$H \rightarrow WW \rightarrow l\nu l\nu$ at ATLAS

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(Chicago 2012 Workshop on LHC Physics in the Higgs Era)

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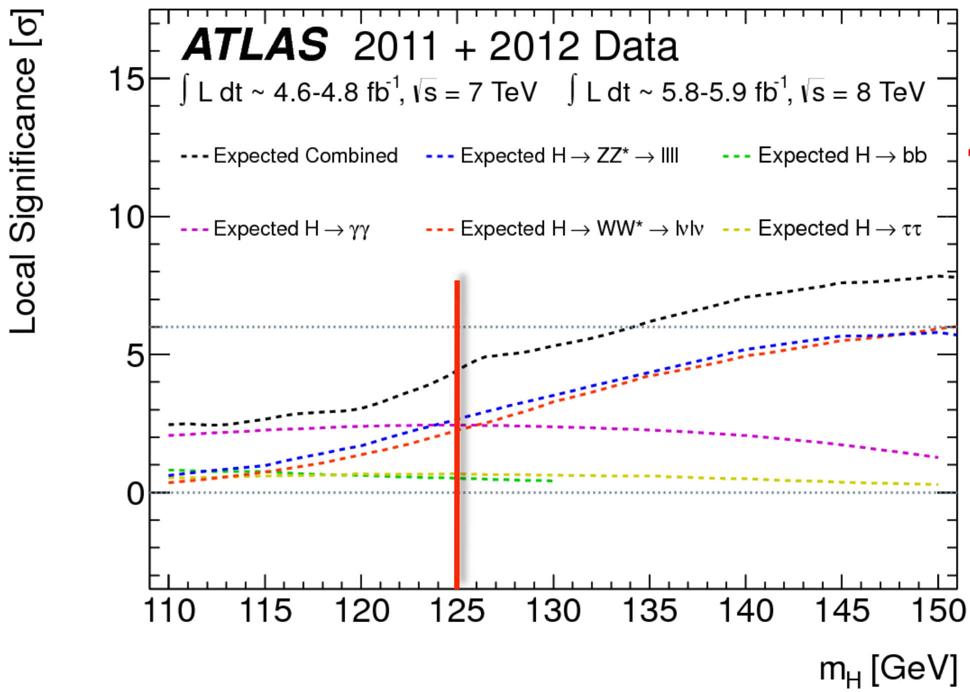
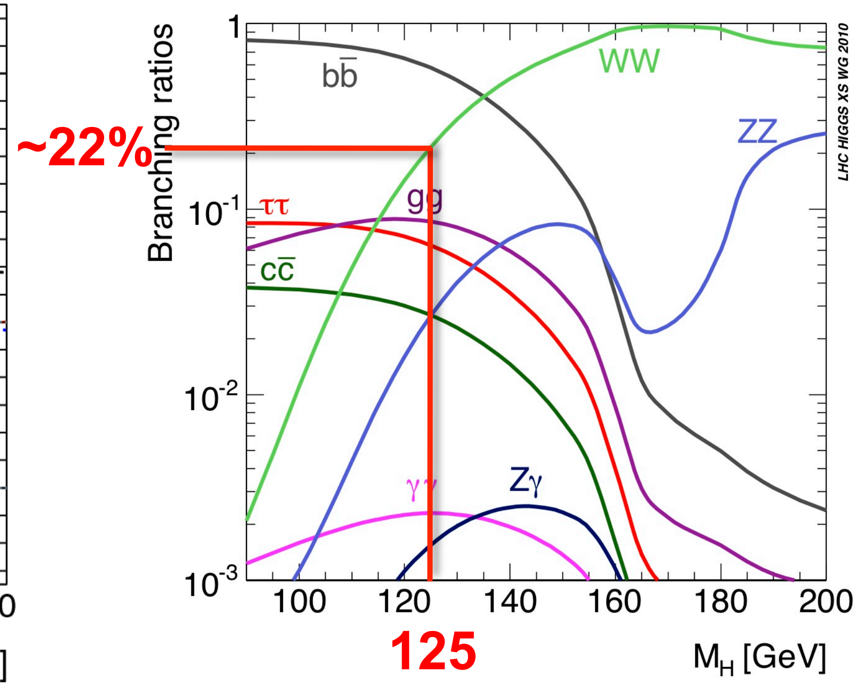
WW → lνlν in context

- The payoff: better signal/background than γγ and more signal yield than ZZ → 4l for m_H ~ 125 GeV
  - → *Important channel for rate ($\mu = \sigma/\sigma_{SM}$) measurement*
- The price: one W off mass shell (no mass resolution), still large backgrounds



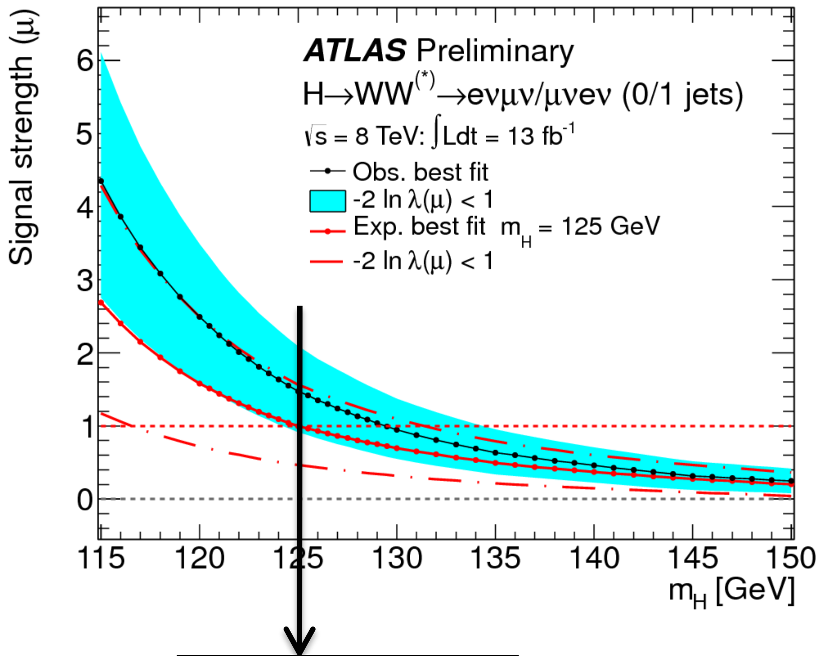


Overview

- We have updated the 2012 $H \rightarrow WW \rightarrow e\nu\mu\nu$ analysis with 13 fb^{-1} of sqrt(s) = 8 TeV data
- Followed strategy used for July analysis
  - → *Still using $e\mu$ only*
  - → *VBF (2-jet analysis) re-optimization and 2011 combination still in progress*
- Rather than going linearly through selection, backgrounds, systematics, and results, skip around a bit to highlight the connections

The Punchline

$13\ fb^{-1}$ Results



$\mu = 1.5 \pm 0.6$

- or, in more detail -

uncertainty on signal and background yields by source:

Source (0-jet)	Signal (%)	Bkg. (%)
Inclusive ggF signal ren./fact. scale	13	-
1-jet incl. ggF signal ren./fact. scale	10	-
PDF model (signal only)	8	-
QCD scale (acceptance)	4	-
Jet energy scale and resolution	4	2
W+jets fake factor	-	5
WW theoretical model	-	5
Source (1-jet)	**Signal (%)**	**Bkg. (%)**
1-jet incl. ggF signal ren./fact. scale	26	-
2-jet incl. ggF signal ren./fact. scale	15	-
Parton shower/ U.E. model (signal only)	10	-
b-tagging efficiency	-	11
PDF model (signal only)	7	-
QCD scale (acceptance)	4	2
Jet energy scale and resolution	1	3
W+jets fake factor	-	5
WW theoretical model	-	3

$$\mu = 1.48^{+0.35}_{-0.33}\,(\text{stat})^{+0.41}_{-0.36}\,(\text{sys theor})\,^{+0.28}_{-0.27}\,(\text{sys exp}) \pm 0.05\,(\text{lumi})$$

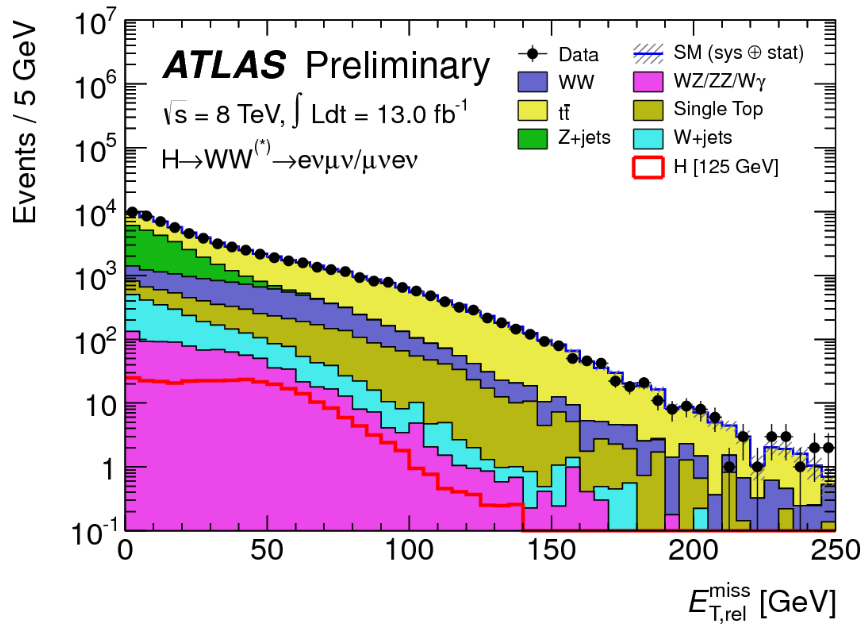
The Basics

Basics 1/3: Dilepton + E_T^{miss}

- 2 oppositely charged leptons (e or μ)
  - → *Electrons selected using tightest ID: calo shower shape, track match, conversion rejection*
  - → *Muons selected as combined ID and MS track (incl. d_0 signif.)*
  - → ***isolated*** *(track and calo for both, cone of 0.3)*
  - → ***p_T(lead) > 25 GeV, p_T(sublead) > 15 GeV***
  - → *m(ll) > 10 GeV*

