Latest results on the SM Higgs boson in the WW decay channel using the ATLAS detector

arXiv:1808.09054, accepted by PRB

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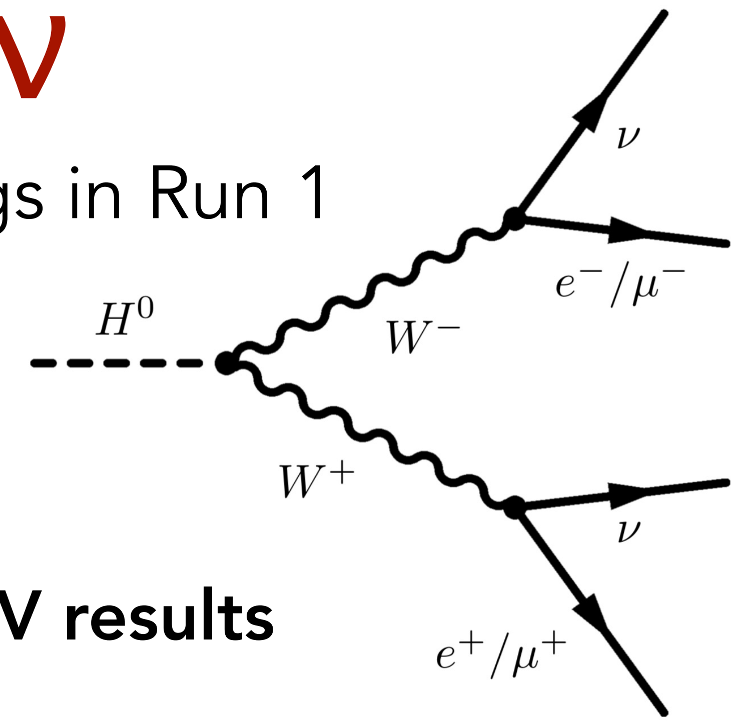
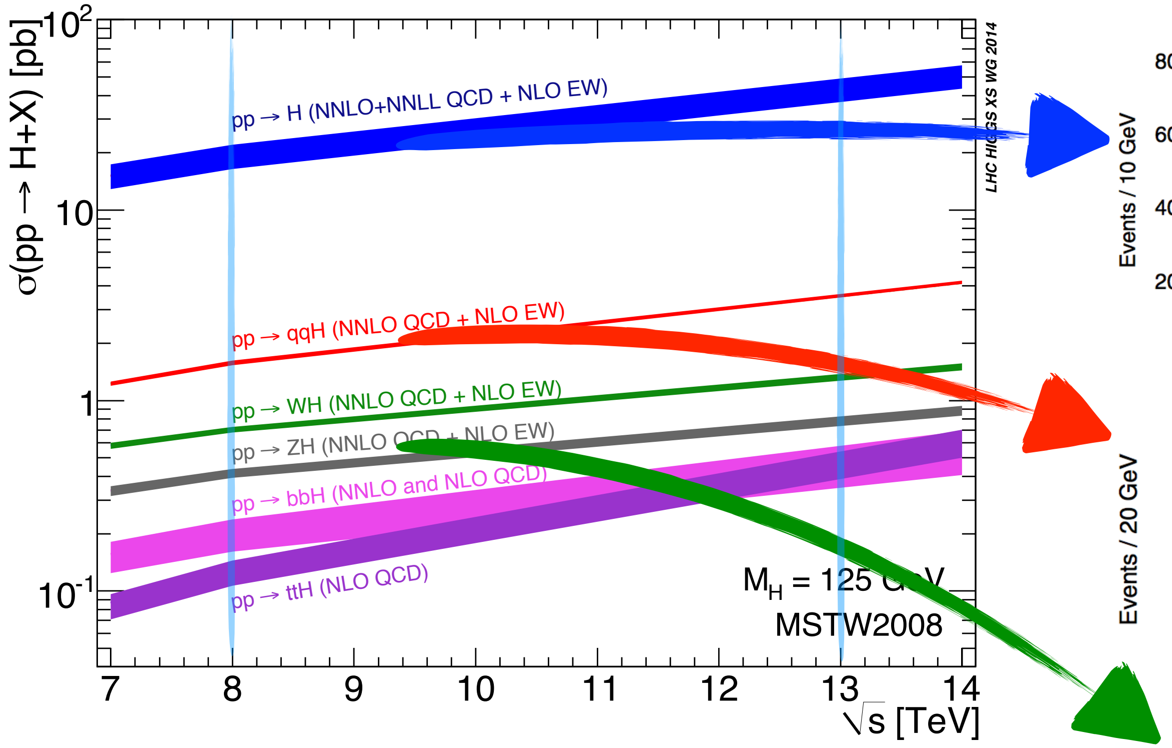
H→WW*→lνlν

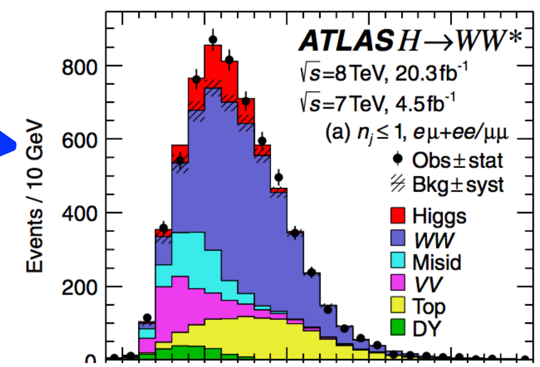
The most precise measurement of the Higgs couplings in Run 1

- WW* channel well-suited for exploring rare production modes
  - Second largest branching ratio: 22%
    - Only H→WW*→lνlν (l=e,μ, →lνν ~2%) analysed: 0.4%
  - **Good S/B** from clean di-lepton signature



