arXiv:1207.7214
arXiv:1207.7235

Higgs?

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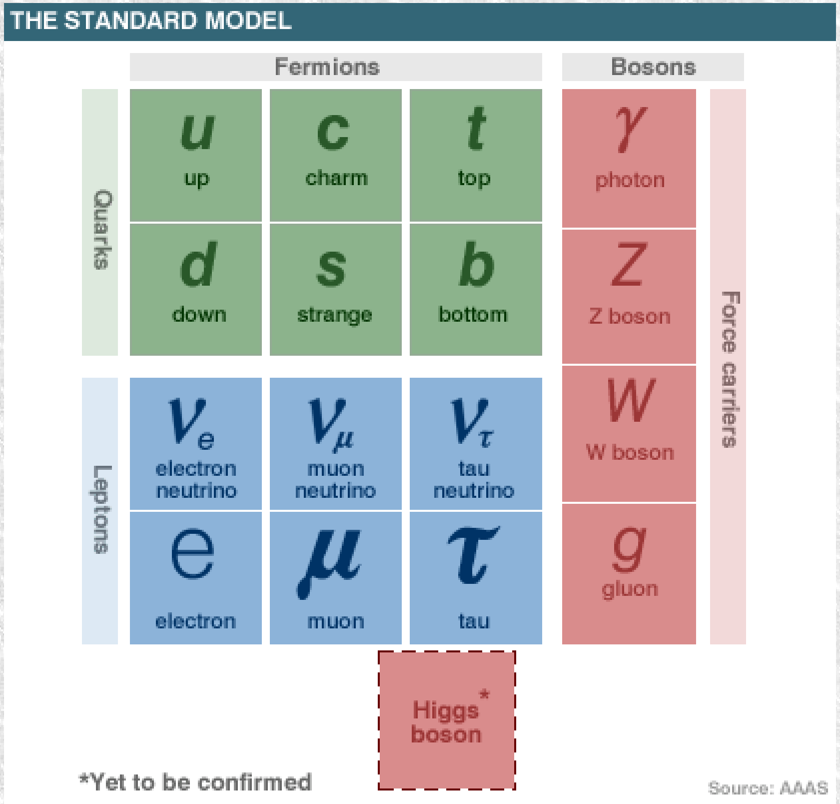
27th August 2012

- **What were we looking for?**
- **What do we know?**
- **What are the implications**

The Standard Model

- $SU(3)_c x SU(2)_L x U(1)$
- 3 pairs of quarks
  – (u,d),(c,s),(t,b)
- 3 pairs of leptons
  - (e, ν_e), (μ,ν_μ), (τ, ν_τ)
- 3 generated forces
  – Electromagnetism, (γ)
  – Weak nuclear force, (W,Z)
  – Strong nuclear force (g)
- The Higgs is needed to break EW symmetry
- Without it the whole Gauge mechanism is questionable



Some Higgs PR points

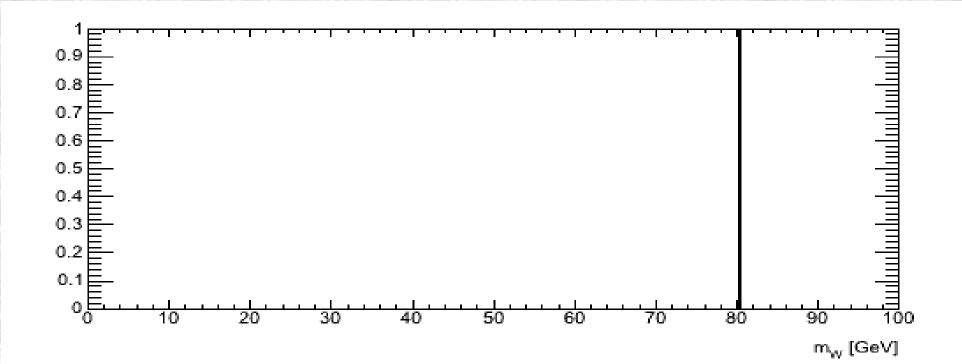
- M. Mangano: “Don't tell people it's simple - it isn't. And stop feeding them false analogies”
  - But we need to say something
- ~~“A kind of a friction with the vacuum”~~
- ~~“Like water/treacle”~~
- ~~“Like a room full of politicians”~~
- “Fermions still travel at the speed of light, but they scatter of the vacuum and take a longer path”

- Well....take your choice.
- Remember – it does not account for the proton mass
  - 99% of the mass in the known universe

The Higgs model

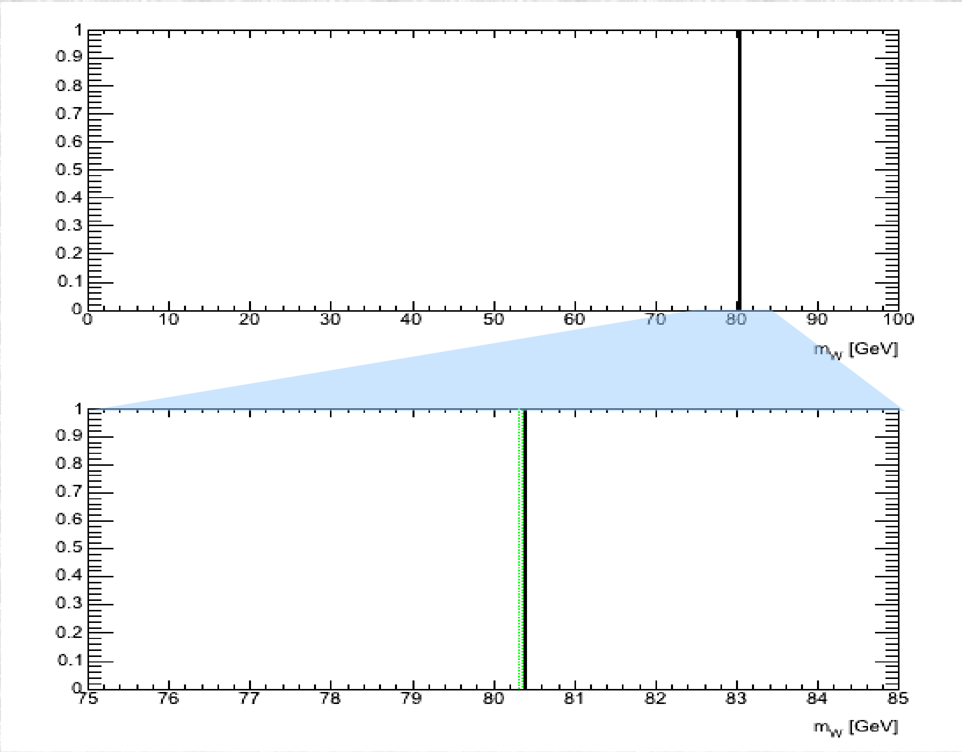
- Mass is an interaction with a field filling the vacuum
  - We cannot escape from it
- The W and Z bosons are intimately linked to it
  - The W mass can be predicted from other forces and masses
  - Allows a test of the model
- The mass for the quarks and leptons can be included
  - But each quark or lepton mass is added 'by hand'
  - It makes no predictions here – and is easily changed
- But we need the Higgs boson
  - Peter's unique contribution
  - Everything about this is predicted – except its mass
    - It is spinless
    - Its production cross-section
    - Decay widths (Fermion widths $\propto m^2$)
  - So we can/should test these

The W mass



- Green band is SM prediction
  - Its width comes from the (unknown) Higgs mass
  - 115 to 600 GeV shown
- Yellow+black band is the measured mass
- They match incredibly
  - Many theories failed this test
  - e.g. technicolor

The W mass



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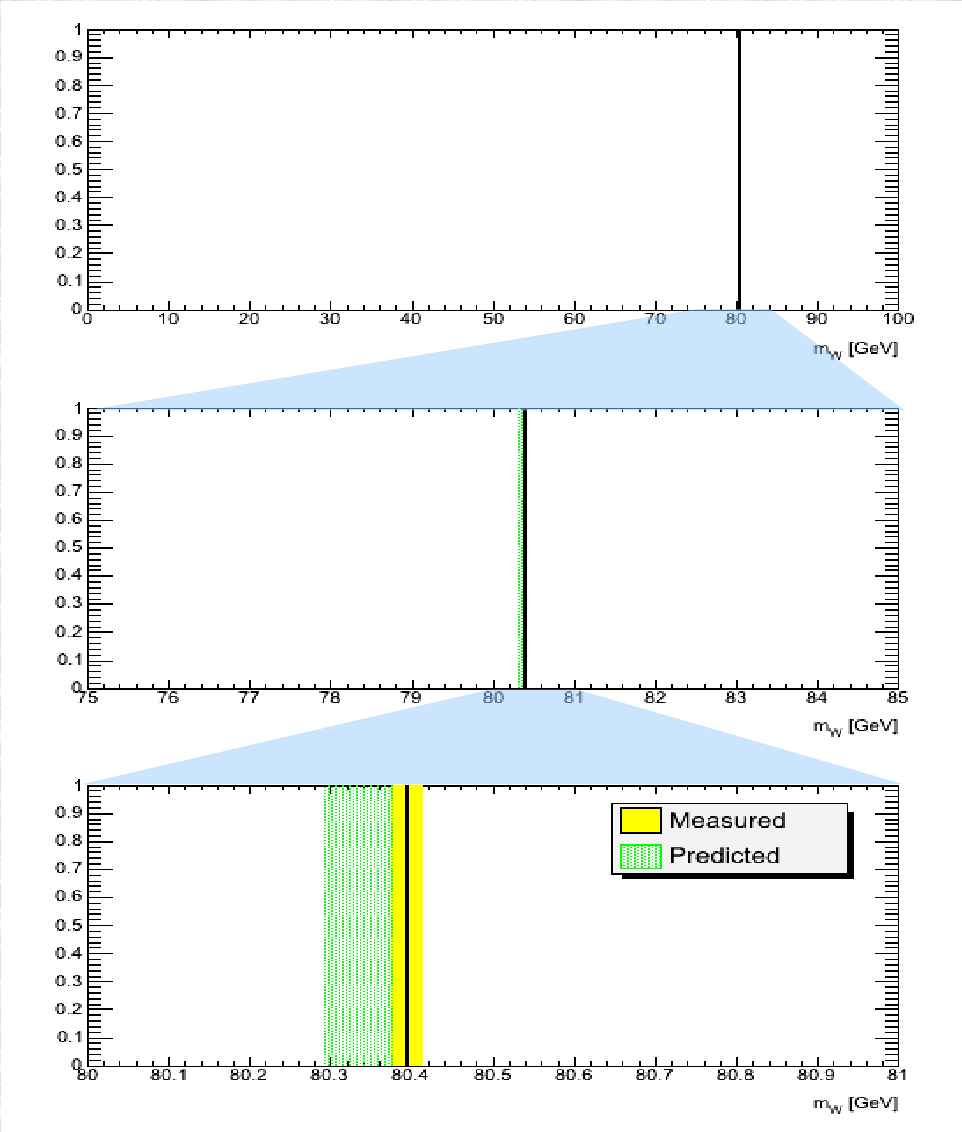
The W mass



- Green band is SM prediction
  - Its width comes from the (unknown) Higgs mass
  - 115 to 600 GeV shown
- Yellow+black band is the measured mass
- They match incredibly
  - Many theories failed this
  - e.g. technicolor
  - But only works at the right edge of the band
    - A light Higgs, near 115GeV
- Nb. This calculation assumes no unknowns

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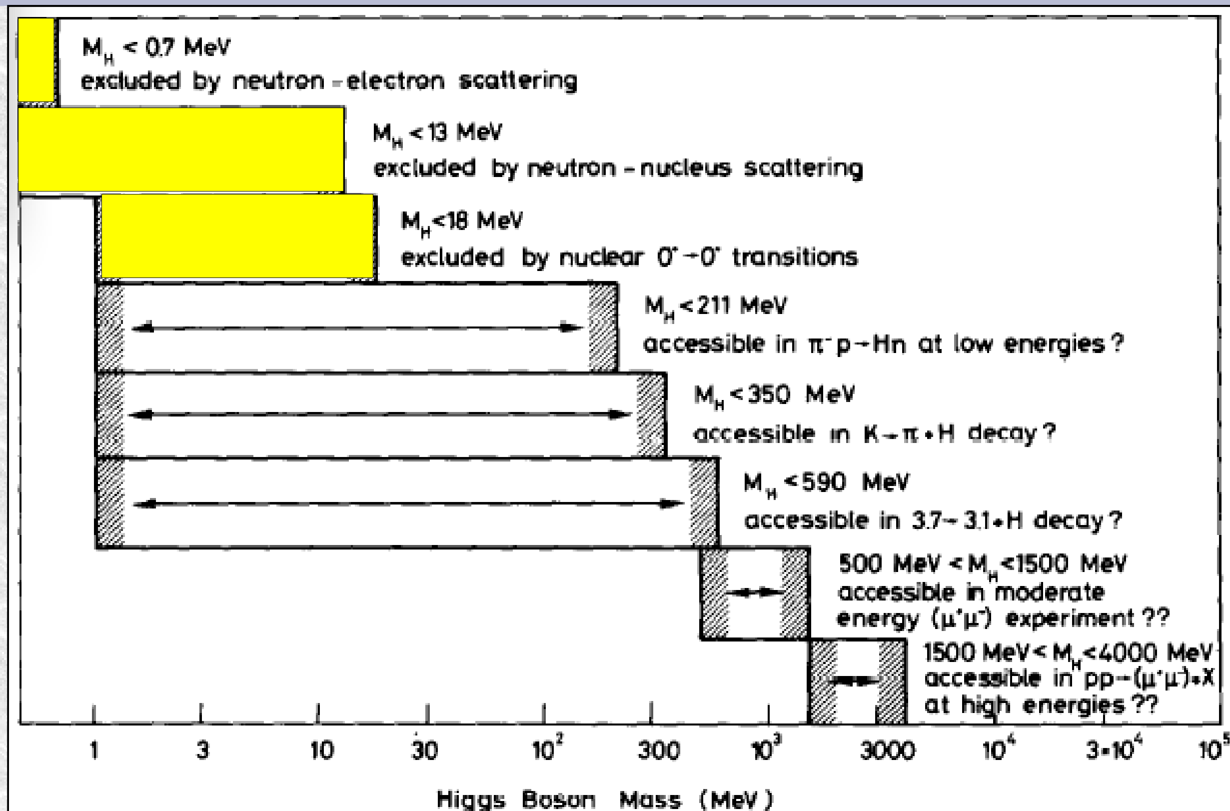
History of the search

- 1964 Brout & Englert, Higgs, Gouralnik, Hagen & Kibble,
  - Not taken too seriously until...
- 1967 Used by G-S-W in the Standard Model
  - Proven to be self-consistent in 1971 (t'hooft, Veltmann)
- 1973 Experimental acceptance of the Standard Model
- 1983 Discovery of W and Z bosons
  - Cementing the SU(2) gauge theory
- 1993 LEP rules out m_H<53 GeV
  - And indirectly excludes m_H>300GeV via EW fit
- 2000 LEP limits reach >114.4 GeV & <204GeV EW fits
- 2011 LHC excludes 130-550GeV, Tevatron 156-175
  - Some indications for a particle at 125?
- 4th July 2012 New particle found at 126GeV
  - Consistent with the Higgs

Nucl. Phys. B 106 (1976) 292.

View from 1975

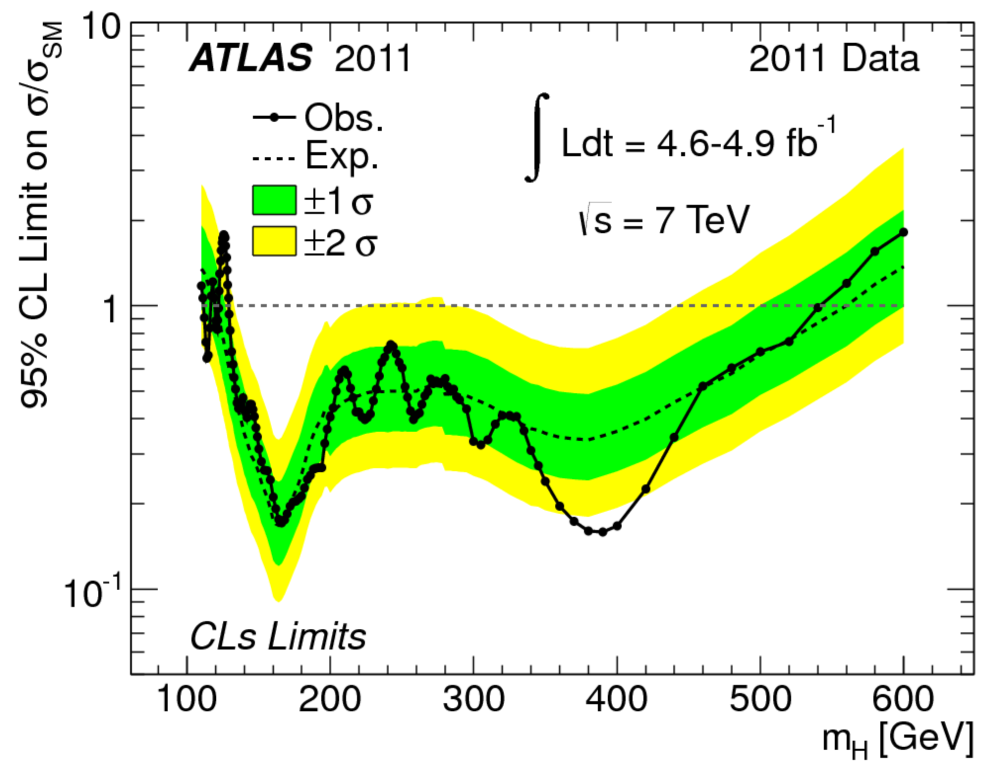


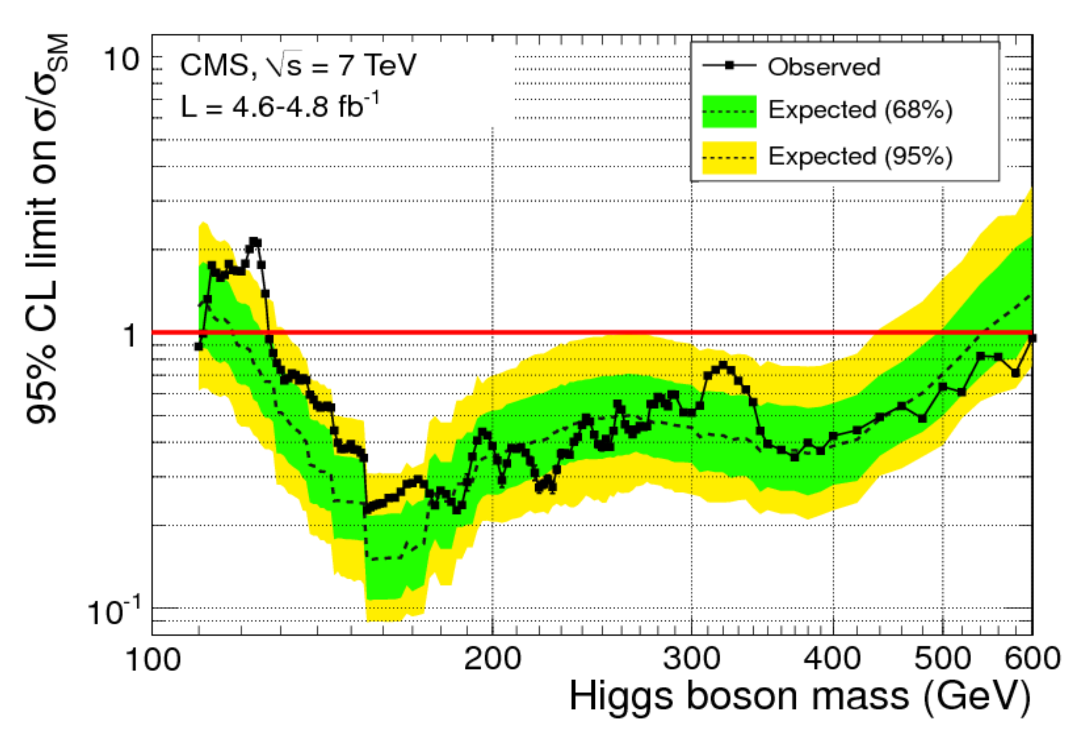
New particle is here

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Hunting the Higgs Boson

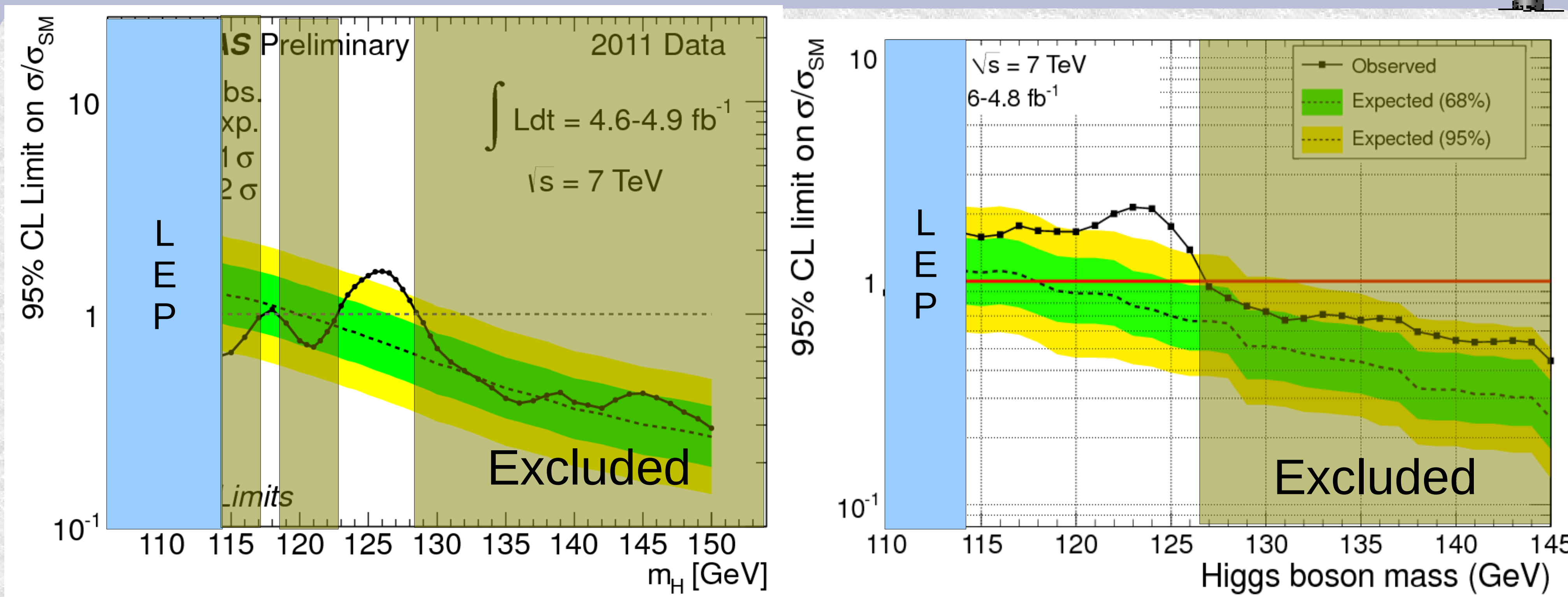
Results, combined





- CMS exclude SM Higgs between 127 and 600GeV
- ATLAS ruled out 129 to 541GeV
  - Plus 111.4-116.6 and 119.4 to 122.1GeV

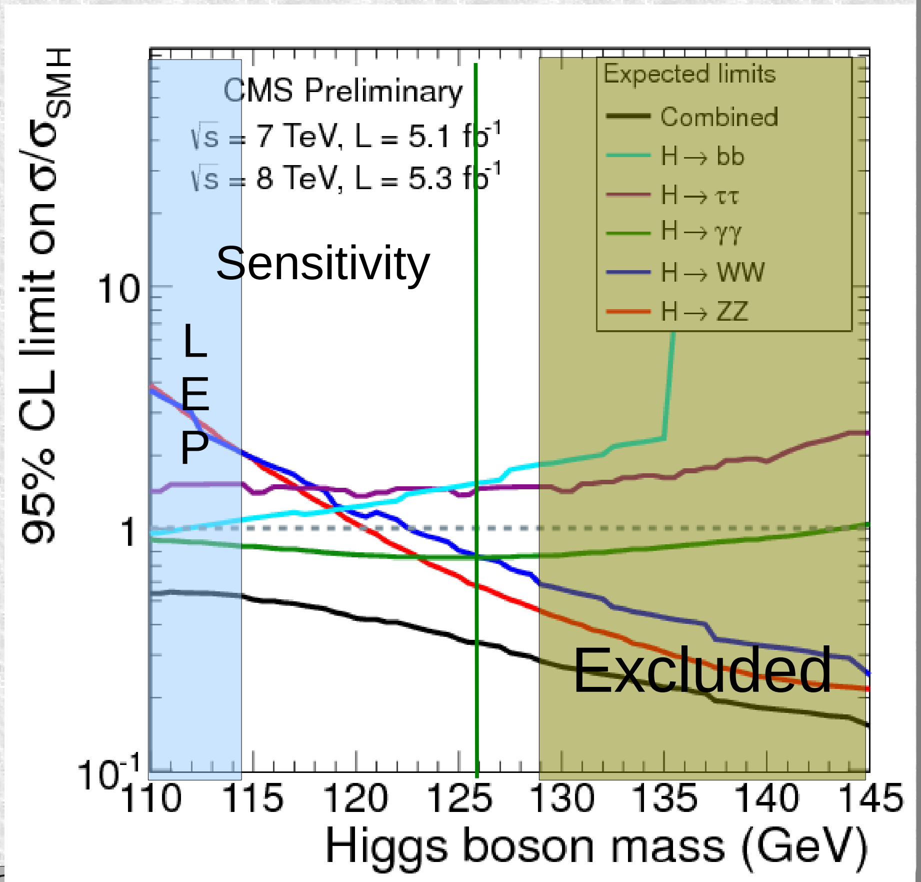
Focus on low mass



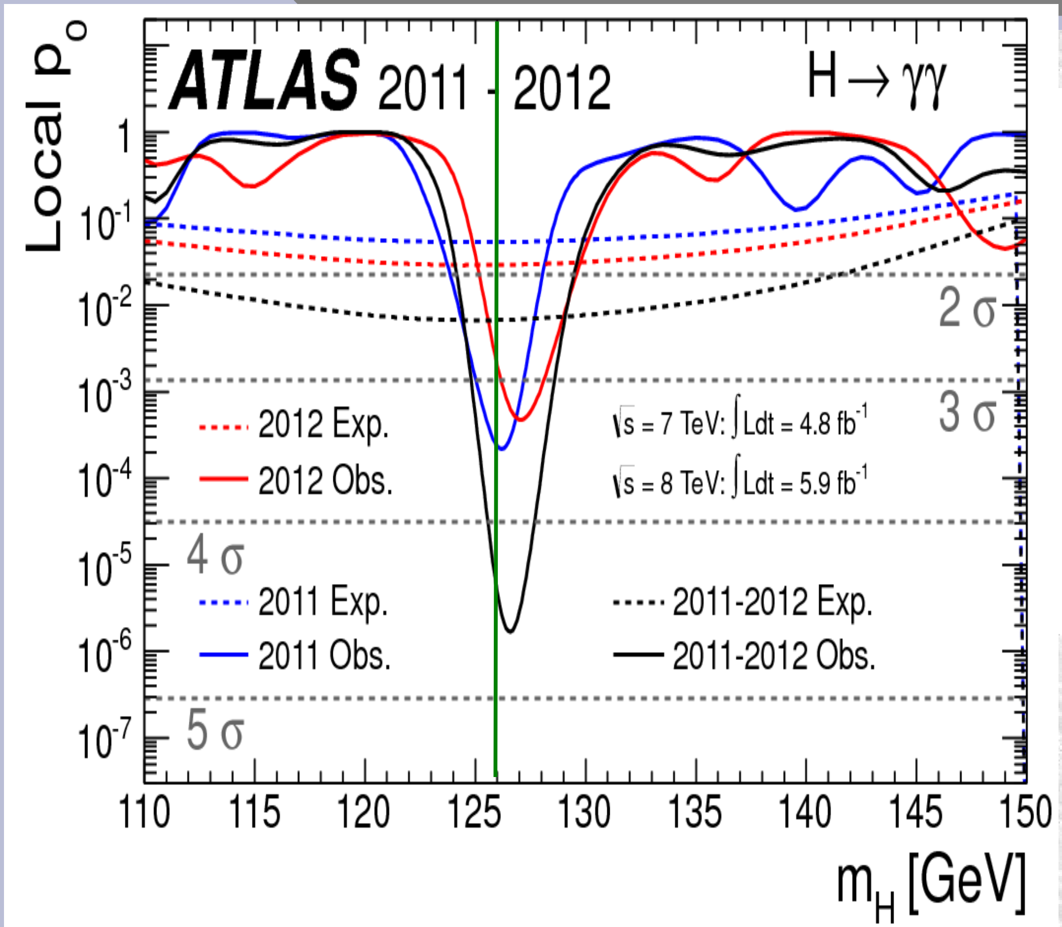
- There is a very small region of interest 115-129GeV
- Around 125 both experiments had unexpectedly bad limits
- Sensitivity a bit marginal in this region – need more data

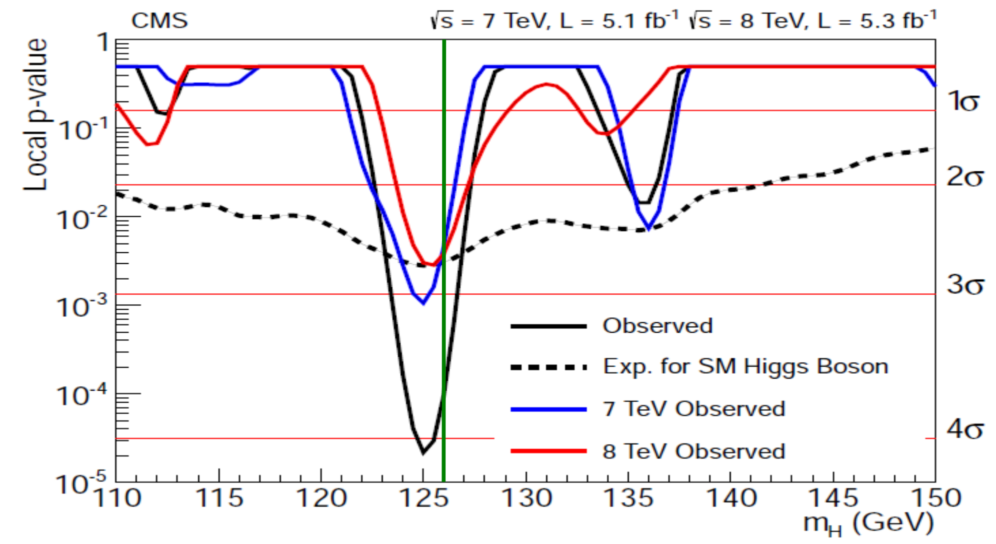
So what did 2012 show?

