Física de Partículas

El boson de Higgs y el Modelo Estándar

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Latin American alliance for
Capacity buildiNG in Advanced physics
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Cofinanciado por el
programa Erasmus+
de la Unión Europea

The Standard Model

- The main elements of the Standard Model of particle physics have been described
- There are 12 fundamental spin-half fermions (particles and anti-particles): Dirac equation
- The interactions between particles are described by the exchange of spin-1 gauge bosons : local gauge principle
- Underlying gauge symmetry of the Standard Model is $U(1)_Y \times SU(2)_L \times SU(3)_c$: EM and weak interactions described by the unified electroweak theory
- Local gauge invariant theories are Renormalisable (‘tHooft)
- The local gauge symmetry of the model would be broken adding the gauge boson masses
- The Higgs Mechanism : generates the masses of the gauge bosons preserving the local gauge invariance

Lagrangian densities

- The dynamics of a quantum field theory are expressed in terms of the Lagrangian density
- Free scalar fields:

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

which corresponds to the Klein-Gordon equation

- For a Dirac spinor:

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

where the spinor satisfies the Dirac equation

- For the EM interaction:

$$\mathcal{L}_{EM} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} \qquad F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$$

yields Maxwell's equations

Lagrangian densities

- The dynamics of a quantum field theory are expressed in terms of the Lagrangian density
- For QED then:

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

free fermion free photon

fermion-photon interaction

- The QCD Lagrangian would be obtained in the same way:

$$\mathcal{L} = -\tfrac{1}{4}\mathbf{G}^{\mu\nu}\cdot\mathbf{G}_{\mu\nu}$$

$$G_i^{\mu\nu} = \partial^{\mu}G_i^{\nu} - \partial^{\nu}G_i^{\mu} - g_S f_{ijk}G_j^{\mu}G_k^{\nu}$$

yielding the self-gluon interactions

Lagrangian densities

- The mass terms are not invariant under the local gauge symmetry:

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

- This works for QED and QCD, but the EW gauge bosons do have mass (and they are large!)
- The fermion mass term is also not gauge invariant

Spontaneous Symmetry Breaking

- Consider a scalar field with the potential:

$$V(\phi) = \tfrac{1}{2}\mu^2\phi^2 + \tfrac{1}{4}\lambda\phi^4$$

$$\begin{aligned}\mathcal{L} &= \tfrac{1}{2}(\partial_\mu\phi)(\partial^\mu\phi) - V(\phi)\\ &= \underset{\substack{\uparrow\\ \text{kinetic energy}}}{\tfrac{1}{2}(\partial_\mu\phi)(\partial^\mu\phi)} - \underset{\substack{\uparrow\\ \text{mass}}}{\tfrac{1}{2}\mu^2\phi^2} - \underset{\substack{\uparrow\\ \text{self-interaction}}}{\tfrac{1}{4}\lambda\phi^4}\end{aligned}$$

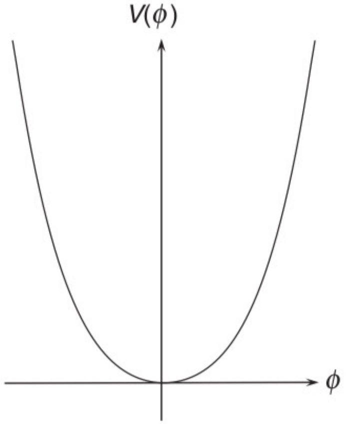
Spontaneous Symmetry Breaking

- Consider a scalar field with the potential:

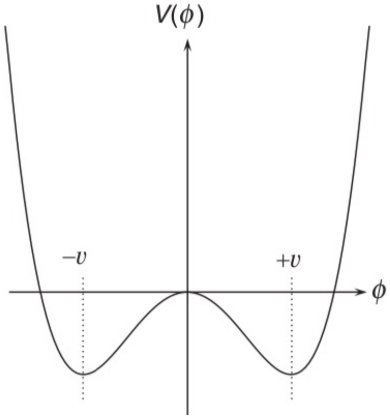
$$
\begin{aligned}
V(\phi) &= \tfrac{1}{2}\mu^2\phi^2 + \tfrac{1}{4}\lambda\phi^4 \\
\mathcal{L} &= \tfrac{1}{2}(\partial_\mu\phi)(\partial^\mu\phi) - V(\phi) \\
&= \tfrac{1}{2}(\partial_\mu\phi)(\partial^\mu\phi) - \tfrac{1}{2}\mu^2\phi^2 - \tfrac{1}{4}\lambda\phi^4
\end{aligned}
$$

- For the potential to have a minimum, $\lambda > 0$

$\mu^2 > 0$



$\mu^2 < 0$

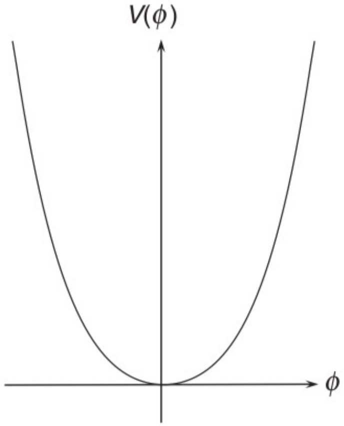


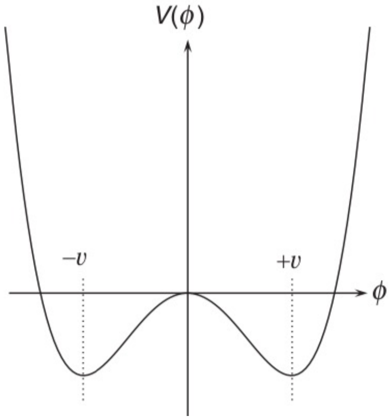
Spontaneous Symmetry Breaking

- Consider a scalar field:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - V(\phi)$$
$$= \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2}\mu^2\phi^2 - \frac{1}{4}\lambda\phi^4$$

- $\mu^2 > 0$ $\mu^2 < 0$





- In the later case, the potential has minima at:

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

Spontaneous Symmetry Breaking

- Consider a scalar field:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - V(\phi)$$
$$= \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2}\mu^2\phi^2 - \frac{1}{4}\lambda\phi^4$$

- $\mu^2 < 0$: the potential has minima at:

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

- The field has non-zero vacuum expectation value v
- Once one of these values is chosen, the symmetry of the Lagrangian is broken: spontaneous symmetry breaking
- This is actually common in nature: ferromagnetism

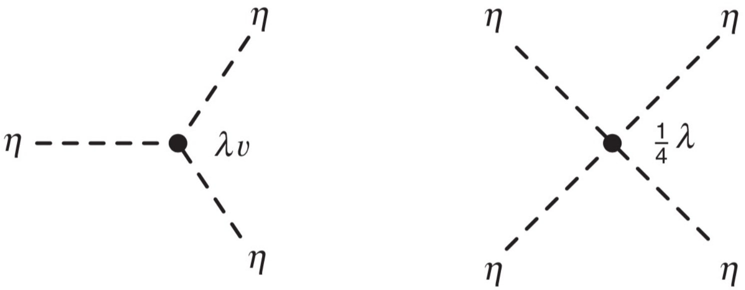
Spontaneous Symmetry Breaking

- If the vacuum state is chosen as +v, the excitations of the field can be obtained considering perturbations around this vacuum state:

$$\phi(x) = v + \eta(x)$$

$$\begin{aligned}\mathcal{L}(\eta) &= \tfrac{1}{2}(\partial_\mu\eta)(\partial^\mu\eta) - V(\eta)\\ &= \tfrac{1}{2}(\partial_\mu\eta)(\partial^\mu\eta) - \tfrac{1}{2}\mu^2(v+\eta)^2 - \tfrac{1}{4}\lambda(v+\eta)^4\end{aligned}$$

$$\mathcal{L}(\eta) = \tfrac{1}{2}(\partial_\mu\eta)(\partial^\mu\eta) - \underset{\underset{\text{mass term}}{\uparrow}}{\lambda v^2\eta^2} - \underbrace{\lambda v\eta^3 - \tfrac{1}{4}\lambda\eta^4}_{\text{self-interaction}} + \tfrac{1}{4}\lambda v^4$$



$$m_\eta = \sqrt{2\lambda v^2} = \sqrt{-2\mu^2}$$

Spontaneous Symmetry Breaking

- So the Lagrangian for the scalar field can be written as:

$$\mathcal{L}(\eta) = \frac{1}{2}(\partial_\mu \eta)(\partial^\mu \eta) - \frac{1}{2}m_\eta^2 \eta^2 - V(\eta), \qquad V(\eta) = \lambda v \eta^3 + \frac{1}{4}\lambda \eta^4$$

- It is the same original Lagrangian but expressed as excitations about the minimum at +v

Spontaneous Symmetry Breaking

- For a complex scalar field:

$$\phi = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2)$$

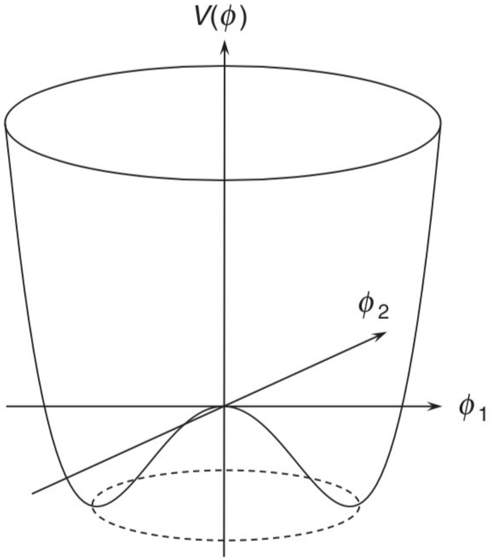
$$\mathcal{L} = \frac{1}{2}(\partial_\mu\phi_1)(\partial^\mu\phi_1) + \frac{1}{2}(\partial_\mu\phi_2)(\partial^\mu\phi_2) - \frac{1}{2}\mu^2(\phi_1^2 + \phi_2^2) - \frac{1}{4}\lambda(\phi_1^2 + \phi_2^2)^2$$

- And again for $\mu^2 < 0$, the potential has infinite minima at:

$$\phi_1^2 + \phi_2^2 = \frac{-\mu^2}{\lambda} = v^2$$

- Choosing one minimum and expanding the field around it:

$$\phi = \frac{1}{\sqrt{2}}(\eta + v + i\xi)$$



Spontaneous Symmetry Breaking

- Choosing one minimum and expanding the field around it:

$$\phi = \frac{1}{\sqrt{2}}(\eta + v + i\xi)$$

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \eta)(\partial^\mu \eta) - \frac{1}{2}m_\eta^2\eta^2 + \frac{1}{2}(\partial_\mu \xi)(\partial^\mu \xi) - V_{int}(\eta, \xi)$$

$$V_{int}(\eta, \xi) = \lambda v \eta^3 + \frac{1}{4}\lambda\eta^4 + \frac{1}{4}\lambda\xi^4 + \lambda v \eta \xi^2 + \frac{1}{2}\lambda\eta^2\xi^2$$

- This is the Lagrangian of a massive field η and a massless field ξ: Goldstone boson

The Higgs Mechanism

- It is the combination of spontaneous symmetry breaking of a complex scalar field and a local gauge symmetry

The Higgs Mechanism

- It is the combination of spontaneous symmetry breaking of a complex scalar field and a local gauge symmetry
- For example, take a U(1) local gauge symmetry

$$\phi(x) \rightarrow \phi'(x) = e^{ig\chi(x)}\phi(x)$$

- The Lagrangian for the scalar field is not invariant under this transformation
- Introduce the covariant derivative :

$$\partial_\mu \rightarrow D_\mu = \partial_\mu + igB_\mu$$

- The Lagrangian is now invariant under the U(1) local symmetry provided that

$$B_\mu \rightarrow B'_\mu = B_\mu - \partial_\mu\chi(x)$$

The Higgs Mechanism

- Introduce the covariant derivative :

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- The Lagrangian is now invariant under the U(1) local symmetry provided that

$$B_\mu \to B'_\mu = B_\mu - \partial_\mu \chi(x)$$

- In the same way we saw before, local gauge invariance implies the existence of a gauge field
- The combined Lagrangian:

$$\mathcal{L} = -\tfrac{1}{4}F^{\mu\nu}F_{\mu\nu} + (D_\mu\phi)^*(D^\mu\phi) - \mu^2\phi^2 - \lambda\phi^4$$

The Higgs Mechanism

- The combined Lagrangian:

$$\mathcal{L} = -\tfrac{1}{4}F^{\mu\nu}F_{\mu\nu} + (D_\mu\phi)^*(D^\mu\phi) - \mu^2\phi^2 - \lambda\phi^4$$