8 TeV results

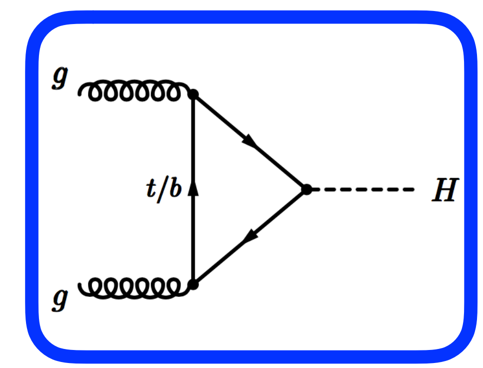


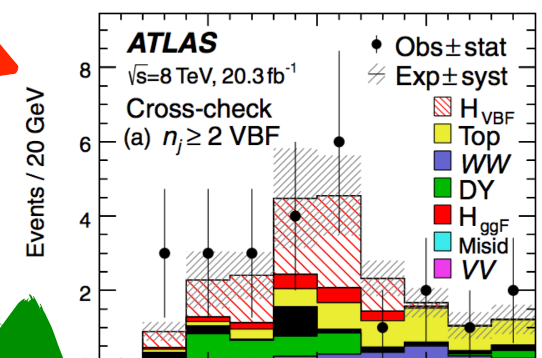


PhysRevD.92.012006

Confirmed: **5.8 σ**

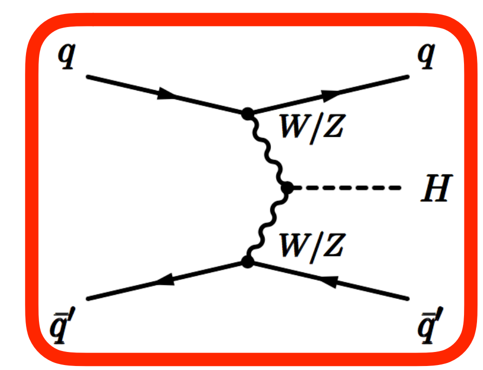
σ_{ggF}=4.6±1.2 pb

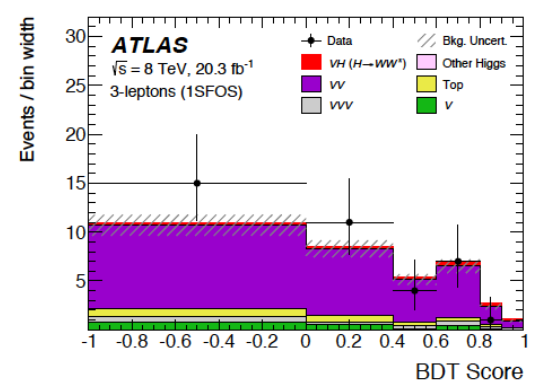




Evidence: **3.2 σ**

σ_{VBF}=0.51±0.20 pb

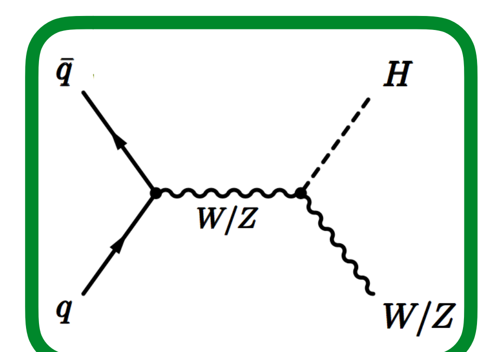


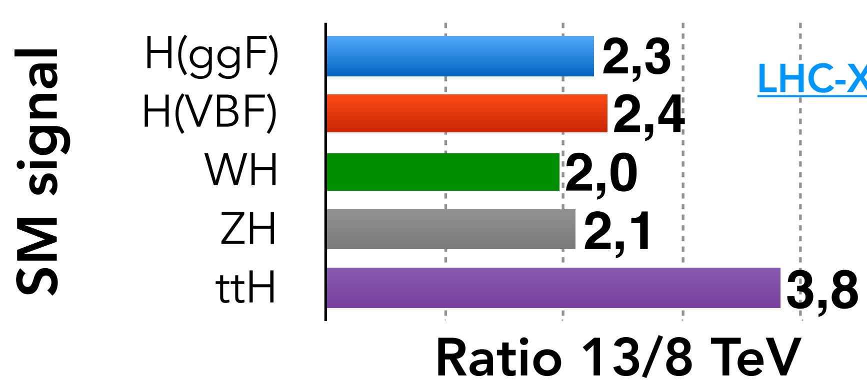


JHEP08(2015)137

Search: **2.5 σ**

μ_{VH}=3

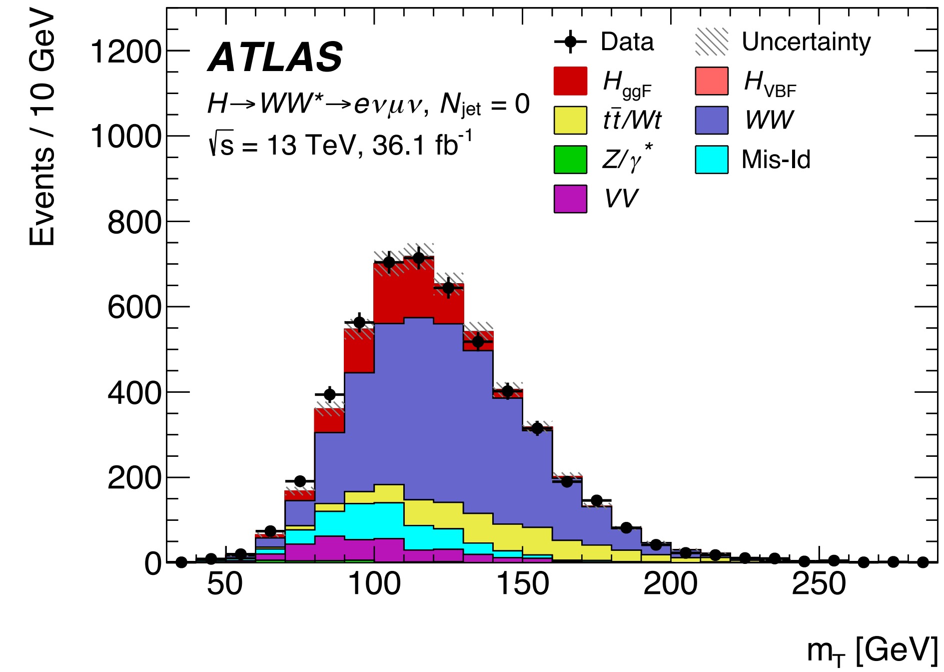




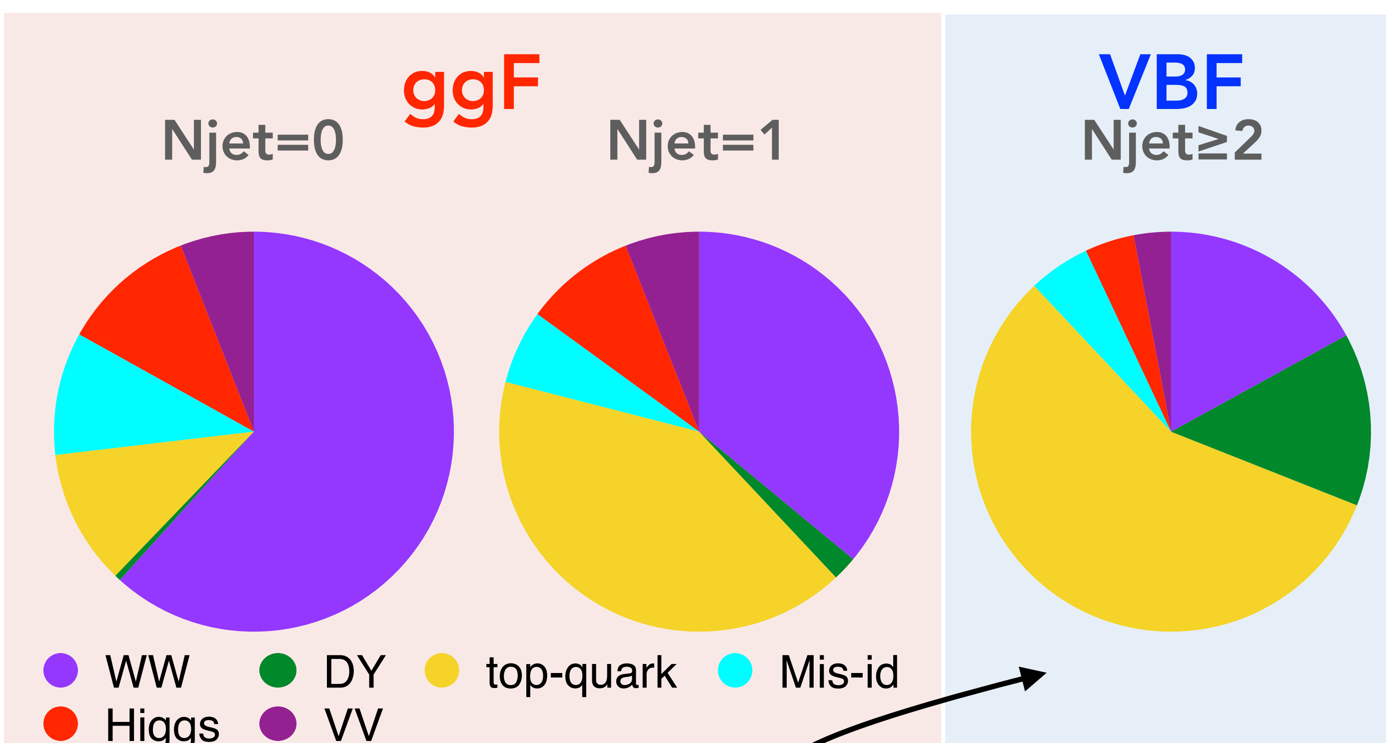
LHC-XS-WG

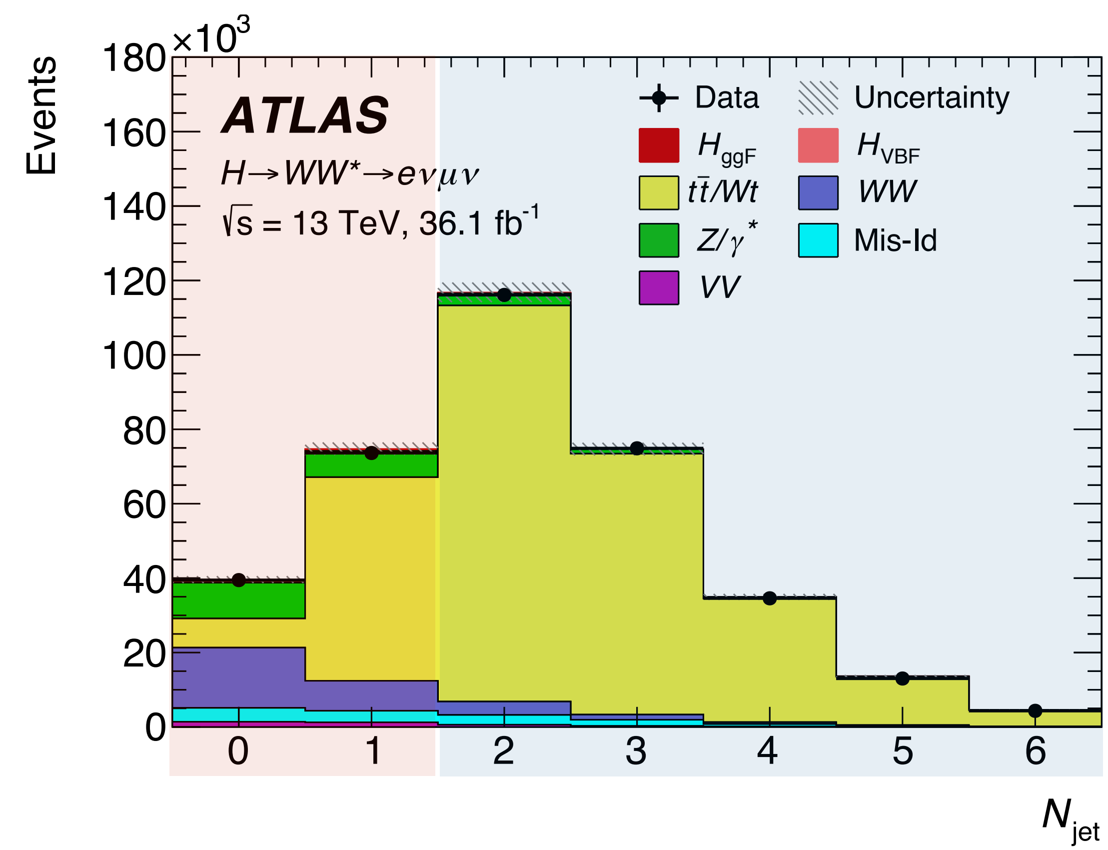
ggF/VBF Higgs Boson

- **Spin zero Higgs**: charged leptons preferentially emitted in same direction
  - m_{ll} and $\Delta\phi_{ll}$ are used in the event selection or in the BDT training
- Signal process can not be fully reconstructed → presence of neutrinos
- **VBF → two jets with large rapidity gap**
  - Suppressed hadronic activity in central region
- **Jets bin categorisation**



$$m_T = \sqrt{(E_T^{\ell\ell} + p_T^{\nu\nu})^2 - |\boldsymbol{p}_T^{\ell\ell} + \boldsymbol{p}_T^{\nu\nu}|^2}$$





NB: Significance further enhanced with a multivariate technique

Backgrounds

Main backgrounds:

- **WW**: estimated with MC simulation, normalisation shape with data for ggF
- **Top** and **Z→ττ**: shape from MC simulation, normalisation estimated with data
- **Mis-Id**: data-driven from events with one lepton satisfying only loose but failing tight ID criteria; fake rate measured in a Z-jet sample

CR	$N_{\text{jet},(p_T>30\ \text{GeV})} = 0$ ggF	$N_{\text{jet},(p_T>30\ \text{GeV})} = 1$ ggF	$N_{\text{jet},(p_T>30\ \text{GeV})} \geq 2$ VBF
WW	$55 < m_{\ell\ell} < 110\ GeV$ $\Delta\phi_{\ell\ell} < 2.6$ $N_{b\text{-jet},(p_T>20\ \text{GeV})} = 0$	$m_{\ell\ell} > 80\ GeV$ $\lvert m_{\tau\tau} - m_Z\rvert > 25\ GeV$ $\max\left(m_T^{\ell}\right) > 50\ GeV$	
$t\bar{t}/Wt$	$N_{b\text{-jet},(20\ \text{GeV}<p_T<30\ \text{GeV})} > 0$ $\Delta\phi(\ell\ell, E_T^{\text{miss}}) > \pi/2$ $p_T^{\ell\ell} > 30\ GeV$ $\Delta\phi_{\ell\ell} < 2.8$	$N_{b\text{-jet},(p_T>30\ \text{GeV})} = 1$ $N_{b\text{-jet},(20\ \text{GeV}<p_T<30\ \text{GeV})} = 0$ $\max\left(m_T^{\ell}\right) > 50\ GeV$ $m_{\tau\tau} < m_Z - 25\ GeV$	$N_{b\text{-jet},(p_T>20\ \text{GeV})} = 1$ central jet veto outside lepton veto
Z/γ^*	$N_{b\text{-jet},(p_T>20\ \text{GeV})} = 0$ $m_{\ell\ell} < 80\ GeV$ no p_T^{miss} requirement $\Delta\phi_{\ell\ell} > 2.8$	$\max\left(m_T^{\ell}\right) > 50\ GeV$ $m_{\tau\tau} > m_Z - 25\ GeV$	central jet veto outside lepton veto $\lvert m_{\tau\tau} - m_Z\rvert \leq 25\ GeV$

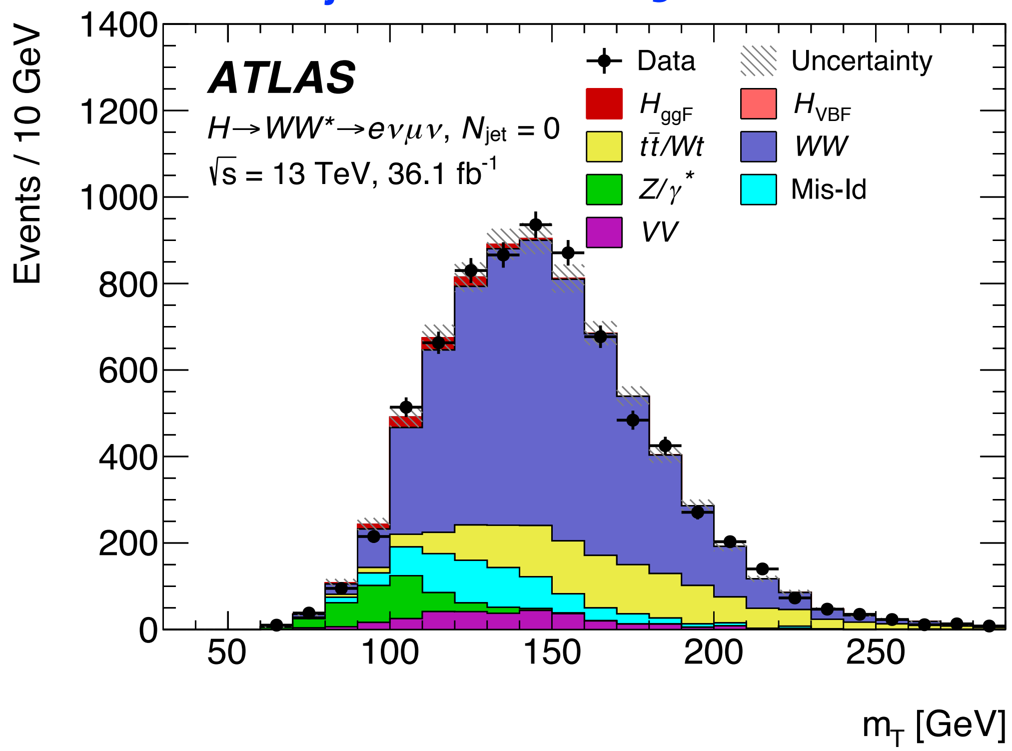
WW background estimation $N_{jet} \leq 1$

- Higgs signal at low m_{ll}
- WW control region at high m_{ll}
- Normalize WW to data in CR

Category	WW
$N_{\text{jet},(p_T>30\ \text{GeV})} = 0$ ggF	1.06 ± 0.09
$N_{\text{jet},(p_T>30\ \text{GeV})} = 1$ ggF	0.97 ± 0.17
$N_{\text{jet},(p_T>30\ \text{GeV})} \geq 2$ VBF	–

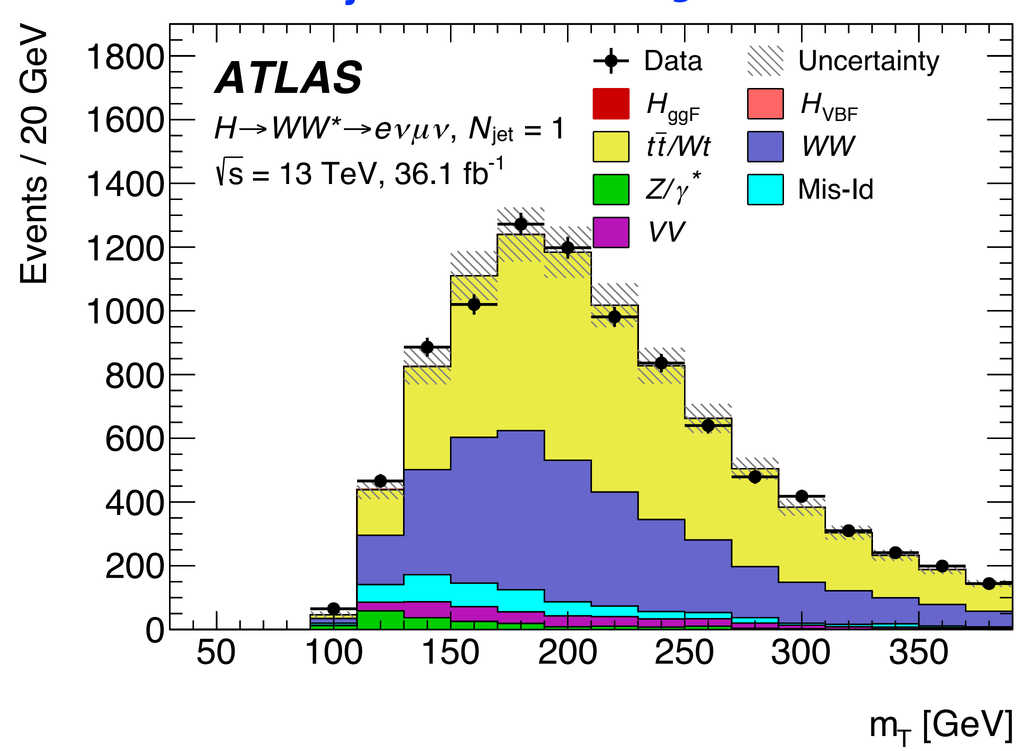
- Main uncertainties:
  - gg → WW in the Signal region
  - QCD and matching scales contribute up to 5%(12%) to $\sigma_{ggF}(\sigma_{VBF})$

N_{jet}=0, Purity: 66%



55 GeV< m_{ll} <110 GeV

N_{jet}=1, Purity: 37%



m_{ll} >80 GeV

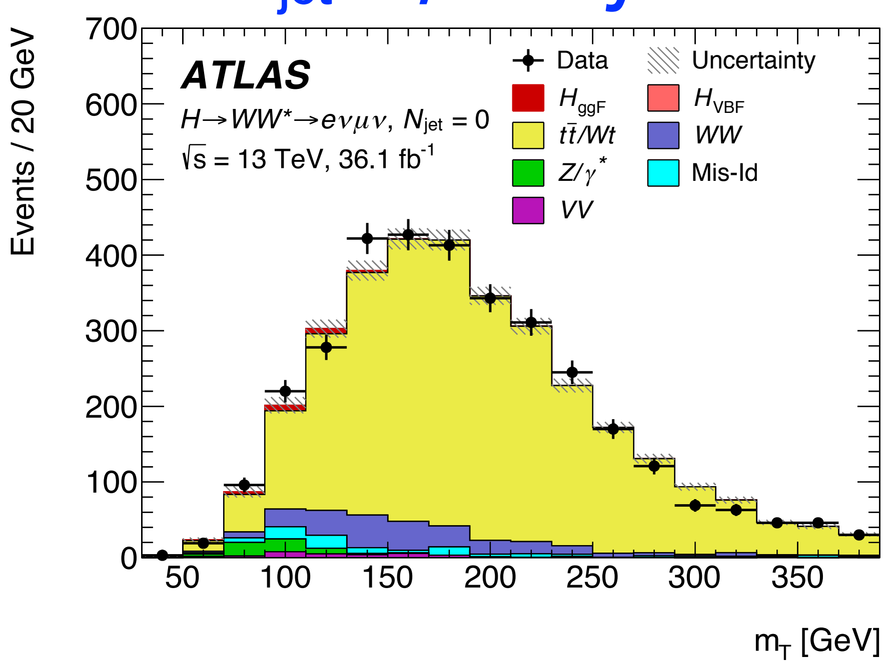
Top-quark background estimation

- Events with 1 b-jet are used as control regions
  - b-jet veto to suppress WW in $N_{jet}=1$
  - Top-quark background normalisation constrained with the control region

