LHC Higgs

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On behalf of the
ATLAS and CMS collaborations

Euro. Phys. Soc.
Grenoble
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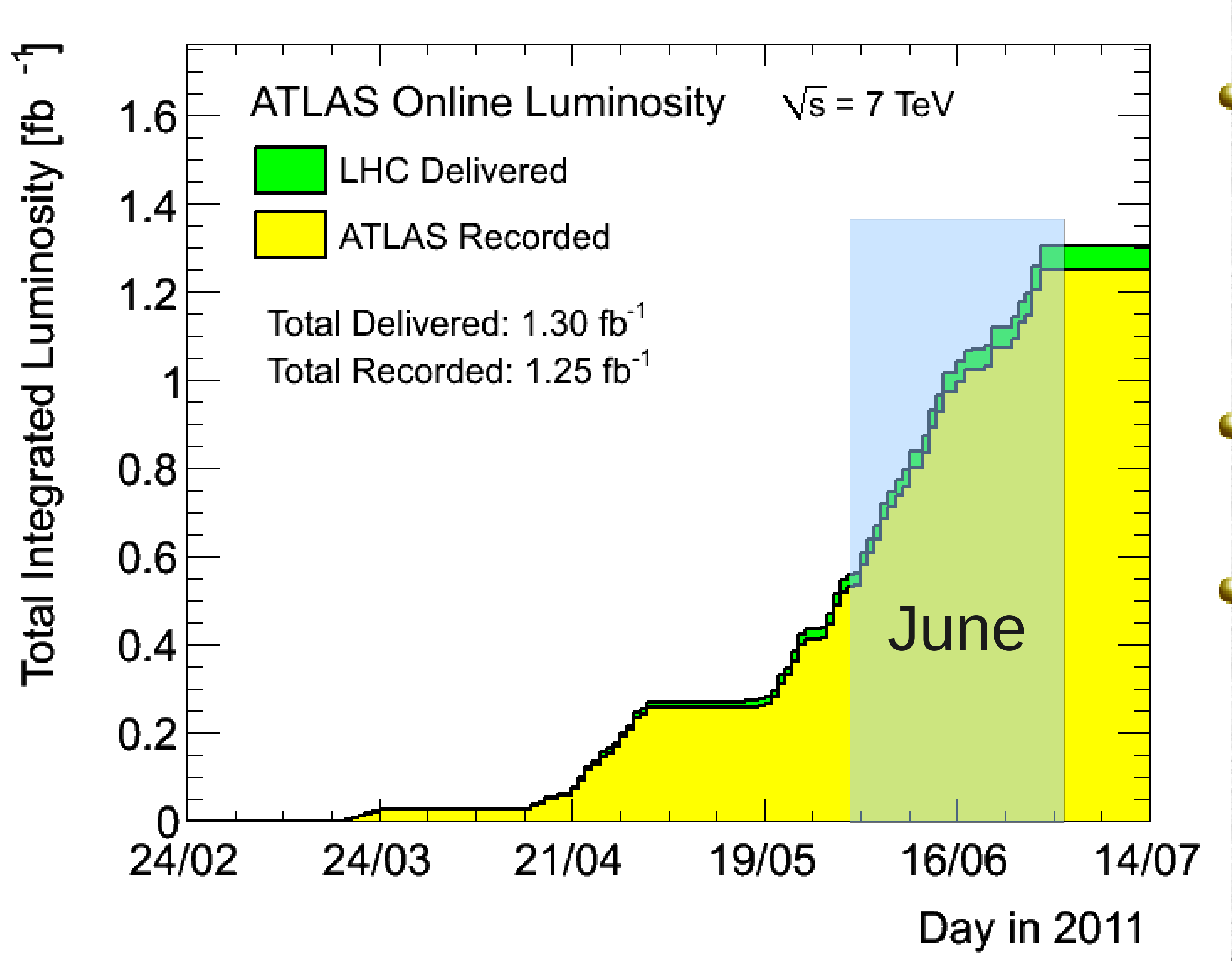
- What is LHC sensitive to?
- Are there any hints?

First: thanks to LHC people!

- ATLAS and CMS asked for $1 fb^{-1}$ for this meeting



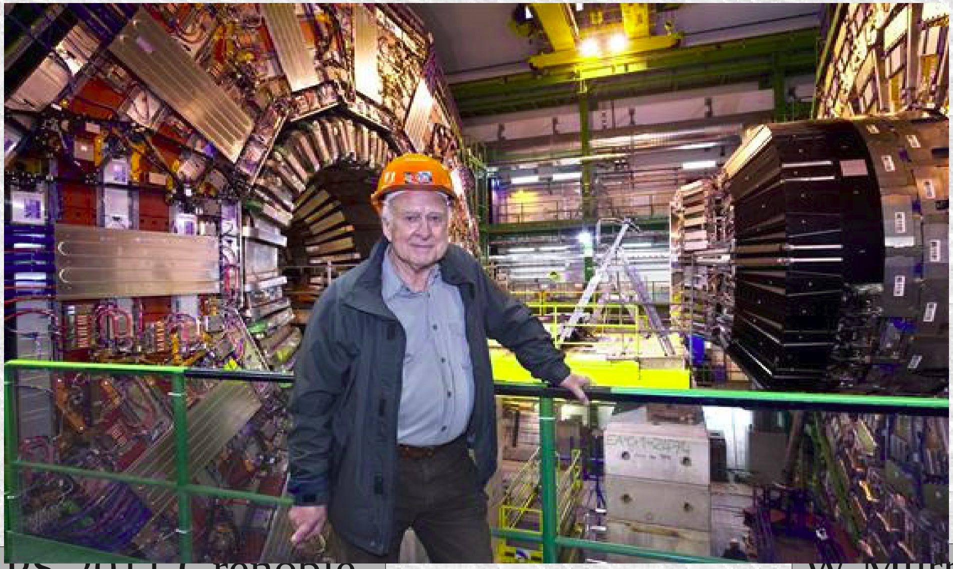
- Steve and all his friends delivered – and more
- Most of it in June
- We have only started digesting this rich meal

Outline

- SUSY Higgs searches
  - 5 Higgs bosons to look for...
  - $H^+ \rightarrow \tau\upsilon$
  - $H^+ \rightarrow cs$
  - $A/H \rightarrow \tau\tau$
- Standard Model searches
  - Low mass (110-130 GeV)
  - Moderate mass (130-200 GeV)
  - High mass (200Gev+)
  - Combination

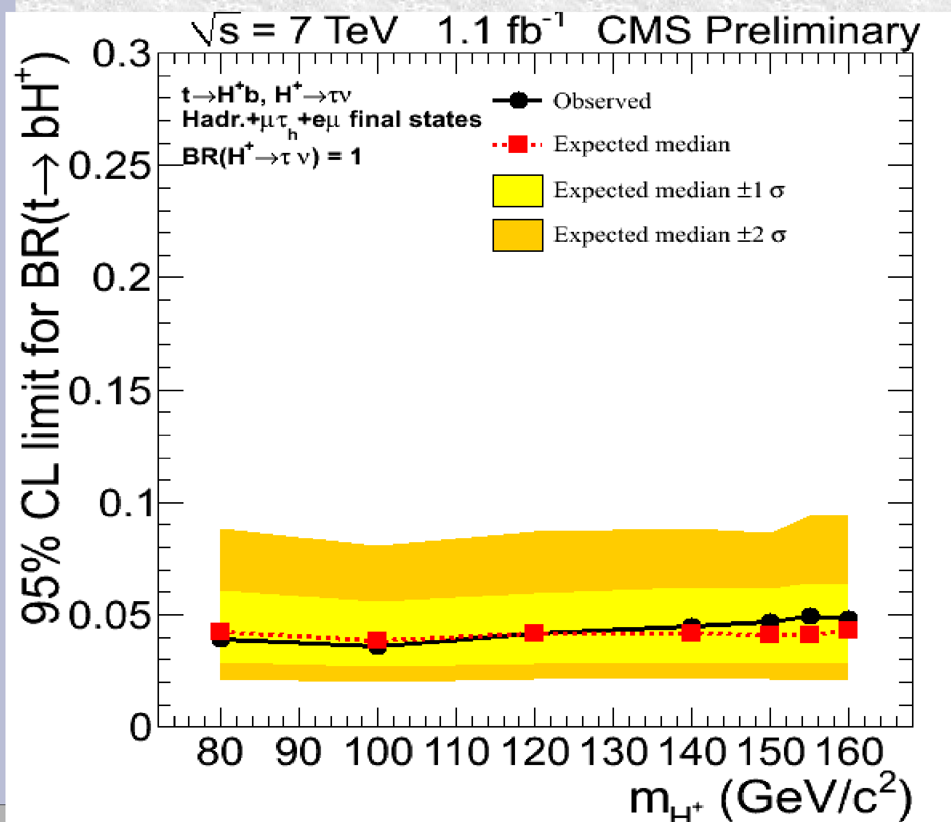
MSSM: Multiple Higgses

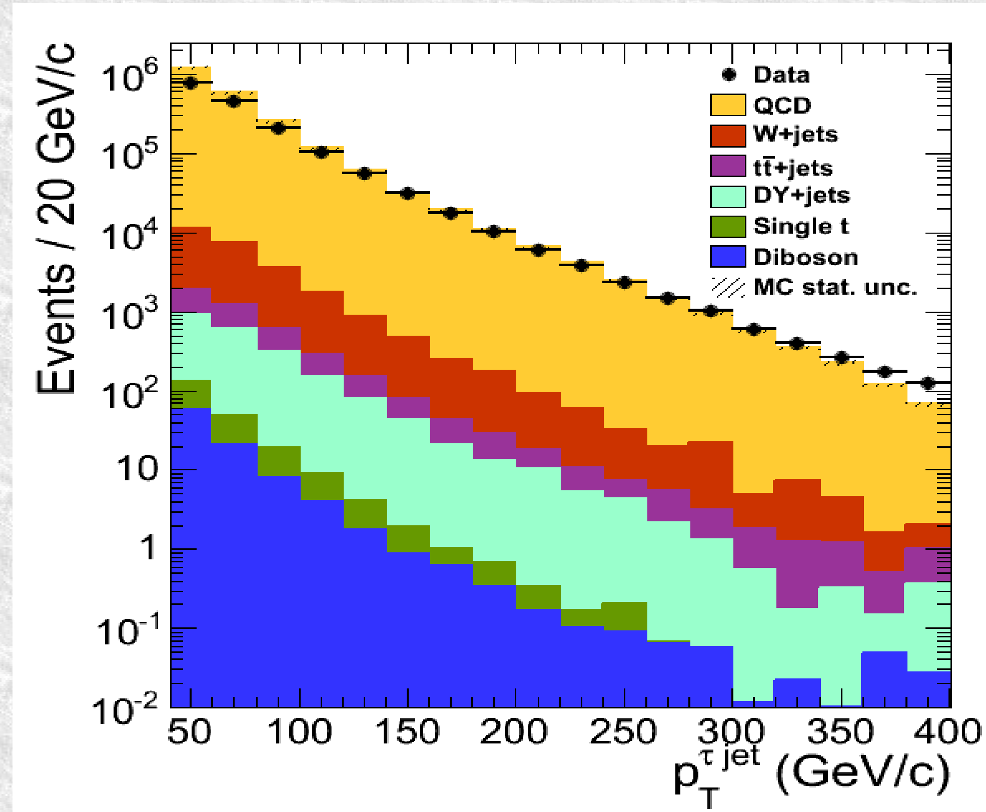
Peter visiting LHC, CMS and ATLAS



Charged Higgs to τν

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

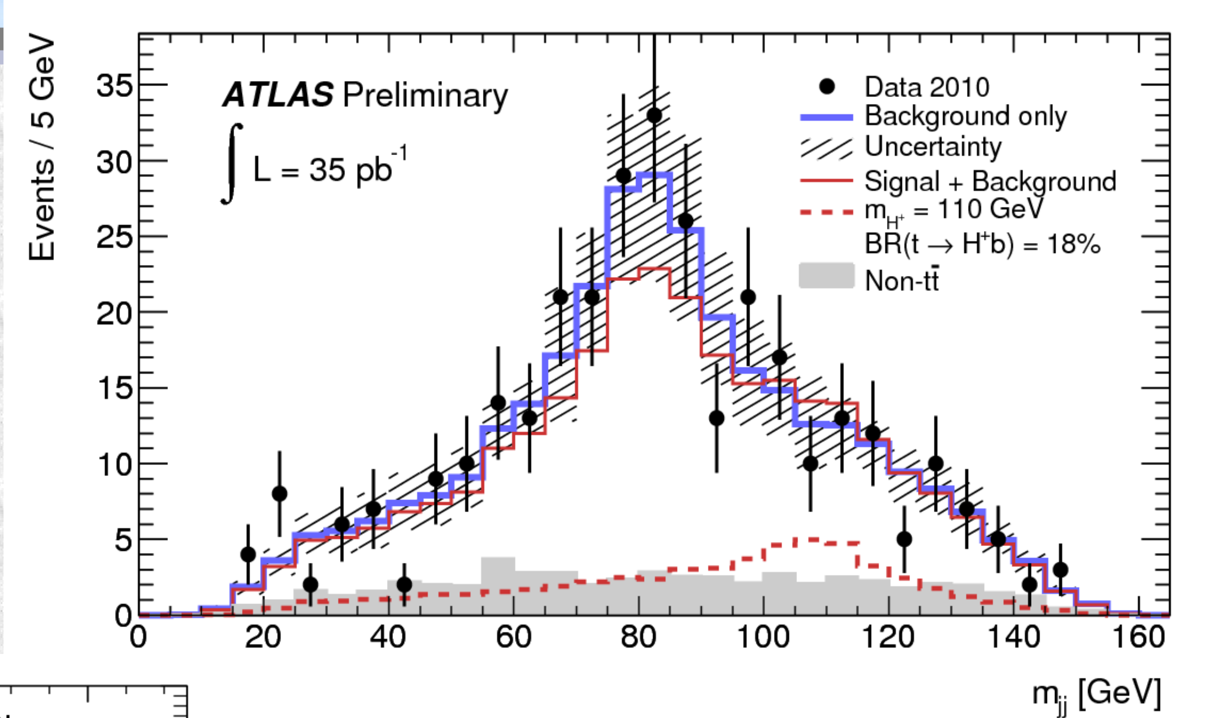


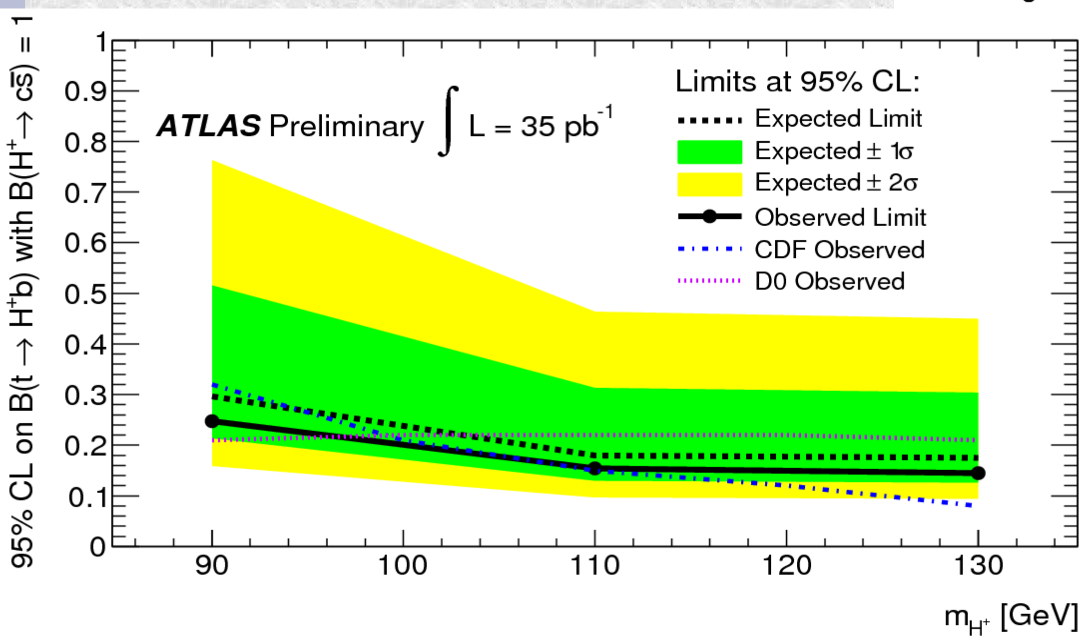


- No evidence so far
- Limits BR(t-H+b) ~4%
  - Far surpassing previous results

Charged Higgs to $c\bar{s}$

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

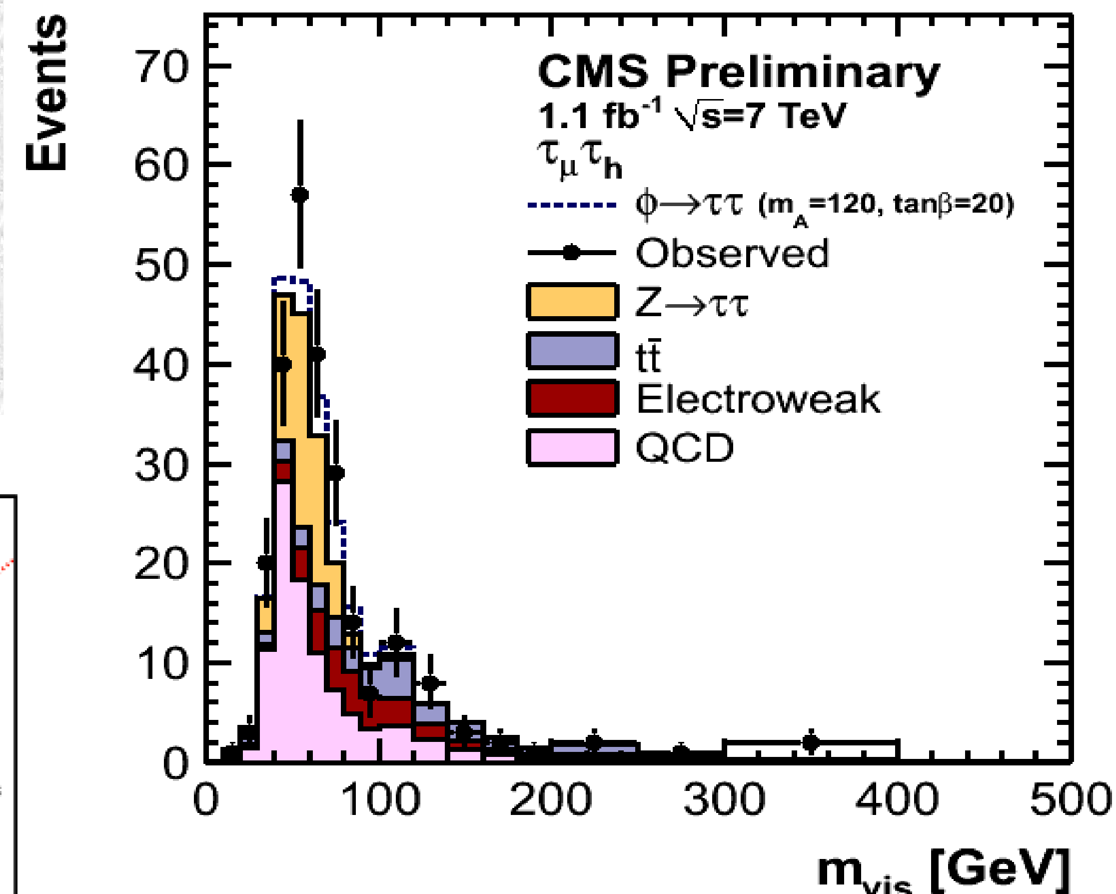


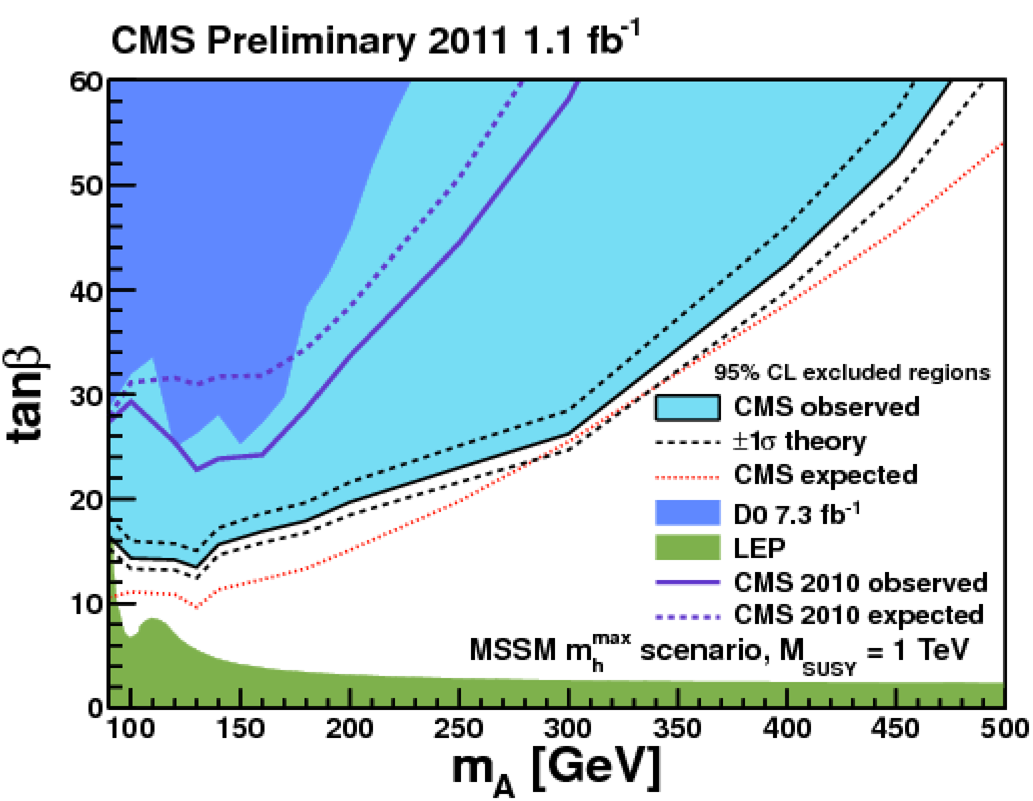


- No sign was seen in 2010
- Limits ~20% level; similar to Tevatron results

$H/A \rightarrow \tau\tau$

- $\Phi \rightarrow \tau\tau$ 2011 CMS
- $e\mu$, $\mu\tau_h$, $e\tau_h$
- Inclusive, b-tag, VBF
- Very nice results





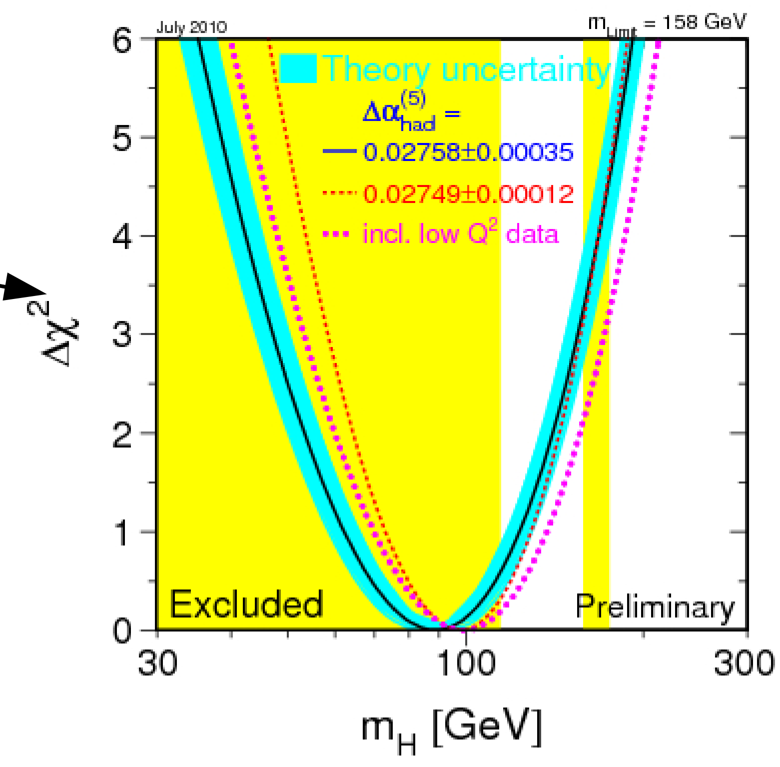
- Exclusion of very large area
  - Note H^+ limit added

Standard Model Higgs

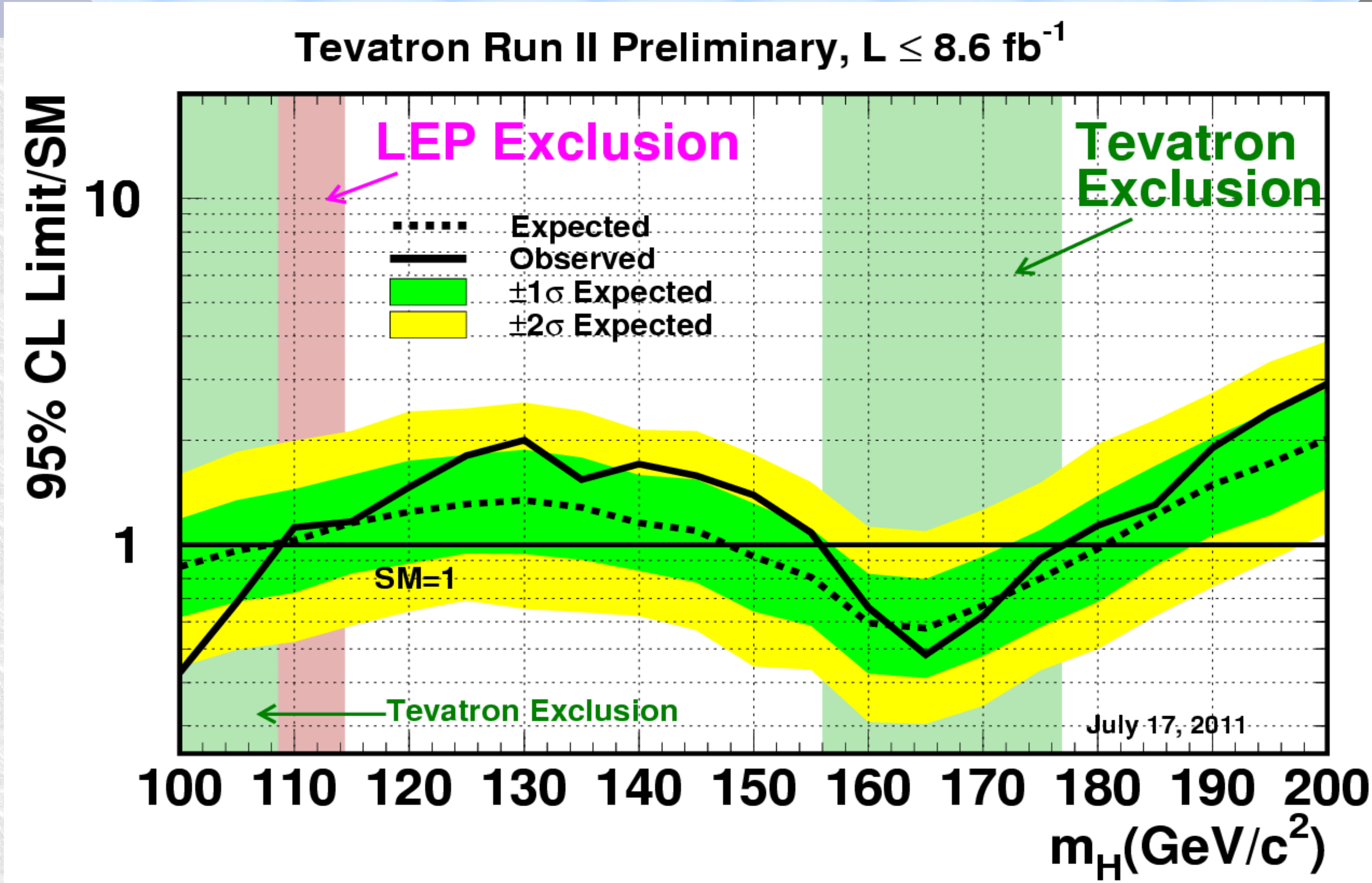
The guaranteed discovery?

Experimental situation

- Electroweak data compatible with the Standard Model
  - m_W is a triumph!
  - Prefers m_H<Tevatron range
- But...it assumes SM is whole story
  - This is not well justifed
  - We know SM is incomplete
    - Gravity? Dark matter? ...
  - Take this with a pinch of salt
- ATLAS & CMS search over a wide range...



