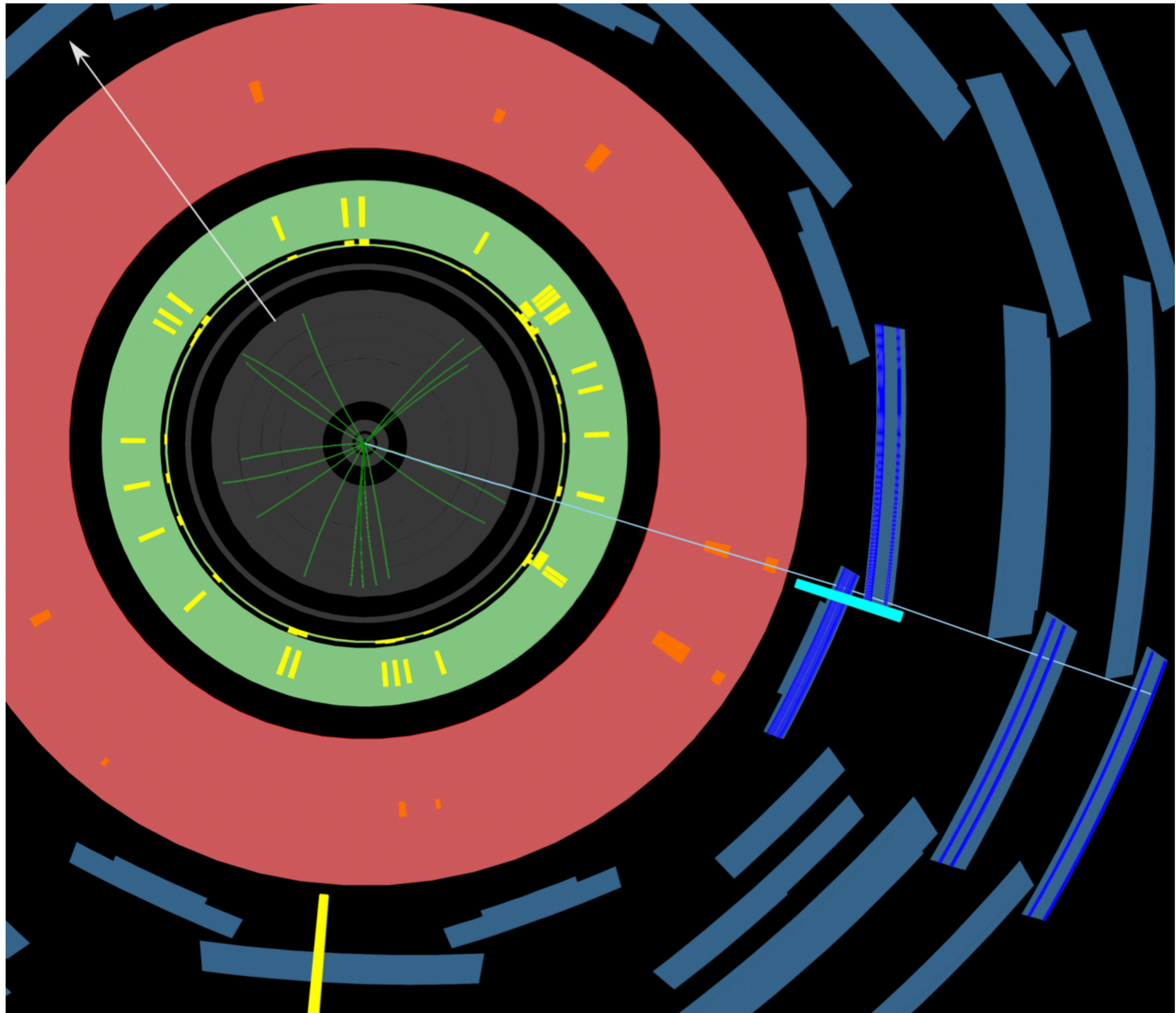
Measurements and interpretations of Simplified Template Cross Sections and differential and fiducial cross sections in Higgs boson decays to two W bosons with the ATLAS detector

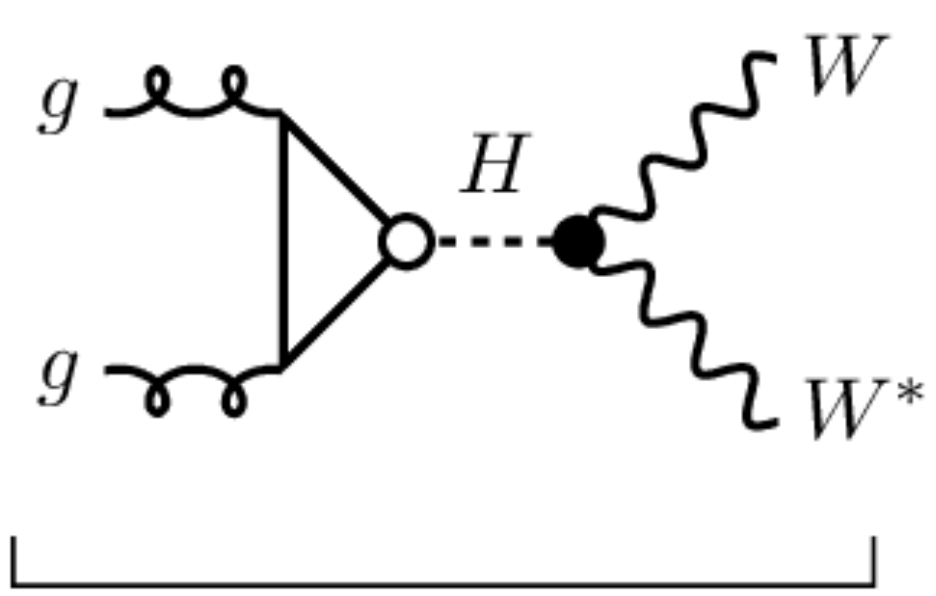


Higgs 2022

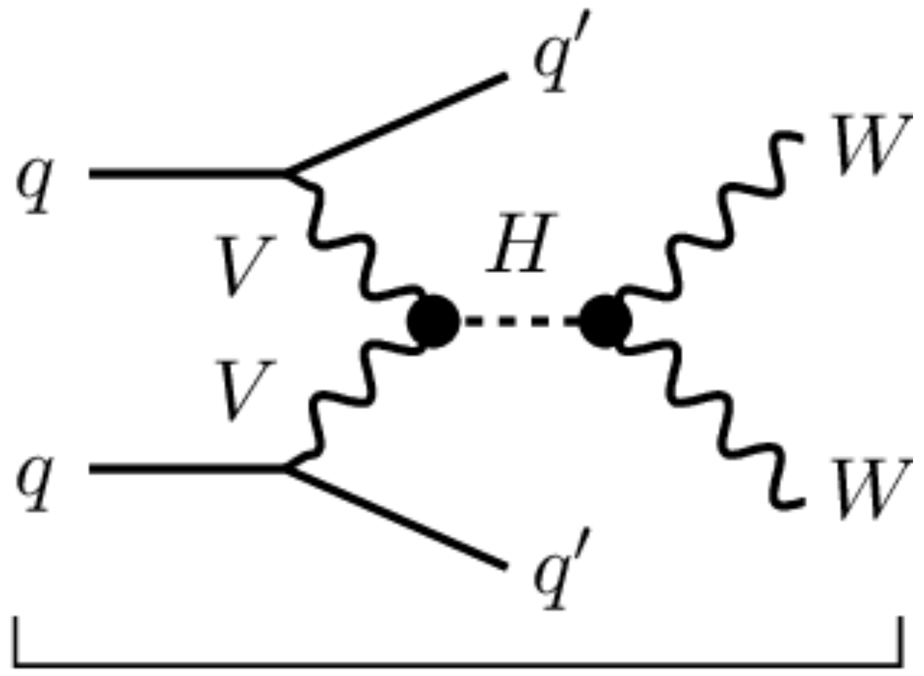
Maria Carnesale - 09/11/2022

Overview

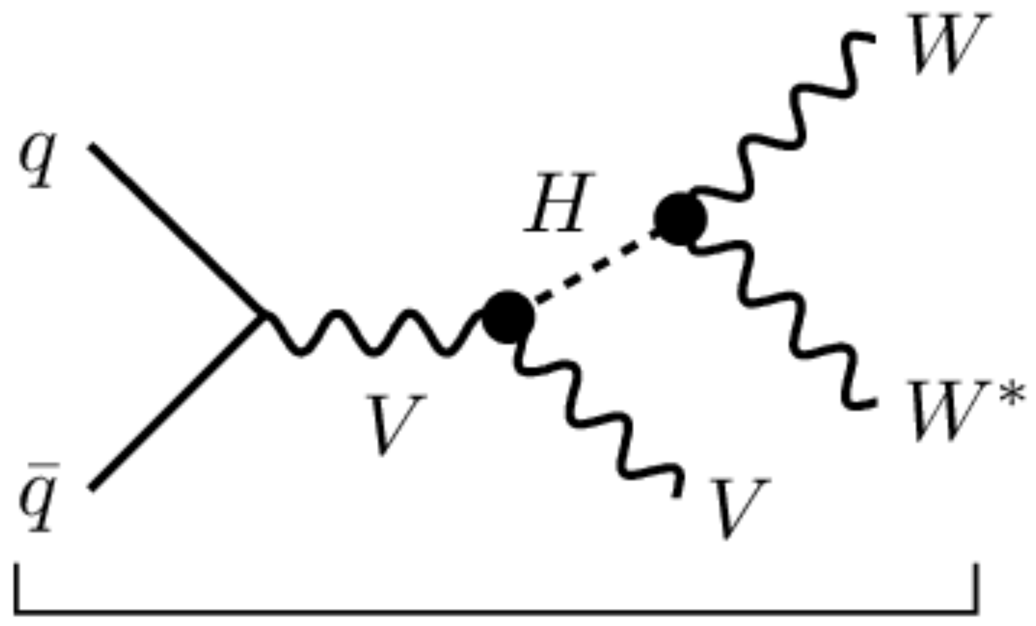
- $H \to WW^*$ coupling measurements and $H \to WW^*$ diff XS measurements with full Run 2 dataset
- For ggF, VBF and VH production modes



ggF production



VBF production



VH production

Full Run-2 Result

- pp collisions at $\sqrt{s} = 13 TeV$ at LHC
- Collected during Run 2 with the ATLAS detector

ggF+VBF: **(HIGG-2021-20)**

- Main changes with respect to the previous ATLAS measurement at $36\, fb^{-1}$
  - Addition of ggF ≥ 2-jet channel
  - Use of deep neural network (DNN) in VBF channel
  - Measurement of cross-sections in kinematic bins ("STXS")

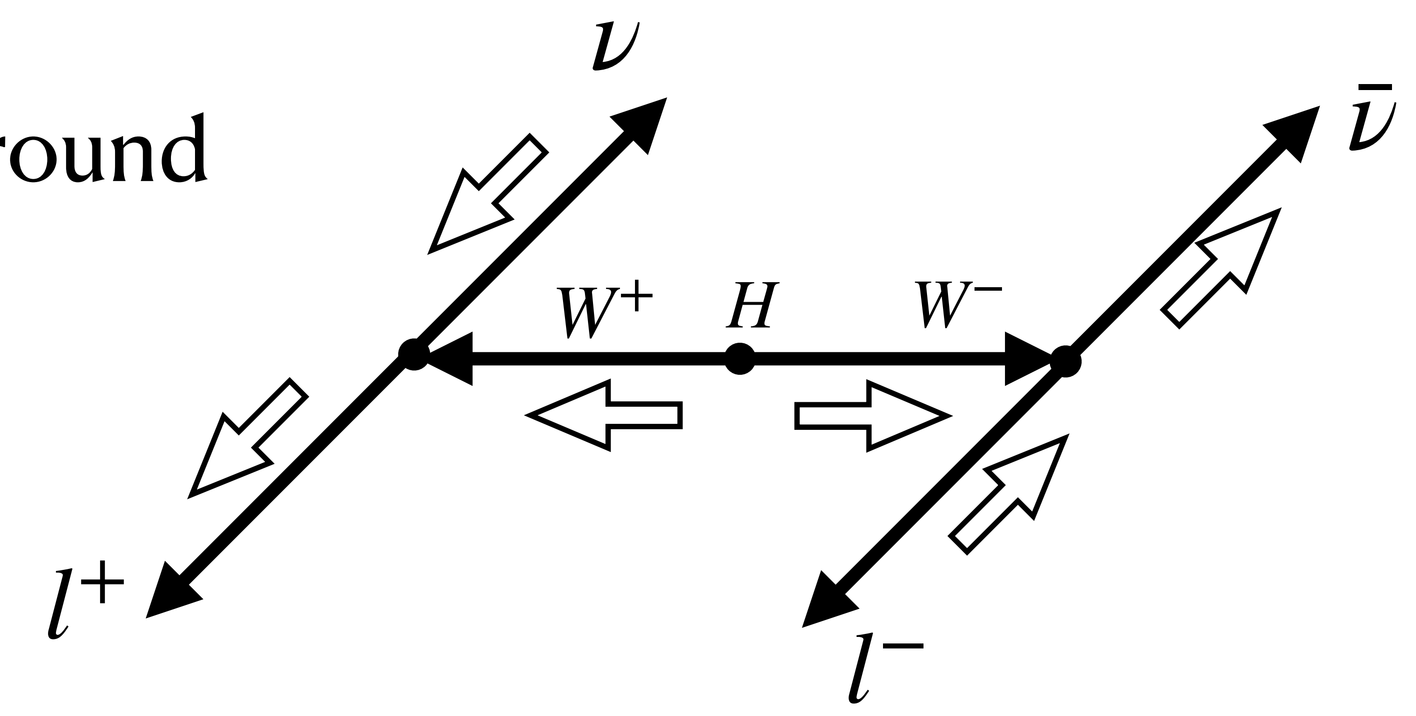
VH (ATLAS-CONF-2022-067):

- Addition wrt to previous ATLAS results at $36 fb^{-1}$
- Addition of 2 leptons channels
- Use of ANN and RNN in 2 leptons and 3 leptons channels

ggF and VBF selection

HIGG-2021-20

- Selection target features of $H \to WW^* \to e\nu\mu\nu$ decay and reduce some common background
  - Single-lepton and dilepton triggers with trigger matching
  - **2 different-flavour, opposite-charge leptons**
  - $p_T^{lead} > 22\ GeV, p_T^{subLead} > 15\ GeV$
  - $m_{ll} > 10\ GeV$
  - $p_T^{miss} > 20\ GeV$ (ggF channels only)



$N_{\text{jet},(p_T>30\text{ GeV})} = 0$ ggF	$N_{\text{jet},(p_T>30\text{ GeV})} = 1$ ggF	$N_{\text{jet},(p_T>30\text{ GeV})} \geq 2$ ggF	$N_{\text{jet},(p_T>30\text{ GeV})} \geq 2$ VBF
$m_{\ell\ell} < 55$ GeV $\Delta\phi_{\ell\ell} < 1.8$		fail central jet veto or fail outside lepton veto $\|m_{jj} - 85\| > 15$ GeV or $\Delta y_{jj} > 1.2$	central jet veto outside lepton veto $m_{jj} > 120$ GeV
ggF 0-1 jet		**ggF 2 jet**	**VBF**

Discriminant

ggF 0-1 jet: m_T

ggF 2 jet: m_T

$$m_T = \sqrt{(E_T^{ll} + E_T^{miss})^2 + |\boldsymbol{p}_T^{ll} + \boldsymbol{E}_T^{miss}|^2}$$

VBF: DNN
Trained to identify VBF against any other process
Using 15 variables:
$m_{jj}, \Delta y_{jj}, p_T^{j_1}, p_T^{j_2}, p_T^{j_3},$
$\sum_l [|2\eta_l - \sum n_j|/\Delta\eta_{jj}], m_{ll}, \Delta\phi_{ll},$
$m_T, m_{l_1j_1}, m_{l_1j_2}, m_{l_2j_1}, m_{l_2j_2}$

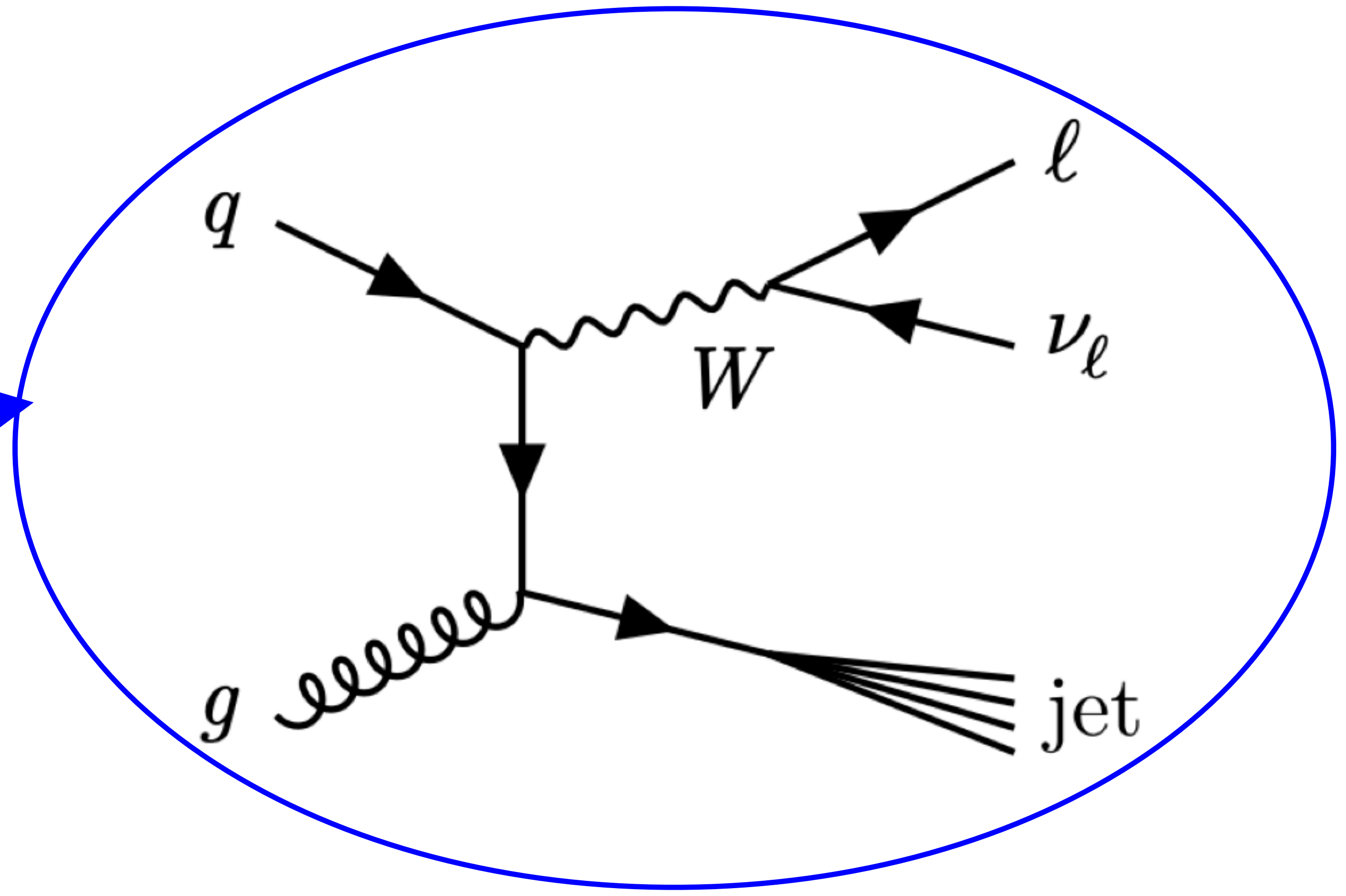
Background estimation

- WW, top and Z+jets : normalization constrained by the control region
- Mis-identified lepton: dominated by W+jets, data-driven method

Definition of 2 regions:
- ID+ID region: both leptons fulfilling analysis identification requirements
- ID+antiID: one of the two leptons fulfilling looser requirements

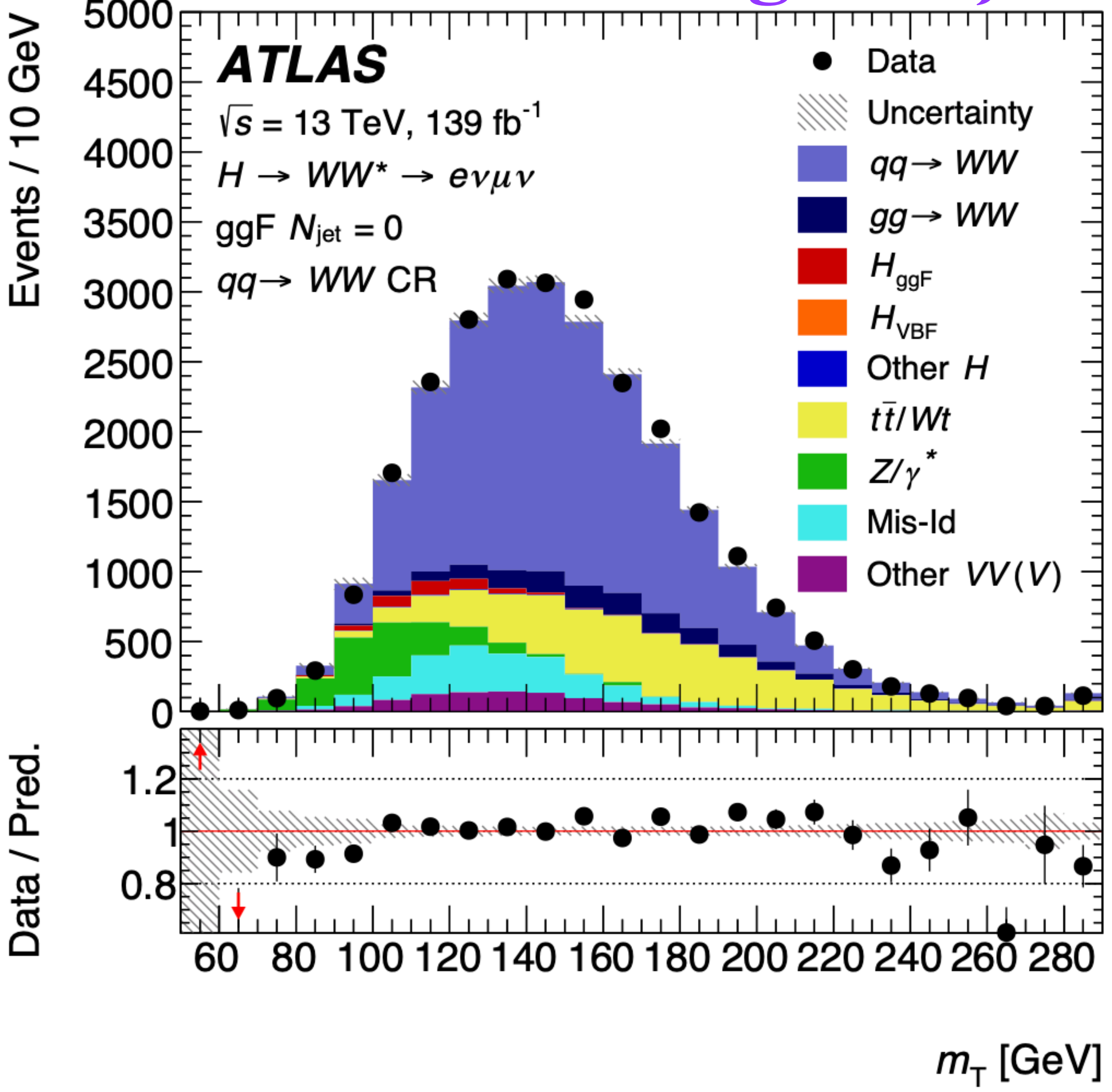
$$N^{W+jets}_{ID+ID} = FF_l \cdot N^{W+jets}_{ID+antiID}$$

