Measurements and interpretations of Simplified Template Cross Sections and differential and fiducial cross sections in Higgs boson decays to two W bosons with the ATLAS detector

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On behalf of
the ATLAS Collaboration

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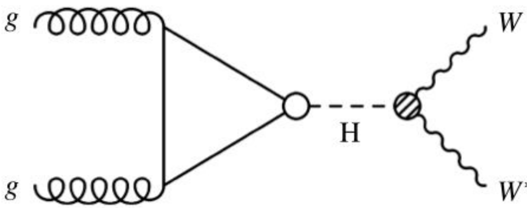
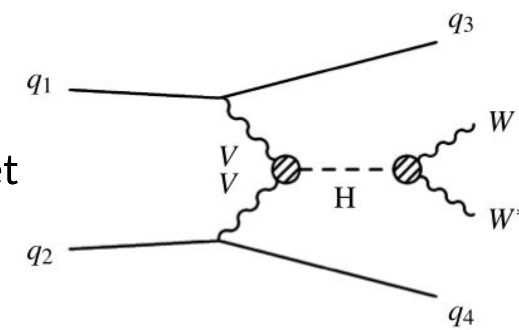
Overview

- 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 Higgs decay channel
- Measure leading Higgs production modes: ggF and VBF
- Previous Higgs->WW* coupling results with ATLAS
  - Run 1, 7-8 TeV data [Phys. Rev. D 92 (2015) 012006]
    - 5.8σ ; $\sigma_{ggf\,(8TeV)} \times B_{H\to WW^*}$ = 4.6 ± 1.2 pb
    - 3.2σ ; $\sigma_{vbf(8TeV)} \times B_{H\to WW^*}$ = 0.51 ± 0.20 pb
  - Run 2, 36/fb of data [Phys. Lett. B 789 (2019) 508]
    - 6.0σ ; $\sigma_{ggf\,(13TeV)} \times B_{H\to WW^*}$ = 11.4 ± 2.2 pb
    - 1.8σ ; $\sigma_{vbf(13TeV)} \times B_{H\to WW^*}$ = 0.5 ± 0.29 pb
- In this talk
  - Higgs->WW* coupling measurements with full Run 2 dataset
    - [ATLAS-CONF-2021-014]
  - EFT interpretation with H->WW and WW measurement
    - [ATL-PHYS-PUB-2021-010]



Gluon fusion Higgs

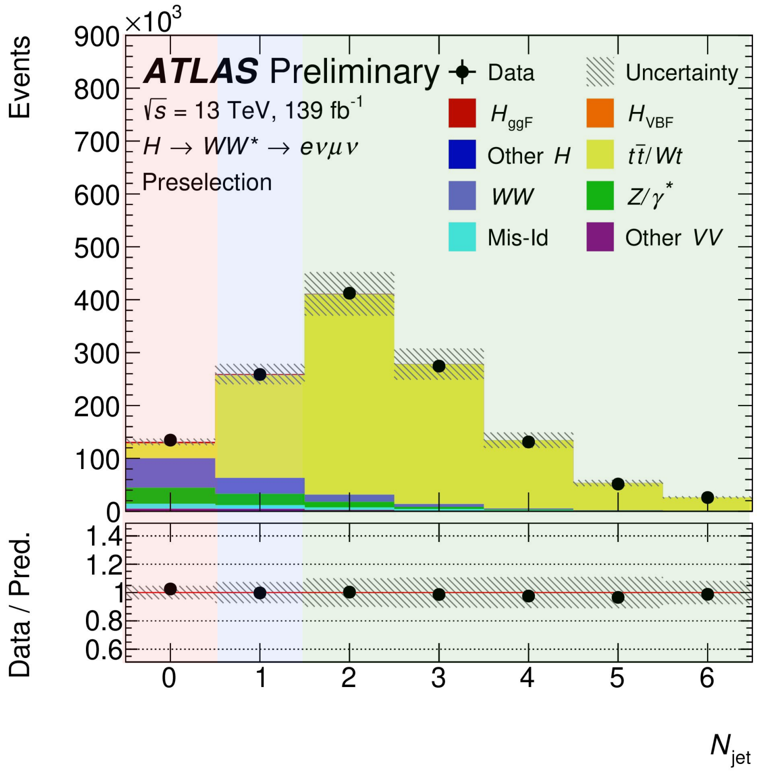


Vector boson fusion Higgs

Analysis strategy

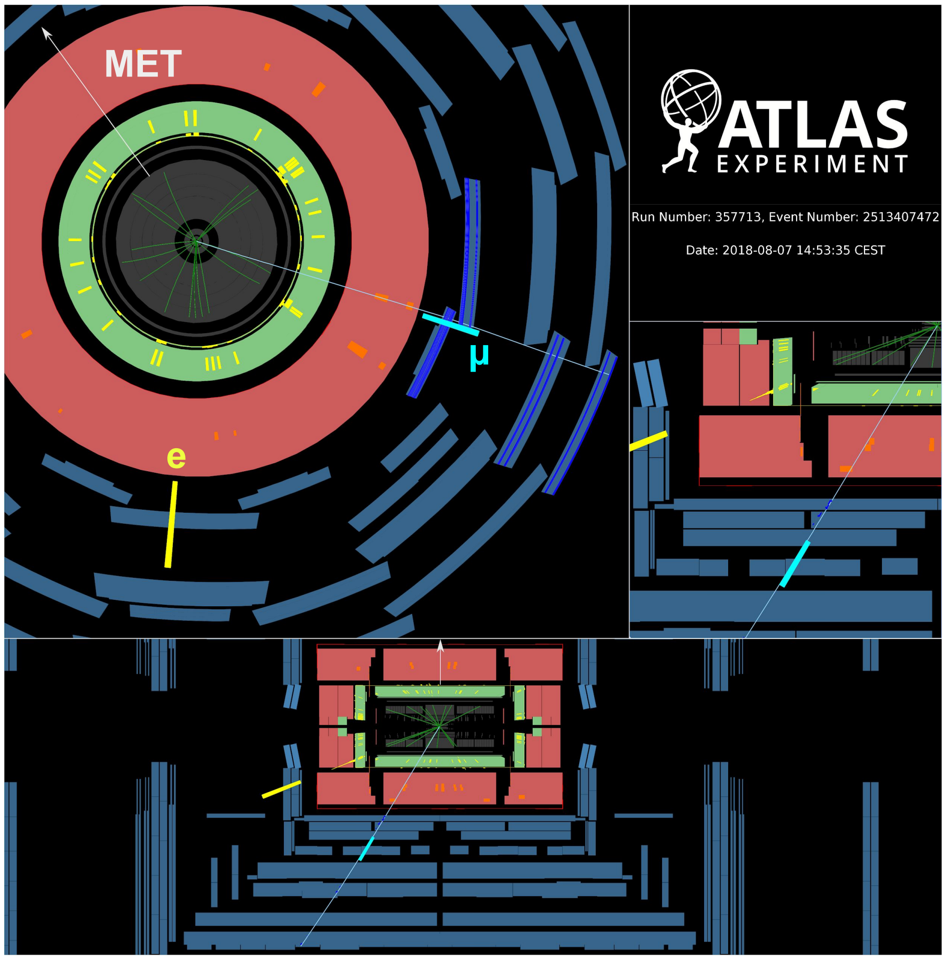
- WW leptonic decay to different flavour : e, μ
  - DF leptonic decay branching ratio 2.3%
  - Best sensitivity among WW decays
  - Largely reduced Z+jets contribution
- Single and dilepton triggers : down to 14 GeV for muon and 17 GeV for electron
- Events separated to jet multiplicity bins: ggF 0 jet, ggF 1 jet, ggF >=2 jet, VBF(>=2 jet)
  - Different background contributions. Different background estimation methods used
- Use m_T instead of m_H because of the presence of missing E_T

$$m_{\mathrm{T}} = \sqrt{(E_{ll} + E_{\mathrm{T}}^{miss})^2 - |p_{ll} + E_{\mathrm{T}}^{miss}|^2}$$

