Have we found the Higgs boson yet?

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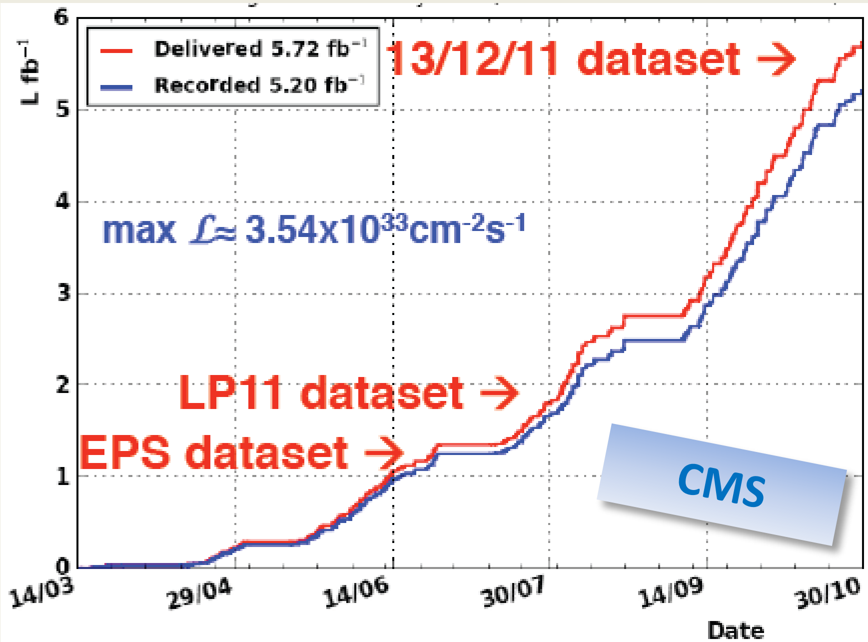
RHUL

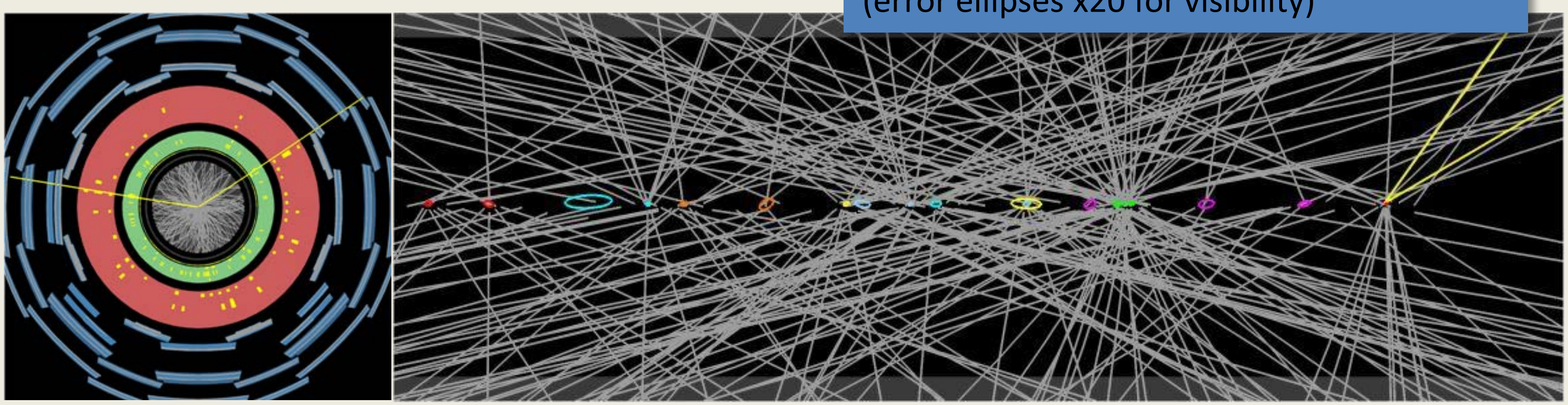
NExT meeting – Sussex, March 14, 2012

The LHC in 2011



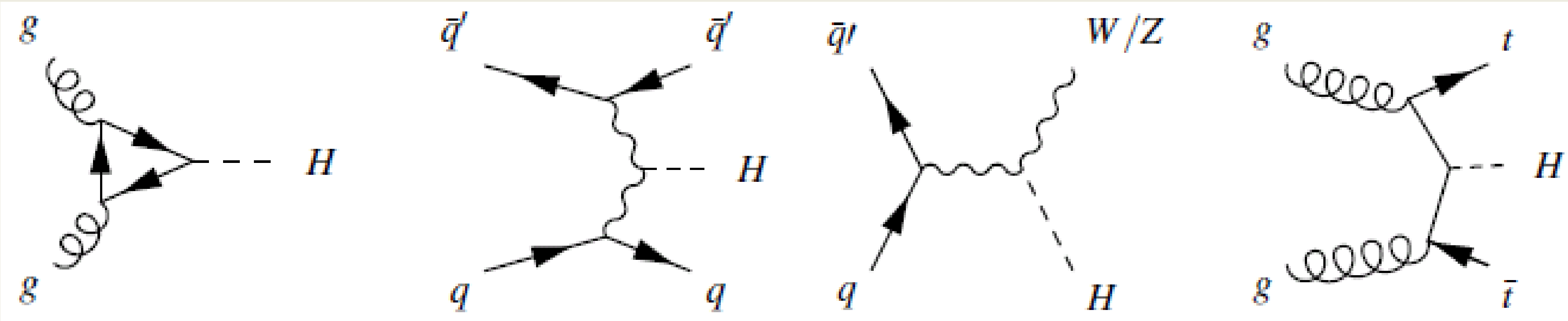
- data taking from mid March to end October
- pp collisions at $\sqrt{s}$ = 7 TeV
- bunch spacing: 50 ns
- integrated luminosity for analysis: 4.6-4.9 fb^{-1}
- instantaneous luminosity x10 wrt start of year
- “low” pileup (Mar-Aug): $\langle\mu\rangle \approx 6$
- significant pileup (Sep-Oct): $\langle\mu\rangle \approx 12$

ATLAS $Z \rightarrow \mu\mu$ event with 20 pp interactions
(error ellipses x20 for visibility)



SM Higgs production modes (LHC)

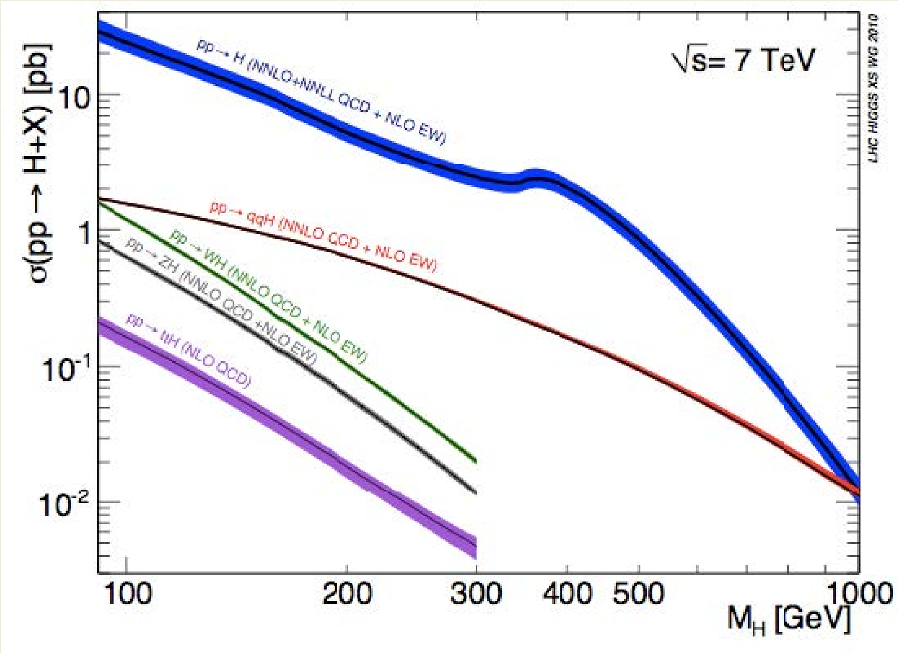
GF – gluon fusion **VBF – vector boson fusion** **WH/ZH** **ttH**



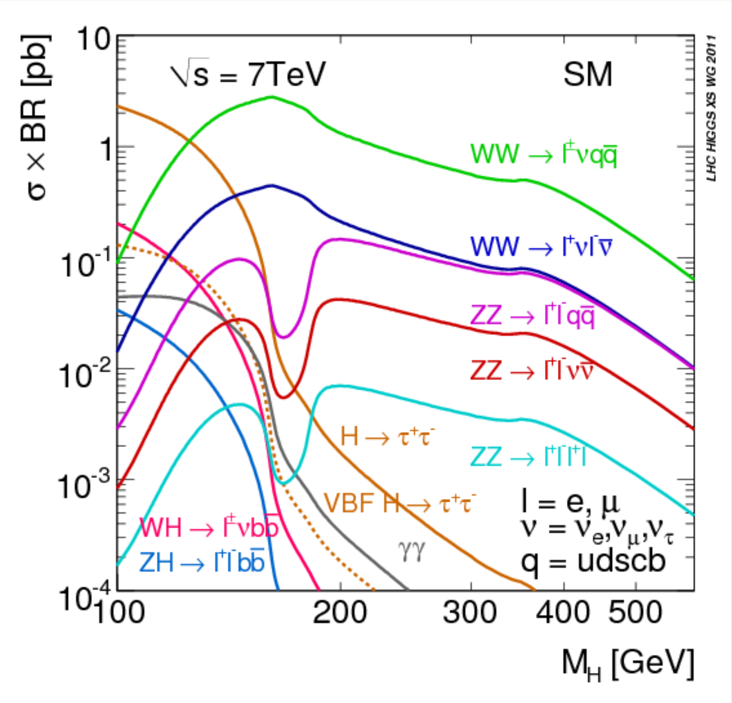
+ dominant mechanism - not feasible in purely hadronic final states .	- ~10% rate + discriminating feature: 2 “tag-jets” .	- lower prod. rate + background suppression using W/Z leptons and/or missing energy (Etmiss) .	- v. low rate at 7 TeV - large hadr. bgds. - not targeted at 7 TeV + bgd supression with b-tagging, leptons, Etmiss, mass constraints

SM Higgs production at the LHC and decay

LHC SM Higgs production cross sections, σ



Prod x Decay: σ x BR



Theoretical uncertainties (QCD scales, PDFs, α_s): from < 5% (VBF, VH) to 10-15% (GF, ttH)

A little (recent) history…

- December 2011: CERN Higgs seminars
- ATLAS and CMS publications at the end of January 2012
- ATLAS and CMS results updated for Moriond 2012
- Many (>20!) ATLAS and CMS publications on 2011 data
- TeVatron: full dataset results released for Moriond 2012

ATLAS and CMS Higgs searches

ATLAS

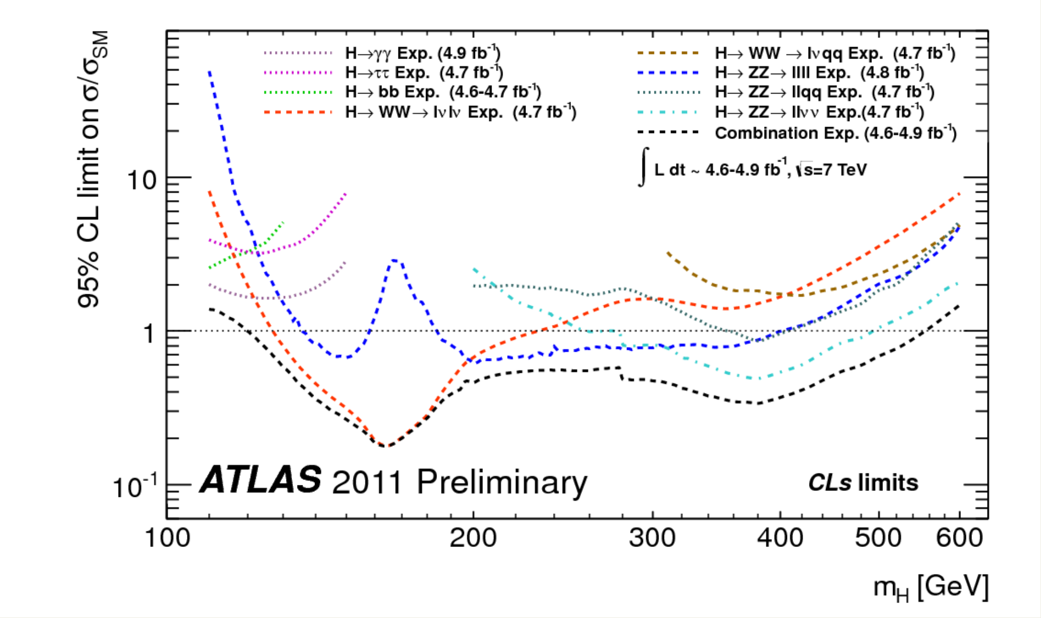
Channel	m_H range (GeV)	Backgrounds	$\mathcal{L}$ (fb^{-1})	Reference
low-m_H, good mass resolution				
$H \to \gamma\gamma$	110-150	$\gamma\gamma$, γj, jj	4.9	arXiv:1202.1414
$H \to ZZ^{(*)} \to 4\ell$	110-600	$ZZ^{(*)}$, $Z+jets$, $t\bar{t}$	4.8	arXiv:1202.1415
low-m_H, limited mass resolution				
$H \to WW^{(*)} \to \ell\nu\ell\nu$	110-600	WW, $t\bar{t}$, $W/Z+jet$	4.7	CONF-2012-012
$H \to \tau\tau(ll, lh, hh)$	100-150	$Z \to \tau\tau$, $t\bar{t}$	4.7	CONF-2012-014
$VH, H \to bb$	110-130	$W/Z+jets$, $t\bar{t}$	4.7	CONF-2012-015
high-m_H				
$H \to ZZ \to \ell\ell\nu\nu$	200-600	$diboson$, $t\bar{t}$, $Z+jets$	4.7	CONF-2012-016
$H \to ZZ \to \ell\ell jj$	200-600	$Z+jets$, $t\bar{t}$, $diboson$	4.7	CONF-2012-017
$H \to WW \to \ell\nu jj$	300-600	$W+jets$, $t\bar{t}$, multijets	4.7	CONF-2012-018

