Cross section measurements of Higgs-> WW*->eνμν in ATLAS

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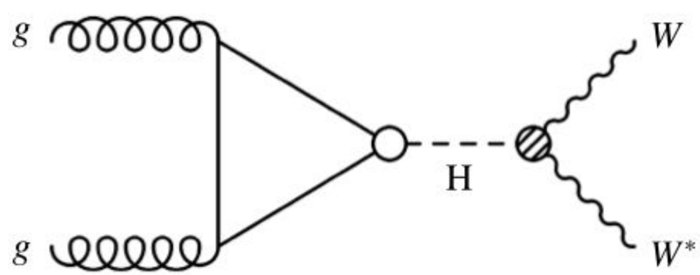
31th July 2019

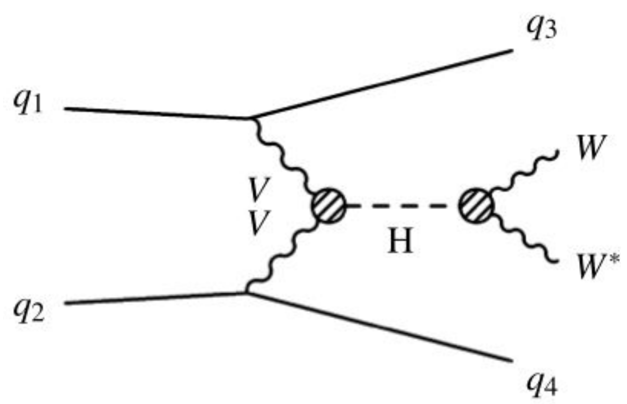
2019 Meeting of the Division of Particles & Fields of American Physical Society

Motivation

- HWW: 2nd Highest branching ratio at 125 GeV
  - H->WW 22% (H->bb 57% , H->ττ 6.2%, H->ZZ 2.8%, H->γγ 0.23%)
  - One of the most sensitive channel in Run 1
- Leading Higgs production modes: ggF and VBF
- Higgs WW in Run 1, 7-8 TeV data
  - 5.8σ ; σ_{ggf} = 4.6 ±1.2 pb
  - 3.2σ; σ_{vbf} = 0.51± 0.20 pb



Gluon fusion Higgs



Vector boson fusion Higgs

Analysis strategy

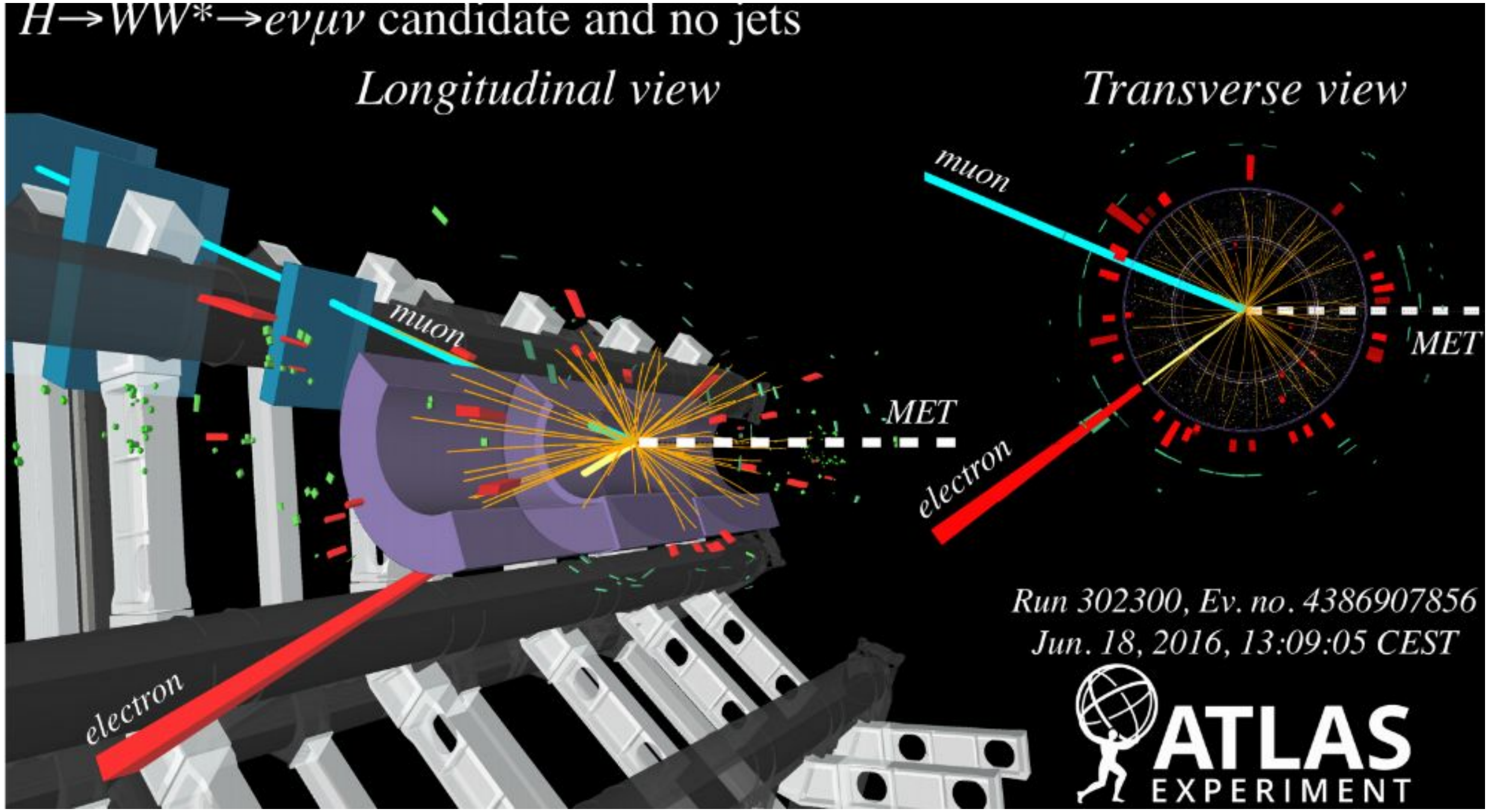
Phys. Lett. B 789 (2019) 508

- LHC run2 2015-2016 13 TeV data (36/fb)
  - 8->13 TeV : GGF/VBF factor of 2.3/2.4; ww : ~ factor of 1.9 ; $t\bar{t}$: ~ factor of 3.4
- WW leptonic decay to different flavour : e, μ
  - Largely reduced Z+jets contribution
  - Best sensitivity among WW decays
- Single and dilepton Triggers : down to 14 GeV for muon and 17 GeV for electron
- Events separated to jet multiplicity bins: ggF 0 jet, ggF 1 jet, VBF(>=2 jet)
  - Different background contributions. Different background estimation methods used
  - Universal jet p_T equal to 30 GeV
    - Better comparison to theory prediction
    - Easier combination with other channels
    - More Top background in 0 jet category compare to a lower p_T jets used in veto
- Use m_T instead of m_H for the presence of missing E_T

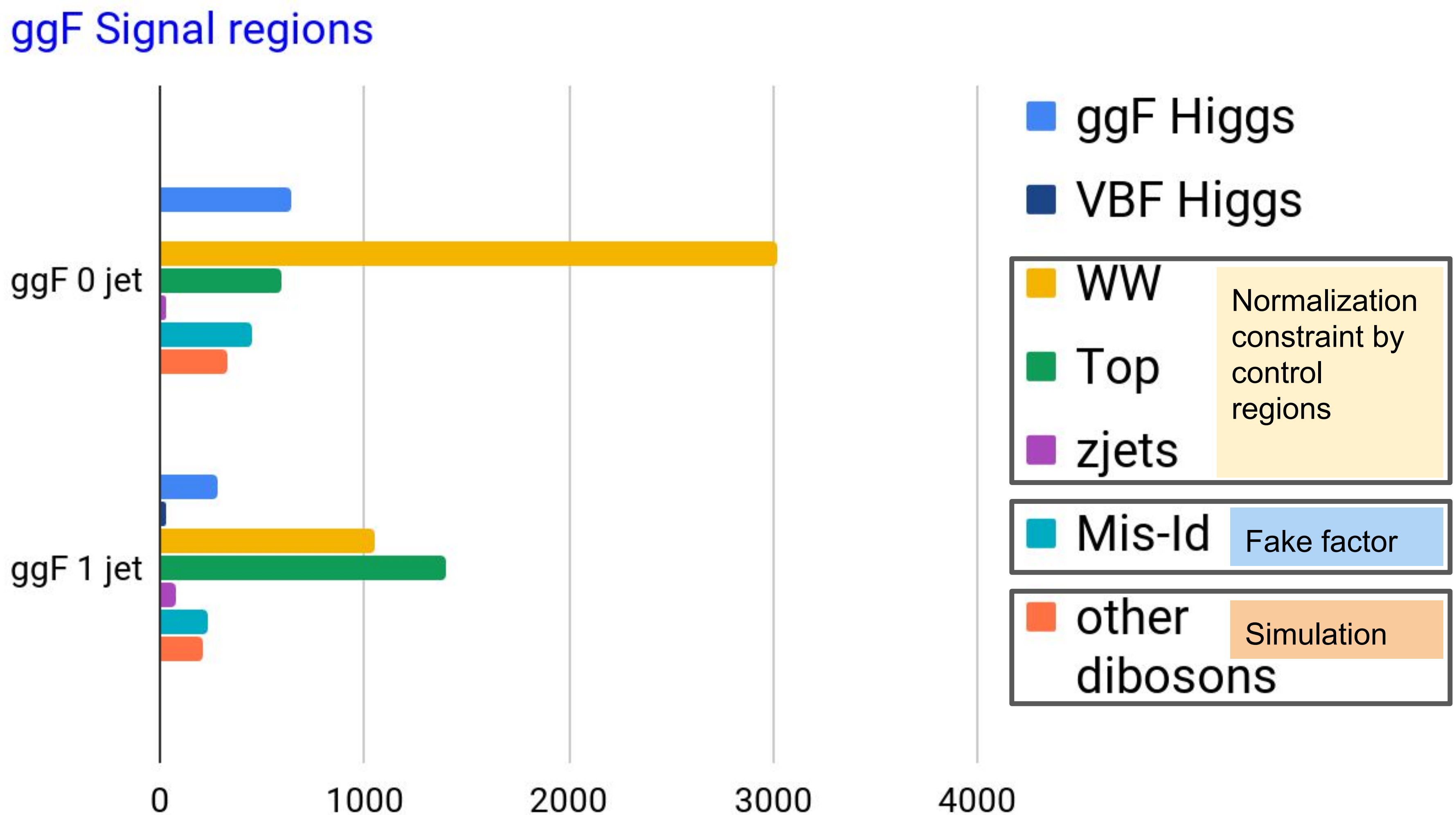
$$m_T = \sqrt{(E_{ll} + E_T^{miss})^2 - |p_{ll} + E_T^{miss}|^2}$$

