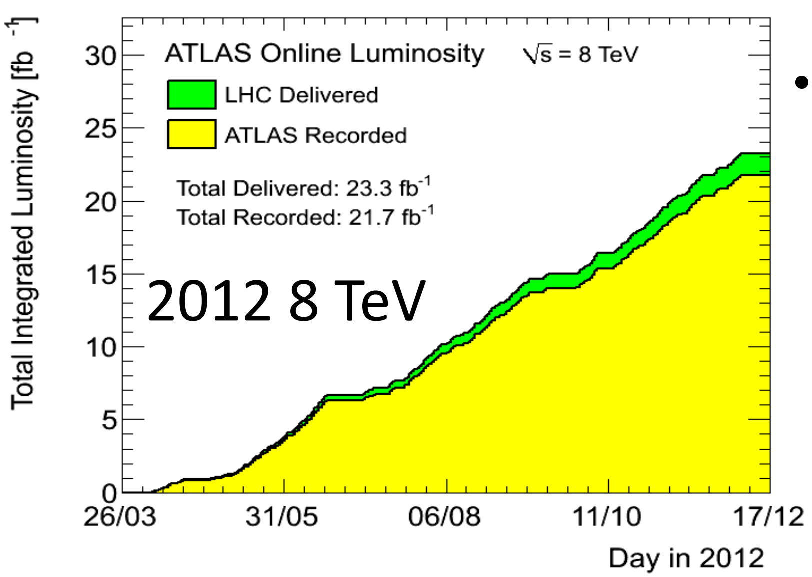
ATLAS H→WW→$l\nu l\nu$

Doug Schaefer

University of Pennsylvania



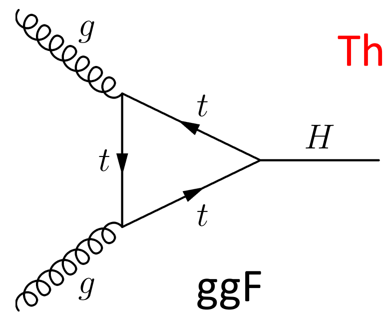
- ATLAS Higgs to WW results
  - July 4, 2013 results submitted to PRB (arXiv :1307.1427)
  - ggF
  - Associated production (WH/ZH)
  - VBF (Ben's talk)

2013 DPF High Energy Conference

Higgs Production on the LHC

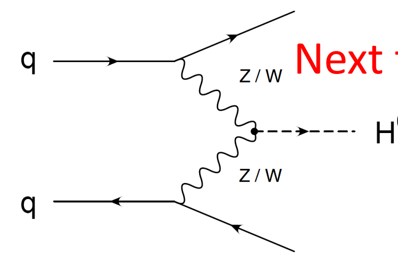
- Main production is gluon-gluon fusion (ggF)
  - Sensitive to new physics in loop
  - Subject of this talk
- Vector boson fusion (VBF) and associated production
  - Sensitive to tree level vector boson couplings
- Sensitivity to spin and couplings to W/Z and top
  - Can measure direct WW/ZZ to Higgs coupling in the qq’→*qq’H* (VBF) channel

This talk

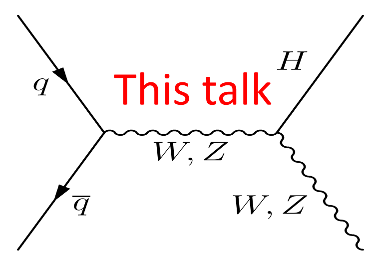


ggF

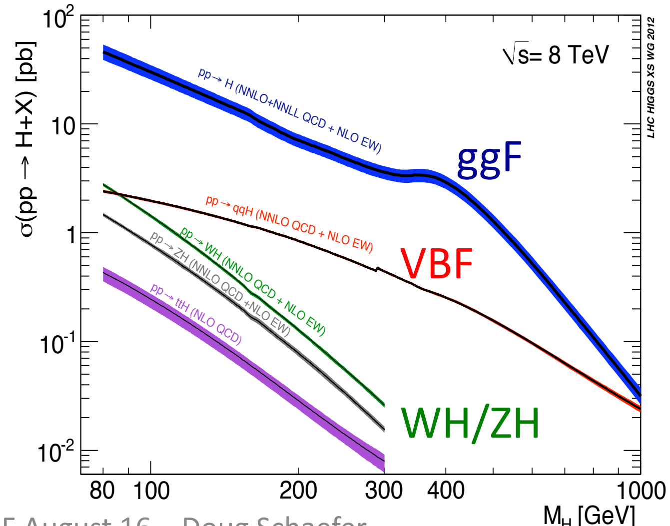
Next talk

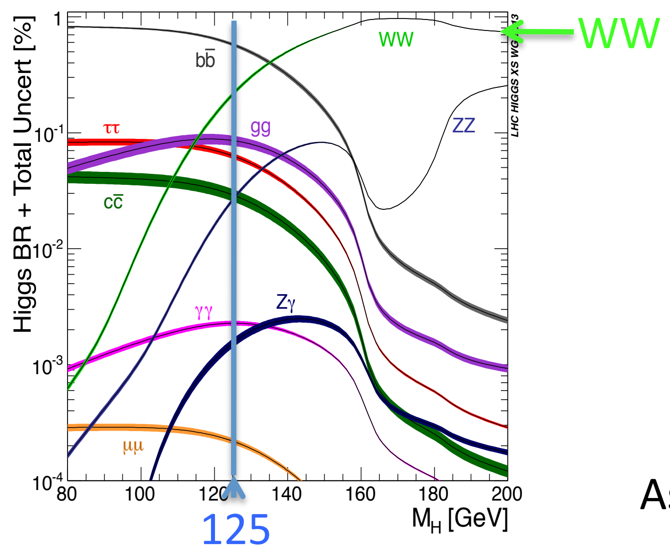


VBF



Associated Production



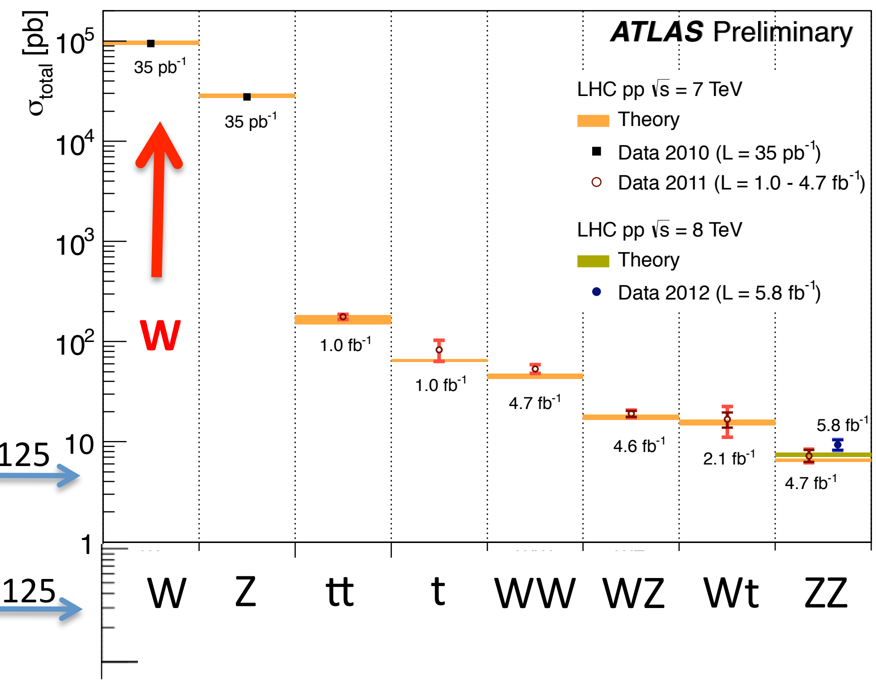


Contending with Many Backgrounds

- Ordered list of most important backgrounds for Higgs with m_H=125 GeV/c^2 in the opposite flavor channel with no accompanying jets

Background	Enters Analysis	Normalized to Data
$WW \to \ell\nu\ell\nu$	irreducible	yes
W+Jet$\to \ell\nu$+jet	jet fakes lepton	yes
$W\gamma$	photon conversion	no
WZ	lose lepton	no
$t\bar{t} \to b\ell\nu\ b\ell\nu$	lose bs	yes
$Wt \to \ell\nu\ b\ell\nu$	lose b	yes
ZZ	irreducible, small	no
$Z\to \tau\tau$	real MET	yes

W+Jets is extremely important for low Higgs mass measurements
- **Large uncertainty (40%)**
- **Similar kinematics to signal**
- **Difficult to simulate**
- **<u>Fully data driven</u>**

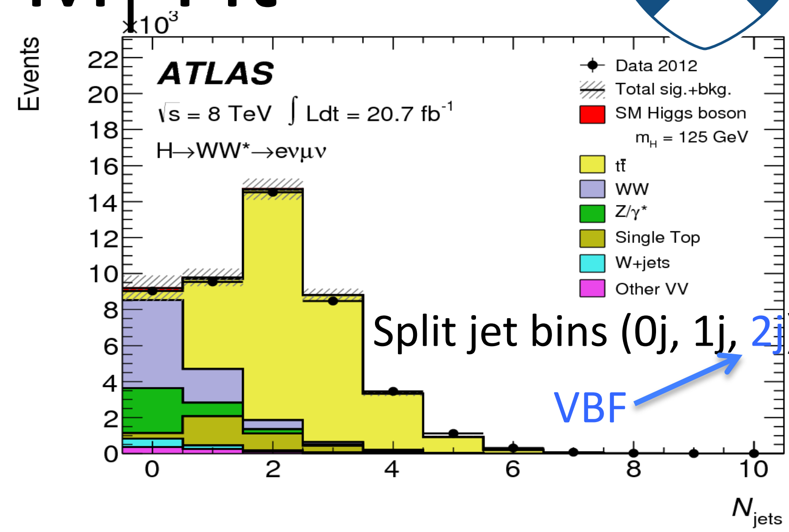


ggF HWW 125

VBF HWW 125

H→WW→lνlν Binned Likelihood M_T Fit

- Single lepton triggers (e,μ)
  - P_T^{lep}>25, 15 GeV (2 opposite sign leptons)
    - Muons (electron) |η|<2.5 (2.47)
    - Isolation and impact parameter selections
  - P_t^{jet}>25 GeV (30 for |η|>2.5)

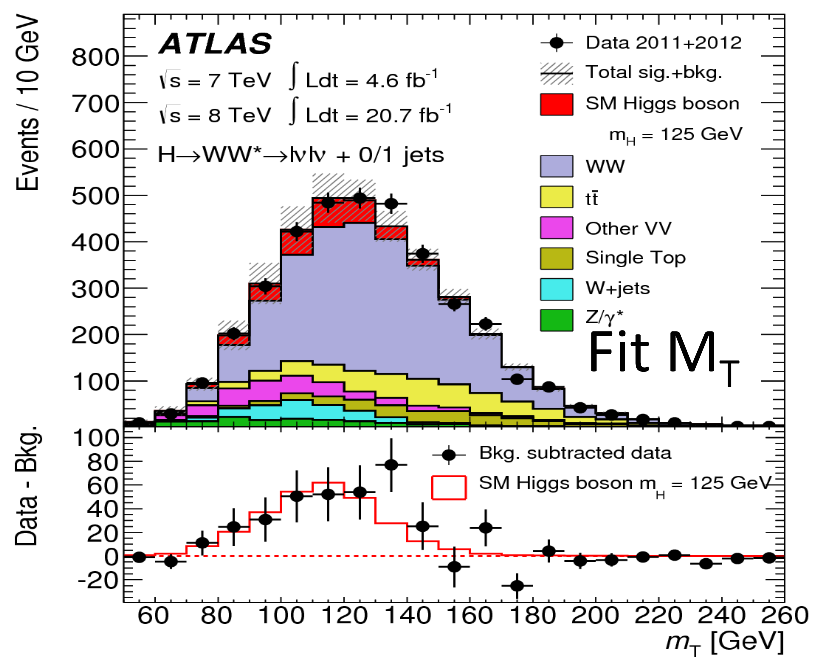


- Split ee, μμ, eμ, and μe
  - Talk focuses on 0j eμ+μe
  - Same flavor
    - Adds 10%
    - Large DY background from MET degradation (~20-30 pp collisions per bunch crossing)

- Fit transverse mass (M_T) distribution
  - 2 bins of M_{ll} in Opposite flavor

$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{E}_T^{miss}|^2}$$

Limited mass resolution

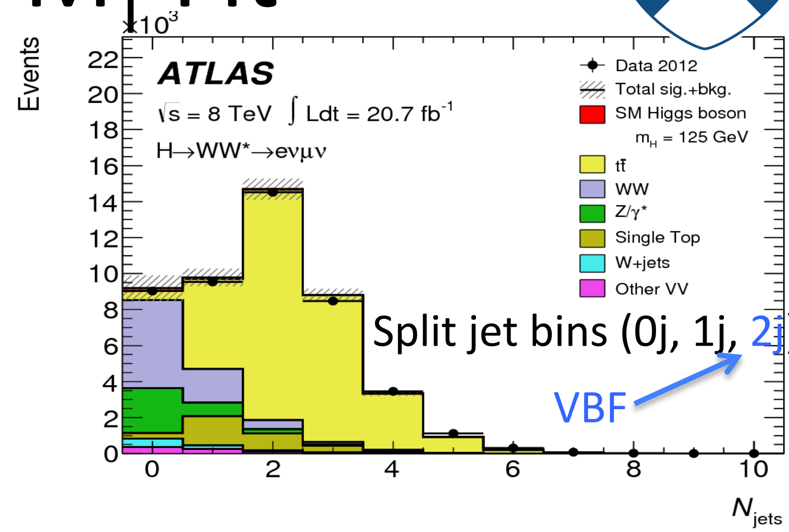


arXiv:1307.1427

H→WW→lνlν Binned Likelihood M_T Fit

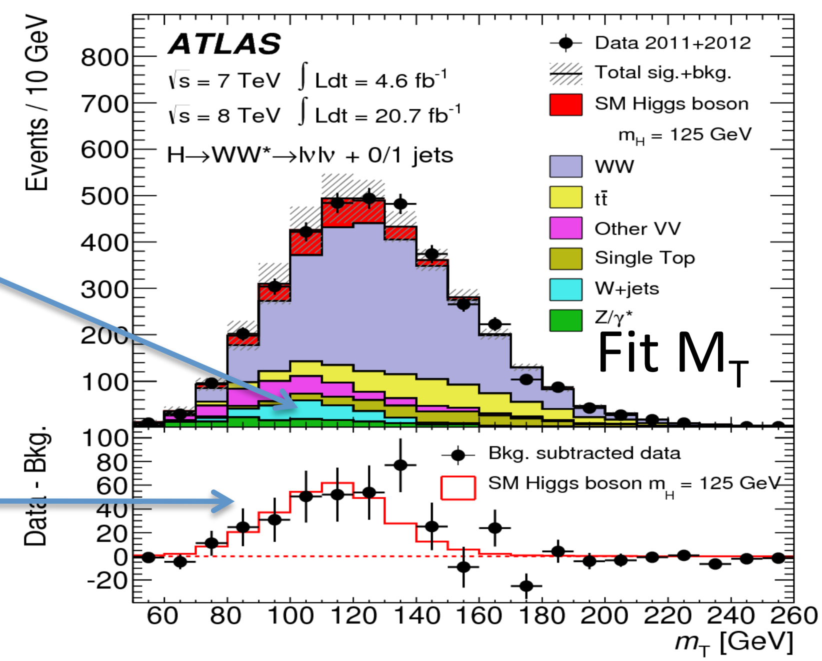
- Single lepton triggers (e,μ)
  - P_T^{lep}>25, 15 GeV (2 opposite sign leptons)
    - Muons (electron) |η|<2.5 (2.47)
    - Isolation and impact parameter selections
  - P_t^{jet}>25 GeV (30 for |η|>2.5)

