Measurement of cross sections and couplings of the Higgs boson in the WW decay channel using the ATLAS detector

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On behalf of the ATLAS collaboration

ICHEP

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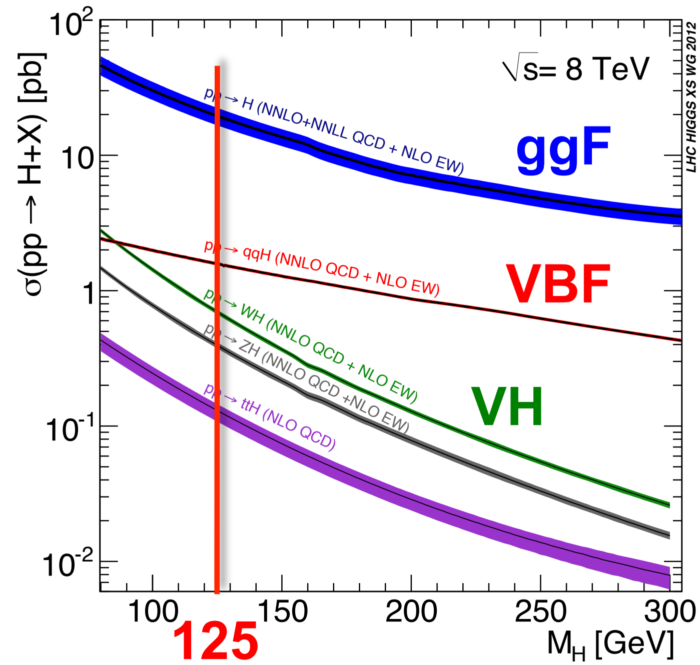
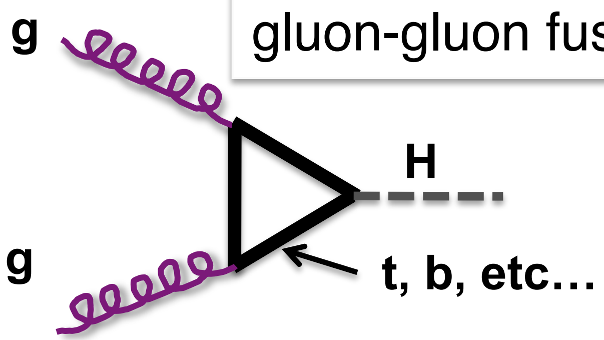
Higgs boson production

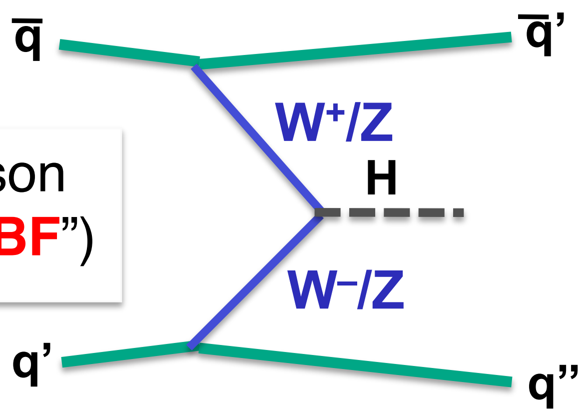
- Higgs boson couplings measurement essential SM consistency test
  - → *Search for rare production modes*
- Continue search for additional states at high mass in parallel



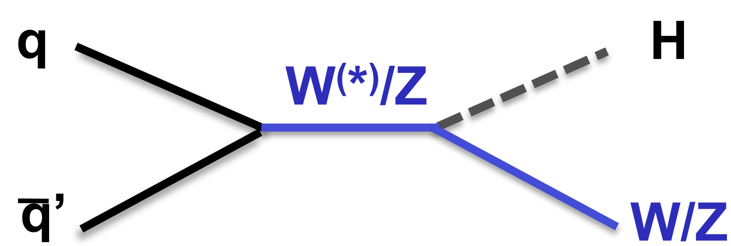
gluon-gluon fusion ("**ggF**")



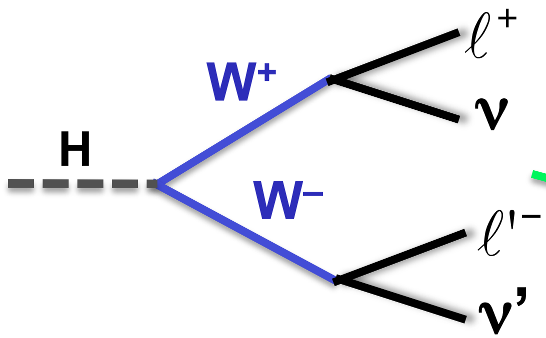
vector boson fusion ("**VBF**")

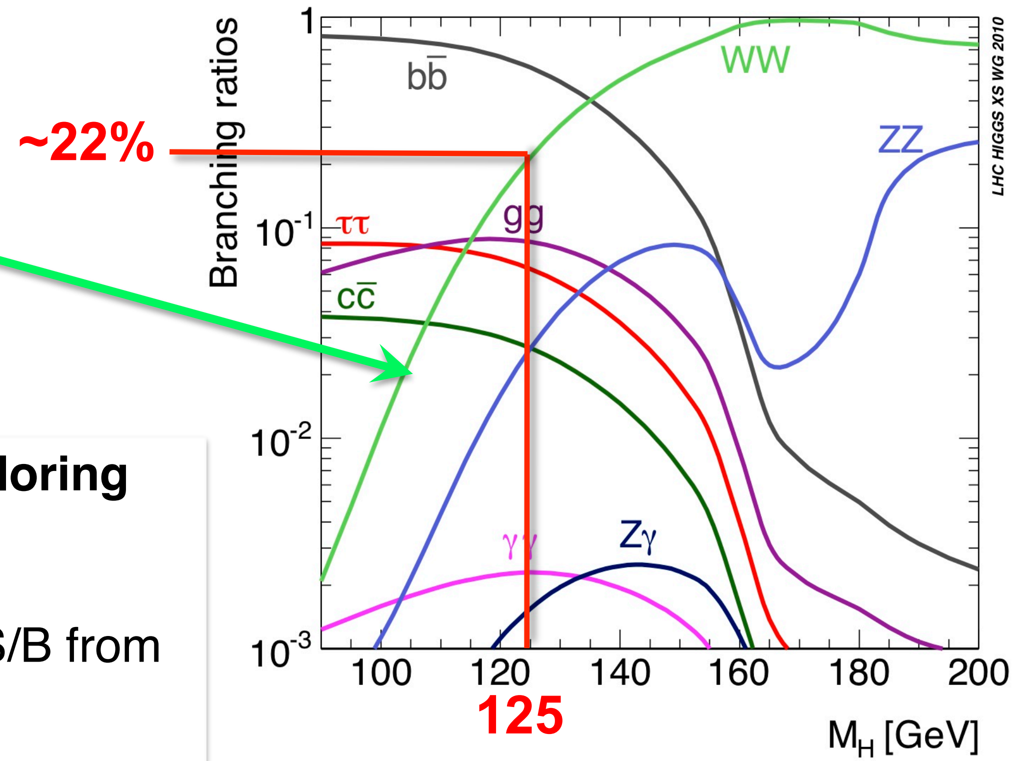


associated production ("**VH**")



$H \to WW \to l\nu l\nu$



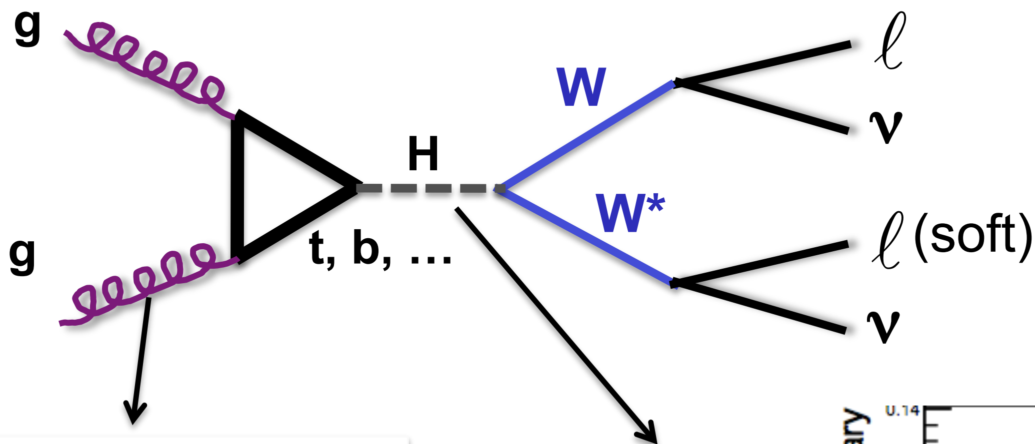


WW channel well-suited to exploring rare production modes and searching at high-mass

Large branching ratio and good S/B from clean dilepton signature

channel	$\sigma(pp \to H)$ @ 8 TeV	BR $(H \to VV)$	BR$(VV \to 4l)$	evt. yield in 20 fb^{-1}	S/B (approx.)
$H \to \gamma\gamma$		0.0023	-	1000	0.03 – 0.5
$H \to ZZ \to 4l$	22.3 pb	0.026	0.0011	130	2
$H \to WW \to l\nu l\nu$		**0.22**	**0.047**	**4700**	**0.1 – 0.4**