- Main uncertainties:
  - b-tagging, 5-6% on $\sigma_{ggF/VBF}$
  - Top modelling, 5% on $\sigma_{ggF/VBF}$

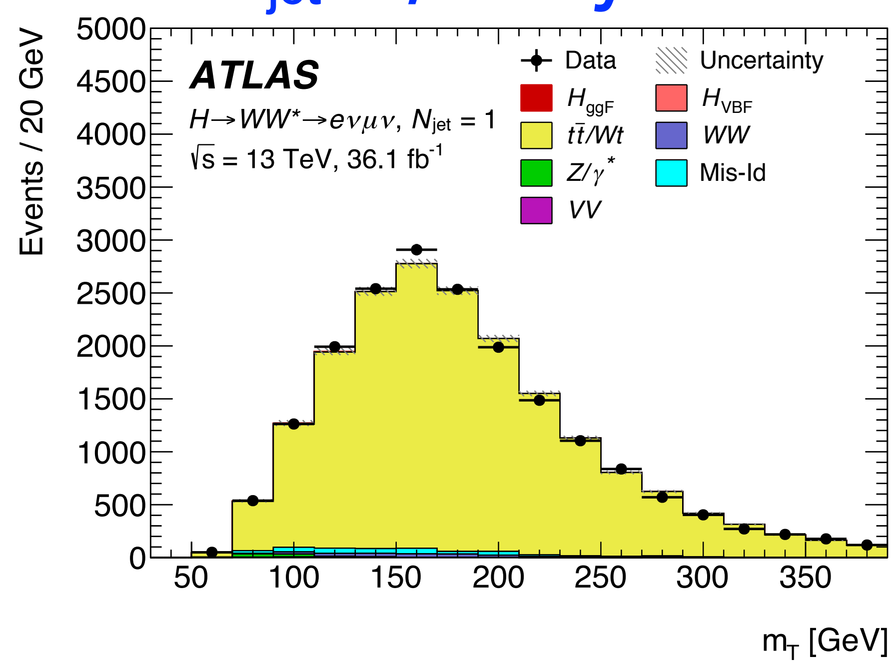
Category	$t\bar{t}/Wt$
$N_{\text{jet},(p_T>30\ \text{GeV})} = 0$ ggF	0.99 ± 0.17
$N_{\text{jet},(p_T>30\ \text{GeV})} = 1$ ggF	0.98 ± 0.08
$N_{\text{jet},(p_T>30\ \text{GeV})} \geq 2$ VBF	1.01 ± 0.01

$N_{jet}=0$, Purity: 87%



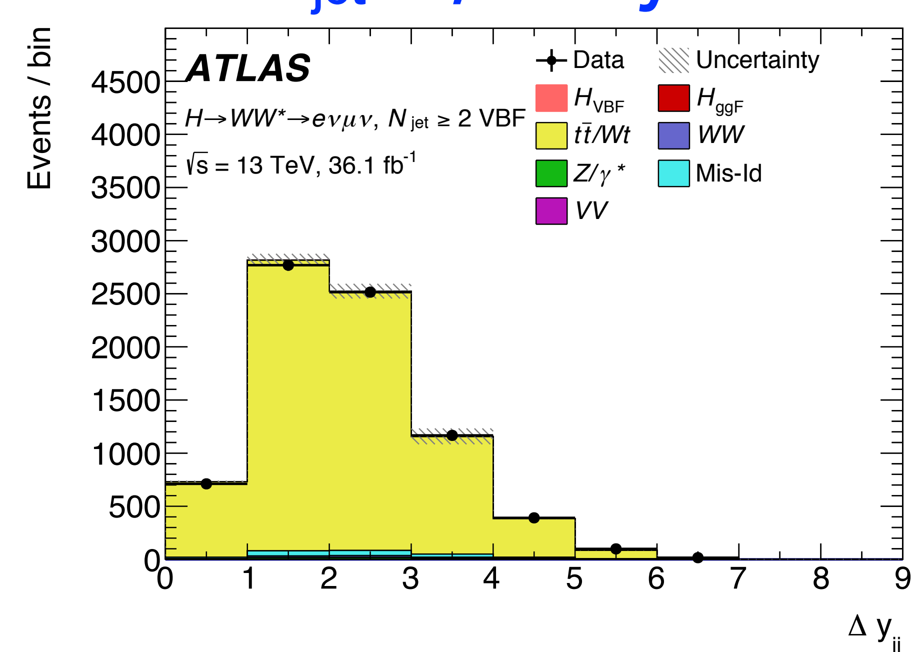
b-jet with 20 GeV<pT<30 GeV

$N_{jet}=1$, Purity: 97%



b-jet with pT>30 GeV

$N_{jet}\geq2$, Purity: 96%

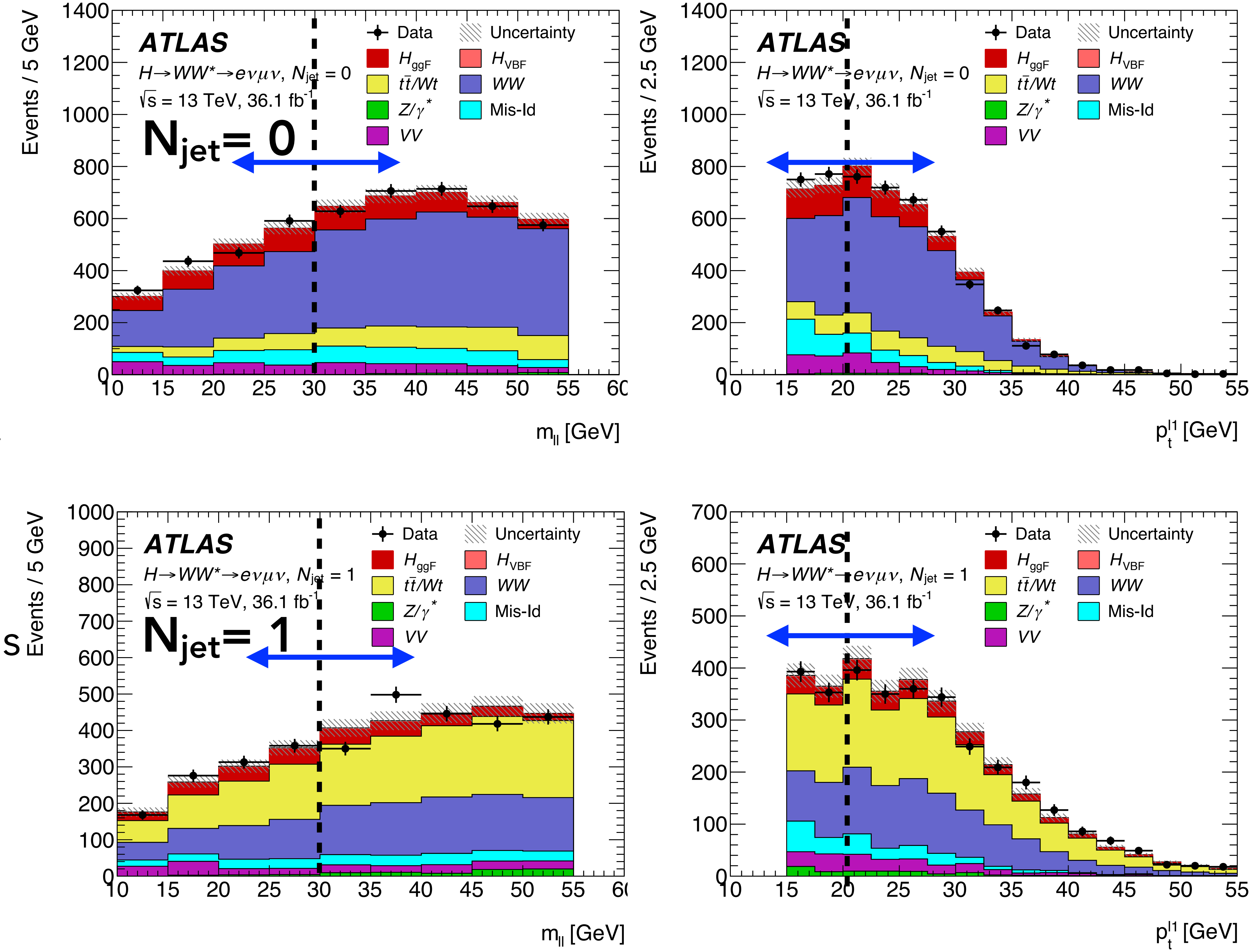


b-jet with pT>20 GeV

Categorisation of the ggF signal region

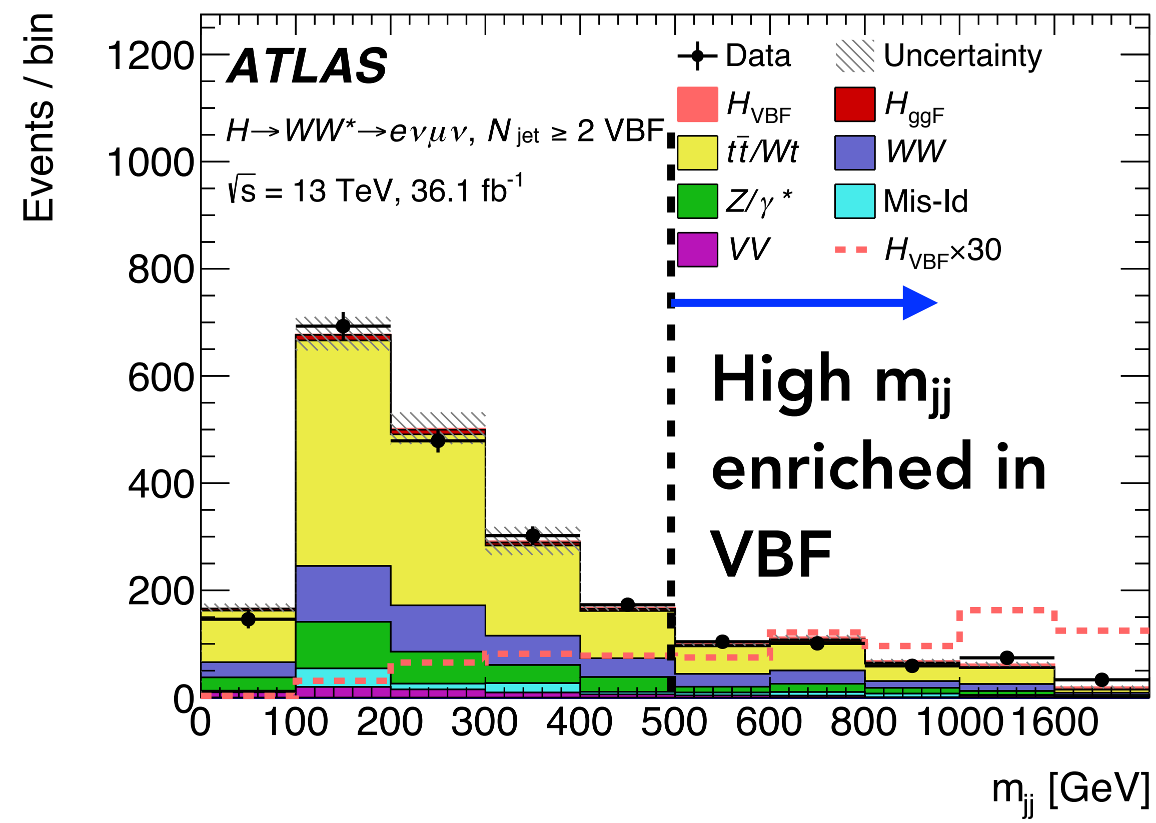
Split SR in m_{ll}, $p_T^{\text{sub-lead lep}}$, and flavour channels eμ/μe

