Measurements of inclusive multi-boson production at ATLAS

Phenomenology 2020 conference

Pittsburgh (virtually), May 2020

Louie Corpe, on behalf of the ATLAS Collaboration

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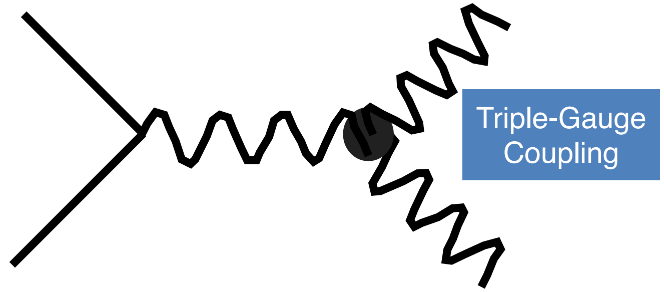
Introduction

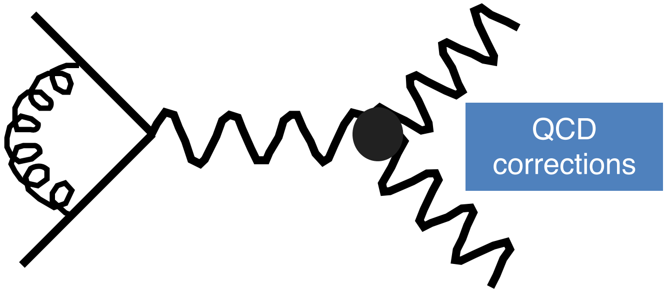
SM processes producing multiple bosons :
- test of EW sector in SM (eg TGC)
- sensitive to perturbative QCD
- sensitive to new physics (eg resonances, effective field theories)
- important SM backgrounds in H measurements or BSM searches

Vector-boson scattering signatures not covered in this talk:
- See dedicated parallel session talk

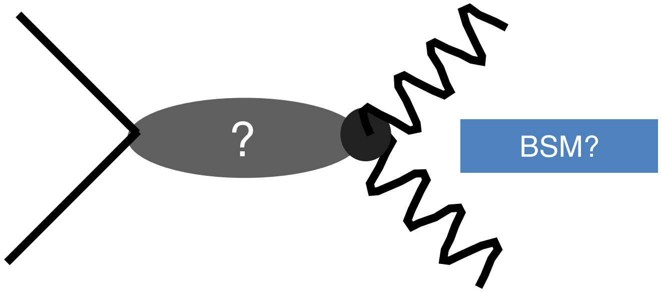
This talk will cover:
- 2 brand-new ATLAS results in Zɣ channel
- signpost to some other ATLAS multi-boson results which have come out in the last year



Triple-Gauge Coupling



QCD corrections



BSM?

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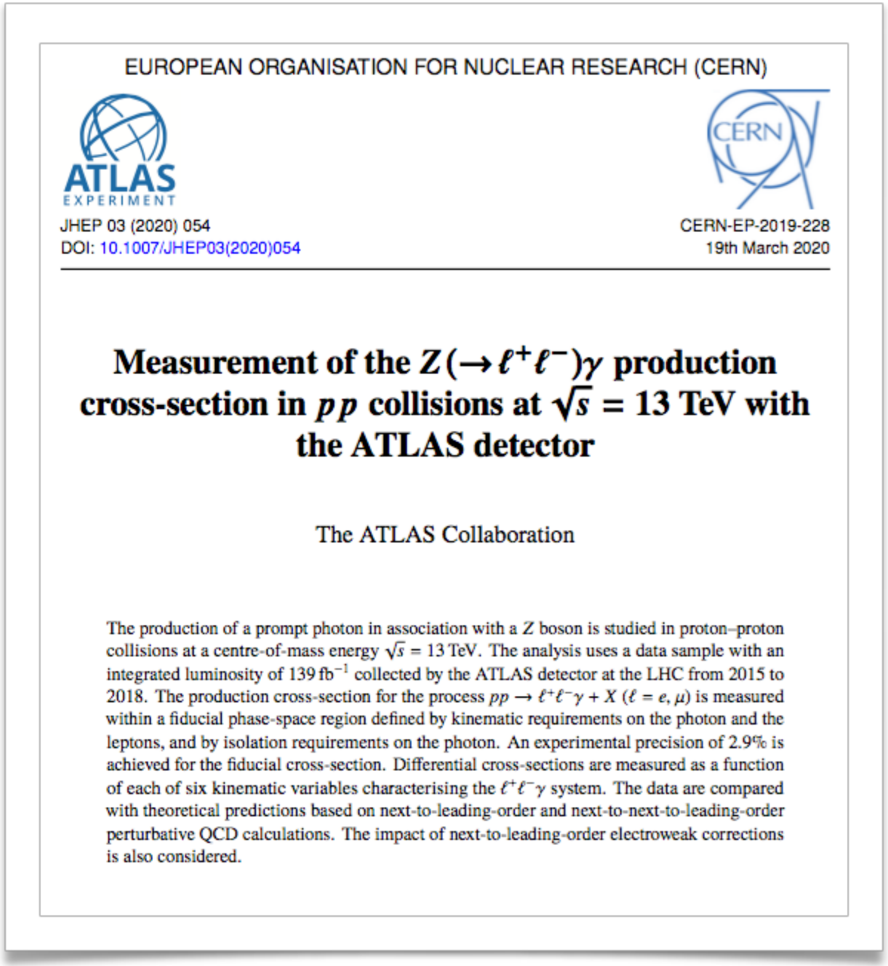
$Z(\rightarrow l^+l^-)\gamma$ production at 13 TeV

JHEP 03 (2020) 054
https://arxiv.org/abs/1911.04813



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

JHEP 03 (2020) 054
DOI: 10.1007/JHEP03(2020)054

CERN-EP-2019-228
19th March 2020

Measurement of the $Z(\rightarrow \ell^+\ell^-)\gamma$ production cross-section in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

The production of a prompt photon in association with a Z boson is studied in proton–proton collisions at a centre-of-mass energy $\sqrt{s} = 13$ TeV. The analysis uses a data sample with an integrated luminosity of 139 fb^{-1} collected by the ATLAS detector at the LHC from 2015 to 2018. The production cross-section for the process $pp \rightarrow \ell^+\ell^-\gamma + X$ ($\ell = e, \mu$) is measured within a fiducial phase-space region defined by kinematic requirements on the photon and the leptons, and by isolation requirements on the photon. An experimental precision of 2.9% is achieved for the fiducial cross-section. Differential cross-sections are measured as a function of each of six kinematic variables characterising the $\ell^+\ell^-\gamma$ system. The data are compared with theoretical predictions based on next-to-leading-order and next-to-next-to-leading-order perturbative QCD calculations. The impact of next-to-leading-order electroweak corrections is also considered.

