Measurement of multiboson production at ATLAS

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On behalf of the ATLAS Collaboration

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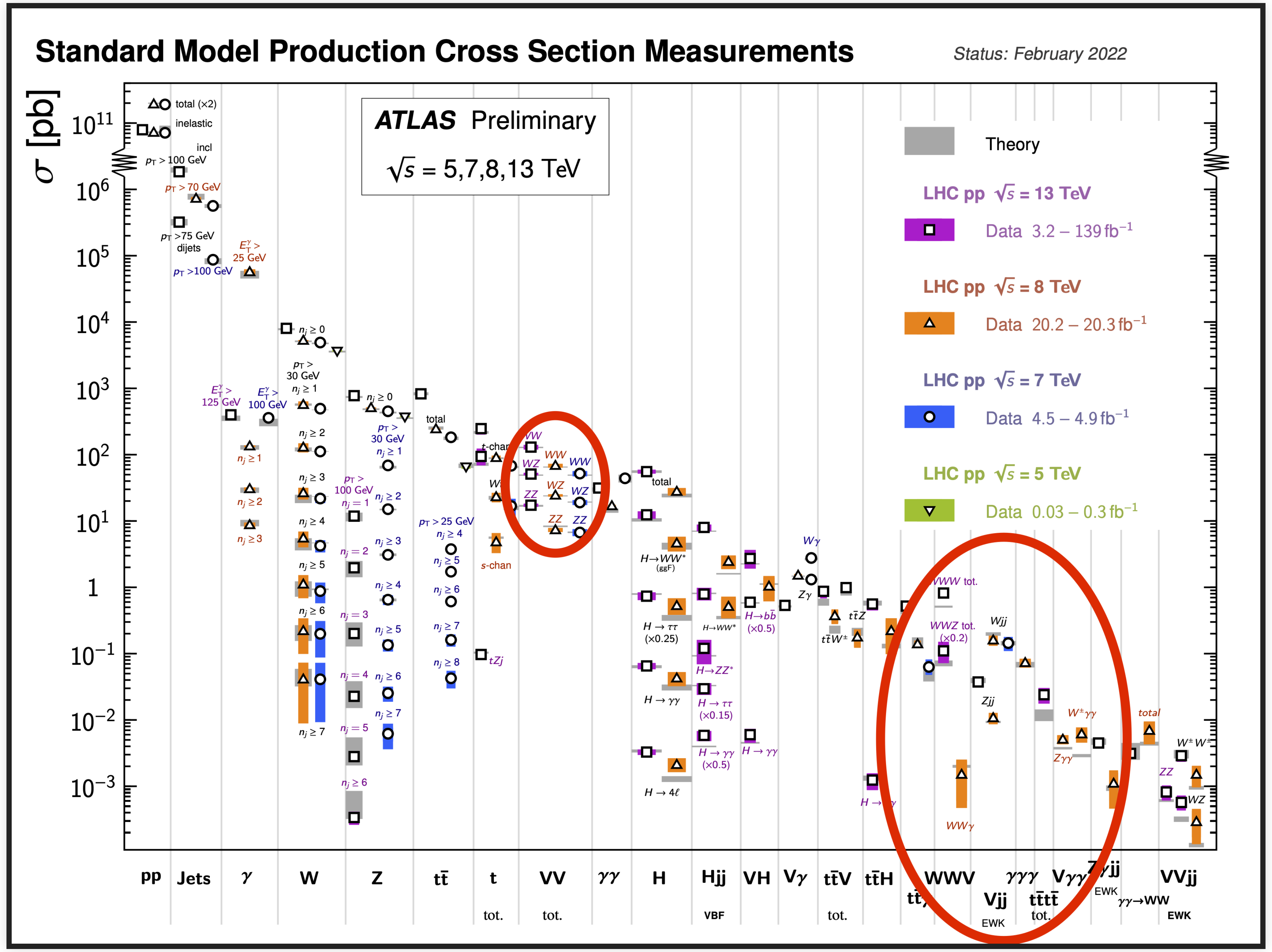
MULTIBOSON MEASUREMENTS

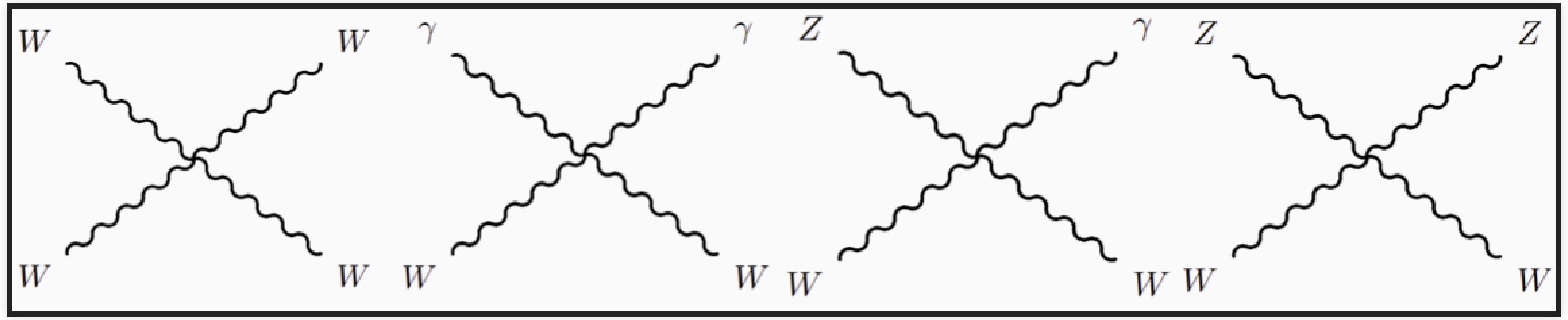
- Multiboson measurements test Standard Model (SM) Electro-weak (EW) self couplings
- Sensitive to Beyond the Standard Model (BSM) physics through anomalous triple and quartic gauge couplings (aQGC and aTGC) in Effective Field Theory (EFT) framework



Results covered

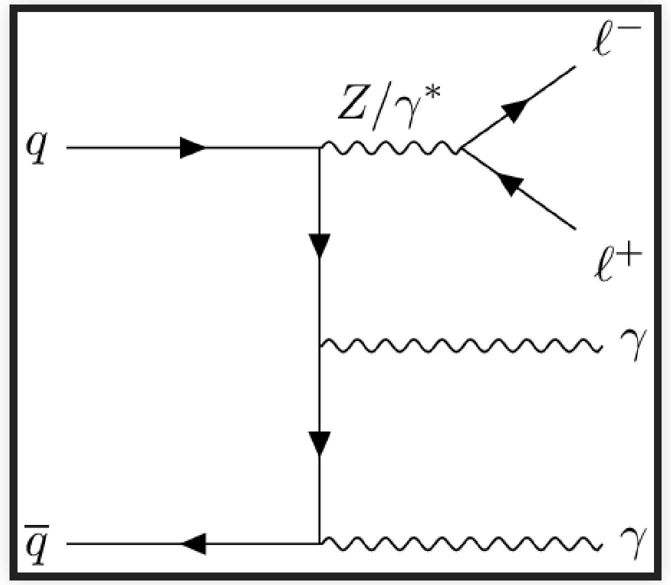
- $Z(\rightarrow \ell\ell)\gamma\gamma$
- $W(\rightarrow \ell\nu)\gamma\gamma$
- $W(\rightarrow \ell\nu)Z(\rightarrow \ell\ell)\gamma$
- $W(\rightarrow e\nu)W(\rightarrow \mu\nu)$+0 jets
- $Z(\rightarrow \ell\ell)Z(\rightarrow \ell\ell)$ polarization

Throughout this presentation: ℓ=electron or muon, full Run 2 data (140 fb^{-1}) at 13 TeV used

