LHC Higgs

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LIP
9th September 2011

- What is LHC sensitive to?
- Are there any hints?

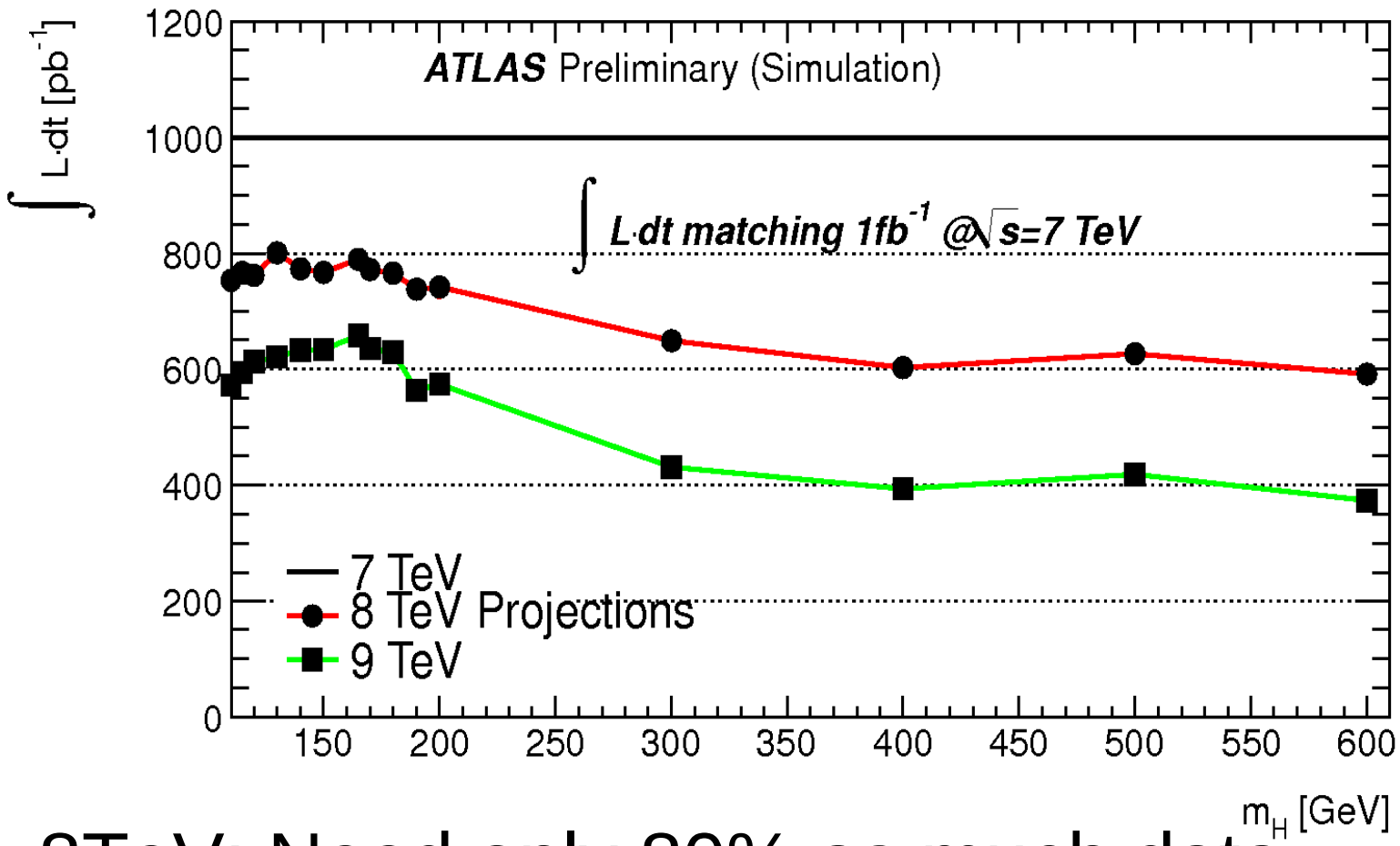
LHC runs, past and future

- The planning model of the years ahead:

Year	Energy TeV	Luminosity	Luminosity, fb^{-1}	
			Per year	Total
2010	7	Up to 10^{32}	0.1	0.1
2011	7	$<5x10^{33}$	5	5
2012	8	$5x10^{33}$	10	15
2013	0	0	0	15
2014	0	0	0	15
2015	13	10^{34}	10	25
2016	13	10^{34}	20	45

- 2.5fb^{-1} delivered so far; results up to 2.3fb^{-1}
- New β* may allow $5x10^{32}cm^{-2}s^{-1}$ this month?

Higgs sensitivity v E_{CMS}



- 8TeV: Need only 80% as much data
  - Less for a high mass Higgs boson
- 9TeV 60% of data suffices

Outline

- Extended Higgs models
  - Minimal SUSY Higgs
    - 5 Higgs bosons to look for...
    - $H^+ \rightarrow \tau\upsilon$
    - $H^+ \rightarrow cs$
    - $A/H \rightarrow \tau\tau$
  - Fermiophobic
  - 4^{th} Generaton models
- Standard Model searches
  - Low mass (110-130 GeV)
  - Moderate mass (130-200 GeV)
  - High mass (200Gev+)
  - Combination

MSSM: Multiple Higgses

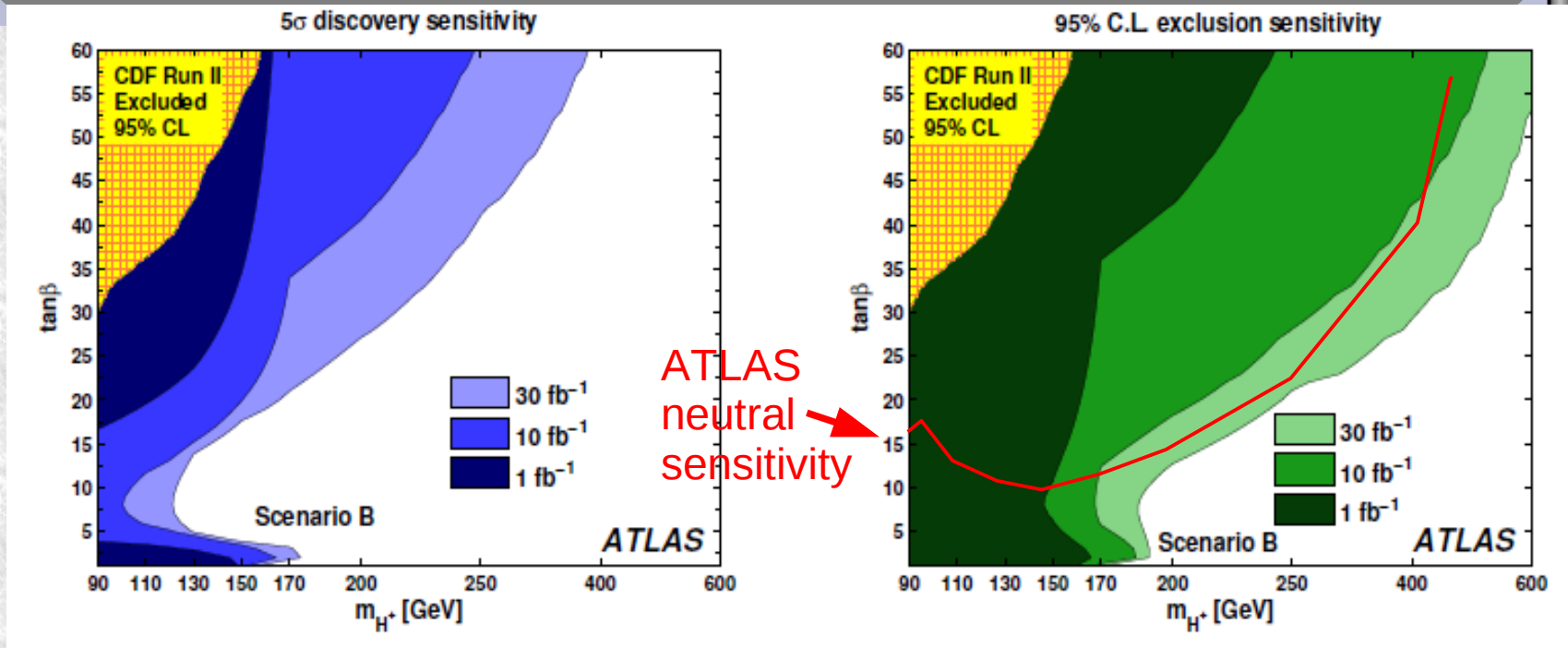
Peter visiting LHC, CMS and ATLAS

Charged Higgs bosons

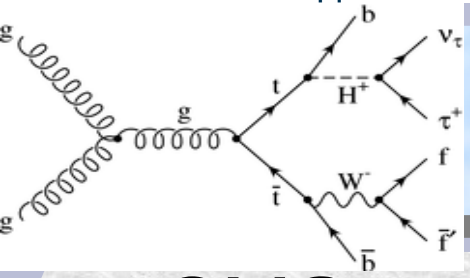
- Attention mostly on
  - $m_{H+} < m_{top}$
  - $H^+ \rightarrow \tau\upsilon$
- The first allows a large production rate via top decay
- The second is expected in high tan-β SUSY

- Both of these should be relaxed
  - ATLAS has studied $H^+ \rightarrow c\bar{s}$ – but only with $35pb^{-1}$

H^+ (at 14TeV)

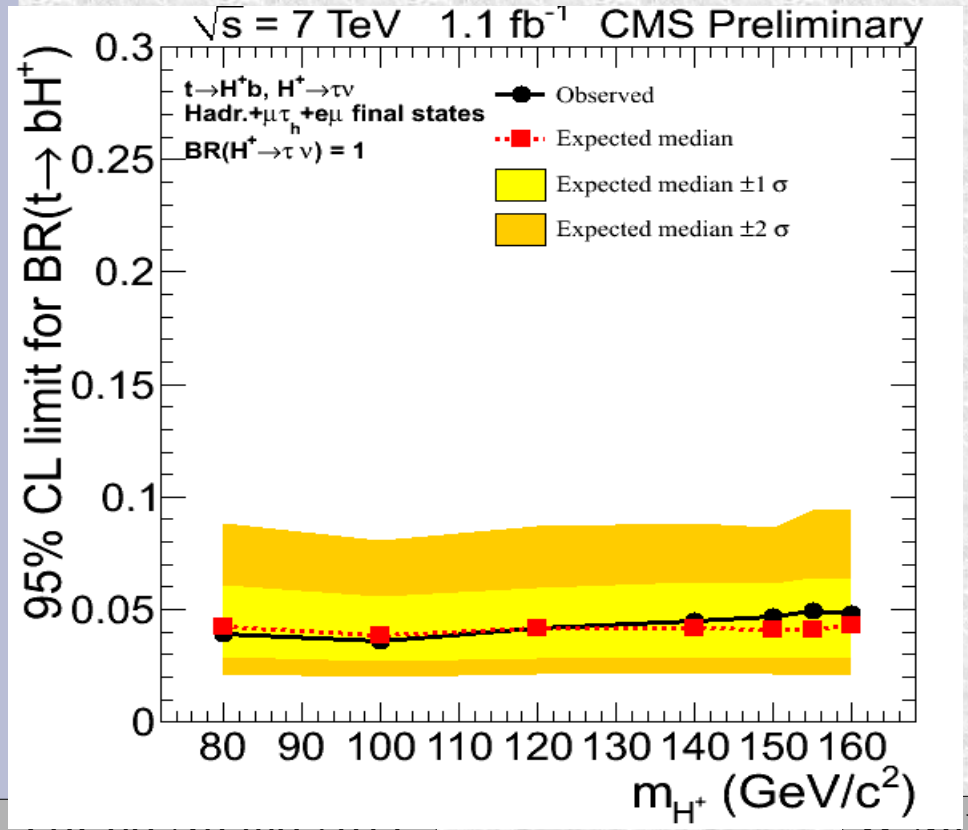


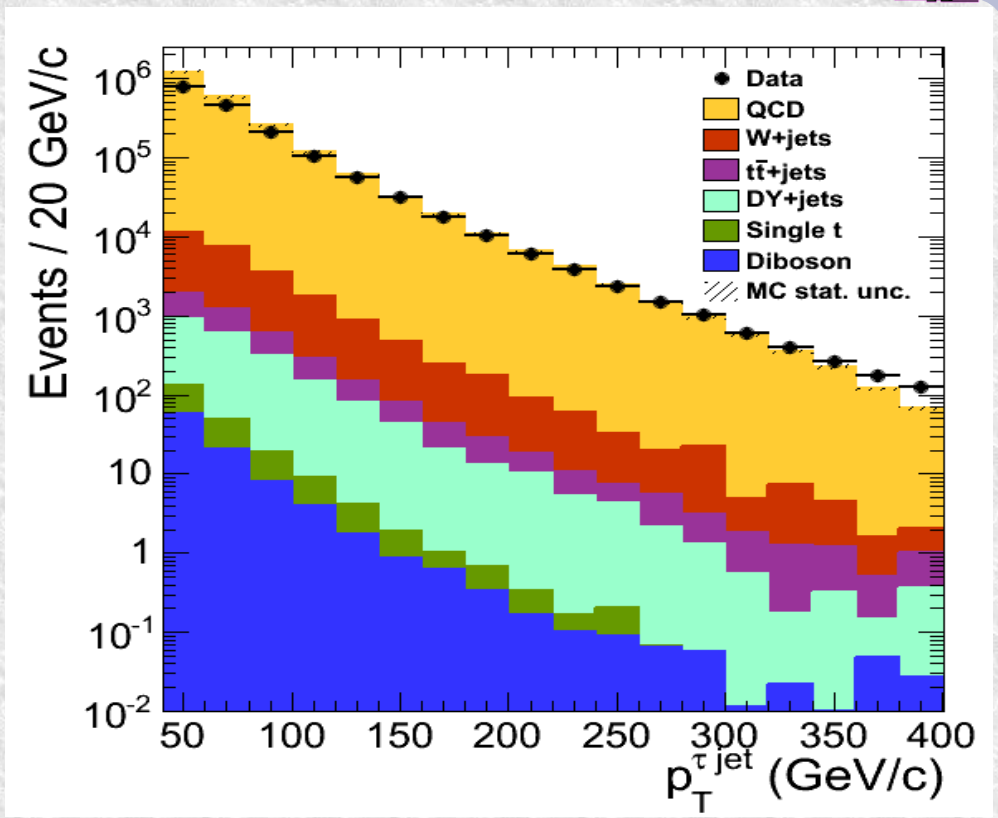
- ATLAS study @ 14TeV
  - Good for $m_H < m_{top}$
  - Lags behind H/A →ττ *in MSSM* for $m_H > m_{top}$
    - Pair production is suppressed by mass?
    - ATLAS sensitivity from $1fb^{-1}$ to H/A is added
  - But experimentally charged Higgs very conclusive



Charged Higgs to τν

- CMS search for top to H^+b, H^+ to τν for $1fb^{-1}$
- Background is mostly $t \rightarrow W+b$



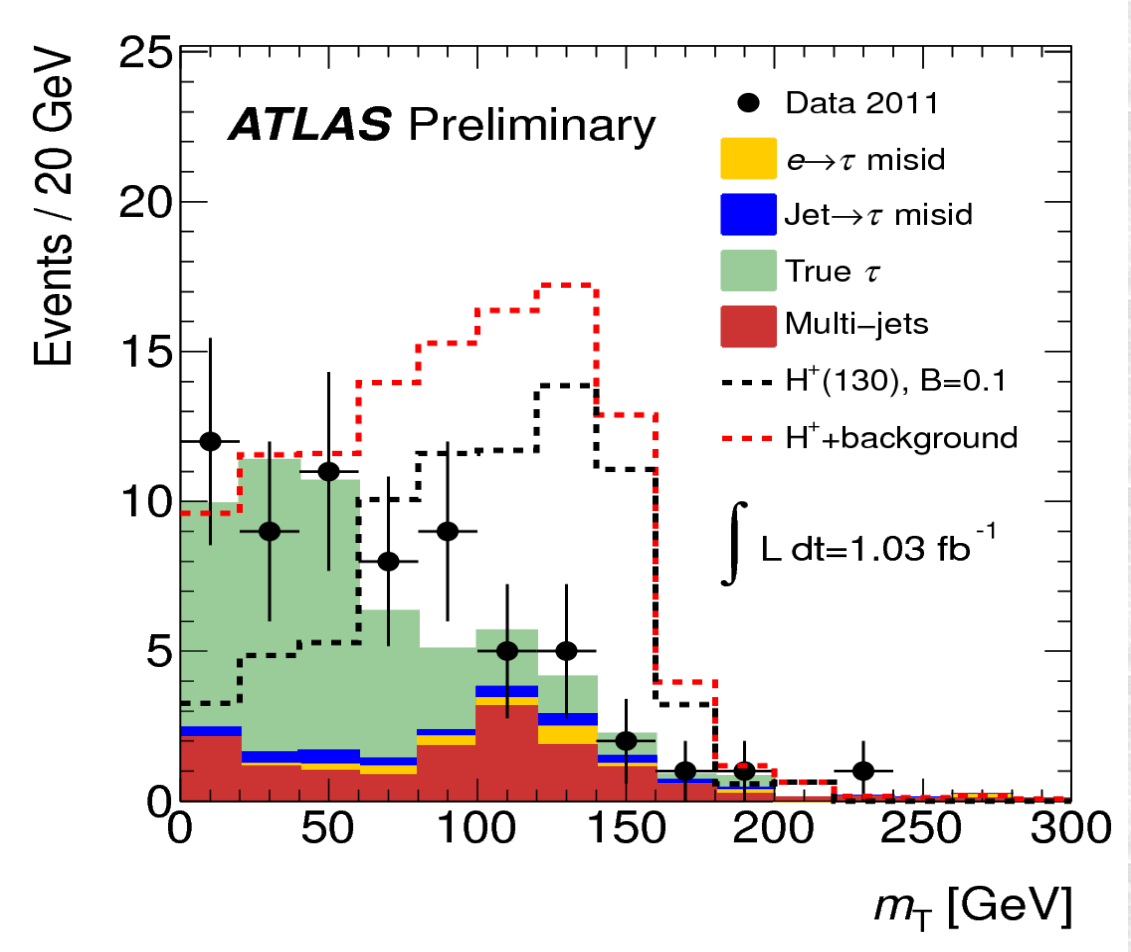


- No evidence so far
- Limits BR(t-H+b) ~4%
  - Far surpassing previous results

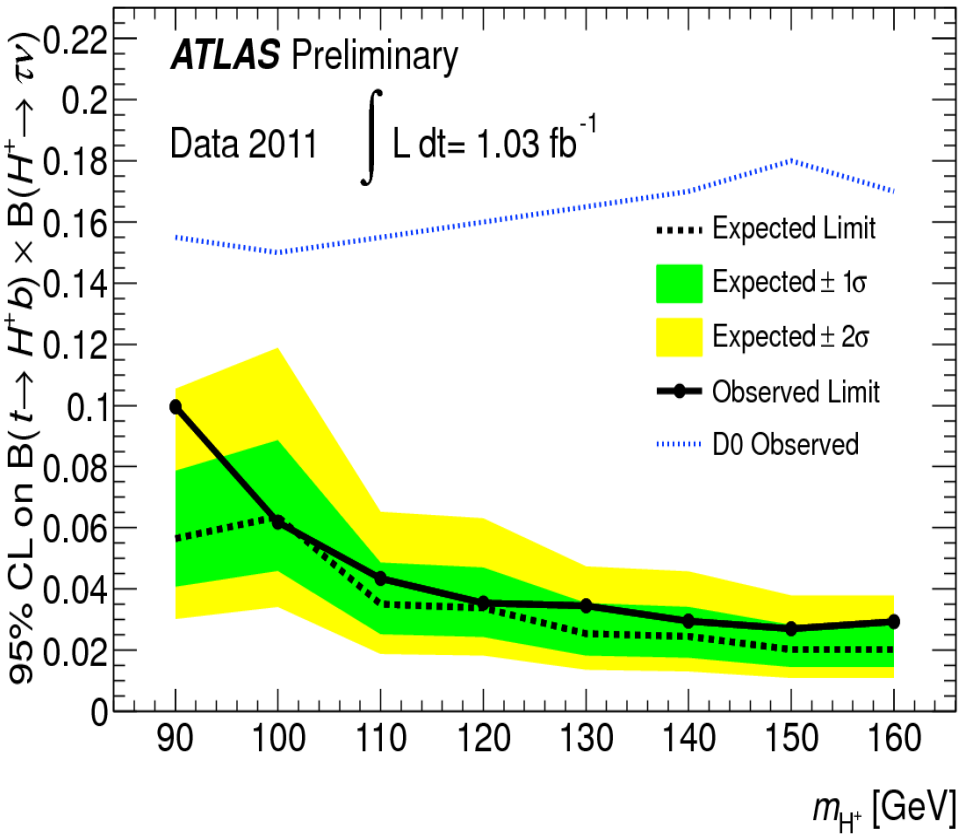
Just out: More H+, ATLAS

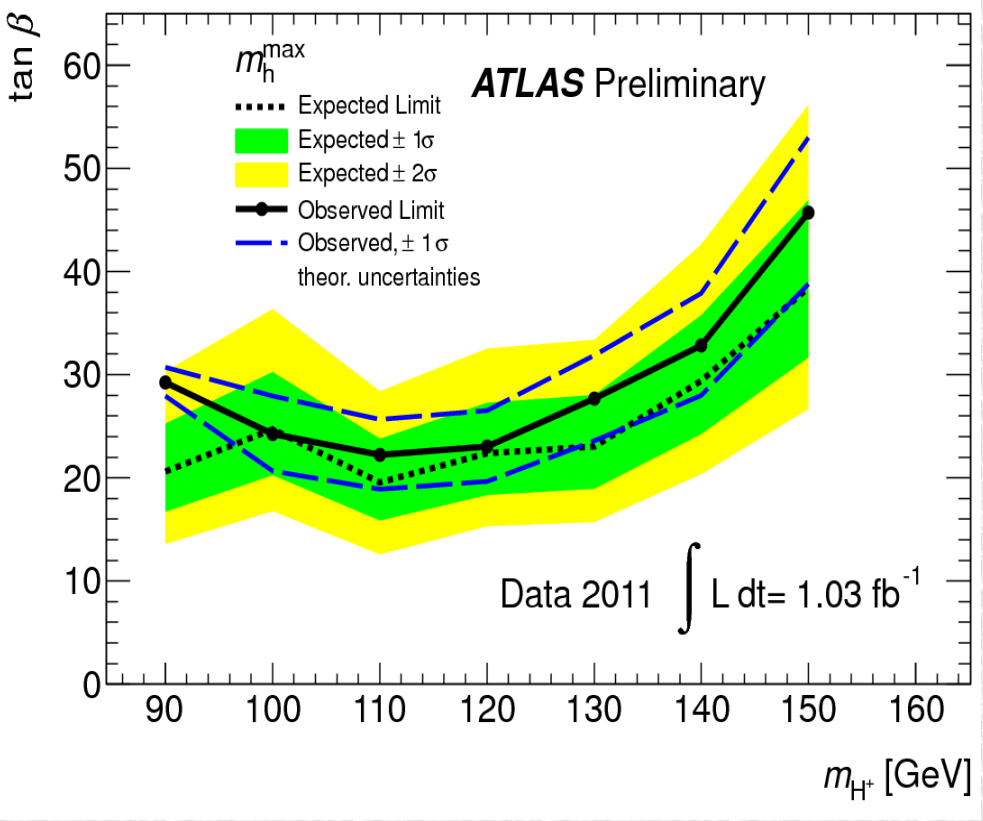
Https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-138/

- H+ is fully hadronic mode
  - Only 1 neutrino
  - Find m_T distribution
- QCD from data
  - Normalised by fit to MET
- τ distributions from embedding method
  - Normalised m_T<40
- Fit m_T>40 for signal



H+ limits

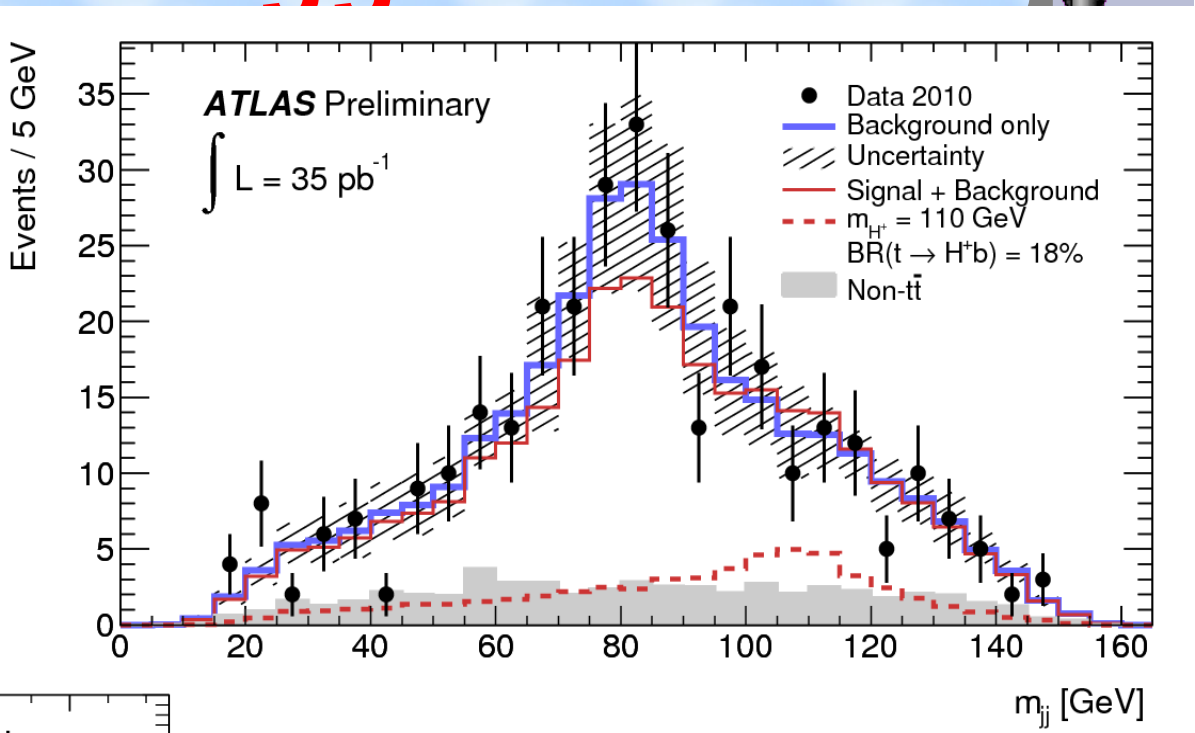


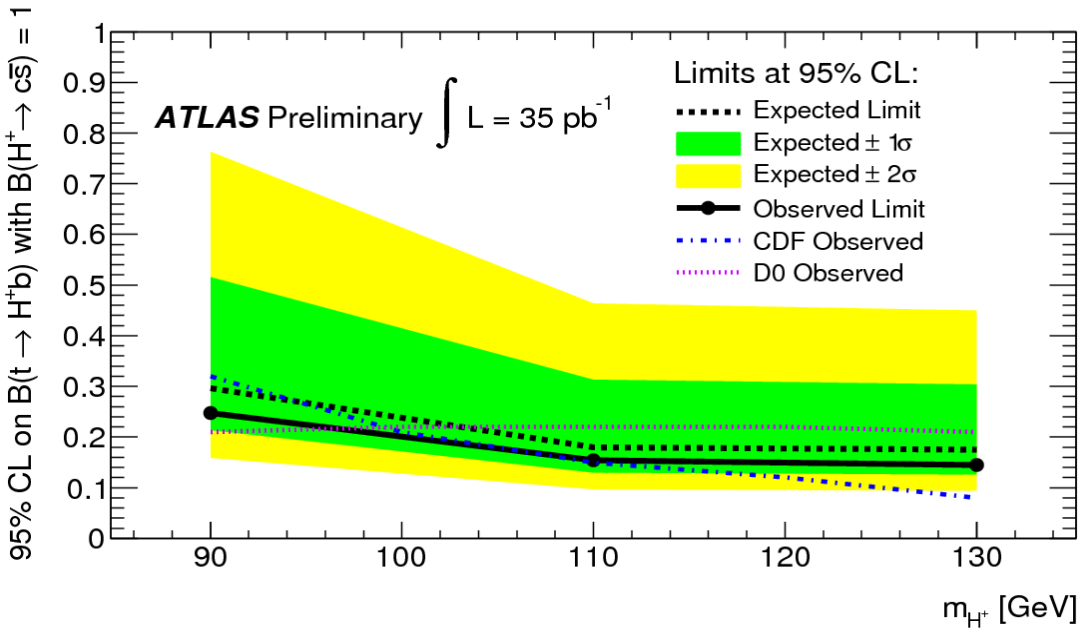


- Most sensitive result for $m_{H+} > 120GeV$
  - Further progress will benefit form similar techniques

Charged Higgs to $c\bar{s}$

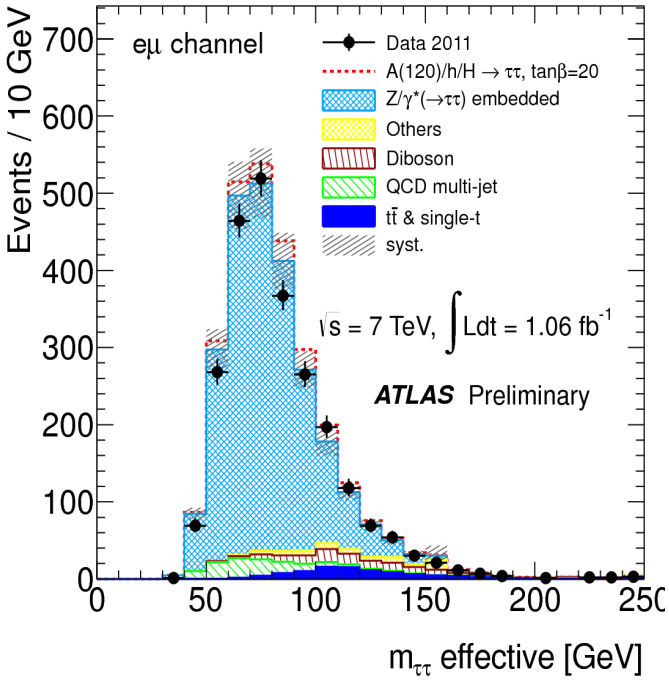
- ATLAS searched for top to H^+b, H^+ to quarks
- Background is mostly $t \rightarrow W+b$

