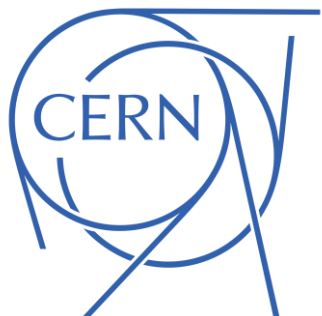




Multiboson measurements in ATLAS

Zihan Zhao (USTC)

on behalf of the ATLAS Collaborations

QCD@LHC | Oct 1st 2026 | University of Oxford

Multiboson physics

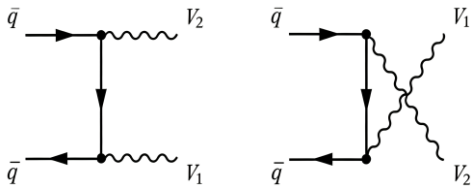
- Test several layers of the Standard Model (SM) and probe for potential physics beyond

Precision Predictions

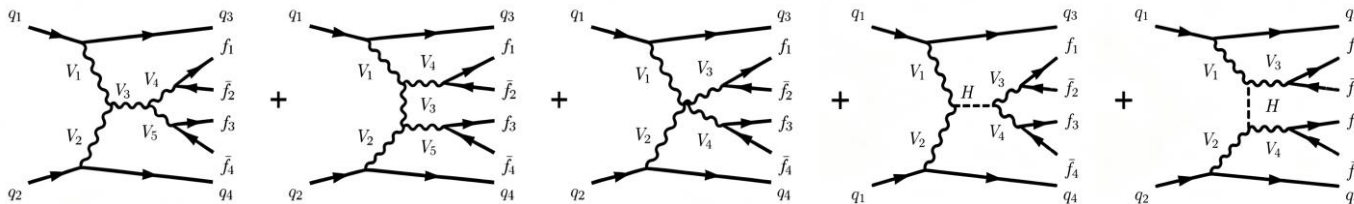
Higher-order QCD/EW calculations
Parton Distribution Functions (PDFs)

Electroweak Gauge Structure

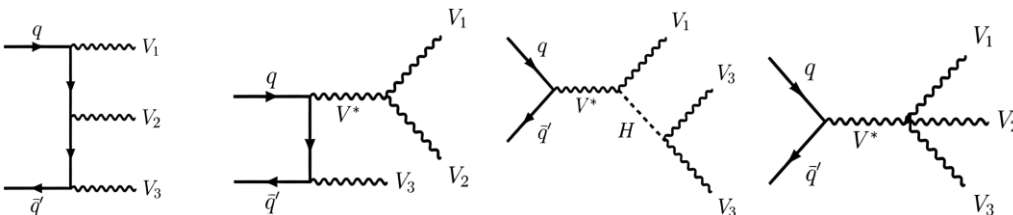
Vector Boson Scattering (VBS), EWSB & unitarity
Anomalous Triple/Quartic Gauge Couplings (aTGC/aQGC)



Diboson



VBS/+jets



Tribosons

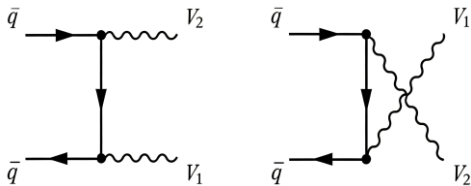
Multiboson measurements

- Three measurements using the full ATLAS Run2 140 fb^{-1} $\sqrt{s} = 13 \text{ TeV}$ proton-proton collision dataset:

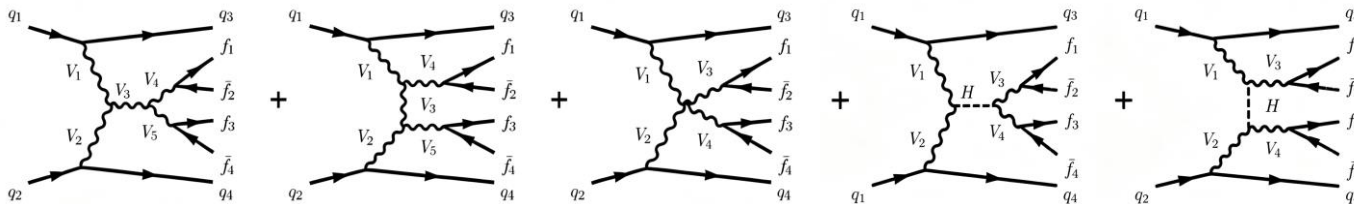
Inclusive $W\gamma$

$ZZ / ZZjj$

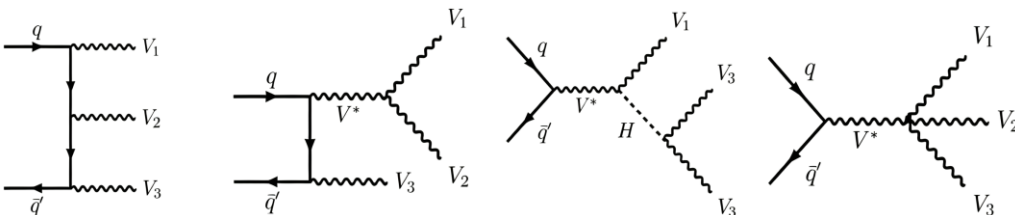
Evidence of $ZZ\gamma$



Diboson



VBS/+jets

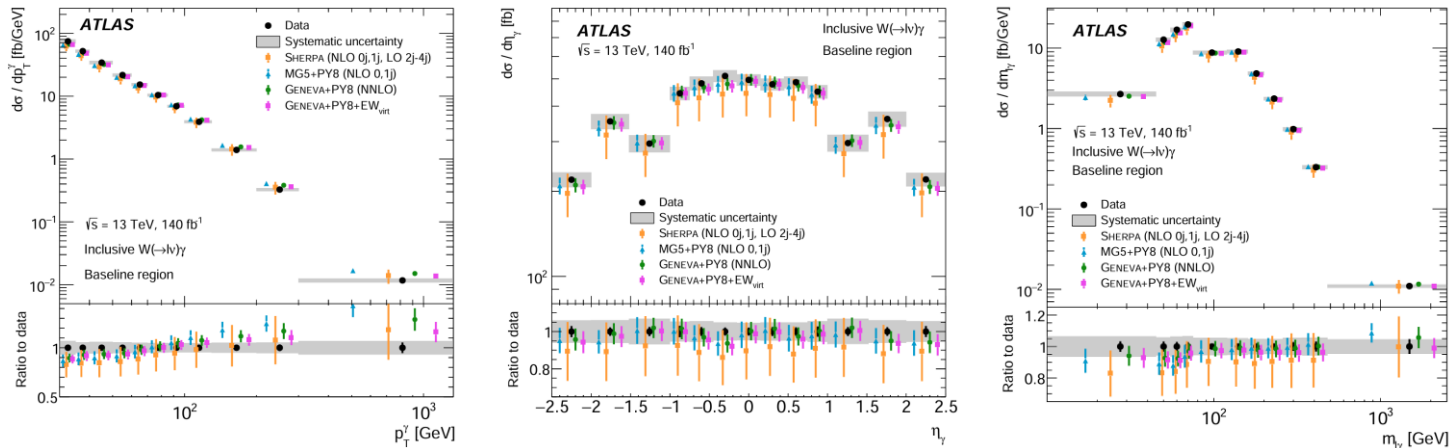
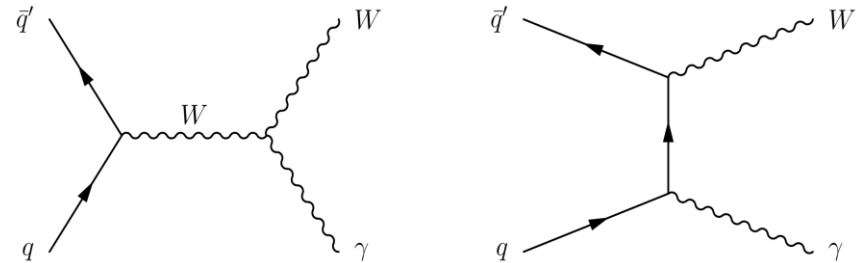


Tribosons

Inclusive $W\gamma$ production

arXiv:2603.22478
EPJC Accepted

- Measurement at 13 TeV with 140 fb^{-1} pp data
- Signal process: $pp \rightarrow W^\pm \gamma \rightarrow e\nu/\mu\nu + \gamma$
- Phase space: $p_T^{l/\gamma} > 30 \text{ GeV}$, $E_T^{\text{miss}} > 40 \text{ GeV}$,
 $m_{l\gamma} < 81 \text{ GeV}$ or $m_{l\gamma} > 101 \text{ GeV}$, $\Delta R_{l\gamma} > 0.8$
- **4 non-prompt backgrounds** estimated via data-driven methods: jet faking photon, jet faking lepton, electron faking photon and photon from pile-up
- **Differential Cross-Sections:**



NNLO QCD + **NLO EW virtual**: the prediction gives the best agreement with data
 play a crucial role at high momentum



Inclusive $W\gamma$ production

arXiv:2603.22478
EPJC Accepted

- Radiation Amplitude Zero (RAZ) effect @LO in QCD

Cancellation at tree-level of
s- and t-channels



The dip↓ at $|\Delta\eta_{l\gamma}| = 0$

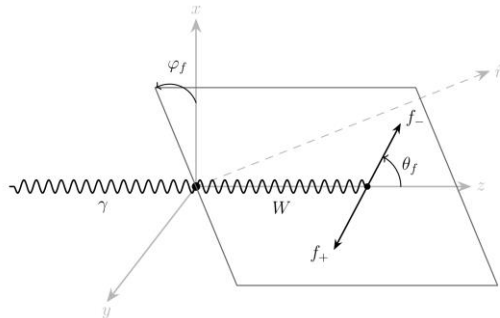
- Polarisation-sensitive observable

$W \rightarrow l\nu$ decay angles (θ_f, ϕ_f)
 (ϕ_f, p_T^Y)

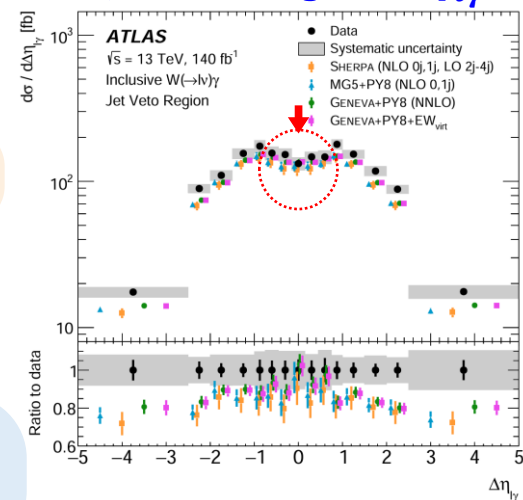
provide direct sensitivity to the
 W boson spin-density matrix