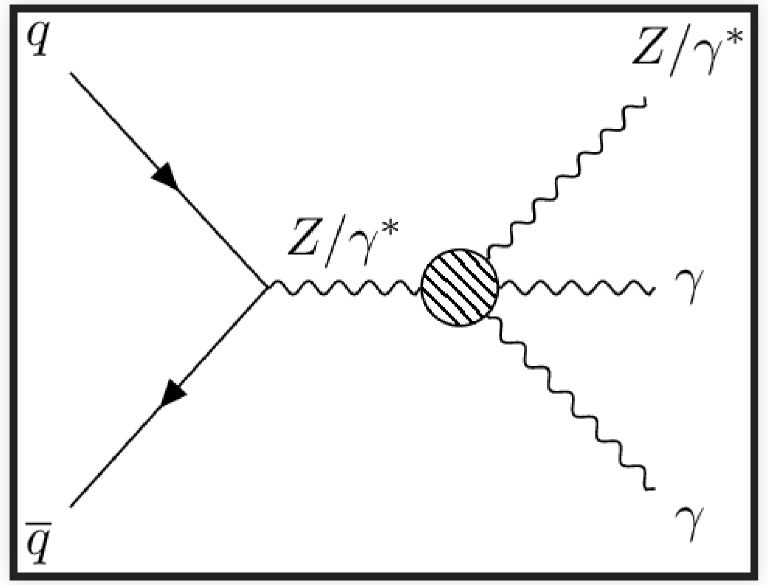


$Z(\to \ell\ell)\gamma\gamma$ PRODUCTION

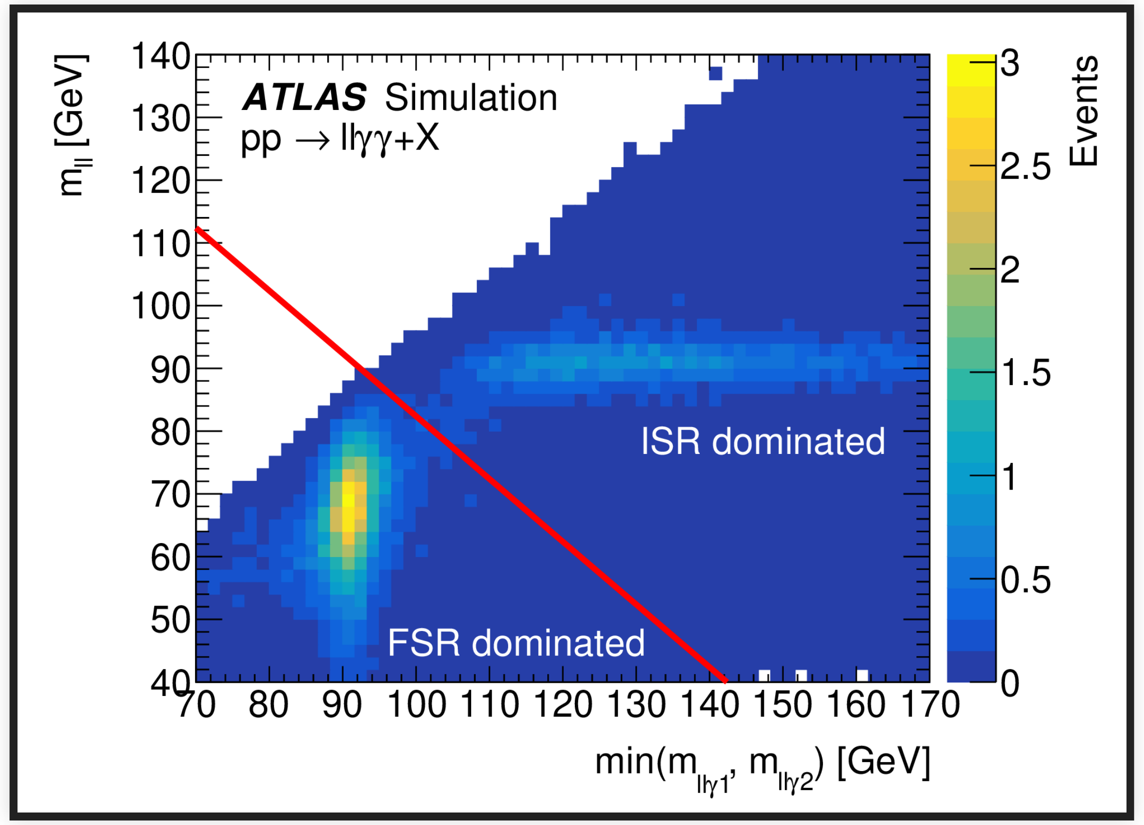
Initial State Radiation Photons



Anomalous Couplings (aQGC)



ISR rejection



- **Fiducial and unfolded cross section measurement.**
- Photons from final state radiation (FSR) removed
  - By considering the invariant mass of lepton pair and each photon
- **Differential cross section measurement in $p_T^{\ell\ell}$ used to constrain dimension-8 Wilson coefficient in EFT framework**
- Main background:
  - Non-prompt photons: data-driven matrix method for $Z\gamma\gamma$, $Z\gamma j, Zj\gamma, Zjj$ normalization
  - $t\bar{t}\gamma\gamma$: normalized with $e\mu$ (non-same flavor) control region
- **Uncertainties: stats limited (12% uncertainty) but non-prompt photon background is dominant systematic (8%)**

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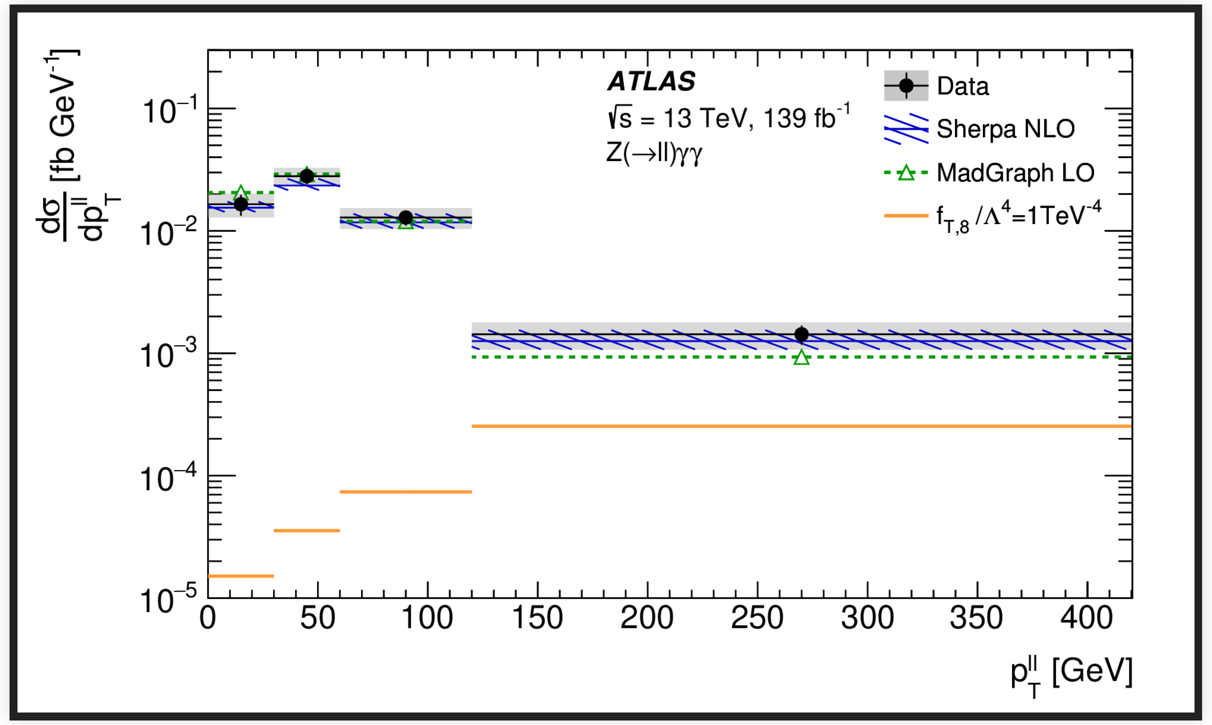
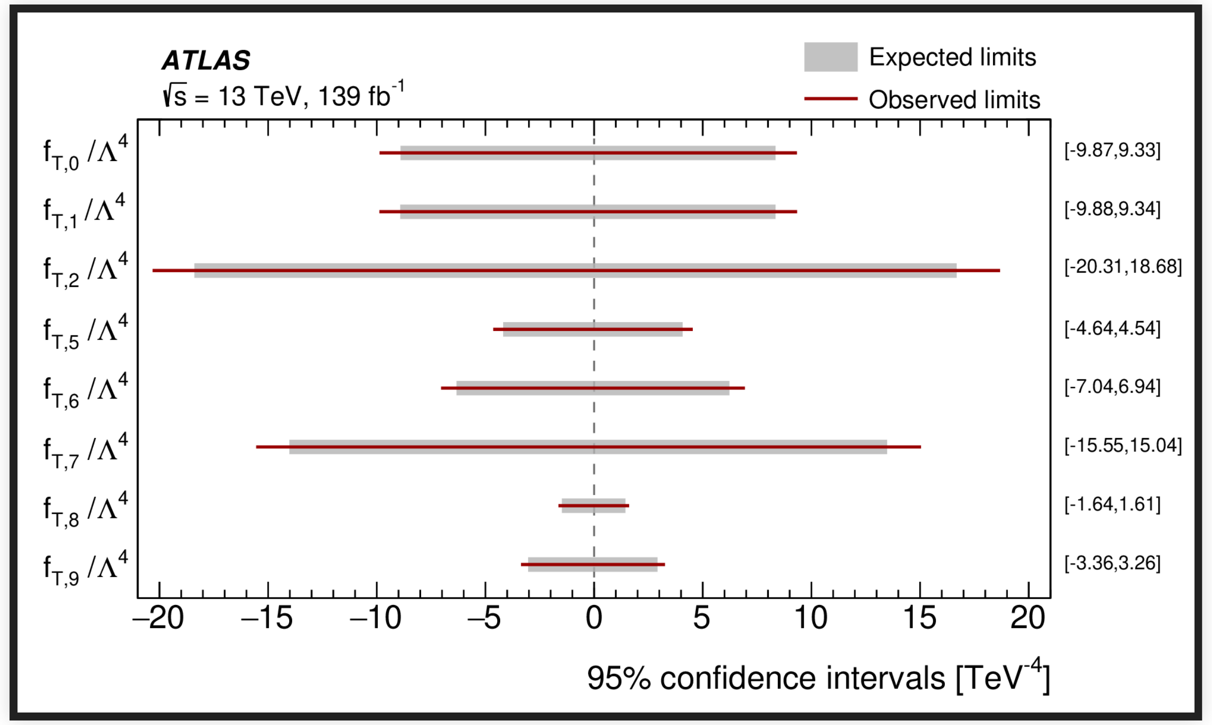
$Z\gamma\gamma$ PRODUCTION: RESULTS

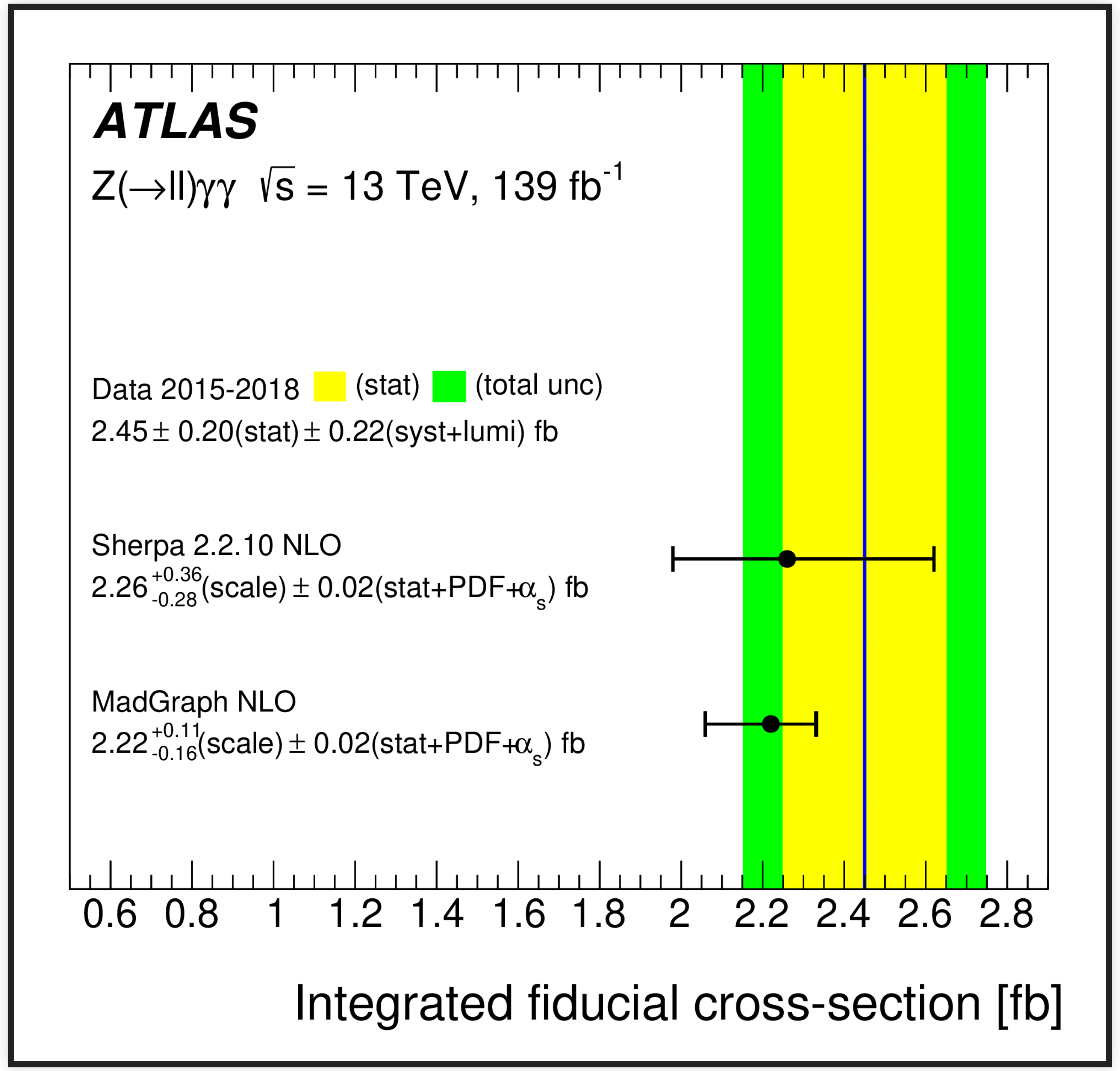
Differential $p_T^{\ell\ell}$ cross section



