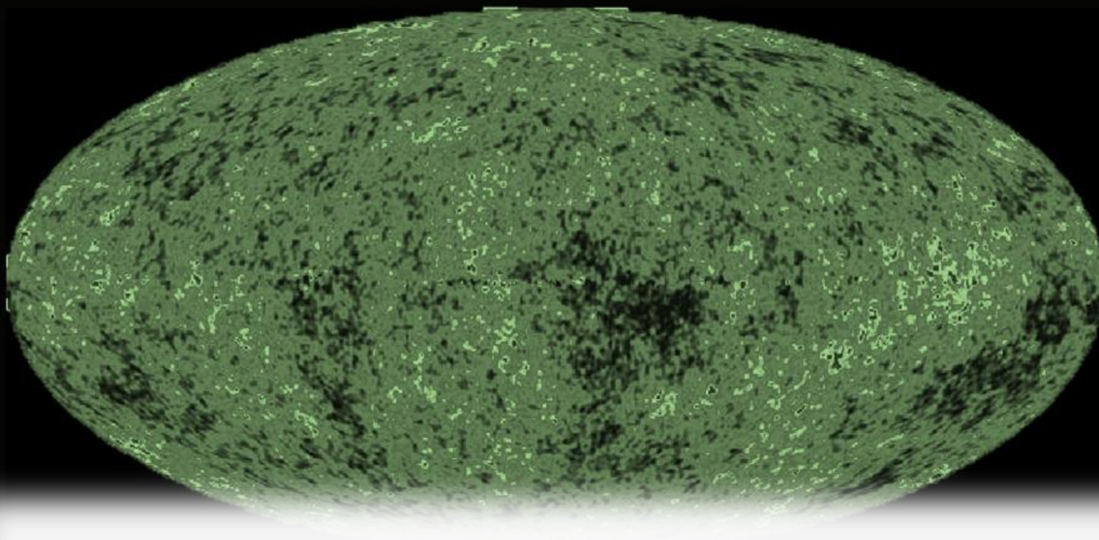
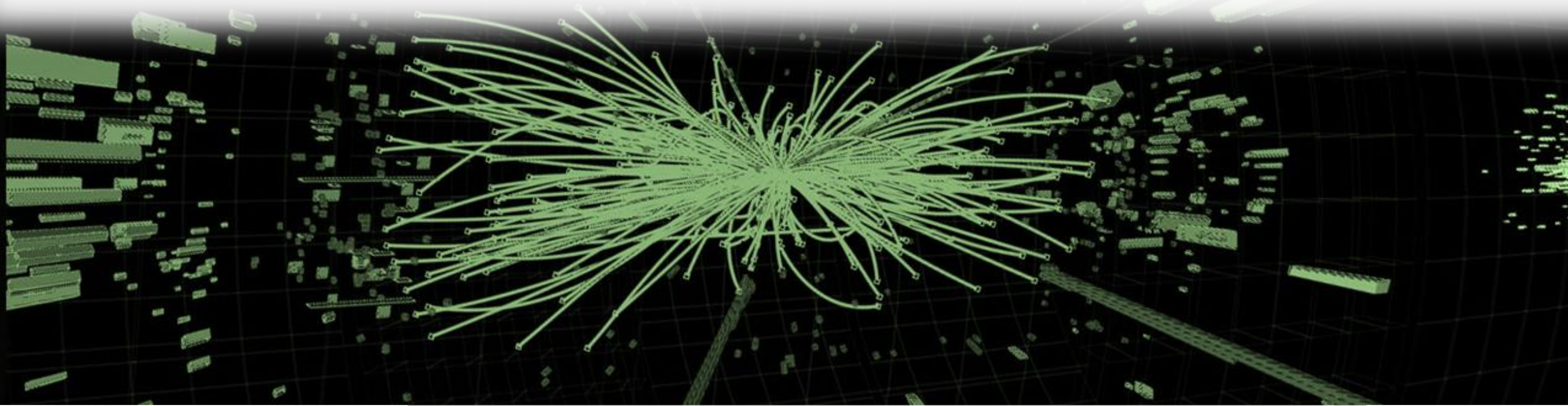


Measurements of multi-boson production including vector-boson scattering at ATLAS



Oleg Kuprash,

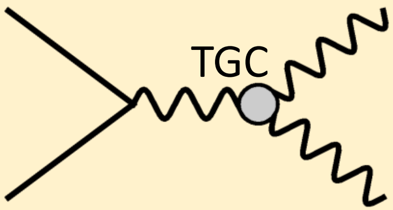
on behalf of the ATLAS Collaboration

32^{nd} Rencontres de Blois

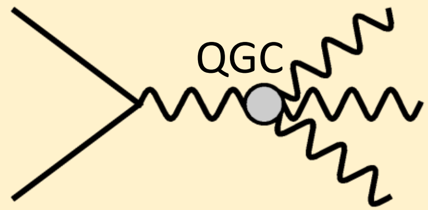
Introduction

Multibosons

Two or more electroweak bosons V: W, Z, γ



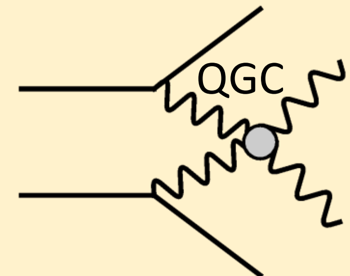
Dibosons



Tribosons

Vector boson scattering

$VV \to VV$



VBS

Signature: VVjj

Why measure multibosons & VBS:

- Test the Standard Model predictions for gauge boson self-interactions and electroweak (EW) symmetry breaking with the Higgs mechanism
- Study for deviations from the Standard Model
  - ➢ Typically parametrized using Effective Field Theory (EFT)

$$L_{\mathrm{EFT}} = L_{\mathrm{SM}} + \sum_i \frac{\bar{C}_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{\bar{C}_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \ldots$$

  - ➢ Expect high sensitivity for operators generating anomalous triple (TGC) and quartic (QGC) gauge couplings

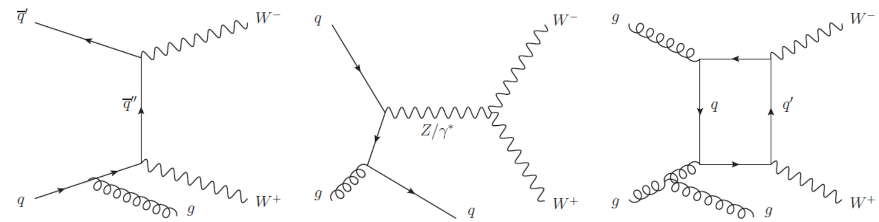
Outline

- Recent ATLAS full Run 2 (139 fb^{-1}) based measurements using *pp* data at 13 TeV:
  - $W^+W^- + \geq 1$ jet, JHEP 06 (2021) 003
  - Four-lepton differential (ZZ), JHEP 07 (2021) 005
  - Observation of WWW, ATLAS-CONF-2021-039
  - $Z(\rightarrow ll)\gamma\, jj$ electroweak, ATLAS-CONF-2021-038
  - $Z(\rightarrow \nu\nu)\gamma\, jj$ electroweak, arXiv:2109.00925, submitted to EPJC
- Combined EFT interpretation of WW, WZ, four-lepton, and Zjj VBF cross sections, ATL-PHYS-PUB-2021-022

WW + ≥1 jet

JHEP 06 (2021) 003

$e^{\pm}\mu^{\mp}, m(e\mu) > 85$ GeV
b-jet veto (20 GeV)
>=1 jet (35 GeV)



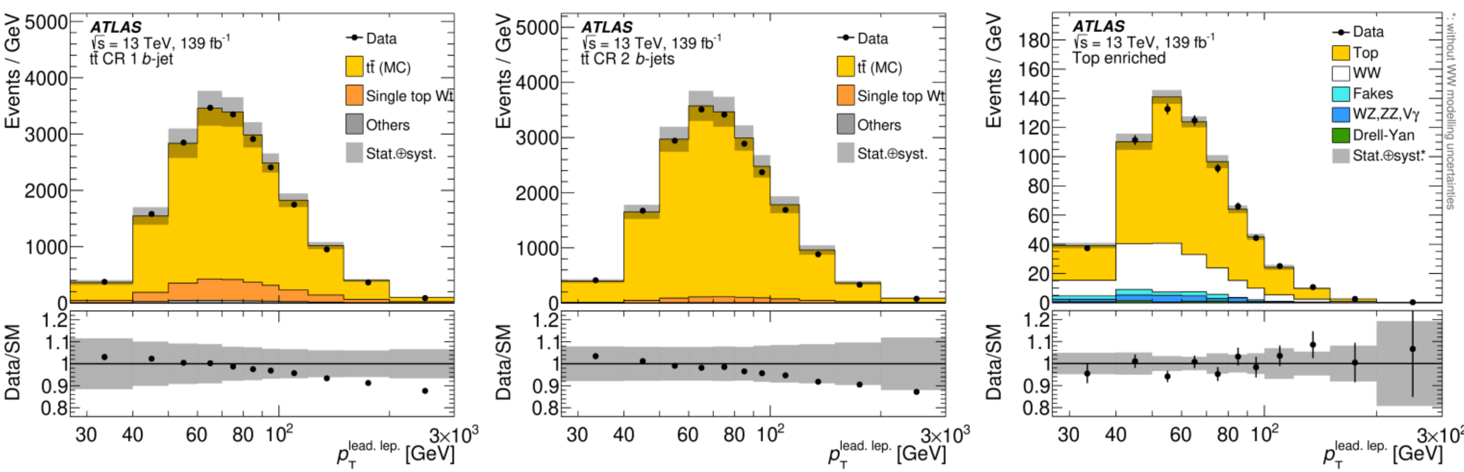
- Extra jet: enhance EFT-SM interference
- Robust estimate of the (dominant) $t\bar{t}$ background using b-jet counting method in 1- and 2 b-jet regions:

	Signal region	
Data	89 239	
Total SM	91 600 ± 2500	
WW	28 100 ± 1200	31%
Total bkg.	63 500 ± 1800	69%
Top	55 800 ± 1500	61%
Drell–Yan	2200 ± 700	2%
Fake leptons	2700 ± 1100	3%
$WZ, ZZ, V\gamma$	2800 ± 500	3%

$$N_{1b}^{t\bar{t}} = N_{1b} - N_{1b}^{\text{others}} = \mathcal{L}\sigma_{t\bar{t}}\varepsilon_{e\mu} \cdot 2\varepsilon_b\,(1 - C_b\varepsilon_b)\ ,$$
$$N_{2b}^{t\bar{t}} = N_{2b} - N_{2b}^{\text{others}} = \mathcal{L}\sigma_{t\bar{t}}\varepsilon_{e\mu} \cdot C_b\varepsilon_b^2\ ,$$
$$N_{0b}^{t\bar{t}} = \mathcal{L}\sigma_{t\bar{t}}\varepsilon_{e\mu} \cdot \left(1 - 2\varepsilon_b + C_b\varepsilon_b^2\right)\ ,$$

Derive $\mathcal{L}\sigma_{t\bar{t}}\varepsilon_{e\mu}$ and ε_b from data
Use $C_b = \varepsilon_{bb}/\varepsilon_b^2$ from $t\bar{t}$ simulation

Technique of Eur. Phys. J. C 80 (2020) 528



Data-driven b-tag counting method:
- correct the $t\bar{t}$ mismodelling
- a factor 5 reduction of $t\bar{t}$ uncertainty!

