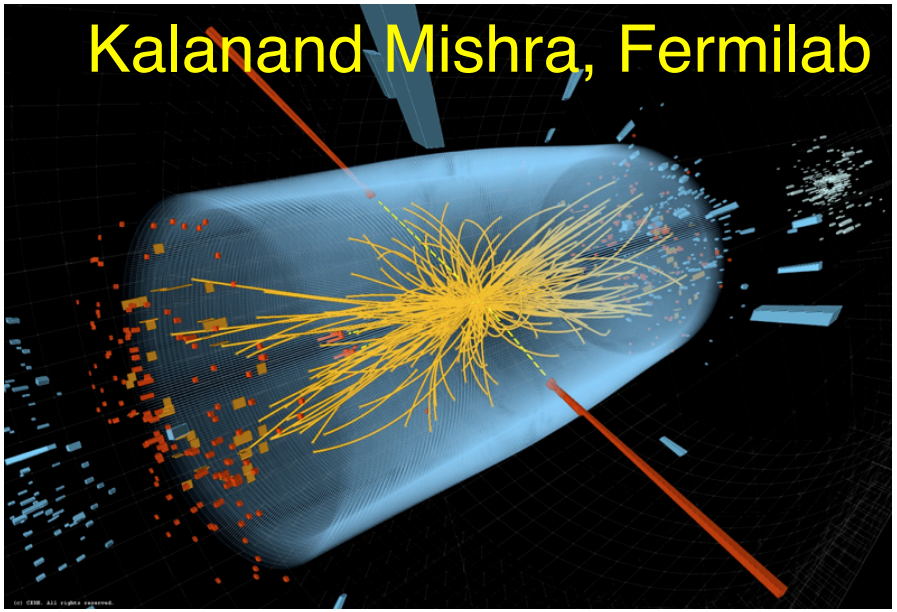
Endgame for the Higgs boson ?

Kalanand Mishra, Fermilab



January 5, 2012

Outline of this talk

- Higgs boson as the agent of "electroweak symmetry breaking"
  - What is Higgs, why we need it, why haven't found yet
- Direct search at the Large Hadron Collider
  - Signal over noise
  - Experimental techniques for discovery
  - Up-to-date results and what they indicate
- Outlook for 2012 and beyond, conclusion.

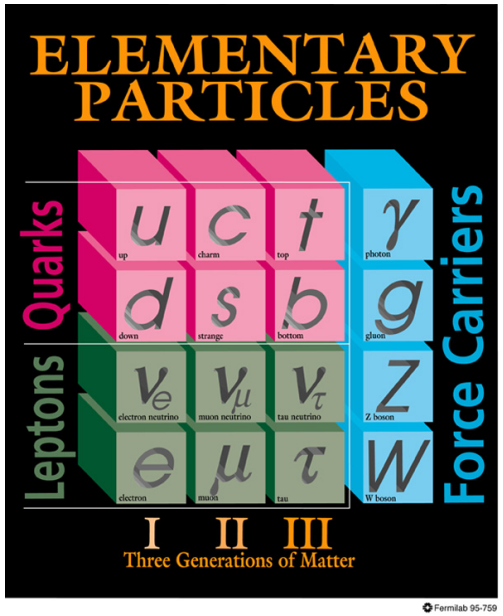
Reminder .....

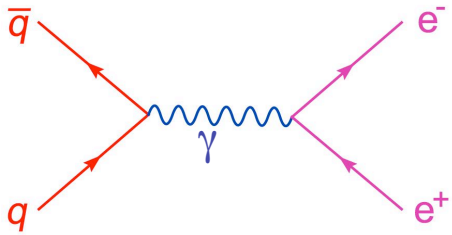
STOP ME if I go too fast or you have questions!!

What is Higgs boson, why we need it ?

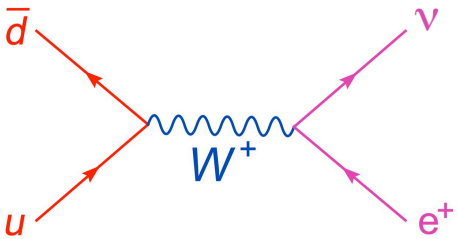
Basics of the Standard Model

- All matter composed of spin ½ fermions
- All forces (except gravity) carried by spin 1 vector bosons

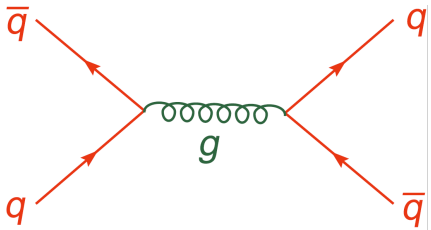




electromagnetism (QED)



weak



strong (QCD)

Weak force carriers− W and Z bosons are massive. So are all the fermions.

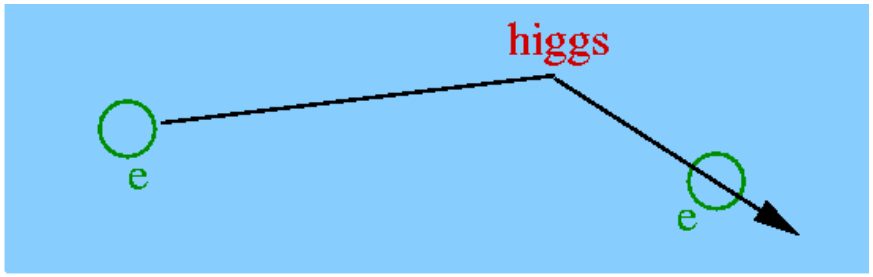
The origin of mass

Fundamental symmetries of nature require that all elementary particles and force carriers be massless,

but in the real world the elementary particles have widely differing masses ➡ so some symmetry must be broken

The Higgs Boson

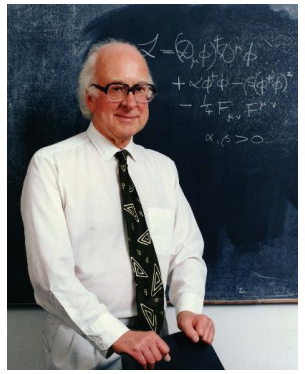
We suspect the vacuum is permeated by a “Higgs field” that is responsible – the quantum of this field is a fundamental scalar.

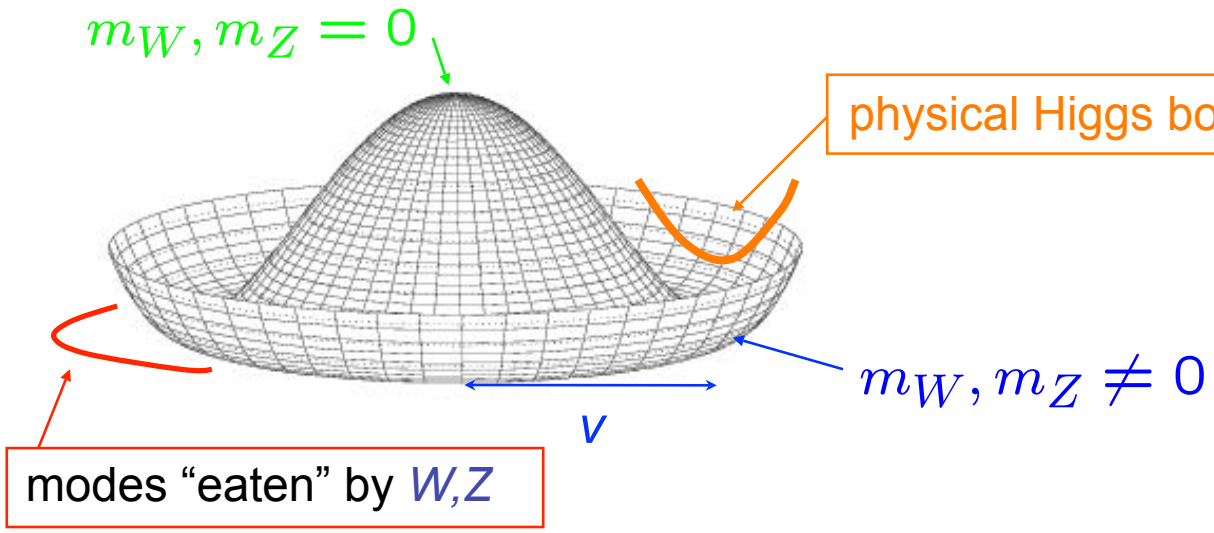


To explain the W mass the Higgs vacuum must be 100 times denser than nuclear matter!!

Higgs Mechanism for symmetry breaking

Brout, Englert, Guralnik, Hagen, Higgs, Kibble (1964)





A cosmic superconductor:
Weak fields screened within 0.003 fm

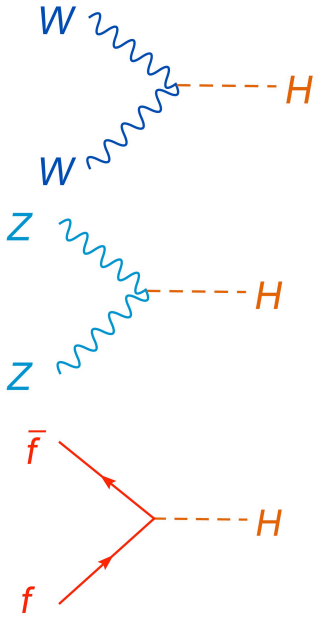
Discovery of the Higgs boson would help verify this approach.

So, why we need Higgs ?

To give masses to the fundamental particles

An elementary spin-0 particle.
Novel experimentally,
but not theoretically

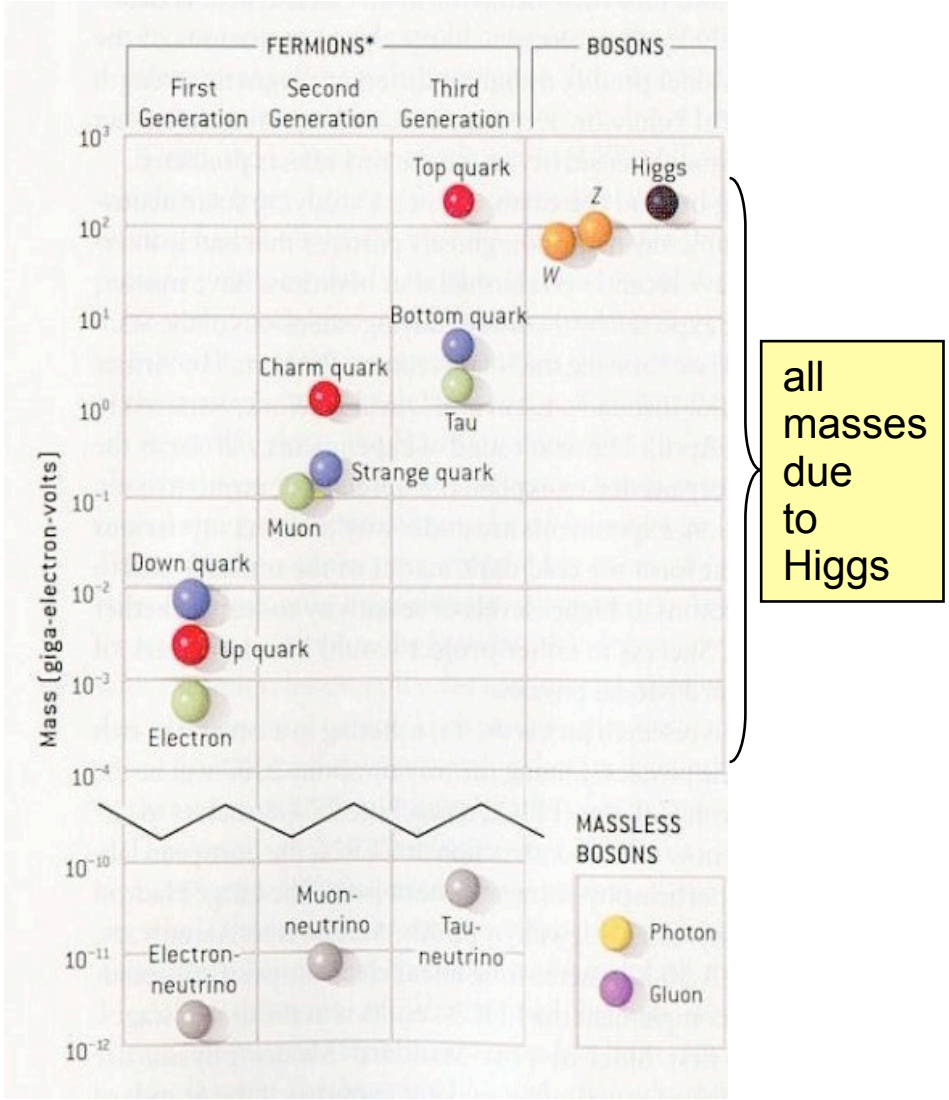
Higgs boson couples to mass:



