Higgs Physics

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What is the Higgs?

The Higgs is an elementary particle

- **with spin zero (scalar);**
- **without electric charge (a priori, it should not see the photons from the electromagnetic interaction...);**
- **without colour (a priori, it should not see the gluons from the strong interaction...).**
- **Between 1964 and 2012 the Higgs was not discovered...**
  The Higgs was invented!
  It was invented for theoretical reasons!!

Higgs invented! Why?

1. to give mass to the particles mediating the weak interaction, $W^{\pm}$ and Z^0;

2. to give mass to the matter particles, eg. electron.

Higgs invented! Why?

1. Why don't you just give a mass to $W^{\pm}$ and Z^0?

It contradicts gauge invariance.

- **Why do you want gauge invariance?**

  A: To keep probabilities smaller than 1!

***Note*: As a side-dish, there is an elegant way to invent interactions called "the gauge principle".**

Higgs invented! Why?

2. Why don’t you just <u>give</u> a mass to the electron?

It contradicts gauge invariance.

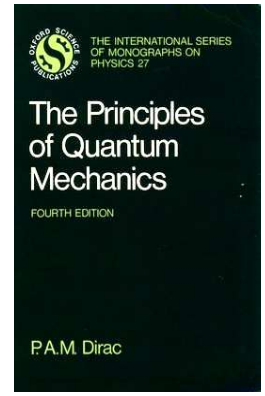
- **<u>How</u> does it contradict gauge invariance?**

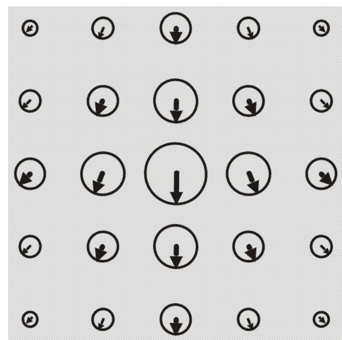
  Answer in steps:
  - **electron sees W ==> e_L must be in a doublet under $SU(2)_L$**
  - **W interaction violates parity maximally ==> e_R is singlet**
  - **mass links left-handed e_L and right-handed electron e_R**
  - **cannot make mass term only with e_L and e_R (need Higgs help)**

Gaugetheories

- QM, QFT ==> complex wfn/field

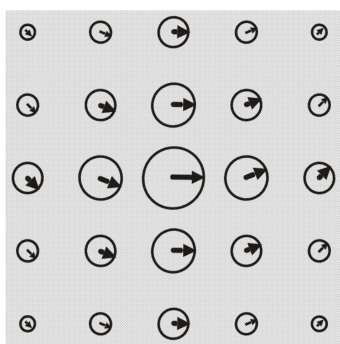
global phase does not matter

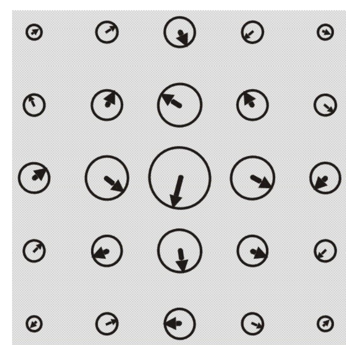




global U(1)

local U(1)

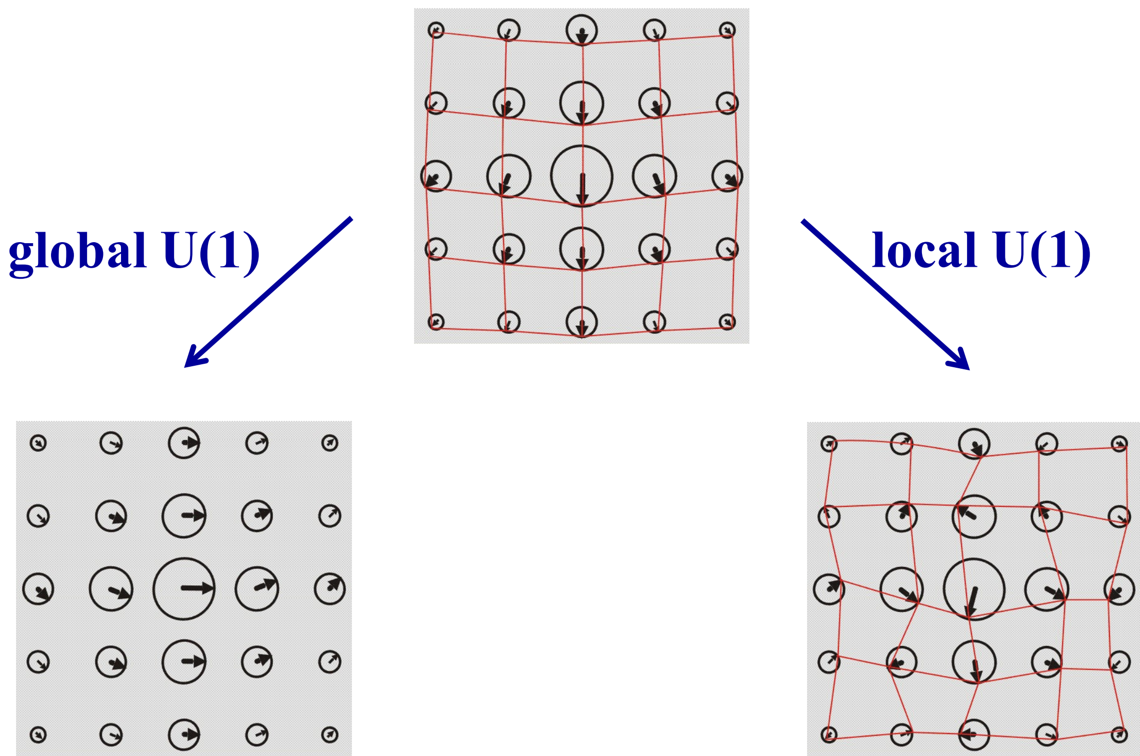




Gauge theories

- QM, QFT ==> local phase matters

connection A_μ takes care of it



Gauge theories

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

$$V(\phi) = m^2 |\phi|^2 \quad \left[+ \lambda |\phi|^4 \right]$$

Euler-Lagrange:

$$0 = -\frac{\partial \mathcal{L}}{\partial \phi^\dagger} + \partial_\mu \frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi^\dagger)} = \left(\partial_\mu \partial^\mu - m^2\right) \phi$$