- The covariant derivative term:

$$\begin{aligned}(D_\mu\phi)^*(D^\mu\phi) &= (\partial_\mu - igB_\mu)\phi^*(\partial^\mu + igB^\mu)\phi \\ &= (\partial_\mu\phi)^*(\partial^\mu\phi) - igB_\mu\phi^*(\partial^\mu\phi) + ig(\partial_\mu\phi^*)B^\mu\phi + g^2B_\mu B^\mu\phi^*\phi\end{aligned}$$

- And the Lagrangian:

$$\begin{aligned}\mathcal{L} = &-\tfrac{1}{4}F^{\mu\nu}F_{\mu\nu} + (\partial_\mu\phi)^*(\partial^\mu\phi) - \mu^2\phi^2 - \lambda\phi^4 \\ &- igB_\mu\phi^*(\partial^\mu\phi) + ig(\partial_\mu\phi^*)B^\mu\phi + g^2B_\mu B^\mu\phi^*\phi\end{aligned}$$

The Higgs Mechanism

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$$- igB_\mu\phi^*(\partial^\mu\phi) + ig(\partial_\mu\phi^*)B^\mu\phi + g^2B_\mu B^\mu\phi^*\phi$$

- Expanding the scalar field around the vacuum state:

$$\phi(x) = \frac{1}{\sqrt{2}}(v + \eta(x) + i\xi(x))$$

- We get the Lagrangian

$$\mathcal{L} = \underbrace{\tfrac{1}{2}(\partial_\mu\eta)(\partial^\mu\eta) - \lambda v^2\eta^2}_{\text{massive } \eta} + \underbrace{\tfrac{1}{2}(\partial_\mu\xi)(\partial^\mu\xi)}_{\text{massless } \xi} - \underbrace{\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + \tfrac{1}{2}g^2v^2B_\mu B^\mu}_{\text{massive gauge field}} - V_{int} + gvB_\mu(\partial^\mu\xi)$$

The Higgs Mechanism

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- Expanding the scalar field around the vacuum state:

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- And we can eliminate the Goldstone boson with a gauge transformation:

$$B_\mu(x) \to B'_\mu(x) = B_\mu(x) + \frac{1}{gv}\partial_\mu \xi(x)$$

$$\mathcal{L} = \underbrace{\tfrac{1}{2}(\partial^\mu \eta)(\partial_\mu \eta) - \lambda v^2 \eta^2}_{\text{massive } \eta} + - \underbrace{\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + \tfrac{1}{2}g^2 v^2 B^{\mu\prime} B'_\mu}_{\text{massive gauge field}} - V_{int}$$

- This is called the unitary gauge
- In the unitary gauge, the fields correspond to the physical particles

The Higgs Mechanism

- In the unitary gauge, the fields correspond to the physical particles

$$\mathcal{L} = \underbrace{\tfrac{1}{2}(\partial^{\mu}\eta)(\partial_{\mu}\eta) - \lambda v^2\eta^2}_{\text{massive } \eta} + - \underbrace{\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + \tfrac{1}{2}g^2v^2B^{\mu\prime}B'_{\mu}}_{\text{massive gauge field}} - V_{int}$$

- Also, the scalar field is entirely real:

$$\phi(x) = \frac{1}{\sqrt{2}}(v + \eta(x)) \equiv \frac{1}{\sqrt{2}}(v + h(x))$$

$$\begin{aligned} \mathcal{L} = & \underbrace{\tfrac{1}{2}(\partial_{\mu}h)(\partial^{\mu}h) - \lambda v^2h^2}_{\text{massive } h \ \textit{scalar}} - \underbrace{\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + \tfrac{1}{2}g^2v^2B_{\mu}B^{\mu}}_{\text{massive gauge boson}} \\ & + \underbrace{g^2vB_{\mu}B^{\mu}h + \tfrac{1}{2}g^2B_{\mu}B^{\mu}h^2}_{h,B \text{ interactions}} - \underbrace{\lambda vh^3 - \tfrac{1}{4}\lambda h^4}_{h \text{ self-interactions}} . \end{aligned}$$

The Higgs Mechanism

- ***The Higgs Mechanism*** : generates the masses of the gauge bosons preserving the local gauge invariance

$$\mathcal{L} = \underbrace{\tfrac{1}{2}(\partial_\mu h)(\partial^\mu h) - \lambda v^2 h^2}_{\text{massive } h \ \textit{scalar}} - \underbrace{\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + \tfrac{1}{2}g^2 v^2 B_\mu B^\mu}_{\text{massive gauge boson}}$$

$$+ \underbrace{g^2 v B_\mu B^\mu h + \tfrac{1}{2}g^2 B_\mu B^\mu h^2}_{h, B \text{ interactions}} - \underbrace{\lambda v h^3 - \tfrac{1}{4}\lambda h^4}_{h \text{ self-interactions}} \, .$$

- EW coupling constants and W mass determine $v = 246$ GeV

The Higgs Mechanism

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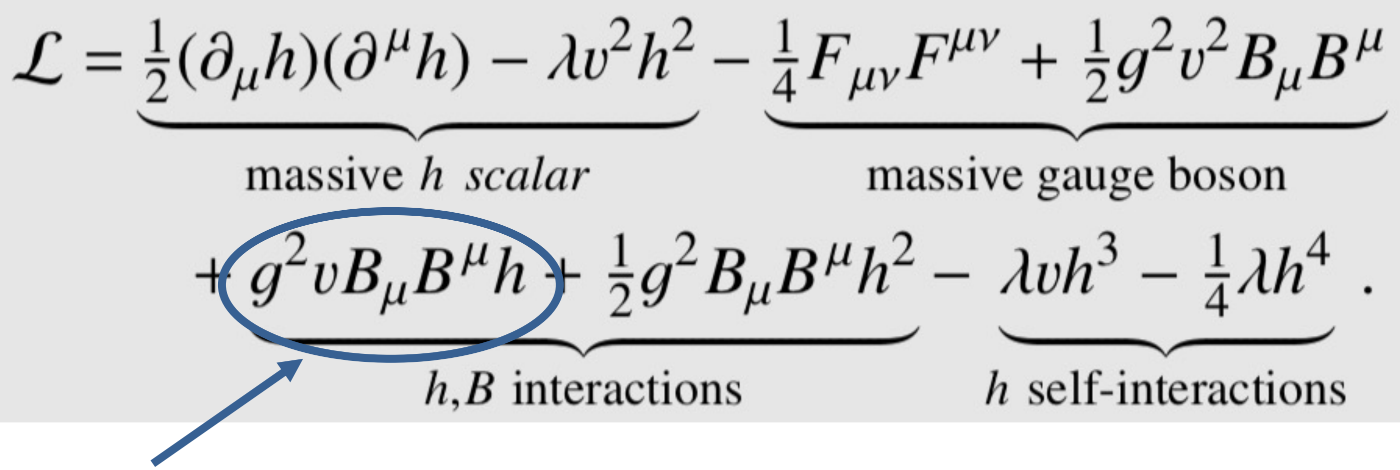

$$\mathcal{L} = \underbrace{\tfrac{1}{2}(\partial_\mu h)(\partial^\mu h) - \lambda v^2 h^2}_{\text{massive } h \ scalar} \underbrace{- \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + \tfrac{1}{2}g^2 v^2 B_\mu B^\mu}_{\text{massive gauge boson}}$$

$$\underbrace{+ \boxed{g^2 v B_\mu B^\mu h} + \tfrac{1}{2}g^2 B_\mu B^\mu h^2}_{h,B \text{ interactions}} \underbrace{- \lambda v h^3 - \tfrac{1}{4}\lambda h^4}_{h \text{ self-interactions}} .$$

- Coupling between vector bosons and the Higgs boson
- EW coupling constants and W mass determine $v = 246$ GeV

The Higgs Mechanism

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$$\mathcal{L} = \underbrace{\tfrac{1}{2}(\partial_\mu h)(\partial^\mu h) - \boxed{\lambda v^2 h^2}}_{\text{massive } h \text{ scalar}} \underbrace{- \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + \tfrac{1}{2}g^2 v^2 B_\mu B^\mu}_{\text{massive gauge boson}}$$

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- Higgs potential: Mass term and self-interactions terms
- Coupling between vector bosons and the Higgs boson
- EW coupling constants and W mass determine $v = 246$ GeV

The Higgs Mechanism

- ***The Higgs Mechanism*** : generates the masses of the gauge bosons preserving the local gauge invariance

$$\mathcal{L} = \underbrace{\tfrac{1}{2}(\partial_\mu h)(\partial^\mu h) - \lambda v^2 h^2}_{\text{massive } h \ scalar} - \underbrace{\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + \tfrac{1}{2}g^2 v^2 B_\mu B^\mu}_{\text{massive gauge boson}}$$

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- Higgs potential: Mass term and self-interactions terms
- Coupling between vector bosons and the Higgs boson
- EW coupling constants and W mass determine $v = 246$ GeV
- Yukawa coupling: interaction term for fermions and the Higgs boson

The Standard Model Higgs

- Higgs Mechanism + $U(1)_Y \times SU(2)_L$
- Three Goldstone bosons: longitudinal polarisation states of the gauge bosons $W^{\pm}, Z$
- One massive neutral scalar field: The Higgs Boson

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

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

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

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

The Standard Model Higgs

- Higgs Mechanism + $U(1)_Y \times SU(2)_L$
- Three Goldstone bosons: longitudinal polarisation states of the gauge bosons $W^{\pm}, Z$
- One massive neutral scalar field: The Higgs Boson

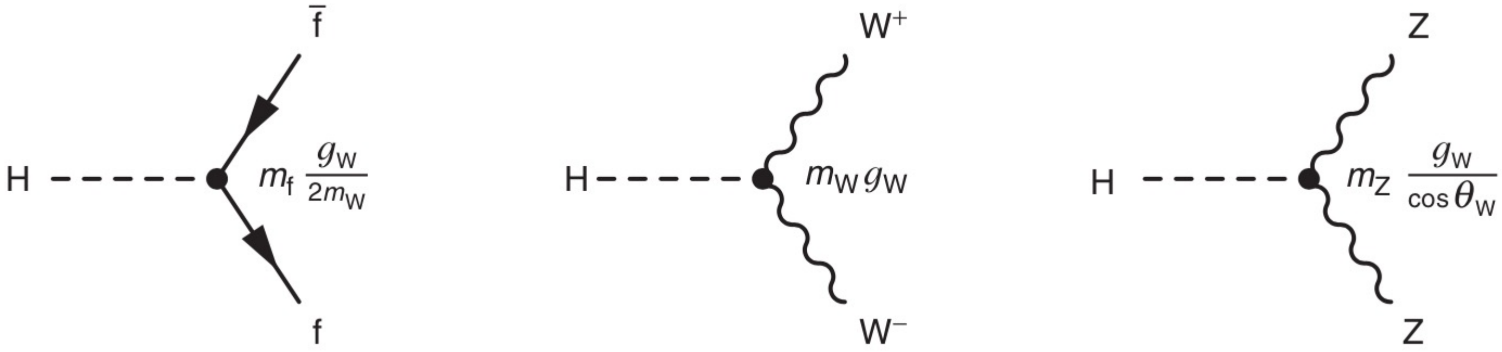
$$m_{\mathrm{H}} = \sqrt{2\lambda}\, v \qquad m_{\mathrm{W}} = \frac{1}{2} g_{\mathrm{W}} v$$

$$v = 246\,\mathrm{GeV}$$

- The mass of the Higgs boson is a free parameter: it can not be predicted by the model
- The Higgs Boson has couplings to all the particles to which it gives mass (therefore many ways it could decay)

