The Higgs Sector

Gauge invariance

- The SM is required to be invariant under gauge transformations
- Global gauge transformations do not pose issues:

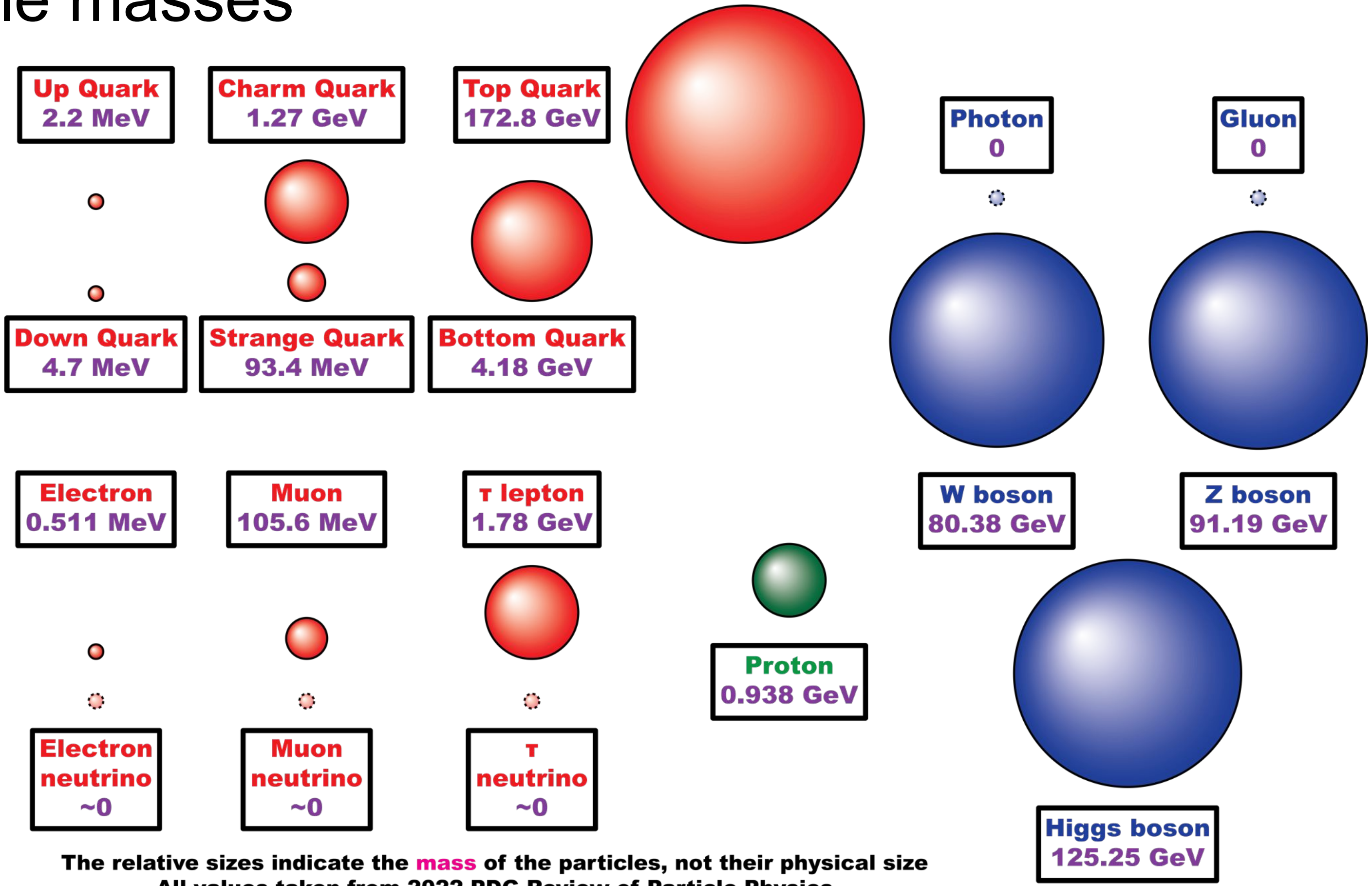
$$\varphi \rightarrow e^{i\alpha}\varphi$$

- Local gauge transformations are not invariant for massive particles:

$$\varphi \rightarrow e^{i\alpha(x)}\varphi$$

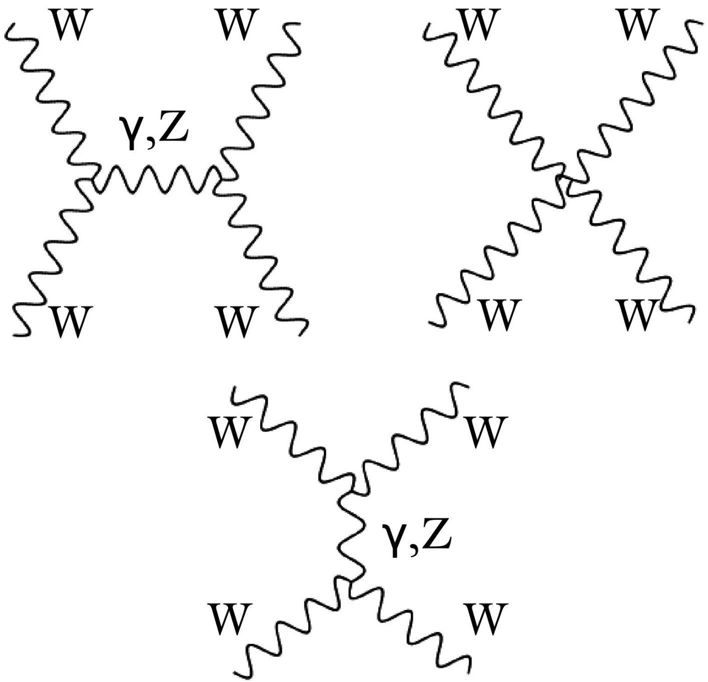
- Therefore gauge invariance requires massless fundamental particles

Particle masses



The relative sizes indicate the mass of the particles, not their physical size
All values taken from 2022 PDG Review of Particle Physics

Vector boson scattering



In the SM, W bosons can scatter off one another. As long as momentum, electric charge, and other fundamental quantities are conserved at each vertex, these are allowed.

