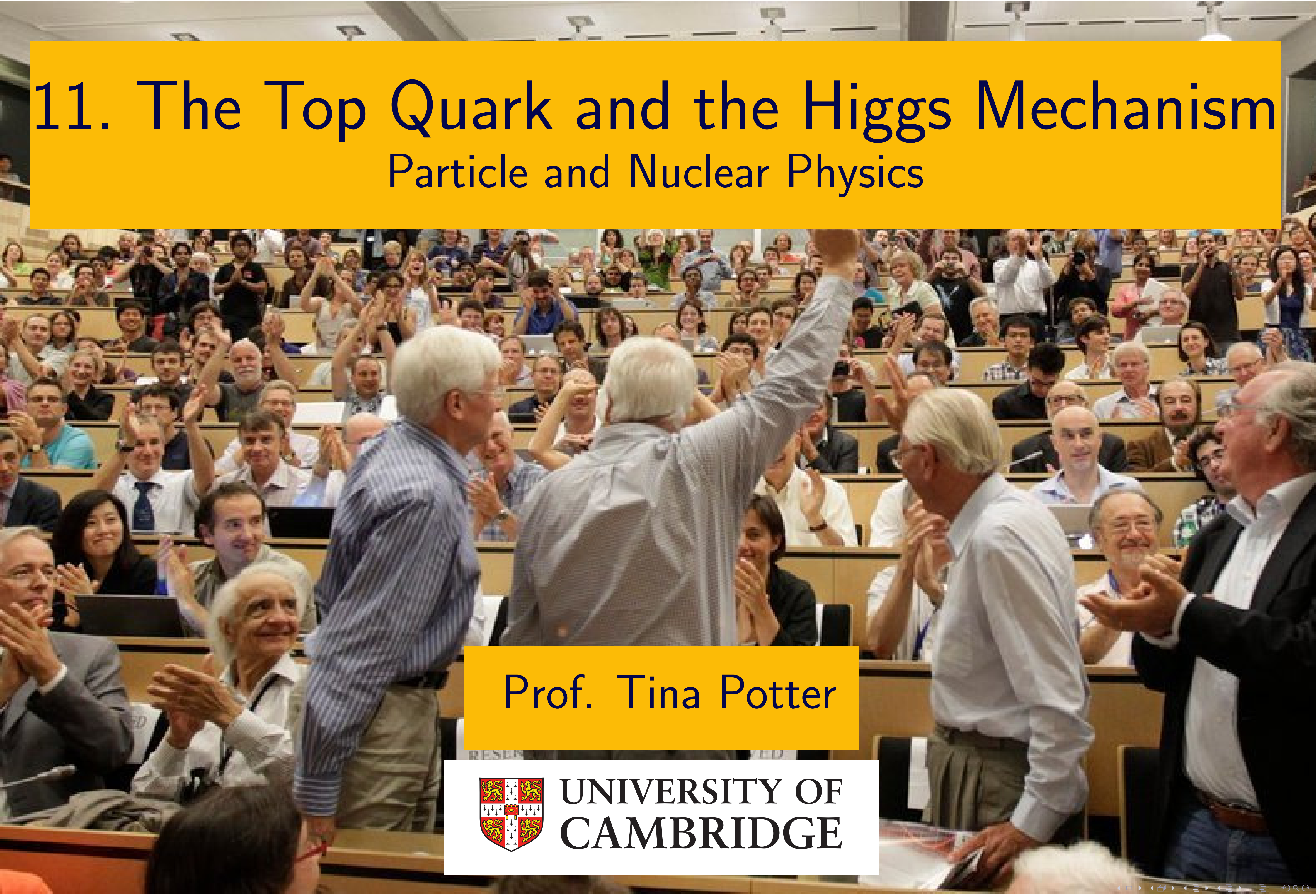

11. The Top Quark and the Higgs Mechanism

Particle and Nuclear Physics

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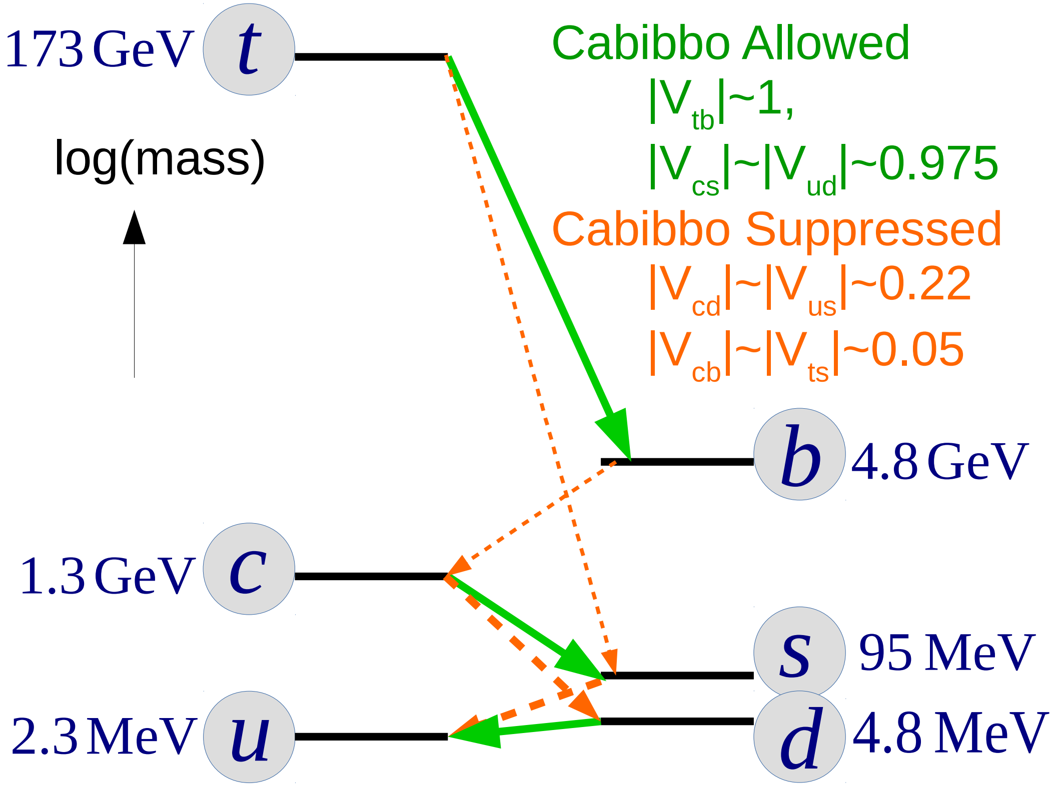
In this section...

- Focus on the most recent discoveries of fundamental particles
- The top quark – prediction & discovery
- The Higgs mechanism
- The Higgs discovery

Third Generation Quark Weak CC Decays

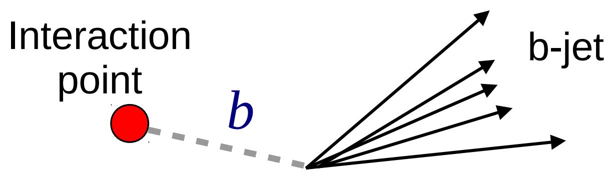


Top quarks are special.

- $m(t) \gg m(b)$ $(> m(W))$
- $\tau_t \sim 10^{-25}\,\mathrm{s} \Rightarrow$ decays before hadronisation
- $V_{tb} \sim 1 \Rightarrow$ BR$(t \to W + b)$=100%

Bottom quarks are also special.

- b quarks can only decay via the Cabbibo suppressed Wcb vertex. V_{cb} is very small – weak coupling!
  $\Rightarrow \tau(b) \gg \tau(u, c, d, s)$
- Jet initiated by b quarks look different to other jets. b quarks travel further from interaction point before decaying. b-jet traces back to a secondary vertex – "b-tagging".