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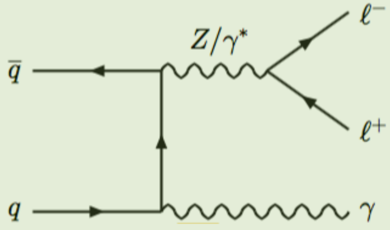
$Z(\rightarrow l^+l^-)\gamma$

- $Z(ll)\gamma$ is particularly clean channel to study EW sector, + dominant SM background in $H\rightarrow Z\gamma$ or $BSM\rightarrow Z\gamma$ searches

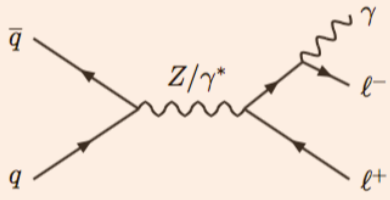
- This paper:139/fb at 13 TeV. Differential particle-level cross-section measurements, unfolded with Bayesian Iterative Technique (2 iterations) wrt:
  - $E_{T,\gamma}$, $|\eta_\gamma|$, $m_{ll\gamma}$,
  - $p^T_{ll\gamma}$, $p^T_{ll\gamma}/m_{ll\gamma}$, $\Delta\phi(ll,\gamma)$

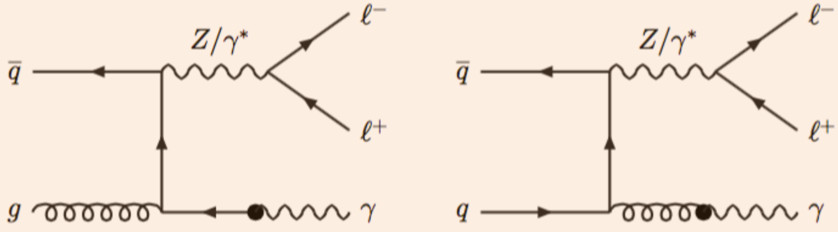
sensitive to pQCD
+ measured for 1st time!

signal ($l = e,\mu$)



suppressed by $(m_{ll}+m_{ll\gamma})>182$ GeV





suppressed with photon isolation

- Data collected with single-e/μ trigger (E_T> 20-26 GeV depending on data period). Efficiency ~99%

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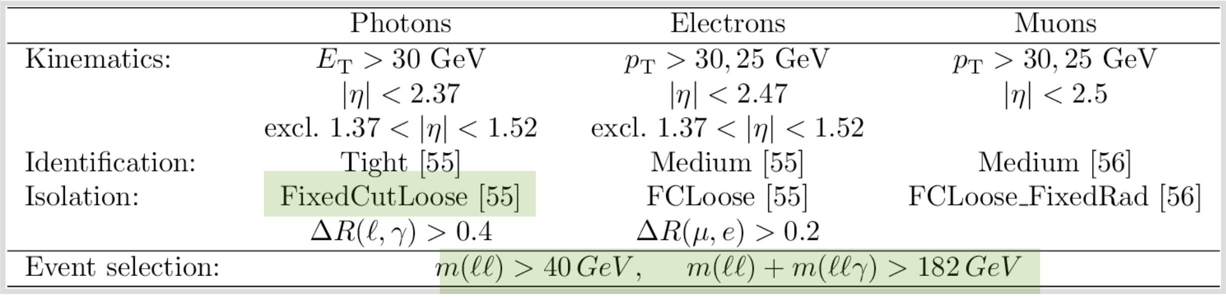
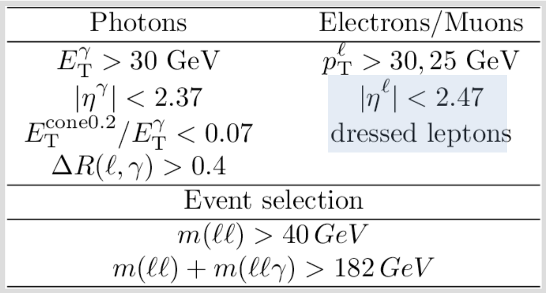
Z(→ l^+l^-)ɣ : Selection

Detector-level selection



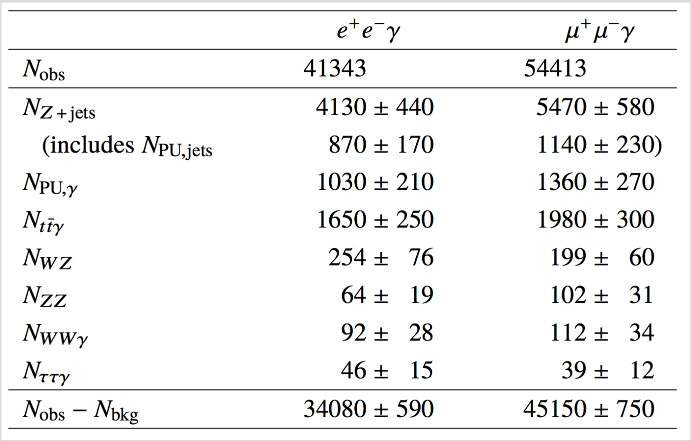
	Photons	Electrons	Muons
Kinematics:	$E_{\mathrm{T}} > 30$ GeV	$p_{\mathrm{T}} > 30, 25$ GeV	$p_{\mathrm{T}} > 30, 25$ GeV
	$\lvert\eta\rvert < 2.37$	$\lvert\eta\rvert < 2.47$	$\lvert\eta\rvert < 2.5$
	excl. $1.37 < \lvert\eta\rvert < 1.52$	excl. $1.37 < \lvert\eta\rvert < 1.52$	
Identification:	Tight [55]	Medium [55]	Medium [56]
Isolation:	FixedCutLoose [55]	FCLoose [55]	FCLoose_FixedRad [56]
	$\Delta R(\ell, \gamma) > 0.4$	$\Delta R(\mu, e) > 0.2$	
Event selection:	$m(\ell\ell) > 40\,GeV$, $m(\ell\ell) + m(\ell\ell\gamma) > 182\,GeV$		

Particle-level selection



Photons	Electrons/Muons
$E_{\mathrm{T}}^{\gamma} > 30$ GeV	$p_{\mathrm{T}}^{\ell} > 30, 25$ GeV
$\lvert\eta^{\gamma}\rvert < 2.37$	$\lvert\eta^{\ell}\rvert < 2.47$
$E_{\mathrm{T}}^{\mathrm{cone0.2}}/E_{\mathrm{T}}^{\gamma} < 0.07$	dressed leptons
$\Delta R(\ell, \gamma) > 0.4$	
Event selection	
$m(\ell\ell) > 40\,GeV$	
$m(\ell\ell) + m(\ell\ell\gamma) > 182\,GeV$	

- Main backgrounds [Data-driven estimates]:
  - Z+jets: 2-dim sideband method, considering probability that jet passes ɣ ID and isolation
  - Pile-up: New method based on estimated *z*-position of ɣ production vertex
    - Pileup: no correlation between *z*-pos of dilepton and photon
    - Hard Scatter: *z*-pos of dilepton and photon should be the same
  - Use high Δz events to get pure PU sample, and extrapolate yield back to SR

