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Lecture 3 - Mr. Higgs goes to Geneva

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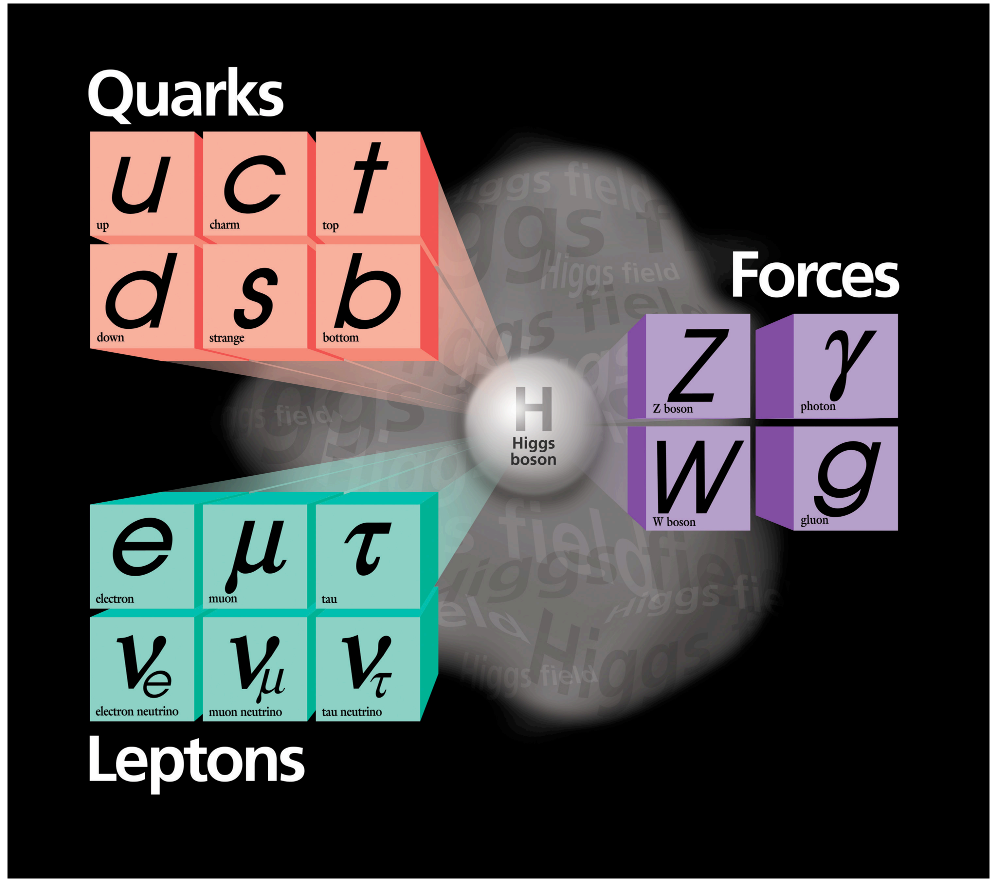
Why do we think a Higgs field exists?

- The SM is really two separate theories - QCD and GSW electroweak
- We know that the electroweak piece must be broken
  - We experience separate E&M and weak forces
  - Also the unified electroweak theory involves massless gauge bosons only
  - We know from the short range of the weak interaction that the gauge bosons mediating the weak force must be quite massive
- **Something has to break the electroweak symmetry and something has to give the W,Z mass**
- It is not just the gauge bosons but all the fermions that are massless
  - **Something has to give them mass as well**



It would be nice if these both could be accomplished by the same means

The Higgs Must Exist ... (Sort of)

- In the 1960's Higgs (and others, namely GSW) showed that the introduction of a single complex scalar field (which now bears his name) could break electroweak symmetry, give mass to the W,Z, and the fermions as well!
  - This is not the only way to achieve these goals (there are others, e.g. technicolor) but it is the simplest and most "elegant"
- So, we are not sure that a Higgs boson will be found at LHC - but we are sure that something that plays the role of the Higgs field instead will show up

"If there is not a Higgs boson, the theory does not make sense at all."
- Peter Higgs, 2004

Recall GSW Electroweak Theory

- The gauge group for the GSW theory is $SU(2)_L \otimes U(1)$
- In it there are 4 massless bosons belonging to a weak isosinglet B^μ and weak isotriplet, W^μ
- The coupling constant for interactions with the B_μ is g'
- The coupling constant for interactions with the W_μ is g_W
- But these particles and interactions are inaccessible to us (at normal energy scales), we can only see the remnants after the underlying symmetry is broken

The Higgs Field

- We want to add something (a new field) to the SM that will initially have $SU(2)_L \otimes U(1)$ symmetry, but is constructed such that when this symmetry is broken (by some, to be specified mechanism) that the massless W_μ and B_μ become the massive W,Z while leaving the photon massless as nature requires
  - It turns out that the addition of a single SU(2) doublet of complex scalar fields does the trick

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_2 + i\phi_4 \end{pmatrix}$$

- In order to provide a mechanism for symmetry breaking we construct a special potential for this field
- Putting these two things together we arrive at the following terms which we add to the SM Lagrangian

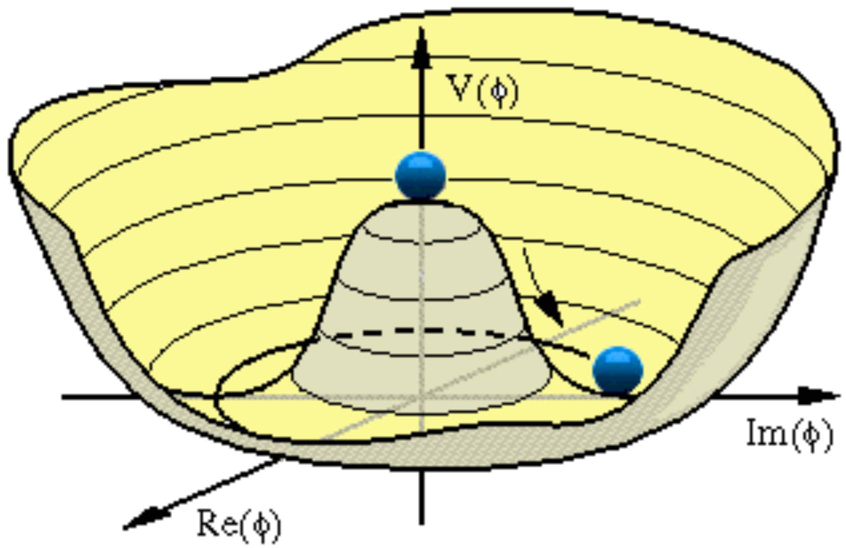
$$\mathcal{L}_\Phi = (D_\mu \Phi)^\dagger (D^\mu \Phi) - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$

$$D_\mu \equiv \partial_\mu + i\frac{g}{2}\sigma \cdot \mathbf{W}^\mu + i\frac{g'}{2} Y B^\mu$$

Higgs Potential

- This Higgs potential is shaped like a Mexican hat
- This potential (by construction) is unusual in that its ground state is a negative (non-zero)
- Above zero (the top of the hat), the potential is symmetric, but below it, i.e. in the ground state (vacuum) there is no symmetry in the radial direction
- As the universe fell into the ground state, electroweak symmetry was “spontaneously” broken

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



$$\frac{\partial V}{\partial(\Phi^\dagger \Phi)} = 0 \rightarrow (\Phi^\dagger \Phi)_{min} = -\frac{\mu^2}{2\lambda} \equiv \frac{v^2}{2}$$

$$\Phi_{min} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$v = 246 \text{ GeV}$$

Spontaneous Symmetry Breaking

- How does the Higgs mechanism break electroweak symmetry?
  - “spontaneous symmetry breaking”
- The phenomena is one we are all familiar with if we have ever eaten at a restaurant
  - The place settings are initially symmetric
  - When the first person sits down, and chooses his cutlery, etc. this breaks the symmetry and the effect of the choice propogates around the table

whose spoons are these?

Higgs Mechanism

- To see how the Higgs mechanism works, i.e. whether it does what we want, we examine expansions about the minimum

$$\Phi_{min} + \delta\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

  - When you do this, it is convenient to identify two components of W^{μ} with the $W^{\pm}$
    - The other component of W_{μ} “mix” with the B_{μ} which we identify with the γ and the Z^0 as follows:

$$\begin{aligned} A_\mu &= B_\mu \cos\theta_{\mathrm{w}} + W_\mu^3 \sin\theta_{\mathrm{w}} \\ Z_\mu &= -B_\mu \sin\theta_{\mathrm{w}} + W_\mu^3 \cos\theta_{\mathrm{w}} \end{aligned}$$

$$\theta_{\mathrm{w}} = 28.7^\circ$$

  - Notice that we seem to have lost 3 d.o.f. wrt to our original (symmetric) formulation
    - These 3 d.o.f. are each absorbed into the longitudinal polarization of the W^+W^- and Z^0, which as massive particles they must possess
  - If you plug our expression for Φ back in our lagrangian, making the notational changes discussed above, you get

$$\begin{aligned} \mathcal{L}_\Phi = \tfrac{1}{2}\partial_\mu H \partial^\mu H + \tfrac{1}{4}g^2(v^2 + 2vH + H^2){W_\mu}^+ W^{\mu -} \\ + \tfrac{1}{8}(g^2 + g'^2)(v^2 + 2vH + H^2)Z_\mu Z^\mu \\ -\frac{\mu^2 v^2}{4} + \mu^2 H^2 - \lambda v H^3 - \frac{\lambda}{4}H^4 \end{aligned}$$

$$m_Z = \tfrac{1}{2}(g^2 + g'^2)^{1/2} v \equiv \frac{1}{2}\frac{gv}{\cos\theta_{\mathrm{w}}}$$

$$m_W = \tfrac{1}{2}gv \rightarrow m_Z = \frac{m_W}{\cos\theta_{\mathrm{w}}}$$

Fermion Masses

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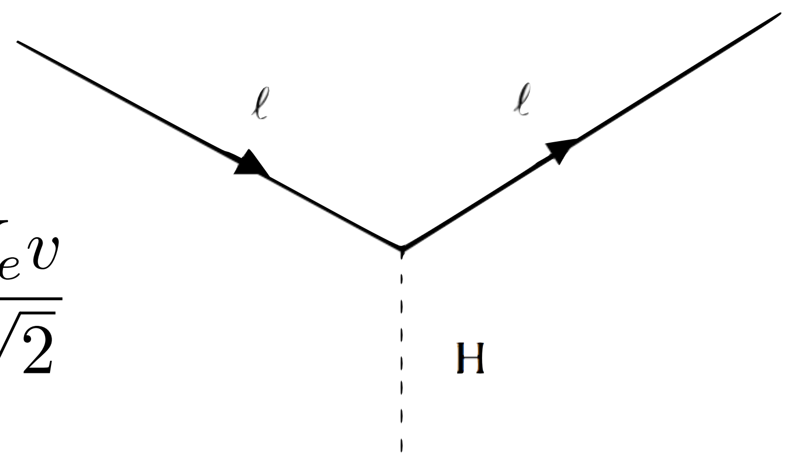
- Similarly if assume you want the higgs to give masses to fermions you must add a Higgs/fermion coupling term to the SM Lagrangian
- These are called Yukawa terms and look like this (using electrons as an example)

$$\mathcal{L}_{Yukawa} = -Y_e(\bar{\chi_L}\Phi e_R + \bar{e_R}\Phi^\dagger \chi_L) \qquad \chi_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L$$