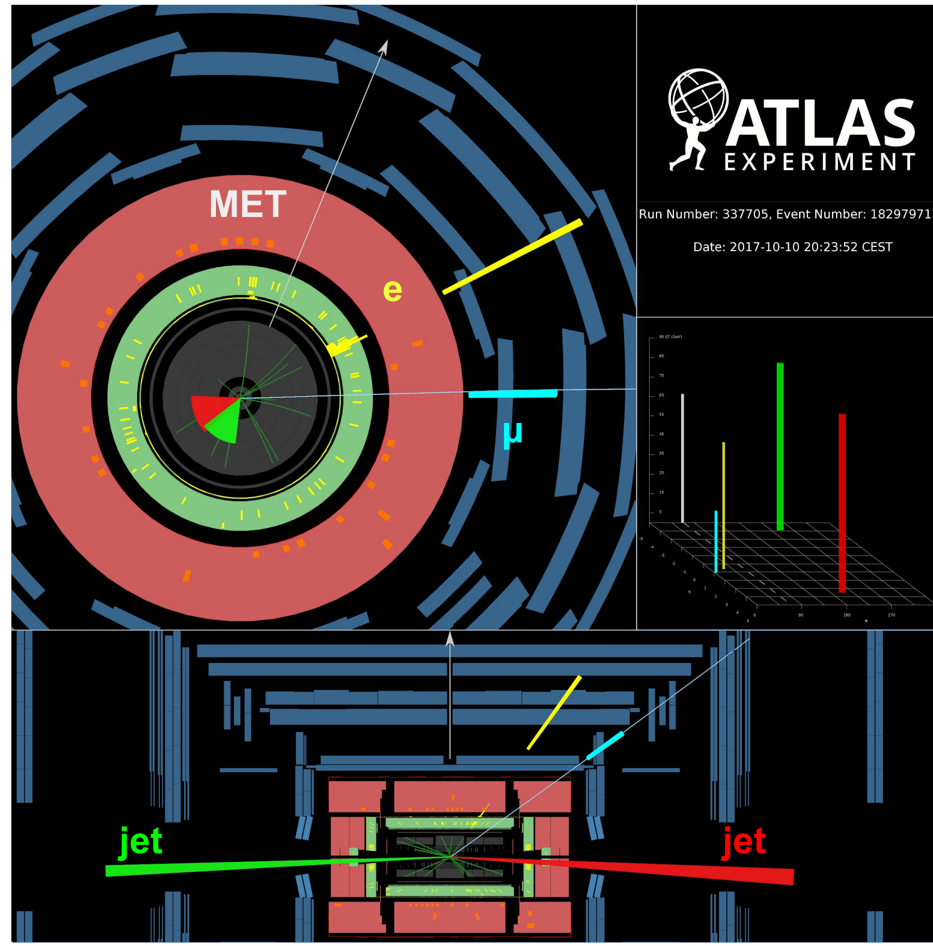


Signal events in ATLAS Detector

ggF

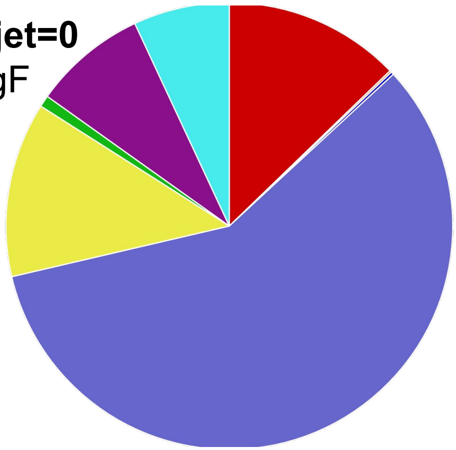


VBF

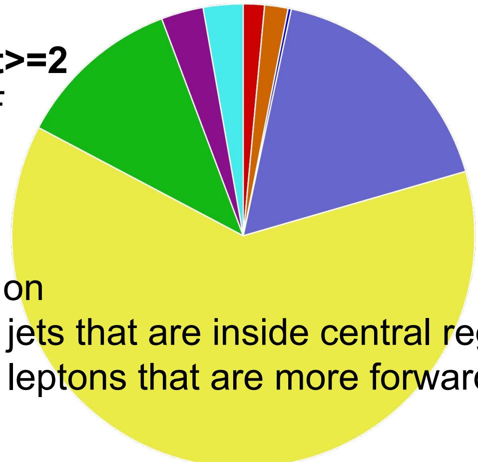


Background fractions in signal regions

Njet=0
ggF

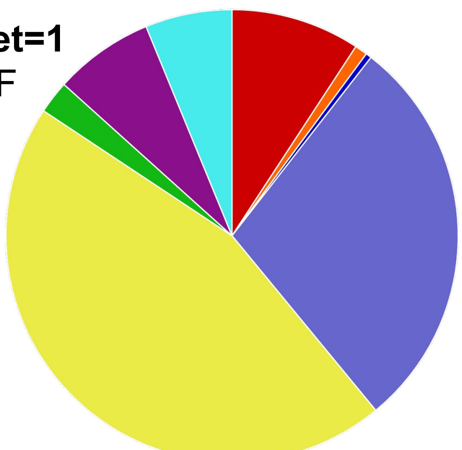


Njet>=2
VBF



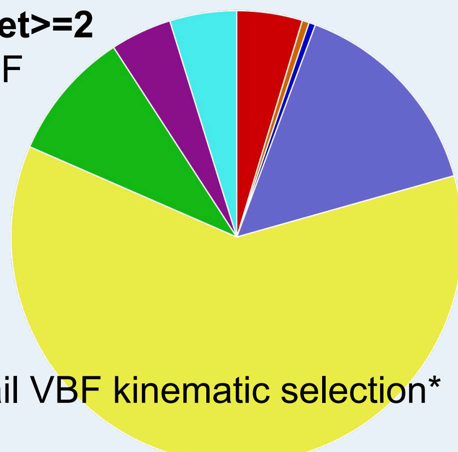
*Veto on
- veto jets that are inside central region
- veto leptons that are more forward than jets

Njet=1
ggF



First time in Run-2

Njet>=2
ggF



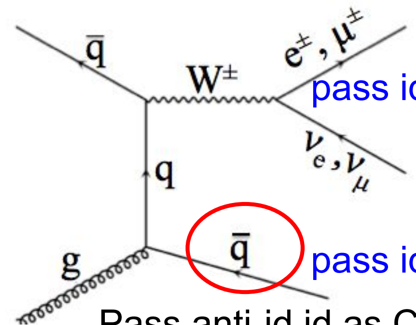
Fail VBF kinematic selection*

H_{ggF} H_{VBF}

$qq \to WW$ Z/γ^* $t\bar{t}/Wt$	Normalization constraint by control regions
Mis-Id	Fake factor
Other VV $gg \to WW$	Simulation

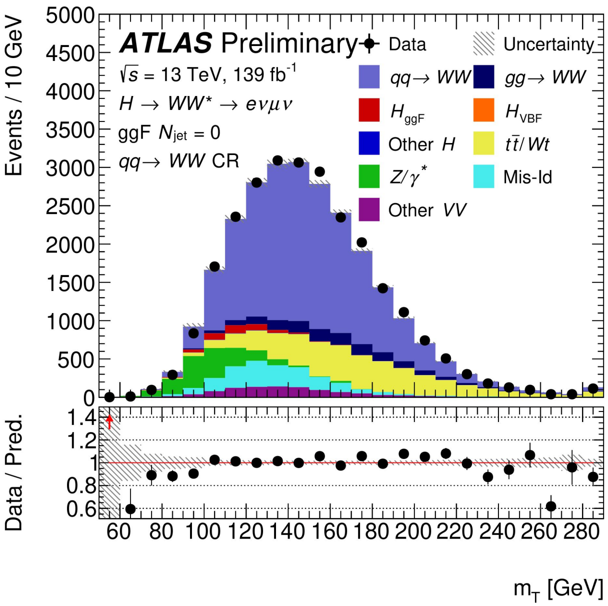
Background estimations

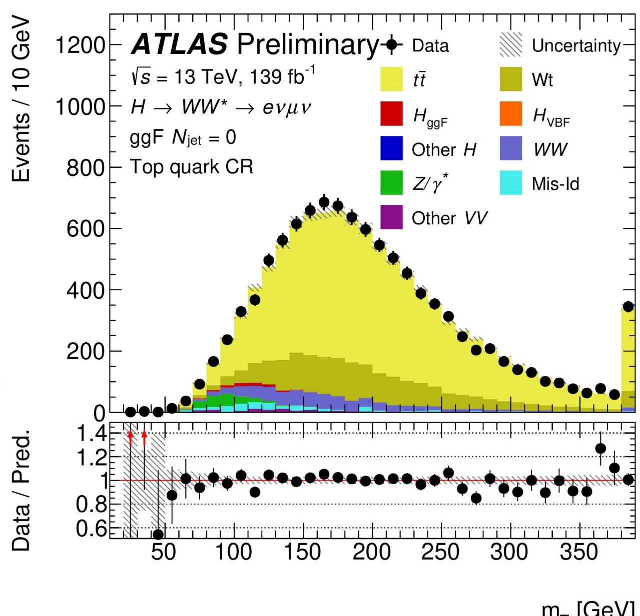
- WW, top and Z jets : Normalisation constrained by the control region
- Mis-identified lepton: Dominated by Wjets, data-driven method
- Other diboson estimated from simulation

