Measurements of multi-boson productions including vector-boson fusion and vector-boson scattering at ATLAS

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on behalf of the ATLAS collaboration

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ATLAS EXPERIMENT

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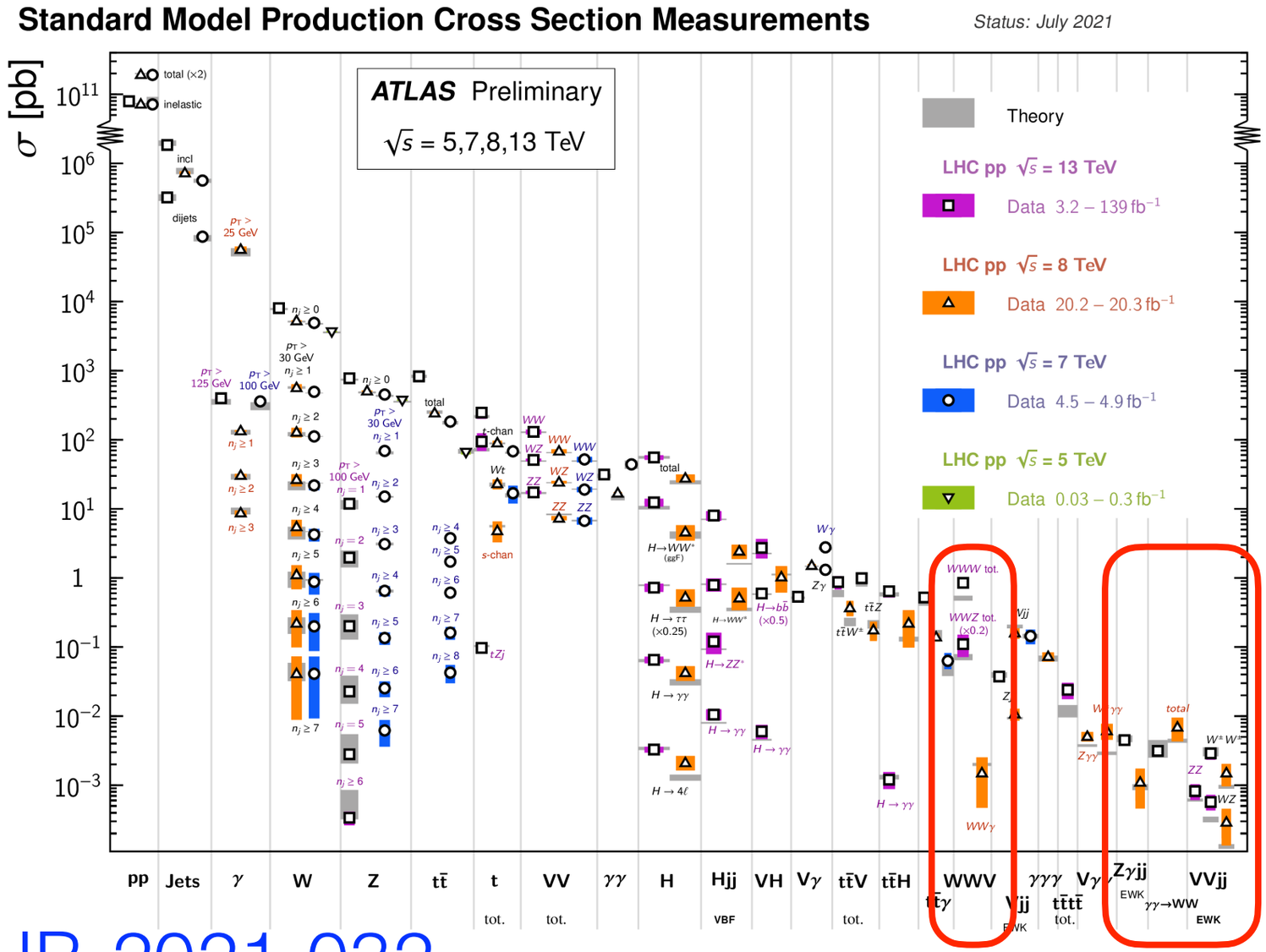
Multi-boson Physics

- Electroweak production, powerful tool to probe the Standard Model
- Vector boson scattering(VBS) directly probes gauge boson self-interactions, non-Abelian structure of the EW interactions
- Rare processes provides discovery opportunities



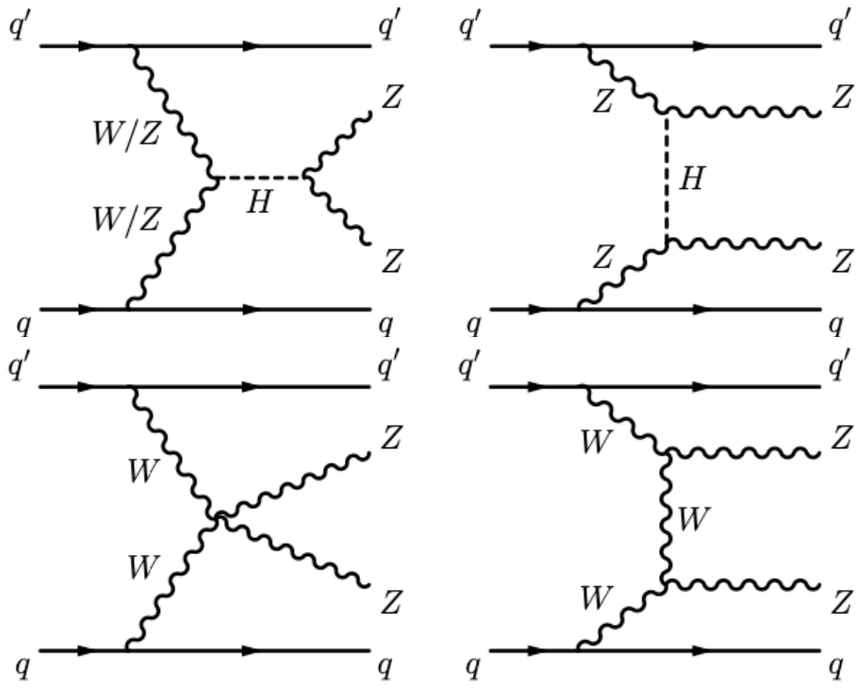
[ATL-PHYS-PUB-2021-032]