- When you plug in our expression for Φ, you get an electron mass term (while leaving the neutrino massless (and an electron/Higgs interaction term)

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H \end{pmatrix}$$

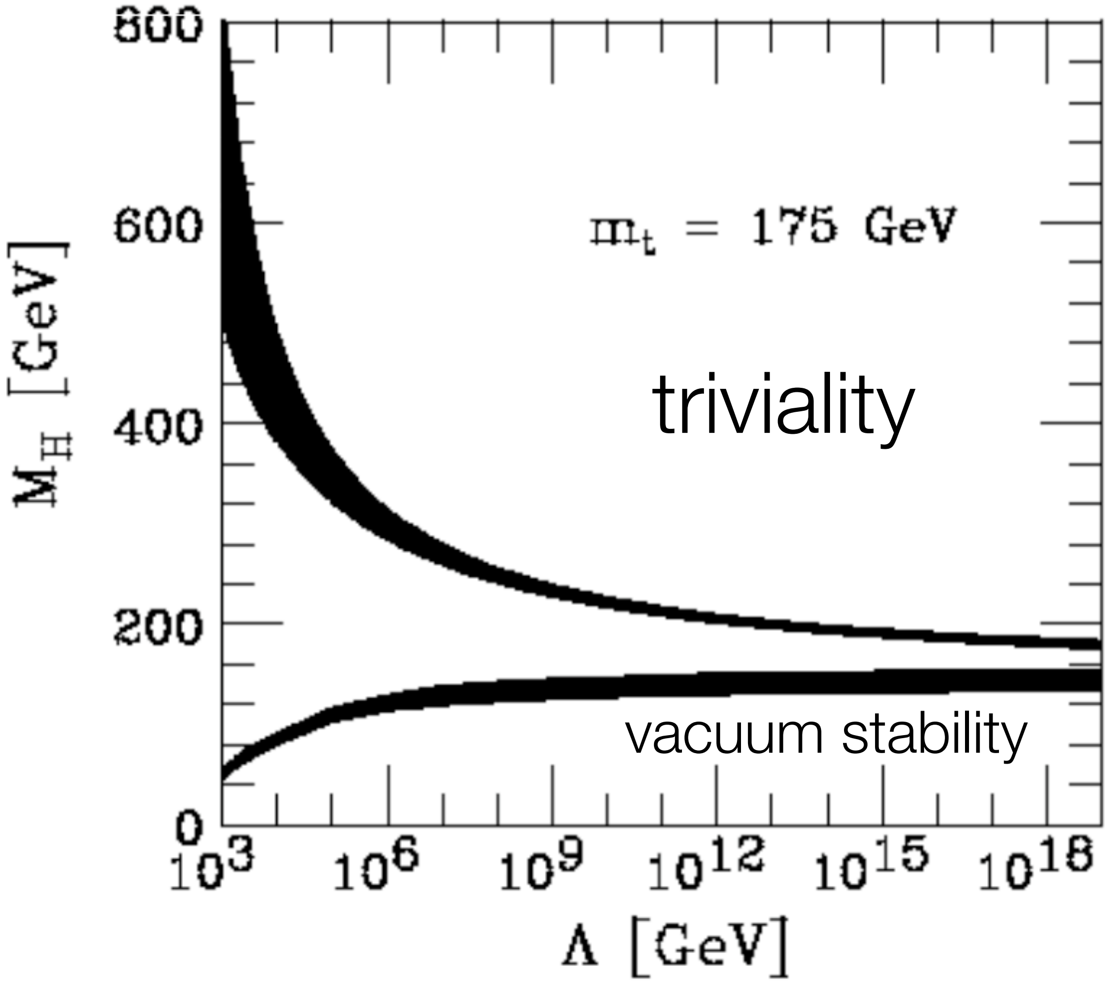
$$\mathcal{L}_{Yukawa} = -\frac{Y_e}{\sqrt{2}}v\bar{e}e - \frac{Y_e}{\sqrt{2}}\bar{e}eH \qquad m_e = \frac{Y_e v}{\sqrt{2}}$$



In order to confirm the existence of a Higgs field (and the Higgs mechanism), we need to find a quanta of this field (Higgs boson)

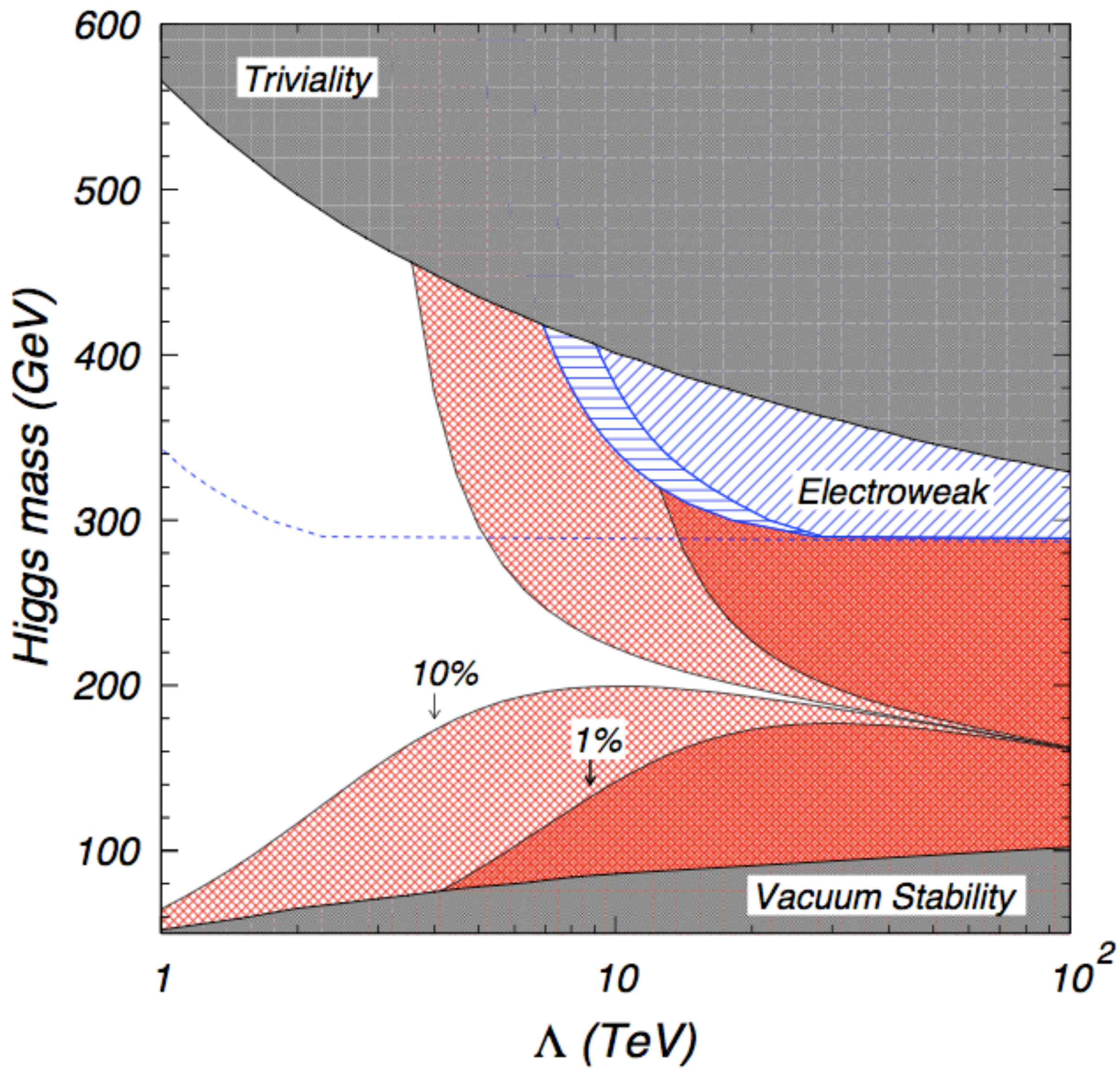
What mass might the Higgs be?

- This is the so-called "chimney" plot places two theoretical bounds on the allowed Higgs Mass
  - Triviality
  - Vacuum stability
- It would seem as if there is a chimney around 180 GeV that extends all the way to the planck scale



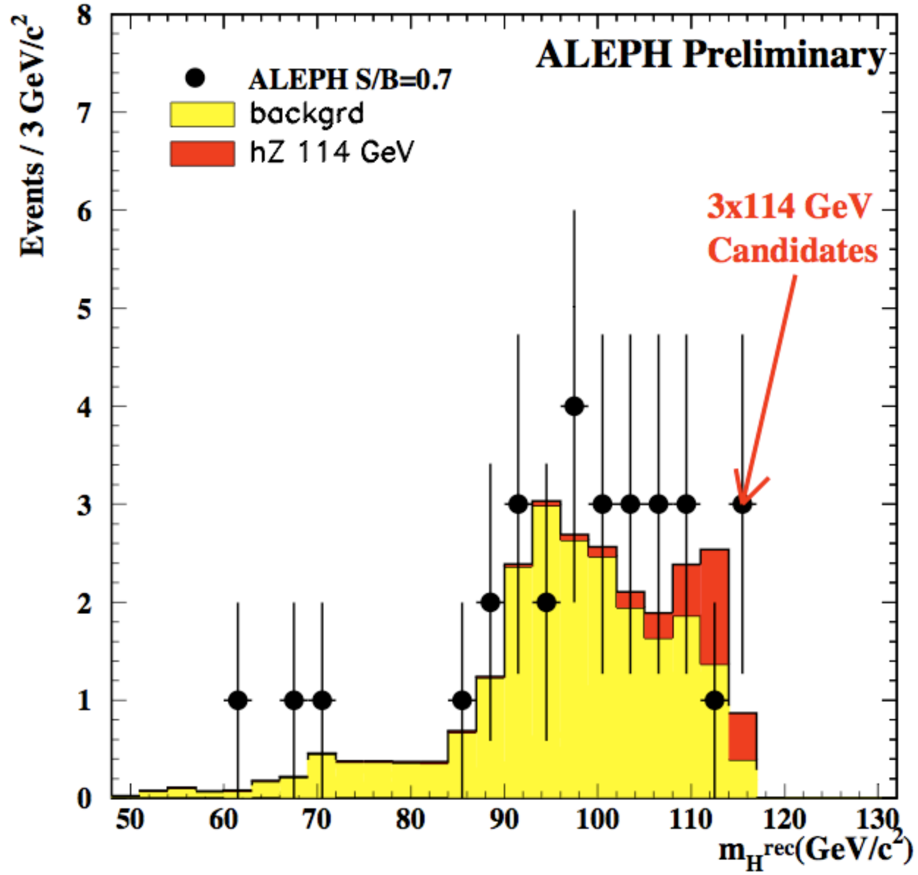
Combining these bounds with “fine tuning” limits

- This graph shows a zoom in (the low lambda region) of the chimney plot
- But now overlaid are curves which indicate the level of fine tuning required to solve the Higgs mass divergence (hierachy) problem
    - To avoid 10% or worse fine tuning, new physics must appear ~1-3 TeV