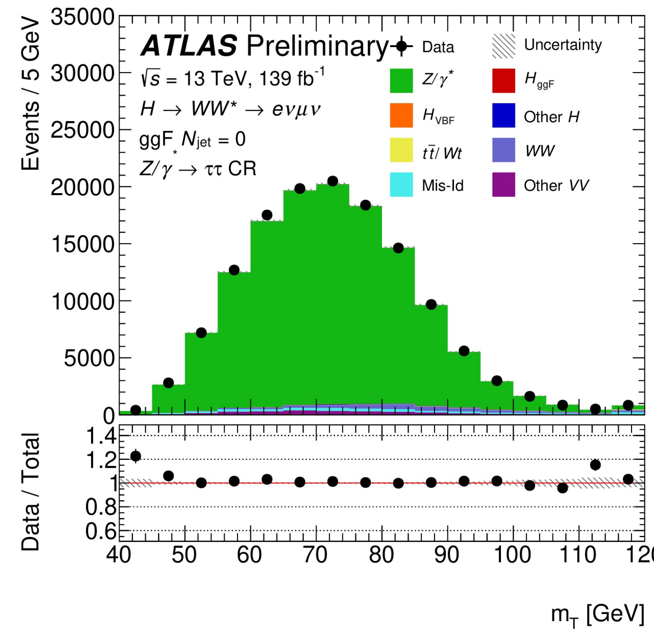


Pass anti-id id as CR

WW 0 jet control region	Top 0 jet control region	Z/γ*->ττ 0 jet control region



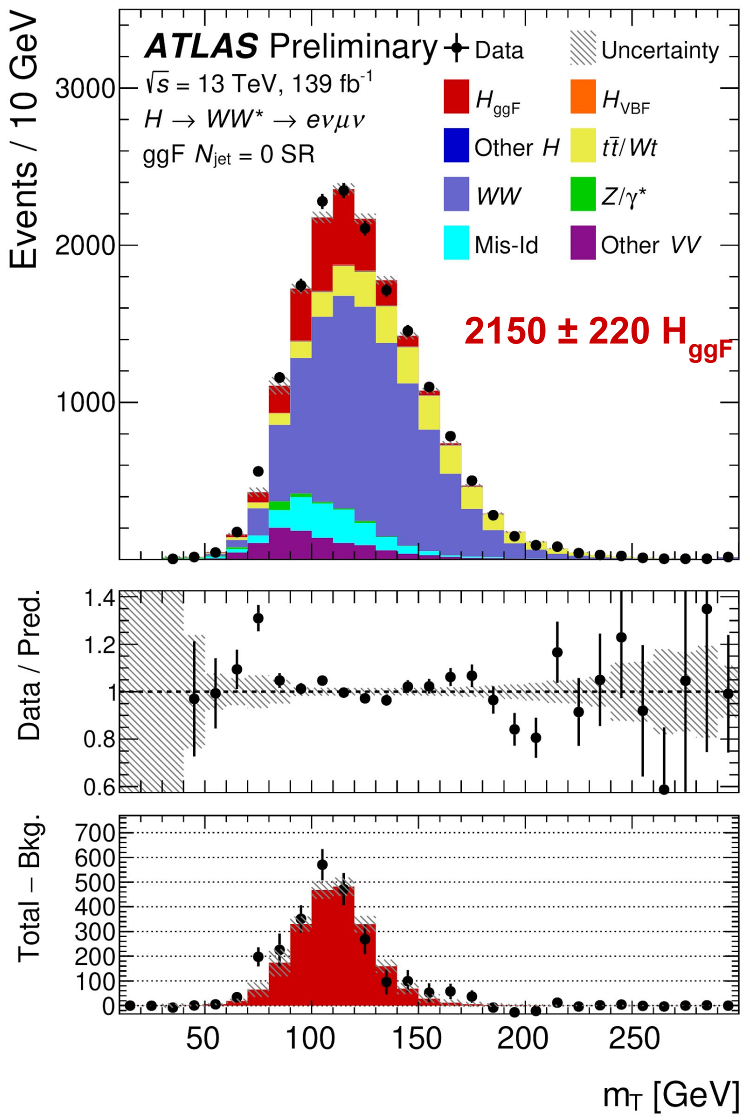


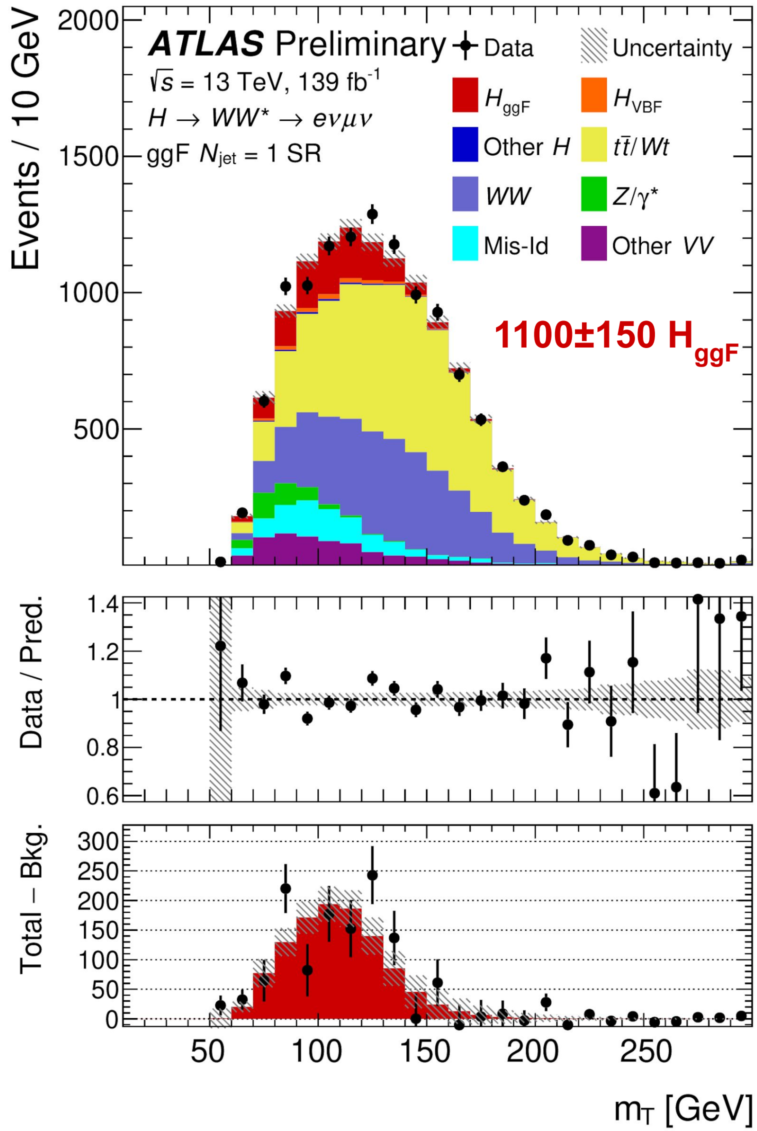


post fit 0 jet control regions

ggF 0,1 jet

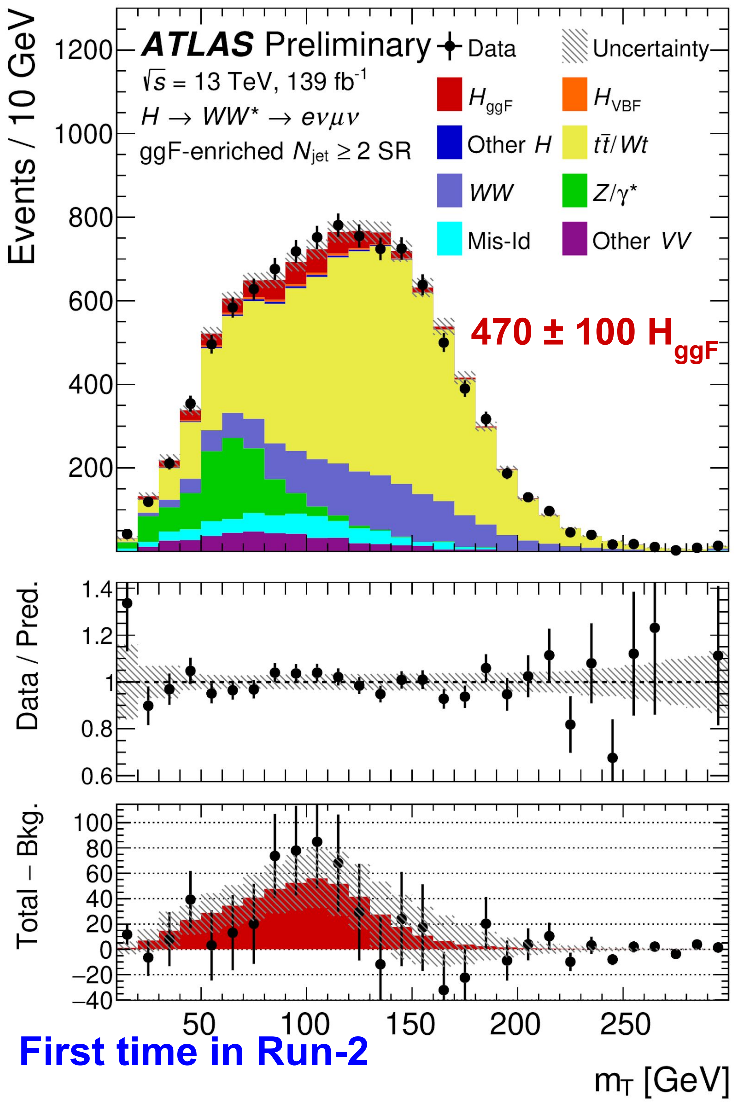
Good post fit m_T modeling in ggF 0, 1 jet SRs