Effective Field Theory (aQGC) interpretation



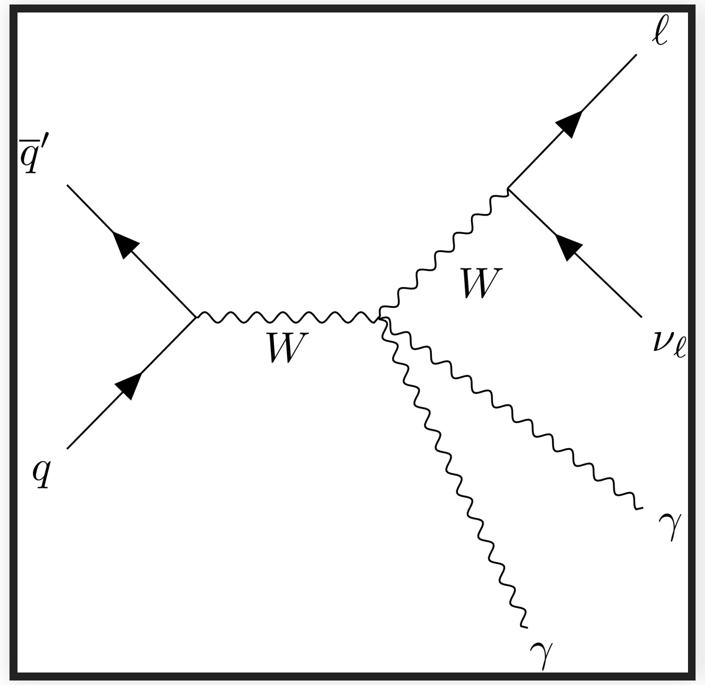
Total cross section

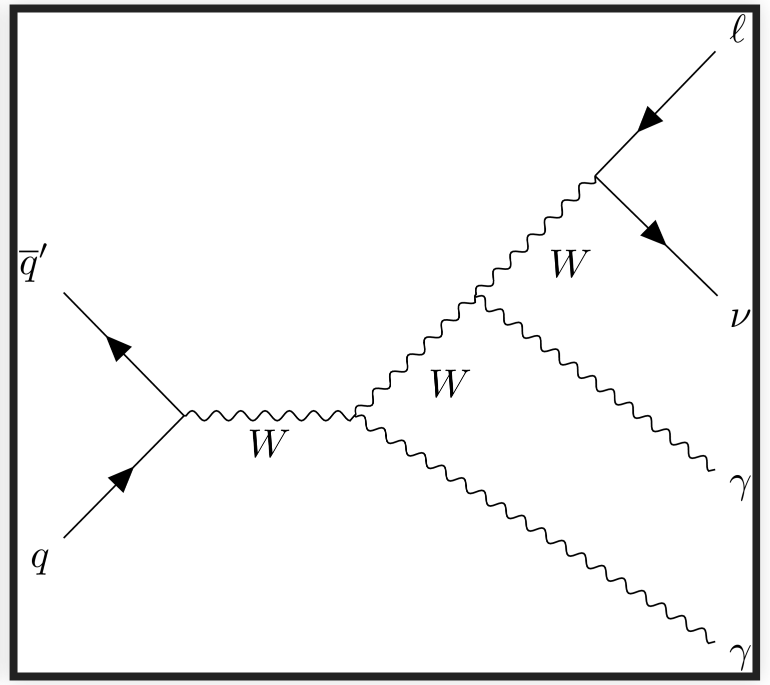


Fidicual cross section measurement with 12% uncertainty

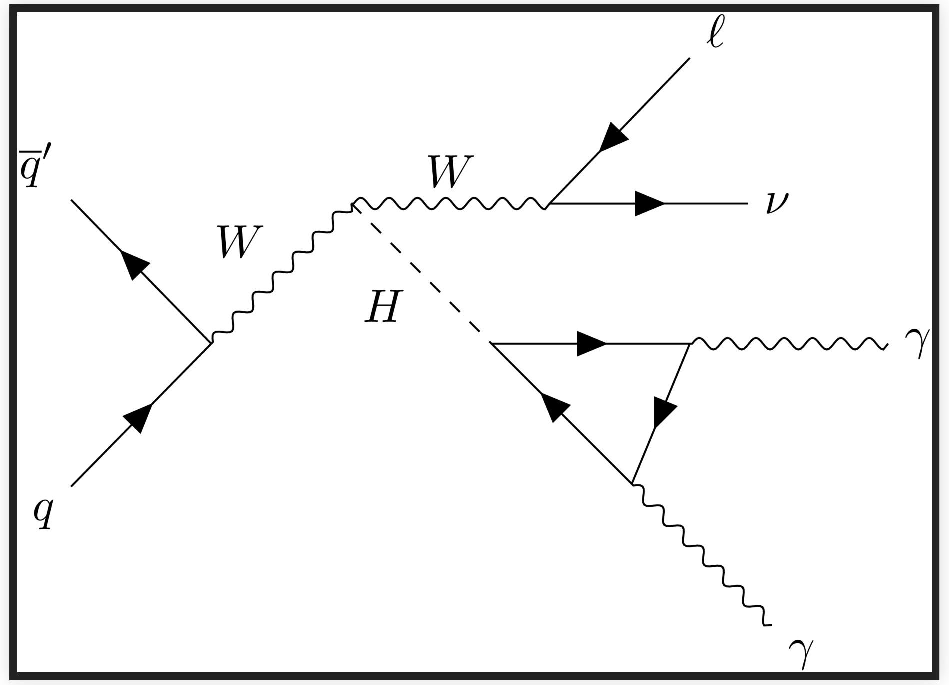
$W(\to \ell\nu)\gamma\gamma$ PRODUCTION

Photons from W



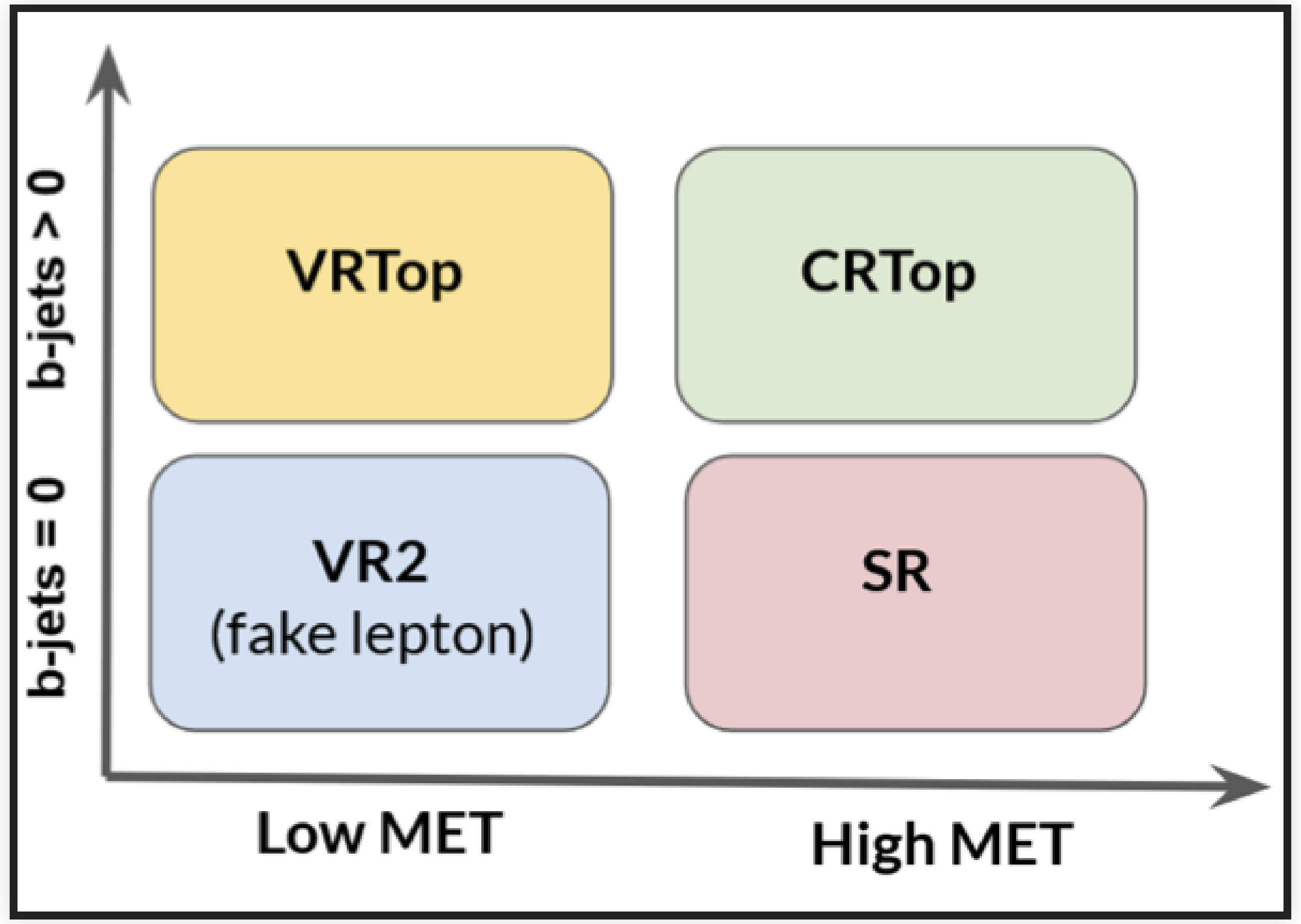


Photons from H



- **Total cross section measurement**
- Photons from ISR, FSR, and W are signal
- **Leptonic τ decays are also considered signal**
- Main background:
  - Non-prompt γ/ℓ and e reco as γ: Various data-driven methods
  - $t\bar{t}\gamma$: normalized with control region which requires b-tagged jets
- **Systematics dominated (13%) from data-driven background estimates**