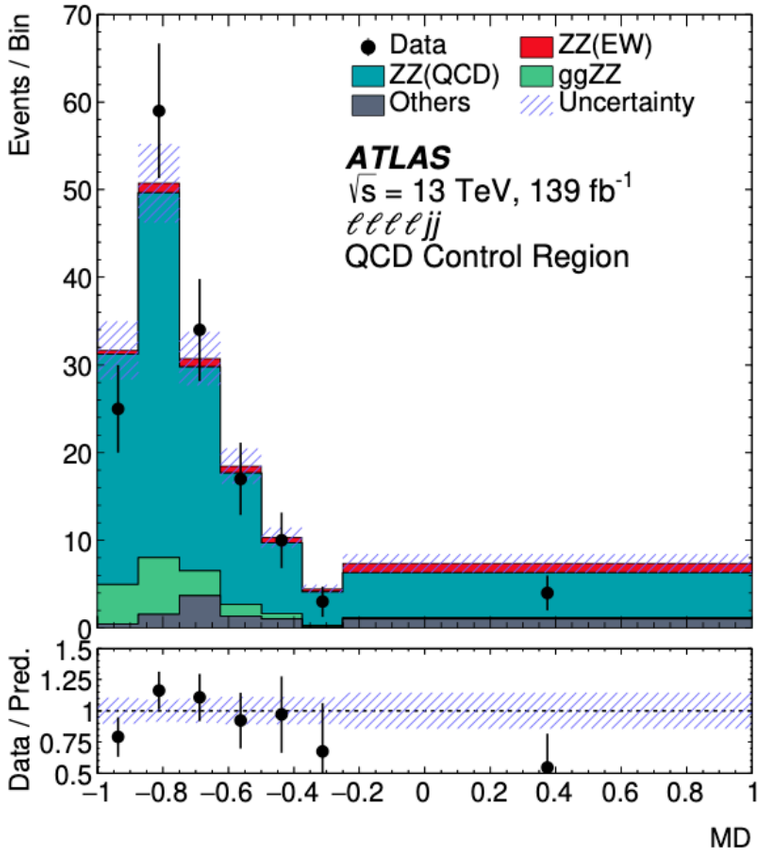
Outline

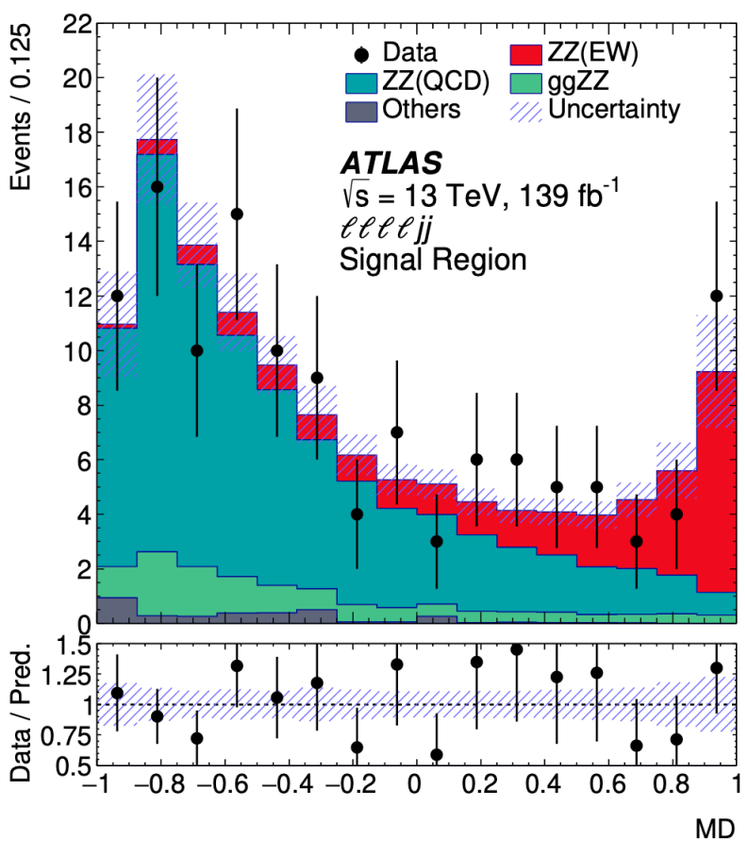
- VBS processes
  - Observation of EW ZZjj
  - Fiducial cross-section measurements of Z(—>ll)γjj New
  - Search for Z(—>νν)γjj New
- Observation of WWW tri-boson process New

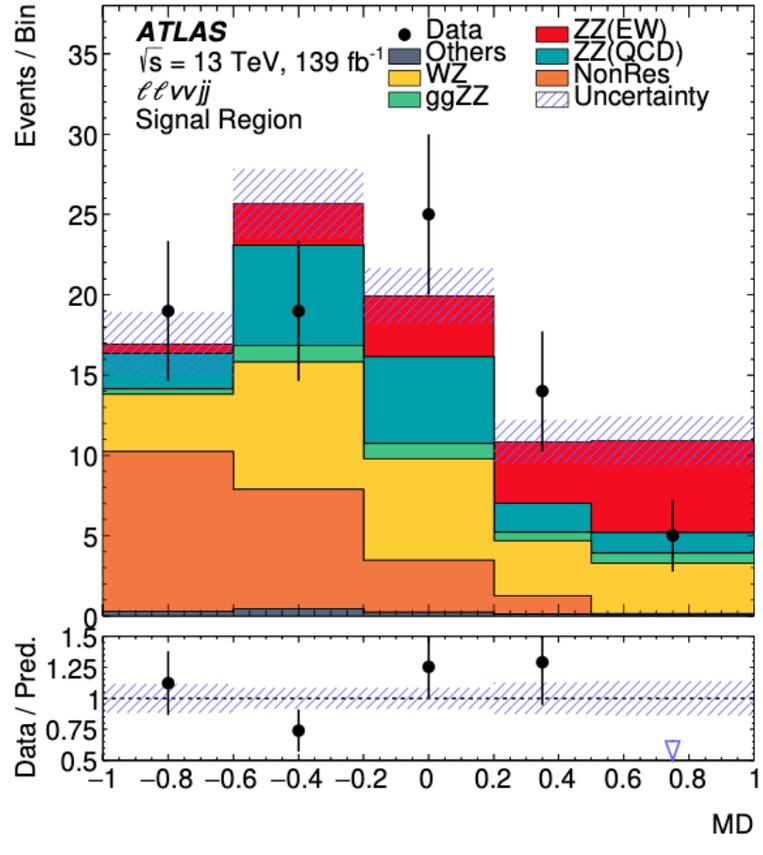
Observation of EW ZZjj

- Very rare process with a fiducial cross section of ~1fb
  - Prevent unitarity violation at TeV scale
- Decay channel ZZ—> 4l, ZZ—>llvv
  - $|\Delta Y_{jj}| > 2$, $m_{jj} > 300$ for 4l (400 for llvv)
- BDT is trained to distinguish between EWK and QCD ZZjj, largely using jet-related variables, m_{jj}, $|\Delta Y_{jj}|$, p_T^{jets}…
- Fitting on the BDT score, gives $\mu_{EW}=1.35\pm0.34$, with significance of 5.5(4.3) σ. $\mu_{QCD}=0.96\pm0.22$









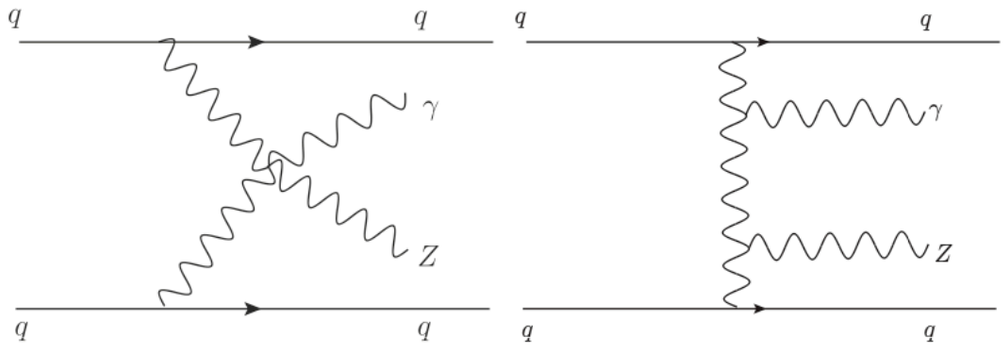
Submitted to Nature Physics arXiv:2004.10612