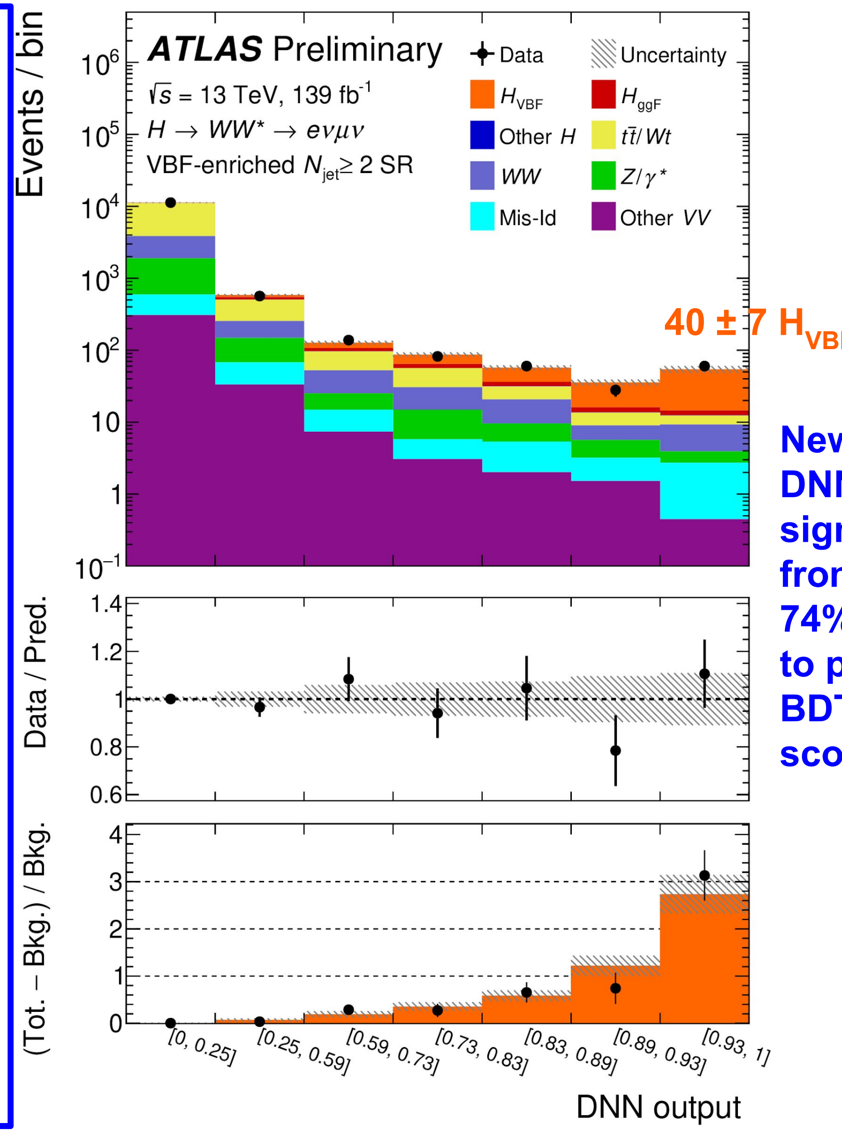


ggF 2 jet and VBF

Good post fit modeling in ggF >=2 jets and VBF SRs



First time in Run-2



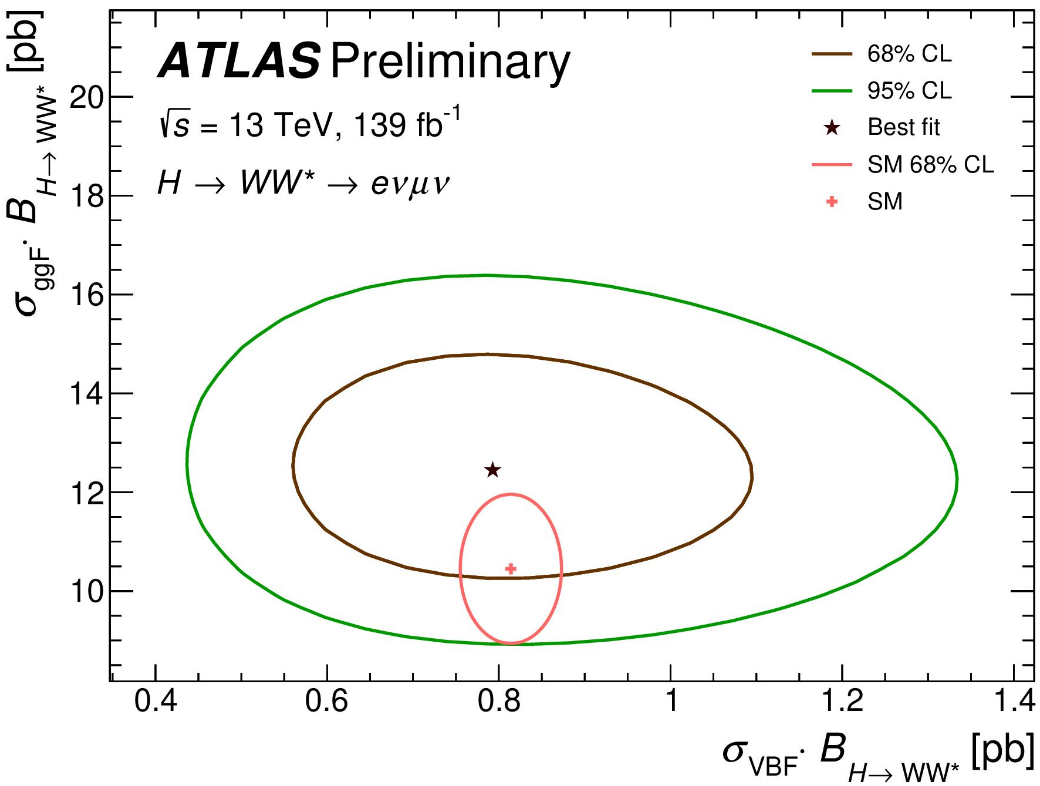
New trained DNN increase signal fraction from 27% to 74% compared to previous BDT in highest score bin

Systematics

Source	ggF $\frac{\Delta\sigma_{\mathrm{ggF}}\cdot\mathcal{B}_{H\to WW^*}}{\sigma_{\mathrm{ggF}}\cdot\mathcal{B}_{H\to WW^*}}$ [%]	VBF $\frac{\Delta\sigma_{\mathrm{VBF}}\cdot\mathcal{B}_{H\to WW^*}}{\sigma_{\mathrm{VBF}}\cdot\mathcal{B}_{H\to WW^*}}$ [%]
Data statistical uncertainties	5	13
Total systematic uncertainties	11	18
MC statistical uncertainties	4	3.2
Experimental uncertainties	6	7
Flavour Tagging	2.4	0.9
Jet energy scale	1.4	3.3
Jet energy resolution	2.3	1.9
$E_{\mathrm{T}}^{\mathrm{miss}}$	1.9	5
Muons	2.1	0.7
Electrons	1.5	0.3
Fake factors	2.4	1.0
Pile-up	2.4	1.3
Luminosity	2.0	2.1
Theoretical uncertainties	8	16
ggF	5	4
VBF	0.7	13
Top	4	5
$Z\tau\tau$	2.0	2.1
WW	4	5
Other VV	3	1.2
Background normalisations	5	5
WW	3.1	0.5
Top	2.4	2.2
$Z\tau\tau$	3.1	4
TOTAL	12	22

- ggF measurements dominated by background theory uncertainties and exp uncertainties
- VBF measurements dominated by signal theory uncertainties and data stat uncertainties

Results



- Results consist with SM prediction
- Newly measured ggF 2jet category reaches 2.2(1.6) σ above the background expectation
- The observed (expected) VBF signal reaches a significance of 6.6 (6.1) σ above the background expectation