Klein-Gordon

Gauge theories

$$\mathcal{L} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi) \qquad V(\phi) = m^2 |\phi|^2 \quad \left[+ \lambda |\phi|^4 \right]$$

global transf. : $\phi \to \phi' = e^{iq\alpha} \phi \quad \Rightarrow \quad \mathcal{L} \to \mathcal{L}$

local transf. : $\phi \to \phi' = e^{iq\alpha(x)} \phi \quad \Rightarrow \quad \mathcal{L} \to \; ?$

$$\begin{aligned} \partial_\mu \phi'^\dagger &= e^{-iq\alpha(x)} \left[\partial_\mu \phi^\dagger - iq\phi^\dagger \, \partial_\mu \alpha(x) \right] \\ \partial^\mu \phi' &= e^{iq\alpha(x)} \left[\partial^\mu \phi + iq\phi \, \partial^\mu \alpha(x) \right] \end{aligned}$$

$$\begin{aligned} (\partial_\mu \phi')^\dagger (\partial^\mu \phi') &= (\partial_\mu \phi)^\dagger (\partial^\mu \phi) \underline{- iq \left[\phi^\dagger (\partial^\mu \phi) - (\partial^\mu \phi)^\dagger \phi \right] \, \partial_\mu \alpha} \\ &\quad \underline{+ q^2 |\phi|^2 (\partial_\mu \alpha)(\partial^\mu \alpha)} \end{aligned}$$

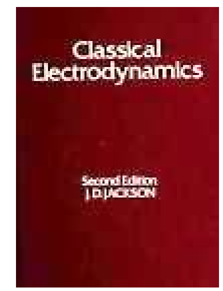
Gauge theories

*** charged particle in EM field ==> minimal coupling**

$$i\partial^\mu \;\rightarrow\; i\partial^\mu - qA^\mu \quad \text{==>} \quad \partial^\mu \;\rightarrow\; \boxed{D^\mu} = \partial^\mu + iqA^\mu$$

covariant derivative

*** gauge transformation of gauge field** $\quad A_\mu \;\rightarrow\; A'_\mu = A_\mu - \partial_\mu \alpha$



$$\begin{aligned}(D_\mu\phi)' &= (\partial_\mu + iq\,A'_\mu)\,e^{iq\alpha(x)}\phi \\ &= e^{iq\alpha(x)}\left[\cancel{iq\,(\partial_\mu\alpha)}\,\phi + (\partial_\mu\phi) + iq\,A_\mu\,\phi - \cancel{iq\,(\partial_\mu\alpha)}\,\phi\right] \\ &= e^{iq\alpha(x)}\;D_\mu\phi\end{aligned}$$

$$\mathcal{L} \;=\; \underbrace{(D_\mu\phi)^\dagger\,(D^\mu\phi)}_{\text{kinetic }\phi\text{ + int. w/ gauge fields}} - \underbrace{V(\phi)}_{\text{self }\phi} - \underbrace{\tfrac{1}{4}F^{\mu\nu}F_{\mu\nu}}_{\text{Electromagnetism (for free!)}} \;\rightarrow\; \mathcal{L}$$

kinetic ϕ + int. w/ gauge fields — **self ϕ** — **Electromagnetism (for free!)**

Gauge theories

the gauge principle

- **ask for gauge invariance of matter field**
- **introduce via the covariant derivative one gauge field for each group generator**
- **include gauge transformations of gauge fields**
- **include kinetic terms for gauge fields ==> interactions of gauge fields**
- **==> gauge fields have no mass**

$$m_A^2 A^\mu A_\mu \quad \not\to \quad m_A^2 A^\mu A_\mu$$

- **==> no longitudinal polarization (only 2 dof)**

★

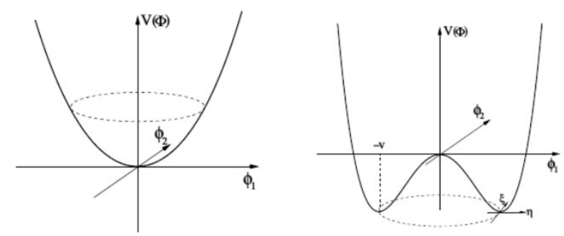
Spontaneous Symmetry Breaking

The Lagrangian has a symmetry which is broken by the vacuum.

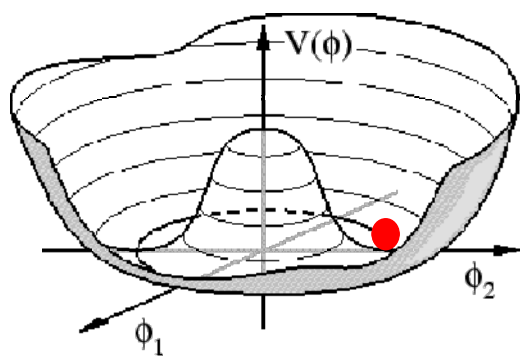
$$V = \mu^2 \left|\phi\right|^2 + \lambda \left|\phi\right|^4$$

*** minimum** $$0 = \left.\frac{\partial V}{\partial \phi^\dagger}\right|_{\rm min} = \phi \left.\left(\mu^2 + 2\lambda|\phi|^2\right)\right|_{\rm min}$$