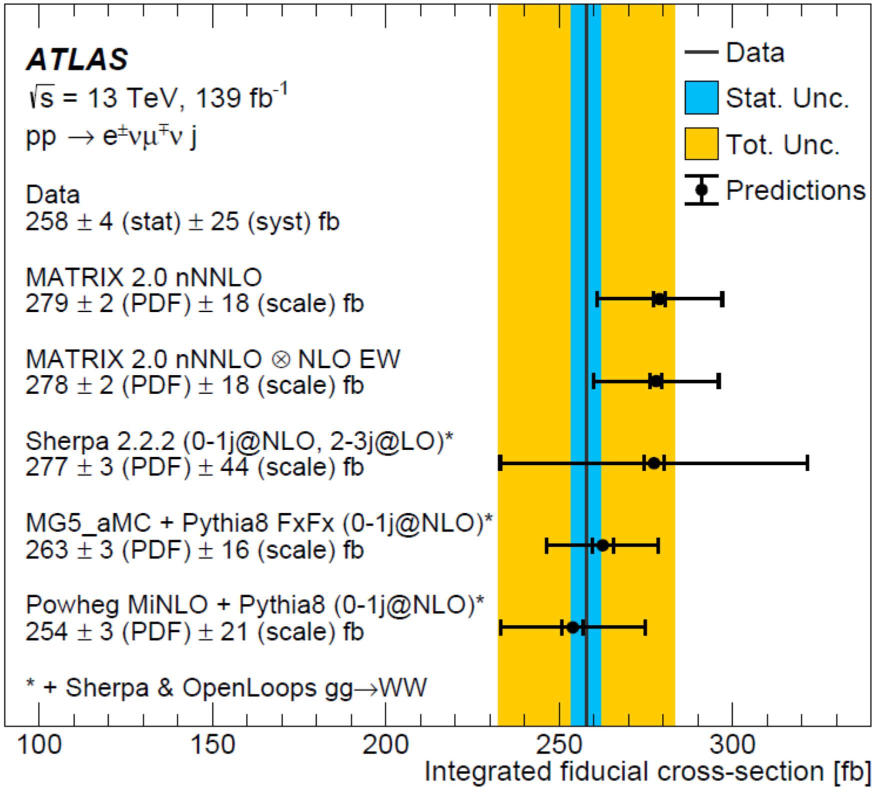
WW + ≥1 jet

JHEP 06 (2021) 003

- Precise measurement: 10% fiducial cross section uncertainty
  - Dominant systematic uncertainty: jet calibration (6%)
- Measurement agrees with state-of-the art theory predictions

$$\sigma^{\text{fid}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{C \times \mathcal{L}}$$

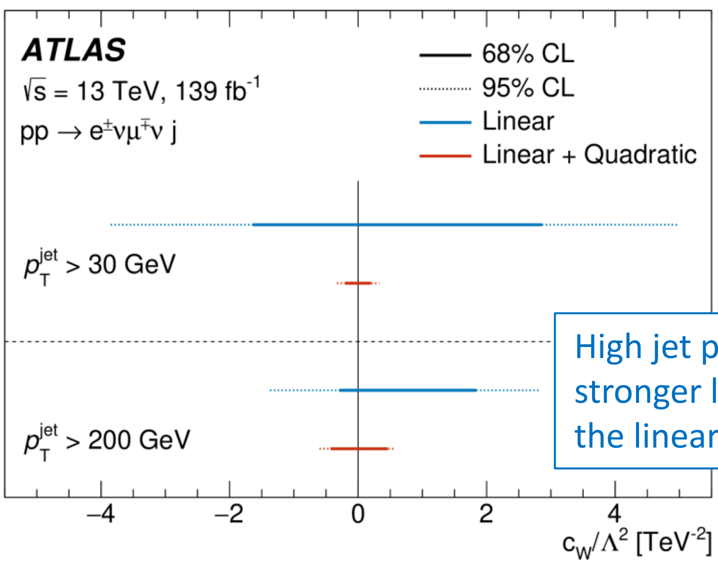
Uncertainty source	Relative effect
Total uncertainty	10%
Signal region statistical uncertainty	1.1%
Data-driven background and MC statistics	1.2%
Jet calibration	6.3%
Top modelling	4.5%
Fake-lepton background	4.3%
Signal modelling	2.7%
Other background	2.3%
Flavour tagging	2.3%
Luminosity	1.9%
Other systematic uncertainties	0.6%



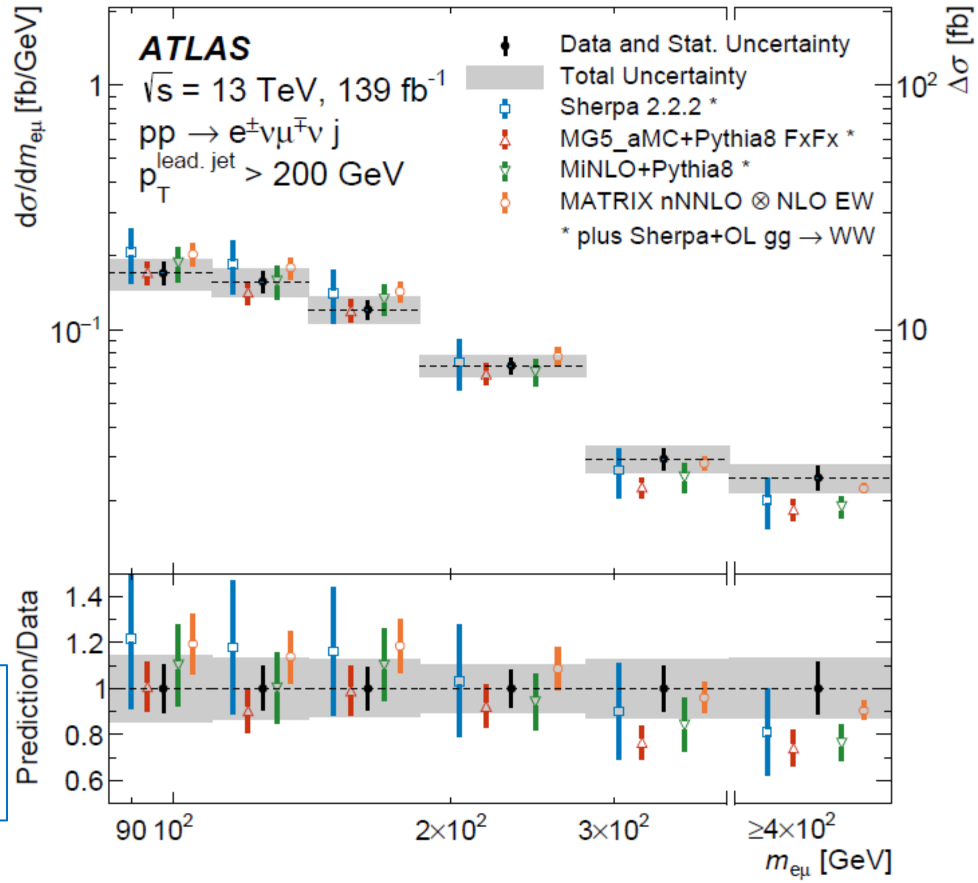
WW + ≥1 jet

JHEP 06 (2021) 003

- Fiducial and differential cross sections (12 variables)
  - Also: extra differential cross sections in high-$p_T^{\text{lead. jet}}$ (>200 GeV) and high-$p_T^{\text{lead. lep}}$ (>200 GeV) regions
- Interpreted within the EFT dim-6 using unfolded $m_{e\mu}$
  - High-$p_{T,\text{jet}}$ region helps to further enhance SM-EFT interference term: $\sigma(c_W) = \sigma_{SM} + c_W\sigma_{int} + c_W^2\sigma_{BSM}$
- Limits on c_W for linearized and quadratic EFT fit (Λ = 1 TeV):



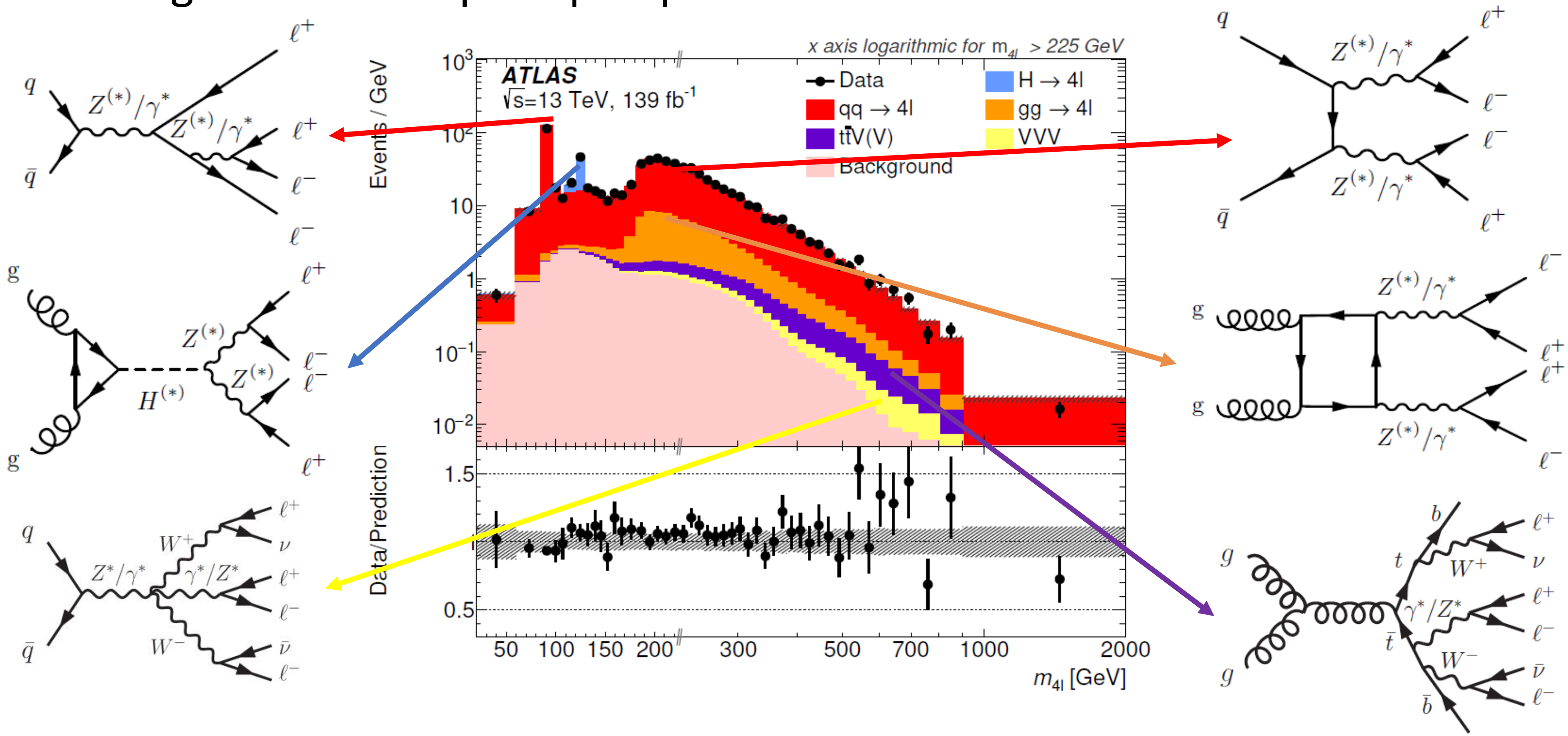
High jet p_T: stronger limits for the linear-only fit