Fake Factors from Z+jets

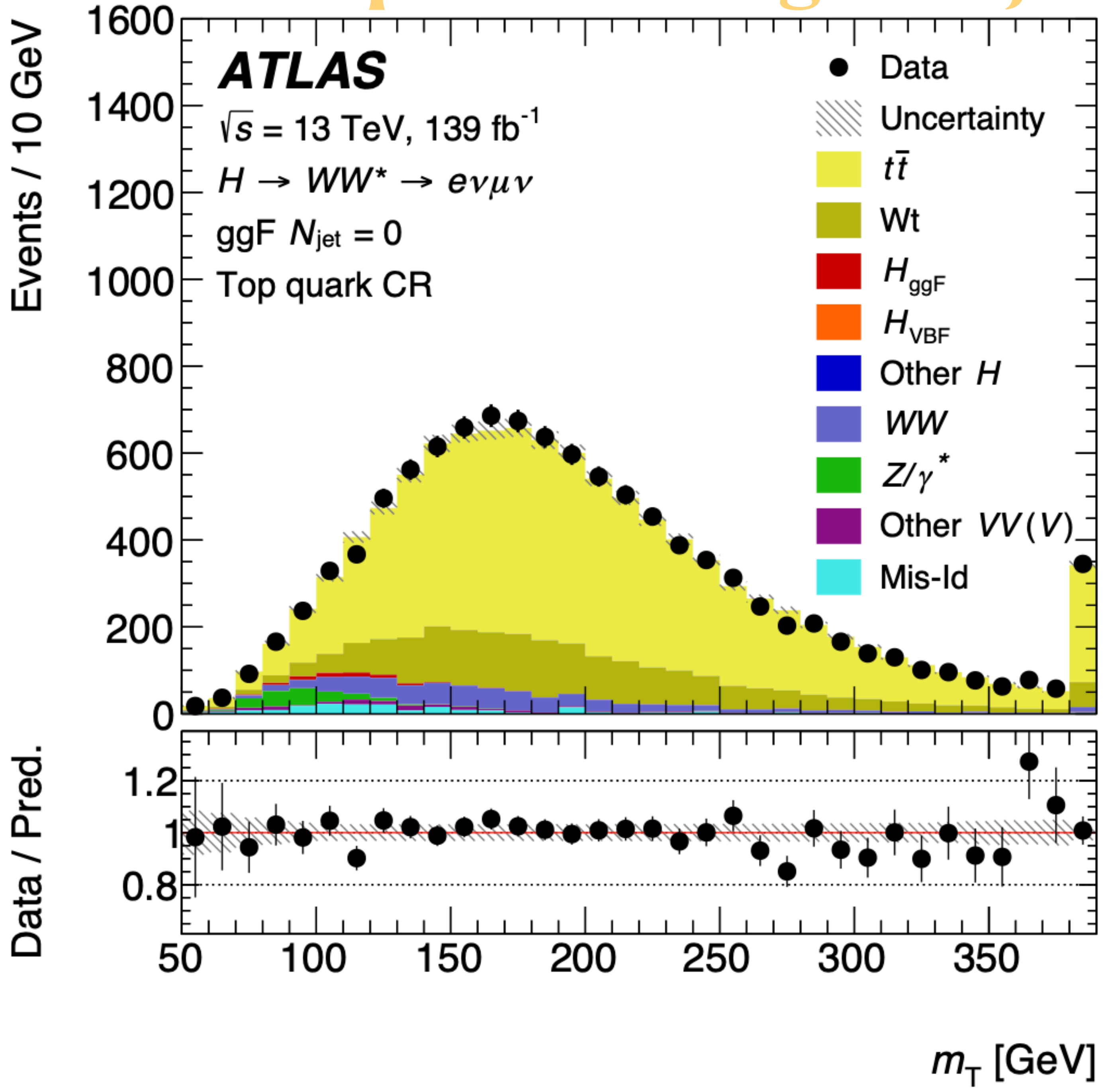


- Other diboson estimated from simulation

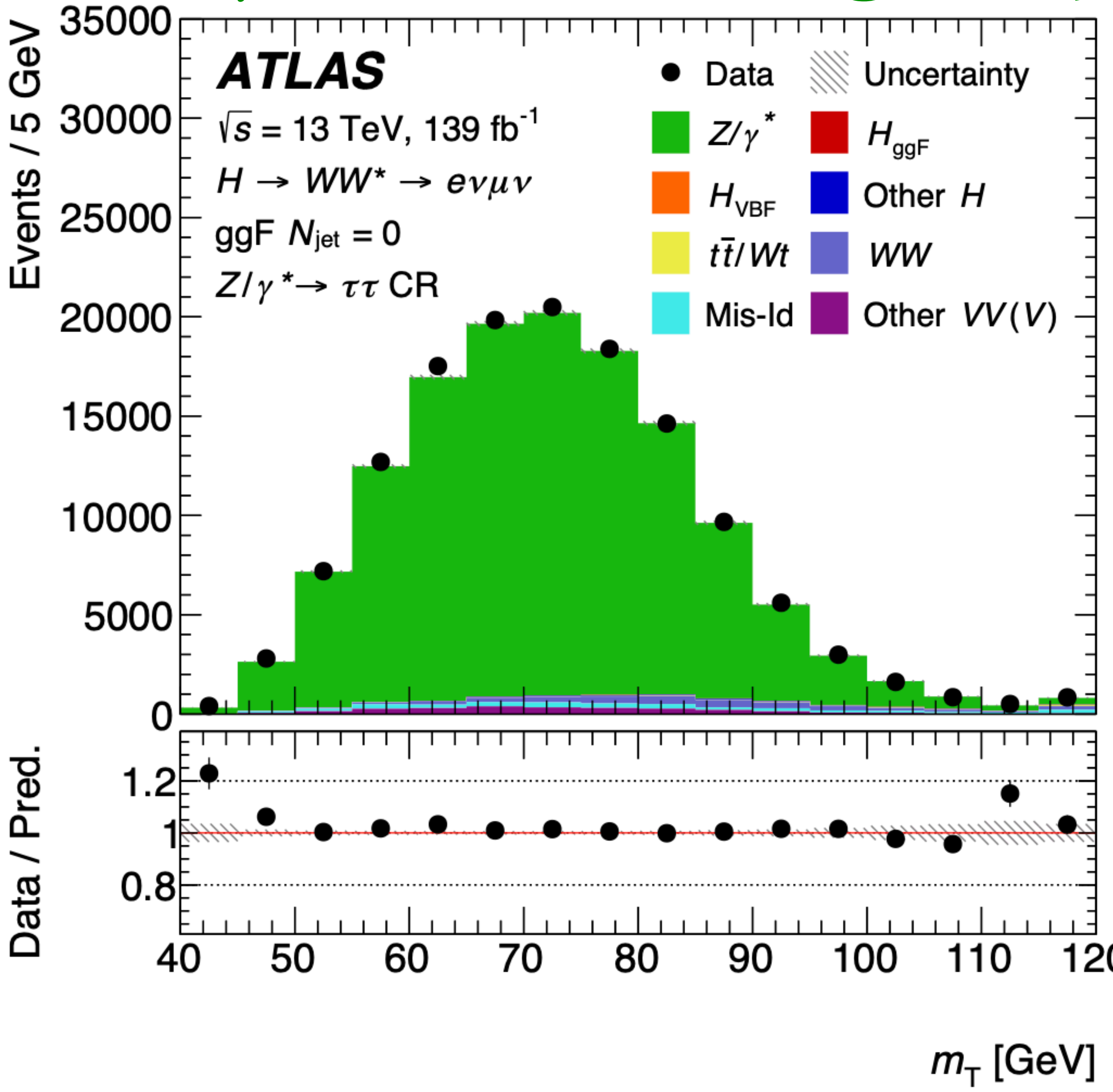
WW control region 0 jet



Top control region 0 jet

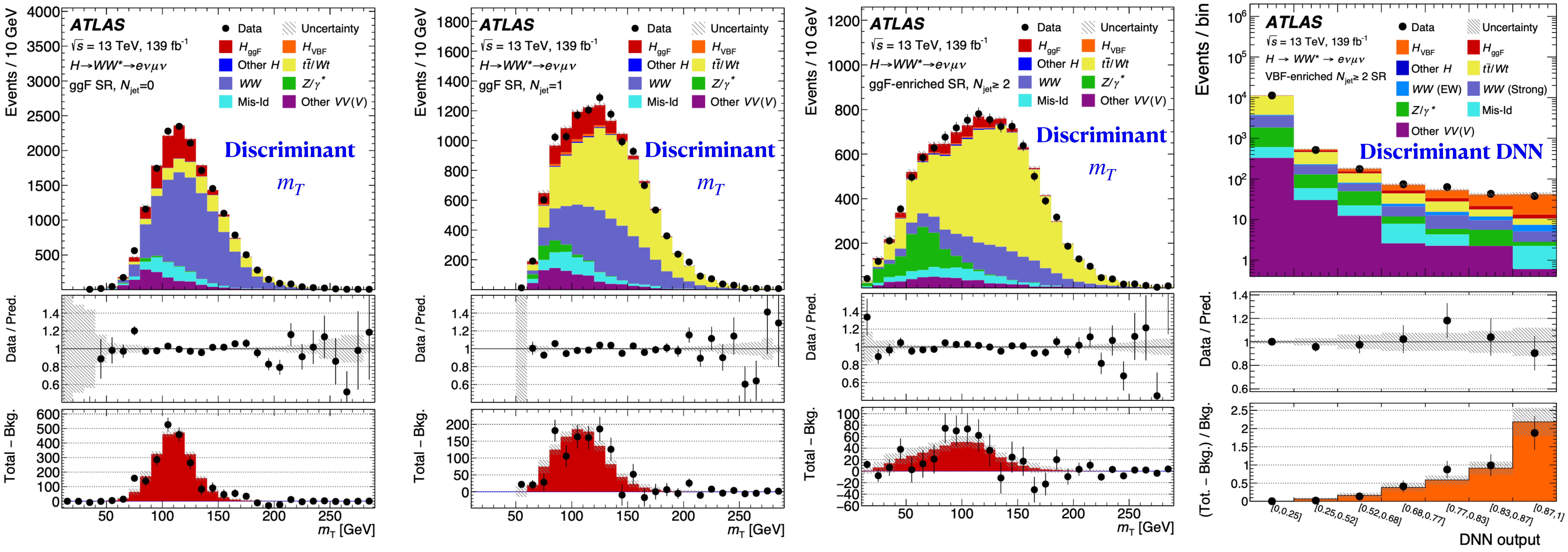


$Z/\gamma \rightarrow \tau\tau$ control region 0 jet

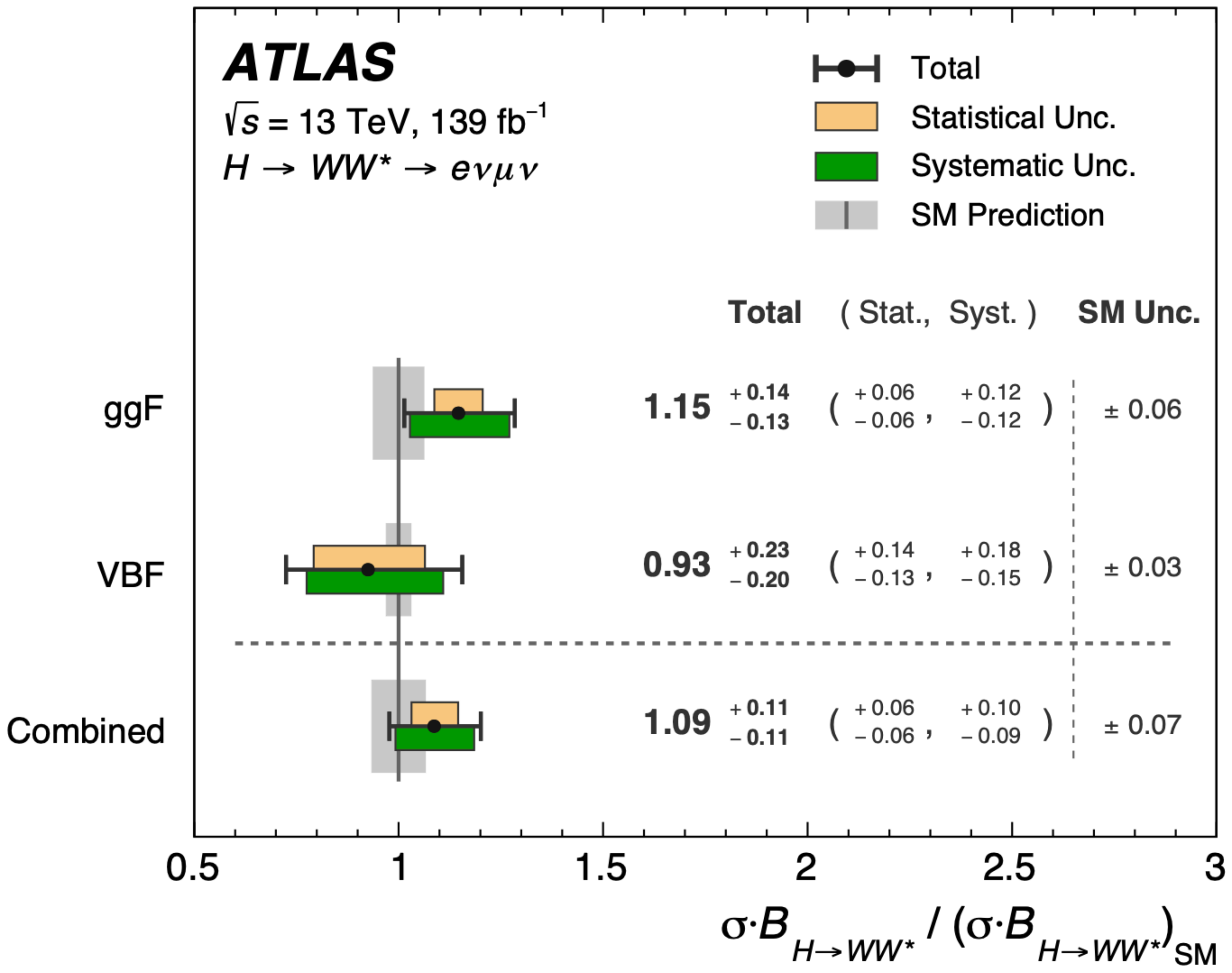


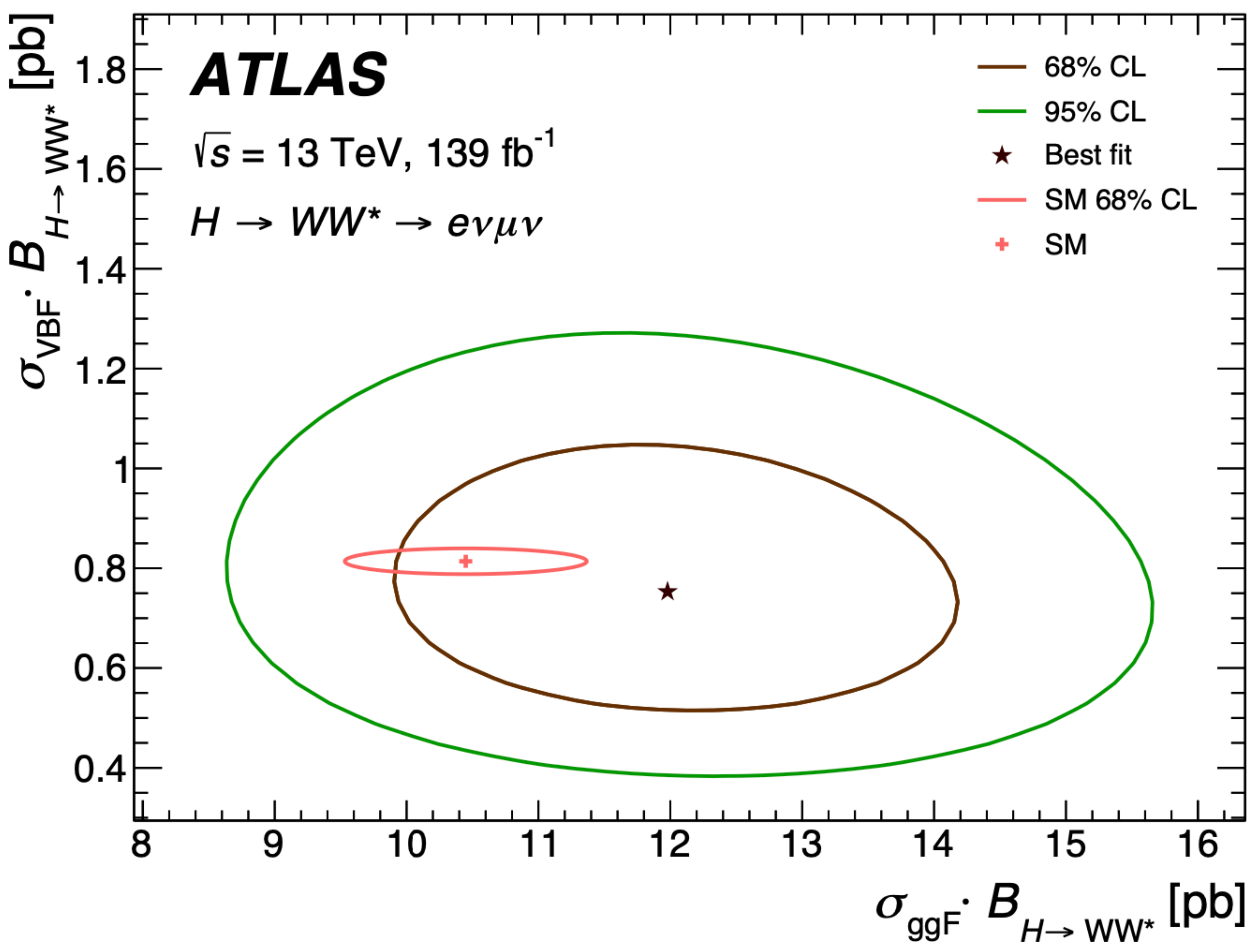
ggF+VBF measurement

- Good post fit modeling in all the 4 signal regions
- VBF-enriched 2 jets: DNN increase signal fraction from 27% to 74% compared to previous analysis BDT in last bin
- ggF and VBF signal strengths measurement with profile likelihood fit to data in SRs and CRs



ggF+VBF measurement





Simultaneous measurement of ggF and VBF signal strengths shows good consistency with the SM

Dominated by systematic uncertainties

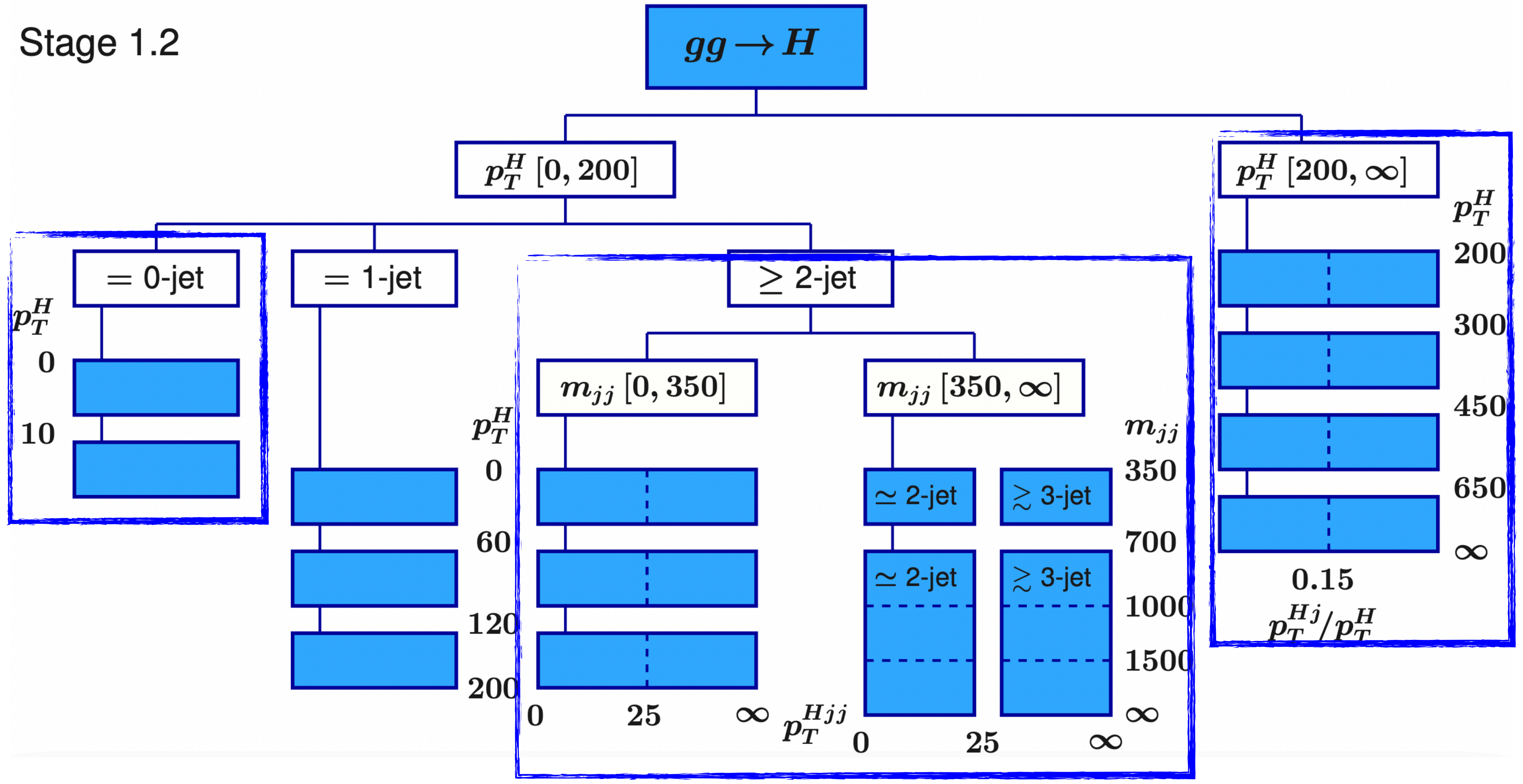
ggF: uncertainties from experimental and theoretical sources are comparable

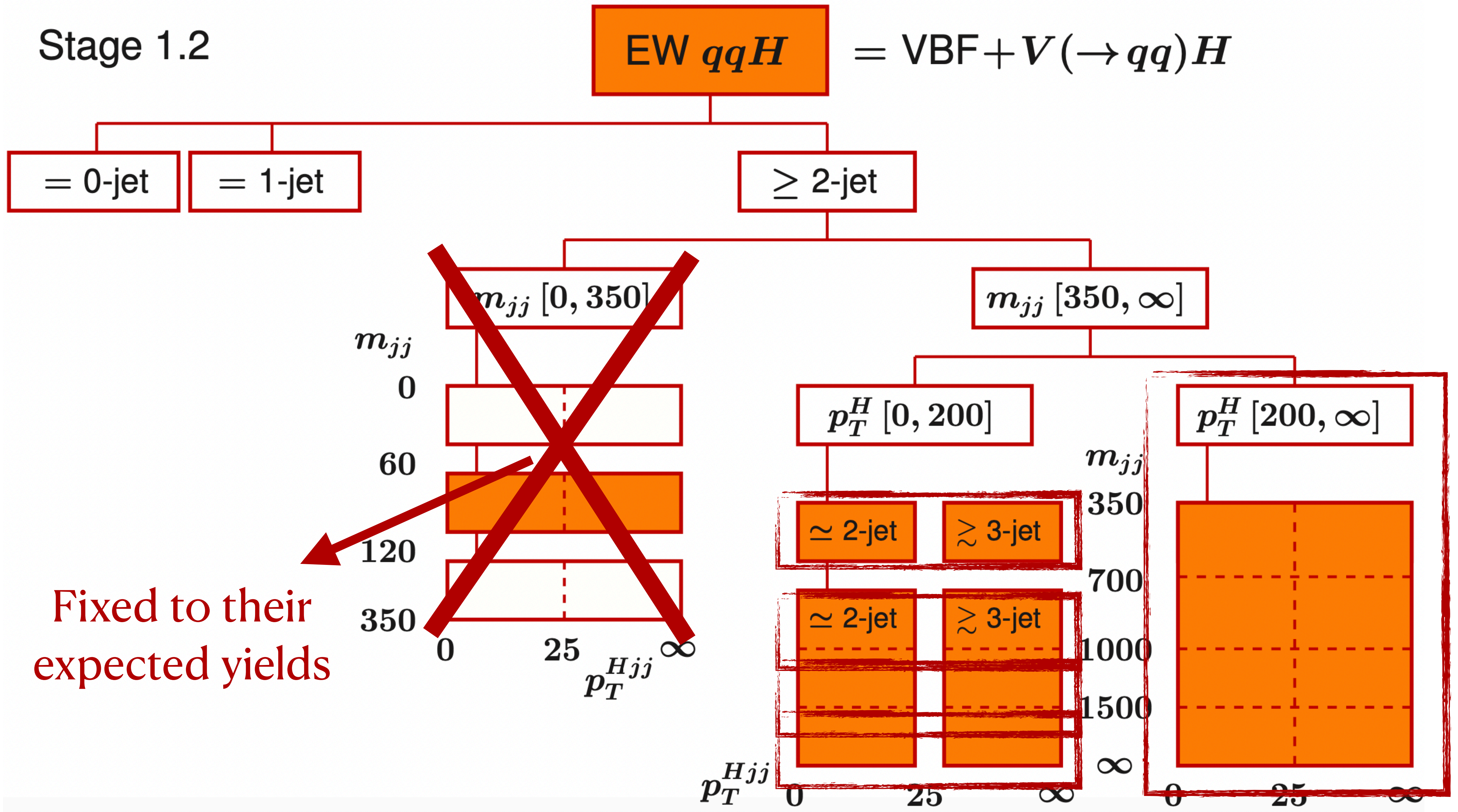
VBF: signal theory unc. are the largest contribution: dominant → modeling of potential jets in addition to the tagging jets.