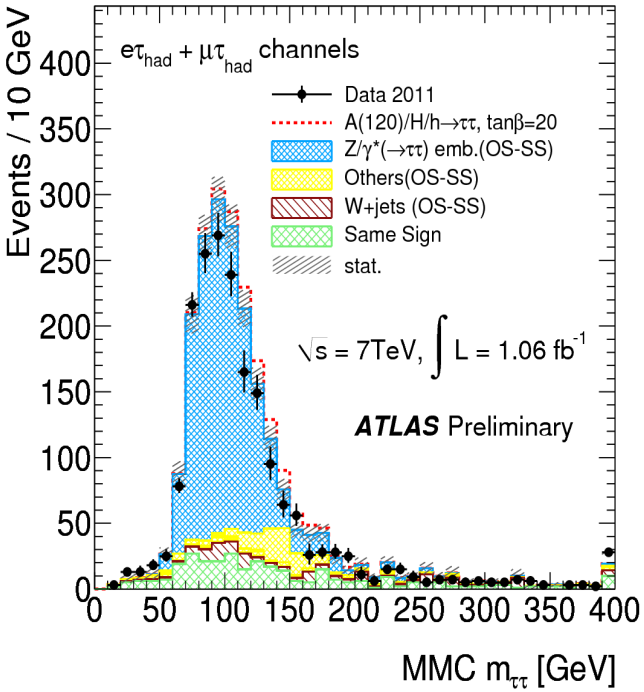


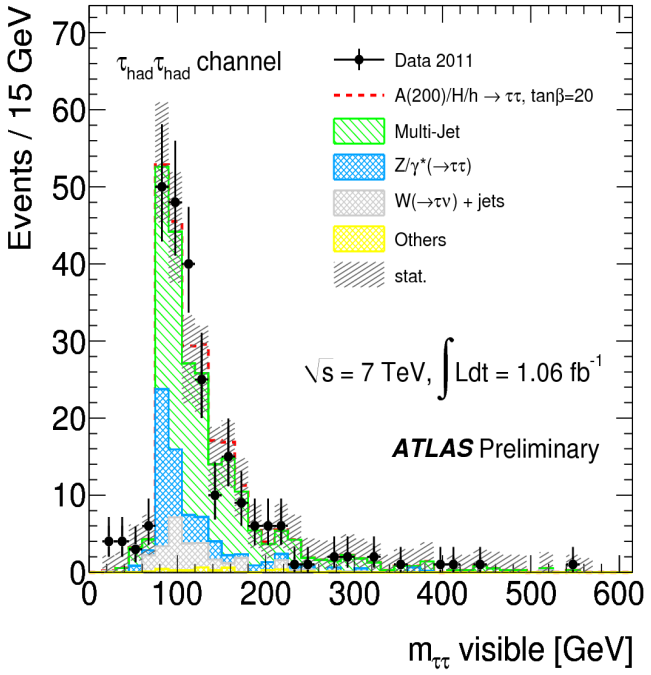


- No sign was seen in 2010
- Limits ~20% level; similar to Tevatron results

ATLAS H→ττ by mode



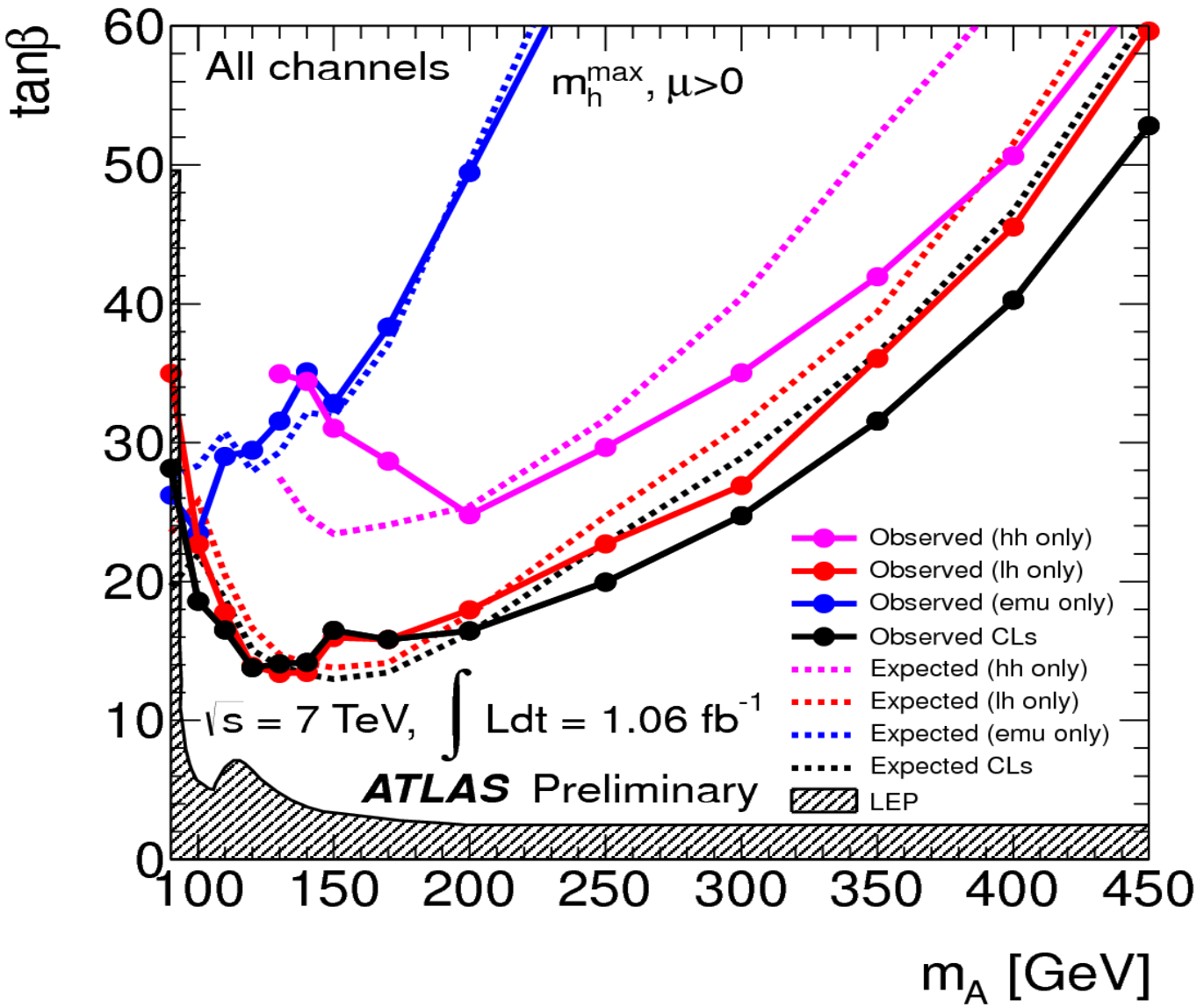




- ll,lh and hh modes compared
  - Different mass methods used for each
- QCD fraction rising left to right
  - But signal rete rising
  - Mass resolution improving

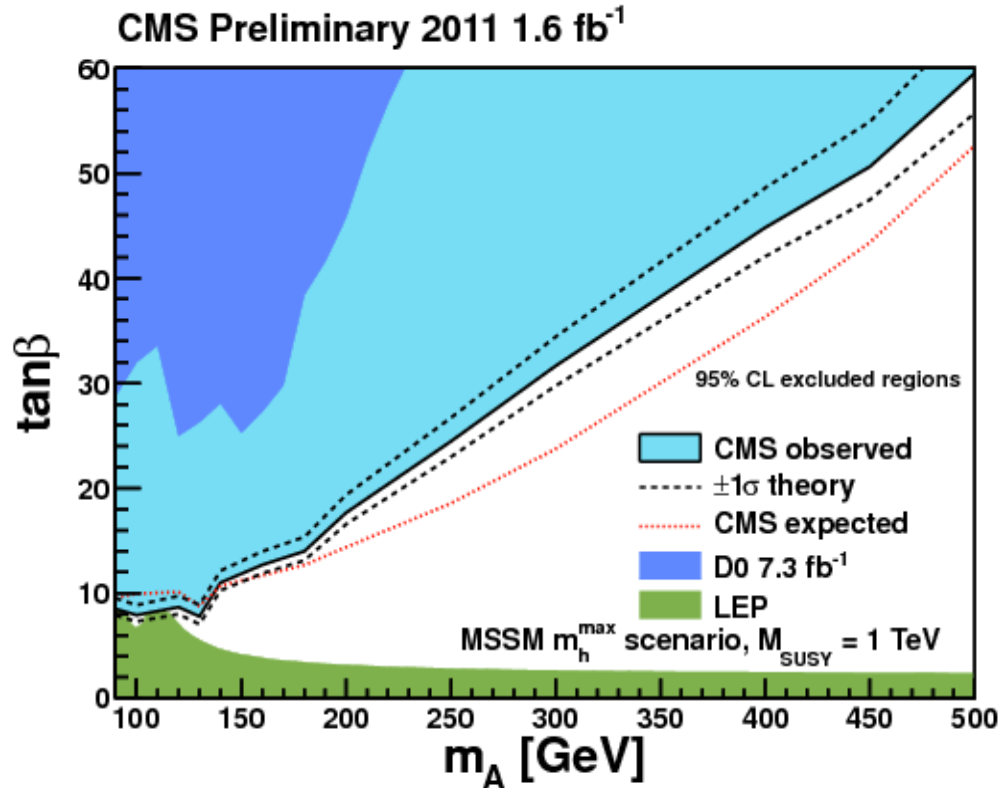
ATLAS H→ττ by mode

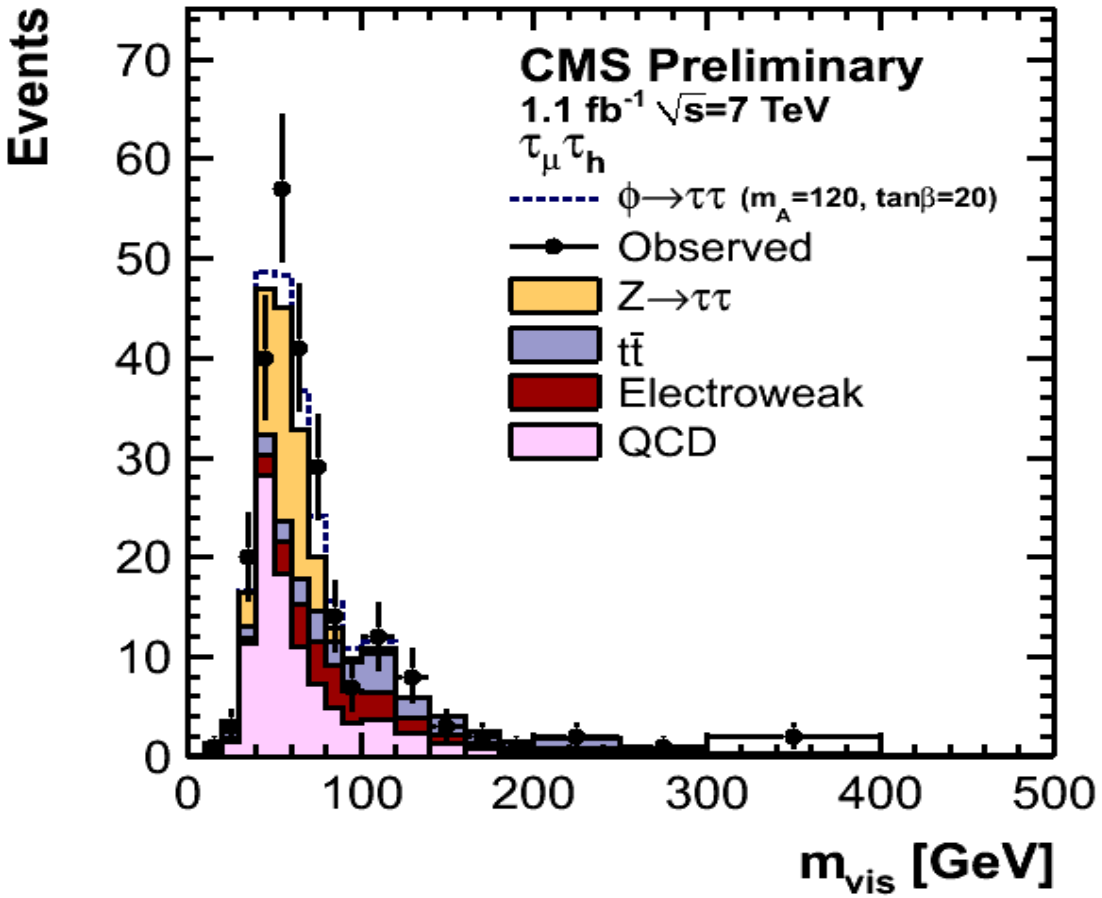
- lh generally most sensitive
- ll mode best when degenerate with Z
  - Mass resolution doesn't help
- hh importance rises with mass



H/A → ττ

- Φ → ττ 2011 CMS
- eμ, μτ_h, eτ_h
- Inclusive, b-tag, VBF
- Very nice results

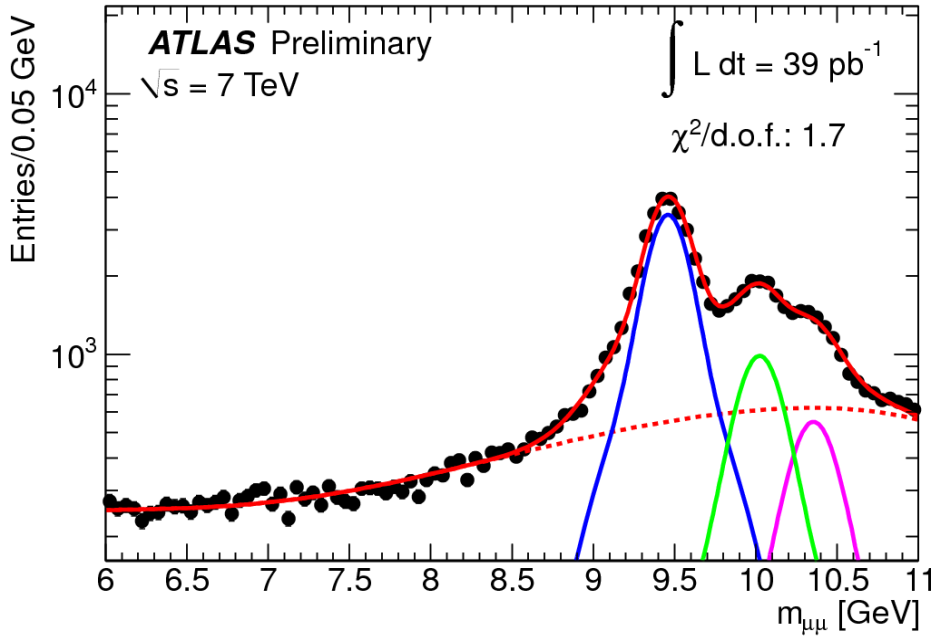


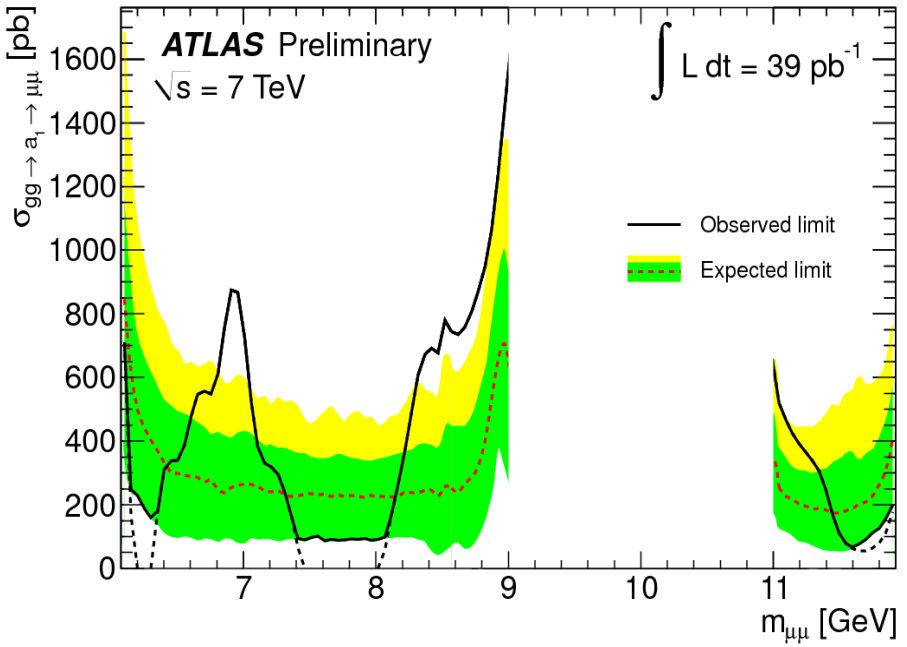


- Exclusion meeting LEP bound

nMSSM a_1

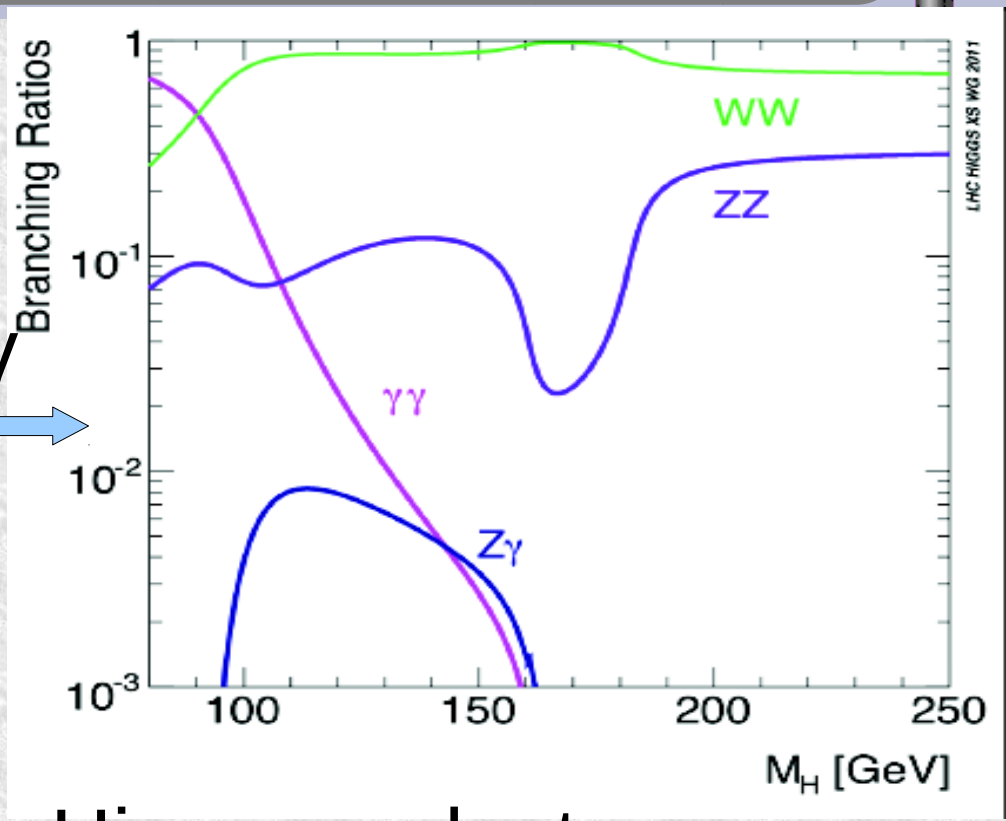
- MSSM plus on scalar Higgs
  - Allows lightest Higgs to be very light.
  - 'ideal' Higgs near upsilon mass
  - ATLAS analysis misses difficult upsilon region
- If SM Higgs missing, such models will gain

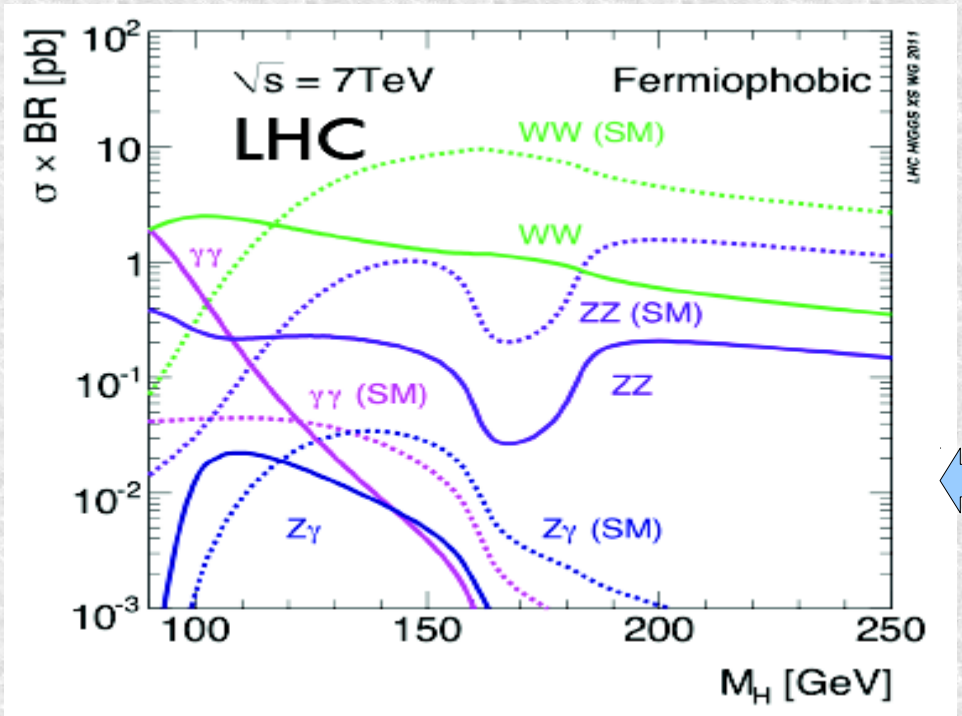




Fermiophobic

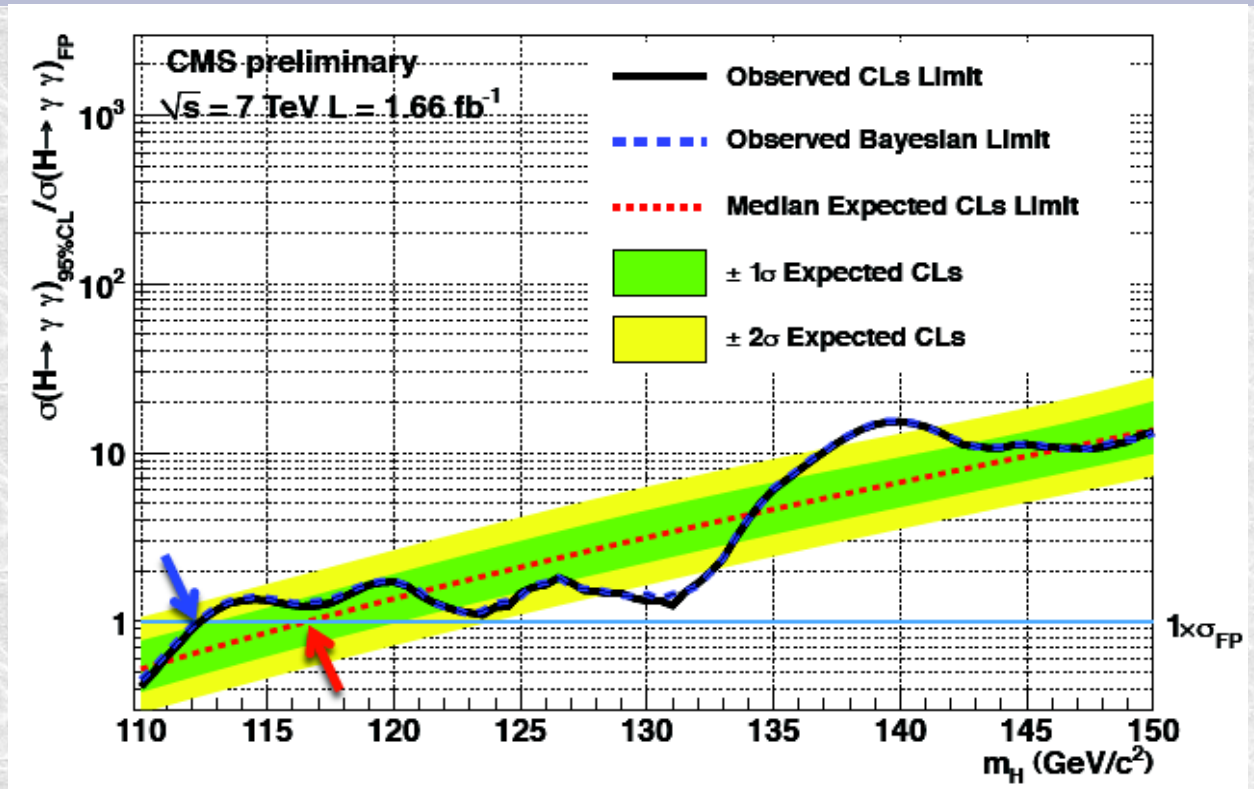
- Higgs produced in VBF or VH
  - No gluon fusion
- Higgs decay enhance γγ





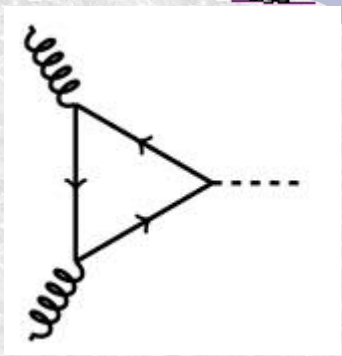
- Higgs product cross-sections
  - Exceed SM < 120
  - Reduced above

Most sensitive FP search



- Expected CMS limit 116.5
  - actual CMS limit 112 due to excess
- CDF/Do expect 111/110.5
  - Actual CDF/D0 114/112.9GeV

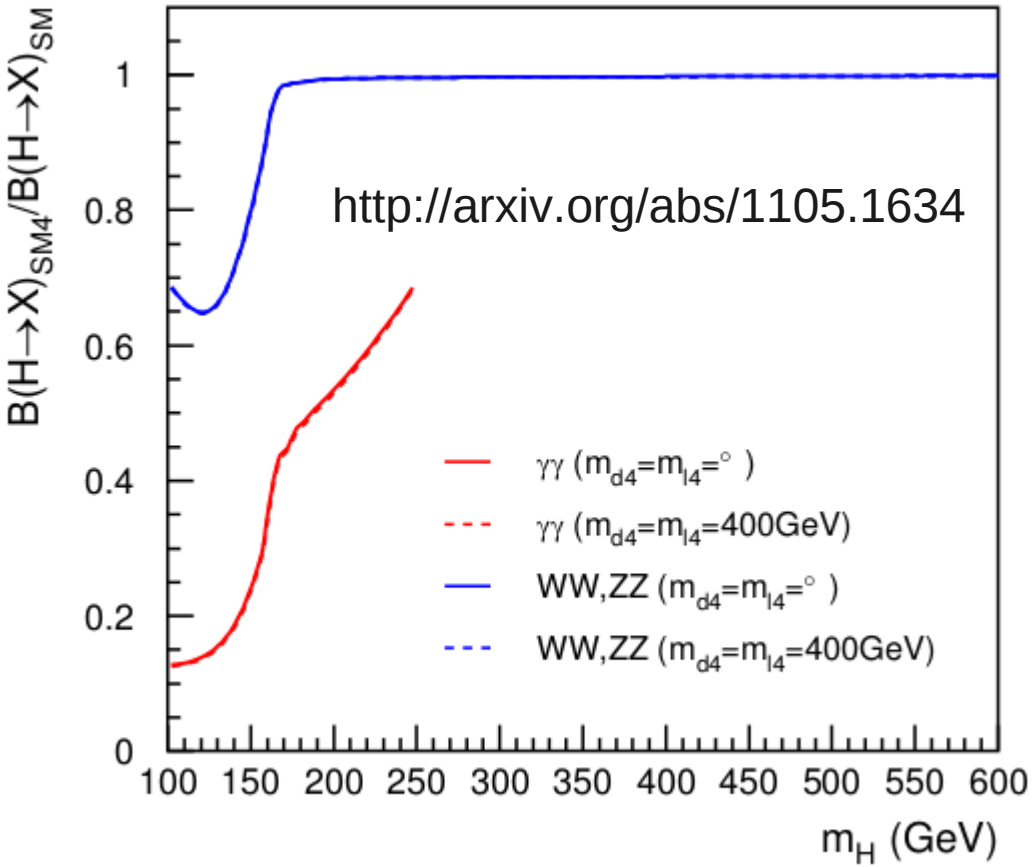
4th Generation model

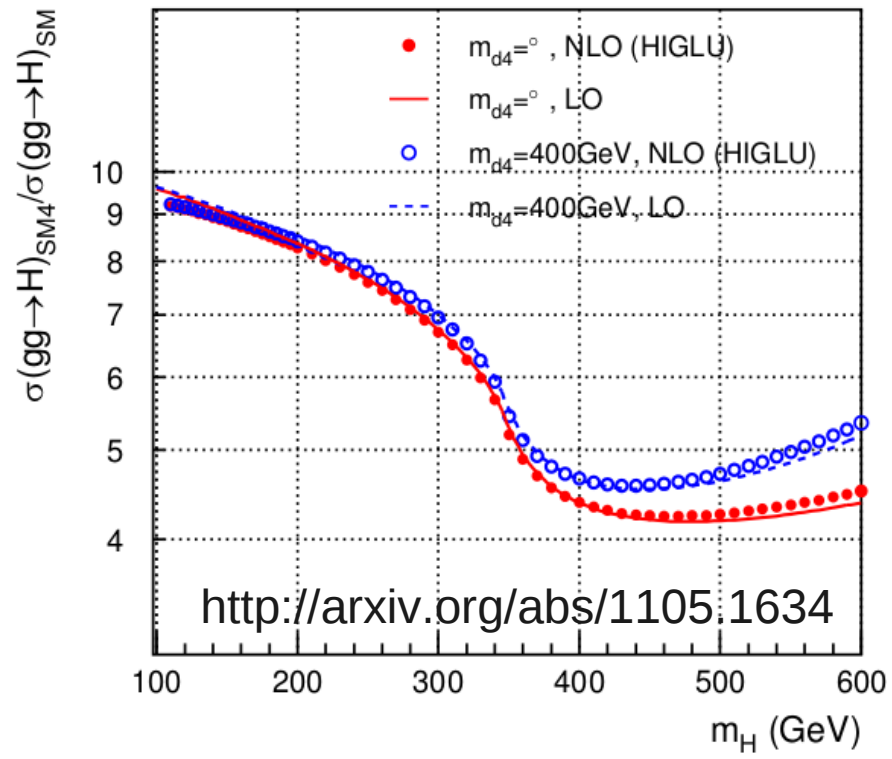


- Why?
  - Heavy particles enhance gluon fusion loop
  - Kinematics like 1/mass
  - Coupling to H like mass
  - Total is mass independent!
- Factor 4-9 enhancement from 4th generation
  - Allowed if m_ν>47GeV
  - We require $m_\nu >> m_W$ - this removes $H \rightarrow \nu\nu$ decay
  - But photon decay is suppressed...
    - Interference and competition with gluons

