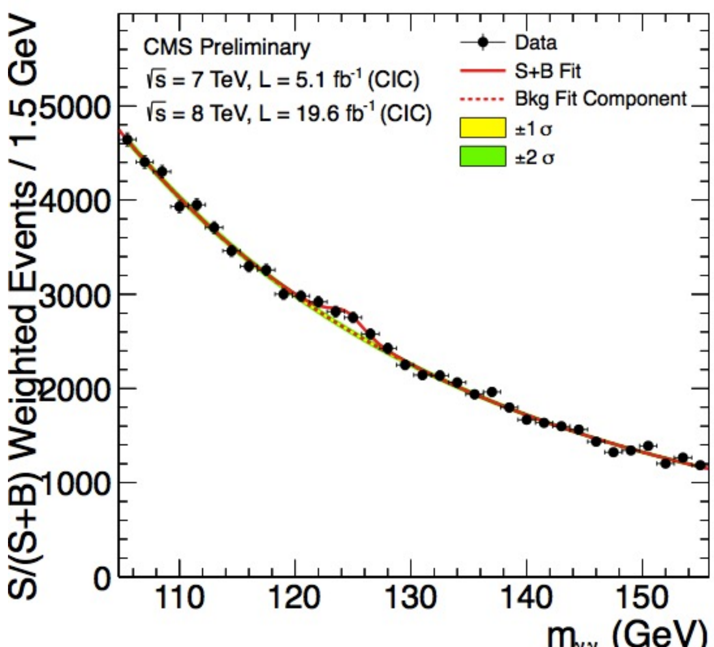


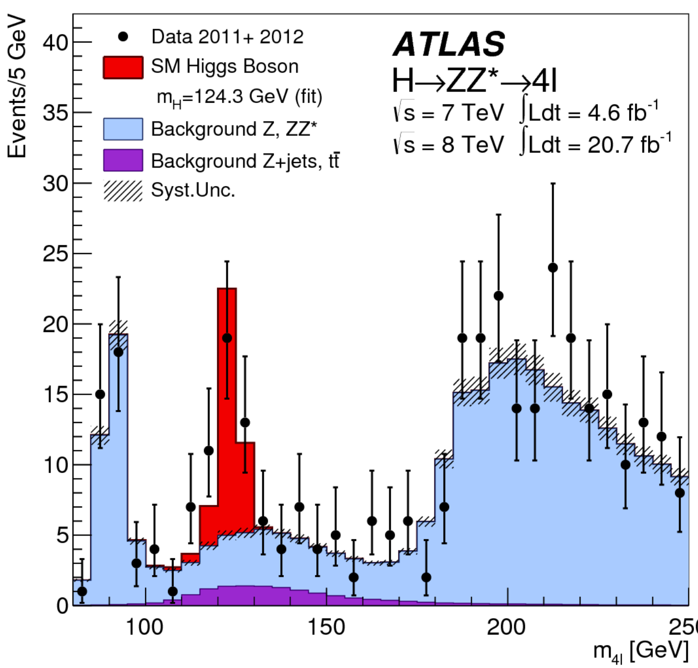
Discovery channels

- Discovery was made in ATLAS and CMS with about 5 fb^{-1} of 7 TeV data and 20 fb^{-1} of 8 TeV data per experiment; several channels combined

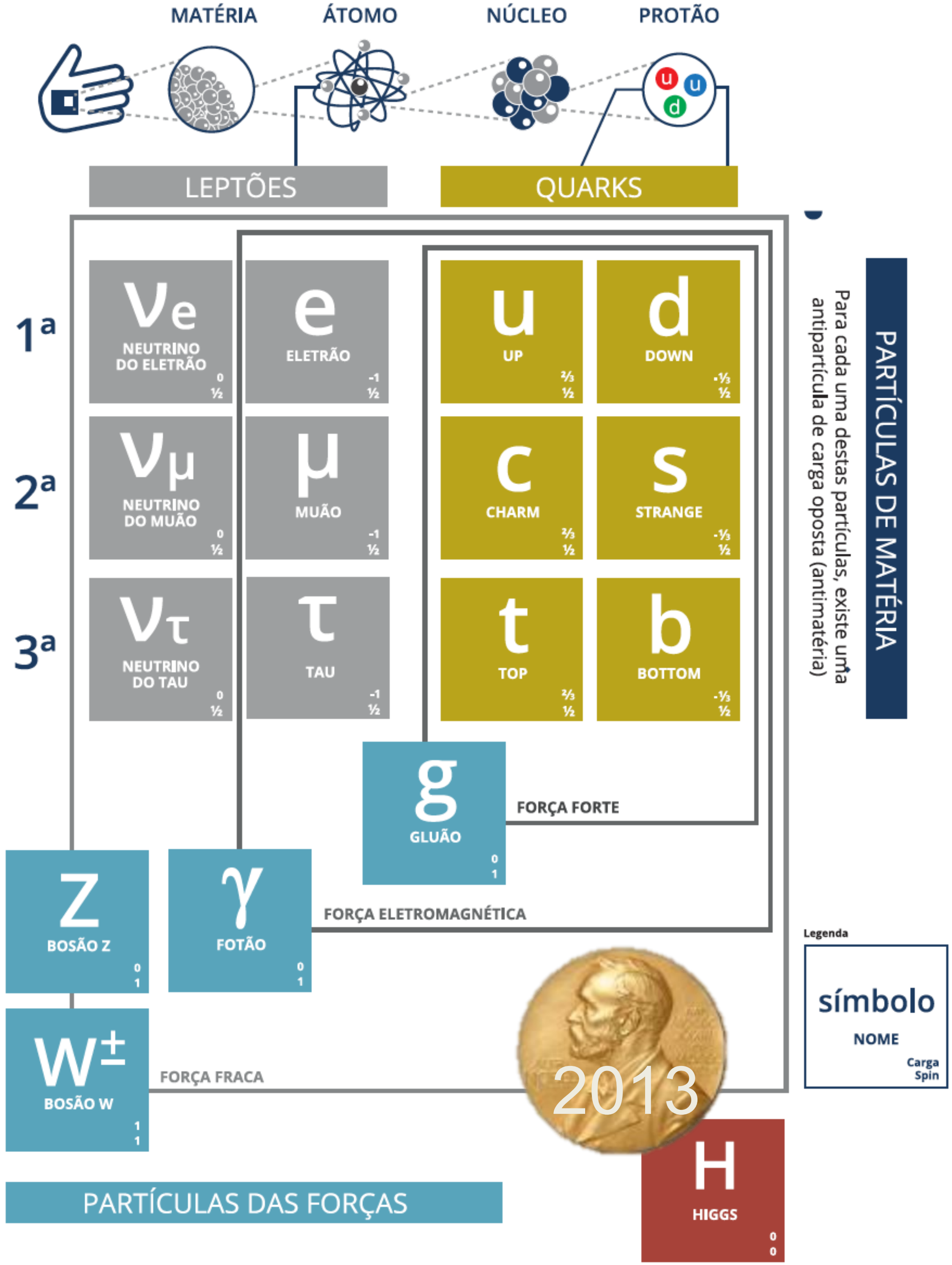
$$h \to \gamma\gamma; h \to ZZ^* \to 4\ell; h \to WW^*; h \to \tau^+\tau^-; h \to b\bar{b}$$

- This means about 400 000 Higgs bosons produced in about 8 000 000 000 000 000 ($8\mathrm{x}10^{15}$) proton collisions
  - Only about 4000 events with Higgs bosons contributed to the discovery

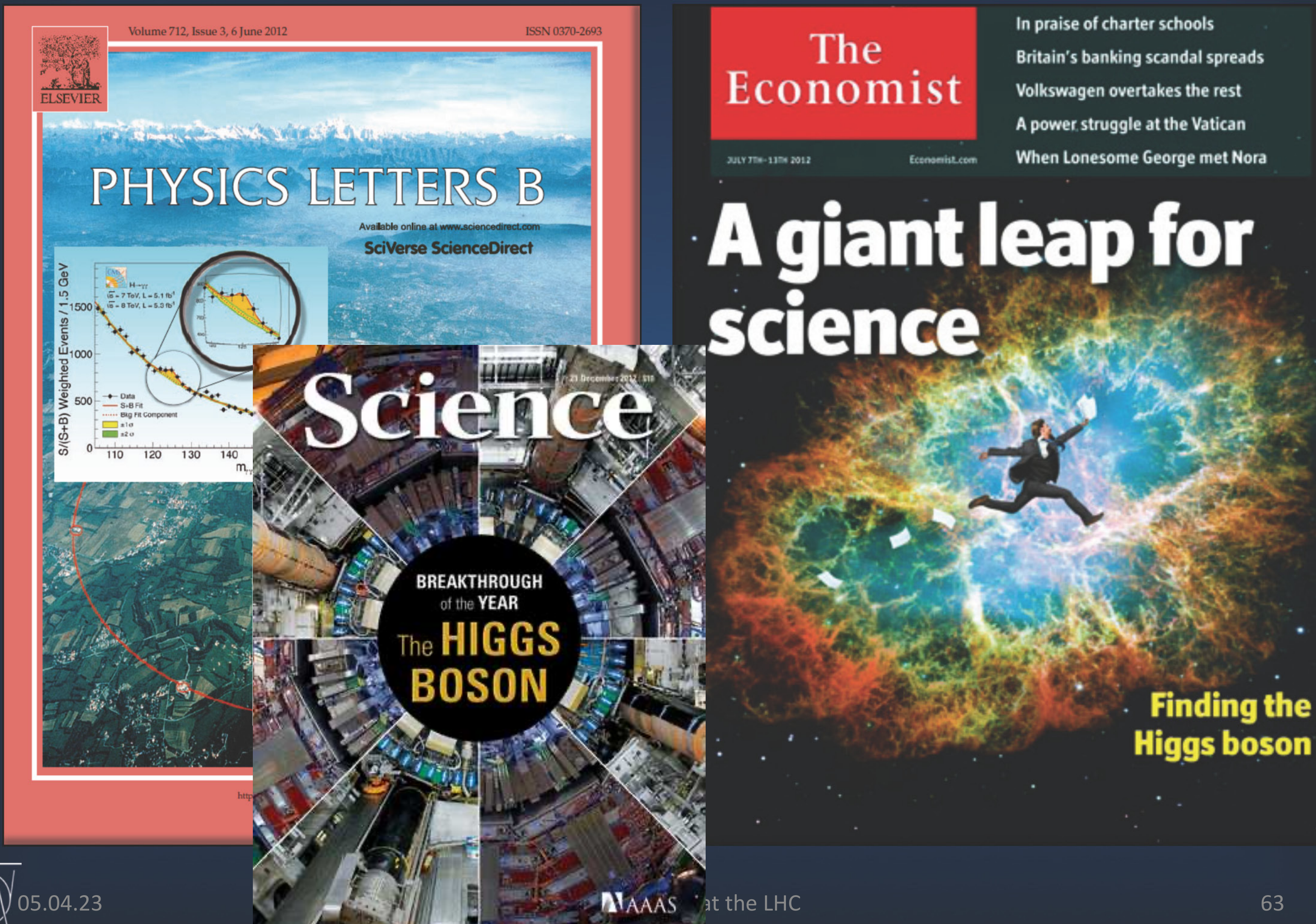


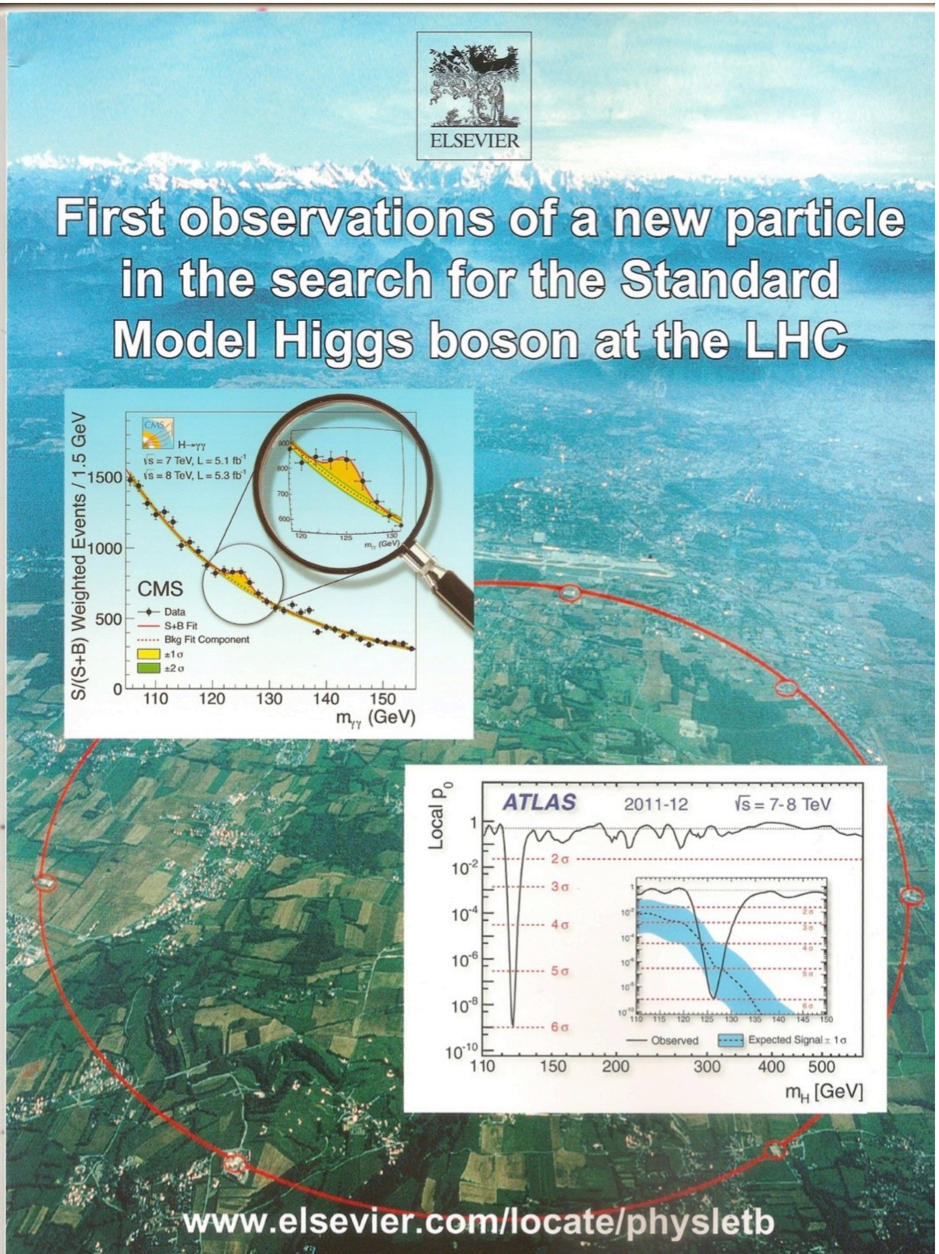


The Standard Model of particle physics <u>completed</u>



A Descoberta do bosão de Higgs





Two quotations from the experimental papers presented in this publication:

"*... The search for the Higgs boson, the only elementary particle in the Standard Model that has not yet been observed, is one of the highlights of the Large Hadron Collider physics program.*"

\- ATLAS Collaboration

"*... The decay to two photons indicates that the new particle is a boson with spin different from one. The results presented here are consistent, ... with expectations for a standard model Higgs boson.*"

\- CMS Collaboration

Best wishes!
Peter Higgs

Some sobering numbers

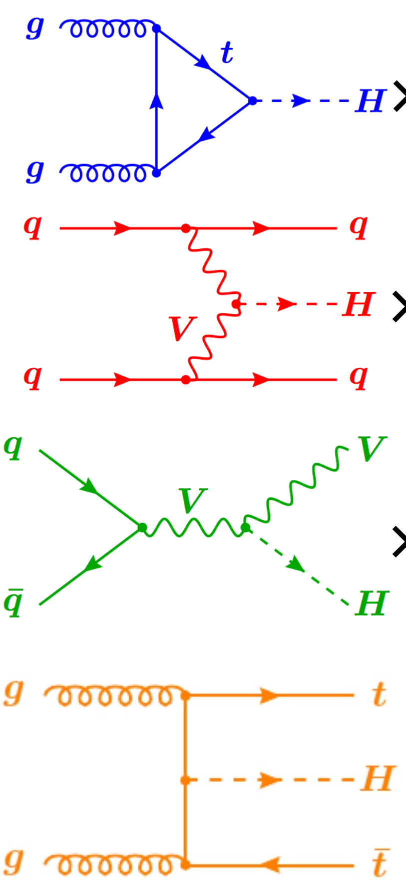
- Data for Higgs discovery in ATLAS: 4.83 fb^{-1} (7TeV) + 20.65 fb^{-1} (8TeV)
- With wild approximations…
  - Total number of collisions: 40 MHz × 3600 s/h × 14 h/day (duty cycle) × 150 days/year × 2 years ≈ 6×10^{14} collisions
  - Including pileup: 90×10^{14} collisions
    - Assume $\langle \mu \rangle \approx 10$ (7 TeV) and $\langle \mu \rangle \approx 20$ (8 TeV)
  - Higgs produced: $N = \mathcal{L}\sigma_{gg\rightarrow H} \approx 25\ fb^{-1} \times 15\ pb$ = 375 000 Higgs bosons
  - Signal events detected in each analysis – after branching ratio, trigger efficiency, offline reconstruction and analysis efficiency etc:
    - $H \rightarrow \gamma\gamma$: ≈ 475 events (arXiv: 1406.3827)
    - $H \rightarrow ZZ$: ≈ 20 events (arXiv: 1406.3827)
    - $H \rightarrow WW$: ≈ 250 events (arXiv: 1412.2641)
    - $H \rightarrow bb$: ≈ 390 events (arXiv: 1409.6212)
    - $H \rightarrow \tau\tau$: ≈ 180 events (arXiv: 1501.04943)
    - Total: ≈ 1300 Higgs events identified
- I.e.
  - ≈ 1300 Higgs detected in 375 000 produced – 0.35%
  - 375 000 Higgs produced in 9×10^{15} collisions – a fraction of 4×10^{-11}

What now?!

Probing the 125 GeV Higgs

$$\kappa_i^2 = \sigma_i / \sigma_i^{SM} \qquad \kappa_f^2 = \Gamma_f / \Gamma_f^{SM} \qquad \mu = \frac{(\sigma \cdot BR)^{Obs.}}{(\sigma \cdot BR)^{SM}} = \kappa_i^2 \cdot \kappa_f^2$$

Production



$\times\kappa_g$

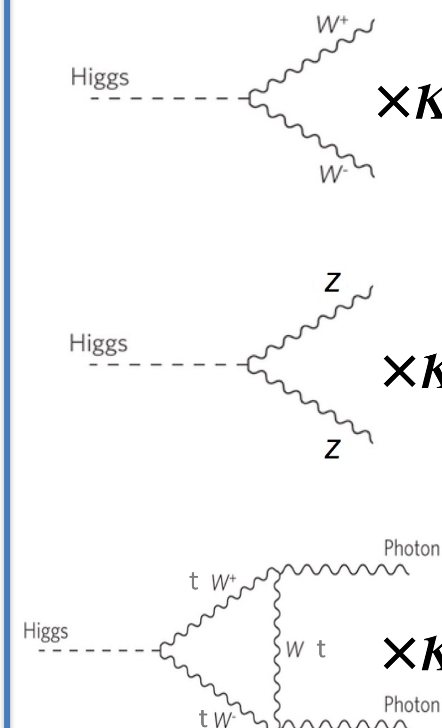
$\times\kappa_{W/Z}$

$\times\kappa_{W/Z}$

$\times\kappa_t$

$\times$

Decay



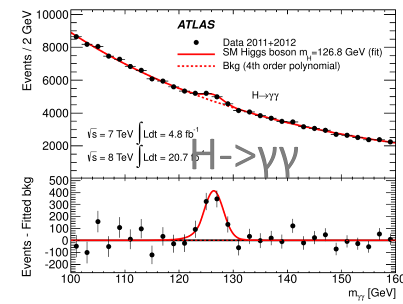
$\times\kappa_W$

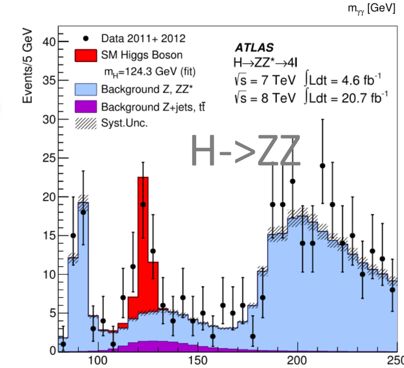
$\times\kappa_Z$

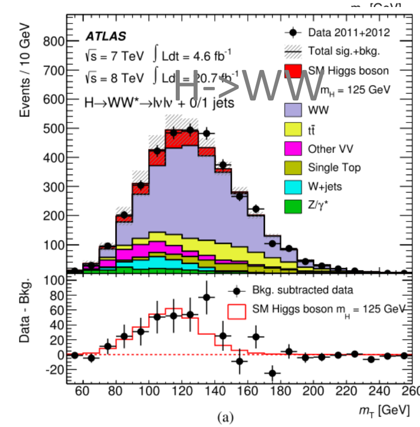
$\times\kappa_\gamma$

FIT

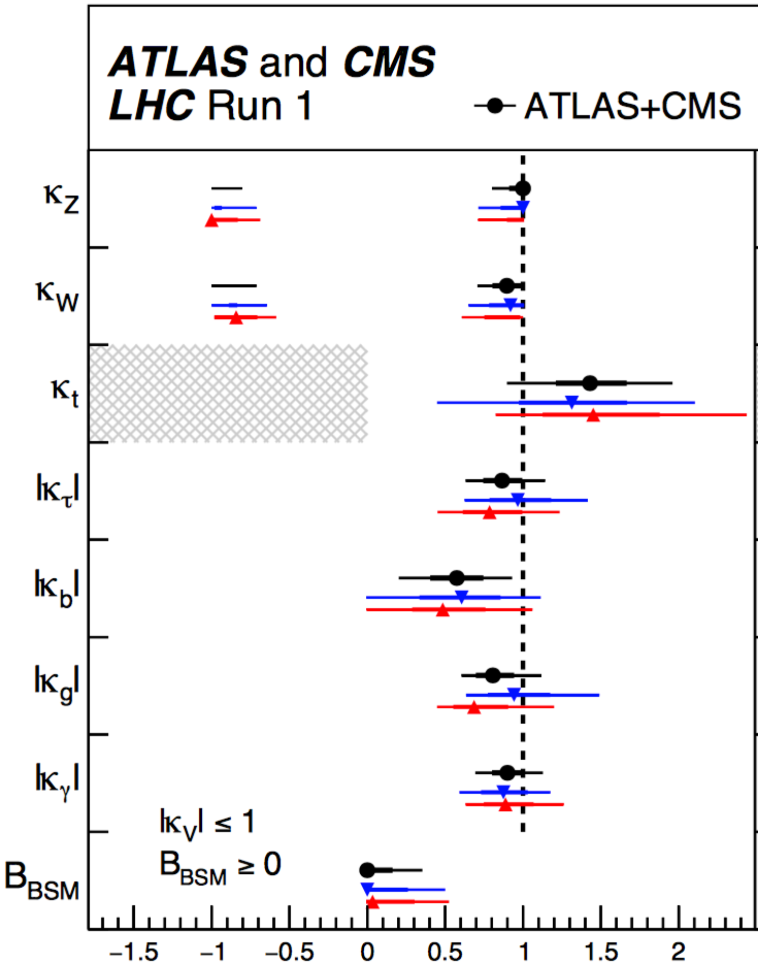
Backgrounds +

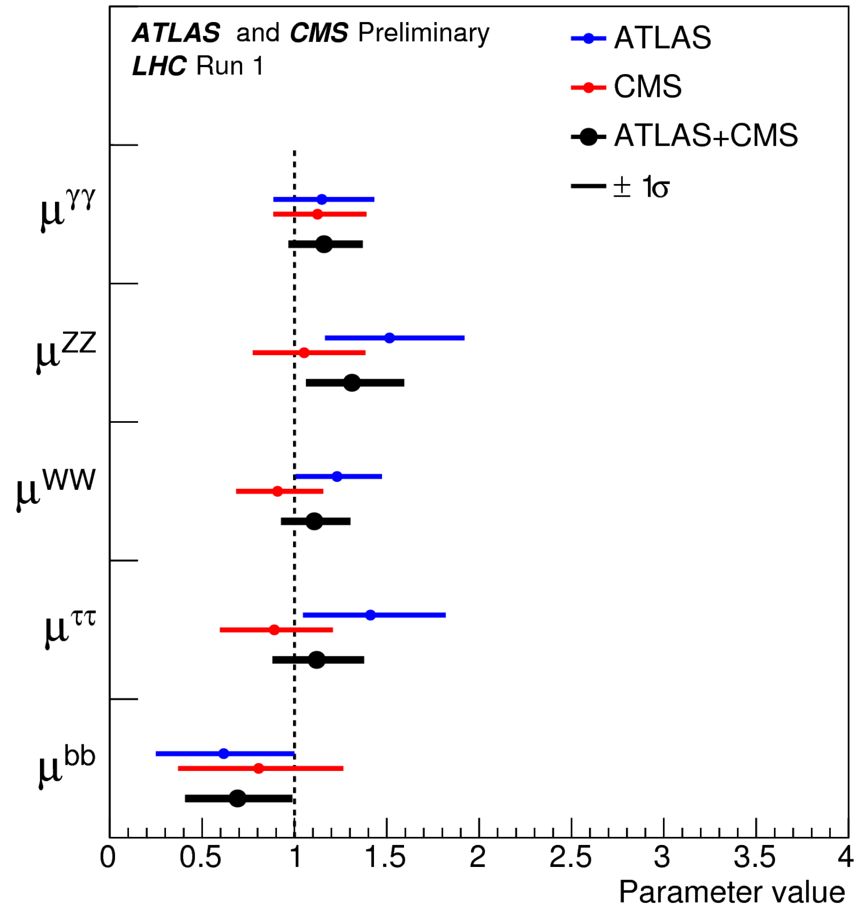






Signal strength measurements

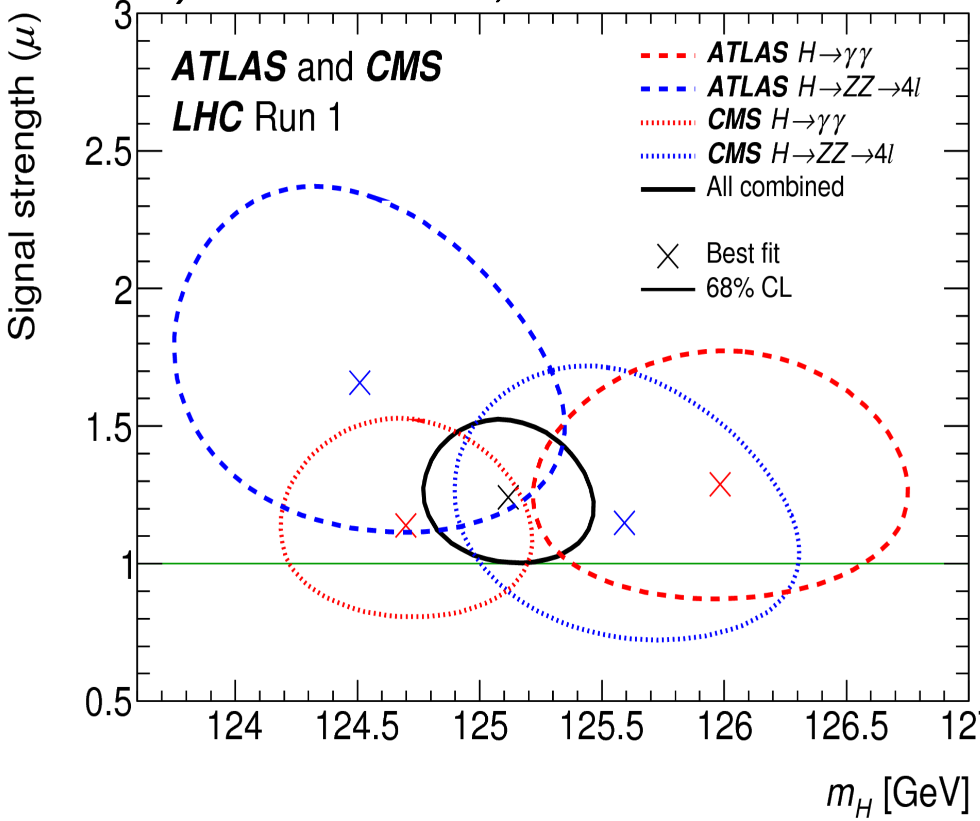




Higgs boson mass

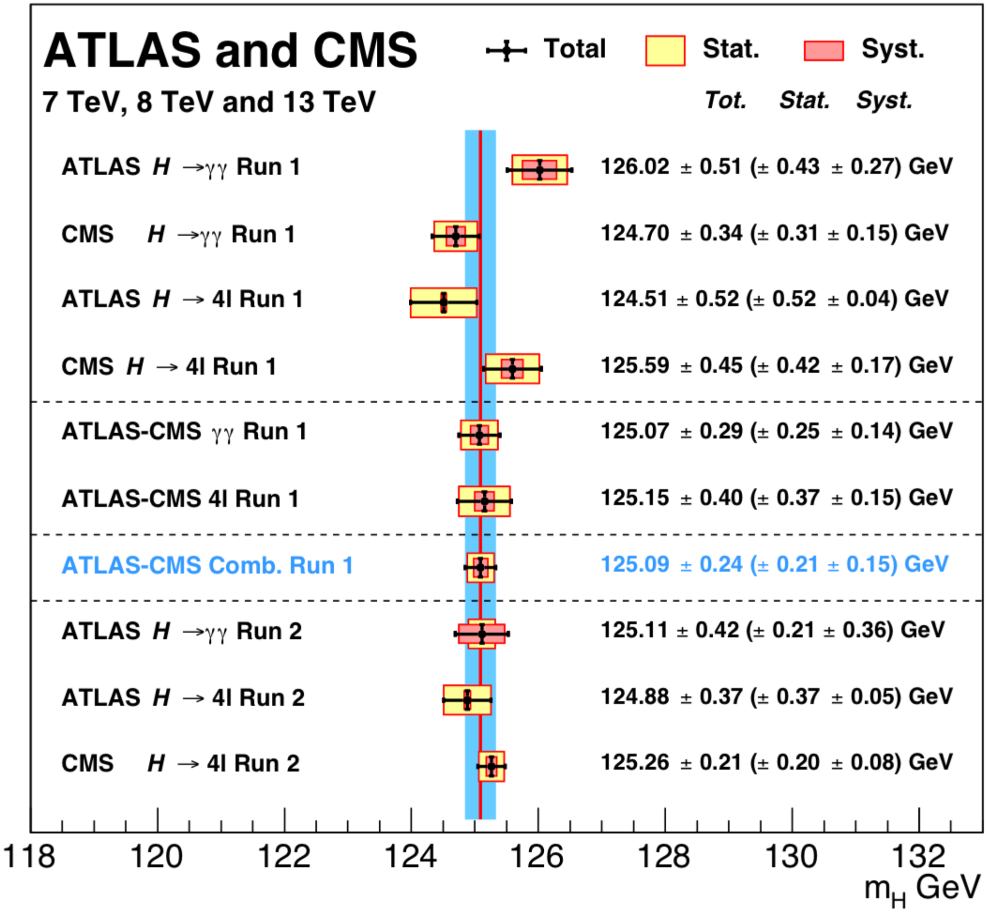
- Mass: around 125GeV
  Was the only unknown SM parameter ☺
- For a while, different mass values were being measured in ATLAS and CMS, and in different channels
- Numbers evolved with accumulated statistics

Phys. Rev. Lett. 114, 191803



Higgs boson mass

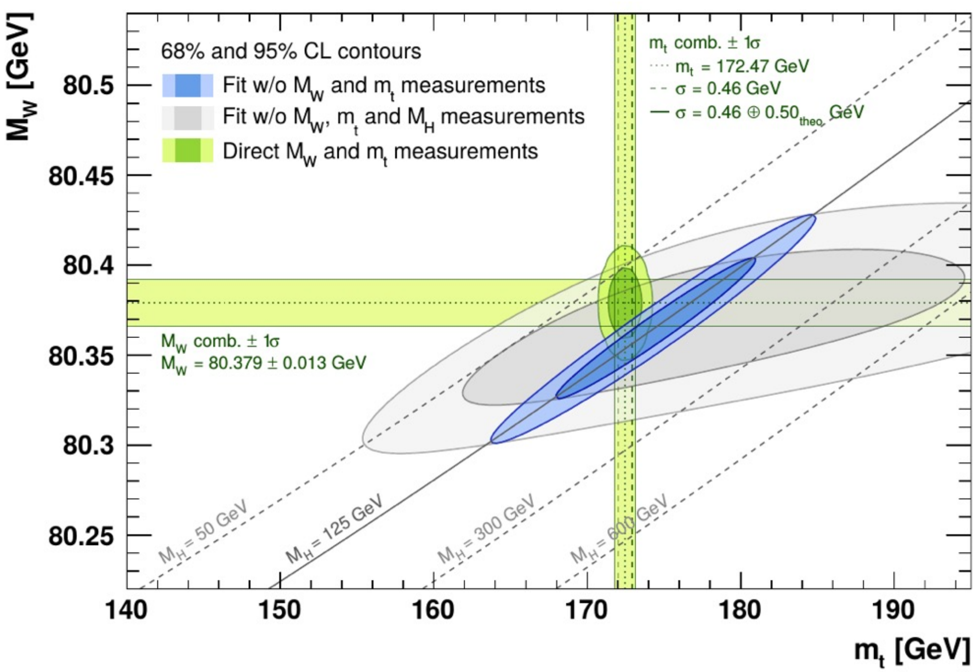
- Mass measurement from
  - H→ZZ*→4l
  - H→ γγ
- Precision at the permille level achieved

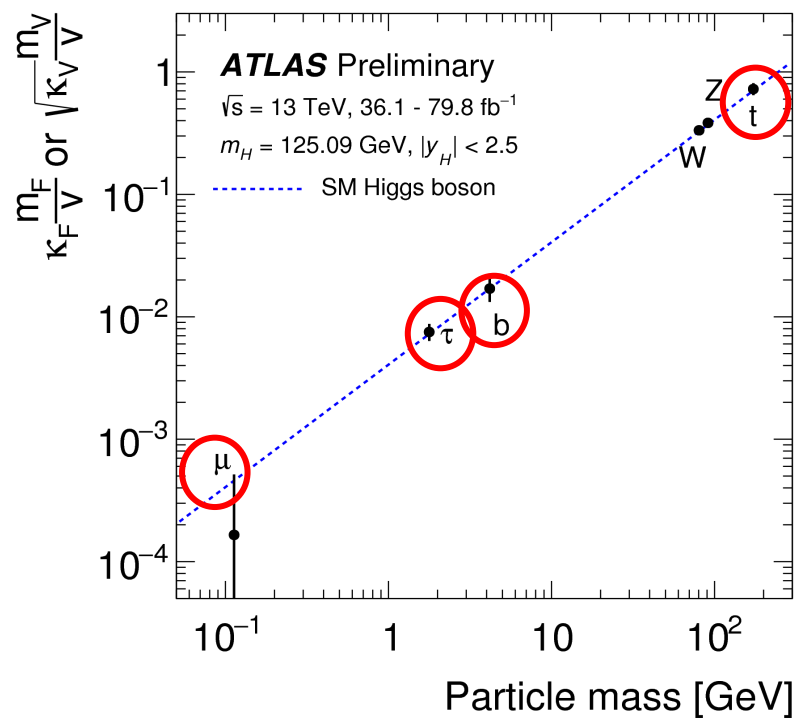


Exploring the electroweak scale

- Precision measurements of m_W, m_t, m_H are stringent tests of the SM at the EW scale
  - E.g. excluding measured m_H, global EW fit gives m_H = 90 ± 21 GeV (1.7 σ tension) driven in part by m_{top}

arXiv:1803.01853



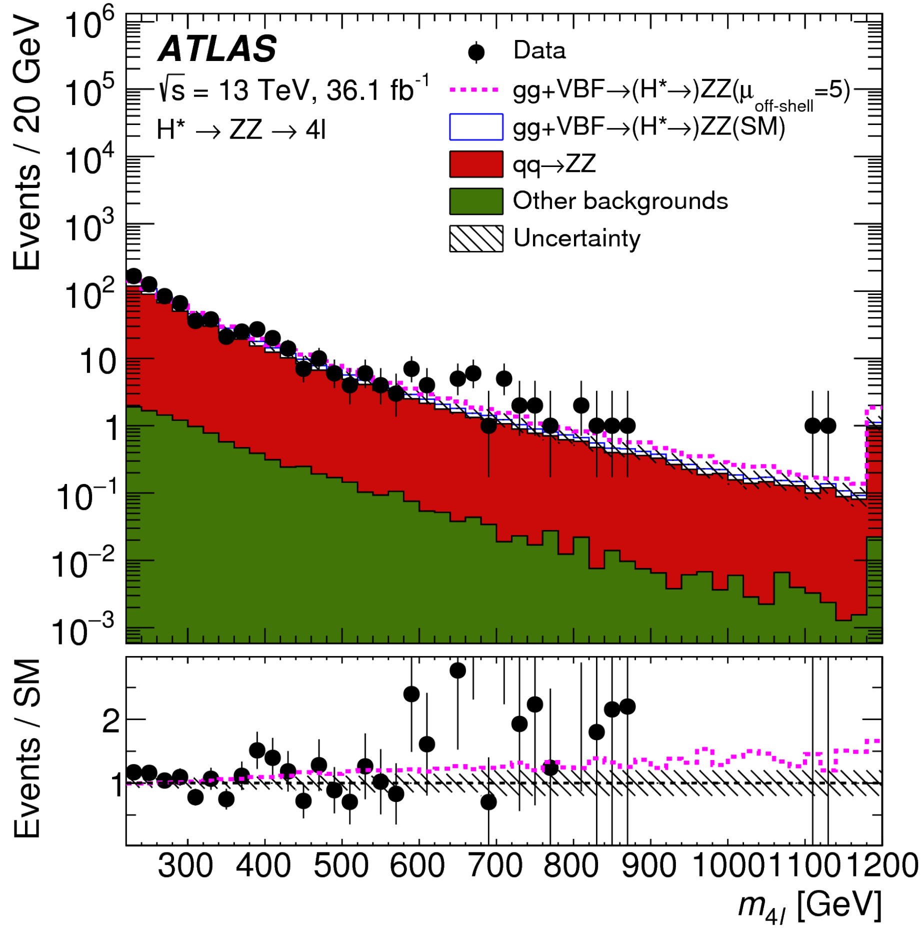


Higgs boson width

- SM Higgs width Γ_H~4.1 MeV
  - Too small to be measured directly
  - Best direct limit from CMS:
    - Γ_H < 1.1GeV @ 95% CL
- Off-shell Higgs production sensitive(*) to Γ_H

$$\frac{\mu_{\mathrm{off-shell}}}{\mu_{\mathrm{on-shell}}} = \frac{\kappa^2_{\mathrm{g,off-shell}} \cdot \kappa^2_{\mathrm{Z,off-shell}}}{\kappa^2_{\mathrm{g,on-shell}} \cdot \kappa^2_{\mathrm{Z,on-shell}}} \frac{\Gamma_H}{\Gamma_H^{SM}}$$

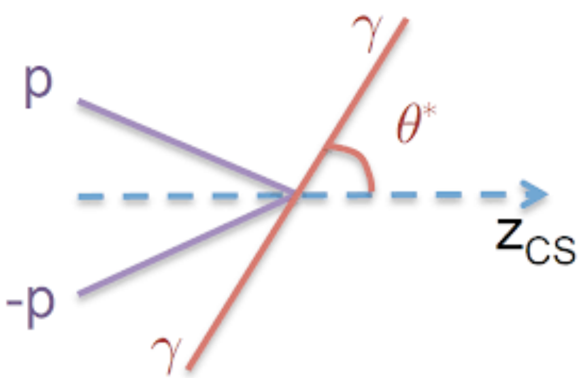
- ATLAS measurement:
  - **pp→H→ZZ→4l** and ZZ→2l2ν
  - **m(H) > 2 m(Z)**
  - 36.1 fb^{-1} of 13 TeV data
  - Observed (expected) limit:
    - Γ_H < 14.4 (15.2) MeV



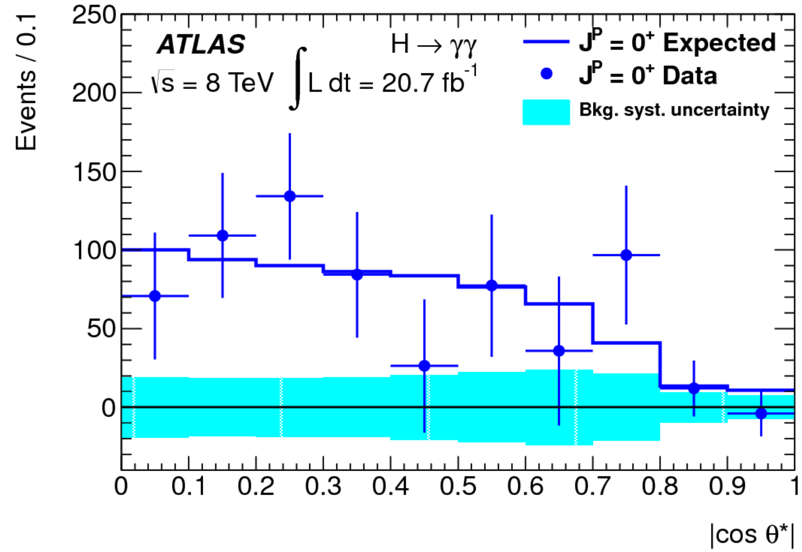
(*) Assume interference term with $gg \to ZZ$ proportional to $\kappa_{g,\text{off-shell}} \cdot \kappa_{Z,\text{off-shell}}$

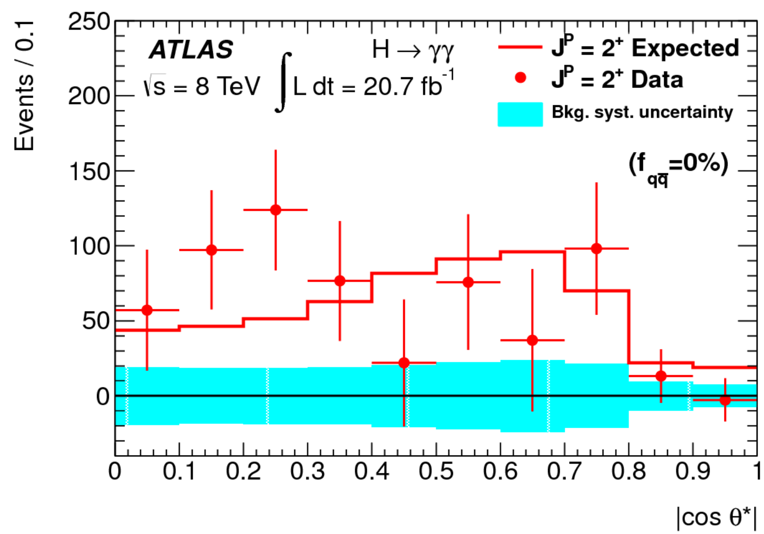
Measuring the Higgs Spin

- Polar angle θ in the rest fram of the diphoton system (Collins-Soper frame)

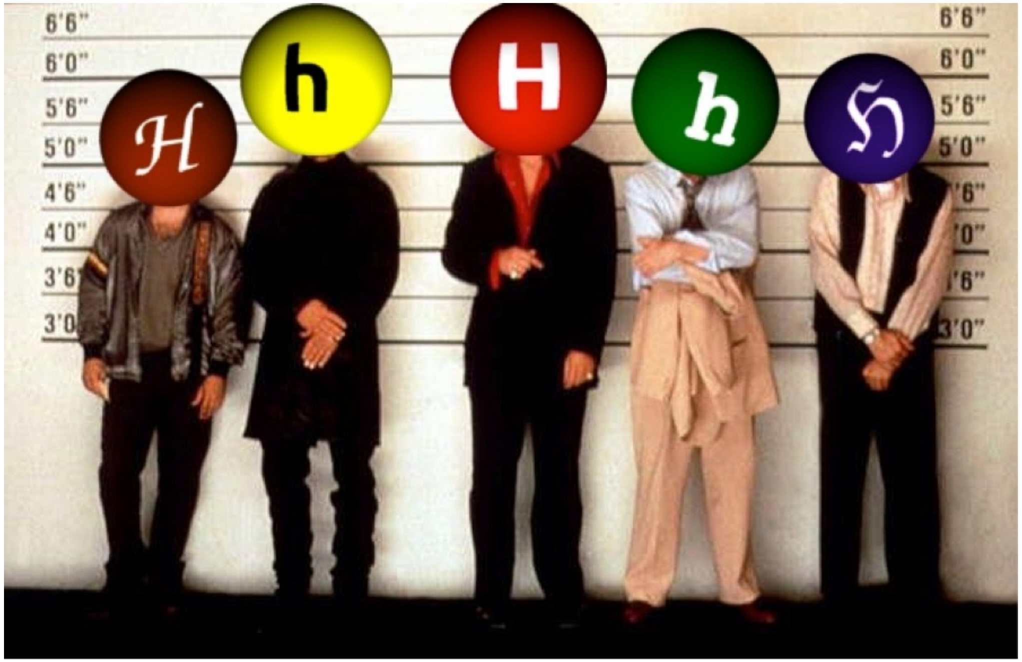


$$|\cos\Theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+\frac{p^2_{T,\gamma\gamma}}{m^2_{\gamma\gamma}}}}\frac{2p_T^{\gamma_1}p_T^{\gamma_2}}{m^2_{\gamma\gamma}}$$



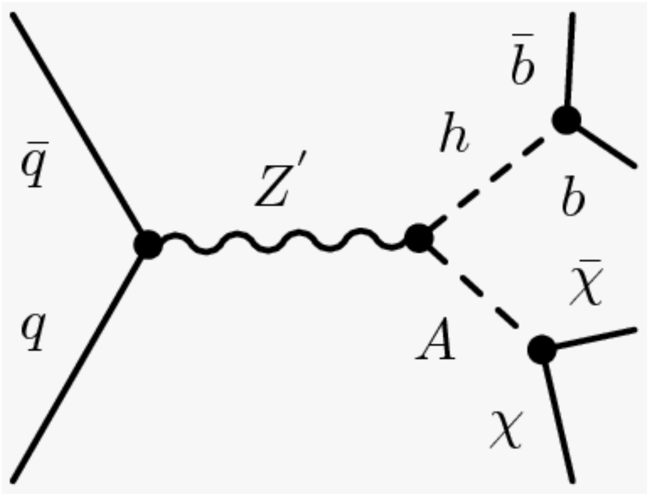


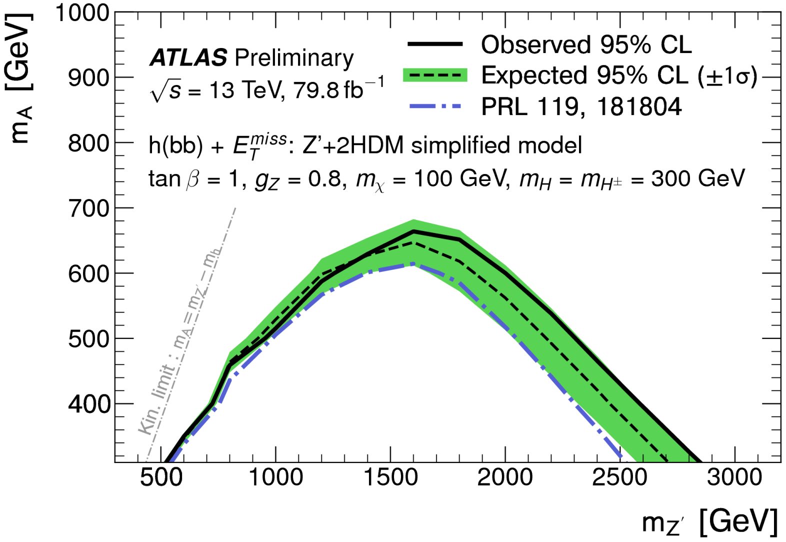
Casting a wider net



Higgs + Dark Matter

- Used 79.8 fb^{-1} of 13 TeV data
  - High E_T^{miss} (>150GeV) and b-tagging to suppress backgrounds
  - Reconstruct b-jets as 2 small jets or merged variable-radius (VR) track jets
- Signal benchmark: Type-II 2HDM + $U(1)_{Z'}$ symmetry (Z'-2HDM)
- Main backgrounds: tt, W/Z+jets
- Excluded region in $m_A - m_{Z'}$ plane



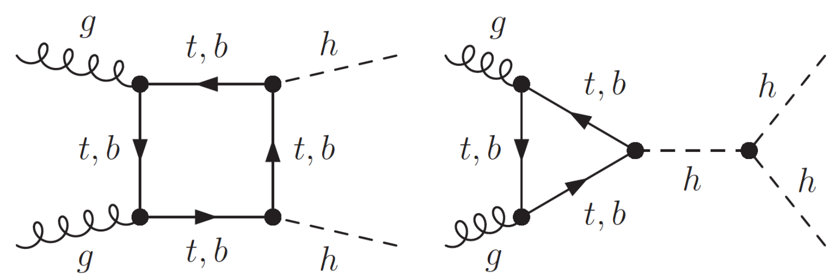


arXiv:1808.00336 [hep-ex]; ATLAS-CONF-2018-043

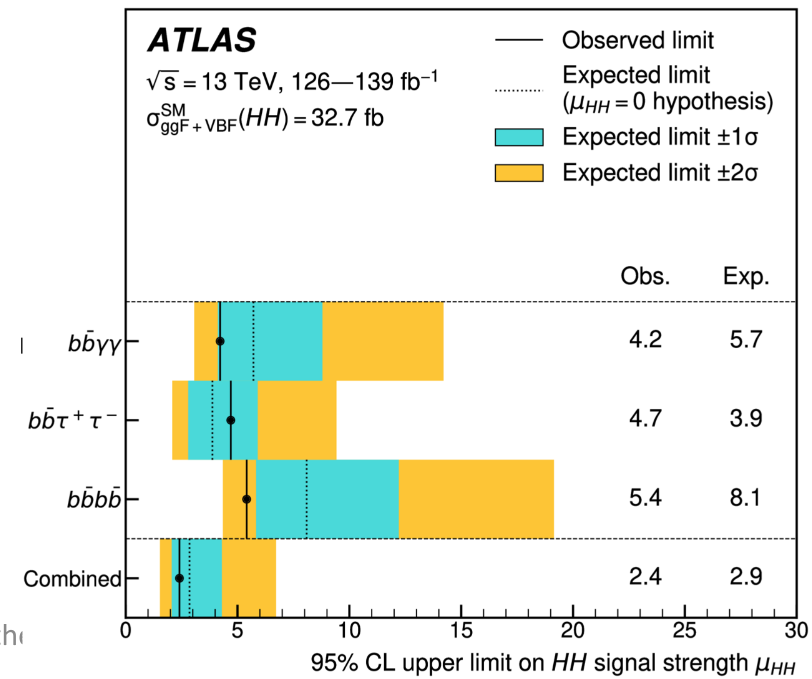
Triple Higgs coupling

- The triple Higgs coupling λ_{HHH} can be probed through di-Higgs production
- Very suppressed in SM!
  - Negative interference between LO diagrams
  - Cross section 1500x less than ggF
- Wide range of decay BR and channel purity

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$

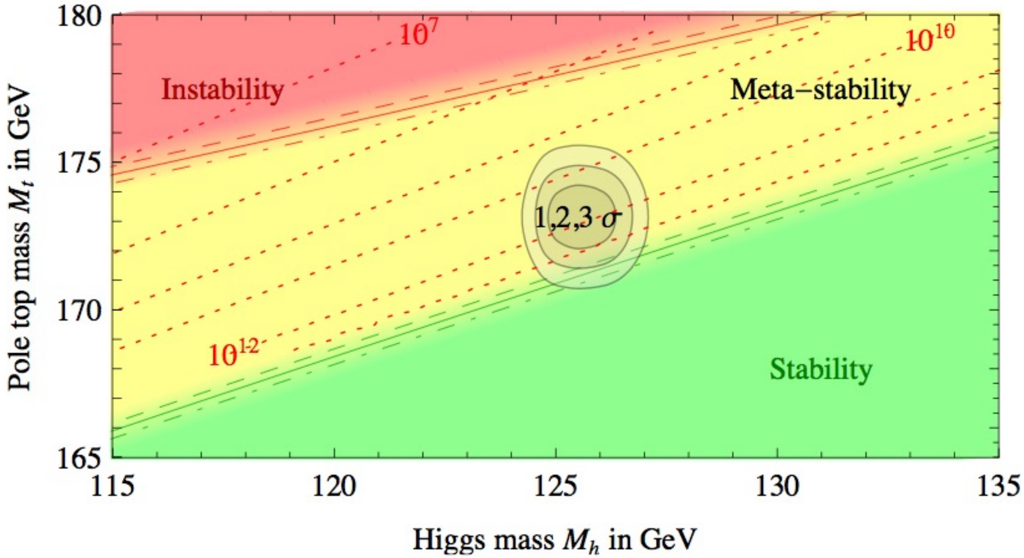


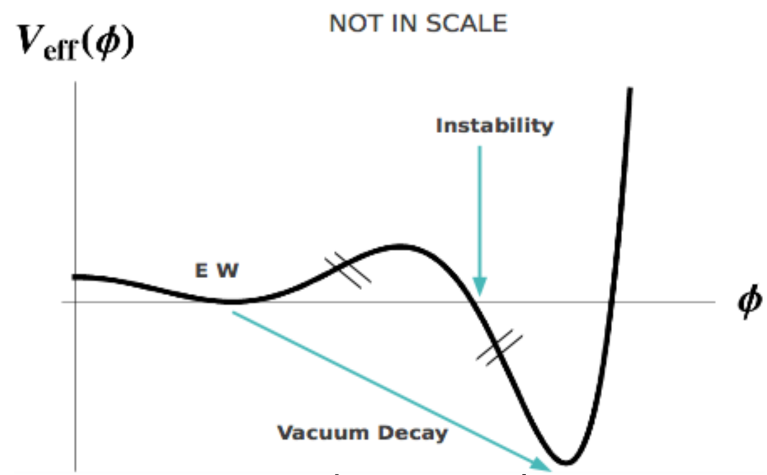
- Combination: at ≈2.5 x SM sensitivity – with ≈ 5% of the HL-LHC luminosity analyzed



Di-Higgs combination plot [here]

A bit of fun…





RG-improved potential

- What if…
  - At higher orders, Higgs potential doesn't have to be stable
  - Depending on m_t and m_H second minimum can be lower than EW minimum ⇒ tunneling between EW vacuum and true vacuum?!
- "For a narrow band of values of the top quark and Higgs boson masses, the Standard Model Higgs potential develops a shallow local minimum at energies of about 10^{16} GeV, where primordial inflation could have started in a cold metastable state", I. Masina, arXiv:1403.5244 [astro-ph.CO]
  - See also: V. Brachina, Moriond 2014 (Phys.Rev.Lett.111, 241801 (2013)), G. Degrassi et al, arXiv:1205.6497v2; R.Contino, Workshop sulla fisica p-p a LHC, 2013

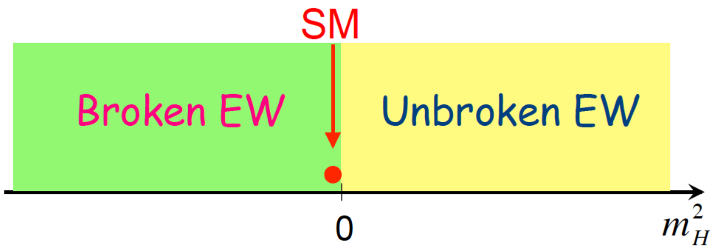
The universe seems to live near a critical condition

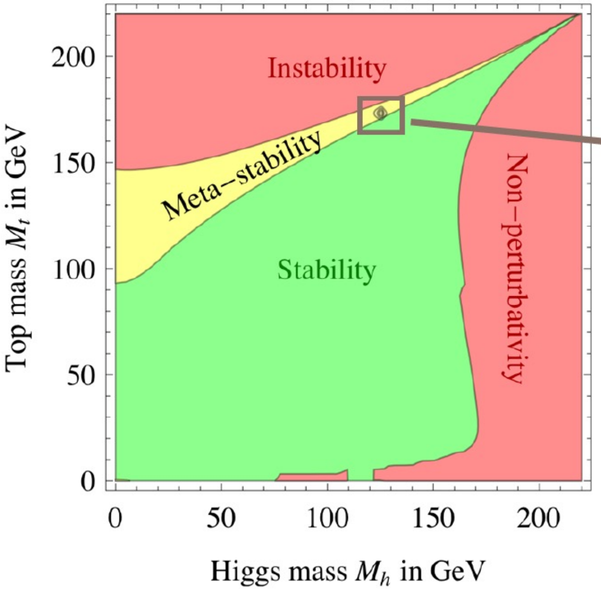
JHEP 1208 (2012) 098

Why?!

Explained by underlying theory?

Anthropic principle?





Higgs @ LIP ATLAS Group

- Exploring Higgs couplings to heavy quarks
- Less well known... Much more space for surprises!
- New physics effects may show up already at leading order

P2 ÍPSILON CULTO FUGAS P3 CINECARTAZ Entrar Assine já

CIÊNCIA › ESPAÇO MEDICINA ECOSFERA

FÍSICA DE PARTÍCULAS

Bosão de Higgs revela que relação mantém com o quark *top*

Investigadores portugueses participaram na descoberta.

PÚBLICO · 4 de Junho de 2018, 19:42 418 PARTILHAS

FÍSICA DE PARTÍCULAS

Bosão de Higgs visto (finalmente) a desintegrar-se em quarks *bottom*

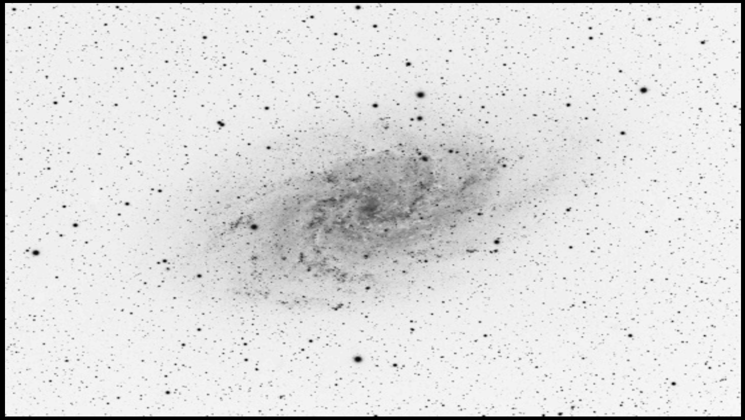
Descoberta anunciada no Laboratório Europeu de Física de Partículas (CERN) é um passo fundamental para perceber como o bosão de Higgs faz com que as partículas fundamentais adquiram massa.