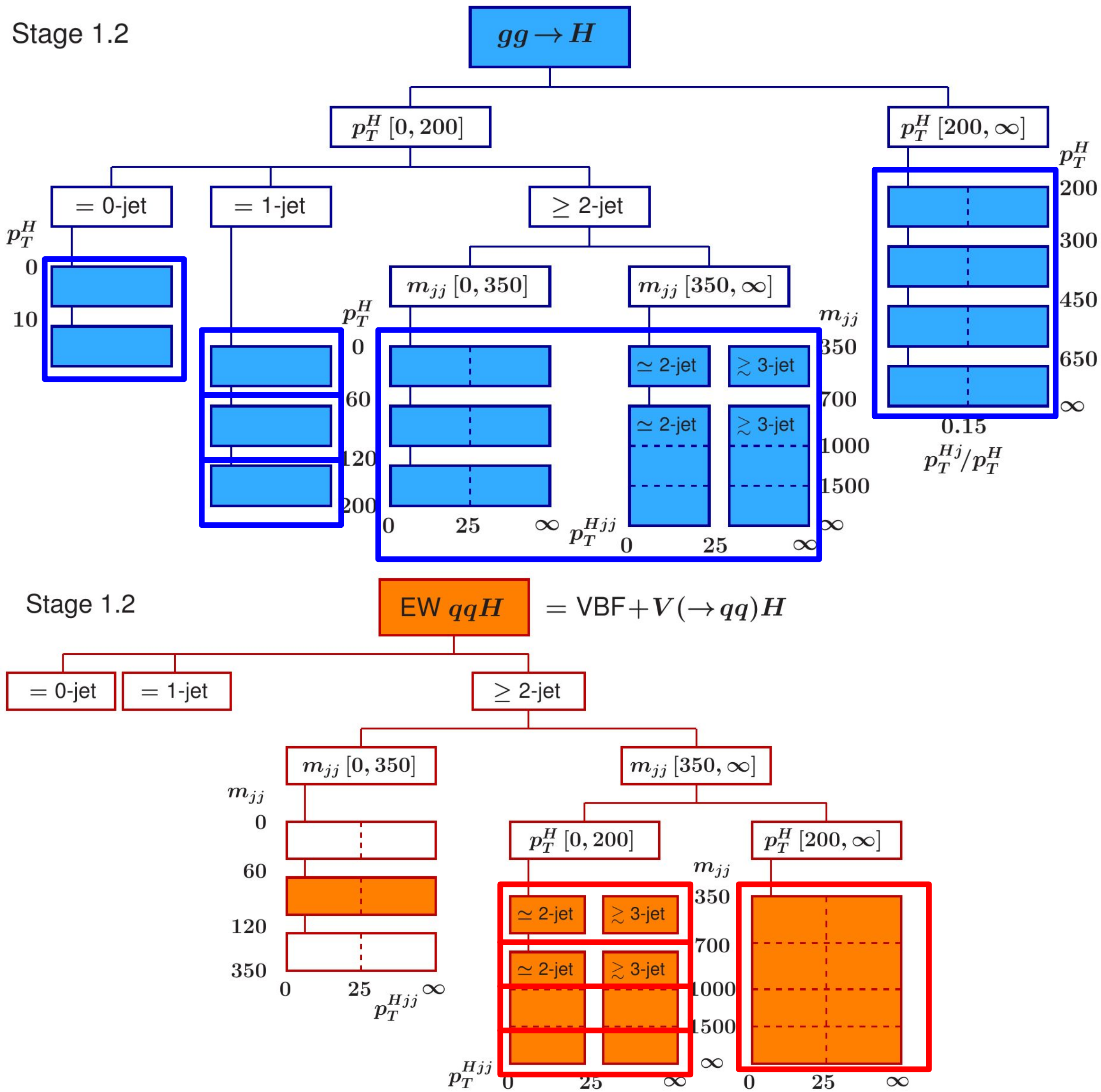
$\sigma_{ggF} \times B_{H\text{->}WW^*}$ = 12.4 ± 1.5 pb

SM $\sigma_{ggF} \times B_{H\text{->}WW^*}$ = 10.4 ± 0.6 pb

$\sigma_{VBF} \times B_{H\text{->}WW^*}$ = 0.79 + 0.19-0.16 pb

SM $\sigma_{VBF} \times B_{H\text{->}WW^*}$ = 0.81 ± 0.02 pb

Simplified template cross section

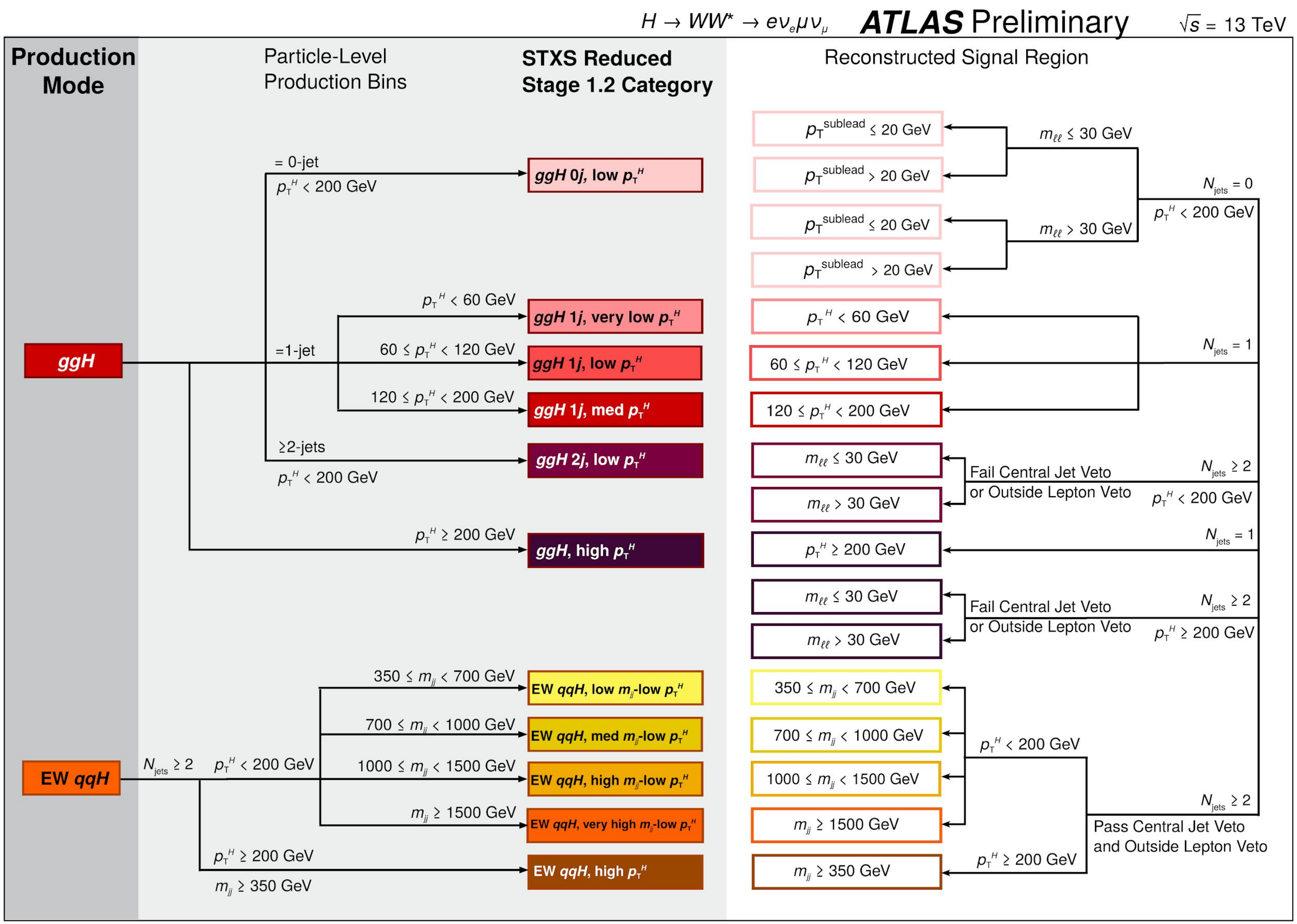


- ➢ Measured STXS **staged 1.2** kinematics bins for ggH and EW qqH production modes
- ➢ Merged into 11 bins based on the analysis sensitivity