The WW signature



Final state

2 charged leptons +
2 neutrinos

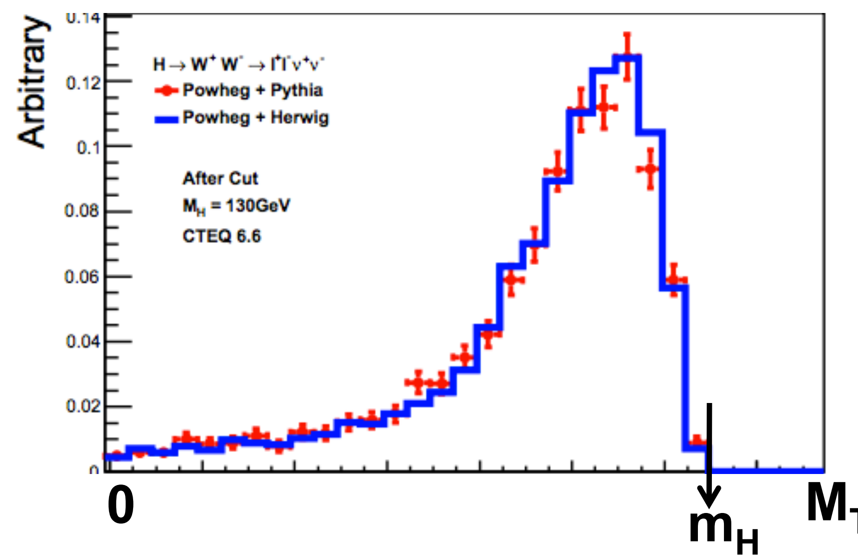
(lνjj important as well for high m_H searches)

jets depend on production mode

spin zero resonance

Can't go bump hunting like γγ or ZZ → 4l channels

Transverse mass M_T: invariant mass without p_z of νs → signal discriminant with edge at m_H



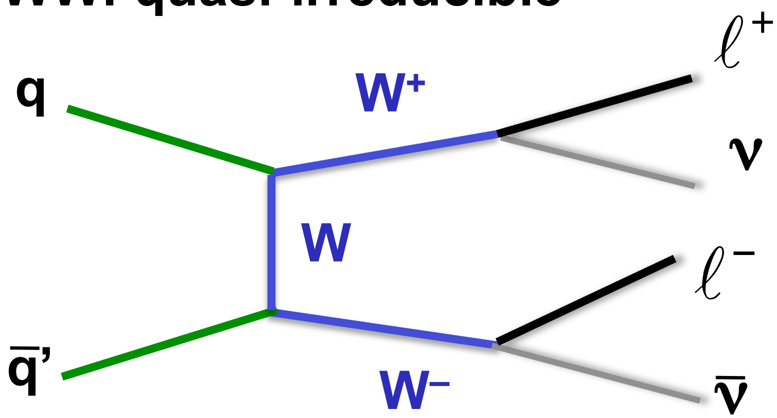
from 1201.3084v1

$$\boxed{M_T^2 = (E_T^{\ell\ell} + E_T^{\text{miss}})^2 - (\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{\text{miss}})^2}$$

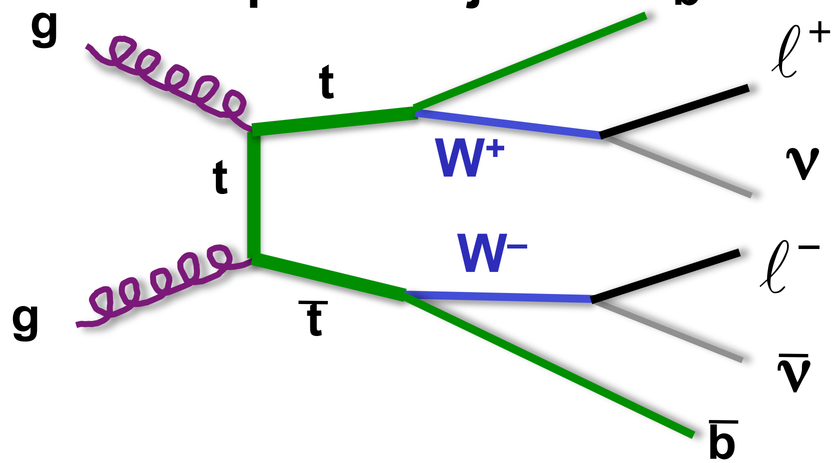
$$(E_T^{\ell\ell})^2 = (\vec{p}_T^{\,\ell\ell})^2 + (m_{\ell\ell})^2$$