- Papers submitted 31st July by CMS and ATLAS
  - Adding 6fb^{-1} of 2012 (half current data) to 5fb^{-1} of 7 TeV
  - Both claiming observation of a new particle
- Focus on region 115-129GeV left from 2011
- ATLAS used only 3 strongest channels:
  - γγ
  - ZZ
  - WW
- CMS used these, but also
  - ττ
  - bb



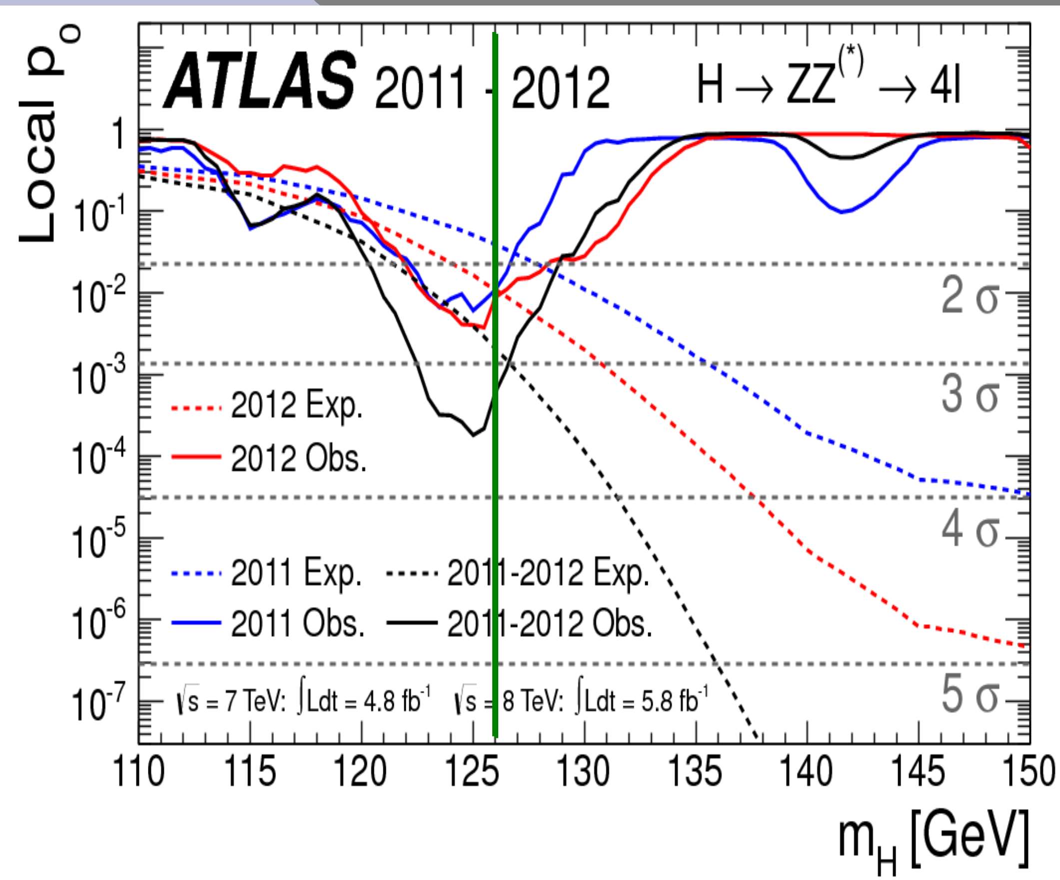
Background Compatibility

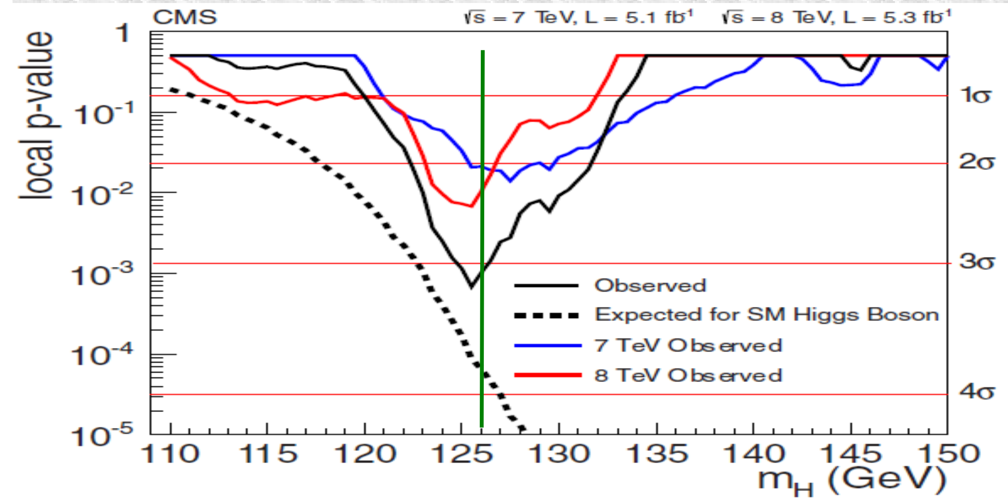




- Peak around 126 in both years, both experiments
- Each experiment with 4-4.5σ observed
- We found something!

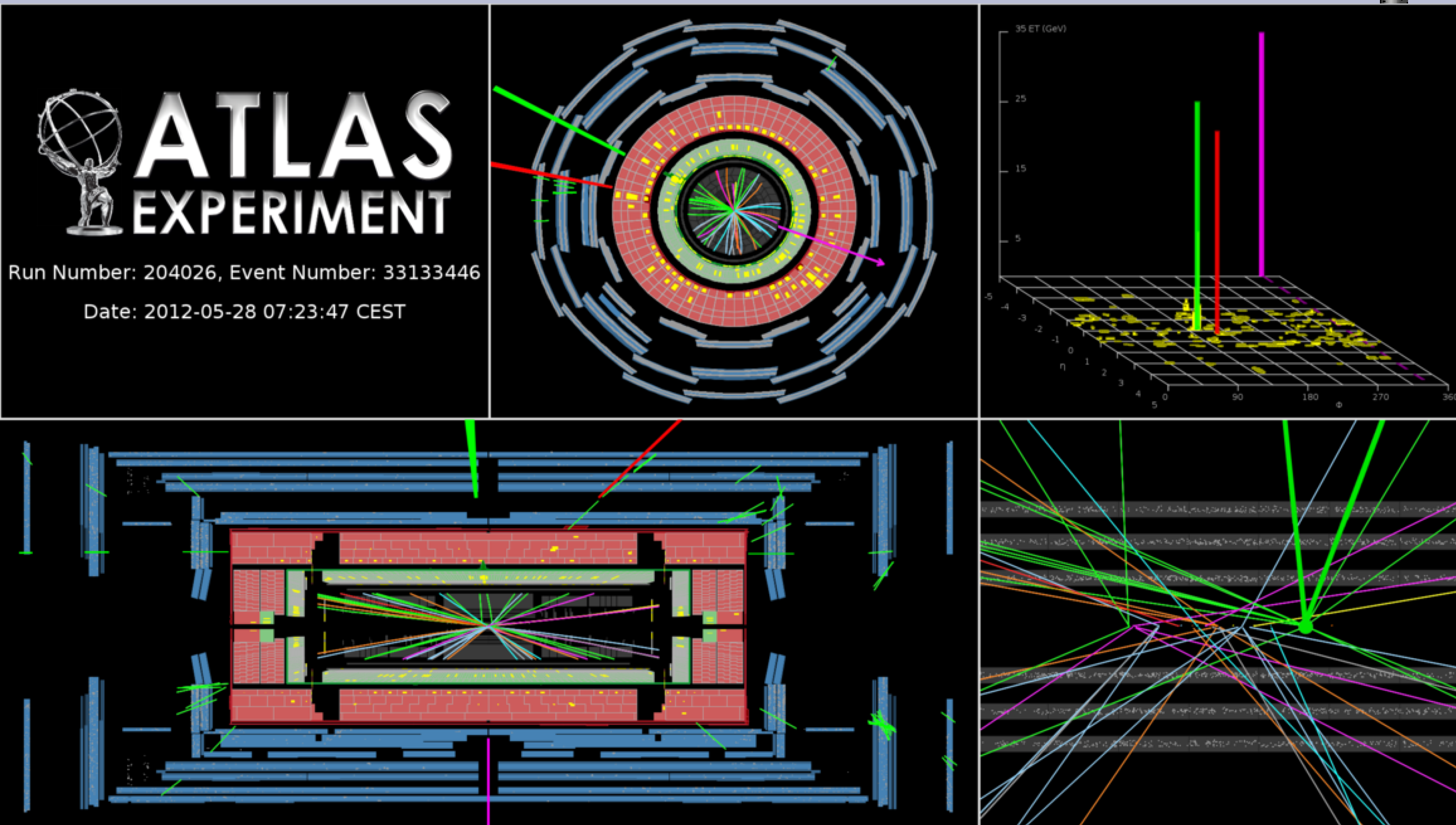
Background compatibility





- Both see over 3sigma excess!
- ATLAS expects about 2.8sigma at 126GeV
- CMS sensitivity nearly 4sigma at 126GeV
  - Modtly use of 4-lepton matrix-element
- Both experiments have 3-3.5σ excesses

$H \rightarrow WW \rightarrow l\nu l\nu$



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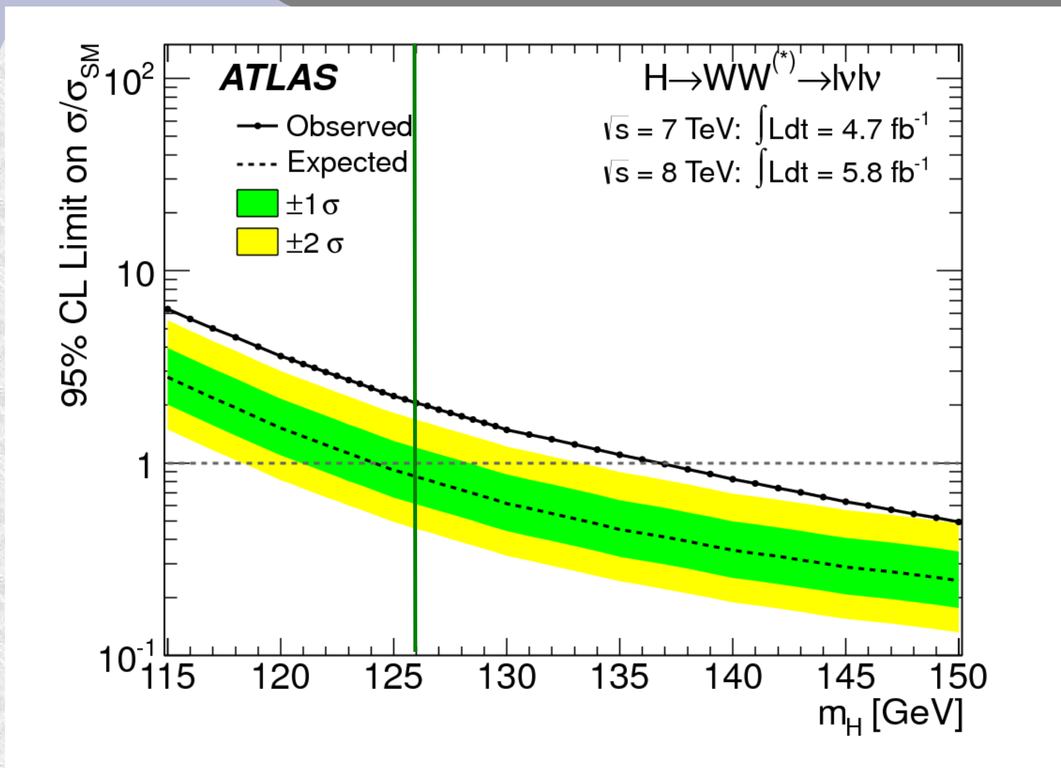
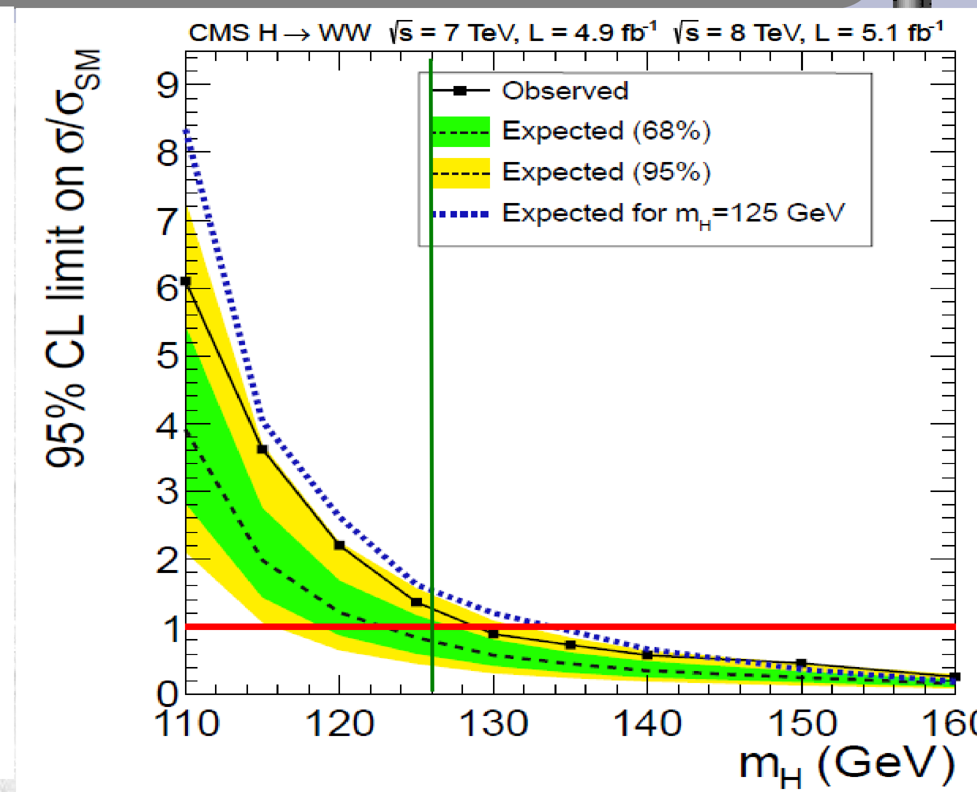
WW limits

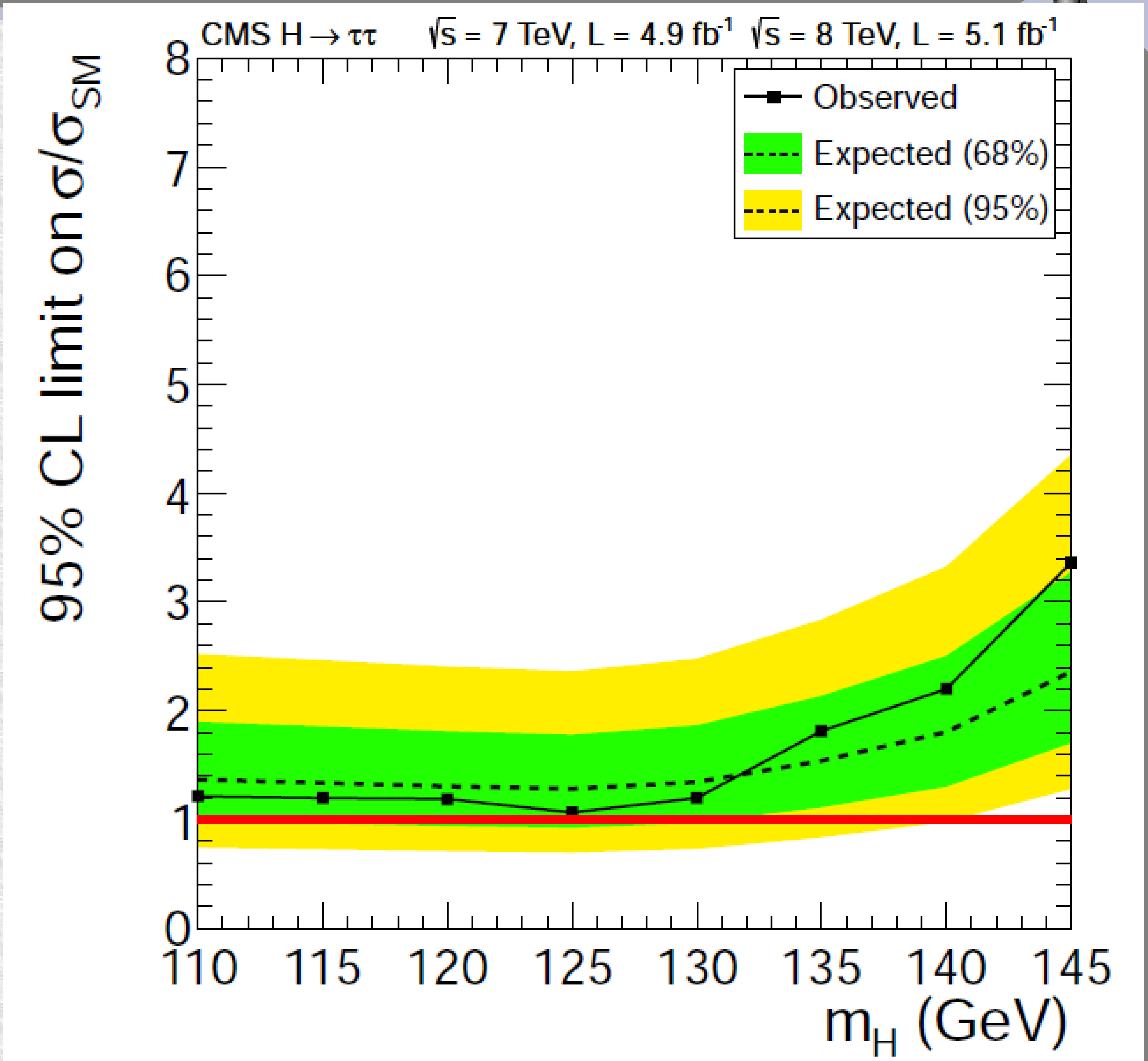




- Both set bad limits
- 2.8sigma excess in ATLAS, 1.6sigma in CMS
- Two neutrinos means mass not well measured
  - So broad excess seen

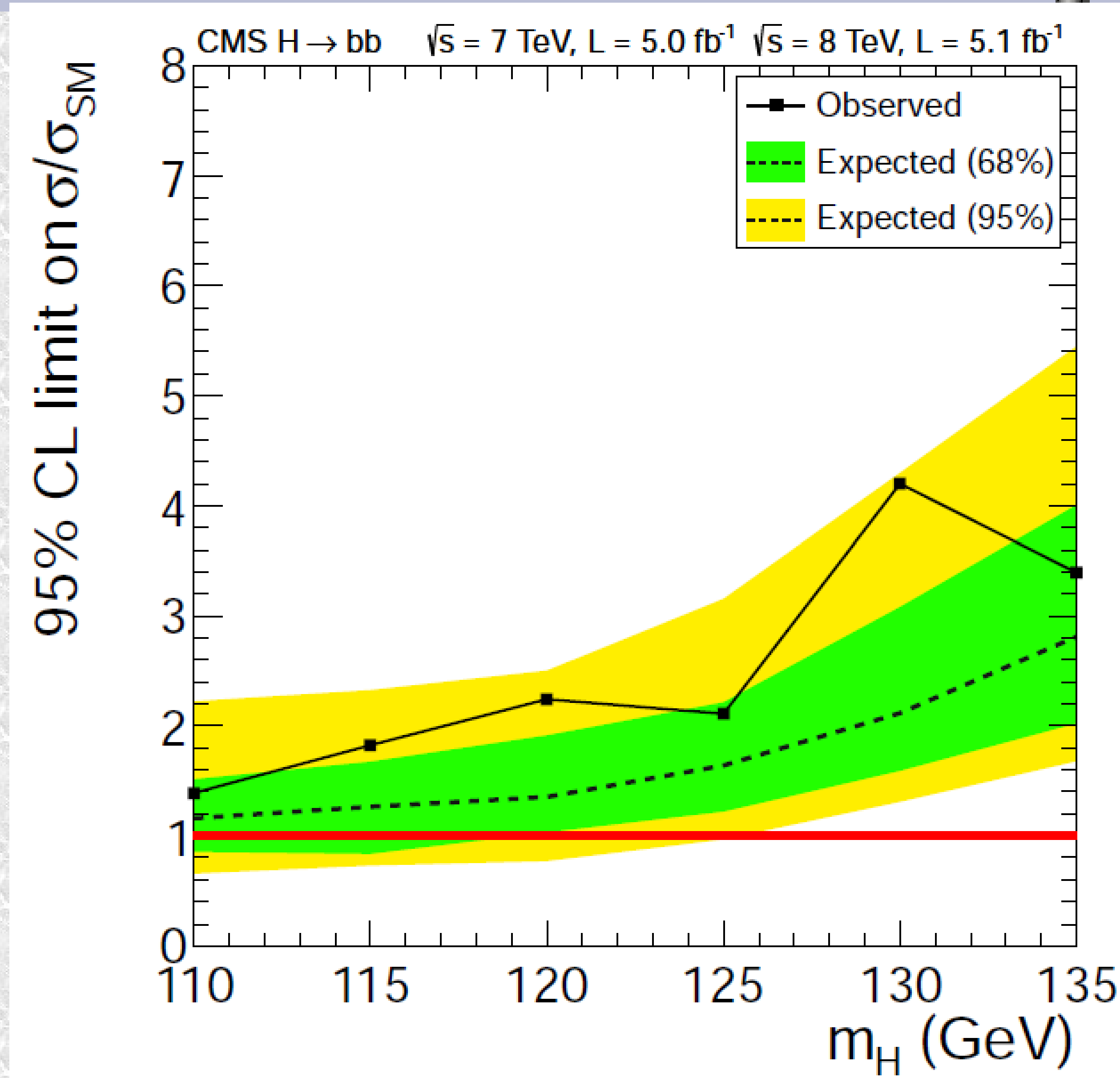
CMS H→ττ limits

- Limits at 1.2xSM at 125GeV
- Almost excludes a signal
  - But doesn't
  - Anyway, break data into enough subsets and one will look odd.
- But it is interesting
  - More data and ATLAS results keenly anticipated

