Looking for the Higgs in WW decays at ATLAS

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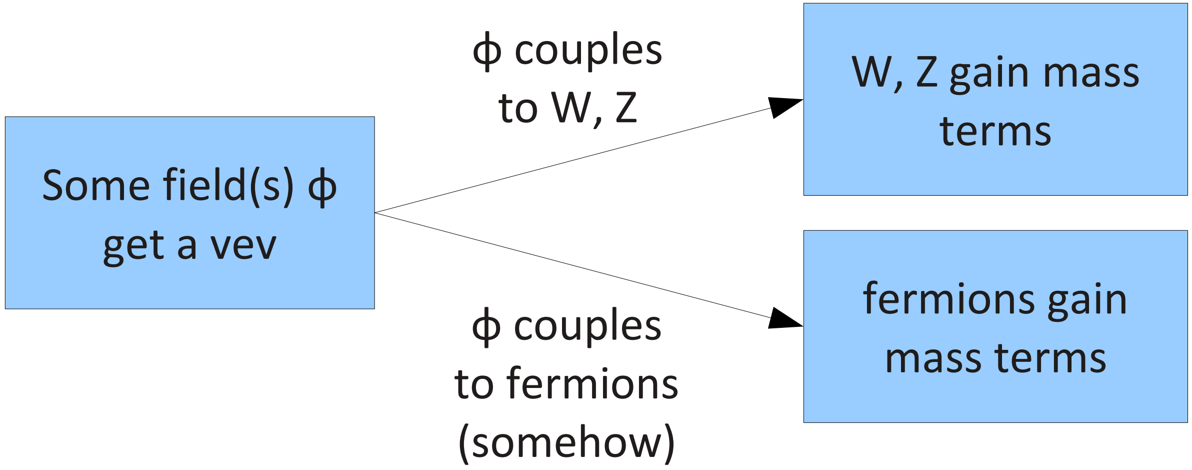
Cornell, 27 Mar 2012

ATLAS EXPERIMENT

http://atlas.ch

Electroweak Symmetry Breaking

- Electroweak symmetry breaking lies at the heart of the extremely successful Standard Model
  - required to give masses to the gauge bosons W and Z; also a way to get masses for chiral fermions
  - much BSM work has revolved around the details of EWSB



The SM Higgs mechanism is (one) implementation of this scheme

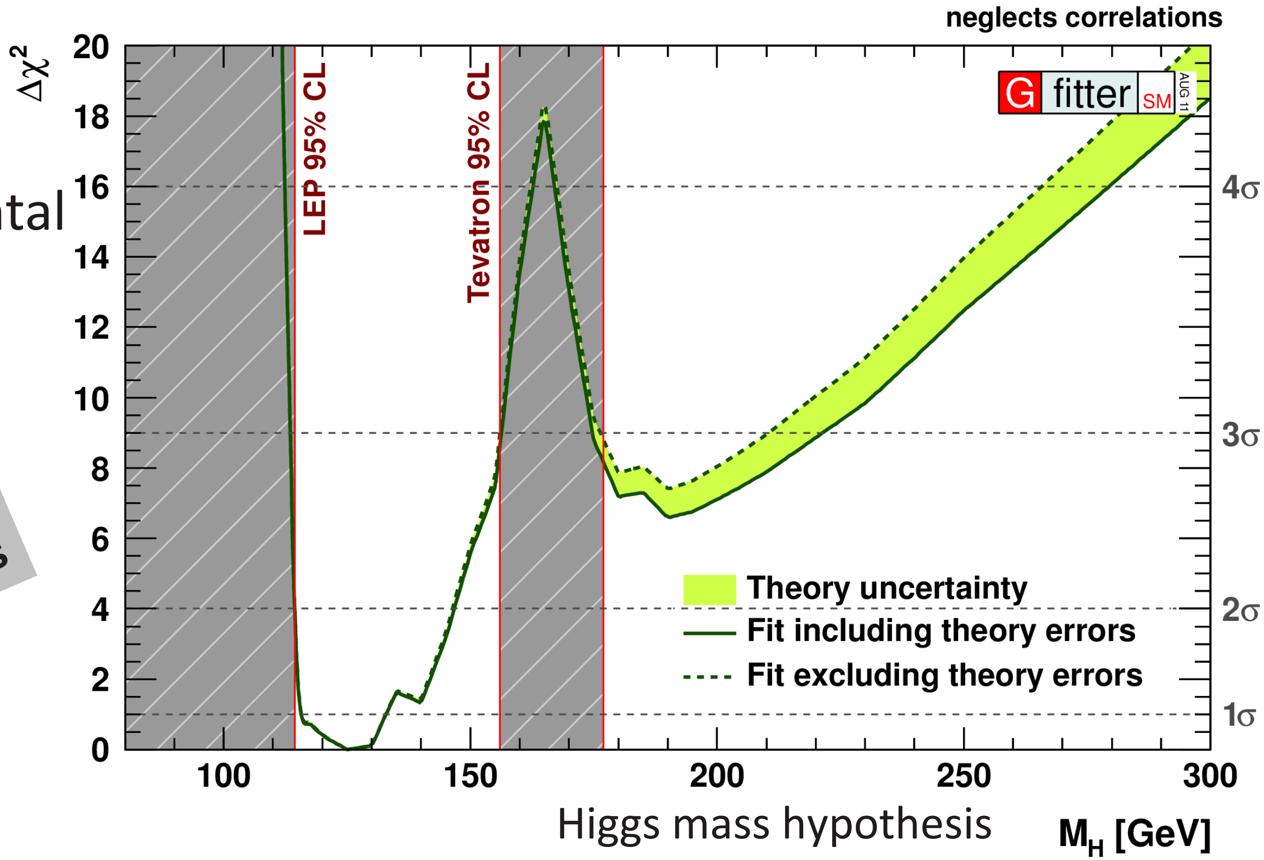
Why the SM Higgs?

- It's cheap (one scalar doublet, one free parameter)
- It's consistent with all available data
- Usually one MSSM Higgs ≈ SM Higgs
- It's a useful benchmark for developing searches for gauge boson resonances

Knowledge before the LHC

Direct exclusion from experimental searches

Doesn't include Winter 2012 Tevatron results



Higgs mass hypothesis

$\Delta\chi^2$ of global electroweak fit + direct exclusion

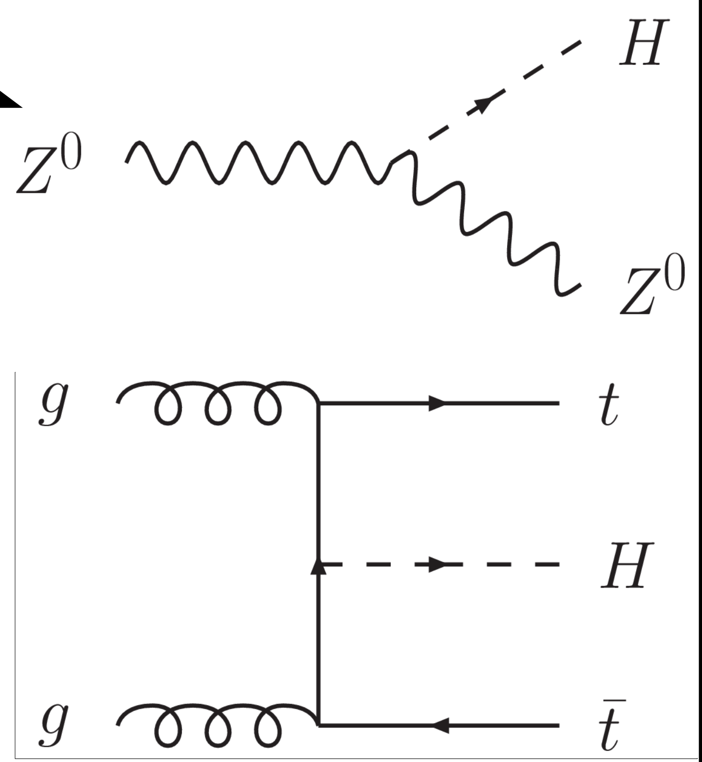
Global electroweak fit favors low mass Higgs

How to Make a Higgs

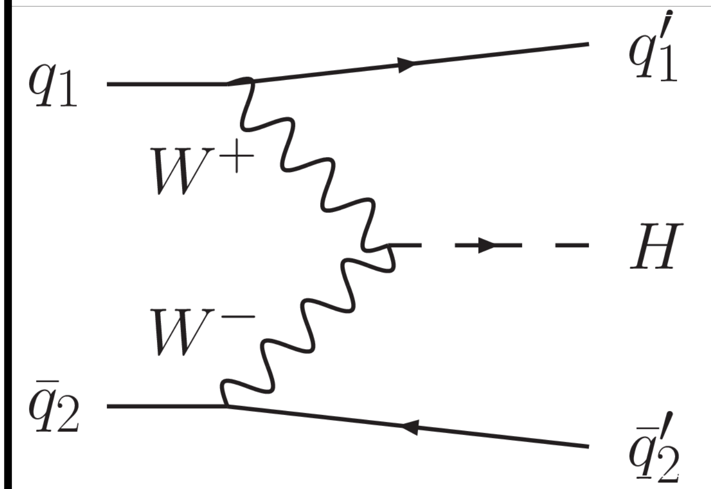
Heavy particles needed.

Dominant in e^+e^-

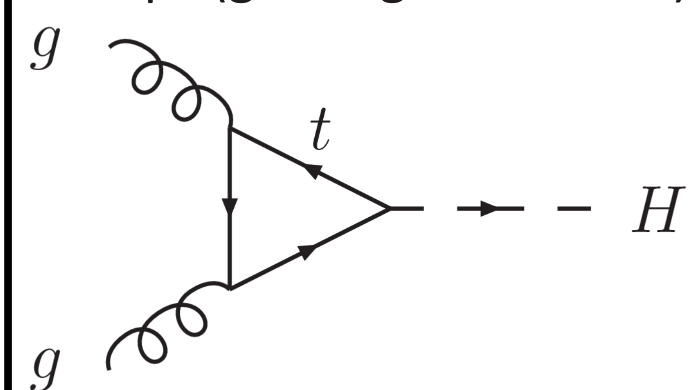
Associated production



Vector boson fusion

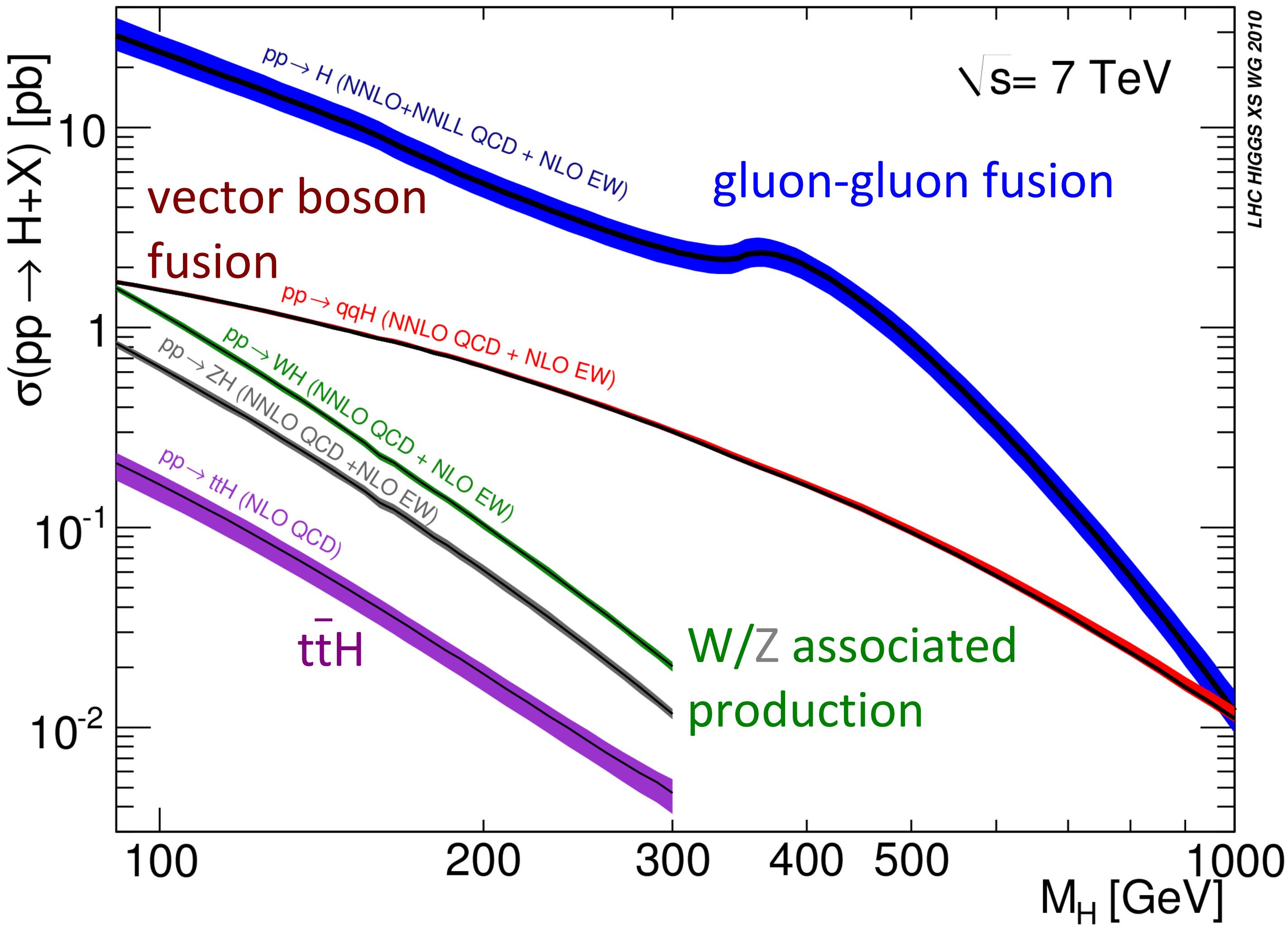


Loops (gluon-gluon fusion)