The Top Quark *(non-examinable)*

The Standard Model predicted the existence of the top quark

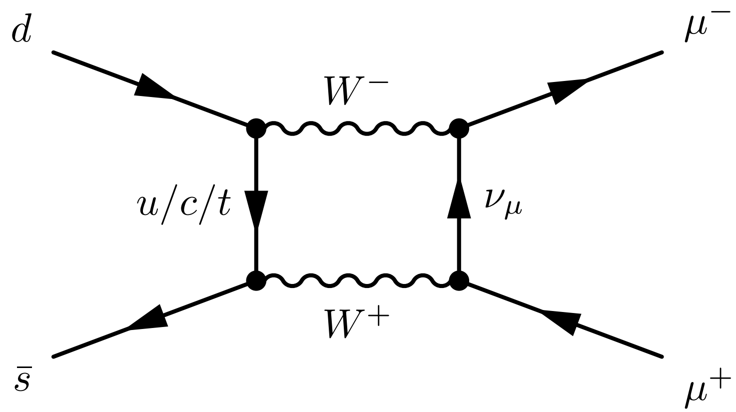
$$\begin{matrix} +\frac{2}{3}e \\ -\frac{1}{3}e \end{matrix} \quad \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

which is required to explain a number of observations.

Example: Non-observation of the decay

$K^0 \rightarrow \mu^+\mu^-$ $\qquad B(K^0 \rightarrow \mu^+\mu^-) < 10^{-9}$

The top quark cancels the contributions from the u and c quarks.



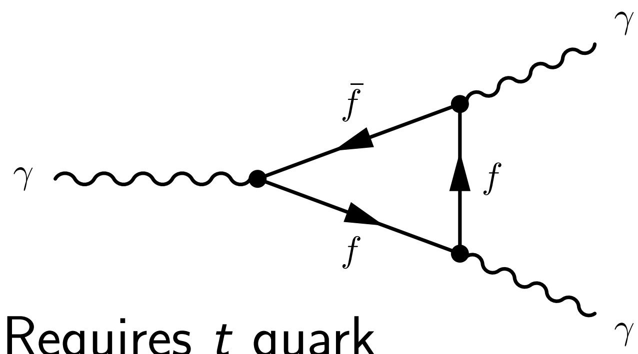
Example: Electromagnetic anomalies

This diagram leads to infinities in the theory unless

$\sum Q_f = 0$

where the sum is over all fermions (and colours)

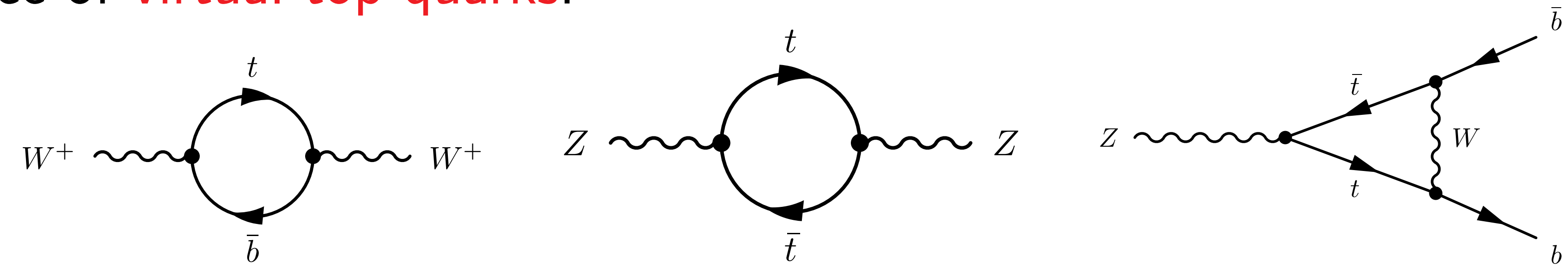
$$\sum_f Q_f = [3 \times (-1)] + \left[3 \times 3 \times \frac{2}{3}\right] + \left[3 \times 3 \times (-\frac{1}{3})\right] = 0$$



Requires t quark

The Top Quark

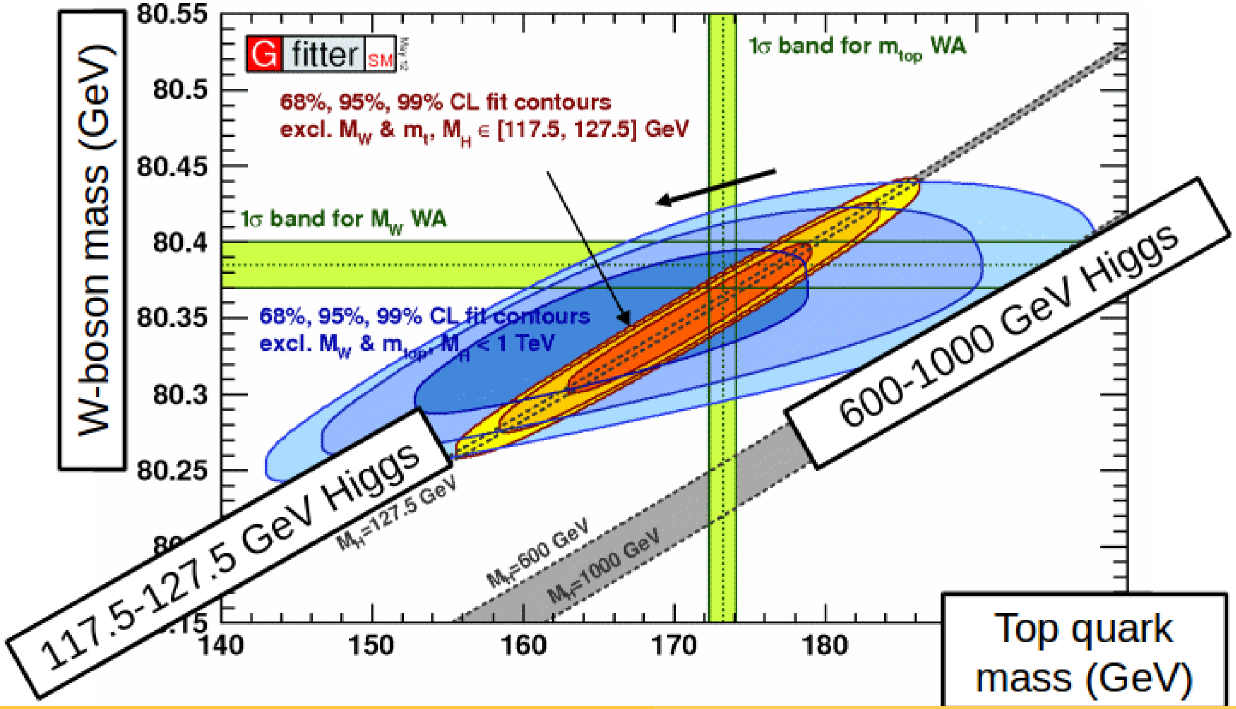
The top quark is too heavy for $Z \to t\bar{t}$ or $W^+ \to t\bar{b}$ so not directly produced at LEP.
However, precise measurements of m_Z, m_W, Γ_Z and Γ_W are sensitive to the existence of virtual top quarks:



Example

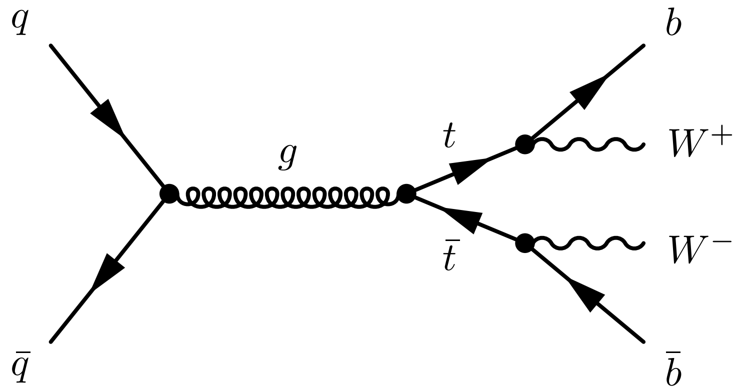
Standard Model prediction

Also depends on the Higgs mass



The Top Quark

- The top quark was discovered in 1994 by the CDF experiment at the worlds (then) highest energy $p\bar{p}$ collider ($\sqrt{s} = 1.8$ TeV), the Tevatron at Fermilab, US.