Four-lepton measurement

JHEP 07 (2021) 005

- 4 leptons with two same-flavour opposite-charge dileptons
- Signal includes on- and off-shell *ZZ*, resonant *Z* and *H* decays, tribosons and $t\bar{t}V(V)$ events -> broad definition, good for reinterpretations
- Background = non-prompt leptons



Four-lepton measurement

[JHEP 07 (2021) 005]

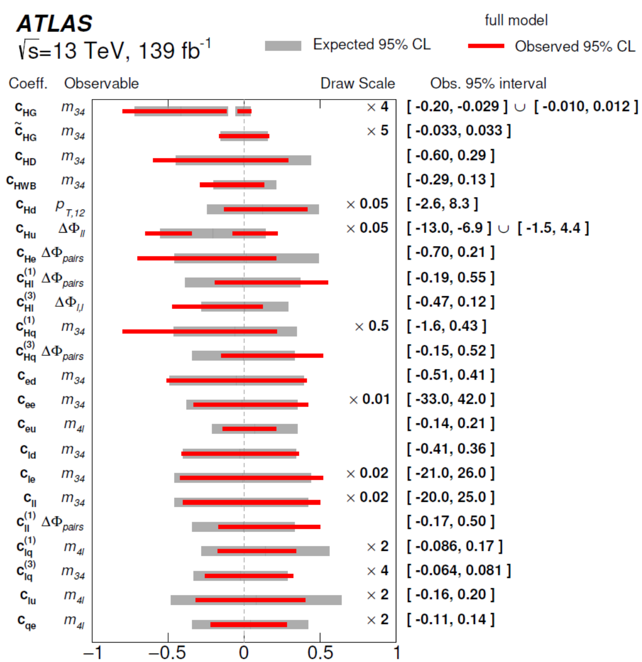
- Integrated and differential cross sections (also in different regions of m_{4l})
- Comprehensive interpretation of results:

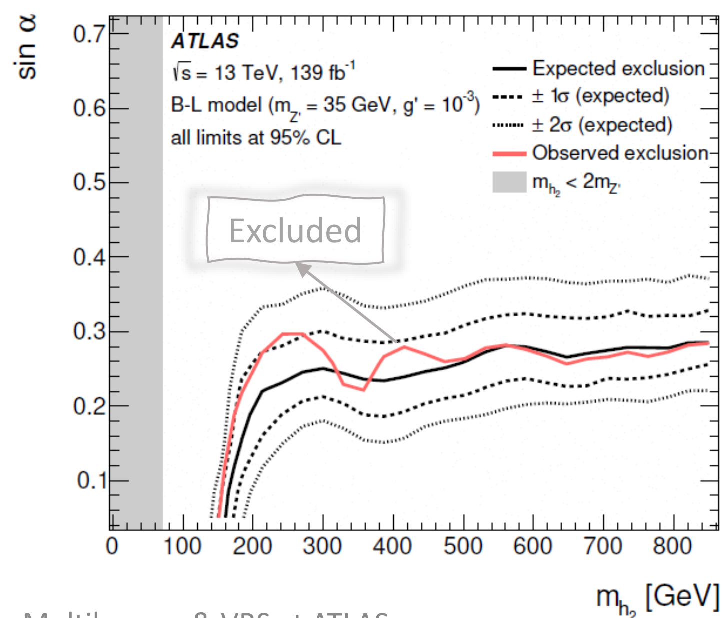
1. Most precise to date $Z \to 4l$ branching ratio measurement

$$\mathcal{B}_{Z\to4\ell} = (4.41 \pm 0.13\,(\text{stat.}) \pm 0.23\,(\text{syst.}) \pm 0.09\,(\text{theory}) \pm 0.12\,(\text{lumi.})) \times 10^{-6}$$
$$= (4.41 \pm 0.30) \times 10^{-6},$$

   ➢ Thanks to 130% acceptance gain compared to previous ATLAS measurement

2. EFT dim-6 limits (22 parameters) using Warsaw basis
3. Limits on parameters of a BSM with a spontaneously broken B-L gauge symmetry



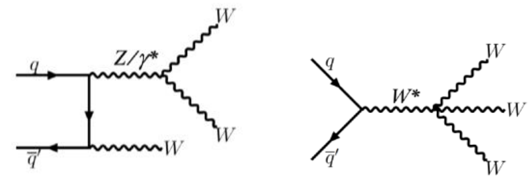


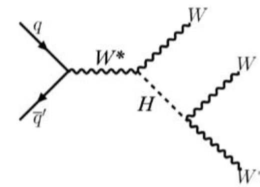
BSM Higgs boson h_2 mixing with the SM Higgs with the mixing angle α

WWW observation

ATLAS-CONF-2021-039

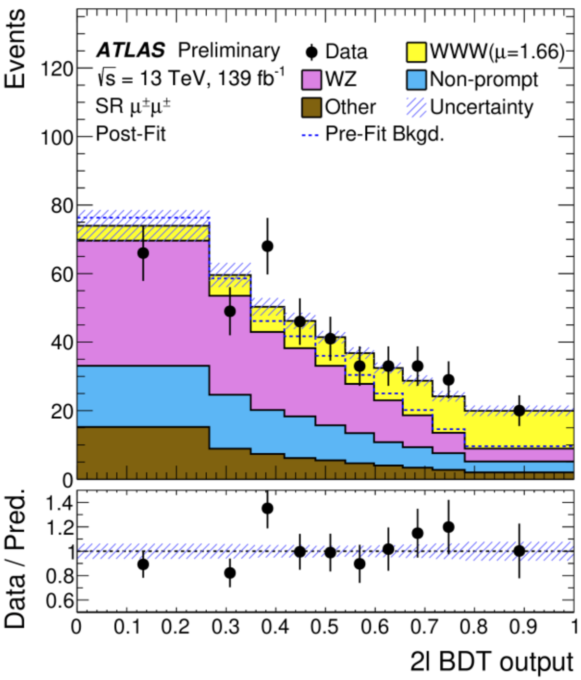
- $l^{\pm}\nu l^{\pm}\nu jj$ (2l) and $l^{\pm}\nu l^{\pm}\nu l^{\mp}\nu$ (3l) channels
  - No same-flavour opposite-sign leptons
- Signal from the fit of the BDT score distribution
  - Simultaneous fit of BDT in 2l and 3l SRs and m(3l) in three WZ CRs

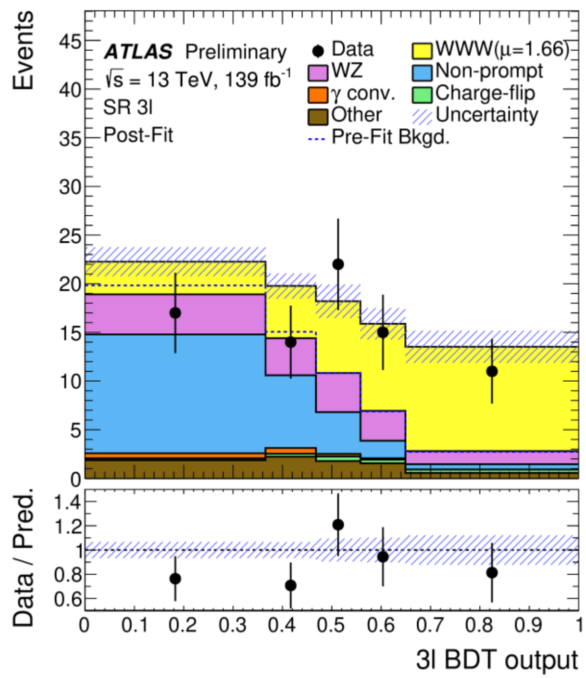


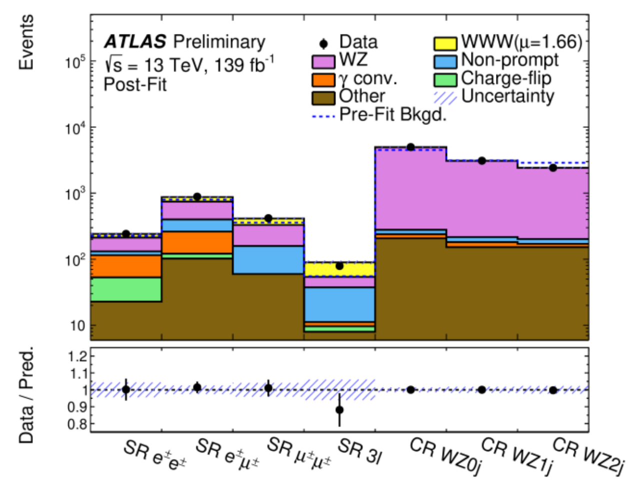


Off-shell WH is part of the signal

	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	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 observation

ATLAS-CONF-2021-039

- The WWW process is **observed for the first time at LHC, with a significance of 8.2σ**

Fit	Observed (expected) significances [σ]	$\mu(WWW)$
$e^{\pm}e^{\pm}$	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)**	**1.66 ± 0.28**

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

$\sigma_{MC} = 511$ fb

- Measured total cross section:

$$\sigma(pp \rightarrow WWW) = 850 \pm 100\,(\text{stat.}) \pm 80(\text{syst.})\ \text{fb}$$

- Higher-order predictions:

	σ (fb)	**Scale unc. (fb)**	**PDF unc. (fb)**	**α_s unc. (fb)**	**Calculation order**	**Ratio NLO to LO or NNLO to NLO**
$W^-W^+W^+$	136	+6/-5	4		NLO in QCD and EW [1]	~1.7
$W^+W^-W^-$	76	+4/-3	2			
WH	293	+1/-2	+6/-5	3	NNLO QCD, NLO EW [2]	1.00 ... 1.05
Total	505					

> 2.5σ tension with the SM

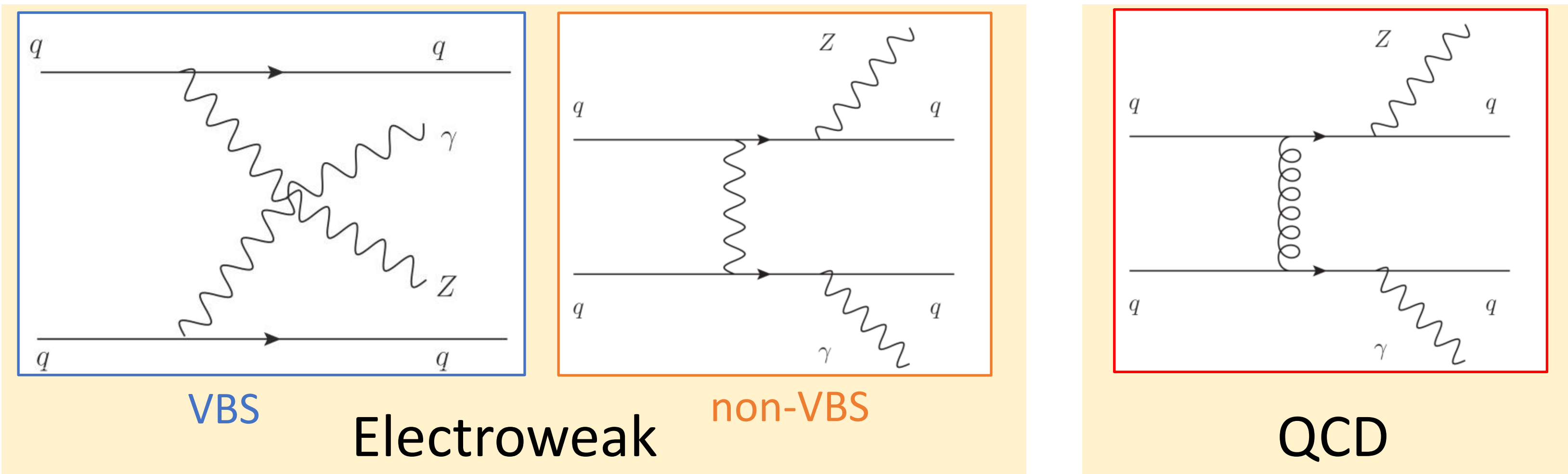
[1] *JHEP* 2017, 34
[2] CERN-2017-002

- Measured cross section consistent between 2l and 3l channels, and between different data taking periods