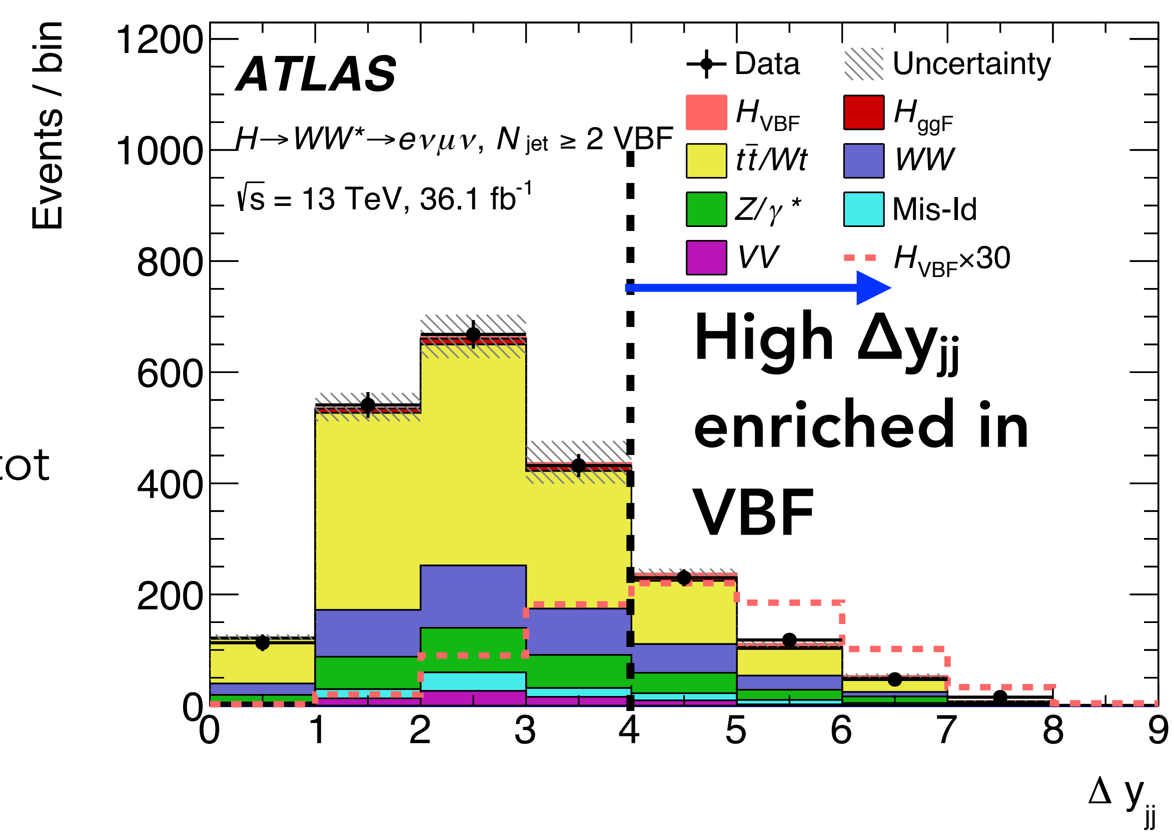
- Improves control of different backgrounds
  - Different background composition in each category
  - Enhances sensitivity
  - Splits defined for both N_{jet}= 0 and N_{jet}= 1 signal regions
- m_T distribution per category
  - 8 bins (6 bins) for N_{jet} =0 (Njet=1)



VBF identification

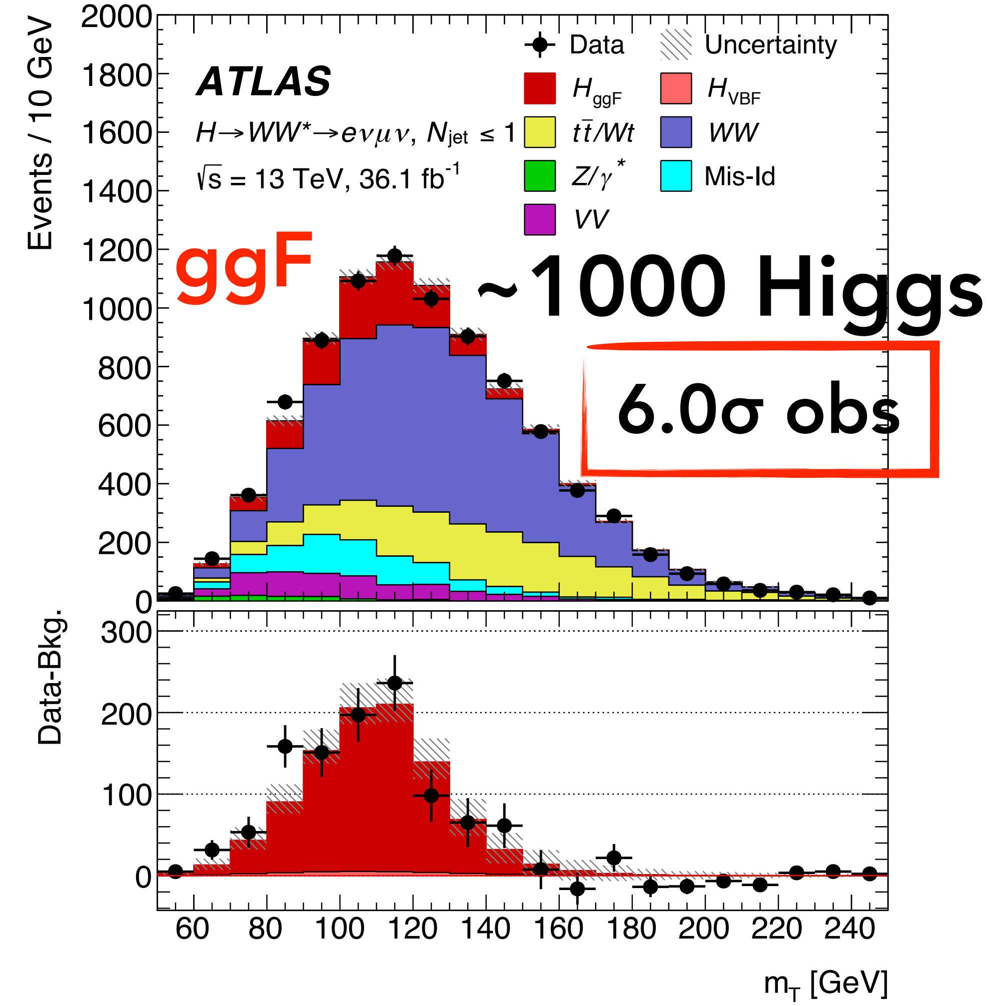
- Selection of VBF Higgs boson candidate
  - Veto presence of extra jets between the two leading jets
  - Central Higgs boson decay
  - Veto Z mass window
- Properties of **H→WW*→eνμν decay** and **VBF topology** are used in a boosted decision tree
  - H→WW*→eνμν: m_{ll}, $\Delta\phi_{ll}$, m_T
  - VBF topology: m_{jj}, Δy_{jj}, $\eta_{centrality}$, $\sum M_{lj}$, p_T^{tot}
- Highest ranked variables: $\mathbf{m_{jj}}$ and $\mathbf{\Delta y_{jj}}$,



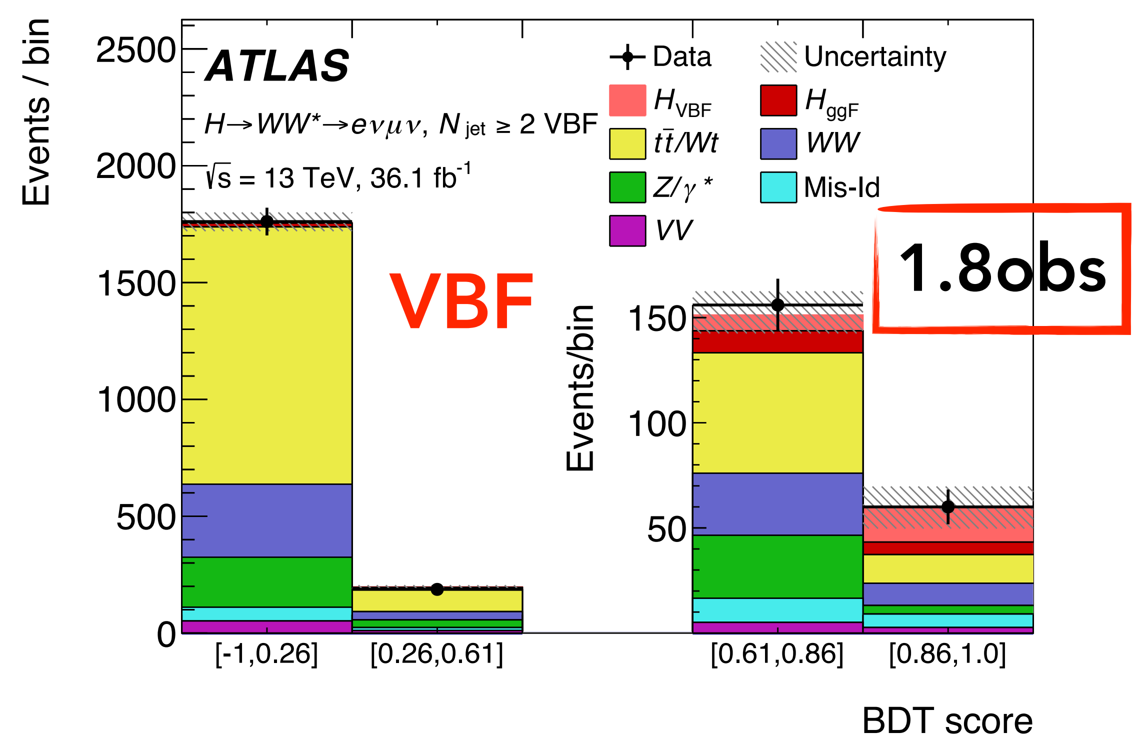


Combined ggF and VBF fit

- Signal regions
  - m_T in **16 ggF SR** categories
  - **BDT with 4 bins** in VBF SR
- Control regions
  - Yield in WW , top-quark and $Z\rightarrow\tau\tau$ CRs for $N_{jet}\leq 1$
  - Yield in $Z\rightarrow\tau\tau$ CR for VBF $N_{jet}\geq 2$
  - BDT in top-quark CR

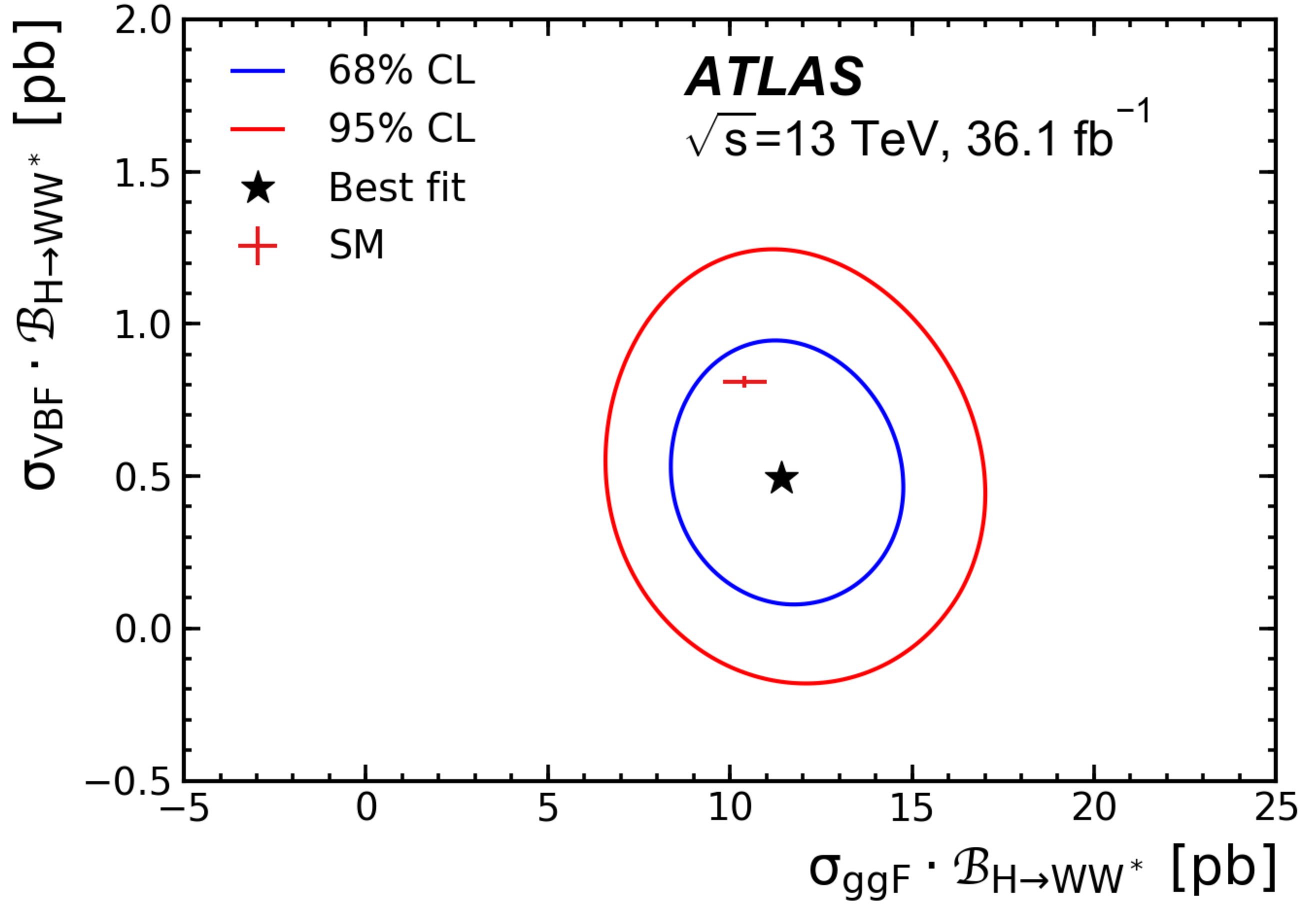


Process	$N_{\rm jet}=0$ ggF	$N_{\rm jet}=1$ ggF	$N_{\rm jet}\geq 2$ VBF Inclusive	$N_{\rm jet}\geq 2$ VBF BDT: [0.86, 1.0]
$H_{\rm ggF}$	639 ± 110	285 ± 51	42 ± 16	6 ± 3
$H_{\rm VBF}$	7 ± 1	31 ± 2	28 ± 16	16 ± 6
WW	3016 ± 203	1053 ± 206	400 ± 60	11 ± 2
VV	333 ± 38	208 ± 32	70 ± 12	3 ± 1
$t\bar{t}/Wt$	588 ± 130	1397 ± 179	1270 ± 80	14 ± 2
Mis-Id	447 ± 77	234 ± 49	90 ± 30	6 ± 2
Z/γ^*	27 ± 11	76 ± 24	280 ± 40	4 ± 1
Total	5067 ± 80	3296 ± 61	2170 ± 50	60 ± 10
Observed	5089	3264	2164	60



$H \to WW^* \to e\nu\mu\nu$ @ 13TeV

- All results extracted by the **simultaneous fit** of all the ggF and VBF SRs and CRs
- One parameter of interest per production mode
- Cross-sections times branching fraction and signal strength



