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# The ATLAS Higgs boson discovery from the WW\* perspective

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**corrinne mills, “on behalf of HSG3”**

*University of Illinois at Chicago*

*Fermi National Accelerator Laboratory*

HiggsDiscovery@10 Symposium

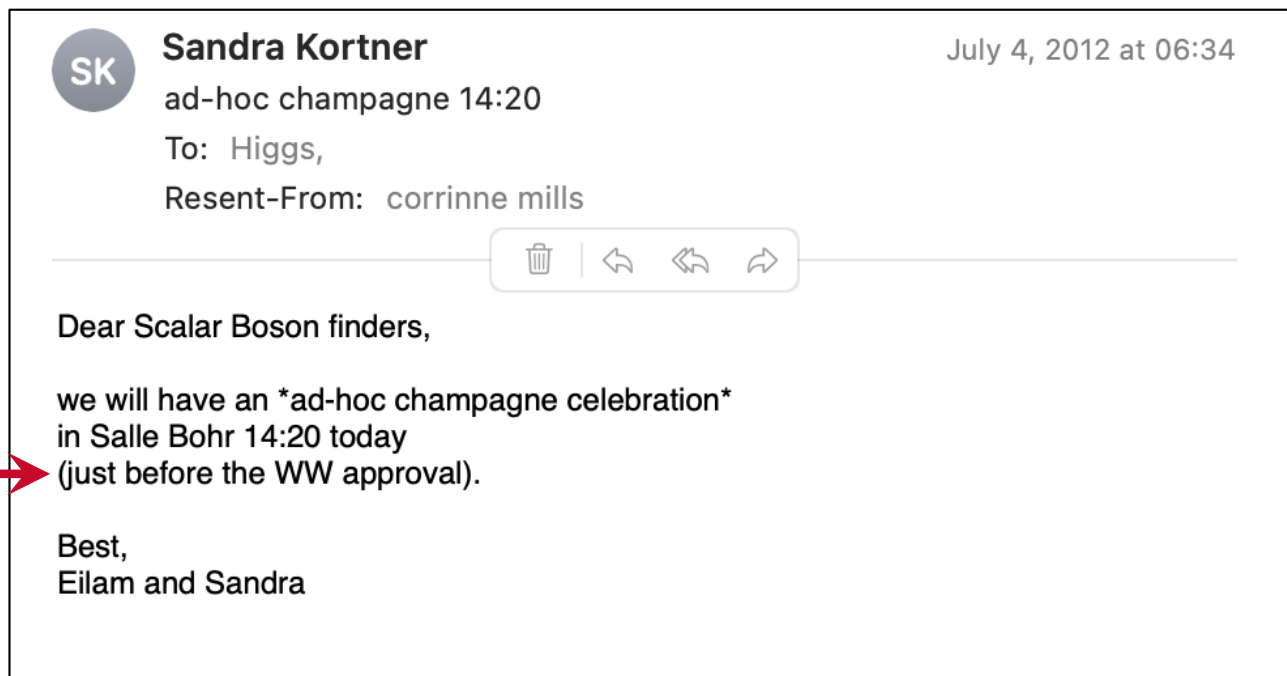
*University of Birmingham*

30 June 2022



# Where was I on 4 July 2012?

- Not in the main auditorium: the line filled up overnight
- Still working hard the night before, because the ATLAS HWW analysis was not yet approved



# Overview

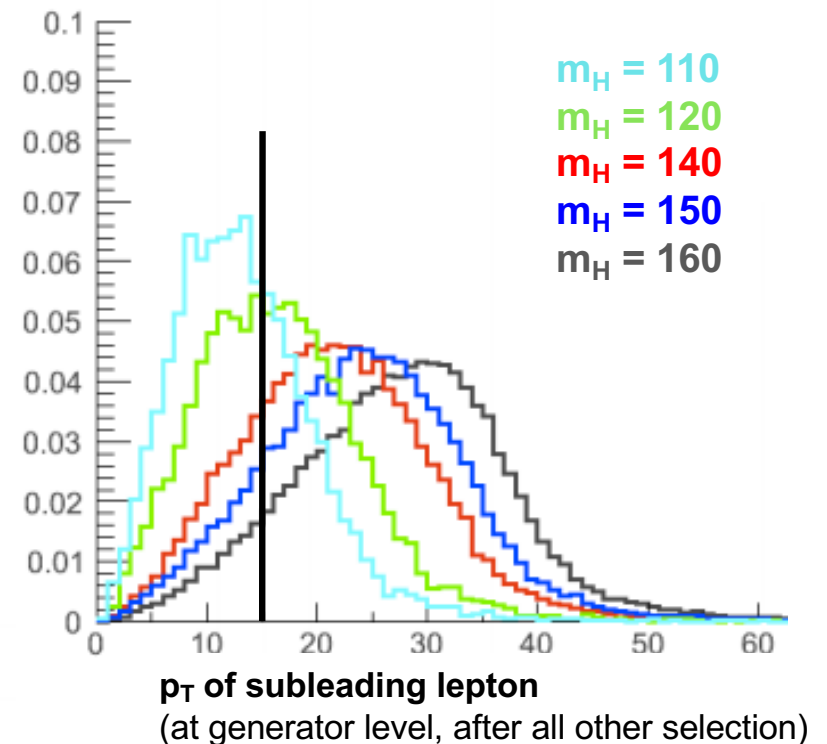
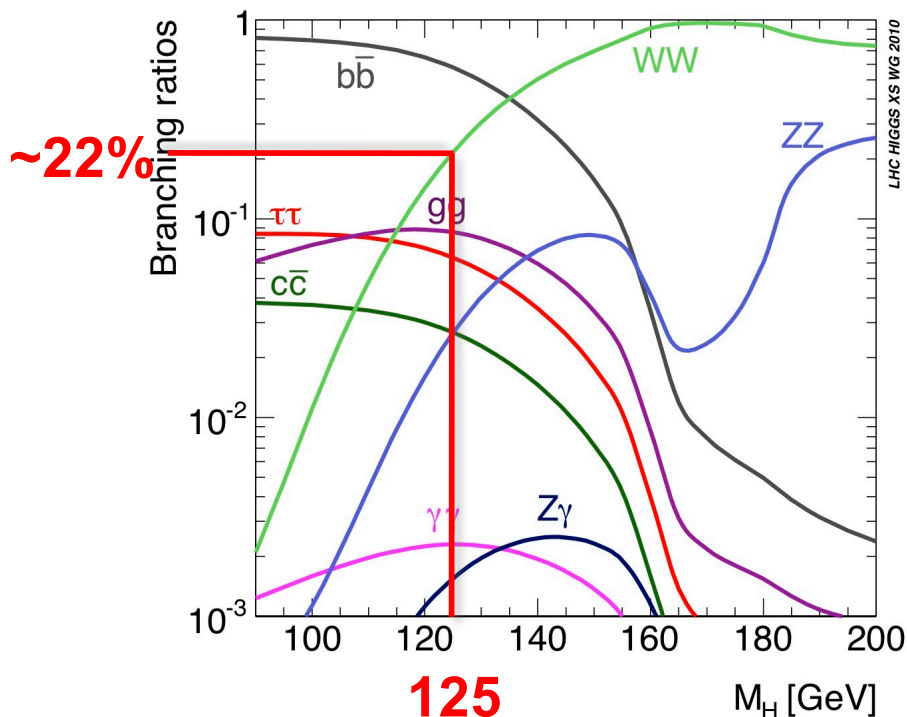
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- In the end, pulled together the analysis in time to be part of the discovery paper
- How did we do it?
  - *HWW in a nutshell*
  - *Ambiguous evidence and the decision to blind*
  - *Work hard, play hard*
  - *“Success-oriented schedule”*
  - *Background reviews and MC bottlenecks*
  - *Eventual triumph*
- This talk is more of a social than scientific history, and very much my personal perspective, focused on the time right around the discovery

**All credit for the work achieved goes to my incredible collaborators, all opinions and mistakes are purely my own**

# Why $H \rightarrow WW \rightarrow l\nu l\nu$ ?

- **The payoff:** better signal yield than  $\gamma\gamma$  and  $ZZ \rightarrow 4l$ , better S/B than  $b\bar{b}$
- **The price:** For  $m_H < 2M_W$ , W off mass shell (no mass resolution), large backgrounds, acceptance shrinks as  $m_H$  decreases one W is virtual and subleading leptons are lower  $p_T$