6 gg->H

5 EW qqH

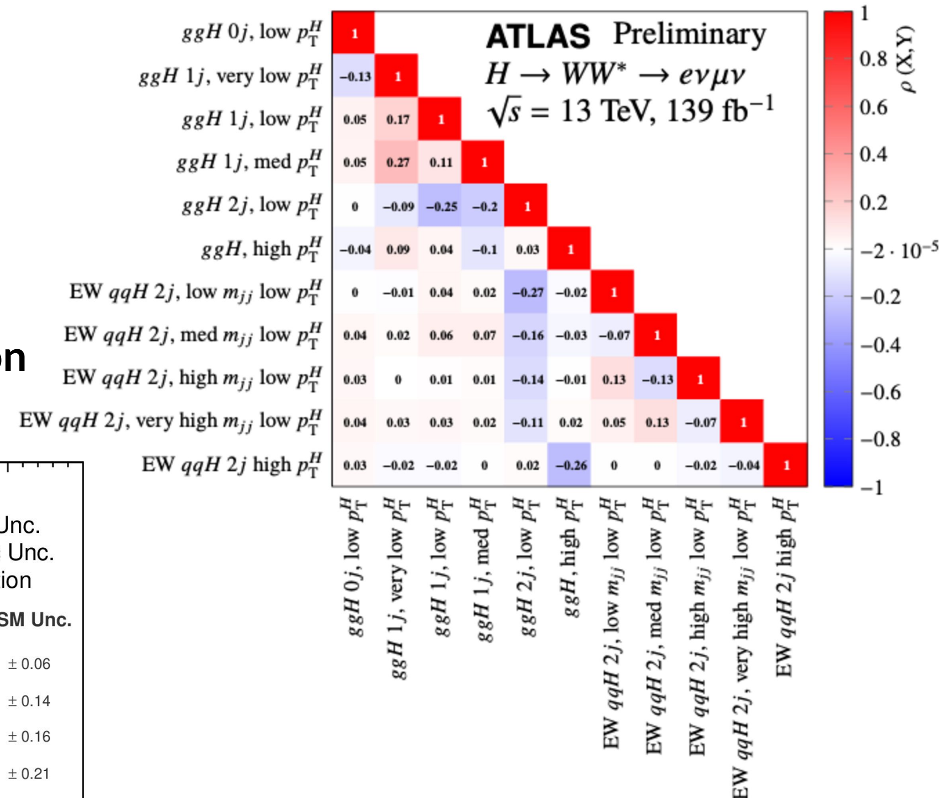
Simplified template cross section

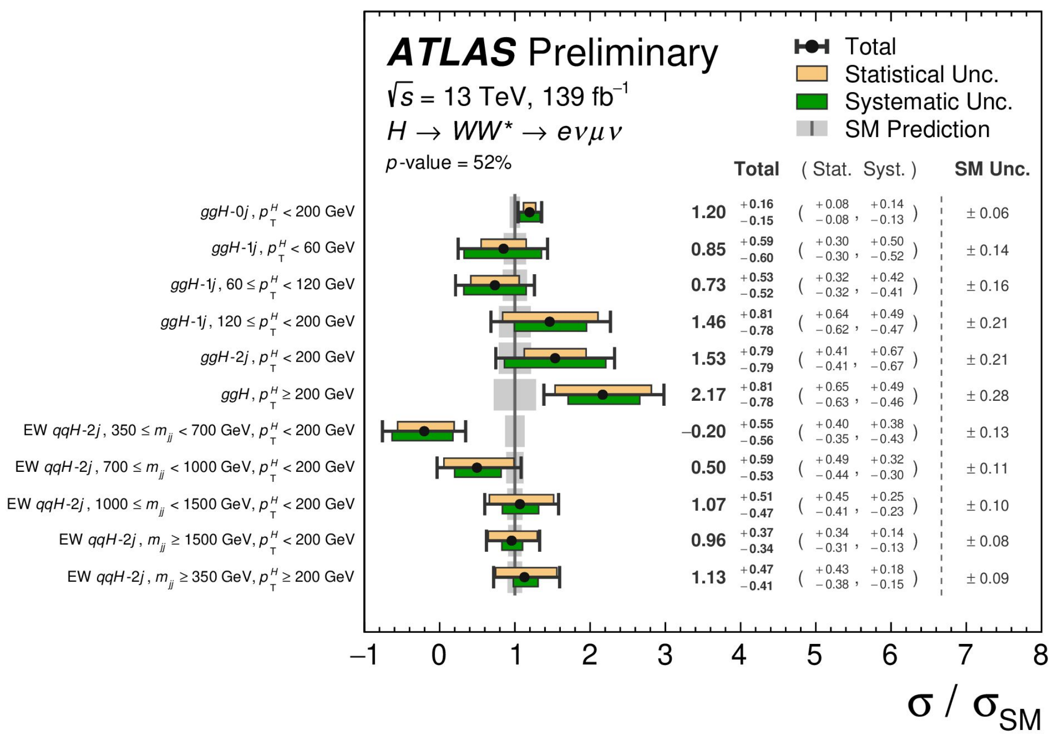


- STXS : analysis methods are similar to the coupling measurement
- 17 reconstructed SRs and 27 CRs to extract 11 STXS kinematic bins
- Additional SRs to improve signal background separation
- Multiple control regions in p_TH and m_{jj} bins

Simplified template cross section

- ➢ Low $p_T H$, m_{jj}: systematic ≥ statistical uncertainties
- ➢ High $p_T H$, m_{jj}: statistically limited
- ➢ Compatible with SM
- ➢ **EW qqH sensitivity comparable with latest ATLAS HZZ*, Hγγ, VH(bb) STXS combination**



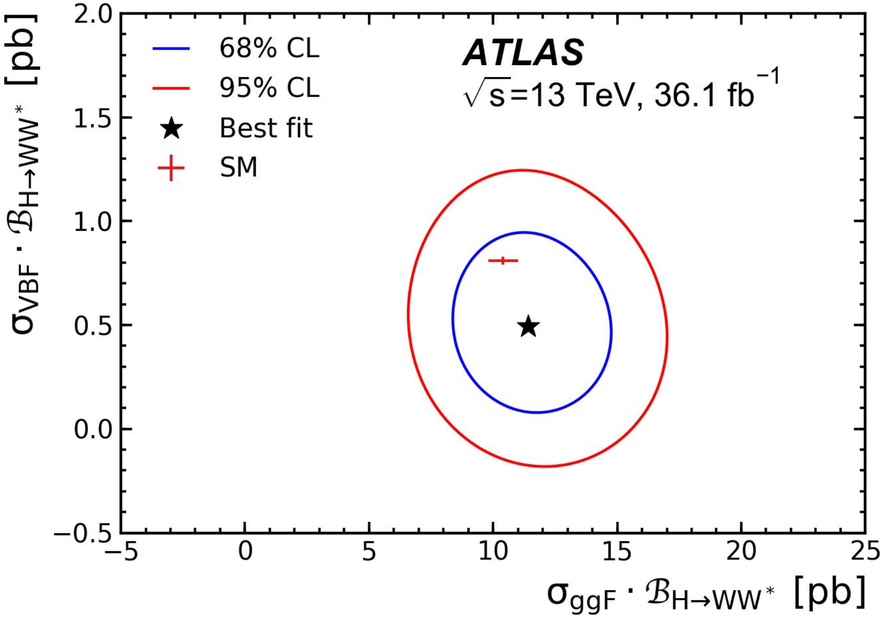


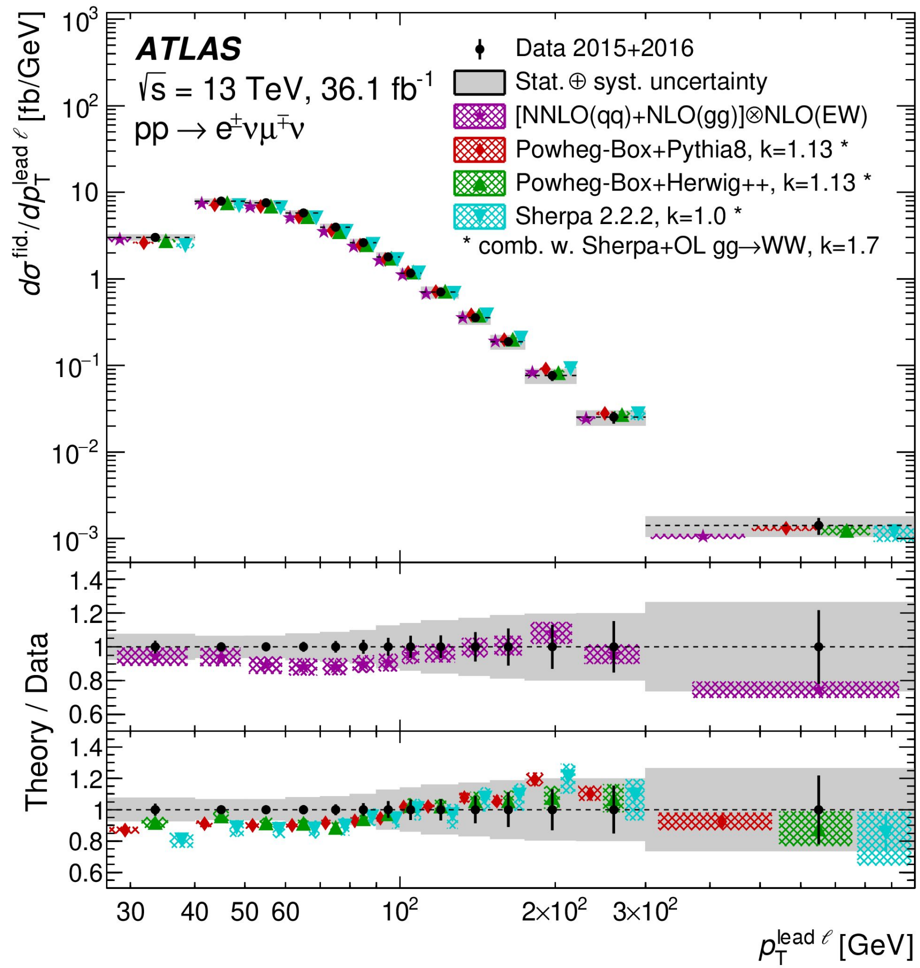
- ➢ Small correlations in general
- ➢ Larger anti-correlations mainly from detector resolution effects
- ➢ Larger positive correlations from common systematic uncertainties

