Jet vetoes and tagging in Higgs boson studies in ATLAS

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Topical Workshop on
Jet Vetoes and Jet Multiplicity Observables at the LHC
IPPP, Durham, July 2013

Outline

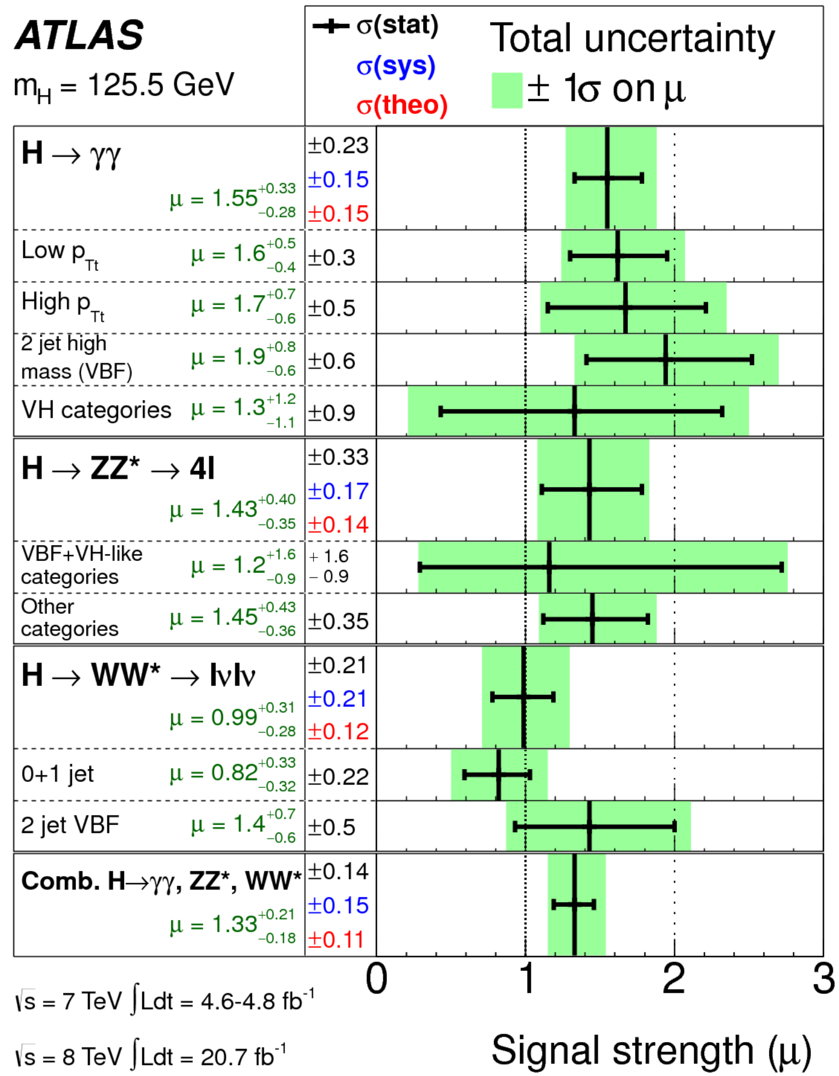
- Introduction and disclaimer
- Rejecting background and separating production modes
  - $H \to WW$, $H \to \gamma\gamma$, $H \to ZZ^*$, $H \to \tau\tau$
- Constraining backgrounds from data
  - VH, $H \to bb$ (ttH in backup)
- Jet observables in $H \to \gamma\gamma$
- Conclusions

Many thanks to Jeppe Andersen, Daniel Maitre and the IPPP System administrators!!

Word of wisdom: never, ever, go to a workshop without a backup of your talk! ☺

Higgs Physics

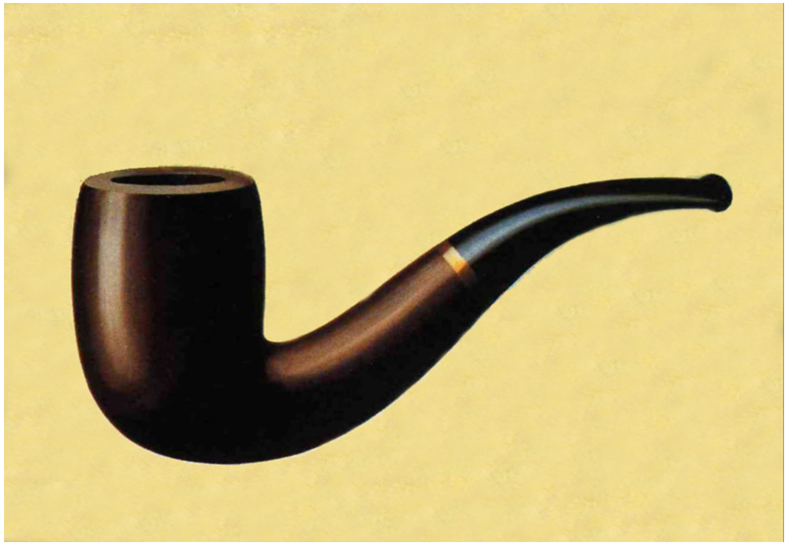
- One year after the Higgs boson discovery by ATLAS & CMS:
  - arXiv:1307.1427, 1307.1432 [hep-ex]
  - Clear observation in:
    - H→γγ (7.4σ)
    - H→ZZ (6.6σ)
    - H→WW (3.8σ @ mH=125GeV)
  - 3.3σ evidence for Vector Boson Fusion (VBF) production
  - Evidence for $J^P = 0^+$; models with J^P=0-, 1-, 1+, 2+ rejected at 97.8% confidence level or better
  - 2–3σ evidence for H→ττ, H→bb from LHC and Tevatron
- Current results consistent with Standard Model Higgs
- But this is not the subject of this talk!...



arXiv:1307.1427,[hep-ex]

Disclaimer

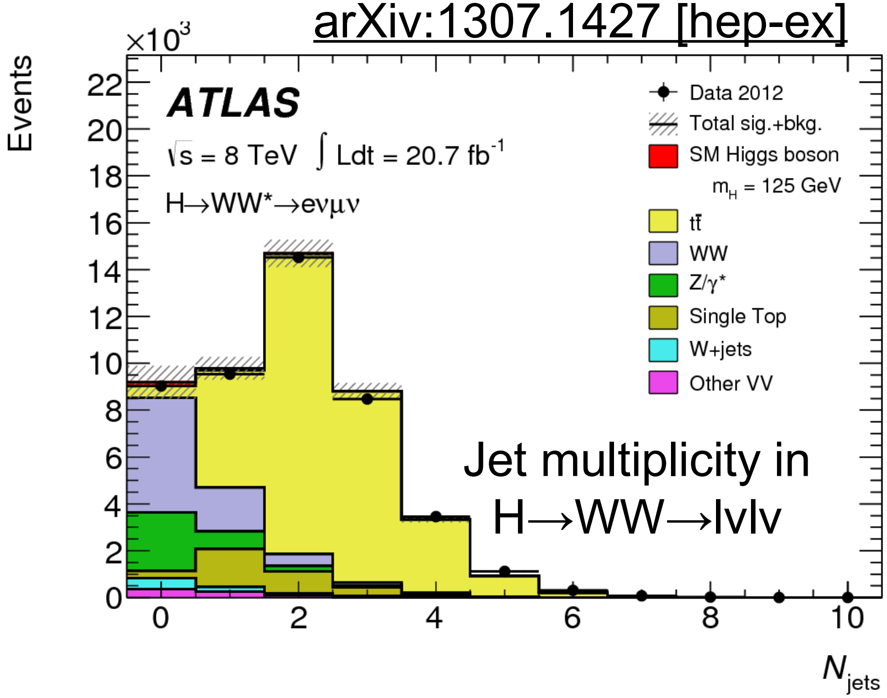
Ceci n’est pas une présentation sur les résultats du boson de Higgs!



- This talk, will NOT focus on Higgs physics results
  - Concentrate on use of jets & jet vetoes in Higgs analyses
  - Still...some results shown or in backup

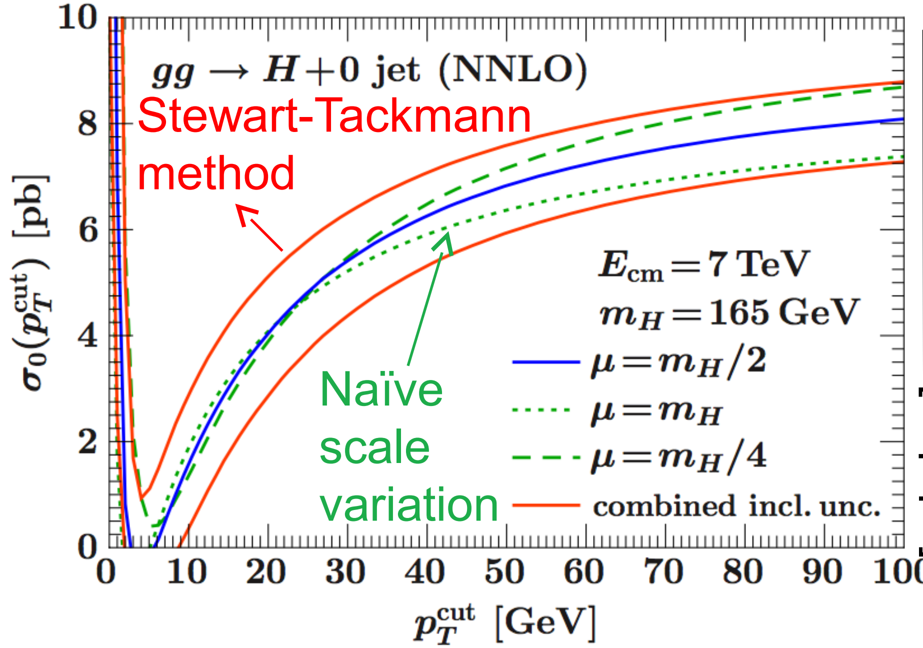
- Many analyses are performed and optimized in exclusive Njet categories
  - $H\to\gamma\gamma$, $H\to ZZ^*$, $H\to WW$, $H\to\tau\tau$, $H\to bb$
- Jet multiplicity is essential to separate different production modes
  - Gluon-fusion, Vector Boson Fusion, VH, ttH
- Backgrounds for many analyses are strongly jet-bin dependent
  - In both the level and background composition
  - Often crucial to constrain backgrounds from data in control regions defined by the number of jets passing some kinematic selection

arXiv:1307.1427 [hep-ex]



But…

- Naïve variation of μ_f and μ_r scales underestimates cross section uncertainties in exclusive Njet bins
  - Problem arises from numerical cancellation between log terms in perturbative expansion
  - Depends on jet pT cut and is especially bad for usual values of jet p_T cut: 20-30 GeV



arXiv:1107.2117 [hep-ph]

$$\sigma_0(p^{cut}) \approx \sigma_B[(1+\alpha_s+\alpha_s^2+\ldots)-(\alpha_s(L^2+L+1)+\alpha_s^2(L^4+\ldots+1)+\ldots)]$$

- More robust method proposed by Stewart and Tackmann
  - Treats uncertainties in fixed-order cross sections for N and N+1 jets as uncorrelated
- Scale uncertainty in signal for each Njet bin can be leading uncertainty (e.g. H→WW)

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

arXiv:1307.1427 [hep-ex]

$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$

$H \to WW^{(*)} \to l\nu l\nu$

- Signature:
  - Same/different flavour leptons: ee, μμ, eμ
  - Split into 0, 1, ≥2 jet
  - See later for ≥2 jet (VBF)

- Backgrounds:
  - WW: dominant in Njet=0
  - Top: tt + single top
  - Drell-Yan: Z/γ*
    - ee/μμ: from fake ETmiss
    - eνμν: from Z/γ*→ττ→eμ+X
  - Additional backgrounds:
    - W+jets
    - Other diboson: WZ, ZZ, Wγ

- Focus on ≤1 jet WW→eνμν:
  - 0-/1-jet to reject top background

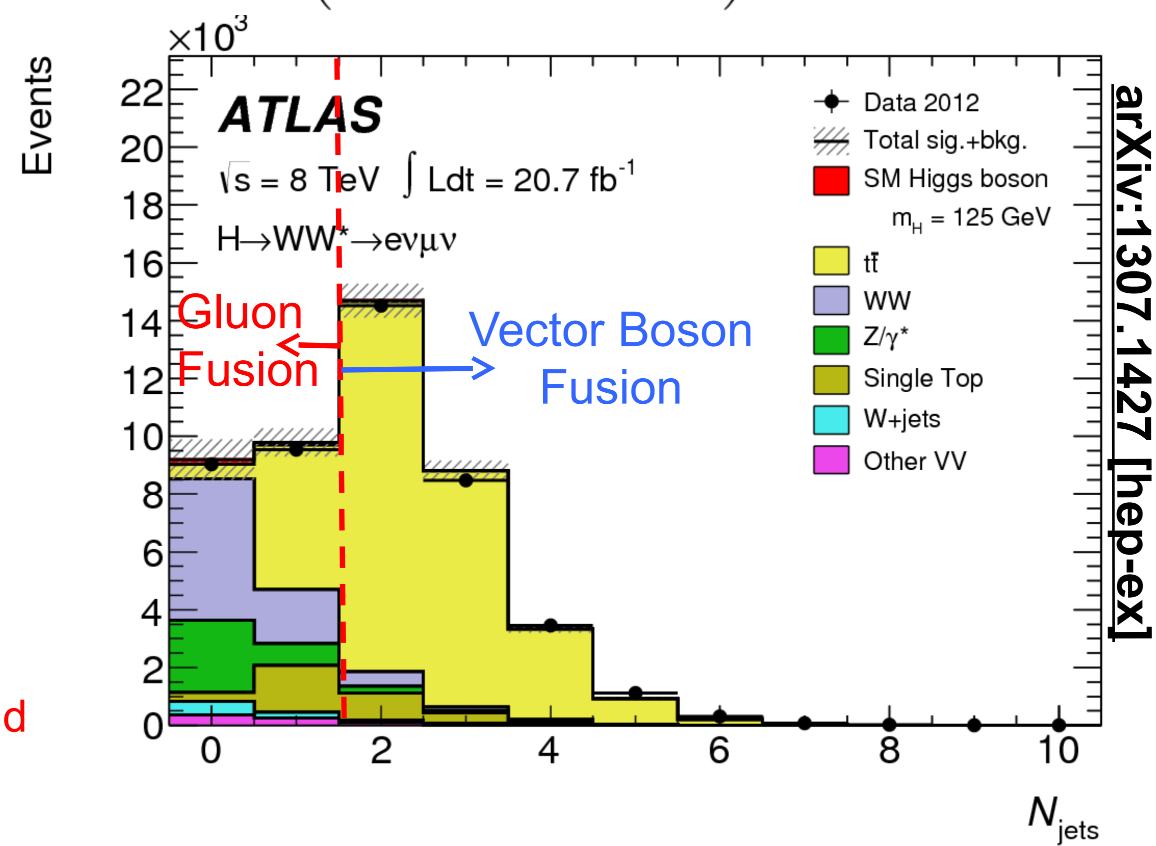
- Neutrinos

=> Use transverse mass mT

=> Low sensitivity to Higgs mass

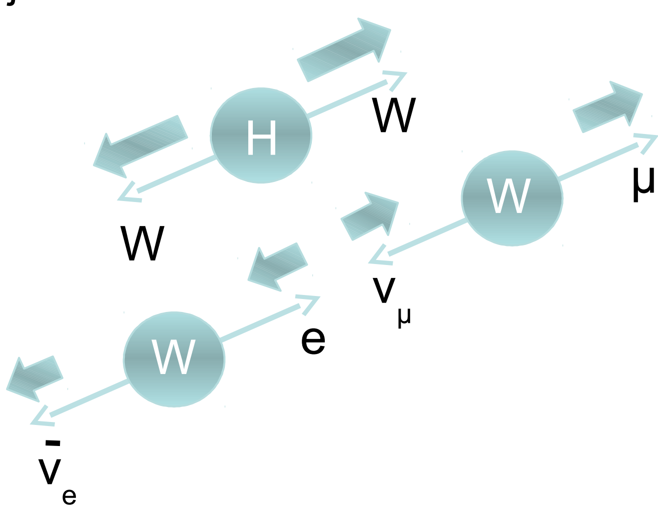
Search for Higgs in mT distribution

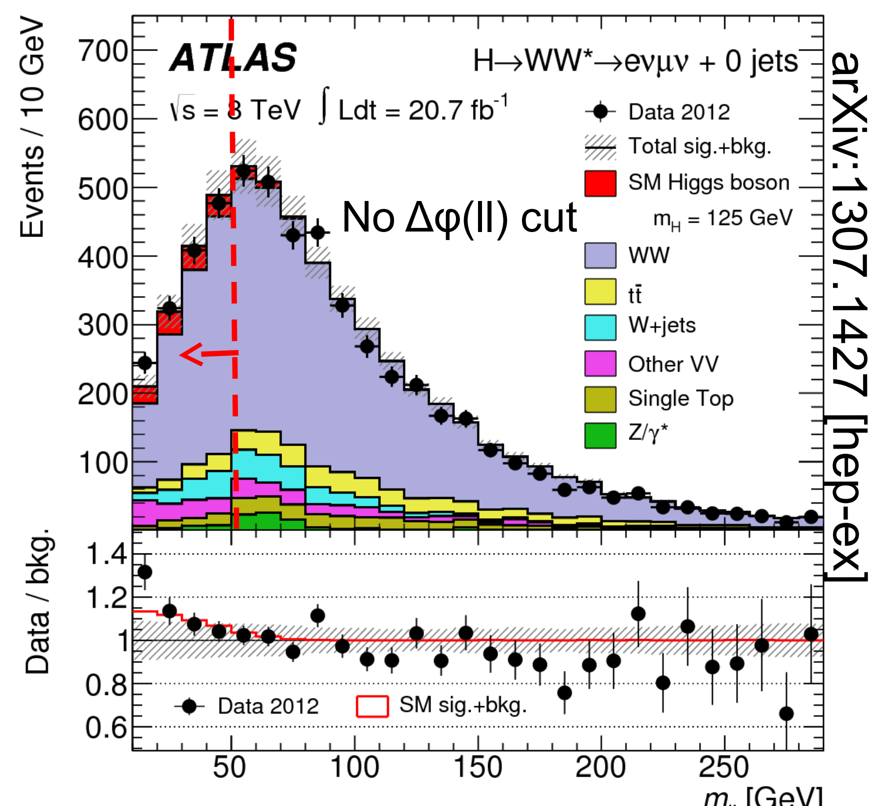
$$m_T^2 = \left(\sqrt{m_{ll}^2 + |\vec{p}_{T ll}|^2} + E_T^{\text{miss}}\right)^2 - \left(\vec{p}_{T ll} + \vec{E}_T^{\text{miss}}\right)^2$$