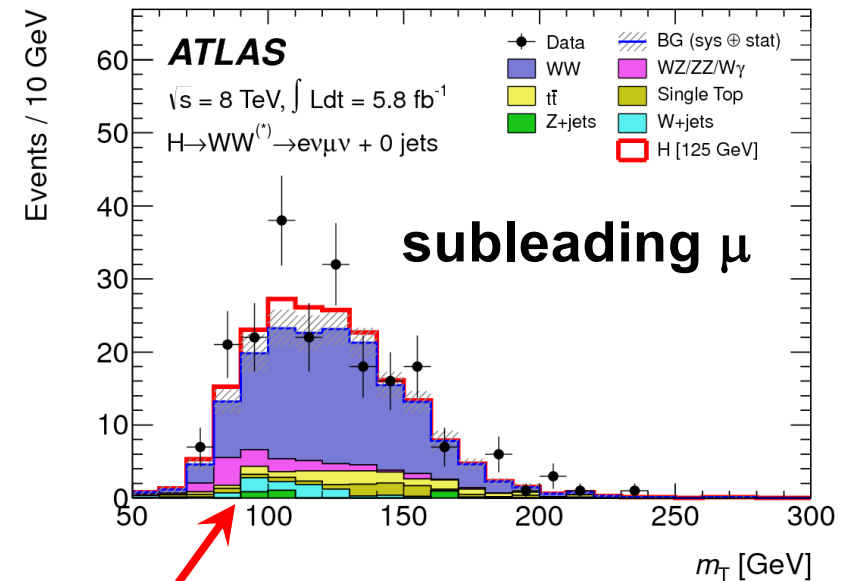
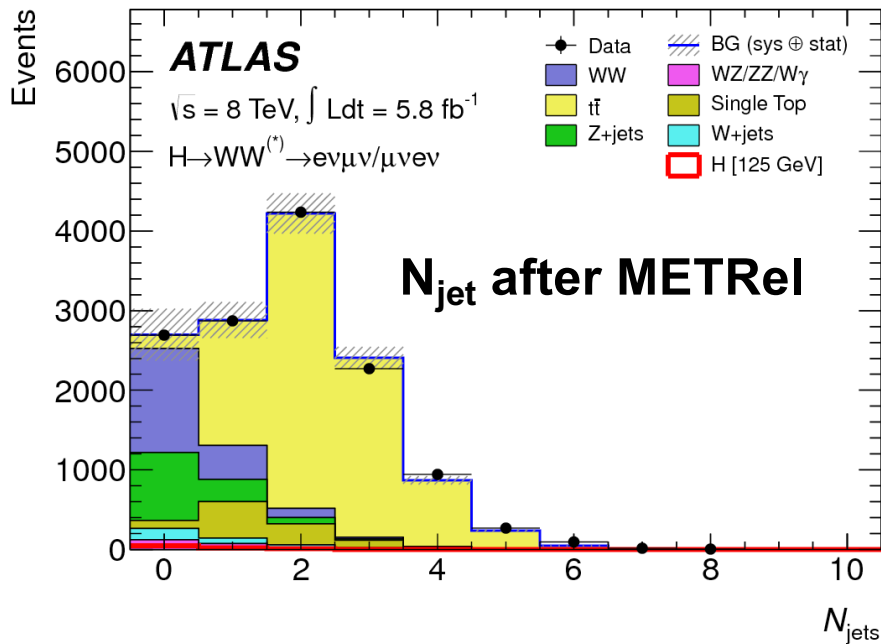


# Analysis binning

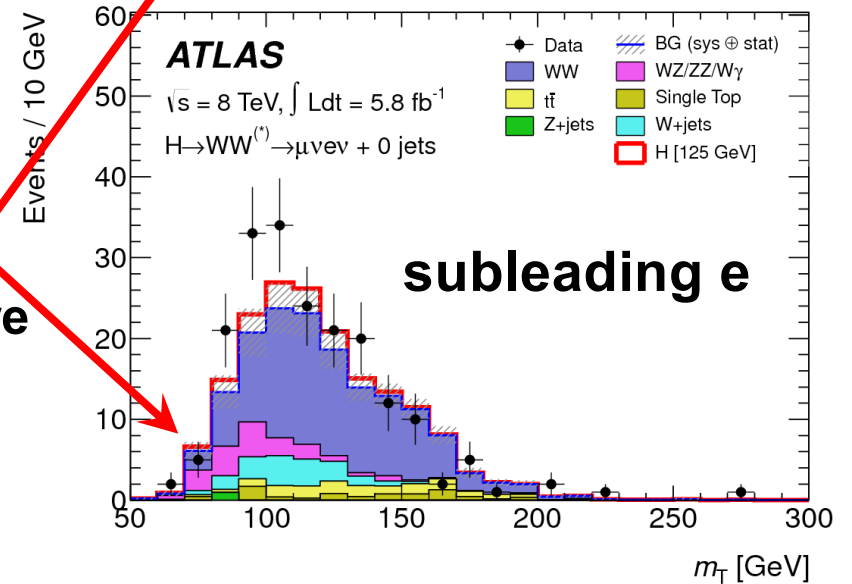
- Subdivide analysis to benefit from different S/B and background composition in different final states

→ *By number of jets 0, 1,  $\geq 2$*

→ *Into  $(e\mu, \mu e)$  sub-channels where second lepton is subleading*



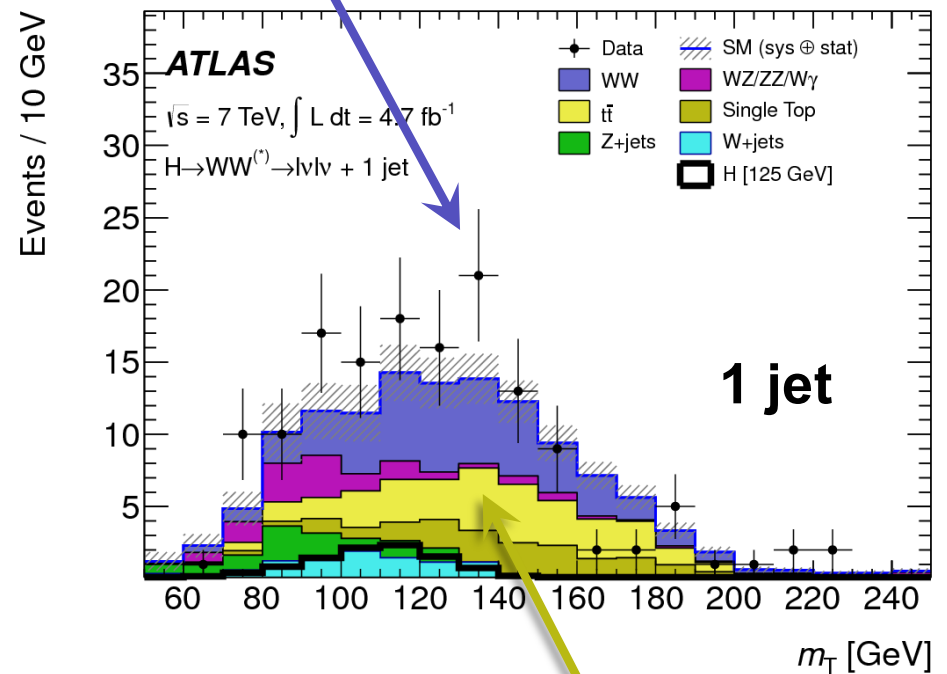
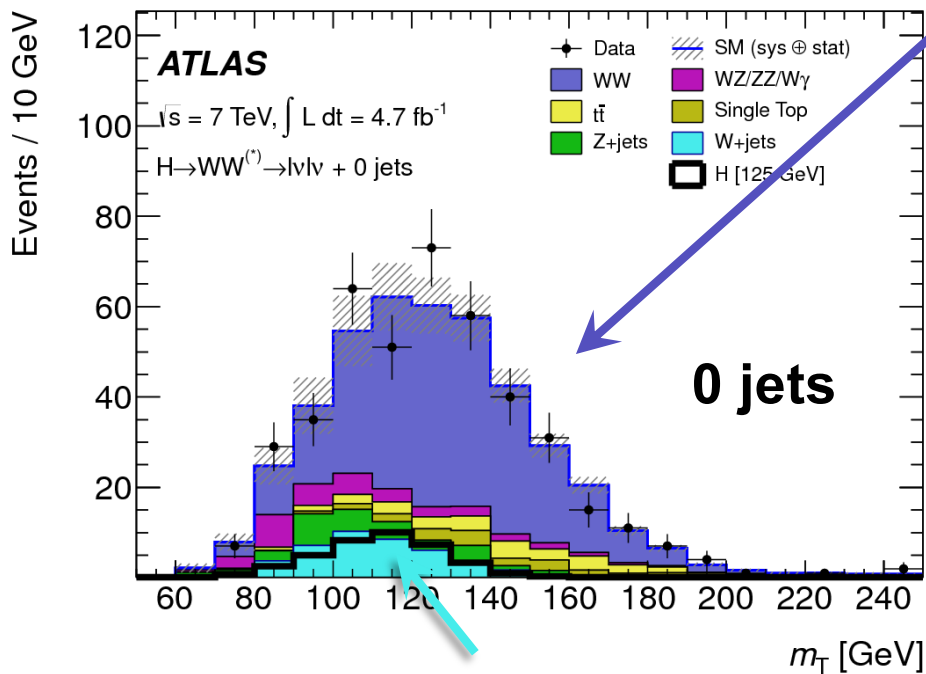
compare  
**W+jets**  
**(cyan)**