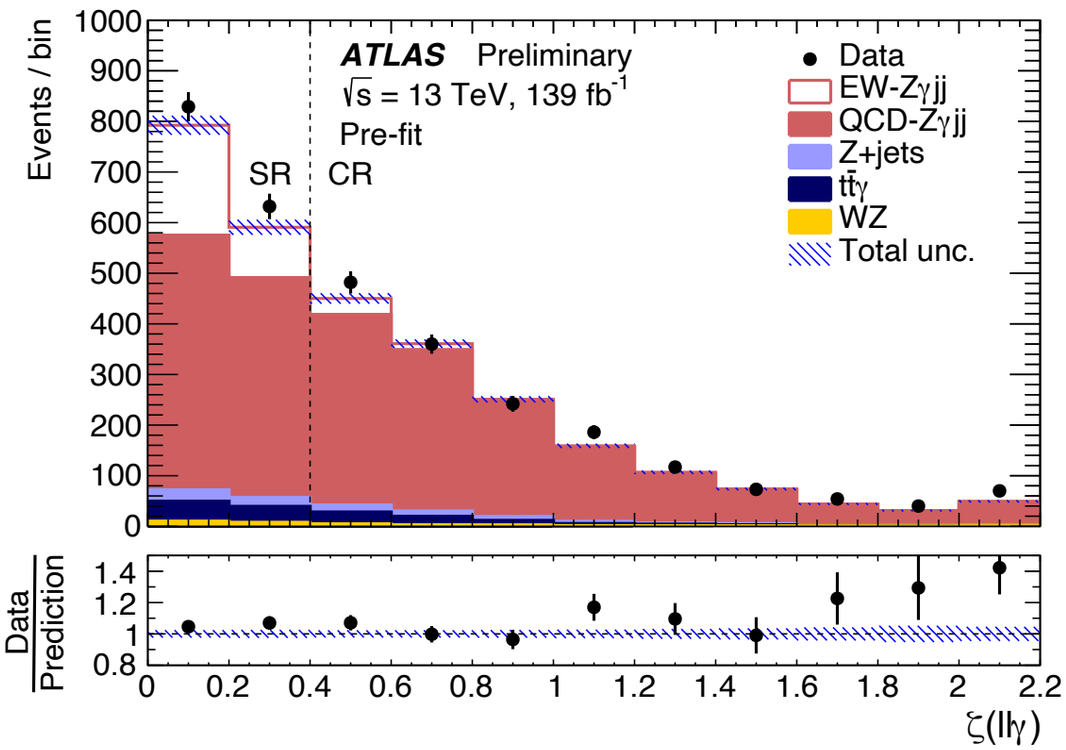
Measurement of Z(—>ll)γjj

- Probes the non-SM neutral quartic gauge couplings.
- VBF topology: large rapidity gap between the jets $|\Delta Y_{jj}| > 1$
- Centrality of llγ relative to the tagging jets

$$\zeta(\ell\ell\gamma) = \left| \frac{y_{\ell\ell\gamma} - (y_{j_1} + y_{j_2})/2}{y_{j_1} - y_{j_2}} \right|,$$