Event Selection

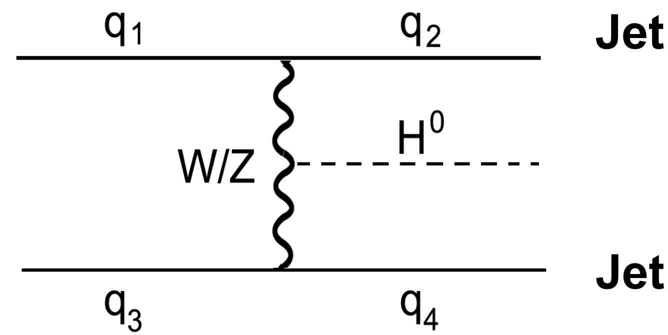
- Scalar Higgs and V-A W coupling mean small lepton separation
  - ➢ Small angle Δφ(ll) and small invariant dilepton mass mll
- Count jets with pT>25 GeV in tracker (|η|<2.4) pT>30 GeV in 2.4<|η|<4.5
- In 0-jet analysis dilepton system mostly balances momentum of ν's:
  - ➢ Require large Δφ between dilepton system and ETmiss and high dilepton pT
- In 1-jet analysis – veto events containing b-jets to reject top
- Dedicated cuts to suppress Z→ττ
- Use variety of ETmiss variables:
  - ➢ For robustness against pileup
  - ➢ ET,relmiss, pTmiss, ET,STVFmiss
  - ➢ Reject Drell-Yan



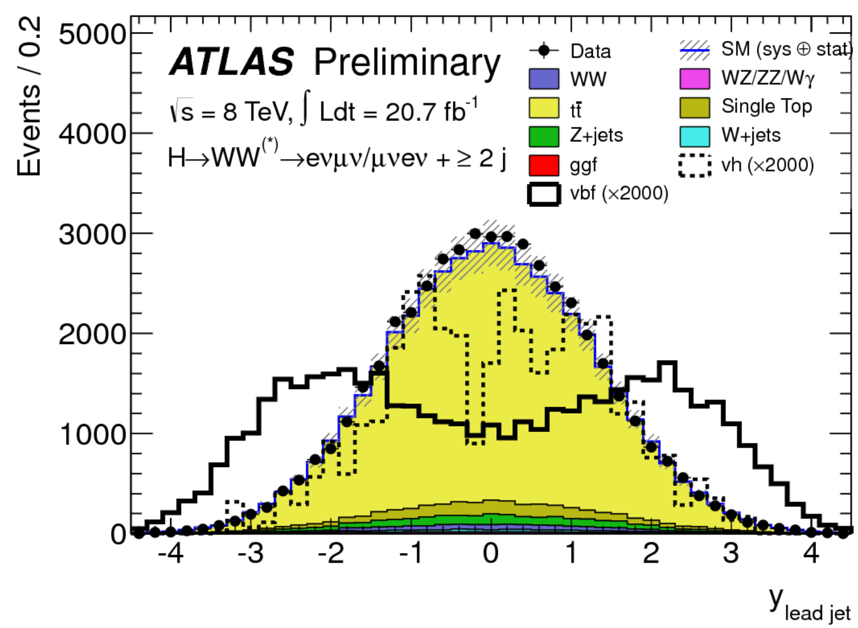


H→WW(*)→eνμν – ≥2 jet

- Signature:
  - Dominated by VBF
  - But with gluon-fusion contamination
  - Background dominated by top
  - Use kinematics of 2 ***tag jets*** in selection



- Additional selection:
  - Reject top: b-tag veto
  - Use VBF topology:
    - Rapidity gap Δy between tag jets
    - High di-jet invariant mass Mjj > 500 GeV
    - No additional central jets pT > 20 GeV
    - Leptons in rapidity gap between tag jets



- Top background:
  - Normalize from control region with 1 b-tagged jet: 0.59±0.07 (stat) MC@NLO

- Count jets to select VBF final state
  - Theory uncertainty in central-jet veto

Theory Uncertainties on H→WW

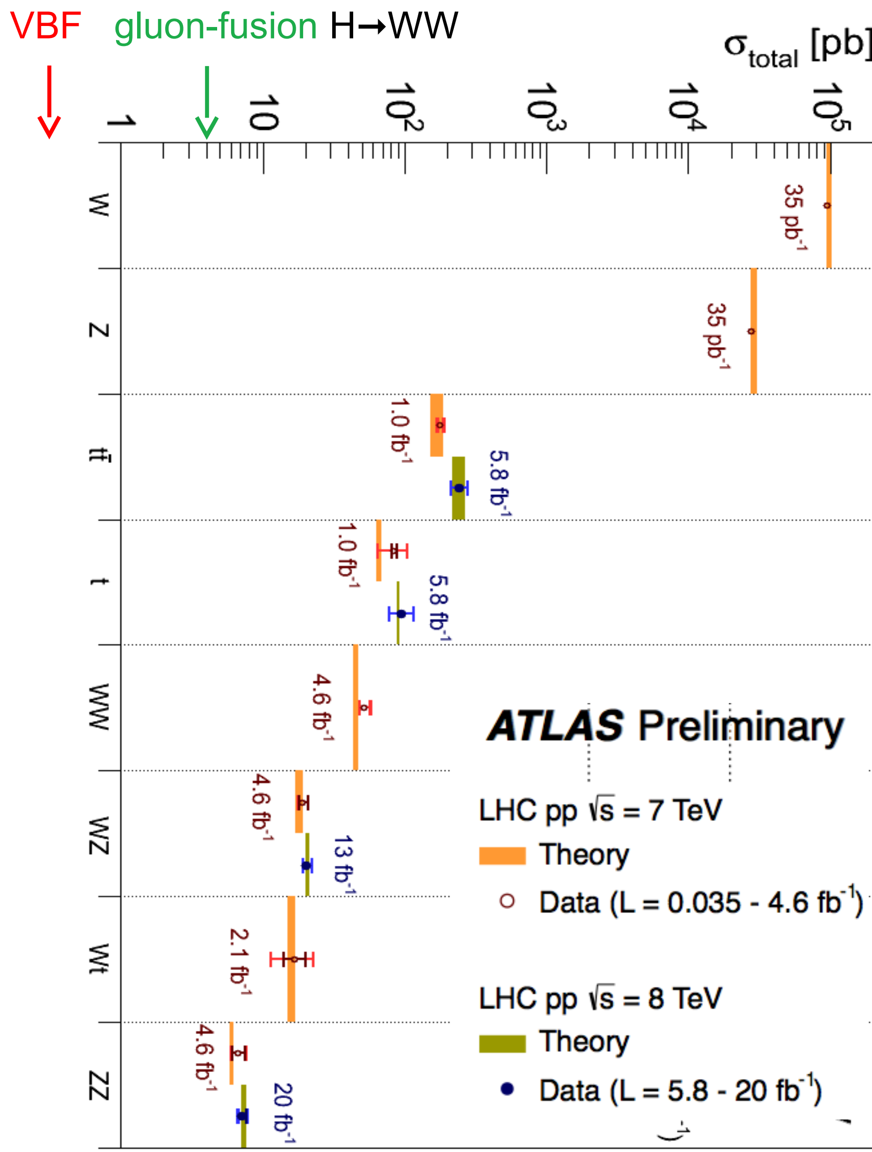
- Underlying event and parton shower models
  - Powheg+Pythia8 vs MC@NLO+Herwig: 3% (0-jet), 10% (1-jet)
  - ≥2-jet: Powheg+Pythia6 (UE/no UE): 9% (gluon fusion), 3% (VBF)
- PDF uncertainties: gluon fusion 8%, 3-4% VBF and VH
- QCD renormalization and factorization scale variations
  - Stewart-Tackmann (1107.2117 [hep-ph]) procedure for gluon fusion cross sections in N_{parton}≥0 (±8%), ≥1 (±20%), ≥2 (±70%)
  - Renormalisation and factorization scales varied independently by factor 2 while keeping their ratio between 0.5 and 2
  - Anti-correlation from event migration in N_{jet} bins: 17% (0-jet) and 37% (1-jet)
  - Same method used for gluon-fusion contribution to signal in ≥2 jet bin
  - Consider gluon-fusion events with ≥2 jets (ignoring central-jet veto) and ≥3 jets where at least one jet would fail central-jet veto
  - <1% uncertainty from QCD scale uncertainty on VBF signal
  - Additional 4% uncertainty from effect of QCD scale variation on acceptance

Leading Systematic Uncertainties

- Leading systematic uncertainties on signal yield are theoretical
  - Depend strongly on the number of jets category
- Uncertainties on main backgrounds constrained by control regions
  - Remaining theory uncertainty from extrapolation to signal region

Source	Signal processes (%)			Background processes (%)		
	$N_{\rm jet}=0$	$N_{\rm jet}=1$	$N_{\rm jet}\geq 2$	$N_{\rm jet}=0$	$N_{\rm jet}=1$	$N_{\rm jet}\geq 2$
Theoretical uncertainties						
QCD scale for ggF signal for $N_{\rm jet}\geq 0$	13	-	-	-	-	-
QCD scale for ggF signal for $N_{\rm jet}\geq 1$	10	27	-	-	-	-
QCD scale for ggF signal for $N_{\rm jet}\geq 2$	-	15	4	-	-	-
QCD scale for ggF signal for $N_{\rm jet}\geq 3$	-	-	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
$f_{\rm recoil}$ efficiency	1	1	-	4	2	-

Backgrounds



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/CombinedSummaryPlots

Background		Estimate
W→lν	Jet fakes leptons	Data
Z→ee/μμ Z→ττ	Fake ETmiss Real ETmiss	Data
t→blν	b jet	Data
Irreducible	Large!	Data
WZ→lνll	Loose lepton	MC
W→lν	b jet	Data
Irreducible	Small	MC

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Top Background

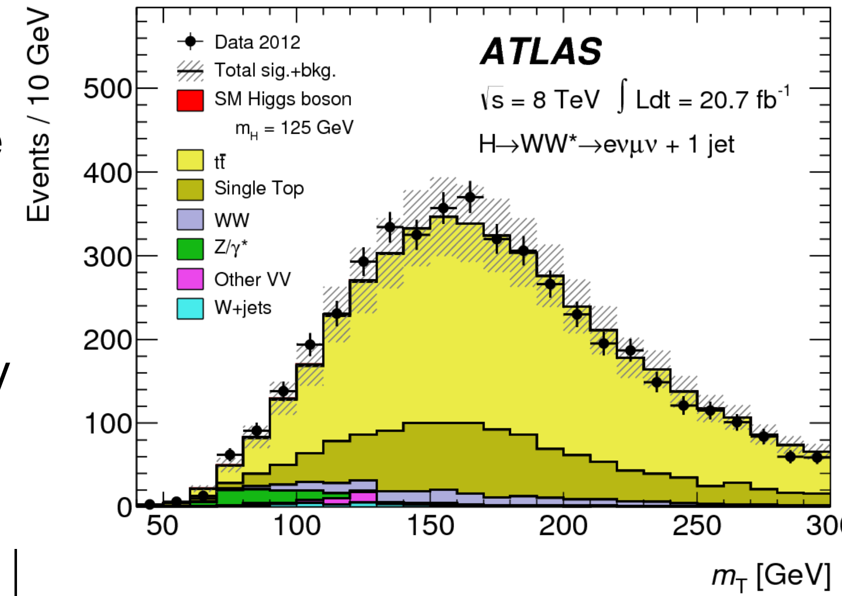
0-jet bin:

- Relax Njet cut to get top-rich data sample
- Normalize using 0-jet fraction from MC
- f = 1.07 ±0.03 (stat) ± 0.09 (syst) correction from Control Region defined by Njet>0 and Nb-tag=1
- 13% total uncertainty

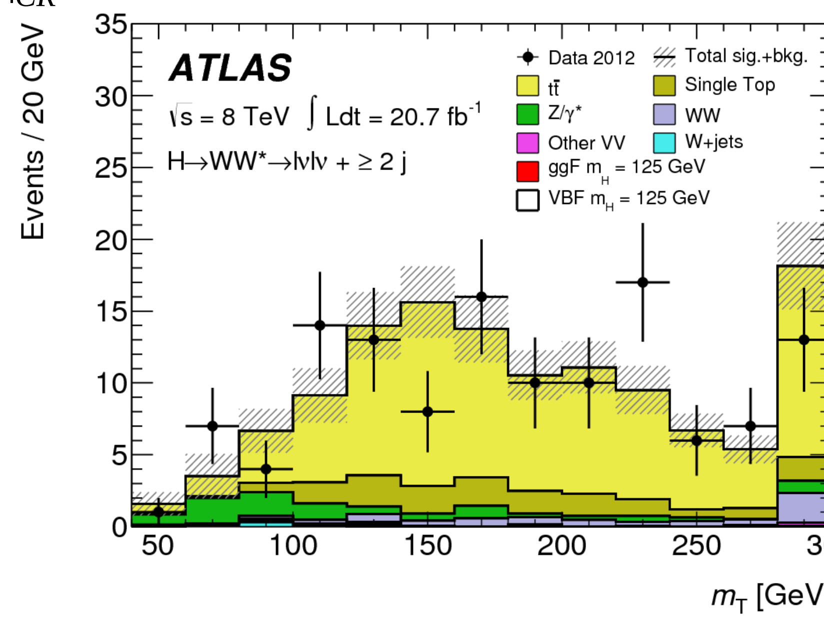
$$N_{t\bar{t}} = [N_{Data}^{\geq 0\ jet} - N_{MC/Data}^{non-top}] \times \left.\frac{N_{0-jet}^{t\bar{t}}}{N_{\geq 0\ jet}^{t\bar{t}}}\right|_{MC} \times \left. f_{1b-tag}\right|_{CR}$$

1-jet and 2-jet bins (top is dominant)