1 σ compatible with SM

σ_{ggF}= 10.4±0.6 pb

σ_{VBF}=0.81±0.02 pb

$$\sigma_{ggF} \cdot \mathcal{B}_{H\to WW^*} = 11.4^{+1.2}_{-1.1}(\text{stat.})^{+1.2}_{-1.1}(\text{theo syst.})^{+1.4}_{-1.3}(\text{exp syst.})\text{ pb} = 11.4^{+2.2}_{-2.1}\text{ pb}$$

$$\sigma_{VBF} \cdot \mathcal{B}_{H\to WW^*} = 0.50^{+0.24}_{-0.22}(\text{stat.}) \pm 0.10(\text{theo syst.})^{+0.12}_{-0.13}(\text{exp syst.})\text{ pb} = 0.50^{+0.29}_{-0.28}\text{ pb}$$

$$\mu_{ggF} = 1.10^{+0.10}_{-0.09}(\text{stat.})^{+0.13}_{-0.11}(\text{theo syst.})^{+0.14}_{-0.13}(\text{exp syst.}) = 1.10^{+0.21}_{-0.20}$$

$$\mu_{VBF} = 0.62^{+0.29}_{-0.27}(\text{stat.})^{+0.12}_{-0.13}(\text{theo syst.}) \pm 0.15(\text{exp syst.}) = 0.62^{+0.36}_{-0.35}$$

Systematic Uncertainties

ggF cross-section systematic dominated (exp:12%, theo:10%)

VBF cross-section statistic dominated (46%)

Source	$\Delta\sigma_{\mathrm{ggF}} \cdot \mathcal{B}_{H\to WW^*}$ [%]	$\Delta\sigma_{\mathrm{VBF}} \cdot \mathcal{B}_{H\to WW^*}$ [%]
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

MC statistic has a large contribution

Main theo. unc.:
- Signal QCD scales
- gg→WW, WW PS
- top-quark modelling

Main theo. unc.:
- QCD scales on ggF in VBF phase space
- VBF MC modelling
- WW missing higher order

H→WW*→eνμν @ 13TeV

- Presented the **ggF and VBF cross-sections times branching ratio** in the H→WW*→eνμν using 36 fb^{-1}
- ggF measurement dominated by the systematic uncertainty
- VBF measurement will gain from including the 2017/18 data
- **A lot a room of improvements for the run 2 legacy paper**
- Challenge ahead
  - Data with very high pile-up
  - Reduce Mis-Id contamination and impact of its uncertainties
  - Control uncertainties on the SM WW
- H→WW*→eνμν plays an important role in the Higgs boson combination

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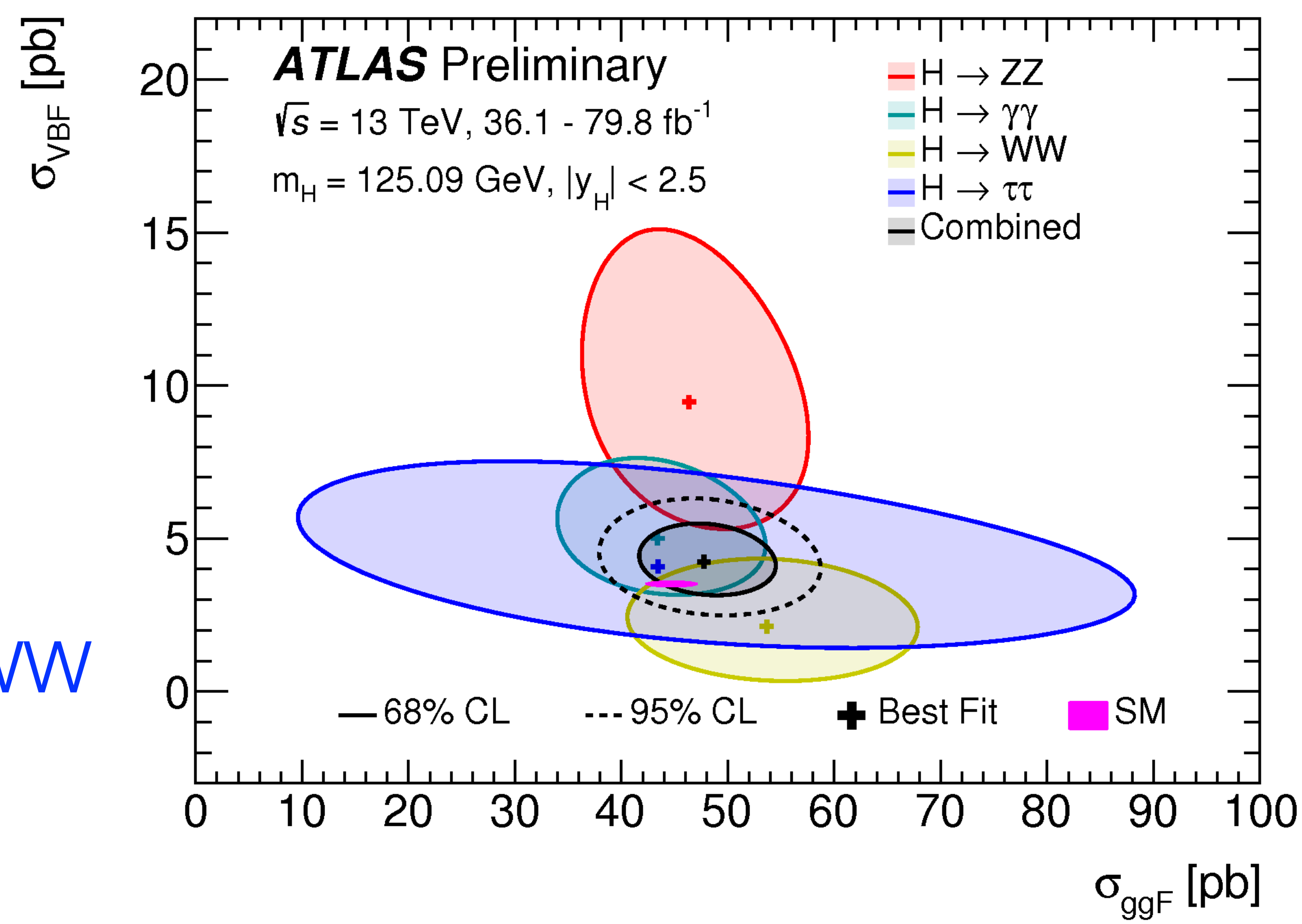
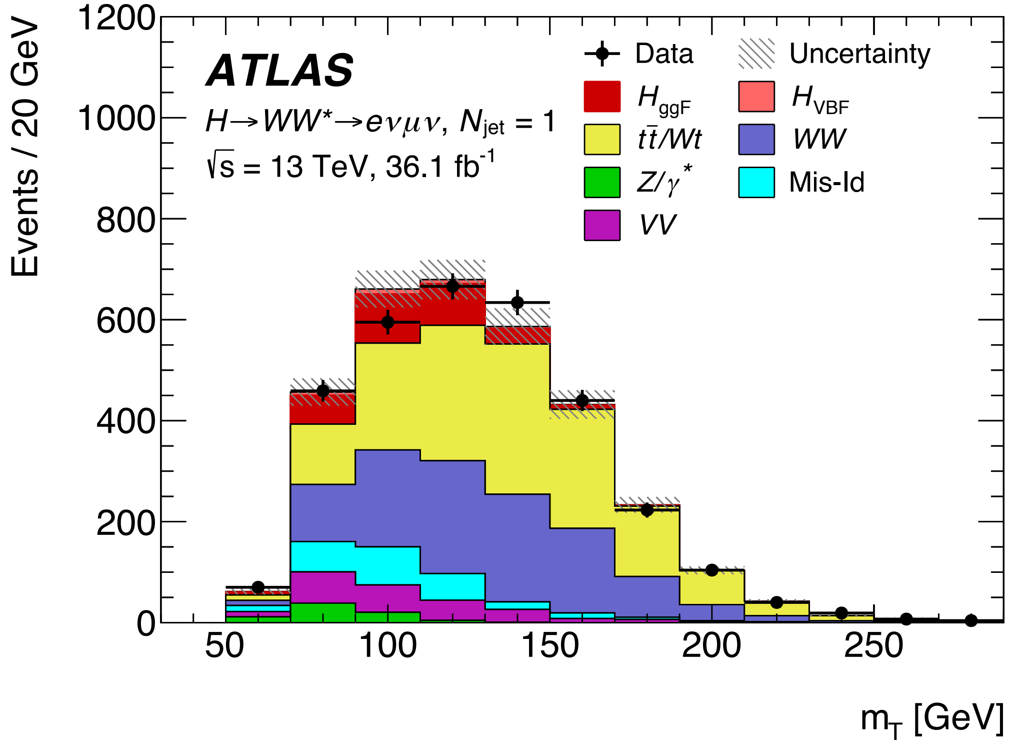
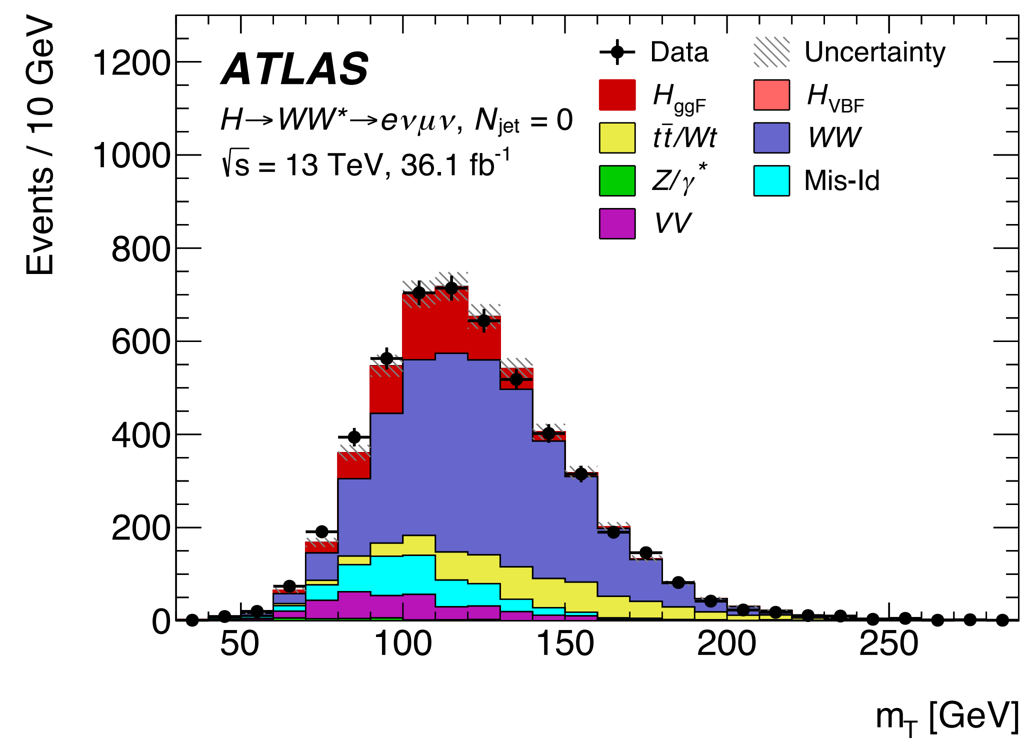