Source	$\frac{\Delta\sigma_{ggF+VBF}\cdot\mathcal{B}_{H\to WW^*}}{\sigma_{ggF+VBF}\cdot\mathcal{B}_{H\to WW^*}}$ [%]	$\frac{\Delta\sigma_{ggF}\cdot\mathcal{B}_{H\to WW^*}}{\sigma_{ggF}\cdot\mathcal{B}_{H\to WW^*}}$ [%]	$\frac{\Delta\sigma_{VBF}\cdot\mathcal{B}_{H\to WW^*}}{\sigma_{VBF}\cdot\mathcal{B}_{H\to WW^*}}$ [%]
Data statistical uncertainties	4.6	5.1	15
Total systematic uncertainties	9.5	11	18
MC statistical uncertainties	3.0	3.8	4.9
Experimental uncertainties	5.2	6.3	6.7
Flavor tagging	2.3	2.7	1.0
Jet energy scale	0.9	1.1	3.7
Jet energy resolution	2.0	2.4	2.1
E_T^{miss}	0.7	2.2	4.9
Muons	1.8	2.1	0.8
Electrons	1.3	1.6	0.4
Fake factors	2.1	2.4	0.8
Pileup	2.4	2.5	1.3
Luminosity	2.1	2.0	2.2
Theoretical uncertainties	6.8	7.8	16
ggF	3.8	4.3	4.6
VBF	3.2	0.7	12
WW	3.5	4.2	5.5
Top	2.9	3.8	6.4
$Z\tau\tau$	1.8	2.3	1.0
Other *VV*	2.3	2.9	1.5
Other Higgs	0.9	0.4	0.4
Background normalizations	3.6	4.5	4.9
WW	2.2	2.8	0.6
Top	1.9	2.3	3.4
$Z\tau\tau$	2.7	3.1	3.4
Total	10	12	23

Measurements in STXS: ggF + VBF

- Results are extended with measurement of cross-sections in kinematic bins prescribed by the Simplified Template Cross-Section (STXS) framework
- Cross-section measured are defined by STXS Stage 1.2 splitting, with bins merged according to analysis sensitivity

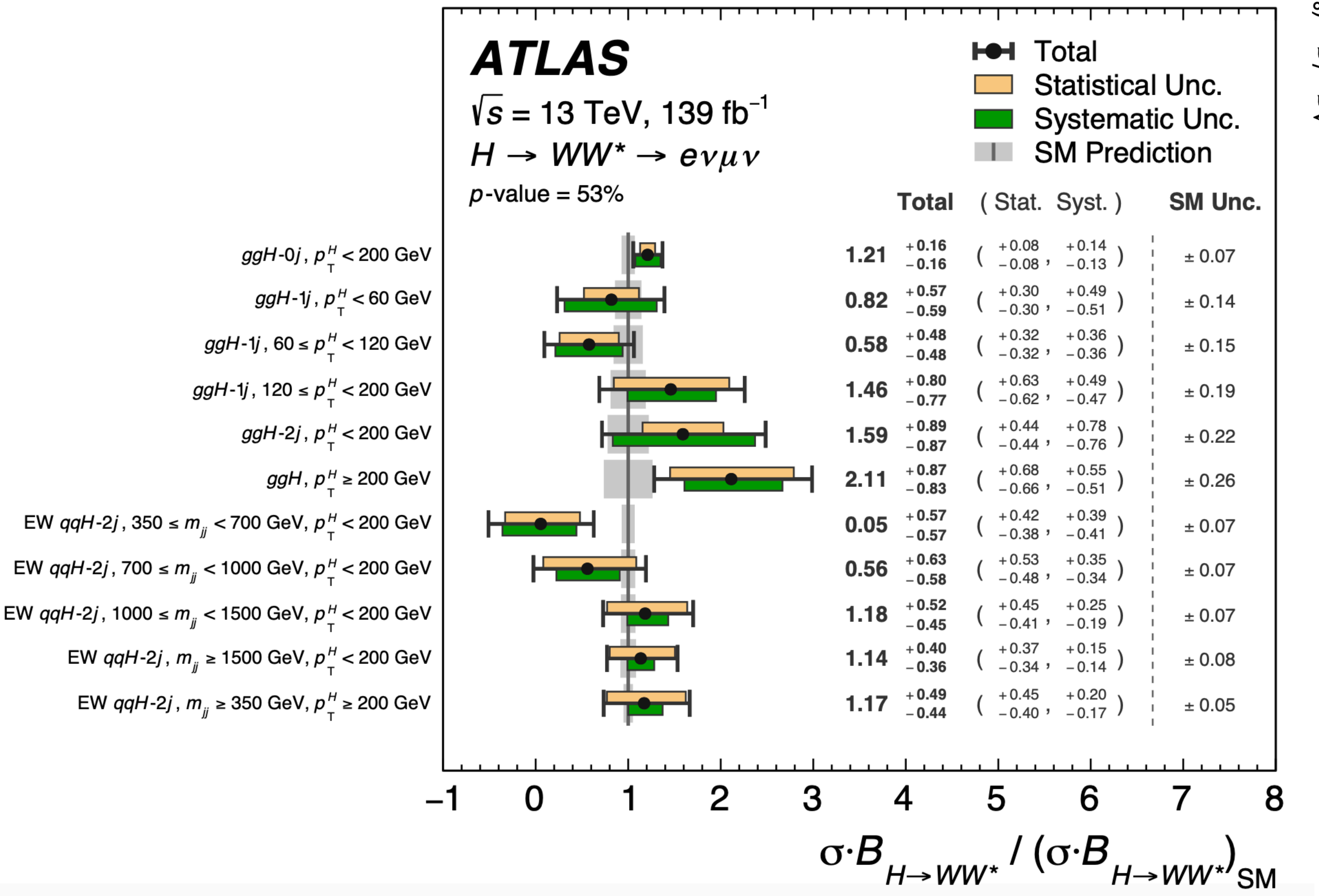


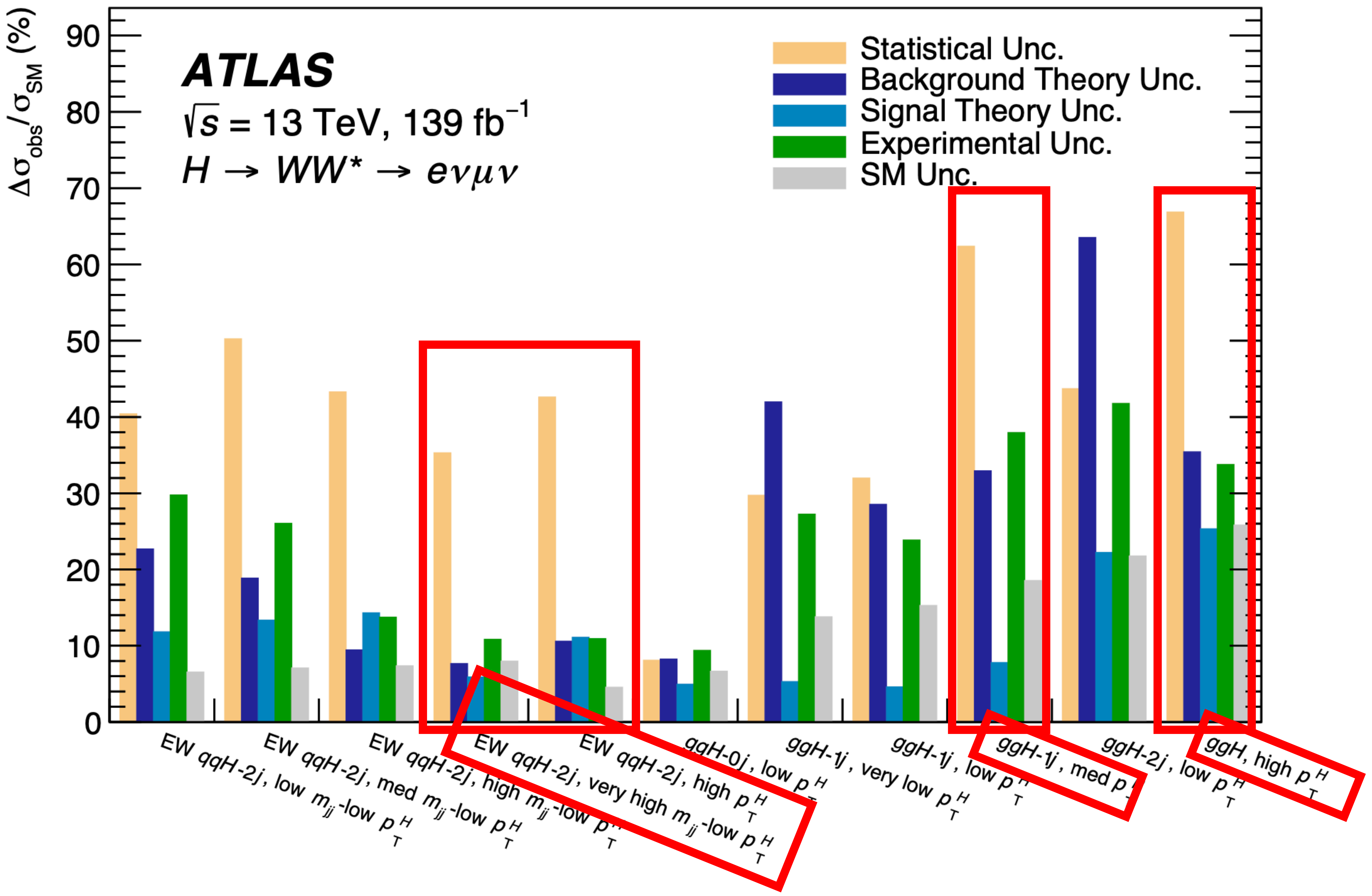


ggH production:
6 POIs, targeted by 0, 1 and ≥ 2-jet ggF signal regions further split by p_T^H.

EW qqH production:
5 POIs, targeted by ≥ 2-jet VBF signal region split by m_{jj}, p_T^H.

Measurements in STXS: ggF + VBF





- **Low p_T^H, m_{jj}**: syst ≥ stat unc.
- **High p_T^H, m_{jj}**: stat. limited
- Compatible with SM
- EW qqH sensitivity comparable with latest ATLAS HZZ^*, $H\gamma\gamma$, VH(bb) STXS combination

Differential XS for ggF production

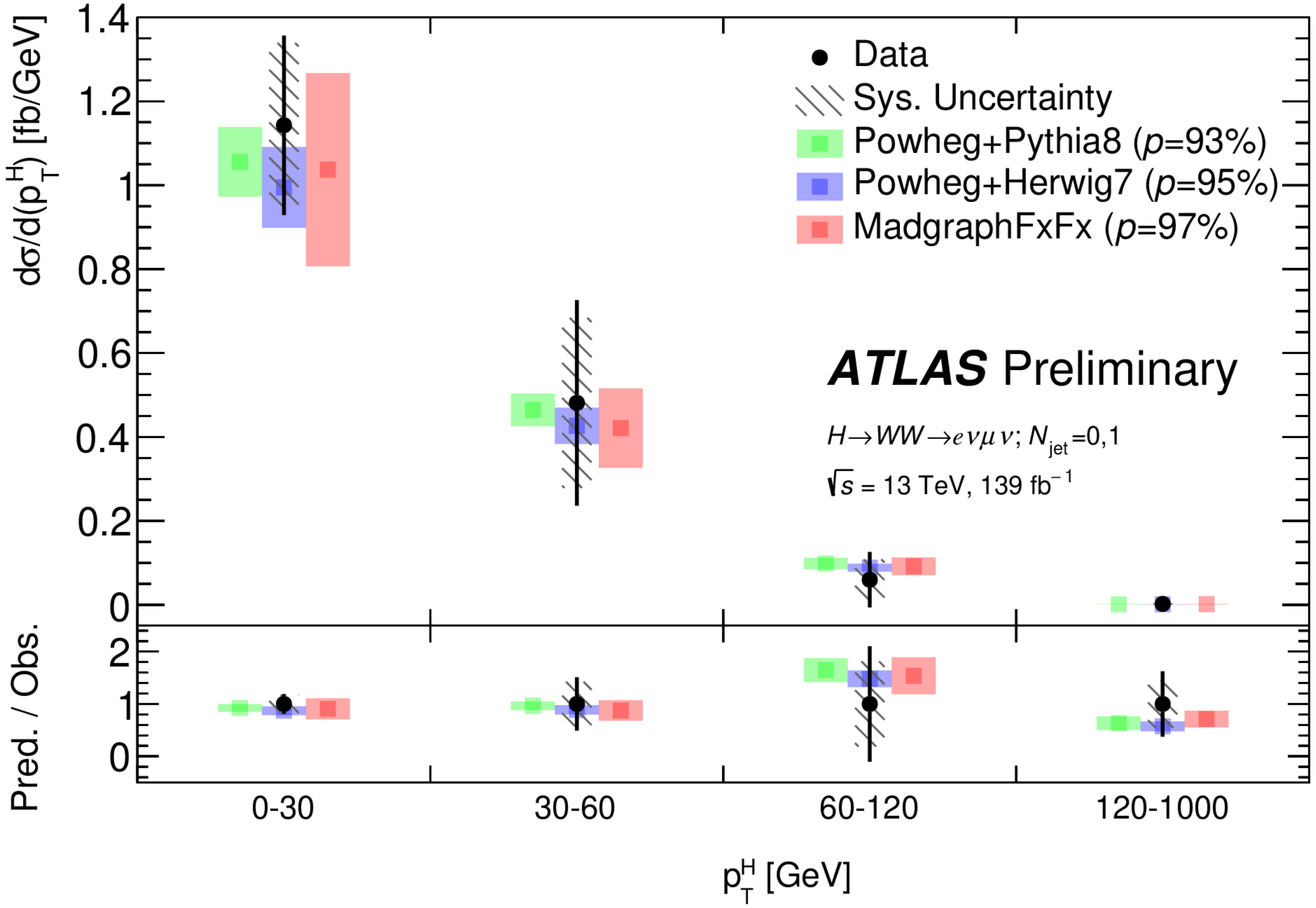
Signal region definition

Category	$N_{\text{jet},(p_T>30\text{ GeV})}=0$	$N_{\text{jet},(p_T>30\text{ GeV})}=1$
Common Selection	Exactly two isolated leptons ($\ell=e,\mu$) with opposite charge $p_T^{\text{lead}}>22$ GeV , $p_T^{\text{sublead}}>15$ GeV $\lvert\eta_e\rvert<2.5$, $\lvert\eta_\mu\rvert<2.5$, $p_T^{jet}>30$ GeV $m_{\ell\ell}>10$ GeV $E_T^{\text{miss, track}}>20$ GeV	
Background rejection	$N_{b\text{-jet},(p_T>20\text{ GeV})}=0$	
	$\Delta\phi(\ell\ell,E_T^{\text{miss}})>\pi/2$ $p_T^{\ell\ell}>30$ GeV	$\max(m_T^\ell)>50$ GeV $m_{\tau\tau}<m_Z-25$ GeV
	$m_T>80$ GeV	
$H\to WW^*\to\ell\nu\ell\nu$ topology	$m_{\ell\ell}<55$ GeV $\Delta\phi_{\ell\ell}<1.8$	

$|y|<2.47$and gaps are excluded $1.37<|y|<1.52$

Fiducial region definition

Same cuts at particle level + $|y_{ll}|<2.5$ to match ATLAS coverage constraints



Other measured distributions

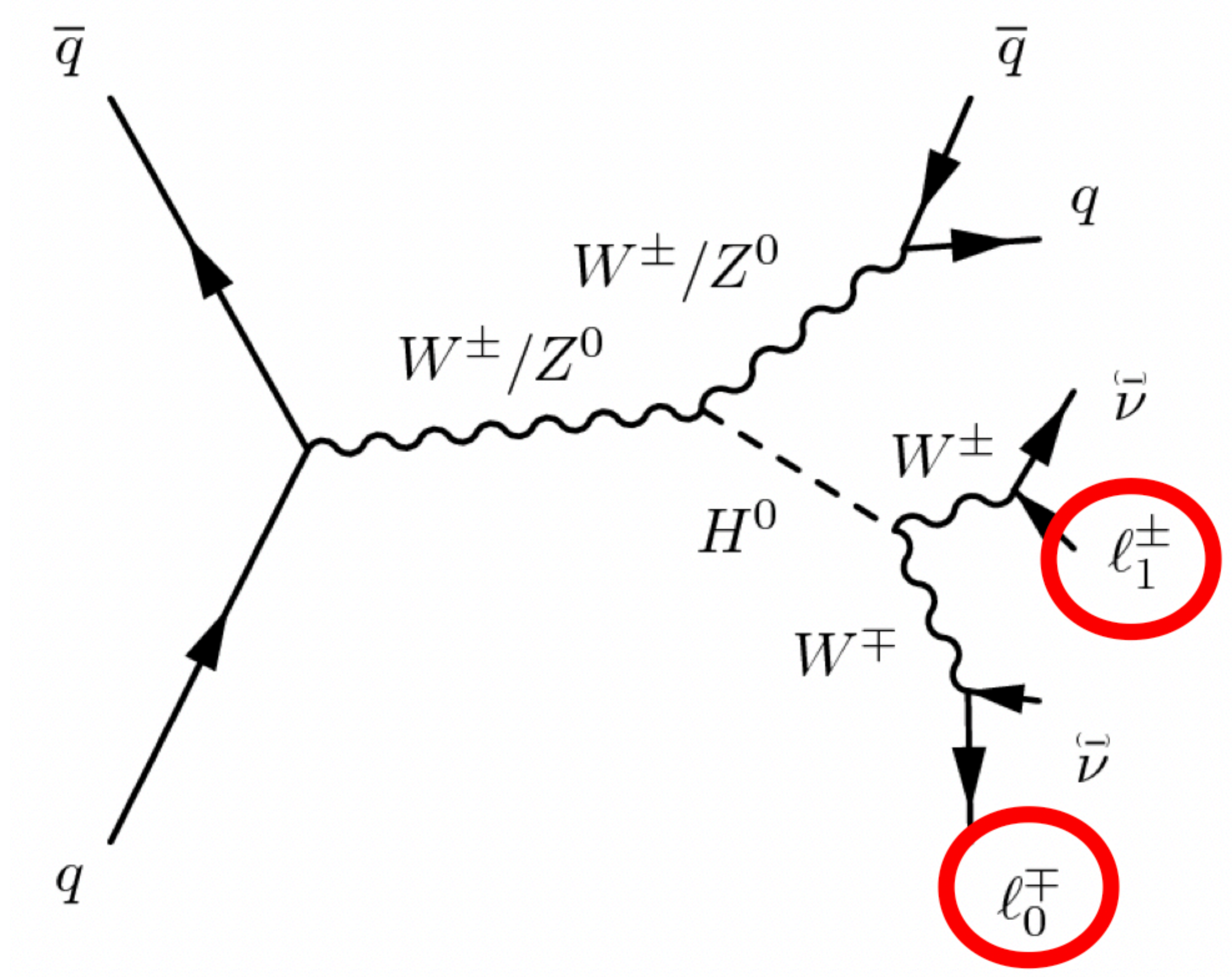
$|y_{j0}|, p_T^H, p_T^{l0}, p_T^{ll}, m_{ll}, y_{ll}, \Delta\phi_{ll}, cos(\theta*)$

- **Leading uncertainties:**
  - related to jet and muon reconstruction
  - theory uncertainties associated with the top and WW and with $V\gamma$ modelling
  - data-driven bkg estimates for misid. objects and uncertainties related bkg normalization from CRs
- **No significant differences measured XS and their SM MC prediction** (p-value characterizes compatibility between data and predictions)
  - The total XS (sum over all bins) are compatible with each other for all observables

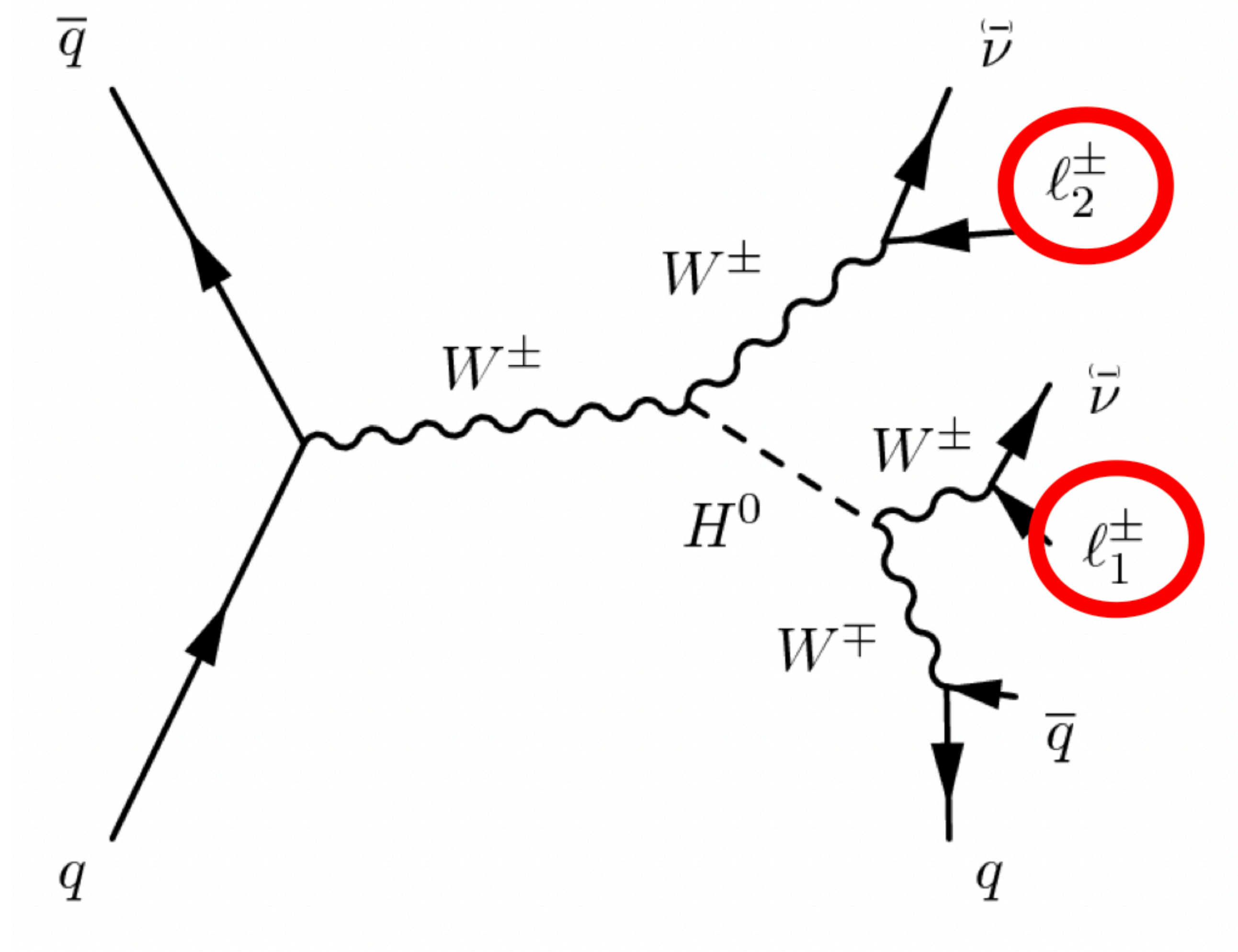
VH analysis strategy

ATLAS-CONF-2022-067

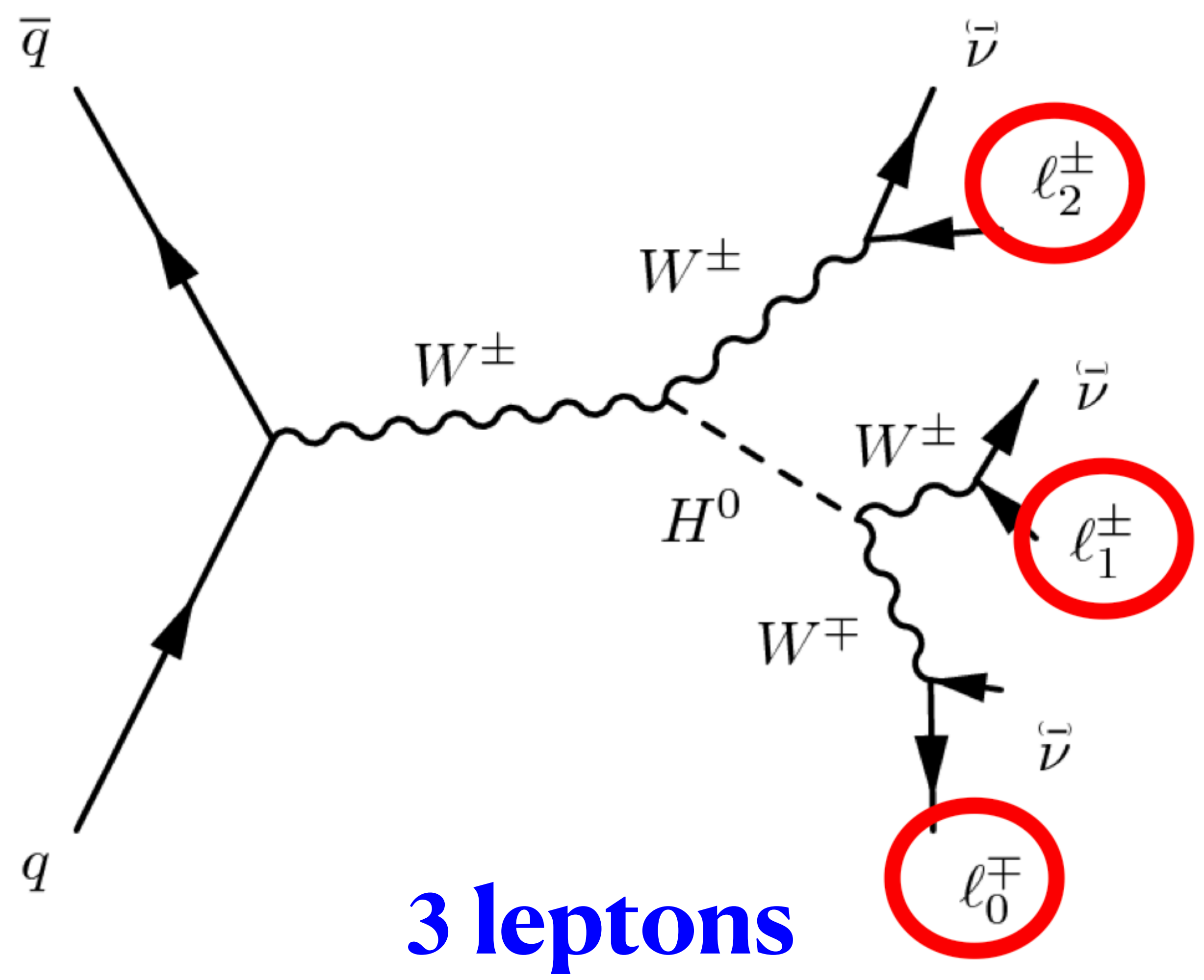
- Four channels targeting different signal signatures are analyzed with 6 categories
- **MVA is employed in all categories**