# All about the backgrounds

**“We need a control region we can control”**

**Non-resonant WW diboson background: high- $m_{ll}$  control region**

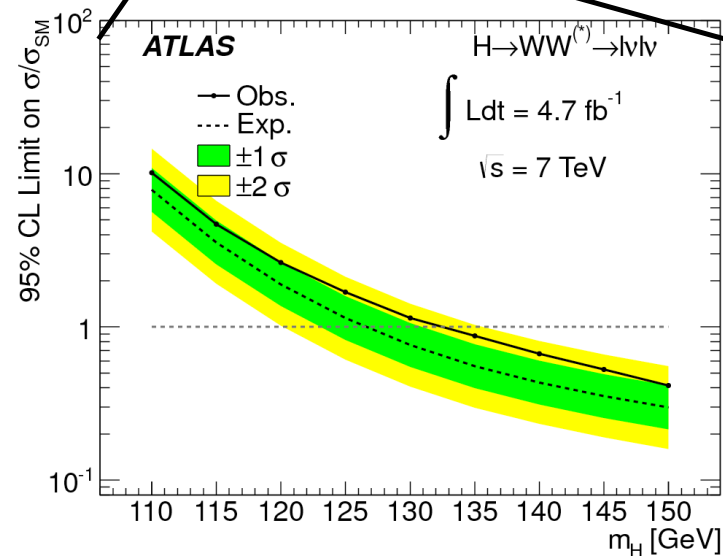
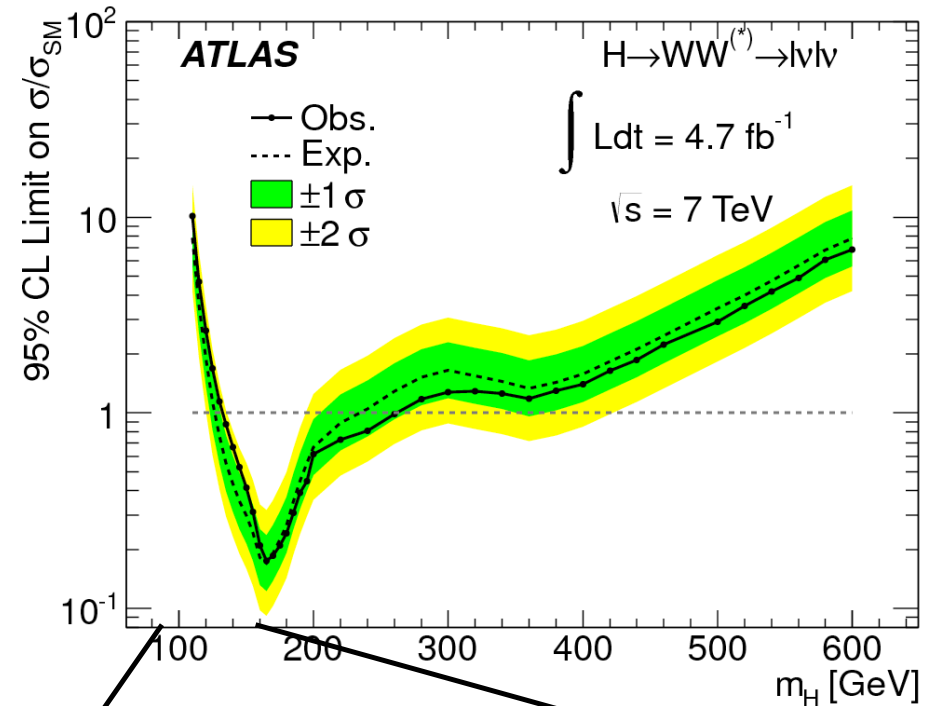
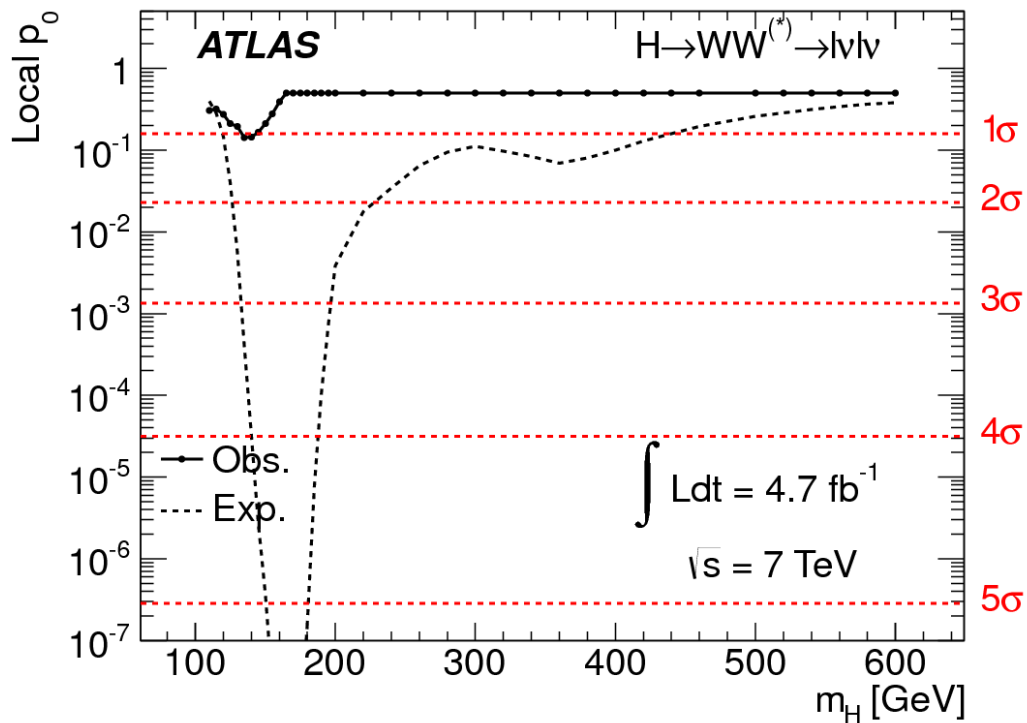


**W+jets with a “fake” lepton: purely data with MC used to set systematics**

**$t\bar{t}$  and single top: b-tagged control regions**

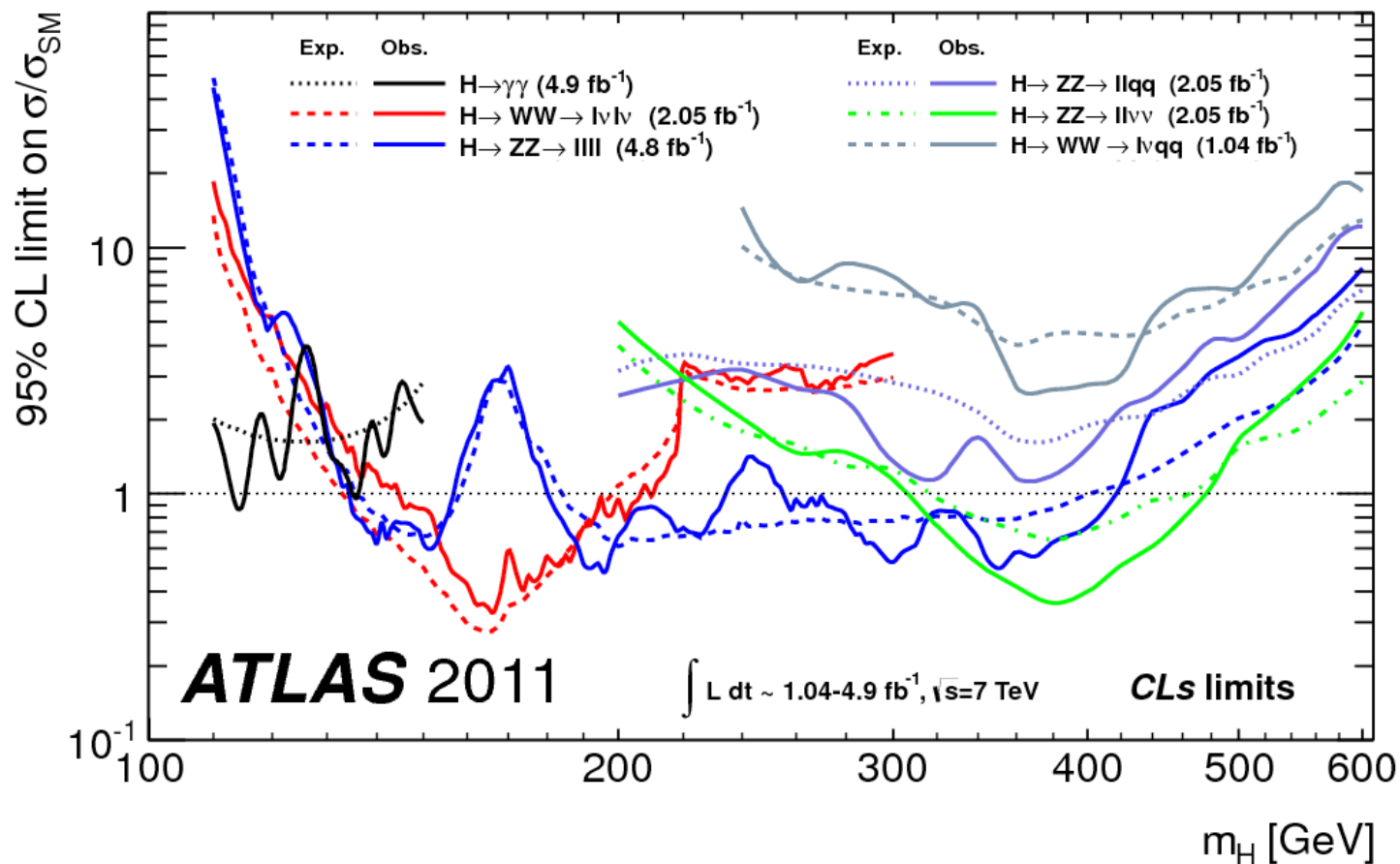
# 2011 ATLAS HWW

The 7 TeV analysis results were ambiguous: lowest p-value observed is 0.15 (we didn't even quote a signal strength)