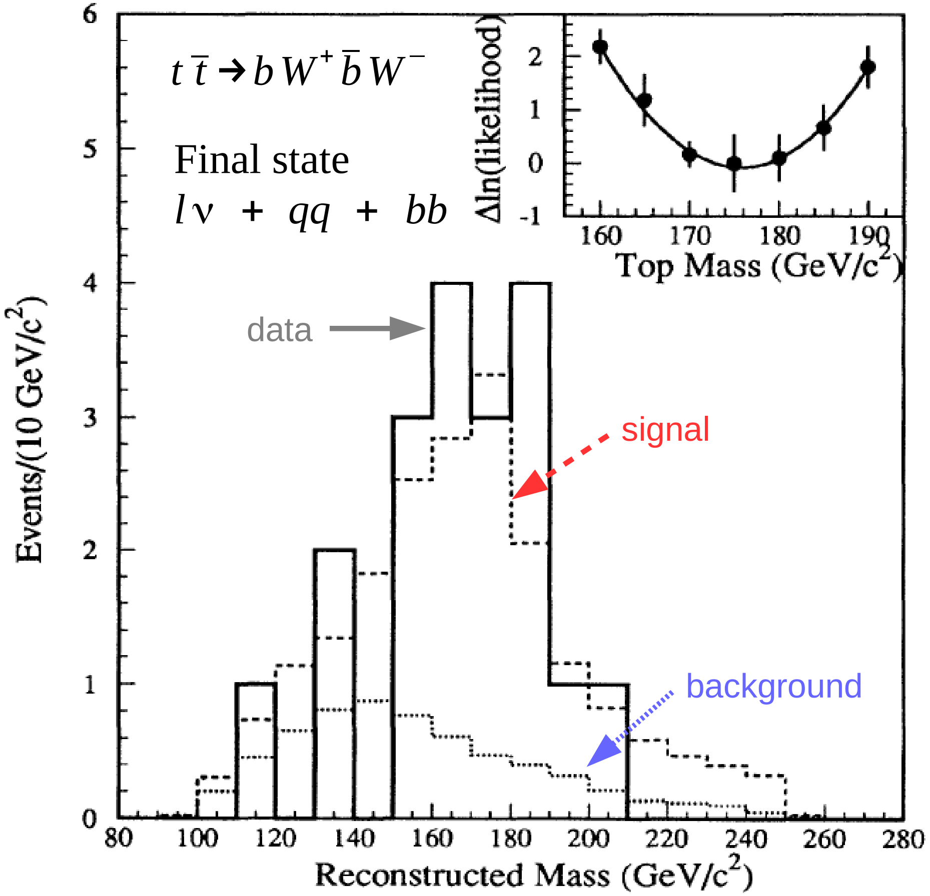
Final state $W^+W^-b\bar{b}$
Mass reconstructed in a similar manner to m_W at LEP, i.e. measure jet/lepton energies/momenta.

- $V_{tb} \sim 1$, so decay of top quark is ∼100% $t \to bW^+$
- $m_t \gg m_W$, so the W^+ is real. The weak decay is just as fast as a strong decay ($\sim 10^{-25}$s), so the quark has no time to hadronise

  $\Rightarrow$ there are no t-hadrons
- Possible top quark decays are $t \to bq\bar{q}$ or $t \to b\ell\nu_\ell$
- In hadron collisions, multijet final states are the norm – for rare processes it's much easier to look for leptonic decays, accompanied by b-quark jets.

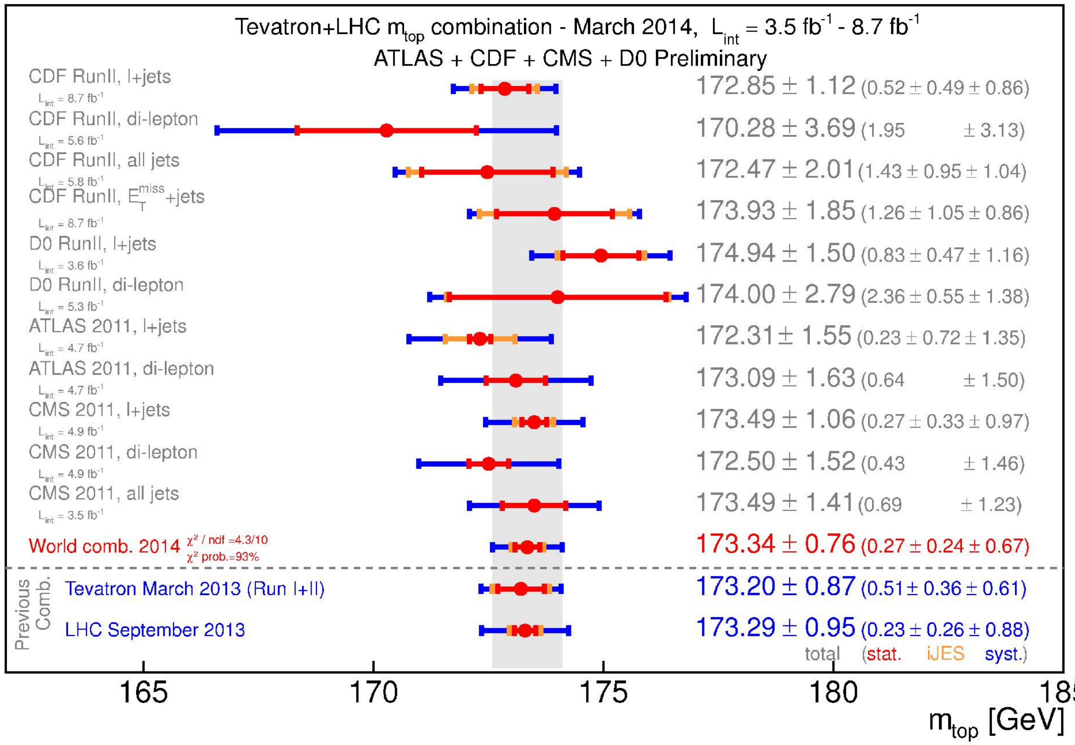
First observation of top (1995)

CDF collaboration published first PRL **74** 2626 (1995)



Current status

Results from LHC as well as Tevatron. All consistent, and in agreement with indirect expectation from LEP data.



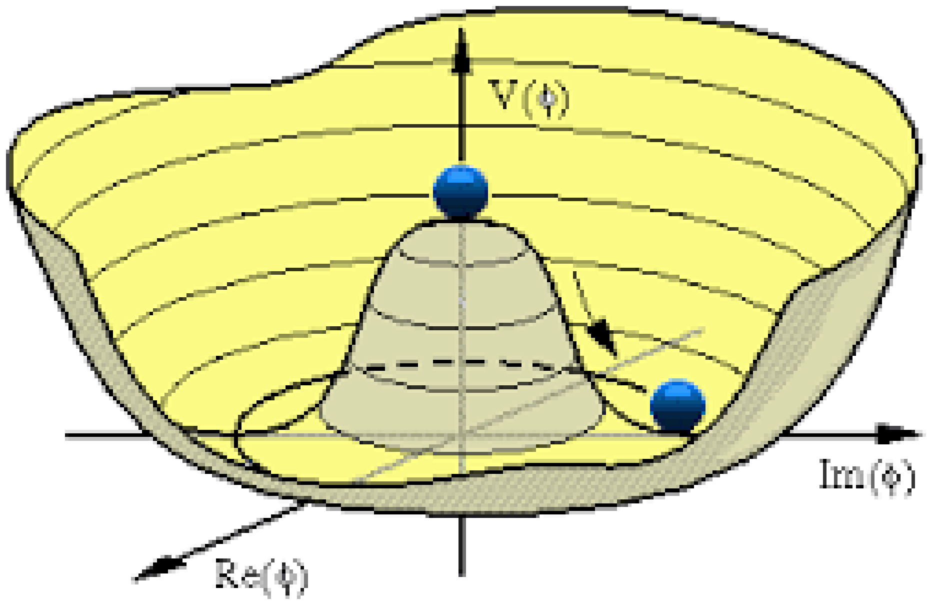
Higgs mechanism and the Higgs Boson

- Recall – the Klein-Gordon equation for massive bosons is:

$$\frac{\partial^2\psi}{\partial t^2} = \left(\boldsymbol{\nabla}^2 - m^2\right)\psi$$

- However, the term $m^2\psi$ (or $\frac{1}{2}m^2\psi^2$ in the Lagrangian formulation), is not gauge invariant.
- So in gauge field theories, the gauge bosons should be massless. OK for QED and QCD, but plainly not for $W^\pm$ and Z.
- The Higgs mechanism tries to fix this. Imagine introducing a scalar Higgs field ϕ, which has interactions with the $W^\pm$ and Z fields, with coupling strength y, giving a term in Lagrangian $y\phi\psi\psi$.
- Looks like a mass term ($\propto \psi^2$). Mass of the bosons becomes effectively related to their coupling to the Higgs field.
- Requires the vacuum (lowest energy state of space) to have a non-zero expectation value for the Higgs field. How can this come about?

