Multiboson measurements with the ATLAS detector

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on behalf of the ATLAS Collaboration

WG3: Electroweak Physics and Beyond the Standard Model

May 5, 2026

DIS2026

Outline

- ➢ Scope and Goals: why **multibosons** ?!
- ➢ **Measurement of $W\gamma$**
- ➢ **Measurement of Electroweak ZZ *and* $ZZjj$**
- ➢ **$ZZ\gamma$ Production**

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to EPJ C

Submitted to: Eur. Phys. J. C

CERN-EP-2026-078
25th March 2026

https://doi.org/10.48550/arXiv.2603.22478

Measurement and interpretation of inclusive $W\gamma$ production in proton–proton collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector

The ATLAS Collaboration

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to EPJ C

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CERN-EP-2025-243
20th November 2025

https://doi.org/10.48550/arXiv.2511.15569

Measurements of $ZZ \to \ell\ell\nu\nu$ and $ZZjj \to \ell\ell\nu\nu jj$ productions in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to PRL

Submitted to: PRL

CERN-EP-2026-038
February 20, 2026

https://doi.org/10.48550/arXiv.2602.17165

Evidence of $ZZ\gamma$ production with the ATLAS detector

The ATLAS Collaboration

Why multibosons ?!

Processes with heavy bosons and photons in the final states unable us to probe of the electroweak sector (EWK) of the Standard Model (SM)

Today:

- **Inclusive diboson productions (EWK + QCD)**
  - ✓ $WW, WZ, ZZ, Z\gamma, W\gamma$
- **VBF and VBS (EWK enhanced)**
  - ✓ $Z + jj, W + jj$ and $ZZ + jj$
- **Triboson productions**
  - ✓ $WWW, WWZ, WZZ, WZ\gamma, ZZ\gamma$

Why multibosons ?!

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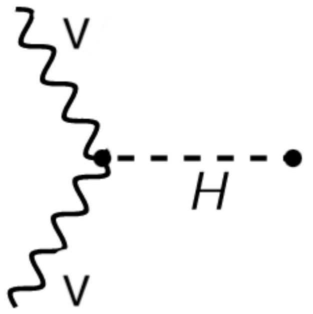
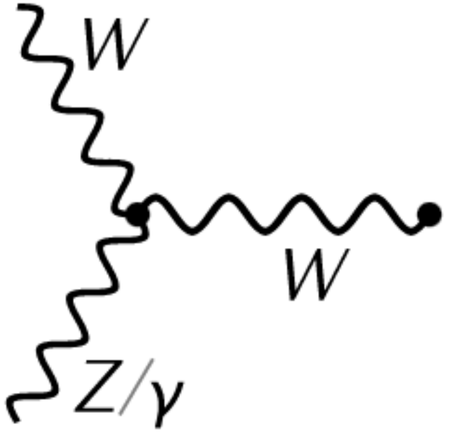
  - ✓ $WW, WZ, ZZ, Z\gamma, W\gamma$
- **VBF and VBS (EWK enhanced)**
  - ✓ $Z + jj, \cancel{W + jj}$ and $ZZ + jj$

    not ready yet
- **Triboson productions**
  - ✓ $WWW, WWZ, WZZ, WZ\gamma, ZZ\gamma$

Scope: Electroweak (EW) Gauge Couplings

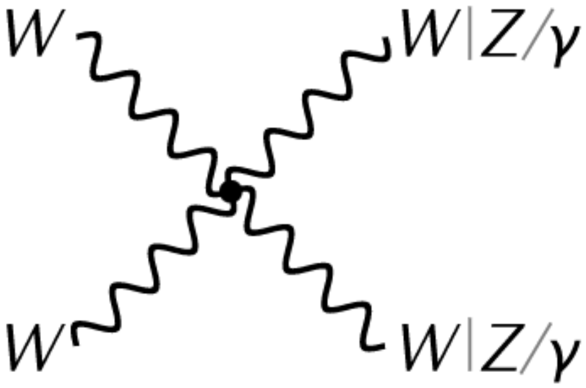
Exploration at the LHC of electroweak symmetry breaking in all aspects. In particular, the **self-couplings of the vector gauge bosons** are completely specified in the Standard Model (SM), as are the couplings of the Higgs boson to the vector bosons (V=W,Z) once the Higgs mass is known.





Vector Boson Fusion (VBF)

The only **triple gauge couplings (TGC)** allowed in the SM are $\boldsymbol{WWZ}$ **and** $\boldsymbol{WW\gamma}$. There are no ZZZ, $ZZ\gamma$, $Z\gamma\gamma$, or $\gamma\gamma\gamma$ couplings in the SM.



Vector Boson Scattering (VBS)

The only **quartic gauge couplings (QGC)** allowed in the SM are **WWWW, WWZZ, WWZγ and WWγγ**. There are no ZZZZ or γγγγ couplings in the SM.

Goals in general

1. In ~ 2014, **EWK VBF** production mechanism of Higgs created a vast interest in *H*+jets and *Z*+jets production as a function of N_{jets} in the final states.

2. Better understand strong **QCD** ***Vjj,*** and ***VVjj*** as background for Higgs and rare electroweak physics (e.g. ***VVV***), as well as for other precise Standard Model (SM) measurements and searches at the LHC. **Thus, tuning of event generators at NLO (and now NNLO).**

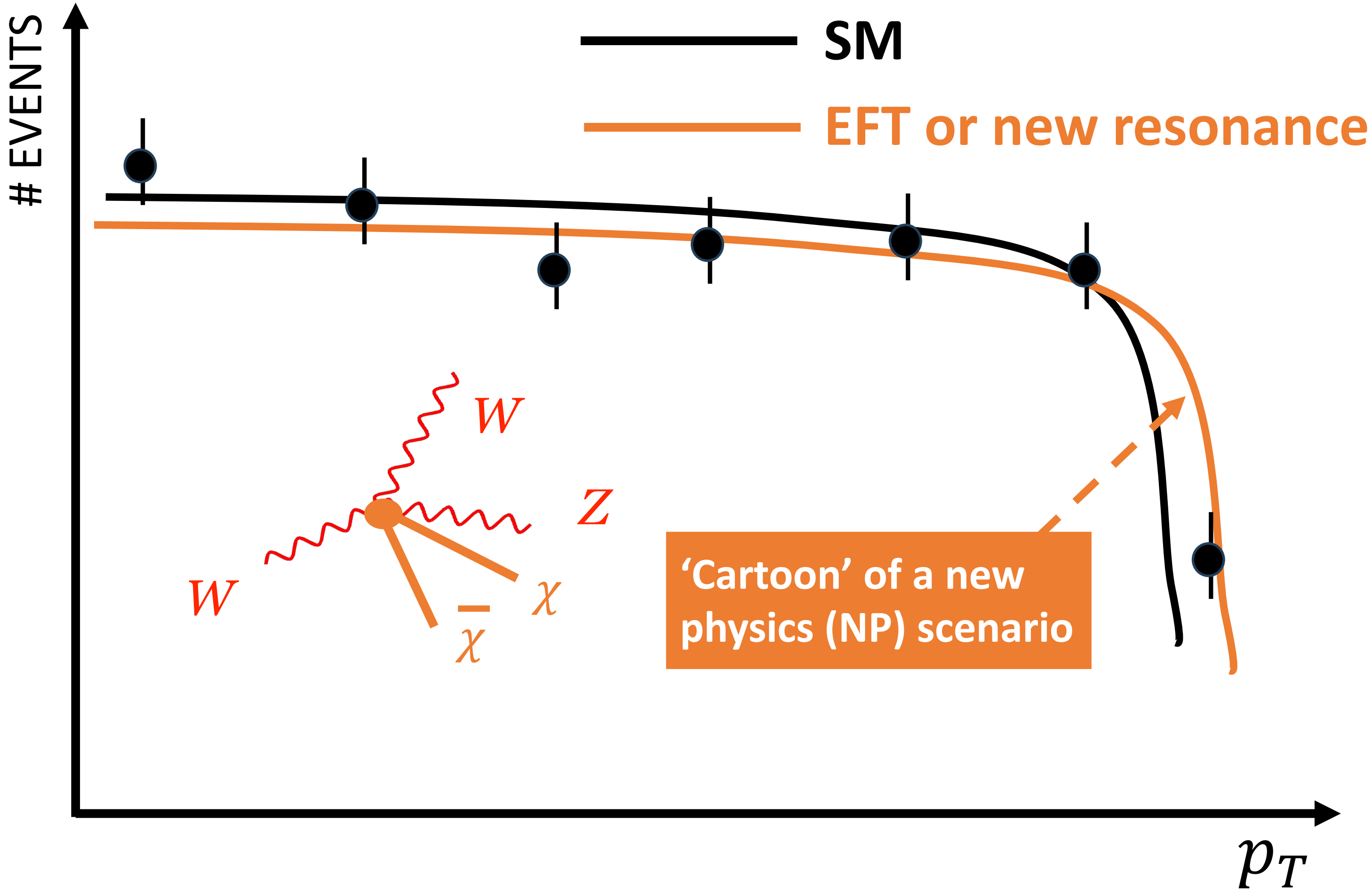
3. Study the **rare** electroweak (EWK) production of ***Vjj, VVjj*** and ***VVV***.

4. Triple and Quartic Gauge **couplings** precise probe for testing the SM.

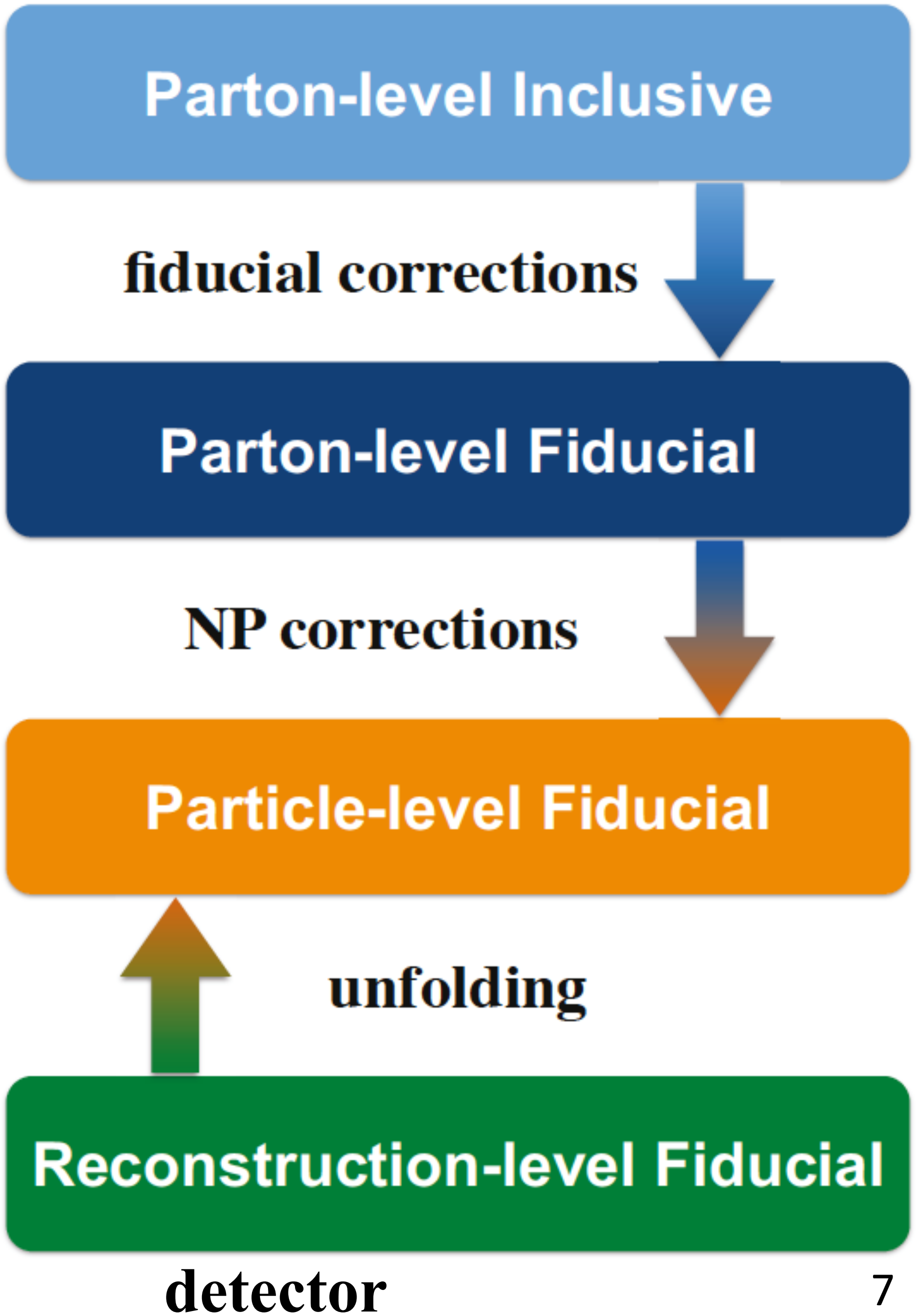
Why multibosons ?!

Standard Model Effective Field Theory (SMEFT)

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{C_i^{(7)}}{\Lambda^3}\mathcal{O}_i^{(7)} + \sum_i \frac{C_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)}$$



Unfolding to particle-level



Dataset Run-2

$\boldsymbol{W\gamma}$

arXiv:2603.22478

$\boldsymbol{ZZ \to \ell\ell\nu\nu}$ and $\boldsymbol{ZZjj \to \ell\ell\nu\nu jj}$