Access helicity interference

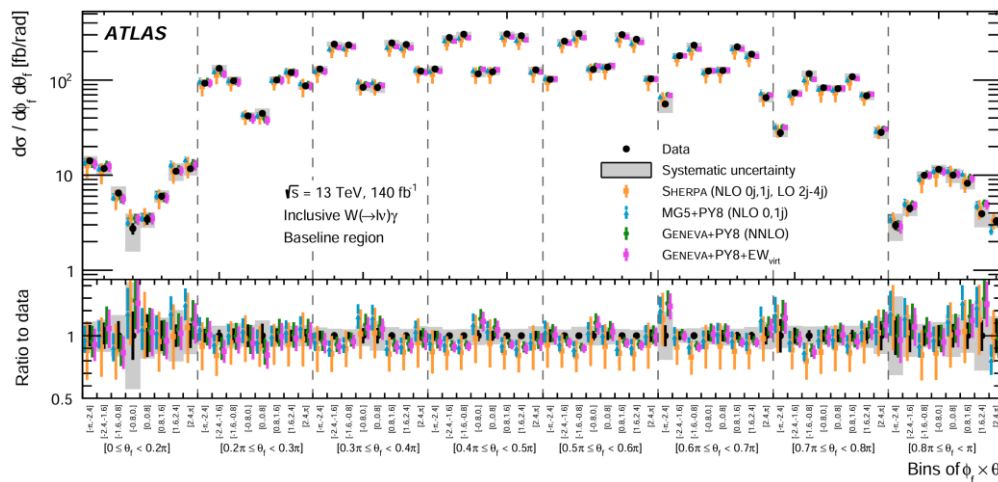
Could enhance EFT sensitivity



Jet Veto Region $\Delta\eta_{l\gamma}$



(θ_f, ϕ_f)



CP sensitivity

- SMEFT interference leads to asymmetries in **CP-odd** observables, dimension-6: $\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \tilde{\mathcal{O}}_i$

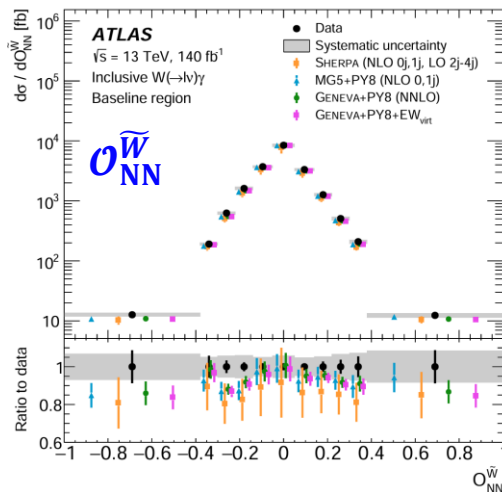
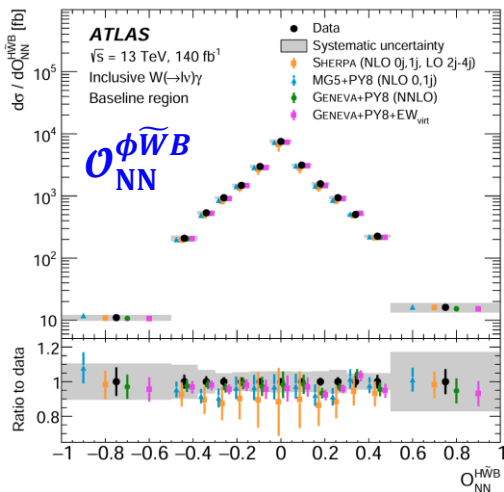
$W\gamma$ process sensitive to

$$\begin{aligned}\tilde{\mathcal{O}}_{\tilde{W}} &= \varepsilon_{ijk} \tilde{W}_{\mu\nu}^i W^{j\nu\rho} W_{\rho}^k{}^\mu, \\ \tilde{\mathcal{O}}_{\Phi\tilde{B}} &= \Phi^\dagger \Phi B^{\mu\nu} \tilde{B}_{\mu\nu}, \\ \tilde{\mathcal{O}}_{\Phi\tilde{W}} &= \Phi^\dagger \Phi W^{i\mu\nu} \tilde{W}_{\mu\nu}^i, \\ \tilde{\mathcal{O}}_{\Phi\tilde{W}B} &= \Phi^\dagger \sigma^i \tilde{W}^{i\mu\nu} B_{\mu\nu}.\end{aligned}$$

$\mathcal{O}_{\phi\tilde{W}B}$ and $\mathcal{O}_{\tilde{W}}$ CP violation operators affecting Higgs/multiboson interactions

$$|\mathcal{M}_{\text{BSM}}|^2 = |\mathcal{M}_{\text{SM}}|^2 + \boxed{2\text{Re}\{\mathcal{M}_{\text{SM}}\mathcal{M}_{\text{d6}}^*\}} + |\mathcal{M}_{\text{d6}}|^2$$

- Neural-network-based CP-odd observable [[arXiv:2209.05143](https://arxiv.org/abs/2209.05143), [Phys. Lett. B 832 \(2022\) 137246](https://arxiv.org/abs/2209.05143)]



Wilson coefficient	Observable	Includes $ \mathcal{M}_{\text{d6}} ^2$	k -factor	95% CL [TeV^{-2}]	
				Expected	Observed
$c_{H\tilde{W}B}/\Lambda^2$	$\mathcal{O}_{\tilde{W}B}^{H\tilde{W}B}$	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	$[-0.20, 0.21]$	$[-0.31, 0.07]$

Limits on $c_{H\tilde{W}B}$ factor 2.5 better than previous measurements using other final states.