Higgs potential



- Suppose the Higgs field ϕ (actually a complex doublet) has self interactions yielding

$$V(\phi) = a\phi^4 - b\phi^2$$

- The equilibrium point, $\phi = 0$, respects the symmetry, but is unstable.
- The stable equilibrium point is at $|\phi^2_{\rm GS}| = b/2a$. The symmetry is "spontaneously broken".
- A weak boson propagating in the Higgs field will appear to have a mass $\sim y\phi_{\rm GS}$.
- Expanding about the ground state $V(\phi_{\rm GS} + x) = V_{\rm min} + 2bx^2$
- So can get excitations of the Higgs field about the minimum. These form the physical Higgs scalar boson, H – the observable physical manifestation of the operation of the Higgs mechanism.

Classical analogue of the Higgs mechanism

(non-examinable)

- Maxwell's equations lead to waves travelling at velocity c, hence to massless photons.
- Consider waves propagating in a charged plasma, with electron density n per unit volume.

Plasma: $\vec{J} = ne\vec{v}; \quad m_e \frac{\partial \vec{v}}{\partial t} = e\vec{E} \quad \Rightarrow \frac{\partial \vec{J}}{\partial t} = \frac{ne^2 \vec{E}}{m_e}$

Maxwell:

$$\vec{\nabla} \wedge \vec{\nabla} \wedge \vec{E} = -\nabla^2 \vec{E} = \vec{\nabla} \wedge \left(-\frac{\partial \vec{B}}{\partial t} \right) = -\frac{\partial \vec{\nabla} \wedge \vec{B}}{\partial t} = -\frac{\partial}{\partial t} \left(\mu_0 \vec{J} + \frac{1}{c^2} \frac{\partial \vec{E}}{\partial t} \right)$$

$$= -\frac{\mu_0 n e^2 \vec{E}}{m_e} - \frac{1}{c^2} \frac{\partial^2 \vec{E}}{\partial t^2} \qquad \Rightarrow \nabla^2 \vec{E} - \frac{1}{c^2} \frac{\partial^2 \vec{E}}{\partial t^2} = \frac{\mu_0 n e^2 \vec{E}}{m_e}$$

- Compare with Klein-Gordon. Photon propagates with effective mass

$$m_{\text{eff}}^2 = \frac{\hbar \mu_0 n e^2}{m_e c^2}$$

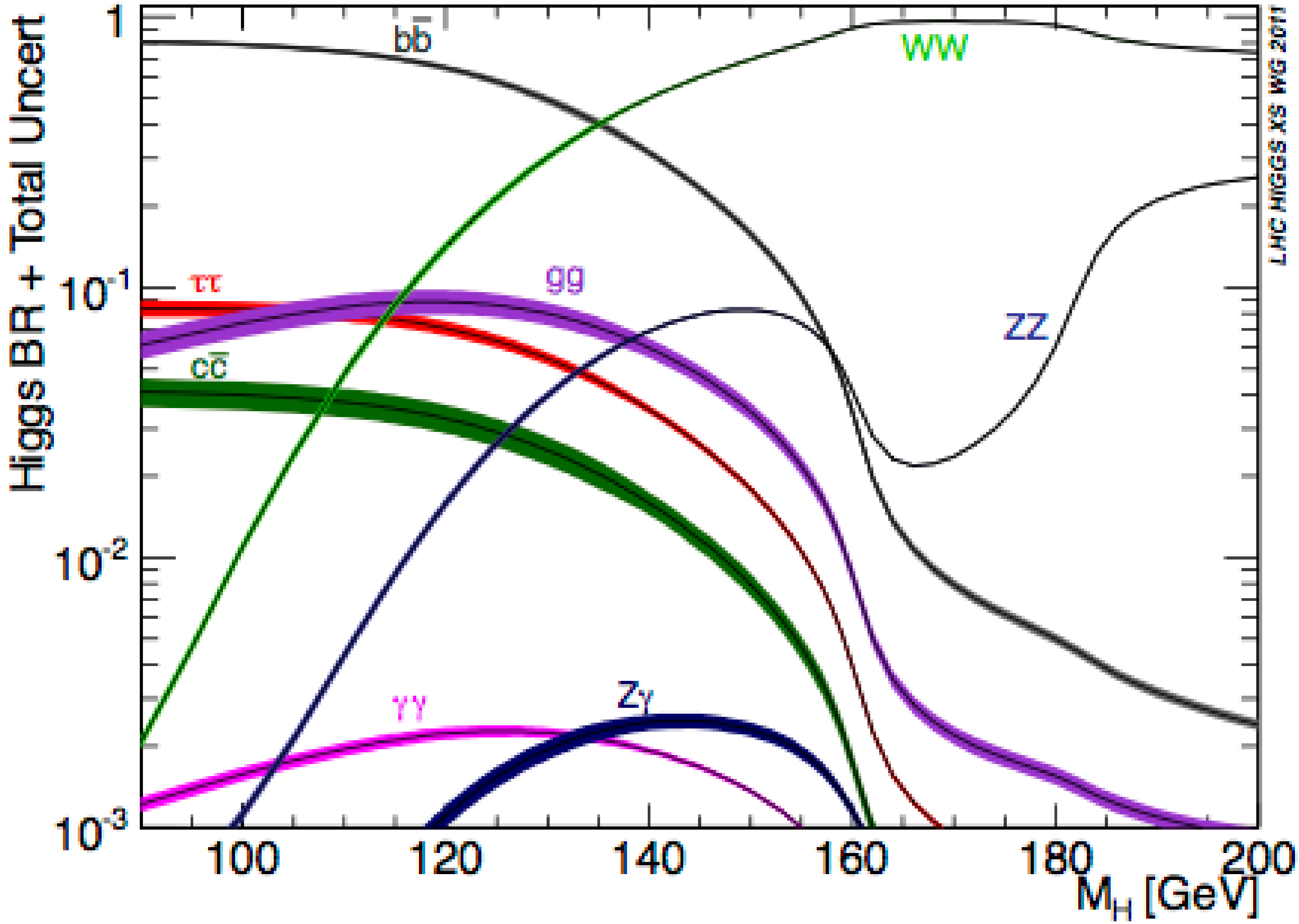
Note $m_{\text{eff}} \propto e$, the coupling.

Higgs theory summary

- Gauge bosons (and also fermions) are intrinsically massless, and need to be so to satisfy Gauge Invariance.
- Nevertheless, interactions with the Higgs field make particles look like they have mass.
- Apparent masses are controlled by free parameters called Yukawa Couplings (the strength of the coupling to the Higgs field)
- A Higgs Boson arises as an excitation of the Higgs field. It must be a scalar particle to make everything work.
- The Higgs Boson has a mass, but the mass is not predicted by the theory – we have to find it experimentally.
- The Higgs Boson has couplings to all the particles to which it gives mass (and so has many ways it could decay), all fully calculable and determined by the theory as a function of its (a priori unknown) mass.