arXiv.2511.15569

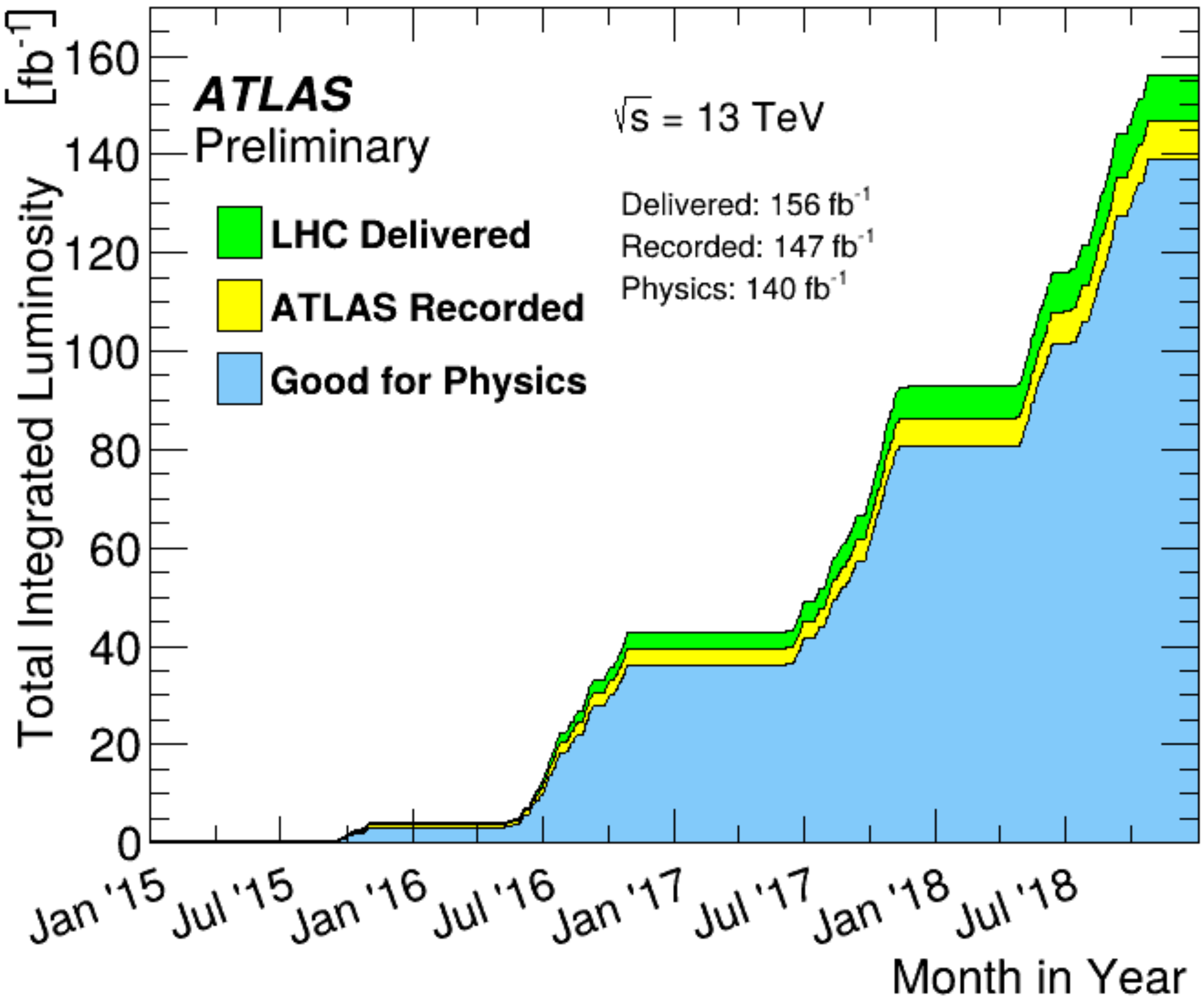
$\boldsymbol{ZZ\gamma}$

arXiv.2602.17165

$\sqrt{s}$ = 13 TeV

Run2 period: 2015 - 2018

Total Physics: 140 fb^{-1}



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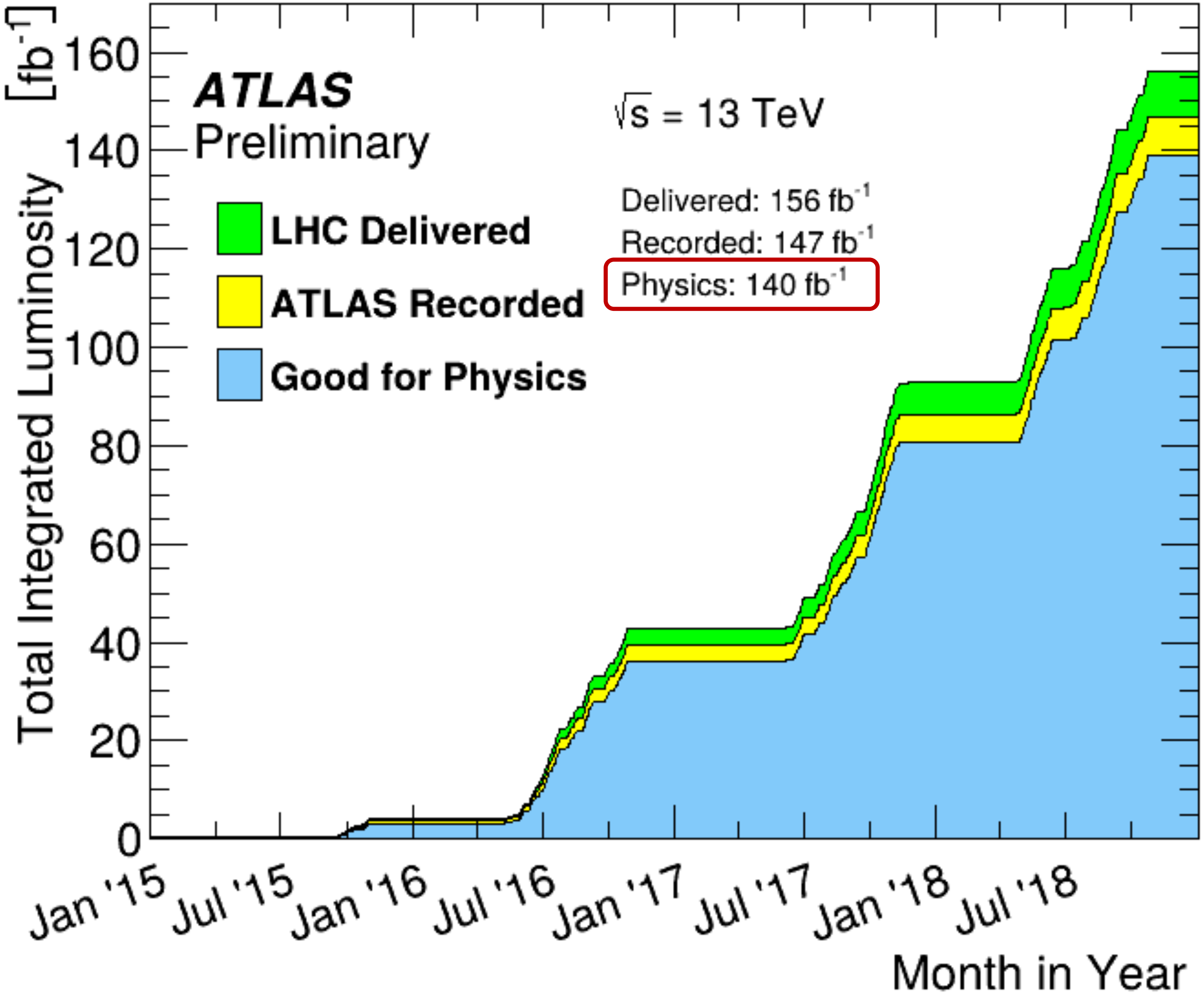
$\sqrt{s}$ = 13 TeV

Run2 period: 2015 - 2018

Total Physics: 140 fb^{-1}

Analyses only possible due to large dataset



$W\gamma$

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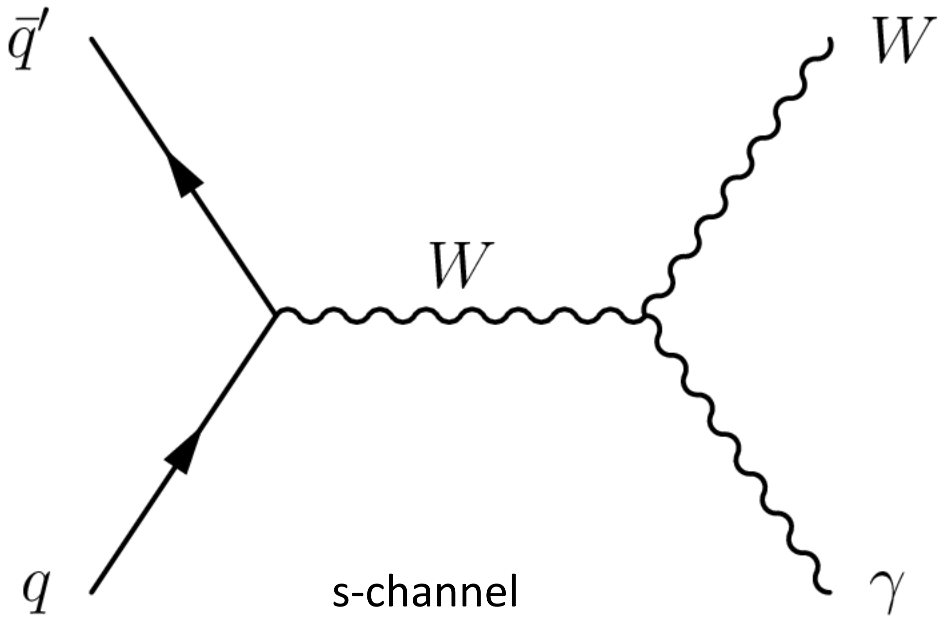
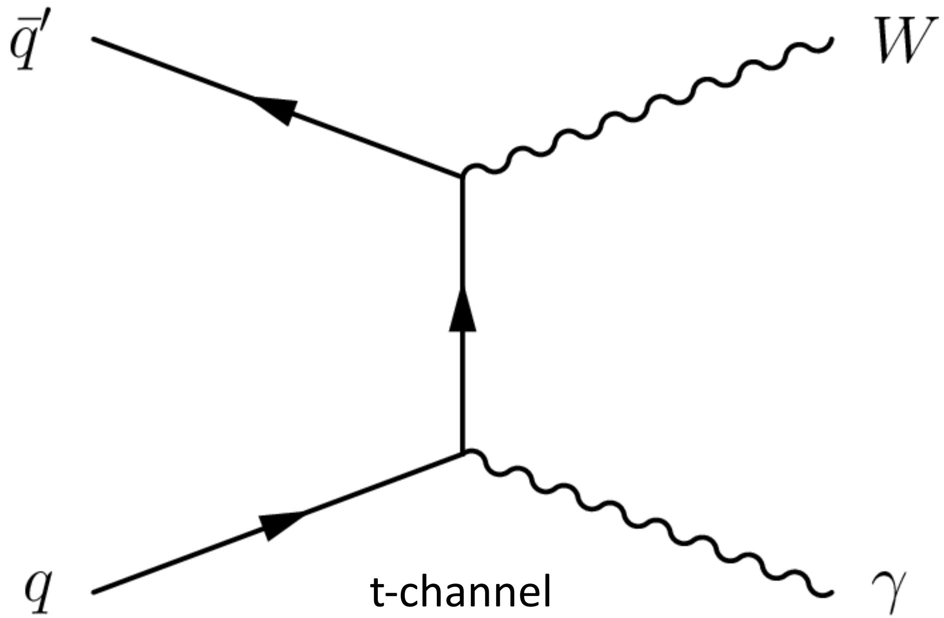
Measurements of $W\gamma \to \ell\nu\gamma$ ($\ell = e$ or μ)

- $W\gamma$ was first studied by ATLAS using Run-1 data (at $\sqrt{s} = 7$ TeV):
  Phys. Rev. D87 (2013) 112003 and Erratum: Phys. Rev. D 91
- **Measured differential cross sections of 16 characteristic observables: statistics limited!**
- **One lepton with $p_T^{\ell} > 30$ GeV, missing energy ($p_T^{\text{miss}} > 40$ GeV) & a photon ($p_T^{\gamma} > 30$ GeV)**
- **Main background is jets faking lepton and photon (about 1%-4%) - data driven estimations**
- **Compared to NLO and NNLO generators, as well as EFT interpretation**



s-channel



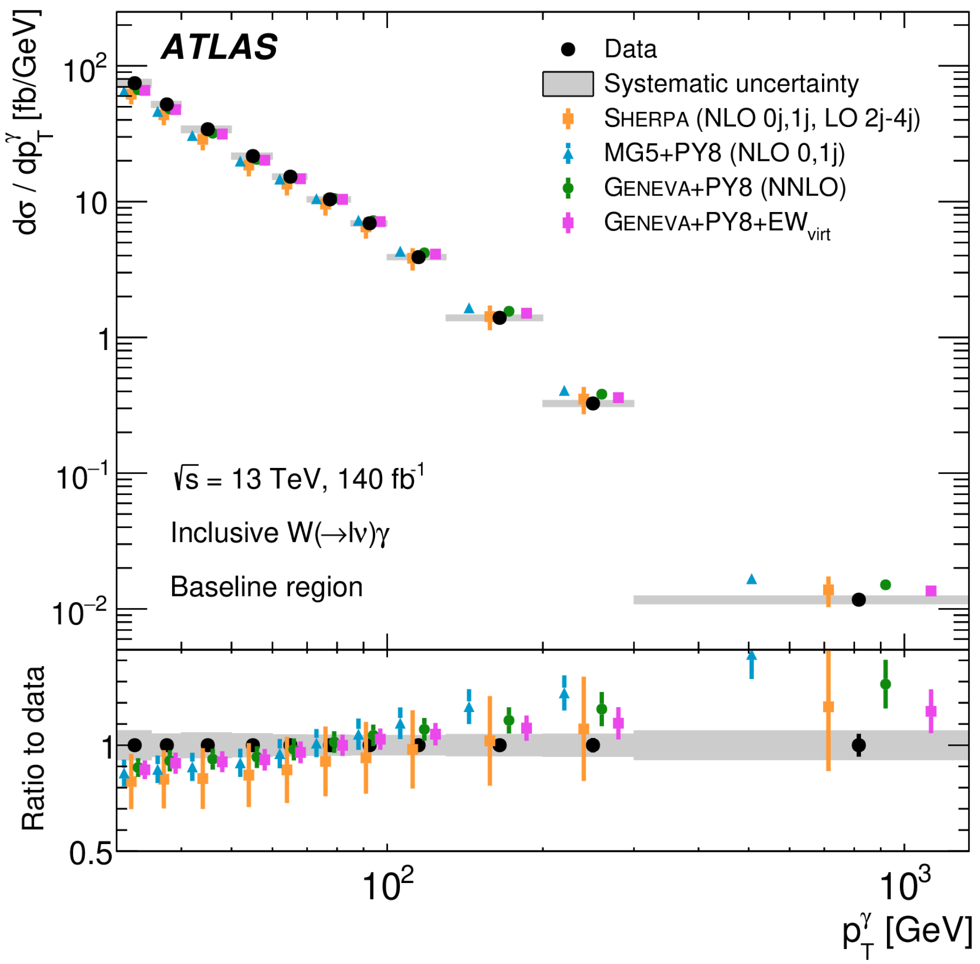
t-channel

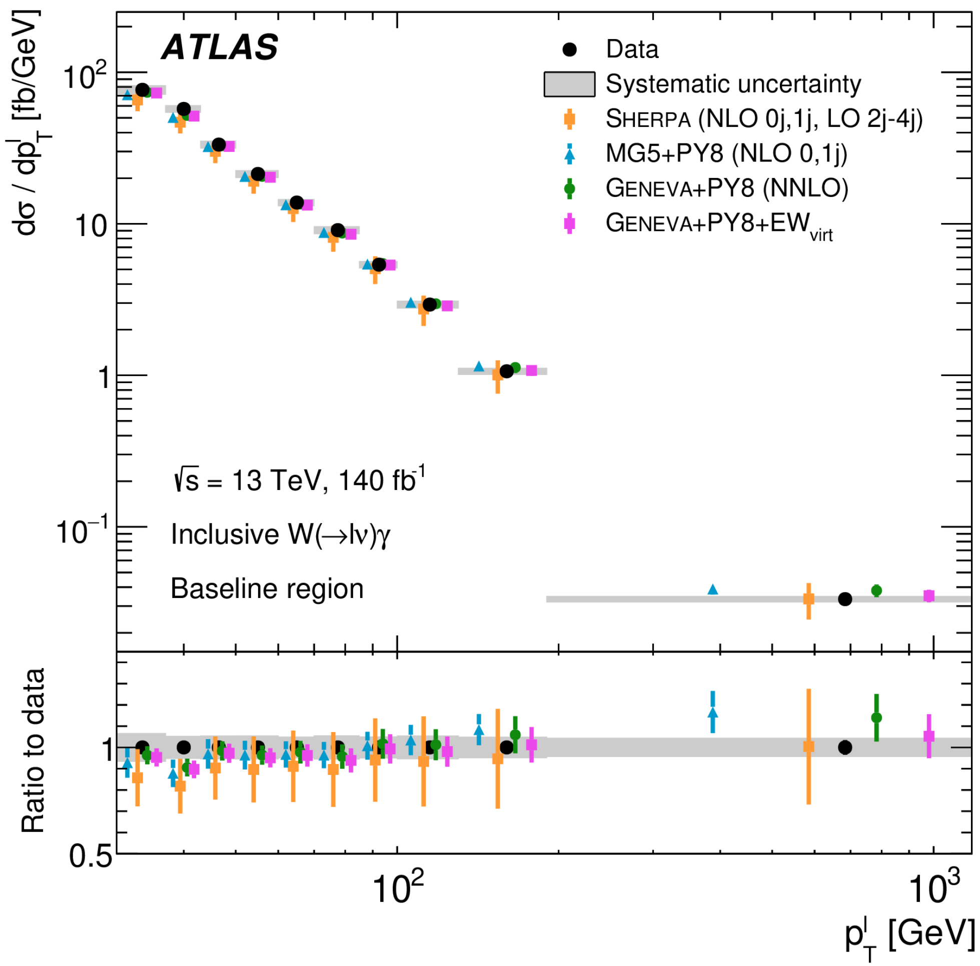
Measurements of $W\gamma \to \ell\upsilon\gamma$ ($\ell = e$ or μ)