Back-up

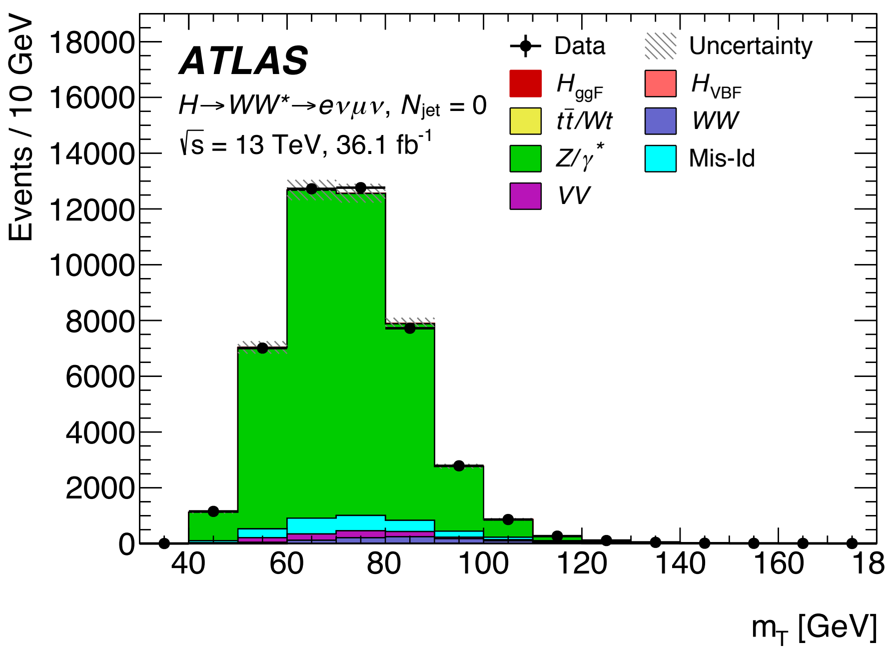
Discriminant variable in ggF SRs



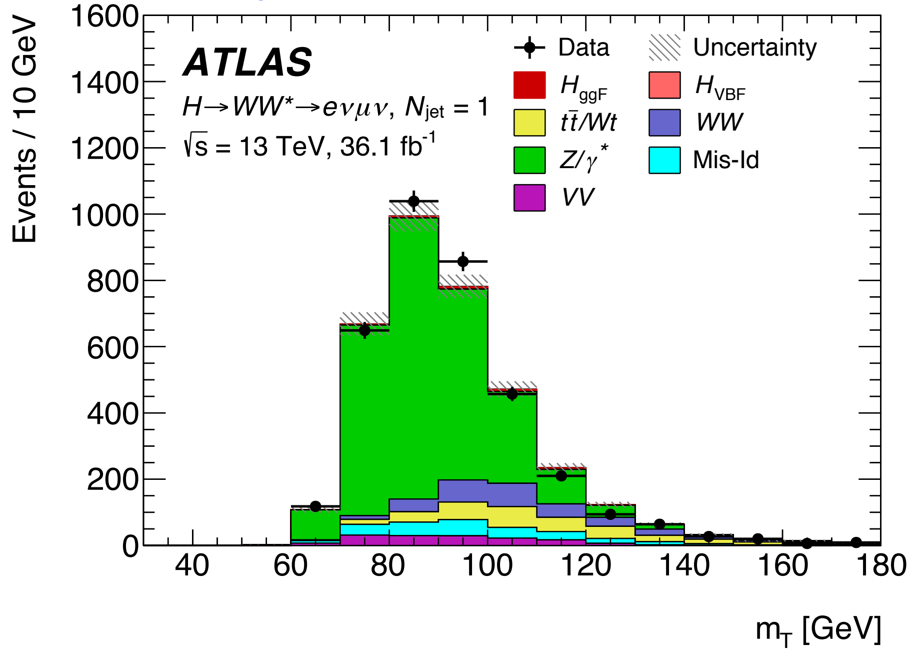


Z→ττ background estimation

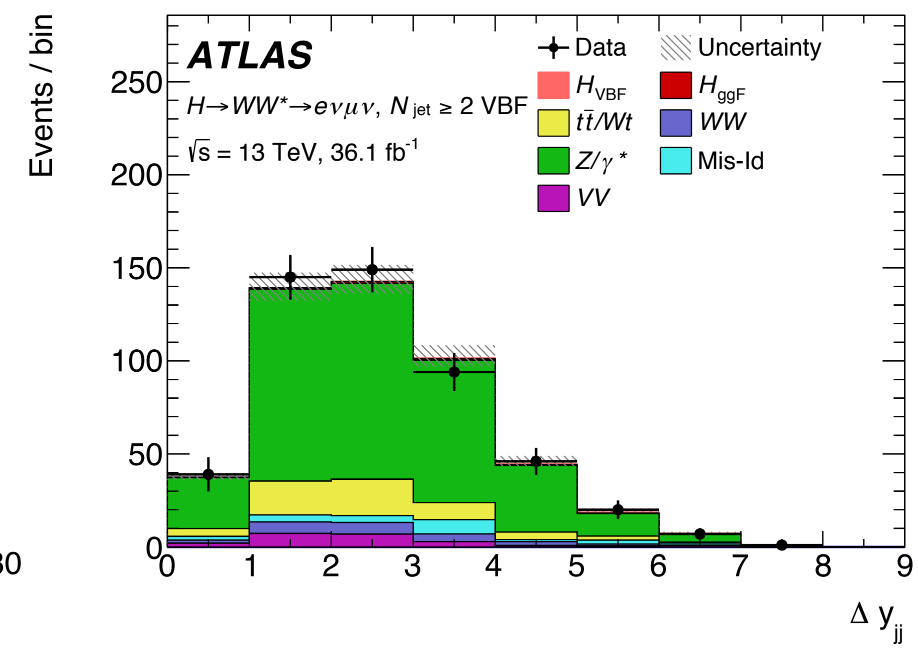
N_{jet}=0, Purity: 90%



N_{jet}=1, Purity: 70%



N_{jet}≥2, Purity: 73%



MC Samples

- Monte Carlo generators used to model the signal and background processes with the corresponding product of cross section and the branching ratio for the Higgs boson production are 13 TeV

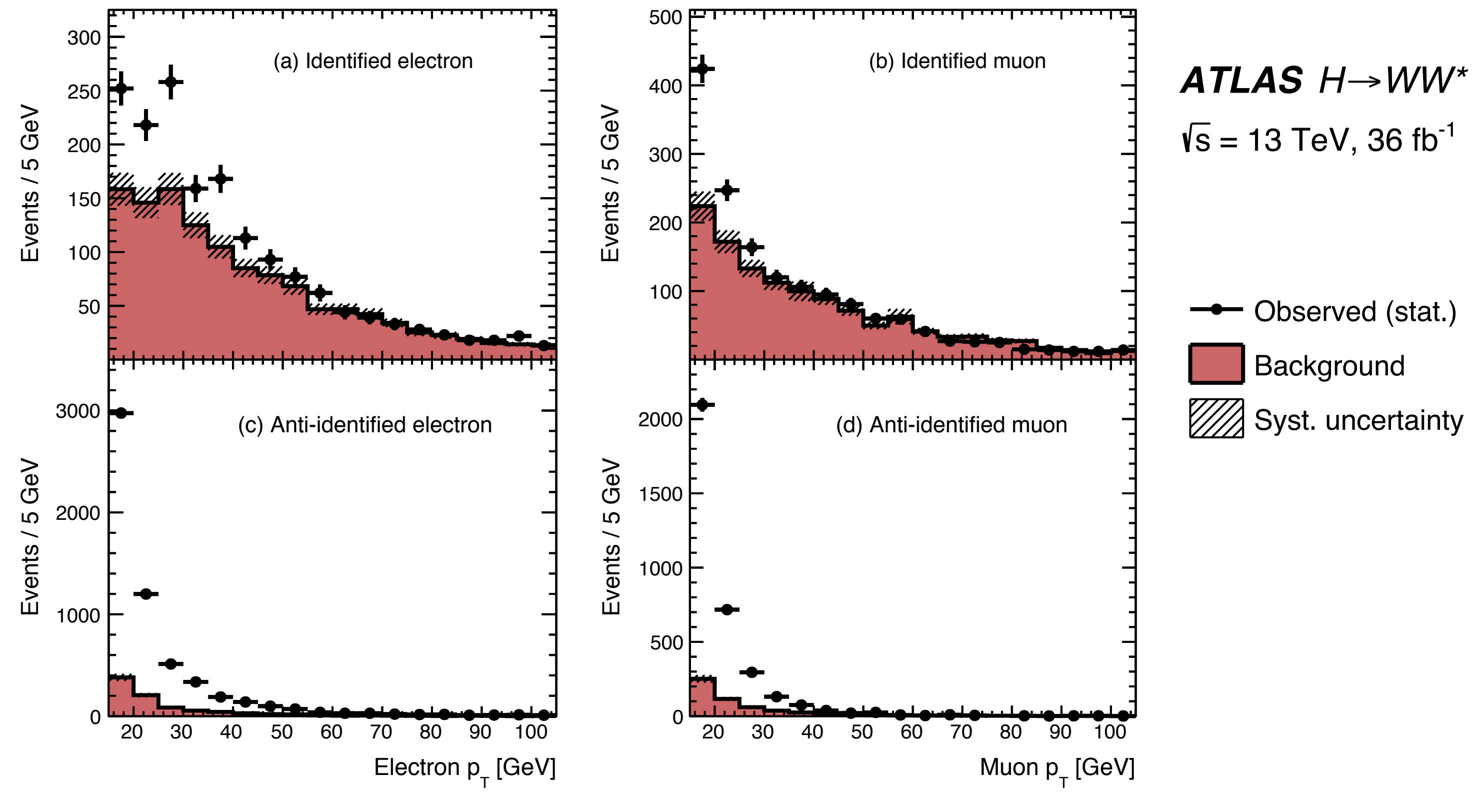
Process	Matrix element (alternative)	PDF set	UEPS model (alternative model)	Prediction order for total cross-section
ggF H	POWHEG-BOX v2 NNLOPS [16,8,10] (MG5_AMC@NLO [46,47])	PDF4LHC15 NNLO [9]	PYTHIA 8 [14] (Herwig 7 [48])	N^3LO QCD + NLO EW [24,25,26,27,28]
VBF H	POWHEG-BOX v2	PDF4LHC15 NLO	PYTHIA 8 (Herwig 7)	NNLO QCD + NLO EW [24,29,30,31]
VH	POWHEG-BOX v2 [49]	PDF4LHC15 NLO	PYTHIA 8	NNLO QCD + NLO EW[50,51,52]
$qq \to WW$	SHERPA 2.2.2 [32,32,33] (POWHEG-BOX v2, MG5_AMC@NLO)	NNPDF3.0NNLO [34]	SHERPA 2.2.2 [35,36] (Herwig++ [48])	NLO [37]
$gg \to WW$	SHERPA 2.1.1 [37]	CT10 [53]	SHERPA 2.1	NLO [38]
$WZ/V\gamma^*/ZZ$	SHERPA 2.1	CT10	SHERPA 2.1	NLO [37]
$V\gamma$	SHERPA 2.2.2 (MG5_AMC@NLO)	NNPDF3.0NNLO	SHERPA 2.2.2 (CSS variation [35,54])	NLO [37]
$t\bar{t}$	POWHEG-BOX v2 [55] (SHERPA 2.2.1)	NNPDF3.0NLO	PYTHIA 8 (Herwig 7)	NNLO+NNLL [56]
Wt	POWHEG-BOX v1 [57] (MG5_AMC@NLO)	CT10 [53]	PYTHIA 6.428 [58] (Herwig++)	NLO [57]
Z/γ^*	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	NNLO [59,60]

Event Selection

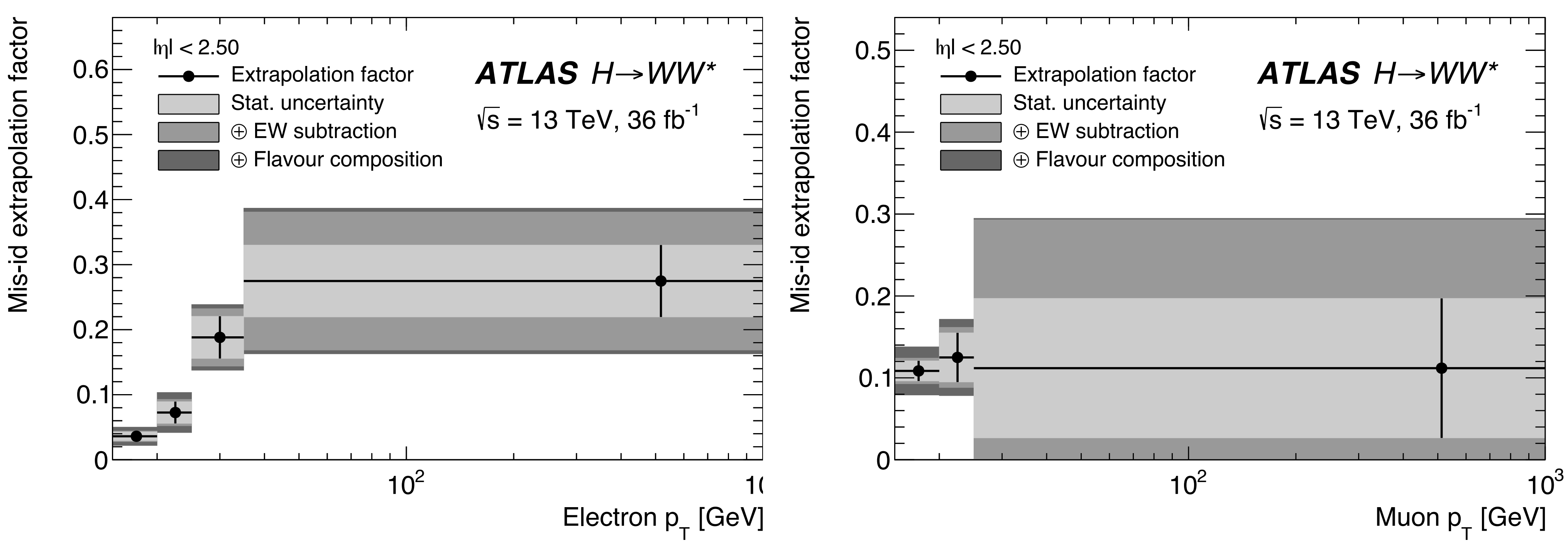
Category	$N_{\mathrm{jet},(p_{\mathrm{T}}>30\ \mathrm{GeV})}=0$ ggF	$N_{\mathrm{jet},(p_{\mathrm{T}}>30\ \mathrm{GeV})}=1$ ggF	$N_{\mathrm{jet},(p_{\mathrm{T}}>30\ \mathrm{GeV})}\geq 2$ VBF
Preselection	Two isolated, different-flavour leptons ($\ell = e, \mu$) with opposite charge $p_{\mathrm{T}}^{\mathrm{lead}}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

Mis-identified lepton background

- **W+jets** (Mis-Id) evaluated from Z+jets data and corrected for expected differences with W+jets
- **Challenges:**
  - Reduce W+jets background while using low p_T leptons



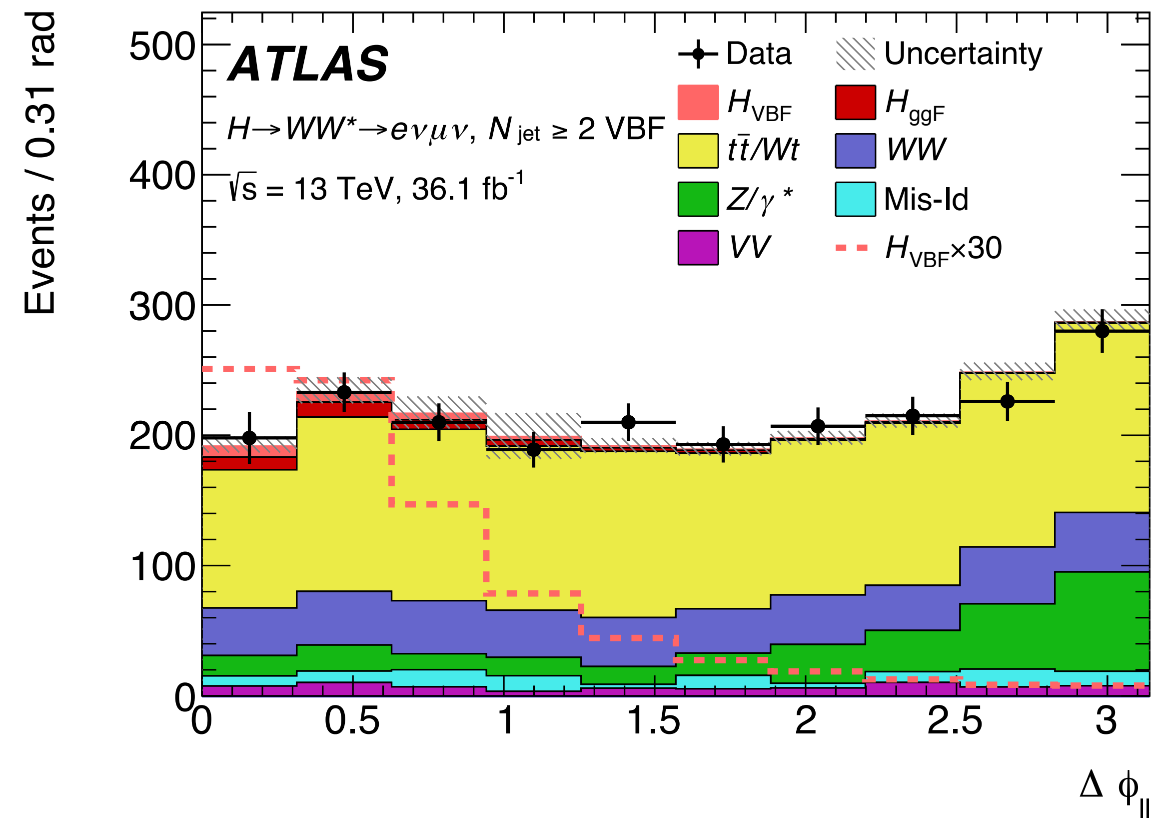
$$FF(p_T, \eta) = \frac{N_{e(\mu),ID}}{N_{e(\mu),anti-ID}}$$