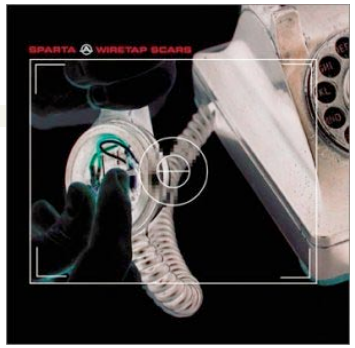
$$2\frac{m_W^2}{v}\eta^{\mu\nu}$$

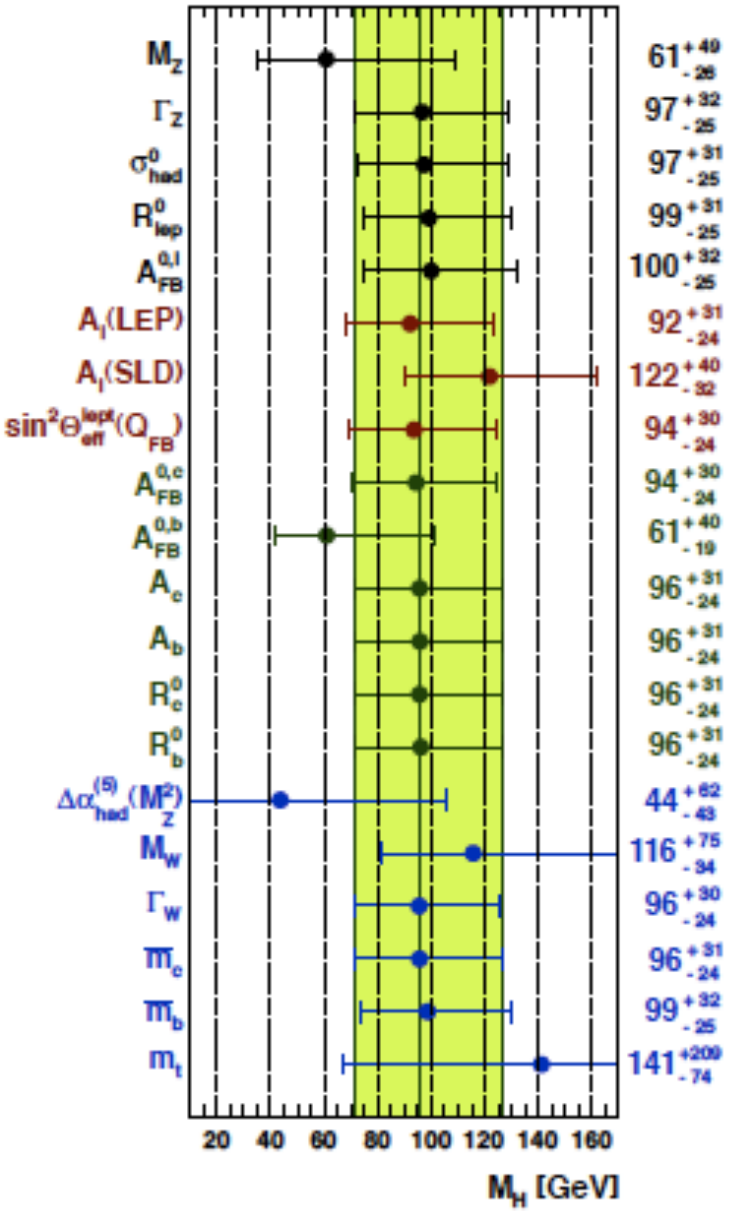
$$2\frac{m_Z^2}{v}\eta^{\mu\nu}$$

$$\frac{m_f}{v}$$

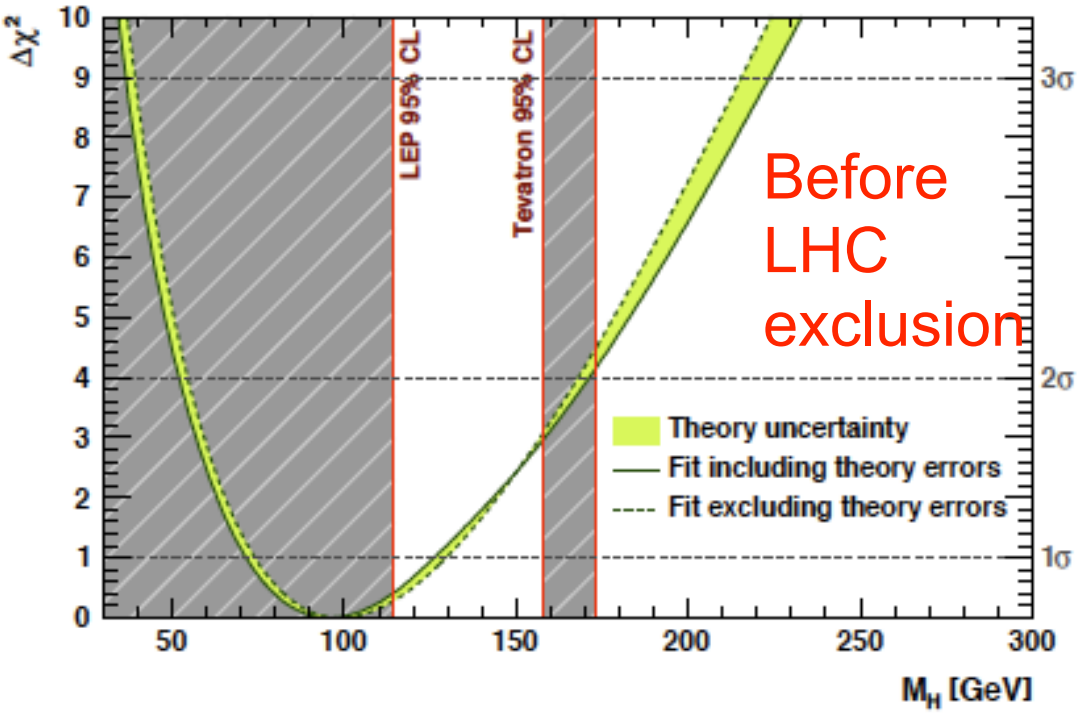


Whispers of the Higgs Boson





GFitter group, July 2011:
arxiv: 1107.0975



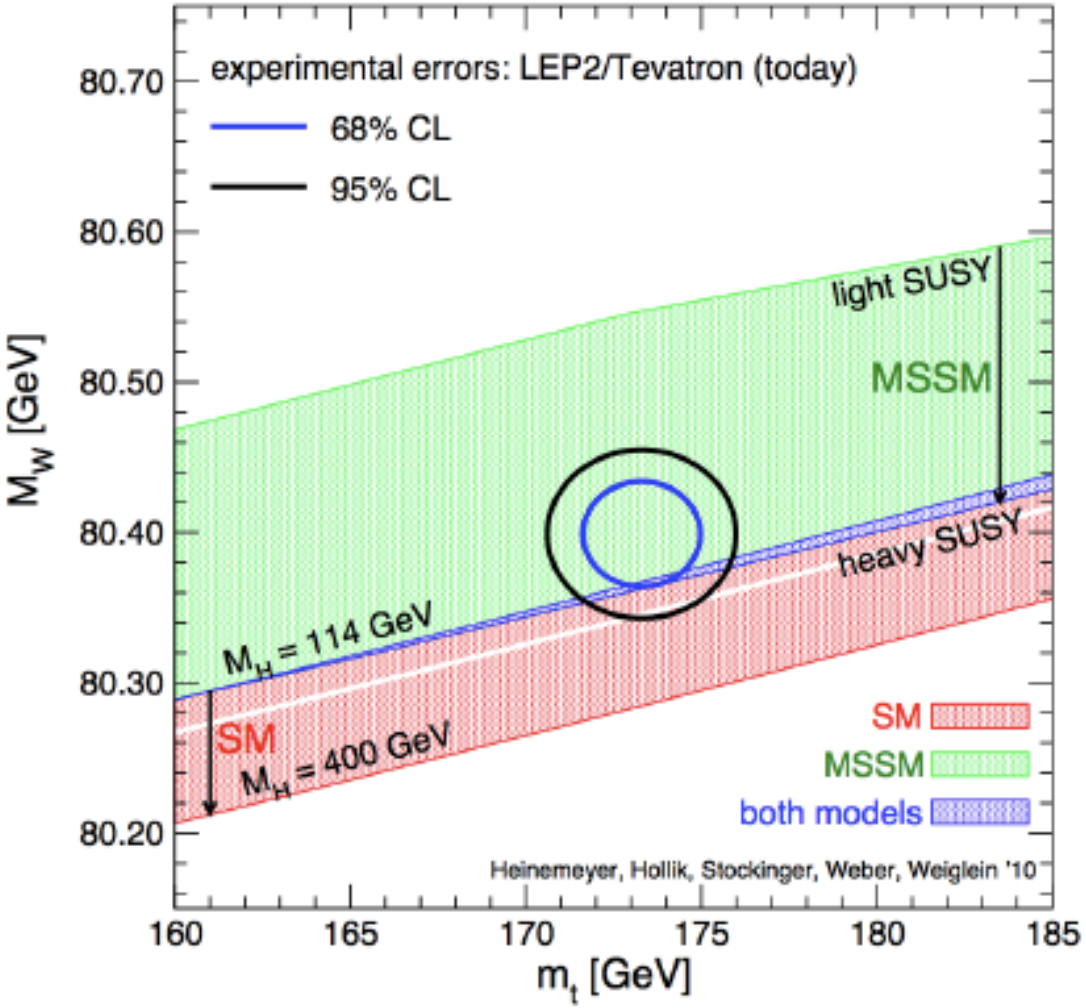
Before LHC exclusion

Are they all hearing the same whispers??

Or, is there more to the whisper ?

W boson mass

Jan Stark, Lepton Photon '11



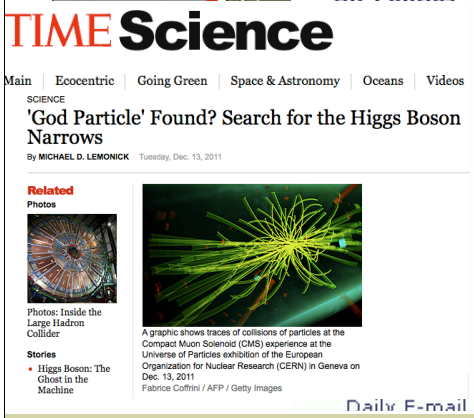
For equal contribution to the Higgs mass uncertainty need:
$\Delta M_W \approx 0.006\, \Delta M_t$.

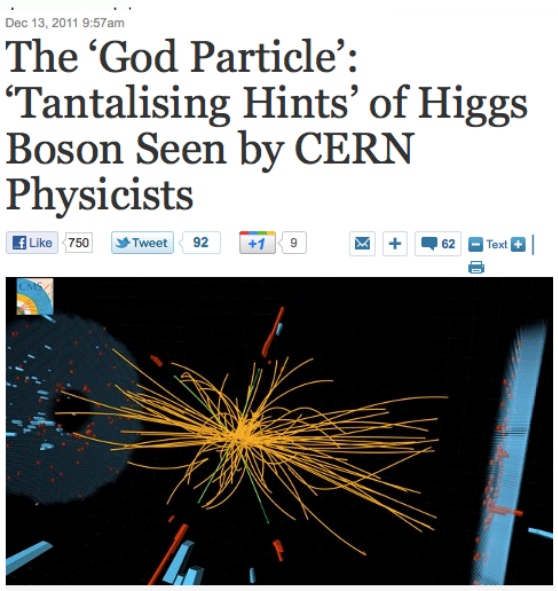
Current Tevatron average:
$\Delta M_t = 0.9$ GeV
$\Rightarrow$ would need: $\Delta M_W = 5$ MeV

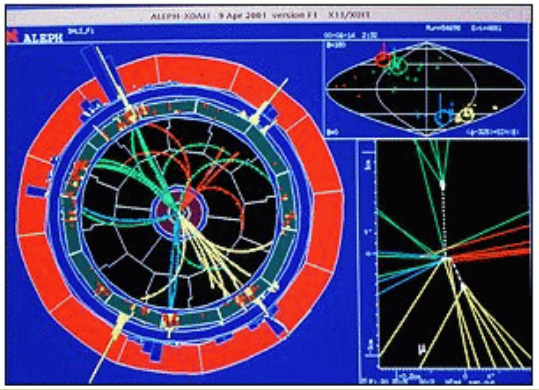
Currently have: $\Delta M_W = 23$ MeV

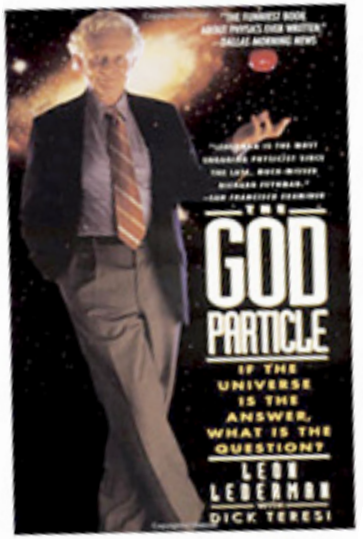
At this point, *i.e.* after all the precise top mass measurements from the Tevatron, the limiting factor here is ΔM_W, not ΔM_t .