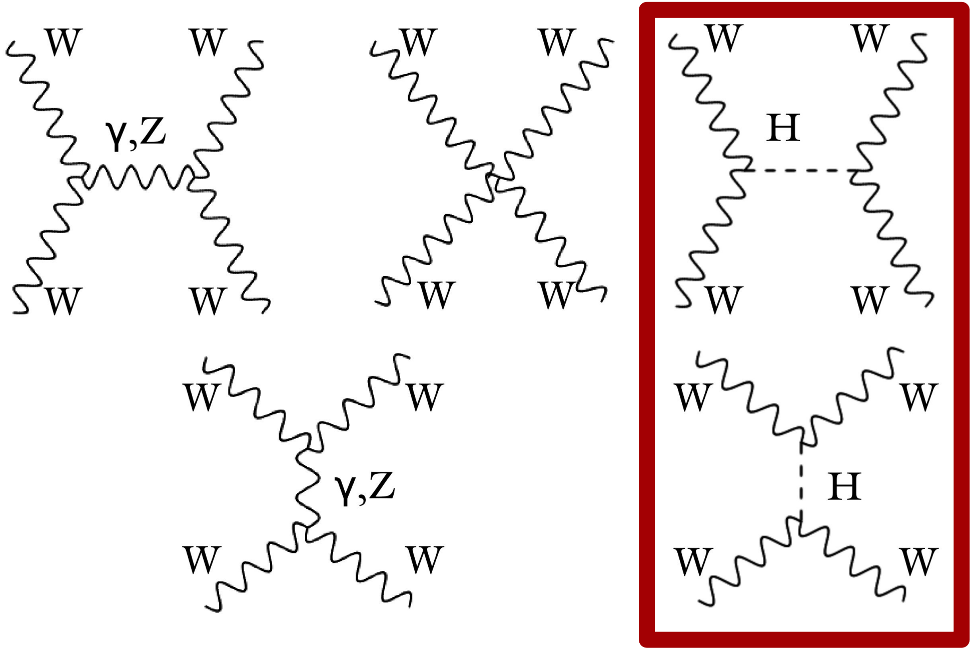
The probability of this scattering (proportional to a_0) as a function of energy (E) is:

$$a_0 = \frac{g^2 E^2}{16\pi M_W^2}$$

g ~ 0.654

This is problematic as E increases. The scattering probability is greater than 1 (and continues to diverge)!!!

Vector boson scattering



Adding a scalar boson fixes this issue.

When the new diagrams are included, a_0 becomes:

$$a_0 = \frac{g^2 M_H^2}{16\pi M_W^2}$$

This is independent of E!

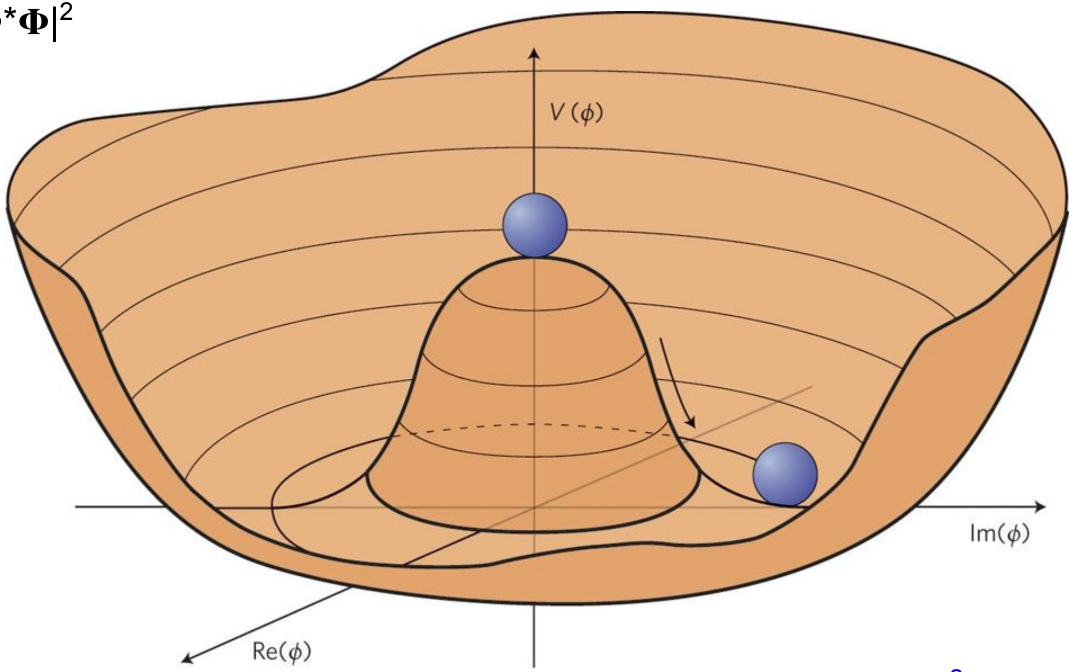
As long as $m_H \lesssim 130$ GeV, a_0 remains physical for a total scattering probability less than 100%

The Higgs mechanism

- Introduction of a complex doublet scalar field (Higgs field)
- Scalar field potential defined with an asymmetric minimum
  - Spontaneous symmetry breaking and non-zero vacuum expectation value (vev)
  - vev is known to be 246 GeV due to measured m_W
- Broken symmetry results in 4 degrees of freedom
  - Three give the $W^{\pm}$ and Z^0 bosons mass
- Fourth degree of freedom results in the Higgs boson (H)
- H is a massive spin-0 scalar boson
- Similarly, the Yukawa coupling to the scalar field gives rise to fermion masses
- Fundamental particle masses can be seen as interactions with the Higgs field