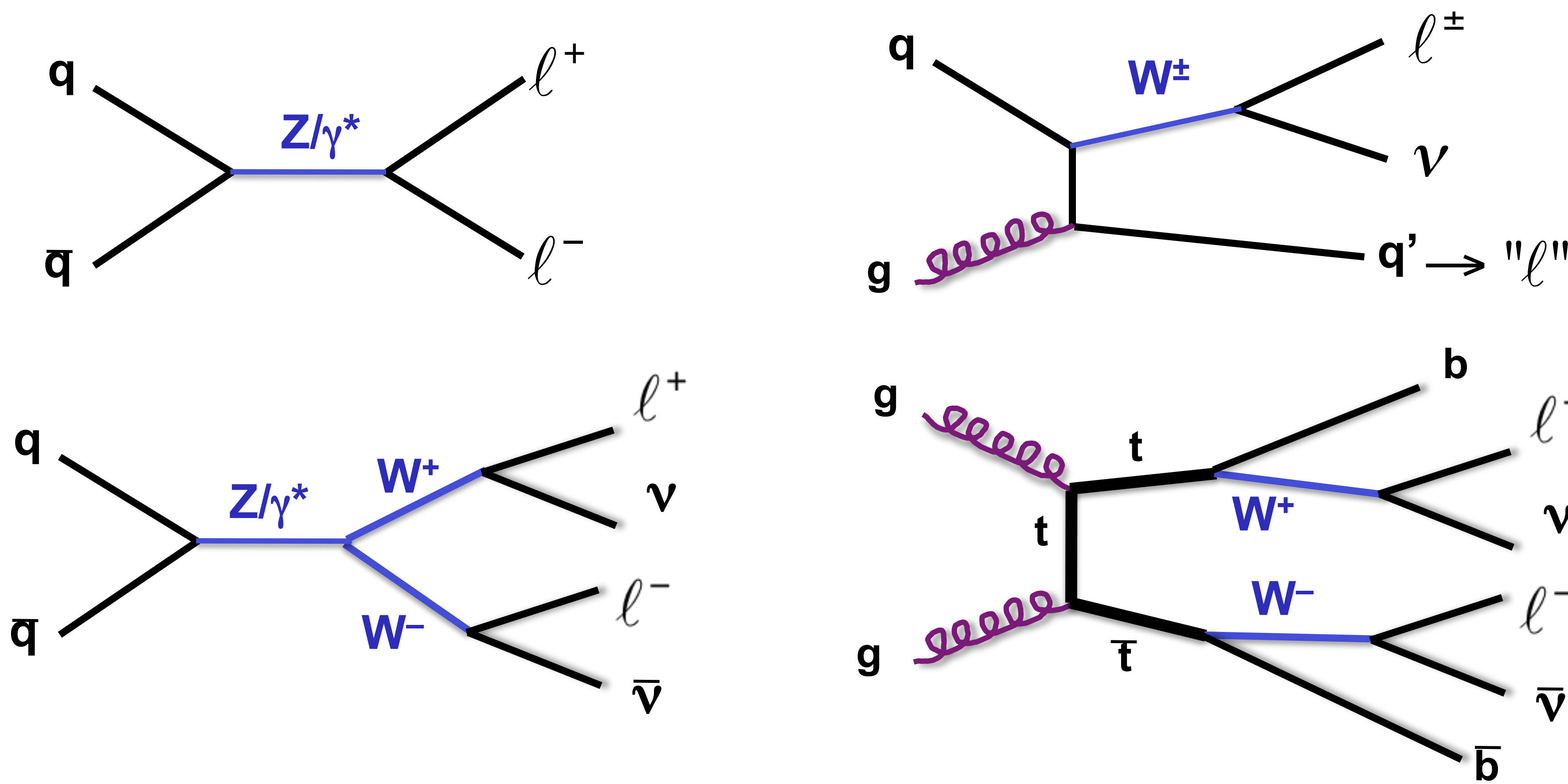
- **$E_T^{(miss,rel)}$ > 25 GeV**

- Jets: anti-k_T 0.4 (analysis binned in N_{jet})
  - → *p_T > 25 GeV (p_T > 30 GeV for |η| > 2.5)*



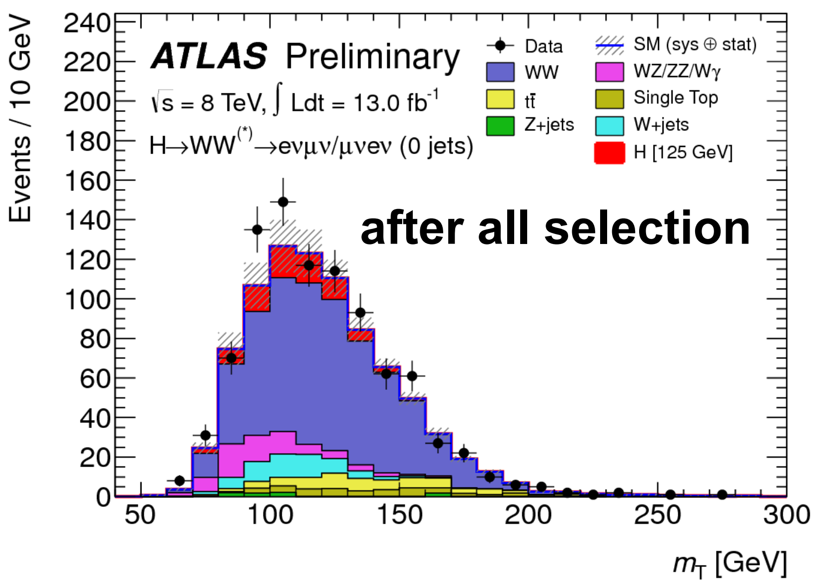
Basics 2/3: Backgrounds

What do you get when you select dilepton events with E_T^{miss}?



Basics 3/3: Statistical Interpretation

- Profile log likelihood $\mathcal{L}(\mu,\theta)$ for statistical interpretation
  - → *Fit for free parameter* **signal strength μ** = *ratio of observed signal yield to SM Higgs prediction*
  - → *Systematic uncertainties represented by* **nuisance parameters *θ***
- Not true cut-and-count: fit dilepton m_T distribution
- Evaluate p_0 using test statistic $q_\mu = -2\ln\left(\mathcal{L}(\mu,\hat{\hat{\theta}}_\mu)/\mathcal{L}(\hat{\mu},\hat{\theta})\right)$

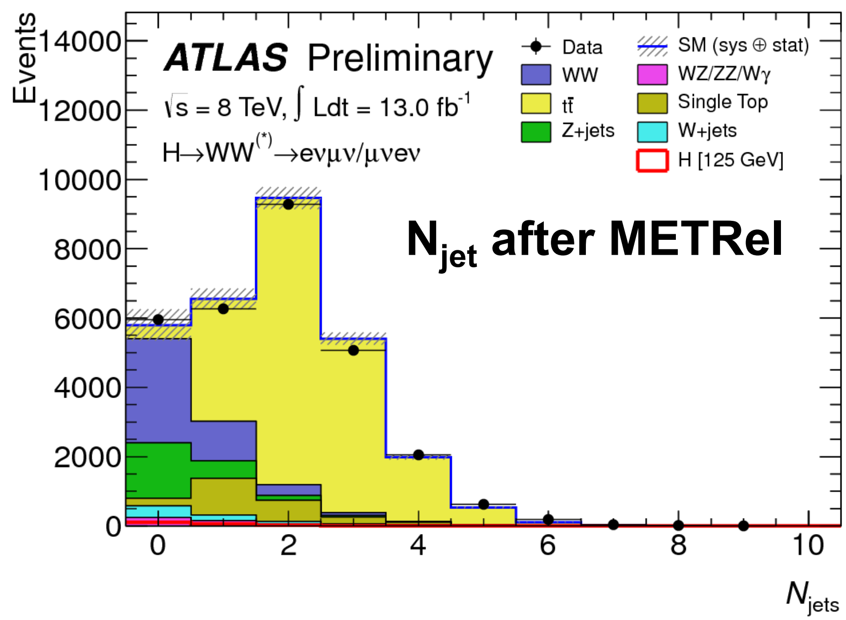


$$m_T^2 = (E_T^{\ell\ell} + E_T^{\rm miss})^2 - (\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{\rm miss})^2$$

The Details

Jet binning

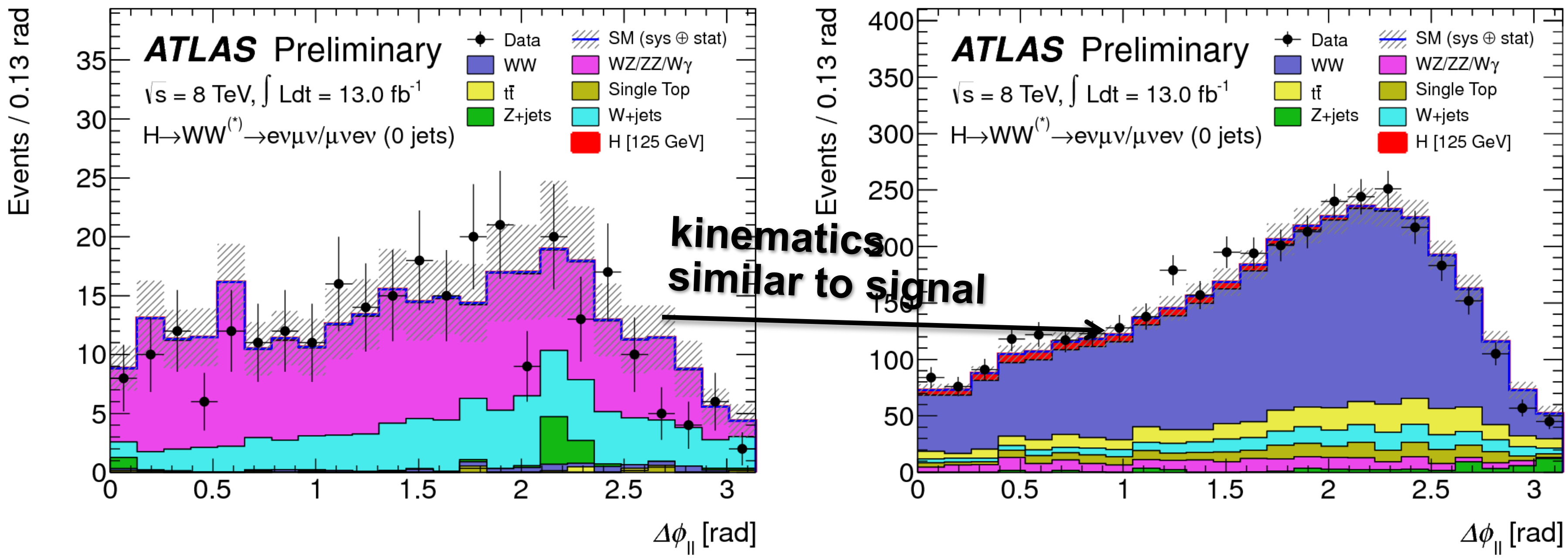
- ggF signal mostly has zero jets
- Reject dominant top BG, for a price (systematics)
  - → *experimental: **jet energy scale and resolution** (4% on 0-jet signal yield)*
  - → *theoretical: **QCD scale uncert. of 17% and 30%** on 0-jet and 1-jet total signal yield (partially anti-correlated; evaluated using Stewart-Tackmann prescription)*



- Jets: anti-k_T 0.4
  - → *$p_T > 25$ GeV ($p_T > 30$ GeV for $|\eta| > 2.5$)*
  - → *$|\eta| < 4.5$*
  - → *associate to primary vertex using tracks*