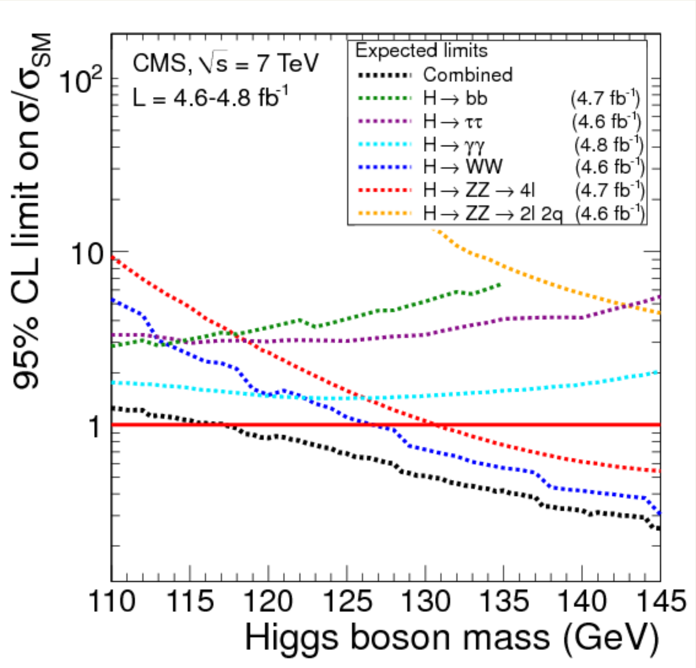
CMS

	Channel	m_H range (GeV)	Luminosity (fb^{-1})	Sub-channels	m_H resolution
new	$H \to \gamma\gamma$	110–150	4.8	2	1–2%
	$H \to \tau\tau \to e\tau_h/\mu\tau_h/e\mu + X$	110–145	4.6	9	20%
new	$H \to \tau\tau \to \mu\mu + X$	110–140	4.5	3	20%
new	$WH \to e\mu\tau_h/\mu\mu\tau_h + \nu$'s	100–140	4.7	2	20%
	$(W/Z)H \to (e\nu/\mu\nu/ee/\mu\mu/\nu\nu)(bb)$	110–135	4.7	5	10%
	$H \to WW^* \to 2\ell 2\nu$	110–600	4.6	5	20%
new	$WH \to W(WW^*) \to 3\ell 3\nu$	110–200	4.6	1	20%
	$H \to ZZ^{(*)} \to 4\ell$	110–600	4.7	3	1–2%
	$H \to ZZ^{(*)} \to 2\ell 2q$	130–164 200–600	4.6	6	3% 3%
	$H \to ZZ \to 2\ell 2\tau$	190–600	4.7	8	10–15%
	$H \to ZZ \to 2\ell 2\nu$	250–600	4.6	2	7%

Sensitivity of SM Higgs searches

Expected 95% CL exclusion limits on σ/σ_{SM}





Sensitivity depends on integrated luminosity, production cross-section, decay branching fractions, selection efficiency, and background levels

Most sensitive channels are:

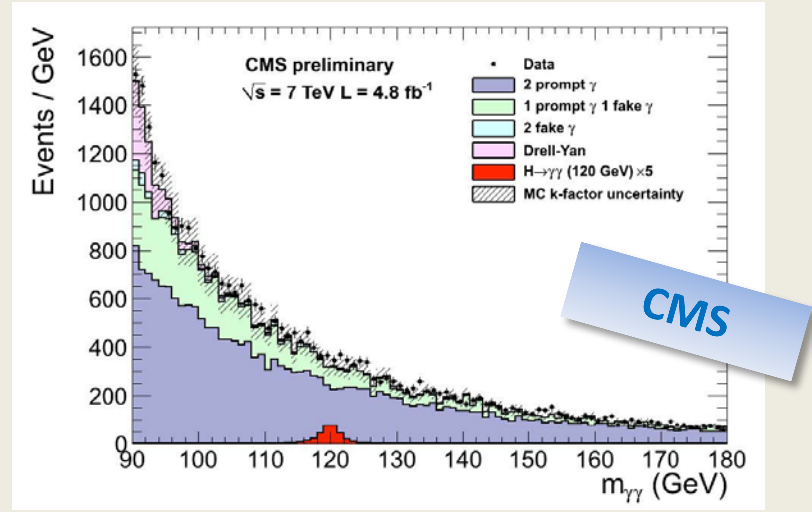
Low mass (eg for m_H=125 GeV): H-$\gamma\gamma$, H-ZZ-4ℓ, H-WW-$\ell\nu\ell\nu$

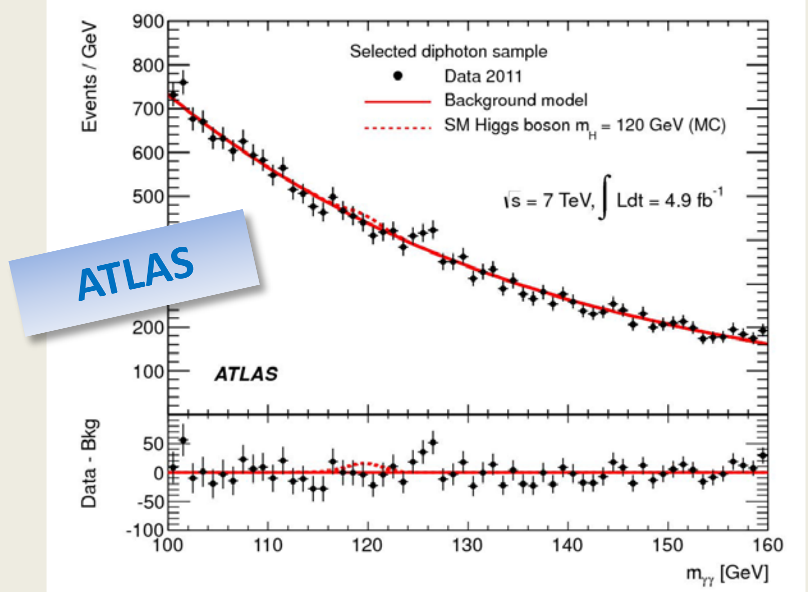
High mass: single most sensitive channel is H-ZZ-$\ell\ell\nu\nu$

95%CL exclusion sensitivity is not same as discovery sensitivity… but close enough

$H \to \gamma\gamma$

- small branching ratio ~ 1 – 2 x 10^{-3}
- $110 \leq m_H \leq 150$ GeV
- clear signature: two high p_T isolated photons
- excellent $m_{\gamma\gamma}$ mass resolution: 1-3%
- continuum backgrounds:
  irreducible $\gamma\gamma$ QCD
  reducible γj, jj, ee Drell-Yan
- very good γ–jet separation needed

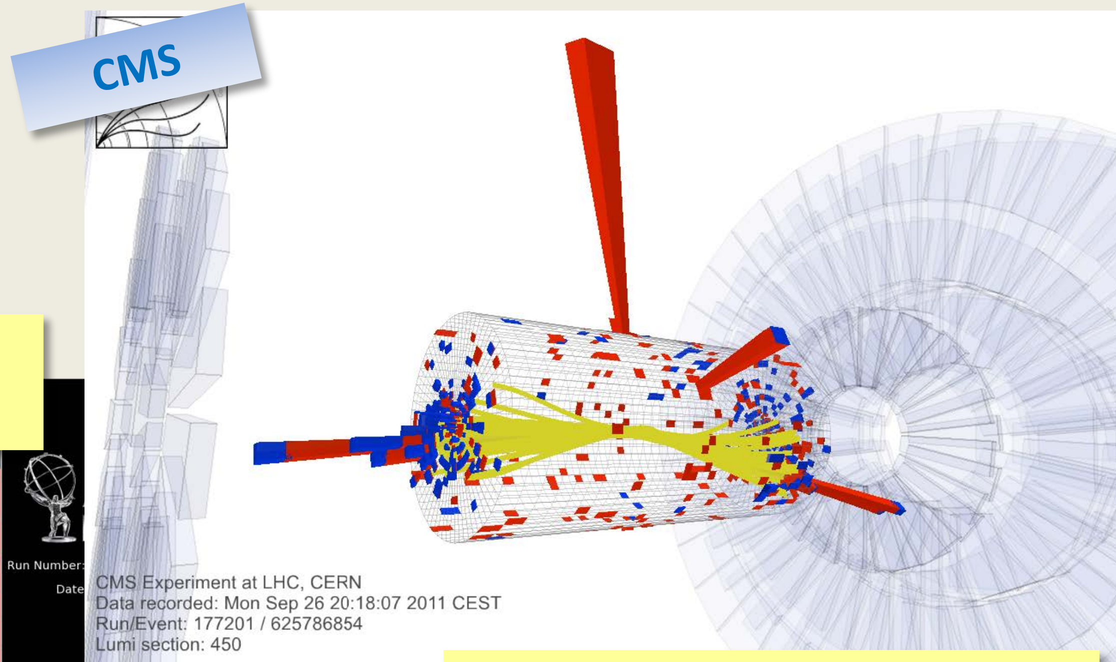




- both experiments categorise events in many sub-classes, for improved sensitivity

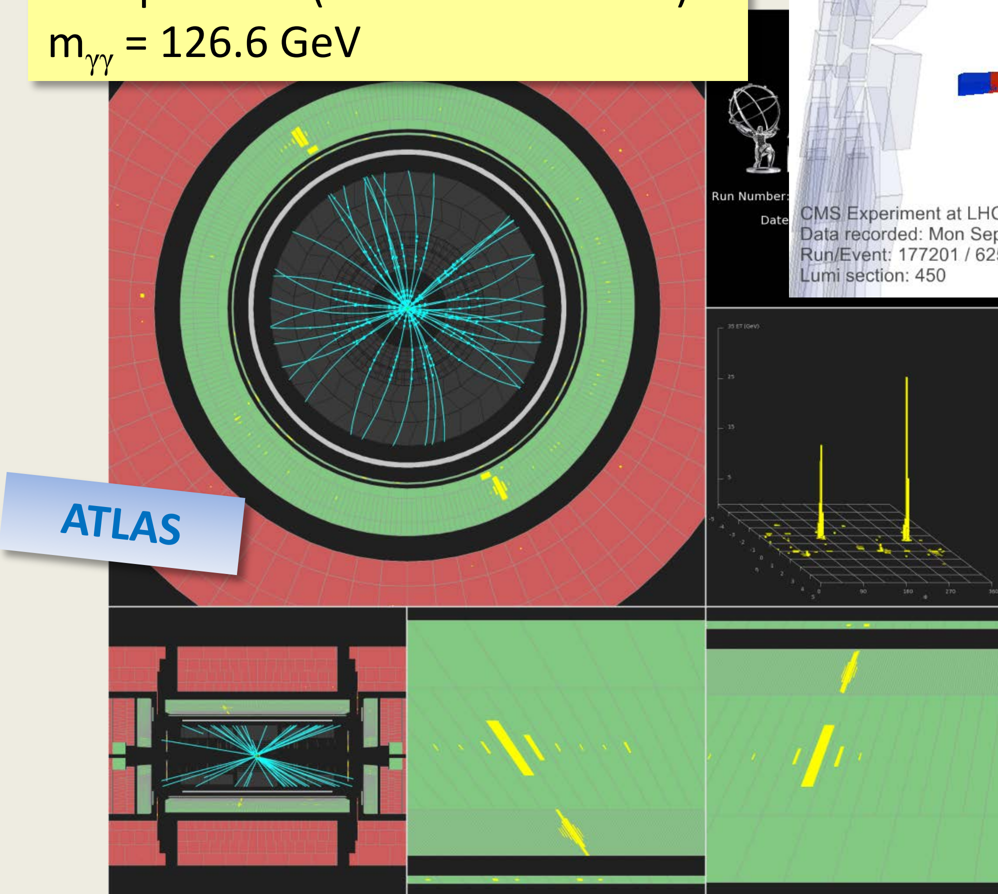
- CMS targets VBF explicitly ($\gamma\gamma$ + 2 fwd-bwd jets), ATLAS does this less directly