Electroweak production of Zγjj

See the plenary talk by Philip Sommer

- Electroweak production mode includes VBS and non-VBS contributions



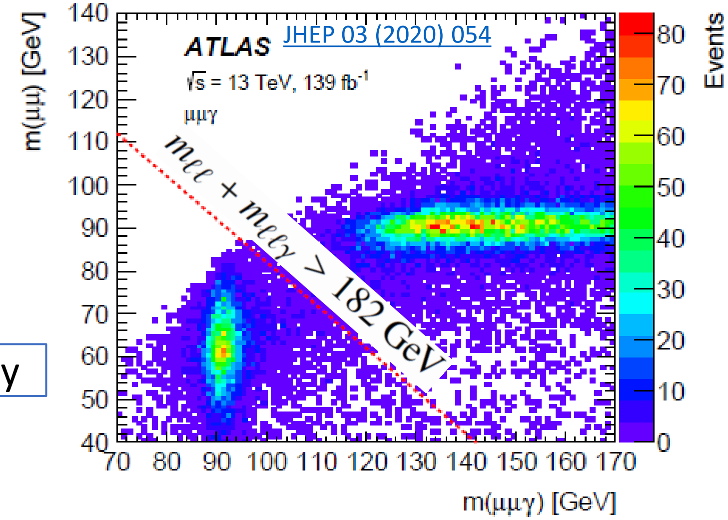
- Contributions from VBS and non-VBS diagrams are not separable from each other in a gauge invariant way -> measure electroweak production
- EW and QCD production modes interfere (if same initial and final states)
- EW, QCD, and interference terms are separable from each other at LO
- EW mode: quarks not colour-connected, low hadronic activity expected in the gap between two jets -> rapidity gap and high dijet invariant mass

Electroweak production of Z(→*ll*)γ jj

ATLAS-CONF-2021-038

- Considered are Z boson decays to electrons or muons

Lepton	$p_{\mathrm{T}}^{\ell} > 20, 30(\text{leading})$ GeV, $\lvert\eta_\ell\rvert < 2.47$ $N_\ell \geq 2$	
Photon	$E_{\mathrm{T}}^{\gamma} > 25$ GeV, $\lvert\eta_\gamma\rvert < 2.37$ $E_{\mathrm{T}}^{cone20} < 0.07 E_{\mathrm{T}}^{\gamma}$ $\Delta R(\ell,\gamma) > 0.4$	
Jet	$p_{\mathrm{T}}^{jet} > 50$ GeV, $\lvert y_{jet}\rvert < 4.4$ $\lvert\Delta y\rvert > 1.0$ $m_{jj} > 150$ GeV remove jets if $\Delta R(\gamma, j) < 0.4$ or if $\Delta R(\ell, j) < 0.3$	Select VBS topology ($\lvert\Delta y\rvert$, m_{jj})
Event	$m_{\ell\ell} > 40$ GeV $m_{\ell\ell} + m_{\ell\ell\gamma} > 182$ GeV $\zeta(\ell\ell\gamma) < 0.4$ $N_{jets}^{gap} = 0$	Suppress QED FSR ($m_{\ell\ell} + m_{\ell\ell\gamma}$) Central Z and gamma: region dominated by EW mode ($\zeta(\ell\ell\gamma)$)



Zgamma centrality:

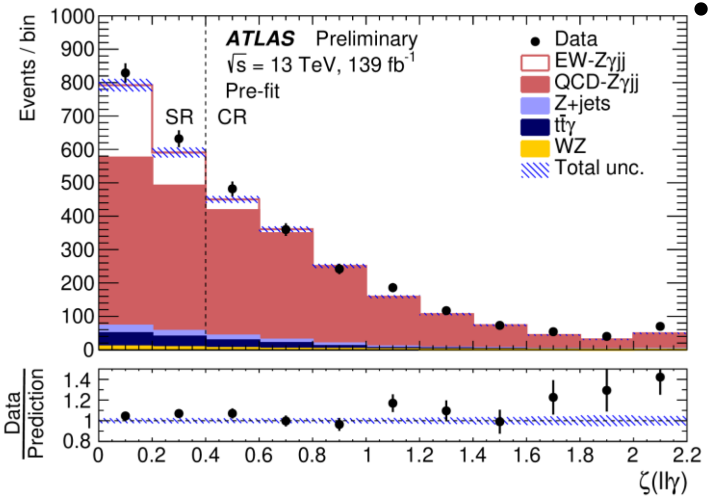
$$\zeta(\ell\ell\gamma) = \left|\frac{y_{\ell\ell\gamma} - (y_{j_1} + y_{j_2})/2}{y_{j_1} - y_{j_2}}\right|$$

- Signal modelling:
  - EW: MadGrapn5_aMC@NLO at LO
  - QCD: MadGraph5_aMC@NLO merged with 0,1 extra jets at NLO; Sherpa 2.2.2 for cross checks
  - Interference: MadGraph5_aMC@NLO at LO (assigned as uncertainty on EW)

Electroweak production of Z(→*ll*)γ jj

ATLAS-CONF-2021-038

- Zgamma centrality used to separate signal and QCD control regions



- SR dominated by QCD-induced mode:

Sample	SR	CR
$N_{EW-Z\gamma jj}$	300 ± 36	55 ± 7
$N_{QCD-Z\gamma jj}$	987 ± 55	1352 ± 60
$N_{t\bar{t}\gamma}$	72 ± 11	59 ± 9
N_{WZ}	17 ± 3	14 ± 3
N_{Z+jets}	85 ± 30	143 ± 43
Total	1461 ± 38	1624 ± 40
N_{obs}	1461	1624

Source	Size [%]
Electron/photon calibration	± 0.3
Photon	± 0.3
Backgrounds	± 1.0
Electron	± 1.1
Flavour tagging	± 1.1
Muon	± 1.1
MC stat.	± 1.4
Pileup	± 2.6
Jets	± 4.7
QCD-Zγjj modelling	$^{+4.8}_{-4.3}$
EW-Zγjj modelling	$^{+5.7}_{-4.6}$
Data stat.	± 8.8
Total	$^{+13.4}_{-12.6}$

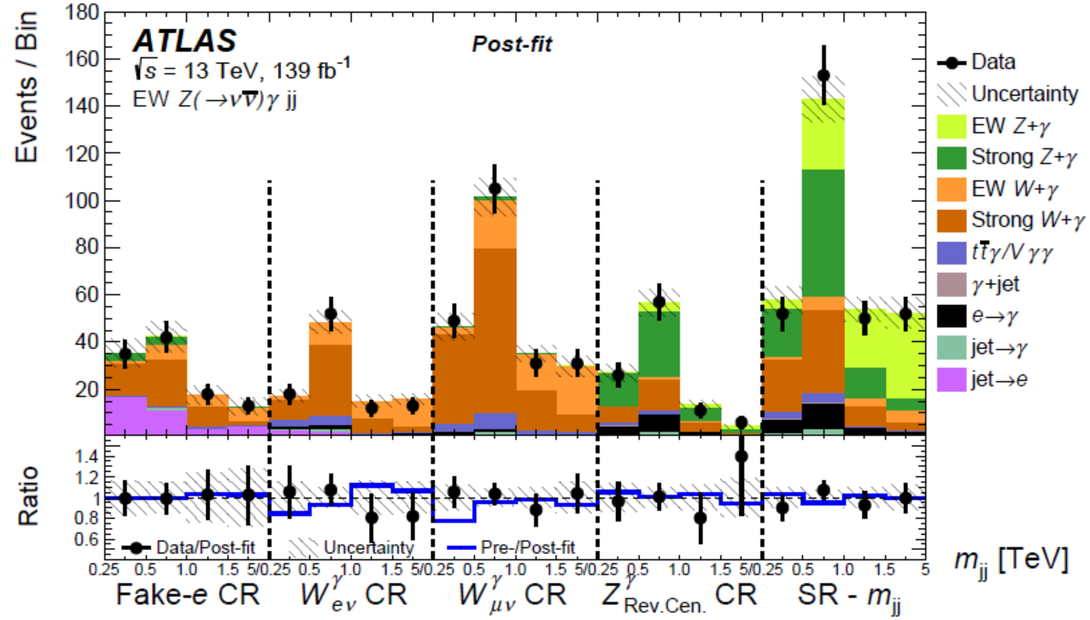
- Use m_{jj} as a template variable in SR and CR
- Fit normalization of the EW signal in SR, and (separate) normalizations of QCD mode in SR and CR
- Largest systematics due to signal modelling and jets
- Measured cross section: $\sigma_{EW} = 4.49 \pm 0.40\ (\text{stat.}) \pm 0.42\ (\text{syst.})\ \text{fb}$
- Theory (MC) prediction: $\sigma_{EW}^{pred} = 4.73 \pm 0.01\ (\text{stat.}) \pm 0.15\ (\text{PDF})^{+0.23}_{-0.22}\ (\text{scale})\ \text{fb}.$
- EW-induced production **observed with a significance of 10σ** (11σ expected)

Electroweak production of Z(→νν)γ jj

[arXiv:2109.00925](https://arxiv.org/abs/2109.00925), submitted to EPJC

- Z bosons decays to neutrinos considered

Observable	Requirements
N_{jet} with $p_T > 25$ GeV	≥ 2
$\lvert\eta(j_{1,2})\rvert$	< 4.5
$p_T(j_1)$ [GeV]	> 60
$p_T(j_2)$ [GeV]	> 50
$\Delta R(j,\ell)$	> 0.4
$\lvert\Delta\eta_{jj}\rvert$	> 3.0
C_3	< 0.7
m_{jj} [TeV]	> 0.5
truth-E_T^{miss} [GeV]	> 150
$\Delta\phi(\text{truth-}\vec{E}_T^{\text{miss}}, j_i)$	> 1.0
$p_T(\gamma)$ [GeV]	$> 15, < 110$
$\lvert\eta(\gamma)\rvert$	< 2.37
$E_T^{\text{cone20}}/E_T^{\gamma}$	< 0.07
$\Delta R(\gamma, \text{jet-or-}\ell)$	> 0.4
C_γ	> 0.4
$\Delta\phi(\text{truth-}\vec{E}_T^{\text{miss}}, \gamma)$	> 1.8
N_ℓ with $p_T > 4$ GeV and $\lvert\eta\rvert < 2.47$	0