- Split ee, μμ, eμ, and μe
  - Talk focuses on 0j eμ



W+jets has similar kinematics to signal and a large uncertainty

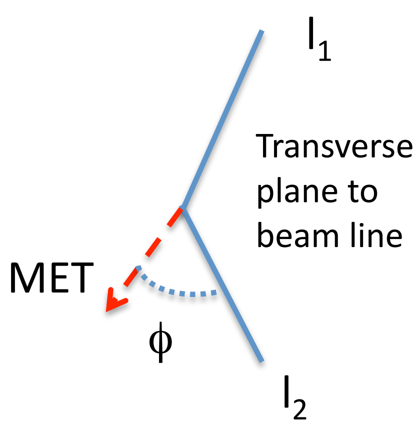
Signal

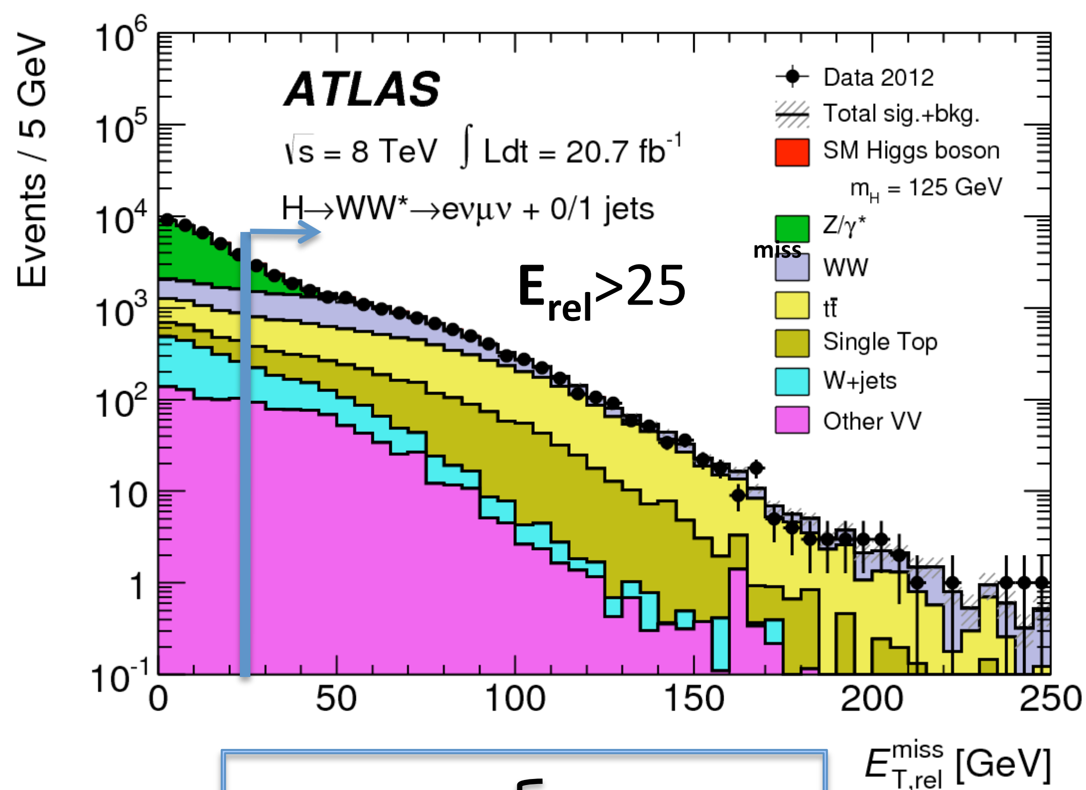


arXiv:1307.1427

0 Jet Signal Selection

- E^{miss}_{rel} is sensitive to the direction of MET along objects
  - Leptonic τ decays
- Much harsher MET requirement for the same flavor
  - METRel>45 GeV



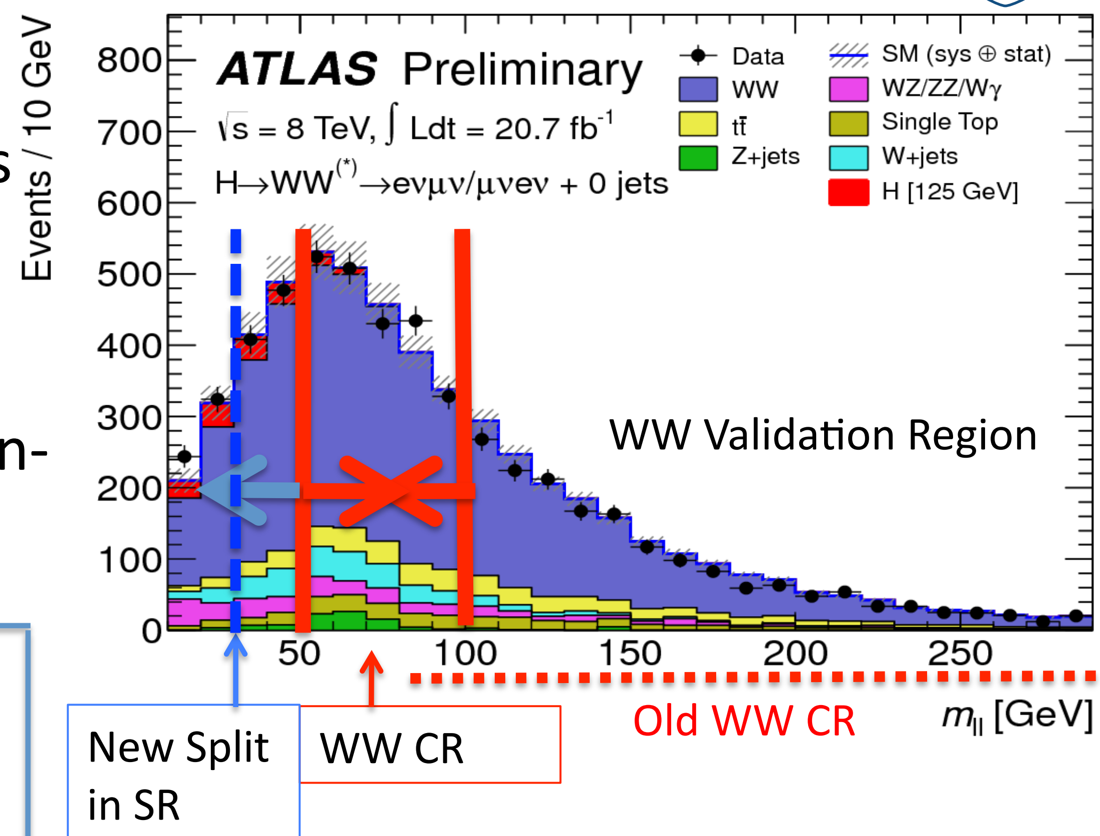


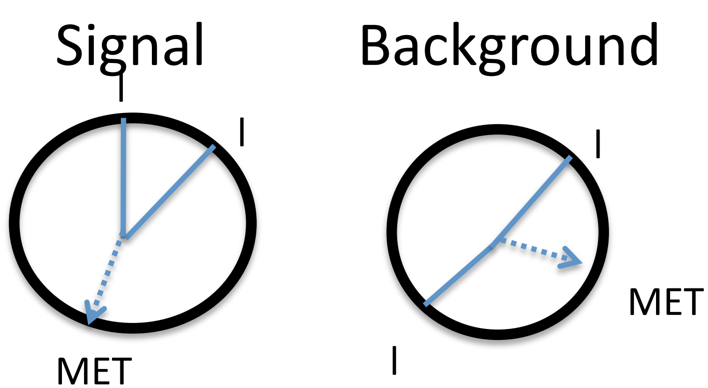
$$E^{miss}_{rel} = MET \times \begin{cases} 1, & \phi > \pi/2 \\ \sin\phi, & \text{else} \end{cases}$$

arXiv:1307.1427

0 Jet Signal Selection and WW Modeling

- Higgs spin-0+V-A decays provide collinear leptons
  - $P_T^{ll}>30$ GeV
  - $M_{ll}<50$ GeV
  - $\Delta\phi_{ll}<1.8$
- See Lashkar's talk for non-spin-0 specific analysis



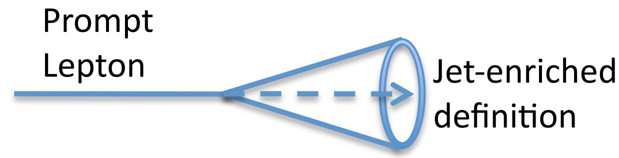


- **Total Uncertainty on WW**
  - <u>74% of 0jet background</u>
  - 7.4% in 0jet
  - Includes theoretical and statistical shape uncertainties
  - Experimentally dominated

arXiv:1307.1427

W+Jet Modeling

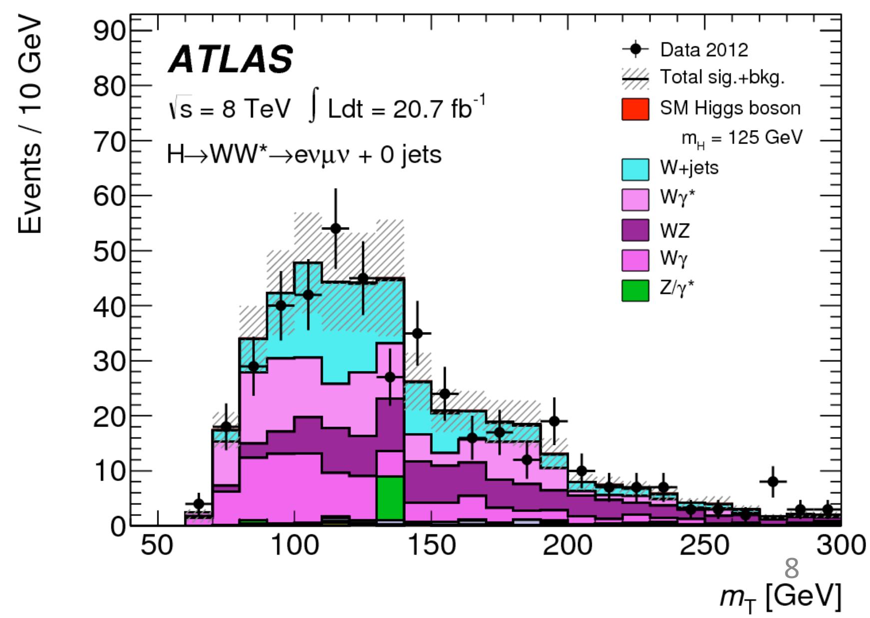
$$N_{W+Jets} = \sum_{i}^{Events} f_{jet} * \left(\quad \right)$$



f_{jet} is the "transfer factor" from jet enriched leptons to our isolation definitions.

- Fully data driven
- **f_{jet}**
  - Derived from QCD CR in data
  - ~40% uncertainty
- Modeling is validated with same sign lepton pairs

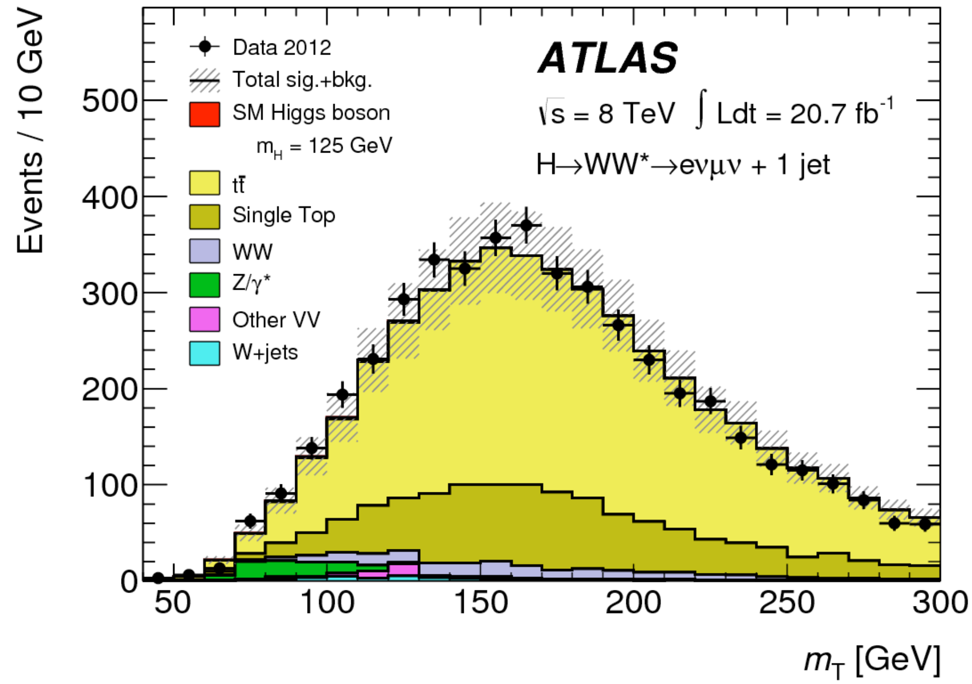
Same Sign Validation



arXiv:1307.1427

Top Estimate

- ~2% of top events are in the 0 jet (unlikely)
  - Large uncertainty (13%)
- Use data driven method to correct simulation
  - Jet Veto Survival Fraction (JVSP)
  - Basically: probability to miss 2 jets
- Ratio to simulation is 1.11± 0.14
- 1 jet uses a b-tagged CR

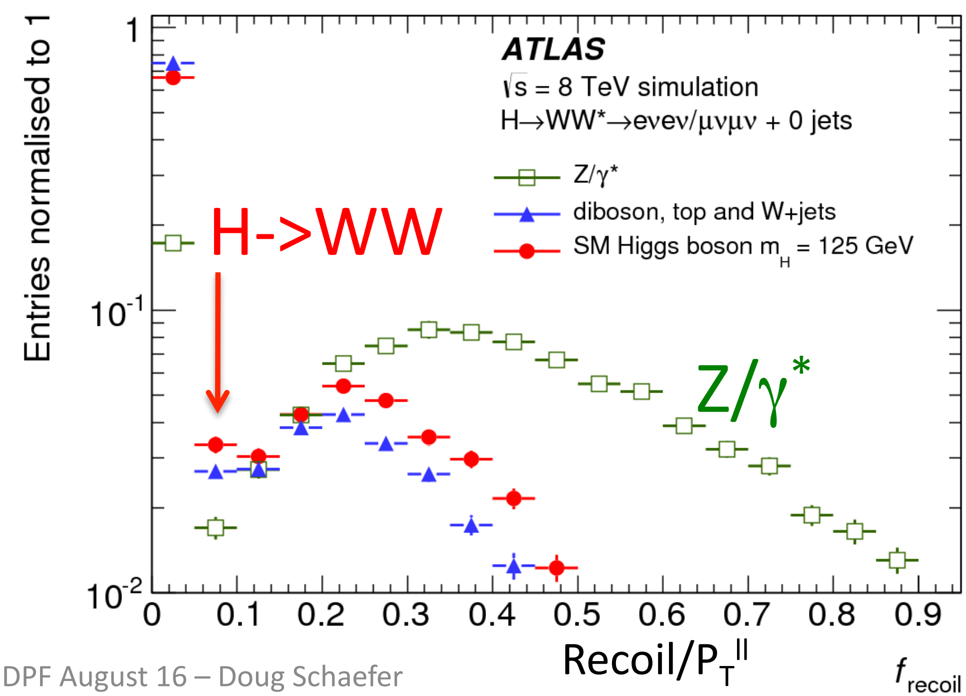


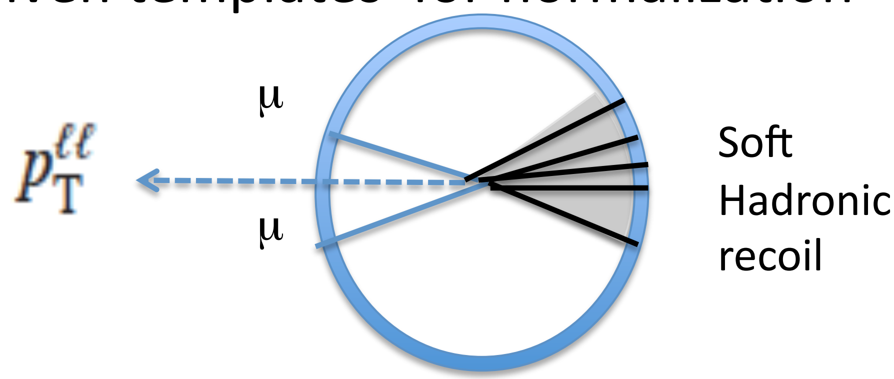
Jet Bin	% background	Top background
0 jet	5%	39 ± 5
1 jet	36%	95 ± 28

 arXiv:1307.1427

Same Flavor: PacMan

- Z/γ^* enters because MET mis-measures some soft hadronic activity
- Measure soft hadronic recoil (jets with P_T<25 GeV)
  - Reduces DY by a factor 5
- Adapted to 1j using P_T^{ll+jet}
- Fit for Z/γ^* normalization using driven templates for normalization





Recoil measurement in 0 jet events

Summary of Backgrounds

	$N_{\text{jet}} = 0$	$N_{\text{jet}} = 1$
Observed	831	309
Signal	100 ± 21	41 ± 14
Total background	739 ± 39	261 ± 28
WW	551 ± 41	108 ± 40
Other VV	58 ± 8	27 ± 6
Top-quark	39 ± 5	95 ± 28
Z+jets	30 ± 10	12 ± 6
W+jets	61 ± 21	20 ± 5