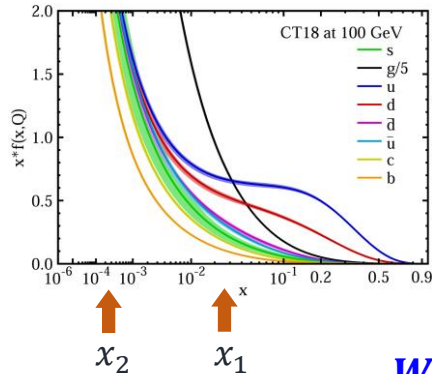


Inclusive $W\gamma$ production

PDF sensitivity: the Diboson Boost Asymmetry

Phys. Rev. D 106, L051301 (2022)

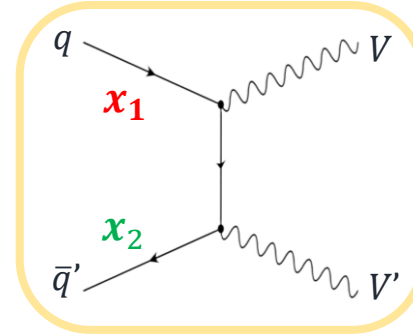
@LHC: $x_{1(\text{larger})} \sim \mathcal{O}(10^{-3})$ to 0.1
 $x_{2(\text{smaller})} \sim \mathcal{O}(10^{-4})$ to $\mathcal{O}(10^{-3})$



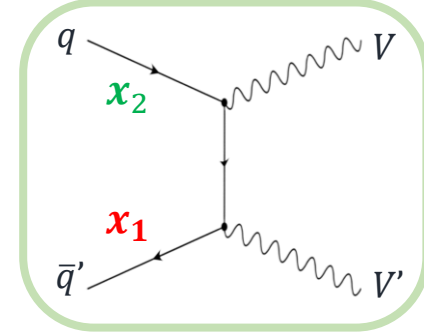
$$x_{1,2} = \frac{\sqrt{Q_T^2 + M^2}}{\sqrt{s}} \cdot e^{\pm|Y|} \quad ? \rightarrow$$

The mix of x_1/x_2
 The mix of QCD information

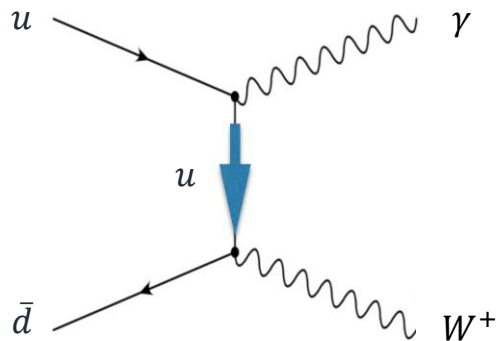
diboson



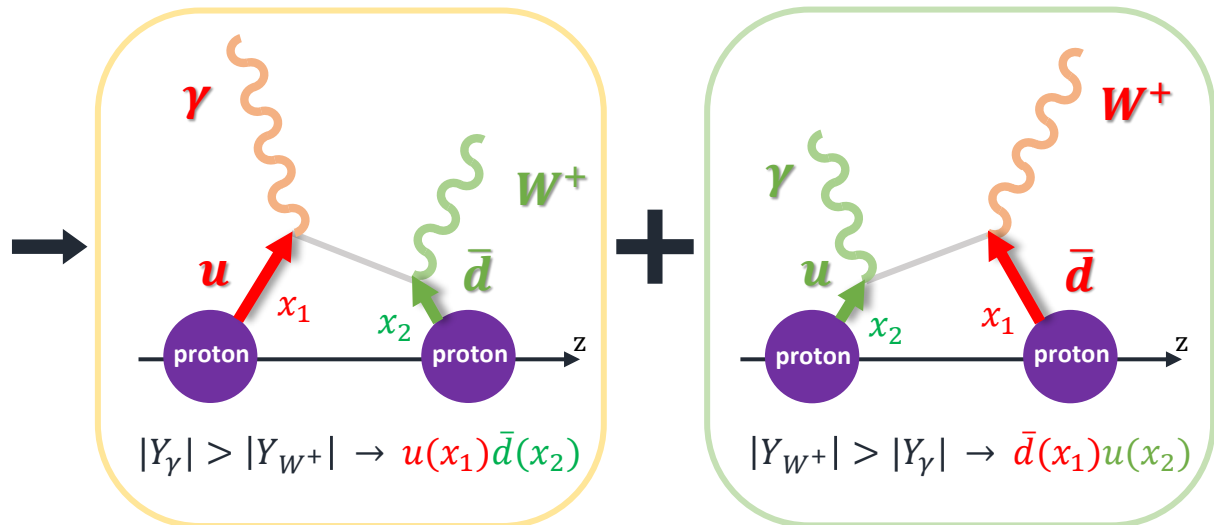
vs



$W^+\gamma$ Boost Asymmetry: $A_{\text{boost}}^{W^+\gamma} = \frac{N(|\eta_\gamma| > |\eta_{l^+}|) - N(|\eta_\gamma| < |\eta_{l^+}|)}{N(|\eta_\gamma| > |\eta_{l^+}|) + N(|\eta_\gamma| < |\eta_{l^+}|)}$