Higgs boson couplings

- The Higgs Boson has couplings to all the particles to which it gives mass



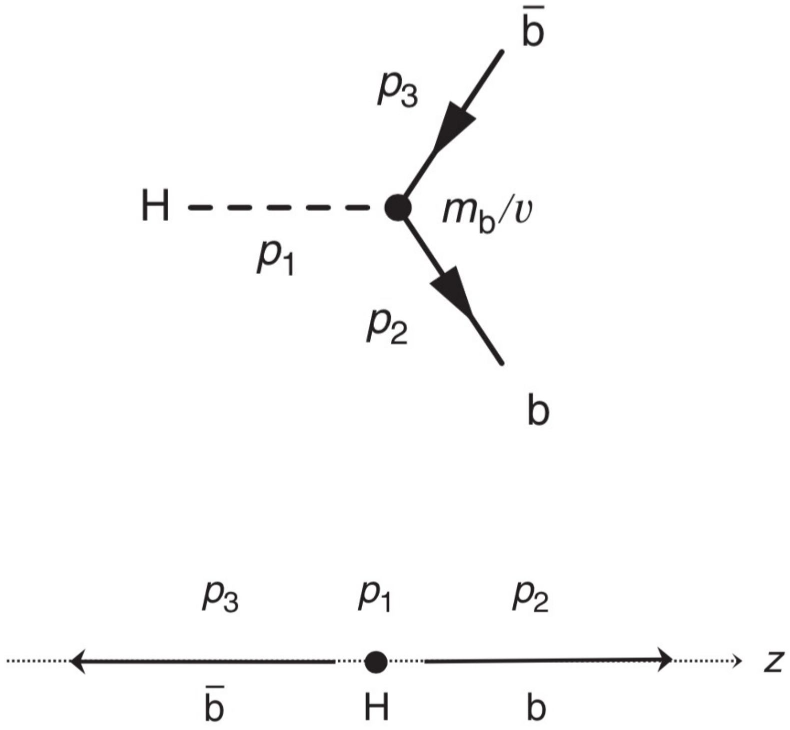
- The couplings are proportional to the masses of the particles coupling to the Higgs boson

Higgs boson decays

- We can calculate the decay of the Higgs into quarks, for example a b-quark pair:

$$\mathcal{M} = \frac{m_\mathrm{b}}{v}\overline{u}(p_2)v(p_3) = \frac{m_\mathrm{b}}{v}u^\dagger\gamma^0 v$$

$$\begin{aligned} p_2 &\approx (E, 0, 0, E) \\ p_3 &\approx (E, 0, 0, -E) \\ E &= m_\mathrm{H}/2 \end{aligned}$$



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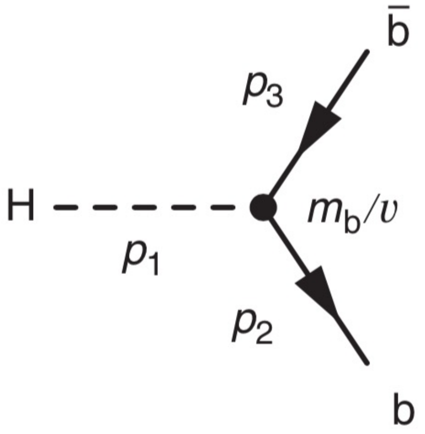


- The spinors:

$$u_\uparrow(p_2) = \sqrt{E}\begin{pmatrix}1\\0\\1\\0\end{pmatrix},\ u_\downarrow(p_2) = \sqrt{E}\begin{pmatrix}0\\1\\0\\-1\end{pmatrix},\ v_\uparrow(p_3) = \sqrt{E}\begin{pmatrix}1\\0\\-1\\0\end{pmatrix}\ v_\downarrow(p_4) = \sqrt{E}\begin{pmatrix}0\\-1\\0\\-1\end{pmatrix}$$

b-quark $(\theta = 0, \phi = 0)$ $\overline{\mathrm{b}}$-antiquark $(\theta = \pi, \phi = \pi)$

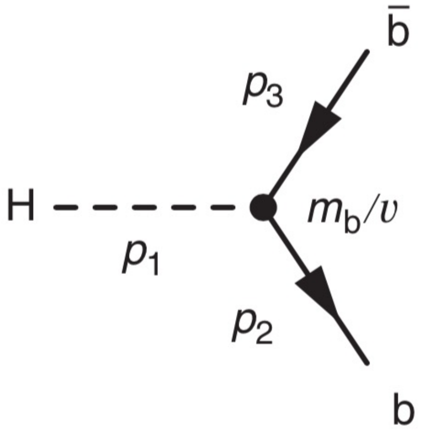
Higgs boson decays

- We can calculate the decay of the Higgs into quarks, for example a b-quark pair:

$$\mathcal{M} = \frac{m_\mathrm{b}}{v}\overline{u}(p_2)v(p_3) = \frac{m_\mathrm{b}}{v}u^\dagger\gamma^0 v$$

$$p_2 \approx (E,0,0,E)$$

$$p_3 \approx (E,0,0,-E)$$



- Only two spin configurations are non-zero ($b\overline{b}$ produced in spin zero state)

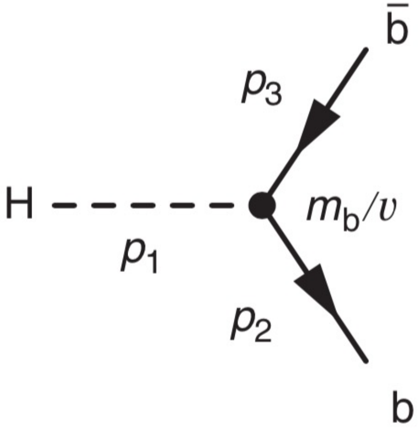
$$\mathcal{M}_{\uparrow\uparrow} = -\mathcal{M}_{\downarrow\downarrow} = \frac{m_\mathrm{b}}{v}2E$$

- No angular dependence: the Higgs is a scalar

Higgs boson decays

- We can calculate the decay of the Higgs into quarks, for example a b-quark pair

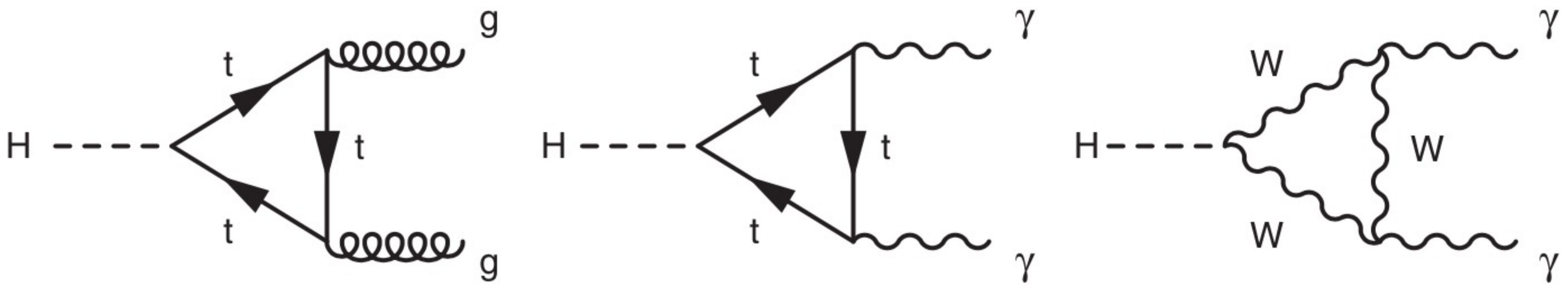
$$\langle|\mathcal{M}|^2\rangle = |\mathcal{M}_{\uparrow\uparrow}|^2 + |\mathcal{M}_{\downarrow\downarrow}|^2 = \frac{m_b^2}{v^2}8E^2 = \frac{2m_b^2m_H^2}{v^2}$$



$$\Gamma(H \to b\overline{b}) = 3 \times \frac{m_b^2 m_H}{8\pi v^2}$$

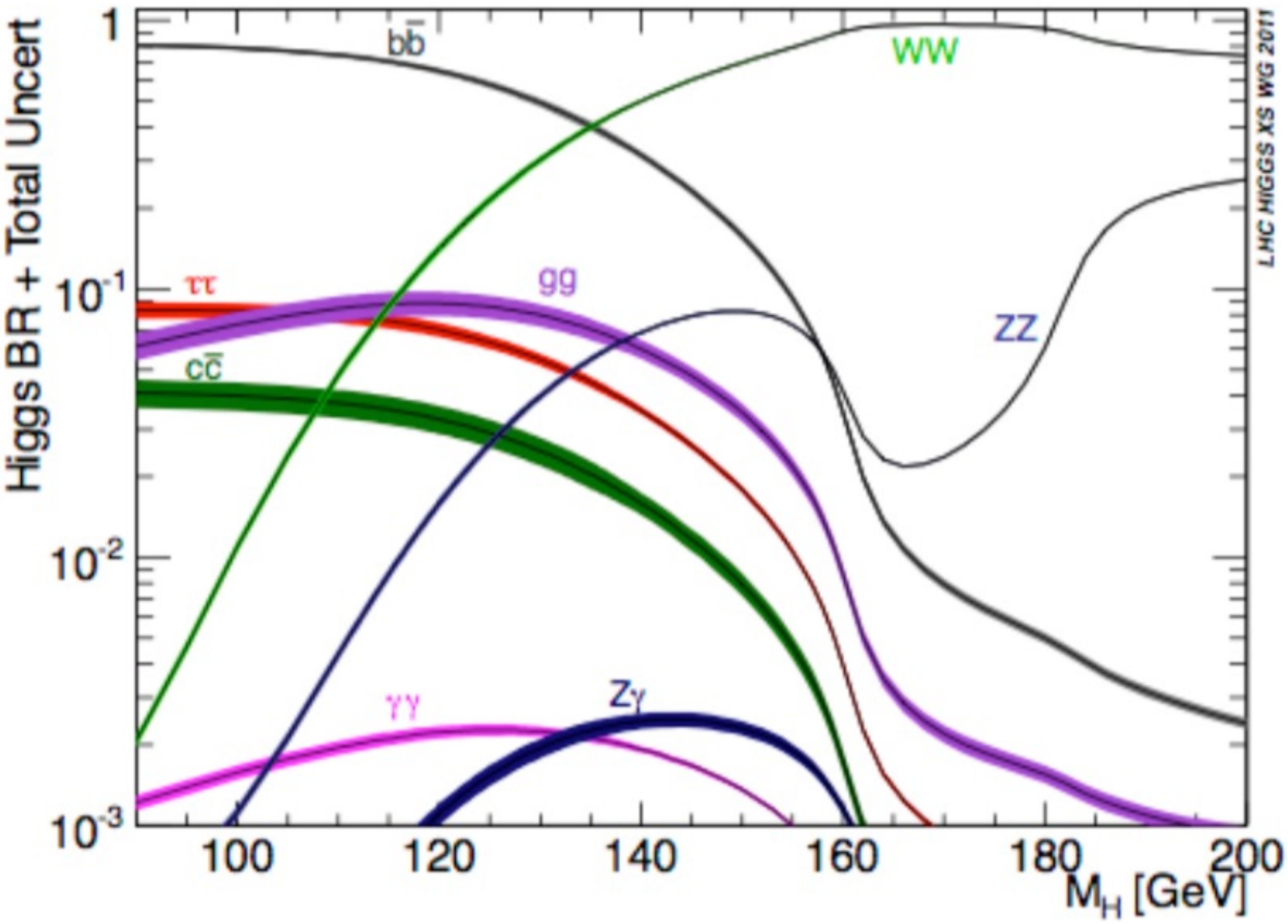
Higgs boson decays

- The Higgs boson can also decay to massless particles via virtual particles



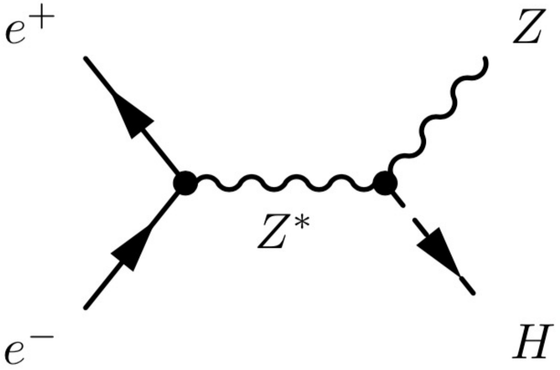
- These decays can compete with the decays to fermions and the off-mass-shell gauge bosons: masses of the particles in the loops are large