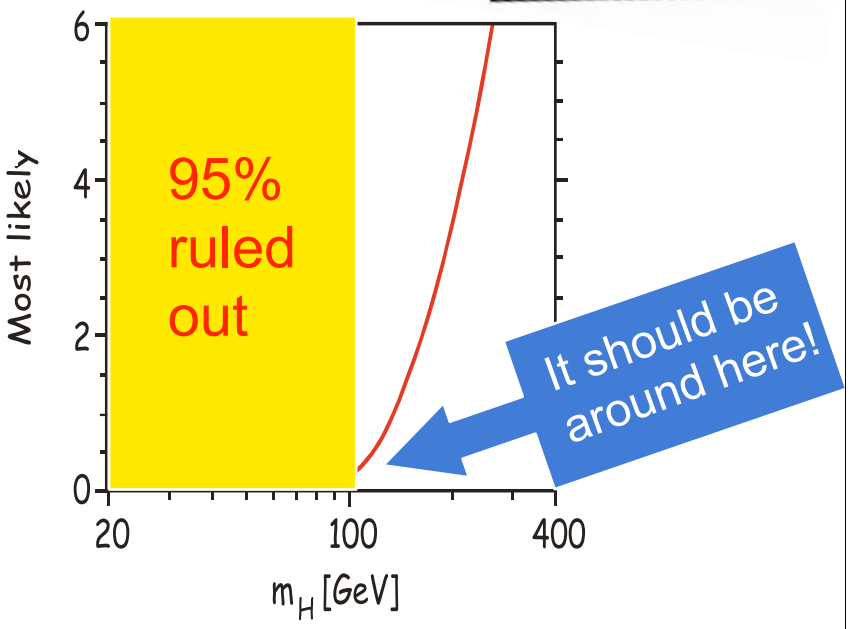
Where is Higgs ? Does it even exist ?











Direct search at LHC

Direct search for the Higgs at hadron colliders

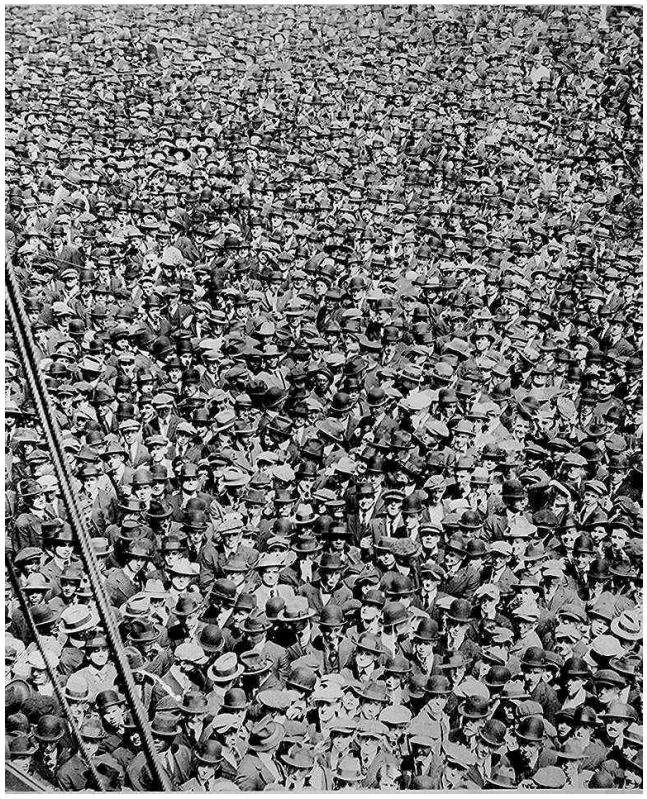
Look for evidence at the scene !!!

How to pick out of a crowd?

What are the backgrounds?

e^+e^- colliders

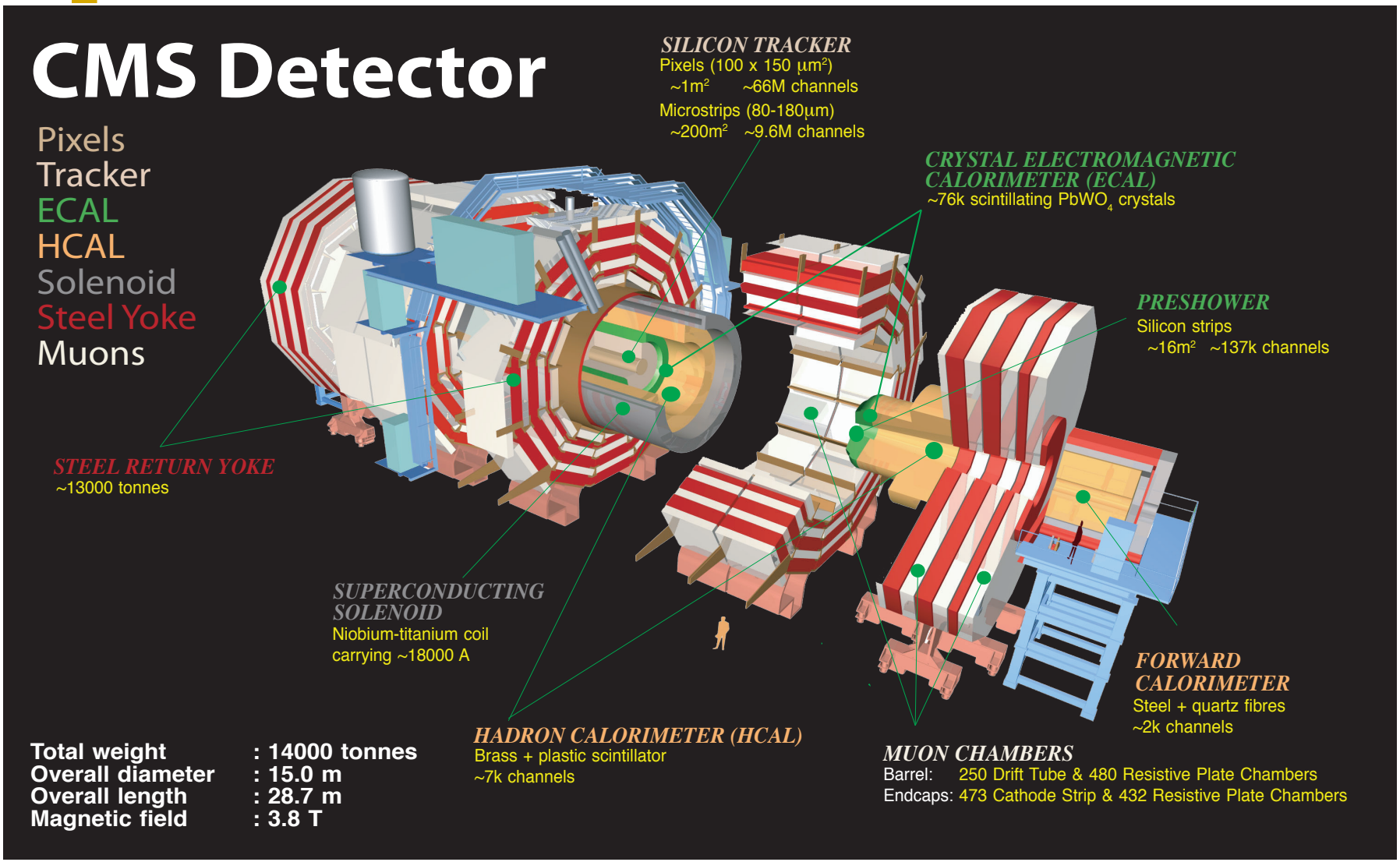
vs.



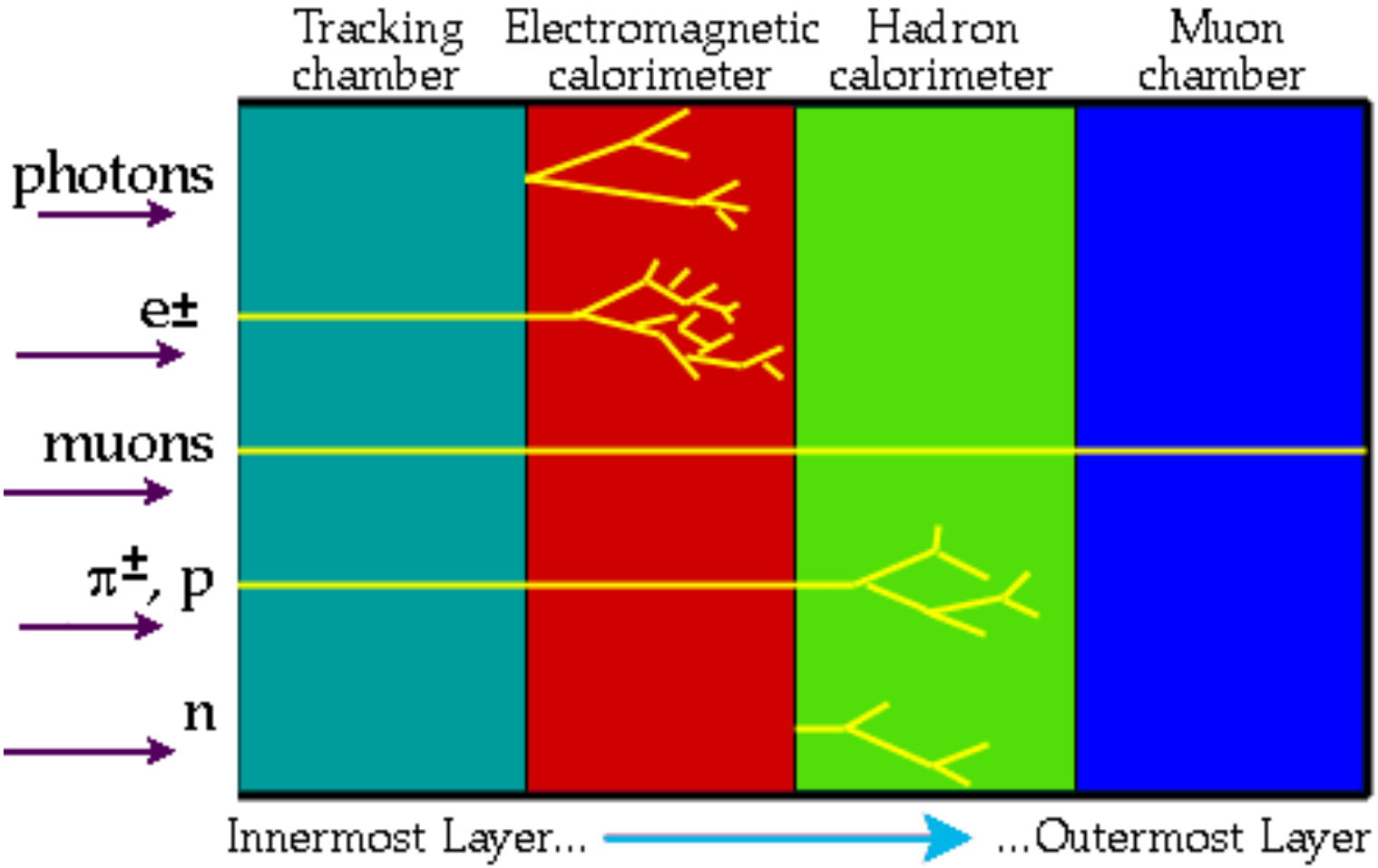
hadron colliders

The Large Hadron Collider at CERN

And one of its main detectors

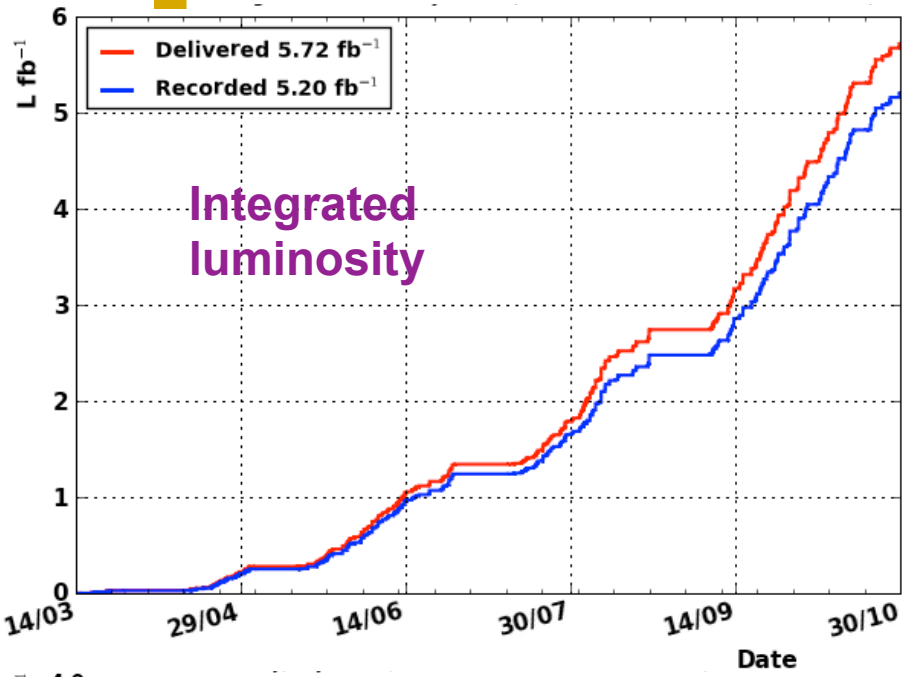


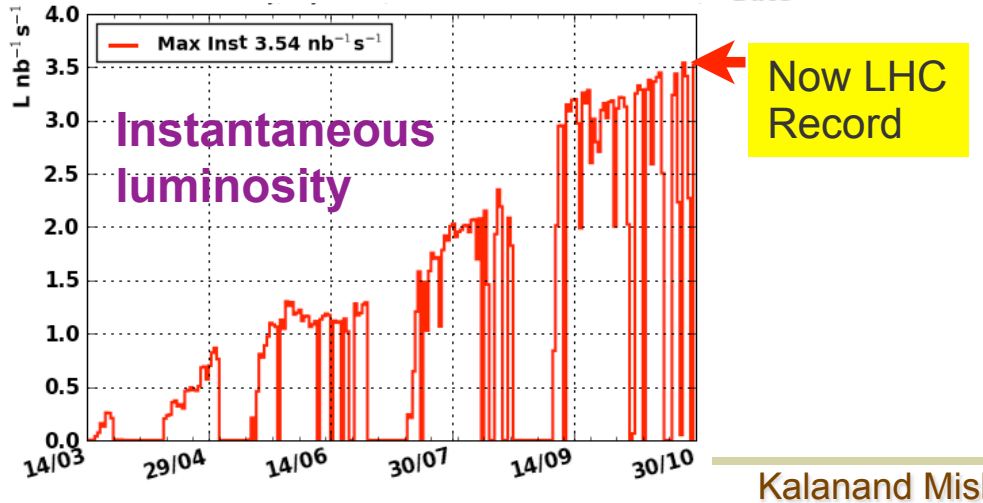
Identifying Particle Signatures



CMS trigger system can identify specific signatures online

Clearly in a different era than Tevatron





In the present ~ 5 fb^{-1} dataset we have (after selection cuts):

