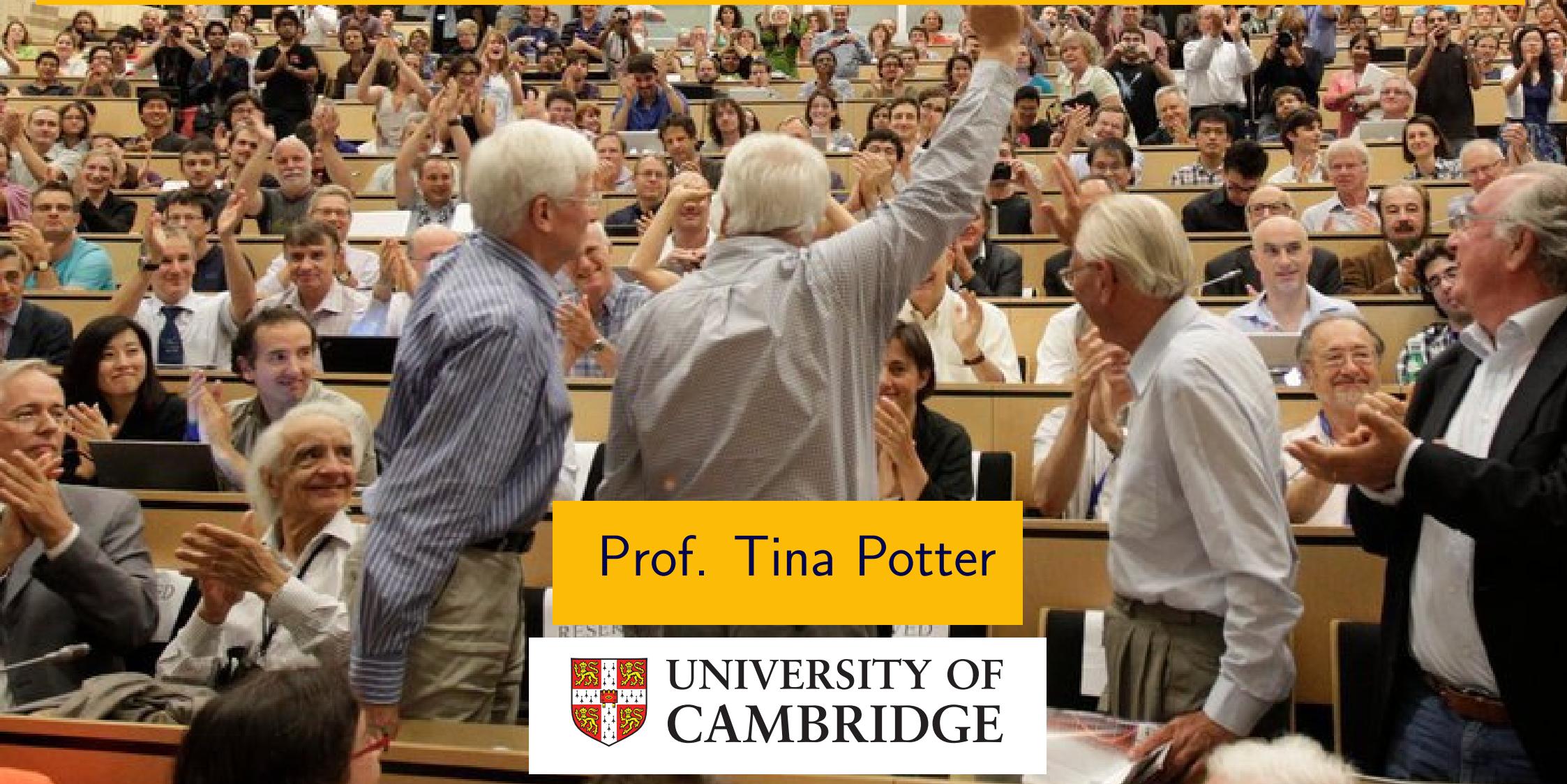


# 11. The Top Quark and the Higgs Mechanism

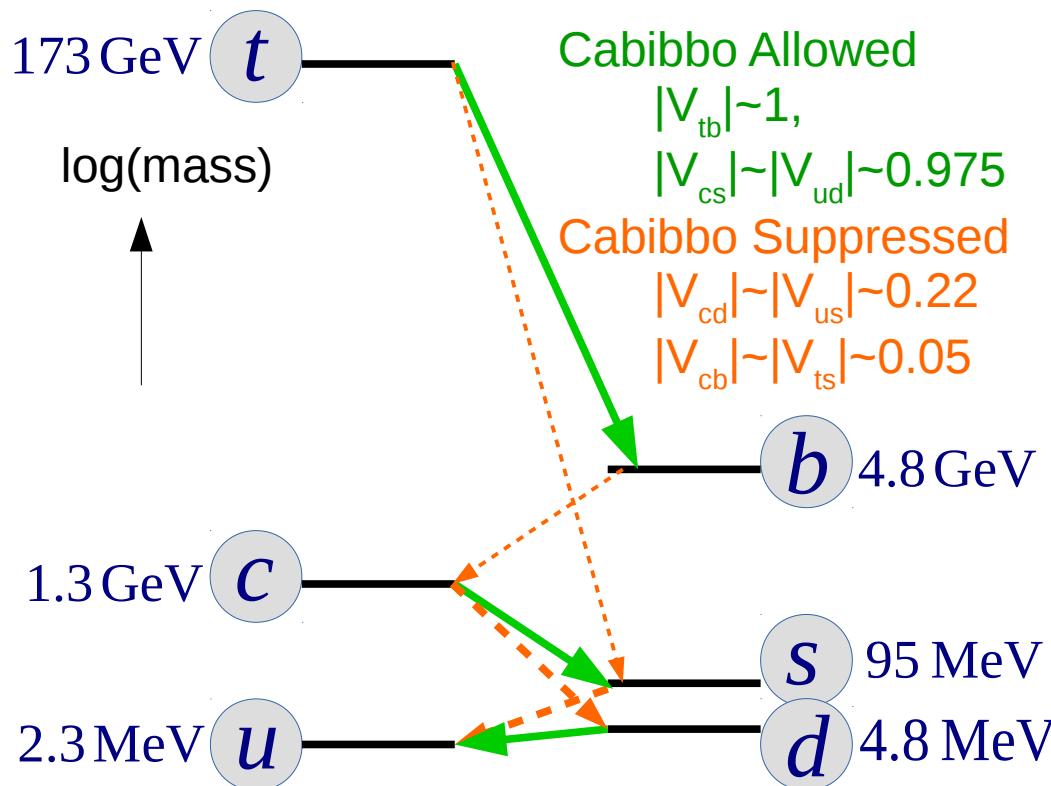
## Particle and Nuclear Physics



# 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.**

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

**Bottom quarks are also special.**

- $b$  quarks can only decay via the Cabibbo 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

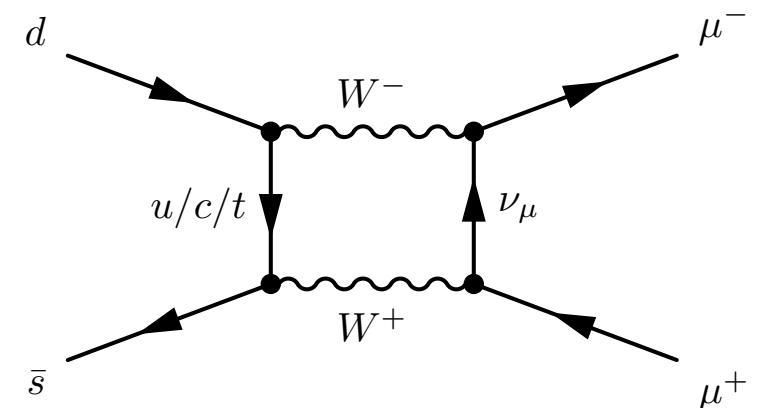
$$+\frac{2}{3}e \quad \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

which is required to explain a number of observations.