H→γγ candidate events

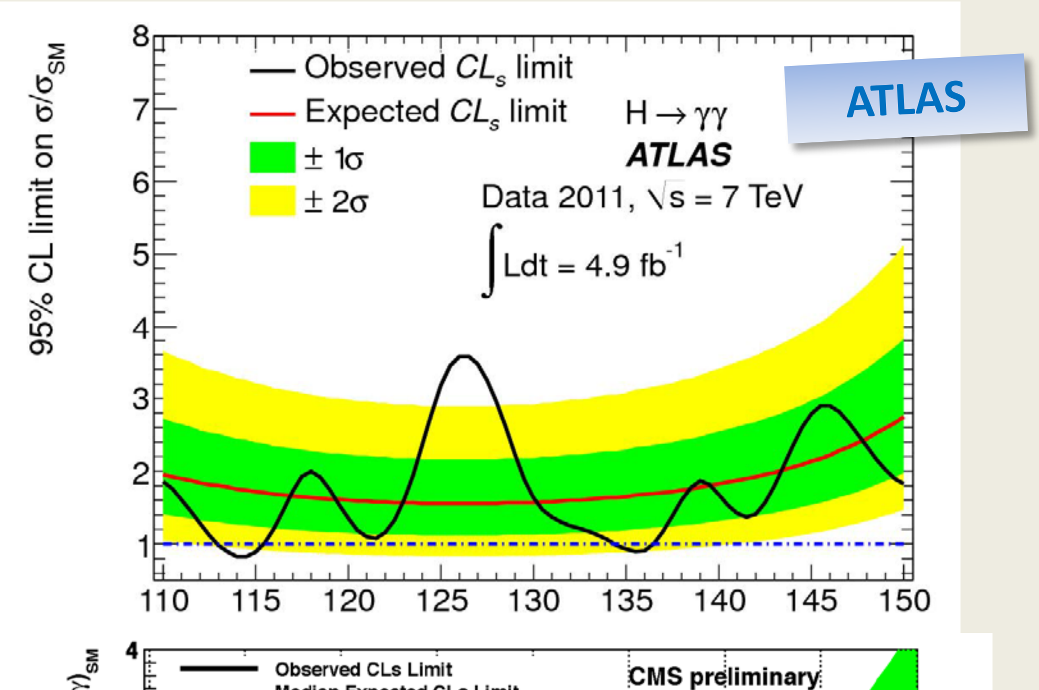


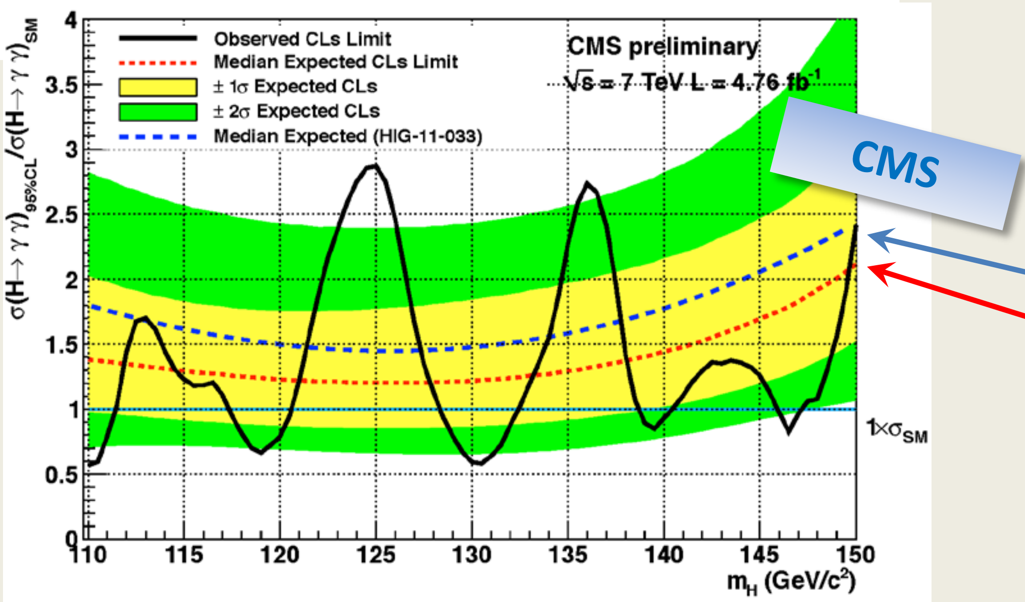
VBF candidate!
$m_{\gamma\gamma}$ = 121.9 GeV

Two photons (both unconverted)
$m_{\gamma\gamma}$ = 126.6 GeV



H→γγ results: 95%CL exclusion limits





Excess of events in ATLAS and CMS around $m_{\gamma\gamma} \approx 125$ –126.5 GeV

CMS also sees a smaller excess at $m_{\gamma\gamma} \approx 136$ GeV

Compare event selection:

- Cut-based
- Multi-Variate Analysis (BDT)

Quantifying the significance of an excess

p_0 is the probability that a background-only experiment is more signal-like than observed in data (**local** p_0 value: for a *given* m_H hypothesis)

>> p_0 probabilities can easily be converted into standard deviations (significance)

The **global** p_0 is the probability that a background only-experiment would produce a local significance more signal-like than observed *anywhere in the search region*

>> this so-called Look Elsewhere Effect (LEE) *reduces* the local significance.

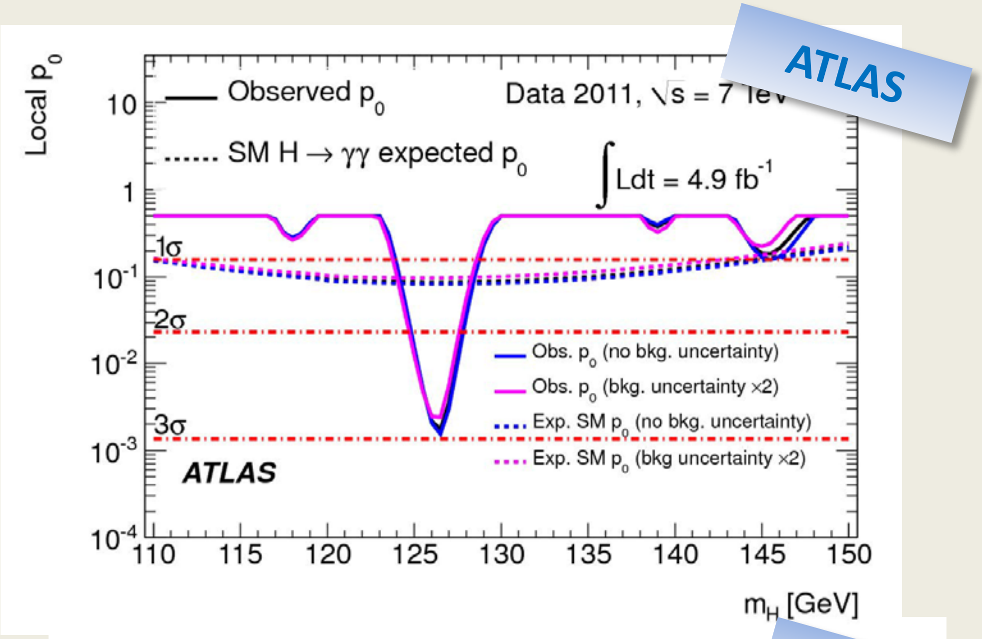
$H \rightarrow \gamma\gamma$ results: quantifying excesses

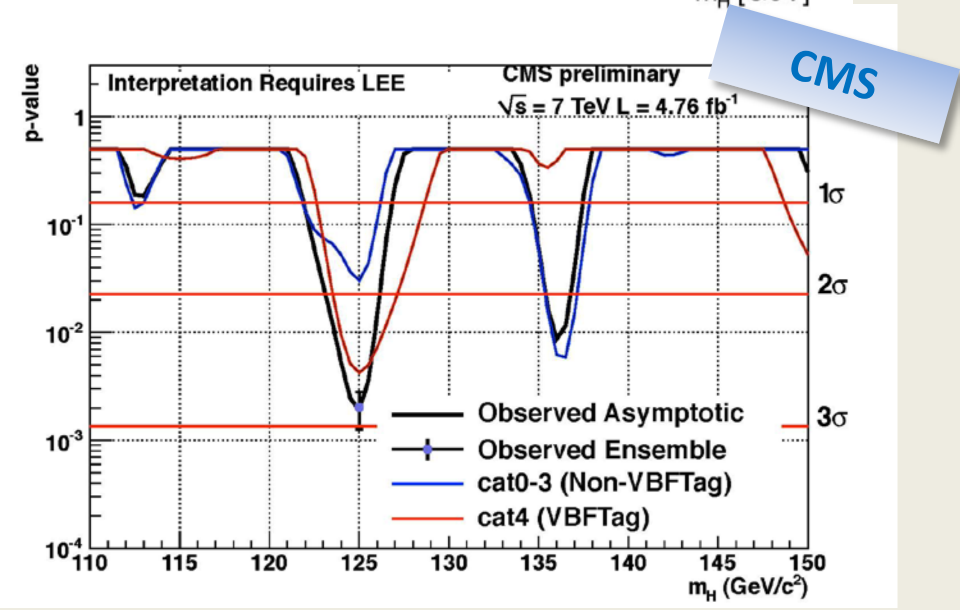
p_0 value plots

Maximum significances near 125 GeV:

	Local signif.	Global signif.
ATLAS	2.8σ	1.5σ
CMS	2.9σ	1.6σ

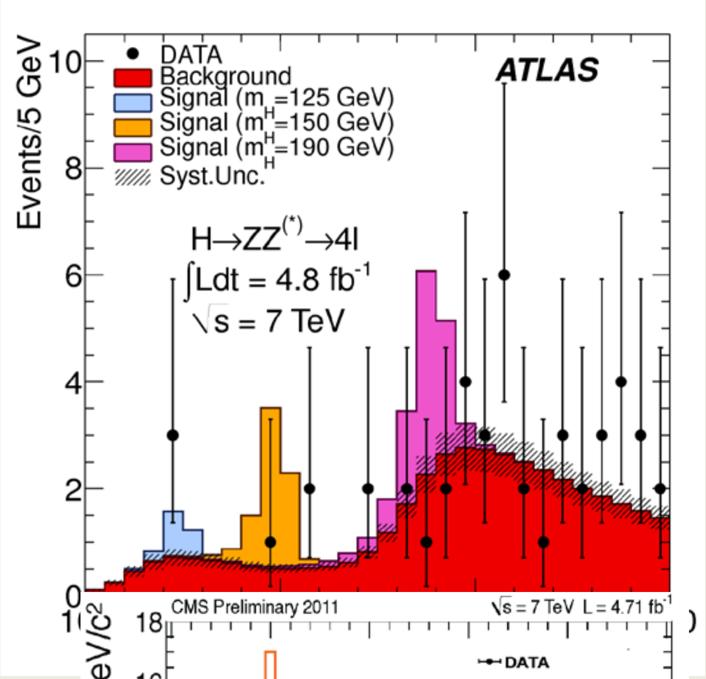
(LEE effect evaluated in **110 < m_H < 150 GeV** search region)

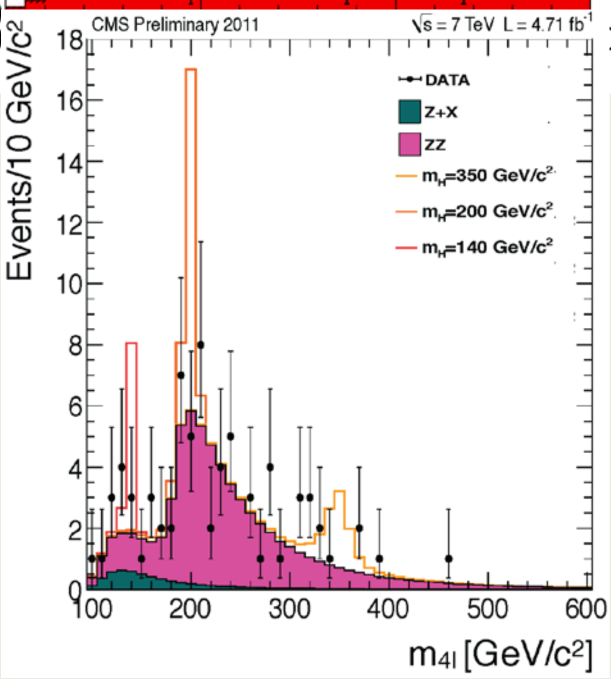


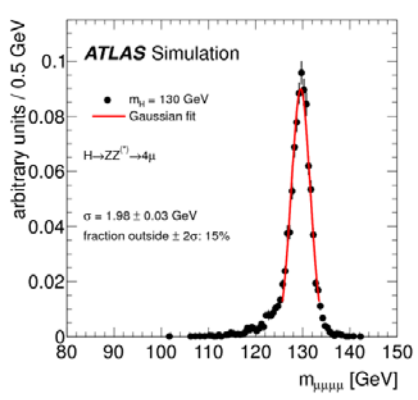


$H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ (4e, 2e2μ, 4 μ)

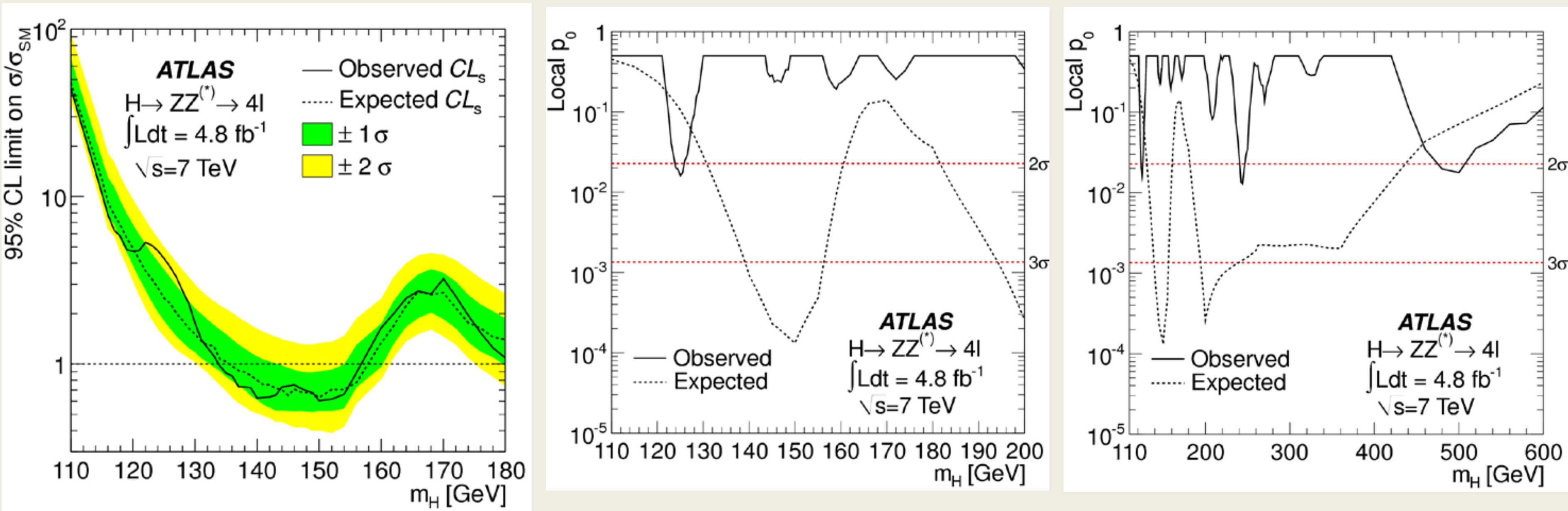
- small branching ratio: between 1‰ and 1%
- $100 < m_H < 600$ GeV
- excellent mass resolution, $m_{4\ell}$: ≈ 1-2%
- very clear signature:
  2 high mass isolated ee/μμ pairs
- high lepton (e/μ) id, down to low p_T = 7 GeV
- backgrounds:
  irreducible: ZZ
  reducible: Z+jets, Zbb, tt, WZ