ggF 0, 1 jet analysis

- Signal selections
  - Spin 0 Higgs decay and W boson V-A topology : $M_{ll} < 55$ GeV, $\Delta\Phi_{ll} < 1.8$
  - Background rejection 0,1 jet category:
    - b jet veto in both 0,1 jet category
    - $MET_{track} > 20$ GeV ; $\Delta\Phi(ll,met) > 1.57$; $max(mT_W) > 50$ GeV; $p_T ll > 30$GeV ; veto $m_{\tau\tau}$



Background in ggF signal region



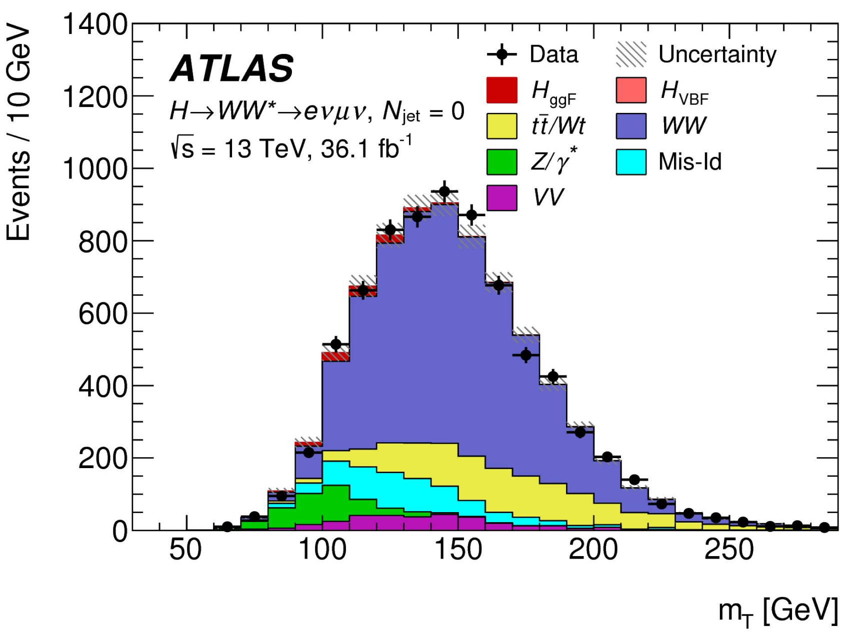
WW and Z+jet background estimations

Normalisation constrained by the control region.
Simultaneous fit of all the ggF and VBF SRs and CRs

WW 0 jet control region

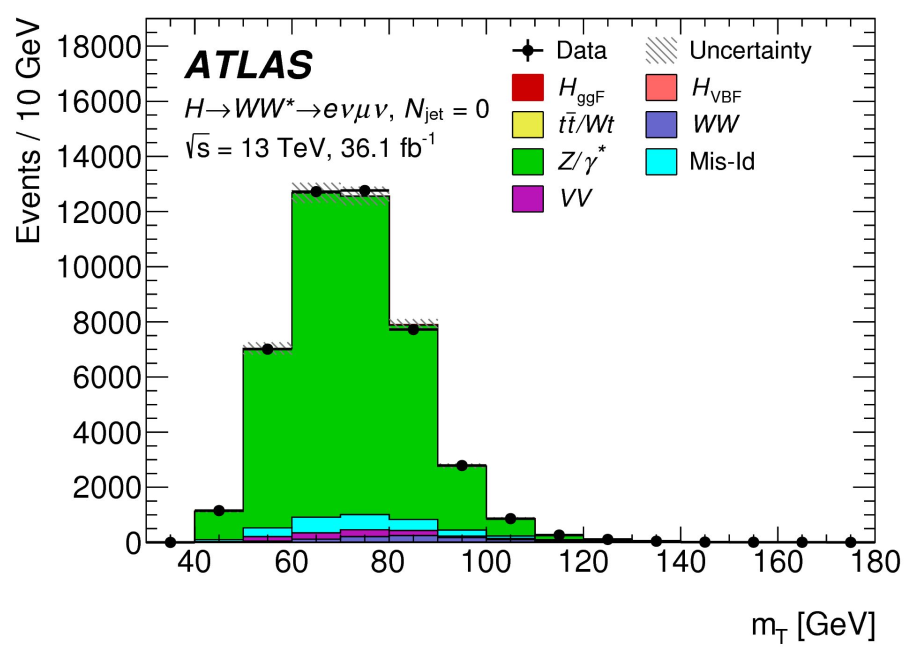
- Othognal mll (55 GeV < mll < 110 GeV)
- loosen $\Delta\phi_{ll}$(<2.6)
- Purity: 63%

gg→ WW and WW scale ~ 6%



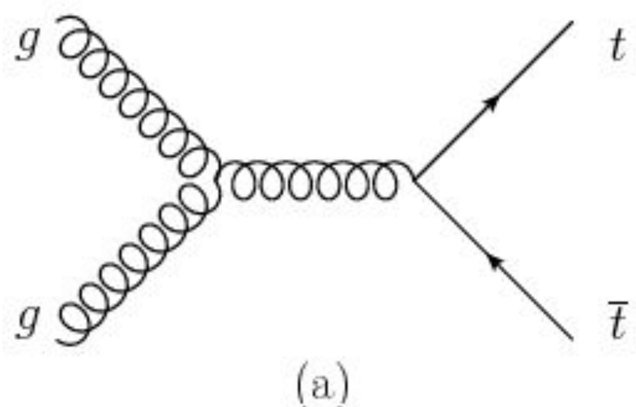
Z/γ*->ττ 0 jet control region

- Flip Δϕll (>2.8)
- Loosen mll (< 80 GeV)
- purity: 90%

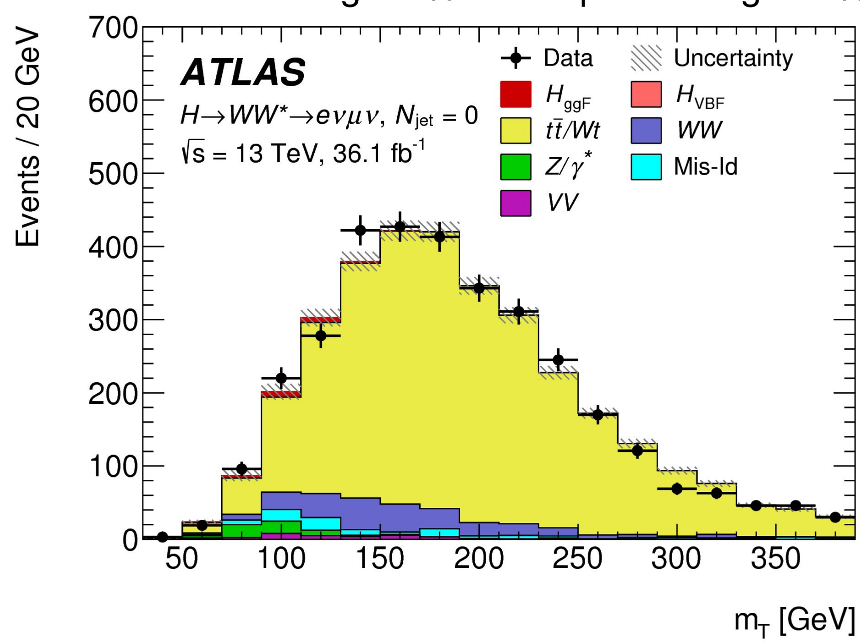


Top background estimations

- Top background can have different flavor in final state
  - High production cross section
  - Enrich low p_T QCD radiated jets
- Rise the jet p_T threshold from 25 to 30 GeV for theory comparison
  - More top background in signal region
  - Event with 25-30 GeV jets now in ggF 0 jet
  - Veto events with 20-30 GeV bjet
- Top control region for top background estimation
  - Required one 20-30 GeV b tag jet
  - 81% purity