$Q_u^2 = 4 \times Q_d^2$:
 γ preferentially couples to u



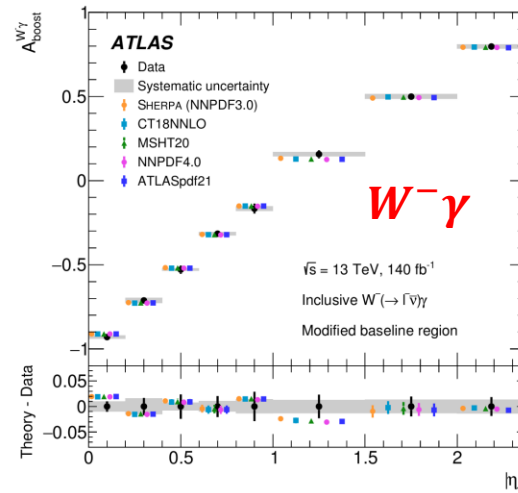
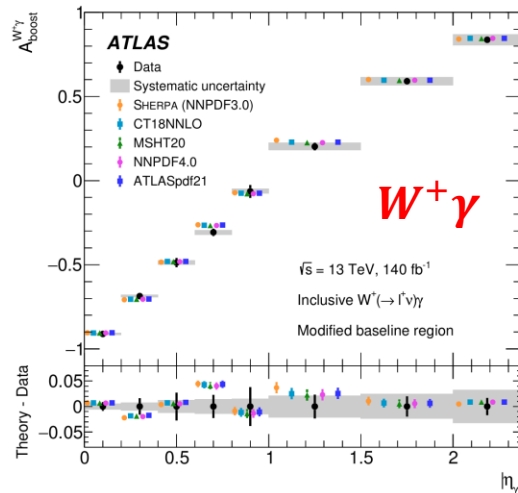
PDF sensitivity: the Diboson Boost Asymmetry

$$A_{\text{boost}}^{W^\pm\gamma} = \frac{N(|\eta_\gamma| > |\eta_{\ell^\pm}|) - N(|\eta_\gamma| < |\eta_{\ell^\pm}|)}{N(|\eta_\gamma| > |\eta_{\ell^\pm}|) + N(|\eta_\gamma| < |\eta_{\ell^\pm}|)}$$

	$ \eta_\gamma > \eta_l $	$ \eta_\gamma < \eta_l $
$W^+\gamma$	$u(x_1)\bar{d}(x_2)$	$\bar{d}(x_1)u(x_2)$
$W^-\gamma$	$\bar{u}(x_1)d(x_2)$	$d(x_1)\bar{u}(x_2)$

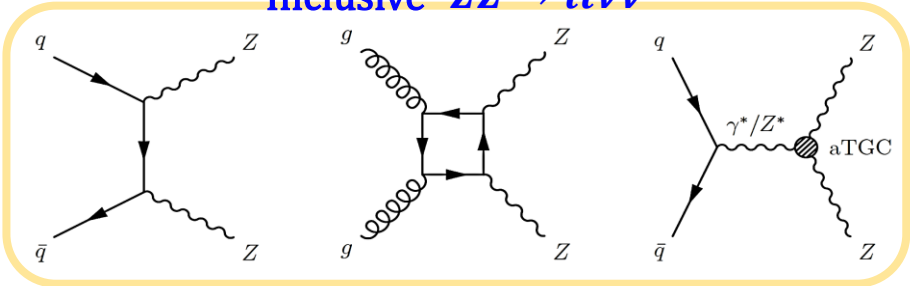
$$A_{\text{boost}}^{W^+\gamma} = 0.033 \pm 0.012(\text{stat.}) \pm 0.009(\text{sys.}) \pm 0.003(\text{th.})$$

$$A_{\text{boost}}^{W^-\gamma} = -0.091 \pm 0.012(\text{stat.}) \pm 0.017(\text{sys.}) \pm 0.002(\text{th.})$$



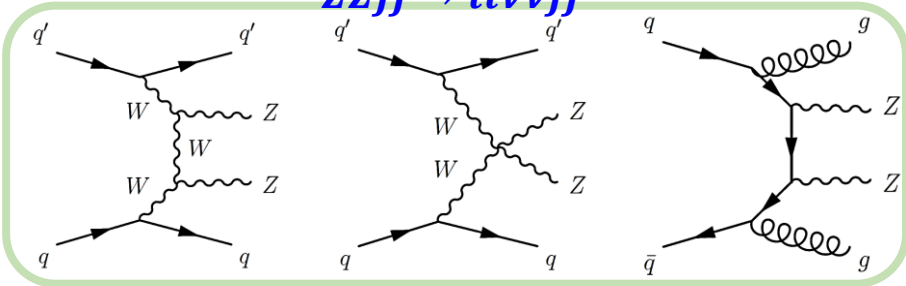
$ZZ \rightarrow ll\nu\nu$ and $ZZjj \rightarrow ll\nu\nu jj$ production

Inclusive $ZZ \rightarrow ll\nu\nu$



a sensitive probe of neutral aTGCs

$ZZjj \rightarrow ll\nu\nu jj$



(a)QGCs

Physics motivation

- Precision test of the SM through total and differential ZZ cross-sections
- Probe for BSM phenomena
- $2l2\nu$ is complementary to $4l$, but with a larger branching ratio and higher EFT sensitivity