- ζ < 0.4 as signal region, ζ > 0.4 as control region

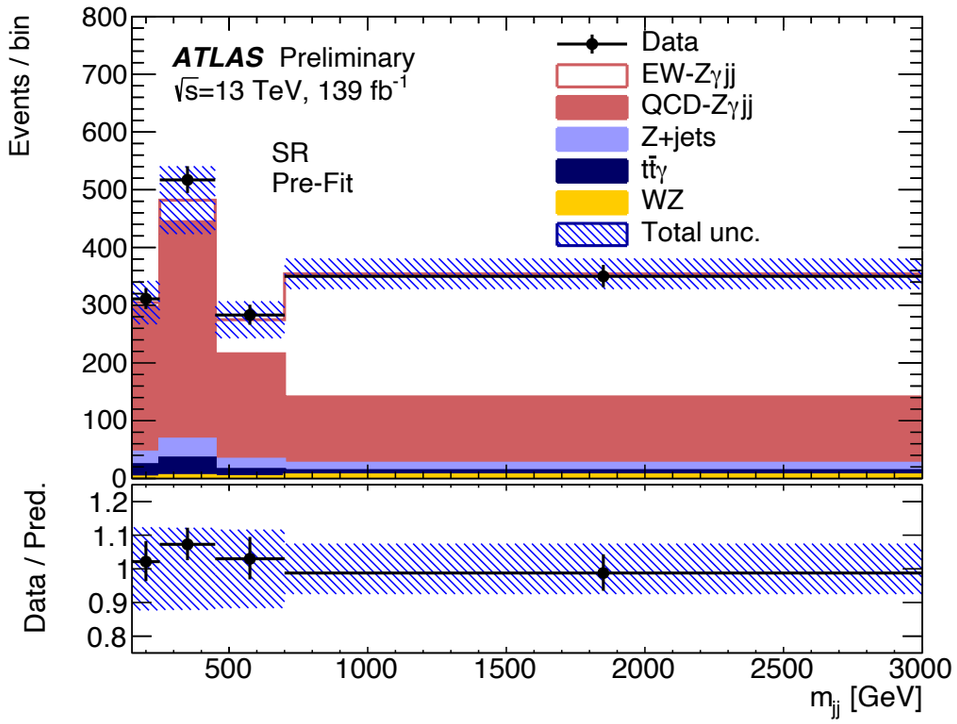


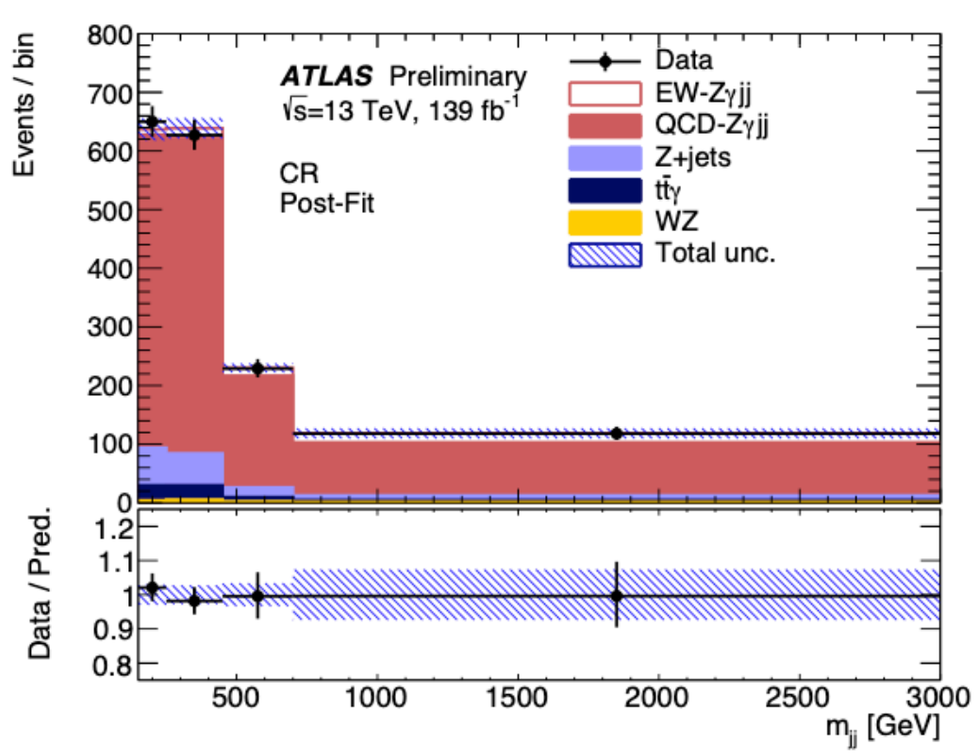


ATLAS-CONF-2021-038

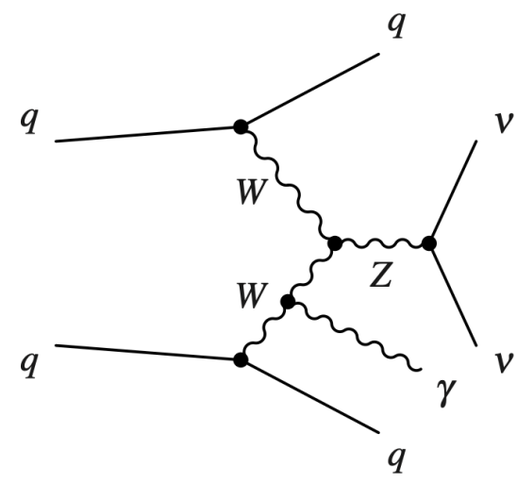
Measurement of Z(—>ll)γjj

- Simultaneous fit in SR and CR on m_{jj} distribution
  - μ_{EW}, $\mu_{QCD\text{-}SR}$, $\mu_{QCD\text{-}SR}$
- EWK fiducial XS:
  - Measured: $4.49 \pm 0.4(stat.) \pm 0.42(syst.) fb$
  - Pred: $4.73 \pm 0.01(stat.) \pm 0.15(PDF)^{+0.23}_{-0.22}(scale) fb$
  - Observation of well over 10 σ
- QCD process included:
  - Measured: $\sigma_{EW+QCD} = 20.6 \pm 0.6\ (\text{stat.})^{+1.2}_{-1.0}\ (\text{syst.})\ \text{fb},$
  - Predicted(MG5): $\sigma^{pred}_{EW+QCD} = 20.4 \pm 0.1\ (\text{stat.}) \pm 0.2\ (\text{PDF})^{+2.6}_{-2.0}\ (\text{scale})\ \text{fb}.$

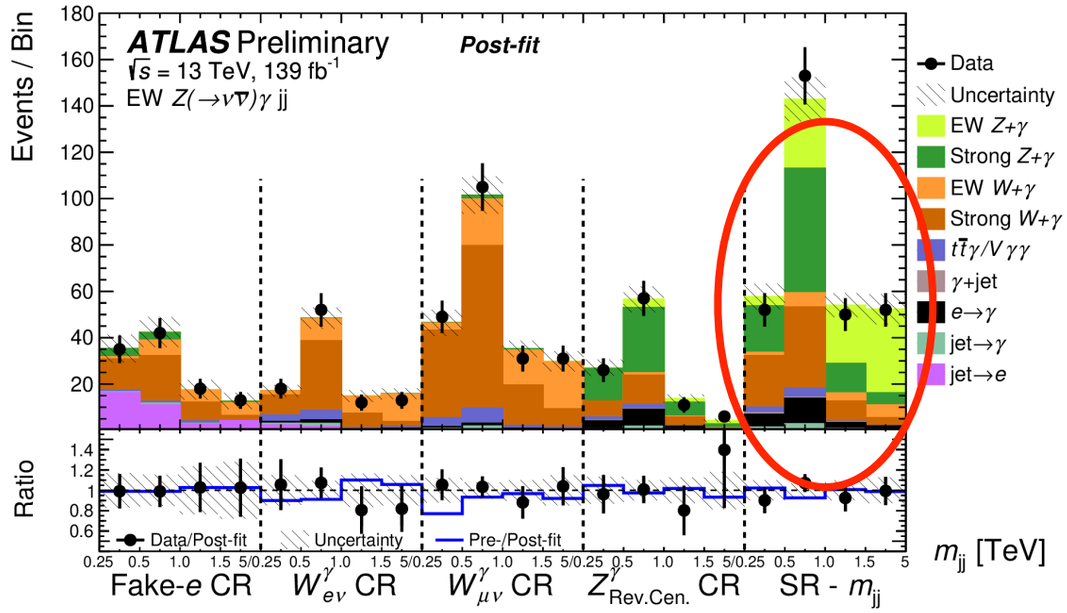


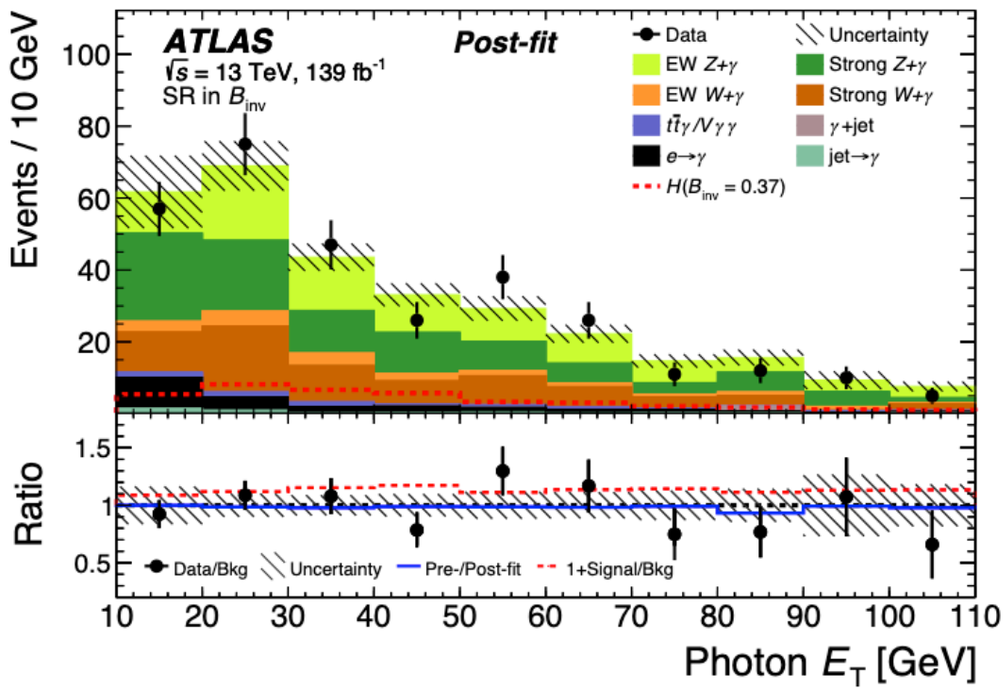


Observation of Z(—>νν)γjj



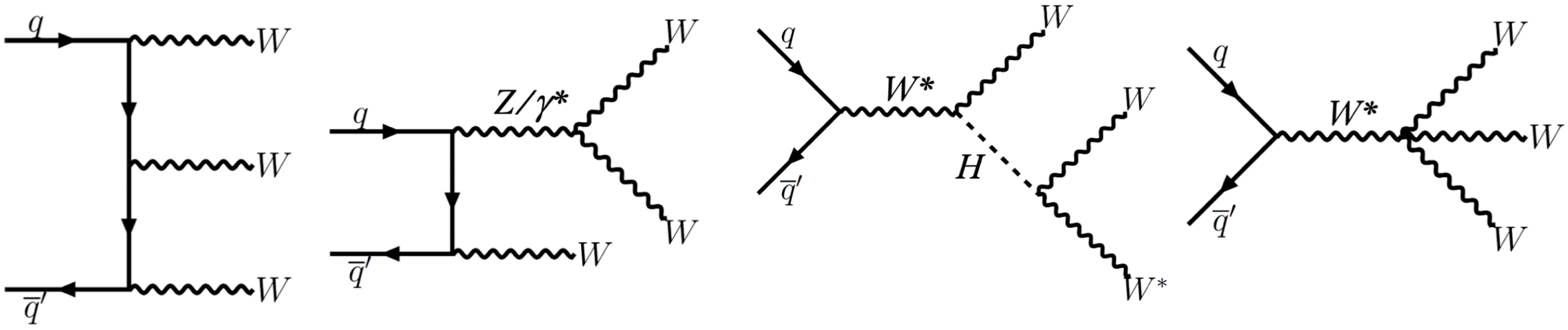
- First observation of Z(νν)γjj with 5.2(5.1) σ significance
  - $|\Delta\eta_{jj}| > 3$, $m_{jj} > 250$ GeV
  - $\Delta\phi_{jj} < 2.5$ to suppress multijet
- Using multiple control region to constrain background during the fit
- Measured signal strength $\mu_{EW} = 1.03 \pm 0.25$
- Also sets limits on invisible Higgs decay