~ 30 M $W \rightarrow \mu\nu, e\nu$ events

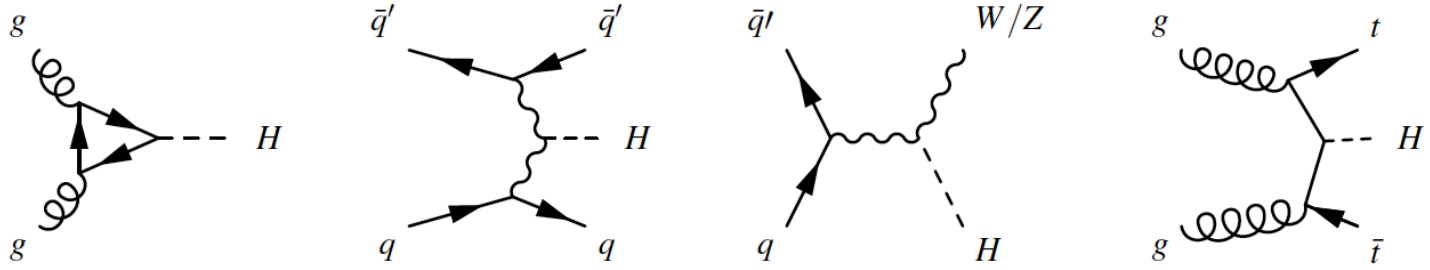
~ 3 M $Z \rightarrow \mu\mu, ee$ events

~ 60000 top-pair events

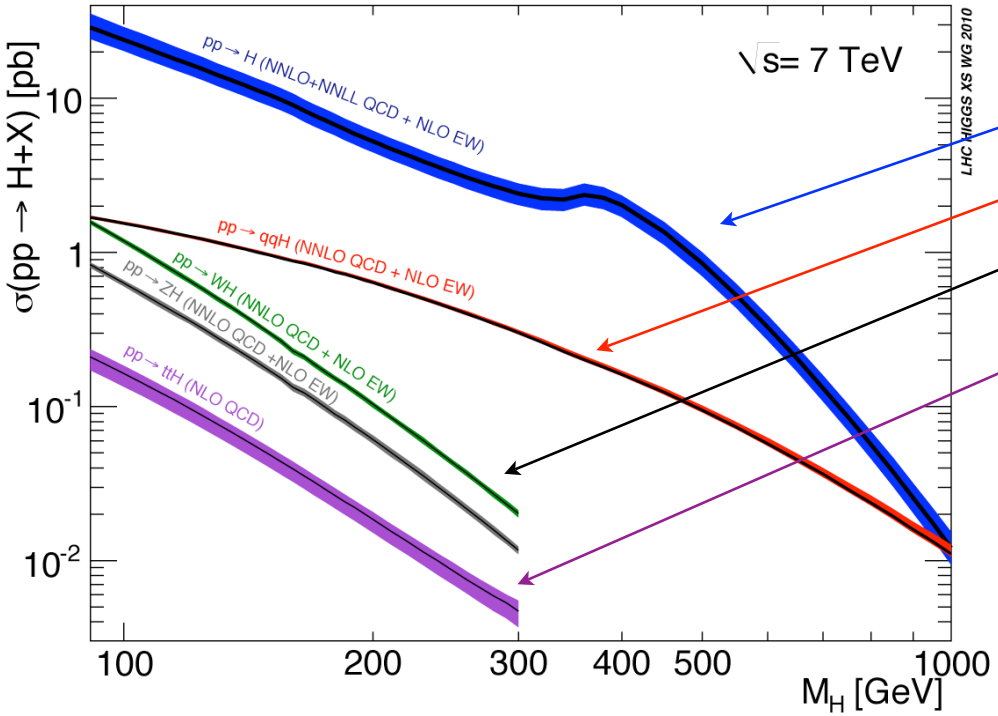
→ factor ~2 (W, Z) to 10 (top) more than total CDF and D0 datasets combined

→ will allow more and more precise studies of a larger number of processes

How will we find it at LHC ?



(a) $gg \to H$ (b) VBF (c) VH (d) $t\bar{t}H$



Gluon-gluon fusion

Vector boson fusion

in association with W,Z

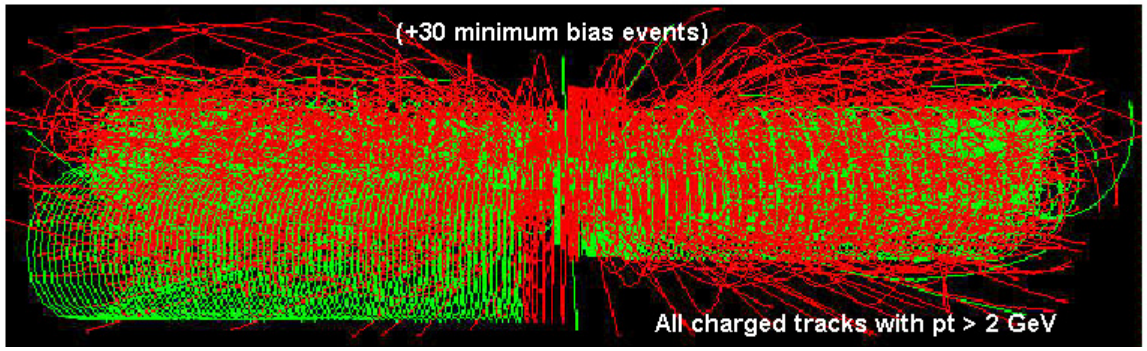
in association with tt

gg→H is the dominant production mechanism

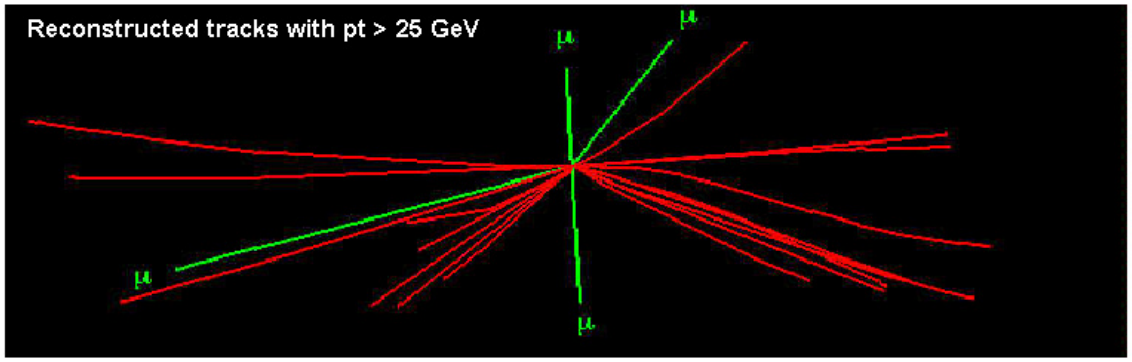
But this is the first part of the story of Higgs hunt ....

More challenging than a needle in a haystack …

Starting from this event…



We look for this "signature"



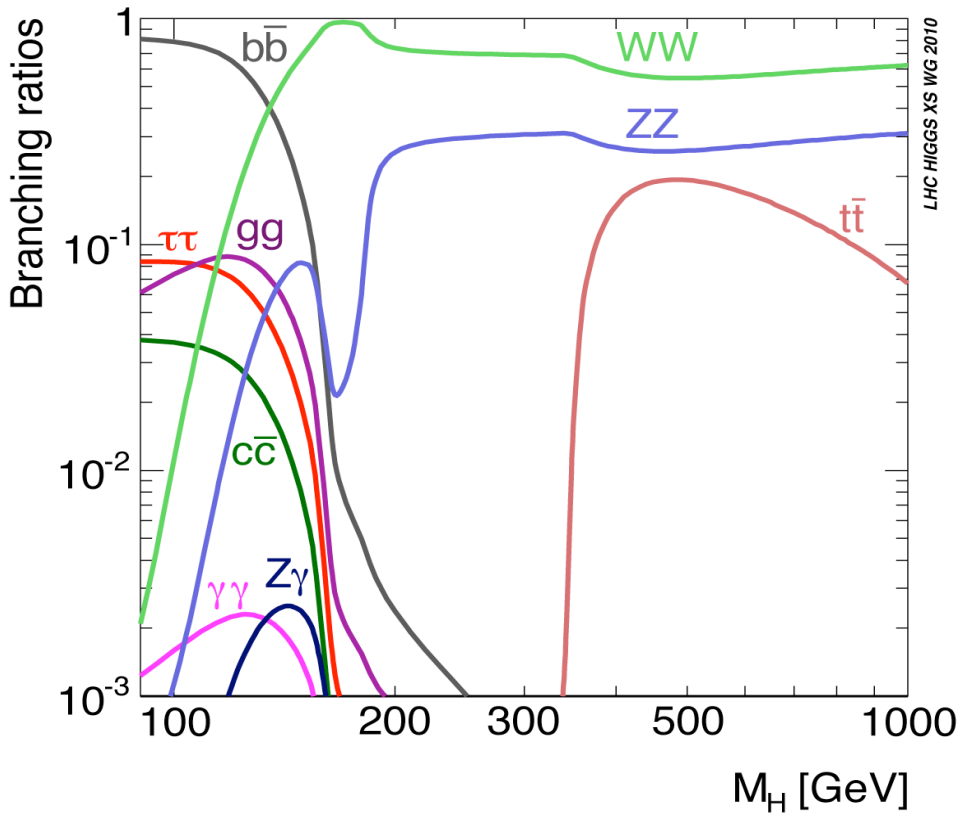
- 800,000,000 proton-proton interactions per second
- ~100,000,000 electronic channels
- 0.0002 Higgs / second

Selectivity: 1 in 10^{13}

Like looking for 1 person in a thousand world populations

Or for a needle in 20 million haystacks!

Possible "Disguises" (decay modes)



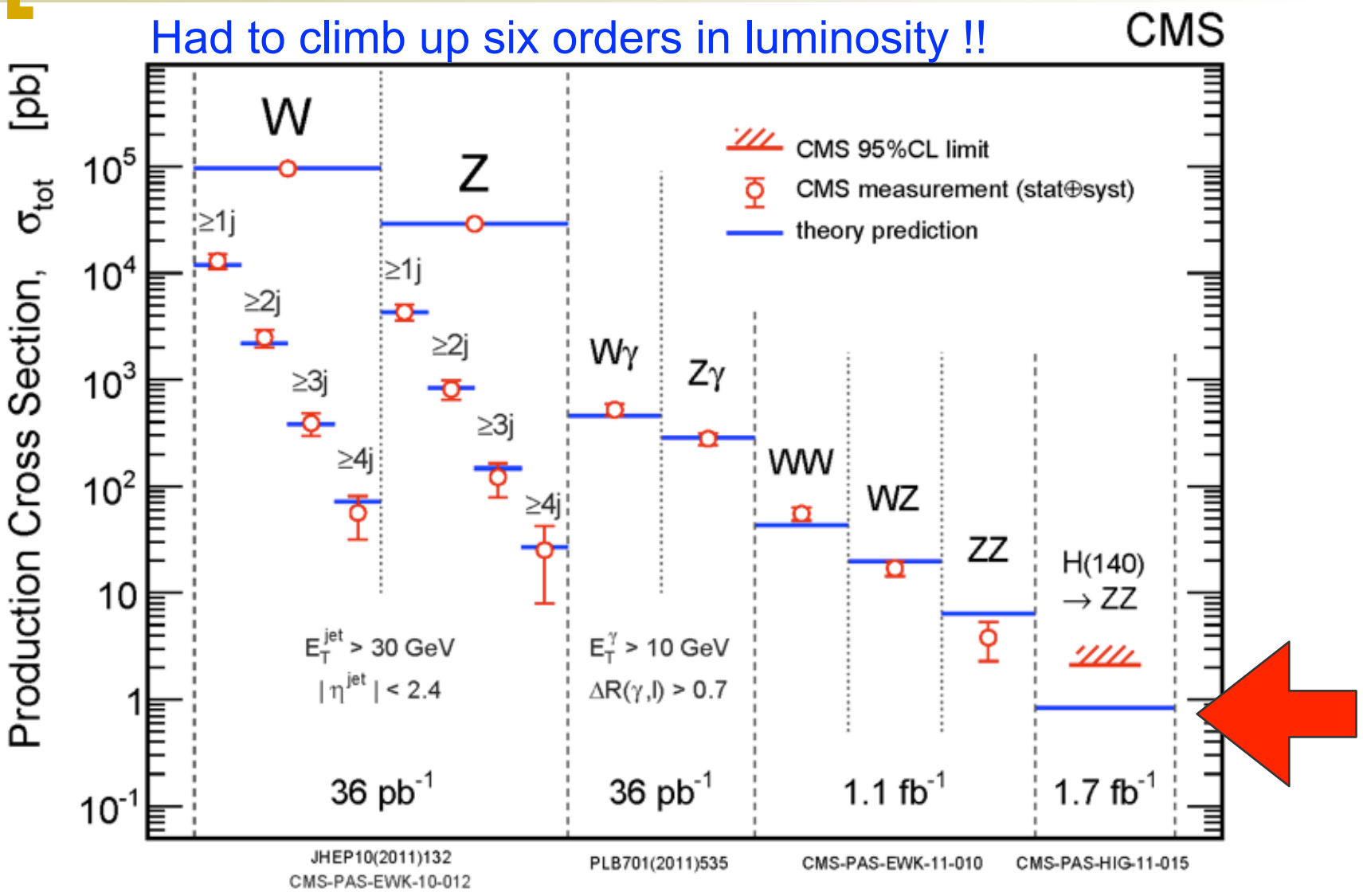
SM decay probabilities, or "branching ratios"