Dominant at LHC

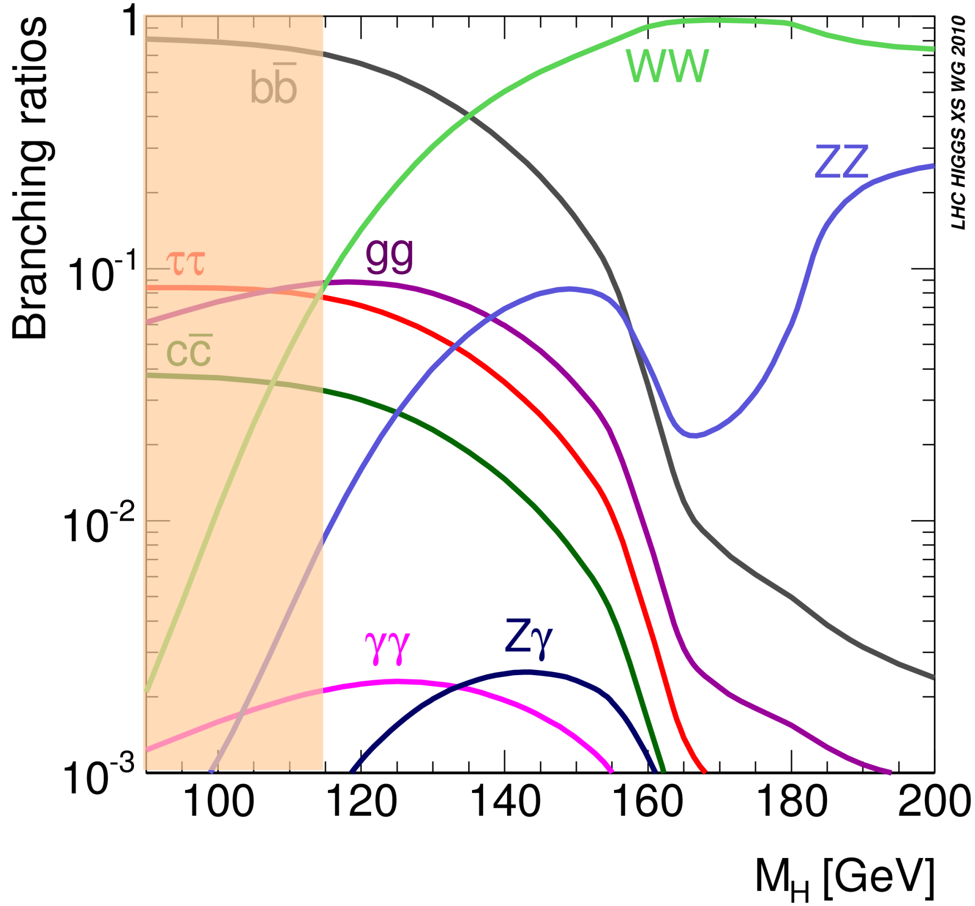
LHC Higgs Production



At 14 TeV, rates are 3x-10x bigger

Higgs Branching Fractions

LHC Higgs WG



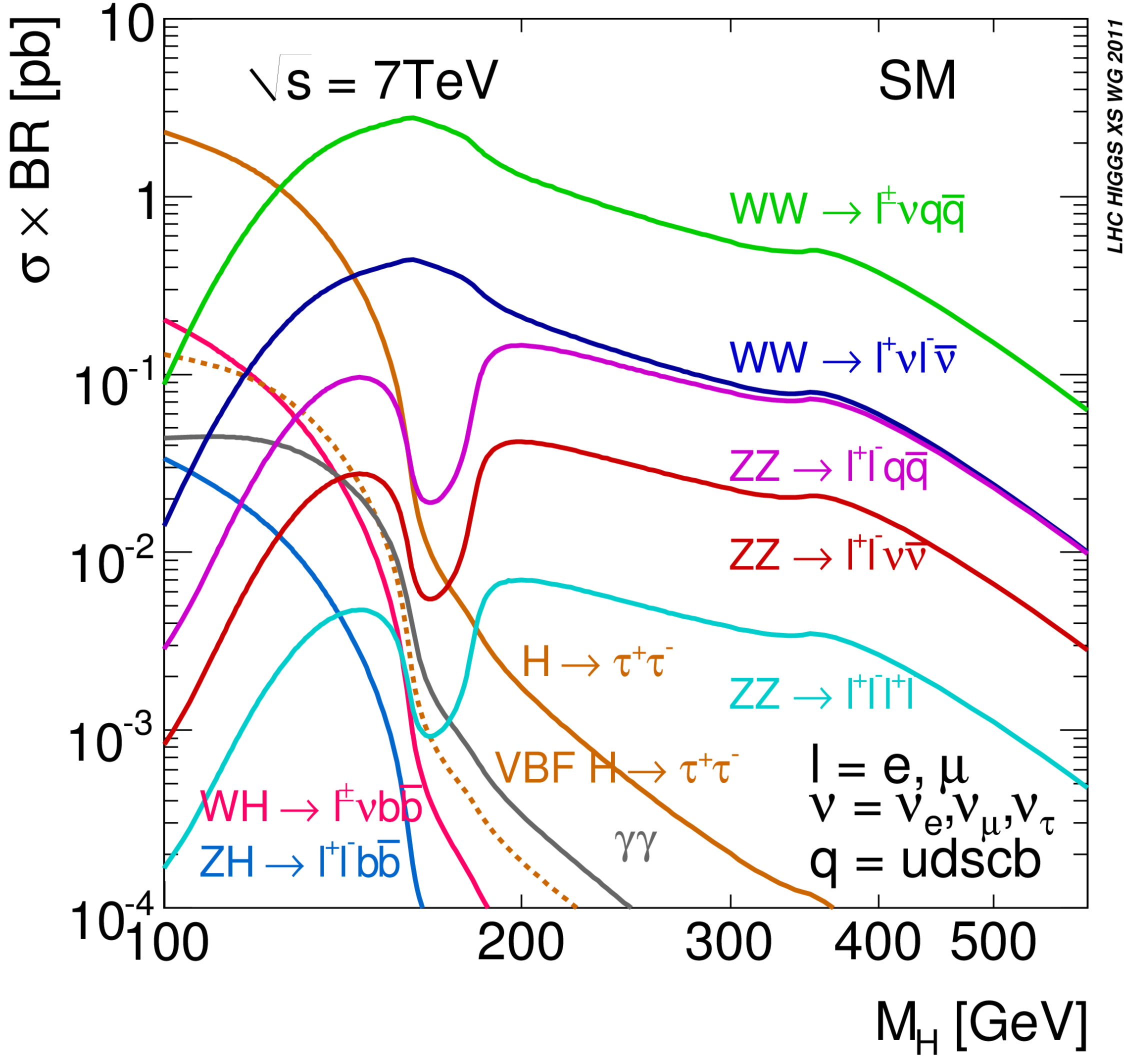
LEP exclusion

BR(H → WW) ~ 10% (or much higher) in entire LEP-allowed region

Motivation for ℓνℓν

Less boosted objects
Harder to do $q\bar{q}$, $Z \rightarrow \nu\nu$

More boosted objects
Can discriminate $q\bar{q}$, $Z \rightarrow \nu\nu$



For $120 < M_H < 200$ GeV, ℓνℓν generally most powerful channel

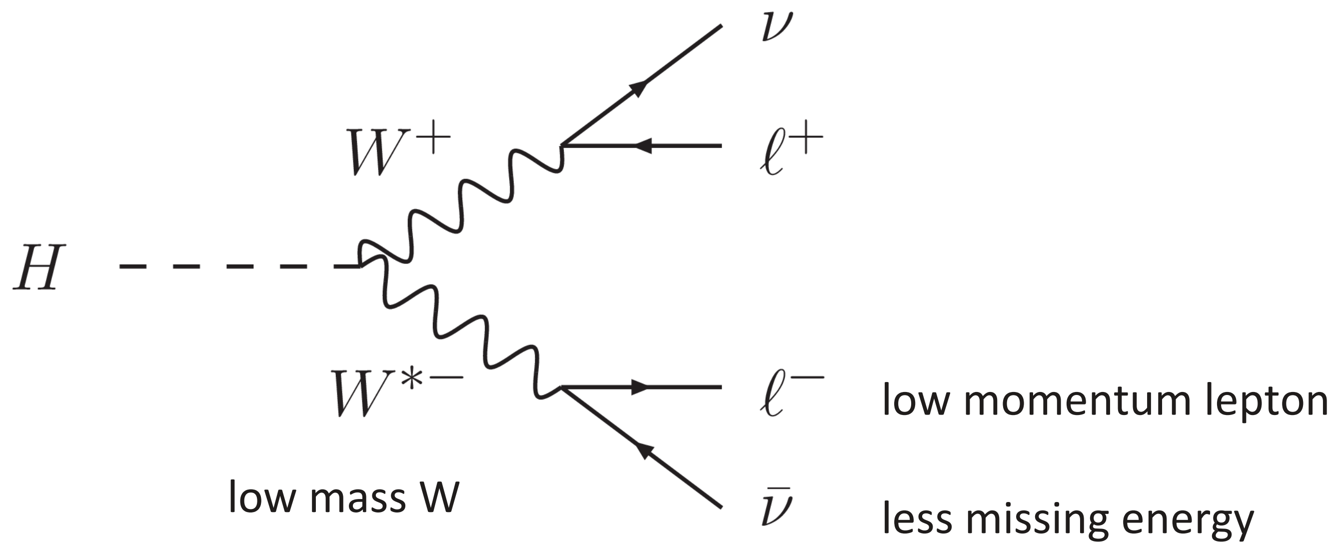
accessible in gluon-gluon fusion

Low Mass WW/ZZ

How does H → WW or ZZ happen for $m_H < 2m_W$ or $2m_Z$?

- One of the gauge bosons is a virtual W* or Z* with a low mass.
- Its decay products will have low momentum.

→ Asymmetric lepton momentum selection



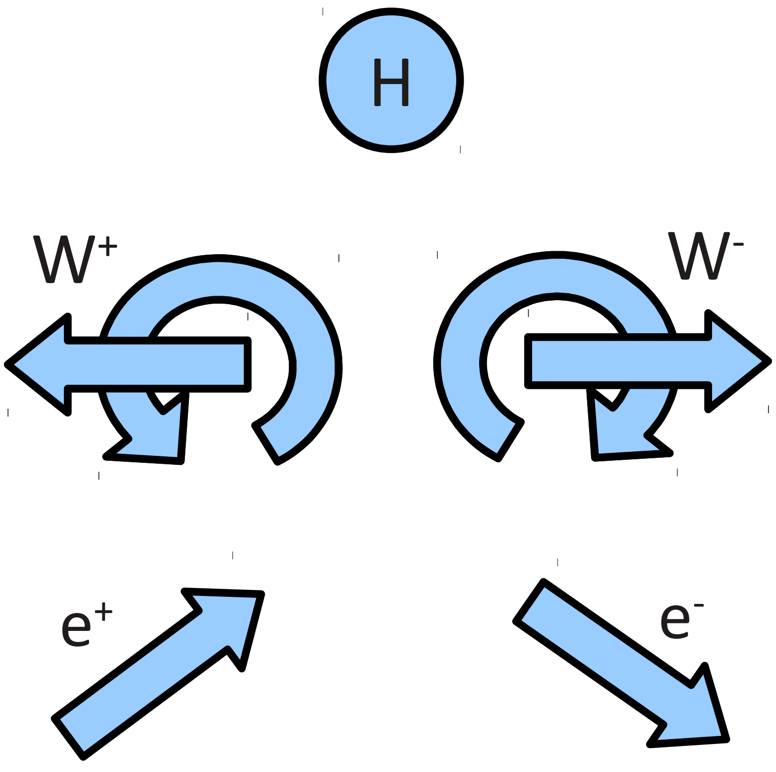
$H \rightarrow WW \rightarrow \ell\nu\ell\nu$ @ LHC

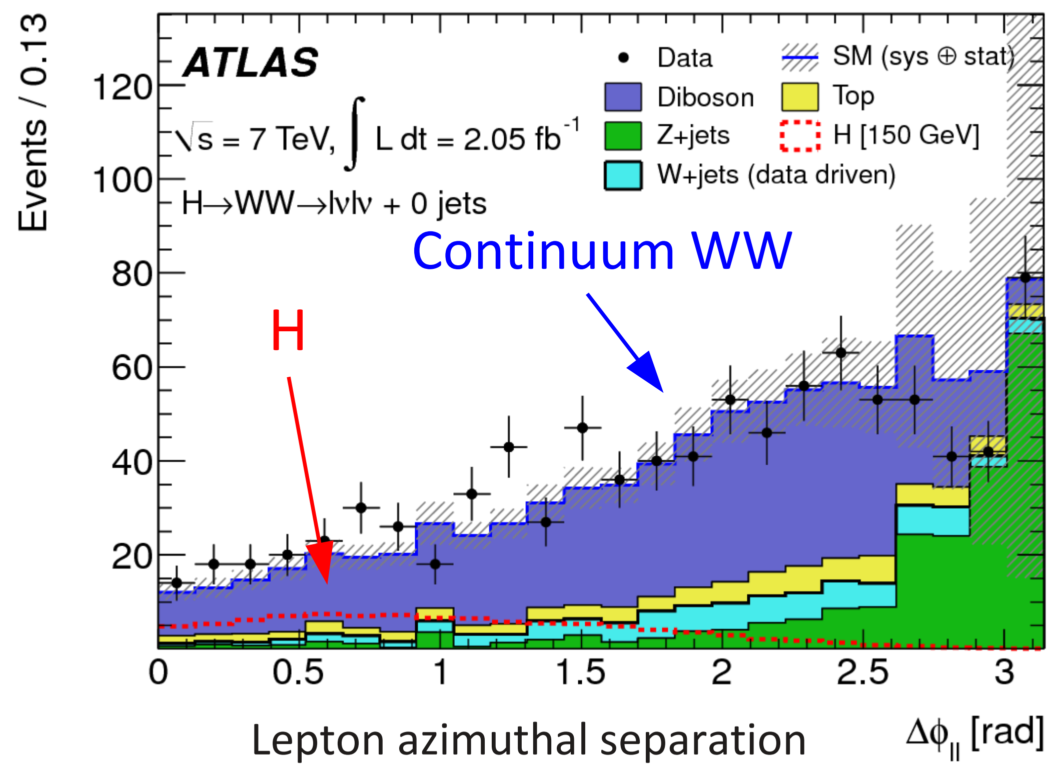
- Signal is 2 leptons + missing energy, and 0 or 1 jets (top production typically gives ≥ 2 jets)
- Worst background is continuum $pp \rightarrow WW$. Higgs signal differs from this in mass and angular distribution.
- Other backgrounds:
  - Z+fake missing energy
  - top
  - W+leptons from hadron decays
  - $pp \rightarrow WZ/ZZ/Z\gamma/W\gamma$

4.7 fb^{-1} analysis
ATLAS-CONF-2012-012

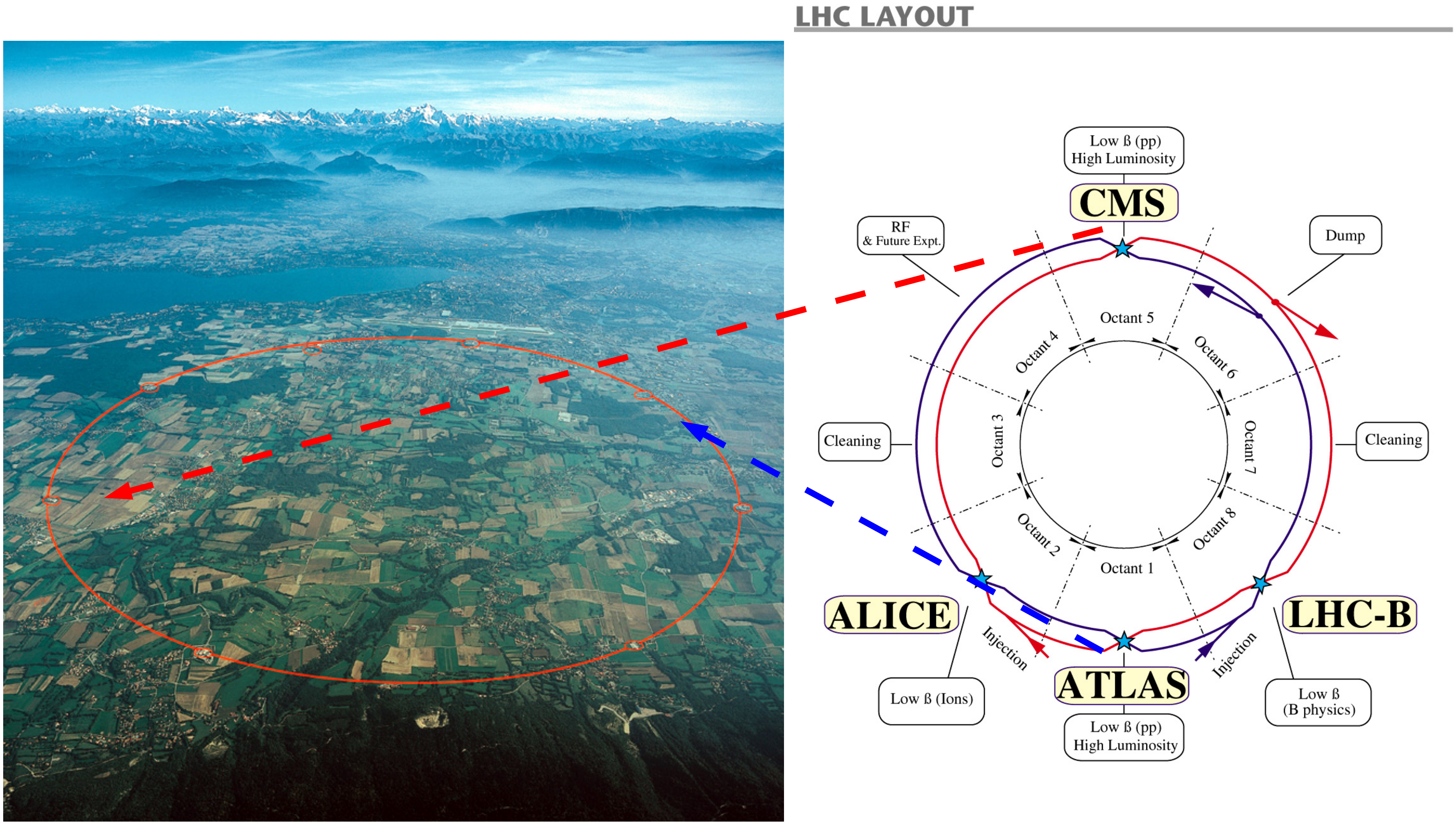
Angular Distributions

- H is a scalar, the daughter Ws must have total spin 0.
  - Chiral decays to leptons → lepton angular correlation





The LHC



CERN AC _ EI2-4A_ V18/9/1997

Proton-proton collider at CERN in Geneva, Switzerland

2011 operation: collisions at 7 TeV center of mass energy

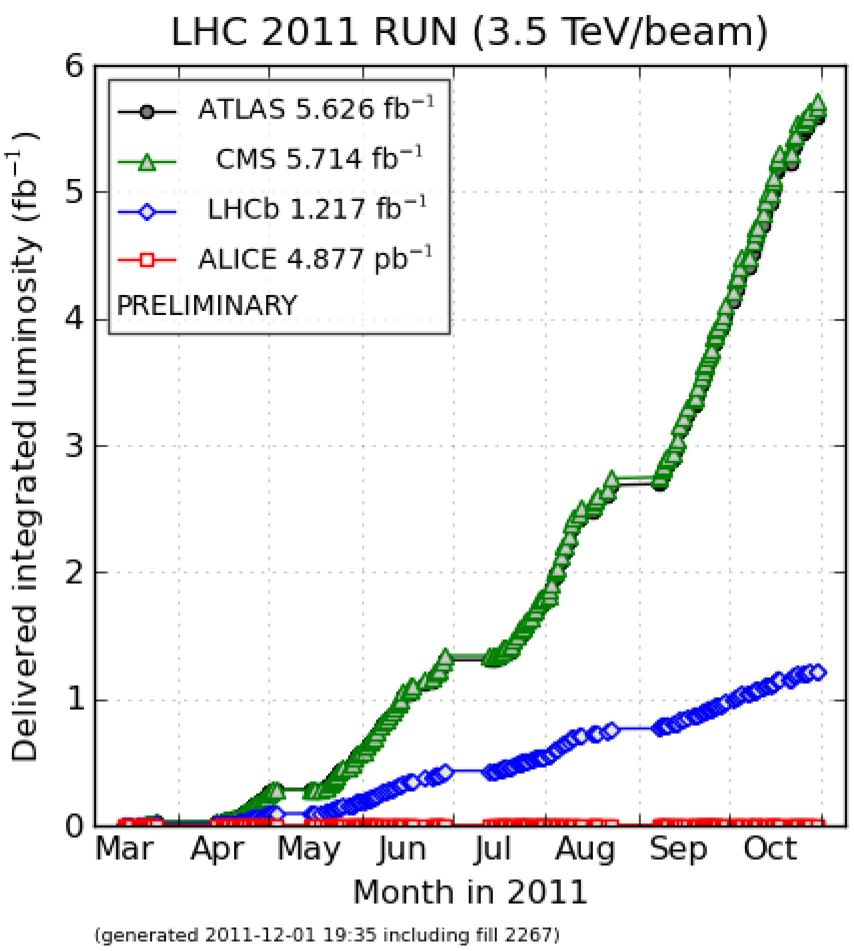
2 general purpose experiments: ATLAS and CMS