4th Generation Rates

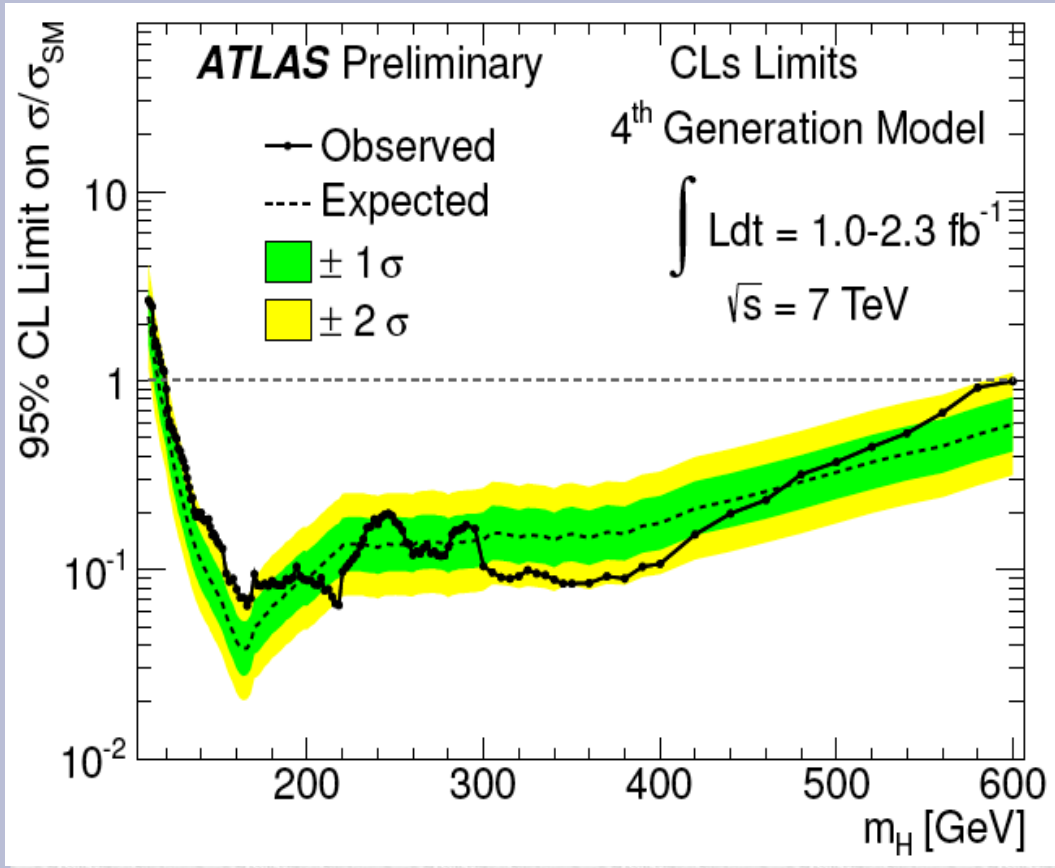
- Production rates enhance
- High mass -> minimum

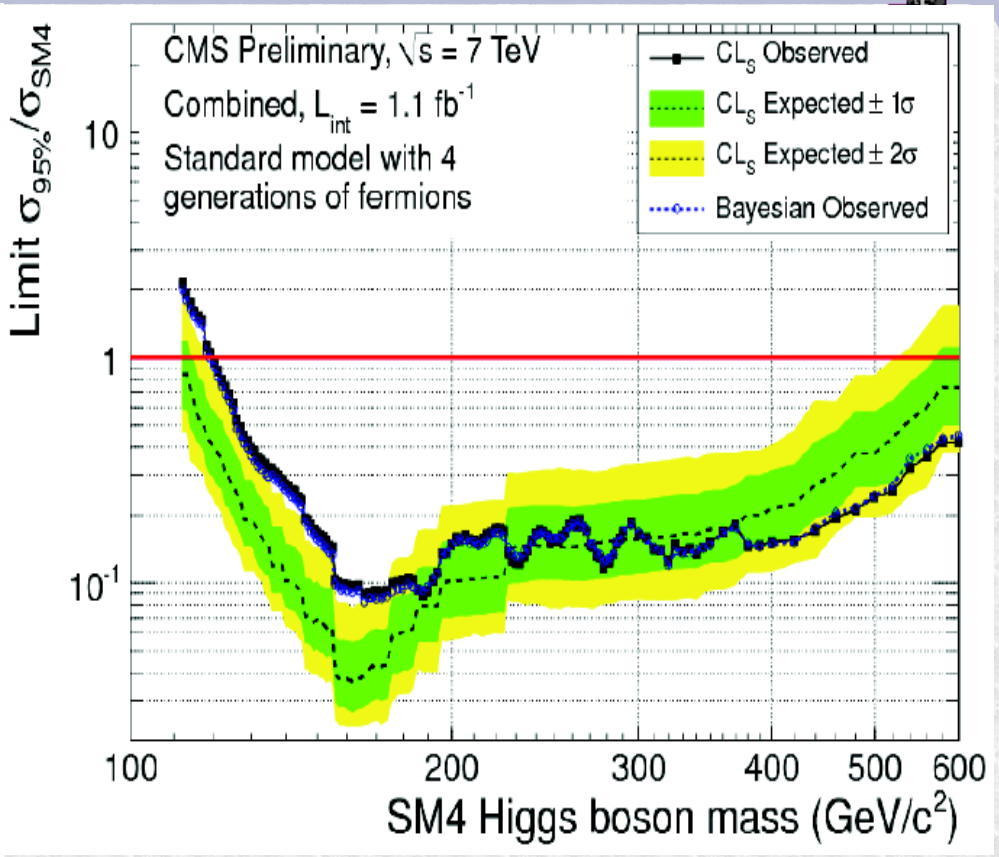




- High-mass decay rates stable
- Low mass colourless decay suppressed

Higgs + heavy 4th Generation





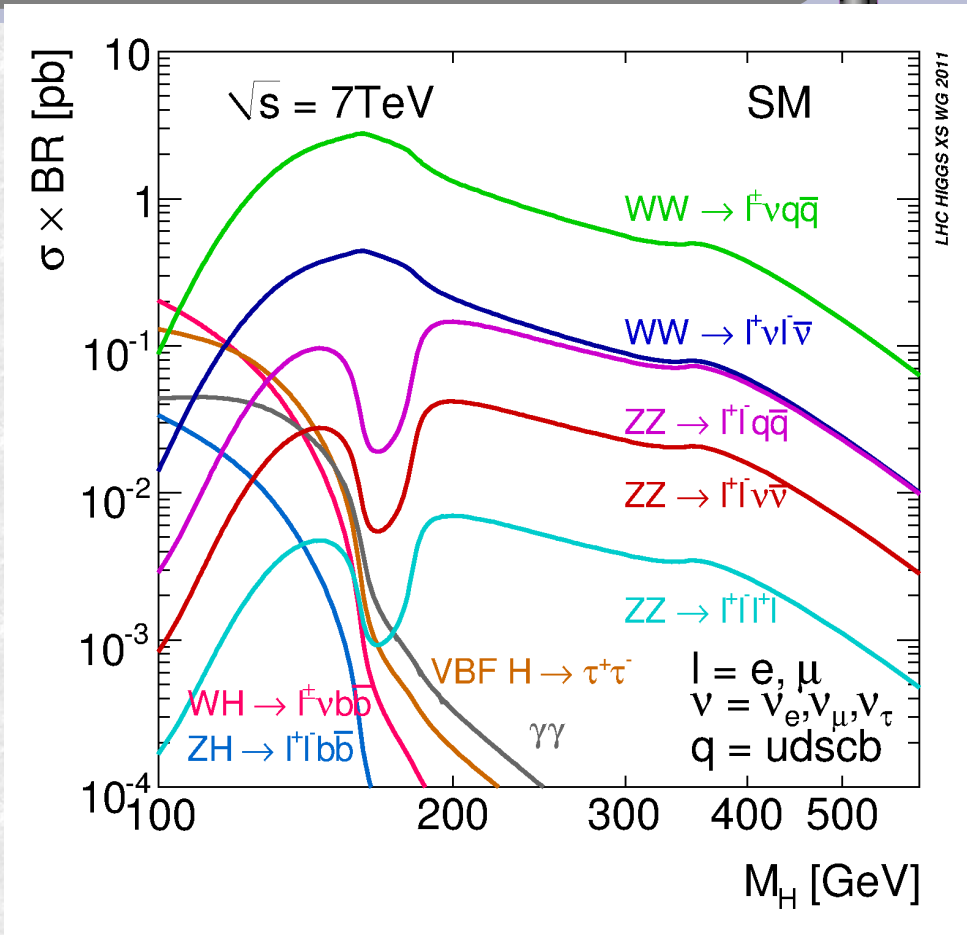
- CMS and ATLAS exclude ~120GeV to 600GeV
  - ATLAS/CMS expected 116/112 to 600

Standard Model Higgs

The guaranteed discovery?

Higgs cross-sections

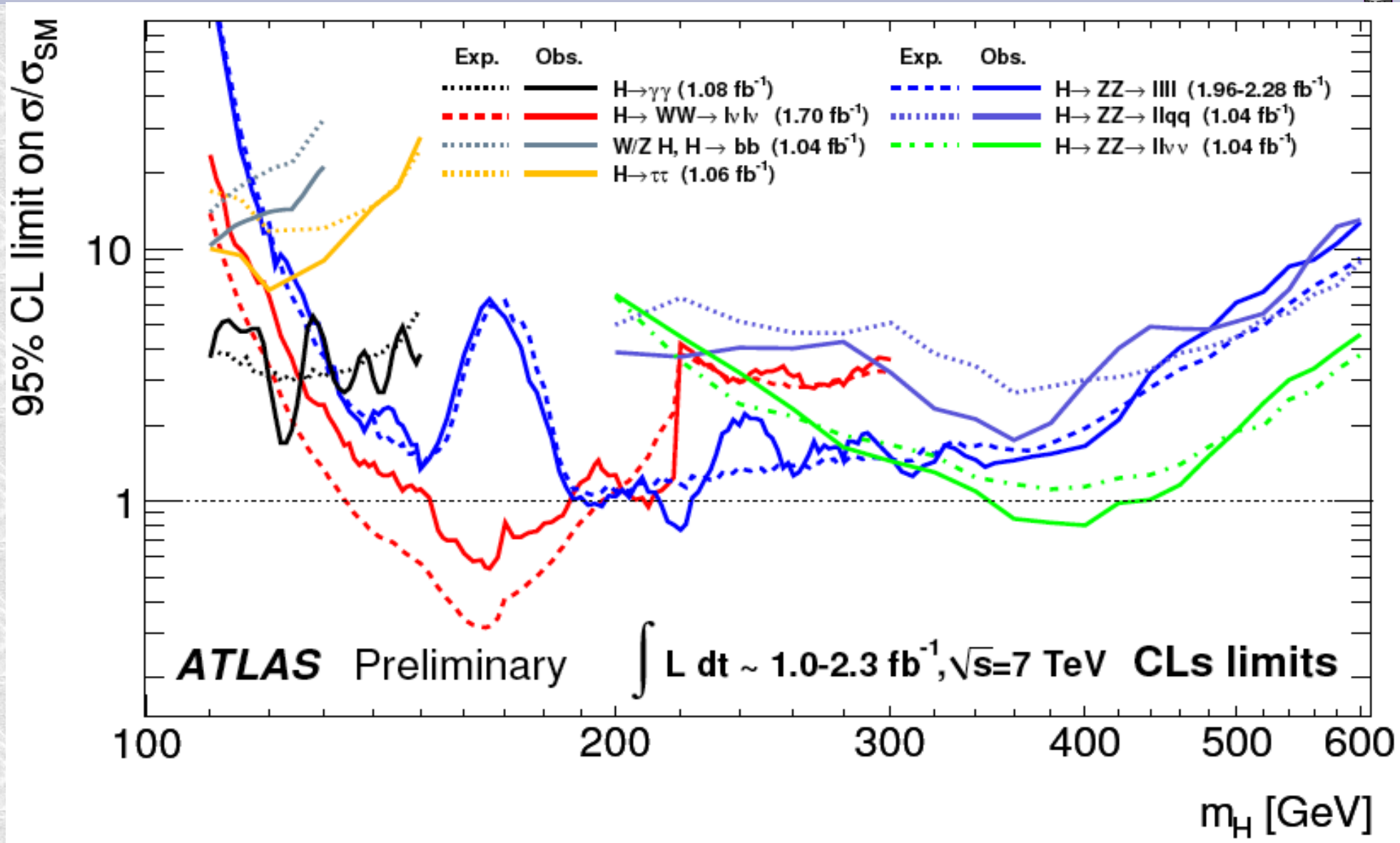
- H→ZZ
  - ZZ→llll: Golden mode
  - ZZ→llνν: Good High mass
  - ZZ→llbb: Also high-mass
- H→WW
  - WW→lνlν: Most sensitive
  - WW→lνqq: highest rate
- H→γγ
  - Rare, best for low mass
- H→ττ
  - Good s/b, low mass,rare
- H→bb
  - $t\bar{t}H$, WH, ZH useful but hard



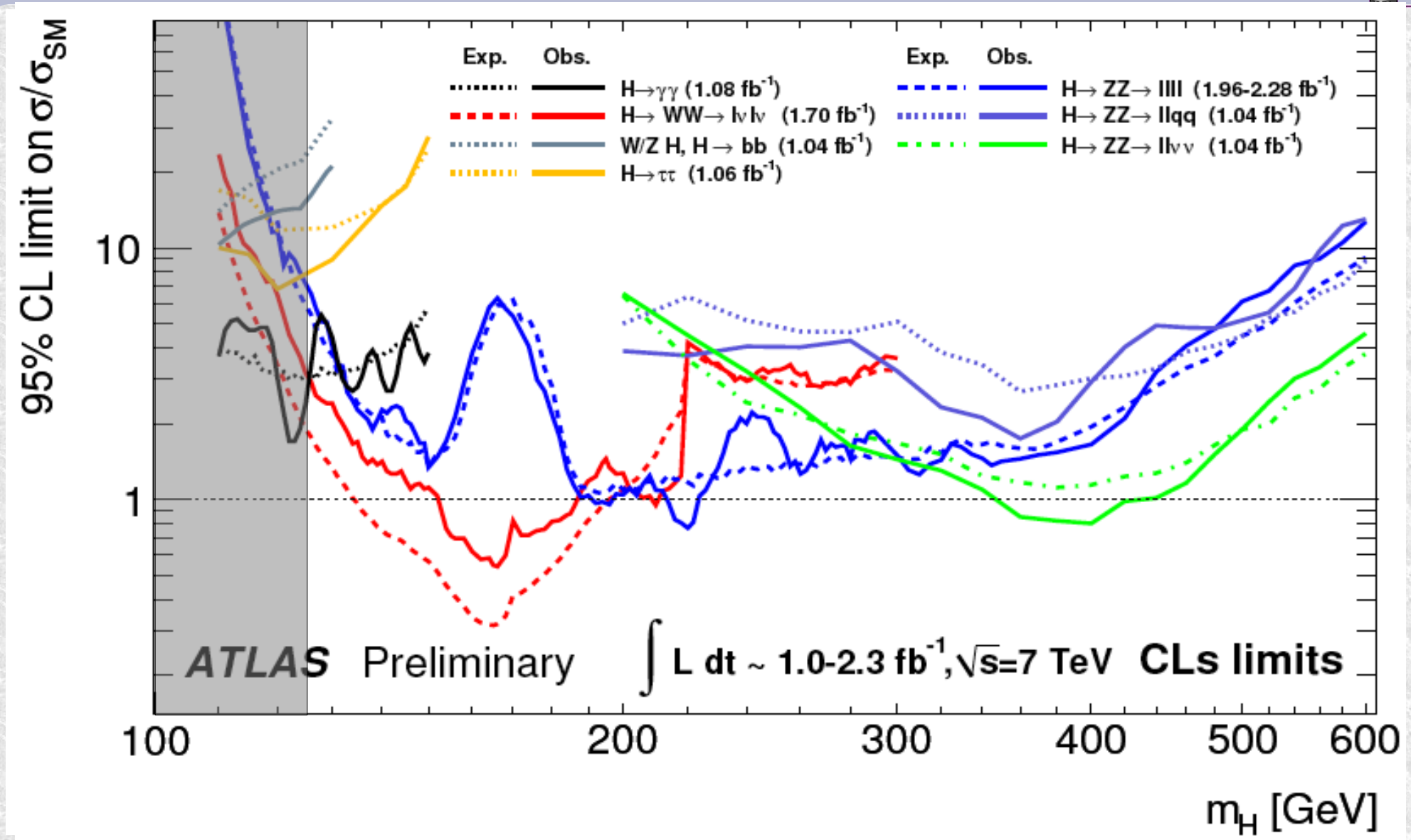
Channels used

H decay mode	ATLAS	CMS	Tevatron
ττ	--	Inclusive+VBF	H/VH/VBF
bb	lυH, llH	lυH, llH, υυH	lυH, llH, υυH
γγ	Inclusive	Inclusive	Inclusive
WW→lνlν	0jet, 1 jet m<240	0jet, 1jet, VBF	0j / 1j / 2j / 1l
WW→lνqq	0jet, 1jet	--	0jet, 1jet
ZZ→llll	Inclusive	Inclusive	--
ZZ→llνν	Jet veto	b jet veto	--
ZZ→llbb	Inclusive	Inclusive	--

Channels reviewed (ATLAS)

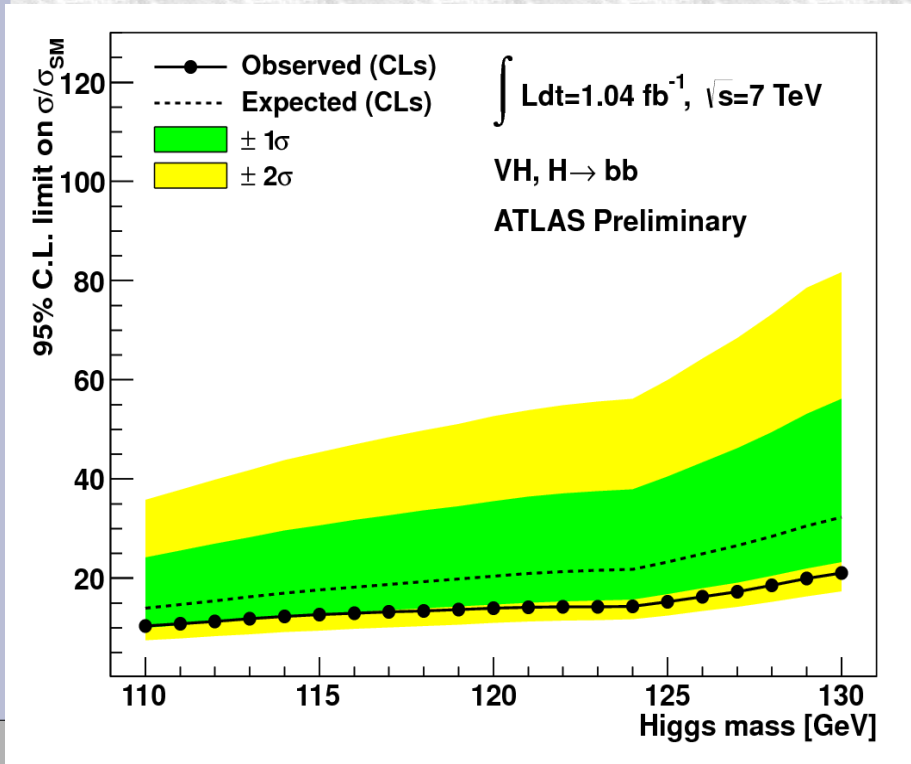


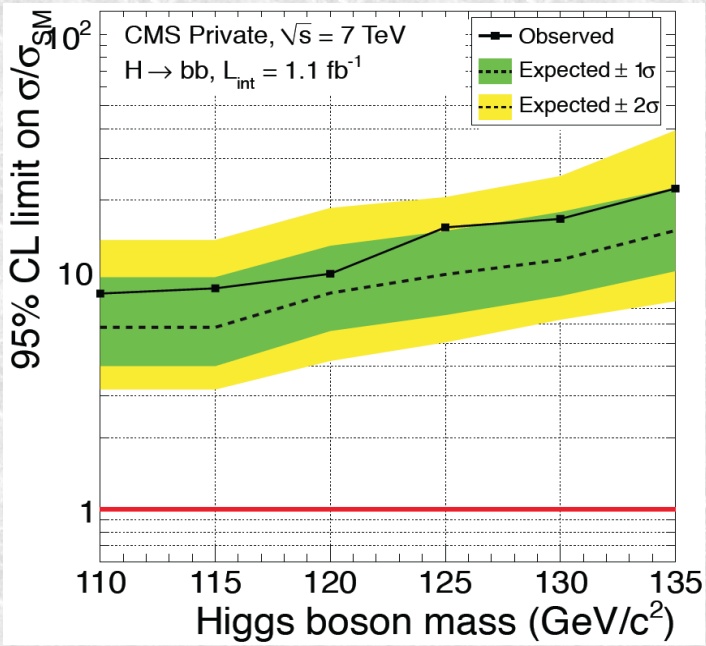
Low mass searches



VH, H → bb

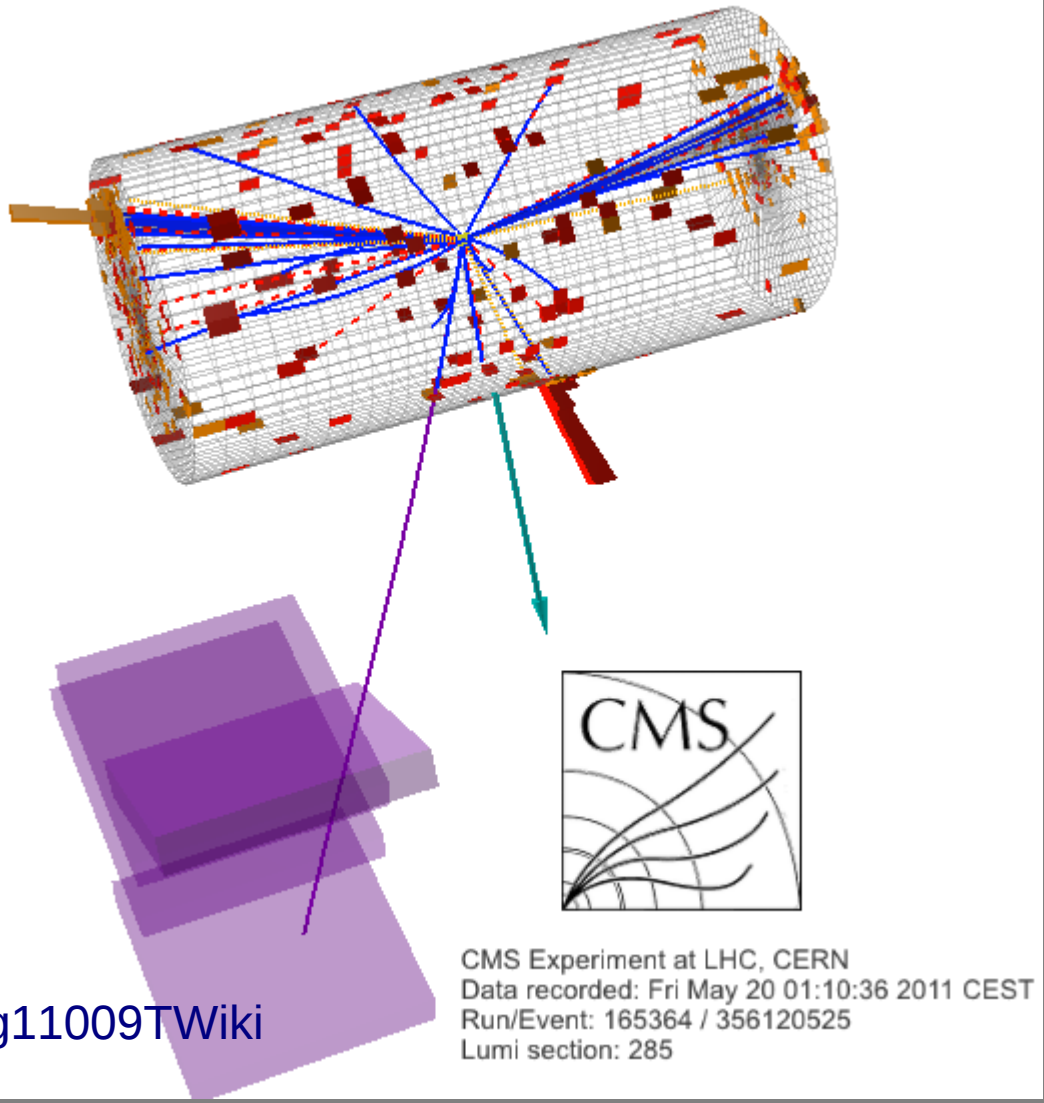
- Very different optimisations in ATLAS & CMS
  - Sensitivity is ~ 15xSM in ATLAS
  - 6xSM in CM
- Neither is yet very sensitive, opposite fluctuations





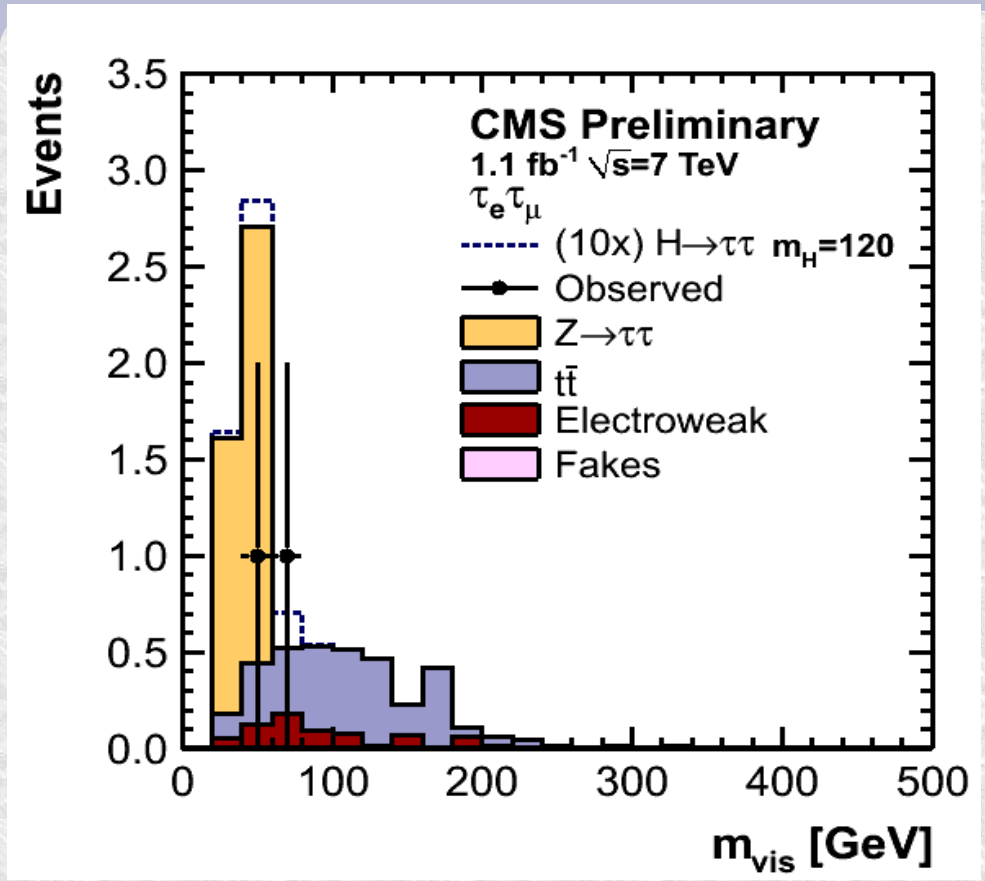
H → ττ

- CMS showed 2011 SM results
- Including VBF search
  - With a beautiful picture
    - μ-τ candidate
    - Two forward jets
      - Mass 580GeV
    - Little central activity
  - Looks just as advertised
- e-μ, μ-μ, μ-τ, e-τ channels studied
- Details are here:

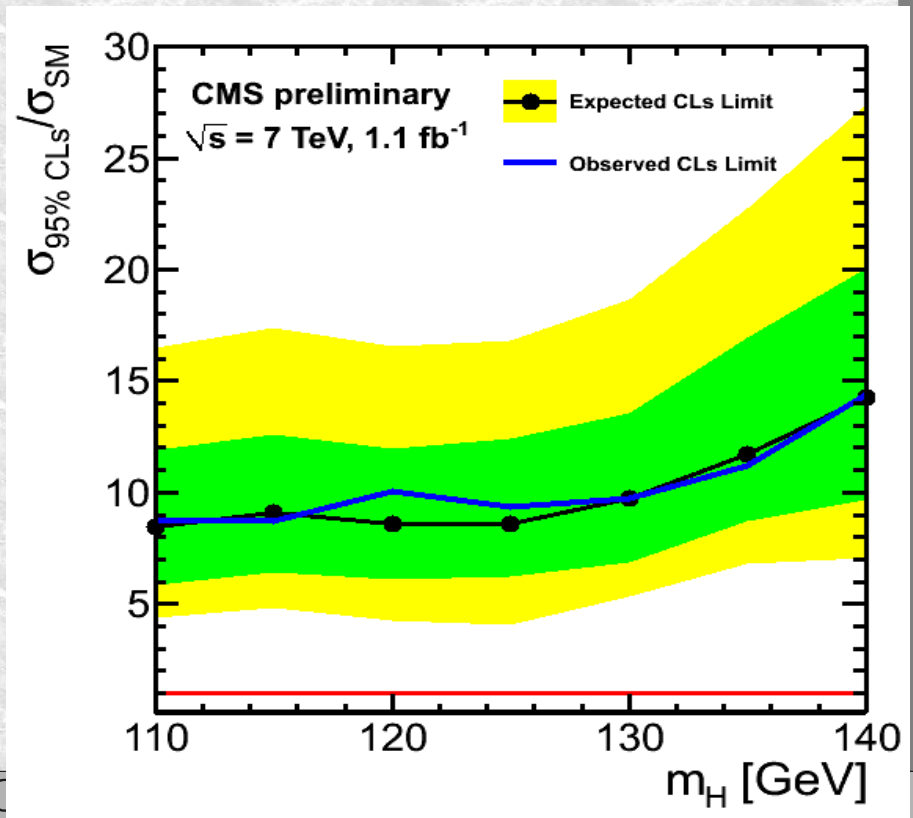


https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig11009TWiki

H → ττ results



- e-μ VBF channel (left) is cleanest
  - Mass calculation can improve



- Limits around 9xSM
  - At 115-125 (where we need this most)

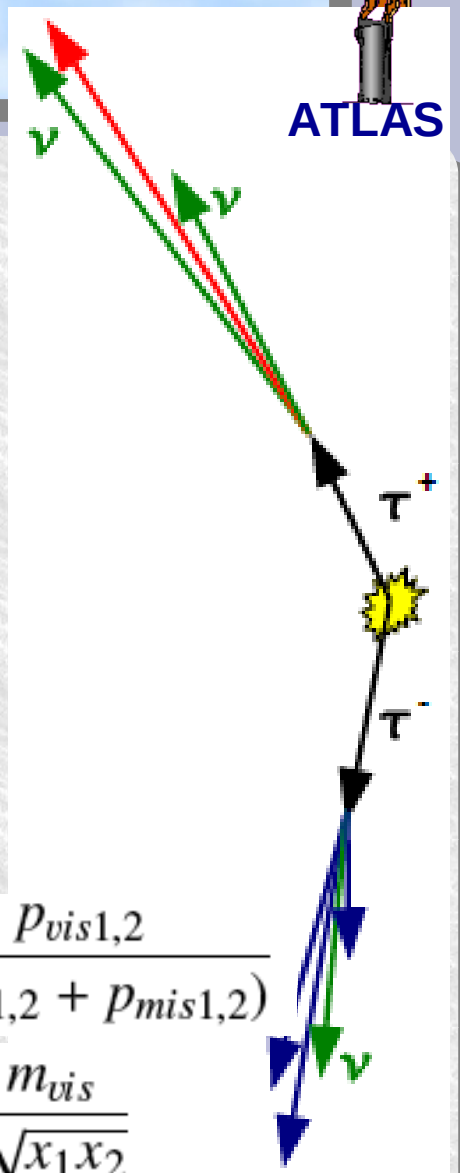
ATLAS H→ττ

Good for SM Higgs in the mass range mH=110-140 GeV
Three classes of final states, depending on the τ-decay:
- lepton-lepton, *ll*
- lepton-hadron, *lh*
- hadron-hadron, *hh*

ATLAS has studied the *ll* and *lh* final states
Most important backgrounds:
- Z/γ* → ll + jets (→ττ is largely irreducible); W→lυ + jets; dibosons, ttbar and single top, QCD jets

Selection for ll:
- 2e, or 2μ or 1e1μ with pTe > 15 GeV |ηe|<2.47; pTμ > 10 GeV |ημ|<2.5; opposite charge required
- At least 1 jet with pTj > 40 GeV |ηj|<4.5;
- ETmiss > 30 GeV for 2e and 2μ, > 20 for 1e1μ

ll finale state: reconstruct the tau momentum in the collinear approximation
Apply dilepton invariant mass and topological cuts
→Study the tau-tau invariant mass



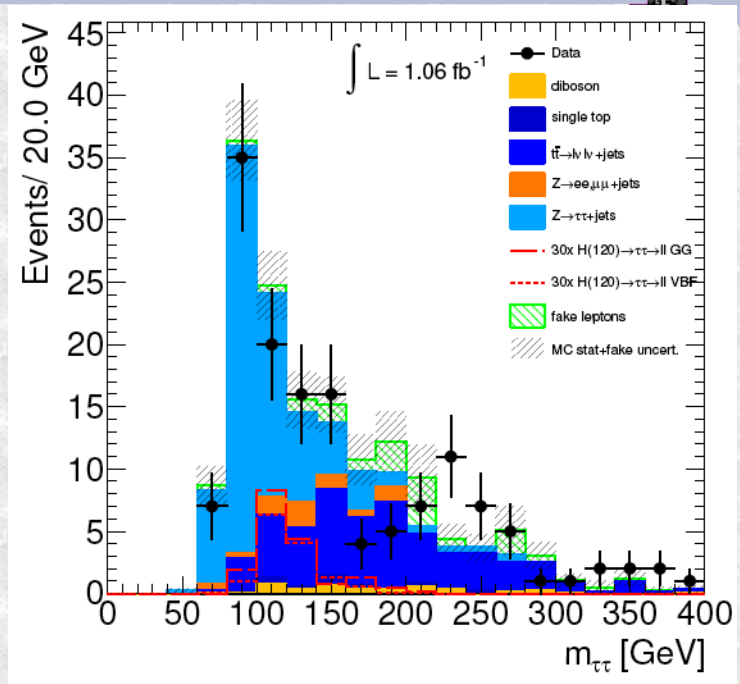
$$x_{1,2} = \frac{p_{vis1,2}}{(p_{vis1,2} + p_{mis1,2})}$$

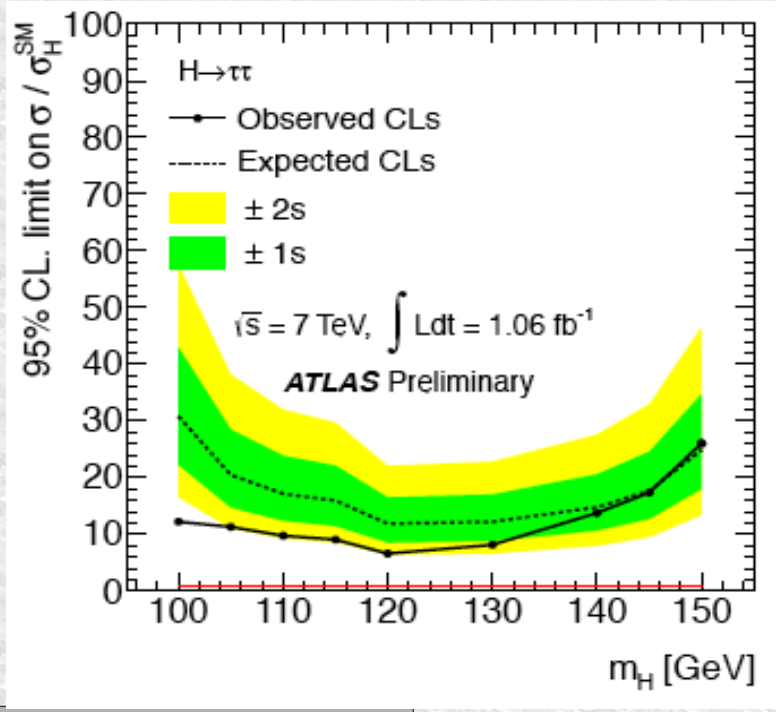
$$m_{\tau\tau} = \frac{m_{vis}}{\sqrt{x_1 x_2}}$$

Collinear approximation

ATLAS H→ττ

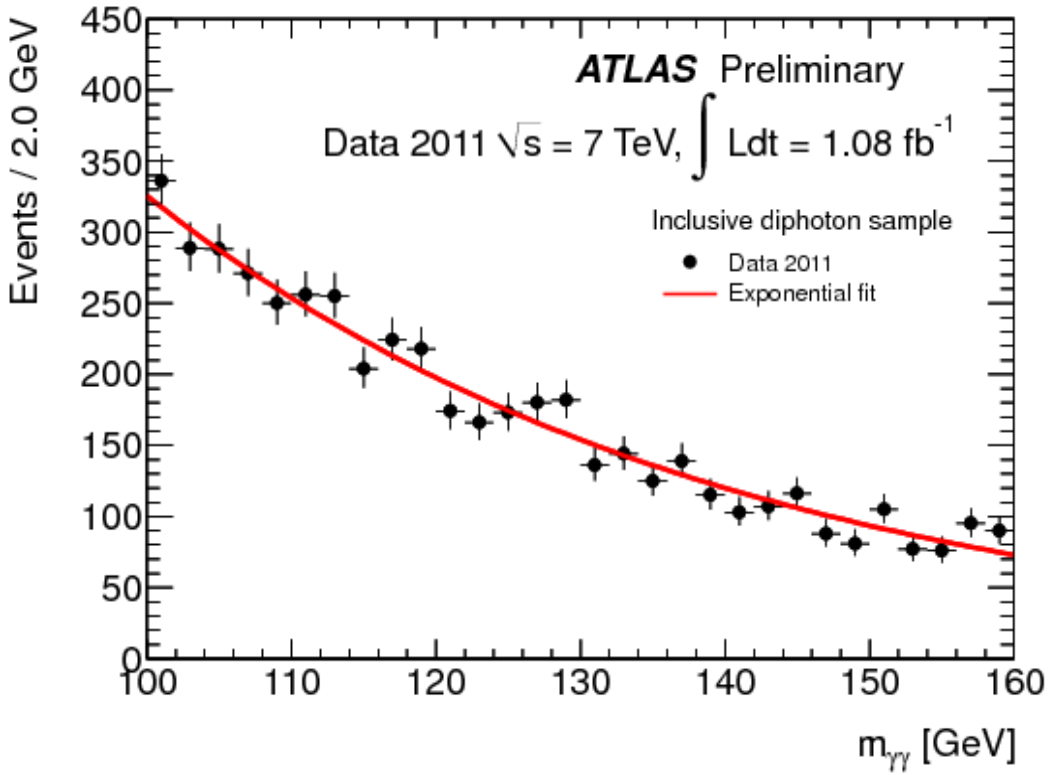
- MSSM H→ττ→lh result reused
- Also add ll+jet
  - Sensitive to VBF process
  - Jet boosts ττ system, allows colinear mass

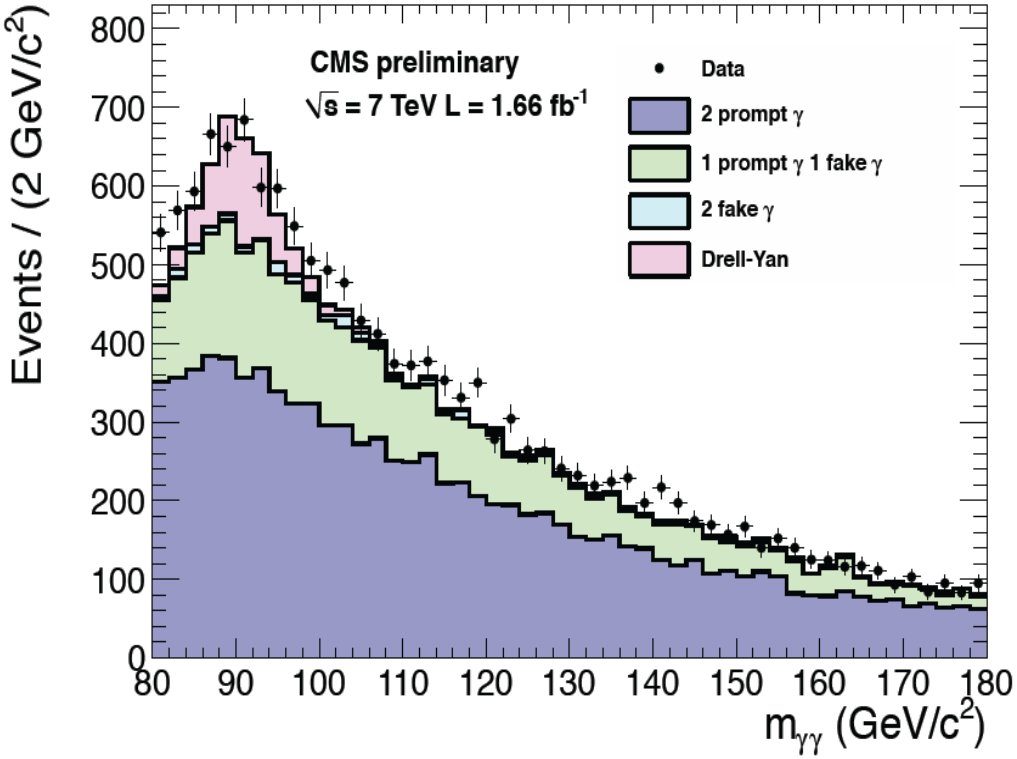




- Combined result shown to left
- Two sigma deficit at low m_H
- Sensitivity 15xSM, obs 10x

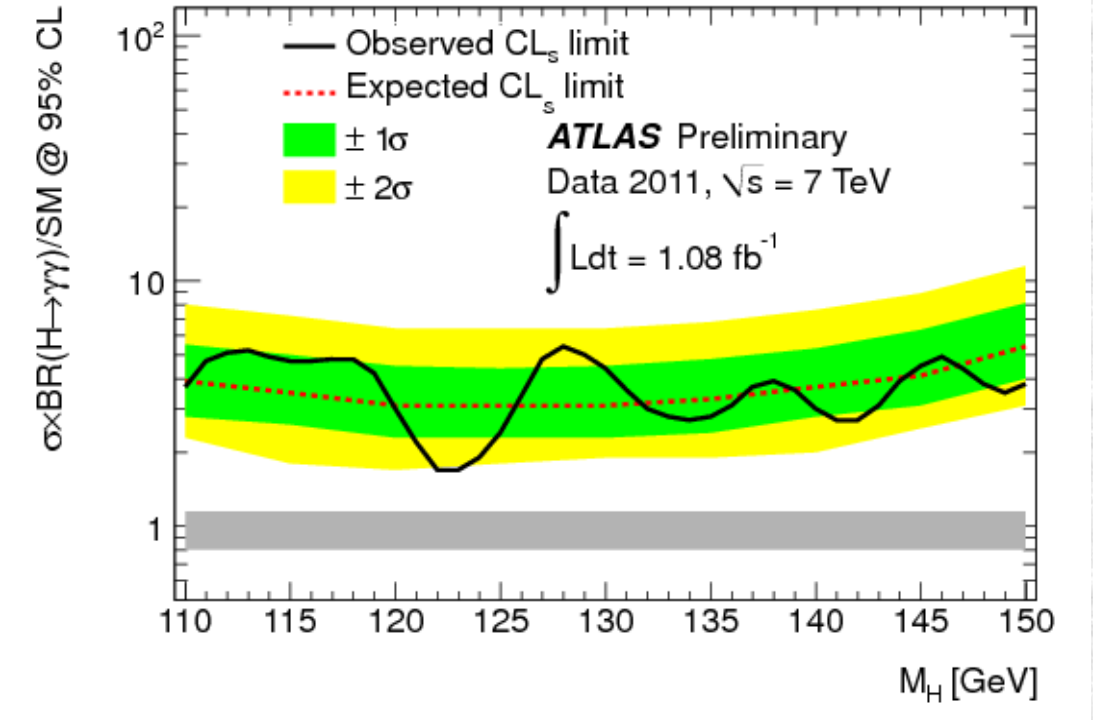
H → γ γ

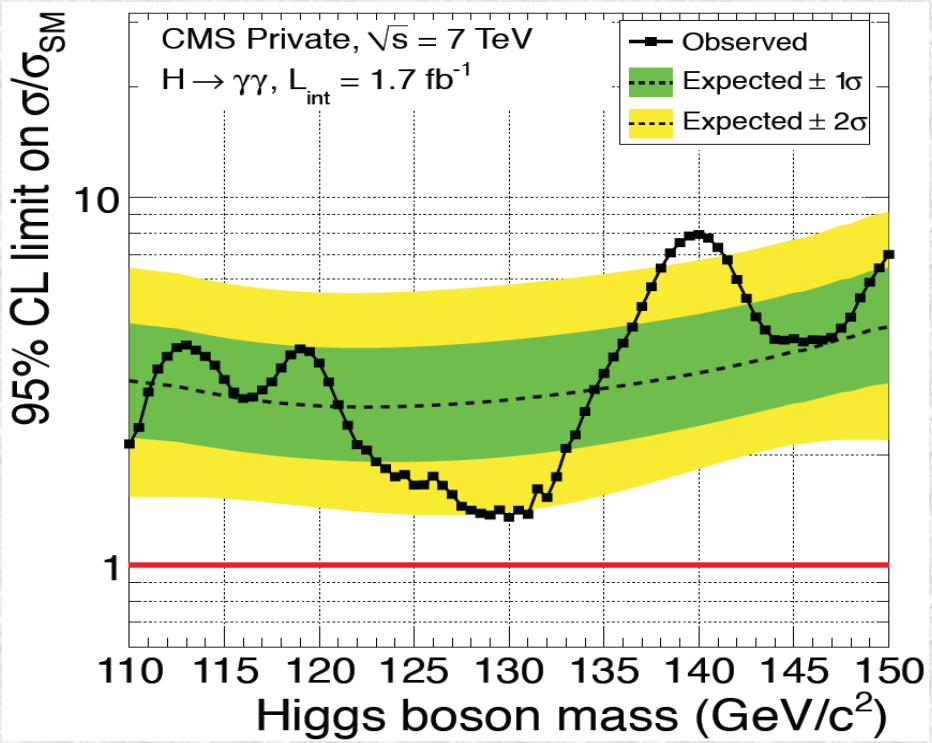




- Invariant mass spectra similar
  - Real yy events dominant for both experiments
- Fit to this spectrum, looking for sharp peak
  - Both divide events into quality categories

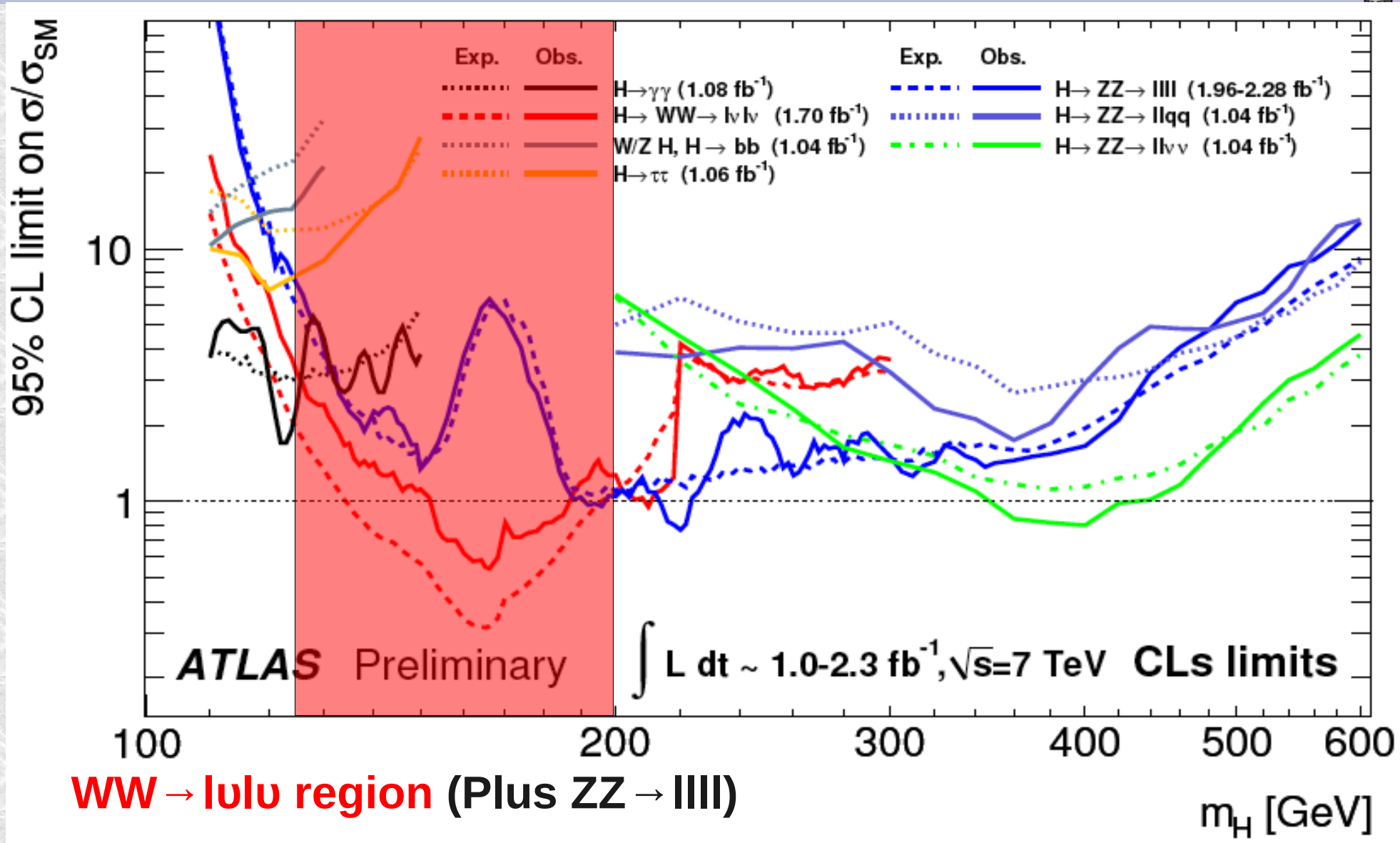
H → γγ limits





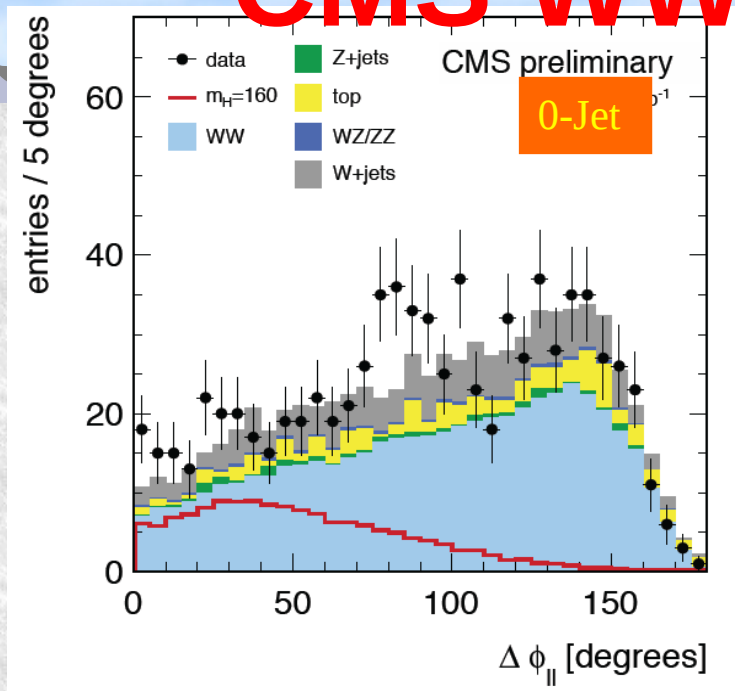
- ATLAS (left) and CMS (right) results similar
  - CMS have used more luminosity
- Expected limits 2.5-4 x SM strength
  - Observed fluctuates down to1.5

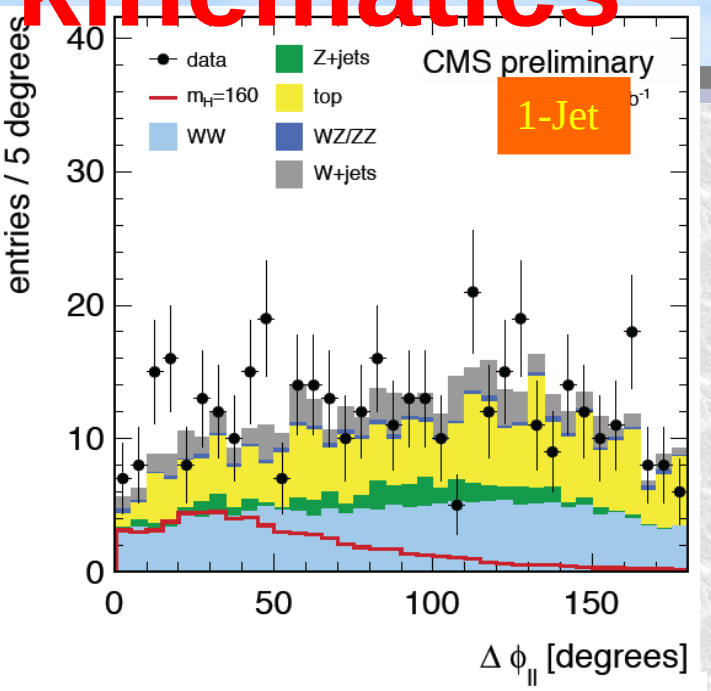
Intermediate searches

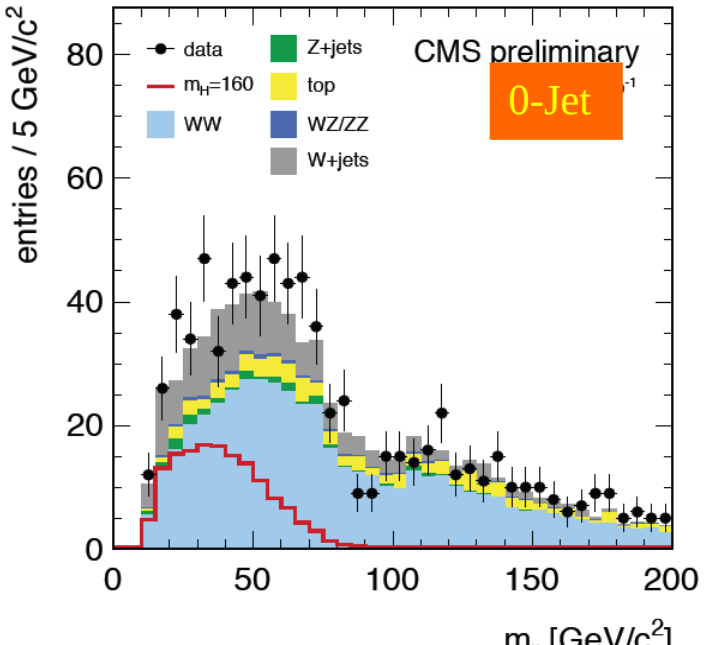


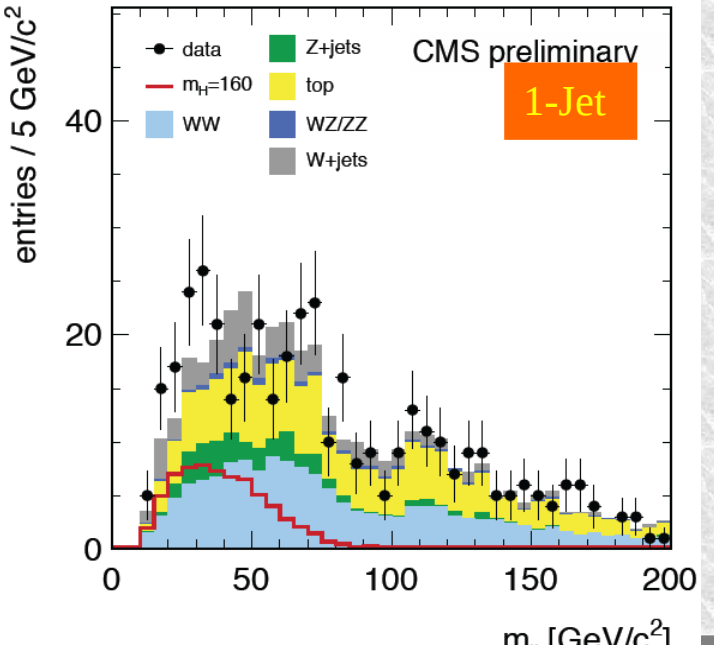
WW→lνlν region (Plus ZZ→llll)