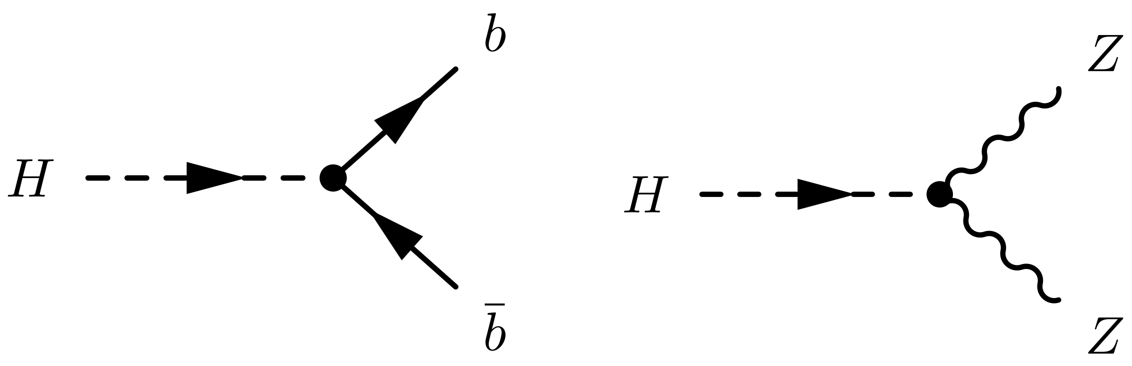
Higgs boson decays

- Higgs Boson interacts via couplings which are proportional to masses.
- Higgs boson therefore decays preferentially to the heaviest particles that are kinematically accessible, depending on its mass.

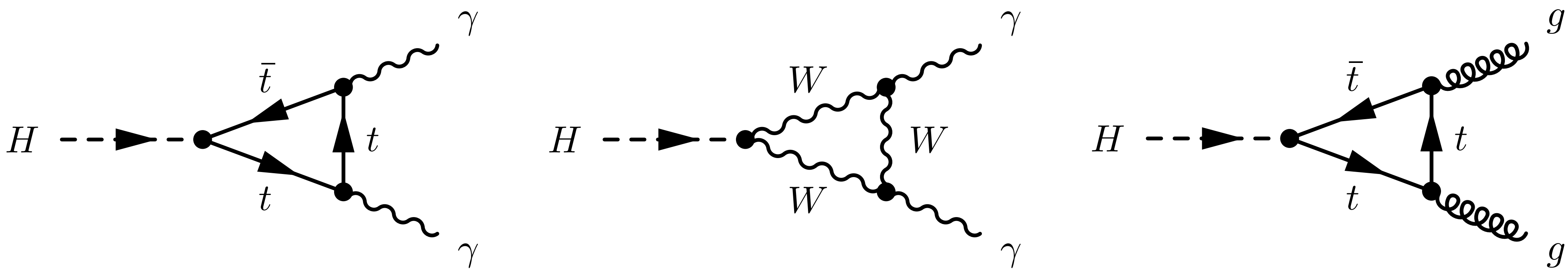


Higgs decay mechanisms

Directly to two fundamental fermions or bosons, coupling to mass, e.g.



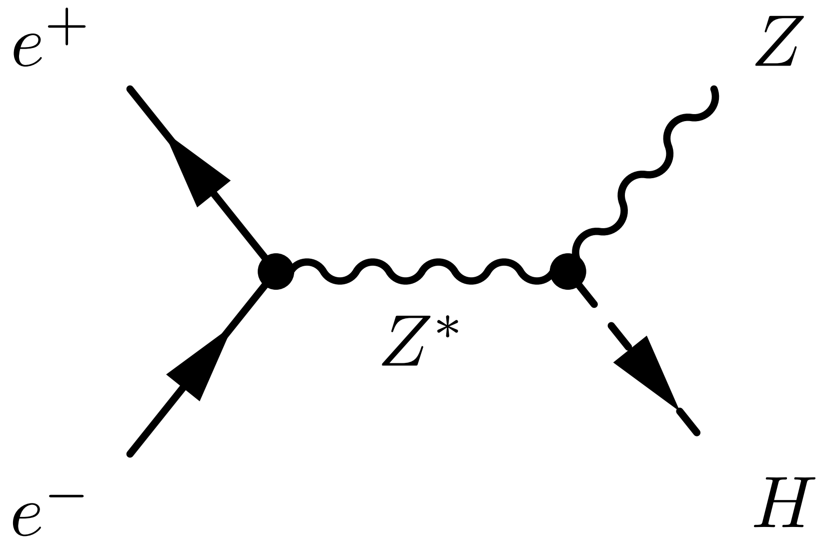
Indirectly to massless particles (photons or gluons) via massive loops



Higgs at LEP

Higgs Production at LEP (Large Electron Positron Collider – 1990s):

If $m_H < \sqrt{s} - m_Z$



"Higgsstrahlung" mechanism

In 2000, LEP operated with $\sqrt{s} \sim 207$ GeV, therefore had the potential to discover Higgs boson if $m_H < 116$ GeV.

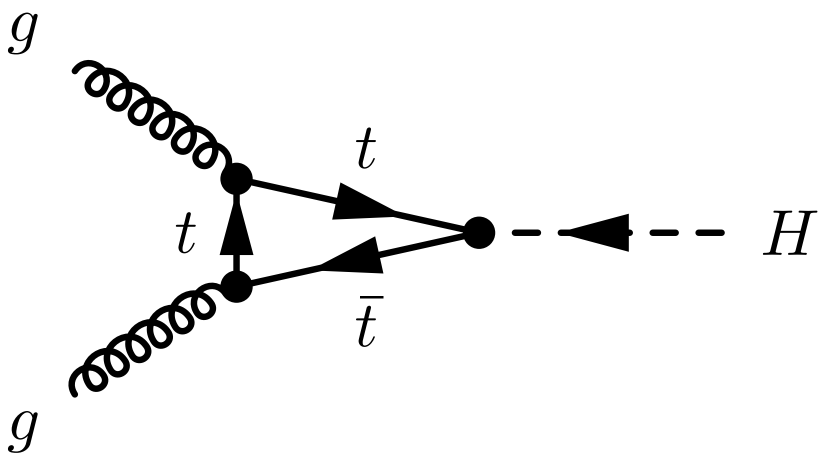
Searches were conducted in many possible final states (different decays for Z and H). All negative.

Ultimately, LEP excluded a Higgs Boson with a mass below 114 GeV.

Higgs at Large Hadron Collider

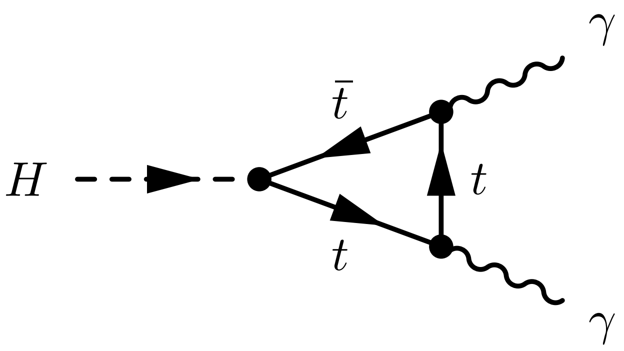
Higgs Production at the LHC

The dominant Higgs production mechanism at the LHC is

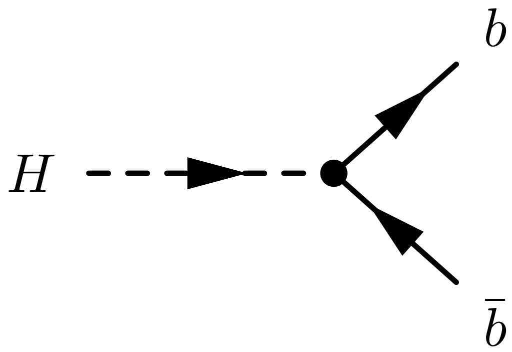


"Gluon fusion"