2011 LHC Performance

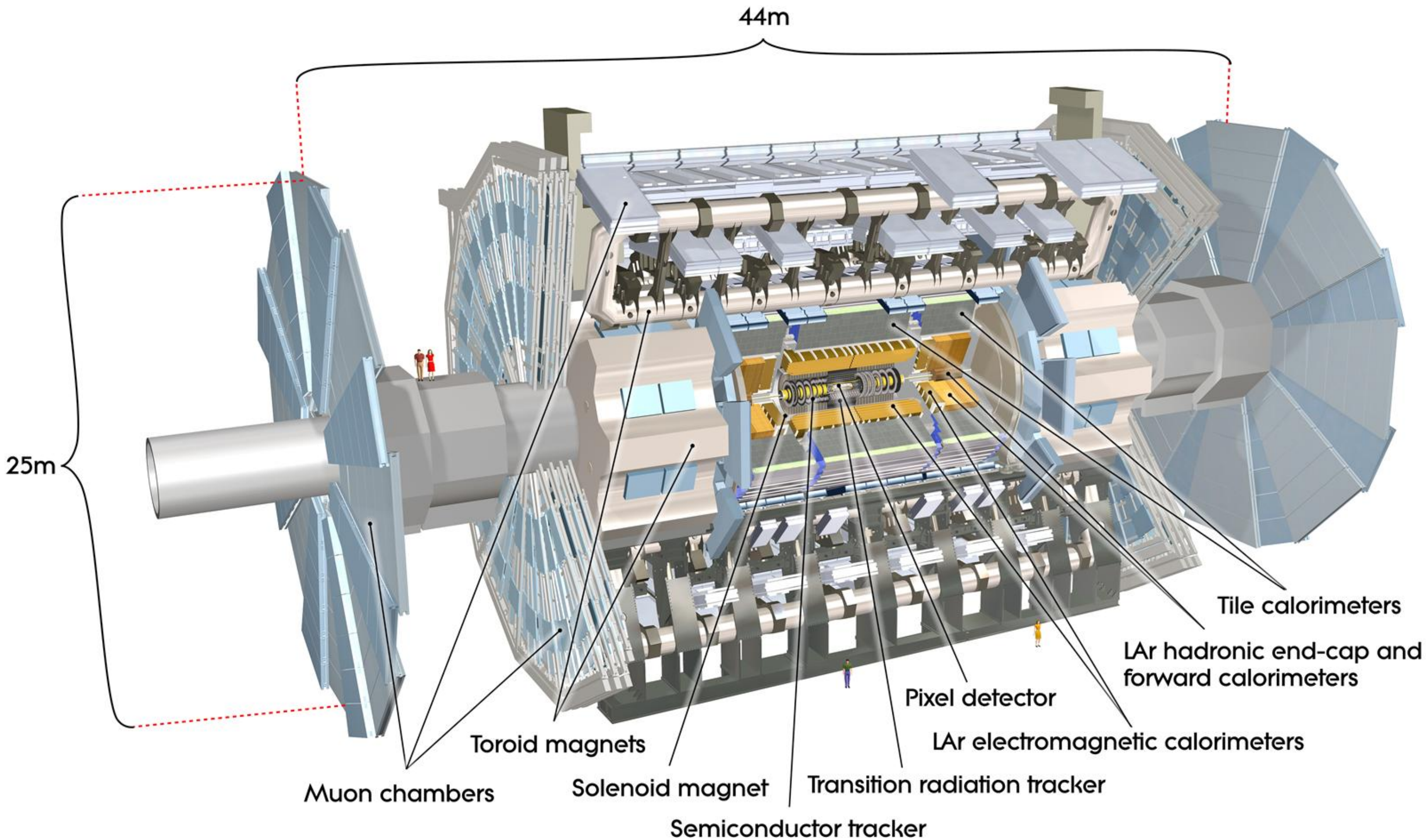
Very successful run in 2011 at 7 TeV center of mass energy

> 5.6 fb^{-1} delivered to both ATLAS and CMS

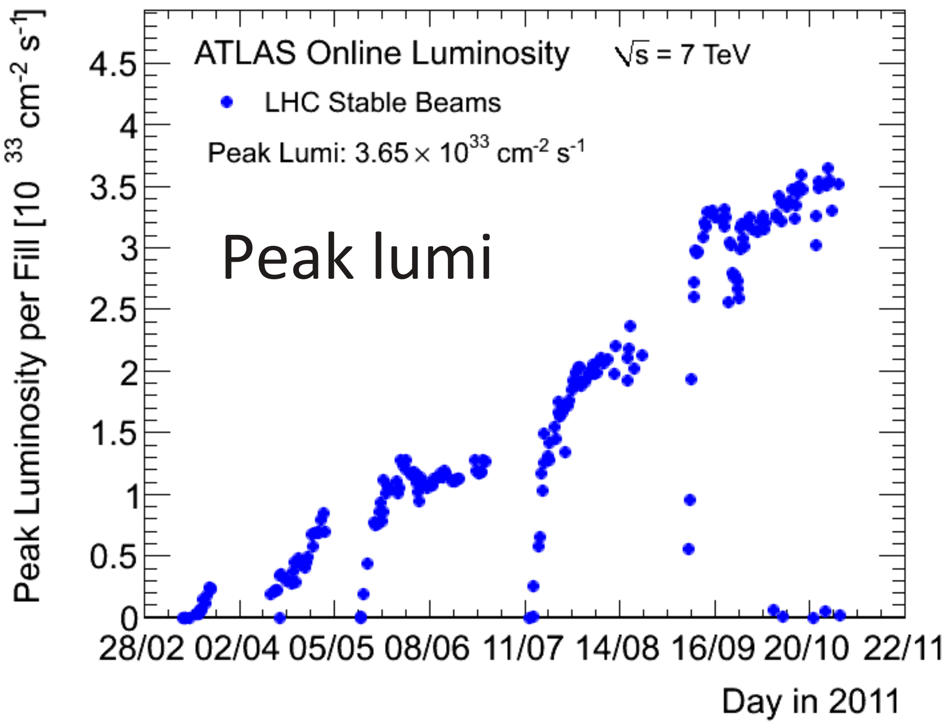
We had to adjust to significant changes in beam parameters over the year

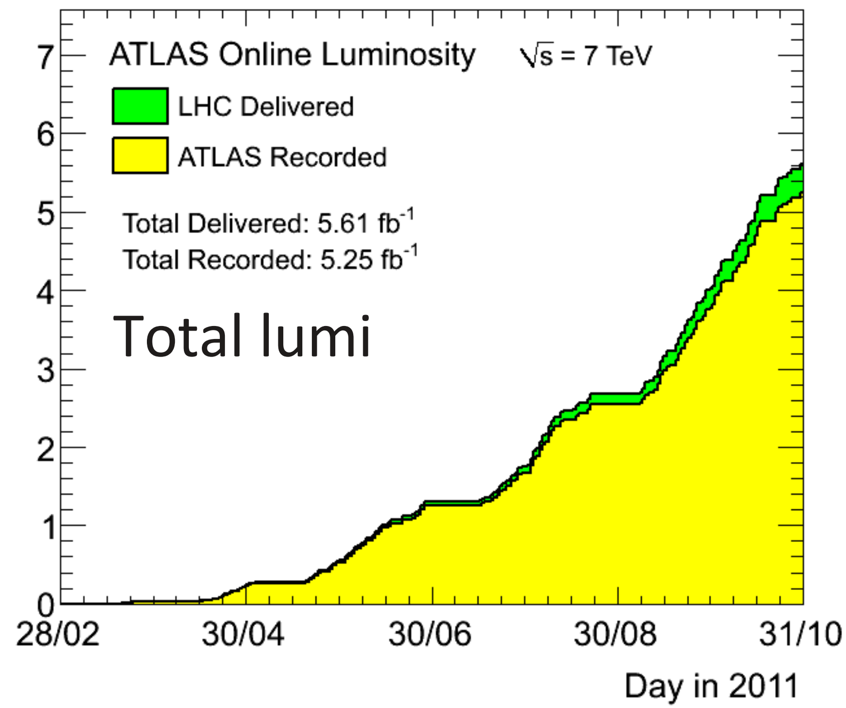


ATLAS Detector



ATLAS Data-Taking





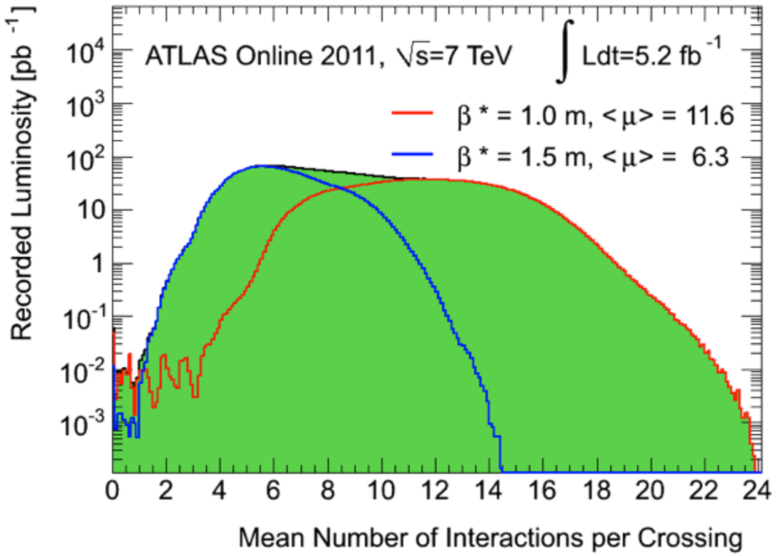
Inner Tracking Detectors			Calorimeters				Muon Detectors				Magnets	
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.8	99.6	99.2	97.5	99.2	99.5	99.2	99.4	98.8	99.4	99.1	99.8	99.3

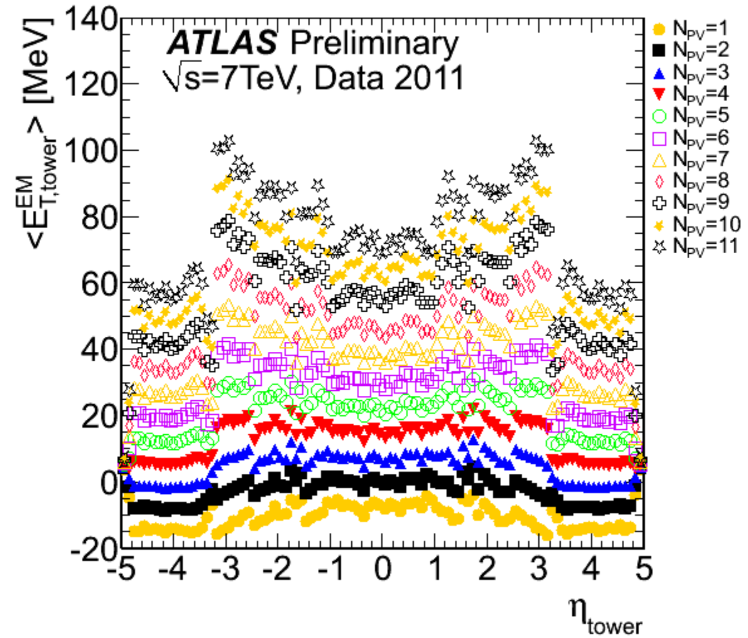
Luminosity weighted relative detector uptime and good quality data delivery during 2011 stable beams in pp collisions at √s=7 TeV between March 13th and October 30th (in %), after the summer 2011 reprocessing campaign

Percent of data good for various subdetectors

Pileup: Multiple Collisions

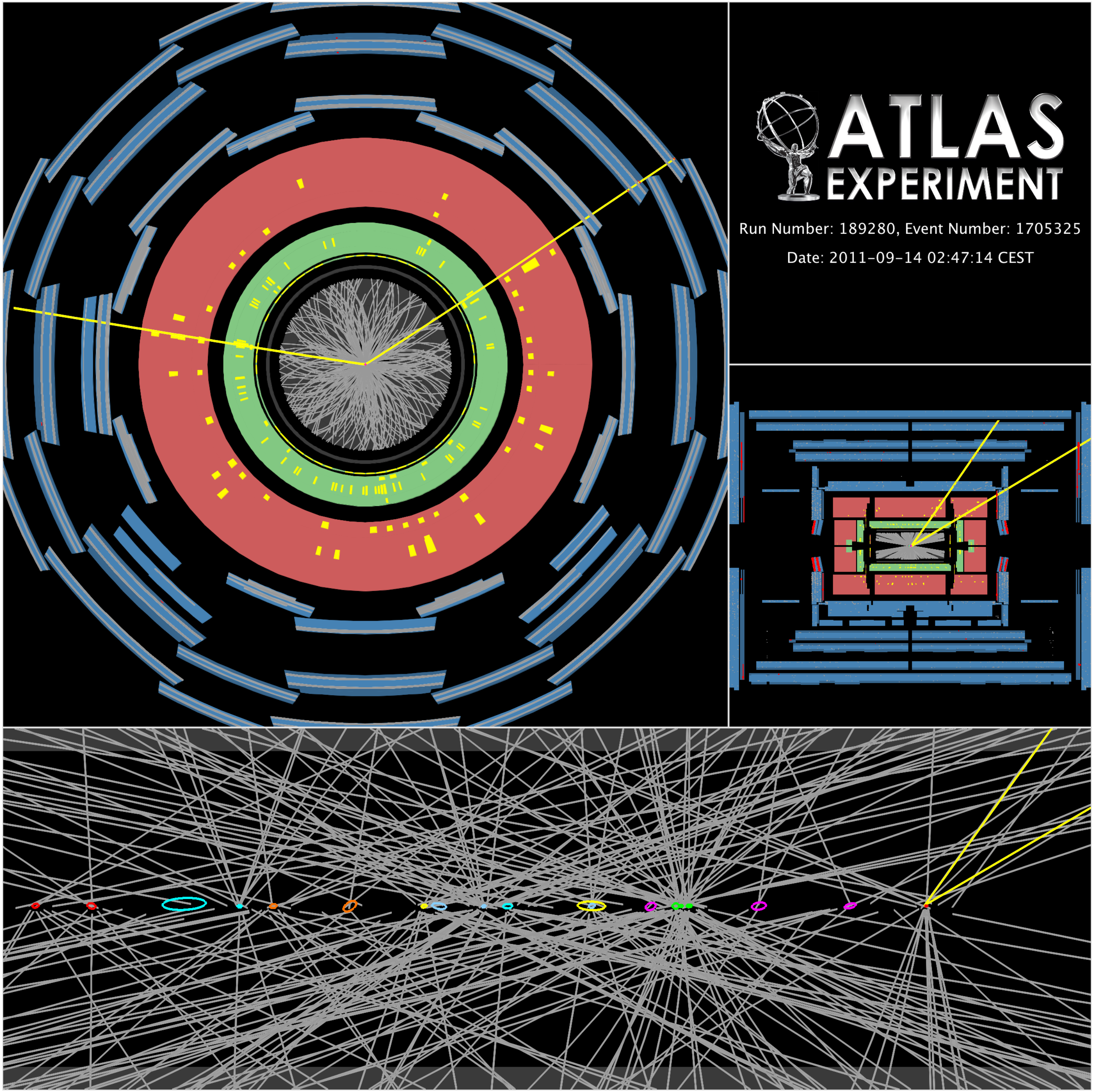
- To achieve luminosity, multiple collisions are allowed in one bunch crossing: extra energy in detectors, additional particle tracks
- Detectors may have memory of previous bunch crossing
- Degradation of resolution for calorimeter measurements, collision position
  - And an effect on reconstruction CPU!
- Handled by data-driven techniques and simulations
- 2012: expect mean of **30** or more!





Z → μμ

20 vertices

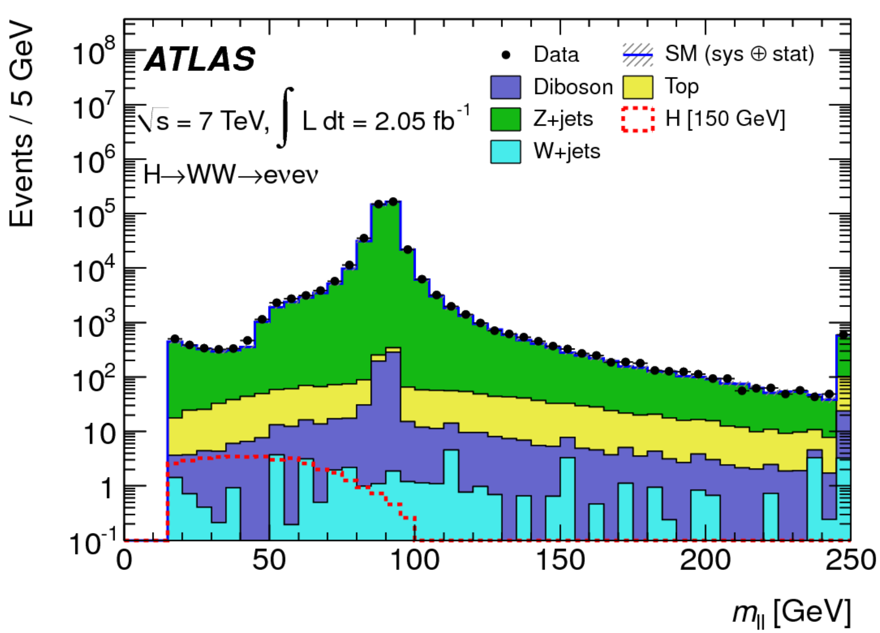


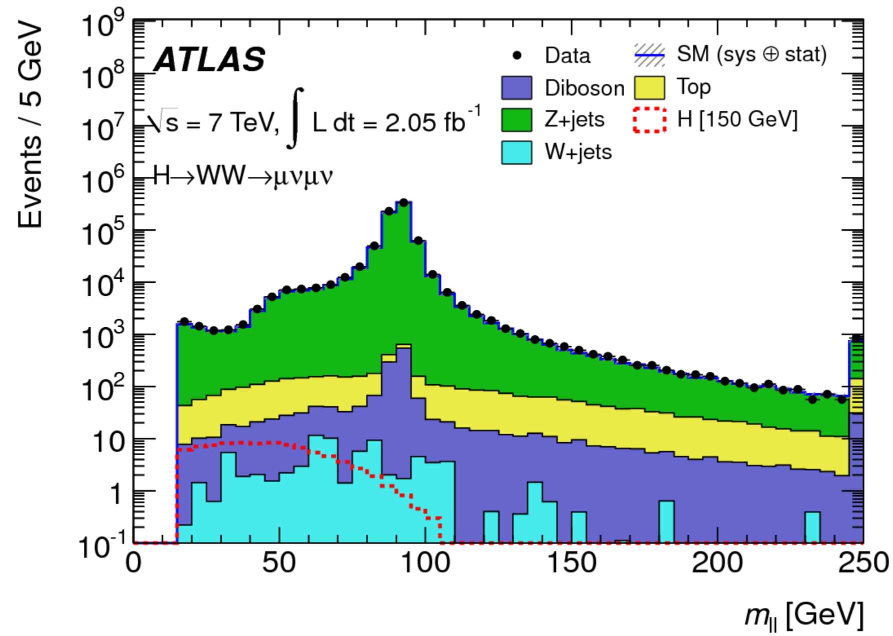
Event Preselection

- Two oppositely charged isolated leptons (e, μ)
  - Leading lepton $p_T > 25$ GeV; subleading lepton $p_T > 15$ GeV (μ)
  - electrons allowed with $|\eta| < 2.47$ (excluding a barrel-endcap crack region); muons allowed with $|\eta| < 2.4$
  - lepton tracks must be consistent with primary vertex
  - leptons must be isolated from other tracks and calorimeter energy
- Triggers:
  - Use unprescaled inclusive single lepton triggers with full efficiency at $p_T \approx$ 20-23 GeV