- Normalize MC in control region:
  - ➢Remove cuts on Δφ(ll) and mll
  - ➢Require 1 b-tagged jet
- Correction factors applied to MC:
  - ➢0-jet: 1.04±0.02 (stat); 1-jet: 0.59±0.07 (stat)
- Total uncertainty: 28% (0-j), 39% (1-j)



top 1-jet control region

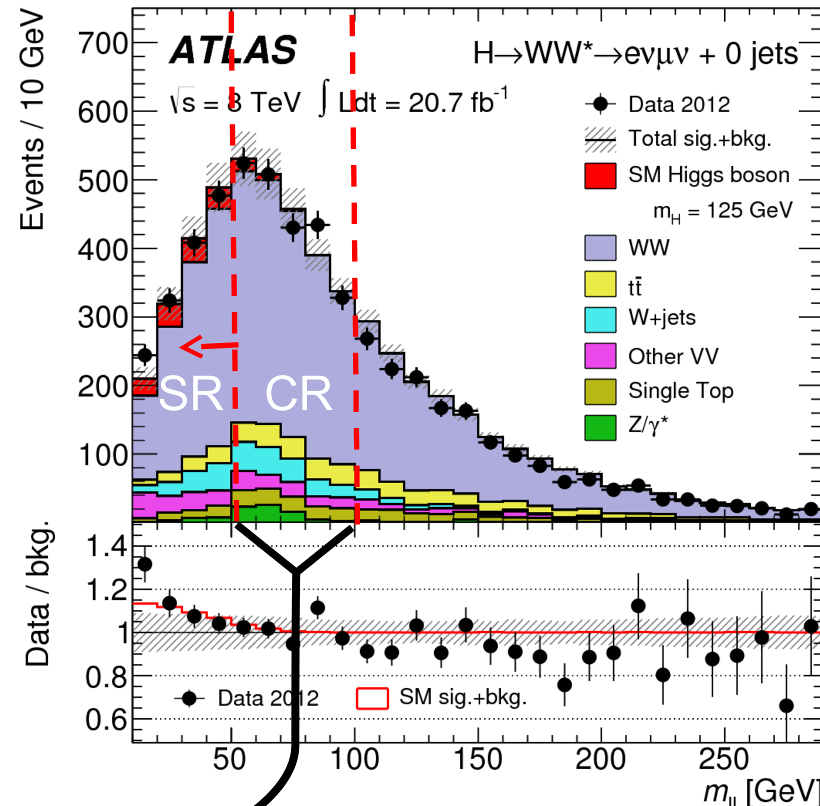


Top 2-jet control region

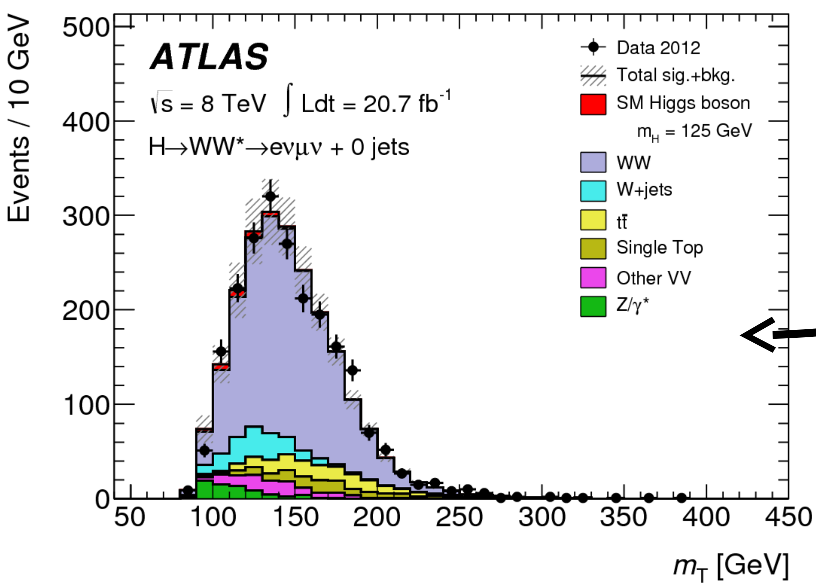
WW Background

0/1-jet bin: dominant/large

- Remove m(ll) cut
- Change mll cut to define control region
  - 0-jet: 50 < m(ll) < 100GeV
  - 1-jet: m(ll) > 80GeV
- Normalize in mT distribution
- Normalization factors:
  - 0-jet: 1.16±0.04 (stat)
  - 1-jet: 1.03±0.06 (stat)
  - Total uncertainty 7.4% (0-jet) 37% (1-jet)



arXiv:1307.1427 [hep-ex]



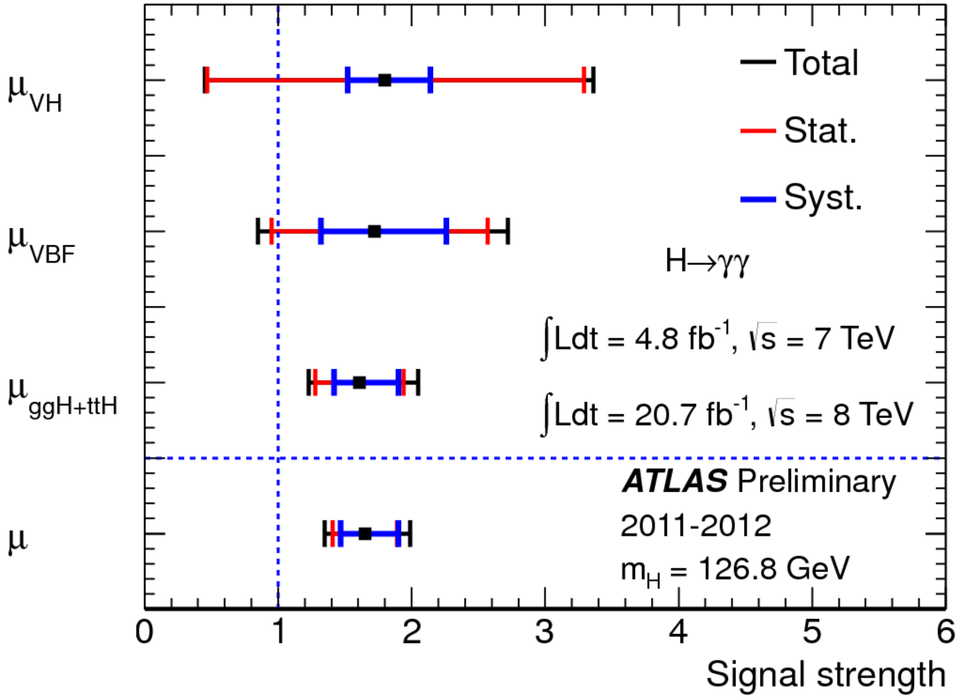
2-jet bin: small

- Take from simulation

Other Examples

$H \rightarrow \gamma\gamma$:

- Multivariate discriminant used to select VBF events
- Theory uncertainty according to Gangal & Tackmann, arXiv:1302.5437 [hep-ph]



$H \rightarrow ZZ^*$:

- ≥2-jets category to select VBF
- QCD scale uncertainty: Stewart-Tackmann, arXiv:1107.2117 [hep-ph]

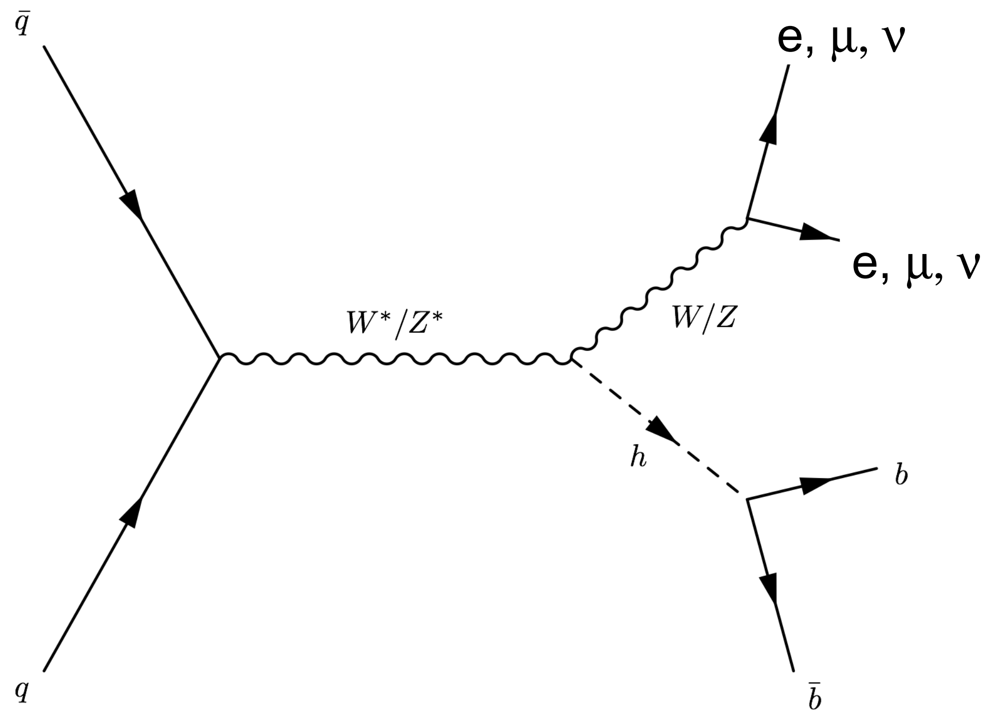
$H \rightarrow \tau\tau$:

- Classify events into ≤ 5 categories:
  - Events failing cuts for each category considered in following one
  - 2-jet VBF, 2-jet Boosted, 2-jet VH, 1-jet, 0-jet
- QCD scale uncertainty: Stewart-Tackmann, arXiv:1107.2117 [hep-ph]

Constraining backgrounds

VH with H→bb

- VERY New result!
  - ATLAS-CONF-2013-079
  - Full run I data:$20fb^{-1}+5fb^{-1}$
  - Previously $13fb^{-1}+5fb^{-1}$



- Common Event Selection:
  - 0, 1 or 2 leptons (e or μ)
  - p_T^{lep}>(10)25GeV
  - 2 or 3 jets in signal region
  - p_T^{j}>(20)45GeV (sub)leading
  - |η(jet)| < 2.5 (tracker acceptance)
  - E_T^{miss} > 120GeV for 0-lepton

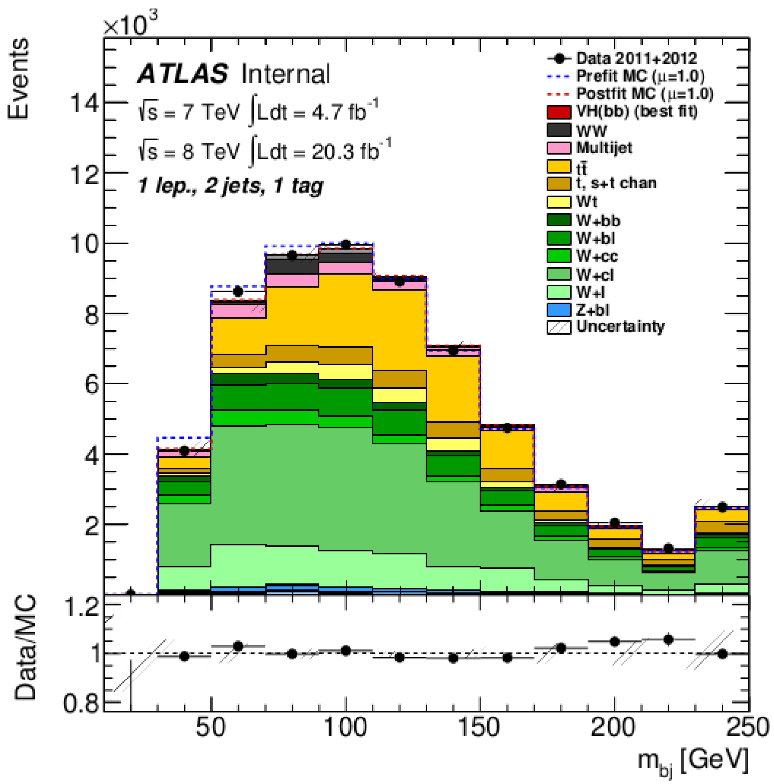
Additional selection cuts in each channel for vector boson selection and QCD rejection

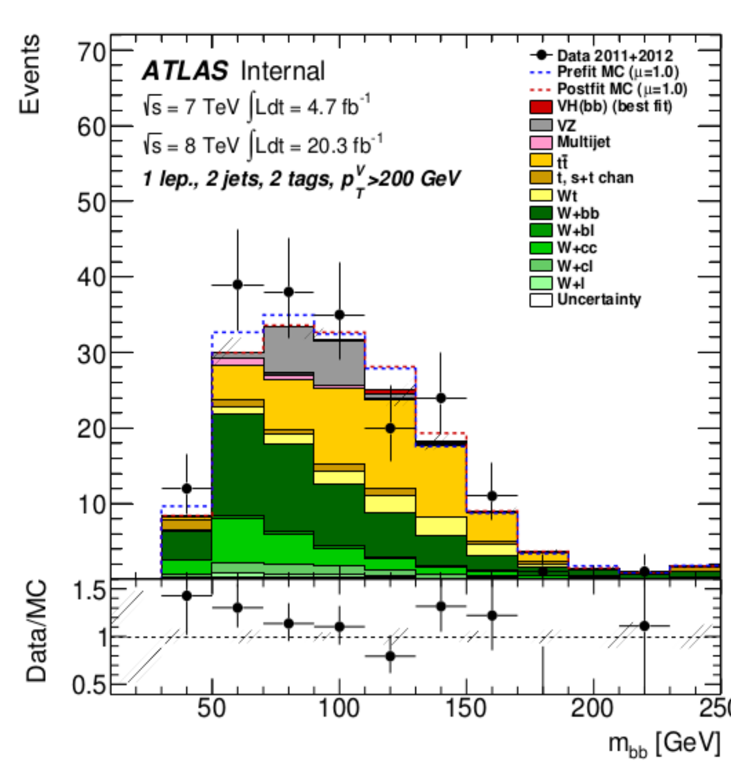
p_T^V (GeV)	0-90 1,2-lepton	90-120 1,2-lepton	120-160 0,1,2-lep	160-200 0,1,2-lep	>200 0,1,2-lep
ΔR(jj)	0.7-3.4	0.7-3.0	0.7-2.3	0.7-1.8	<1.4

Constraining backgorunds

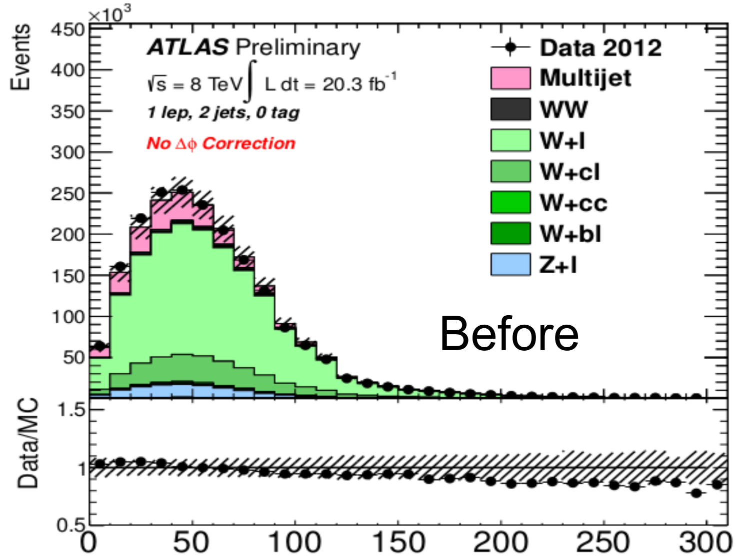
	2-jet 0-b	2-jet 1-b	2-jet 2-b	3-jet 2-b	e+μ, >=3jet
3 p_T^V bins x 0-lep	Control	Control	Signal	Signal	
5 p_T^V bins x 1-lep	Control	Control	Signal	Signal	
5 p_T^V bins x 2-lep	Control	Control	Signal	Signal	Control

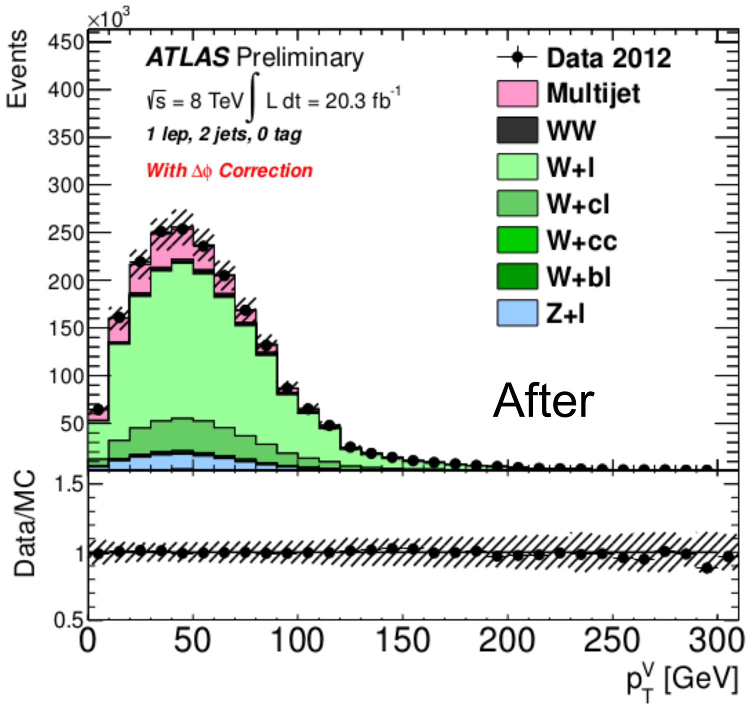
Simultaneous fit to Signal and Control regions to constrain top, Wbb, Wcc, Wc...