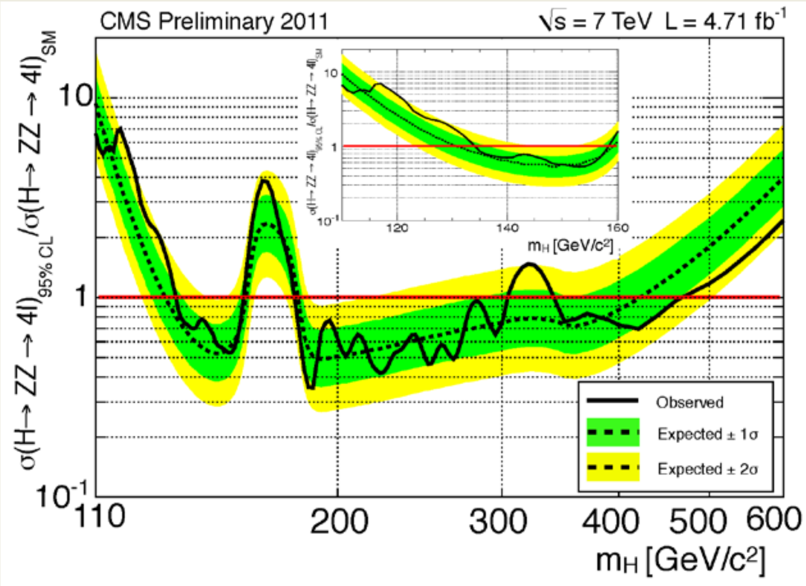
ATLAS: $H \to 4\ell$

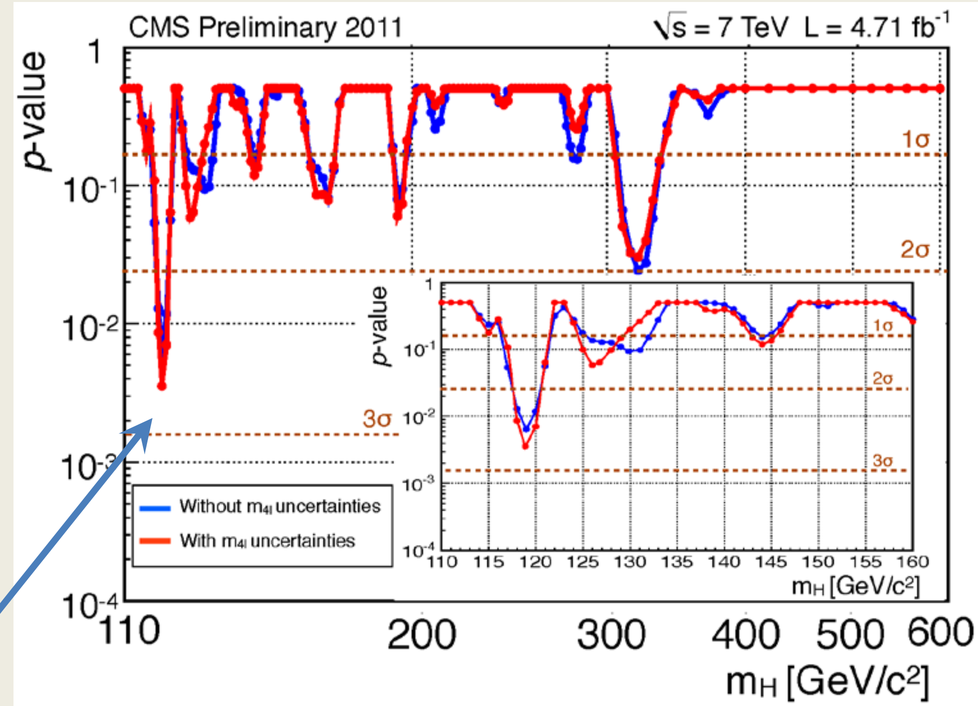


Excesses seen at m_H = **125** GeV (2.1σ) , 244 GeV (2.2σ) and 500 GeV (2.1σ) (local significances)

"Once the look-elsewhere effect is considered, none of these excesses are significant."

CMS: $H \to 4\ell$



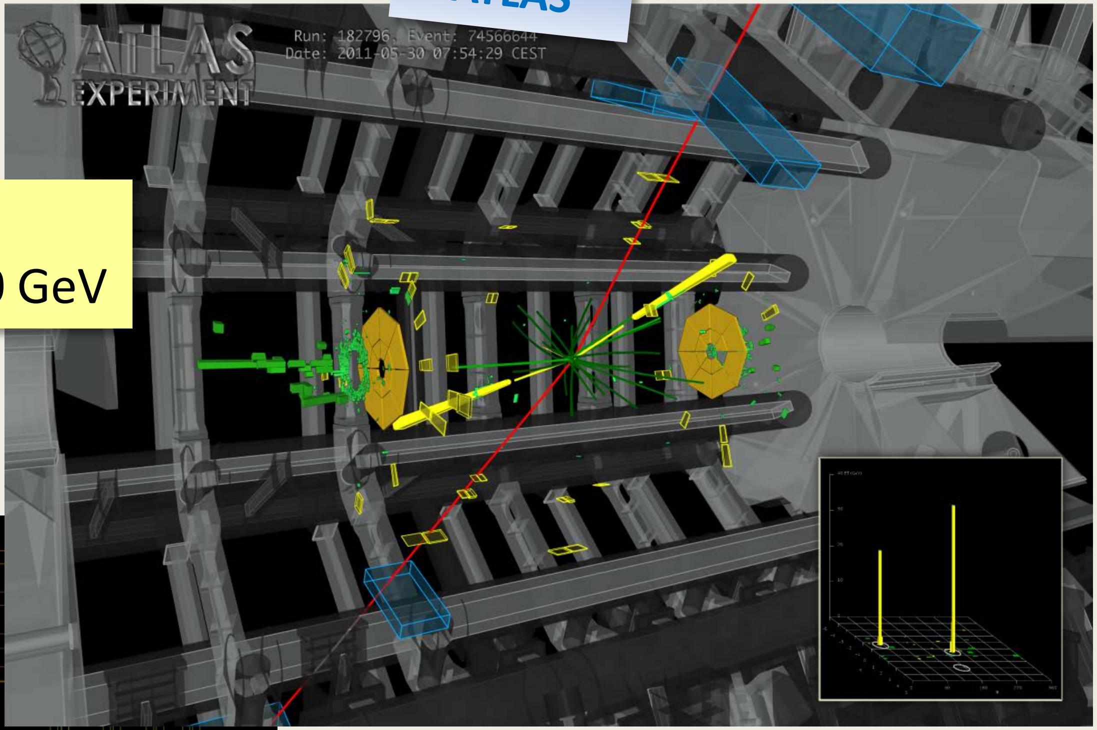


Largest excess seen at m_H = 119.5 GeV: local significance 2.5 σ

Look elsewhere effect in 110-160 GeV, reduces this to a global significance of 1.6 σ

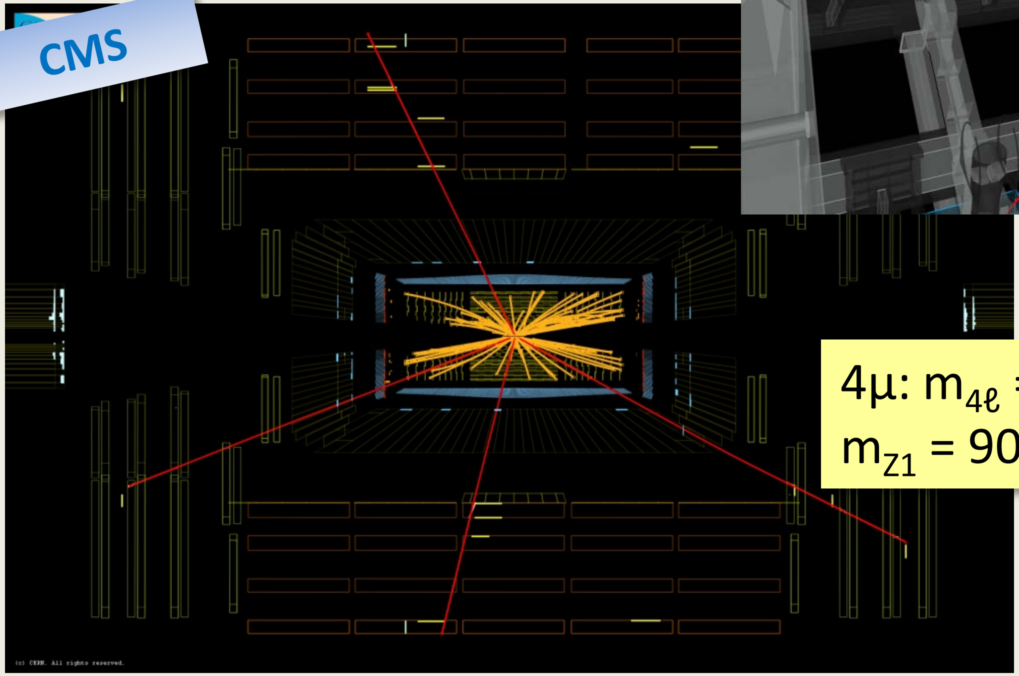
$H \to ZZ^{(*)} \to 4\ell$ candidate events

ATLAS



2e2μ: $m_{4\ell}$ = 124.3 GeV
m_{12} = 76.8 GeV; m_{34} = 30.0 GeV

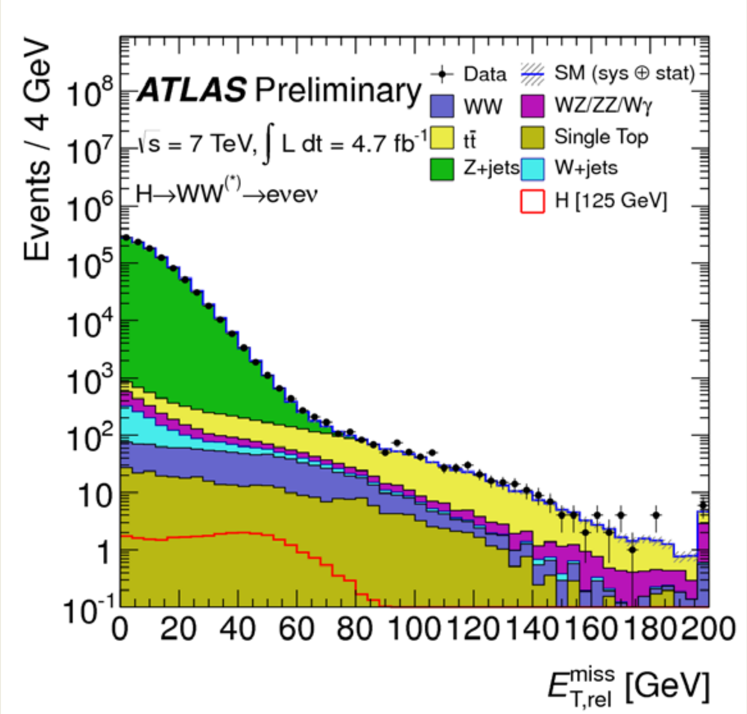
CMS

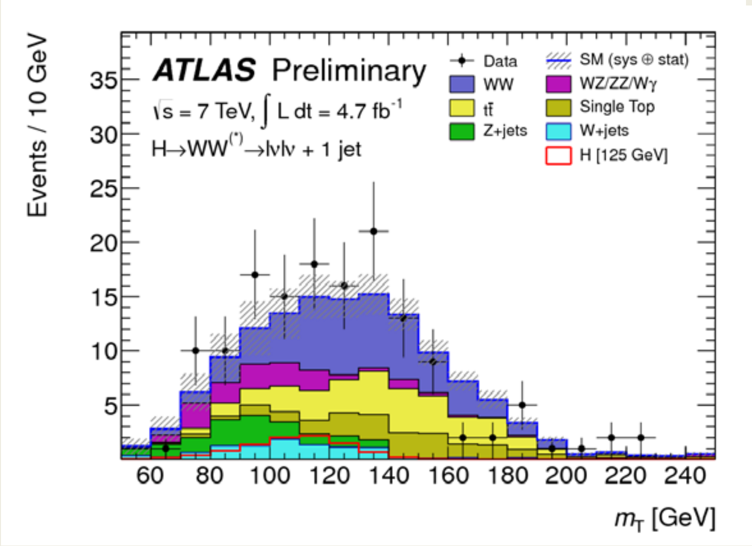


4μ: $m_{4\ell}$ = 119 GeV
m_{Z1} = 90 GeV; m_{Z2} = 25 GeV

$H \to WW^{(*)} \to \ell\nu\ell\nu$

- most sensitive channel in $125 < m_H < 200$ GeV
- $110 < m_H < 600$ GeV
- however: limited mass resolution, can't reconstruct m_H fully (as 2ν emmitted)
- signature: 2 high p_T isolated leptons
  + missing transverse energy
- main backgrounds:
  irreducible: WW
  reducible: Z+jets, WZ, ZZ, tt, W+jets