CMS WW kinematics



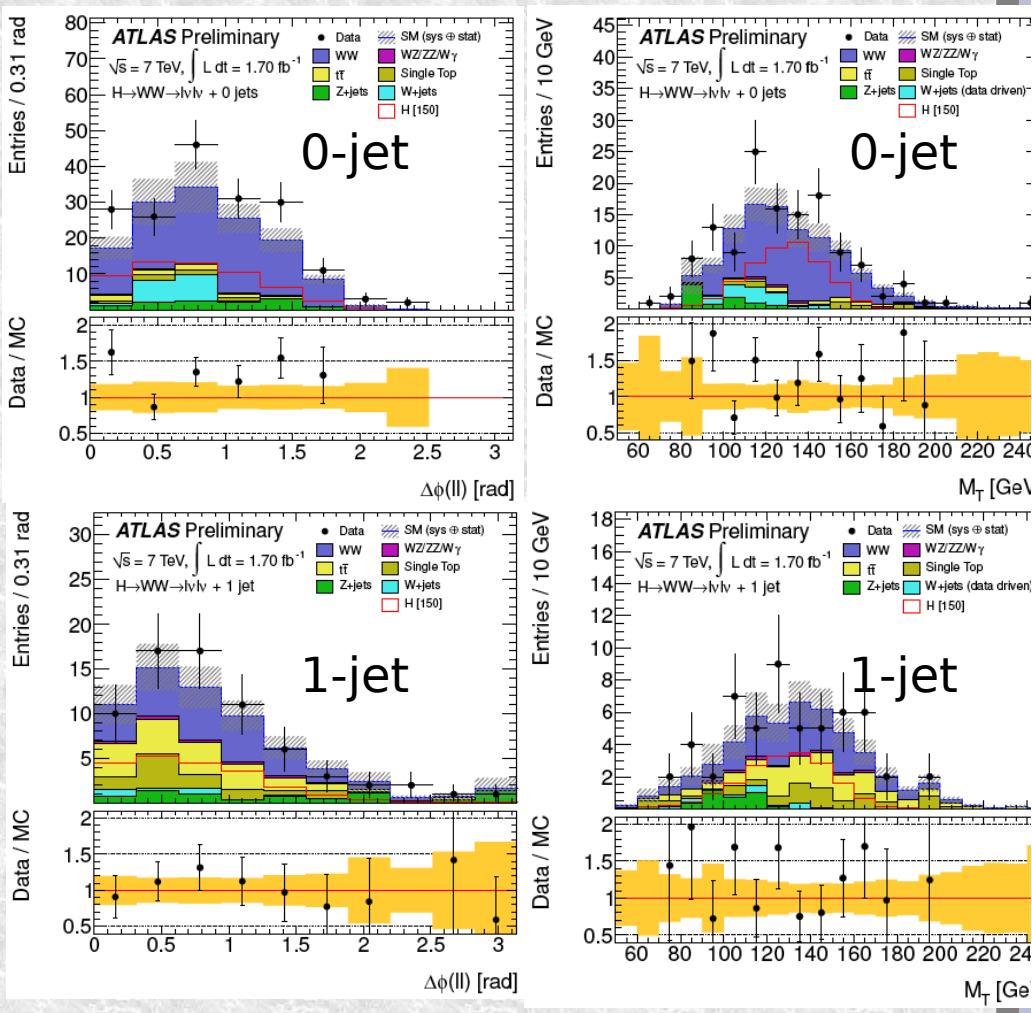




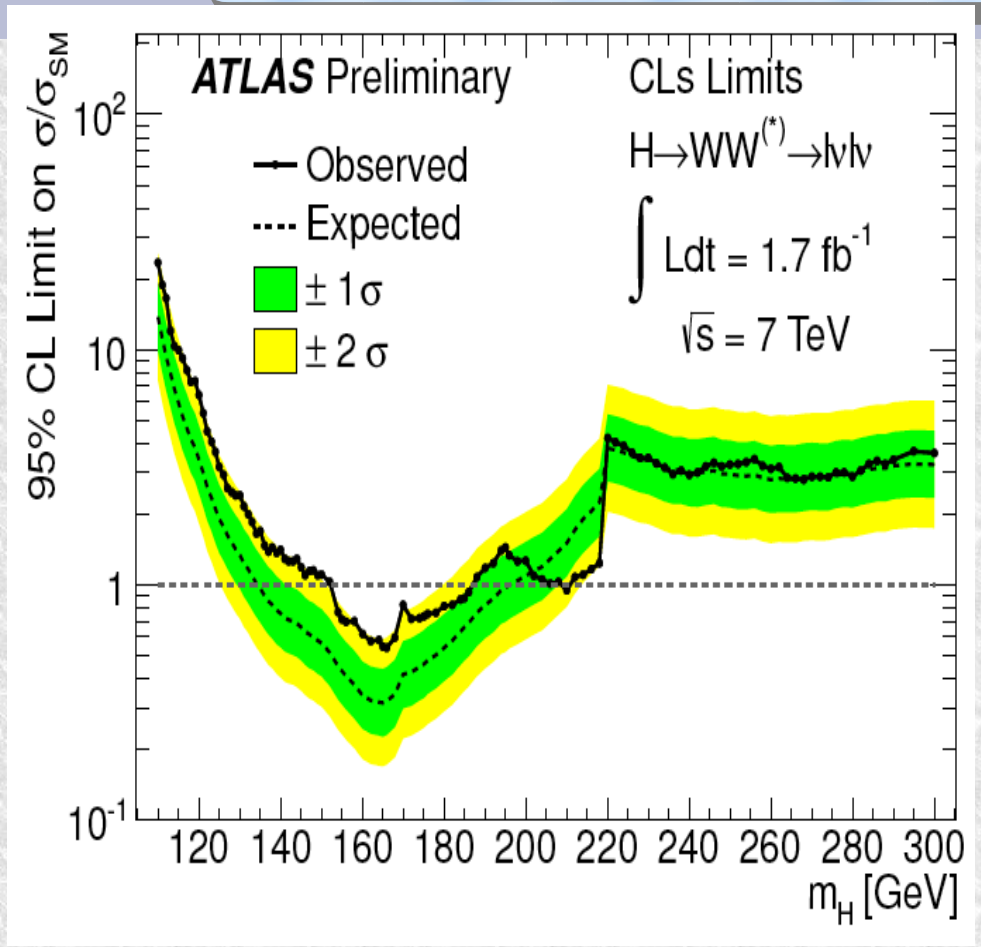


ATLAS WW m_T

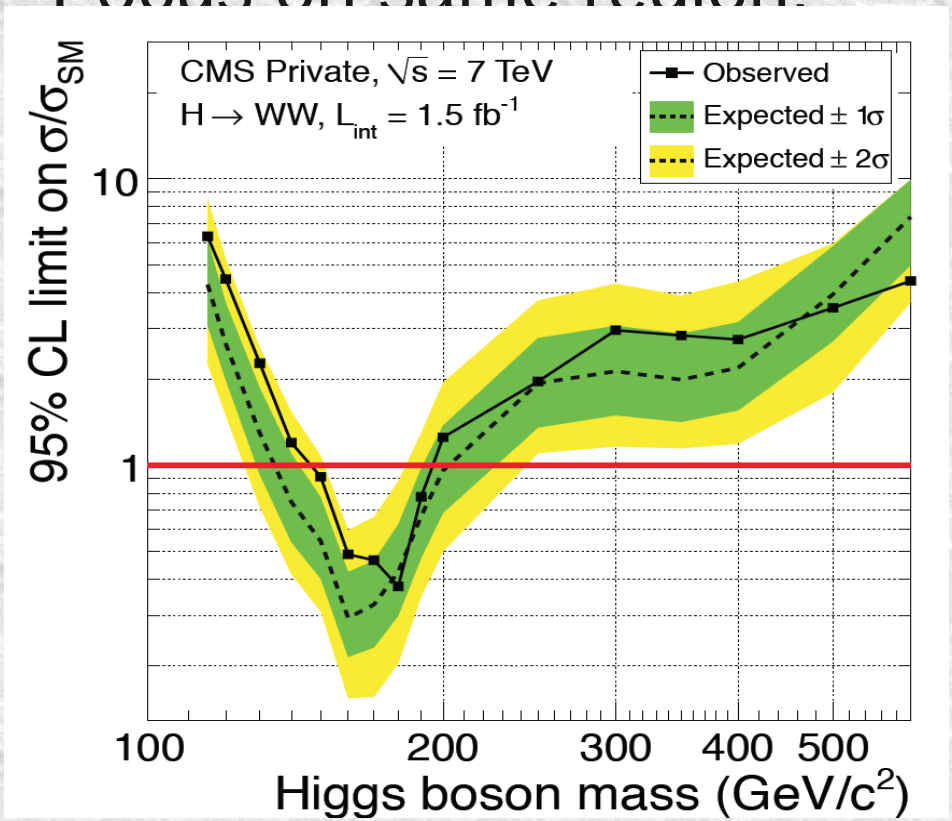
- Some excess of events
  - Mostly 0 jet
  - Reduced c/f 1fb^{-1} results



WW → lνlν

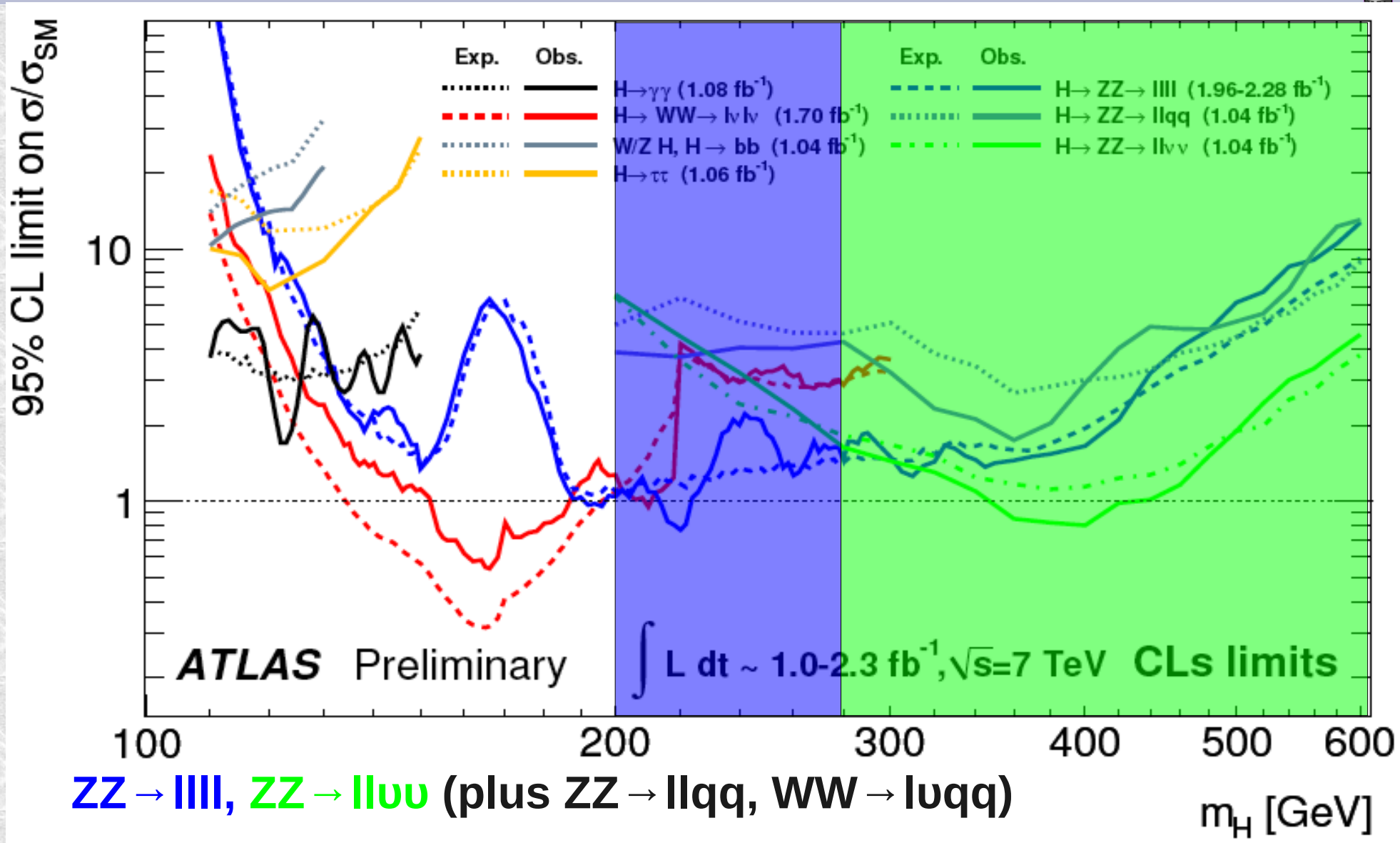


Focus on same region:



- ATLAS (left) exclude m_H 154-186 (exp: 135-196)
- CMS (right) exclude: m_H 147-194 (exp: 136-200)

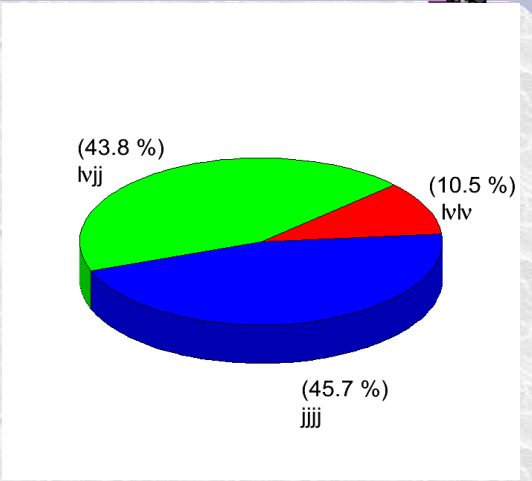
High mass searches



ZZ → llll, ZZ → llνν (plus ZZ → llqq, WW → lνqq)

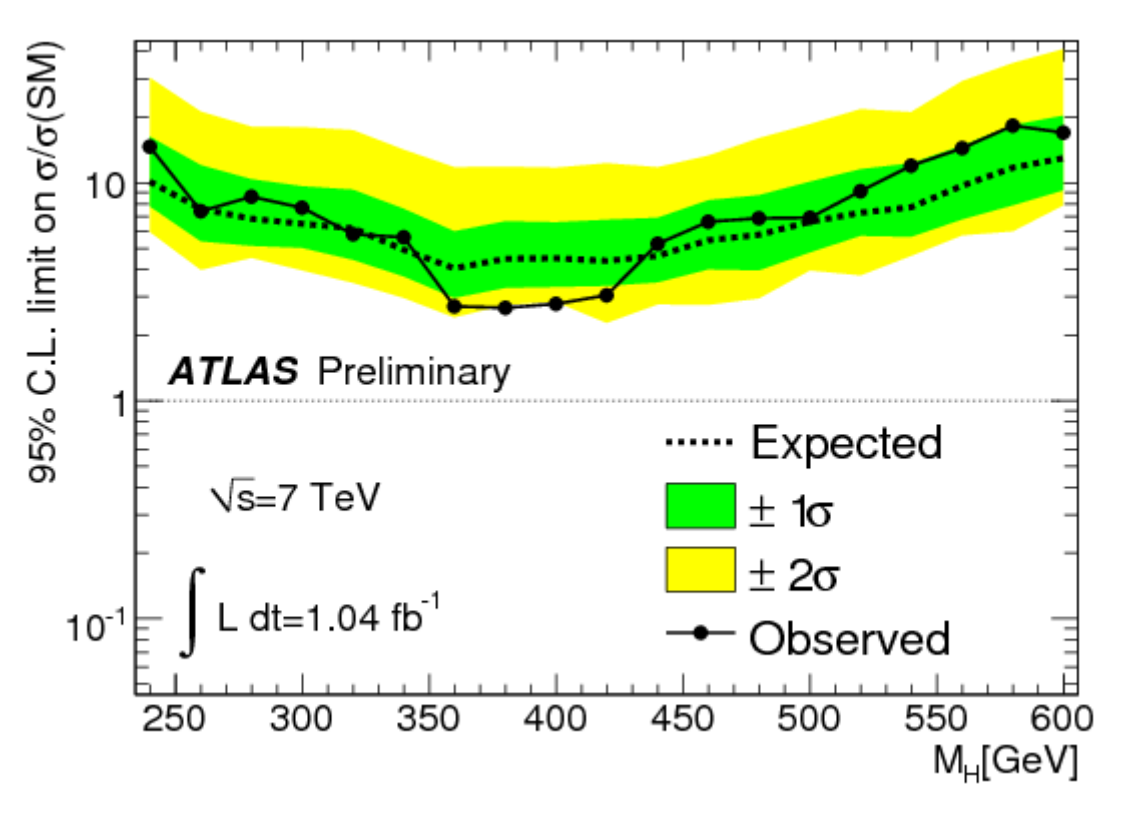
WW → lνqq

- Largest Higgs BR for high mass
- Presence of charged lepton gives good QCD rejection
- But, like in $t\bar{t}$, semileptonic mode allows mass reconstruction
- Suffers from LARGE background from W+jets
  - But smooth background
  - Signal is a bump
  - Analysis is relatively straightforward

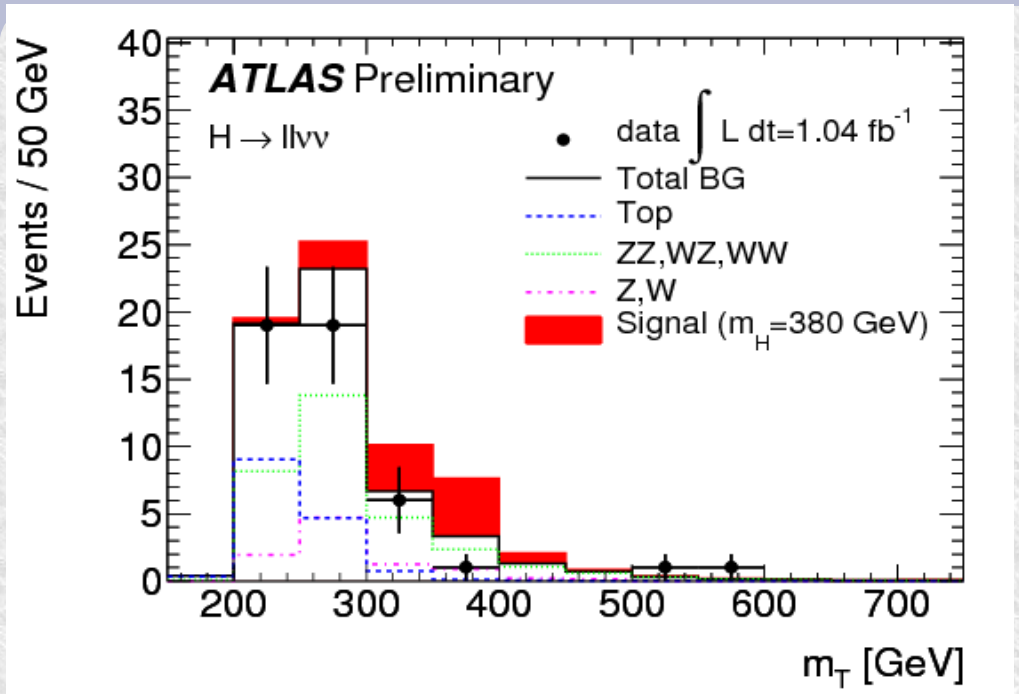


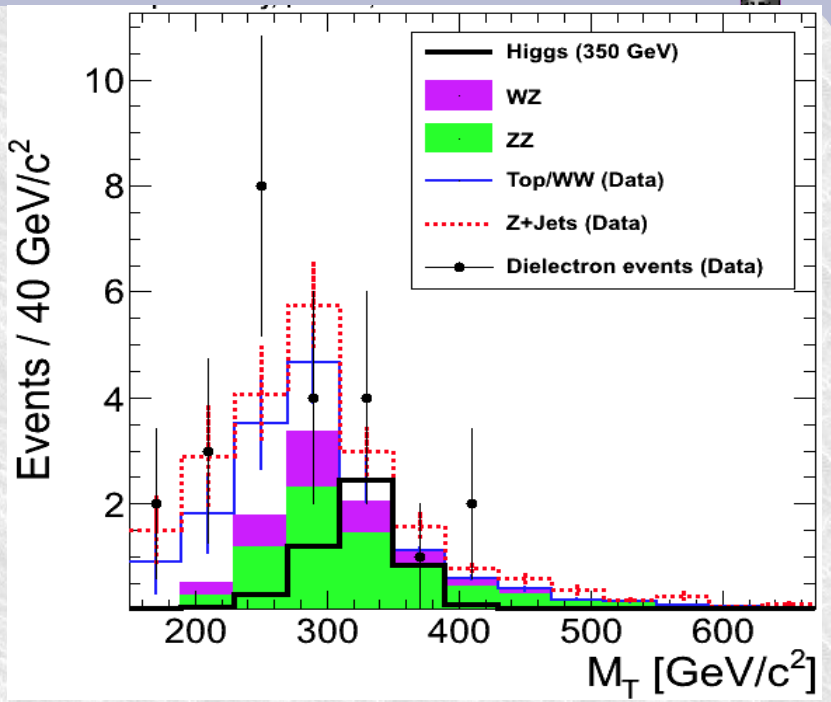
WW → lνqq

- Sensitive to five to ten times SM cross-section
- Limits 'lucky' around 400GeV
  - Exclude 2xSM
- No excess anywhere



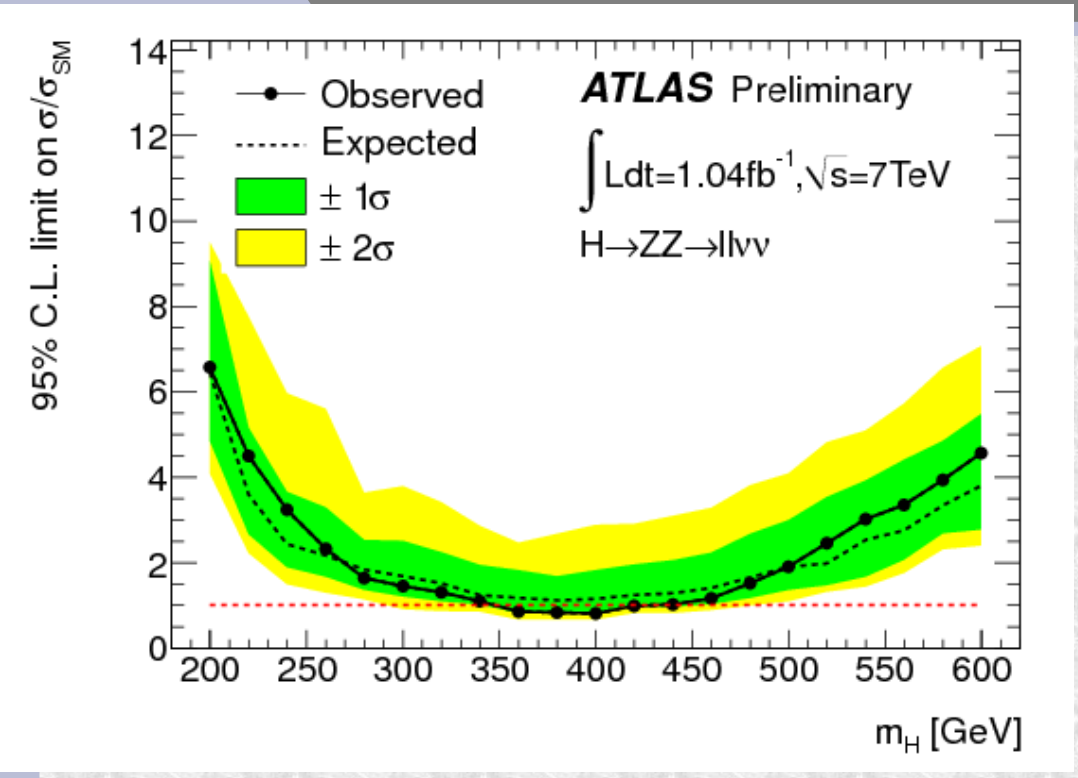
ZZ → llνν

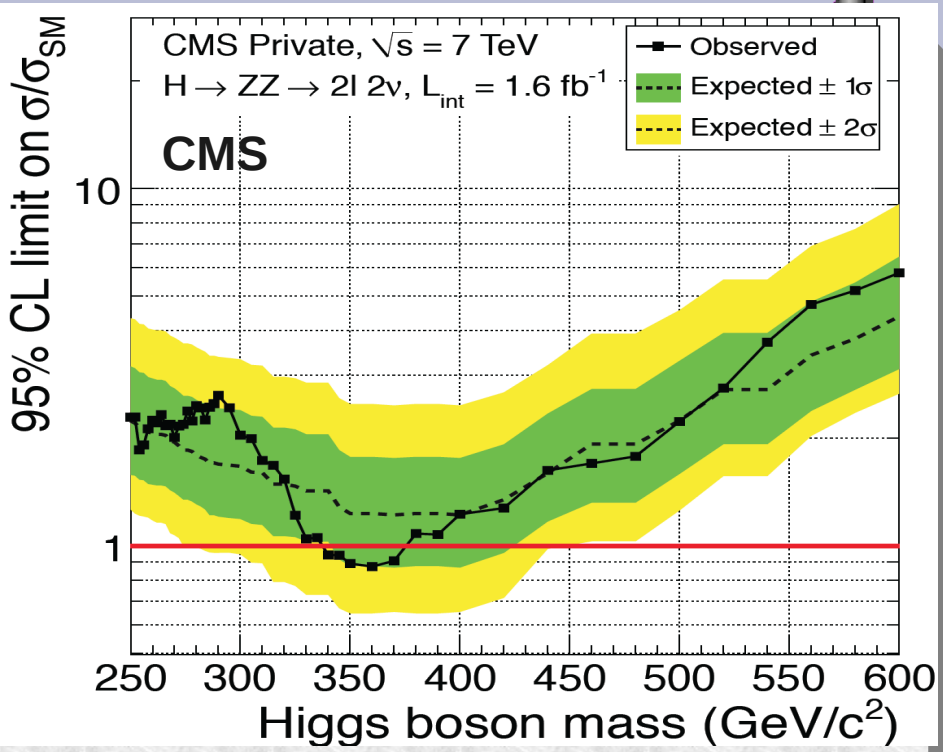




- ATLAS (left) and CMS (right)
- Harder E_T^{miss} and δφ cuts at high mass
- Each of these excludes the mass shown

ZZ → llνν

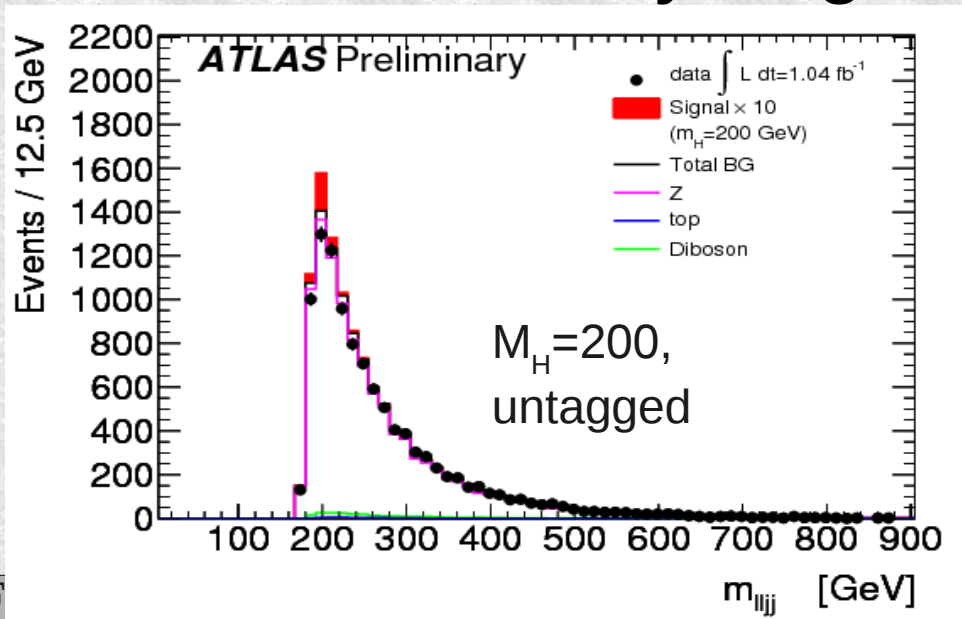


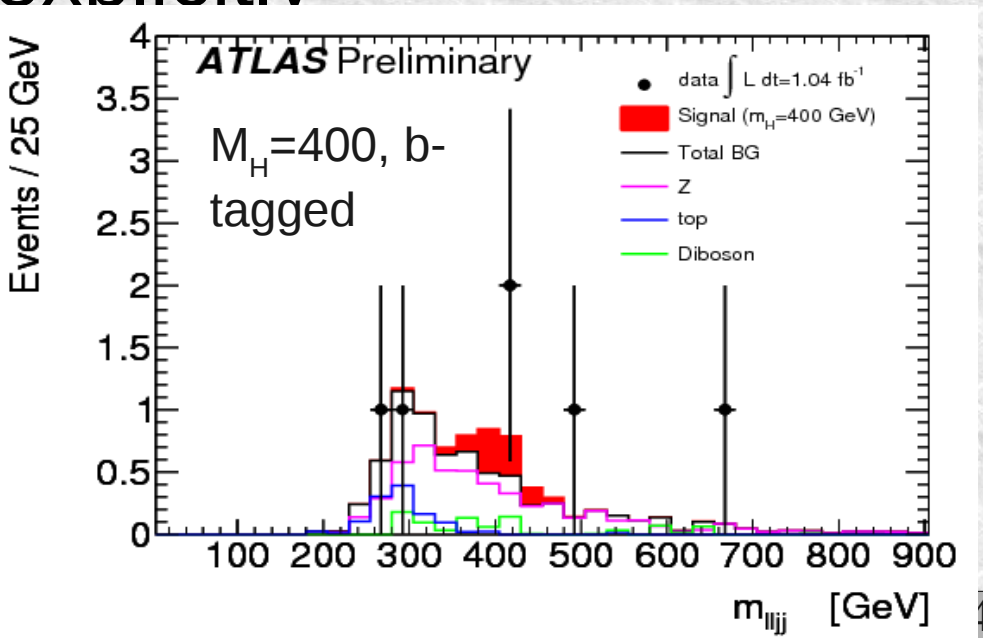


- ATLAS (left) and CMS (right)
- These searches exclude 100GeV wide region
- Both searches best sensitivity ~1.5xSM
  - Both got lucky