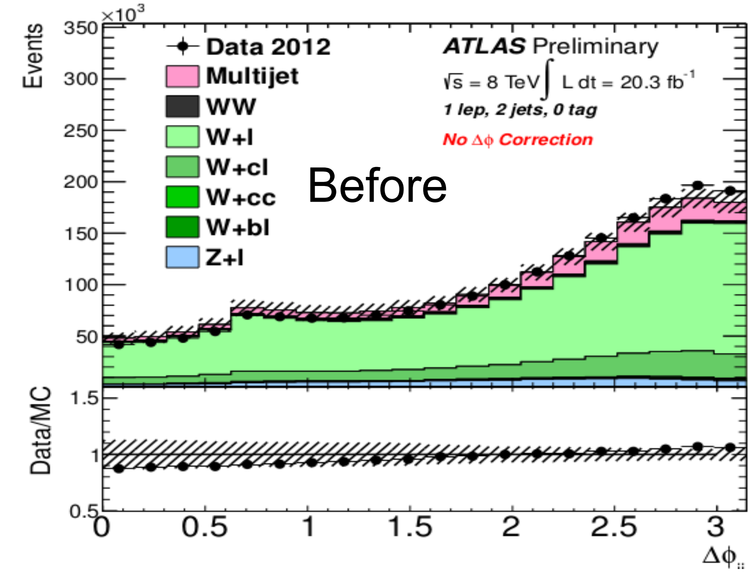
Background Modeling: $\Delta\phi(jj)$, p_T^V

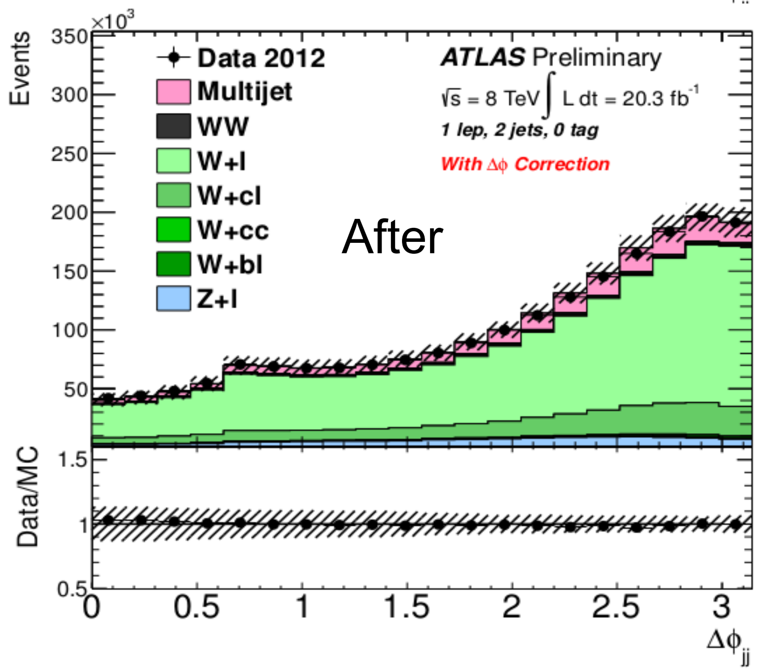




- Analysis relies on binning in p_T^V to enhance sensitivity
- Background vector boson transverse momentum modeling is crucial
- p_T^V found to be mismodeled
- Strong correlation with $\Delta\phi(jj)$
- Correct model by reweighting with a weight linear in $\Delta\phi(jj)$
- Also improves modeling of bb mass

Background Modeling: $\Delta\phi(jj)$, p_T^V





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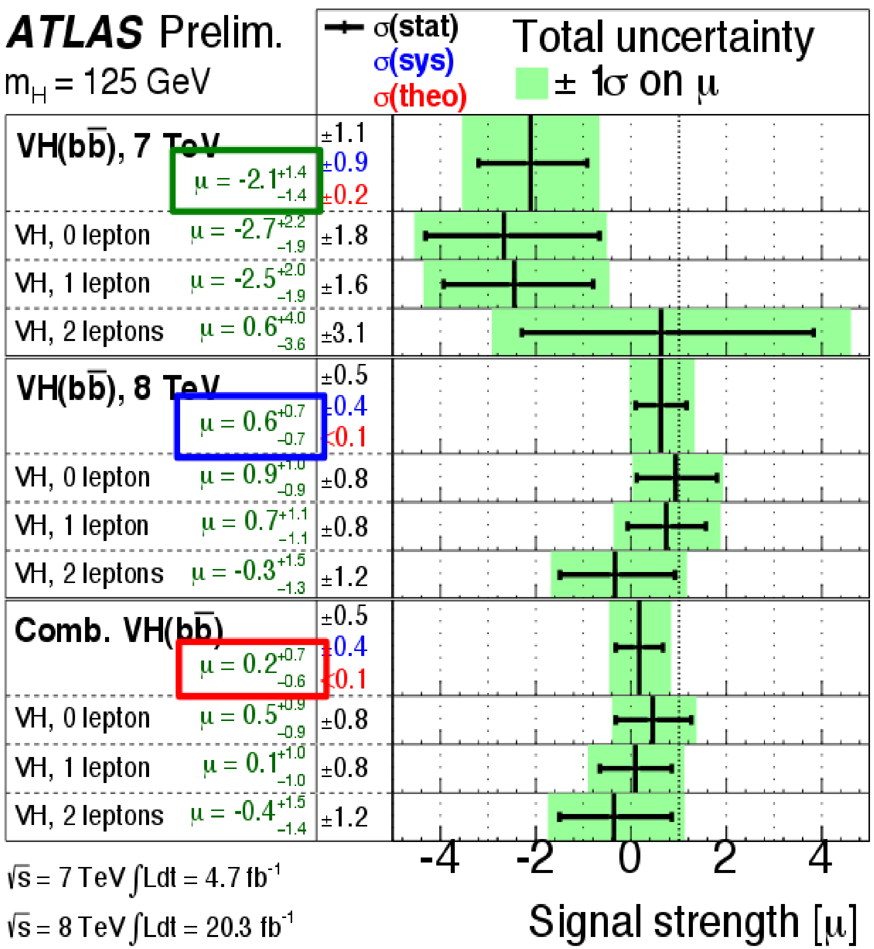
- p_T^V found to be mismodeled
- Strong correlation with $\Delta\phi(jj)$
- Correct model by reweighting with a weight linear in $\Delta\phi(jj)$
- Also improves modeling of bb mass
- Also reweight top pT from measurement

VH with H→bb: Results

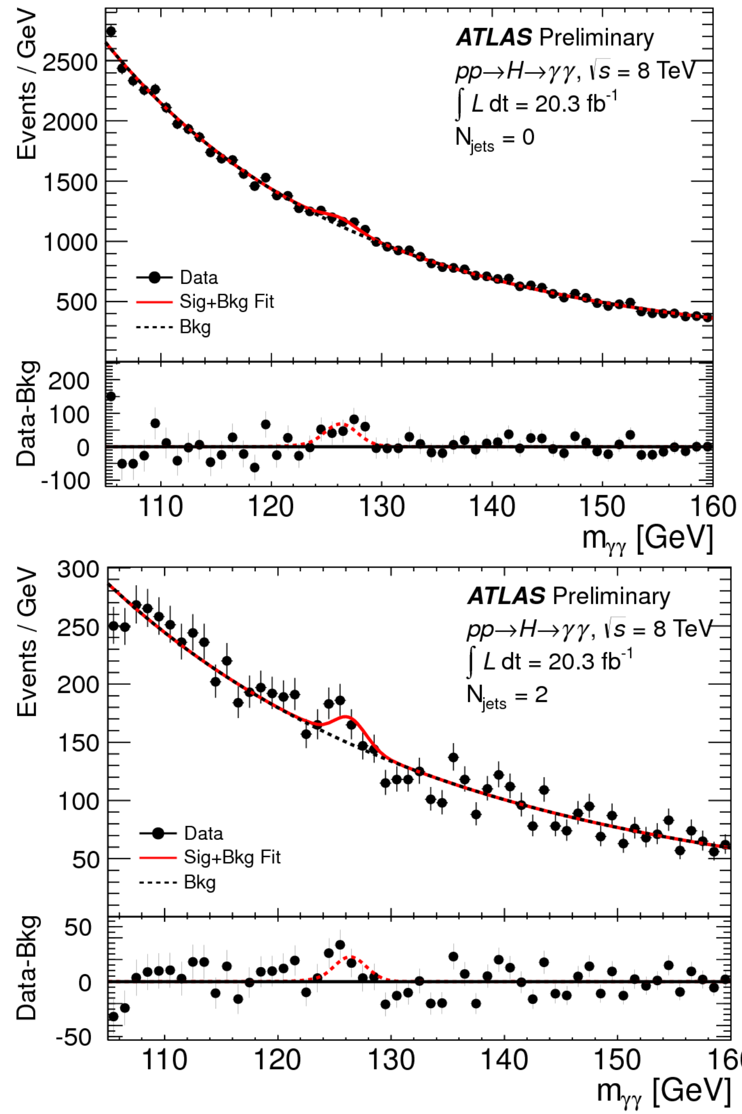


- Large gain (35%) in significance wrt previous analysis (13fb-1 @ 8TeV)
  - Optimizations and reduced systematic uncertainties (b-tag...)
  - SM-consistent 4.8σ observation of VZ→Vbb – validation! (not shown)
- Higgs search consistent with SM Higgs or no Higgs
- Need more data to make observation
- Signal strength: $\mu = 0.2^{+0.7}_{-0.6}$

Measuring N_{jets} and veto fraction

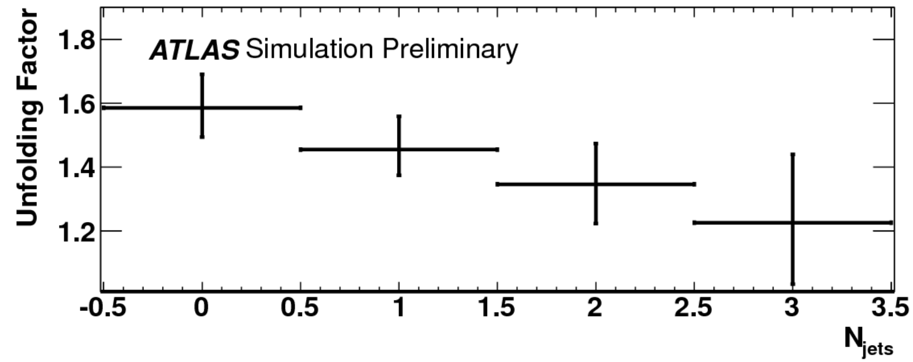
H→γγ Differential Cross Section

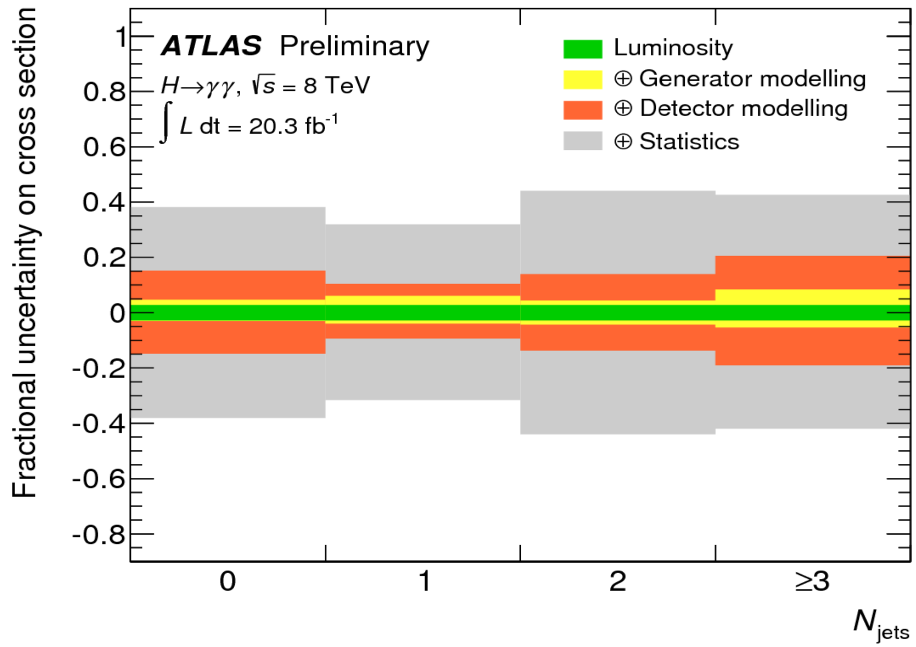
- VERY NEW result!
  - ATLAS-CONF-2013-072
- Dfferential cross section extracted in:
  - $p_T(\gamma\gamma)$, $|y^{\gamma\gamma}|$, $|\cos\theta^*|$
  - N_{jet}, $p_T(j1)$, $p_T(\gamma\gamma jj)$, $\Delta\phi(jj)$
- Fiducial region:
  - $|\eta(\gamma)|<2.37$ (excl. $1.37<|\eta|<1.56$)
  - $105<m\gamma\gamma<160$GeV
  - $p_T(\gamma\gamma)/m\gamma\gamma>(0.25)0.35$ (sub)lead γ
  - $p_T(\text{jet})>30$GeV, $|y_{jet}|<4.4$



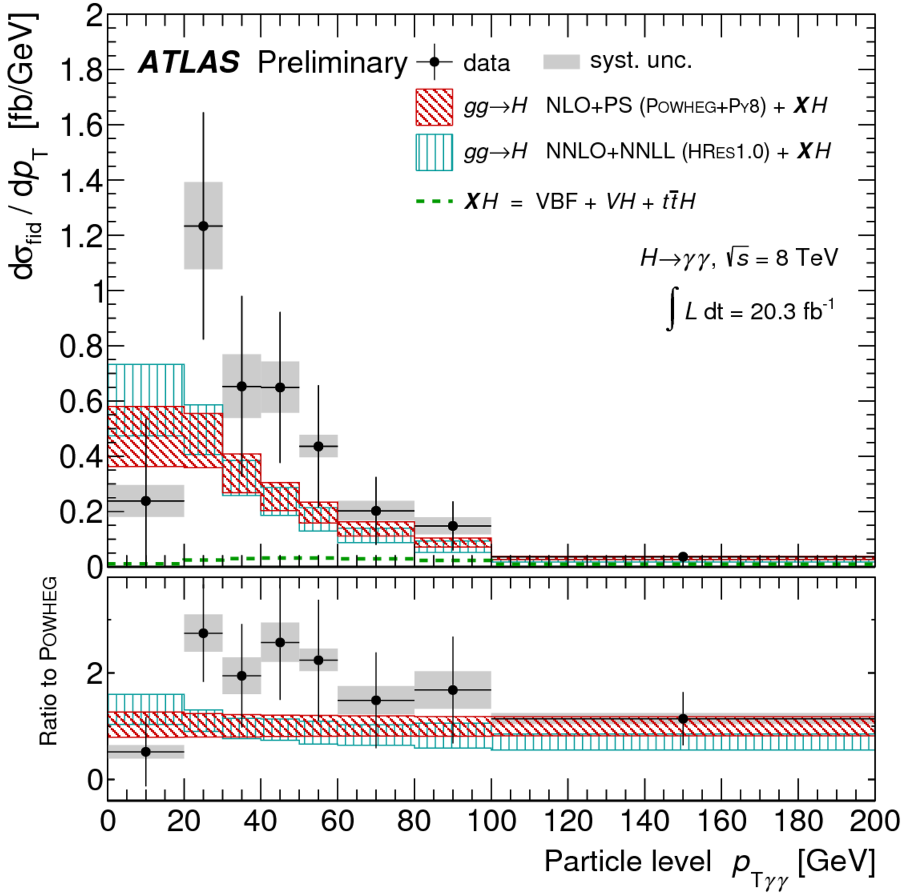
Cross Section Unfolding

- Modeling: S and B PDFs
  - Signal: Crystal Ball + Gaussian parametrized as function of m_H
  - ggF/VBF (Powheg),VH/ttH (Py8)
  - Background: e^{ax+bx2} fit in sidebands
  - Compared to $\gamma\gamma$ and γj from Sherpa and multijet from Pythia
- Signal extraction:
  - Partition data in bins: e.g. N_{jet}=0,1,...
  - Simultaneous S+B fit to all bins of observable in $m\gamma\gamma$ distribution
- Bin-by-bin unfolding:
  - Correction factors $c_i=n_i^{particle}/n_i^{reco}$ used to unfold fiducial cross section
  - Particle-level jets smeared by detector/response matrix
  - Uncertainties propagated through correction factors