EFT interpretation of H->WW and WW measurement

Phys. Lett. B 789 (2019) 508

Eur. Phys. J. C 79 (2019) 884

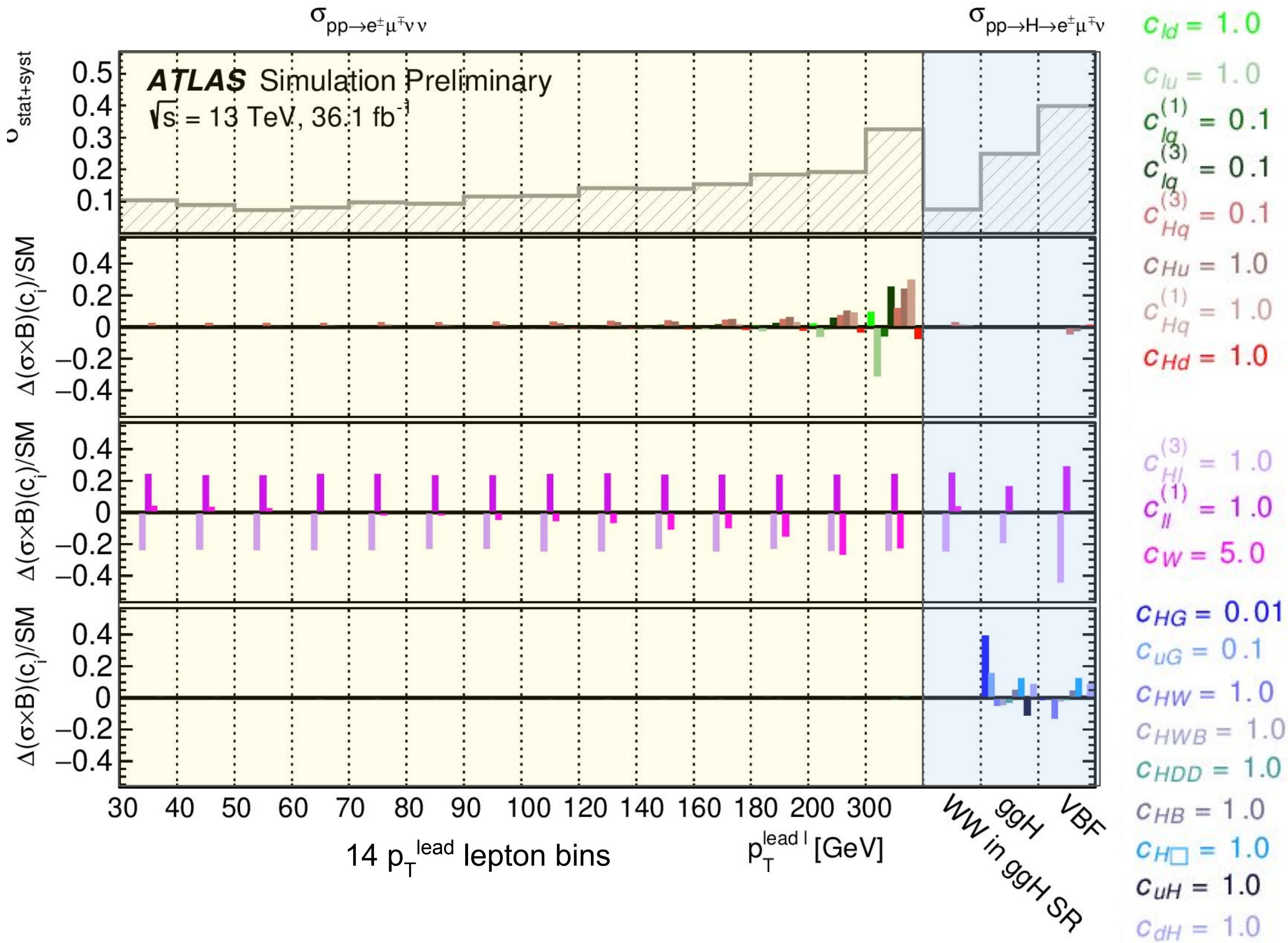




- Interpretation uses 36/fb H->WW* and WW measurement
- EFT fit combined HWW signal strength measurements with WW unfolded $p_T^{\text{lead lep.}}$ distribution
- WW CR of H->WW is replaced by WW measurement

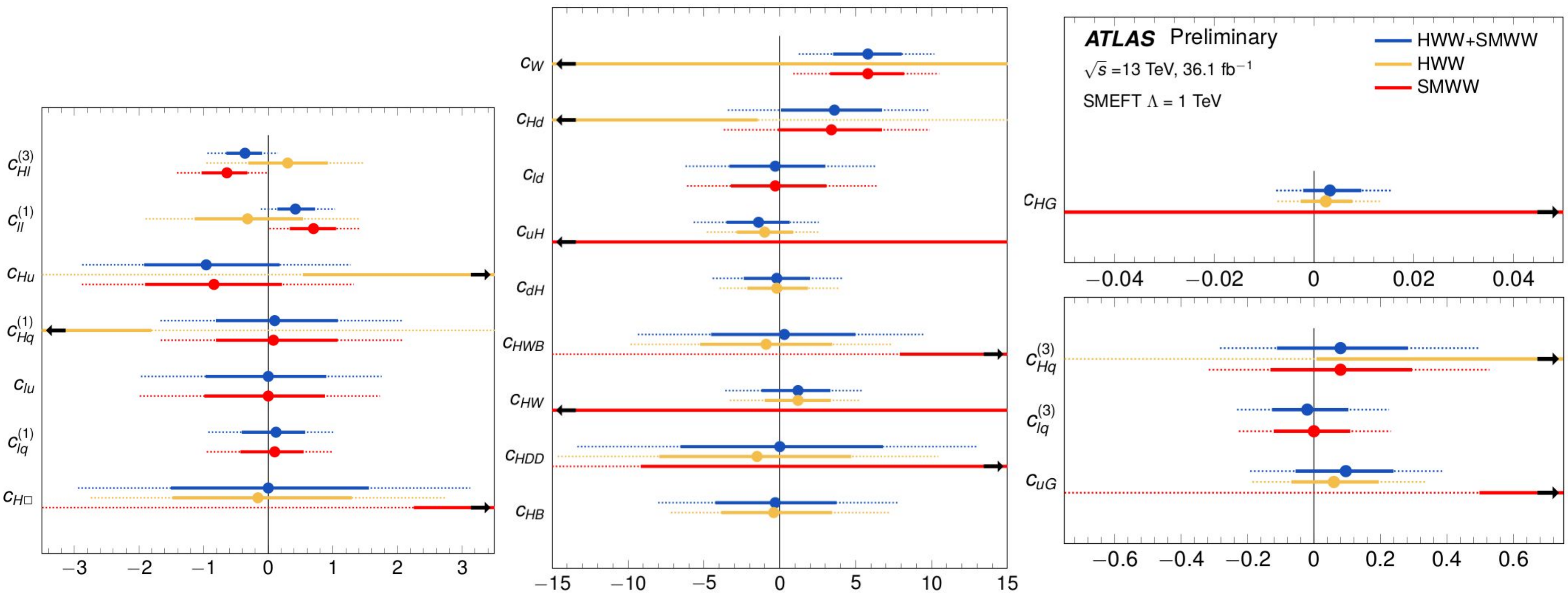
2 signal strength parameters + 14 $p_T^{\text{lead lep.}}$ bins

Sensitivity of Wilson coefficients



Wilson coefficient limits

- Limits for 20 CP-even Wilson coefficients
  - Fitting single Wilson coefficient while fixing the other coefficients to zero
  - Agrees with SM prediction at the level of 2σ or better
  - Measured coefficients with higher sensitivities:
    - C_{HG} , C_{uG} : ggF Higgs production
    - $C^{(3)}_{Hq}$: qq->WW and VBF Higgs production
    - $C^{(3)}_{lq}$: high energy p_T^{lead} lepton tail