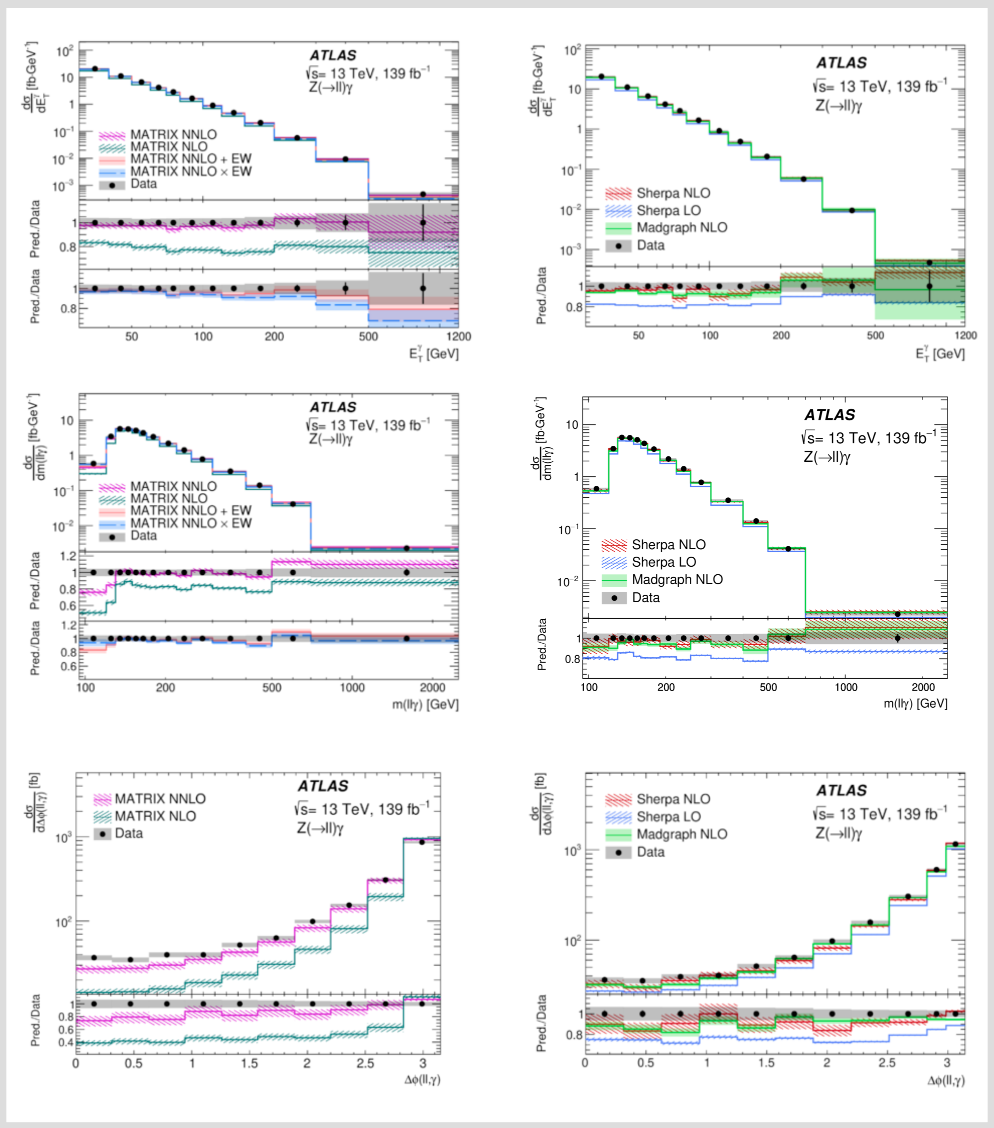


	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$
N_{obs}	41343	54413
$N_{Z+\mathrm{jets}}$	4130 ± 440	5470 ± 580
(includes $N_{\mathrm{PU,jets}}$	870 ± 170	1140 ± 230)
$N_{\mathrm{PU},\gamma}$	1030 ± 210	1360 ± 270
$N_{t\bar{t}\gamma}$	1650 ± 250	1980 ± 300
N_{WZ}	254 ± 76	199 ± 60
N_{ZZ}	64 ± 19	102 ± 31
$N_{WW\gamma}$	92 ± 28	112 ± 34
$N_{\tau\tau\gamma}$	46 ± 15	39 ± 12
$N_{\mathrm{obs}} - N_{\mathrm{bkg}}$	34080 ± 590	45150 ± 750

Dominant uncertainties:

Integrated Luminosity [~1.7%]
Z+jets and PU backgrounds [~1.4%]
Photon ID/Isolation [~1.3%]
Total: ~3% syst, ~0.5% stat

Z(→ l^+l^-)γ : Results



- MadGraph NLO, Sherpa NLO and MATRIX NNLO underestimate cross-section by 3-6% (within uncertainties)
- MATRIX NNLO EW corrections also included (additively / multiplicatively). Reduce prediction by ~1% overall, largest change at high E^{γ}_T, (similar to the difference between NLO / NNLO)
- Spectra shapes in agreement with observation, although some differences in MATRIX NNLO at low **$m_{ll\gamma}$, $\Delta\phi(ll,\gamma)$**
- Overall, precision of measurement for inclusive cross-section is 2.9%: factor two improvement over ATLAS 8TeV

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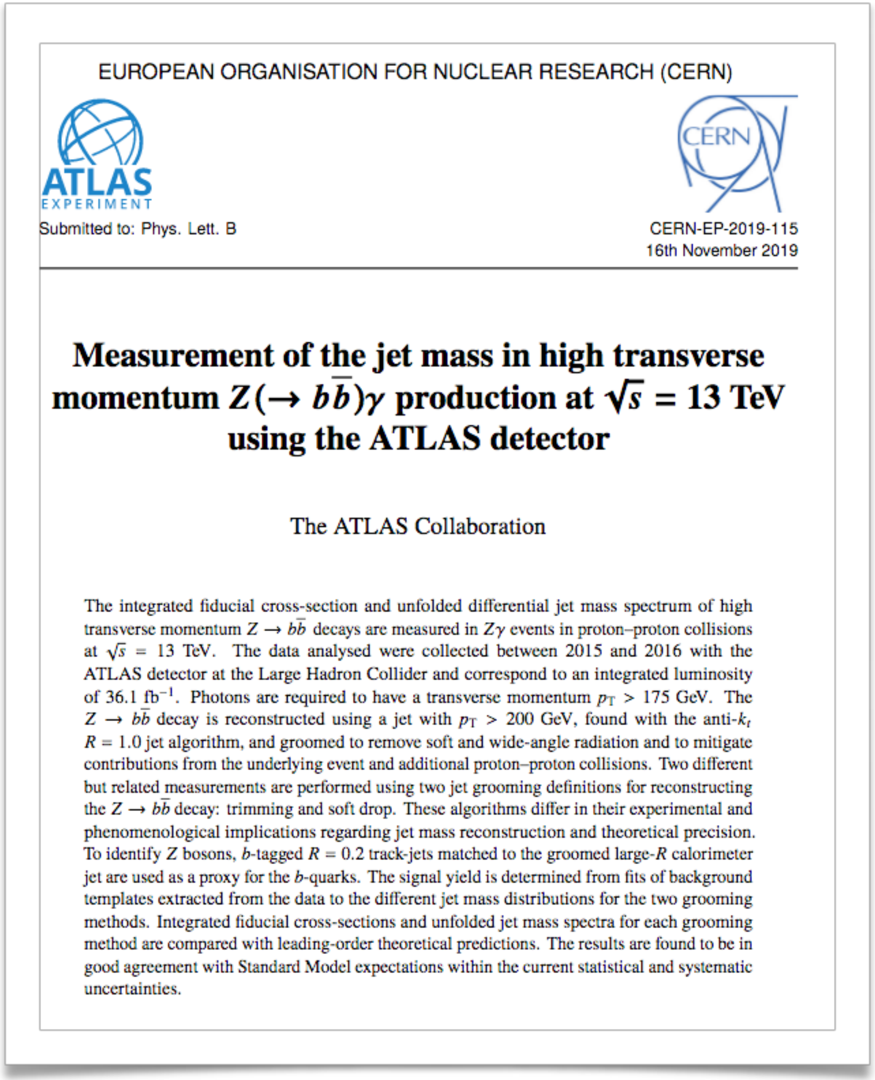
Boosted Z(→ bb)ɣ production at 13 TeV

Submitted to PLB
https://arxiv.org/abs/1907.07093



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: Phys. Lett. B

CERN-EP-2019-115
16th November 2019

Measurement of the jet mass in high transverse momentum $Z(\to b\bar{b})\gamma$ production at $\sqrt{s} = 13$ TeV using the ATLAS detector

The ATLAS Collaboration

The integrated fiducial cross-section and unfolded differential jet mass spectrum of high transverse momentum $Z \to b\bar{b}$ decays are measured in $Z\gamma$ events in proton–proton collisions at $\sqrt{s} = 13$ TeV. The data analysed were collected between 2015 and 2016 with the ATLAS detector at the Large Hadron Collider and correspond to an integrated luminosity of 36.1 fb^{-1}. Photons are required to have a transverse momentum $p_{\text{T}} > 175$ GeV. The $Z \to b\bar{b}$ decay is reconstructed using a jet with $p_{\text{T}} > 200$ GeV, found with the anti-k_t $R = 1.0$ jet algorithm, and groomed to remove soft and wide-angle radiation and to mitigate contributions from the underlying event and additional proton–proton collisions. Two different but related measurements are performed using two jet grooming definitions for reconstructing the $Z \to b\bar{b}$ decay: trimming and soft drop. These algorithms differ in their experimental and phenomenological implications regarding jet mass reconstruction and theoretical precision. To identify Z bosons, b-tagged $R = 0.2$ track-jets matched to the groomed large-R calorimeter jet are used as a proxy for the b-quarks. The signal yield is determined from fits of background templates extracted from the data to the different jet mass distributions for the two grooming methods. Integrated fiducial cross-sections and unfolded jet mass spectra for each grooming method are compared with leading-order theoretical predictions. The results are found to be in good agreement with Standard Model expectations within the current statistical and systematic uncertainties.