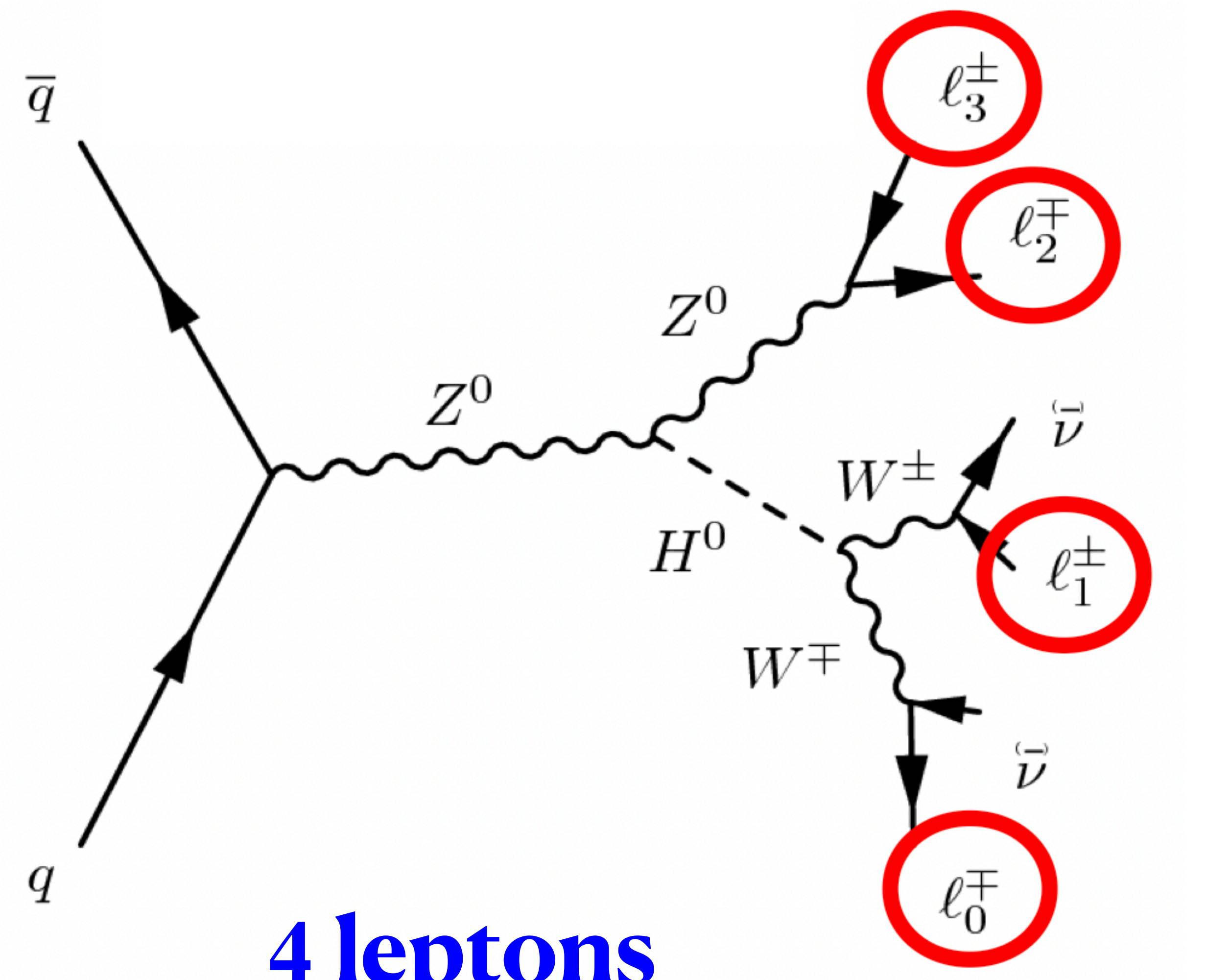
2 leptons opposite sign (OS)



2 leptons same sign (SS)



3 leptons



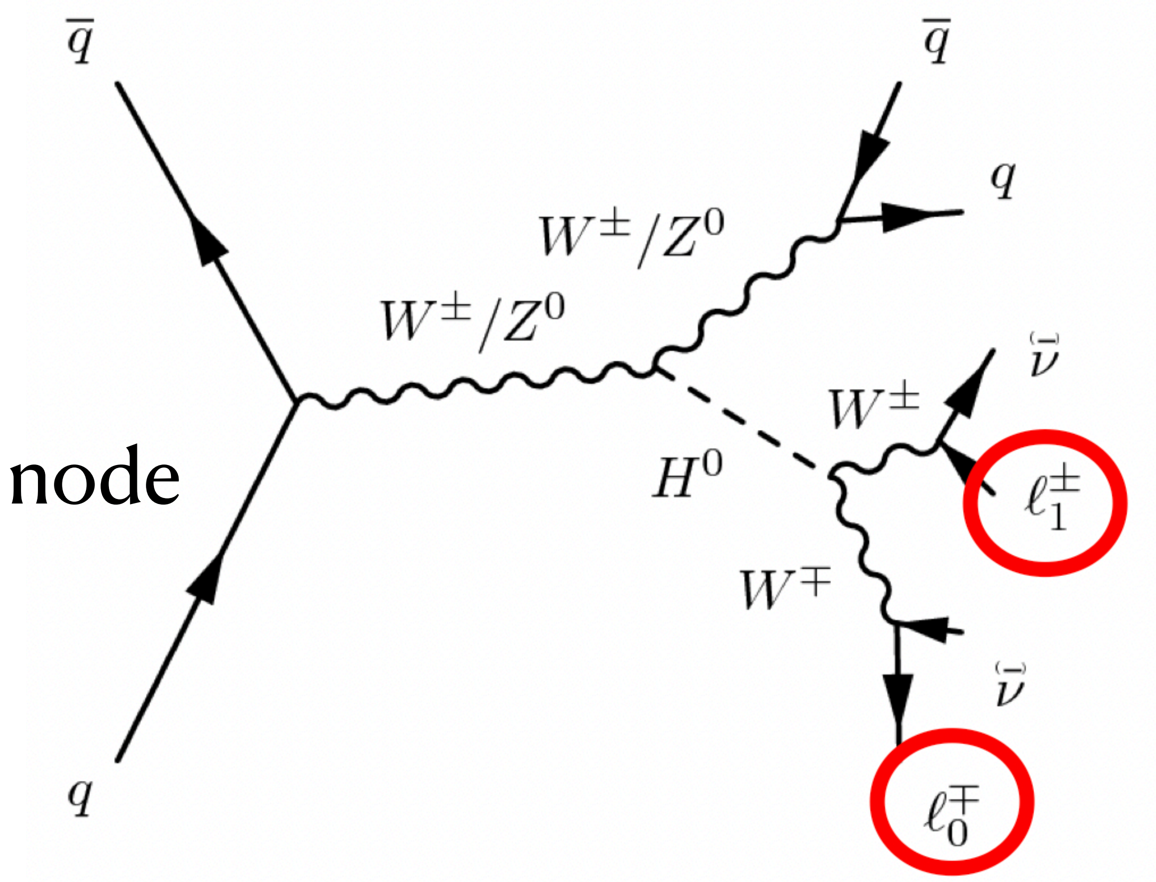
4 leptons

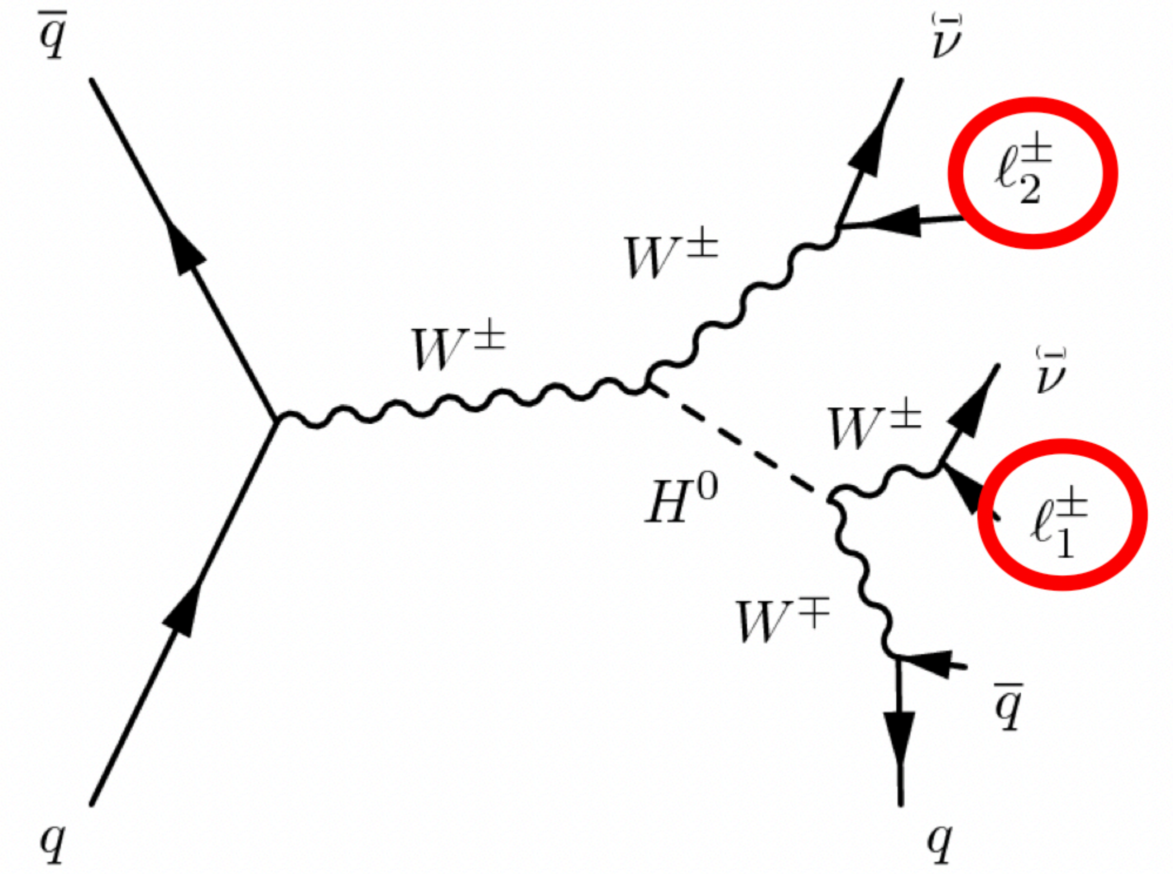
VH 2 leptons opposite sign (OS)

- ANN trained with 19 input variables of leptons, jets, E_T^{miss}
- 6 output nodes: VH, ggF, VBF, top, Z +jets and WW processes

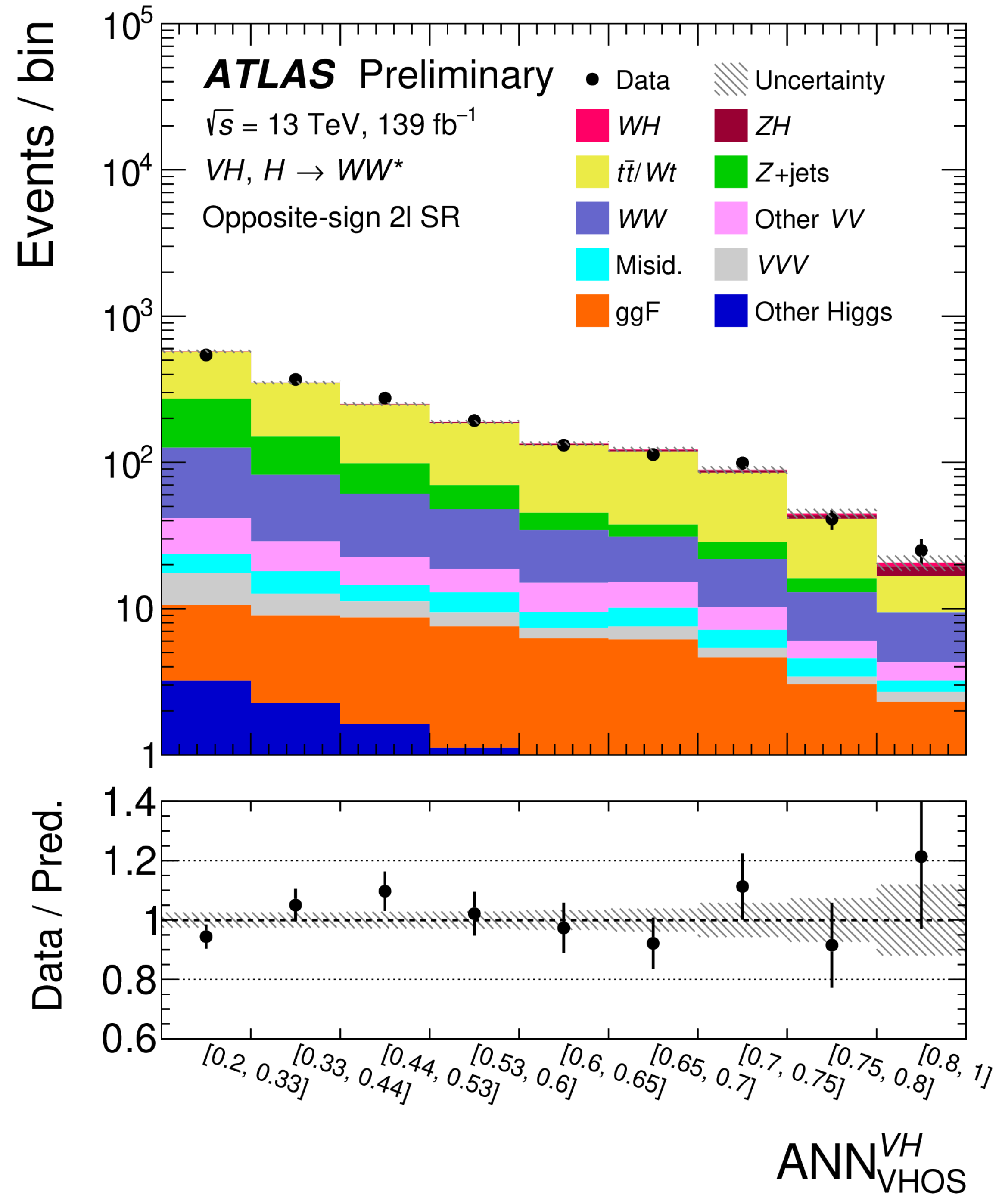
$$\sum_i ANN^i_{VHOS} = 1$$

- One SR and three CRs for major bkg norm are defined using 4 ANN output node
  - SR for $ANN^{VH}_{VHOS} > 0.2$
  - CR for $t\bar{t}$, Wt, Z+jets, WW