❖**Inclusive kinematics**: p_T of the photon and lepton: NLO vs NNLO

Sherpa & MG5+PY8 overestimate at large p_T; while Geneva+PY8+EW_{virt} agrees best

NNLO QCD increase cross-section & hint of NLO EW important at high momentum





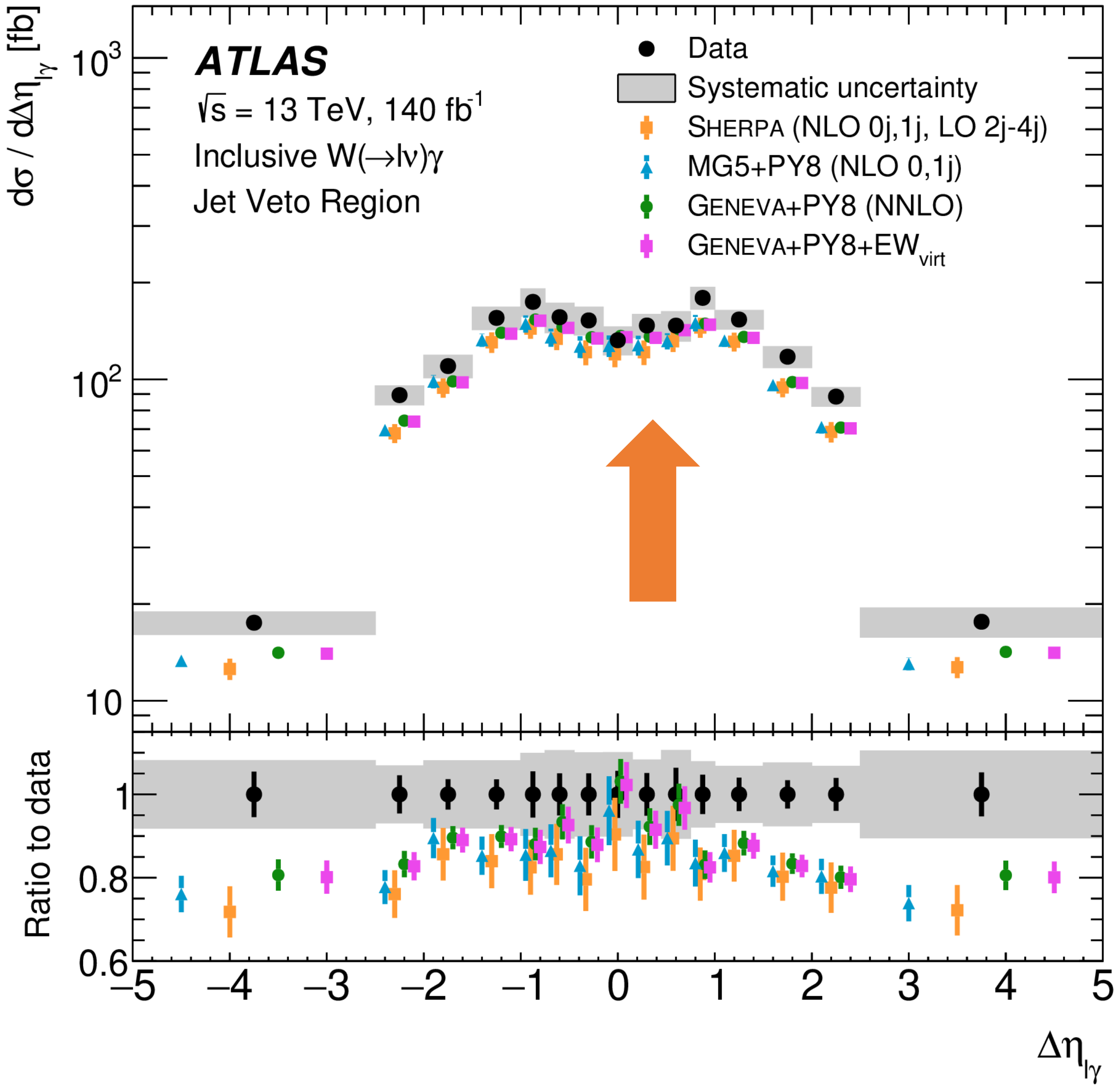
Measurements of $W\gamma \to \ell\upsilon\gamma$ ($\ell = e$ or μ)

❖ Radiation Amplitude Zero (**RAZ**):

At leading-order (LO) in the SM, interference between s-channel, and the t- and u-channel creates cancellation restored by high-order QCD corrections.

SM/data consistent with unity

Dip at the angular separation in pseudorapidity $\Delta\eta_{\ell\gamma}$ is a characteristic of RAZ.
(cool yeah !!!)



Measurements of $W\gamma \to \ell\upsilon\gamma$ ($\ell = e$ or μ)

PDF-sensitive observables: probe the proton $\bar{u}d \to W^-$ *vs* u$\bar{d} \to W^+$

❖ $W\gamma$ boost asymmetry (measured separately for events containing *leptons* and *antileptons*) untangle contributions of valence versus sea quarks (NNPDF4.0$_{\text{NNLO}}$ PDF set)

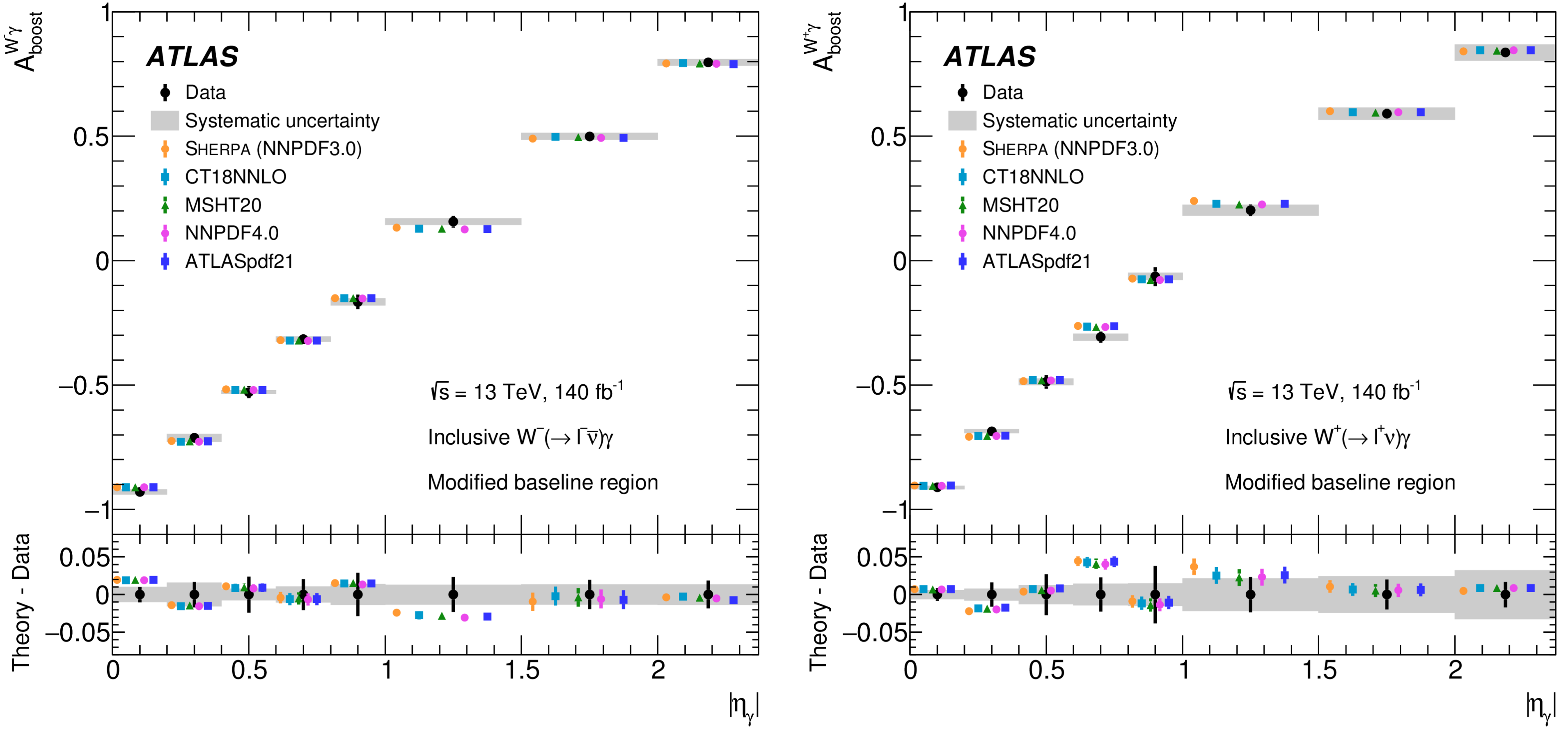
$$A_{\text{boost}}^{W^-\gamma} = -0.091 \pm 0.012(\text{stat.}) \pm 0.017(\text{sys.}) \pm 0.002(\text{th.}), \quad A_{\text{boost}}^{W^+\gamma} = 0.033 \pm 0.012(\text{stat.}) \pm 0.009(\text{sys.}) \pm 0.003(\text{th.}).$$

$$A_{\text{boost}}^{W\gamma} = \frac{\sigma_\gamma^{\text{fwd}} - \sigma_\gamma^{\text{cent}}}{\sigma_\gamma^{\text{fwd}} + \sigma_\gamma^{\text{cent}}}$$

with

$\sigma_\gamma^{\text{fwd}}$ when $|\eta_\gamma| > |\eta_\ell|$

$\sigma_\gamma^{\text{cent}}$ when $|\eta_\gamma| < |\eta_\ell|$



SM predictions

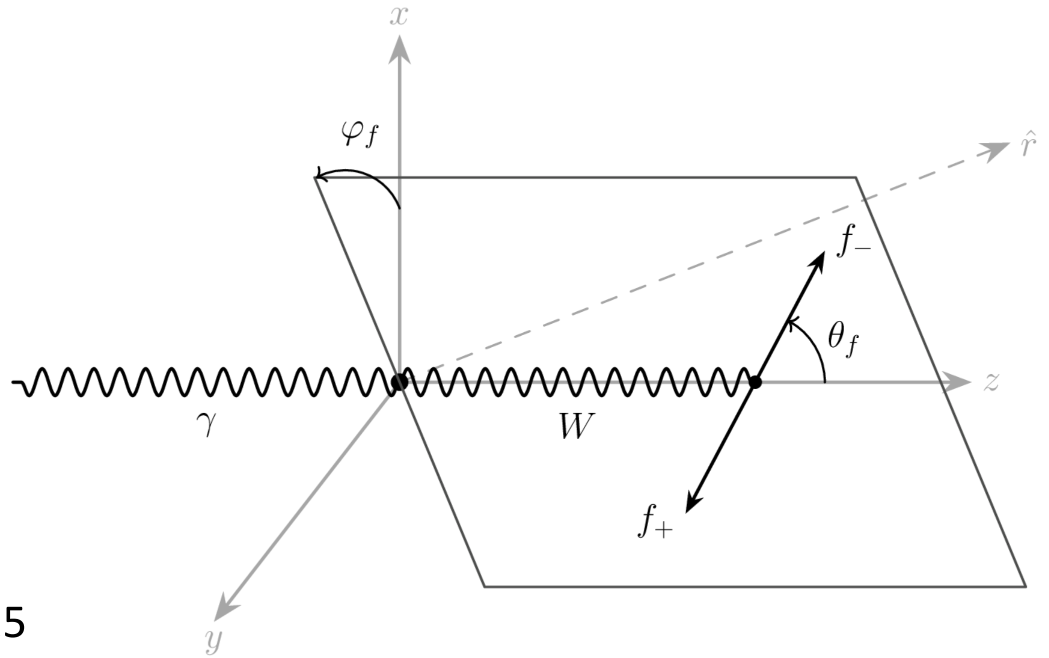
-0.101 ± 0.003 for the $W^-\gamma$

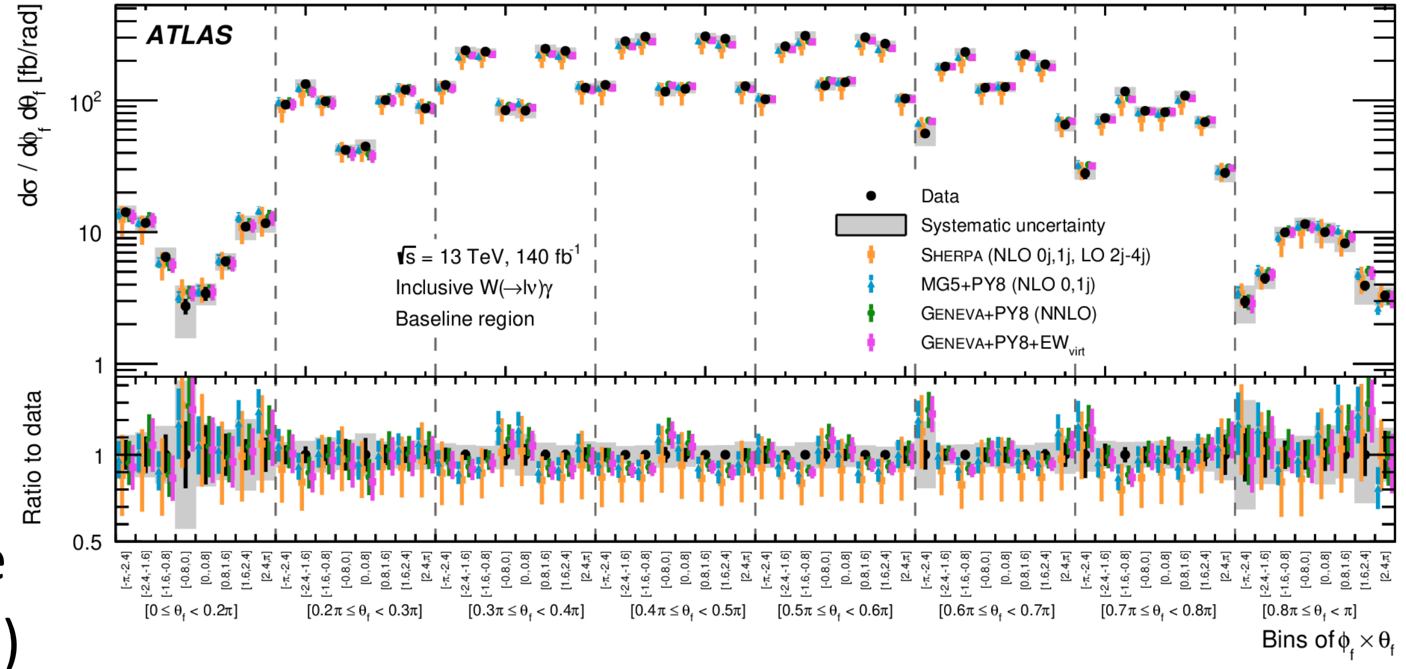
0.043 ± 0.003 for the $W^+\gamma$

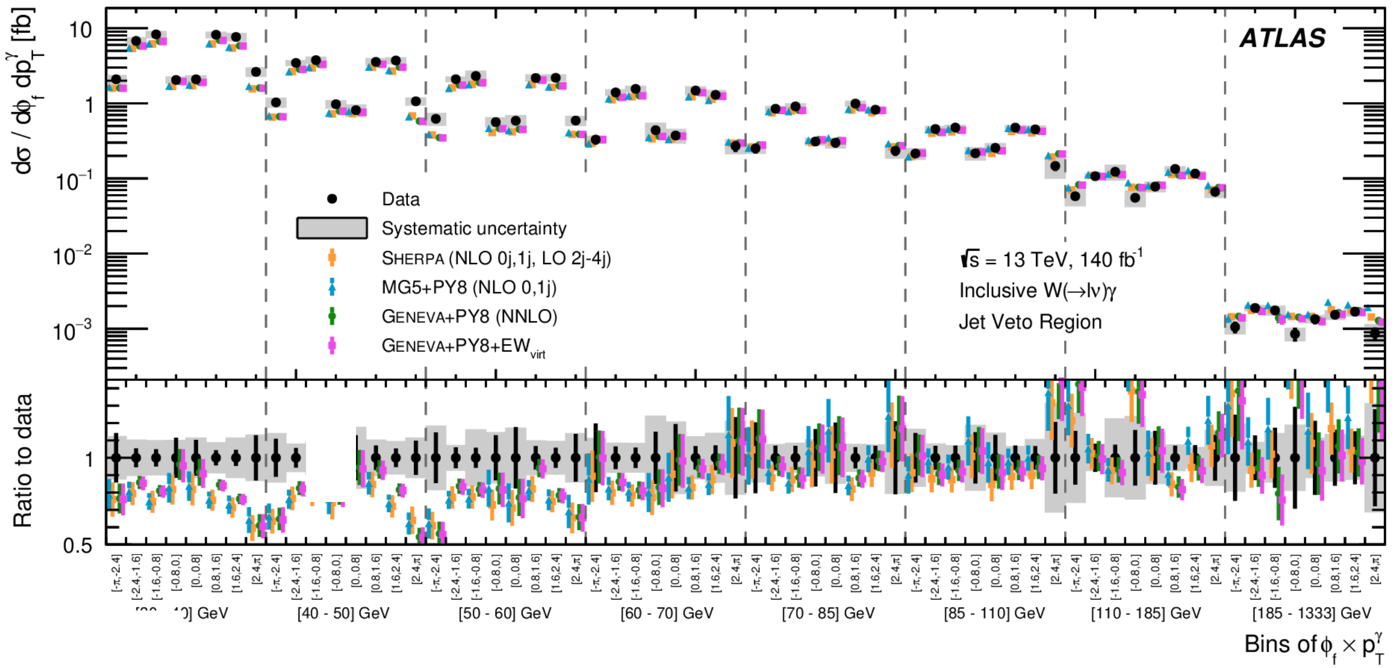
$W\gamma \rightarrow \ell\upsilon\gamma$