Uncertainties include anti-correlations

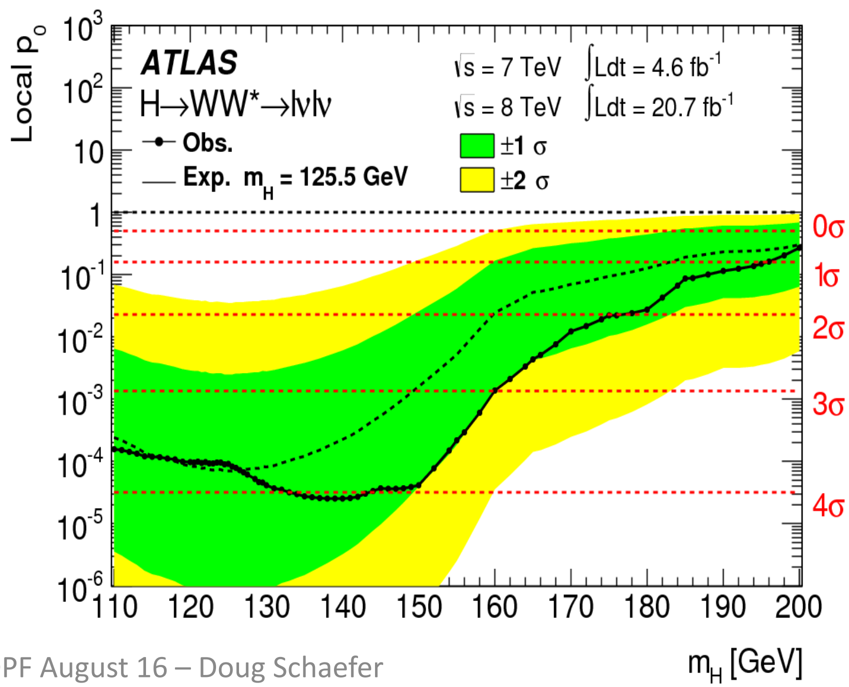
Largest background

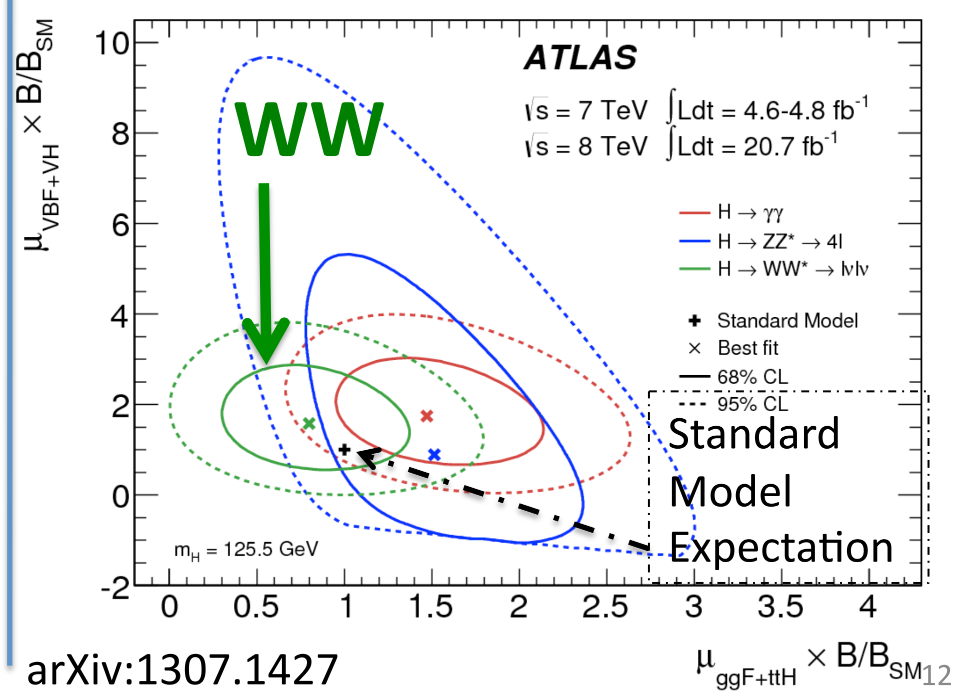
- Signal and background summed over ee+μμ+eμ

Fit Results

- Best p_0 is 4.0 σ_{SM} at m_H = 140 GeV/c^2
- Reject the no Higgs hypothesis at 3.8 σ_{SM} at m_H = 125.5 GeV/c^2

- Signal strength (μ) is 1 for SM (m_H = 125.5 GeV/c^2)
  - μ_H= 0.8 ± 0.3 only 0+1jet
  - μ_H= 1.0 ± 0.3 with VBF

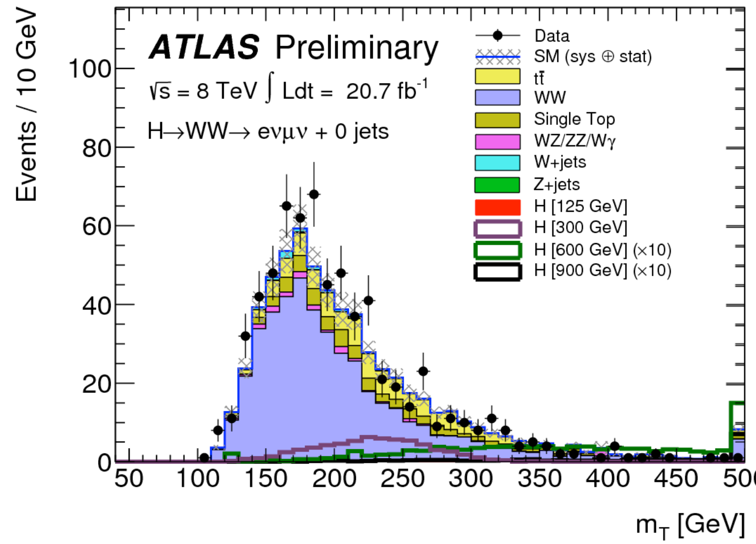




arXiv:1307.1427

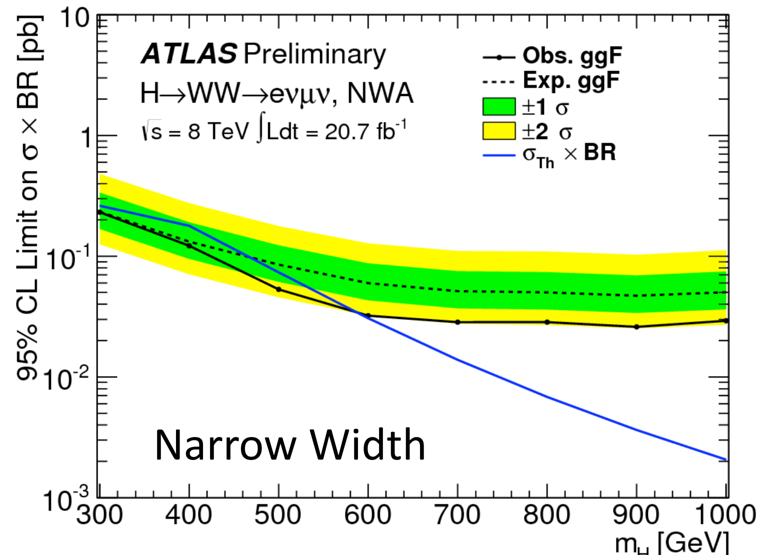
Dedicated High Mass Search H→WW

- Extend search for an additional SM Higgs to 1TeV (125 GeV Higgs is a background)
- 8TeV dataset 20.7/fb eμ • {0,1,VBF}

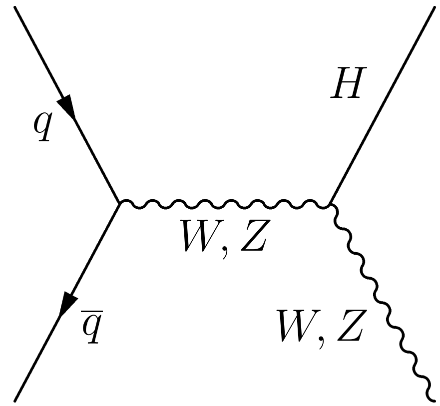


- Low mass cut → High mass cut
  - $M_{ll}<50 \rightarrow M_{ll}>50$ GeV
  - $|\Delta\varphi_{ll}|<1.8 \rightarrow |\Delta\eta_{ll}|<1.0$

- Consider two lineshape scenarios:
  - Narrow width approx. (NWA)
  - Standard Model (SM)
    - Exclude SM XS at 95% CL from 260 < M_H< 642 GeV with VBF



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-067/



Associated Production H→WW

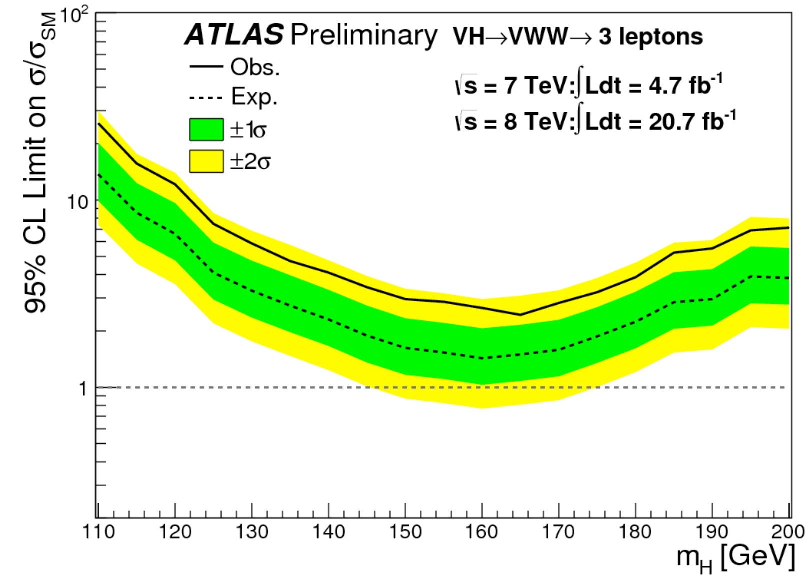
- Sensitive to direct Higgs to W/Z coupling (no loops)

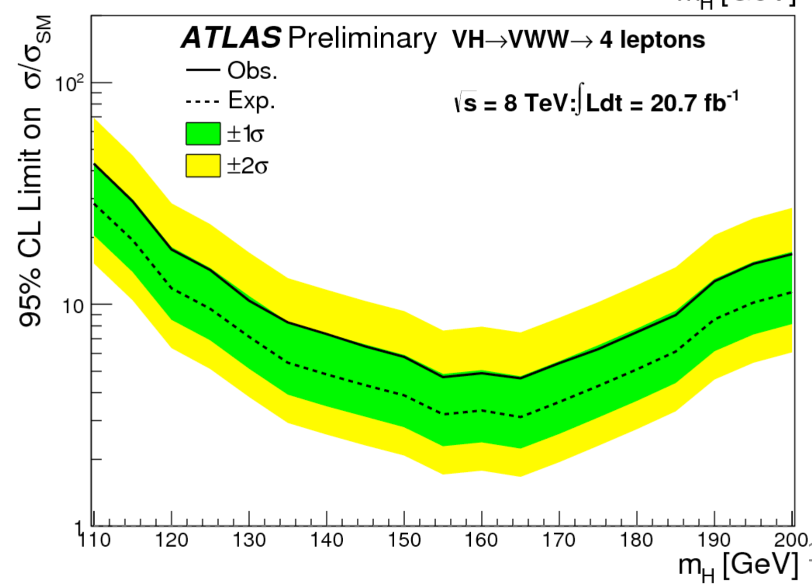
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-075/

ZH/WH Associated Higgs Analysis

(New For EPS)

- **<u>WH→*lν lνlν*</u>**
  - Search for 3 isolated leptons+MET
  - Split analysis into Z enriched and Z depleted regions
  - Expected limit is 4.0 σ_{SM} and observed is 7.5 at $m_H = 125$
  - **1.7 σ excess mainly in Z depleted region**
- **<u>ZH→*ll lνlν*</u>**
  - Search for 4 isolated leptons+MET
  - Split analysis into 1 SF OS and 2 SF OS pairs and uses V-A higgs decay
  - Expected limit is 9.6 σ_{SM} and observed is 14.3 at $m_H = 125$
  - **1.5 σ excess**





Previously 2011 only

Conclusion

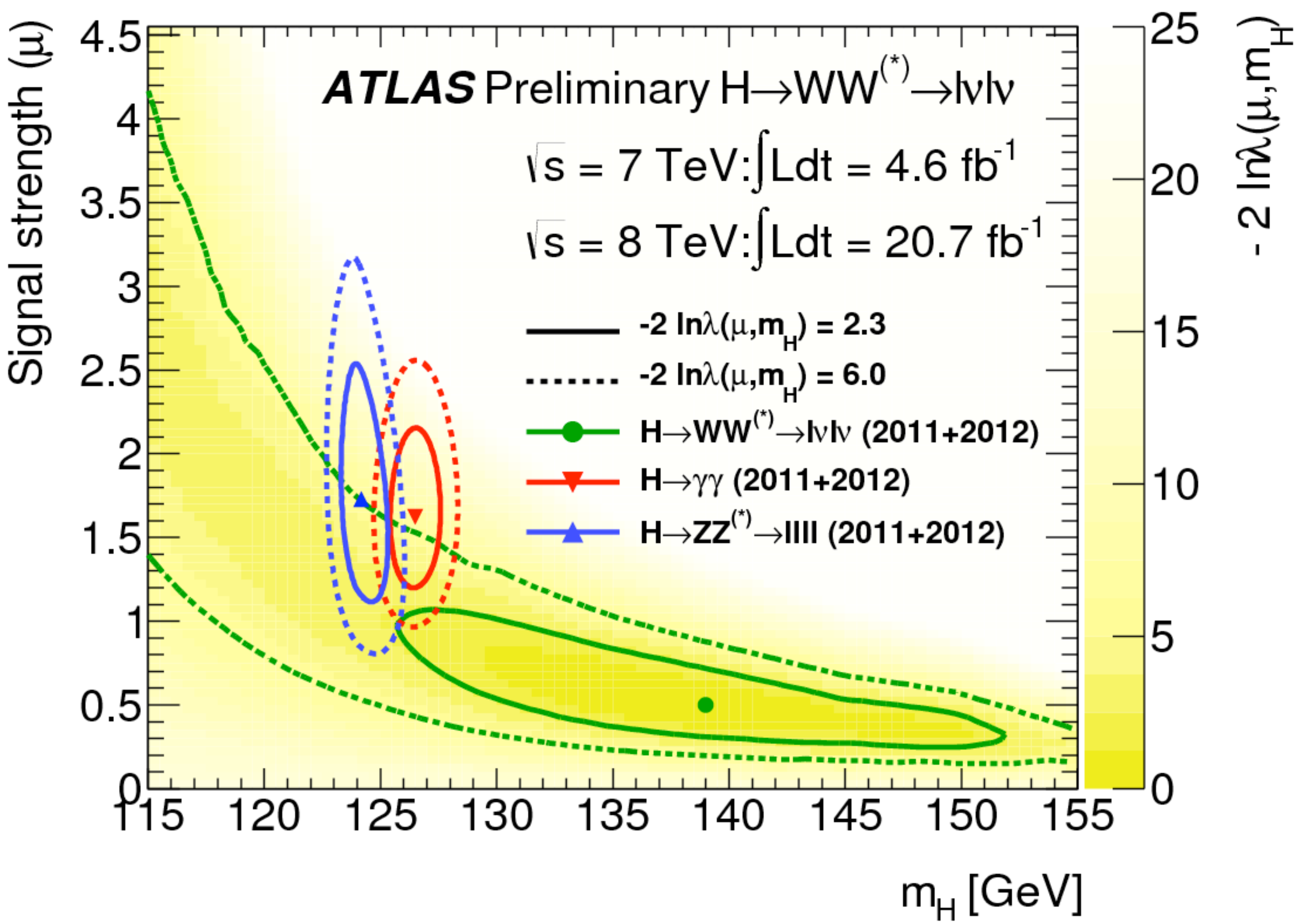
- The cross-section and signal strength are consistent with the standard model Higgs

$$\sigma(pp \to H) \cdot \mathcal{B}(H \to WW)_{m_H=125\ \text{GeV}} = 6.0\ ^{+1.2}_{-1.1}\ (\text{stat})\ ^{+0.8}_{-0.7}\ (\text{syst theor})\ ^{+0.6}_{-0.5}\ (\text{syst exp})\ ^{+0.4}_{-0.3}\ (\text{lumi})\ \text{pb}$$

- No evidence for an additional higher mass Higgs with mass less than 642 GeV
- Small excesses observed the WH/ZH analyses
- Wait until 2015 for 13-14 TeV data