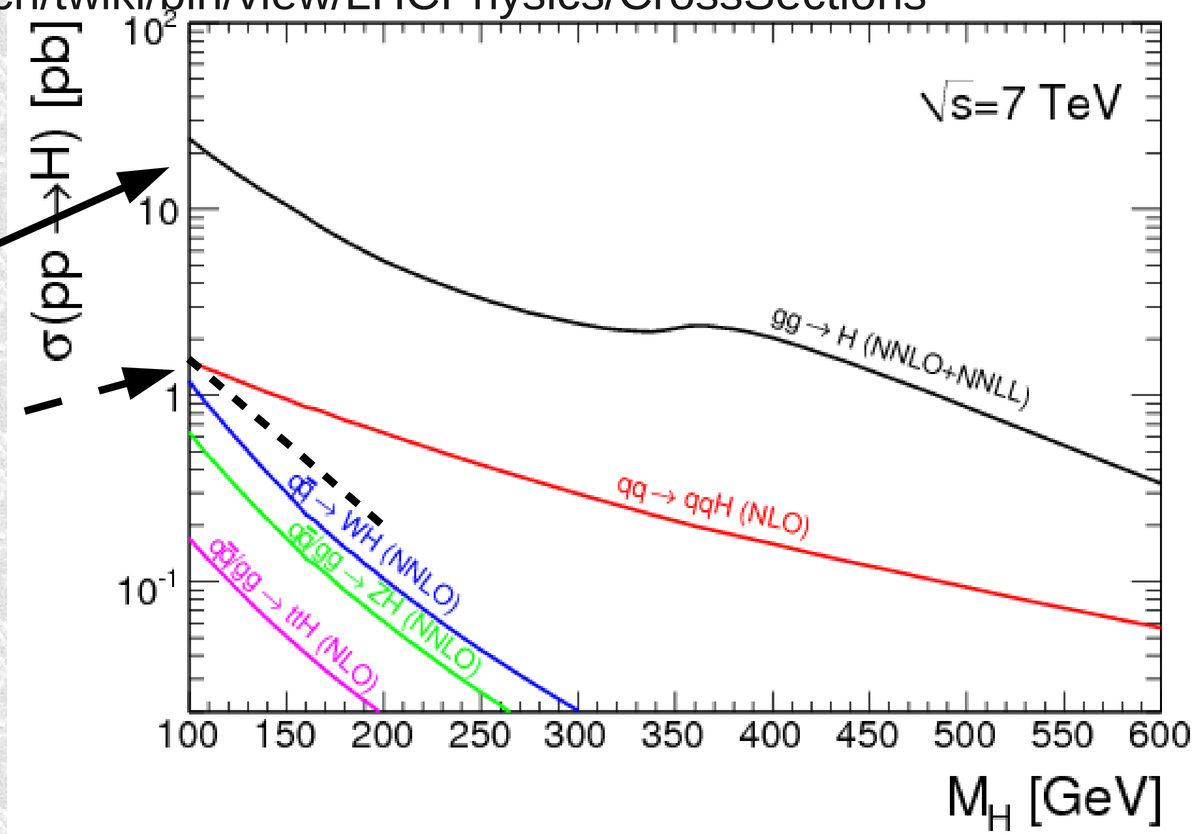
Tevatron results



LHC Higgs production

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

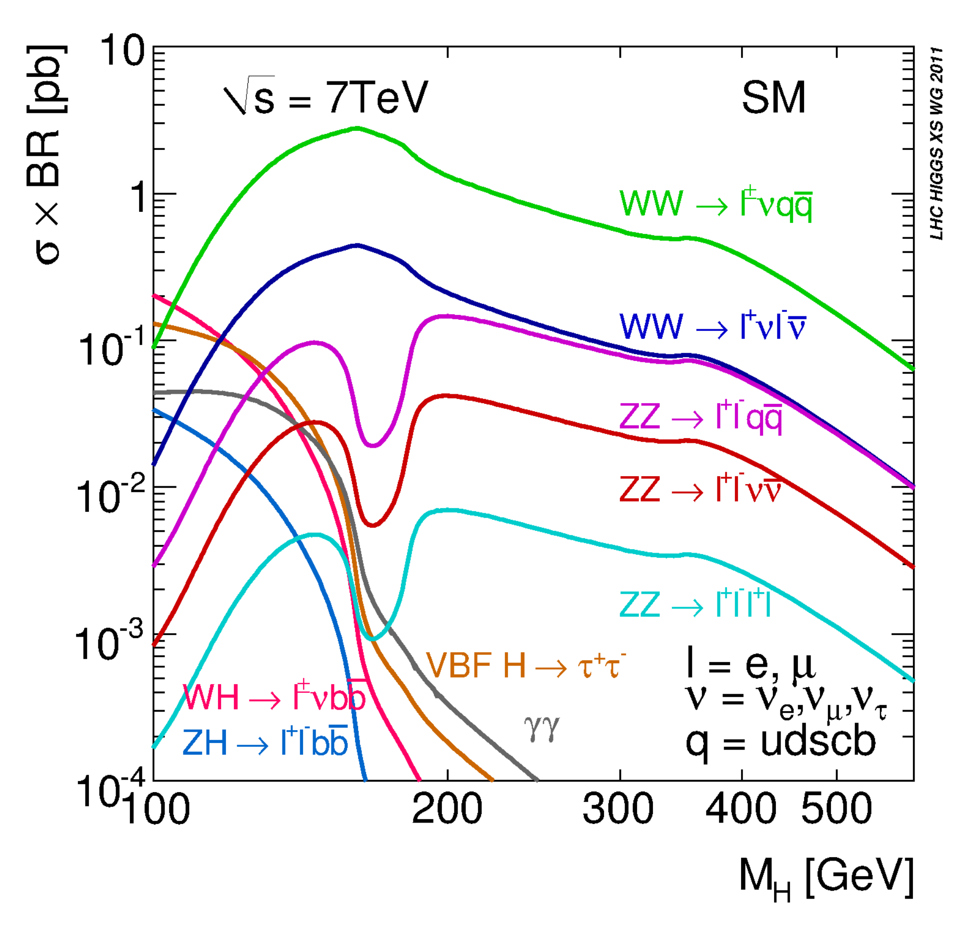
- Higgs cross-sections for gluon fusion
  —— LHC
  ------ TeVatron
- Gluon fusion at least 10x higher cross-section



- Backgrounds to WW,ZZ,γγ are $q\bar{q}$ annihilation
  - s/b better in these channels than Tevatron
  - But it is worse in associated modes

Higgs cross-sections

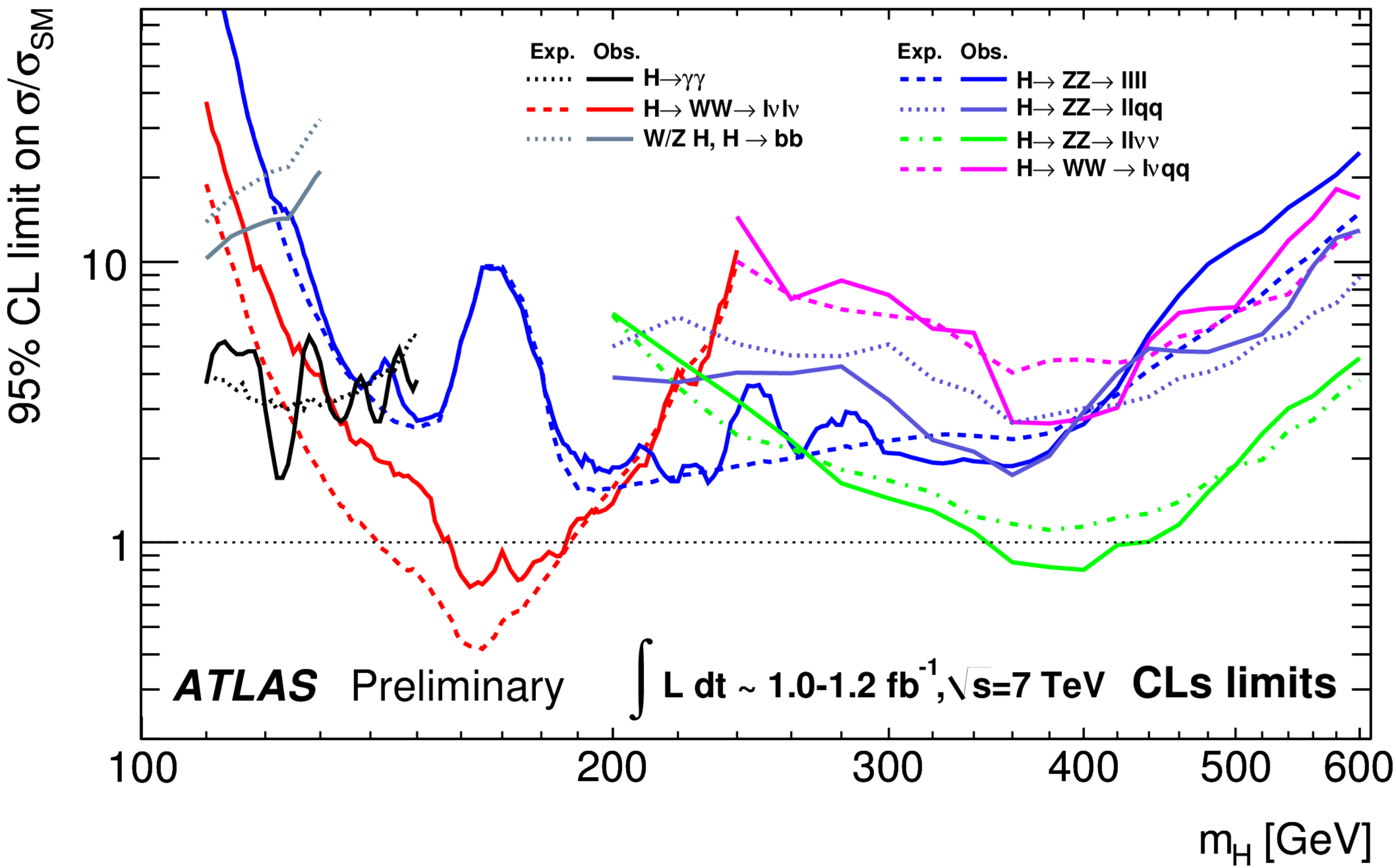
- H → ZZ
  - ZZ → llll: Golden mode
  - ZZ → llνν: Good High mass
  - ZZ → llbb: Also high-mass
- H → WW
  - WW → lνlν: Most sensitive
  - WW → lνqq: highest rate
- H → γγ
  - Rare, best for low mass
- H → ττ
  - Good s/b, low mass,rare
- H → bb
  - $t\bar{t}$H, WH, ZH useful but hard



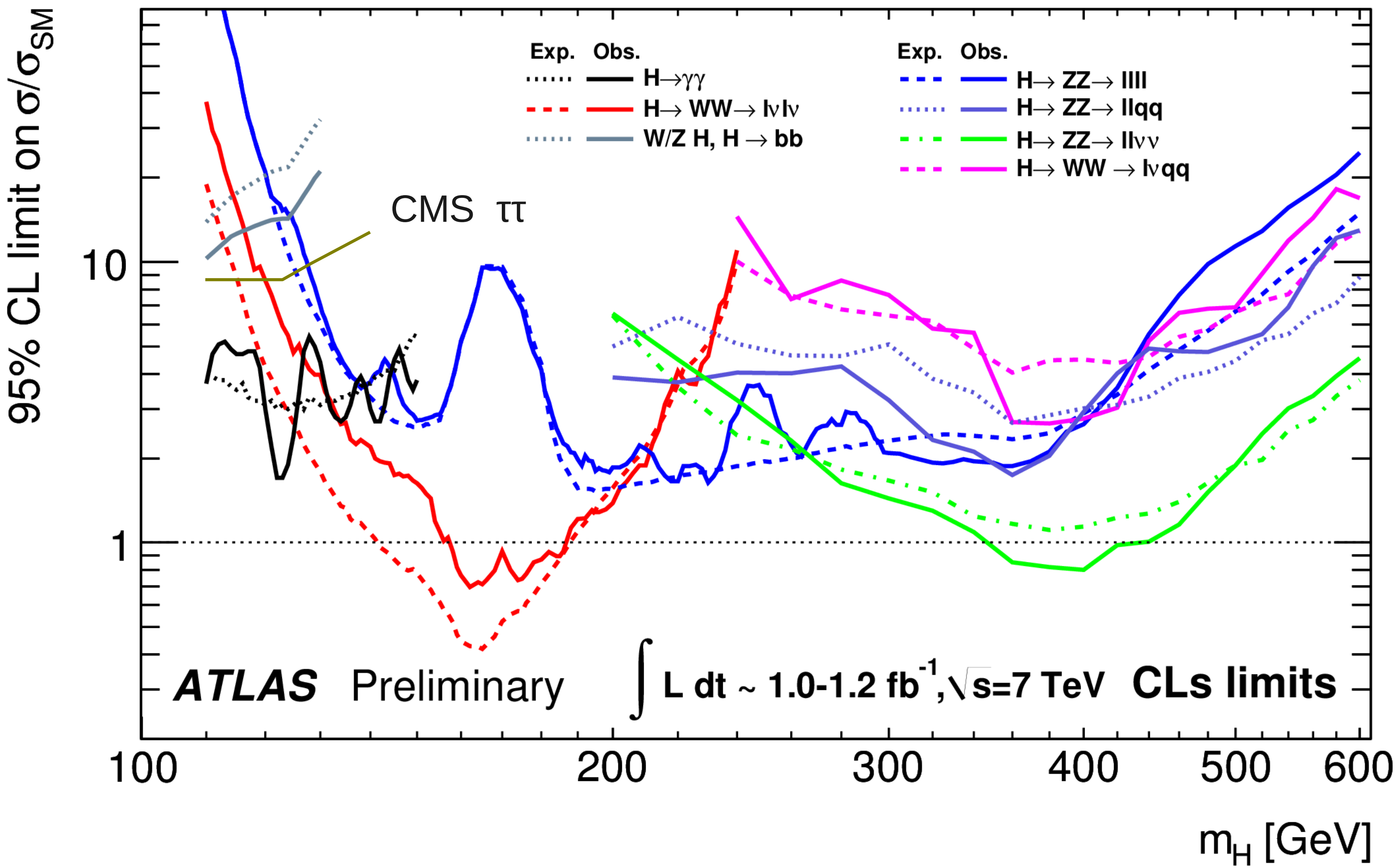
Channels used

H decay mode	ATLAS	CMS	Tevatron
ττ	--	Inclusive+VBF	H/VH/VBF
bb	lυH, llH	--	lυH, llH, υυH
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	--

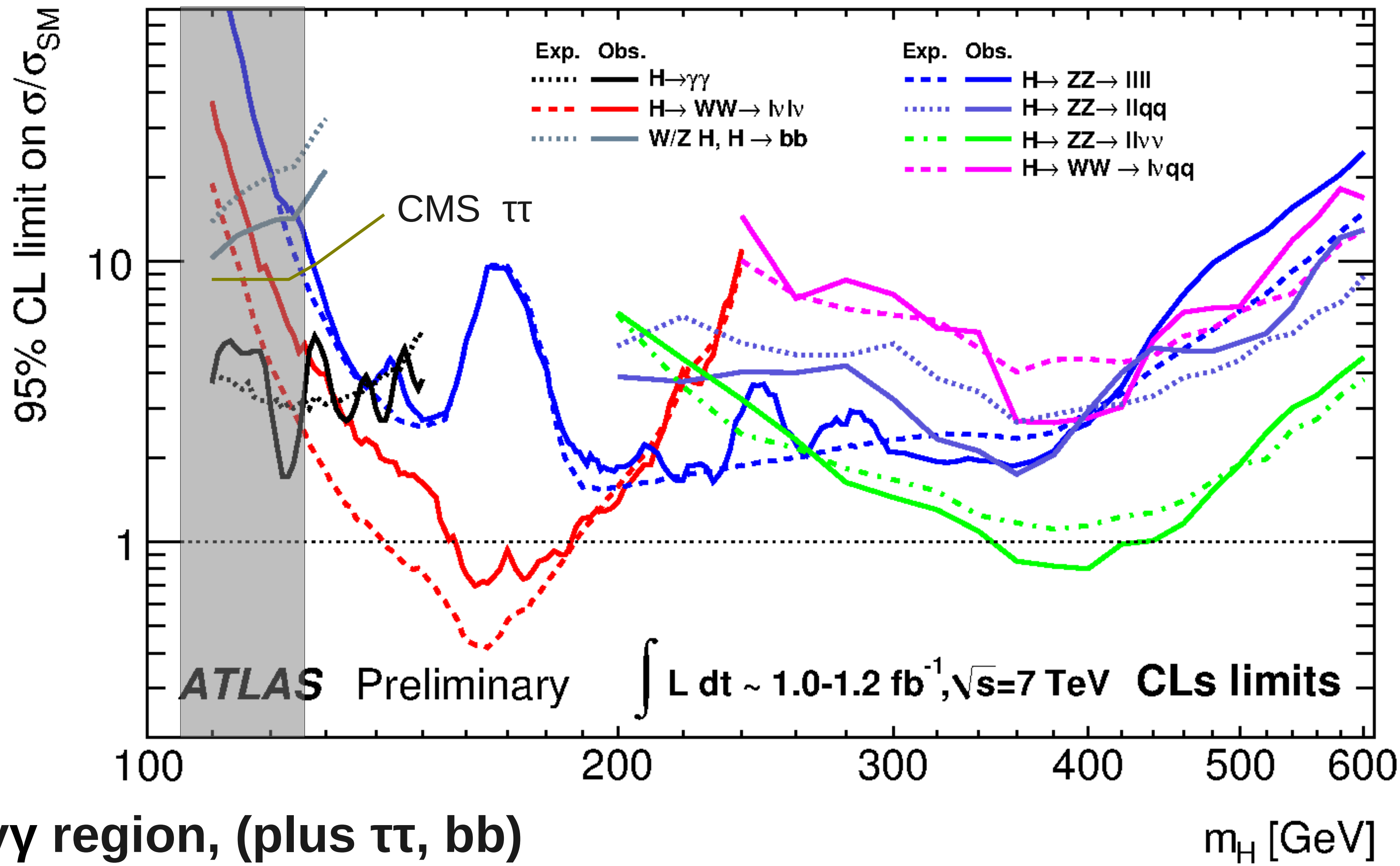
Channels reviewed (ATLAS)



Channels reviewed



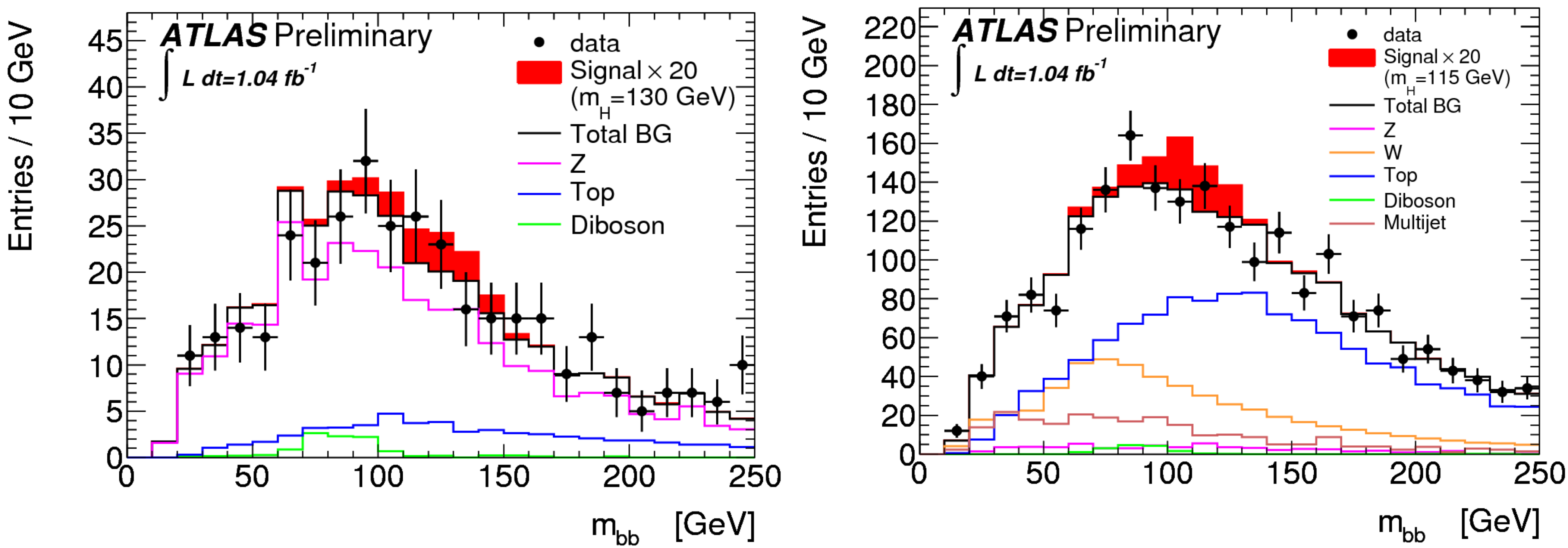
Low mass searches



γγ region, (plus ττ, bb)

VH, H → bb

- H → bb is dominant decay mode for light Higgs
  - But very hard to do due to huge bb backgrounds
  - ATLAS tried WH and ZH modes inclusively:

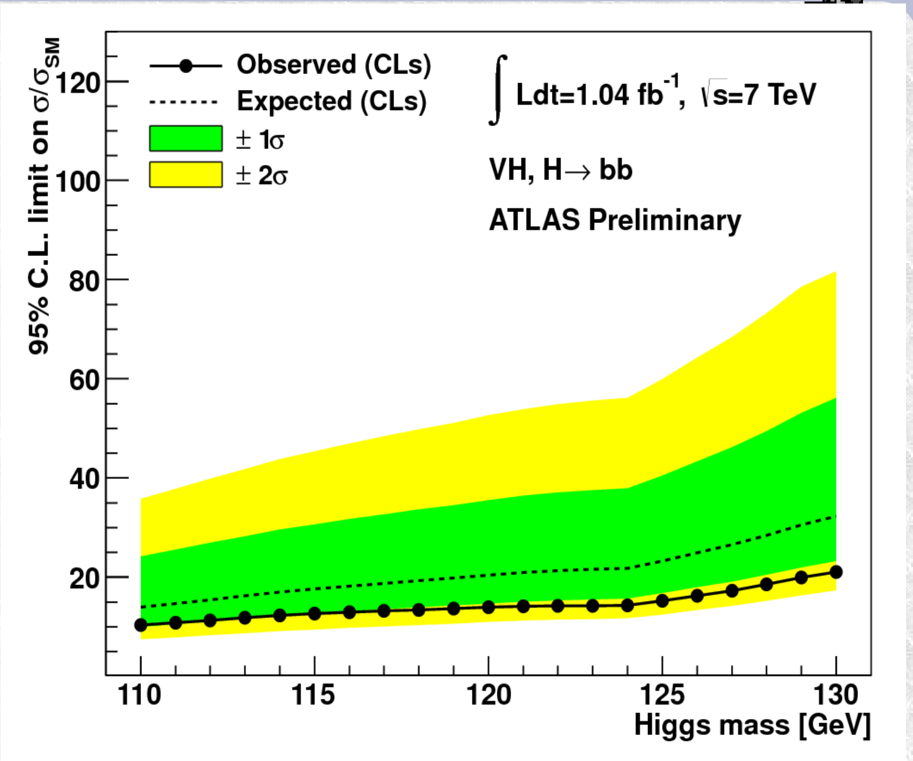


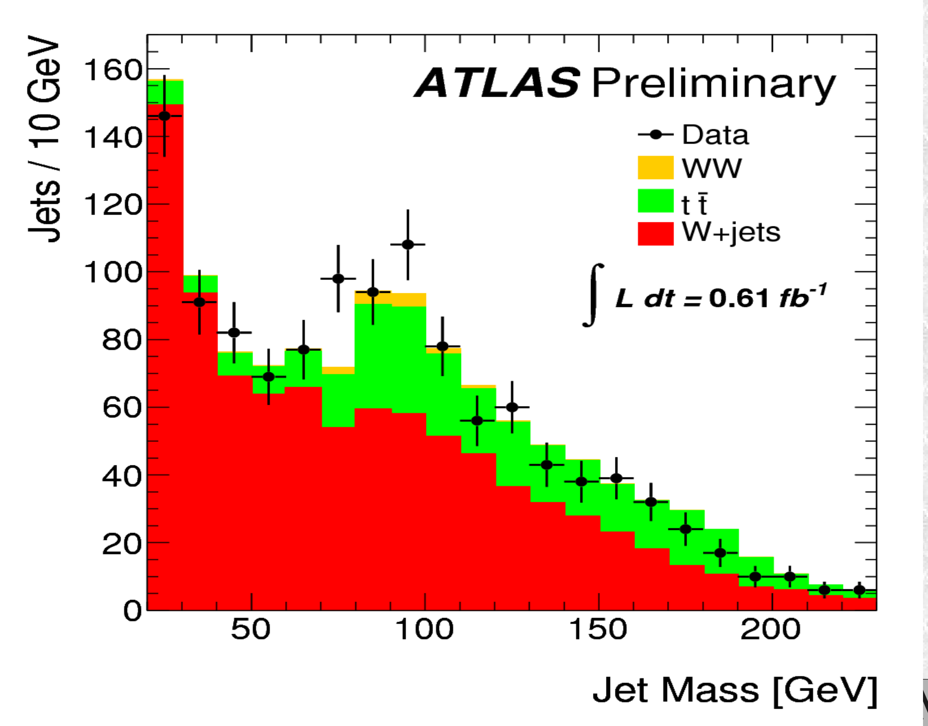
- Note signal increased by factor 20

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-103/

VH, H → bb

- Top and Wjj/Wbb backgrounds fitted to data
  - Shapes from simulation
- Sensitivity is ~ 15xSM

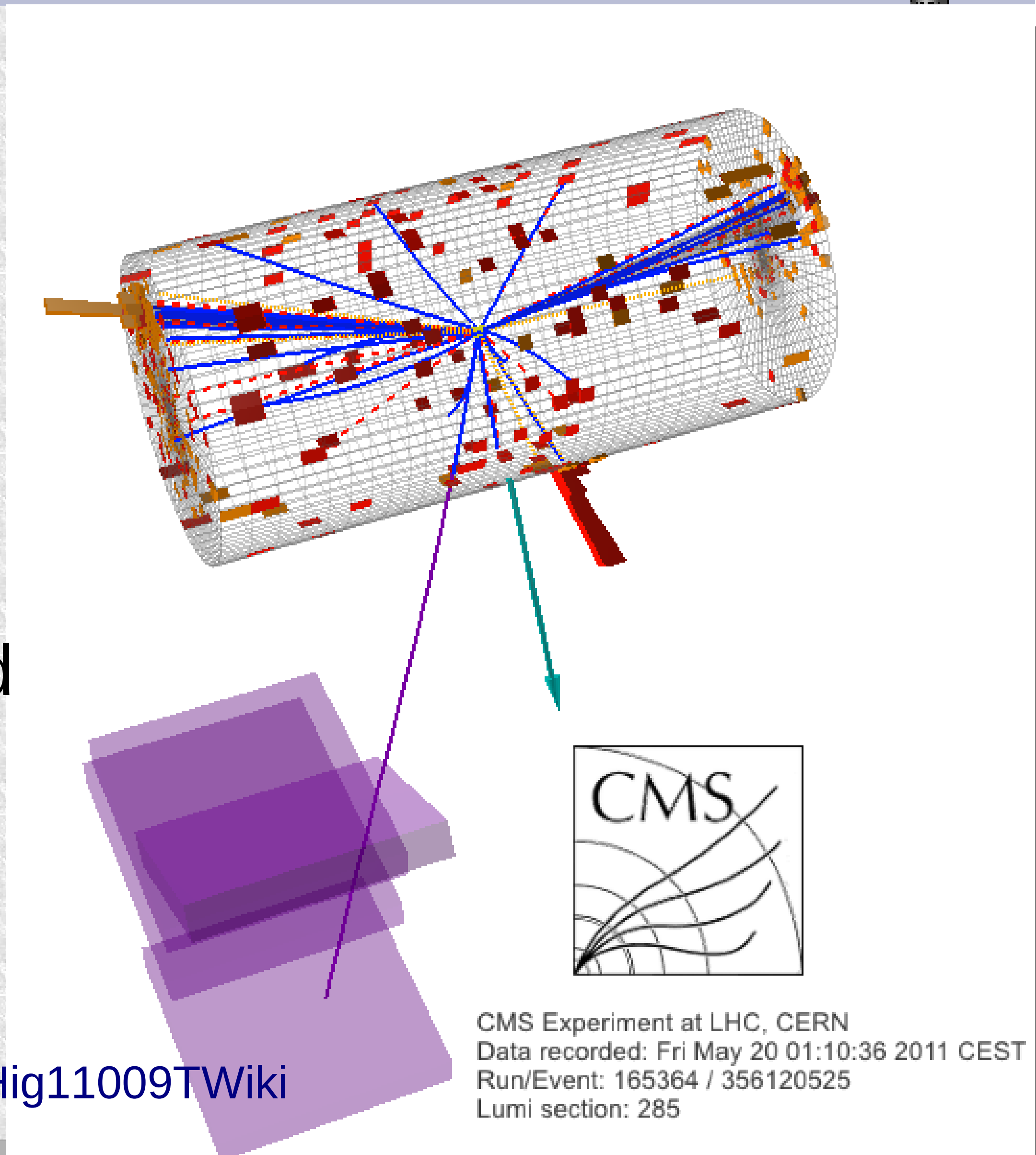




- Subjet analysis should help
  - W+'fatjet' studies suggest W to qq from tt → WbWb seen
  - Ready to search for H to bb

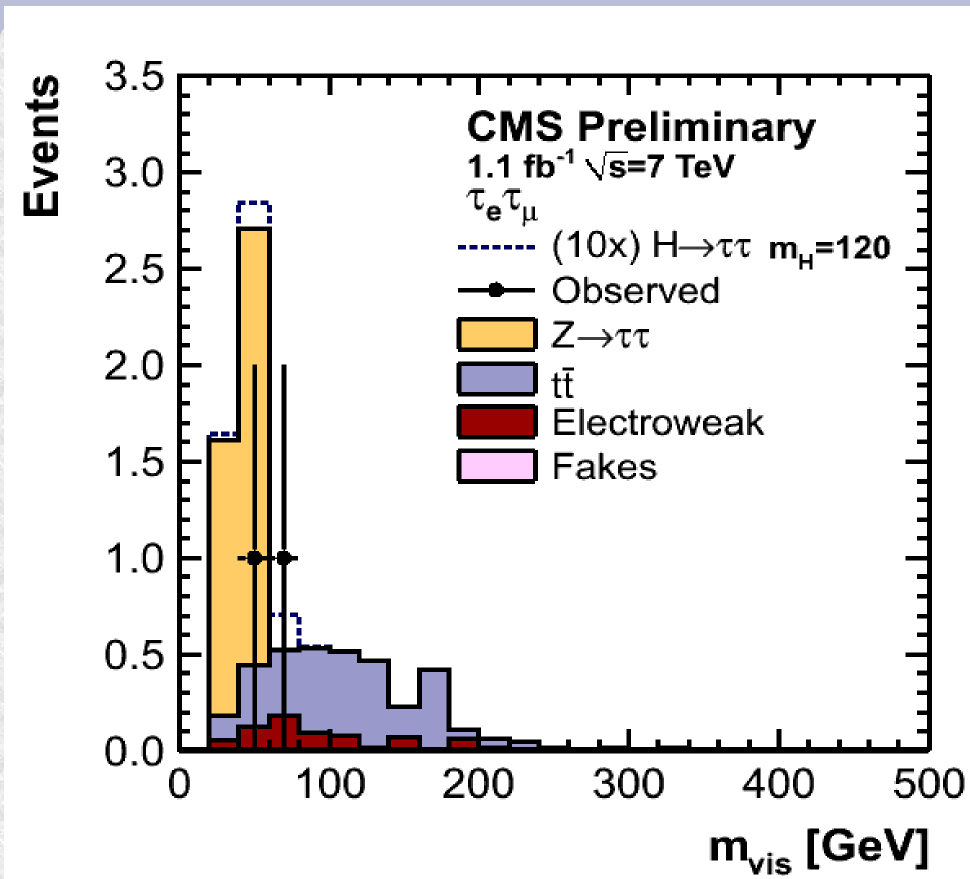
$H \rightarrow \tau\tau$

- 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:

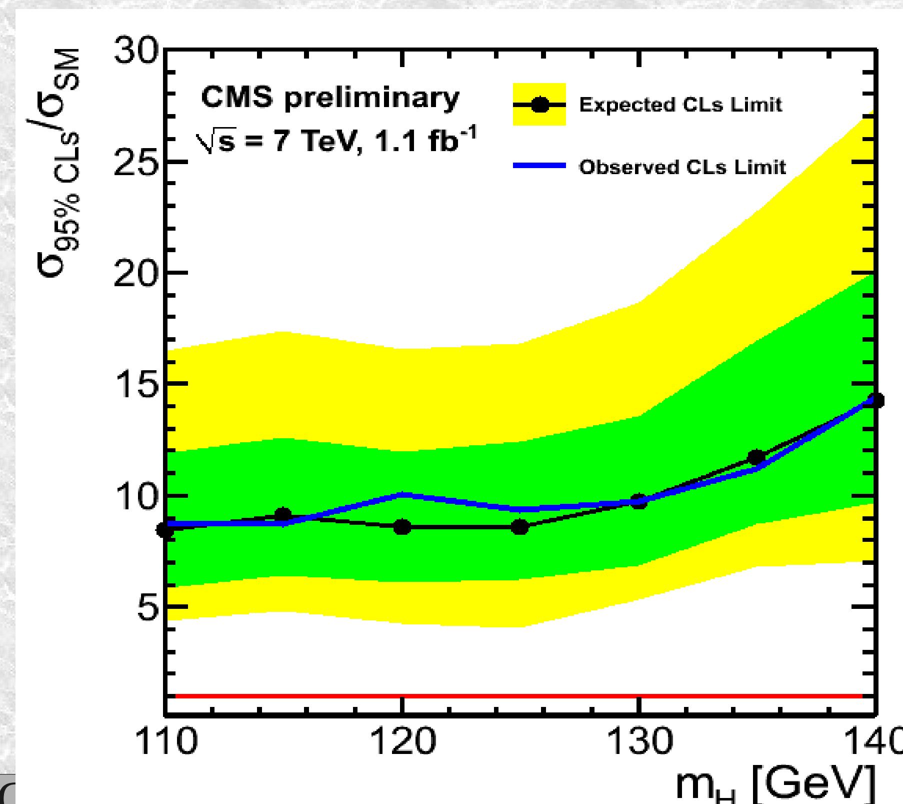


https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig11009TWiki

H → ττ results



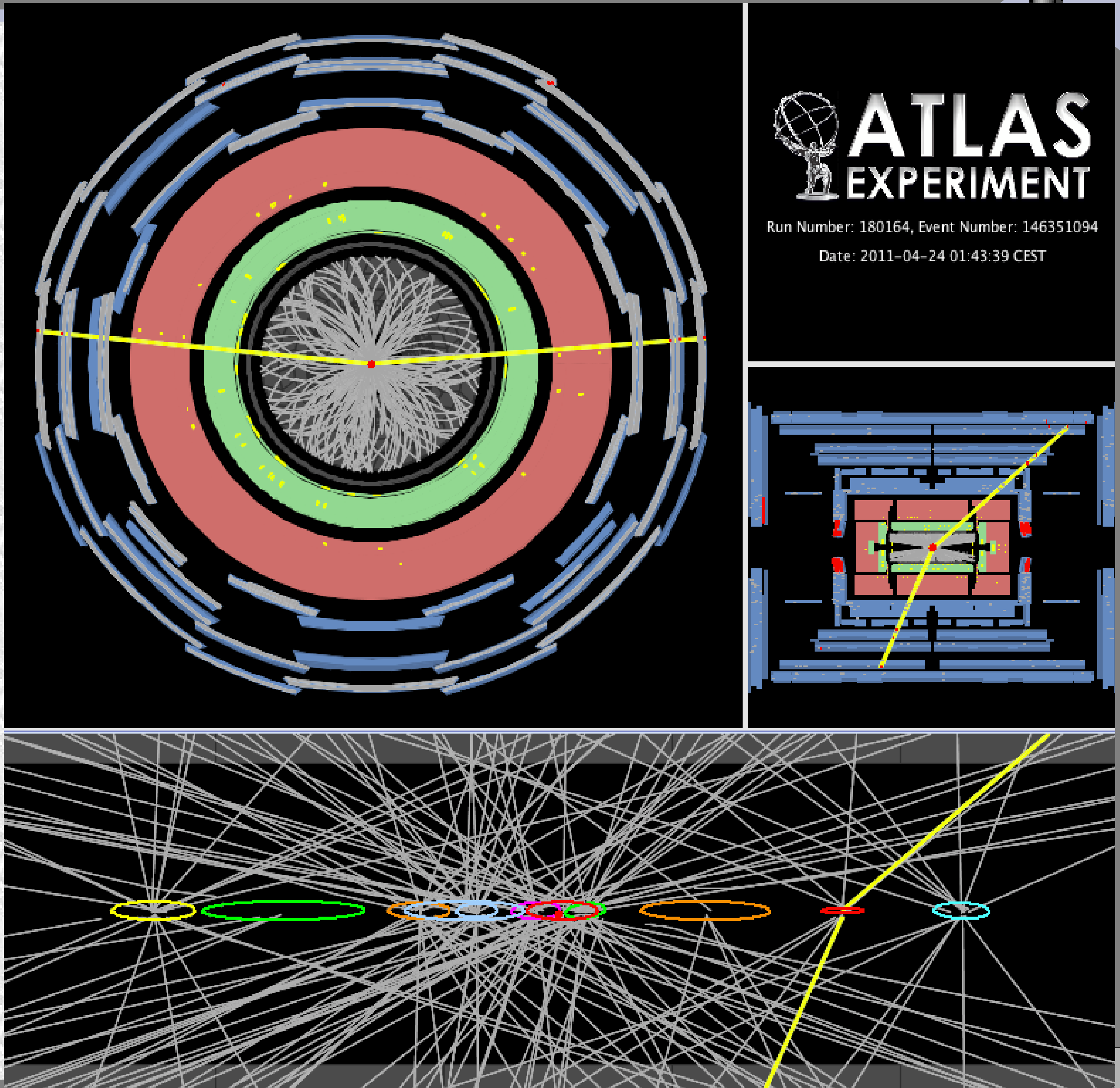
- e-μ VBF channel (left) is cleanest
  - Mass calculation can improve