The Higgs potential

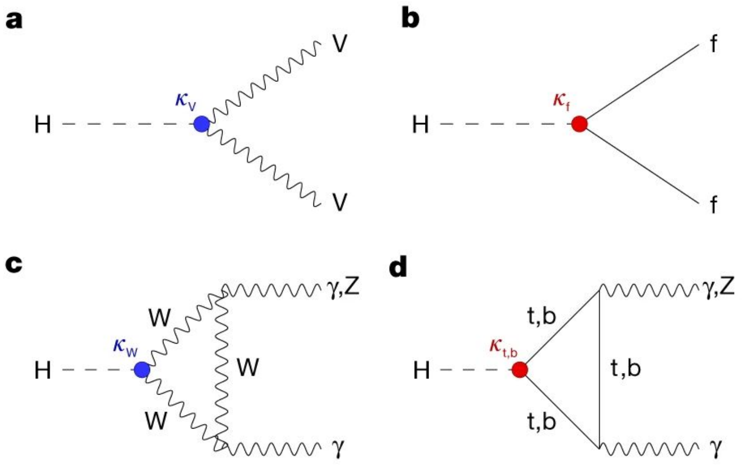
Higgs Field: scalar field $\mathbf{\Phi}$ with potential
$V(\mathbf{\Phi}) = \mu^2 \mathbf{\Phi}^* \mathbf{\Phi} + \lambda |\mathbf{\Phi}^* \mathbf{\Phi}|^2$

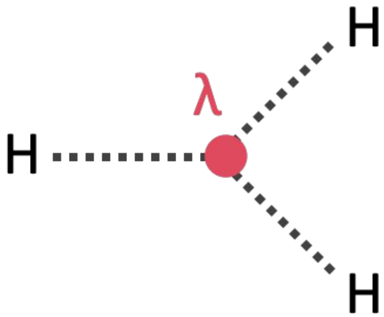


If $\lambda > 0$ and $\mu^2 < 0$, spontaneous symmetry breaking occurs and particles gain mass

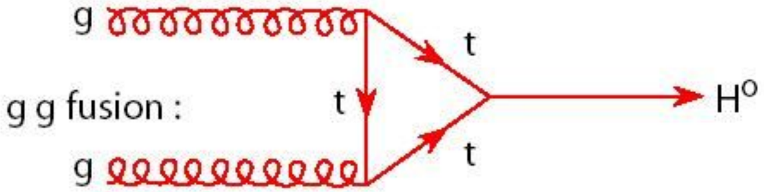
Higgs boson couplings

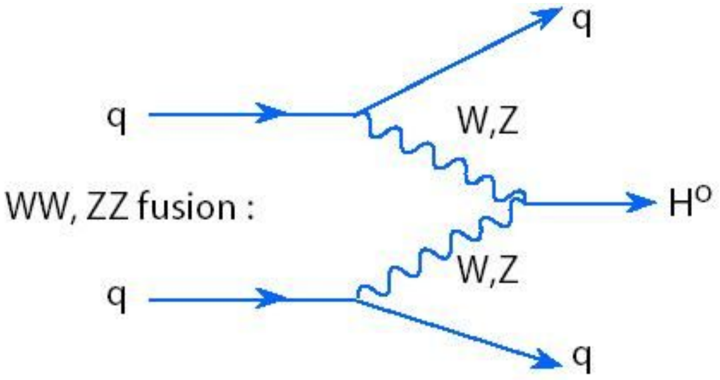
- H couples to most SM particles proportionally to their mass
  - Proportionality differs between fermions and vector bosons
- Higgs boson self-coupling driven by a different mechanism
- Couplings to massless particles (γ,g) through heavy particle loops