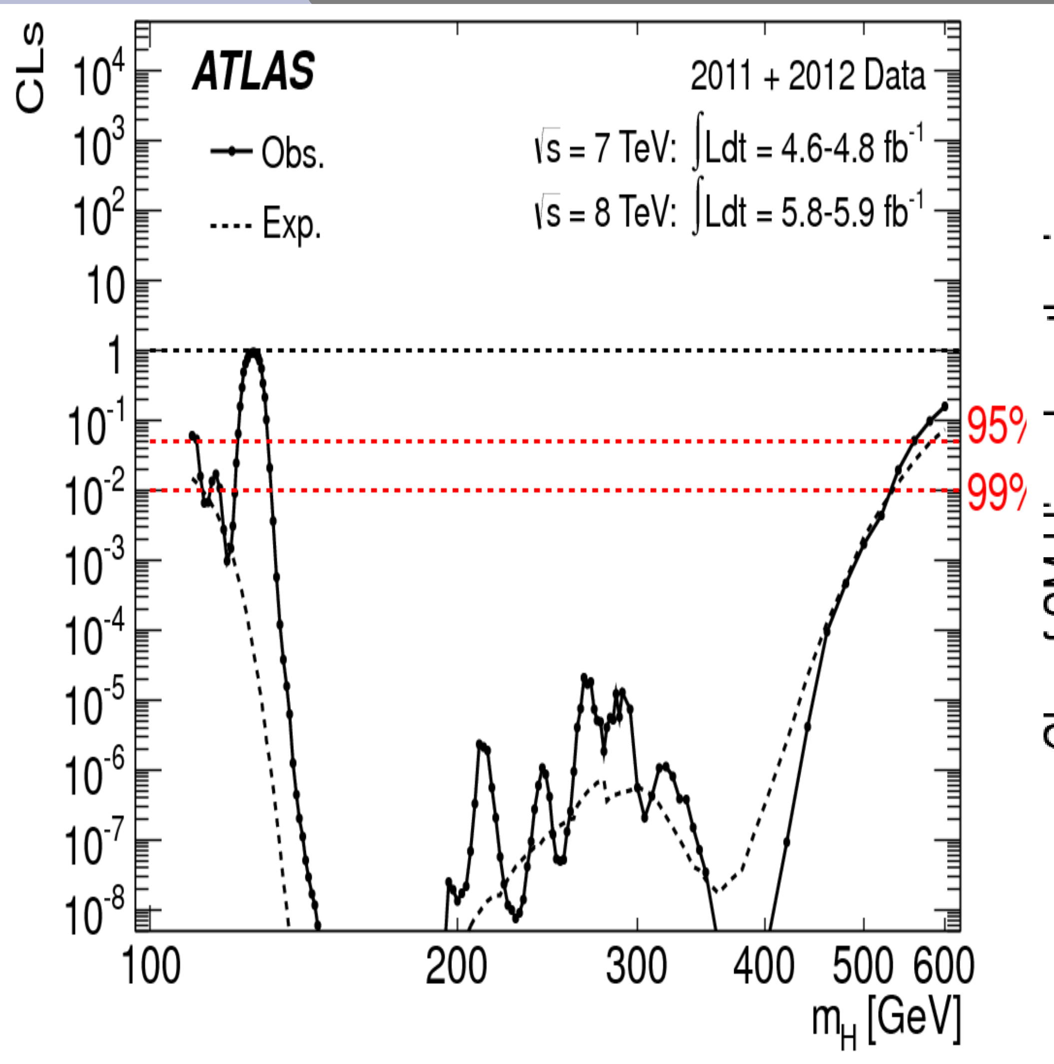


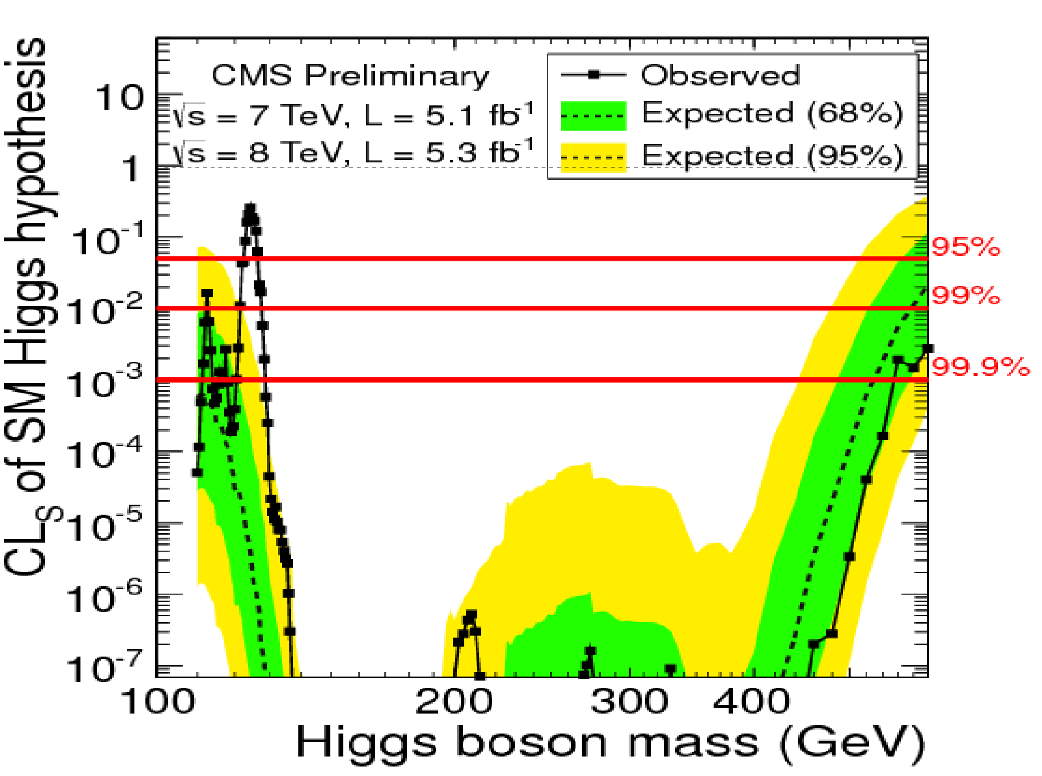
CMS H→bb results

- The expected limit is 1.6xSM strength
  - 2.1x is observed
- Small excess of 0.7σ
  - 1.6σ would have been expected for a Higgs
- So this is not very conclusive today
  - The improvement is remarkable, passing H→γγ at low mass



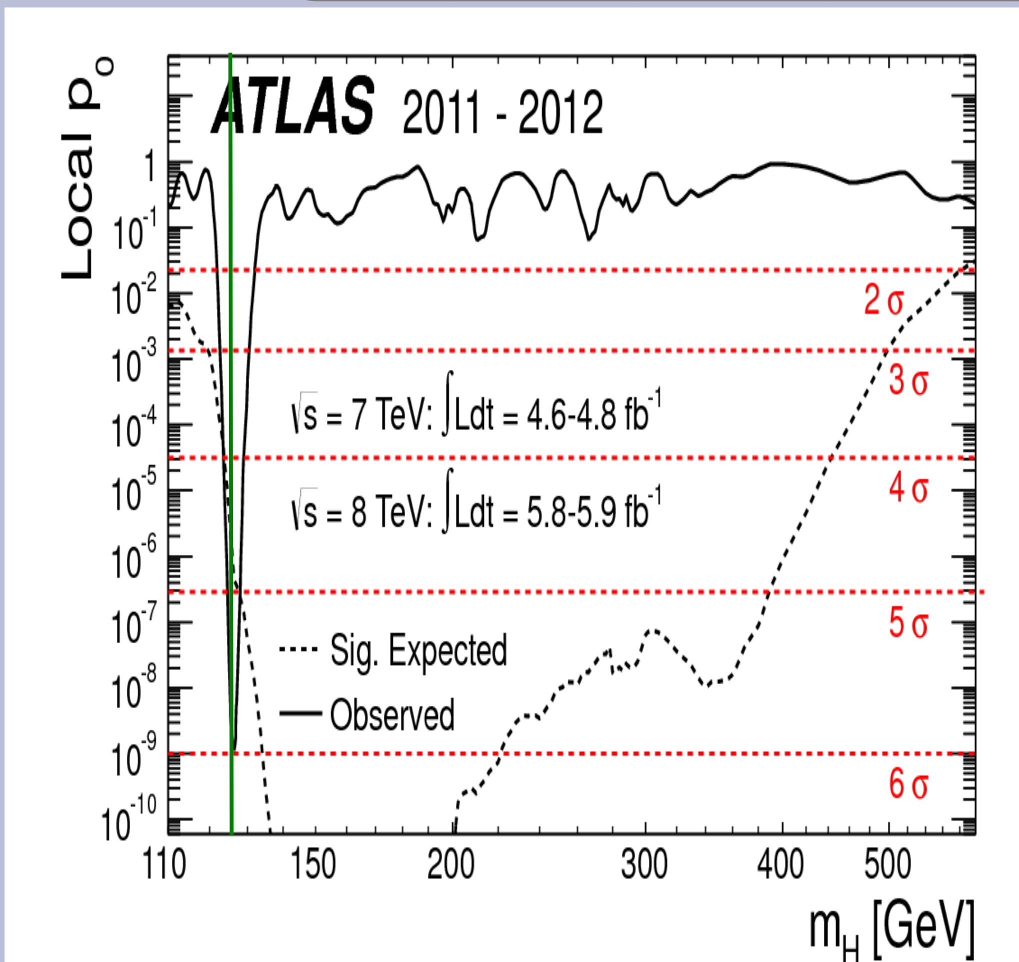
Combined limits

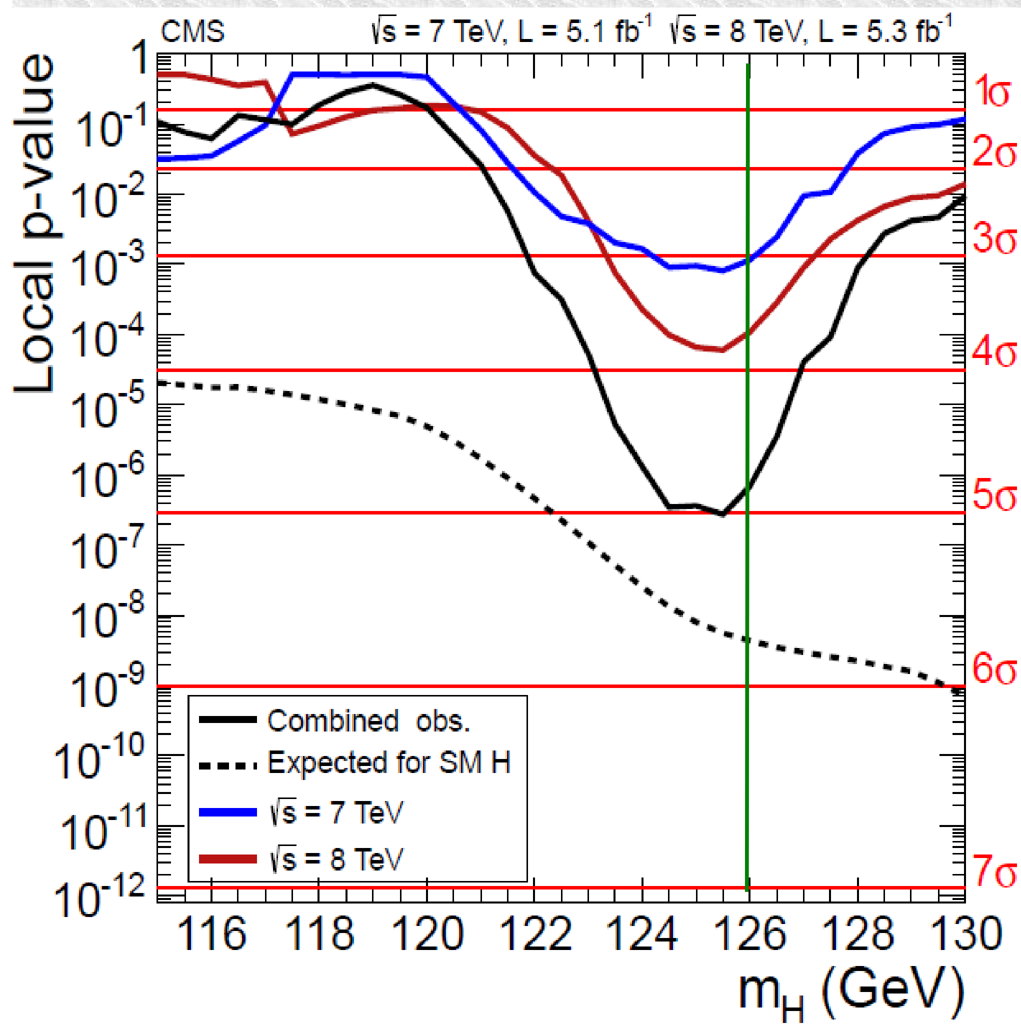




- Both experiments exclude nearly all mass range at high confidence

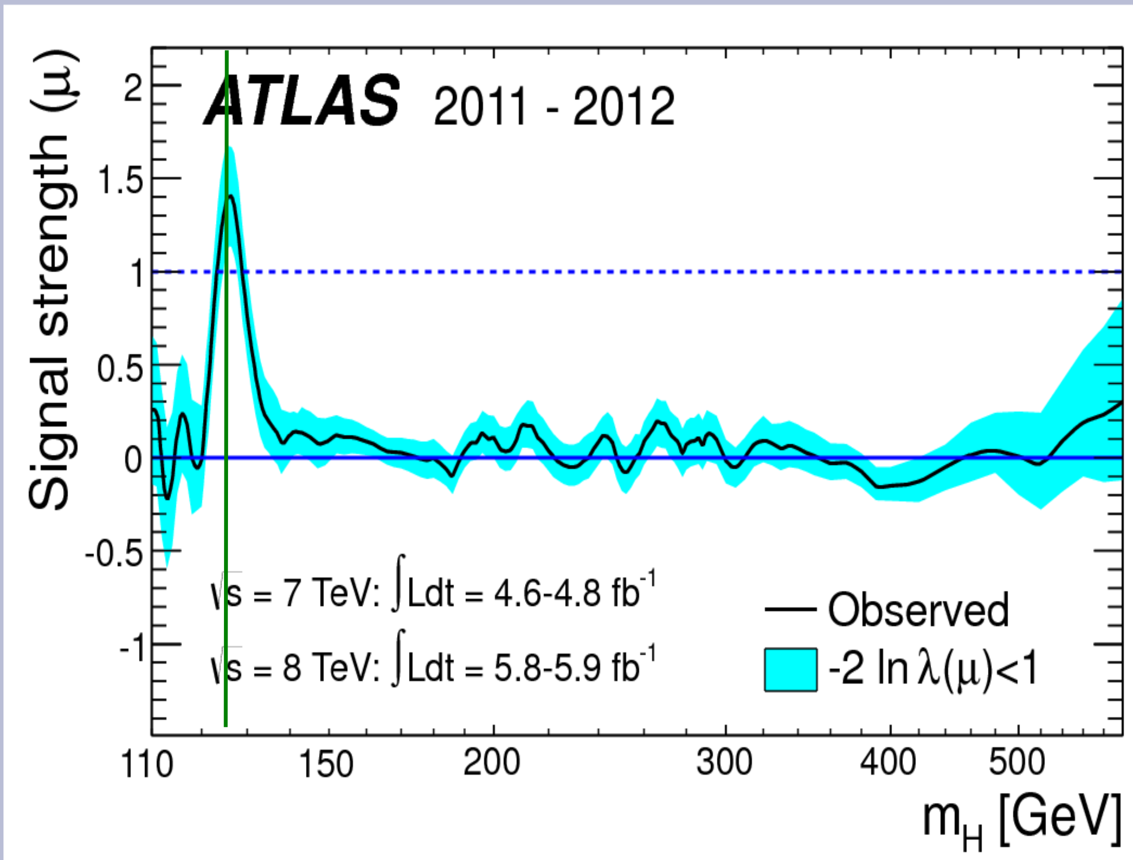
The Combined Results

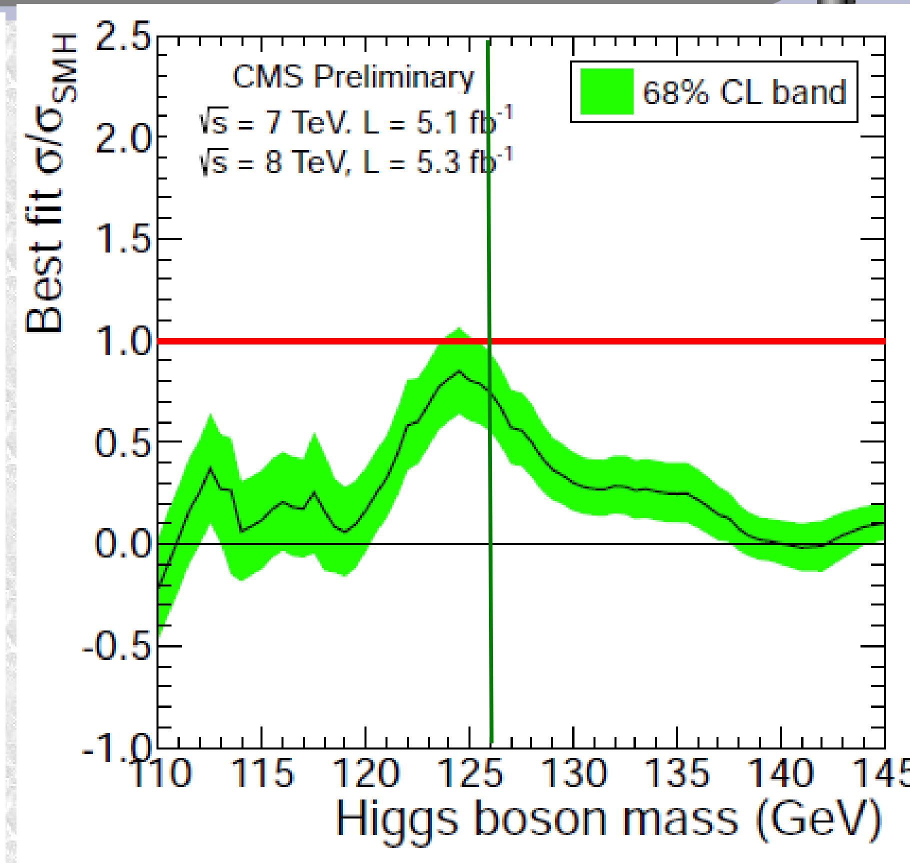




- Probabilities 10^{-7} to 10^{-9}
- Consistent in 2 experiments...we got it

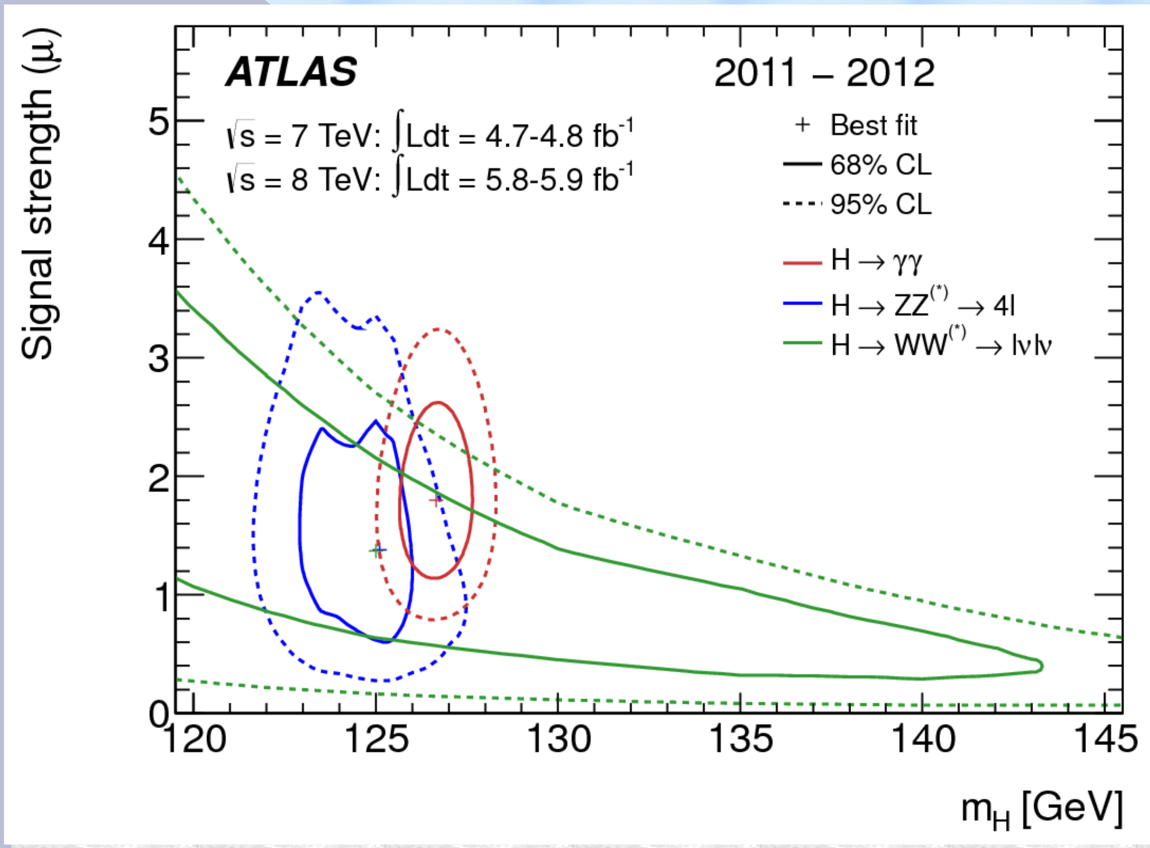
The Combined Results

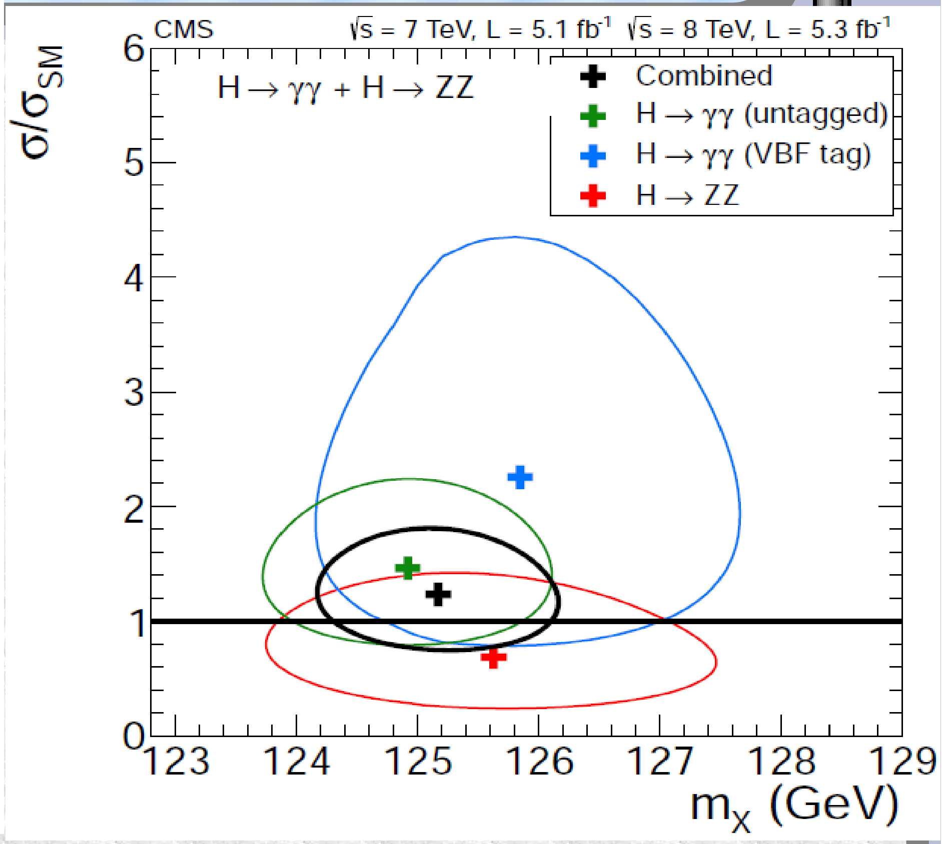




- The best-fit μ versus m_H
  - Compatible with 0 for hundreds of GeV
  - Compatible with 1 at 126....

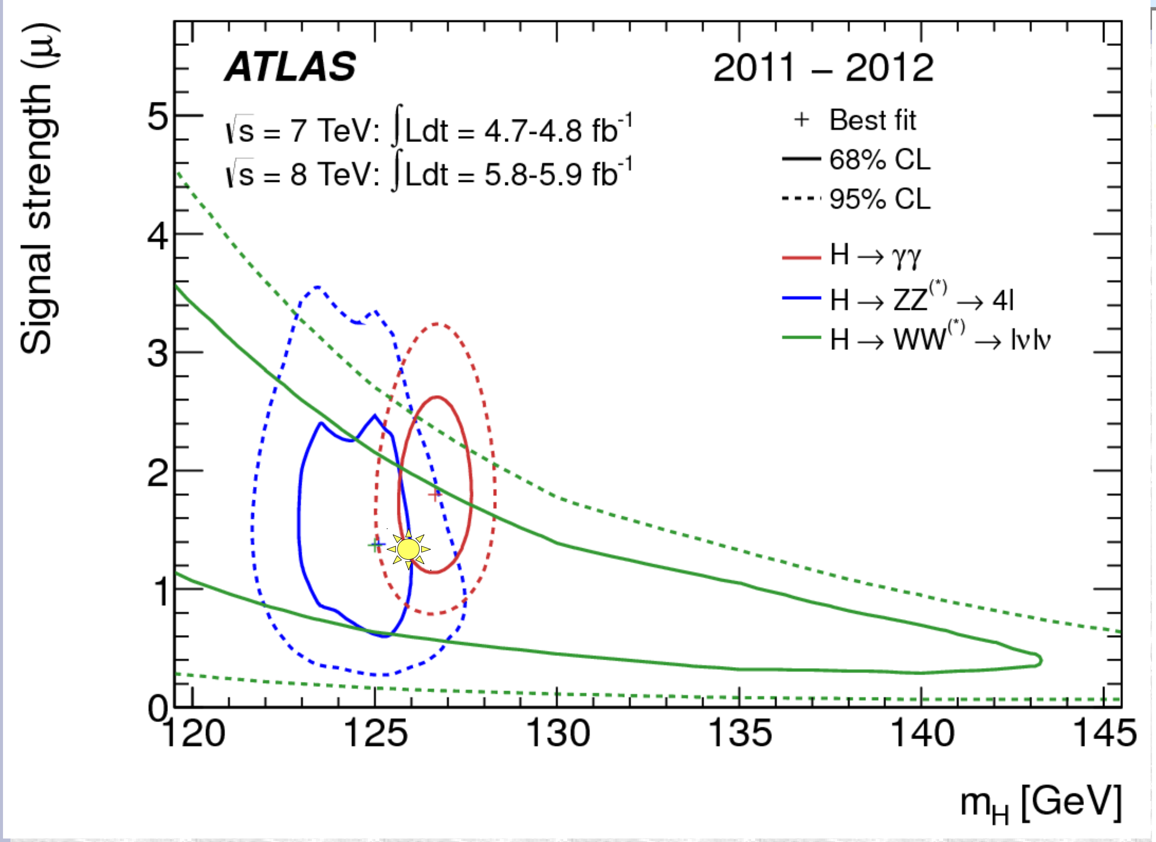
Rate versus Mass

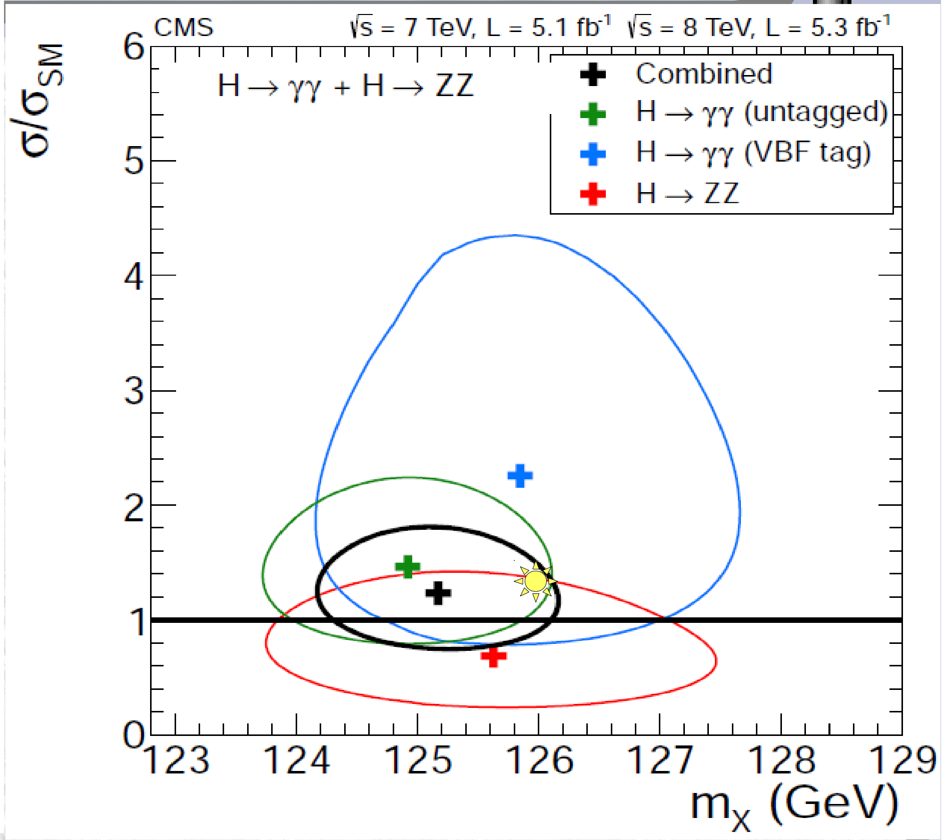




- 2D fits of rate and mass reduce model dependence
  - ATLAS: m_H=126±0.4±0.4
  - CMS m_H=125.3±0.4±0.5