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

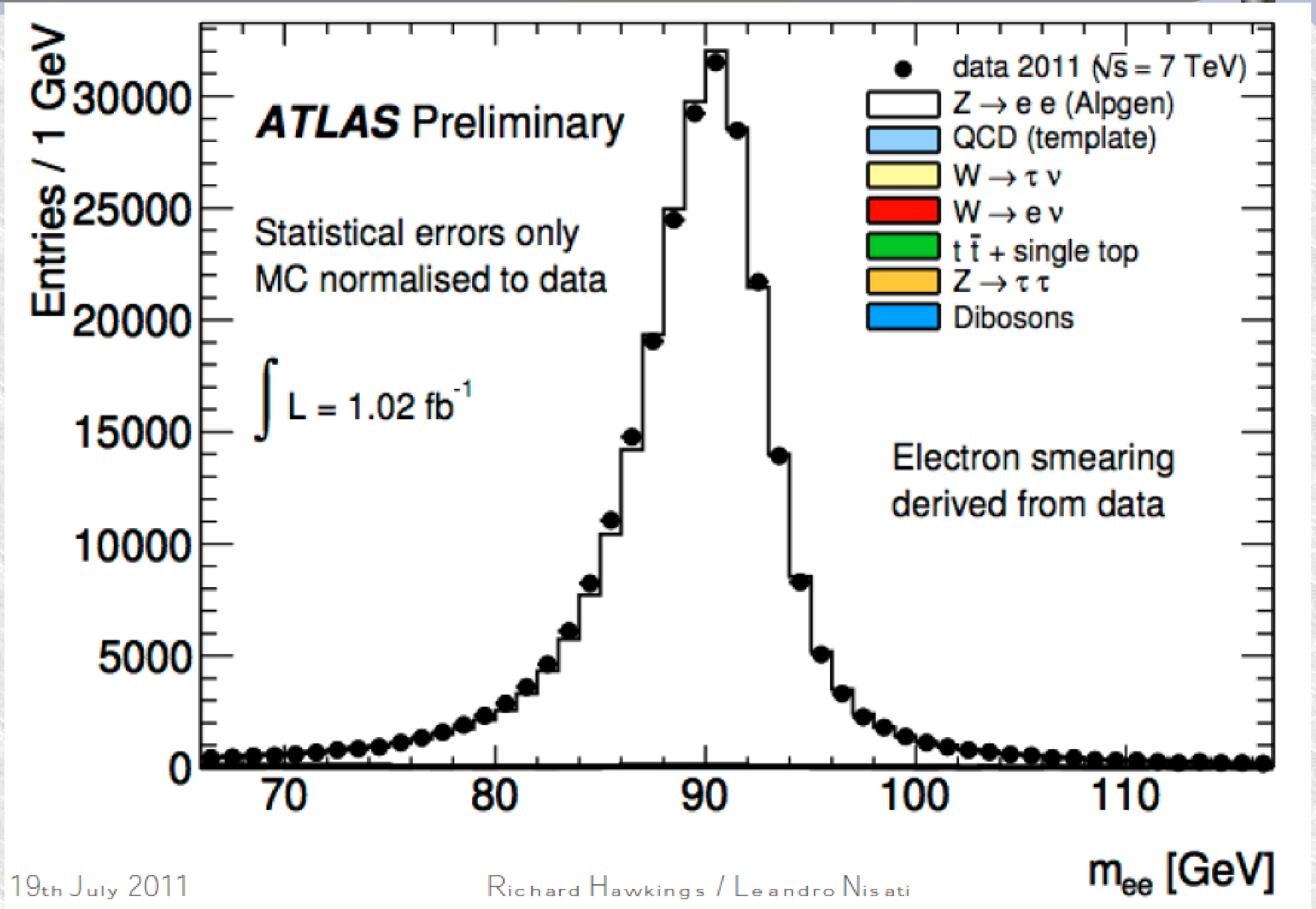
$H \rightarrow \gamma\,\gamma$

- Rare decay
- $110<m_H<150$
- Tough ECAL requirements
  - Mass resolution tested in $Z \rightarrow ee$
  - Need vertex position too
    - Pileup!
- Good jet rejection also essential



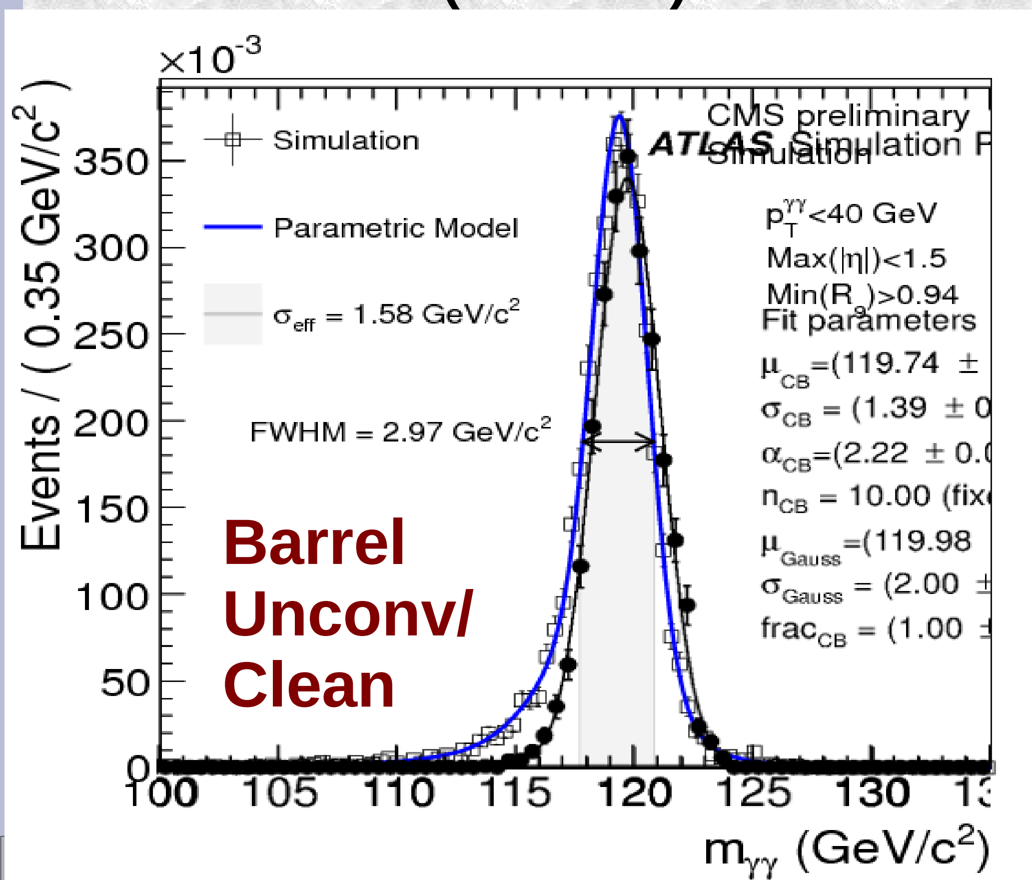
H → γγ

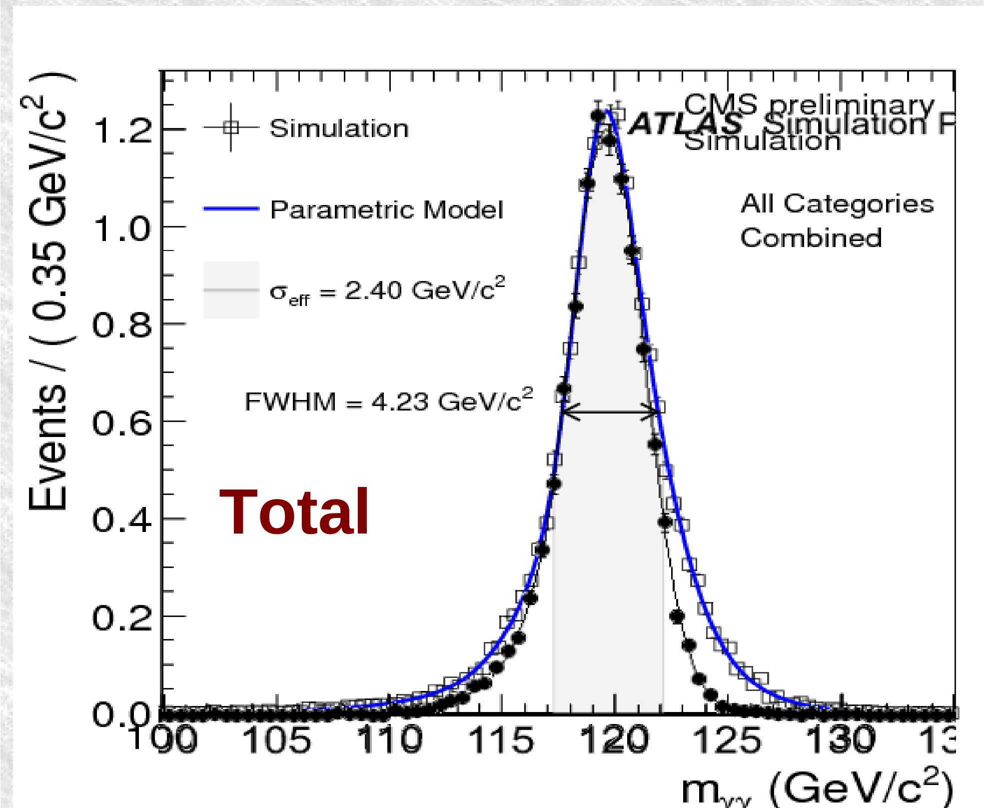
- Photon resolution verified using the Z peak
- Different e/γ response in MC largest systematic uncertainty



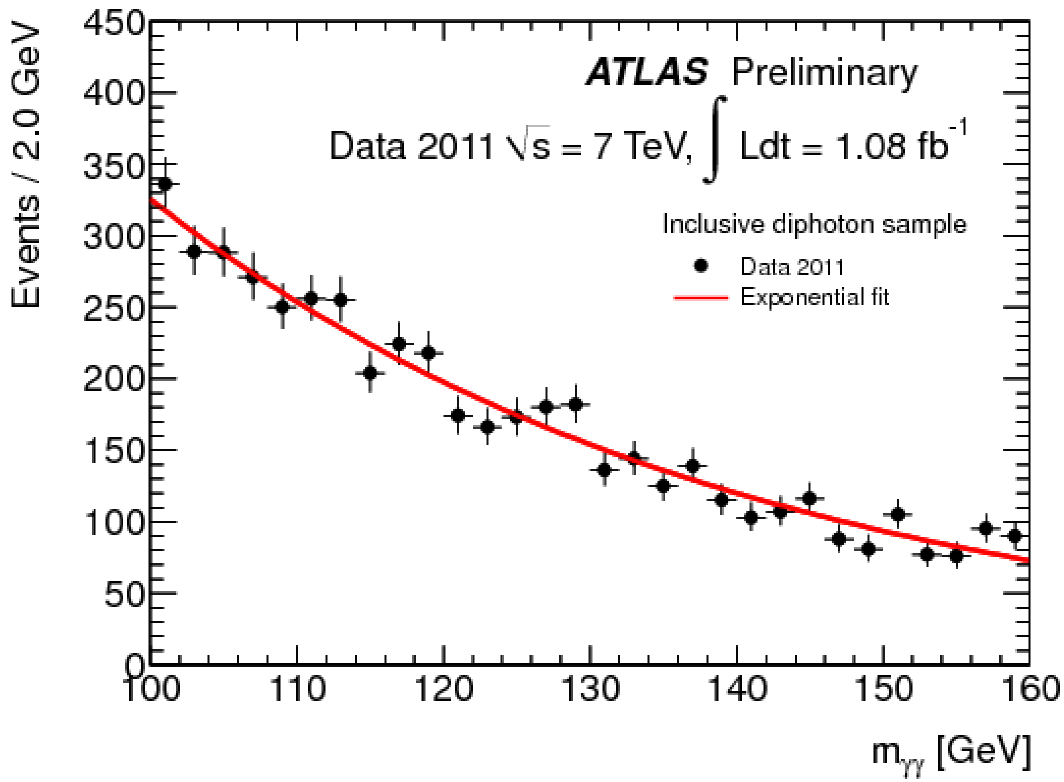
Higgs mass resolution

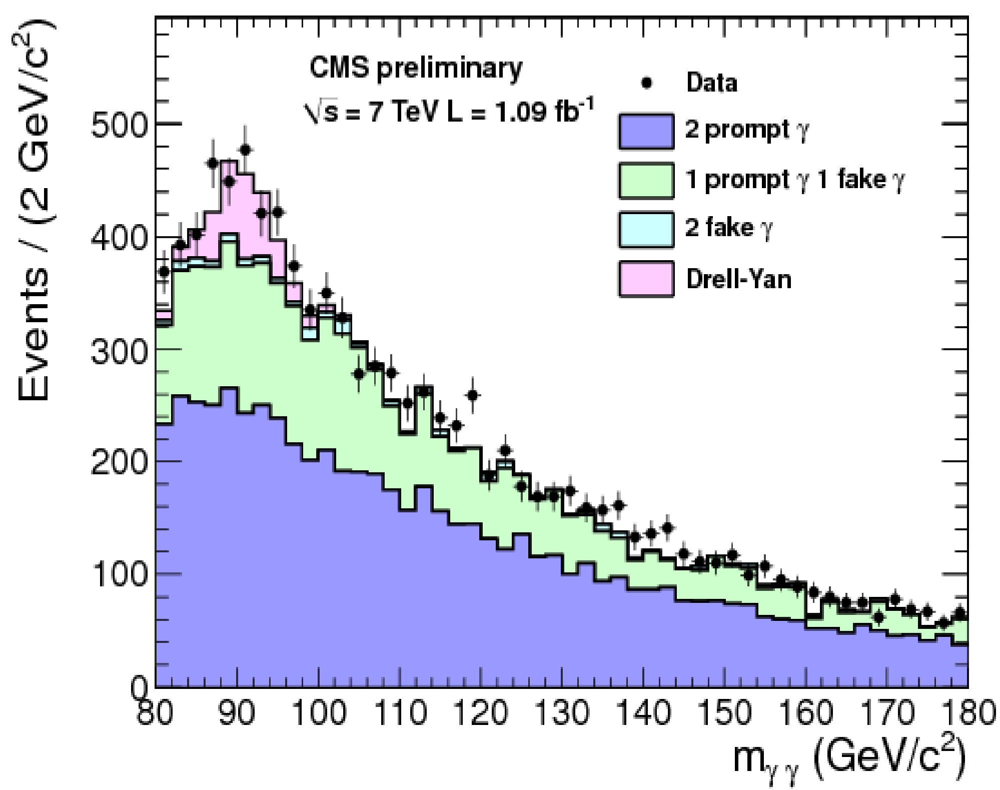
- No good calibration in data
  - Until we find Higgs!
  - Has to be simulated
- ATLAS (black) and CMS (blue) compared





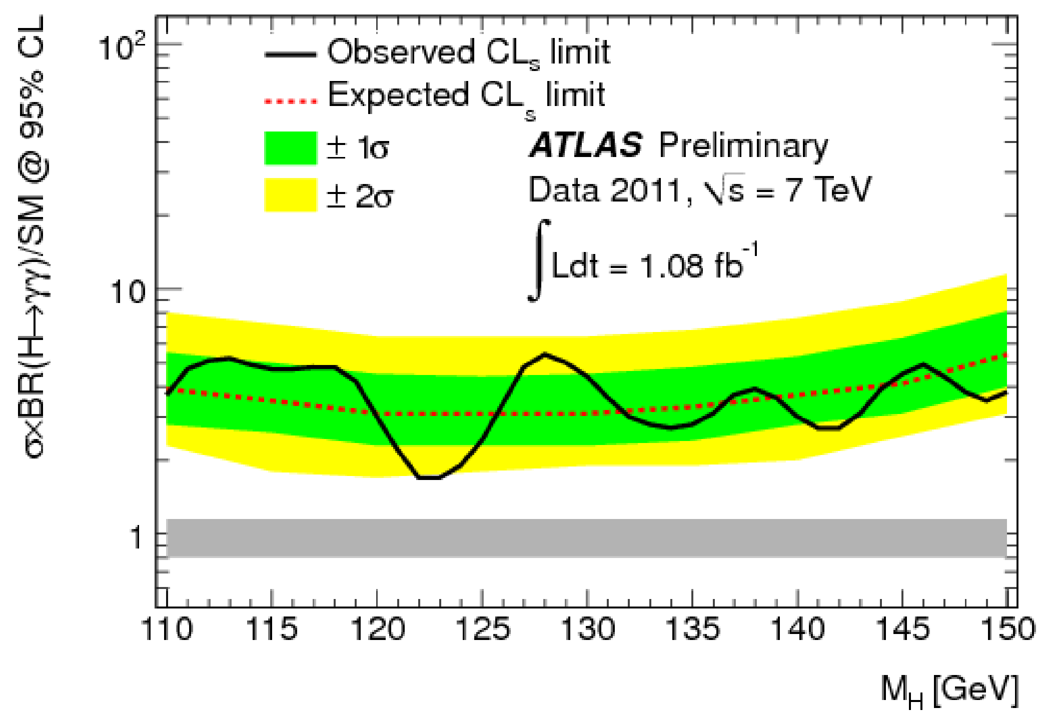
H → γ γ

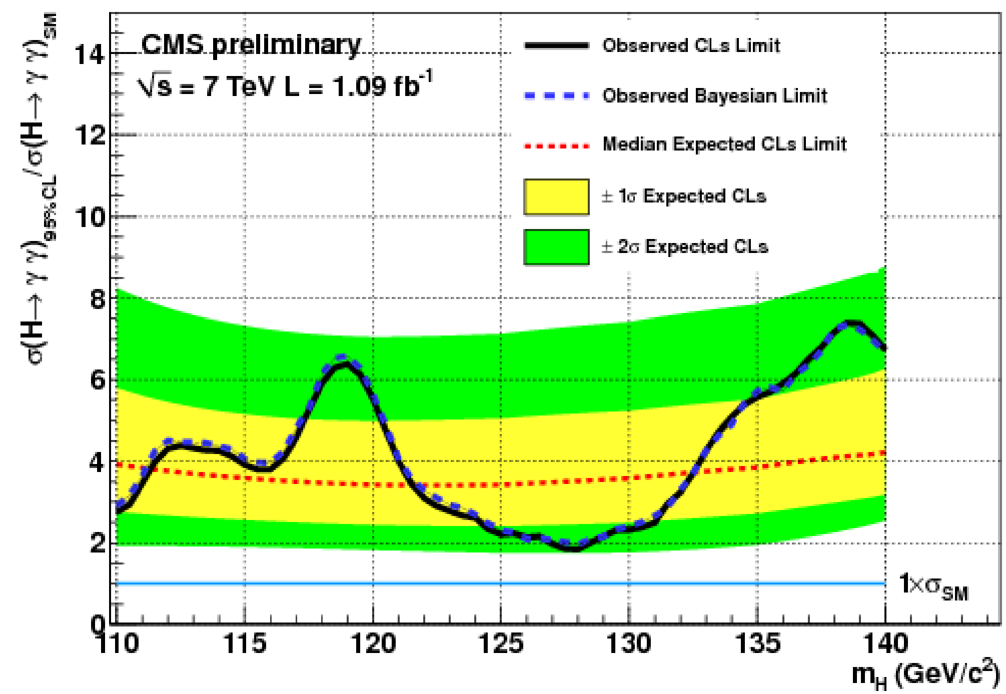




- Invariant mass spectra similar
  - Real γγ events dominant for both experiments
- Fit to this spectrum, looking for sharp peak
  - Both divide events into quality categories

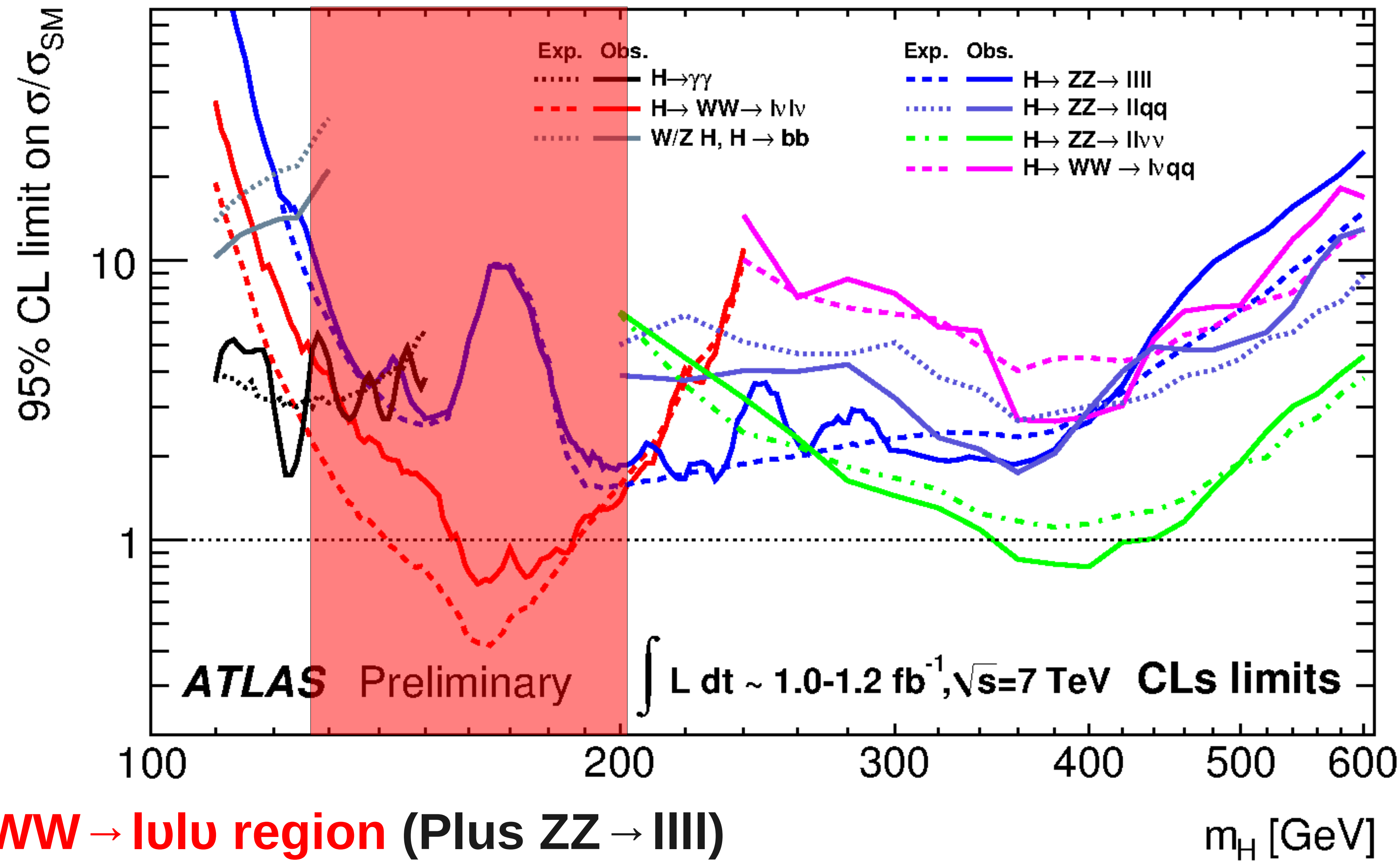
H → γγ limits





- ATLAS (left) and CMS (right) results similar
- Expected limits 3-4 x SM strength
  - Observed fluctuates down to 2..
  - Closing in even here, the hardest place for LHC

Intermediate searches



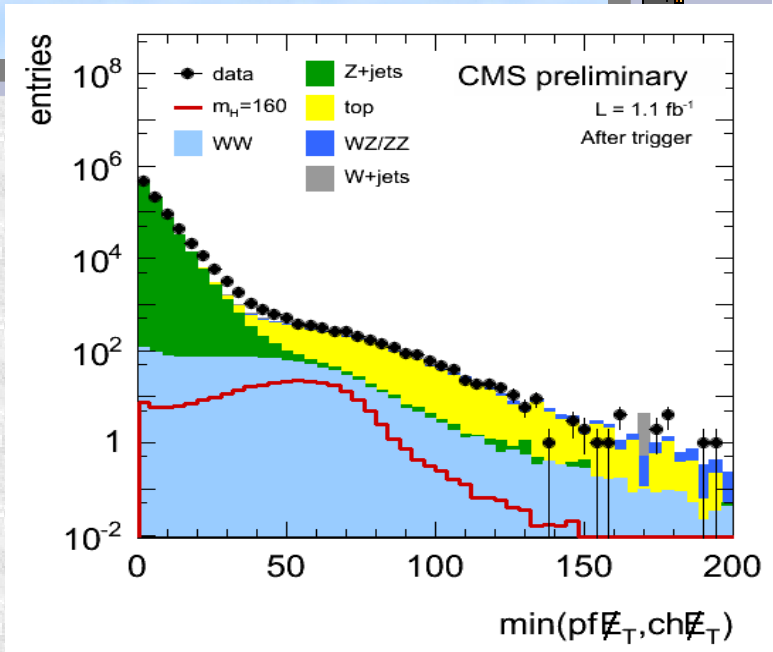
WW→lυlυ region **(Plus ZZ→llll)**

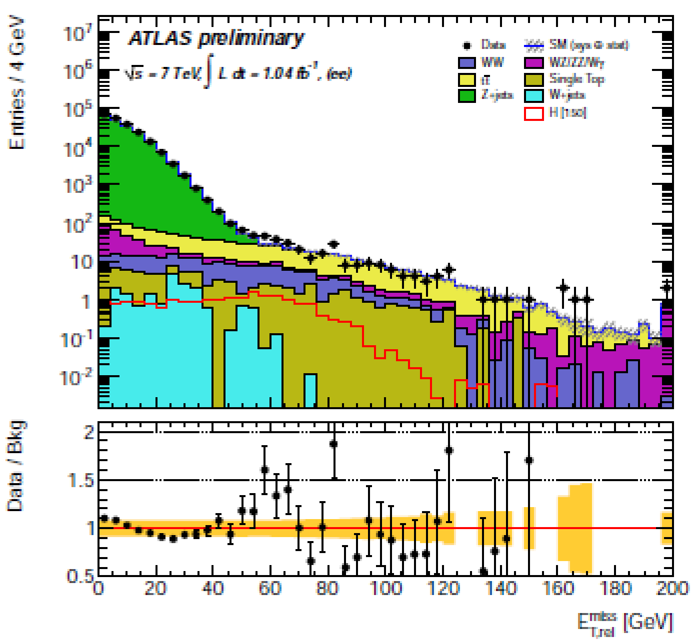
WW → lνlν

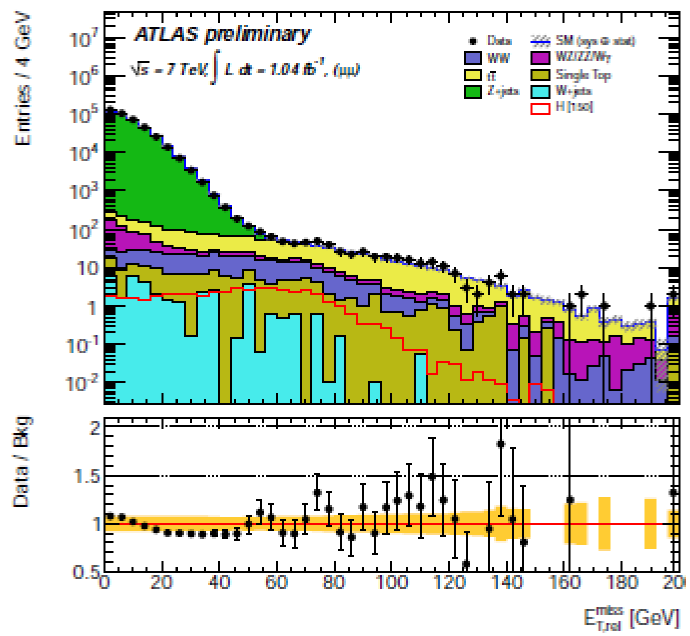
- The most sensitive channel for $130<m_H<200$
  - Here is where the excess comes
  - But poor mass information due to neutrinos
- Good trigger, reasonable rate
  - Largest background is non-resonant WW
    - Also top when looking at WW+1 jet
  - Backgrounds measured from control regions
- Request two leptons
  - 15-25 GeV (ATLAS) 10-25GeV (CMS)
- Require missing E_T (E_t^{rel}) and $p_T(ll)$ for WW
- Select signal area with $\Delta\varphi$ and m_{ll} selections
  - CMS using cut-based and multivariate
  - ATLAS prefers cut-based at this stage.