- Largest backgrounds normalizations constrained in dedicated control regions

- EW $Z(\rightarrow \nu\nu)\gamma\, jj$ process **observed with a significance 5.2σ** (expected 5.1σ)
- Measured cross section $\sigma^{\text{fid.}}_{Z(\rightarrow\nu\nu)\gamma\text{EW}} = 1.31 \pm 0.20(\text{stat}) \pm 0.20(\text{syst})$ fb
- Theory (MC with NLO K-factors): 1.27 ± 0.17 fb.
- Upper limit of 0.37 at 95% C.L. set on Higgs branching ratio to invisible particles

EFT interpretation

ATL-PHYS-PUB-2021-022

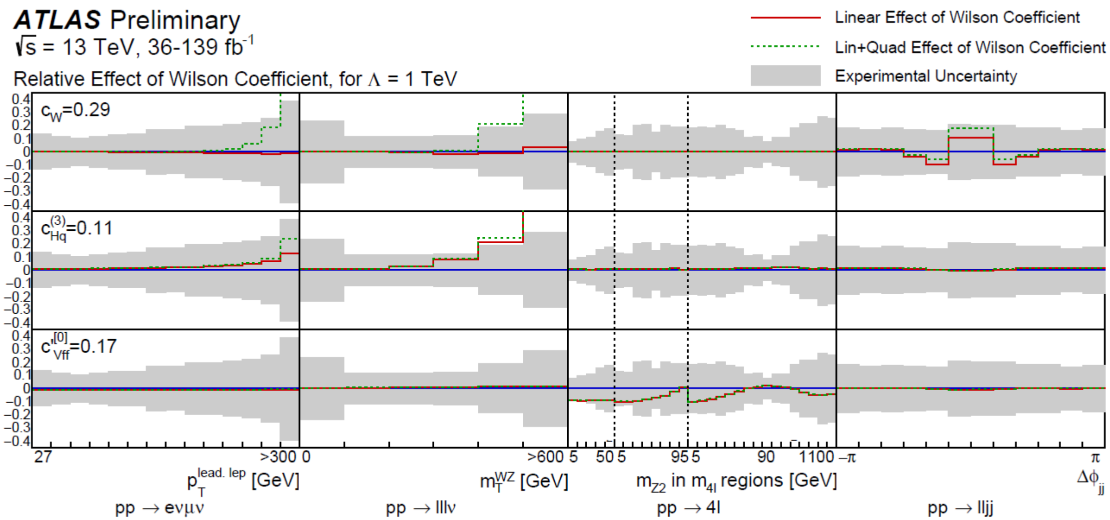
- Combined analysis of ATLAS published measurements:
  - Zjj via Vector Boson Fusion (VBF) with 139 fb^{-1}, Eur. Phys. J. C 81 (2021) 163
  - Diboson WW with 36 fb^{-1}, Eur. Phys. J. C 79 (2019) 884
  - Diboson WZ with 36 fb^{-1}, Eur. Phys. J. C 79 (2019) 535
  - Inclusive four-lepton with 139 fb^{-1}, JHEP 07 (2021) 005
- EFT dimension-6 with 33 CP-even operators, using Warsaw basis
- The information contained in data is not sufficient to constrain all 33 operators
- Identify sensitive directions from eigenvalue decomposition of the covariance matrix
  - Construct a modified basis with linear combinations of the Warsaw basis operators
  - Linear combinations of operators constrained (two Wilson coefficients c_W and $c_{Hq}^{(3)}$ and 13 combinations of other Wilson coefficients)
- The expansion of the cross section contains linear and quadratic terms in Wilson coefficients $c_i^{(6)}$:

$$\sigma \propto |\mathcal{M}_{\mathrm{SMEF}} = |\mathcal{M}_{\mathrm{SM}}|^2 + \sum_i \frac{c_i^{(6)}}{\Lambda^2} 2\mathrm{Re}\left(\mathcal{M}_i^{(6)} \mathcal{M}_{\mathrm{SM}}^*\right) + \sum_i \frac{\left(c_i^{(6)}\right)^2}{\Lambda^4} \left|\mathcal{M}_i^{(6)}\right|^2 + \sum_{i<j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} 2\mathrm{Re}\left(\mathcal{M}_i^{(6)} \mathcal{M}_j^{(6)*}\right) + O\left(\Lambda^{-4}\right)$$

- Quadratic terms are of the same order as those of EFT dimension-8 interfering with the SM
  - EFT dim-8 not considered in the model -> report limits based on linear and linear+quadratic fits; difference gives estimate of missing $1/\Lambda^4$ terms

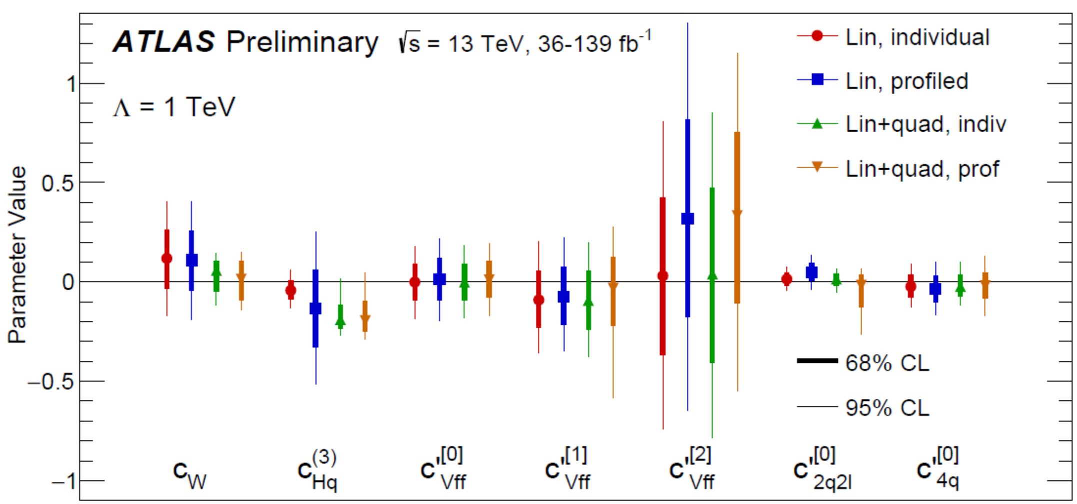
EFT interpretation

ATL-PHYS-PUB-2021-022



- Correlation of systematics between measurements taken into account

Correlated Uncertainty Source	WW	WZ	4ℓ	VBF Z
Luminosity (correlated part)	✓	✓	✓	✓
Luminosity 2015/16	✓	✓	✓	✓
Luminosity 2017/18			✓	✓
Lepton efficiency (correlated part)	✓	✓	✓	✓
Pile-up modelling	✓	✓	✓	✓
Pile-up jet suppression	✓			✓
Jet energy scale (Pile-up modelling)	✓			✓
Jet energy scale η-inter-calibration	✓			✓



$c'^{[0]}_{Vff} \approx 0.81c_{HWB} + 0.38c_{HD} + 0.13c^{(1)}_{Hl} + 0.37c^{(3)}_{Hl} - 0.14c^{(1)}_{ll} + 0.12c^{(1)}_{Hq}$

$c'^{[1]}_{Vff} \approx 0.73c^{(1)}_{Hl} - 0.28c^{(3)}_{Hl} - 0.48c_{He} + 0.38c^{(1)}_{ll} + 0.13c^{(1)}_{Hq}$

$c'^{[2]}_{Vff} \approx 0.37c_{HWB} + 0.17c_{HD} - 0.31c^{(1)}_{Hl} - 0.53c^{(3)}_{Hl} + 0.25c_{He} + 0.59c^{(1)}_{ll} - 0.21c^{(1)}_{Hq}$

$c'^{[0]}_{2q2l} \approx -0.37c^{(1)}_{lq} + 0.89c^{(3)}_{lq} - 0.11c_{lu} - 0.21c_{eu} - 0.13c_{qe}$

$c'^{[0]}_{4q} \approx 0.11c^{(11)}_{qq} + 0.22c^{(18)}_{qq} + 0.95c^{(31)}_{qq} - 0.2c^{(38)}_{qq}$

- Limits at 95% CL for linear and linear+quadratic fits (to illustrate the effect of truncation of EFT expansion)
- Fits of individual coefficients (with others set to zero) as well as combined fit
- No deviations from SM found

Step forward towards global EFT interpretations!

Summary

- Run 2 ATLAS measurements and interpretations continuing to come
- Presented today:
  - $W^+W^- + \geq 1$ jet, JHEP 06 (2021) 003
  - Four-lepton differential, JHEP 07 (2021) 005
  - **8.2σ** observation of WWW, ATLAS-CONF-2021-039
  - Observation of the electroweak production:
    - ✓ $Z(\to ll)\gamma\, jj$ with **10σ**, ATLAS-CONF-2021-038
    - ✓ $Z(\to \nu\nu)\gamma\, jj$ with **5.2σ**, arXiv:2109.00925, submitted to EPJC
  - Combined EFT interpretation of WW, WZ, four-lepton, and Zjj VBF cross sections, ATL-PHYS-PUB-2021-022 -> important step forward towards larger joint EFT interpretations (multiboson+Higgs+top)
- Looking forward to higher precision results and new observations with Run 3 data!

Backup

c_W limit comparison

ATLAS EFT interpretation

Parameter	Linear fit					Linear-plus-quadratic fit				
		68% CI Bound.		95% CI Bound.			68% CI Bound.		95% CI Bound.	
	Best fit	Lower	Upper	Lower	Upper	Best fit	Lower	Upper	Lower	Upper
c_W	0.11	-0.04	0.26	-0.19	0.40	0.01	-0.09	0.10	-0.14	0.15

ATLAS Zjj VBF 139 fb-1

Wilson coefficient	Includes $\vert\mathcal{M}_{d6}\vert^2$	95% confidence interval [TeV^{-2}] Expected	Observed	p-value (SM)
c_W/Λ^2	no	[−0.30, 0.30]	[−0.19, 0.41]	45.9%
	yes	[−0.31, 0.29]	[−0.19, 0.41]	43.2%
$\tilde{c}_W/\Lambda^2$	no	[−0.12, 0.12]	[−0.11, 0.14]	82.0%
	yes	[−0.12, 0.12]	[−0.11, 0.14]	81.8%
c_{HWB}/Λ^2	no	[−2.45, 2.45]	[−3.78, 1.13]	29.0%
	yes	[−3.11, 2.10]	[−6.31, 1.01]	25.0%
$\tilde{c}_{HWB}/\Lambda^2$	no	[−1.06, 1.06]	[0.23, 2.34]	1.7%
	yes	[−1.06, 1.06]	[0.23, 2.35]	1.6%

- Ordered from most to least constrained when considering both linear and quadratic terms
- Warsaw or HISZ basis
- $c_W \approx c_{WWW}/14.2$

CMS WW 35 fb-1

Coefficients (TeV^{-2})	68% confidence interval expected	68% confidence interval observed	95% confidence interval expected	95% confidence interval observed
c_{WWW}/Λ^2	[−1.8, 1.8]	[−0.93, 0.99]	[−2.7, 2.7]	[−1.8, 1.8]
c_W/Λ^2	[−3.7, 2.7]	[−2.0, 1.3]	[−5.3, 4.2]	[−3.6, 2.8]
c_B/Λ^2	[−9.4, 8.4]	[−5.1, 4.3]	[−14, 13]	[−9.4, 8.5]