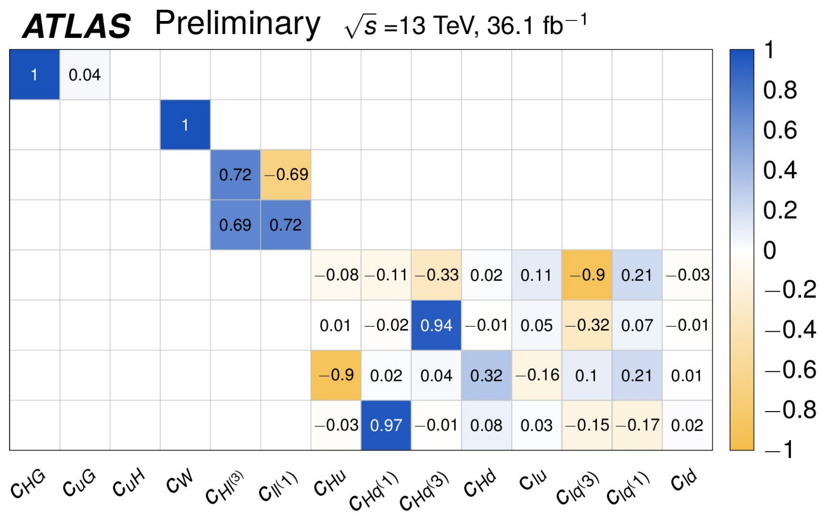
Rotation in coefficient space

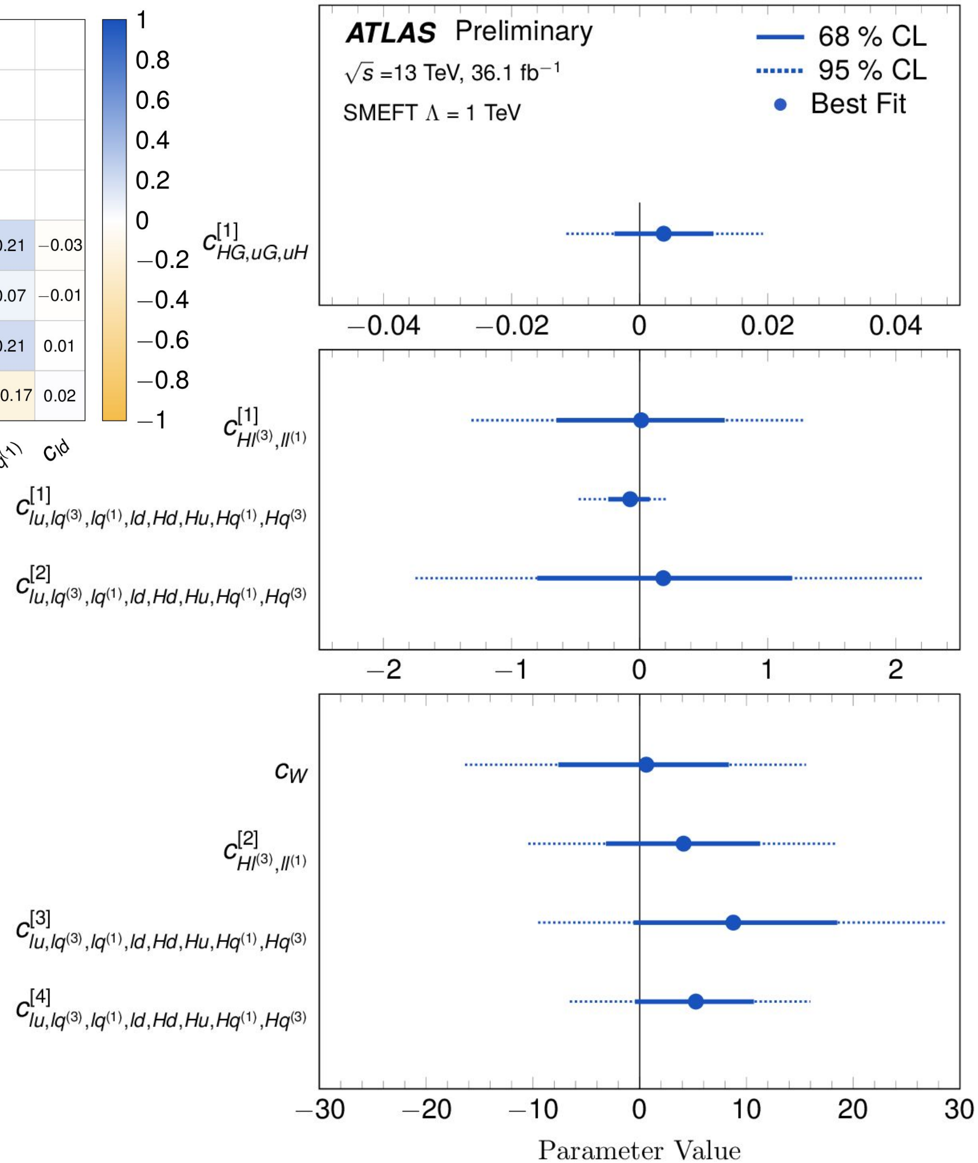
ggF H production

Weak boson Self couplings

G_F

Effective boson fermion, 4-fermion couplings





- ➢ Identify operator groups with similar impacts on process
- ➢ Eigenvector decomposition in each group to find the sensitive directions
- ➢ Simultaneous fit of 8 groups of Wilson coefficients

Conclusion and outlook

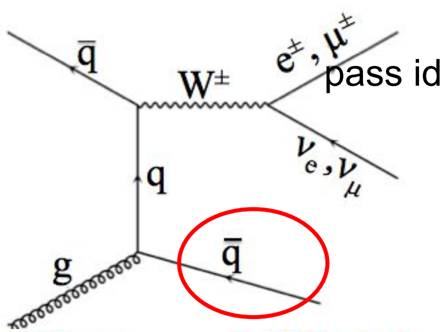
- H->WW* couplings measurements extended to full Run 2 (139/fb) dataset
  - $\sigma_{ggF} \times B_{H\to WW^*}$, $\sigma_{VBFF} \times B_{H\to WW^*}$ and STXS results consistent with SM prediction
  - VBF H->WW* observation achieved thanks to improved sensitivity using DNN
  - ggF+2jet channel included for the first time in Run-2
- EFT interpretation
  - Constraint effects of 20 CP-even Wilson coefficients individually
  - Simultaneous fit of 8 groups of Wilson coefficients
  - No significant deviations from SM prediction
  - Proof-of-principle: Methods build towards extended usage
- Outlook
  - Current published results already provide high competitive sensitivity
  - Still room to improve full Run 2 results
    - Improve lepton identification, btagging
    - Theory uncertainties
    - Finer granularity for STXS bins (for example ggF 2 jet)
  - VH production mode to come
  - Extend the EFT interpretation to new results

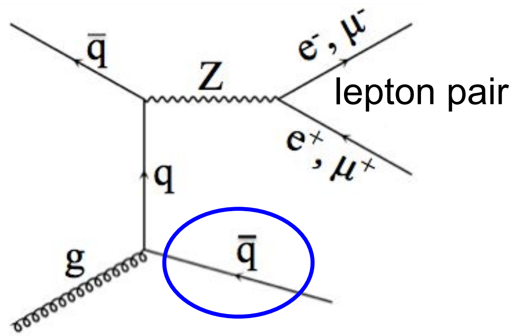
Thank you !

Back up

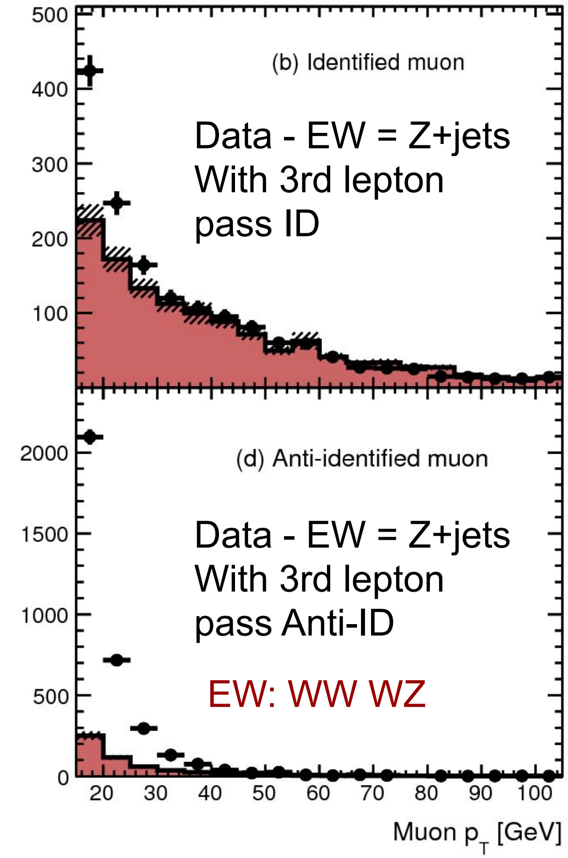
Misidentified Leptons

- 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





Z+jet control region



3rd reconstructed lepton

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

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

Fake Factor

Correction Factor

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

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.

<table>
<tr><th>Category</th><th>$N_{\text{jet},(p_T>30\ \text{GeV})} = 0$ ggF</th><th>$N_{\text{jet},(p_T>30\ \text{GeV})} = 1$ ggF</th><th>$N_{\text{jet},(p_T>30\ \text{GeV})} \geq 2$ VBF</th></tr>
<tr><td rowspan="2">Preselection</td><td colspan="3">Two isolated, different-flavour leptons ($\ell = e, \mu$) with opposite charge
$p_T^{\text{lead}} > 22$ GeV, $p_T^{\text{sublead}} > 15$ GeV
$m_{\ell\ell} > 10$ GeV</td></tr>
<tr><td colspan="2">$p_T^{\text{miss}} > 20$ GeV</td><td></td></tr>
<tr><td rowspan="3">Background rejection</td><td colspan="3">$N_{b\text{-jet},(p_T>20\ \text{GeV})} = 0$</td></tr>
<tr><td rowspan="2">$\Delta\phi(\ell\ell, E_T^{\text{miss}}) > \pi/2$
$p_T^{\ell\ell} > 30$ GeV</td><td>$\max\left(m_T^{\ell}\right) > 50$ GeV</td><td></td></tr>
<tr><td colspan="2">$m_{\tau\tau} < m_Z - 25$ GeV</td></tr>
<tr><td>$H \to WW^* \to e\nu\mu\nu$ topology</td><td colspan="2">$m_{\ell\ell} < 55$ GeV
$\Delta\phi_{\ell\ell} < 1.8$</td><td>central jet veto
outside lepton veto</td></tr>
<tr><td>Discriminant variable
BDT input variables</td><td colspan="2">m_T</td><td>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}</td></tr>
</table>

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="2">$t\bar{t}/Wt$</td><td rowspan="2">$N_{b\text{-jet},(20\ \text{GeV}<p_\mathrm{T}<30\ \text{GeV})}>0$
$\Delta\phi(\ell\ell,E_\mathrm{T}^{\text{miss}})>\pi/2$
$p_\mathrm{T}^{\ell\ell}>30$ GeV
$\Delta\phi_{\ell\ell}<2.8$</td><td>$N_{b\text{-jet},(p_\mathrm{T}>30\ \text{GeV})}=1$
$N_{b\text{-jet},(20\ \text{GeV}<p_\mathrm{T}<30\ \text{GeV})}=0$
$\max\left(m_\mathrm{T}^{\ell}\right)>50$ GeV</td><td>$N_{b\text{-jet},(p_\mathrm{T}>20\ \text{GeV})}=1$
central jet veto</td></tr>
<tr><td colspan="2">$m_{\tau\tau}<m_Z-25$ GeV
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>

STXS Higgs combination (ATLAS)