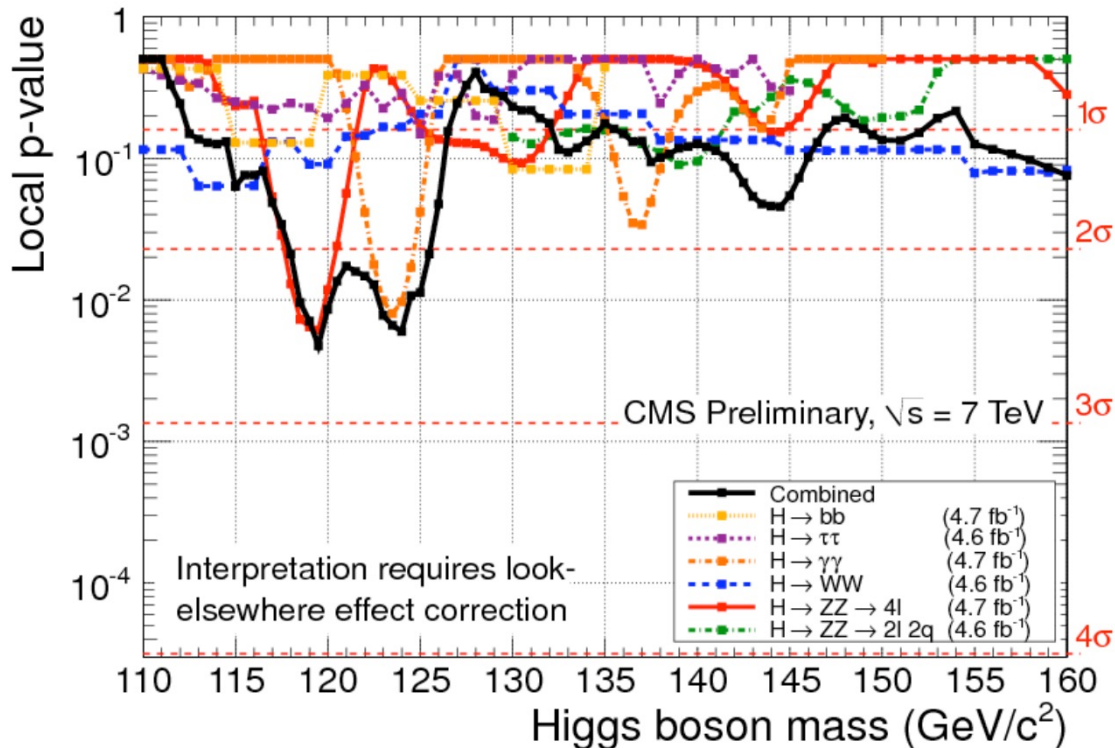


# Back up to December 2011

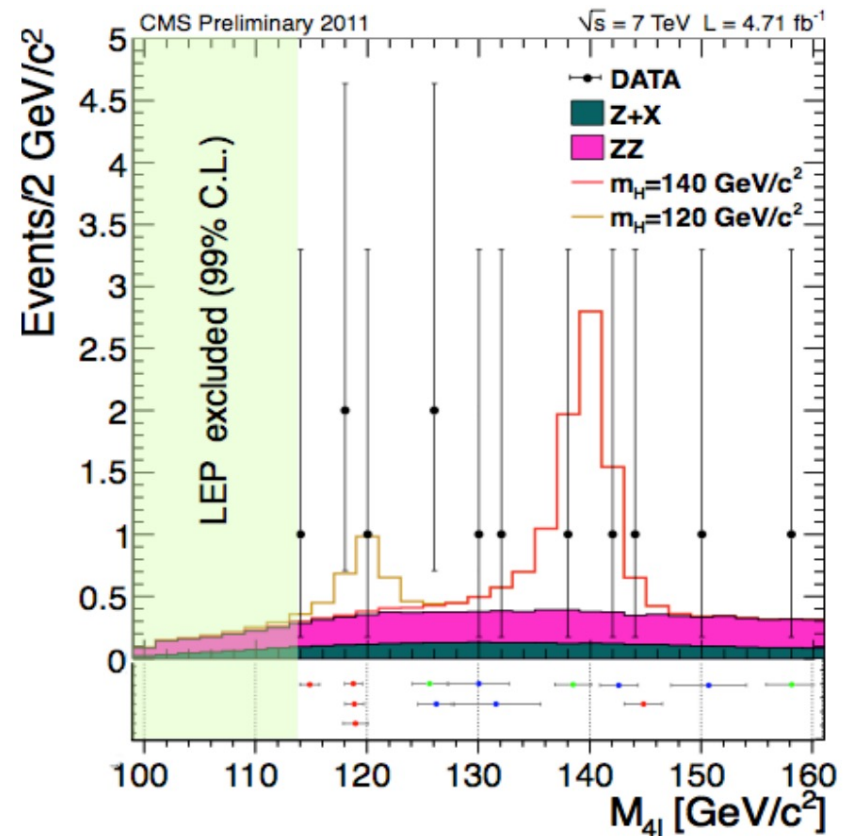
- December 2011 CERN Council meeting included  $H \rightarrow ZZ \rightarrow l\nu l\nu$  and  $H \rightarrow \gamma\gamma$  updated to include all 2011 data
  - Note WW relevance even with half the data



# CMS 2011 results

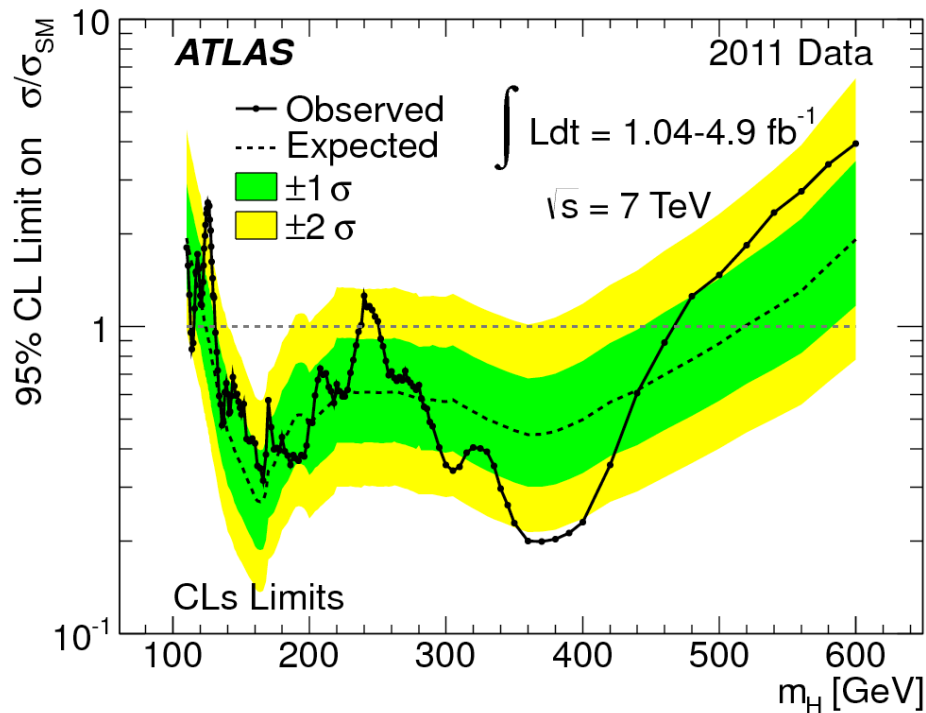


- All channels included but significance driven by  $\gamma\gamma$  and  $4l$



- The high-mass-resolution channels and (mildly) disagree on the mass  
 → *Based on a handful of events*
- Interesting but not yet convincing**

# ATLAS 2011 results

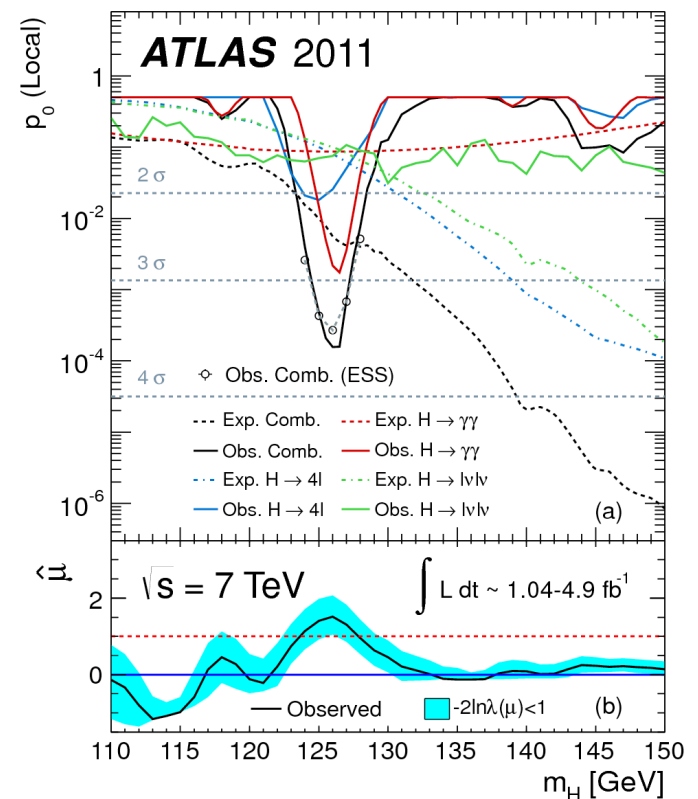


- Local significance at 126 GeV  $3.5\sigma$ , but  $\sim 1.4\%$  probability ( $2.2\sigma$ ) to see such a fluctuation in the background *somewhere*
- Exciting but ambiguous
- We see  $3\sigma$  fluctuations *all the time*

→ 750 GeV diphoton bump, anyone?

c. mills (UIC+FNAL)

- Combine data in multiple channels (bosonic only)
  - $\gamma\gamma$ ,  $WW$  ( $lvlv$ ,  $lvjj$ ),  $ZZ$  ( $4l$ ,  $llvv$ ,  $lljj$ )



# Blinding to see clearly

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- Full disclosure: I was rooting against the SM Higgs
- The physics message was ambiguous
- **I worried that we could continue to see *nothing* in the WW channel and that no one would believe us in the excitement of the discovery rush**
- Blind analysis was common on other experiments (notably BaBar), but not common practice at the Tevatron or the LHC
  - *Tended to be reserved for precision measurements, needed a well-defined signal and usually associated with a mass window*
- I proposed that we blind the HWW analysis and suggested how we do it.