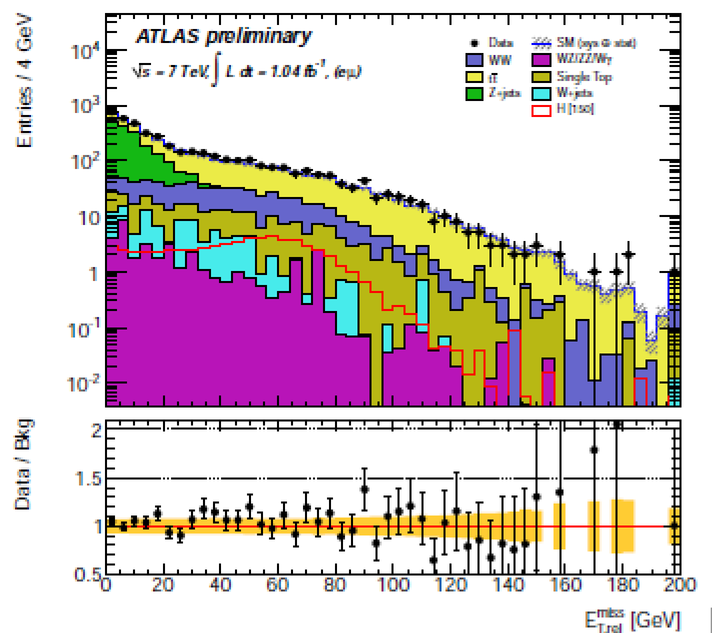
WW → lνlν

- Missing E_T
  - Vital tool against Z+jets events
    - costs in signal rate
  - Rate of backgrounds here measured in data

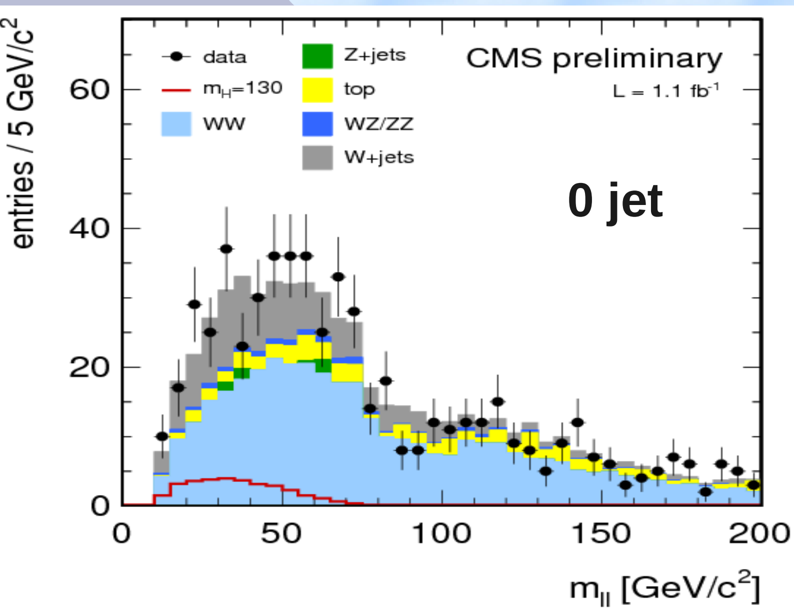




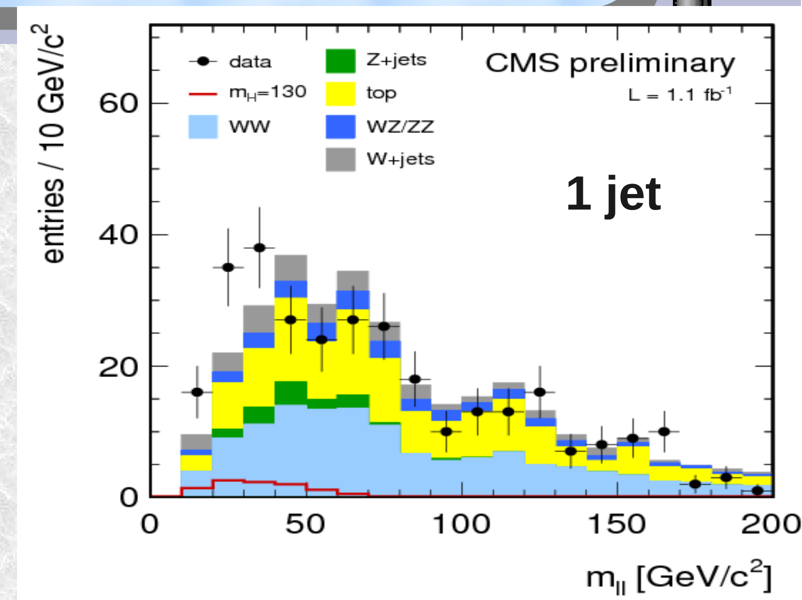


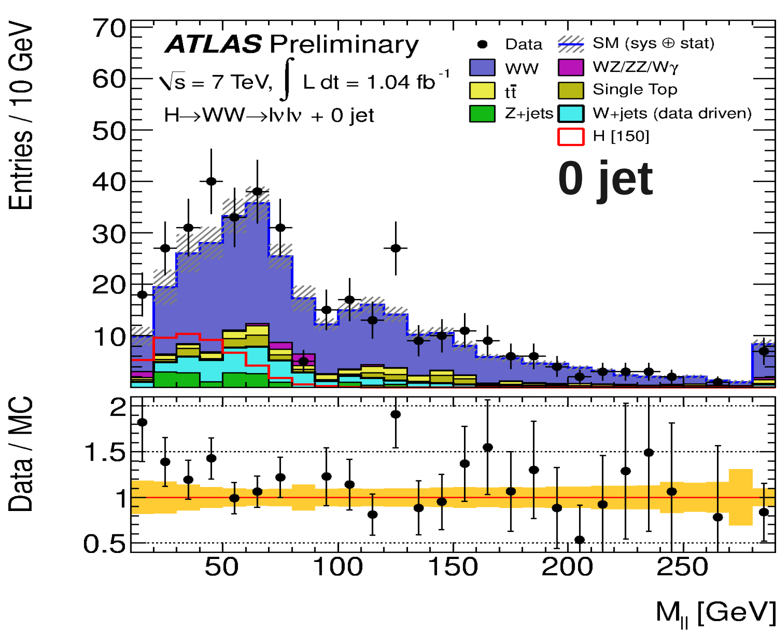


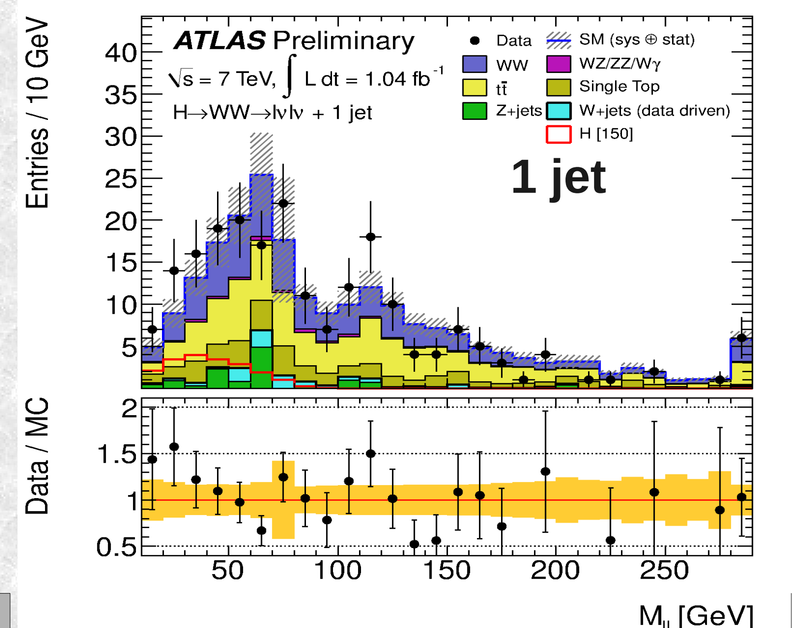
m_{ll} in WW → lνlν



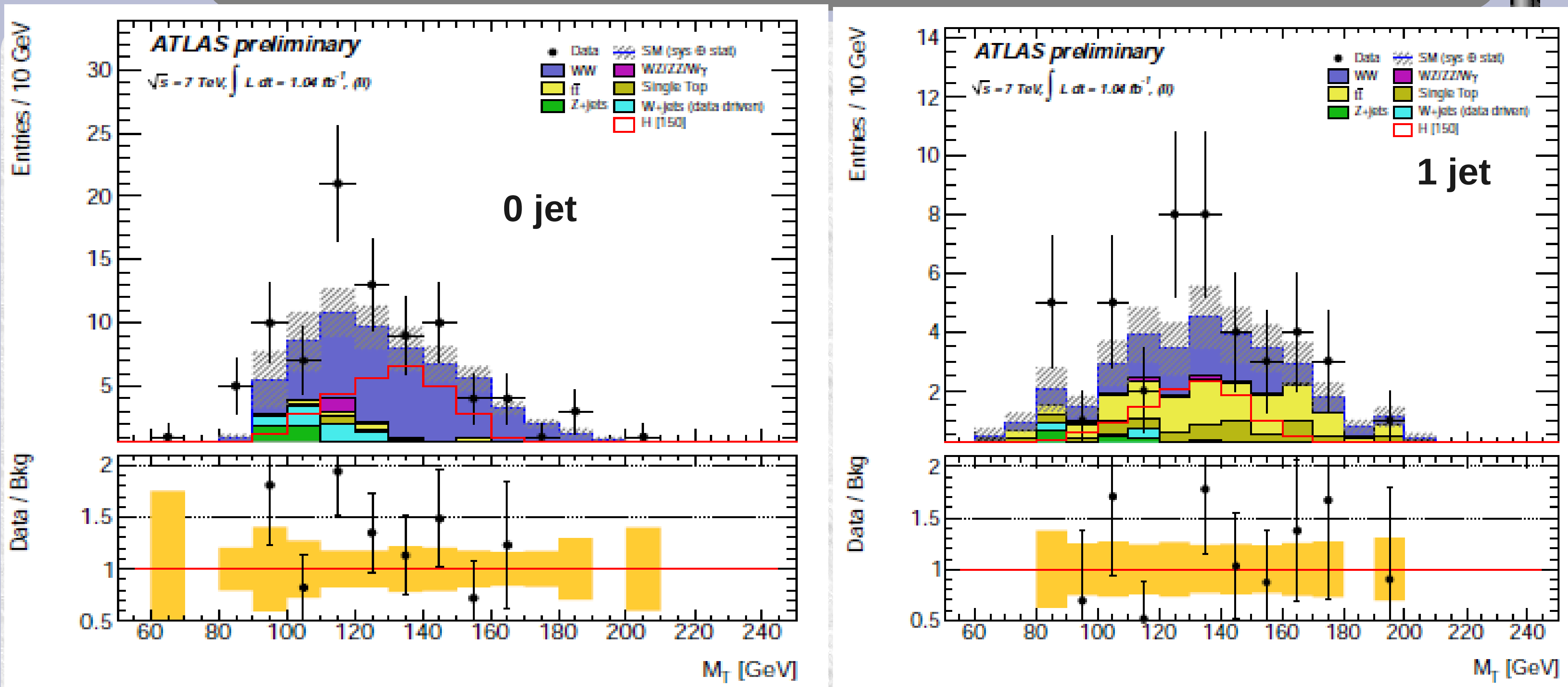
- Top: CMS
  - p_T, m_{ll}, $\Delta\Phi_{ll}$, m_T uncut
- Bottom: ATLAS
  - m_{ll}, $\Delta\Phi_{ll}$, m_T uncut
- Excess?
  - ATLAS and CMS
  - 1-jet largest?







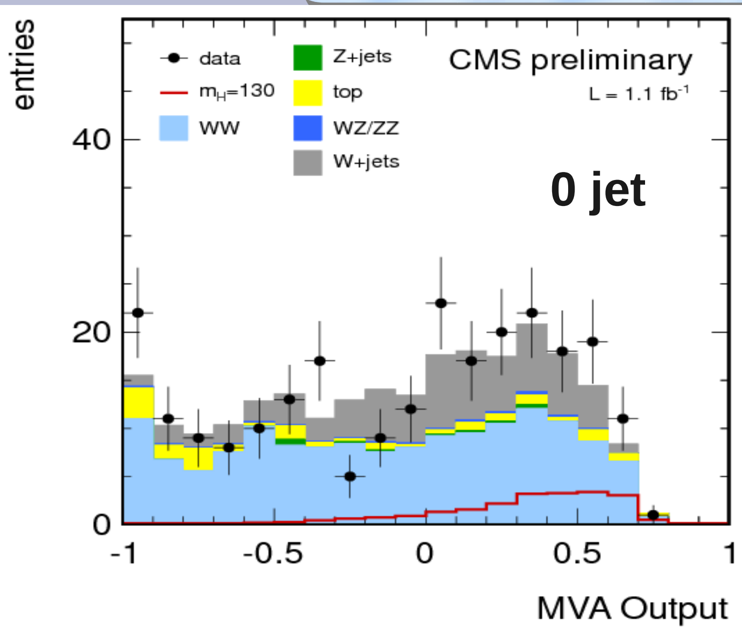
ATLAS WW → lνlν

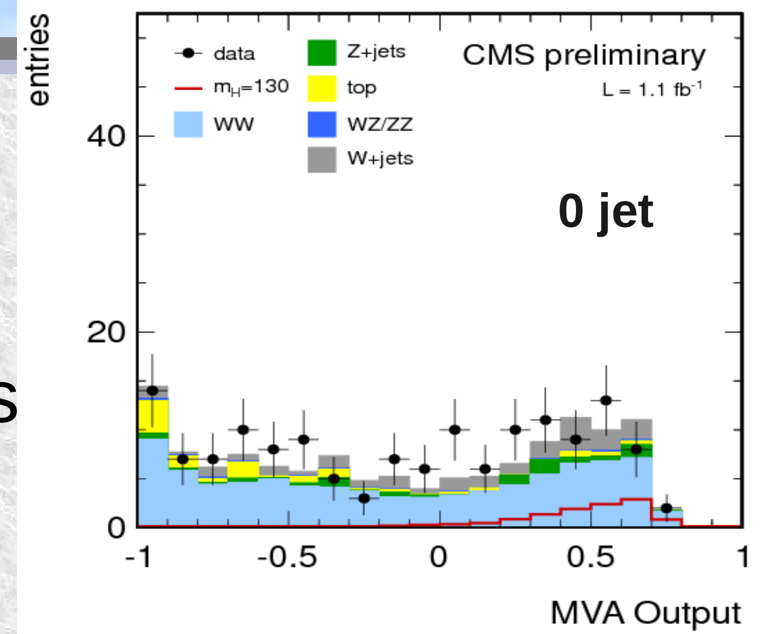


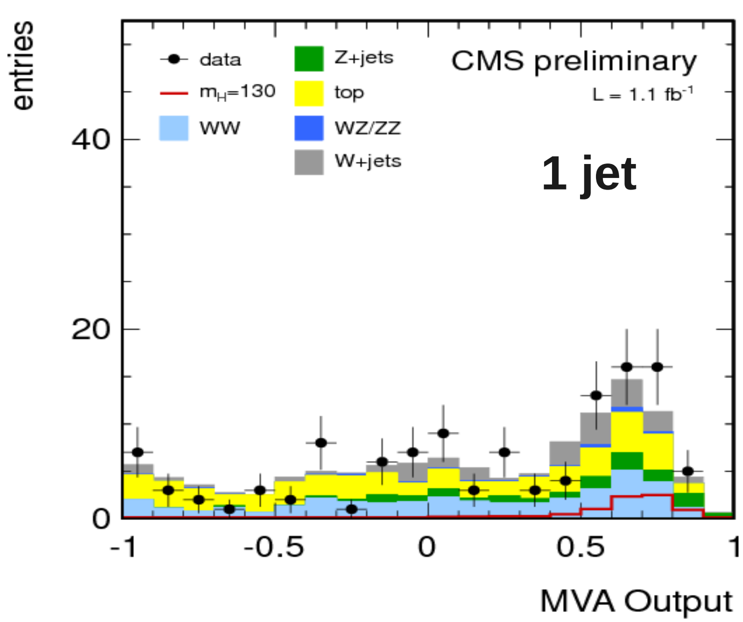
- Final m_T for ATLAS events
  - A window here 25% m_H wide selects final events
  - Some tendency for events to be same flavour

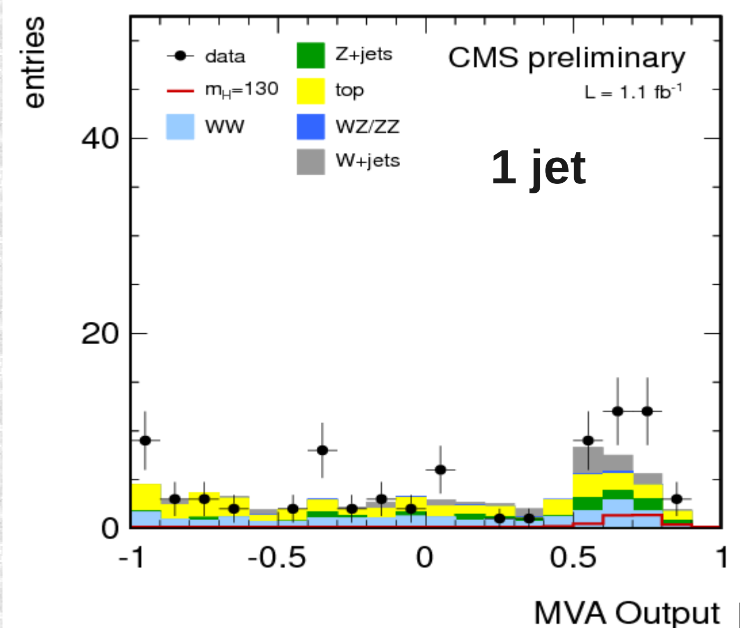
CMS WW → lνlν

- Final analysis plots:
  - Boosted decision trees
- Top 0jet, bottom 1-jet
- Left: eμ Right: ee/μμ
- Windows here select candidates

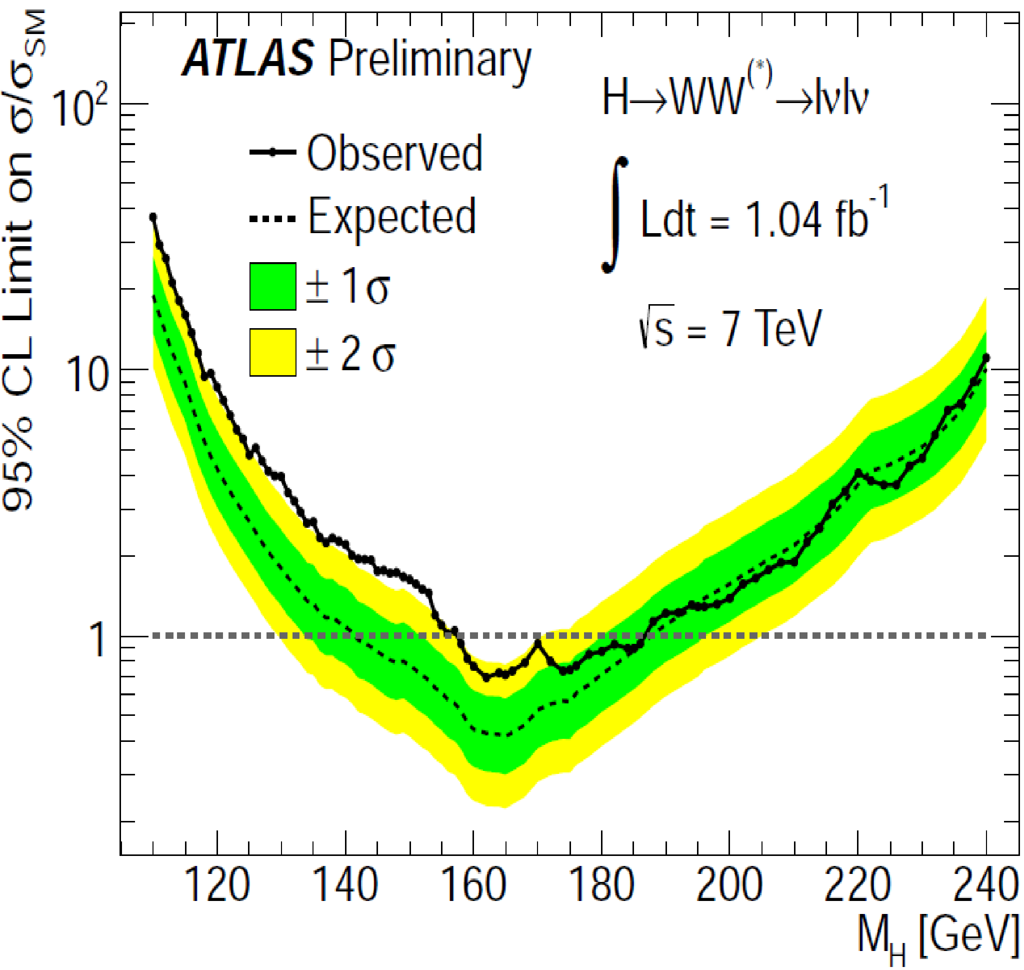


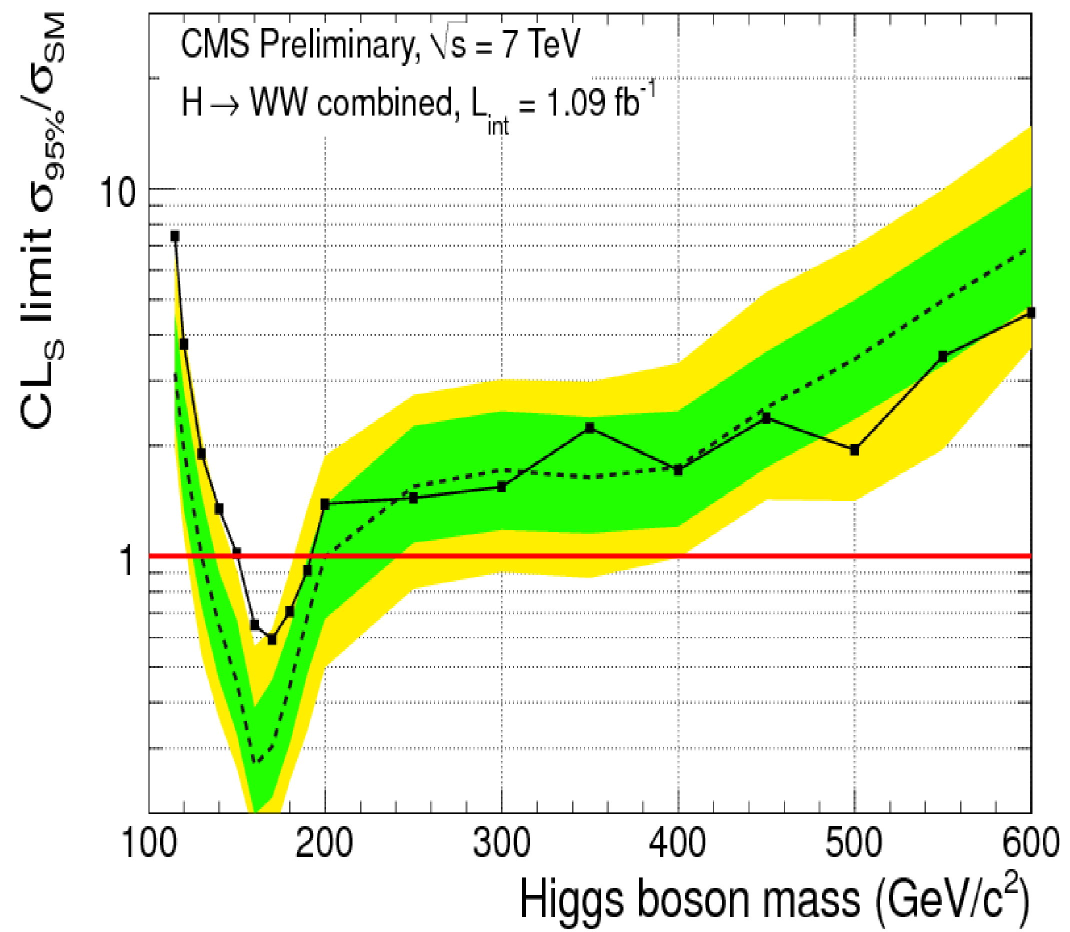






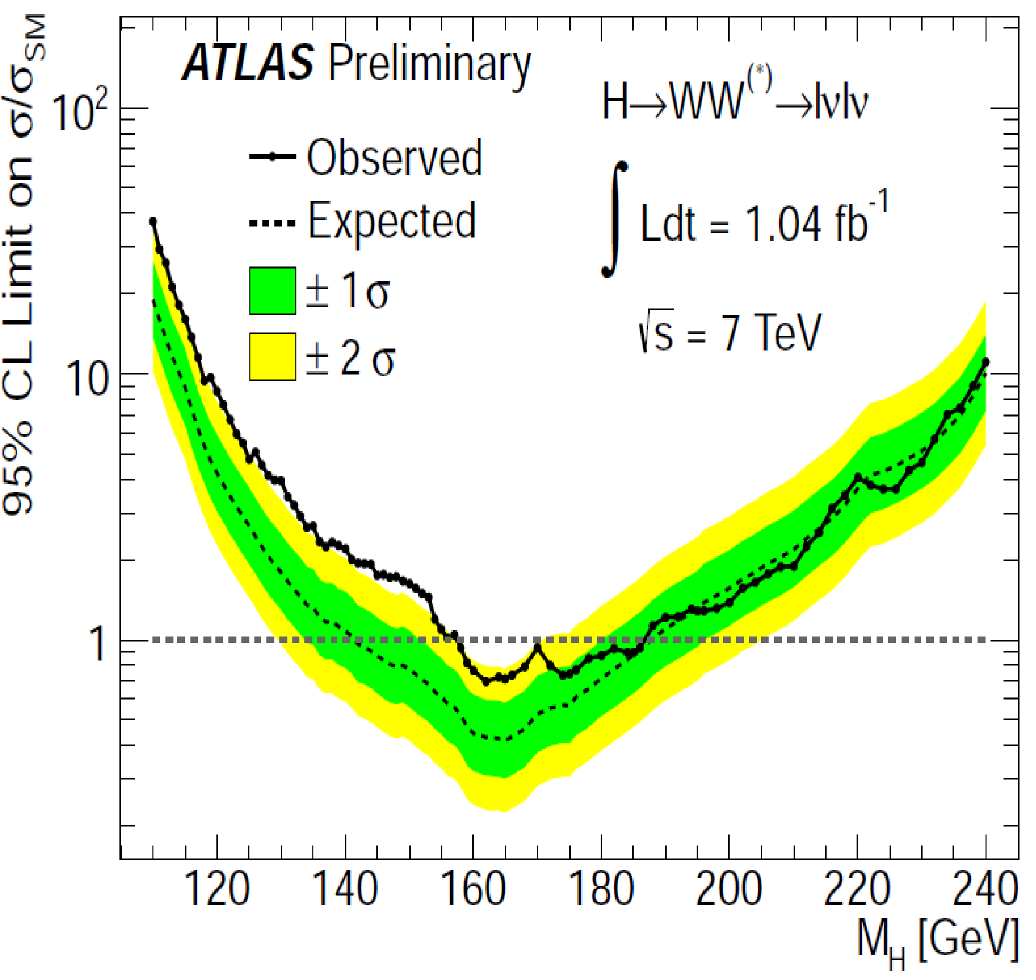
WW → lνlν



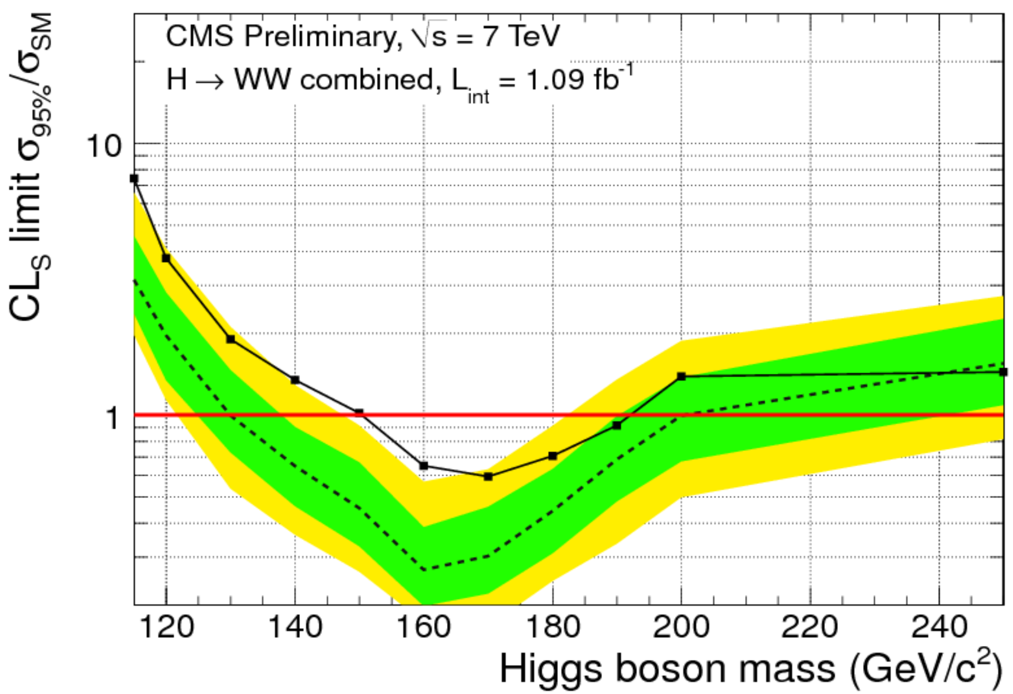


- ATLAS (left) exclude m_H 158-186 (exp: 142-186)
- CMS (right) exclude: m_H 150-193 (exp: 130-200)

WW → lνlν



Focus on same region:



- ATLAS (left) exclude m_H 158-186 (exp: 142-186)
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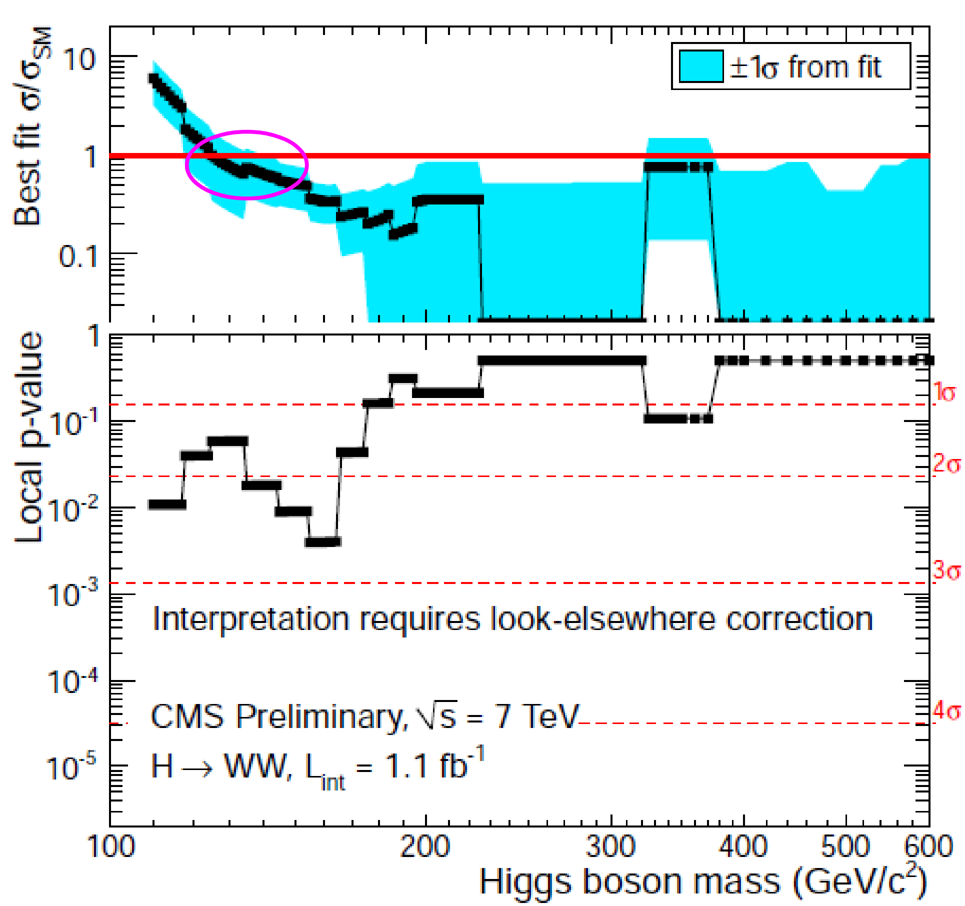
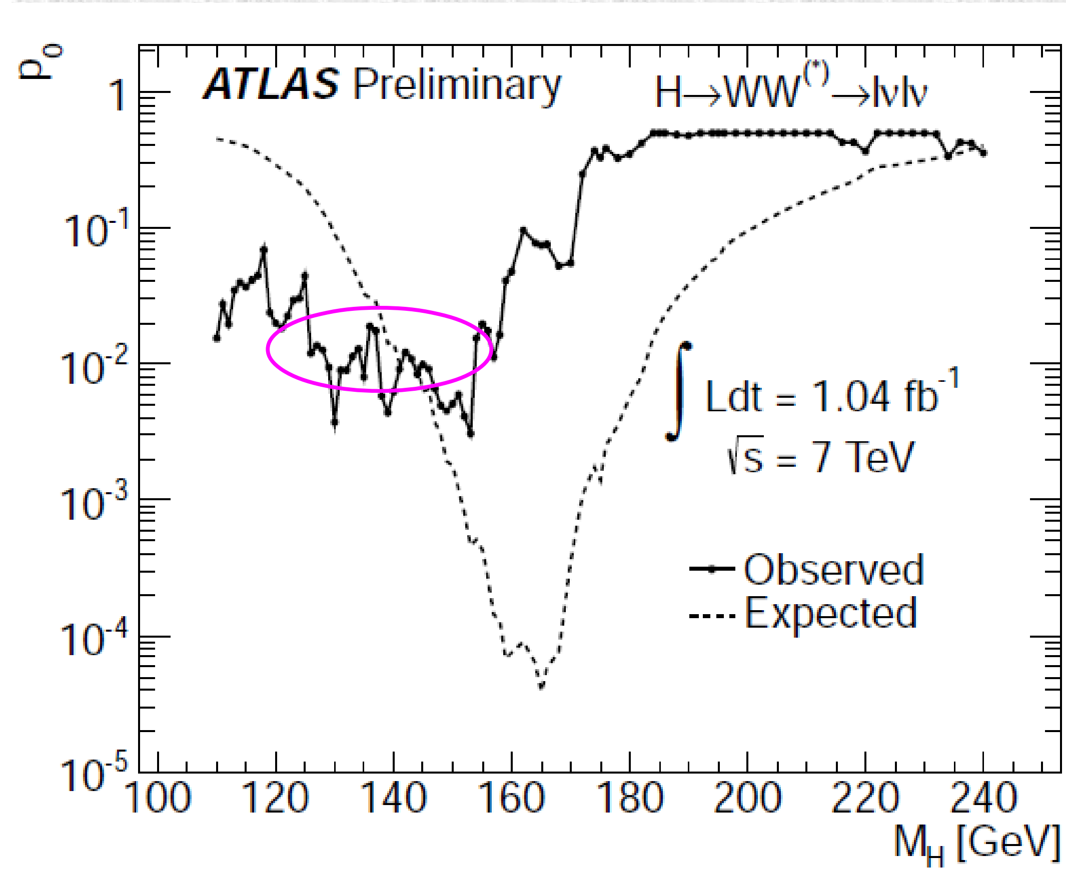
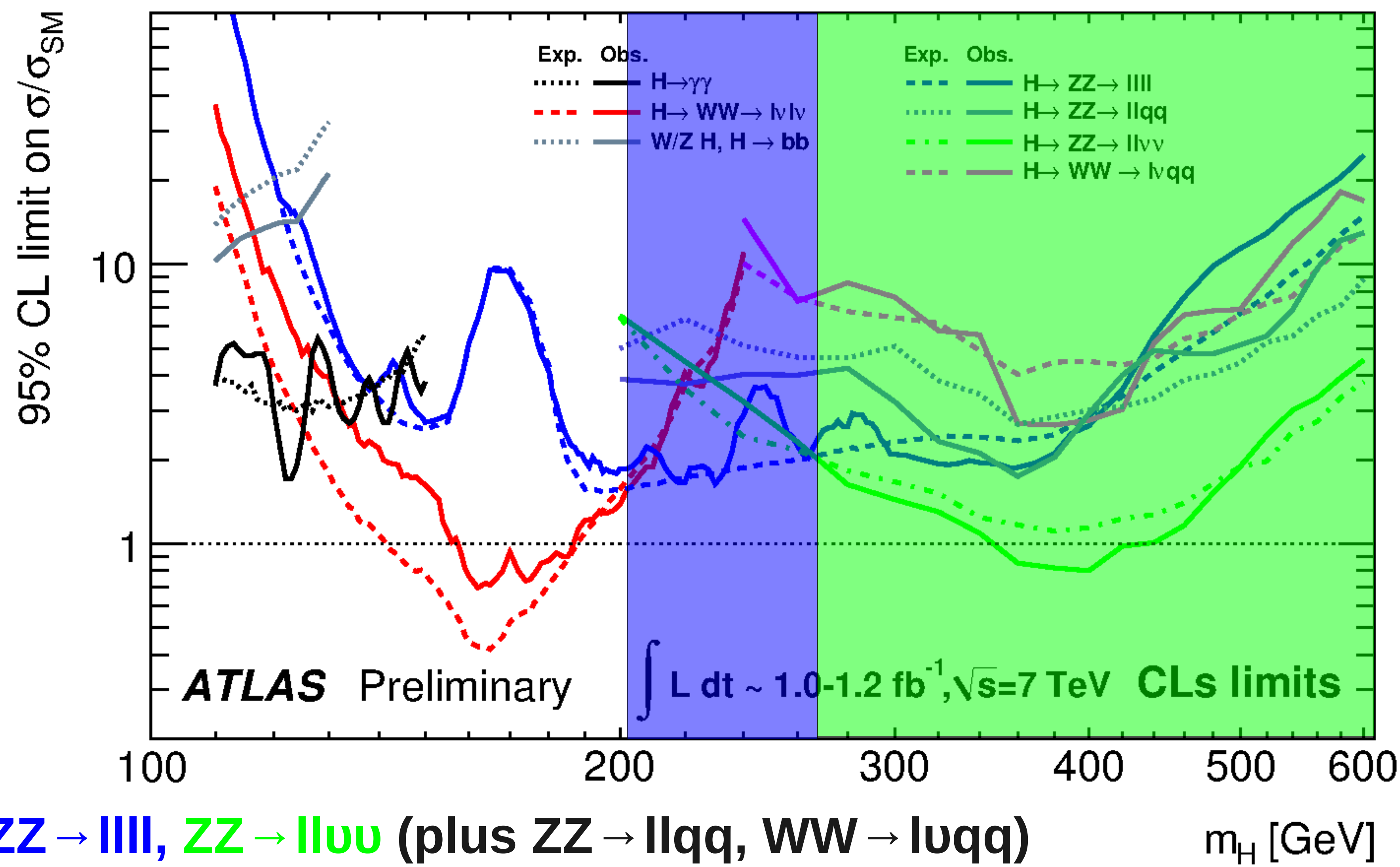
WW → lνlν