Backgrounds

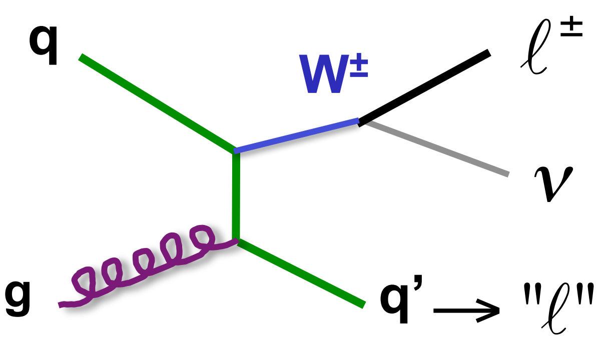
WW: quasi-irreducible



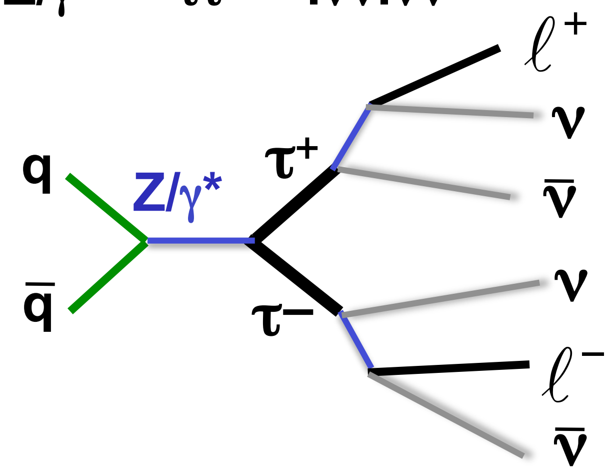
top: has b-jets



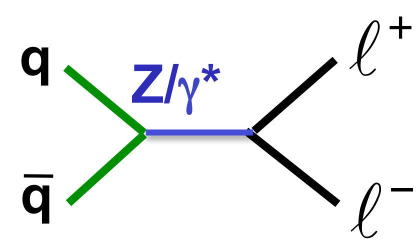
W+jets: fake leptons



Z/γ* → ττ → lννlνν

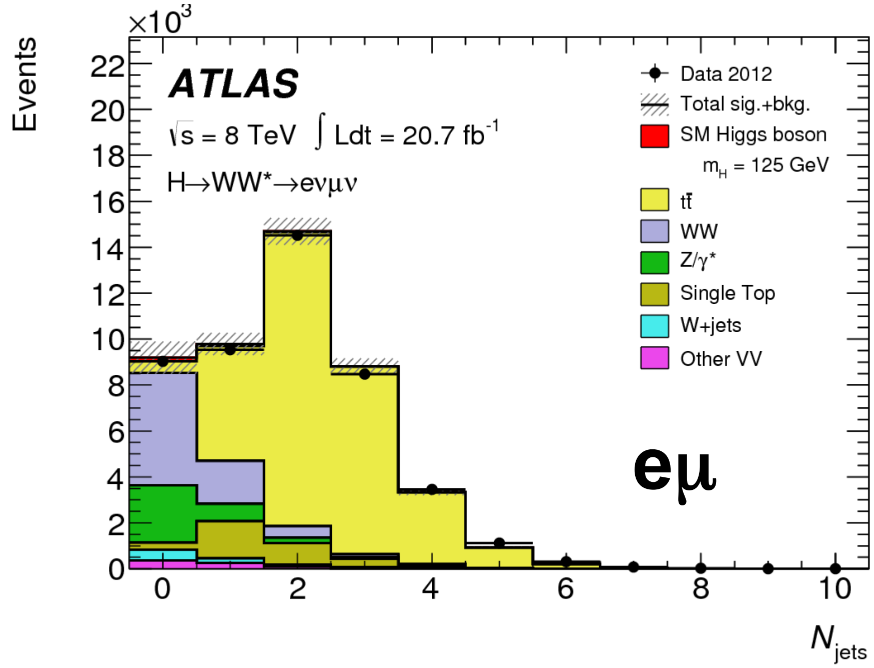


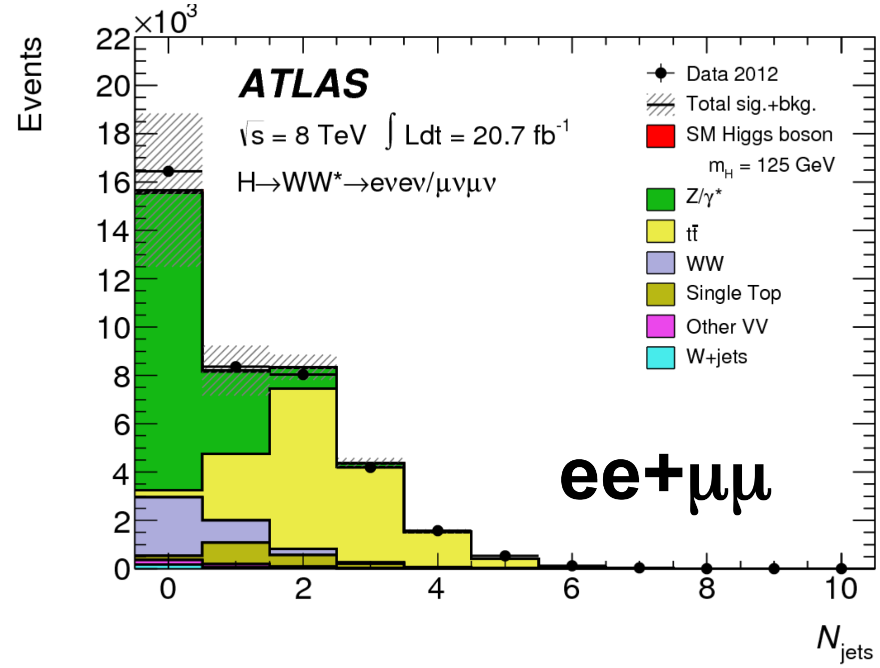
Z/γ*: no νs



Analysis strategy

Starting point: dilepton data after missing transverse energy cut



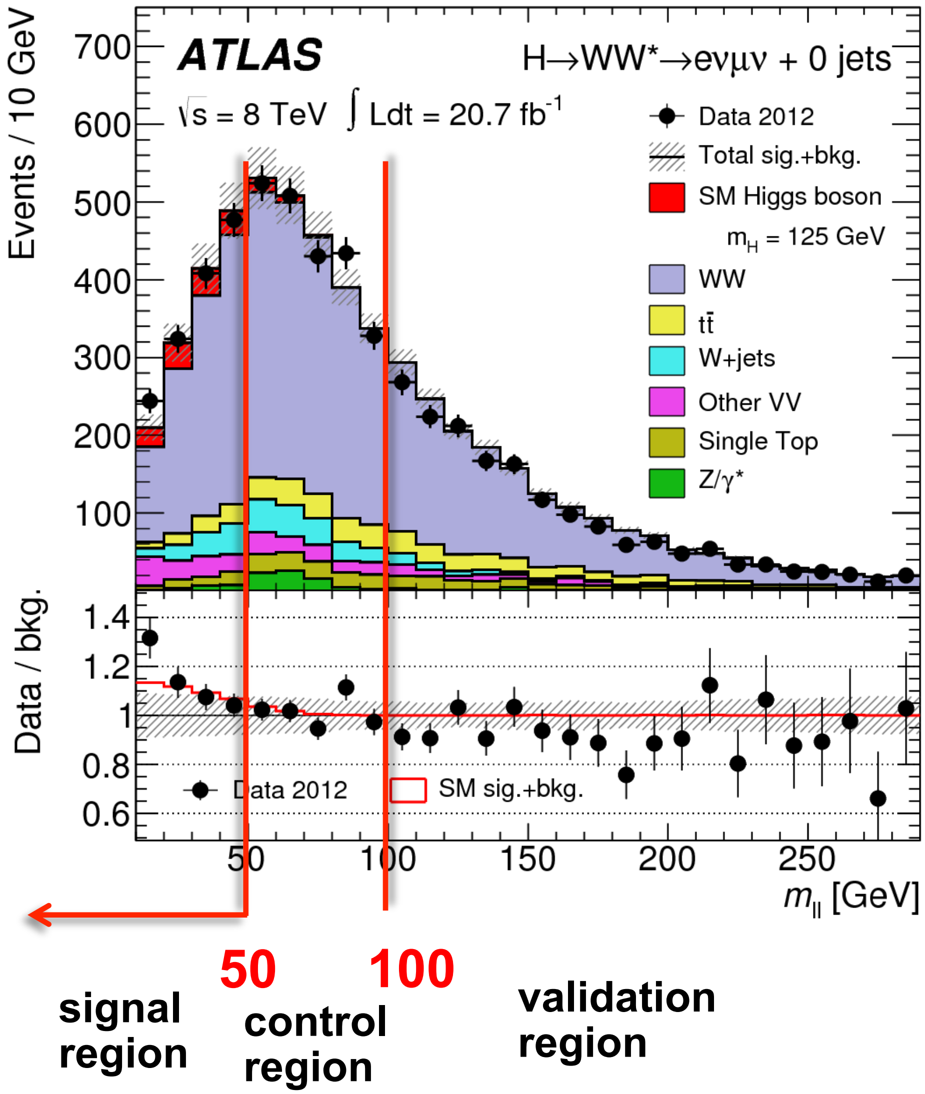


1. Categorize events by number of jets, number of leptons, lepton flavors

   → *Separate by production mode and background composition*

2. Cut away backgrounds and normalize to control regions enriched in a particular background but orthogonal to the signal region

WW – quasi-irreducible



WW is dominant ggF background

7.4% total uncertainty in 0-jet

→ 1.6% from theory

1) Normalize to data

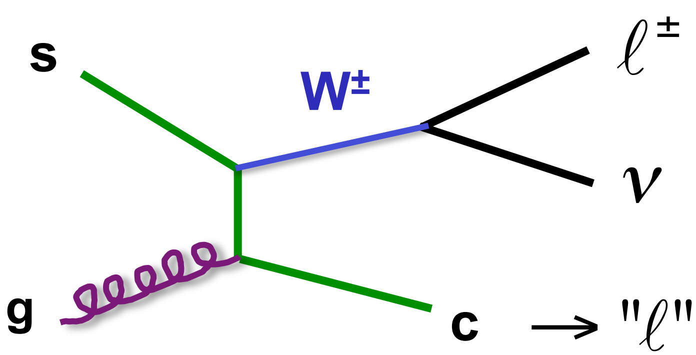
2) subtract other contributions

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

3) extrapolate using simulation

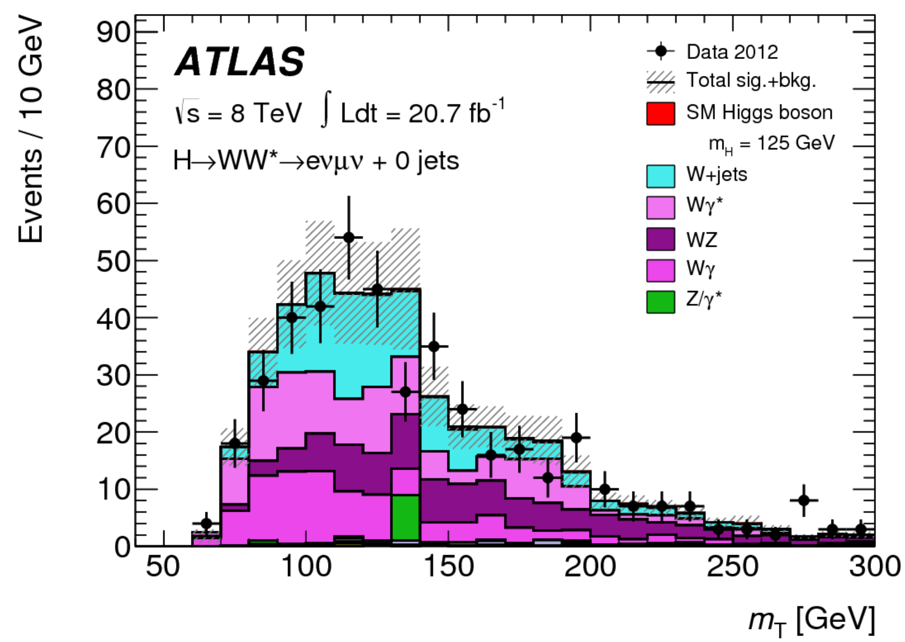
Dilepton invariant mass m_{ll} is a good signal discriminant because the spin-0 of the Higgs boson, combined with V-A structure of W decay correlates lepton directions

W+X backgrounds



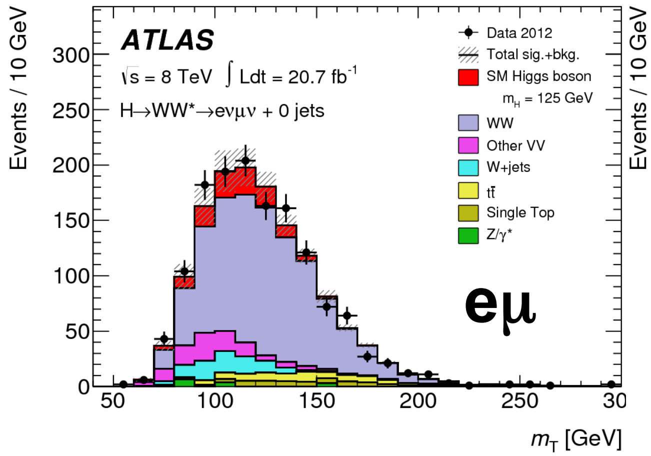
- **W+jets: isolation / ID on 2nd lepton separates SR and CR**
- Transfer factor for extrapolation to SR from dijet data
- Stringent lepton ID / isolation → "fake" leptons, particularly muons, are often true leptons from heavy-flavor hadron decays
  - → *40-45% uncertainty on fake factor from sample composition*

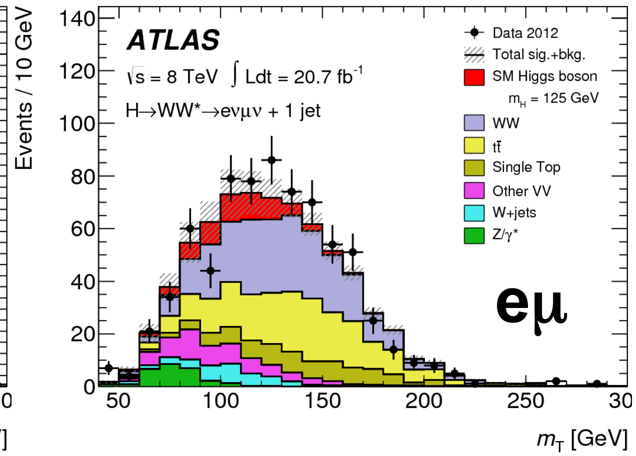
- **"Same-sign validation region"**
- **WZ, Wγ*, Wγ** estimated from theory + MC simulation
  - → *14% total uncertainty in 0-jet category*
  - → *Z, γ, and γ* produce lepton with same or opposite charge as W with equal probability*