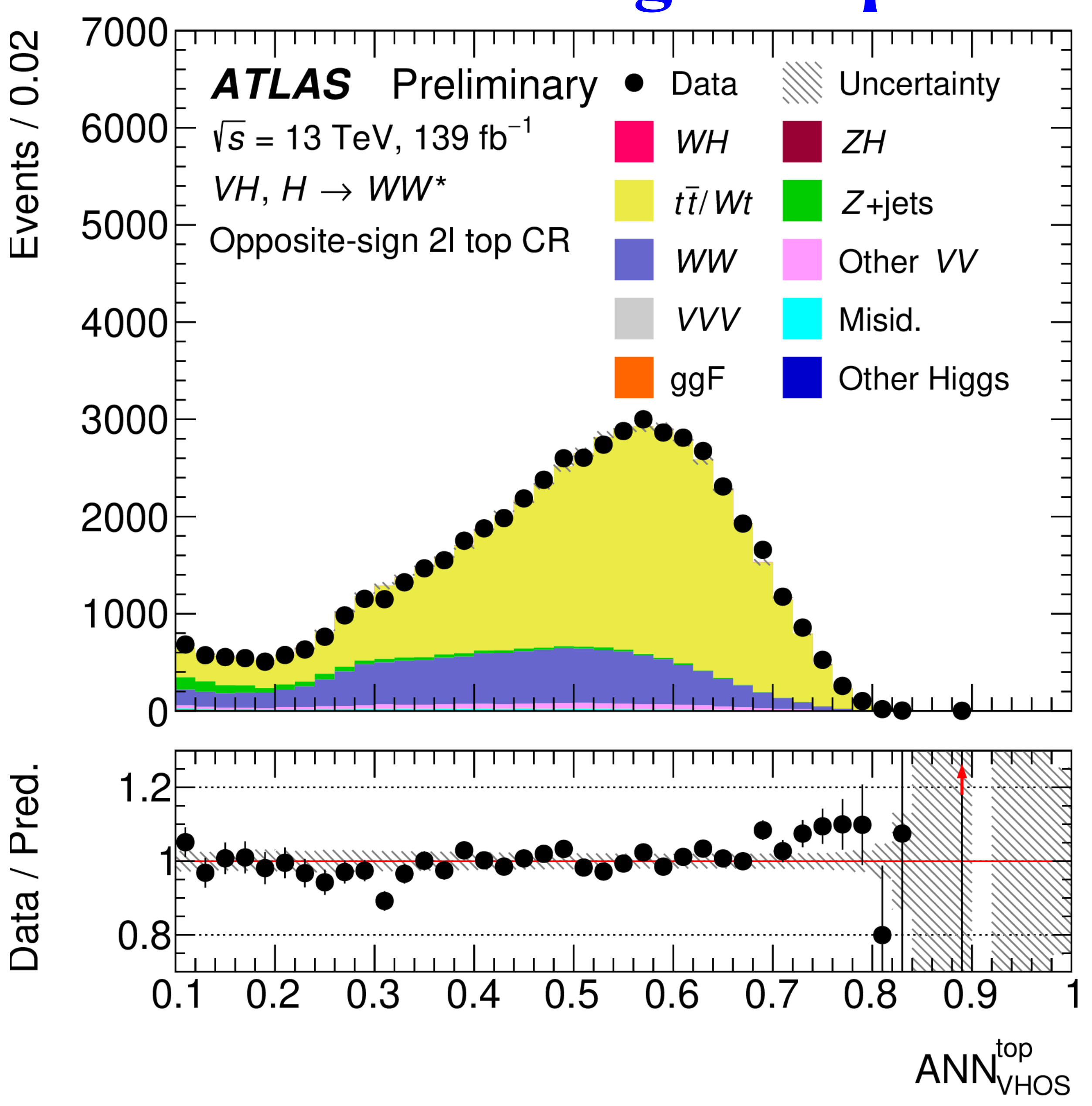




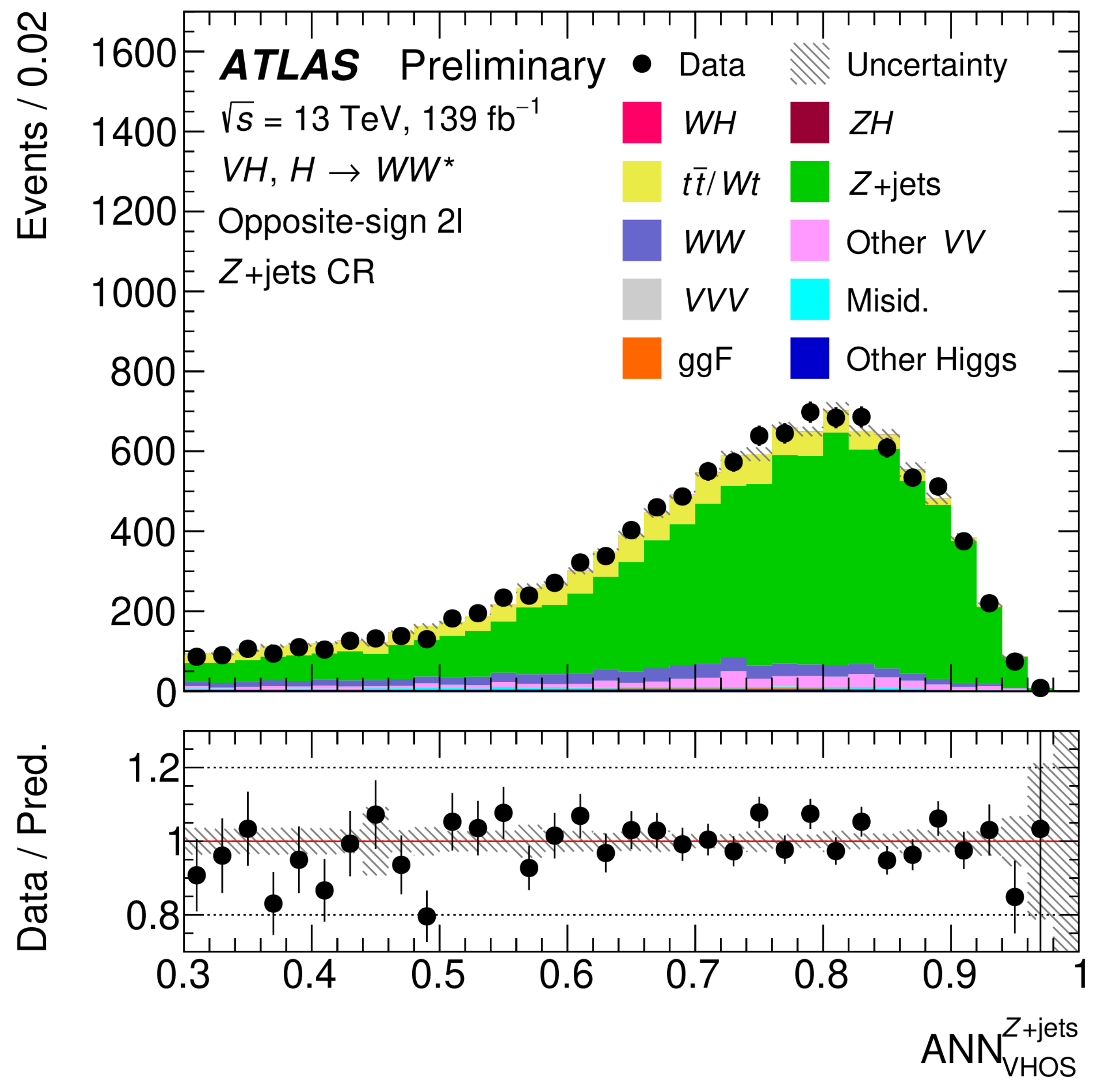
Signal region



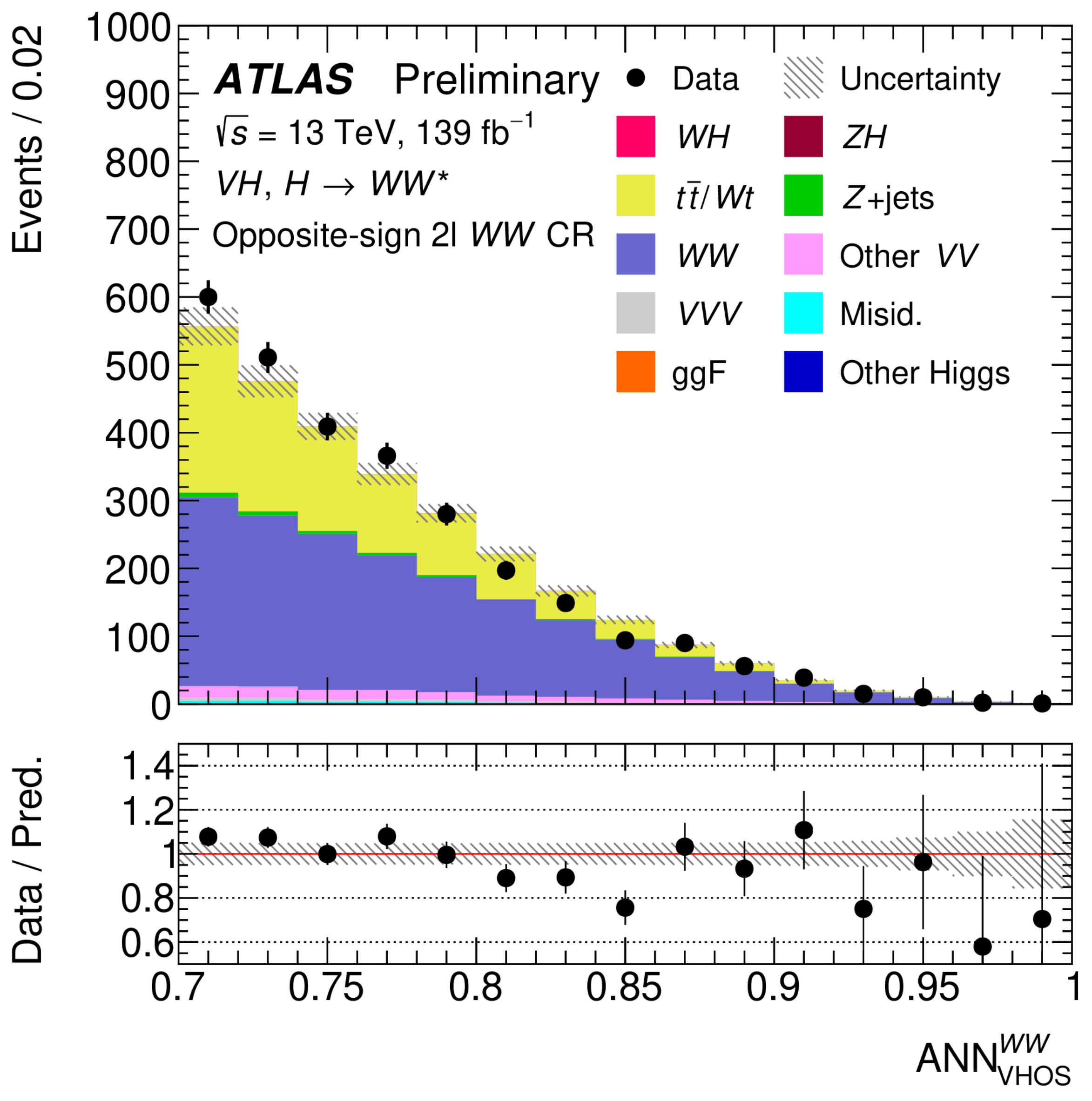
Control region top



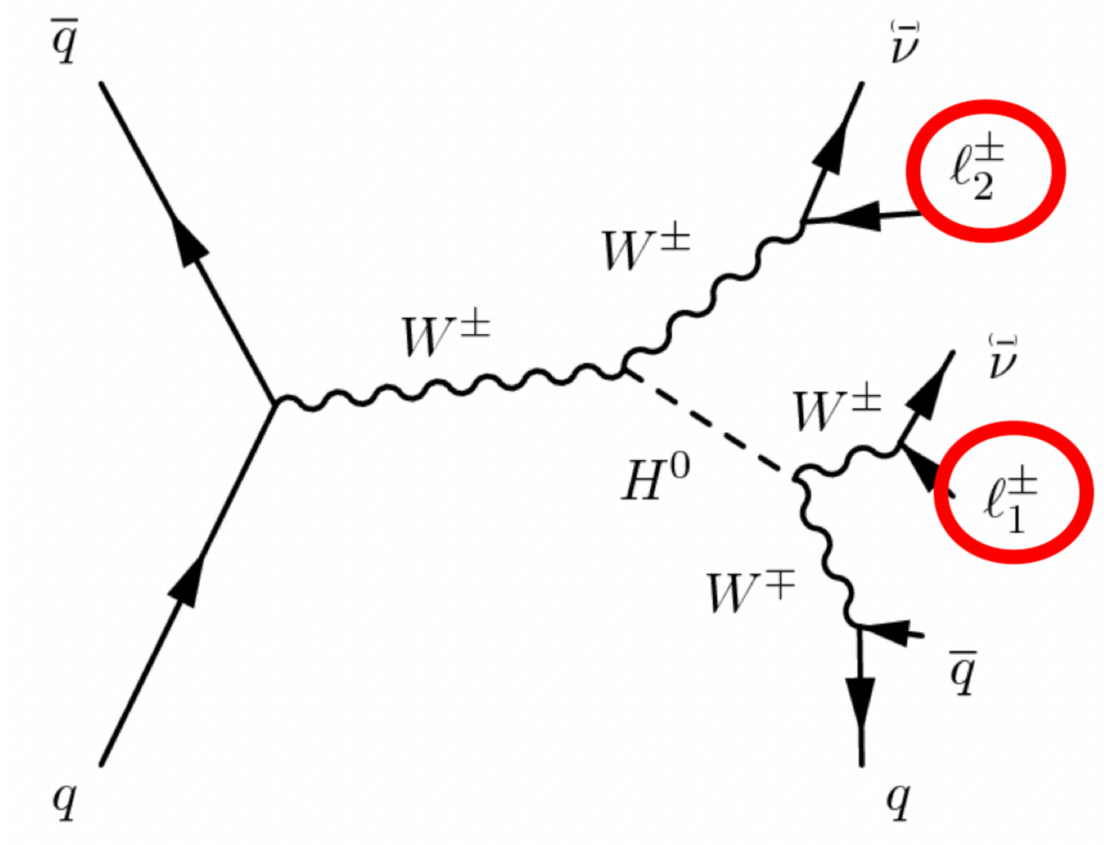
Control region Zjets



Control region WW

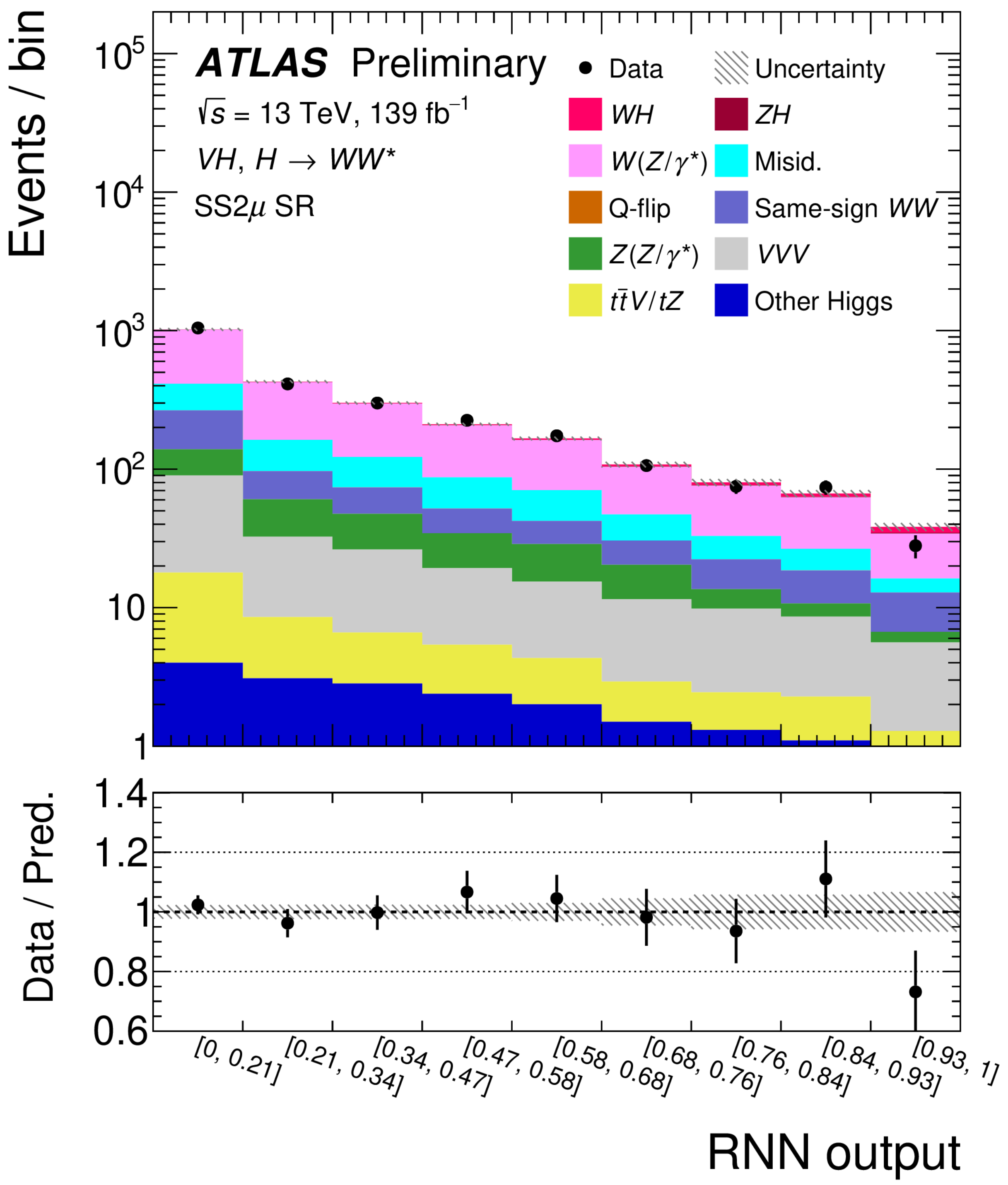


VH 2 leptons same sign (SS)

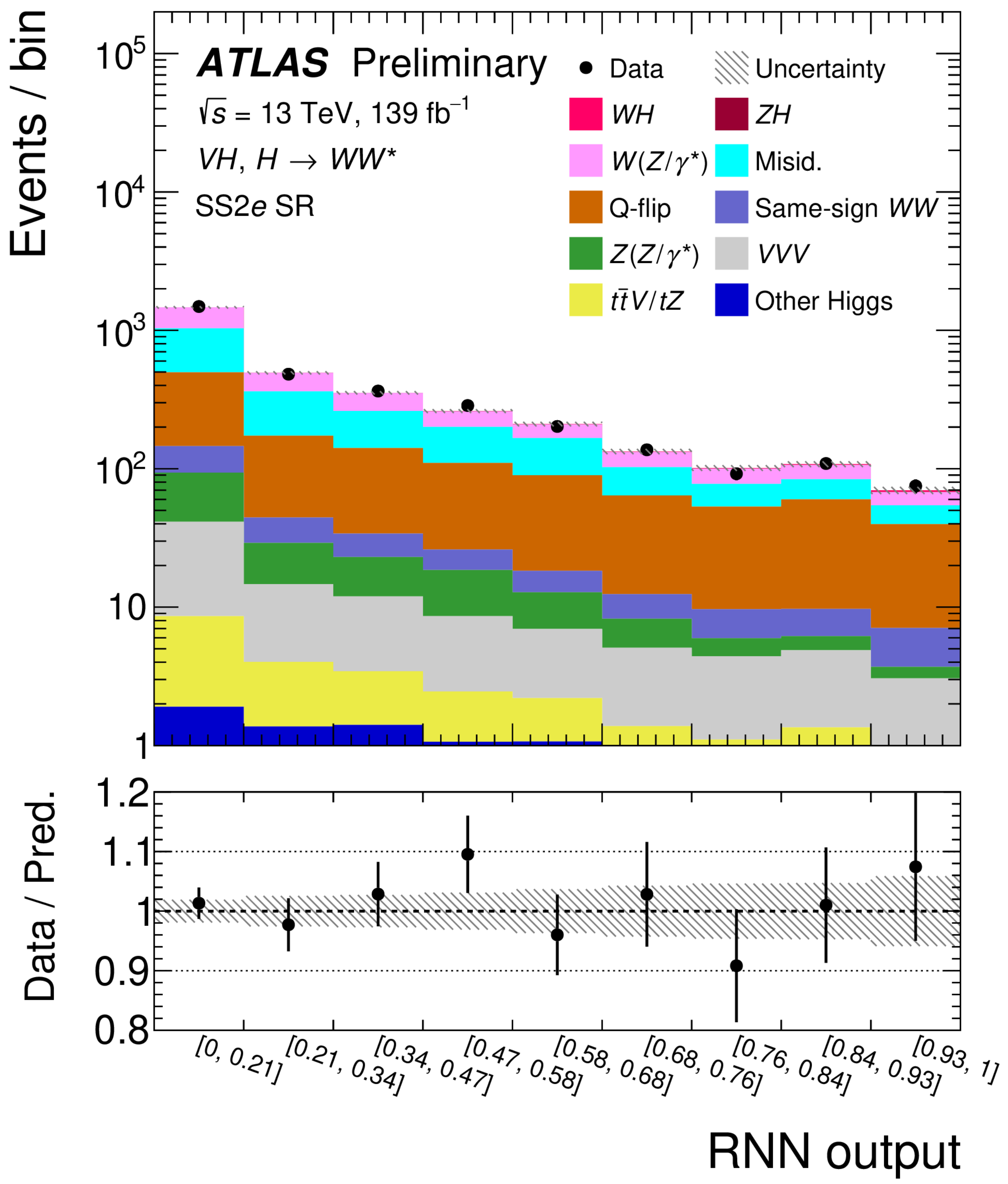


- Requiring exactly 2 leptons (no additional lepton with $p_T > 10$ GeV to reject WZ)
- At least 1 jet is required
- 3 different SRs depending on the lepton flavor: SS2μ, SS2e and SSDF
- RNN trained against dominant background WZ using p_T, η and ϕ of leptons, jets and E_T^{miss} as inputs
- WZ bkg is normalized in the SR with a floating normalization factor

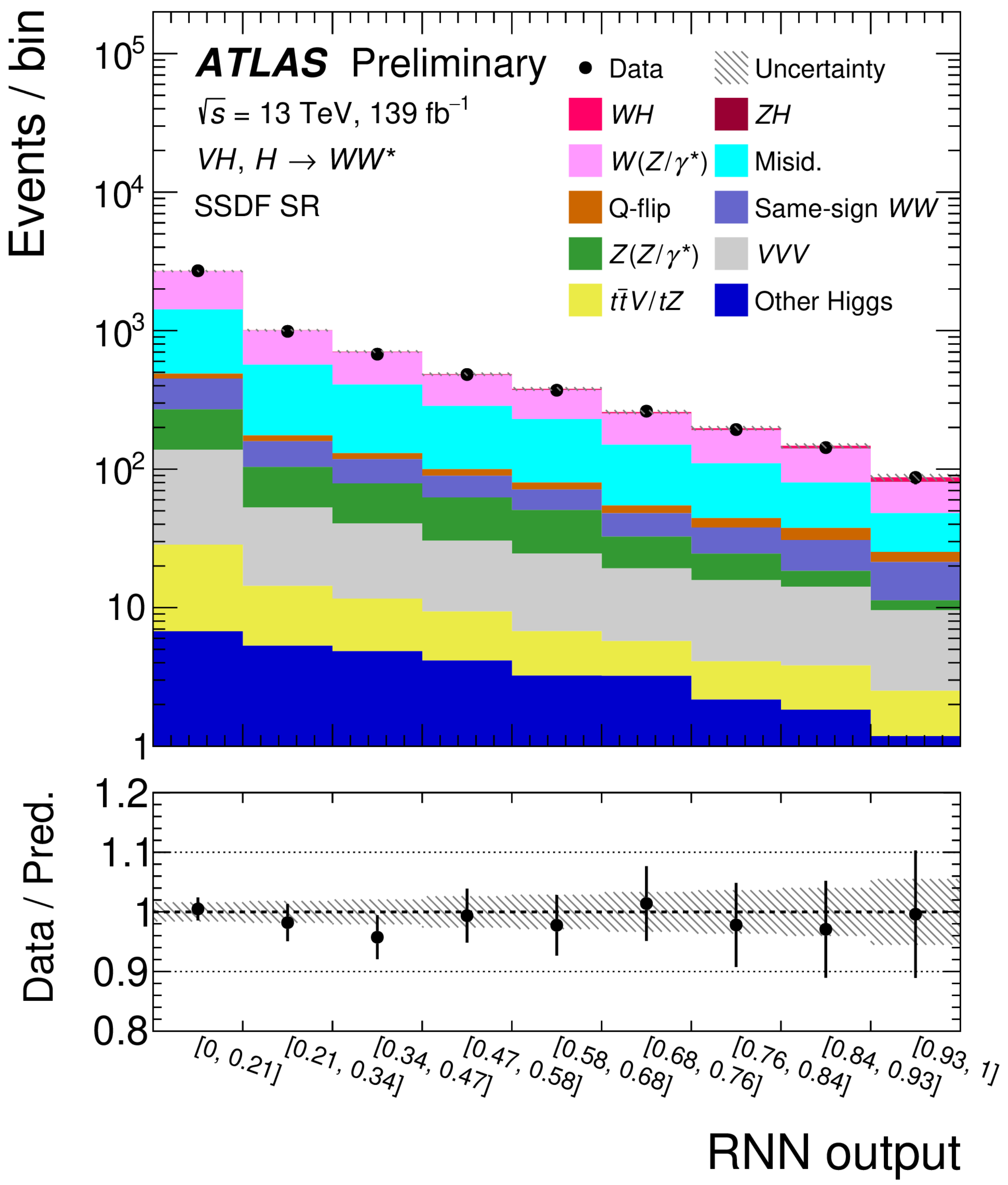
Signal region 2μ



Signal region $2e$



Signal region DF

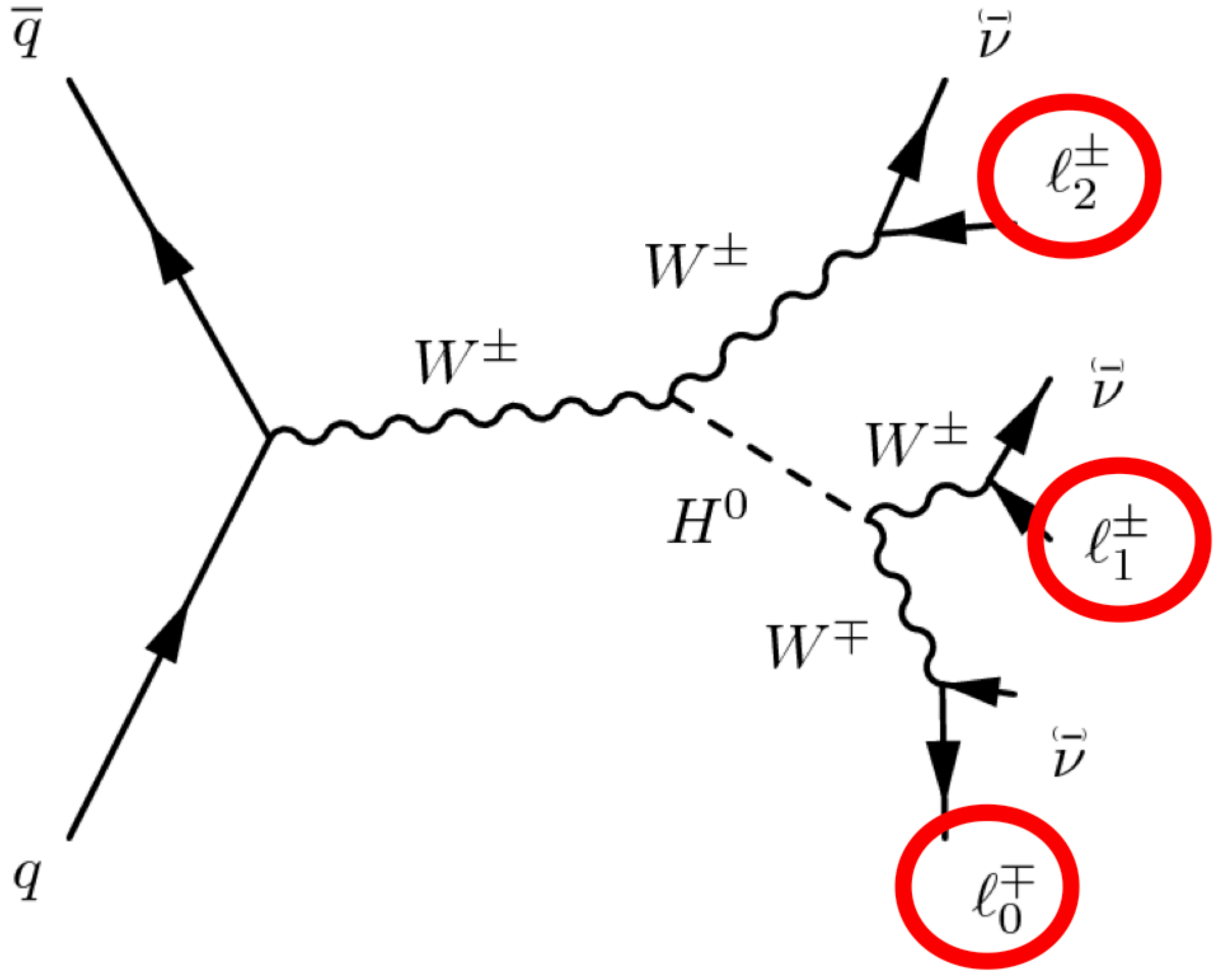


VH (WH) 3 leptons

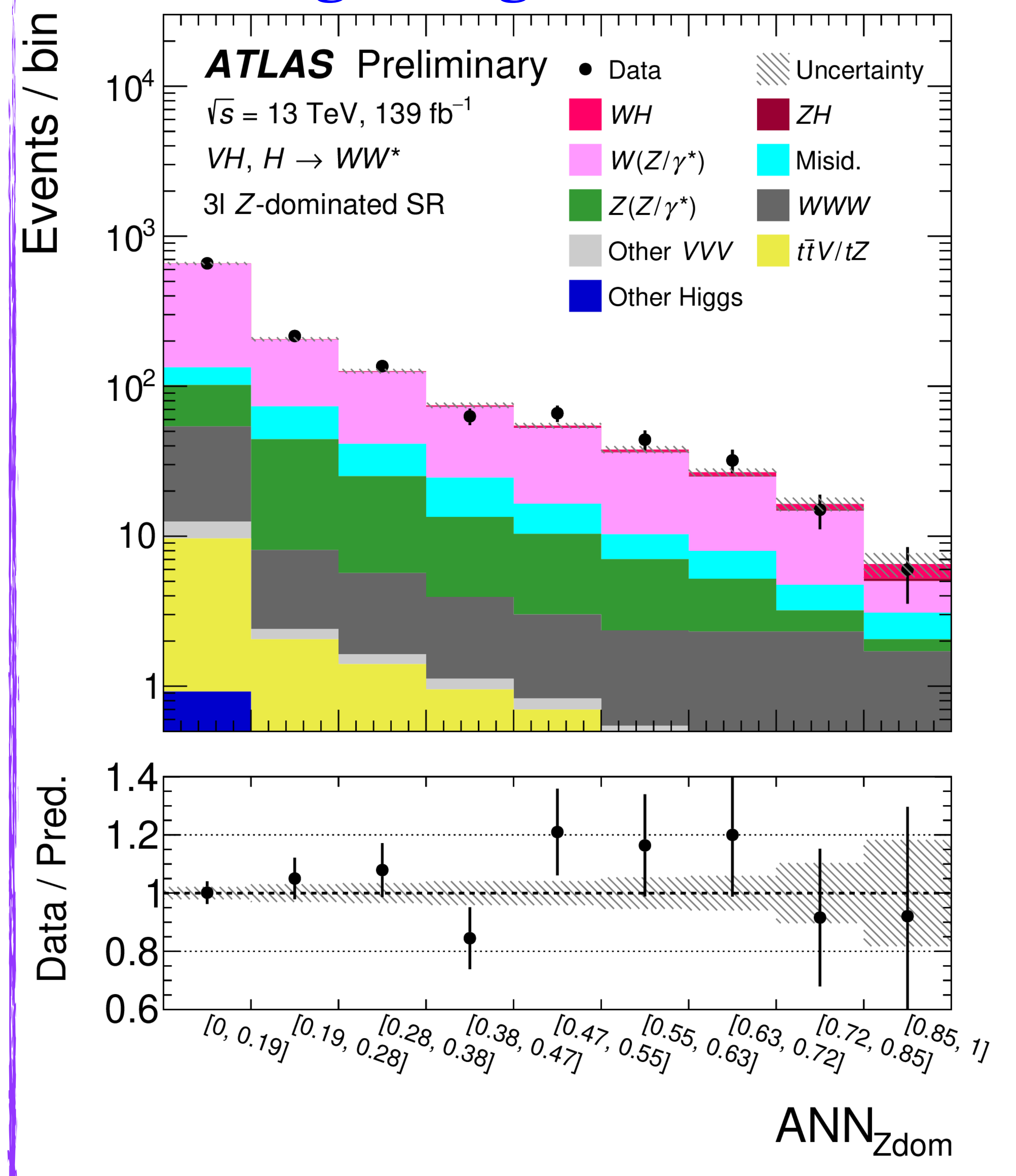
Two signal regions depending on the number of same flavor opposite sign pairs of leptons

