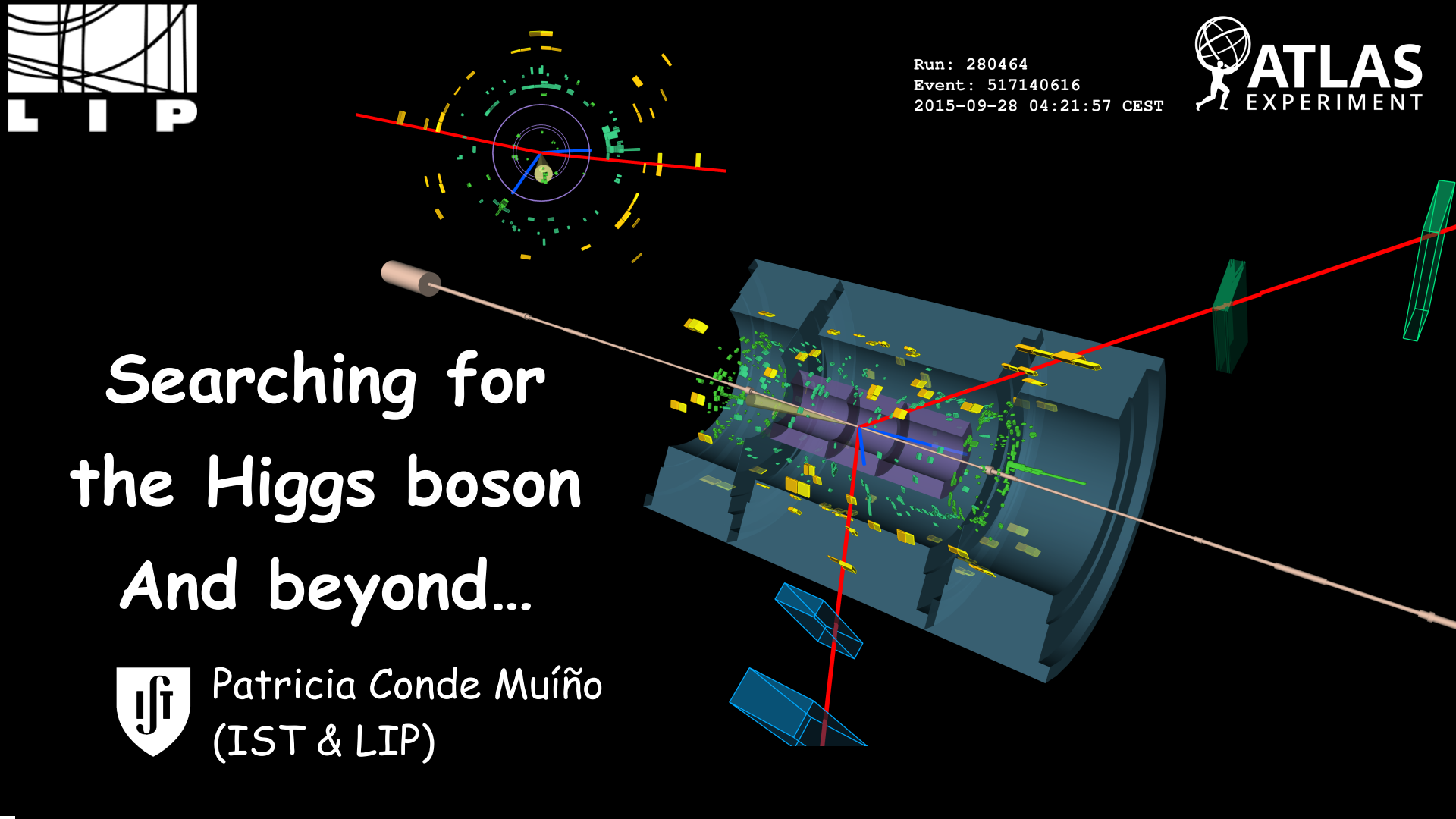
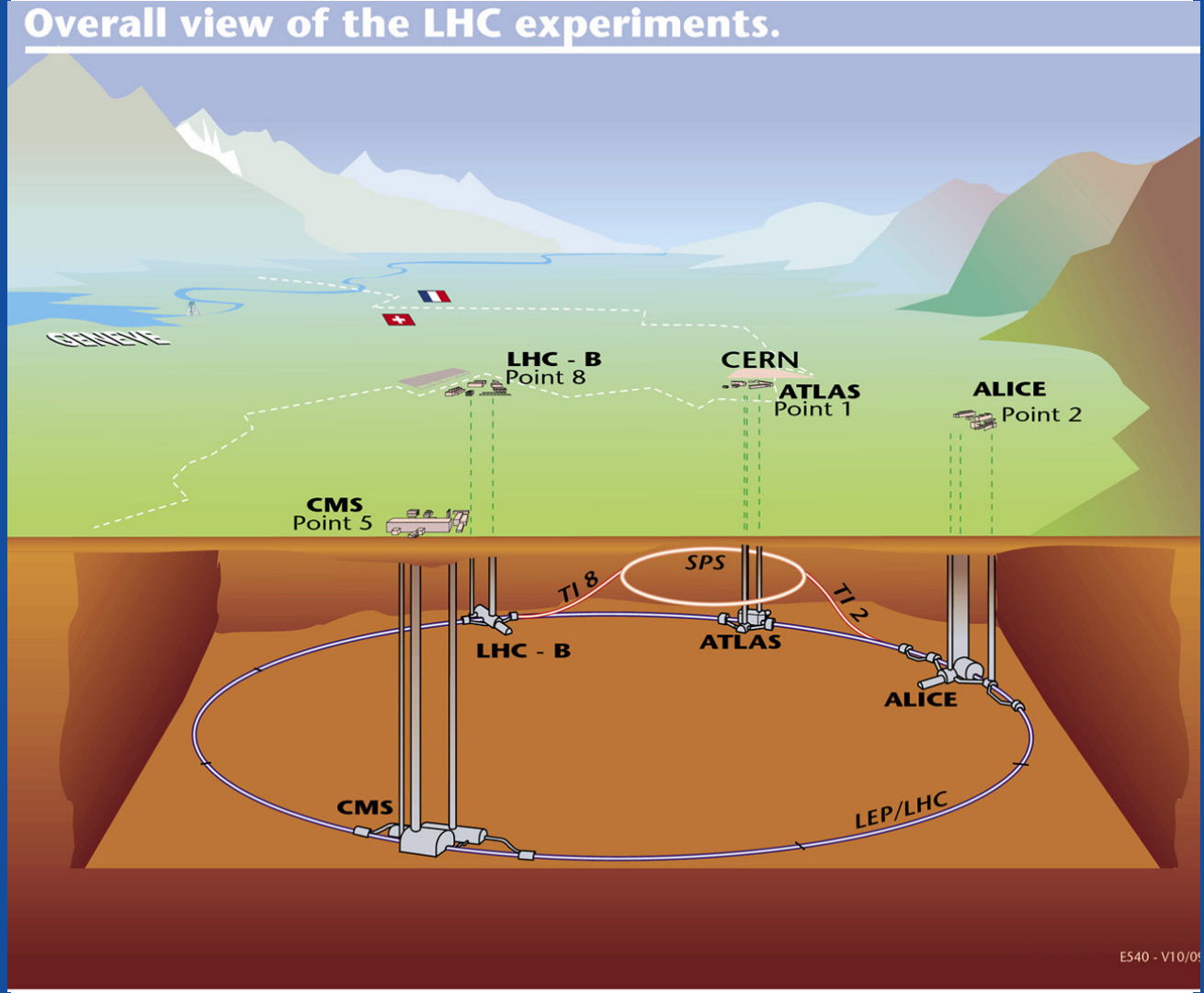

Run: 280464
Event: 517140616
2015-09-28 04:21:57 CEST
ATLAS
EXPERIMENT
LIP
Searching for
the Higgs boson
And beyond...
Patricia Conde Muíño
(IST & LIP)

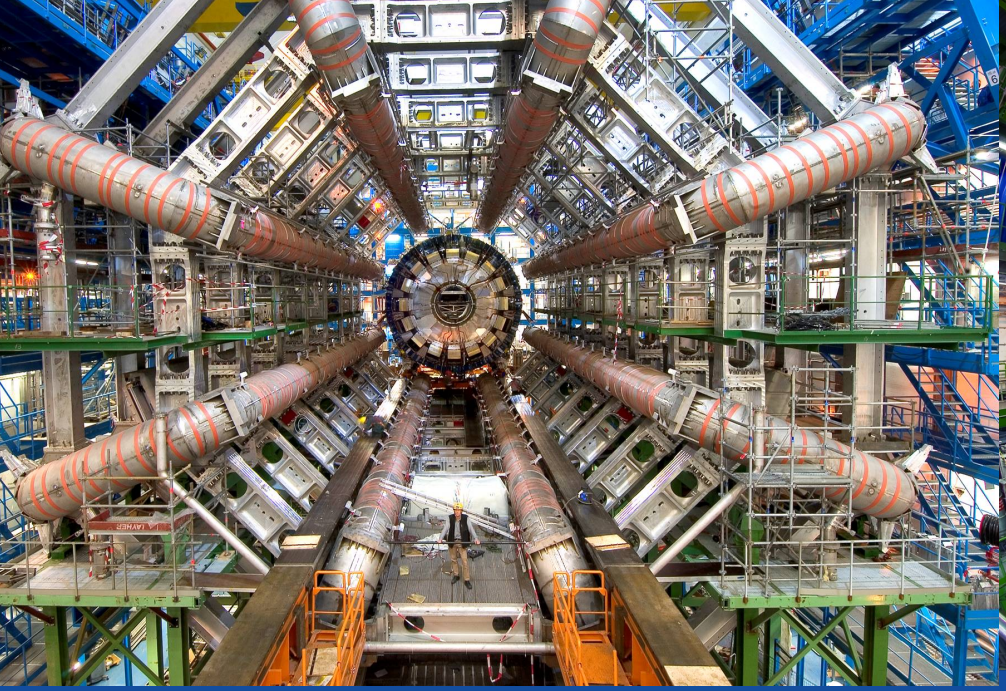
O LHC

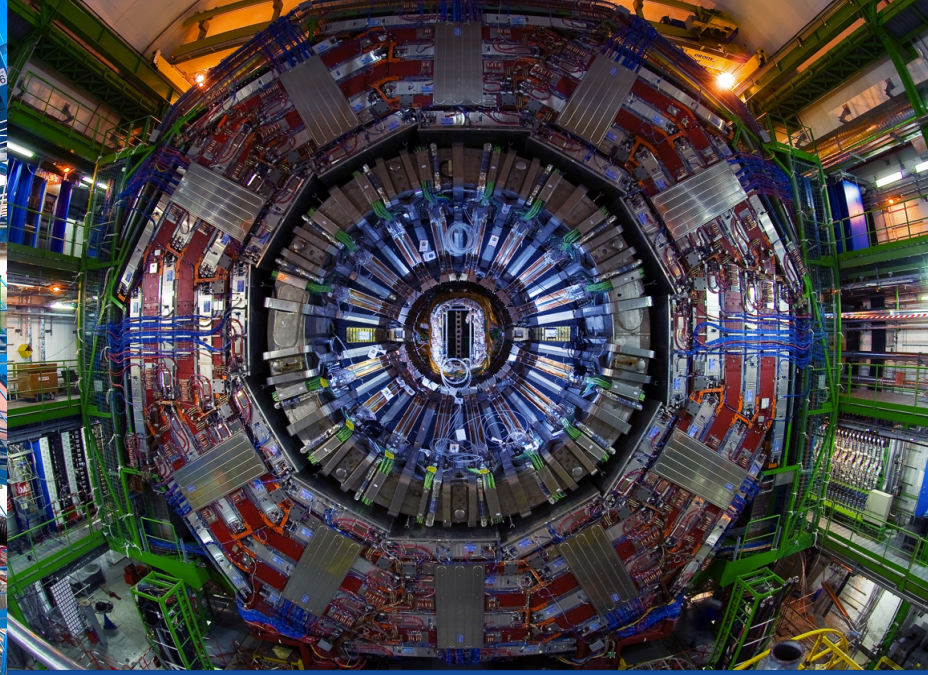
- 27 km de perímetro
- Most energetic collider ever built: $\sqrt{s} = 7{,}8{,}13{,}13.6\ \text{TeV}$
- Proton bunches collide 40 M times per second
- Up to 60 collisions/bunch crossing

LHC

- 100 m underground
- 4 main experiments:
  - ATLAS, CMS, ALICE, LHCb
- Other smaller experiments



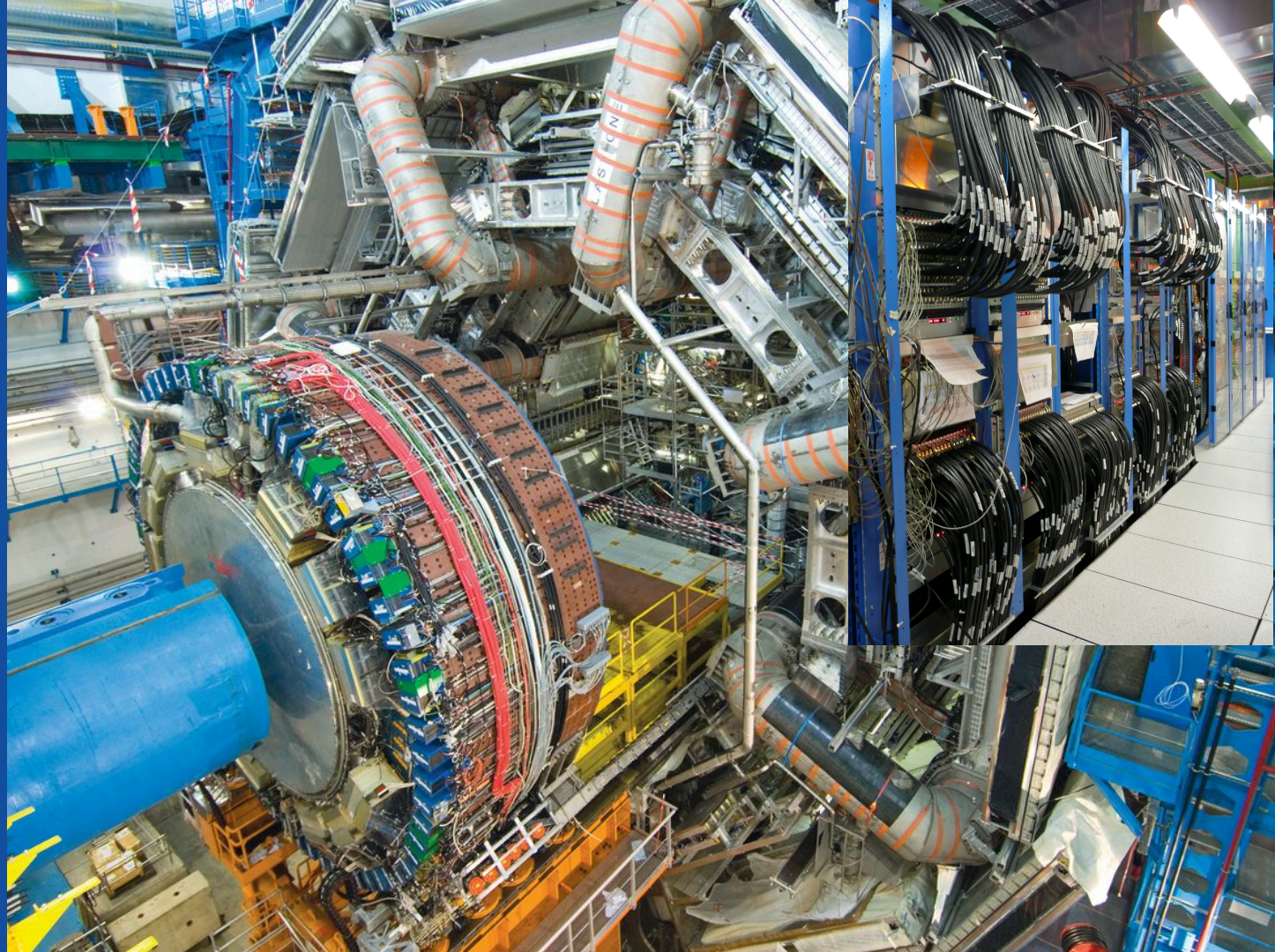




The ATLAS and CMS Detectors

The detectors

- Specialised detectors
- Cutting edge technology
- 10^8 electronic channels
- Home made fastest electronics