Higgs boson decay channels



Higgs boson at LEP

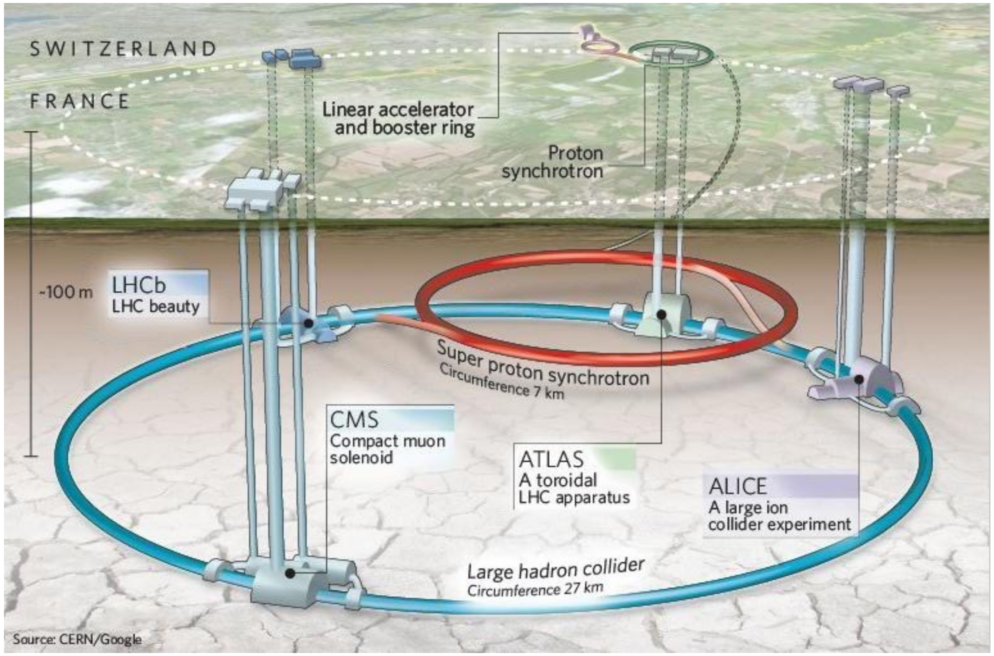
- The Higgs could have been seen at LEP through a "Higgsstrahlung" process:



- However, LEP operated at a maximum of $\sqrt{s} = 207$ GeV, so the Higgs boson mass would have to be $m_H < 116$ GeV to have been seen
- LEP excluded a Higgs Boson with a mass below 114 GeV
- The EW precision tests measurements put limits on the size of quantum loop corrections: $m_H < 150$ GeV

The Large Hadron Collider

- Located at CERN, Geneva, Switzerland
- pp collisions at $\sqrt{s} = 13$ TeV
- 4 Experiments:
  ATLAS
  CMS
  LHCb
  ALICE
- 2010-2011: $\sqrt{s} = 7$ TeV
- 2012: $\sqrt{s} = 8$ TeV
- 2015-2018: $\sqrt{s} = 13$ TeV
- 2022-2025: $\sqrt{s} = 14$ TeV
- 2026-?: High Luminosity LHC

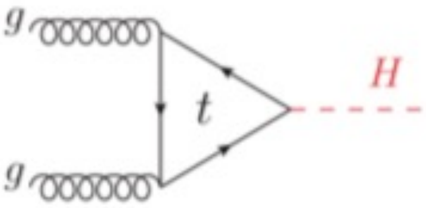


Source: CERN/Google

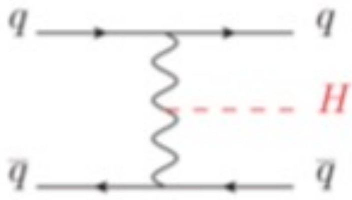
- One of its main goals was to find the Higgs boson

Higgs boson production at the LHC

- Gluon fusion process

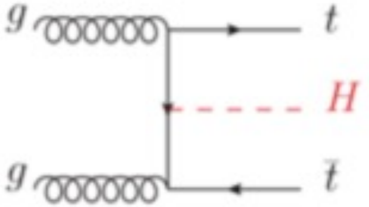


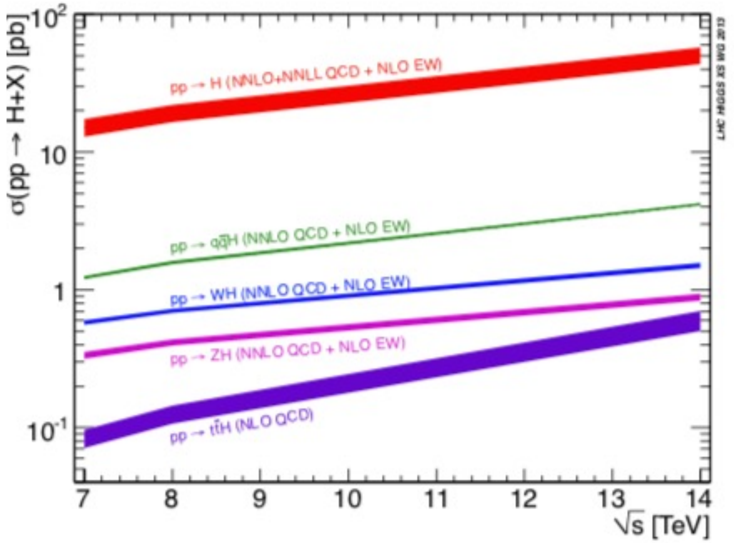
- Vector Boson Fusion (two forward jets and a large rapidity gap)



- W and Z Associated Production

- Top Associated Prod.

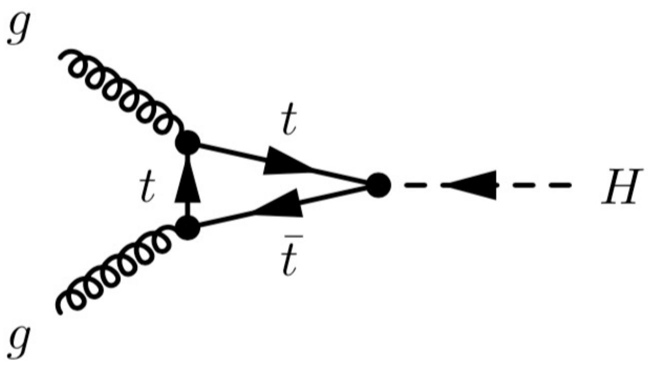




Production process	Cross section [pb]		Order of calculation
	$\sqrt{s}$ = 7 TeV	$\sqrt{s}$ = 8 TeV	
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW)+~NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.334 ± 0.013	0.414 ± 0.016	NNLO(QCD)+NLO(EW)
$[ggZH]$	0.023 ± 0.007	0.032 ± 0.010	NLO(QCD)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NNLO(QCD) + 4FS NLO(QCD)
ttH	0.086 ± 0.009	0.129 ± 0.014	NLO(QCD)
tH	0.012 ± 0.001	0.018 ± 0.001	NLO(QCD)
	17.4 ± 1.6	22.3 ± 2.0	

Higgs boson production at the LHC

- The dominant production mechanism is "Gluon fusion"



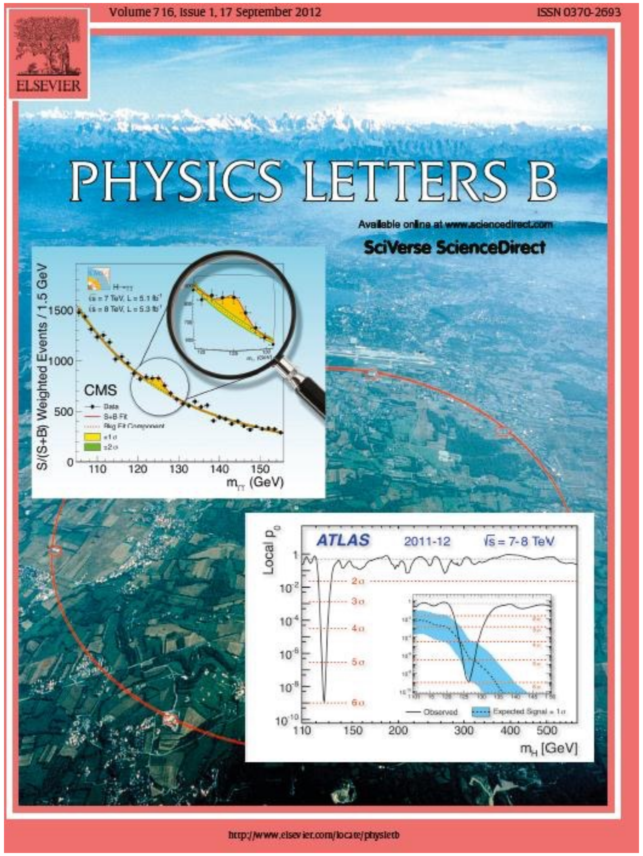
- The cross section can be obtained in terms of the underlying gluon-gluon to Higgs cross section:

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

- Detailed knowledge of PDFs for the proton essential

Higgs boson discovery

ATLAS and CMS reported the observation of a new particle with a mass of around 126 GeV in the search for the Higgs boson on July 4th 2012



Volume 716, Issue 1, 17 September 2012

ISSN 0370-2693

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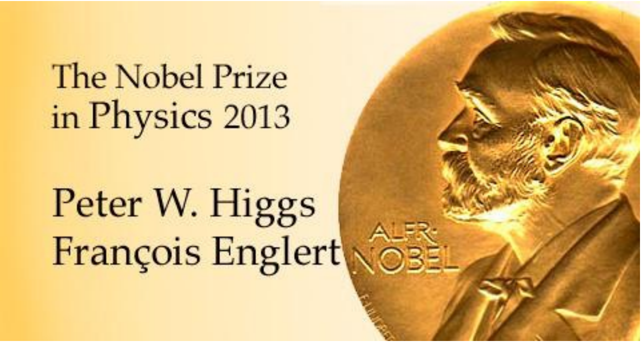
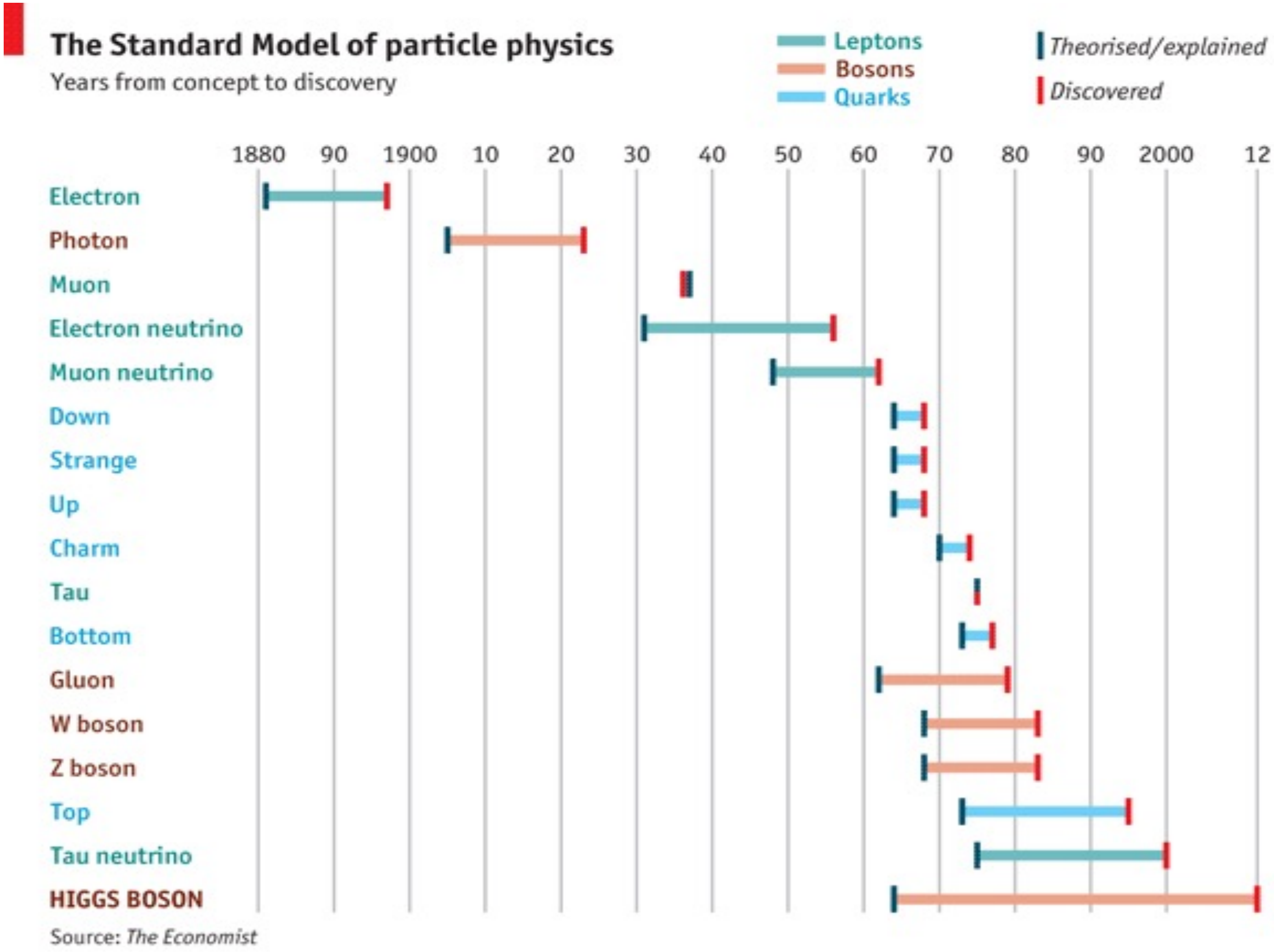