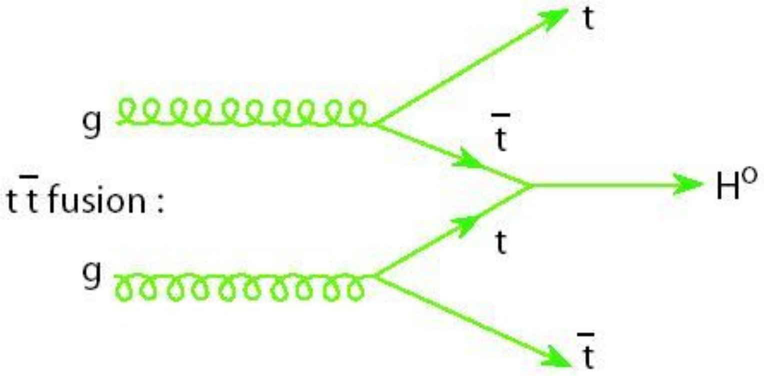


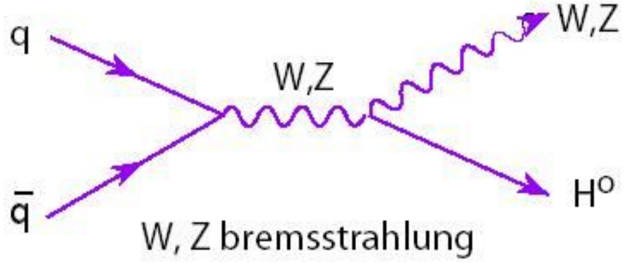


Higgs boson production - leading modes

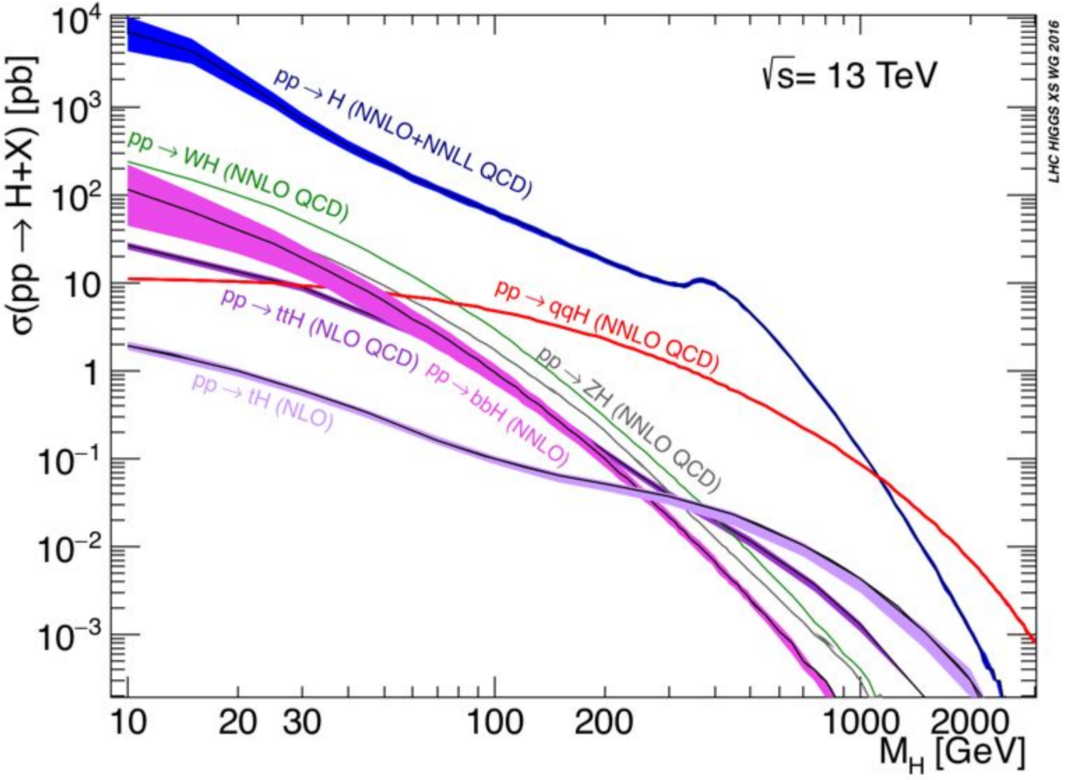






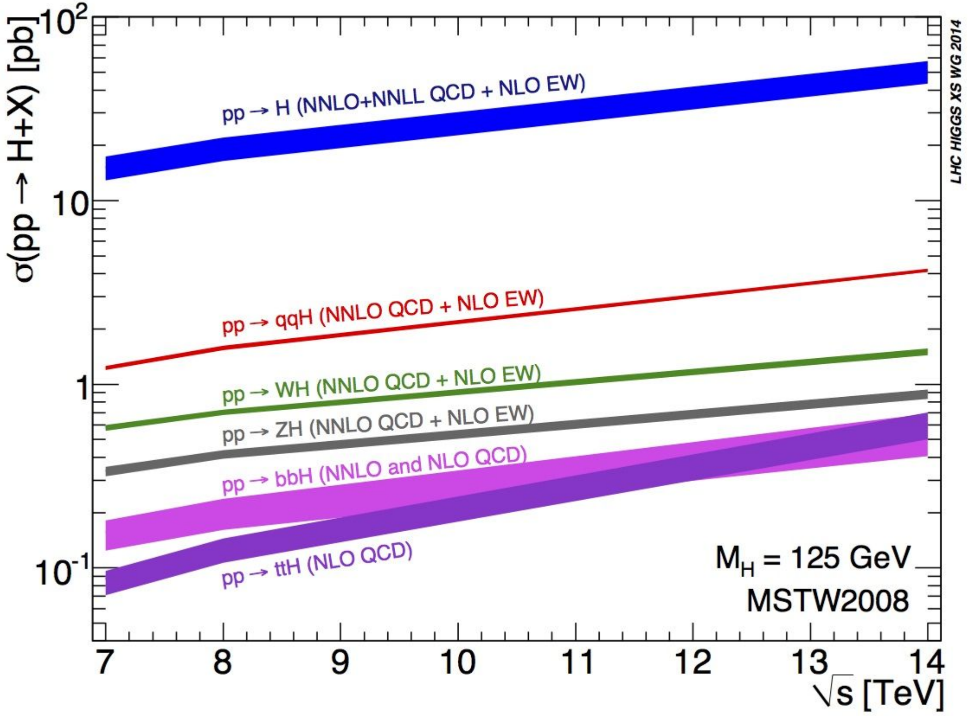


Higgs boson cross-section

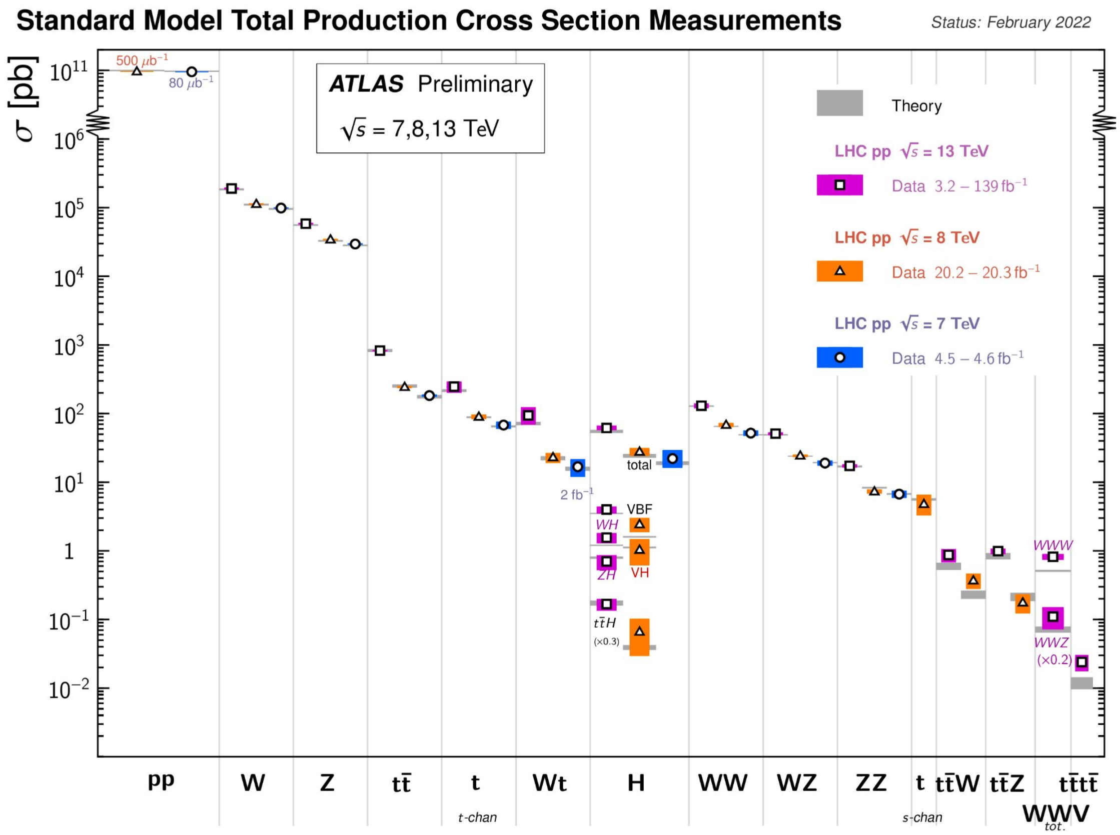


Higgs boson cross-section

- Production cross-section increases with increasing collision energy
- Many “background” processes do not increase as quickly with energy