Looking into the origins of the universe

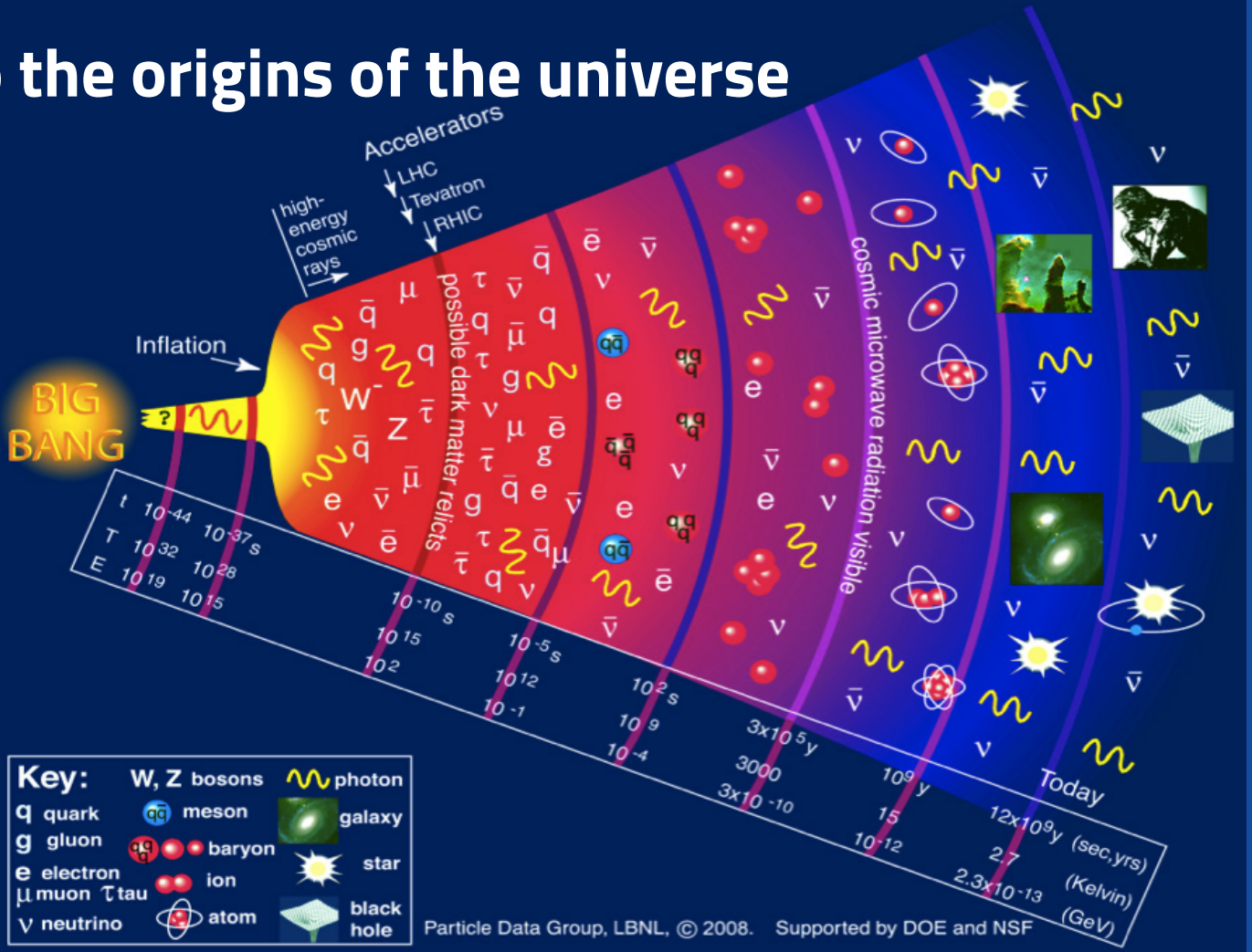
How did the Universe form?

Why are we made of matter and not anti-matter?

What is dark matter?

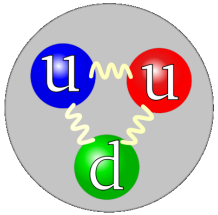
What are the fundamental building blocks of matter?

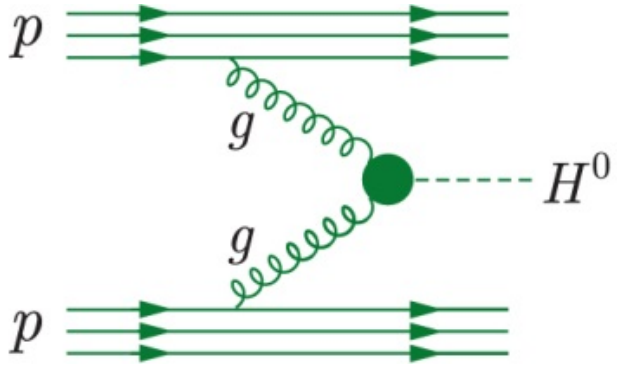
...



Produção do bosão de Higgs no LHC

- Modo mais provável:

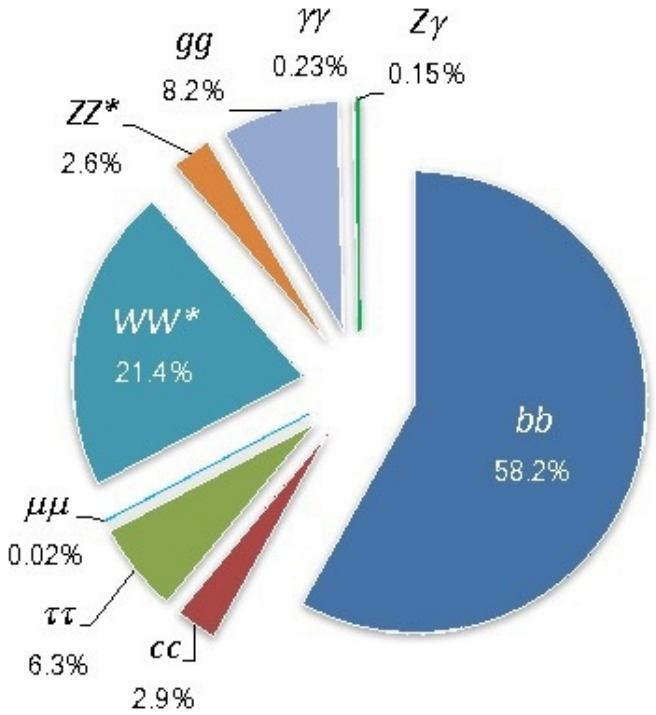




$$\sigma(pp \to HX) = \int_0^1 \int_0^1 g(x_1) g(x_2) \sigma(gg \to H) \mathrm{d}x_1 \mathrm{d}x_2,$$

Modos de decaimento do Higgs no MP

- O bosão de Higgs decai imediatamente!
- Observamos as partículas estáveis produzidas no seu decaimento



Canal de procura: modo de produção + modo de decaimento

Standard Model backgrounds

Production cross section of

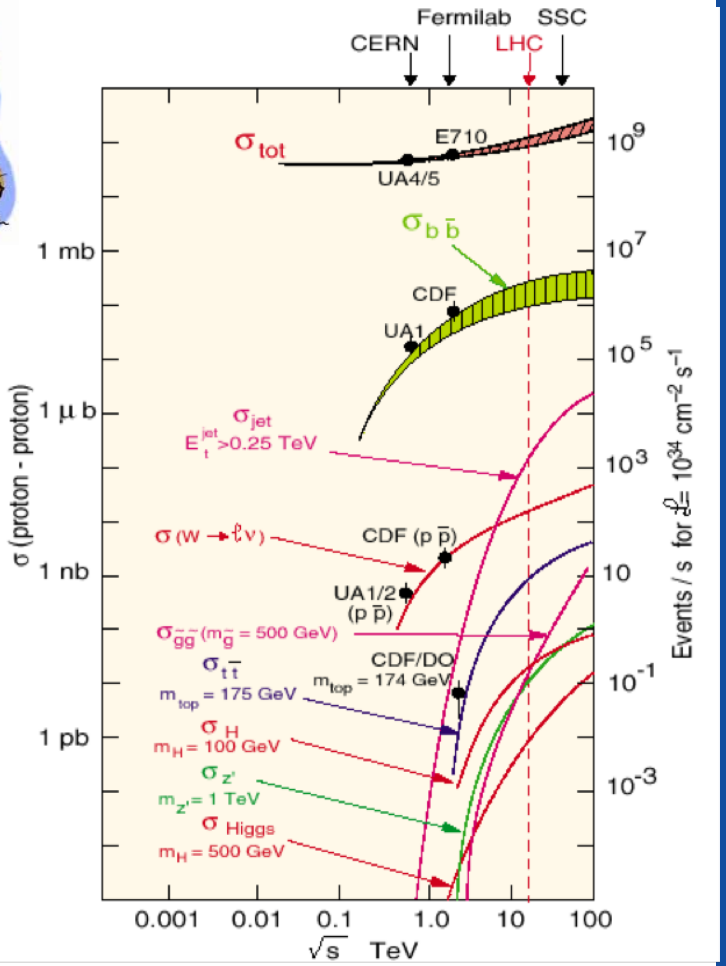
- Jets ~10^8 larger than σ_H
- B-jets ~10^7 times larger than σ_H
- W-bosons: nearly 10000 times higher than σ_H

We need

- Clear experimental signatures in the detector

For H→bb search:

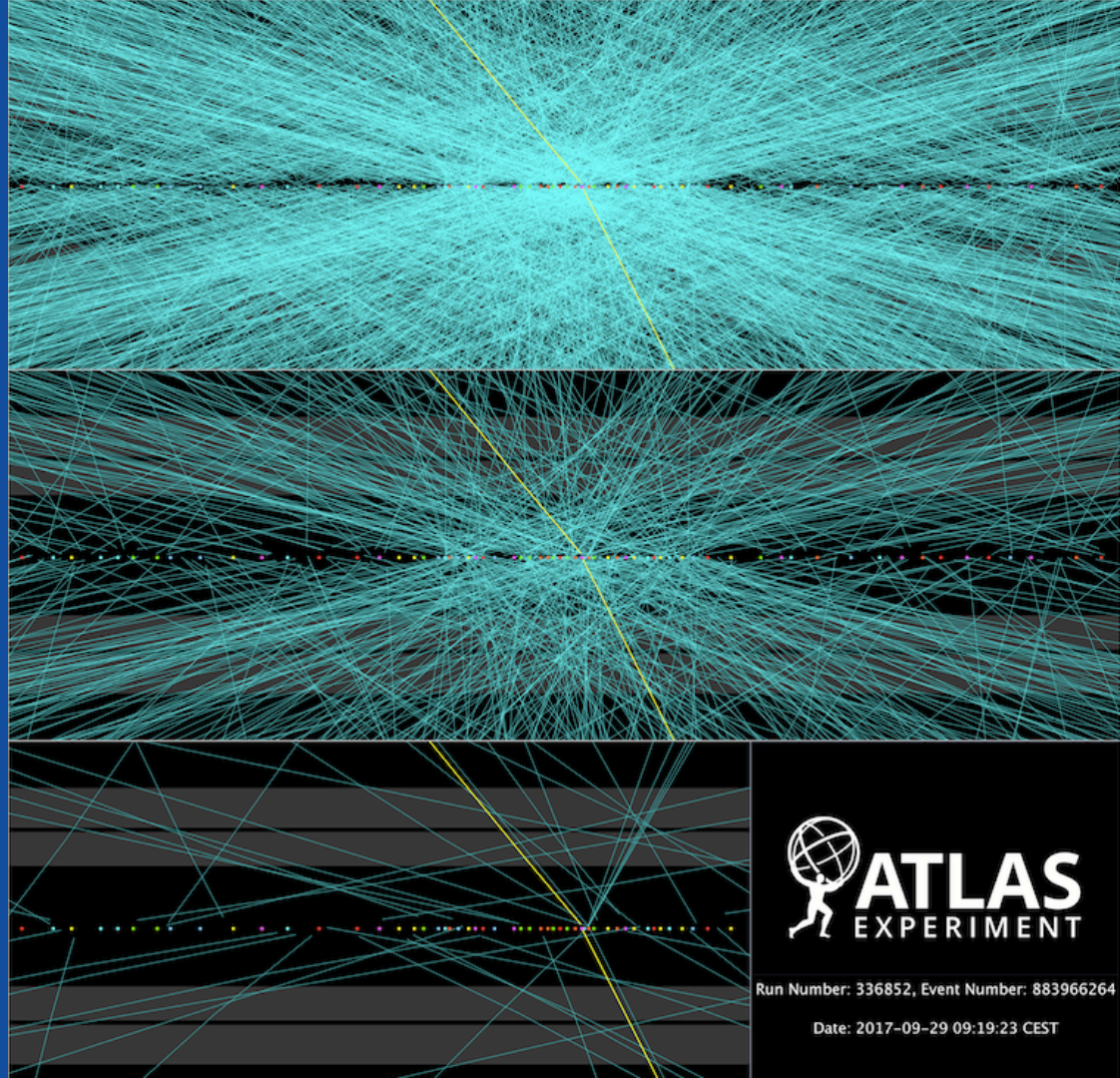
- Use sub-dominant production modes
  - Associated production with vector bosons
  - Vector boson fusion