**Example:** Non-observation of the decay

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

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



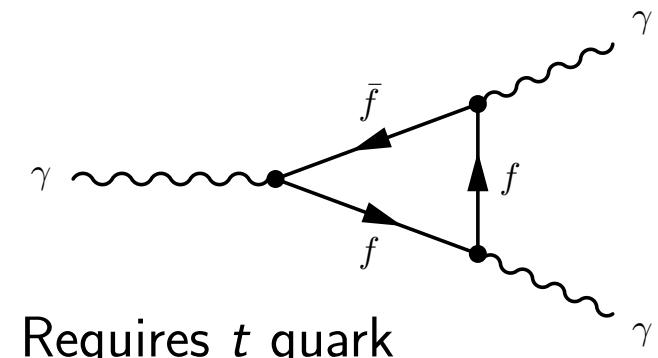
**Example:** Electromagnetic anomalies

This diagram leads to infinities in the theory unless

$$\sum Q_f = 0$$

where the sum is over all fermions (and colours)

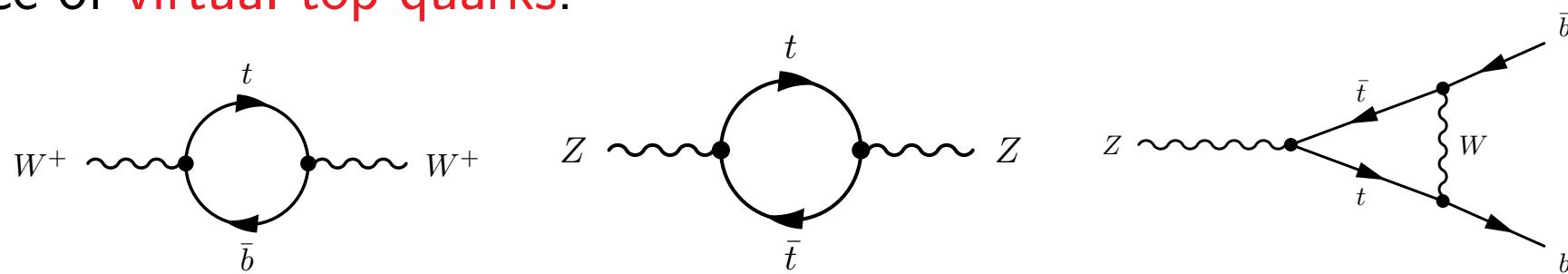
$$\sum_f Q_f = [3 \times (-1)] + \left[ 3 \times 3 \times \frac{2}{3} \right] + \left[ 3 \times 3 \times \left( -\frac{1}{3} \right) \right] = 0$$



# The Top Quark

The top quark is too heavy for  $Z \rightarrow t\bar{t}$  or  $W^+ \rightarrow t\bar{b}$  so not directly produced at LEP.

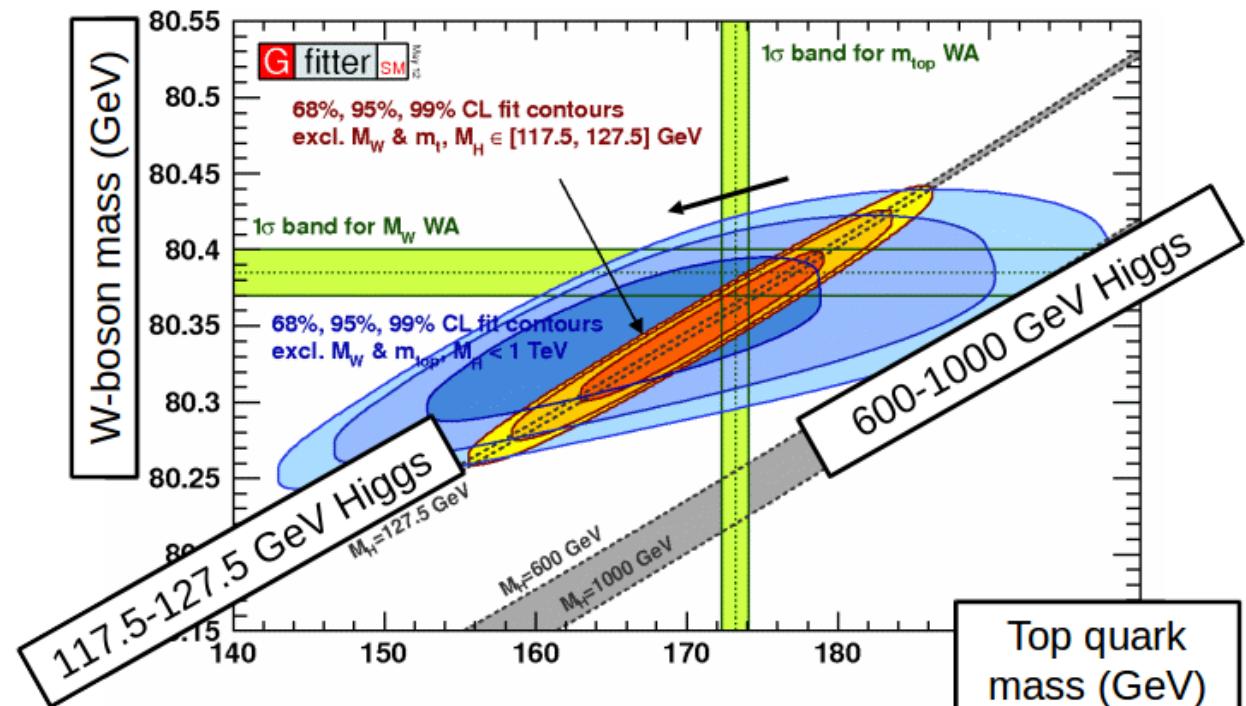
However, precise measurements of  $m_Z$ ,  $m_W$ ,  $\Gamma_Z$  and  $\Gamma_W$  are sensitive to the existence of **virtual top quarks**:



## Example

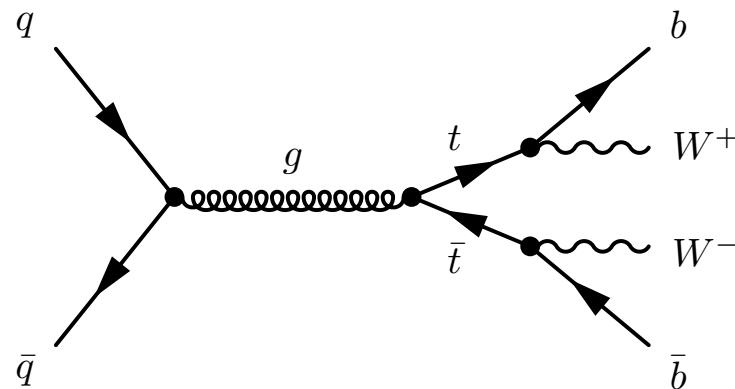
Standard Model  
prediction

Also depends on  
the Higgs mass



# The Top Quark

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



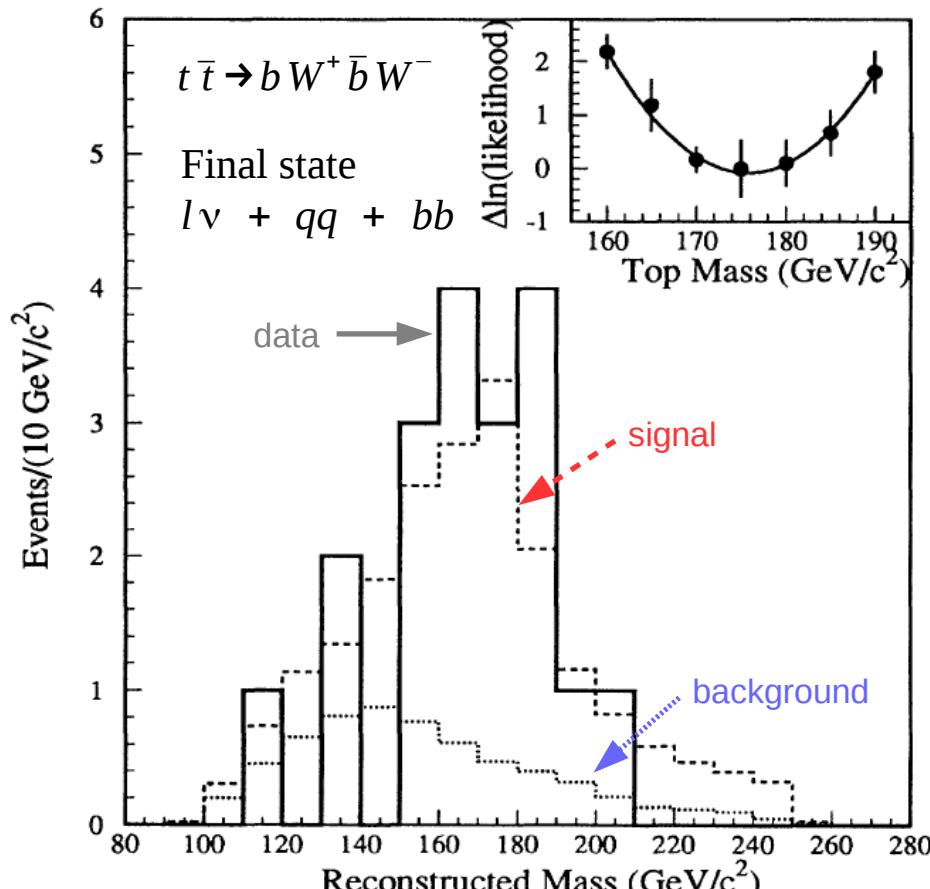
Final state  $W^+ W^- b\bar{b}$

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  $\sim 100\% t \rightarrow bW^+$
- $m_t \gg m_W$ , 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  $t \rightarrow bq\bar{q}$  or  $t \rightarrow b\ell\nu_\ell$
- 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.

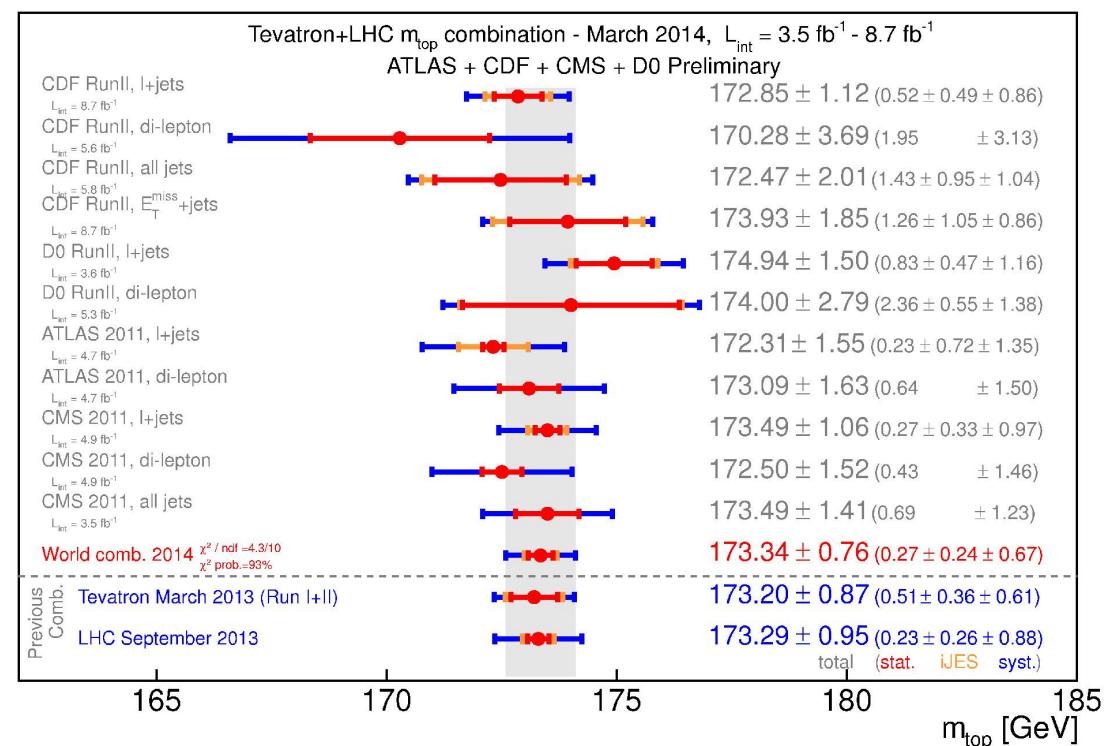
# First observation of top (1995)

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.



# But in 2025...

(non-examinable)

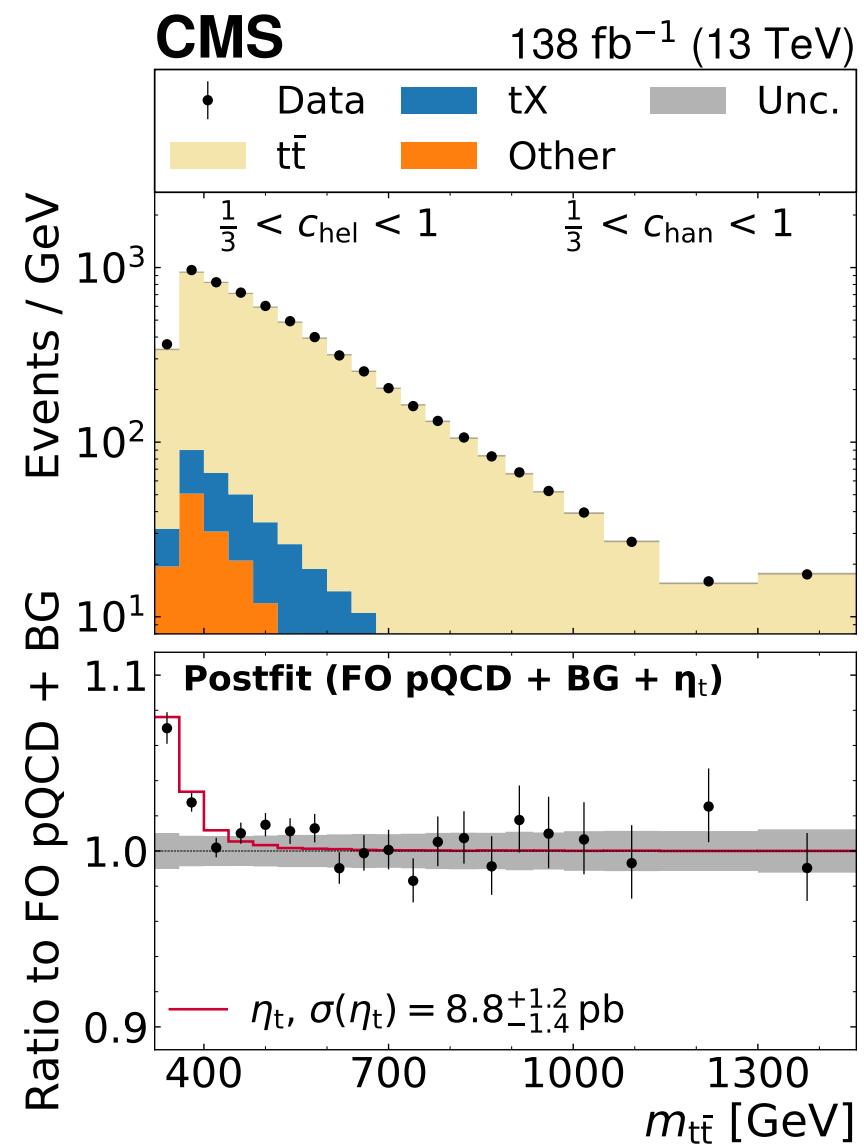
... came the observation of Toponium, the bound state of  $t\bar{t}$ .

First seen by CMS in Rep. Prog. Phys. 88 (2025) 087801,  
<https://arxiv.org/abs/2503.22382>

This is not a stable hadron.