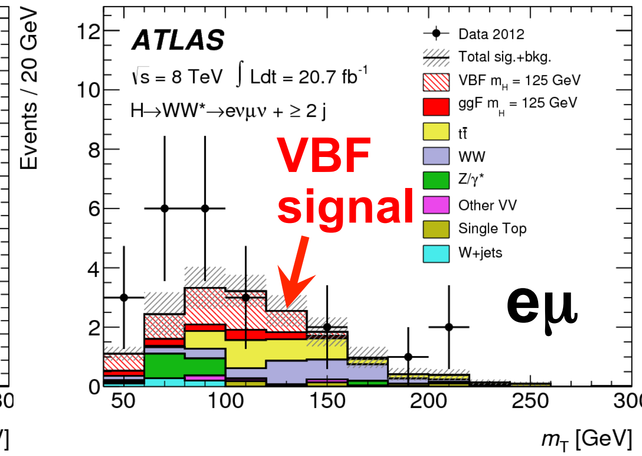


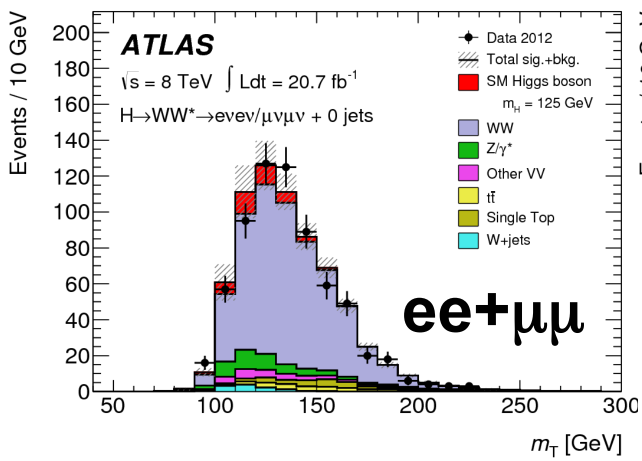
The raw data

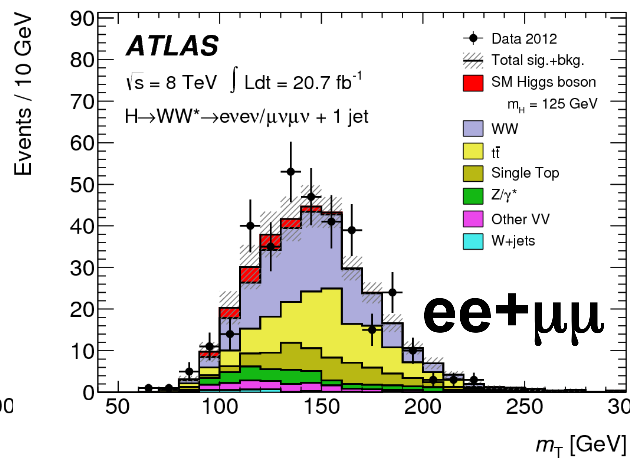
0 jet **1 jet** **2 jet (VBF)**

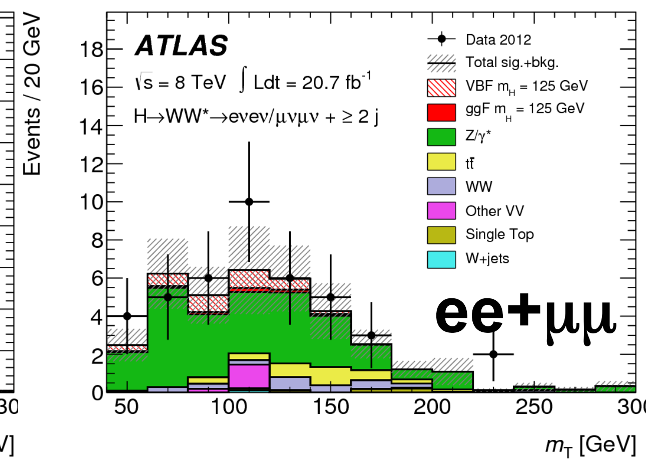




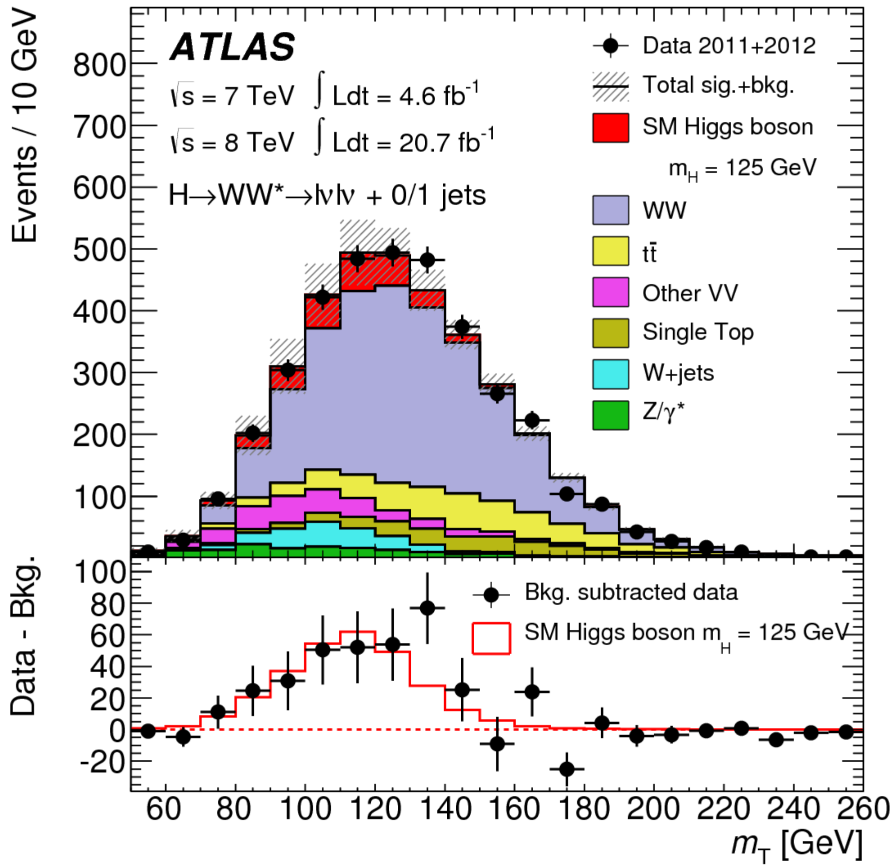






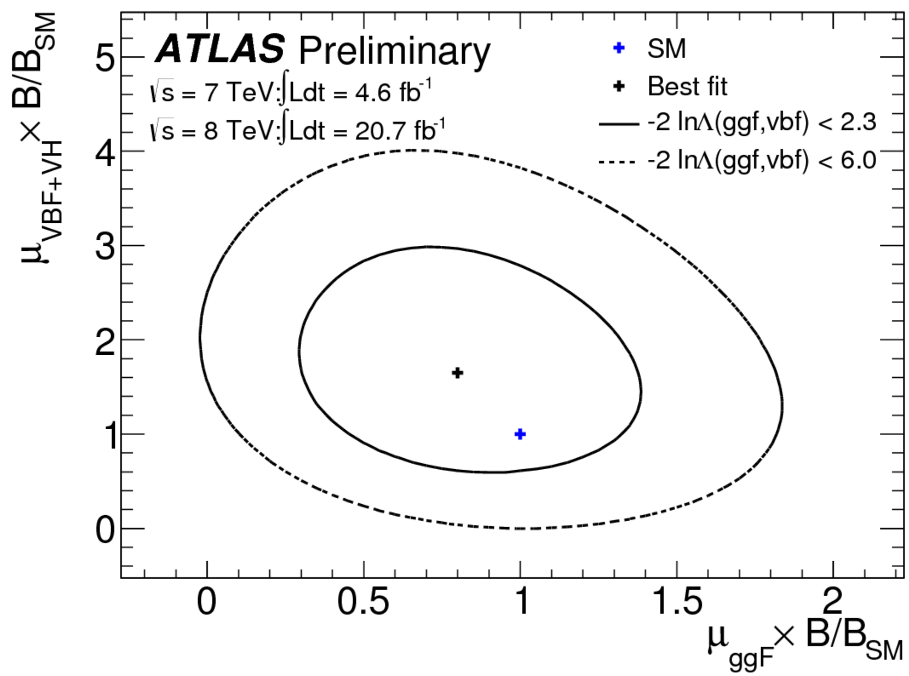


lνlν signal strength



VBF vs. ggF: **virtual contributions for ggF only**

Sensitive to BSM particles in the loops



Combined WW → lνlν signal strength μ = σ/σ_{SM} (2011+2012, all Njet):

μ = 0.99 ± 0.21 (stat.) ± 0.21 (sys)

μ_{ggF} = 0.8 ± 0.2 (stat.) ± 0.3 (syst.)

μ_{VBF} = 1.7 ± 0.7 (stat.) ± 0.4 (syst.)