- completely determined by m_H
- still rich set of possibilities

Many "disguises" very effective at hadron colliders ($b\bar{b}$, $c\bar{c}$, gg)

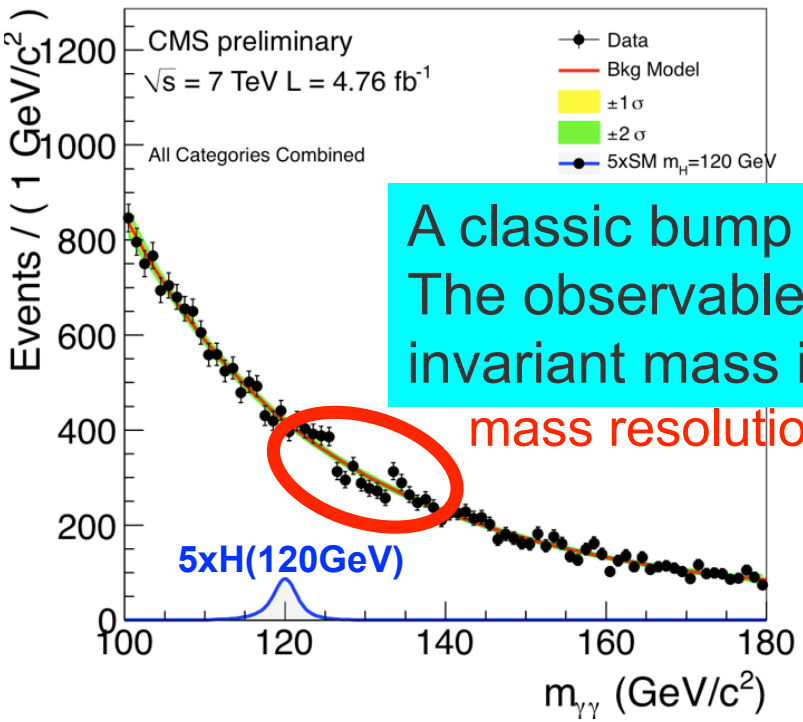
Why we haven't found it yet ?

Had to climb up six orders in luminosity !!



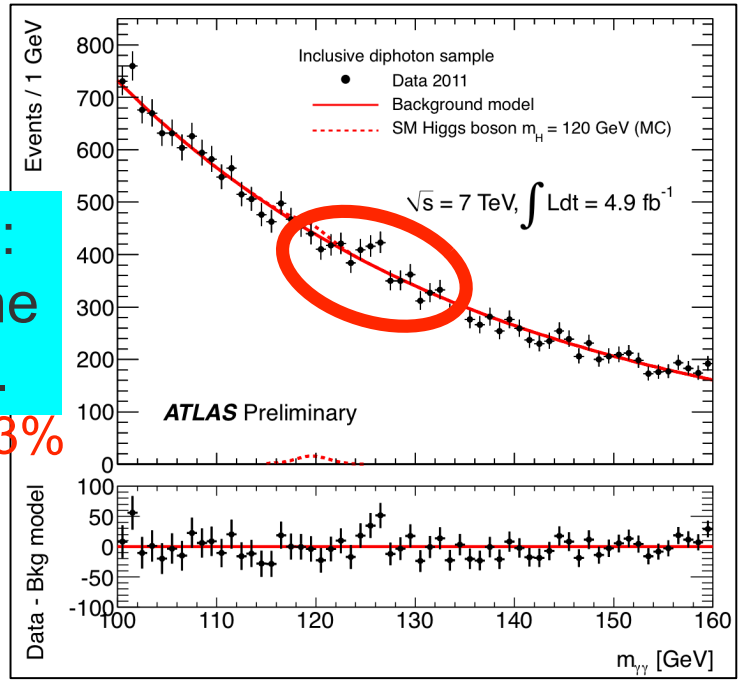
Experimental measurements

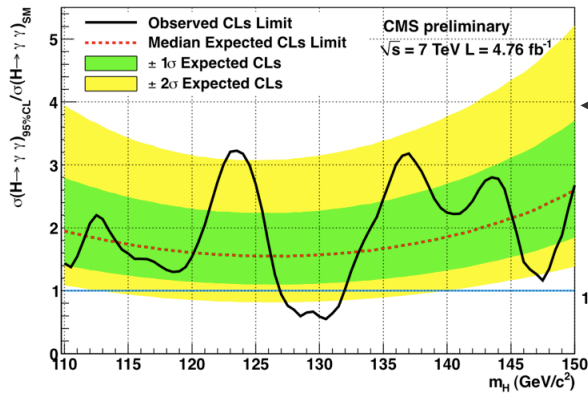
Sample direct search: gg→H→γγ



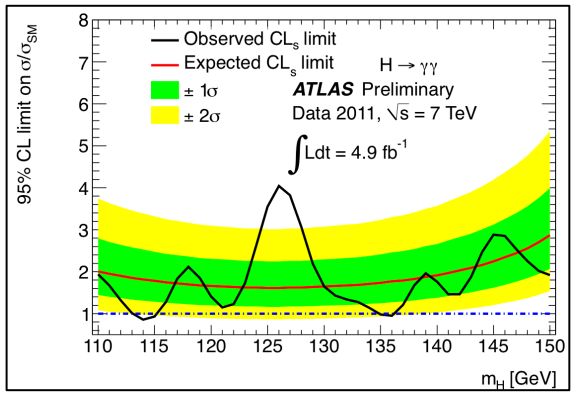
A classic bump hunt:
The observable is the invariant mass itself.