Background estimation strategy for $t\bar{t}\gamma$



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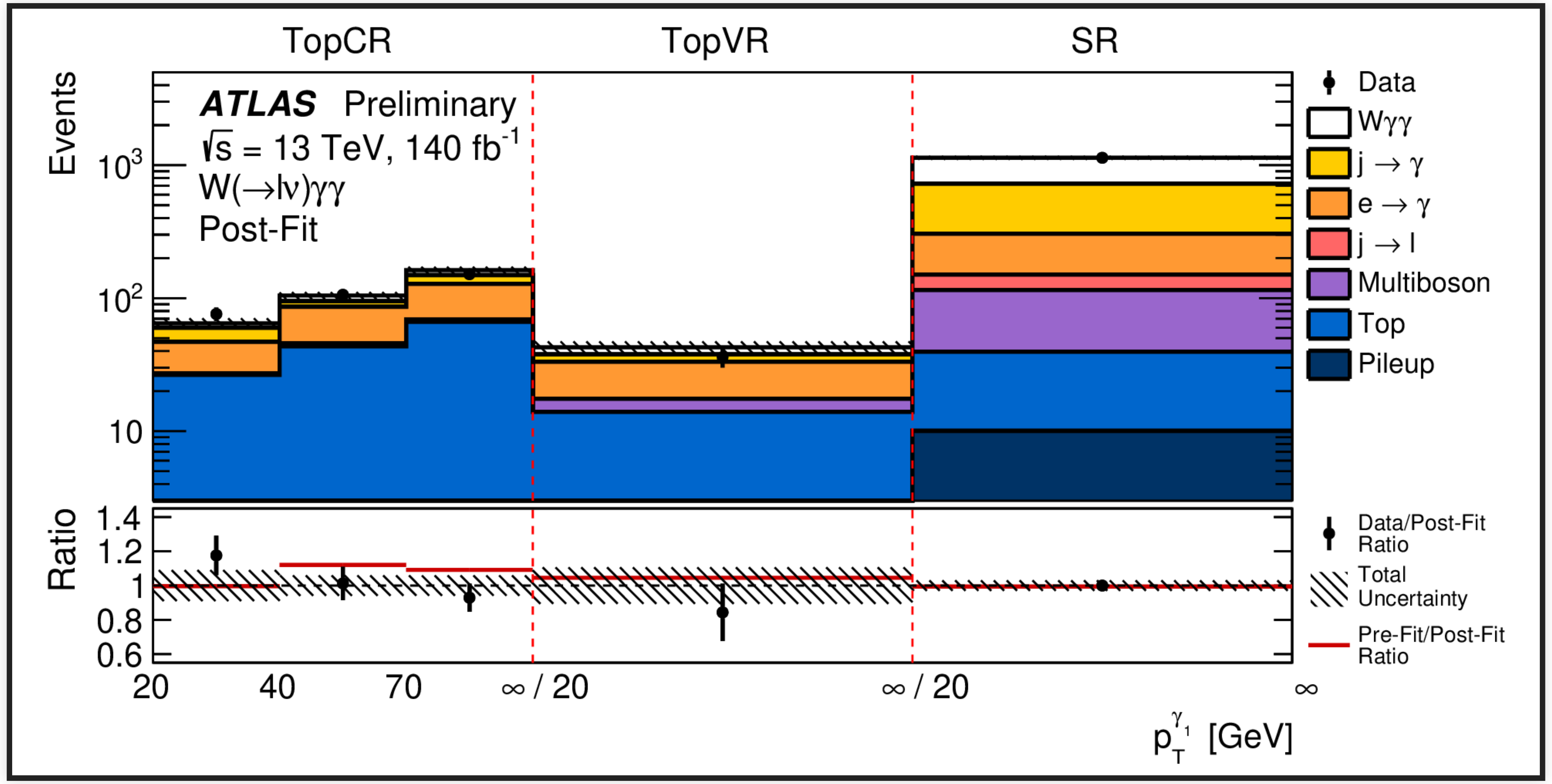
$W\gamma\gamma$ PRODUCTION: RESULTS

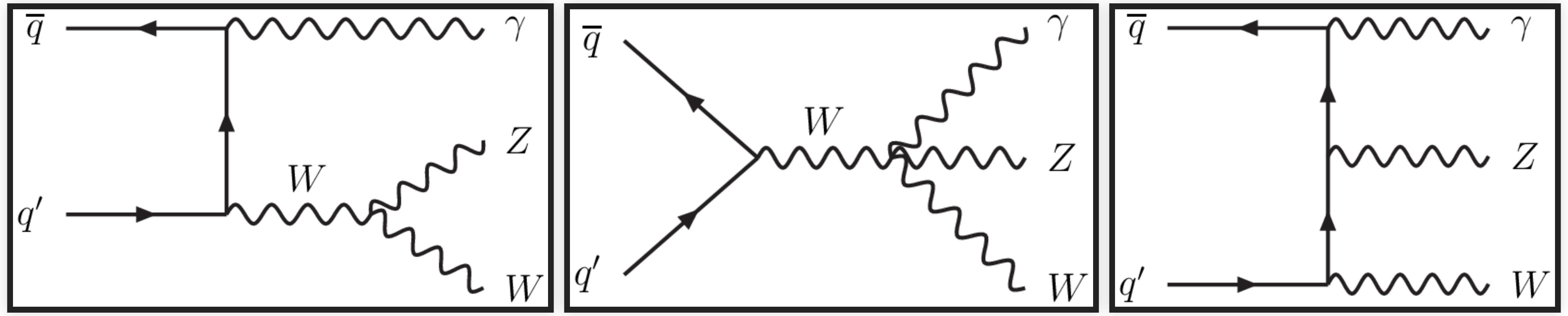
Source	SR	TopCR
$W\gamma\gamma$	410 ± 60	28 ± 5
Non-prompt $j \to \gamma$	420 ± 50	42 ± 20
Misidentified $e \to \gamma$	155 ± 11	120 ± 9
Multiboson ($WH(\gamma\gamma)$, $WW\gamma$, $Z\gamma\gamma$)	76 ± 13	5.2 ± 1.7
Non-prompt $j \to \ell$	35 ± 10	–
Top ($tt\gamma$, $tW\gamma$, $tq\gamma$)	30 ± 7	136 ± 32
Pileup	10 ± 5	–
Total	$1\,136 \pm 34$	332 ± 18
Data	$1\,136$	333



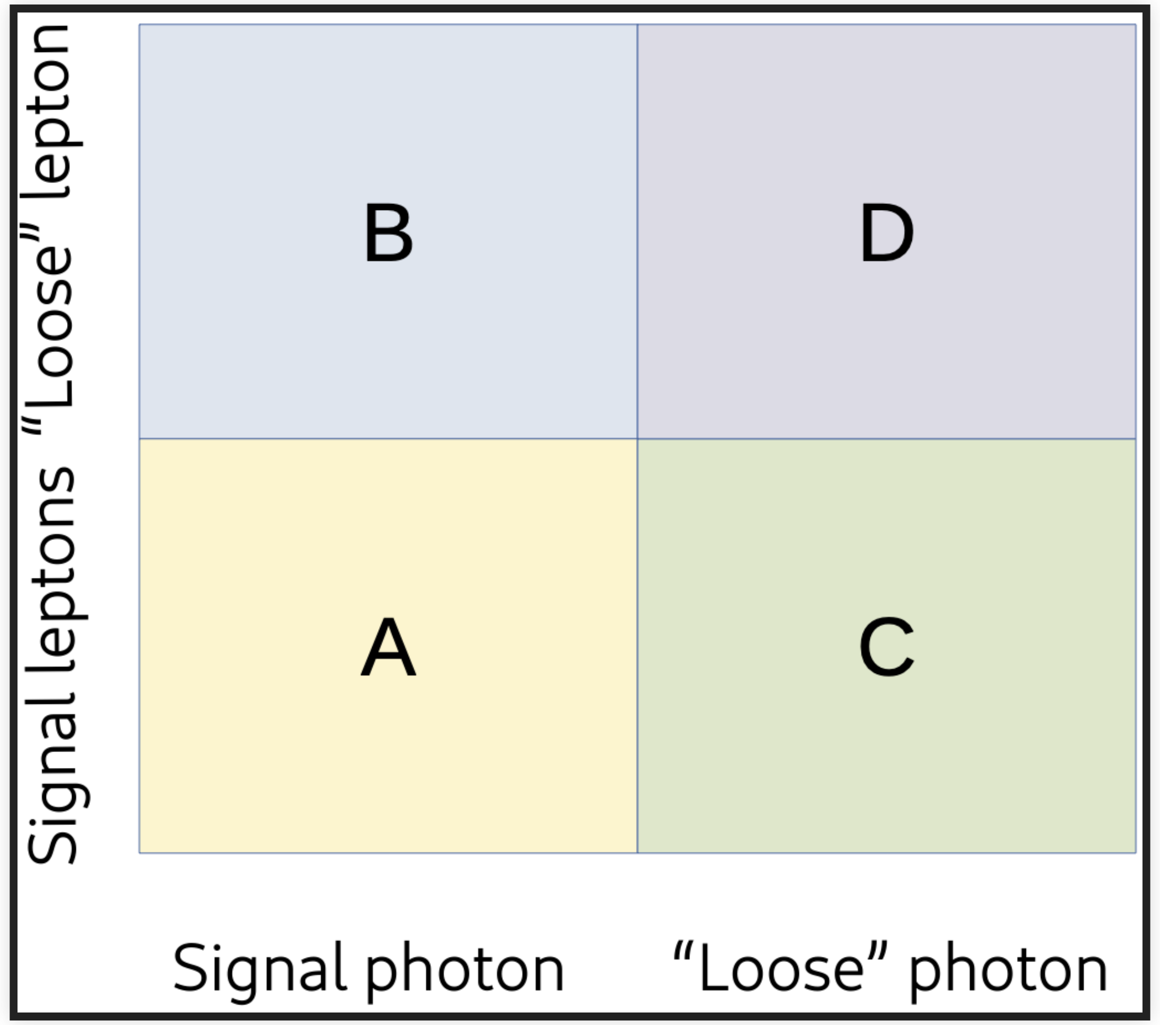
FIRST OBSERVATION OF $W(\to \ell\nu)\gamma\gamma$ (5.6σ OBSERVED AND EXPECTED)!