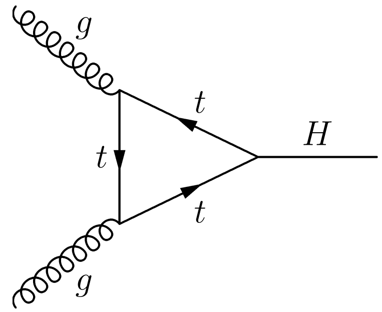
Backup

Signal Strength



Summary of Backgrounds

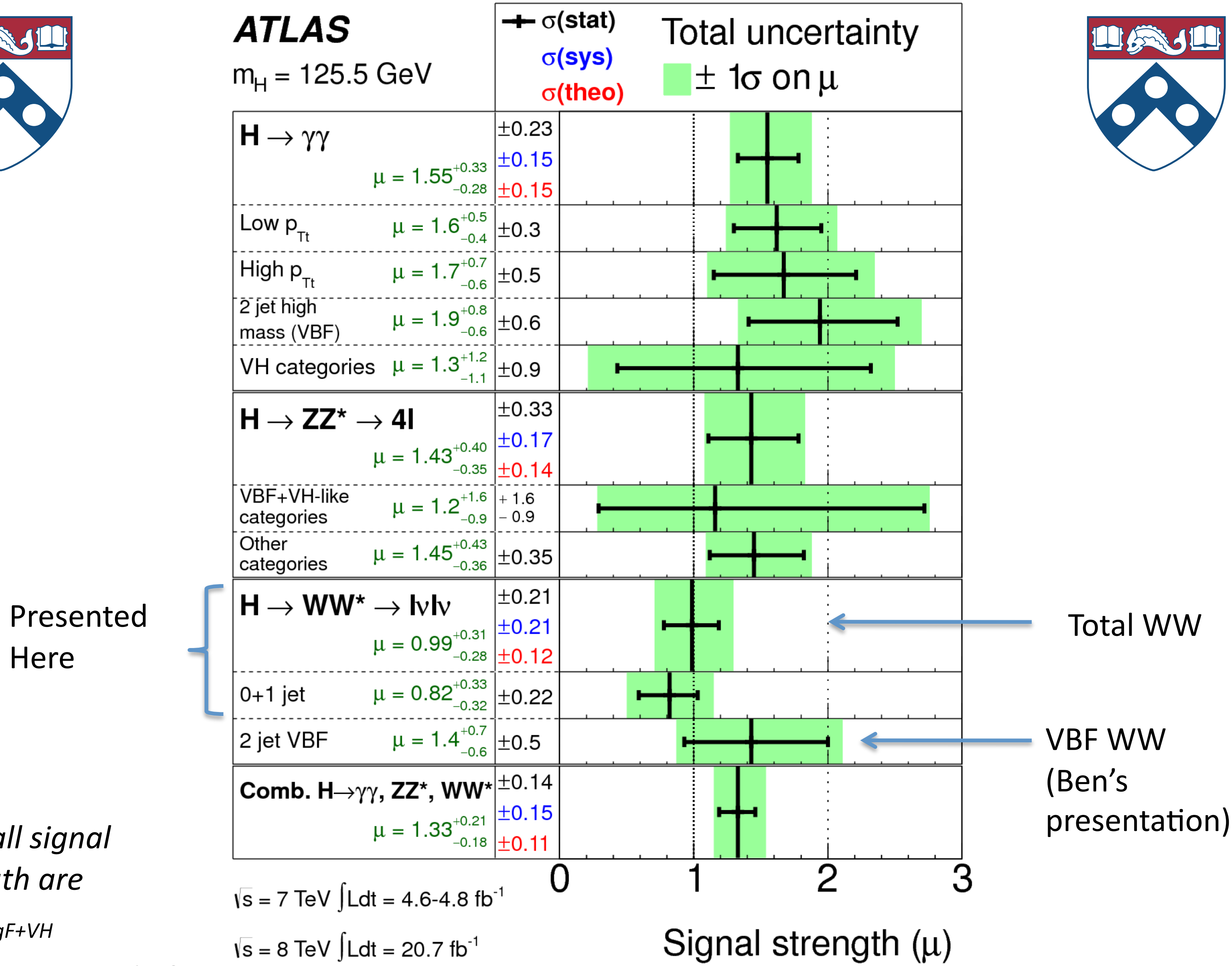
Source	$N_{jet} = 0$	$N_{jet} = 1$
Theoretical uncertainties on total signal yield (%)		
QCD scale for ggF, $N_{jet} \geq 0$	+13	-
QCD scale for ggF, $N_{jet} \geq 1$	+10	−27
QCD scale for ggF, $N_{jet} \geq 2$	-	−15
QCD scale for ggF, $N_{jet} \geq 3$	-	-
Parton shower and underlying event	+3	−10
QCD scale (acceptance)	+4	+4
Experimental uncertainties on total signal yield (%)		
Jet energy scale and resolution	5	2
Uncertainties on total background yield (%)		
WW transfer factors (theory)	±1	±2
Jet energy scale and resolution	2	3
b-tagging efficiency	-	+7
f_{recoil} efficiency	±4	±2



$H \to WW \to l\nu l\nu$ (rate)

- $l\nu l\nu$ means $e\nu e\nu$, $e\nu\mu\nu$, and $\mu\nu\mu\nu$
- 2012 Analysis (20.7/fb):
  - Split into 2 bins in m_{ll}
  - New WW CR (closer to SR)
  - Same flavor channel
  - VBF analysis (Ben's talk)
  - ZH/WH (3l+4l) (New for EPS)
- Re-analysis of 2011 (4.6 /fb)
  - Updated to match 2012
    - WW (MC@NLO -> Powheg)
    - Tightened isolation to reduce W+jets

http://arxiv.org/abs/1307.1427

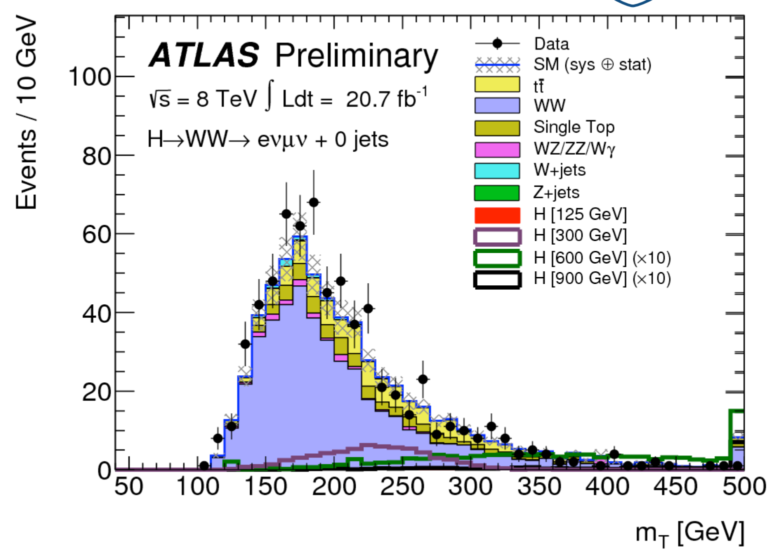


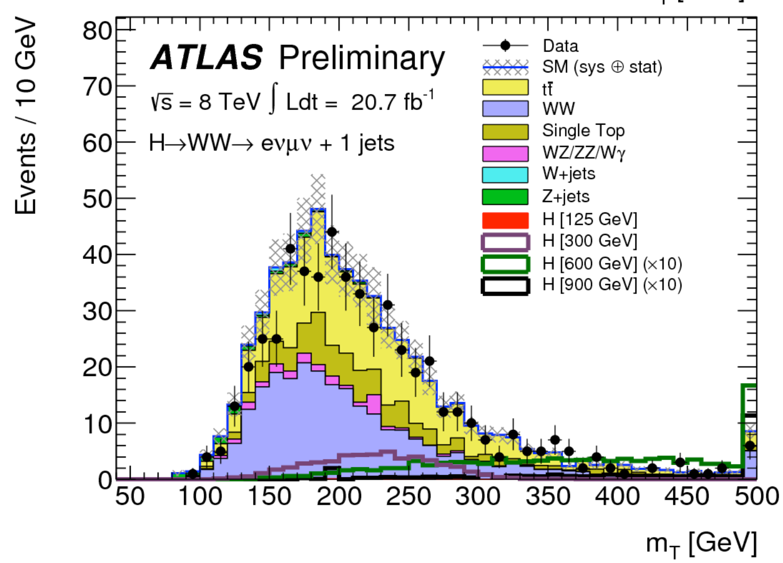
Note all signal strength are $\mu_{VBF+ggF+VH}$

Dedicated High Mass Search
H→WW

(New For EPS)

- Extends the search for an additional SM Higgs to 1TeV
- Full 8TeV dataset 20.7/fb
- Opposite flavor channel
  - 0+1jet
  - VBF (not discussed)
- Selection similar to low mass
  - M_{ll}>50 GeV (M_{ll}<50)
  - $|\Delta\eta_{ll}|$<1.0 ($|\Delta\varphi_{ll}|$<1.8)
  - WW CR has $|\Delta\eta_{ll}|$>1.0
  - Fit M_T

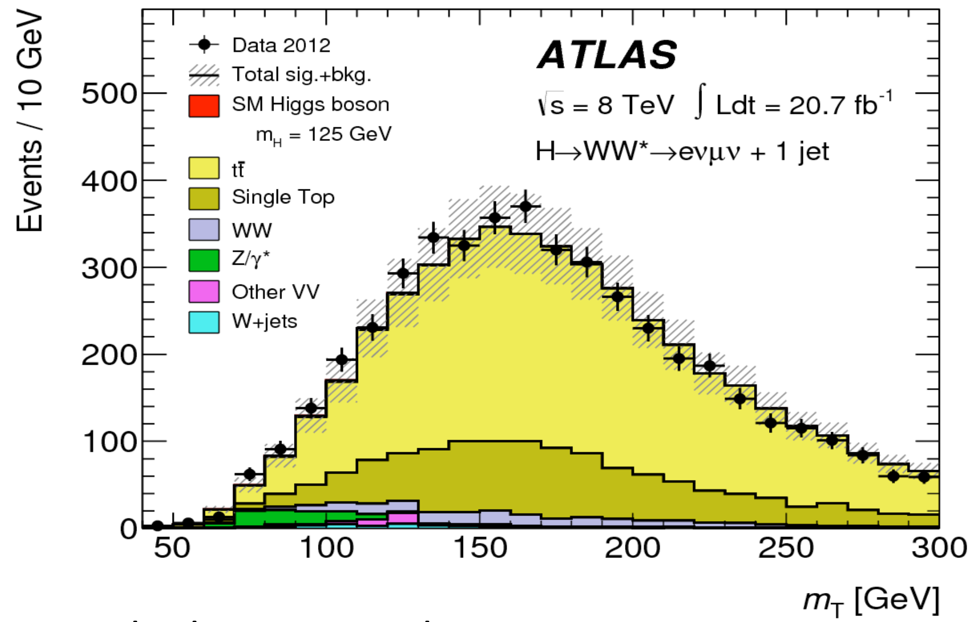




https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-067/

Top Estimate

- 0 jet top estimate is simulation corrected using jet veto survival probability (JVSF)
  - b jet control region is very pure in data
  - Measure jet survival probability in data and simulation
- JSVF Probability is small but has large uncertainty (17%)
- Ratio to simulation is 1.11+/- 0.19
- 1 jet uses a b-tagged CR



In the b tag control region,

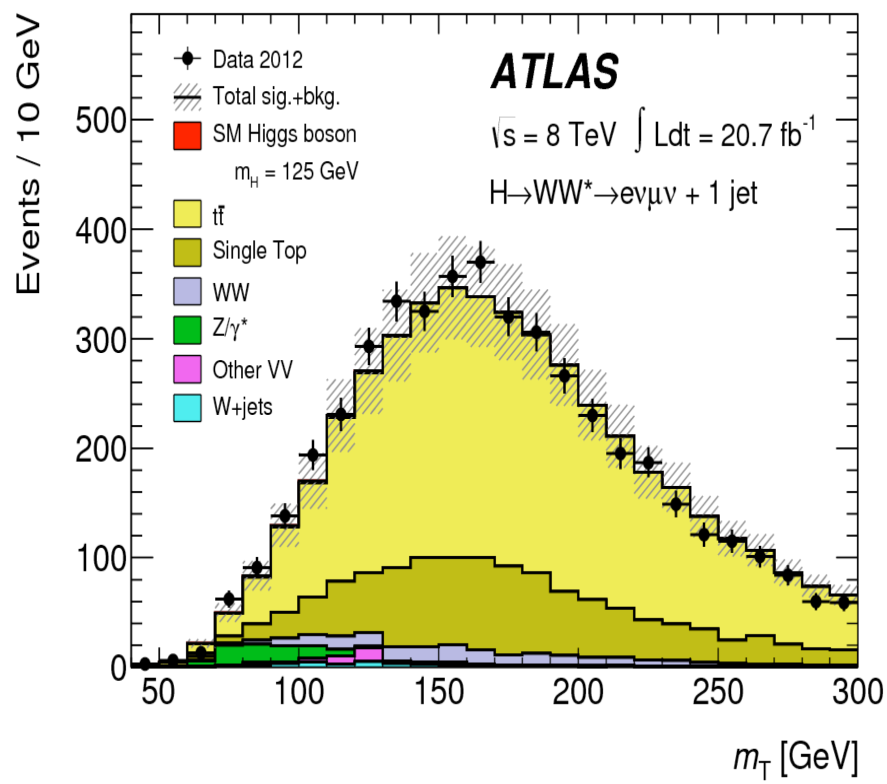
$$P^{b\text{-}tag} = \text{Prob(no additional jets)} = \frac{\text{No additional jets}}{\text{1 or more b tags}}$$

For the 0 jet top estimate,

$$Top\ estimate = N_{MC} * \left(\frac{P^{b-tag,\ Data}}{P^{b-tag,\ MC}}\right)^2$$

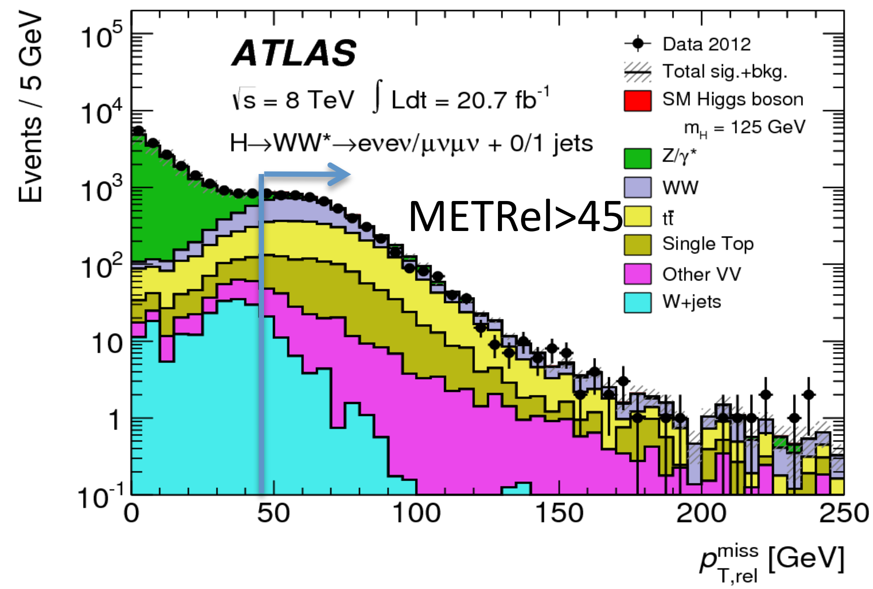
Top Estimate (continued)

- 1 jet analyses use b tagged jet events as a control region
  - Relax m_{ll} and $\Delta\phi_{ll}$ cuts
  - Kinematics are well modeled
  - Very pure top sample
  - Top background is normalized to the control region
    - 1.11 +/- 0.05 (stat) in 1 jet
    - 1.01 +/- 0.26 (stat) in 2 jet
  - Ratio of ttbar and single top is fixed by the simulation

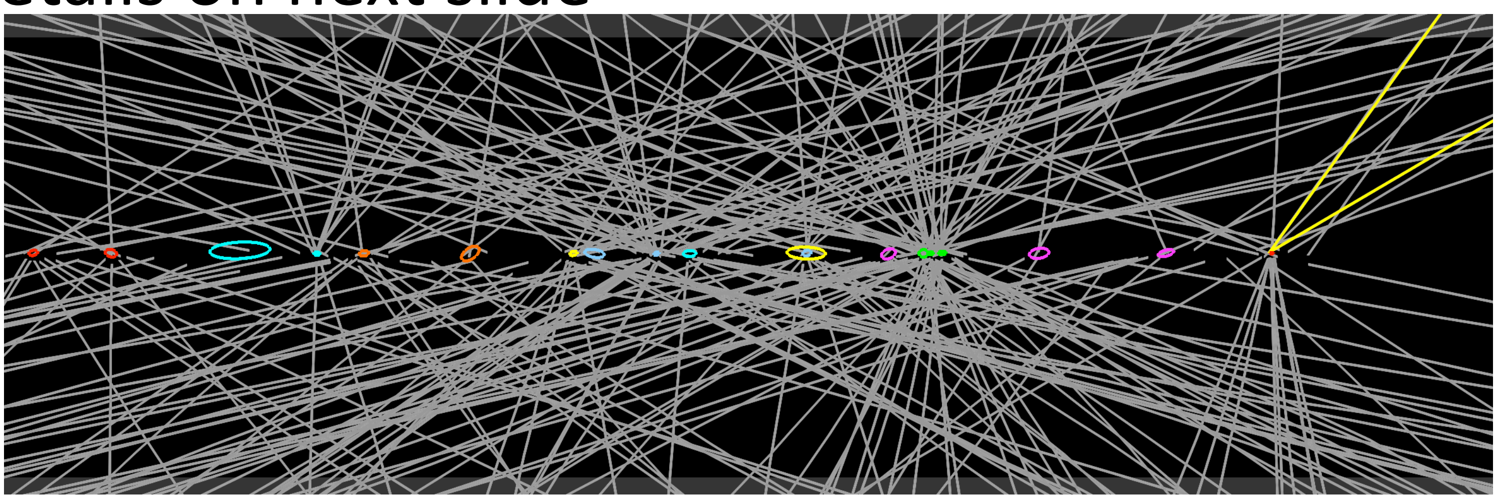


Same Flavor Channel

- ee and μμ swamped by DY background
- Adopt stringent MET cuts
  - METRel>45 GeV
- Measure hadronic recoil with soft jets (P_T>10 GeV)
  - Details on next slide