The Nobel Prize
in Physics 2013

Peter W. Higgs
François Englert

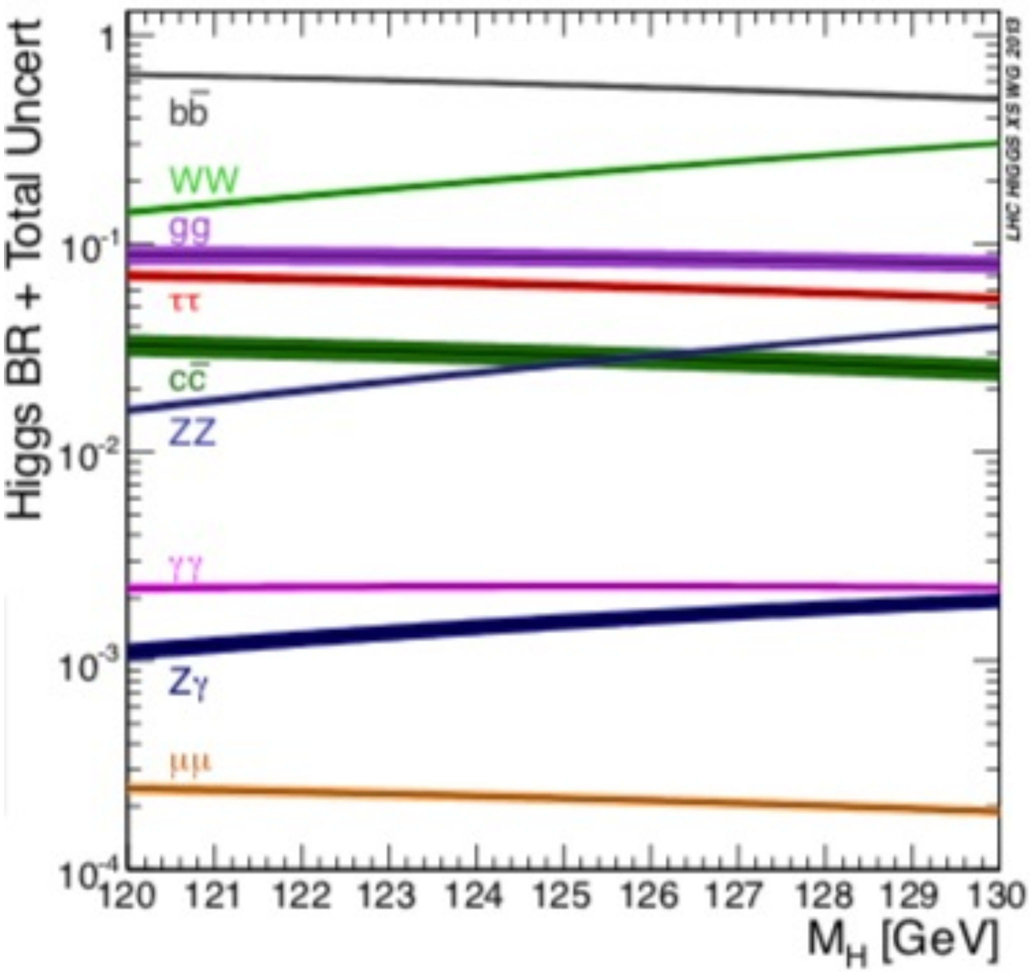
Higgs boson discovery



Source: *The Economist*

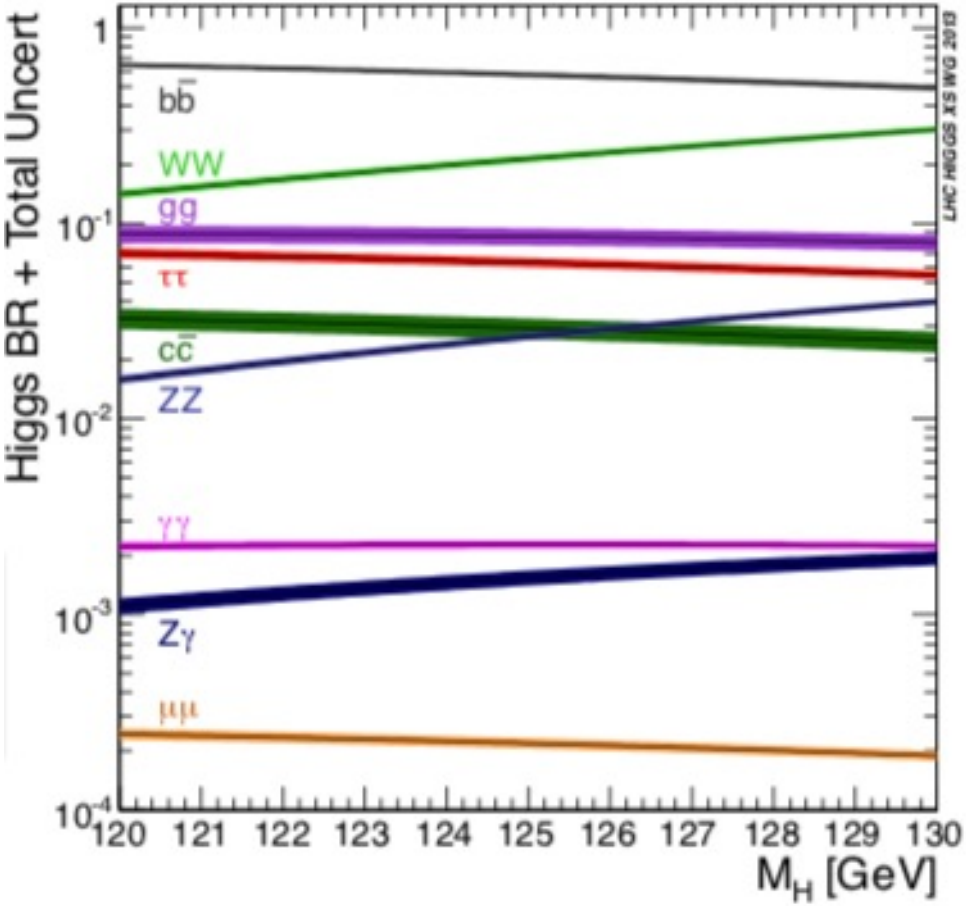
Higgs boson decay channels

- Dominant: bb (57%)
- WW channel (22%)
- ττ channel (6.3%)
- ZZ channel (3%)
- cc channel (3%)
- γγ channel (0.2%)
- Zγ (0.2%)
- μμ channel (0.02%)



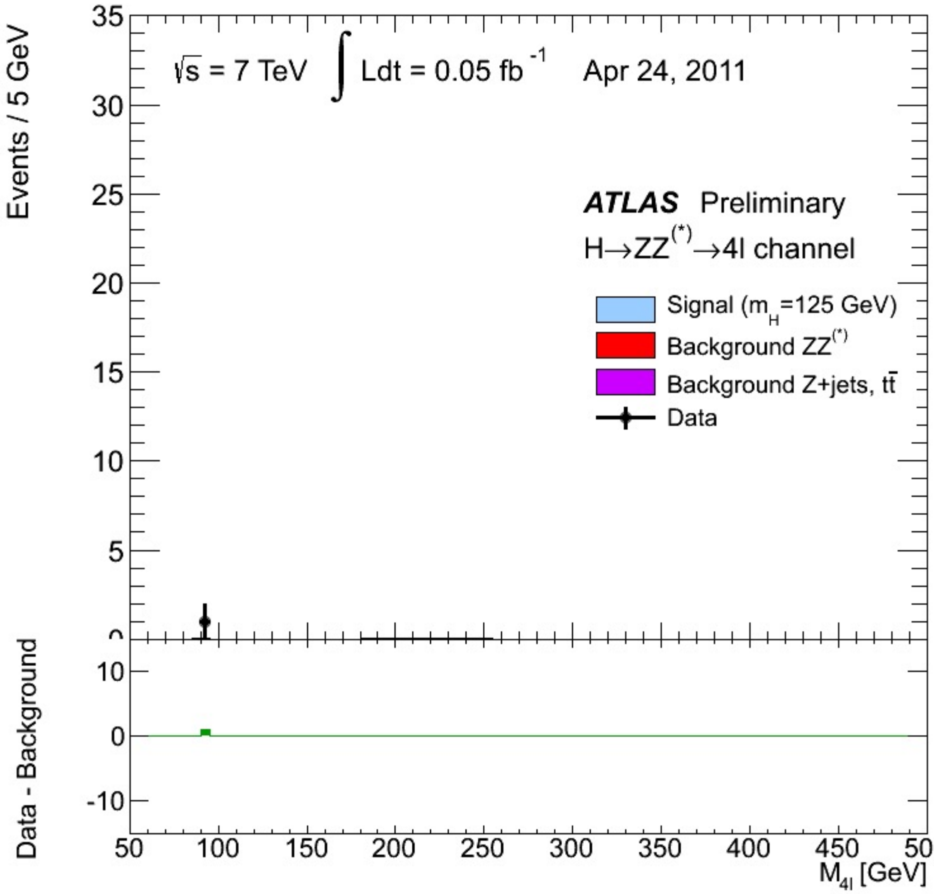
Higgs boson decay channels

- bb (57%): large QCD background
- WW channel (22%): WW → *lνlν* - Missing energy coming from the neutrinos
- ττ channel (6.3%): Missing energy coming from the neutrinos
- ZZ channel (3%) - Discovery
- cc channel (3%)
- γγ channel (0.2%) - Discovery
- Zγ (0.2%)
- μμ channel (0.02%)



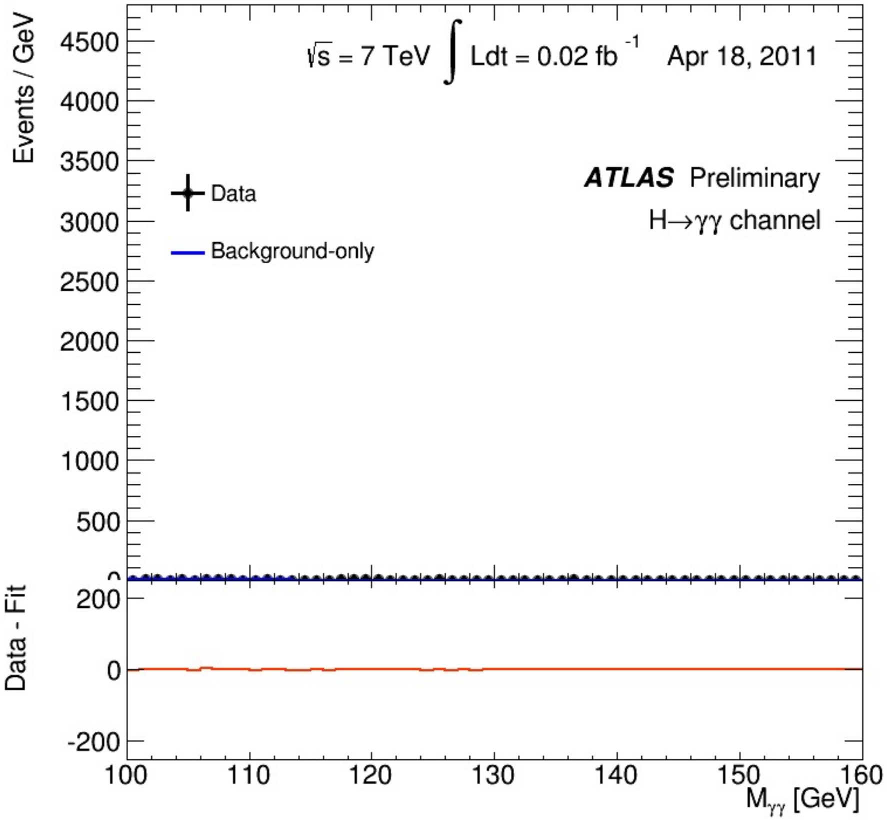
Z channel

- Distinctive topology (4 leptons)
- Reconstruct invariant mass of the 4 leptons
- Channel with high s/b ratio
- Backgrounds can be estimated from MC
- Very low rate due to branching fractions of ZZ and Z to leptons
- Trailing lepton at low pT
- Typically one Z boson is on-mass shell