PÚBLICO · 28 de Agosto de 2018, 17:47

2018: Hbb and Htt couplings demonstrated
2020: CP of ttH coupling in ttH, H->γγ
2022: ttH, H->bb fiducial cross section
2022: Preliminary results for CP of ttH coupling studied in ttH, H->bb

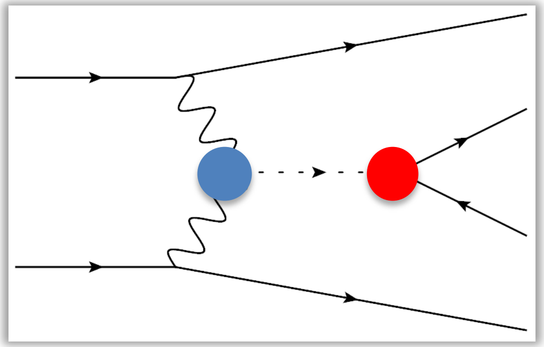
ttH CP measurement

- Sakharov conditions for a matter-dominated universe require CP violation
- Known CP-violating processes:
  - From complex phases in CKM-matrix - quark mixing
  - Maybe in PNMS-matrix as well - neutrino mixing
- BUT: insufficient, by orders of magnitude
- CP violation in Higgs sector?
  - Possible in some models with extended Higgs sector (e.g. some 2HDMs)
  - Need **mixing** of scalar (CP-even) and pseudo-scalar (CP-odd) Higgs states
- What do we know about Higgs CP properties?
  - In the SM, Higgs scalar is a CP eigenstate with $J^{CP} = 0^{++}$
  - Pure $J^P = 0^-$ hypothesis for observed Higgs boson was ruled out in Run 1
  - But a **large** CP-odd admixture is not ruled out



How to search for a CP-odd admixture?

- Effect of CP-odd components on **bosonic couplings** parametrized as expansion with higher order terms suppressed by powers of scale of new physics Λ
- Could explain why a CP-odd admixture has not been seen



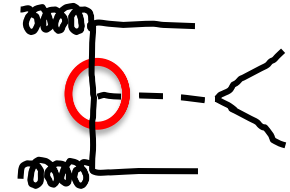
- **Fermionic couplings** are affected at tree level
- Mixing angle α between CP-even and CP-odd coupling components
- More notable for heavier fermions due to enhanced coupling

$$\mathcal{L}_{VVH} = \mathcal{L}_{VVH,SM} + \frac{1}{\Lambda^2} c\, \phi \widetilde{V}_{\mu\nu} V^{\mu\nu} + \ldots$$

$$\mathcal{L}_{ffH} = \kappa'_f y_f \phi \bar{\psi}_f (\cos\alpha + i\gamma_5 \sin\alpha)\psi_f$$

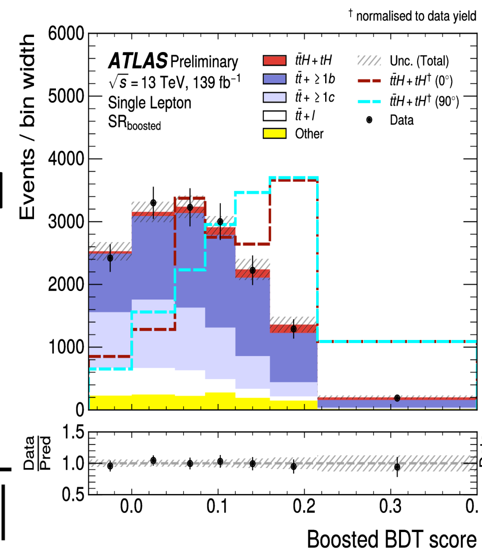
ATLAS-CONF-2022-016 (16 March 2022)

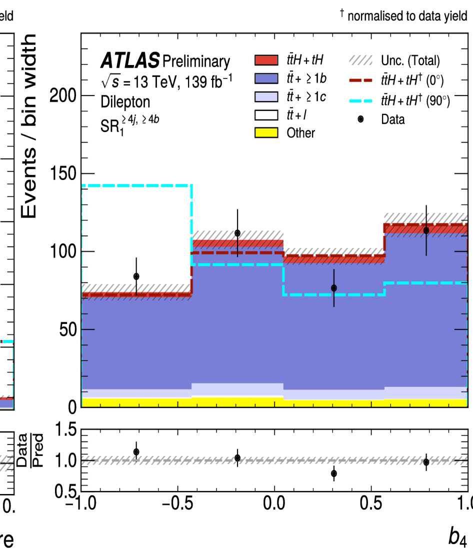
H-top Coupling in ttH/tH production



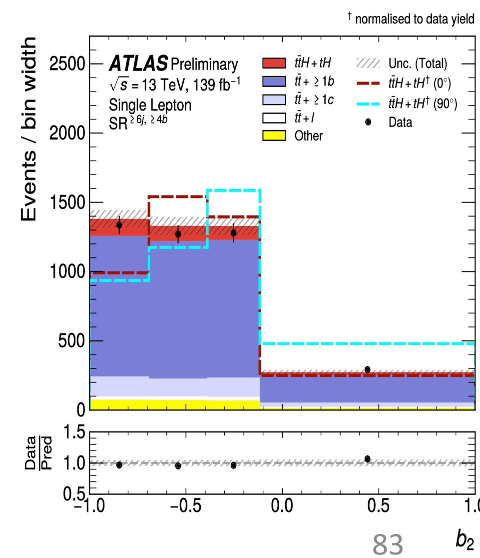
- Calculate CP-sensitive observables $\boldsymbol{b_2}$ and $\boldsymbol{b_4}$ from top-quark 3-momenta
- Use different observables in combined fit depending on region

$$b_2 = \frac{(\vec{p}_1 \times \hat{n}) \cdot (\vec{p}_2 \times \hat{n})}{|\vec{p}_1||\vec{p}_2|} \qquad b_4 = \frac{p_1^z p_2^z}{|\vec{p}_1||\vec{p}_2|}$$

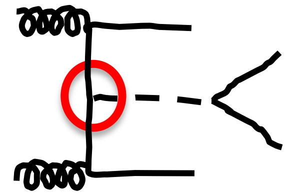




Channel (PSR)	Final SRs and CRs	Classification BDT selection	Fitted observable
Dilepton ($\mathrm{PSR}^{\geq 4j, \geq 4b}$)	$\mathrm{CR}_{\text{no-reco}}^{\geq 4j, \geq 4b}$	–	$\Delta\eta_{\ell\ell}$
	$\mathrm{CR}^{\geq 4j, \geq 4b}$	BDT∈ [−1, −0.086)	b_4
	$\mathrm{SR}_1^{\geq 4j, \geq 4b}$	BDT∈ [−0.086, 0.186)	b_4
	$\mathrm{SR}_2^{\geq 4j, \geq 4b}$	BDT∈ [0.186, 1]	b_4
ℓ+jets ($\mathrm{PSR}^{\geq 6j, \geq 4b}$)	$\mathrm{CR}_1^{\geq 6j, \geq 4b}$	BDT∈ [−1, −0.128)	b_2
	$\mathrm{CR}_2^{\geq 6j, \geq 4b}$	BDT∈ [−0.128, 0.249)	b_2
	$\mathrm{SR}^{\geq 6j, \geq 4b}$	BDT∈ [0.249, 1]	b_2
ℓ+jets ($\mathrm{PSR}_{\text{boosted}}$)	$\mathrm{SR}_{\text{boosted}}$	BDT∈ [−0.05, 1]	Classification BDT score



H-top Coupling in ttH/tH production



Simultaneous fit in all regions

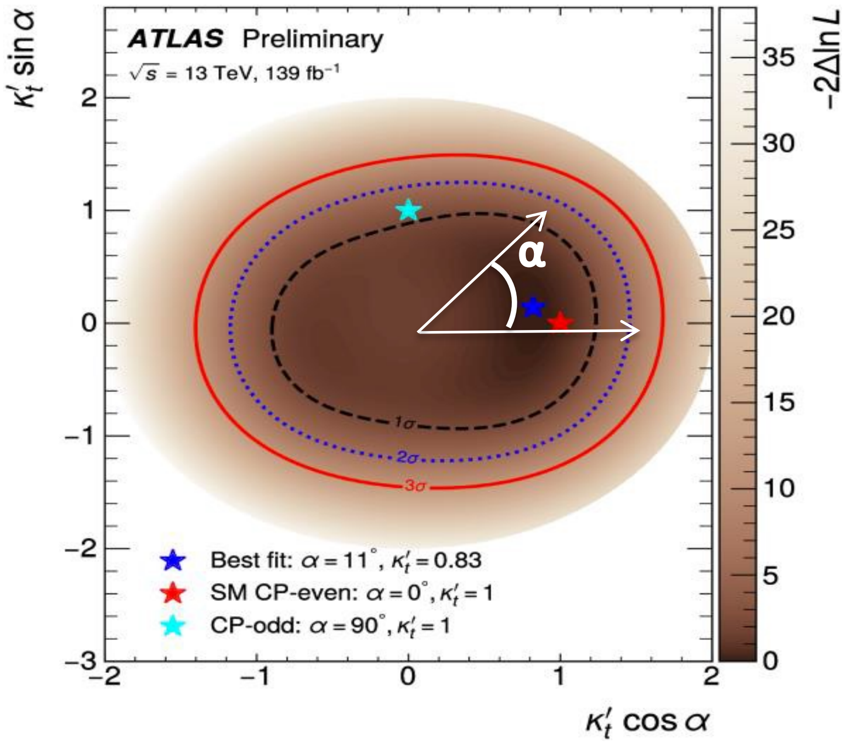
- **$\mu = 0.83^{+0.30}_{-0.46}$**
- **$\alpha = 11° {}^{+55}_{-77}$**

Expected:

- $\mu = 1.0^{+0.25}_{-0.27}$
- $\alpha = 0° {}^{+49}_{-50}$
- Pure CP-odd (α = 90°) disfavoured at **1.2 σ**

Complementary to previous ttH(H→γγ) analysis:

- Phys. Rev. Lett. 125 (2020) 061802
- Pure CP-odd (α = 90°) excluded at **3.9 σ**
- Limit on **|α| < 43°** at 95% C.L.

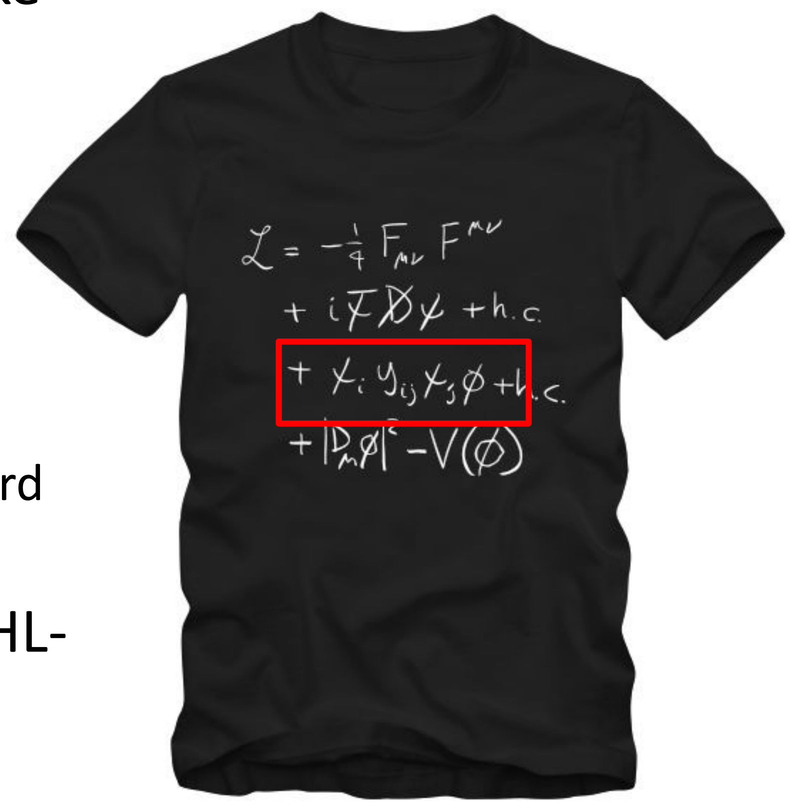


$$\boxed{\mathcal{L}_{t\bar{t}H} = -\kappa_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t}$$

Summary

- Higgs sector measurements look SM-like so far
- **But there is new physics out there!**
- The Higgs is:
  - The only fundamental scalar
  - Connected to EW symmetry breaking
  - A great window to look beyond the Standard Model
- And we have only collected ≈5% of all HL-LHC data!

Watch this space!




TRUST NO ONE
STAY TUNED!

Questions?

Thank you for your interest!

jgoncalo@lip.pt

LIP

1290 FACULDADE DE CIÊNCIAS E TECNOLOGIA UNIVERSIDADE D COIMBRA

IDPASC

ATLAS EXPERIMENT

spfísica DIVISÃO DE FÍSICA DE PARTÍCULAS

FCT

Cofinanciado por:

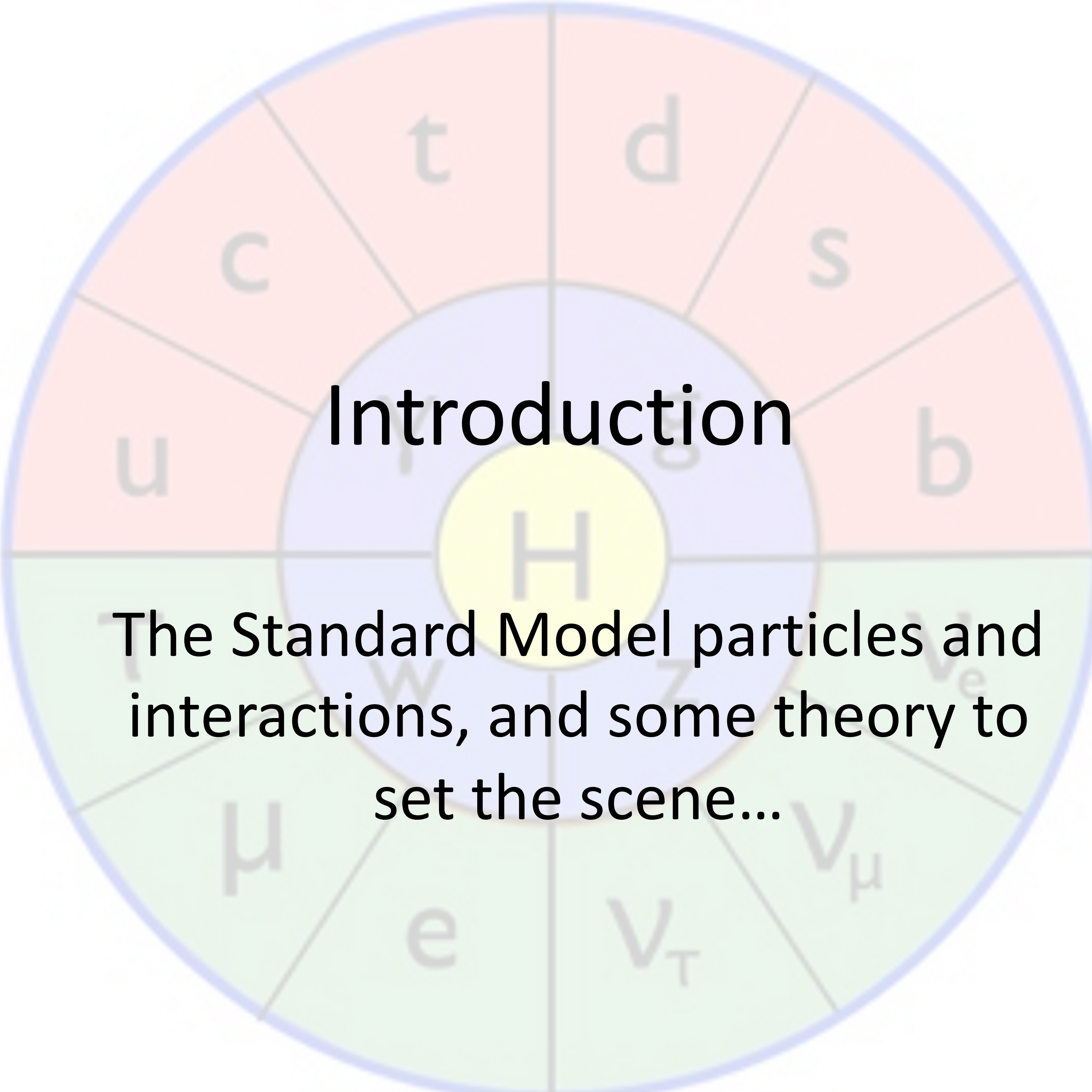
COMPETE 2020

PORTUGAL 2020

UNIÃO EUROPEIA
Fundos Europeus Estruturais e de Investimento

Outlook

- What is the Higgs boson and what is it good for?
- How did we find it?
- Why do we care?
- And what comes next?

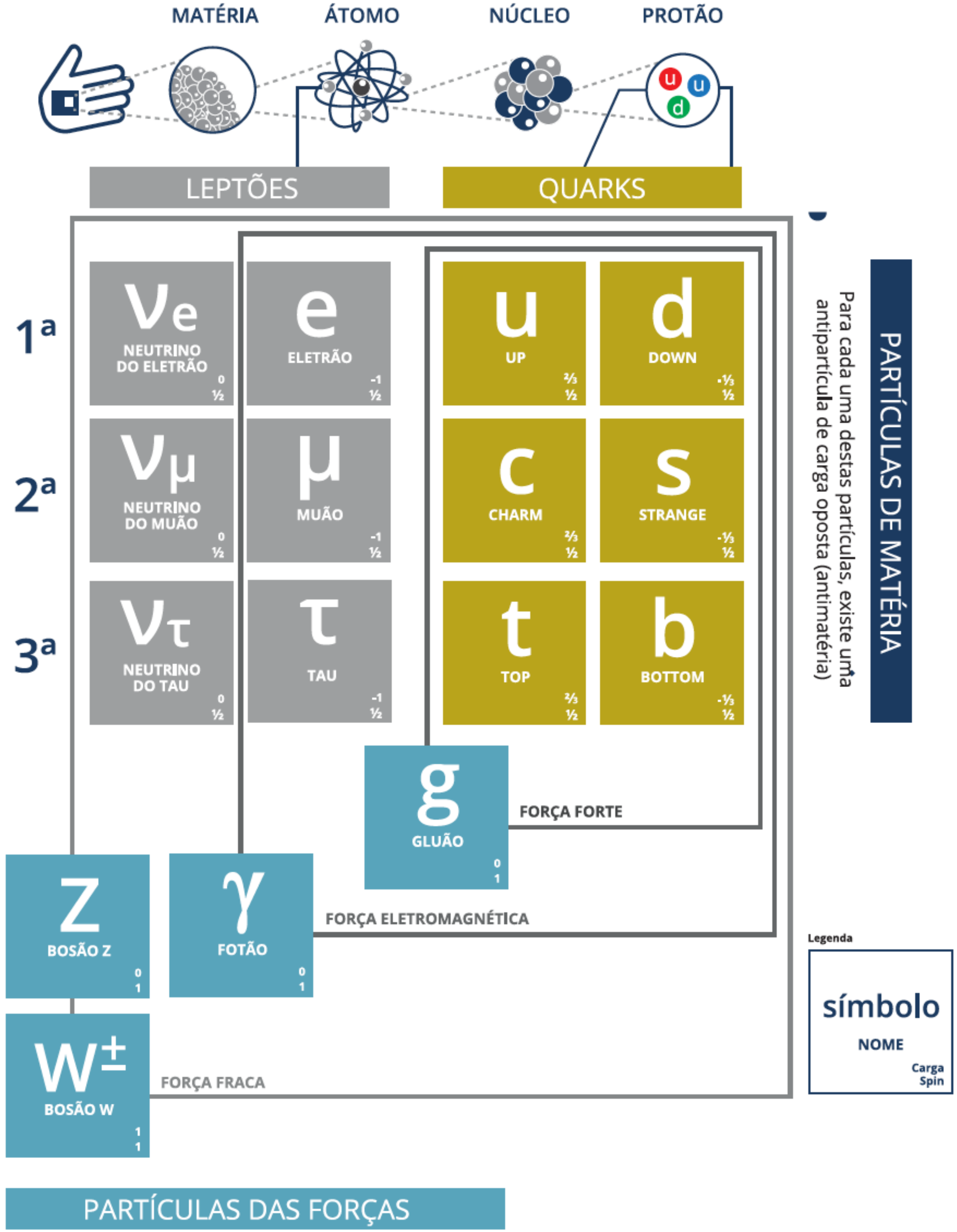


Introduction

The Standard Model particles and interactions, and some theory to set the scene…

Fundamental particles and forces

- Electromagnetic:
  - Carried by photons
  - Acts on electrical charge
- Weak:
  - Carried by:
    - $W^{\pm}$ (charged current)
    - Z^0 (neutral current)
  - Acts on weak isospin
- Strong:
  - Carried by 8 gluons
  - Acts on colour



Lagrangians, symmetries and all that

Lagrangians in classical mechanics

The equations of motion of a system are derived from a scalar **Lagrangian** function of **generalized coordinates** and **velocities** (time derivatives of the coordinates)

$$L(q, \dot{q}) = T - V$$

From minimizing the action S, get the **Euler-Lagrange equations**:

$$S = \int dt L(q_i, \dot{q}_i) \qquad \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = 0$$

For a point particle in a potential U, with $q_i = x, y, z$

$$L = \frac{1}{2}m\dot{q}_i^2 - U(q_i) \qquad \frac{d}{dt}(m\dot{q}_i) + \frac{\partial U}{\partial q_i} = 0 \qquad m\ddot{q}_i = -\frac{\partial U}{\partial q_i}$$

Symmetries and conservation laws

Noether's theorem:

If a system has a continuous symmetry property, then there are corresponding quantities whose values are conserved in time.

Simplest case:

Coordinates not explicitly appearing in the Lagrangian => Lagrangian invariant over a transformation of these coordinates

Example: point mass m orbiting in the field of a fixed mass M

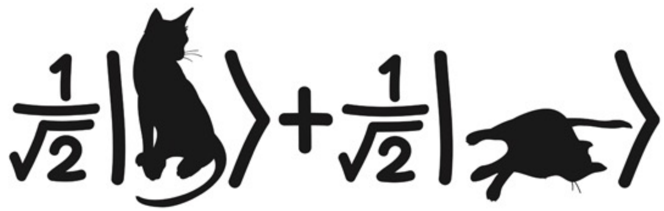
$$L(r,\phi,\dot{r},\dot{\phi}) = T - V = \frac{1}{2}m\dot{r}^2 + \frac{1}{2}mr^2\dot{\phi}^2 + \frac{GMm}{r}$$

Since the lagrangian doesn't depend explicitly on φ (symmetry with respect to rotations in space), the Euler-Lagrange equation gives

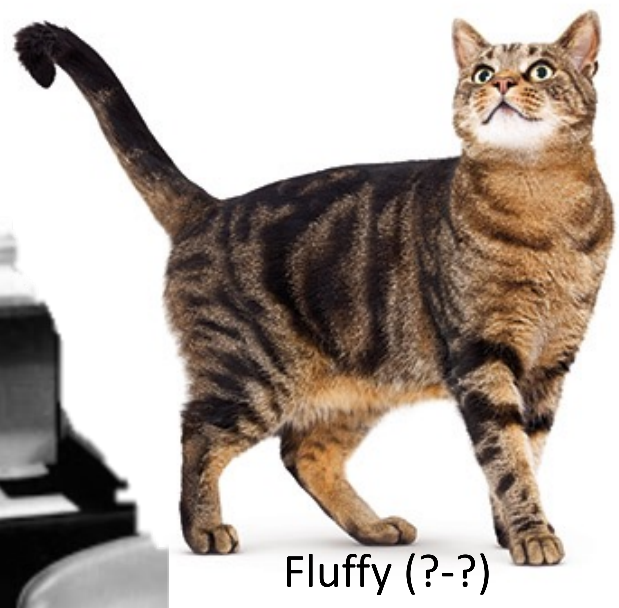
$$\frac{d}{dt}\left(\frac{\partial L}{\partial\dot{\phi}}\right) = 0 \Leftrightarrow \frac{\partial L}{\partial\dot{\phi}} = mr^2\dot{\phi} = J$$

Where the angular momentum J is a constant of motion!

Let’s go to quantum fields...



Richard Feynman
(1918 - 1988)

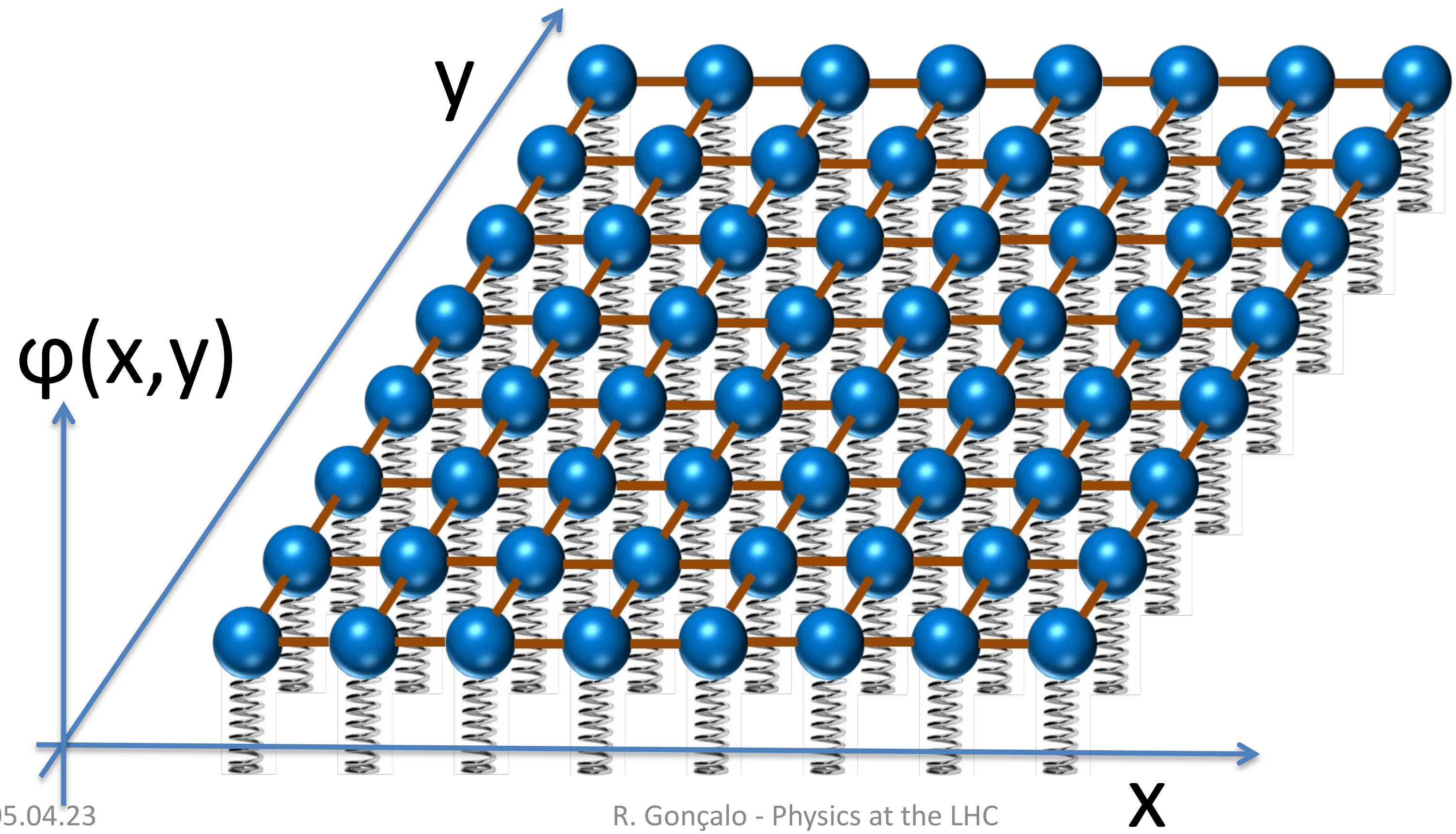


Fluffy (?-?)

Erwin
Schrödinger
(1887 - 1961)

Now in quantum field theory…

Imagine space as an infinite continuum of balls and springs, where each ball is connected to its neighbours by elastic bands. **Particles are perturbations of this field**



Generalized coordinates are now **fields** (dislocation of each spring)

$$q_i \rightarrow \phi_i(x^\mu)$$

In a relativistic theory we must treat space and time coordinates on an equal footing, so the derivatives in the classical equations are now

$$\frac{d}{dt}, \nabla \rightarrow \partial_\mu = \left(\frac{\partial}{\partial t}, \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right)$$

In place of a Lagrangian we have a **Lagrangian density** (we call it Lagrangian anyway, just to be confusing)

$$L(q_i, \tfrac{dq_i}{dt}) \rightarrow \mathcal{L}(\phi_i, \partial_\mu \phi_i) \quad \text{with:} \quad L = \int \mathcal{L} d^3\boldsymbol{x}$$

The new Euler-Lagrange equation now becomes

$$\partial_\mu\left(\frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi_i)}\right) - \frac{\partial \mathcal{L}}{\partial \phi_i} = 0$$

- Example Lagrangians and equations of motion:
- Klein-Gordon Lagrangian for spin 0 particles (scalars):

$$\mathcal{L}_{KG} = \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2} m^2 \phi^2$$

$$\boxed{\partial_\mu \partial^\mu \phi + m^2 \phi = 0}$$

- Dirac Lagrangian for spin ½ particles (fermions):

$$\mathcal{L}_D = i\bar{\psi}\gamma^\mu \partial_\mu \psi - m\bar{\psi}\psi$$

$$\boxed{i\gamma^\mu \partial_\mu \psi - m\psi = 0}$$

- Proca Lagrangian for spin 1 (vector) particles:

$$\mathcal{L}_P = \frac{-1}{16\pi}(\partial^\mu A^\nu - \partial^\nu A^\mu)(\partial_\mu A_\nu - \partial_\nu A_\mu) + \frac{1}{8\pi} m^2 A^\nu A_\nu$$

$$\boxed{\partial_\mu(\partial^\mu A^\nu - \partial^\nu A^\mu) + m^2 A^\nu = 0}$$

- Important:

Mass terms in Lagrangian are quadratic in the fields

Global gauge invariance

Take the Dirac Lagrangian for a spinor field ψ representing a spin-½ particle, for example an electron:

$$\mathcal{L} = i\hbar\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi$$

It is invariant under a global U(1) phase transformation like:

$$\psi(x) \rightarrow \psi'(x) = e^{iq\chi}\psi(x)$$

Where χ is a constant

$$\mathcal{L}' = e^{-iq\chi}e^{iq\chi}(i\hbar\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi) = \mathcal{L}$$

Note: gauge invariance of the Dirac equation can be demonstrated to lead to conservation of probability current j^{μ}

$$j^{\mu} = (\rho, \mathbf{J}) = \overline{\psi}\gamma^{\mu}\psi$$

Local gauge invariance and interactions

If $\chi = \chi(x)$ then we get extra terms in the Lagrangian:

$$\begin{aligned}\mathcal{L}' &= ie^{-iq\chi}\bar{\psi}\gamma^{\mu}[e^{iq\chi}\partial_{\mu}\psi + iq(\partial_{\mu}\chi)e^{iq\chi}\psi] - me^{-iq\chi}e^{iq\chi}\bar{\psi}\psi \\ &= \mathcal{L} - q\bar{\psi}\gamma^{\mu}(\partial_{\mu}\chi)\psi\end{aligned}$$

But we can now make the Lagrangian invariant by adding an ***interaction term*** with a new **gauge** field $\boldsymbol{A_\mu}$ which transforms as:

$$A_{\mu} \rightarrow A'_{\mu} = A_{\mu} - \partial_{\mu}\chi$$

We get:

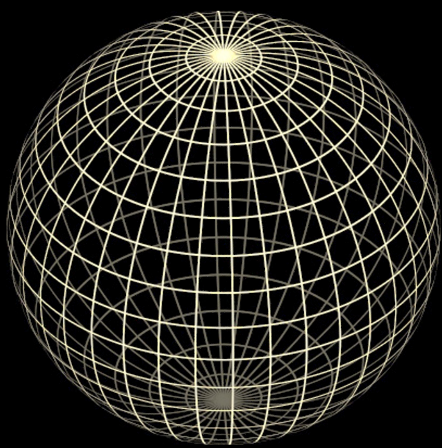
$$\mathcal{L} = i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi - q\bar{\psi}\gamma^{\mu}A_{\mu}\psi$$

Note:

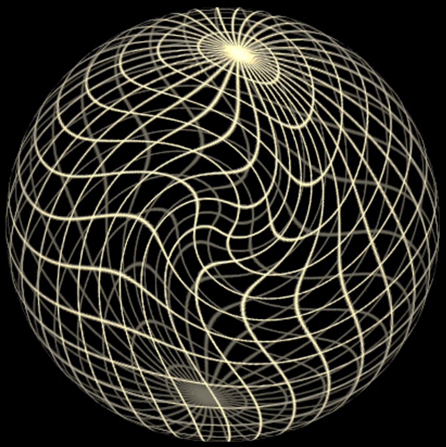
1. The new gauge field $\boldsymbol{A_\mu}$ is the photon in QED
2. The mass of the fermion is the coefficient of the term on $\bar{\psi}\psi$
3. There is no term in $\boldsymbol{A_\mu A^\mu}$ (the photon has zero mass)

$$\psi(x) \to \psi'(x) = e^{iq\chi}\psi(x)$$

Original sphere



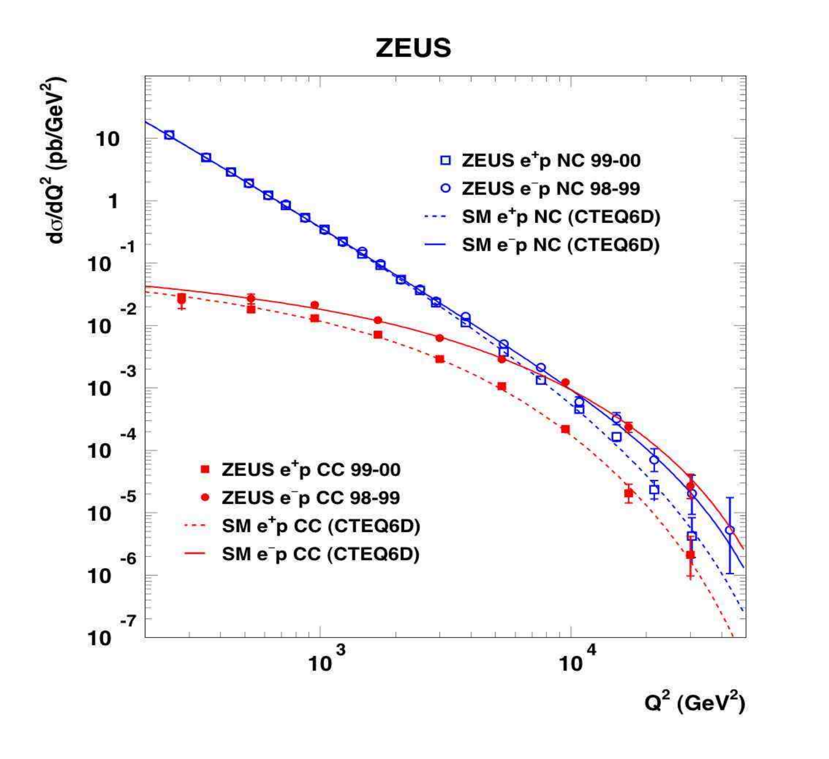
Local transformação



χ = **constant**

$\chi = \chi\,(x)$

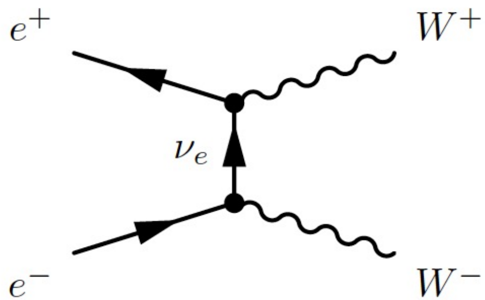
Weak Neutral Currents and Electroweak Unification

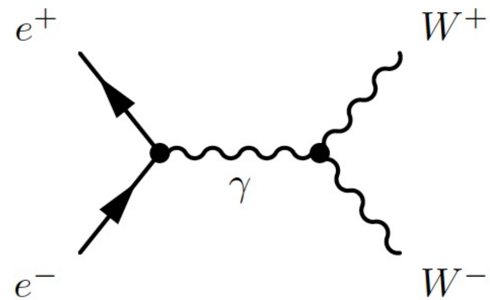


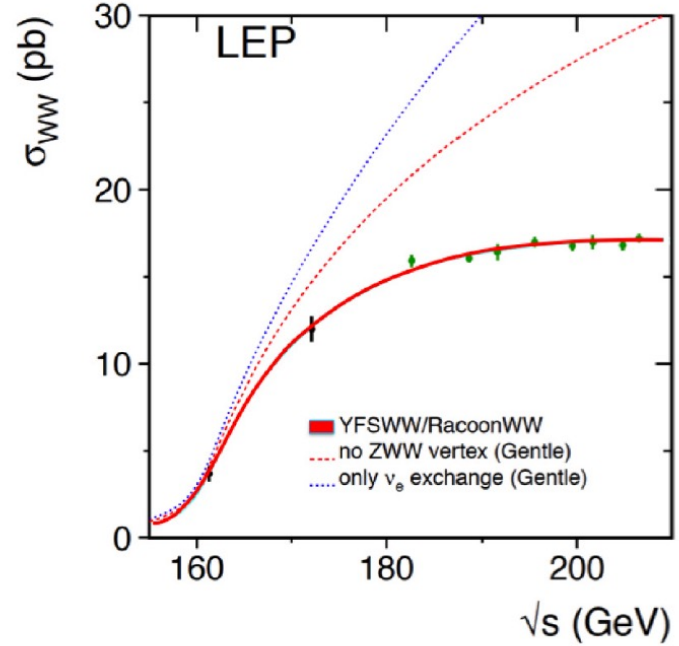
Electroweak Unification

- Weak CC interactions explained by $W^{\pm}$ boson exchange
- $W^{\pm}$ bosons are charged, thus they couple to the γ

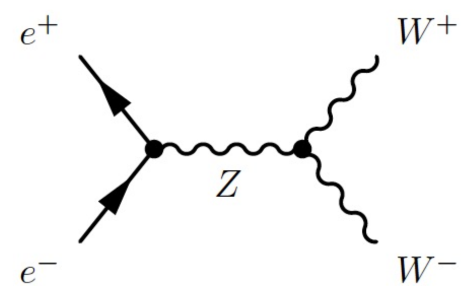
Consider $e^-e^+ \to W^+W^-$: 2 diagrams (+interference)







- Cross-section diverges at high energy
- Divergence cured by introducing Z boson
- Extra diagram for $e^-e^+ \to W^+W^-$
- Idea only works if γ, $W^{\pm}$, Z couplings are related



$\Rightarrow$ **Electroweak Unification**

Sheldon Glashow's "stumbling block"

- There are hints that EM and weak interactions have a common origin
  - Similar gauge structure
  - $W^{\pm}$ couples to charge
- But there are obvious differences:
  - Different masses of $W^{\pm}$, Z and photon
  - Structure of the vertex is different

PARTIAL-SYMMETRIES OF WEAK INTERACTIONS

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Received 9 September 1960

Abstract: Weak and electromagnetic interactions of the leptons are examined under the hypothesis that the weak interactions are mediated by vector bosons. With only an isotopic triplet of leptons coupled to a triplet of vector bosons (two charged decay-intermediaries and the photon) the theory possesses no partial-symmetries. Such symmetries may be established if additional vector bosons or additional leptons are introduced. Since the latter possibility yields a theory disagreeing with experiment, the simplest partially-symmetric model reproducing the observed electromagnetic and weak interactions of leptons requires the existence of at least four vector-boson fields (including the photon). Corresponding partially-conserved quantities suggest leptonic analogues to the conserved quantities associated with strong interactions: strangeness and isobaric spin.

1. Introduction

At first sight there may be little or no similarity between electromagnetic effects and the phenomena associated with weak interactions. Yet certain remarkable parallels emerge with the supposition that the weak interactions are mediated by unstable bosons. Both interactions are universal, for only a single coupling constant suffices to describe a wide class of phenomena: both interactions are generated by vectorial Yukawa couplings of spin-one fields ††. Schwinger first suggested the existence of an "isotopic" triplet of vector fields whose universal couplings would generate both the weak interactions and electromagnetism — the two oppositely charged fields mediate weak interactions and the neutral field is light [2]). A certain ambiguity beclouds the self-interactions among the three vector bosons; these can equivalently be interpreted as weak or electromagnetic couplings. The more recent accumulation of experimental evidence supporting the $\Delta I = \frac{1}{2}$ rule characterizing the non-leptonic decay modes of strange particles indicates a need for at least one additional neutral intermediary [3]).

The mass of the charged intermediaries must be greater than the K-meson mass, but the photon mass is zero — surely this is the principal stumbling block in any pursuit of the analogy between hypothetical vector mesons and photons. It is a stumbling block we must overlook. To say that the decay intermediaries

Electroweak Gauge Theory

- Postulate invariance under a gauge transformation like:

$$\psi \to \psi' = e^{ig\vec{\sigma}.\vec{\Lambda}(\vec{r},t)}\psi$$

  an "SU(2)" transformation (σ are 2x2 matrices).
- Operates on the state of "weak isospin" – a "rotation" of the isospin state.
- Invariance under SU(2) transformations $\Rightarrow$ three massless gauge bosons (W_1, W_2, W_3) whose couplings are well specified.
- They also have self-couplings.

But this doesn't quite work...
Predicts W and Z have the same couplings – not seen experimentally!

Electroweak Gauge Theory

The solution...

- Unify QED and the weak force $\Rightarrow$ electroweak model
- "SU(2)xU(1)" transformation
  U(1) operates on the "weak hypercharge" $Y = 2(Q - I_3)$
  SU(2) operates on the state of "weak isospin, I"
- Invariance under SU(2)xU(1) transformations $\Rightarrow$ four massless gauge bosons W^+, W^-, W_3, B
- The two neutral bosons W_3 and B then **mix** to produce the physical bosons Z and γ
- Photon properties must be the same as QED $\Rightarrow$ predictions of the couplings of the Z in terms of those of the W and γ
- Still need to account for the masses of the W and Z. This is the job of the Higgs mechanism (later).

The GWS Model

The Glashow, Weinberg and Salam model treats EM and weak interactions as different manifestations of a single unified electroweak force (Nobel Prize 1979)

Start with 4 massless bosons W^+, W_3, W^- and B. The neutral bosons mix to give physical bosons (the particles we see), i.e. the $W^\pm$, Z, and γ.

$$\begin{pmatrix} W^+ \\ W_3 \\ W^- \end{pmatrix} ; \quad B \quad \rightarrow \quad \begin{pmatrix} W^+ \\ Z \\ W^- \end{pmatrix} ; \quad \gamma$$

Physical fields: W^+, Z, W^- and A (photon).

$$Z = W_3 \cos\theta_W - B \sin\theta_W$$

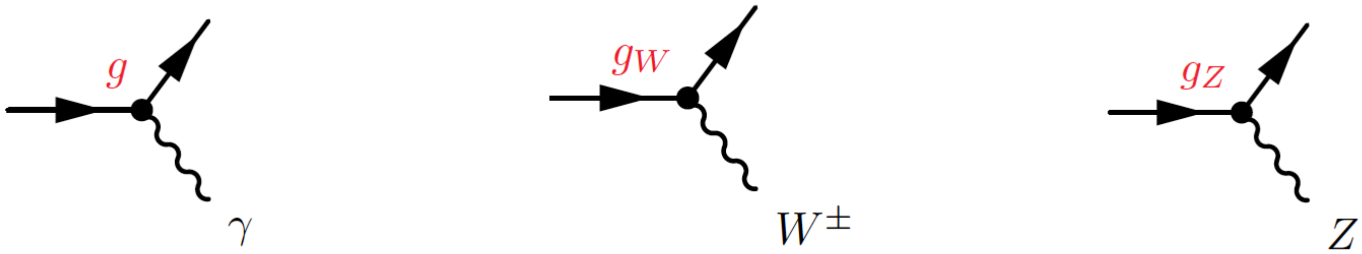
$$A = W_3 \sin\theta_W + B \cos\theta_W \qquad \theta_W \text{ Weak Mixing Angle}$$

$W^\pm$, Z "acquire" mass via the Higgs mechanism.

The GWS Model

The beauty of the GWS model is that it makes exact predictions of the $W^{\pm}$ and Z masses and of their couplings with only 3 free parameters.

Couplings given by α_{EM} and θ_W



$$\alpha_{EM} = \frac{e^2}{4\pi} \quad g \sim e \qquad g_W = \frac{e}{\sin\theta_W} \qquad g_Z = \frac{e}{\sin\theta_W \cos\theta_W} = \frac{g_W}{\cos\theta_W}$$

Masses also given by G_F and θ_W

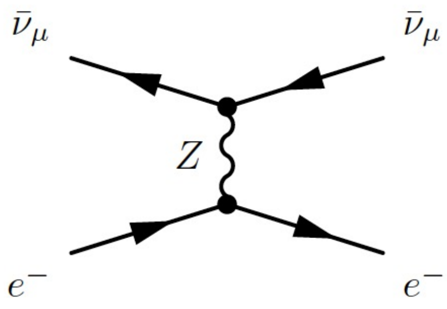
From Fermi theory

$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8m_W^2} = \frac{e^2}{8m_W^2\sin^2\theta_W} \qquad m_{W^{\pm}} = \left(\frac{\sqrt{2}e^2}{8G_F\sin^2\theta_W}\right)^{1/2} \qquad m_Z = \frac{m_W}{\cos\theta_W}$$

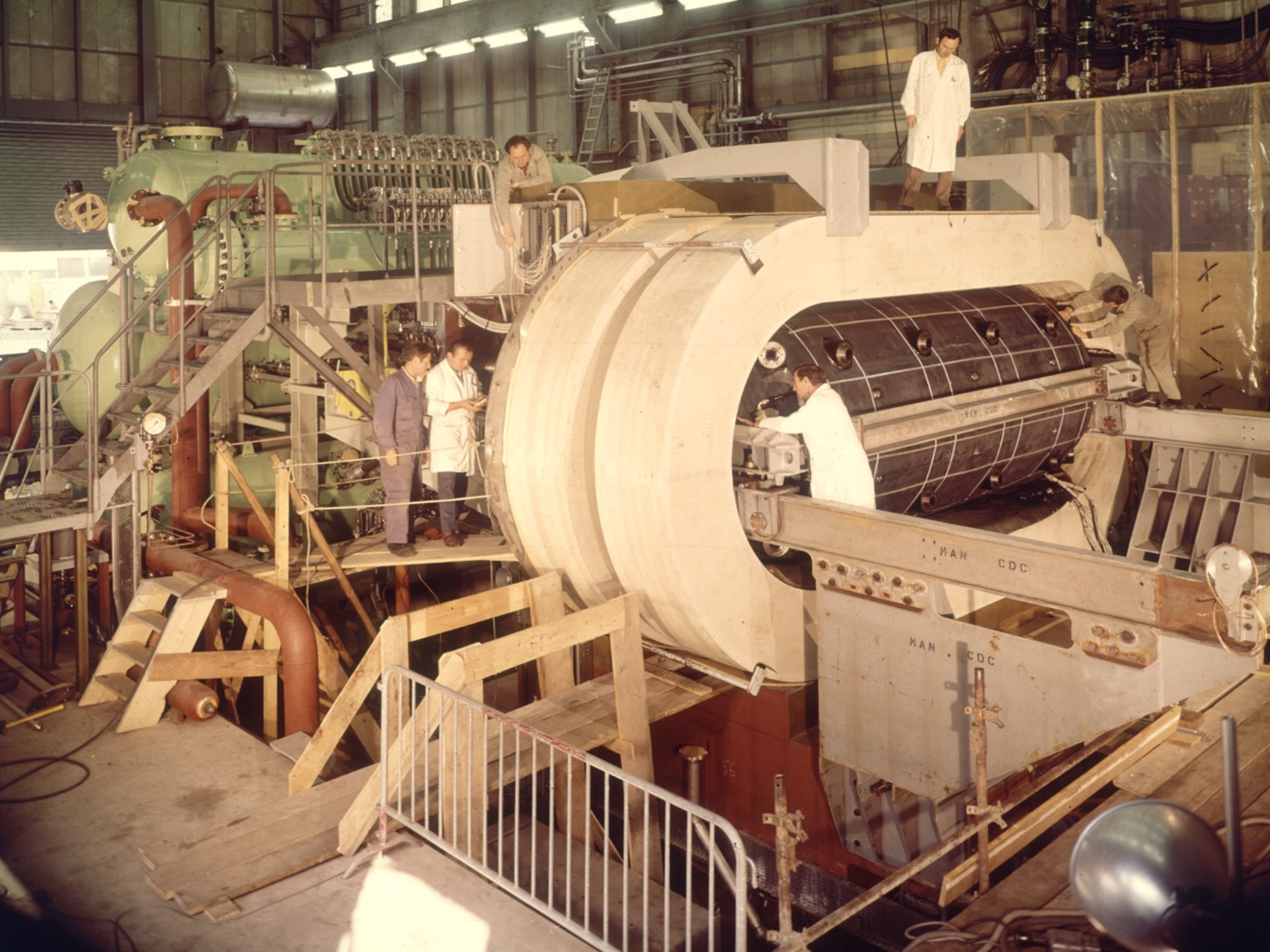
If we know α_{EM}, G_F, $\sin\theta_W$ (from experiment), everything else is defined.

Evidence for the GWS model

- **Discovery of Neutral Currents (1973)**
  The process $\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^-$ was observed.
  Only possible Feynman diagram (no $W^\pm$ diagram).
  Indirect evidence for Z.



Gargamelle Bubble Chamber at CERN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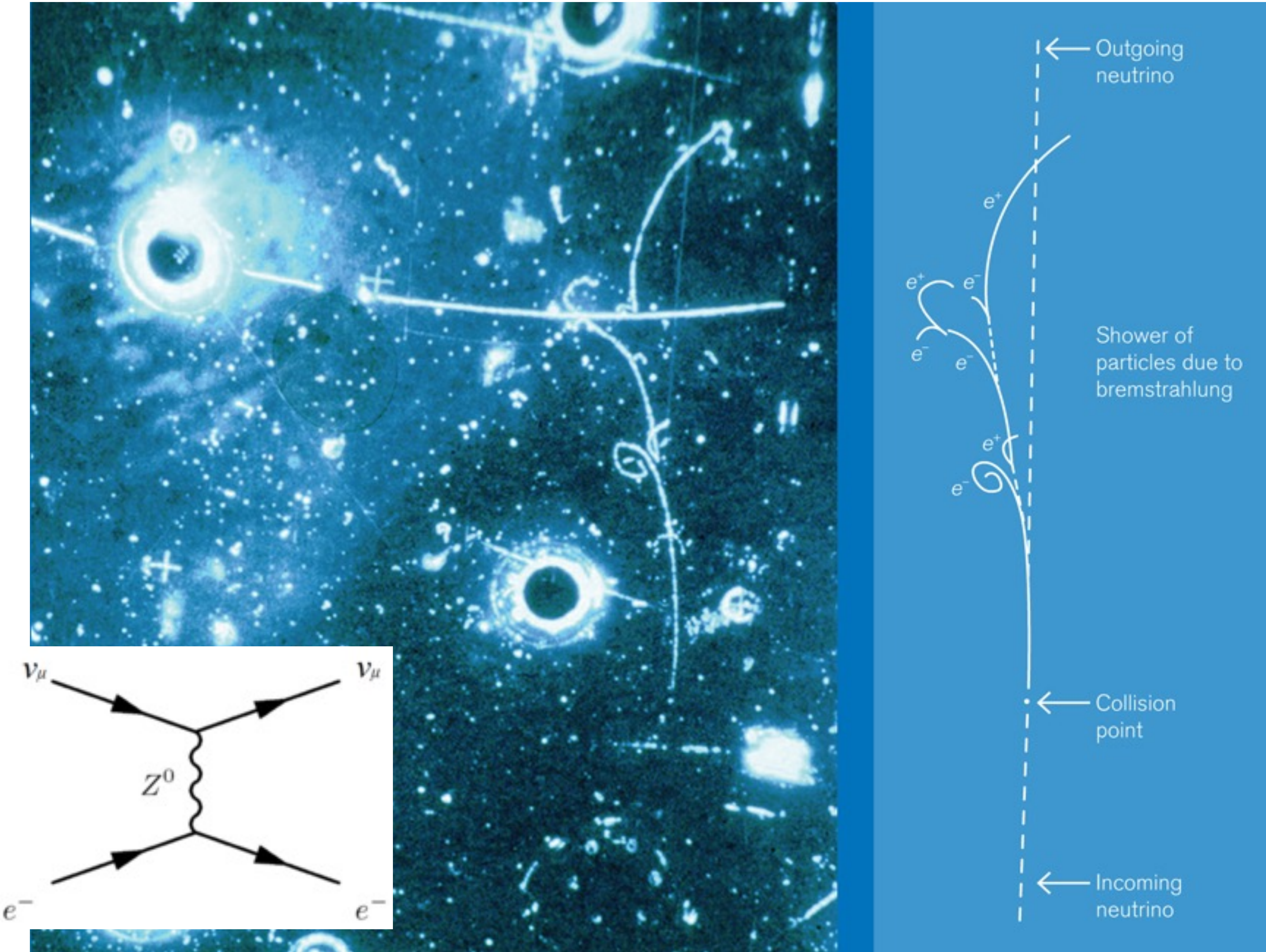
MAN CDC


ν_μ
ν_μ
Z^0
e^-
e^-
Outgoing neutrino
e^+
e^+
e^-
e^-
e^-
Shower of particles due to bremstrahlung
e^+
e^-
Collision point
Incoming neutrino

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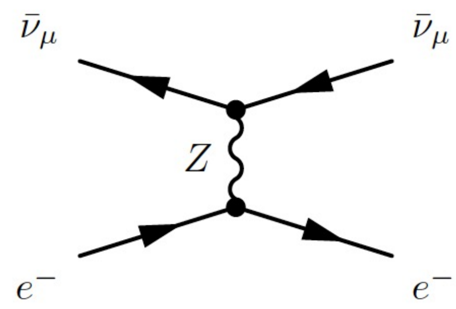
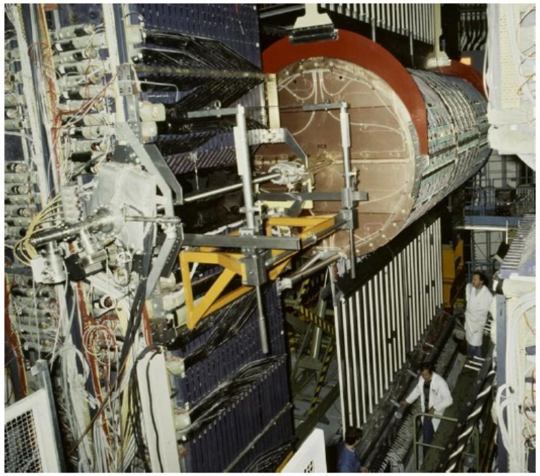
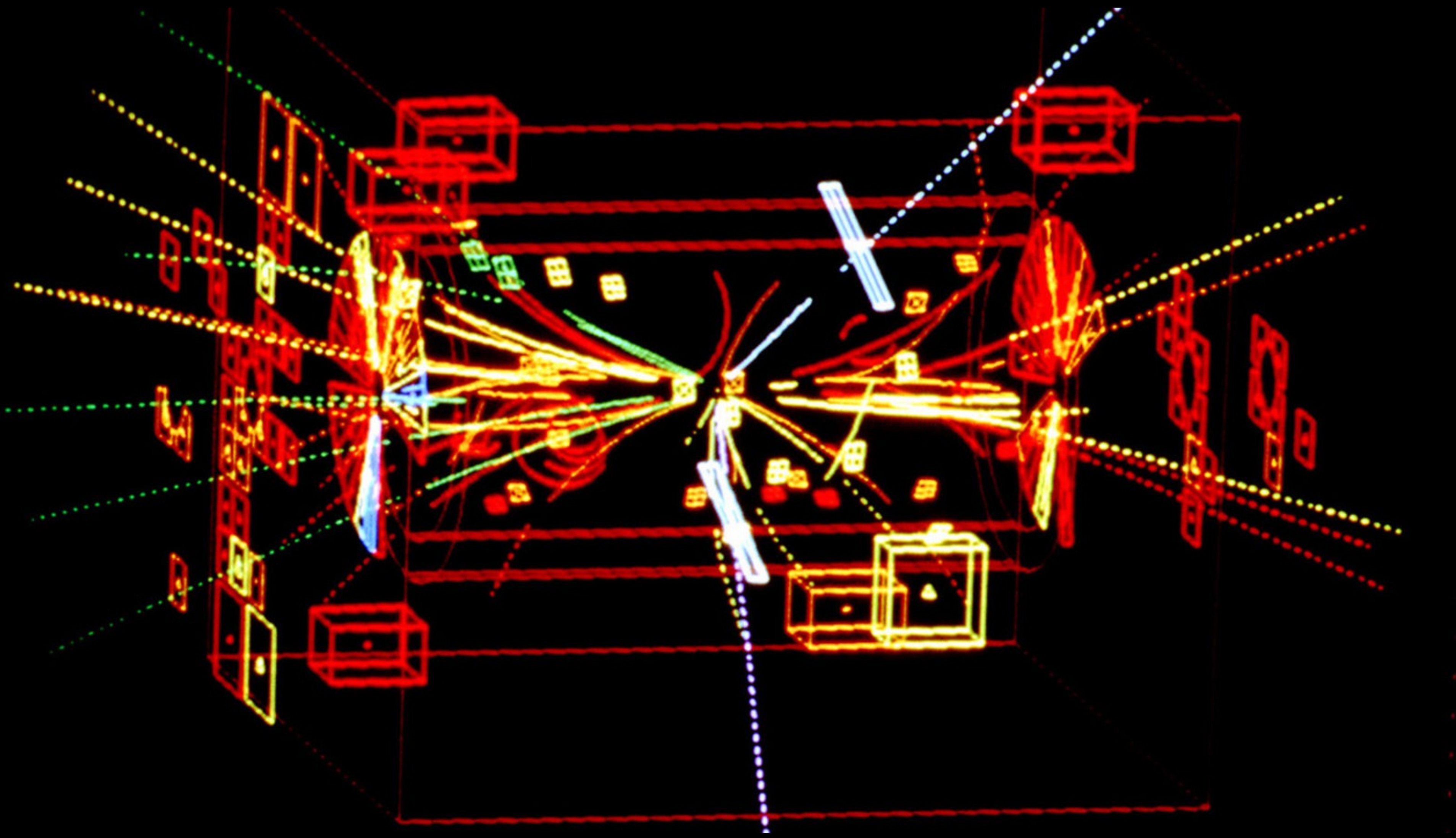


- **Direct Observation of $W^\pm$ and Z (1983)**
  First direct observation in $p\bar{p}$ collisions at $\sqrt{s} = 540\ \mathrm{GeV}$ via decays into leptons

$$p\bar{p} \to W^\pm + X \quad \hookrightarrow e^\pm \nu_e, \mu^\pm \nu_\mu \qquad p\bar{p} \to Z + X \quad \hookrightarrow e^+ e^-, \mu^+ \mu^-$$

UA1 Experiment at CERN
Used Super Proton Synchrotron
(now part of LHC!)