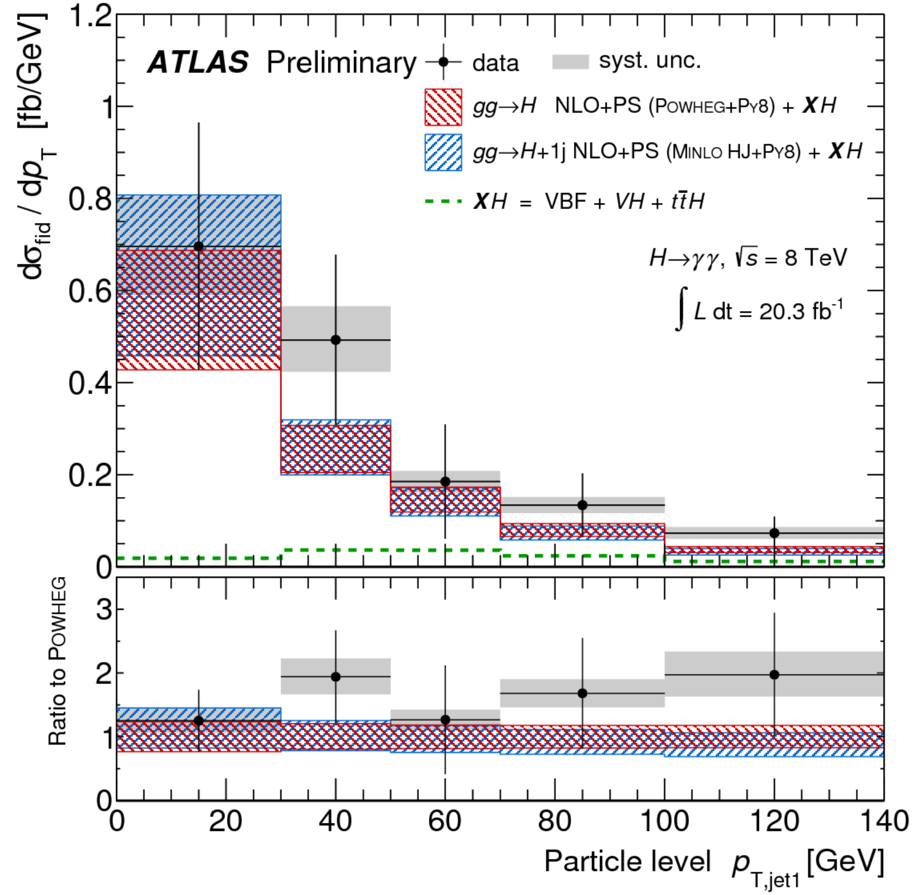




Results

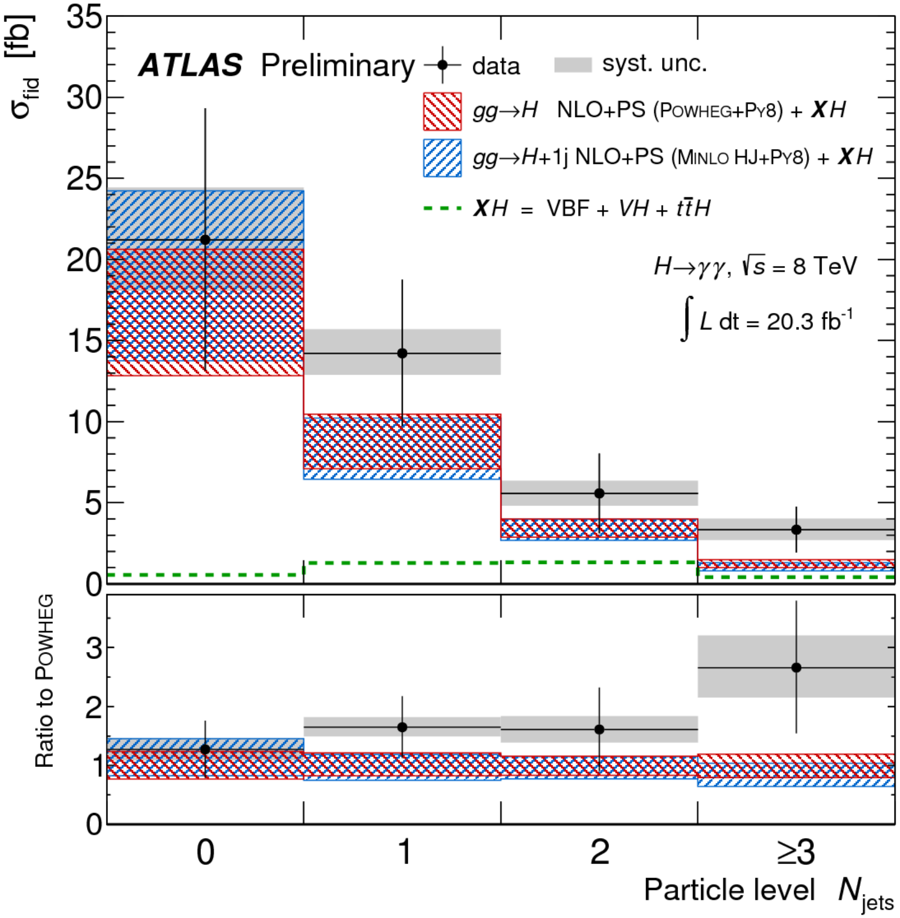


ATLAS Preliminary
data
syst. unc.
gg→H NLO+PS (POWHEG+PY8) + XH
gg→H NNLO+NNLL (HRES1.0) + XH
XH = VBF + VH + tt̄H
H→γγ, √s = 8 TeV
∫ L dt = 20.3 fb-1
dσfid / dpT [fb/GeV]
Ratio to POWHEG
Particle level pTγγ [GeV]



ATLAS Preliminary
data
syst. unc.
gg→H NLO+PS (POWHEG+PY8) + XH
gg→H+1j NLO+PS (MINLO HJ+PY8) + XH
XH = VBF + VH + tt̄H
H→γγ, √s = 8 TeV
∫ L dt = 20.3 fb-1
dσfid / dpT [fb/GeV]
Ratio to POWHEG
Particle level pT,jet1 [GeV]

Results



ATLAS Preliminary
data
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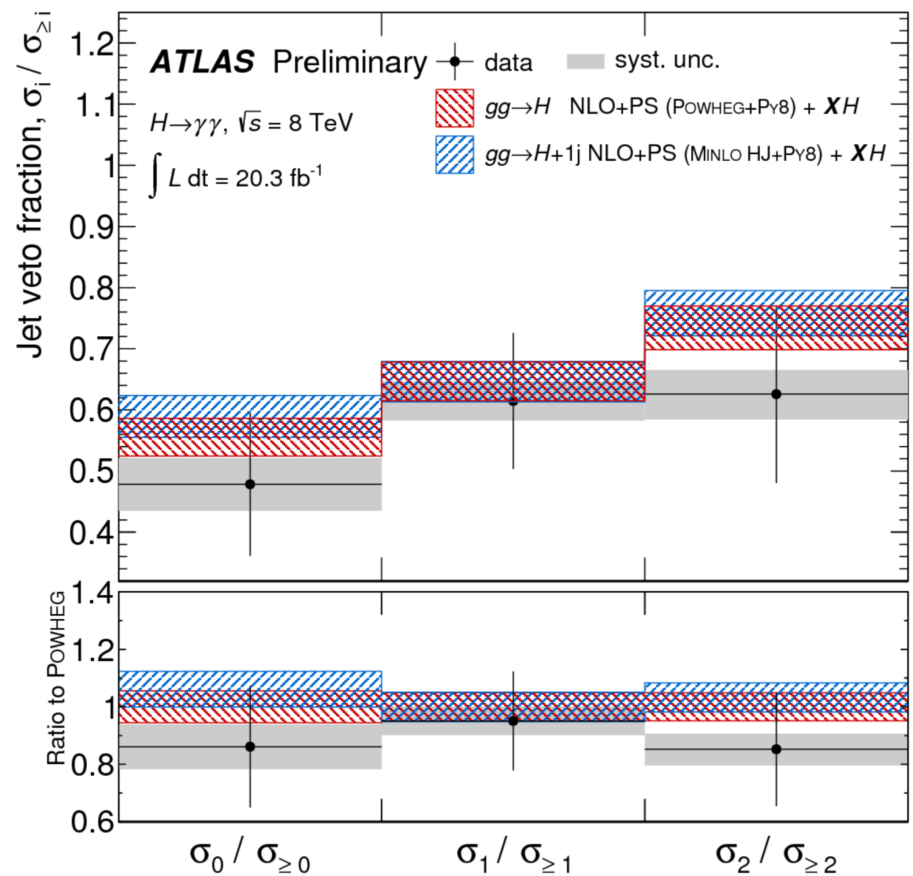
gg→H NLO+PS (POWHEG+PY8) + XH
gg→H+1j NLO+PS (MINLO HJ+PY8) + XH
XH = VBF + VH + tt̄H
H→γγ, √s = 8 TeV
∫L dt = 20.3 fb-1
σfid [fb]
Ratio to POWHEG
0
1
2
≥3
Particle level Njets



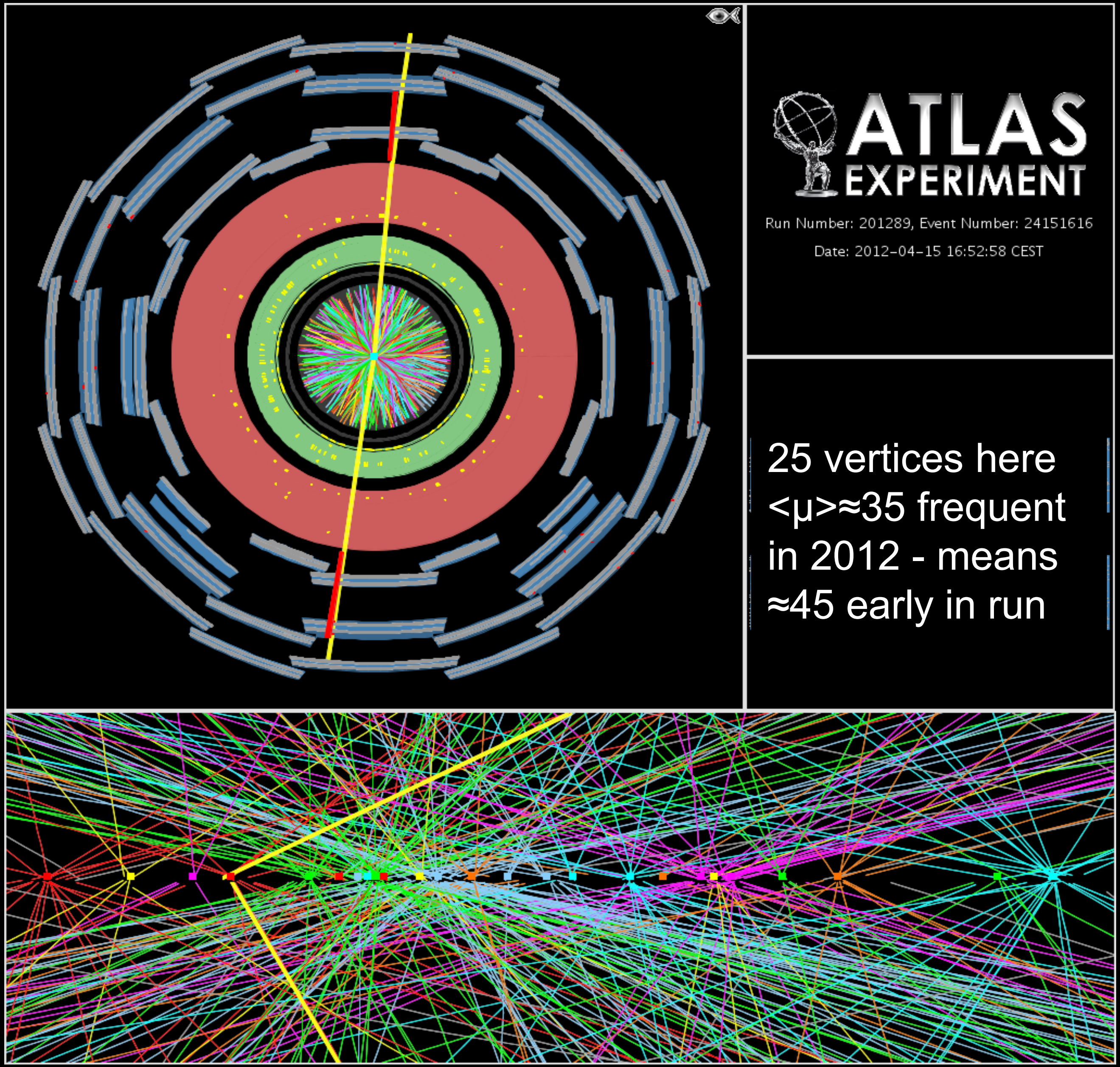
ATLAS Preliminary
data
syst. unc.
H→γγ, √s = 8 TeV
∫L dt = 20.3 fb-1
gg→H NLO+PS (POWHEG+PY8) + XH
gg→H+1j NLO+PS (MINLO HJ+PY8) + XH
Jet veto fraction, σi / σ≥i
Ratio to POWHEG
σ0 / σ≥0
σ1 / σ≥1
σ2 / σ≥2

Conclusions

- Jet counting is essential for:
  - optimizing analyses
  - rejecting backgrounds
  - selecting exclusive initial and final states
  - constraining uncertainties
- Being used in all main ATLAS Higgs analyses
- Trustable results require good understanding of theory uncertainties in exclusive jet bins
  - As well as of correlations between bins and jet flavour fractions!

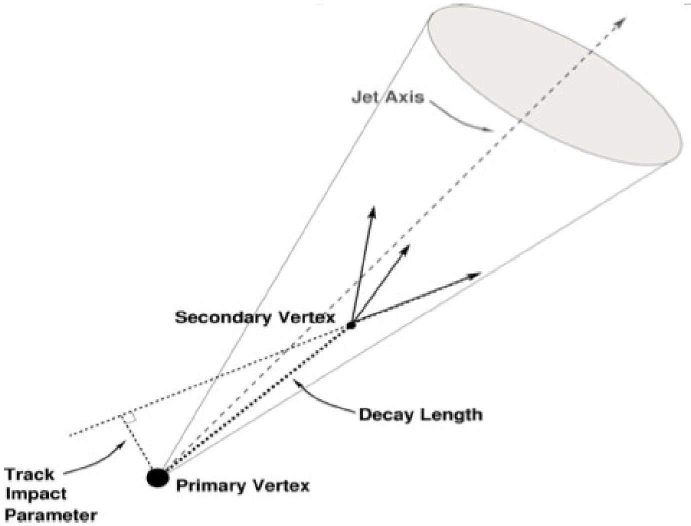
Bonus slides

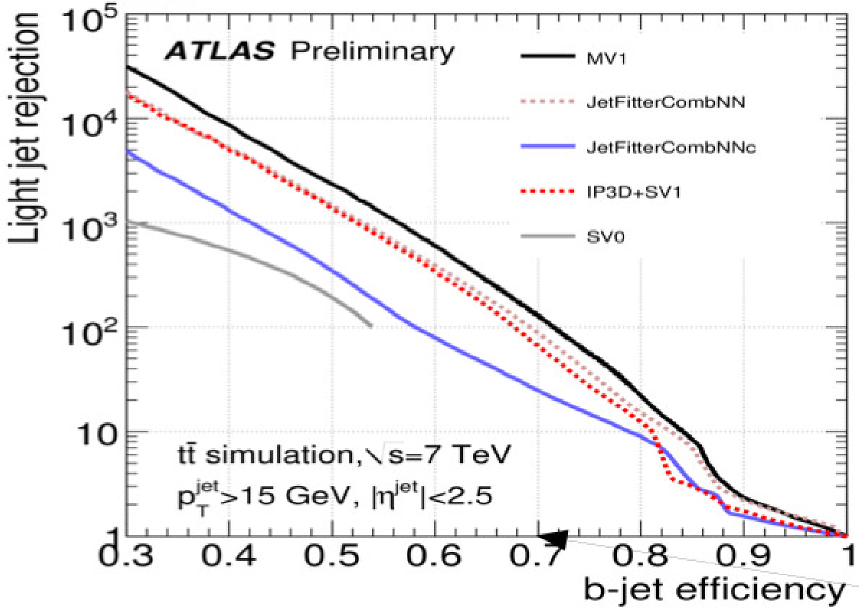
Pileup



25 vertices here
<μ>≈35 frequent
in 2012 - means
≈45 early in run

B-tagging



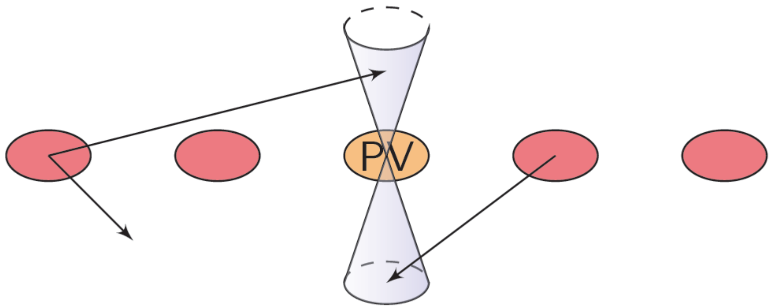


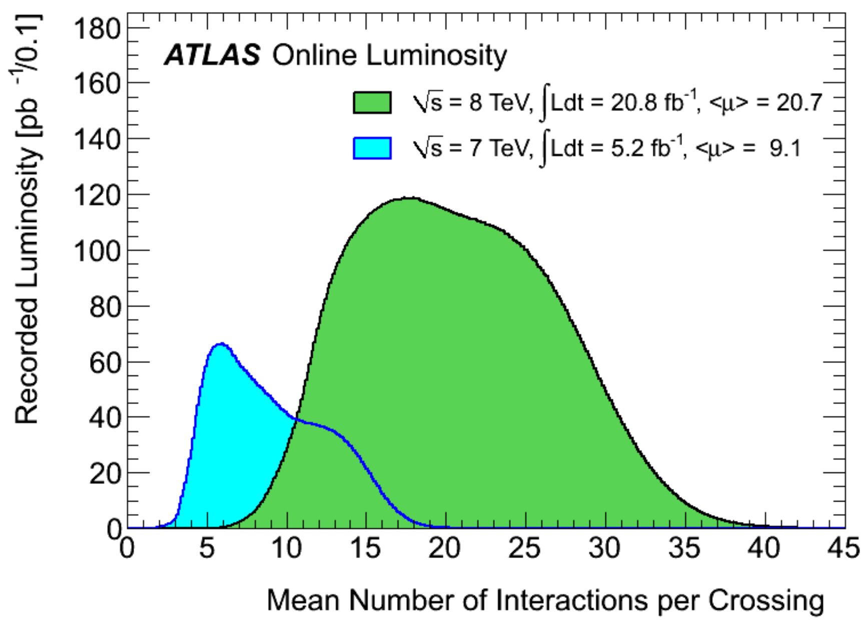
- Algorithms to identify heavy flavour content in reconstructed jets
- Impact parameter of tracks in jet
  - **IP3D** uses track weights based on longitudinal and transverse IP significance
- Displaced secondary vertex
  - **SV1** reconstructs inclusive displaced vertex
  - **JetFitter** reconstructs multiple vertices along implied b-hadron line of flight
    - Cascade decay topologies
- Advanced NN based algorithms
  - **JetFitterCombNN**: IP3D+JetFitter
  - **MV1**: IP3D+JetFitterCombNN+SV1

MC calibration results illustrated with MV1 @ 70% b-jet efficiency

Pileup & Its Consequences

- Jets polluted by additional particles
- Degradation of ETmiss resolution
  - Some of the objects used in ETmiss may belong to different beam crossings
- Worsening of Isolation observables
  - e.g. in electron reconstruction
- Ambiguity in hard-scatter vertex identification
  - e.g. H → γγ





H→WW Monte Carlo

Table 1: Monte Carlo generators used to model the signal and background processes in which all of the W and Z decay channels are included in the corresponding product of the cross section (σ) and branching fraction ($\mathcal{B}$) at $\sqrt{s} = 8$ TeV. Masses are given in units of GeV. Details are given in the text.