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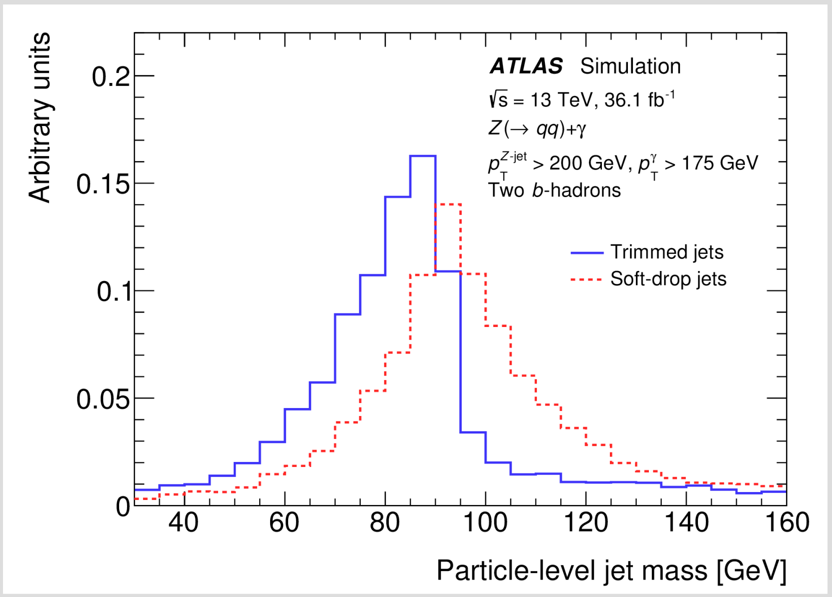
Z(→bb)ɣ

- *Z(bb)ɣ*: well-defined channel to measure boosted *Z* to high-p_T jets
- important for systematics + identification in H->bb at high-p_T
- also sensitive to potential TeV-scale resonances to di-bosons

- The ɣ is useful trigger handle, high-p_T requirement enhances signal over dominant ɣ+jet background

- This result: 36.1/fb at 13 TeV to make particle-level measurements of jet mass spectrum using 2 different jet grooming definitions: “Trimming” and “Soft Drop”



Trimmed Jets: designed for mass resolution and stability versus pileup. Re-cluster components of initial R=1.0 anti-k_t jet, into R=0.2 k_t sub-jets and removing those with p_T less than 5% of parent jet.

Soft-drop jets: designed to remove soft/wide-angle radiation in IR-safe way, by re-clustering initial R=1.0 anti-k_t jet using Cambridge-Aachen algorithm, and removing softer subjets unless certain conditions met

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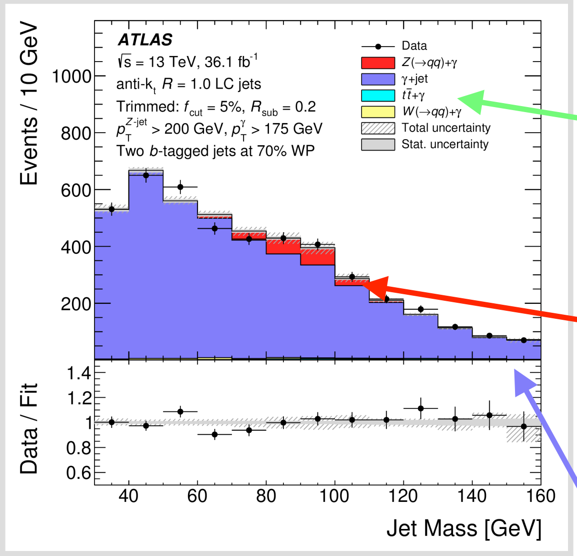
Z(→bb)ɣ : Selection

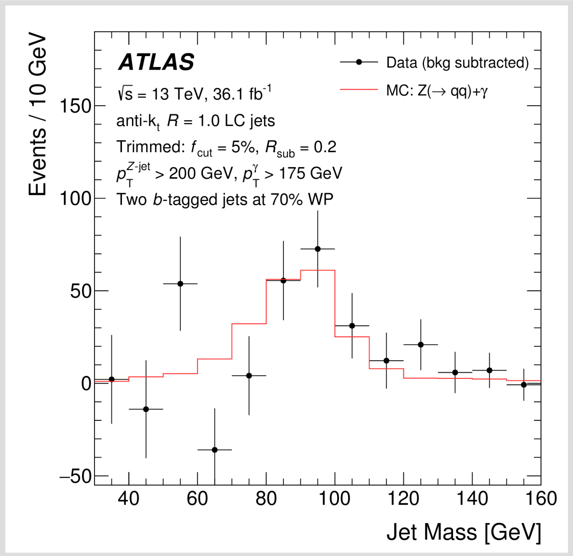
Background subtraction



other minor bkgs from simulation

signal shape est. from simulation

main bkg estimated using data-driven transfer factors from control regions inverting photon ID/ isolation