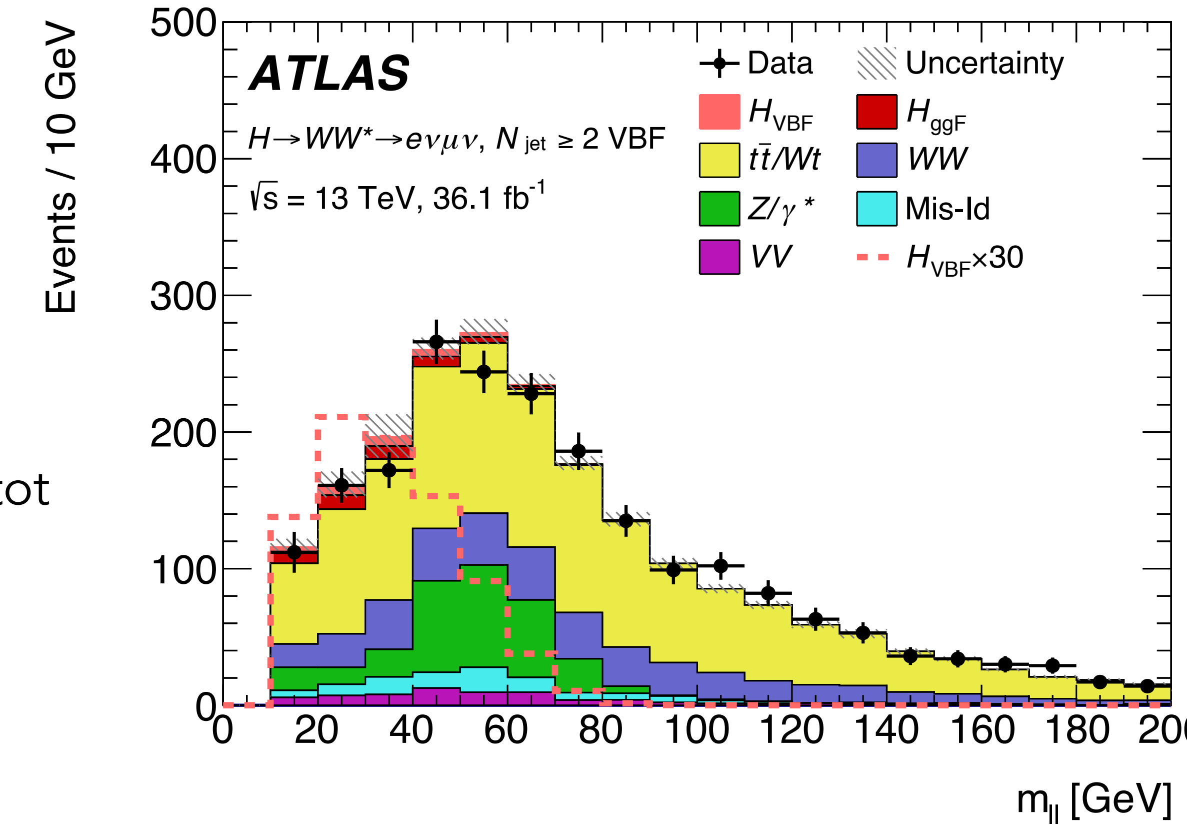


✤FF applied in control region with 1 ID and 1anti-ID leptons to predict the Mis-ID in the ID+ID region

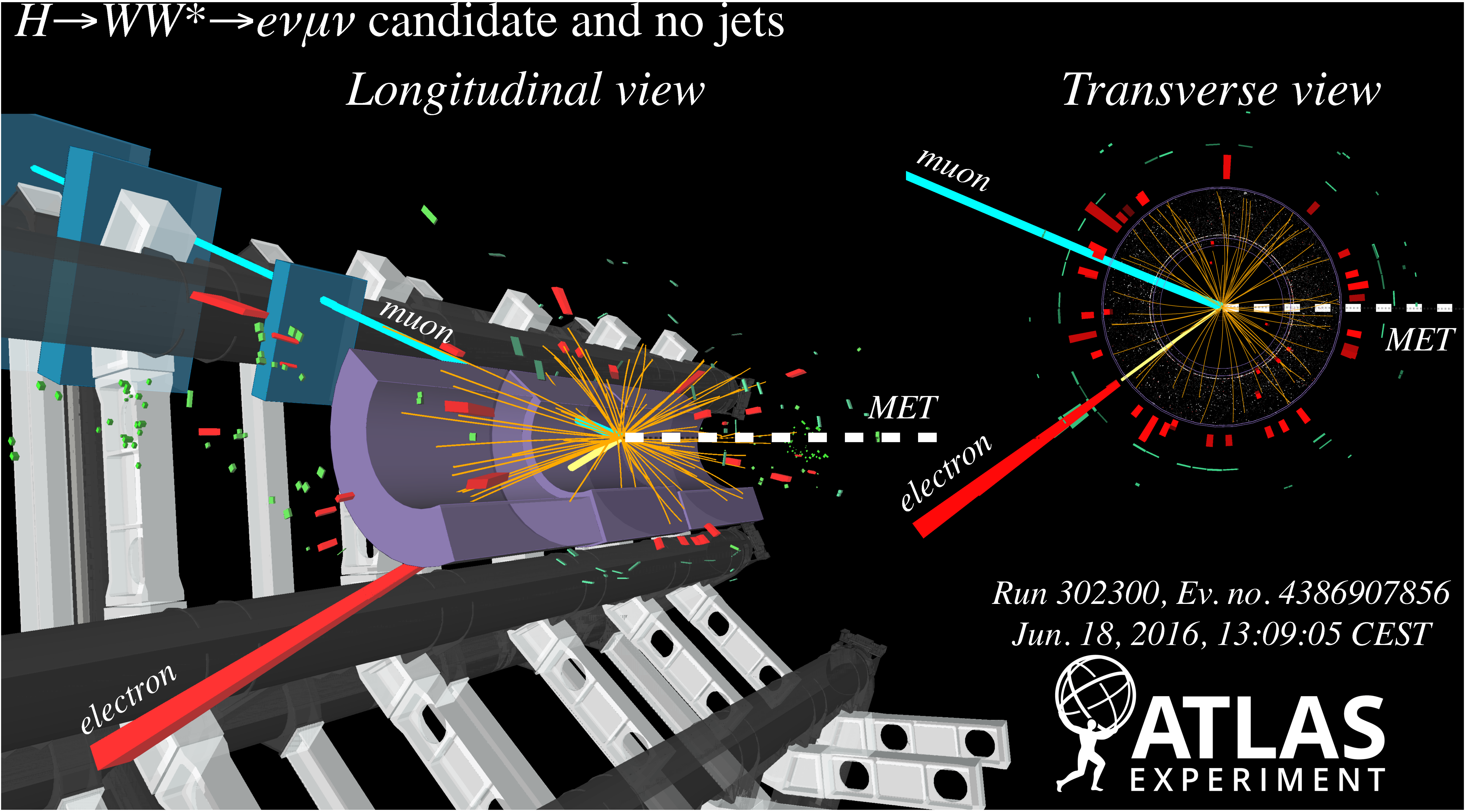
VBF identification

- Selection of VBF Higgs boson candidate
  - Veto presence of extra jets between the two leading jets
  - Central Higgs boson decay
  - Veto Z mass window
- Properties of **$H \to WW^* \to e\nu\mu\nu$ decay** and **VBF topology** are used in a boosted decision tree
  - $H \to WW^* \to e\nu\mu\nu$: m_{ll}, $\Delta\phi_{ll}$, m_T
  - VBF topology: m_{jj}, Δy_{jj}, $\eta_{centrality}$, $\sum M_{lj}$, p_T^{tot}
- Highest ranked variables: $\mathbf{m_{jj}}$ and $\mathbf{\Delta y_{jj}}$,