Cross section measurement

Uncertainties on the signal strength $\mu = \sigma/\sigma_{SM}$

Category	Source	Uncertainty, up (%)	Uncertainty, down (%)
Statistical	Observed data	+21	−21
Theoretical	Signal yield ($\sigma \cdot \mathcal{B}$)	+12	−9
Theoretical	WW normalisation	+12	−12
Experimental	Objects and DY estimation	+9	−8
Theoretical	Signal acceptance	+9	−7
Experimental	MC statistics	+7	−7
Experimental	W+ jets fake factor	+5	−5
Theoretical	Backgrounds, excluding WW	+5	−4
Luminosity	Integrated luminosity	+4	−4
Total		+32	−29

- $\mu = \sigma/\sigma_{SM}$; measured cross section $\sigma = \mu \times \sigma_{SM}$
- Remove uncertainties on signal cross section but not acceptance

$(\sigma \bullet Br(H \rightarrow WW))_{obs,\ 8\ TeV}$ **= 6.0 ± 1.1 (stat.) ± 0.8 (theo.) ± 0.7 (expt.) ± 0.3 (lumi.) pb**
= 6.0 ± 1.6 pb

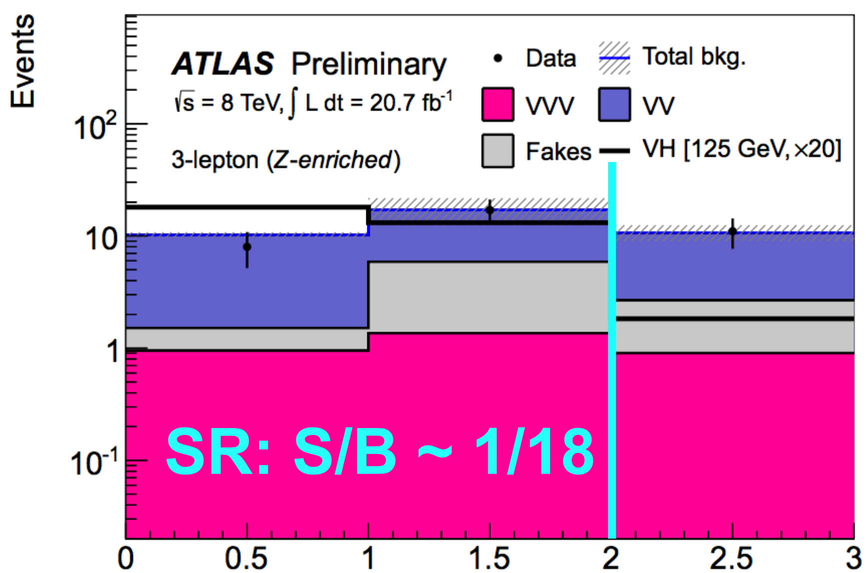
$(\sigma \bullet Br(H \rightarrow WW))_{exp,\ 8\ TeV}$ **= 4.8 ± 0.7 pb**

VH, H → WW Signal Regions

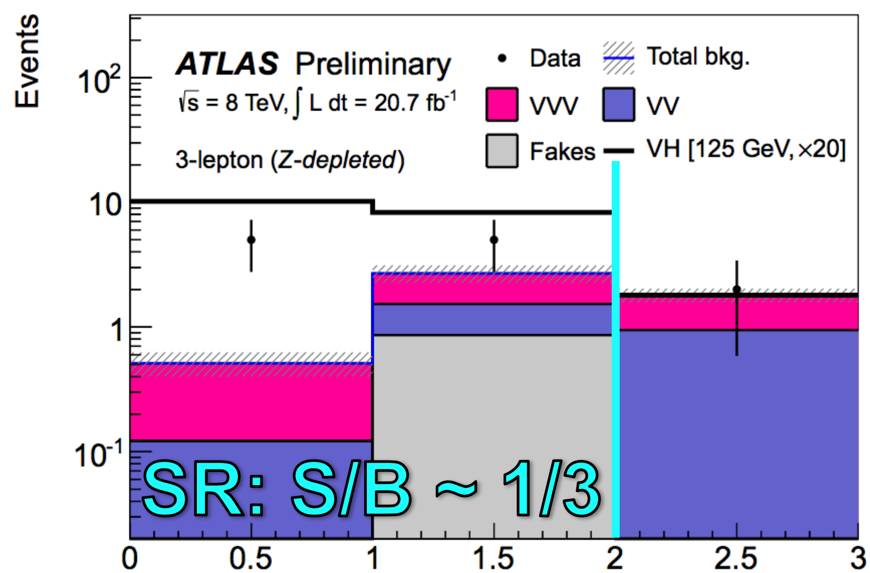
Clean 3-lepton (WH) and 4-lepton (ZH) signatures, additional info on HWW vertex (complement to VBF mode)

4-lepton: 2 OS pairs, one with $|m_{ll} - m_Z| < 10$ GeV
1 event expected, S/B ~ 1/5
→ *zero* observed

WH: Z-enriched category
(OS same-flavor pair)



WH: Z-depleted category
(no OS same-flavor pair)



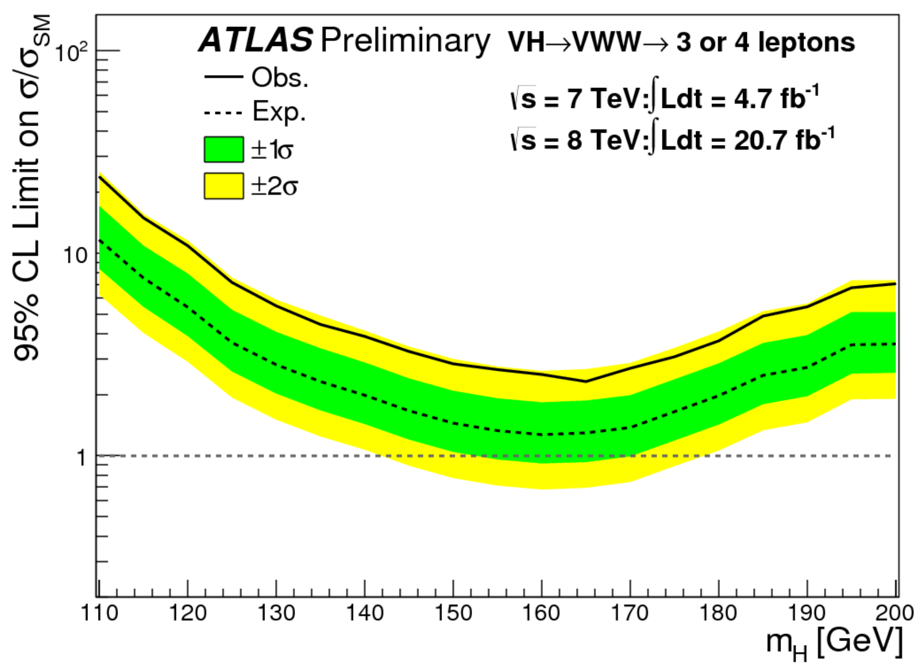
minimum ΔR between any two leptons: same physics as $\Delta\varphi(ll)$ and m_{ll}

VH, H → WW Results

cross section limits (@95% confidence) and
significance of excess over BG for m_H=125 GeV

	expected	observed	significance
WH (8 TeV)	**5.2** x σ_{SM}	**10** x σ_{SM}	**2.3** σ (p_0 = 1.2%)
ZH (8 TeV)	**9.6** x σ_{SM}	**14** x σ_{SM}	**1.5** σ (p_0 = 7.2%)
Combined (7+8 TeV)	**3.6** x σ_{SM}	**7.2** x σ_{SM}	**2.0** σ (p_0 = 2.1%)

- No SM sensitivity yet but observed limit higher than expected one



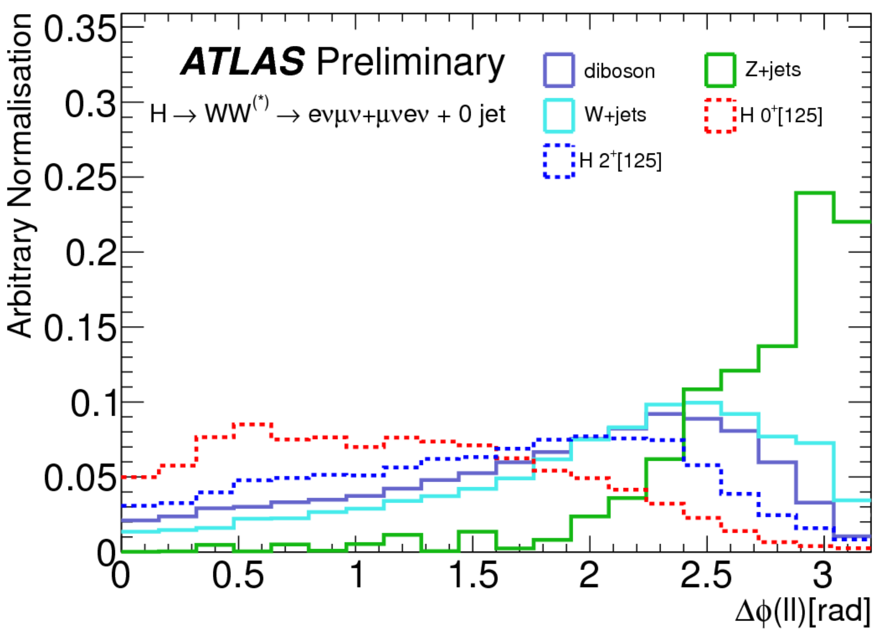
The Road Ahead

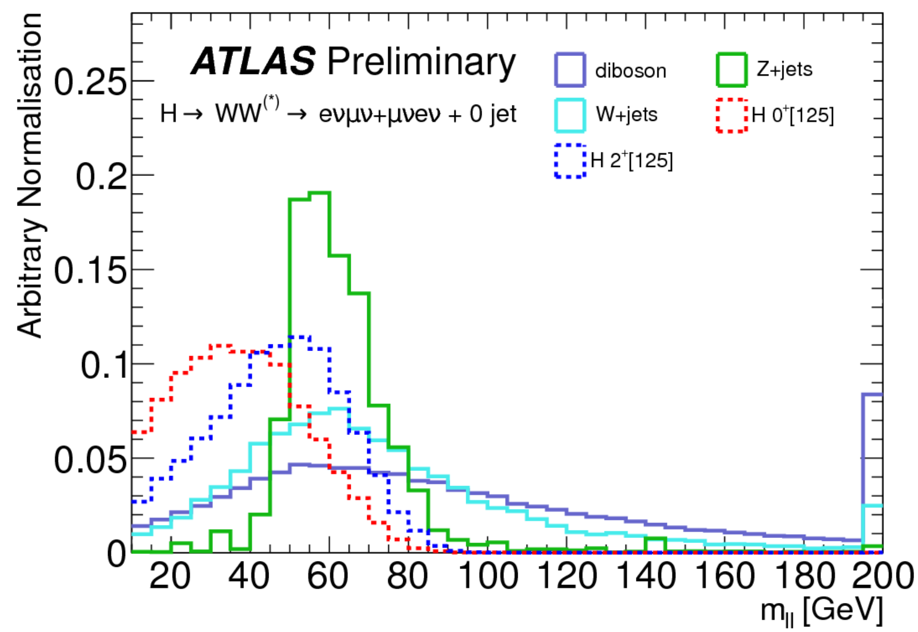
- WW was essential to discovery, combined rate measurement, and connecting the new particle to electroweak symmetry breaking
- Now: Is this the **SM Higgs boson or something more interesting?**
  - → *WW channel can address this from multiple angles*
    - + Good S/B and large branching ratio
    - - Challenging backgrounds in ggF and VBF
  - → *ggF and VBF modes key inputs to coupling measurement combinations*
  - → *Search for rarer production modes (WH, VH, ttH…)*
  - → *Properties measurements (starting from spin)*
  - → *Search at high mass for additional states*
- 13 TeV run (2015-2017) will bring much-needed data and stronger statements in response to all of these questions