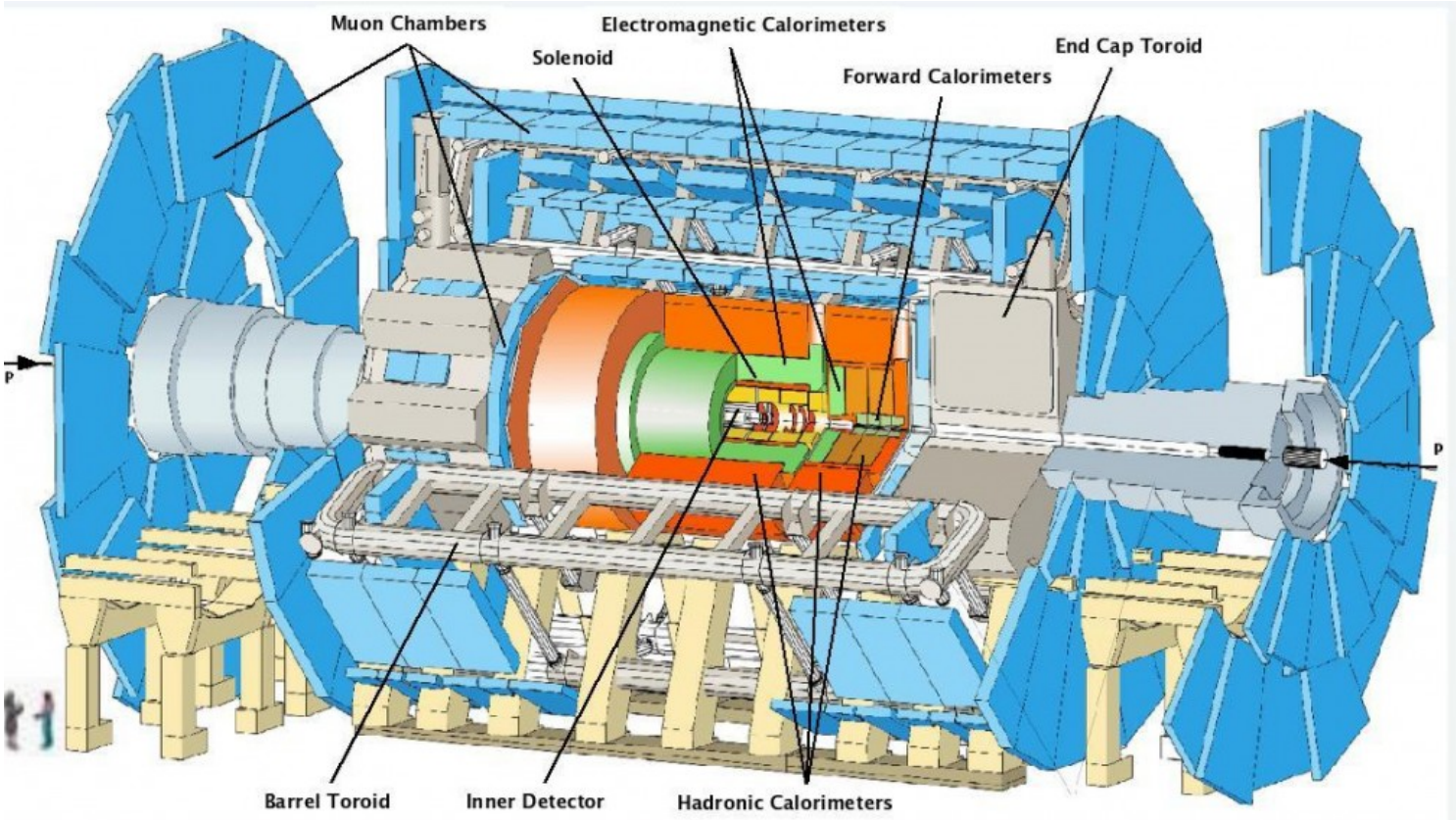
Pile-up

- Event with a $Z \rightarrow \mu\mu$ decay

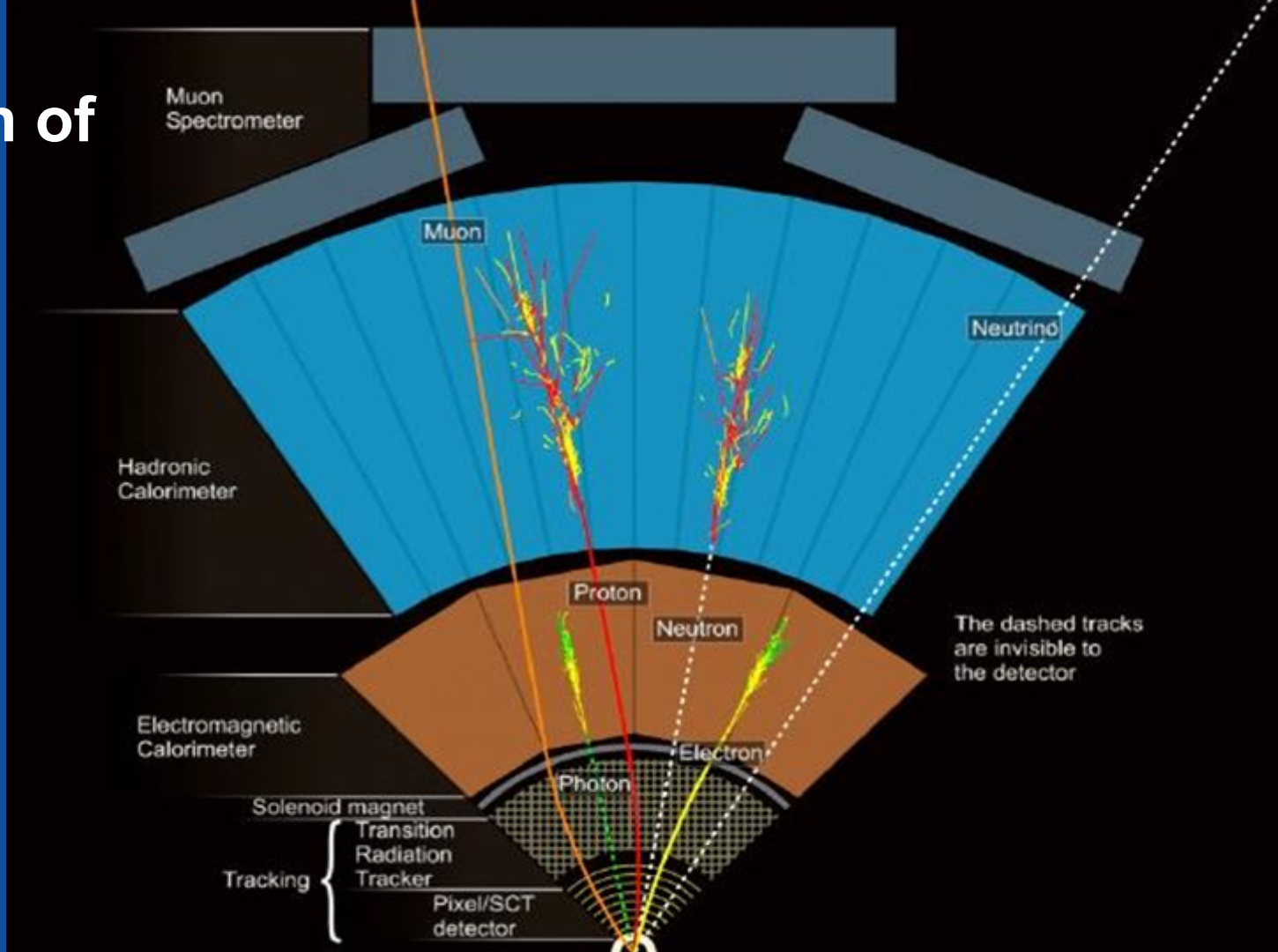
  plus 65 additional pp interactions
- Very difficult to reconstruct and distinguish different particles