Standard Model cross-sections



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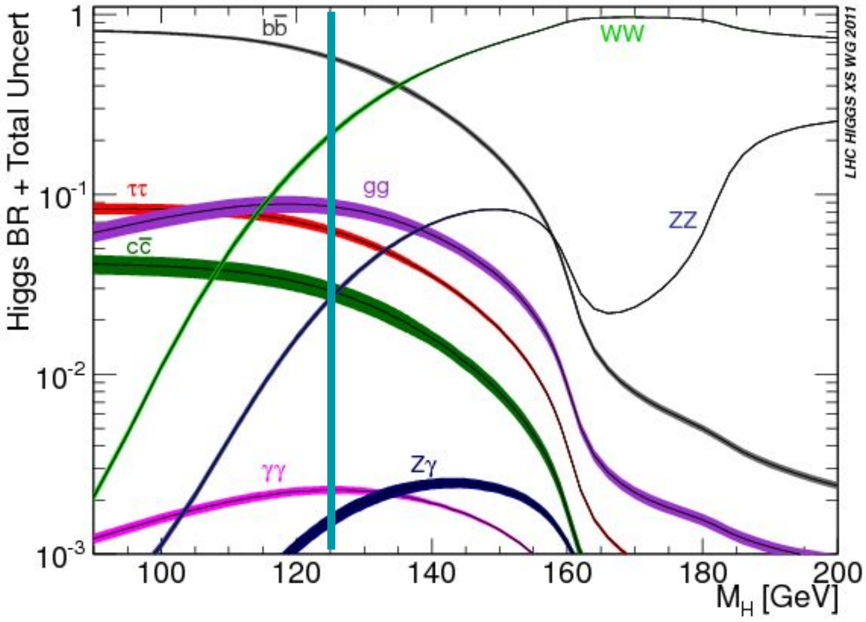
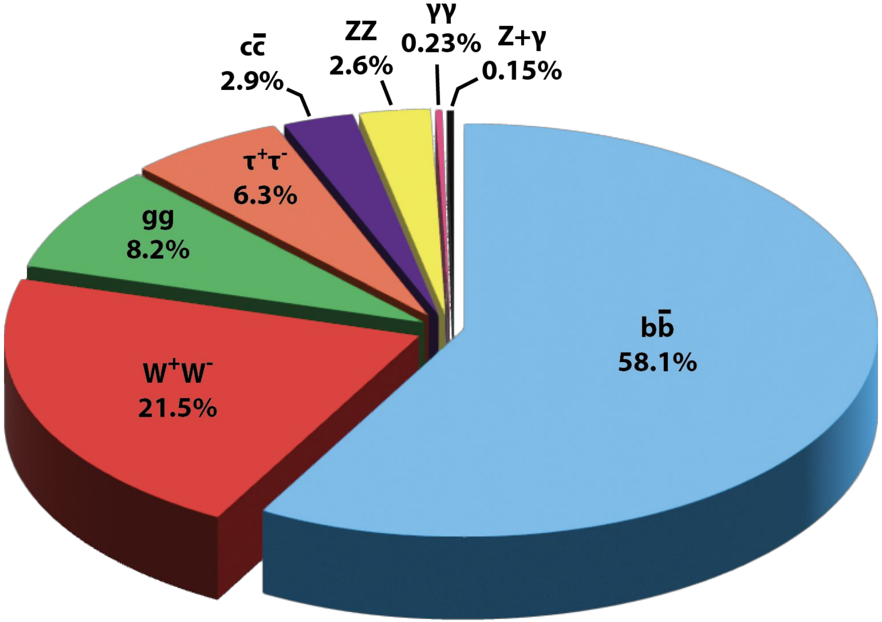
Higgs boson branching ratios

- The probability of H to decay into a given final state is normalize to one as a branching ratio (BR)
- Determined by coupling strength and kinematic constraints
    - Dependent on m_H

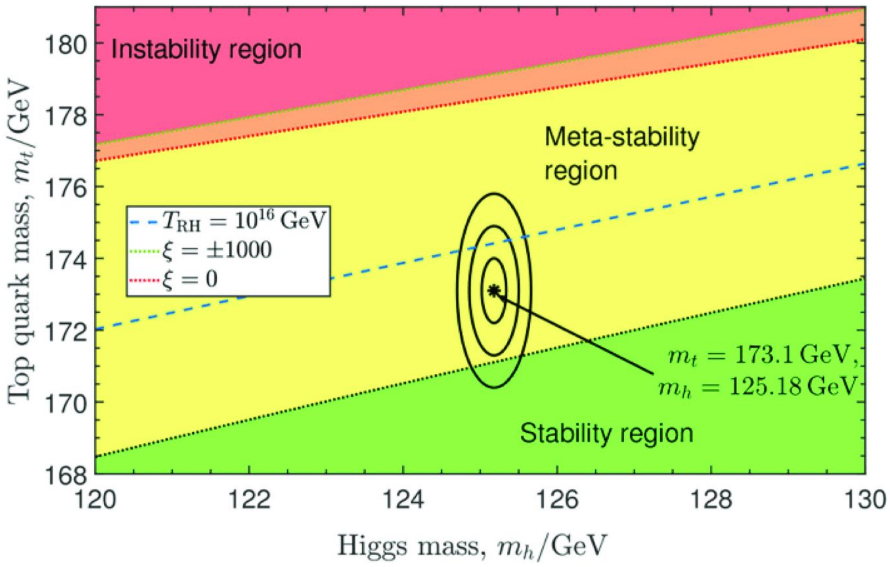


Higgs boson branching ratios



Higgs boson mass

- Theoretical and experimental constraints on mH existed before observation
- LEP results excluded mH < 114 GeV
- Indirect measurements indicated mH < 150 GeV
- Vacuum stability also set constraints on possible values