backup

Spin measurement

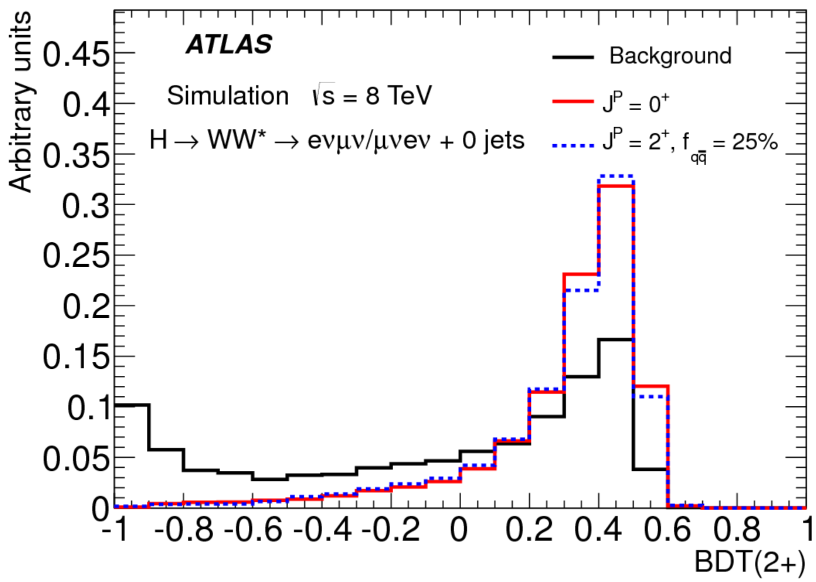
- Test spin hypothesis with kinematic variables through a BDT
  - → *No direct measurement of angles (cannot reconstruct rest frame)*
- Use ggF eμ zero-jet category → highest sensitivity
  - → *Then loosen requirements on spin-sensitive variables: $m_{ll} < 80$ GeV, $p_T^{ll} > 20$, $\Delta\varphi(ll) < 2.8$*

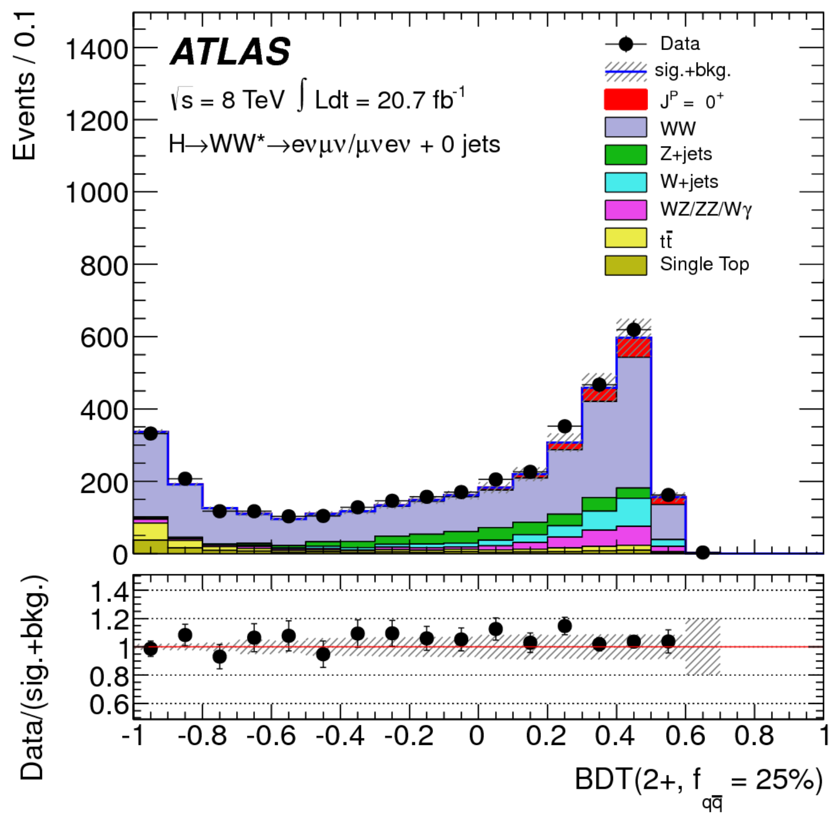




Spin measurement

- Train two BDTs
  - → *One for SM signal (0^+) against background*
  - → *Second for alternate spin/parity hypothesis (2^+, 1^+, 1^-) against background*
- Fit data to discriminate hypotheses
- 2^+ excluded at ≥ 95% CL by WW

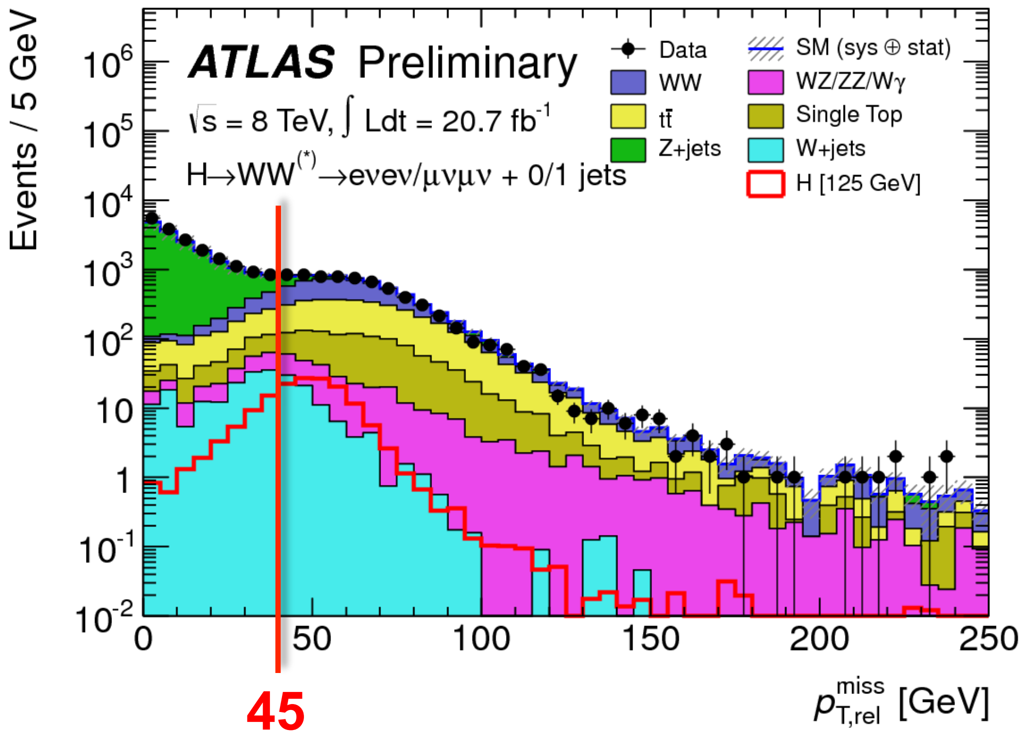




Drell Yan (Z/γ*)

Measure missing transverse energy **only with tracks**: more robust against extra interactions (pileup)

$$\vec{E}_T^{miss} = -\sum_{\text{objects}\, i} \vec{p}_T^{\,\text{object}}$$



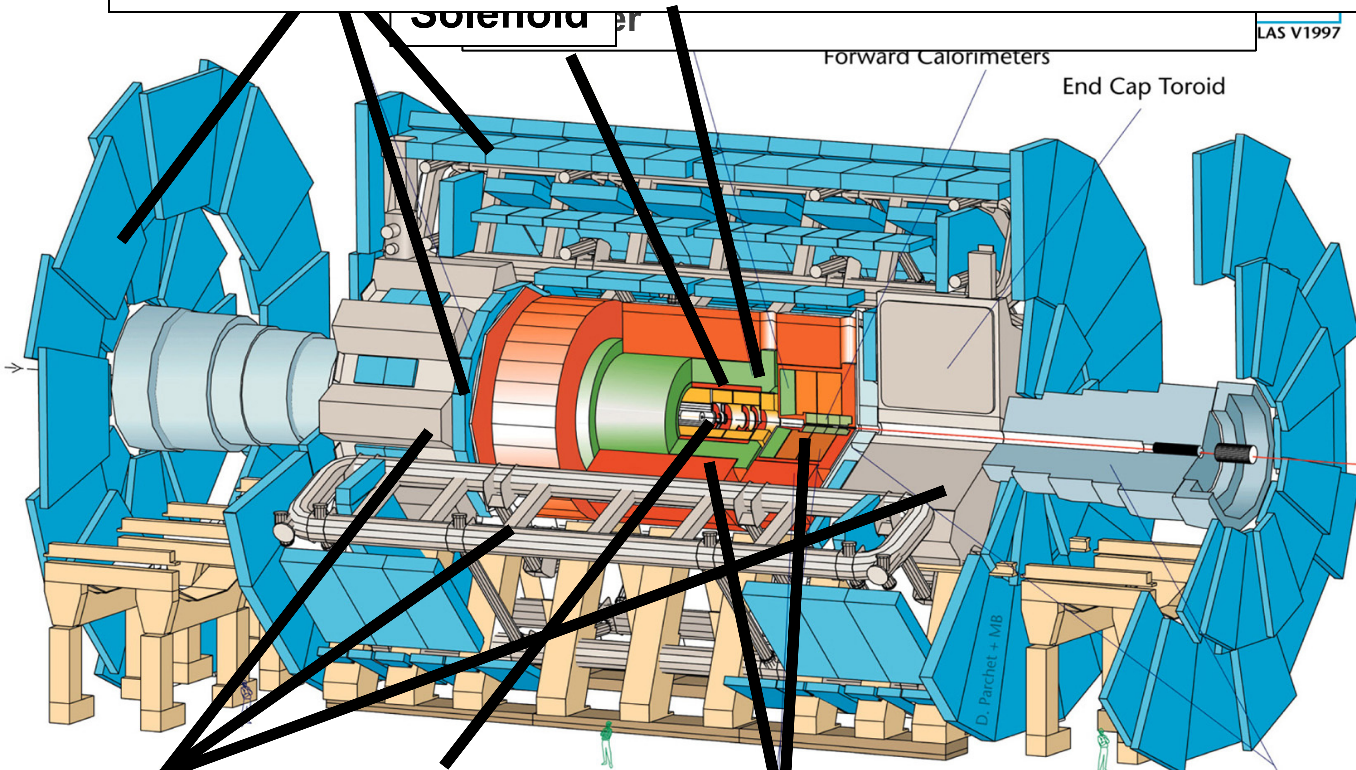
- Left: additional rejection after initial E_T^{miss} requirement
  - → *First inclusion of ee+μμ channels in 2012 WW analysis*