# Blinding the Analysis

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- Design requirements:
  - $S/B < 2\%$  at all times
  - Leave control regions intact
- Not possible to blind WW analysis for all  $m_H$ 
  - Judgement call: what we really care about is the low  $m_H$  signal region
- How to define the signal region?
  - $\Delta\phi(\ell\ell)$  and  $m(\ell\ell)$  cuts
  - Transverse mass bound corresponding to lower bound for 110 and upper bound for 140 → veto  $(0.75)(110) < m_T < (1.0)(140)$

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**Blinded Region**

**$82.5 < M_T < 140$**

and

$\Delta\phi(\ell\ell) < 1.8$

and

$m_{\ell\ell} < 50$

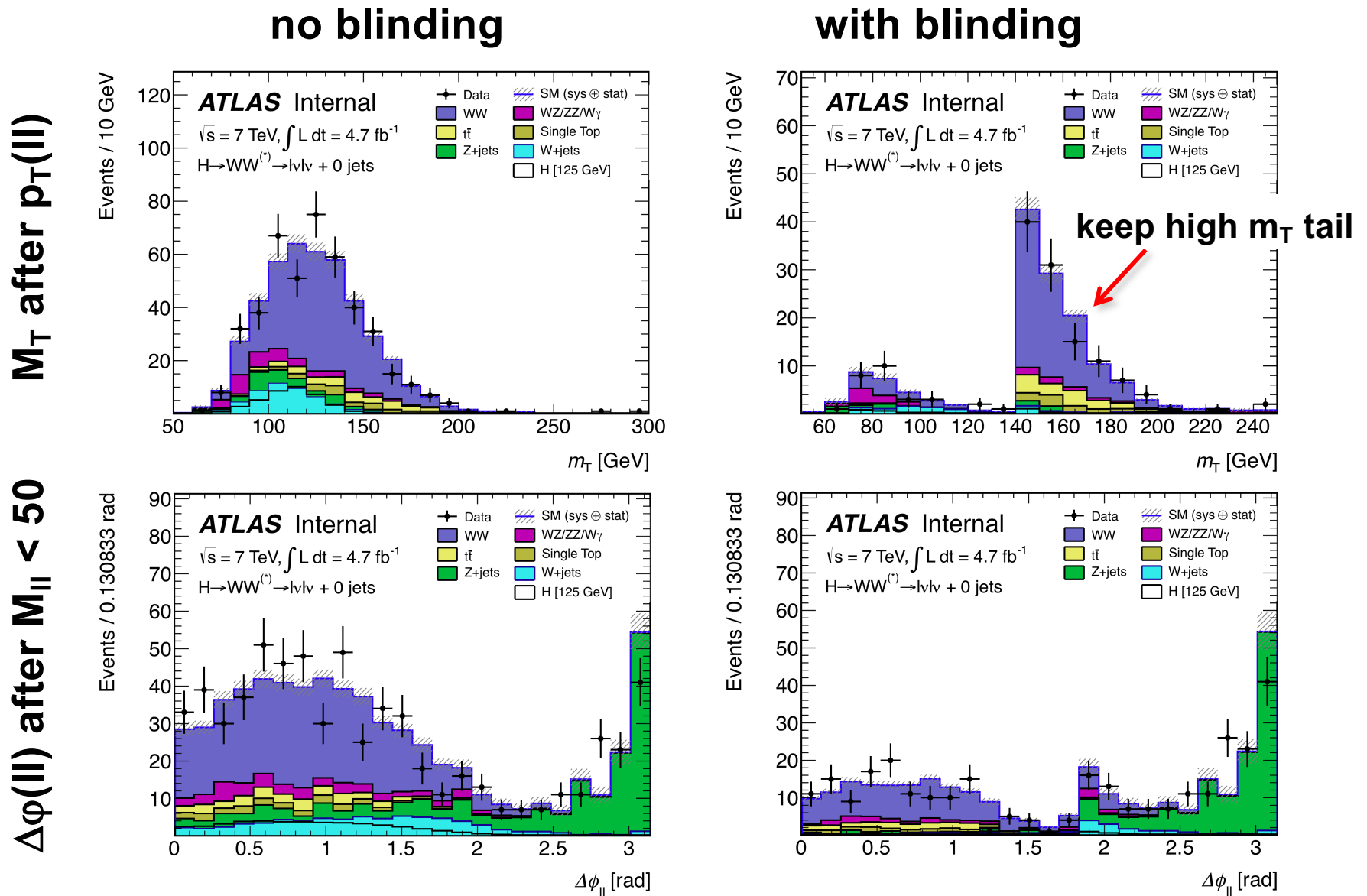
and

0 jets or 0 b-tags

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# Effect of Blinding (2011 H + 0 jet)



Old internal plots for illustration only



Legendary **workshop** in **Ischia, Italy** in  
March 2012

Review of every aspect of the analysis,  
lessons learned from 2011

Lots of ... informal discussion

Emerged with a plan



photo B. Di Micco



# The Challenge

- Many things had become clear:
  - Stellar performance of LHC in 2011  $\Rightarrow$  could have  $5 \text{ fb}^{-1}$  by July/ICHEP
  - If the 2011 signals in  $\gamma\gamma$ , ZZ  $\rightarrow$  4l data are both real, we **will** see it in WW.
  - If the 4l signal is spurious, WW will stay consistent with BG-only hypothesis
  - Cost of integrated luminosity is instantaneous luminosity: MET resolution deteriorates

Text reads: “high-pileup data will be challenging to understand... limited time to adapt”



Lead analysis contact  
Pierre Savard

# The Strategy



HSG3 convener  
Jianming Qian

photo B. Di Micco

Produced 40-page document detailing selection, optimization, etc, for approval by EdBoard:

Not reviewed, for internal circulation only



## ATLAS NOTE

ATL-COM-PHYS-2012-555

June 6, 2012

Draft version 0.2



- 1 Plans for the Standard Model Higgs boson search in the  $H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$
- 2 decay channel in 2012

# “Success-oriented schedule”

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- We had a number of them. This one also turned out to not be true.

## Success-Oriented Schedule



- June 8 (today): Finalizing event selection (almost...)  
EdBoard meeting: event selections, theory and top backgrounds
- June 15: All critical MC samples available;  
EdBoard meeting: Z/DY backgrounds, W+jets background
- June 22: Unblinding decision;  
Discussion of data/MC agreements in control regions;  
All pre-unblinding supporting notes and draft CONF note ready
- June 25: follow up  
Discussion data/MC agreements in signal regions;  
Statistical interpretations, draft CONF note with unblinding results;
- June 27: CONF note  
Higgs group approval and collaboration circulation
- June 29/July 2: follow up discussions
- July 4: final signoff

courtesy Jianming Qian

# The reality of MC and data

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- Recall the plethora of data and MC required to model all the backgrounds
- **MC samples were major bottleneck for HWW**
  - *Priority behind  $H \rightarrow 4\ell$  -- understandable, but had a cost*
  - *My 18 June notes indicate a number of samples “still missing”;  $t$ -channel single top “buggy”*
- **The 2012 data had higher pileup**
  - *I have a lot of notes about MET*
  - *Effects on lepton isolation (and therefore fakes), jet counting*
- Small surprises in background modeling due to filling in things
  - *Nothing major, but costs time*
- Pages of control region plots to check

# So many meetings

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- Daily meetings of the group during crunch time
- Detailed internal review of each background in mini-workshops  
→ *I have notebook entries titled “Top Background Showdown”*
- Essentially continuous interaction with the EdBoard  
→ *4 supporting notes,  $O(100)$  pages each IIRC*