$\mu^2 > 0$ $$\langle \phi \rangle = 0$$



$\mu^2 < 0$



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

= 174 GeV

Spontaneous Symmetry Breaking

Homework 1

★

*** polar parametrization** $\phi(x) = e^{i\xi(x)/v} \frac{1}{\sqrt{2}} \left[v + h(x) \right]$

$$V = \mu^2 \left|\phi\right|^2 + \lambda \left|\phi\right|^4$$

$$\mu^2 + \lambda v^2 = 0$$

potential

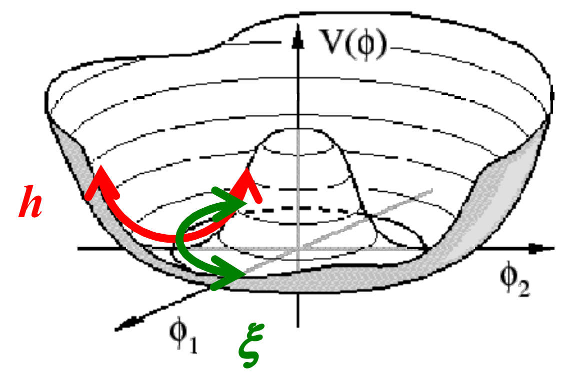
$$V = \underbrace{(-\mu^2)}_{\frac{1}{2} m_h^2} h^2 \left[1 + \frac{h}{2v} \right]^2$$

no $\frac{1}{2} m_\xi^2\ \xi^2$ term

*** Goldstone Theorem**

- **L invariant under continuous group**
- **vev breaks n generators**

==> there are n massless Goldstone bosons



The SSB/gauge miracle

PROBLEMS

1. Gauge symmetry ==> massless Gauge boson

   (2 ⊥ polarizations)

2. SSB ==> massless Goldstone boson

   (1 dof/broken generator)

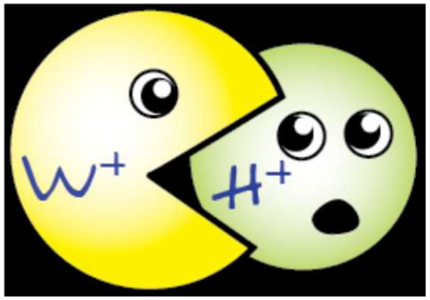
2. solves 1.

(2 ⊥ polarizations) + Go b. “eaten” as longitudinal pol. ==> massive Gauge boson

F. Englert and R. Brout, PRL 13 (1964) 321.
P. W. Higgs, Phys.Lett. 12 (1964) 132, PRL 13 (1964) 508.
G. Guralnik, C. Hagen, and T. Kibble, PRL 13 (1964) 585.

The SSB/gauge miracle

The W^+ “eats” the Goldstone boson and makes it its longitudinal dof.



Flip Tanedo:
https://www.quantumdiaries.org/2011/10/10/who-ate-the-higgs/.
http://www.quantumdiaries.org/2011/06/19/helicity-chirality-mass-and-the-higgs/.

The SSB/gauge miracle

Homework 2

★

*** polar parametrization** $\phi(x) = e^{i\xi(x)/v} \frac{1}{\sqrt{2}} [v + h(x)]$

$(\partial_\mu \phi)^\dagger (\partial^\mu \phi)$

$$|D\phi|^2 = |(\partial + iq\, A)\, \phi|^2 = \left|(\partial + iq\, A)\, e^{i\xi/v} \frac{1}{\sqrt{2}} [v + h]\right|^2$$

$$= \frac{1}{2} \left|(\partial h) + i(v+h) \left[\frac{(\partial \xi)}{v} + q\, A\right]\right|^2$$

$$= \frac{1}{2}(\partial_\mu h)(\partial^\mu h) + \frac{1}{2}(qv)^2 \left[A_\mu + \frac{1}{qv}\partial_\mu \xi\right]^2 \left[1 + \frac{h}{v}\right]^2$$

$= A'_\mu$ (gauge transf.)

mass term for A'_μ

The SSB/gauge miracle

- the massless GoB ξ disappears
- it is absorbed as the longitudinal polarization of A'_μ
  (dof 2 + 1 = 3)
- A'_μ gets a mass proportinal to v
- there is a new massive scalar field h "the Higgs boson"
- the coupling of hAA is proportional to m_A^2
- the fermions also get mass through Higgs
- the couplings hff are proportional to m_f

The Higgs Mechanism

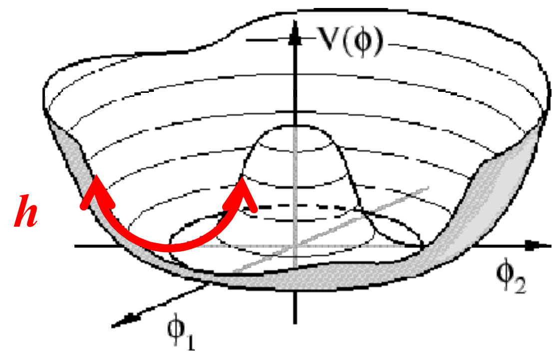
*** polar parametrization** $\phi(x) = e^{i\xi(x)/v} \frac{1}{\sqrt{2}} [v + h(x)]$

kinetic term $(\partial_\mu \phi)^\dagger (\partial^\mu \phi) = \frac{1}{2}(\partial_\mu h)(\partial^\mu h) + \frac{1}{2}(\partial_\mu \xi)(\partial^\mu \xi) \left[1 + \frac{h}{v}\right]^2$

potential $V = \underbrace{(-\mu^2)}_{\frac{1}{2} m_h^2} h^2 \left[1 + \frac{h}{2v}\right]^2$

$$\boxed{\frac{v}{\sqrt{2}} = \langle \phi \rangle = \sqrt{\frac{-\mu^2}{2\lambda}}}$$ **= 174 GeV**