Polarization-sensitive observables: θ_f, φ_f and p_T^γ

- θ_f versus φ_f probes W boson spin density matrix (baseline)
- φ_f versus p_T^γ sensitive EFT interference effects that grows with energy (jet veto)
- Ratio SM/data consistent with unity







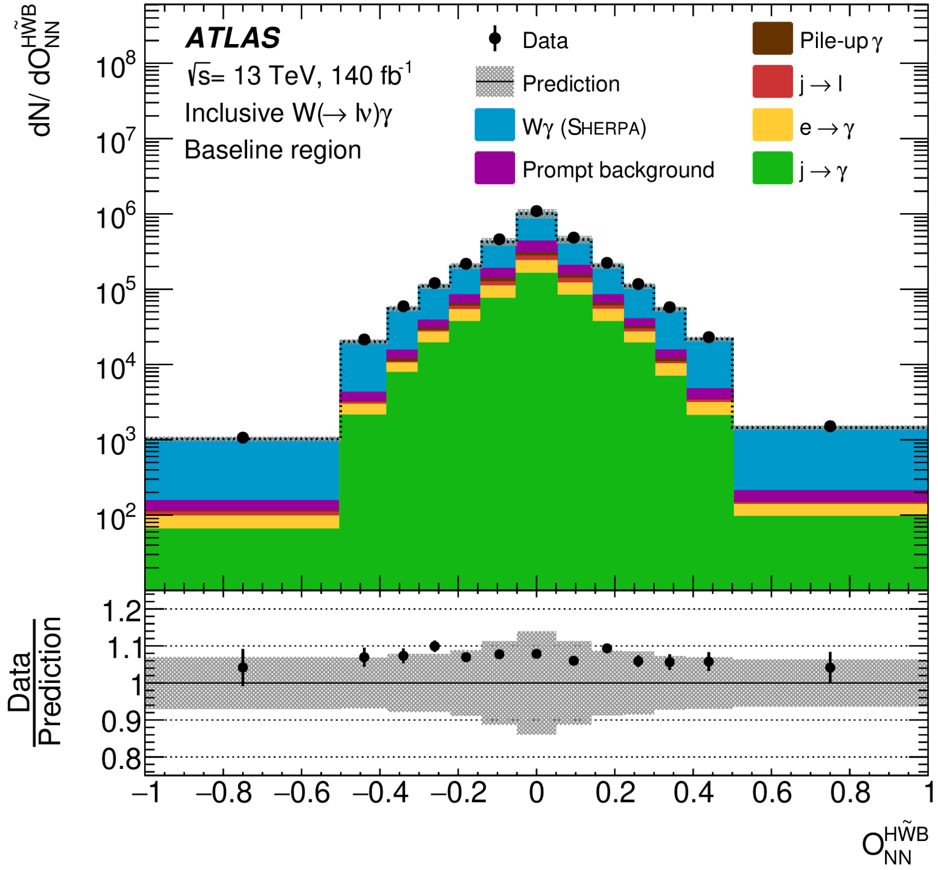
Measurements of $W\gamma \to \ell\upsilon\nu$ ($\ell = e$ or u)

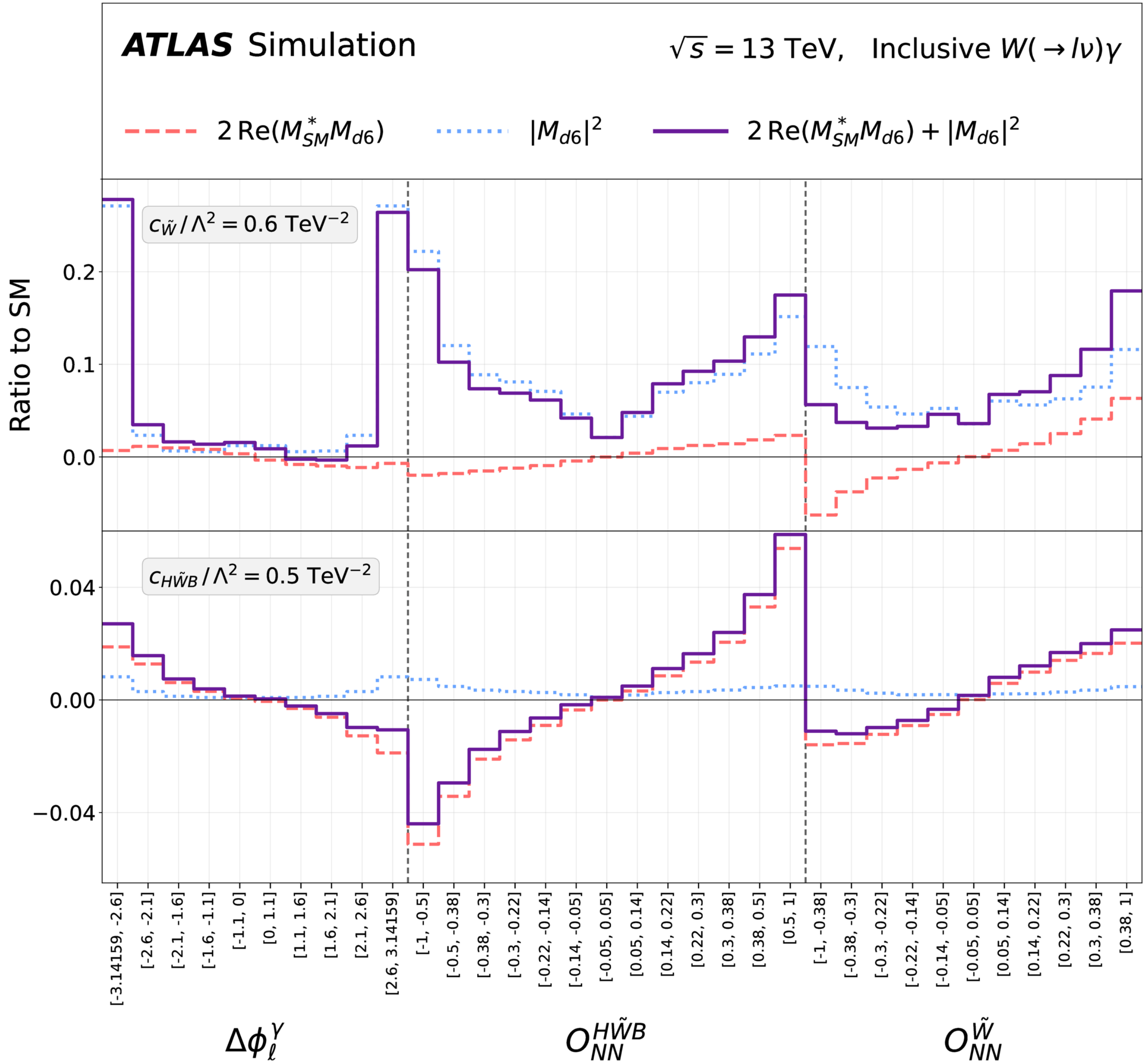
CP-sensitive observables:

φ_f versus p_T^γ and $O_{NN} = P_+ - P_-$

- NN is trained to distinguish between constructive & destructive interferences

$$|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + 2\mathrm{Re}(\mathcal{M}_{SM}^*\mathcal{M}_{d6}) + |\mathcal{M}_{d6}|^2$$





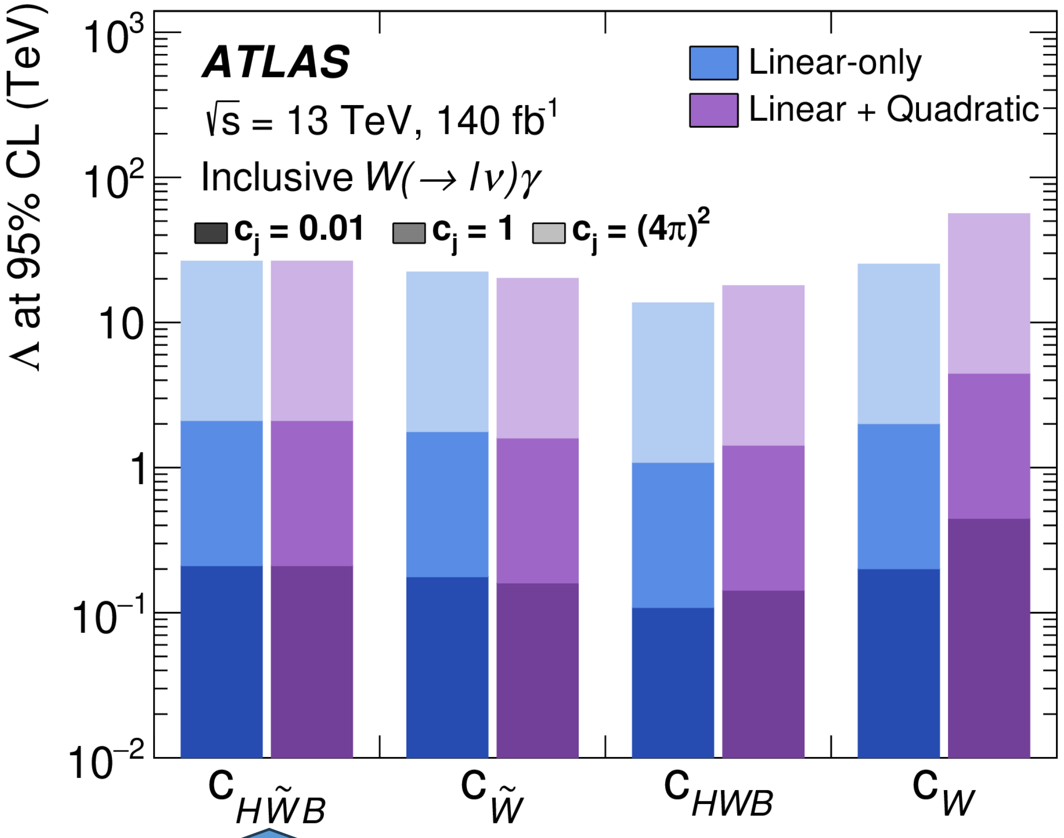
EFT interpretation of $W\gamma \to \ell\nu\gamma\ (\ell = e \text{ or } \mu)$

CP-sensitive observables:

- c_W, c_{HWB} (CP-even)
- $\tilde{c}_W, \tilde{c}_{H\tilde{W}B}$ (CP-odd)

$$\sigma_i^{\mathrm{SMEFT}} = \sigma_i^{\mathrm{SM}} + \frac{c}{\Lambda^2}\sigma^{\mathrm{int}} + \frac{c^2}{\Lambda^4}\sigma^{\mathrm{d6}}$$

Wilson coefficient	Observable	Includes $\lvert\mathcal{M}_{d6}\rvert^2$	k-factor	95% CL [TeV^{-2}] Expected	Observed
c_W/Λ^2	$\phi_f \times p_T^\gamma$	no	no	$[-0.37, 0.38]$	$[-0.42, 0.36]$
		yes	no	$[-0.12, 0.11]$	$[-0.06, 0.06]$
		no	yes	$[-0.23, 0.25]$	$[-0.28, 0.21]$
		yes	yes	$[-0.09, 0.09]$	$[-0.05, 0.05]$
$c_{\tilde{W}}/\Lambda^2$	$O_{\mathrm{NN}}^{\tilde{W}}$	no	no	$[-0.53, 0.54]$	$[-0.74, 0.23]$
		yes	no	$[-0.61, 0.36]$	$[-0.67, 0.19]$
		no	yes	$[-0.32, 0.32]$	$[-0.45, 0.14]$
		yes	yes	$[-0.43, 0.25]$	$[-0.54, 0.11]$
c_{HWB}/Λ^2	$\phi_f \times p_T^\gamma$	no	no	$[-1.21, 0.90]$	$[-0.67, 1.21]$
		yes	no	$[-0.97, 0.82]$	$[-0.47, 0.67]$
		no	yes	$[-0.84, 0.62]$	$[-1.09, 0.50]$
		yes	yes	$[-0.76, 0.60]$	$[-0.58, 0.38]$
$c_{H\tilde{W}B}/\Lambda^2$	$O_{\mathrm{NN}}^{H\tilde{W}B}$	no	no	$[-0.39, 0.39]$	$[-0.59, 0.13]$
		yes	no	$[-0.39, 0.39]$	$[-0.60, 0.13]$
		no	yes	$[-0.20, 0.21]$	$[-0.31, 0.07]$
		yes	yes	$[-0.20, 0.21]$	$[-0.31, 0.07]$



Linear term drives the sensitivity even when taking quadratic term into account

Limit on $\tilde{c}_{H\tilde{W}B}$ improves by 2.5 compares to previous measurements using other final states