Event Selection	Cut	$ZZ \rightarrow ll\nu\nu$	$ZZjj \rightarrow ll\nu\nu jj$
		Inclusive Requirement	VBS-like Requirement
Event Preselection	Trigger Vertex	Fire at least one lepton trigger At least one vertex with 2 or more tracks	Fire at least one lepton trigger At least one vertex with 2 or more tracks
Selection Pair Requirement	leading and subleading lepton p_T	30 GeV, 20 GeV	30 GeV, 20 GeV
	SFOS lepton pair	SFOS lepton pair	SFOS lepton pair
		$80 < m_{ll} < 100\text{GeV}$	$80 < m_{ll} < 100\text{GeV}$
	MET	$> 110\text{GeV}$	$> 150\text{GeV}$
	$\Delta R(l, l)$	< 1.8	< 1.8
	$\Delta\Phi(Z, MET)$	> 2.2	> 2.2
	ET_{miss}/HT	> 0.65	> 0.65
	b-jets	$= 0$	$= 0$
	$p_T^{lead.jet}$ and $p_T^{subleading jet}$	-	$> 30\text{GeV}$

- Measurement at 13 TeV with $140\text{ fb}^{-1} pp$ data



$ZZ \rightarrow ll\nu\nu$ and $ZZjj \rightarrow ll\nu\nu jj$ production

arXiv:2511.15569
EPJC Accepted

Cross-Sections

- Simultaneous profile-likelihood fit in SRs and CRs

Signal strength parameters

Background normalisation factors

- Statistical uncertainty dominant

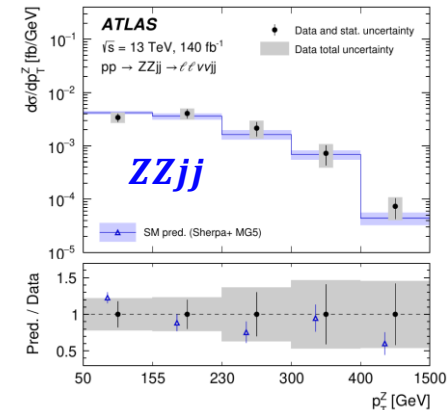
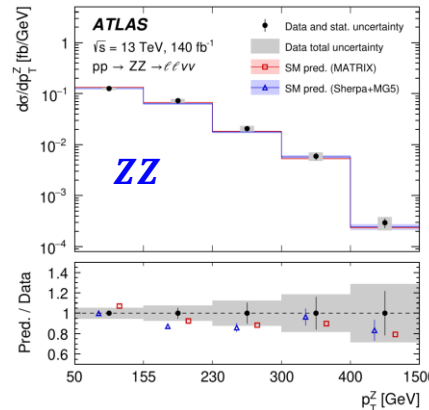
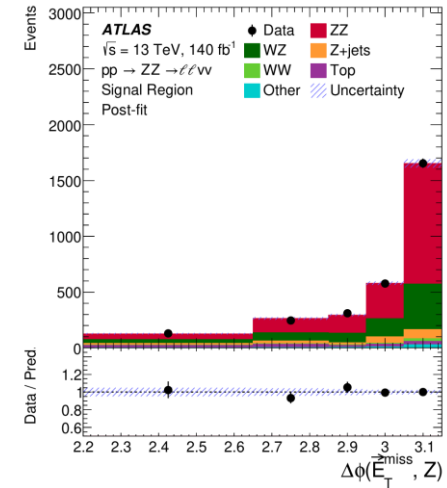
$$\sigma_{ZZ}^{\text{fid}} = 21.03 \pm 0.73 (\text{stat}) \pm 0.57 (\text{exp}) \pm 0.18 (\text{theory}) \pm 0.18 (\text{lumi}) \text{ fb}$$

- Total cross-sections

	ZZ	$ZZjj$
Measured	$21.0 \pm 1.0 \text{ fb}$	$0.96^{+0.18}_{-0.16} \text{ fb}$
SHERPA+MADGRAPH5	$20.1 \pm 1.1 \text{ fb}$	$0.94 \pm 0.20 \text{ fb}$
MATRIX	$21.03 \pm 0.30 \text{ fb}$	

- Differential cross-sections
- Good agreement with SM

Post-fit $\Delta\phi(\vec{E}_T^{\text{miss}}, Z)$



ZZ → llνν and ZZjj → llννjj production ZZ

arXiv:2511.15569
EPJC Accepted

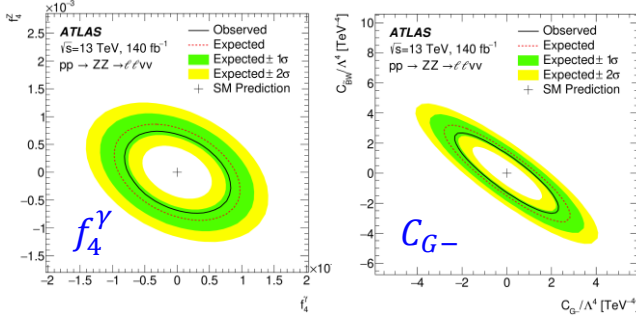
Probing anomalous gauge boson self-interaction couplings

aTGC

- Vertex Function approach $g_{ZZV}\Gamma_{ZZV}^{\alpha\beta\mu} = e \frac{P^2 - m_V^2}{m_Z^2} [if_4^V(P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}) + if_5^V \epsilon^{\mu\alpha\beta\rho}(q_1 - q_2)_\rho]$

p_T^Z
in llνν SR

- SMEFT approach $\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(8)}}{\Lambda^4} \mathcal{O}_i^{(8)}$