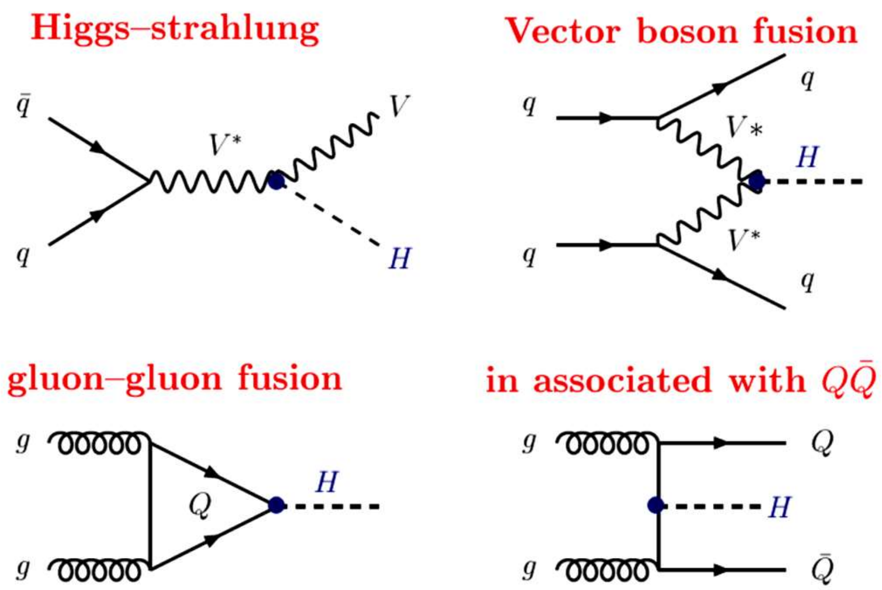
$$\boxed{m_h = \sqrt{-2\mu^2}}$$ **= 125 GeV**

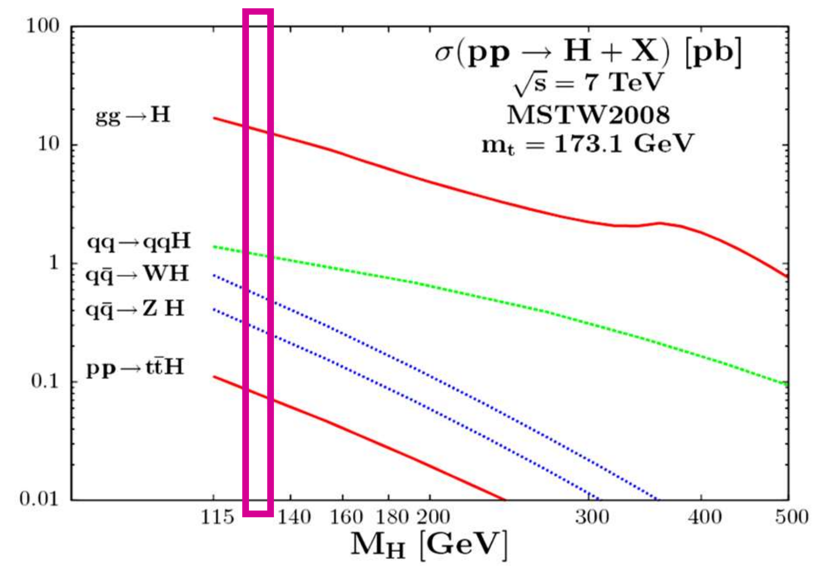


==> All SM parameters fixed; all predictions

1 Higgs: Predictions

- **Production**





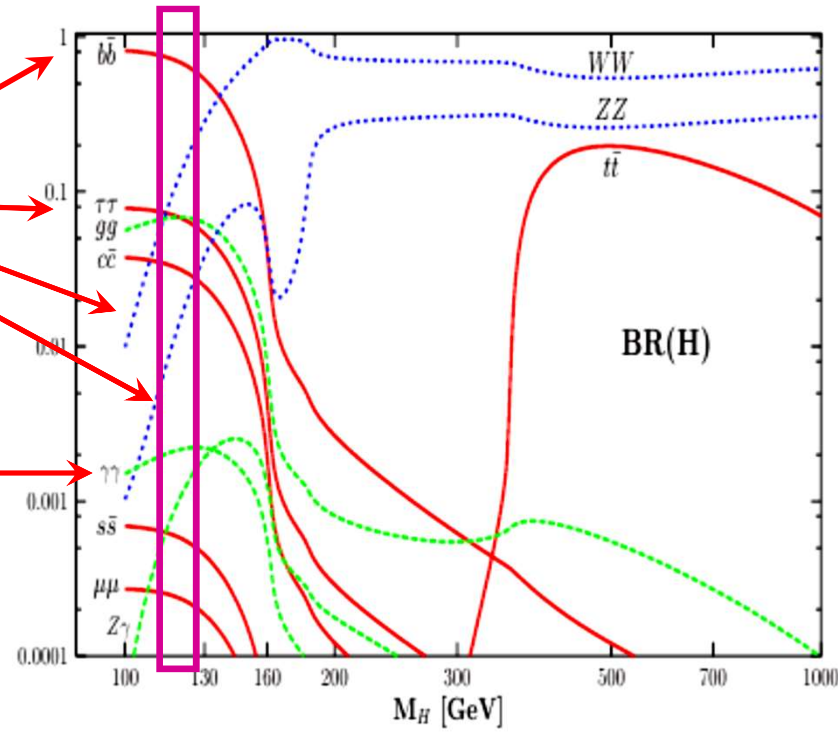
Djouadi Phys. Rept. 457 (2008), 459 (2008)