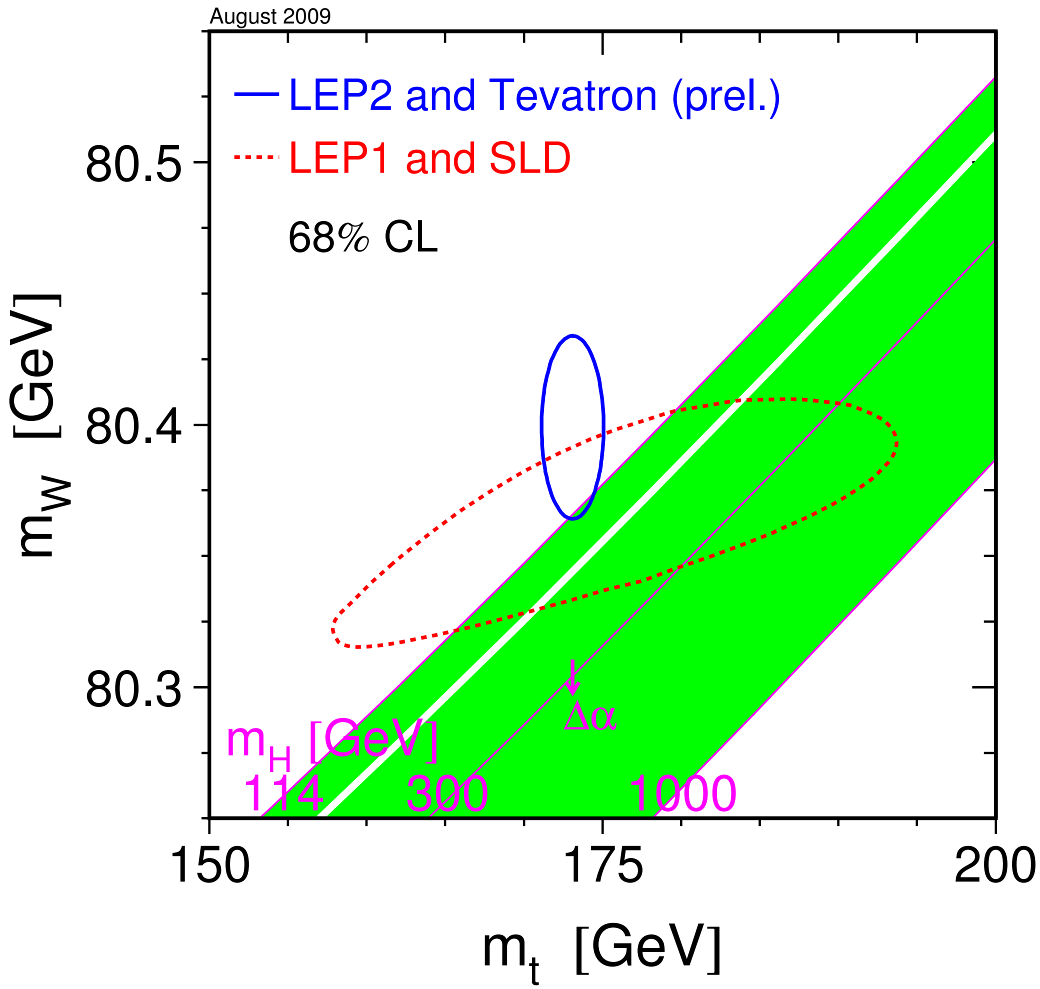
State of the Search for the Higgs Boson

- In the same tunnel that now houses LHC, there used to be another collider called LEP
- LEP searched for the Higgs in e^+e^- collisions at up to $\sqrt{s}$ = 209 GeV
- While at least one of the 4 experiments saw a few candidate events at 115 GeV, nothing conclusive was observed … and LEP had to shut down to make room for the LHC :(



Search for the Higgs (cont.)

- The Tevatron at Fermilab was passed the baton where they could set indirect bounds on the mass of a SM Higgs boson by combining precision electroweak data with
  - (Ever more precise) measurements of the mass of the W boson and top quark
  - These masses are sensitive to m_H through loop corrections

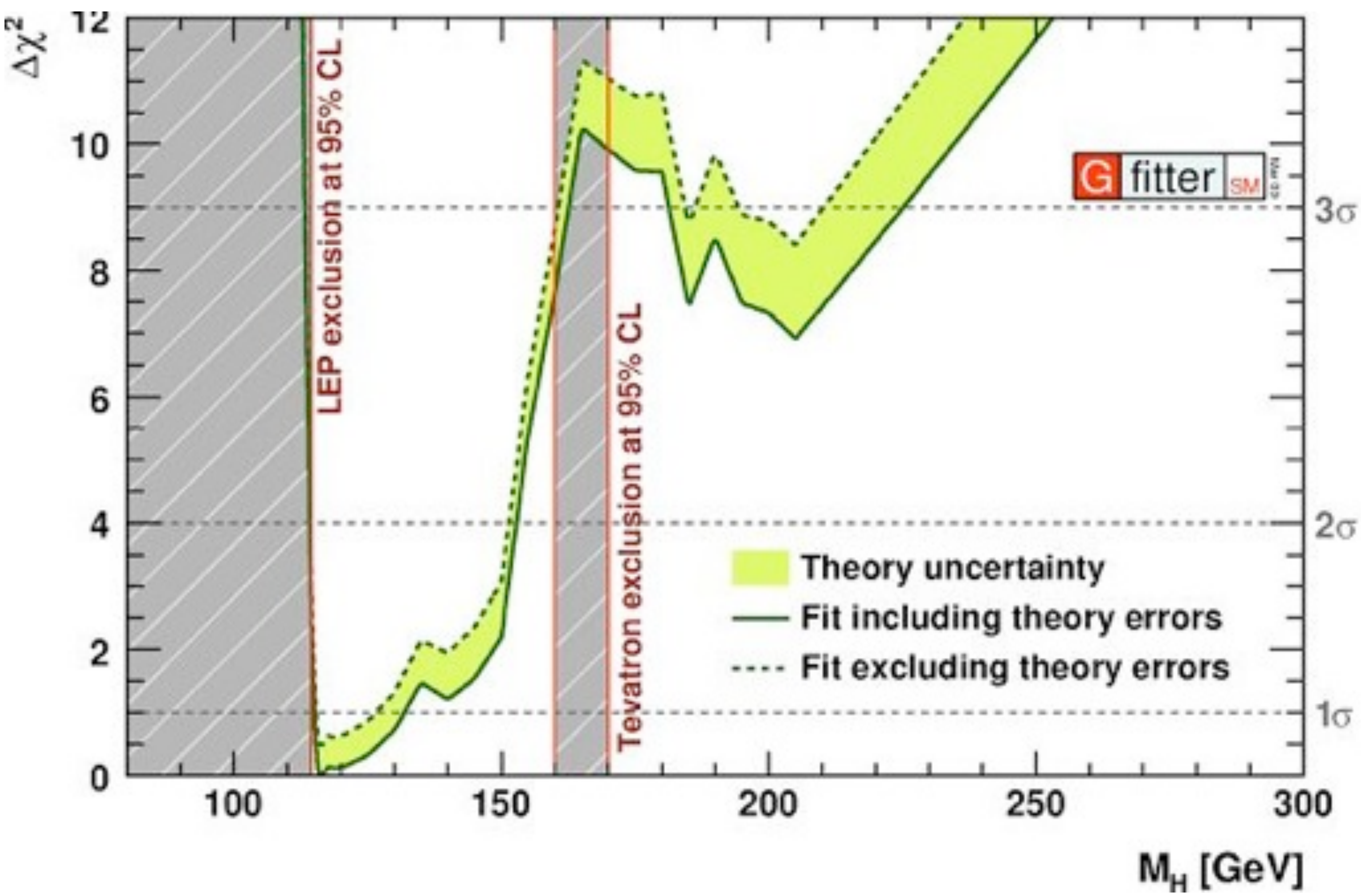


These measurements seem to favor a light higgs

Search for the Higgs (cont.)

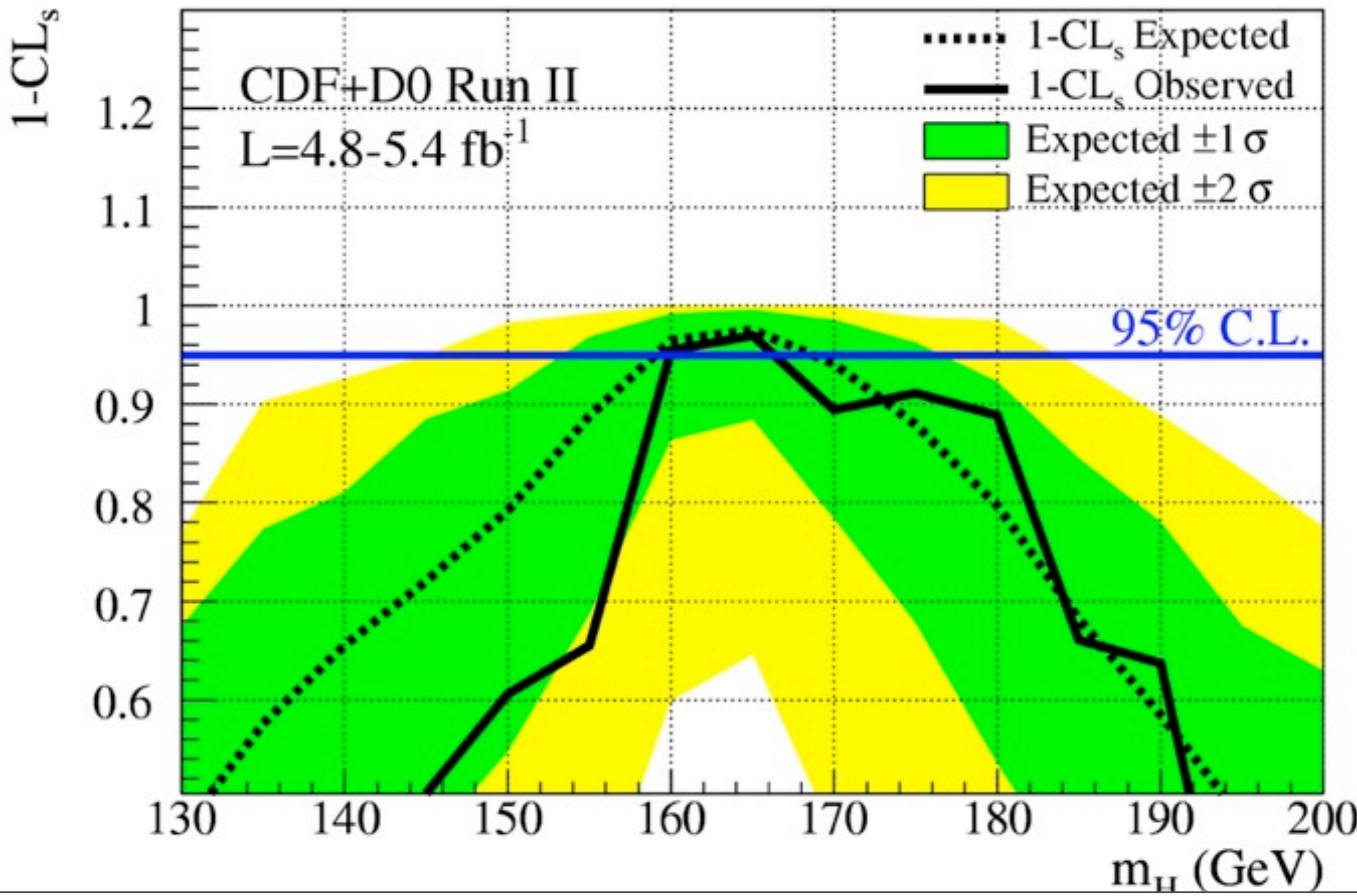
- The Tevatron experiments have, of course, also performed direct searches for Higgs in in ppbar collisions at up to √s = 2 TeV