[EXOT-2021-17]

Triboson - WWW

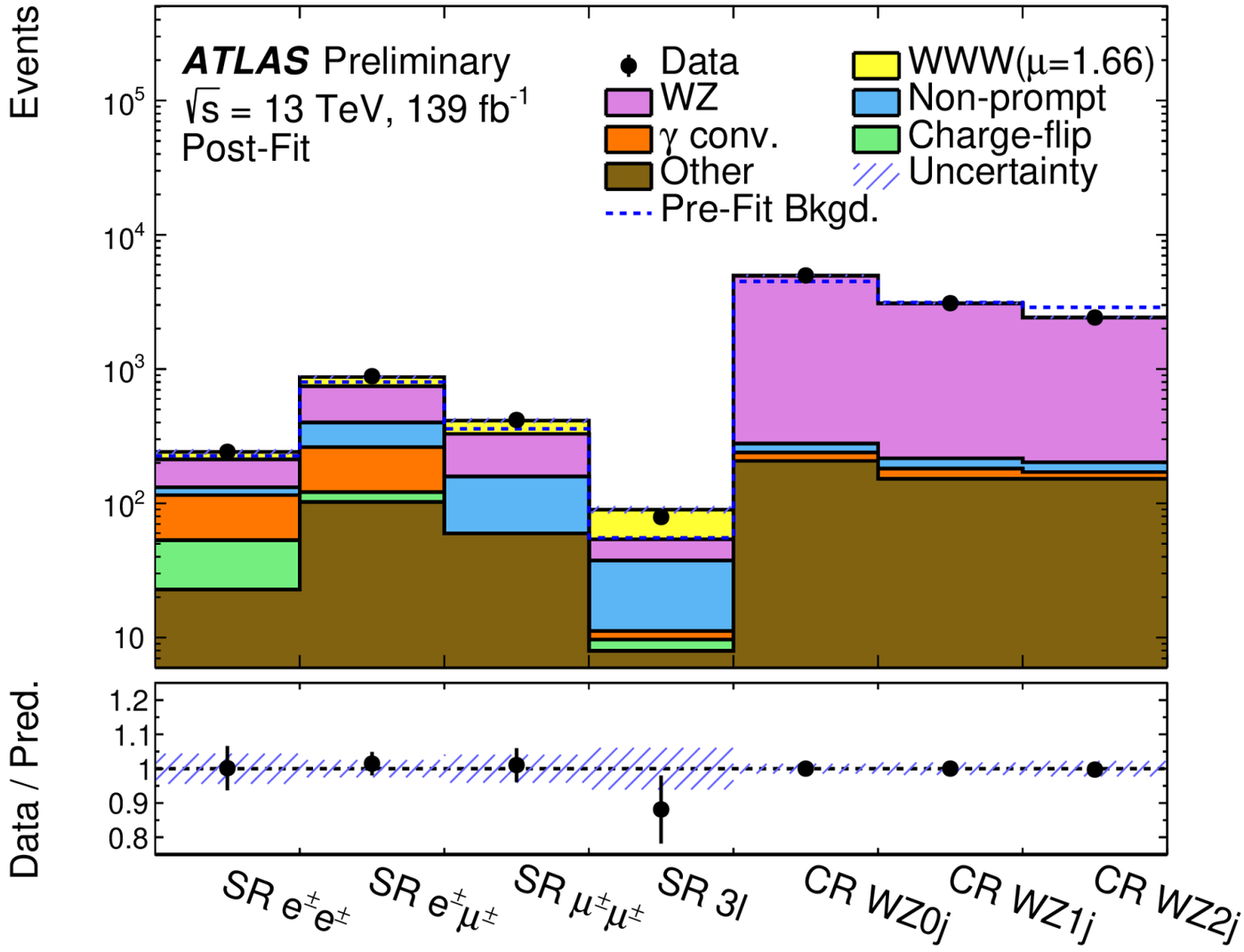


- One of the rarest SM processes, sensitive to aTGC/ aQGC
  - Off-shell WH—>WW* is also included as signal
- Two channels:
  - WWW—>l±νl±νjj, same-sign di-leptons plus 2 jets
    - More channels based on lepton flavor: ee, eμ, μμ
  - WWW—>l±νl∓νl±ν, no same-flavor opposite-sign lepton pairs