The ATLAS detector

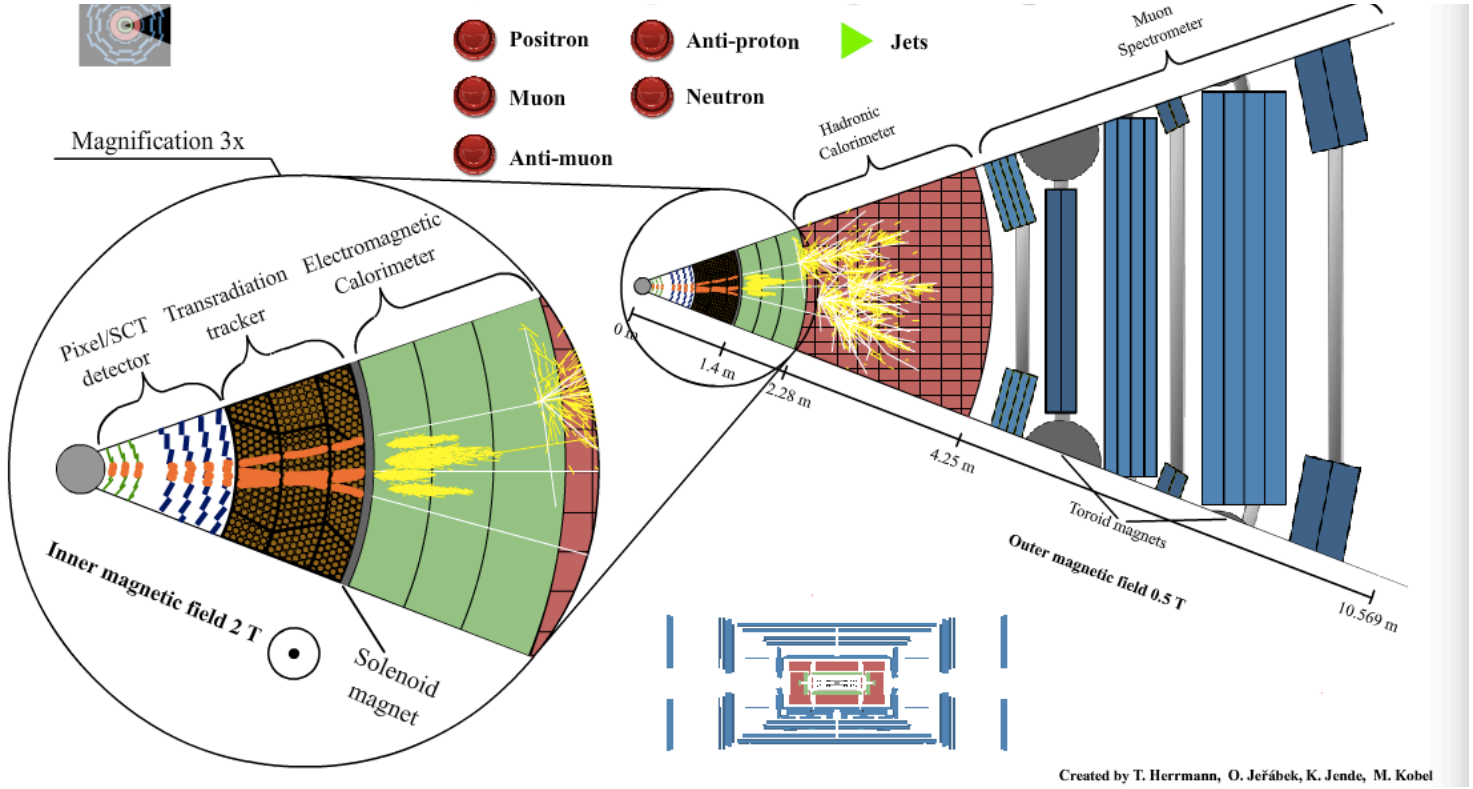


Identification of particles in ATLAS



Jets

- Quarks/ gluons hadronize producing a colimated spray of particles: jets

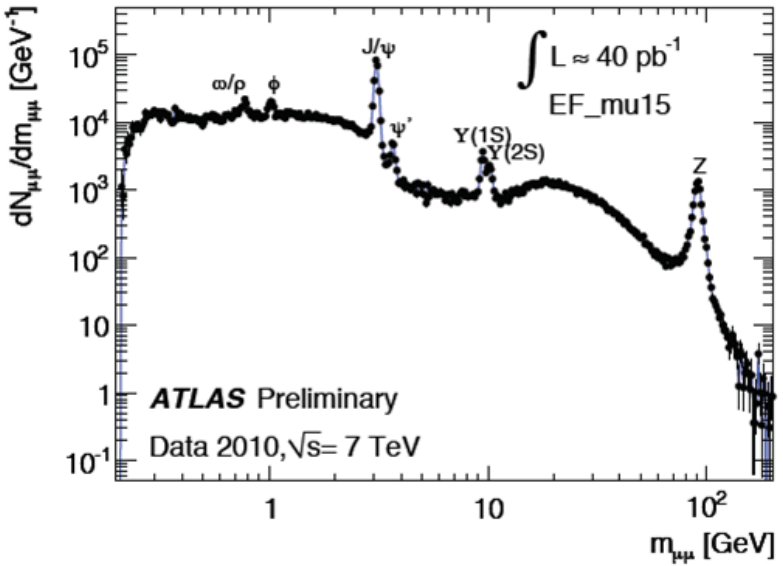


Reconstrução das partículas

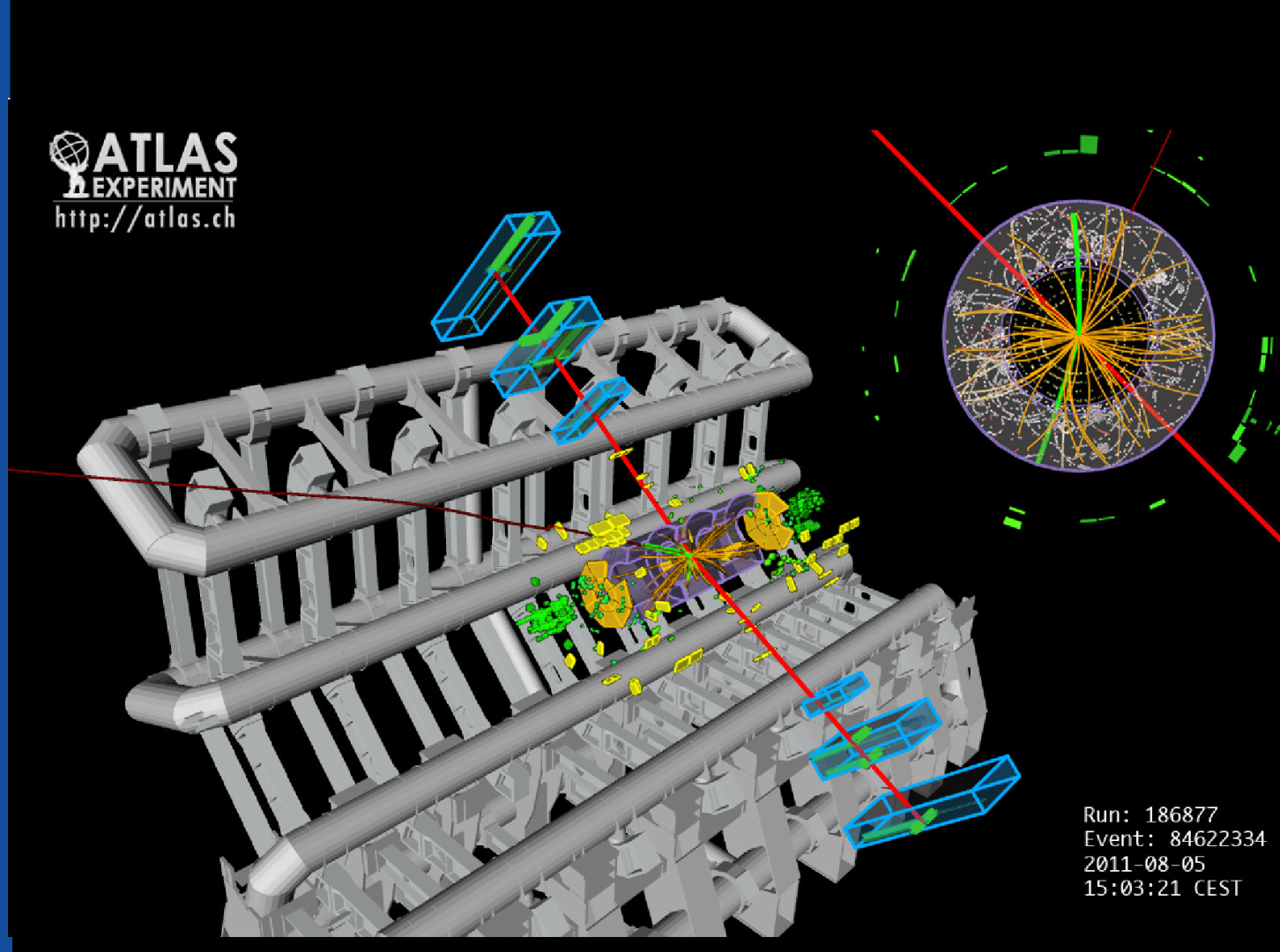
- A traves das propriedades das partículas produzidas na desintegração podemos inferir as propriedades do Higgs:

$$- E^2 = (mc^2)^2 + (pc)^2$$

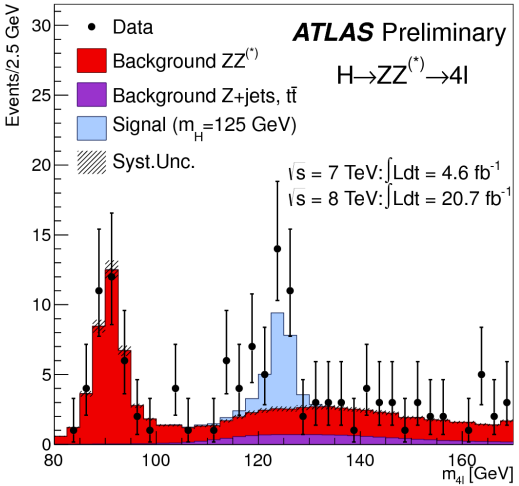
20 anos de física das partículas num só histograma



$H \rightarrow ZZ \rightarrow 4\ell$



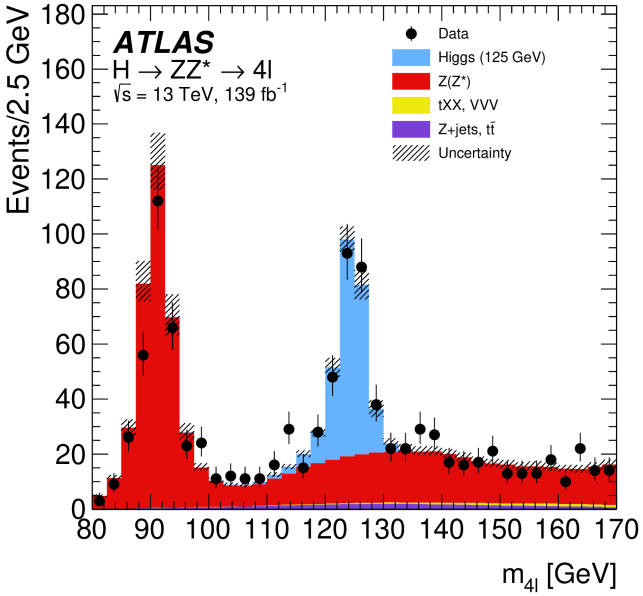
H→ZZ→4ℓ results



➢ ATLAS peak at 124.3 GeV

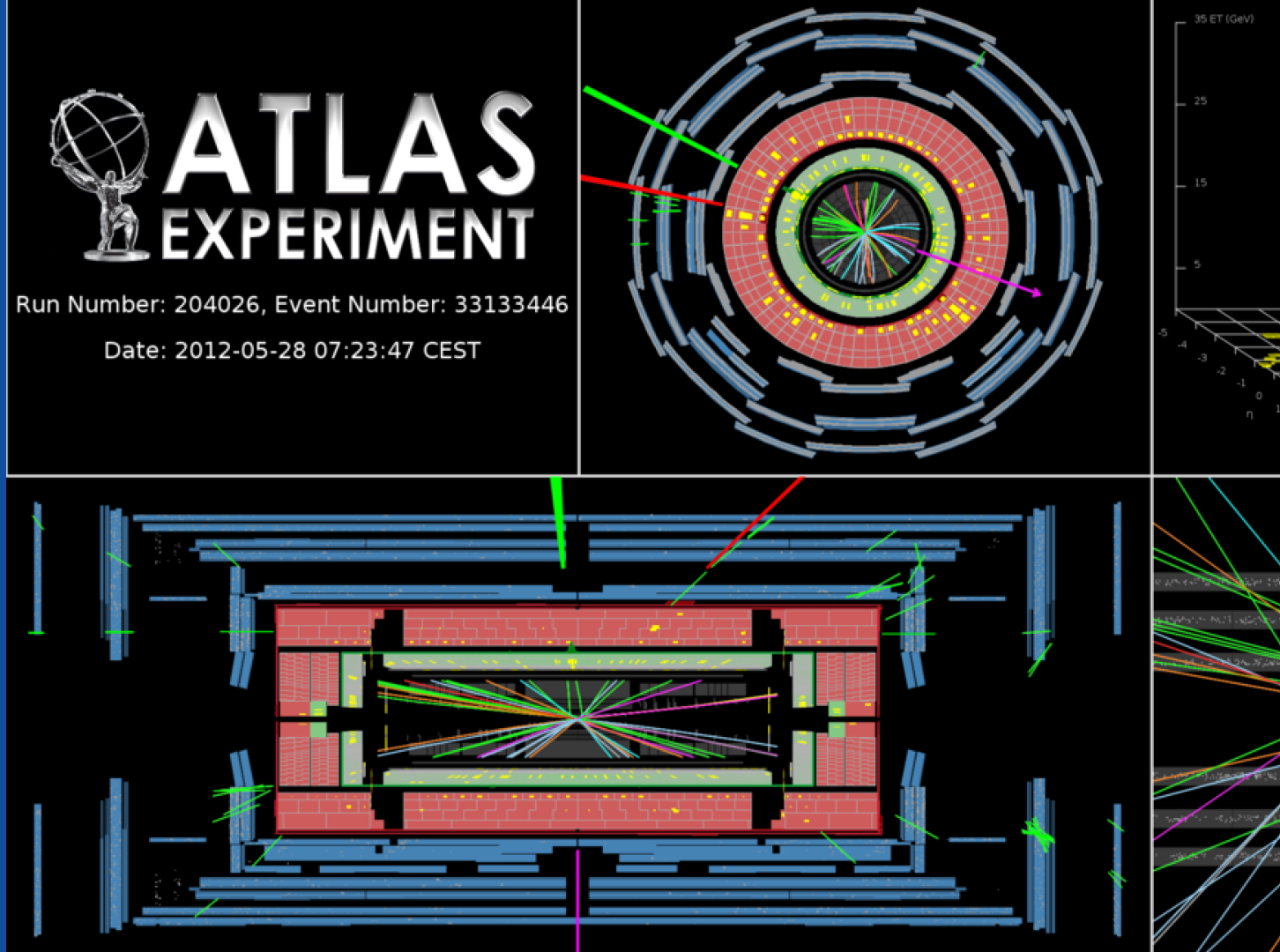
Probabilidade de flutuação do fundo
~ 0.000000000001

➢ Run 2 results



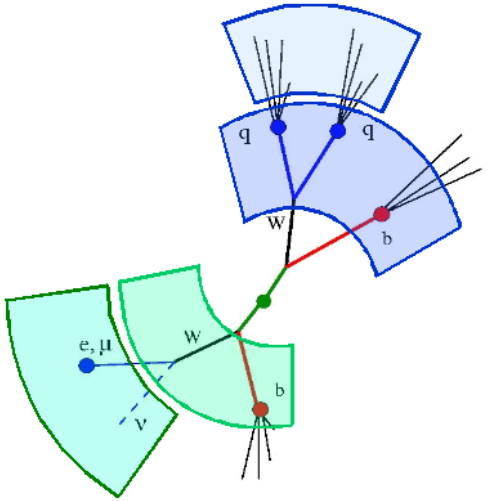
H→WW→

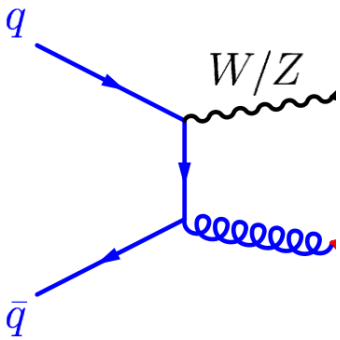
eν $\mu\nu$

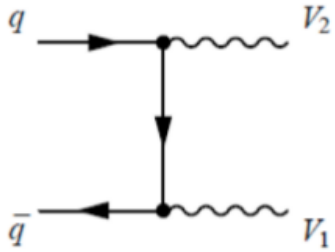

ATLAS
EXPERIMENT
Run Number: 204026, Event Number: 33133446
Date: 2012-05-28 07:23:47 CEST
35 ET (GeV)
25
15
5
η

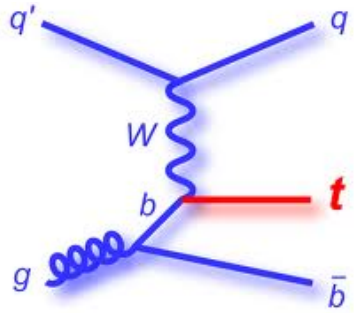
H→WW* →$e\nu\mu\nu$

- Second largest BR (22%)
- Clean signature: 2 leptons, large missing E_T
- Many SM backgrounds