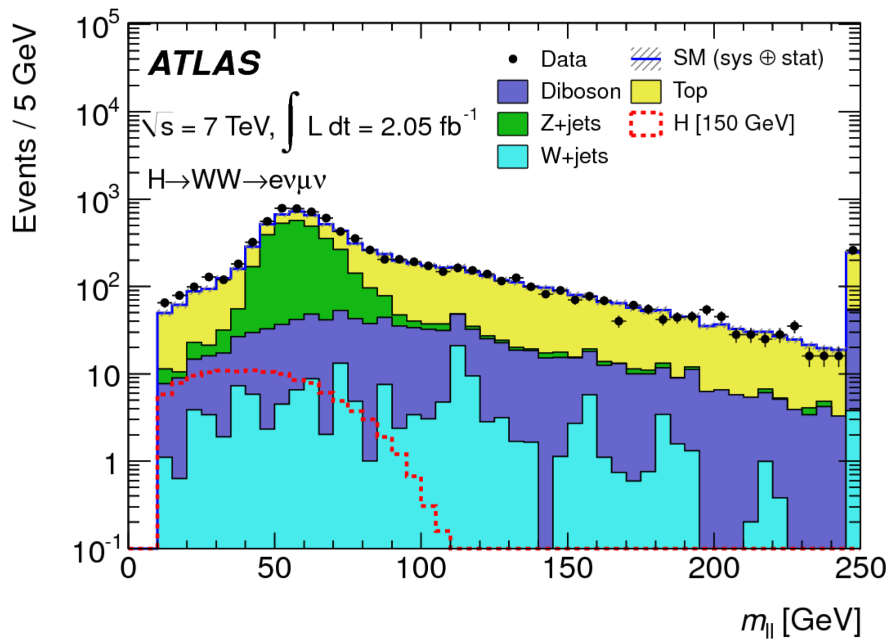
Electron efficiency: 71%
Muon efficiency: 92%

Understanding at Preselection





earlier version of analysis



The METRel variable

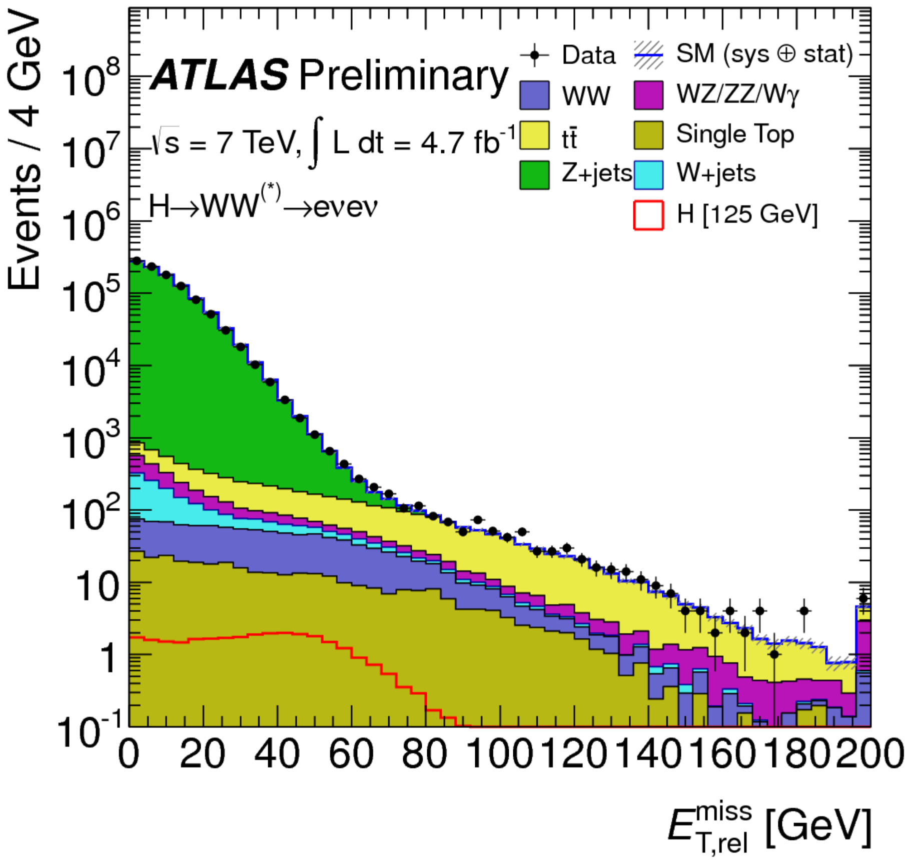
- To suppress fake missing energy near a lepton or jet, the "relative" variable METRel is defined:

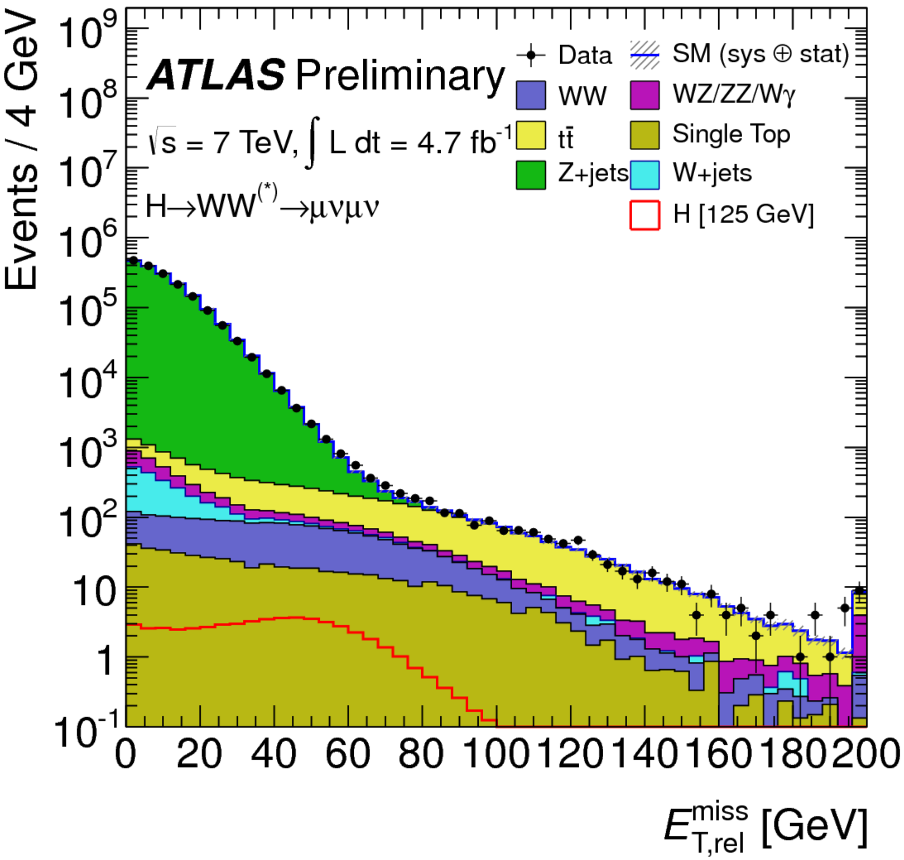
$$E_{\mathrm{T,rel}}^{\mathrm{miss}} = \begin{cases} E_{\mathrm{T}}^{\mathrm{miss}} & \text{if } \Delta\phi \geq \pi/2 \\ E_{\mathrm{T}}^{\mathrm{miss}} \cdot \sin\Delta\phi & \text{if } \Delta\phi < \pi/2 \end{cases}$$

  where Δϕ is the smallest azimuthal angle to a lepton or jet candidate.

- Preferentially selects a topology where the leptons are near each other.

METRel Distribution





- MET resolution very sensitive to pileup
- Modeled well in our MC

Channel separation

Same-flavor channels have large Z/γ^* backgrounds.
Looser cuts can be used in eμ.

μμ/ee:

- $M_{ll} > 12$ GeV [remove ϒ]
- $|M_{ll} - M_Z| > 15$ GeV
  [orthogonality to $ZZ \rightarrow 2\ell2\nu$]
- METRel > 45 GeV

eμ:

- $M_{ll} > 10$ GeV
  [remove sequential B decays]
- METRel > 25 GeV

Additional Topological Cuts

0 jet events:

- $p_T(ll) > 30$ GeV [Z removal]

1 jet events:

- b-jet veto (80% efficiency) [top removal]
- $p_T(ll+jet+MET) < 30$ GeV [below threshold jet veto]
- $Z \rightarrow \tau\tau$ veto

2+ jet events:

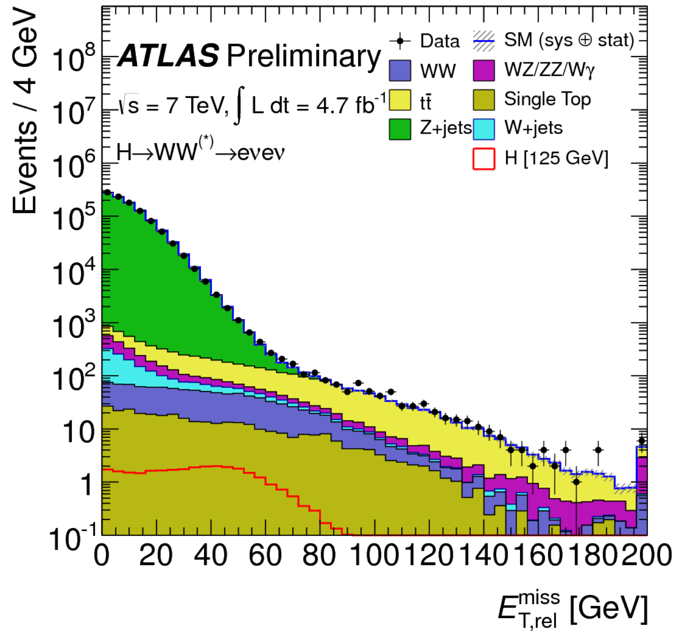
- 1 jet cuts, plus
- 2 tag jets with opposite η, $|\Delta\eta_{jj}| > 3.8$, $m_{jj} > 500$ GeV
- No additional jets with $|\eta| < 3.2$

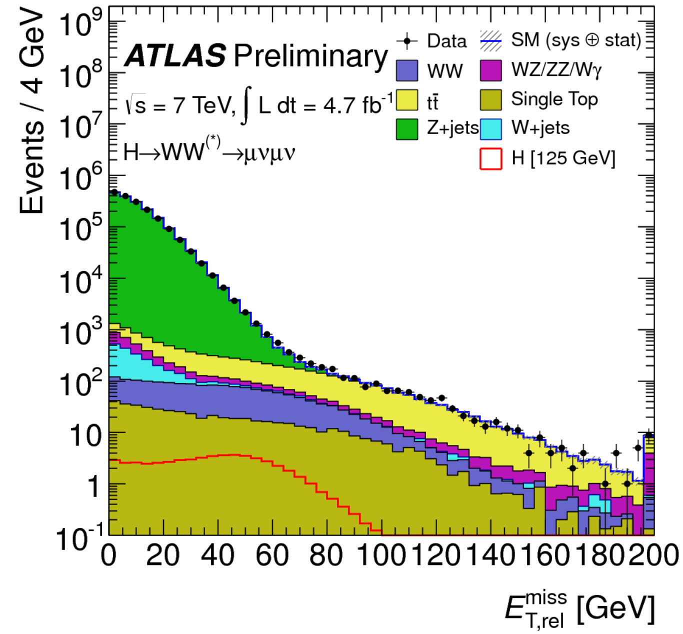
Common ($m_H < 200$ GeV) :

- $M_{ll} < 50$ [top, WW, Z removal]
- $\Delta\phi_{ll} < 1.8$ rad

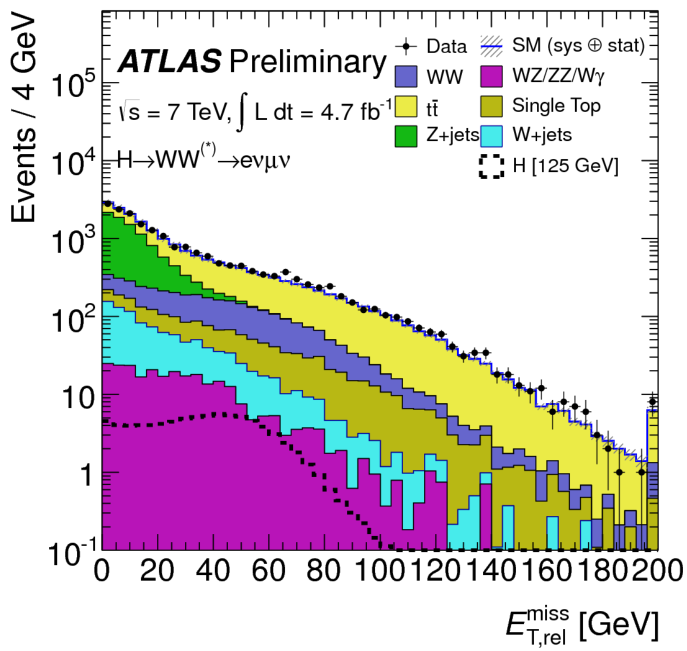
H → WW (low mass)

Z/γ* rejection:
Require missing energy





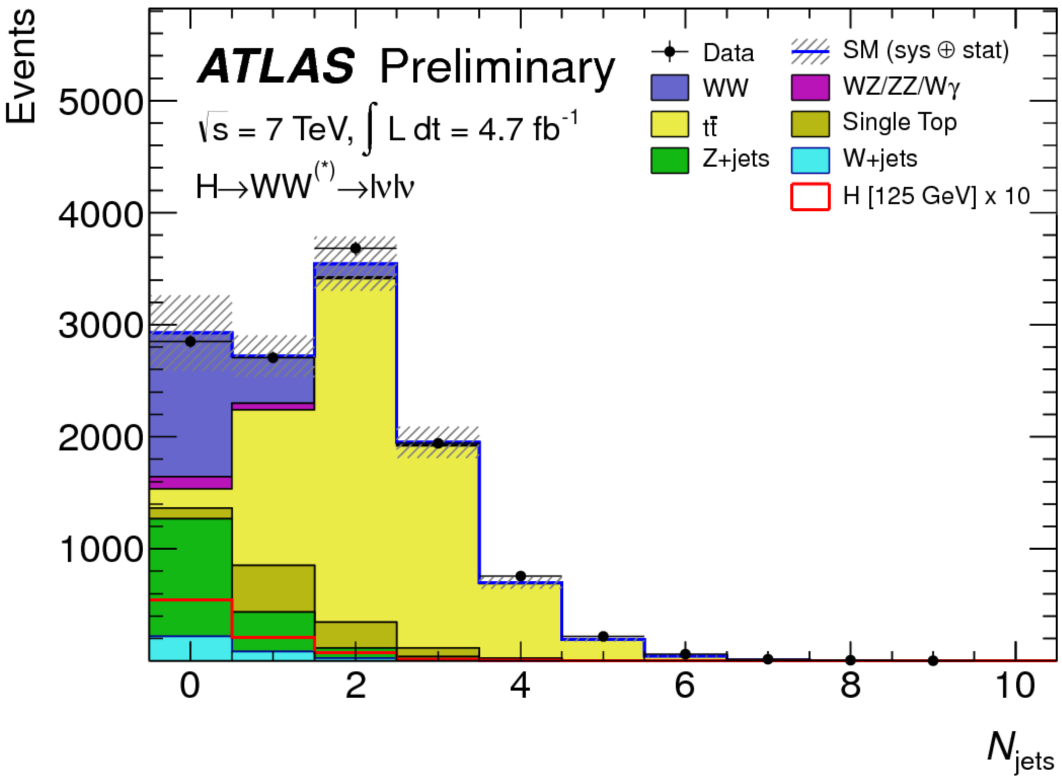
Less important for eμ



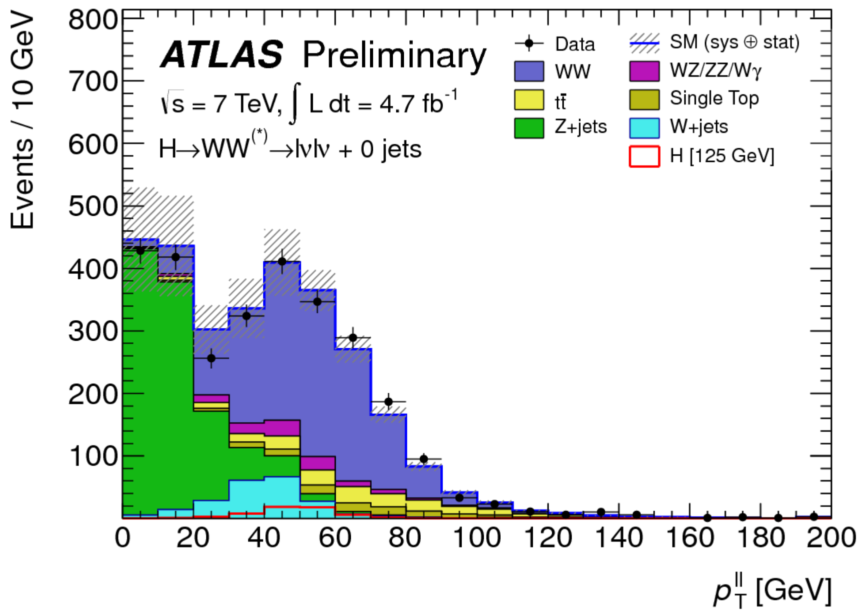
H → WW (low mass)

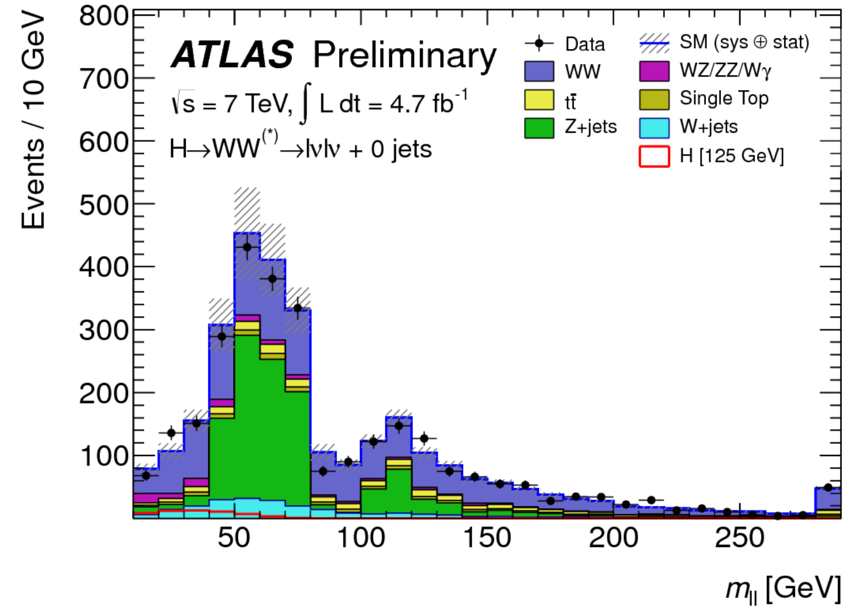
Top rejection:
Require 0 or 1 jet, *or* 2+ jets events consistent with vector boson fusion