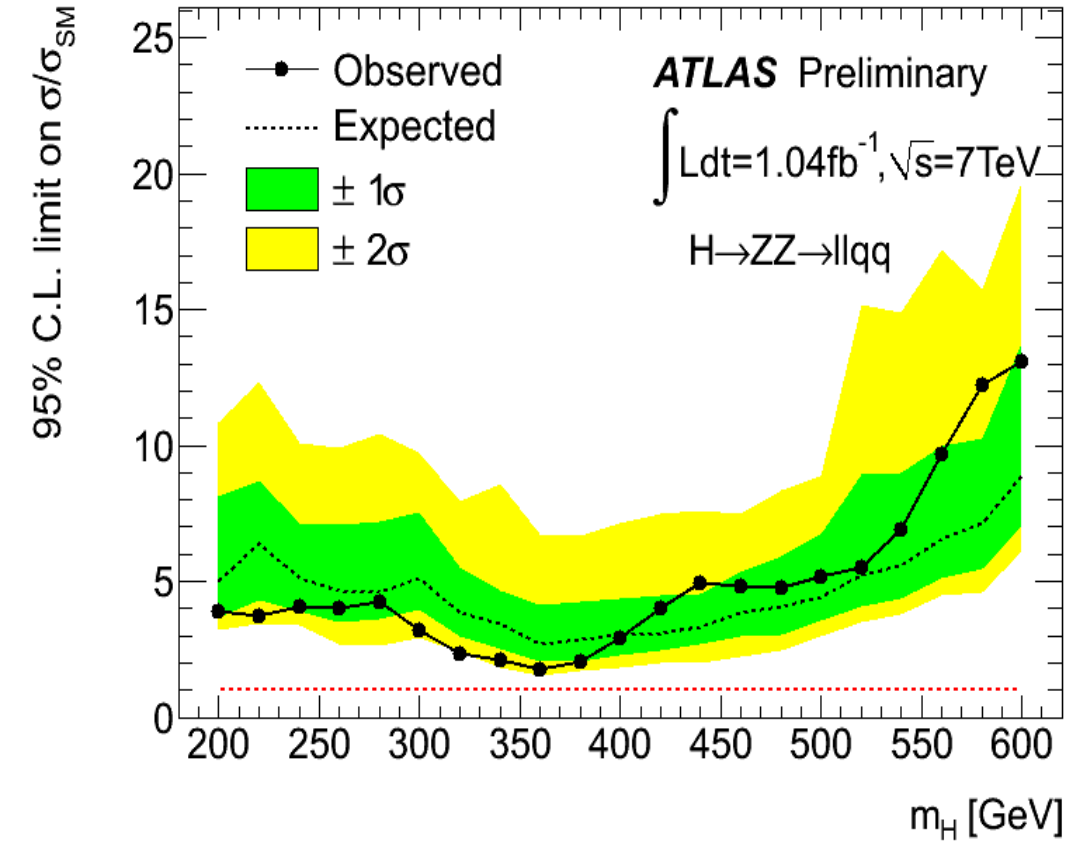
ZZ → llqq

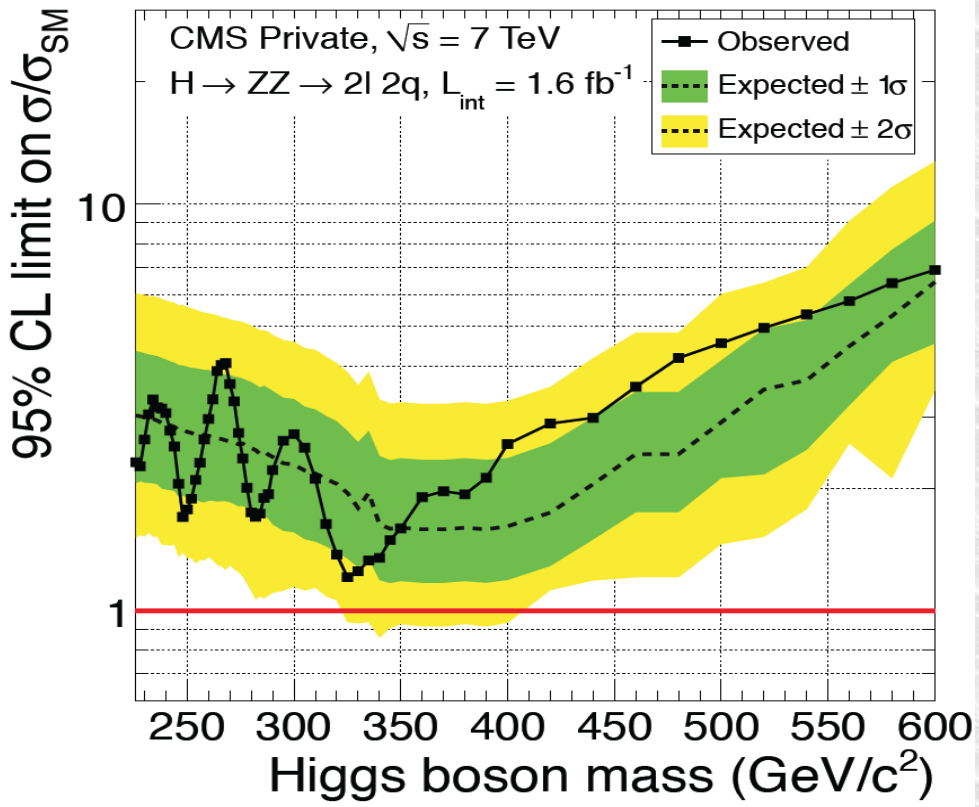
- Highest rate for a ZZ process
  - Good for Higgs boson mass over 200GeV
- Use 2/3 subchannels:
  - Z to light quarks (inclusively)
    - CMS use quark/gluon tagging to enhance signal
  - Z to b quarks
- CMS use decay angles explicitly





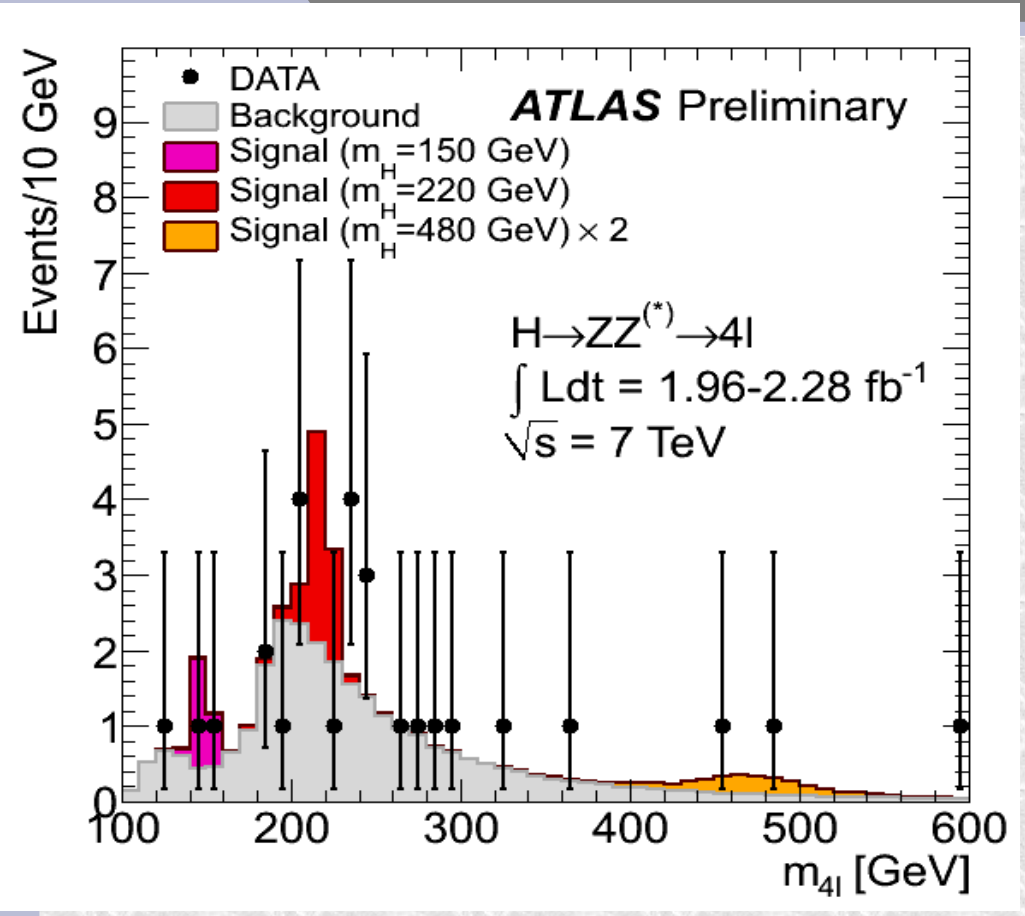
llqq

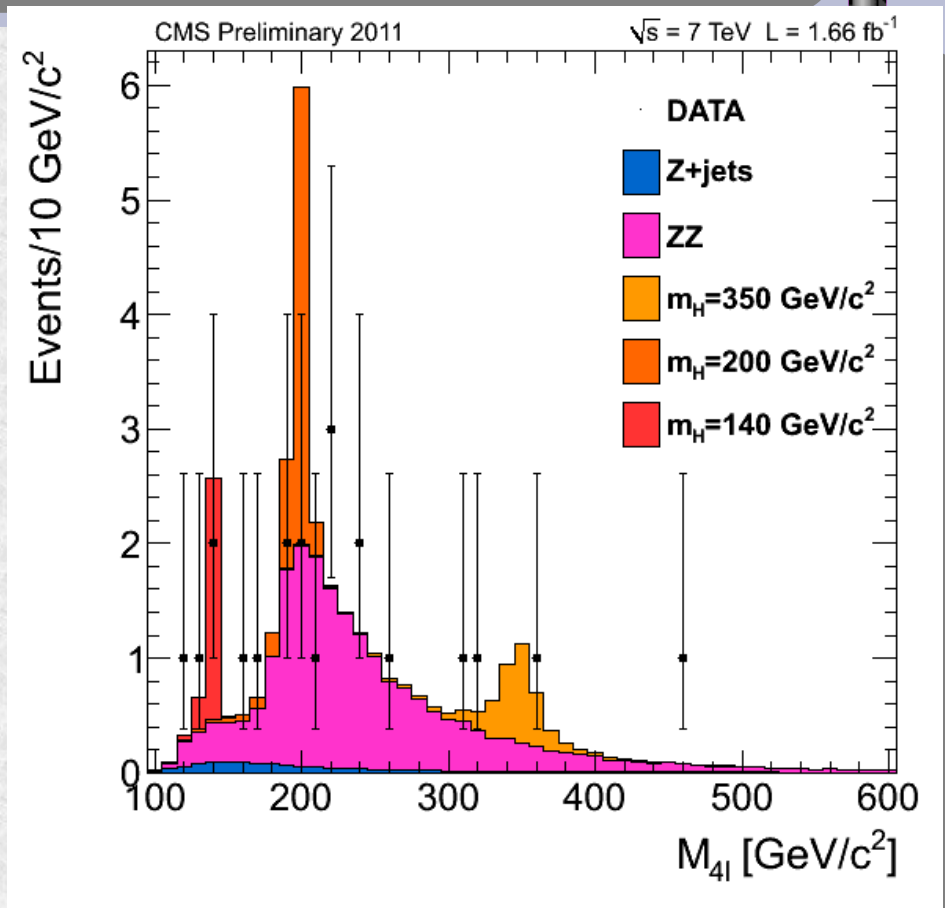




- CMS sensitivity 2xSM, ATLAS 3xSM at 350-400
- Fluctuations never up to 2σ

$ZZ^{(*)} \rightarrow llll$

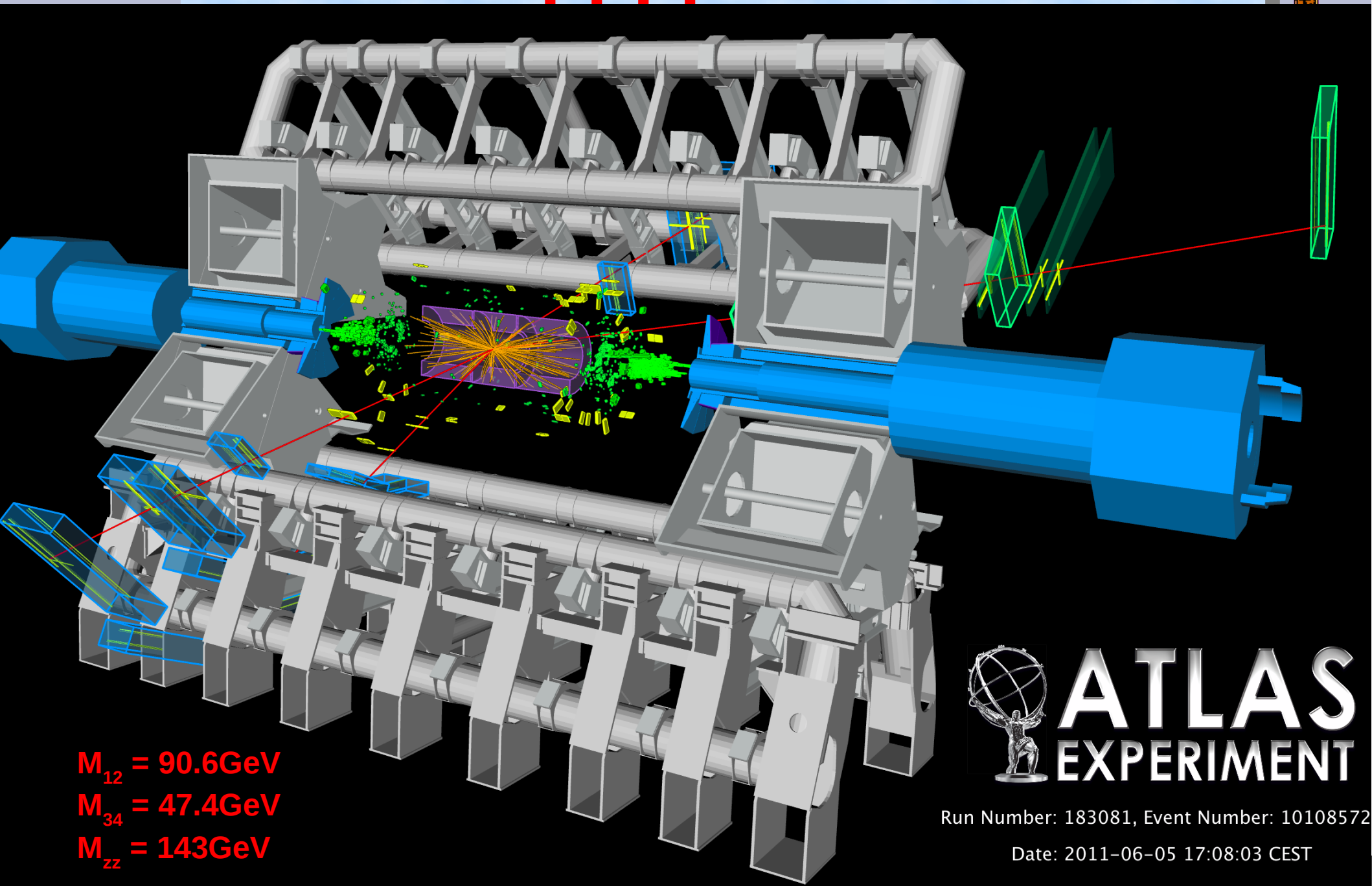




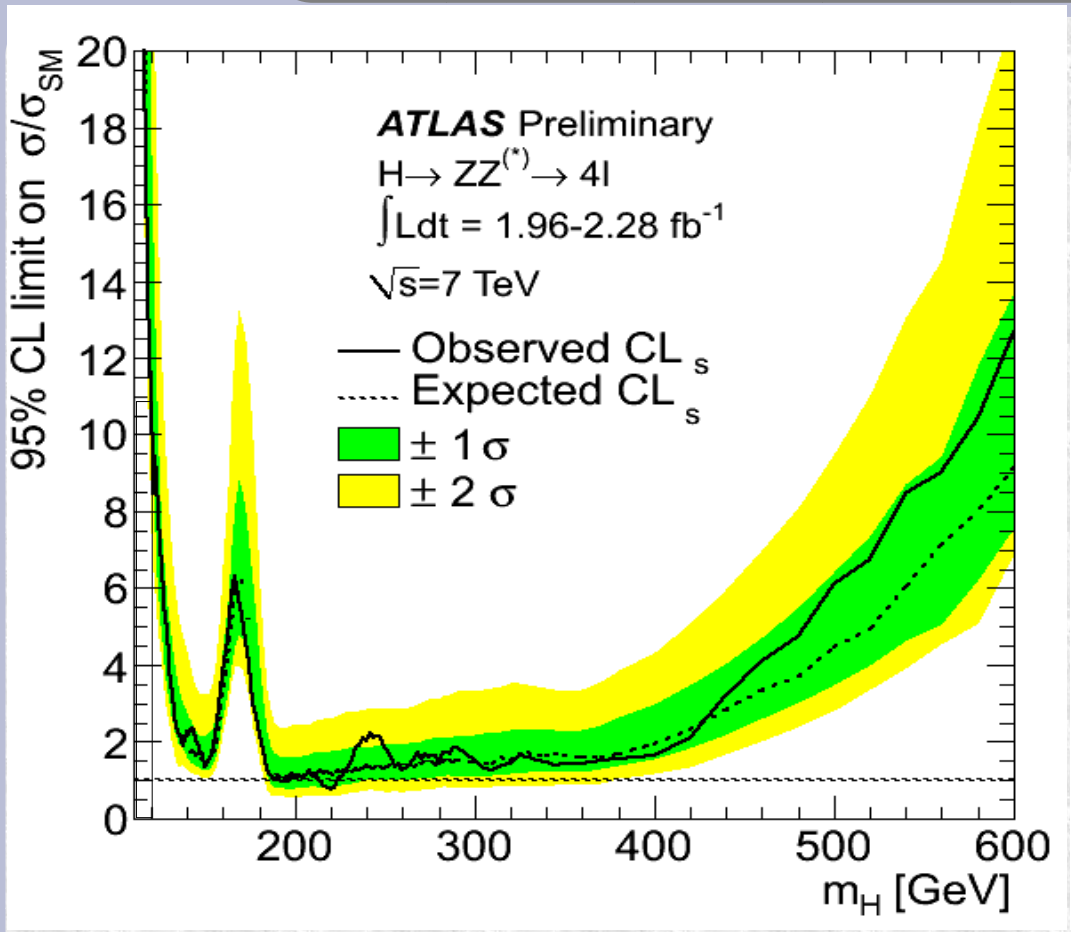
- Both experiments have local excesses
- But no new candidates below 150GeV since 1fb^{-1}

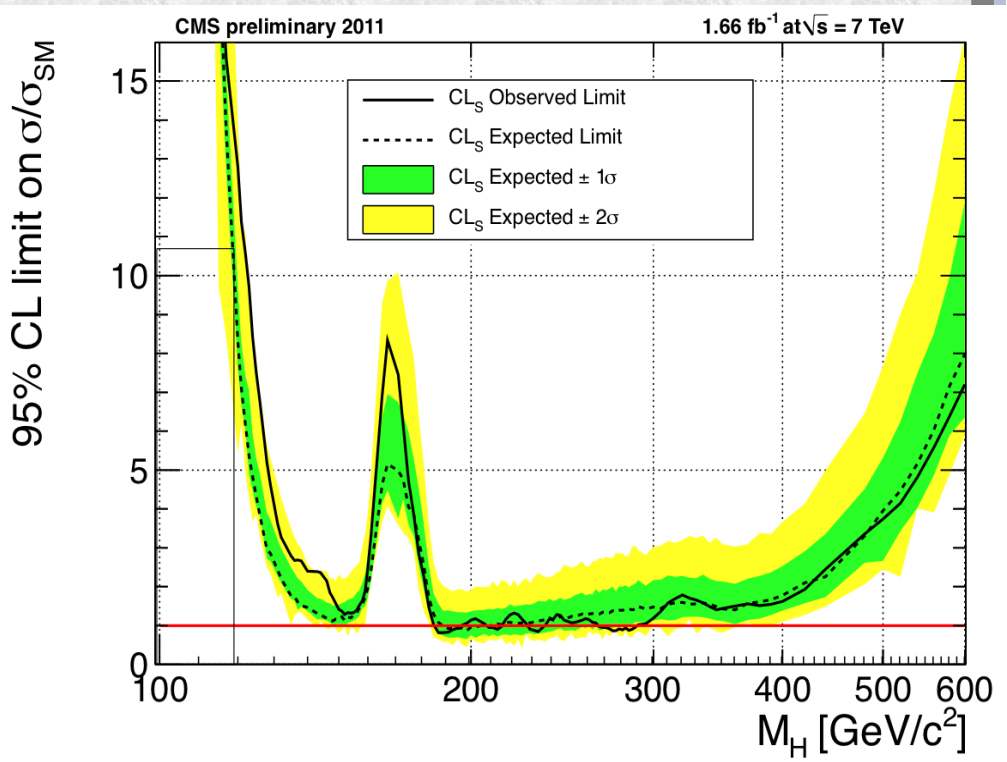
Science & Technology Facilities Council
Rutherford Appleton Laboratory

$ZZ^* \rightarrow \mu\mu\mu\mu$ candidate



$ZZ^{(*)} \rightarrow llll$





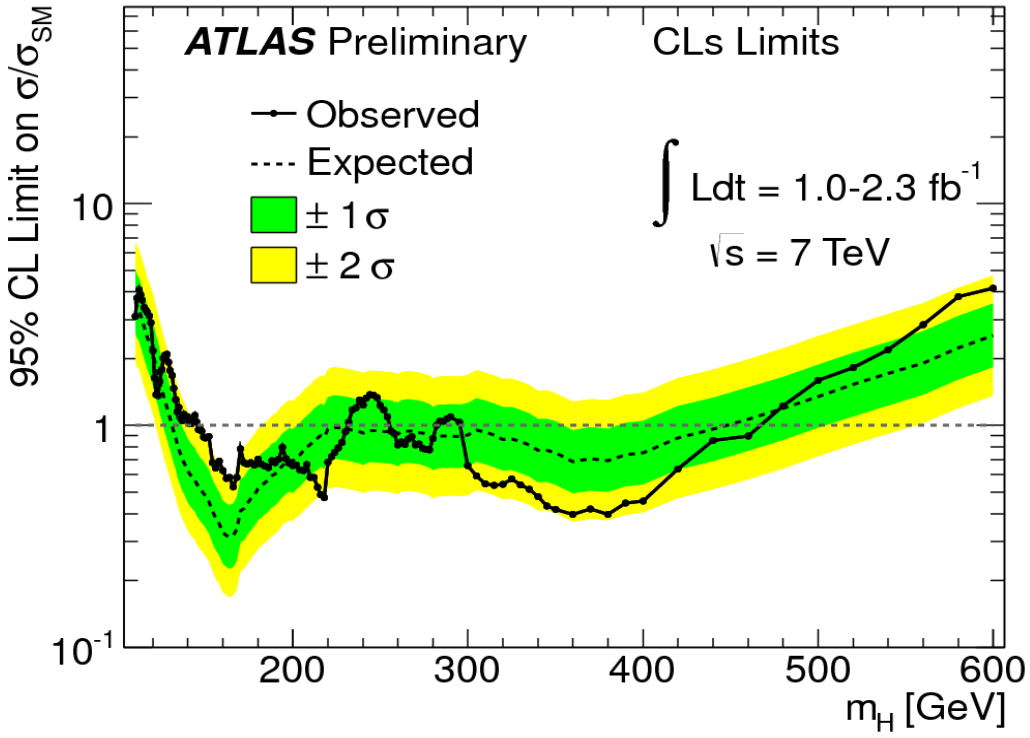
- Both experiments have small exclusions
- Soon this channel will have large ones
  - Some small differences in detailed comparison

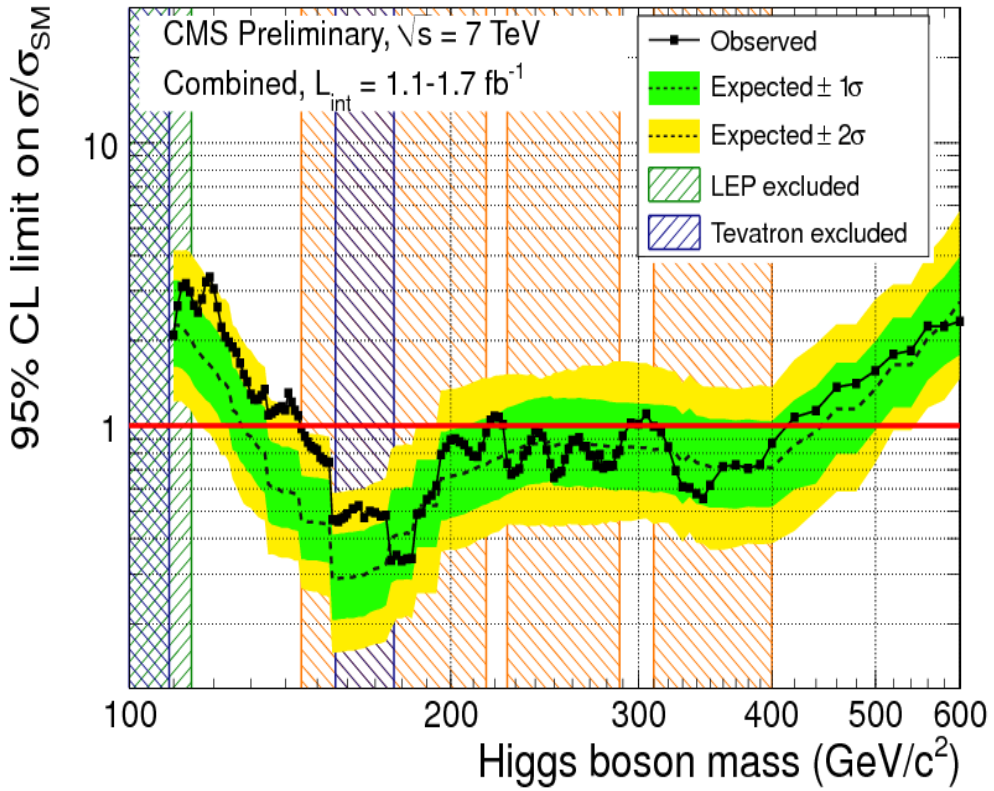
ATLAS / CMS combinations

- The SM Higgs is a very well-defined thing
  - Tell us the mass and we know the rest
- So we know what to expect in all these channels
  - We put them together for optimal sensitivity.
  -
- Needs precise understanding of the theory
  - LHC cross-section working group did a great job
  - We have an agreed set of rates to work with
- So what do the combinations look like?

The Combined Results

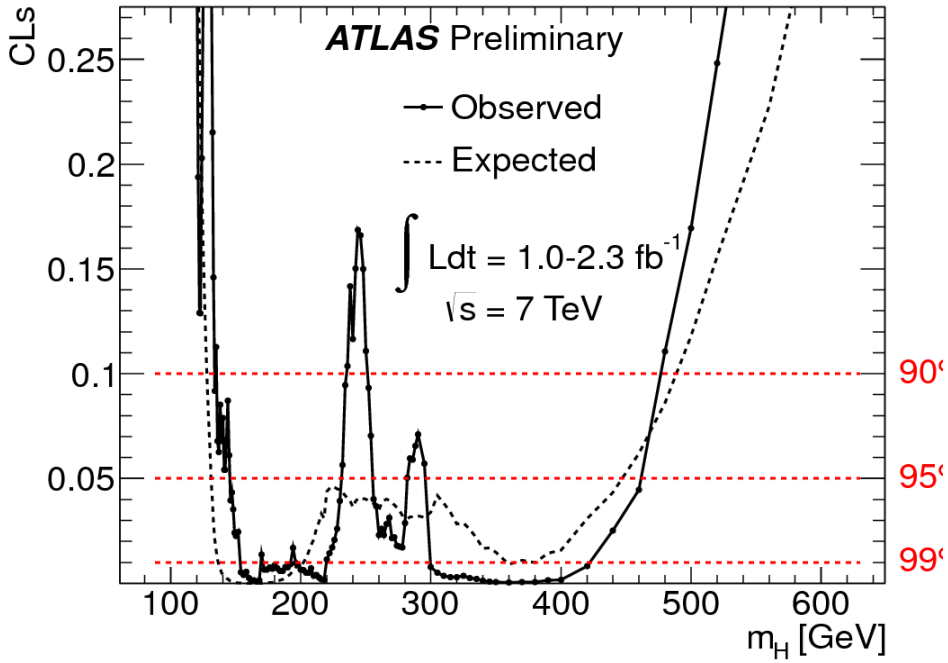
The Standard Model

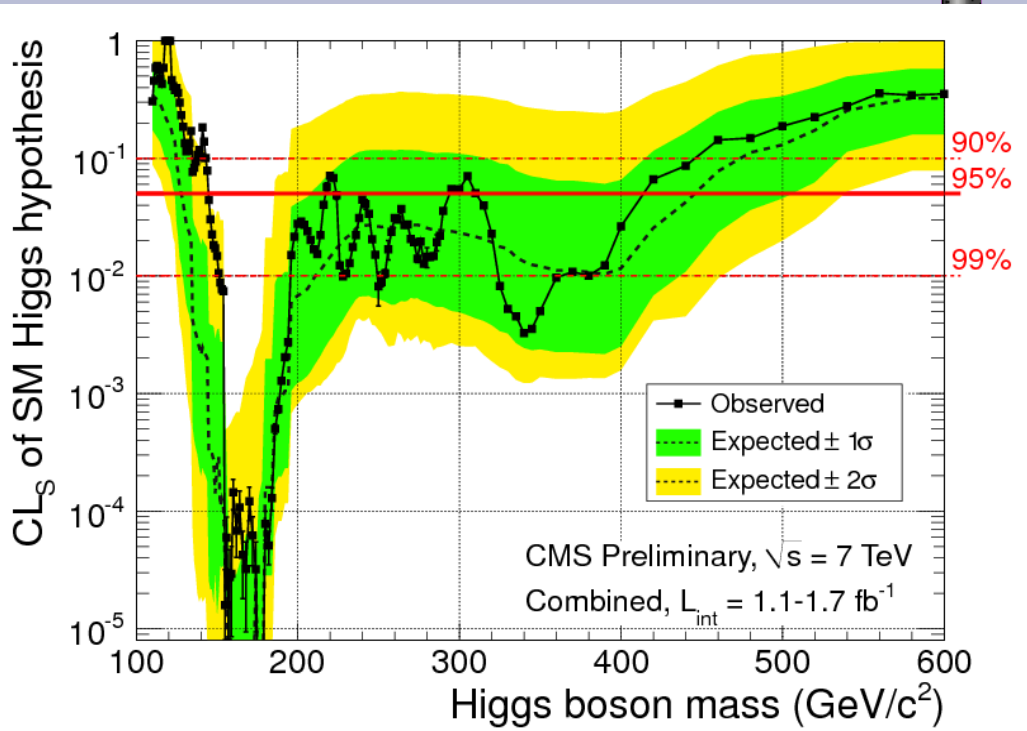




- ATLAS and CMS exclude 145 to 460GeV together
  - Islands (e.g. 300) not formally excluded, but are close
- Focus on 114-145GeV

How well excluded?