It is a quasi-bound  ${}^1S_0$  state when a  $t$  and  $\bar{t}$  are produced at rest and exchange gluons.

Observation agrees with SM prediction.



# Higgs mechanism and the Higgs Boson



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

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

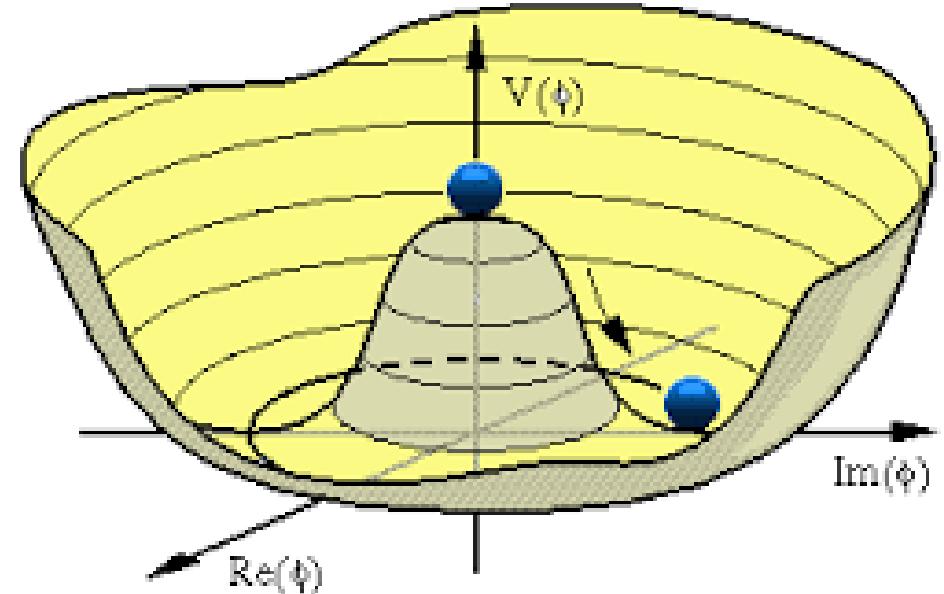
- However, the term  $m^2\psi$  (or  $\frac{1}{2}m^2\psi^2$  in the Lagrangian formulation), is not gauge invariant.
- So in gauge field theories, the gauge bosons should be **massless**. OK for QED and QCD, but plainly not for  $W^\pm$  and  $Z$ .
- The Higgs mechanism tries to fix this. Imagine introducing a **scalar Higgs field**  $\phi$ , 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  $\phi$  (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  $|\phi_{\text{GS}}^2| = b/2a$ . The symmetry is **“spontaneously broken”**.
- A weak boson propagating in the Higgs field will appear to have a mass  $\sim y\phi_{\text{GS}}$ .
- Expanding about the ground state  $V(\phi_{\text{GS}} + x) = V_{\text{min}} + 2bx^2$
- 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:**  $\vec{J} = n e \vec{v}; \quad m_e \frac{\partial \vec{v}}{\partial t} = e \vec{E} \quad \Rightarrow \frac{\partial \vec{J}}{\partial t} = \frac{n e^2 \vec{E}}{m_e}$

**Maxwell:**

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

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

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

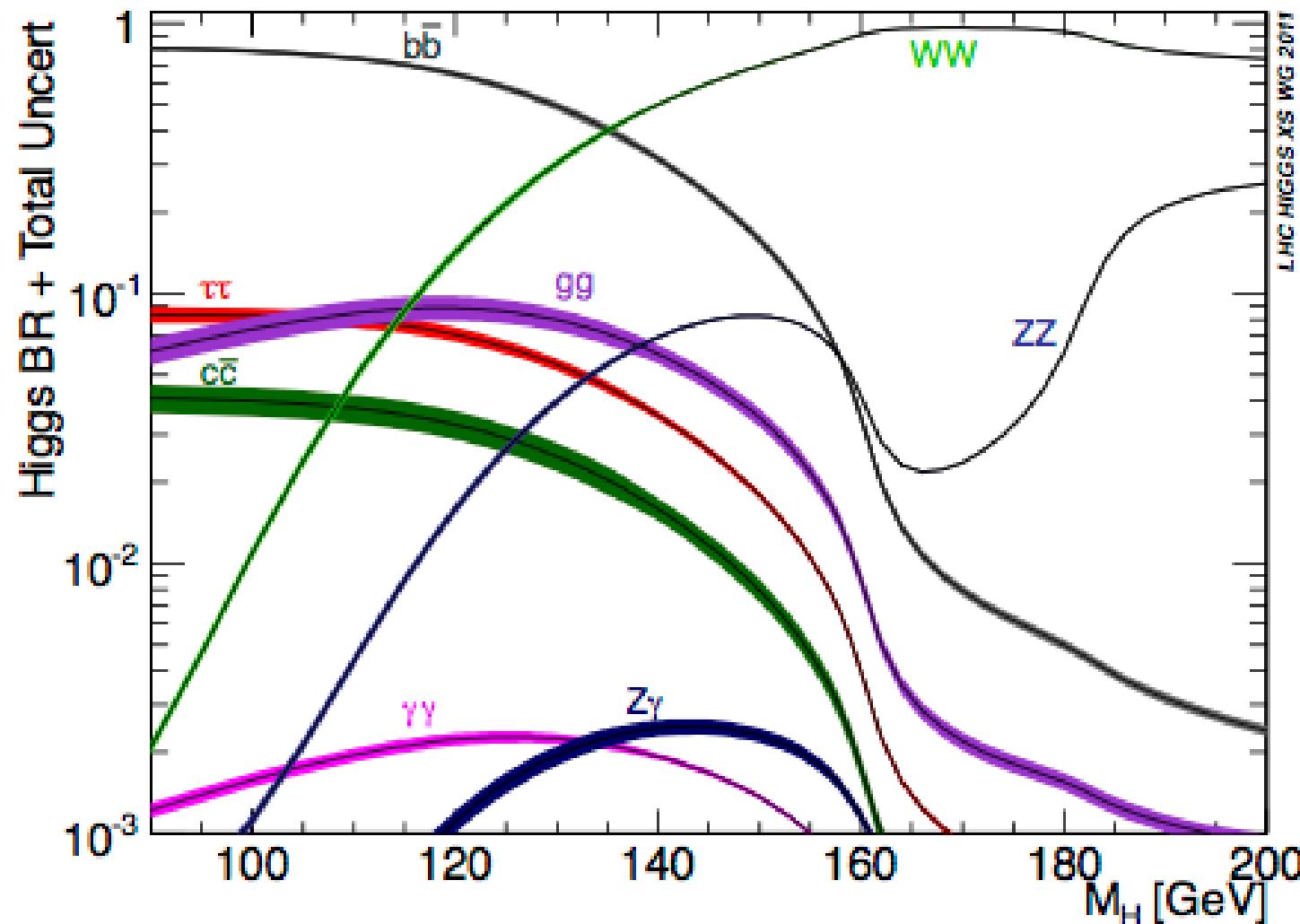
Note  $m_{\text{eff}} \propto e$ , the coupling.

# 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.

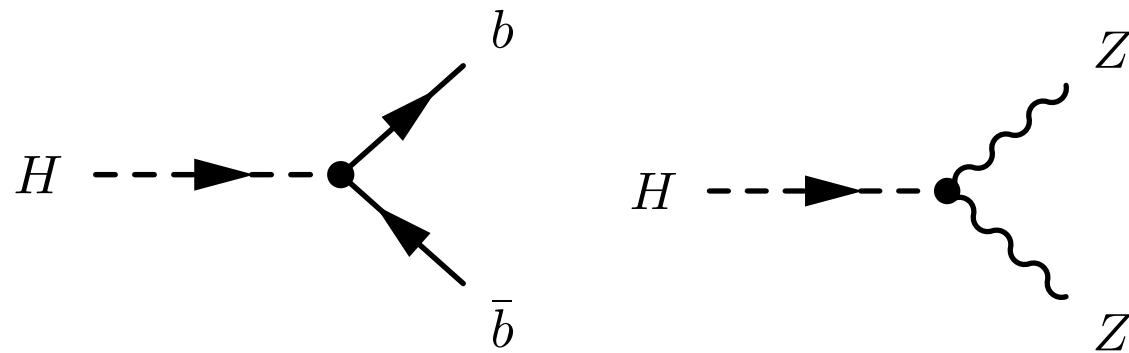
# Higgs boson decays

- 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.