Markkanen, Rajantie, Stopyra

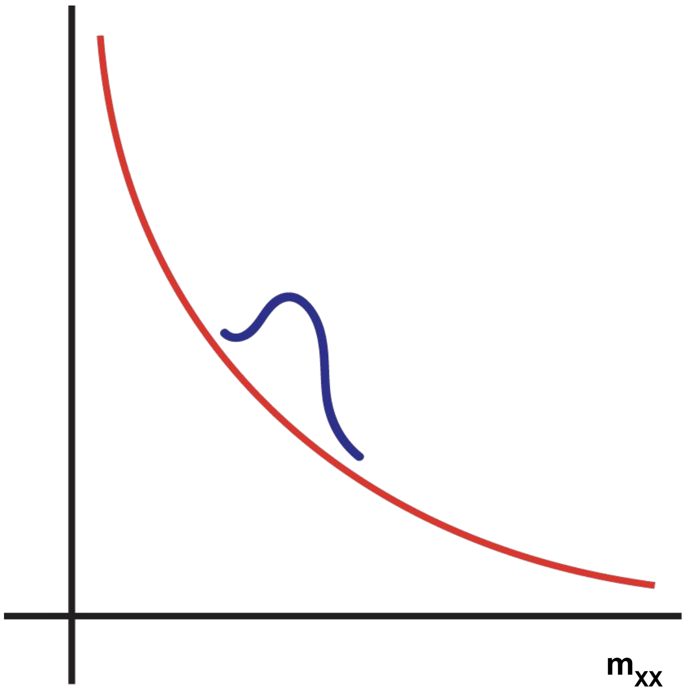
Search channels

There are a few decay modes that were used to discover the Higgs boson. They have the advantage of having very “clean” signatures that are easy to identify over background collisions. Other decay modes have since been observed and are important for measuring the properties of the Higgs boson.

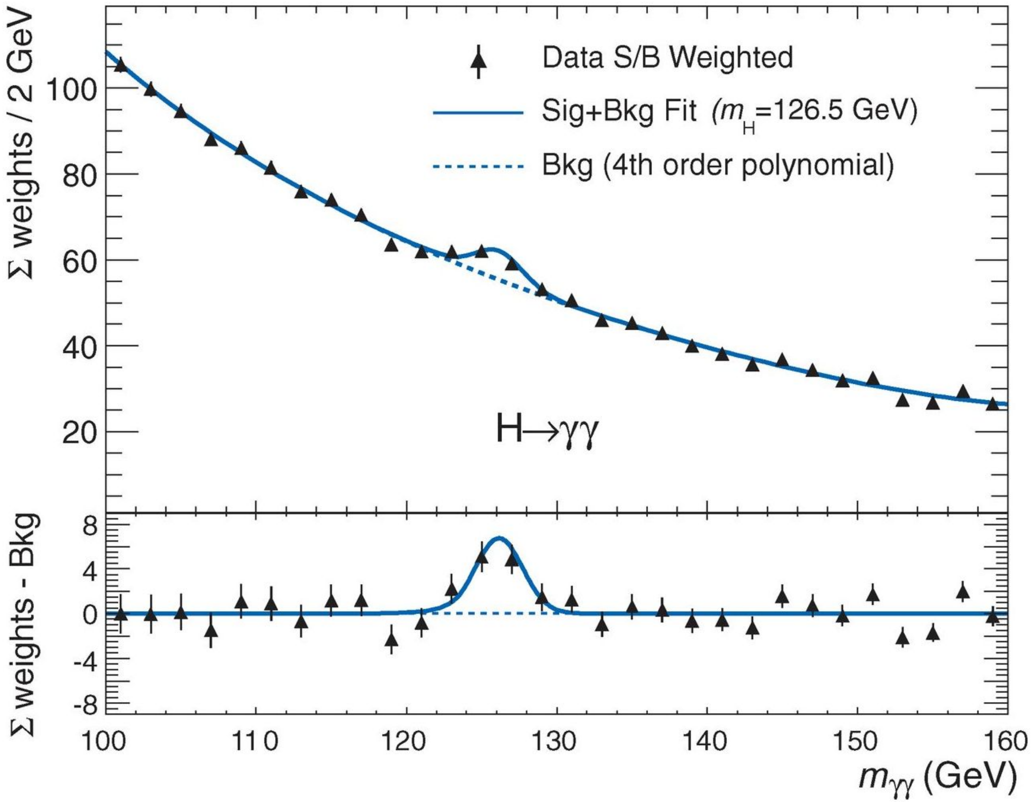
Decay mode	**What it looks like…**
$H \rightarrow \gamma\gamma$	Two very high-energy photons in the detector
$H \rightarrow ZZ^* \rightarrow 4l$	Four high-momentum charged leptons (electrons or muons). Each pair has opposite electric charge and corresponds to the decay of an intermediate Z boson

Resonance search

- Can add two particles with 4-vectors together to get an invariant mass, m_{xx}
- If the particles are uncorrelated, m_{xx} will be stochastic and produce a falling distribution
- If the particles come from the decay of a heavy particle, they will appear as a localized peak in the m_{xx} distribution
    - Peak location corresponds to heavy particle mass
- This is known as a resonance