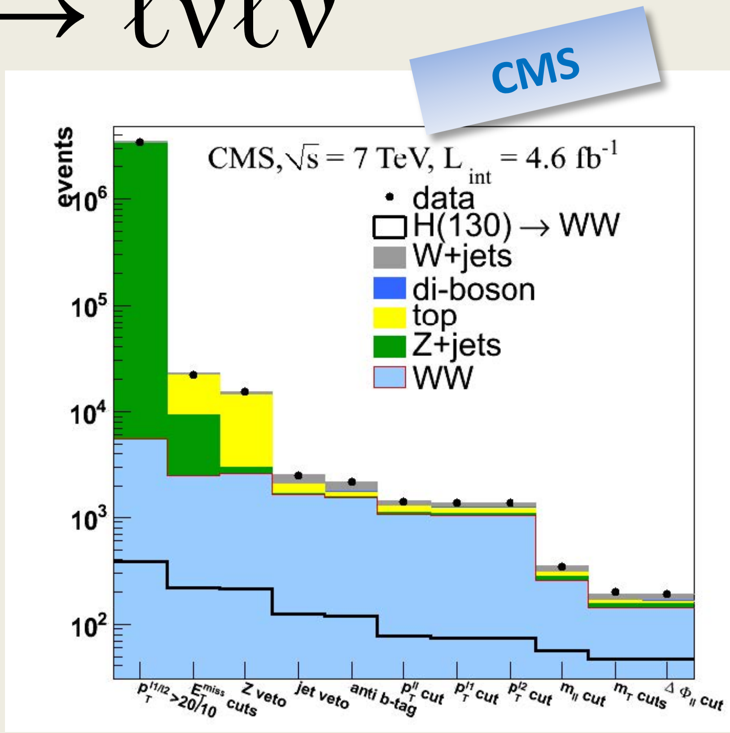
$H \to WW^{(*)} \to \ell\nu\ell\nu$

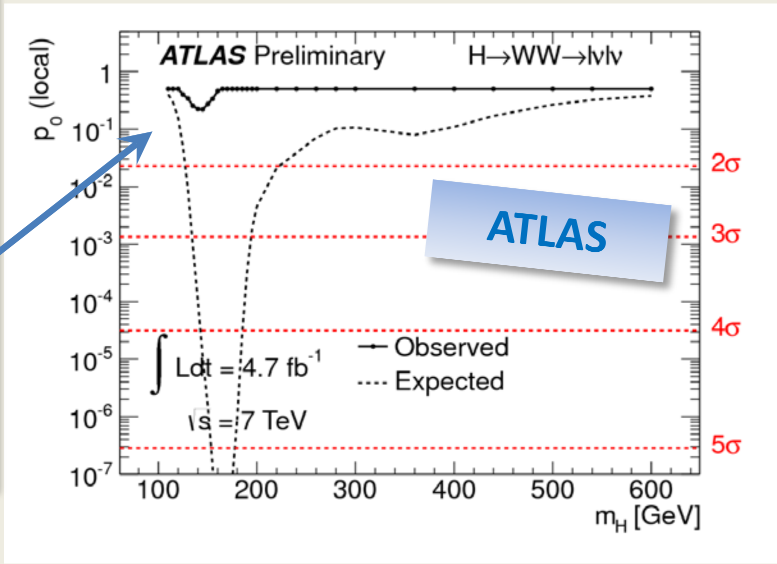
- **No significant excesses** seen by either ATLAS or CMS in latest analyses.

- **ATLAS result in Dec. 2011** (based on 2.1 fb^{-1})
  was 1.4σ broad excess,
  consistent with 1.4σ SM Higgs expectation.

- This result has in the meantime
  been updated to the full dataset (4.7 fb^{-1}),
  a new H+2-jet (VFB) category has been added, and
  m_T discriminant is now used (cf sliding window).
  ➔ Sensitivity improved by 15%.

- the data in this channel are now more consistent with the background-only scenario (0.2 σ)





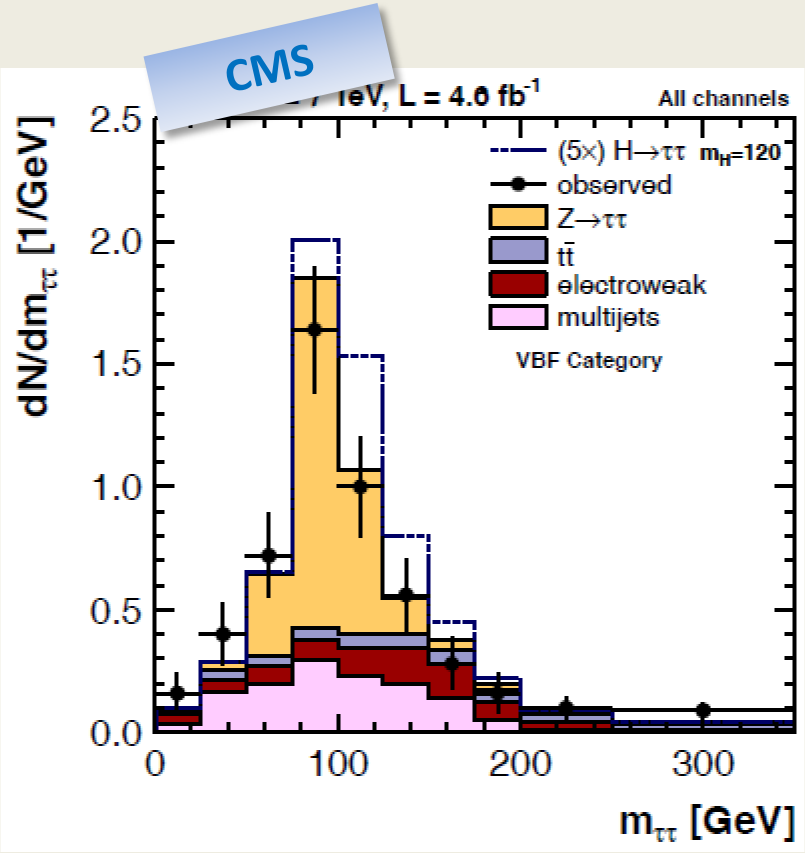
Additional searches

In low-m_H region ($100 < m_H < 160$ GeV)

- $H \rightarrow \tau\tau$ ($\ell\ell$, $\ell\tau_h$, $\tau_h\tau_h$)
- WH ($H\rightarrow\tau\tau$) $\rightarrow e\mu\tau_h / \mu\mu\tau_h + \nu$'s (CMS only)

- VH ($H \rightarrow bb$) $\rightarrow bb\ell\nu$, $bb\ell\ell$, $bb\nu\nu$

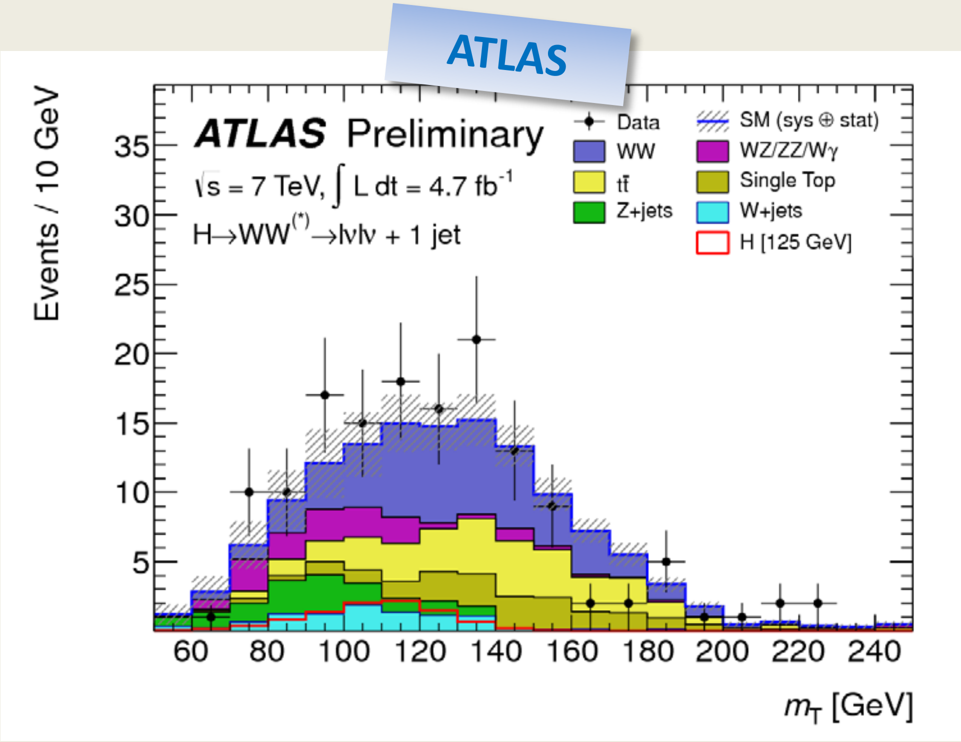
- WH ($H\rightarrow WW^{(*)}$) $\rightarrow 3\ell3\nu$ (CMS only)



Additional searches

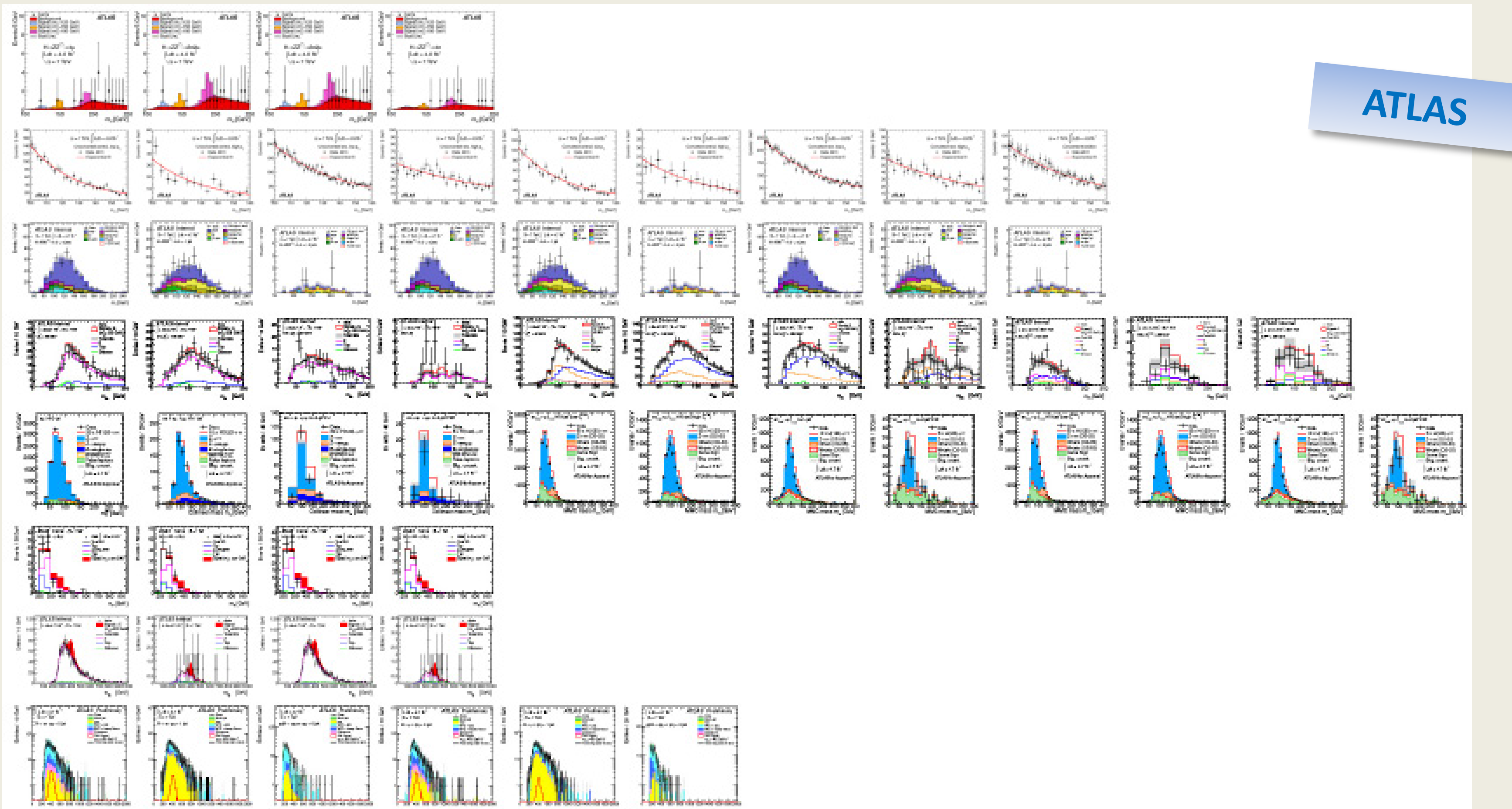
In high-mH region

- $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$
- $H \rightarrow ZZ \rightarrow \ell\ell\tau\tau$ (CMS only)
- $H \rightarrow ZZ \rightarrow \ell\ell jj$
- $H \rightarrow WW \rightarrow \ell\nu jj$