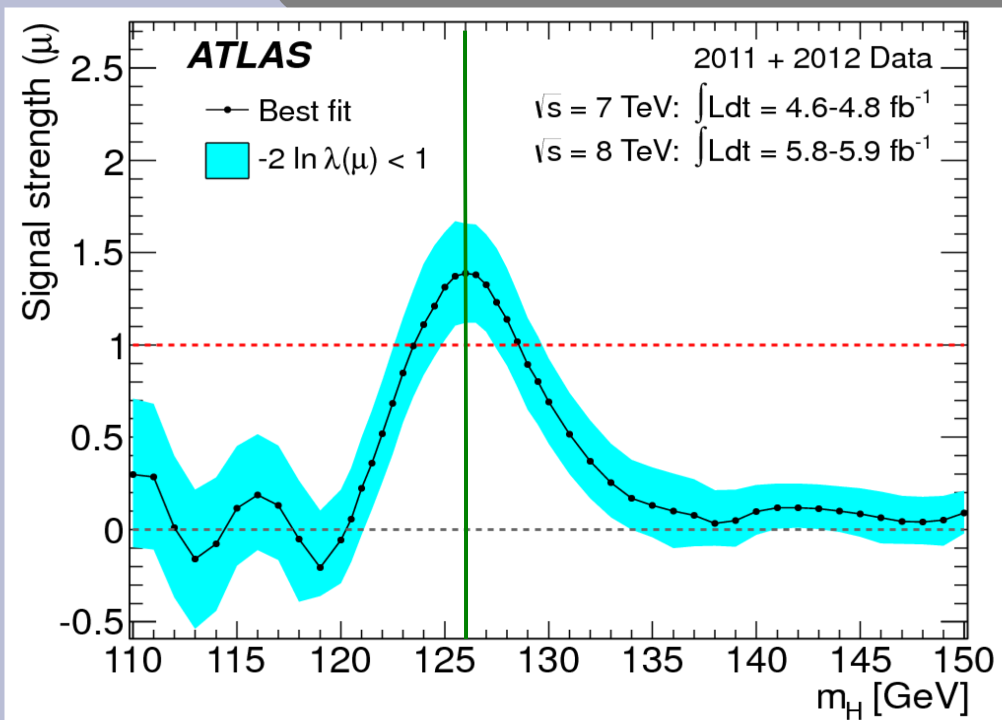
Rate versus Mass

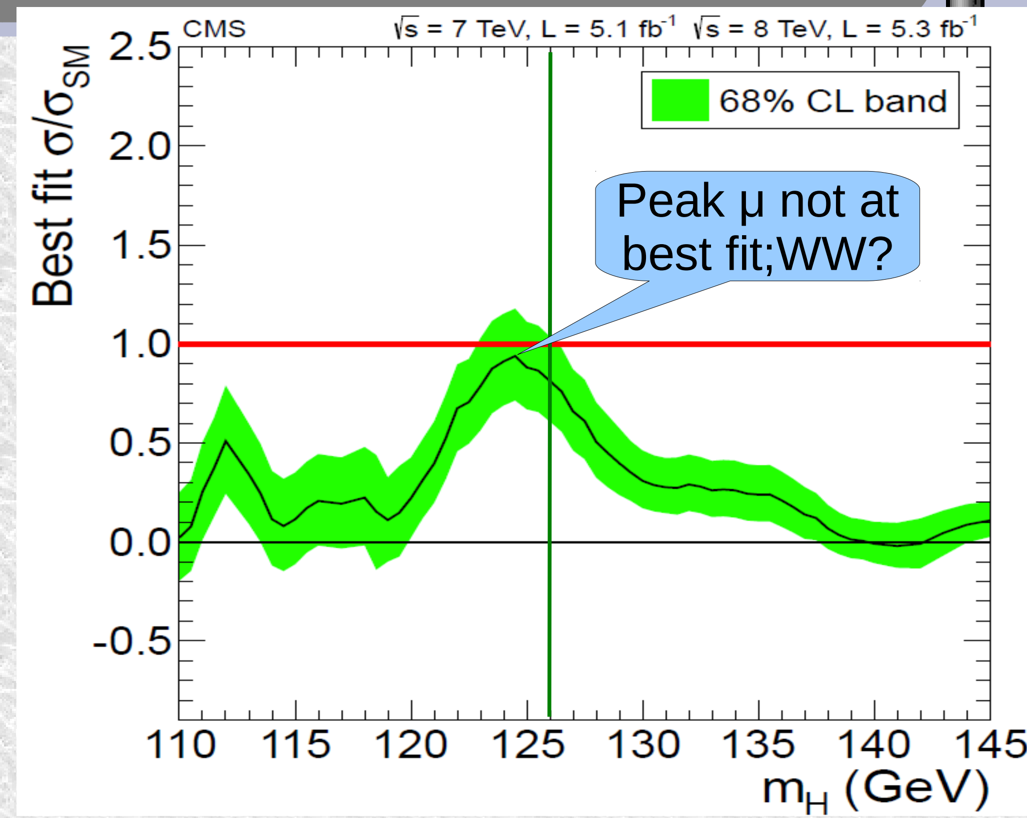




- 2D fits of rate and mass reduce model dependence
  - ATLAS: m_H=126±0.4±0.4
  - CMS m_H=125.3±0.4±0.5
- (126GeV, μ=1.3) fits in all 6 1-sigma elipses!

The Combined Results





- For a signal at 126 (or 125.3):
  - ATLAS just over a sigma above SM rate, 1.4±0.3 @126
  - CMS just under a sigma below, 0.87±0.23@125.3GeV
- This is consistent with a SM Higgs

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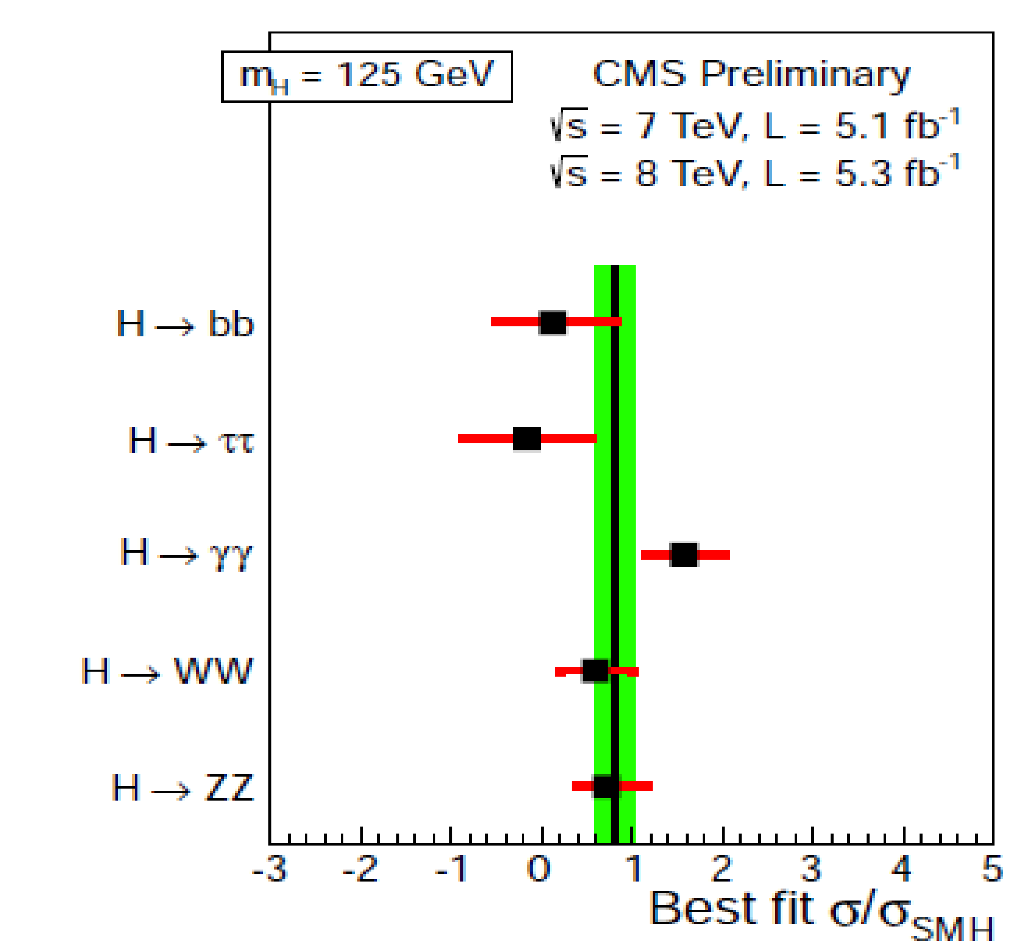
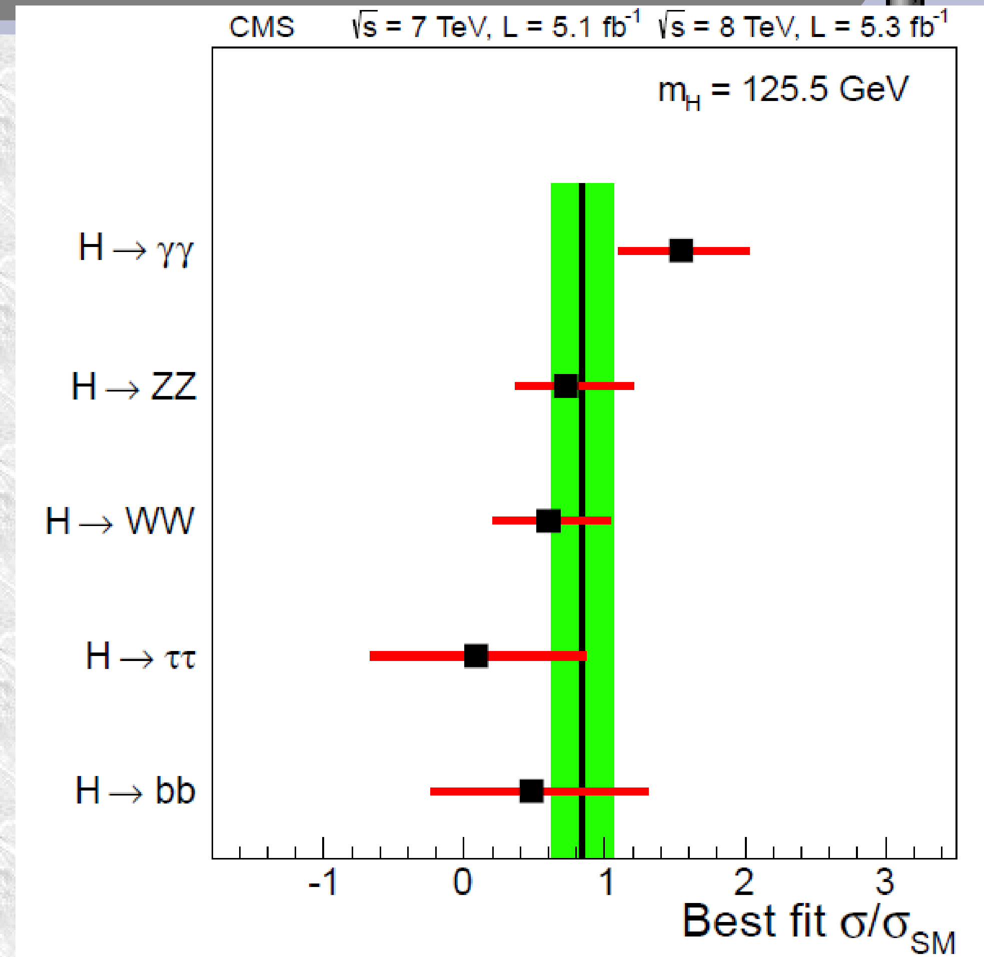
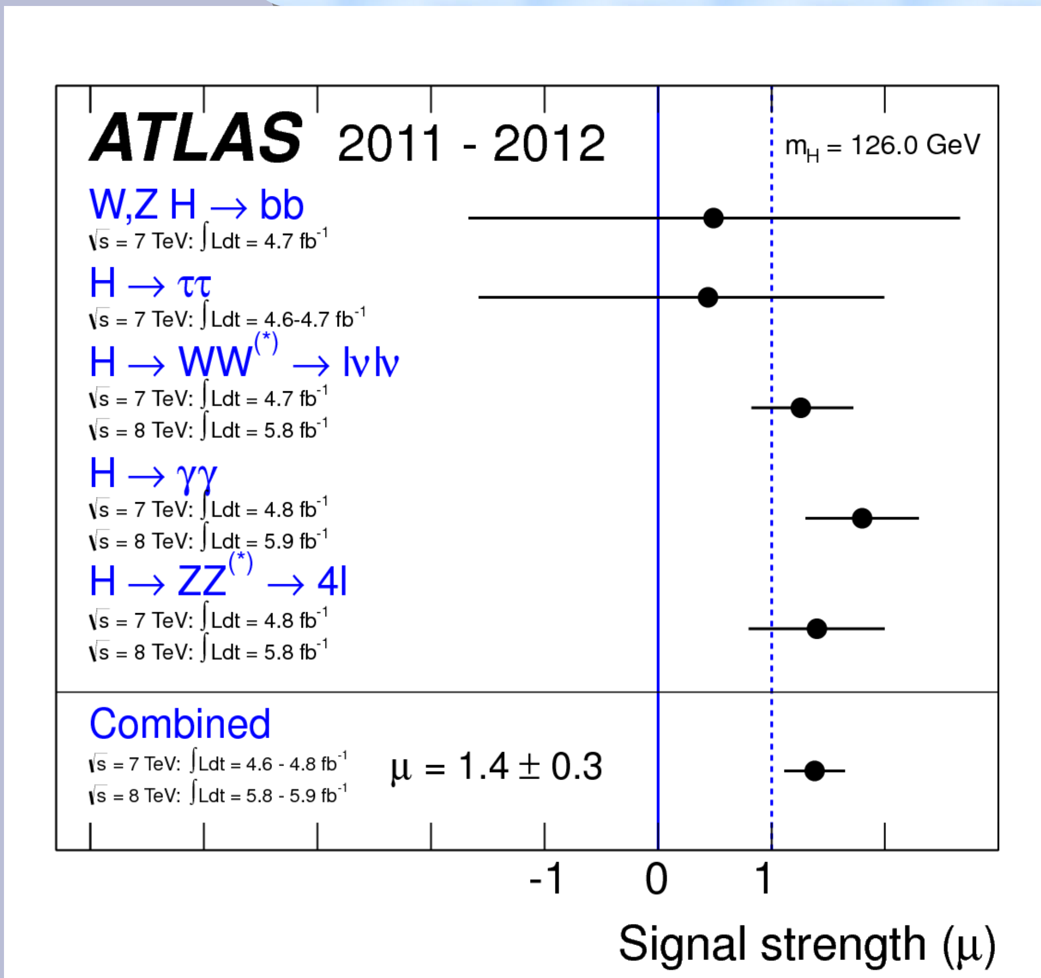
CMS channel results

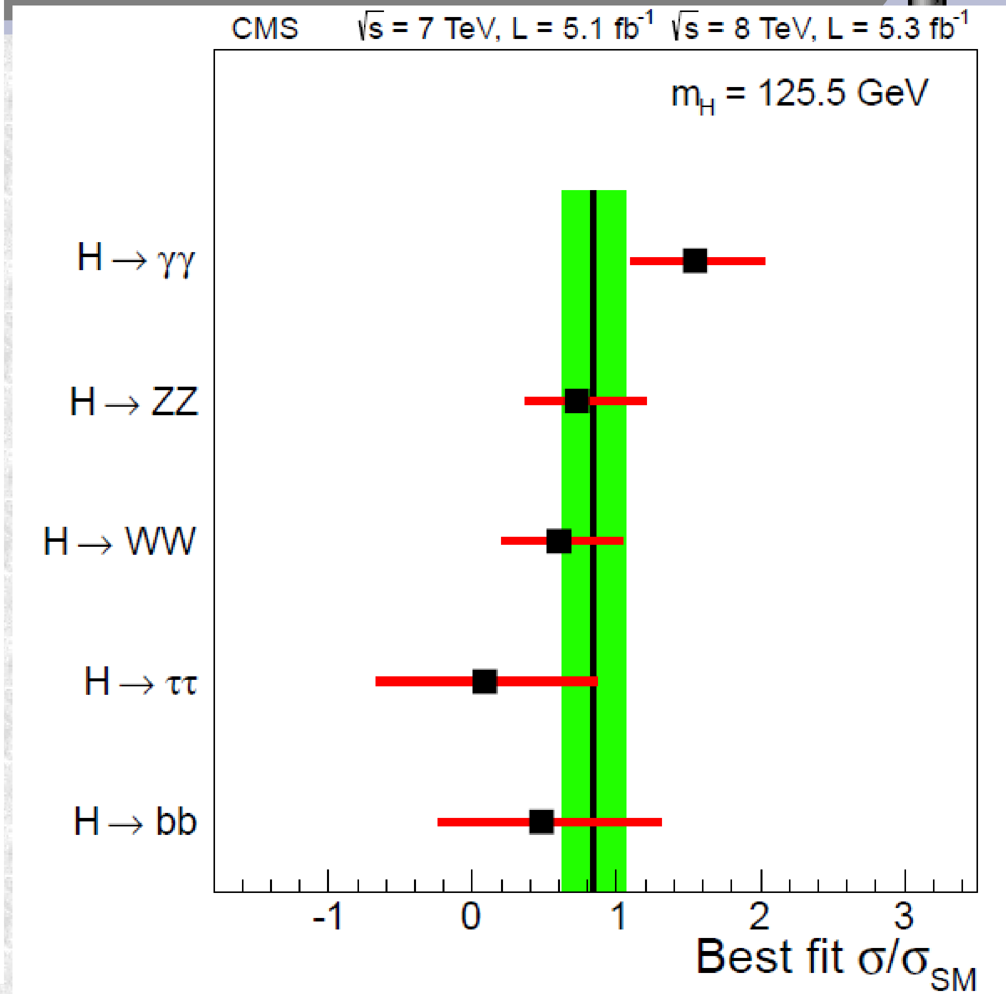




- I was confused by CMS results on Saturday
  - I had the final results, but I remembered the one at 125.
  - ττ and bb are changed quite a bit by this

Channel results

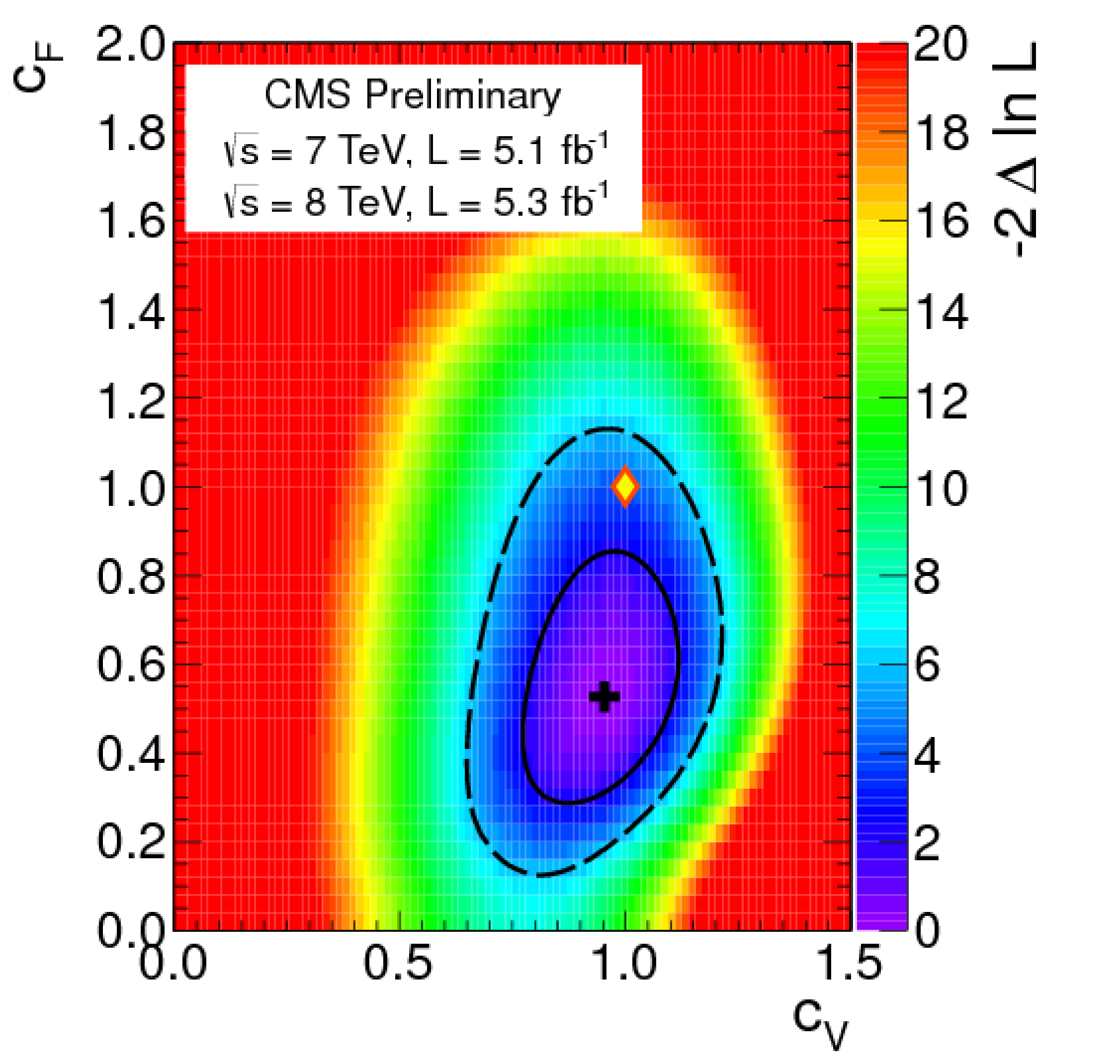




- Most channels favour a signal
  - More powerful ones (WW,ZZ,γγ) all do.
  - Is there too much γγ? Not really at the moment.

Interpreting couplings

- LHC measures rates
  - Cross-sections times branching ratios
- The theory starts from couplings
  - e.g. WWH
- We do not have enough data to unfold μ,τ,t,W,Z couplings
  - loops may have new particles?
  - Other decays?
- CMS assume Vector and Fermions scale together
  - Vector looks good
  - Some fermion tension



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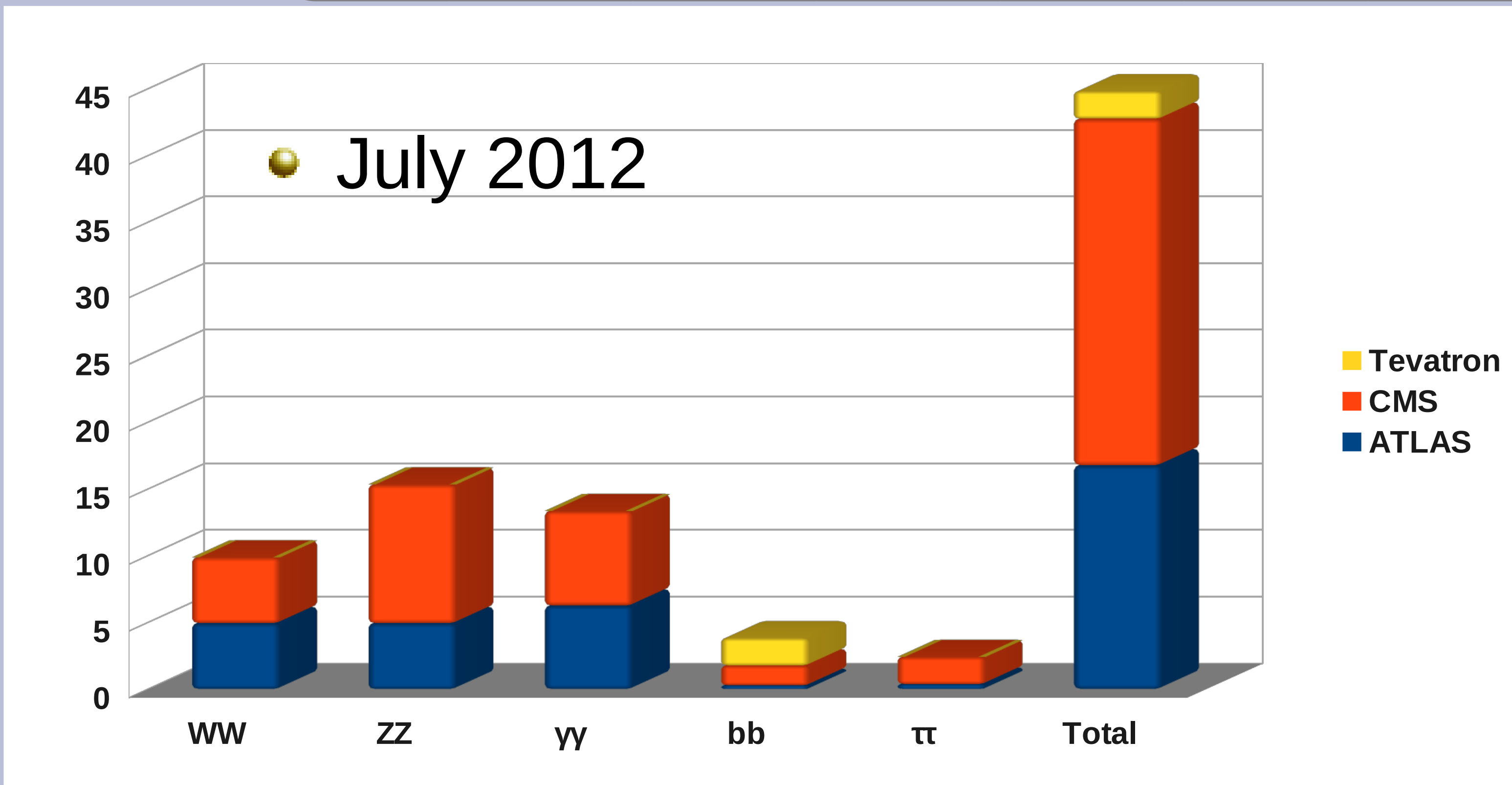
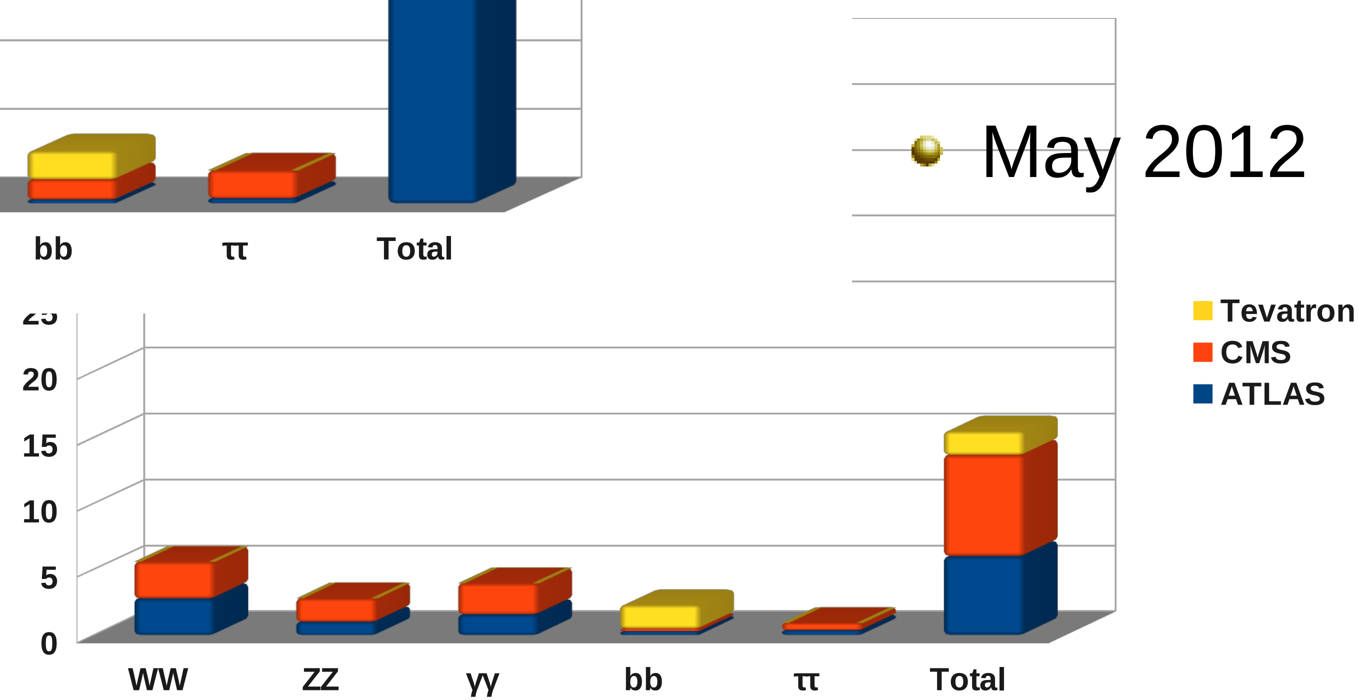
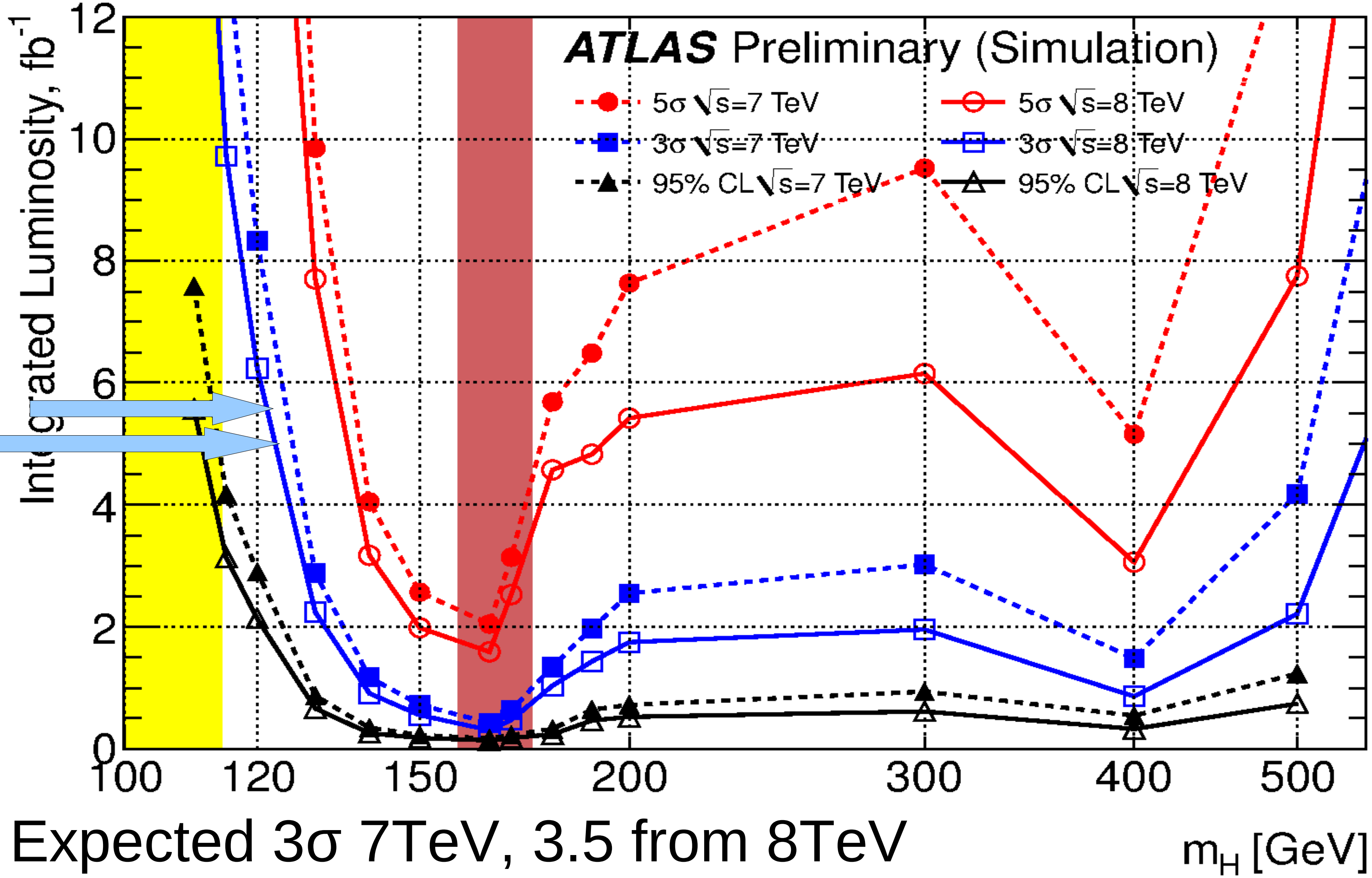
Weights of channels