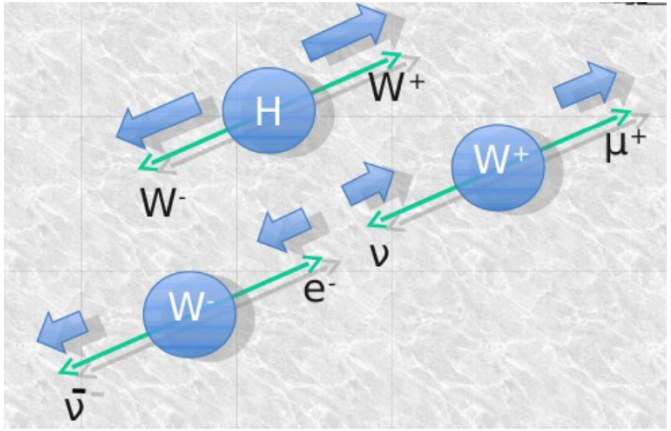


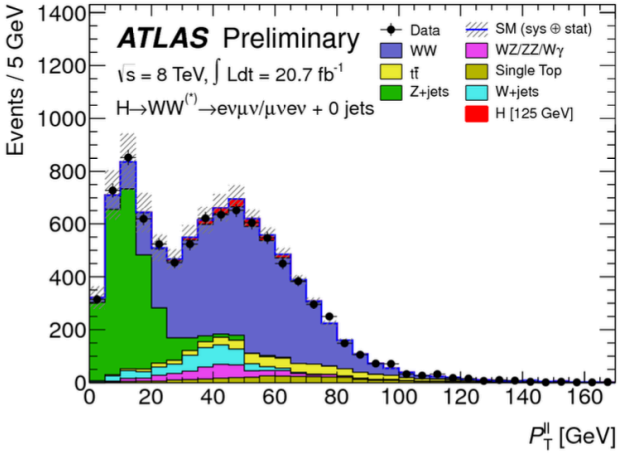


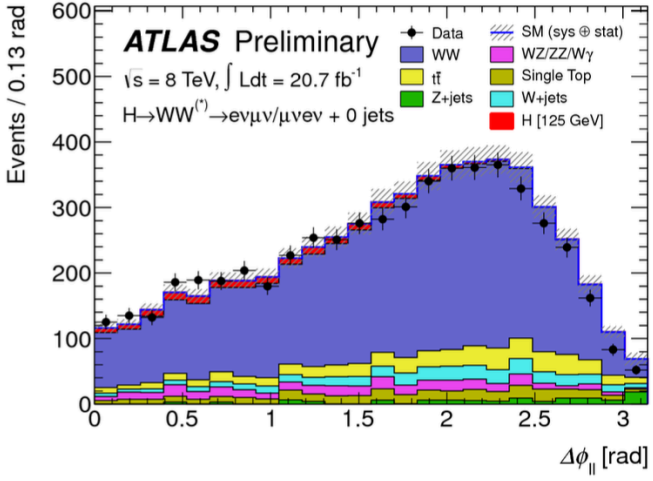


Event selection

- Use the Higgs event characteristics to reject background events

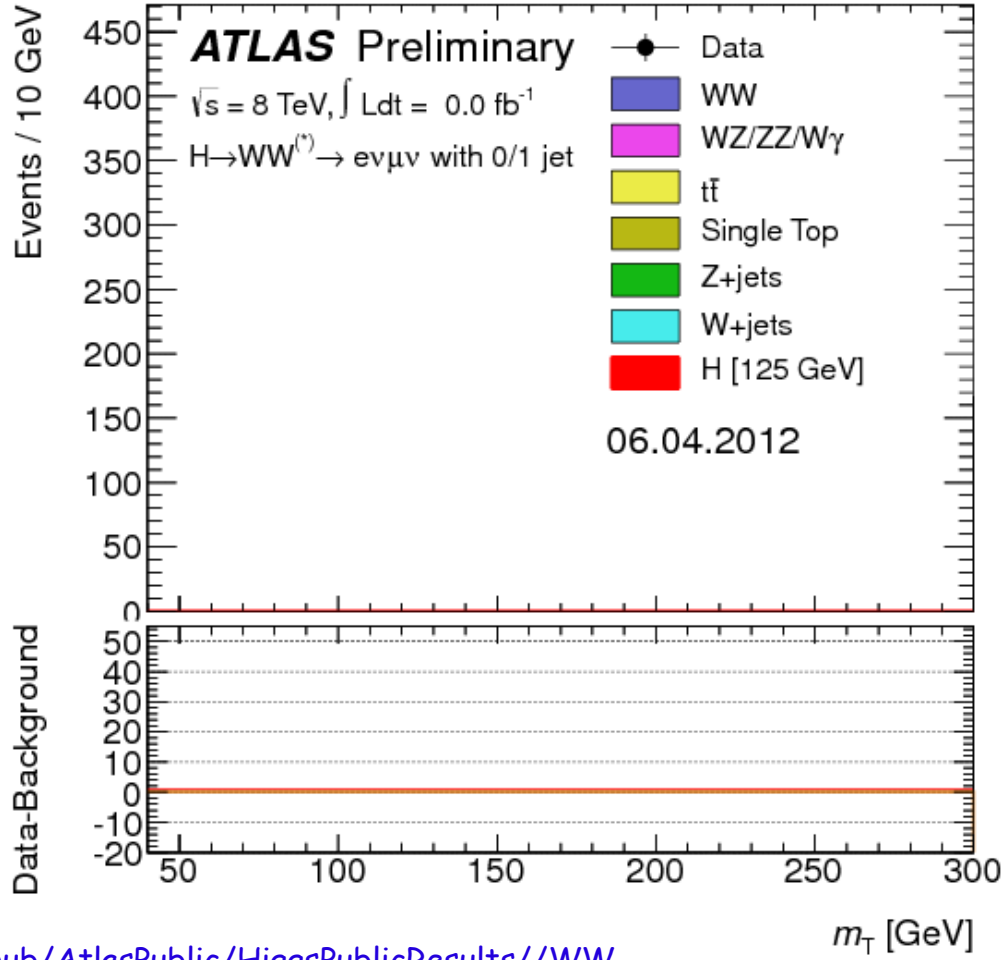






$H \rightarrow WW \rightarrow \ell\nu\,\ell\nu$

- At the beginning data compatible with background only
- As statistics increases we see an excess
- Compatible with SM Higgs boson!!

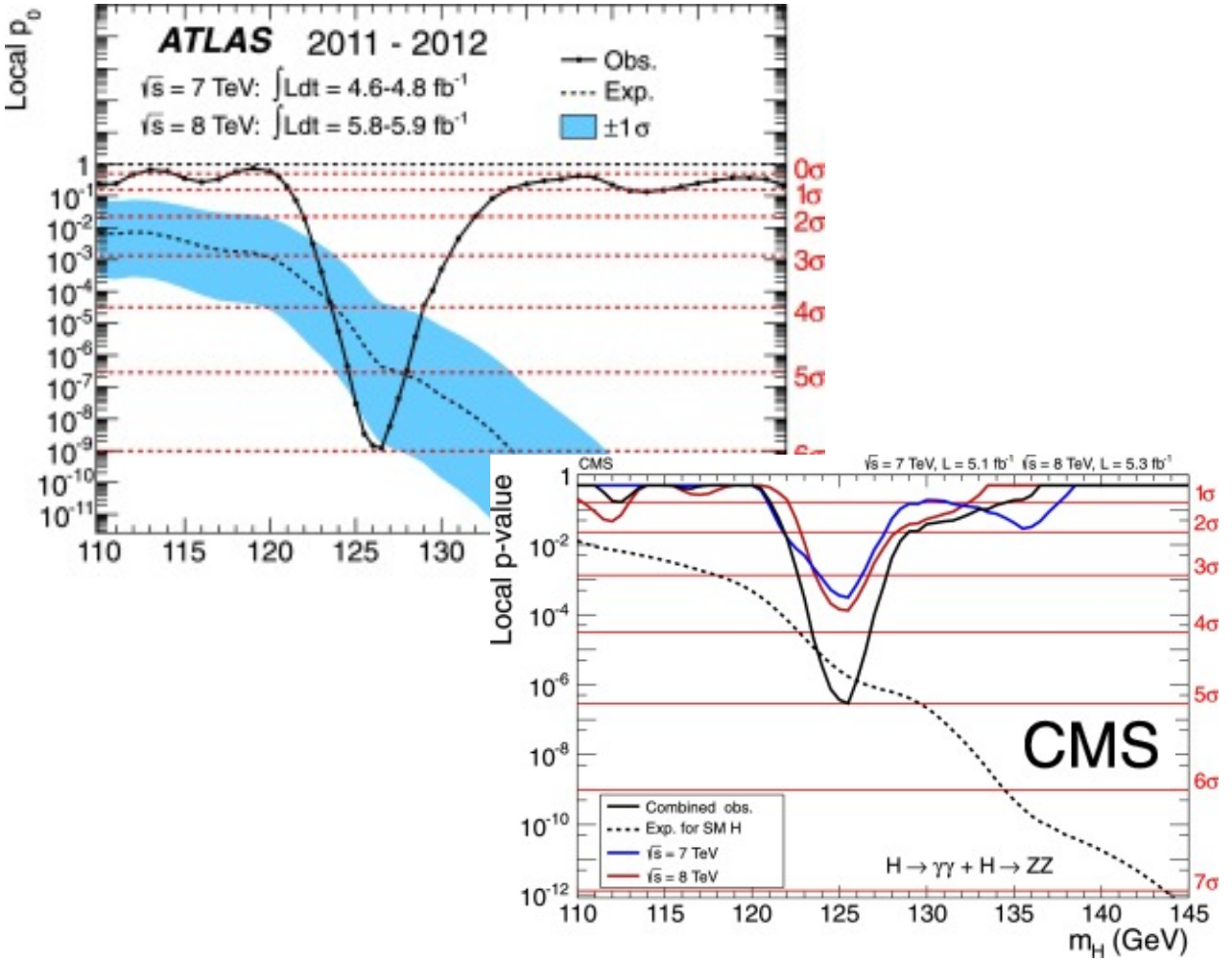


https://twiki.cern.ch/twiki/pub/AtlasPublic/HiggsPublicResults//WW-FixedScale.gif

Combinando resultados

Probabilidade de fluctuação do fundo:

0,000000001

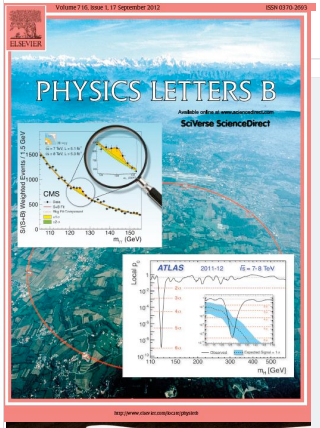


Nova partícula

Encontramos uma nova partícula!!!

mas... será o bosão de Higgs???

Huge mediatic event



And now… What?

The last missing piece of the SM?

SM Higgs Lagrangian after symmetry breaking

$$\mathscr{L}_{SM} = D_\mu H^\dagger D_\mu H - (y_{ij} H \bar{\psi}_i \psi_j + h.c.) + \mu^2 H^\dagger H - \frac{\lambda}{2}(H^\dagger H)^2$$

Bosons

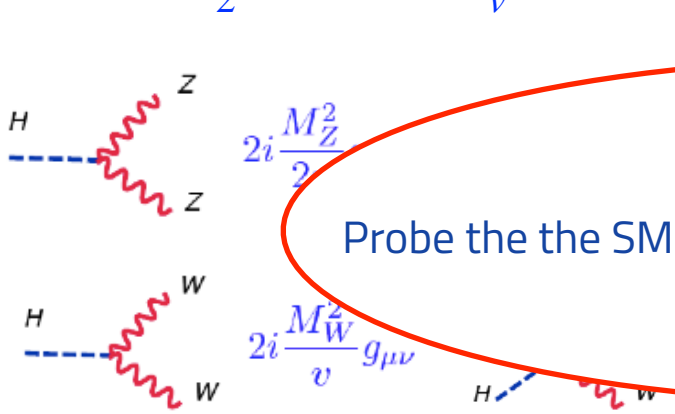
$$(m_W^2 W^{\mu+} W_\mu^- + \frac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0)(1 + \frac{h}{v})^2$$

Fermions

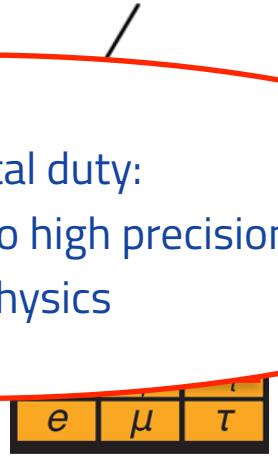
$$-\sum_f m_f \bar{f} f (1 + \frac{h}{v})$$

Higgs potential

$$\frac{1}{2} m_h^2 h^2 + \lambda_3 v h^3 + \frac{1}{4} \lambda_4 h^4$$

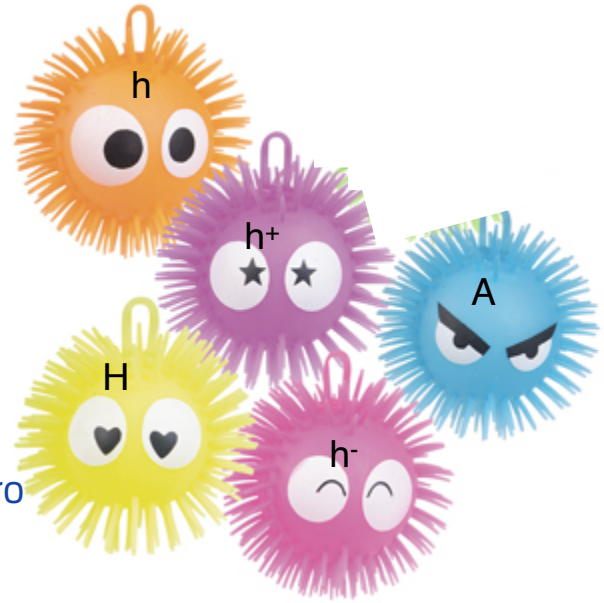


Experimental duty:
Probe the the SM Lagrangian to high precision and search for new physics



Que outra coisa pode ser?

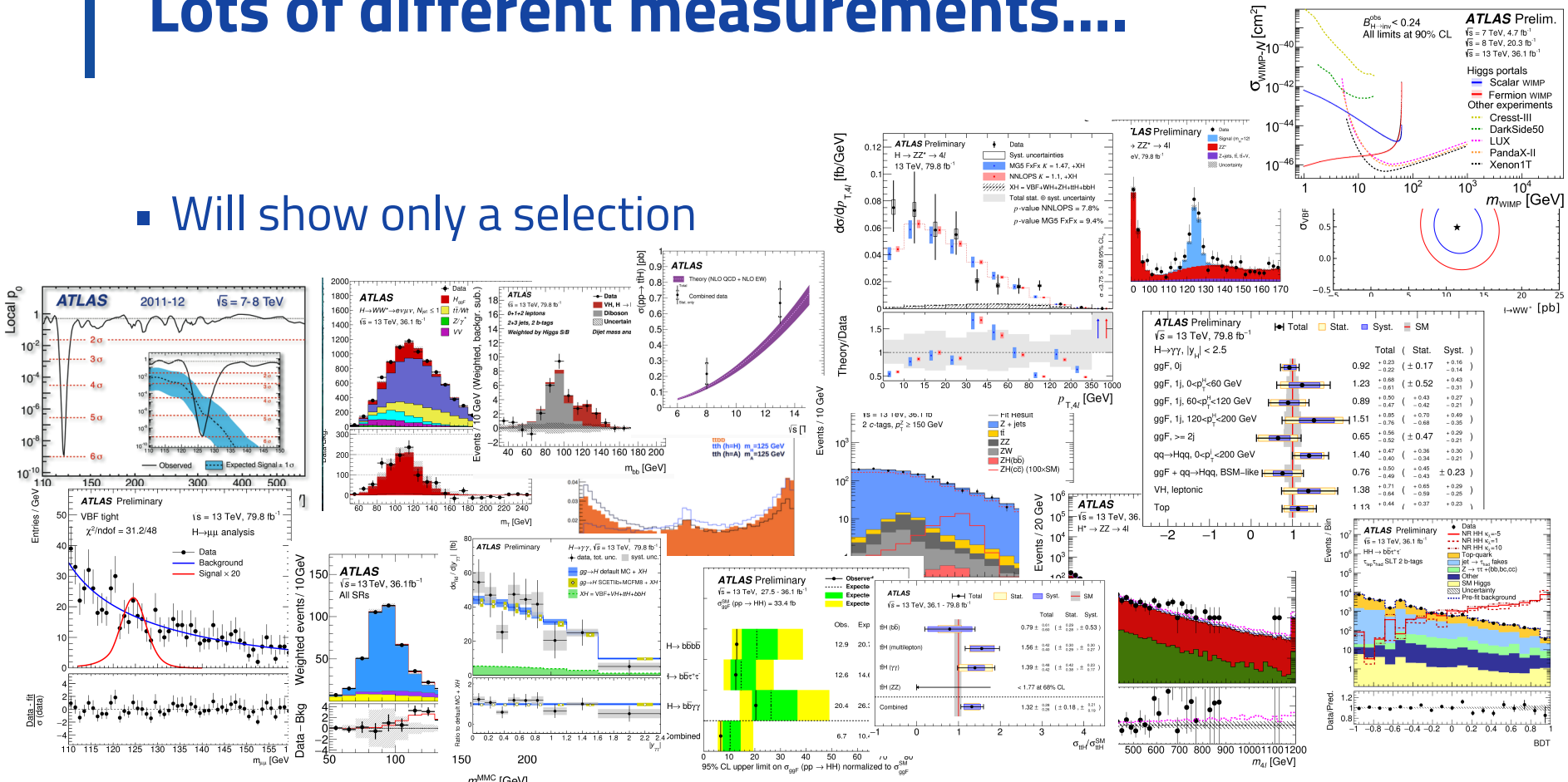
- Ter um bosão de Higgs é a opção mais simples no Modelo Padrão
- Podería haver 5 Higgses!
  - A partícula descoberta agora podería ser o Higgs mais ligeiro
- Super-Symmetry (SUSY)
  - Também há 5 bosões de Higgs
- Tecnicolor
  - O bosão de Higgs seria um estado ligado de tecniquarks
- ...