Z-dominated category (1/2 SFOS pairs)

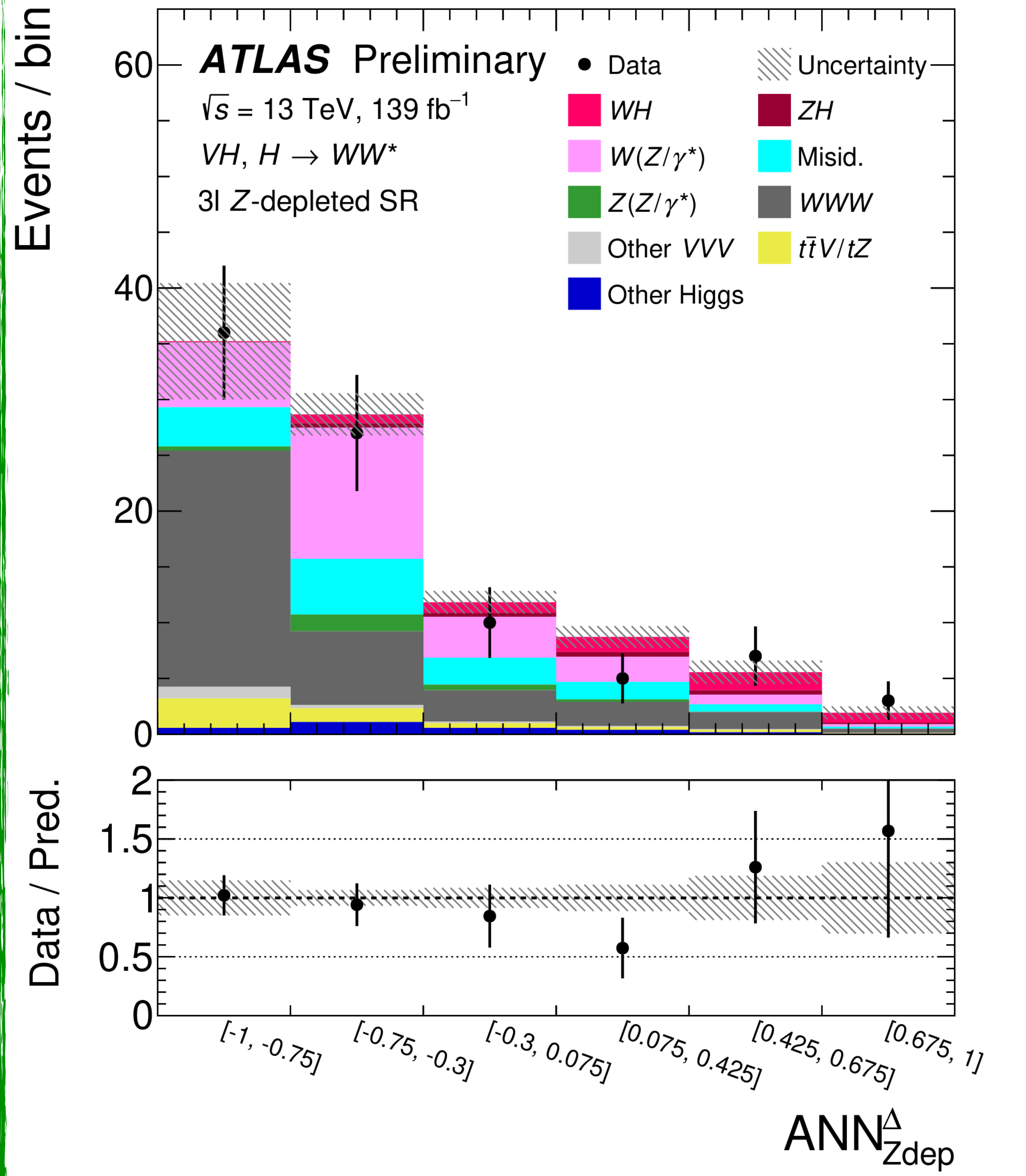
- Major bkg involve Z: $|m_{ll} - m_Z| > 25GeV$
- 2 WZ CRs (0 jets and ≥ 1 jet) defined reversing Z
- **ANN binary classifier** trained against WZ using 15 input variables (leptons, E_T^{miss}) → used as final discriminant



Signal region 1/2 SFOS



Signal region 0 SFOS



Z-depleted category (0 SFOS pair)

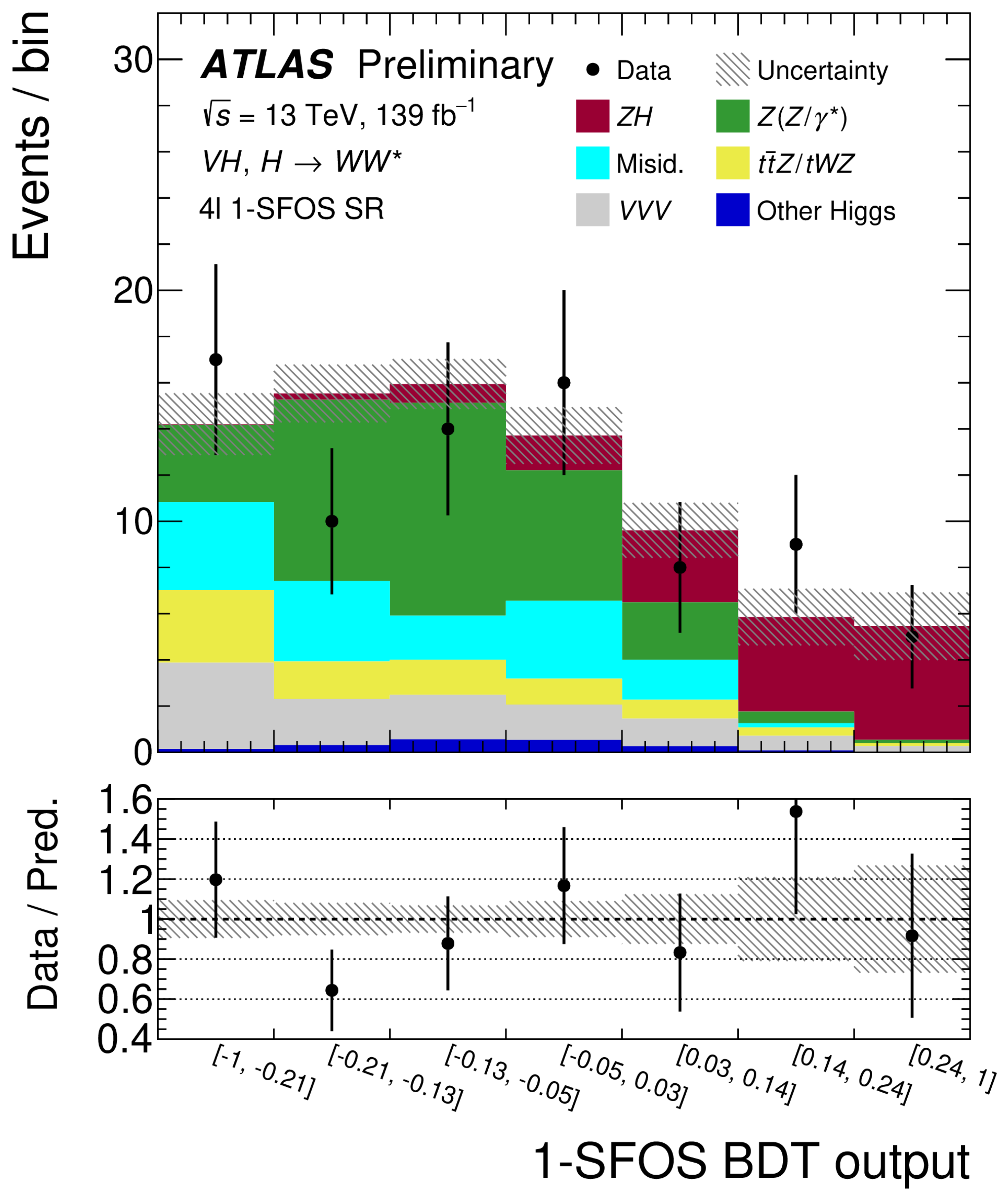
- Dominant bkgs: $t\bar{t}$, $W(Z/\gamma)$, WWW
  - WWW normalized in the SR with a floating WWW NF
  - Use the same WZ CRs for WZ normalization
- **ANN with 4 output nodes**
  - $ANN_{WH}, ANN_{WWW}, ANN_{WZ}, ANN_{t\bar{t}}$
  - using 26 input variables (leptons, jets and E_T^{miss})
- $ANN_{t\bar{t}} \geq 0.25$ to suppress $t\bar{t}$ background
- final discriminant

$$ANN^{\Delta}_{dep} = ANN_{WH} - ANN_{WWW} - ANN_{WZ}$$

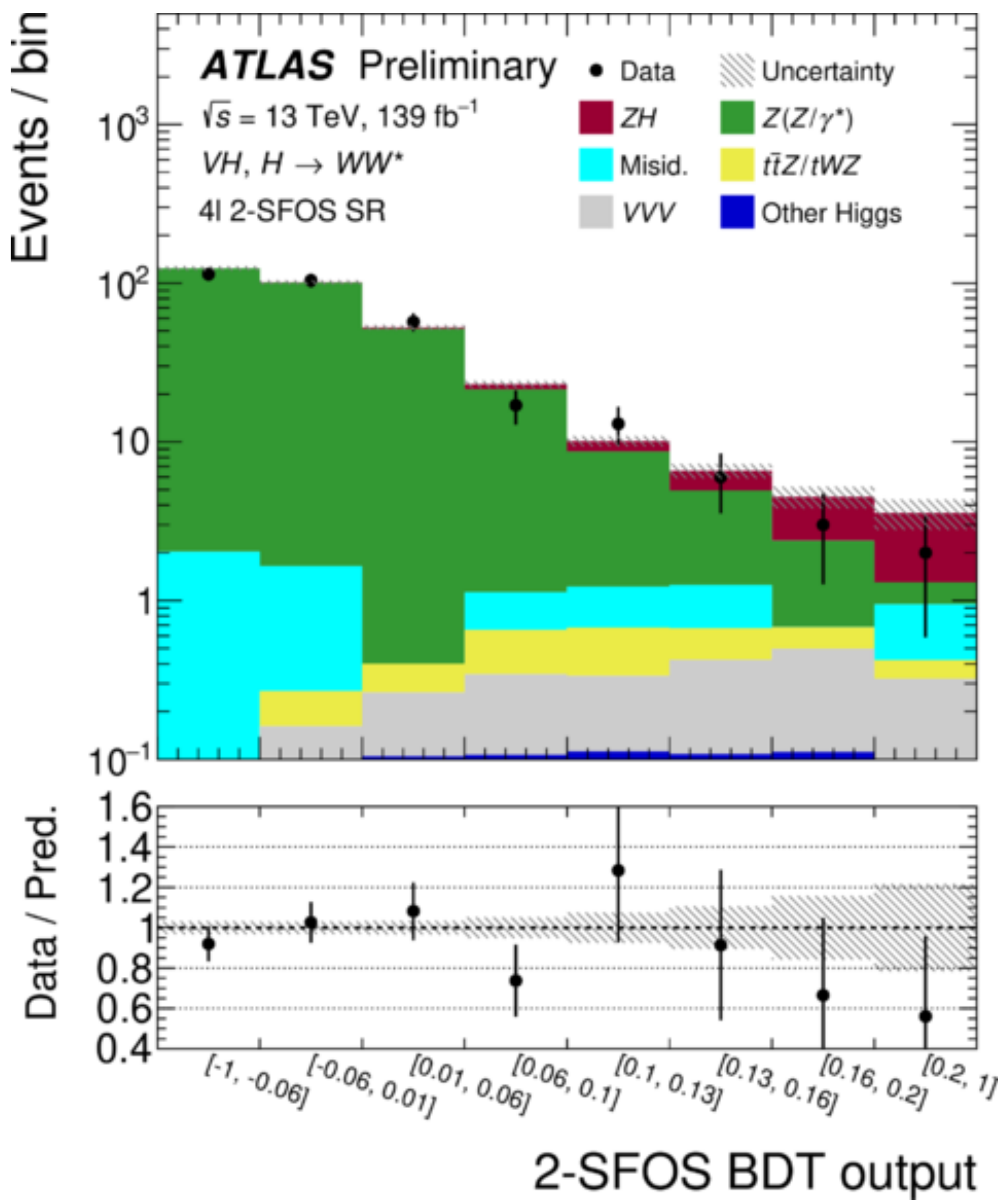
VH (ZH) 4 leptons

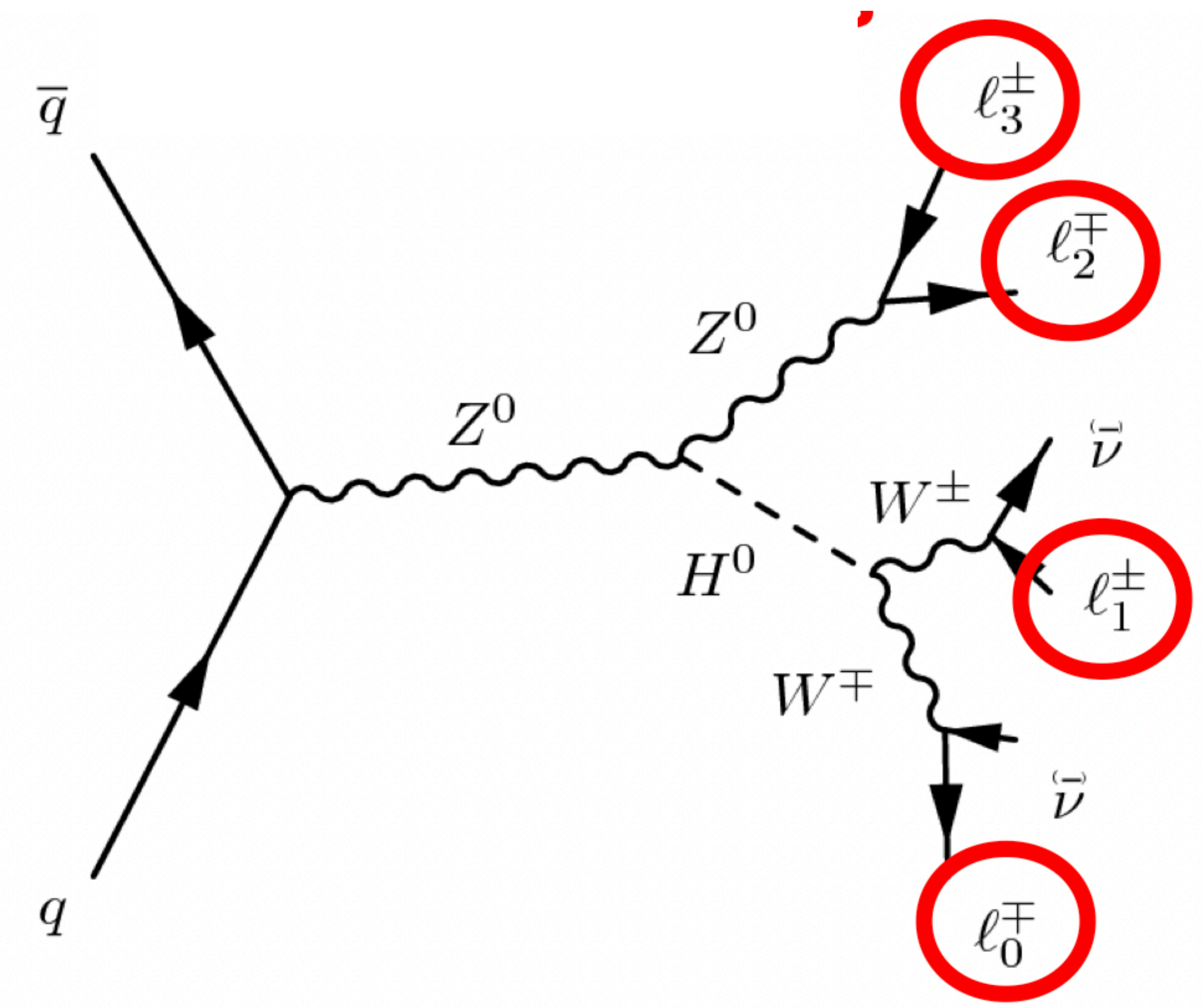
- Two signal regions depending on the number of same flavor opposite sign pairs of leptons
- 2 different BDTs trained with 13 input variables (leptons, E_T^{miss}, N_{jets}) for each SR
  - Trained against all backgrounds

Signal region 1SFOS



Signal region 2SFOS

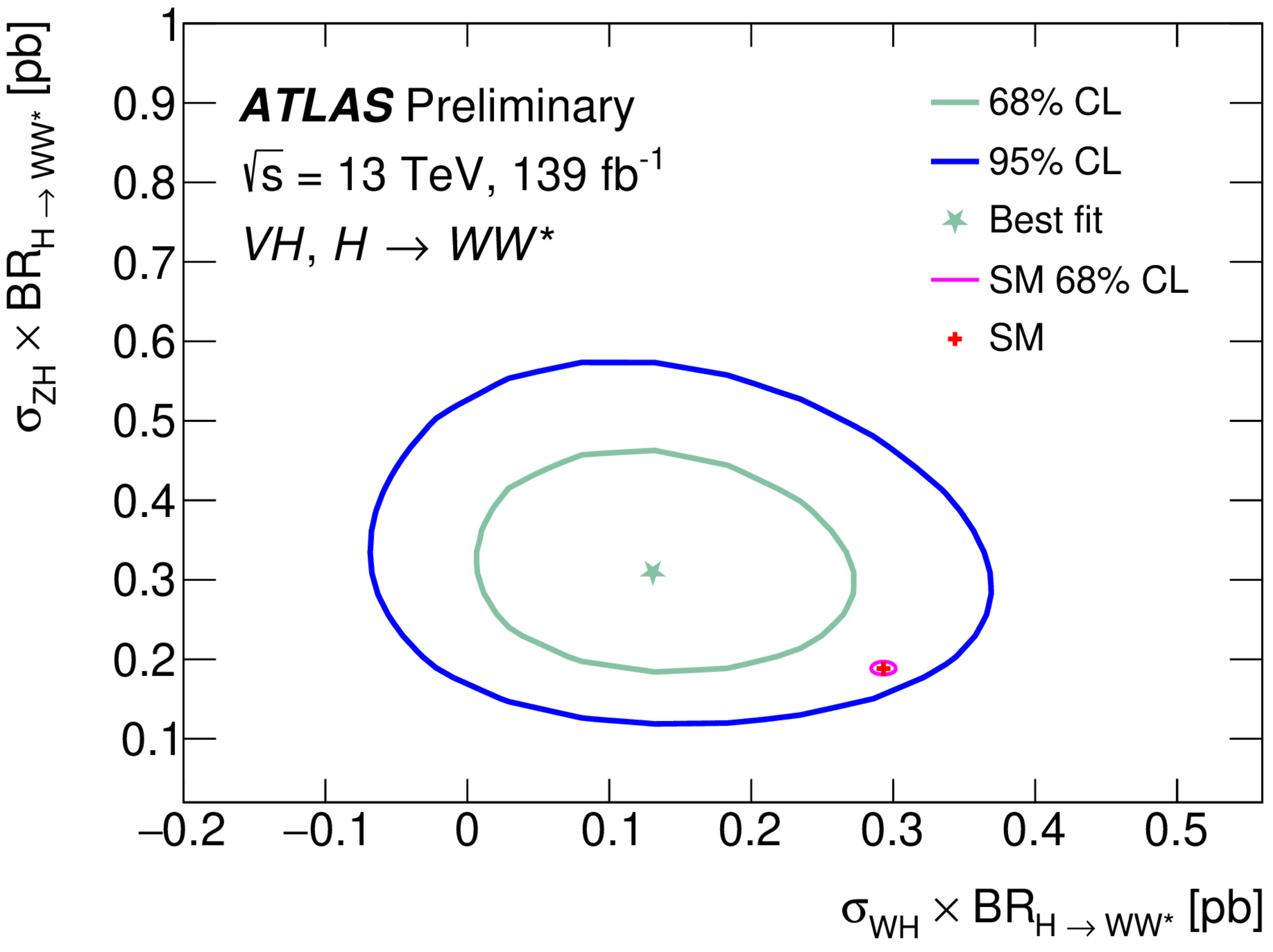




- l2, l3: SFOS lepton pair with mass closest to mZ , from Z decay (90%)
- l0, l1: from Higgs decay

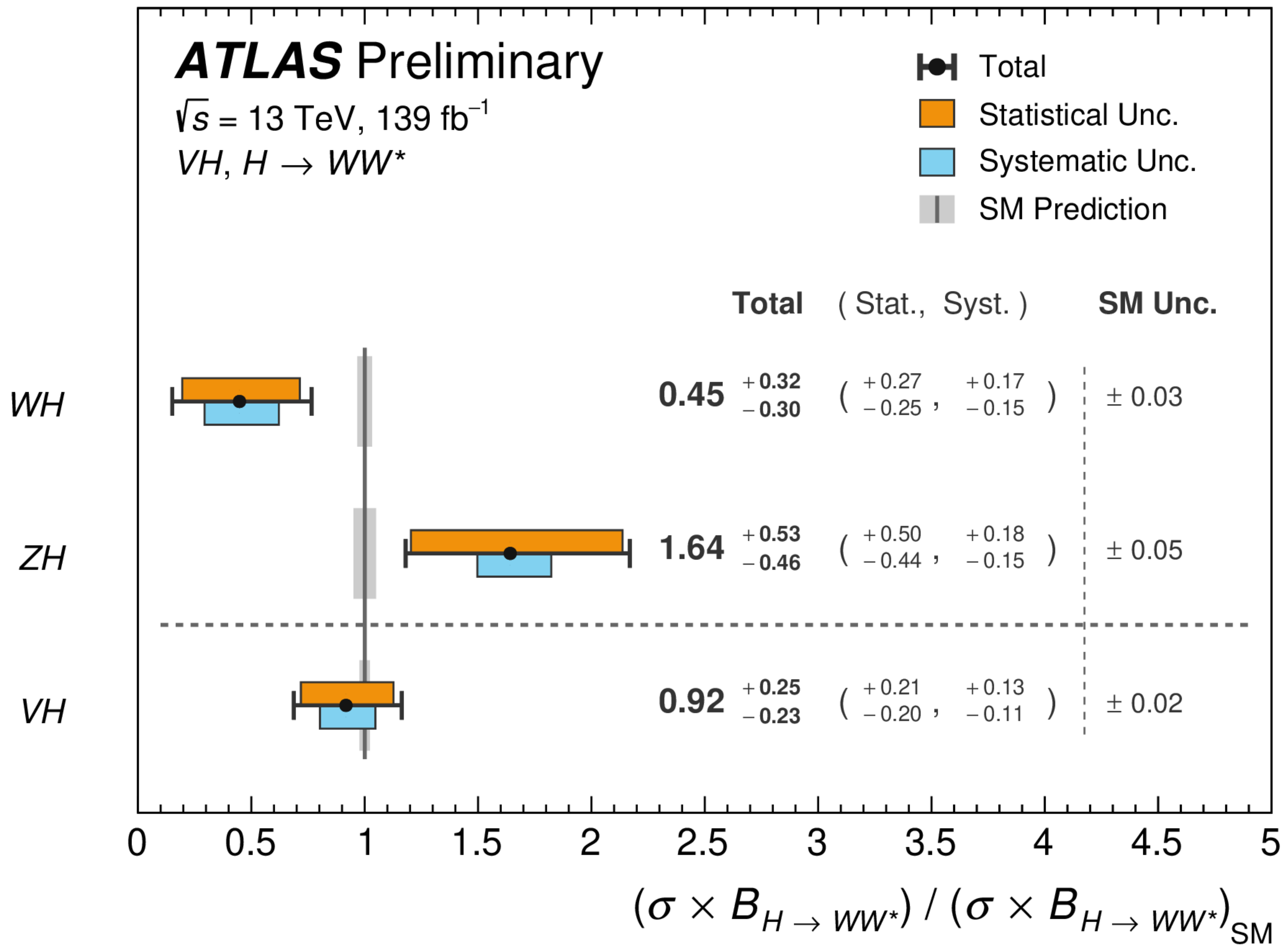
- 1 SFOS SR: ZZ from the $\tau\tau$ decay
- 2 SFOS SR: large ZZ contribution, lower sensitivity
  - $m_{l_0 l_1} < 50GeV$ → reduce ZZ by 87%
  - **ZZCR:** $|m_{l_2 l_3} - m_Z| < 10GeV, m_{l_0 l_1} > 50GeV$