Signal	MC generator	$\sigma \cdot \mathcal{B}$ (pb)
ggF	P [30]+P 8 [31]	0.44
VBF	P +P 8	0.035
VH	P 8	0.13

Background	MC generator	$\sigma \cdot \mathcal{B}$ (pb)
$q\bar{q}, gq \to WW$	P +P 6 [32]	5.7
$q\bar{q}, gq \to WW + 2j$	Sherpa [33] with no $\mathcal{O}(\alpha_s)$ terms	0.039
$gg \to WW$	GG2WW 3.1.2 [34, 35]+H [36]	0.16
$t\bar{t}$	MC@NLO [37]+H	240
Single top: tW, tb	MC@NLO+H	28
Single top: tqb	AcerMC [38]+P 6	88
Z/γ^*, inclusive	A +H	16000
$Z^{(*)} \to \ell\ell + 2j$	Sherpa processes up to $\mathcal{O}(\alpha_s)$	1.2
$Z^{(*)}Z^{(*)} \to 4\ell$	P +P 8	0.73
$WZ/W\gamma^*, m_{Z/\gamma^*} > 7$	P +P 8	0.83
$W\gamma^*, m_{\gamma^*} \leq 7$	MadGraph [39–41]+P 6	11
$W\gamma$	A +H	370

- ggF signal at NNLO in QCD, with NLO corrections in EW, QCD soft-gluon resummations up to NNLL
- VBF signal with approximate NNLO QCD corrections and full NLO QCD and EW corrections
- *VH signal* up to NNLO QCD corrections and NLO EW corrections

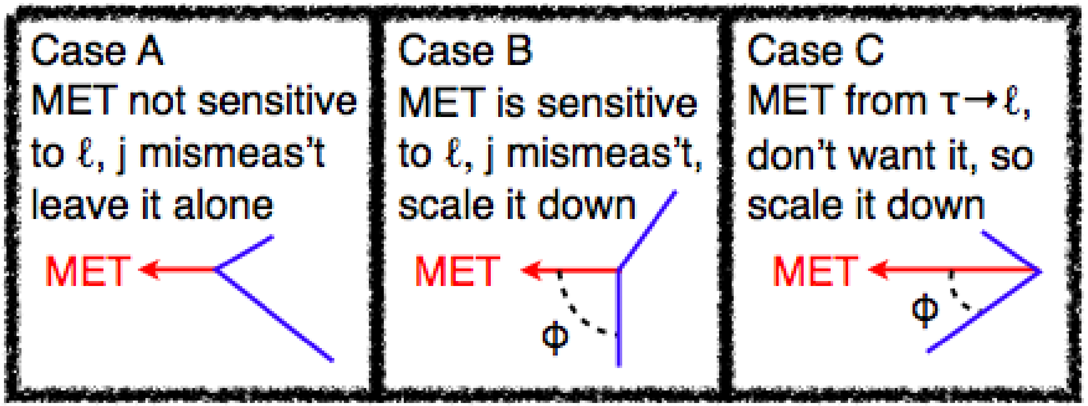
H→WW Selection

Table 2: Selection listing for 8 TeV data. The criteria specific to $e\mu + \mu e$ and $ee + \mu\mu$ are noted as such; otherwise, they apply to both. Pre-selection applies to all N_{jet} modes. The rapidity gap is the y range spanned by the two leading jets. The $m_{\ell\ell}$ split is at 30 GeV. The modifications for the 7 TeV analysis are given in Section 6 and are not listed here. Energies, masses, and momenta are in units of GeV.

Category	$N_{\text{jet}} = 0$	$N_{\text{jet}} = 1$	$N_{\text{jet}} \geq 2$
Pre-selection	Two isolated leptons ($\ell = e, \mu$) with opposite charge Leptons with $p_{\text{T}}^{\text{lead}} > 25$ and $p_{\text{T}}^{\text{sublead}} > 15$ $e\mu + \mu e$: $m_{\ell\ell} > 10$ $ee + \mu\mu$: $m_{\ell\ell} > 12$, $\lvert m_{\ell\ell} - m_Z \rvert > 15$		
Missing transverse momentum and hadronic recoil	$e\mu + \mu e$: $E_{\text{T,rel}}^{\text{miss}} > 25$ $ee + \mu\mu$: $E_{\text{T,rel}}^{\text{miss}} > 45$ $ee + \mu\mu$: $p_{\text{T,rel}}^{\text{miss}} > 45$ $ee + \mu\mu$: $f_{\text{recoil}} < 0.05$	$e\mu + \mu e$: $E_{\text{T,rel}}^{\text{miss}} > 25$ $ee + \mu\mu$: $E_{\text{T,rel}}^{\text{miss}} > 45$ $ee + \mu\mu$: $p_{\text{T,rel}}^{\text{miss}} > 45$ $ee + \mu\mu$: $f_{\text{recoil}} < 0.2$	$e\mu + \mu e$: $E_{\text{T}}^{\text{miss}} > 20$ $ee + \mu\mu$: $E_{\text{T}}^{\text{miss}} > 45$ $ee + \mu\mu$: $E_{\text{T,STVF}}^{\text{miss}} > 35$ -
General selection	- $\lvert \Delta\phi_{\ell\ell,MET} \rvert > \pi/2$ $p_{\text{T}}^{\ell\ell} > 30$	$N_{b\text{-jet}} = 0$ - $e\mu + \mu e$: $Z/\gamma^* \to \tau\tau$ veto	$N_{b\text{-jet}} = 0$ $p_{\text{T}}^{\text{tot}} < 45$ $e\mu + \mu e$: $Z/\gamma^* \to \tau\tau$ veto
VBF topology	- - - -	- - - -	$m_{jj} > 500$ $\lvert \Delta y_{jj} \rvert > 2.8$ No jets ($p_{\text{T}} > 20$) in rapidity gap Require both ℓ in rapidity gap
$H \to WW^{(*)} \to \ell\nu\ell\nu$ topology	$m_{\ell\ell} < 50$ $\lvert \Delta\phi_{\ell\ell} \rvert < 1.8$ $e\mu + \mu e$: split $m_{\ell\ell}$ Fit m_{T}	$m_{\ell\ell} < 50$ $\lvert \Delta\phi_{\ell\ell} \rvert < 1.8$ $e\mu + \mu e$: split $m_{\ell\ell}$ Fit m_{T}	$m_{\ell\ell} < 60$ $\lvert \Delta\phi_{\ell\ell} \rvert < 1.8$ - Fit m_{T}

ETmiss Reconstruction

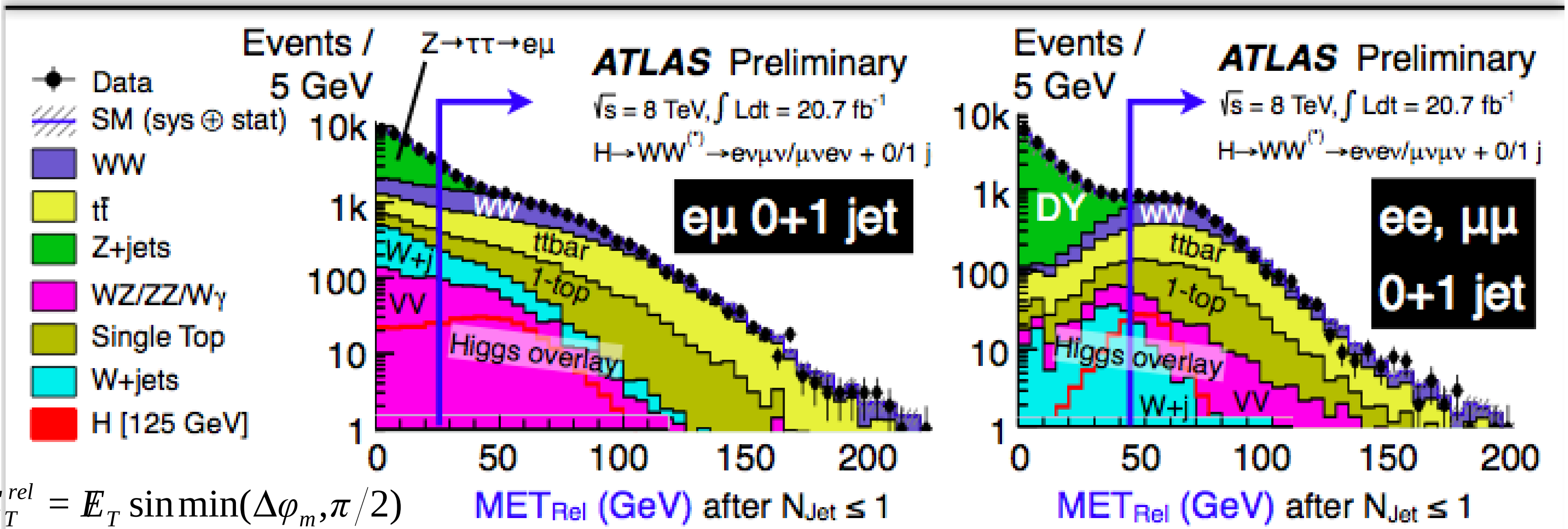
MET kills DY; for ee & μμ, use soft hadronic recoil (see back-up p26).



Diagrams in transverse plane wrt the beam line

Scale MET relative to ℓ or j

- A: $MET_{Rel} = MET$
- B, C: $= MET \cdot \sin\Delta\phi$, wrt nearest ℓ or jet in same φ-hemisph.



$$E_T^{rel} = E_T \sin\min(\Delta\varphi_m, \pi/2)$$

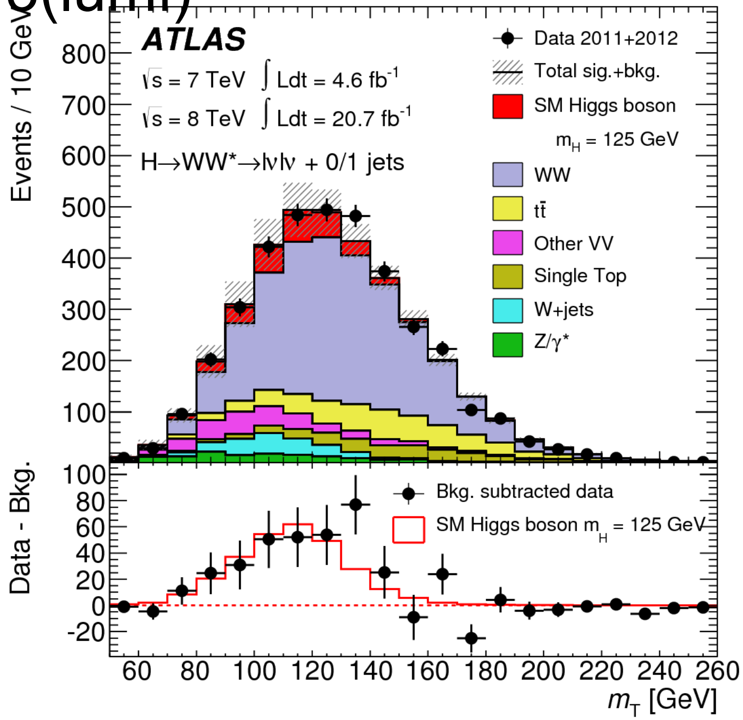
$$\Delta\varphi_m = \min\Delta\varphi(l/jet, E_T)$$

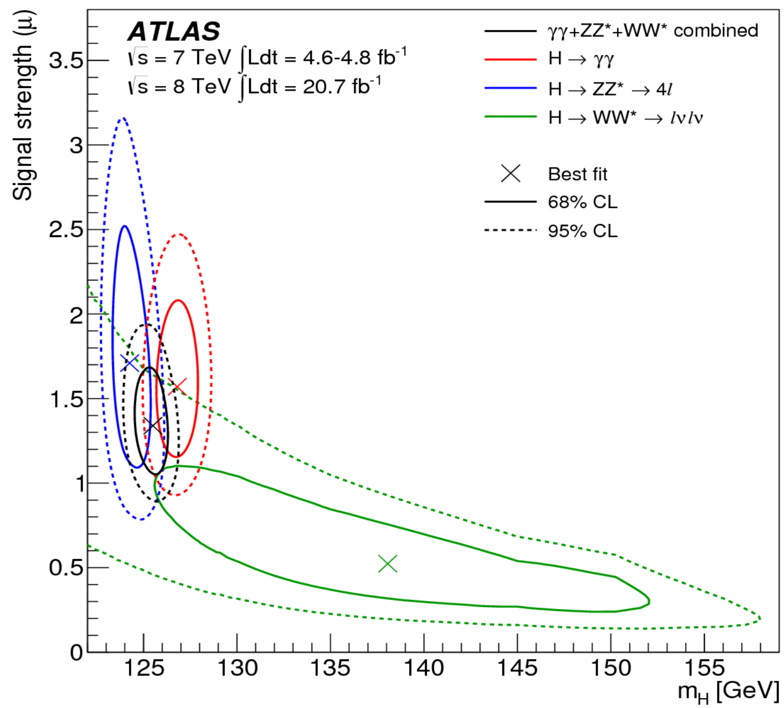
H→WW(*)→lνlν Results

- Signal searched in mT distribution in all analysis categories
  - ➢ High-pT neutrinos give poor mass resolution => broad p0 minimum
- At mH=125GeV:
  - ➢ Significance of 3.8σ
  - ➢ Signal strength μ = 1.01±0.31

$$m_T^2 = \left(\sqrt{m_{ll}^2 + |\vec{p}_{Tll}|^2} + E_T^{\rm miss}\right)^2 - \left(\vec{p}_{Tll} + \vec{E}_T^{\rm miss}\right)^2$$

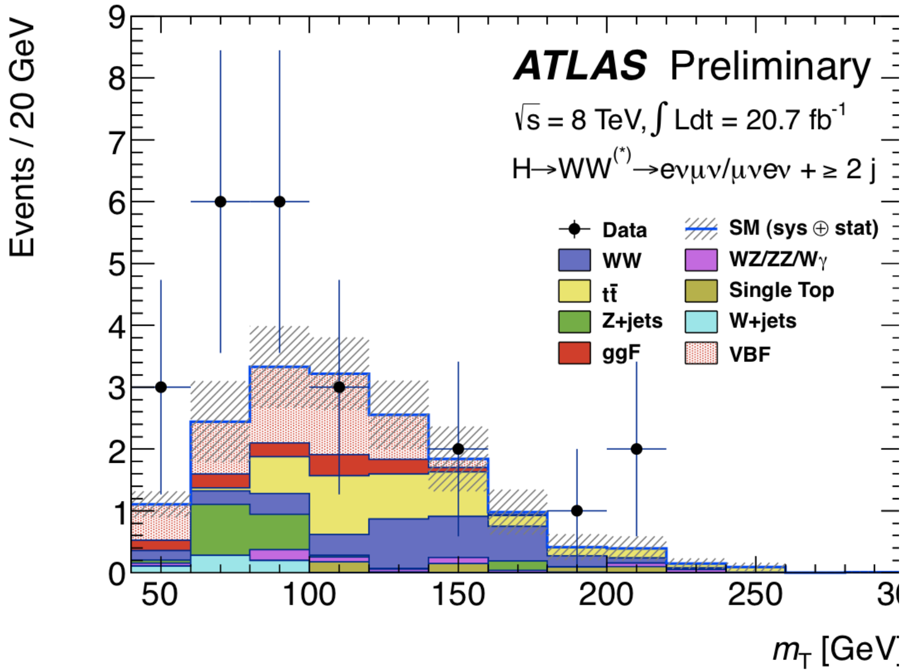
- σ×BR (pb, 8TeV) = 6.0 ±1.1(stat) ±0.8(theo.) ±0.7(exp.) ± 0.3(lumi)