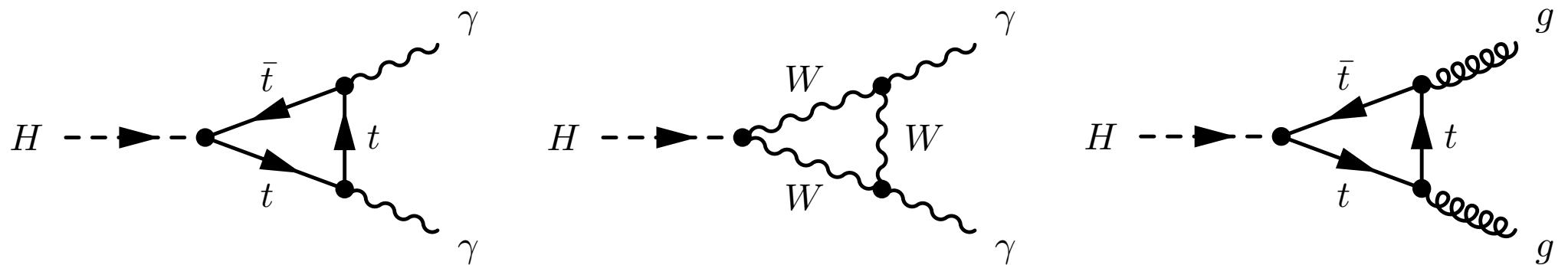


# Higgs decay mechanisms

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



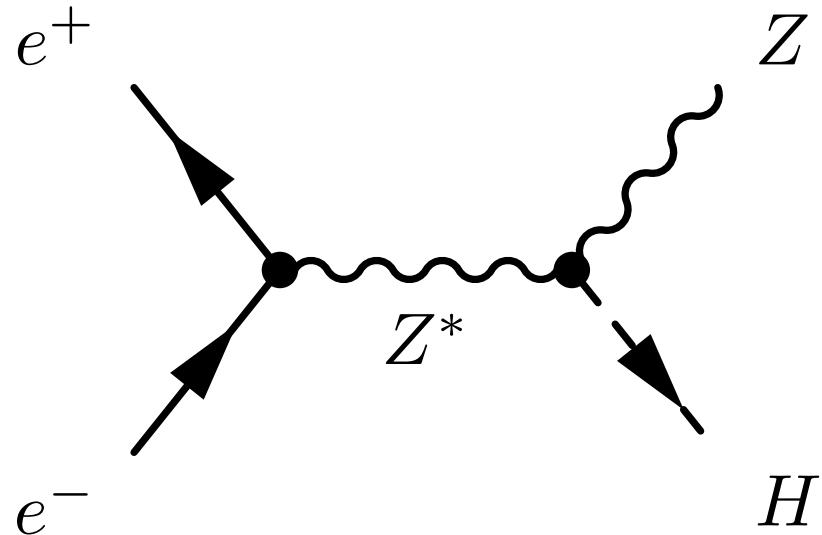
Indirectly to massless particles (photons or gluons) via massive loops



# 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.

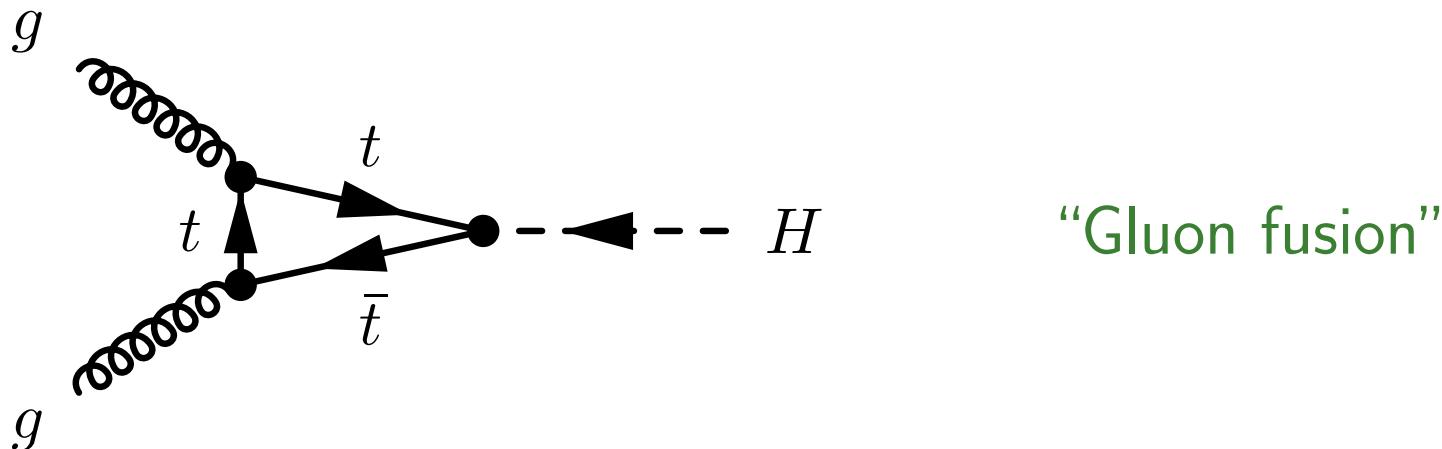
Searches were conducted in many possible final states (different decays for  $Z$  and  $H$ ). All negative.

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

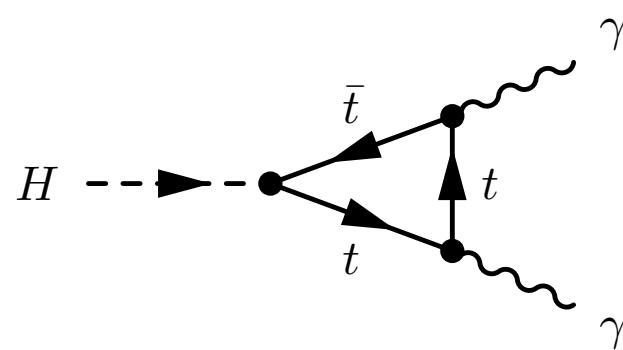
# Higgs at Large Hadron Collider

## Higgs Production at the LHC

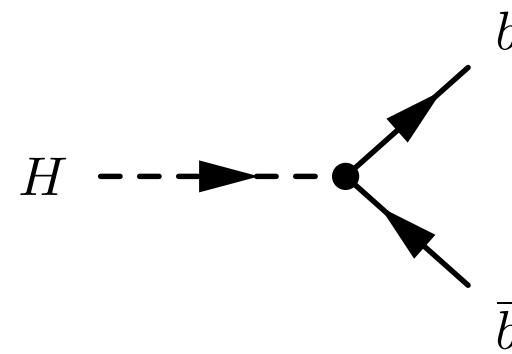
The dominant Higgs production mechanism at the LHC is