Previsões menos precisas que no caso do Higgs do SM

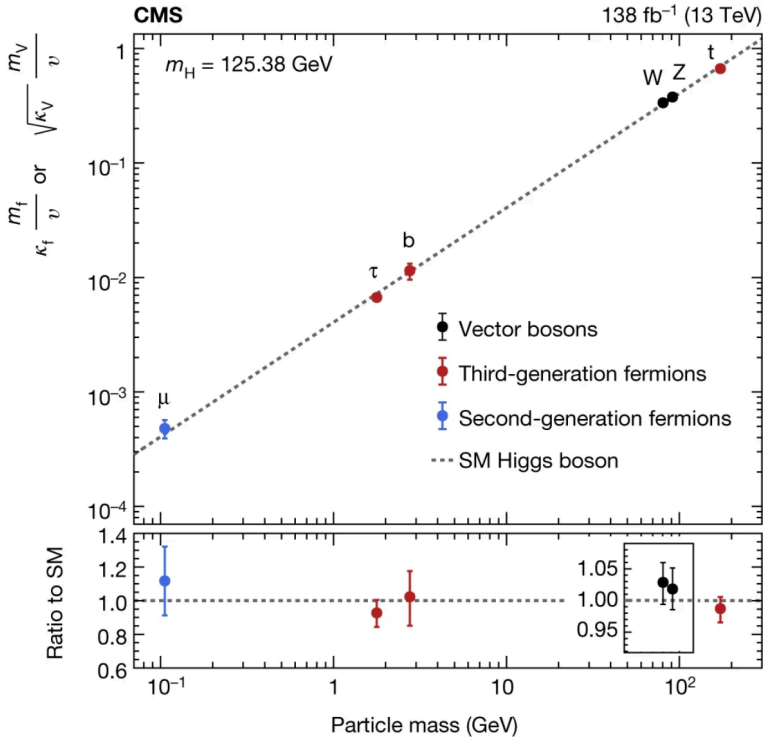
Lots of different measurements....

- Will show only a selection



10 years of Higgs boson measurements

- Measured its interactions with W, Z, t, b, τ, μ
- Differential distributions
- Spin/CP properties
- Searching for rare decays, exotic decays, CP-violation in the Higgs sector, …

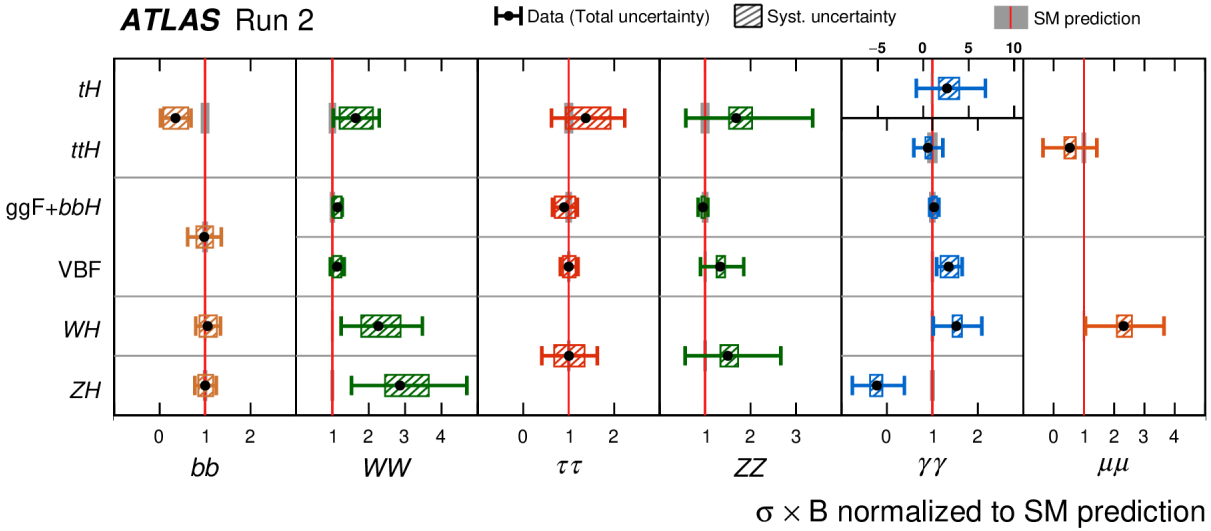


Higgs boson couplings to bosons & fermions

- Direct measurement of $\sigma \times BR$

Precision ATLAS & CMS

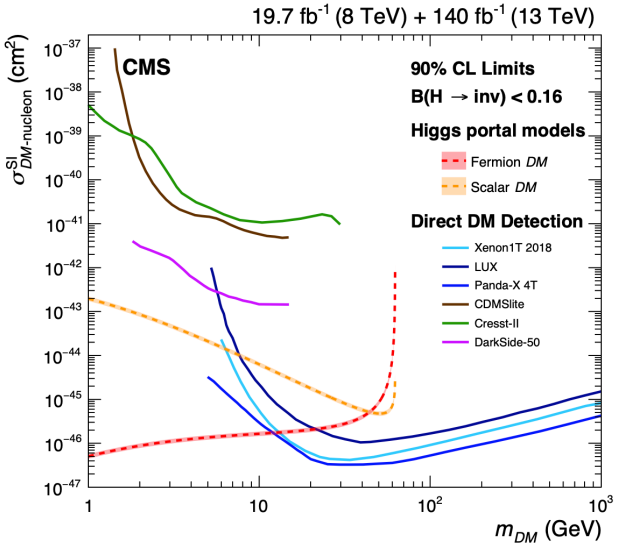
- ggF: better than 10%
- Other production modes: 10-20%



- ATLAS p-value: 72%
- Similar results for CMS

New particles? What about dark matter?

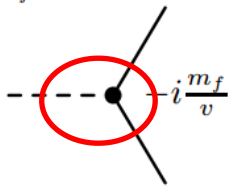
- Couplings to new particles?
  - Search for invisible Higgs decays
    - Nothing observed yet…
    - $BR(H \rightarrow invis) < 0.18$