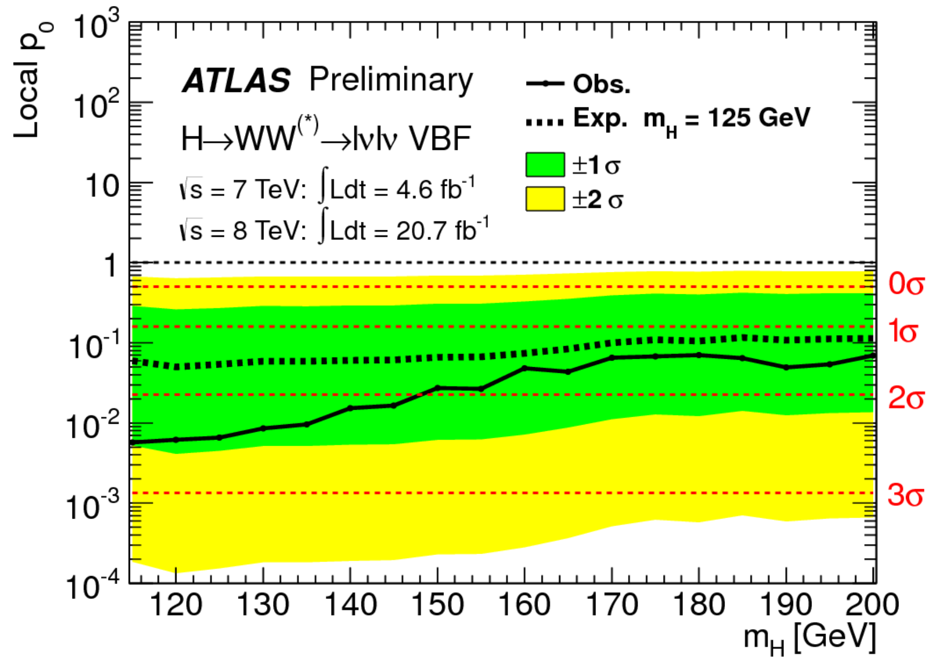




H→WW(*)→eνμν VBF Results

- Signal searched in mT distribution of 2-jet category
- At mH=125GeV:
  - ➢ Significance of 2.5σ
  - ➢ Signal strength μVBF = 1.66±0.79
- Results consistent with Standard Model



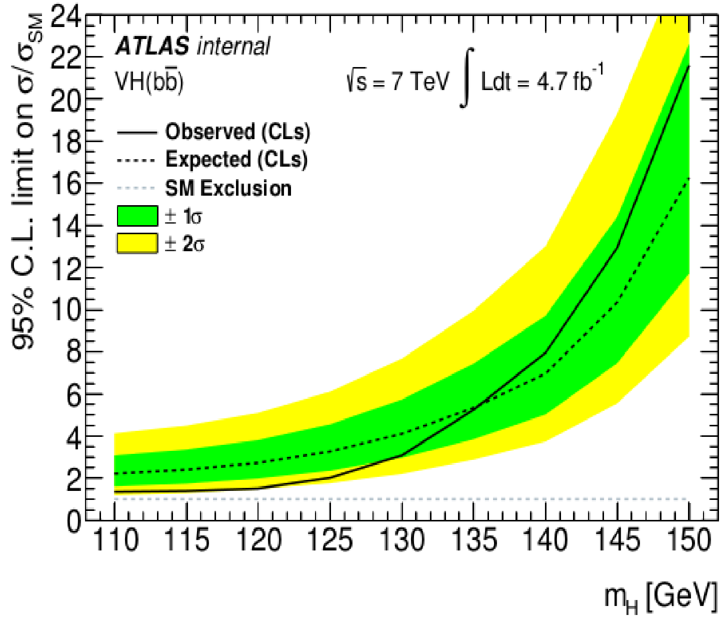


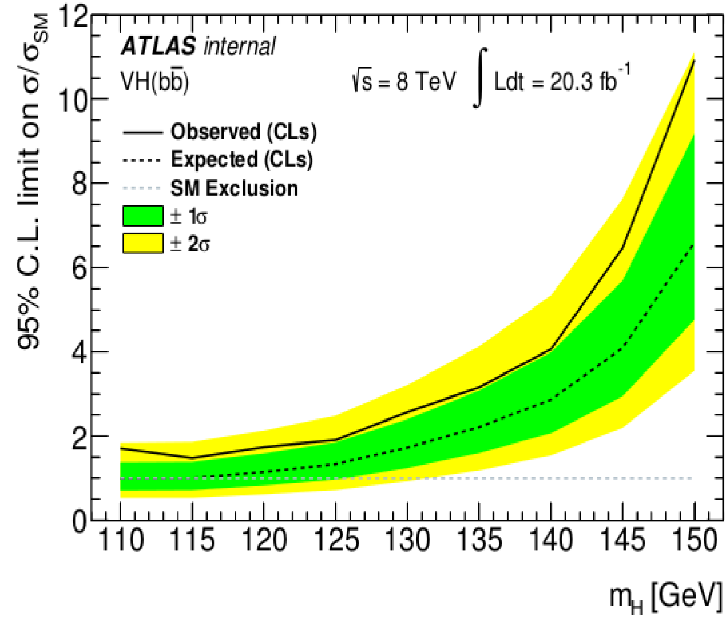
VH, H→bb cuts

Object	0-lepton	1-lepton	2-lepton
Leptons	0 loose leptons	1 tight lepton + 0 loose leptons	1 medium lepton + 1 loose lepton
Jets	2 b-tags $p_T^{\text{jet}_1} > 45$ GeV $p_T^{\text{jet}_2} > 20$ GeV $+ \leq 1$ extra jets		
Missing E_T	$E_T^{\text{miss}} > 120$ GeV $p_T^{\text{miss}} > 30$ GeV $\Delta\phi(\boldsymbol{E}_{\mathbf{T}}^{\mathbf{miss}}, \boldsymbol{p}_{\mathbf{T}}^{\mathbf{miss}}) < \pi/2$ $\min[\Delta\phi(\boldsymbol{E}_{\mathbf{T}}^{\mathbf{miss}}, \text{jet})] > 1.5$ $\Delta\phi(\boldsymbol{E}_{\mathbf{T}}^{\mathbf{miss}}, b\bar{b}) > 2.8$	$E_T^{\text{miss}} > 25$ Gev	$E_T^{\text{miss}} < 60$ GeV
Vector Boson	-	$m_T^W < 120$ GeV	$83 < m_{\ell\ell} < 99$ GeV

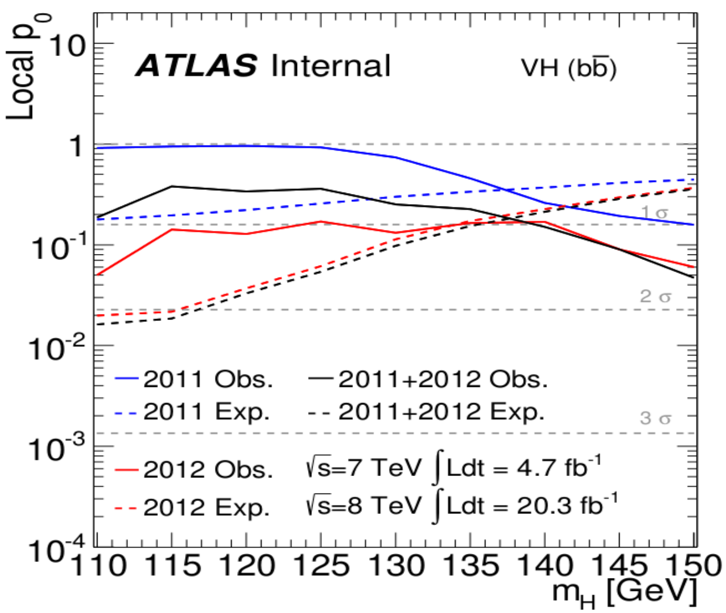
	p_T^V [GeV]	0-90	90-120	120-160	160-200	>200
All Channels	$\Delta R(b,\bar{b})$	0.7-3.4	0.7-3.0	0.7-2.3	0.7-1.8	<1.4
1-lepton	E_T^{miss} [GeV]	>25				>50
	m_T^W [GeV]	40-120			<120	

VH Search Results

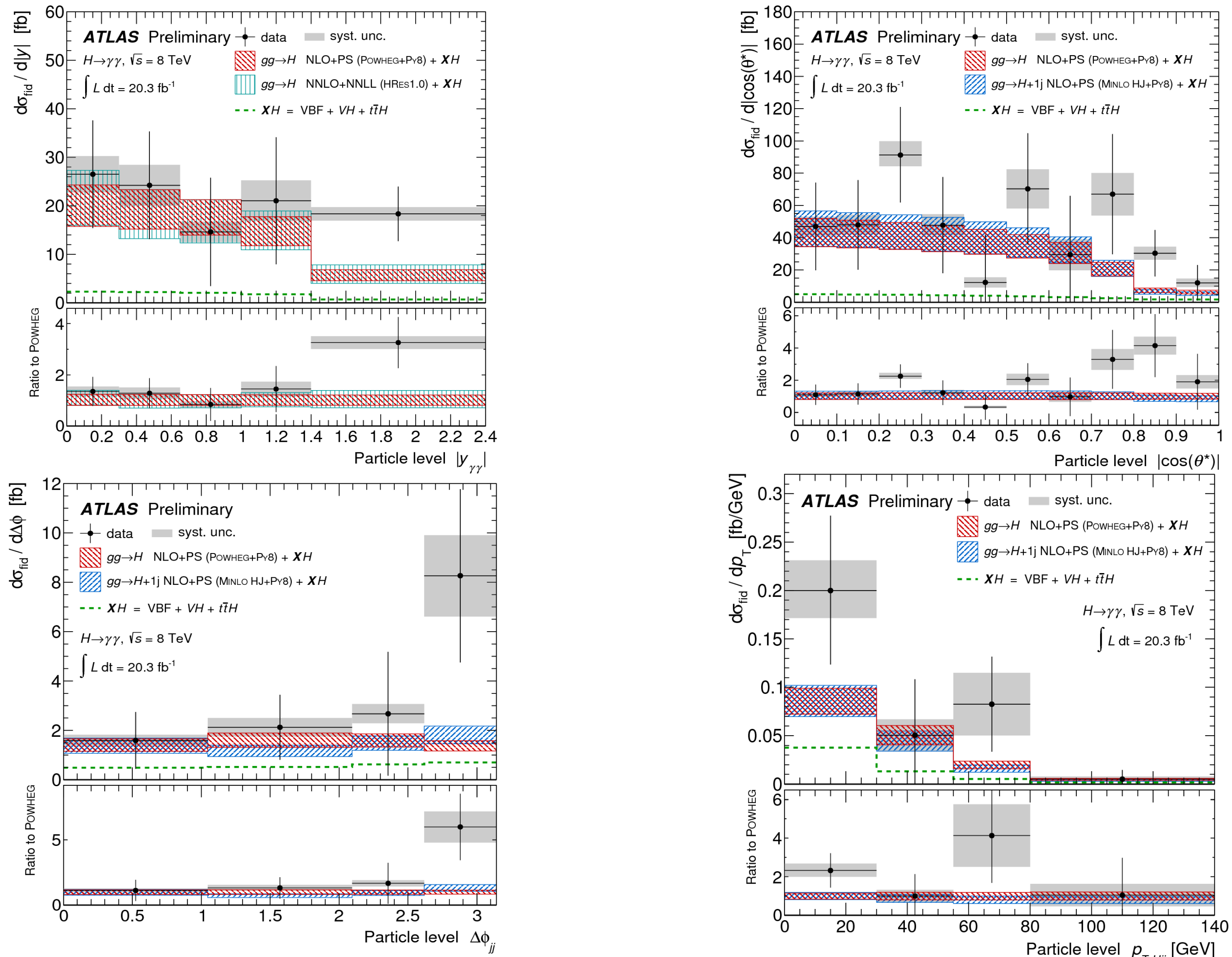




Process	Scale factor
$t\bar{t}$	1.13 ± 0.05
Wb	0.89 ± 0.15
Wcl	1.05 ± 0.14
Zb	1.30 ± 0.07
Zcl	0.89 ± 0.48

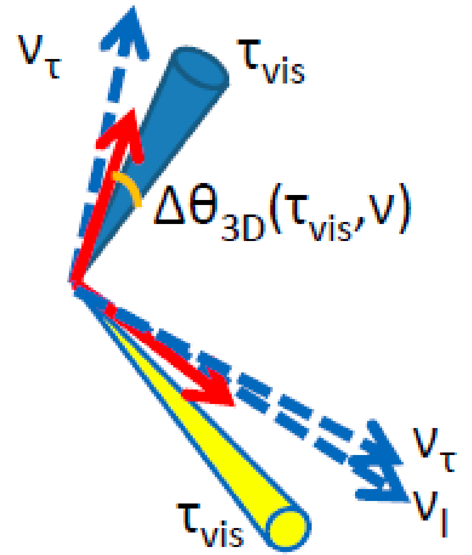


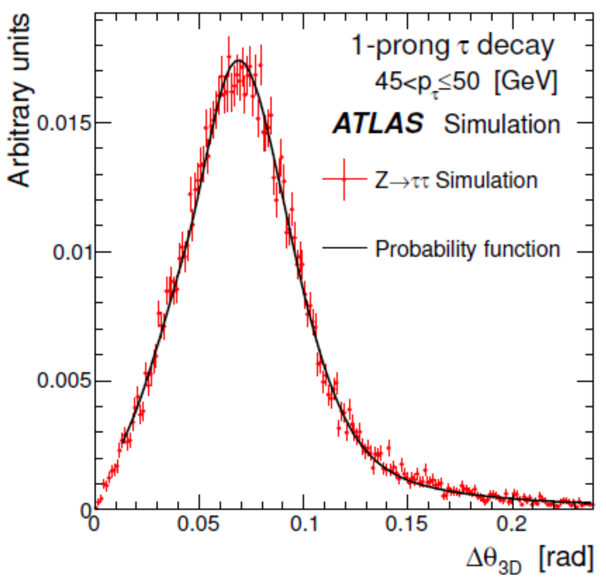
H→γγ Differential Cross Section

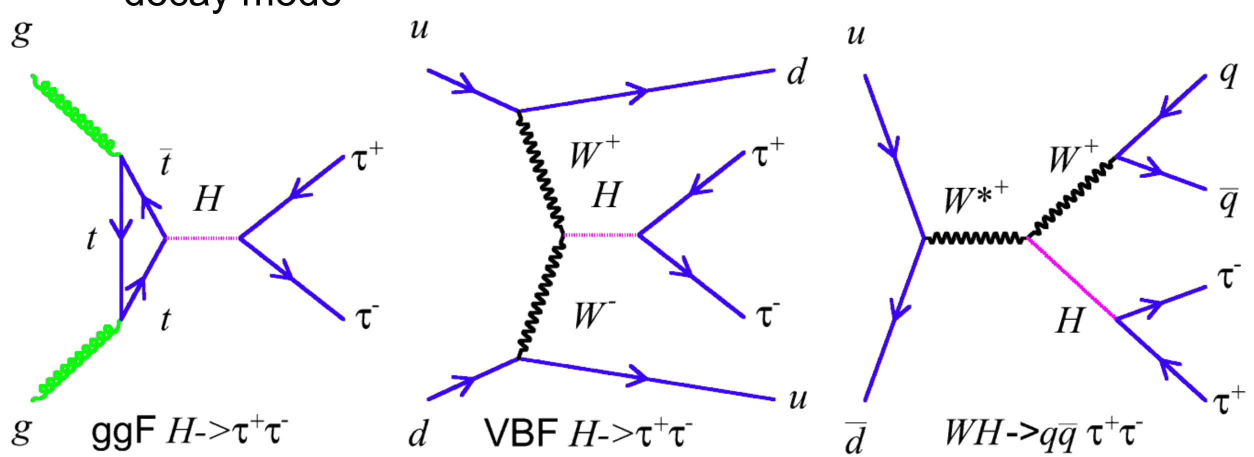


H→ττ analysis

- Analysed 4.6fb-1 (7TeV) + 13fb-1 (8TeV)
  - ATLAS-CONF-2012-160: https://cdsweb.cern.ch/record/1493624
- Three ττ decay modes:
  - "lep-lep": ll4ν; "lep-had": lτhad3ν; "had-had": τhadτhadνν (l=e/μ)
- Three production channels:
  - gluon fusion, Vector boson fusion (VBF), WH/ZH production
- τ identification: BDT based on calorimeter and tracking
- mττ reconstructed with Missing Mass Calculator (MMC)
  - Kinematic fit to τ, ETmiss in Δφ(τvis,ν) parameter space using Δθ3D(τvis,ν) template from simulation as PDF
  - Mass resolution from 13% to 20% depending on kinematics and decay mode





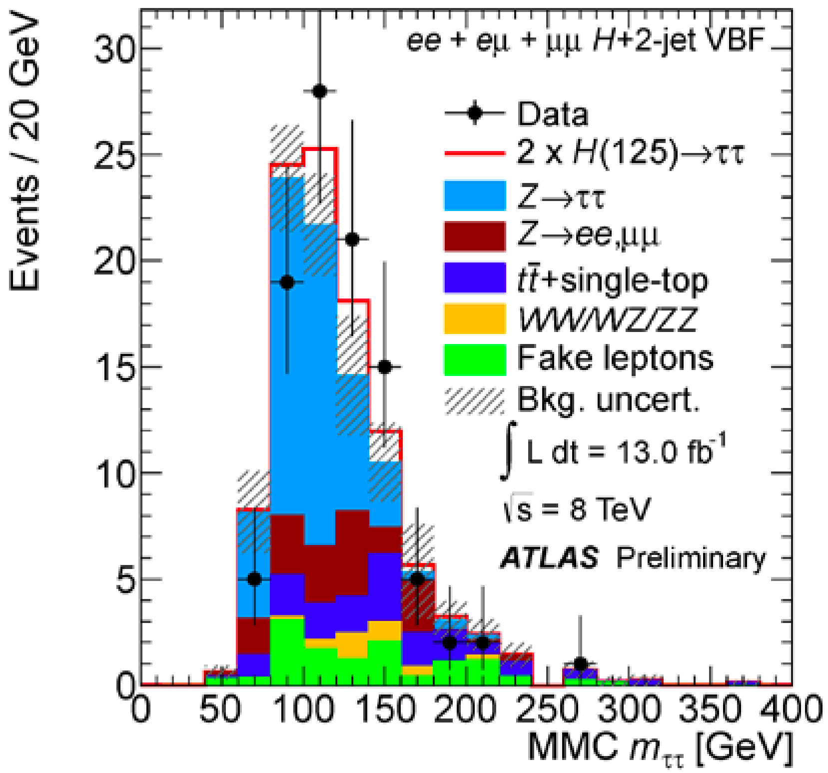


H→ττ→ll4ν (lep-lep)