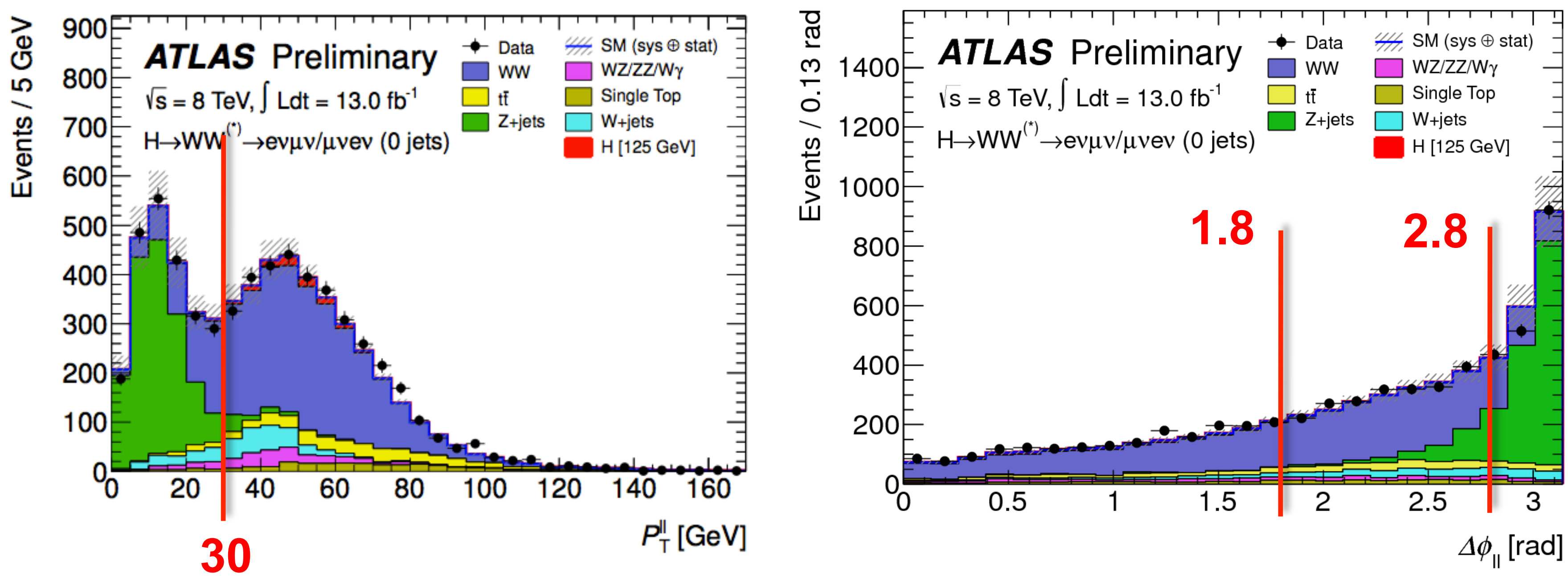
W+X

- **W+jets: "fake factor"** (ratio of identified to anti-identified leptons in a QCD-enriched sample) multiplied by W+denominator distribution
  - → *50% err. on fake factor (sample dependence, EWK subtraction, pileup, trigger bias)*
  - → *5% uncertainty on total BG yield 0, 1 jet bin: compare 8%, 16% total!*
  - → *Motivation for rather extreme isolation cuts*
- Wγ, Wγ* not insignificant, estimate from Monte Carlo (MadGraph)
- Validate in same-charge events (below: after METRel, jet veto, $p_T(ll)$)



$p_T(ll)$ and $Z \rightarrow \tau\tau$

distributions after jet veto



- Most Z/γ* background in eμ is from ττ
  - → *0 jet: reject by requiring $p_T(ll) > 30$ GeV*
  - → *1 jet: reject by veto on M(ττ), reconstructed using collinear approx.*
- Normalize remaining BG using data with m(ll) < 80, Δφ(ll) > 2.8

1-jet analysis: top and the b-veto

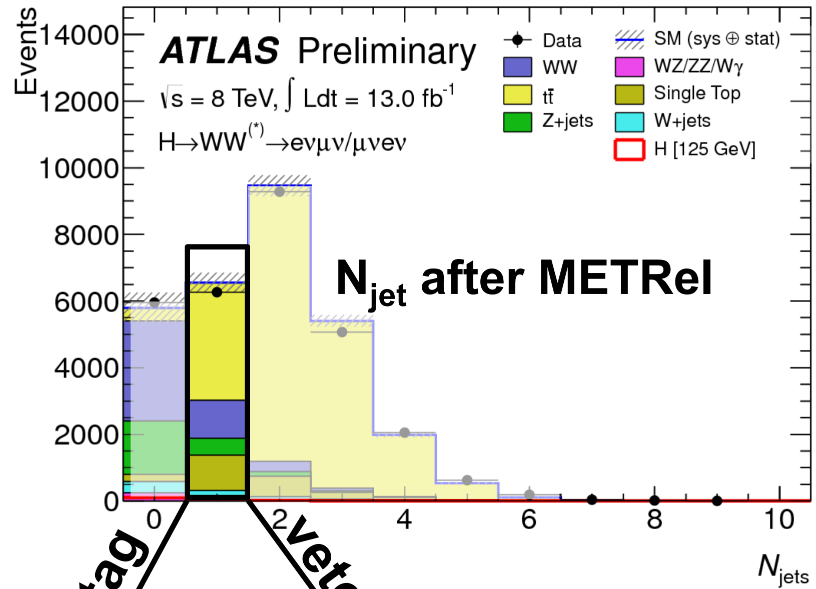
Veto b-tagged jets for signal region

- → *85% b-jet efficiency operating point ⇒ aggressive veto, only 85% efficien for signal*
- → *Uncertainty on efficiency 5-18%*
- → *Largest BG in 1-jet SR, 44% of total*

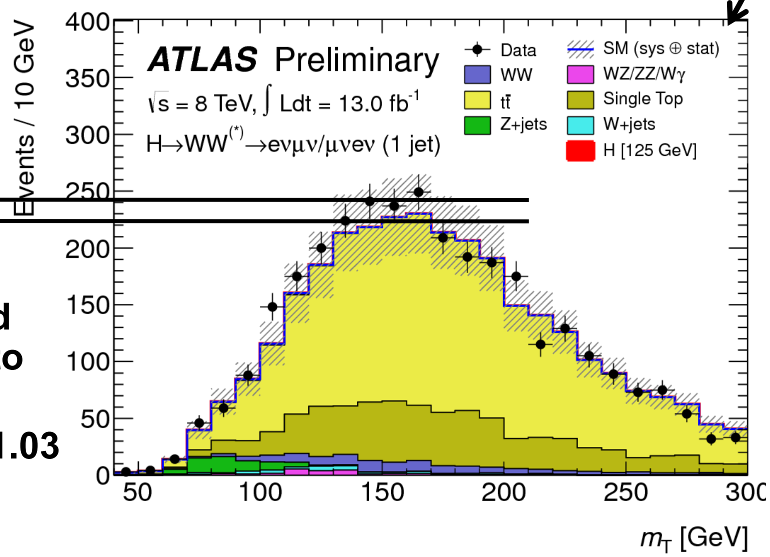
Tagged events form control region

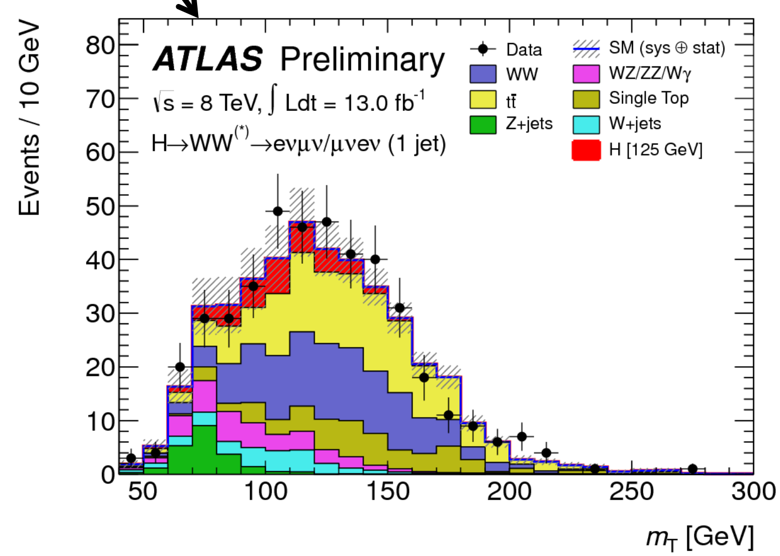
Total uncertainty on 1-jet top = 37%

b-tagging is leading systematic on 1-jet background yield, at 11%



normalize background prediction to CR data, scale by ~ 1.03

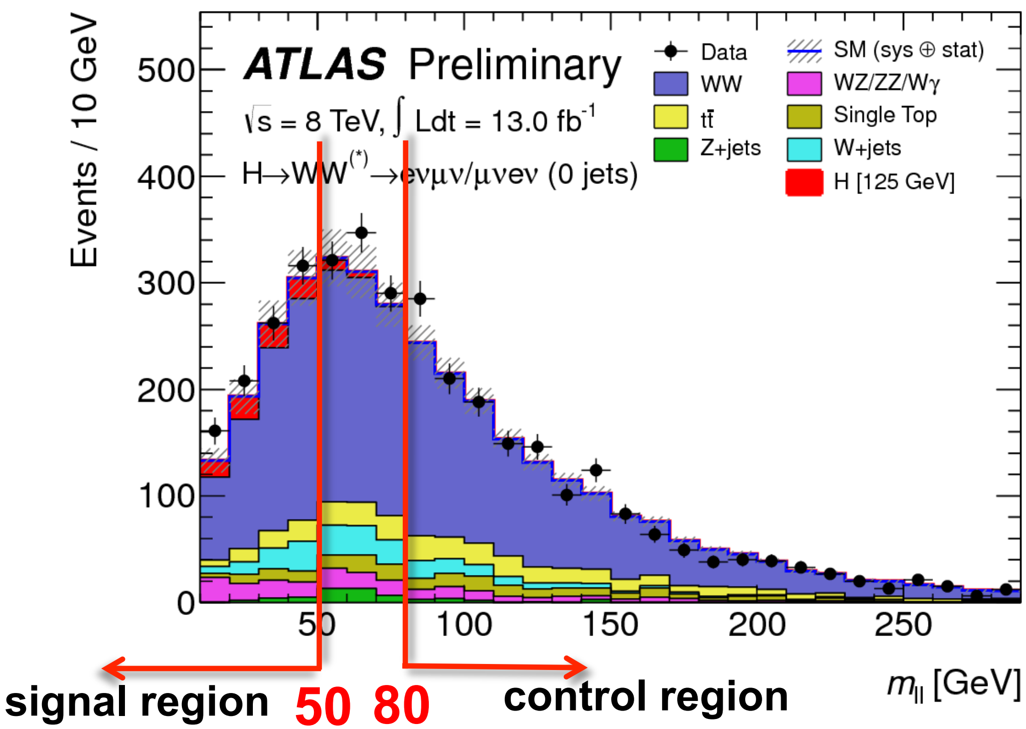




m(ll) and WW: control regions

- WW dominant background
- Reduce uncertainties by normalizing WW+{0,1} jet backgrounds to data in signal-depleted "control regions" CR