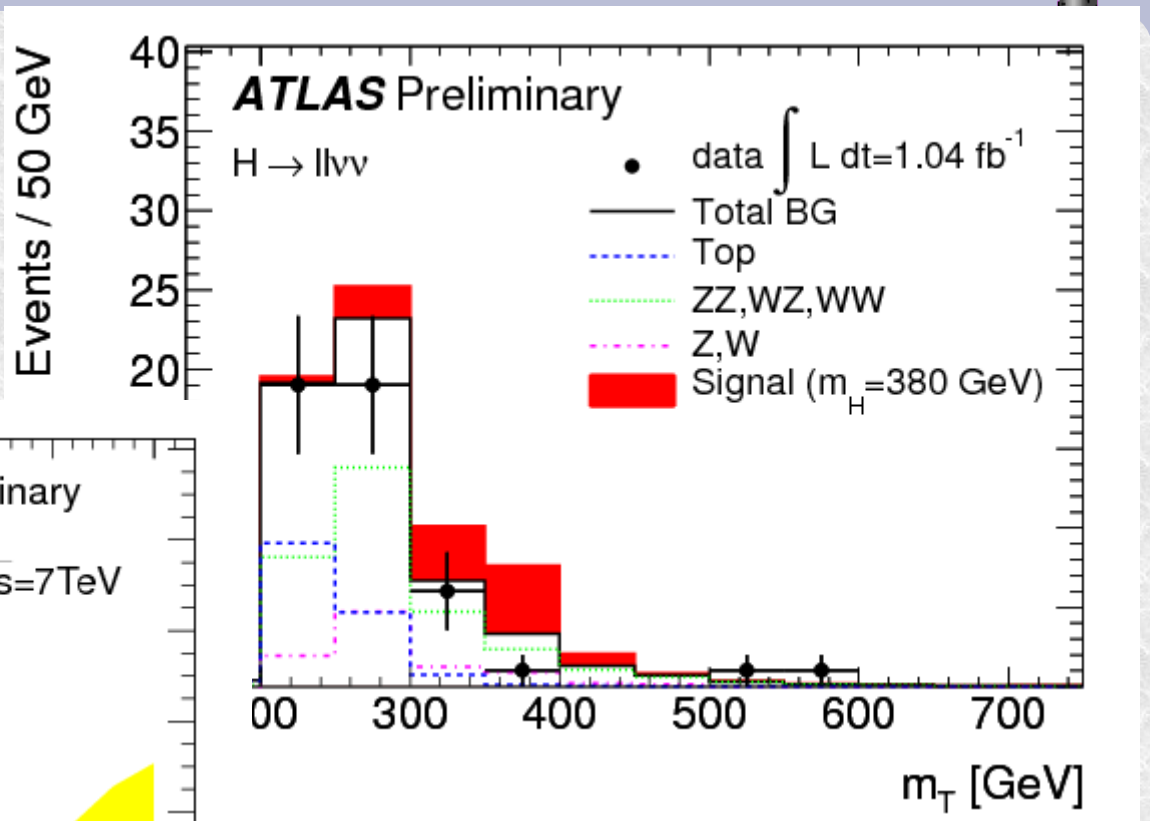
- All mH 140-500 disfavoured by both experiments
  - Need a combination to know how strongly
  - But the 'islands' seem to be in trouble
- Much is excluded at 99% or better
  - Soon, I guess, this will apply to a very wide region

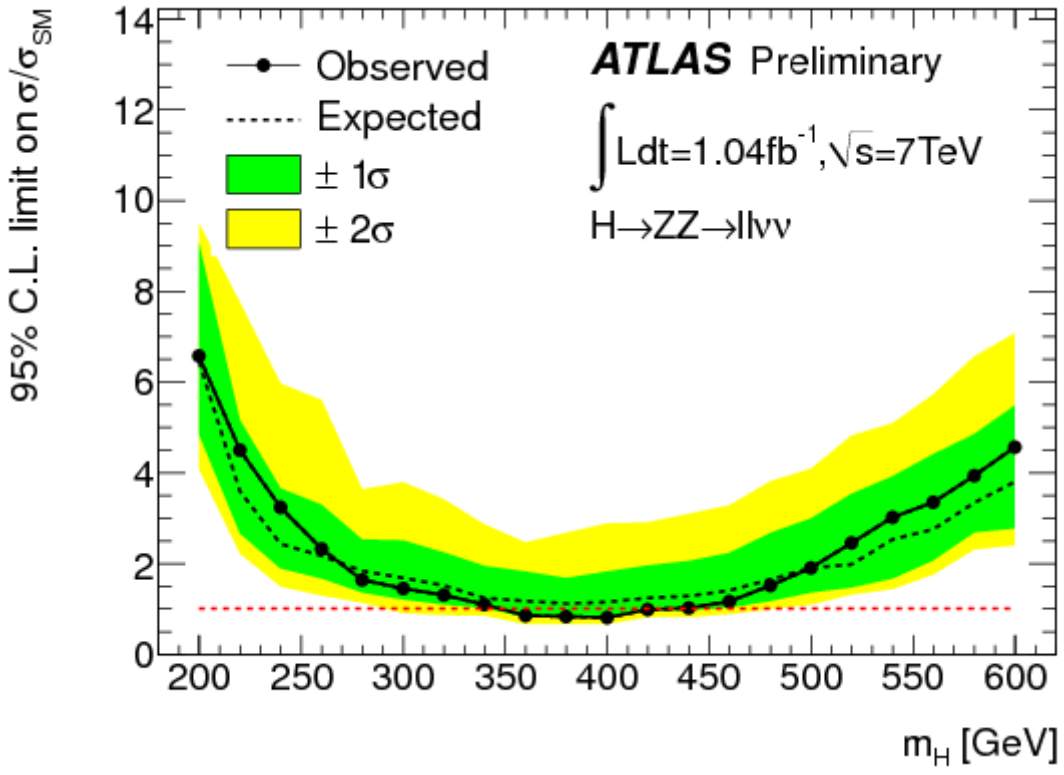
High mass Higgs?

- Exclusion goes up to 460GeV
  - There is in fact an excess beyond this in ATLAS
- This could be where the Higgs boson lies
  - Somewhat easier to get to 600GeV than to 114GeV
  - Doable with $4fb^{-1}$, combining two experiments probably needed
- But theory is becoming tricky
  - Four-fermion interference is not treated
    - See Reisaburo's talk from monday
  - The electroweak fits of course raise problems
- Will briefly discuss this option

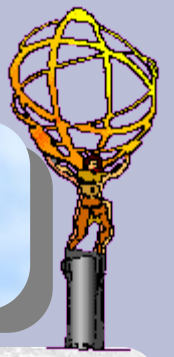
H → ZZ → 2l 2υ (l = e,μ)

- ATLAS & CMS best channel for m_H>300
- High mass almost background free





- Scaling faster than $1/\sqrt{l}$
- Should extend to 550+ by end of 2011

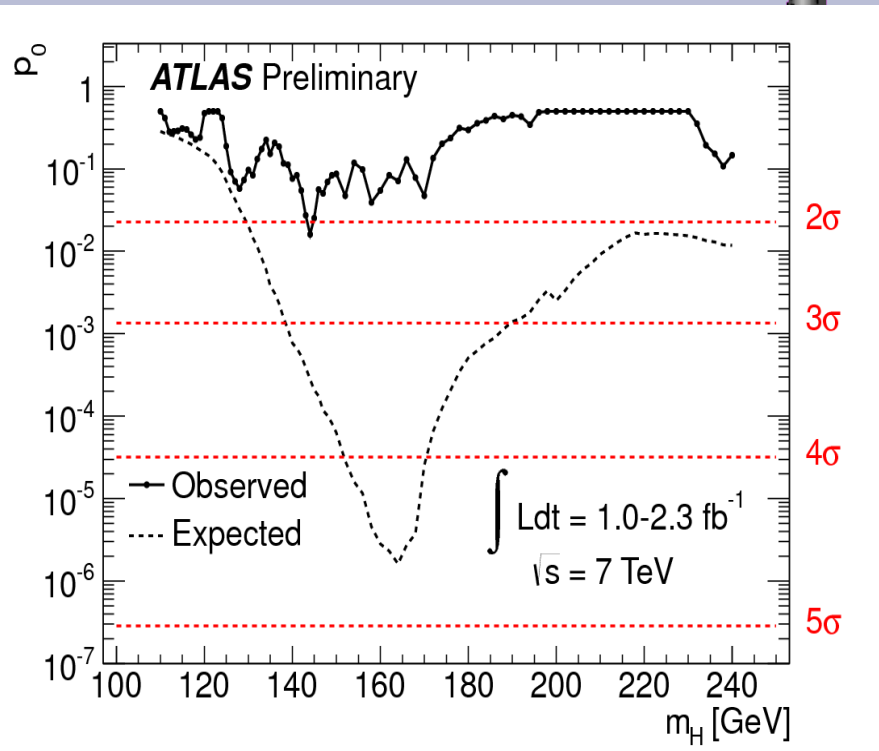


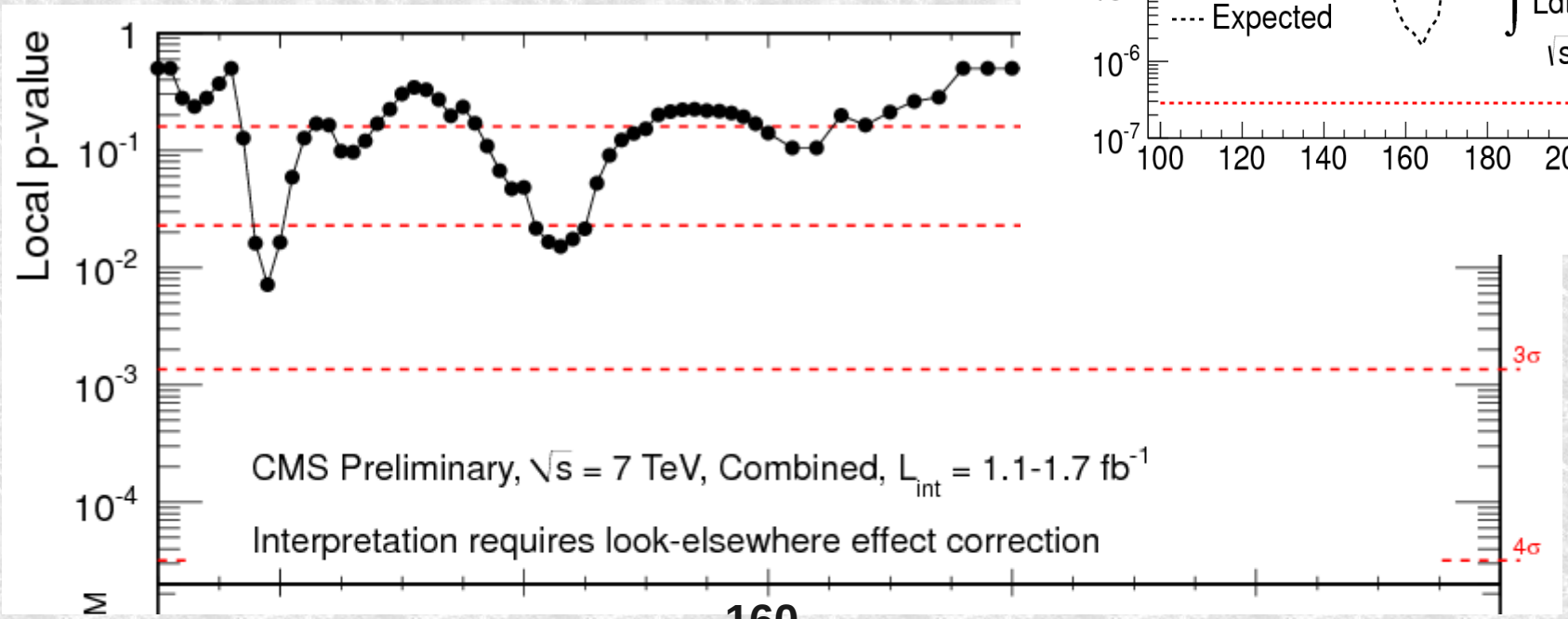
Low Mass

- The focus is now on the region below 145GeV
  - i.e. 114-145GeV
- The lower the mass the harder it is at LHC
  - Will look at 114 as example

Where might it be?

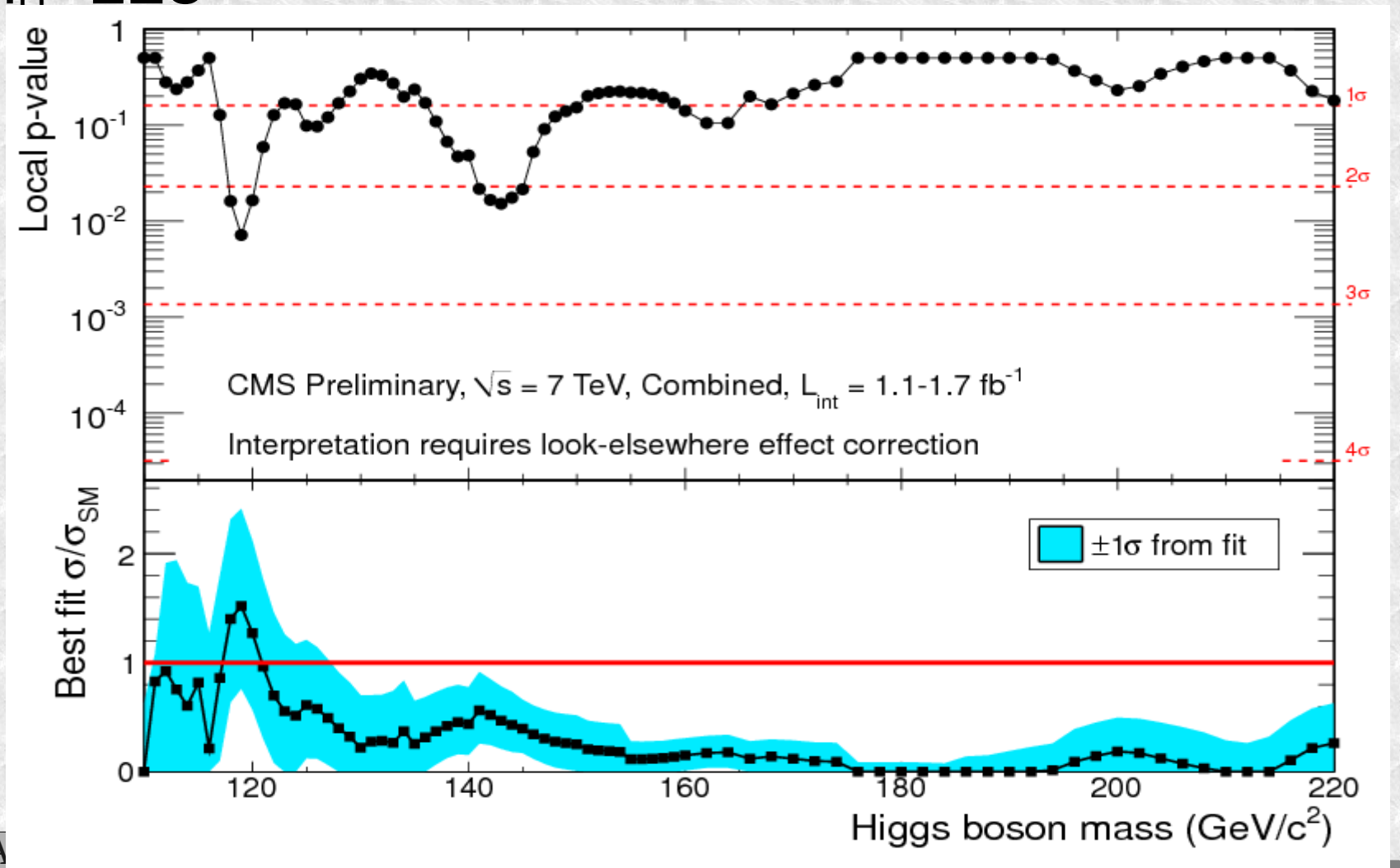
- Small excesses everywhere:
  - 114 to 144 both ATLAS+CMS
- With more data any point might look interesting
  - But...





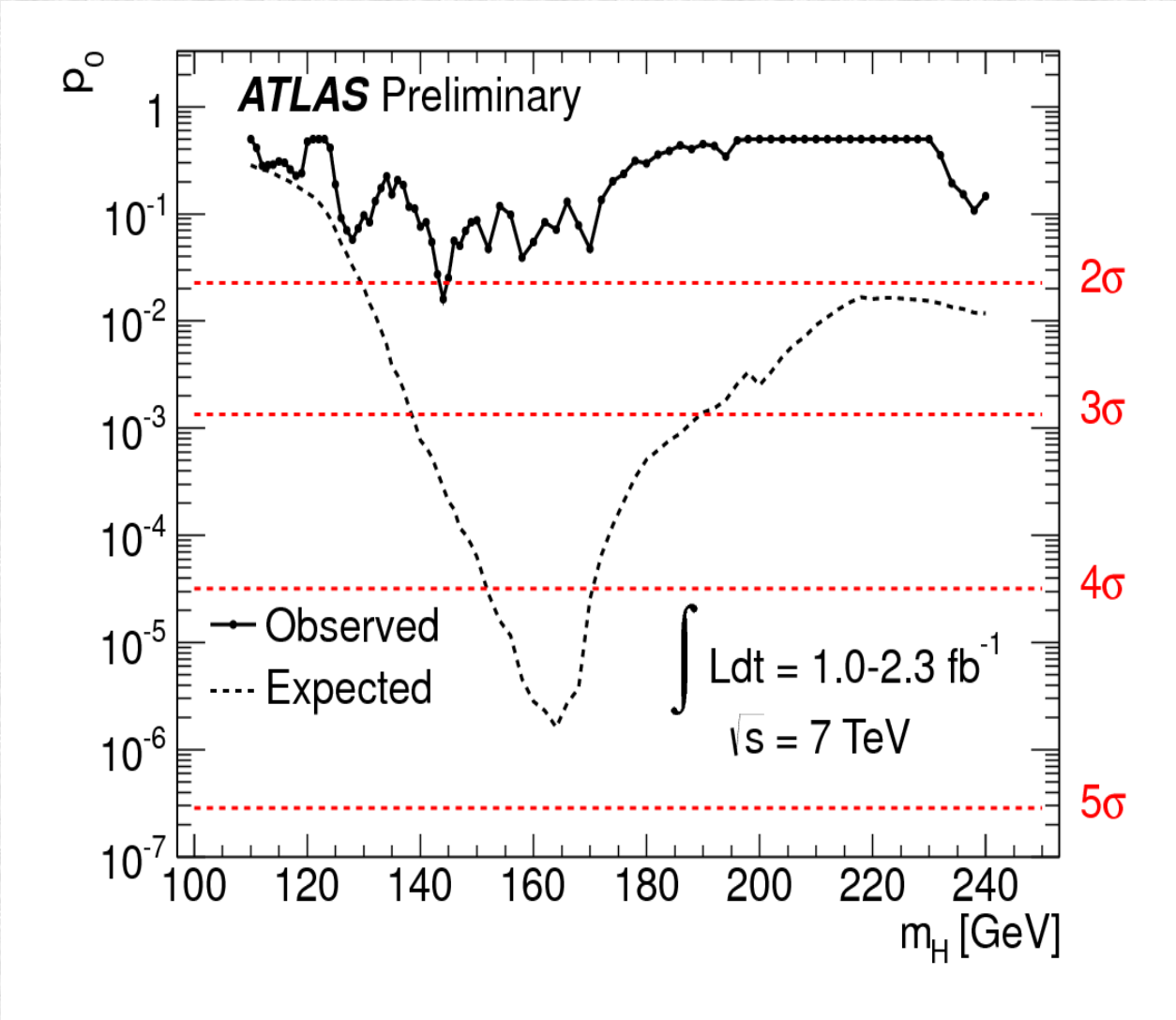
Where is Higgs hiding?

- CMS have significance below expected for m_H>125



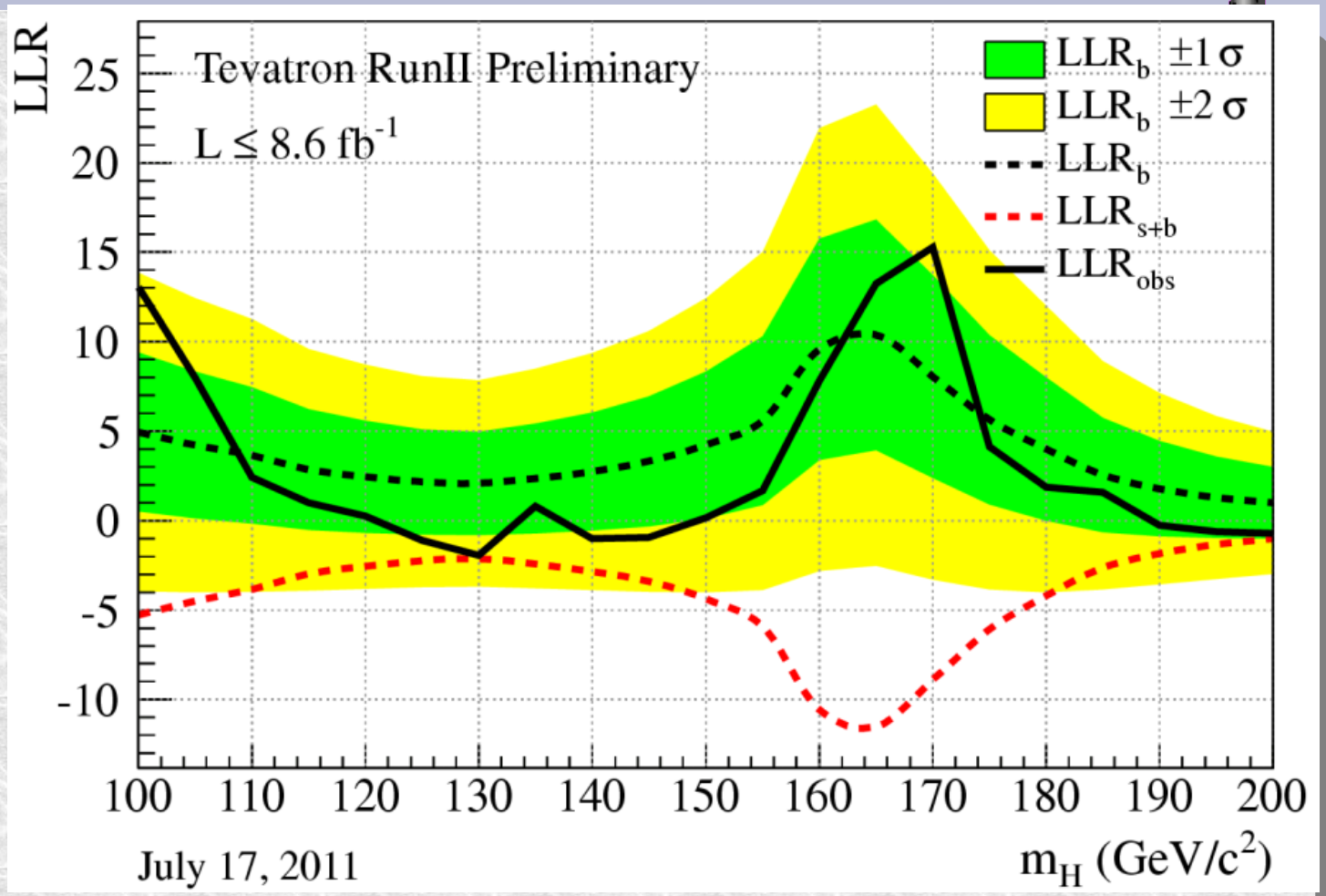
Where is Higgs hiding?

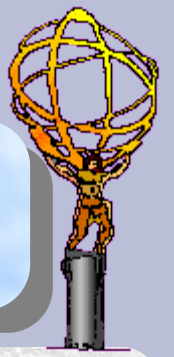
- ATLAS has a deficit c/f SM Higgs for almost all masses
- Not a lot, but 'unlucky'



Where might it be?

- What about the Tevatron?
- Also less signal than would be expected at all masses





So where is the boson?

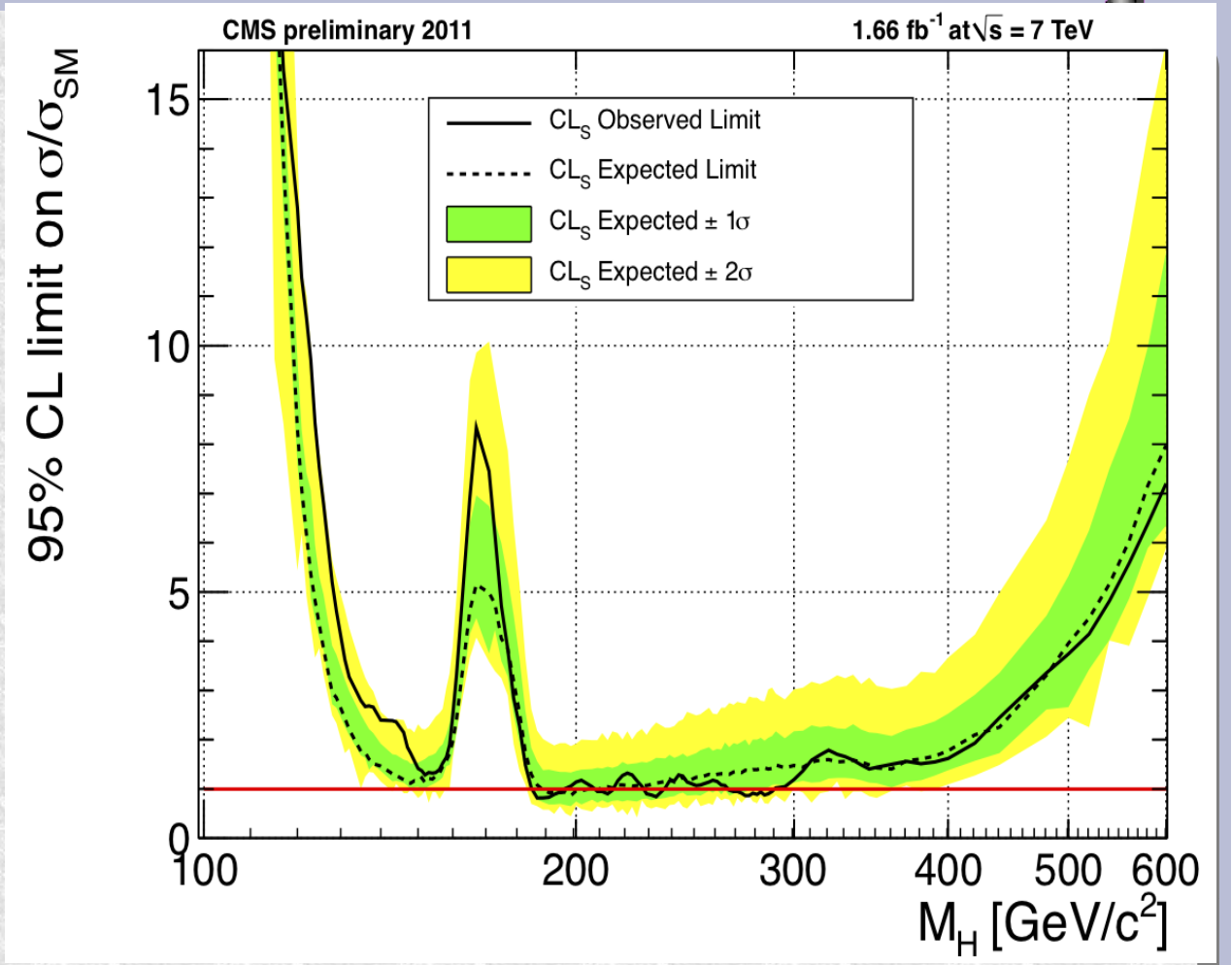
- The first fb^{-1} showed big excess over background
- The second fb^{-1} had little sign of anything
- The 3rd and 4th are an undiscovered country

- We have a lot of possibilities, and we should take nothing for granted.