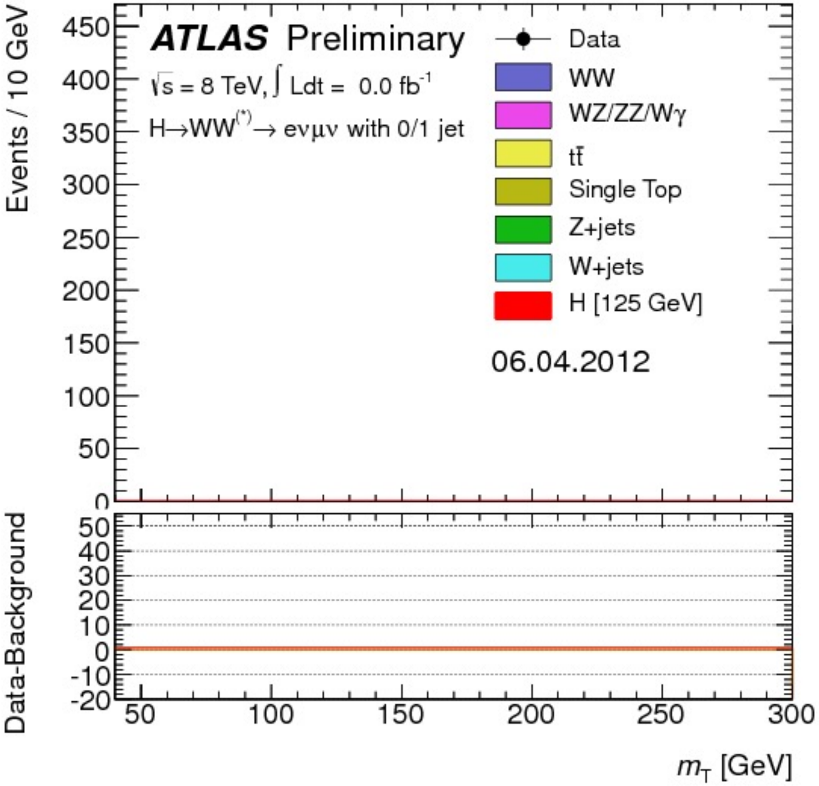
$\gamma\gamma$ channel

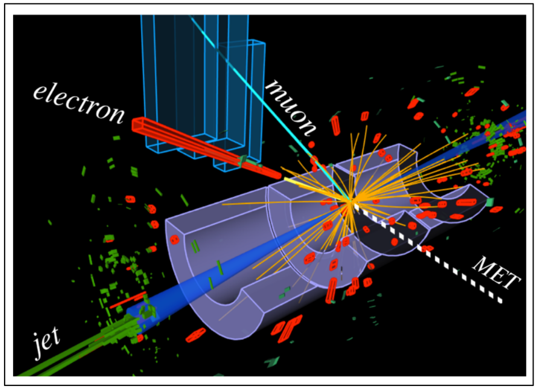
- Distinctive topology
- Reconstruct invariant mass of the 2 photons
- Main production and decay processes occur through loops
- High mass resolution channel O(1%) allowing data driven estimate of background
- Low signal over background
- Very simple selection cuts
- Relies on the quality of the detector response and the reconstruction



WW channel

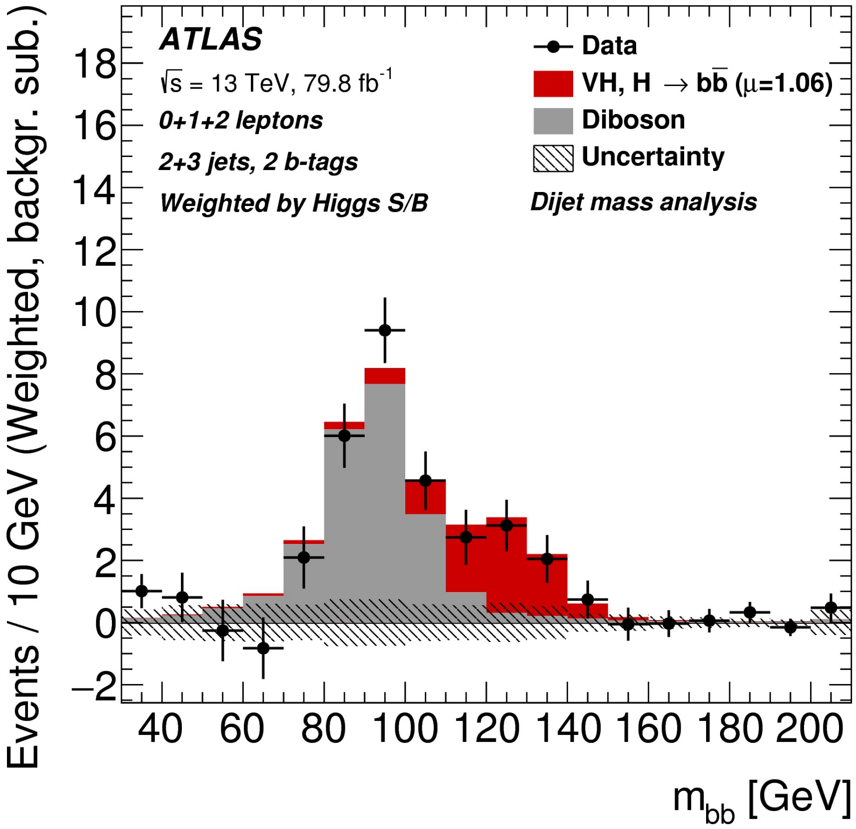
- Requires good simulation of backgrounds and control regions in the data
- The mass resolution is spoiled by the neutrinos in the leptonic decays
- Large event rate, but also large backgrounds from the WW and top production





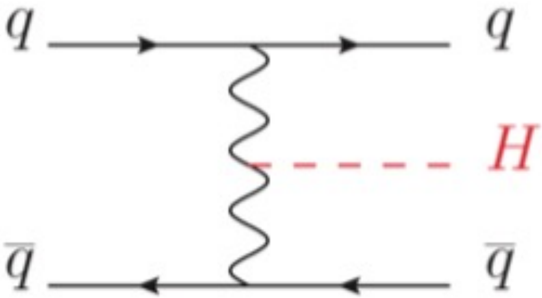
bb channel

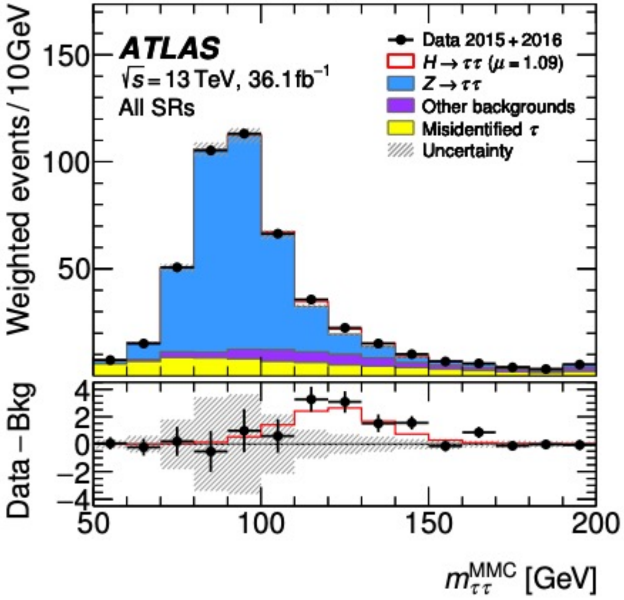
- Analysis based on three main channels: WH and ZH
  - 0 “leptons” (for neutrino decays of the Z)
  - 1-lepton (W decaying to an electron or a muon)
  - 2-leptons (Z decaying to electrons or muons)
- Main background is V+jets (in particular b-jets)
- Very important measurement of VZ process with Z to b quarks as a check



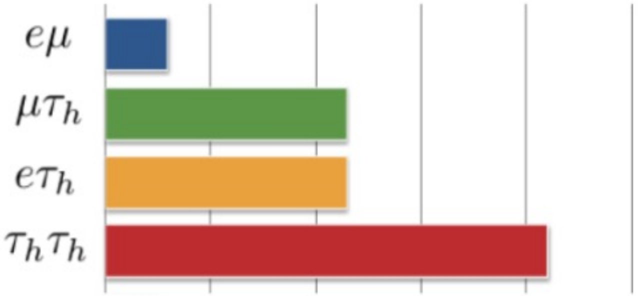
$\tau\tau$ channel (VBF)

- Background is Z production with two jets
- Several channels depending on the decay mode of the tau
- Data driven methods: e.g. the embedding of taus in Z to di-muon events



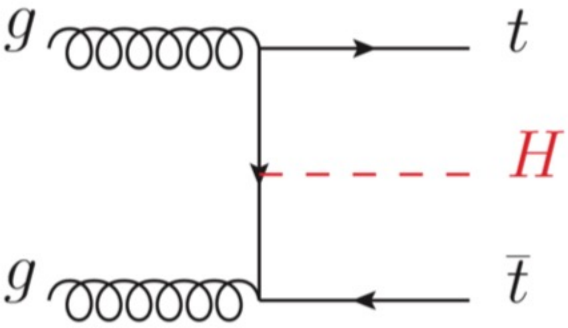


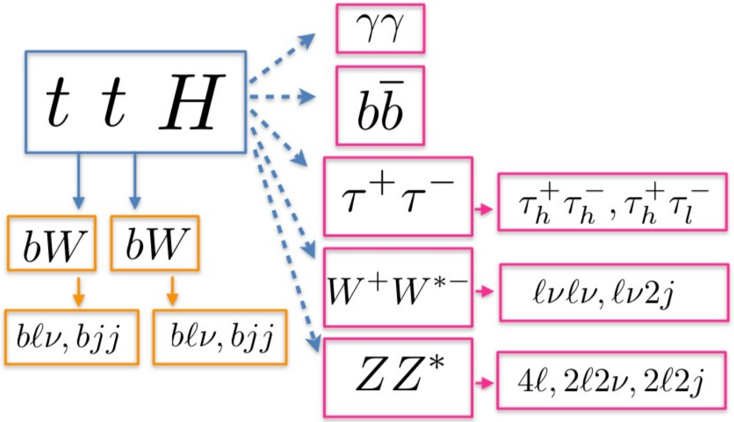
Tau to leptons ~18% (rest is hadrons)



ttH channel

- Direct probe of the top Yukawa coupling
- Large number of complex final states: b-jets, leptons, taus and photons
- ttH (bb):
  - Very large backgrounds of top pair production associated with b jets
  - Dominated by background modelling uncertainties
- ttH (WW, ZZ and tau tau):
  - “multi-lepton” channel
  - Large number of topologies, backgrounds of jets faking leptons





$t\ t\ H$

bW → $b\ell\nu, bjj$

bW → $b\ell\nu, bjj$

$\gamma\gamma$

$b\bar{b}$

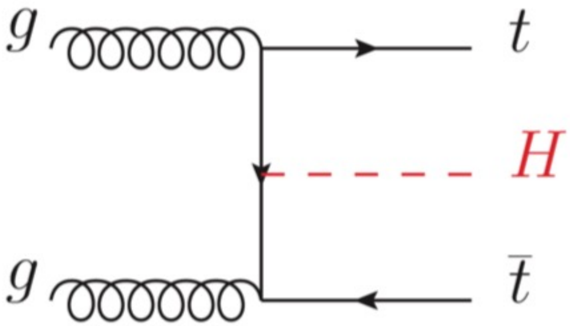
$\tau^+\tau^-$ → $\tau_h^+\tau_h^-, \tau_h^+\tau_l^-$

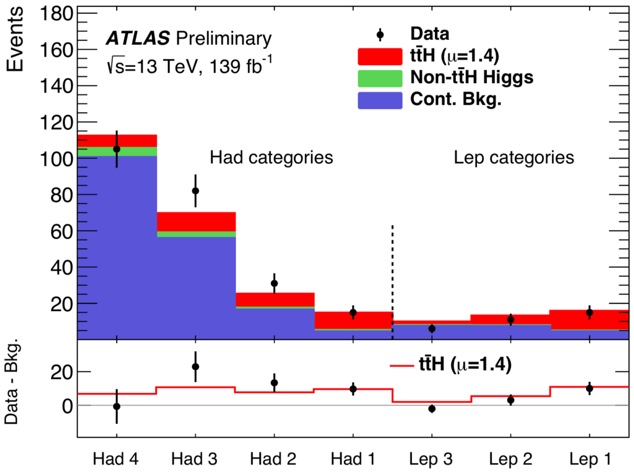
W^+W^{*-} → $\ell\nu\ell\nu, \ell\nu 2j$