- BR(H→ττ→ll4ν) = 12.4%

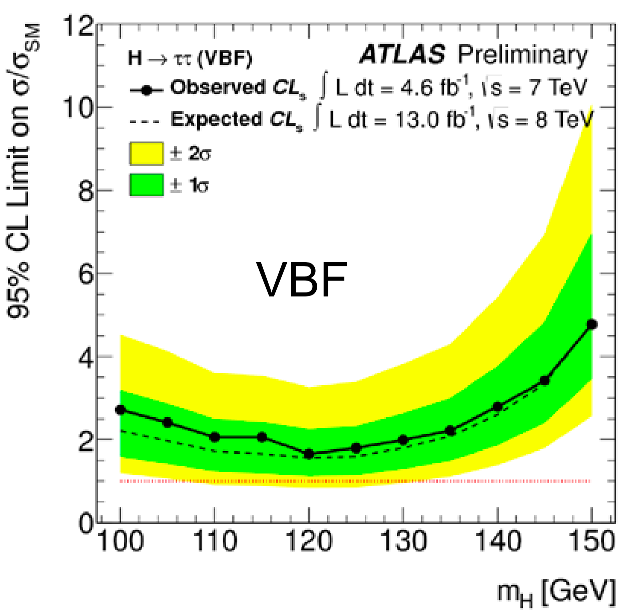
- 5 mutually exclusive categories (all using b-jet veto):
  1. **2-jet VBF**: PT(j) > 25 GeV, Δη(jj) > 3.0, m(jj) > 400 GeV
  2. **Boosted**: NOT 2-jet VBF, **PT(ττ) > 100 GeV**
  3. **2-jet VH**: NOT Boosted and Δη(jj) < 2.0, 30 GeV < m(jj) < 160 GeV
  4. **1-jet**: NOT 2-jet VBF, Boosted, or 2-jet VH, and m(ττj) > 225 GeV
  5. **0-jet**: oppositely charged leptons, 30 < m(ll) < 100 GeV, PT(ll) > 35 GeV, Δφ(ll) > 2.5 (not used at 8 TeV)

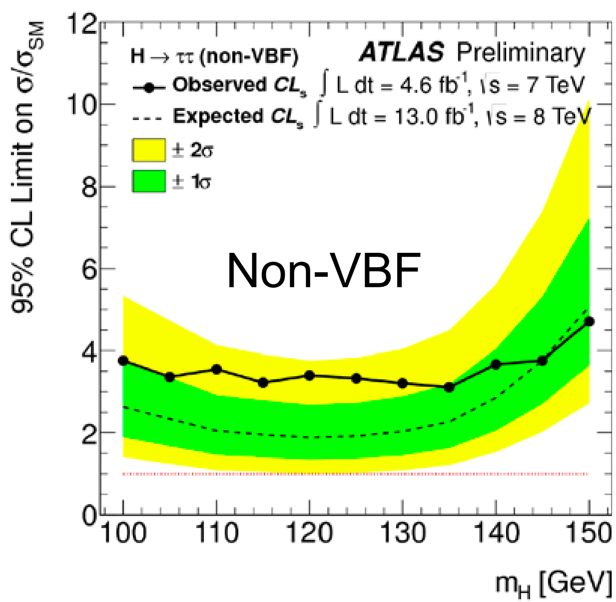
- Backgrounds:
  - Dominant: Z → ττ
  - Z → ττ estimated using "embedding": replace mu in real Z→μμ events with simulated τ's of same momentum
  - Z → ee/μμ backgrounds determined from data: simulations normalized to control regions
  - Fake leptons: determined from data using templates, fitted in control regions with relaxed lepton identification criteria

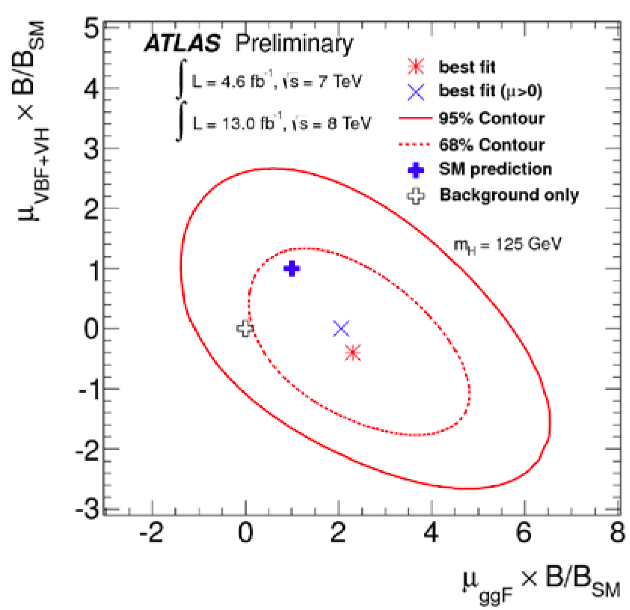


H→ττ results

- Total of 25 channels combined (13 for 7TeV, 12 for 8TeV)
- Small excess, consistent with SM Higgs hypothesis (and to lesser extent, with background-only)
  - Best-fit signal strength μ value at 125 GeV is $\mu = 0.7 \pm 0.7$
- Combined local significance for mH = 125 GeV is 1.1σ observed (1.7σ expected)
- Observed (expected) exclusion is 1.9 (1.2) times the SM predicted value (μ=1)
- Separating out VBF categories broad excess seen in non-VBF categories



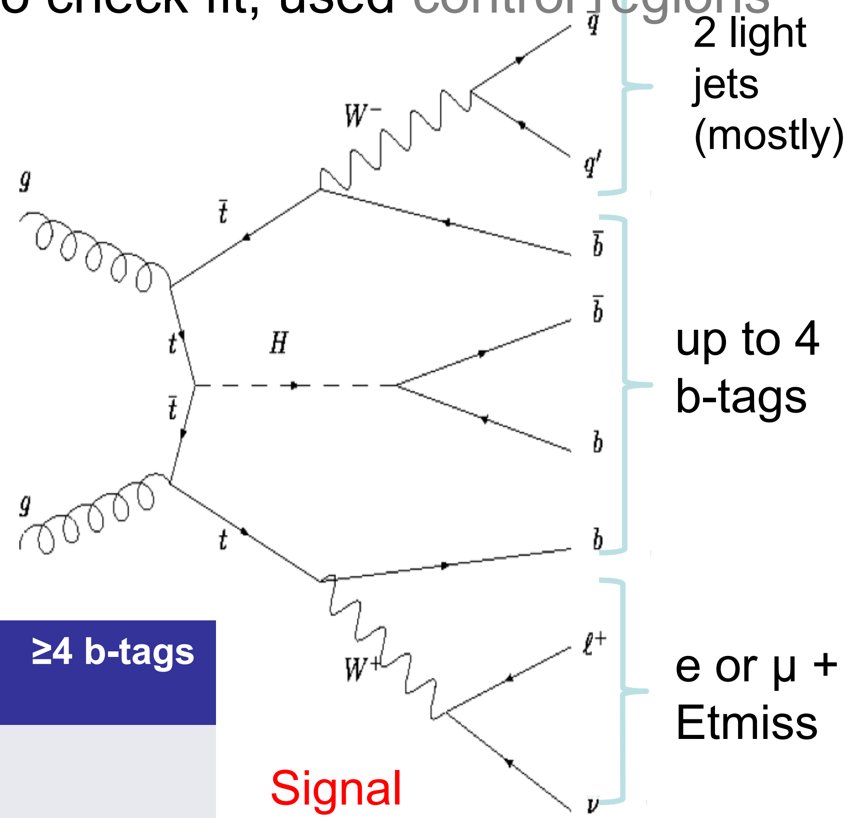




ttH, H→bb Analysis

- ATLAS-CONF-2012-135:
  - 4.7fb-1 at √s = 7 TeV
- 9 categories based on jet & b-tag multiplicity
  - Signal enriched: (5 jets, ≥6 jets) x (3,≥4 b-tag)
  - Other categories are background enriched to constrain those backgrounds
  - Njet uncertainty from varying parameters in MC model
- Final discriminants
  - mbb for ≥6 jets and ≥3 b-tag categories
    - Kinematic fit to reconstruct tt system
  - Hthad = ∑pT,jet for other categories

- Backgrounds constrained in limits fit by profiling nuisance parameters
- To check fit, used control regions



	0 b-tags	1 b-tag	2 b-tags	3 b-tags	≥4 b-tags
4 jets	HThad	HThad		HThad	
5 jets	HThad	Hthad	HThad	HThad	HThad
≥6 jets	HThad	HThad	HThad	mbb	mbb

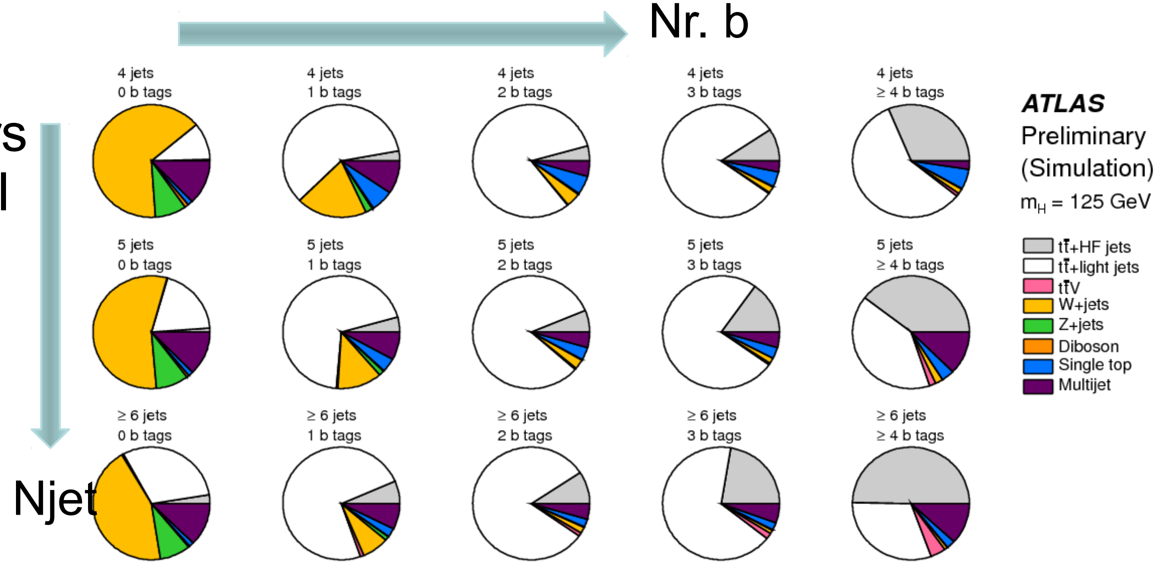
Signal
Background
Control regions

ttH, H→bb Reconstruction

- To constrain uncertainties:
- Categories of Njet & Nb-tag:
  - Signal enriched: (5 jets, ≥6 jets) x (3, ≥4 b-tag)
- Statistical analysis with discriminants:
  - ≥6 jets / ≥3 b-tag: mbb
  - Other: Hthad = ∑pT,jet
- Profile nuisance parameters from fit to data in statistical analysis

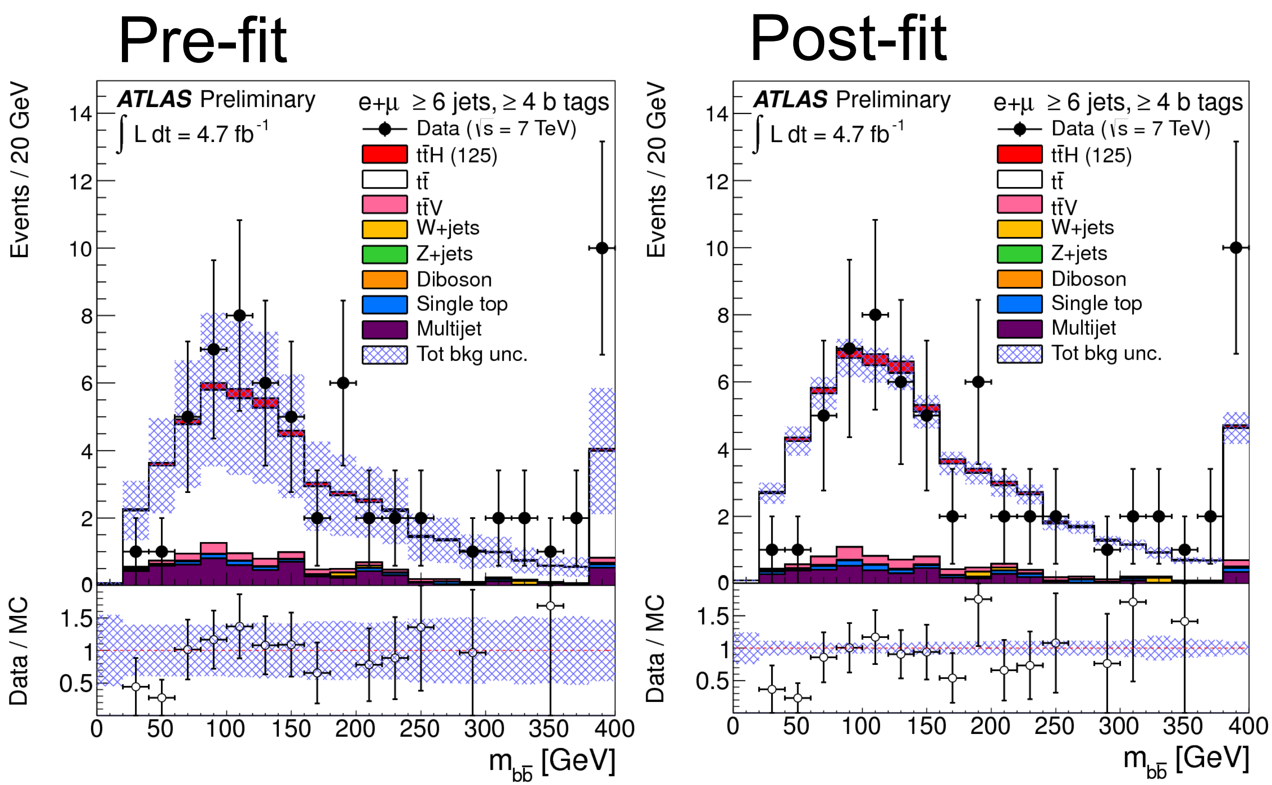
	0 b-tags	1 b-tag	2 b-tags	3 b-tags	≥4 b-tags
4 jets	HThad	HThad		HThad	
5 jets	HThad	HThad	HThad	HThad	HThad
≥6 jets	HThad	HThad	HThad	mbb	mbb

Signal
Background
Control regions



Statistical Analysis

- Main systematic uncertainties due to b-tagging and theory understanding of tt + heavy flavour production
- Experiment: bin-to-bin migrations from jet energy scale & b-tagging
- Theory: rely on models in Monte Carlo to extrapolate backgrounds to signal region
  - Could be missing something on theory uncertainty



ttH Systematic Uncertainties

- **tt+heavy-flavour** fractions: vary by 50% - theory studies suggest cross section uncertainty is 50-75% ; should be weighted down by the fraction of this background. Fit puts it at 30%.

- **tt modeling** (Alpgen):
  - **Qfac**: (±2.3%) The factorization scale for the hard scatter is varied by a factor of two up and down relative to the original scale, Q2 = Σpartonsm2+ p2T
  - **kTfac**: (±9.2%) The renormalisation scale associated with the evaluation of αs at each local vertex in the matrix element calculation is varied by a factor of two up and down relative to the original scale, kT , between two partons.
  - Functional form of the factorization scale (**iqopt2**): (± 13%) Default choice (=1) for dynamic factorization scale, Q2 = Σpartonsm2+ p2T, changed to Q2 = *x*1*x*2s. This has an order of magnitude larger effect than Qfac.

- **tt cross section**: +9.9 -10.7% using NNLO Hathor.
- **Jet Energy scale**: 16 eigenvectors recommended by the jet/ETmiss group are varied.
- **b, c and light tagging**: 9 (btag),5(ctag) eigenvectors recommended by b-tagging group are varied for heavy flavours and the one value for light flavours.
- **QCD Multijets**: Mostly in the electron channel. Correlated 50% uncertainty plus uncorrelated statistical estimate in each channel (66% in 6 jet 4 b-tag)
- **ttH parton shower modelling**: 1-5% effect at mH = 120 GeV