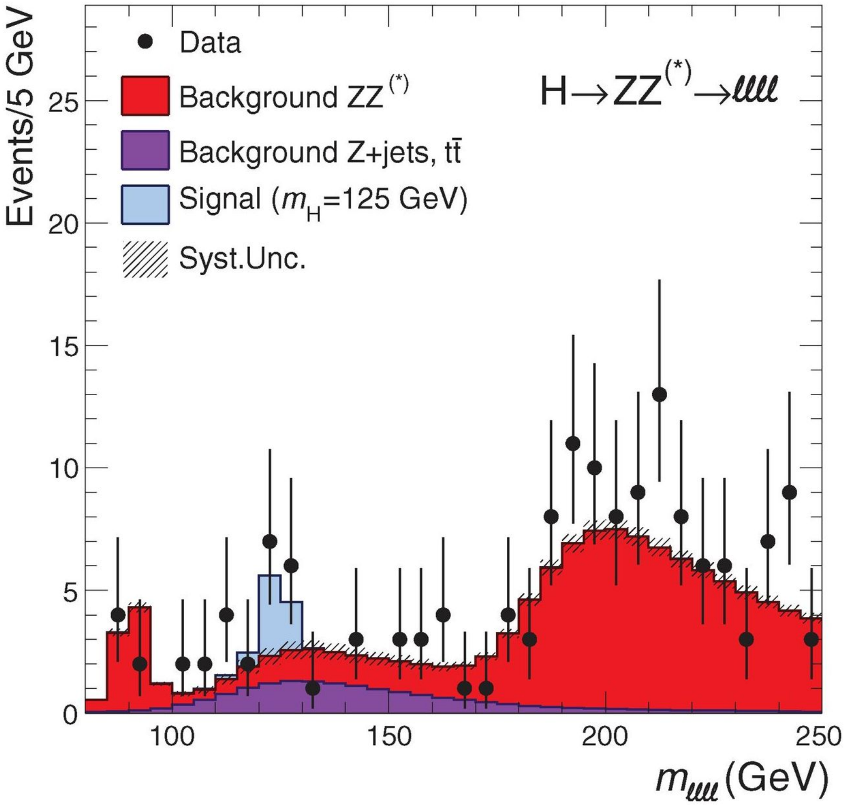


H➞γγ observation



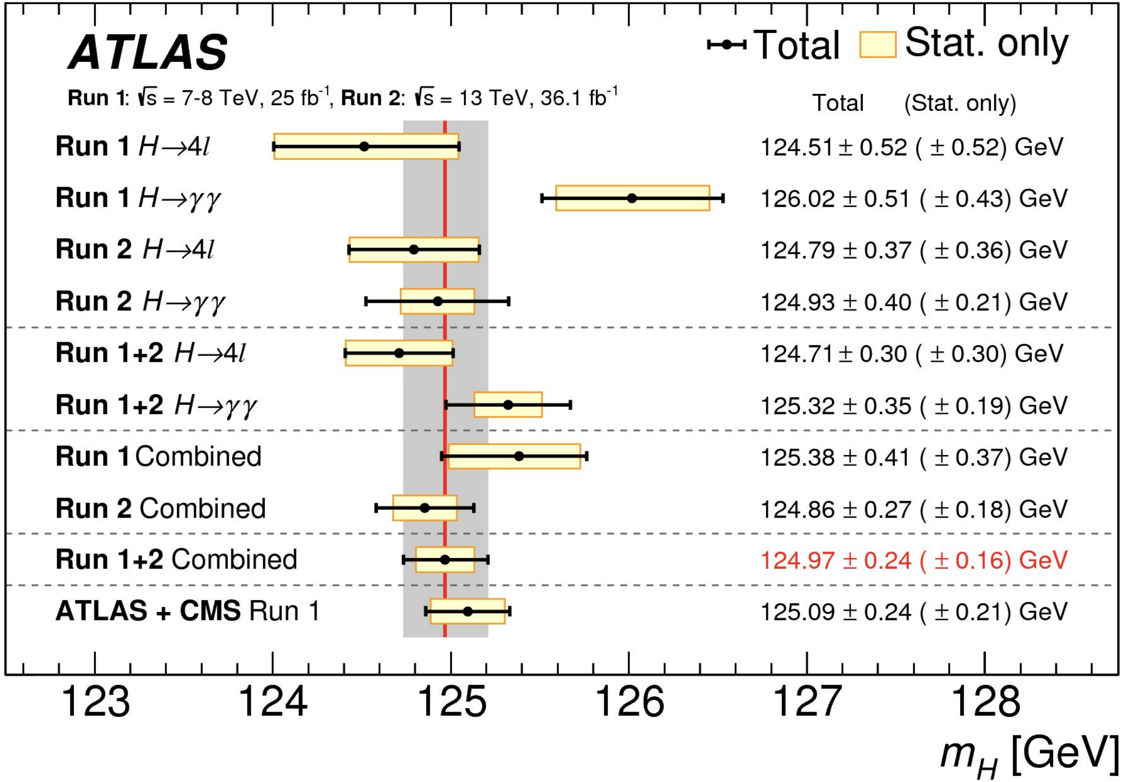
Science Vol. 338 no. 6114 pp. 1576-1582

H→ZZ*→4l observation



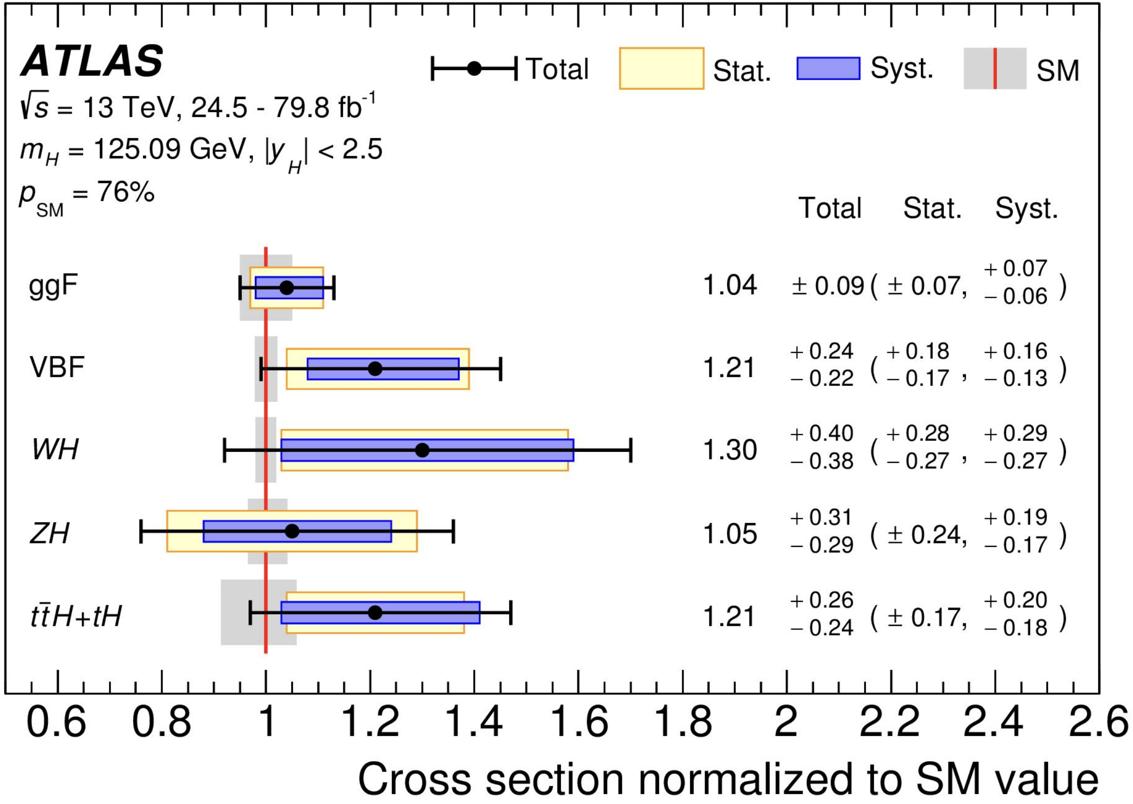
[Science Vol. 338 no. 6114 pp. 1576-1582]

Mass measurements