$W(\to \ell\nu)Z(\to \ell\ell)\gamma$ PRODUCTION

- Measurement total cross section of $WZ\gamma$ production
- **$WZ\gamma$ has not yet been observed**
- Suppress FSR by only considering $m_{\ell\ell}$ >81 GeV and $\Delta R(\ell,\gamma)$>0.1
- Leptons/photon not allowed to come from taus
- Main background:
  - Non-prompt γ/ℓ: data-driven methods
  - ZZ and $ZZ\gamma$: normalized with control region which requires b-tagged jets
- Stat limited (15% uncertainty) with dominant systematic from data-driven background estimates (but also from data stats in loose lepton/photon region)

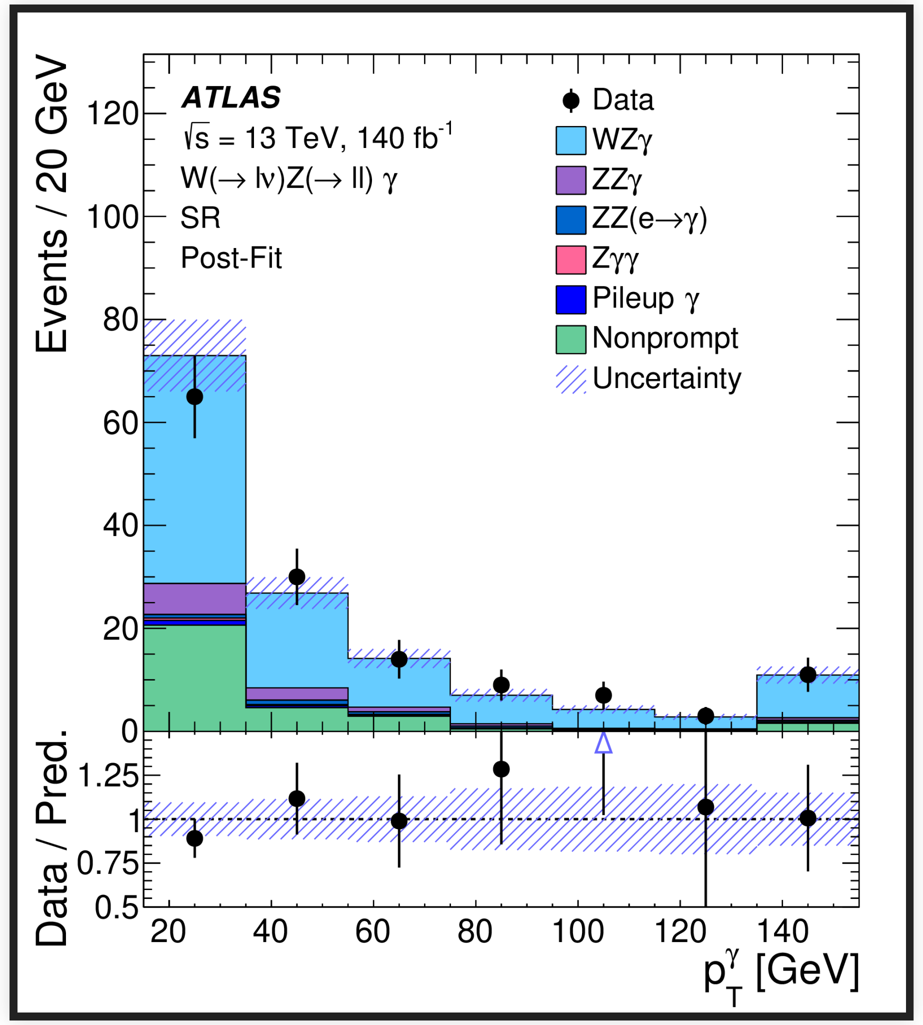


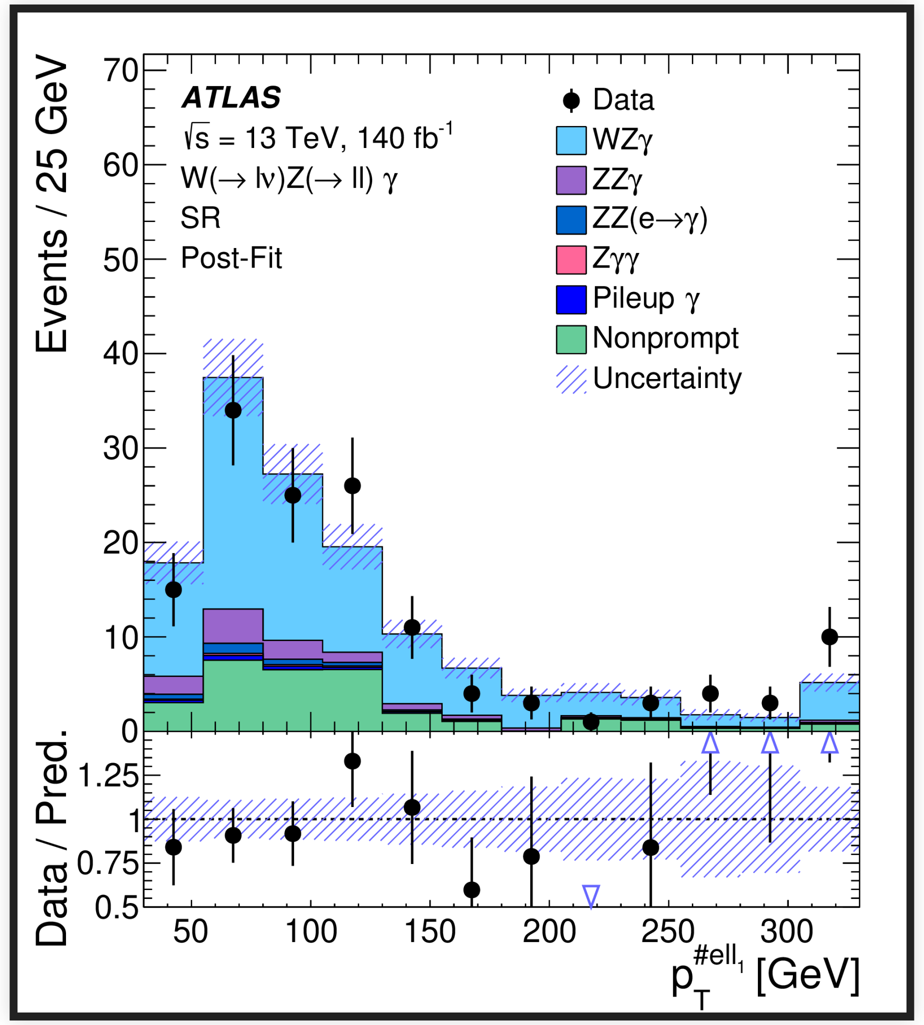
Data-driven background estimation

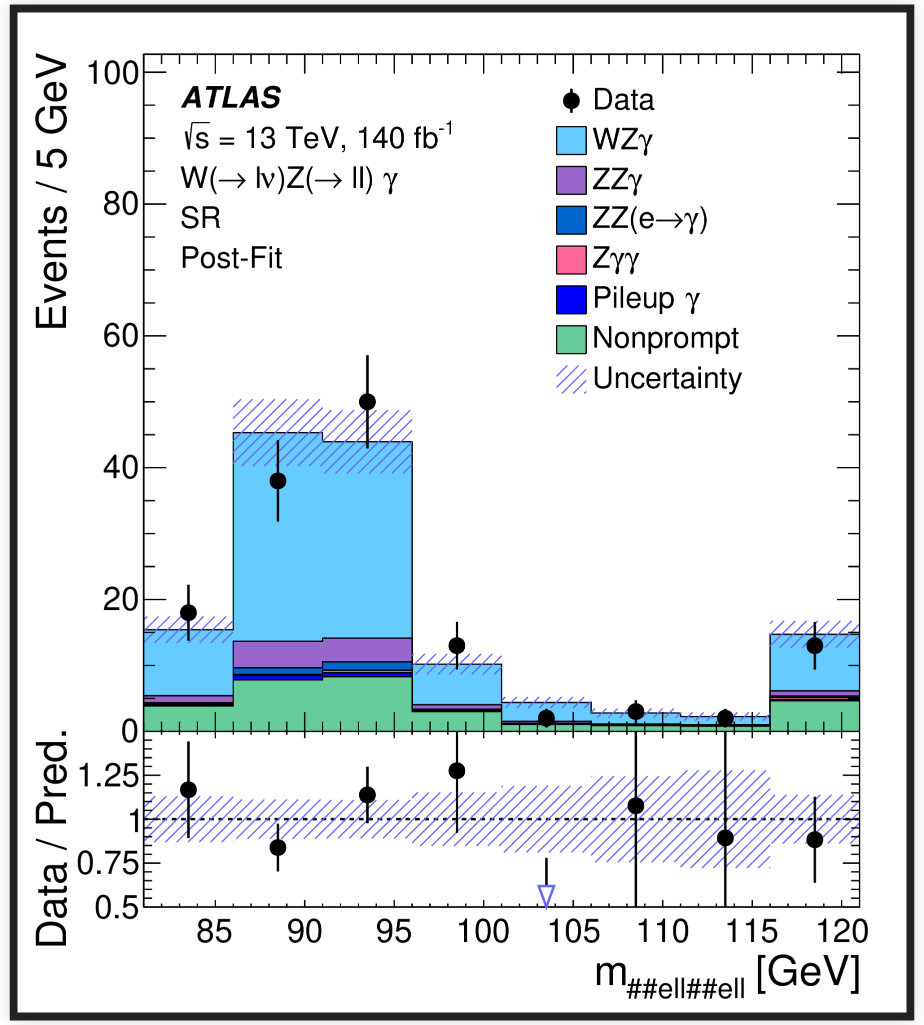


Submitted to PRL (arXiv:2305.16994)