Assumes Gaussian – not true



Projections



- Expected 3σ 7TeV, 3.5 from 8TeV
  - about right

Diversion: bias in discovery

- Not ATLAS/CMS opinions – just my doodlings

How is the search done?

- Pick an m_H hypothesis
- Fit for signal strength at that m_H
  - Compare with expectations for a signal at that mass
- Plot the results as a function of m_H

- So what is wrong?

How is the search done?

- Pick an m_H hypothesis
- Fit for signal strength at that m_H
  - Compare with expectations for a signal at that mass
- Plot the results as a function of m_H

- So what is wrong?
  - Nothing.
  - Unless you then use the results to pick out one mass

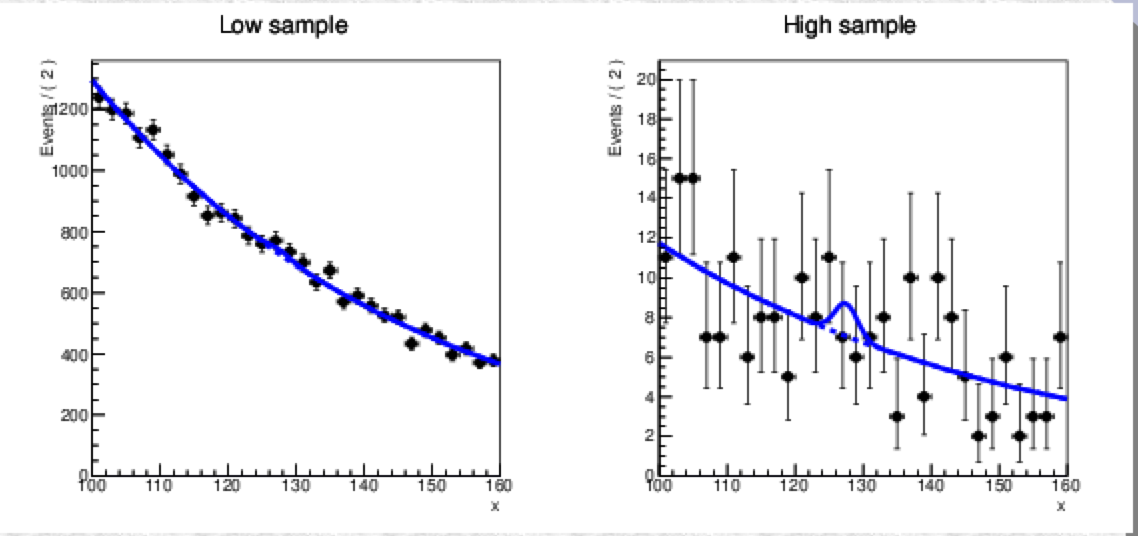
- The above procedure assumes

$$m_H^{tested} \equiv m_H^{true}$$

- So lets start with that....

Dummy experiment

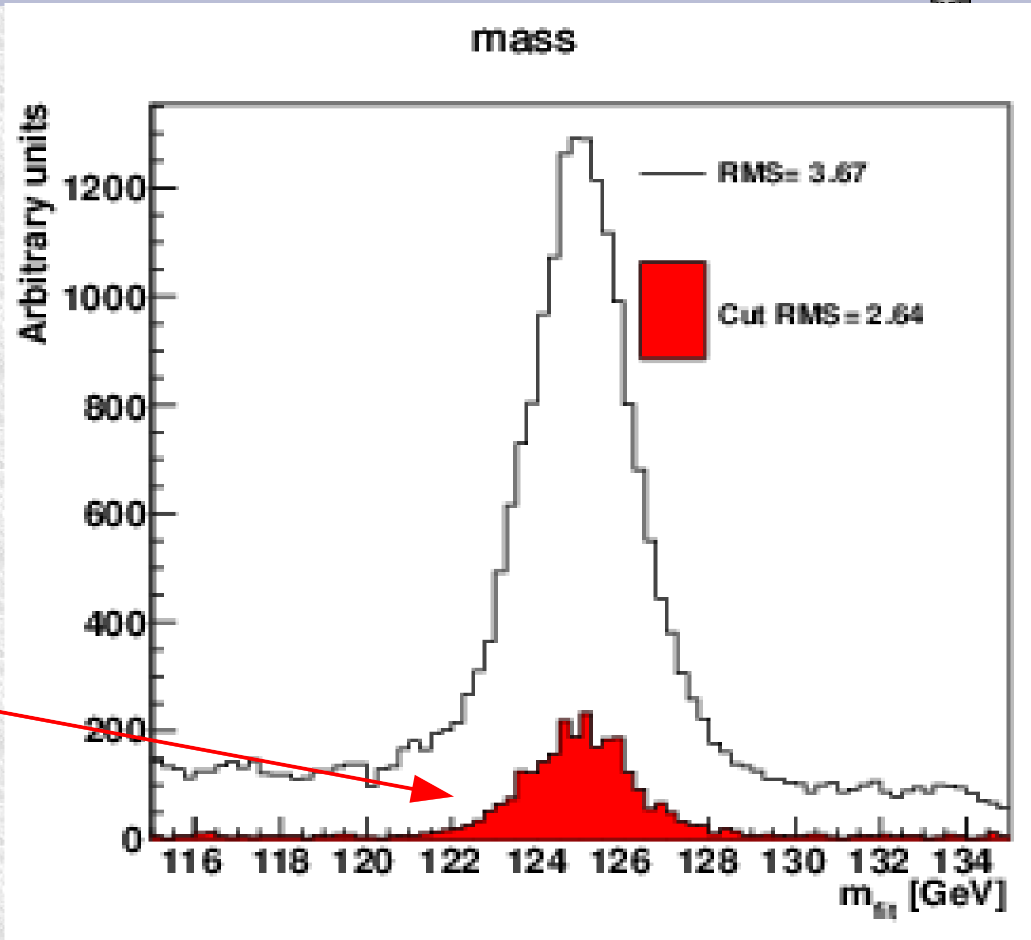
- Like ATLAS search
  - 22K background and 55 signal
  - Two categories
    - 90% signal, 99% bkd.
    - 10% signal, 1% bkd.
  - Mass resolution 1.7GeV



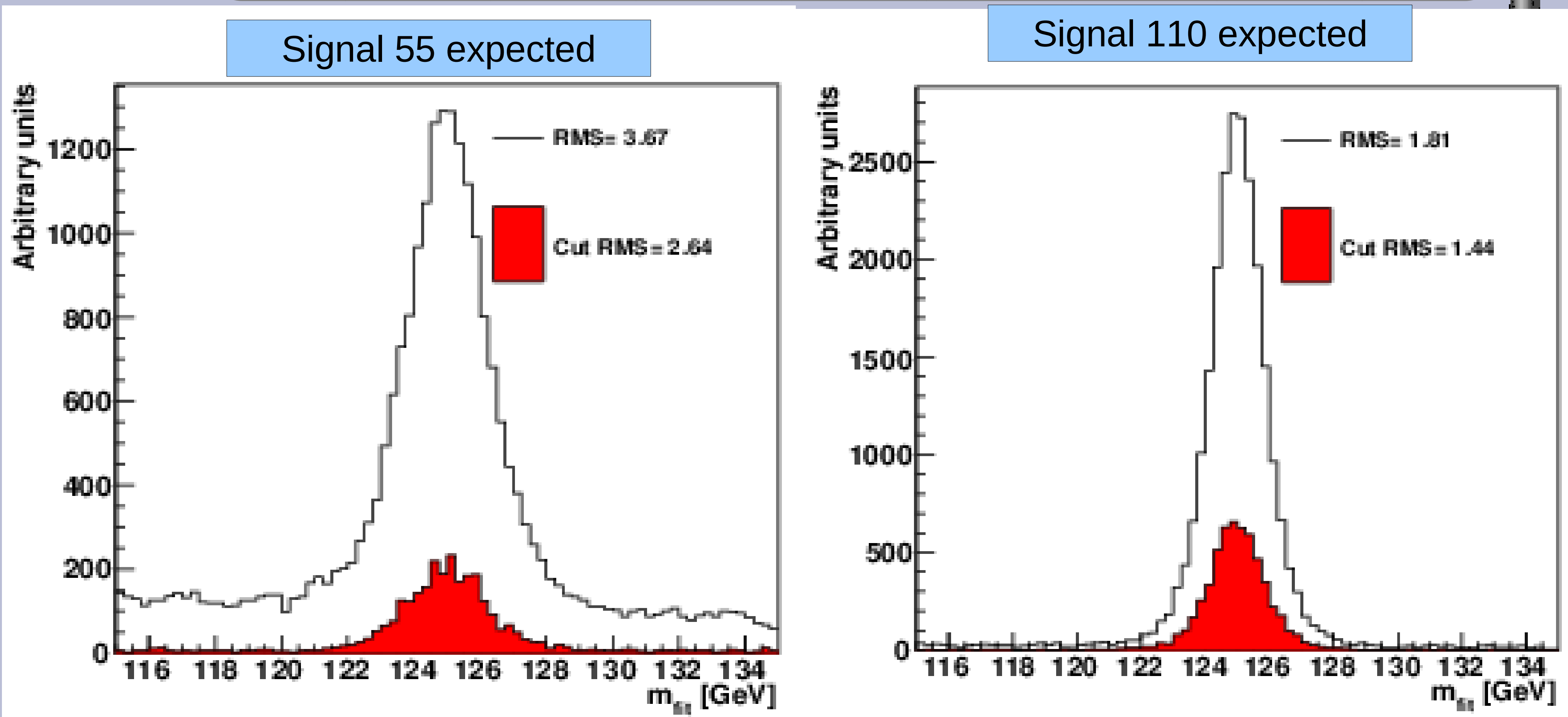
- A bit like the ATLAS γγ search in 2011
  - but just a dummy designed following their papers
  - Parameters designed to have 1.4σ expected sensitivity
- Make toy MC investigations *with a signal*
  - Inject signal
  - Constrain μ to be non-negative
  - Fit with mass fixed or floating to compare results

Fitted Mass distribution

- ML fit in minuit
  - Fit 2 background slopes and rates and 1 signal rate
  - Scan 115-135 first
- Quite often the best fit has NOTHING to do with the signal
  - RMS 3.7 (in this window!)
- RED selects 'lucky' experiments with 2.5-3σ observed excess
  - 2xexpected, as ATLAS/CMS
  - Cluster but RMS still 2.6GeV
- ATLAS+CMS 2011 masses compatible!



Dependence on TRUE signal



- Injecting 2xSM ≠ observing 2xSM.
- Even with 2.5-3σ observed, RMS depends on *true* signal

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OK, so $m_H^{fitted} \neq m_H^{true}$

- The resolution on m_H is worse than the per-event resolution!
  - The statistics is dominated by background fluctuations

- Imagine a 'perfect' (Asimov) signal
- Add a fluctuating background under it
  - Just above and just below peak gives 2 chances to fluctuate
  - Odds are one of them fluctuates up
  - The signal gets pulled to that point
  - And grows in size!
- This is not included in the ATLAS/CMS 'expected p-values for signal' because they assume $m_H^{fitted} = m_H^{true}$

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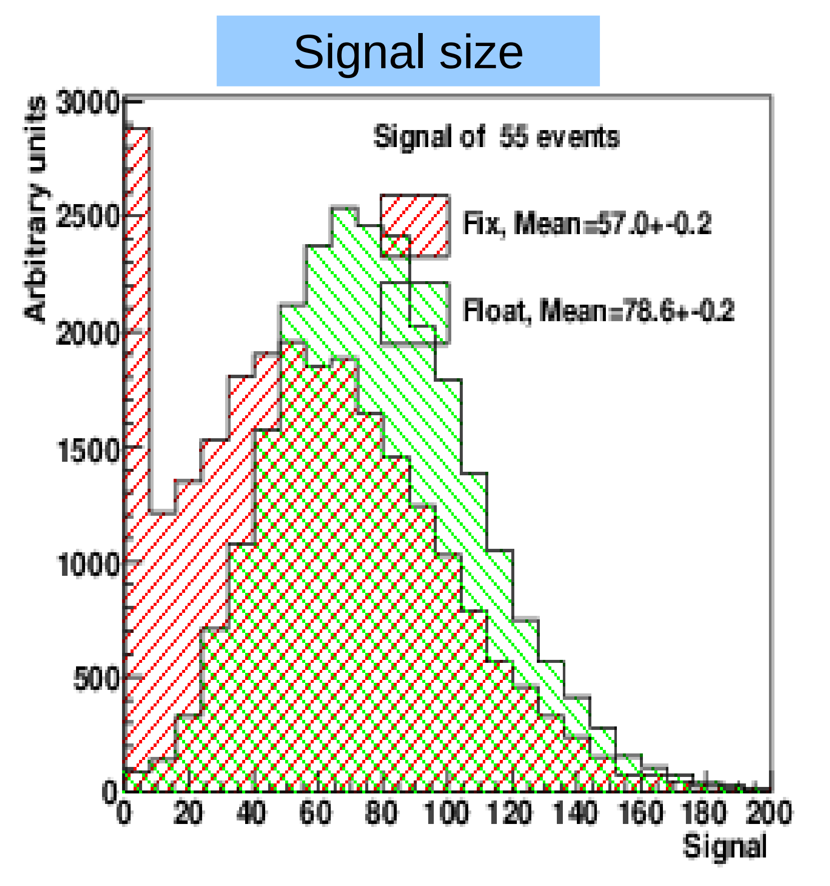
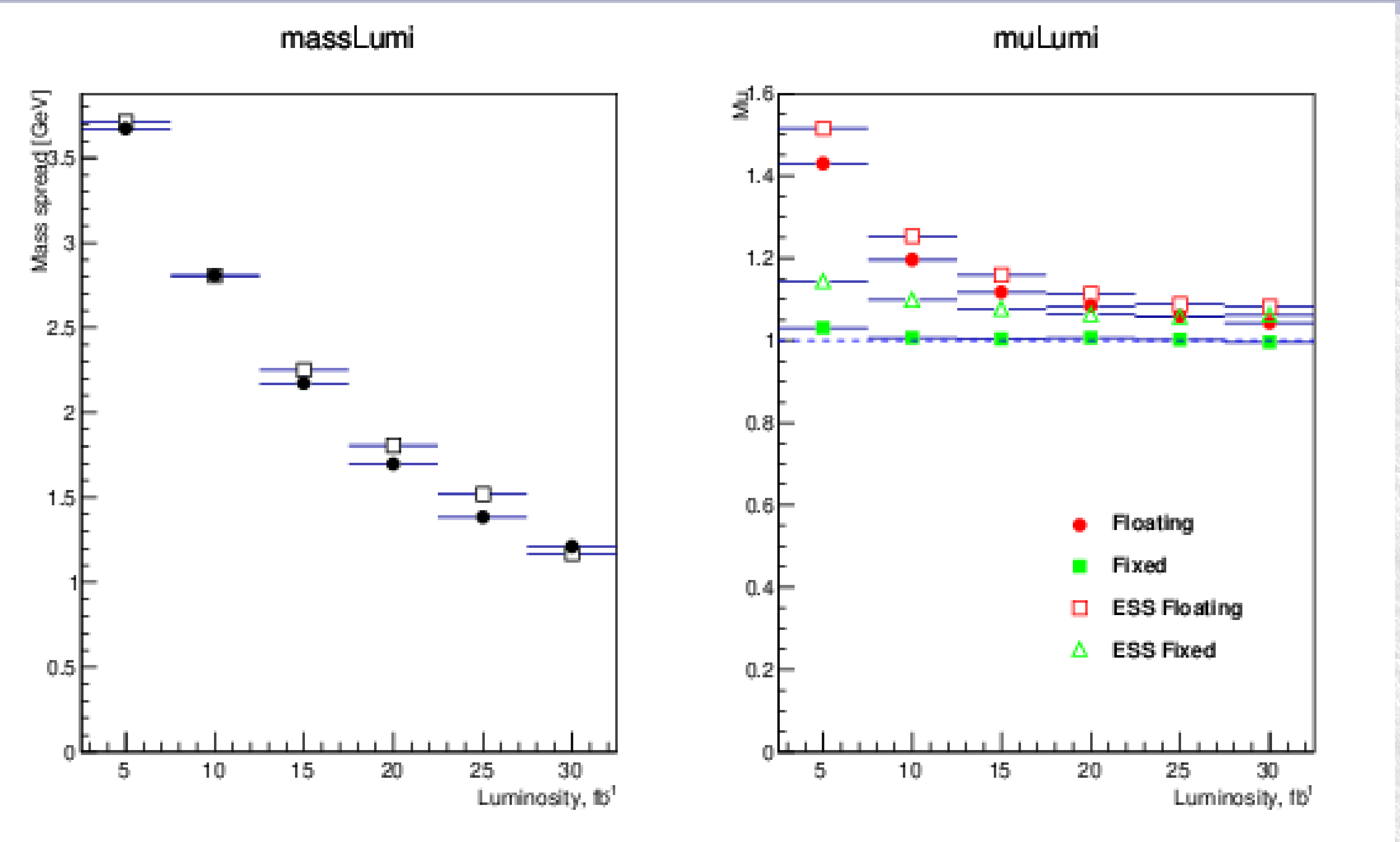
How large is effect on μ?



- Red injects at 125 and tests at 125 – as expts. Do
  - 4% bias, coming from μ≥0
- Green injects at 125 and fits with m_H free
  - **43% bias!**

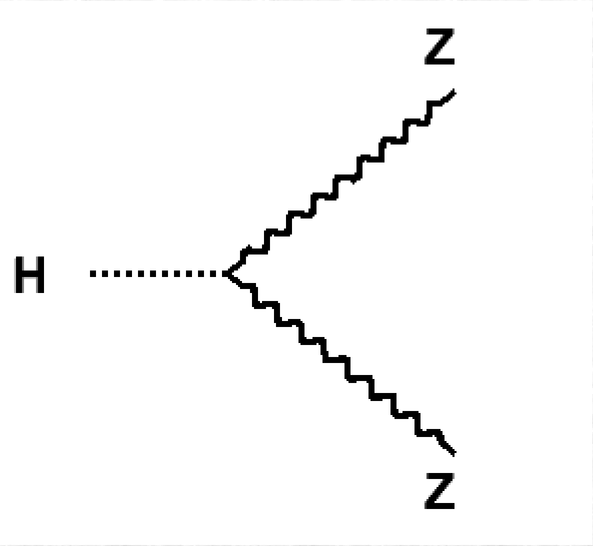
Evolution with data?



- Mass accuracy improves a little faster than $\sqrt{\mathscr{L}}$
- Bias in signal rate drops like $1/\mathscr{L}$
  - Note ESS (0.7% between channels) makes μ bias even bigger

Problem: H to ZZ

- As a photon only couples to charged particles a Z only interacts with those with weak hypercharge
- The Z is neutral
  - Charge and hypercharge
- ZZH vertex shows the H must be weak charged
  - But in $H \rightarrow ZZ$ where does the charge go?



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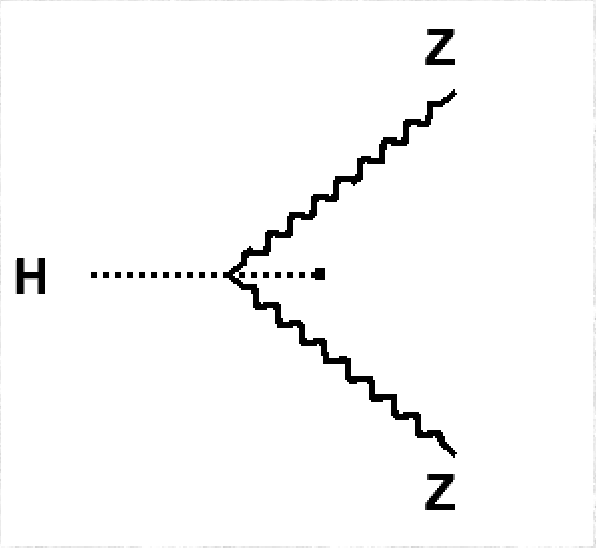
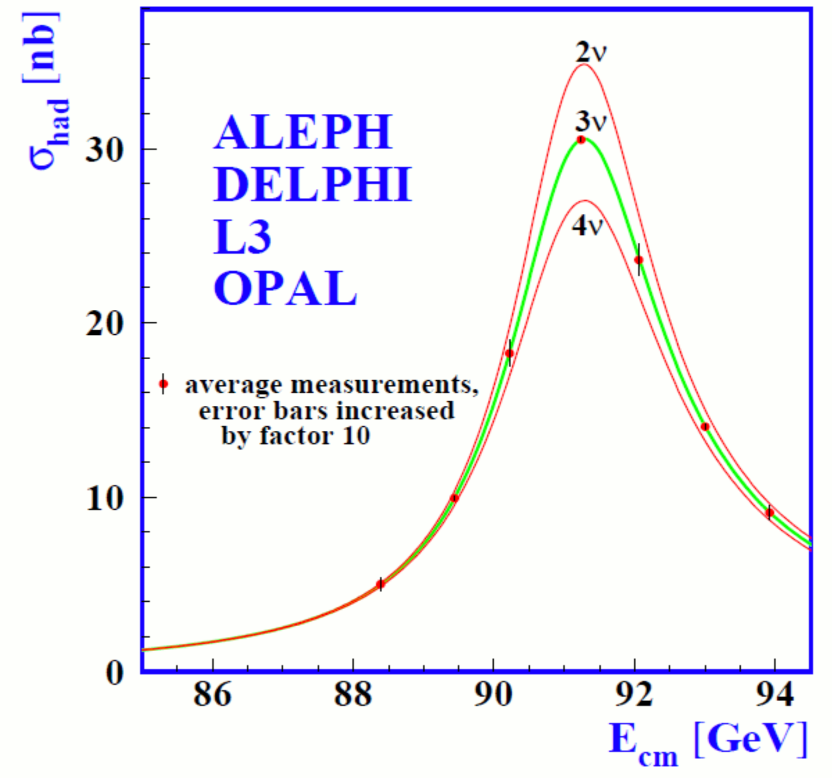
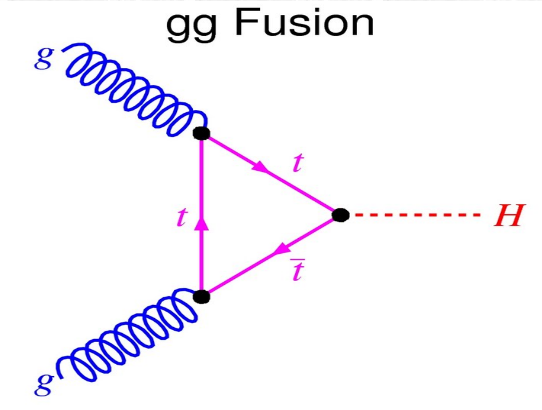
- The Z is neutral
  - Charge and hypercharge
- ZZH vertex shows the H must be weak charged
  - But in $H \rightarrow ZZ$ where does the charge go?
- It is really a 4-point coupling
  - One leg 'grounded' in the vacuum
- The ZZ decay is telling is the vacuum is really important
  - An active participant in interactions
  - With a (weak) charge!
- The apparent 3 point couplings come from $-\lambda[(v+h)/\sqrt{2}]^4$ – but v is the VeV



How many generations?

- LEP showed there are just 3 light neutrinos
  - hence 3 generations?
- Now we know neutrinos have mass maybe $2m_\nu > m_Z$?
  - This case not excluded
- But Higgs production is mostly through gluon fusion
  - Virtual top in a loop
  - A new heavier quark would increase the rate a lot
  - Whatever mass the quark had
- Much harder to believe in a 4th generation today.