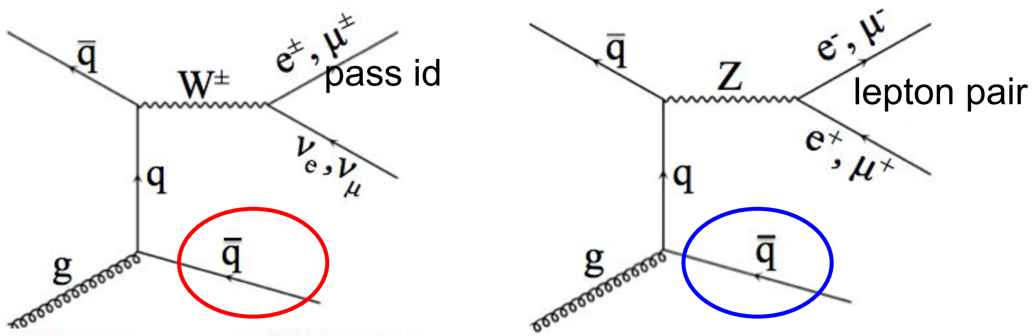


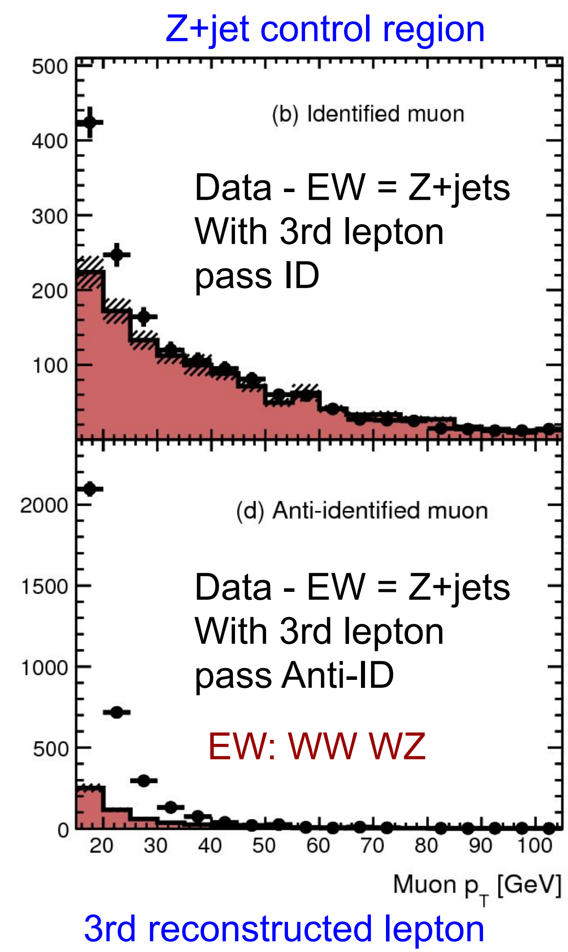
btag ~ 4% and Top modeling ~ 5 %



Misidentified Leptons

- Jets reconstructed as isolated lepton (e,μ) : W+jets dominate (Not well modeled in simulation)
- Data driven estimation via W+jet control region (id+anti-id)
- Fake factor estimated with Z+jets enrich region
  - 3 reconstructed leptons
  - A lepton pair close to Z mass window
  - The left lepton for measuring fake factor





$$N^{W+\text{jets}}_{\text{id+id}} = N^{W+\text{jets}}_{\text{id+anti-id}} \times \text{FF} \times \text{CF}$$

$$N^{W+\text{jets}}_{\text{id+anti-id}} = (N_{\text{id+anti-id}} - N^{\text{EW}}_{\text{id+anti-id}})$$

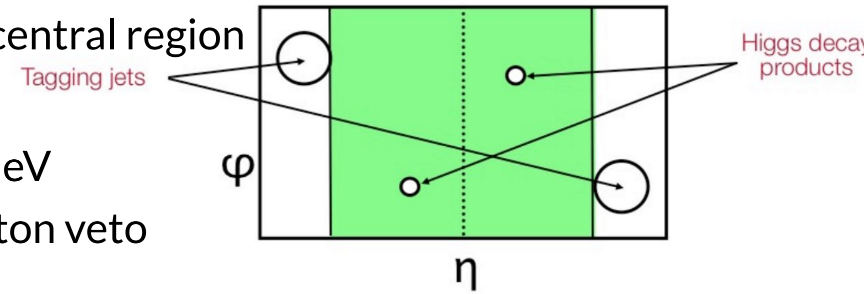
Fake Factor

Correction Factor

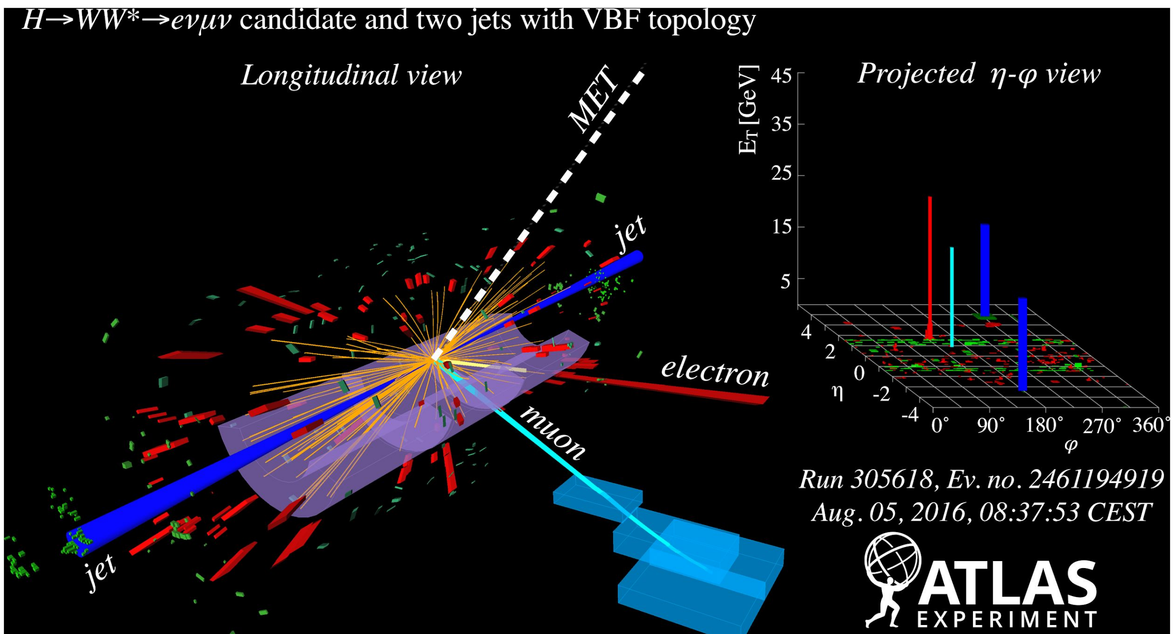
$$\text{FF}(p_T, \eta) = \frac{N_{\text{id}}(p_T, \eta)}{N_{\text{anti-id}}(p_T, \eta)} \qquad \text{CF} = \left[\frac{\text{FF}(W+\text{jets})}{\text{FF}(Z+\text{jets})}\right]_{\text{MC}}$$

VBF analysis

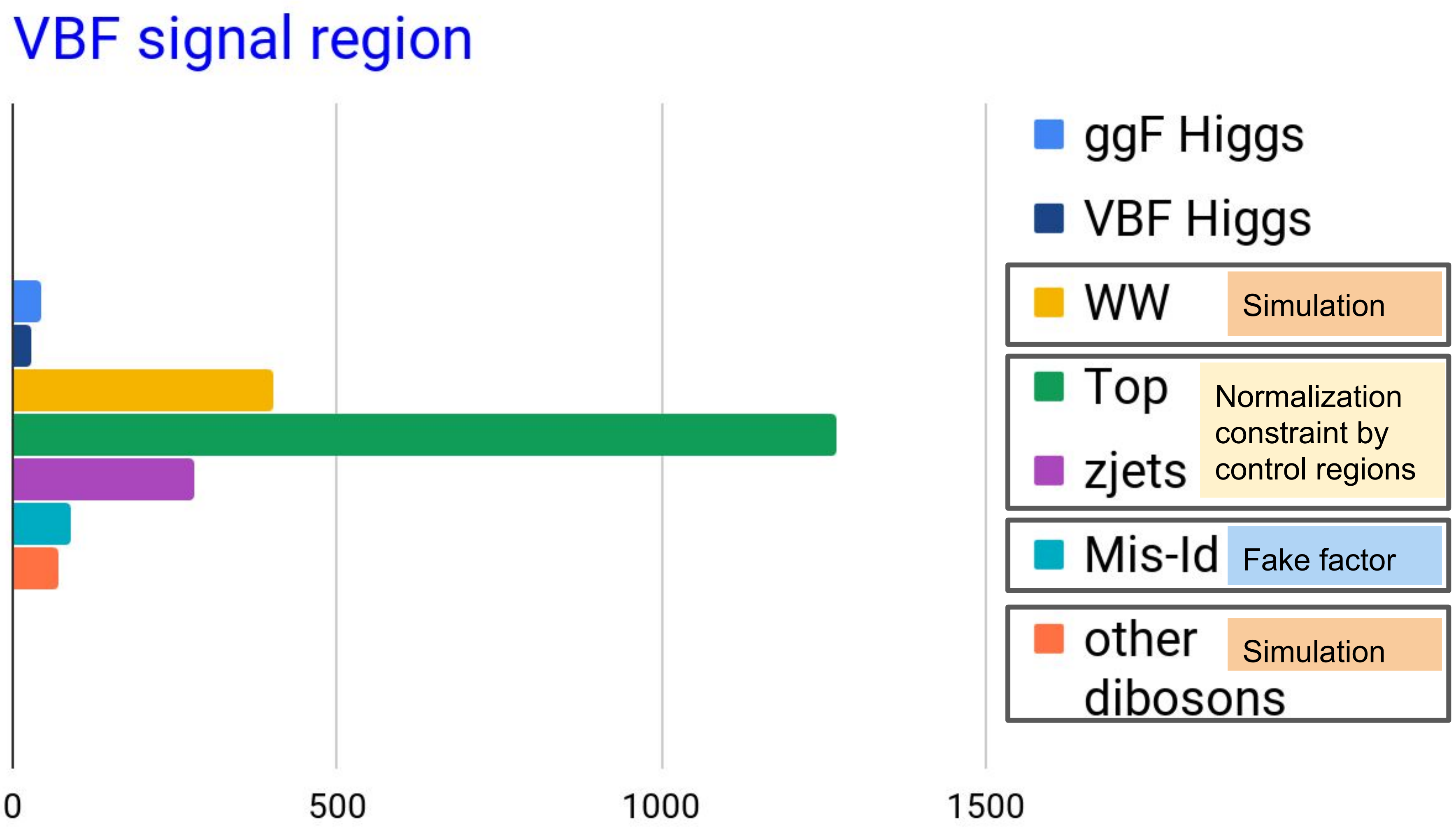
- Probe Higgs interaction with vector boson
  - Two energetic jet with little jet activity in central region