  → *Extrapolate in m(ll)*



uncertainties:
extrapolation
[experimental + theoretical]

$$N_{SR} = \left(\frac{N^{MC}_{SR}}{N^{MC}_{CR}}\right)\left(N^{\text{data}}_{CR} - N^{\text{other}}_{CR}\right)$$

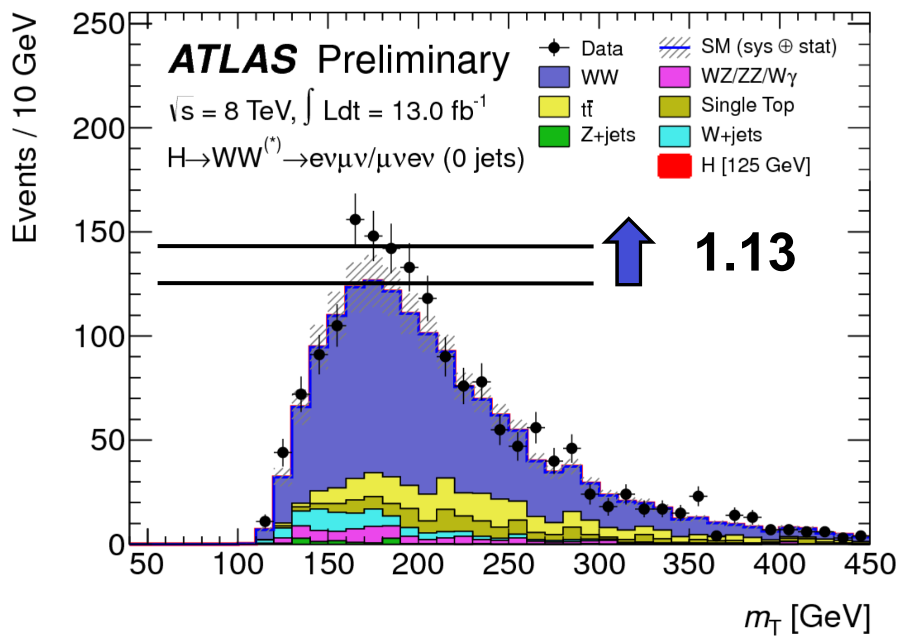
CR statistics

"background subtraction" or "crosstalk"

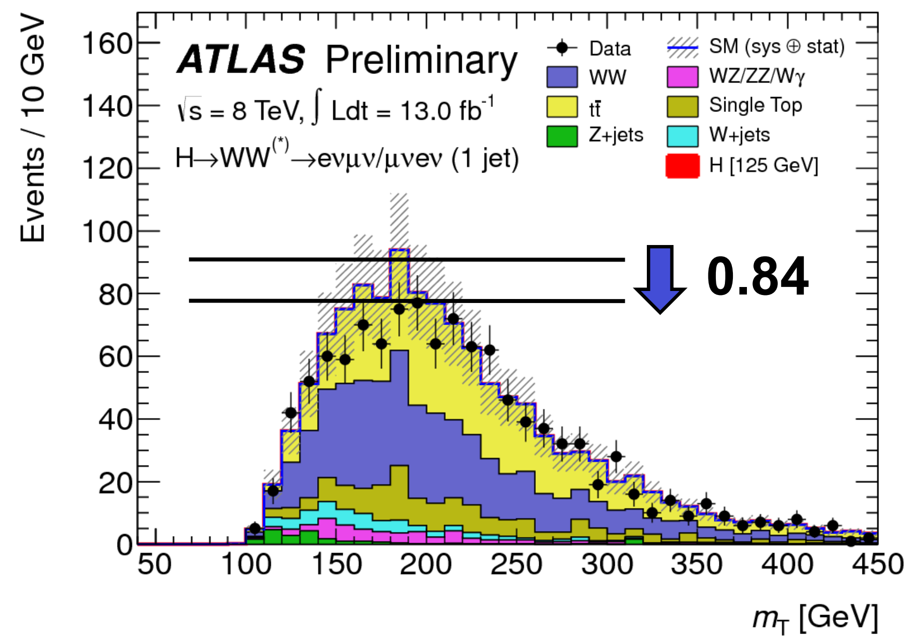
m(ll) and WW

- POWHEG+PYTHIA8 model for WW
  - → *better model of lepton kinematics than MC@NLO (ICHEP model)*
- Worse model of jet multiplicity, but correct for this by design

0-jet WW control region



1-jet WW control region

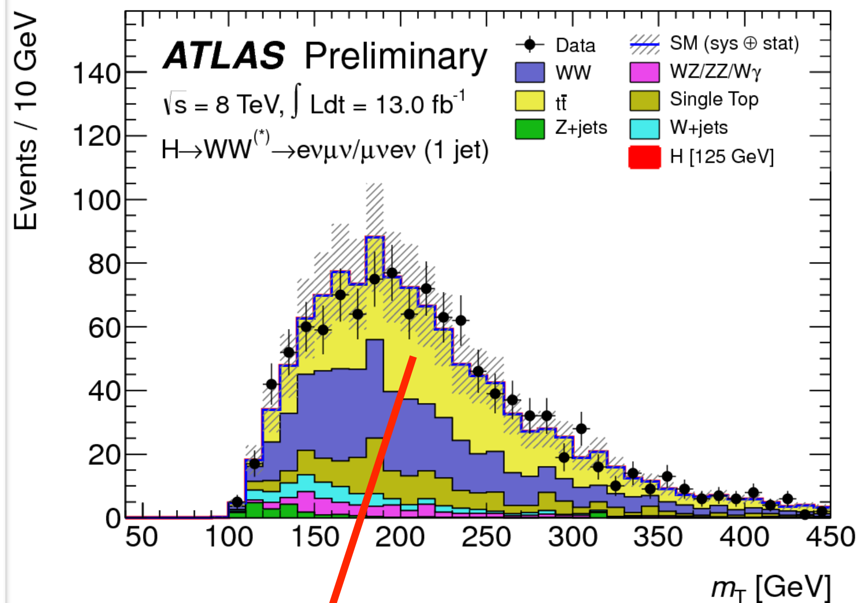


Systematics on WW + top

Theoretical uncertainties:

- QCD **scale** and **PDFs**, usual prescription
- **Parton shower and underlying event**: Pythia8 / Pythia6 / Herwig
- **Modelling and shape**: MC@NLO vs. MCFM
- shape syst. applied in fit

WW background extrapolation uncertainties				
	Scale	PDFs	PS/UE	Modelling
α_{WW}^{0j}	2.5%	3.7%	4.5%	3.5%
α_{WW}^{1j}	4%	2.9%	4.5%	3.5%



summary of uncertainties:

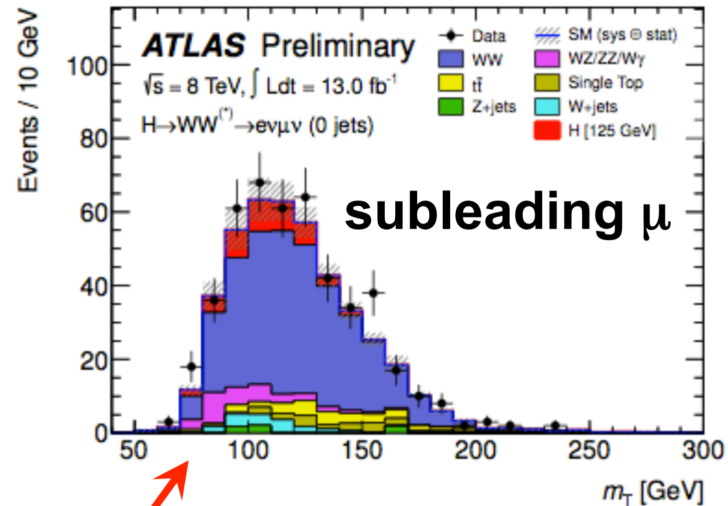
Background	Stat. (%)	Theory (%)	Expt. (%)	Crosstalk (%)	Total (%)
WW, $H+$ 0-jet	3.3	7.2	1.5	6.2	13
WW, $H+$ 1-jet	9	8	12	34	54
top, $H+$ 1-jet	2	8	29	1	37

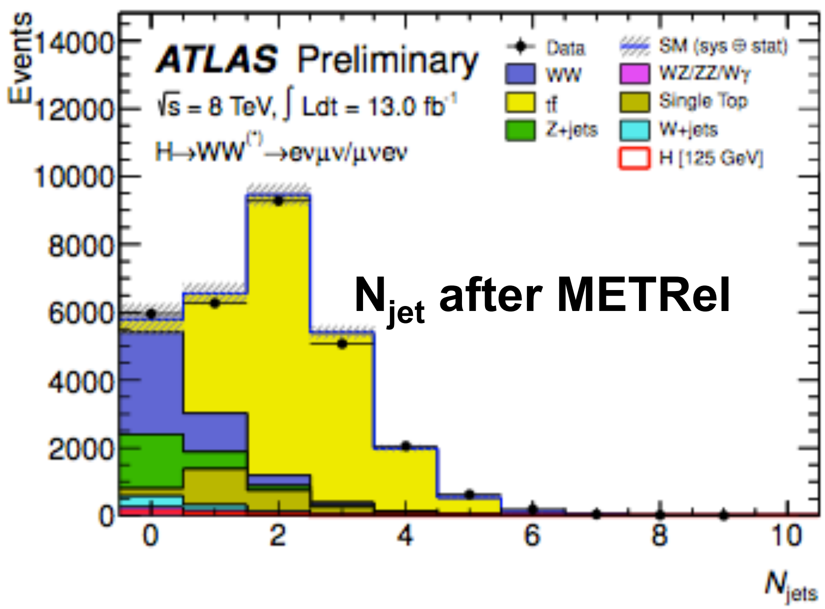
corelations correctly treated in fit: total 1-jet BG uncertainty is 16%