ATLAS WW+0 jets 36 fb-1

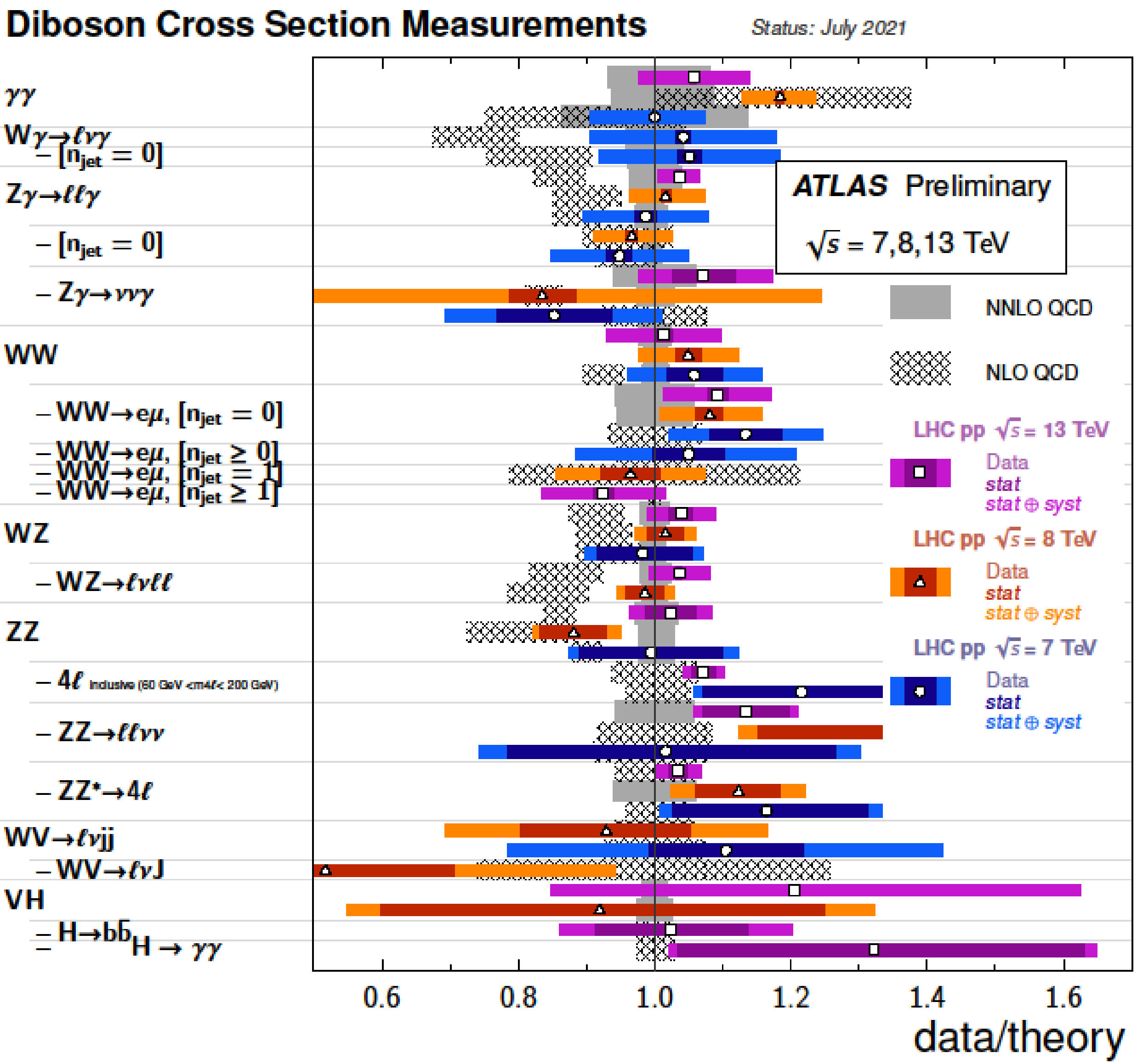
Operator	95% CL (linear and quadratic terms)	95% CL (linear terms only)
c_{WWW}/Λ^2	[−3.4 TeV^{-2} , 3.3 TeV^{-2}]	[−179 TeV^{-2} , −17 TeV^{-2}]
c_W/Λ^2	[−7.4 TeV^{-2} , 4.1 TeV^{-2}]	[−13.1 TeV^{-2} , 7.1 TeV^{-2}]
c_B/Λ^2	[−21 TeV^{-2} , 18 TeV^{-2}]	[−104 TeV^{-2} , 101 TeV^{-2}]

ATLAS WW+>=1 jet 139 fb-1

Jet p_T	Linear only	68% CI obs.	95% CI obs.	68% CI exp.	95% CI exp.
> 30 GeV	yes	[−1.64, 2.86]	[−3.85, 4.97]	[−2.30, 2.27]	[−4.53, 4.41]
> 30 GeV	no	[−0.20, 0.20]	[−0.33, 0.33]	[−0.28, 0.27]	[−0.39, 0.38]
> 200 GeV	yes	[−0.29, 1.84]	[−1.37, 2.81]	[−1.12, 1.09]	[−2.24, 2.10]
> 200 GeV	no	[−0.43, 0.46]	[−0.60, 0.58]	[−0.38, 0.33]	[−0.53, 0.48]

Diboson measurements overview

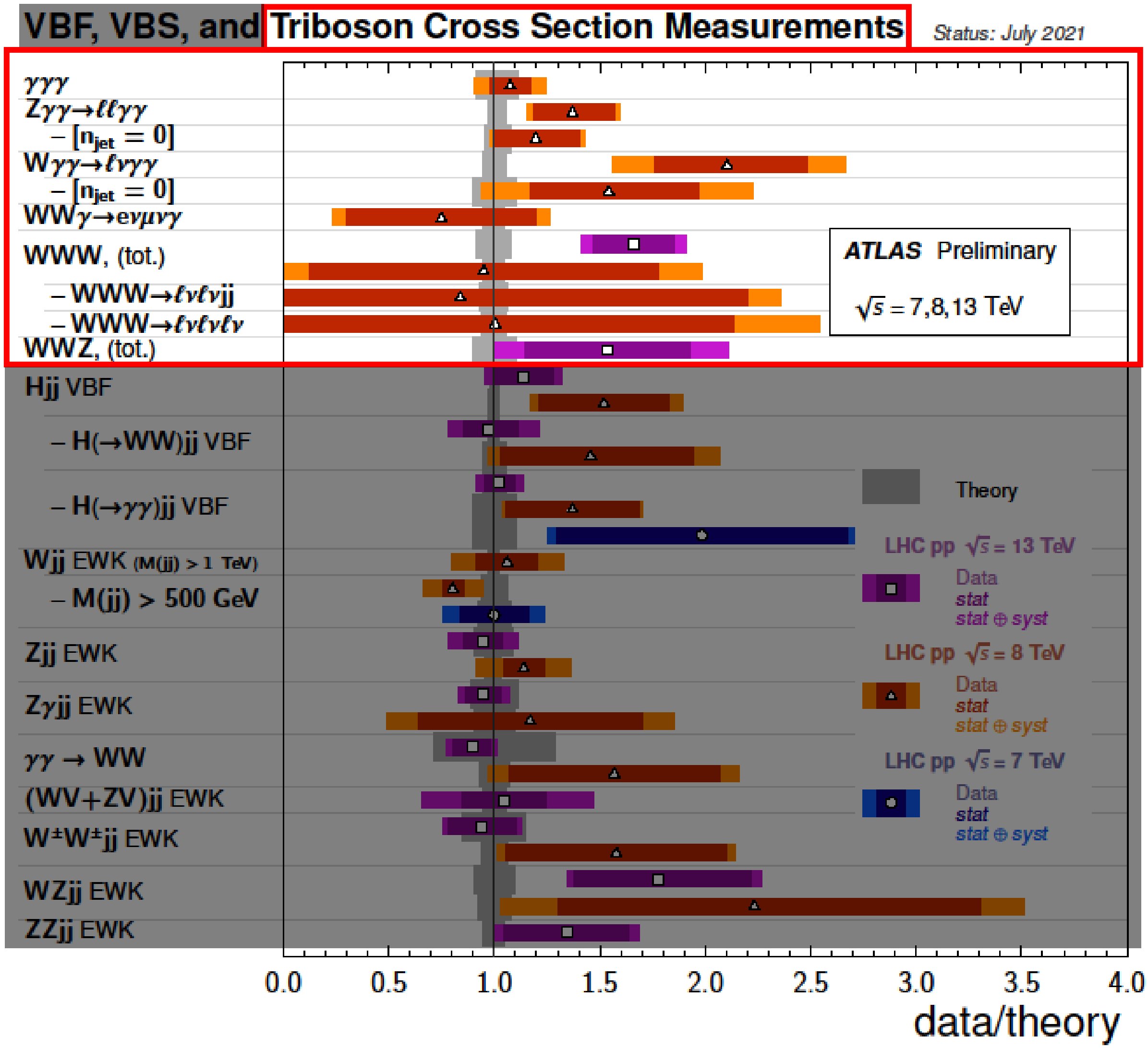
ATL-PHYS-PUB-2021-032



- Remarkable agreement between measured diboson cross sections and NNLO QCD predictions

Triboson measurements overview

ATL-PHYS-PUB-2021-032



- ~2 sigma disagreement between measurement and theory for Wγγ and WWW
  - ➢ No NNLO calculations (yet)

Partial decay width Z to four leptons

$\Gamma(\ell^+\ell^-\ell^+\ell^-)/\Gamma_{total}$ **Γ_6/Γ**

Here ℓ indicates either e or μ. The branching fractions in this node are given within the phase-space defined by the requirements that (i) the 4-lepton invariant mass is between 80 GeV and 100 GeV, and (ii) any opposite-sign same-flavor lepton pair has a di-lepton invariant mass larger than 4 GeV.