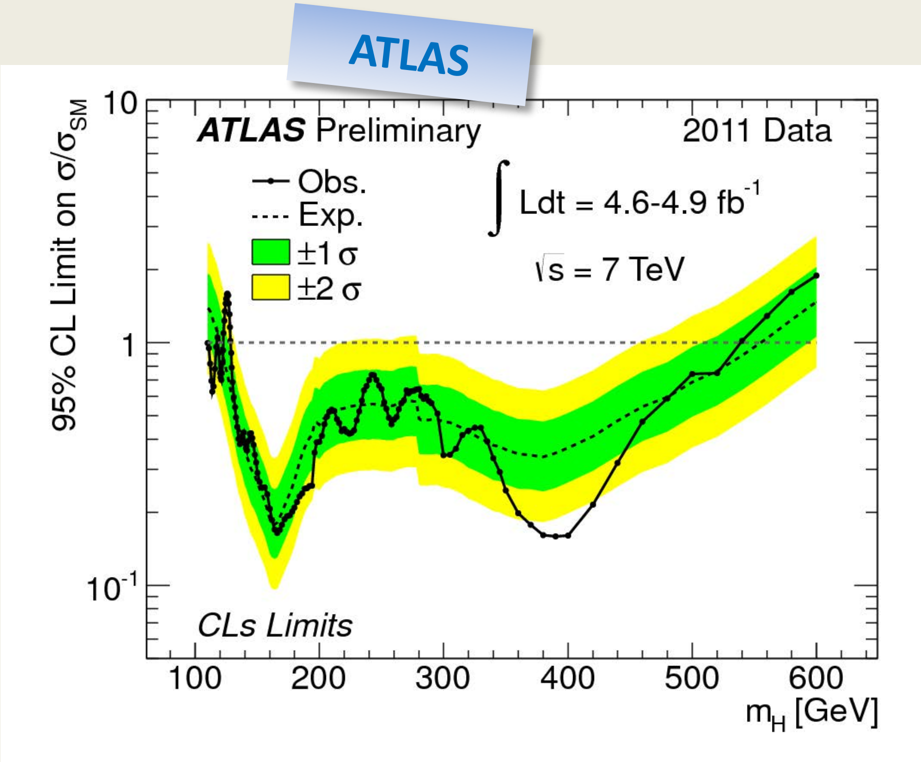
Combinations: putting it all together…

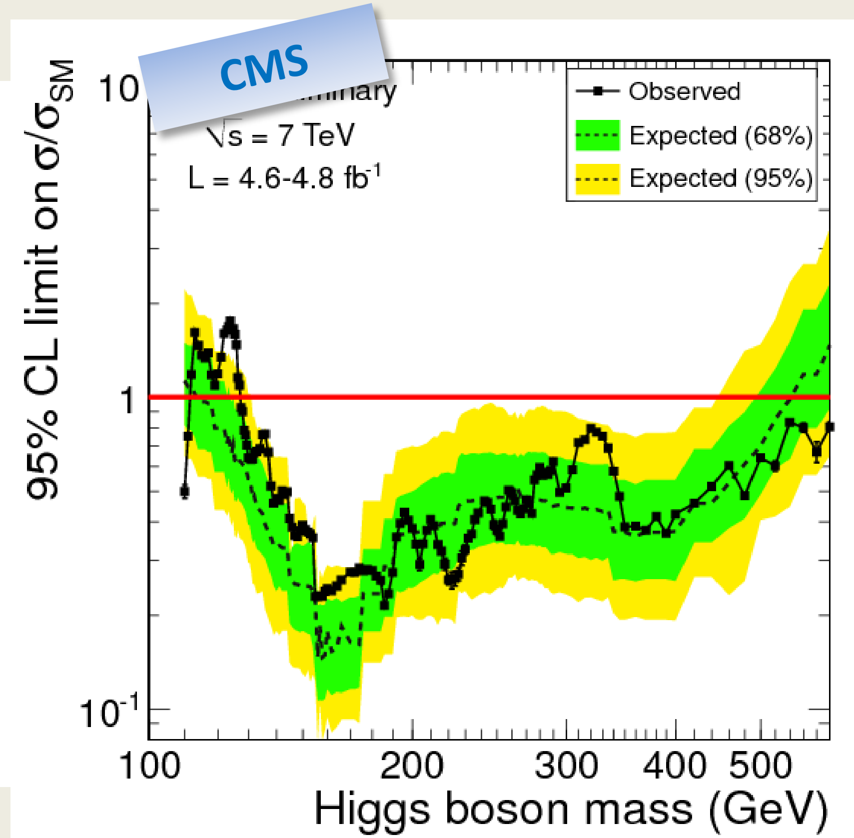
S Kortner, Moriond EW 2012



March 2012: TWO *separate* combinations: ATLAS combination and CMS combination

SM Higgs Exclusion limits





95% CL exclusion:

110.0 – 117.5, 118.5 – 122.5, 129 – 539 GeV

(120 – 555 GeV expected)

99% CL exclusion:

130 – 486 GeV

95% CL exclusion:

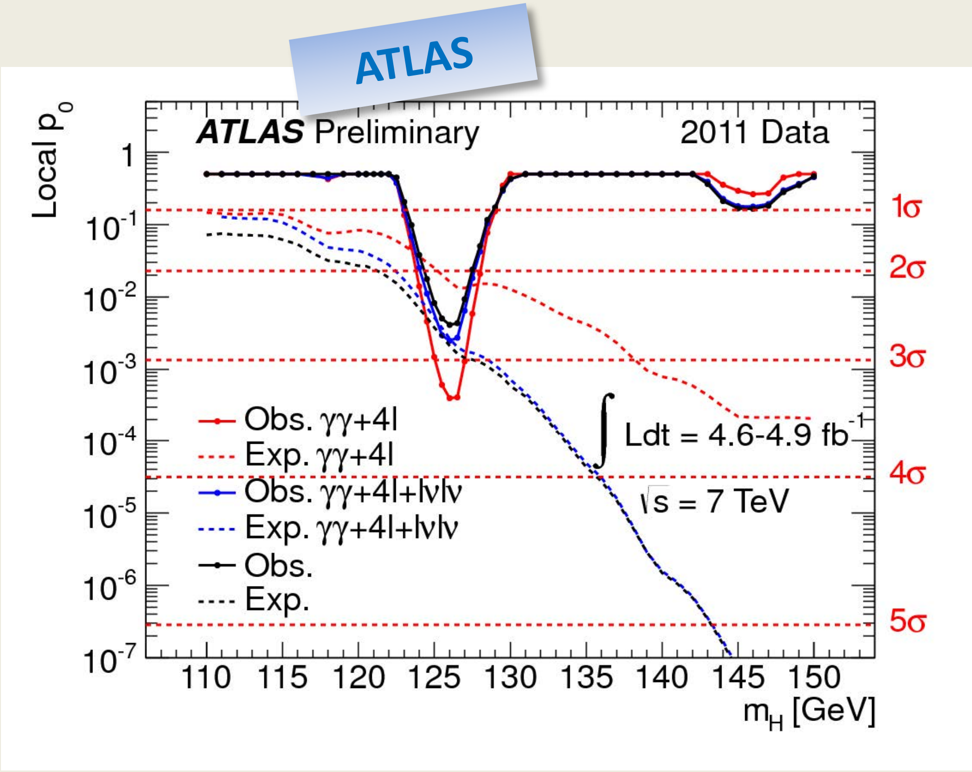
127.5 – 600 GeV

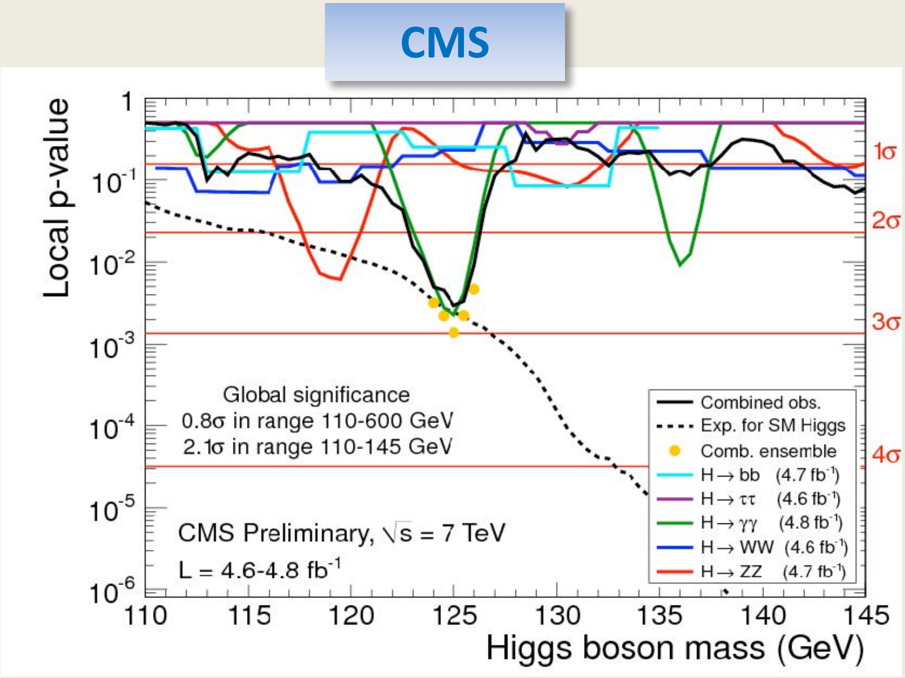
(114.5 – 543 GeV expected)

99% CL exclusion:

129 – 525 GeV

Incompatibility with background-only hypothesis



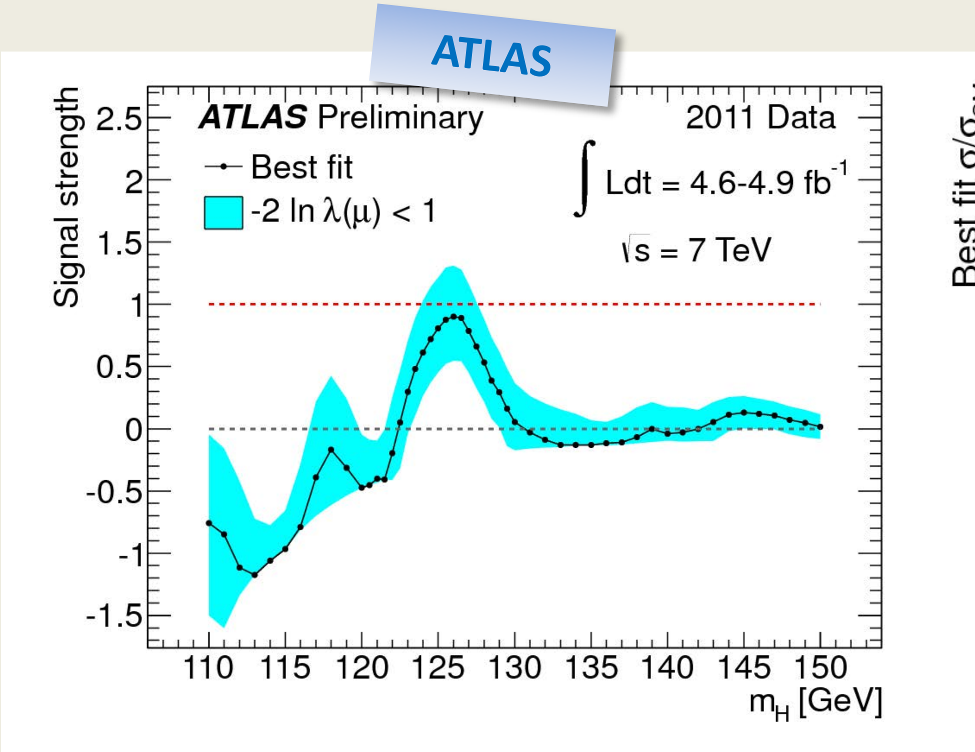


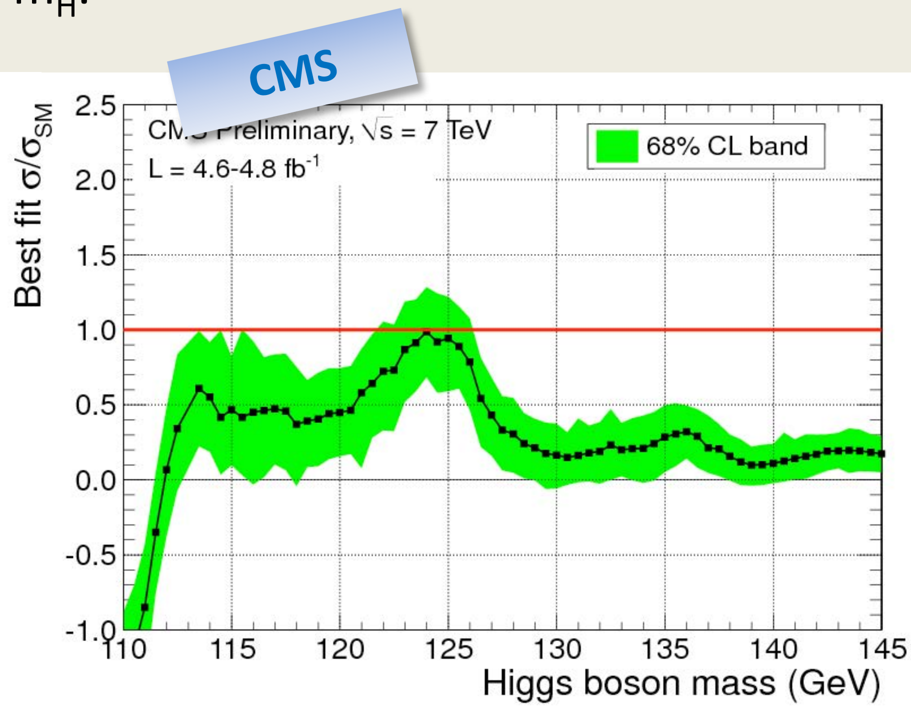
ATLAS:
Maximum observed local significance is **2.5σ**, observed at **m_H=126.5 GeV**

CMS:
Maximum observed local significance is **2.8σ**, observed at **m_H=125 GeV**

Compatibility with SM Higgs signal?

- Best-fit Higgs signal strength, $\mu = \sigma/\sigma_{SM}$.
- Scale all channels coherently at every m_H.