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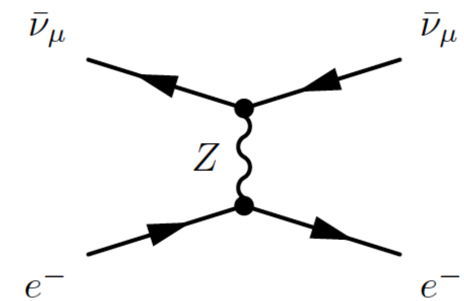

- **Direct Observation of $W^\pm$ and Z (1983)**
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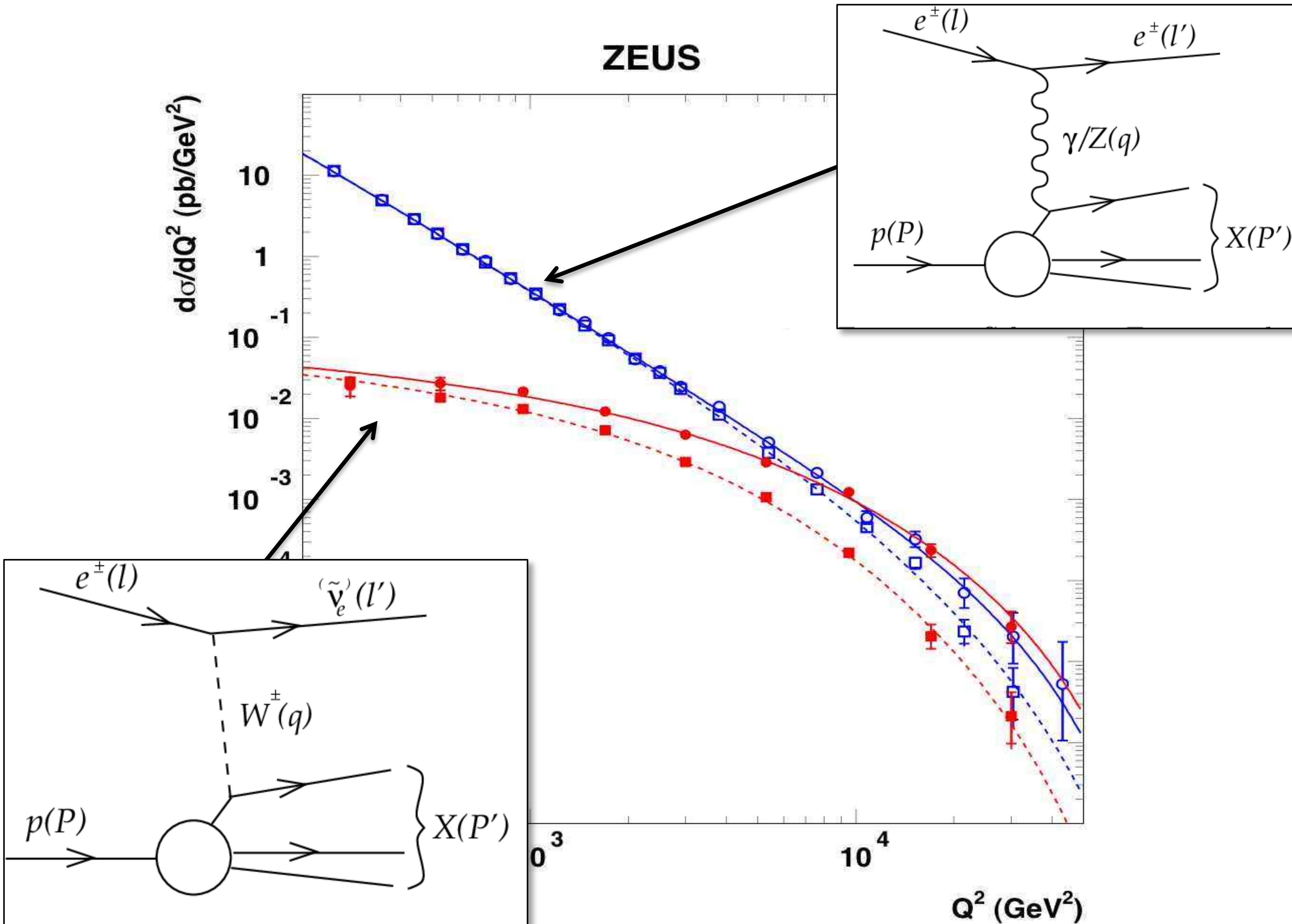
  $\hookrightarrow e^\pm \nu_e, \mu^\pm \nu_\mu \qquad \hookrightarrow e^+e^-, \mu^+\mu^-$

- **Precision Measurements of the Standard Model (1989-2000)**
  LEP e^+e^- collider provided many precision measurements of the Standard Model.

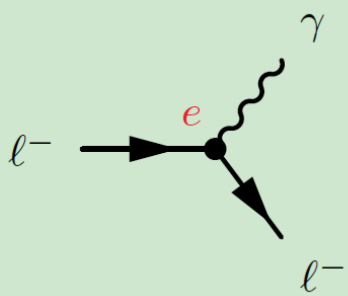
- Wide variety of different processes consistent with GWS model predictions and measure same value of

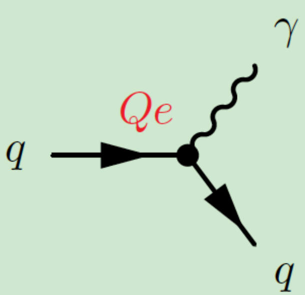
$$\sin^2\theta_W = 0.23113 \pm 0.00015 \qquad \theta_W \sim 29^\circ$$


ZEUS
dσ/dQ² (pb/GeV²)
Q² (GeV²)
e±(l)
e±(l′)
γ/Z(q)
p(P)
X(P′)
ν̃e(l′)
W±(q)

Strength of fundamental interactions

Electromagnetic (QED)



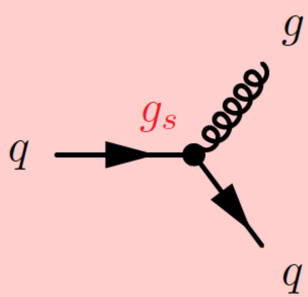


$$\alpha = \frac{e^2}{4\pi}$$

$q = u, d, s, c, b, t$

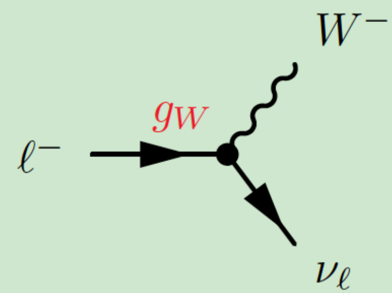
+ antiparticles

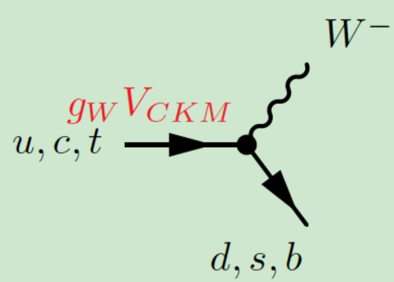
Strong (QCD)



$$\alpha_s = \frac{g_s^2}{4\pi}$$

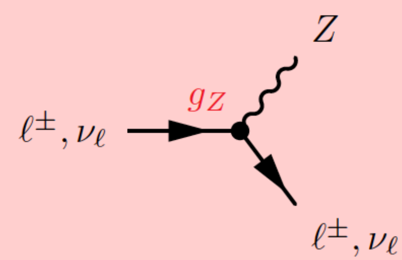
Weak CC

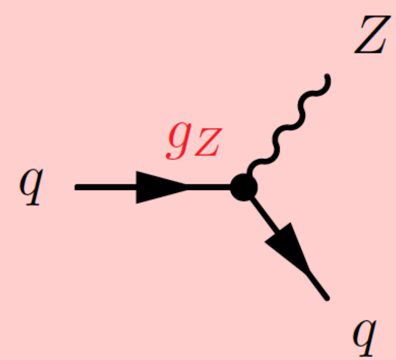




$$\alpha_W = \frac{g_W^2}{4\pi}$$

Weak NC





$$g_Z = \frac{g_W}{\cos\theta_W}$$

Now for the problems...

Problem 1: Mass of elementary particles and gauge bosons

What if we add a photon mass term to the QED Lagrangian?

$$\mathcal{L}_{QED} = \bar{\psi}(i\gamma^\mu\partial_\mu - m_e)\psi - e\bar{\psi}\gamma^\mu\psi A_\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_\gamma A_\mu A^\mu$$

To keep the Lagrangian gauge invariant (against a local $\mathrm{U}(1)$ local phase transformation) the photon field transforms as:

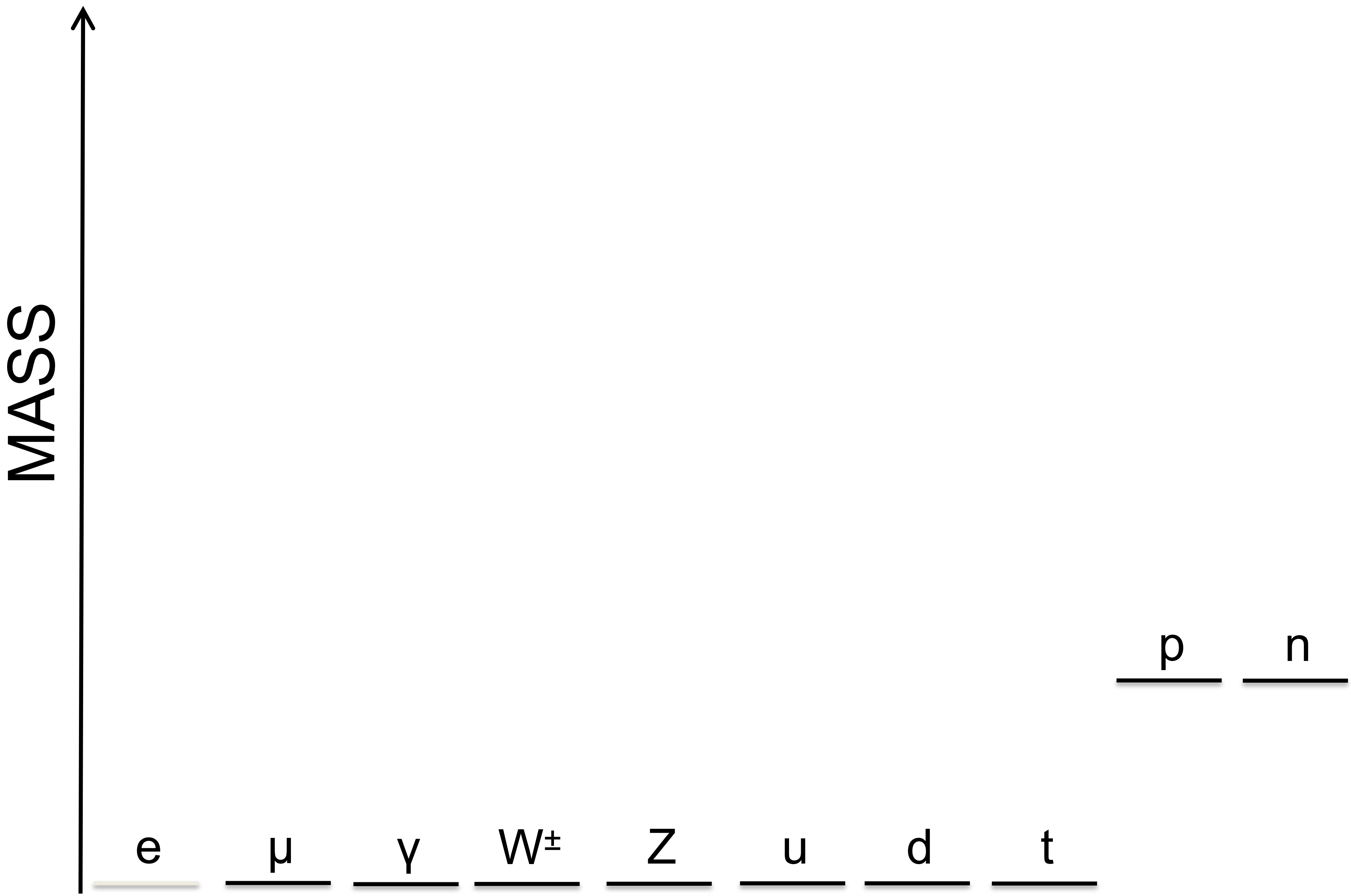
$$A_\mu \rightarrow A'_\mu = A_\mu - \partial_\mu\chi$$

But the A^μ mass term breaks the Lagrangian invariance:

$$\frac{1}{2}m_\gamma A_\mu A^\mu \rightarrow \frac{1}{2}m_\gamma(A_\mu - \partial_\mu\chi)(A^\mu - \partial^\mu\chi) \neq \frac{1}{2}m_\gamma A_\mu A^\mu$$

For the $SU(2)_L$ gauge symmetry transformations of the **weak interaction** the fermion mass term $m_e\psi\psi$ also breaks invariance!

It should not work…



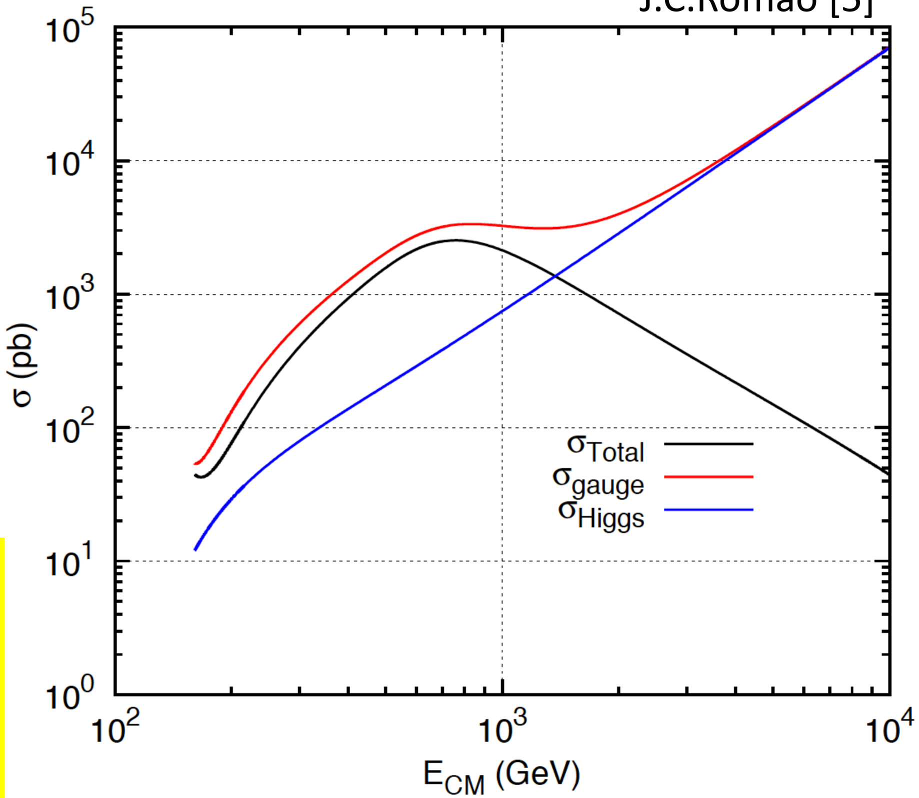
Problem 2:

Longitudinal gauge-boson scattering

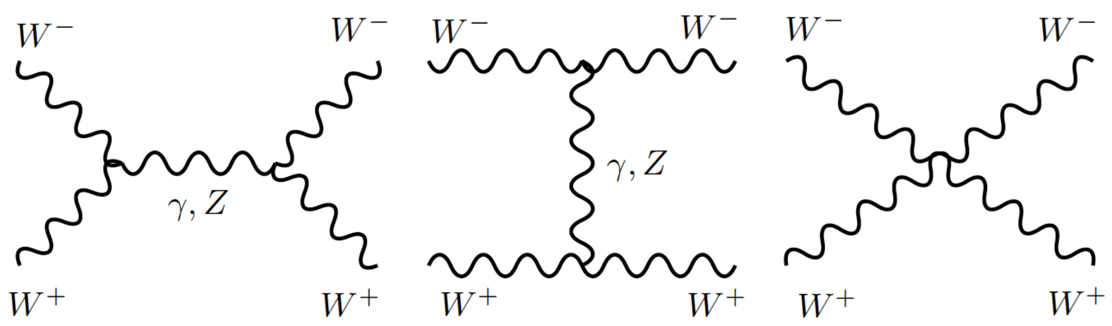
In the absence of the Higgs, some processes have cross sections that grow with the centre of mass energy of the collision… i.e. breaks unitarity!

The Higgs regulates the cross section through negative interference

J.C.Romão [5]



Bottom line: **the SM (without the Higgs mechanism) results in wrong calculations and breaks down for massive particles**



Feynman diagrams contributing to longitudinal WW scattering

The Higgs Mechanism

- Introduce a SU(2) doublet of spin-0 complex fields

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi 4 \end{pmatrix}$$

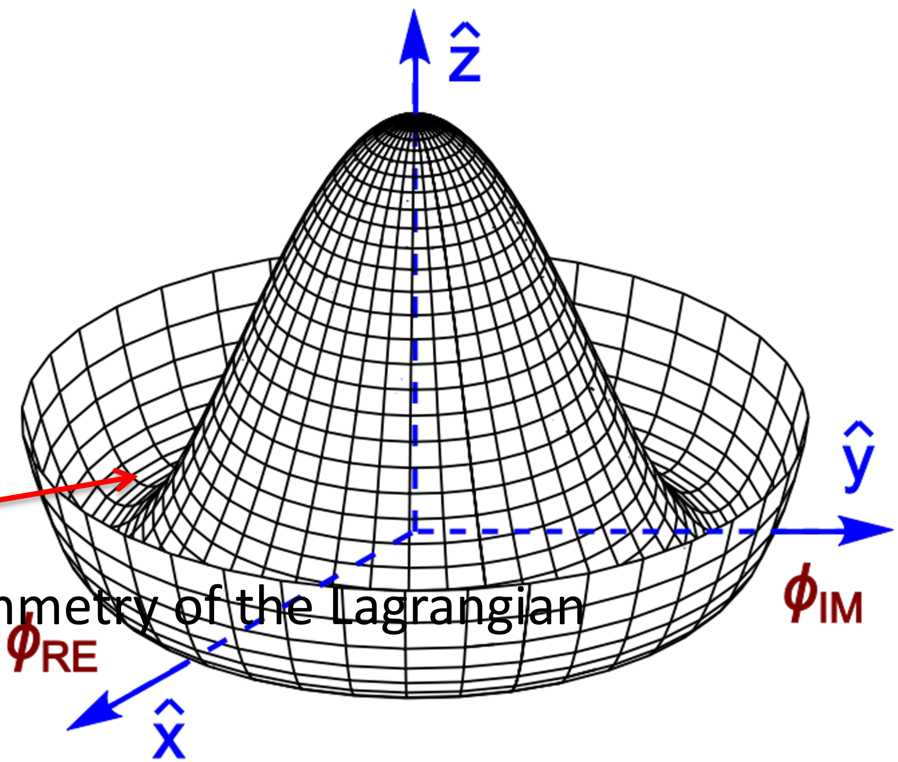
- New Lagrangian term:

$$\mathcal{L} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi)$$

- With a potential

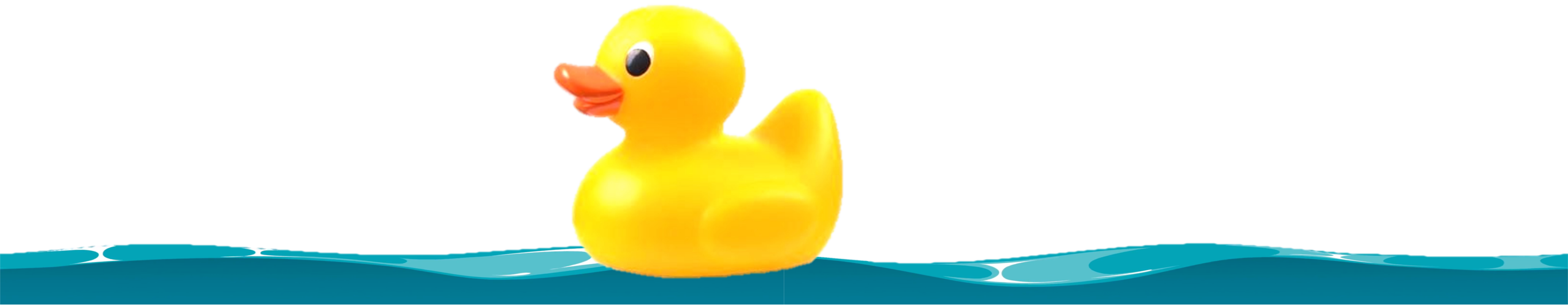
$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

- For λ>0, μ^2>0 the potential has a minimum at the origin
- For λ>0, μ^2<0 the potential has an infinite number of minima at:

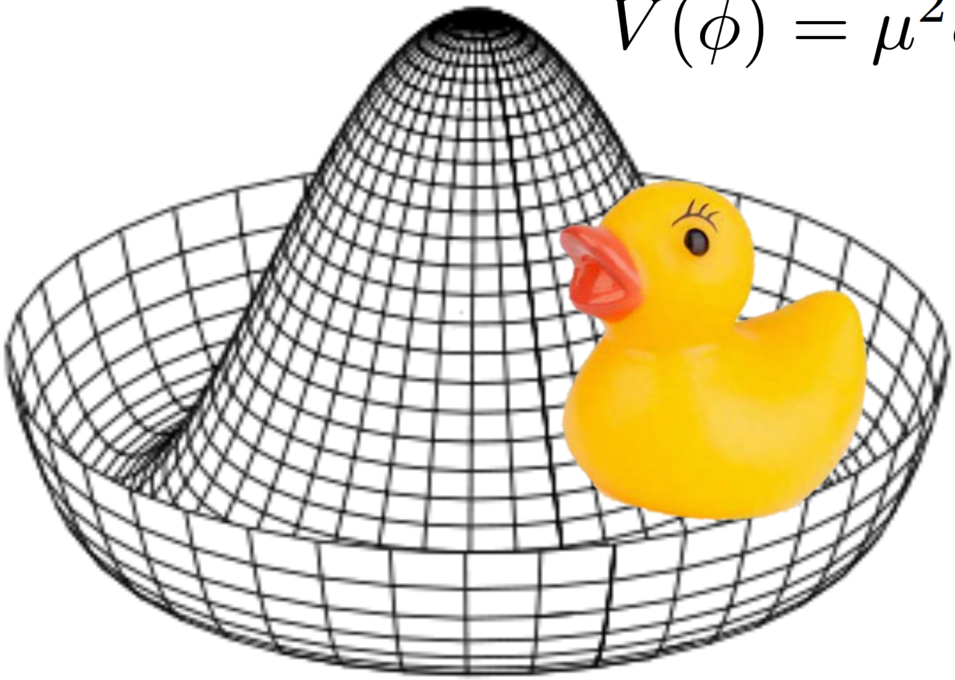


The cl $|\phi| = \frac{v}{\sqrt{2}} = \sqrt{-\frac{\mu^2}{2\lambda}}$

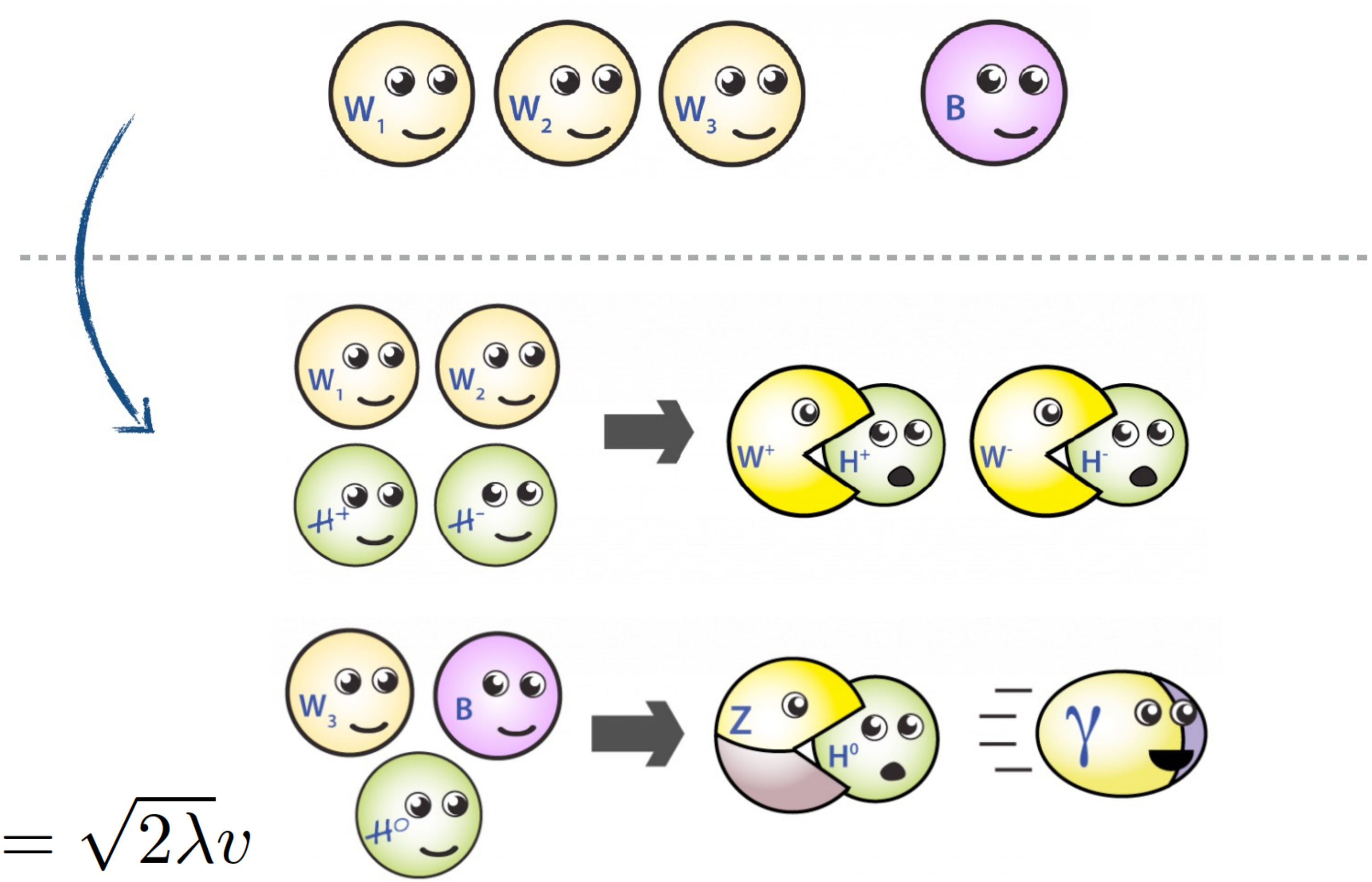
energy state of the field) breaks the symmetry of the Lagrangian



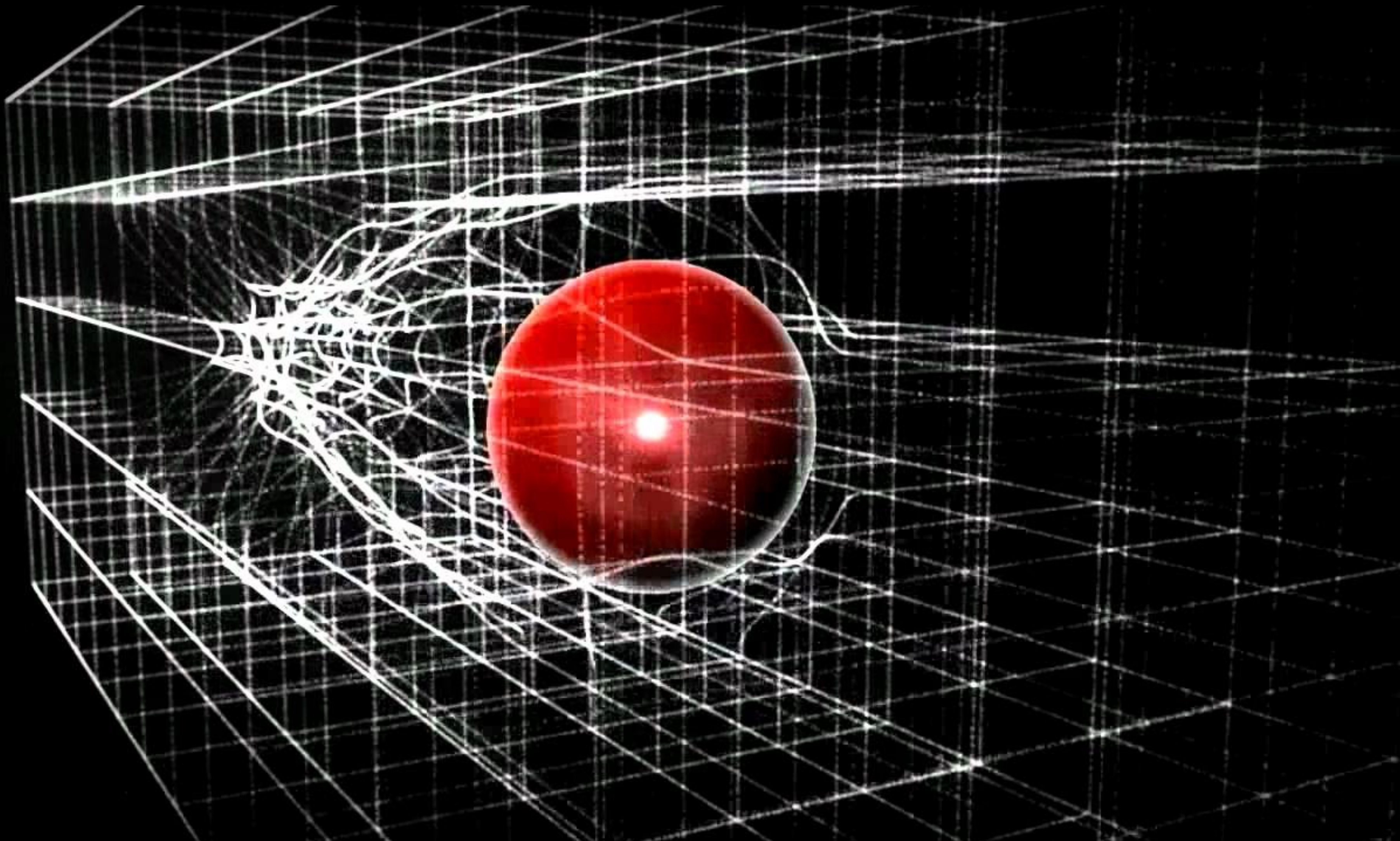
$$V(\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$



EWK Symmetry Breaking in Pictures



$$m_h = \sqrt{2\lambda} v$$



Higgs Properties

- Mass $m_h = \sqrt{2\lambda}v$
- Spin: 1 degree of freedom => 0
- Couplings:
- To gauge bosons

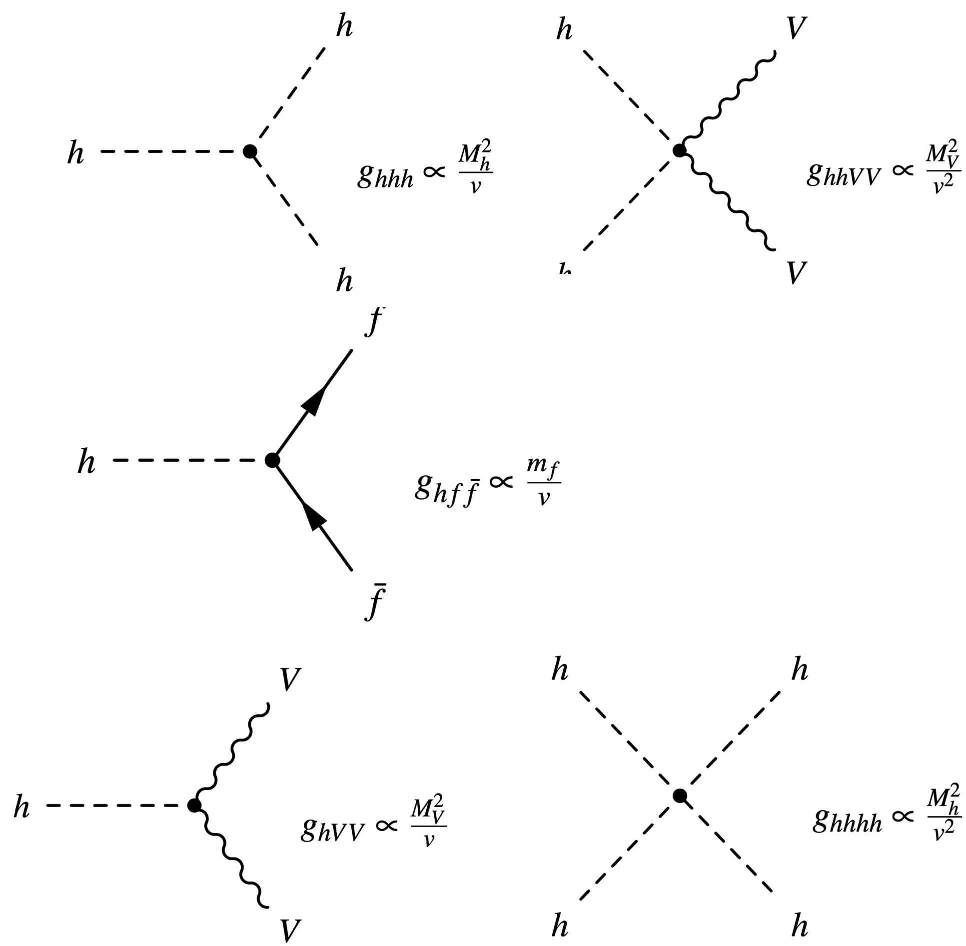
$$g_{hVV} \propto \frac{M_V^2}{v} \quad g_{hhVV} \propto \frac{M_V^2}{v^2}$$

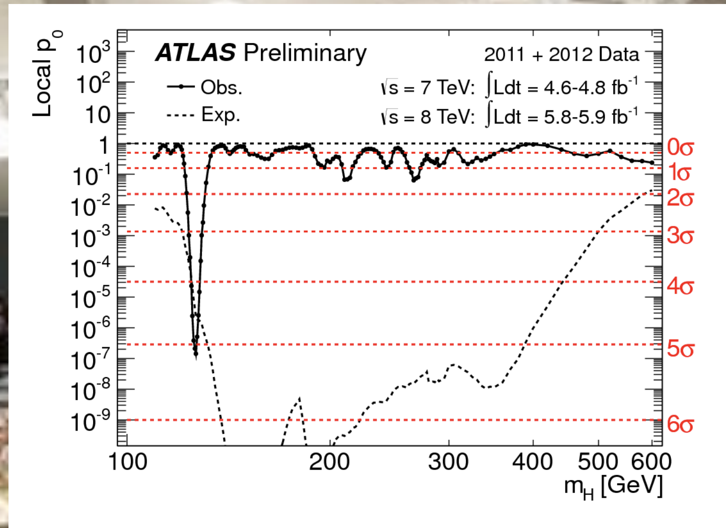
- Yukawa couplings to fermions

$$g_{hf\bar{f}} \propto \frac{m_f}{v}$$

- Self-couplings

$$g_{hhh} \propto \frac{M_h^2}{v} \quad g_{hhhh} \propto \frac{M_h^2}{v^2}$$





The Long Way to Discovery

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

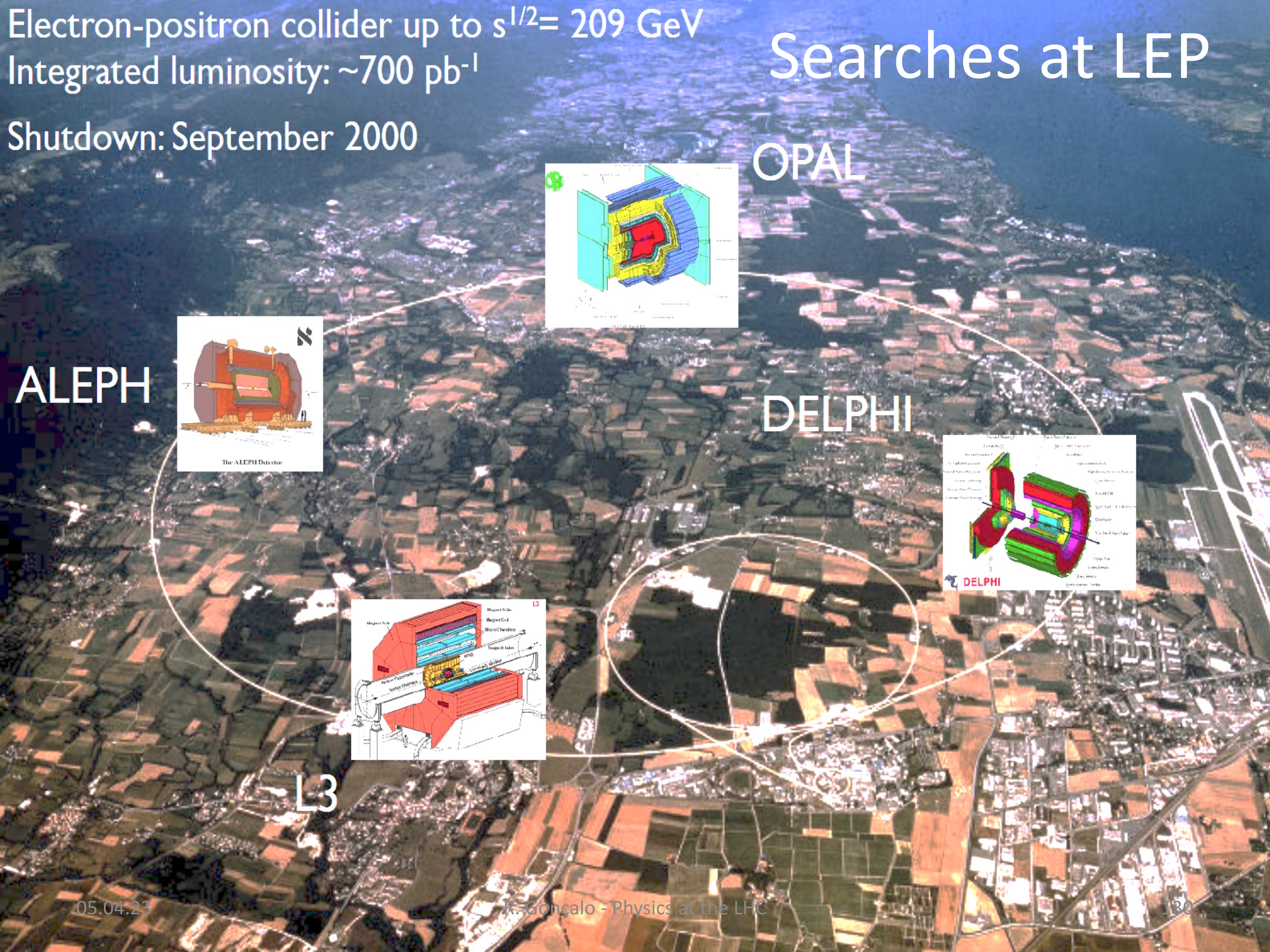
Received 7 November 1975

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3),4)] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Searches at LEP

Electron-positron collider up to $s^{1/2}$= 209 GeV
Integrated luminosity: ~700 pb^{-1}

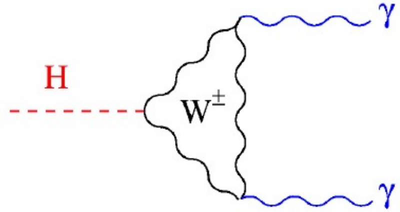
Shutdown: September 2000



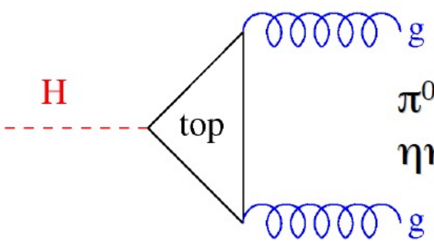
Low-mass searches at LEP

The decay branching ratios depend only on m_H:

- $m_H < 2m_e$: $H \rightarrow \gamma\gamma$ + large lifetime;



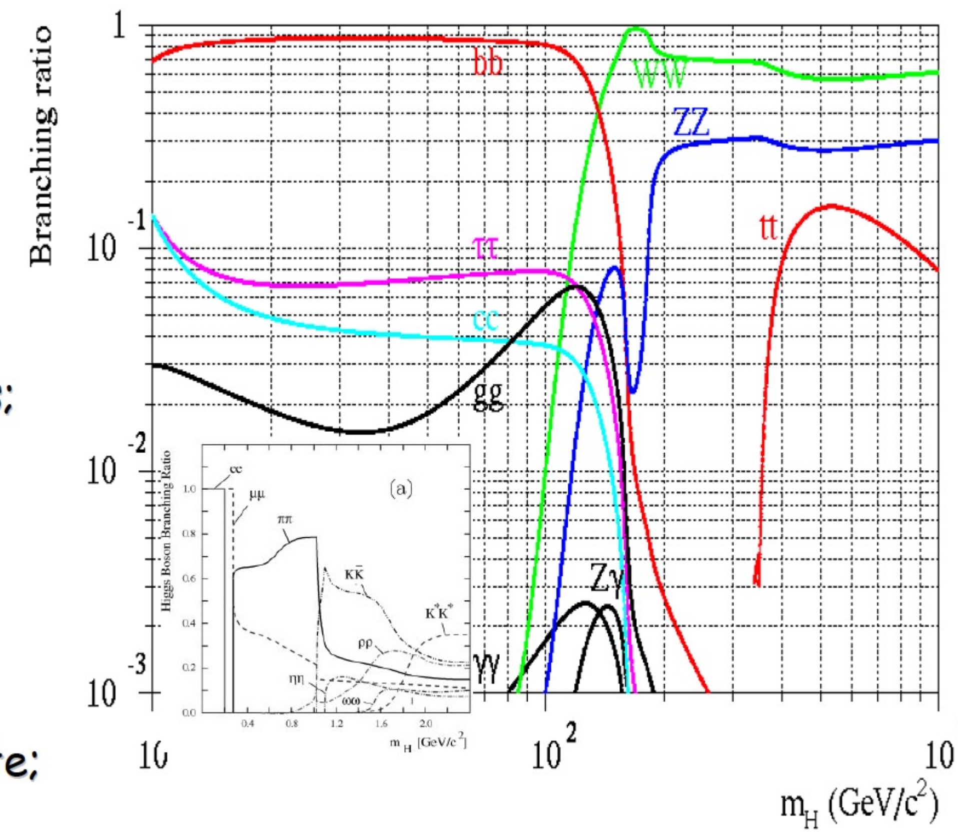
- $m_H < 2m_\mu$: $H \rightarrow e^+e^-$ dominates;
- $m_H < 2m_\pi$: $H \rightarrow \mu^+\mu^-$ dominates;
- $m_H <$ 3 - 4 GeV: $H \rightarrow gg$ dominates;



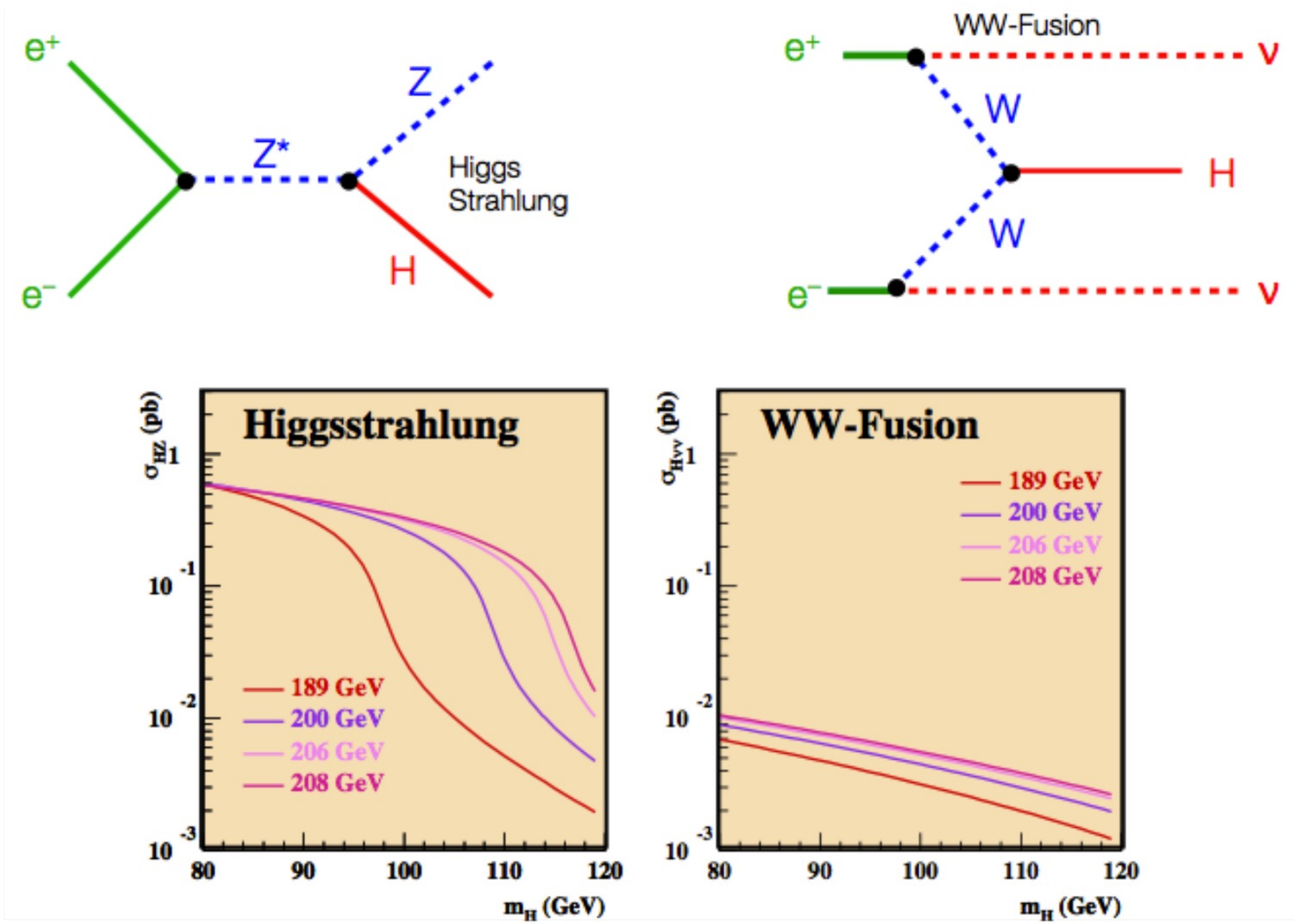
$\pi^0\pi^0$, $\pi^+\pi^-$, KK, $\eta\eta$, … etc

- $m_H < 2m_b$: $H \rightarrow \tau^+\tau^-$ and $c\bar{c}$ dominate;

- $m_H > 2m_b$ up to 1000 GeV/c^2:



Higher-mass Higgs production at LEP



Summary of all Higgs candidates found at LEP

Invariant mass of all candidates

In total 17 candidates selected

- 15.8 background events expected

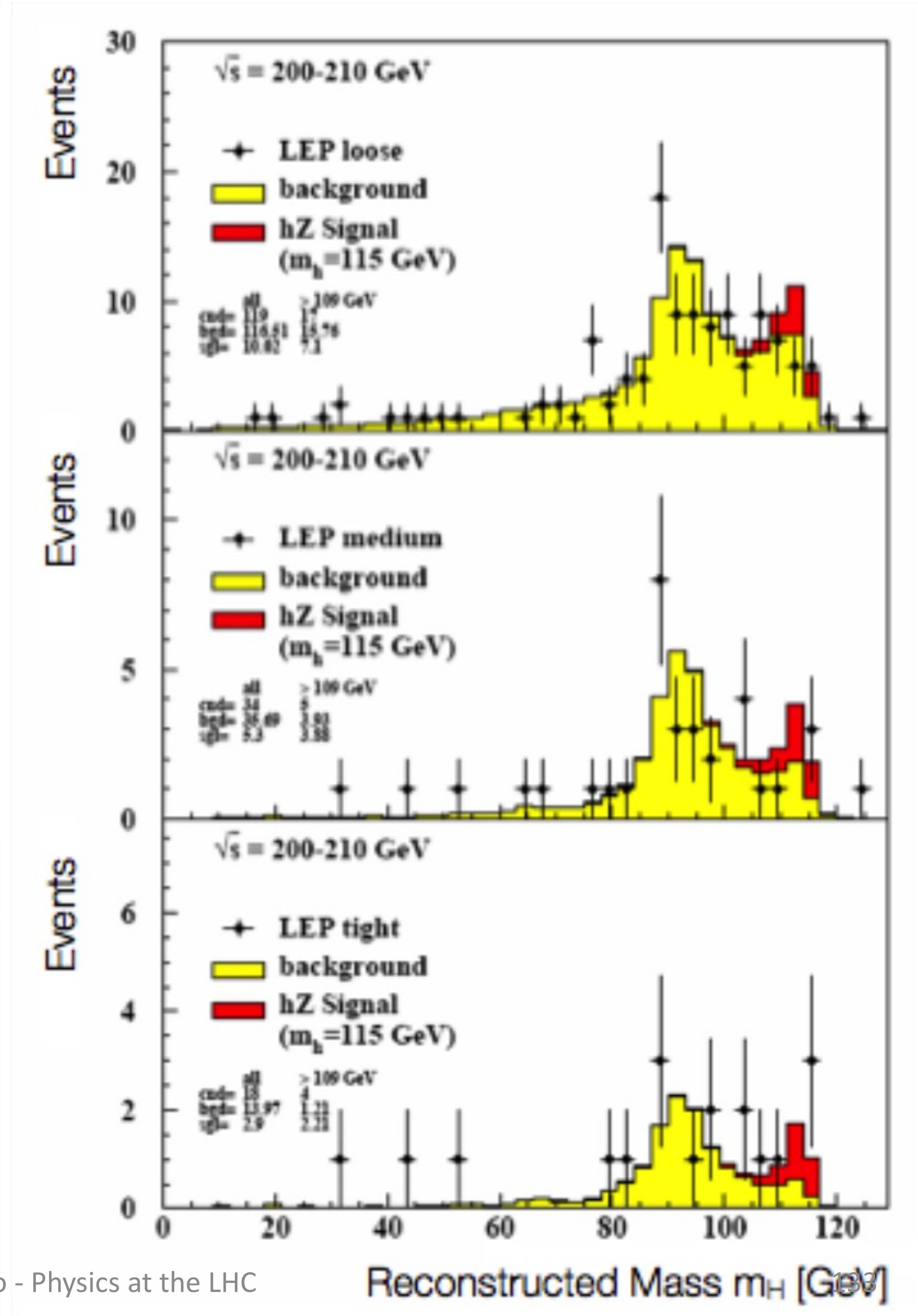
Expectation for m_H=115 GeV

- 8.4 events

Corresponding excess was not observed

Final verdict from LEP

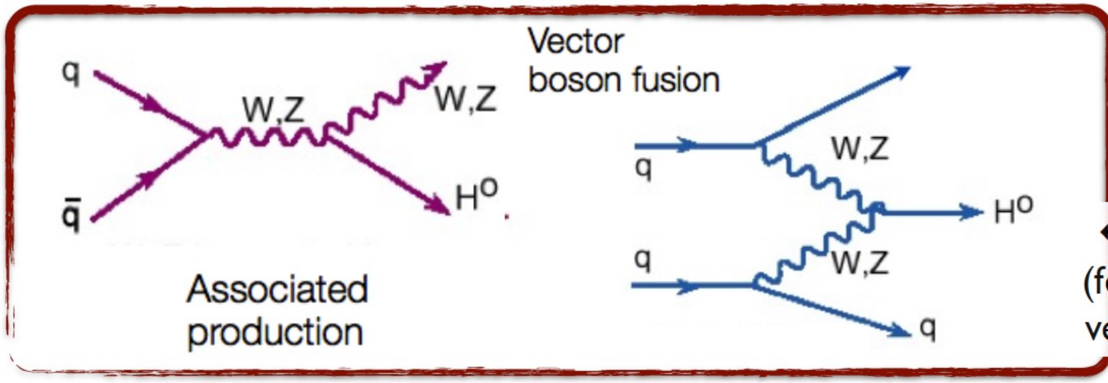
m_H>114.4 GeV @ 95% CL



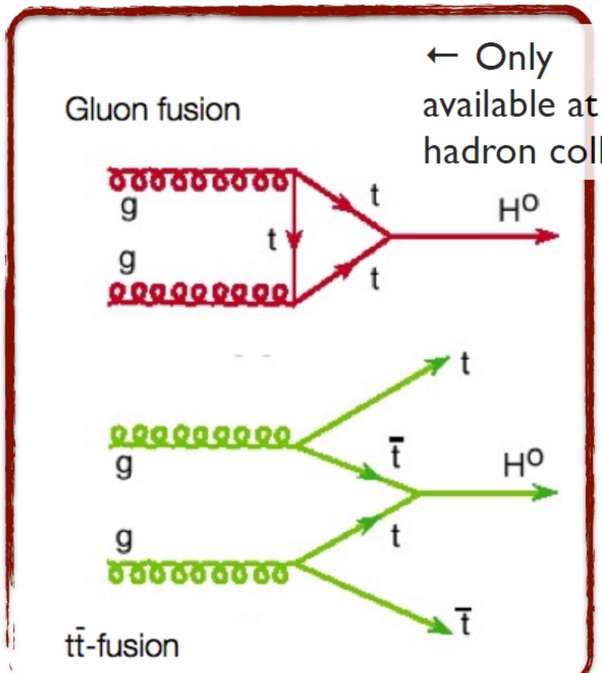
Searches at the Tevatron

Proton-anti-proton collider at $s^{1/2}$=1.96 TeV
First superconducting accelerator
Shutdown: 30 September 2011
Almost 10 fb^{-1} of data for analysis

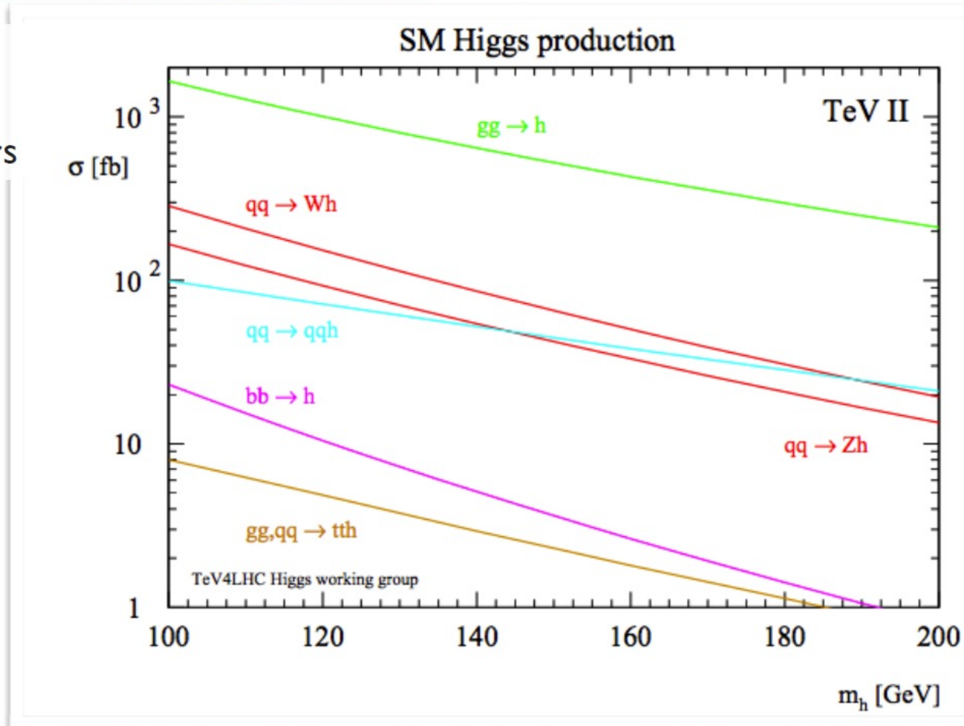
Higgs production at the Tevatron



← (fermion annihilation and vector boson scattering)



← Only available at hadron colliders



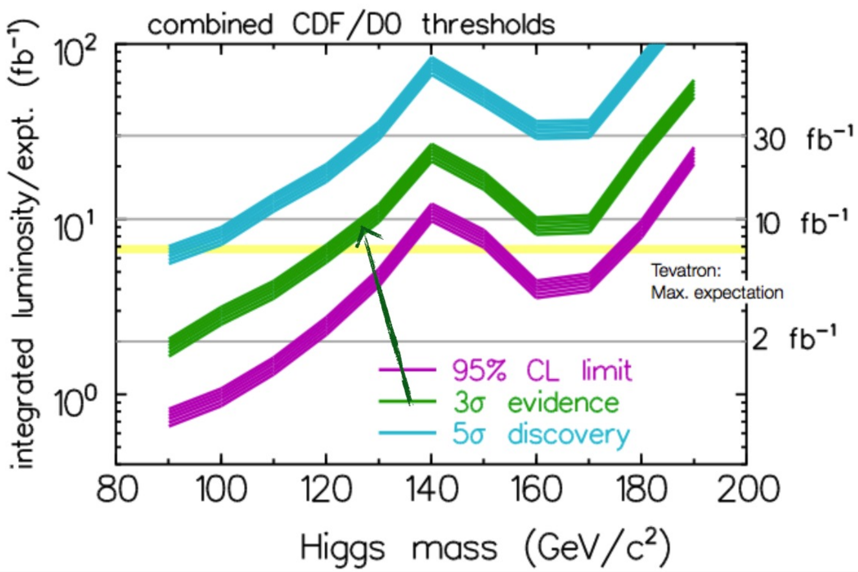
The final stand of the Tevatron

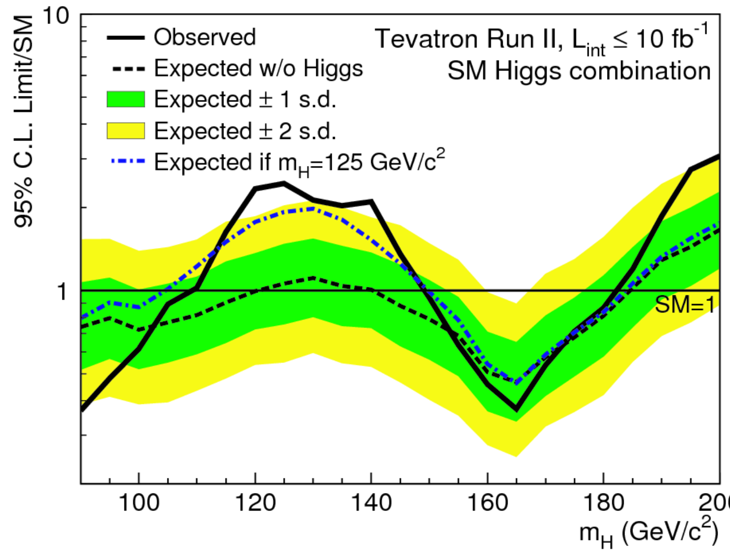
- By the end of its lifetime, the Tevatron had very sophisticated analyses of a huge number of channels