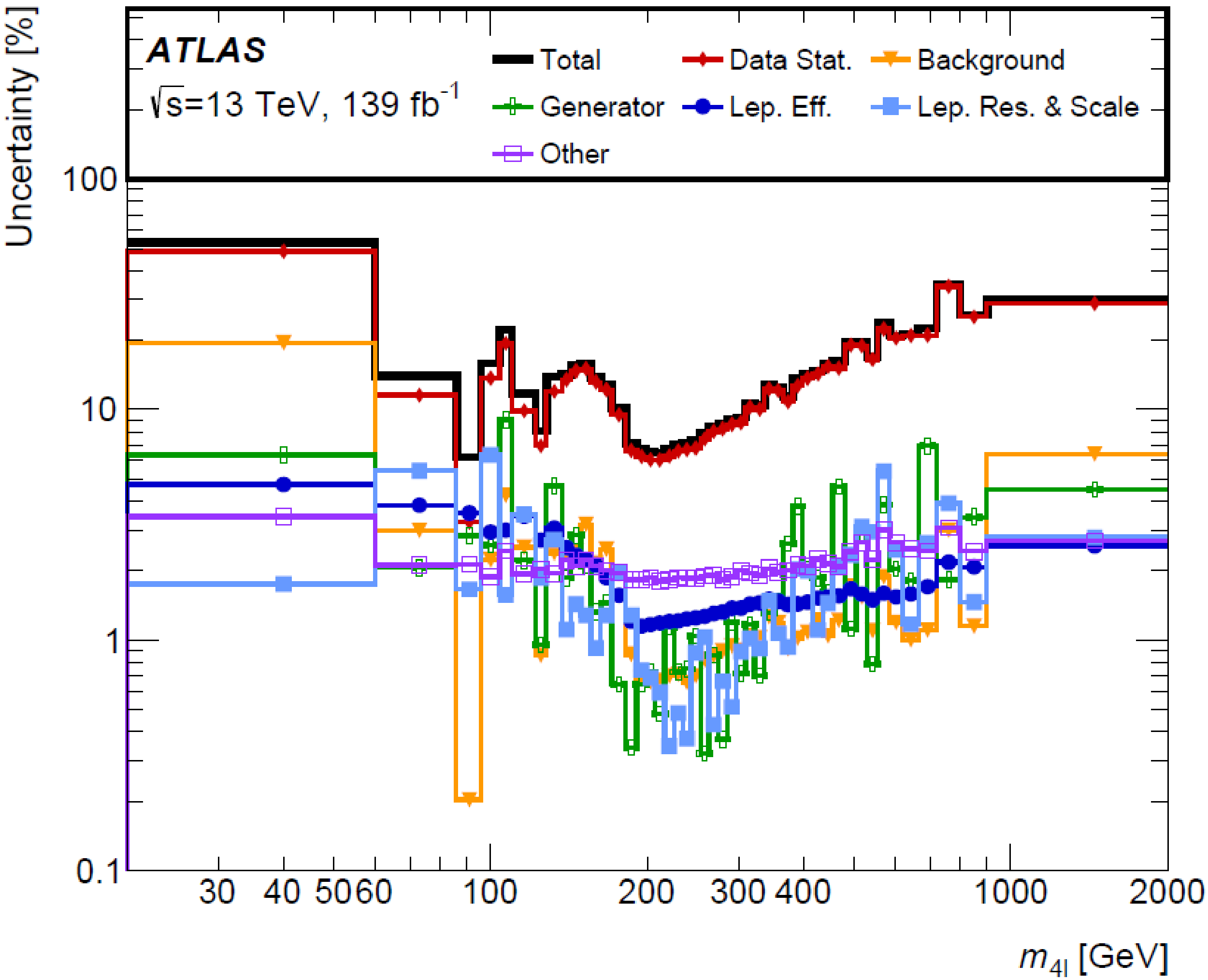
VALUE (units 10^{-6})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
4.63±0.21 OUR AVERAGE					
$4.70 \pm 0.32 \pm 0.25$		[1] AABOUD	19N	ATLS	E^{pp}_{cm} = 13 TeV
$4.83^{+0.23}_{-0.22}{}^{+0.35}_{-0.32}$	509	[2] SIRUNYAN	18BT	CMS	E^{pp}_{cm} = 13 TeV
$4.9\ ^{+0.8}_{-0.7}\ ^{+0.4}_{-0.2}$	39	[3] KHACHATRY...	16CC	CMS	E^{pp}_{cm} = 13 TeV
$4.31 \pm 0.34 \pm 0.17$	172	AAD	14N	ATLS	E^{pp}_{cm} = 7, 8 TeV
$4.6\ ^{+1.0}_{-0.9} \pm 0.2$	28	[4] CHATRCHYAN	12BN	CMS	E^{pp}_{cm} = 7 TeV

- ATLAS new result:

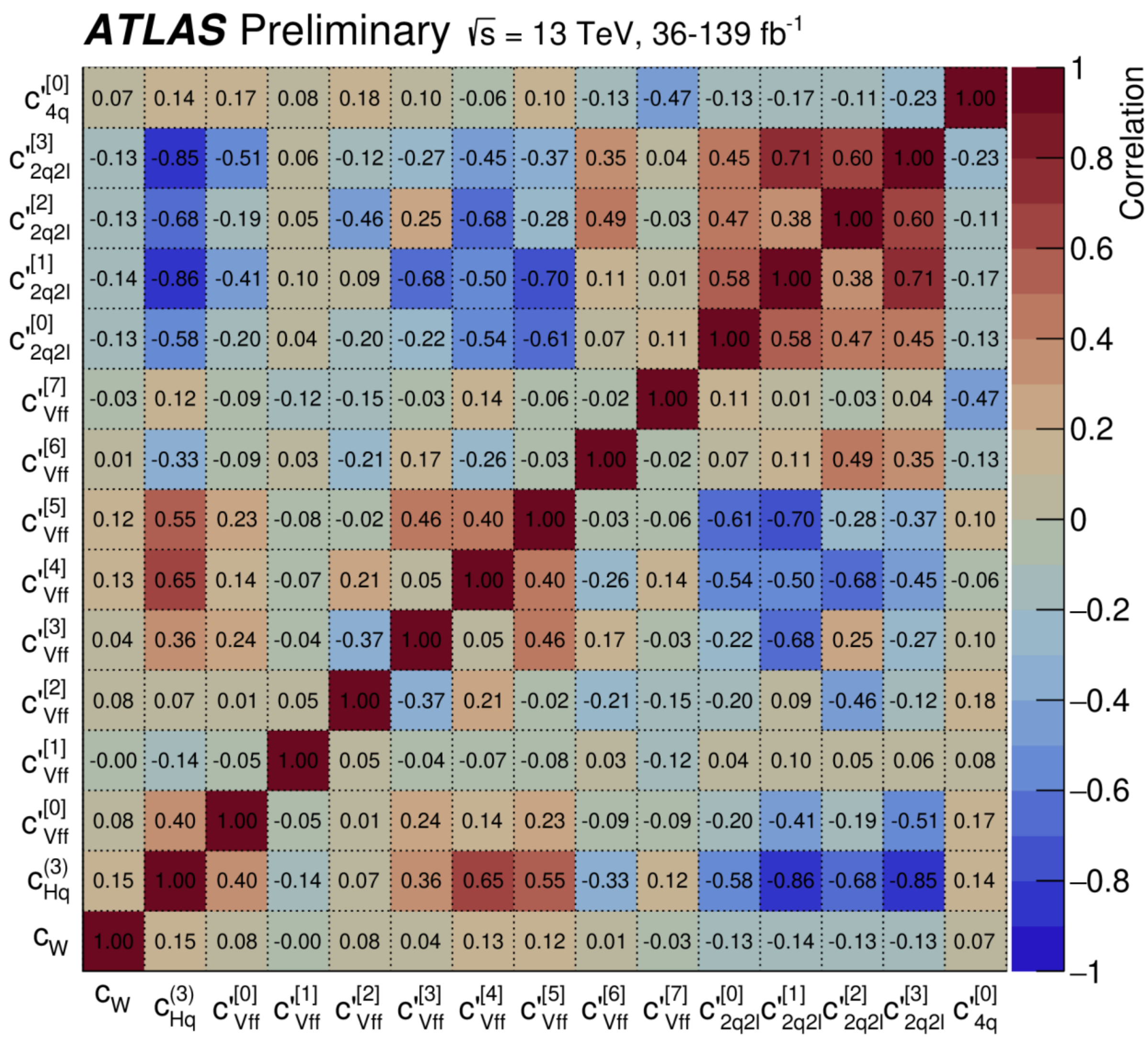
$$\mathcal{B}_{Z\to 4\ell} = (4.41 \pm 0.13\,(\text{stat.}) \pm 0.23\,(\text{syst.}) \pm 0.09\,(\text{theory}) \pm 0.12\,(\text{lumi.})) \times 10^{-6}$$
$$= (4.41 \pm 0.30) \times 10^{-6},$$

Lepton number (p_T ordered)	p_T thresholds old (GeV)	p_T thresholds new (GeV)
1	20	20
2	15	10
3	10	5 (7)
4	5 or 15 (7)	5 (7)

Z to four leptons - uncertainties



Combined EFT interpretation - parameter correlations

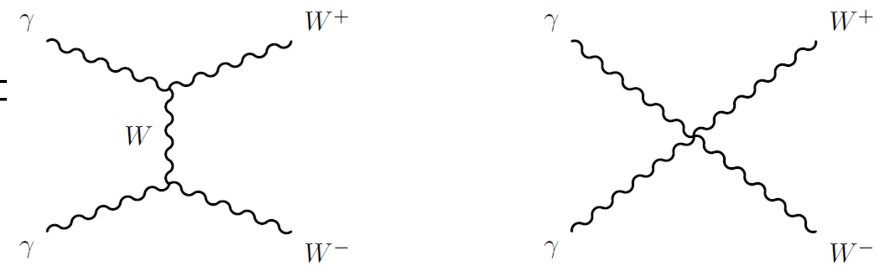


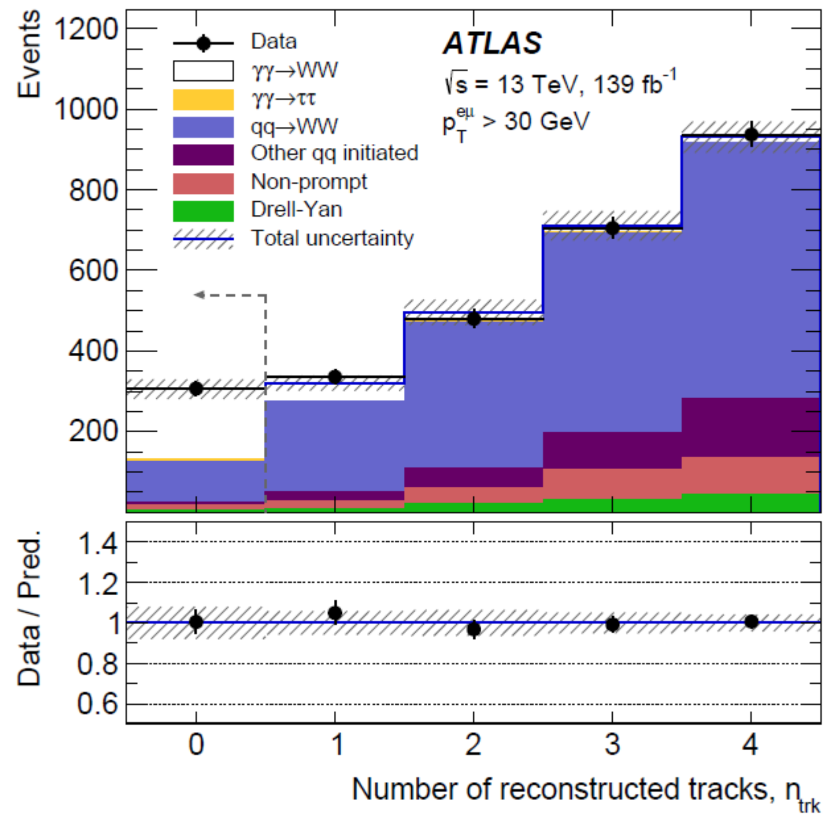
Observation of γγ→WW

[Phys. Lett. B 816 (2021) 136190](https://doi.org/10.1016/j.physletb.2021.136190)

ATLAS, 13 TeV, 139 fb^{-1}

- Opposite-sign, opposite-flavour $e^{\pm}\mu^{\mp}$
- Intact or dissociated protons
- Exclusive production; exclusivity defined using central detector cuts, $n_{trk} = 0, p_{T,track} > 500$ MeV
- At LO, process only proceeds via EW gauge boson self-couplings
- Largest background: inclusive $qq \to WW$
- Proton dissociation not included in the signal model -> data-driven correction