The ATLAS Detector

Muon Detectors: large radii for precise momentum measurement

Precision: Drift tubes (MDT) and Cathode Strip Chambers (CSC)

Trigger: Resistive Plate Chamber (RPC) and Thin Gap Chamber (TGC)



Toroids

Inner Detector (tracking):

Pixels (sili

SCT (silico

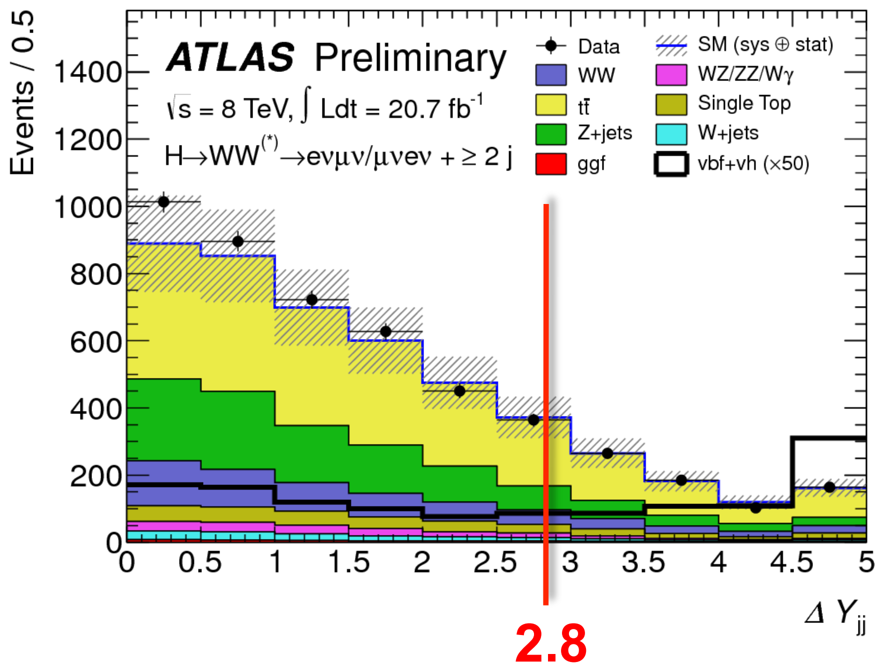
TRT (straw

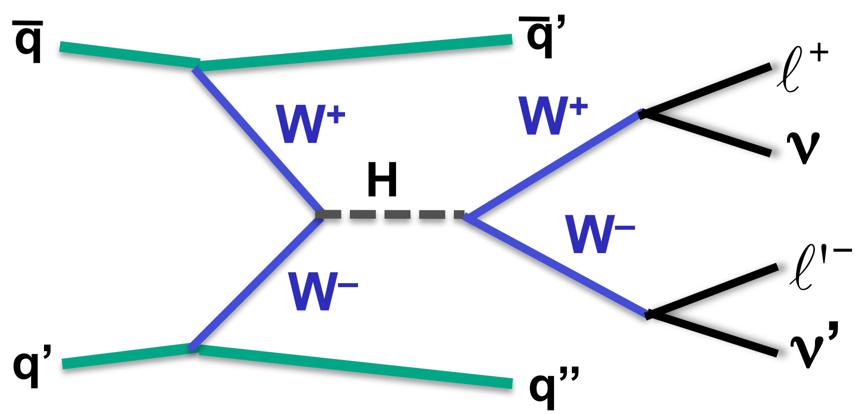
Hadronic calorimeter (jets, hadrons)

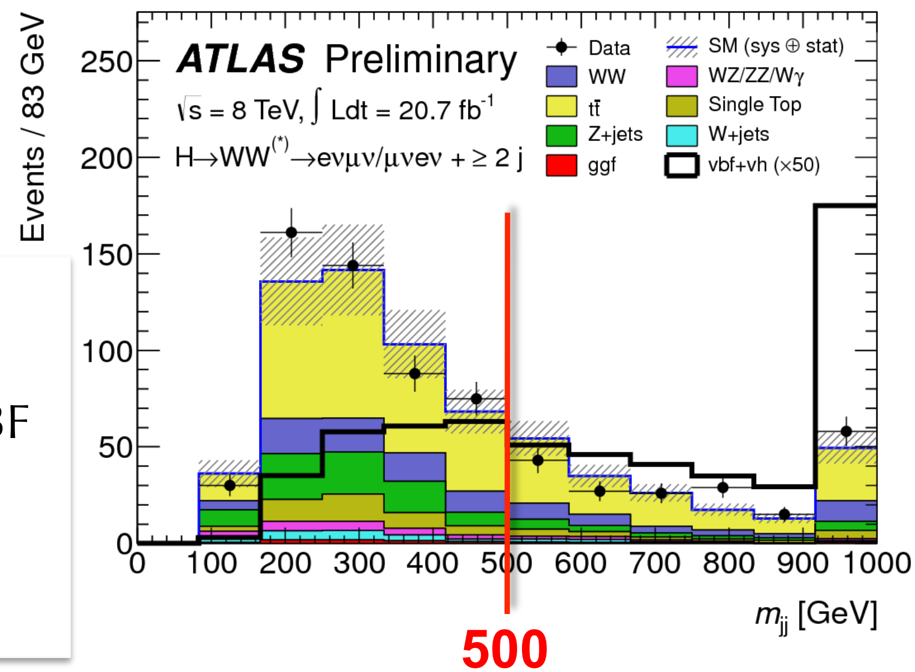
Steel absorber + scintillator

LAr with copper/tungsten absorber

Top background to VBF







≥ 2-jet data *after* a b-veto: *still* top-dominated

Reject further background with unique VBF signature: **energetic well-separated jets**

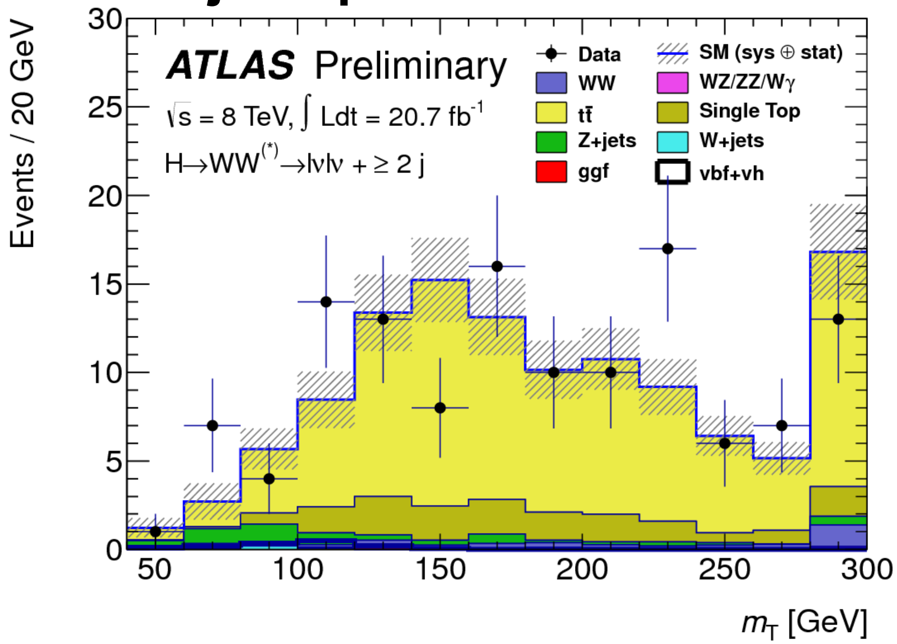
These cuts reject additional **95% of total background but cost 70% of VBF signal**

Estimating top in VBF phase space

Uncertainties on top normalization			
stat.	**theory**	**exp.**	**total**
10%	15%	29%	39%

- Normalize to control region (like WW)
  - → *Apply all VBF jet cuts, extrapolate from b-tagged → b-vetoed*