- By that time the LHC was collecting data and analysing it very fast

- The CDF and D0 experiments obtained an excess of around 3 standard deviations in the mass range $115<M_H<140$ GeV

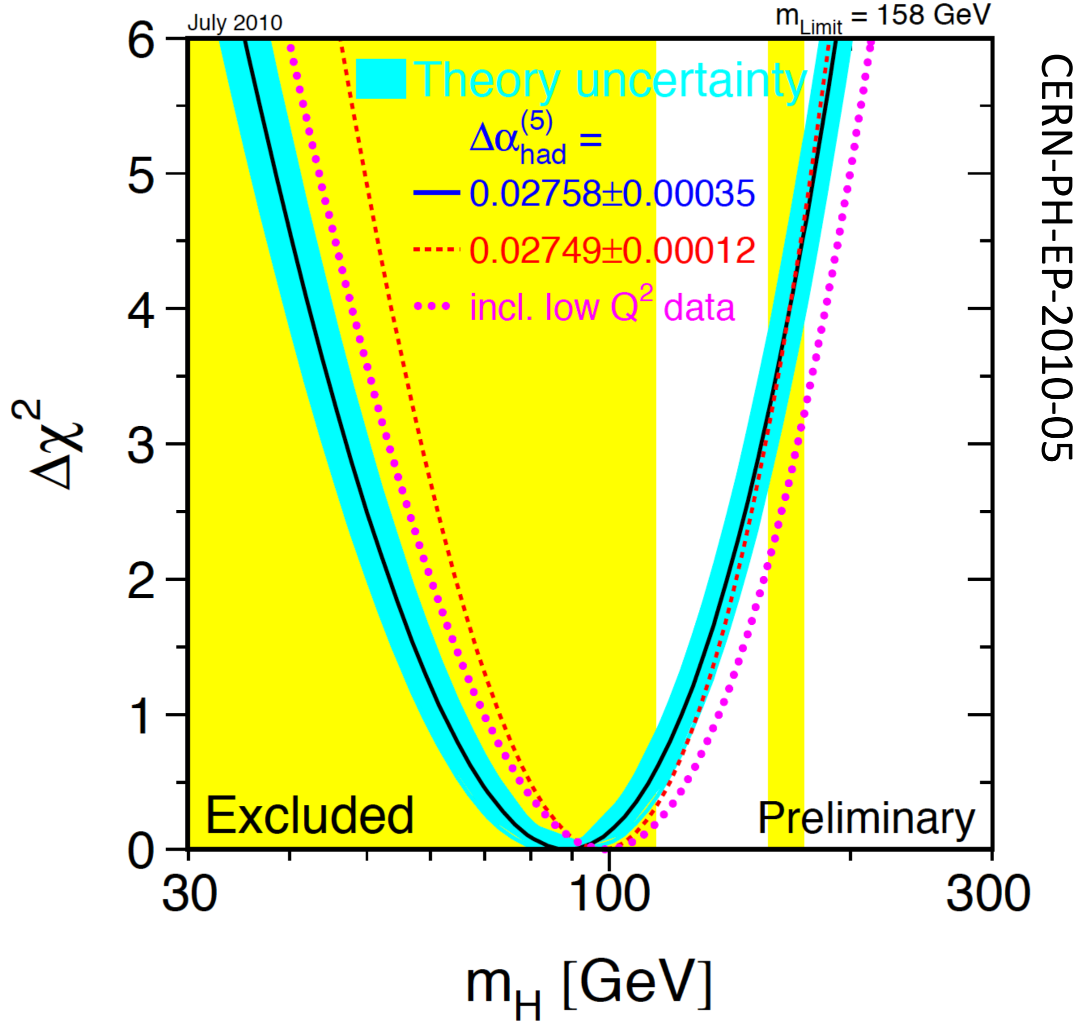
- Not enough to claim discovery, but consistent with the LHC results





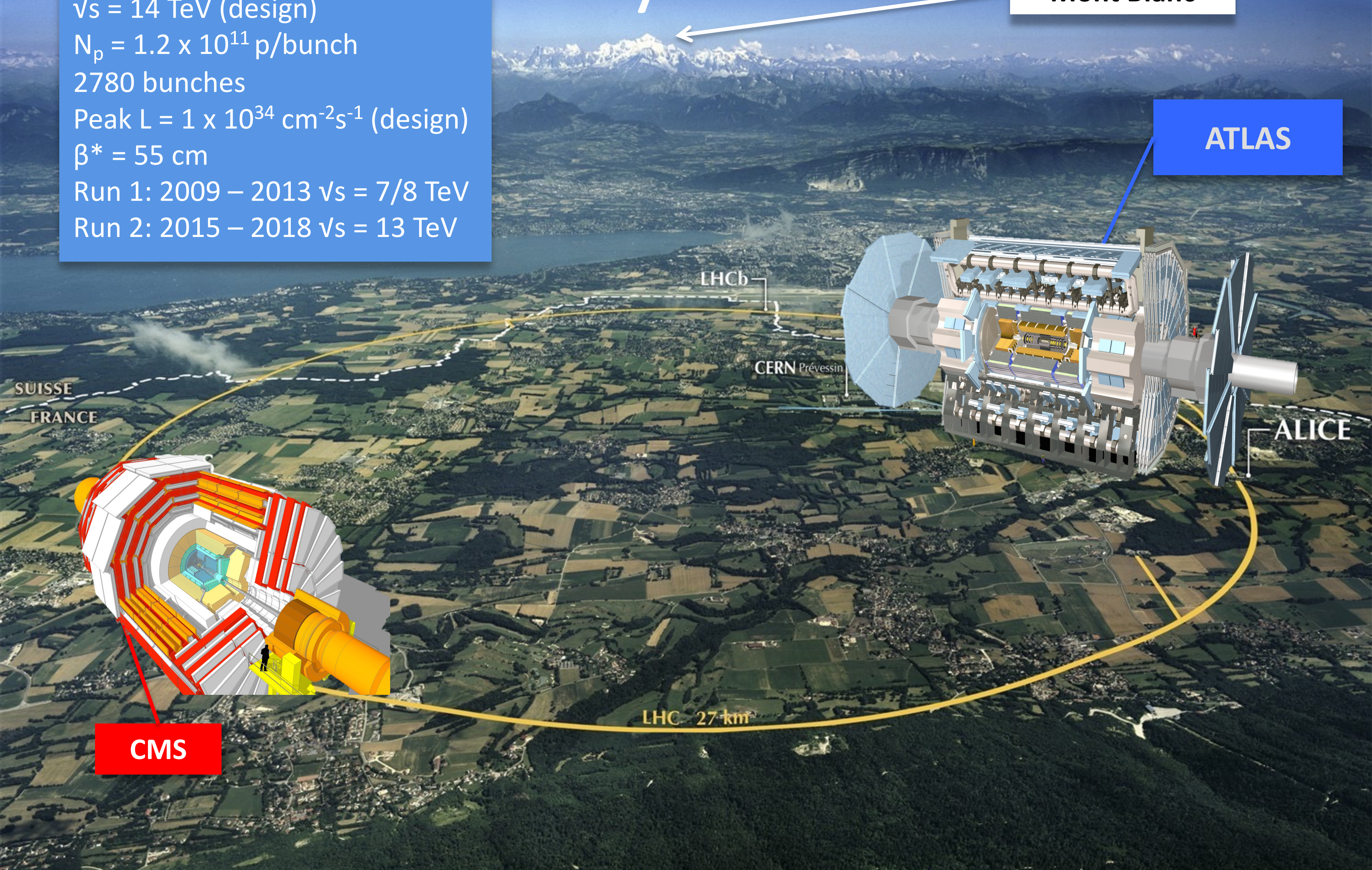
LEP and Tevatron: the Blue Band Plot

- Decades of searches in several experiments...
- By July 2010:
  - LEP+Tevatron+SLD limits
  - Higgs excluded for m_h<114.4 GeV at 95% CL
  - Plus between 158 and 175 GeV

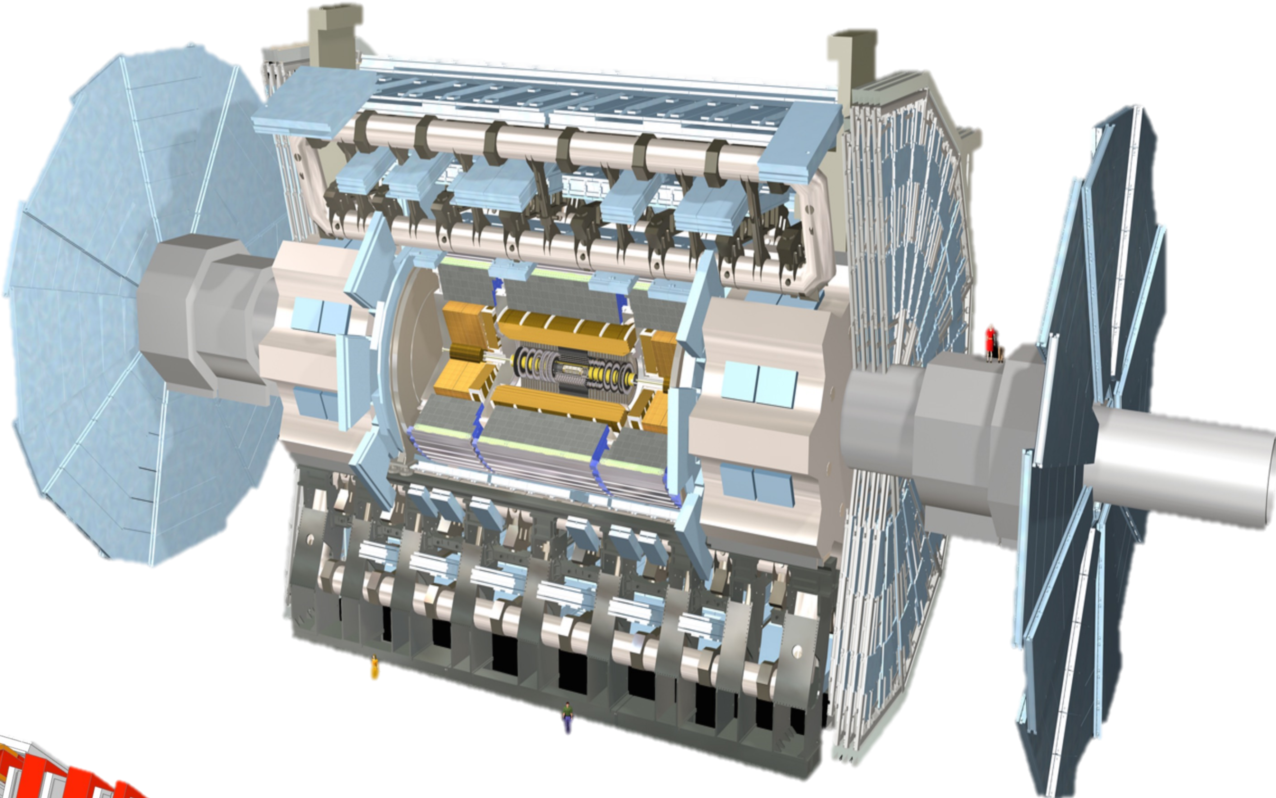


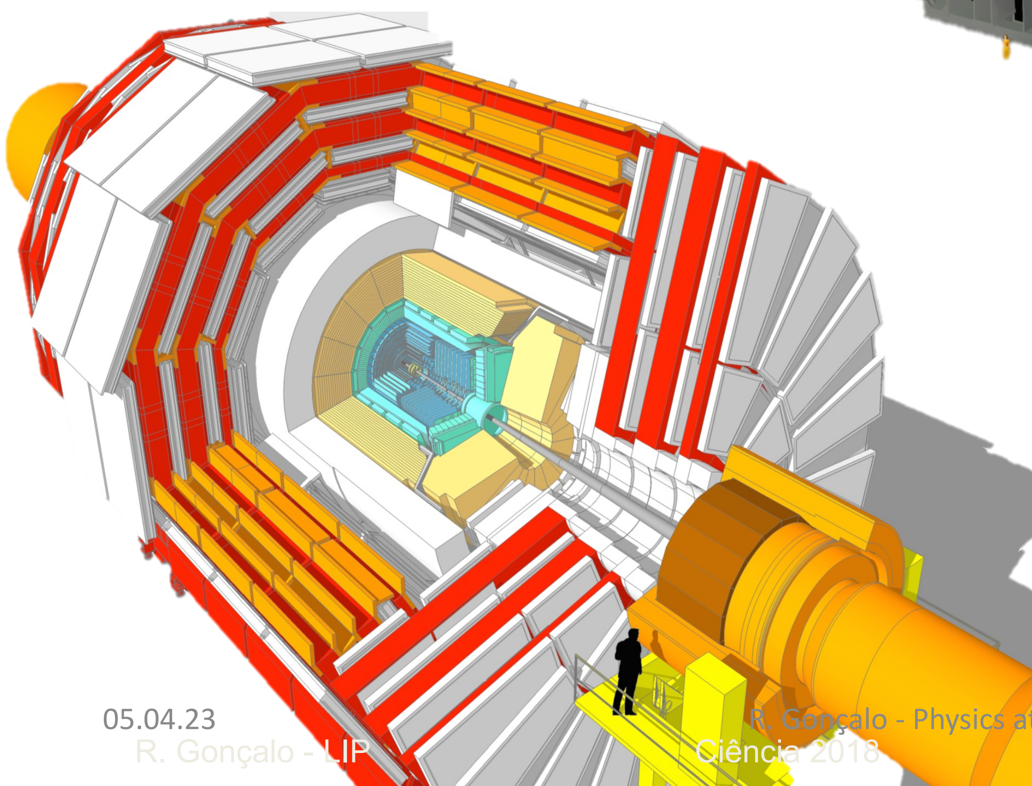
Discovery at the LHC

Design (p-p run):
$\sqrt{s}$ = 14 TeV (design)
$N_p = 1.2 \times 10^{11}$ p/bunch
2780 bunches
Peak $L = 1 \times 10^{34}$ $cm^{-2}s^{-1}$ (design)
β^* = 55 cm
Run 1: 2009 – 2013 $\sqrt{s}$ = 7/8 TeV
Run 2: 2015 – 2018 $\sqrt{s}$ = 13 TeV

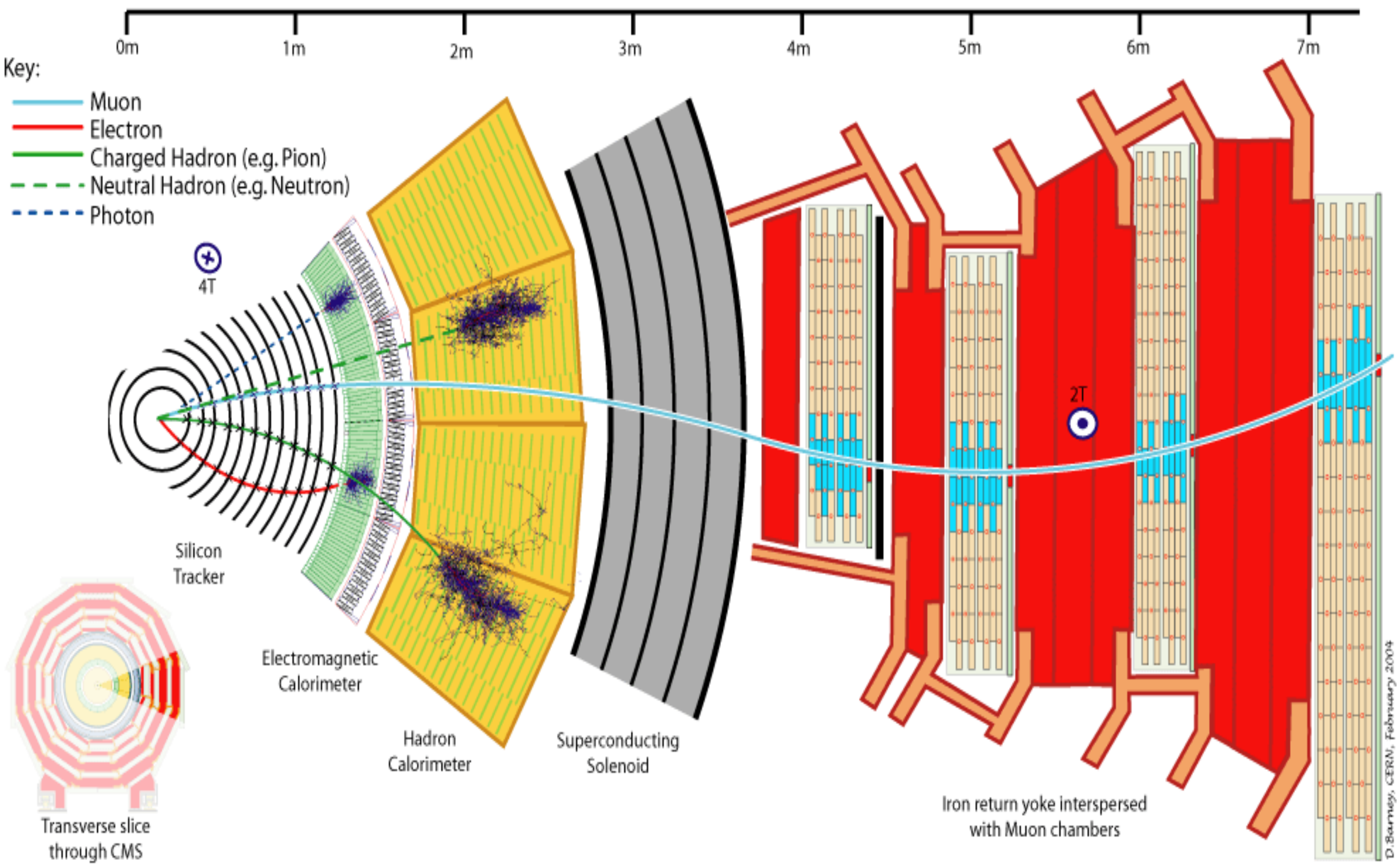


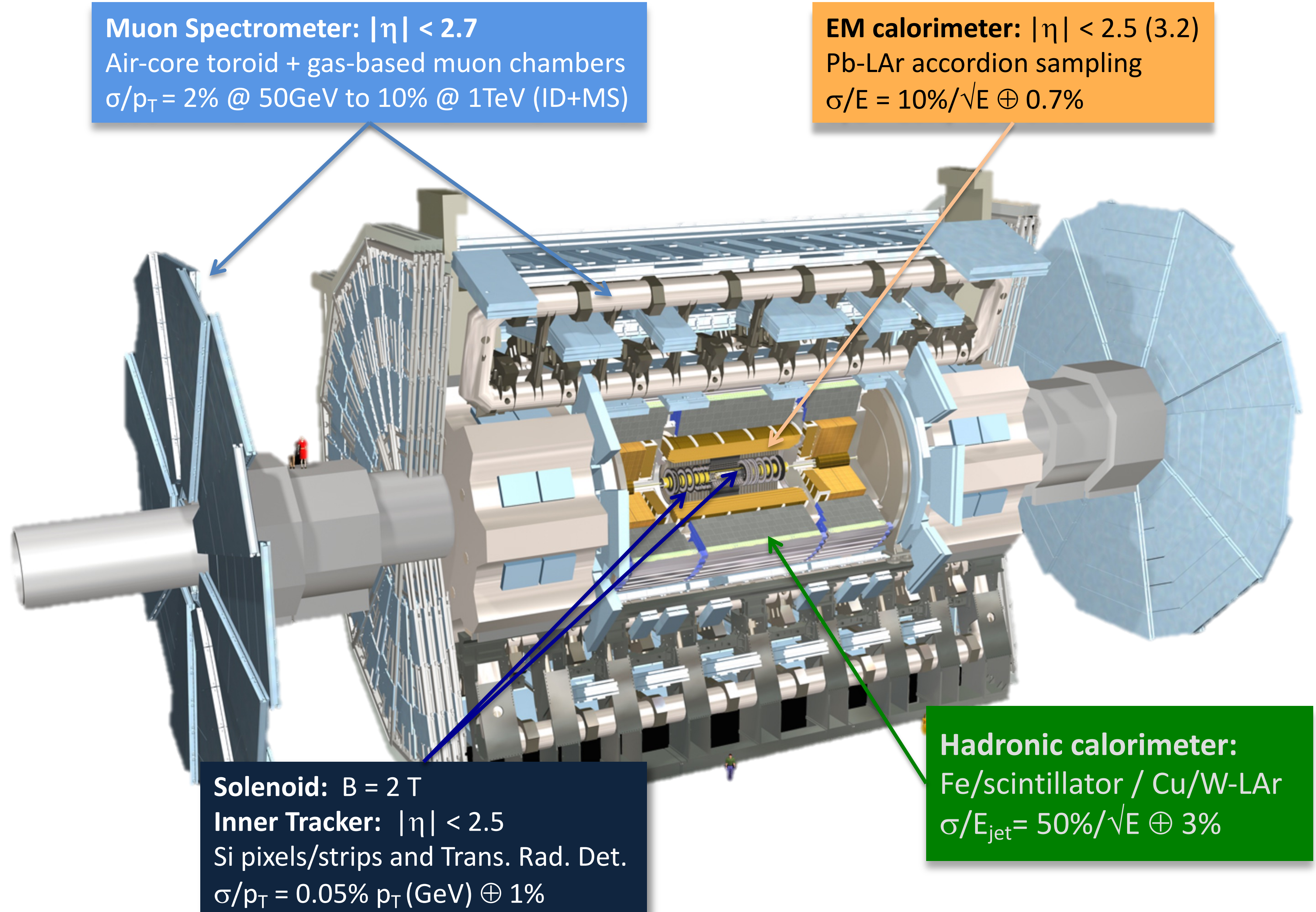
ATLAS
3000 colaboradores
175 institutos de 38 países
L = 44 m, ∅ ≈ 25 m, 7 000 t

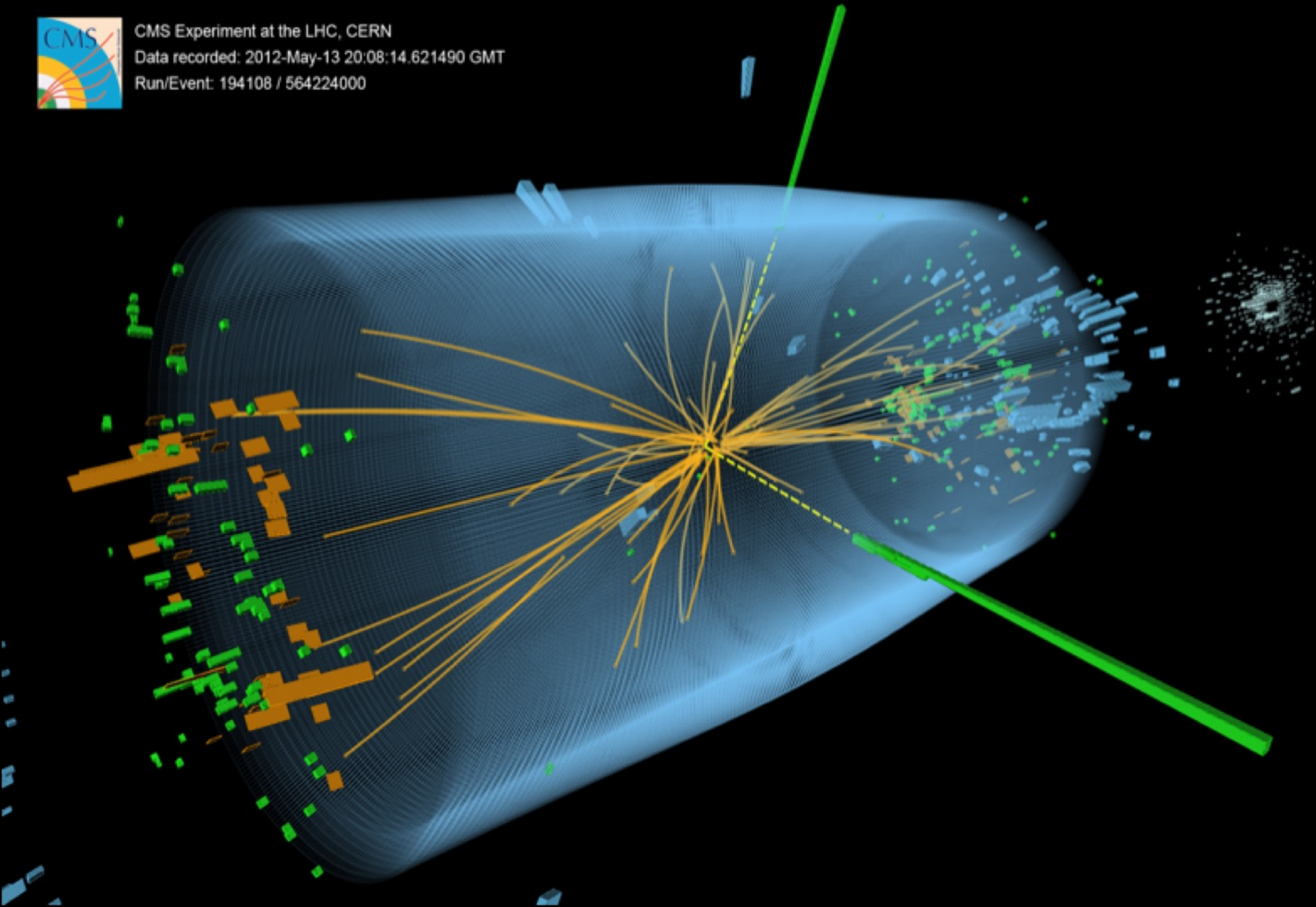




CMS
3800 colaboradores
199 institutos de 43 países
L = 22 m, ∅ ≈ 15 m, 14 000 t

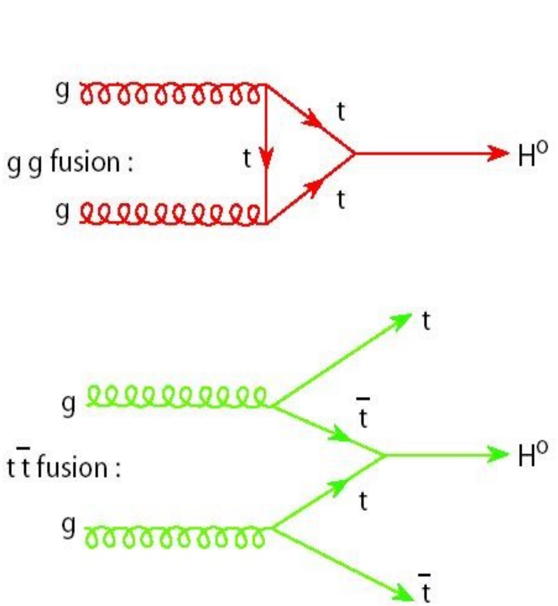

0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

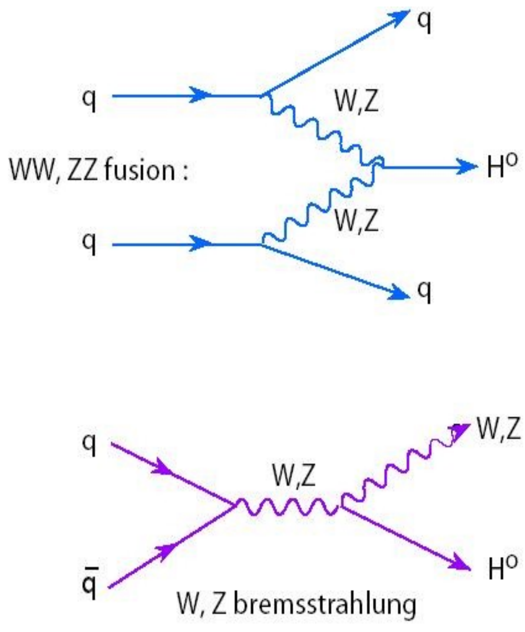

Muon Spectrometer: $|\eta| < 2.7$
Air-core toroid + gas-based muon chambers
σ/p_T = 2% @ 50GeV to 10% @ 1TeV (ID+MS)
EM calorimeter: $|\eta| < 2.5$ (3.2)
Pb-LAr accordion sampling
$\sigma/E = 10\%/\sqrt{E} \oplus 0.7\%$
Hadronic calorimeter:
Fe/scintillator / Cu/W-LAr
$\sigma/E_{jet} = 50\%/\sqrt{E} \oplus 3\%$
Solenoid: B = 2 T
Inner Tracker: $|\eta| < 2.5$
Si pixels/strips and Trans. Rad. Det.
$\sigma/p_T = 0.05\%\ p_T\,(\mathrm{GeV}) \oplus 1\%$

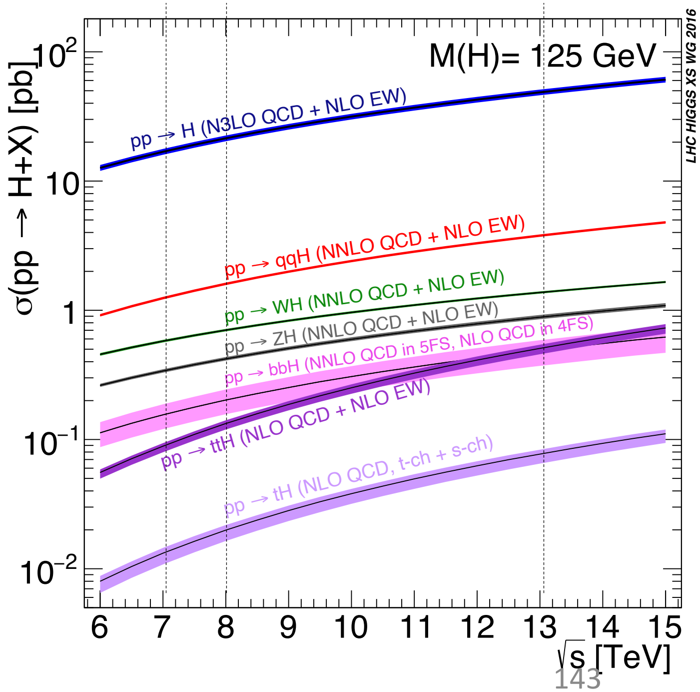

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

Higgs @ the LHC

- Many different production and decay mechanisms
  - Span 3 orders of magnitude in cross section and branching ratio
  - Some very clean decays with low BR (γγ, 4l)
  - Other very difficult with higher rates (bb, WW, ττ,...)
- Access Higgs properties through combination of different channels







Higgs @ the LHC

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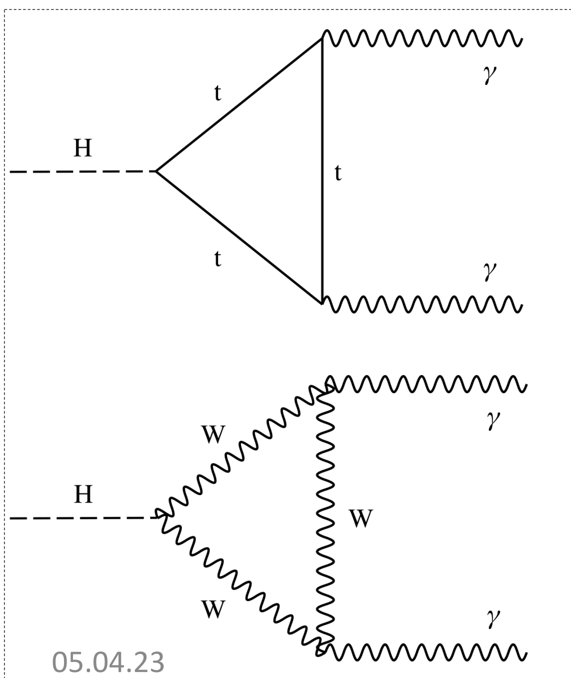
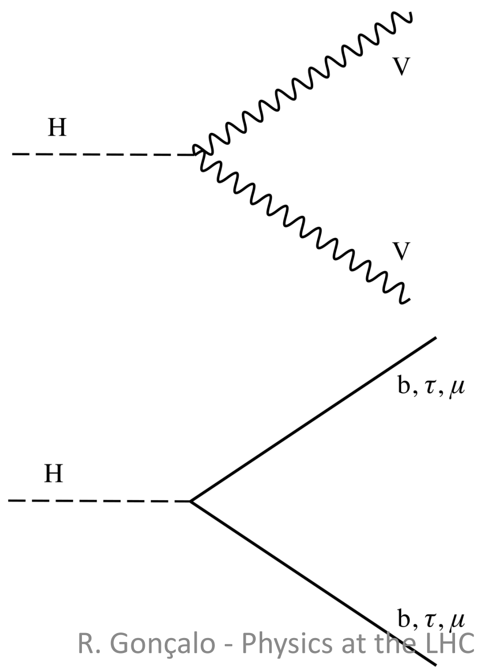
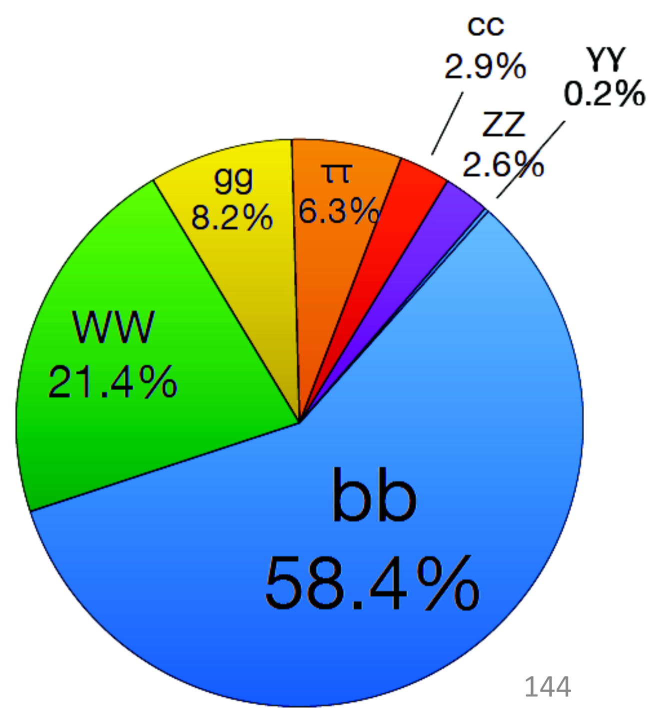
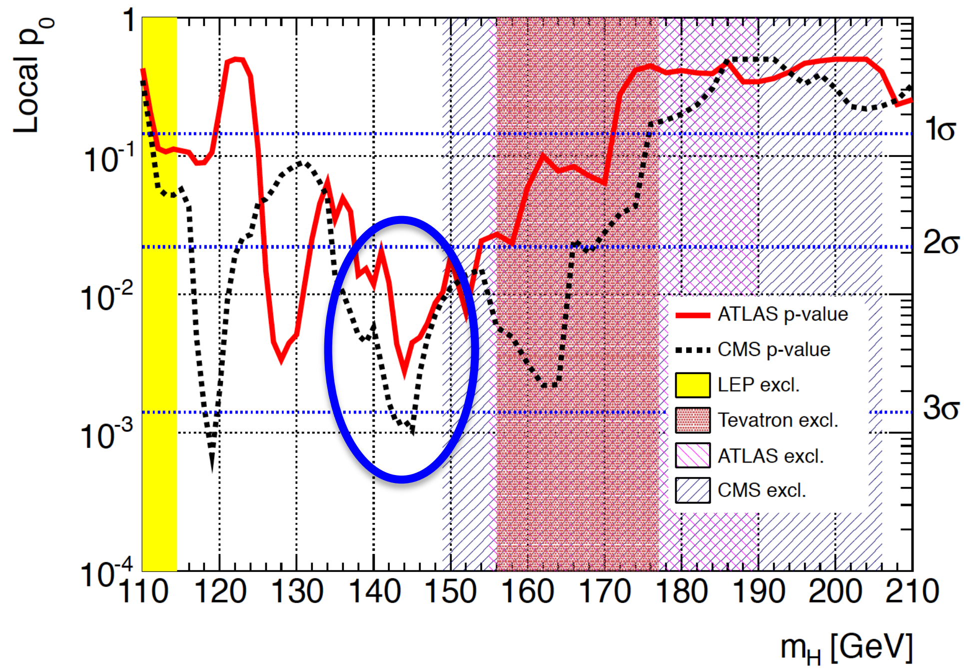




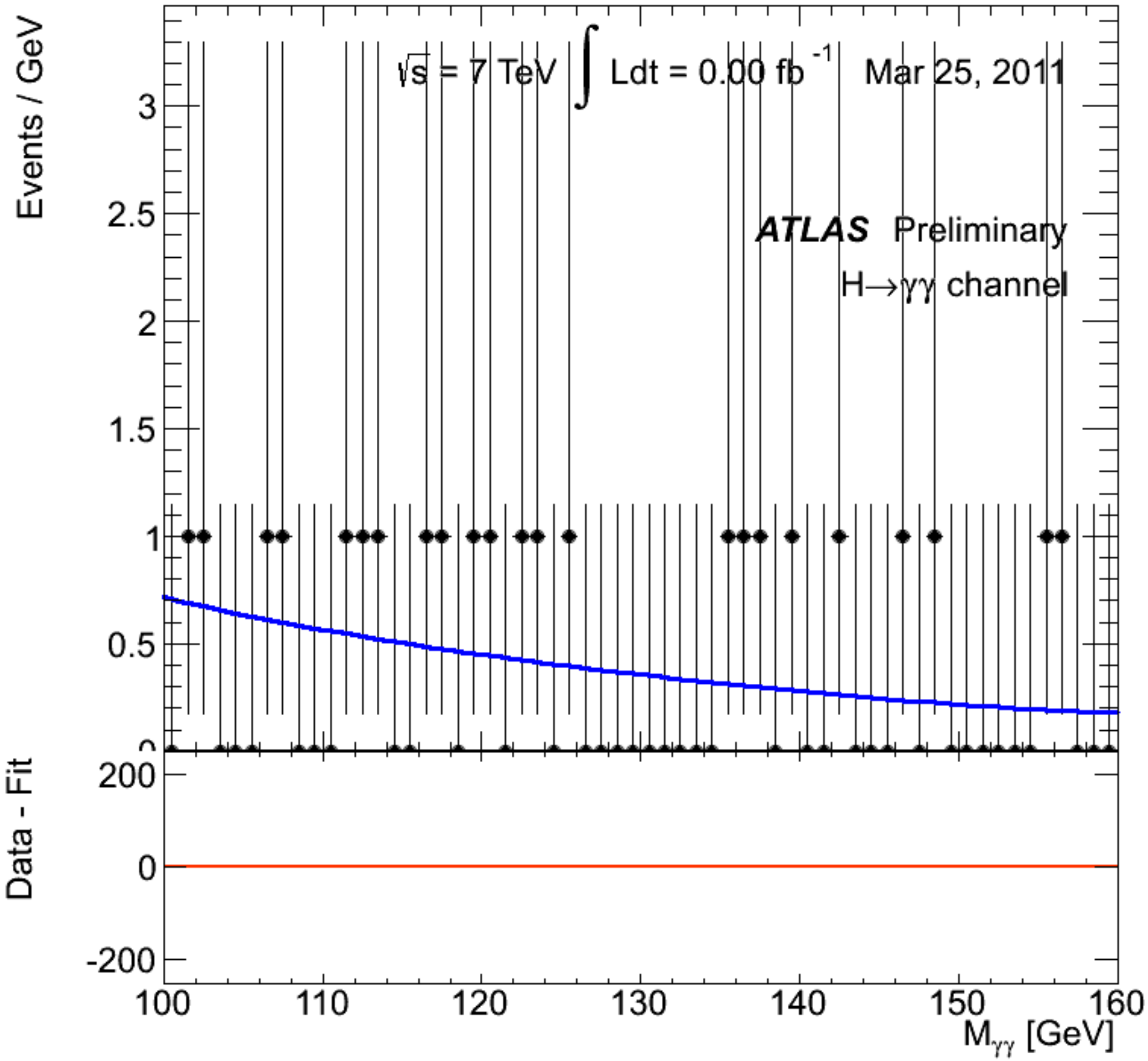


It takes time to get it right

EPS-HEP 2011 conference [6]



2012: Descoberta do bosão de Higgs: H->$\gamma\gamma$

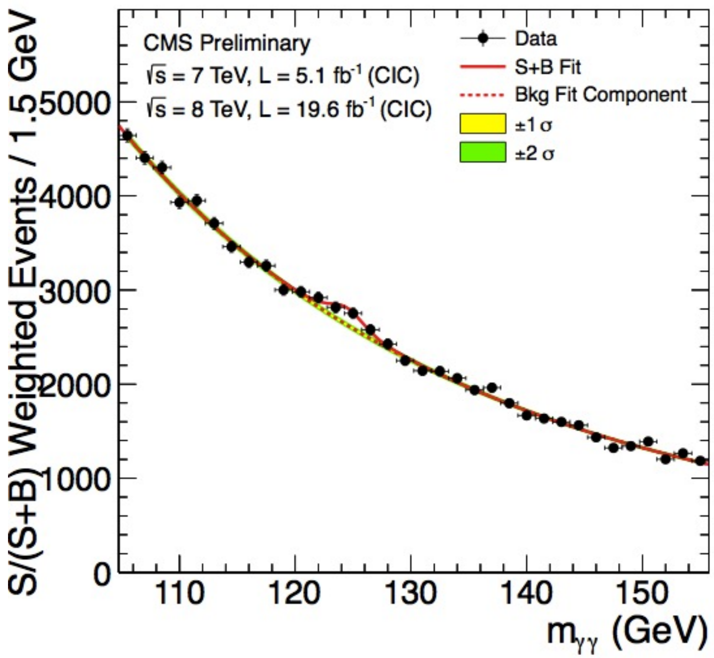


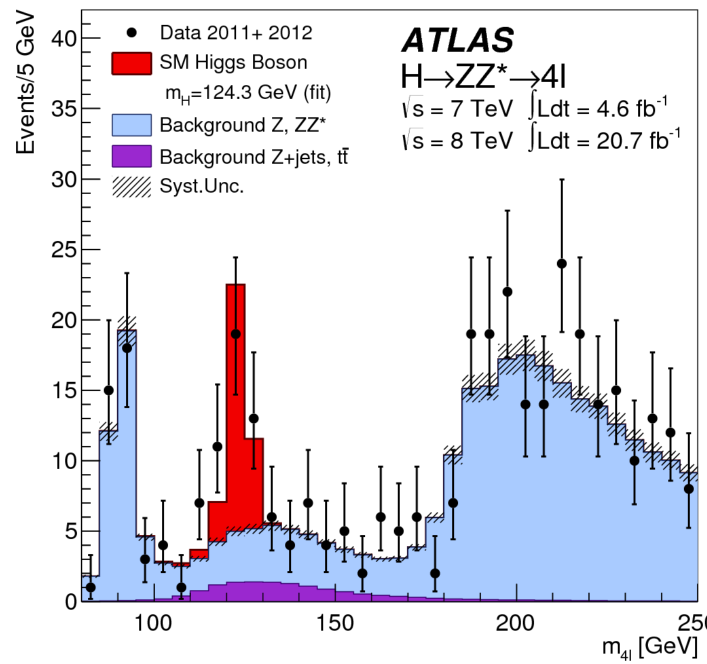
Discovery channels

- Discovery was made in ATLAS and CMS with about 5 fb^{-1} of 7 TeV data and 20 fb^{-1} of 8 TeV data per experiment; several channels combined

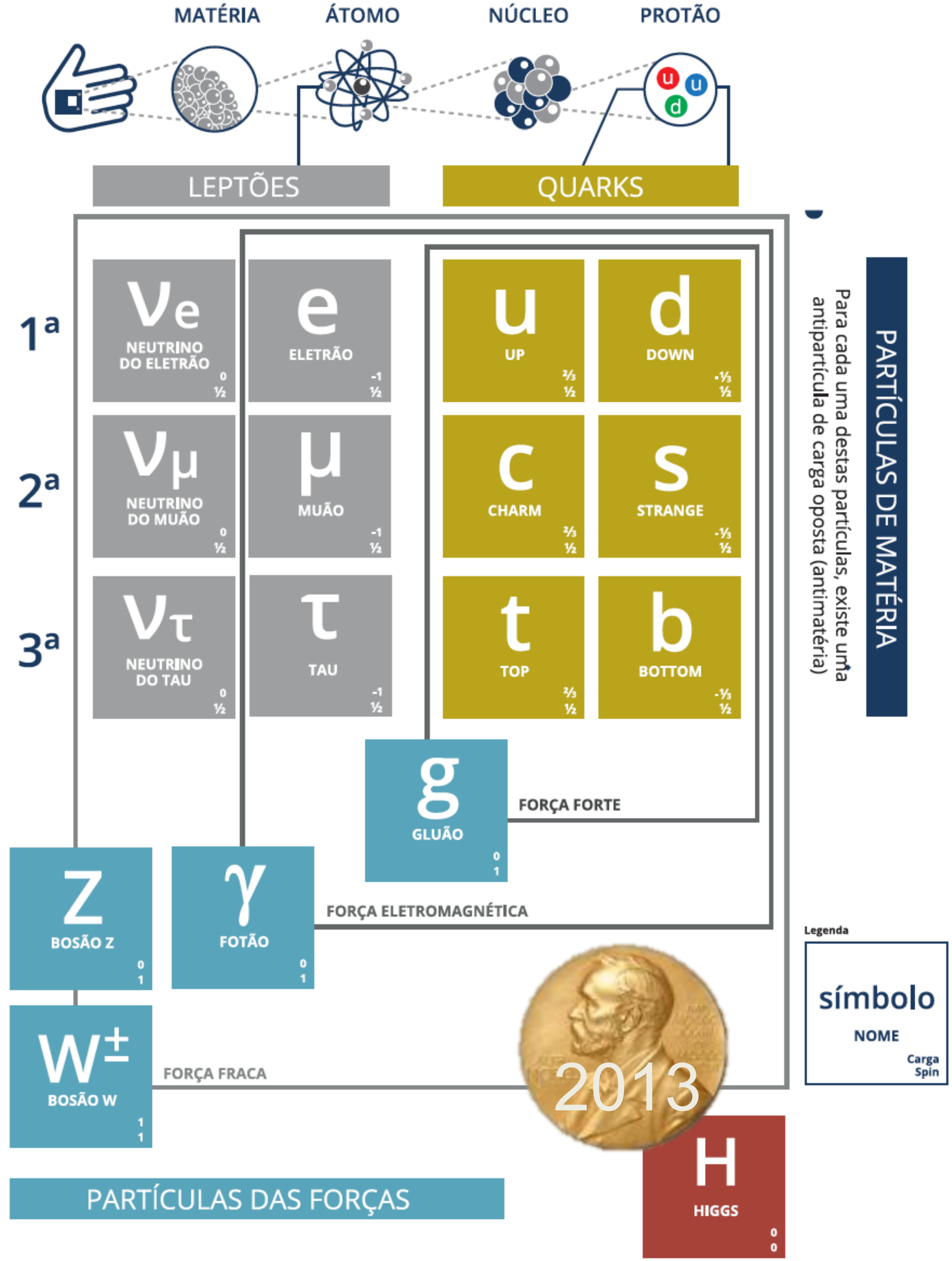
$$h \to \gamma\gamma; h \to ZZ^* \to 4\ell; h \to WW^*; h \to \tau^+\tau^-; h \to b\bar{b}$$

- This means about 400 000 Higgs bosons produced in about 8 000 000 000 000 000 ($8\text{x}10^{15}$) proton collisions
  - Only about 4000 events with Higgs bosons contributed to the discovery

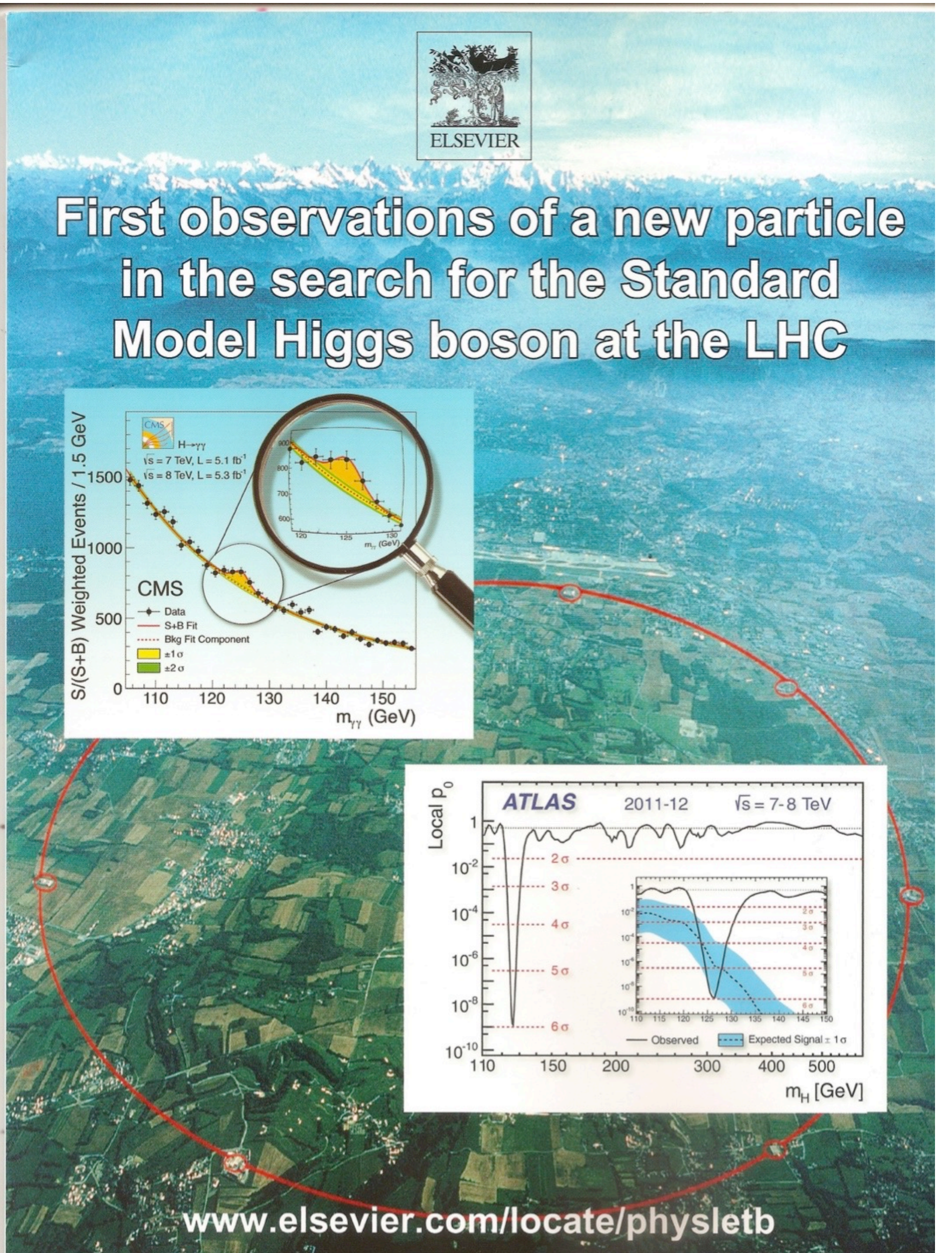




The Standard Model of particle physics <u>completed</u>



A Descoberta do bosão de Higgs



Two quotations from the experimental papers presented in this publication:

"*... The search for the Higgs boson, the only elementary particle in the Standard Model that has not yet been observed, is one of the highlights of the Large Hadron Collider physics program.*"

\- ATLAS Collaboration

"*... The decay to two photons indicates that the new particle is a boson with spin different from one. The results presented here are consistent, ... with expectations for a standard model Higgs boson.*"

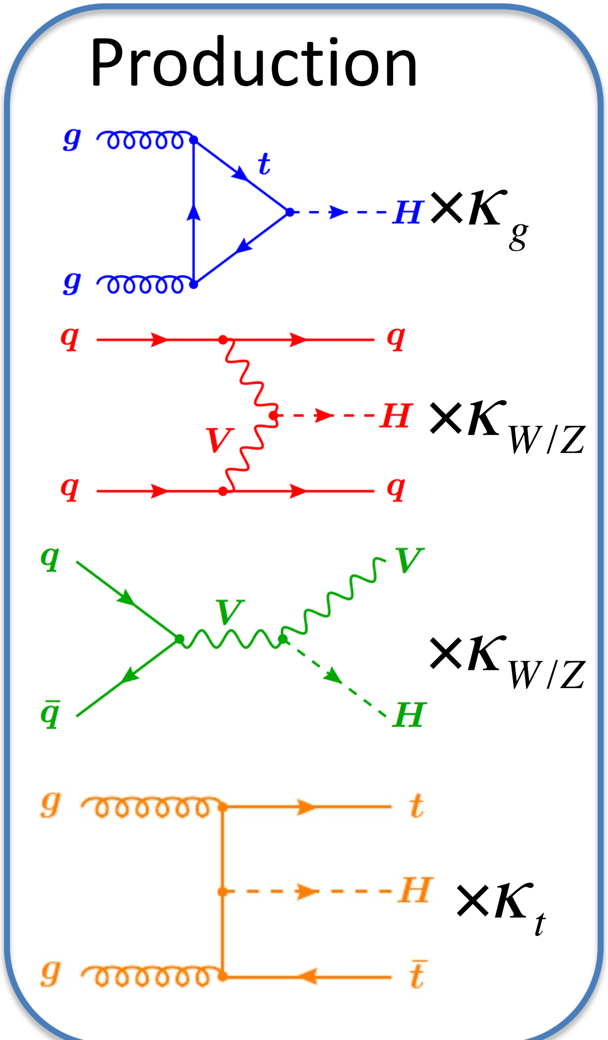
\- CMS Collaboration

Best wishes!
Peter Higgs

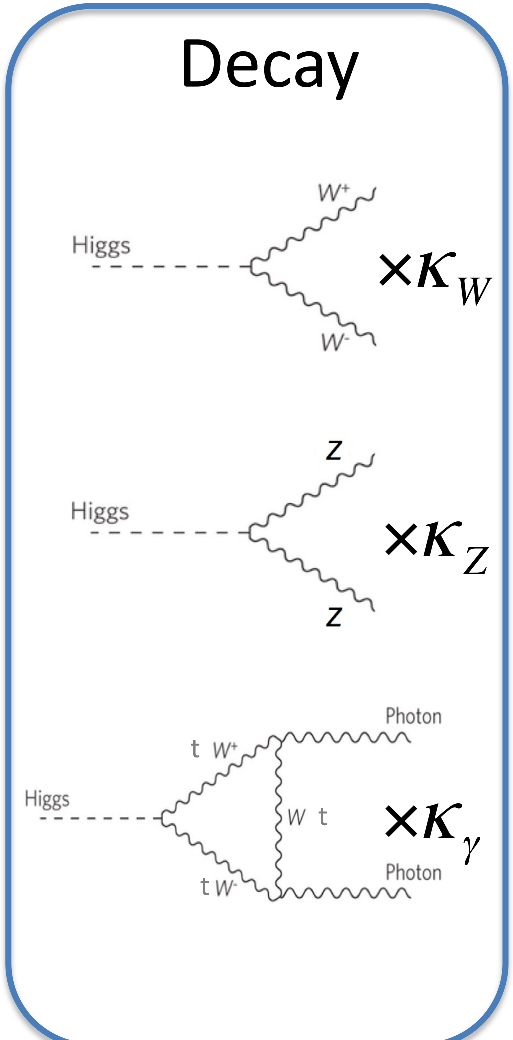
What now?!