In 1+ jet bins, impose a b-jet veto



H → WW + 0 jet (low mass)



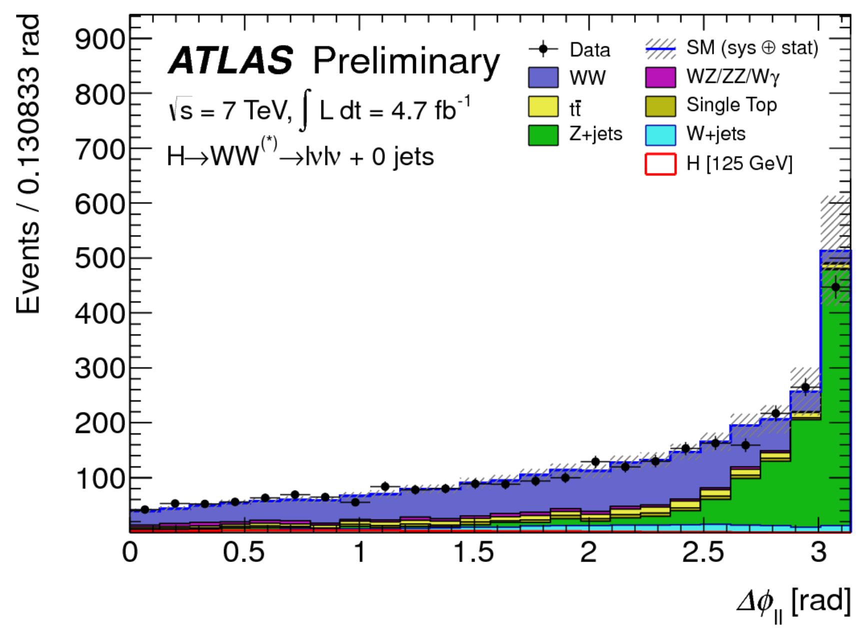


Z/γ*, WW rejection (0 jet):

→ Require m_{ll} < 50 GeV

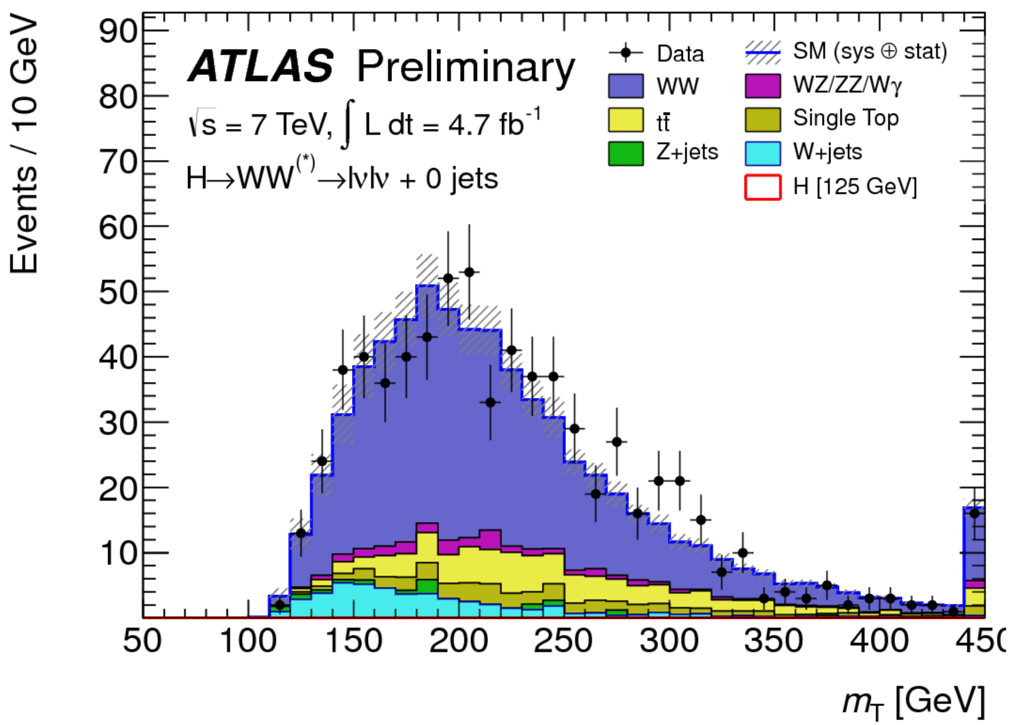
→ Require $\Delta\phi_{ll}$ < 1.8

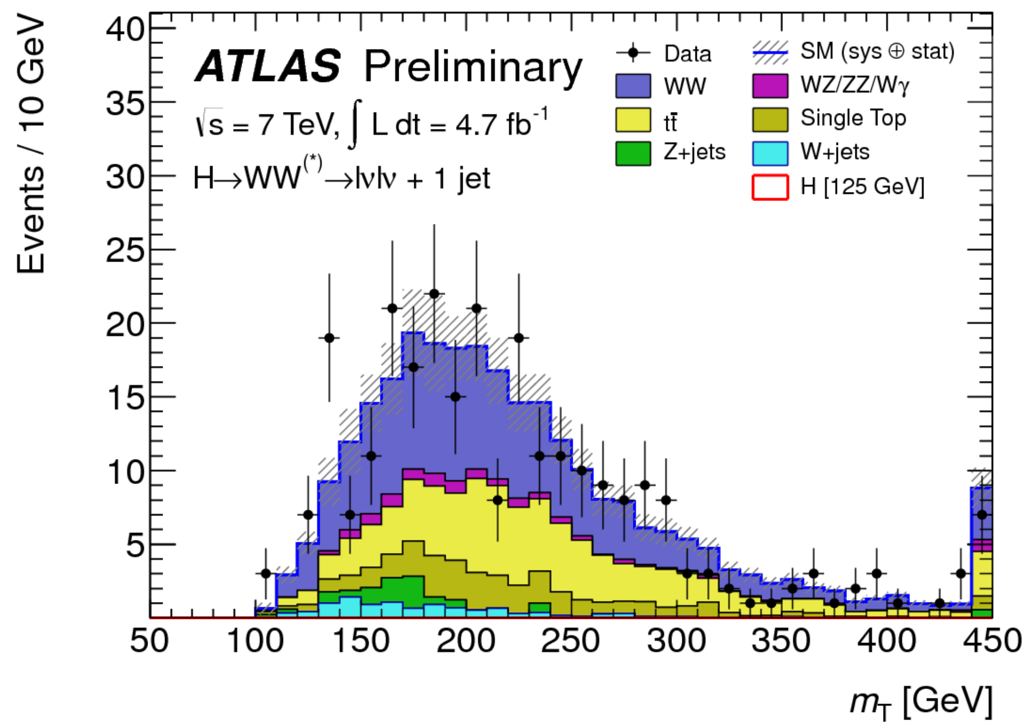
→ Require large total momentum of two lepton system



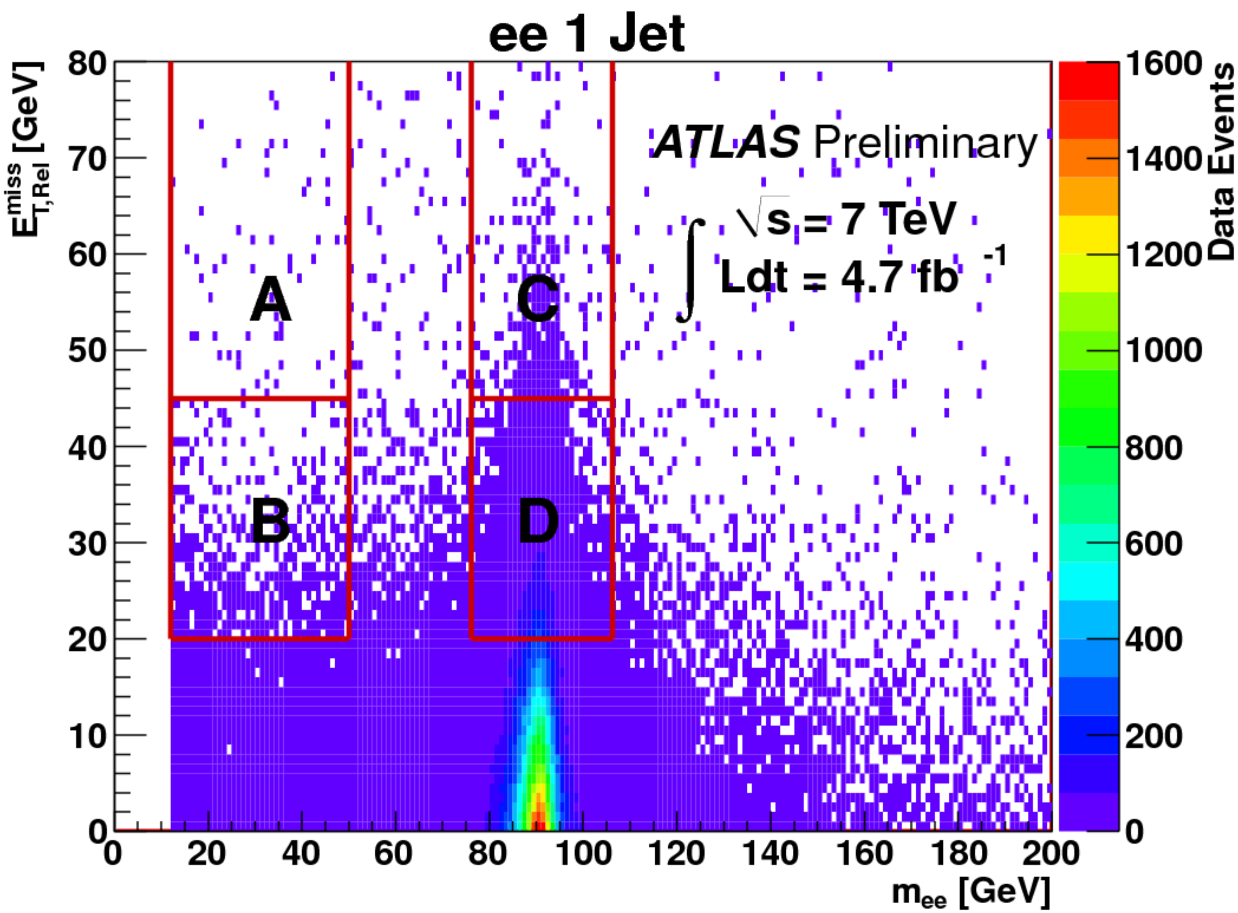
WW Normalization

- Define control region by releasing Δϕ cut and requiring m_{ll} > 80 GeV for eμ, (M_Z + 15) GeV for ee/μμ
- Float normalization in the fit in both signal and control regions, connecting them by a MC-derived ratio of WW yield





Z/γ* Normalization

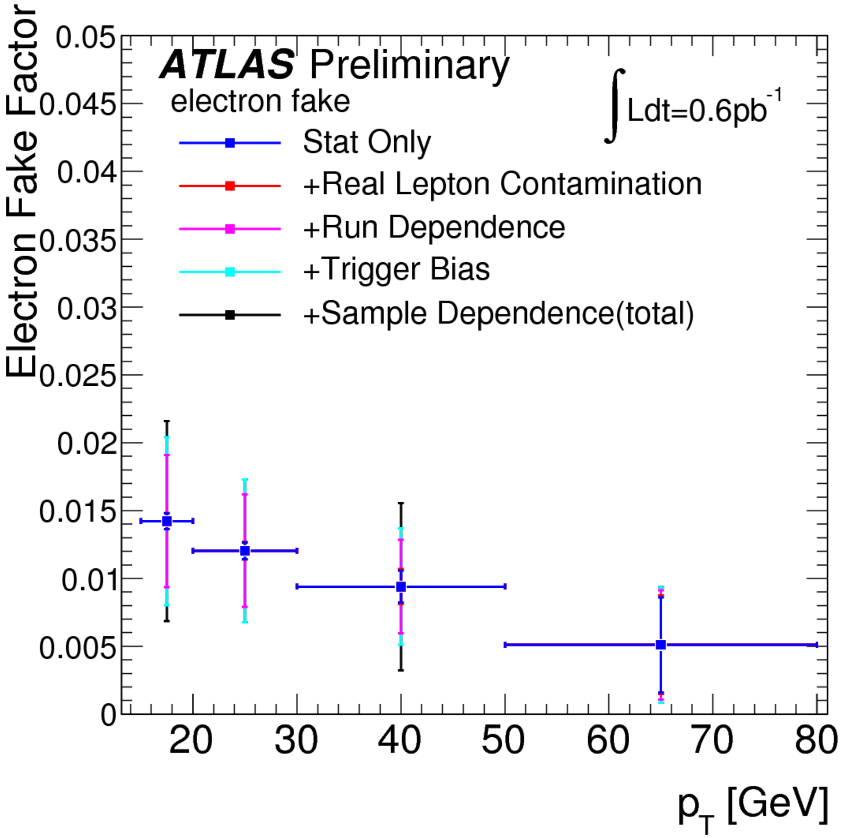


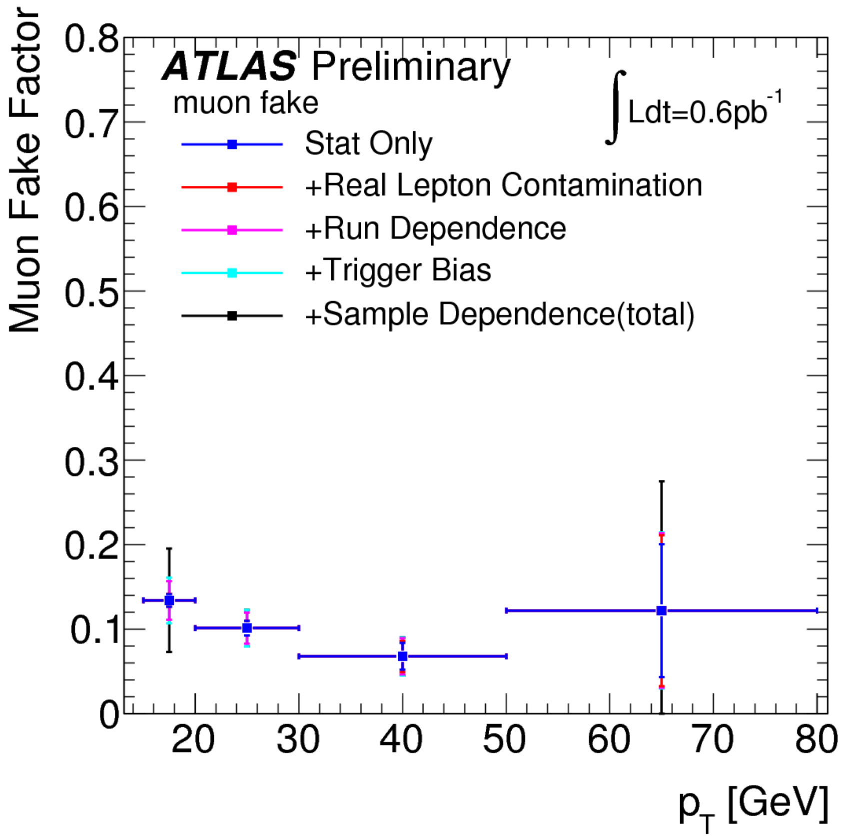
Assume m_{ll} and MET are uncorrelated after all cuts except $\Delta\phi_{ll}$; then take

$$A_{expected}\ [\text{signal}] = (C/D) \times B$$

Assign systematic uncertainty from how well this procedure works in MC

W+jets Background





jet → lepton fake rate estimated using multijet events

Determine a "fake factor" ratio between low-quality lepton candidates and ones that pass our cuts

Then find events with one tight and one low-quality lepton and scale by fake factor. Systematic uncertainty 30-100%

Top Background

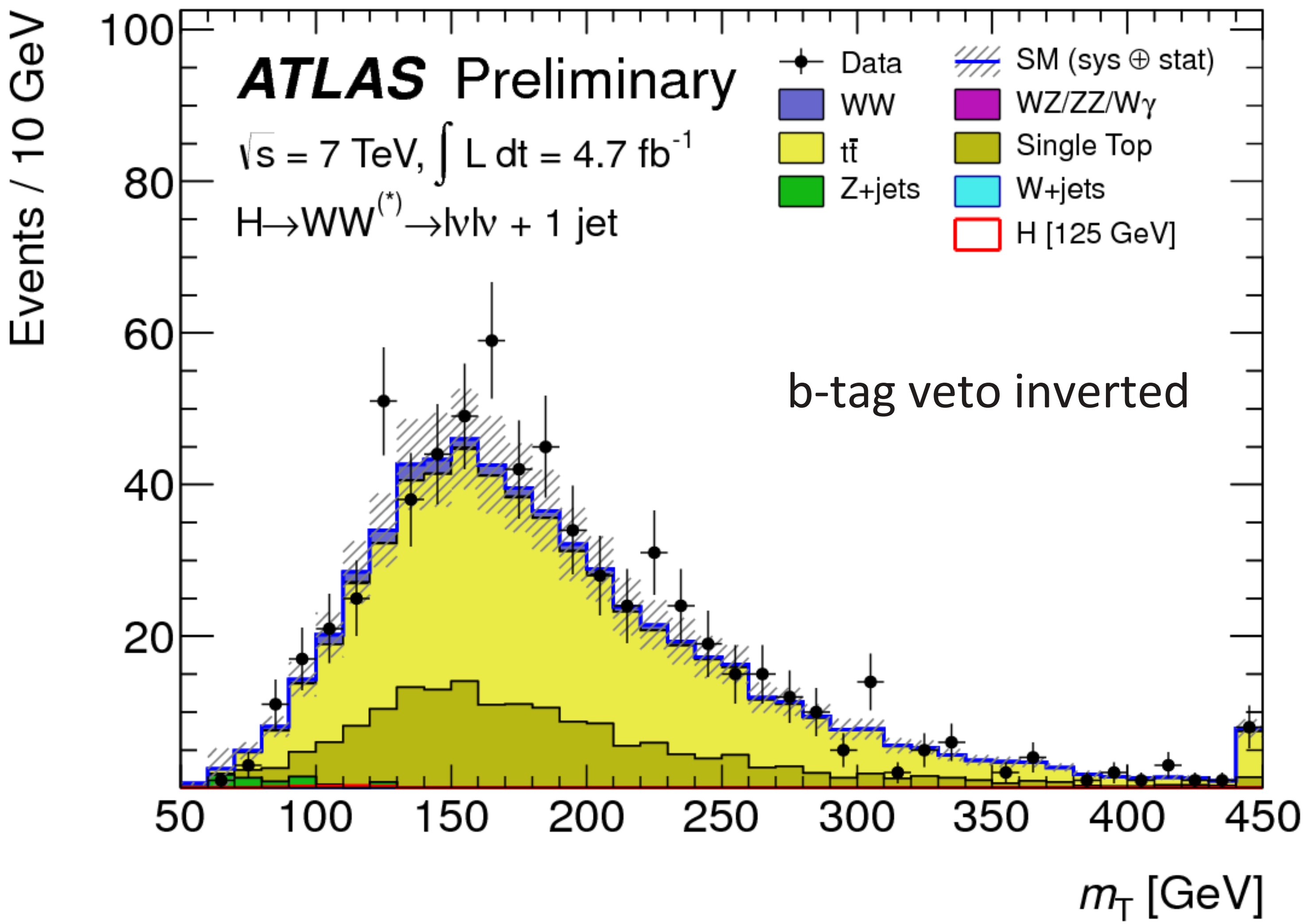
1 jet events:

- invert the b-tag veto, use known tagging efficiency.