20 Collisions



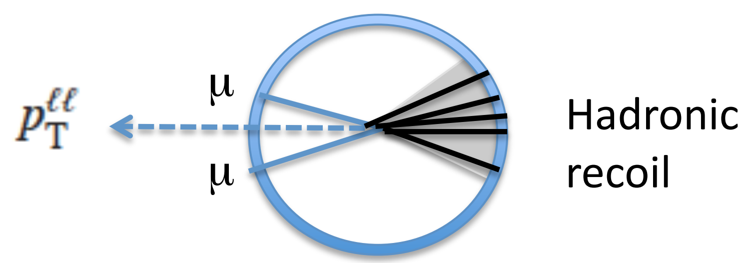
PacMan

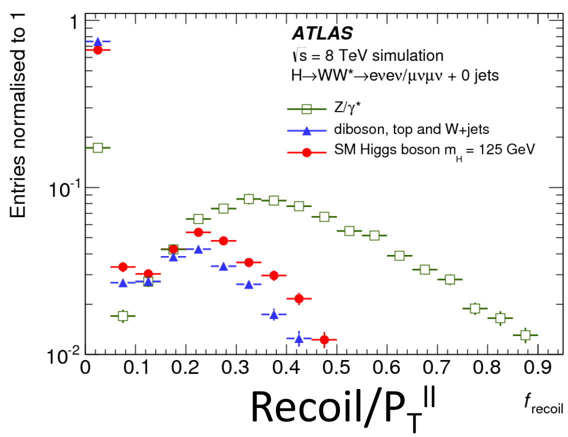
- Measures hadronic recoil
  - Reduces DY by a factor 5
- Adapted to 1j using P_T^{llj}
- Fit using data driven templates for normalization

Recoil Variable

Pileup weight

$$\frac{|\sum_{\text{jets with } p_T > 10\text{ GeV}} |\text{JVF}| \times \vec{p}_T^{\,\text{jet}}|}{p_T^{\ell\ell}}.$$





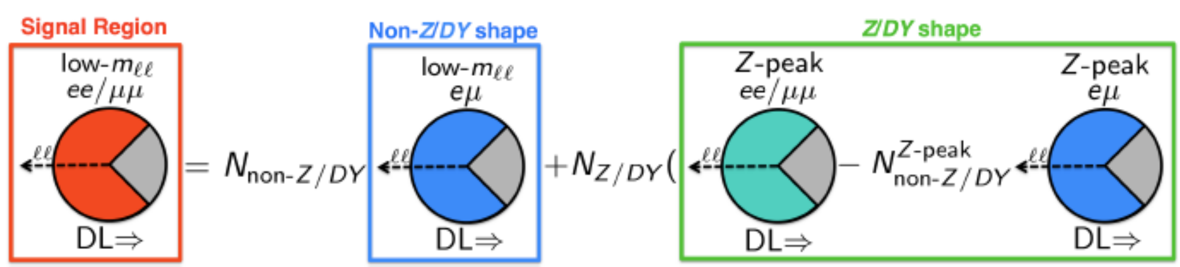


Figure 48: Scheme representing the Z/DY estimate procedure (the Pacman method).

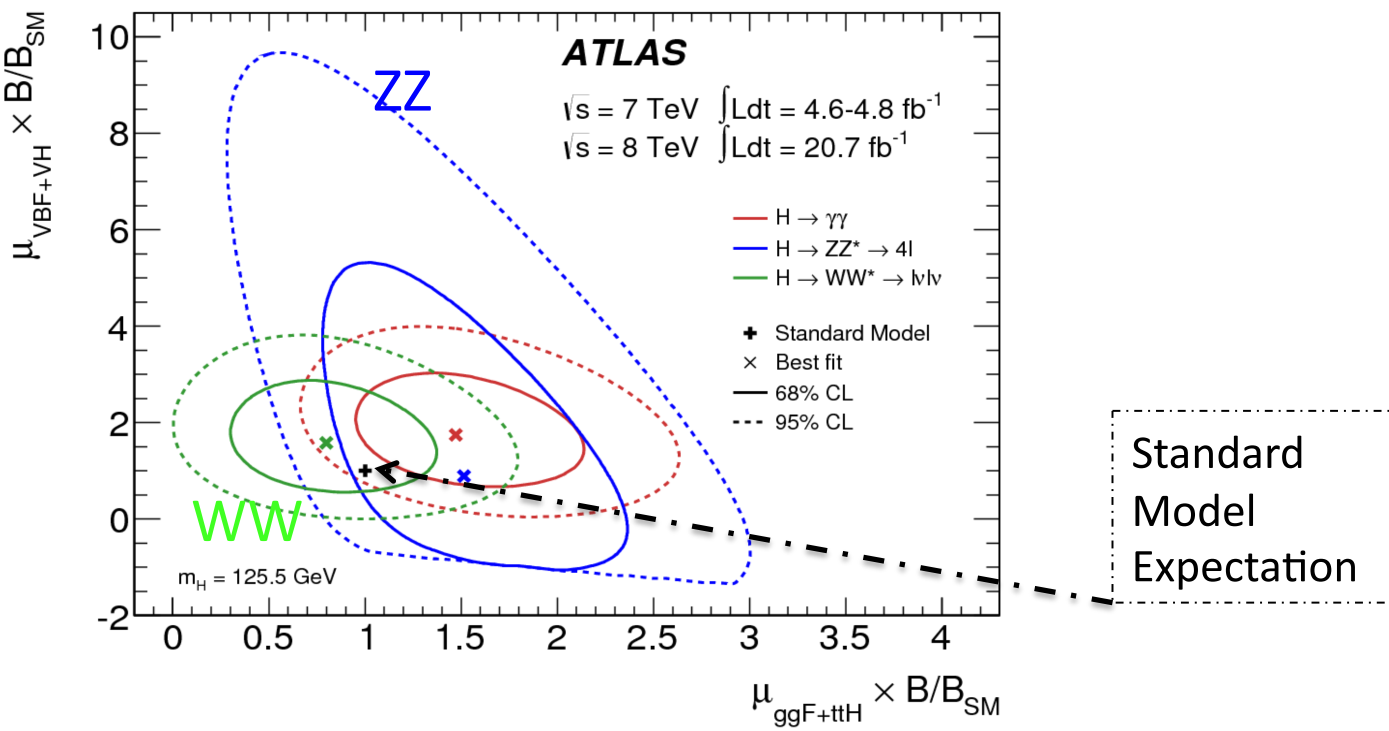
Coupling Results

WW

- WW has limited mass resolution
- μ_H= 1.0 +/- 0.3 at m_H = 125.5 GeV/c^2
  - μ_{VBF}= $1.6 \pm^{0.8}_{0.7}$

ZZ

- ZZ has very good mass resolution
  - 1 VBF with 120<m_{4l}<130 GeV
    - 0.4 VBF expected (S/B~1)
  - 1 VH Candidate (m_{4l}=270 GeV)
- μ_H= 1.4 +/- 0.4 at m_H = 125.5 GeV/c^2



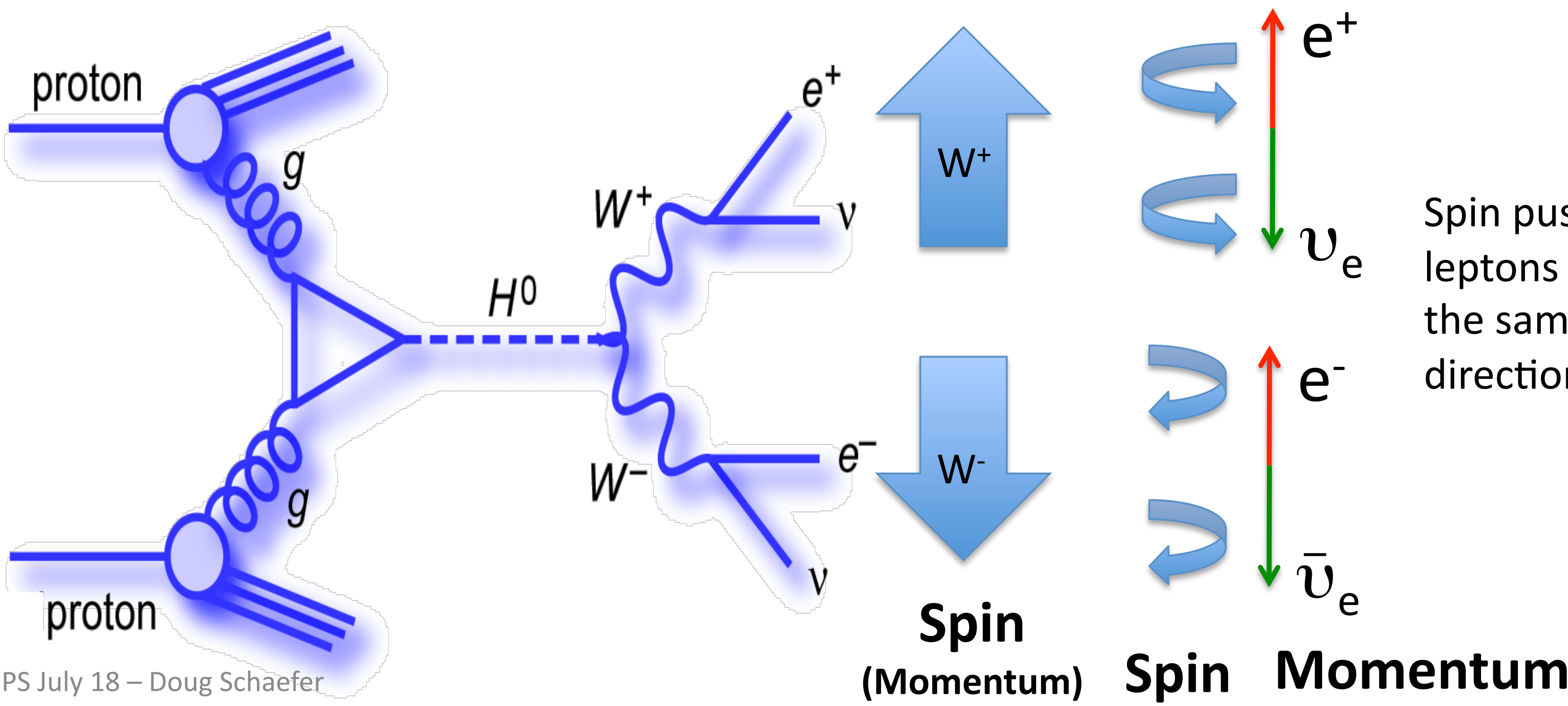
$H \rightarrow WW$ *Events*

Table 9: For the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis of the 8 TeV data, the numbers of events observed in the data and expected from signal ($m_H = 125.5$ GeV) and backgrounds inside the transverse mass regions $0.75\, m_H < m_T < m_H$ for $N_{jet} \leq 1$ and $m_T < 1.2\, m_H$ for $N_{jet} \geq 2$. All lepton flavours are combined. The total background as well as its main components are shown. The quoted uncertainties include the statistical and systematic contributions, and account for anticorrelations between the background predictions.

	$N_{jet} = 0$	$N_{jet} = 1$	$N_{jet} \geq 2$
Observed	831	309	55
Signal	100 ± 21	41 ± 14	10.9 ± 1.4
Total background	739 ± 39	261 ± 28	36 ± 4
WW	551 ± 41	108 ± 40	4.1 ± 1.5
Other VV	58 ± 8	27 ± 6	1.9 ± 0.4
Top-quark	39 ± 5	95 ± 28	5.4 ± 2.1
Z+jets	30 ± 10	12 ± 6	22 ± 3
W+jets	61 ± 21	20 ± 5	0.7 ± 0.2

H→WW Analysis Hinges on Spin

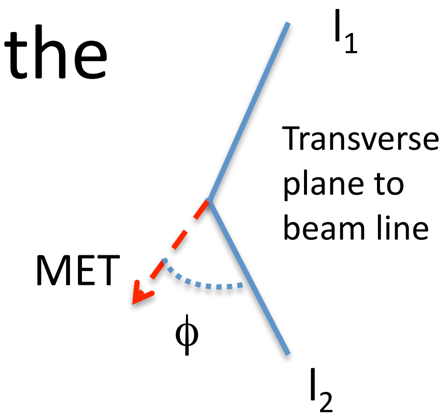
- Most cuts are motivated by the spin 0 nature of the Higgs boson
  - Weak (V-A) decays cause the leptons to be collinear
  - One lepton (e,μ) is opposite W momentum
  - Clean signature of 2 leptons + Missing Transverse Energy (MET)



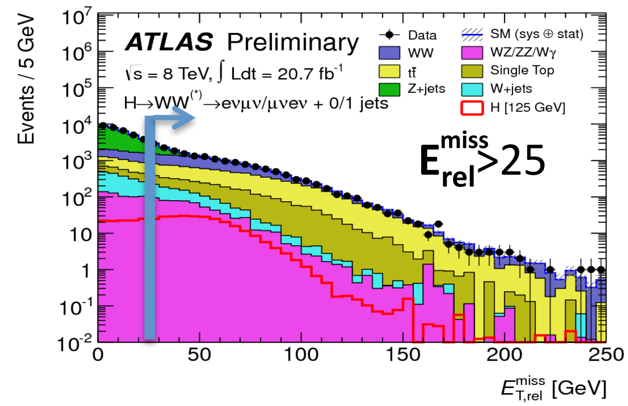
Spin pushes the leptons to be in the same direction

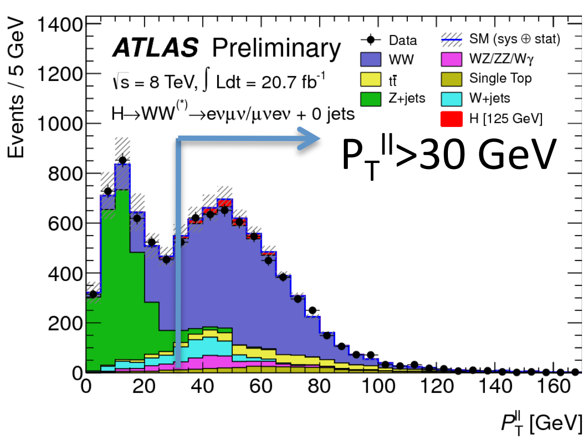
0 Jet Signal Selection

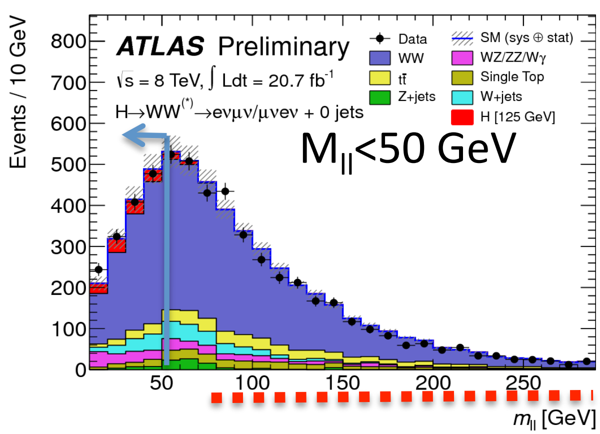
- E^{miss}_{rel} is sensitive to the direction of MET along objects
  - τ decays
- **Higgs spin+V-A decays provide collinear leptons**

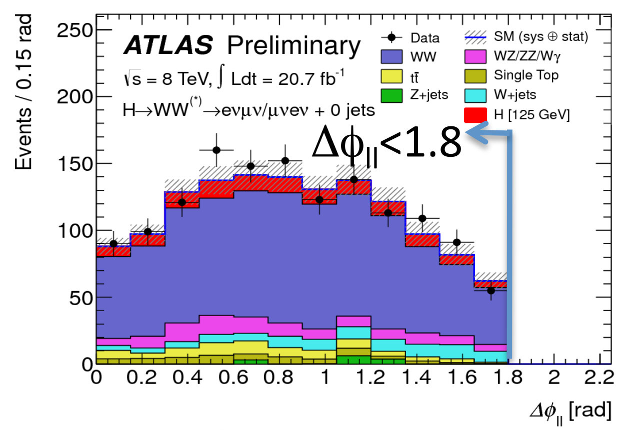


$$E^{miss}_{rel} = MET \times \begin{cases} 1, & \phi > \pi/2 \\ \sin\phi, & \text{else} \end{cases}$$