Probing the 125 GeV Higgs

$$\kappa_i^2 = \sigma_i / \sigma_i^{SM} \qquad \kappa_f^2 = \Gamma_f / \Gamma_f^{SM} \qquad \mu = \frac{(\sigma \cdot BR)^{Obs.}}{(\sigma \cdot BR)^{SM}} = \kappa_i^2 \cdot \kappa_f^2$$

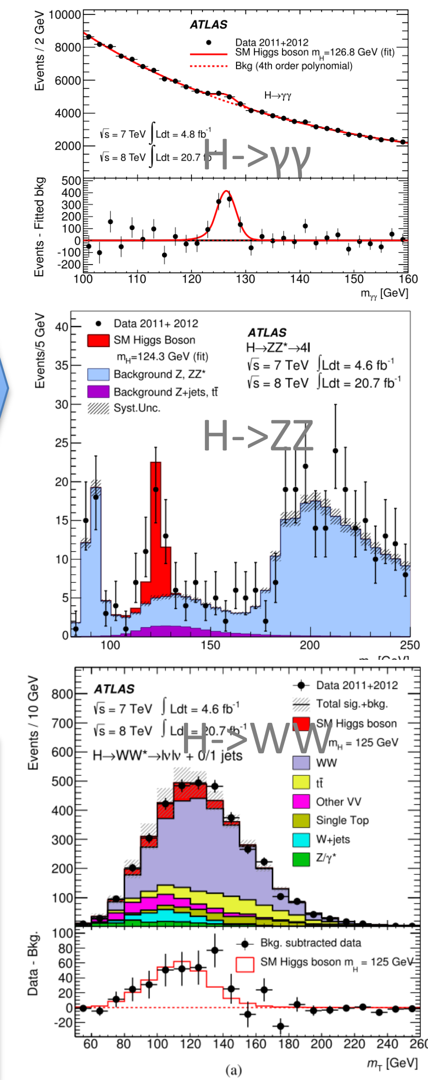


×

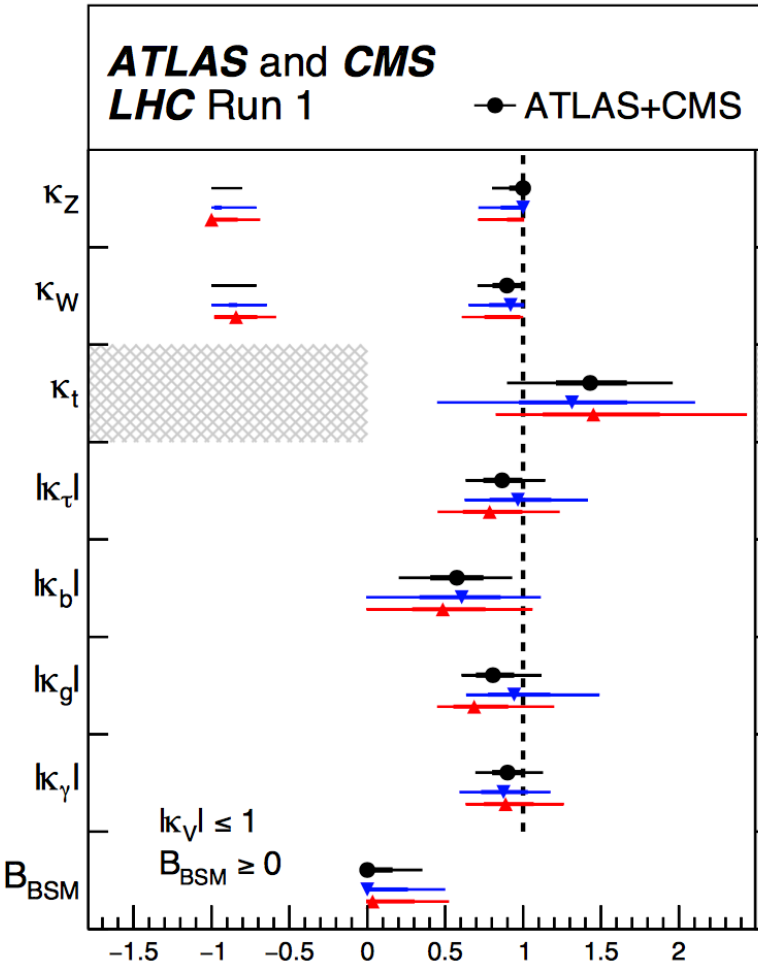


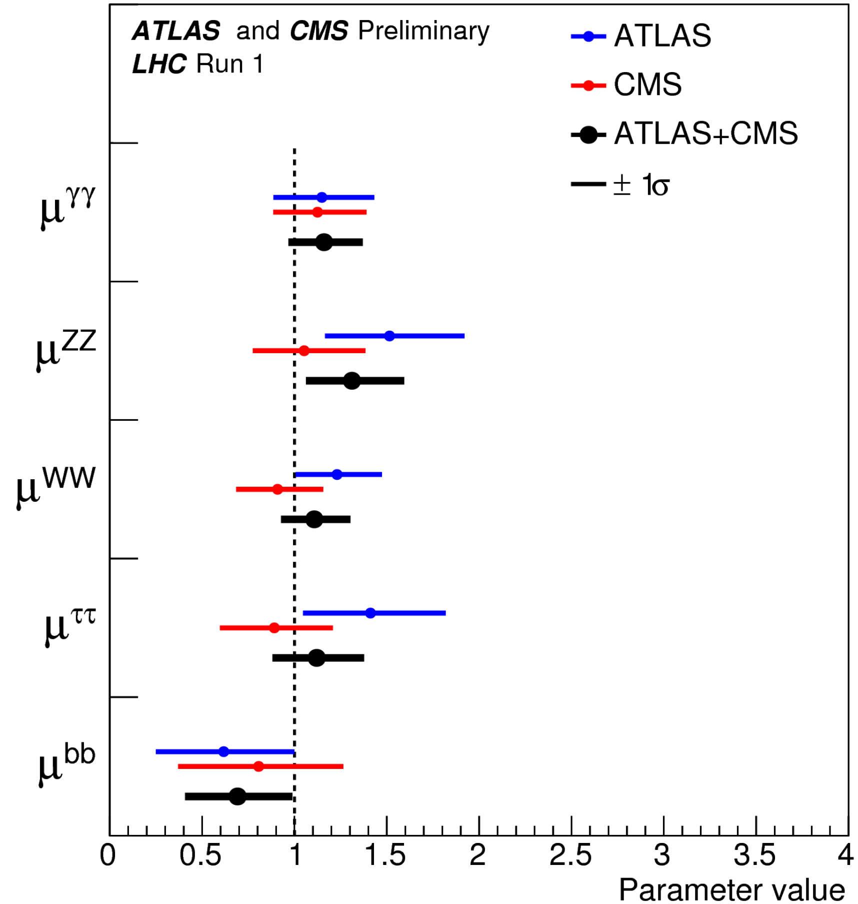
FIT

Backgrounds +



Signal strength measurements

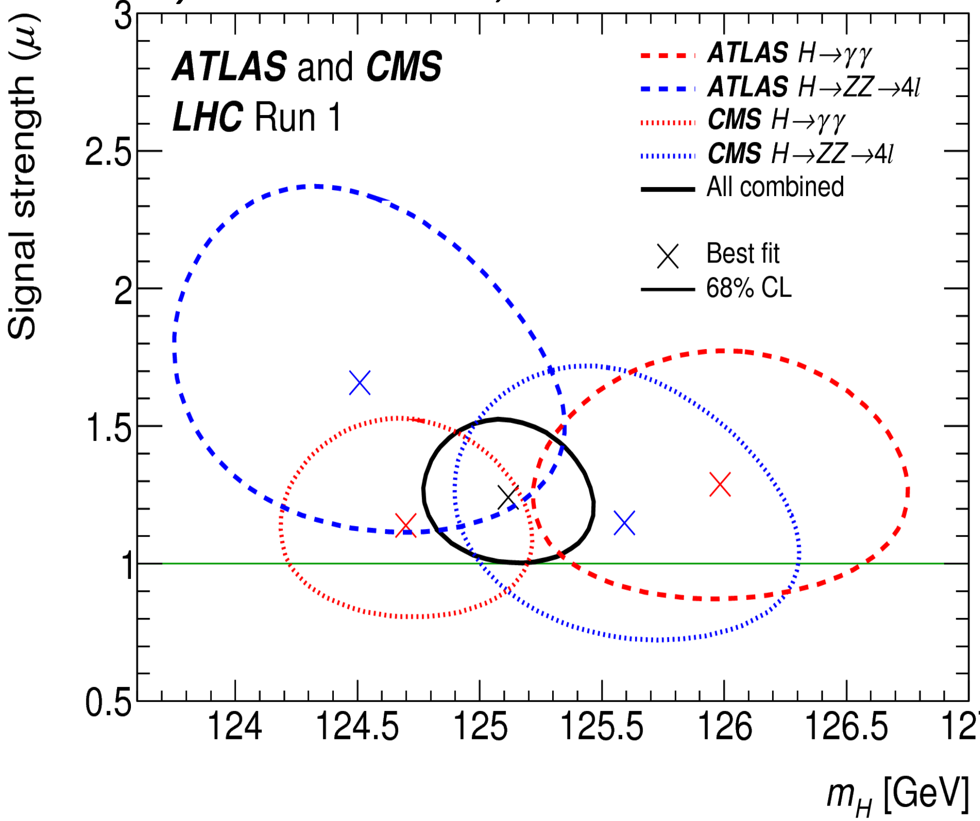




Higgs boson mass

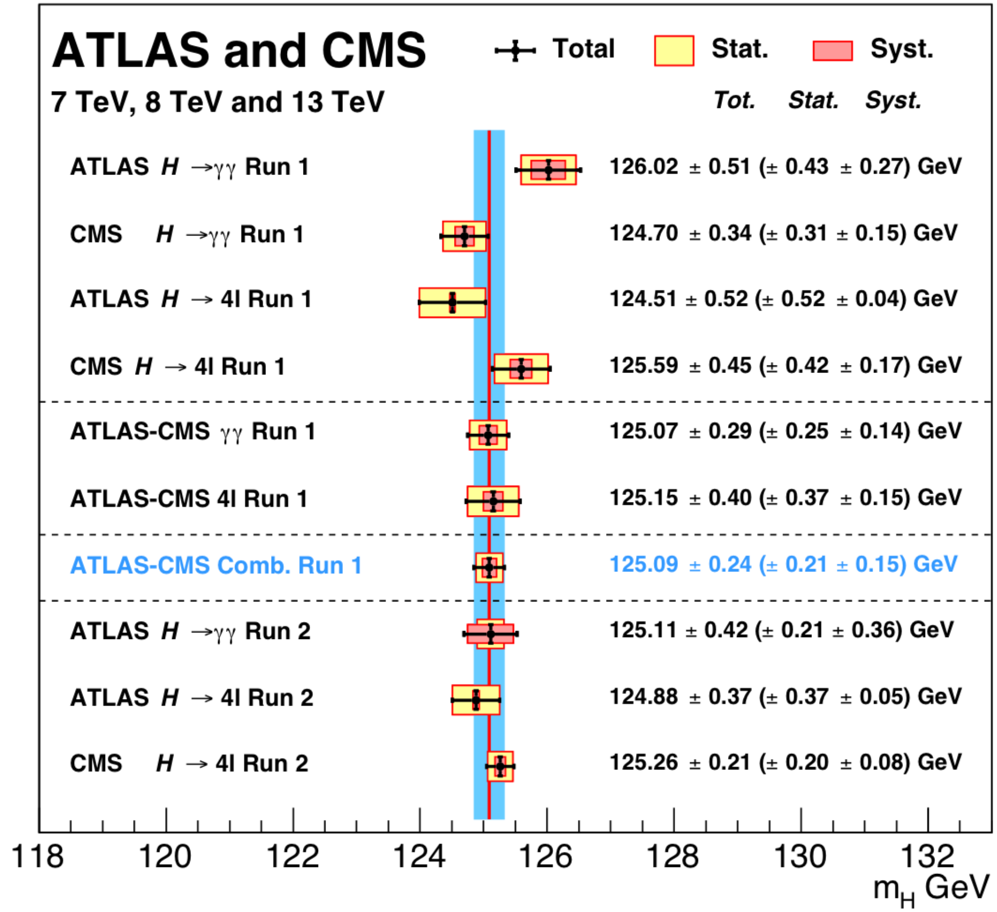
- Mass: around 125GeV
  Was the only unknown SM parameter ☺
- For a while, different mass values were being measured in ATLAS and CMS, and in different channels
- Numbers evolved with accumulated statistics

Phys. Rev. Lett. 114, 191803



Higgs boson mass

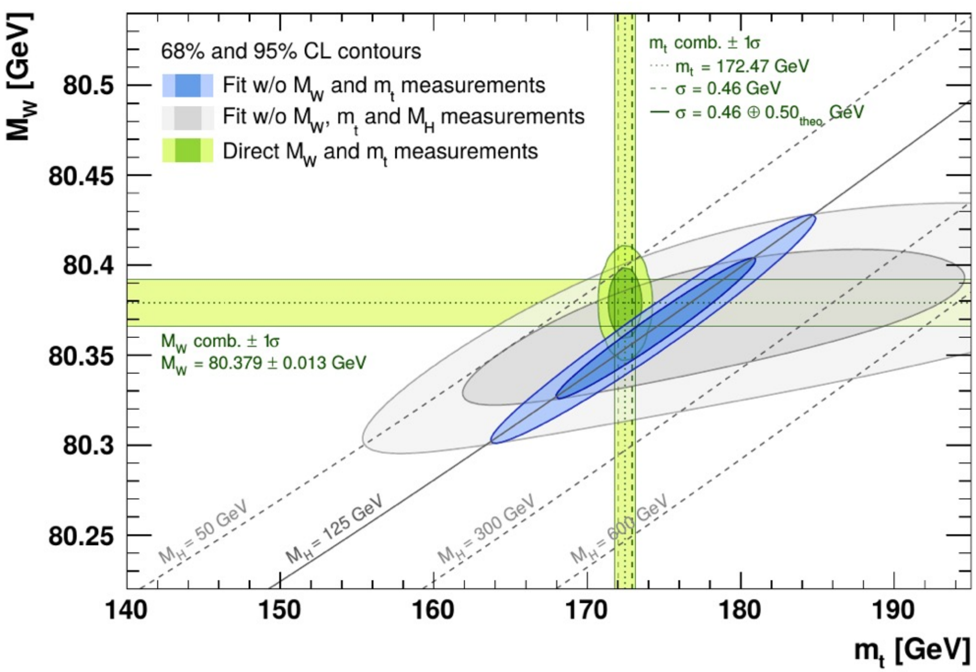
- Mass measurement from
  - H→ZZ*→4l
  - H→ γγ
- Precision at the permille level achieved

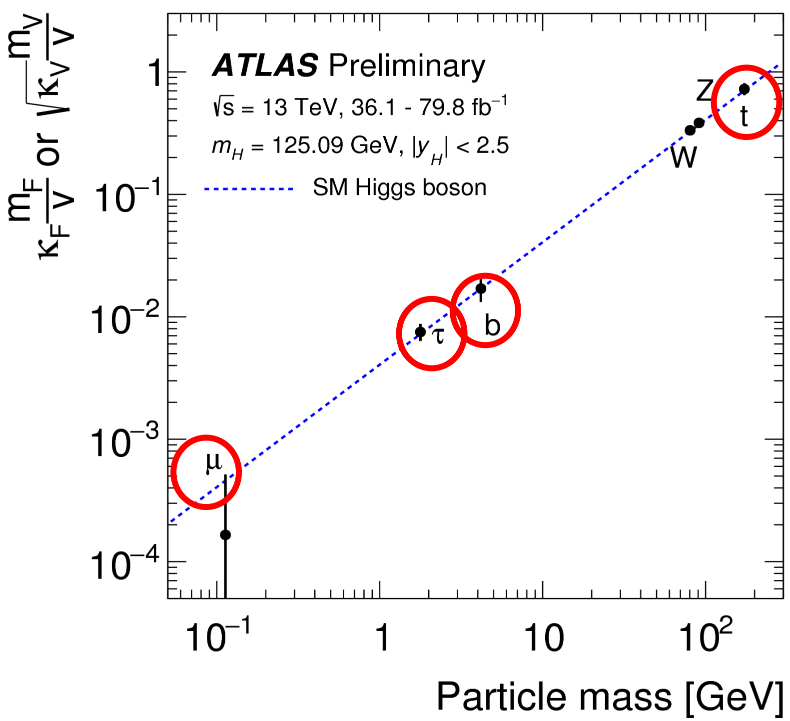


Exploring the electroweak scale

- Precision measurements of m_W, m_t, m_H are stringent tests of the SM at the EW scale
  - E.g. excluding measured m_H, global EW fit gives $m_H = 90 \pm 21$ GeV (1.7 σ tension) driven in part by m_{top}

arXiv:1803.01853



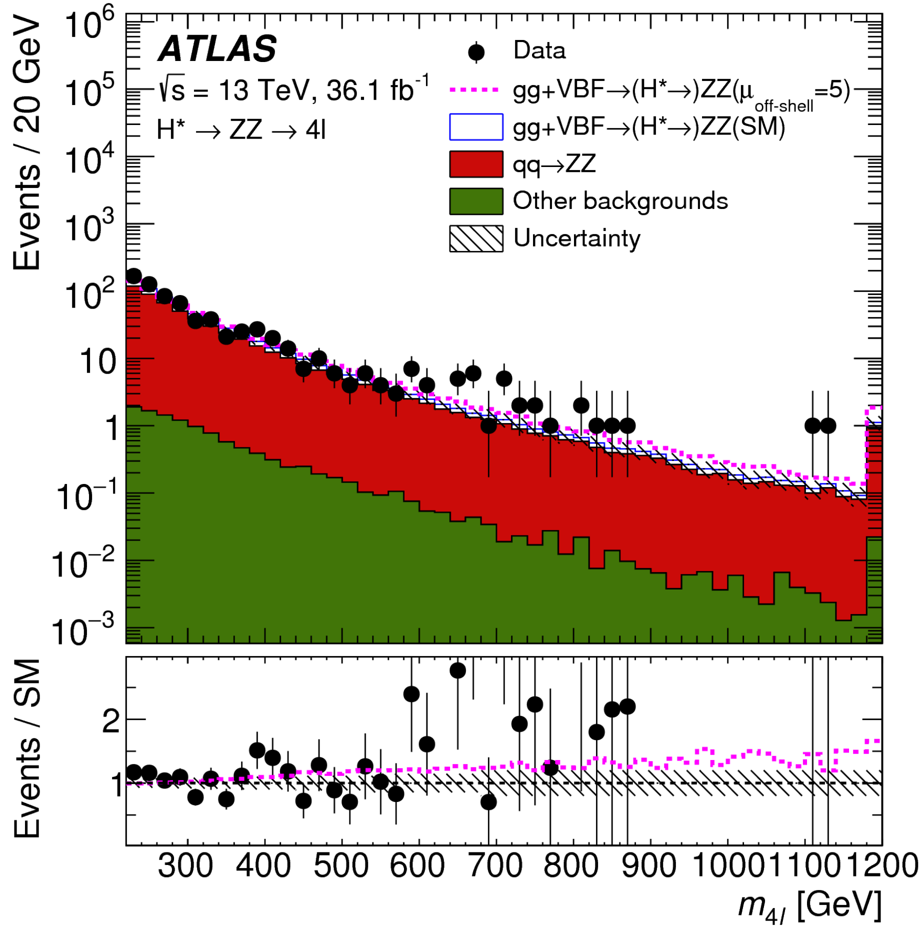


Higgs boson width

- SM Higgs width Γ_H~4.1 MeV
  - Too small to be measured directly
  - Best direct limit from CMS:
    - Γ_H < 1.1GeV @ 95% CL
- Off-shell Higgs production sensitive(*) to Γ_H

$$\frac{\mu_{\mathrm{off-shell}}}{\mu_{\mathrm{on-shell}}} = \frac{\kappa^2_{\mathrm{g,off-shell}} \cdot \kappa^2_{\mathrm{Z,off-shell}}}{\kappa^2_{\mathrm{g,on-shell}} \cdot \kappa^2_{\mathrm{Z,on-shell}}} \frac{\Gamma_H}{\Gamma_H^{SM}}$$

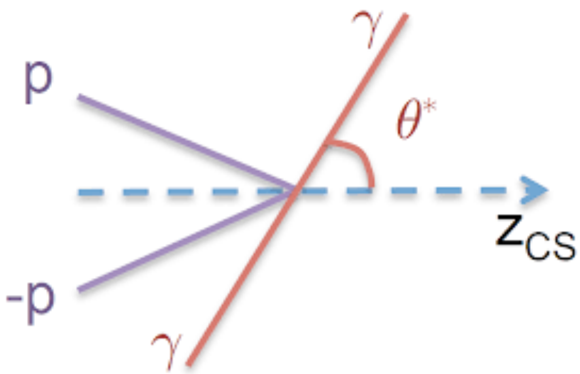
- ATLAS measurement:
  - **pp→H→ZZ→4l** and ZZ→2l2ν
  - **m(H) > 2 m(Z)**
  - 36.1 fb^{-1} of 13 TeV data
  - Observed (expected) limit:
    - Γ_H < 14.4 (15.2) MeV



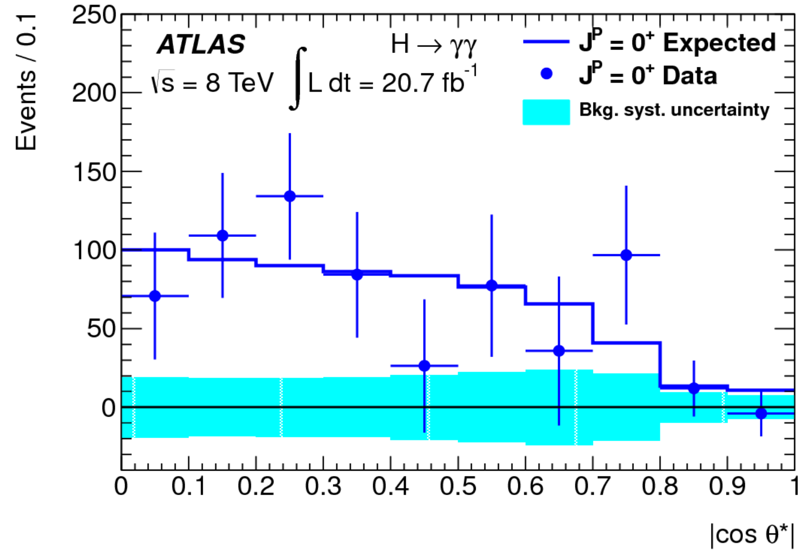
(*) Assume interference term with $gg \to ZZ$ proportional to $\kappa_{g,\text{off-shell}} \cdot \kappa_{Z,\text{off-shell}}$

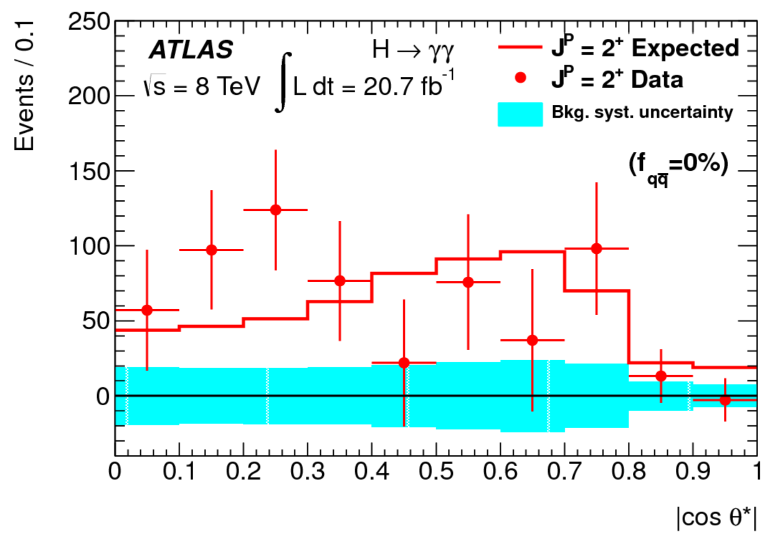
Measuring the Higgs Spin

- Polar angle θ in the rest fram of the diphoton system (Collins-Soper frame)

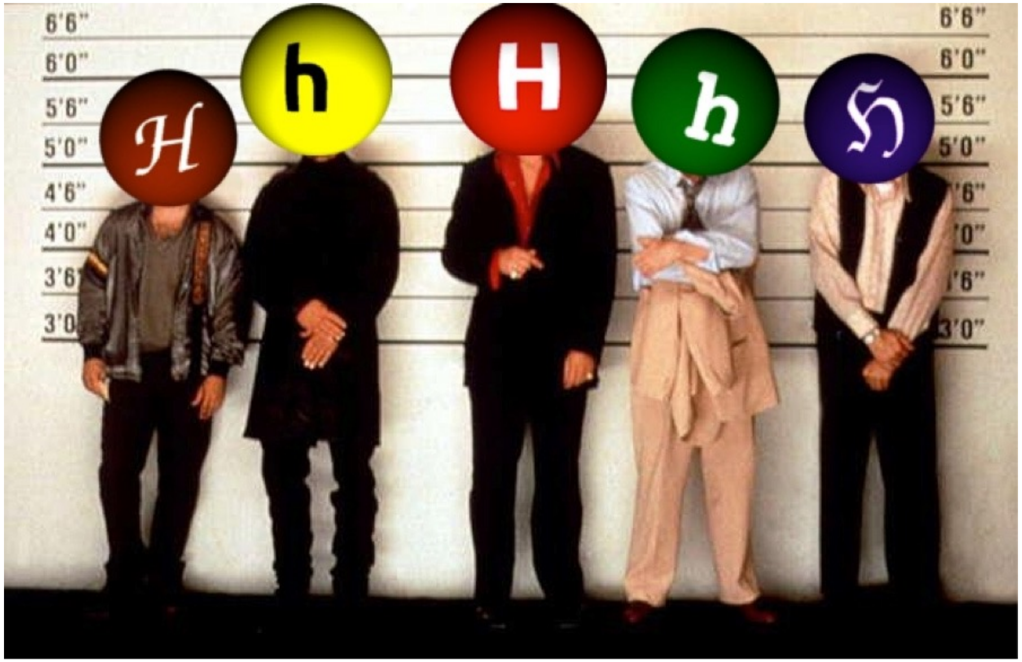


$$|\cos\Theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+\frac{p_{T,\gamma\gamma}^2}{m_{\gamma\gamma}^2}}}\frac{2p_T^{\gamma_1}p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$

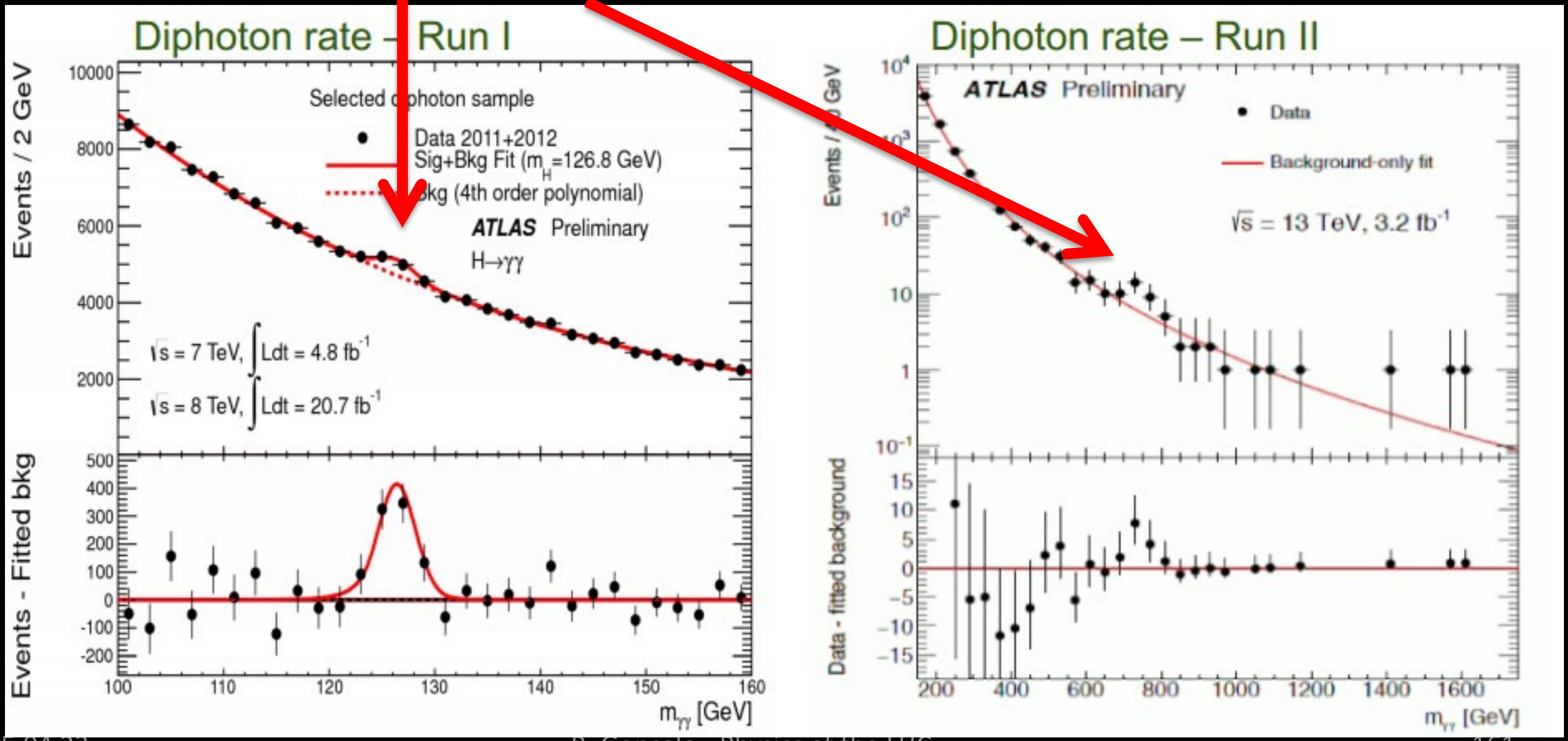




Casting a wider net

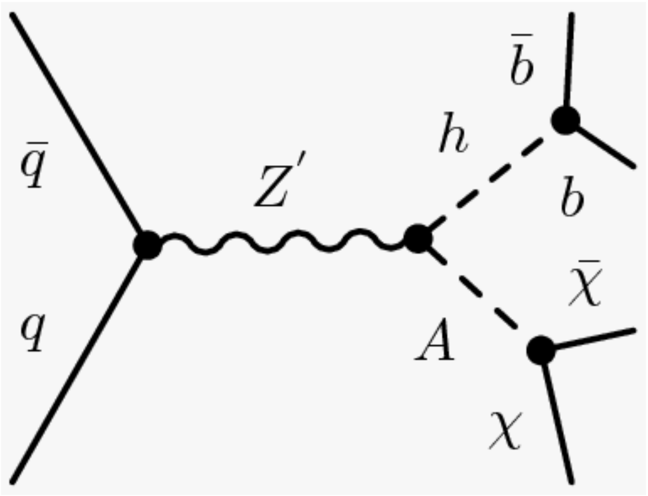


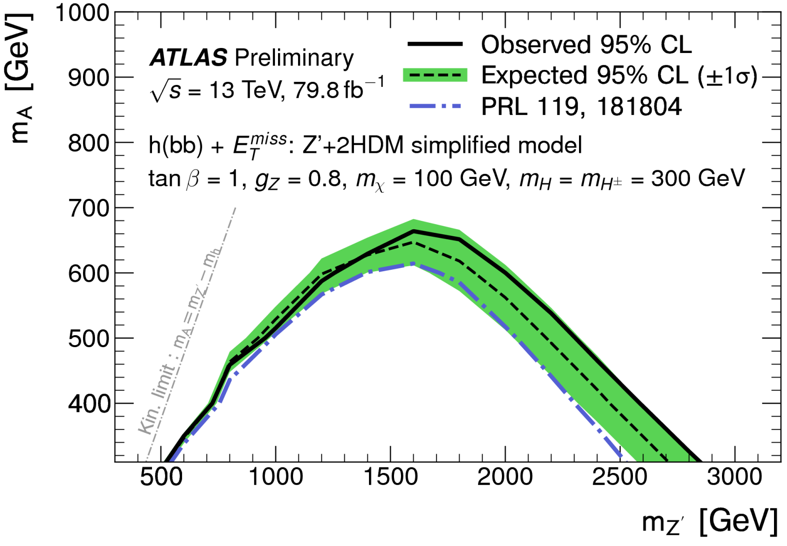
Additional Higgs bosons?



Higgs + Dark Matter

- Used 79.8 fb^{-1} of 13 TeV data
  - High E_T^{miss} (>150GeV) and b-tagging to suppress backgrounds
  - Reconstruct b-jets as 2 small jets or merged variable-radius (VR) track jets
- Signal benchmark: Type-II 2HDM + $U(1)_{Z'}$ symmetry (Z'-2HDM)
- Main backgrounds: tt, W/Z+jets
- Excluded region in $m_A - m_{Z'}$ plane

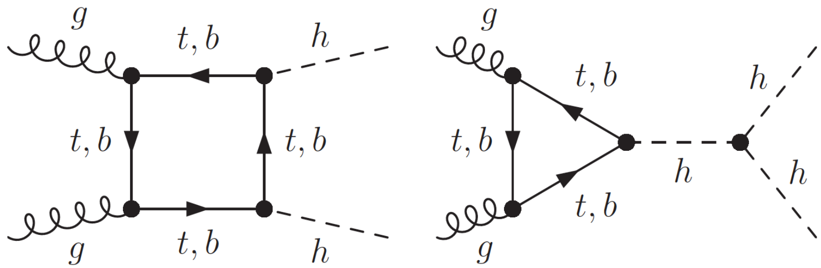


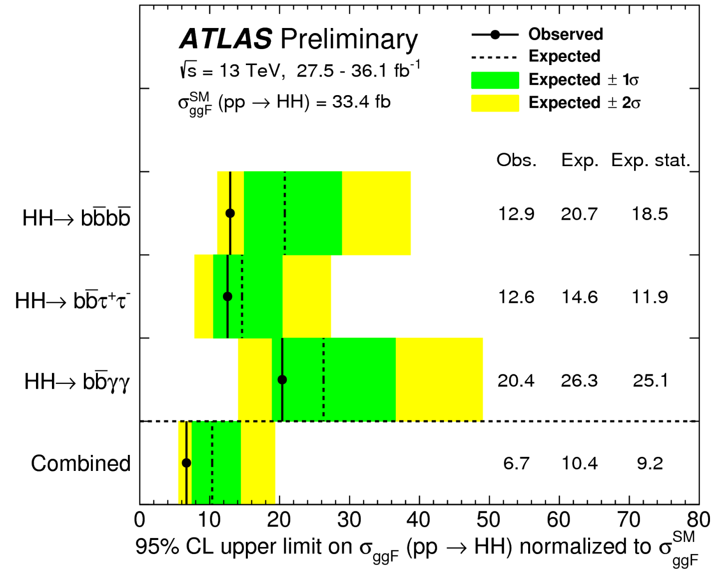


Triple Higgs coupling

- The triple Higgs coupling λ_{HHH} can be probed through di-Higgs production
- Very suppressed in SM!
  - Negative interference between LO diagrams
  - Cross section 1500x less than ggF
- Wide range of decay BR and channel purity
- bbττ analysis:
  - Used 36 fb^{-1} of 13 TeV data
  - Final state BR(bbττ)=7%
  - Non-Resonant 95% CL limit:
    μ < 12.7 observed (14.8 expexcted)
- Combination: at ≈10 x SM sensitivity – with 3% of the HL-LHC luminosity analyzed

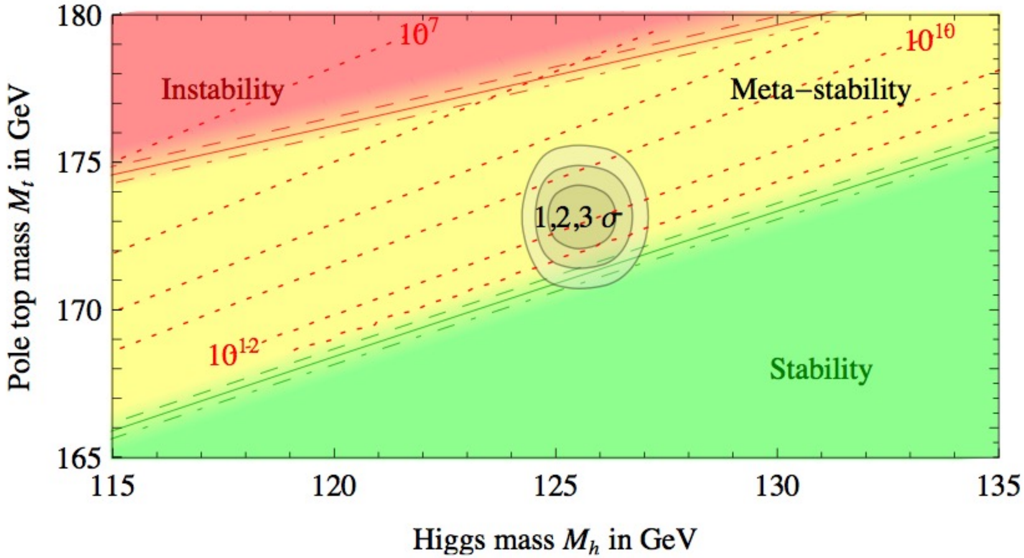
$$V(\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

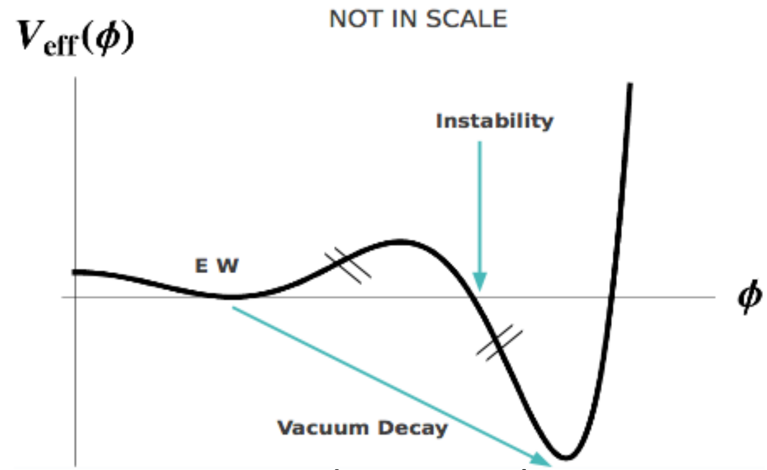




Di-Higgs combination plot [here]

A bit of fun…





RG-improved potential

- What if…
  - At higher orders, Higgs potential doesn't have to be stable
  - Depending on m_t and m_H second minimum can be lower than EW minimum ⇒ tunneling between EW vacuum and true vacuum?!
- "For a narrow band of values of the top quark and Higgs boson masses, the Standard Model Higgs potential develops a shallow local minimum at energies of about 10^{16} GeV, where primordial inflation could have started in a cold metastable state", I. Masina, arXiv:1403.5244 [astro-ph.CO]
  - See also: V. Brachina, Moriond 2014 (Phys.Rev.Lett.111, 241801 (2013)), G. Degrassi et al, arXiv:1205.6497v2; R.Contino, Workshop sulla fisica p-p a LHC, 2013

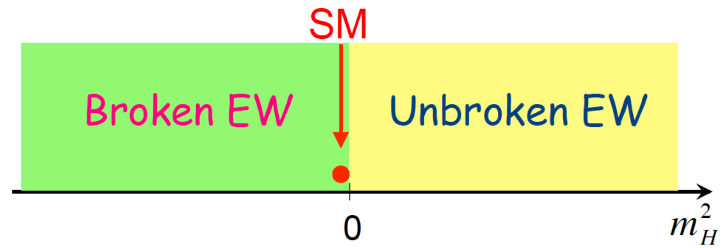
The universe seems to live near a critical condition

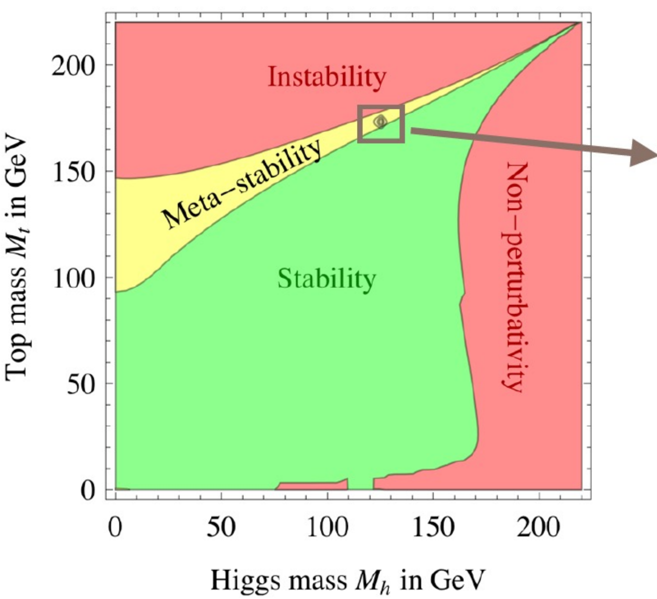
JHEP 1208 (2012) 098

Why?!

Explained by underlying theory?

Anthropic principle?





Yukawa coupling to fermions

2018

≡ P P2 ÍPSILON CULTO FUGAS P3 CINECARTAZ Entrar Assine já

CIÊNCIA › ESPAÇO MEDICINA ECOSFERA

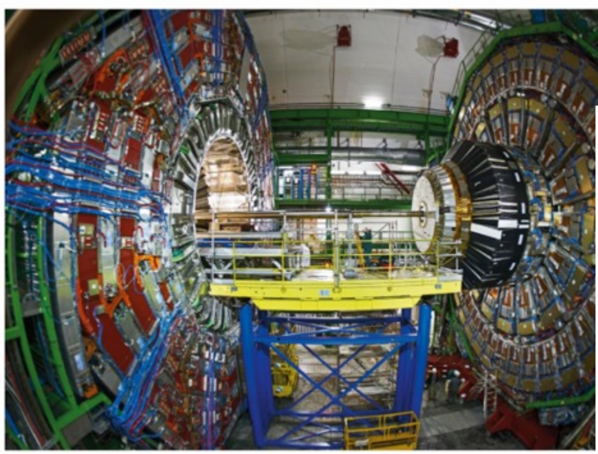
FÍSICA DE PARTÍCULAS

Bosão de Higgs revela que relação mantém com o quark *top*

Investigadores portugueses participaram na descoberta.

PÚBLICO • 4 de Junho de 2018, 19:42

418 PARTILHAS



O detector CMS no grande acelerador de partículas LHC, em Genebr

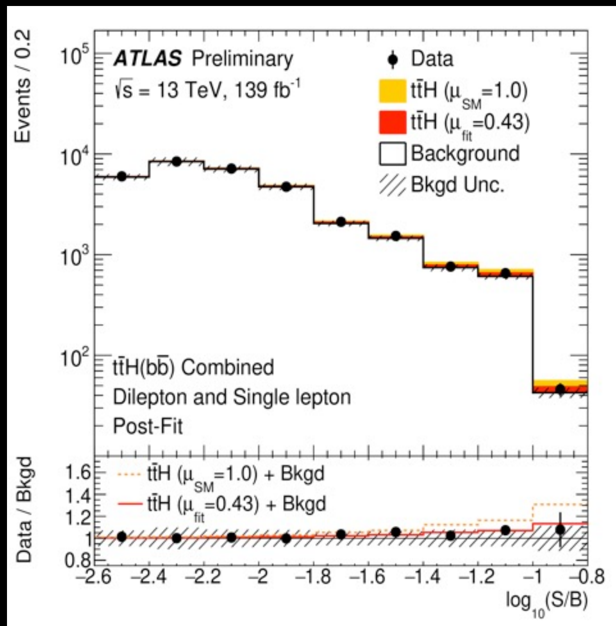
FÍSICA DE PARTÍCULAS

Bosão de Higgs visto (finalmente) a desintegrar-se em quarks *bottom*

Descoberta anunciada no Laboratório Europeu de Física de Partículas (CERN) é um passo fundamental para perceber como o bosão de Higgs faz com que as partículas fundamentais adquiram massa.

PÚBLICO • 28 de Agosto de 2018, 17:47

And many many more...



ATLAS CONF Note

ATLAS-CONF-2020-058

29th October 2020

Measurement of the Higgs boson decaying to b-quarks produced in association with a top-quark pair in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

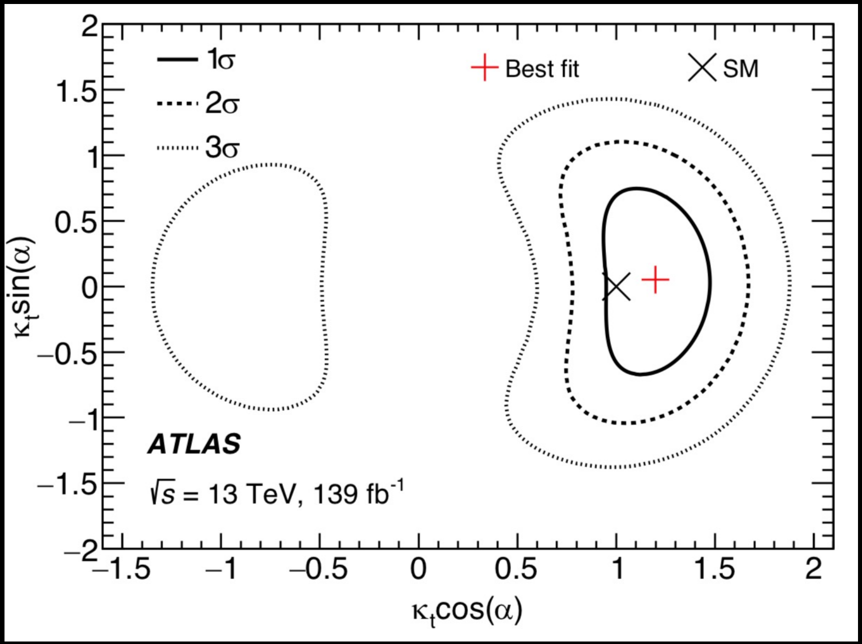
The ATLAS Collaboration

The associated production of a Higgs boson with a top-quark pair is measured in events characterised by the presence of one or two electrons or muons. The Higgs boson decay into a b-quark pair is considered. The analysed data, corresponding to an integrated luminosity of 139 fb^{-1}, were collected in proton–proton collisions at the Large Hadron Collider between 2015 and 2018 at a centre-of-mass energy of $\sqrt{s} = 13$ TeV. The measured signal strength, defined as the ratio of the measured signal yield to that predicted by the Standard Model, is $0.43^{+0.36}_{-0.33}$. This result corresponds to an observed (expected) significance of 1.3 (3.0) standard deviations, in agreement with the Standard Model prediction. For the first time, the signal strength is measured differentially in bins of the Higgs boson transverse momentum in the simplified template cross-section framework, including a boosted selection targeting Higgs boson transverse momentum above 300 GeV.

ttH CP measurement

Recent measurement in this channel gives limits to a CP-odd admixture in the Higgs Yukawa coupling

PRL 125 061802



CP violation results in the ATLAS experiment

R. Gonçalo (U.Coimbra / LIP) on behalf of the ATLAS Collaboration

Higgs Hunting, Orsay-Paris, Sep.12-14 2022

CP Violation in the Higgs Sector?

- Sakharov conditions for a matter-dominated universe require CP violation(1)

- Some CP-violating processes are well known and measured:
  - Described with complex phases in CKM-matrix - quark mixing
  - Maybe in PNMS-matrix as well - neutrino mixing
- But insufficient, by orders of magnitude, to explain baryon asymmetry(1)

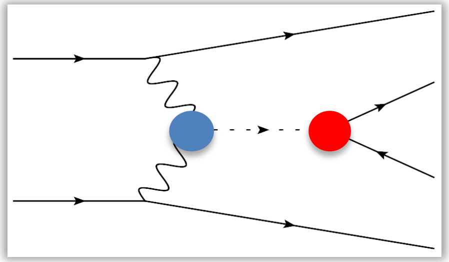
- CP violation in Higgs sector?
  - Possible in some models with extended Higgs sector (e.g. some 2HDMs)
  - M**ixing** of scalar (CP-even) and pseudo-scalar (CP-odd) Higgs states would make CP violation an enticing possibility

- What do we know about Higgs CP properties?
  - In the SM, Higgs scalar is a CP eigenstate with $J^{CP} = 0^{++}$
  - Pure $J^P = 0^-$ hypothesis for observed Higgs boson was ruled out in Run 1(2)
  - But hypothesis of a CP-odd admixture is far from being constrained experimentally!

(1) See e.g. Mod.Phys.Lett.A 9 (1994) 795-810
(2) See e.g. Eur.Phys.J C75 (2015) 476

How to search for a CP-odd admixture?

- Effect of CP-odd components on **bosonic couplings** parametrized as expansion with higher order terms suppressed by powers of scale of new physics Λ
- Could explain why a CP-odd admixture has not been seen

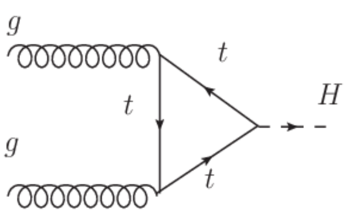


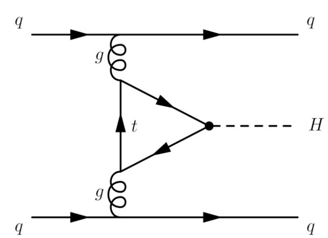
- **Fermionic couplings** are affected at tree level
- Mixing angle α between CP-even and CP-odd coupling components
- More notable for heavier fermions due to enhanced coupling

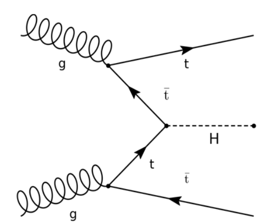
$$\mathcal{L}_{VVH} = \mathcal{L}_{VVH,SM} + \frac{1}{\Lambda^2} c\, \phi \widetilde{V}_{\mu\nu} V^{\mu\nu} + \ldots$$

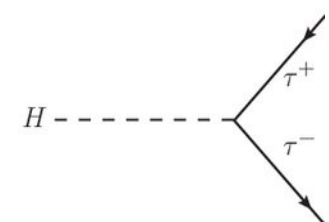
$$\mathcal{L}_{ffH} = \kappa'_f y_f \phi \bar{\psi}_f (\cos\alpha + i\gamma_5 \sin\alpha) \psi_f$$

Fermionic Higgs Couplings



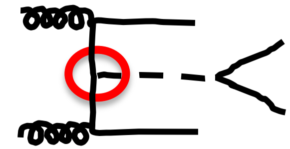






ATLAS-CONF-2022-016 (16 March 2022)

H-top Coupling in ttH/tH production

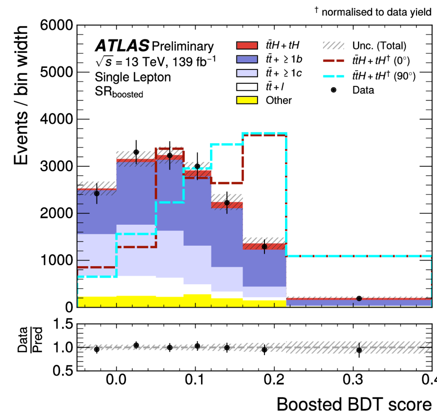


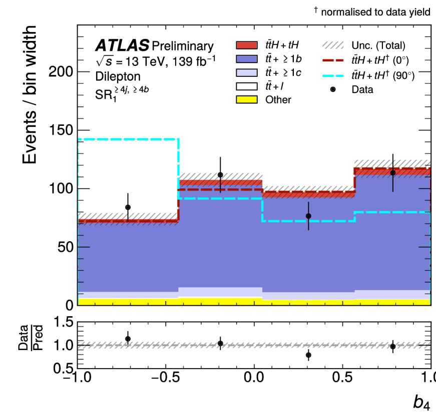
See talk by Neelam in YSF yesterday

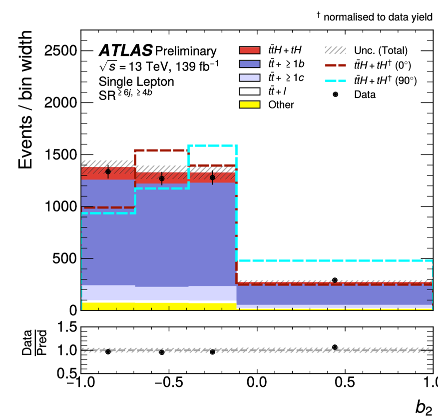
- Calculate CP-sensitive observables $\boldsymbol{b_2}$ and $\boldsymbol{b_4}$ from top-quark 3-momenta
- Use different observables in combined fit depending on region

$$b_2 = \frac{(\vec{p}_1 \times \hat{n}) \cdot (\vec{p}_2 \times \hat{n})}{|\vec{p}_1||\vec{p}_2|} \qquad b_4 = \frac{p_1^z p_2^z}{|\vec{p}_1||\vec{p}_2|}$$

Channel (PSR)	Final SRs and CRs	Classification BDT selection	Fitted observable
Dilepton ($\mathrm{PSR}^{\geq 4j, \geq 4b}$)	$\mathrm{CR}^{\geq 4j, \geq 4b}_{\text{no-reco}}$	–	$\Delta\eta_{\ell\ell}$
	$\mathrm{CR}^{\geq 4j, \geq 4b}$	BDT$\in [-1, -0.086)$	b_4
	$\mathrm{SR}^{\geq 4j, \geq 4b}_1$	BDT$\in [-0.086, 0.186)$	b_4
	$\mathrm{SR}^{\geq 4j, \geq 4b}_2$	BDT$\in [0.186, 1]$	b_4
ℓ+jets ($\mathrm{PSR}^{\geq 6j, \geq 4b}$)	$\mathrm{CR}^{\geq 6j, \geq 4b}_1$	BDT$\in [-1, -0.128)$	b_2
	$\mathrm{CR}^{\geq 6j, \geq 4b}_2$	BDT$\in [-0.128, 0.249)$	b_2
	$\mathrm{SR}^{\geq 6j, \geq 4b}$	BDT$\in [0.249, 1]$	b_2
ℓ+jets ($\mathrm{PSR}_{\text{boosted}}$)	$\mathrm{SR}_{\text{boosted}}$	BDT$\in [-0.05, 1]$	Classification BDT score

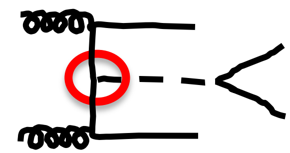






ATLAS-CONF-2022-016 (16 March 2022)

H-top Coupling in ttH/tH production



Simultaneous fit in all regions

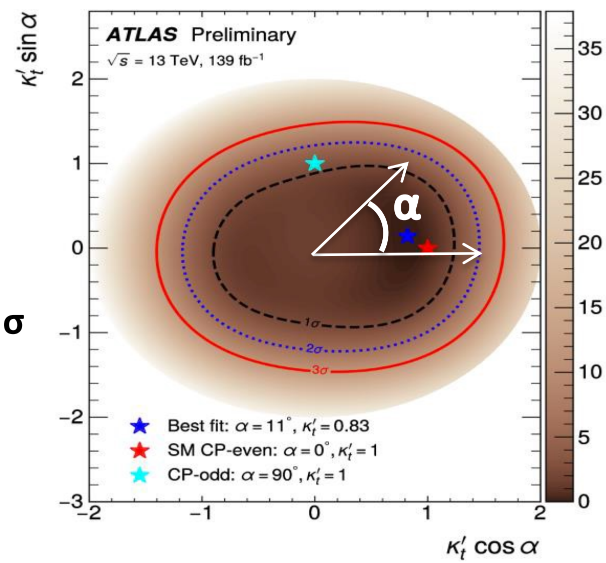
- **$\mu = 0.83^{+0.30}_{-0.46}$**
- **$\alpha = 11° {}^{+55}_{-77}$**

Expected:

- $\mu = 1.0^{+0.25}_{-0.27}$
- $\alpha = 0° {}^{+49}_{-50}$
- Pure CP-odd (α = 90°) disfavoured at **1.2 σ**

Systematics-dominated analysis:

- Dominant uncertainties from tt+≥1b modelling: NLO matching, PS and hadronisation, flavour scheme



Uncertainty source	$\Delta\alpha[°]$	
Process modelling		
Signal modelling	+7.9	-13
$t\bar{t}+\geq 1b$ modelling		
$t\bar{t}+\geq 1b$ 4V5 FS	+26	-40
$t\bar{t}+\geq 1b$ NLO matching	+24	-36
$t\bar{t}+\geq 1b$ fractions	+15	-23
$t\bar{t}+\geq 1b$ FSR	+5.2	-9.9
$t\bar{t}+\geq 1b$ PS & hadronisation	+17	-27
$t\bar{t}+\geq 1b$ $p_T^{b\bar{b}}$ shape	+5.7	-5.3
$t\bar{t}+\geq 1b$ ISR	+15	-26
$t\bar{t}+\geq 1c$ modelling	+7.4	-12
$t\bar{t}$ + light modelling	+2.7	-4.8
b-tagging efficiency and mis-tag rates		
b-tagging efficiency	+9.7	-17
c-mis-tag rates	+7.4	-12
l-mis-tag rates	+2.5	-3

$$\boxed{\mathcal{L}_{t\bar{t}H} = -\kappa_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t}$$

H-top Coupling in ttH/tH production

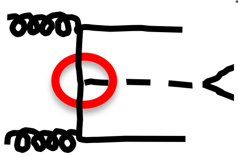
ATLAS-CONF-2022-016 vs Phys. Rev. Lett. 125 (2020) 061802

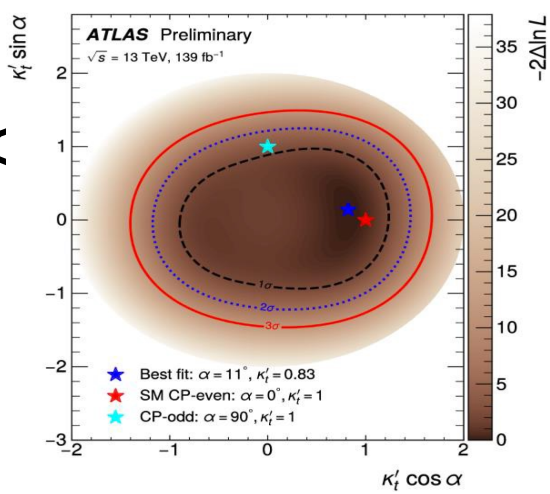
New analysis: ttH (H→bb):

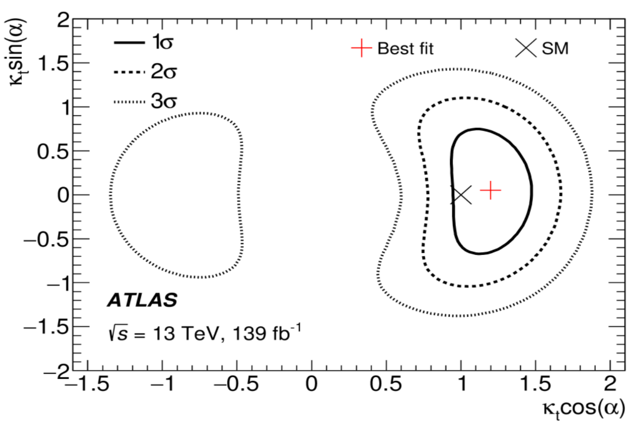
- **$\mu = 0.83^{+0.30}_{-0.46}$** (exp. $\mu = 1.0^{+0.25}_{-0.27}$)
- **$\alpha = 11°\,^{+55}_{-77}$** (exp. $\alpha = 0°\,^{+49}_{-50}$)
- Pure CP-odd (α = 90°) disfavoured at **1.2 σ**

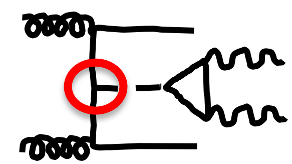
Complementary to previous ttH(H→γγ) analysis:

- Phys. Rev. Lett. 125 (2020) 061802
- Pure CP-odd (α = 90°) excluded at **3.9 σ**
- Limit on **$|\alpha| < 43°$** at 95% C.L.