ATLAS-CONF-2021-039

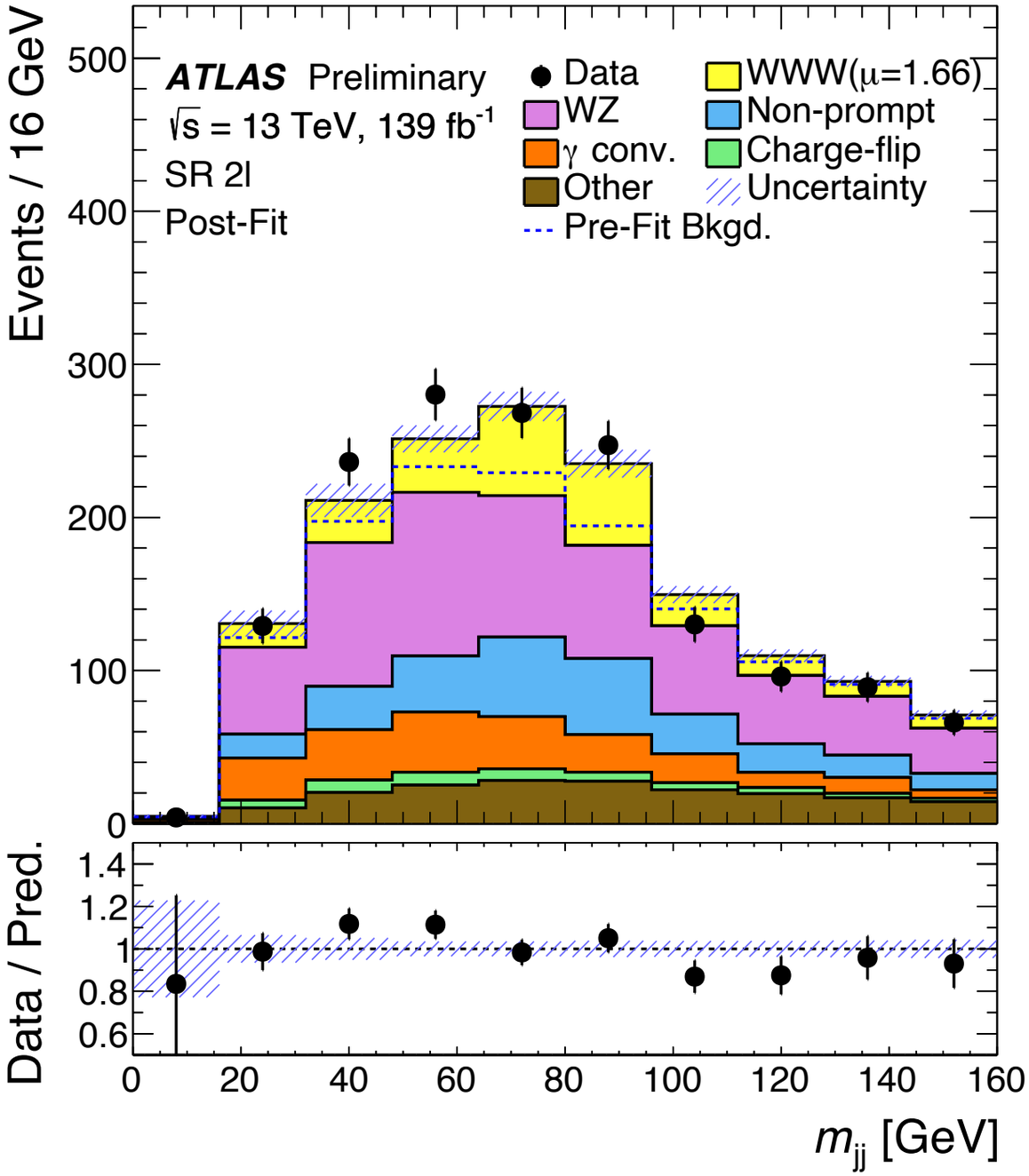
Triboson - WWW

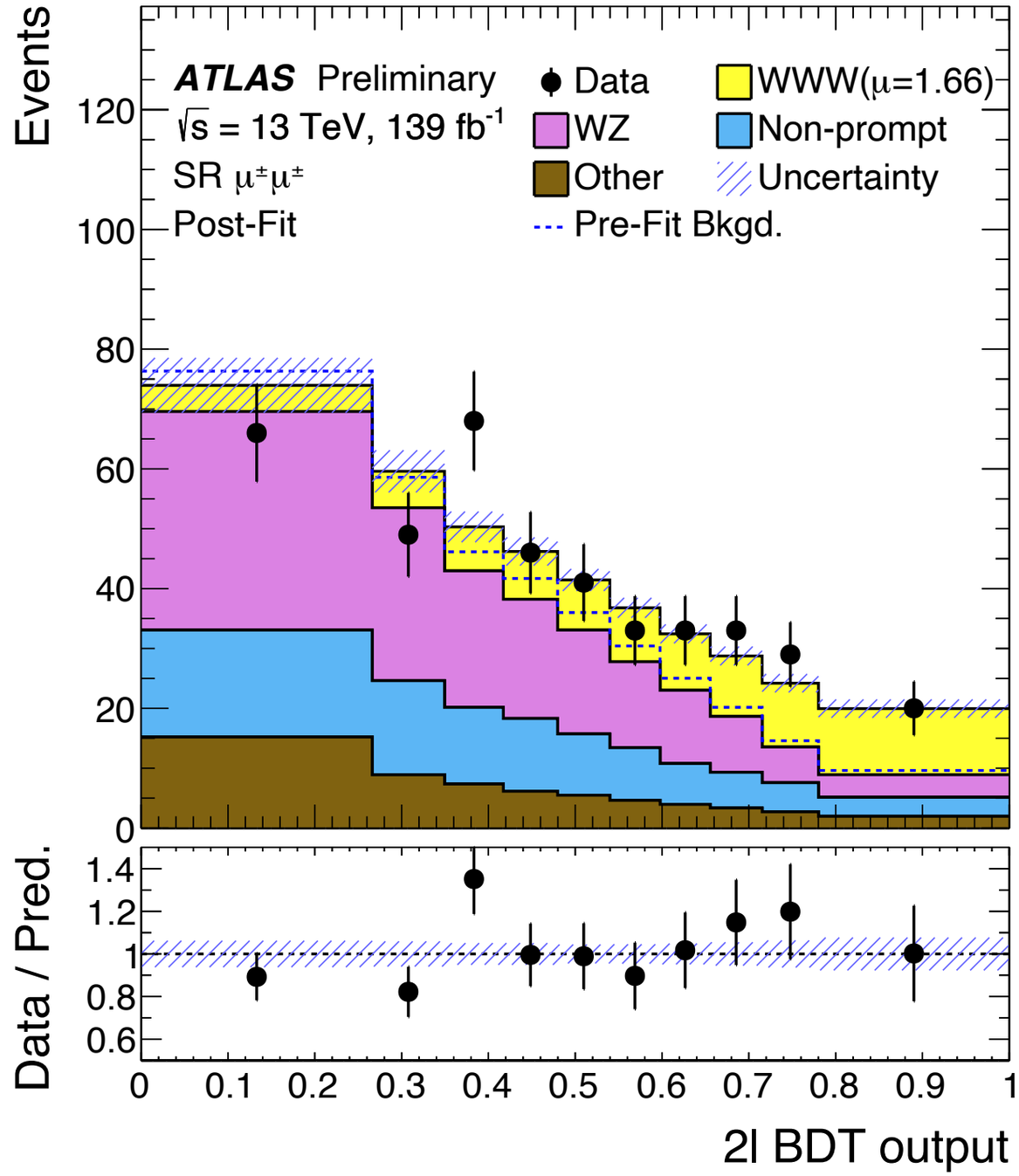
- Signal region:
  - m_{ll}, E_T^{miss} to suppress Z+jets
- Train separate BDT in 2l and 3l channels
  - Variables include m_{jj}, $p_T^{(jet)}$, jet multiplicity, m_{ll}, $p_T^{(lep)}$, E_T^{miss}…
- Main background: WZ, constrained by SFOS control region during simultaneous fit with signal
- Other data-driven background: non-prompt, γ conversion(Vγ), charge-flip
- Other SM background estimated by MC