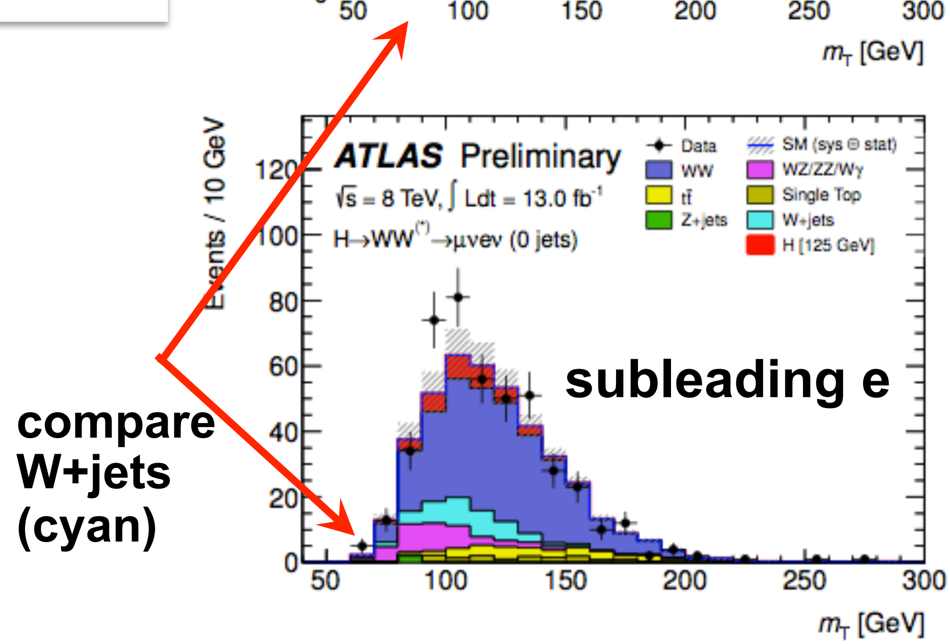
The Results

Signal region, in four parts

- Subdivide analysis to benefit from different S/B and background composition in different final states
  - → *By number of jets 0, 1, ≥ 2*
  - → *Into (eμ, μe) sub-channels where second lepton is subleading*







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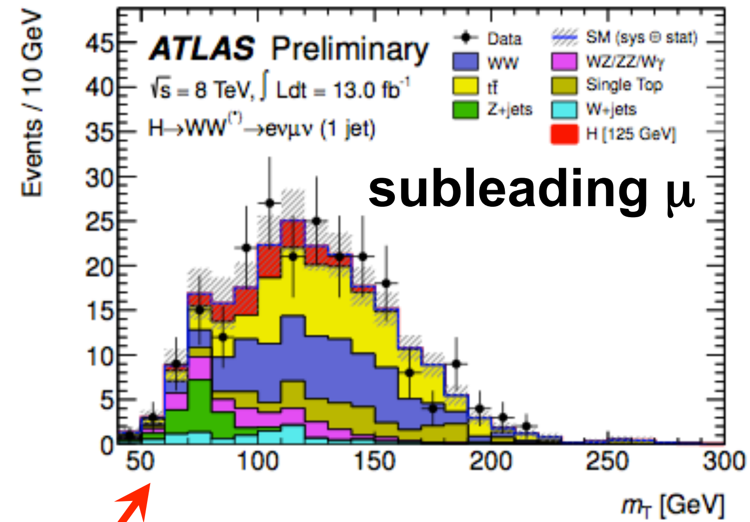
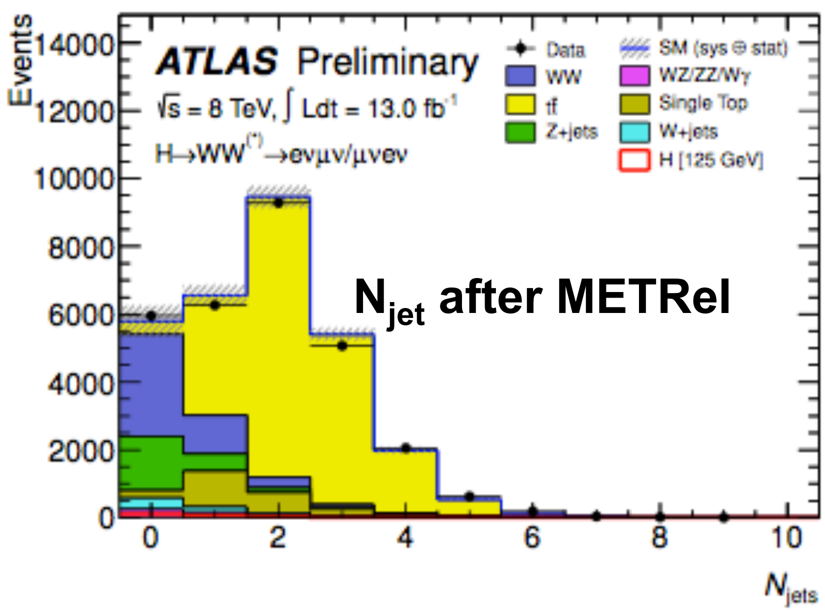
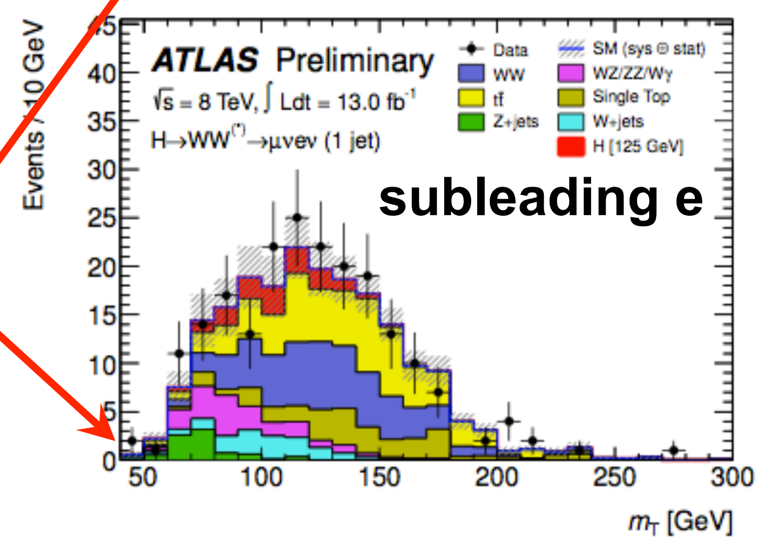
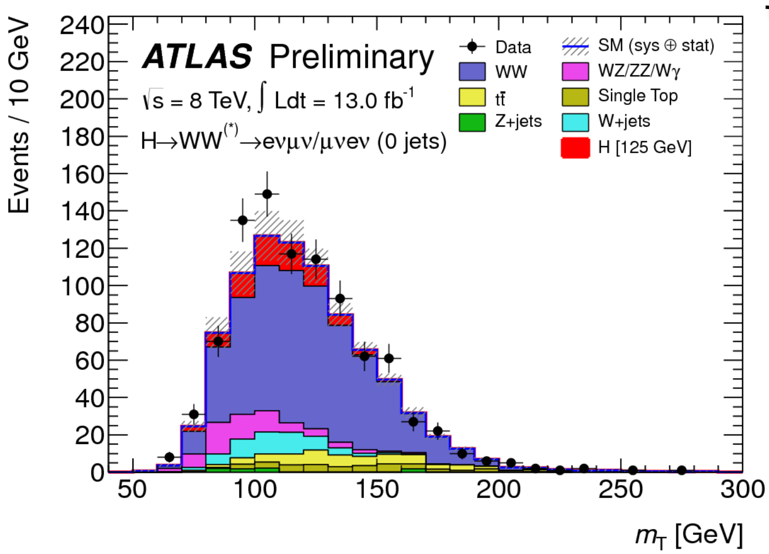


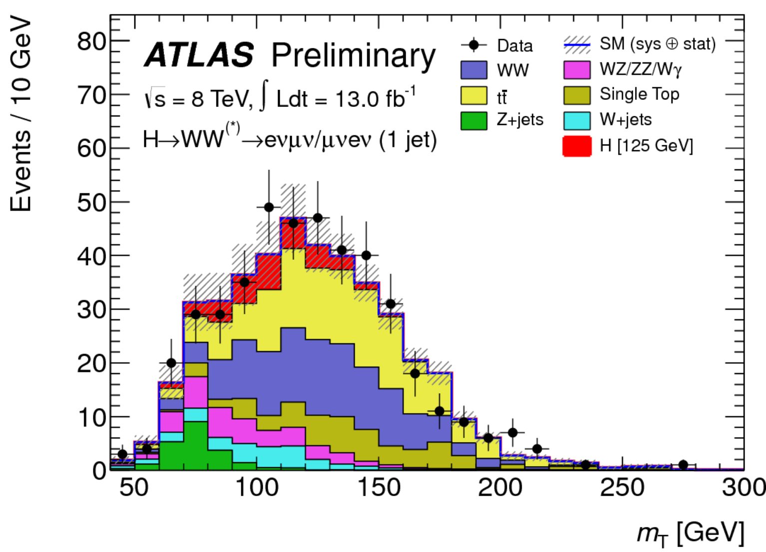


compare W+jets (cyan)