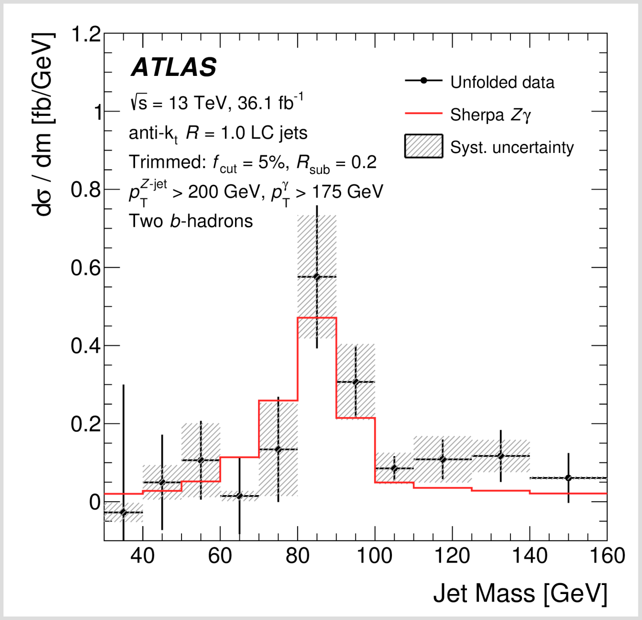


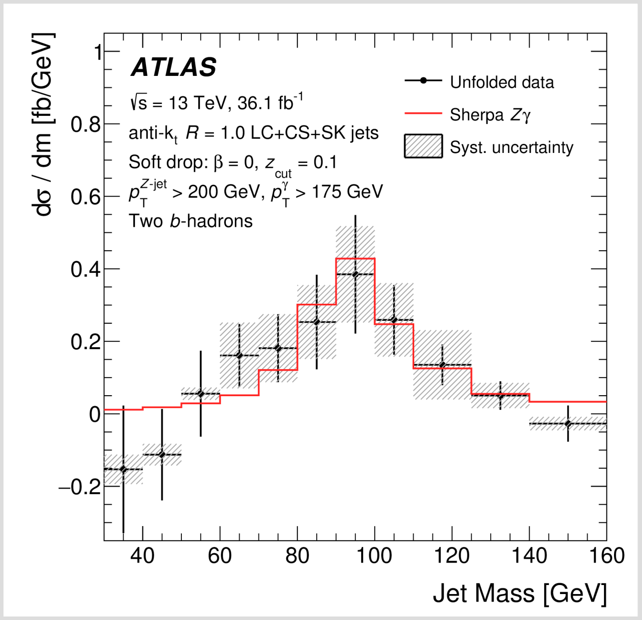
Object/Event	***Criterion***	***Reco-level***	***Particle-level***
b-jets	Radius	R=0.2 (anti-kt)	
	Inputs	tracks with p_T>0.5 GeV, |η|<2.5	
	b-tagging	MV2c10, 70% working point	ghost-associated *b*-hadron
Large-R jets	Inputs	Calorimeter energy deposits	Stable final state particles excluding μ and ν
	Radius	R=1.0 (anti-kt)	
	Grooming	Trimming or Soft-drop	
	p_T	>200 GeV	
	|η|	<2	
	Semileptonic *b*-decays correction	"dressed" with closest muon candidate (p_T>10 GeV, |η|<2) in ΔR<=2	
	Number of *b*-jets	2	
Photons	ID/Isolation	Tight [ref]	pdgID=22
	|η|	[0,1.37] or [1.52, 2.37]	
	p_T	>175 GeV	
Events	Large-R jets	>=1	
	Photons	>=1	
	ΔR (jet, photon)	>1	

Z(→bb)ɣ : Results

Jet definition	$\sigma\ (Z(\to b\bar{b})\gamma,\ p_{\mathrm{T}}^{Z\text{-jet}} > 200$ GeV, $p_{\mathrm{T}}^{\gamma} > 175$ GeV, $30 < m^{Z\text{-jet}} < 160$ GeV) [fb]	
Trimmed jets	Data	17.0 ± 5.0 (stat.) ± 3.6 (syst.)
	SHERPA $Z\gamma$ prediction	13.4 ± 0.2 (stat.)
	MADGRAPH+PYTHIA 8 $Z\gamma$ prediction	9.1 ± 0.1 (stat.)
Soft-drop jets	Data	12.5 ± 4.9 (stat.) ± 3.1 (syst.)
	SHERPA $Z\gamma$ prediction	15.4 ± 0.1 (stat.)
	MADGRAPH+PYTHIA 8 $Z\gamma$ prediction	10.2 ± 0.1 (stat.)

Dominant uncertainties:
Stat uncertainty in fit [30-39%]
Zy modelling [12-15%]
Backgrounds [10-13%]
Jet energy/mass scale/res [9%]
Unfolding [6-9%]
..
Total: 37-46%





Fiducial cross-section measurements and differential jet mass cross-section found to be in agreement with the LO predictions from Sherpa/MG+Py8

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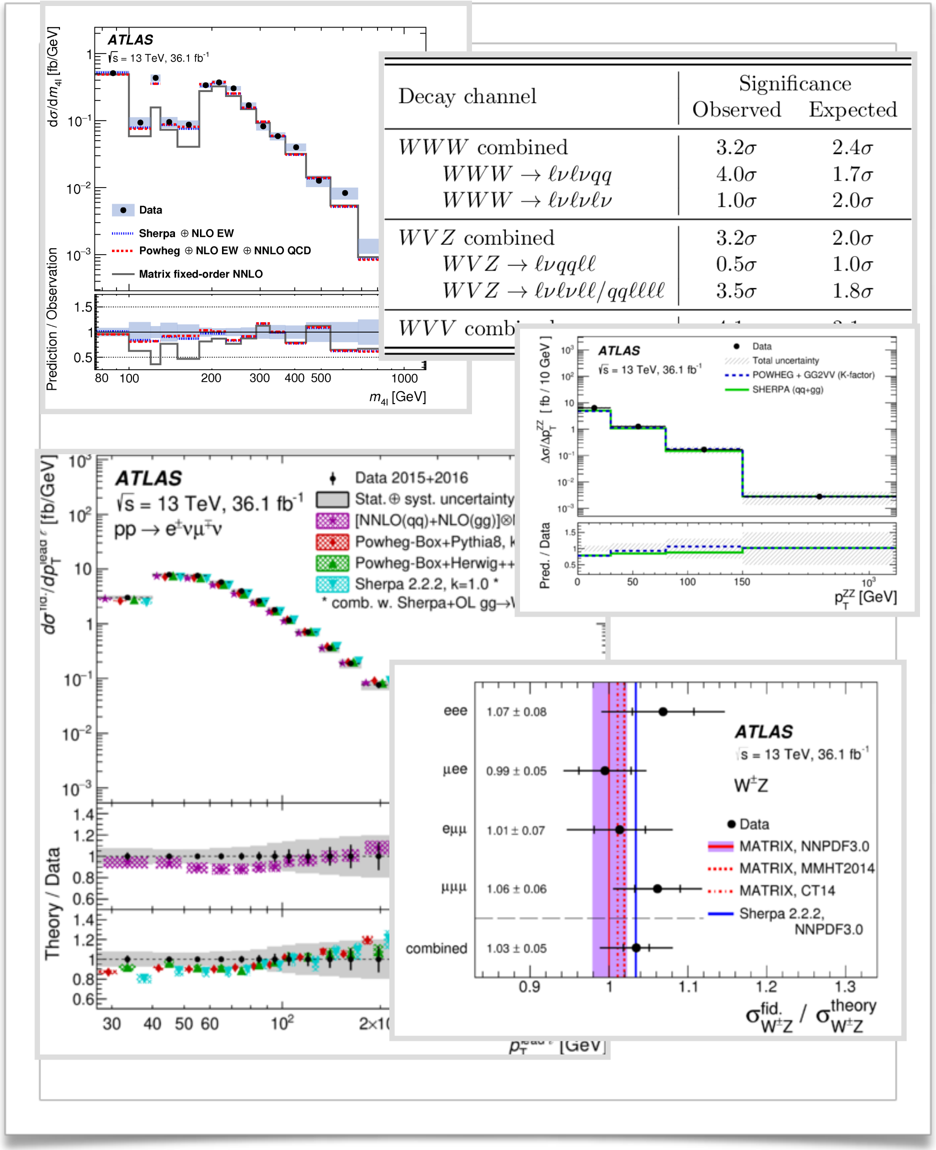
Other ATLAS multi-boson results

Highlights



Decay channel	Significance Observed	Significance Expected
WWW combined	3.2σ	2.4σ
$WWW \to \ell\nu\ell\nu qq$	4.0σ	1.7σ
$WWW \to \ell\nu\ell\nu\ell\nu$	1.0σ	2.0σ
WVZ combined	3.2σ	2.0σ
$WVZ \to \ell\nu qq\ell\ell$	0.5σ	1.0σ
$WVZ \to \ell\nu\ell\nu\ell\ell/qq\ell\ell\ell\ell$	3.5σ	1.8σ
WVV comb		