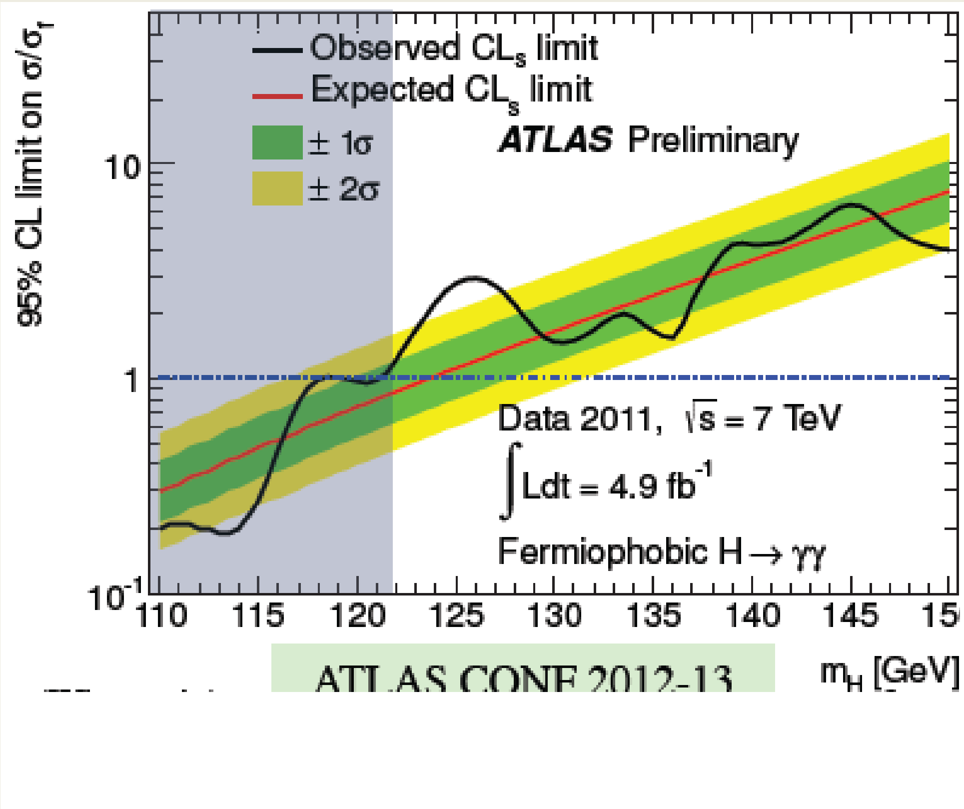


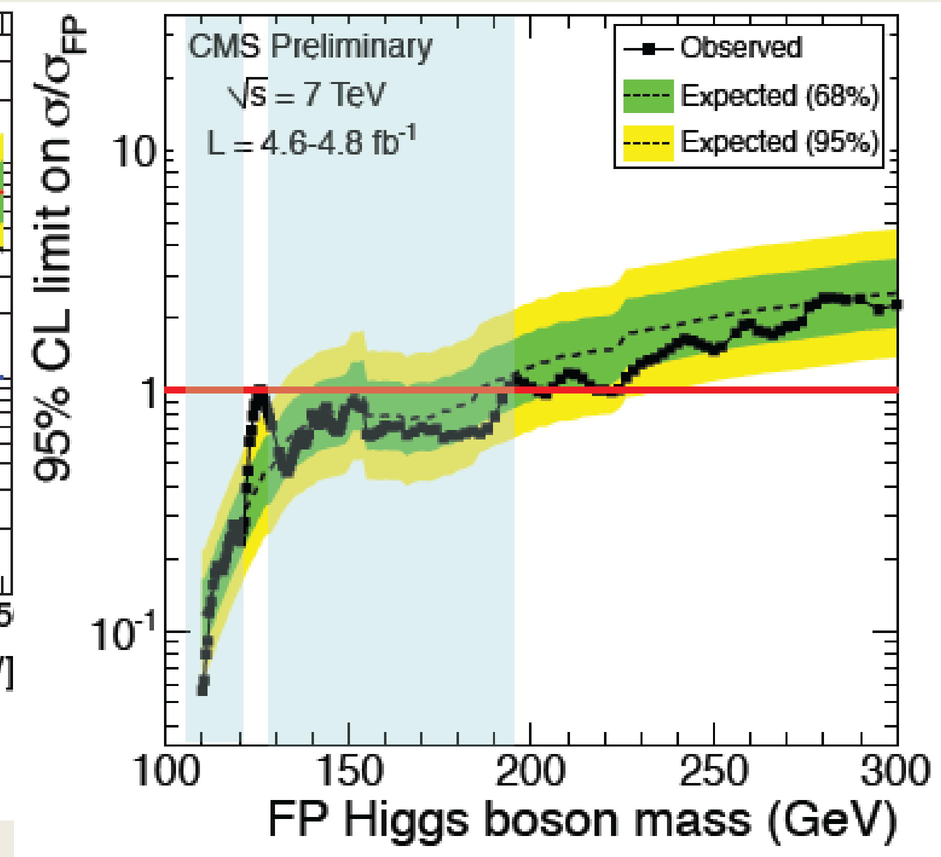
Data from both ATLAS and CMS are consistent with a SM Higgs boson with $m_H \approx 125$ GeV

LHC Plans for 2012

- Increase $\sqrt{s}$ = 8 TeV
- 50 ns bunch spacing
- instantaneous luminosity up to 7×10^{33} $cm^{-2}s^{-1}$ (double the maximum in 2011 – expect even more pileup)
- Deliver 7 fb^{-1} data to each GPD for summer conferences?... And 15-20 fb^{-1} by the end of the year?
- 18 month shutdown starts November 2012 (preparation for higher lumi and $\sqrt{s}$=13-14 TeV)

Beyond the SM: fermiophobic Higgs

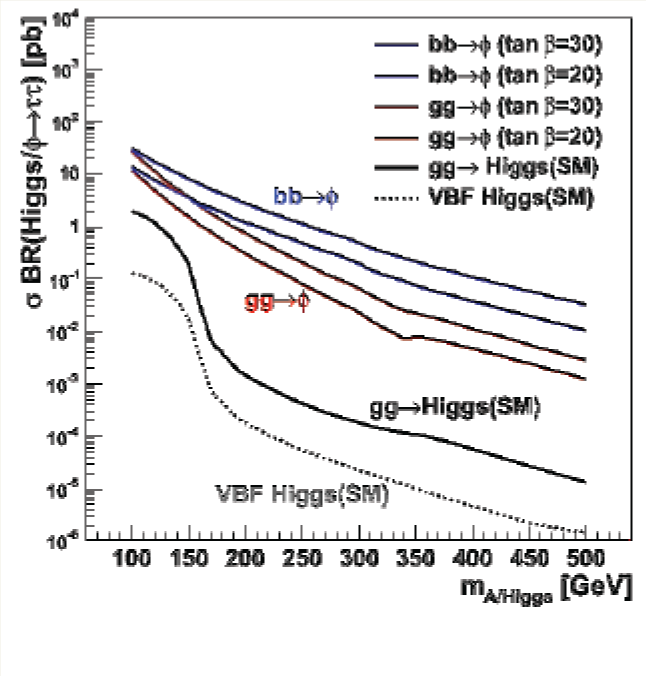


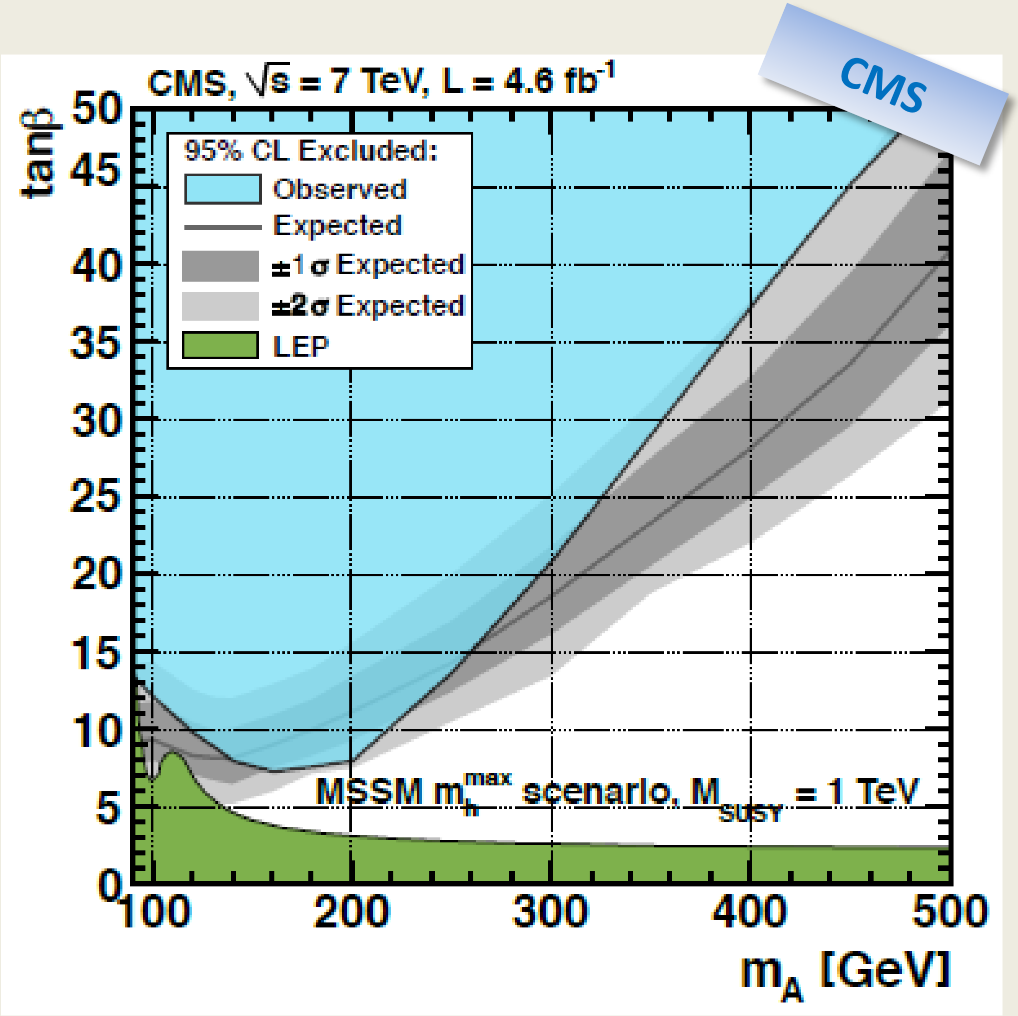


ATLAS: $H \to \gamma\gamma$

CMS: $H \to \gamma\gamma$, WW and ZZ

Beyond the SM: MSSM





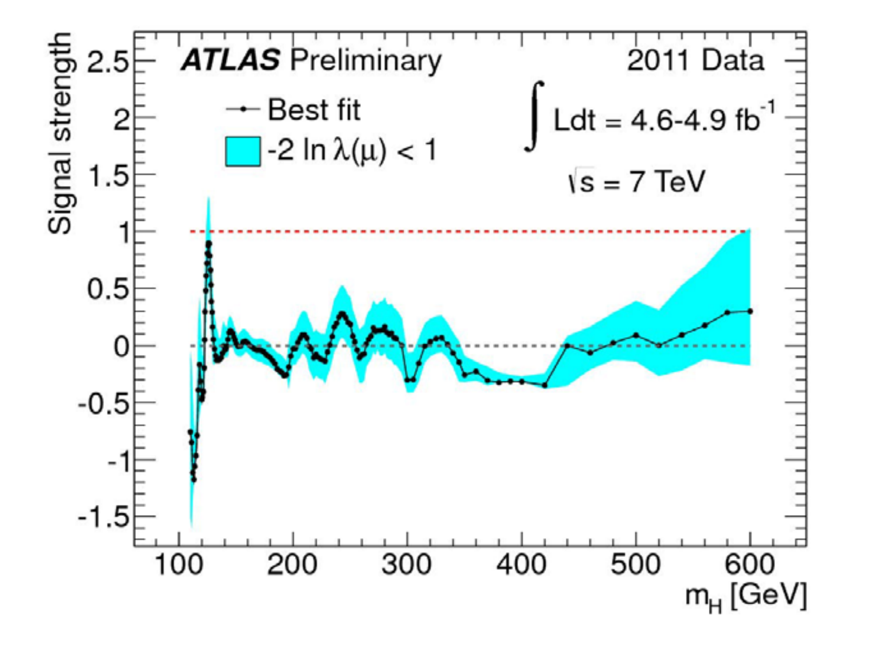
Large tan β: enhanced Higgs couplings to b/τ

+ increased production rates (via b-loops in GF, and also bb production)
+ Use H → ττ searches

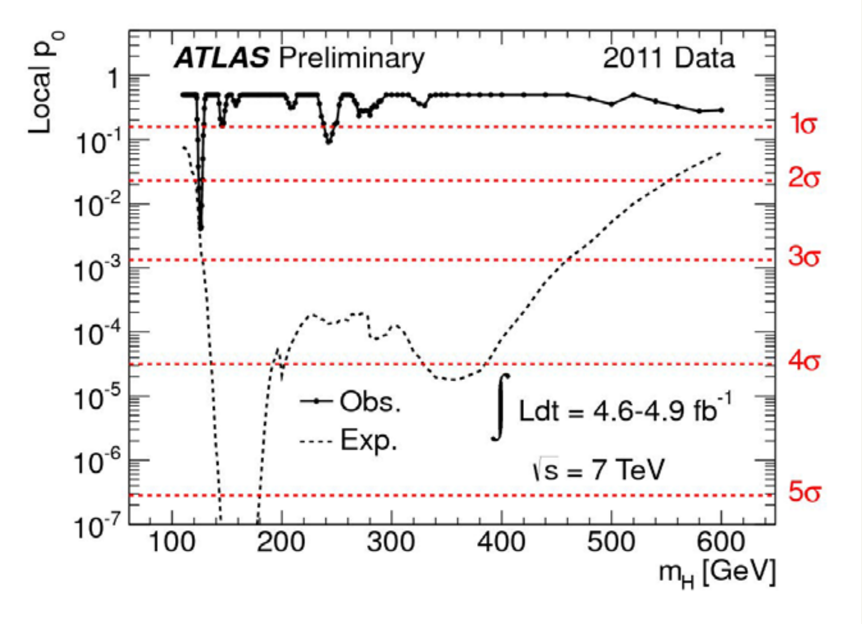
Conclusion

- very exciting 2011 – the most exciting it's been in over a decade
- hints of a possible signal
- we are in a very good position this time (unlike last time...): should be able to settle low mass SM Higgs (either signal at 125, or elsewhere...) this year
- looking forward to an exciting 2012!
- Thanks to Moriond LHC speakers (S Kortner, M Pieri, S Dasu) and colleagues in ATLAS/CMS