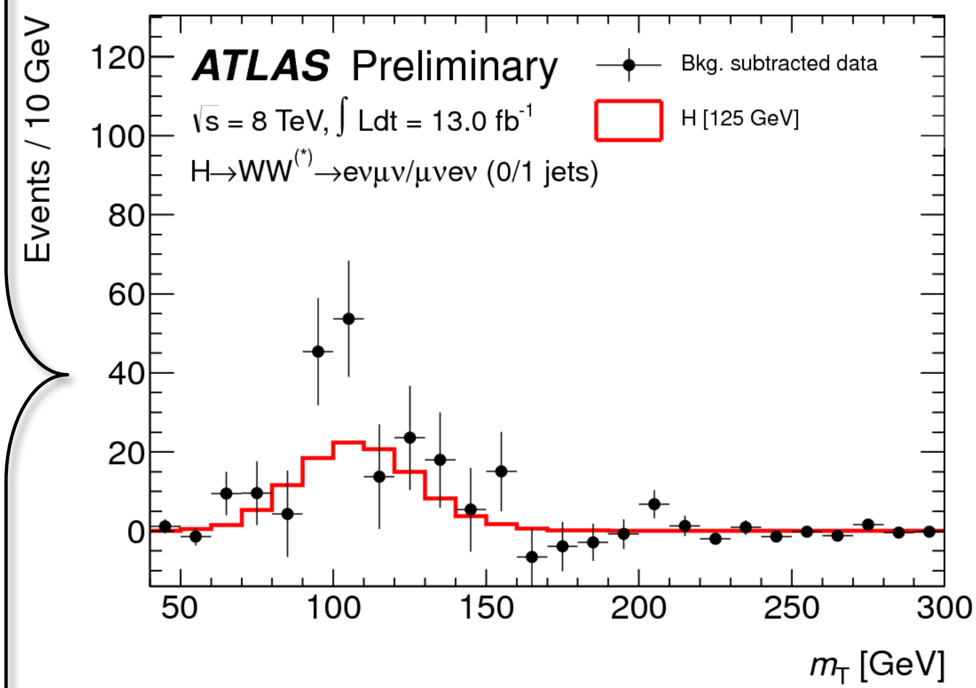


Observed m_T Distribution



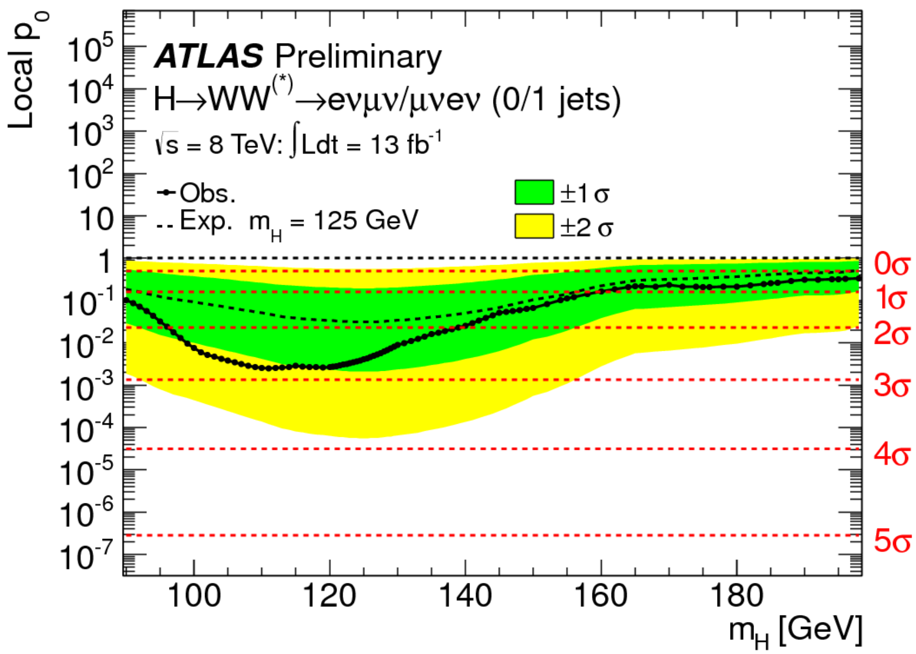


summed 0+1 jet background-subtracted data



The Bottom Line: p_0

	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	$Z/\gamma^* +$ jets	$W +$ jets	Total Bkg.	Obs.
$H+$ 0-jet	45 ± 9	242 ± 32	26 ± 4	16 ± 2	11 ± 2	4 ± 3	34 ± 17	334 ± 28	423
$H+$ 1-jet	18 ± 6	40 ± 22	10 ± 2	37 ± 13	13 ± 7	2 ± 1	11 ± 6	114 ± 18	141

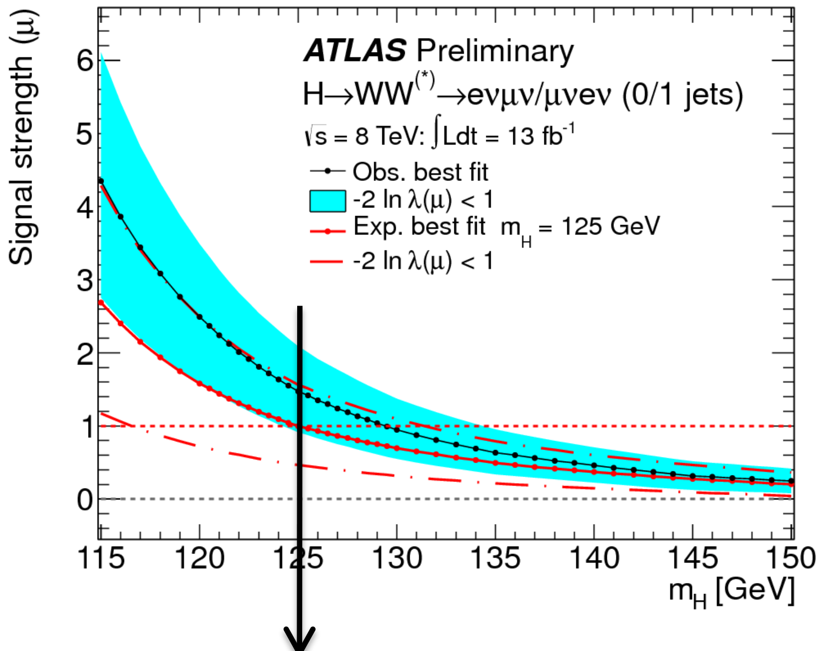


for m_H = 125 GeV:

- **observed p_0 = 4 x 10^{-3} (2.6σ)**
- expected p_0 = 3 x 10^{-2} (1.9σ)

(ICHEP values, 2012 only):
3.1σ observed, 1.6σ expected

Signal Strength and Systematics



$\mu = 1.5 \pm 0.6$

- or, in more detail -

uncertainty on signal and background yields by source:

Source (0-jet)	Signal (%)	Bkg. (%)
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Source (1-jet)	**Signal (%)**	**Bkg. (%)**
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Jet energy scale and resolution	1	3
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$$\mu = 1.48^{+0.35}_{-0.33}\,(\text{stat})^{+0.41}_{-0.36}\,(\text{sys theor})\,^{+0.28}_{-0.27}\,(\text{sys exp}) \pm 0.05\,(\text{lumi})$$

Summary

- Update of July 2012 analysis consolidates evidence for a new Higgs-like particle in the WW → lνlν channel
  - → *2012 observed min. $p_0 = 3 \times 10^{-3}$ or 2.8σ*
  - → *Broad minimum in p_0 centered at $m_H = 125$*
  - → *Signal strength in agreement with Standard Model*

$$\mu = 1.48^{+0.35}_{-0.33}\,(\text{stat})^{+0.41}_{-0.36}\,(\text{sys theor})\,^{+0.28}_{-0.27}\,(\text{sys exp}) \pm 0.05\,(\text{lumi})$$

- What's next:
  - → *Re-optimized VBF result and combination with 2011*
  - → *Updated high-mass and semileptonic ("lνqq") searches*
  - → *ggF analysis: improve background model and reduce systematics*