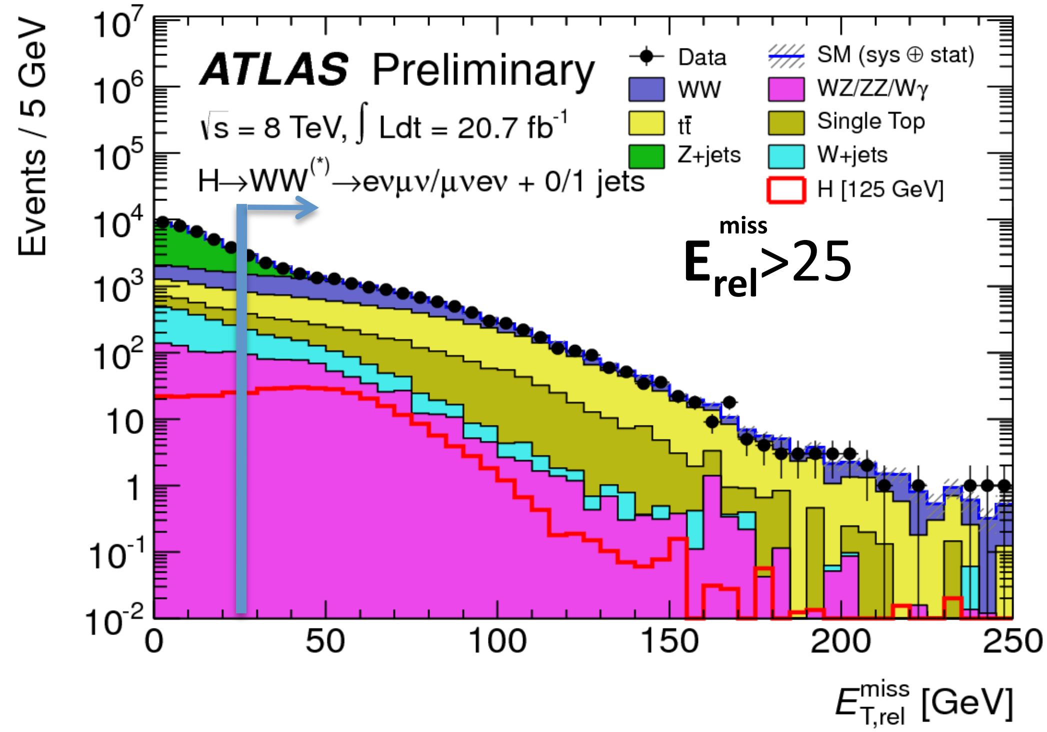


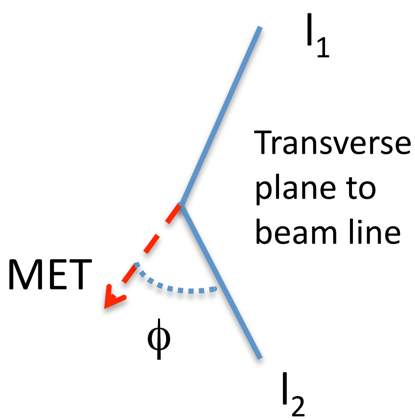


Increasing cut order

0 Jet Signal Selection

- E_{rel}^{miss} is sensitive to the direction of MET along objects
  - τ decays

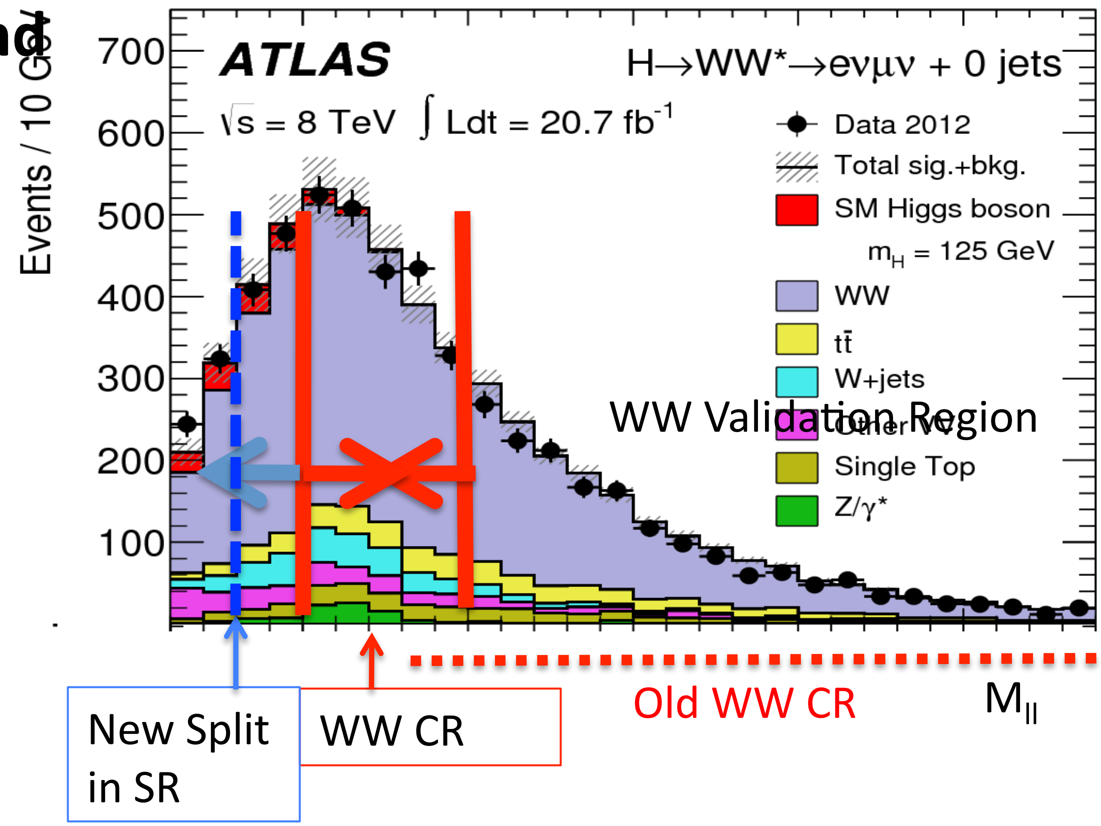




$$E_{rel}^{miss} = MET \times \begin{cases} 1, & \phi > \pi/2 \\ \sin\phi, & \text{else} \end{cases}$$

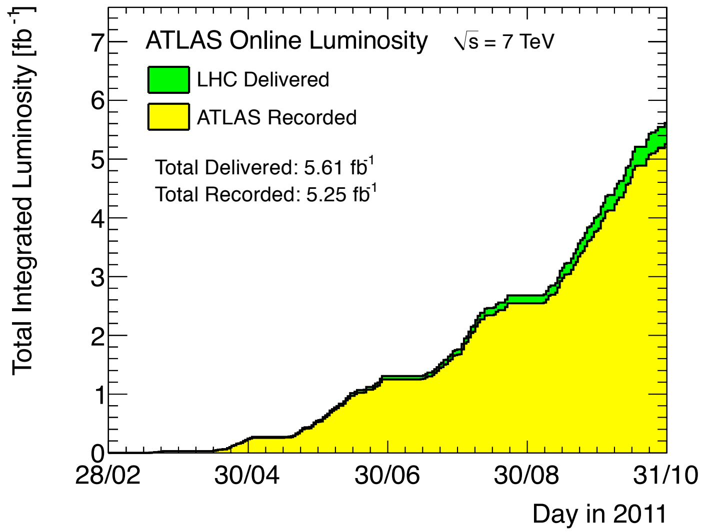
WW Modeling

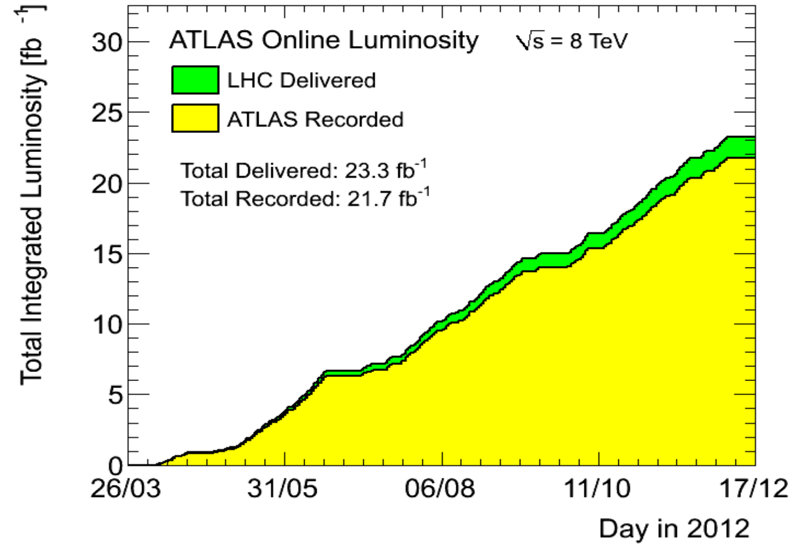
- **SR fraction of background**
  - 74% of 0 jet bkg
  - 38% of 1 jet bkg
- **Control region:**
  - $50<M_{ll}<100$ GeV (was $M_{ll}>80$)
  - Remove $\Delta\phi_{ll}$ cut
  - Closer to SR (reduced uncertainties)
  - Less pure (70% in 0j CR)
- **Normalization in CR**
  - 1.16+/- 0.04 (stat) in 0 jet
  - 1.03 +/- 0.06 (stat) in 1 jet



- **Total Uncertainty on WW**
  - 7.4% in 0jet
  - Includes theoretical and statistical shape uncertainties
  - Experimentally dominated

LHC Luminosity



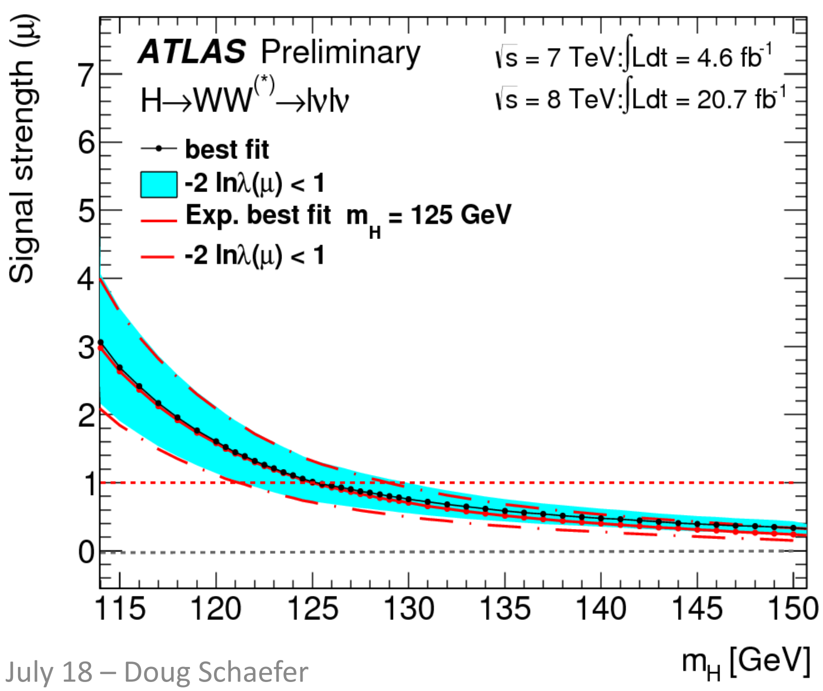


- ATLAS collected data with high efficiency and good data quality
- Presented results combine 4.6 fb^{-1} of 2011 7TeV and 20.7 fb^{-1} of 2012 8 TeV data
- Now wait until 2015 for 14 TeV data

2011+2012 Signal Strength Results

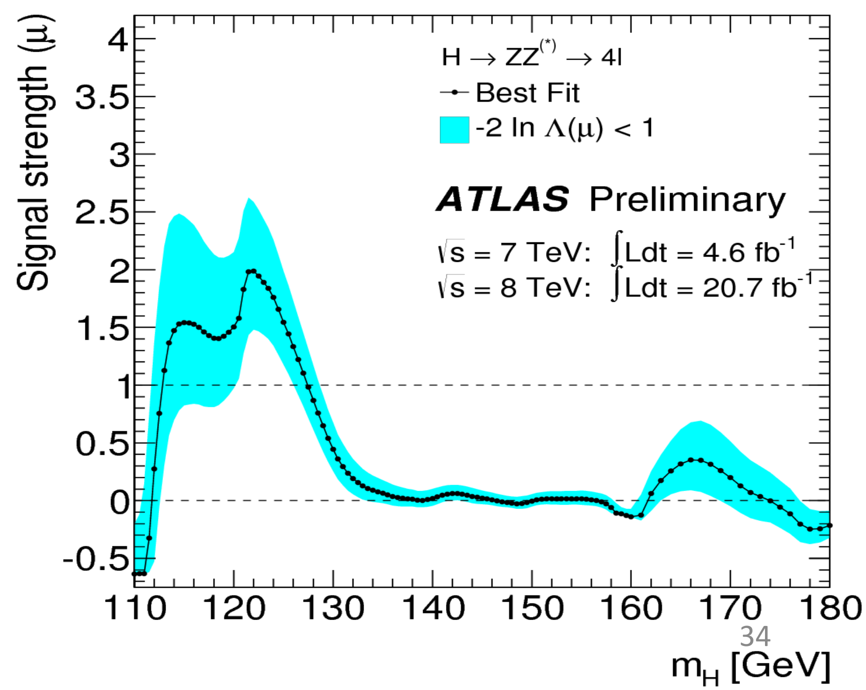
WW

- WW has limited mass resolution
- Signal strength at m_H = 125 GeV/c^2 is 1.0 +/- 0.3



ZZ

- ZZ has very good mass resolution
- Signal strength at m_H = 125.5 GeV/c^2 is 1.5 +/- 0.4



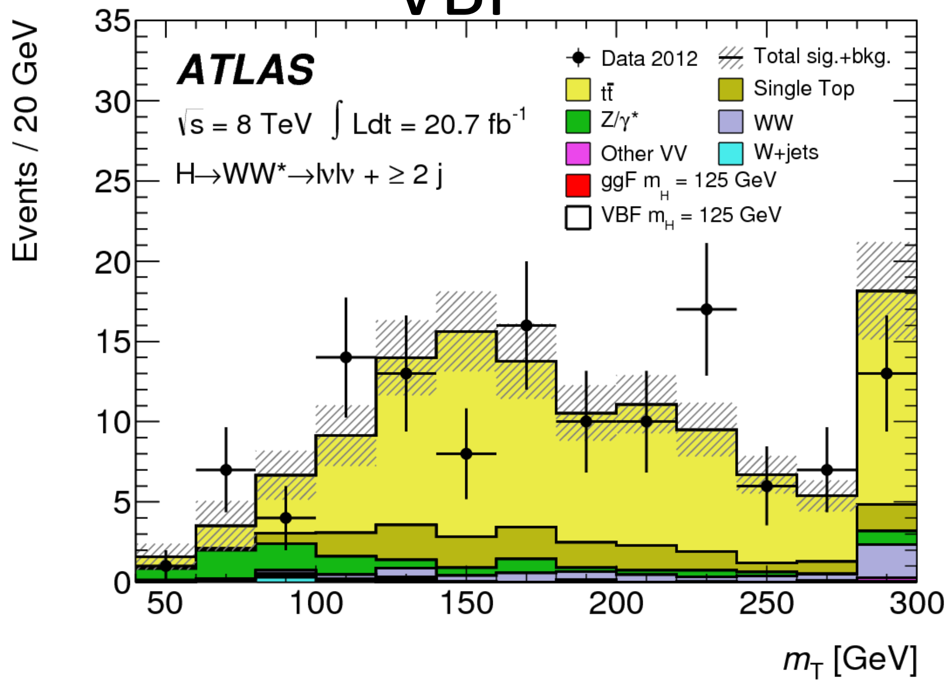
Uncertainties on Signal and Background

- Dominant systematics are signal theoretical uncertainties
- Largest detector systematic is WW normalization and W+Jets uncertainty