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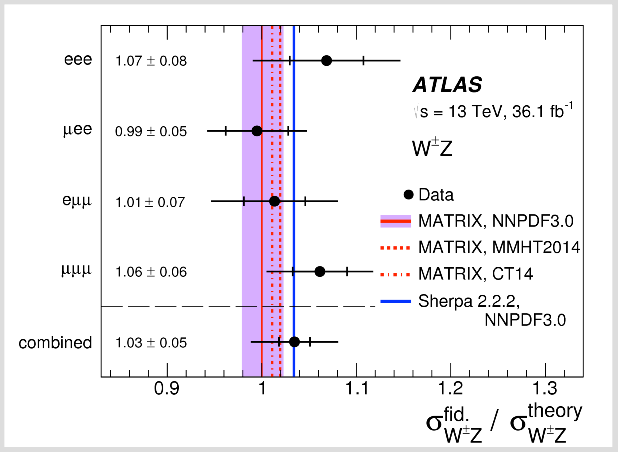
Measurement of WZ production and gauge polarisation 13 TeV with the ATLAS detector

https://arxiv.org/abs/1902.05759
Eur. Phys. J. C 79 (2019) 535

- 36/fb at 13 TeV
- Exploit leptonic decay modes of W and Z
- Cross-sections for W+Z and W-Z, their ratios, and differential measurements
- Measures helicity fractions in the fiducial phase space



	f_0			$f_{\mathrm{L}} - f_{\mathrm{R}}$		
	Data	POWHEG+PYTHIA	MATRIX	Data	POWHEG+PYTHIA	MATRIX
W^+ in W^+Z	0.26 ± 0.08	0.233 ± 0.004	0.2448 ± 0.0010	−0.02 ± 0.04	0.091 ± 0.004	0.0868 ± 0.0014
W^- in W^-Z	0.32 ± 0.09	0.245 ± 0.005	0.2651 ± 0.0015	−0.05 ± 0.05	−0.063 ± 0.006	−0.034 ± 0.004
$W^\pm$ in $W^\pm Z$	0.26 ± 0.06	0.2376 ± 0.0031	0.2506 ± 0.0006	−0.024 ± 0.033	0.0289 ± 0.0022	0.0375 ± 0.0011
Z in W^+Z	0.27 ± 0.05	0.225 ± 0.004	0.2401 ± 0.0014	−0.32 ± 0.21	−0.297 ± 0.021	−0.262 ± 0.009
Z in W^-Z	0.21 ± 0.06	0.235 ± 0.005	0.2389 ± 0.0015	−0.46 ± 0.25	0.052 ± 0.023	0.0468 ± 0.0034
Z in $W^\pm Z$	0.24 ± 0.04	0.2294 ± 0.0033	0.2398 ± 0.0014	−0.39 ± 0.16	−0.156 ± 0.016	−0.135 ± 0.006

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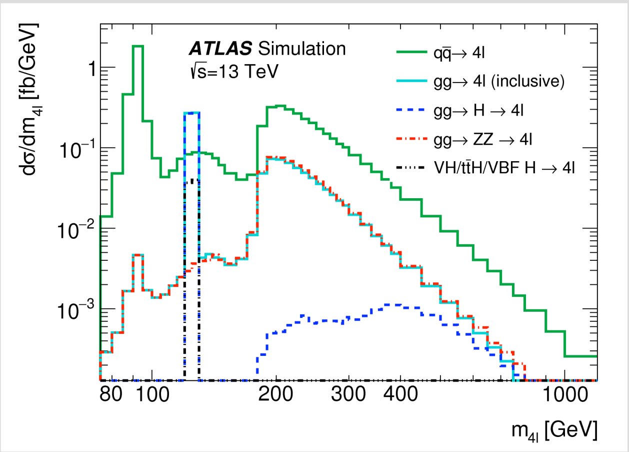
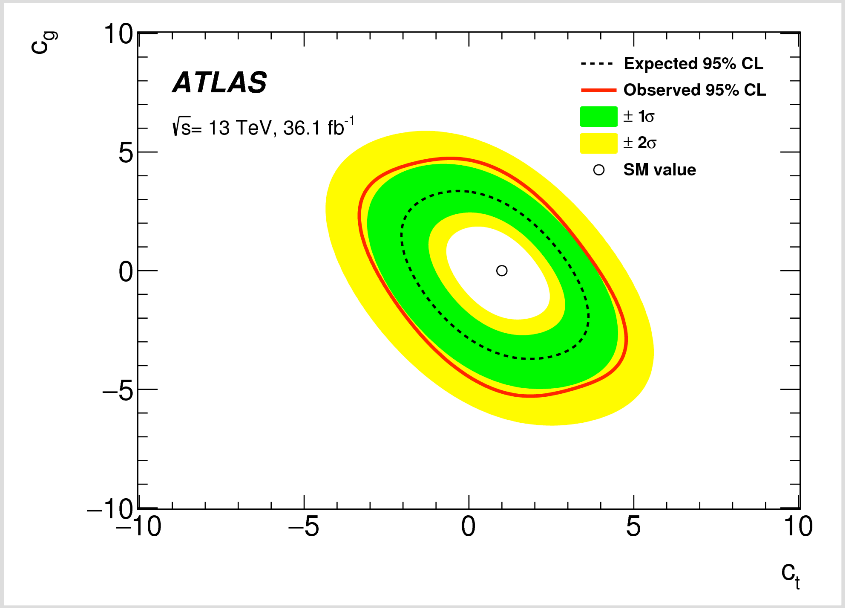
Measurement of the 4 lepton invariant mass distribution at 13 TeV with the ATLAS detector

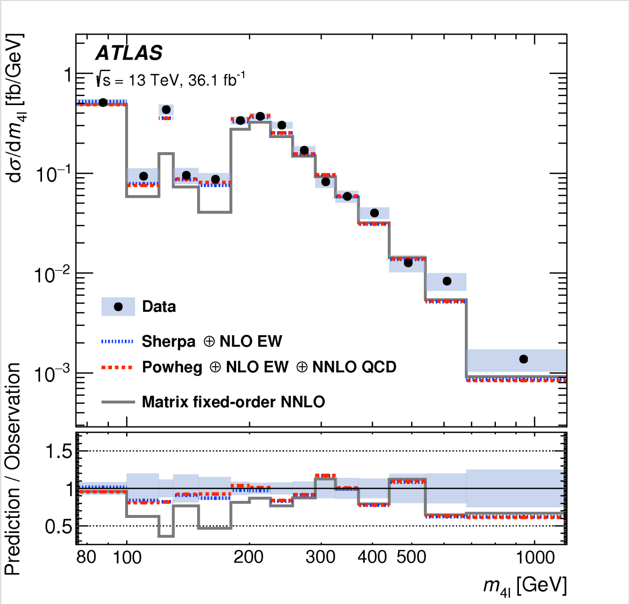
https://arxiv.org/abs/1902.05892

JHEP 04 (2019) 048

- 36/fb at 13 TeV
- Rich spectrum of SM processes
- Differential in m4l
- Double-differential in m4l vs several observables
- Constraints on anomalous Higgs couplings