Observation of γγ→WW

Phys. Lett. B 816 (2021) 136190

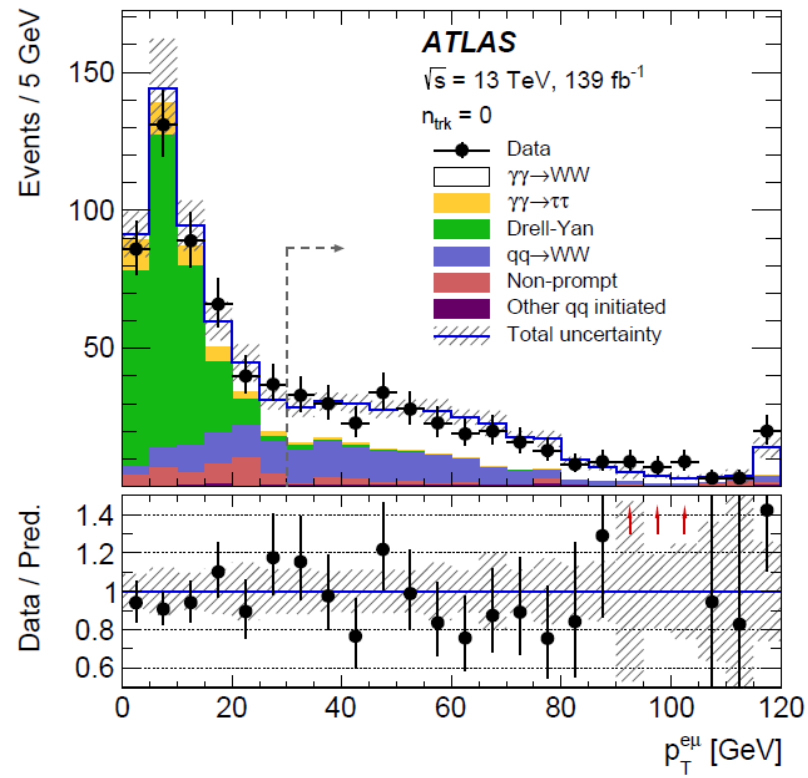
ATLAS, 13 TeV, 139 fb^{-1}

- Many non-standard corrections:
  - ➢ Vertex definition (ATLAS vertex reconstruction biased for exclusive vertices)
  - ➢ MC beamspot width rescaled to data
  - ➢ MC pileup mismodelling correction
  - ➢ Charged particle multiplicity correction
- Fit to data yields in SR and 3 CRs based on values of and
- Measured fiducial cross section

  3.13 ±0.31(stat.) ±0.28(syst.) fb

  - ➢ Agrees with theory corrected for a proton survival factor

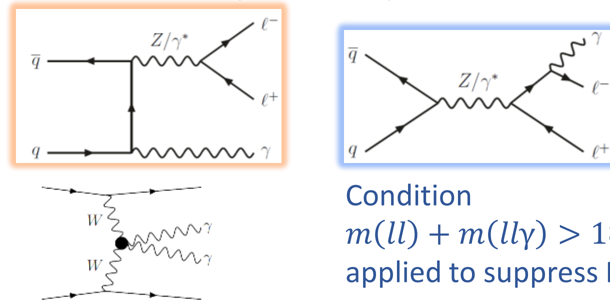
Observed signal significance: 8.4σ



Zγ

JHEP 03 (2020) 054

ATLAS, 13 TeV, 139 fb^{-1}



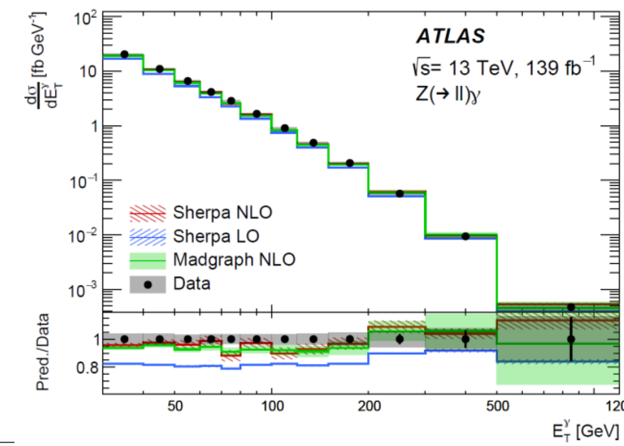
Condition
$m(ll) + m(ll\gamma) > 182$ GeV
applied to suppress FSR

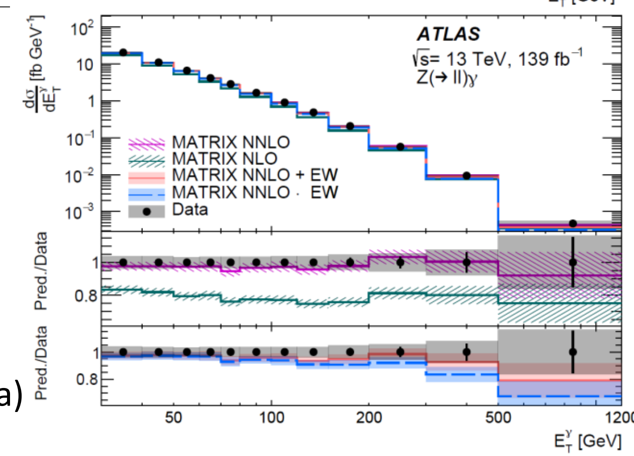
- $e^+e^-\gamma$, $\mu^+\mu^-\gamma$
- No VZγ TGC in SM -> LO diagrams are ISR and FSR
  - ➢ Small contribution from VBS at higher EW orders
- Pileup photon background estimated using converted photons
- Integrated and differential cross sections compared to a number of MC and fixed-order predictions
  - ➢ Generally good description by MATRIX NNLO

2.9% precision!

$\ell^+\ell^-\gamma$	533.7	$\pm$ 5.1 (uncorr)	$\pm$ 11.6 (corr) $\pm$ 9.1 (lumi)		
Sherpa LO	438.9	$\pm$ 0.6 (stat)			
Sherpa NLO	514.2	$\pm$ 5.7 (stat)			
MadGraph NLO	503.4	$\pm$ 1.8 (stat)			
Matrix NLO	444.2	$\pm$ 0.1 (stat)	$\pm$ 4.3 (C_{theory})	$\pm$ 8.8 (PDF)	$^{+16.8}_{-18.9}$ (scale)
Matrix NNLO	518.9	$\pm$ 2.0 (stat)	$\pm$ 5.1 (C_{theory})	$\pm$ 10.8 (PDF)	$^{+16.4}_{-14.9}$ (scale)
Matrix NNLO $\times$ NLO EW	513.5	$\pm$ 2.0 (stat)	$\pm$ 2.7 (C_{theory})	$\pm$ 10.8 (PDF)	$^{+16.4}_{-14.9}$ (scale)
Matrix NNLO + NLO EW	518.3	$\pm$ 2.0 (stat)	$\pm$ 2.7 (C_{theory})	$\pm$ 10.8 (PDF)	$^{+16.4}_{-14.9}$ (scale)

*C_{theory} is a parton-to-particle level correction factor (~0.9, obtained from Sherpa)

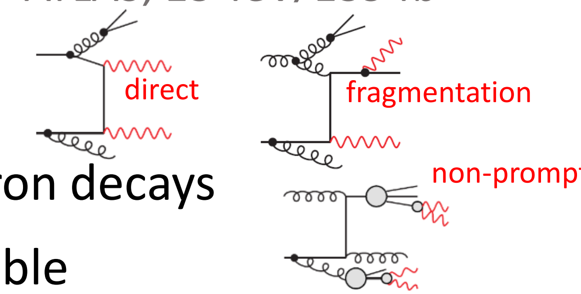




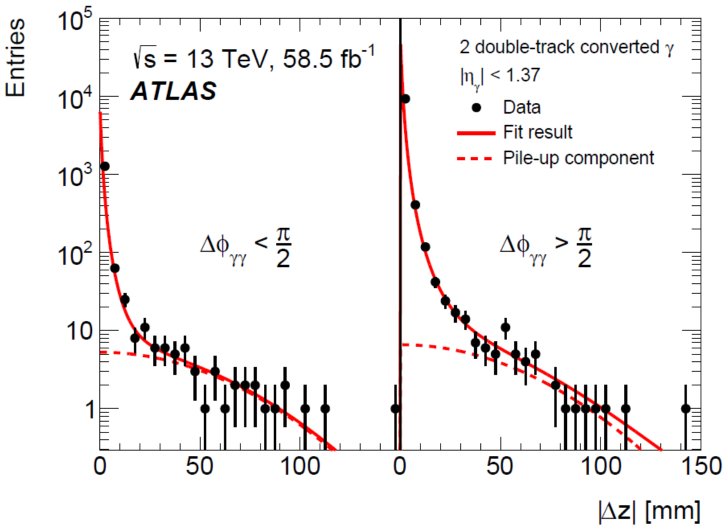
γγ

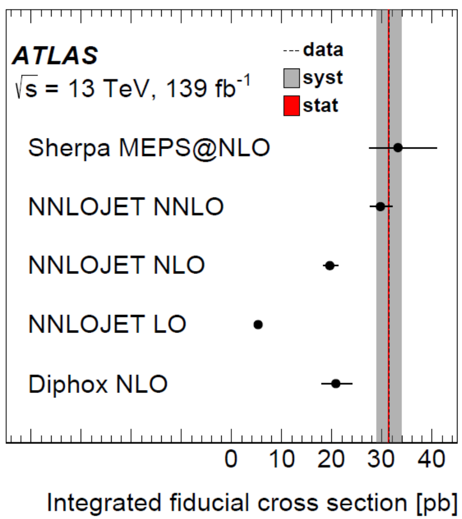
STDM-2017-30 Submitted to JHEP

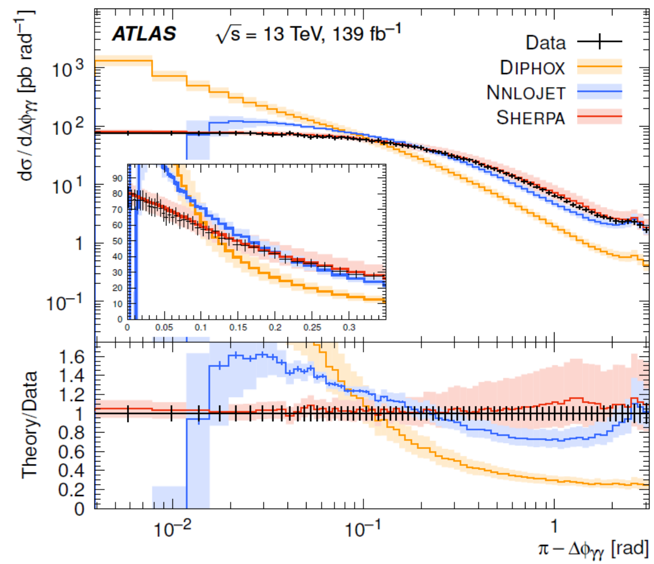
ATLAS, 13 TeV, 139 fb^{-1}



- Signal includes direct and fragmentation photons
- Dominant background: non-prompt photons from hadron decays
- Pileup background normalization from events with double conversions, by fitting $|\Delta z| = |z_{\gamma 1} - z_{\gamma 2}|$







- Integrated cross section described well by Sherpa NLO and NNLOJET NNLO
  - LO and NNLO results differ by a factor of 6!
- Differential cross sections described best by Sherpa
  - Fixed-order predictions fail when the photons are back-to-back -> region sensitive to resummation effects