WZγ PRODUCTION: RESULTS







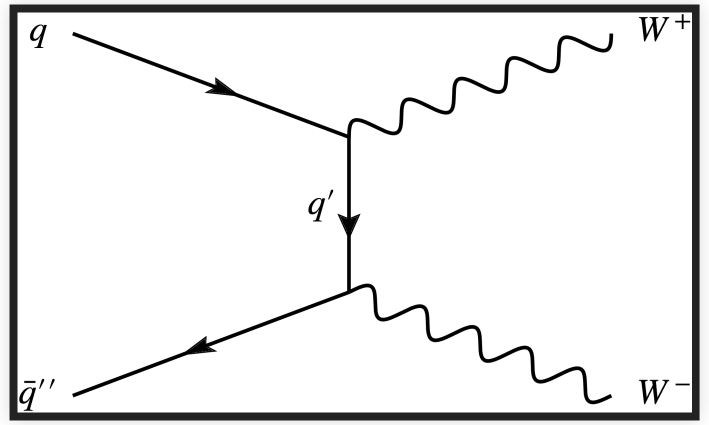
Process	SR	$ZZ\gamma$ CR	$ZZ(e\to\gamma)$ CR
$WZ\gamma$	92 $\pm$ 15	0.21 $\pm$ 0.07	0.56 $\pm$ 0.14
$ZZ\gamma$	10.7 $\pm$ 2.3	23 $\pm$ 5	1.8 $\pm$ 0.4
$ZZ(e\to\gamma)$	3.0 $\pm$ 0.6	0.028 $\pm$ 0.020	30 $\pm$ 6
$Z\gamma\gamma$	1.05 $\pm$ 0.32	0.15 $\pm$ 0.06	0.29 $\pm$ 0.10
Nonprompt background	30 $\pm$ 6	-	-
Pileup γ	1.9 $\pm$ 0.7	-	-
Total yield	139 $\pm$ 12	23 $\pm$ 5	33 $\pm$ 6
Data	139	23	33

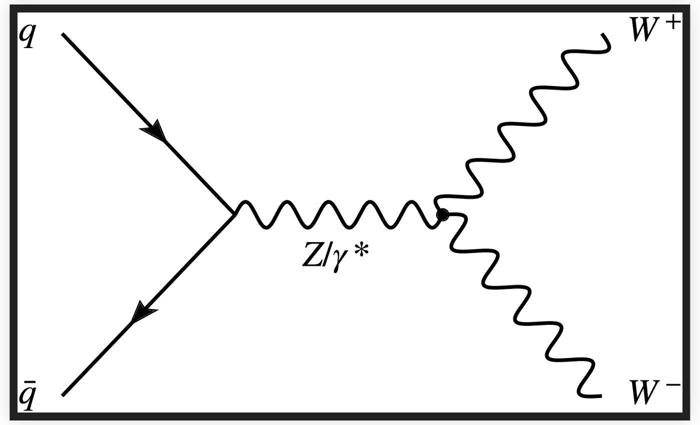
WZγ OBSERVED WITH 6.3σ (5.0σ EXPECTED)

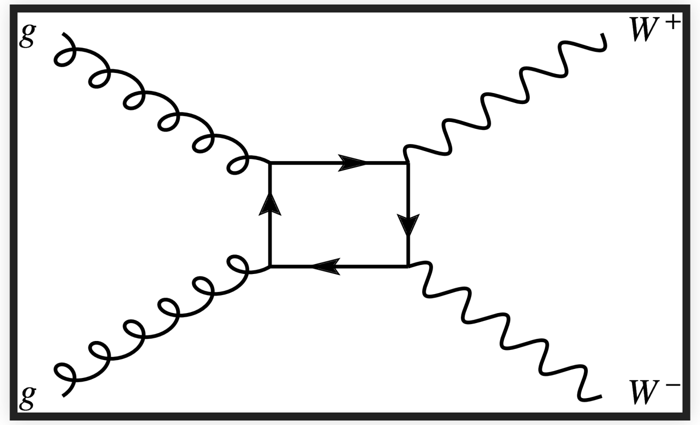
Measured cross section: 1.99 ± 0.34 **fb**

Predicted cross section: 1.49 ± 0.07 **fb (within 1.5σ)**

$W(\rightarrow e\nu)W(\rightarrow \mu\nu)$+0 JETS PRODUCTION

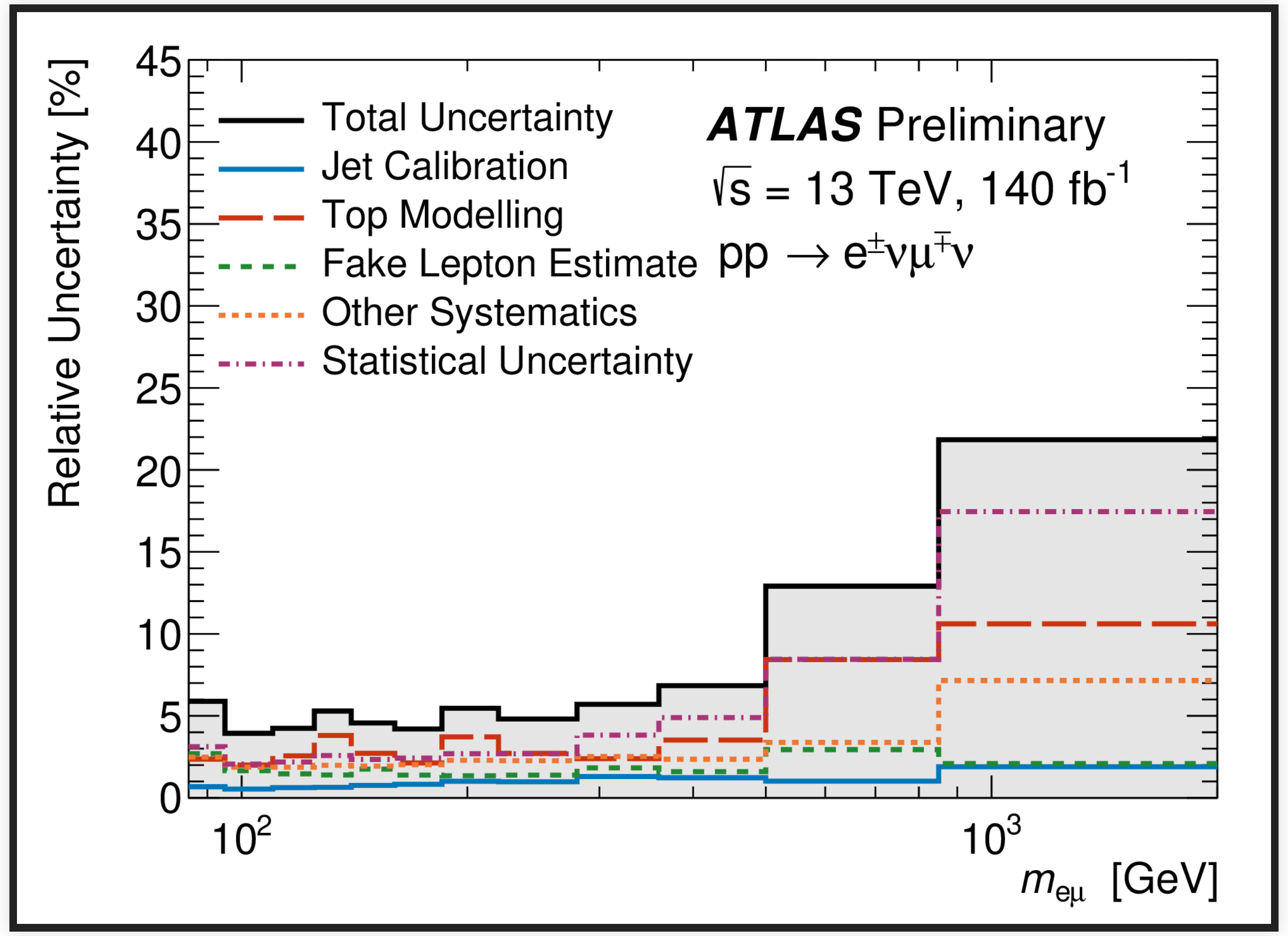






- Fiducial and differential measurement
  - **Fully jet-inclusive signal region (no requirement on jet multiplicity): reduces QCD and experimental uncertainties**
  - **Dynamic jet veto signal region: reduces QCD-EW uncertainties but increases top modeling and jet energy scale uncertainties**
- Major backgrounds: $t\bar{t}$ and non-prompt fake leptons
- **Systematics limited (3%): Top modeling (1.6%) and fake lepton background (1.5%) in both channels (inclusive and veto). Veto SR also has jet calibration as major uncertainty**