VH measurements



$$\sigma_{VH} \times \mathcal{B}_{H\to WW^*} = 0.44 \pm 0.1(\text{stat.})^{+0.07}_{-0.06}(\text{sys.})\ \text{pb}$$
$$\sigma_{WH} \times \mathcal{B}_{H\to WW^*} = 0.13^{+0.08}_{-0.07}(\text{stat.})^{+0.05}_{-0.04}(\text{sys.})\ \text{pb}$$
$$\sigma_{ZH} \times \mathcal{B}_{H\to WW^*} = 0.31^{+0.09}_{-0.08}(\text{stat.})^{+0.04}_{-0.03}(\text{sys.})\ \text{pb}$$

- μ_{WH} and μ_{ZH} represent 1.5 σ and 4.6 σ excess over a scenario with no WH or ZH
- μ_{WH} and μ_{ZH} agree with each other at a level of 2.1σ
- μ_{WH} at 1.8 σ from SM, μ_{ZH} at 1.2 σ
- μ_{ZH} exceeds SM: moderate excess in the 4l 1-SFOS category
- $\mu_{WH} < 1$: moderate deficits in the 3l Z-depleted category and the same-sign 2l channel as compared with the SM prediction



Conclusion

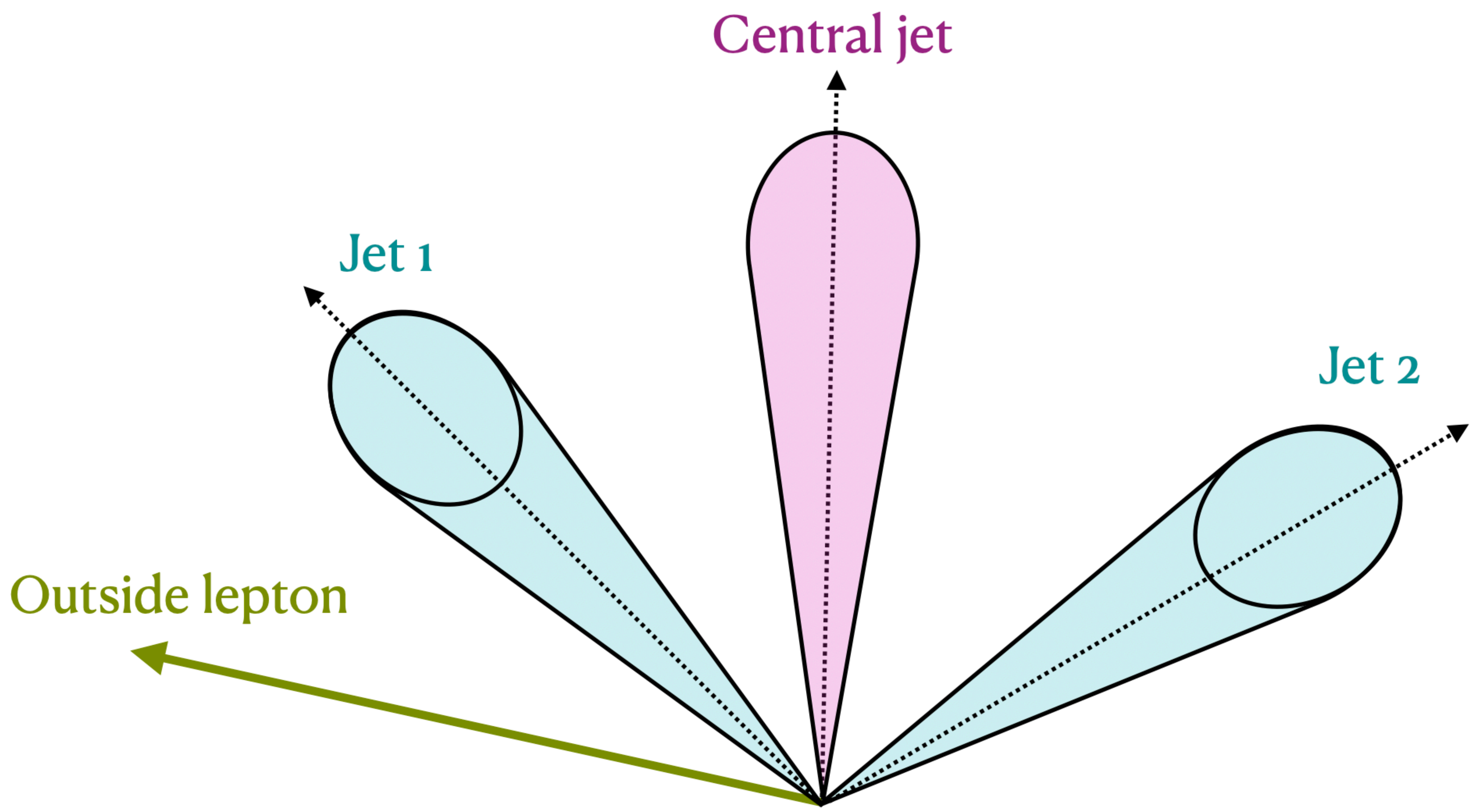
- $H \to WW^*$ couplings measurements extended to full Run-2 ($139fb^{-1}$) dataset
- **ggF+VBF**
  - $\sigma_{ggF} \times BR_{H\to WW^*}$, $\sigma_{VBF} \times BR_{H\to WW^*}$ and STXS results consistent with SM prediction
  - VBF $H \to WW^*$ observation achieved thanks to improved sensitivity using DNN
  - ggF+2jet channel included for the first time in Run-2
  - Measurements in STXS bins also agree with the SM, and (for EW qqH) have a precision competitive with the latest combination of all Higgs results measured with the ATLAS detector [ATLAS-CONF-2020-027]
- **VH**
  - *VH* signal strength is measured to be $0.92^{+0.21}_{-0.20}(stat.)^{0.12}_{-0.14}(syst.)$, corresponding to a 4.6 σ significance over the background-only hypothesis
  - $\sigma_{VH} \times BR_{H\to WW^*}$, $\sigma_{WH} \times BR_{H\to WW^*}$ and $\sigma_{ZH} \times BR_{H\to WW^*}$ results consistent with SM prediction

Back-up slides

CR selection: ggF + VBF

<table>
<tr><th>CR</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>$N_{\text{jet},(p_T>30\text{ GeV})} \geq 2$ ggF</th><th>$N_{\text{jet},(p_T>30\text{ GeV})} \geq 2$ VBF</th></tr>
<tr><td rowspan="5">$qq \to WW$</td><td colspan="3">$N_{b\text{-jet},(p_T>20\text{ GeV})} = 0$</td><td rowspan="5"></td></tr>
<tr><td rowspan="4">$\Delta\phi_{\ell\ell,E_T^{\text{miss}}} > \pi/2$
$p_T^{\ell\ell} > 30$ GeV
$55 < m_{\ell\ell} < 110$ GeV
$\Delta\phi_{\ell\ell} < 2.6$</td><td colspan="2">$m_{\ell\ell} > 80$ GeV</td></tr>
<tr><td rowspan="3">$|m_{\tau\tau} - m_Z| > 25$ GeV
$\max(m_T^{\ell}) > 50$ GeV</td><td>$m_{\tau\tau} < m_Z - 25$ GeV
$m_{T2} > 165$ GeV</td></tr>
<tr><td>fail central jet veto
or fail outside lepton veto</td></tr>
<tr><td>$|m_{jj} - 85| > 15$ GeV
or $\Delta y_{jj} > 1.2$</td></tr>
<tr><td rowspan="5">$t\bar{t}/Wt$</td><td rowspan="5">$N_{b\text{-jet},(20<p_T<30\text{ GeV})} > 0$
$\Delta\phi_{\ell\ell,E_T^{\text{miss}}} > \pi/2$
$p_T^{\ell\ell} > 30$ GeV
$\Delta\phi_{\ell\ell} < 2.8$</td><td>$N_{b\text{-jet},(p_T>30\text{ GeV})} = 1$
$N_{b\text{-jet},(20<p_T<30\text{ GeV})} = 0$</td><td>$N_{b\text{-jet},(p_T>20\text{ GeV})} = 0$</td><td>$N_{b\text{-jet},(p_T>20\text{ GeV})} = 1$</td></tr>
<tr><td colspan="3">$m_{\tau\tau} < m_Z - 25$ GeV</td></tr>
<tr><td rowspan="3">$\max(m_T^{\ell}) > 50$ GeV</td><td>$m_{\ell\ell} > 80$ GeV
$\Delta\phi_{\ell\ell} < 1.8$
$m_{T2} < 165$ GeV</td><td rowspan="3">central jet veto
outside lepton veto</td></tr>
<tr><td>fail central jet veto
or fail outside lepton veto</td></tr>
<tr><td>$|m_{jj} - 85| > 15$ GeV
or $\Delta y_{jj} > 1.2$</td></tr>
<tr><td rowspan="5">Z/γ^*</td><td colspan="4">$N_{b\text{-jet},(p_T>20\text{ GeV})} = 0$</td></tr>
<tr><td colspan="2">$m_{\ell\ell} < 80$ GeV
no p_T^{miss} requirement</td><td>$m_{\ell\ell} < 55$ GeV</td><td rowspan="4">$m_{\ell\ell} < 70$ GeV
$|m_{\tau\tau} - m_Z| \leq 25$ GeV
central jet veto
outside lepton veto</td></tr>
<tr><td rowspan="3">$\Delta\phi_{\ell\ell} > 2.8$</td><td colspan="2">$m_{\tau\tau} > m_Z - 25$ GeV</td></tr>
<tr><td rowspan="2">$\max(m_T^{\ell}) > 50$ GeV</td><td>fail central jet veto
or fail outside lepton veto</td></tr>
<tr><td>$|m_{jj} - 85| > 15$ GeV
or $\Delta y_{jj} > 1.2$</td></tr>
</table>

VBF variables definition



CJV: central jet veto

No jet with $p_T > 30GeV$ in the pseudorapidity gap between the two leading jets

OLV: outside lepton veto

Veto if either of the 2 leptons lies in the pseudorapidity gap between the two leading jets

Mis-identified bkg in ggF + VBF

Requirements for fully identified and anti-identified leptons

Electron identified	Electron anti-identified	Muon identified	Muon anti-identified
$p_T > 15$ GeV		$p_T > 15$ GeV	
$\lvert\eta\rvert < 2.47$,excluding $1.37 < \lvert\eta\rvert < 1.52$		$\lvert\eta\rvert < 2.5$	
$\lvert z_0 \sin\theta\rvert < 0.5$ mm		$\lvert z_0 \sin\theta\rvert < 0.5$ mm	
$\lvert d_0\rvert/\sigma(d_0) < 5$		$\lvert d_0\rvert/\sigma(d_0) < 3$	$\lvert d_0\rvert/\sigma(d_0) < 15$
Pass LHTight if $p_T < 25$ GeV Pass LHMedium if $p_T > 25$ GeV	Pass LHLoose	Pass Quality Tight	Pass Quality Medium
Pass FCTight isolation		Pass FCTight isolation	
AUTHOR = 1			
	Veto against identified electron		Veto against identified muon

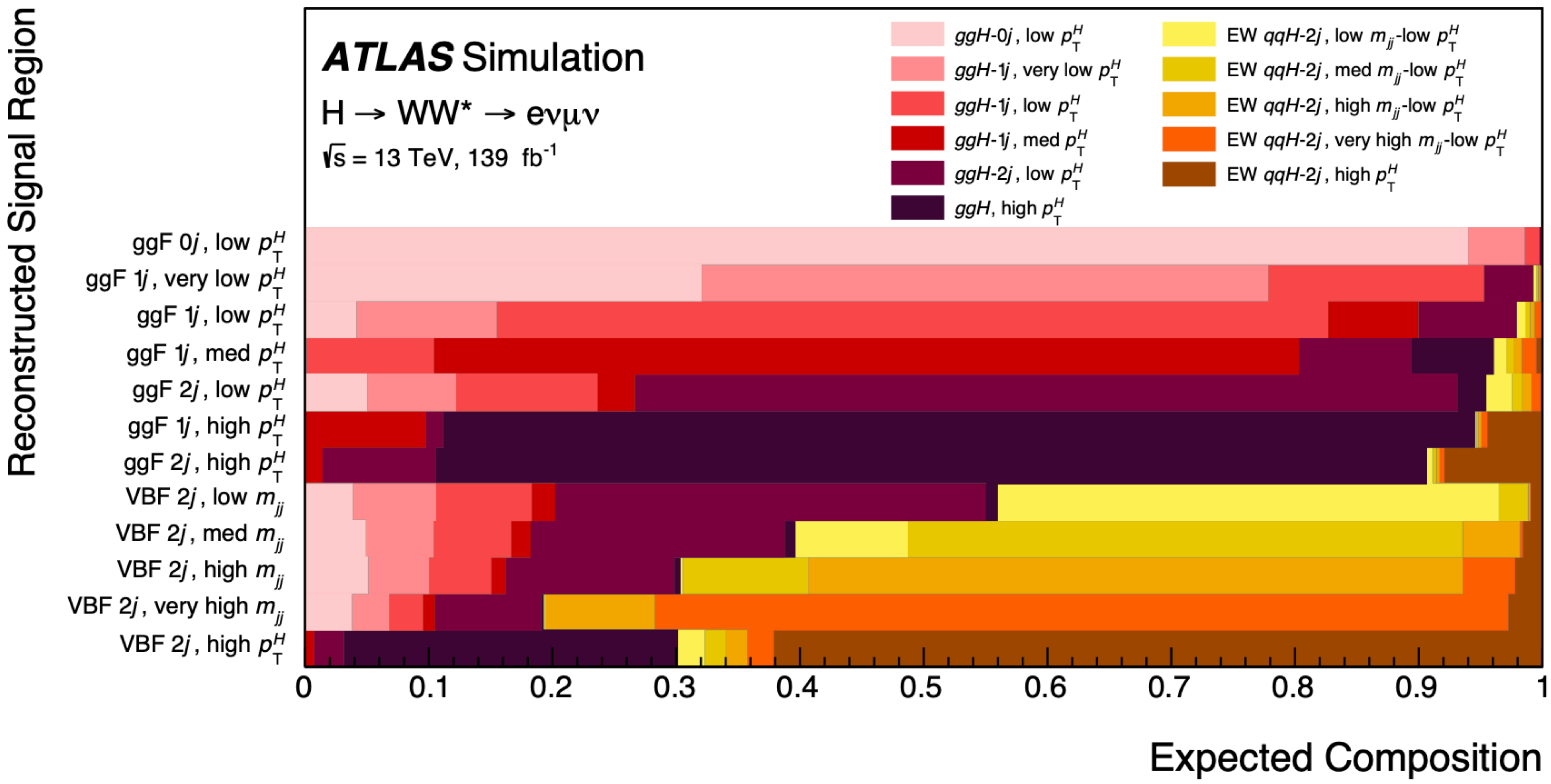
$$N^{W+jets}_{ID+ID} = FF_l \cdot N^{W+jets}_{ID+antiID}$$

$$FF = \frac{\text{ID}}{\text{Anti-ID}} = \frac{N^{i,i,i}_{data} - N^{i,i,i}_{non-Z+jets}}{N^{i,i,a}_{data} - N^{i,i,a}_{non-Z+jets}}$$

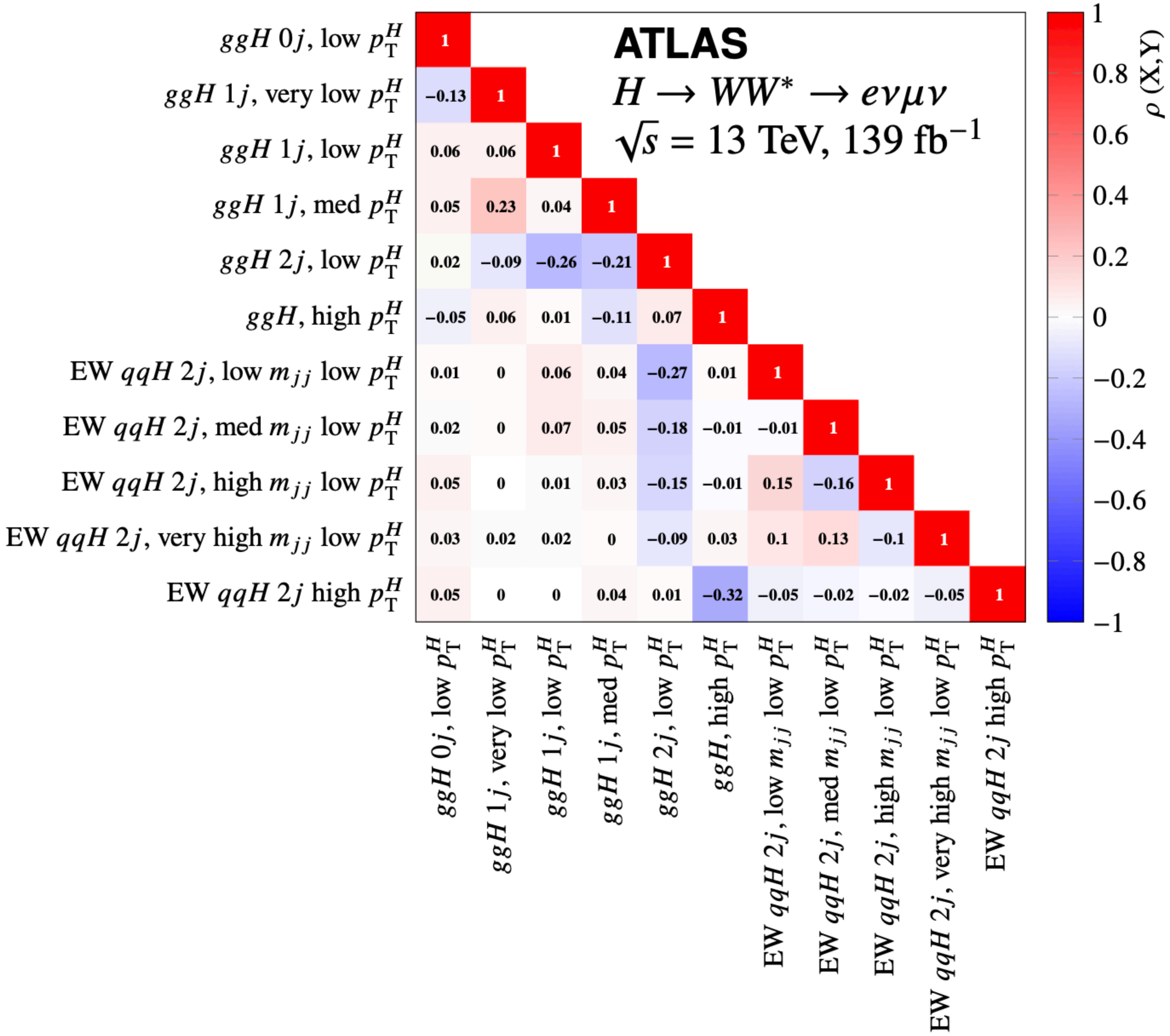
- Anti-id selects non-prompt and fake leptons from hadronic activity
- Z+jets fake factor measured from jets in events with Z candidate
- 3 reconstructed leptons
  - A lepton pair close to Z mass window
  - The left lepton for measuring fake factor
- WZ background normalization factor estimated in CR
- Also syst uncertainties due to EW bkgs (ZZ, WZ, V+gamma) subtraction are considered

Measurements in STXS: ggF + VBF

- Relative SM signal composition in terms of the measured STXS bin for each reco signal bins
- Each reco SR has largest contribution from the truth category it targets

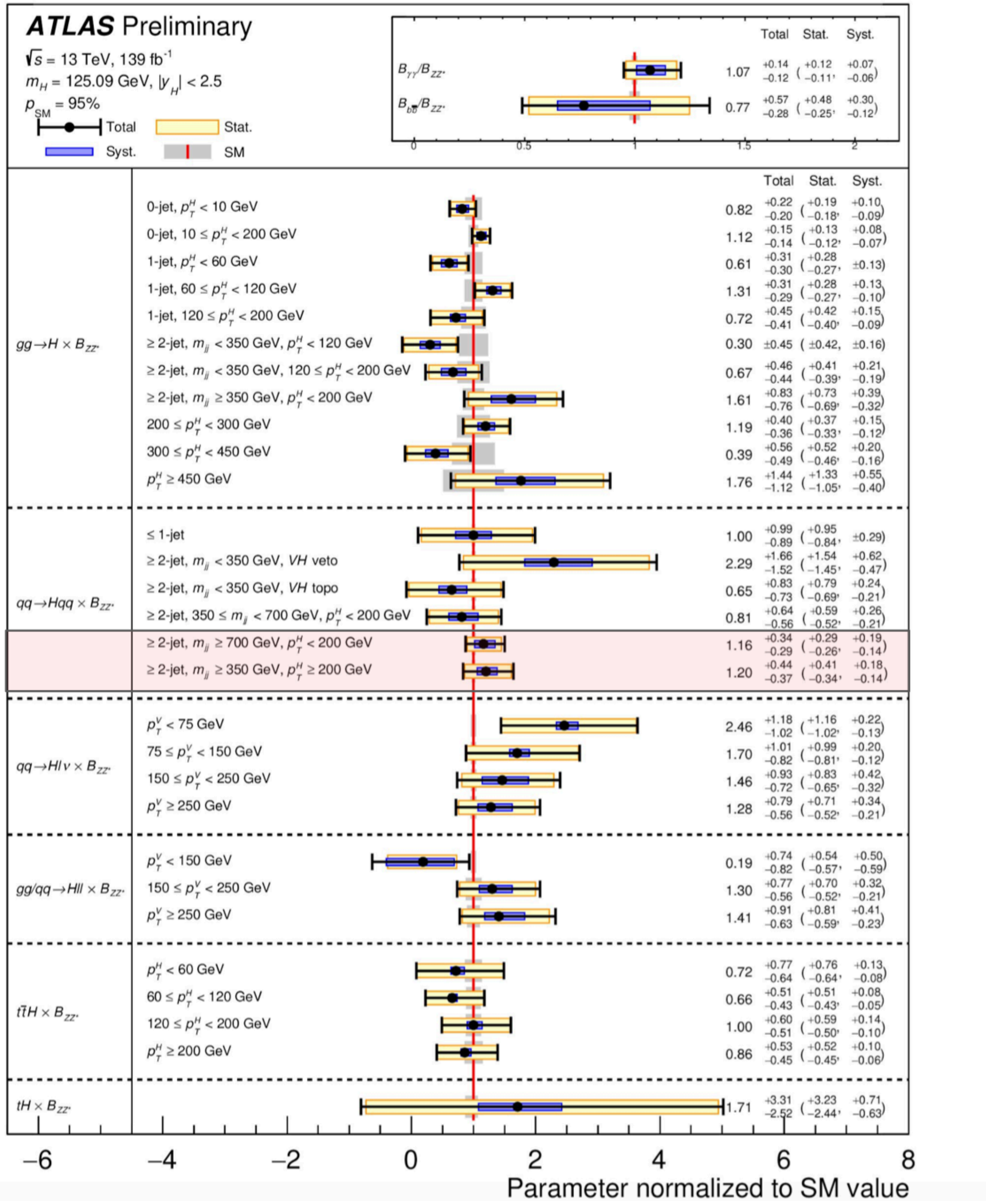


Measurements in STXS: ggF + VBF

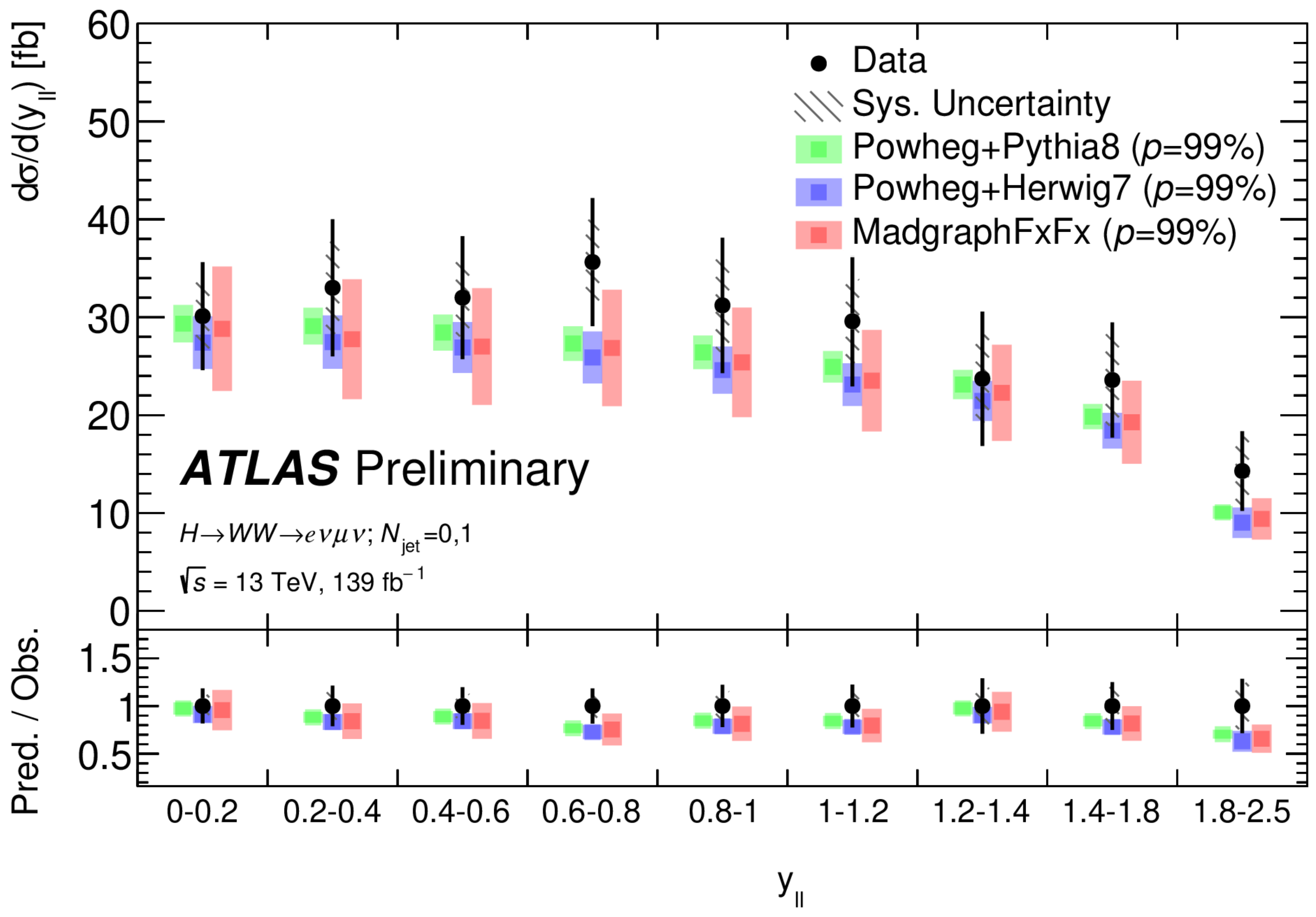


- Small correlations in general
- Larger anti-correlations mainly from detector resolution effects
- Larger positive correlations from common systematic uncertainties