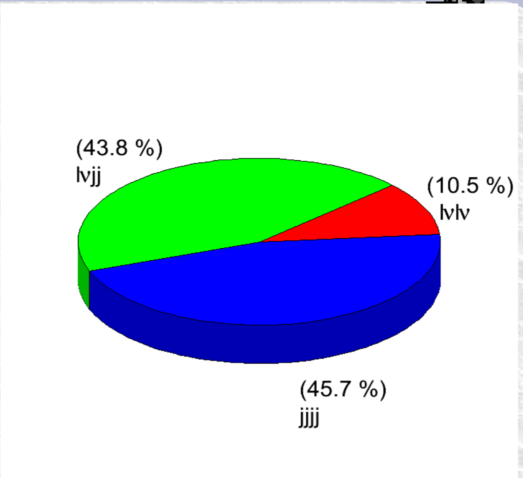
- CMS and ATLAS have excess 110-160GeV
  - Compatible with signal $120<m_H<150$
  - Best match at about 140

High mass searches



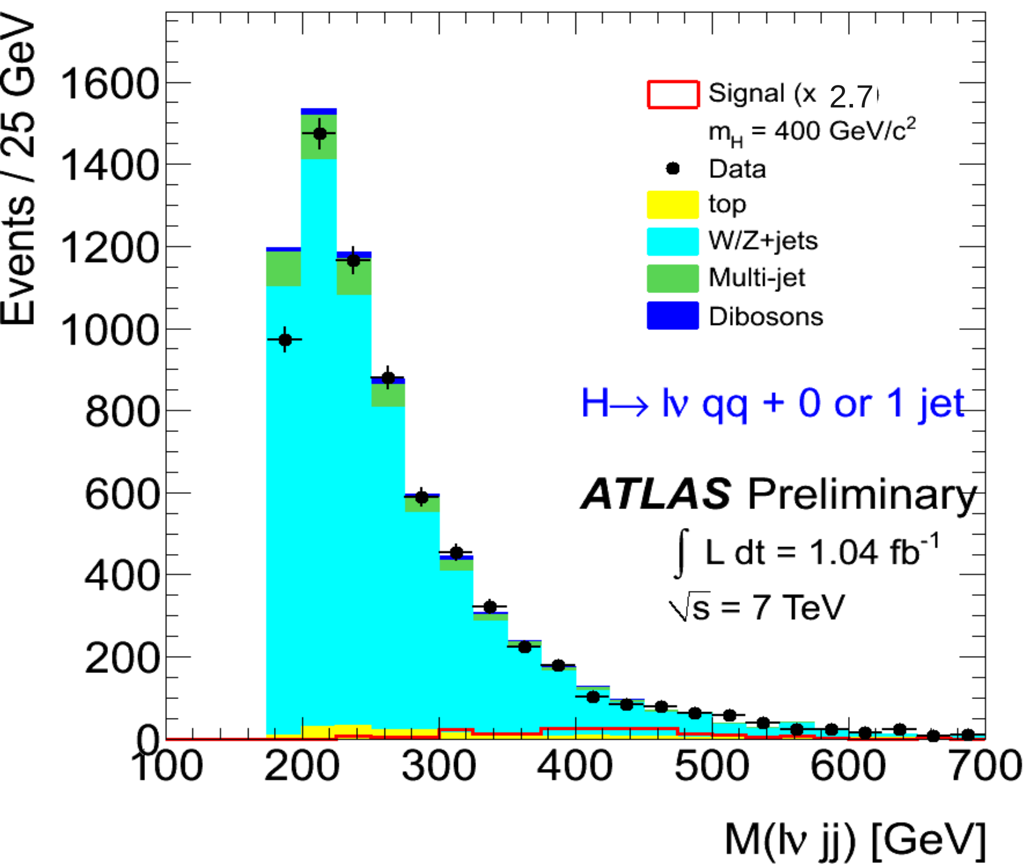
ZZ→llll, ZZ→llυυ (plus ZZ→llqq, WW→lυqq)

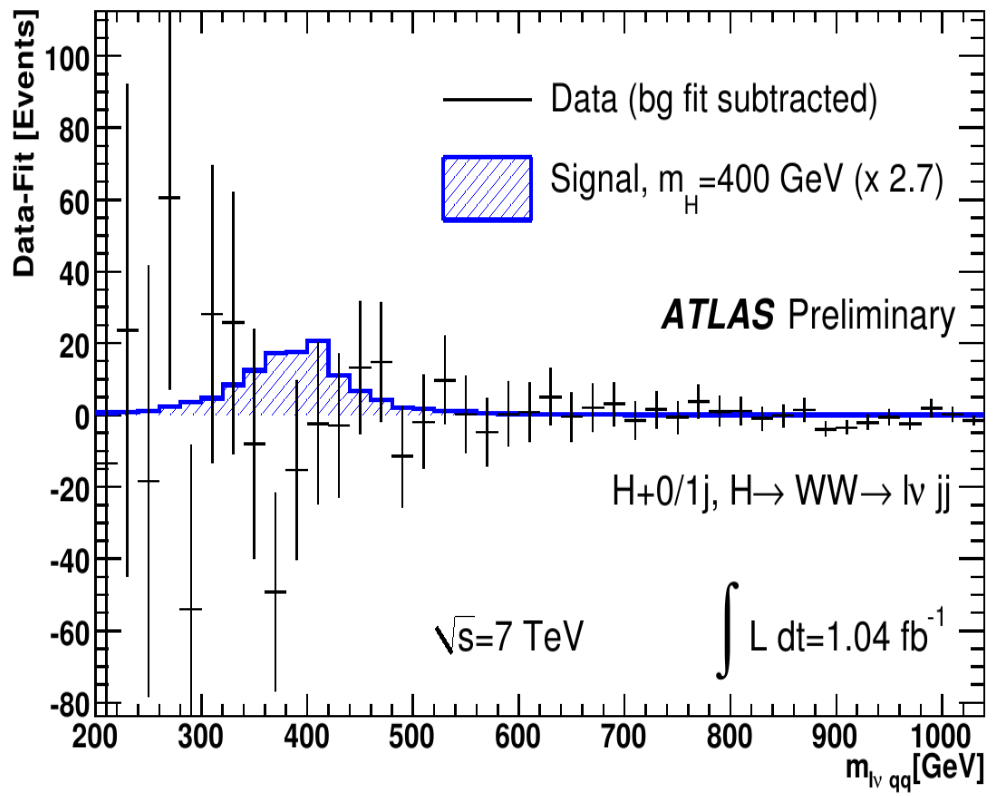
$WW \to l\nu qq$



- 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

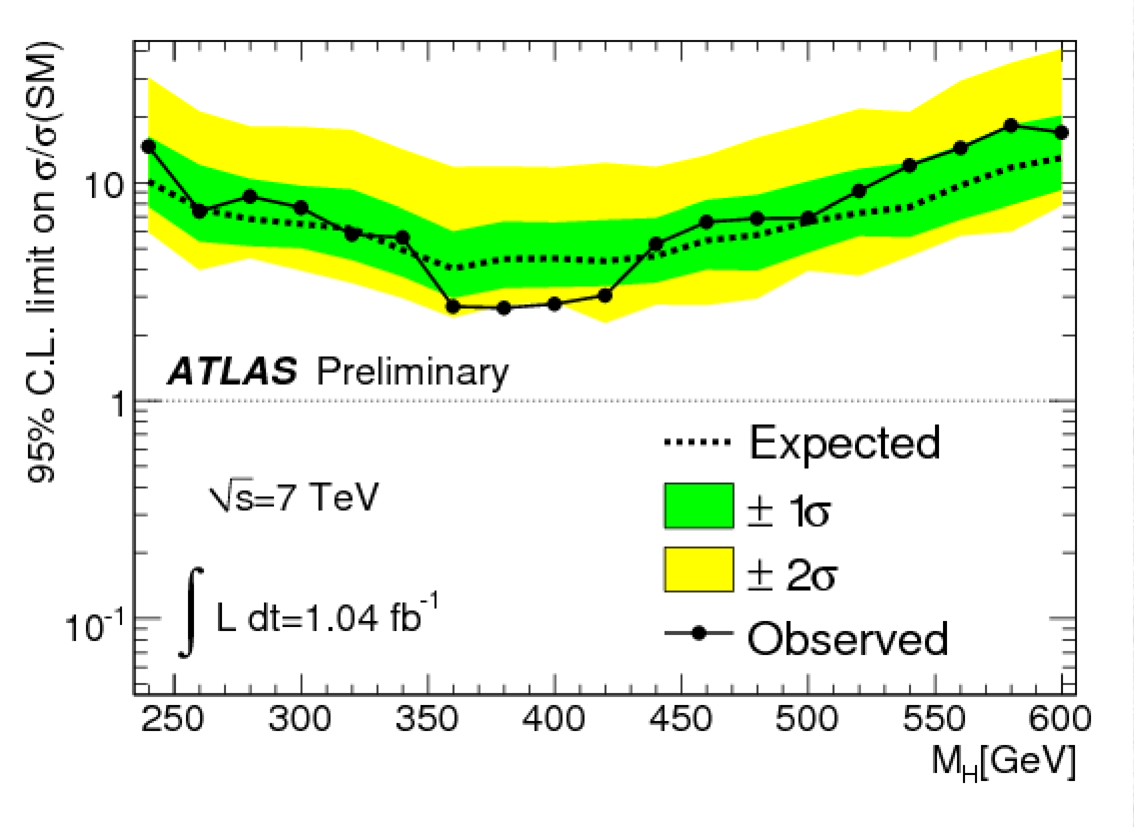




- $M_{l\upsilon qq}$ raw (left) and background-subtracted (right)
  - Sum over the 0 and 1 extra jet searches

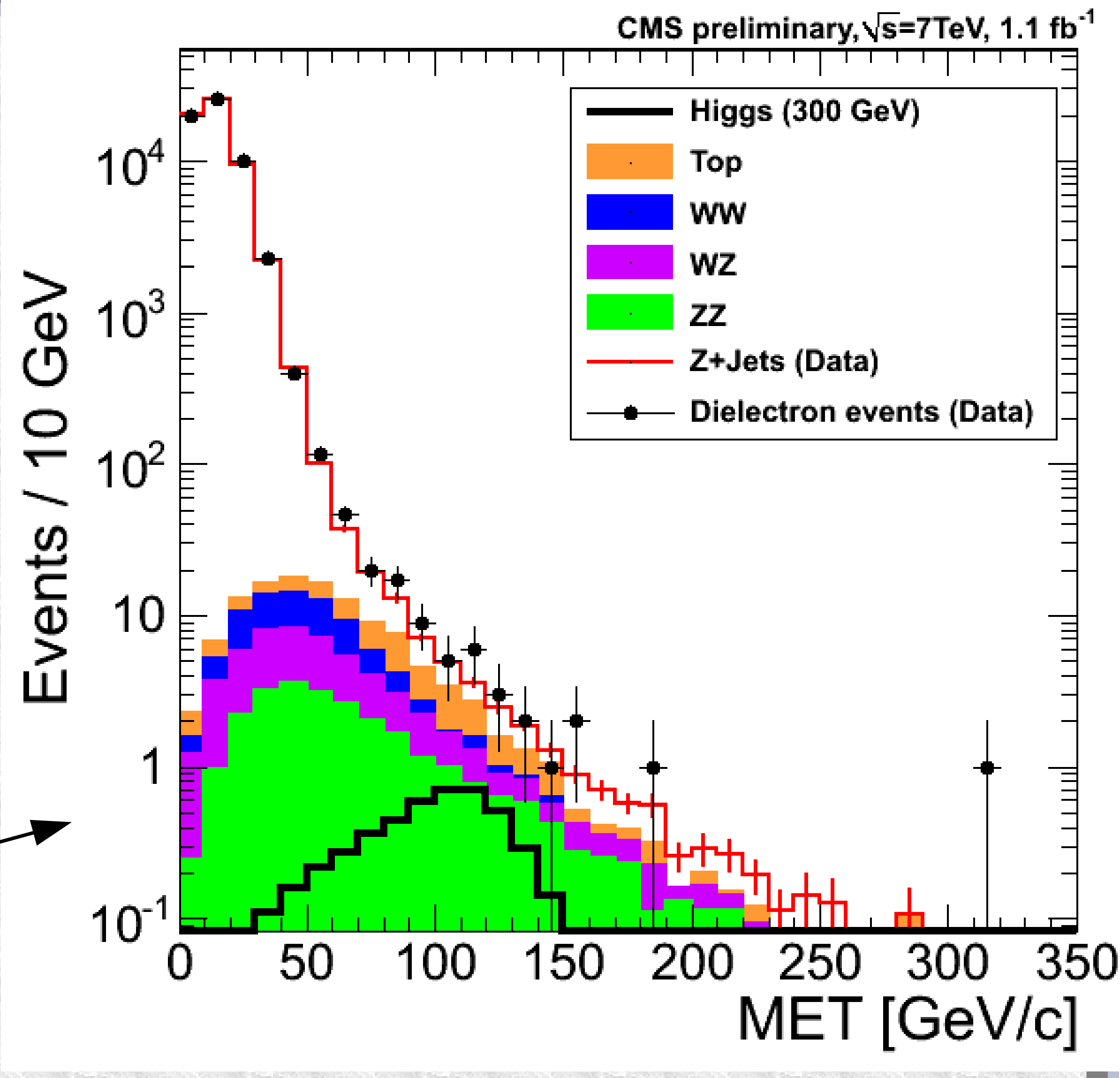
WW→lνqq

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

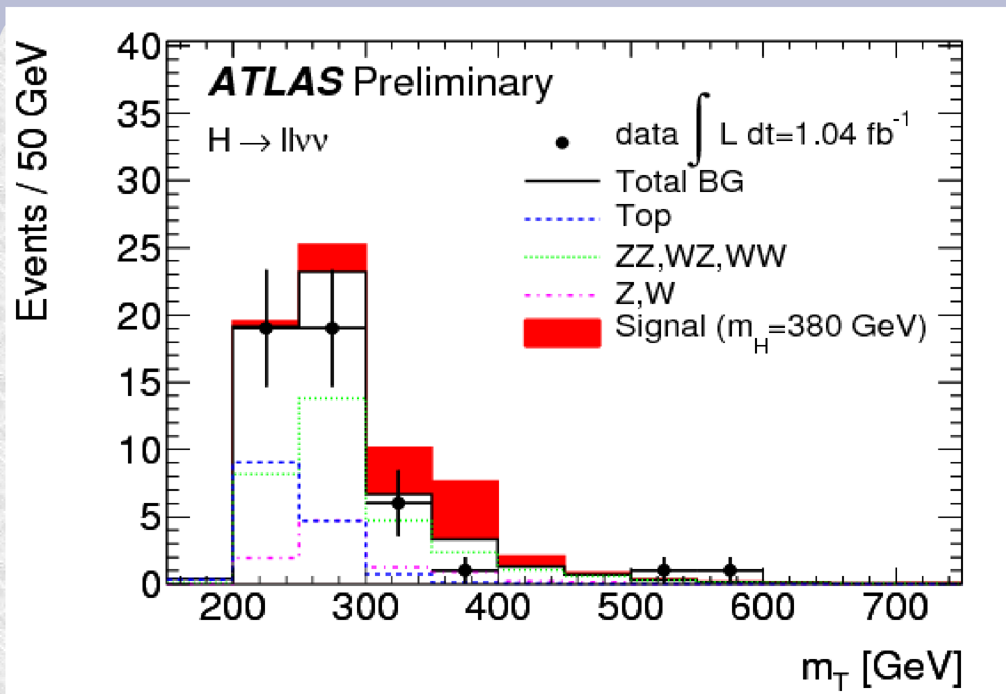


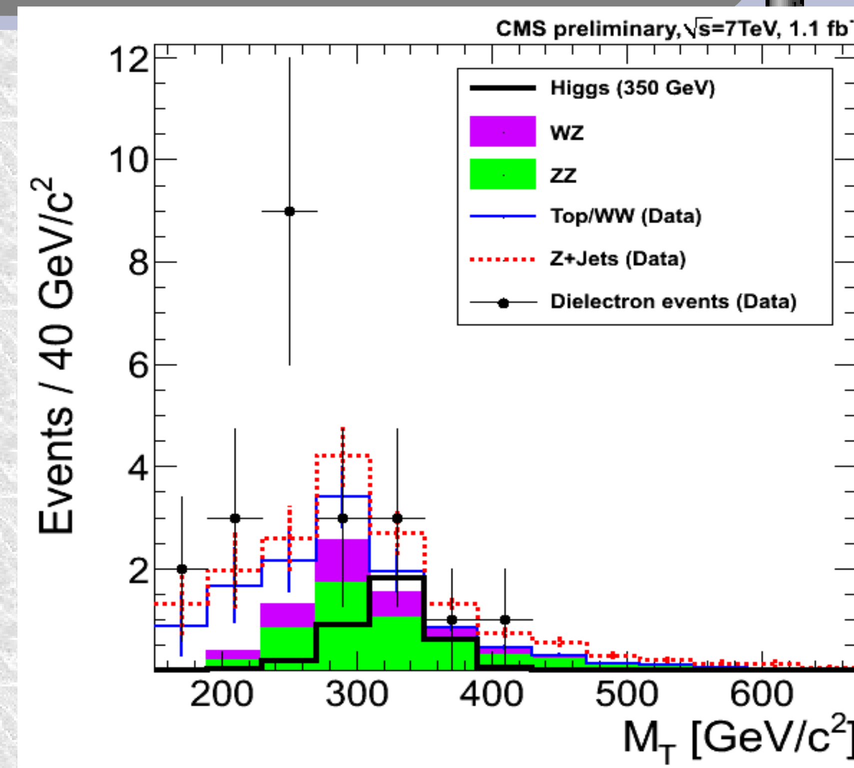
$ZZ \rightarrow ll\nu\nu$

- Clean decay,
  - All leptonic
- Higher rate than llll
  - $Z \rightarrow \nu\nu$ seen through missing energy
  - Only if Z moves
- ► m_H>200GeV
- Needs good MET
  - CMS excellent description of Zs



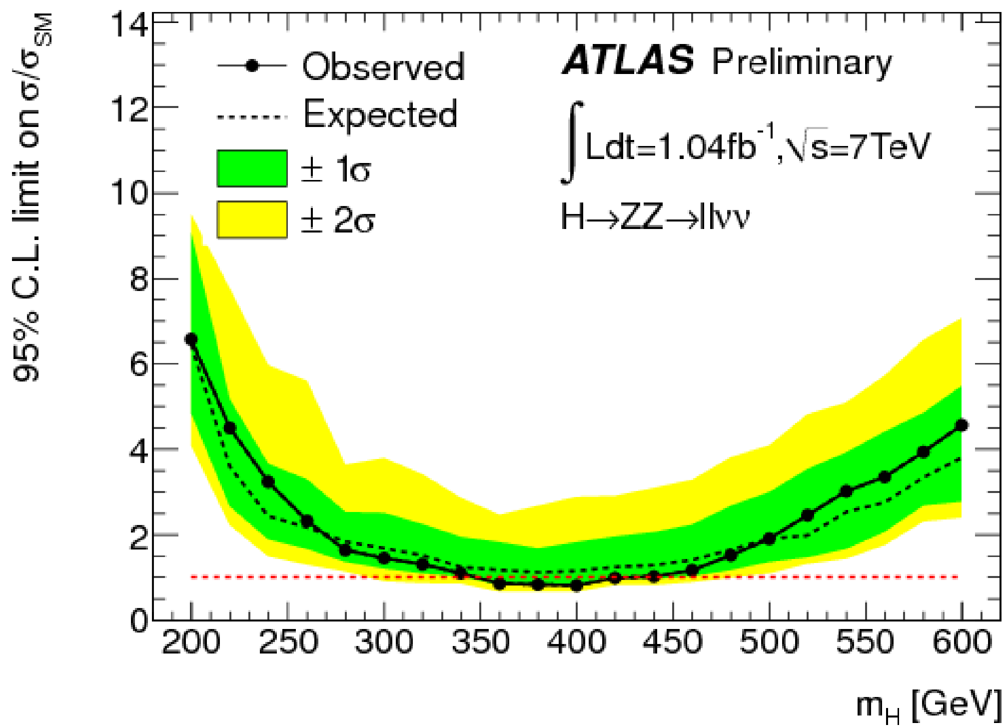
ZZ → llνν

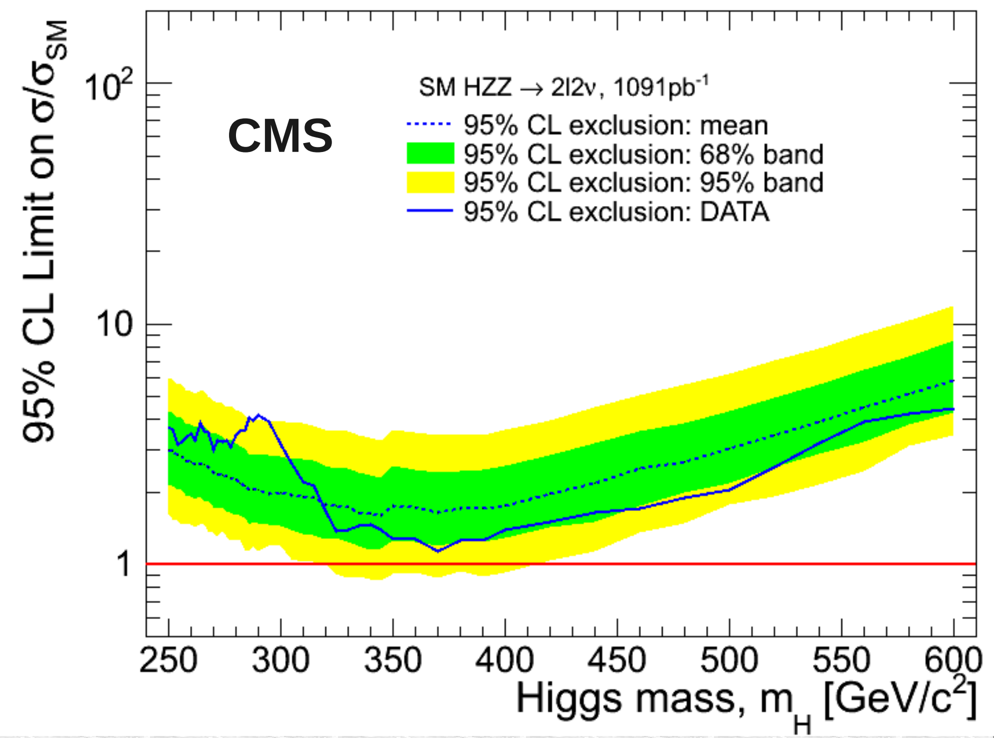




- ATLAS (left) and CMS (right)
- Harder E_T^{miss} and δφ cuts at high mass
- 380GeV is excluded by left figure alone!

$ZZ \rightarrow ll\nu\nu$

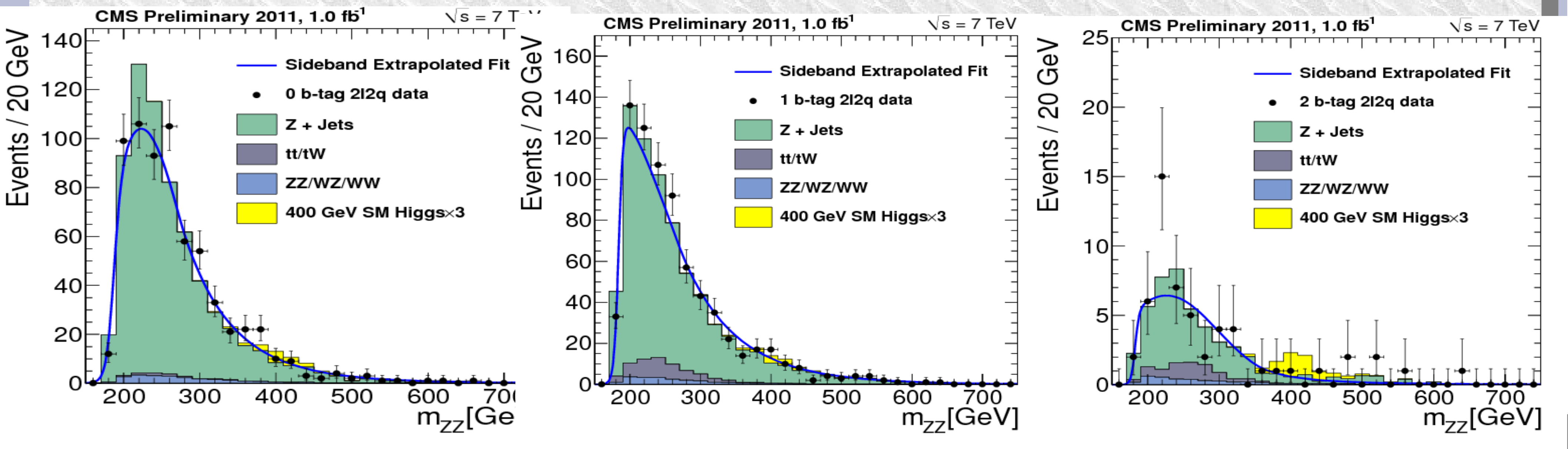




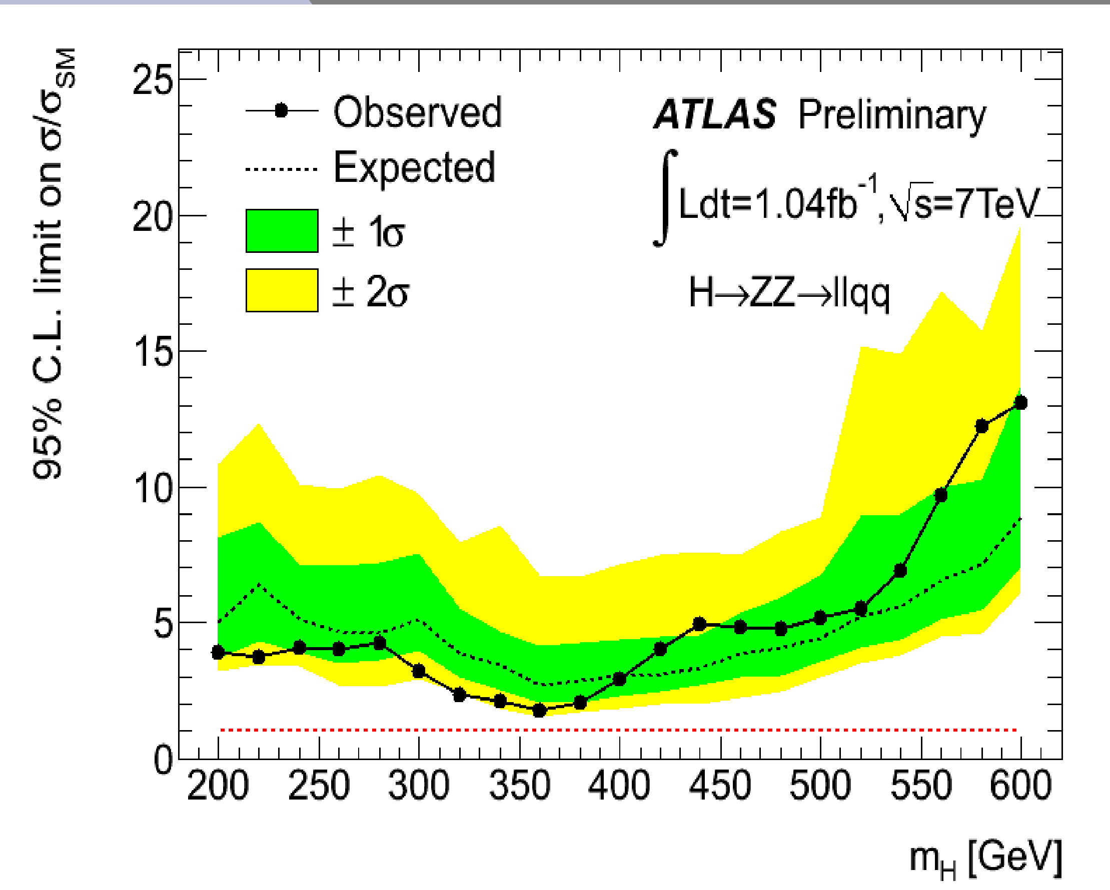
- ATLAS (left) and CMS (right)
- ATLAS excludes 360 to 440 GeV – just!
- Both searches best sensitivity 1-2xSM
  - Both got lucky