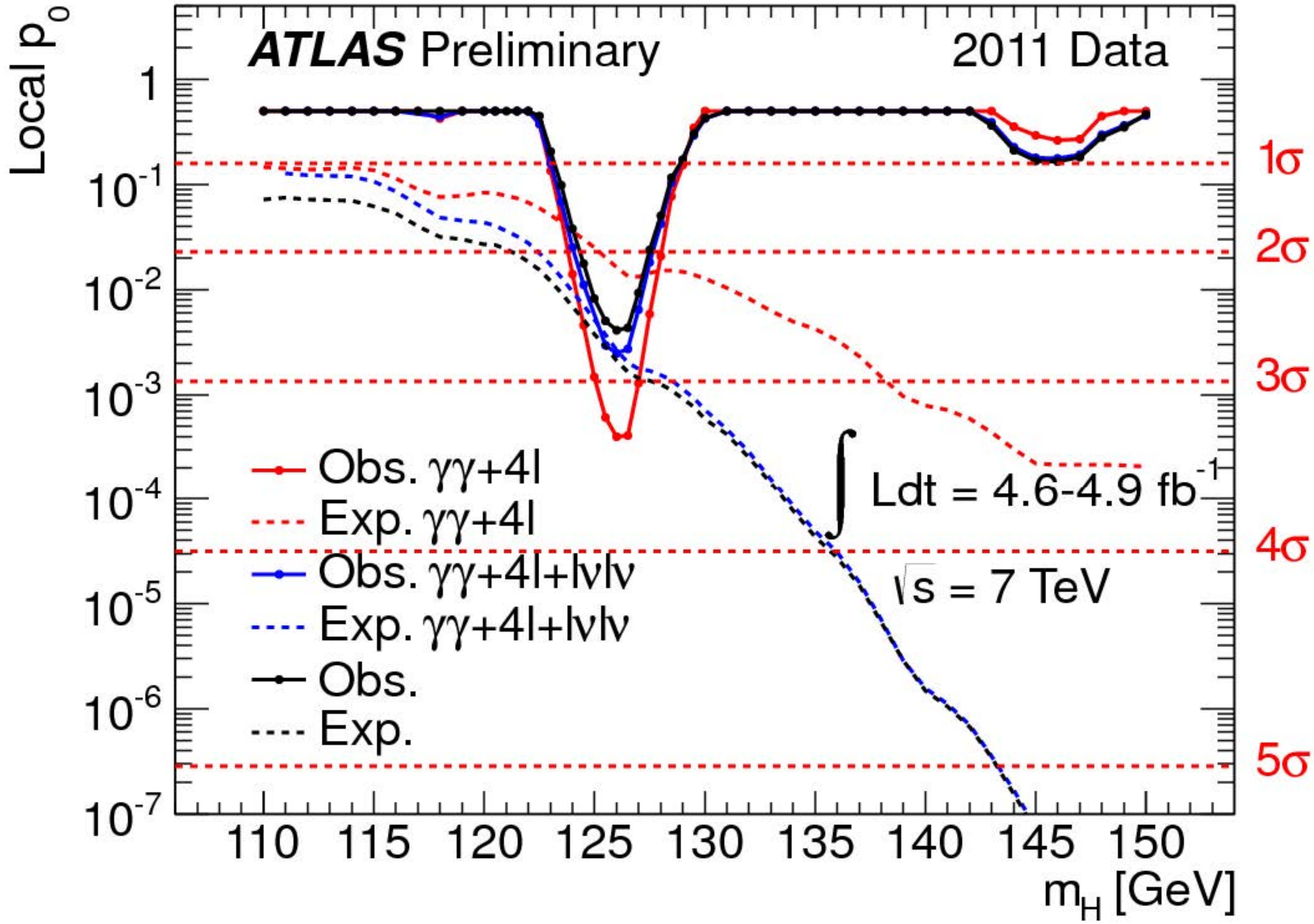
Backup slides



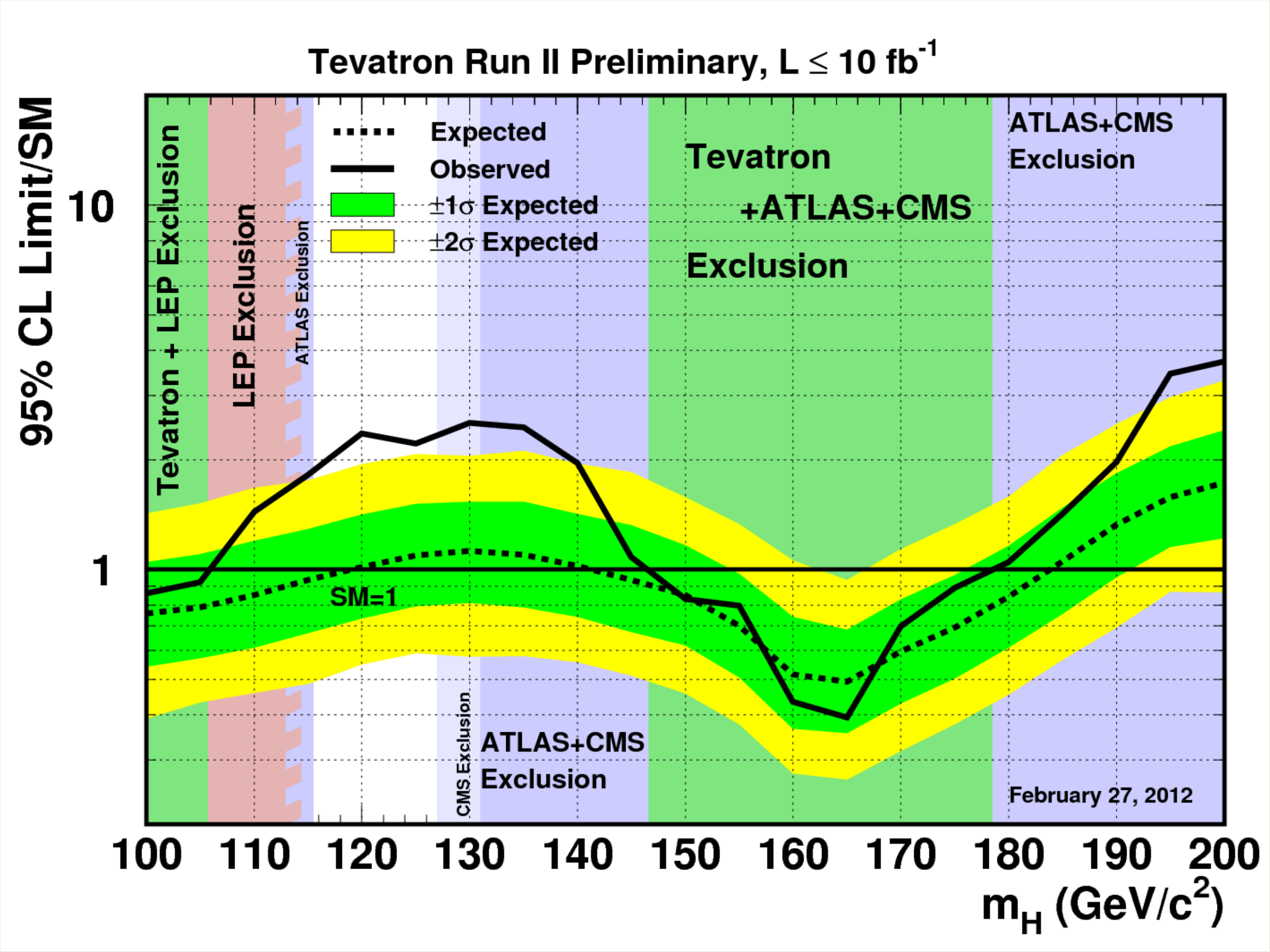
ATLAS Preliminary
2011 Data
Best fit
-2 ln λ(μ) < 1
∫ Ldt = 4.6-4.9 fb-1
√s = 7 TeV
Signal strength
mH [GeV]



ATLAS Preliminary
2011 Data
Obs.
Exp.
∫ Ldt = 4.6-4.9 fb-1
√s = 7 TeV
Local p0
mH [GeV]
1σ
2σ
3σ
4σ
5σ

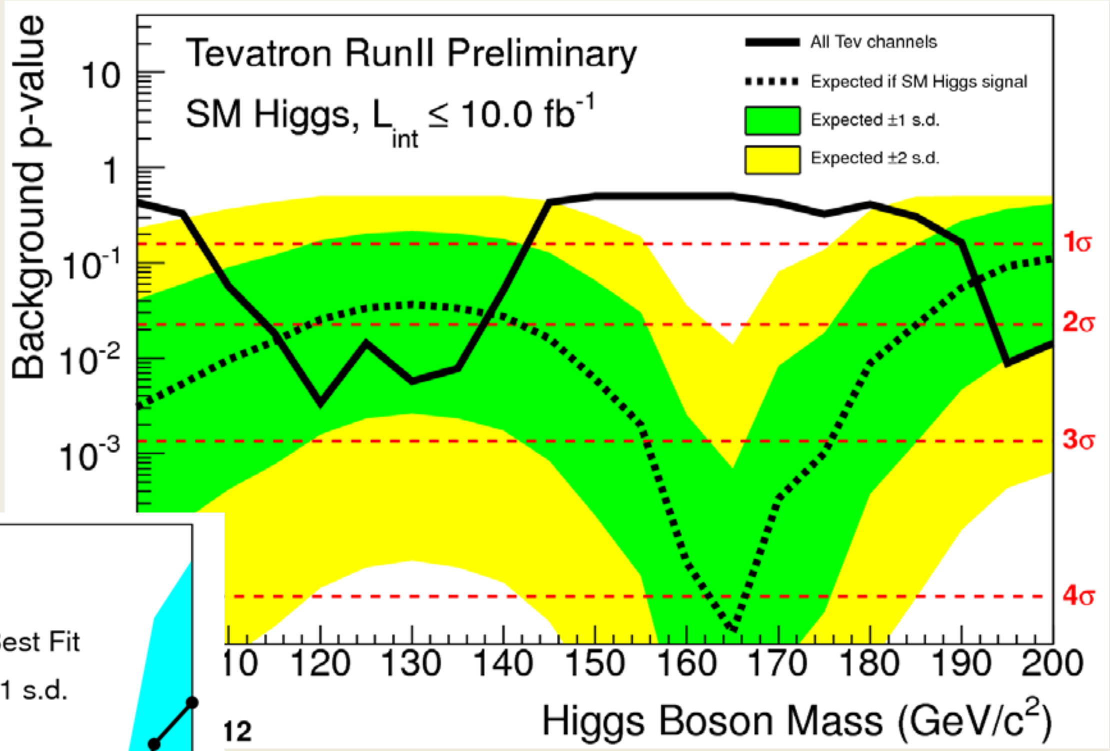

ATLAS Preliminary
2011 Data
Local p_0
m_H [GeV]
Obs. γγ+4l
Exp. γγ+4l
Obs. γγ+4l+lνlν
Exp. γγ+4l+lνlν
Obs.
Exp.
$\int Ldt = 4.6\text{-}4.9\ fb^{-1}$
$\sqrt{s} = 7$ TeV
1σ
2σ
3σ
4σ
5σ

TeVatron

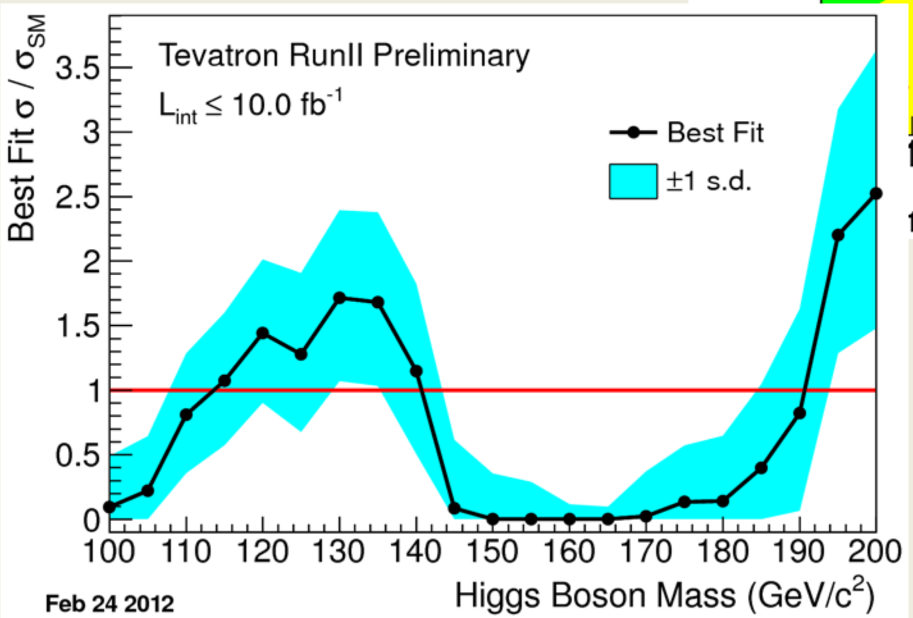


Tevatron Run II Preliminary, L ≤ 10 fb^{-1}
95% CL Limit/SM
Tevatron + LEP Exclusion
LEP Exclusion
ATLAS Exclusion
Expected
Observed
±1σ Expected
±2σ Expected
Tevatron
+ATLAS+CMS
Exclusion
ATLAS+CMS
Exclusion
SM=1
CMS Exclusion
ATLAS+CMS
Exclusion
February 27, 2012
10
1
100
110
120
130
140
150
160
170
180
190
200
m_H (GeV/c^2)

TeVatron



Tevatron RunII Preliminary
SM Higgs, $L_{int} \leq 10.0\ fb^{-1}$
All Tev channels
Expected if SM Higgs signal
Expected ±1 s.d.
Expected ±2 s.d.
Background p-value
10
1
10^{-1}
10^{-2}
10^{-3}
1σ
2σ
3σ
4σ
10 120 130 140 150 160 170 180 190 200
Higgs Boson Mass (GeV/c^2)
12



Tevatron RunII Preliminary
$L_{int} \leq 10.0\ fb^{-1}$
Best Fit
±1 s.d.
Best Fit σ / σ_{SM}
3.5
3
2.5
2
1.5
1
0.5
0
100 110 120 130 140 150 160 170 180 190 200
Higgs Boson Mass (GeV/c^2)
Feb 24 2012