- VBF Analysis
  - >=2 jet, bjet veto(>20 GeV), $m_{\tau\tau}$< mz-25 GeV
  - CJV(central jet veto) 20 GeV, outside lepton veto
- Boosted Decision Tree
  - $\Delta\phi_{ll}$, m_{ll}, mT, | Δy_{jj}, m_{jj}, Σmjl, lep η centrality | pTtot



Background in VBF signal region

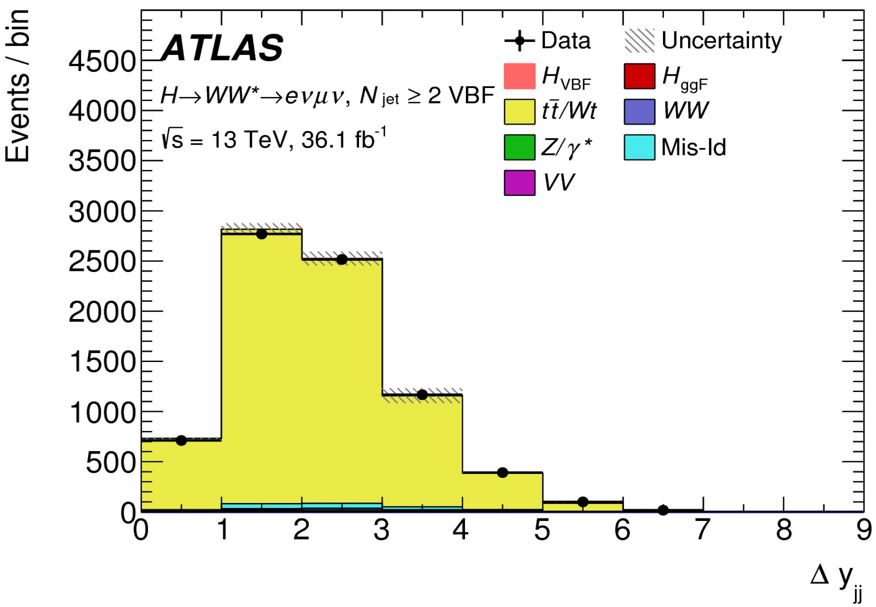


Top and Z+jet background estimations

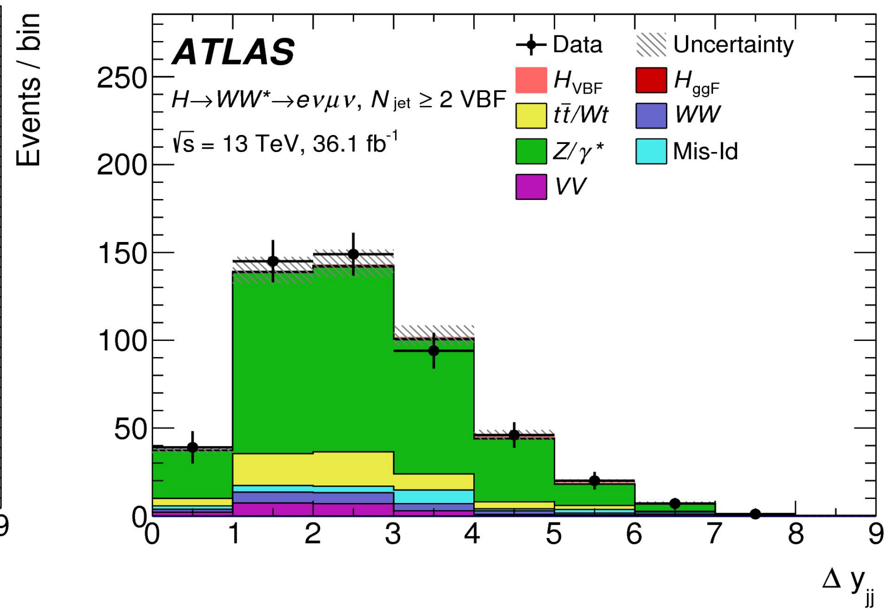
Normalisation constrained by the control region.
Simultaneous fit of all the ggF and VBF SRs and CRs

- bjet veto -> 1 bjet
- Purity: 96%

- Select Mττ 25 GeV mass window
- Purity: 74%



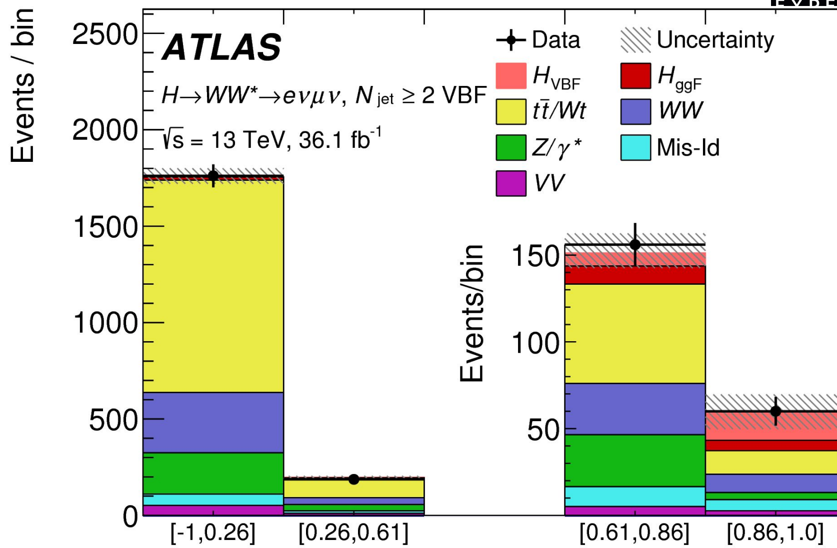
Btag systematic ~ 6 %; top modeling ~5 %

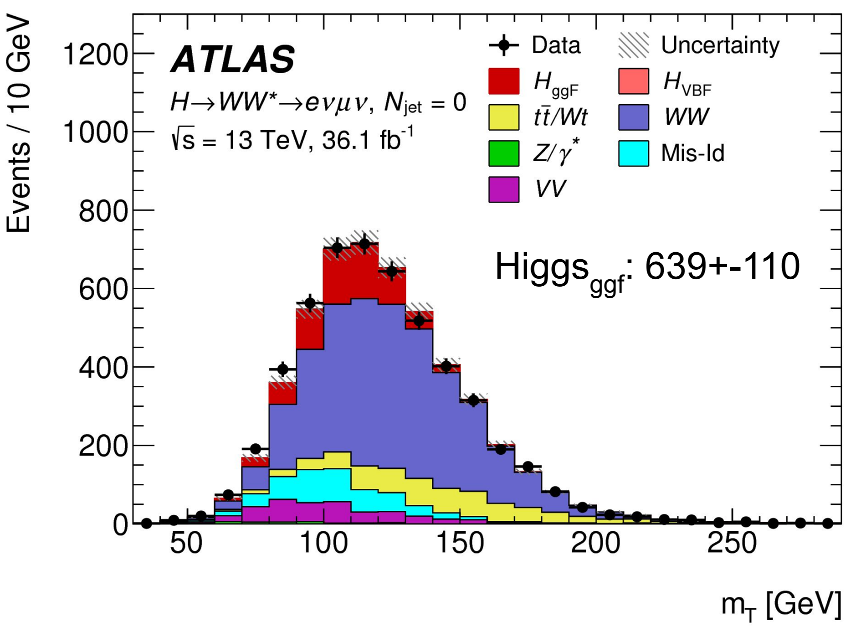


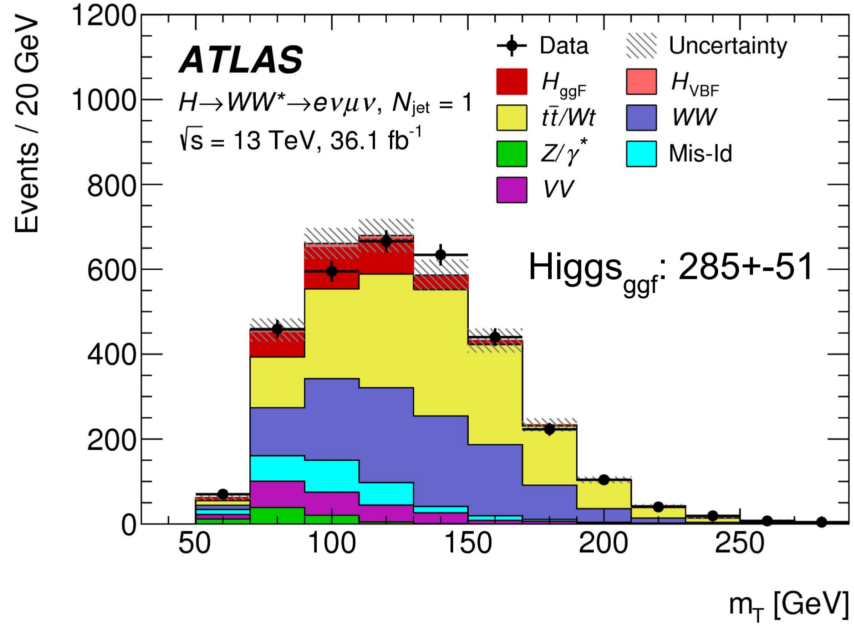
Combined ggF and VBF fit

- ggF 0, 1 jet categories
  - Split SR in mll (WW) , pT sub-lead lep , and flavour channels eμ/μe (mis-id leptons)
  - 8/6 bin MT distributions
- VBF
  - Statistical dominated
  - Single 4 Bin BDT distribution