0-jet events:

- Estimate a jet veto probability from dilepton + MET events with one b-tagged jet:
  P_1 = N(ll+MET+b tag+0jet)/N(ll+MET+b tag)
- Take 2-jet veto probability
  $P_2 = P_1^2$ x correction factor from MC
- Then 0 jet estimated top background is
  P_2 x (N(ll + MET)$_{data}$ – estimated non-top backgrounds)

WW + 1 jet top control

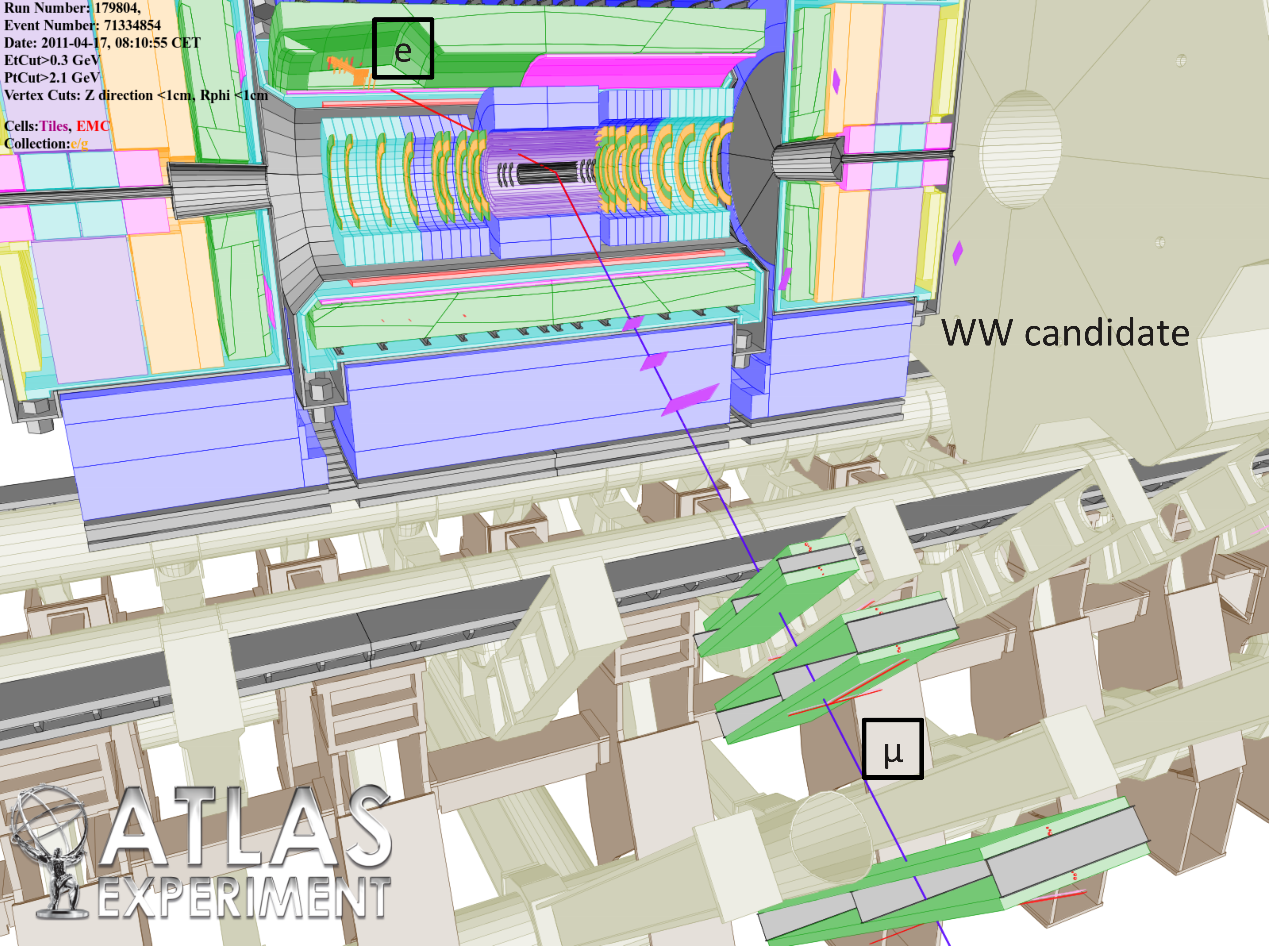


Major Systematics

- As we constrain WW and top backgrounds with control regions, the major systematics are in the extrapolation factors to the signal region, and in the expected Higgs cross-section

Background yield systematics, m_H = 125 GeV hypothesis

Background	0 jet	1 jet
WW	10%	24%
W+jets	~60%	~60%
Z+jets	56%	25%
top	23%	30%
WZ/ZZ/Wγ	25%	60%


Run Number: 179804,
Event Number: 71334854
Date: 2011-04-17, 08:10:55 CET
EtCut>0.3 GeV
PtCut>2.1 GeV
Vertex Cuts: Z direction <1cm, Rphi <1cm
Cells:Tiles, EMC
Collection:e/g
e
μ
WW candidate
ATLAS
EXPERIMENT

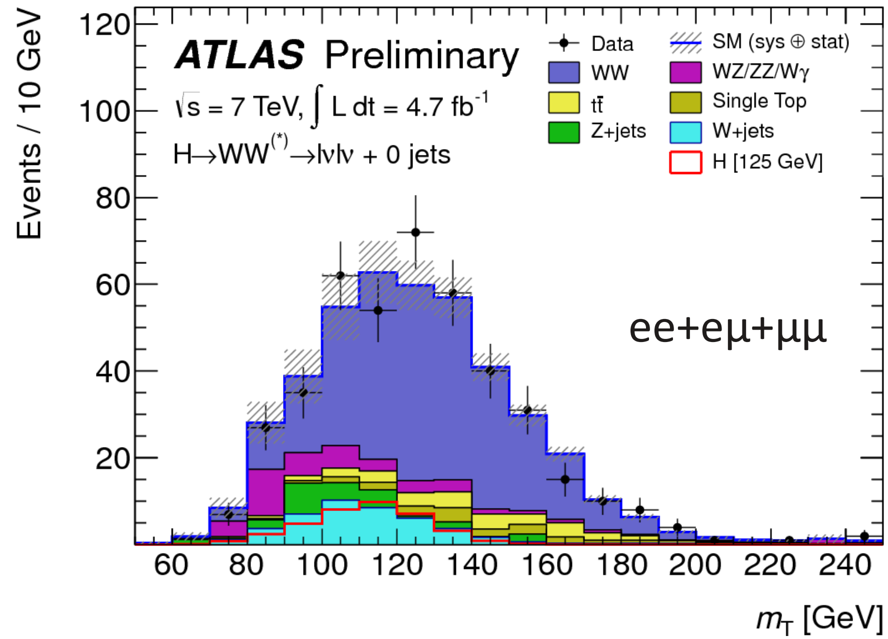
H → WW events

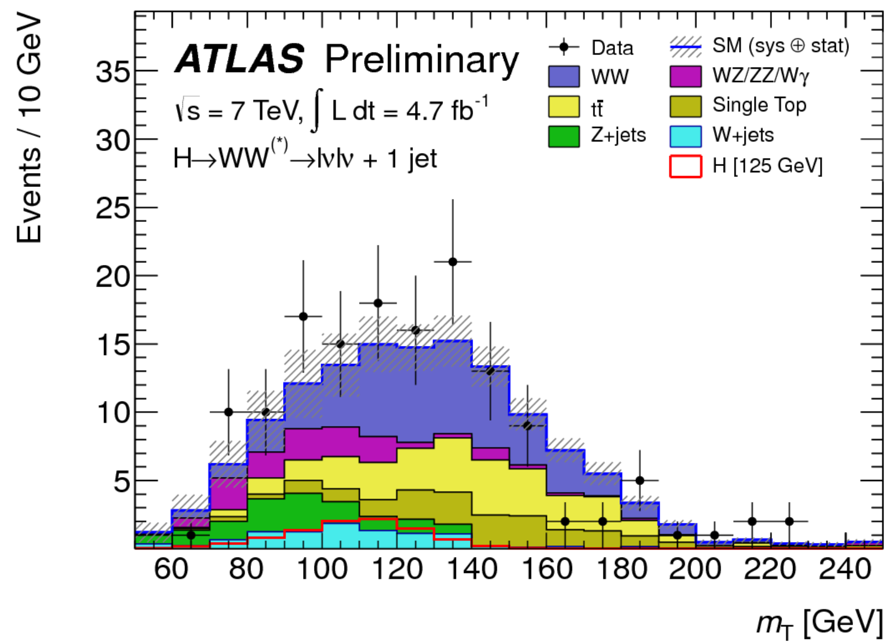
We look at a “transverse mass” variable (defined independently of mass hypothesis)

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

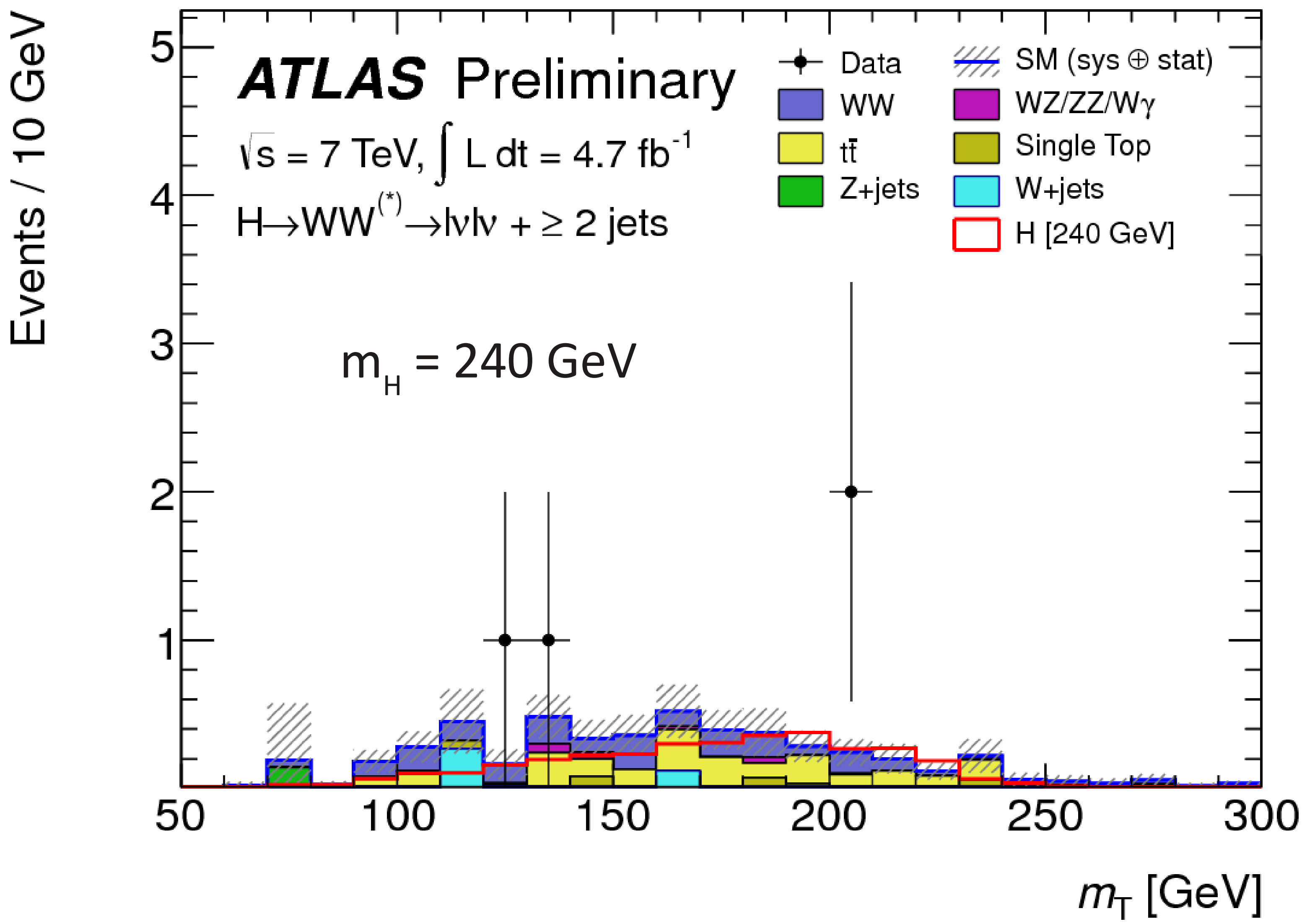
High edge indicates Higgs mass

For each mass hypothesis, fit to a sum of background and signal templates





VBF Channel



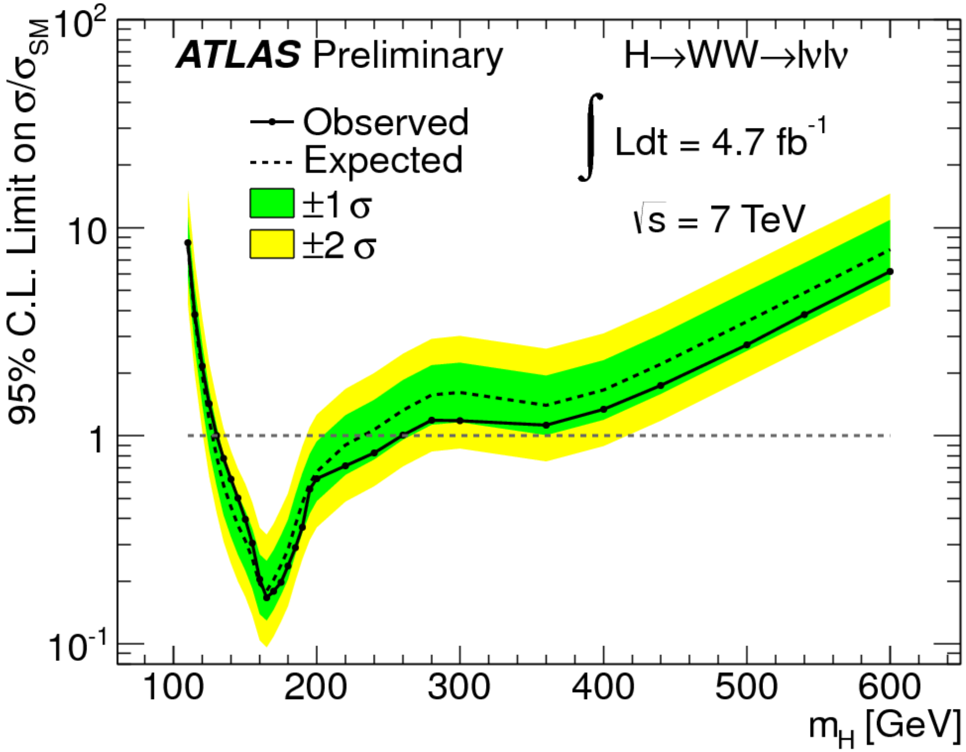
m_H = 240 GeV

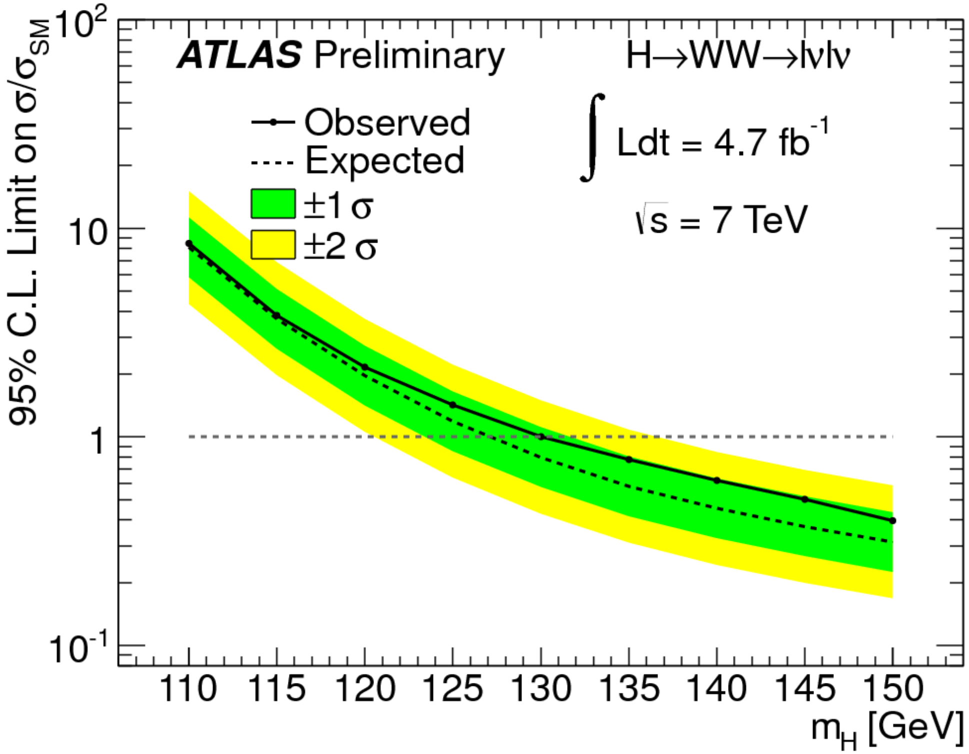
In Numbers (m_H = 125 GeV)