Uncertainties vs $m_{e\mu}$



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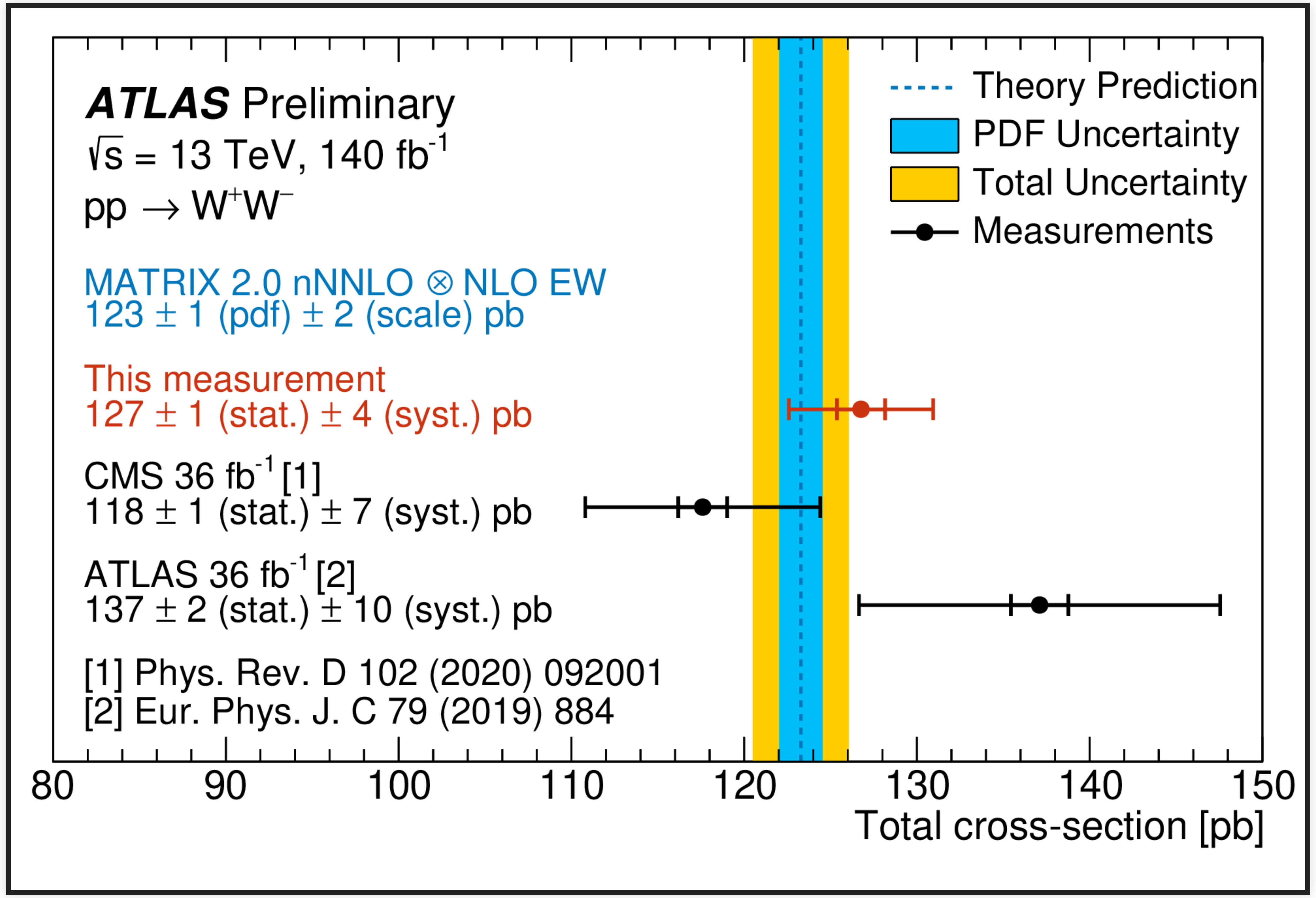
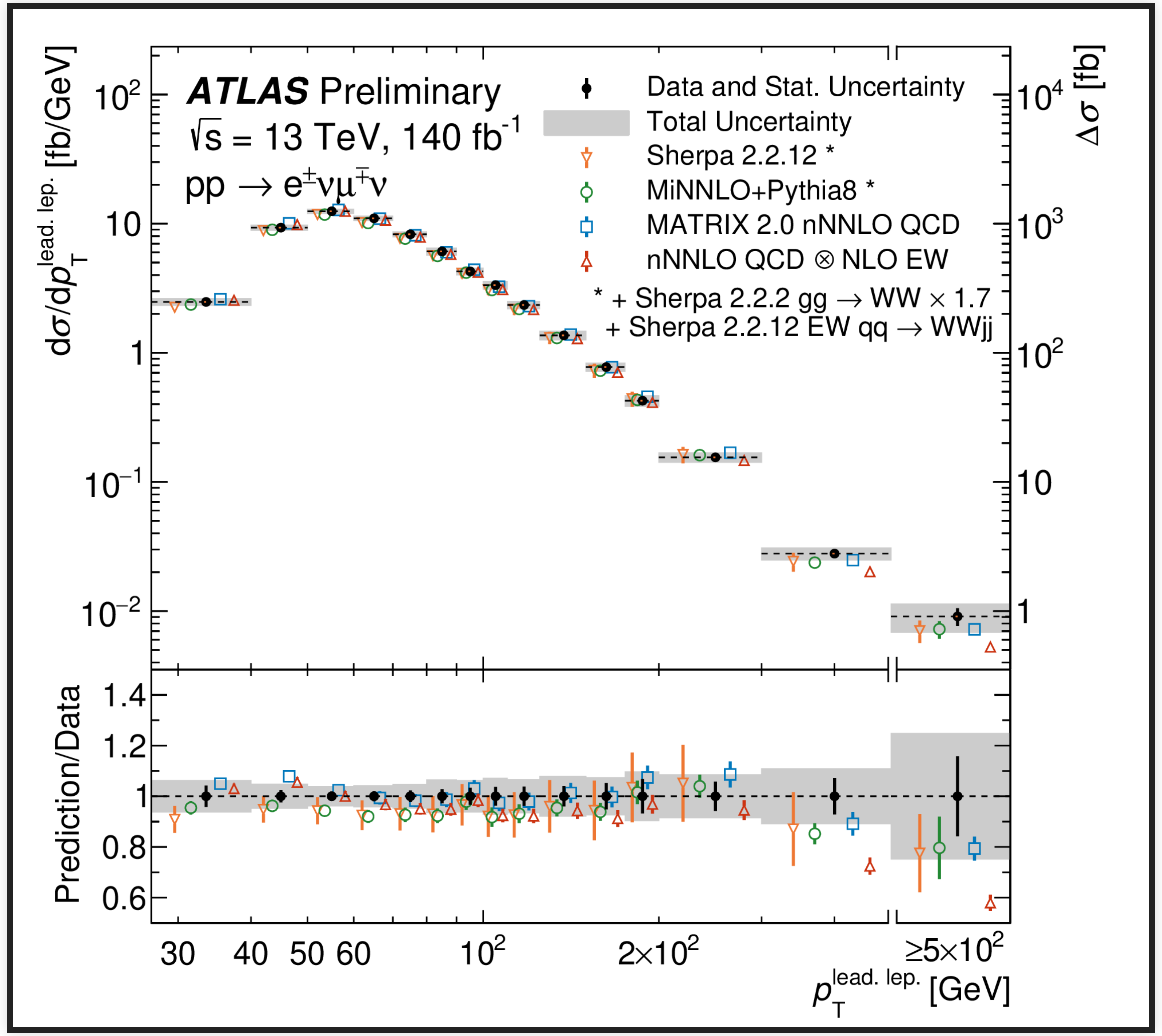
WW +0 JETS PRODUCTION: RESULTS





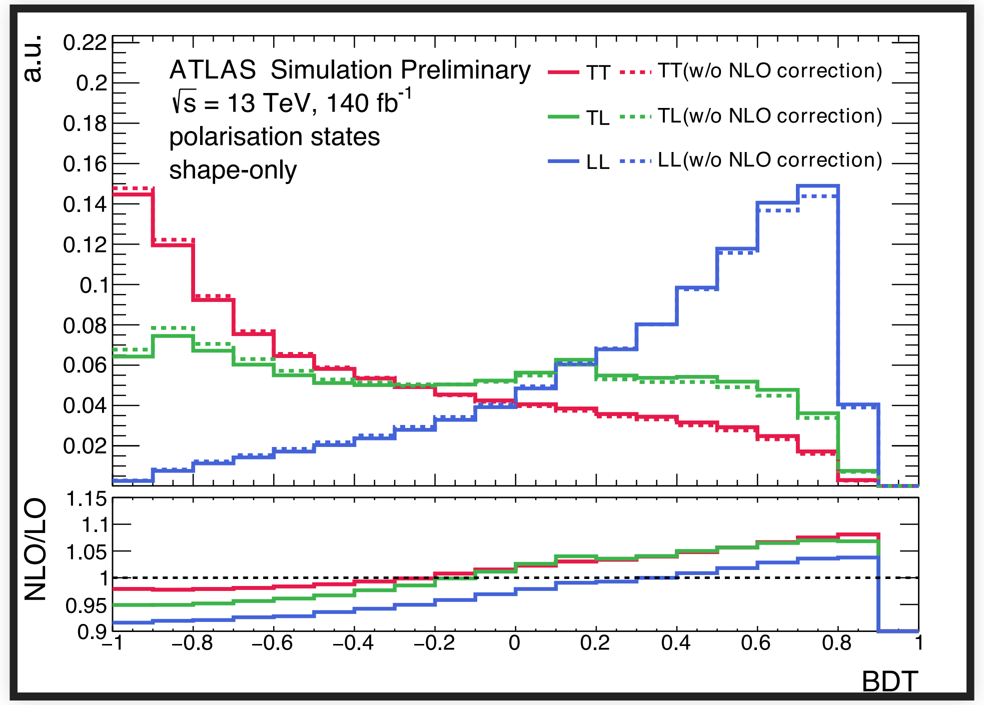
First use of fully jet-inclusive phase space

Most precise WW cross section measurement in hadron-hadron collisions: 3.1% uncertainty vs 6-7% from previous measurements

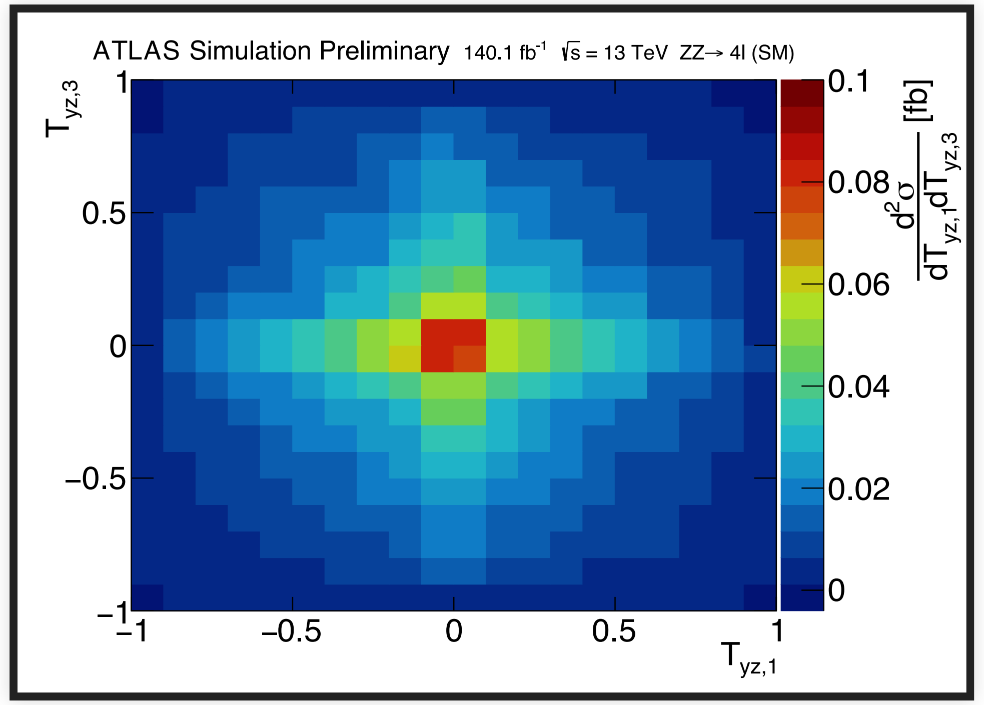
$Z(\to \ell\ell)Z(\to \ell\ell)$ POLARIZATION

- **Search for CP-violation in on-shell $ZZ \to 4\ell$ events**
  - 2 angular observables ($T_{yz,1}$, $T_{yz,3}$) combined into $O_{T_{yz,1},T_{yz,3}}$
- **ZZ polarization measurement using BDT**
  - Longitudinal-Longitudinal (LL) signal vs Transverse-Longitudinal (TL) and Transverse-Tranverse (TT) Z polization background
- Dominant background: fake leptons, data-driven method
- Statistics limited (~25%) with ~10% systematic