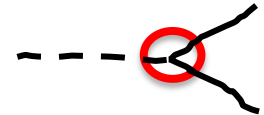


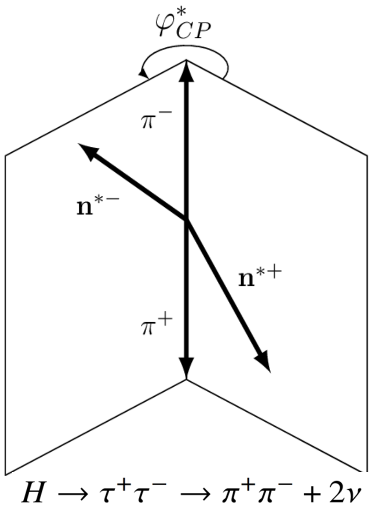


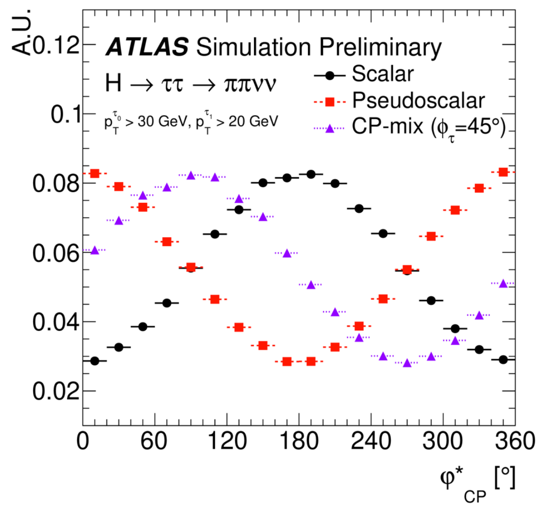


ATLAS-CONF-2022-032 (18 May 2022)

H-τ Coupling in inclusive production







Notation	Decay mode	Branching fraction
ℓ	$\ell^\pm\bar{\nu}\nu$	35.2 %
1p0n	$h^\pm\nu$ $(\pi^\pm\nu)$	11.5 % (10.8 %)
1p1n	$h^\pm\pi^0\nu$ $(\pi^\pm\pi^0\nu)$	25.9 % (25.5 %)
1pXn	$h^\pm \geq 2\pi^0\nu$ $(\pi^\pm 2\pi^0\nu)$	10.8 % (9.3 %)
3p0n	$3h^\pm\nu$ $(3\pi^\pm\nu)$	9.8 % (9.0 %)

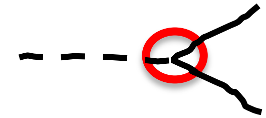
YpXn Y charged pions; X neutral pions

$$\boxed{\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H}$$

- Angle between **τ decay planes** in **H rest frame** sensitive to CP mixing angle ϕ_τ
- Due to neutrinos, use $\boldsymbol{\varphi^{*CP}}$ angle as proxy:
  - Acoplanarity angle between τ decay planes in **Zero Momentum Frame** of **visible** decay products
- φ^{*CP} reconstructed with dedicated methods for semi-exclusive decay modes
  - Total branching ratio in targeted decay modes: 68%

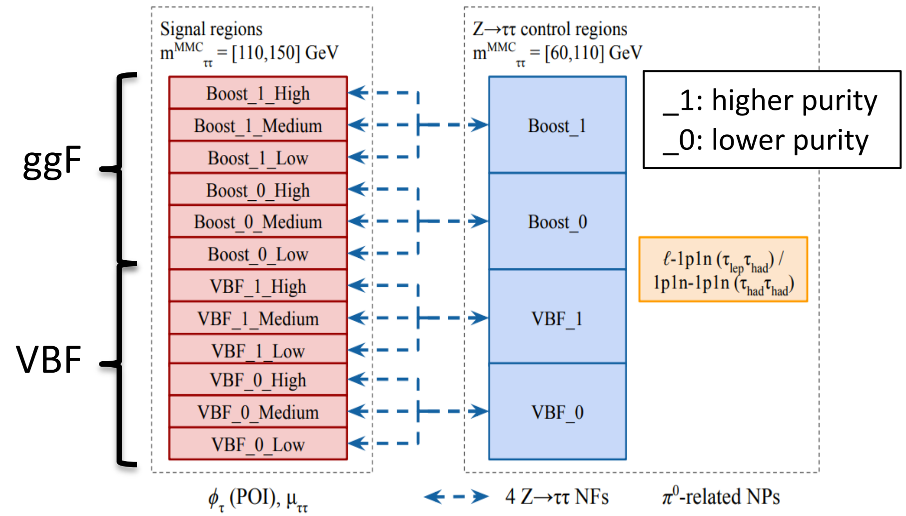
ATLAS-CONF-2022-032 (18 May 2022)

H-τ Coupling in inclusive production



Decay channel	Decay mode combination	Method	Fraction in all τ lepton pair decays
$\tau_{lep}\tau_{had}$	ℓ-1p0n	IP	8.1%
	ℓ-1p1n	IP-ρ	18.3%
	ℓ-1pXn	IP-ρ	7.6%
	ℓ-3p0n	IP-a_1	6.9%
$\tau_{had}\tau_{had}$	1p0n-1p0n	IP	1.3%
	1p0n-1p1n	IP-ρ	6.0%
	1p1n-1p1n	ρ	6.7%
	1p0n-1pXn	IP-ρ	2.5%
	1p1n-1pXn	ρ	5.6%
	1p1n-3p0n	ρ-a_1	5.1%

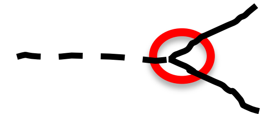
YpXn Y charged pions; X neutral pions



- 24 Signal categories and 10 Control Regions
  - **2 channels** × **VBF** or **Boost** (ggF p_T^H > 100 GeV) × 2 **purity** regions × High/Medium/Low **sensitivity**
- Angle reconstruction requires excellent performance:
  - Particle flow based τ_{had} reconstruction
  - $\pi^0 \rightarrow \gamma\gamma$ and vertex / impact parameter reconstrucion
  - Both efficiency and purity around 80% for dominant decays

[ATLAS-CONF-2022-032](#) (18 May 2022)

H-τ Coupling in inclusive production

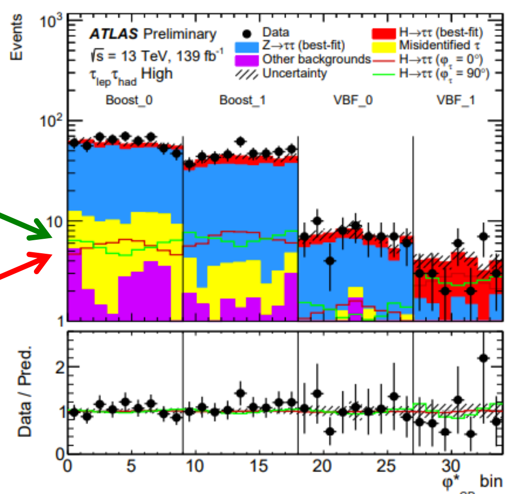


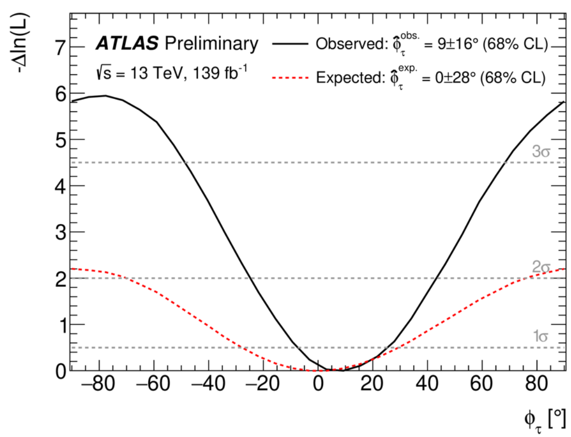
- Simultaneous fit in all regions
- Analysis leaves μ free to float – agnostic with respect to rate effects
- Best fit observed: $\phi_\tau = 9° \pm 16°$ (expected: $\phi_\tau = 0° \pm 28°$)
- Pure CP-odd (α = 90°) disfavoured at 3.4 σ
- Dominant background is Z→ττ: constrained from Control Regions
- Statistics-dominated analysis; dominant systematic uncertainty from jet calibration

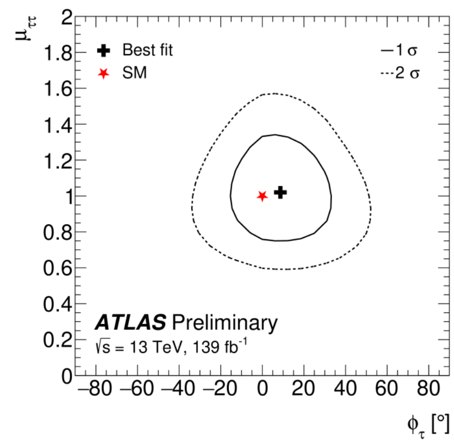
$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H$$

CP-odd

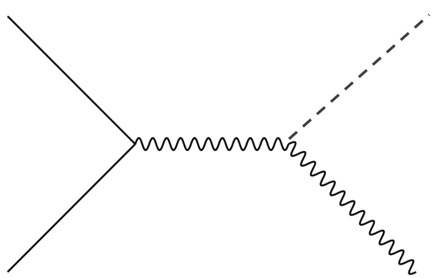
CP-even

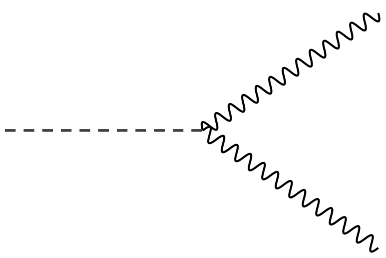


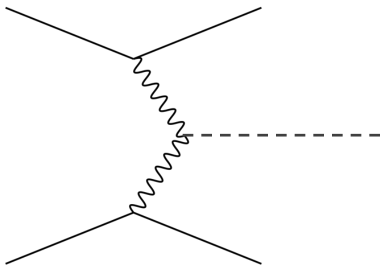




Bosonic Higgs Couplings

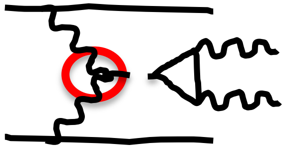






CERN-EP-2022-134 (3 August 2022)

HVV Coupling in Vector Boson Fusion



- New analysis: **VBF H→γγ**
- Consider effective HVV Lagrangian augmented with dimension six **CP-odd** operators
- Strength of CP violation in VBF matrix element can be described by a single parameter(*) giving:

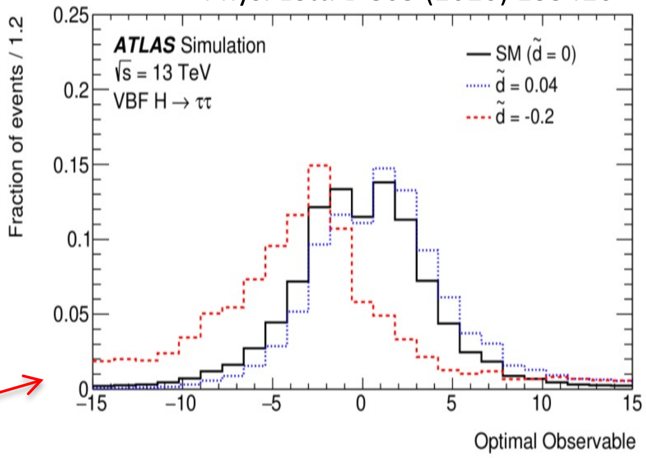
$$\mathcal{M} = \mathcal{M}_{\text{SM}} + \tilde{d} \cdot \mathcal{M}_{\text{CP-odd}}$$

$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + \tilde{d} \cdot 2\,\text{Re}(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{CP-odd}}) + \tilde{d}^2 \cdot |\mathcal{M}_{\text{CP-odd}}|^2$$

- Calculate LO matrix elements using 4-momenta of Higgs and VBF jets
  - Extract initial-state parton momentum fractions from jet momenta
- Use to calculate **Optimal Observable** (OO):
  - Expected to be symmetric with mean value of zero if no CP-violation

$$\boxed{OO = \frac{2Re(\mathcal{M}^*_{SM}\mathcal{M}_{CP-odd})}{|\mathcal{M}_{SM}|^2}}$$

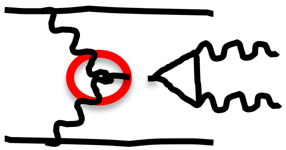
Phys. Lett. B 805 (2020) 135426



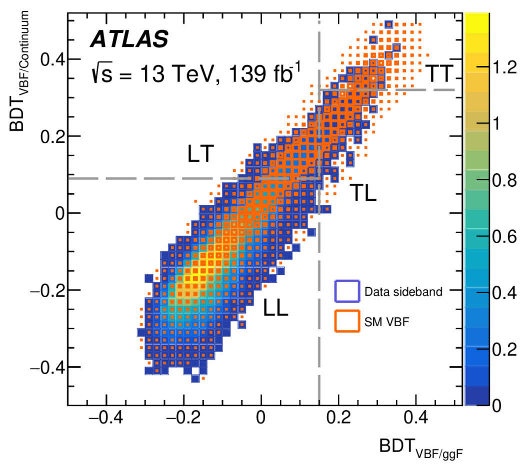
(*) Slightly simplified scenario: see Phys. Lett. B 805 (2020) 135426 , set: $\tilde{d} = \tilde{d}_B$

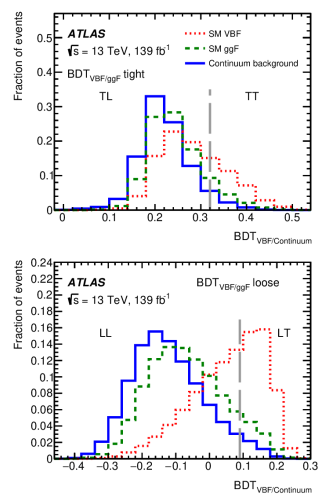
CERN-EP-2022-134 (3 August 2022)

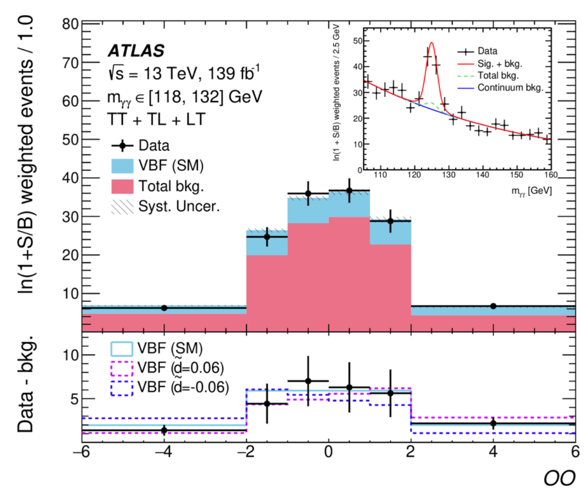
HVV Coupling in Vector Boson Fusion



- Select events with ≥2 photons and ≥2 tag jets (energy flow)
- Increase signal purity with 2 BDTs:
  - **$BDT_{VBF/ggF}$**: separate VBF signal from gluon-fusion Higgs production
  - **BDTVBF/Continuum**: separate VBF signal from continuum diphoton background
- Split into signal regions using BDT output: Tight-Tight (TT); Loose-Tight (LT); Tight-Loose (TL)
- In each OO bin extract signal yield from a fit to the di-photon mass spectrum
- Fit shape of Optimal Observable to extract the coefficient of the interference term $\tilde{d}$
  - Pure **shape analysis** – signal normalisation is left floating in the fit to depend only on interference term

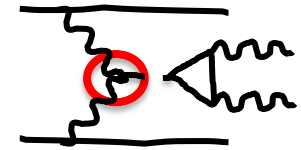




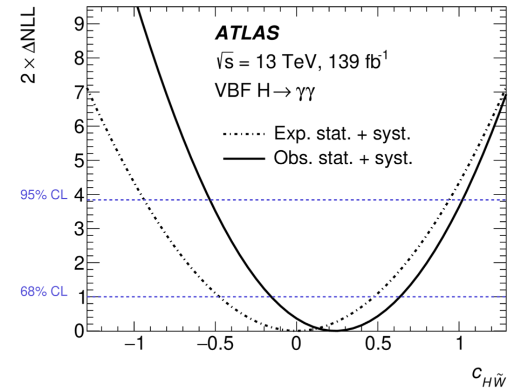


[CERN-EP-2022-134](3 August 2022)

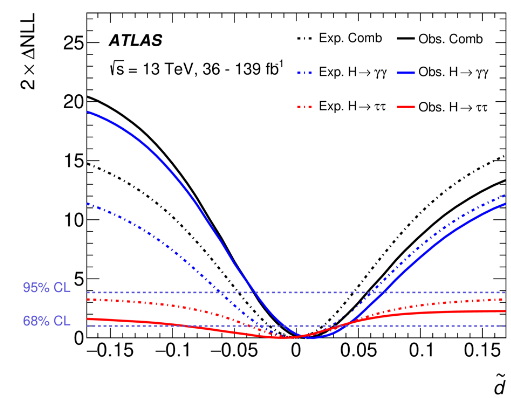
HVV Coupling in Vector Boson Fusion



- Result interpretation with $\tilde{d}$ (HISZ EFT operator basis) but also $c_{H\tilde{W}}$ (Warsaw basis)
  - No improvement from using quadratic term – sensitivity driven by interference
- Results are the **strongest existing bounds** on CP violation in HVV
- Combination with previous analysis of VBF H→ττ (36 fb^{-1})
  - [Phys. Lett. B 805 (2020) 135426]
  - Confidence intervals further improved



	68% (exp.)	95% (exp.)	68% (obs.)	95% (obs.)
$\tilde{d}$ (inter. only)	[−0.027, 0.027]	[−0.055, 0.055]	[−0.011, 0.036]	[−0.032, 0.059]
$\tilde{d}$ (inter.+quad.)	[−0.028, 0.028]	[−0.061, 0.060]	[−0.010, 0.040]	[−0.034, 0.071]
$\tilde{d}$ from $H \to \tau\tau$	[−0.038, 0.036]	–	[−0.090, 0.035]	-
Combined $\tilde{d}$	[−0.022, 0.021]	[−0.046, 0.045]	[−0.012, 0.030]	[−0.034, 0.057]
$c_{H\tilde{W}}$ (inter. only)	[−0.48, 0.48]	[−0.94, 0.94]	[−0.16, 0.64]	[−0.53, 1.02]
$c_{H\tilde{W}}$ (inter.+quad.)	[−0.48, 0.48]	[−0.95, 0.95]	[−0.15, 0.67]	[−0.55, 1.07]



Summary & Outlook

- The search for a CP structure of Higgs boson couplings is being very actively pursued in ATLAS
  - Still much space for CP odd admixture, potential source for CP violation
  - Would be clear evidence for deeper theory, beyond the SM and might address fundamental question of baryon asymmetry

- Results generally in agreement with Standard Model CP-even hypothesis

- Several Run 2 measurements using 139 fb^{-1}
  - Produced about 8 M Higgs bosons in Run 2!
  - A lot to expect from Run 3 and later!

- Today: showed only latest results in this presentation:
  - H-top Coupling in ttH/tH production with H → γγ, H → bb
  - H-τ Coupling in VBF + hhF production
  - HVV Coupling in VBF , H → γγ
  - More Run 2 analyses reaching results soon

Pure CP-odd ttH coupling excluded at 3.9 σ
Pure CP-odd Hττ coupling excluded at 3.4 σ
Strongest existing bounds on $\tilde{d}$ and $c_{H\tilde{W}}$

Backup slides

Higgs Properties

- Mass $m_h = \sqrt{2\lambda}v$
- Spin: 1 degree of freedom => 0
- Couplings:
- To gauge bosons

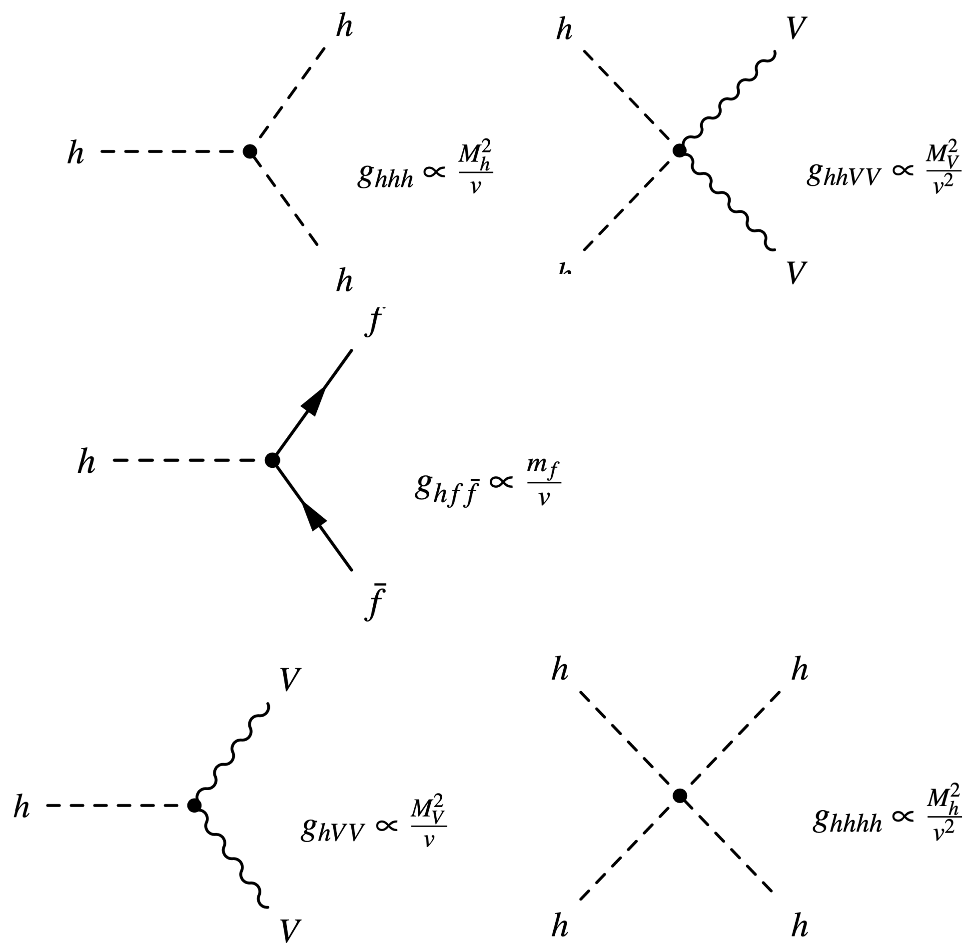
$$g_{hVV} \propto \frac{M_V^2}{v} \quad g_{hhVV} \propto \frac{M_V^2}{v^2}$$

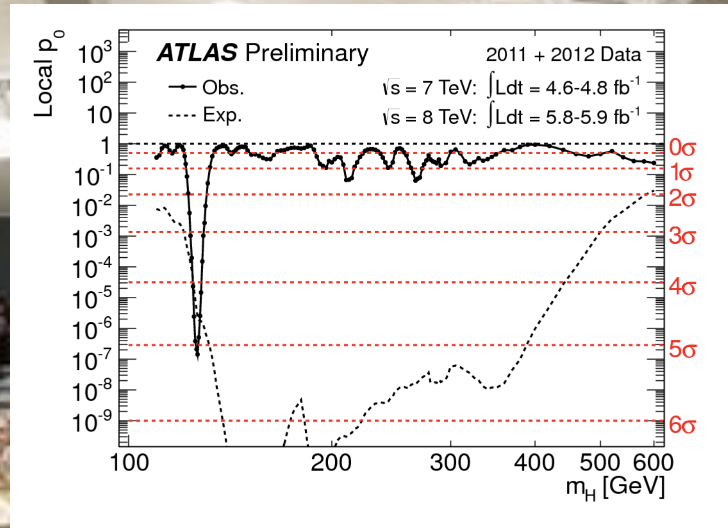
- Yukawa couplings to fermions

$$g_{hf\bar{f}} \propto \frac{m_f}{v}$$

- Self-couplings

$$g_{hhh} \propto \frac{M_h^2}{v} \quad g_{hhhh} \propto \frac{M_h^2}{v^2}$$





The Long Way to Discovery

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

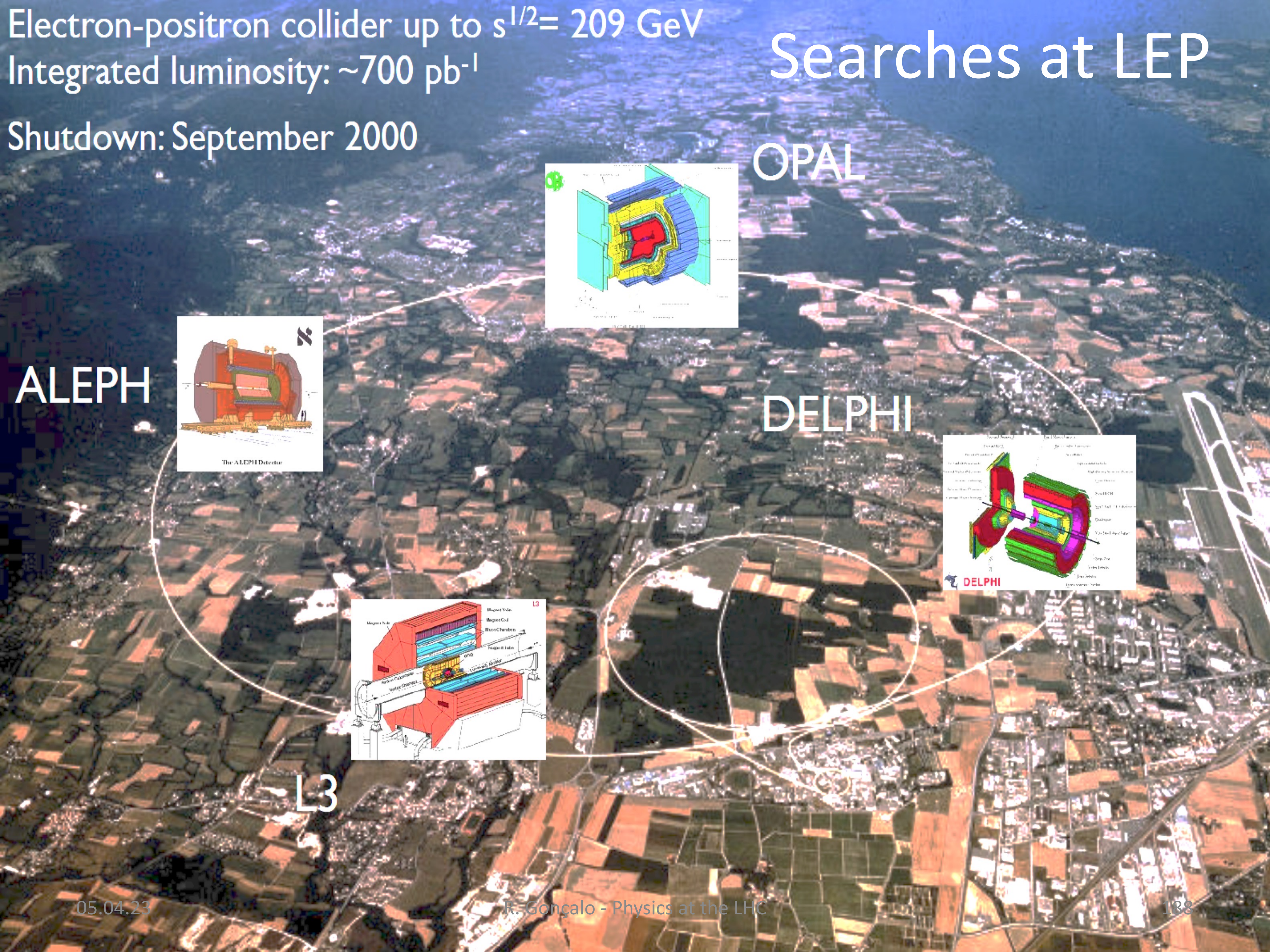
Received 7 November 1975

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3),4)] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Searches at LEP

Electron-positron collider up to $s^{1/2}$= 209 GeV
Integrated luminosity: ~700 pb^{-1}

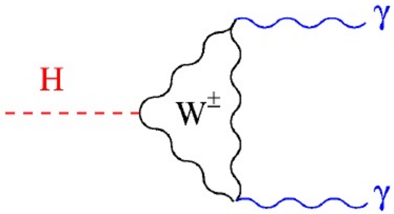
Shutdown: September 2000



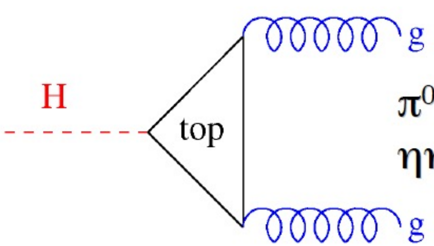
Low-mass searches at LEP

The decay branching ratios depend only on m_H:

- ❑ $m_H < 2m_e$: $H \to \gamma\gamma$ + large lifetime;



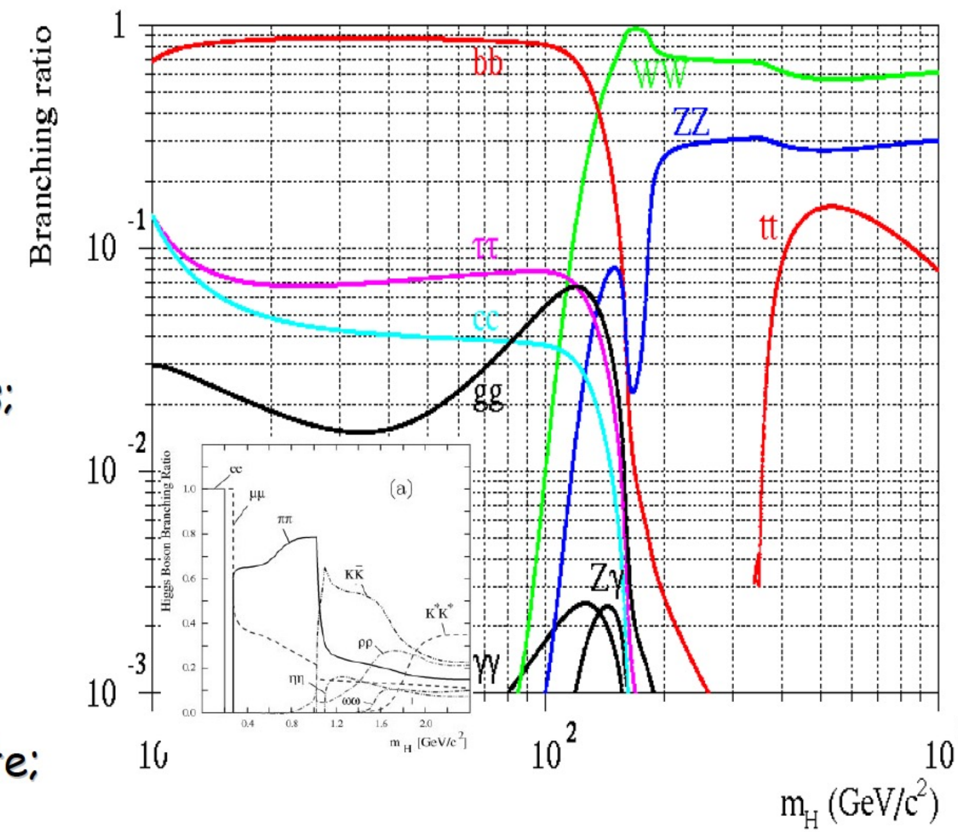
- ❑ $m_H < 2m_\mu$: $H \to e^+e^-$ dominates;
- ❑ $m_H < 2m_\pi$: $H \to \mu^+\mu^-$ dominates;
- ❑ $m_H < 3$ - 4 GeV: $H \to gg$ dominates;



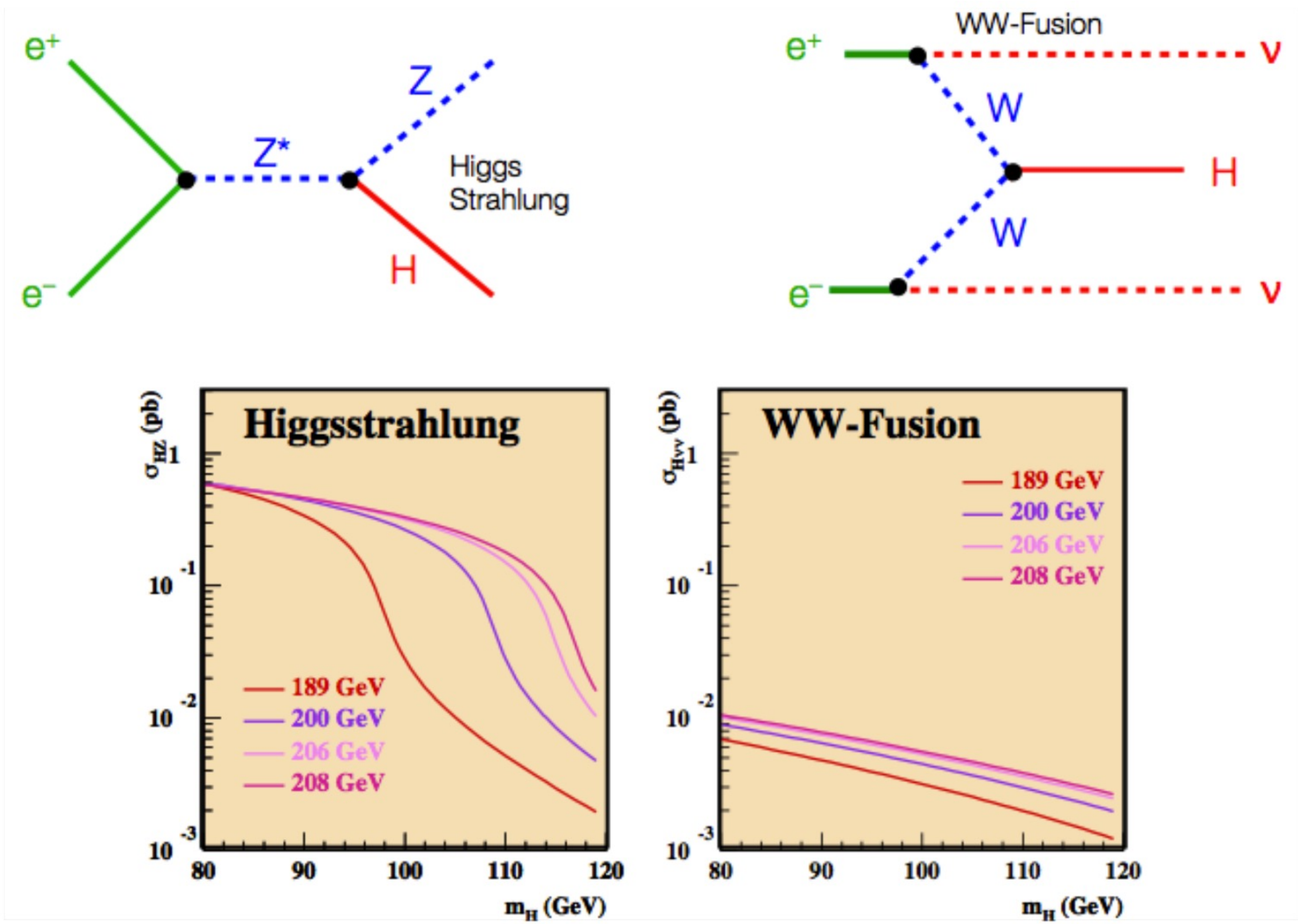
$\pi^0\pi^0$, $\pi^+\pi^-$, KK, $\eta\eta$, ... etc

- ❑ $m_H < 2m_b$: $H \to \tau^+\tau^-$ and $c\bar{c}$ dominate;

- ❑ $m_H > 2m_b$ up to 1000 GeV/c^2:



Higher-mass Higgs production at LEP



Summary of all Higgs candidates found at LEP

Invariant mass of all candidates

In total 17 candidates selected

- 15.8 background events expected

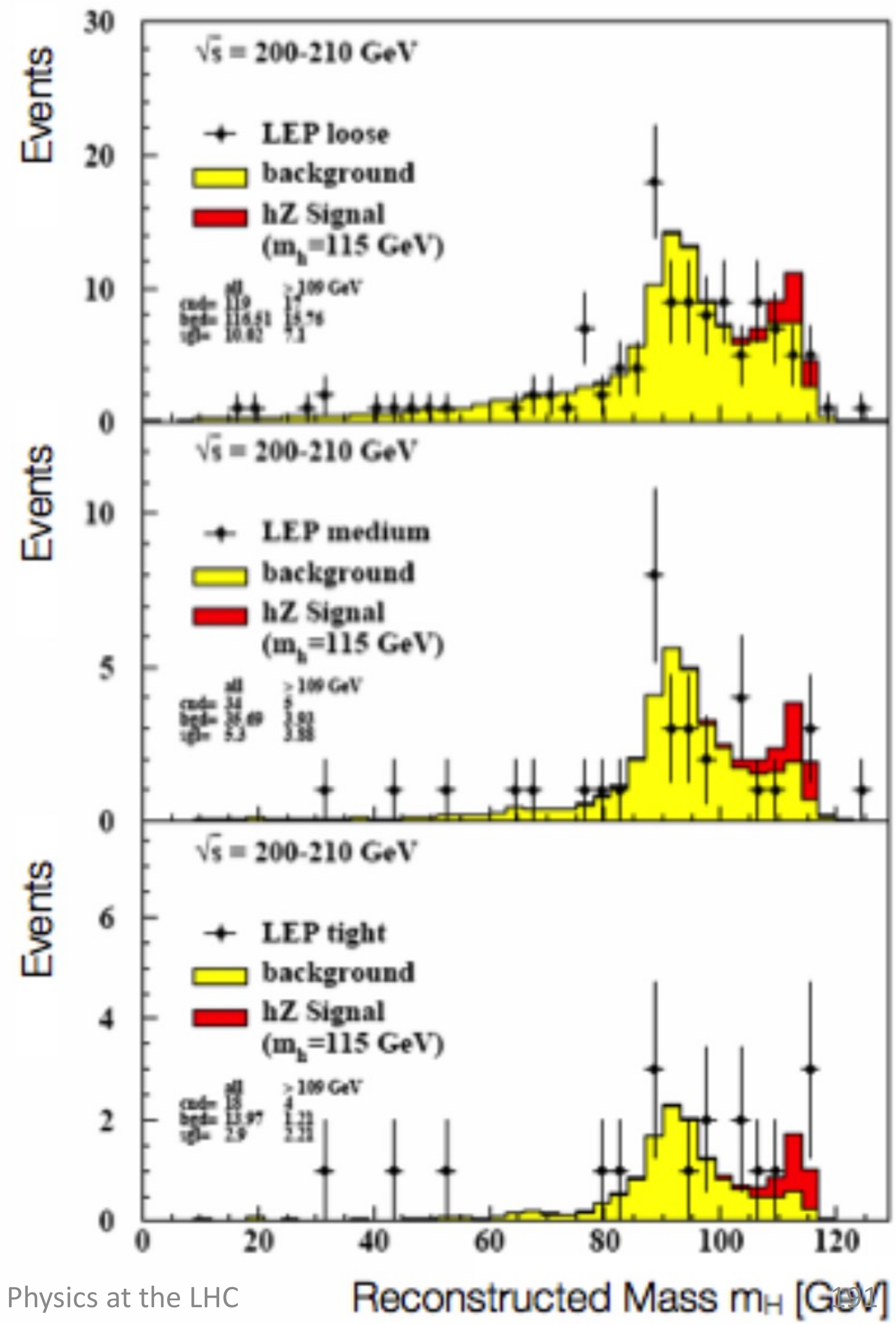
Expectation for m_H=115 GeV

- 8.4 events

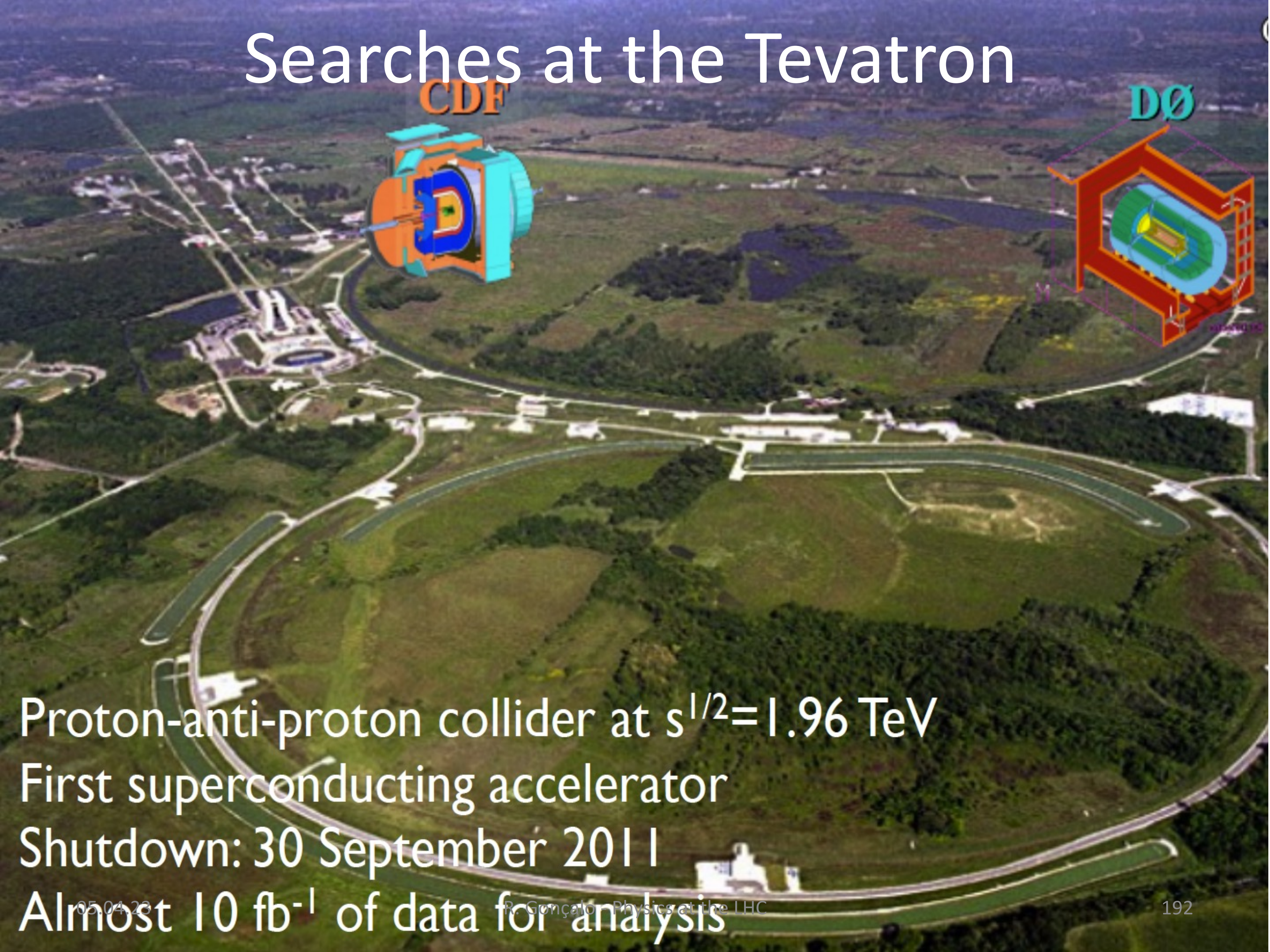
Corresponding excess was not observed

Final verdict from LEP

m_H>114.4 GeV @ 95% CL

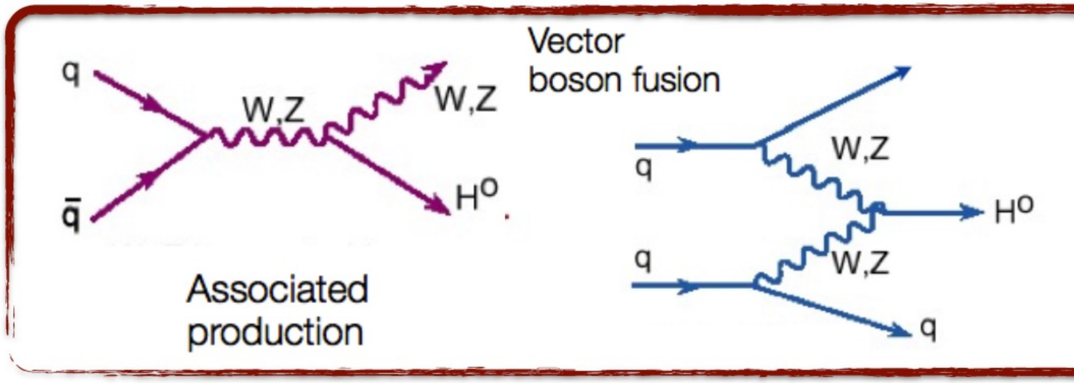


Searches at the Tevatron

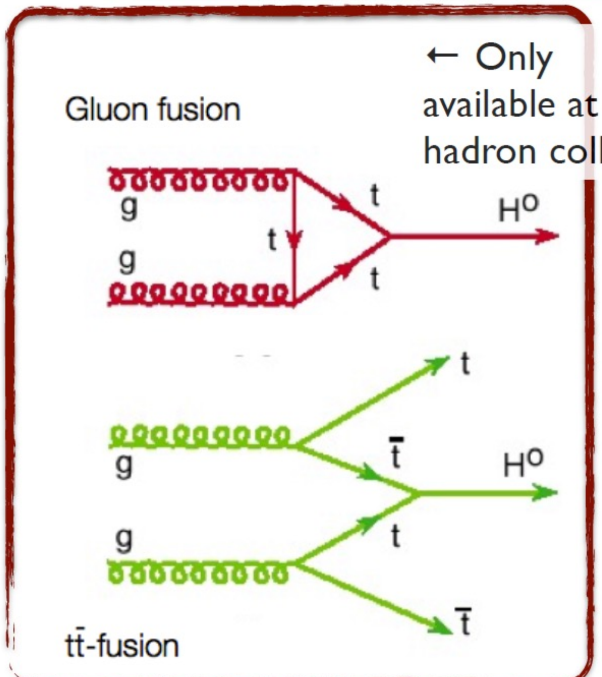


Proton-anti-proton collider at $s^{1/2}$=1.96 TeV
First superconducting accelerator
Shutdown: 30 September 2011
Almost 10 fb^{-1} of data for analysis

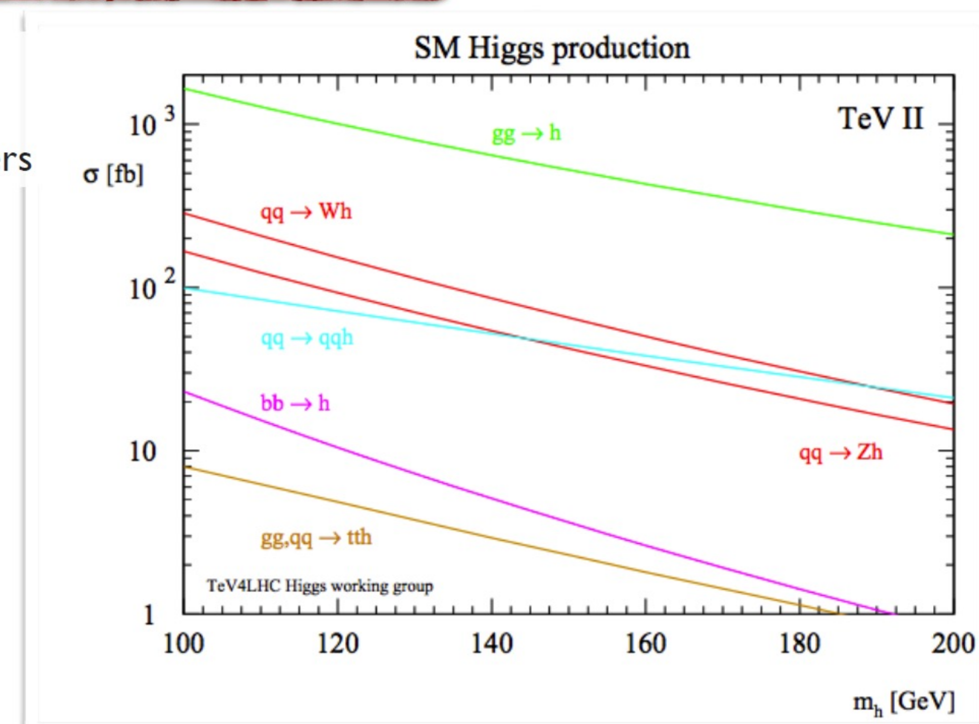
Higgs production at the Tevatron



← (fermion annihilation and vector boson scattering)

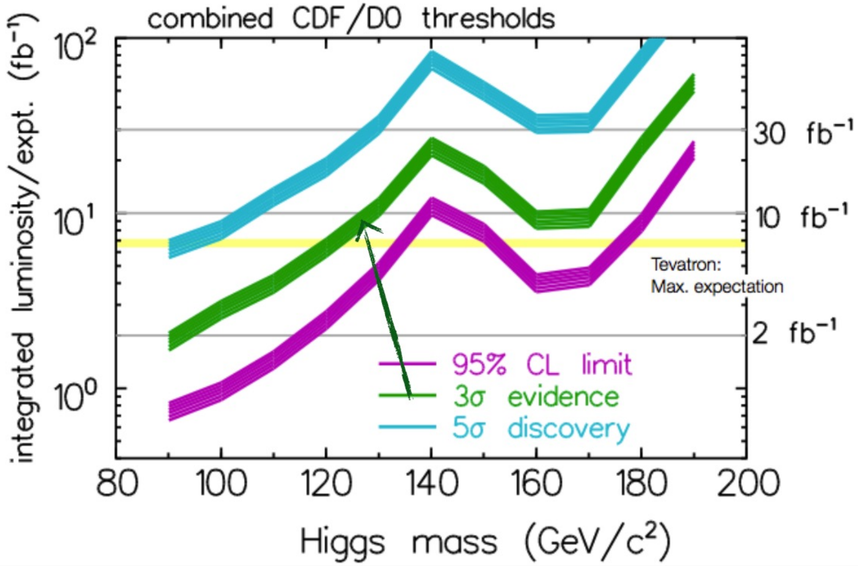


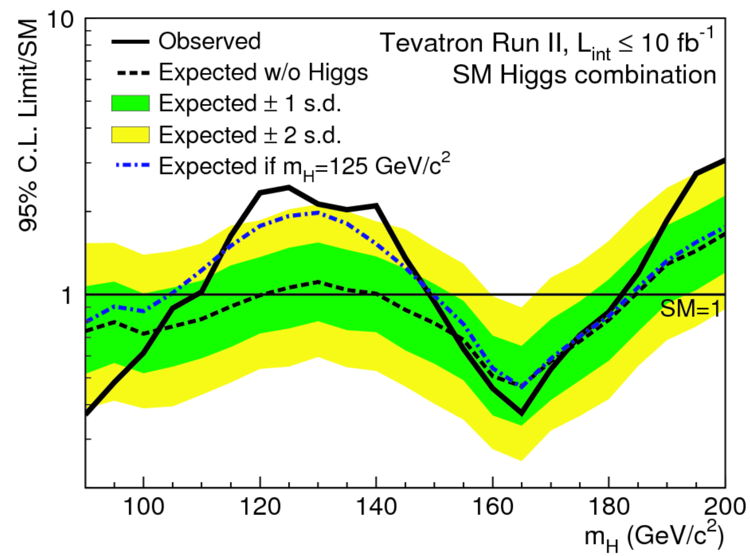
← Only available at hadron colliders



The final stand of the Tevatron

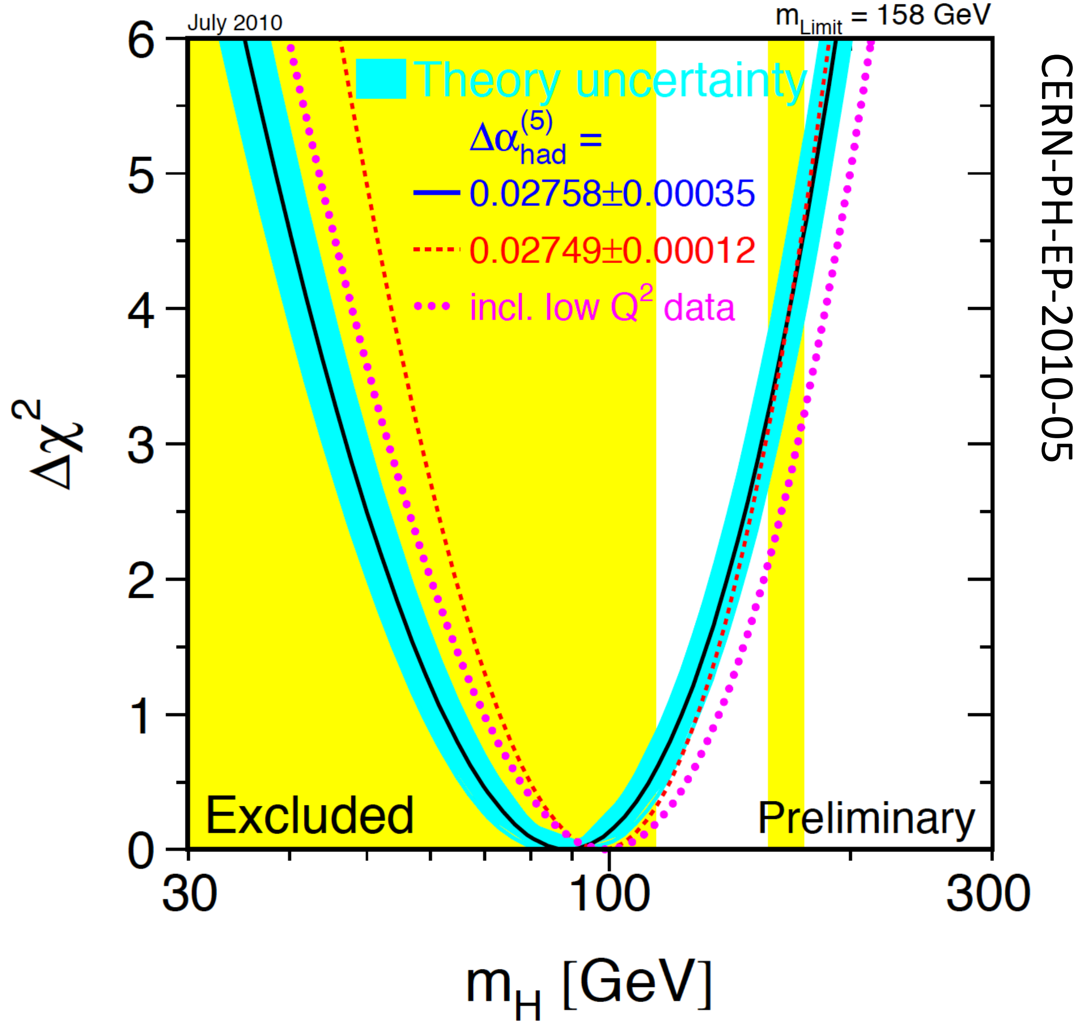
- By the end of its lifetime, the Tevatron had very sophisticated analyses of a huge number of channels
- By that time the LHC was collecting data and analysing it very fast
- The CDF and D0 experiments obtained an excess of around 3 standard deviations in the mass range $115<M_H<140$ GeV
- Not enough to claim discovery, but consistent with the LHC results





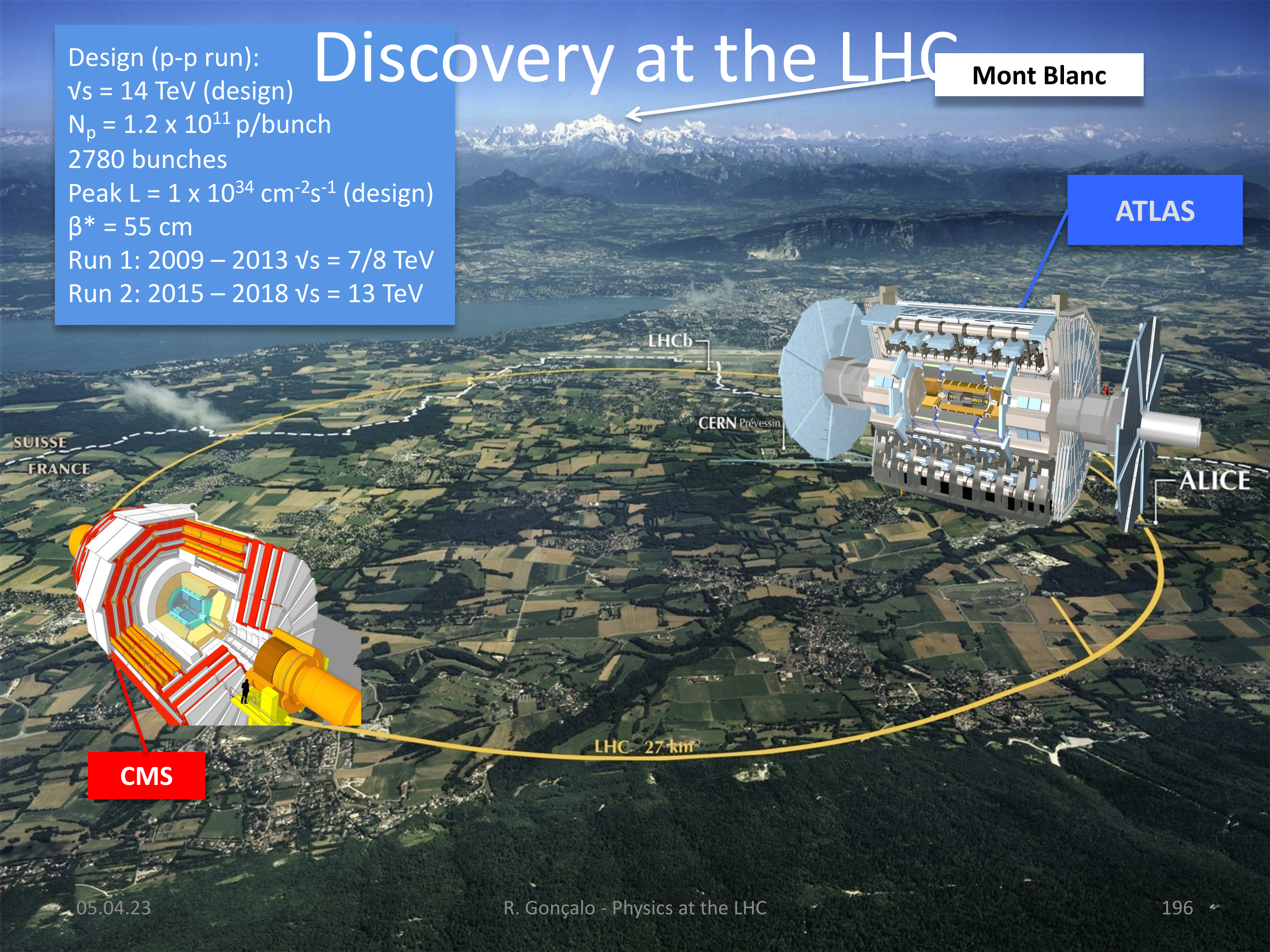
LEP and Tevatron: the Blue Band Plot

- Decades of searches in several experiments...
- By July 2010:
  - LEP+Tevatron+SLD limits
  - Higgs excluded for m_h<114.4 GeV at 95% CL
  - Plus between 158 and 175 GeV