$_jH\bar{\psi}_i\psi_j + \text{h.c.})$

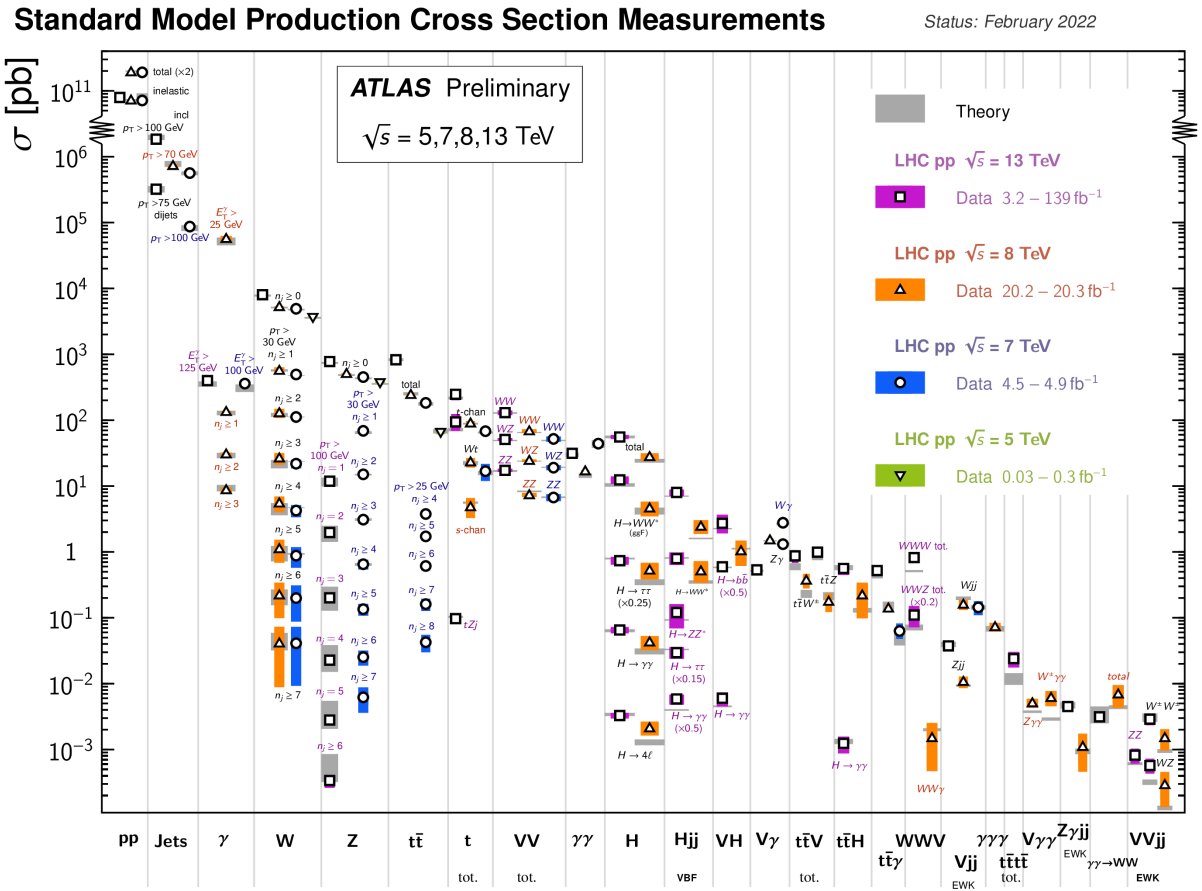
Couplings to fermions

$$-\sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right)$$

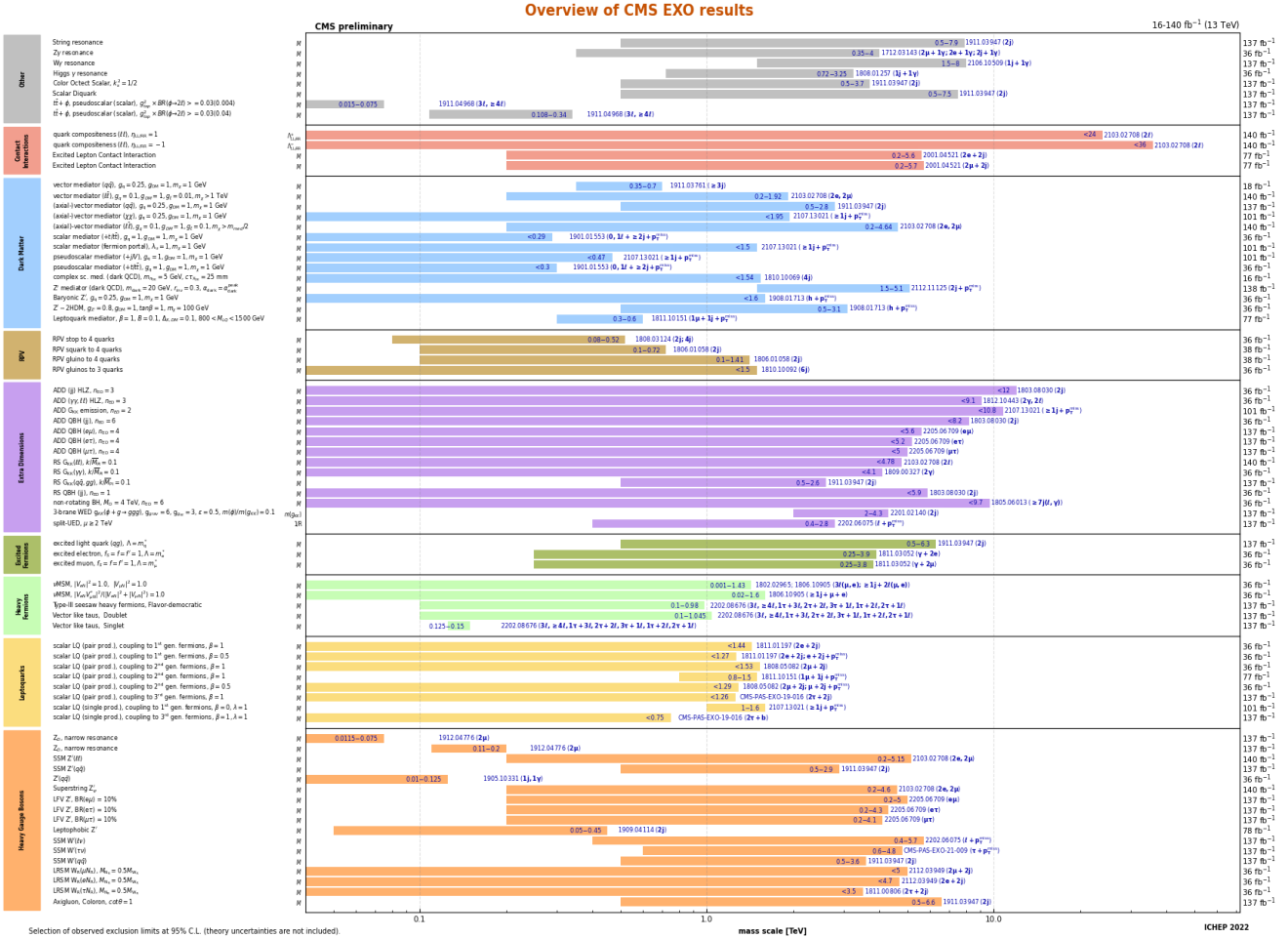


Standard Model Measurements

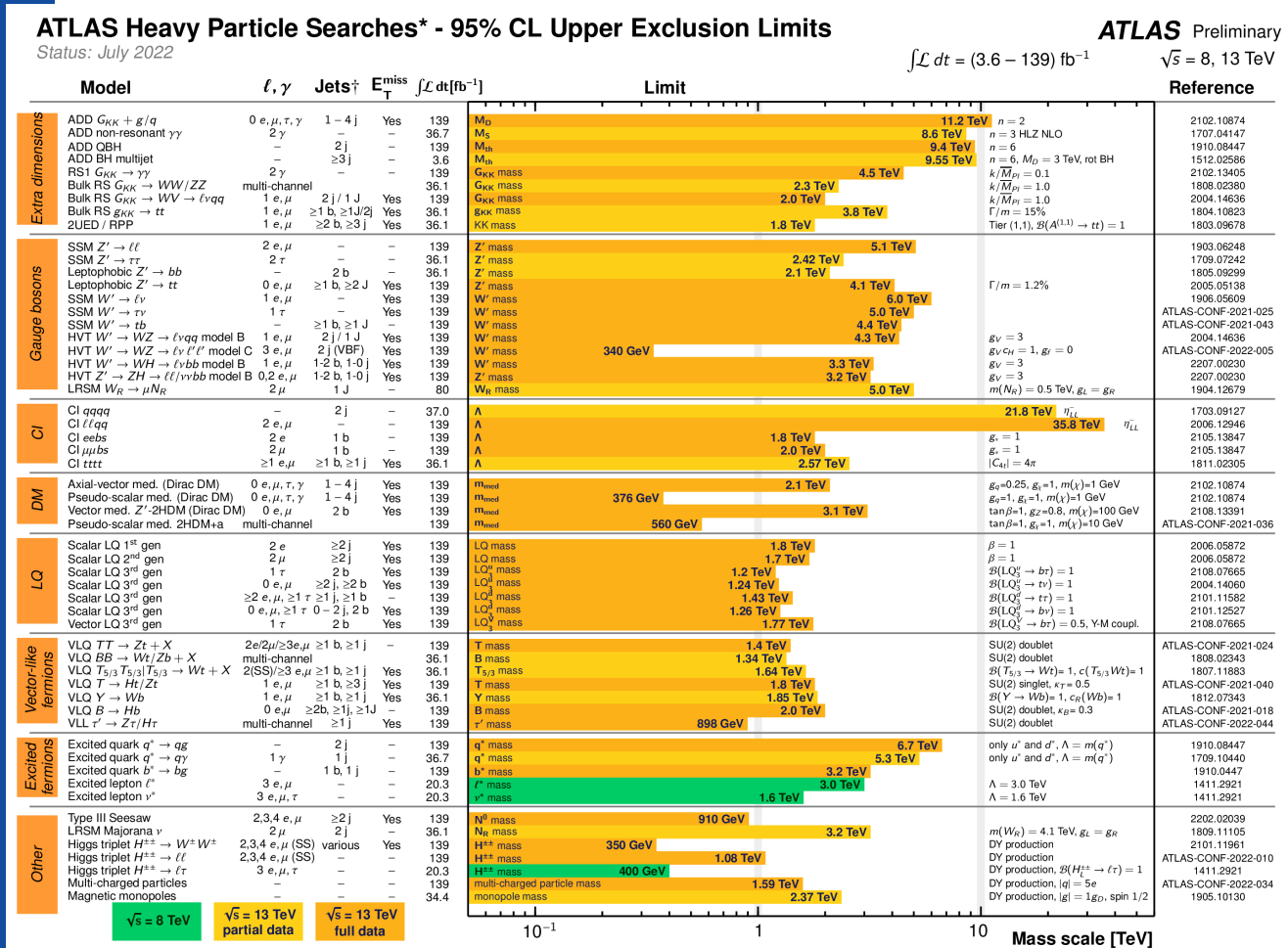
Measured a long list of Standard Model processes!!



Excluded the existence of many new exotic particles at the LHC



And more...

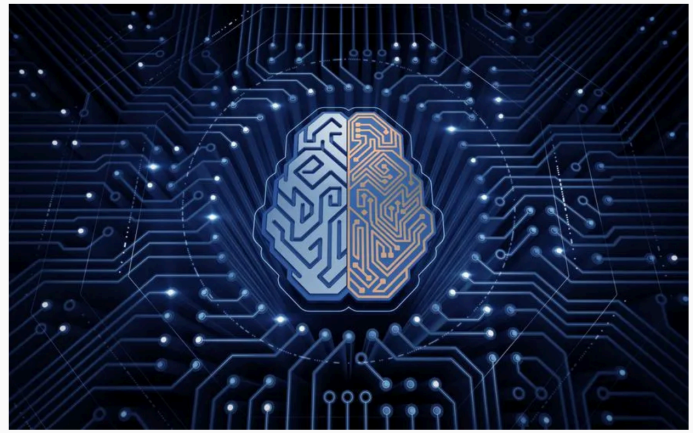

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits
Status: July 2022
ATLAS Preliminary
$\int \mathcal{L}\, dt$ = (3.6 – 139) fb^{-1}
$\sqrt{s}$ = 8, 13 TeV
Model
ℓ, γ
Jets†
E_T^{miss}
$\int \mathcal{L}\, dt$[fb^{-1}]
Limit
Reference
Extra dimensions
ADD $G_{KK} + g/q$ 0 e, μ, τ, γ 1 – 4 j Yes 139 M_D 11.2 TeV $n = 2$ 2102.10874
ADD non-resonant $\gamma\gamma$ 2 γ – – 36.7 M_S 8.6 TeV $n = 3$ HLZ NLO 1707.04147
ADD QBH – 2 j – 139 M_{th} 9.4 TeV $n = 6$ 1910.08447
ADD BH multijet – ≥3 j – 3.6 M_{th} 9.55 TeV $n = 6$, $M_D = 3$ TeV, rot BH 1512.02586
RS1 $G_{KK} \to \gamma\gamma$ 2 γ – – 139 G_{KK} mass 4.5 TeV $k/\overline{M}_{Pl} = 0.1$ 2102.13405
Bulk RS $G_{KK} \to WW/ZZ$ multi-channel 36.1 G_{KK} mass 2.3 TeV $k/\overline{M}_{Pl} = 1.0$ 1808.02380
Bulk RS $G_{KK} \to WV \to \ell\nu qq$ 1 e, μ 2 j / 1 J Yes 139 G_{KK} mass 2.0 TeV $k/\overline{M}_{Pl} = 1.0$ 2004.14636
Bulk RS $g_{KK} \to tt$ 1 e, μ ≥1 b, ≥1J/2j Yes 36.1 g_{KK} mass 3.8 TeV $\Gamma/m = 15\%$ 1804.10823
2UED / RPP 1 e, μ ≥2 b, ≥3 j Yes 36.1 KK mass 1.8 TeV Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$ 1803.09678
Gauge bosons
SSM $Z' \to \ell\ell$ 2 e, μ – – 139 Z' mass 5.1 TeV 1903.06248
SSM $Z' \to \tau\tau$ 2 τ – – 36.1 Z' mass 2.42 TeV 1709.07242
Leptophobic $Z' \to bb$ – 2 b – 36.1 Z' mass 2.1 TeV 1805.09299
Leptophobic $Z' \to tt$ 0 e, μ ≥1 b, ≥2 J Yes 139 Z' mass 4.1 TeV $\Gamma/m = 1.2\%$ 2005.05138
SSM $W' \to \ell\nu$ 1 e, μ – Yes 139 W' mass 6.0 TeV 1906.05609
SSM $W' \to \tau\nu$ 1 τ – Yes 139 W' mass 5.0 TeV ATLAS-CONF-2021-025
SSM $W' \to tb$ – ≥1 b, ≥1 J – 139 W' mass 4.4 TeV ATLAS-CONF-2021-043
HVT $W' \to WZ \to \ell\nu qq$ model B 1 e, μ 2 j / 1 J Yes 139 W' mass 4.3 TeV $g_V = 3$ 2004.14636
HVT $W' \to WZ \to \ell\nu\ell'\ell'$ model C 3 e, μ 2 j (VBF) Yes 139 W' mass 340 GeV $g_V c_H = 1$, $g_f = 0$ ATLAS-CONF-2022-005
HVT $W' \to WH \to \ell\nu bb$ model B 1 e, μ 1-2 b, 1-0 j Yes 139 W' mass 3.3 TeV $g_V = 3$ 2207.00230
HVT $Z' \to ZH \to \ell\ell/\nu\nu bb$ model B 0,2 e, μ 1-2 b, 1-0 j Yes 139 Z' mass 3.2 TeV $g_V = 3$ 2207.00230
LRSM $W_R \to \mu N_R$ 2 μ 1 J – 80 W_R mass 5.0 TeV $m(N_R) = 0.5$ TeV, $g_L = g_R$ 1904.12679
CI
CI $qqqq$ – 2 j – 37.0 Λ 21.8 TeV η_{LL}^- 1703.09127
CI $\ell\ell qq$ 2 e, μ – – 139 Λ 35.8 TeV η_{LL}^- 2006.12946
CI $eebs$ 2 e 1 b – 139 Λ 1.8 TeV $g_* = 1$ 2105.13847
CI $\mu\mu bs$ 2 μ 1 b – 139 Λ 2.0 TeV $g_* = 1$ 2105.13847
CI $tttt$ ≥1 e,μ ≥1 b, ≥1 j Yes 36.1 Λ 2.57 TeV $|C_{4t}| = 4\pi$ 1811.02305
DM
Axial-vector med. (Dirac DM) 0 e, μ, τ, γ 1 – 4 j Yes 139 m_{med} 2.1 TeV g_q=0.25, g_χ=1, $m(\chi)$=1 GeV 2102.10874
Pseudo-scalar med. (Dirac DM) 0 e, μ, τ, γ 1 – 4 j Yes 139 m_{med} 376 GeV g_q=1, g_χ=1, $m(\chi)$=1 GeV 2102.10874
Vector med. Z'-2HDM (Dirac DM) 0 e, μ 2 b Yes 139 m_{med} 3.1 TeV $\tan\beta$=1, g_Z=0.8, $m(\chi)$=100 GeV 2108.13391
Pseudo-scalar med. 2HDM+a multi-channel 139 m_{med} 560 GeV $\tan\beta$=1, g_χ=1, $m(\chi)$=10 GeV ATLAS-CONF-2021-036
LQ
Scalar LQ 1st gen 2 e ≥2 j Yes 139 LQ mass 1.8 TeV $\beta = 1$ 2006.05872
Scalar LQ 2nd gen 2 μ ≥2 j Yes 139 LQ mass 1.7 TeV $\beta = 1$ 2006.05872
Scalar LQ 3rd gen 1 τ 2 b Yes 139 LQ_3^u mass 1.2 TeV $\mathcal{B}(LQ_3^u \to b\tau) = 1$ 2108.07665
Scalar LQ 3rd gen 0 e, μ ≥2 j, ≥2 b Yes 139 LQ_3^u mass 1.24 TeV $\mathcal{B}(LQ_3^u \to t\nu) = 1$ 2004.14060
Scalar LQ 3rd gen ≥2 e, μ, ≥1 τ ≥1 j, ≥1 b – 139 LQ_3^d mass 1.43 TeV $\mathcal{B}(LQ_3^d \to t\tau) = 1$ 2101.11582
Scalar LQ 3rd gen 0 e, μ, ≥1 τ 0 – 2 j, 2 b Yes 139 LQ_3^d mass 1.26 TeV $\mathcal{B}(LQ_3^d \to b\nu) = 1$ 2101.12527
Vector LQ 3rd gen 1 τ 2 b Yes 139 LQ_3^d mass 1.77 TeV $\mathcal{B}(LQ_3^d \to b\tau) = 0.5$, Y-M coupl. 2108.07665
Vector-like fermions
VLQ $TT \to Zt + X$ 2e/2μ/≥3e,μ ≥1 b, ≥1 j – 139 T mass 1.4 TeV SU(2) doublet ATLAS-CONF-2021-024
VLQ $BB \to Wt/Zb + X$ multi-channel 36.1 B mass 1.34 TeV SU(2) doublet 1808.02343
VLQ $T_{5/3}T_{5/3}|T_{5/3} \to Wt + X$ 2(SS)/≥3 e,μ ≥1 b, ≥1 j Yes 36.1 $T_{5/3}$ mass 1.64 TeV $\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1 1807.11883
VLQ $T \to Ht/Zt$ 1 e, μ ≥1 b, ≥3 j Yes 139 T mass 1.8 TeV SU(2) singlet, κ_T= 0.5 ATLAS-CONF-2021-040
VLQ $Y \to Wb$ 1 e, μ ≥1 b, ≥1 j Yes 36.1 Y mass 1.85 TeV $\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1 1812.07343
VLQ $B \to Hb$ 0 e,μ ≥2b, ≥1j, ≥1J – 139 B mass 2.0 TeV SU(2) doublet, κ_B= 0.5 ATLAS-CONF-2021-018
VLL $\tau' \to Z\tau/H\tau$ multi-channel ≥1 j Yes 139 τ' mass 898 GeV SU(2) doublet ATLAS-CONF-2022-044
Excited fermions
Excited quark $q^* \to qg$ – 2 j – 139 q^* mass 6.7 TeV only u^* and d^*, $\Lambda = m(q^*)$ 1910.08447
Excited quark $q^* \to q\gamma$ 1 γ 1 j – 36.7 q^* mass 5.3 TeV only u^* and d^*, $\Lambda = m(q^*)$ 1709.10440
Excited quark $b^* \to bg$ – 1 b, 1 j – 139 b^* mass 3.2 TeV 1910.0447
Excited lepton ℓ^* 3 e, μ – – 20.3 ℓ^* mass 3.0 TeV Λ = 3.0 TeV 1411.2921
Excited lepton ν^* 3 e, μ, τ – – 20.3 ν^* mass 1.6 TeV Λ = 1.6 TeV 1411.2921
Other
Type III Seesaw 2,3,4 e, μ ≥2 j Yes 139 N_1^0 mass 910 GeV 2202.02039
LRSM Majorana ν 2 μ 2 j – 36.1 N_R mass 3.2 TeV $m(W_R) = 4.1$ TeV, $g_L = g_R$ 1809.11105
Higgs triplet $H^{\pm\pm} \to W^\pm W^\pm$ 2,3,4 e, μ (SS) various Yes 139 $H^{\pm\pm}$ mass 350 GeV DY production 2101.11961
Higgs triplet $H^{\pm\pm} \to \ell\ell$ 2,3,4 e, μ (SS) – – 139 $H^{\pm\pm}$ mass 1.08 TeV DY production ATLAS-CONF-2022-010
Higgs triplet $H^{\pm\pm} \to \ell\tau$ 3 e, μ, τ – – 20.3 $H^{\pm\pm}$ mass 400 GeV DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$ 1411.2921
Multi-charged particles – – – 139 multi-charged particle mass 1.59 TeV DY production, $|q| = 5e$ ATLAS-CONF-2022-034
Magnetic monopoles – – – 34.4 monopole mass 2.37 TeV DY production, $|g| = 1g_D$, spin 1/2 1905.10130
$\sqrt{s}$ = 8 TeV
$\sqrt{s}$ = 13 TeV partial data
$\sqrt{s}$ = 13 TeV full data
10^{-1}
1
10
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter j (J).