photo R. Mackeprang

# Crunch time

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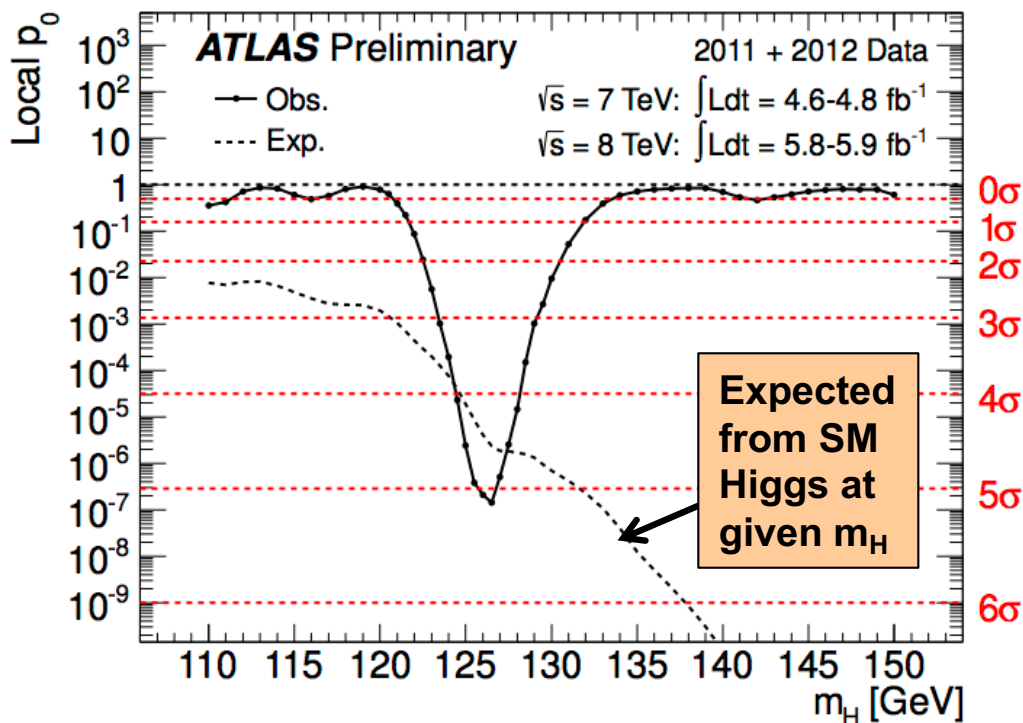
- 26 June: Standing-room-only in Salle Curie for ATLAS weekly
  - *First mention of July 31<sup>st</sup> submission of discovery paper in sync with CMS*
  - **WW has made “heroic” effort, but not to be shown at ICHEP**
  - *Discussion followed:*
    - at ICHEP but not in combination? No.
    - But CMS will have HWW → Fabiola: “Let’s not discuss rumors”
    - Fabiola stands firm that we have rules on analysis review that can be bent but not broken, **need time to understand “delicate” analysis**
    - My notes conclude with “F. answers her phone, which has been ringing on and off for ~30 minutes”
- 27 June: Blinded approval, full conference room in building 6. EVO problems. Daniel F [EdBoard Chair] supports unblinding. Heated technical discussion, followed by **decision to unblind**.
- Later that day: HSG3 daily meeting, “this one different than others”. Looking at the unblinded data distributions, signal region shows excess in the right region



# ATLAS July 4<sup>th</sup> results

- We unblinded before the seminar, but the results were not shown, only  $\gamma\gamma$  and ZZ (for 2012)

→ 7 TeV combination did include WW, tautau, bb



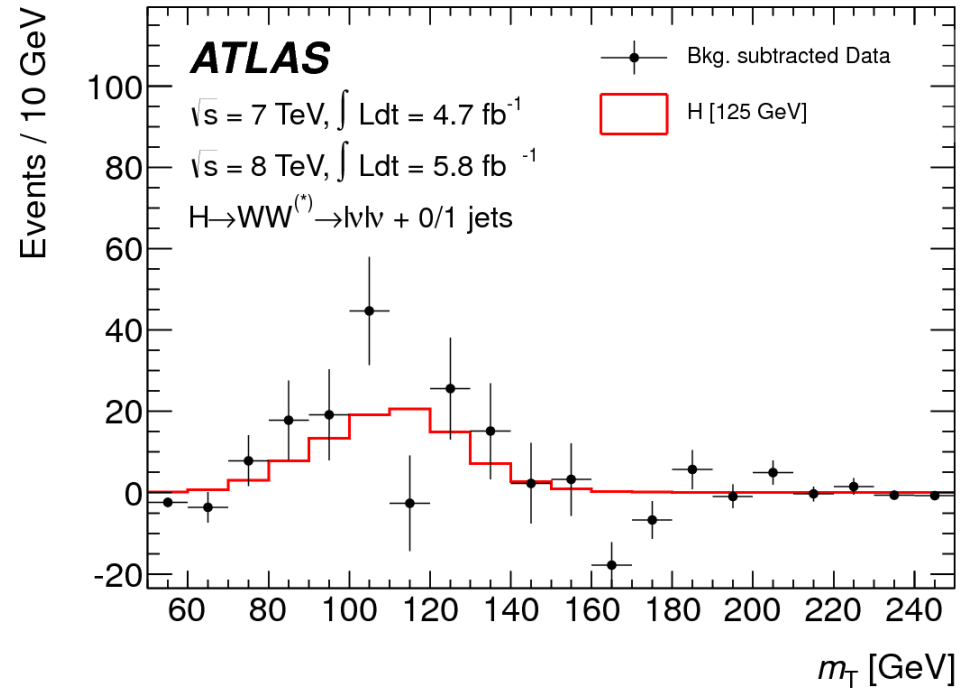
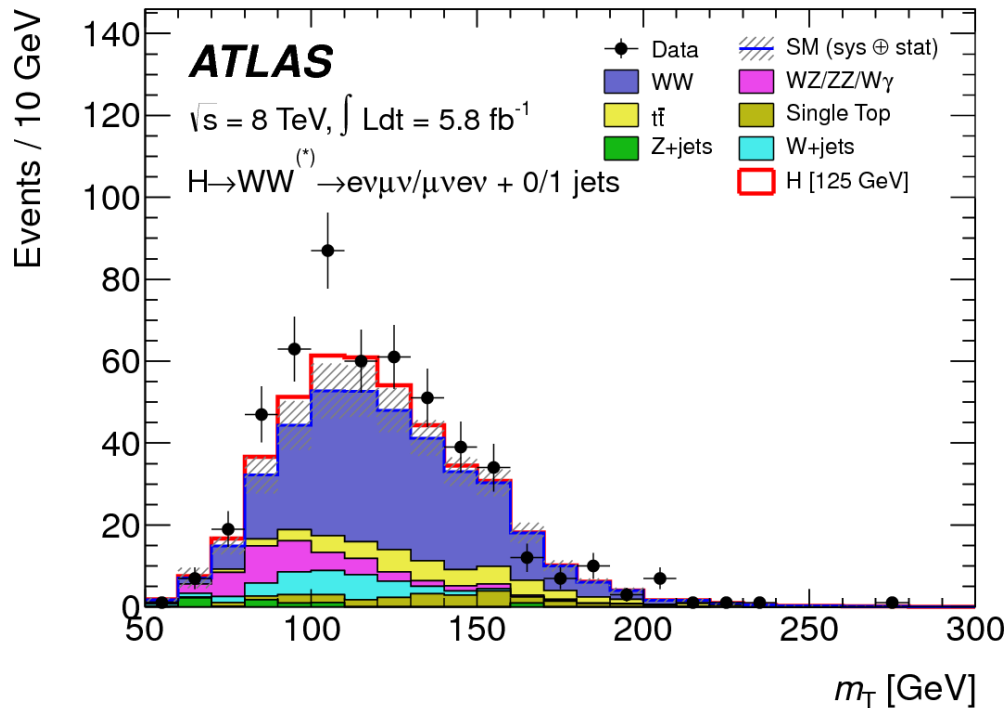
**Global significance**  
4.1-4.3 $\sigma$  depending on  
mass range considered

photo (c) CERN



# July 2012 HWW Results

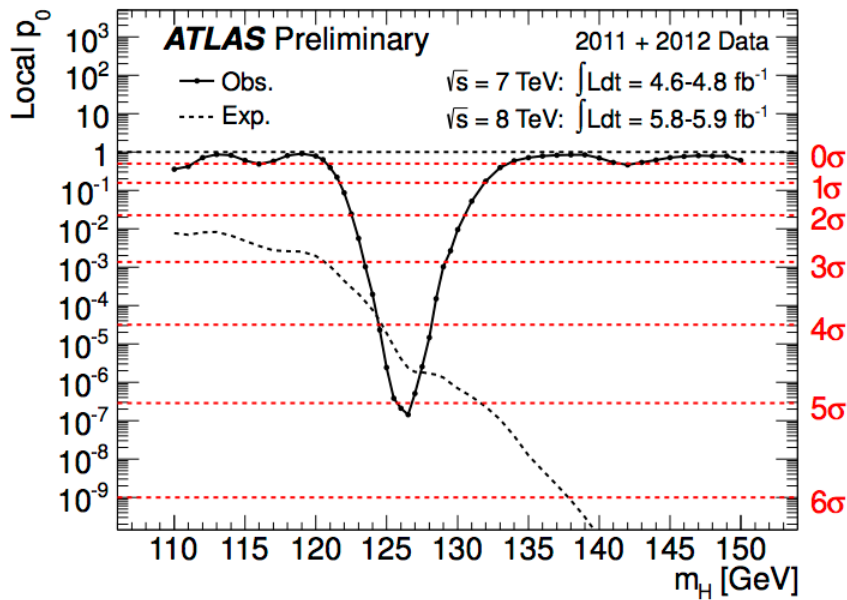
A few days (and many meetings later), we released a CONF note on July 18<sup>th</sup>, in time for Higgs Hunting:



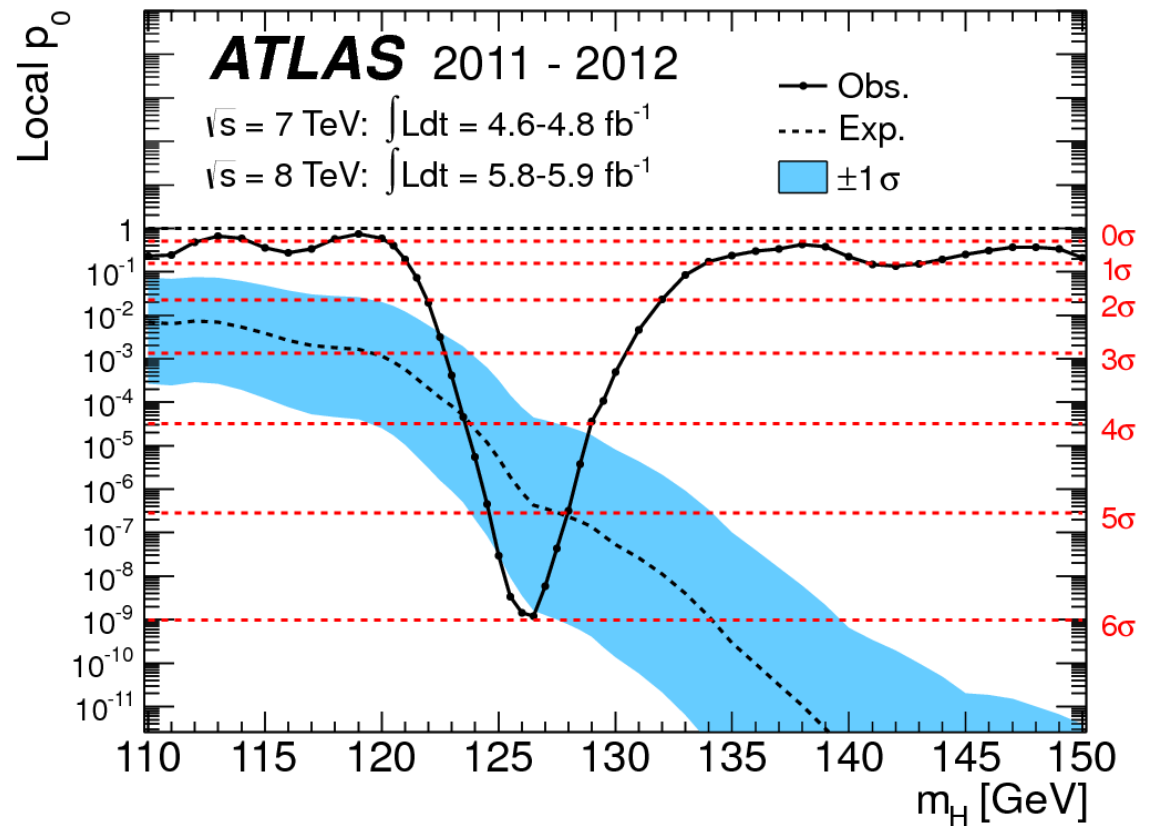
Combined 2011+2012  $p_0$ :  
 **$3 \times 10^{-3}$  ( $2.8\sigma$ ) observed,**  
 **$1 \times 10^{-2}$  ( $2.3\sigma$ ) expected**  
 (for  $m_H = 125 \text{ GeV}$  in both cases)

# July 2012 discovery paper

4 July 2012:  $5.0\sigma$

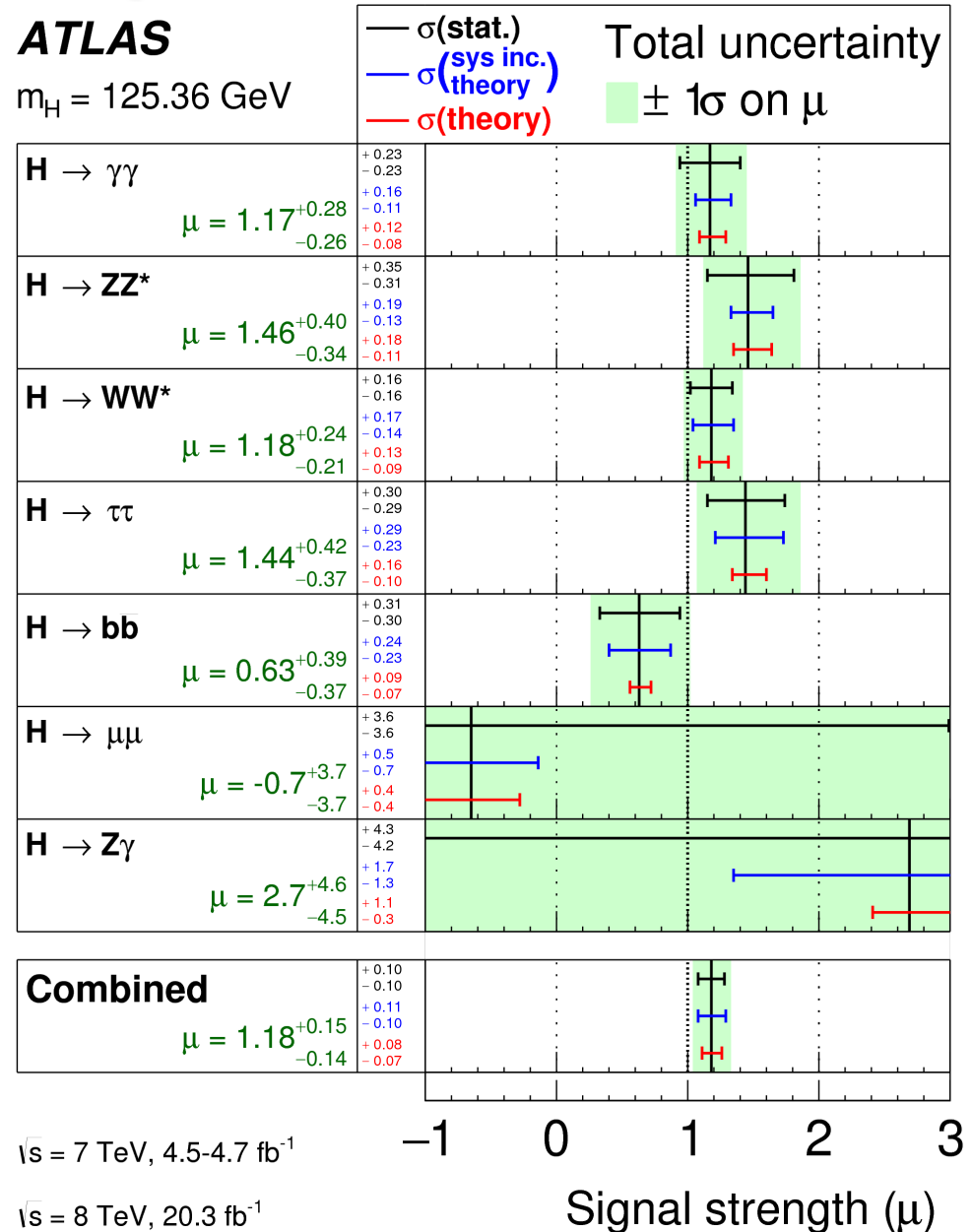


31 July 2012:  $5.9\sigma$



# Legacy

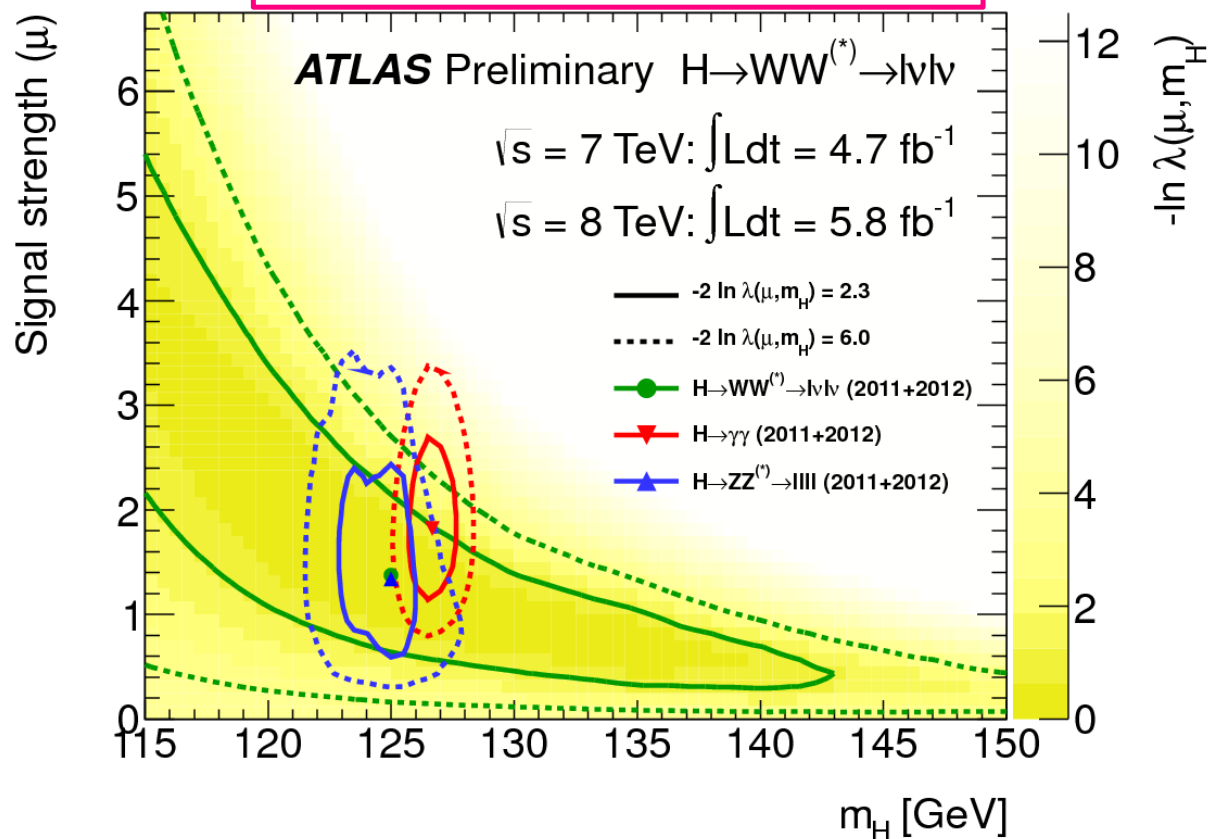
- Foundation of suite of measurements
  - *Couplings, CP properties...*
- Most precise measurement in final Run 1 combination (~20%)
- Increasing sophistication of fit, iterative interaction between analysis design and statistical interpretation
  - *More control regions*
  - *First (?) impact (“tornado”) plots*
  - *Appreciation of correlation between categories, reduction of impact of uncertainties through anticorrelations*
- Formative in careers
  - *Not just in academia: many of the postdocs and students left for careers in industry*