Improving previous
results in this final
state by a factor of 1.7

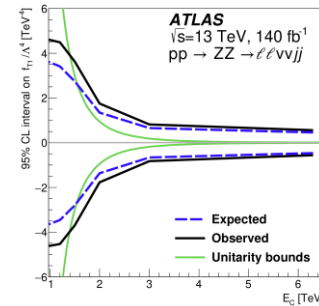
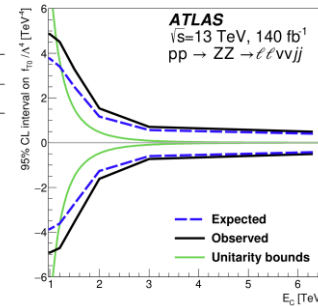
Coefficient	Expected	Observed
f_4^Y	$[-7.7, 7.7] \times 10^{-4}$	$[-6.4, 6.4] \times 10^{-4}$
f_4^Z	$[-6.8, 6.8] \times 10^{-4}$	$[-5.7, 5.7] \times 10^{-4}$
f_5^Y	$[-7.8, 7.7] \times 10^{-4}$	$[-6.4, 6.5] \times 10^{-4}$
f_5^Z	$[-6.9, 6.9] \times 10^{-4}$	$[-5.8, 5.8] \times 10^{-4}$
C_{G+}/Λ^4 [TeV ⁻⁴]	$[-0.36, 0.36]$	$[-0.29, 0.30]$
C_{G-}/Λ^4 [TeV ⁻⁴]	$[-1.1, 1.2]$	$[-0.95, 0.95]$
C_{BW}/Λ^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]	$[-2.4, 2.4]$	$[-2.0, 2.0]$

aQGC

- dim-8 Wilson coefficients

m_T^{ZZ}
in llννjj SR

Wilson Coefficient	No cut-off		$E_c = 1$ TeV		$E_c = 1.5$ TeV	
[TeV ⁻⁴]	Expected	Observed	Expected	Observed	Expected	Observed
f_{T0}/Λ^4	$[-0.42, 0.40]$	$[-0.50, 0.49]$	$[-3.9, 3.8]$	$[-4.9, 4.9]$	$[-2.8, 2.6]$	$[-4.0, 3.4]$
f_{T1}/Λ^4	$[-0.46, 0.46]$	$[-0.56, 0.56]$	$[-3.7, 3.6]$	$[-4.6, 4.6]$	$[-2.9, 2.8]$	$[-3.8, 3.8]$
f_{T2}/Λ^4	$[-0.95, 0.93]$	$[-1.1, 1.1]$	$[-7.7, 7.6]$	$[-9.8, 9.7]$	$[-5.9, 5.6]$	$[-7.7, 7.4]$
f_{T3}/Λ^4	$[-1.3, 1.3]$	$[-1.6, 1.6]$	$[-9.9, 9.9]$	$[-13, 13]$	$[-7.7, 7.4]$	$[-10, 9.7]$
f_{T4}/Λ^4	$[-8.8, 8.5]$	$[-11, 11]$	$[-55, 54]$	$[-69, 69]$	$[-43, 41]$	$[-56, 53]$
f_{T5}/Λ^4	$[-0.75, 0.71]$	$[-0.89, 0.87]$	$[-6.9, 6.7]$	$[-8.7, 8.6]$	$[-4.8, 4.4]$	$[-6.2, 5.8]$
f_{T6}/Λ^4	$[-1.1, 1.1]$	$[-1.4, 1.4]$	$[-6.9, 6.9]$	$[-8.9, 8.9]$	$[-5.4, 5.3]$	$[-7.1, 7.0]$
f_{T7}/Λ^4	$[-2.5, 2.4]$	$[-3.0, 3.0]$	$[-14, 14]$	$[-18, 18]$	$[-12, 12]$	$[-17, 16]$
f_{T8}/Λ^4	$[-0.60, 0.60]$	$[-0.74, 0.74]$	$[-6.7, 6.7]$	$[-8.7, 8.7]$	$[-3.8, 3.8]$	$[-4.9, 4.9]$
f_{T9}/Λ^4	$[-1.3, 1.3]$	$[-1.6, 1.6]$	$[-14, 14]$	$[-18, 18]$	$[-7.9, 7.9]$	$[-10, 10]$

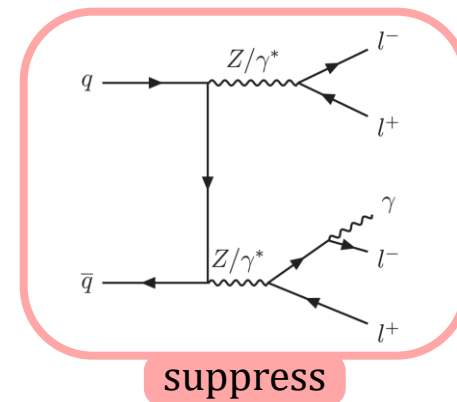
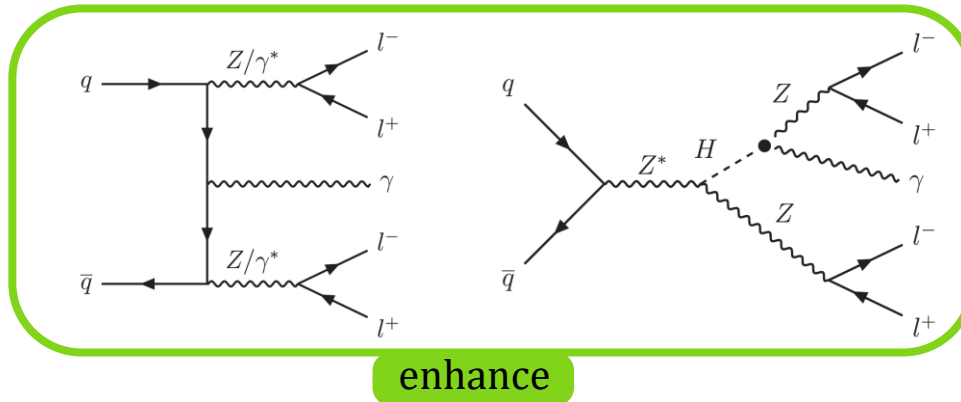