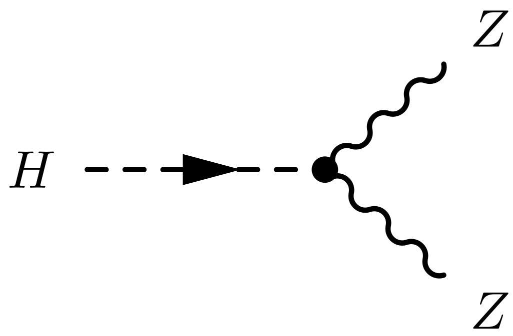
Higgs Decay at the LHC



Low mass



Medium mass

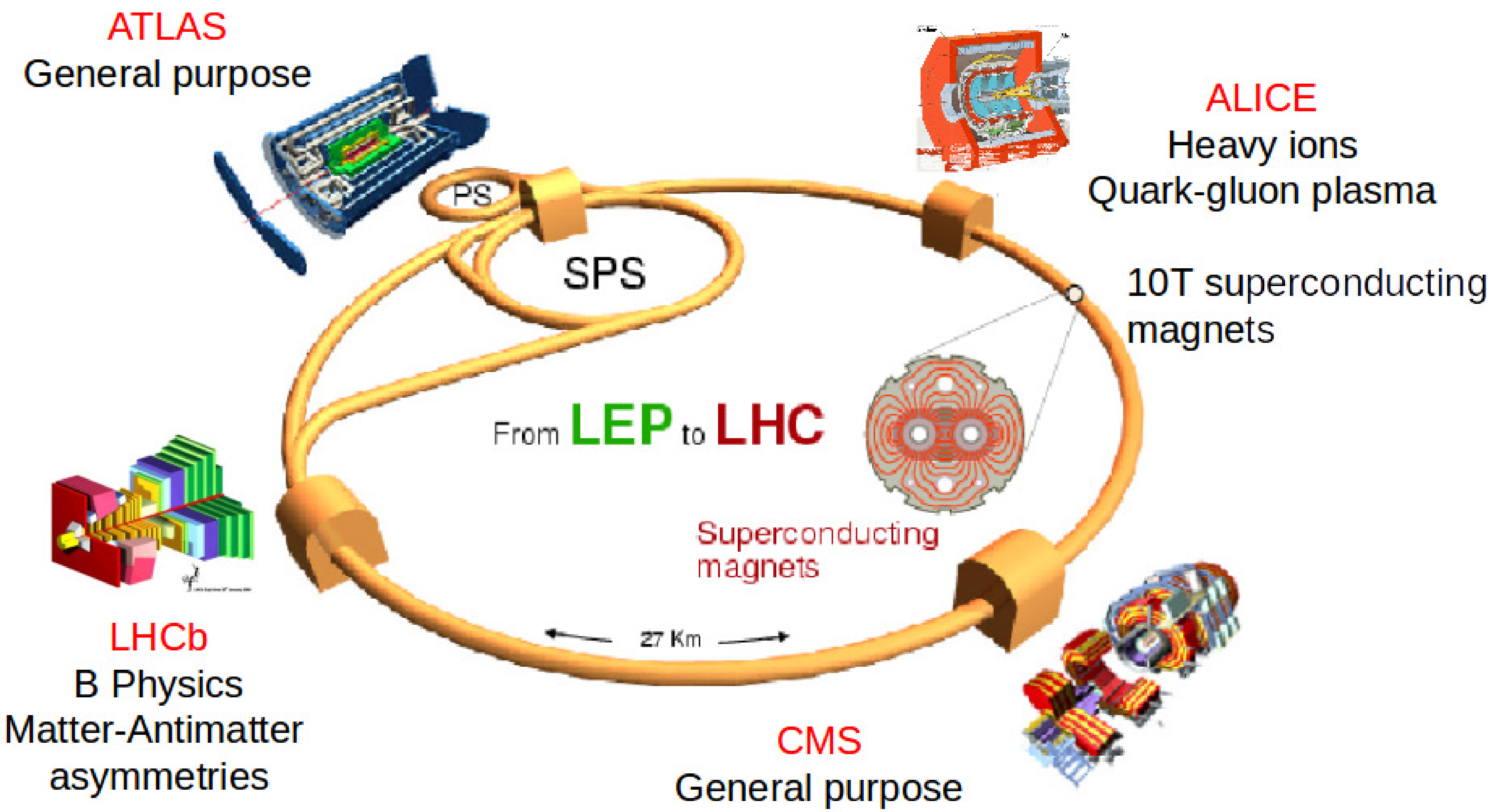


High mass

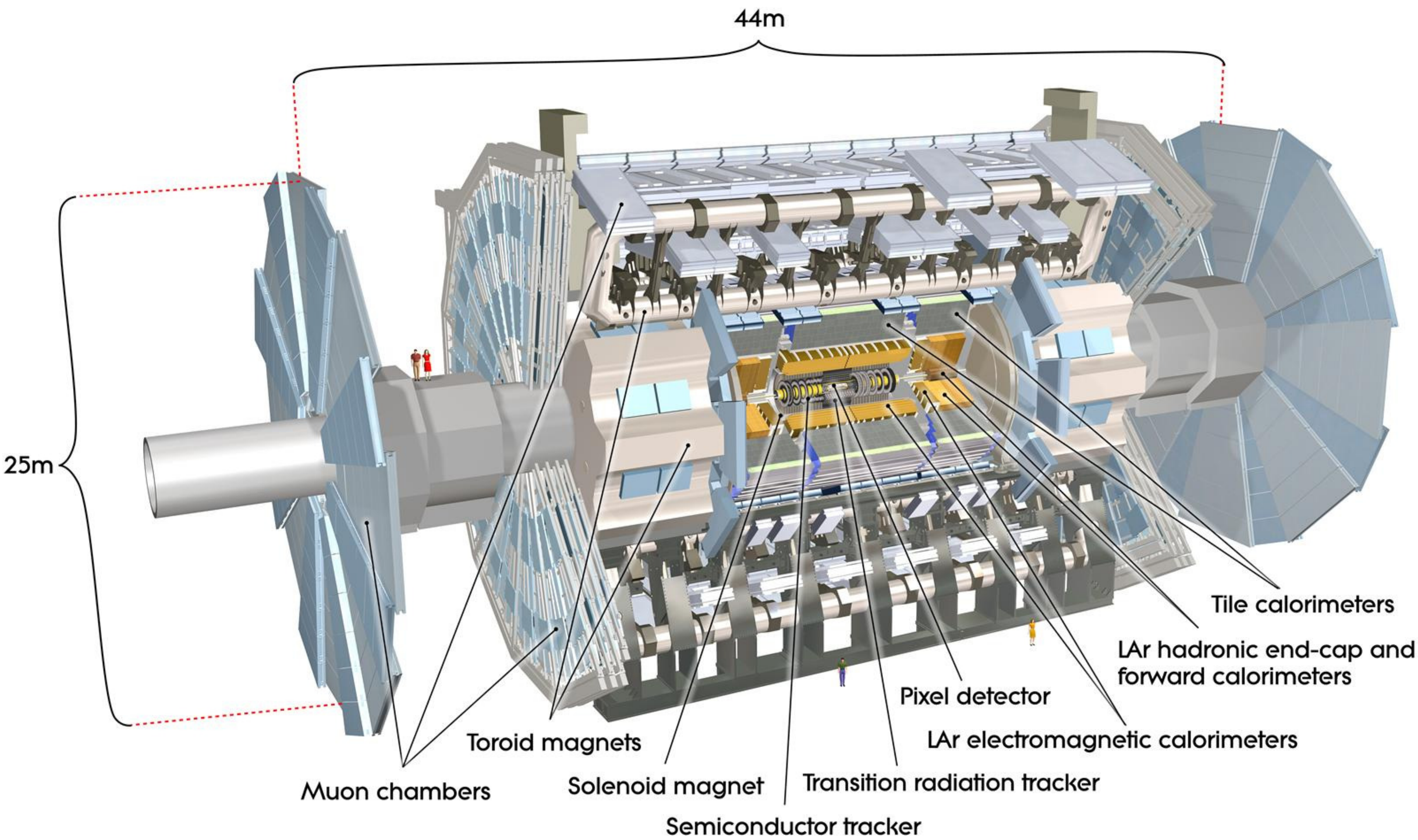
One Z may be virtual

The Large Hadron Collider

The LHC is a new proton-proton collider now running in the old LEP tunnel at CERN. In 2012 $4+4$ TeV; in 2015 $6.5+6.5$ TeV; ultimately $7+7$ TeV



ATLAS – a general purpose LHC detector



Higgs Observations (August 2014)