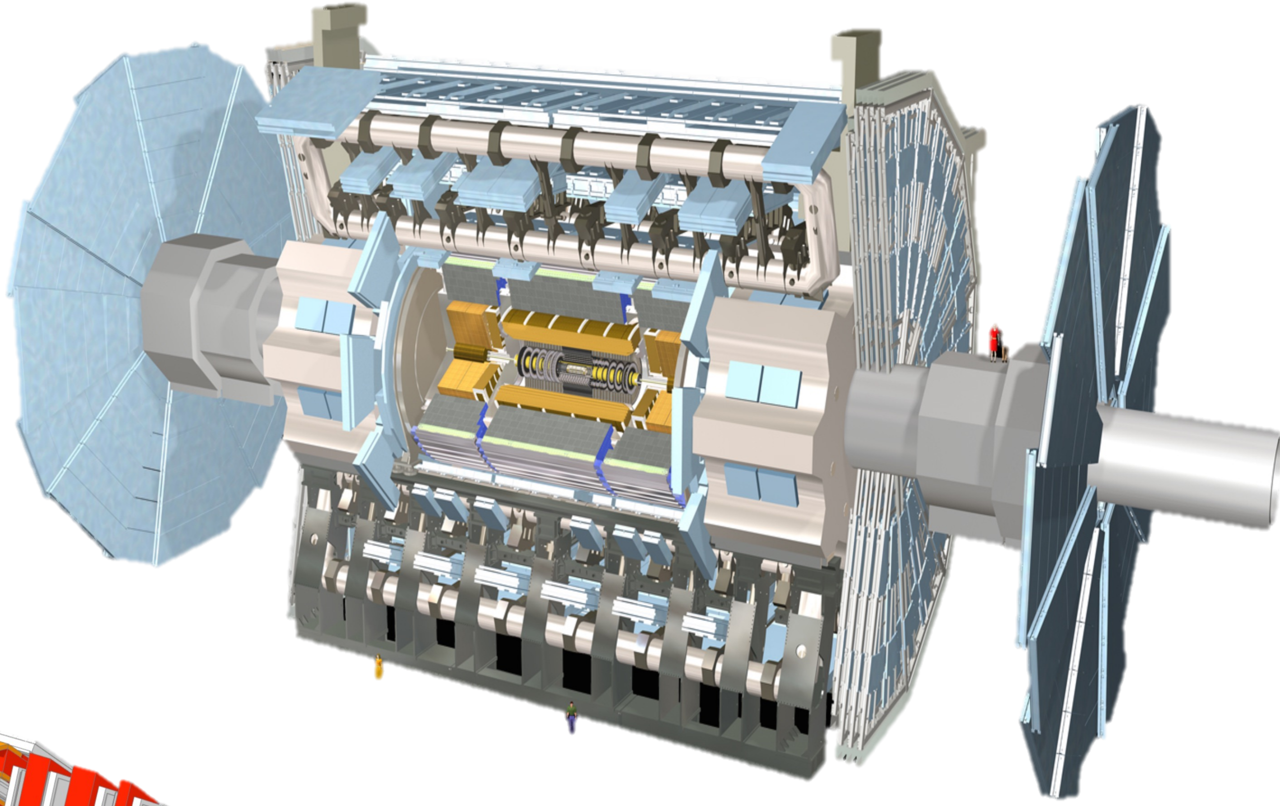


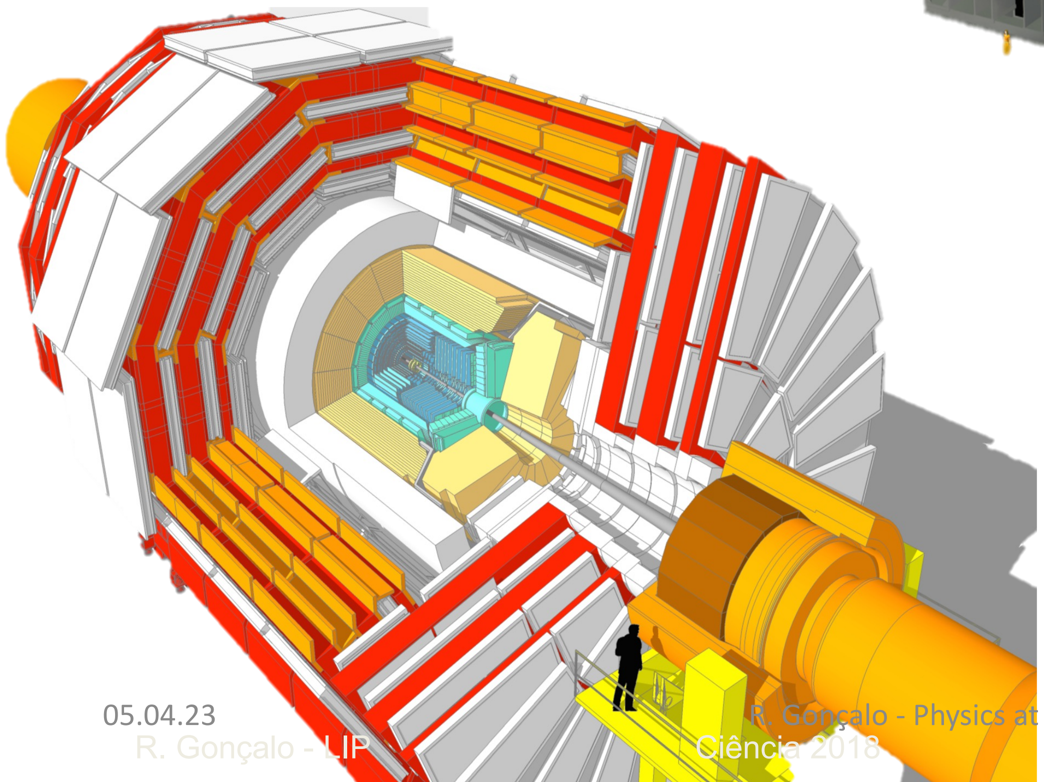
Discovery at the LHC

Design (p-p run):
$\sqrt{s}$ = 14 TeV (design)
$N_p = 1.2 \times 10^{11}$ p/bunch
2780 bunches
Peak $L = 1 \times 10^{34}\ cm^{-2}s^{-1}$ (design)
β^* = 55 cm
Run 1: 2009 – 2013 $\sqrt{s}$ = 7/8 TeV
Run 2: 2015 – 2018 $\sqrt{s}$ = 13 TeV



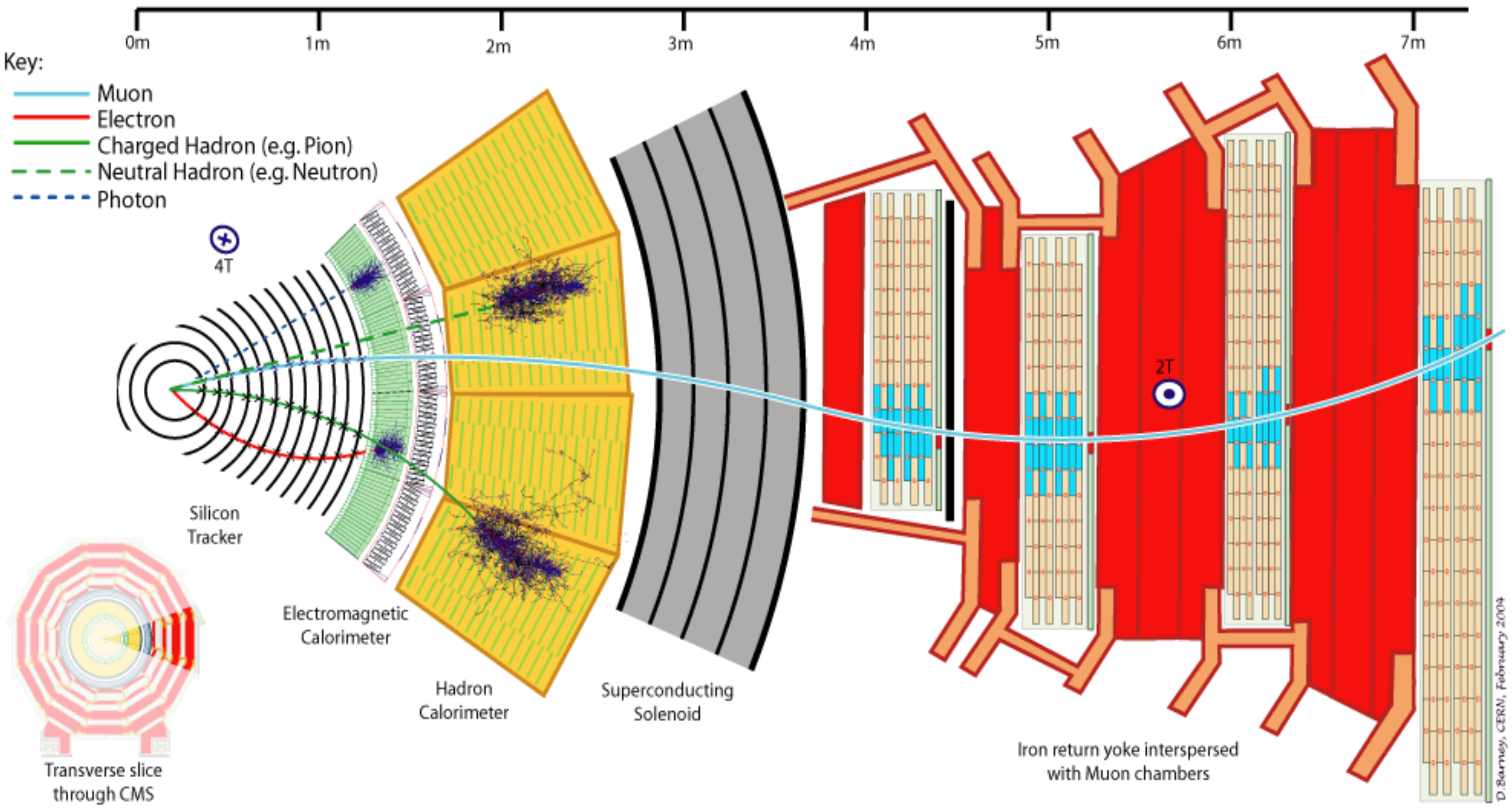
ATLAS
3000 colaboradores
175 institutos de 38 países
L = 44 m, ∅ ≈ 25 m, 7 000 t

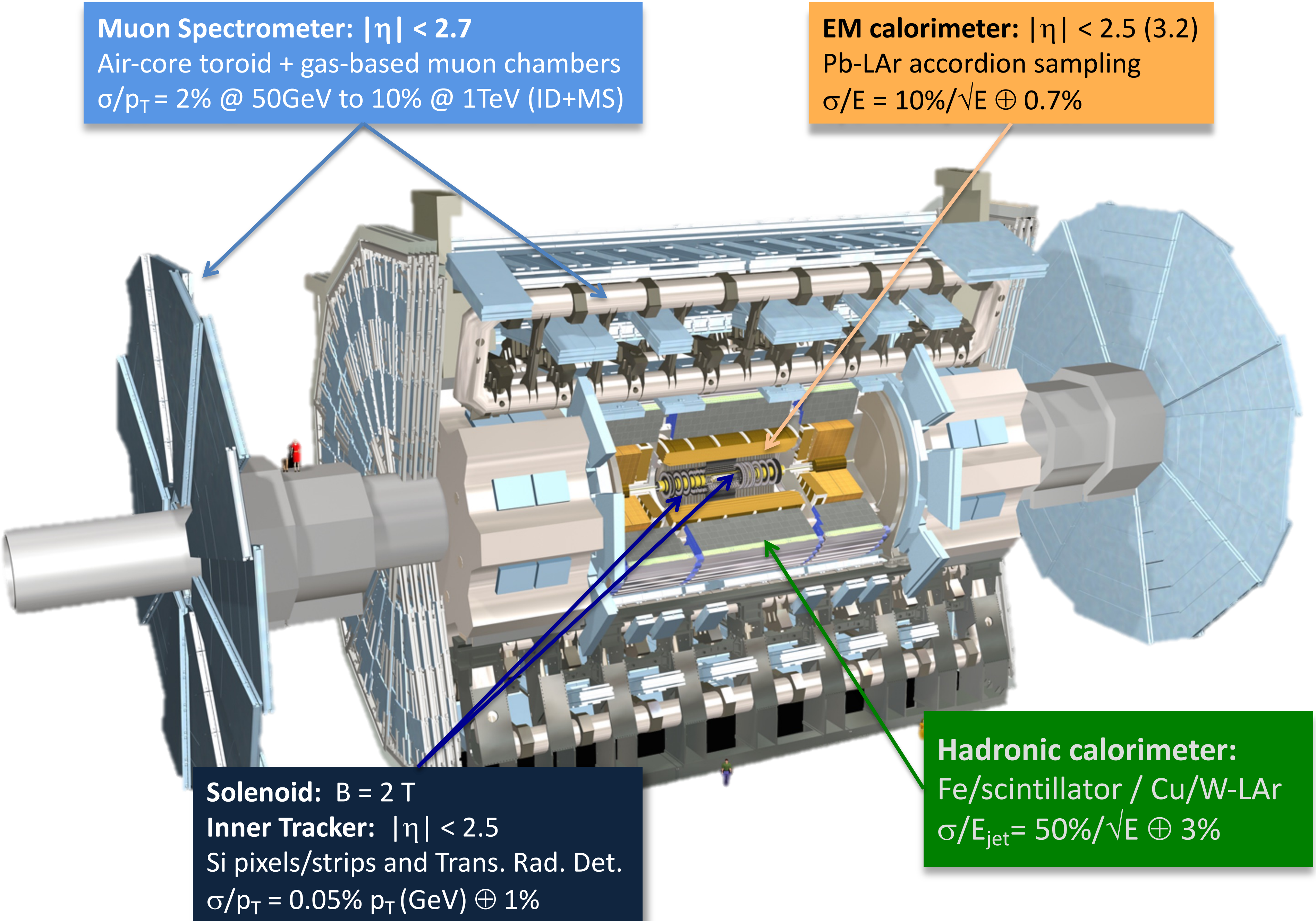


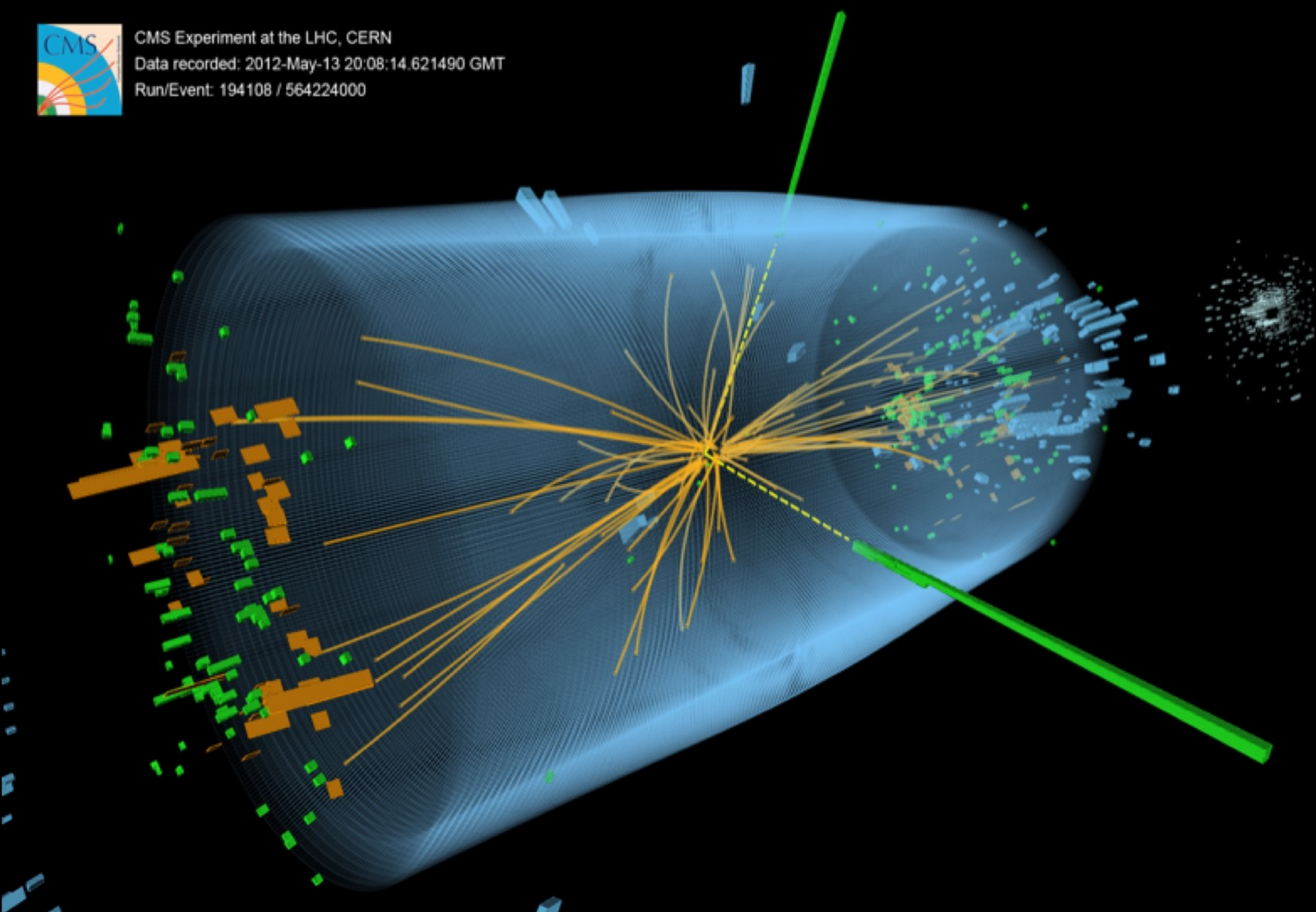


CMS
3800 colaboradores
199 institutos de 43 países
L = 22 m, ∅ ≈ 15 m, 14 000 t

R. Gonçalo - LIP Ciência 2018 197

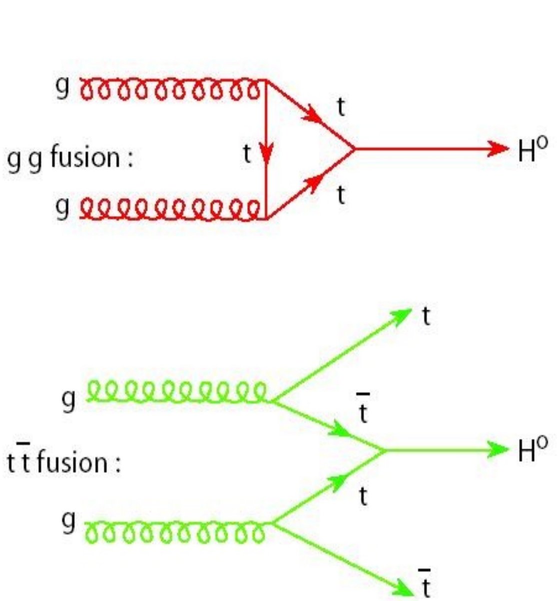

0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

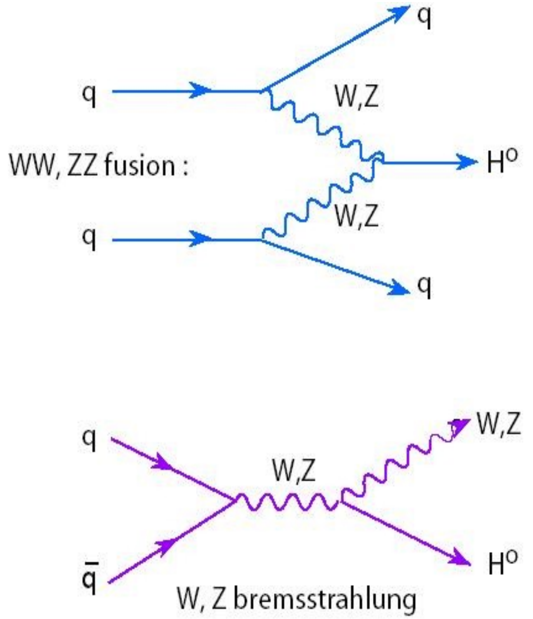

Muon Spectrometer: $|\eta| < 2.7$
Air-core toroid + gas-based muon chambers
σ/p_T = 2% @ 50GeV to 10% @ 1TeV (ID+MS)
EM calorimeter: $|\eta| < 2.5$ (3.2)
Pb-LAr accordion sampling
$\sigma/E = 10\%/\sqrt{E} \oplus 0.7\%$
Solenoid: B = 2 T
Inner Tracker: $|\eta| < 2.5$
Si pixels/strips and Trans. Rad. Det.
$\sigma/p_T = 0.05\%\ p_T\,(\mathrm{GeV}) \oplus 1\%$
Hadronic calorimeter:
Fe/scintillator / Cu/W-LAr
$\sigma/E_{jet} = 50\%/\sqrt{E} \oplus 3\%$

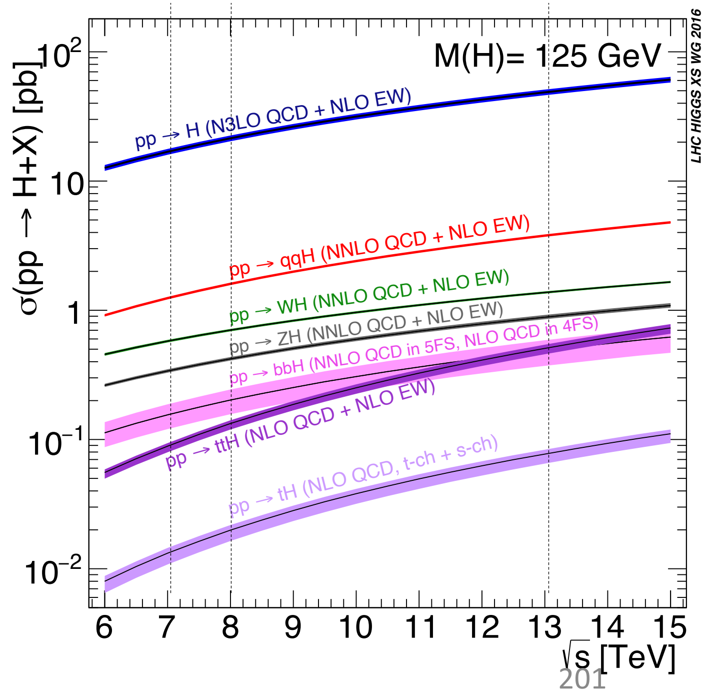

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

Higgs @ the LHC

- Many different production and decay mechanisms
  - Span 3 orders of magnitude in cross section and branching ratio
  - Some very clean decays with low BR (γγ, 4l)
  - Other very difficult with higher rates (bb, WW, ττ,...)
- Access Higgs properties through combination of different channels







Higgs @ the LHC

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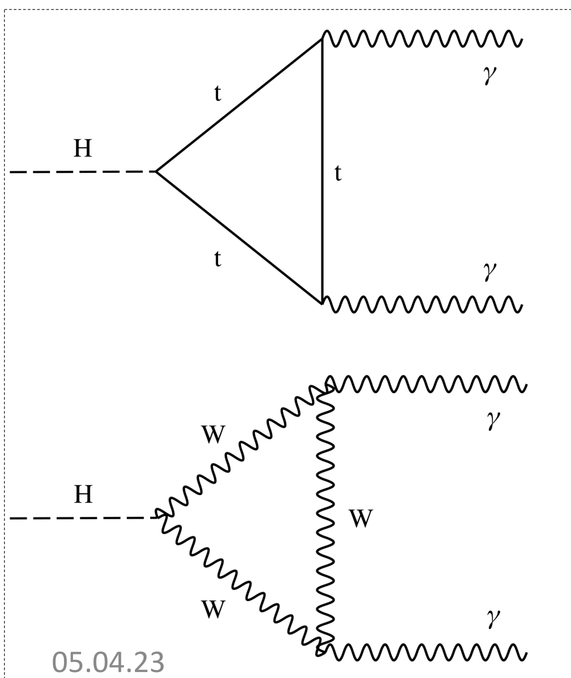
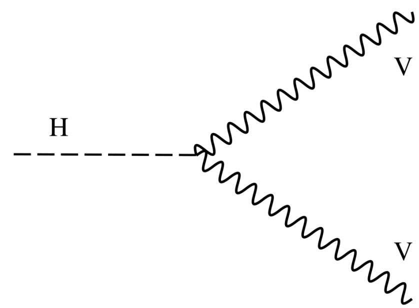
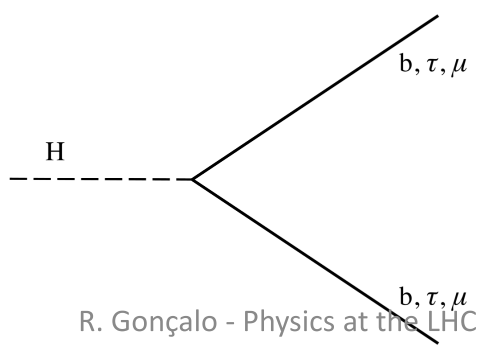
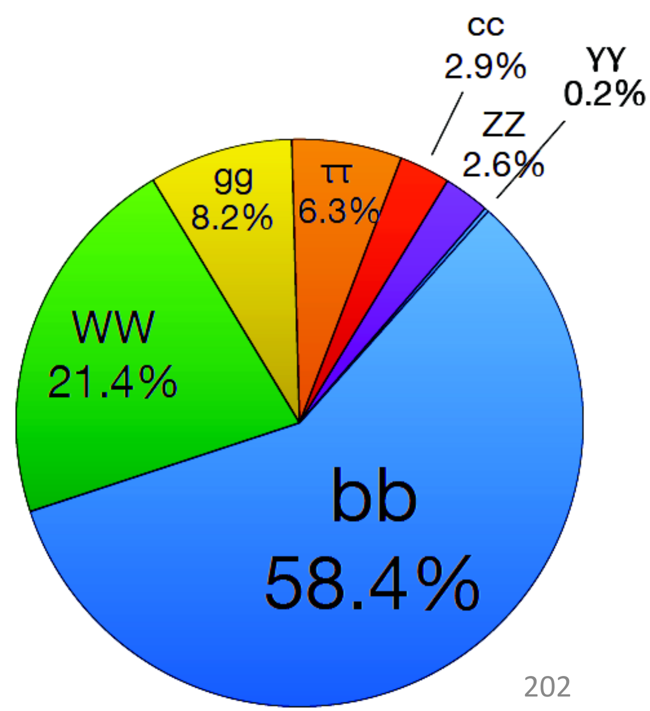


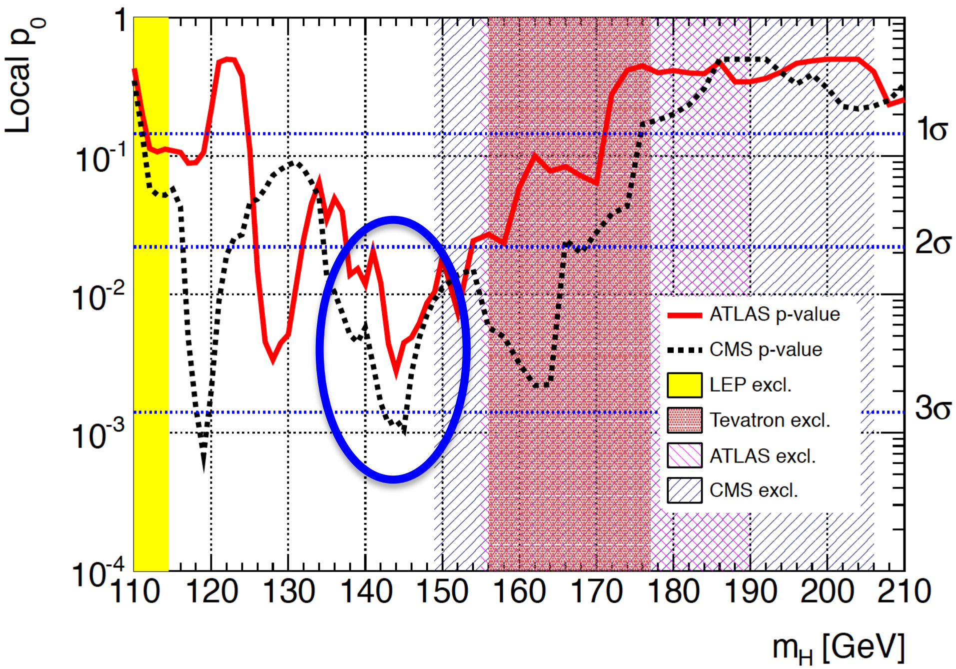




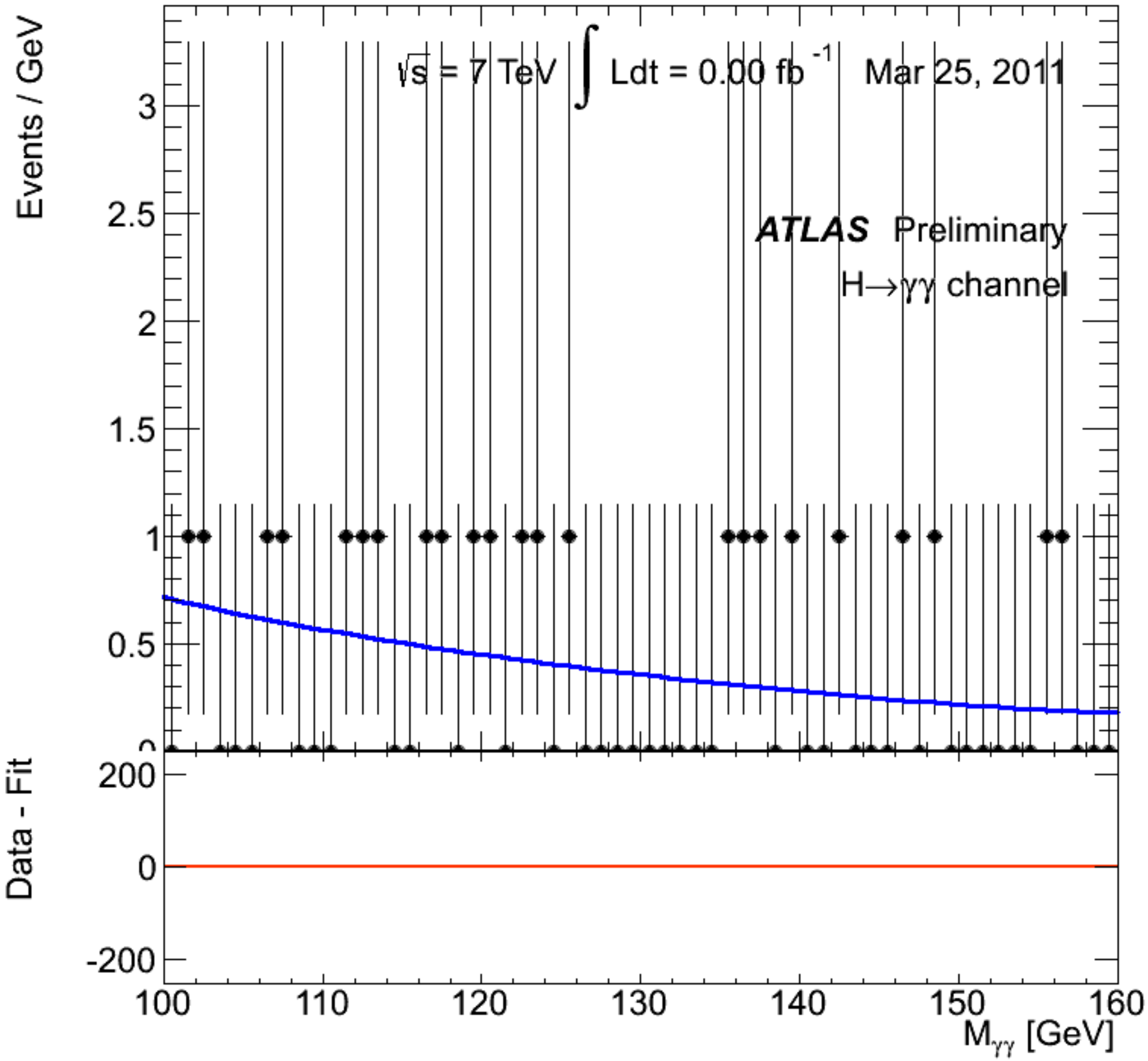


It takes time to get it right

EPS-HEP 2011 conference [6]



2012: Descoberta do bosão de Higgs: H->$\gamma\gamma$

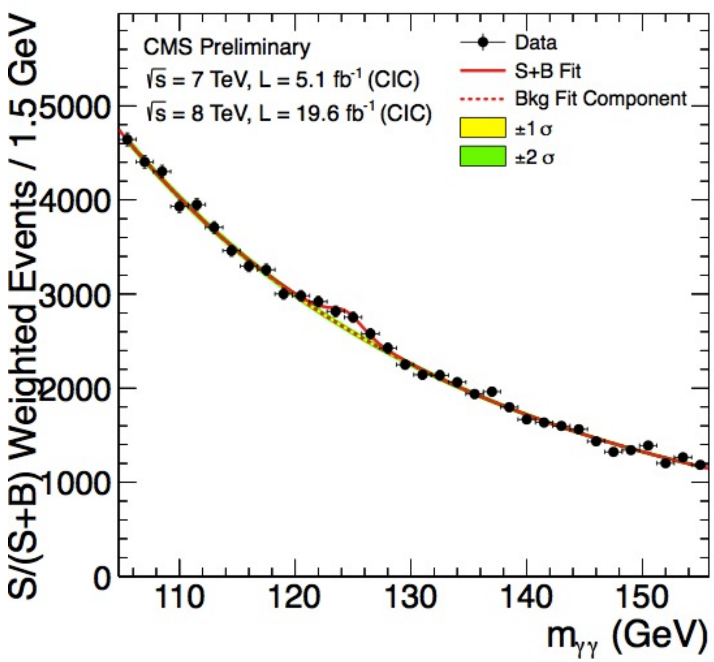


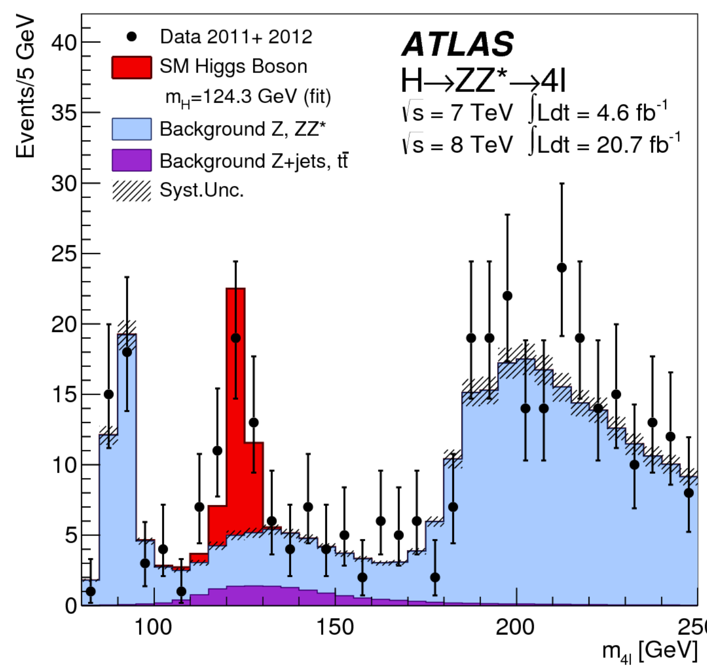
Discovery channels

- Discovery was made in ATLAS and CMS with about 5 fb^{-1} of 7 TeV data and 20 fb^{-1} of 8 TeV data per experiment; several channels combined

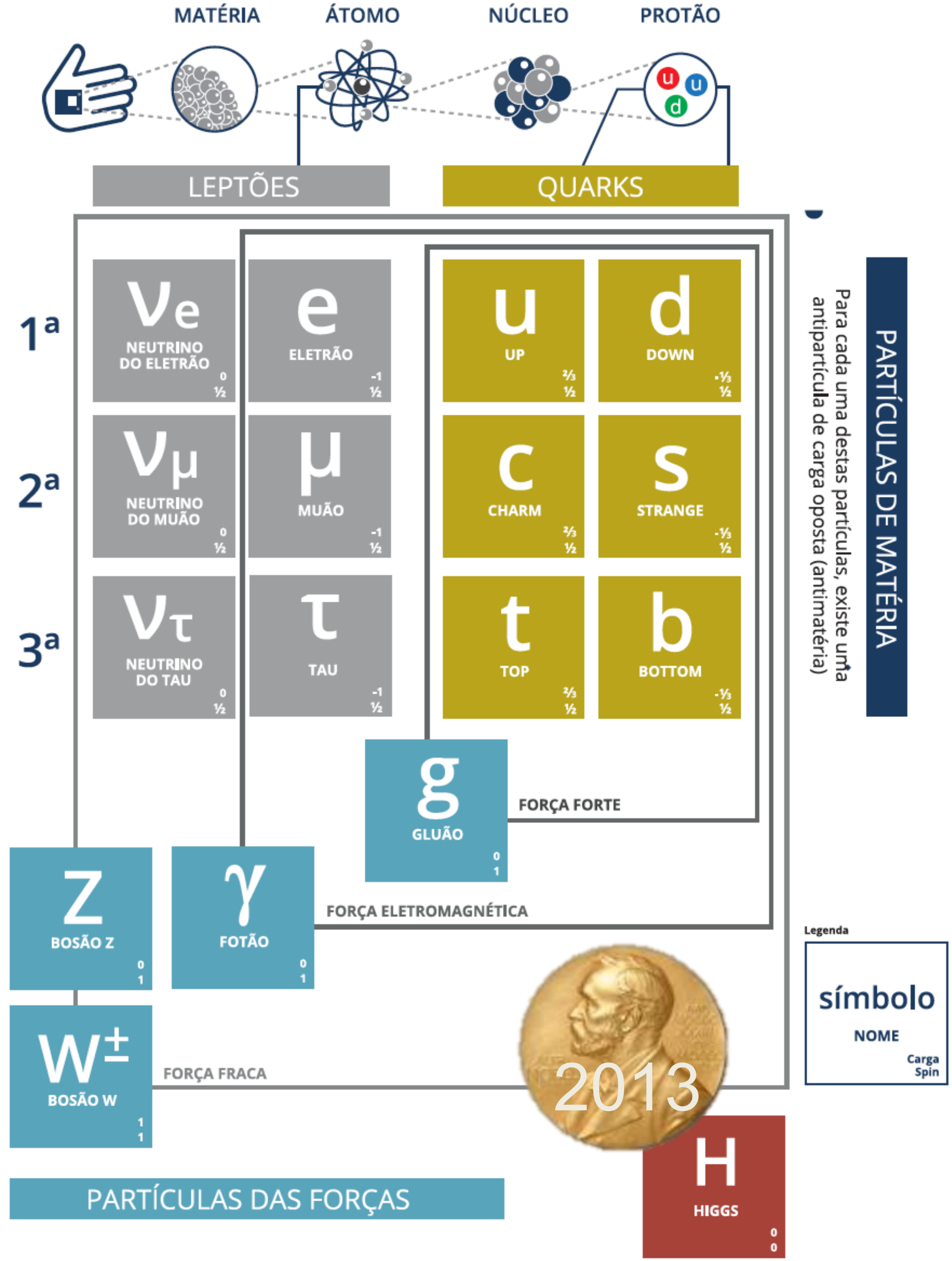
$$h \to \gamma\gamma; h \to ZZ^* \to 4\ell; h \to WW^*; h \to \tau^+\tau^-; h \to b\bar{b}$$

- This means about 400 000 Higgs bosons produced in about 8 000 000 000 000 000 (8×10^{15}) proton collisions
  - Only about 4000 events with Higgs bosons contributed to the discovery

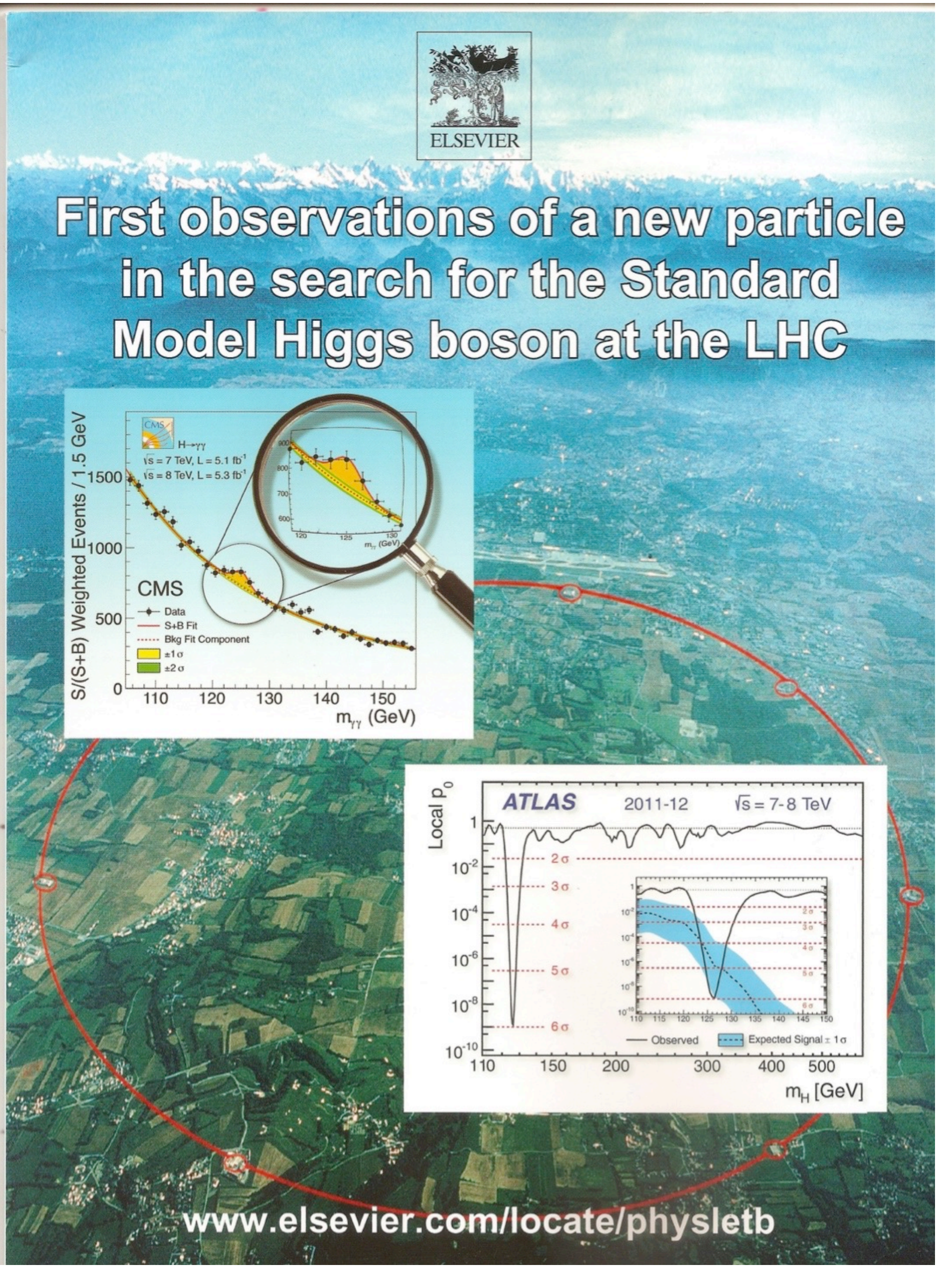




The Standard Model of particle physics <u>completed</u>



A Descoberta do bosão de Higgs



Two quotations from the experimental papers presented in this publication:

"... *The search for the Higgs boson, the only elementary particle in the Standard Model that has not yet been observed, is one of the highlights of the Large Hadron Collider physics program.*"

- ATLAS Collaboration

" ... *The decay to two photons indicates that the new particle is a boson with spin different from one. The results presented here are consistent, ... with expectations for a standard model Higgs boson.*"

- CMS Collaboration

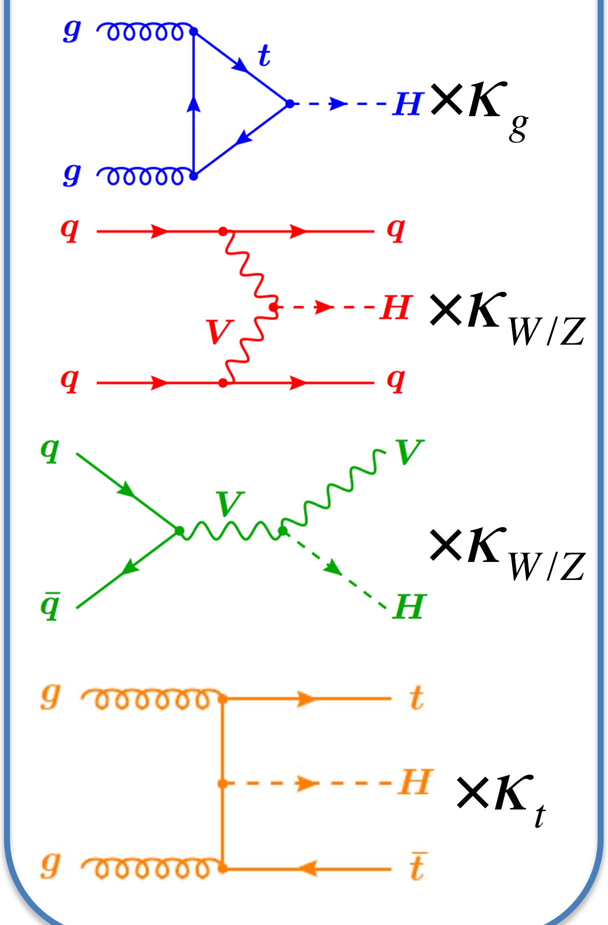
Best wishes!
Peter Higgs

What now?!

Probing the 125 GeV Higgs

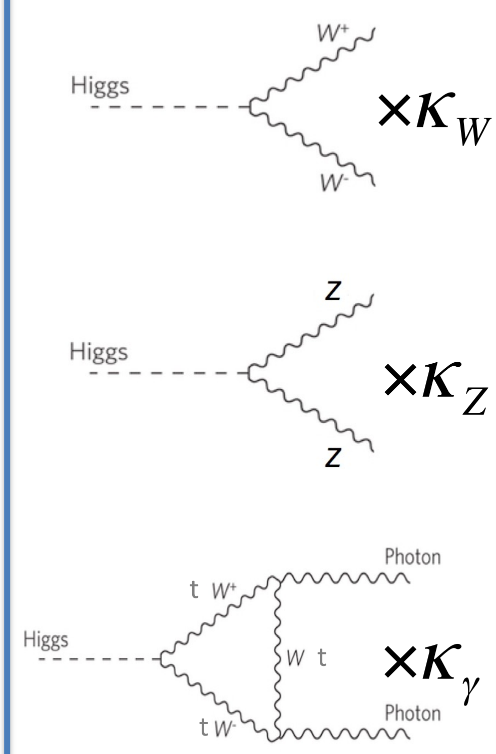
$$\kappa_i^2 = \sigma_i / \sigma_i^{SM} \qquad \kappa_f^2 = \Gamma_f / \Gamma_f^{SM} \qquad \mu = \frac{(\sigma \cdot BR)^{Obs.}}{(\sigma \cdot BR)^{SM}} = \kappa_i^2 \cdot \kappa_f^2$$

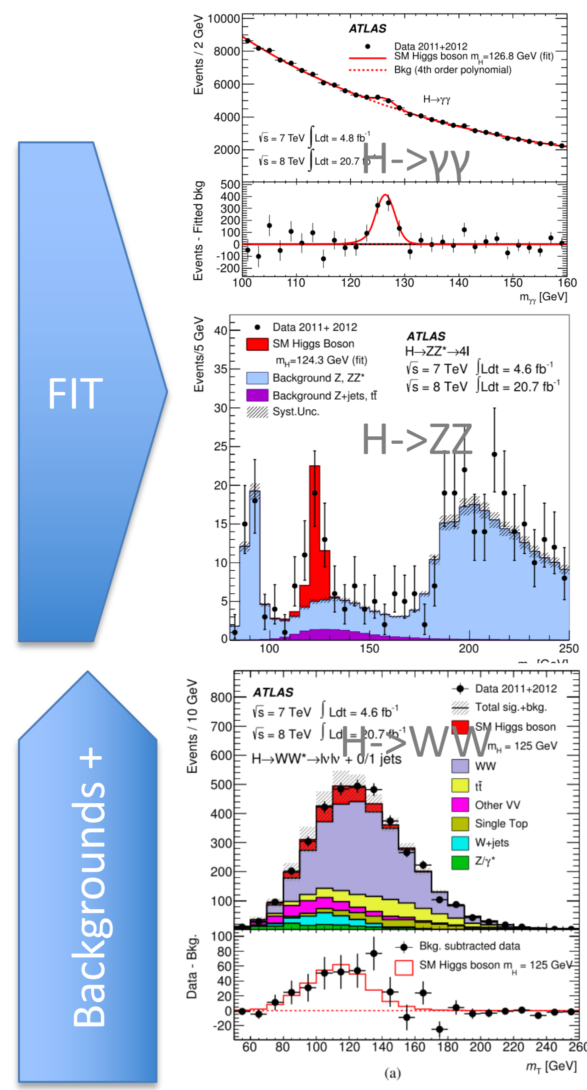
Production



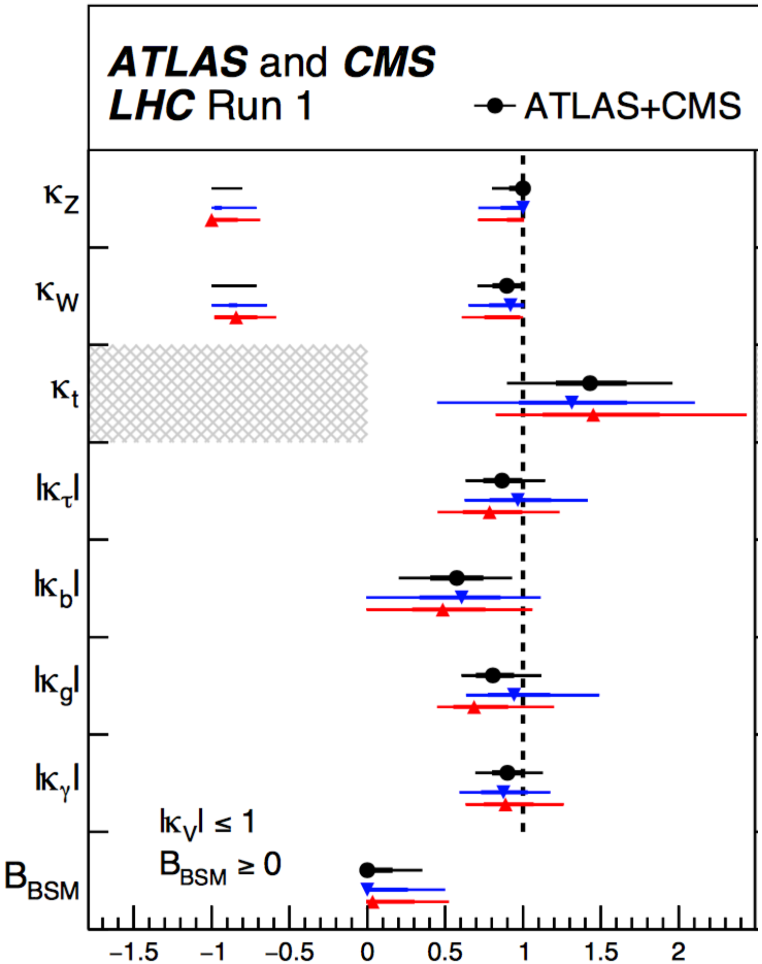
×

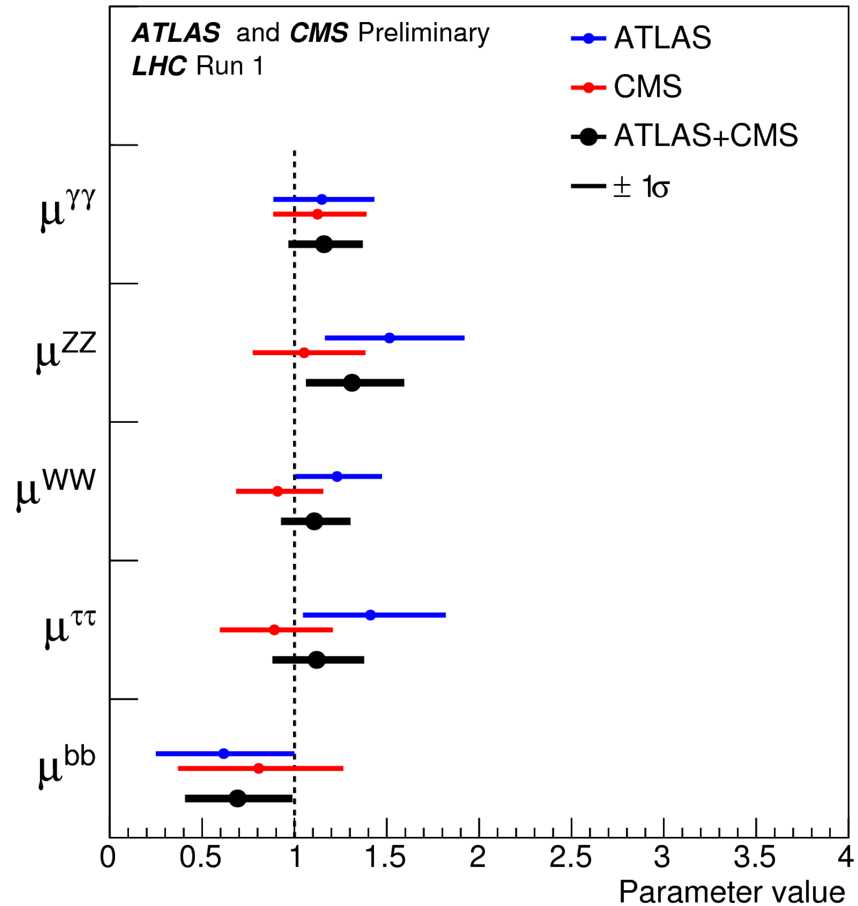
Decay





Signal strength measurements

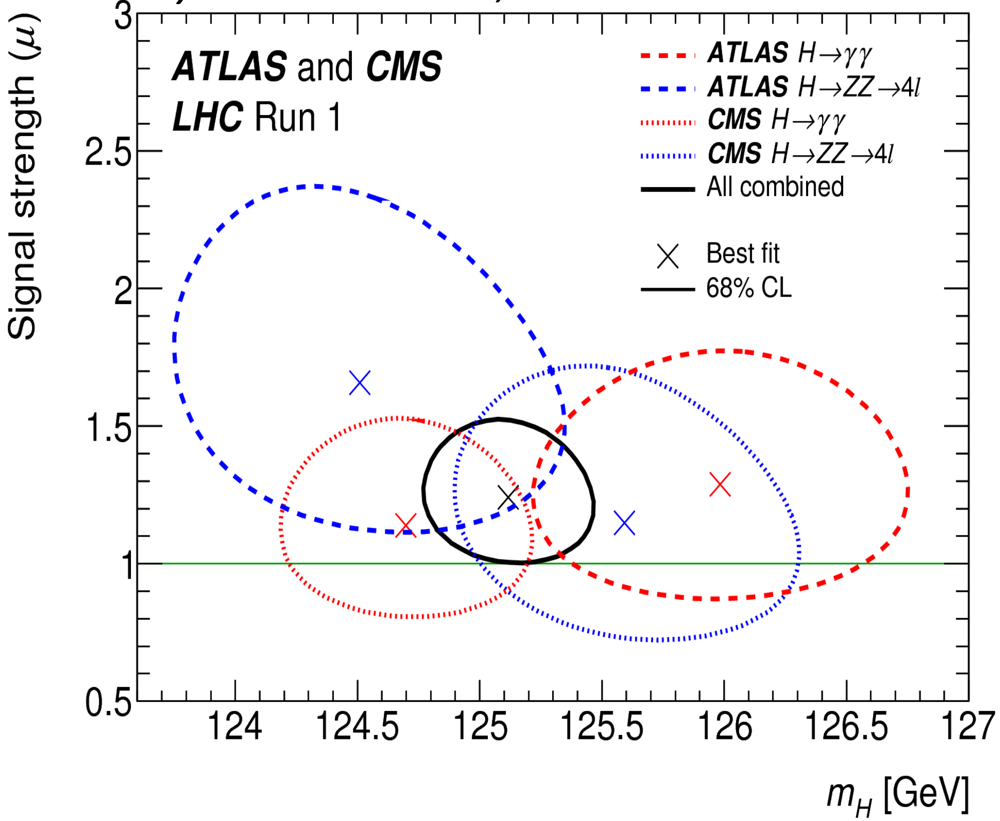




Higgs boson mass

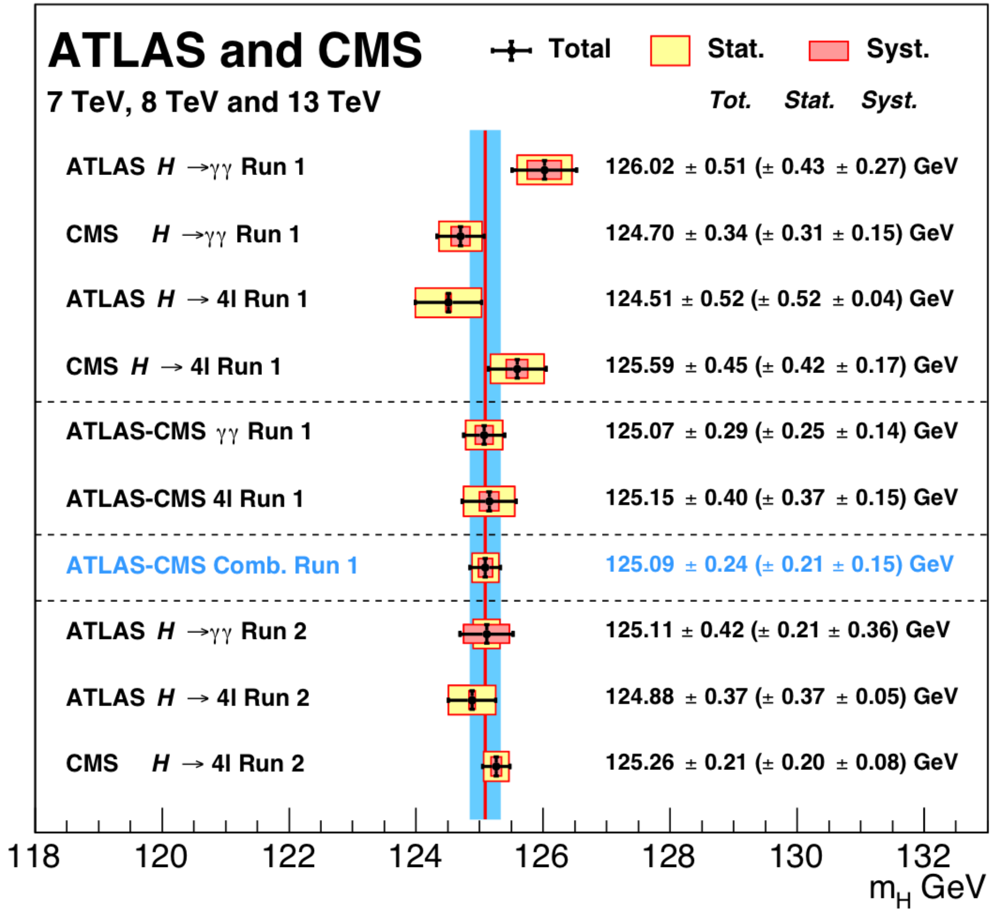
- Mass: around 125GeV
  Was the only unknown SM parameter ☺
- For a while, different mass values were being measured in ATLAS and CMS, and in different channels
- Numbers evolved with accumulated statistics