- With about ⅔ of their ultimate dataset analysed, the Tevatron should have already seen some high mass Higgses if they were going to (and they haven't)



SM H→WW, ZZ already pretty much ruled out

Latest from the Tevatron



Summary of the Experimental Search So Far

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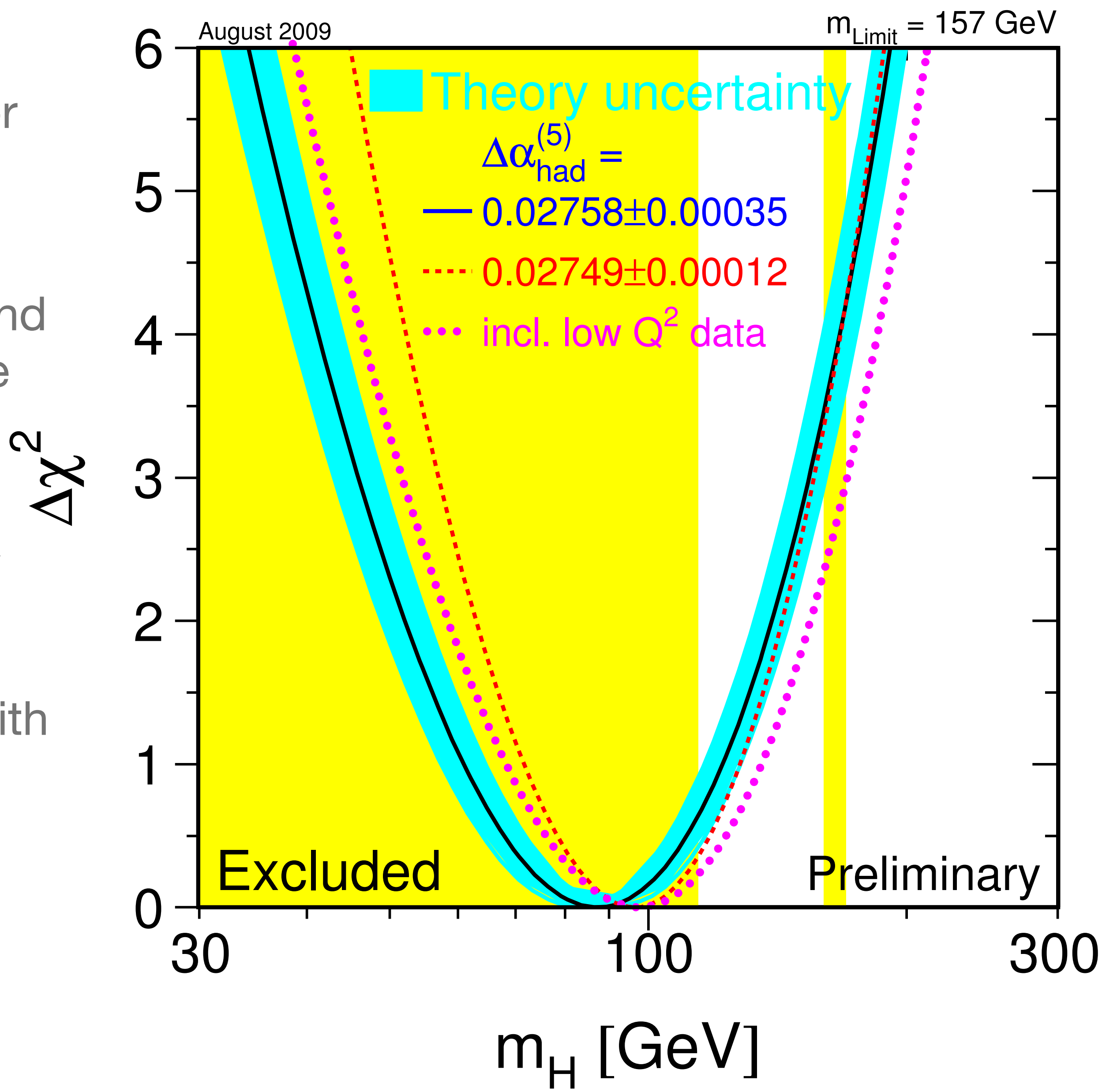
- All the parameters of the SM have been measured except for m_H
- The LEPEWG fits all these to find the most probable value for the Higgs mass
- Currently this mass is ~95 GeV
- This is below, but consistent with the LEP2 direct limit of > 114 GeV



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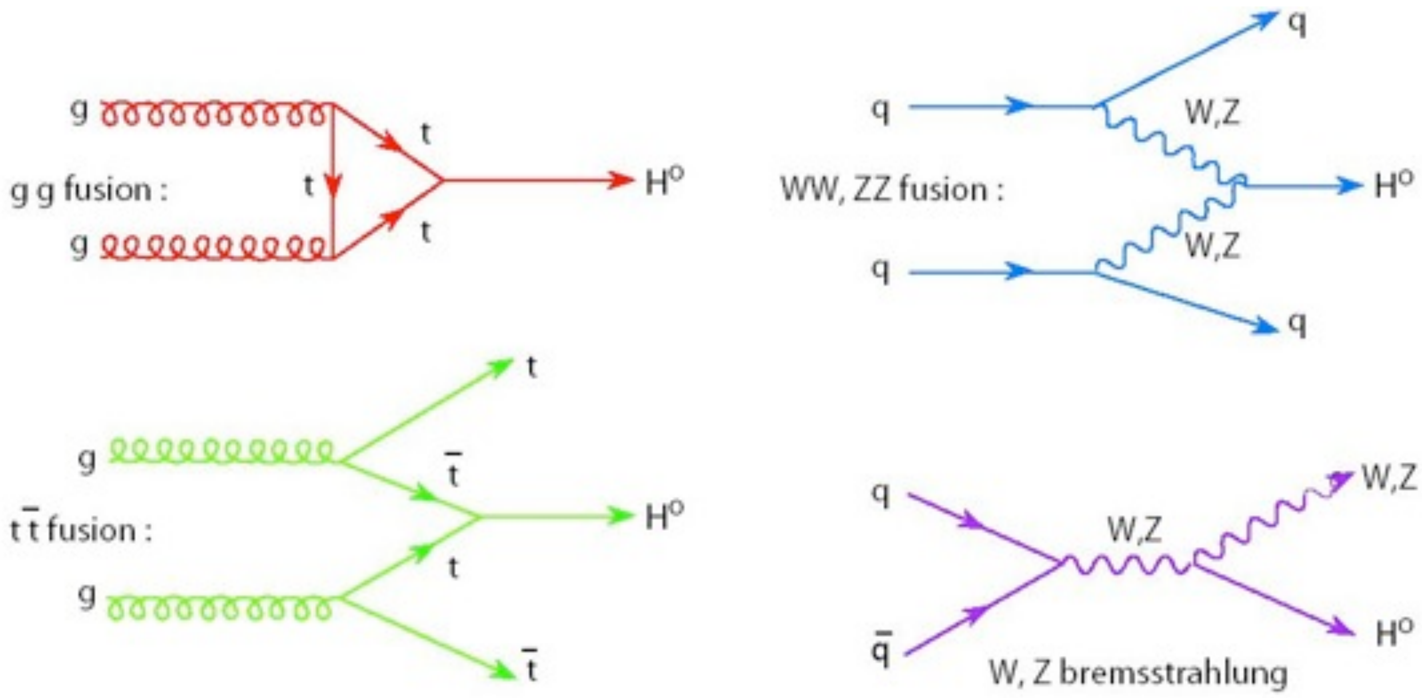
LHC - “Large Higgs Creator”

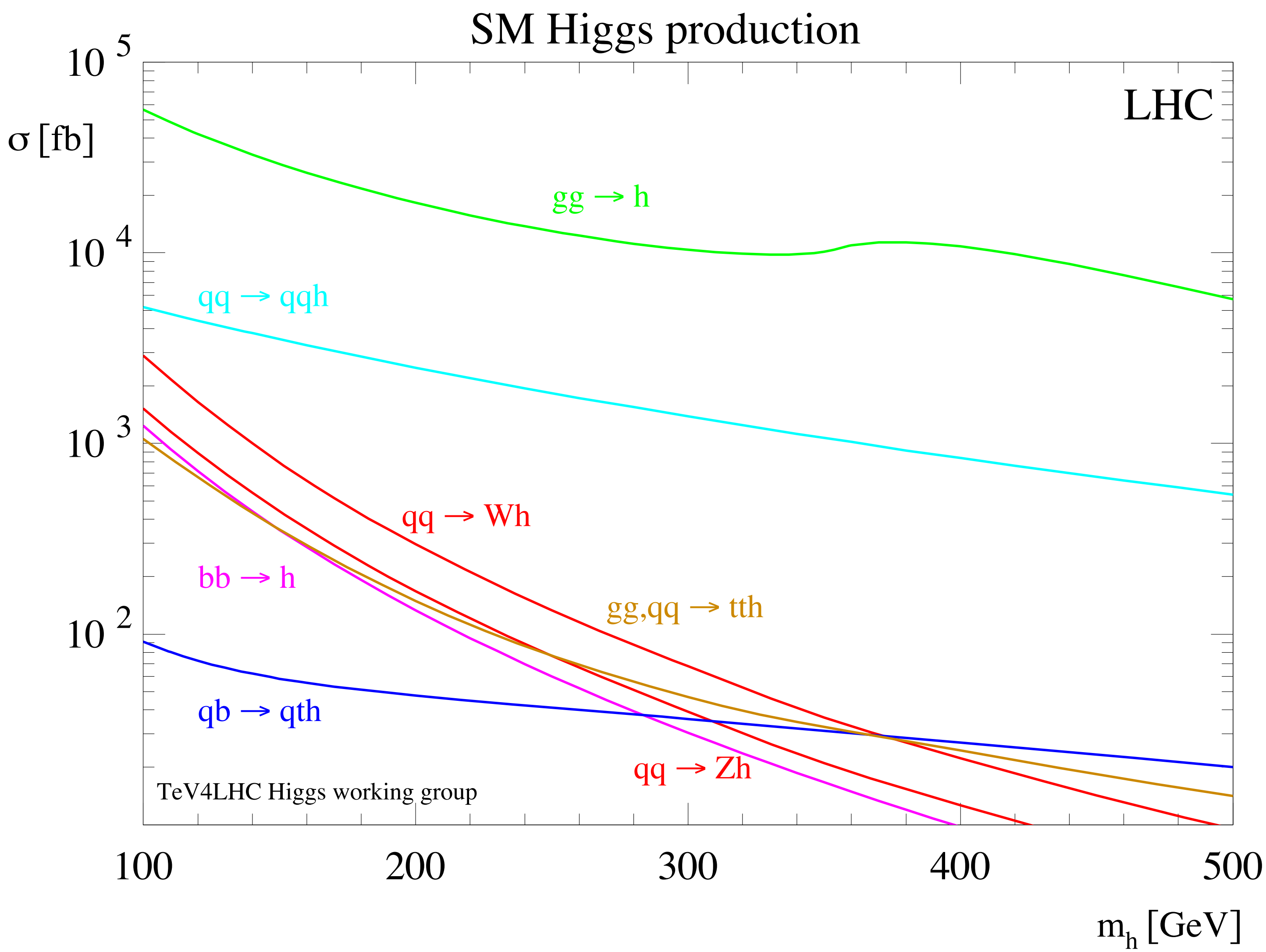
- So, in all likelihood, it will come down to the LHC to discover the Higgs boson
- The Higgs will be produced through a variety of processes at the LHC
  - Some rather copiously (gg fusion)
  - Some pretty rarely (ttH)