ZZ and $ZZjj$

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

Submitted to: EPJ C

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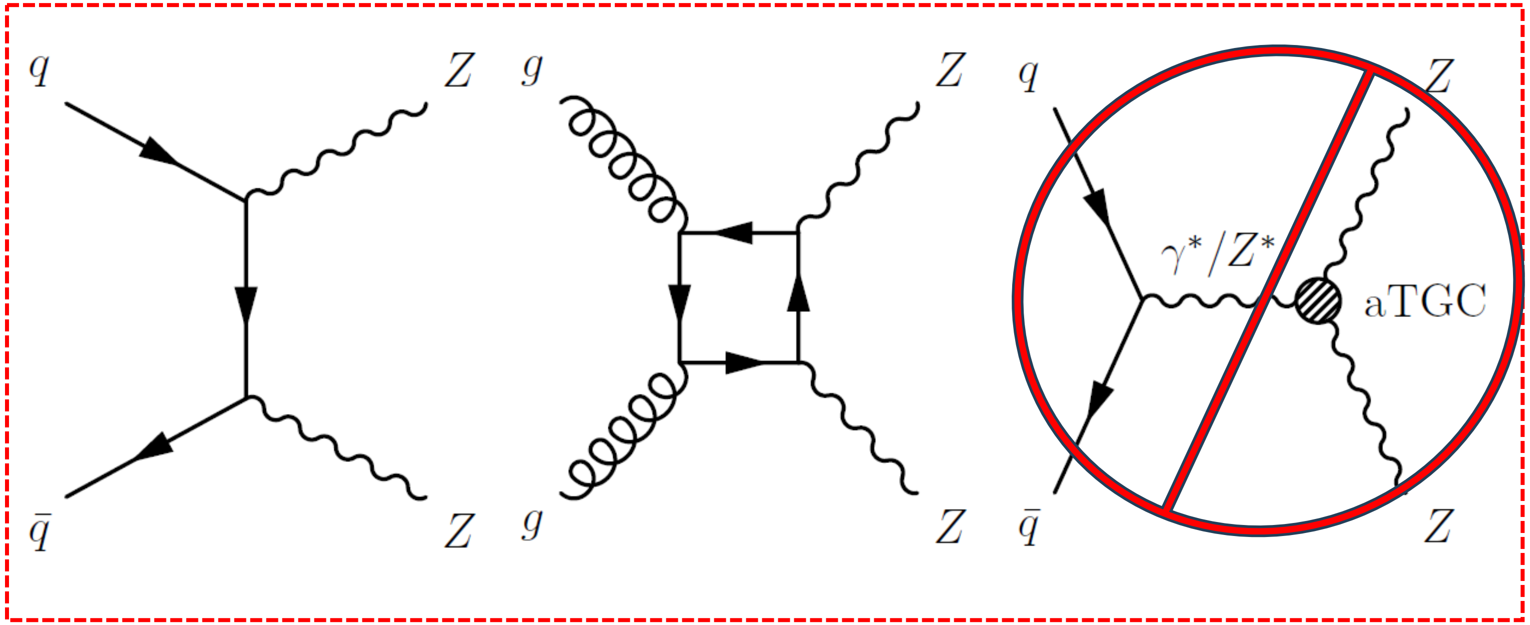
Study of $ZZ(jj) \rightarrow \ell\ell\nu\nu(jj)$ with $\ell = e$ or μ

$80\ \text{GeV} < m_{\ell^+\ell^-} < 100\ \text{Gev}$ & E_T^{miss}

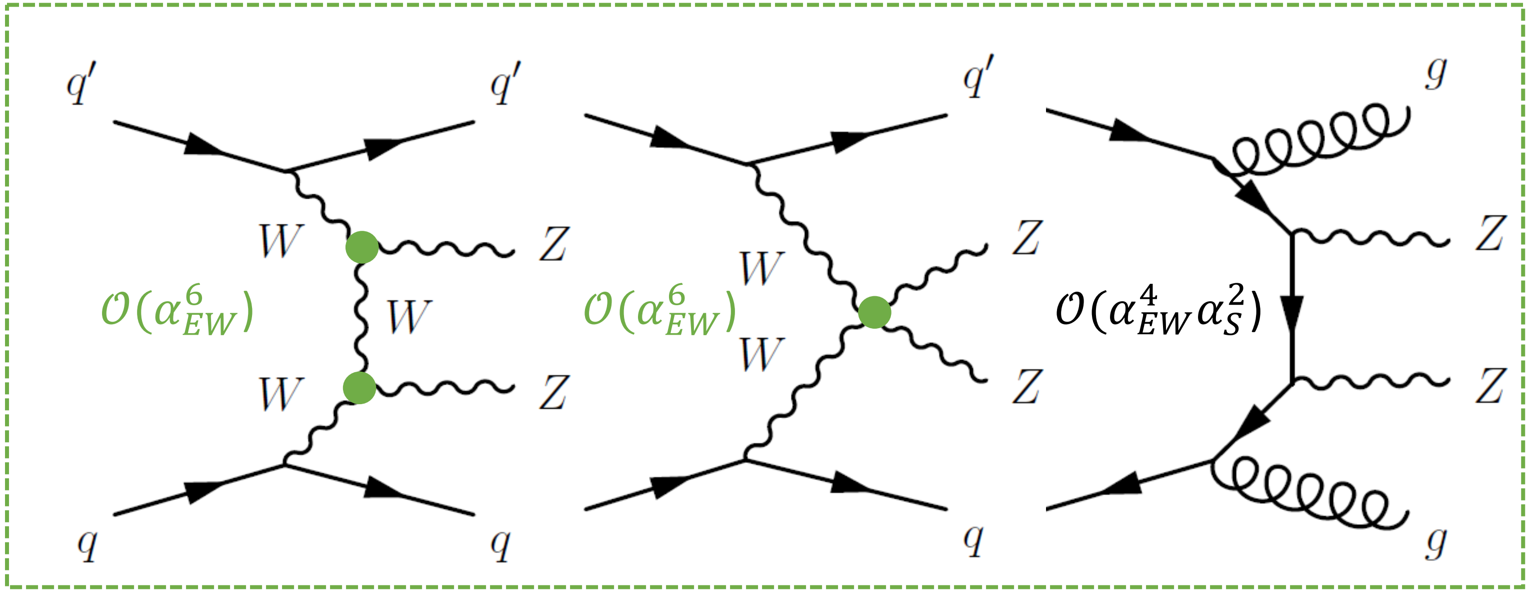
$ZZ \rightarrow \ell\ell\nu\nu$

- ZZ Production (**QCD** dominated)
- ~90% $q\bar{q}$ and ~10% gg
- SM anomalous TGC (aTGC)
- Lagrange Vertex Function (VF) and SMEFT interpretations

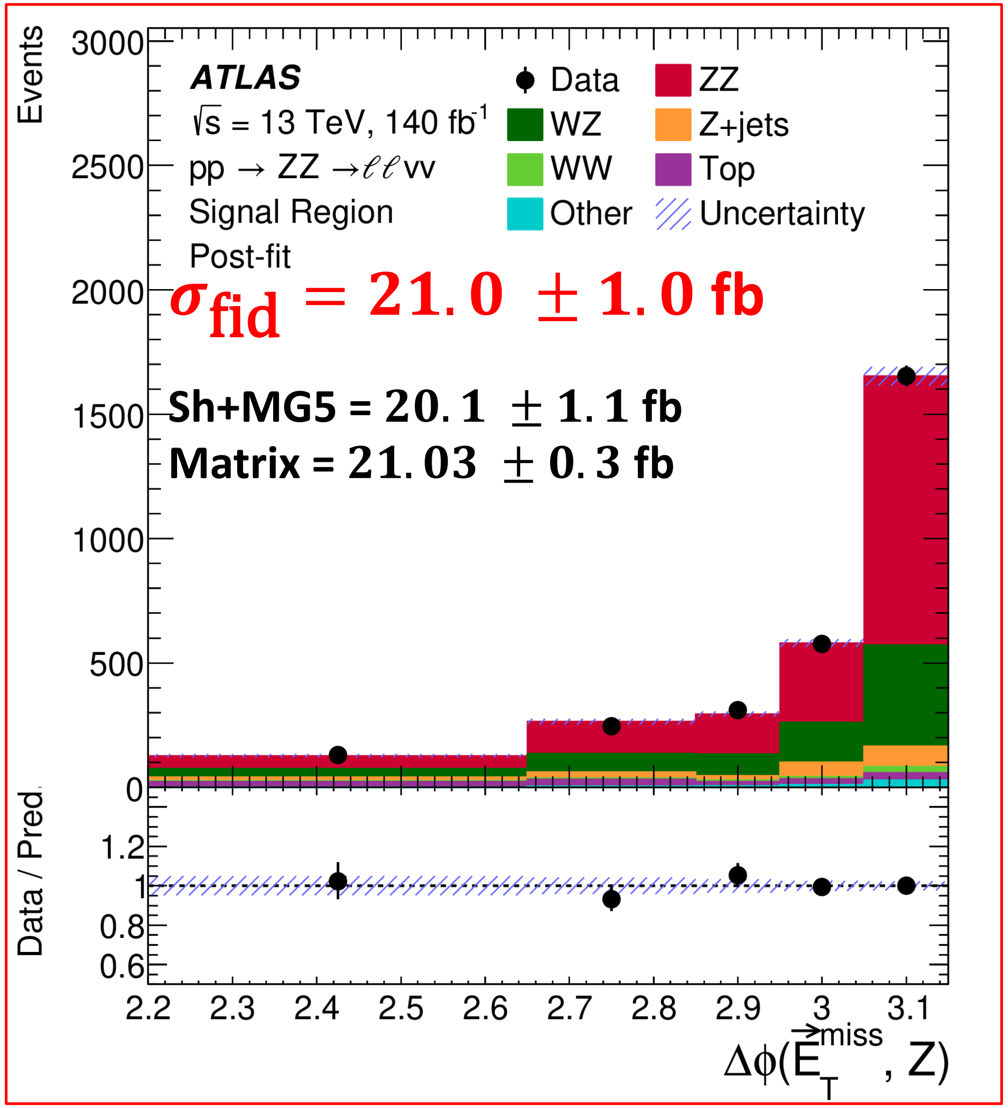


$ZZ + 2\ jets \rightarrow \ell\ell\nu\nu jj$

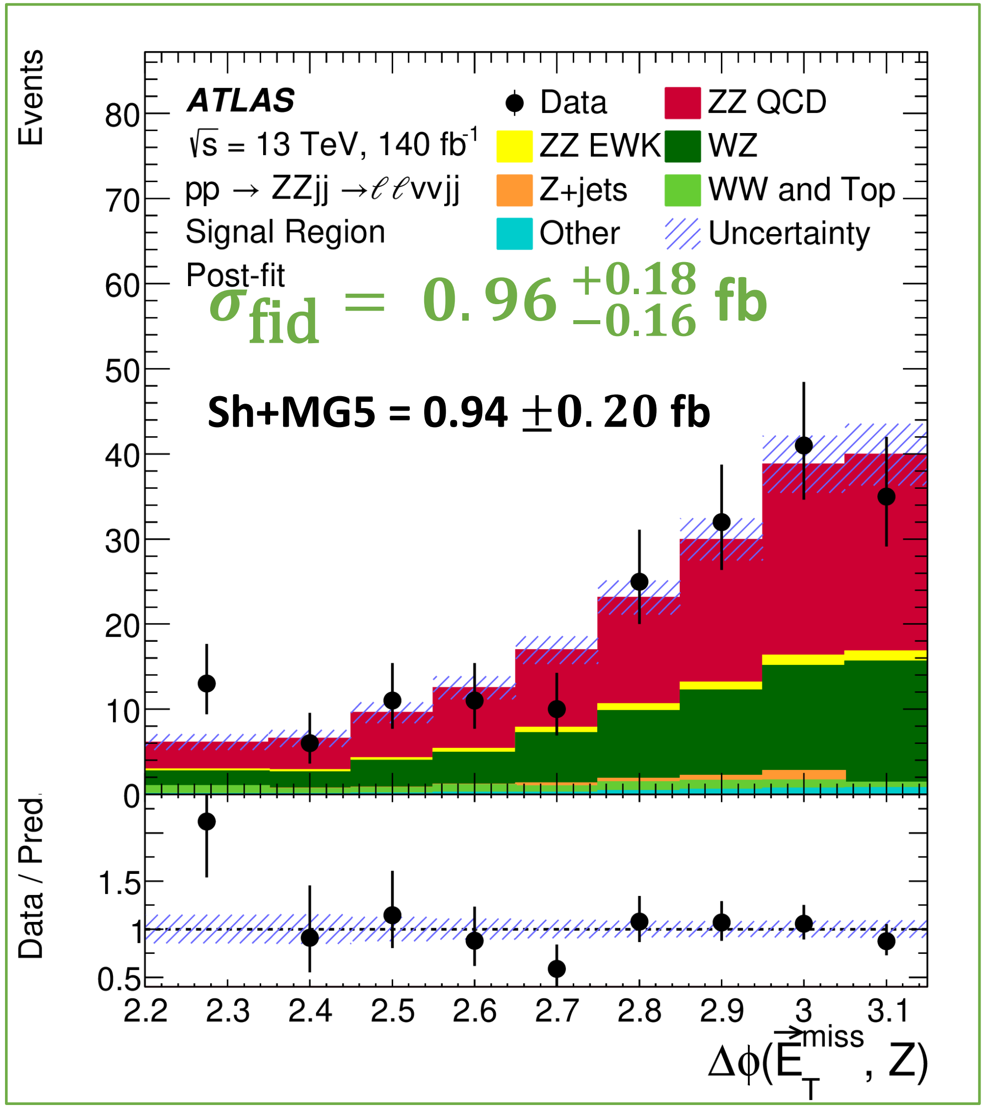
- EW + QCD
- **EW** production with VBF (aTGC) and VBS (aQGC)
- QCD production gg final state
- SMEFT interpretation