Improved by a factor of 2-3 relative to 4ljj channel due to larger statistics



Evidence of $ZZ\gamma$ production

[PRL 137 \(2026\) 091804](#)



$(m_{\ell\ell\gamma} + m_{\ell\ell}) > 2 \cdot m_Z$
FSR (considered to be ZZ)

$$ZZ\gamma \rightarrow l^+l^-l'^+l'^-\gamma$$

- Measurement at 13 TeV with 140 fb^{-1} pp data
- First evidence of $pp \rightarrow ZZ\gamma$: very rare process with two massive bosons
- Data-driven estimation of dominant non-prompt photon background (jet faking gamma), and misidentified lepton background (jet faking leptons)
- Profile likelihood fit to extract signal strength and its uncertainty

Evidence of $ZZ\gamma$ production

[PRL 137 \(2026\) 091804](#)

- Clean signature with ~ 7 signal events and 1 background event
- Measured cross section:

$$\sigma_{ZZ\gamma} = 0.144^{+0.065}_{-0.051}(\text{stat.})^{+0.008}_{-0.004}(\text{syst.}) \text{ fb}$$

and the predicted SM fiducial cross section of $pp \rightarrow l^+ l^- l'^+ l'^- \gamma$ is

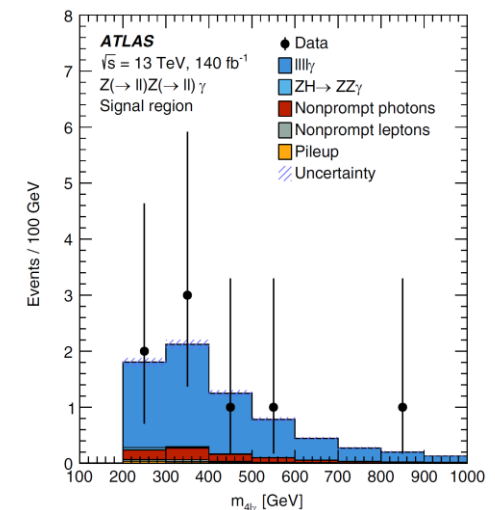
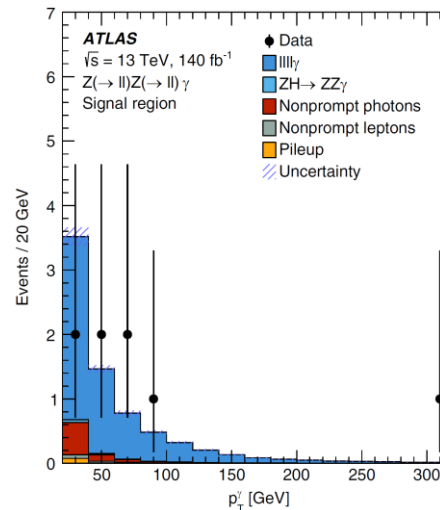
$$\sigma_{\text{fid}}^{\text{SM}} = 0.130 \pm 0.001(\text{stat.}) \pm 0.002(\text{PDF}+\alpha_S) \pm 0.005(\text{scale}) \text{ fb}$$

Observed (expected)
significance:

$$4.4(4.0) \sigma$$

[NLO QCD and LO EW]

	Number of events
Signal	$6.36 \pm 0.09(\text{stat}) \pm 0.18(\text{syst})$
Nonprompt photons	$0.71 \pm 0.02(\text{stat}) \pm 0.13(\text{syst})$
Nonprompt leptons	$0.12 \pm 0.02(\text{stat}) \pm 0.08(\text{syst})$
Pileup	$0.09 \pm 0.002(\text{stat}) \pm 0.02(\text{syst})$
Total background	$0.92 \pm 0.03(\text{stat}) \pm 0.15(\text{syst})$
N_{tot} prediction	$7.28 \pm 0.09(\text{stat}) \pm 0.23(\text{syst})$
N_{tot} data	8



- Outlook: perform Run2+3 analysis to achieve $>5\sigma$ significance and aQGC studies



Summary

ATLAS Run2 140 fb⁻¹ :

Evidence of $ZZ\gamma$

~ 7 signal events

First evidence



~ 1700 signal events

$ZZ / ZZjj$

~ 110 signal events

aTGC, aQGC,
EFT constraints



~ 150000 signal events

Inclusive $W\gamma$

QCD differentials,
PDFs,
W polarization,
EFT constraints

- From rare-process evidence to precision measurements
- Future key challenge: Systematic uncertainties (e.g. balance background rejection against signal efficiency in $W\gamma$ measurement), Continued understanding of photon isolation treatment at particle level...
- OUTLOOK:
Run 3 & HL-LHC → higher statistics + new techniques and new observables → more precise differential measurements → SM / BSM (EFT) sensitivity

Backup

unique PDF information from Boost Asymmetry

Phys. Rev. D 106, L051301 (2022)

Valence quark
@ smaller x_2 region

Sea quark
@ larger x_1 region