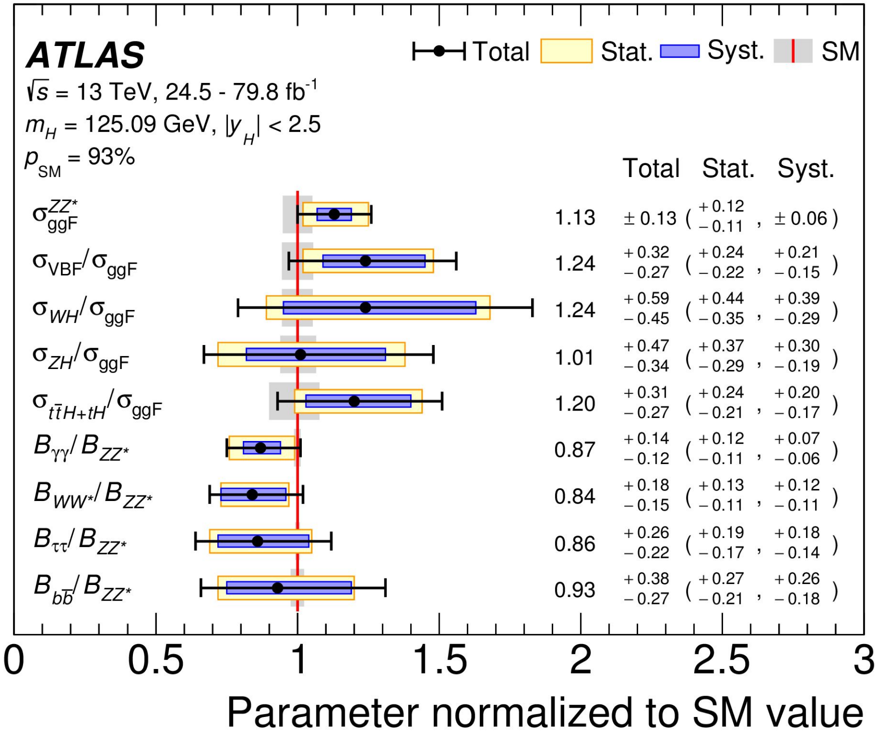
Phys. Lett. B 784 (2018) 345

Cross-section measurements



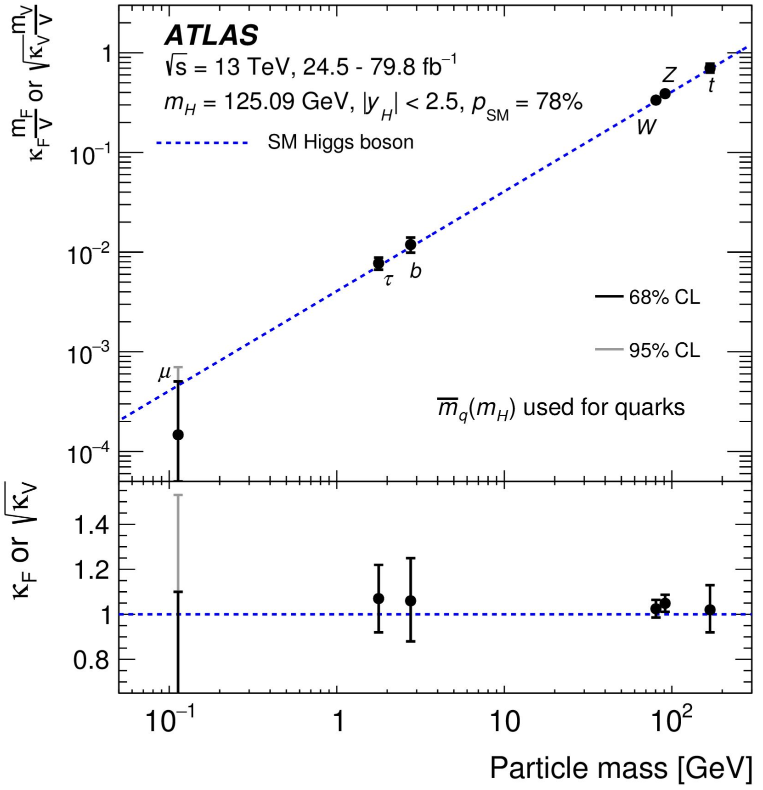
Phys. Rev. D 101 (2020) 012002

Decay measurements



Phys. Rev. D 101 (2020) 012002

Coupling measurements



Phys. Rev. D 101 (2020) 012002