Phys. Rev. Lett. 114, 191803



Higgs boson mass

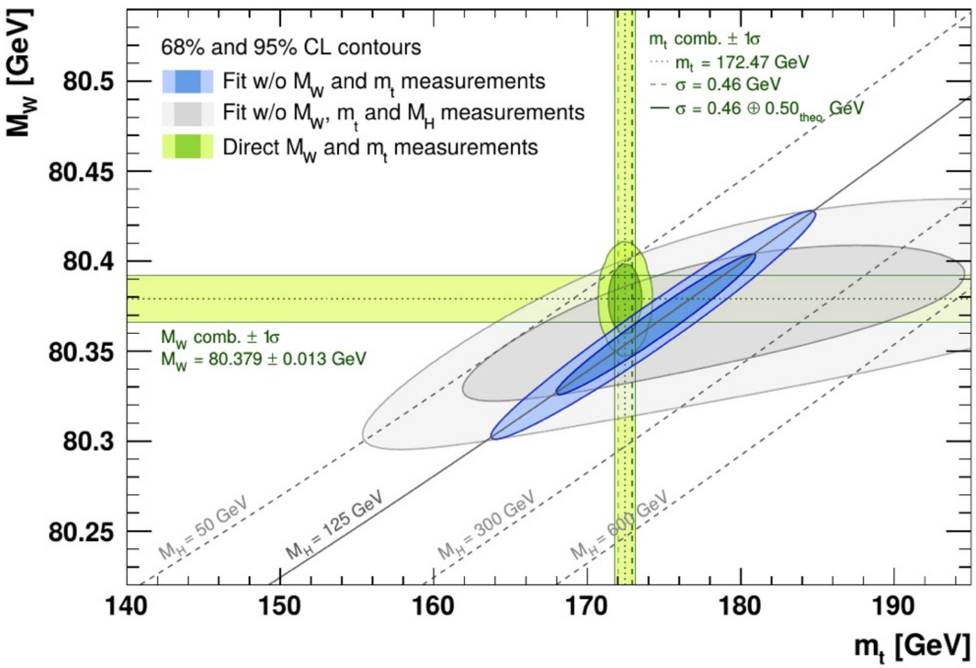
- Mass measurement from
  - H→ZZ*→4l
  - H→ γγ
- Precision at the permille level achieved

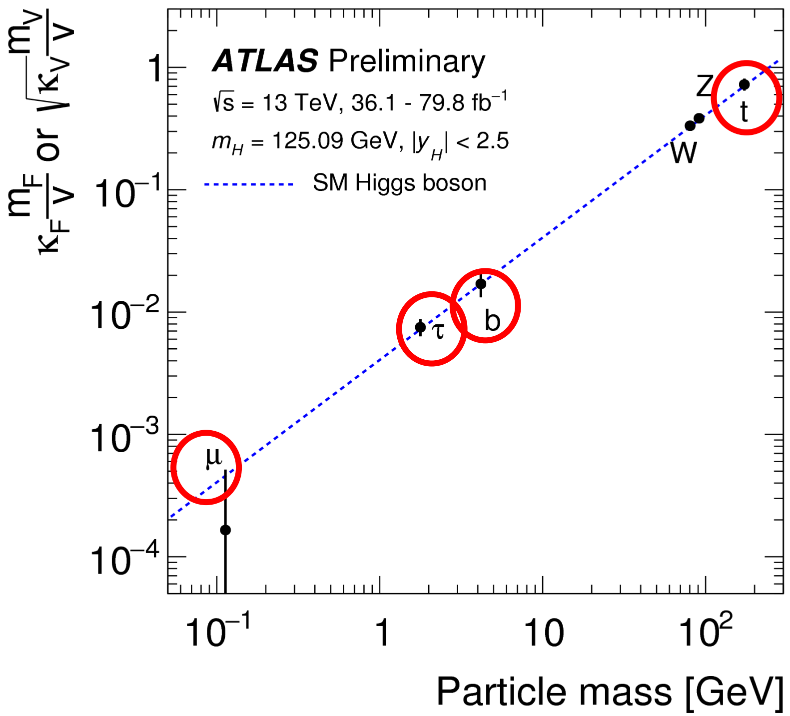


Exploring the electroweak scale

- Precision measurements of m_W, m_t, m_H are stringent tests of the SM at the EW scale
  - E.g. excluding measured m_H, global EW fit gives $m_H = 90 \pm 21$ GeV (1.7 σ tension) driven in part by m_{top}

arXiv:1803.01853



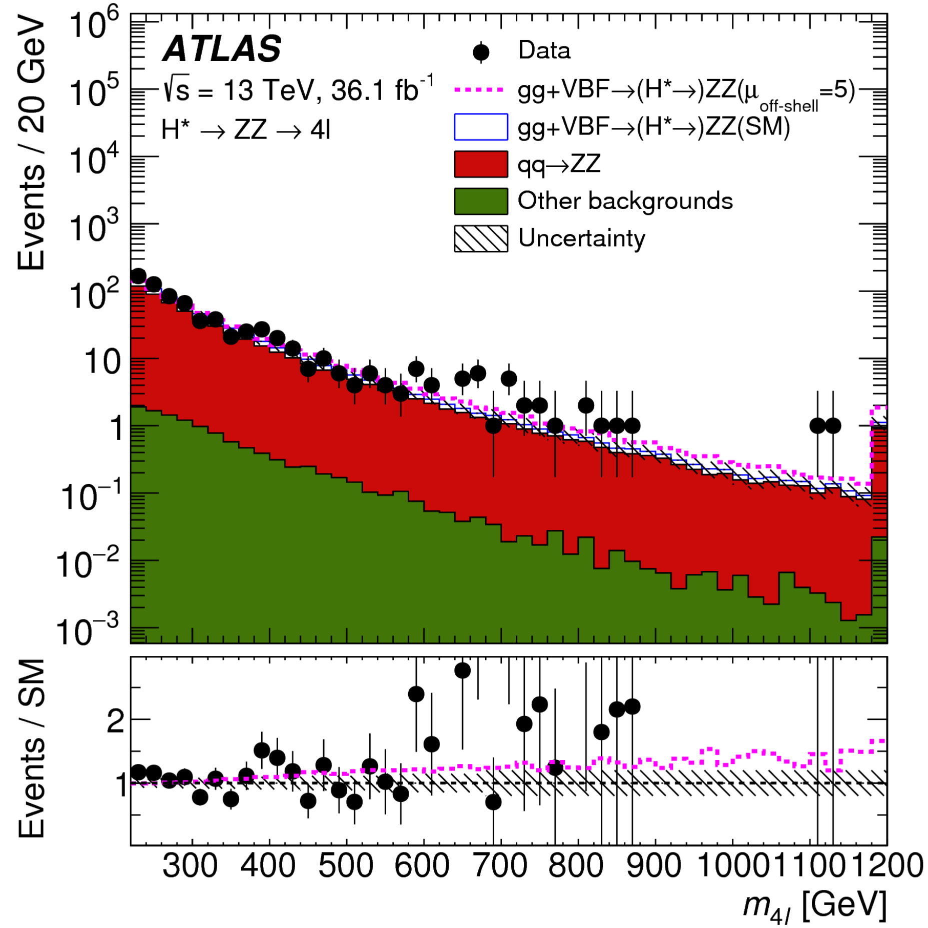


Higgs boson width

- SM Higgs width Γ_H~4.1 MeV
  - Too small to be measured directly
  - Best direct limit from CMS:
    - Γ_H < 1.1GeV @ 95% CL
- Off-shell Higgs production sensitive(*) to Γ_H

$$\frac{\mu_{\mathrm{off-shell}}}{\mu_{\mathrm{on-shell}}} = \frac{\kappa^2_{\mathrm{g,off-shell}} \cdot \kappa^2_{\mathrm{Z,off-shell}}}{\kappa^2_{\mathrm{g,on-shell}} \cdot \kappa^2_{\mathrm{Z,on-shell}}} \frac{\Gamma_H}{\Gamma_H^{SM}}$$

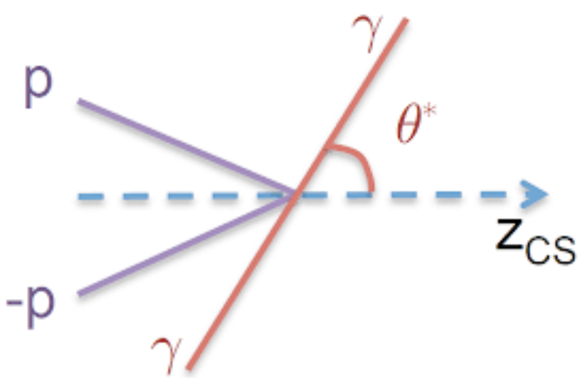
- ATLAS measurement:
  - **pp→H→ZZ→4l** and ZZ→2l2ν
  - **m(H) > 2 m(Z)**
  - 36.1 fb^{-1} of 13 TeV data
  - Observed (expected) limit:
    - Γ_H < 14.4 (15.2) MeV



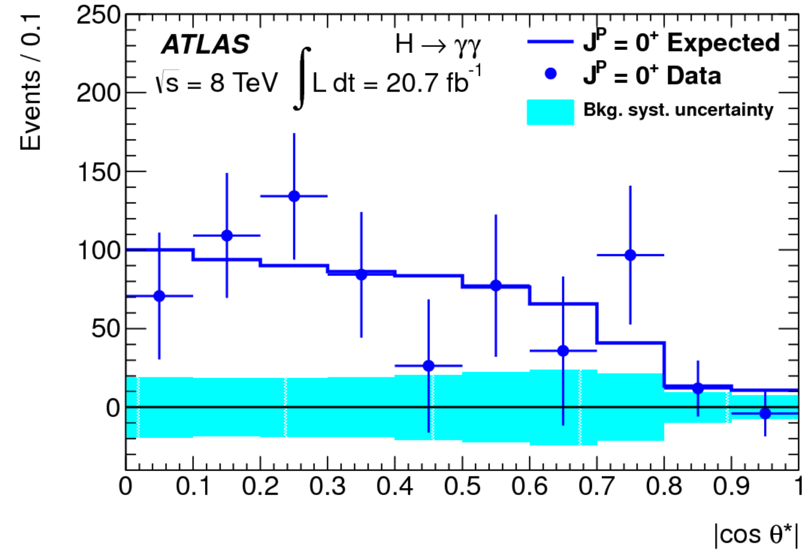
(*) Assume interference term with $gg \to ZZ$ proportional to $\kappa_{g,\text{off-shell}} \cdot \kappa_{Z,\text{off-shell}}$

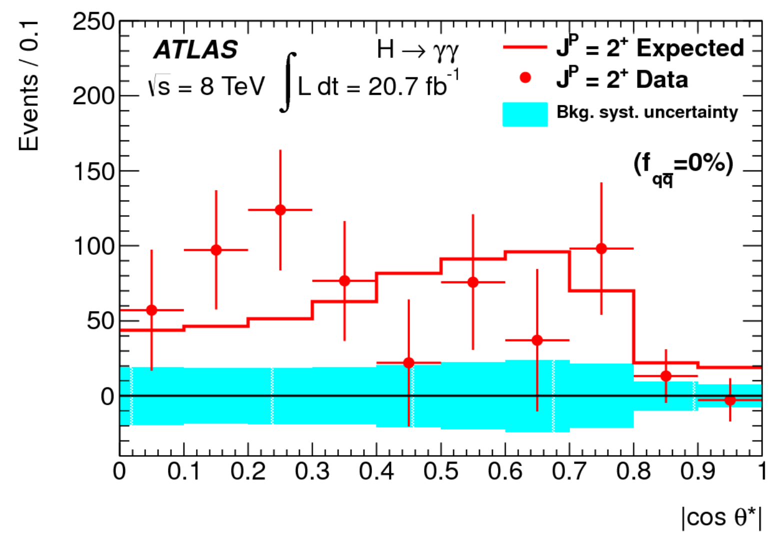
Measuring the Higgs Spin

- Polar angle θ in the rest fram of the diphoton system (Collins-Soper frame)

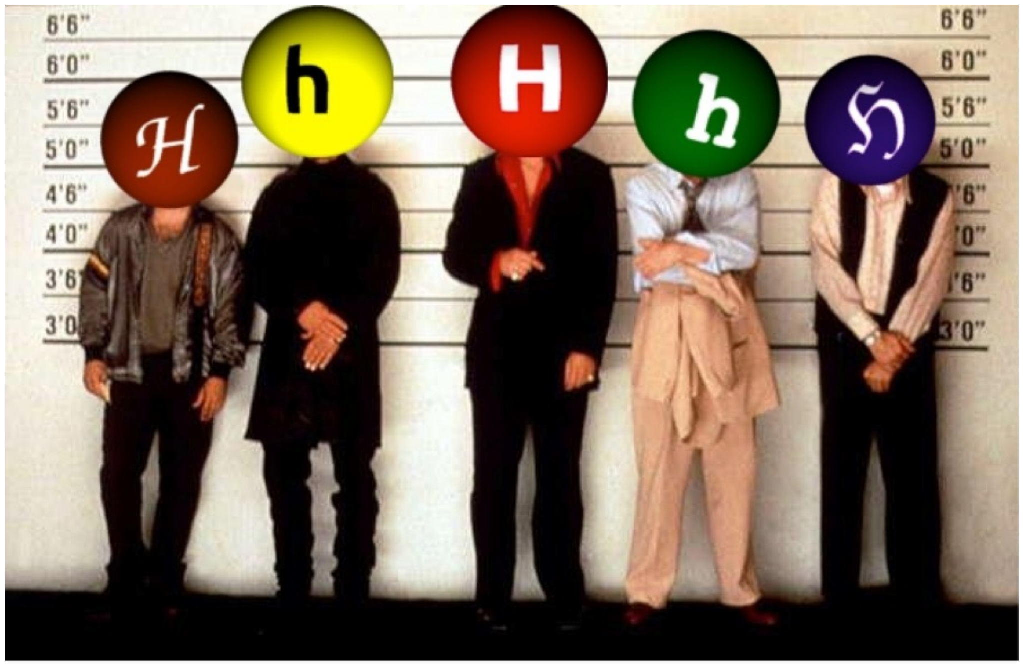


$$|\cos\Theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+\frac{p^2_{T,\gamma\gamma}}{m^2_{\gamma\gamma}}}}\frac{2p_T^{\gamma_1}p_T^{\gamma_2}}{m^2_{\gamma\gamma}}$$



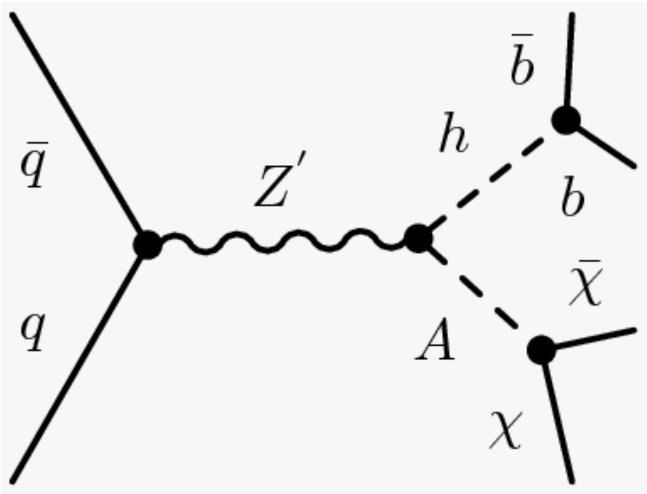


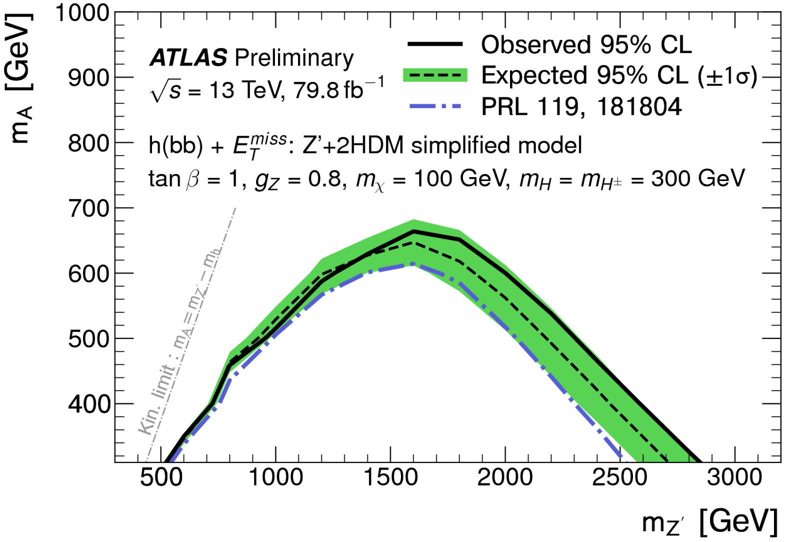
Casting a wider net



Higgs + Dark Matter

- Used 79.8 fb^{-1} of 13 TeV data
  - High E_T^{miss} (>150GeV) and b-tagging to suppress backgrounds
  - Reconstruct b-jets as 2 small jets or merged variable-radius (VR) track jets
- Signal benchmark: Type-II 2HDM + $U(1)_{Z'}$ symmetry (Z'-2HDM)
- Main backgrounds: tt, W/Z+jets
- Excluded region in $m_A - m_{Z'}$ plane

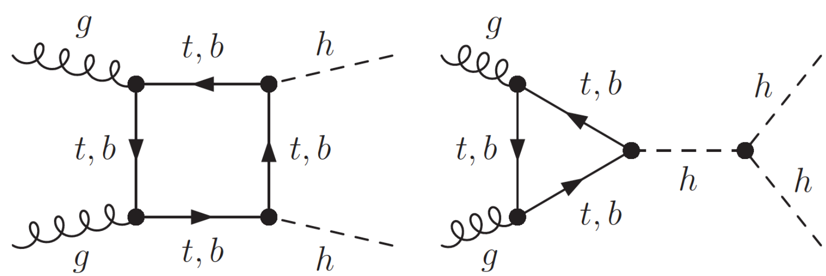


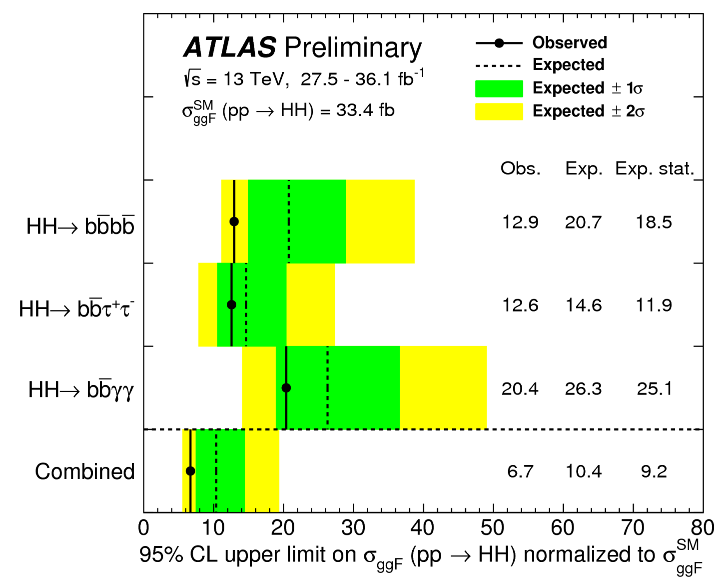


Triple Higgs coupling

- The triple Higgs coupling λ_{HHH} can be probed through di-Higgs production
- Very suppressed in SM!
  - Negative interference between LO diagrams
  - Cross section 1500x less than ggF
- Wide range of decay BR and channel purity
- bbττ analysis:
  - Used 36 fb^{-1} of 13 TeV data
  - Final state BR(bbττ)=7%
  - Non-Resonant 95% CL limit:
    μ < 12.7 observed (14.8 expexcted)
- Combination: at ≈10 x SM sensitivity – with 3% of the HL-LHC luminosity analyzed

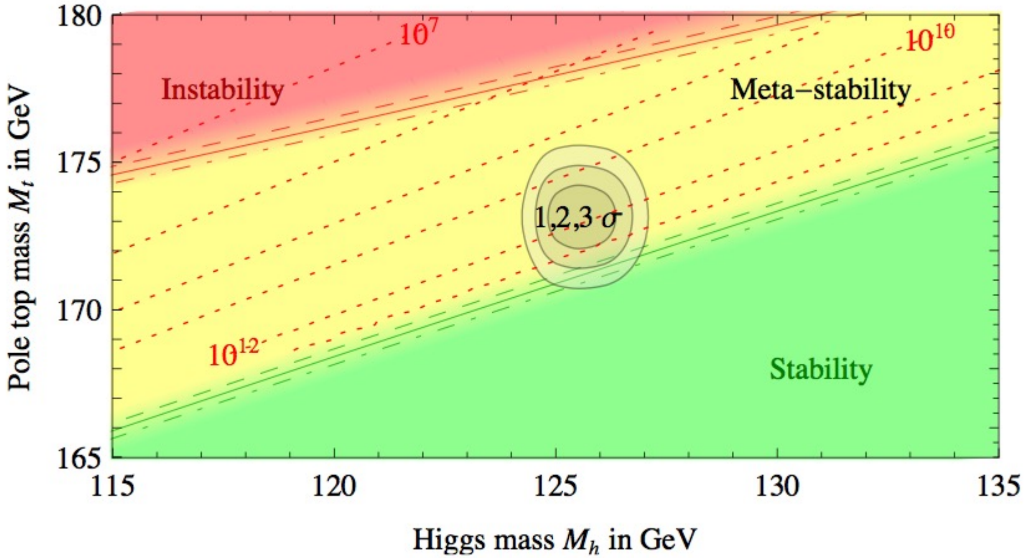
$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$

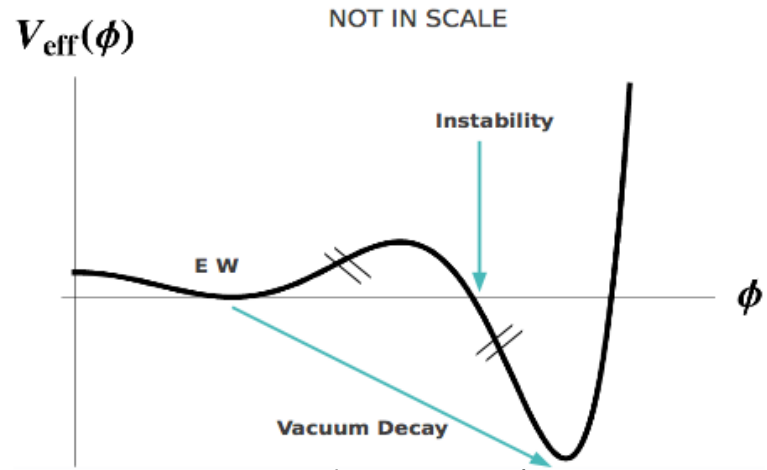




Di-Higgs combination plot here

A bit of fun…





RG-improved potential

- What if…
  - At higher orders, Higgs potential doesn't have to be stable
  - Depending on m_t and m_H second minimum can be lower than EW minimum ⇒ tunneling between EW vacuum and true vacuum?!
- "For a narrow band of values of the top quark and Higgs boson masses, the Standard Model Higgs potential develops a shallow local minimum at energies of about 10^{16} GeV, where primordial inflation could have started in a cold metastable state", I. Masina, arXiv:1403.5244 [astro-ph.CO]
  - See also: V. Brachina, Moriond 2014 (Phys.Rev.Lett.111, 241801 (2013)), G. Degrassi et al, arXiv:1205.6497v2; R.Contino, Workshop sulla fisica p-p a LHC, 2013

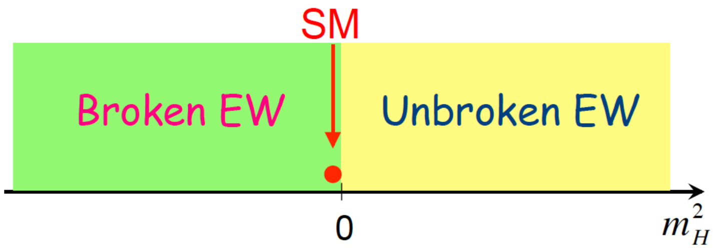
The universe seems to live near a critical condition

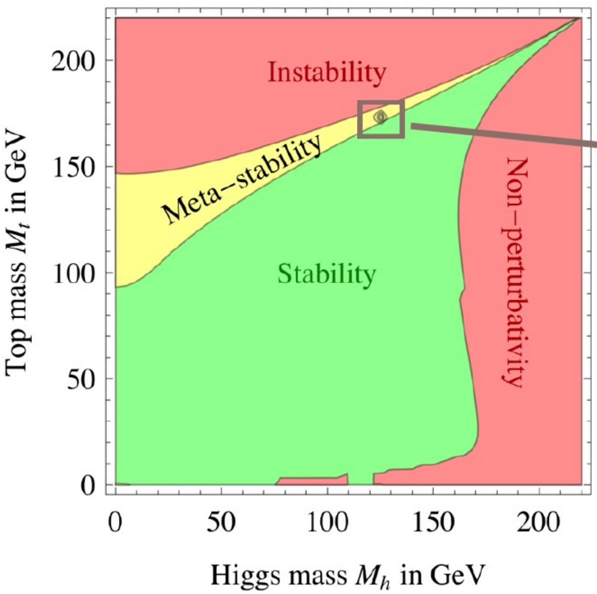
JHEP 1208 (2012) 098

Why?!

Explained by underlying theory?

Anthropic principle?





Higgs @ LIP ATLAS Group

- Exploring Higgs couplings to heavy quarks
- Less well known… Much more space for surprises!
- New physics effects may show up already at leading order

P2 ÍPSILON CULTO FUGAS P3 CINECARTAZ Entrar Assine já

CIÊNCIA › ESPAÇO MEDICINA ECOSFERA

FÍSICA DE PARTÍCULAS

Bosão de Higgs revela que relação mantém com o quark *top*

Investigadores portugueses participaram na descoberta.

PÚBLICO · 4 de Junho de 2018, 19:42 418 PARTILHAS

FÍSICA DE PARTÍCULAS

Bosão de Higgs visto (finalmente) a desintegrar-se em quarks *bottom*

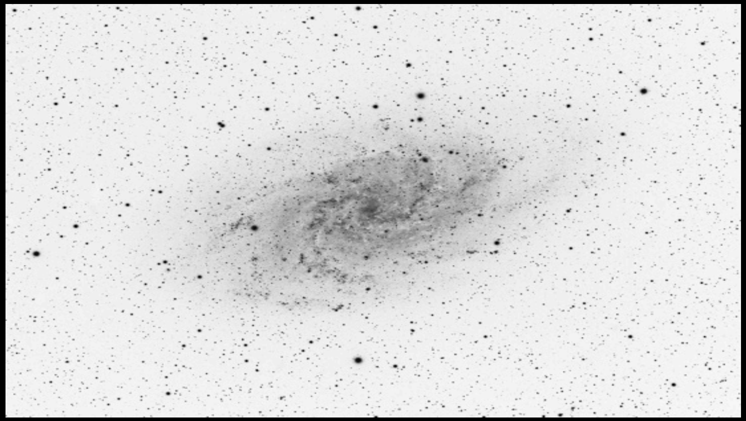
Descoberta anunciada no Laboratório Europeu de Física de Partículas (CERN) é um passo fundamental para perceber como o bosão de Higgs faz com que as partículas fundamentais adquiram massa.

PÚBLICO · 28 de Agosto de 2018, 17:47

2018: Hbb and Htt couplings demonstrated
2020: CP of ttH coupling in ttH, H->γγ
2022: ttH, H->bb fiducial cross section
2022: Preliminary results for CP of ttH coupling studied in ttH, H->bb

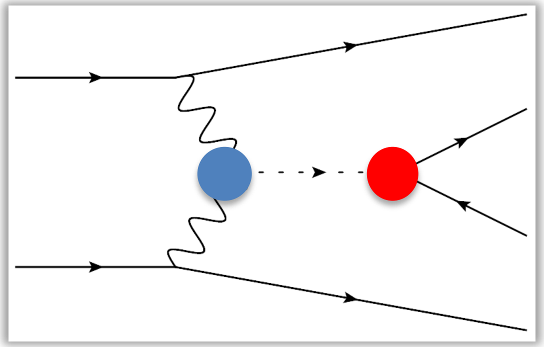
ttH CP measurement

- Sakharov conditions for a matter-dominated universe require CP violation
- Known CP-violating processes:
  - From complex phases in CKM-matrix - quark mixing
  - Maybe in PNMS-matrix as well - neutrino mixing
- BUT: insufficient, by orders of magnitude
- CP violation in Higgs sector?
  - Possible in some models with extended Higgs sector (e.g. some 2HDMs)
  - Need **mixing** of scalar (CP-even) and pseudo-scalar (CP-odd) Higgs states
- What do we know about Higgs CP properties?
  - In the SM, Higgs scalar is a CP eigenstate with $J^{CP} = 0^{++}$
  - Pure $J^P = 0^-$ hypothesis for observed Higgs boson was ruled out in Run 1
  - But a **large** CP-odd admixture is not ruled out



How to search for a CP-odd admixture?

- Effect of CP-odd components on **bosonic couplings** parametrized as expansion with higher order terms suppressed by powers of scale of new physics Λ
- Could explain why a CP-odd admixture has not been seen



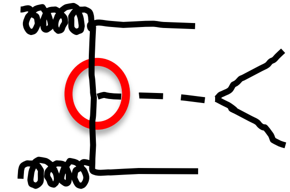
- **Fermionic couplings** are affected at tree level
- Mixing angle α between CP-even and CP-odd coupling components
- More notable for heavier fermions due to enhanced coupling

$$\mathcal{L}_{VVH} = \mathcal{L}_{VVH,SM} + \frac{1}{\Lambda^2} c\,\phi \widetilde{V}_{\mu\nu} V^{\mu\nu} + \ldots$$

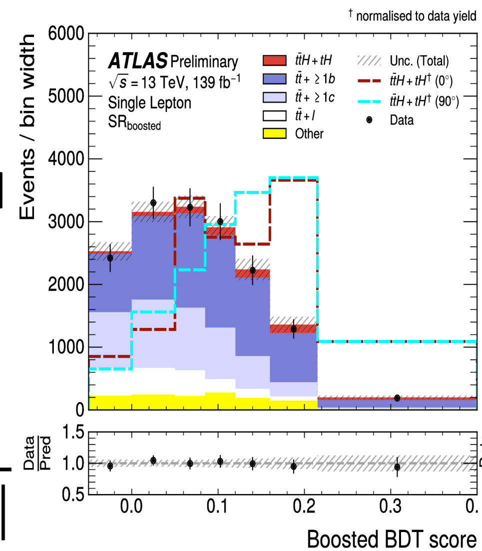
$$\mathcal{L}_{ffH} = \kappa'_f y_f \phi \bar{\psi}_f (\cos\alpha + i\gamma_5 \sin\alpha)\psi_f$$

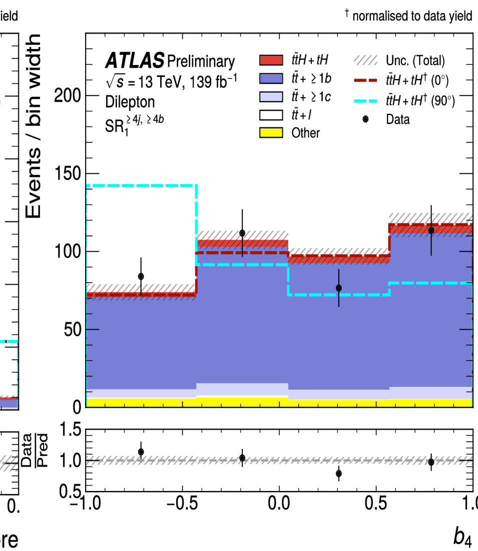
ATLAS-CONF-2022-016 (16 March 2022)

H-top Coupling in ttH/tH production



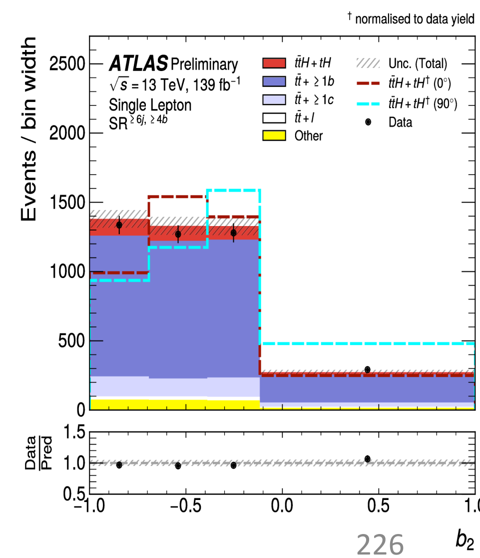
- Calculate CP-sensitive observables $\boldsymbol{b_2}$ and $\boldsymbol{b_4}$ from top-quark 3-momenta
- Use different observables in combined fit depending on region



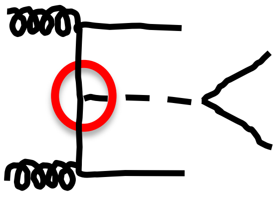


$$b_2 = \frac{(\vec{p}_1 \times \hat{n}) \cdot (\vec{p}_2 \times \hat{n})}{|\vec{p}_1||\vec{p}_2|} \qquad b_4 = \frac{p_1^z p_2^z}{|\vec{p}_1||\vec{p}_2|}$$

Channel (PSR)	Final SRs and CRs	Classification BDT selection	Fitted observable
Dilepton (PSR$^{\geq 4j, \geq 4b}$)	CR$^{\geq 4j, \geq 4b}_{\text{no-reco}}$	–	$\Delta\eta_{\ell\ell}$
	CR$^{\geq 4j, \geq 4b}$	BDT$\in [-1, -0.086)$	b_4
	SR$_1^{\geq 4j, \geq 4b}$	BDT$\in [-0.086, 0.186)$	b_4
	SR$_2^{\geq 4j, \geq 4b}$	BDT$\in [0.186, 1]$	b_4
ℓ+jets (PSR$^{\geq 6j, \geq 4b}$)	CR$_1^{\geq 6j, \geq 4b}$	BDT$\in [-1, -0.128)$	b_2
	CR$_2^{\geq 6j, \geq 4b}$	BDT$\in [-0.128, 0.249)$	b_2
	SR$^{\geq 6j, \geq 4b}$	BDT$\in [0.249, 1]$	b_2
ℓ+jets (PSR$_{\text{boosted}}$)	SR$_{\text{boosted}}$	BDT$\in [-0.05, 1]$	Classification BDT score



H-top Coupling in ttH/tH production



Simultaneous fit in all regions

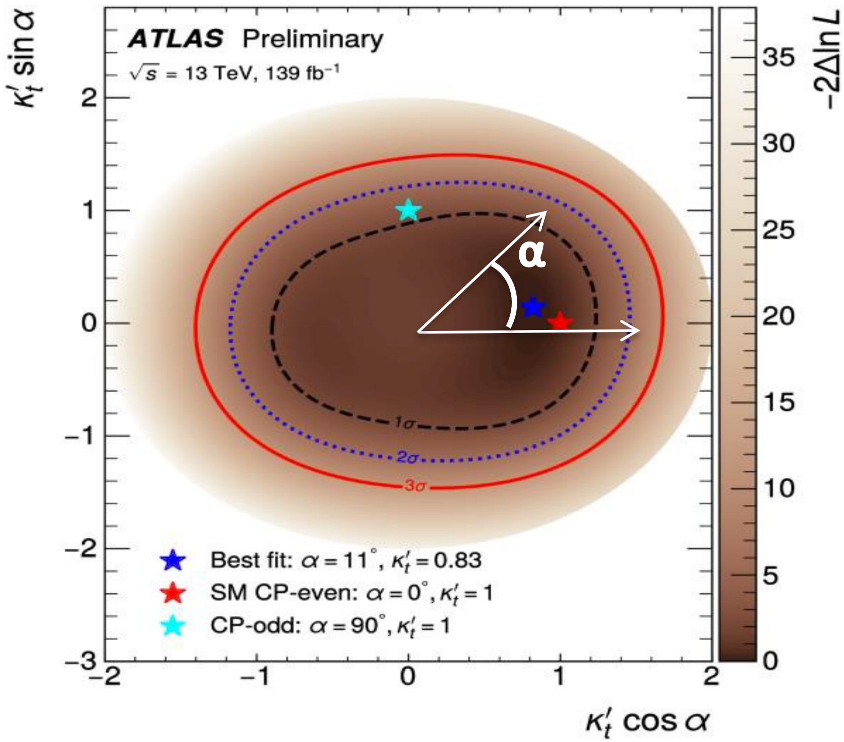
- **$\mu = 0.83^{+0.30}_{-0.46}$**
- **$\alpha = 11°\ ^{+55}_{-77}$**

Expected:

- $\mu = 1.0^{+0.25}_{-0.27}$
- $\alpha = 0°\ ^{+49}_{-50}$
- Pure CP-odd (α = 90°) disfavoured at **1.2 σ**

Complementary to previous ttH(H→γγ) analysis:

- Phys. Rev. Lett. 125 (2020) 061802
- Pure CP-odd (α = 90°) excluded at **3.9 σ**
- Limit on **|α| < 43°** at 95% C.L.

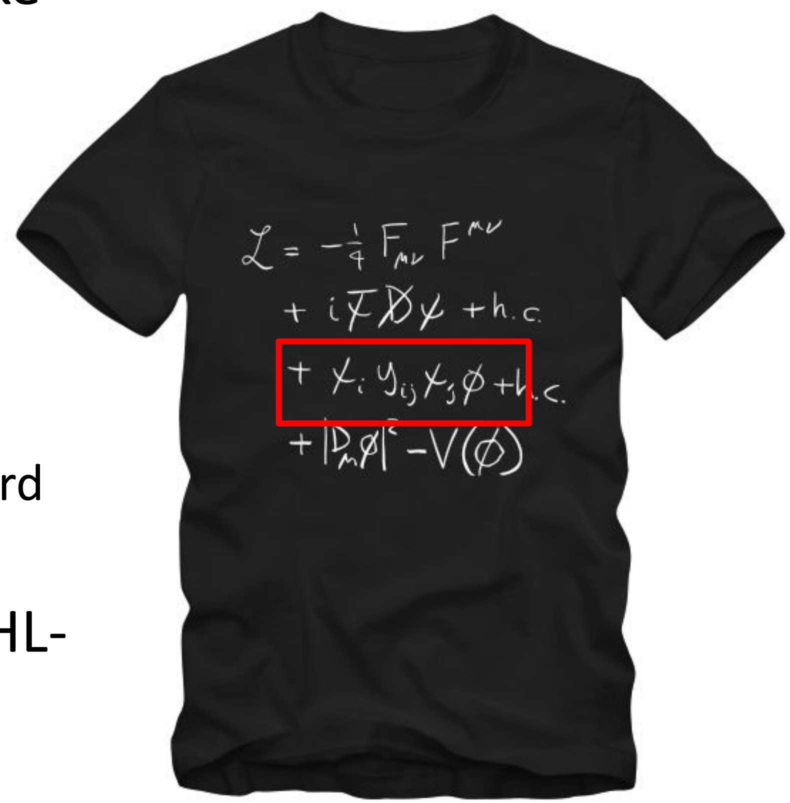


$$\boxed{\mathcal{L}_{t\bar{t}H} = -\kappa_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t}$$

Summary

- Higgs sector measurements look SM-like so far
- **But there is new physics out there!**
- The Higgs is:
  - The only fundamental scalar
  - Connected to EW symmetry breaking
  - A great window to look beyond the Standard Model
- And we have only collected ≈5% of all HL-LHC data!

Watch this space!

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THE TRUTH IS OUT THERE.

Questions?

Thank you for your interest!

jgoncalo@lip.pt

LIP

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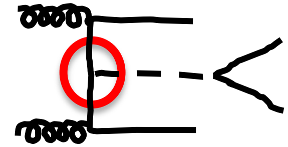
Fundos Europeus Estruturais e de Investimento

ATLAS-CONF-2022-016 (16 March 2022)

H-top Coupling in ttH/tH production

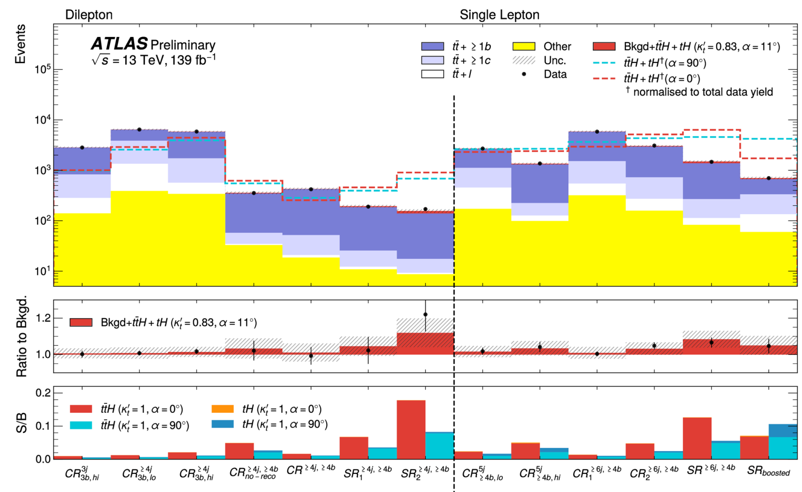


- Recent analysis with H→bb decay
  - High branching ratio, but challenging backgrounds
  - Complementary to previous ttH(H→γγ) analysis
- Two channels:
  - Lepton+jets: target 1 semi-leptonic top decay – dedicated boosted region targets p_T^H>200 GeV using large-R jets (R=1, m_j > 50 GeV)
  - Dilepton: target 2 semi-leptonic top decays
- Reconstruct top and Higgs candidates in regions
  - "Reconstruction" BDT selects jet combinations to build top and Higgs candidates
  - "Classification" BDT separates signal (trained on ttH) from background

See talk by Neelam in YSF yesterday

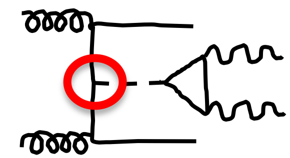
PSR: Preliminary Signal Region (before classification BDT)

Region	Dilepton $\mathrm{PSR}^{\geq 4j,\geq 4b}$	Dilepton $\mathrm{CR}^{\geq 4j,3b}_{\mathrm{hi}}$	Dilepton $\mathrm{CR}^{\geq 4j,3b}_{\mathrm{lo}}$	Dilepton $\mathrm{CR}^{3j,3b}_{\mathrm{hi}}$	ℓ+jets $\mathrm{PSR}^{\geq 6j,\geq 4b}$	ℓ+jets $\mathrm{CR}^{5j,\geq 4b}_{\mathrm{hi}}$	ℓ+jets $\mathrm{CR}^{5j,\geq 4b}_{\mathrm{lo}}$	ℓ+jets $\mathrm{PSR}_{\mathrm{boosted}}$
N_{jets}	≥ 4			$= 3$	≥ 6	$= 5$		≥ 4
$N_{b-\mathrm{tag}}$ @85%	–				≥ 4			
$N_{b-\mathrm{tag}}$ @77%	–				–			$\geq 2^{\dagger}$
$N_{b-\mathrm{tag}}$ @70%	≥ 4	$= 3$			≥ 4			–
$N_{b-\mathrm{tag}}$ @60%	–	$= 3$	< 3	$= 3$	–	≥ 4	< 4	–
$N_{\mathrm{boosted\ cand.}}$	–				0			≥ 1

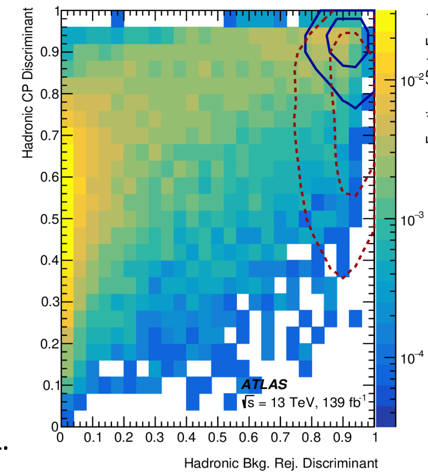


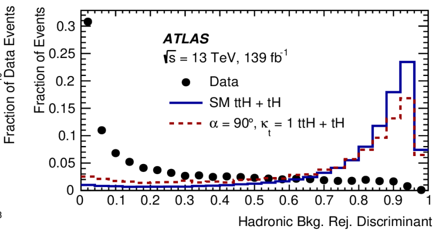
Phys. Rev. Lett. 125 (2020) 061802

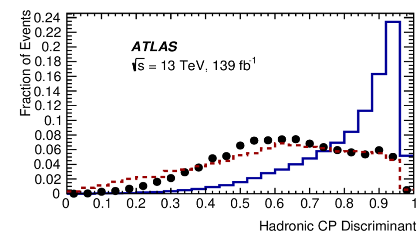
H-top Coupling in ttH/tH production



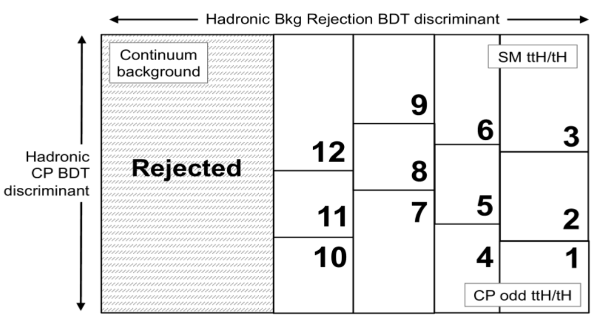
- Reconstruct Leptonic or Hadronic **γγ + top** events
- Two BDTs to define 2D space:
  - Reject **continuum background** and
  - Enrich **in CP-odd-like** events (kinematic and angular variables)
- Simultaneous fit to $\mathbf{m_{\gamma\gamma}}$ in 2D regions defined by BDT outputs
  - Established **5σ** observation of **ttH(γγ)**
  - Assuming SM decay get $\mu = 1.43^{+0.33}_{-0.31}(\text{stat})^{+0.17}_{-0.14}(\text{sys})$
  - Set upper limit of 12×SM for **tH** production
  - Pure **CP-odd** (α = 90°) excluded at **3.9 σ** and **|α|>43°** at 95% C.L.
  - Statistics-dominated analysis

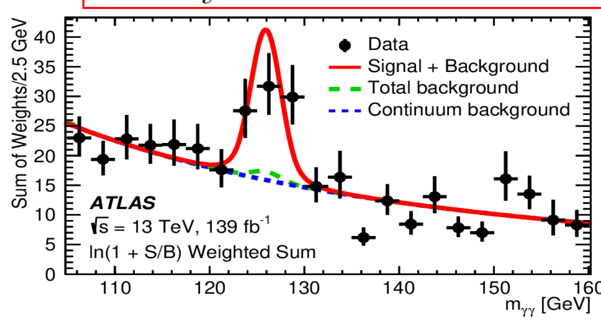


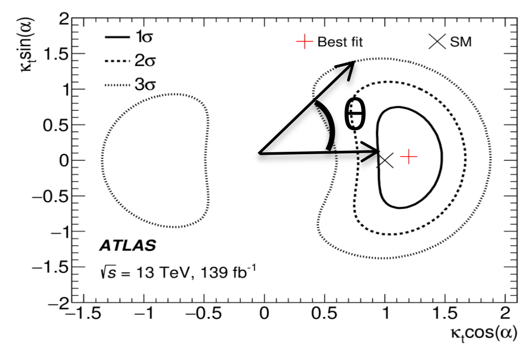




$$\boxed{\mathcal{L} = -\frac{m_t}{v}\{\bar{\psi}_t \kappa_t [\cos(\alpha) + \mathrm{i}\sin(\alpha)\gamma_5]\psi_t\}H}$$



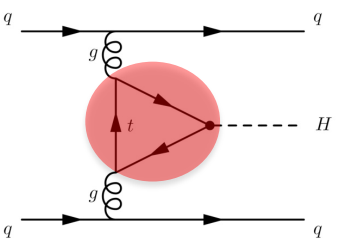




Eur. Phys. J. C 82 (2022) 622

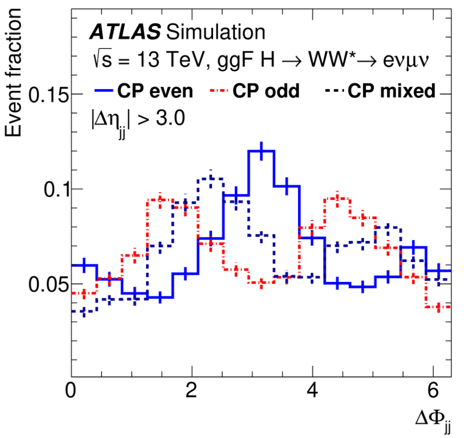
Hgg Effective Coupling

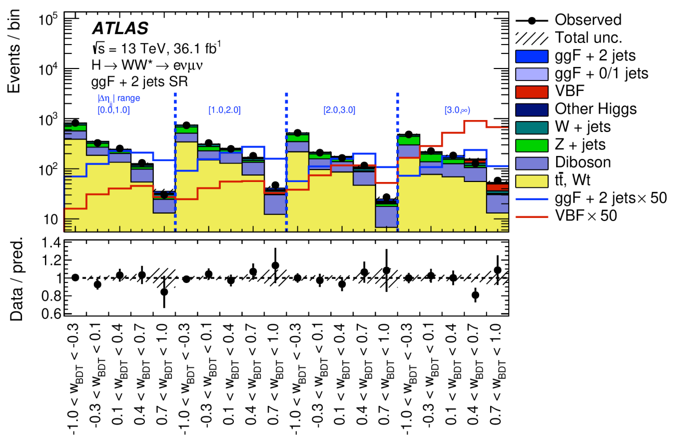
- Depending on the production mode, H+2 jets probse CP violation (for ggF) or W/Z polarization (for VBF)
- In gluon fusion:
  - Effective vertex either or top Yukawa coupling or BSM particles in loop
  - Use BDT to separate signal and background (no CP sensitivity)
  - Classify H+2jets into 4x5 categories according to |Δη| and BDT score

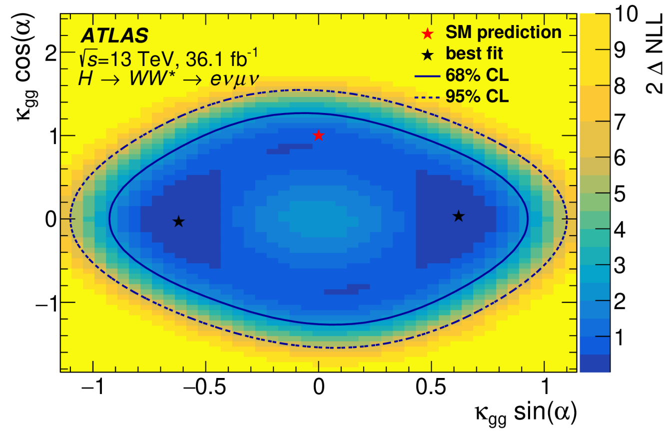


$$\boxed{\mathcal{L}_0^{\text{loop}} = -\frac{g_{Hgg}}{4}\left(\kappa_{gg}\cos(\alpha)G^a_{\mu\nu}G^{a,\mu\nu} + \kappa_{gg}\sin(\alpha)G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right)H}$$

$$\tan(\alpha) = 0.0 \pm 0.4(\text{stat.}) \pm 0.3(\text{syst.})$$







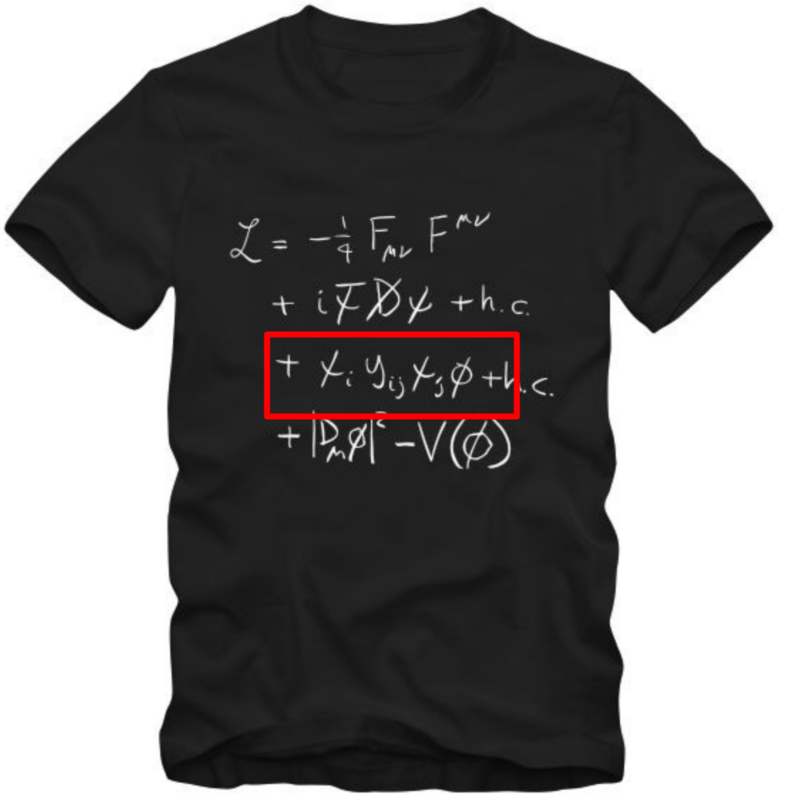
- Search for changed **shapes** of differential cross sections due to CP-odd observables (2nd term)
- Or on process **rates** (cross sections) from 3rd term – but other BSM scenarios can change rates

$$|\mathscr{M}|^2 = |\mathscr{M}_{\mathrm{SM}}|^2 + 2 \cdot c_i \cdot \mathrm{Re}(\mathscr{M}^*_{\mathrm{SM}} \mathscr{M}_{\text{CP-odd}}) + c_i^2 \cdot |\mathscr{M}_{\text{CP-odd}}|^2.$$

See e.g. arXiv:2208.02338 [hep-ex], arXiv:1008.3869v3 [hep-ph], or C.Grefe, ICHEP’22

Summary

- Higgs sector measurements look SM-like so far
- **But there is new physics out there!**
- Higgs is a unique particle at the center of the Standard Model edifice
- It is the only fundamental scalar and connected to electroweak symmetry breaking
- A great window to look beyond the Standard Model
- And we have only collected ≈150 fb^{-1} of 3000 fb^{-1} of 13 TeV data expected at the HL-LHC

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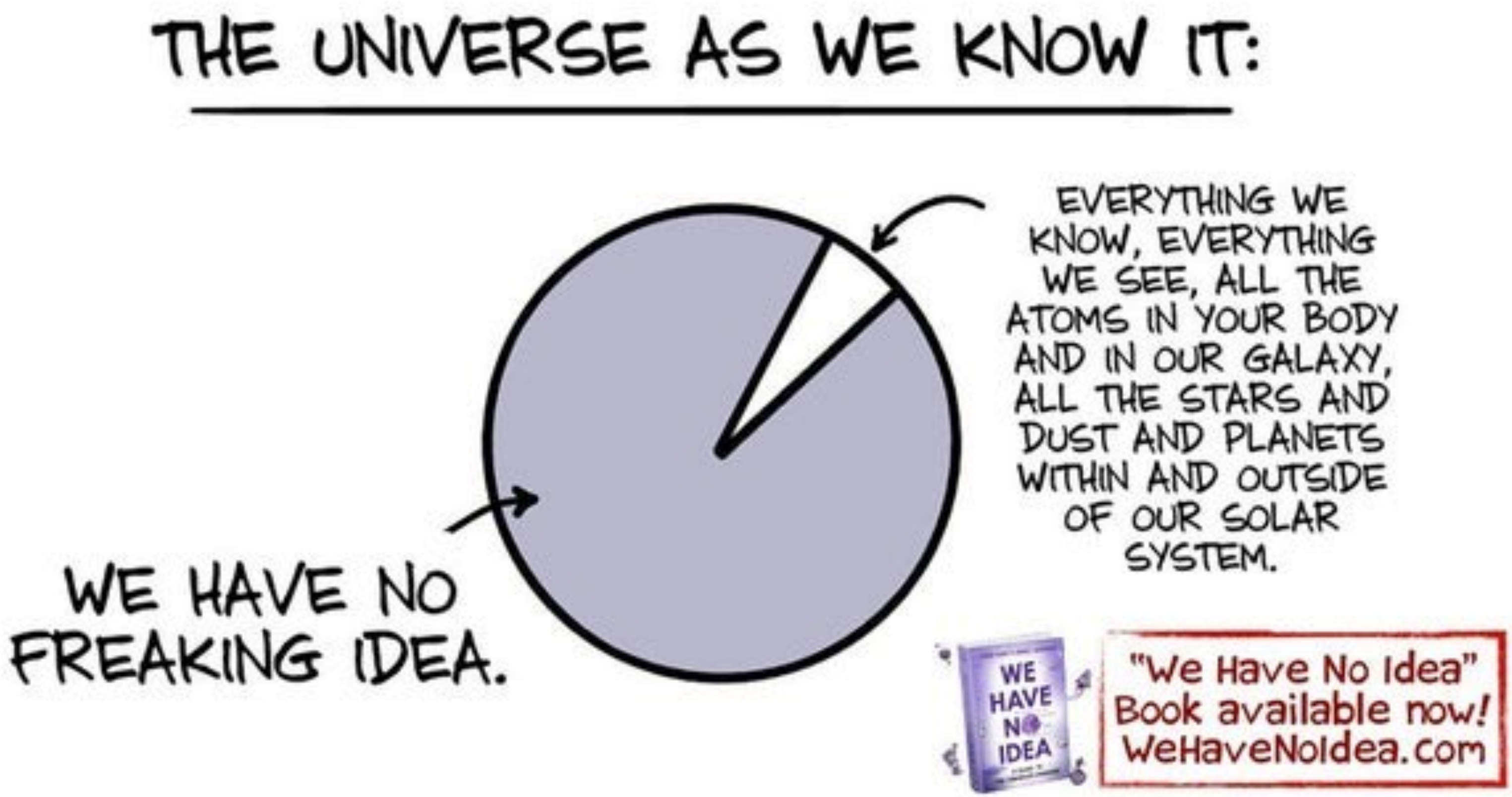
want to believe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EVERYTHING WE KNOW, EVERYTHING WE SEE, ALL THE ATOMS IN YOUR BODY AND IN OUR GALAXY, ALL THE STARS AND DUST AND PLANETS WITHIN AND OUTSIDE OF OUR SOLAR SYSTEM.
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