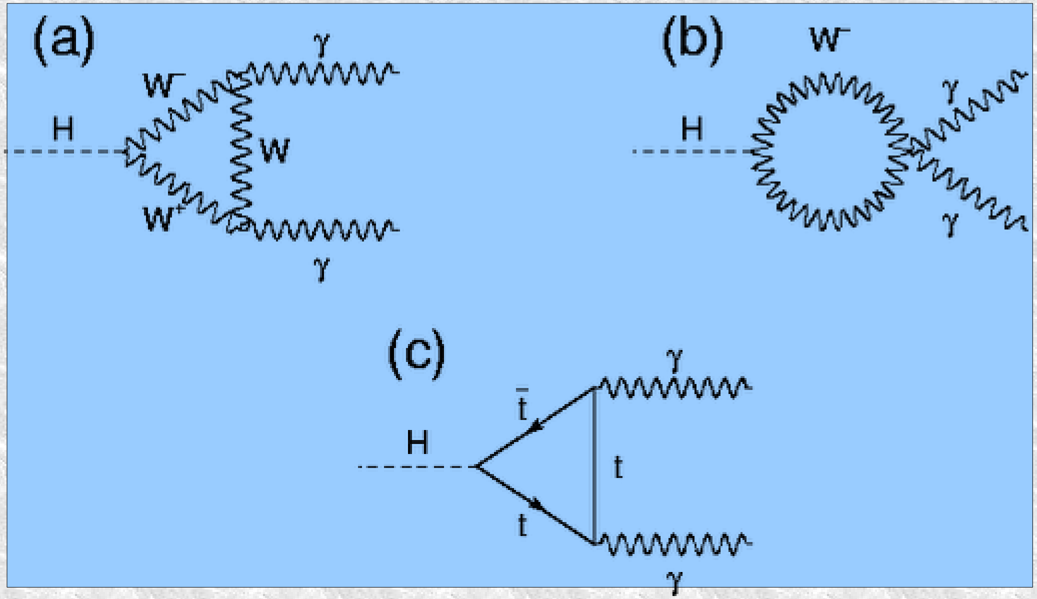


How many generations?

- What if $2m_\nu > m_Z$?
  - This case not excluded
- Then the Higgs Br into neutrinos could absorb most of the signal and supress all other couplings
  - Cancelling off the gluon loop enhancement
- Can we eliminate that?
  - We can look for this (very large) invisible Br directly
  - Or compare ggF and VBF production rates
- One or other can probably close this hole
  - But this needs to be studied

H → γγ decay

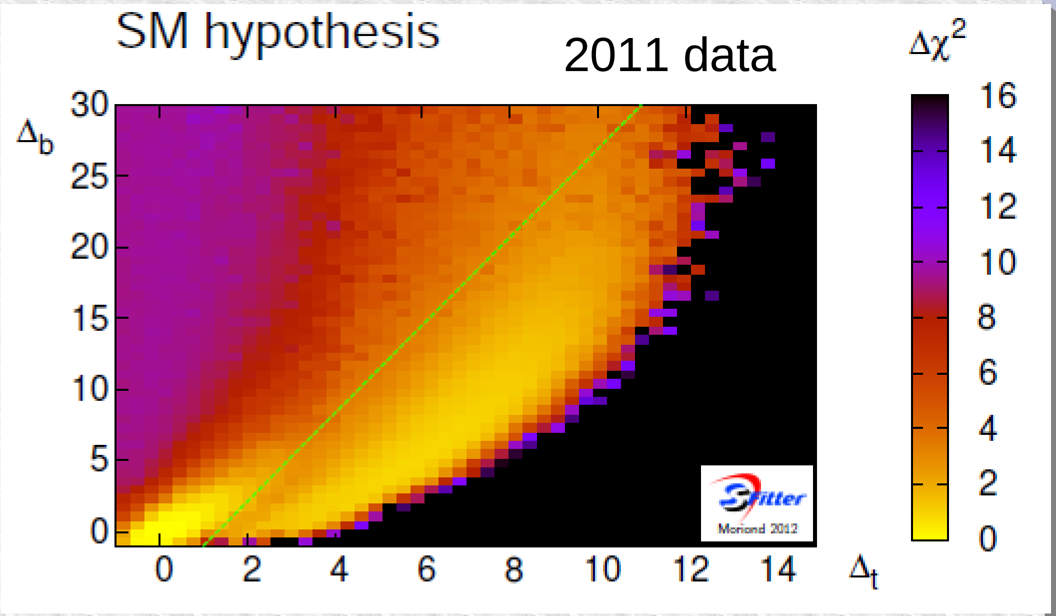
- The SM decay is a competition between fermion and boson loops
  - Opposite sign
  - Like Heirarchy problem
- W dominates
- So increasing tt coupling decreases Br γγ
  - Unless it is increased maybe x6, rises again
- But add a new boson and it increases
  - e.g. Stau or stop
- Or reduce the coupling to b quarks
  - This raises all other Br.



http://inspirehep.net/record/1123909/

ttH and sFitter

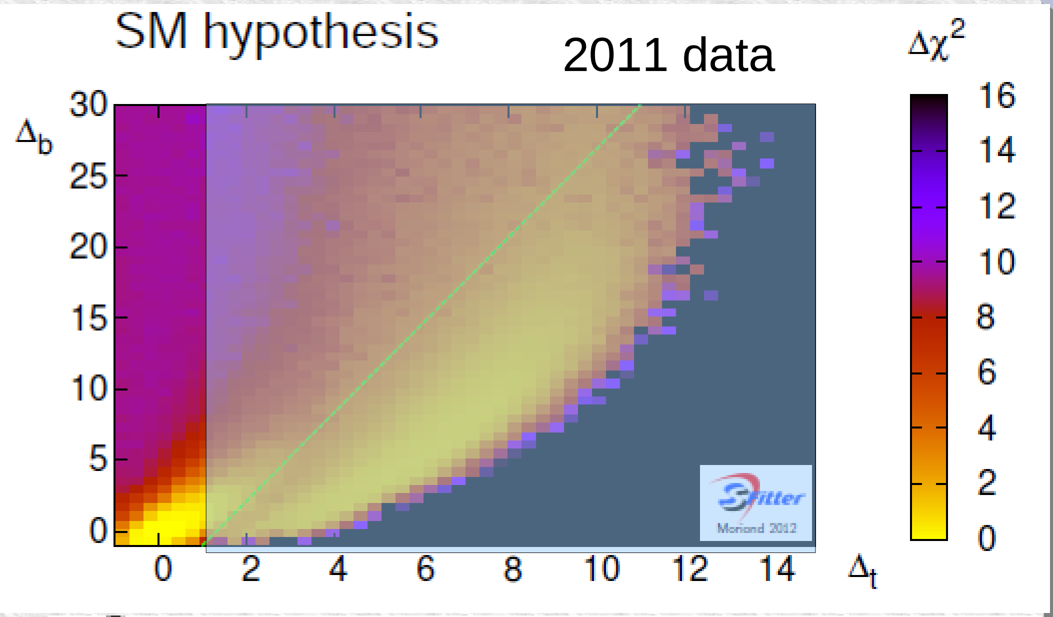
- In fits to couplings excess in γγ can be explained by a very strong coupling to tt
  - It overwhelms the W coupling
- With an enhanced b coupling which leaches Br from other decays
  - But cannot enhance b much at it is 60%



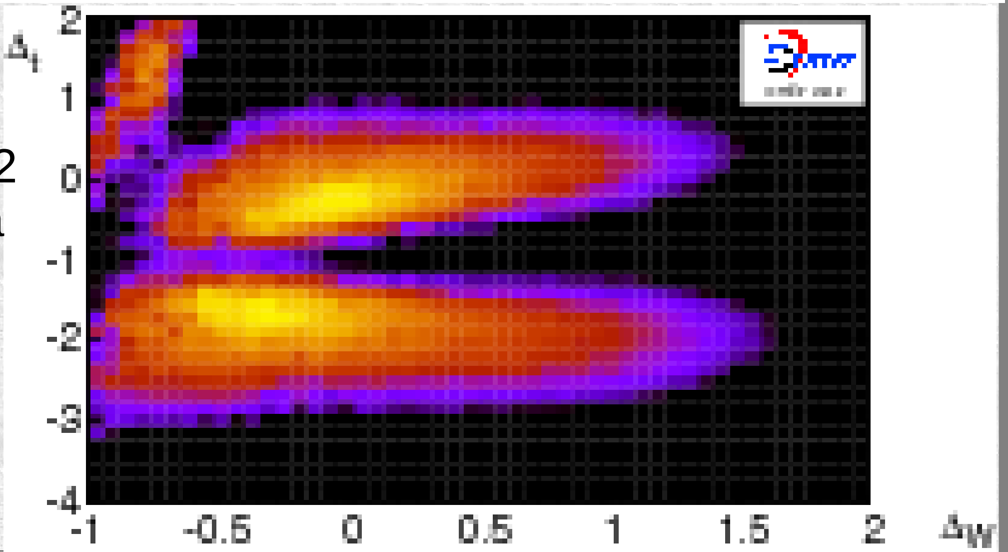
http://inspirehep.net/record/1123909/

ttH and sFitter

- In fits to couplings excess in γγ can be explained by a very strong coupling to tt
  - It overwhelms the W coupling
- With an enhanced b coupling which leaches Br from other decays
  - But cannot enhance b much at it is 60%
- This would be clear in ttH
  - CMS bound, 4xSM, cuts off this plot

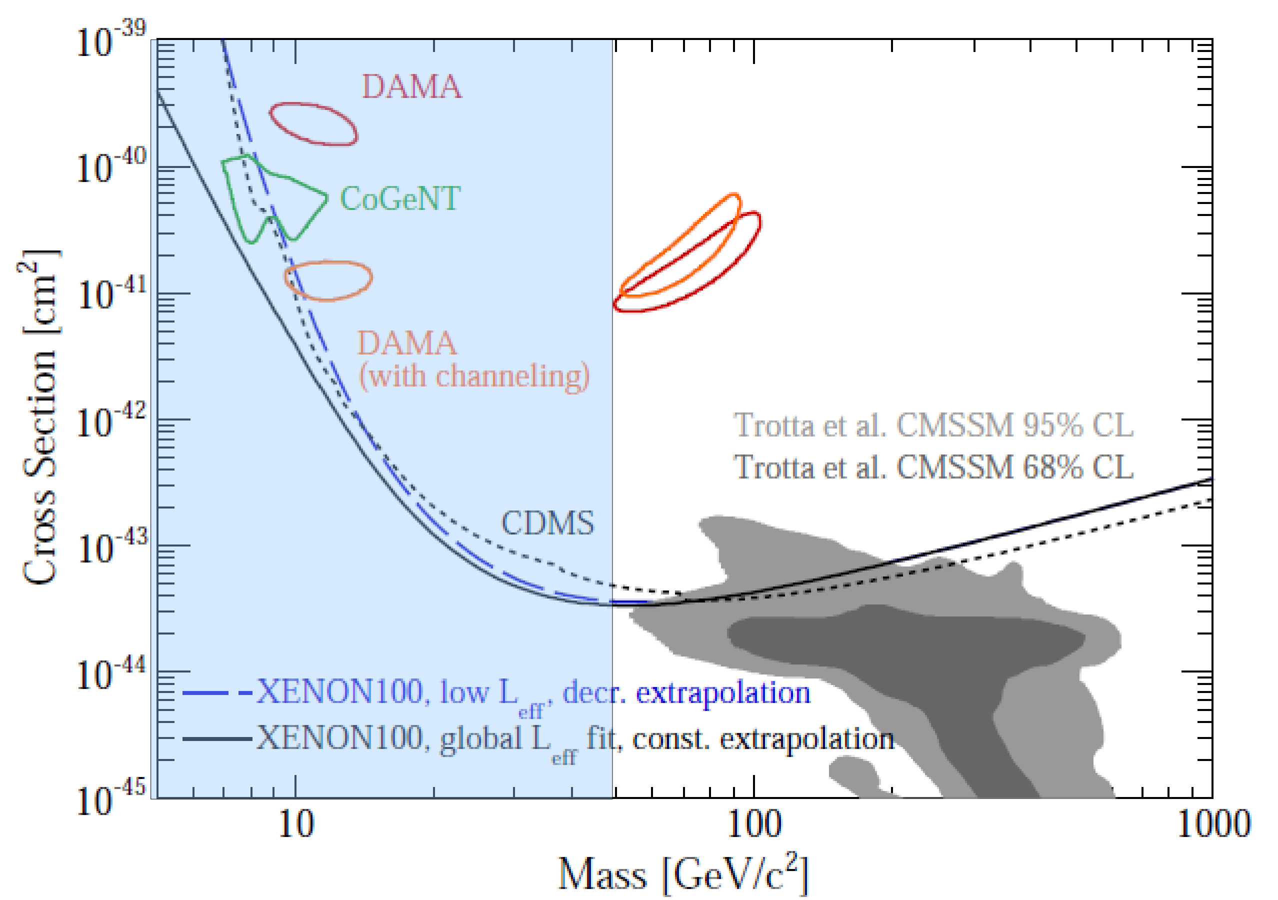


2012 data



Dark Matter?

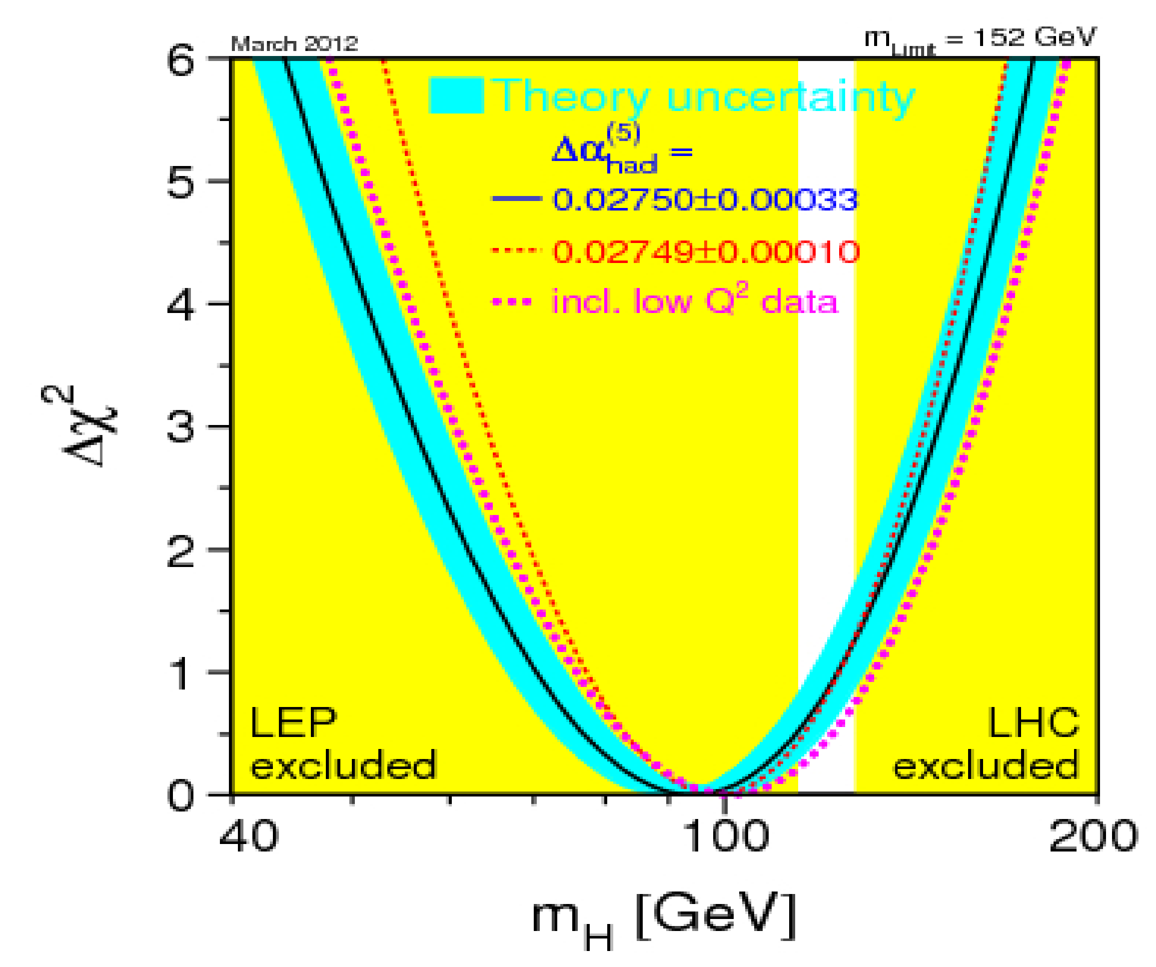
- If this is a Higgs, in many models it couples strongly to dark matter
  http://physics.uoregon.edu/~soper/TeraHiggs2012/Tait.pdf
- If 5-50GeV dark matter, some models are excluded
- This needs more study
  - Unless it has been done already?



Xenon plot from ArXiv: 1005.0380v3

SUSY prediction from: JHEP 0812:024,2008

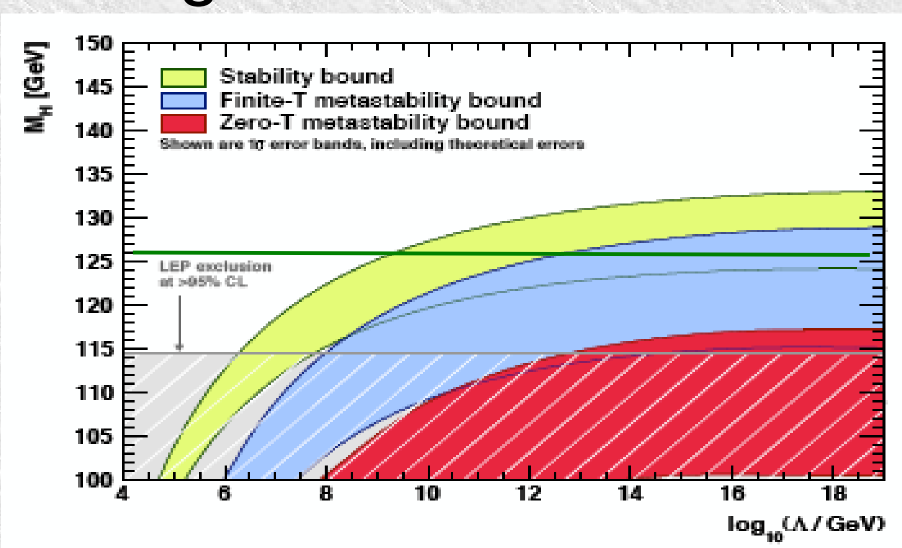
What does 125-126 tell us?



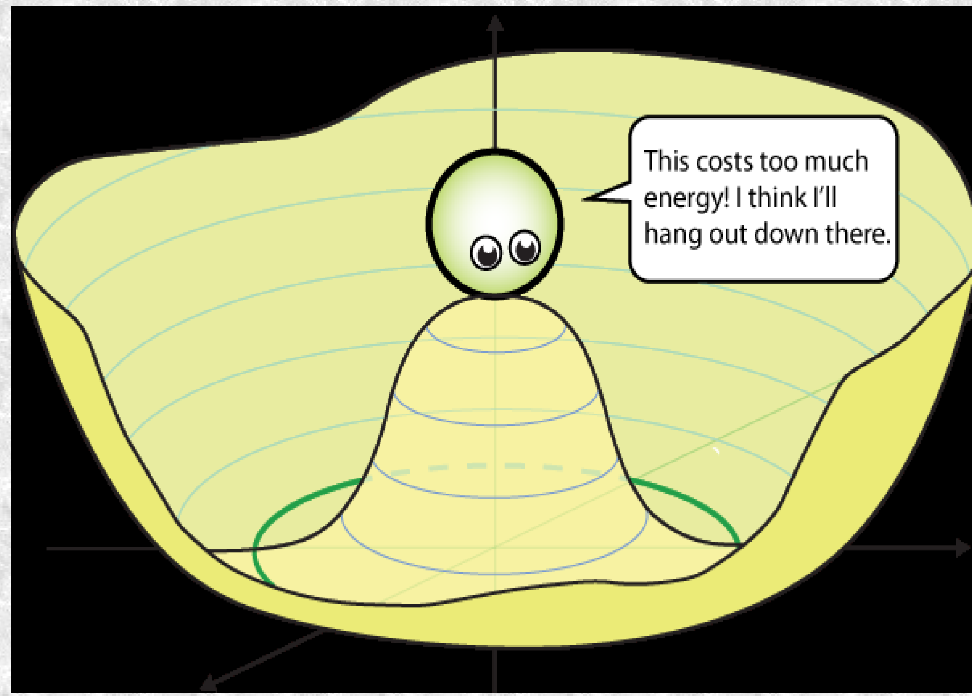
- In SM $m_H=94^{+29}_{-24}$GeV
  - So observed mass fits SM with no additions

What does 125-126 tell us?

- But up to what mass scale?
- The $|\phi|^4$ runs to lower value with energy due to top loops
  - Faster for heavier top
- If $m\overline{H}$ is small $|\phi|^4$ goes negative



$$V(\phi) = -\lambda/2|\phi|^2 + g/4!|\phi|^4$$



- 125 GeV is the divide
  - Appears to be meta-stable

What does 125-126 tell us?

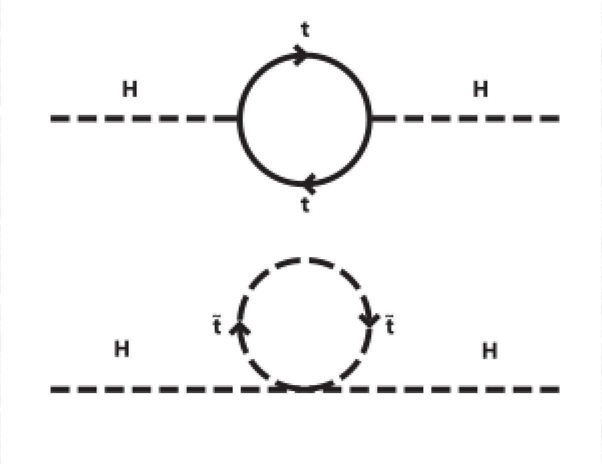
- But *why* is m_H so low?
- The Higgs potential:

$$V(\phi)=-\lambda/2|\phi|^2+g/4!|\phi|^4$$

- Suffers from loop correction like the top loop (right)
- These drive the $|\phi|^4$ mass gets quantum corrections from the highest scale in the theory

$$m_H^2=m_{H,bare}^2+(10^{16}\mathrm{GeV})^2$$

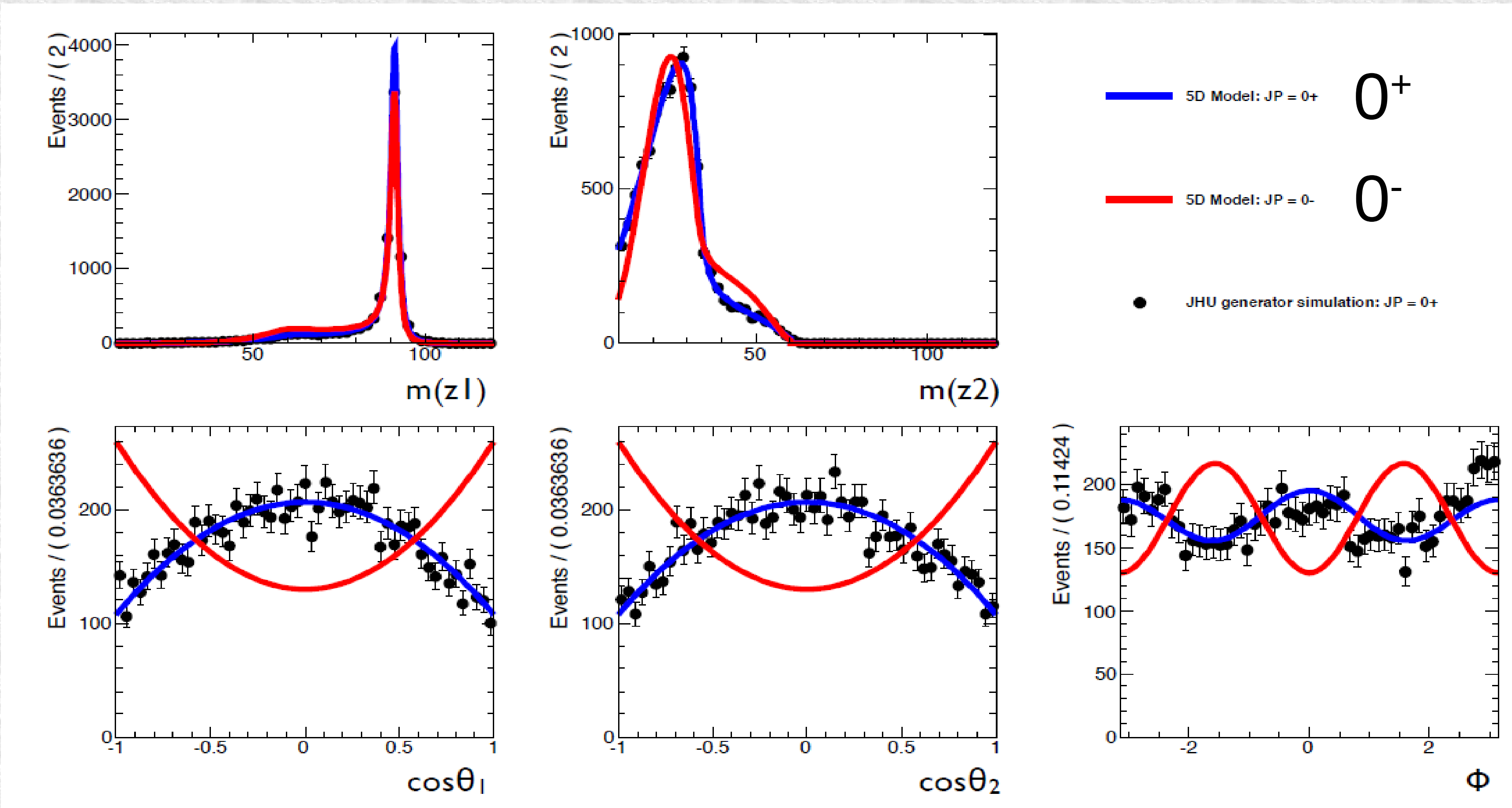
- So expect $m_H \sim 10^{16}$!
- This 'heirarchy problem' motivates supersymmetry
  - Corrections from superparticles cancel the particles and m_H is allowed (forced!) to be light
- SUSY enthusiasts happy!!