Many unanswered questions remain…

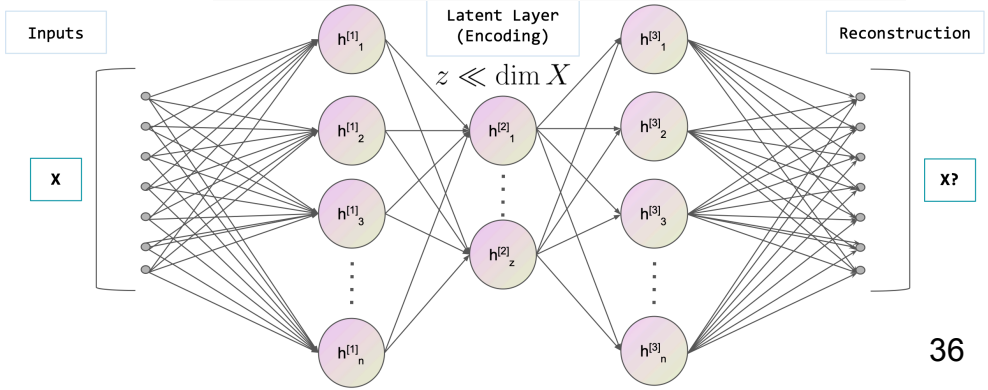
- Why is there a matter-antimatter asymmetry in the Universe?
- What are dark matter and dark energy?
- Why is gravity so weak?
- Why is the Higgs boson so light (naturalness/hierarchy problem)?
- How precise is the SM?
- Why three fermion families?
- Why do neutral leptons, charged leptons and quarks behave differently?
- What is the origin of neutrino masses and oscillations?
- Are there other fundamental particles?
- …

Searching for the unknown…

- Train deep learning models to learn SM background and provide an anomaly score for New Physics
  - Increases search generality
- Reconstruction error is a measurement of anomaly

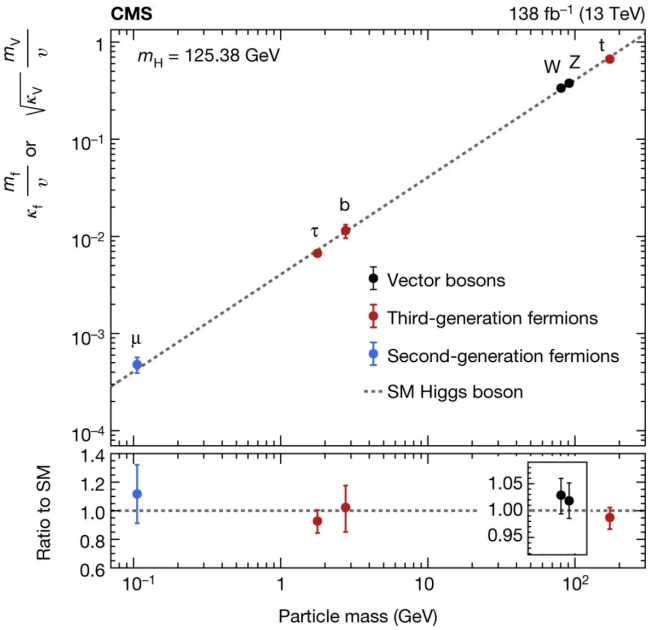


Artificial Intelligence FOTOLIA - SERGEY TARASOV



Conclusions

- The Higgs boson provides an optimal ground to probe the SM predictions and search for new physics!
- Outstanding performance of the LHC and the CMS and ATLAS detectors
  - Large increase in the available pp collisions
- A wealth of new results on SM Higgs boson studies
  - Main decay and production modes now observed in each experiment!!
- All results are compatible with SM predictions
- Searches for new physics and additional Higgs bosons continue
  - Much more data to come!



Thanks!

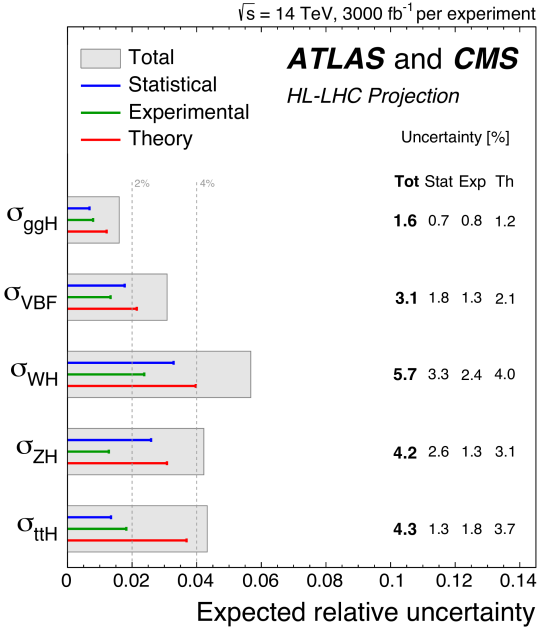
Acknowledgments

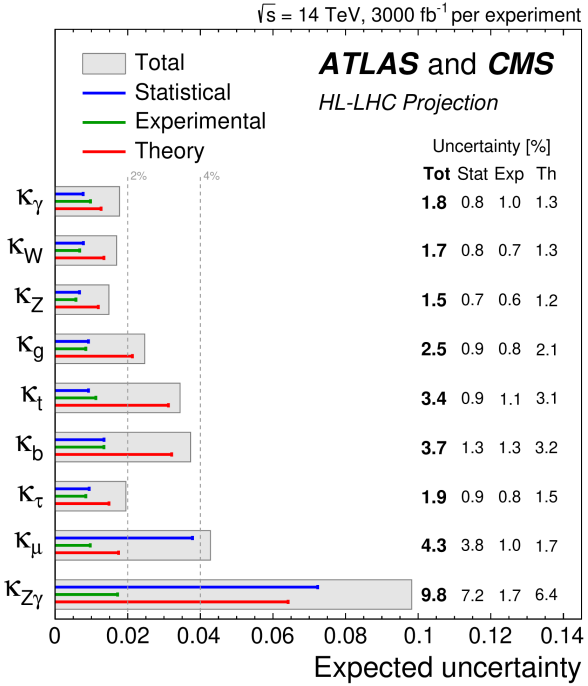
REPÚBLICA PORTUGUESA

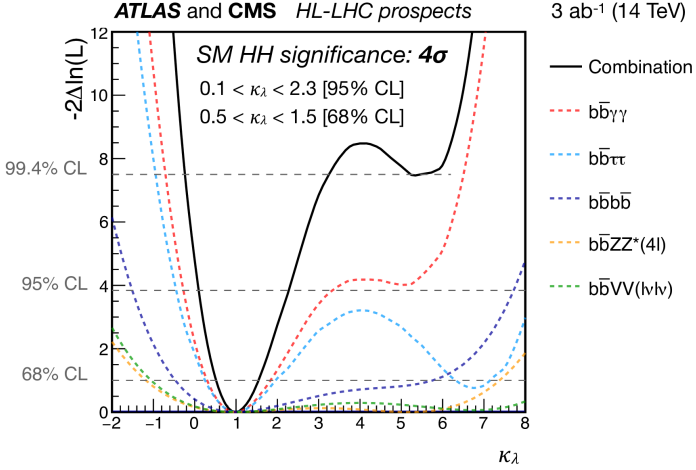
FCT Fundação para a Ciência e a Tecnologia

Backup

High Luminosity LHC expectations

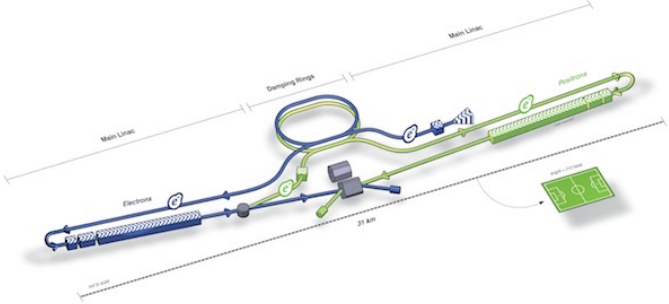




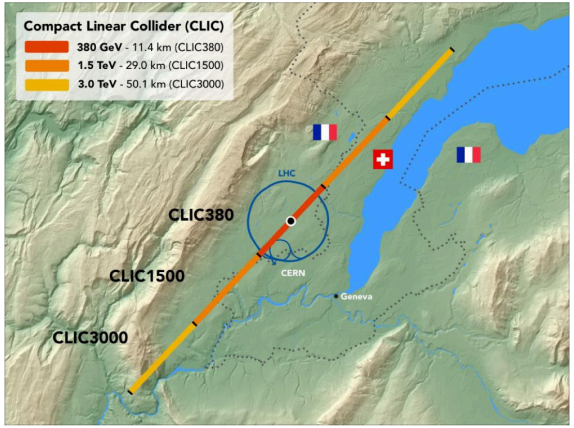


e^+e^- colliders

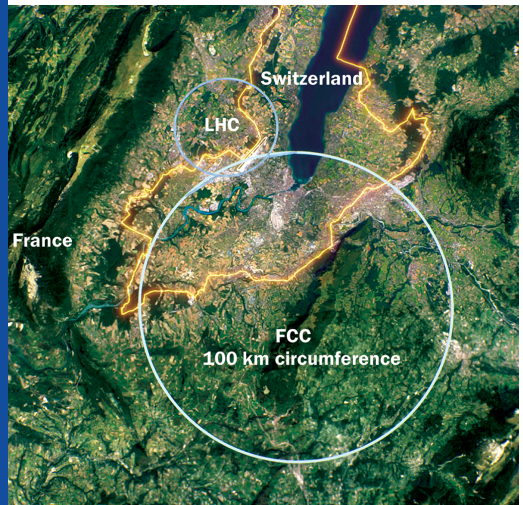
International Linear Collider



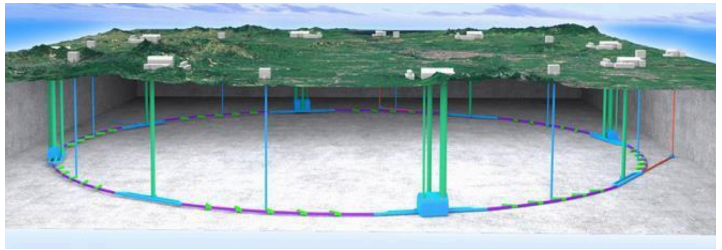
Compact Linear Collider



Future Circular Collider

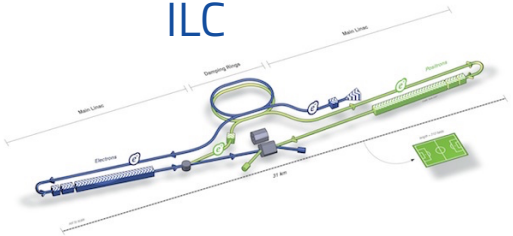


Circular Electron Positron Collider

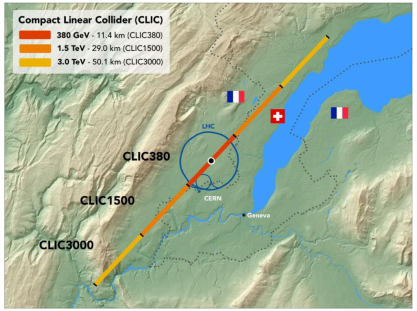


e^+e^- colliders — operation goals

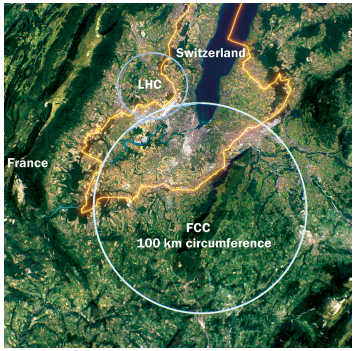
ILC



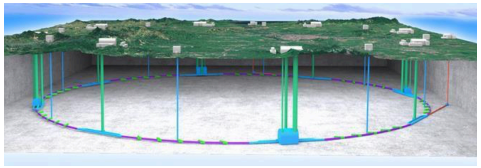
CLIC



FCC



CEPC



ILC, Japan

250 GeV, 11 y → 2 ab^{-1}
500 GeV, 8.5 y 4 ab^{-1}
1000 GeV, 8.5 y 8 ab^{-1}

CLIC, CERN

380 GeV, 8 y → 1 ab^{-1}
1500 GeV, 7 y 2.5 ab^{-1}
3000 GeV, 8.5 y 5 ab^{-1}

FCC-ee, CERN

m_Z, 4 y → 150 ab^{-1}
2 x m_W, 1-2 y → 10 ab^{-1}
240 GeV, 3 y → 5 ab^{-1}
2 x m_{top}, 5y → 1.5 ab^{-1}

CEPC, China

m_Z, 2 y → 16 ab^{-1}
2 x m_W, 1 y → 2.6 ab^{-1}
240 GeV, 7 y → 5.6 ab^{-1}

Precision physics

- Complementarity ee/eh/hh colliders

kappa-0-HL	HL+FCC-ee$_{240}$	HL+FCC-ee	HL+FCC-ee (4 IP)	HL+FCC-ee/hh	HL+FCC-eh/hh	HL+FCC-hh	HL+FCC-ee/eh/hh
κ_W [%]	0.86	0.38	0.23	0.27	0.17	0.39	0.14
κ_Z [%]	0.15	0.14	0.094	0.13	0.27	0.63	0.12
κ_g [%]	1.1	0.88	0.59	0.55	0.56	0.74	0.46
κ_γ [%]	1.3	1.2	1.1	0.29	0.32	0.56	0.28
$\kappa_{Z\gamma}$ [%]	10.	10.	10.	0.7	0.71	0.89	0.68
κ_c [%]	1.5	1.3	0.88	1.2	1.2	–	0.94
κ_t [%]	3.1	3.1	3.1	0.95	0.95	0.99	0.95
κ_b [%]	0.94	0.59	0.44	0.5	0.52	0.99	0.41
κ_μ [%]	4.	3.9	3.3	0.41	0.45	0.68	0.41
κ_τ [%]	0.9	0.61	0.39	0.49	0.63	0.9	0.42
Γ_H [%]	1.6	0.87	0.55	0.67	0.61	1.3	0.44

only FCC-ee@240GeV

only FCC-hh

ALL COMBINED