mass resolution 1−3%

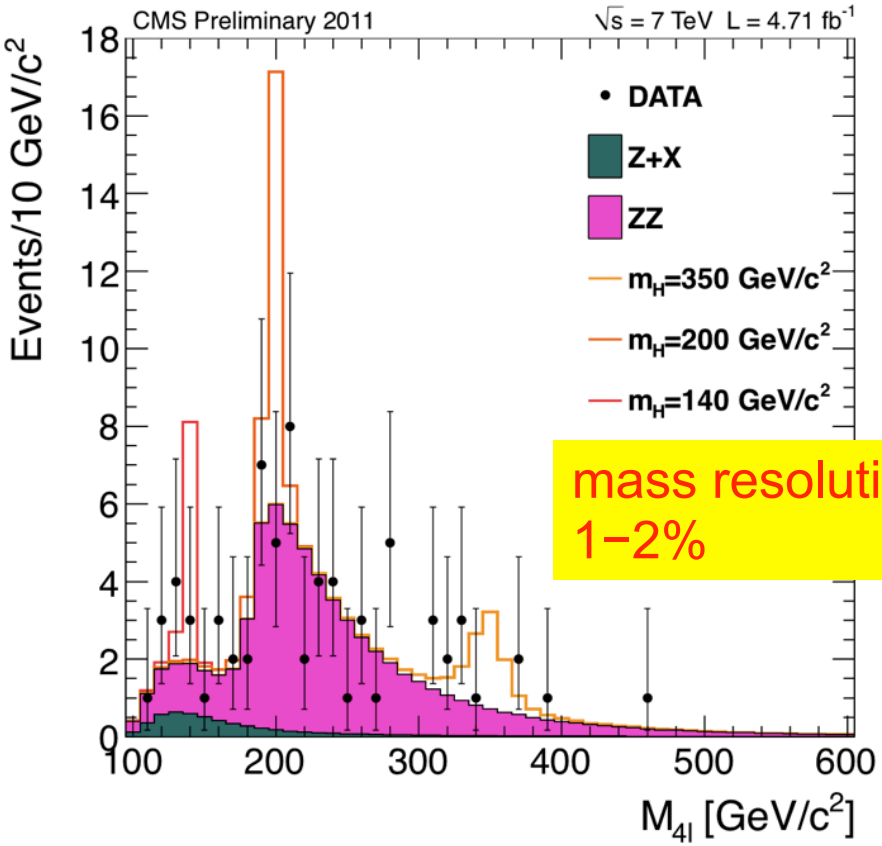




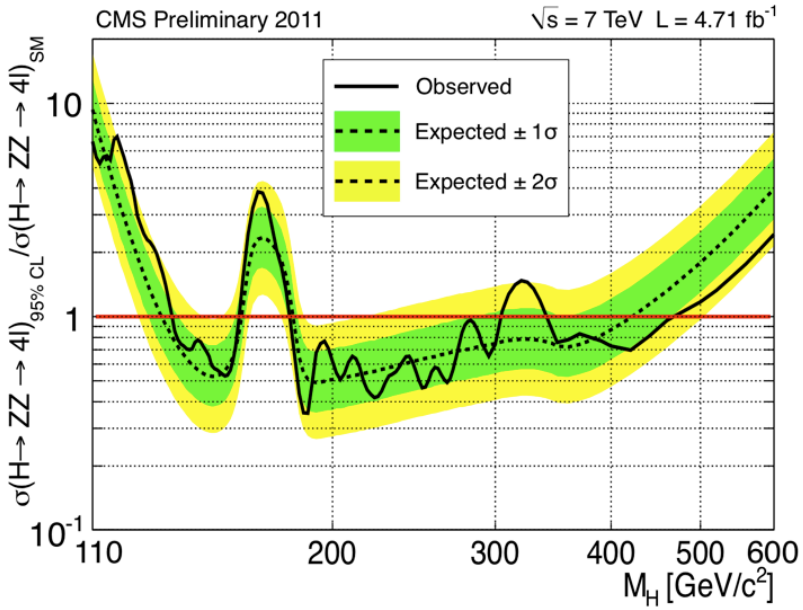
95% CL exclusion limits

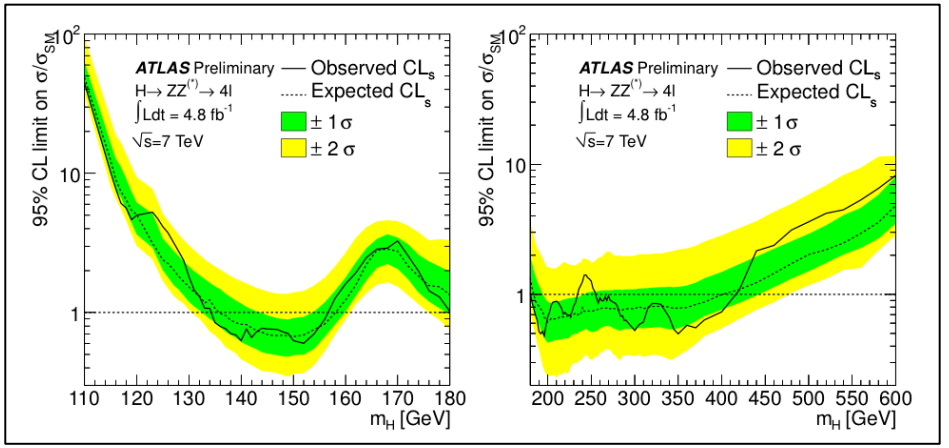


Another example: gg→H→ZZ(*)→4 leptons



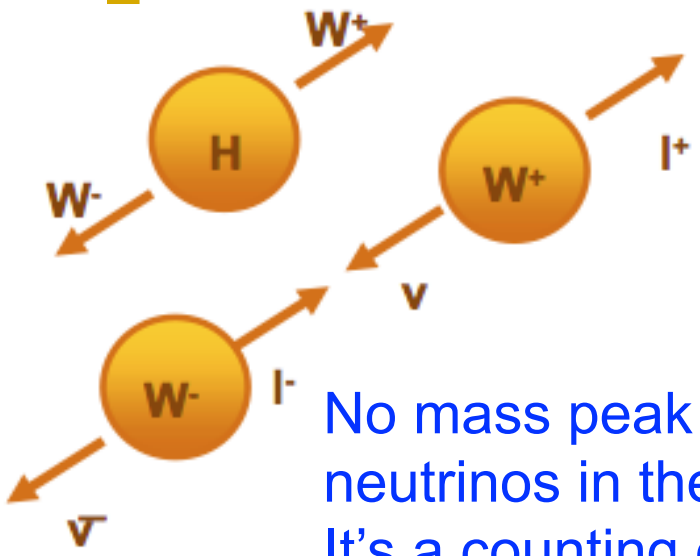
mass resolution 1−2%

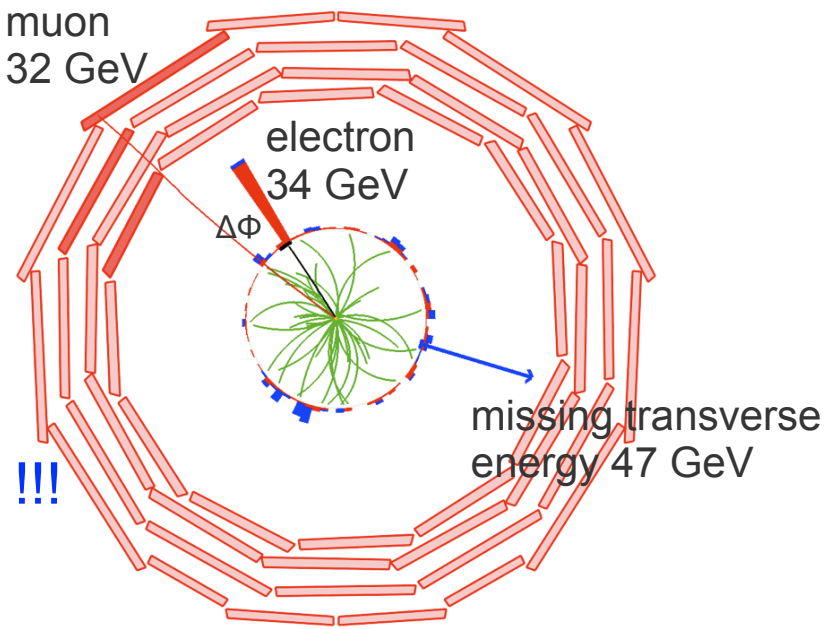




Golden channel at LHC due to small background. Again, the observable is the invariant mass.

Third example: H→WW(*)→2l 2ν

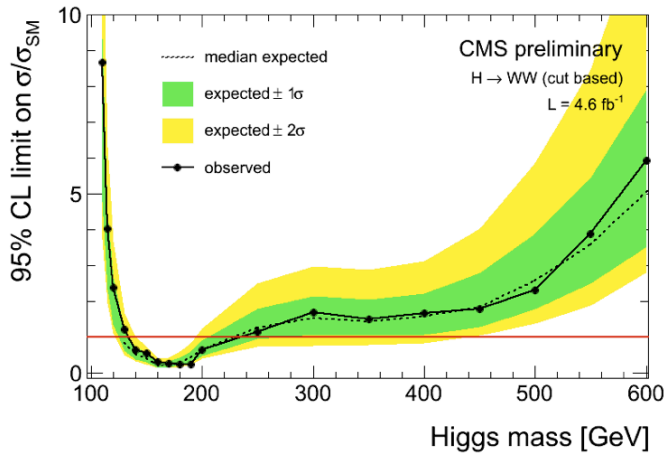




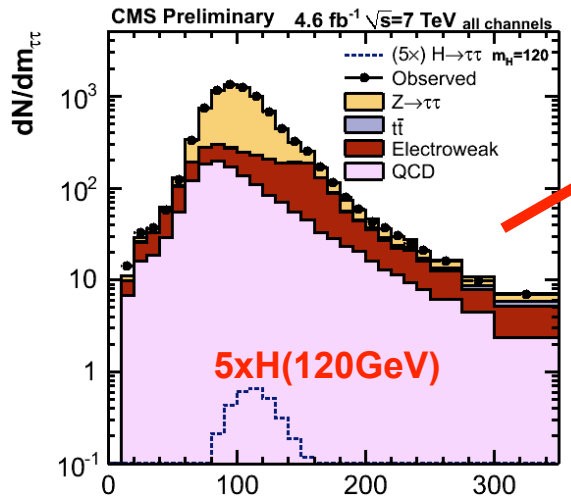
No mass peak (two neutrinos in the final state) !!!
It's a counting experiment.
Small ΔΦ between the two leptons (Higgs spin-0, produced at rest)

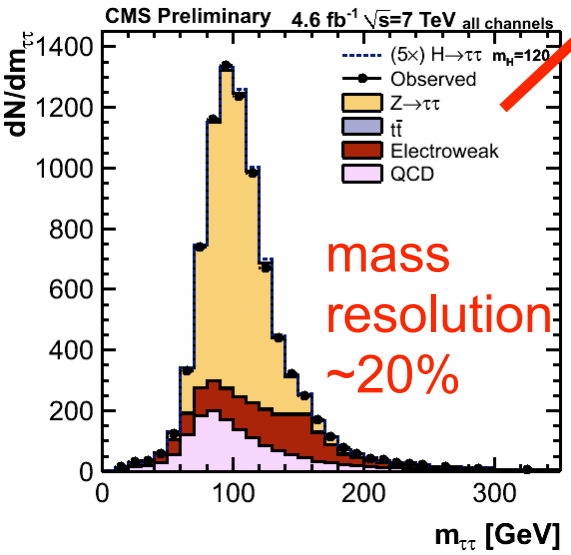
mass resolution ~20%

This channel has been a work horse for Higgs search because of its mass reach.

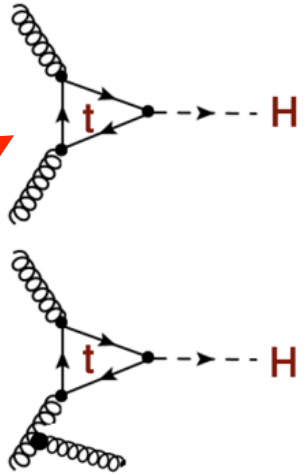


Fourth example: H→ττ (for low Higgs mass)





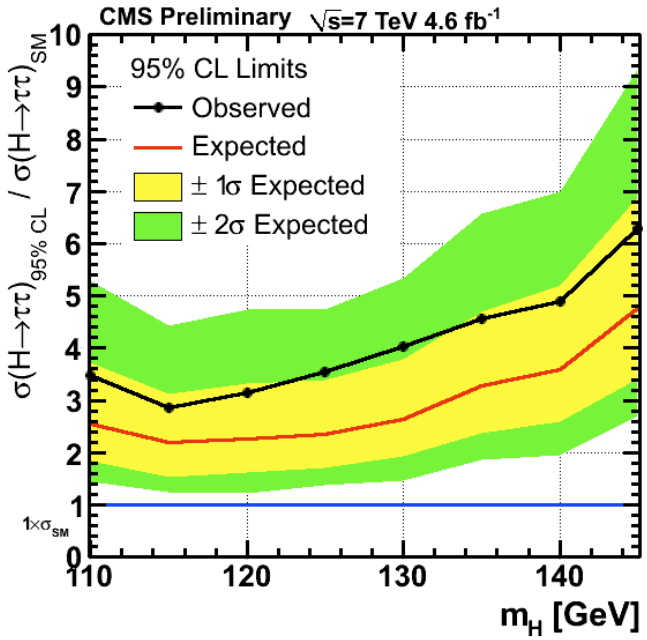
mass resolution ~20%



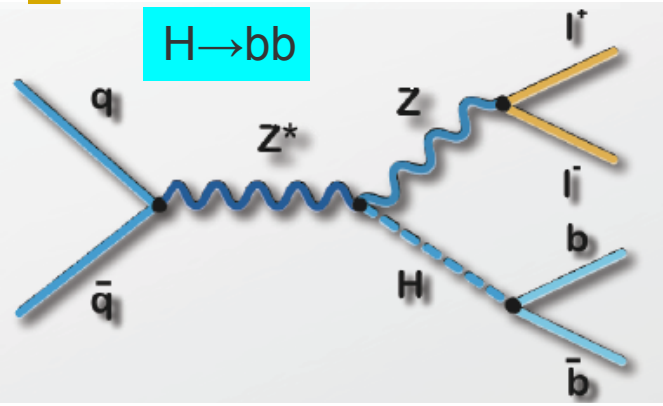
SM-0/1 jet
0 jets >30 GeV or 1 jet<150 GeV

SM-Boosted
One jet Pt>150 GeV
No other jets>30 GeV

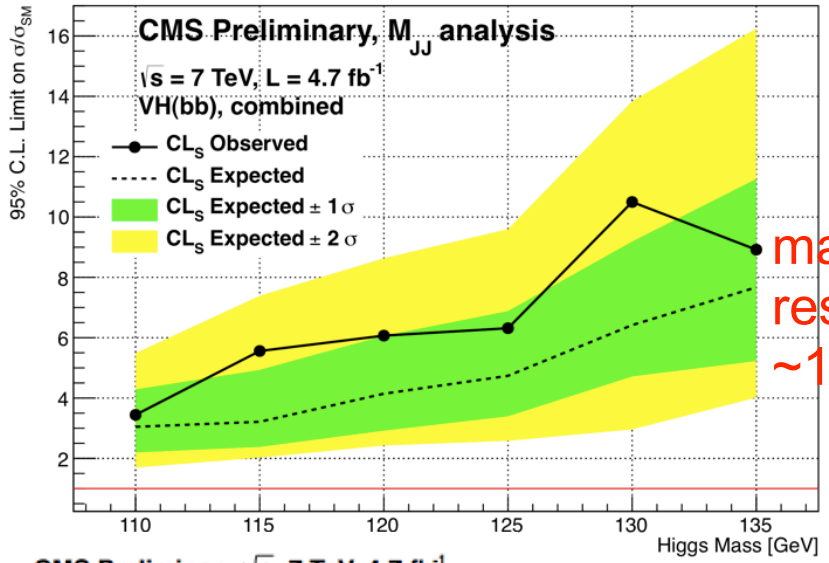
Can get enhanced if contribution from SUSY particles or 4th generation.