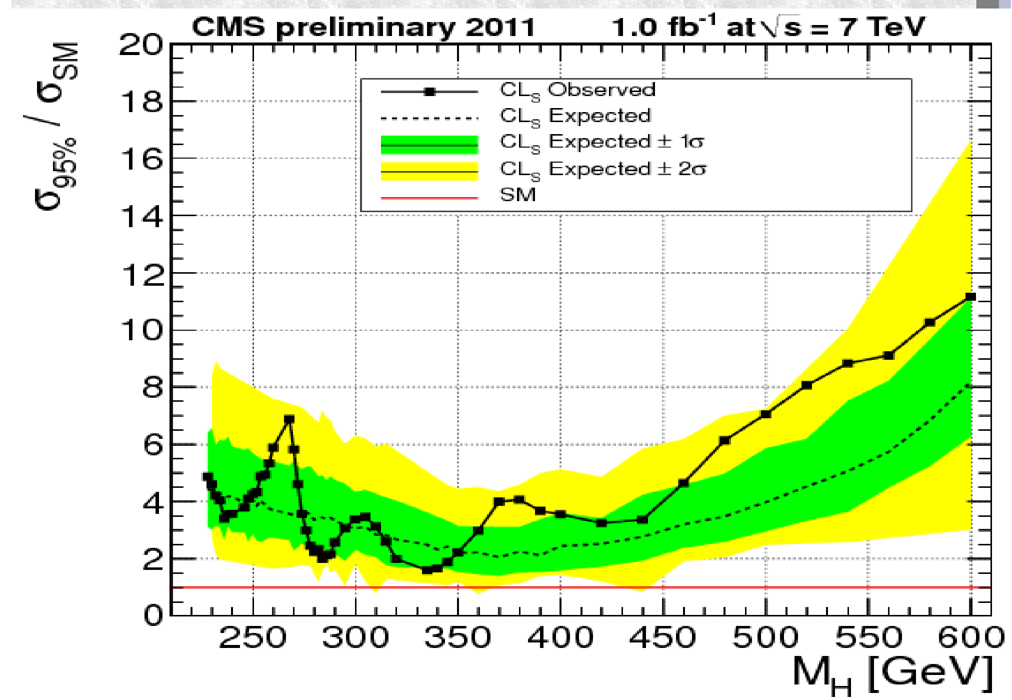
ZZ→llqq

- 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



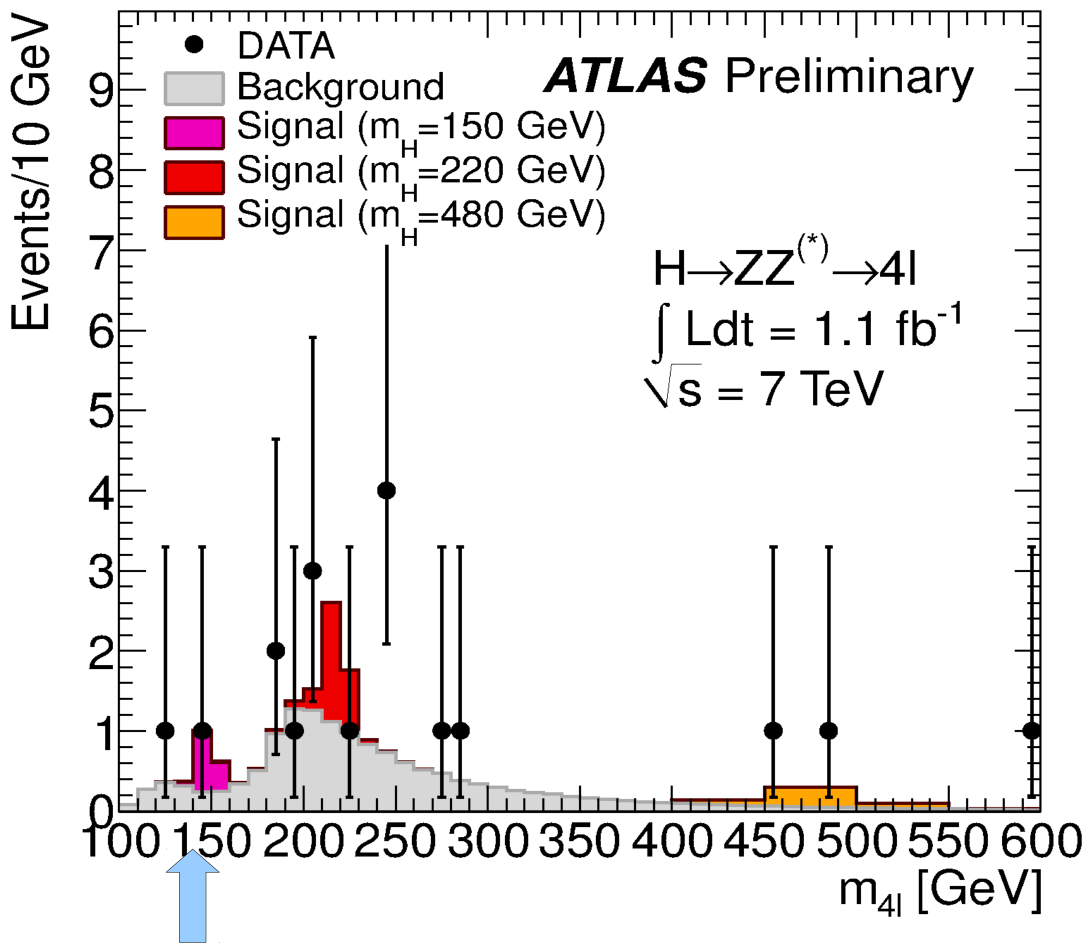


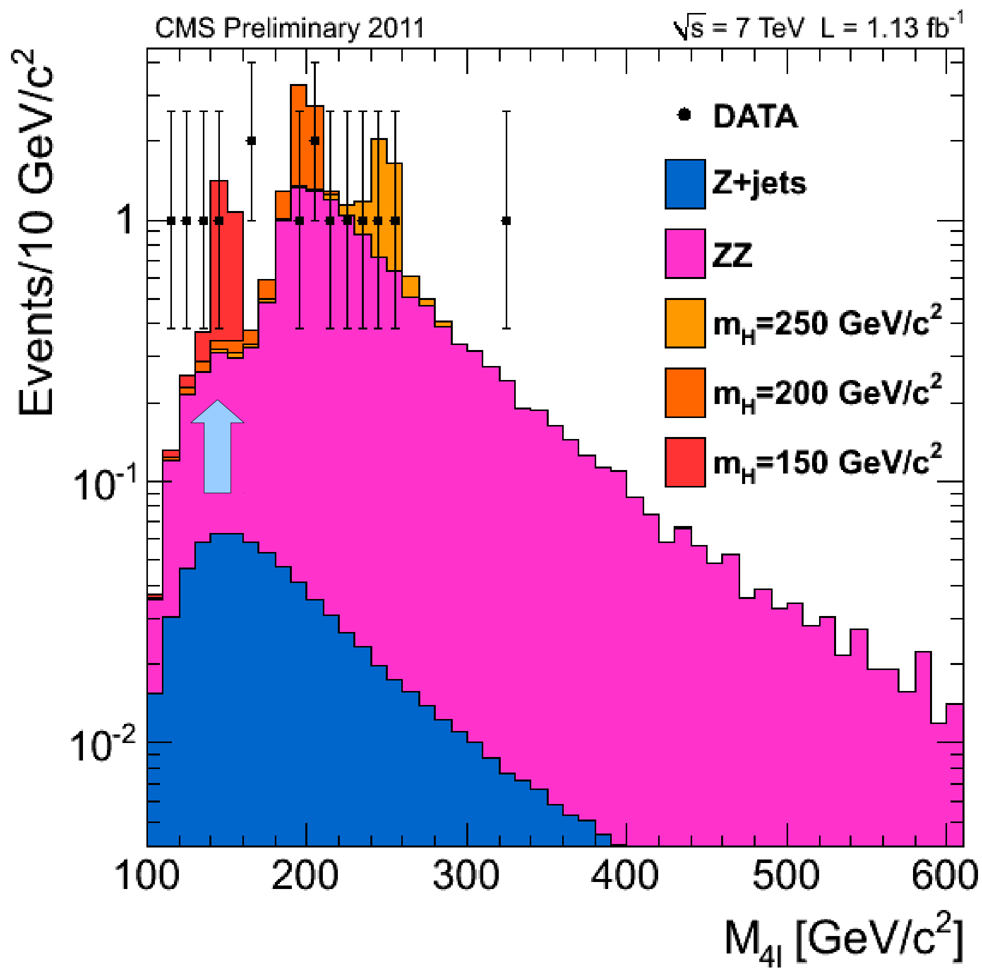
- CMS sensitivity 2xSM, ATLAS 3xSM at 350-400
- Fluctuations never up to 2σ

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

- Require 4 identified leptons
  - Backgrounds already rather low
- At least one pair compatible with Z peak
  - For m_H < 180GeV one will be off-shell
  - At higher masses require both compatible.
- Background from:
  - Zbb can produce two leptons from the b decay
  - $t\bar{t} \rightarrow l\nu bl\nu b$ can give the same issue
- So suppress:
  - b quarks with impact parameters cuts
  - Fakes with isolation
- Background largely genuine $ZZ^{(*)}$

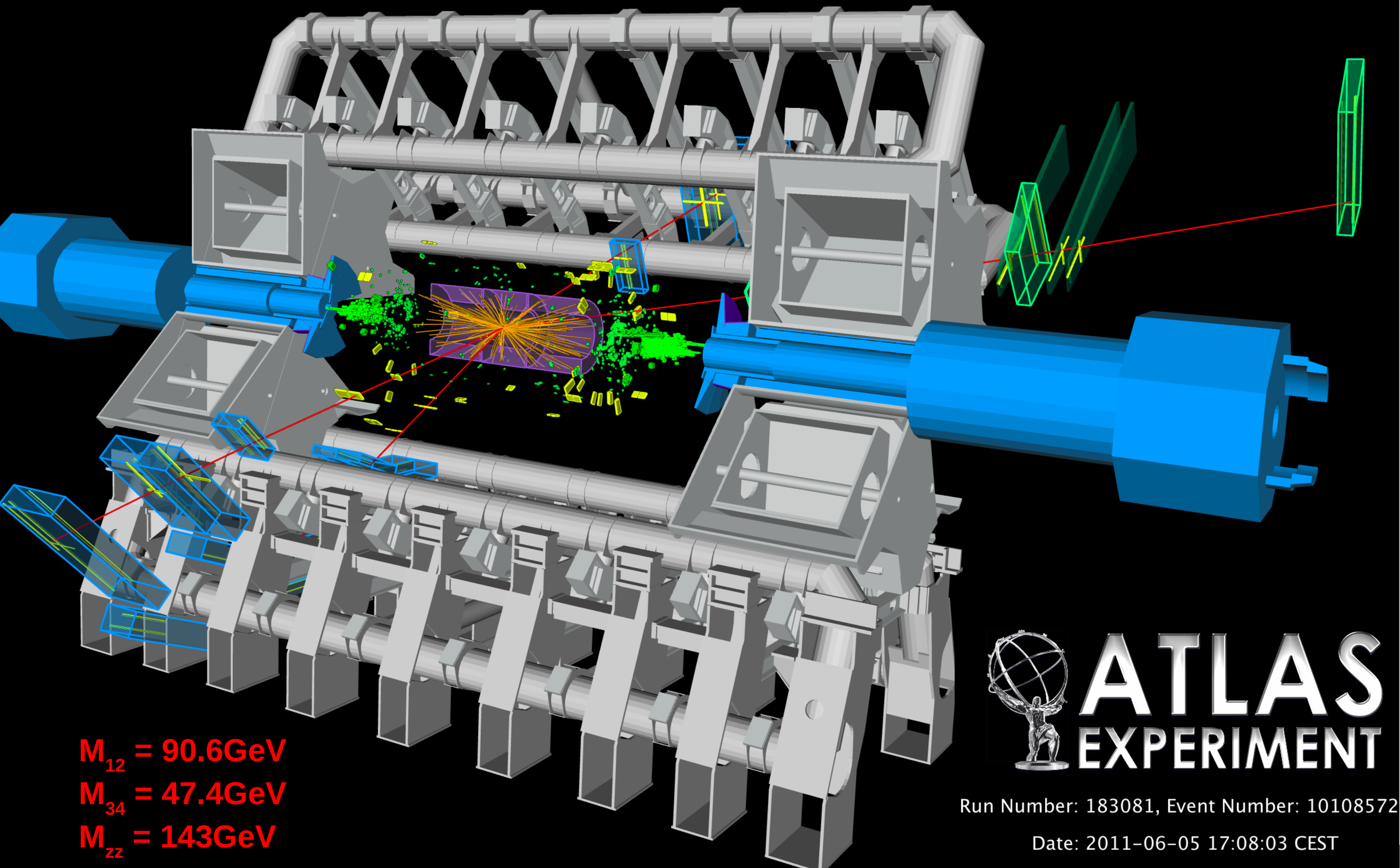
ZZ$^{(*)}$ → llll



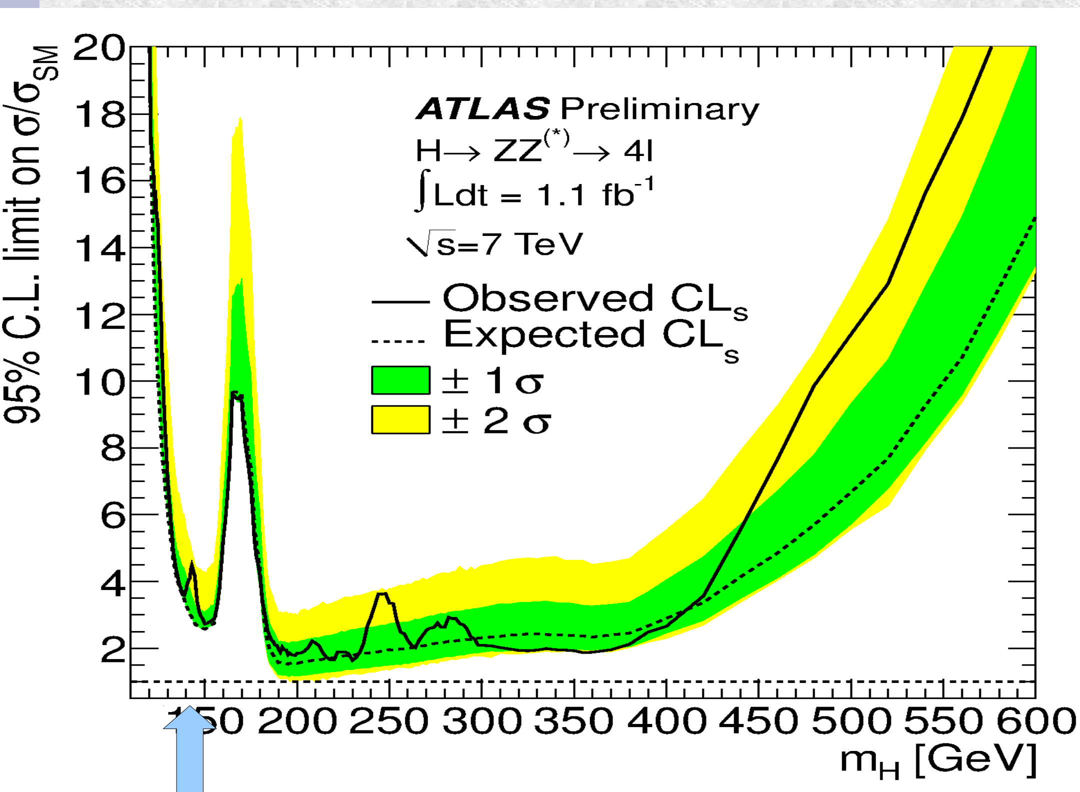


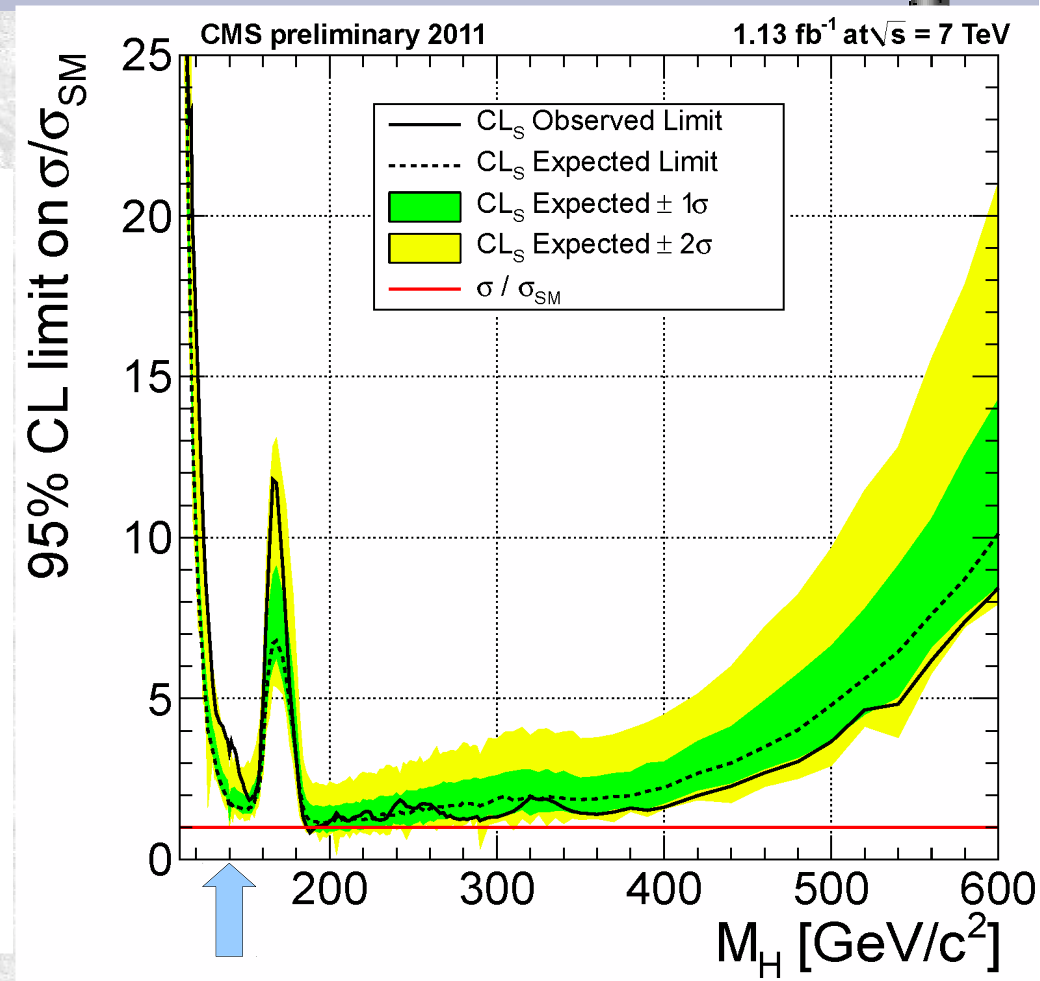
- Both experiments collect a few too many events
- ATLAS near 245, CMS below 180

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



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



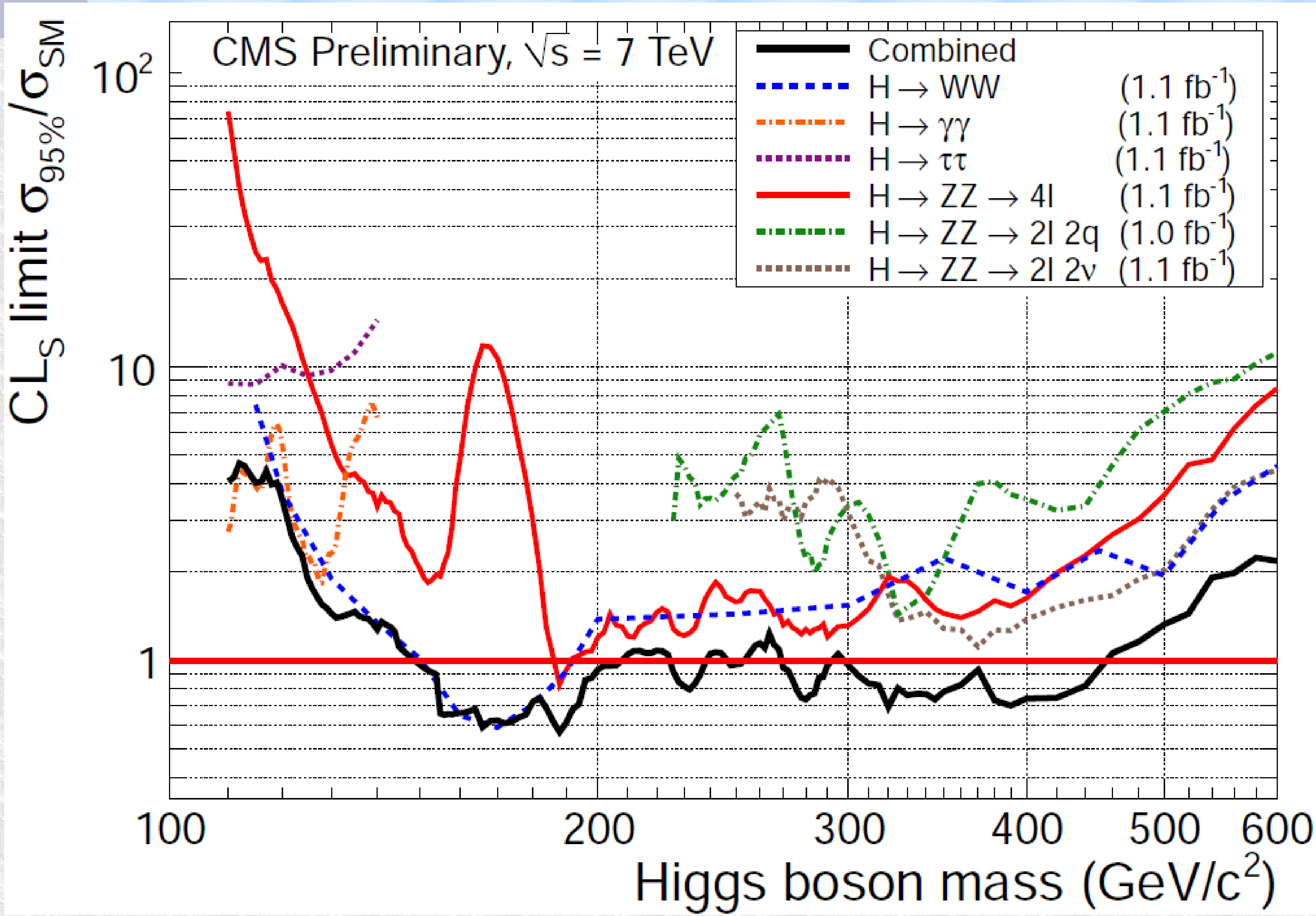


- CMS (just) excludes SM at 195; ATLAS not there
- Small excess visible near 140

ATLAS / CMS combinations

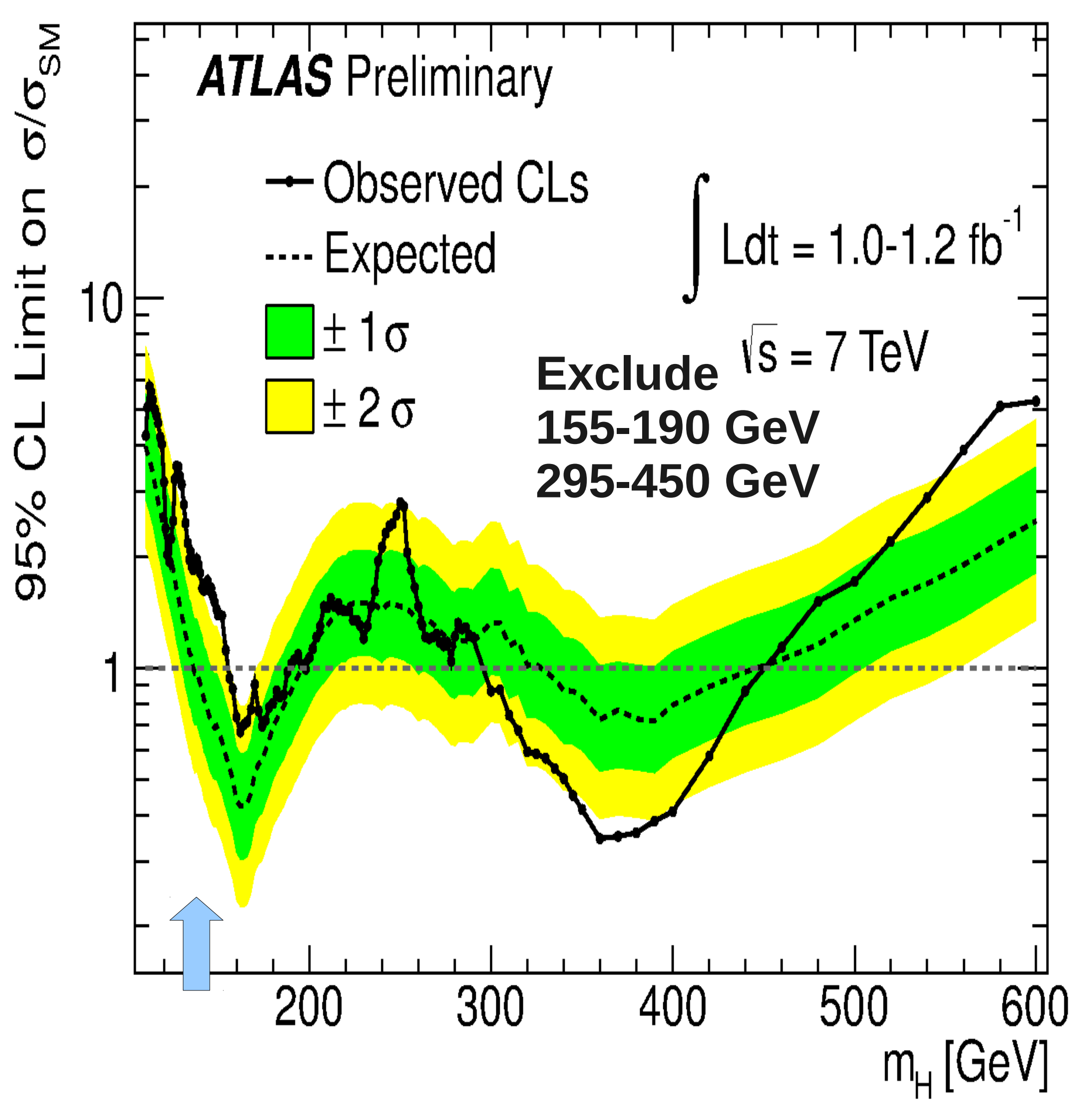
- The SM Higgs is a very well-defined thing
  - Tell us the mass and we know the rest
- So we know what to expect in all these channels
  - We put them together for optimal sensitivity.
  -
- Needs precise understanding of the theory
  - LHC cross-section working group did a great job
  - We have an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

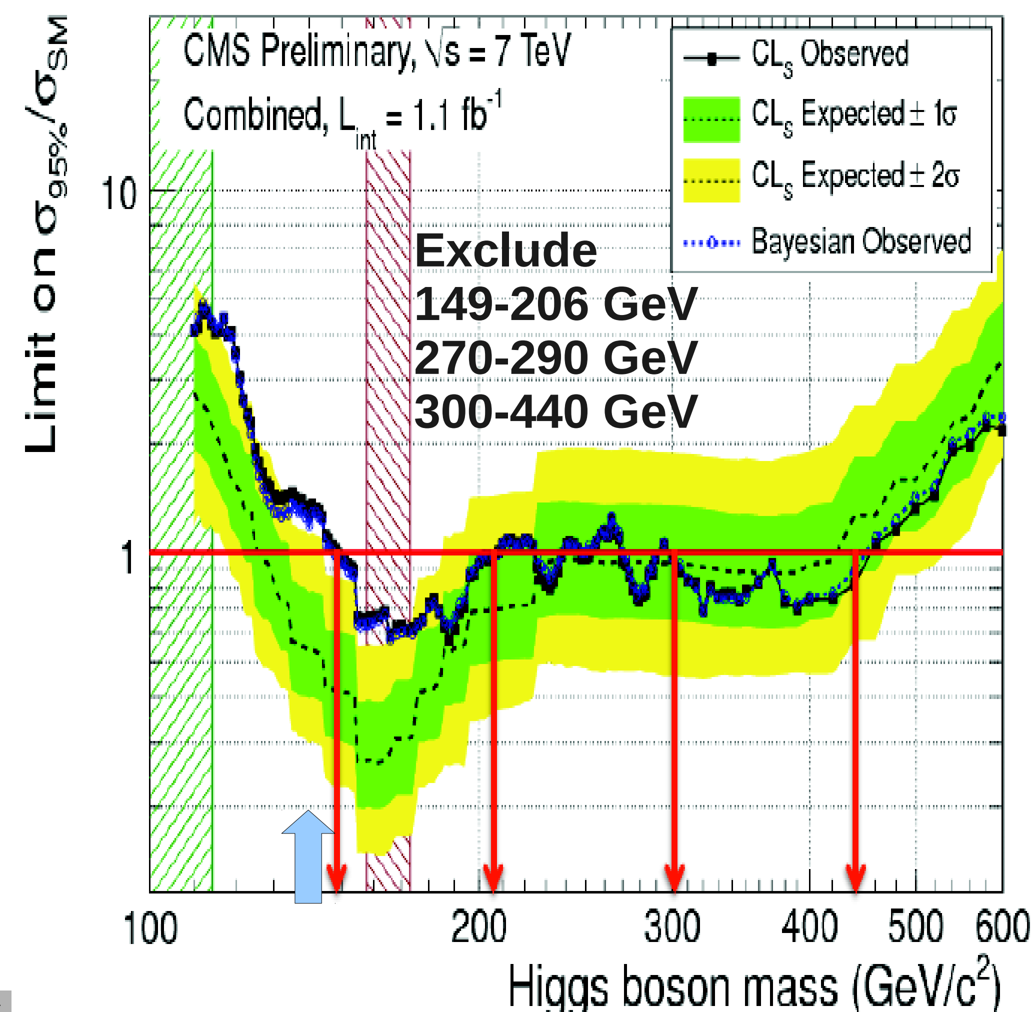
CMS channels compared



ATLAS & CMS limits

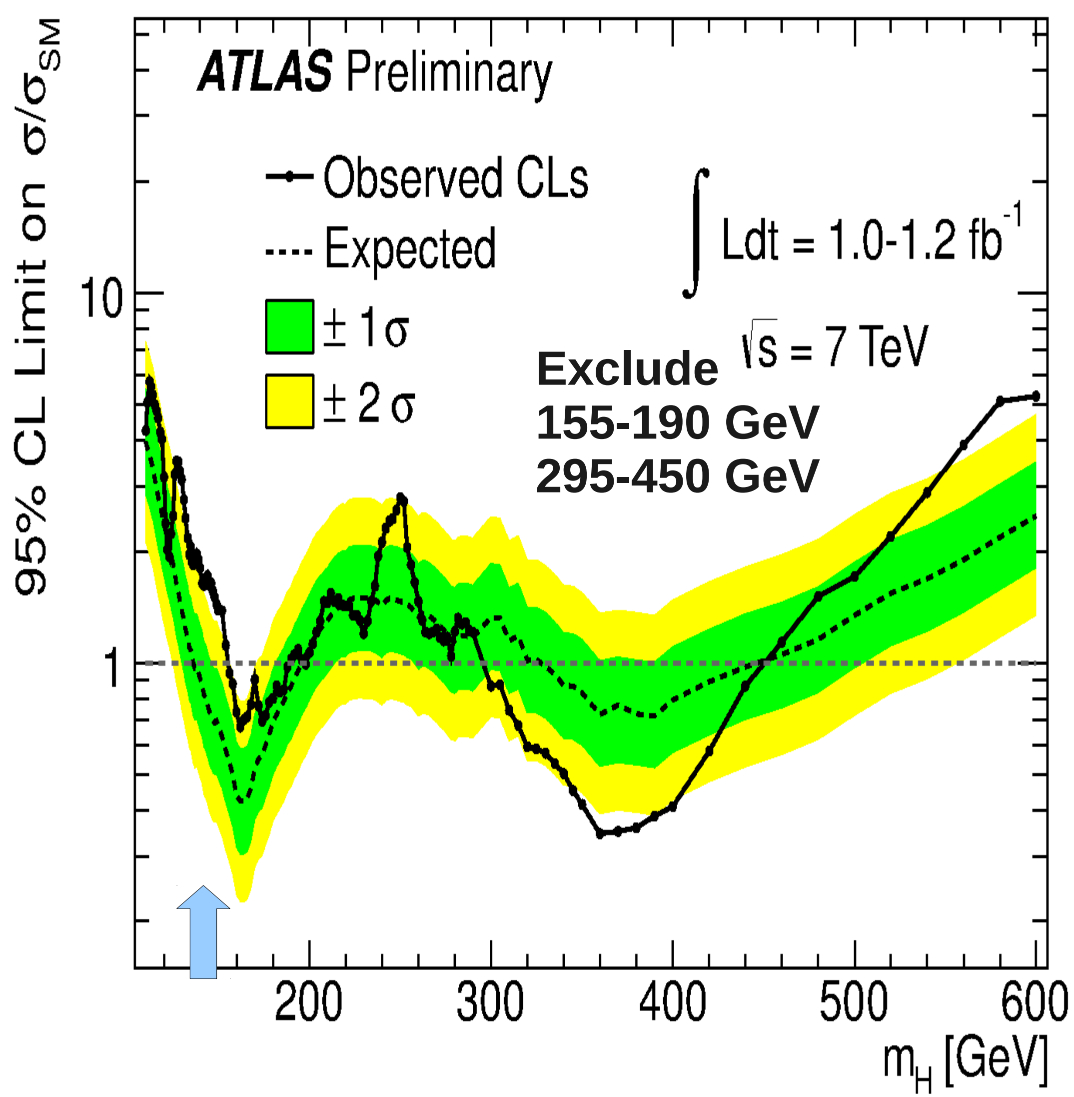
Sensitivities differ in detail
But on average similar