2-jet top CR



Normalize to data

subtract other processes

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

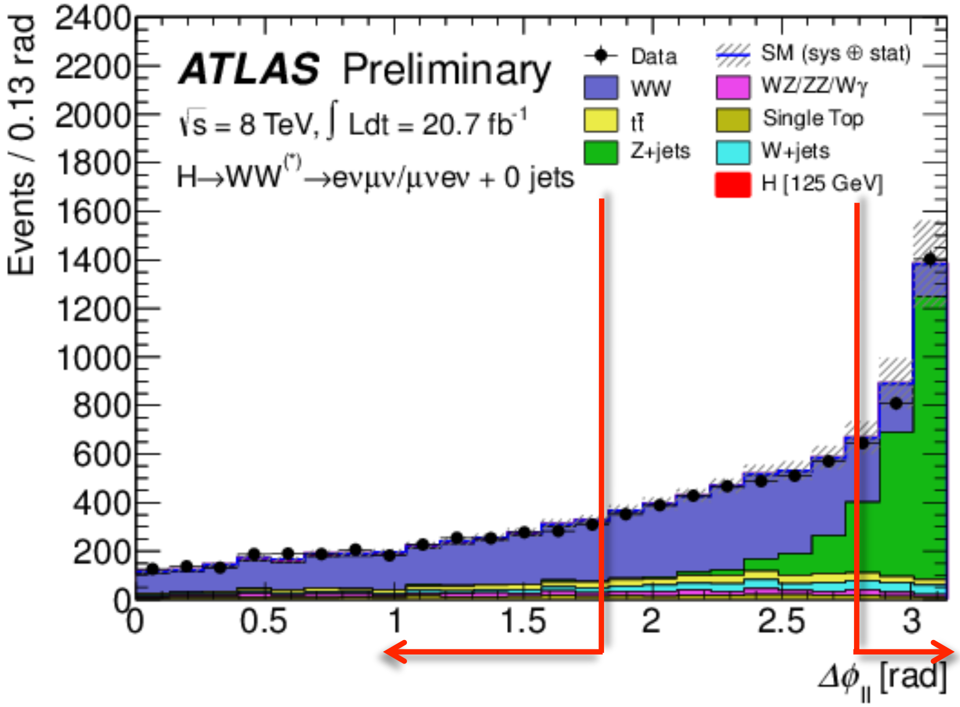
extrapolate using simulation

Full systematic uncertainties

Source	Signal processes (%) $N_{jet}=0$	$N_{jet}=1$	$N_{jet}\geq 2$	Background processes (%) $N_{jet}=0$	$N_{jet}=1$	$N_{jet}\geq 2$
Theoretical uncertainties						
QCD scale for ggF signal for $N_{jet}\geq 0$	13	-	-	-	-	-
QCD scale for ggF signal for $N_{jet}\geq 1$	10	27	-	-	-	-
QCD scale for ggF signal for $N_{jet}\geq 2$	-	15	4	-	-	-
QCD scale for ggF signal for $N_{jet}\geq 3$	-	-	4	-	-	-
Parton shower and UE model (signal only)	3	10	5	-	-	-
PDF model	8	7	3	1	1	1
$H\rightarrow WW$ branching ratio	4	4	4	-	-	-
QCD scale (acceptance)	4	4	3	-	-	-
WW normalisation	-	-	-	1	2	4
Experimental uncertainties						
Jet energy scale and resolution	5	2	6	2	3	7
b-tagging efficiency	-	-	-	-	7	2
f_{recoil} efficiency	1	1	-	4	2	-

$Z/\gamma^* \rightarrow \tau\tau \rightarrow l\nu\nu l\nu\nu$

Reduce uncertainties by normalizing dominant background to data in signal-depleted "control regions" (CR)



signal region **1.8** **2.8** **control region**

Normalize to data

subtract other processes

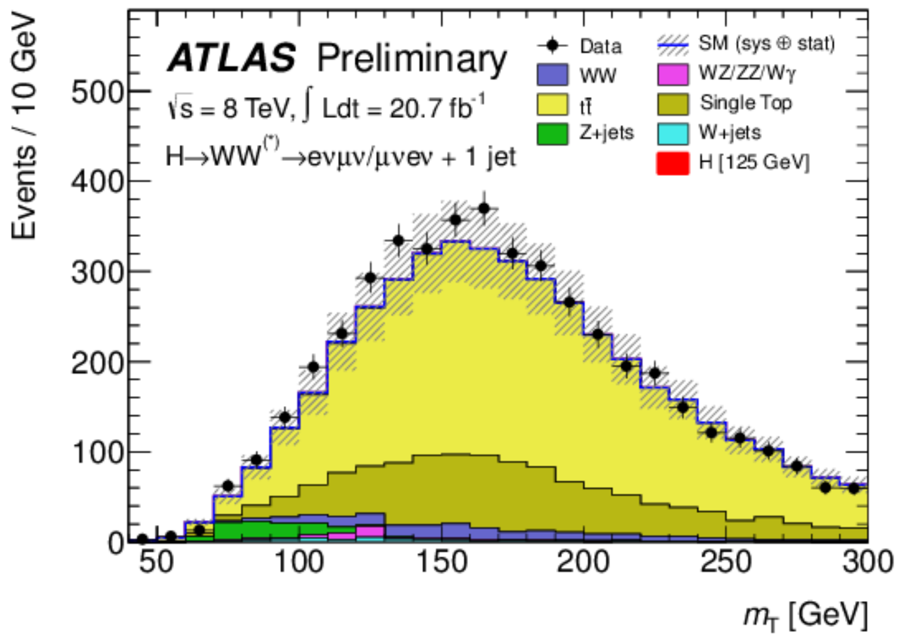
$$N_{SR} = \left(\frac{N_{SR}^{MC}}{N_{CR}^{MC}}\right)\left(N_{CR}^{\mathrm{data}} - N_{CR}^{\mathrm{other}}\right)$$

extrapolate using simulation

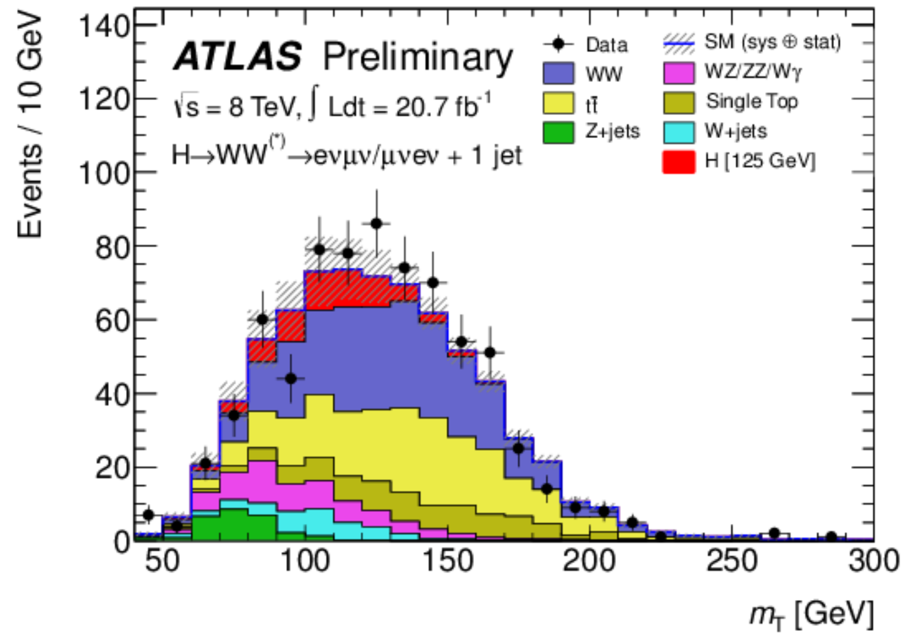
Azimuthal lepton opening angle $\Delta\varphi$(ll) works well for the same reasons

1-jet analysis: top and the b-veto

control region: b-jet tag



signal region: b-jet veto



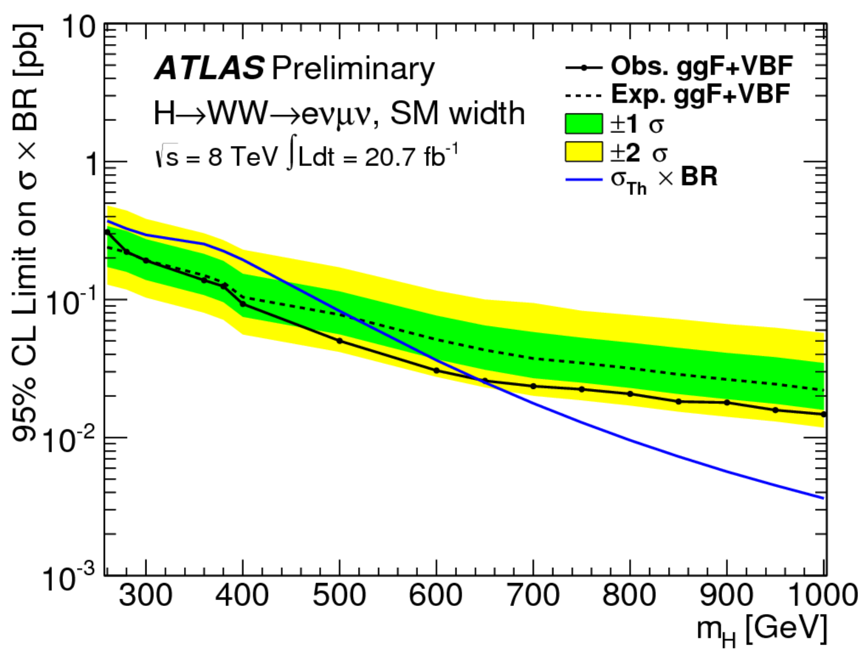
Extrapolate from tag to veto

Experimental systematics dominate (*b*-tag efficiency calibration)

High-mass / BSM WW searches

- High-mass searches now explicitly BSM
- Include SM-like, narrow-width, 2HDM signal models

Combine ggF and VBF channels for SM-like hypothesis (assume production cross section ratio unchanged from SM)



2HDM: general BSM Higgs model, neural-net based search

heavy H masses up to ~200 GeV excluded (model + mixing angle dependent