1 Higgs: Predictions

also

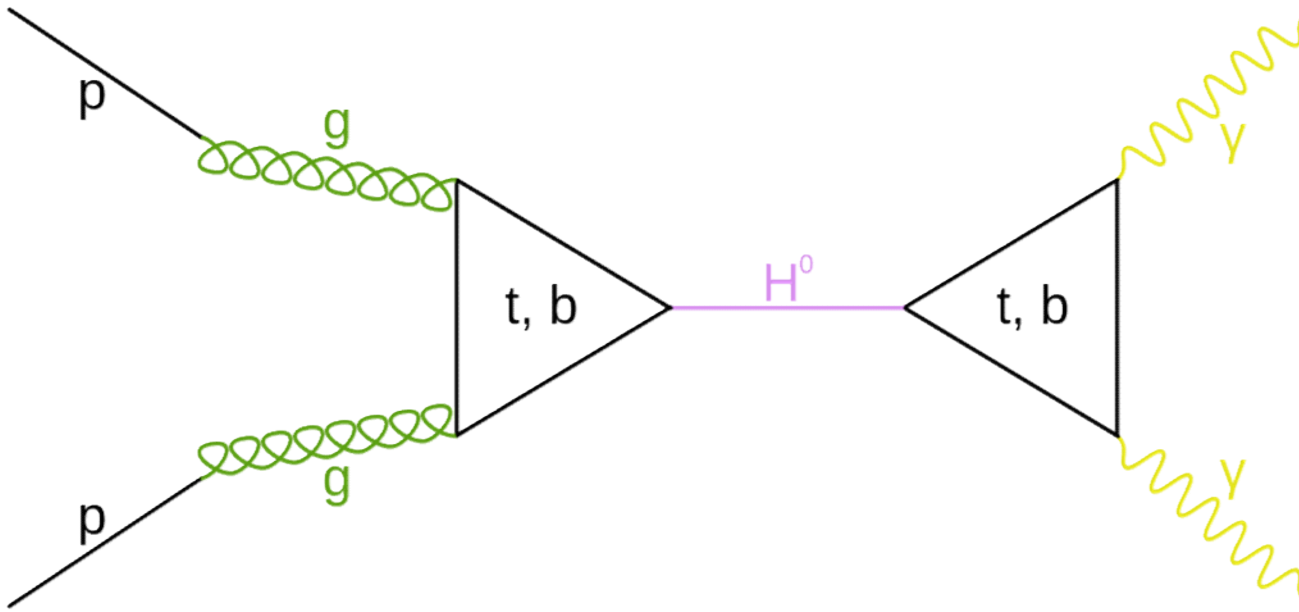
- **Decay**

discovered here!!!

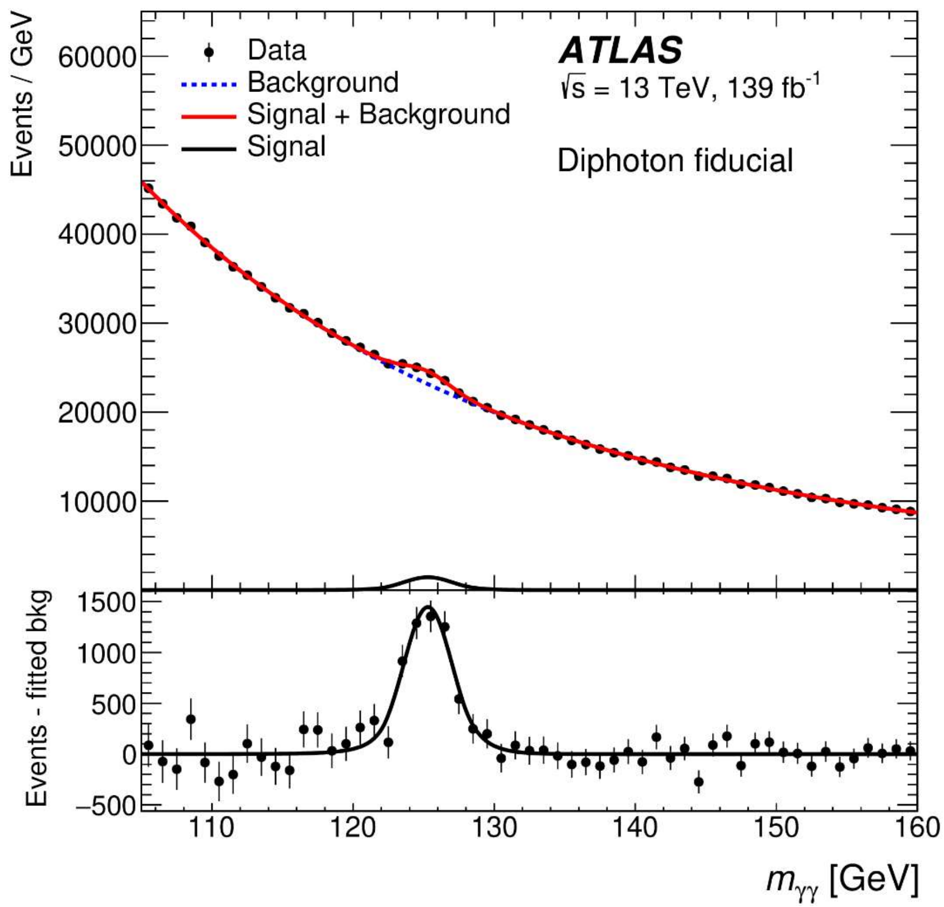


In the SM, rates related to known particle masses.