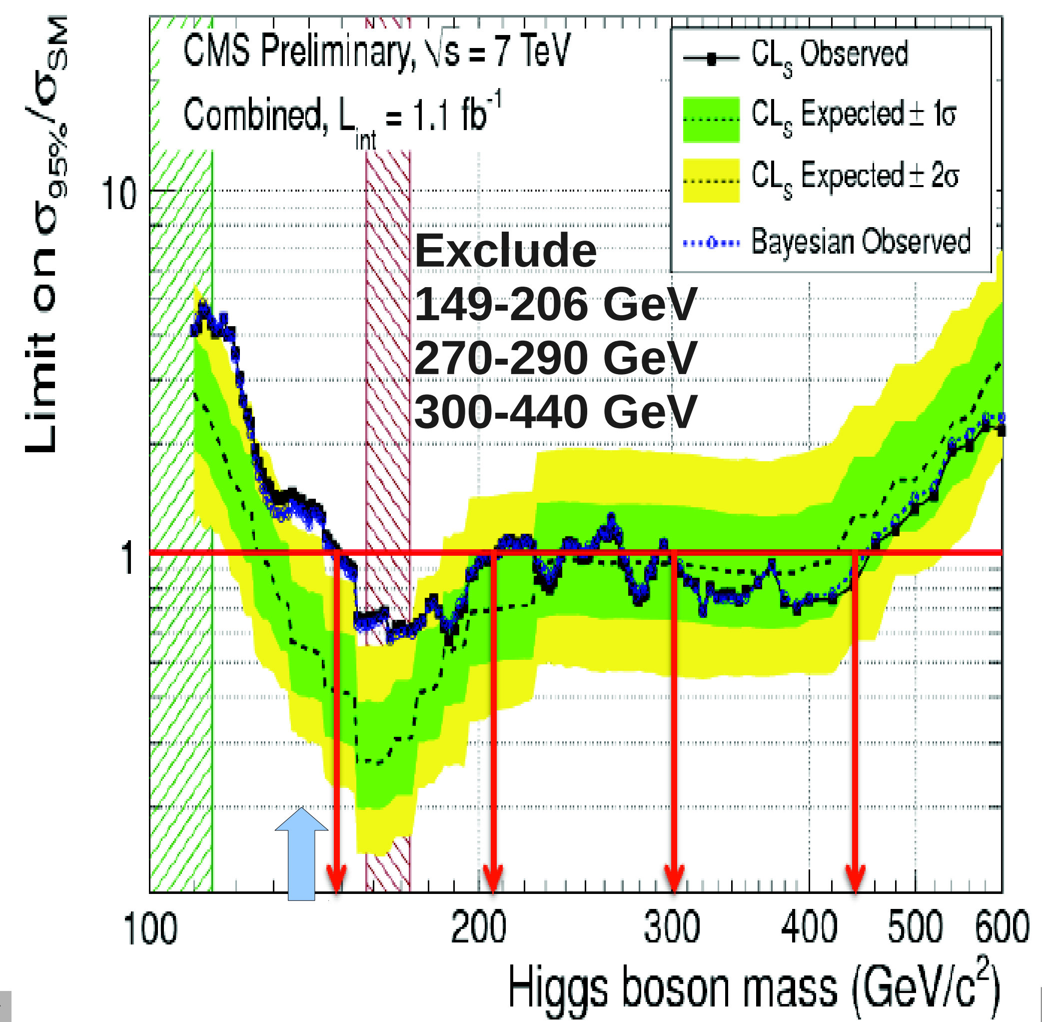




ATLAS & CMS limits

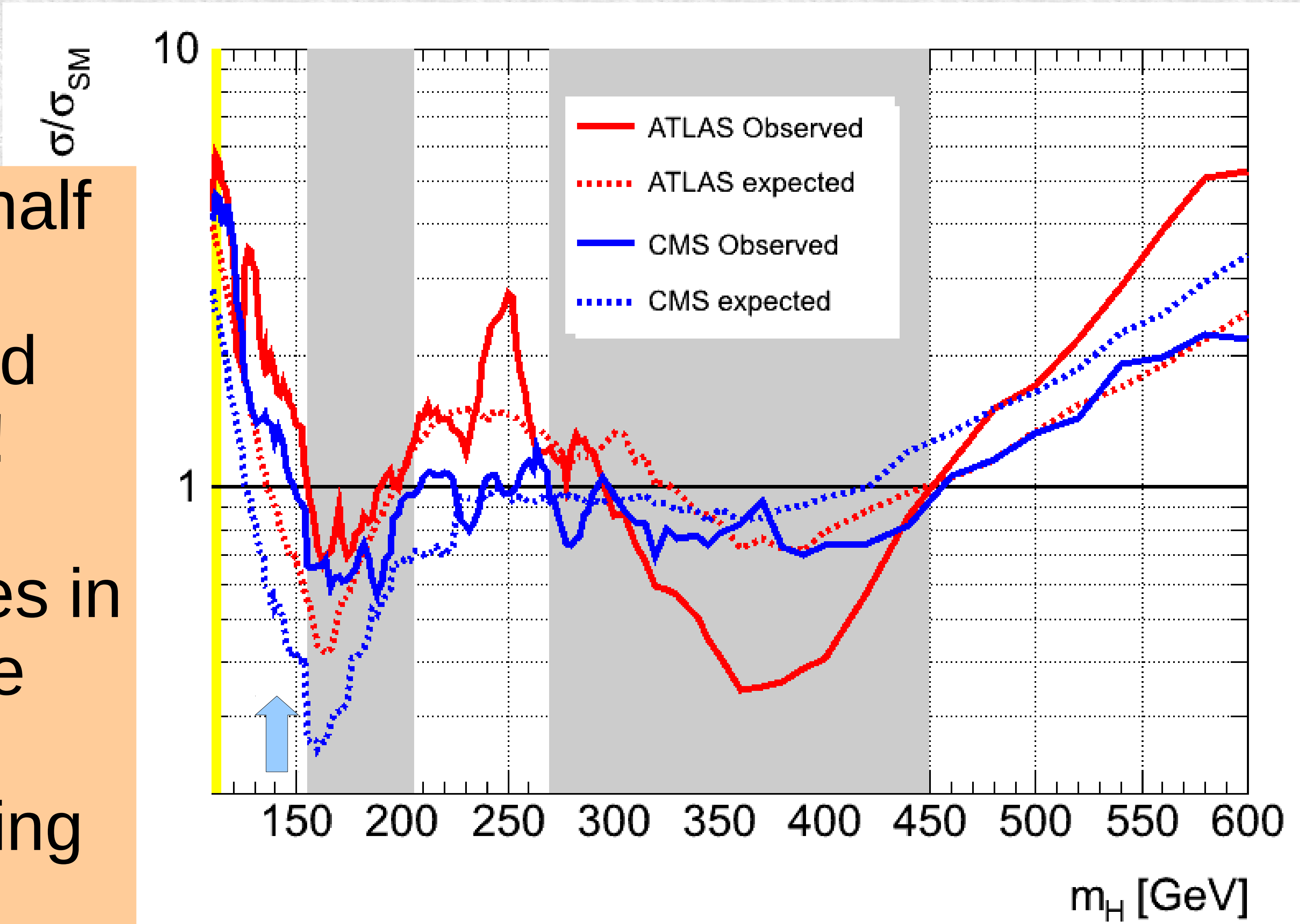
I *personally* conclude
155-206 & 270-450 GeV

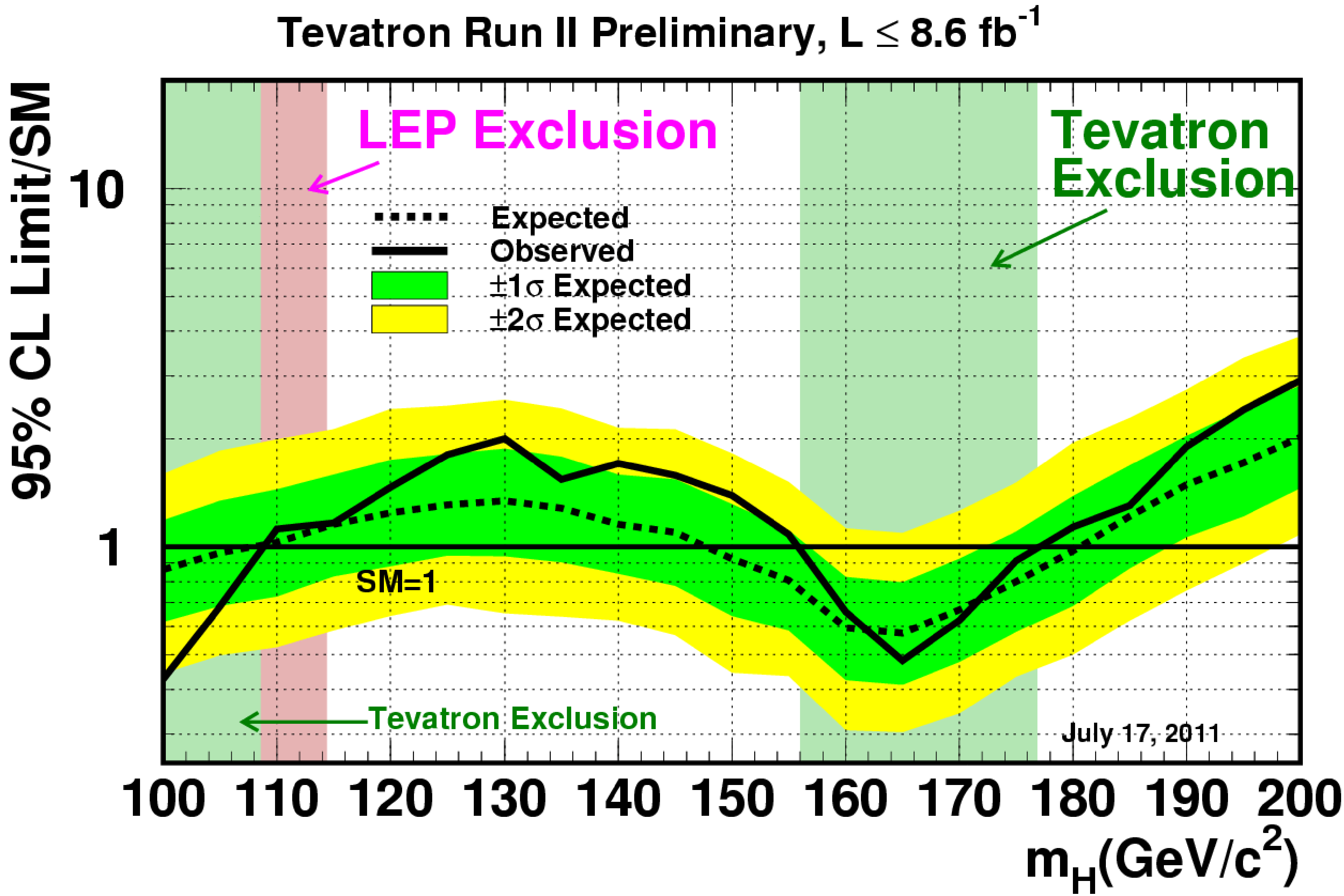


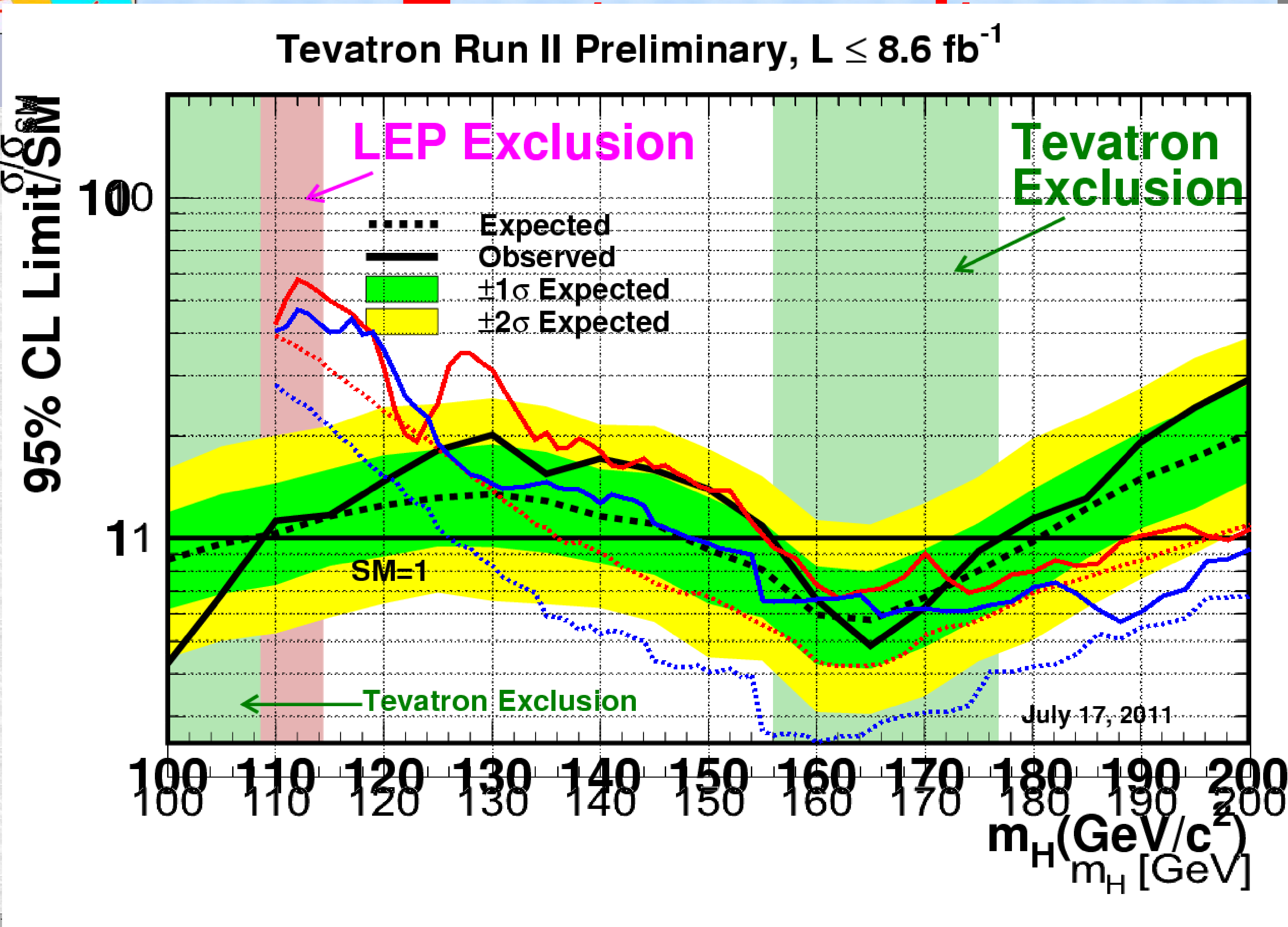


CMS and ATLAS

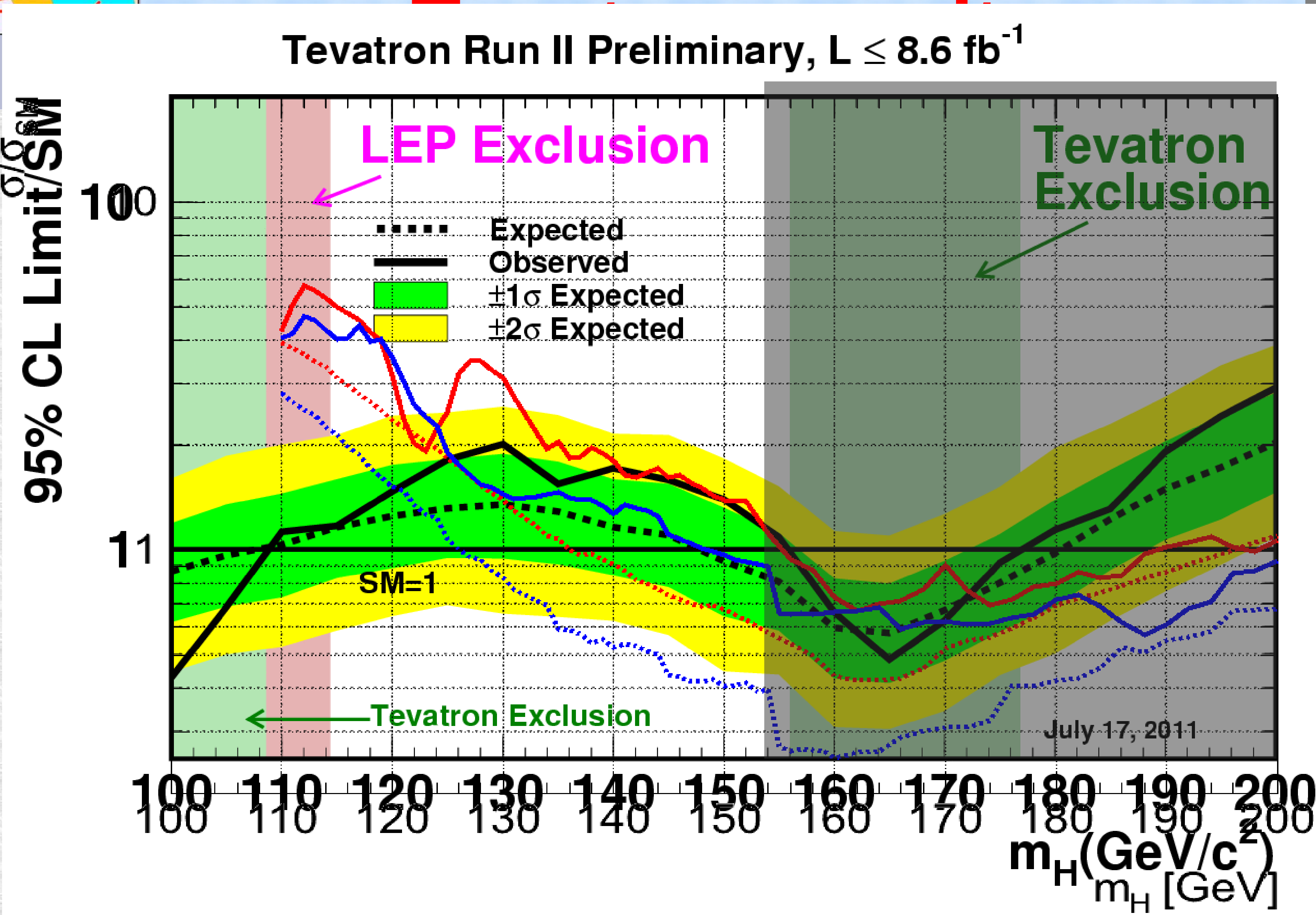
- Nearly half the plot excluded already!
- Hints of excesses in all 3 free regions
- Interesting times!



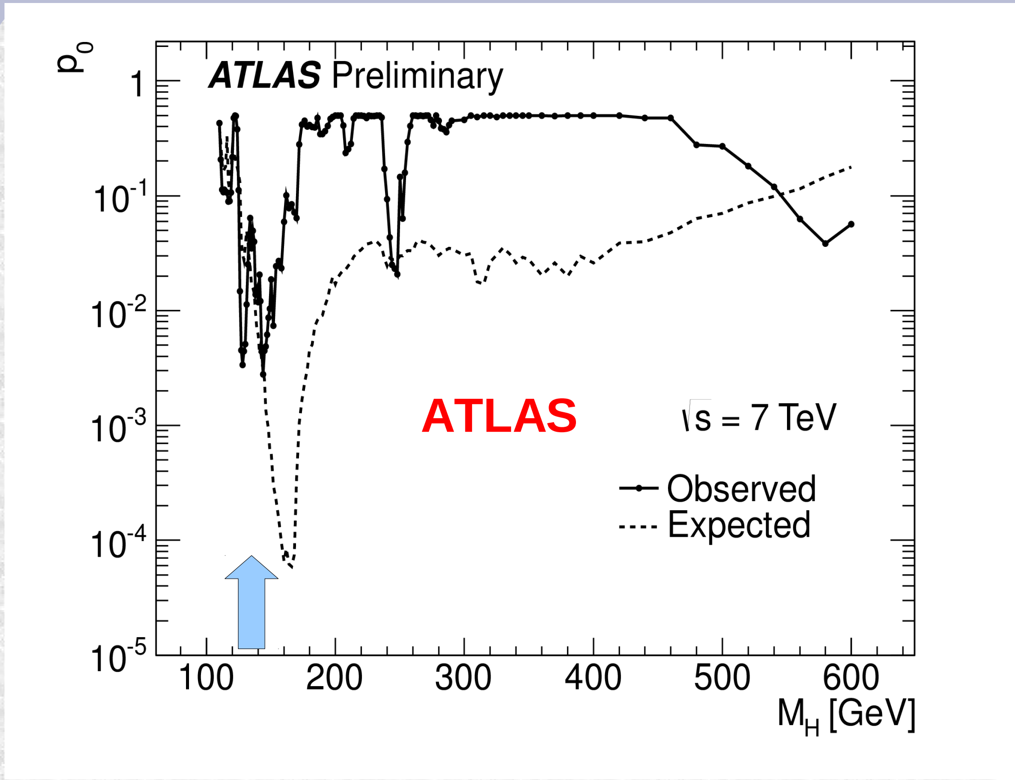

Tevatron Run II Preliminary, L ≤ 8.6 fb^{-1}
95% CL Limit/SM
10
1
LEP Exclusion
Tevatron Exclusion
Expected
Observed
±1σ Expected
±2σ Expected
SM=1
Tevatron Exclusion
July 17, 2011
100 110 120 130 140 150 160 170 180 190 200
m_H(GeV/c^2)

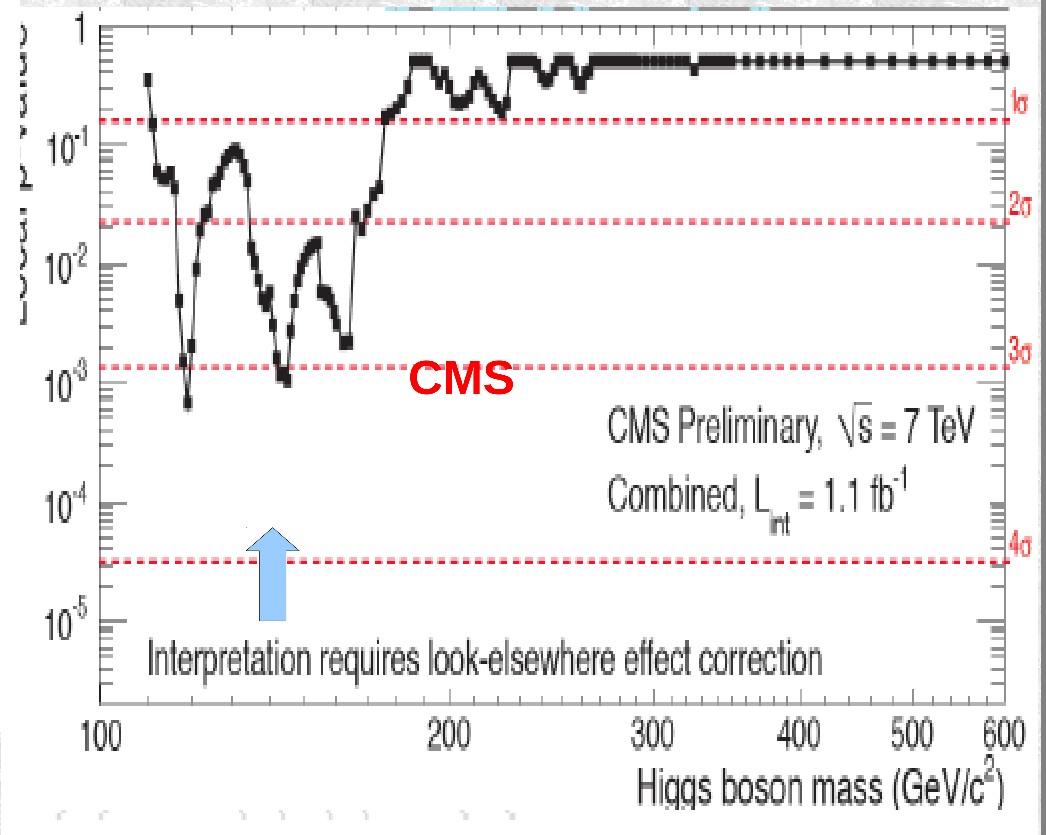


Tevatron Run II Preliminary, L ≤ 8.6 fb-1
95% CL Limit/SM
LEP Exclusion
Tevatron Exclusion
Expected
Observed
±1σ Expected
±2σ Expected
SM=1
Tevatron Exclusion
July 17, 2011
10
1
100 110 120 130 140 150 160 170 180 190 200
mH(GeV/c2)
mH [GeV]


Tevatron Run II Preliminary, L ≤ 8.6 fb-1
95% CL Limit/SM
σ/σSM
LEP Exclusion
Tevatron Exclusion
Expected
Observed
±1σ Expected
±2σ Expected
SM=1
Tevatron Exclusion
July 17, 2011
100
1
100 110 120 130 140 150 160 170 180 190 200
mH(GeV/c2)
mH [GeV]

Combined p-value





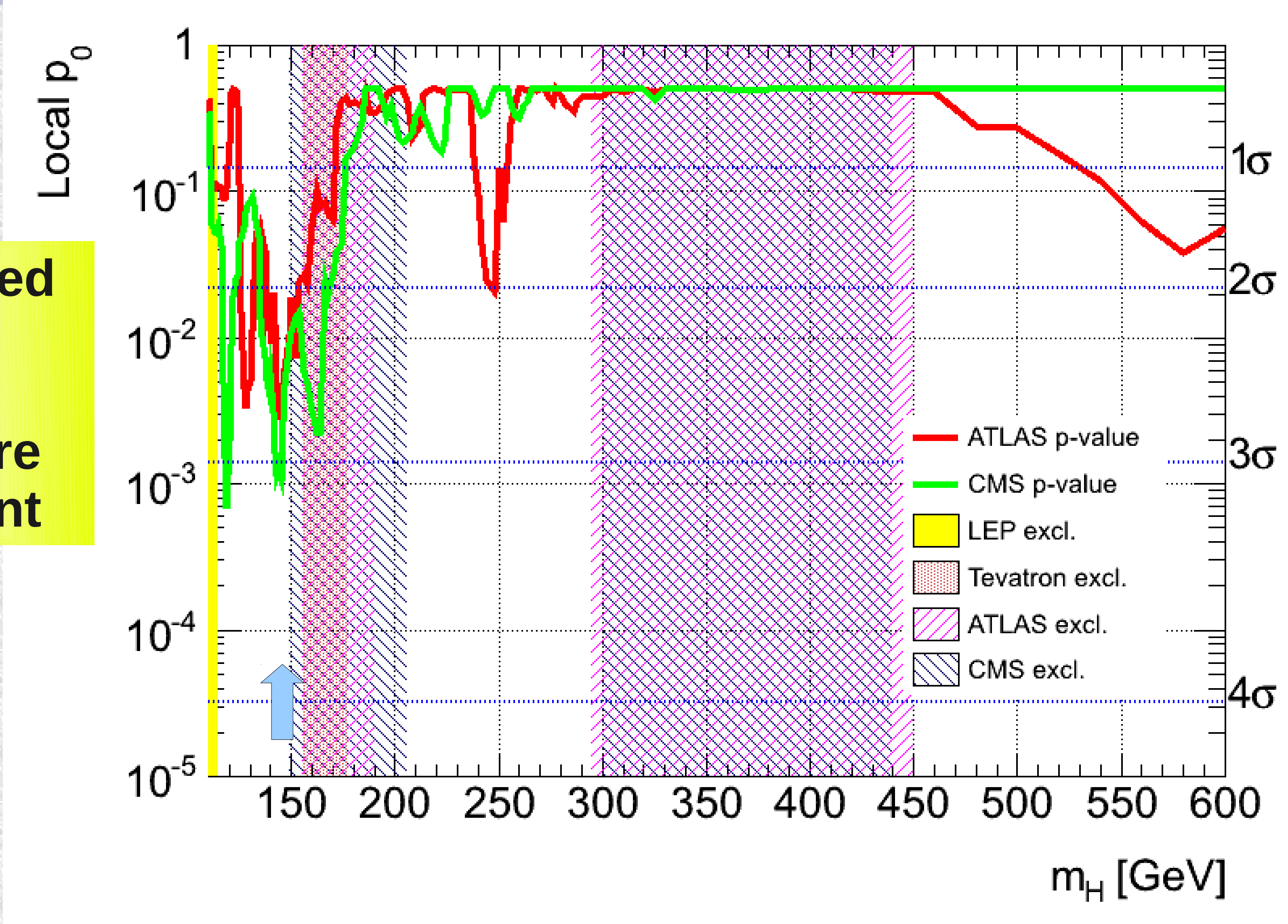
- Fraction of time background fluctuates so far
  - Beware: there is a look 'elsewhere effect'
- Both experiments have excess at low mass

P-values compared

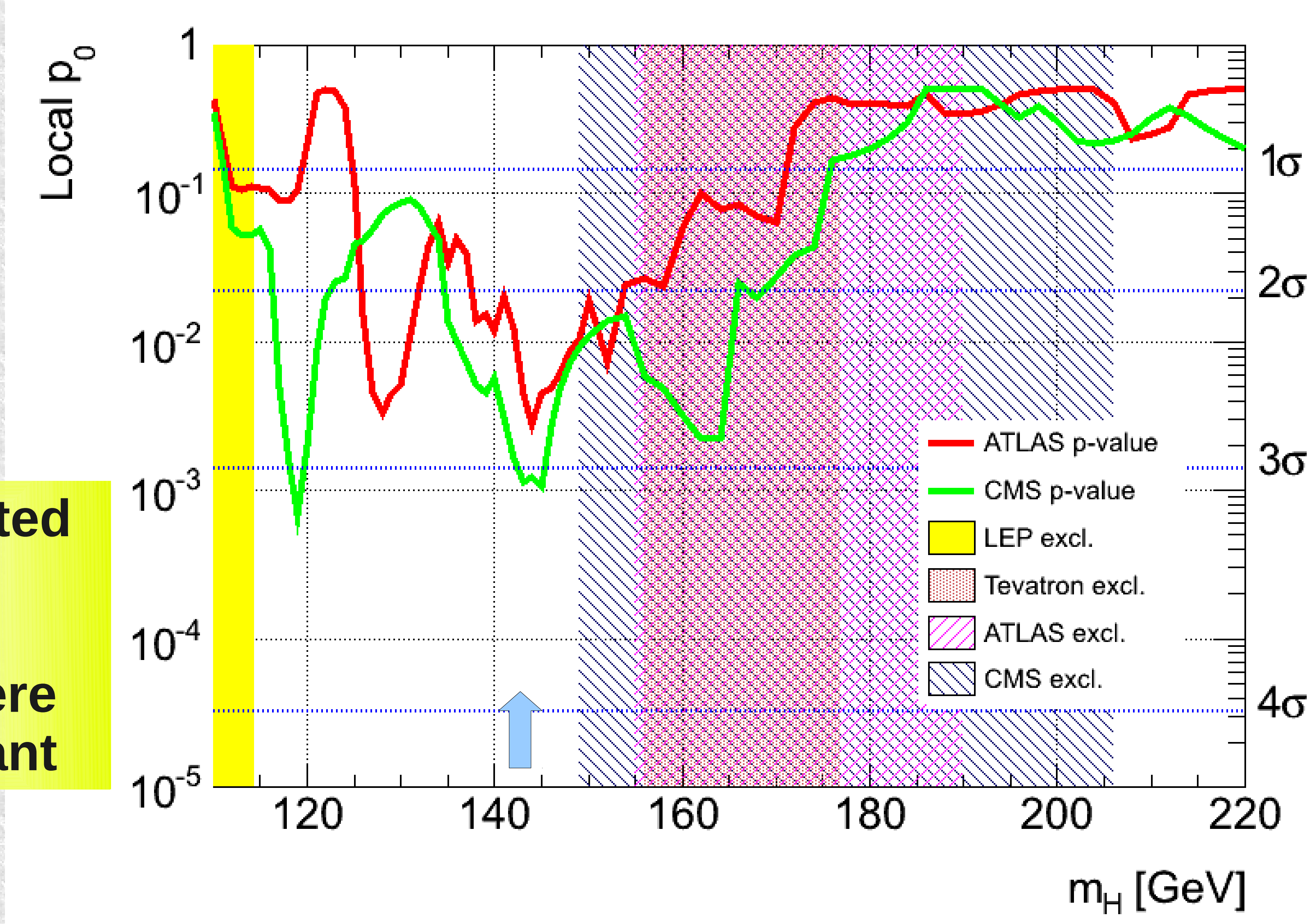
Some correlated uncertainties

Look-elsewhere effect important

High-mass excesses not corroborated



P-values at low mass



Some correlated uncertainties

Look-elsewhere effect important

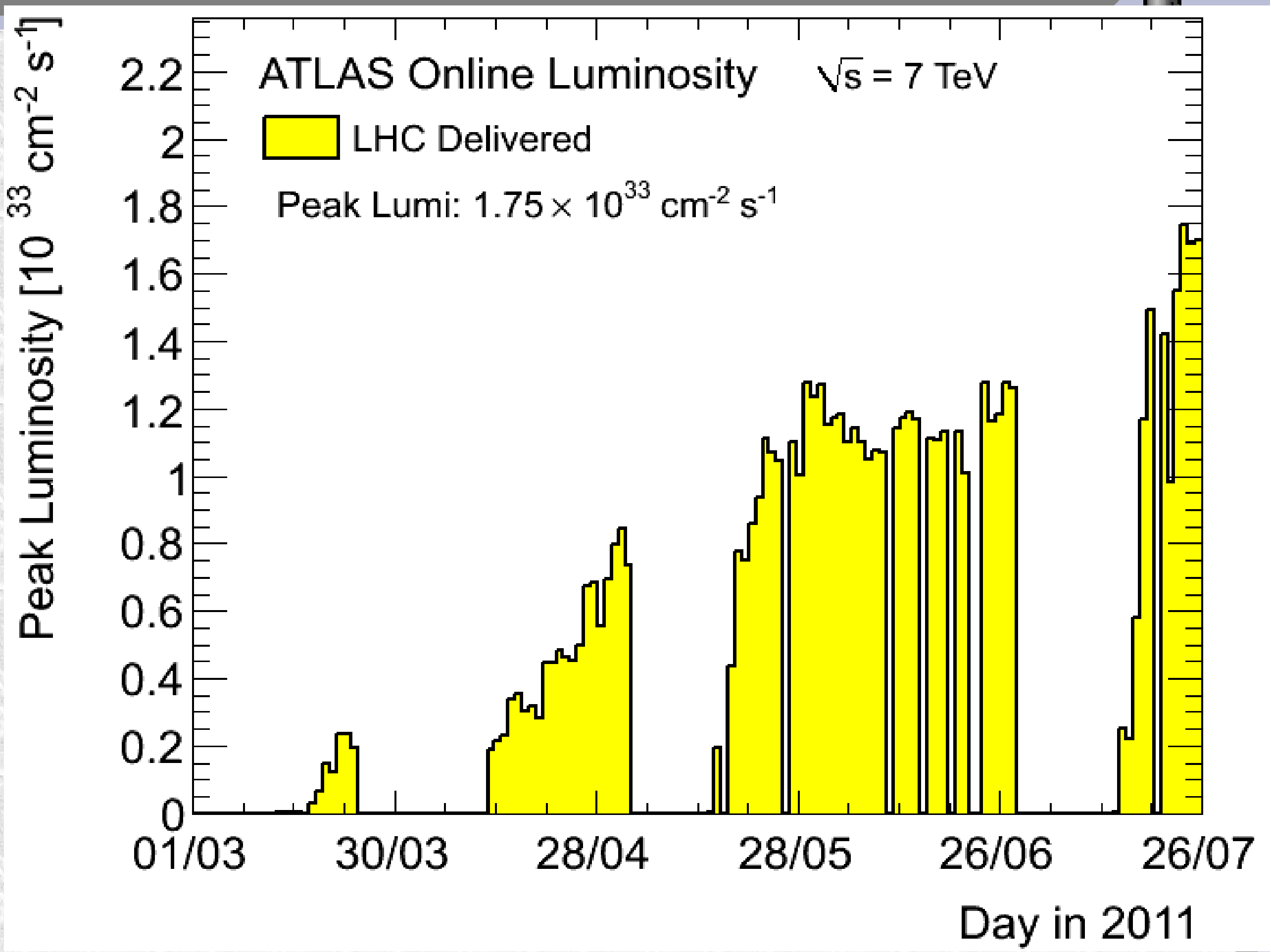
LHC combination

- The combination of results is complex
  - Fits with over 100 parameters are running
    - But are not ready for this meeting
    - Beware. There is NONSENSE even on CERN WWW pages
- The limits have large common systematic errors
  - Especially on signal cross-section
- The WW analyses driving excess have similar modeling in both groups
- LHC-HCG will provide update as soon as possible

Stay Tuned

Where do we go from here?