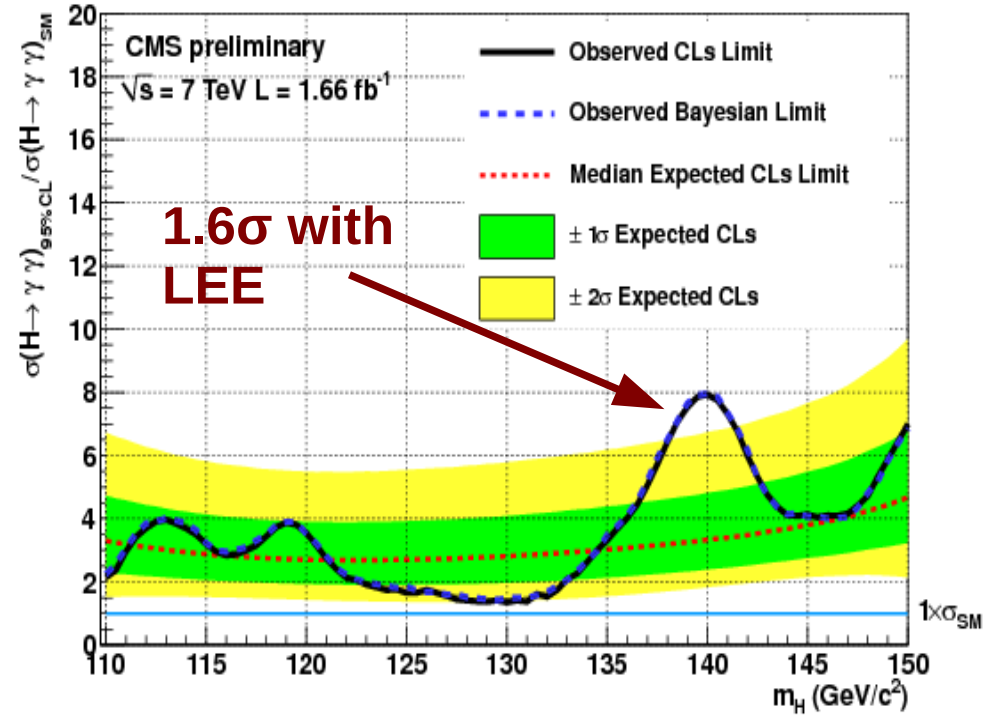
How do we progress?

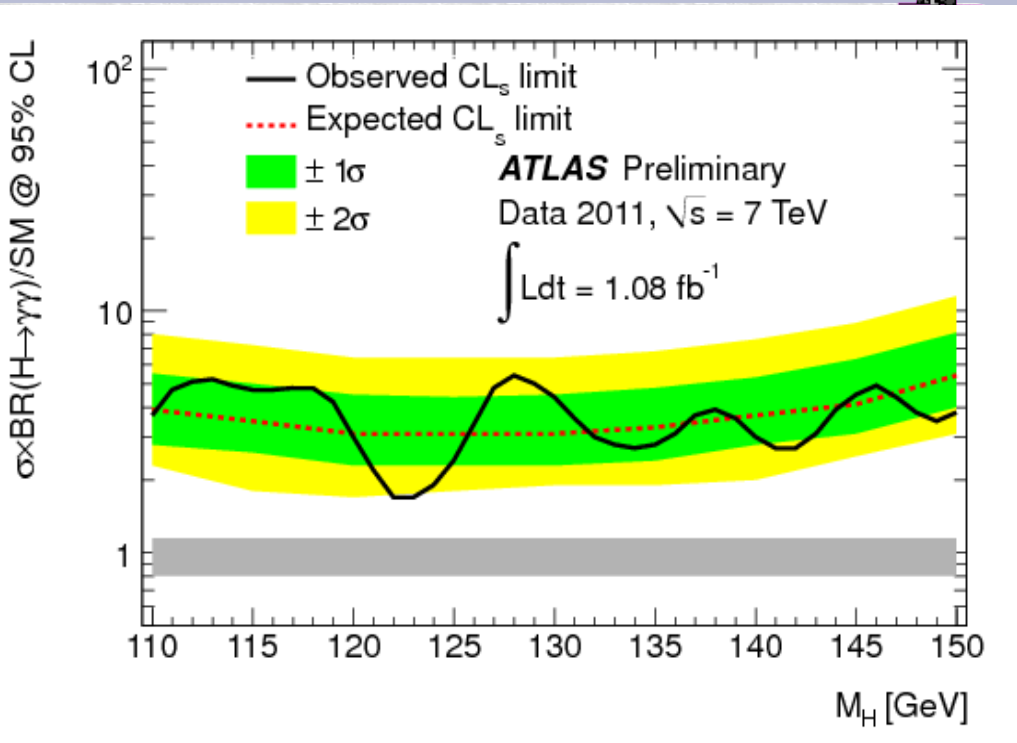
H → ZZ → 4l (l = e,μ)

- Golden channel is low rate for m_H<140
- Still improving faster than $1/\sqrt{\ell}$
- Need very low lepton p_T thresholds
  - Hard with pileup?



H → γγ

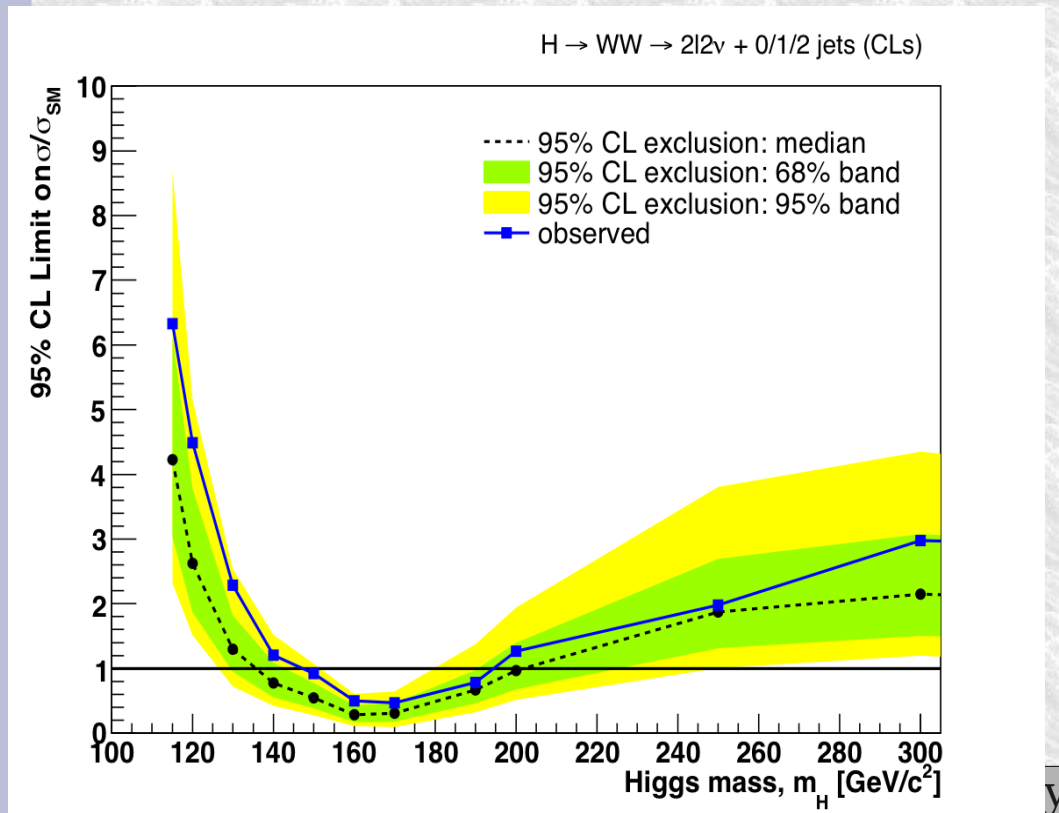


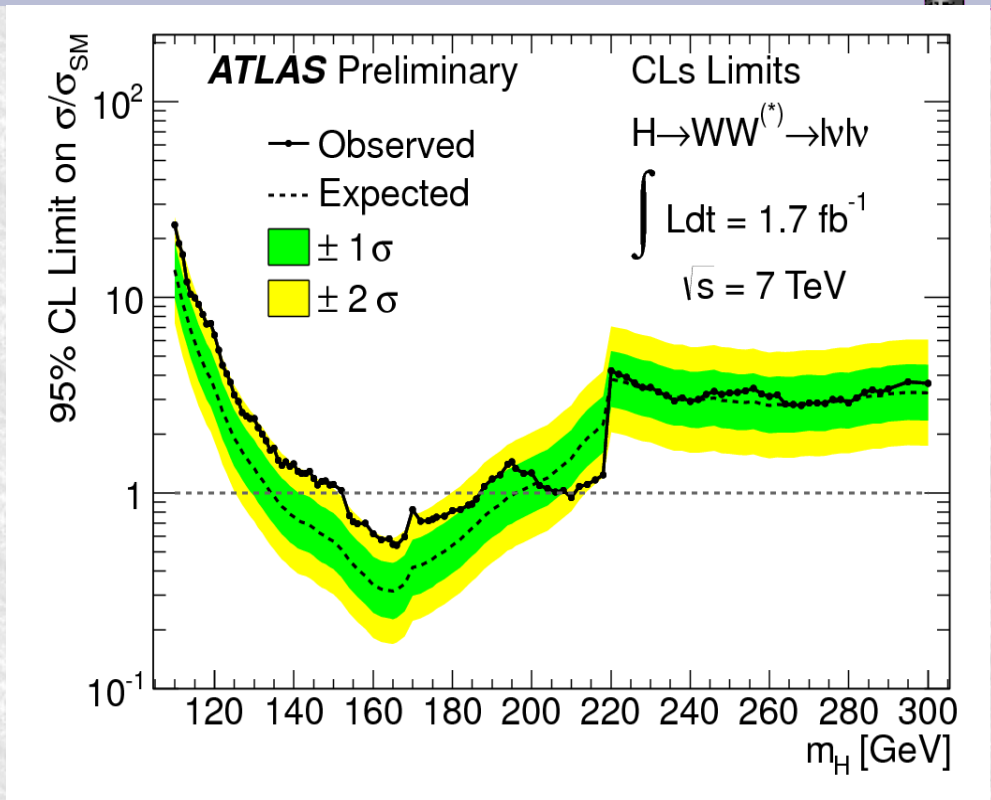


- Searches in categories
  - Detector resolution,
  - P_T – CMS only
- Not yet using cosθ*, n_{jets}, explicit η_{Higgs}
- Resolution is key work area for both experiments

H → WW

- CMS and ATLAS similar
  - Systematics important
- VBF not ATLAS
  - Not critical for low mass

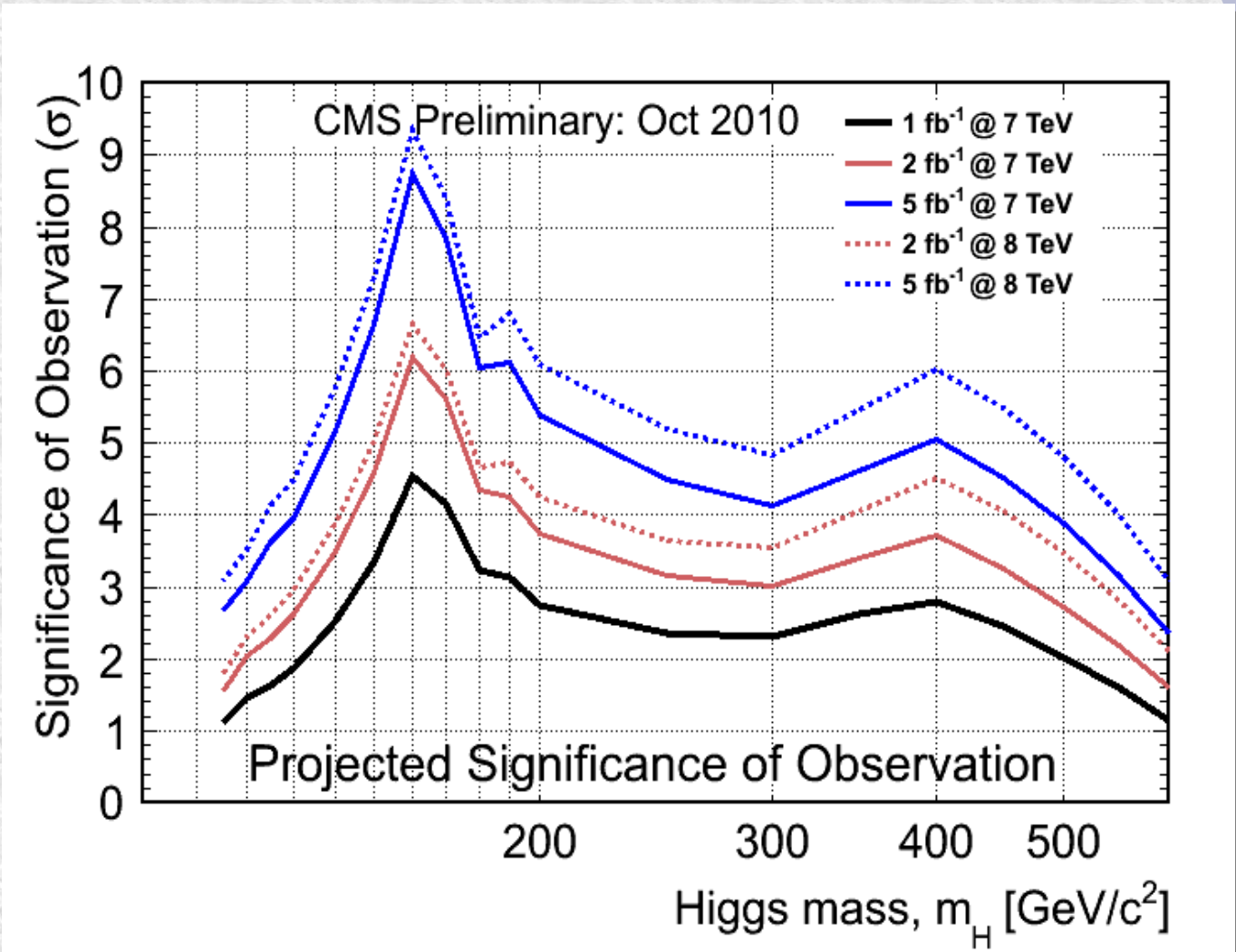




- CMS has lower p_T threshold
  - benefits 115GeV
  - 4x CMS vs 6x ATLAS

Signal significancee

- 5fb^{-1} has large sensitivity in each experiment
- Projections slightly optimistic at 115
  - Need γγ resolution!
  - Or SM cover needs combination



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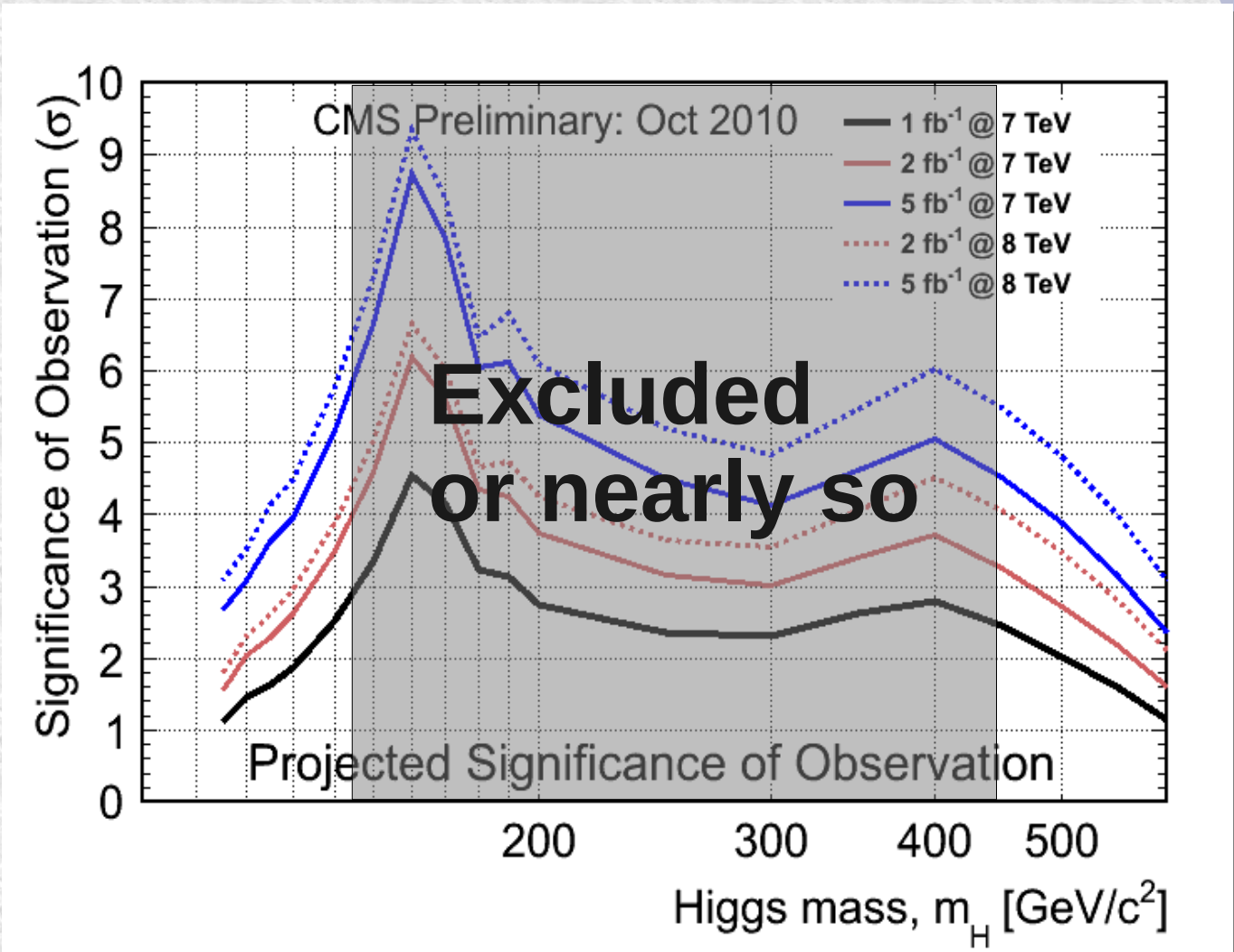
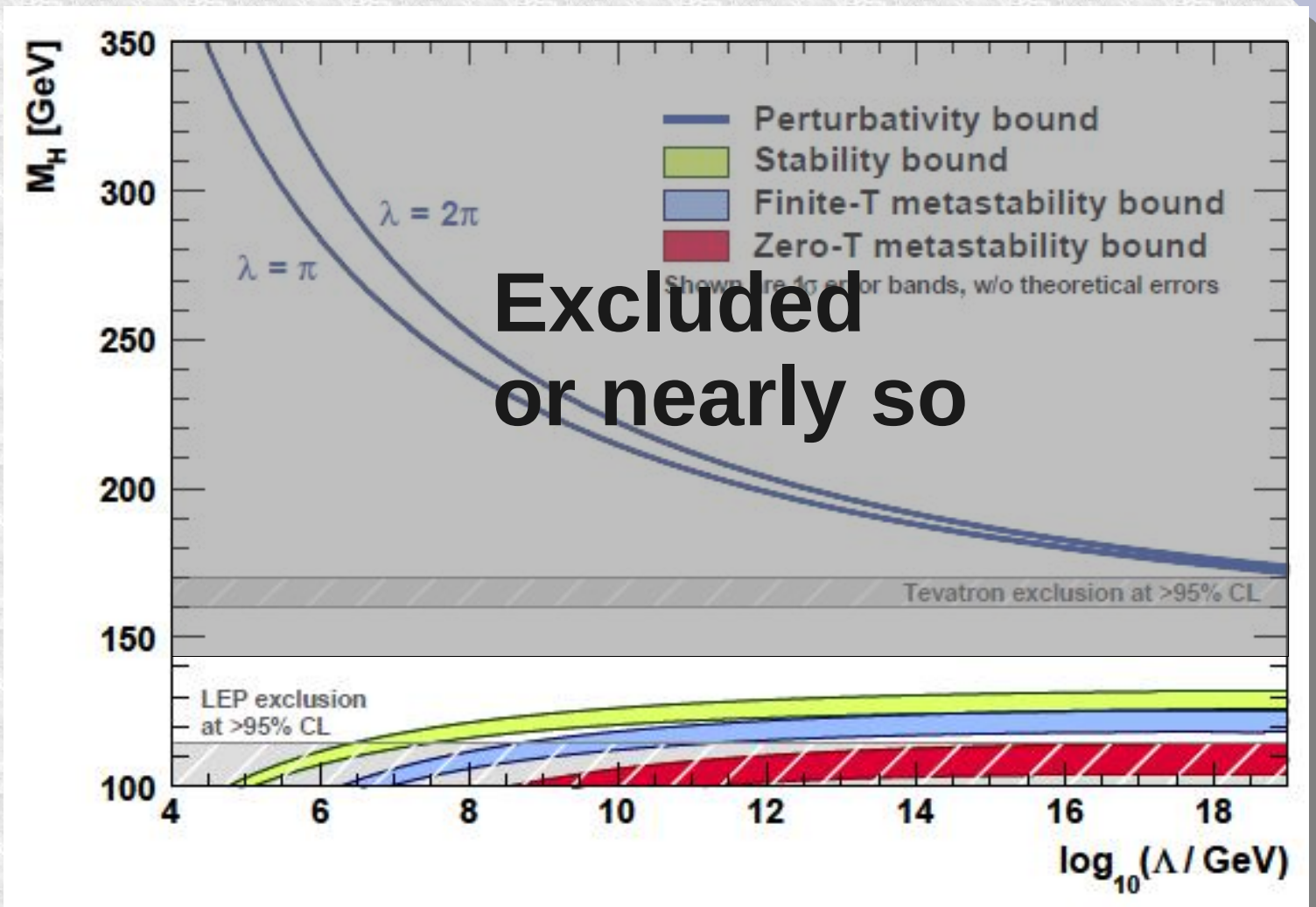


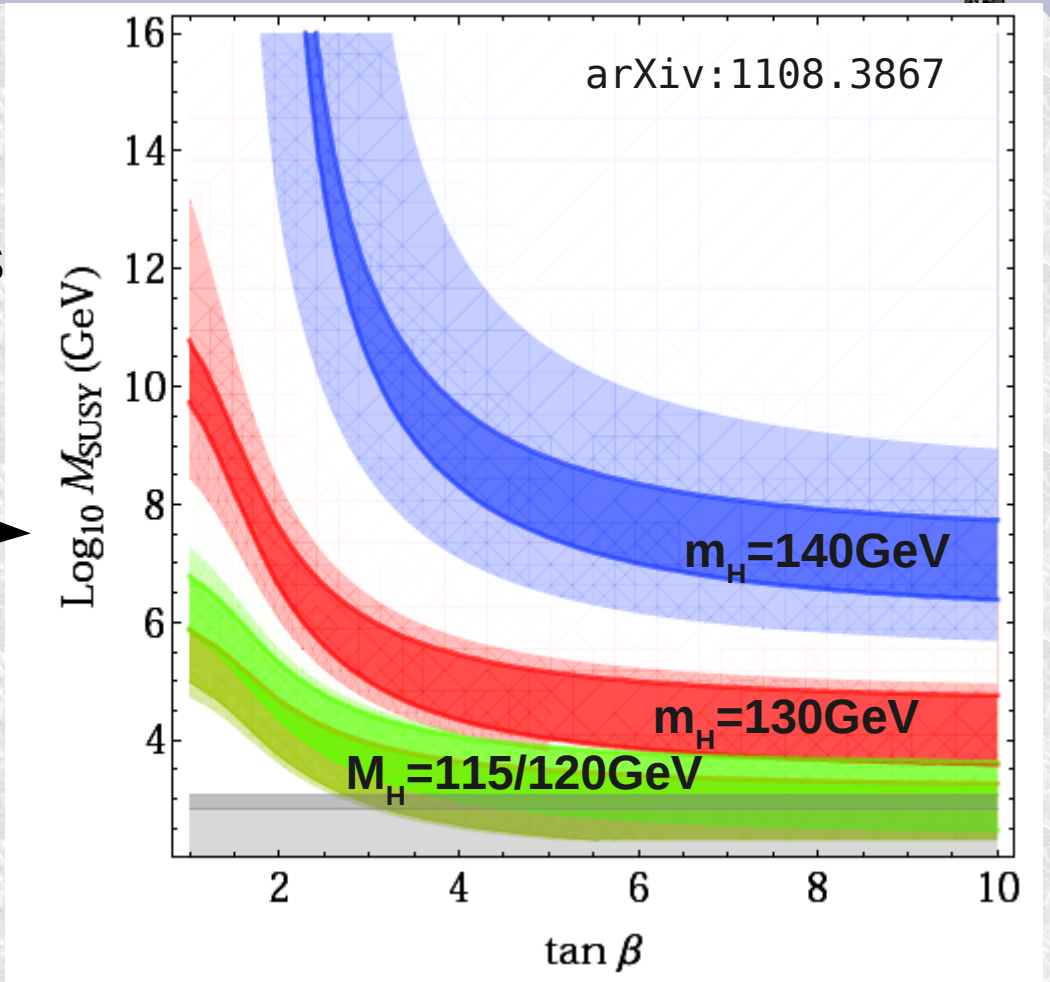
Higgs Stability

- Only small stable region left
- Are we heading into region where Higgs demands new physics?
- Know very soon!



Upper bound on M_{SUSY}

- The lighter MSSM scalar is below m_Z
  - Before radiative corrections
  - from m_{top}
  - and M_{SUSY} ($\approx m_{STOP}$)
- Implications for M_{SUSY} from measuring m_H are shown
- Grey band is search limit
- M_H=130GeV or above does not exclude SUSY – but it makes it experimentally inaccessible



The better news

- Many channels contribute to low mass discovery
  - H→γγ
    - Gluon fusion, VBF, vector boson associated
  - H→ZZ
    - Gluon fusion
  - H→WW
    - Gluon fusion, VBF
  - H→ττ
    - VBF
  - H→bb
    - Vector boson/top associated
- Measurements studies follow discovery fast
  - Checking the Higgs properties will be possible
    spin, parity, Br....

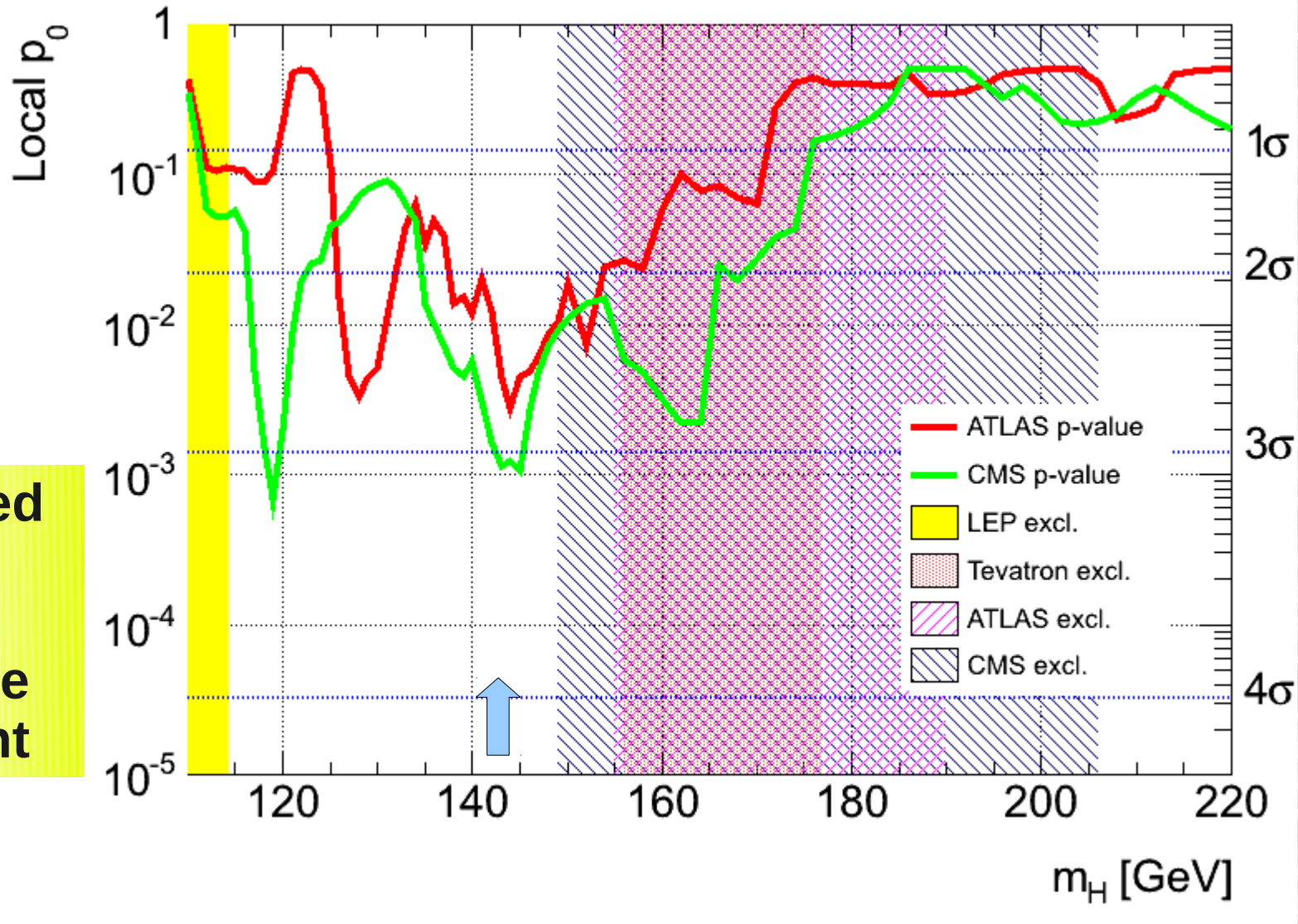
Summary

- The SM Higgs range has been massively reduced
  - 145 GeV to 460GeV has only small islands
    - The 'desert' is looking unlikely
  - Thanks to the LHC people who made it possible
- 2011 has produced 2.5fb^{-1} so far
  - possibility to double it in last few weeks?
  - Record luminosity today, 2.7x10^{33}cm^{-2}s^{-1}
- 5fb^{-1} at 7TeV should give ATLAS/CMS
  - Over 2σ Higgs evidence COMBINED for any mass
  - 3σ for all bar 115

Summary 2012

- Running in 2012…
  - Assumed order of 15fb^{-1}
- LHC combination will offer 5σ sensitivity to many SM Higgs
  - Unless m_H~115; then 3.5σ+
- Convincing evidence for absence?
  - In which case many BSM models will be explored

P-values at low mass



Some correlated uncertainties

Look-elsewhere effect important