Quantum Field Theory is compulsory



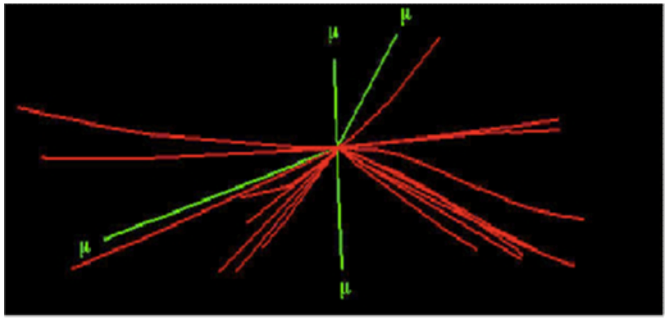
1 Higgs: Detection

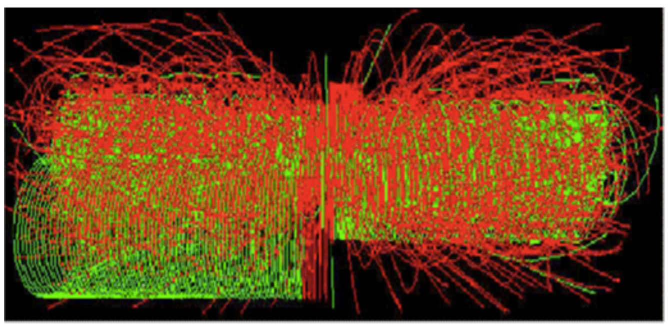


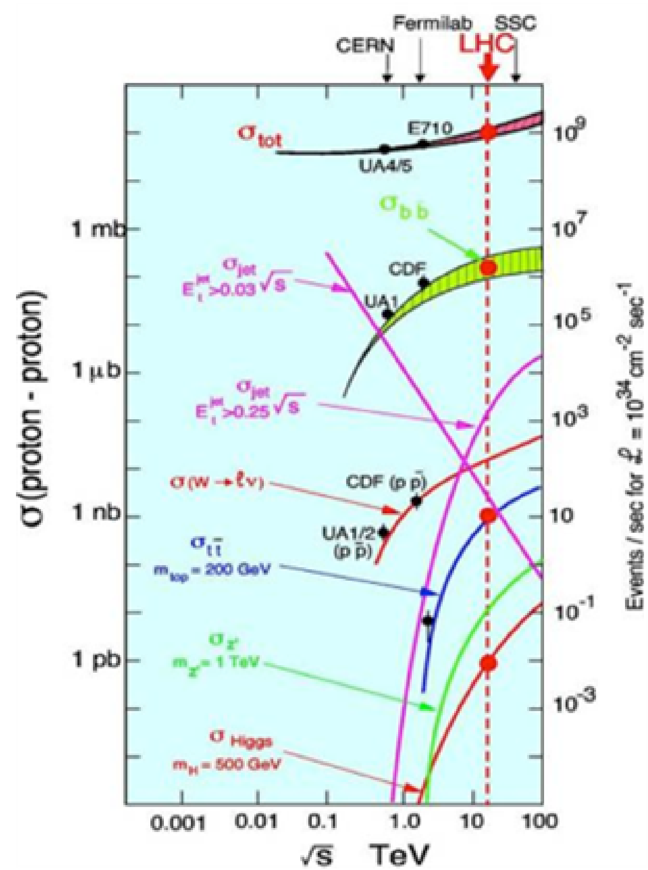
ATLAS: 9300 h --> γγ

thanks to: Patricia Conde Muíño

1 Higgs: Detection







thanks to: Ricardo Gonçalo

1 Higgs: Detection ★

Higgs boson production at the LHC (in Run-2 numbers)

LHC = *'Large Higgs Creator'*

During Run-2, the LHC produced almost **8 million Higgs bosons**!

H(125 GeV) — approximate numbers

Channel	Produced		Selected	Mass resolution
$H \to \gamma\gamma$	18,200		6,440	1–2%
$H \to ZZ^*$	210,000	$(\to 4\ell)$	210	1–2%
$H \to WW^*$	1,680,000	$(\to 2\ell 2\nu)$	5,880	20%
$H \to \tau\tau$	490,000		2,380	15%
$H \to bb$	4,480,000		9,240	10%

A. Hoecker, CERN

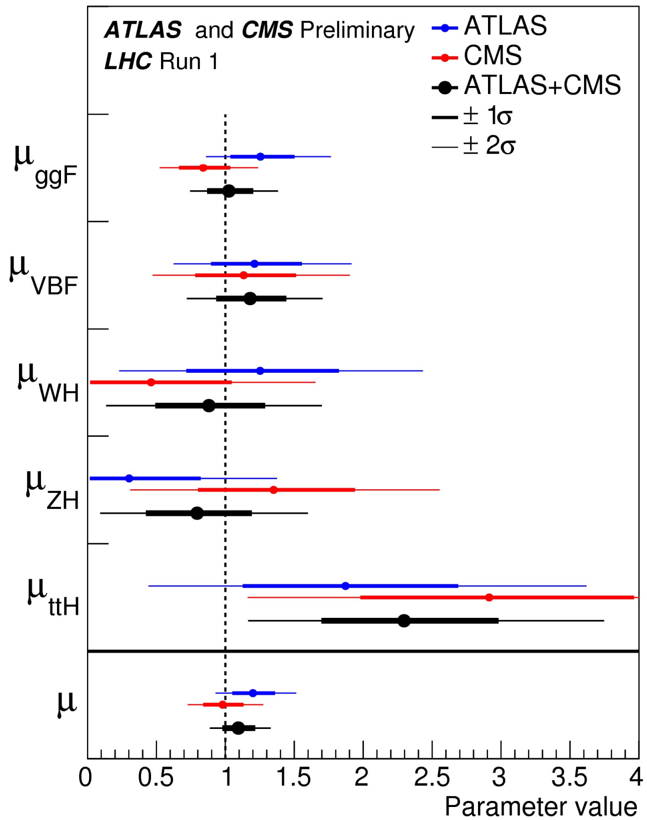
While this is enormous, the number of selected events is much smaller, due to:

- *Need to select final states with small backgrounds (typically require a lepton) and good resolution to measure the small Higgs signal*
- *Small branching ratios for lepton final states*