$ZZ \to \ell\ell\nu\nu$ Fiducial cross-section



$ZZjj \to \ell\ell\nu\nu jj$ Fiducial cross-section

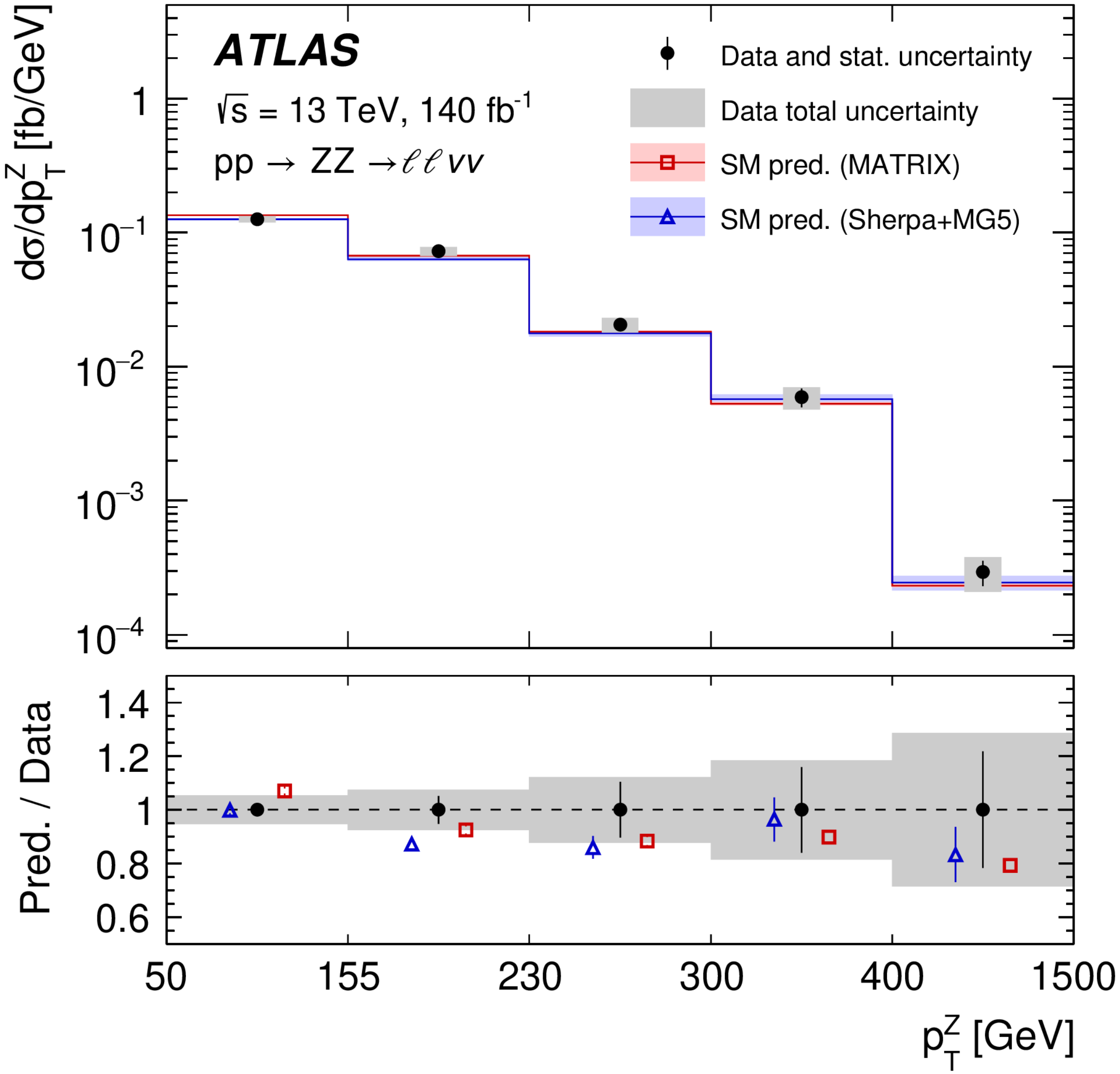


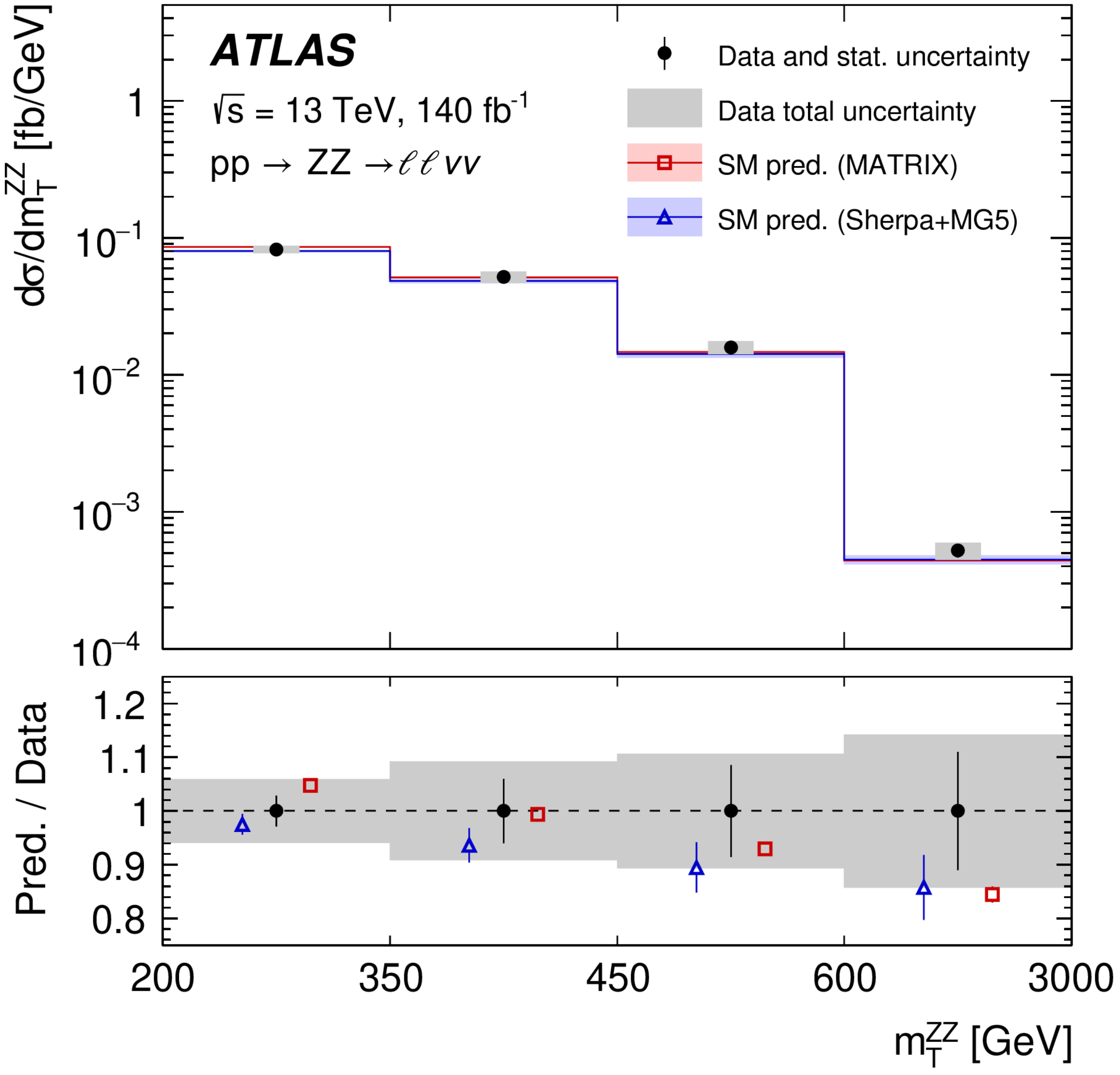
Total cross-section extrapolated to $m_{\ell\ell}$ and $m_{\nu\nu} \in [66, 116]$GeV

$\sigma^{\text{total}}_{\text{measured}}(pp \to ZZ) = 15.38 \pm 0.81$ pb with Matrix $= 15.40 \pm 0.38$ pb

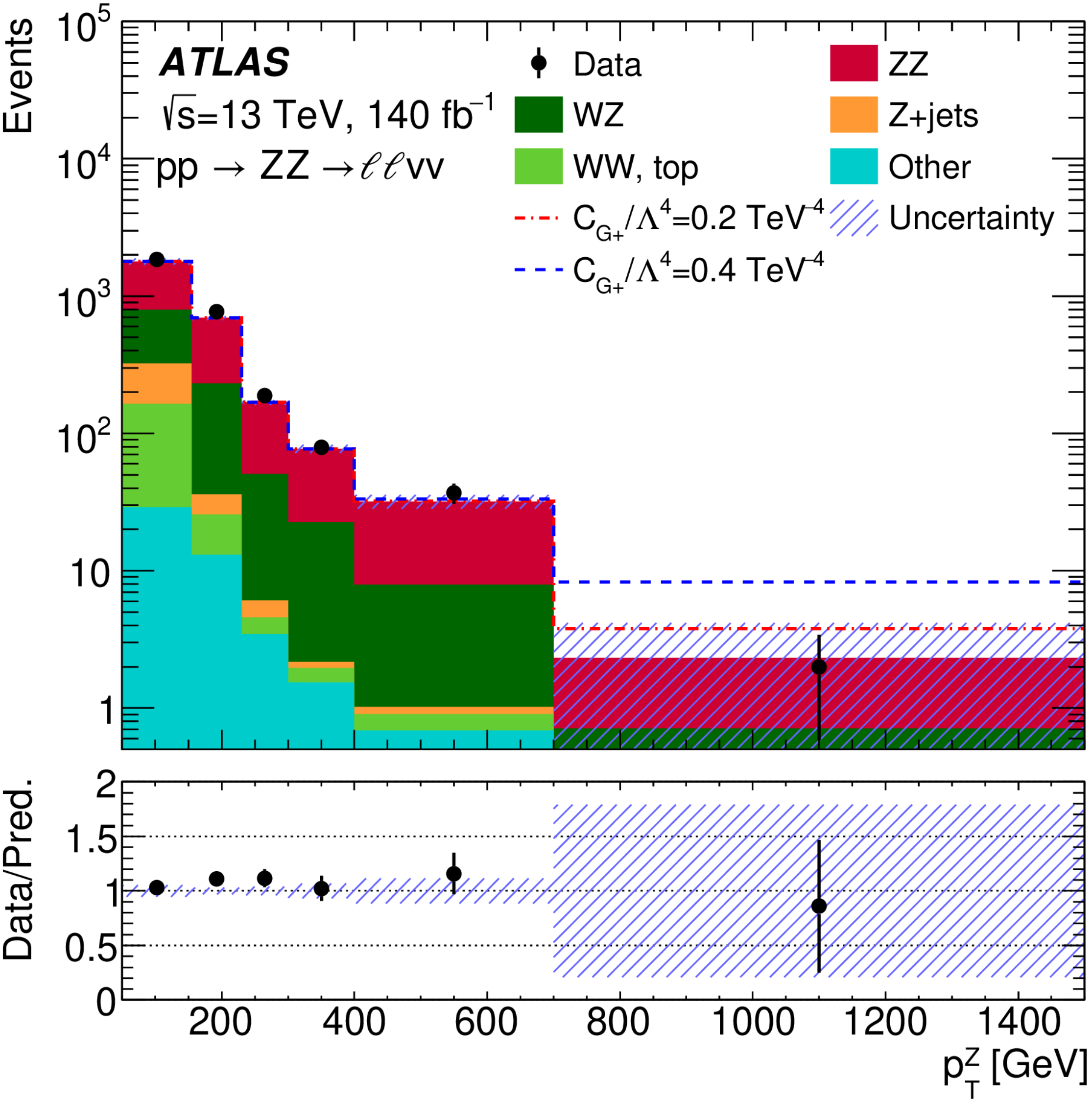
Study of $ZZ \to \ell\ell\nu\nu$ with $\ell = e$ or μ

Differential Cross-Sections





Limit on <u>*aTGC*</u> from $ZZ \to \ell\ell\nu\nu$



Best observables to probe anomalous triple-gauge-coupling
Results obtained by setting all other aTGC parameters to zero

Lagrange Vertex Function (VF)

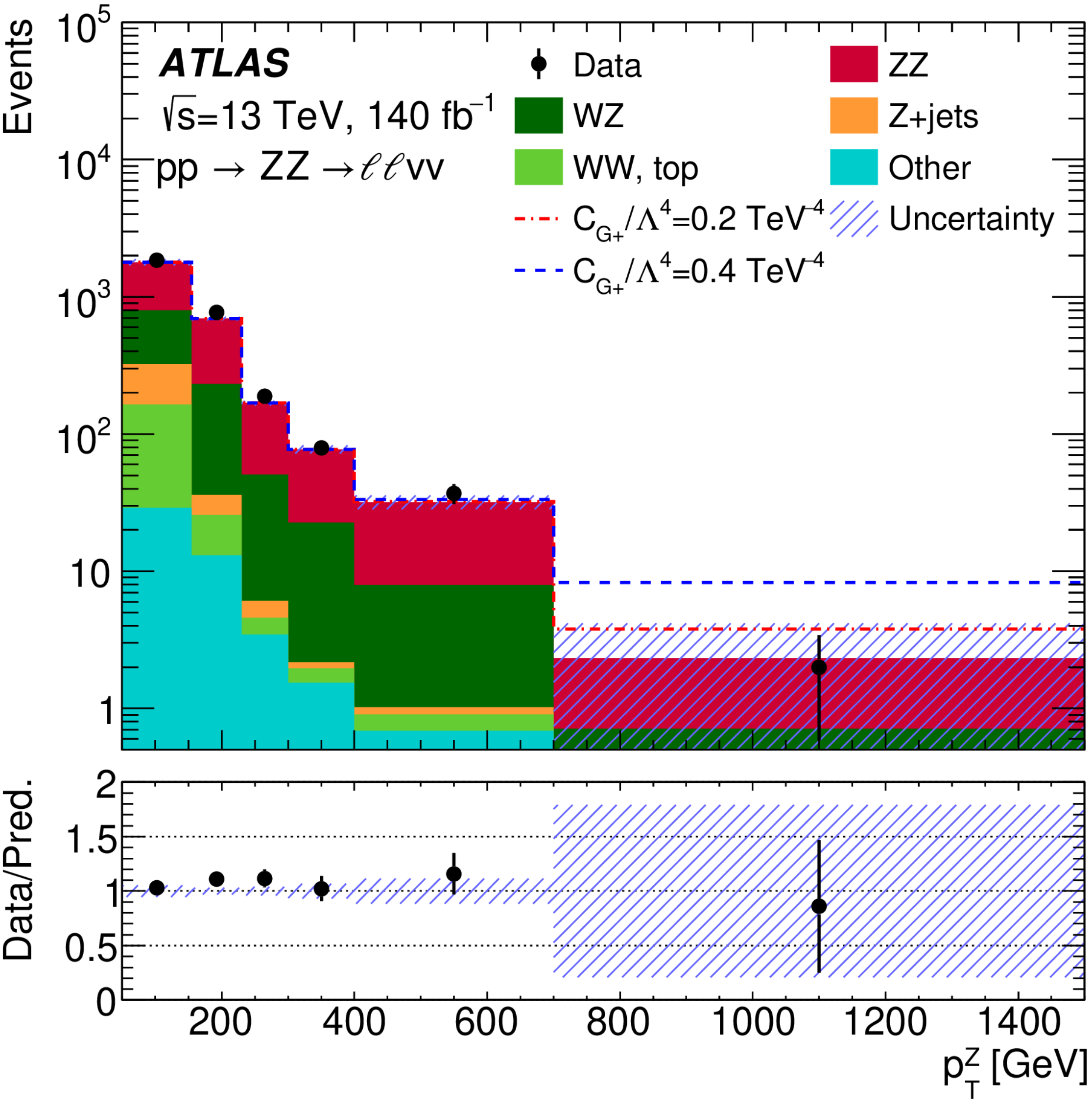
$$g_{ZZV}\Gamma^{\alpha\beta\mu}_{ZZV} = e\frac{P^2 - m_V^2}{m_Z^2}\left[i f_4^V (P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}) + i f_5^V \epsilon^{\mu\alpha\beta\rho}(q_1 - q_2)_\rho\right]$$

Coefficient	Expected	Observed
f_4^γ	$[-7.7,\ 7.7] \times 10^{-4}$	$[-6.4,\ 6.4] \times 10^{-4}$
f_4^Z	$[-6.8,\ 6.8] \times 10^{-4}$	$[-5.7,\ 5.7] \times 10^{-4}$
f_5^γ	$[-7.8,\ 7.7] \times 10^{-4}$	$[-6.4,\ 6.5] \times 10^{-4}$
f_5^Z	$[-6.9,\ 6.9] \times 10^{-4}$	$[-5.8,\ 5.8] \times 10^{-4}$
C_{G+}/Λ^4 [TeV^{-4}]	$[-0.36,\ 0.36]$	$[-0.29,\ 0.30]$
C_{G-}/Λ^4 [TeV^{-4}]	$[-1.1,\ 1.2]$	$[-0.95,\ 0.95]$
$C_{\tilde{B}W}/\Lambda^4$ [TeV^{-4}]	$[-1.3,\ 1.3]$	$[-1.1,\ 1.1]$
C_{BB}/Λ^4 [TeV^{-4}]	$[-1.6,\ 1.6]$	$[-1.3,\ 1.3]$
C_{BW}/Λ^4 [TeV^{-4}]	$[-2.9,\ 2.9]$	$[-2.4,\ 2.4]$
C_{WW}/Λ^4 [TeV^{-4}]	$[-2.4,\ 2.4]$	$[-2.0,\ 2.0]$

EFT

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i^{(8)}}{\Lambda^4} O_i^{(8)}$$