Sven will discuss allowed SUSY space

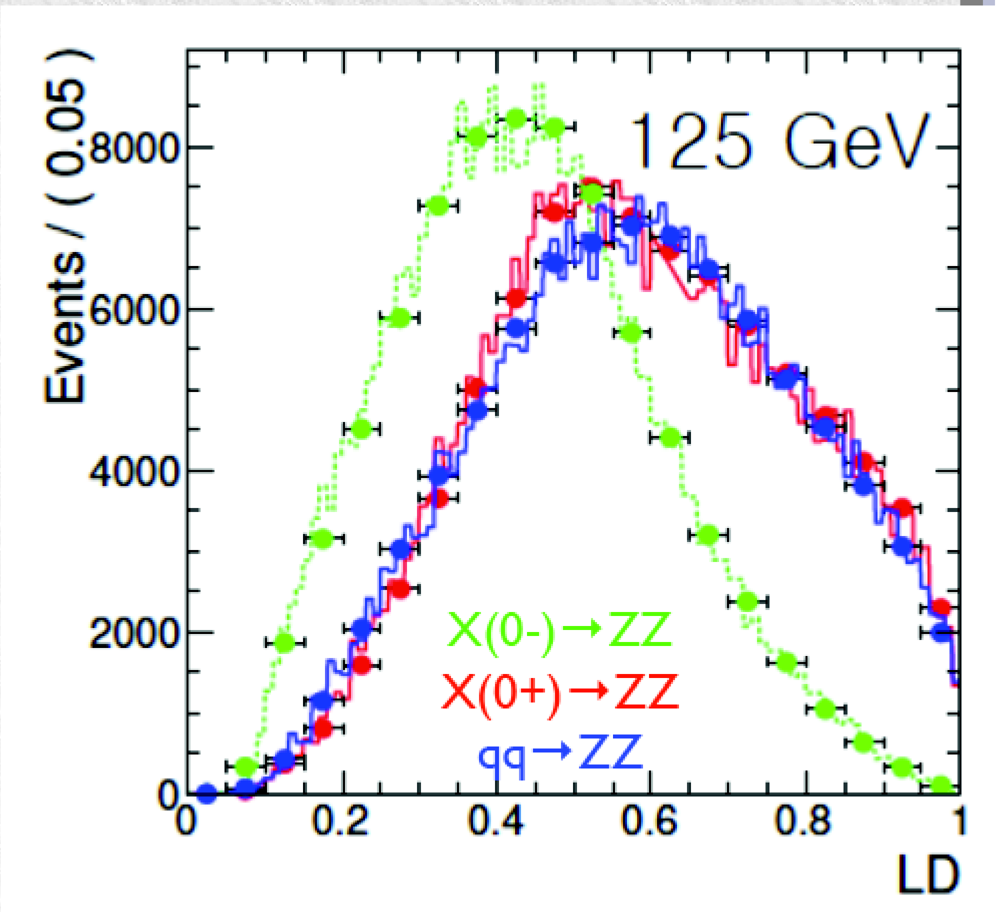
Spin and parity

- Borrowed from Yanyan Gao's talk at LPCC
  https://indico.cern.ch/getFile.py/access?contribId=51&sessionId=5&resId=0&materialId=slides&confId=173388
- Use the 'MELA' to determine properties. e.g.:



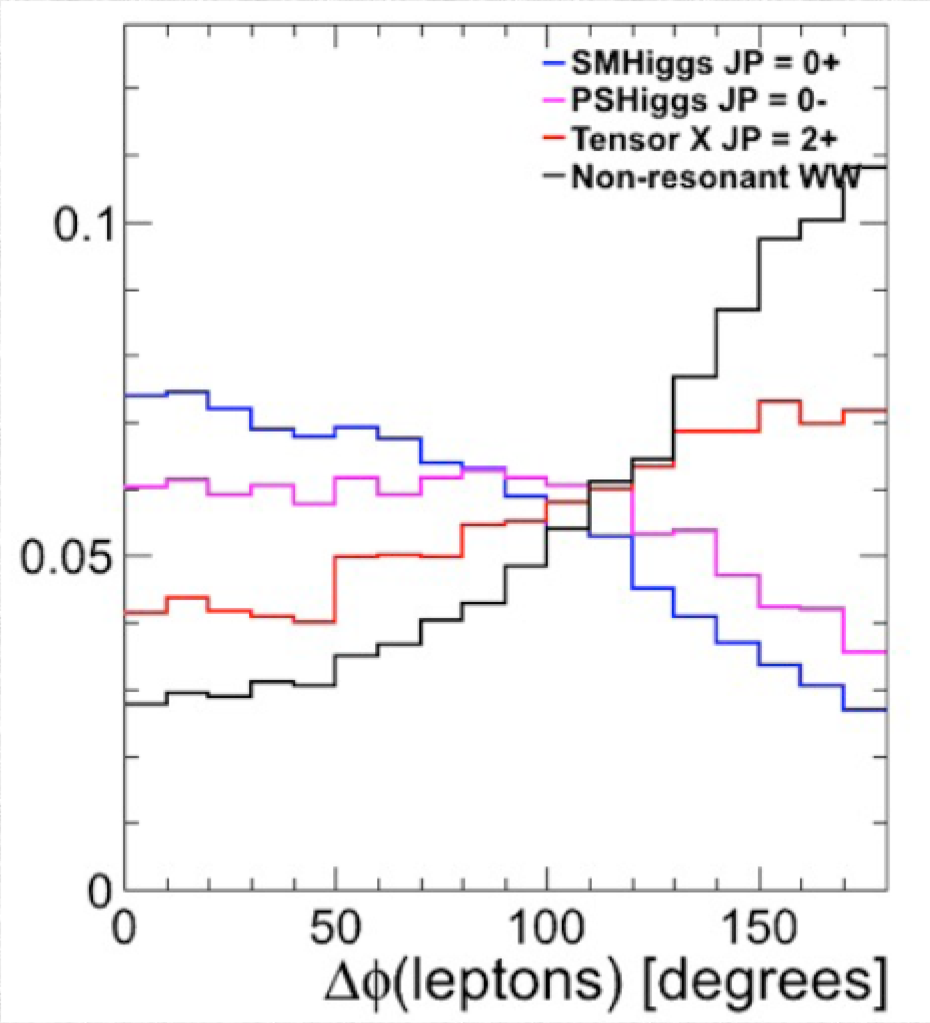
Parity likelihood discriminant

- Build likelihood to compare these
- 2sigma separation between 0^+ and 0^- expected from ZZ for $20fb^{-1}$
  - 3σ for $30fb^{-1}$ at 8TeV
  - WW also helps
- So separation looks possible
  - Combining two experiment helps?
- Note that this only applies to pure states
  - Mixed CP would project out 0+ in ZZ decay anyway...



J=0 v J=2

- WW search seems natural
  - The spin 0 lepton alignment was a major reason to look
  - But with experimental cuts it is not so clear
- MELA analysis suggests 3σ between 0^+ and 2^+ states
  - Acceptance/background not fully allowed for
  - 2^- is not as easy to reject
  - Tensor structure may not be favourable
    - Which helicities are filled?
- I think this is needing work
  - But 2012 will shed some light



So what do we know?

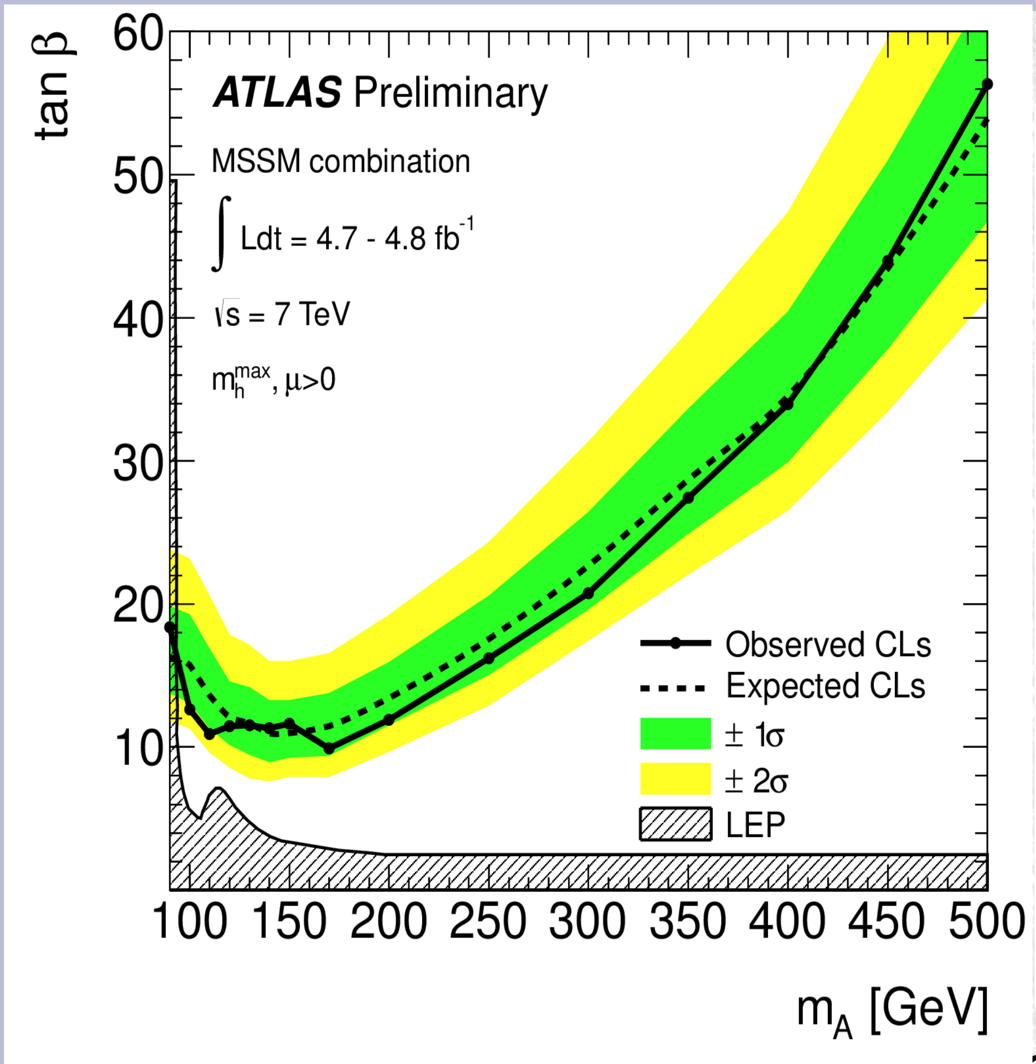
Higgs Mass	Measured – agrees with SM Higgs
Spin	Should be 0. We know it is integer, and not 1
Parity	Should be plus. Unknown
Charge	Zero, as it should be
Lifetime	Unknown, but narrow resonance and no obvious flight, OK.
Interaction with W,Z	Rates in WW,ZZ look as expected. LEP actually fixes these to ~5% already IF SM Higgs
Interaction with matter (quarks/leptons)	ATLAS information weak here CMS bb+ττ combination 2σ low. No LHC proof this exists But Tevatron has around 3σ evidence - twice expected
Interaction with gluons	WW/ZZ rates (assuming LEP) mean this as expected This actually constrains a 4^{th} generation very hard
Interaction with photons	1.6±0.4 (CMS) and 1.8±0.5 (ATLAS) This is ~2σ high

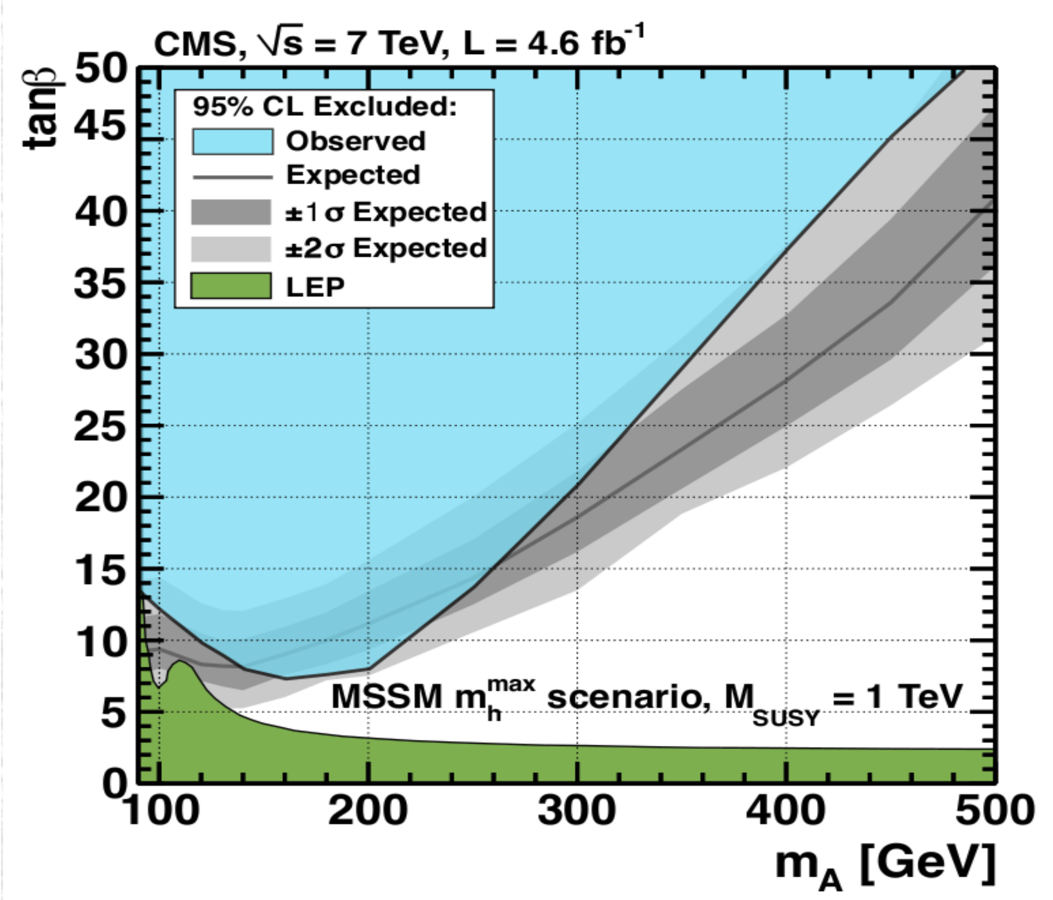
- It is consistent with the SM Higgs
  - With reasonable statistical fluctuations

SUSY Higgs

- The new boson might be h or H from 5 SUSY Higgses
  - h,H,A, H^+,H^-
- The most likely in the lightest, h
  - This is bound to be below ~130GeV in most scenarios
    - Sven will discuss this
  - The others could then be almost any higher mass
    - May or may not ever turn up at LHC
  - The relatively large mass, 126GeV suggests:
    - High SUSY mass scale
    - And/or light stop – near top mass
  - Interestingly, light stau/stop could increase $h\rightarrow\gamma\gamma$ rate
- Alternatively it could be the heaviest, H
  - That would mean the others are all around 100-150GeV
  - If so H^+/H^- at least should be found this year
- Nb: SUSY allows another neutral Higgs <120 or >130
  - No reason to let up!

MSSM Higgs

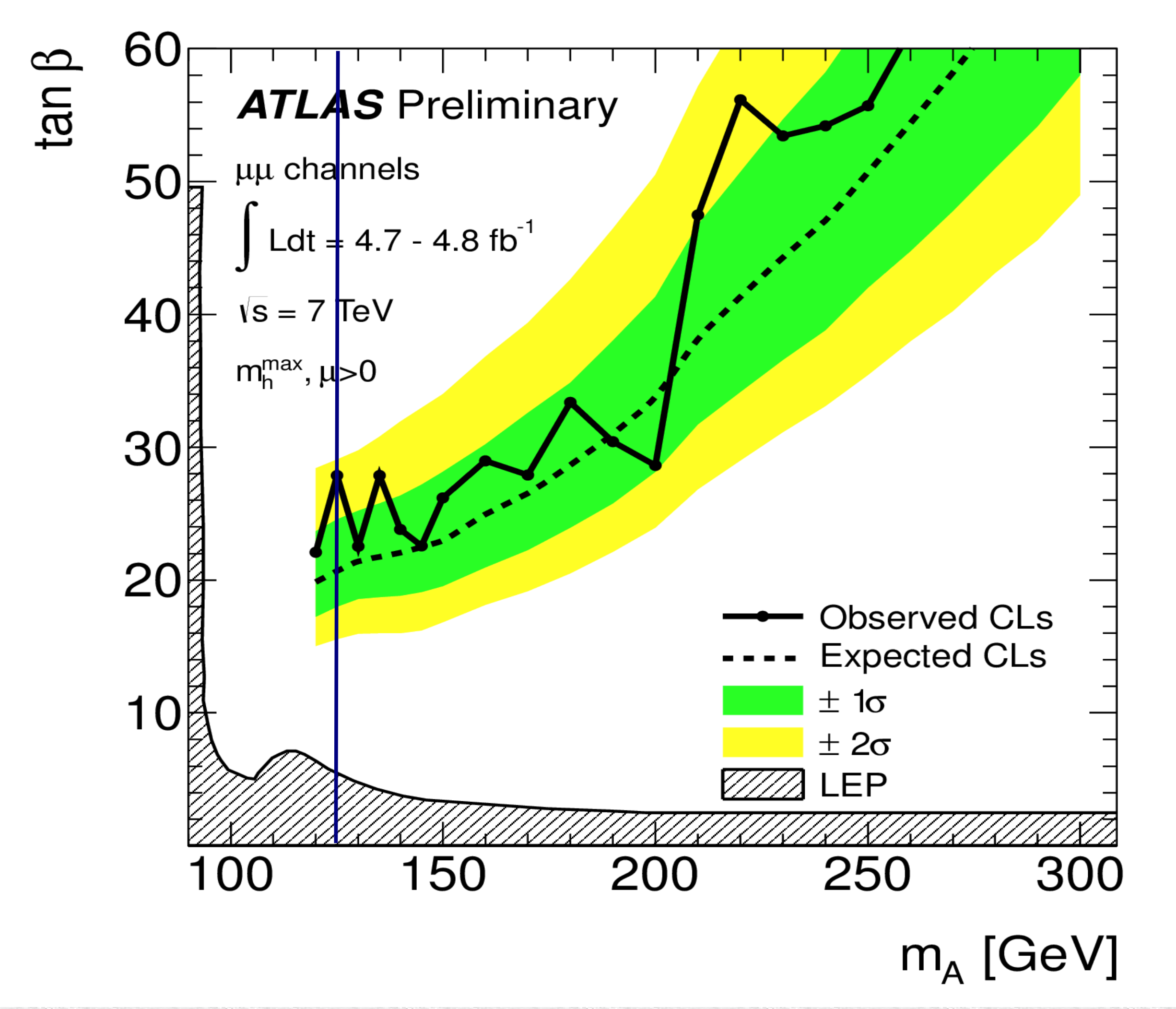




- Limits squeeze low-mass second doublet
  - ATLAS and CMS have different ideas of the LEP limit!

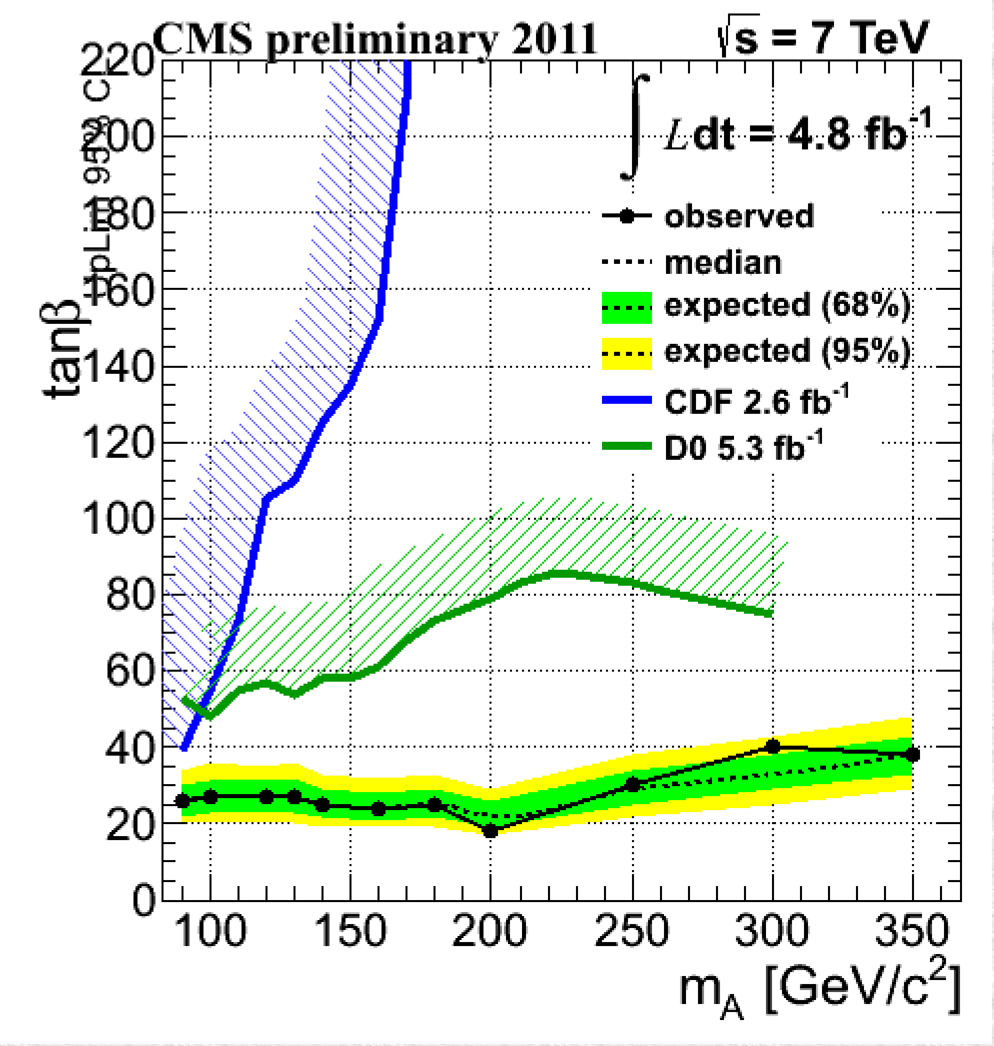
MSSM H/A → μμ

- An amusing observation:
- ATLAS search for Φ → μμ turns up a peak at 125 GeV
- Probably of no great importance – 1.5σ deviations happen **all** the time
- But we should measure H → μμ
- Plus H → ee decay too!

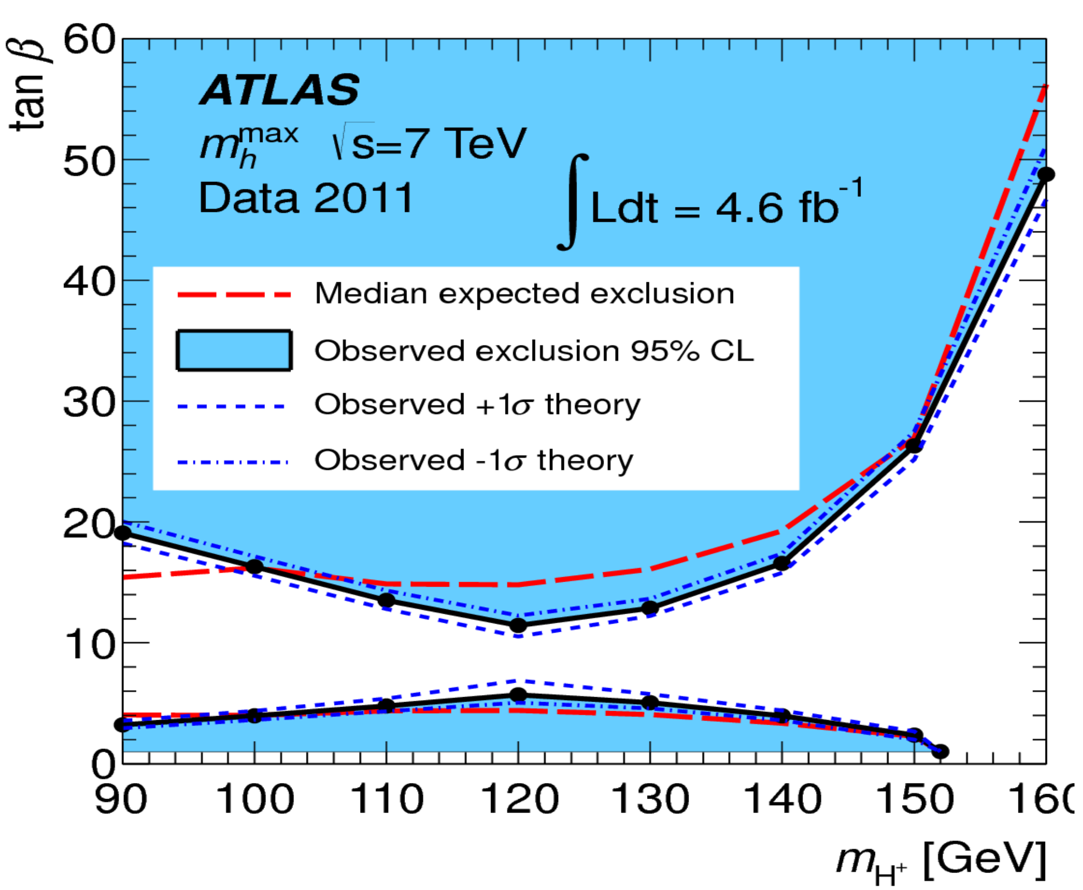


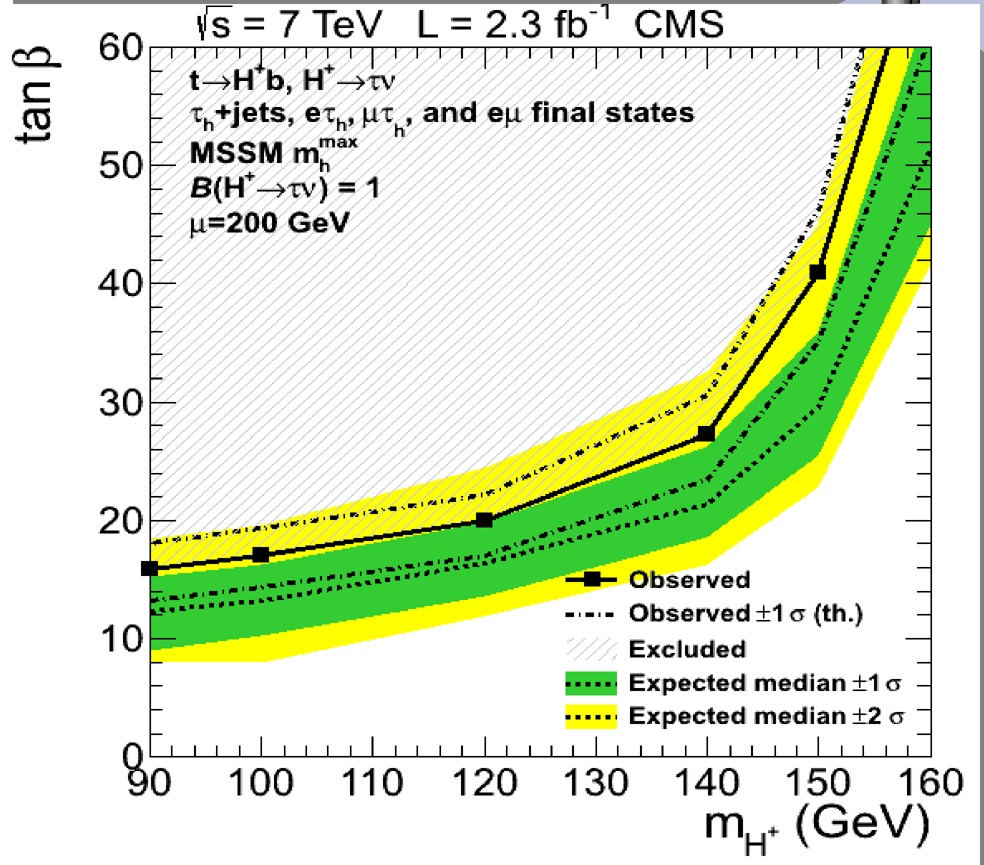
MSSM bbΦ→bbbb

- CMS only at LHC
- Two modes:
  - Leptonic trigger
  - B jet trigger
- This plot appears without full explanation
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig12027TWiki
  - I THINK it combined both searches
  - Individual results at tanβ~50-60 at 350GeV
- Powerful new constraint on MSSM
  - But in simple benchmarks ττ is more powerful



Charged Higgs at LHC





- Space for charged Higgs below m_t getting squeezed
  - Next round will aim for m_t exclusion tanβ independent
  - Probably can exclude new boson is Heavy MSSM H?

What about the Higgs field?

- A unique prediction of the Higgs mechanism is the field filling space
  - Unlike light, you turn it off and it is still there
  - More like water filling the sea
- The density of this field is ruled out by big-bang cosmology
  - It is 120 orders of magnitude larger than dark energy – and the opposite sign
- So why are we so sure it is there?