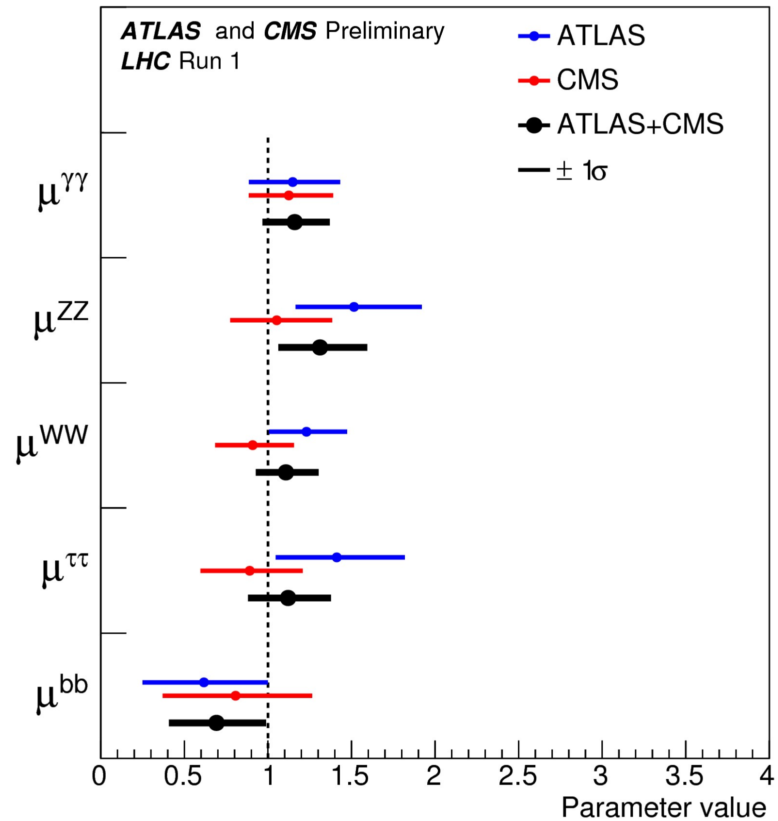
Bernd Stelzer **thanks to: Patricia Conde Muíño**

1 Higgs: Detection

SM BRs assumed



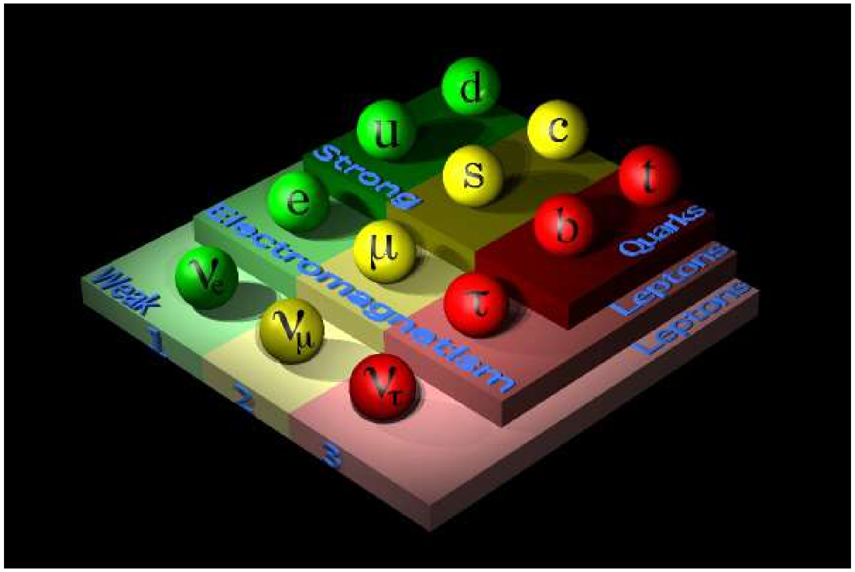
SM production assumed



Why 1 Higgs?

- **# Spin 1 fixed by gauge group:**
  SU(3)xSU(2)xU(1) => $W^{\pm}$, Z^0, γ, $g_{1..8}$

- **Nothing fixes # Spin 1/2:**
  Settled by experiment



- **Nothing fixes # Spin 0:**
  MUST be settled by experiment

Novelties in Multi-Higgs

- **Multiple spin-0 particles**
  - **Neutral:** **Scalar (h, H)**
    Pseudoscalar (A)
    Mixed (h1, h2, h3)
  - **Charged ($H^{\pm}$)**

- **Rich vacuum structure**
  - **May have charge breaking minimum**
  - **May have two local minima of unequal depths**

Novelties in Multi-Higgs

- CP violation in the Higgs sector
  - Theory: Explicit
Spontaneous
  - Experiment: Scalar-pseudoscalar mixing
Mixing of charged Higgs
Diagonal coupling to fermions
Off-diagonal coupling to fermions (FCNSI)

Scalar potential of the 2HDM

$$\begin{aligned} V_H &= m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{H.c.} \right] \\ &+ \tfrac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \tfrac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ &+ \left[\tfrac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \lambda_6 (\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \lambda_7 (\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + \text{H.c.} \right], \end{aligned}$$

Branco, Ferreira, Lavoura, Rebelo, Sher, JPSilva
Phys. Rept. 516 (2012)

Particle content of the 2HDM ★

- **Higgs basis (β)**

$$H_1 = \begin{bmatrix} G^+ \\ (v + H^0 + iG^0)/\sqrt{2} \end{bmatrix}, \quad H_2 = \begin{bmatrix} H^+ \\ (R + iI)/\sqrt{2} \end{bmatrix}$$

- **5 physical states**

β – α

$H^\pm$

$$\begin{bmatrix} h \\ H \\ A \end{bmatrix} = \begin{bmatrix} . & . & 0 \\ . & . & 0 \\ 0 & 0 & . \end{bmatrix} \begin{bmatrix} H^0 \\ R \\ I \end{bmatrix}$$

Lavoura and JPSilva, PRD 50, 4619 (1994)