$Higgs_{VBF}$:42+-16
$Higgs_{ggF}$:28+-16



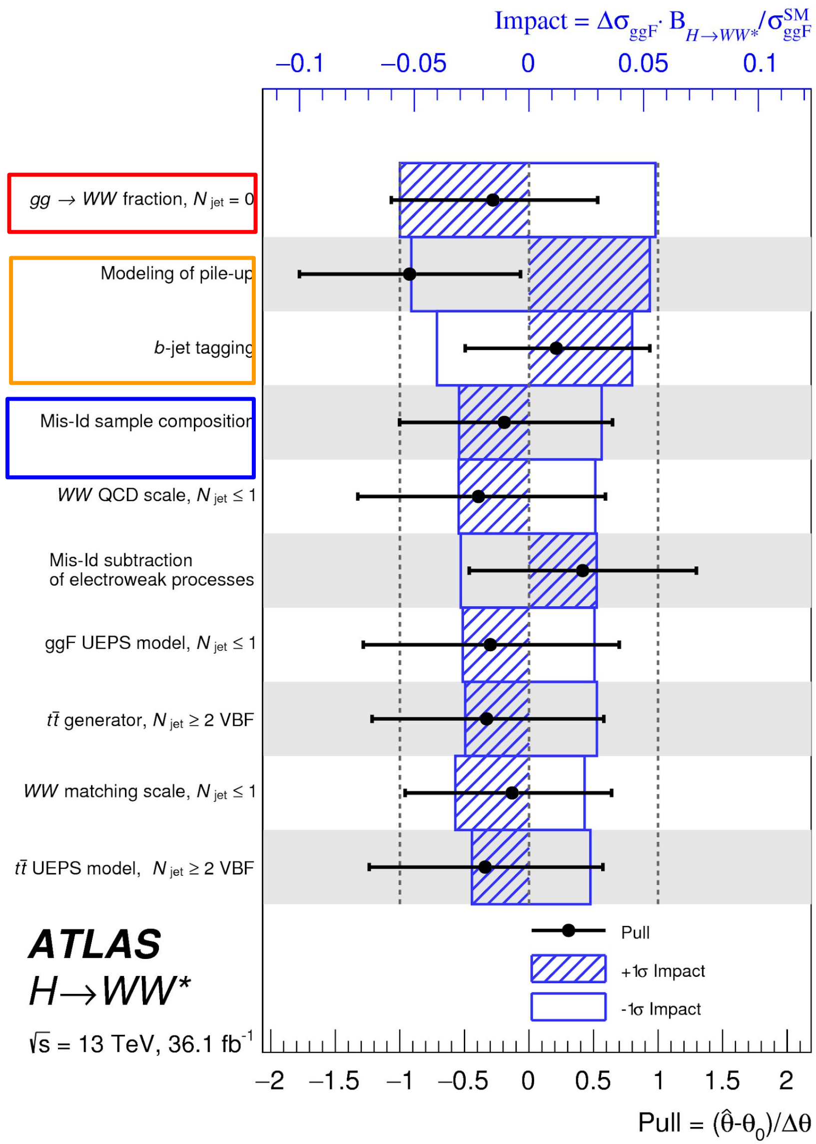




Systematics

- ggF
  - WW theory uncertainties (gg->ww)
  - Pile up modeling , btag
  - mis-identified lepton(flavour composition)
- VBF
  - MC Statistics
  - ggF, WW theory uncertainties(generator, PSUE)

Source	$\Delta\sigma_{ggF} \cdot \mathcal{B}_{H\to WW^*}$ [%]	$\Delta\sigma_{VBF} \cdot \mathcal{B}_{H\to WW^*}$ [%]
Data statistics	10	46
CR statistics	7	9
MC statistics	6	21
Theoretical uncertainties	10	19
ggF signal	5	13
VBF signal	<1	4
WW	6	12
Top-quark	5	5
Experimental uncertainties	8	9
b-tagging	4	6
Modelling of pile-up	5	2
Jet	2	2
Lepton	3	<1
Misidentified leptons	6	9
Luminosity	3	3
TOTAL	18	57



Results

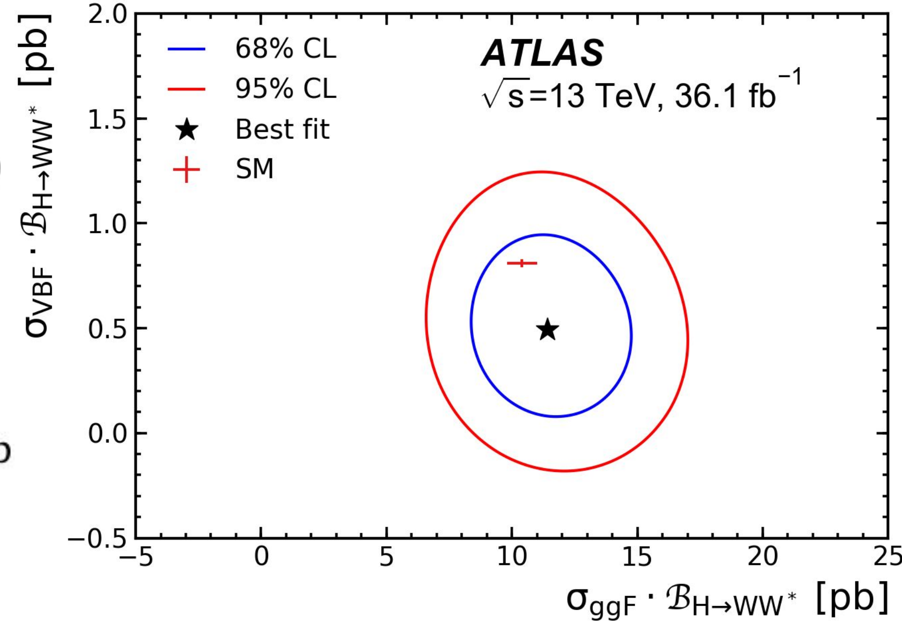
- Cross section x branching ratio

$$\sigma_{\mathrm{ggF}} \cdot \mathcal{B}_{H\to WW^*} = 11.4^{+1.2}_{-1.1}(\mathrm{stat.})^{+1.2}_{-1.1}(\mathrm{theo\ syst.})^{+1.4}_{-1.3}(\mathrm{exp\ syst.})\ \mathrm{pb}$$

$\sigma ggF_{SM} = 10.4 \pm 0.6$ pb

$$\sigma_{\mathrm{VBF}} \cdot \mathcal{B}_{H\to WW^*} = 0.50^{+0.24}_{-0.22}(\mathrm{stat.}) \pm 0.10(\mathrm{theo\ syst.})^{+0.12}_{-0.13}(\mathrm{exp\ syst.})\ \mathrm{pb}$$

$\sigma VBF_{SM} = 0.81 \pm 0.02$ pb



- Signal strength (σ/σ_{SM})

$$\mu_{\mathrm{ggF}} = 1.10^{+0.10}_{-0.09}(\mathrm{stat.})^{+0.13}_{-0.11}(\mathrm{theo\ syst.})^{+0.14}_{-0.13}(\mathrm{exp\ syst.})$$

$$\mu_{\mathrm{VBF}} = 0.62^{+0.29}_{-0.27}(\mathrm{stat.})^{+0.12}_{-0.13}(\mathrm{theo\ syst.}) \pm 0.15(\mathrm{exp\ syst.})$$

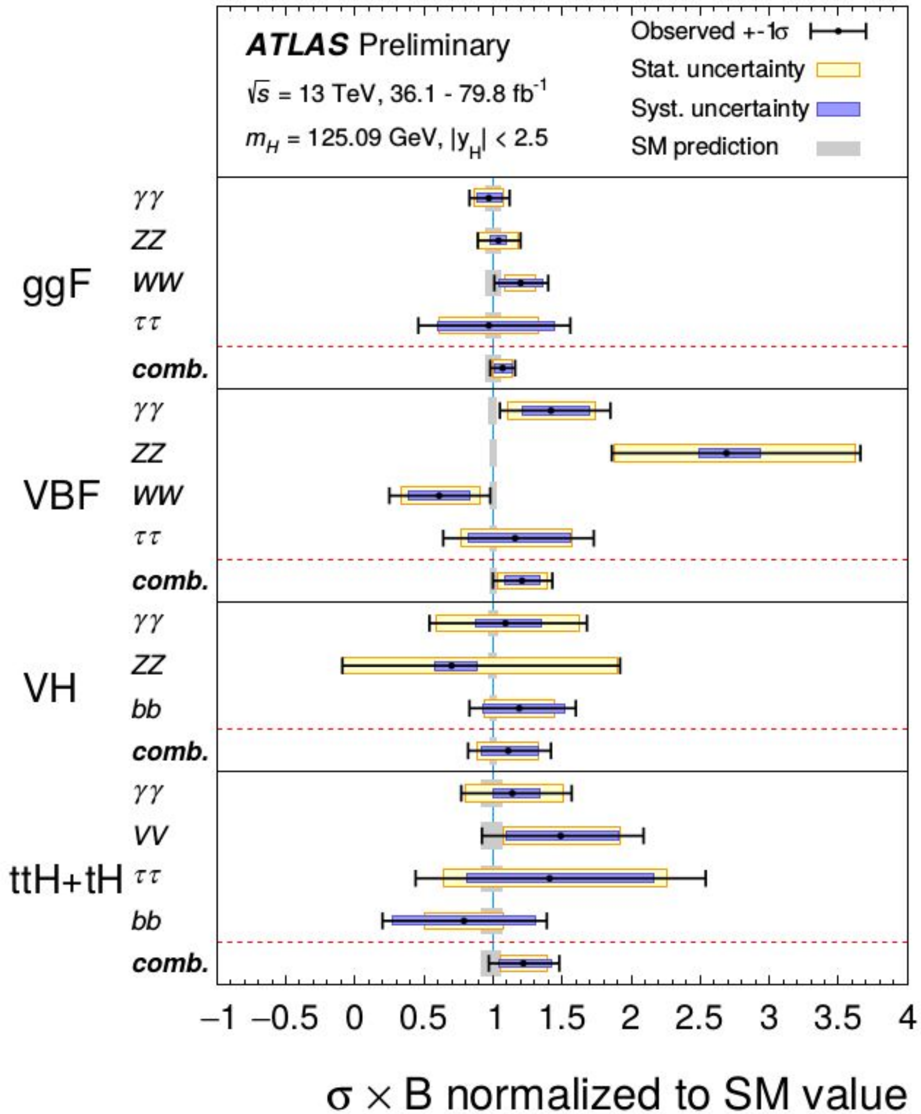
- Observed (expected) significances
  - ggF :6.0(5.3) σ
  - VBF:1.8(2.6) σ