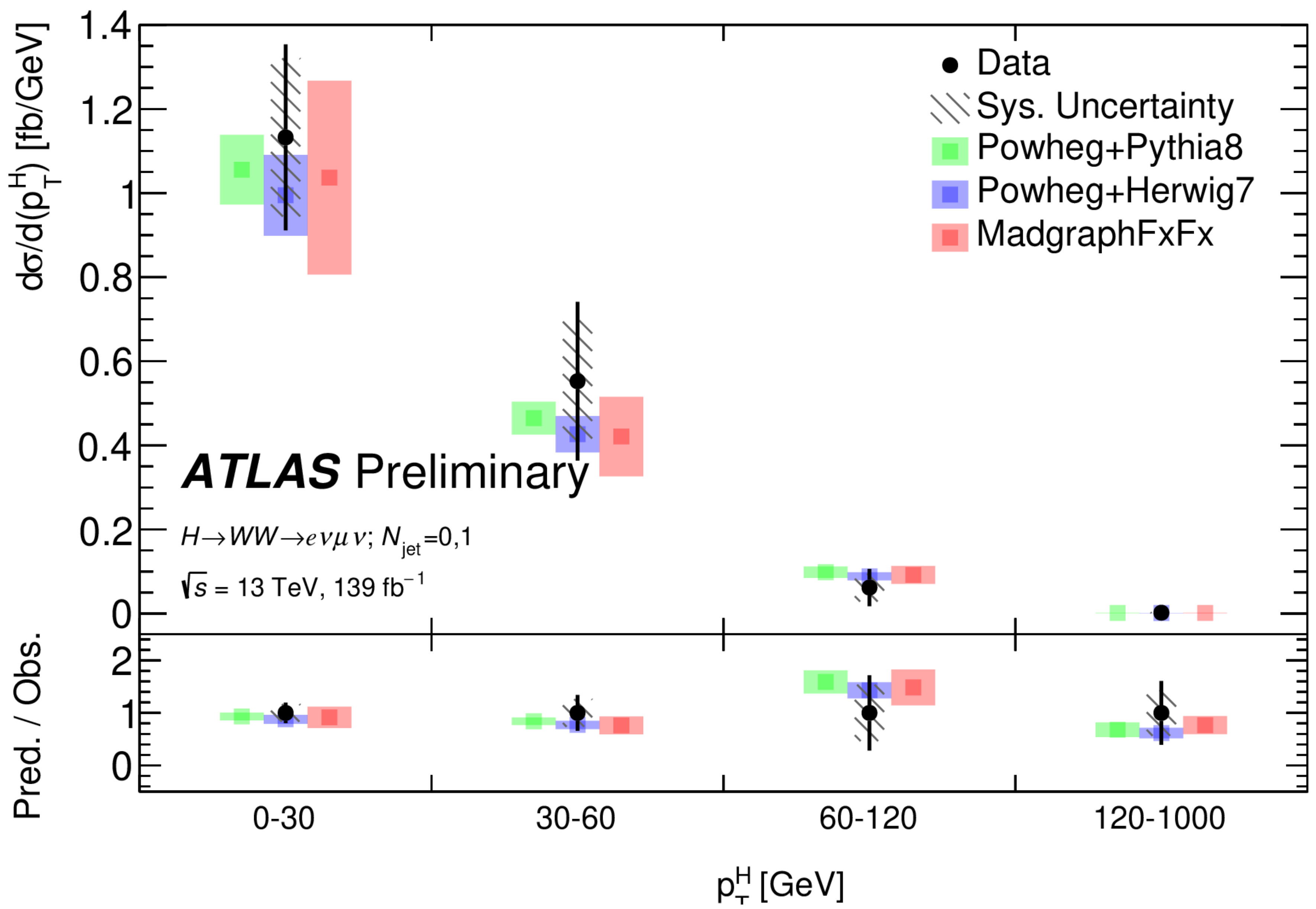
STXS Higgs combination (ATLAS)



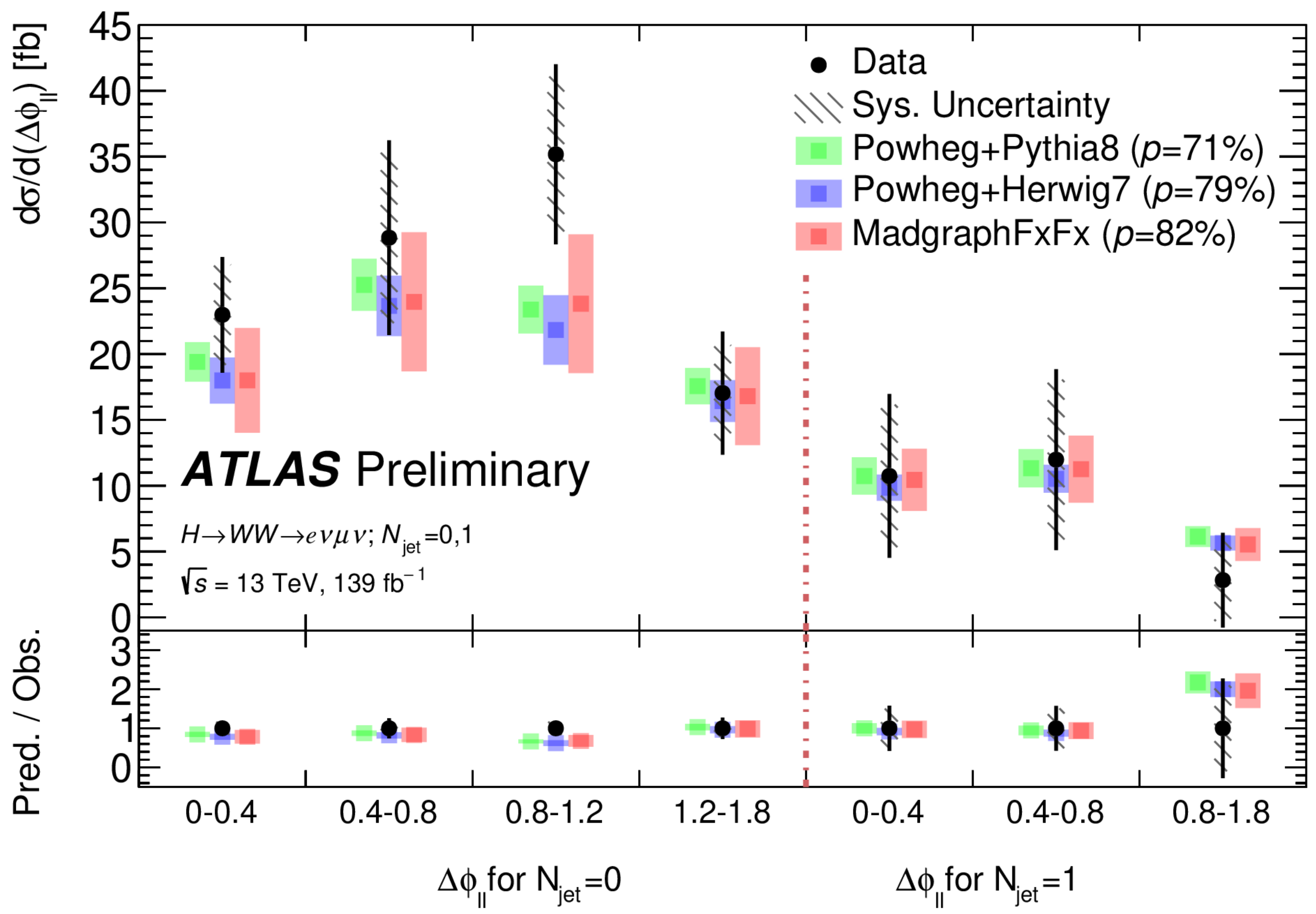
ggF diff XS



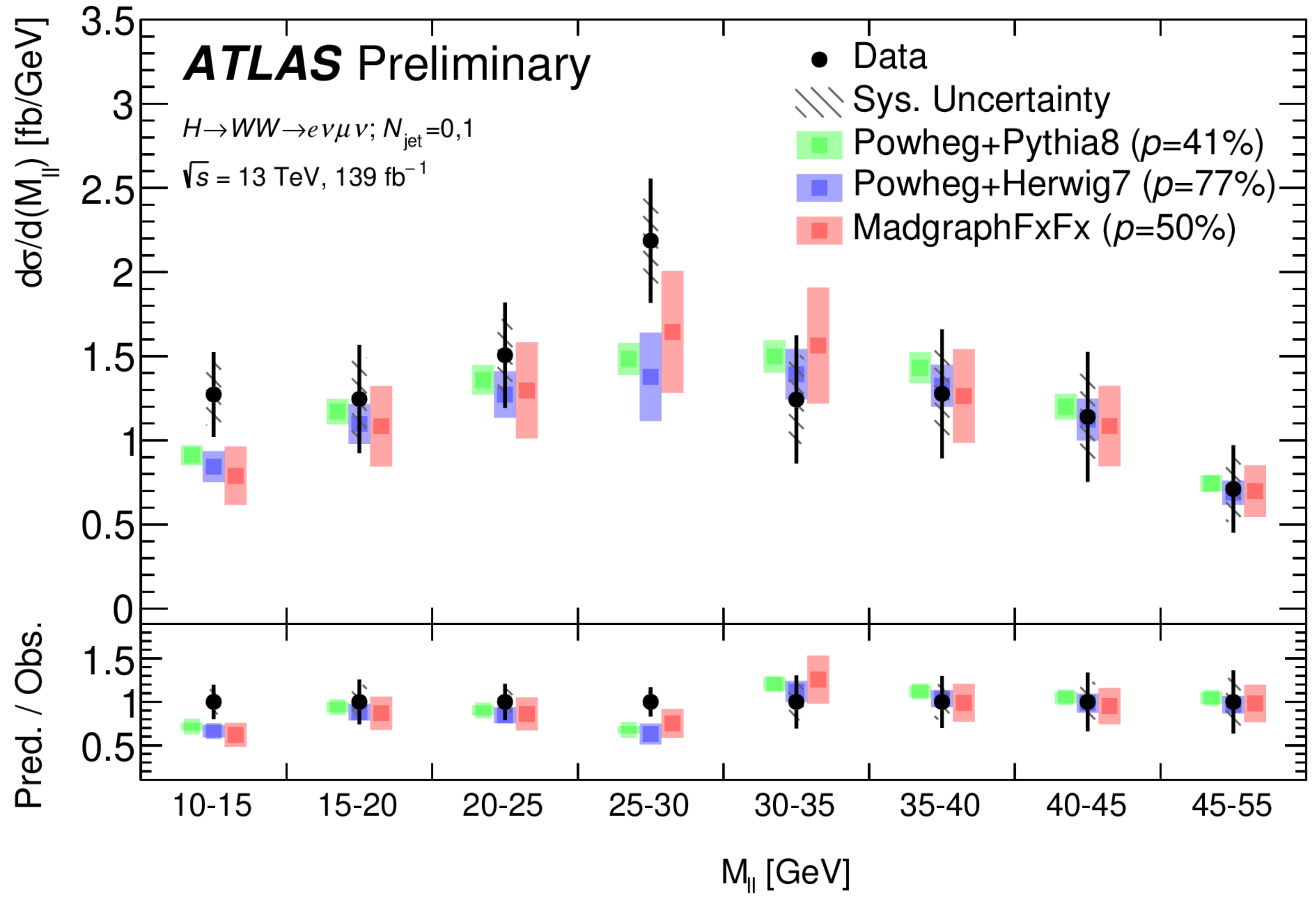
dσ/d(y_ll) [fb]
Data
Sys. Uncertainty
Powheg+Pythia8 (p=99%)
Powheg+Herwig7 (p=99%)
MadgraphFxFx (p=99%)
ATLAS Preliminary
H→WW→eνμν; N_jet=0,1
√s = 13 TeV, 139 fb⁻¹
Pred. / Obs.
0-0.2 0.2-0.4 0.4-0.6 0.6-0.8 0.8-1 1-1.2 1.2-1.4 1.4-1.8 1.8-2.5
y_ll



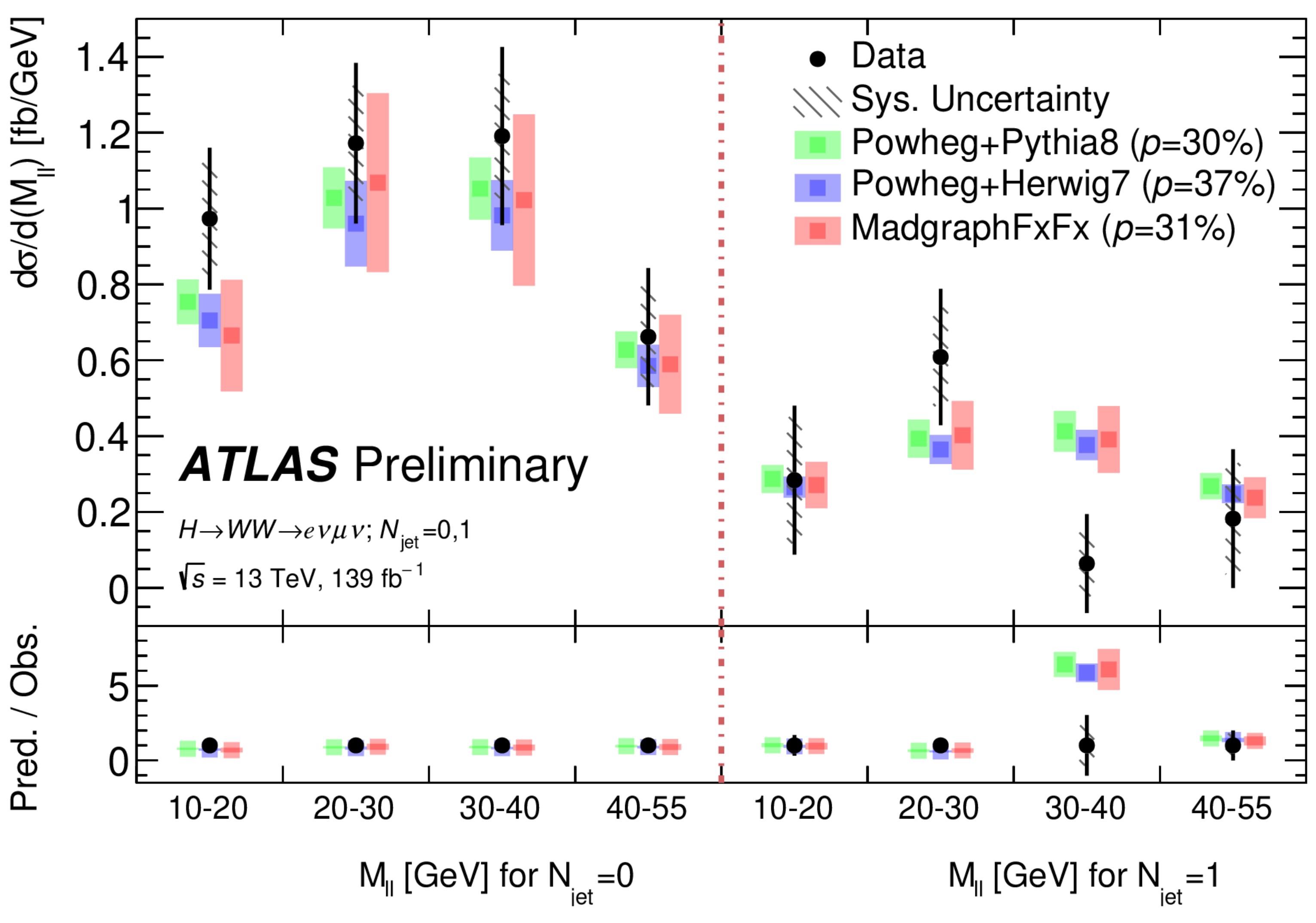
dσ/d(p_T^H) [fb/GeV]
Data
Sys. Uncertainty
Powheg+Pythia8
Powheg+Herwig7
MadgraphFxFx
ATLAS Preliminary
H→WW→eνμν; N_jet=0,1
√s = 13 TeV, 139 fb⁻¹
Pred. / Obs.
0-30 30-60 60-120 120-1000
p_T^H [GeV]



dσ/d(Δφ_ll) [fb]
Data
Sys. Uncertainty
Powheg+Pythia8 (p=71%)
Powheg+Herwig7 (p=79%)
MadgraphFxFx (p=82%)
ATLAS Preliminary
H→WW→eνμν; N_jet=0,1
√s = 13 TeV, 139 fb⁻¹
Pred. / Obs.
0-0.4 0.4-0.8 0.8-1.2 1.2-1.8 0-0.4 0.4-0.8 0.8-1.8
Δφ_ll for N_jet=0
Δφ_ll for N_jet=1



dσ/d(M_ll) [fb/GeV]
ATLAS Preliminary
H→WW→eνμν; N_jet=0,1
√s = 13 TeV, 139 fb⁻¹
Data
Sys. Uncertainty
Powheg+Pythia8 (p=41%)
Powheg+Herwig7 (p=77%)
MadgraphFxFx (p=50%)
Pred. / Obs.
10-15 15-20 20-25 25-30 30-35 35-40 40-45 45-55
M_ll [GeV]



dσ/d(M_ll) [fb/GeV]
Data
Sys. Uncertainty
Powheg+Pythia8 (p=30%)
Powheg+Herwig7 (p=37%)
MadgraphFxFx (p=31%)
ATLAS Preliminary
H→WW→eνμν; N_jet=0,1
√s = 13 TeV, 139 fb⁻¹
Pred. / Obs.
10-20 20-30 30-40 40-55 10-20 20-30 30-40 40-55
M_ll [GeV] for N_jet=0
M_ll [GeV] for N_jet=1

VH selection

Category	2ℓ		3ℓ		4ℓ	
	OS	SS	Z-dominated	Z-depleted	1-SFOS	2-SFOS
Minimum lepton p_T [GeV]	15	15	15	15	10	10
Number of leptons	2	2	3	3	4	4
Total lepton charge	0	± 2	± 1	± 1	0	0
Number of SFOS pairs	0	0	1 or 2	0	1	2
Minimum $\Delta R_{\ell\ell}$	0.1	0.4	0.1	0.1	0.2 ($\ell_0\ell_1$)	
Minimum $m_{\ell\ell}$ [GeV]	10	–	12 (smallest SFOS)	–	12 (all SFOS) or 10 (all DFOS)	
Number of jets	≥ 2	≥ 1	–	–	–	–
Number of b-tagged jets	0	0	0	0	0	0
$\lvert m_{\ell\ell} - m_Z \rvert$ [GeV]	–	> 20 ($e^{\pm}e^{\pm}$)	> 25 (all SFOS)	–	–	–
$m_{\ell\ell}$ [GeV]	–	–	–	–	–	< 50 ($\ell_0\ell_1$)
E_T^{miss} [GeV]	–	–	> 30	–	–	–

VH analyses final fit

- Signal regions and control regions used In the final fit for all the differentVH channels
- 2 fits implemented:
- 1 POI for VH production (ZH and WH completely correlated)
- 2 POIs, one for WH and one for ZH

Channels	Regions included	POIs	NFs
VH 2ℓ DFOS	DFOS SR, Z+jets CR, Top CR, WW CR	μ_{VH}	$\mu_{Z+\text{jets}}$, μ_{Top}, μ_{WW}
WH 2ℓ SS	SS2L 3 SRs	μ_{WH}	μ_{WZ}
WH 3ℓ Z-dominated	Z-dominated SR, WZ 0 jet CR, $WZ \geq$ 1 jet CR	μ_{WH}	μ_{WZ0j}, $\mu_{WZ\geq1j}$
WH 3ℓ Z-depleted	Z-depleted SR , WZ 0 jet CR, $WZ \geq$ 1 jet CR	μ_{WH}	μ_{WZ0j}, $\mu_{WZ\geq1j}$, μ_{WWW}
ZH 4ℓ	1-SFOS SR, 2-SFOS SR, ZZ CR	μ_{ZH}	μ_{ZZ}

VH analysis uncertainty breakdown

Source	$\frac{\Delta(\sigma_{VH} \times \mathcal{B}_{H\to WW^*})}{\sigma_{VH} \times \mathcal{B}_{H\to WW^*}}$ [%]	$\frac{\Delta(\sigma_{WH} \times \mathcal{B}_{H\to WW^*})}{\sigma_{WH} \times \mathcal{B}_{H\to WW^*}}$ [%]	$\frac{\Delta(\sigma_{ZH} \times \mathcal{B}_{H\to WW^*})}{\sigma_{ZH} \times \mathcal{B}_{H\to WW^*}}$ [%]
Statistical uncertainties in data	22.3	57.9	28.4
Systematic uncertainties	13.3	36.6	9.9
Statistical uncertainties in simulation	6.4	14.4	5.9
Experimental systematic uncertainties	5.2	9.8	6.0
Electrons	1.2	1.8	1.6
Muons	2.5	2.8	4.1
Jet energy scale	0.7	2.3	0.5
Jet energy resolution	0.6	2.8	0.6
Flavour tagging	0.9	1.4	0.8
Missing transverse momentum	0.6	0.4	0.9
Pile-up	1.1	1.5	0.8
Luminosity	2.3	2.4	2.1
Mis-identified leptons	2.9	7.1	2.7
Charge-flip electrons	1.5	4.5	0.1
Theoretical uncertainties	6.0	18.6	4.7
WH	2.3	2.8	0.1
ZH	0.7	0.7	3.4
WW	1.0	3.3	0.3
$W(Z/\gamma^*)$ 0-jet	3.2	11.3	0.3
$W(Z/\gamma^*)$ $\geq$1-jets	0.2	0.8	0.4
$Z(Z/\gamma^*)$	0.8	1.5	0.6
VVV	2.4	12.7	0.3
Top	2.9	5.5	2.5
Z+jets	1.8	3.4	1.5
RNN shape uncertainty for $W(Z/\gamma^*)$	8.8	27.3	0.3
Floating normalisations	0.1	0.2	0.1
Total	26.0	71.0	30.1