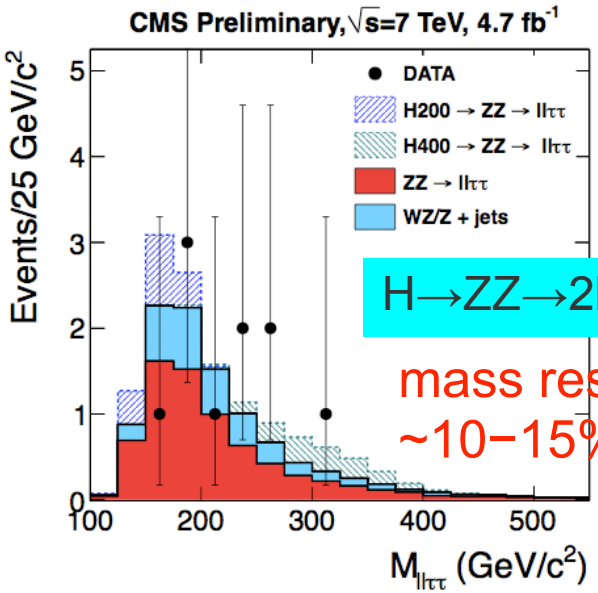
Other channels also help



Associated production

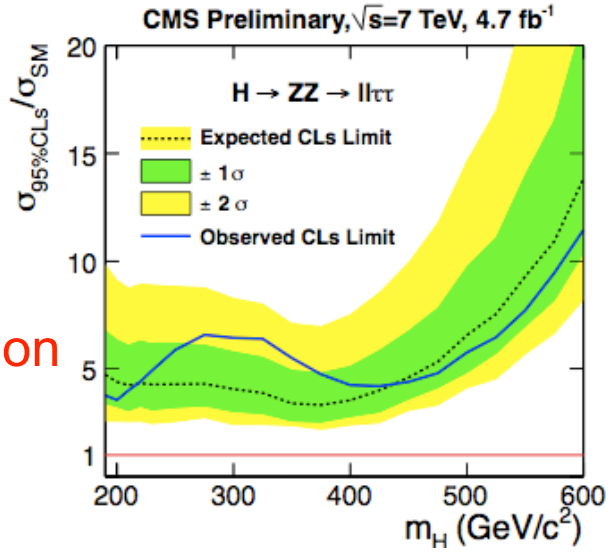


mass resolution ~10%



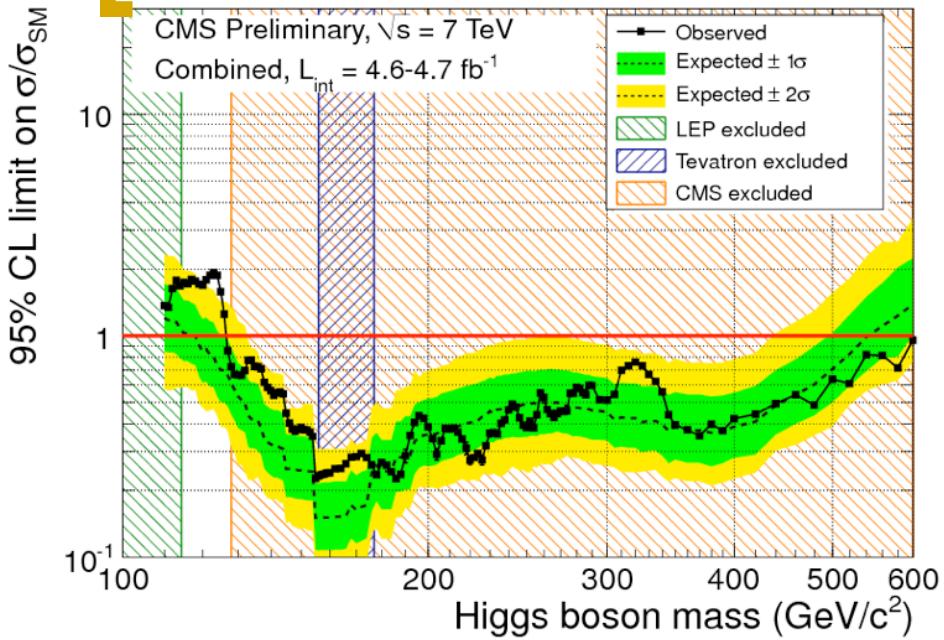
H→ZZ→2l 2τ

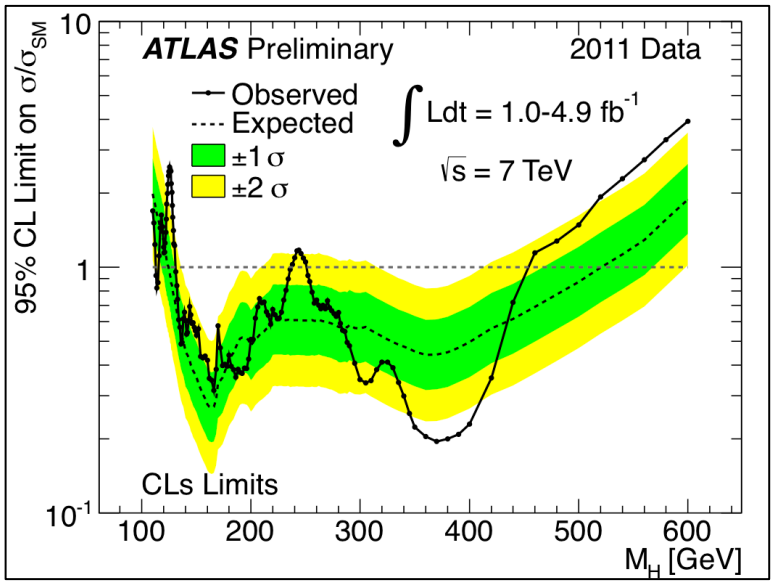
mass resolution ~10−15%

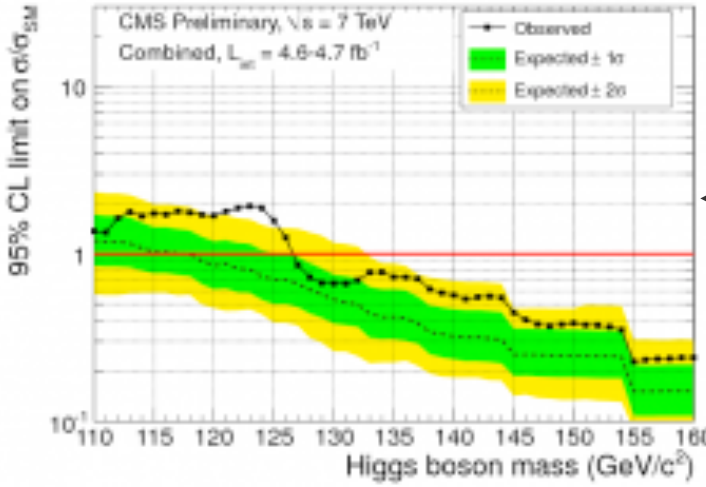


I completely skipped several other channels, but hopefully you got the idea....

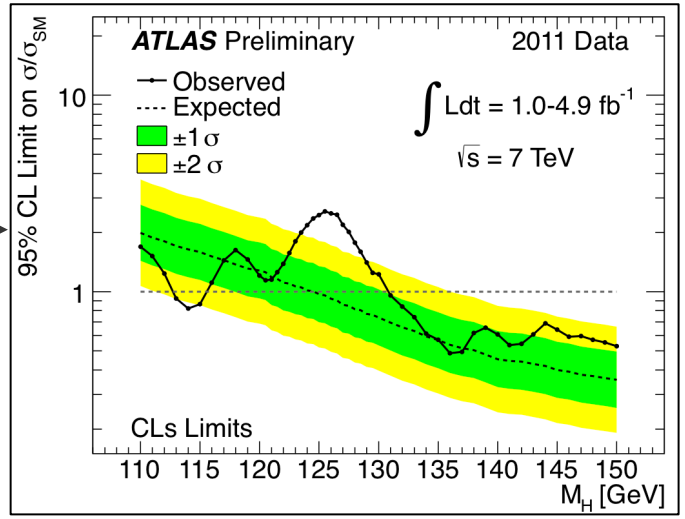
Putting it all together







Zoomed in to low Higgs mass region



Conclusions from official presentations on Dec 13

	CMS	ATLAS
Exclude (95% CL) Higgs with m_H	**127−600 GeV**	**131−453 GeV**
Observe an excess at m_H	123.8 GeV	126.5 GeV
local significance	2.6 σ (1.9 σ /LLE)	3.6 σ (2.3 σ /LLE)
$H \to \gamma\gamma$	2.3 σ	2.8 σ
$H \to ZZ^* \to 4l$	0.4 σ	2.1 σ
$H \to WW^{(*)} \to l\nu l\nu$	1.0 σ	1.4 σ
SM Higgs expectation:	2.8 σ local	2.4 σ local
Excess compatible with Higgs	Yes	Yes

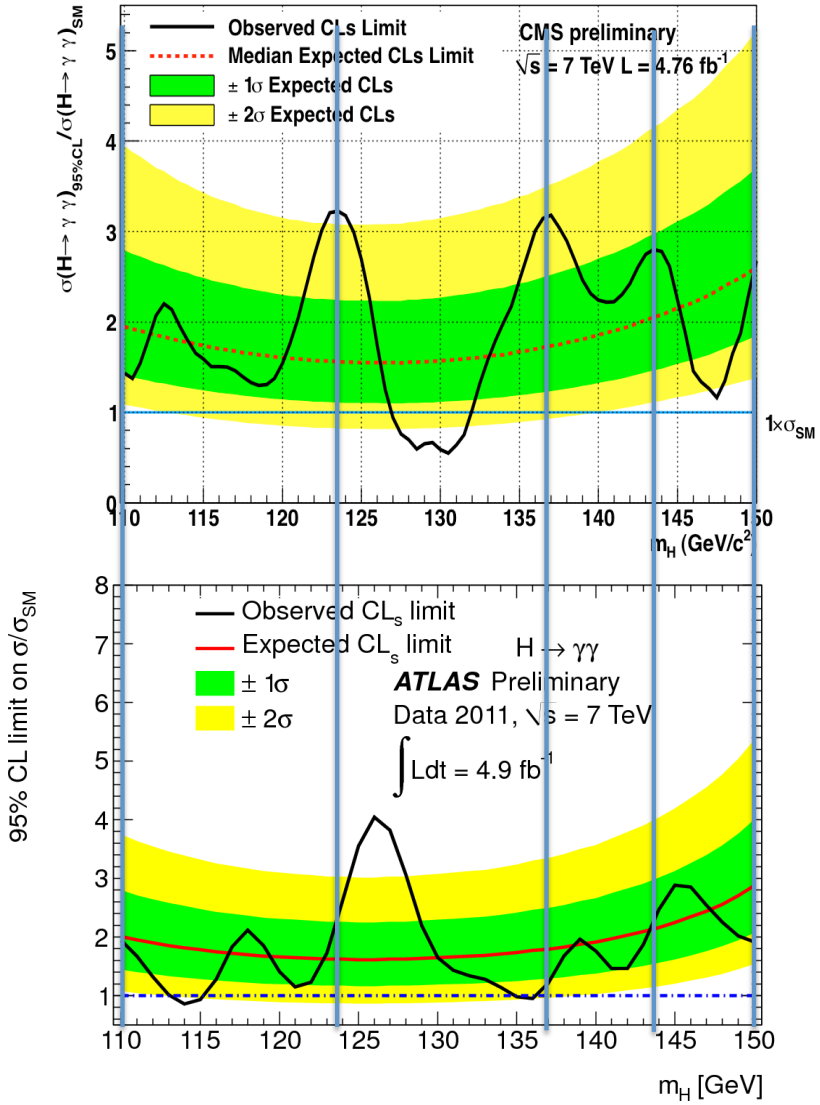
Few notes ....

- CMS sees another 2.6 σ local excess at 119.5 GeV !
- CMS excludes SM Higgs with 99% CL in $128 < m_H < 525$ GeV.
- ATLAS also excludes 112.7−115.5 GeV but misses 237−251 GeV.

See detailed presentations by both spokespersons at:

http://indico.cern.ch/conferenceDisplay.py?confId=164890

Do ATLAS and CMS see the same thing ?



CMS

110-150 GeV

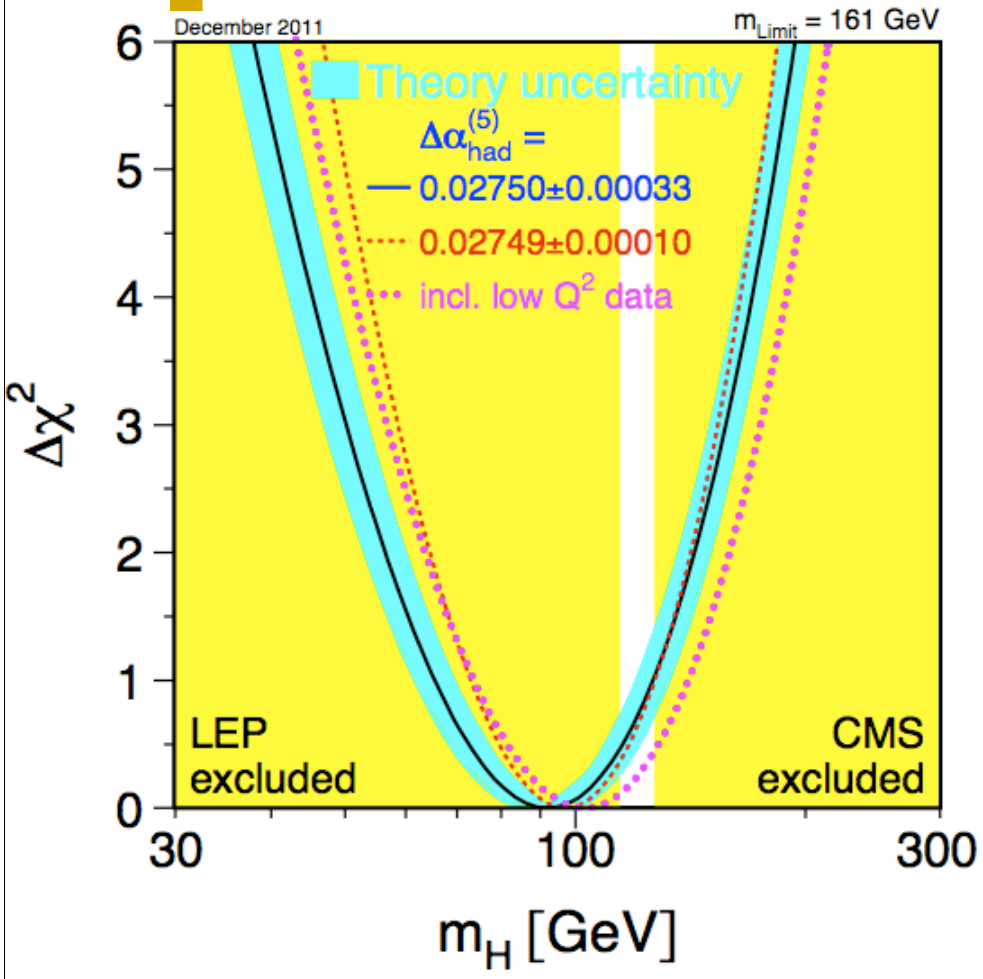
Atlas

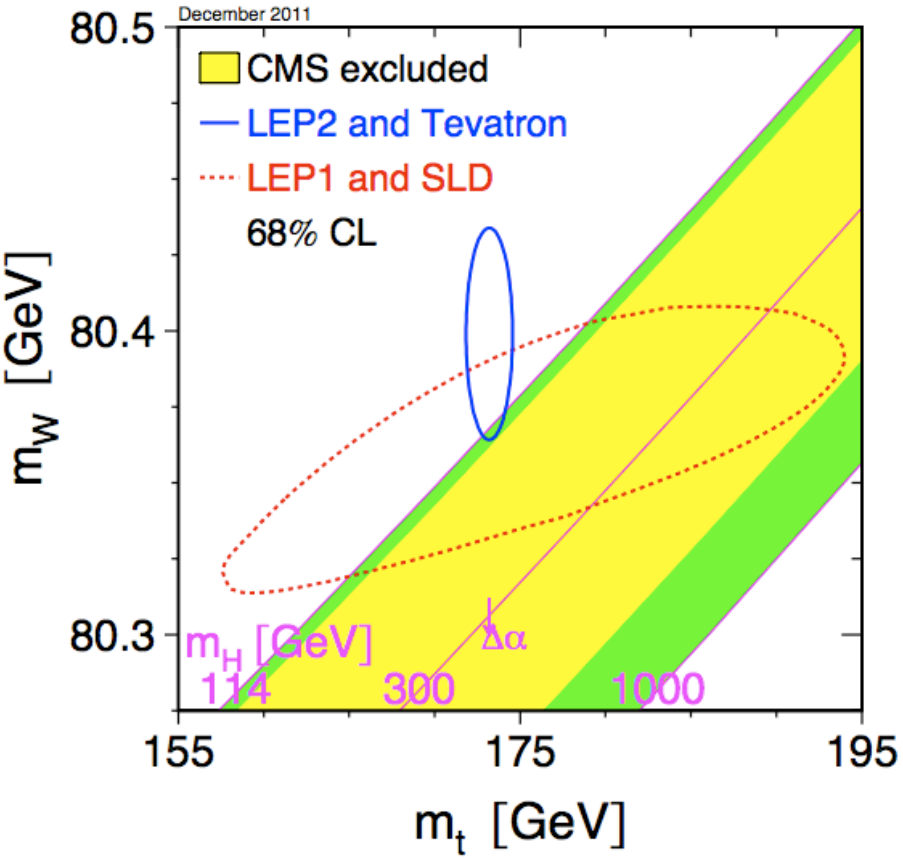
Lets focus on H→γγ

- The mass resolution in this channel is ~1 GeV.
- ATLAS peak is at 126.5 GeV, CMS at 123.8 GeV.
- Both collaborations have made multiple cross checks of their energy scale. ES is not a factor.