Higgs decay combination (ATLAS)

ATLAS-CONF-2018-031

VBF observed/expected Significance:6.5σ/5.3σ

With only ATLAS data



Outlook

- Full ~ 139/fb of data
  - ggF analysis is systematic dominated, VBF is statistical dominated
  - Increasing data -> larger gain for VBF analysis
- WW uncertainties
  - Better control of WW background with the MT2 variable in ggF 1 jet and VBF analysis
  - WW theory uncertainties
    - Largest background in the ggF 0 jet category. Uncertainty from gg->WW (NLO calculation)
    - VBF category : WW generator uncertainties
- Pile up increasing (<μ> 2016: 25.1, 2017: 37.8, 2018:36.1)
  - Pile up in isolation, Pile up jet rejection.
- Particle flow jets and btag improvements
- Goal for full run 2
  - 2 jet category : ggF 2 jet, VH analysis
  - STXS, standard Fiducial Cross Section measurement =>Channel combinations=> Interpretations
  - Differential Cross Section measurement => Interpretations

  * Interpretations: kappa framework, SMEFT fit, BSM models .....

Thank you !

Back up

Signal region selection

Event selection criteria used to define the signal regions in the $H \to WW^* \to e\nu\mu\nu$ analysis. For the $N_{\text{jet}} \geq 2$ VBF signal region, the input variables used for the boosted decision tree (BDT) training are also reported.

Category	$N_{\text{jet},(p_T>30\text{ GeV})} = 0$ ggF	$N_{\text{jet},(p_T>30\text{ GeV})} = 1$ ggF	$N_{\text{jet},(p_T>30\text{ GeV})} \geq 2$ VBF
Preselection	Two isolated, different-flavour leptons ($\ell = e, \mu$) with opposite charge (all categories) $p_T^{\text{lead}} > 22$ GeV, $p_T^{\text{sublead}} > 15$ GeV (all categories) $m_{\ell\ell} > 10$ GeV (all categories) $p_T^{\text{miss}} > 20$ GeV (0-jet and 1-jet ggF)		
Background rejection	$N_{b\text{-jet},(p_T>20\text{ GeV})} = 0$ (all categories) $\Delta\phi(\ell\ell, E_T^{\text{miss}}) > \pi/2$ $p_T^{\ell\ell} > 30$ GeV	$\max\left(m_T^{\ell}\right) > 50$ GeV $m_{\tau\tau} < m_Z - 25$ GeV (1-jet ggF and VBF)	
$H \to WW^* \to e\nu\mu\nu$ topology	$m_{\ell\ell} < 55$ GeV $\Delta\phi_{\ell\ell} < 1.8$ (0-jet and 1-jet ggF)		central jet veto outside lepton veto
Discriminant variable BDT input variables	m_T (0-jet and 1-jet ggF)		BDT m_{jj}, Δy_{jj}, $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, m_T, $\sum_{\ell} C_{\ell}$, $\sum_{\ell,j} m_{\ell j}$, p_T^{tot}

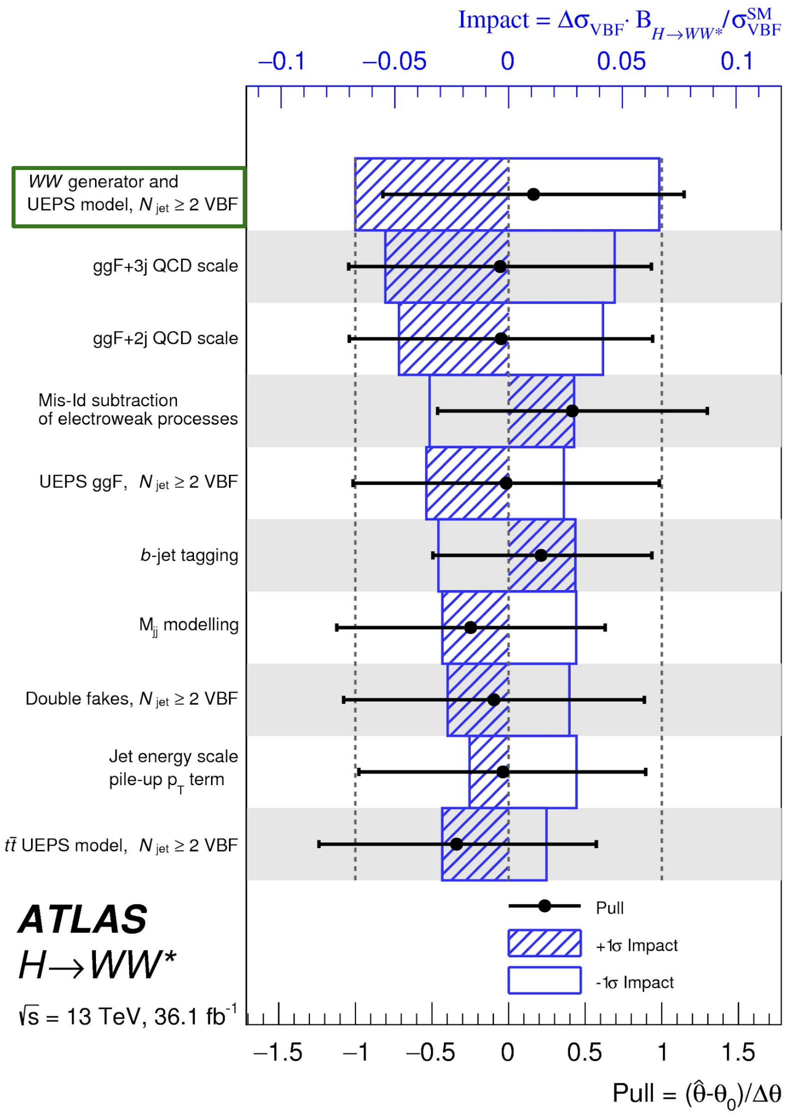
Control region selection

Table 3

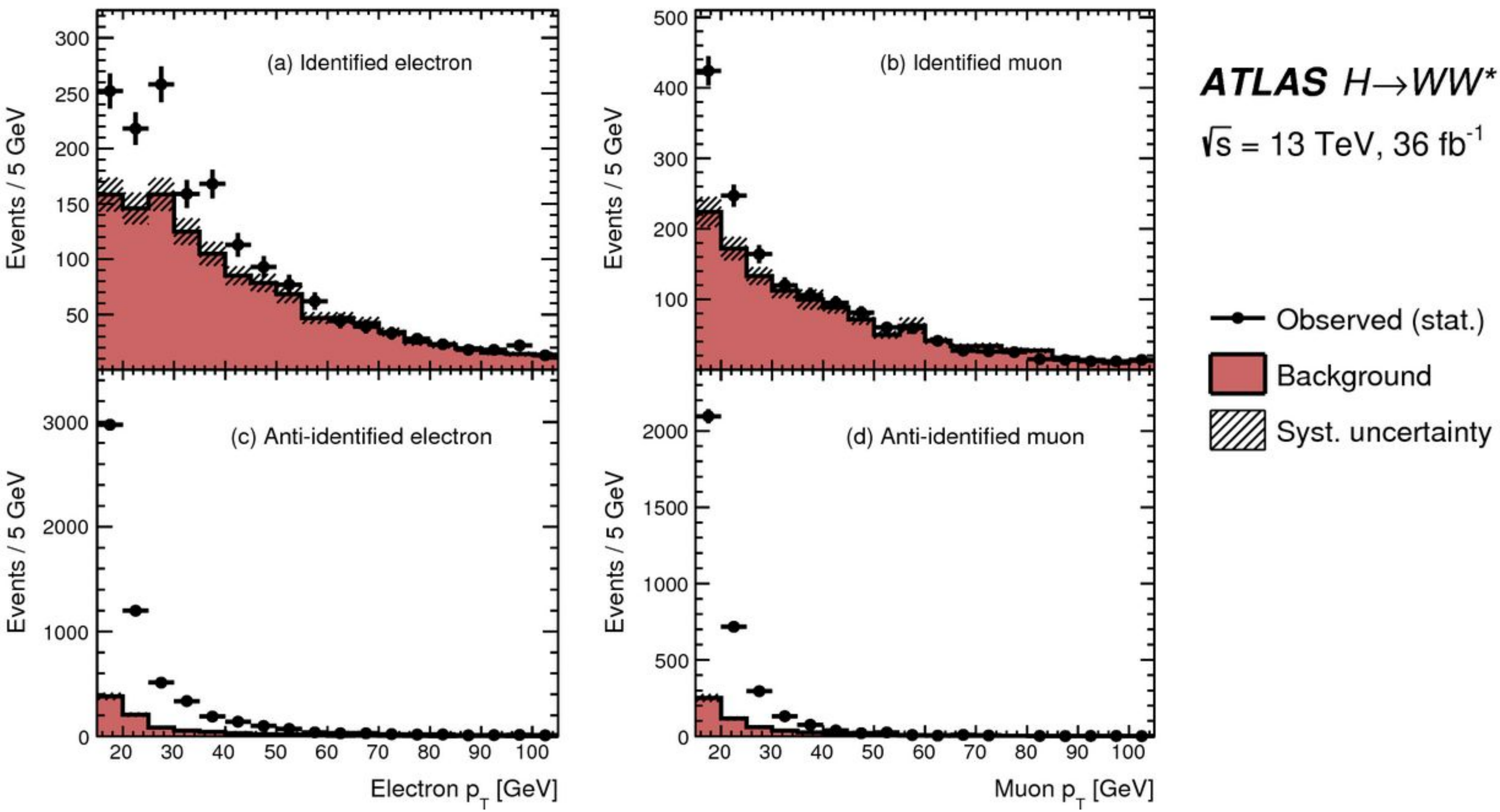
Event selection criteria used to define the control regions. Every control region selection starts from the selection labelled "Preselection" in Table 2. $N_{b\text{-jet},(20\ \text{GeV}<p_{\mathrm{T}}<30\ \text{GeV})}$ represents the number of b-jets with 20 GeV $< p_{\mathrm{T}} <$ 30 GeV.