H + 0-jet	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	Z/γ^* + jets	W + jets	Total Bkg.	Obs.
Jet Veto	54.5 ± 0.2	1285 ± 79	106 ± 6	175 ± 12	95 ± 7	1038 ± 28	217 ± 4	2916 ± 115	2851
$m_{\ell\ell} < 50$ GeV	43.8 ± 0.2	316 ± 20	48 ± 5	30 ± 2	19 ± 2	157 ± 13	69 ± 2	640 ± 34	644
$p_T^{\ell\ell}$ cut	38.8 ± 0.2	285 ± 18	41 ± 4	28 ± 2	18 ± 2	24 ± 7	49 ± 2	444 ± 27	441
$\Delta\phi_{\ell\ell} < 1.8$	37.7 ± 0.2	279 ± 17	39 ± 4	27 ± 2	18 ± 2	23 ± 7	44 ± 1	429 ± 27	427
H + 1-jet	**Signal**	**WW**	**$WZ/ZZ/W\gamma$**	**$t\bar{t}$**	**$tW/tb/tqb$**	**Z/γ^* + jets**	**W + jets**	**Total Bkg.**	**Obs.**
1 jet	21.1 ± 0.1	390 ± 55	59 ± 4	1433 ± 80	430 ± 25	357 ± 17	82 ± 3	2752 ± 170	2707
b-jet veto	19.5 ± 0.1	360 ± 51	55 ± 4	401 ± 23	134 ± 8	333 ± 16	73 ± 3	1356 ± 92	1371
$\lvert p_T^{tot}\rvert < 30$ GeV	13.0 ± 0.1	252 ± 35	33 ± 3	171 ± 10	78 ± 5	105 ± 8	35 ± 2	674 ± 55	685
$Z \to \tau\tau$ veto	13.0 ± 0.1	246 ± 34	32 ± 3	165 ± 10	75 ± 5	85 ± 7	35 ± 2	638 ± 53	645
$m_{\ell\ell} < 50$ GeV	10.2 ± 0.1	54 ± 7	14 ± 2	32 ± 2	18 ± 2	26 ± 4	12 ± 1	156 ± 14	171
$\Delta\phi_{\ell\ell} < 1.8$	9.4 ± 0.1	49 ± 7	14 ± 2	30 ± 2	17 ± 2	13 ± 3	10 ± 1	134 ± 13	145
H + 2-jet	**Signal**	**WW**	**$WZ/ZZ/W\gamma$**	**$t\bar{t}$**	**$tW/tb/tqb$**	**Z/γ^* + jets**	**W + jets**	**Total Bkg.**	**Obs.**
opp. hemispheres	3.8 ± 0.1	46 ± 1	6 ± 1	138 ± 3	21 ± 1	34 ± 4	8 ± 1	253 ± 5	269
$\lvert\Delta\eta_{jj}\rvert > 3.8$	1.8 ± 0.1	8.3 ± 0.4	0.9 ± 0.2	19.2 ± 0.9	2.2 ± 0.4	8.0 ± 2.0	1.5 ± 0.4	40.2 ± 2.3	40
$m_{jj} > 500$ GeV	1.3 ± 0.1	3.9 ± 0.3	0.4 ± 0.1	6.9 ± 0.4	0.7 ± 0.2	0.9 ± 0.4	0.7 ± 0.3	13.6 ± 0.8	13
$m_{\ell\ell} < 80$ GeV	0.9 ± 0.1	1.1 ± 0.2	0.1 ± 0.1	1.1 ± 0.2	0.2 ± 0.1	0.3 ± 0.3	0.2 ± 0.2	2.9 ± 0.5	2
$\Delta\phi_{\ell\ell} < 1.8$	0.8 ± 0.1	0.7 ± 0.1	0.1 ± 0.1	0.7 ± 0.2	negl.	0.3 ± 0.3	negl.	1.8 ± 0.4	1
Control Regions	**Signal**	**WW**	**$WZ/ZZ/W\gamma$**	**$t\bar{t}$**	**$tW/tb/tqb$**	**Z/γ^* + jets**	**W + jets**	**Total Bkg.**	**Obs.**
WW 0-jet	0.1 ± 0.1	465 ± 3	25 ± 2	85 ± 2	41 ± 2	9 ± 2	48 ± 2	673 ± 5	698
WW 1-jet	0.1 ± 0.1	126 ± 2	10 ± 1	83 ± 2	33 ± 2	9 ± 2	11 ± 1	272 ± 4	269
Top 1-jet	1.1 ± 0.1	21 ± 1	1.5 ± 0.2	422 ± 4	165 ± 3	6 ± 2	negl.	615 ± 6	675

Lepton Channels	0-jet ee	0-jet $\mu\mu$	0-jet $e\mu$	1-jet ee	1-jet $\mu\mu$	1-jet $e\mu$
Total bkg.	58 ± 5	114 ± 10	257 ± 13	21 ± 3	37 ± 5	76 ± 6
Signal	3.8 ± 0.1	9.0 ± 0.1	25 ± 0.2	1.1 ± 0.1	2.3 ± 0.1	6.0 ± 0.1
Observed	52	138	237	19	36	90

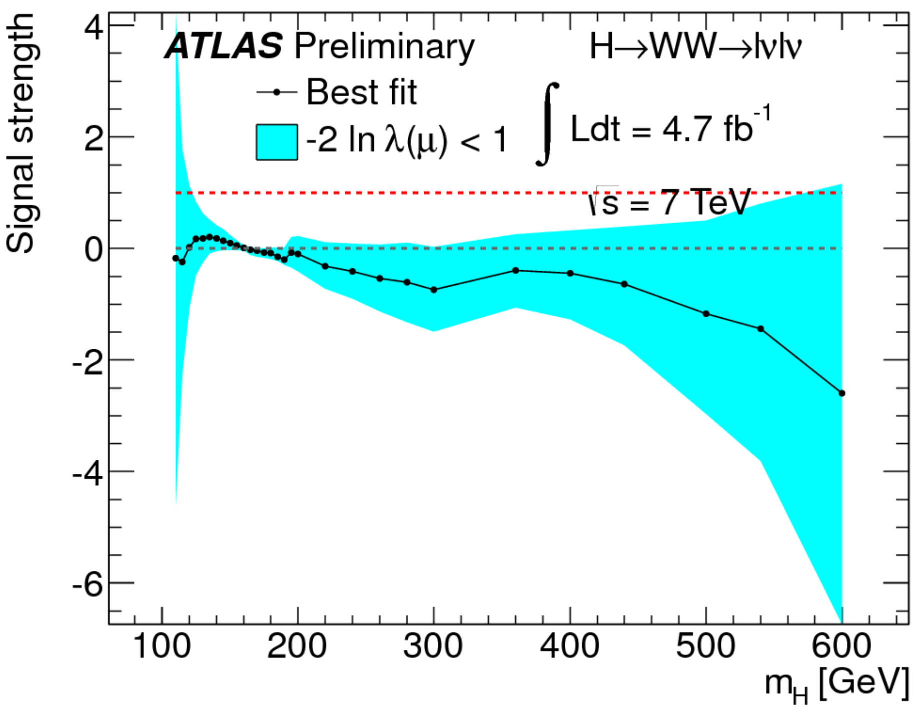
H → WW Limits

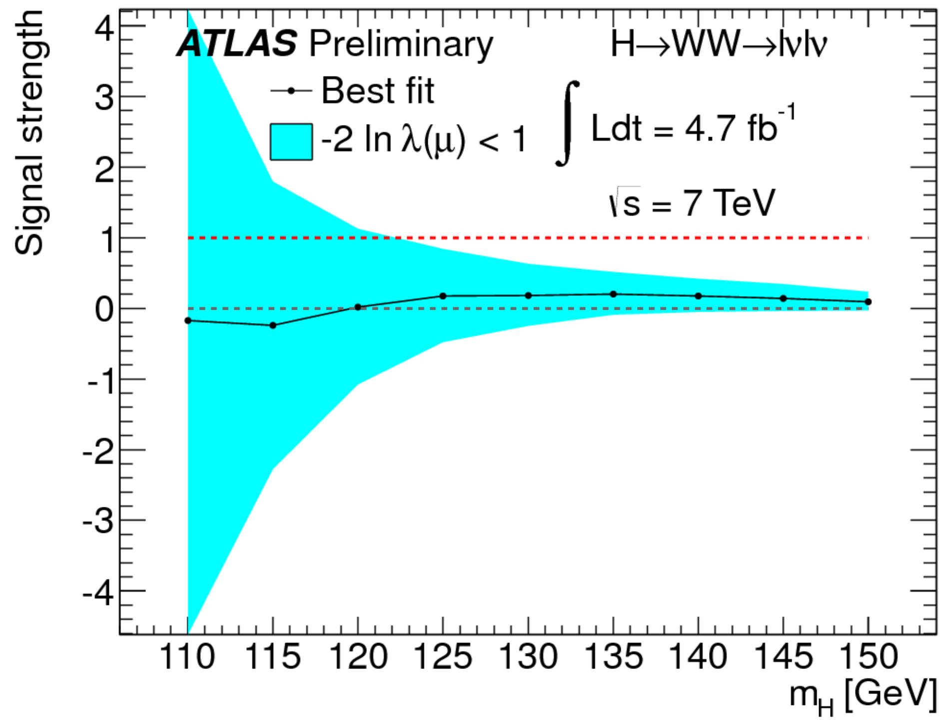




Excluded: 130-260 GeV

H → WW Signal Strength





Not incompatible with m_H = 125 GeV but no strong evidence either

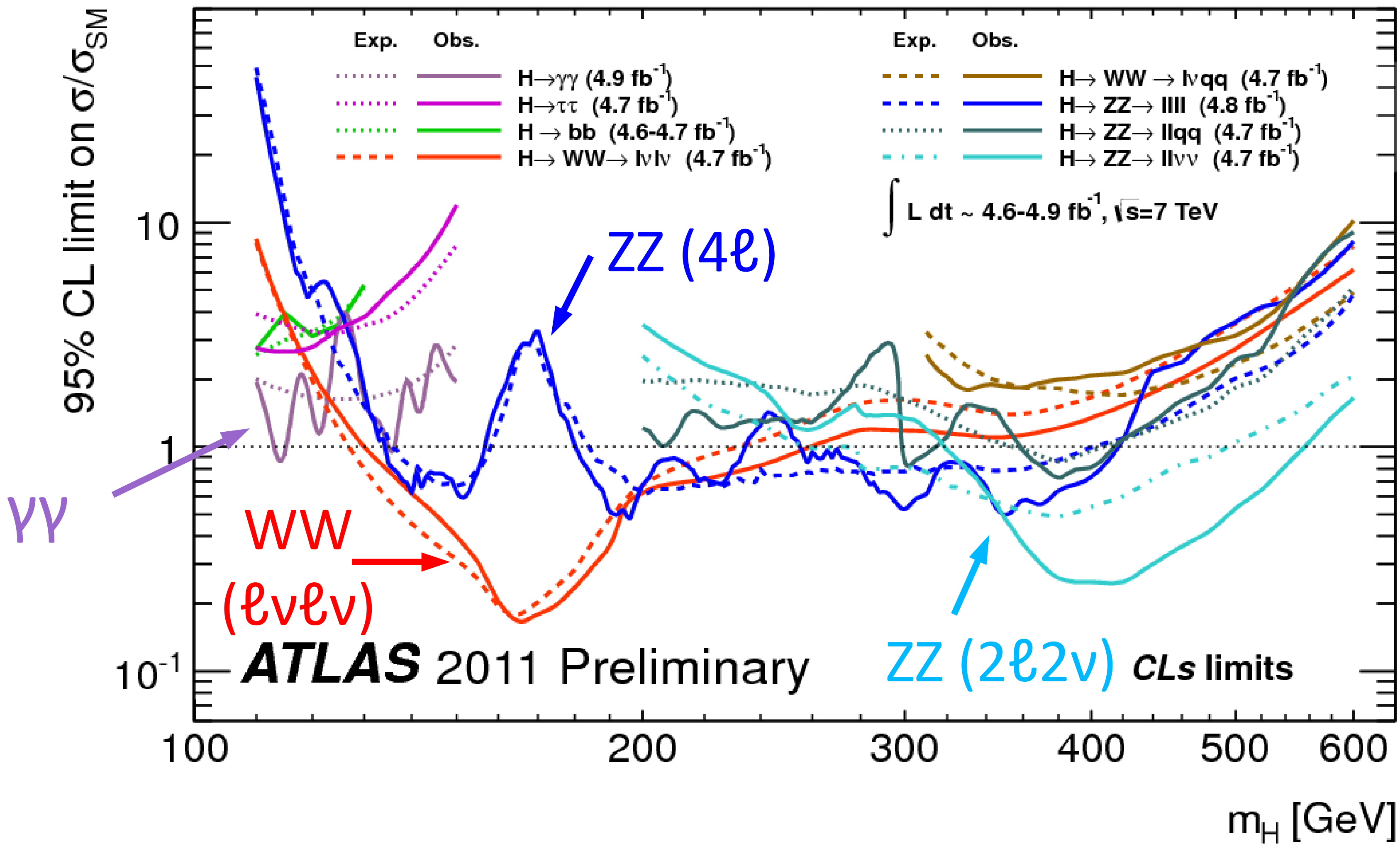
H → WW: the Future

- Prepare for 2012 data: understand how to handle high pileup well
- Lower subleading lepton threshold below 15 GeV
  - critical to help close the low mass window
- Add hadronic tau decays
- Improve significance with better acceptance and efficiency optimization
- More sophisticated use of additional kinematic information (multivariate techniques, matrix element ...)

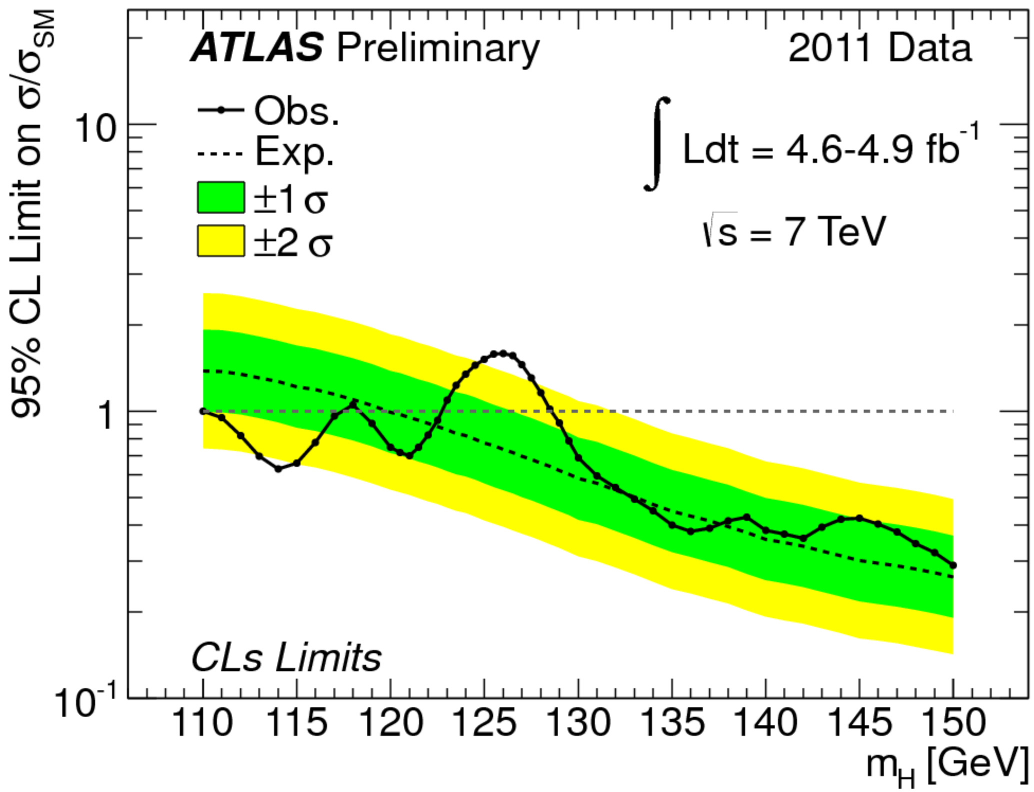
Limit Results

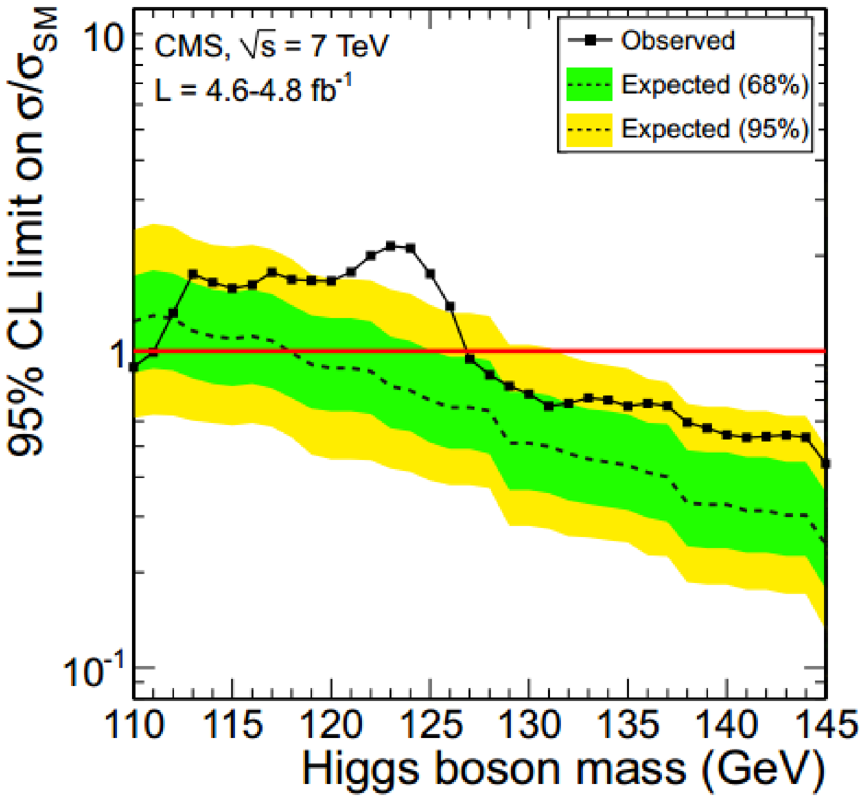
Includes additional analyses

Limits at 95% C.L.