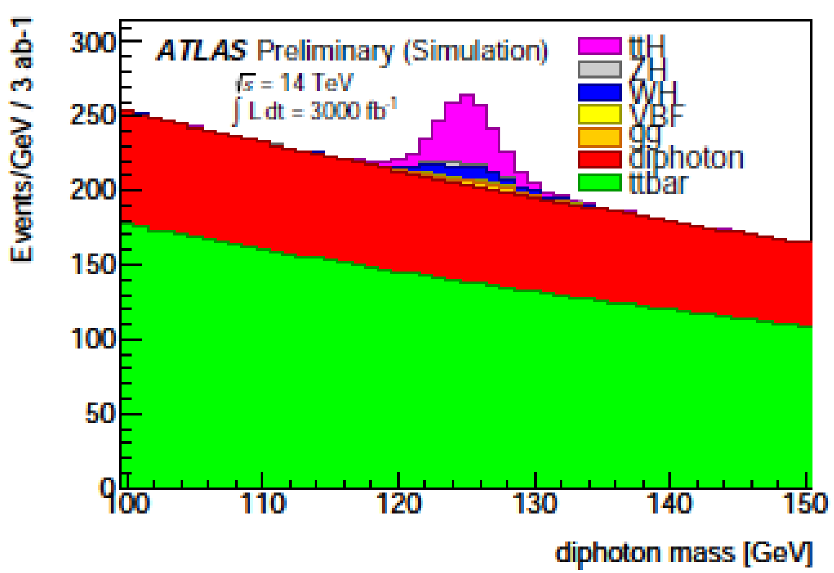
- This really means we don't have a QM theory of gravity
- But we should measure the self-coupling of the Higgs
  - Events with two Higgses at once at SLHC might do that
  - $bb\gamma\gamma$ studied in ATLAS Krakow input – $3ab^{-1}$ might get there
  - $bb\tau\tau$ also suggested http://arxiv.org/abs/1206.5001

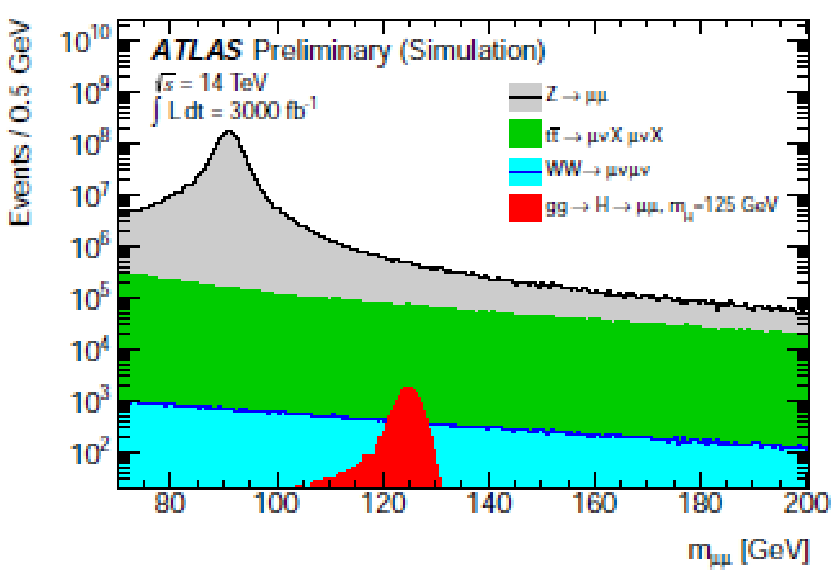
Next Steps for Higgs studies

- Proton Colliders
  - LHC runs to 2021 for 300fb^{-1} at 14TeV delivered
  - SLHC calls for 3000fb^{-1} LHC running to 2030
    - Natural extension of LHC, 30% rise in √s sensitivity
  - DLHC – 33TeV proton beam with 20T magnets in the LHC tunnel (or even stronger)
  - VLHC – a larger proton ring up to 200 km is considered
- Electron colliders
  - ILC – 250-500GeV, up to 1TeV later, linear collider
  - CLIC – 3000GeV linear collider
  - LEP-3 – 240GeV e^+e^- ring in LHC tunnel
  - Several proposals for 60-100km ring ee machines
- Muon collider?
  - νSTORM at Fermilab is muon storage ring for neutrino physics
  - It would develop some technologies useful to a muon collider

SLHC and ATLAS

- LHC runs to 2022
- 300fb^{-1} at 14TeV expected
  - SLHC is proposed thereafter - 3000fb^{-1}
- ttH,H→γγ and H→μμ are two interesting studies





- But in general Higgs couplings must gain from factor 10 more data!

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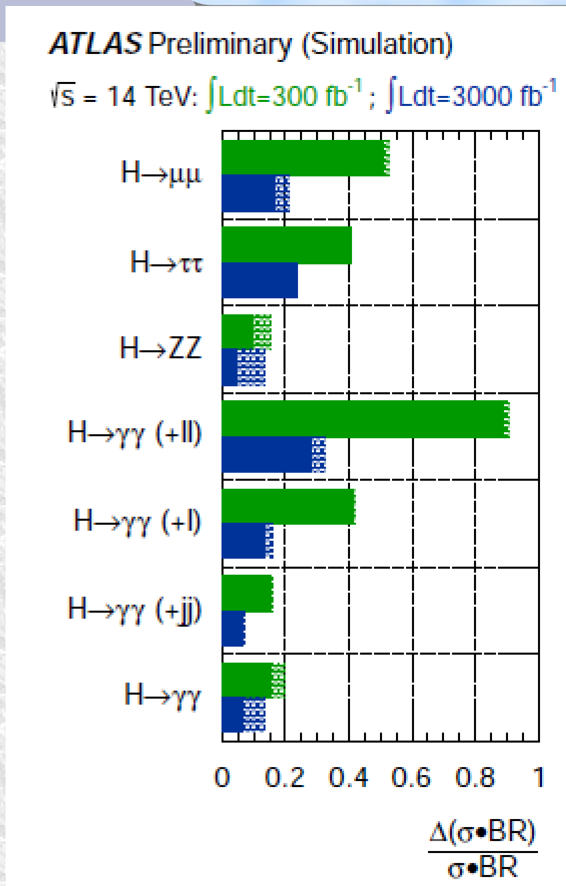
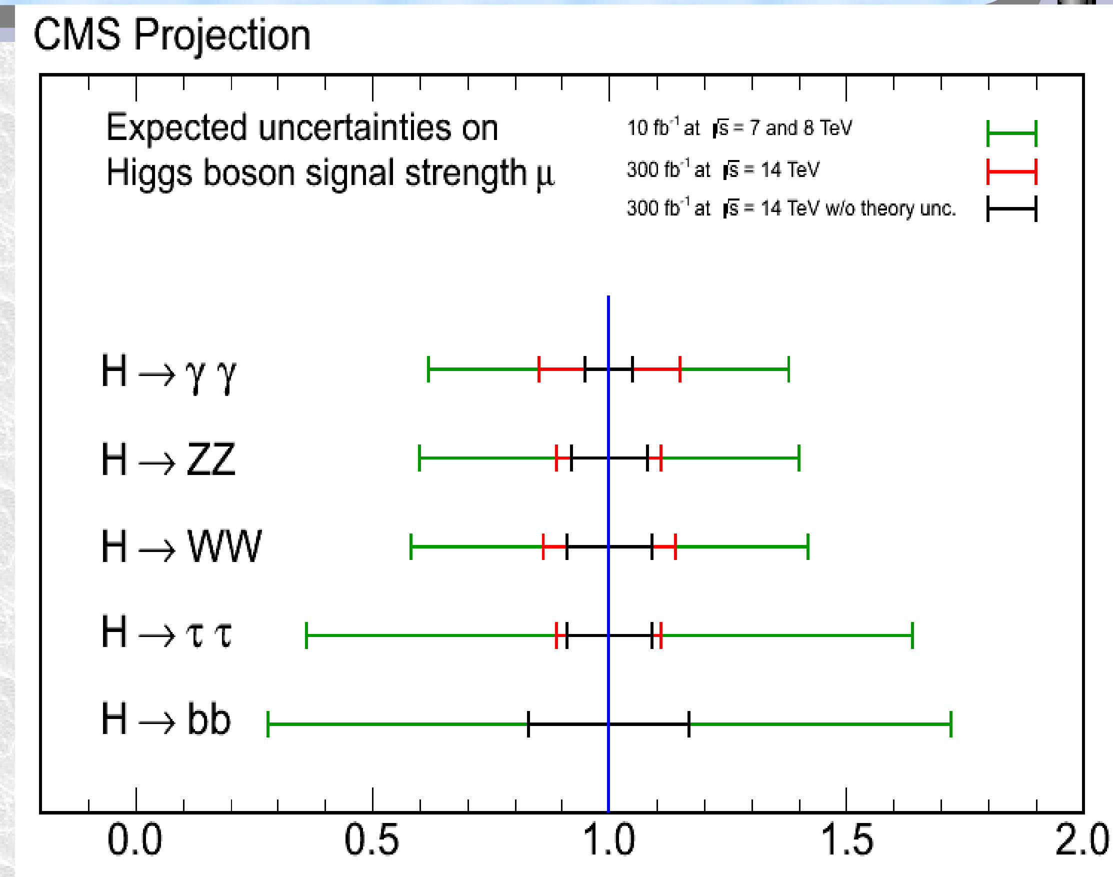
Krakow: signal rate errors





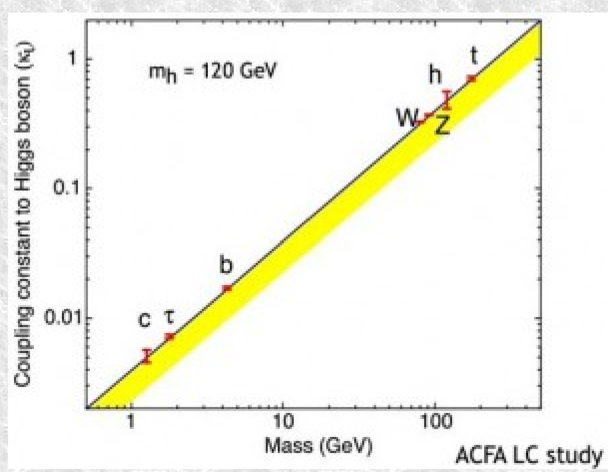
- Interesting to compare ATLAS and CMS expectations
  - Pretty close for ZZ and γγ
  - Factor 3 apart for ττ at $300 fb^{-1}$
- We need to understand this!

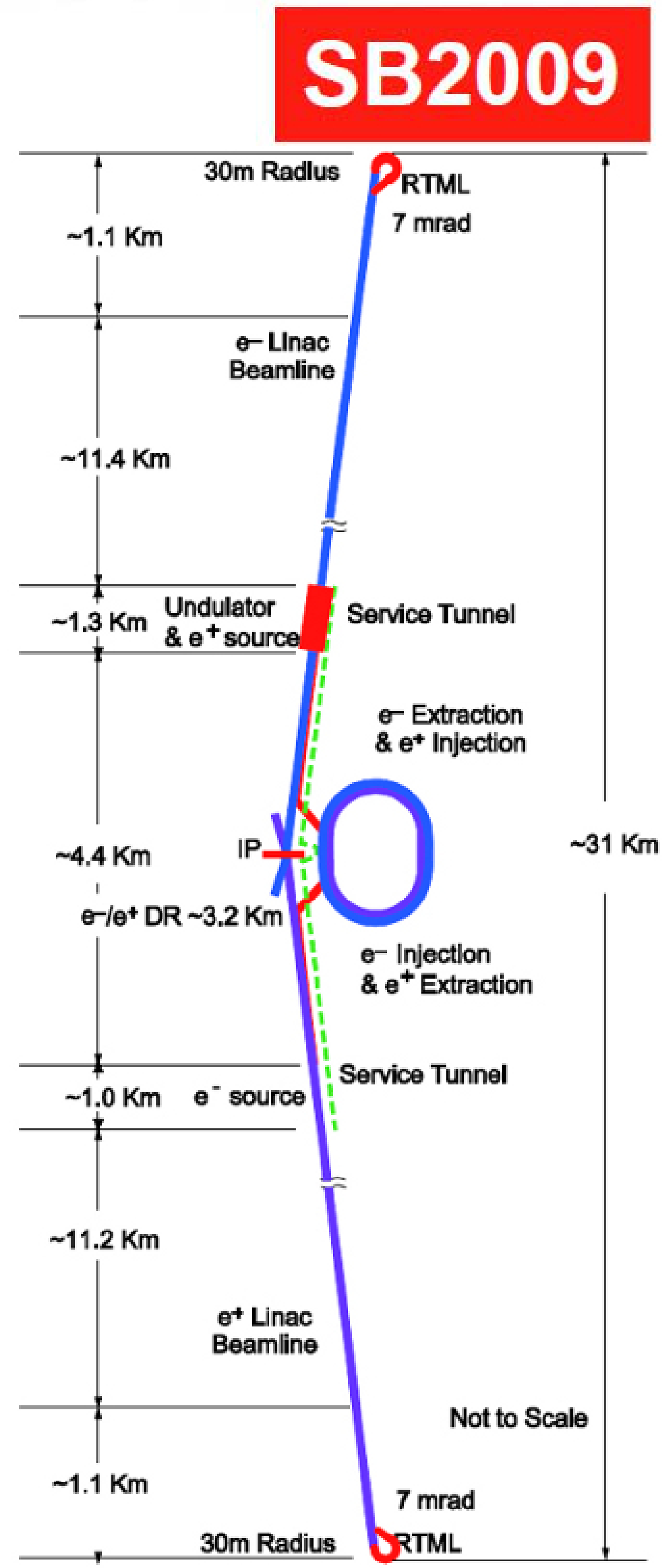
SLHC as Higgs factory

- Increasing luminosity, factor 10, to $10^{35}cm^{-2}s^{-1}$
  - New proton linac & focus elements needed
  - Pileup increases by similar factor, 300 events/BX?
  - New trackers, calorimetry readout, TDAQ needed to cope
- Beams are rapidly 'burnt-off'
  - It may be helpful to limit luminosity early on
  - Extends beam lifetime, limits pileup
- Going from $300fb^{-1}$ to $3000fb^{-1}$ at 14 TeV
  - $H\rightarrow ZZ$ go from 300 to 3000
  - Improved measurements clear in ZZ, γγ,
    - $H\rightarrow\mu\mu$ and Zγ can be measured
  - WW, bb, ττ will be improved – but systematics hard to know
  - Self-coupling in HH $\rightarrow$bbγγ and bbττ looks just possible
    - Again, estimates of systematics difficult

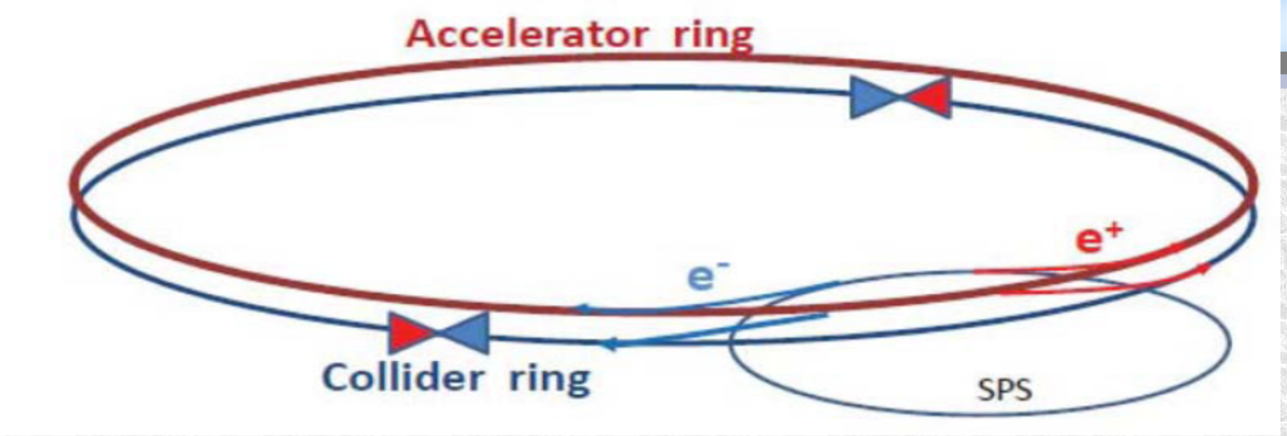
ILC

- Well known proposal for high-energy linear ee collider.
  - Much cleaner collisions than LHC
  - But cost/GeV of RF cavities in high
  - Power bill tends to be large too
- Can make Higgs bosons
  - 10,000 ZH/year
- Sensitive to all, including invisible
  - LHC can never be sure of total rate
- Accurate measure:
  - c, τ, b, W, Z, t
  - hh coupling too
    - Just
- Sensitive to light SUSY





LEP-3?



- LEP3 is an e^+e^- storage ring, maybe in the LHC tunnel
  - $\sqrt{s}$=240GeV
  - 4 bunch mode gives $10^{34}cm^{2}s^{-1}$.
  - Dual-ring allows 'top-up mode' to maintain average luminosity.
  - $100fb^{-1}$ per year
  - 20,000 ZH events per year/experiment
  - 50MW/beam synchrotron loss
- Physics programme:
  - 1 'year' at 91GeV – 10^{11} Z^0
  - 1 'year' at 160 GeV – sub -MeV statistical precision on m_W
  - 5 'years' at 240 GeV – 100,000 HZ/experiment

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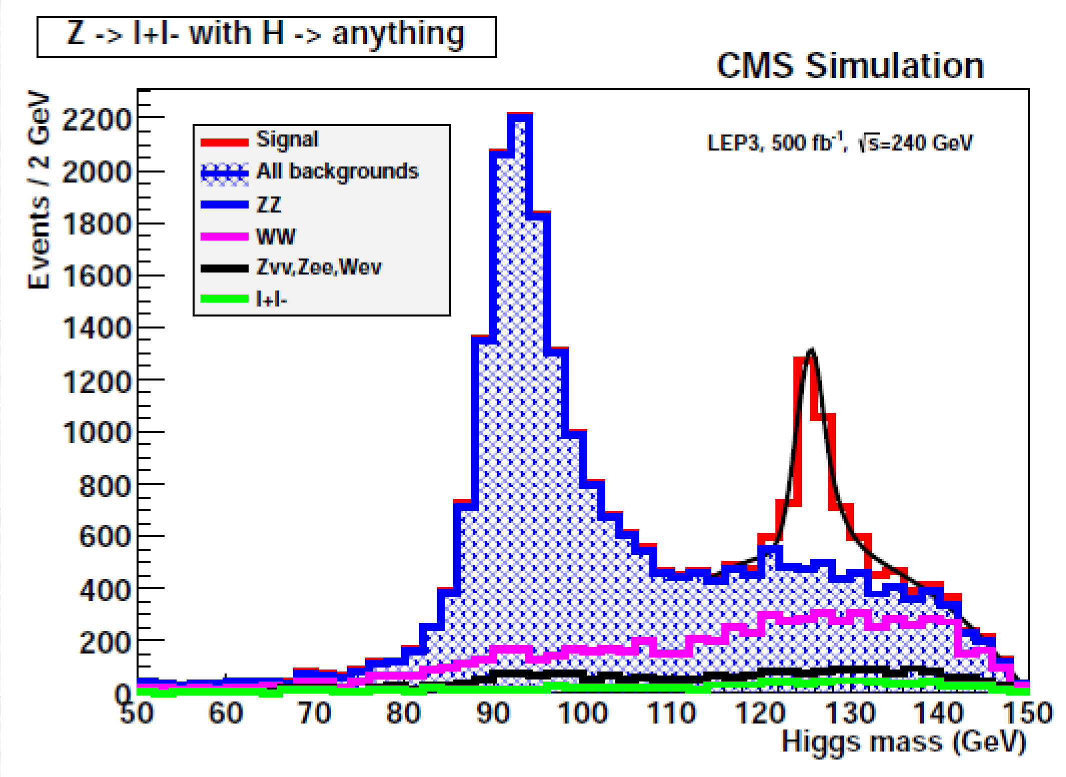
Higgs studies potential

	ILC	LEP3 (2)	LEP3 (4)	LHC
σ_{HZ}	3%	2.7%	1.9%	–
$\sigma_{HZ} \times BR(H \to b\bar{b})$	1%	1.2%	0.8%	–
$\sigma_{HZ} \times BR(H \to \tau^+\tau^-)$	6%	3.1%	2.2%	–
$\sigma_{HZ} \times BR(H \to \text{invisible})$	?	1%	0.7%	–
g_{HZZ}	1.5%	1.3%	1%	13%
g_{Hbb}	1.6%	1.5%	1%	21%
$g_{H\tau\tau}$	3%	2.0%	1.5%	13%
g_{Hcc}	4%	?	?	?
g_{HWW}	4%	?	?	11%

- The electron machine beats LHC for Higgs coupling
  - But ttH is not doable at LEP-3
  - Higgs self-coupling is tough anywhere – but impossible LEP-3

LEP 3 dream

- The ideal schedule from LEP-3 side is to run in 2022
  - LHC has delivered 300fb^{-1}
  - ATLAS and CMS might be available
  - CMS simulations indicate it can do the physics:
  - $Z\rightarrow ll$, $H\rightarrow X$ shown



- The problem is: SLHC would be cancelled!
  - This is a difficult choice
- One which I believe deserves to be studied
- Maybe postponing to after SLHC or building a new tunnel is better

Summary

- After 48 years we have found something remarkably like the SM Higgs boson:
  - 'A Higgs boson'; Rolf Heuer
- We need to establish what we have and what clues it has about the next level of understanding
  - We will know more by Christmas for sure
- The detectors ATLAS+CMS perform superbly
- In 2012 LHC is working remarkably well
  – 13fb^{-1} delivered in 2012 so far
  – By 2021, 300fb^{-1} at 14TeV will allow first precise studies
- We need to consider now the next steps

Is the model complete?

- The Standard Model is not the whole story:
  - It does not include gravity
  - It has no explanation for dark matter – 90% of the matter in the Universe
  - Dark Energy is a mystery...
  - The matter-antimatter asymmetry is not understood
  - We would like to understand WHY
    - Why 3 copies of the electron?
    - Why are the masses 'just so'
- So we search for 'Physics Beyond the Standard Model'
  - We know it is there
  - We just don't know were to look

LHC-HCG

- Group set up to combine ATLAS+CMS Higgs
  - Double data set – more science possible
- Combination of LP (August 2011) data was made
  - But not repeated
- Machinery is oiled
  - Common (theory) assumptions/systematics
  - Definitions and procedures for interpretation
  - Software (roostats) for handling mathematics &data
- Will be used when required
  - But it needs revision for properties measurement - ongoing

LHC-HCG

- Group set up to combine ATLAS+CMS Higgs
  - Double data set – more science possible
- Combination of EPS (July) data was made
  - But by LP (August) it was unhelpful
  - Individual experiments had big increases in data
  - Results did not confirm excess seen in July
- Machinery is oiled
  - Common (theory) assumptions/systematics
  - Definitions and procedures for interpretation
  - Software (roostats) for handling mathematics &data
- Ready to be used when required

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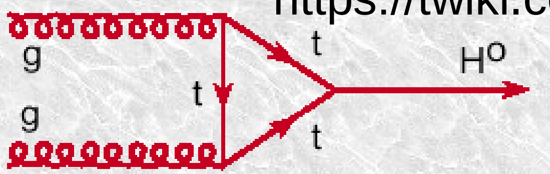
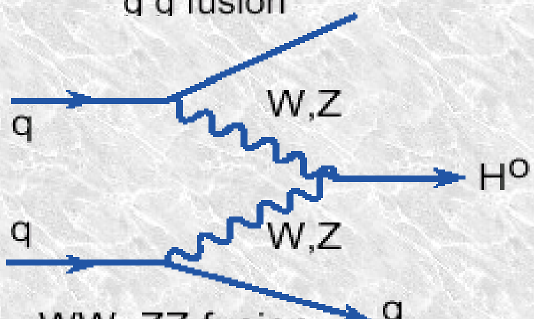
Higgs production

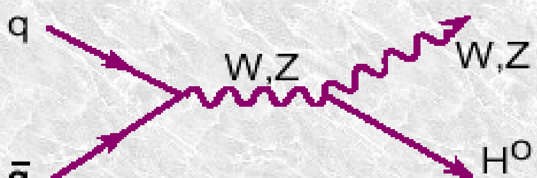
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections



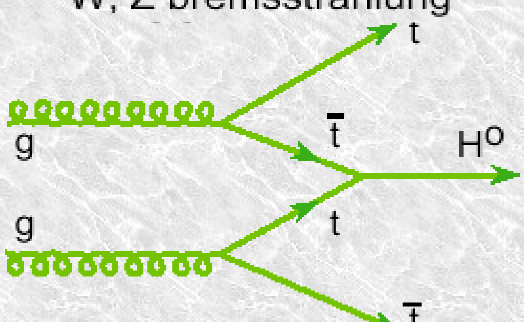
g g fusion



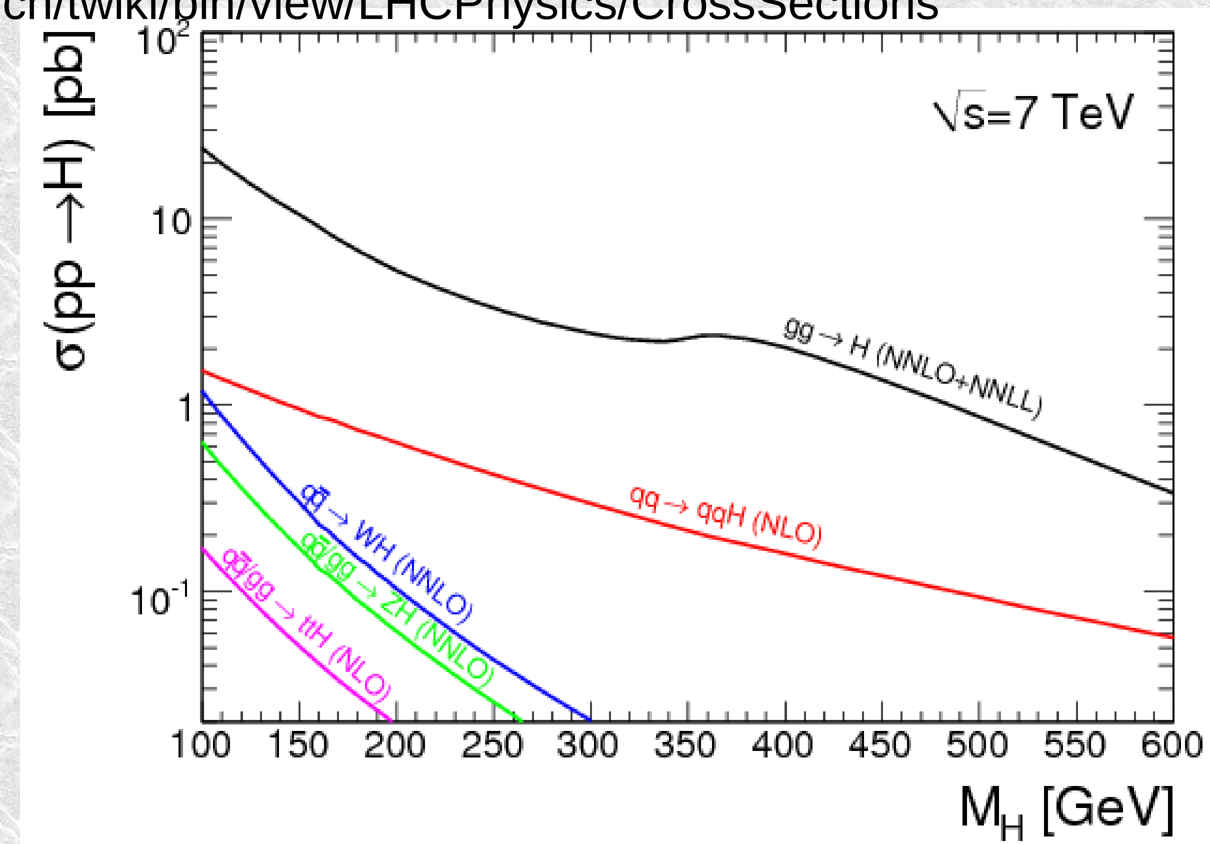
WW, ZZ fusion



W, Z bremsstrahlung



t t̄ fusion



- Gluon fusion has the highest rate
- Others give extra 'tags'
  - which make the event more distinct

Coupling estimates