If a Higgs exists, it will be produced at the LHC,finding it however, is another matter

Higgs Production Cross-sections

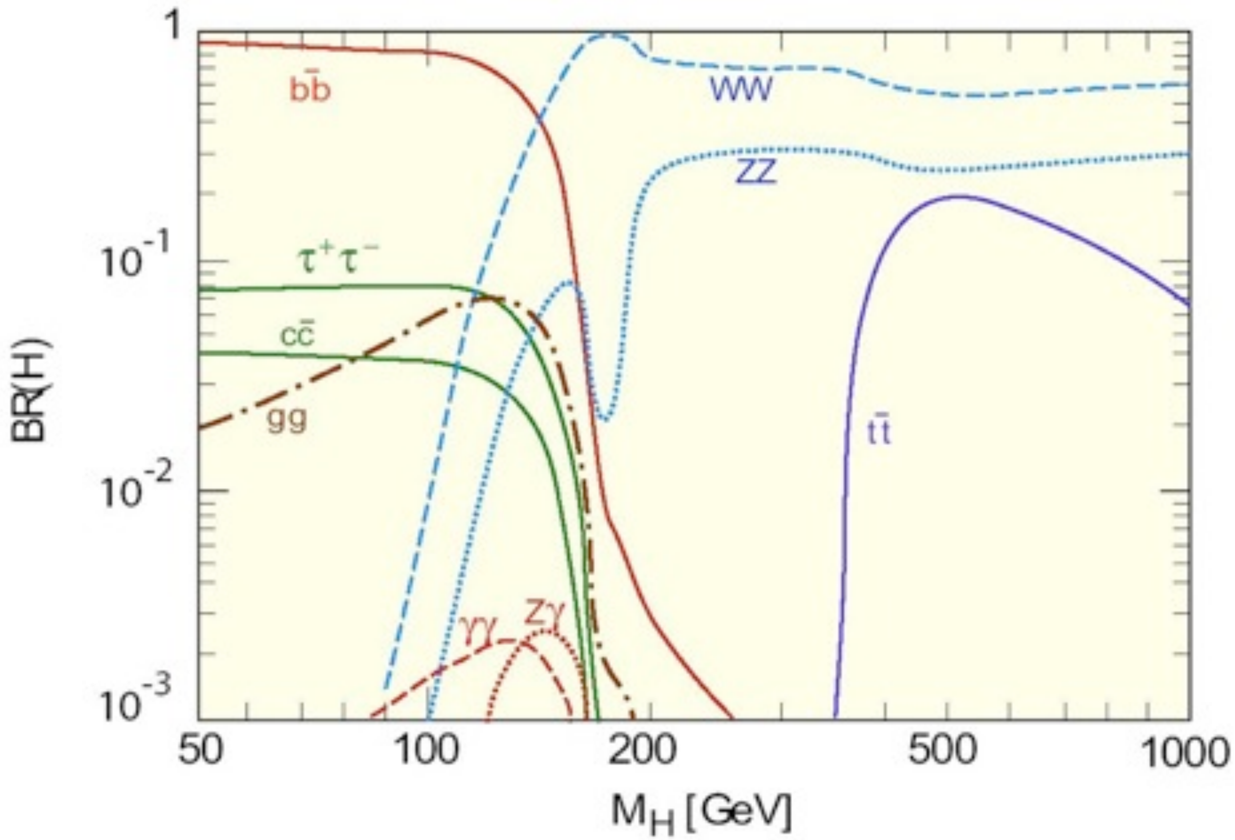
- With cross-sections of 100's of pb, significant number of Higgs will be produced by the LHC in a very short amount of time (weeks-months)
- It will likely take much longer than that to claim a discovery, however, why?



Higgs Decay Modes

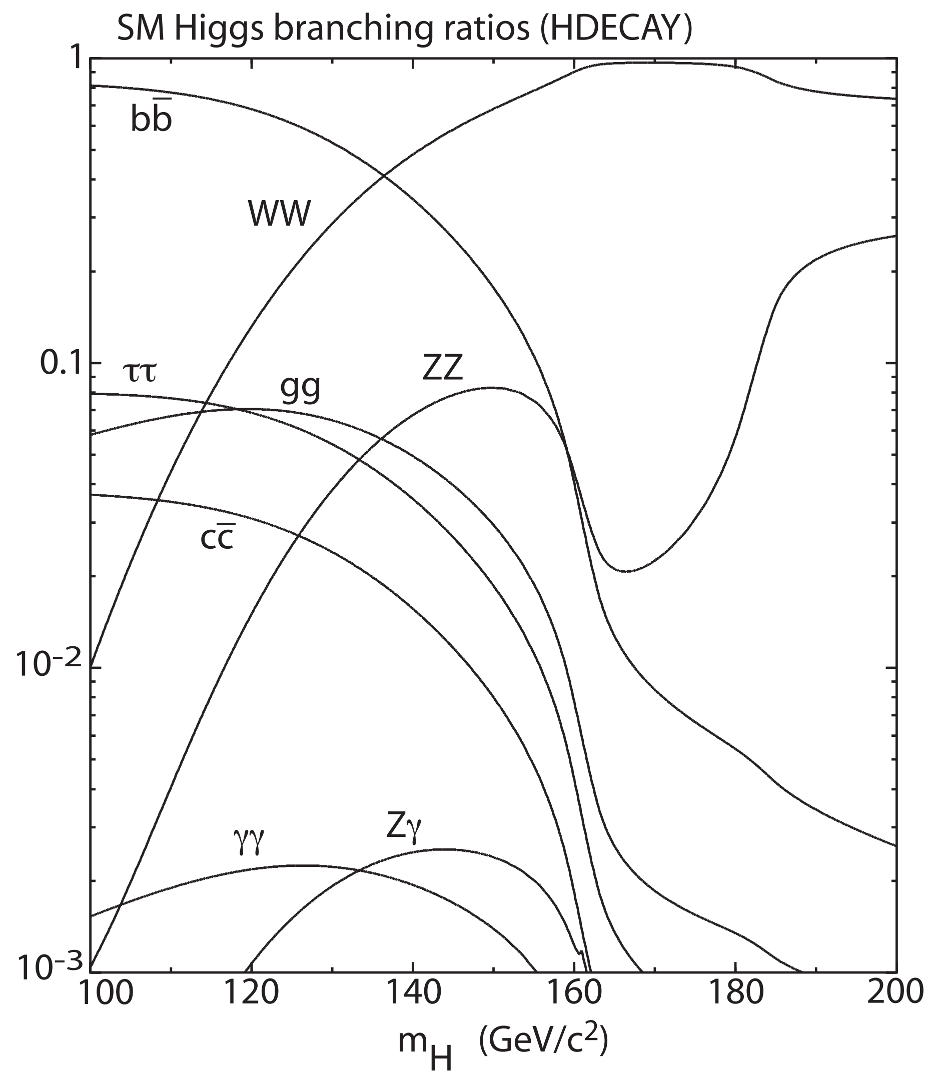
- For m_H < 1 TeV, there are essentially three different mass regions (**low, intermediate, high**) which are characterised by different decay modes

- The decay modes change as a function of m_H since the Higgs couples to mass and likes to decay to the heaviest



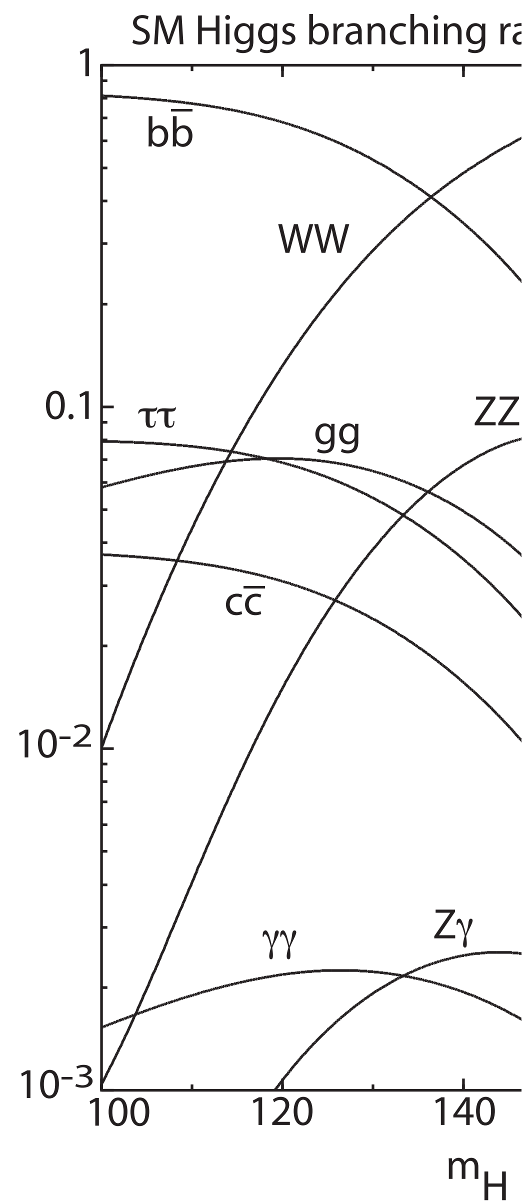
Higgs BR (Zoom in, $m_H < 200$)

- Low ($m_H < 130$)
  - Dominantly decays to bbbar (jets)
- High ($m_H > 160$)
  - Dominantly decays to bosons which can subsequently decay to leptons
- Intermediate ($130 < m_H < 160$)
  - Difficult region which does not have a dominant decay mode
- Each of these regions, requires a different search strategy
  - We'll look at the low & high mass cases