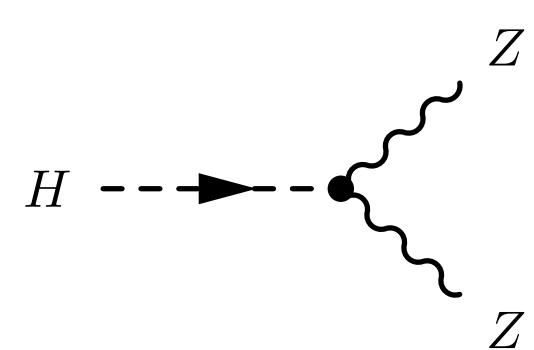
## Higgs Decay at the LHC



Low mass



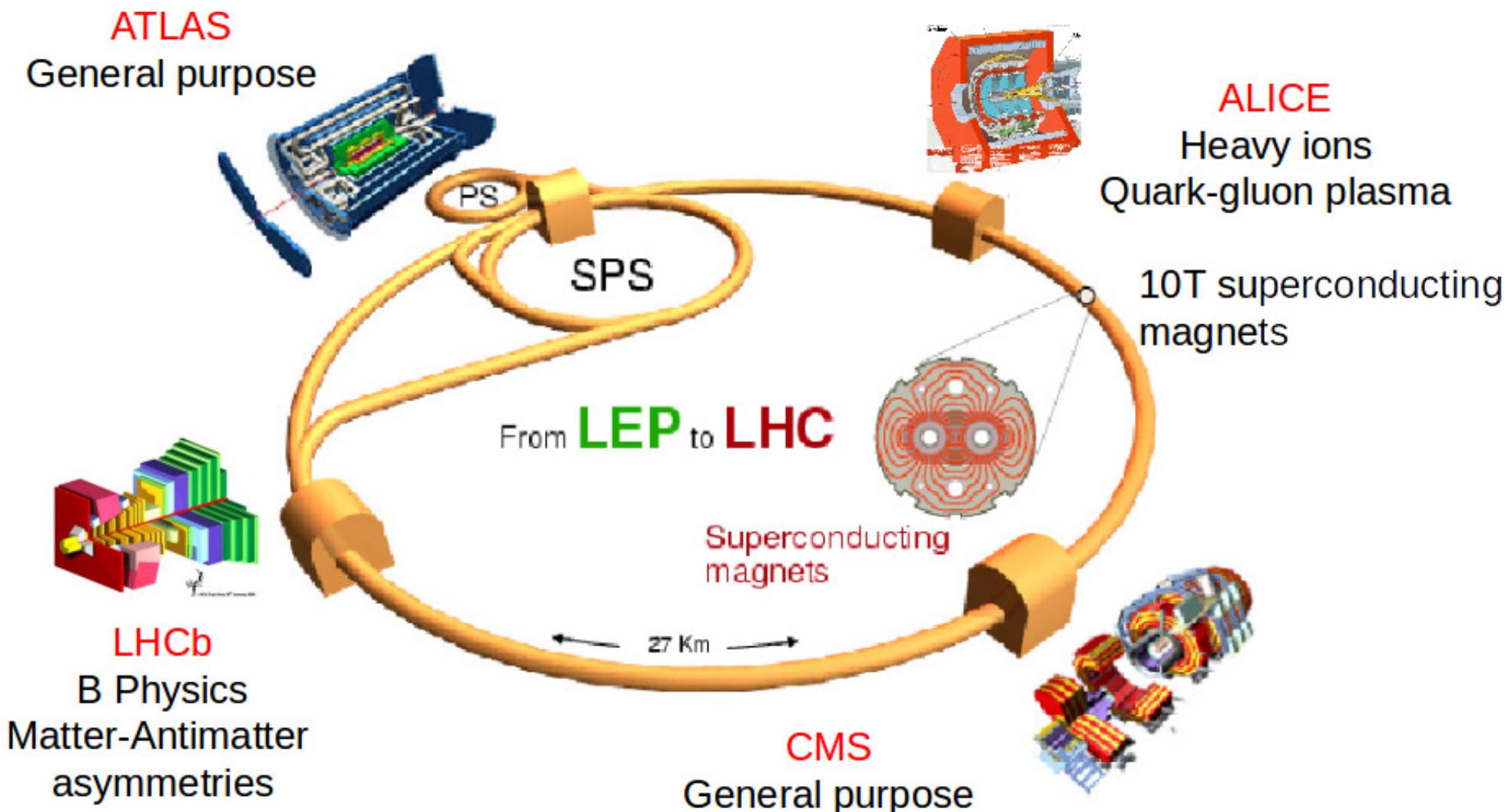
Medium mass



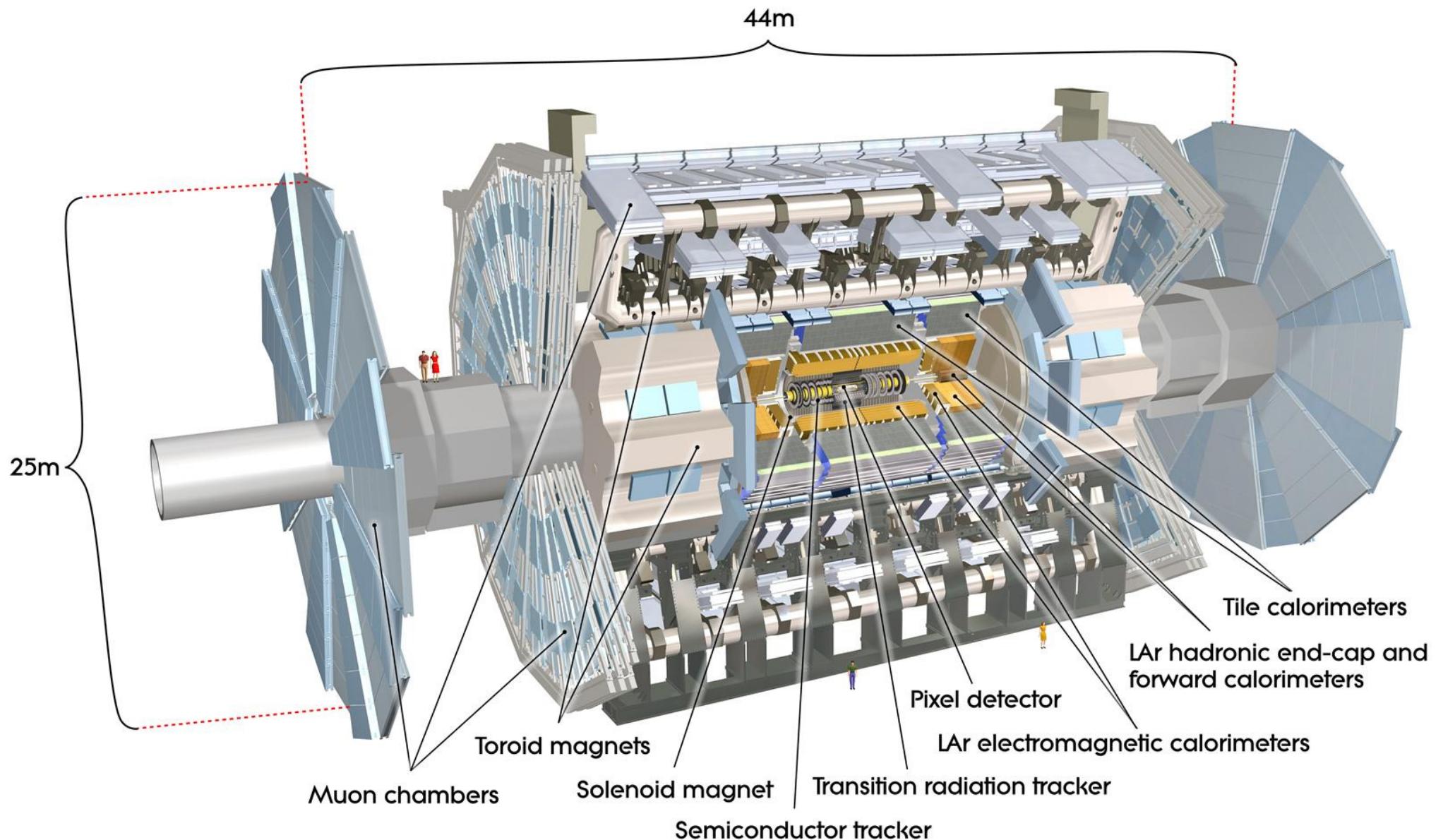
High mass  
One  $Z$  may be virtual

# 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)

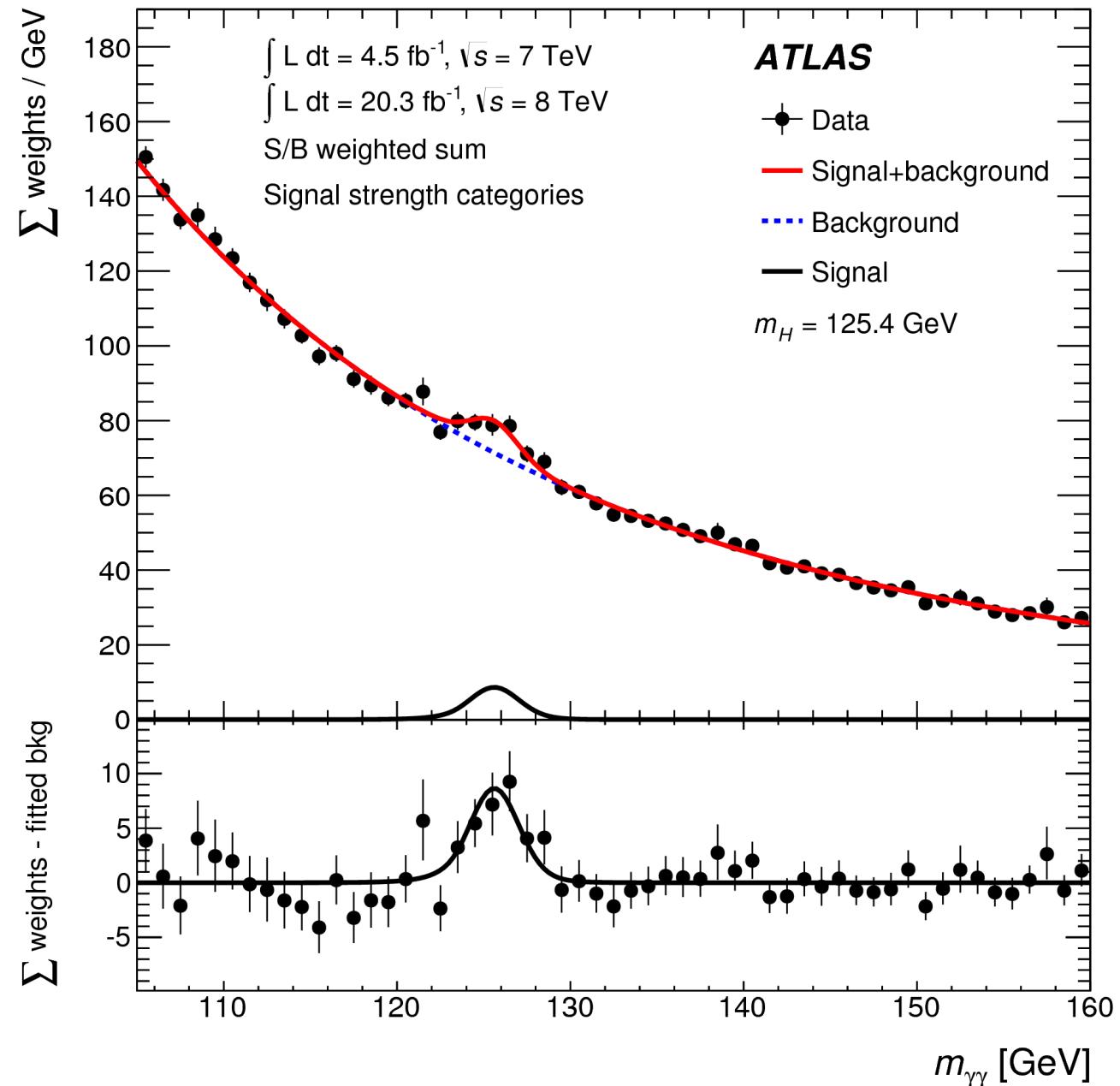