Limit on aTGC from $ZZ \to \ell\ell\nu\nu$



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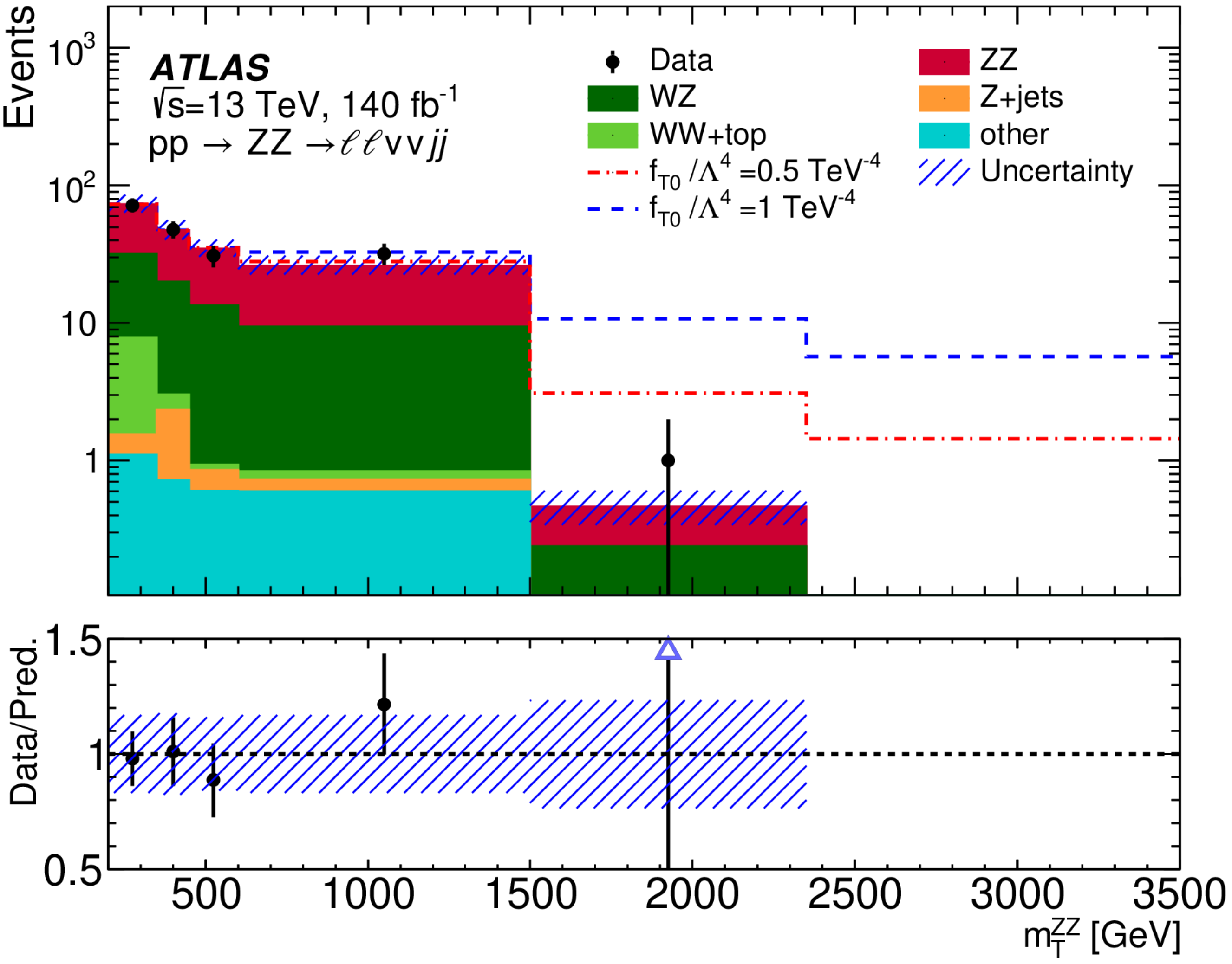
Coefficient	Expected	Observed
f_4^γ	$[-7.7,\ 7.7]\times 10^{-4}$	$[-6.4,\ 6.4]\times 10^{-4}$
f_4^Z	$[-6.8,\ 6.8]\times 10^{-4}$	$[-5.7,\ 5.7]\times 10^{-4}$
f_5^γ	$[-7.8,\ 7.7]\times 10^{-4}$	$[-6.4,\ 6.5]\times 10^{-4}$
f_5^Z	$[-6.9,\ 6.9]\times 10^{-4}$	$[-5.8,\ 5.8]\times 10^{-4}$
C_{G+}/Λ^4 [TeV^{-4}]	$[-0.36,\ 0.36]$	$[-0.29,\ 0.30]$
C_{G-}/Λ^4 [TeV^{-4}]	$[-1.1,\ 1.2]$	$[-0.95,\ 0.95]$
$C_{\tilde{B}W}/\Lambda^4$ [TeV^{-4}]	$[-1.3,\ 1.3]$	$[-1.1,\ 1.1]$
C_{BB}/Λ^4 [TeV^{-4}]	$[-1.6,\ 1.6]$	$[-1.3,\ 1.3]$
C_{BW}/Λ^4 [TeV^{-4}]	$[-2.9,\ 2.9]$	$[-2.4,\ 2.4]$
C_{WW}/Λ^4 [TeV^{-4}]	$[-2.4,\ 2.4]$	$[-2.0,\ 2.0]$

EFT

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i^{(8)}}{\Lambda^4}O_i^{(8)}$$

Limit on aQGC $ZZ(jj) \to \ell\ell\nu\nu(jj)$

SMEFT for dimension-8 operator



Wilson Coefficient	No cut-off	
$[\mathrm{TeV}^{-4}]$	Expected	Observed
f_{T0}/Λ^4	$[-0.42, 0.40]$	$[-0.50, 0.49]$
f_{T1}/Λ^4	$[-0.46, 0.46]$	$[-0.56, 0.56]$
f_{T2}/Λ^4	$[-0.95, 0.93]$	$[-1.1, 1.1]$
f_{T3}/Λ^4	$[-1.3, 1.3]$	$[-1.6, 1.6]$
f_{T4}/Λ^4	$[-8.8, 8.5]$	$[-11, 11]$
f_{T5}/Λ^4	$[-0.75, 0.71]$	$[-0.89, 0.87]$
f_{T6}/Λ^4	$[-1.1, 1.1]$	$[-1.4, 1.4]$
f_{T7}/Λ^4	$[-2.5, 2.4]$	$[-3.0, 3.0]$
f_{T8}/Λ^4	$[-0.60, 0.60]$	$[-0.74, 0.74]$
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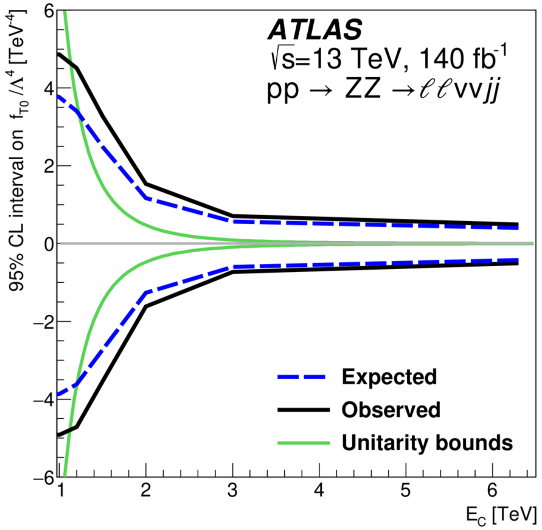

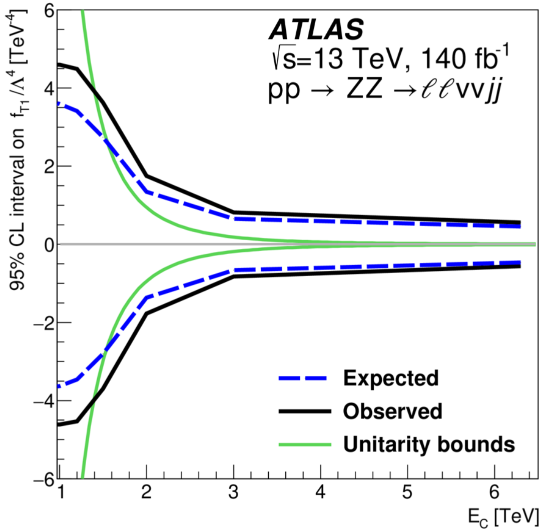

The most stringent constraints are obtained from m_T^{ZZ} for f_{T0} and f_{T1}.
The present limits are better by x2 relative to previous ATLAS results obtained with $ZZ \to 4\ell$ events (arXiv: 2308.12324).

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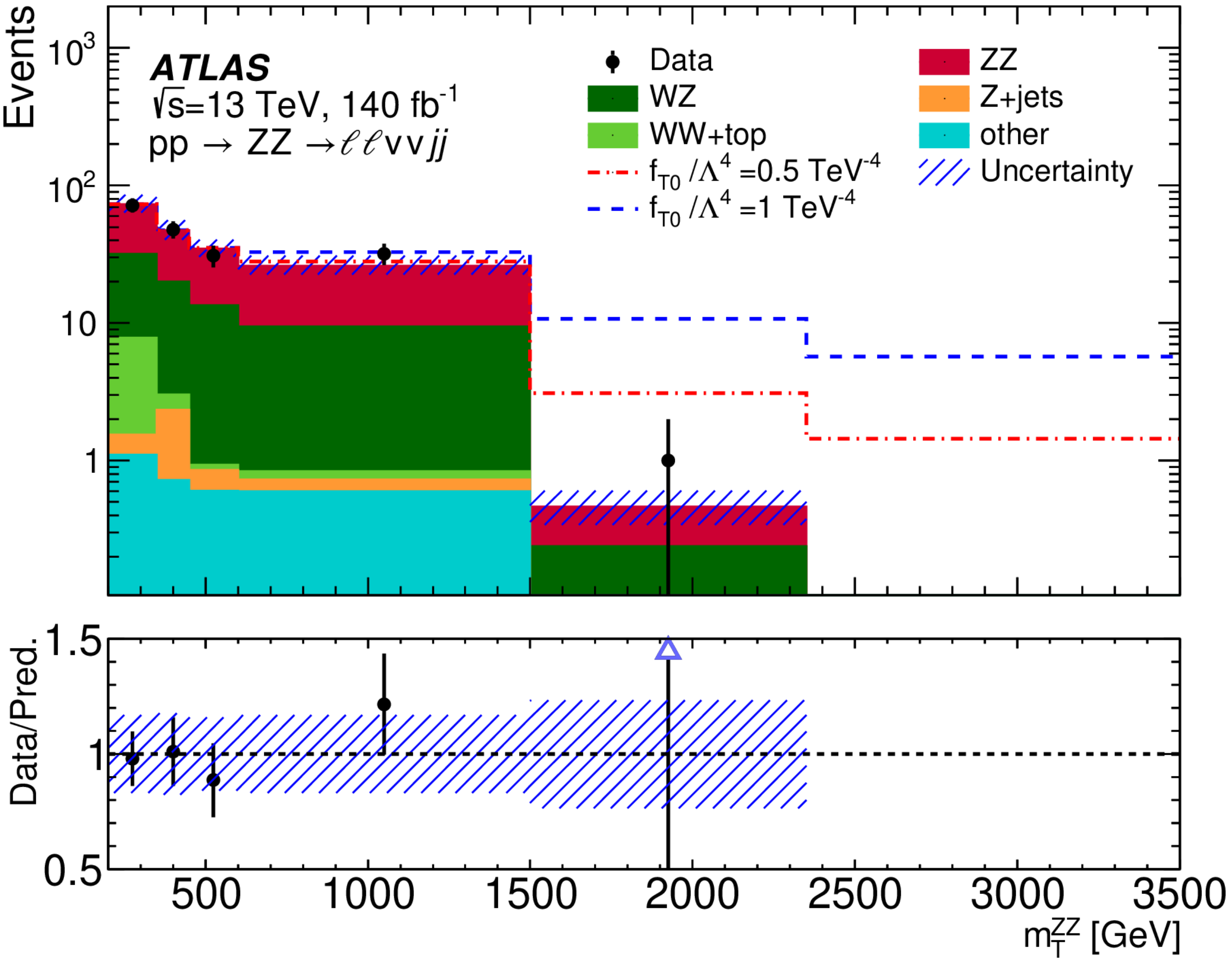

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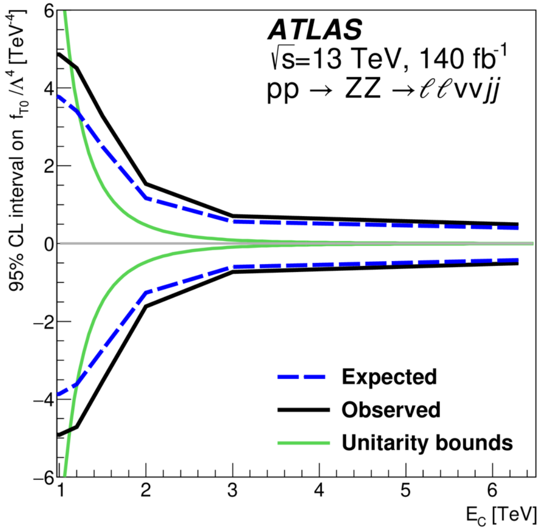

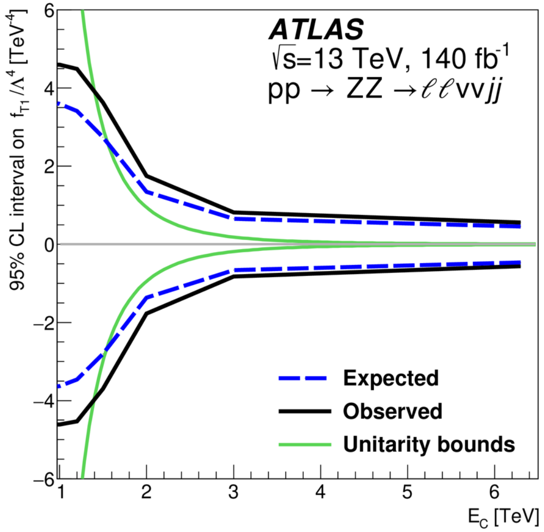

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$ZZ\gamma$

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

Submitted to: PRL

CERN-EP-2026-038
February 20, 2026

Evidence of $ZZ\gamma$ production with the ATLAS detector

The ATLAS Collaboration

Carleton UNIVERSITY

WG3: Electroweak Physics and Beyond the Standard Model

DIS2026

May 5, 2026

Evidence of $ZZ\gamma \rightarrow \ell\ell\ell\ell\gamma$ with $\ell = e$ or μ

First evidence by ATLAS of **$ZZ\gamma$** production (4.4σ)

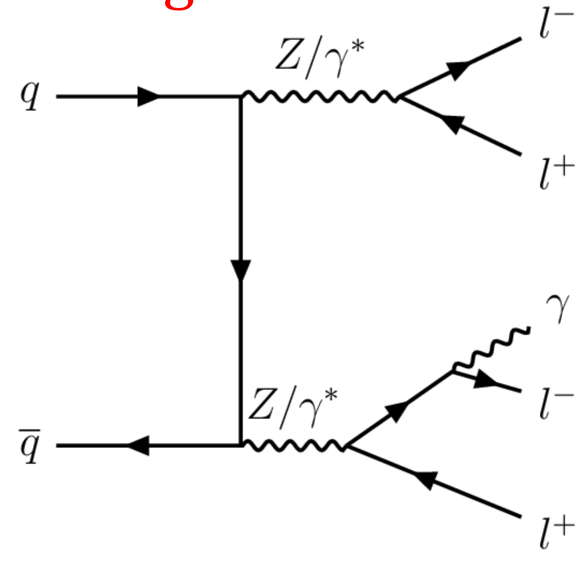
- Signal is triboson and ZH production
- Mitigate ZZ with FSR photon by vetoing event with any $\ell\ell\gamma$ closer to m_Z and enforcing