# Conclusions

- HWW powerful measurement of couplings
  - *Enormous challenge in data and MC modeling, each background an analysis in itself*
  - *Rigor of statistical treatment*
  - *Deep understanding of physics objects in changing conditions*
- Discovery relied on an incredible team, working cohesively
  - *Foundations built over decades*
  - *Privilege to be a part of it*

**The Famous Banana Plot**

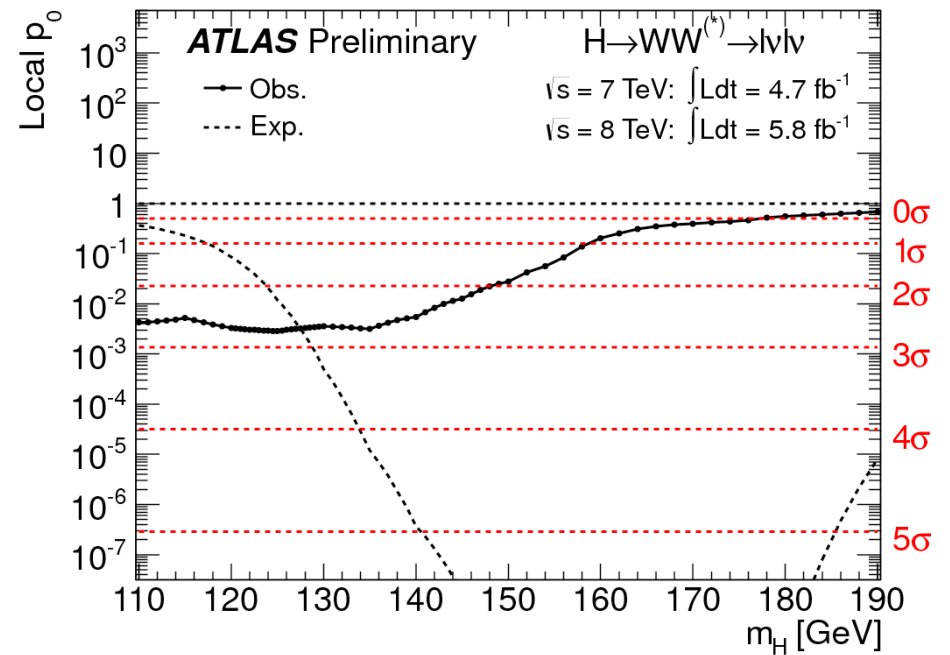
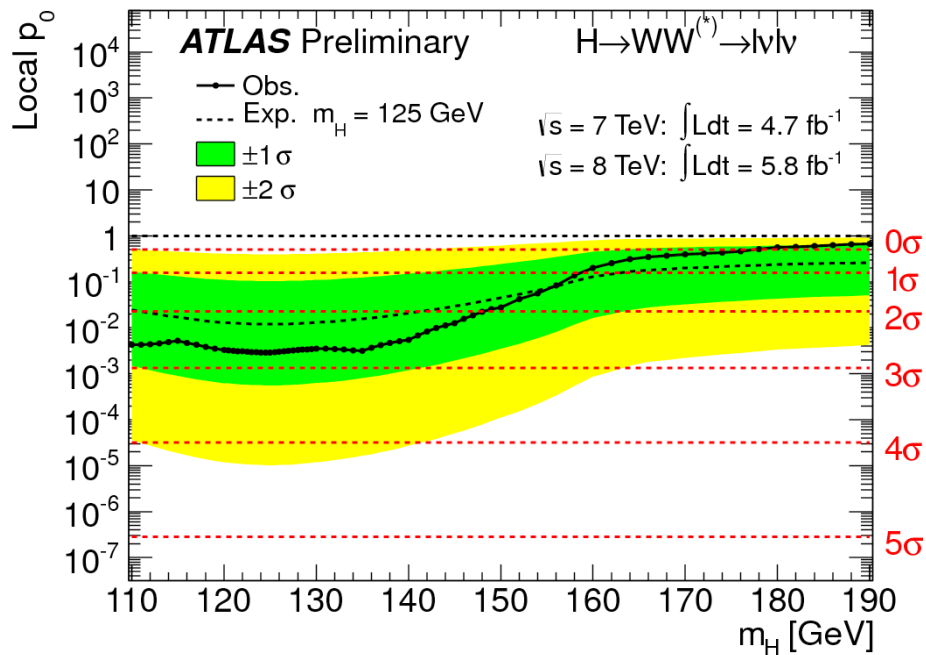




# Backup

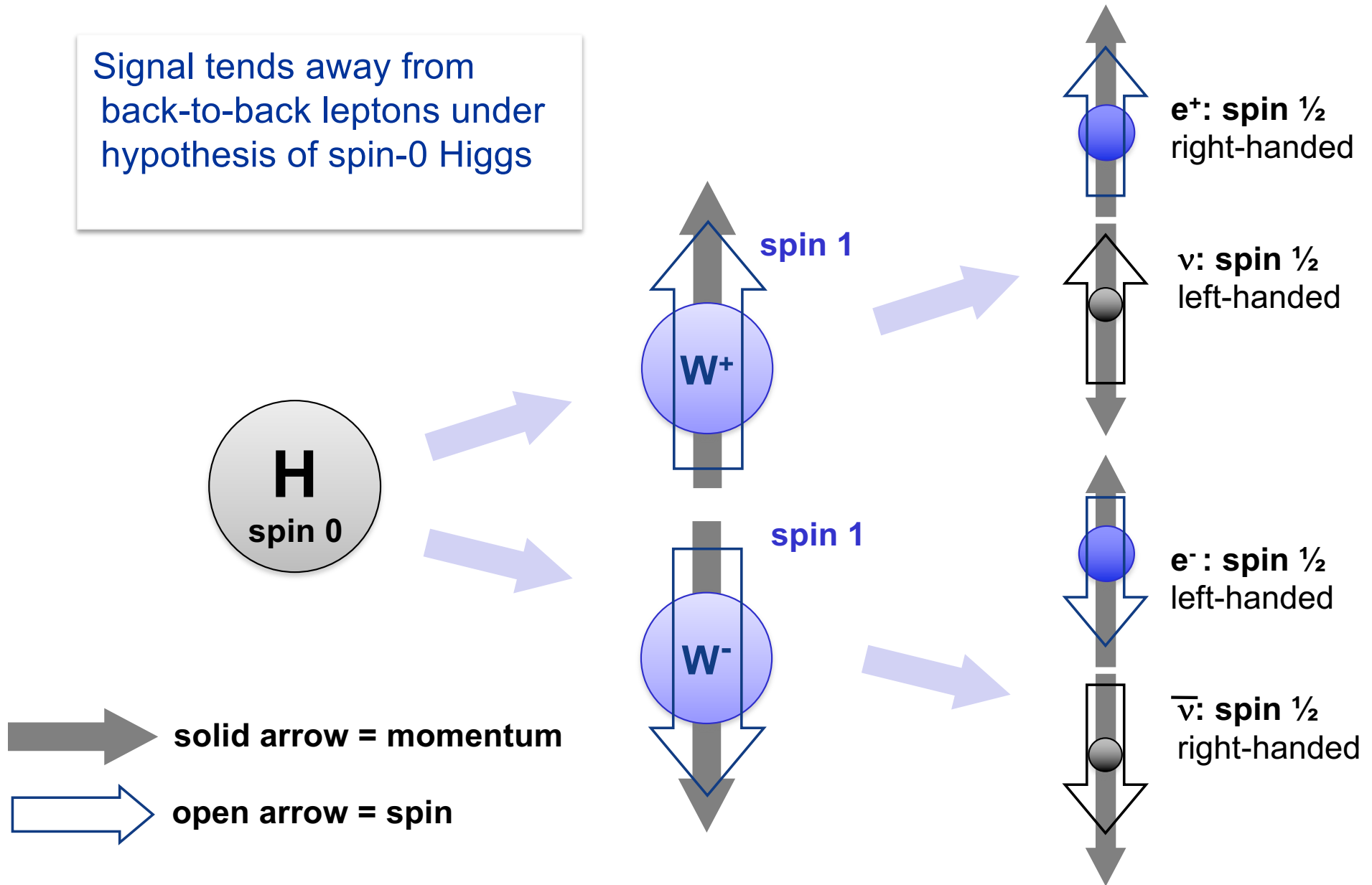


# July 2012 results



# Topological cuts $\Delta\phi(l), m_{ll}$

Signal tends away from back-to-back leptons under hypothesis of spin-0 Higgs





# Transverse mass

- Like invariant mass, but drop missing  $p_z$  information
- Canonical example: **W decay** to one  $e/\mu$  and one neutrino
- H to WW is a **four-body decay**