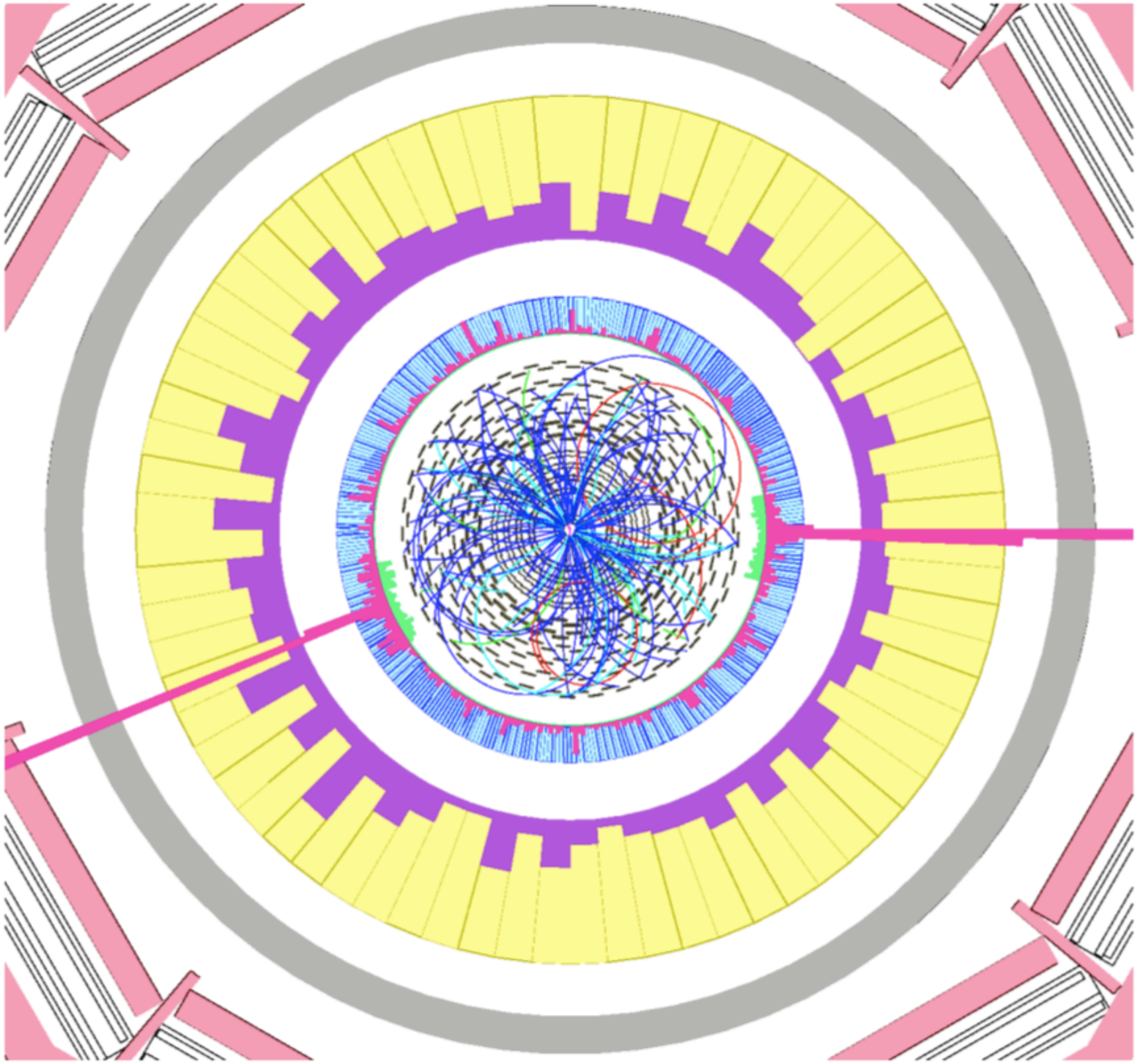
Low Mass Higgs

- As we have seen, there are a lot of hints pointing at a low mass Higgs
  - Unfortunately, this is also one of the most difficult regions to find it
  - In the dominant production mode (gluon fusion), the dominant decay mode (bbbar) is essentially useless due to the overwhelming QCD backgrounds
  - Only two ways to proceed:
    - Look for rarer associated production modes (and use accompany particles to distinguish the event from background)
    - Look for rare decay modes that provide cleaner signatures (e.g. $H\rightarrow\gamma\gamma$)



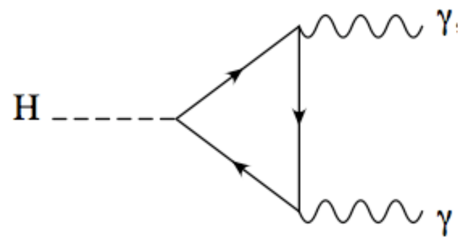
E.g. Diphoton Signal at CMS

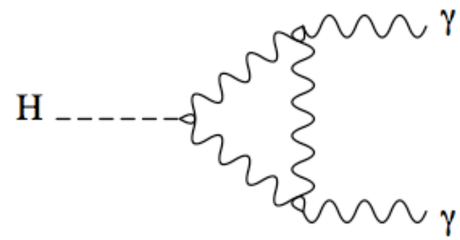
Rare (Br ~ 10^{-3})
But Clean

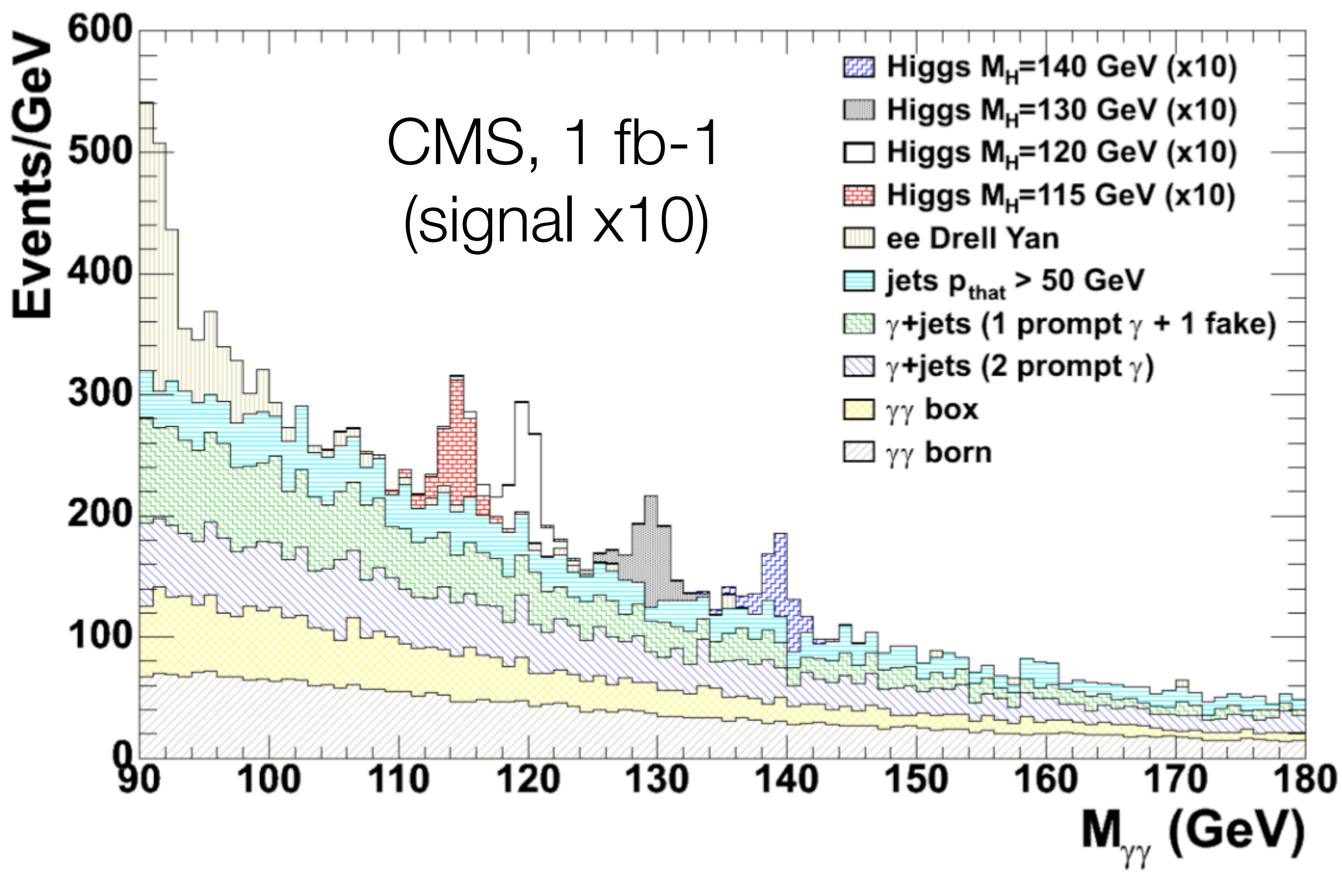


Higgs to γγ

- Take advantage of the excellent photon resolution to see a narrow peak above continuum background
- Need at least 10 fb^{-1}

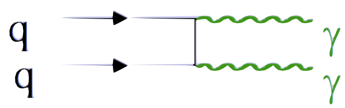




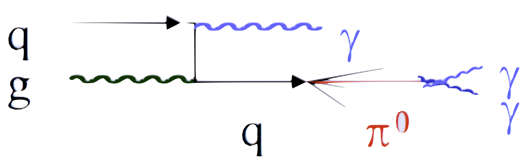


Main backgrounds:

γγ irreducible background

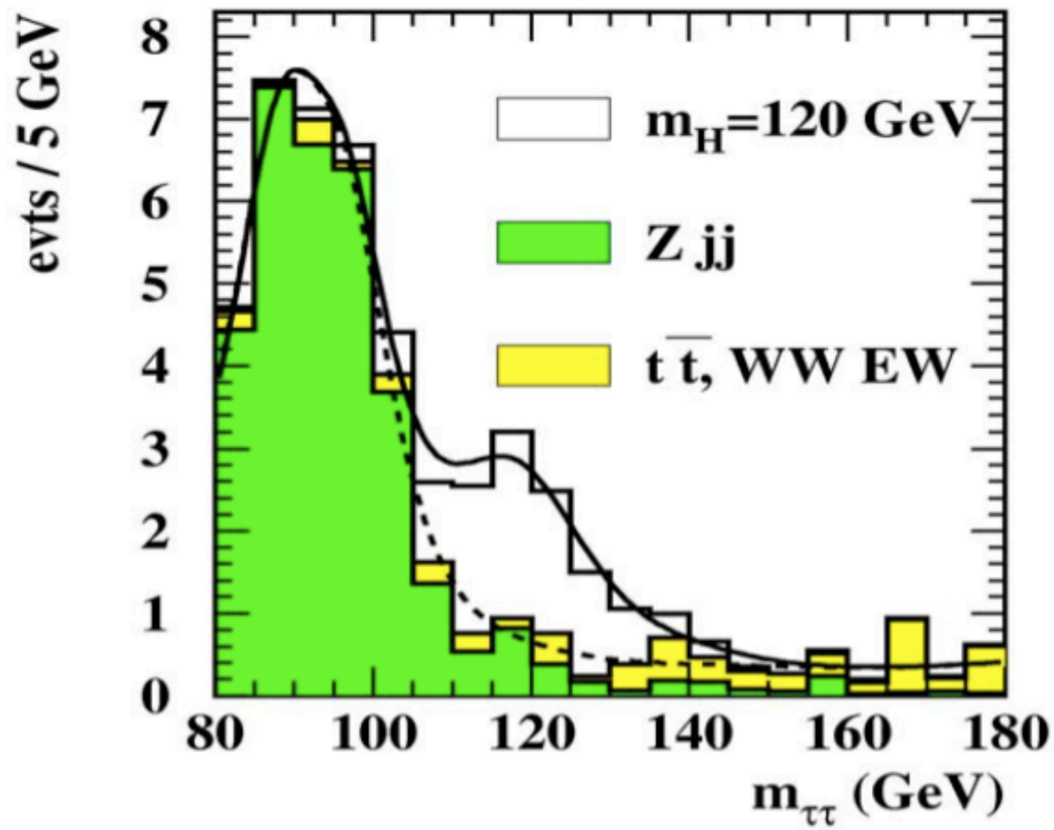


γ-jet and jet-jet (reducible)