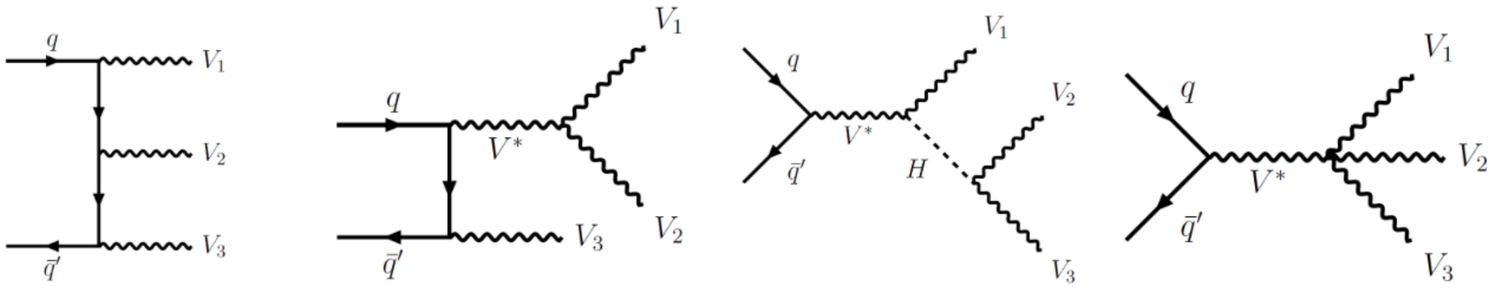


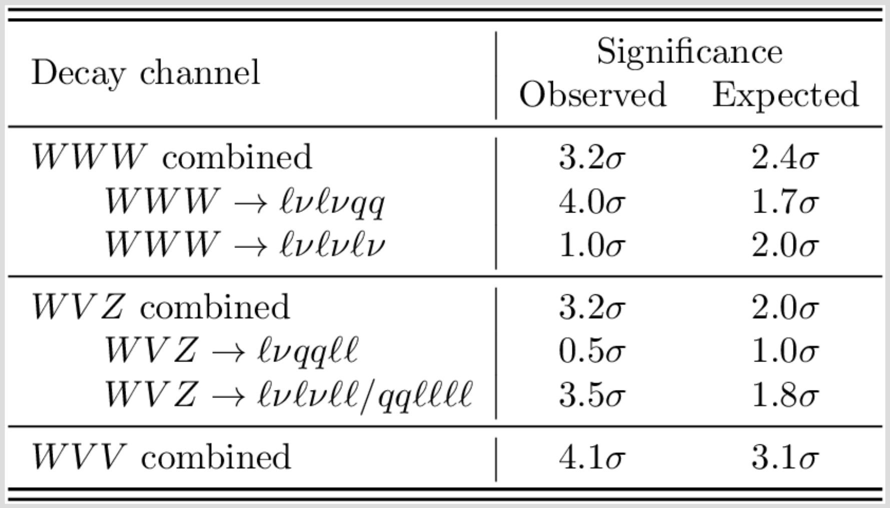


Evidence for the production of three massive vector bosons with the ATLAS detector

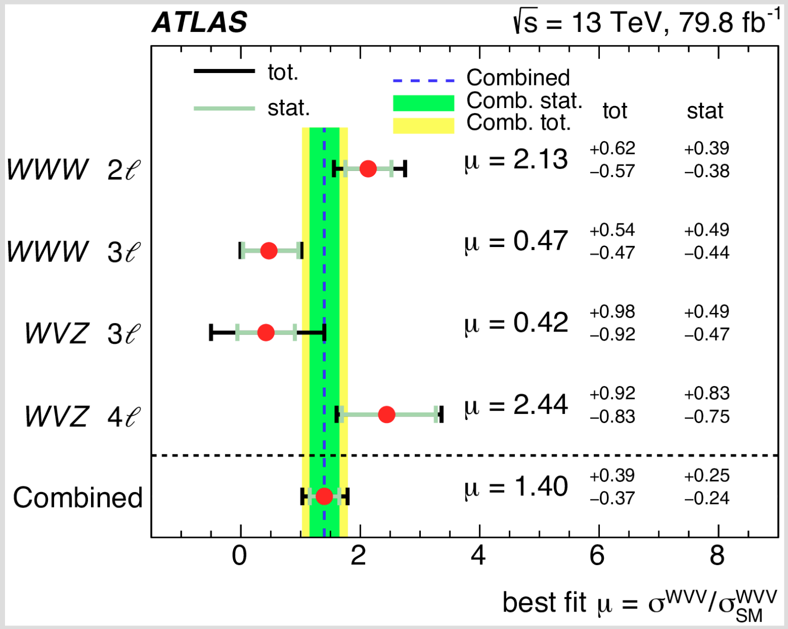
- 79.8/fb at 13 TeV
- Covers WWW, WWZ, WZZ in 2-, 3-, 4-lepton channels

https://arxiv.org/abs/1903.10415
Phys. Lett. B 798 (2019) 134913





Decay channel	Significance Observed	Significance Expected
WWW combined	3.2σ	2.4σ
$WWW \to \ell\nu\ell\nu qq$	4.0σ	1.7σ
$WWW \to \ell\nu\ell\nu\ell\nu$	1.0σ	2.0σ
WVZ combined	3.2σ	2.0σ
$WVZ \to \ell\nu qq\ell\ell$	0.5σ	1.0σ
$WVZ \to \ell\nu\ell\nu\ell\ell/qq\ell\ell\ell\ell$	3.5σ	1.8σ
WVV combined	4.1σ	3.1σ



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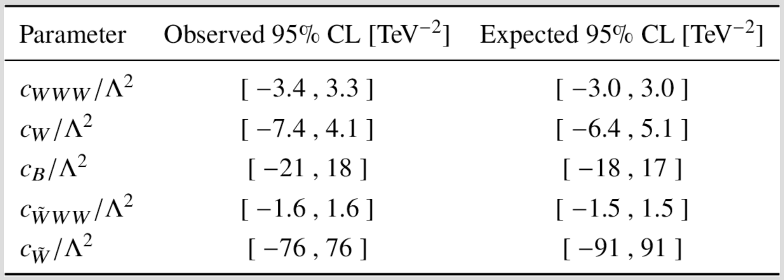
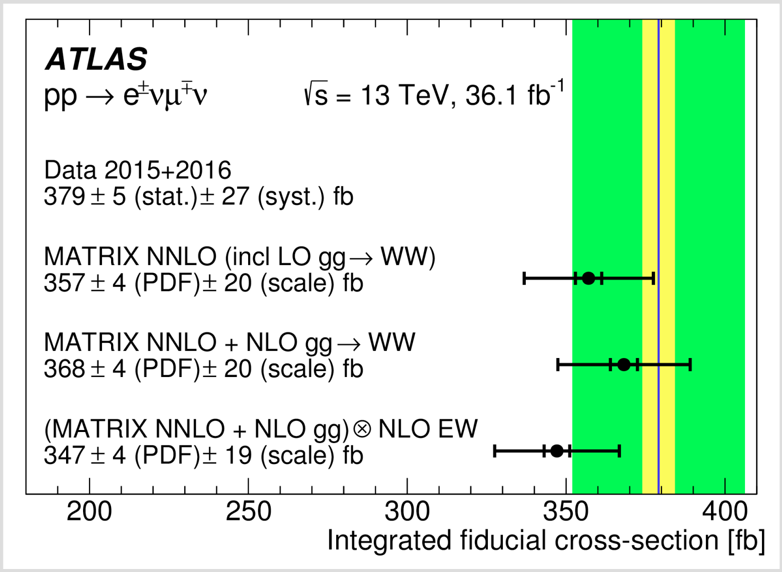
Measurement of fiducial and differential WW production cross-sections at 13 TeV with ATLAS

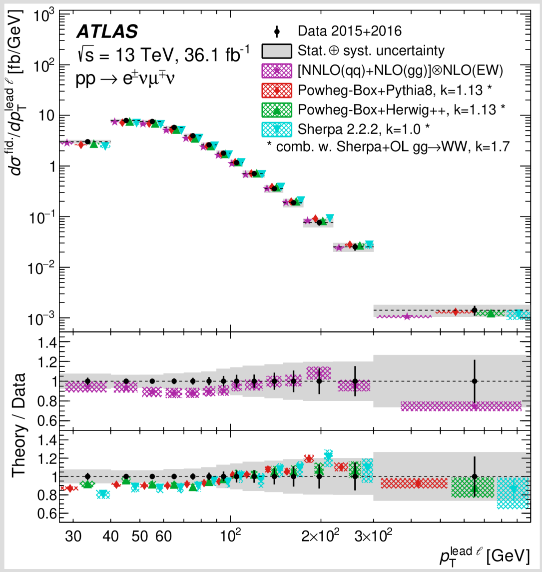
- 36.1/fb at 13 TeV
- Selects opposite-flavour-lepton events to target WW-> eνμν
- events with high-p_T jets are excluded to suppress top background
- Fiducial and differential cross-sections
- **EFT interpretation on anomalous gauge couplings** [more info in backup]