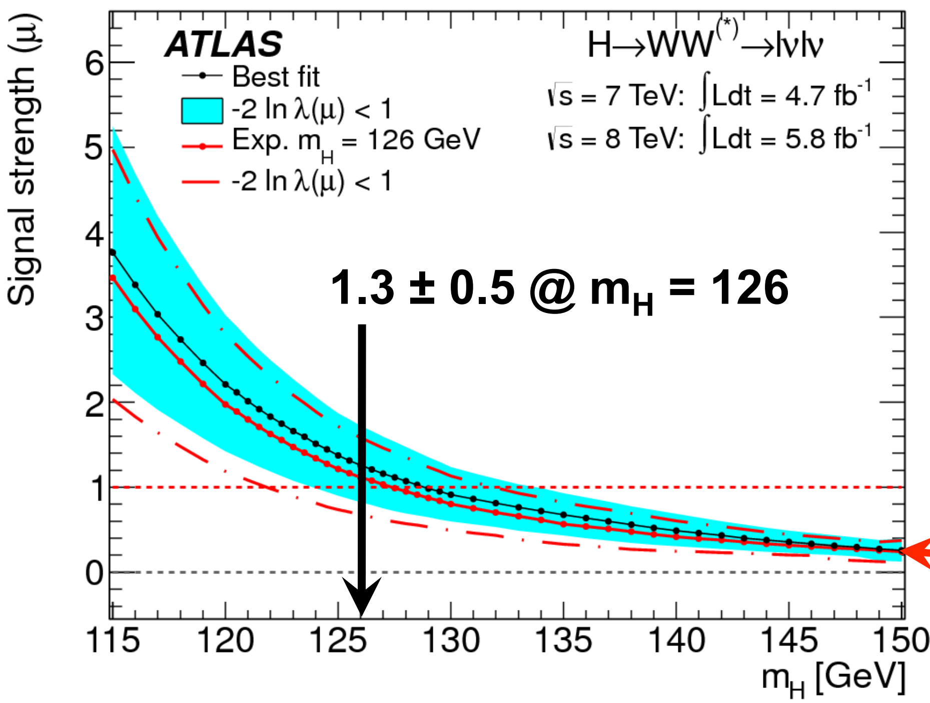
backup

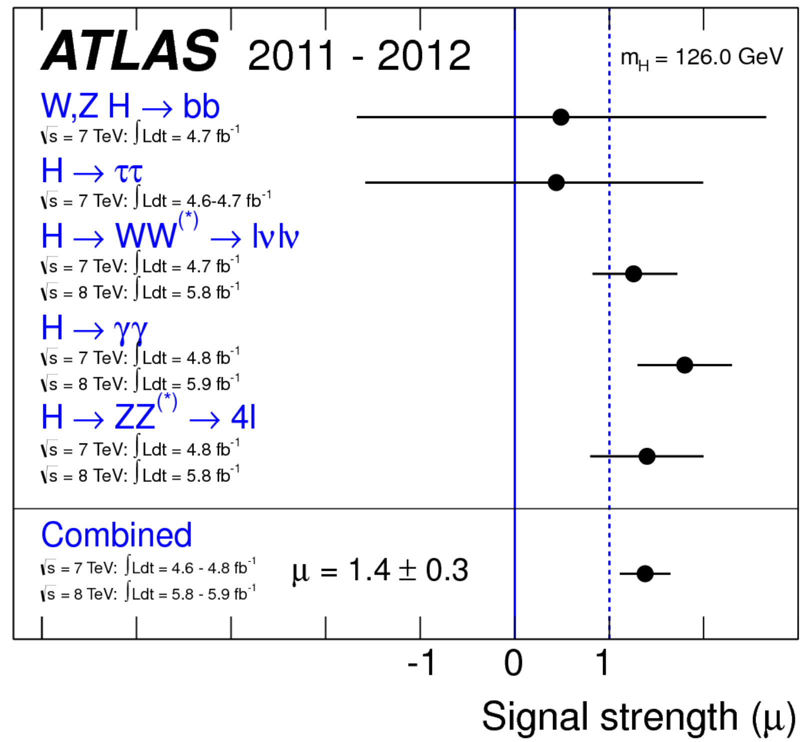
July 2012 Results

Signal Strength μ for 2011 + 2012 combined

→ *comparable to other channels,*

→ ***best individual measurement of μ!***





Expected curve for m_H = 126: behavior consistent with expectation

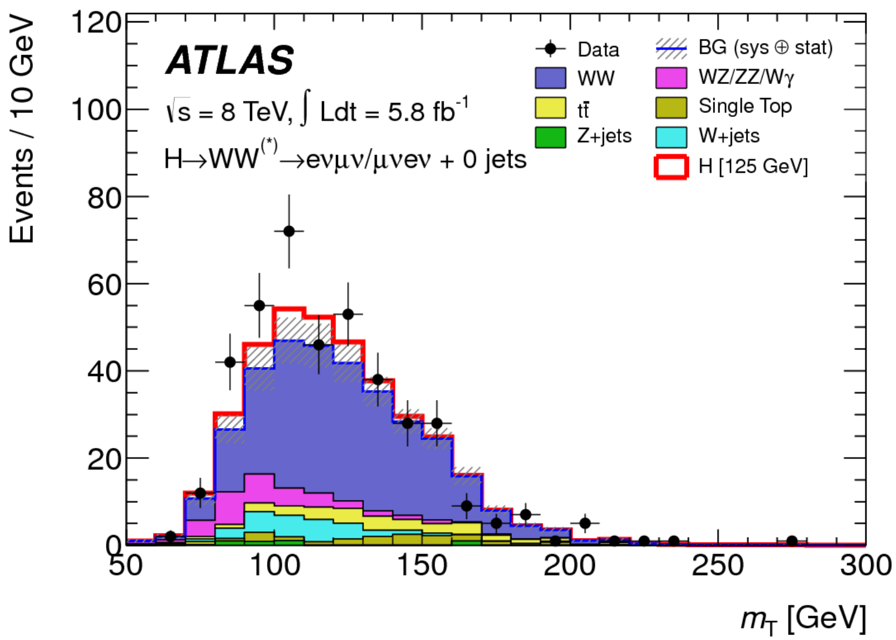
July 2012 Results

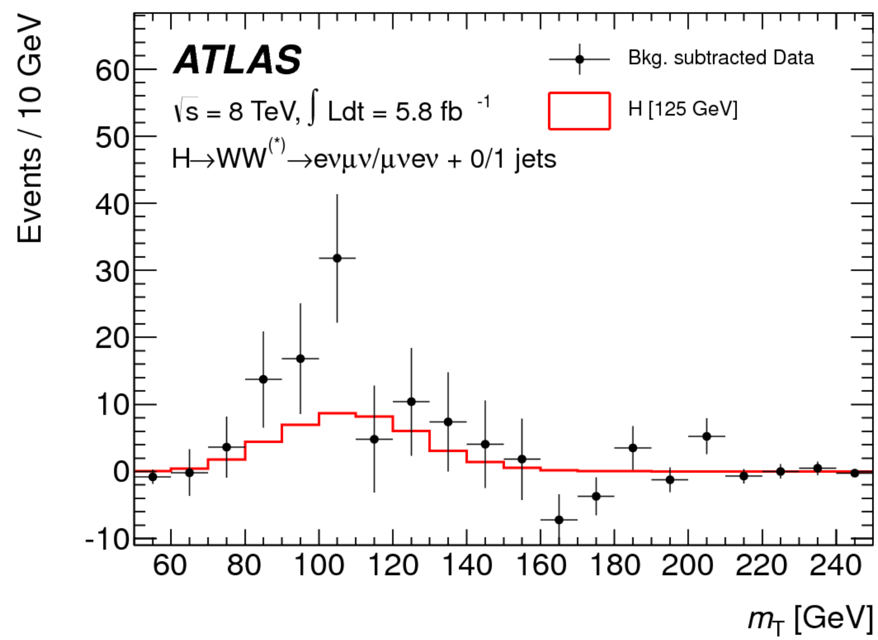
Signal and BG with systematics for different jet bins

m_T cut applied to be "indicative of analysis sensitivity"

Note different treatment of WW, top systematics compared to Nov. note

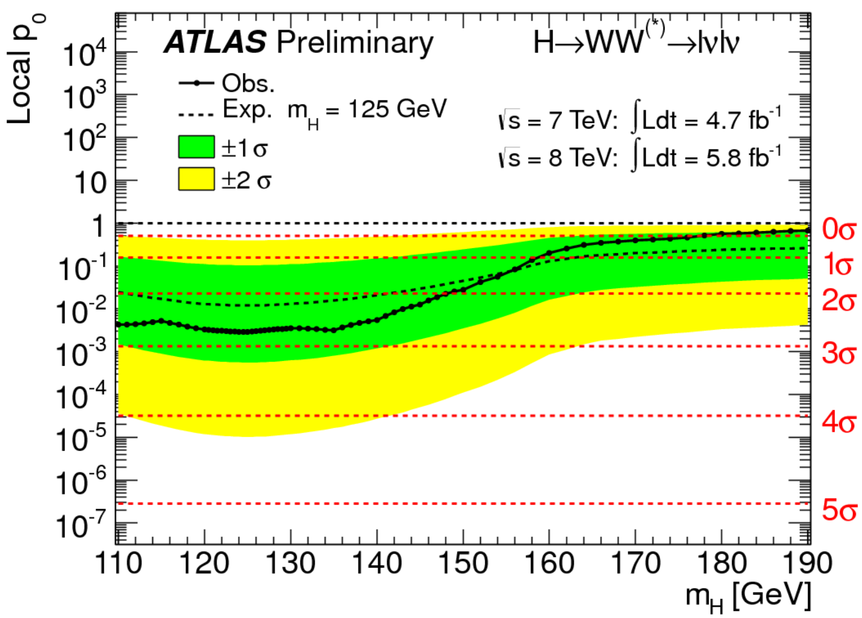
	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	$Z/\gamma^* +$ jets	$W +$ jets	Total Bkg.	Obs.
$H+$ 0-jet	20 ± 4	101 ± 13	12 ± 3	8 ± 2	3.4 ± 1.5	1.9 ± 1.3	15 ± 7	142 ± 16	185
$H+$ 1-jet	5 ± 2	12 ± 5	1.9 ± 1.1	6 ± 2	3.7 ± 1.6	0.1 ± 0.1	2 ± 1	26 ± 6	38
$H+$ 2-jet	0.34 ± 0.07	0.10 ± 0.14	0.10 ± 0.10	0.15 ± 0.10	-	-	-	0.35 ± 0.18	0

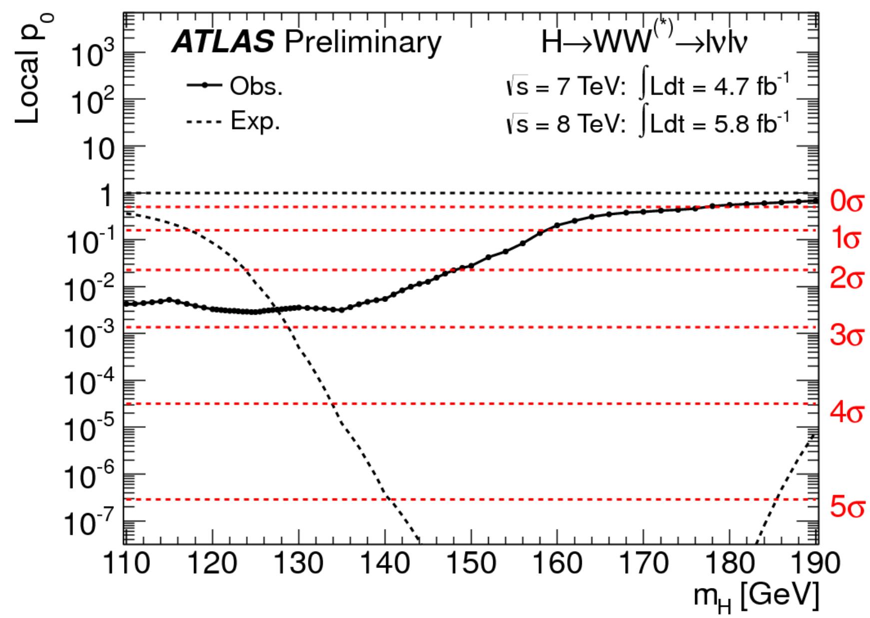




July 2012 results

- Combined 2011+2012 p_0: **3 x 10^{-3} (2.8σ) observed**, 1 x 10^{-2} (2.3σ) expected





Event Selection Summary

0 jet analysis

→ ***$\Delta\varphi$(ll,MET) > $\pi/2$ to clean up events with fake MET (rejects few events)***

→ *p_T(ll) > 30 GeV*

1 jet analysis

→ *b-jet veto*

→ *$Z \rightarrow \tau\tau$ veto ($|m_{\tau\tau}-m_Z| >$ 25GeV)*

→ ***p_T(tot) cut removed***

Common "topological" selection

→ *m(ll) < 50 GeV*

→ *$\Delta\varphi$(ll) < 1.8*

Candidate event **blinding** to remove phase space with significant m_H ~ 125 GeV signal

→ *pass preselection*

→ *zero jets or no b-tagged jet*

→ *m(ll) < 50 GeV*

→ *$\Delta\varphi$(ll) < 1.8*

→ *82.5 < m_T < 140 GeV*

Full 13 fb^{-1} Cutflow

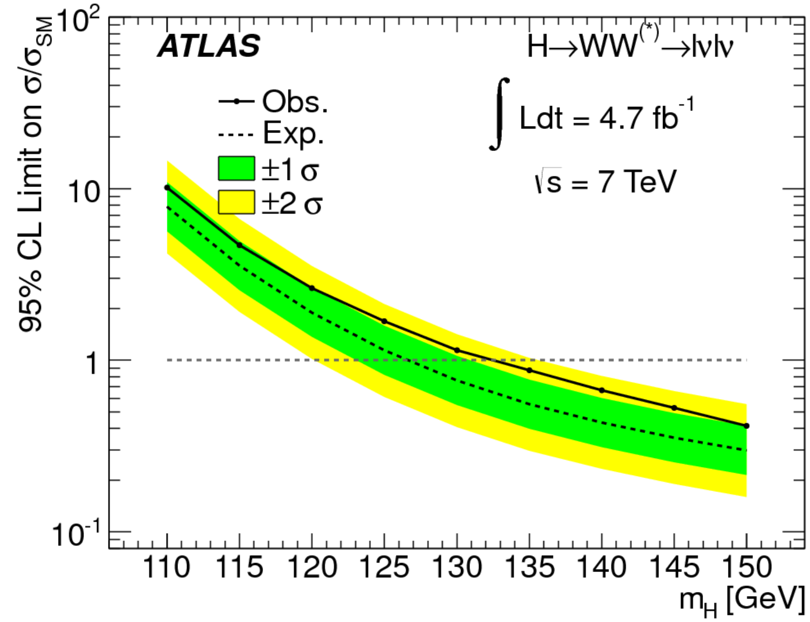
Cutflow evolution in the different signal regions