- More data!
  - The universal cry
    - It is coming fast
  - A month might double dataset?
- Better analysis
  - Many possible improvements
  - Unlikely to be conclusive



- LHC combination
  - Will allow to test compatibility of datasets
  - Many possibilities will be excluded soon

Summary

- With $1fb^{-1}$ the LHC dominates the SM Higgs
- We exclude
  - 155-190GeV and 295-450GeV (ATLAS)
  - 149-206GeV and 300-440GeV (CMS)
  - 155-206GeV and 295-450 GeV (Very Safe)
    - LHC combination will exclude much more
- Interesting hints emerge
  - e.g. 144GeV ~2.9σ in both experiments
  - Minutes of LEPC 56th meeting (3rd Nov. 2000):

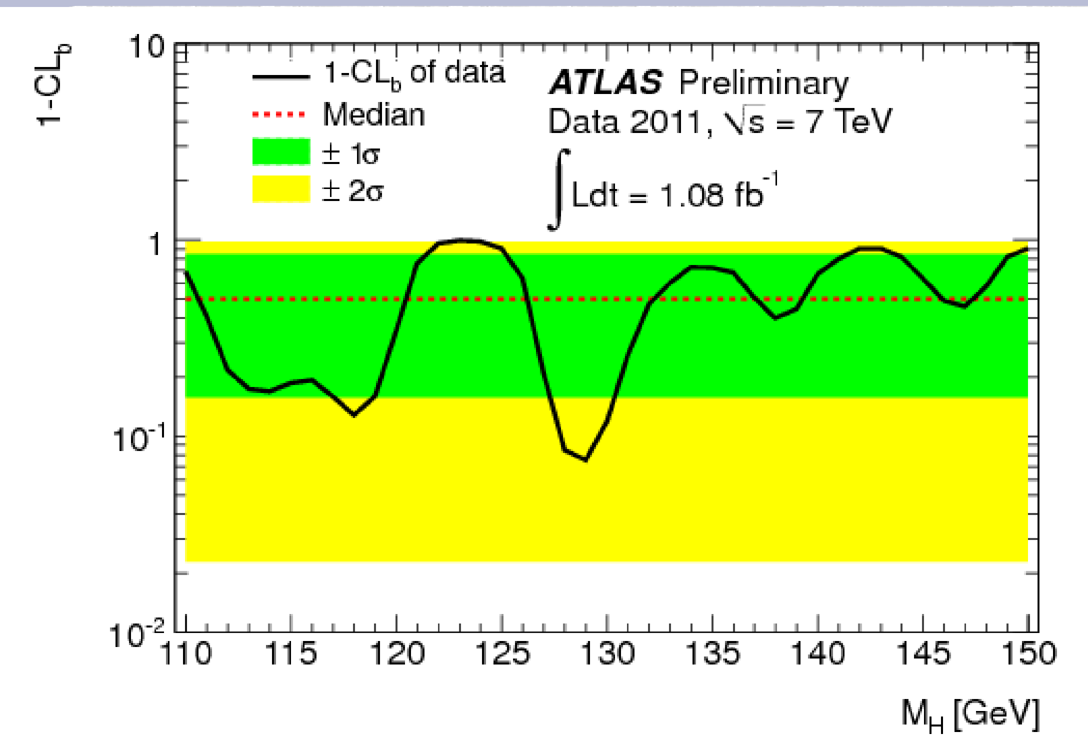
`The committee noted that there is unfortunately no single channel that is background-free.'

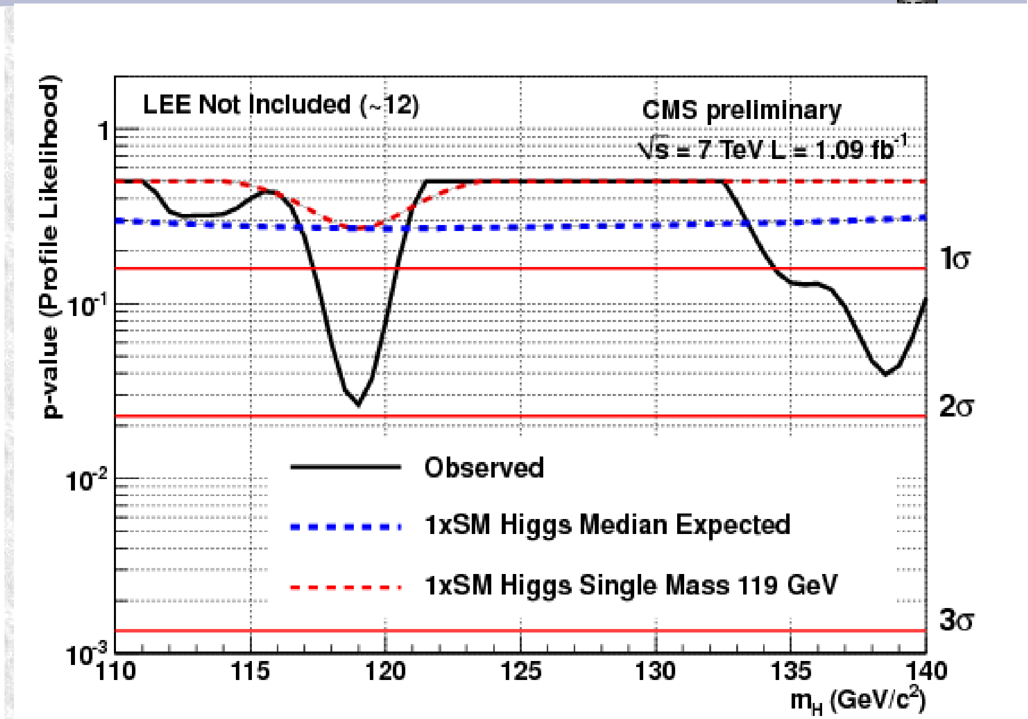
Celebration

- ATLAS and CMS Higgs toasting getting to EPS

Backup

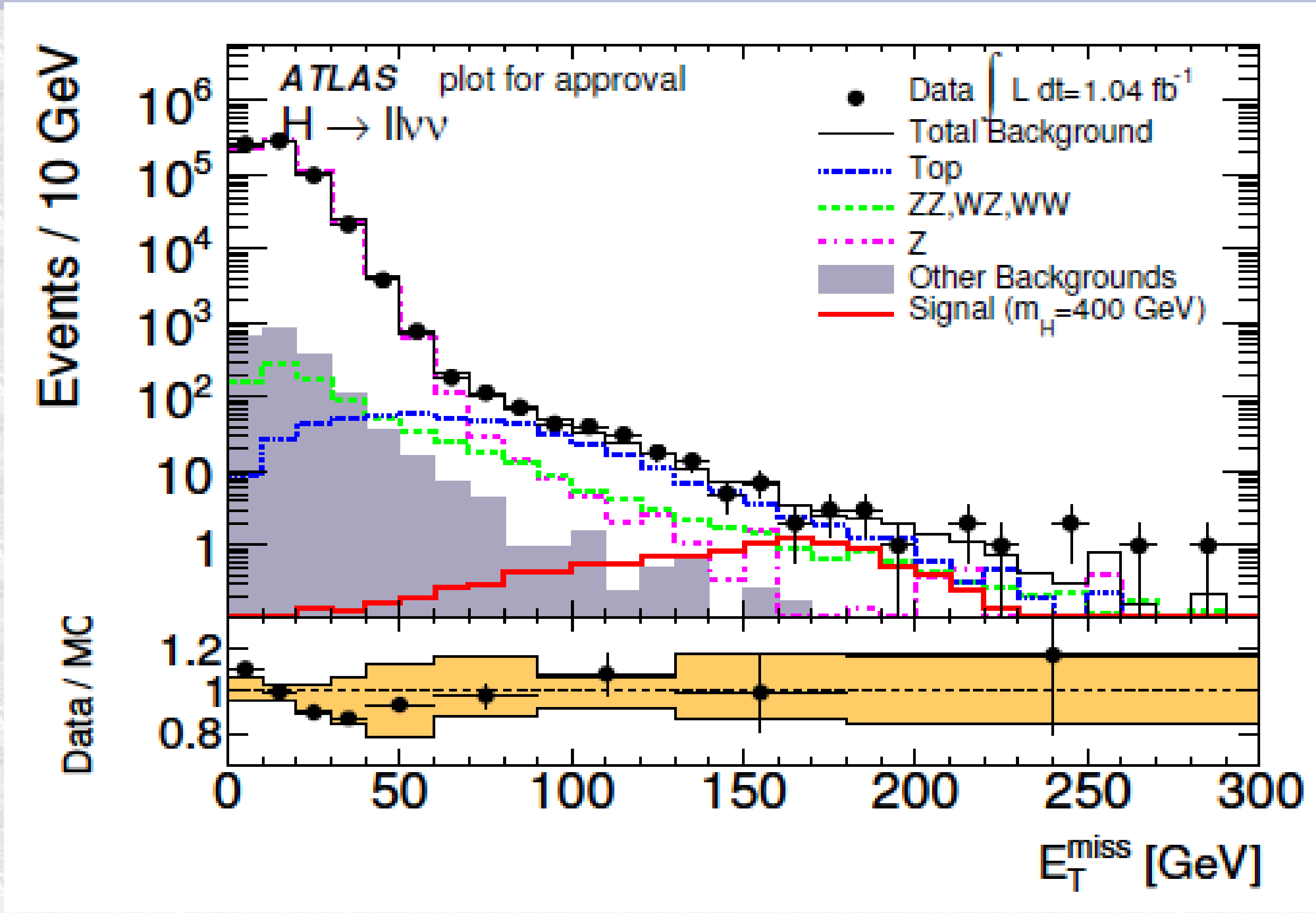
H→γγ: Any excess?





- ATLAS (left) and CMS (right) results similar
- Small excess at 119, 128 and 138.
  - But they contradict each other
  - Entirely normal background fluctuations

Missing E_T reconstruction



- Z plus jets shows well-controlled E_T miss

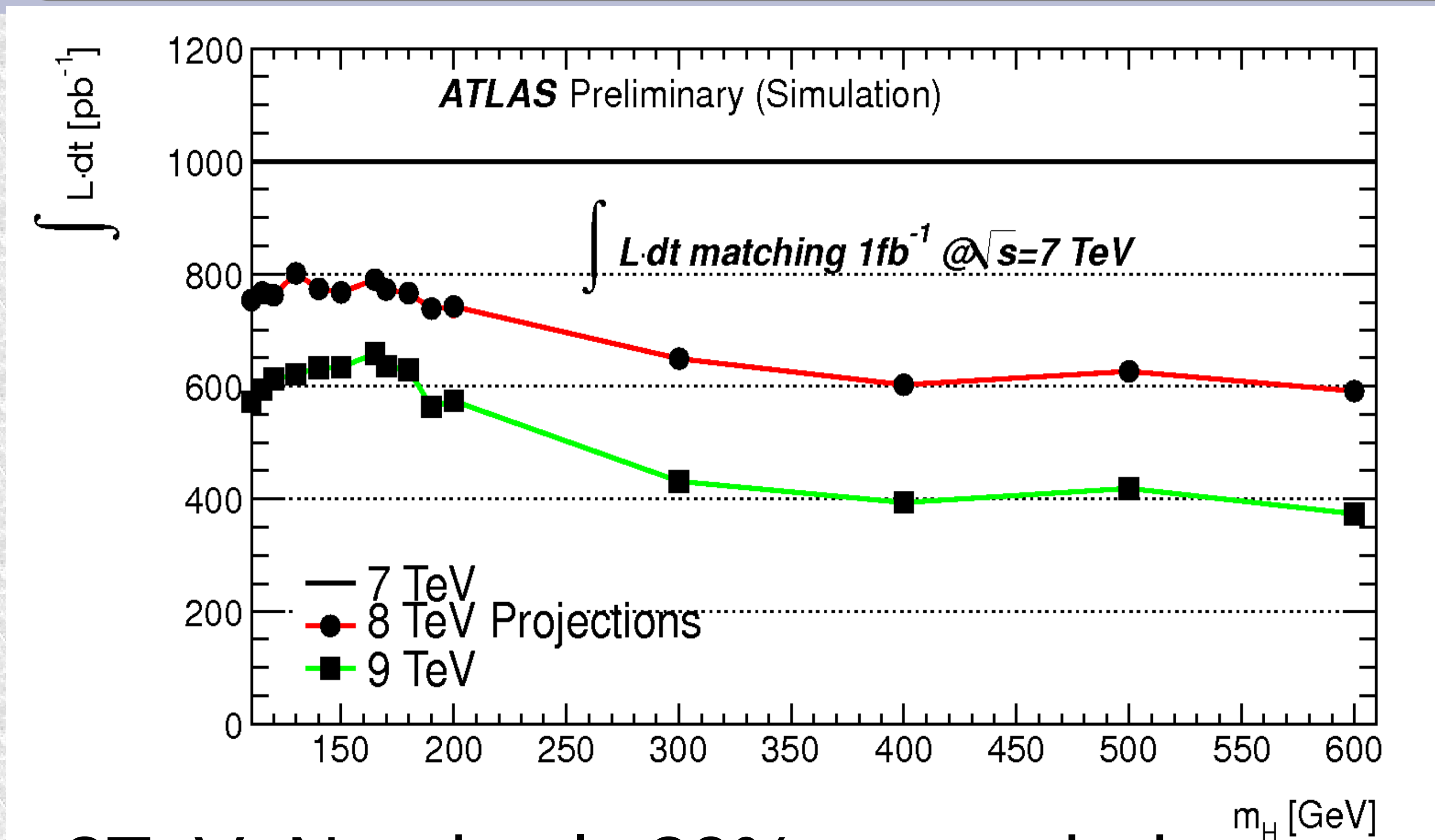
$WW \rightarrow l\nu l\nu$

- Event rates numerically

Event Rates

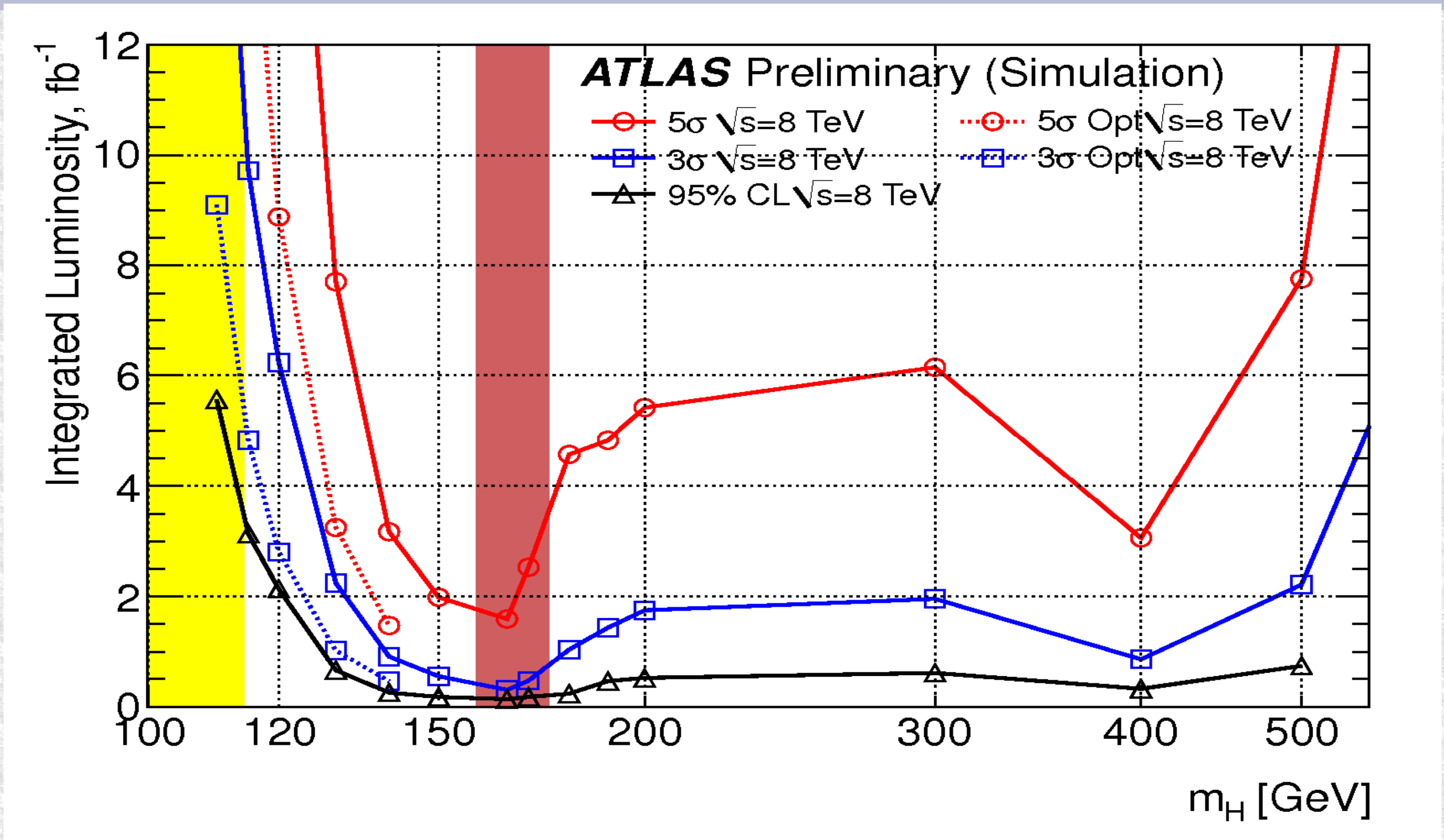
		Nominal		$\mu = 0$		$\mu = 1$		
m_H (GeV)	Lepton Flavors	Signal	Total Bkg.	Signal	Total Bkg.	Signal	Total Bkg.	Observed
150 H+0j	ee	3.1	4.7	0	5.7	3.1	4.4	7
	$e\mu$	10.6	17.2	0	20.8	10.4	15.7	21
	$\mu\mu$	6.8	10.9	0	13.4	6.7	10.1	21
150 H+1j	ee	0.94	2.2	0	2.3	1.05	1.98	4
	$e\mu$	4.0	9.0	0	8.8	4.4	7.0	8
	$\mu\mu$	2.3	4.0	0	4.2	2.5	3.0	9
180 H+0j	ee	4.2	6.3	0	6.8	4.0	4.5	3
	$e\mu$	11.8	19.1	0	20.9	11.3	12.7	25
	$\mu\mu$	7.8	13.5	0	14.7	7.4	9.6	16
180 H+1j	ee	1.60	4.9	0	4.9	1.44	4.4	5
	$e\mu$	5.5	14.6	0	12.3	4.9	10.1	8
	$\mu\mu$	3.4	6.5	0	6.4	3.1	4.5	12

Higgs sensitivity v E_{CMS}



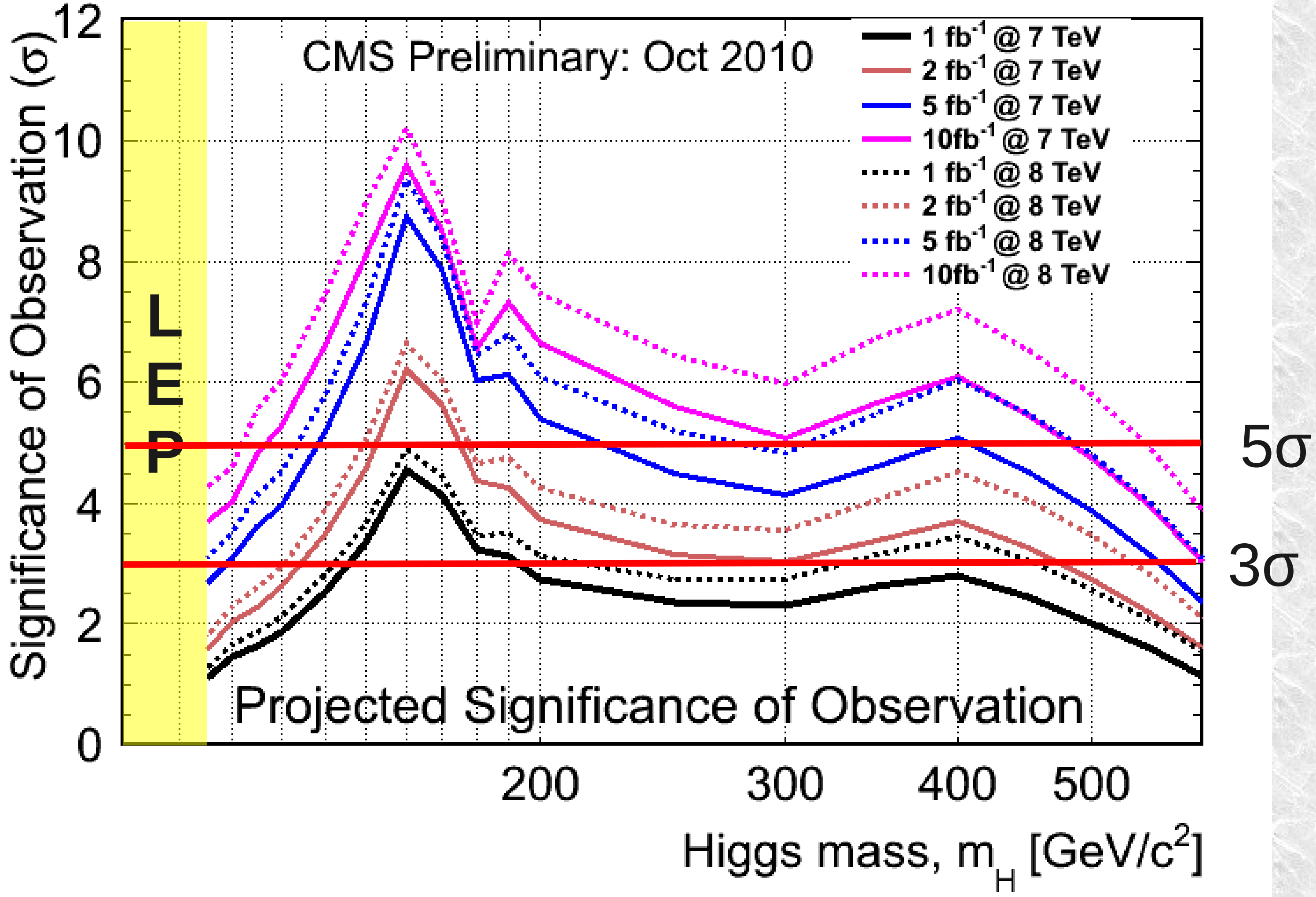
- 8TeV: Need only 80% as much data
  - Less for a high mass Higgs boson
- 9TeV 60% of data suffices

Sensitivity of Higgs search

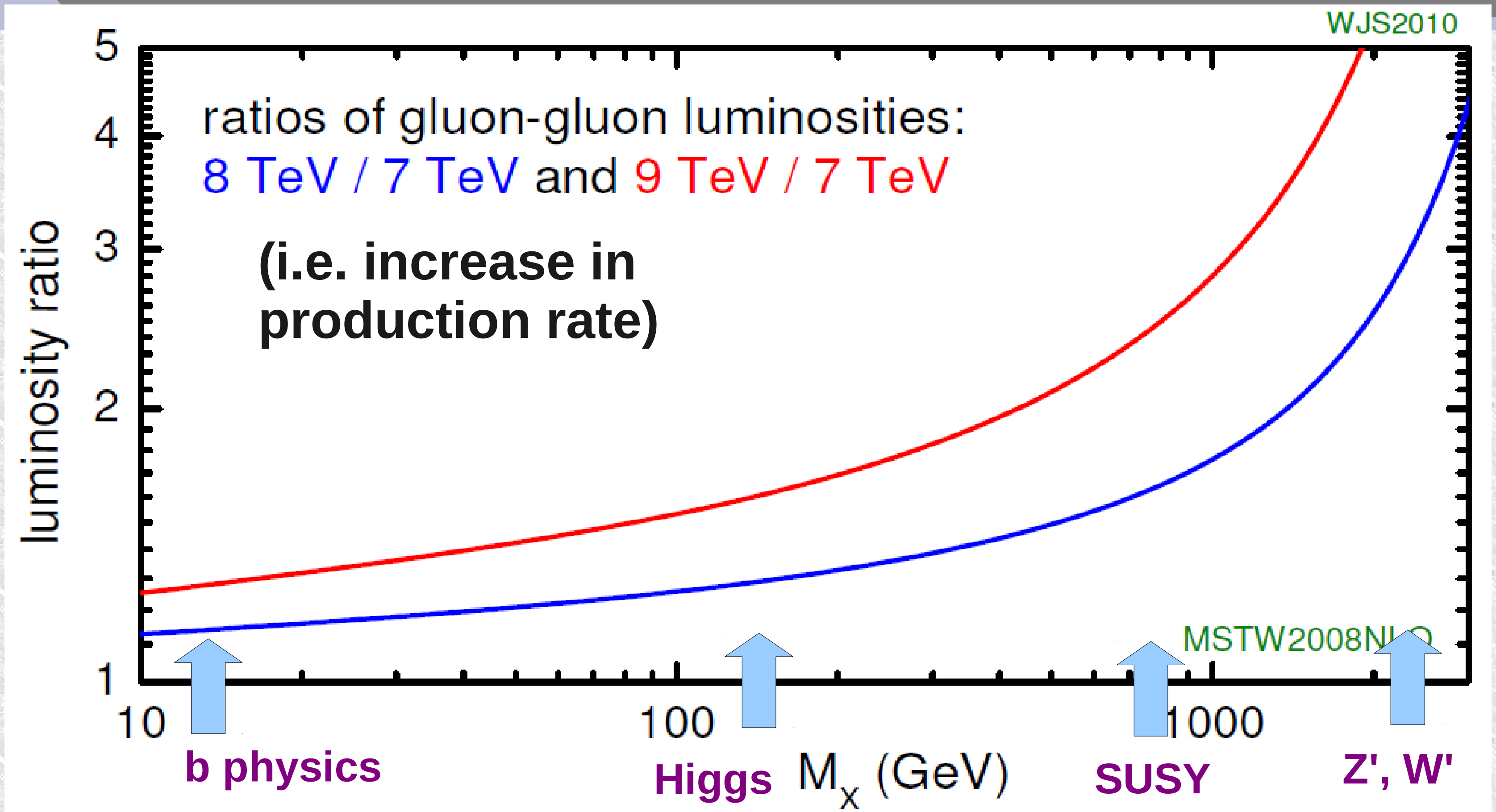


5fb^{-1} at 8TeV gives 3σ for 114 to >500GeV

Sensitivity to SM Higgs



Effect of raising E_{CMS}



- 8TeV: 10% to factor 4 increases
  - Doubled for 9TeV
  - Higgs increased by 30%

Thanks to James Stirling

E-W symmetry breaking

$$SU(3) \times SU(2) \times U(1)$$

- This gauge symmetry predicts γ,W,Z,gluons
  - Requires them to be massless
- Symmetry breaking is needed for masses

Why do we need the Higgs?

Fermions | **Gauge Symmetries** ⇒ **Bosons, Interactions**

families,
with leptons

$$\begin{pmatrix}\nu_L \\ e_L\end{pmatrix}, \nu_R, e_R$$

and quarks

$$\begin{pmatrix}u_L \\ d_L\end{pmatrix}, u_R, d_R$$

U(1)$_Y$: $\psi(x) \to \exp\left[i\frac{g'}{2}Y_\psi\,\omega(x)\right]\psi(x)$

SU(2)$_L$: $\psi_L(x) \to \exp\left[i\frac{g}{2}\vec{\sigma}.\vec{\theta}(x)\right]\psi_L(x)$

SU(3)$_c$: $\psi_q(x) \to \exp\left[i\frac{g_s}{2}\lambda_a\theta^a(x)\right]\psi_q(x)$

γ : QED

Z, $W^\pm$: Weak

$$\tan\vartheta_W = \frac{g'}{g}$$

gluons : QCD

A mass term couples L & R and would violate SU(2)$_L$

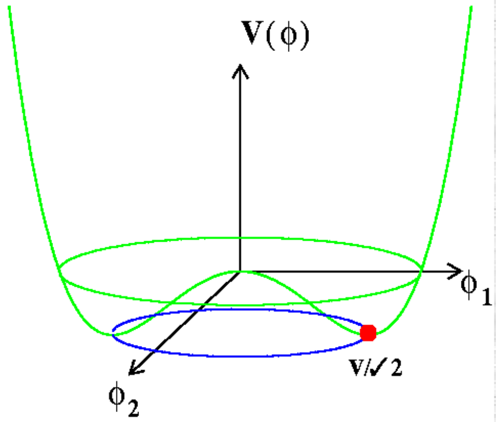
Solution: The Higgs mechanism

Thanks: P. Janot

What is Higgs' mechanism?

- **Doublet of $SU(2)_L$, $\Phi=(\Phi_1,\Phi_2)$**
- **Potential respects $SU(2)_L$**
  But Vacuum does not!

$$V(\Phi) = \frac{\lambda}{3!}\left\{\overline{\Phi}\Phi - v^2/2\right\}^2$$



Fermions:

Interact with Higgs field slows them down → generates mass

Bosons:

$SU(2)_L$ interact, gain mass

$U(1)_\gamma$ and $SU(3)_c$ do not, massless

3 degrees of freedom in Boson masses
4th becomes fundamental scalar