Indirect indications from LEP that Higgs mass should be not far above 115 GeV.

Dominant decay modes are all difficult:

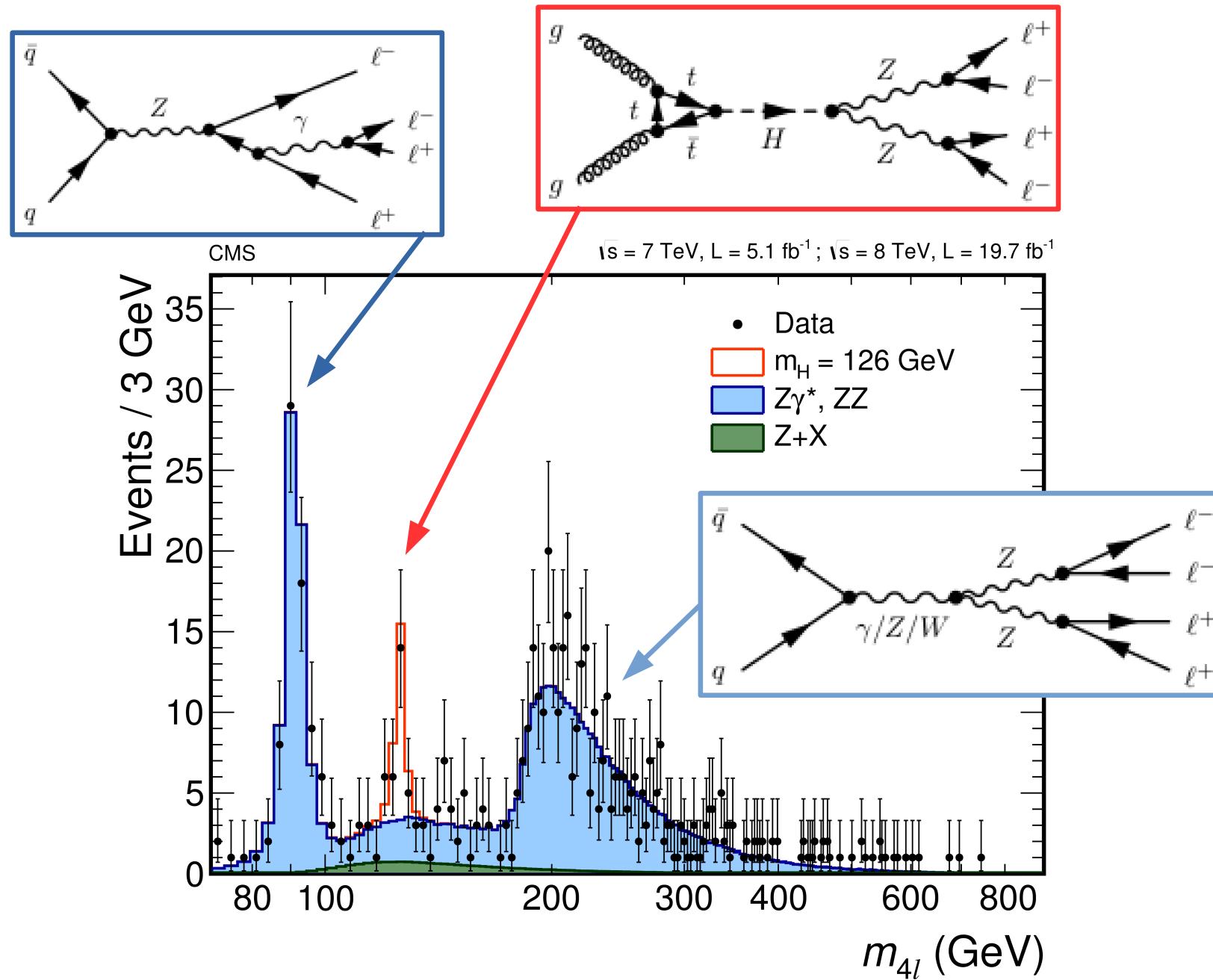
- $b\bar{b}$ ,  $c\bar{c}$   
(swamped by QCD jets)
- $W^+W^-$ ,  $\tau^+\tau^-$   
(missing neutrinos)

Best options are the rare decays:

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



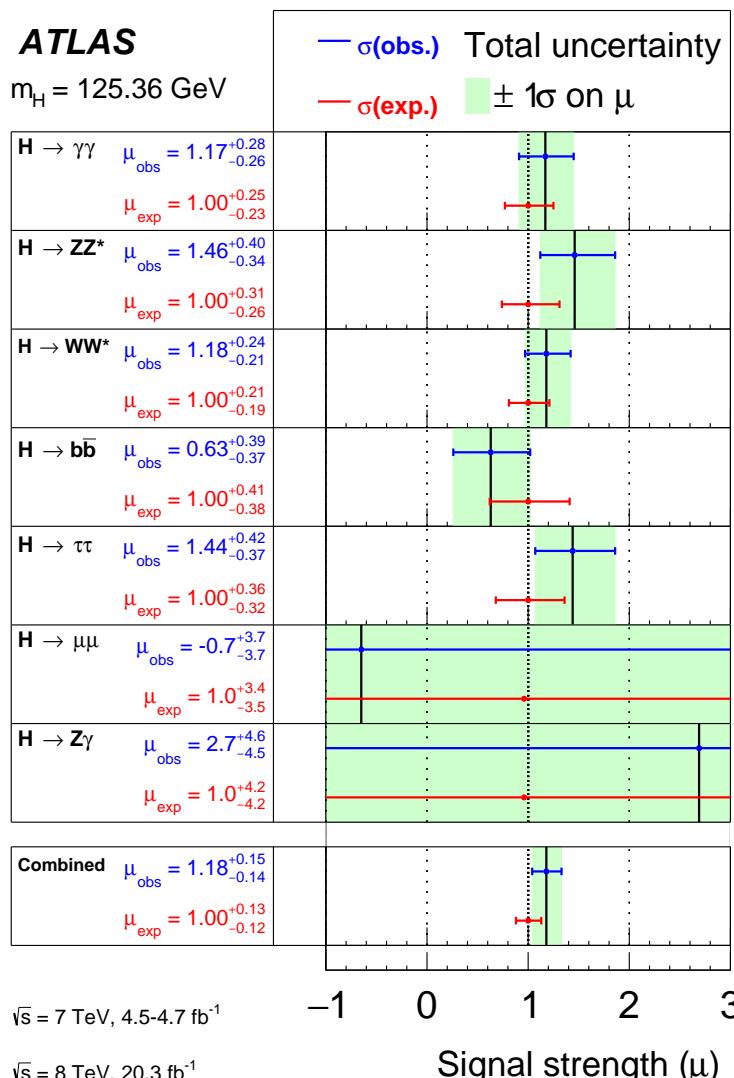
# $H \rightarrow ZZ \rightarrow 4\ell$



# Higgs Boson Discovery

ATLAS

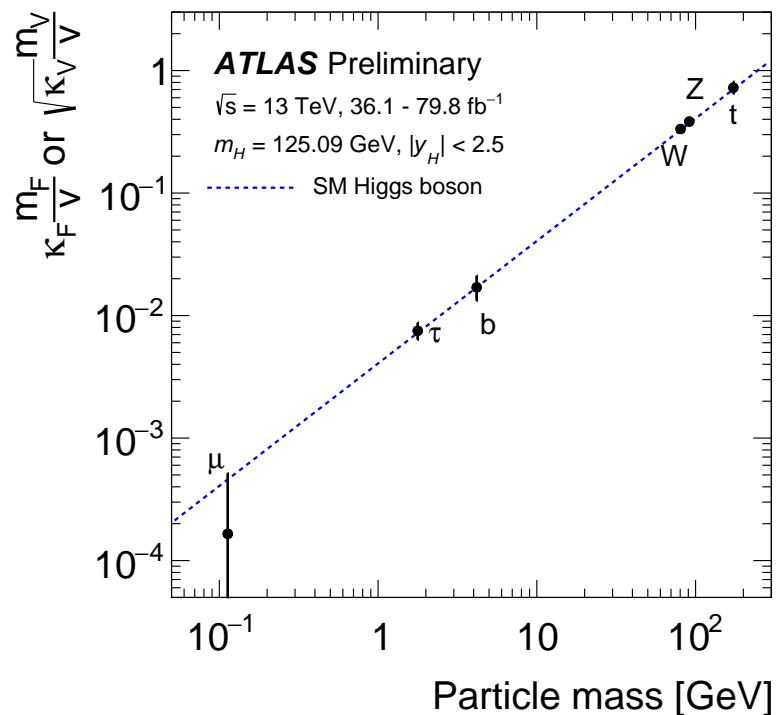
$m_H = 125.36 \text{ GeV}$



Convincing signal consistent with  $m(H) = 125 \text{ GeV}$  – seen in multiple decay modes & in two experiments.

Is it **the** Higgs boson of the SM?

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



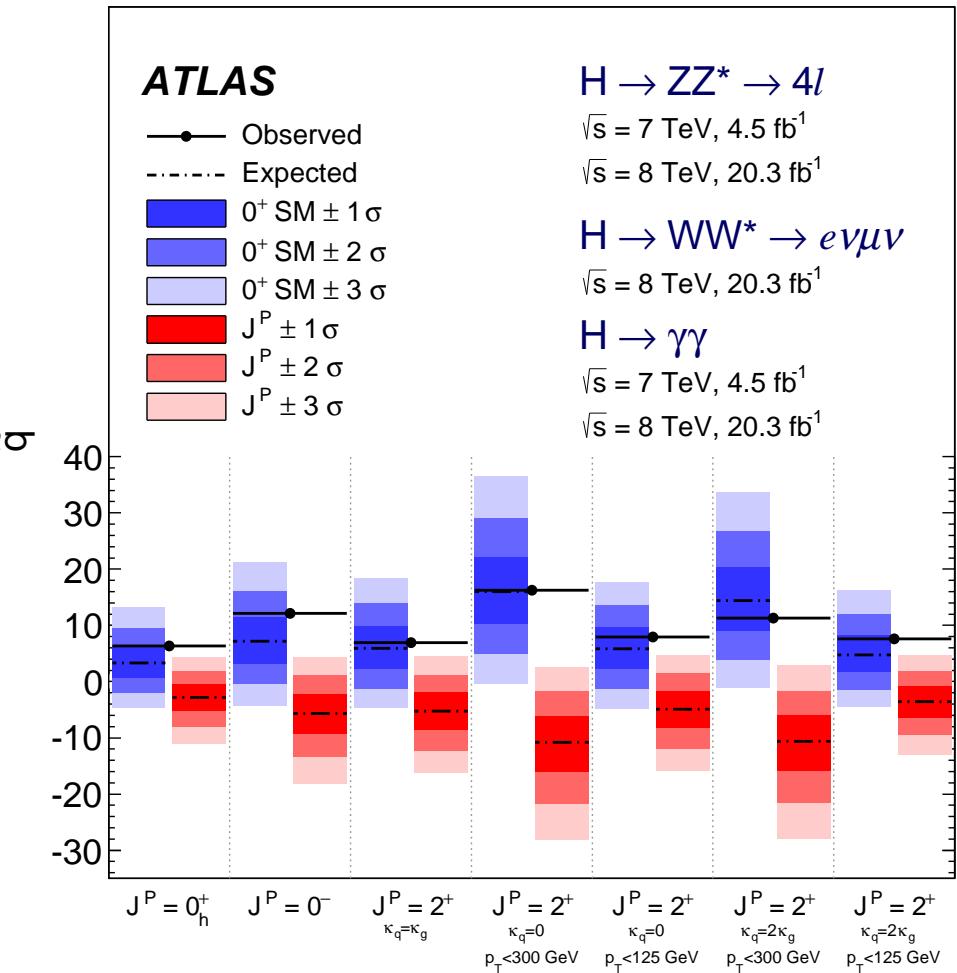
Check branching ratios and couplings.  
Look ok so far...

# 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 125 GeV. It is **the** Higgs boson of the Electroweak Standard Model.  
Work continues to determine all the Higgs properties precisely to see if any surprises are hiding...

Problem Sheet: q.28

Up next...

Section 12: Beyond the Standard Model