Draw your own conclusions !

What are the implications of the new results ?





Probably the last iteration of these iconic plots. End of an industry!

Changing Gears

What if we find SM Higgs in 2012 ?

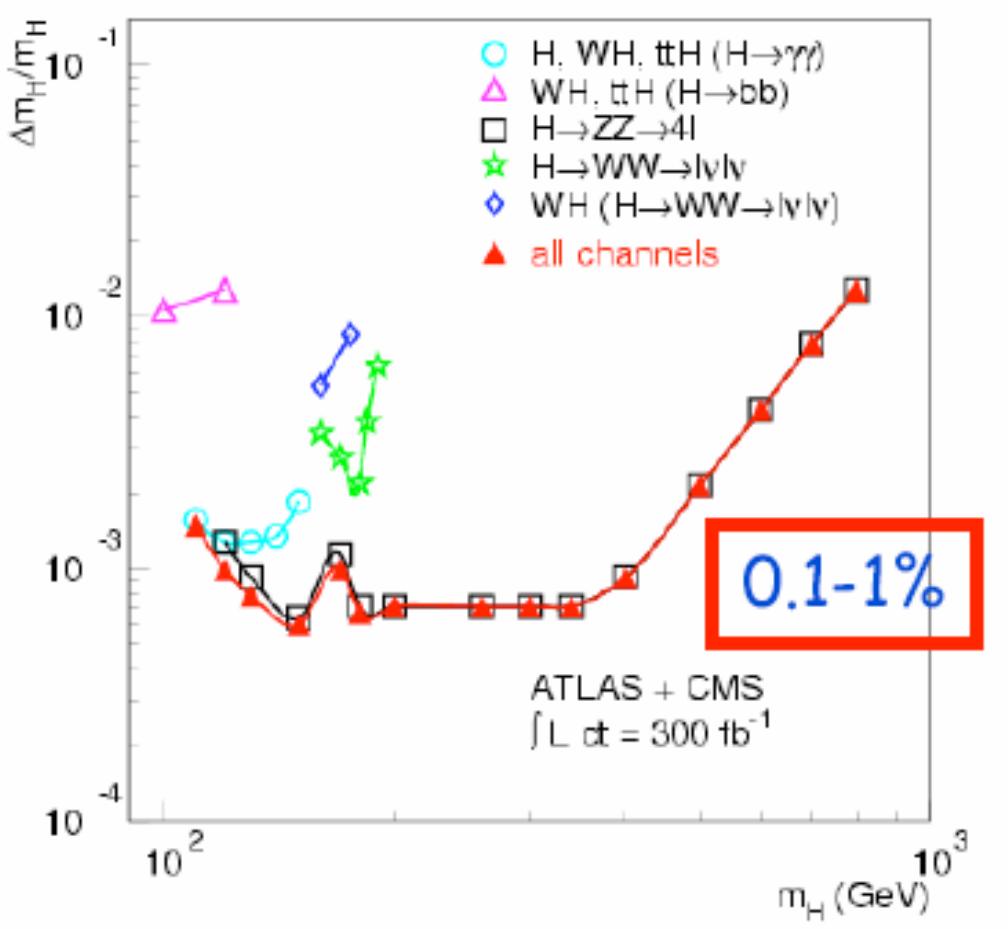
How do we know what we have found?

- After discovery we need to check it really is the Higgs boson
- Measure it's properties:
  - The mass
  - The spin (very difficult…)
  - The branching ratio into all fermions
    - Verify coupling to mass
  - The total width (very difficult…)
    - Are there invisible decays?
- Check they are consistent with Higgs boson

But spin-0 will be confirmed if detected in $gg \rightarrow H$ production and $H \rightarrow \gamma\gamma$ decay or $H \rightarrow WW \rightarrow l\nu l\nu$ decay with small $\Delta\Phi$.

Higgs discovery will tell us the center-of-mass energy of the future lepton collider. Precision study of Higgs properties will then become a major part of the physics program for the HEP field.

Well-defined task: Measure its mass and couplings



- Measure couplings of Higgs to as many particles as possible
  - H→ZZ, WW
  - H→ γγ
  - H→bb, ττ
- In all production modes:
  - gg→H (tH coupling)
  - WW→H (WH coupling)
- Verify that Higgs boson couples to mass

To measure Higgs self coupling & spin we'll need lepton collider.

What if we do not find the SM Higgs ???

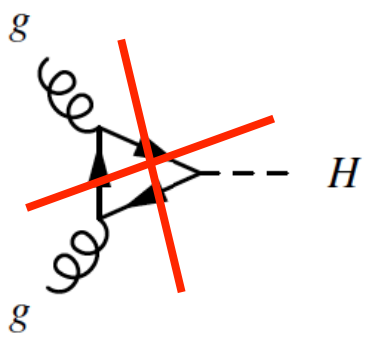
If no Standard Model Higgs ...

Fermiophobic Higgs is approximately the last line of defense.....

✦HWW and HZZ couplings: EWK symmetry breaking via the Higgs mechanism dictates couplings of the Higgs boson to W, Z

✦Yukawa couplings of H to fermions are a convenient, but admittedly ad hoc solution for the fermion mass problems

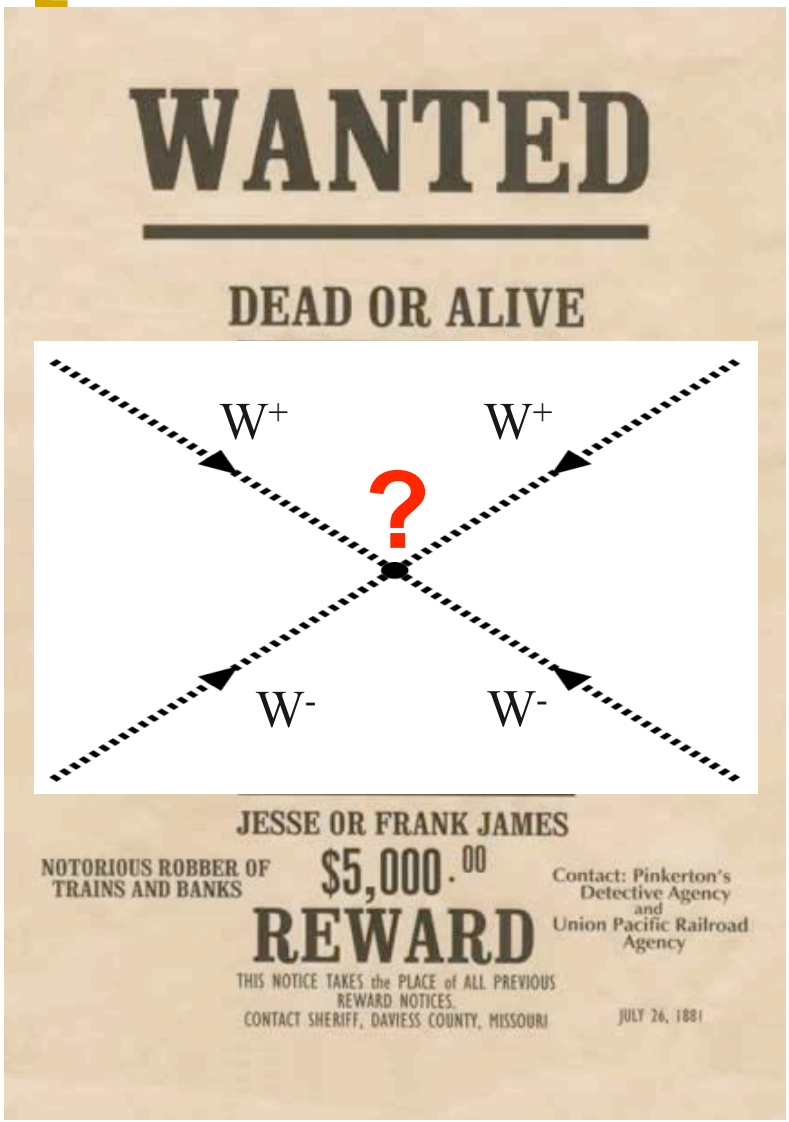
✦If the EWK-symmetry-breaking Higgs boson has nothing to do with fermion masses (consistently possible in 2HDM), then…



gg→H is not possible anymore: production rate drops by a factor of 10. Decays: for M_H > 160 GeV Higgs decays to WW, ZZ. For M_H < 160 GeV H→ff decays are gone; γγ and WW enhanced.

LHC will be able to exclude Fermiophobic Higgs upto M_H = 400 GeV with 30 fb^{-1} data, so hopefully using 2012 data.

Portrait of a Troublemaker

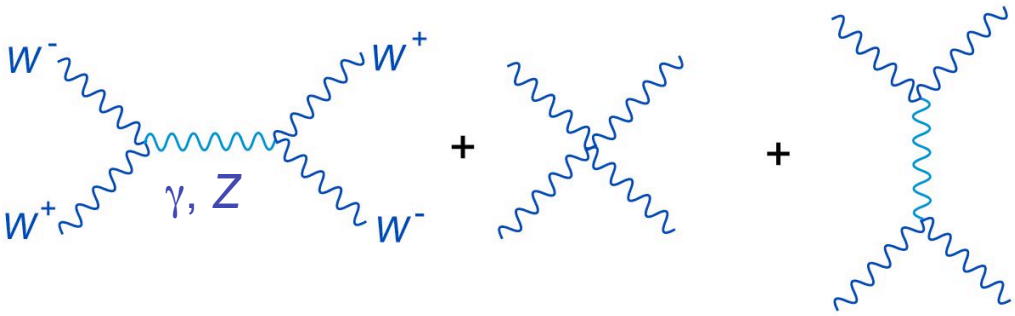


- This diagram is where the SM gets into trouble.
  Why ? I have the technical explanation on the next slide.
- It's vital that we measure this coupling, whether or not we see a Higgs.

With 100 fb^{-1} data we will be fully sensitive to probing anomaly in WW scattering

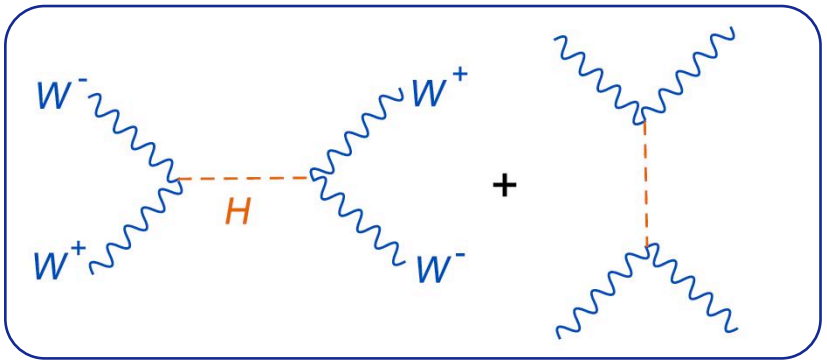
Probability is no longer conserved !???

If no Higgs, the theoretical framework of SM is in big trouble



$$= \frac{g^2 E^2}{2m_W^2}(1+\cos\theta)$$

unitarity violated: grows as E^2



$$= -\frac{g^2 E^2}{2m_W^2}(1+\cos\theta)$$

no problem now!

Higgs exchange needed to prevent unitarity violation in WW scattering at high energies ➜ New phenomena required at the TeV scale

Summary

☑ Higgs boson is the last missing piece in the Standard Model
- And arguably the most important SM particle
- Precision EWK and direct searches have told us where to look
- If the Higgs boson exists it has to be in the mass range 115−127 GeV

☑ Likely discovery and initial characterization will occur in 2012
- Need 10−20 fb^{-1} luminosity per experiment (CMS and ATLAS)

☑ Life may well be much more interesting if we completely exclude the simplest Standard Model Higgs !!!
- Some other mechanism must kick in to prevent unitarity violation ⇒ something has to be found at the LHC

☑ More new exciting results to come after full analysis of the 2011 data. Eagerly waiting for the 2012 run.

Backup slides

101 of symmetry breaking ?

Consider a smooth ball at the top of a very smooth symmetric hill

The ball can roll in either direction

… there is a left-right symmetry

But the ball can only fall in one direction

… the symmetry is broken