Eg. qqH, H→ττ

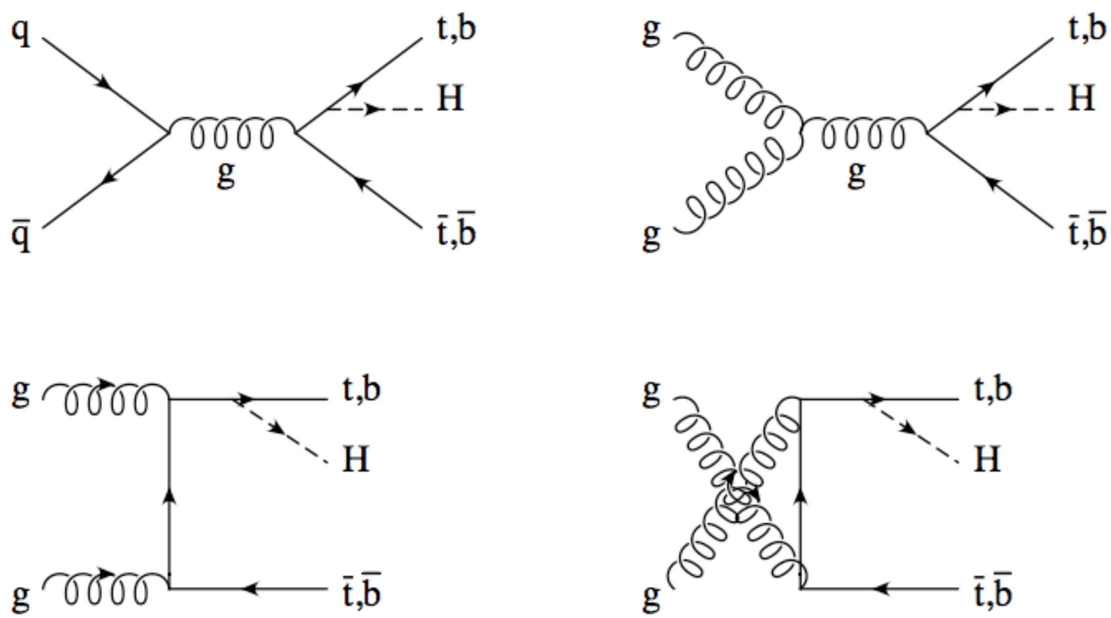
- Selects Higgs bosons with a large p_T (boost)
  - Make a collinear approximation (assume neutrinos in tau decays are in same direction as visible decay products)
  - With this assumption, reconstruct Higgs mass
  - With enough integrated luminosity, can see a clear excess over backgrounds in ditau mass spectrum



Httbar?

- Can in principle try same trick with Higgs produced in association with a top quark pair

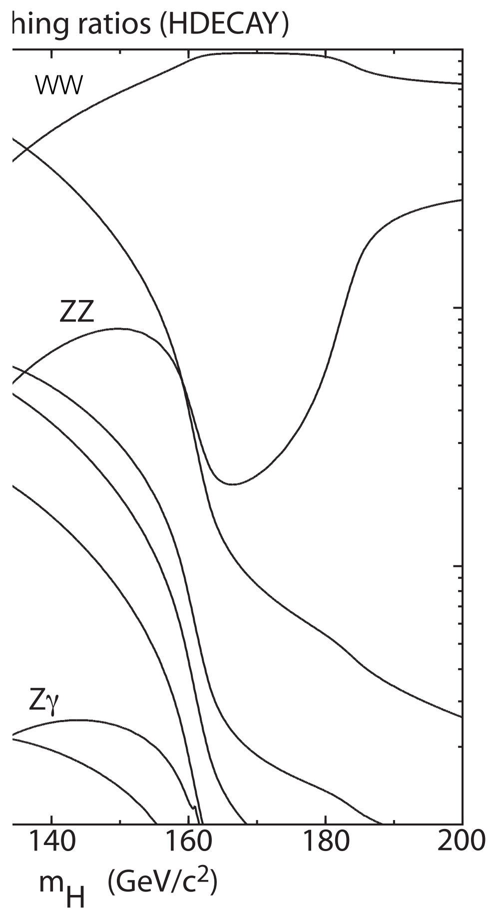
- All top decay modes have been examined and unfortunately this does not seem to be a viable discovery mode (e.g. see [J. Phys. G.:Nucl. Part. Phys. 34 (2007) N221-N250])



The problems are the combinatorics in the mass reconstruction as well as reducible and irreducible tt+jets backgrounds

High Mass Higgs

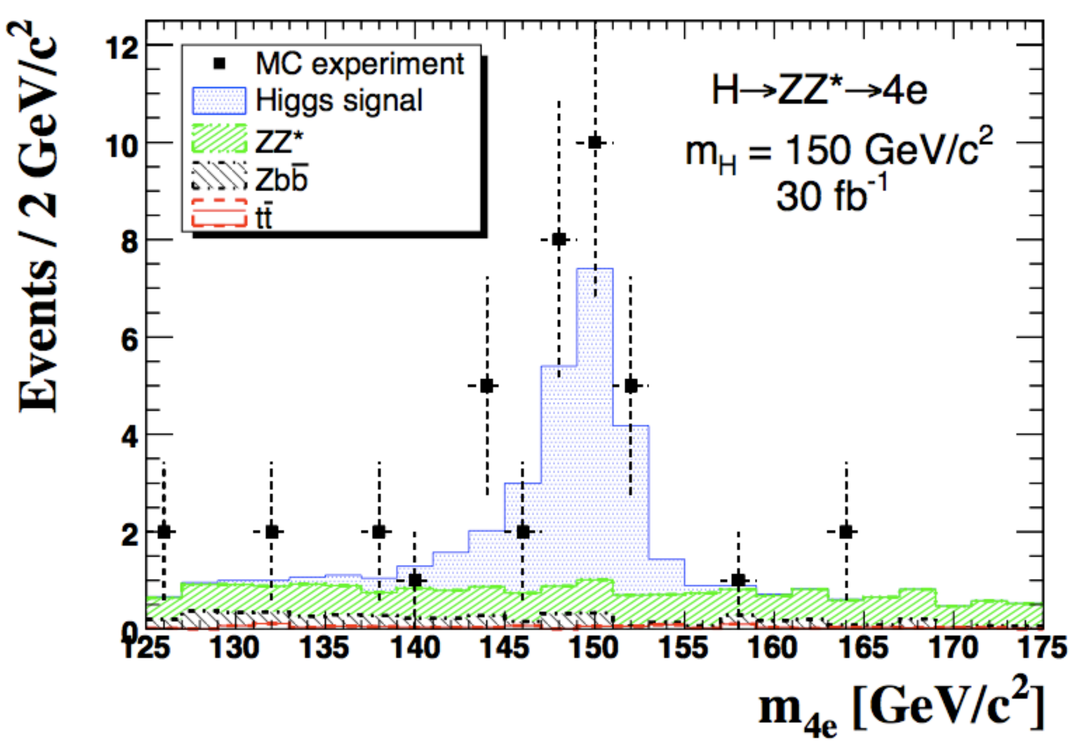
- By contrast, finding a High Mass higgs is a piece of cake
- Both $H \rightarrow WW \rightarrow l\nu l\nu$, and $H \rightarrow ZZ \rightarrow 4l$ are viable search modes
    - Their multi-lepton signatures makes them relatively easy to discern above background
    - Both are easier if both bosons are on shell ($m_H > 160$ for WW mode, $m_H > 180$ for ZZ mode), though this is less important for the ZZ case
    - $H \rightarrow ZZ \rightarrow 4l$ is considered by many to be the "golden mode" for the Higgs search



Even the golden mode will take some time

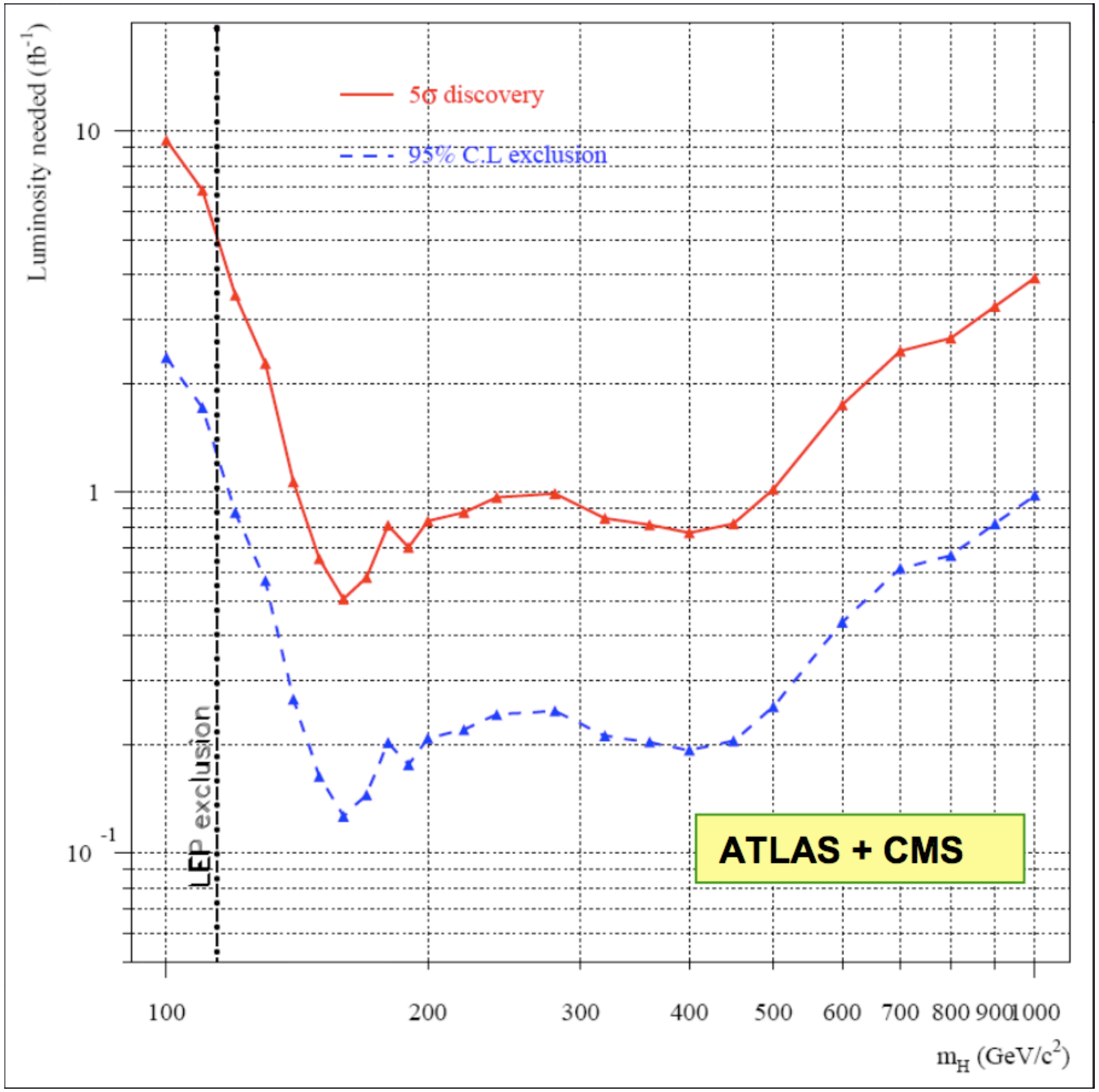
- Both electronic and muonic decays of the ZZ pair are viable
- After all cuts are applied (essentially 4 isolated leptons, two with OS which form an on-shell Z mass), very little background is left and a clear signal can be observed
- Nonetheless, will take a year or so (> 10 fb^{-1}) for a single experiment)