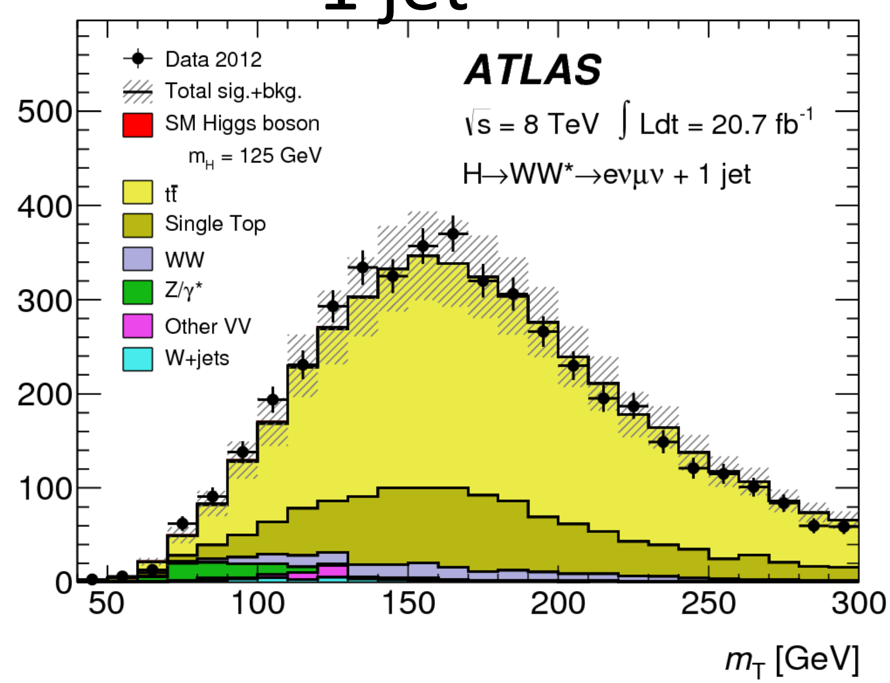
Uncertainties on combined $\hat{\mu}$		
Source	σ_{up} (%)	σ_{down} (%)
Statistical uncertainty	+22	-21
Signal yield ($\sigma \cdot \mathcal{B}$)	+13	-10
Signal acceptance	+9	-7
WW normalisation, theory	+12	-12
Other backgrounds, theory	+4	-4
W+jets fake rate	+4	-6
Experimental + bkg subtraction	+9	-9
MC statistics	+7	-8
Total uncertainty	+31	-29

HWW Top CRs

VBF

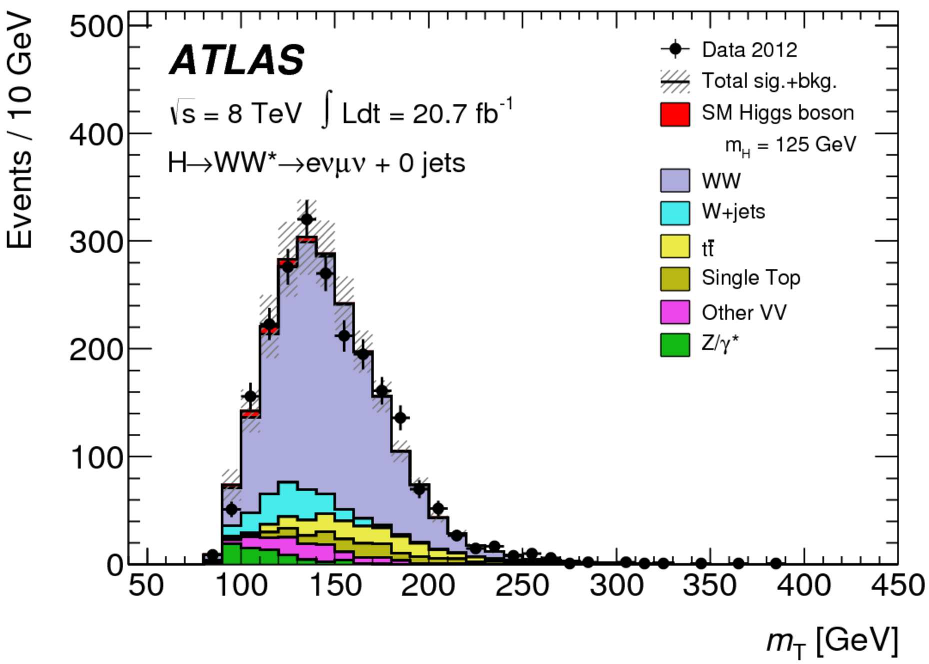


1 jet

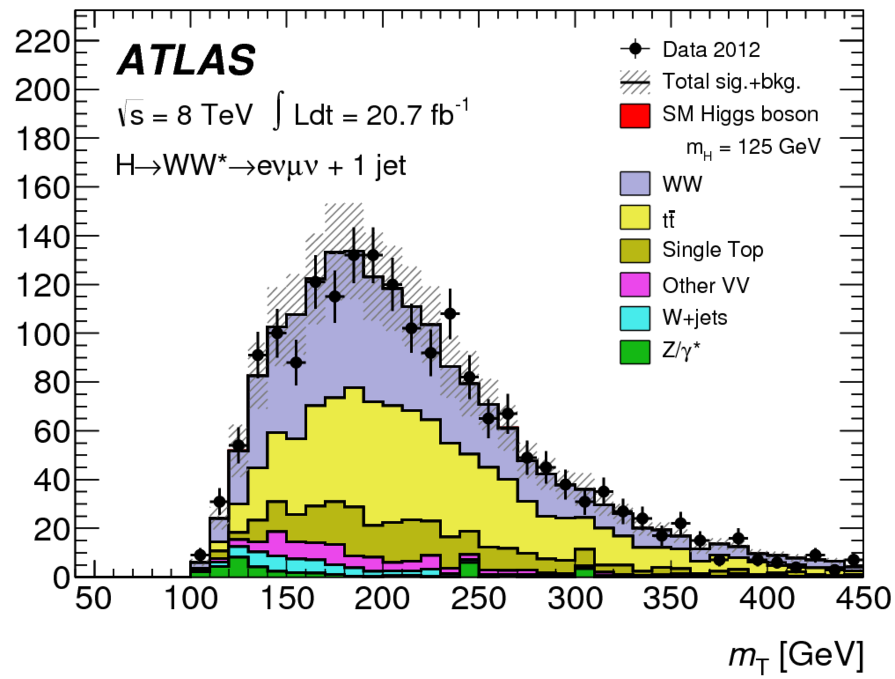


HWW WW CRs

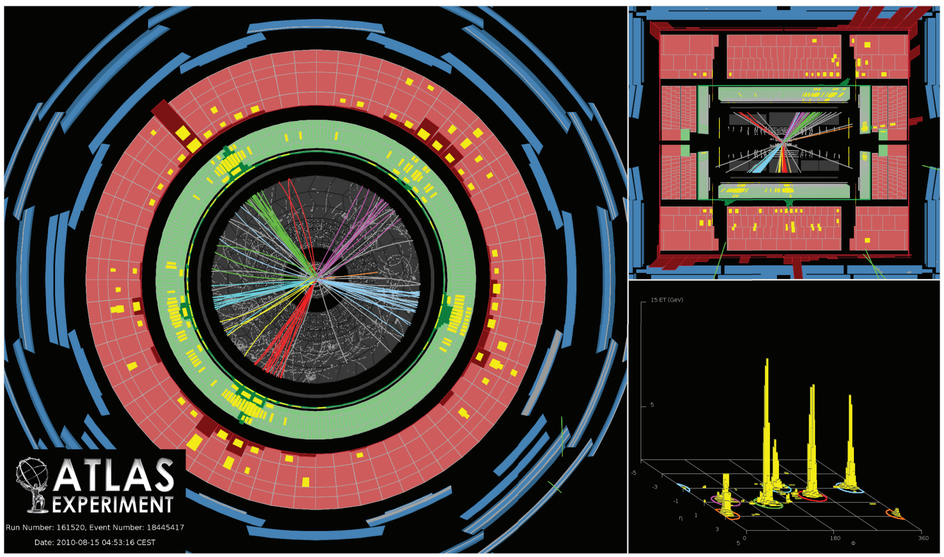
0 jet



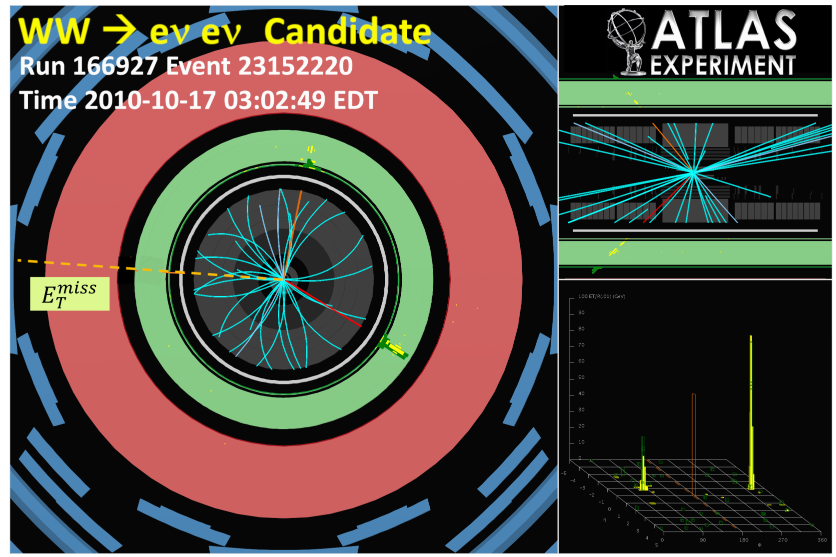
1 jet



W+Jet Modeling



Multi-Jet Event

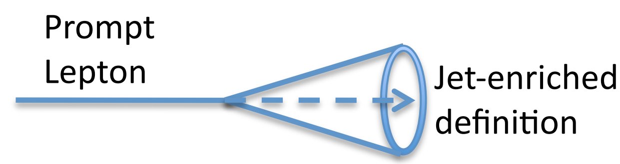


Electron Candidates

- W+Jet→lν jet (jet fakes lepton)
- Gluon and quark showering (jets) can mimic the signature of an isolated electron or muon
- Does not happen very often, but we have a lot of jets!

W+Jet Modeling (continued)

$$N_{W+Jets} = \sum_{i}^{Events} f_{jet}(\quad)$$



f_{jet} is the "transfer factor" from jet enriched leptons to our isolation definitions.

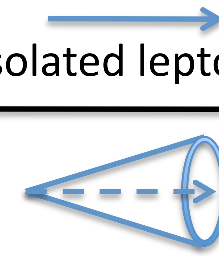
- Important background
  - Kinematics are very similar to low mass Higgs
  - Not modeled well by simulation (MC)
- Data driven method
  - Model jets imitating prompt leptons using a "transfer factor"
  - Predict all kinematic distributions
  - Make the same event selections to these events

W+Jet Modeling (continued)

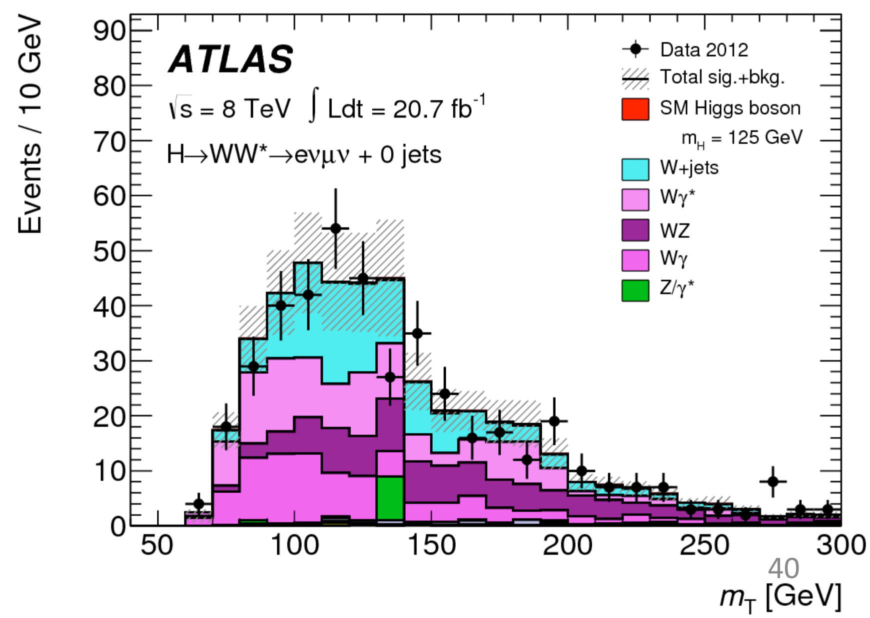
- ~40% uncertainties in "transfer factor"
  - Differences in jet P_T spectrum
  - Differences in jet flavor composition
- Modeling is validated with same sign lepton pairs

Measure in a multi-jet sample

$$f_{jet} = \frac{\text{(Isolated leptons)}}{\text{("jet-enriched" leptons)}}$$

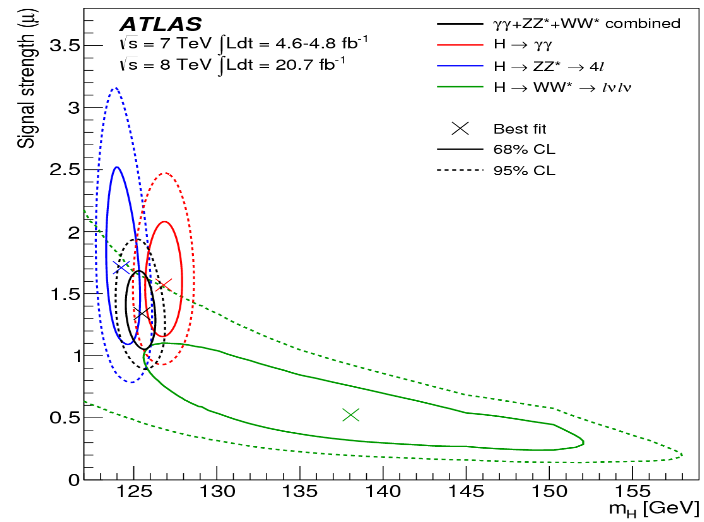


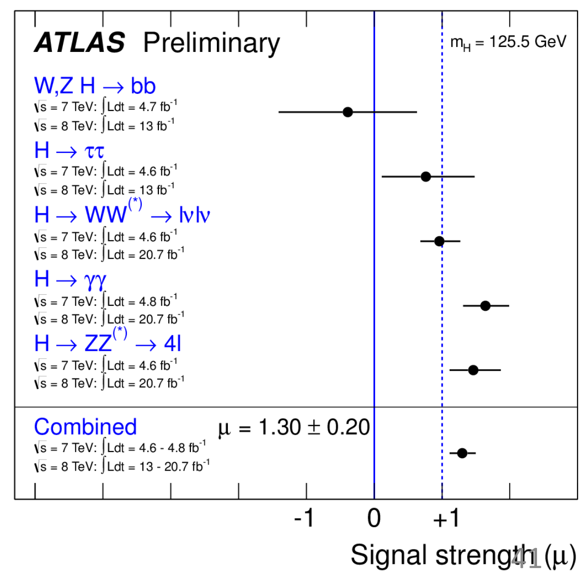
Same Sign Validation



Signal Strength Across Analyses

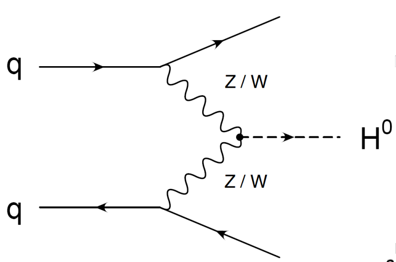
- Combine 2011 and 2012 data
- H->WW
  - Does not have mass resolution
  - Has the best estimate of signal strength because of the large branching fraction
- All analyses are consistent with a standard model Higgs



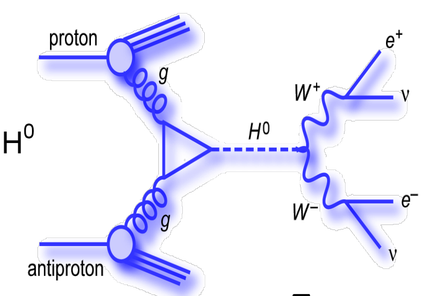


Compare ggF to VBF

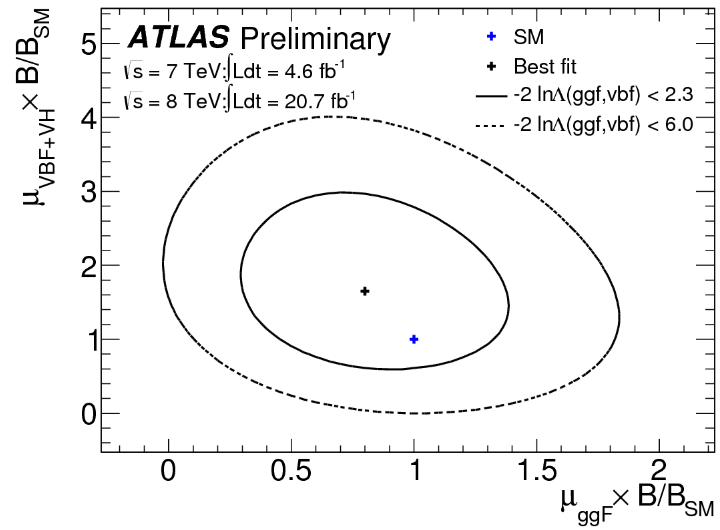
- Currently, we have more sensitivity to the gluon-gluon fusion (ggF)
  - ggF is sensitive to new physics
- VBF limit is dominated by the 2 jet limit