WWW 2l channel

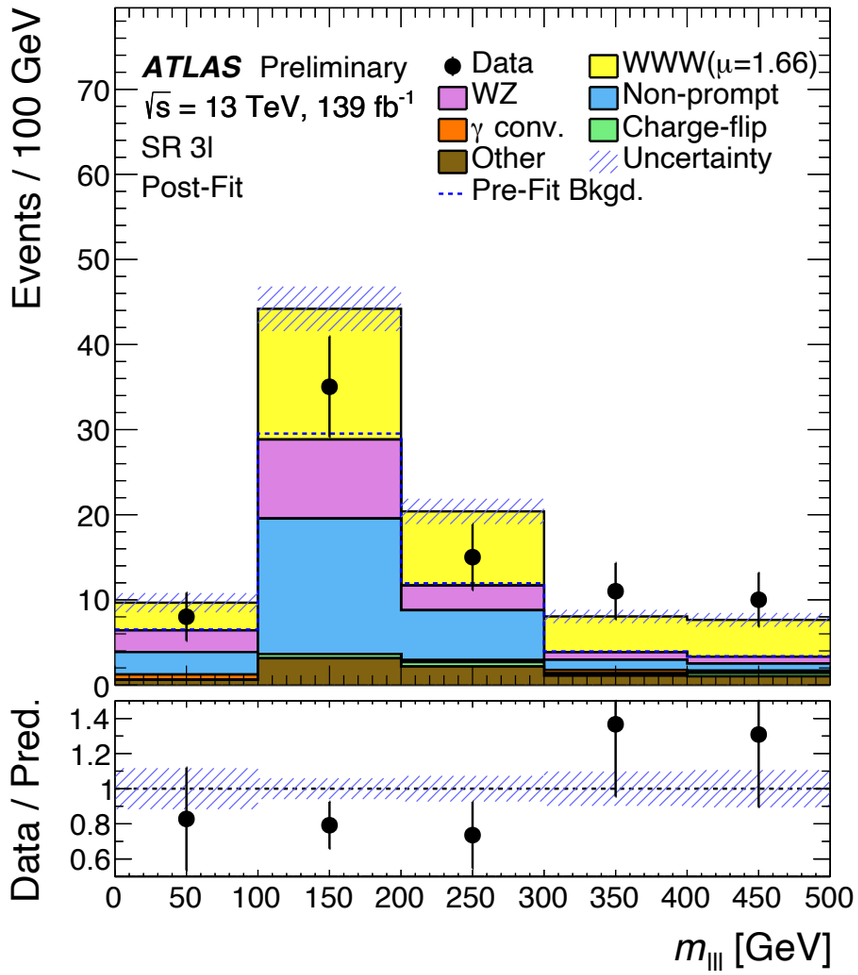
- Post-fit data/MC comparison

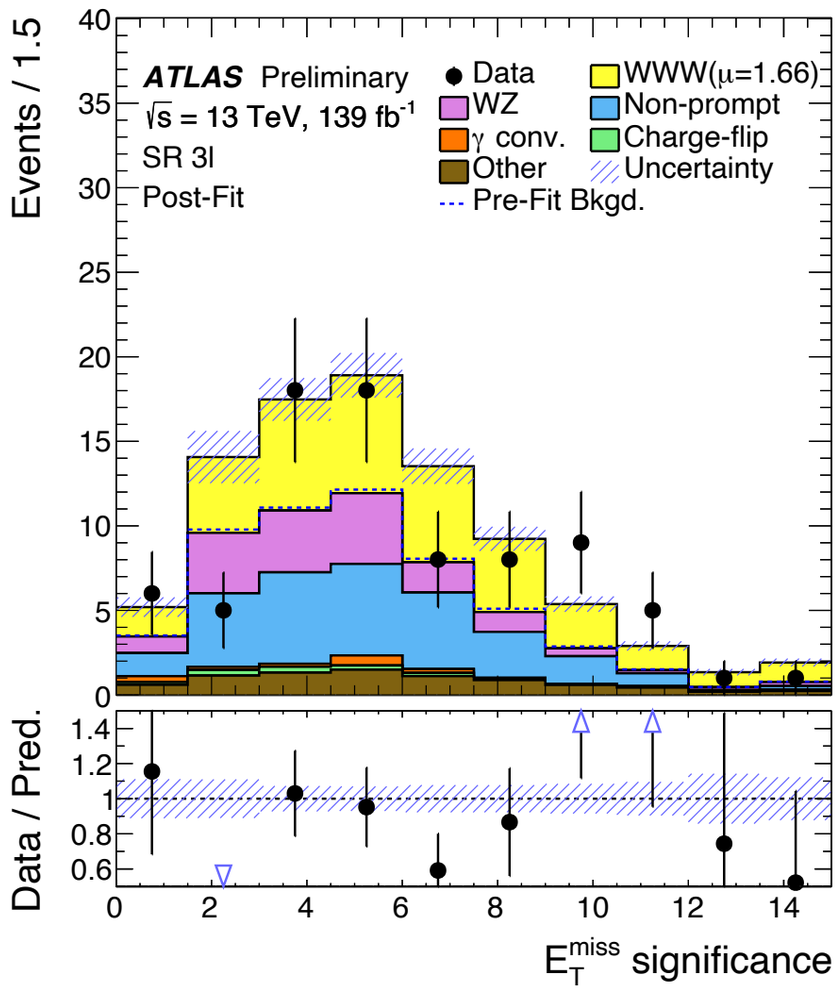


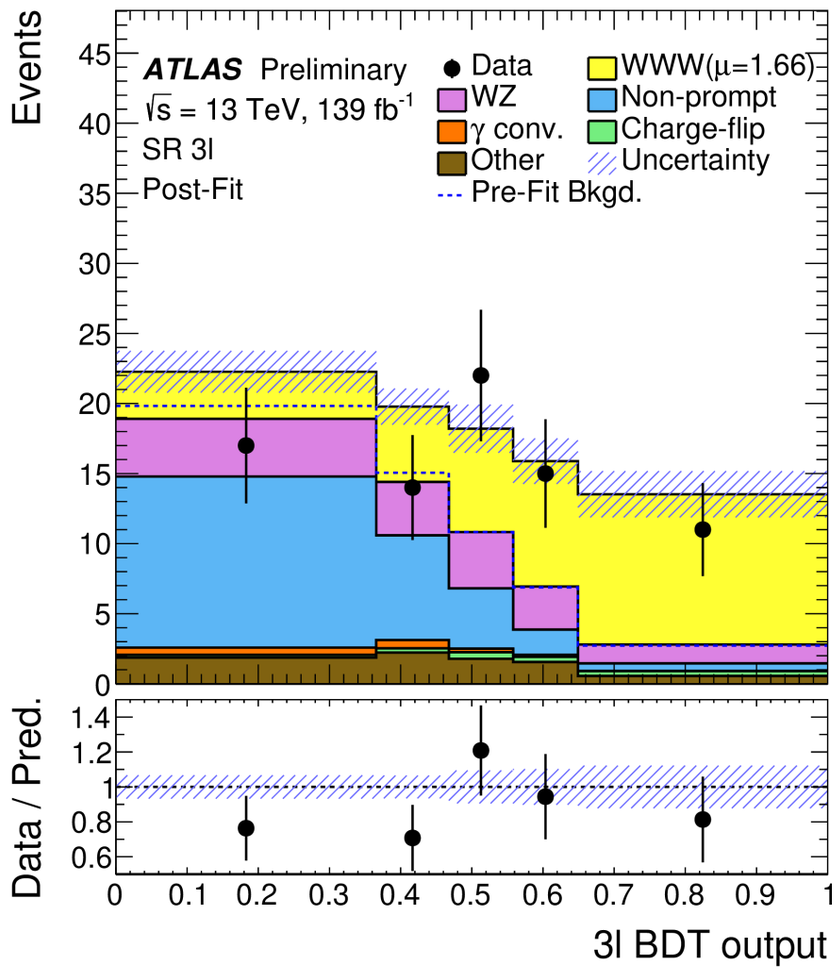


WWW 3l channel

- Post-fit data/MC comparison







Triboson - WWW

- Signal strength

$$prediction = \mu \cdot s + b$$

Signal Strength	Normalization Factors		
$\mu(WWW)$	$WZ + 0$ jets	$WZ + 1$ jet	$WZ + \geq 2$ jets
1.66 ± 0.28	1.12 ± 0.11	0.98 ± 0.04	0.88 ± 0.18

- Total observed(expected) significance of 8.2(5.4) σ
- Also measured production cross section
  - 850 ± 100 (stat.) ± 80 (syst.) fb

Fit	Observed (expected) significances $[\sigma]$	$\mu(WWW)$
$e^{\pm}e^{\pm}$	2.3 (1.4)	1.69 ± 0.79
$e^{\pm}\mu^{\pm}$	4.6 (3.1)	1.57 ± 0.40
$\mu^{\pm}\mu^{\pm}$	5.6 (2.8)	2.13 ± 0.47
2ℓ	6.9 (4.1)	1.80 ± 0.33
3ℓ	4.8 (3.7)	1.33 ± 0.39
Combined	**8.2 (5.4)**	$\mathbf{1.66 \pm 0.28}$