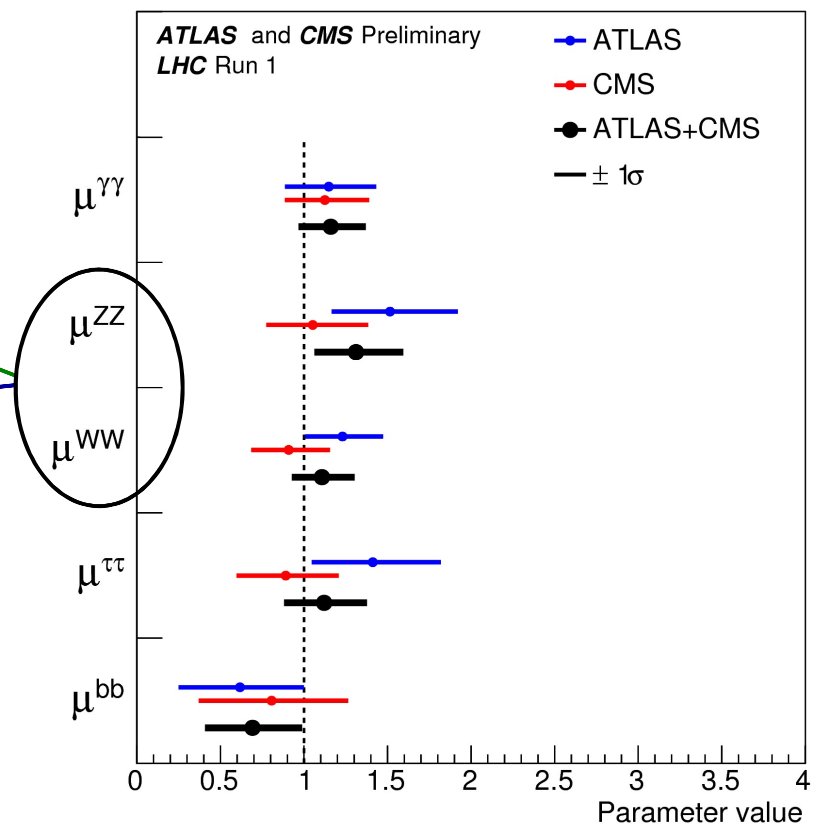
Higgs couplings in 2HDM: V

SM production assumed

Standard possibility: h = 125 GeV

$$g_{hVV} = g_{hVV}^{SM} \sin(\beta - \alpha)$$

$$g_{HVV} = g_{HVV}^{SM} \cos(\beta - \alpha)$$



Remarkable possibility: H = 125 GeV
(still allowed)

$$g_{AVV} = 0$$

Pure pseudoscalar 125 GeV ruled out

Strong limits from LHC

★

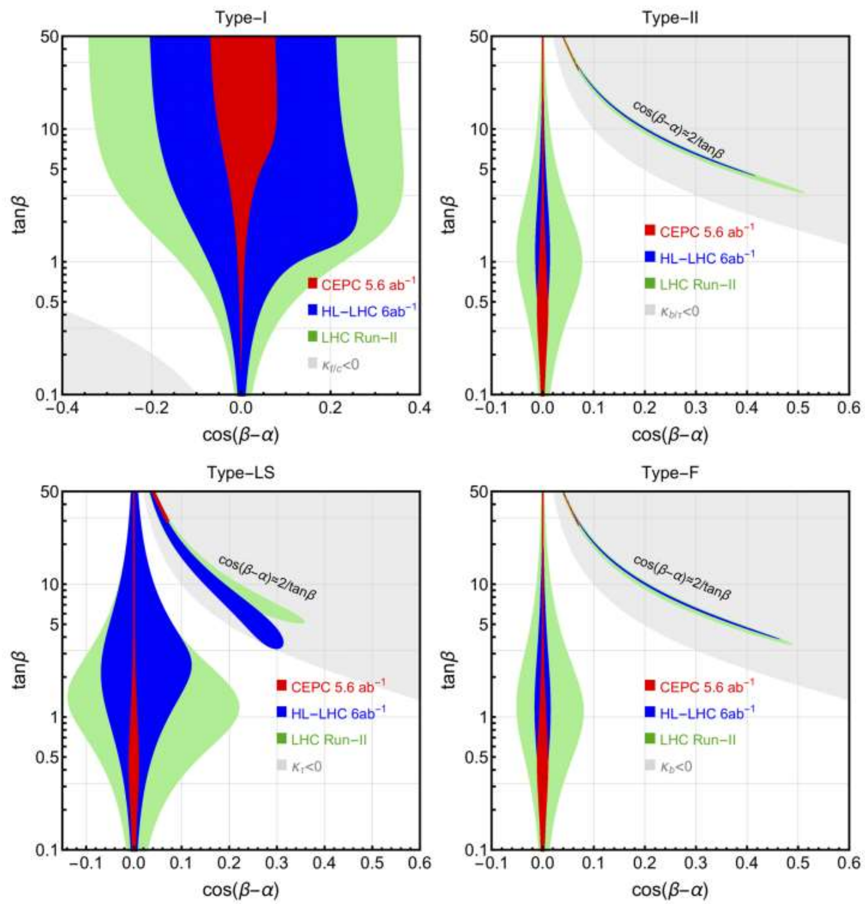


Fig. 1 The allowed region in the plane of $\tan\beta$ - $\cos(\beta-\alpha)$ at 95% C.L. for the four types of 2HDM, given LHC Run-II (green), HL-LHC (blue) and CEPC (red) Higgs precision measurements. For future measurements, we assume that the measurements agree with SM predictions. The gray represent the wrong-sign Yukawa regions discussed at Sect. 2.2, with $\kappa_U\kappa_V < 0$ for Type-I, $\kappa_b\kappa_V < 0$ for Type-II and Type-F, $\kappa_\tau\kappa_V < 0$ for Type-II and Type-LS. . The colored "arm" regions for the Type-II, L and F are the allowed wrong-sign Yukawa regions correspondingly

Wei Su, Eur. Phys. J. C (2021) 81:404

Conclusions

- **We have entered a new phase in the study of Elwk SB: the precision phase**
- **The # of Higgs is to be determined experimentally**
- **Current experiments already constrain the models**

Conclusions

- **Radical situations still viable: eg. scalar coupling to up and pseudoscalar coupling to down**
- **Beware of panic vacuum**
- **Multi-Higgs models constitute a very exciting and active field**

Multi-Higgs Workshops