<table>
<tr><th>CR</th><th>$N_{\text{jet},(p_{\mathrm{T}}>30\ \text{GeV})} = 0$ ggF</th><th>$N_{\text{jet},(p_{\mathrm{T}}>30\ \text{GeV})} = 1$ ggF</th><th>$N_{\text{jet},(p_{\mathrm{T}}>30\ \text{GeV})} \geq 2$ VBF</th></tr>
<tr><td rowspan="3">WW</td><td>$55 < m_{\ell\ell} < 110$ GeV
$\Delta\phi_{\ell\ell} < 2.6$</td><td>$m_{\ell\ell} > 80$ GeV
$|m_{\tau\tau} - m_Z| > 25$ GeV</td><td rowspan="3"></td></tr>
<tr><td colspan="2">$N_{b\text{-jet},(p_{\mathrm{T}}>20\ \text{GeV})} = 0$</td></tr>
<tr><td></td><td>$\max\left(m_{\mathrm{T}}^{\ell}\right) > 50$ GeV</td></tr>
<tr><td rowspan="4">$t\bar{t}/Wt$</td><td>$N_{b\text{-jet},(20\ \text{GeV}<p_{\mathrm{T}}<30\ \text{GeV})} > 0$</td><td>$N_{b\text{-jet},(p_{\mathrm{T}}>30\ \text{GeV})} = 1$
$N_{b\text{-jet},(20\ \text{GeV}<p_{\mathrm{T}}<30\ \text{GeV})} = 0$</td><td>$N_{b\text{-jet},(p_{\mathrm{T}}>20\ \text{GeV})} = 1$</td></tr>
<tr><td>$\Delta\phi(\ell\ell, E_{\mathrm{T}}^{\text{miss}}) > \pi/2$</td><td>$\max\left(m_{\mathrm{T}}^{\ell}\right) > 50$ GeV</td><td>central jet veto</td></tr>
<tr><td>$p_{\mathrm{T}}^{\ell\ell} > 30$ GeV</td><td colspan="2">$m_{\tau\tau} < m_Z - 25$ GeV</td></tr>
<tr><td>$\Delta\phi_{\ell\ell} < 2.8$</td><td></td><td>outside lepton veto</td></tr>
<tr><td rowspan="3">Z/γ^*</td><td colspan="3">$N_{b\text{-jet},(p_{\mathrm{T}}>20\ \text{GeV})} = 0$
$m_{\ell\ell} < 80$ GeV</td></tr>
<tr><td colspan="2">no $p_{\mathrm{T}}^{\text{miss}}$ requirement</td><td>central jet veto</td></tr>
<tr><td>$\Delta\phi_{\ell\ell} > 2.8$</td><td>$\max\left(m_{\mathrm{T}}^{\ell}\right) > 50$ GeV
$m_{\tau\tau} > m_Z - 25$ GeV</td><td>outside lepton veto
$|m_{\tau\tau} - m_Z| \leq 25$ GeV</td></tr>
</table>

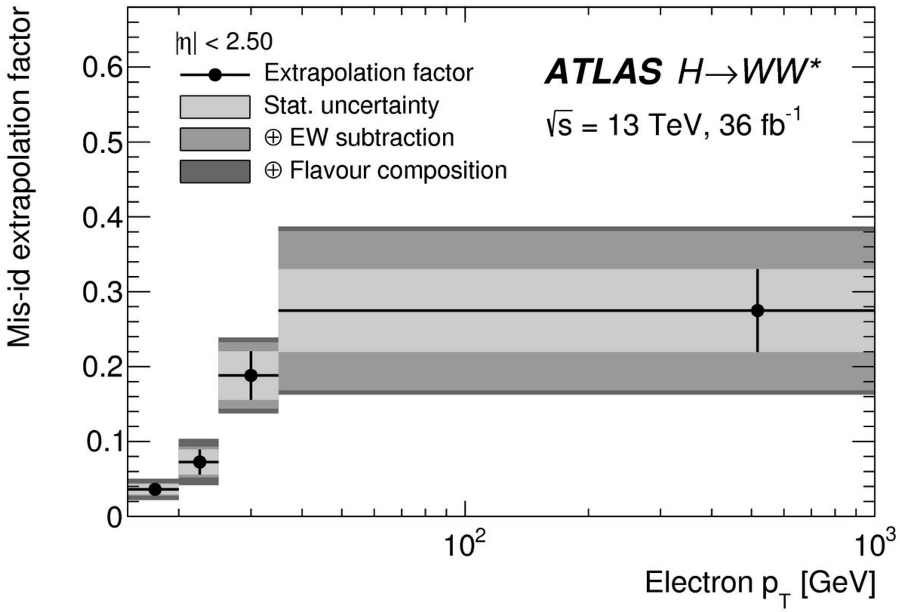
VBF uncertainties



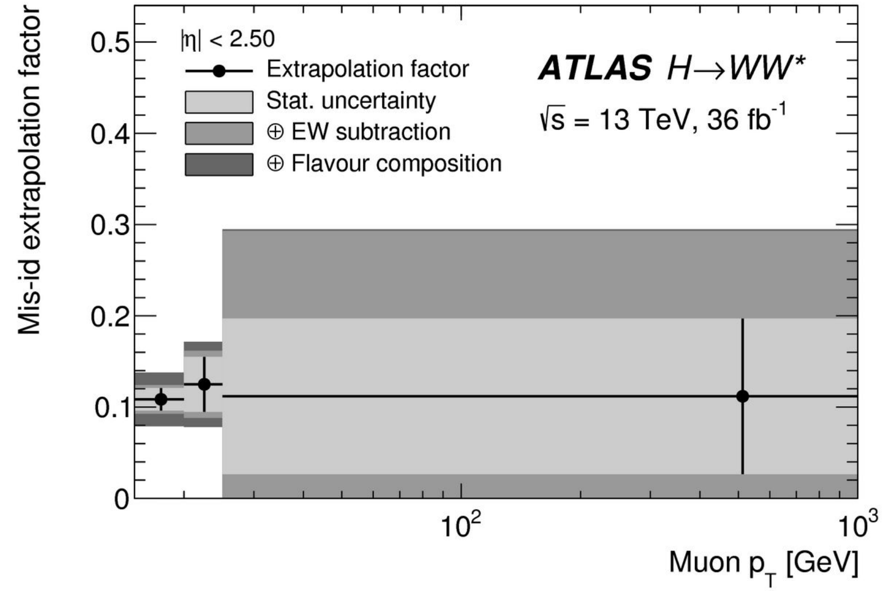
Z+jet control region



Fake Factor



|η| < 2.50
Extrapolation factor
Stat. uncertainty
⊕ EW subtraction
⊕ Flavour composition
ATLAS H→WW*
√s = 13 TeV, 36 fb-1
Mis-id extrapolation factor
Electron pT [GeV]



|η| < 2.50
Extrapolation factor
Stat. uncertainty
⊕ EW subtraction
⊕ Flavour composition
ATLAS H→WW*
√s = 13 TeV, 36 fb-1
Mis-id extrapolation factor
Muon pT [GeV]

Double fakes and trigger by fake

- Double fake
  - Events with double fake is counted twice in fake estimation eq in slide 8
  - Subtract the double count
    - N_{QCD}(anti-ID anti-ID) * fe * fμ

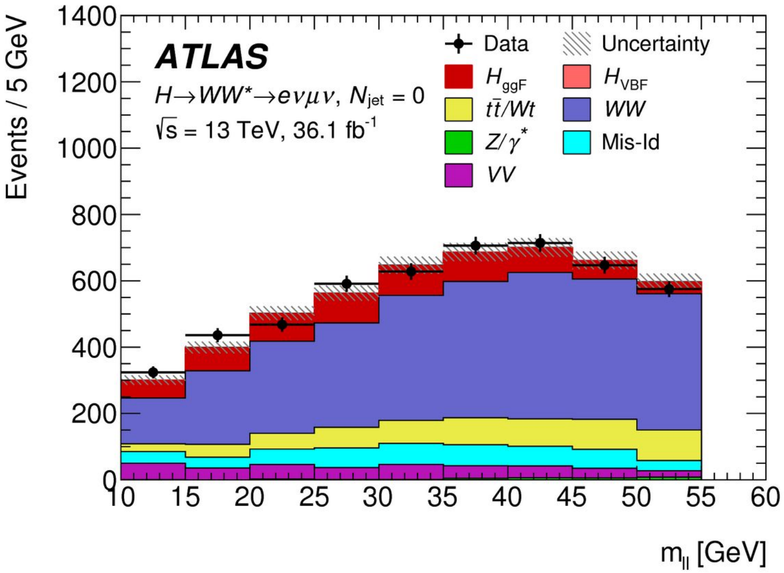
$$
\begin{aligned}
N_{id,id}^{QCD\ corr} &= N_{e,\mu}^{QCD} \cdot f^{QCD} \\
&= (N_{e,\mu}^{data} - N_{e,\mu}^{EW\ MC}) \cdot (-f_{\mu}^{Z} f_{e}^{Z}) \\
&= N_{e,\mu}^{QCD} \cdot (-f_{\mu}^{Z} f_{e}^{Z})
\end{aligned}
$$