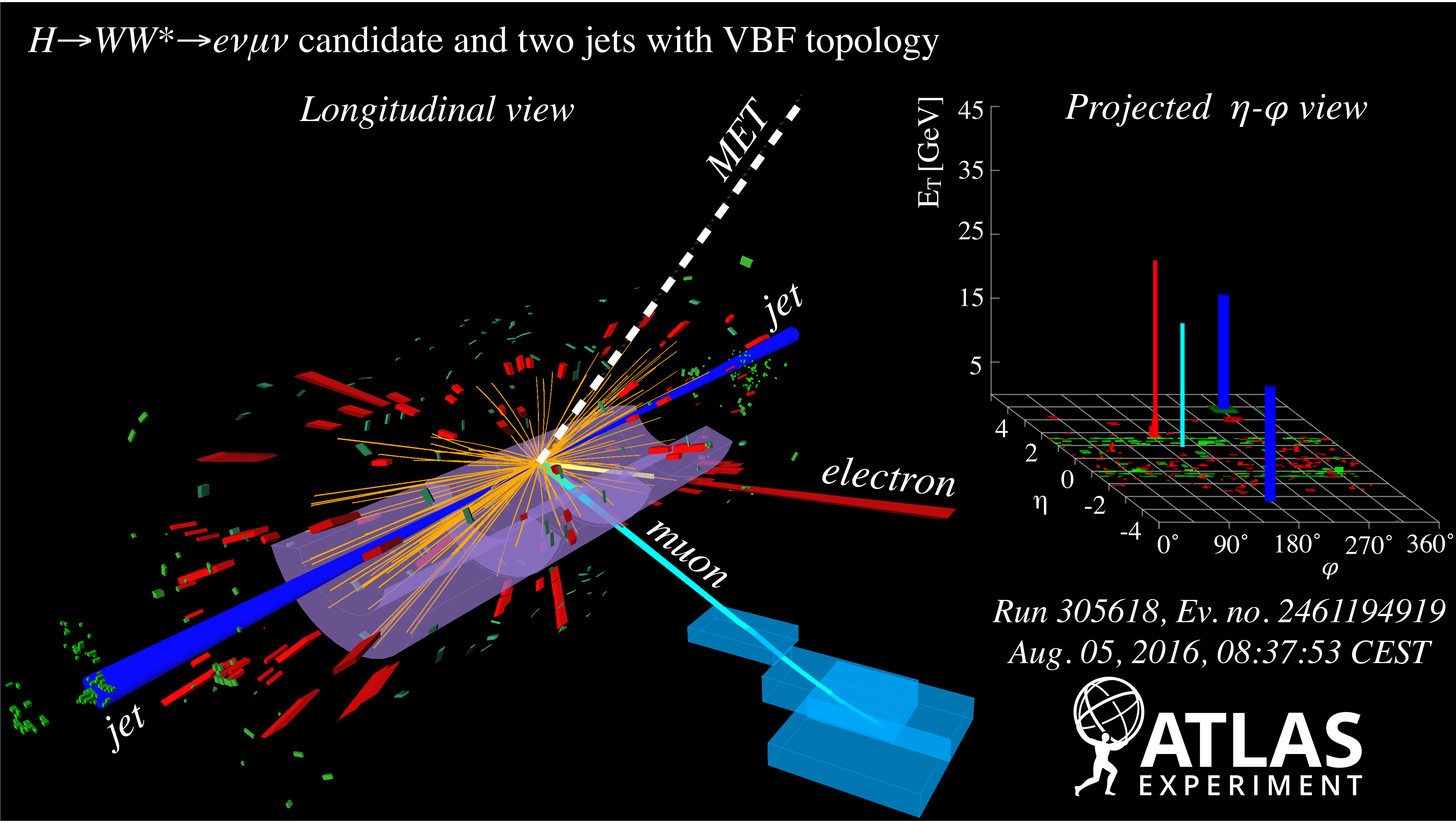




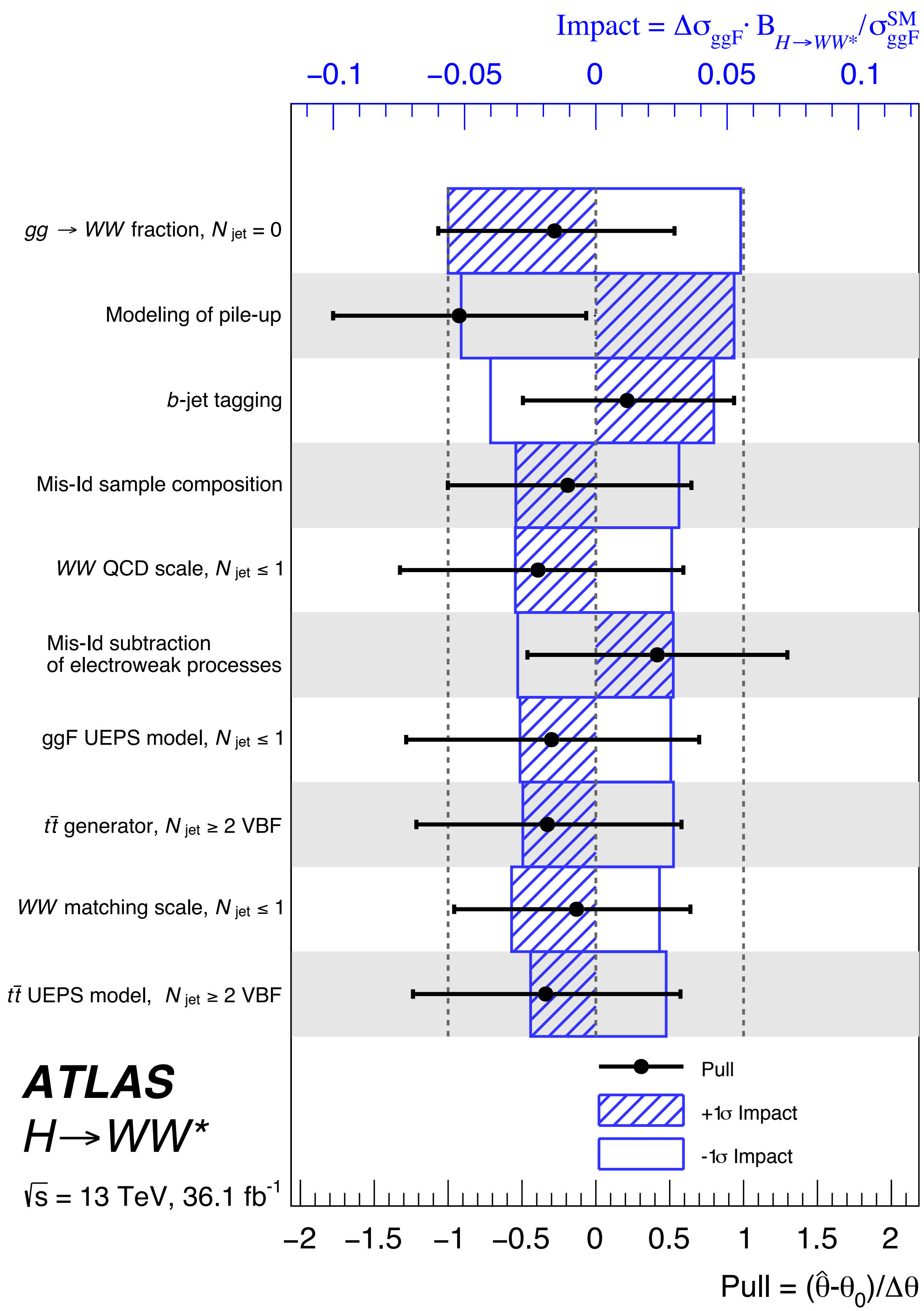
ggF channels

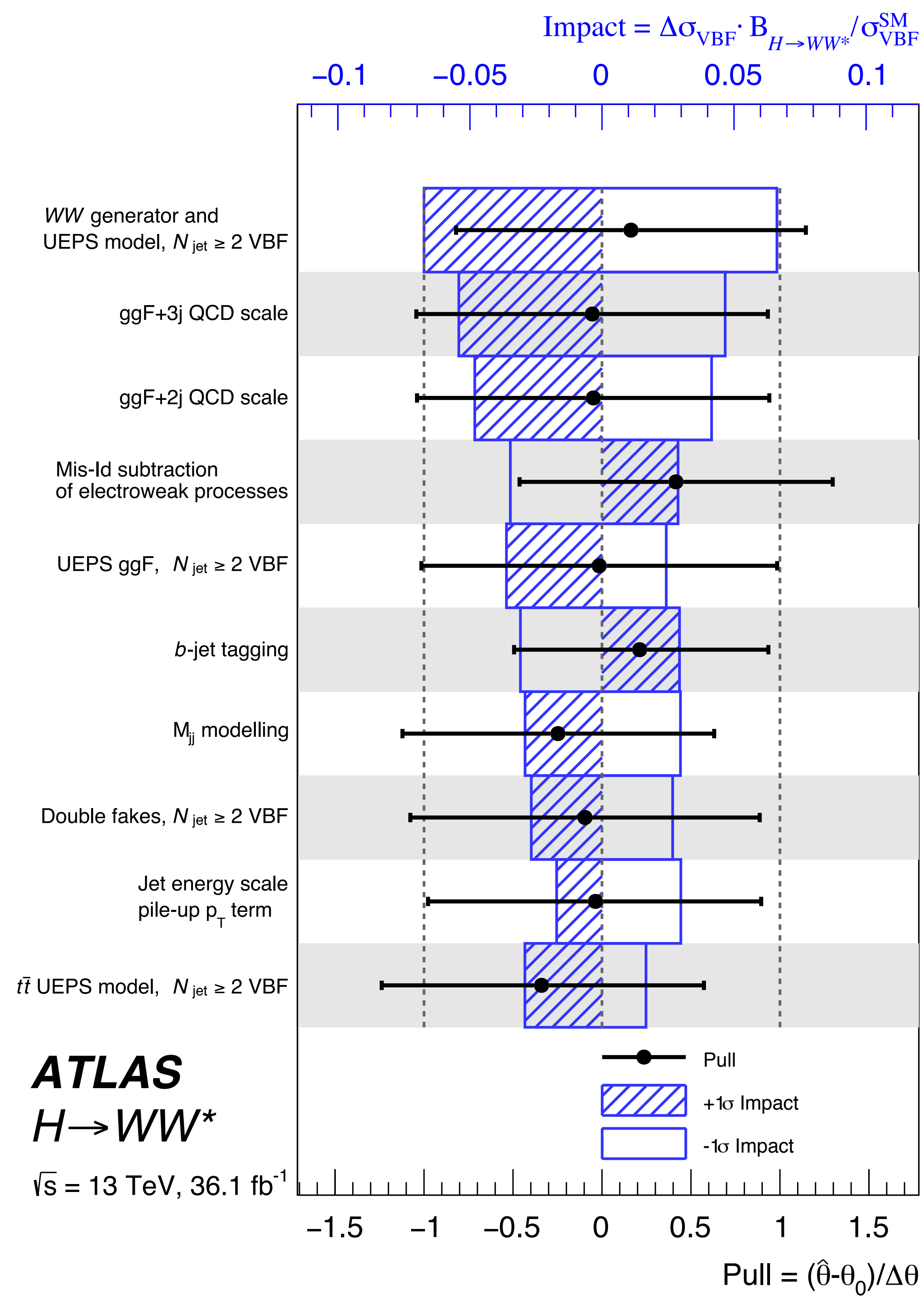


VBF channels

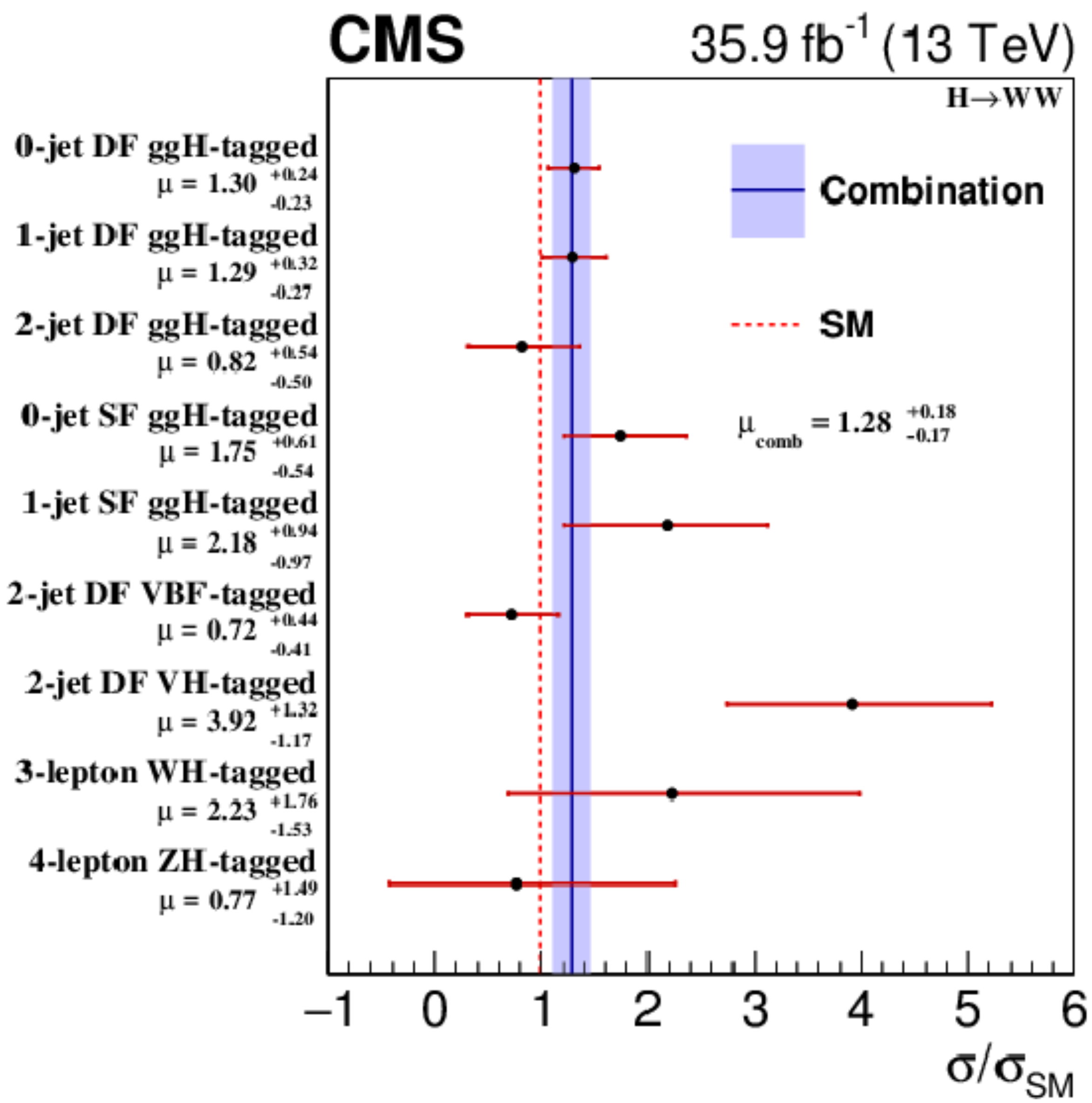


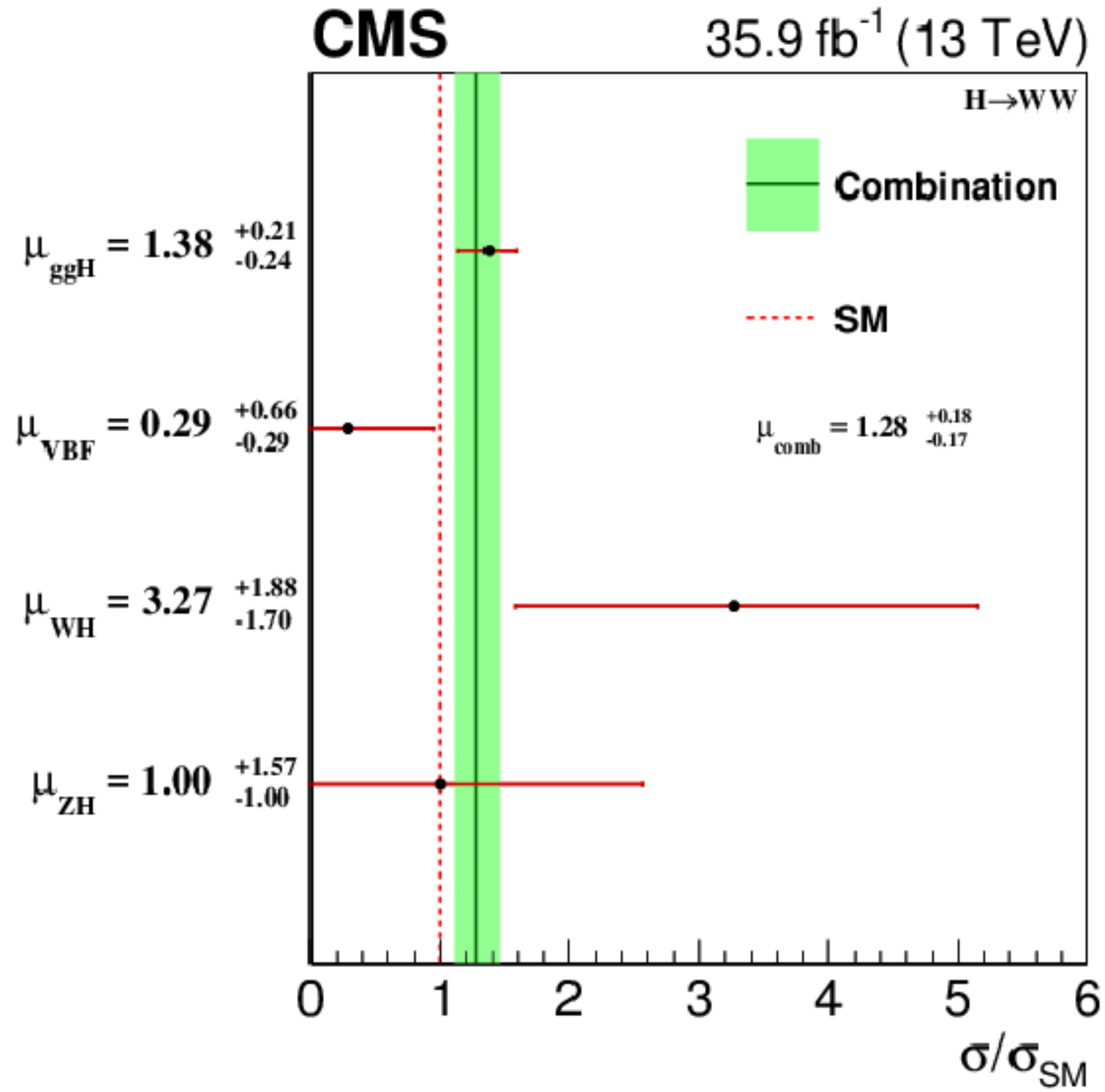
H→WW*→eνμν @ 13TeV





CMS Results





$$\hat{\mu} = 1.28^{+0.18}_{-0.17} = 1.28 \pm 0.10(\text{stat})^{+0.11}_{-0.11}(\text{syst})^{+0.10}_{-0.07}(\text{theo.})$$

- Main theoretical uncertainties are ggF cross section and jet bin migration
- Main experimental systematics come from the background rates, luminosity, and lepton identification efficiencies