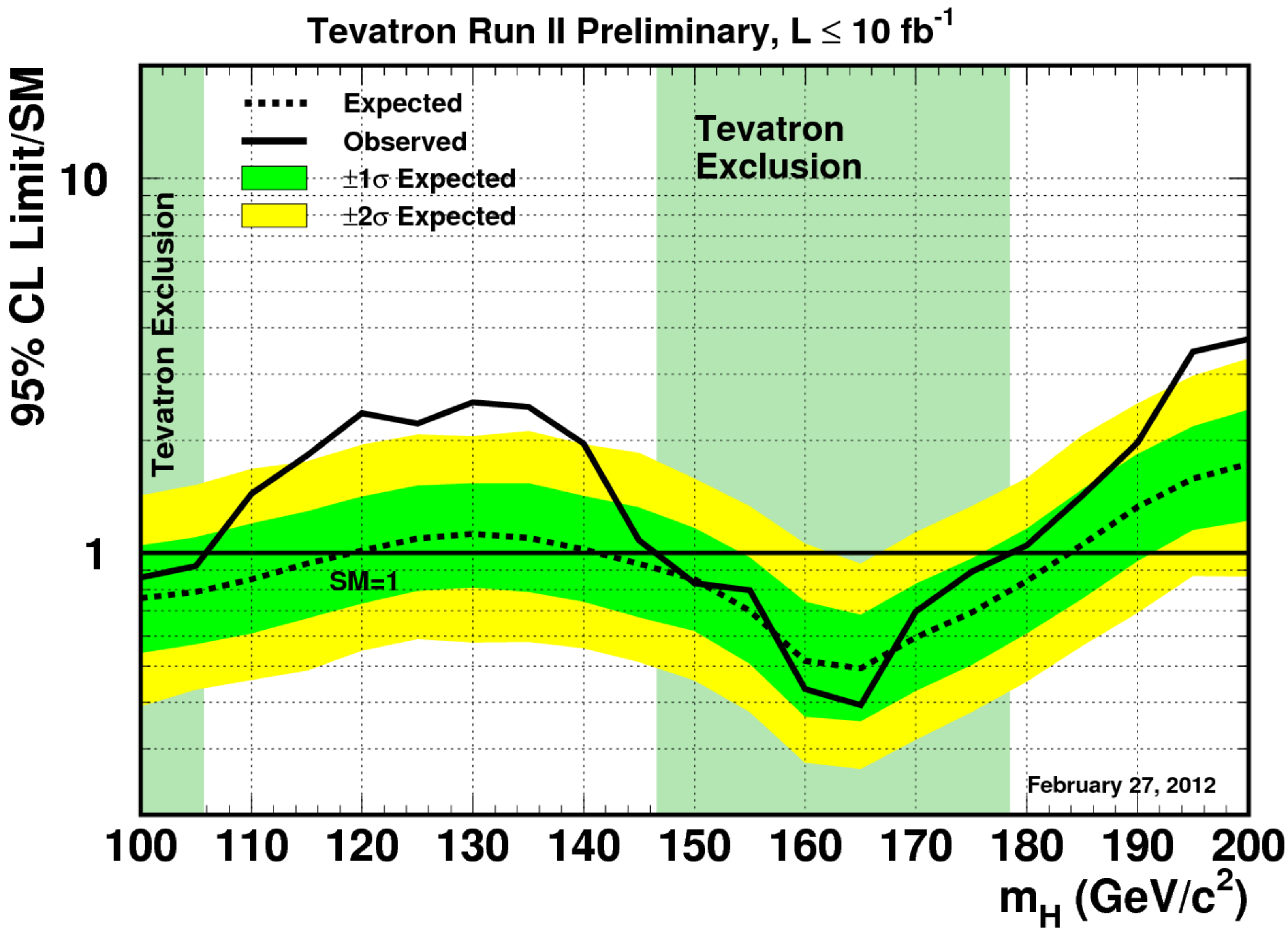
Low-Mass Combinations



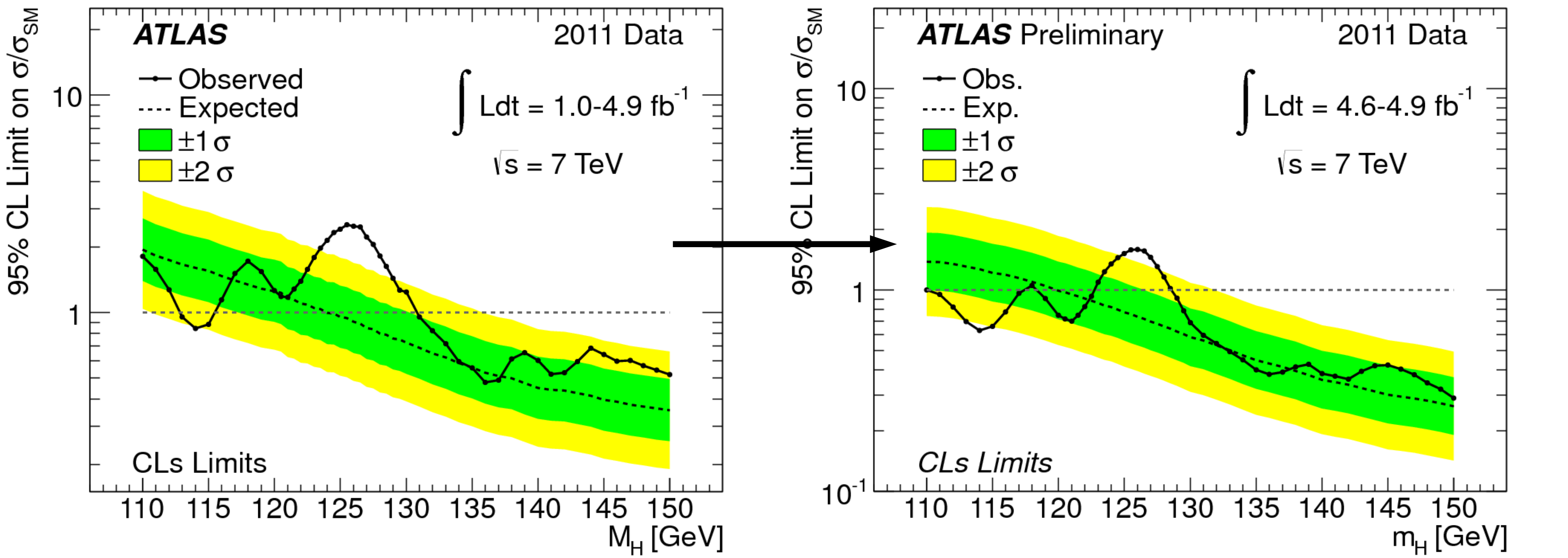


Plots **are not** corrected for the "look-elsewhere" effect:
if you look at enough points you'll see something eventually

Tevatron Exclusion

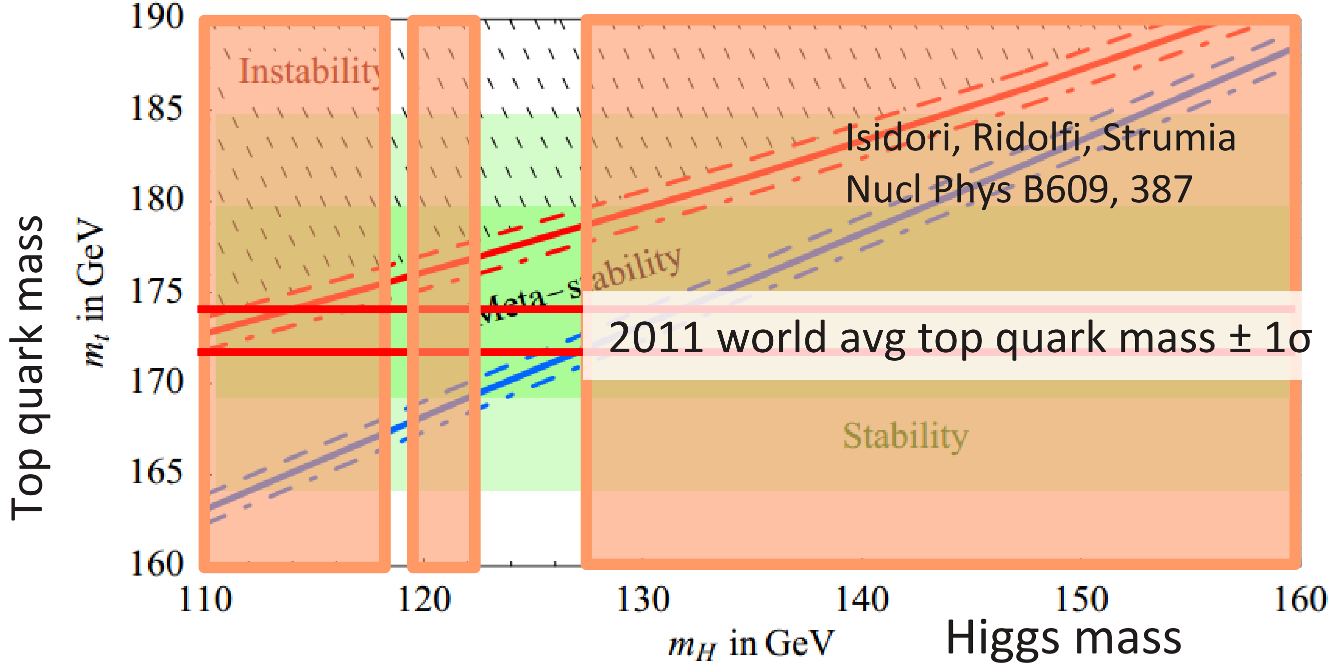


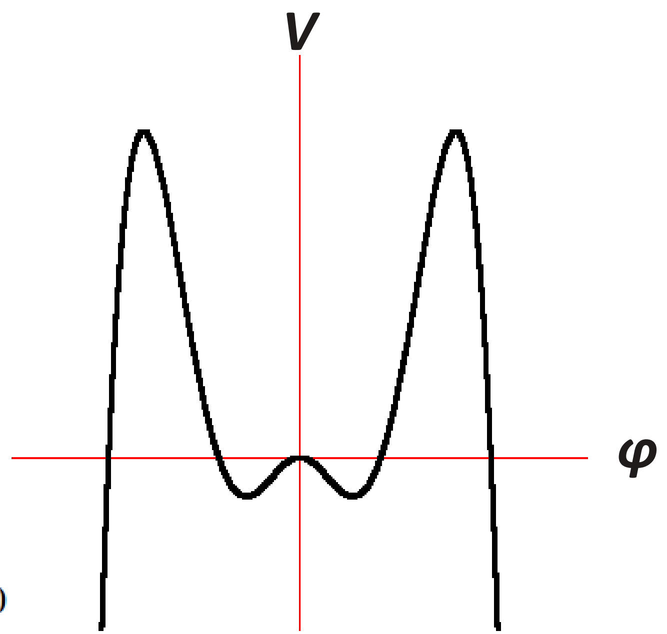
Changes since December



Vacuum Stability

- Higher-order corrections to the Higgs potential may make it go very negative for large field values
  - big effect at low mass; driven by top quark contribution
- Our vacuum may be metastable
- Additional physics before the Planck scale can stop this





Looking Forward

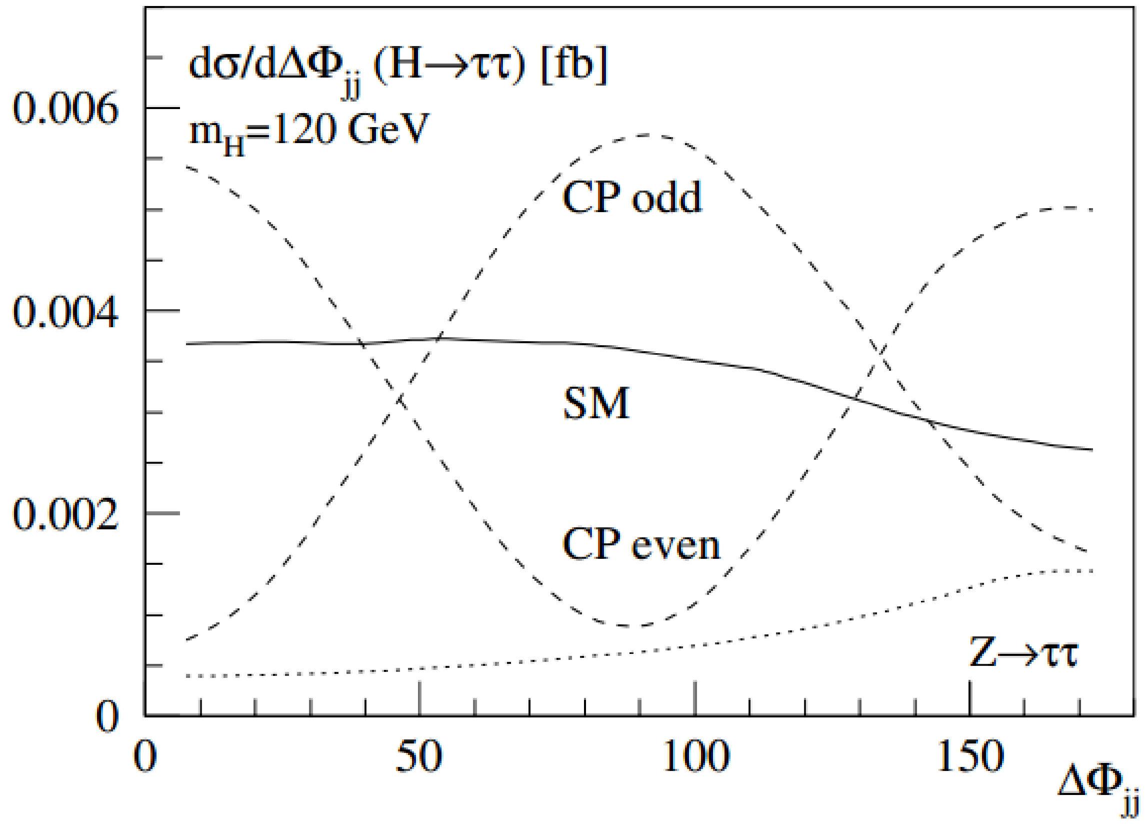
Do we find a Higgs candidate?

- Yes:
  - Are the coupling ratios right? Need to probe as many decays and production channels as possible
  - Is there only one Higgs boson?
  - Is there anything else going on in WW scattering?
- No:
  - Is it produced less often/decays strangely? Need to check in VBF channels
  - What unitarizes WW scattering?
- Need studies to understand power of LHC vs other accelerator concepts

Probing the HWW vertex

VBF production of H candidate can reveal anomalous HWW couplings

Plehn, Rainwater, Zeppenfeld PRL88 (2002) 051801

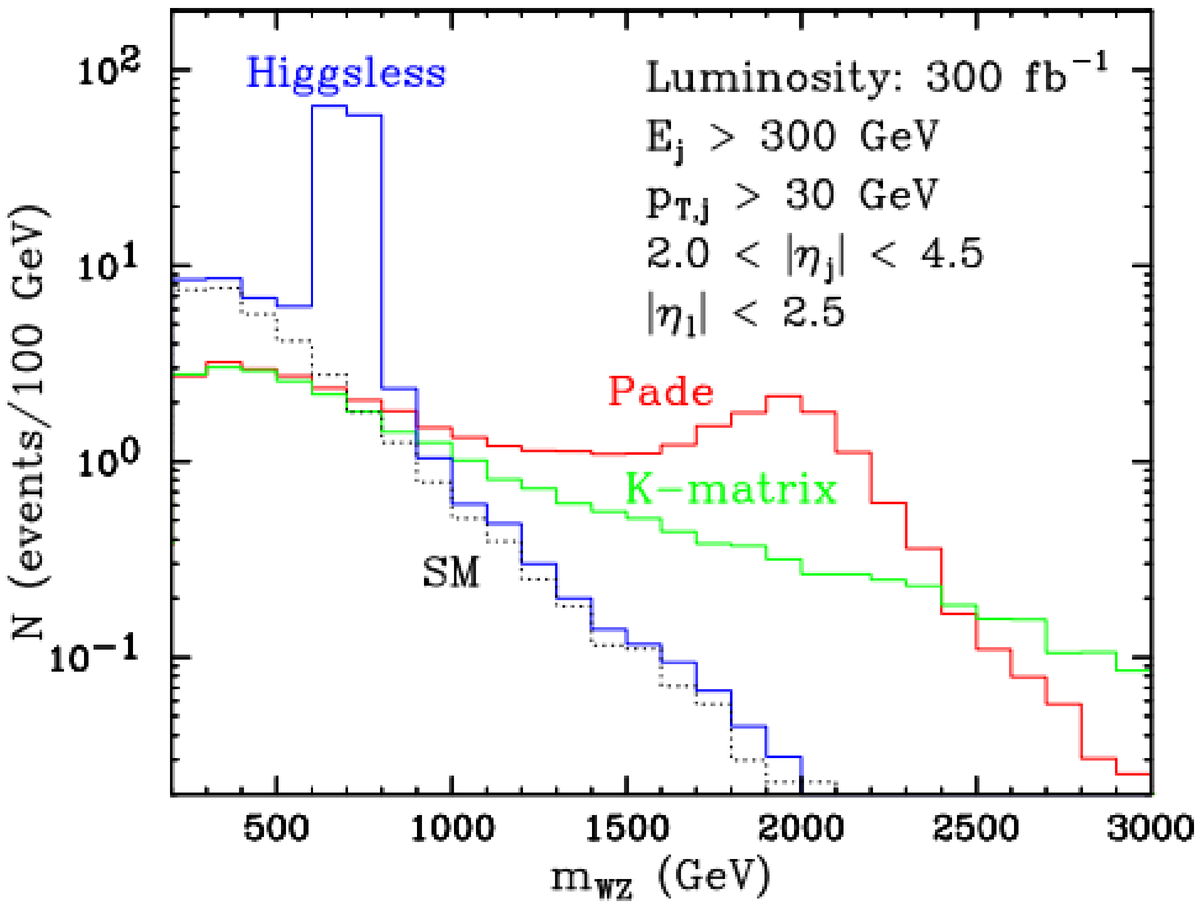


Azimuthal angular separation of tag jets in VBF

Unitarizing VV

Look at vector boson fusion events for VV scattering

Birkedal, Matchev, Perelstein (hep-ph/0508185)



Conclusion

- The H → WW channel at ATLAS excludes

  $130 < m_H < 260$ GeV

  at 95% CL.
- We are actively working on improvements to improve sensitivity, and planning for the future.
- Looking forward to 2012 and beyond, both for this channel and Higgs/EWSB physics in general.