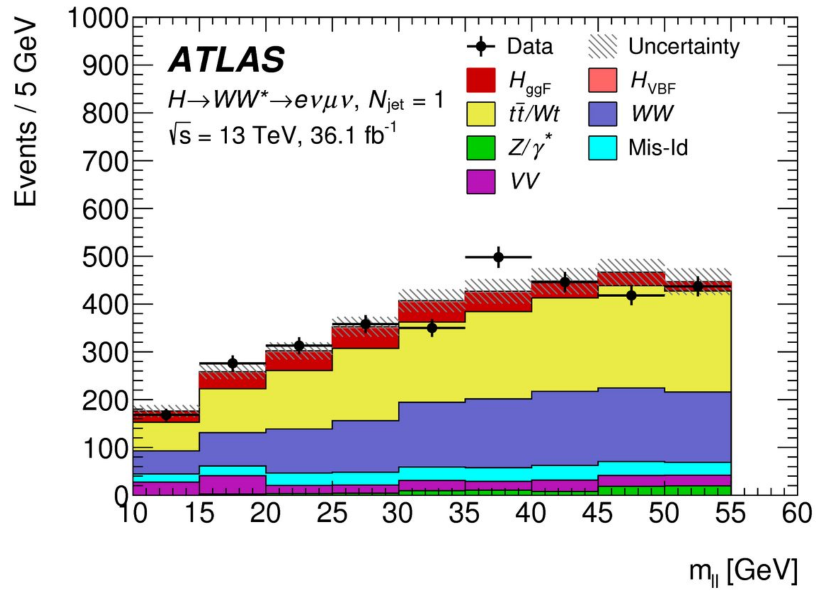
  - More double fake in (eμ) event and higher jet multiplicity bin
    - Small effect on ggF analysis
    - Effect of double fakes ~ 25% for VBF eμ categories
- Trigger by fake (trigger selection tighter than anti-ID lepton)
  - Measured in Dijet enrich sample (signal lepton + jet), requiring trigger selection in the fake factor measurement.
  - More in event with leading leptons are fake
  - More in muon trigger by fakes for each categories ~15%
  - Leading Electron trigger by fakes are ~5%

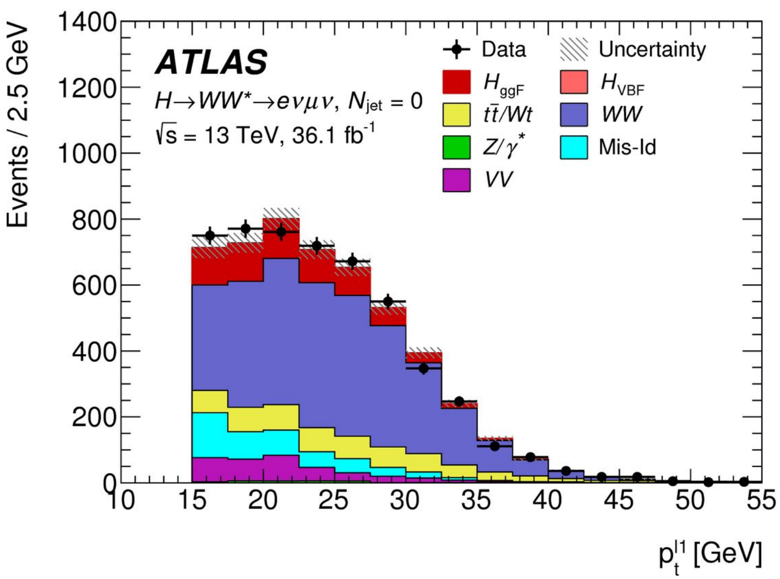
GGF Post-fit

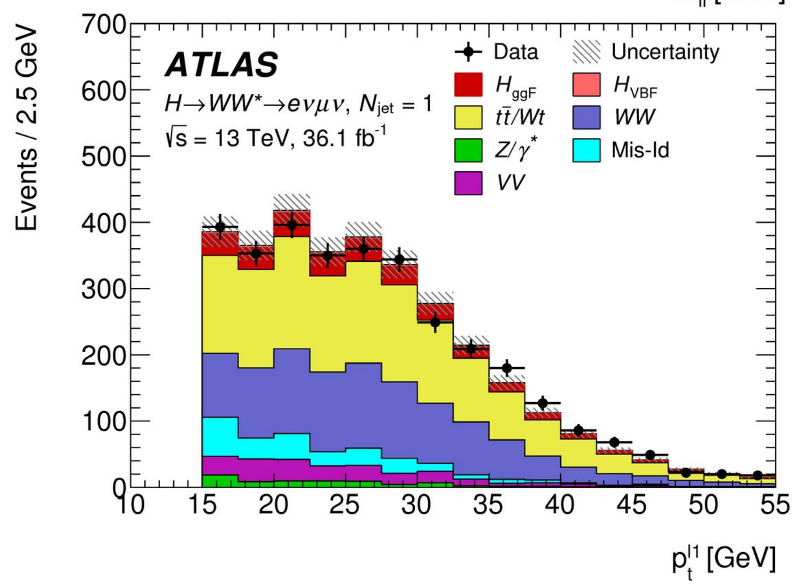
ggF 0 jet

ggF 1 jet

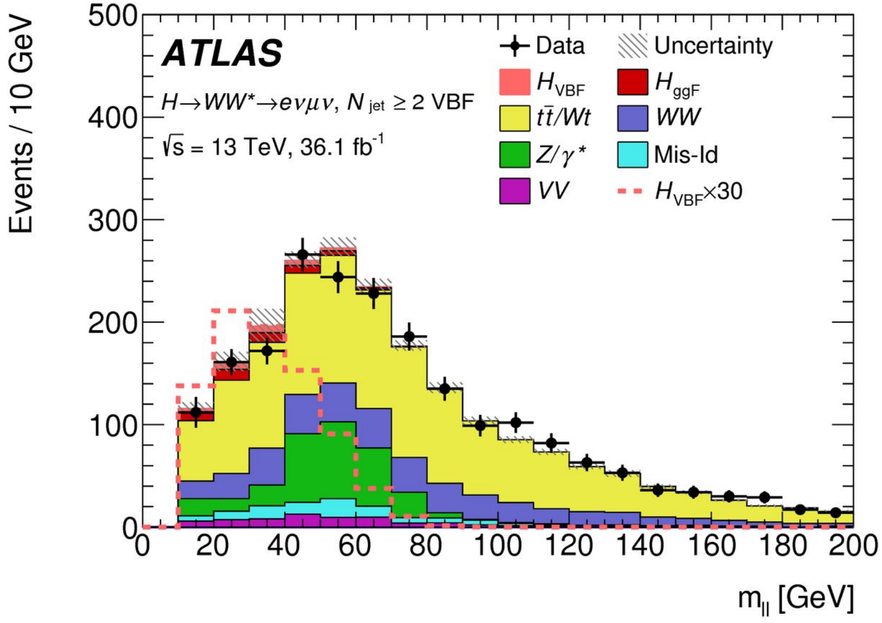




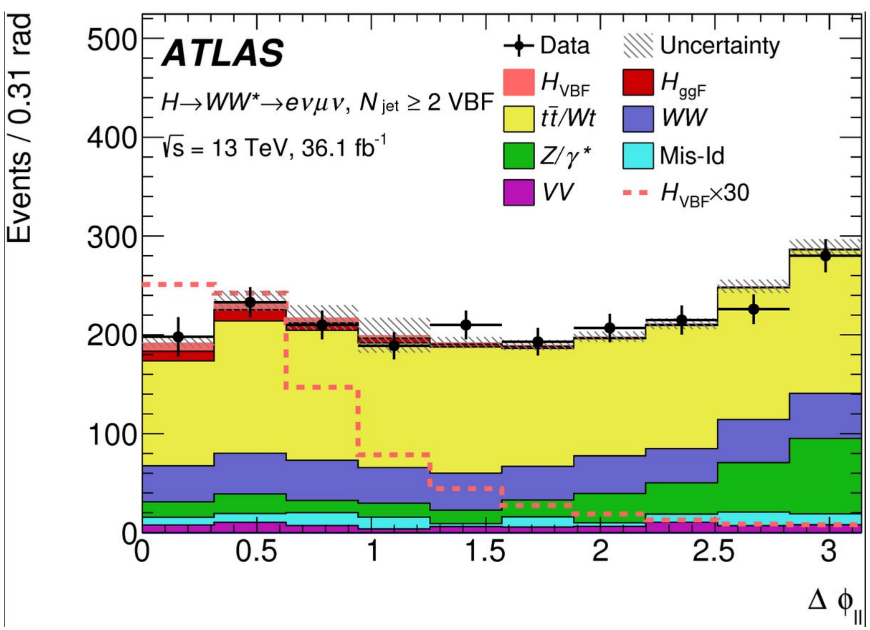




VBF post-fit



ATLAS
$H\rightarrow WW^*\rightarrow e\nu\mu\nu$, $N_{jet} \geq 2$ VBF
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
Data
Uncertainty
H_{VBF}
H_{ggF}
$t\bar{t}/Wt$
WW
Z/γ^*
Mis-Id
VV
$H_{VBF}\times 30$
Events / 10 GeV
m_{ll} [GeV]



ATLAS
$H\rightarrow WW^*\rightarrow e\nu\mu\nu$, $N_{jet} \geq 2$ VBF
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
Data
Uncertainty
H_{VBF}
H_{ggF}
$t\bar{t}/Wt$
WW
Z/γ^*
Mis-Id
VV
$H_{VBF}\times 30$
Events / 0.31 rad
$\Delta\phi_{ll}$