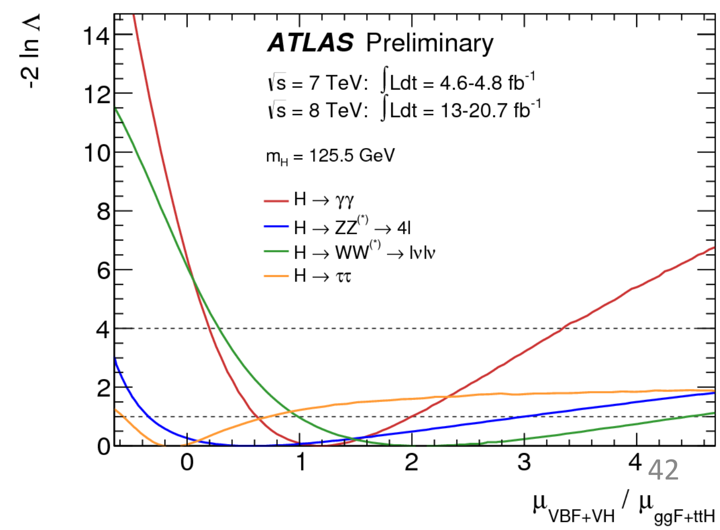


VBF



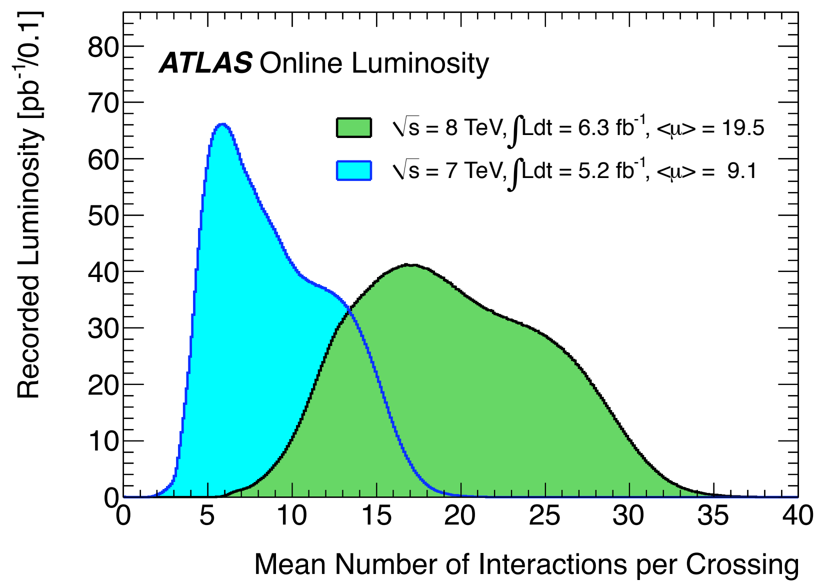
ggF



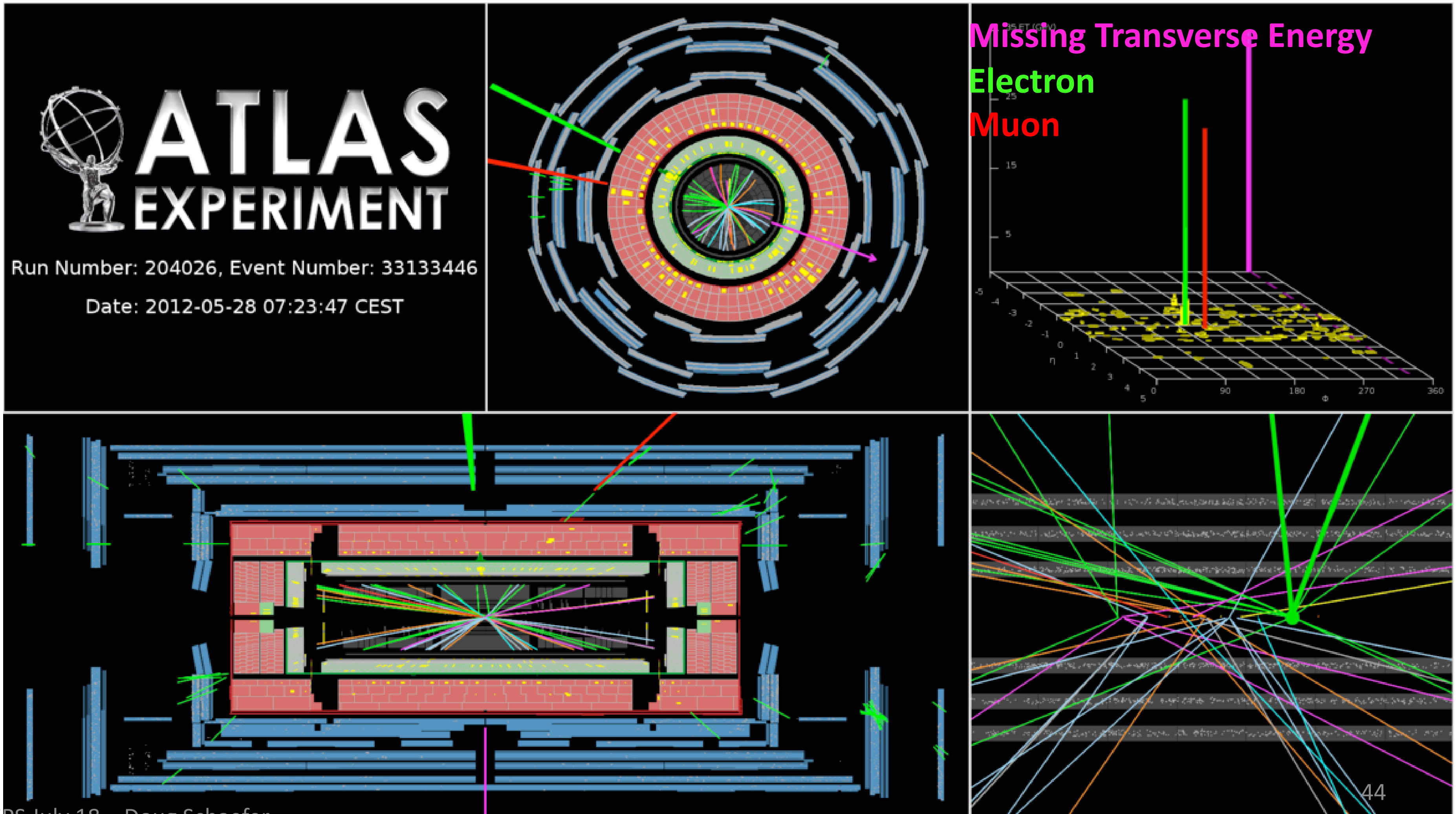


Event Selection

- In 2011, same and opposite flavor channels were used
- In 2012, increase interactions per proton bunch crossing adversely affected the missing transverse energy (MET) resolution
  - Same flavor has special treatment
- The following slides show the event selection for 2012 8 TeV data VBF channel

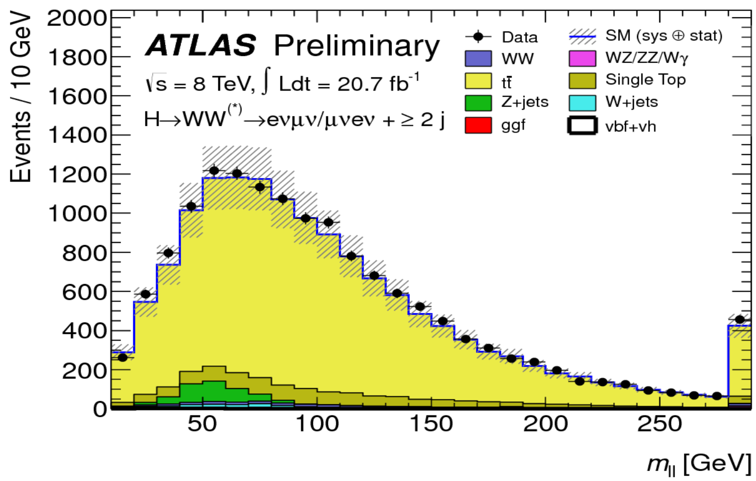


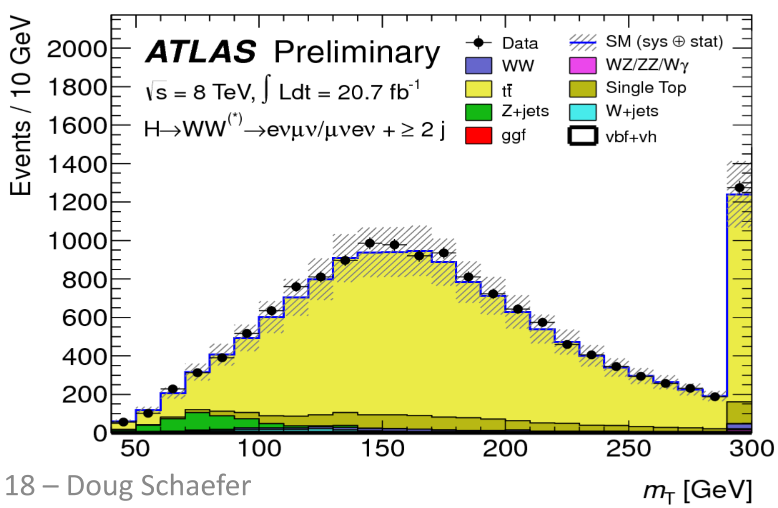
eμ Event Display

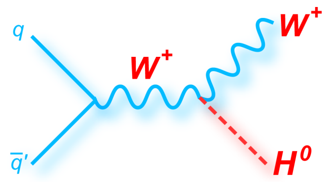


Data Driven Top Normalization

- Use 1 btagged jet sample to normalize top at each cut
- Top is NLO generator, so it is not expected to get 2 or more ISR/FSR correct.
  - Derive an uncertainty by comparing to Alpgen, Sherpa, and Powheg ttbar

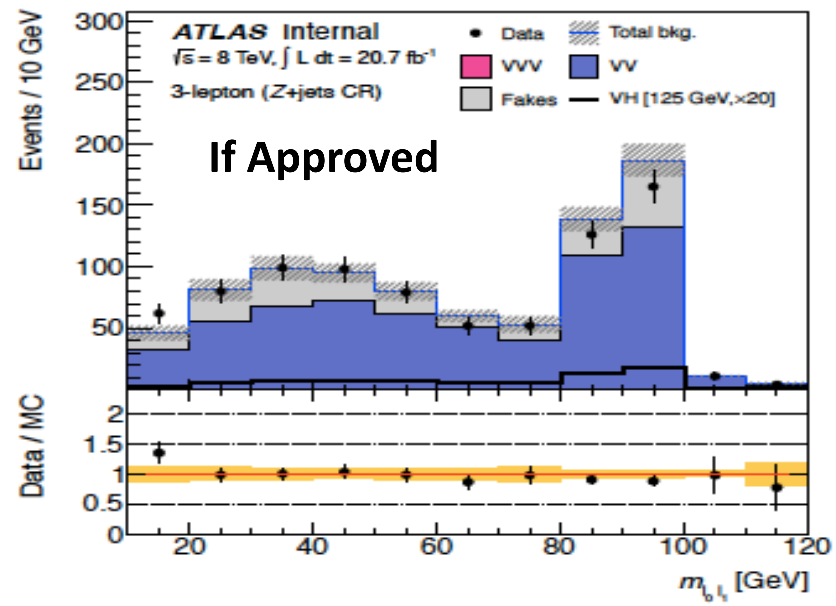


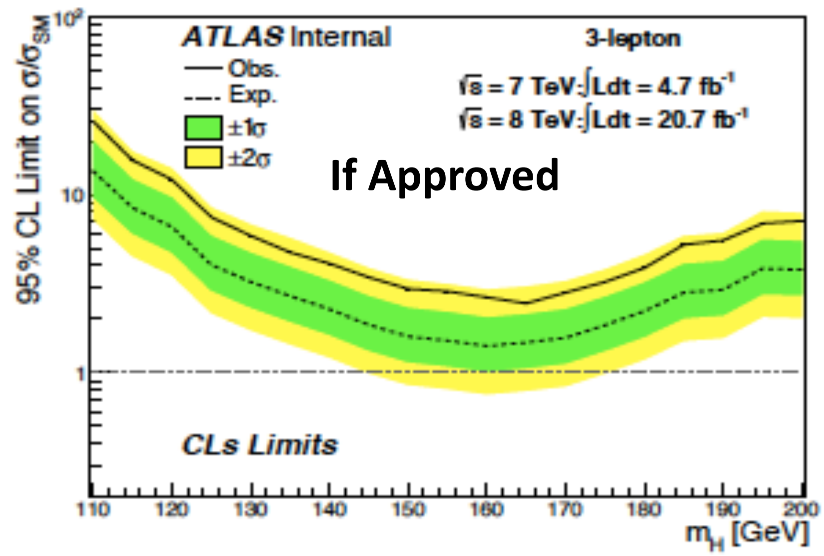




WH Higgs Strahlung Analysis

- Sensitive to direct Higgs to W coupling (no loops)
- WH→$l\nu l\nu l\nu$
  - Search for 3 isolated leptons+MET
- Split analysis into Z enriched and Z depleted regions
- Current expected limit is 4.0 σ_{SM} and observed is 7.5 at m_H = 125
  - 1.7 σ excess
  - Excess is mainly from the Z depleted region

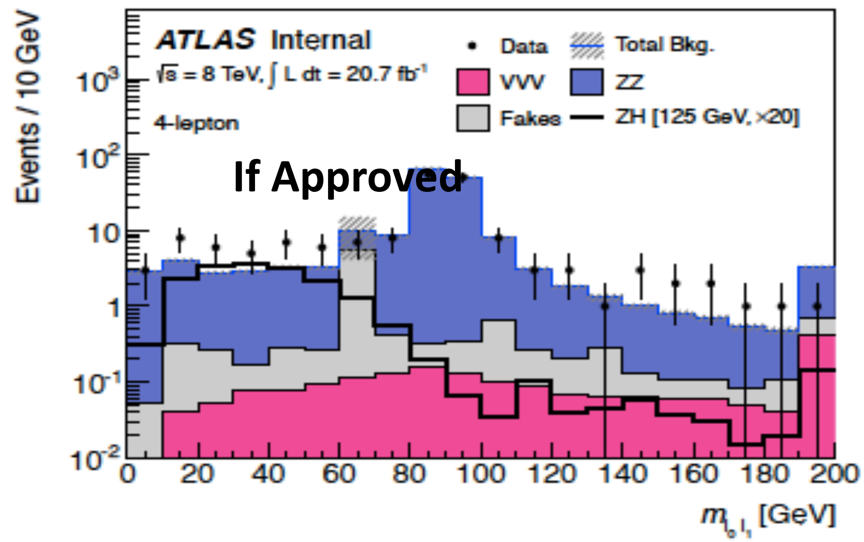


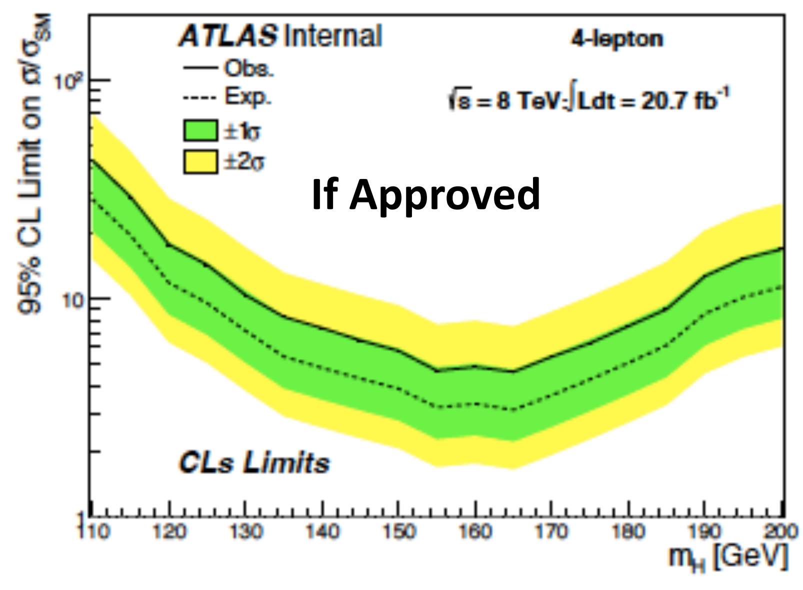


Previously 2011 only

ZH Higgs Strahlung Analysis

- Sensitive to direct Higgs to Z/W coupling (no loops)
- ZH→$ll\ l\nu l\nu$
  - Search for 4 isolated leptons+MET
- Split analysis into 1 SF OS and 2 SF OS pairs
  - Low M_{ll} for H->WW leptons
- Current expected limit is 9.6 σ_{SM} and observed is 14.3 at m_H = 125
  - 1.5 σ excess





Previously 2011 only