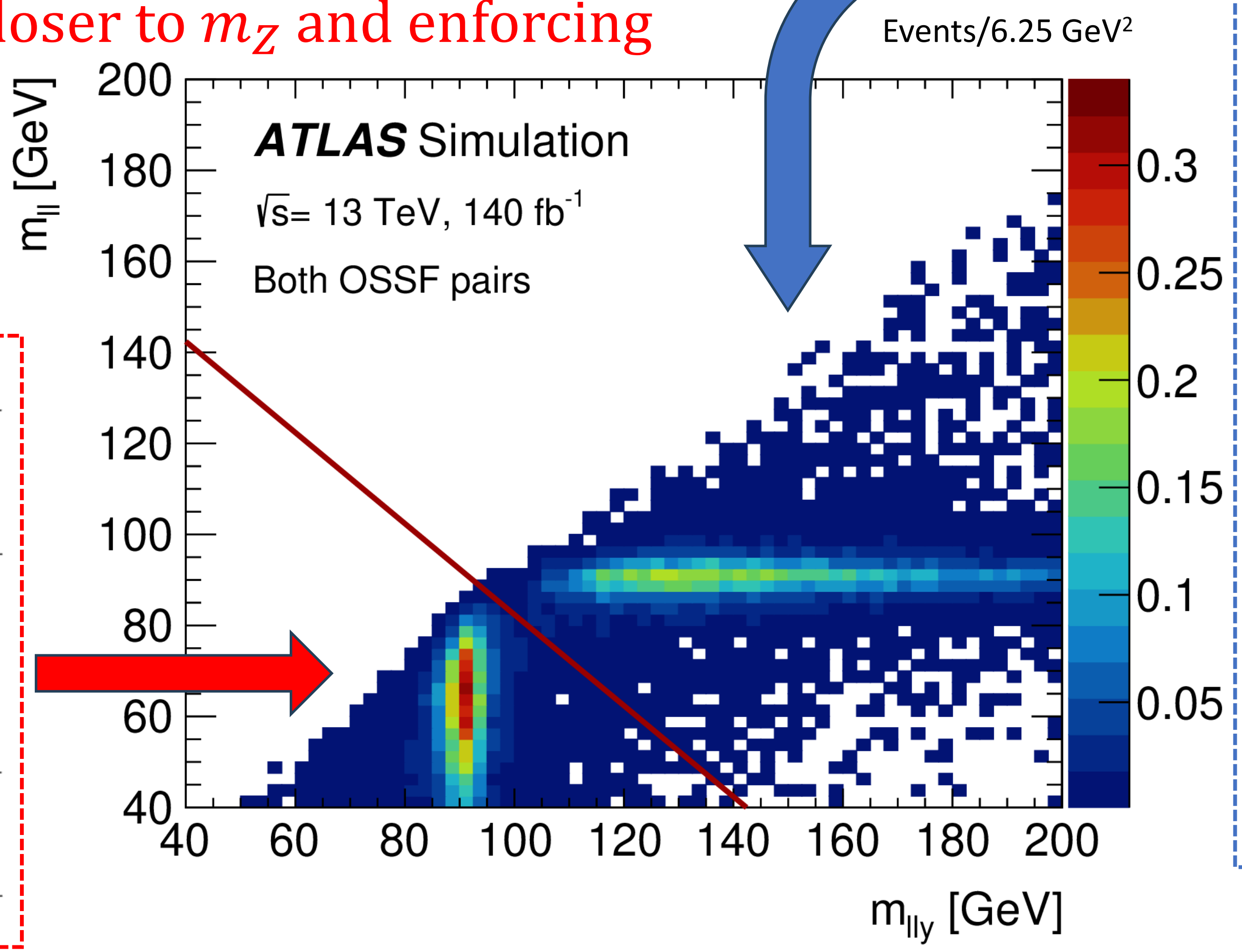
$m_{\ell\ell} > 40\ GeV$

Minimize $|m_{\ell\ell} - m_Z|$

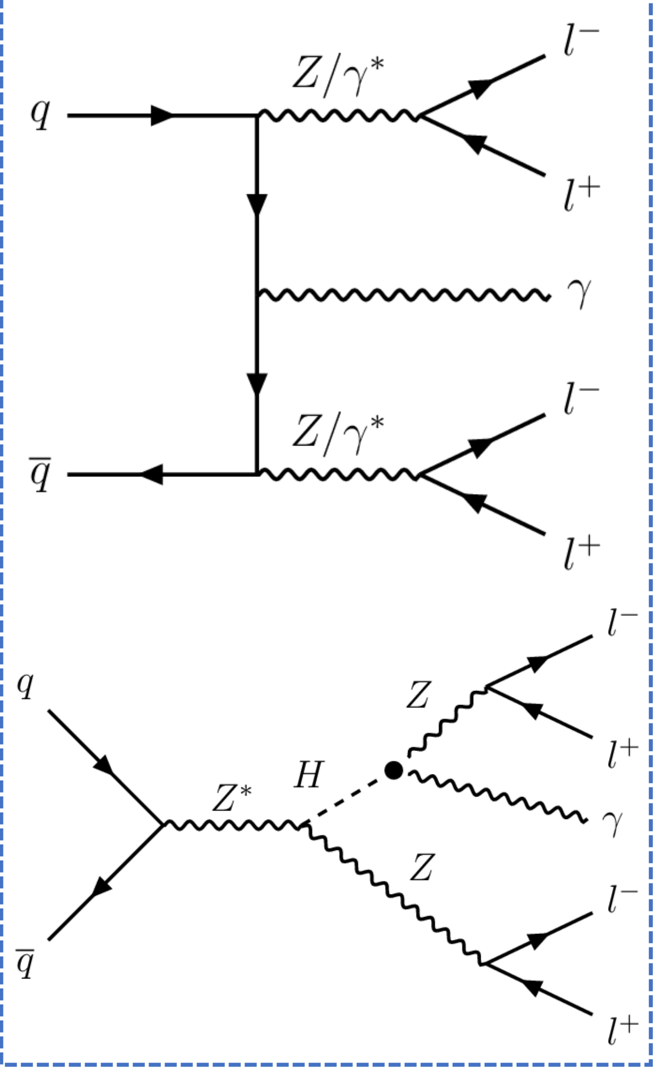
$m_{\ell\ell\gamma} + m_{\ell\ell} > 2m_Z$

Not Signal





Signal Definition



Evidence of $ZZ\gamma \to \ell\ell\ell\ell\gamma$ with $\ell = e$ or μ

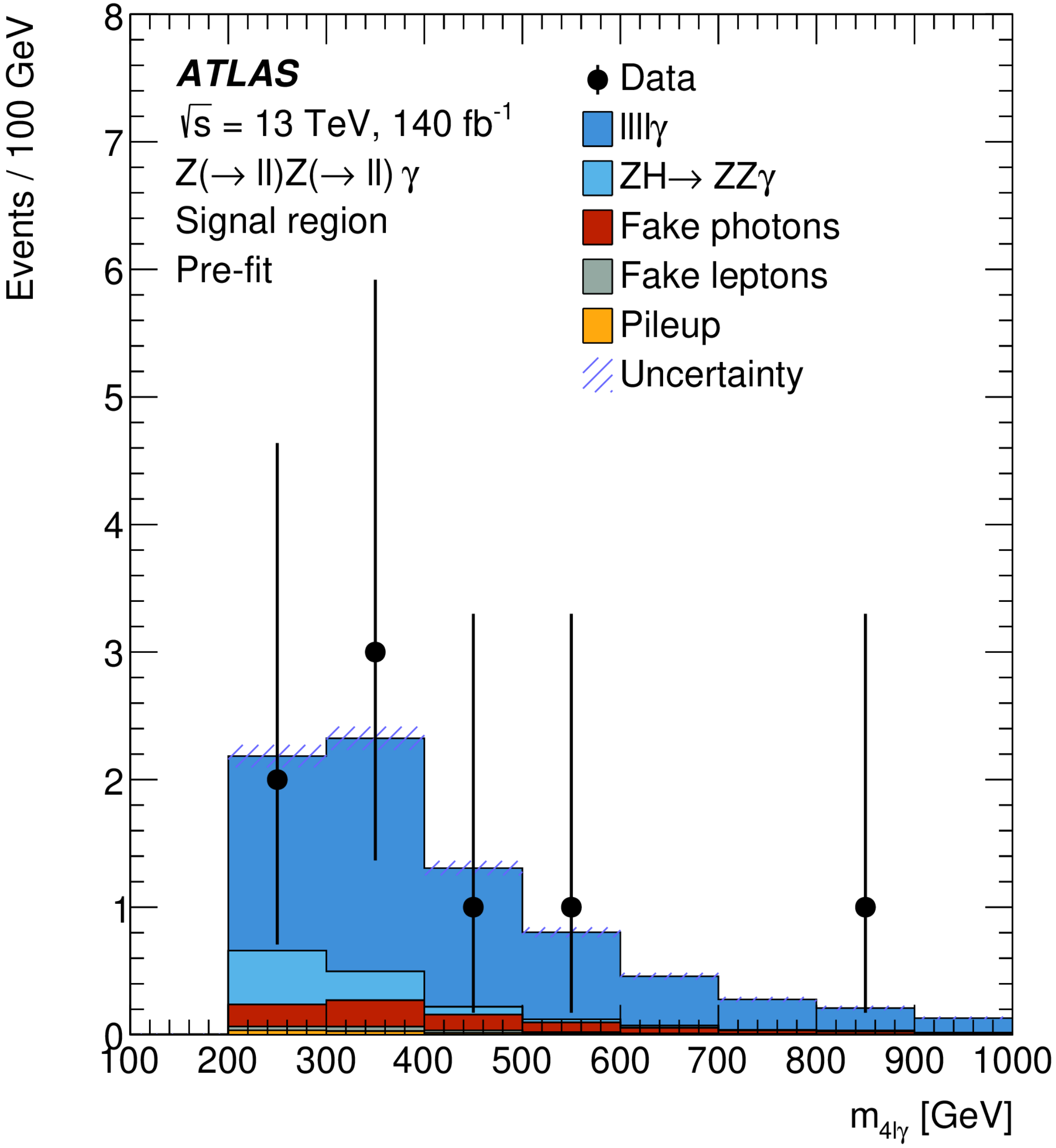
- Same flavour opposite sign lepton pairs (OSSF pairs) compatible with Z boson mass
- High signal purity
- Main background is fake photons and fake leptons
- Profile likehood fit combining three channels: $4e, 2e2\mu, 4\mu$
- Measurement of the *fitted* signal strength is statically limited

$$\mu_{ZZ\gamma} = 1.01\ ^{+0.45}_{-0.36}\,(\text{stat.})\ ^{+0.05}_{-0.03}\,(\text{syst.})$$

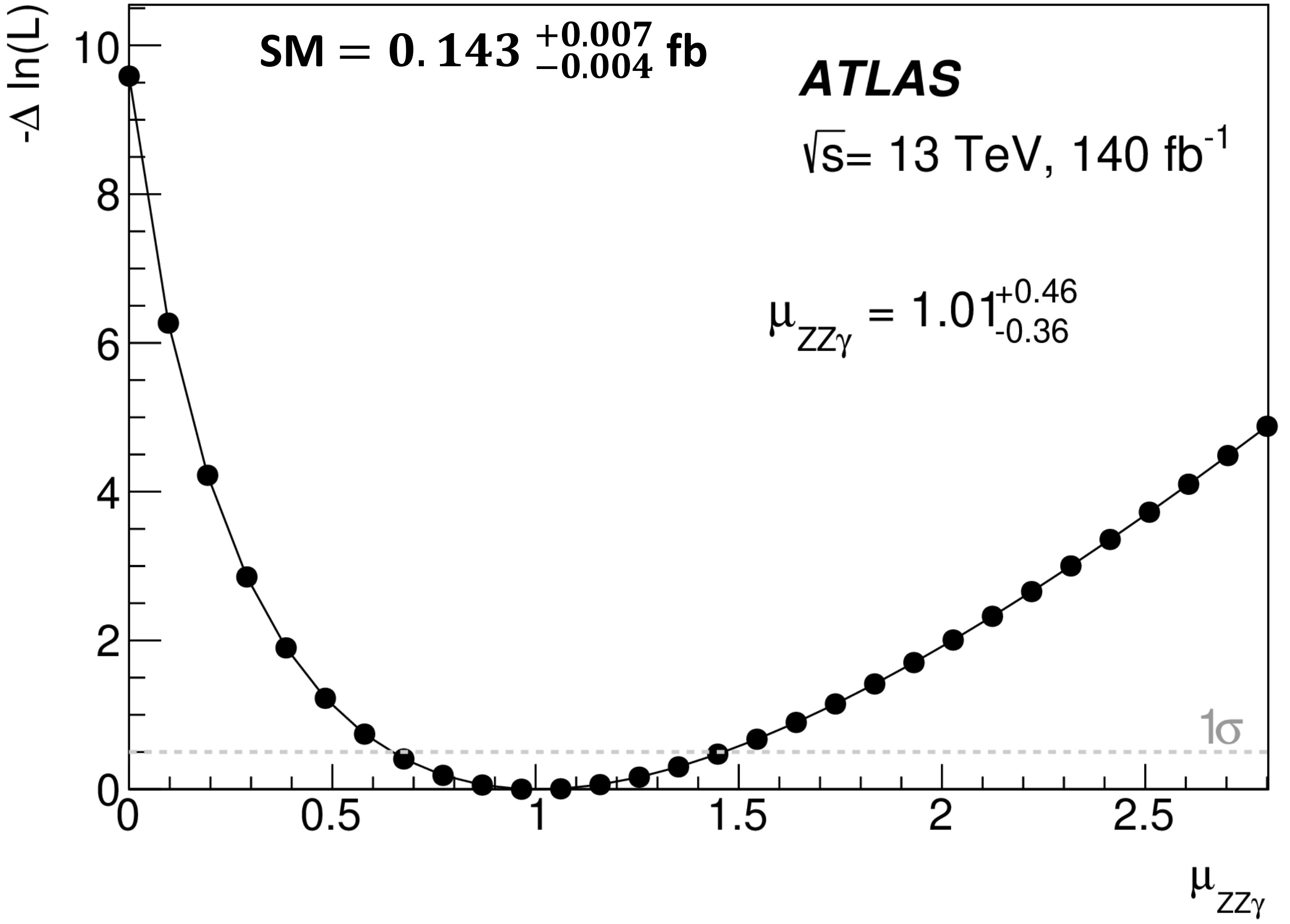
	Electrons	Muons	Photon
Trigger	single and dilepton trigger		–
Multiplicity	≥ 2 OSSF pairs		≥ 1 photon
Kinematics	$p_T > 30, 25, 10, 10\,\text{GeV}$		$p_T > 20\,\text{GeV}$
	$\lvert\eta\rvert < 2.47$	$\lvert\eta\rvert < 2.5$	$\lvert\eta\rvert < 2.37$
Excluded	$1.37 < \lvert\eta\rvert < 1.52$	–	$1.37 < \lvert\eta\rvert < 1.52$

	Number of events
SHERPA 2.2.11 $4\ell\gamma$	6.28 ± 0.09 (stat.) ± 0.18 (syst.)
POWHEG+PYTHIA8 $ZH \to ZZ\gamma$	0.76 ± 0.03 (stat.) ± 0.03 (syst.)
Signal	7.04 ± 0.09 (stat.) ± 0.18 (syst.)
Fake photons	0.71 ± 0.02 (stat.) ± 0.13 (syst.)
Fake leptons	0.12 ± 0.02 (stat.) ± 0.08 (syst.)
Pileup	0.09 ± 0.002 (stat.) ± 0.02 (syst.)
Total background	0.92 ± 0.03 (stat.) ± 0.15 (syst.)
N_{tot} prediction	7.96 ± 0.09 (stat.) ± 0.23 (syst.)
$\boldsymbol{N_{\text{tot}}}$ **data**	8

Evidence of $ZZ\gamma \to \ell\ell\ell\ell\gamma$ with $\ell = e$ or μ



$$\sigma_{\text{fid}} = 0.144\ ^{+0.064}_{-0.051}\ (\text{stat.})\ ^{+0.007}_{-0.005}\ (\text{syst.})\ \text{fb}$$



Summary

Today: a suite of full Run-2 ATLAS results on multibosons!

Physics only accessible due to large dataset acquired at Run-2

Conclusion: pp → $VV, VVjj$ and VVV topologies provide:

- ➢ Exploration of data for EWK and QCD processes: tuning MC Generators
- ➢ Self-couplings of the vector gauge bosons:
  - ✓ **All anomalous couplings reported today are consistent with zero**

✓ **Triboson: 4.4σ evidence established for $ZZ\gamma$**

✓ Focus shifting to differential cross section measurements: $W\gamma$ and ZZ & $ZZjj$

✓ **Fiducial and differential cross sections are the most model independent** characterization of the events (detector to particle-level fiducial phase space)

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Thank You! Any questions?

My institute and collaboration

Carleton UNIVERSITY

ATLAS EXPERIMENT

My funding in Canada

NSERC CRSNG

INNOVATION

Canada Foundation for Innovation

Fondation canadienne pour l'innovation

Extra backup slides

More on EFT <u>Thursday</u> by Lydia Brenner

EFT measurements in ATLAS