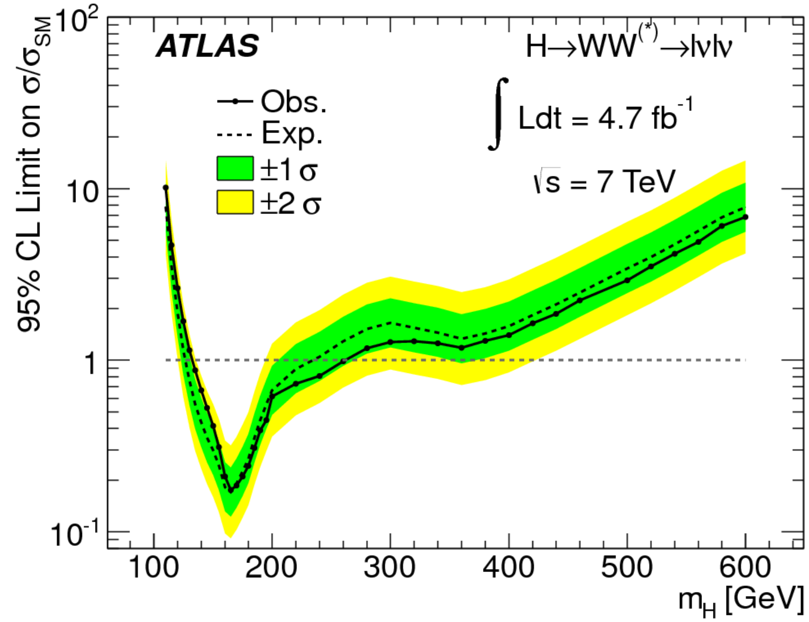
$H+0$-jet	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	$Z/\gamma^* +$ jets	$W+$ jets	Total Bkg.	Obs.
Jet veto	110 ± 1	3004 ± 12	242 ± 8	387 ± 8	215 ± 8	1575 ± 20	340 ± 5	5762 ± 28	5960
$\Delta\phi_{\ell\ell,E_T^{miss}} > \pi/2$	108 ± 1	2941 ± 12	232 ± 8	361 ± 8	206 ± 8	1201 ± 21	305 ± 5	5246 ± 28	5230
$p_{T,\ell\ell} > 30$ GeV	99 ± 1	2442 ± 11	188 ± 7	330 ± 7	193 ± 8	57 ± 8	222 ± 3	3433 ± 19	3630
$m_{\ell\ell} < 50$ GeV	78.6 ± 0.8	579 ± 5	69 ± 4	55 ± 3	34 ± 3	11 ± 4	65 ± 2	814 ± 9	947
$\Delta\phi_{\ell\ell} < 1.8$	75.6 ± 0.8	555 ± 5	68 ± 4	54 ± 3	34 ± 3	8 ± 4	56 ± 2	774 ± 9	917
$H+1$-jet	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	$Z/\gamma^* +$ jets	$W+$ jets	Total Bkg.	Obs.
One jet	59.5 ± 0.8	850 ± 5	158 ± 7	3451 ± 24	1037 ± 17	505 ± 9	155 ± 5	6155 ± 33	6264
b-jet veto	50.4 ± 0.7	728 ± 5	128 ± 5	862 ± 13	283 ± 10	429 ± 8	126 ± 4	2555 ± 20	2655
$Z \to \tau\tau$ veto	50.1 ± 0.7	708 ± 5	122 ± 5	823 ± 12	268 ± 9	368 ± 8	122 ± 4	2411 ± 19	2511
$m_{\ell\ell} < 50$ GeV	37.7 ± 0.6	130 ± 2	39 ± 2	142 ± 5	55 ± 4	99 ± 3	30 ± 2	495 ± 8	548
$\Delta\phi_{\ell\ell} < 1.8$	34.9 ± 0.6	118 ± 2	35 ± 2	134 ± 5	52 ± 4	22 ± 2	24 ± 1	386 ± 8	433

above: stat. uncertainties only
below: add m_T cut and systematics

2011 Analysis

- Possible signal at $m_H \sim 125$ in γγ, ZZ → 4l channels
- Ambiguous results from WW → lνlν





The ATLAS Detector

•Muon Detectors

- Precision: Drift tubes (MDT) and Cathode Strip Chambers (CSC)
- Trigger: Resistive Plate Chamber (RPC) and Thin Gap Chamber (TGC)

- Liquid Argon (LAr) with lead
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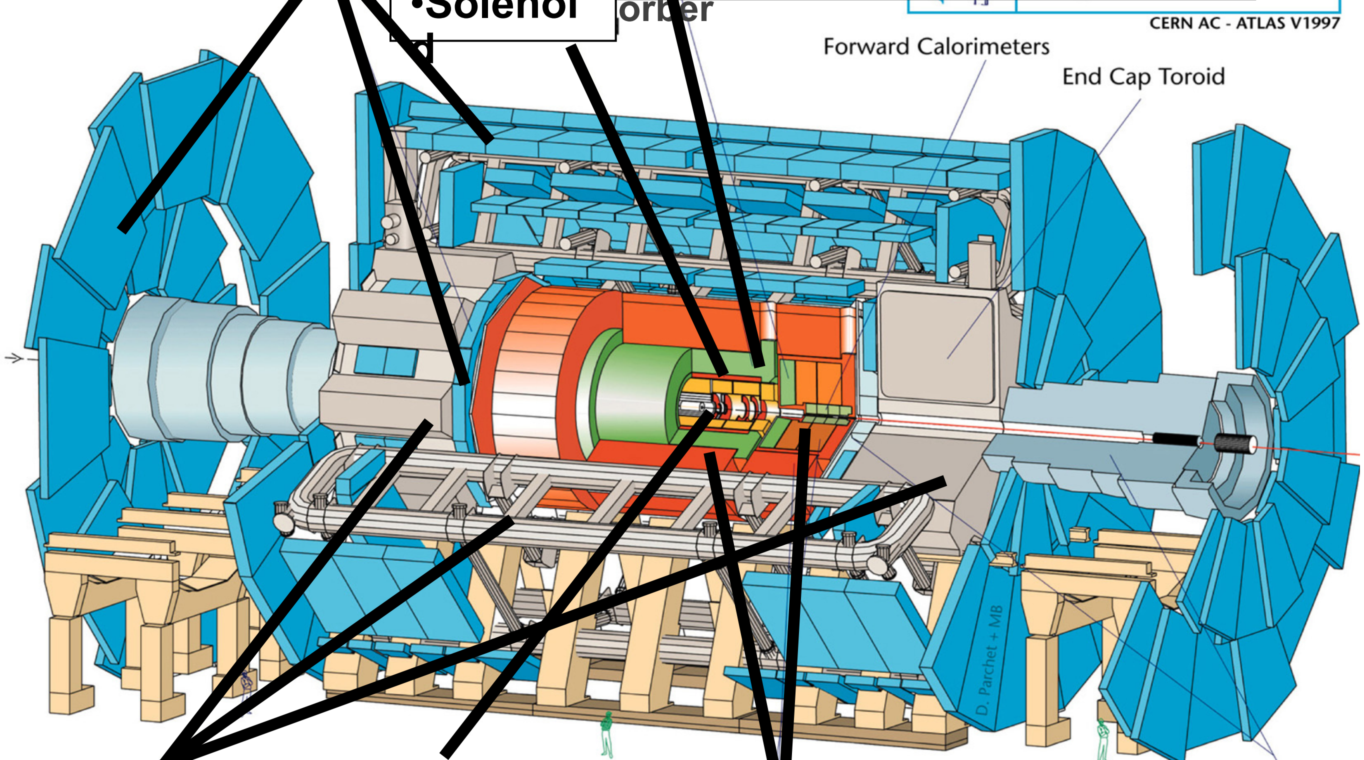
**•Solenoi
d**



•Toroids

•Inner Detector (tracking):

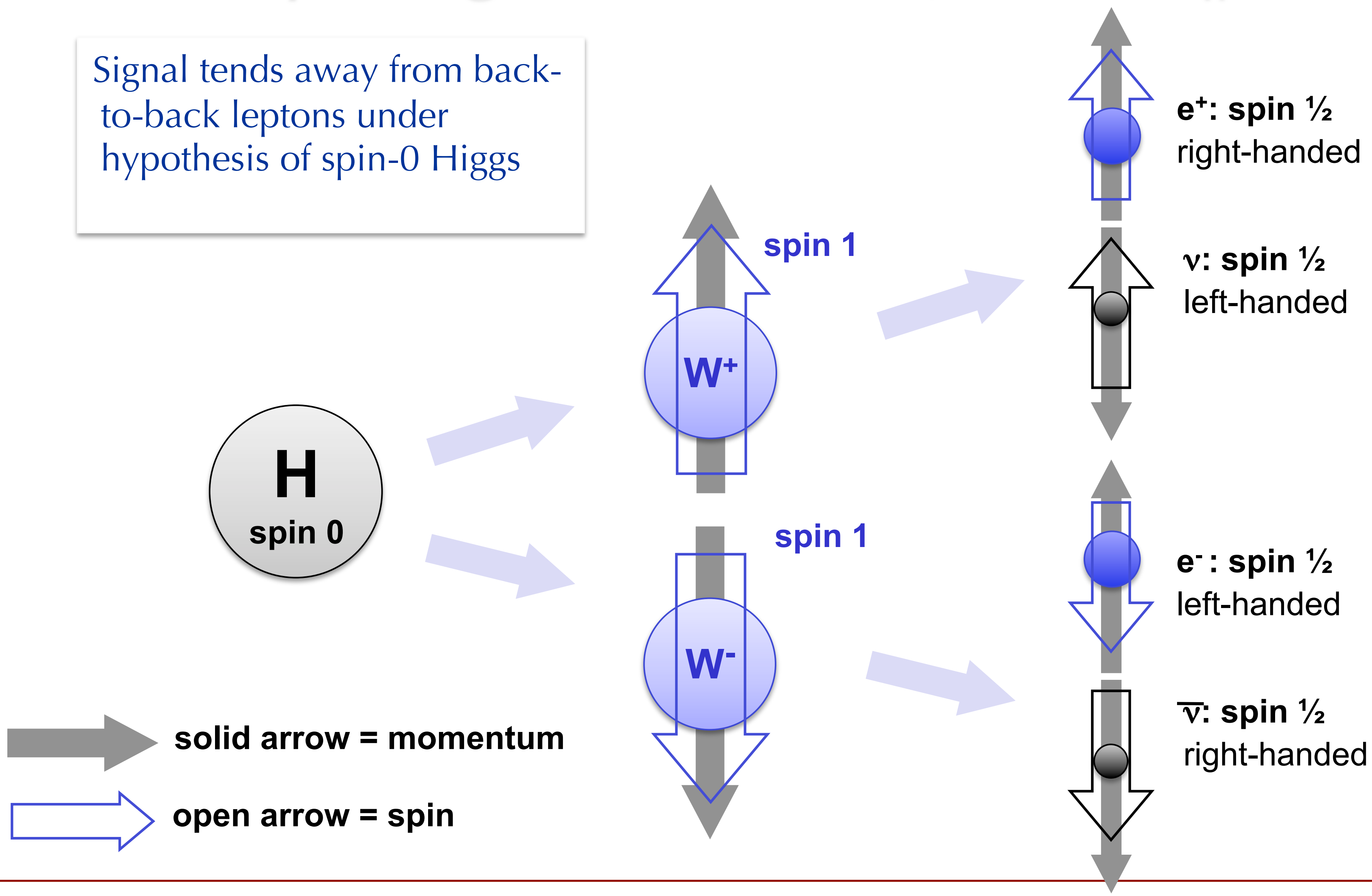
- Pixels (sili
- SCT (silico
- TRT (straw

•Hadronic calorimeter

- Steel absorber + scintillator
- LAr with copper/tungsten absorber

Topological cuts $\Delta\varphi(ll)$, m_{ll}

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



Blinding the Analysis

- 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?
  - → *$\Delta\varphi(ll)$ and $m(ll)$ cuts*
  - → *Transverse mass bound corresponding to lower bound for 110 and upper bound for 140 → veto $(0.75)(110) < m_T < (1.0)(140)$*

***2* how we blinded the analysis**

Blinded Region
$82.5 < M_T < 140$
and
$\Delta\varphi(ll) < 1.8$
and
$m_{ll} < 50$
and
0 jets or 0 b-tags