CMS - 4e mode



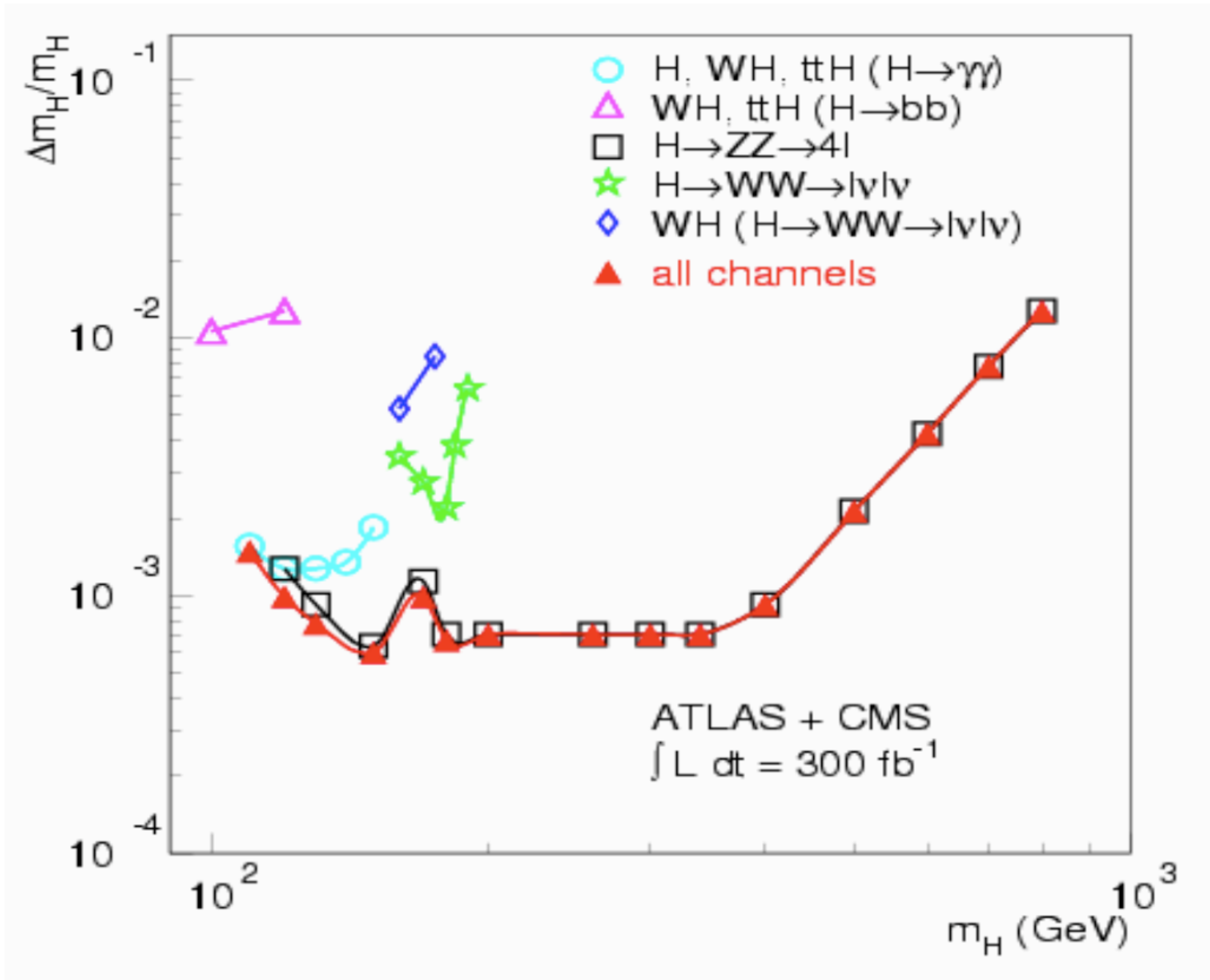
How long will a discovery take?

- In this plot (which I suggest you take with a healthy dose of scepticism), the claim is made that the LHC needs < 5 fb^{-1} to claim a higgs discovery
  - Combining results from all channels
  - Combining results from ATLAS & CMS



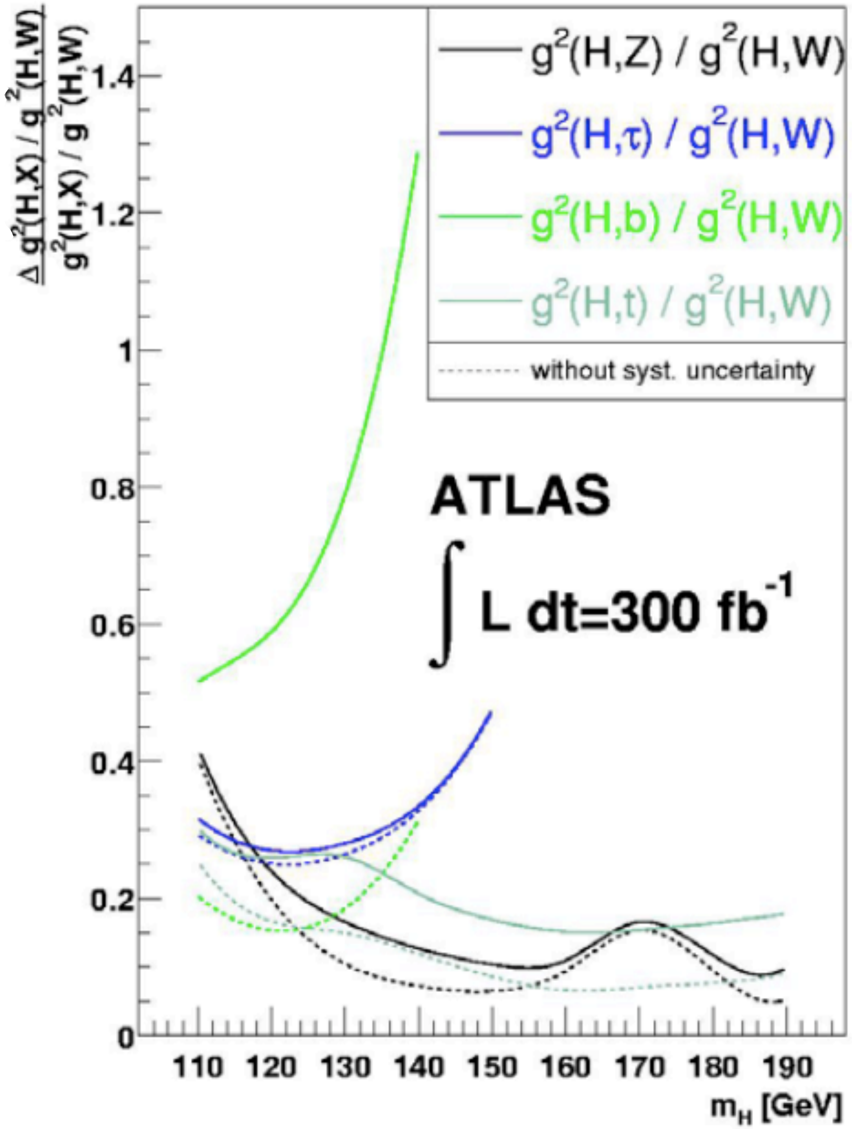
What about the Mass?

- A similar plot for combined measurements of m_H (assuming a discovery has been made) shows the asymptotic precision expected at the LHC
  - Dominated by ZZ→4l, and γγ modes
  - 0.1% precision over large mass

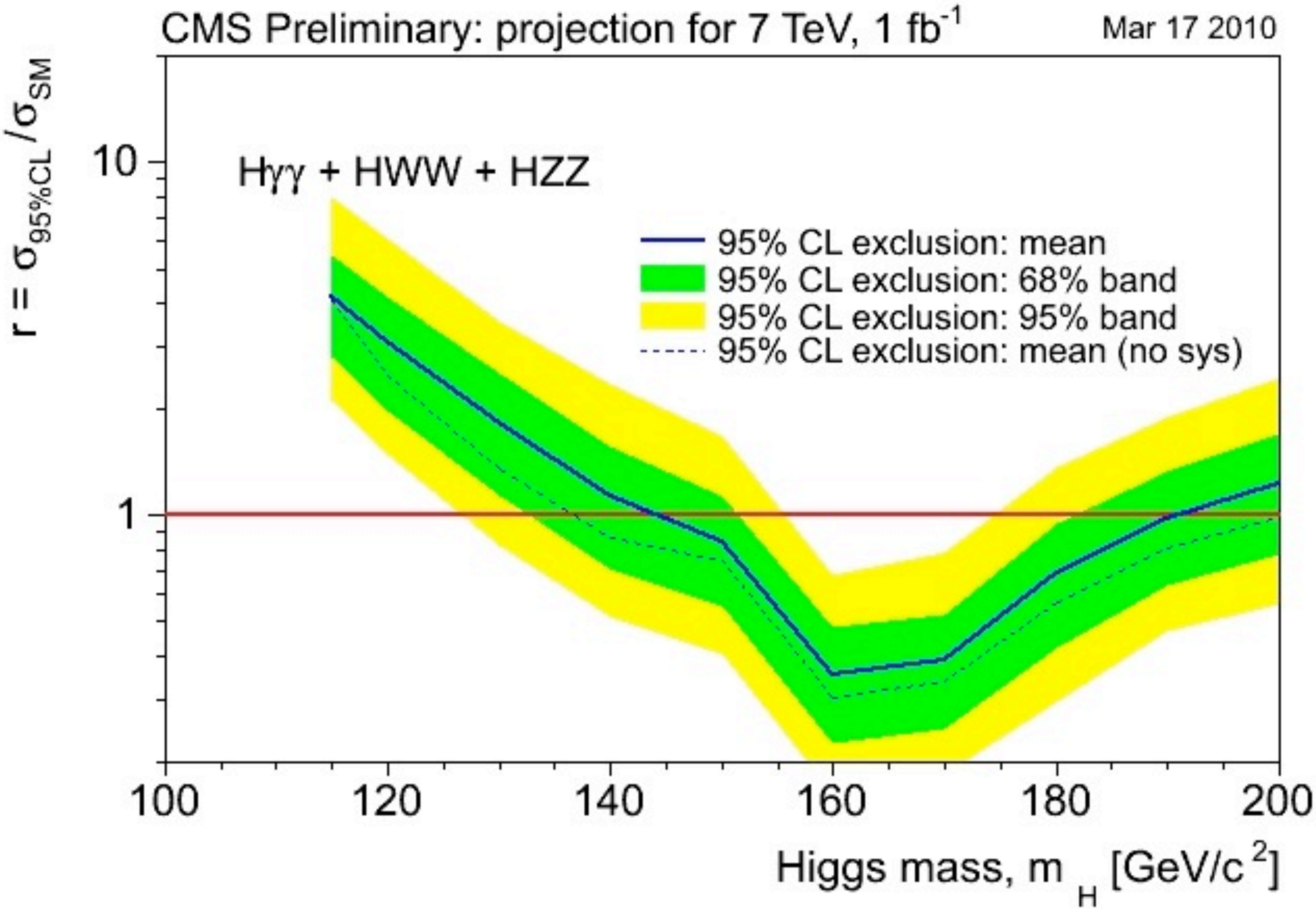


How will we know it's a Higgs?

- Measure its properties - does it fit with SM requirements?
  - Mass consistent with SM? (as discussed)
  - Spin 0? (e.g. angular distributions amongst 4l in H→ZZ)
  - Couplings (can measure relative couplings, compare to SM expectations - see right)
- Might not be enough … could need ILC



That was all based on 10 TeV, what about at 7 TeV?



Summary

- The Standard Model needs a Higgs (or something like it)
- The LHC will find a Higgs if it exists, though it may take some time
- A low mass Higgs in particular (which current theory & measurements favor), will be difficult (best mode is $H \rightarrow \gamma\gamma$)
- A high mass Higgs will be easier (but is increasingly unlikely)
- The introduction of a scalar field, i.e. the Higgs, causes the hierarchy problem as we have discussed, next lecture we will look at theories which attempt to address this problem