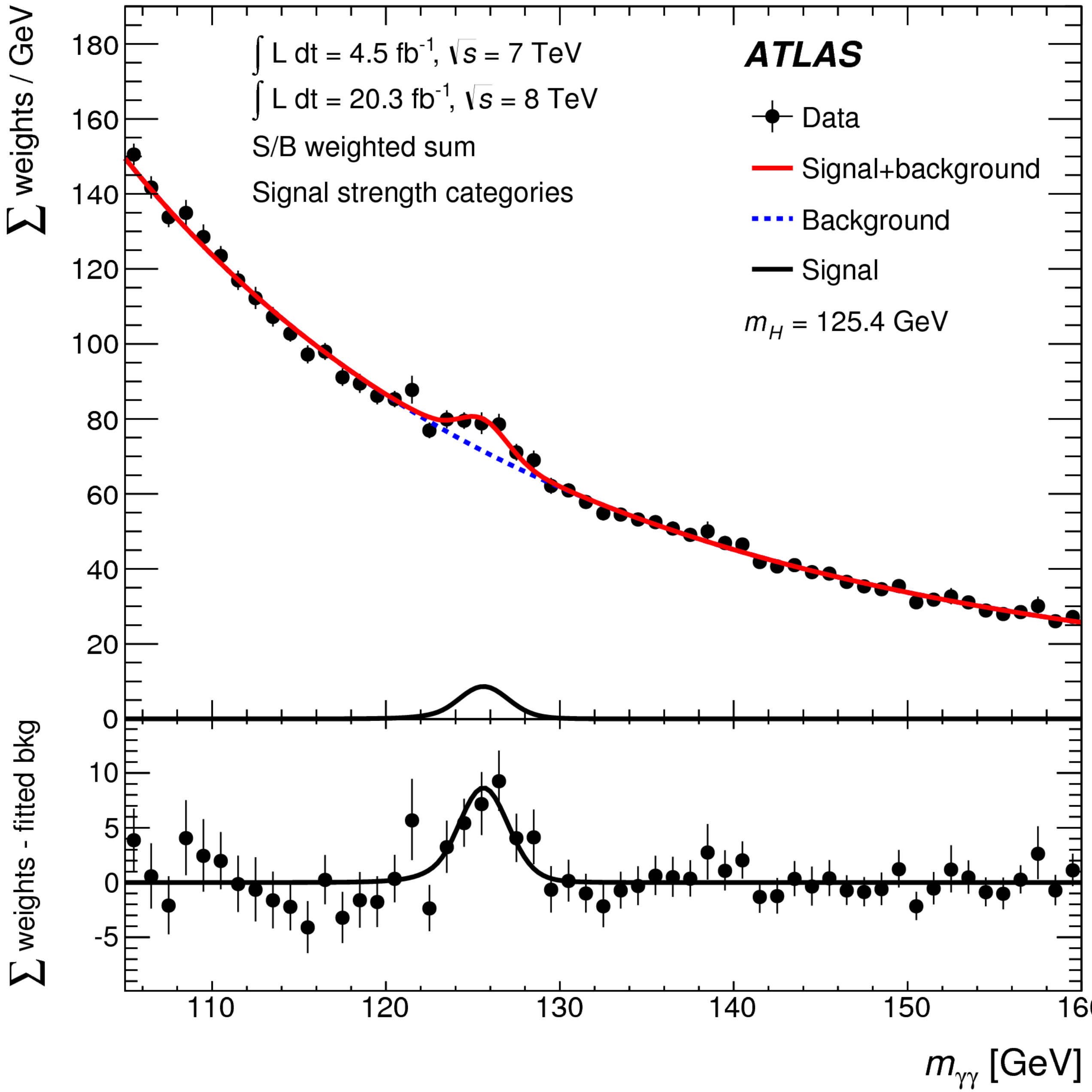
Indirect indications from LEP that Higgs mass should be not far above 115 GeV.

Dominant decay modes are all difficult:

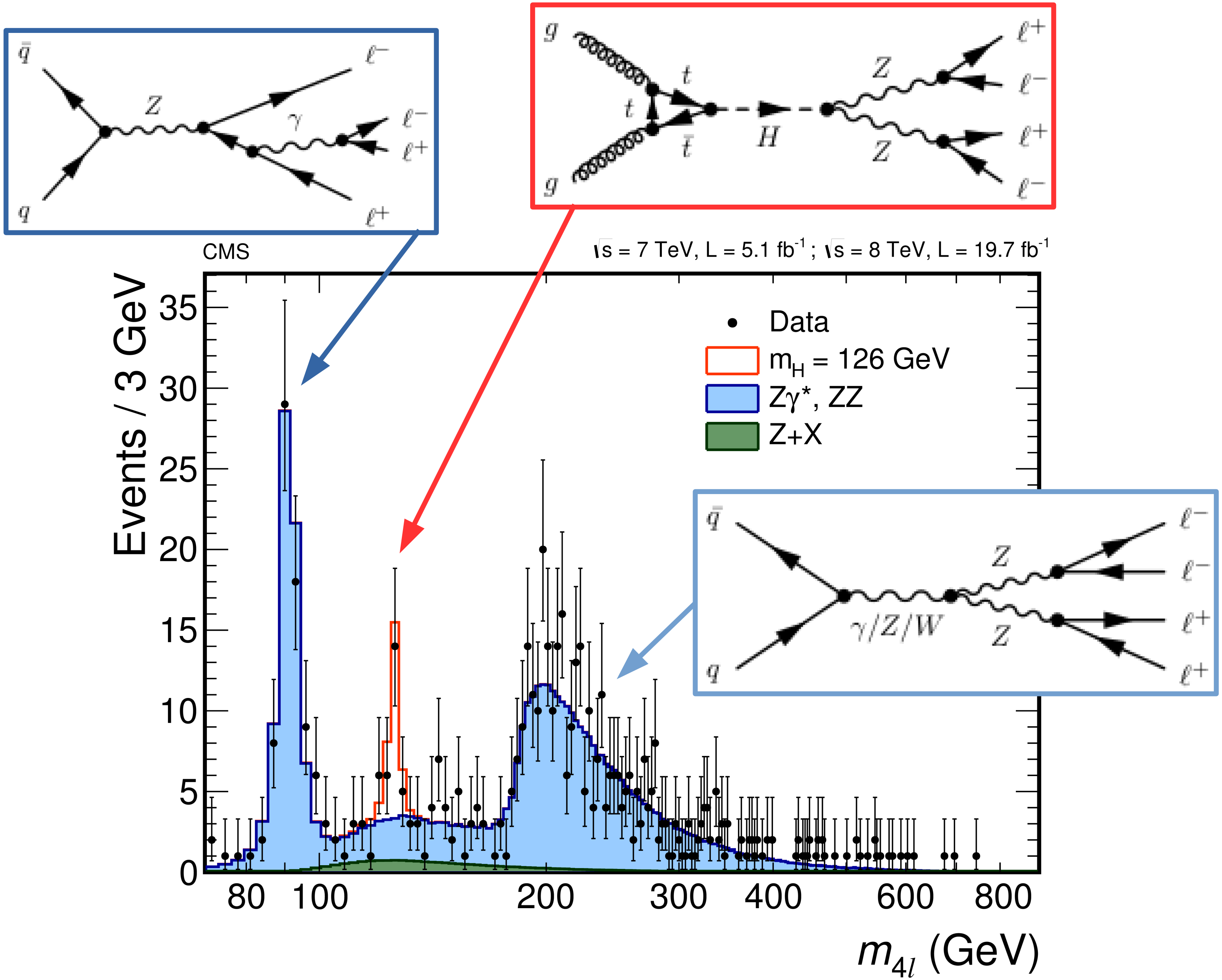
- $b\bar{b}$, $c\bar{c}$
  (swamped by QCD jets)
- W^+W^-, $\tau^+\tau^-$
  (missing neutrinos)

Best options are the rare decays:

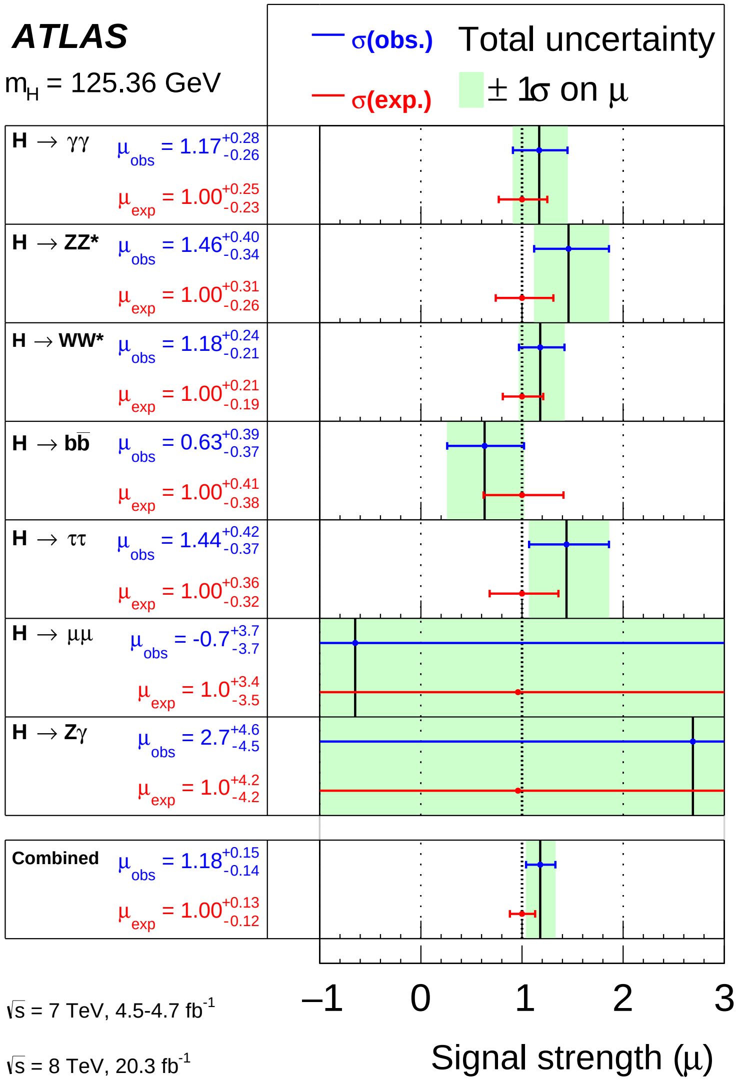
- $ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$
  $\gamma\gamma$



$H \to ZZ \to 4\ell$



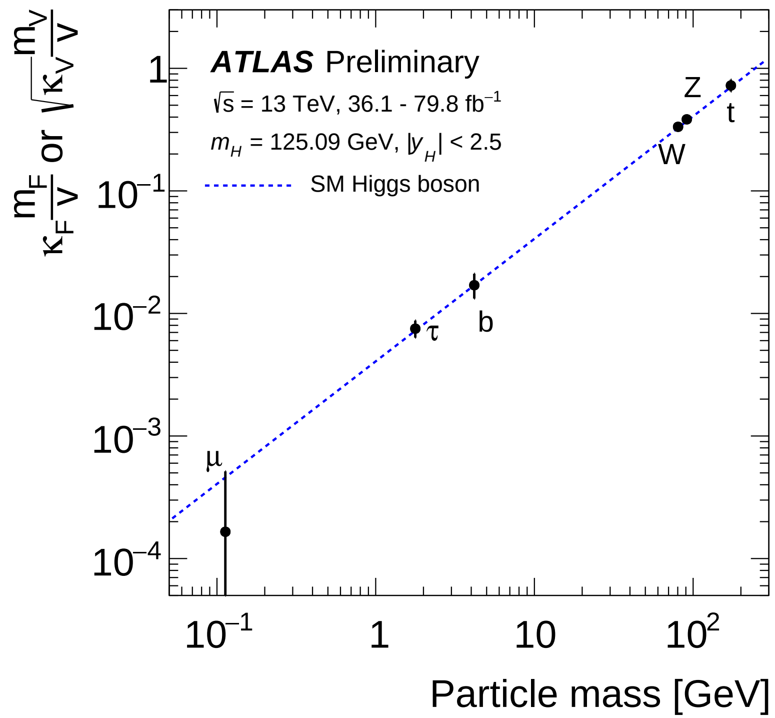
Higgs Boson Discovery



Convincing signal consistent with $m(H) = 126\ \mathrm{GeV}$ – seen in multiple decay modes & in two experiments.

Is it the Higgs boson of the SM?

Need to check its quantum numbers (should be $J^P = 0^+$).



Check branching ratios and couplings.

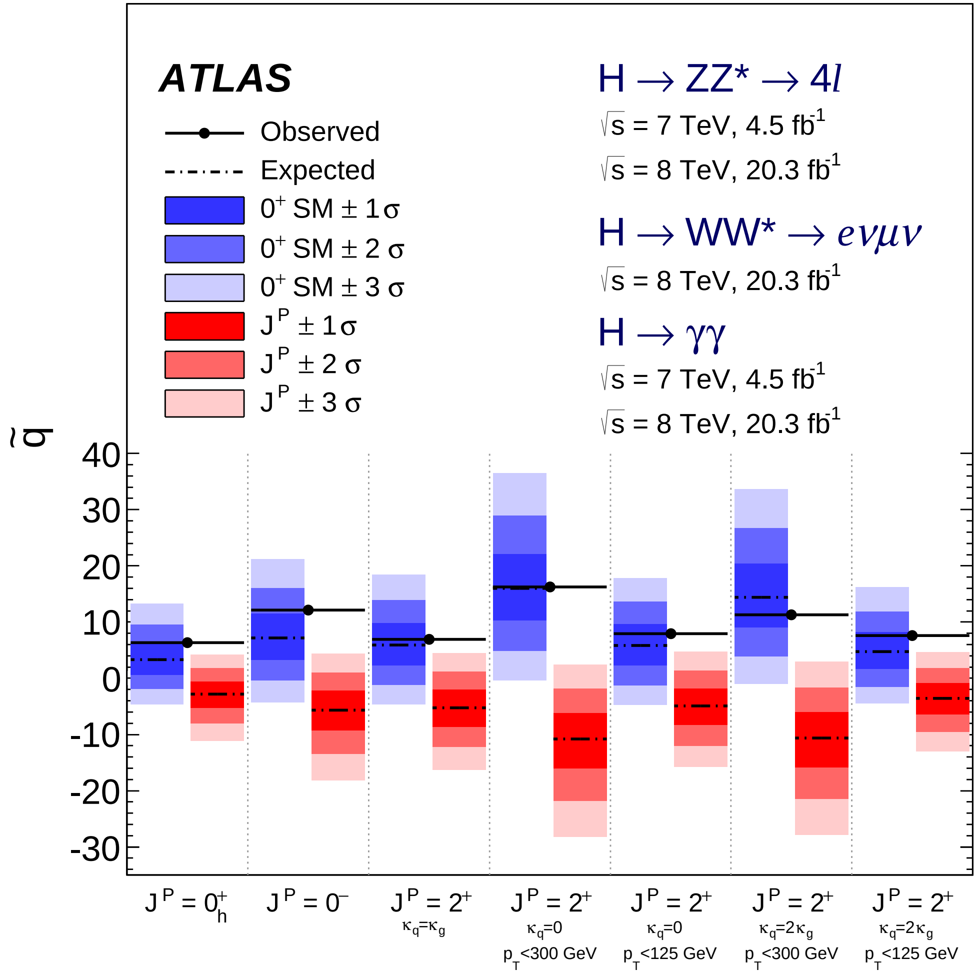
Look ok so far...

Higgs spin+parity?

Studied using angular distributions of decay products

So far it looks like the 0^+ SM Higgs.

Alternative spin-parity possibilities are disfavoured.



Summary

- Top quark – observed, and compatible with other precise electroweak measurements.
- Electroweak theory depends on the Higgs mechanism to endow particles with mass. This is a non-standard feature, which needs experimental verification.
- Higgs boson – detected in 2012 at 126 GeV.
  Work continues to determine the properties of the boson and check whether it is **the** Higgs boson of the Electroweak Standard Model.

Problem Sheet: q.28

Up next...
Section 12: Beyond the Standard Model