Summary

- VBS EWK ZZjj processes observed with 5.5σ (4.3σ expected)
- Fiducial cross section of Z(—>ll)γjj processes measured to be 4.49±0.58 fb
- Z(—>νν)γjj is observed for the first time 5.2σ (5.1σ expected)
- WWW processed is observed for the first time 8.2σ (5.4σ expected)

backup

Z(—>ll)γjj phase space

Lepton	$p_{\mathrm{T}}^{\ell} > 20, 30(\text{leading})\ \text{GeV}, \quad \lvert\eta_{\ell}\rvert < 2.47$ $N_{\ell} \geq 2$
Photon	$E_{\mathrm{T}}^{\gamma} > 25\ \text{GeV}, \quad \lvert\eta_{\gamma}\rvert < 2.37$ $E_{\mathrm{T}}^{cone20} < 0.07 E_{\mathrm{T}}^{\gamma}$ $\Delta R(\ell, \gamma) > 0.4$
Jet	$p_{\mathrm{T}}^{jet} > 50\ \text{GeV}, \quad \lvert y_{jet}\rvert < 4.4$ $\lvert\Delta y\rvert > 1.0$ $m_{jj} > 150\ \text{GeV}$ remove jets if $\Delta R(\gamma, j) < 0.4$ or if $\Delta R(\ell, j) < 0.3$
Event	$m_{\ell\ell} > 40\ \text{GeV}$ $m_{\ell\ell} + m_{\ell\ell\gamma} > 182\ \text{GeV}$ $\zeta(\ell\ell\gamma) < 0.4$ $N_{jets}^{gap} = 0$

Table 1: Summary of selection criteria applied at particle level.

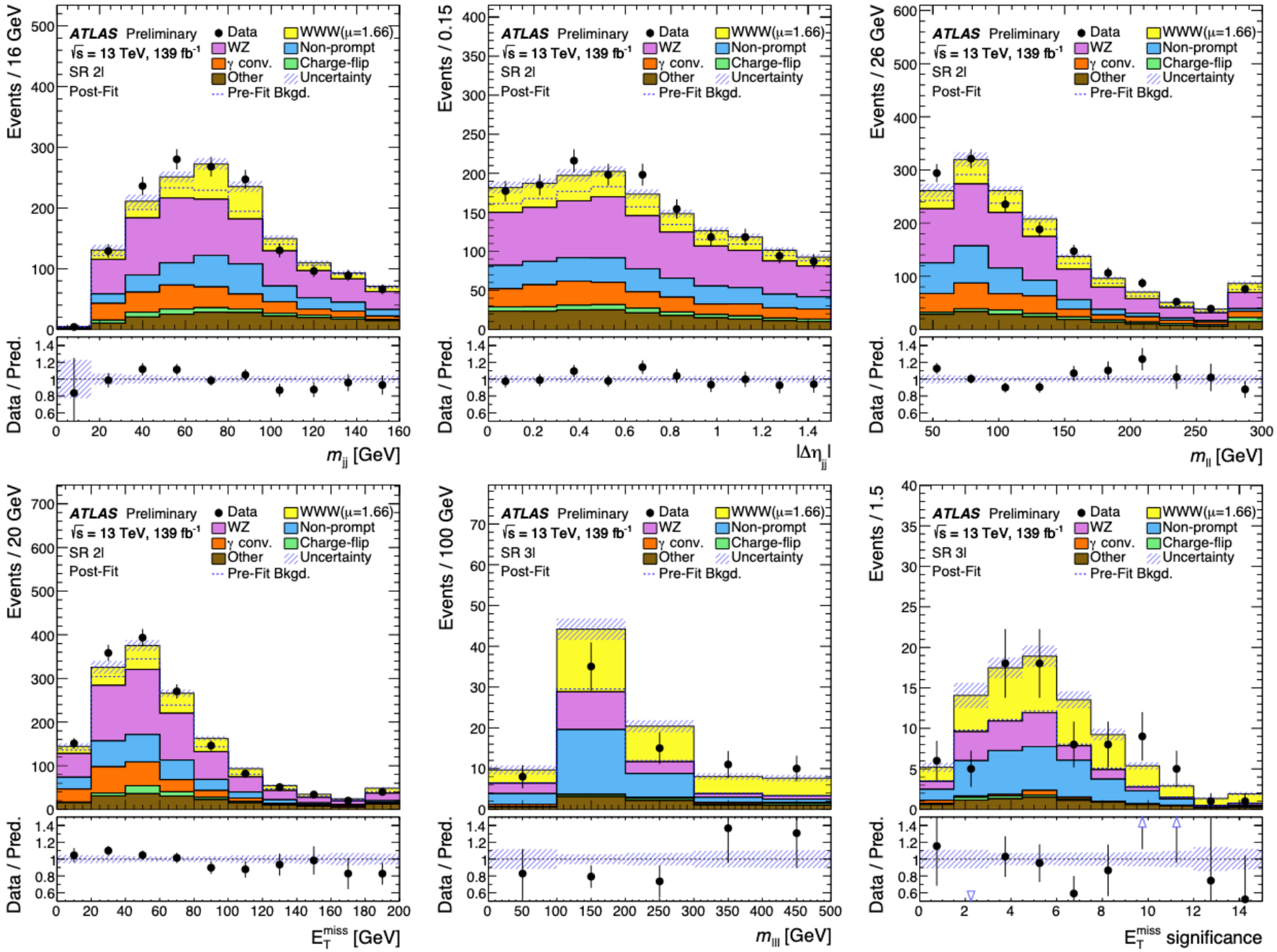
WWW BDT variables

2ℓ	3ℓ
$\lvert m_{jj} - m_W \rvert$	$E_{\mathrm{T}}^{\mathrm{miss}}$ significance $\times 10/E_{\mathrm{T}}^{\mathrm{miss}}$
p_{T} (forward jet)	$p_T(\ell_2)$
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	$N(\mathrm{jets})$
$p_T(j_2)$	same flavor $m_{\ell\ell}$
minimum $m(\ell, j)$	$m_T(\ell\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}})$
$m(\ell_2, j_1)$	$m(\ell_2, \ell_3)$
$N(\mathrm{jets})$	$\Delta\phi(\ell\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}})$
p_{T} (ℓ_2)	minimum $\Delta R(\ell, \ell)$
$m_{\ell\ell}$	p_{T} (ℓ_3)
$\lvert \eta(\ell_1) \rvert$	$m_T(\ell_2, E_{\mathrm{T}}^{\mathrm{miss}})$
$N(\mathrm{leptons\ in\ jets})$	$E_{\mathrm{T}}^{\mathrm{miss}}$ significance
$m(\ell_1, j_1)$	

WWW yield

	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	3ℓ
WWW	29.3 ± 4.4	128 ± 19	84 ± 12	35.8 ± 5.2
WZ	80.6 ± 5.7	344 ± 22	171 ± 10	16.4 ± 1.4
Charge-flip	30.3 ± 7.2	18.8 ± 4.5	–	1.7 ± 0.4
γ conversions	62.1 ± 8.7	142 ± 15	–	1.5 ± 0.1
Non-prompt	16.6 ± 4.1	138 ± 24	98 ± 21	26.3 ± 2.9
Other	22.8 ± 3.7	102 ± 15	59.7 ± 9.0	8.0 ± 0.9
Total predicted	242 ± 11	872 ± 22	414 ± 17	89.7 ± 5.4
Data	242	885	418	79

WWW data/mc plots



WWW uncertainty

Uncertainty source	$\Delta\sigma/\sigma$ [%]
Data-driven background	5.3
Prompt-lepton-background modeling	3.3
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	2.8
MC statistics	2.8
Lepton	2.1
Luminosity	1.9
Signal modeling	1.5
Pile-up modeling	0.9
Total systematic uncertainty	9.5
Data statistics	11.2
WZ normalizations	3.3
Total statistical uncertainty	11.6