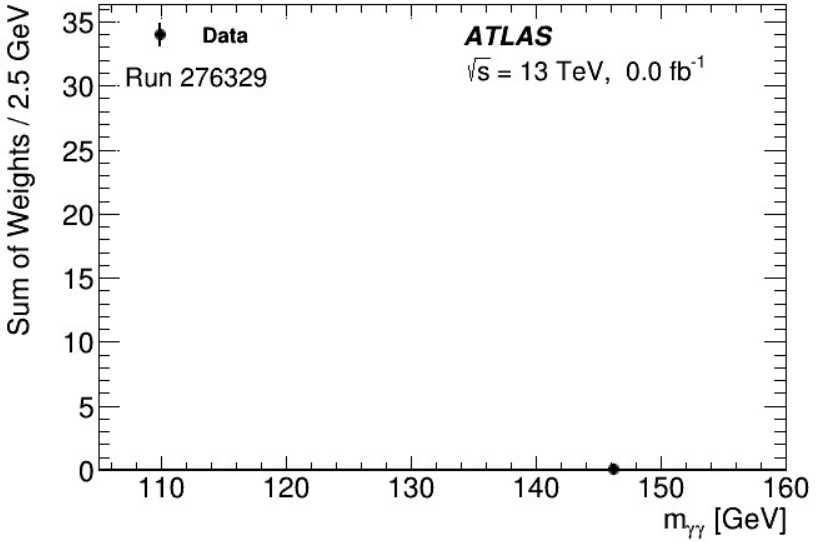
ZZ^* → $4\ell, 2\ell 2\nu, 2\ell 2j$

ttH channel

- Direct probe of the top Yukawa coupling
- ttH ($\gamma\gamma$):
  - Most sensitive channel
  - Background and signal modelled using analytic functions

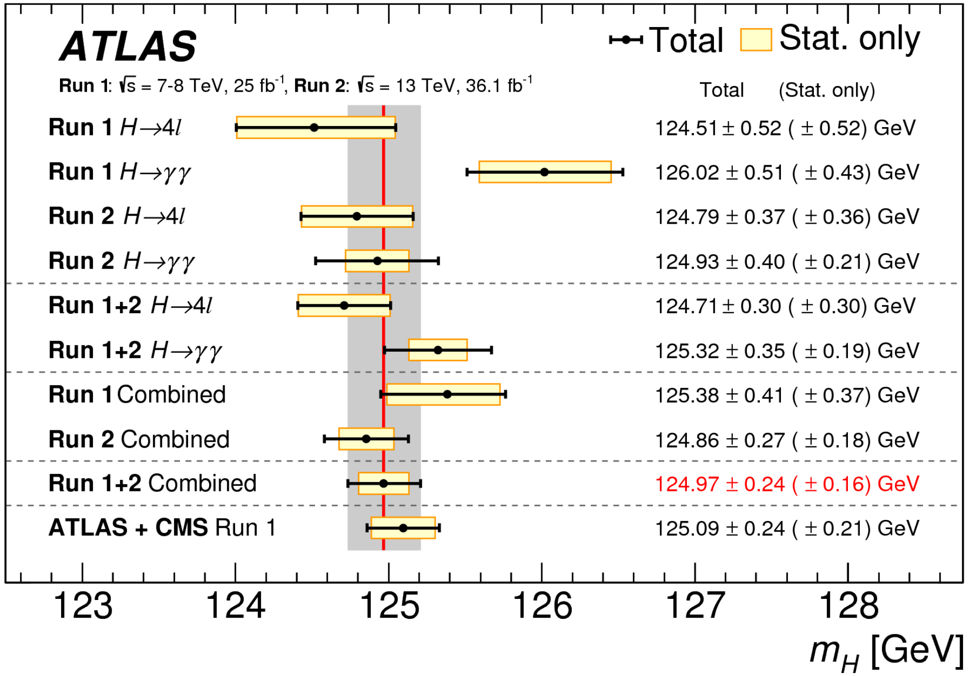






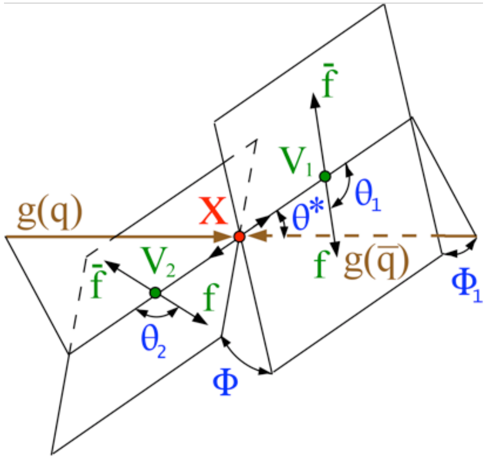
Higgs Boson mass

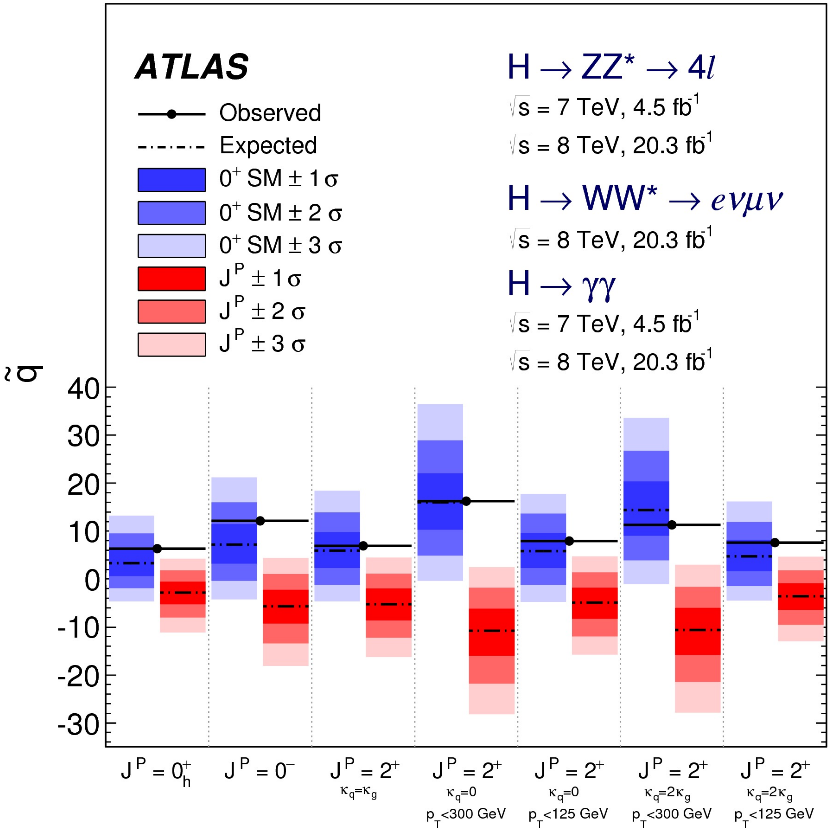
- Measurement done exclusively in the diphoton and 4-leptons channel
- Optimizing the analysis in categories with best mass resolution (photon, electron and muons energy response)
- Reached at Run 1 a precision of 0.2%.
- Among the most precise measurements done at the LHC in 2013



Higgs Boson spin/parity

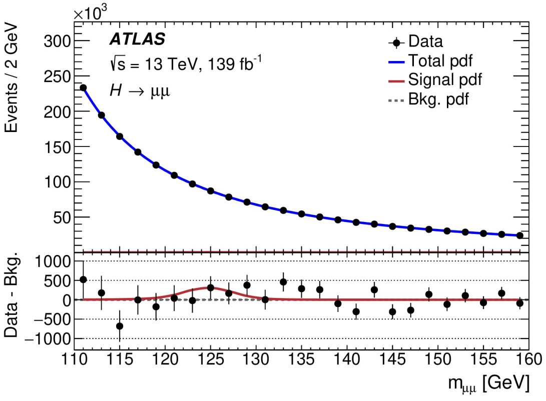
- So far, all the data is consistent with a Higgs boson with $J^P = 0^+$
- Angular analysis of ATLAS and CMS rule out spin 2 with 99.9% C.L

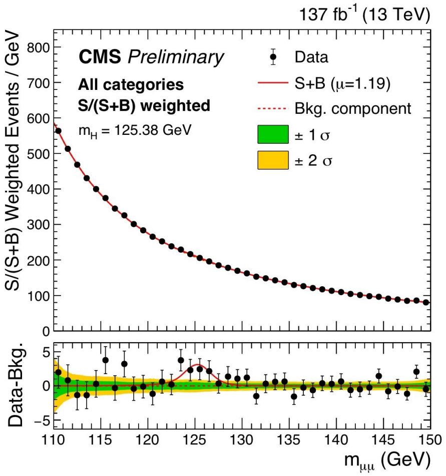




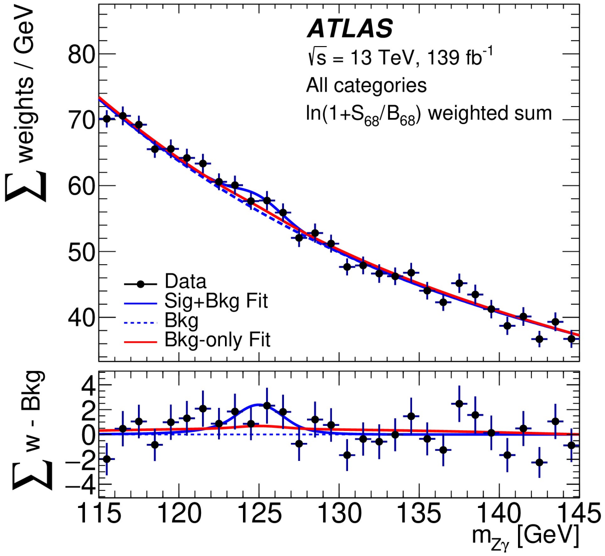
Other Higgs decays

- $\mu\mu$: ATLAS significance ~2σ
  CMS significance ~3σ



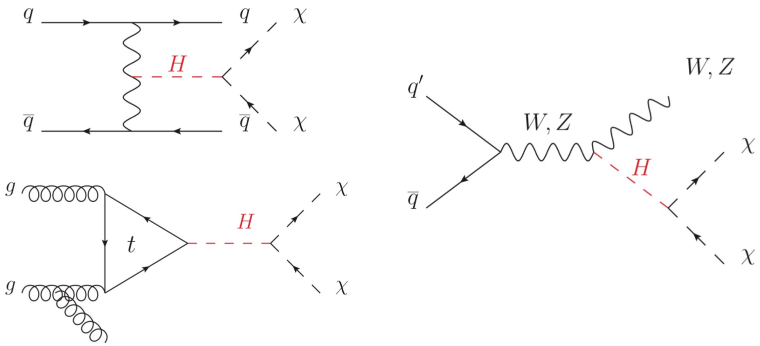


- $Z\gamma$: data consistent with background



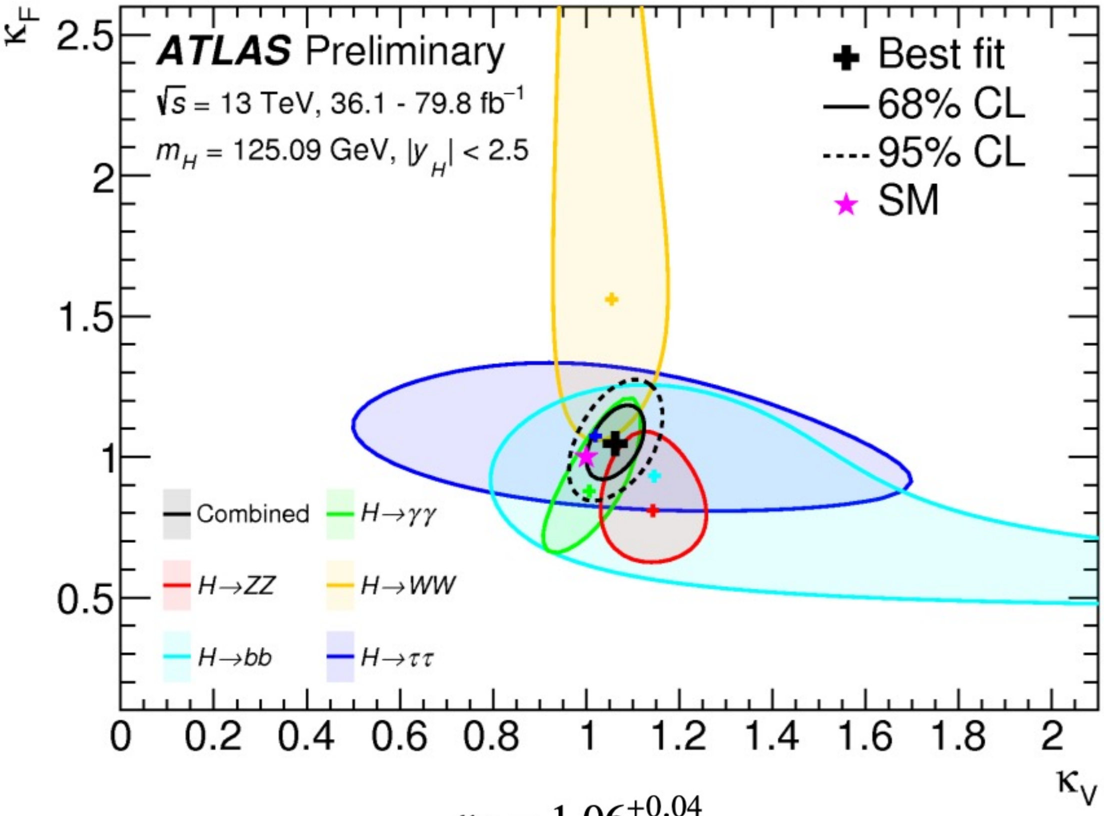
- Invisible decays:

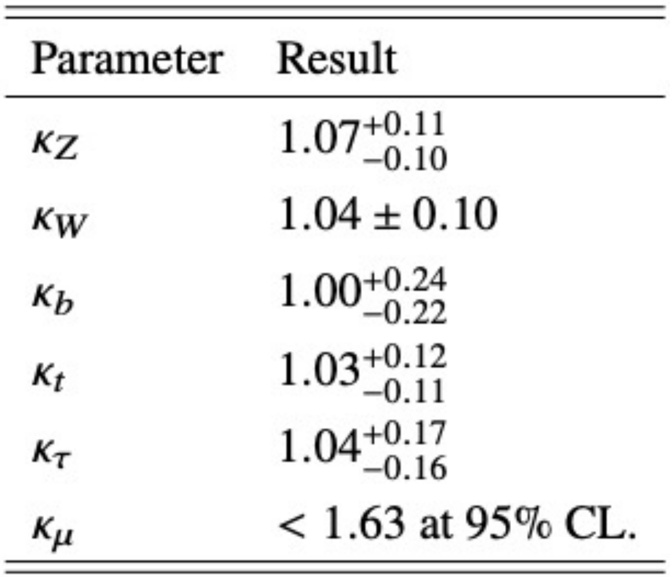
$$Br(H \to \chi) < 0.20$$



Couplings measurements

- Couplings from ATLAS 13 TeV measurements



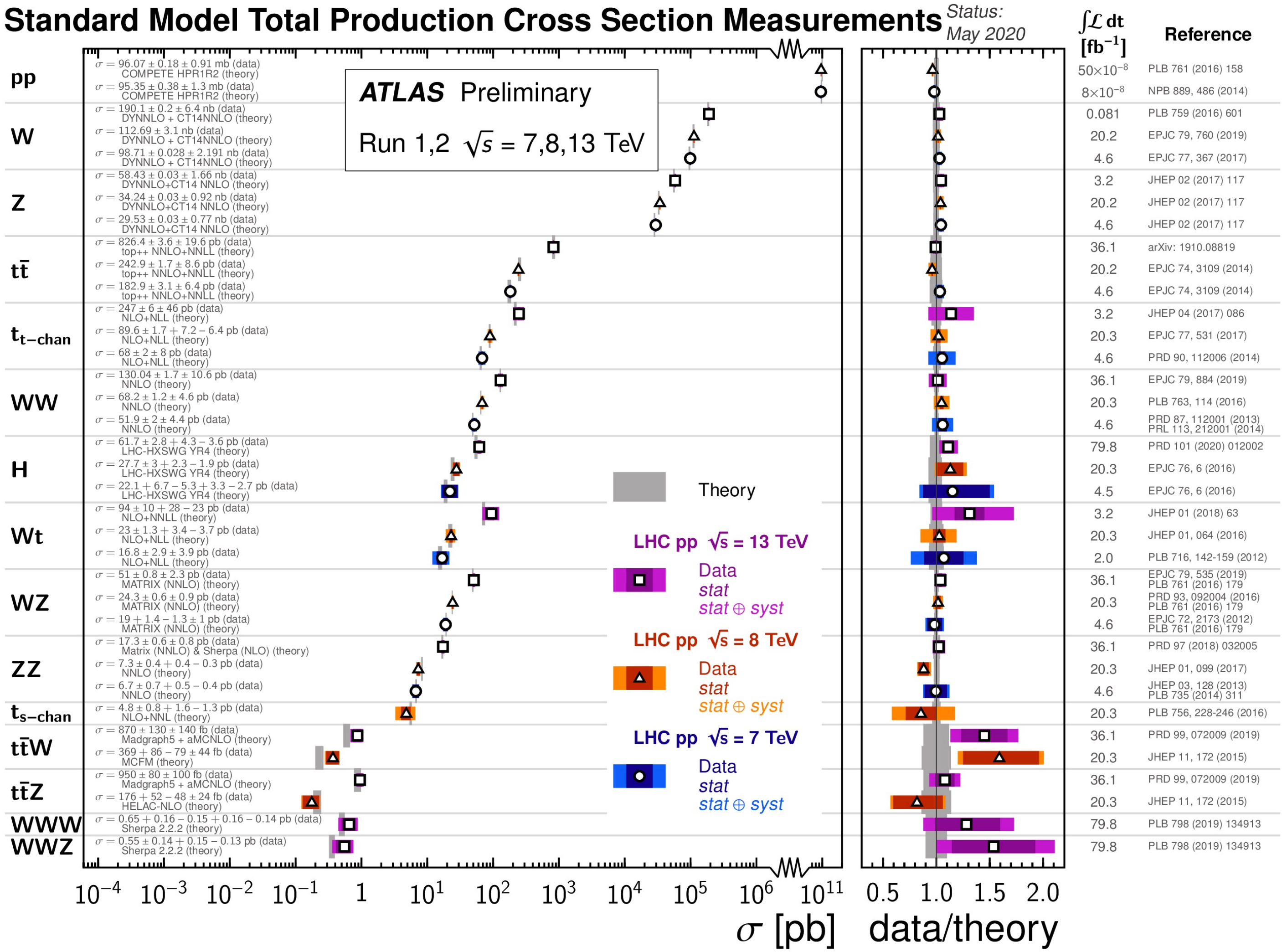


Parameter	Result
κ_Z	$1.07^{+0.11}_{-0.10}$
κ_W	1.04 ± 0.10
κ_b	$1.00^{+0.24}_{-0.22}$
κ_t	$1.03^{+0.12}_{-0.11}$
κ_τ	$1.04^{+0.17}_{-0.16}$
κ_μ	< 1.63 at 95% CL.

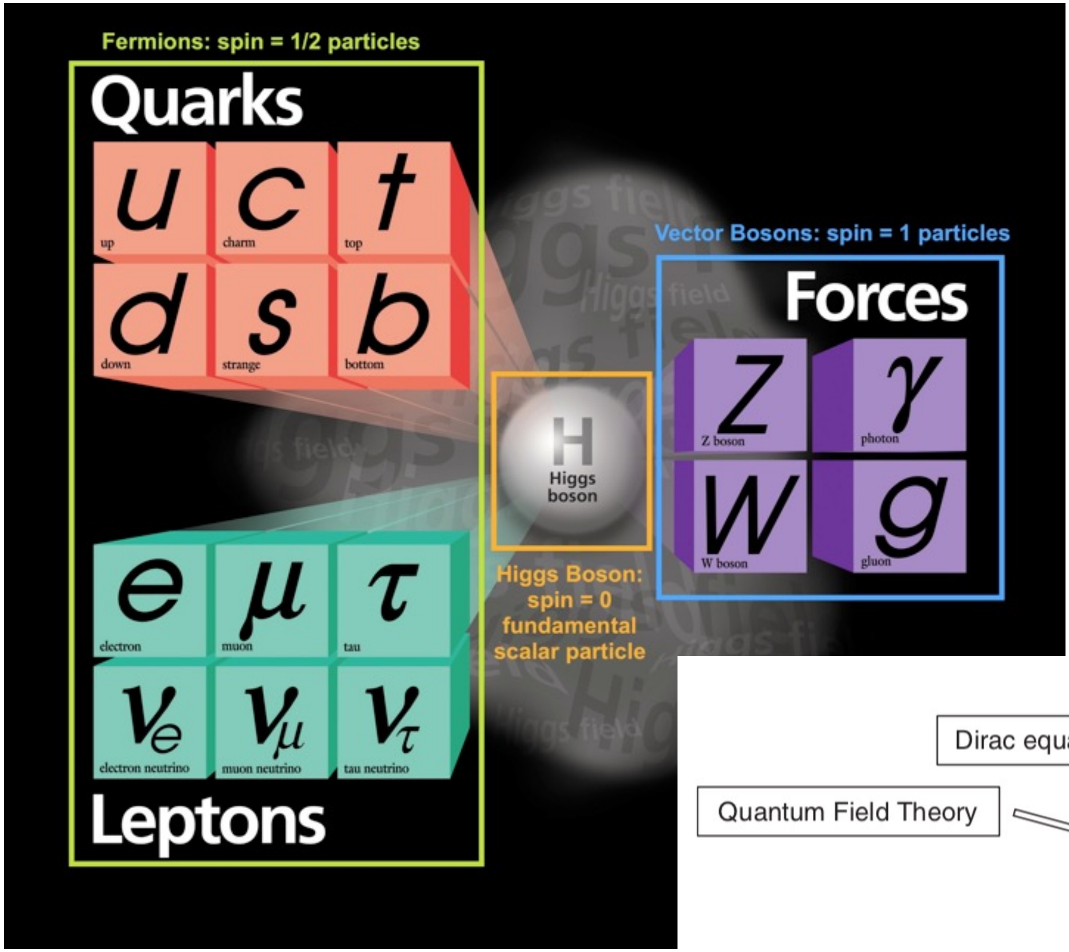
$$\kappa_V = 1.06^{+0.04}_{-0.04}$$

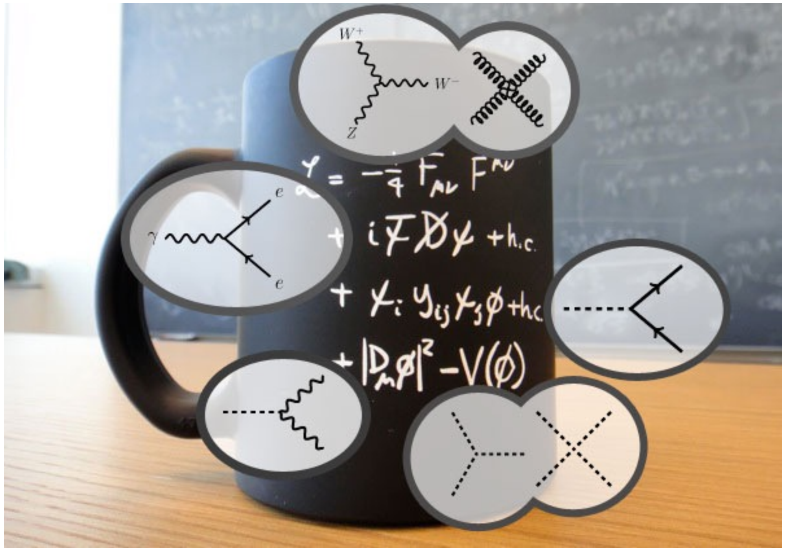
$$\kappa_F = 1.05^{+0.09}_{-0.09}.$$

Many SM measurements



The Standard Model - complete





Experimental data

Dirac equation

Gauge principle

Quantum Field Theory

Higgs mechanism

Standard Model

Experimental tests

Beyond The Standard Model

The Standard Model successfully describes all existing particle physics data, but it is not the ultimate theory

It does not answer some fundamental questions:

- Why are the masses between generations so different? Why 3 generations?
- What is Dark Matter? – WIMP: cold dark matter?
- What is responsible for the matter-antimatter asymmetry in the Universe?
- Can the forces be unified? Is there an energy scale where the couplings constants converge?
- Why is there only one Higgs boson?
- How do we include gravity?

Summary

- Over the past 50 years our understanding of particle physics has changed dramatically
- The Standard Model of particle physics is a great achievement: tested to high precision at various experiments, all experimental data are in agreement with it
- The particle discovered at the LHC in 2012 is looking increasingly like the SM Higgs boson

- As we have seen from the many examples in the course, it takes huge efforts and a lot of time to close the gap between theory and experiment
- These efforts will continue to show us the way to elucidate what lies beyond the Standard Model