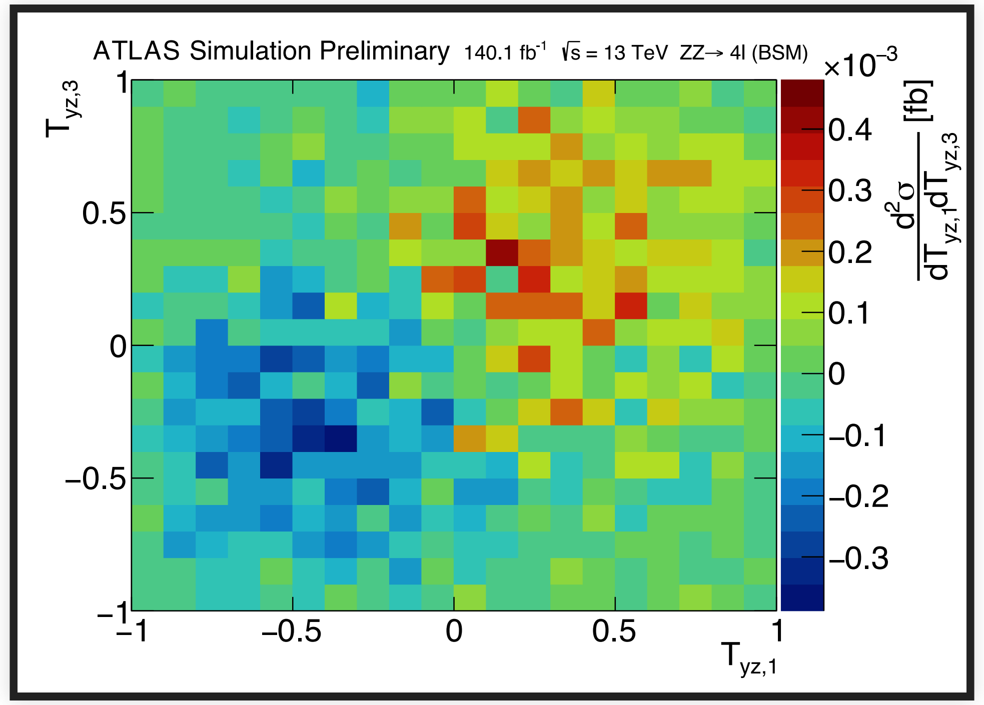
BDT output for ZZ polarization



CP sensitive angular variables for SM



CP sensitive angular variables for BSM



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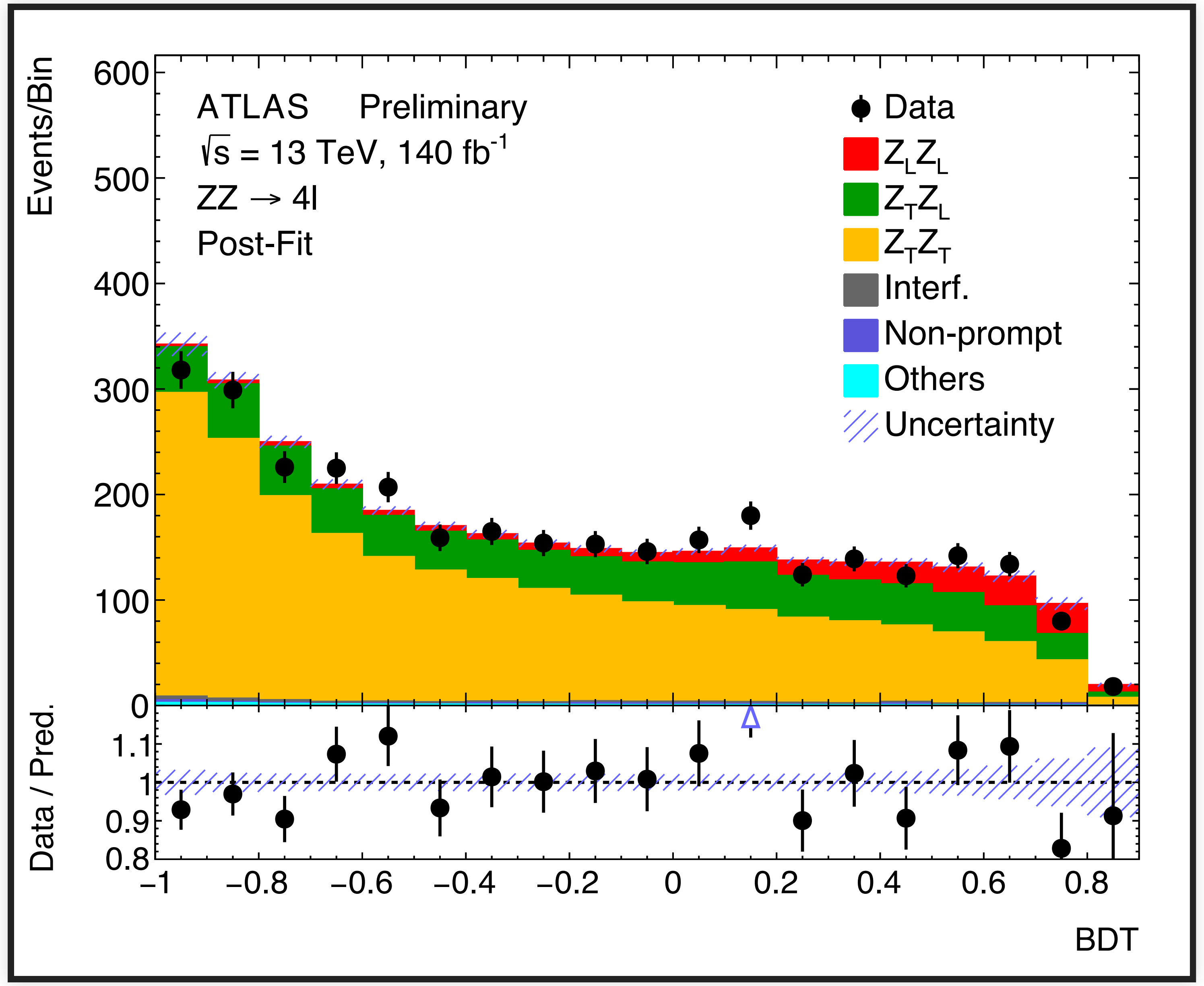
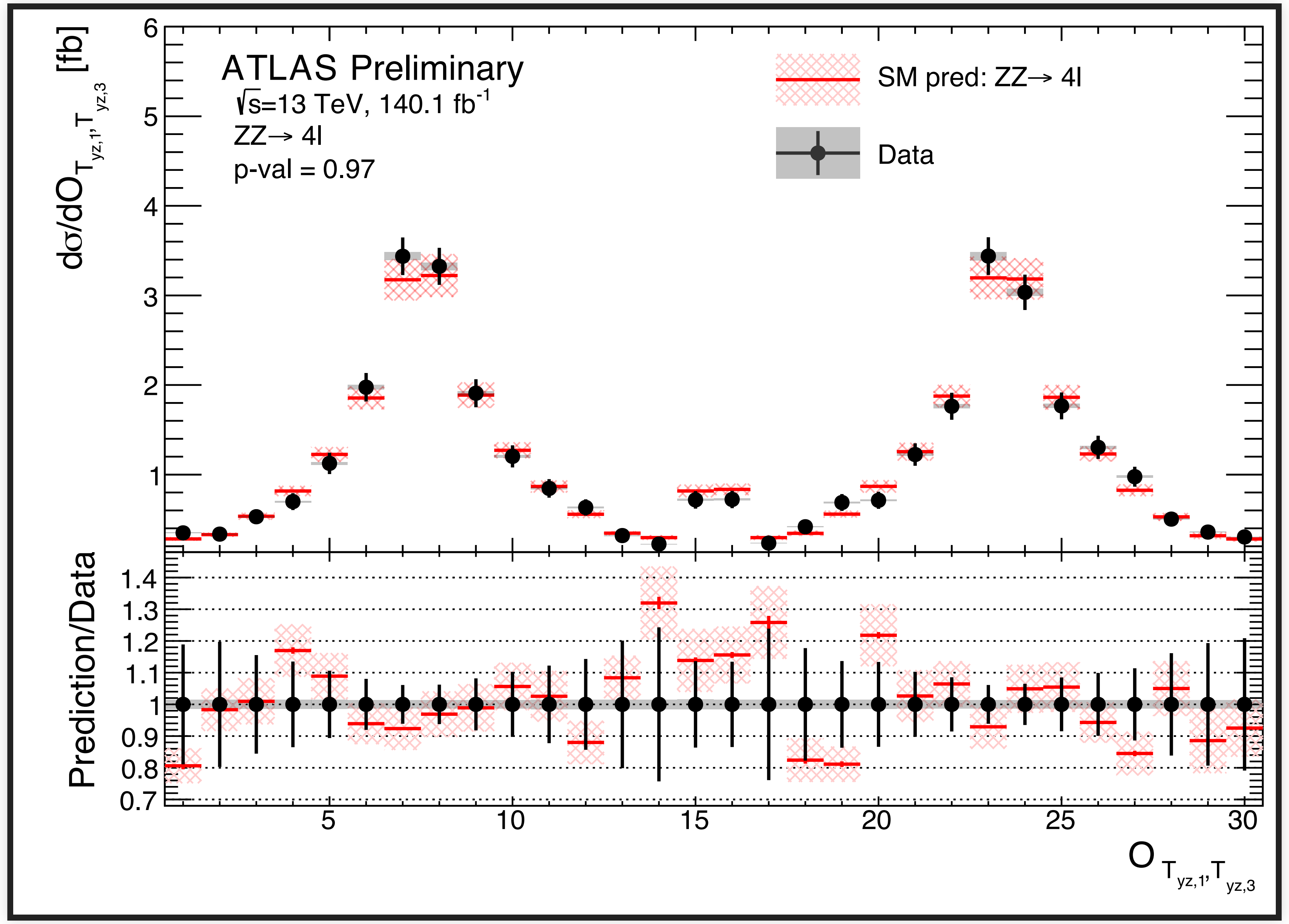
ZZ POLARIZATION: RESULTS

Polarization



Z_LZ_L production cross section measured at 4.3σ (3.8σ) observed (expected) at 2.44 ± 0.59 fb. SM prediction 2.09 ± 0.10 fb

CP



No significant deviations from SM observed

SUMMARY

- Multiboson measurements probe SM EW sector and are sensitive to BSM contributions (aTGC and aQGC)
- Many new multiboson results this year exploiting the full Run 2 data set
- First observation of $\mathrm{WZ\gamma}$ and $\mathrm{W\gamma\gamma}$
- Some of the most precise cross section measurements of WW and $\mathrm{Z\gamma\gamma}$
  - Including many differential cross section measurements
  - Interpreted in terms of EFT framework
- New ZZ polarization and CP measurement
- Future: Run 3 multiboson measurement efforts are ongoing

THANK YOU!