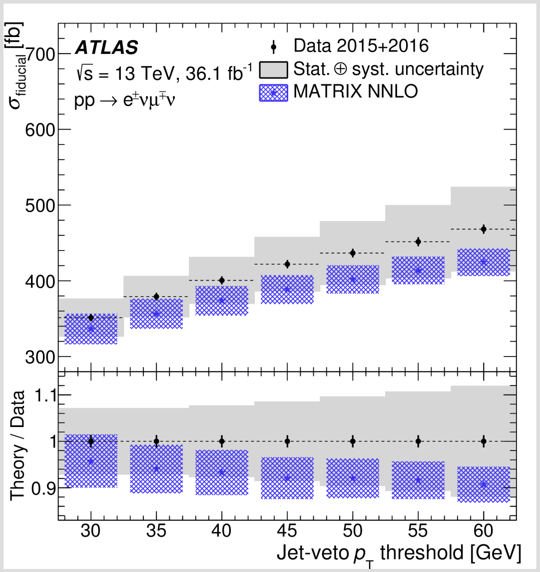
https://arxiv.org/abs/1905.04242
Eur. Phys. J. C 79 (2019) 884



Parameter	Observed 95% CL [TeV^{-2}]	Expected 95% CL [TeV^{-2}]
c_{WWW}/Λ^2	[−3.4 , 3.3]	[−3.0 , 3.0]
c_{W}/Λ^2	[−7.4 , 4.1]	[−6.4 , 5.1]
c_{B}/Λ^2	[−21 , 18]	[−18 , 17]
$c_{\tilde{W}WW}/\Lambda^2$	[−1.6 , 1.6]	[−1.5 , 1.5]
$c_{\tilde{W}}/\Lambda^2$	[−76 , 76]	[−91 , 91]







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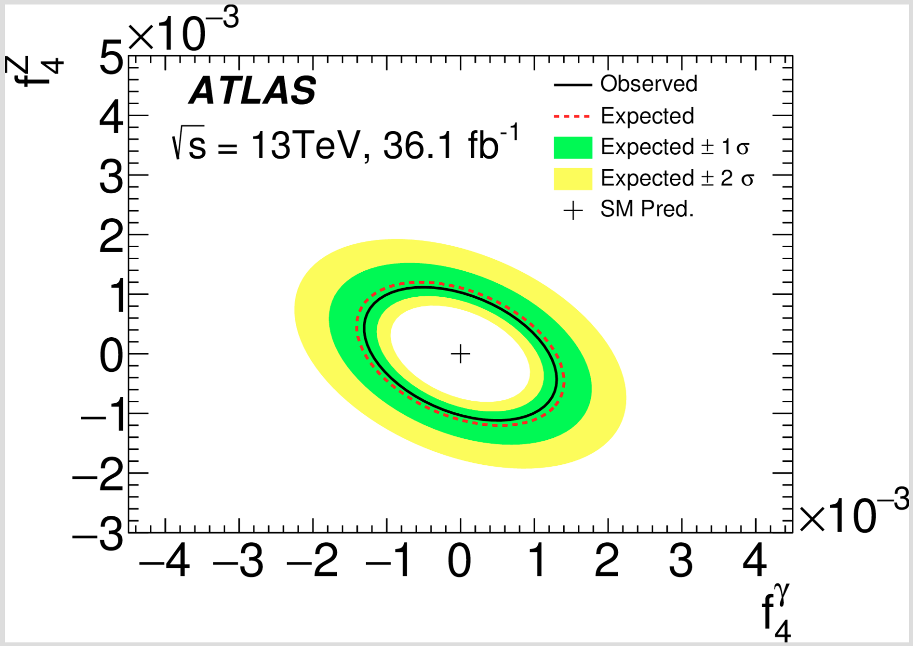
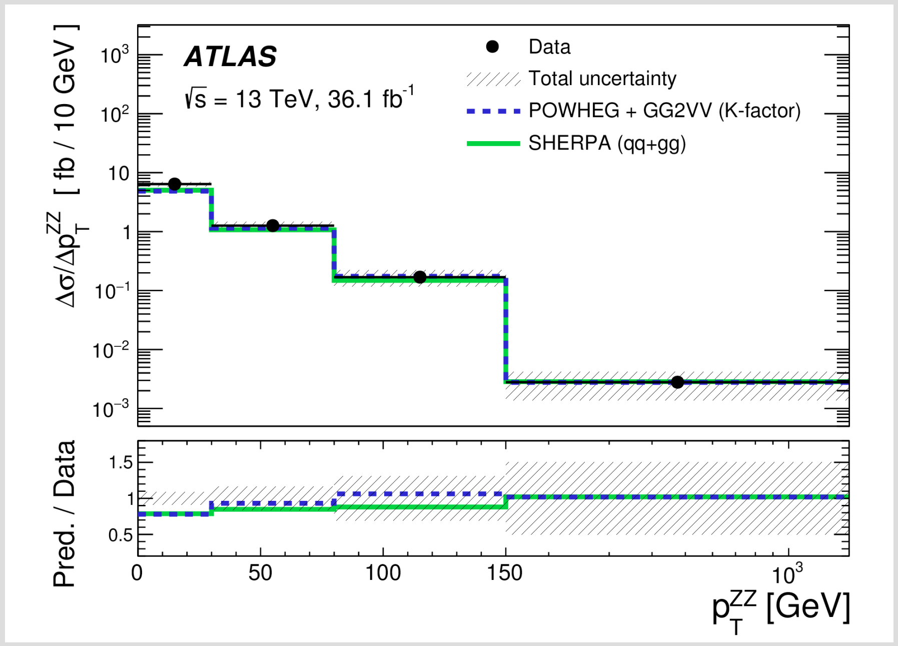
Measurement of ZZ production in the llvv final state at 13 TeV with ATLAS

https://arxiv.org/abs/1905.07163
JHEP 10 (2019) 127

- 36.1/fb at 13 TeV
- Integrated cross-sections measured with an uncertainty of 7%, along with differential measurements
- Constraints on anomalous TGC





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Thank you!

Questions?

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Extra material

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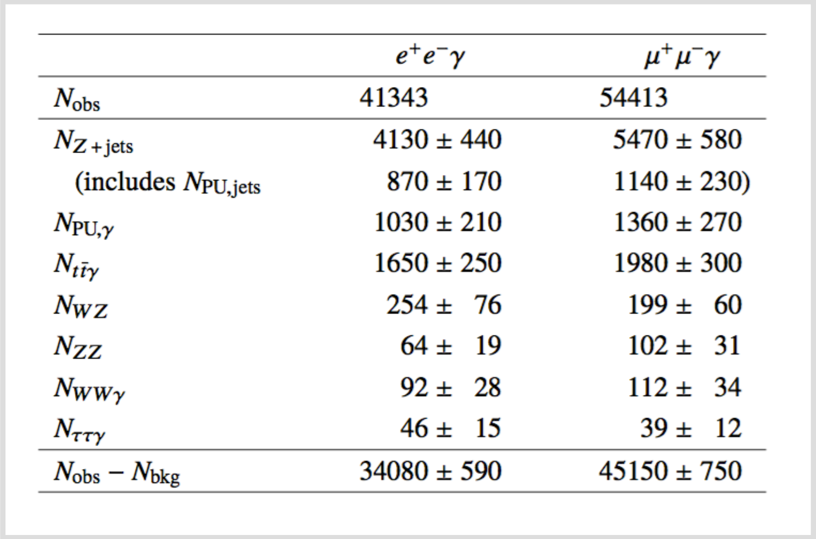
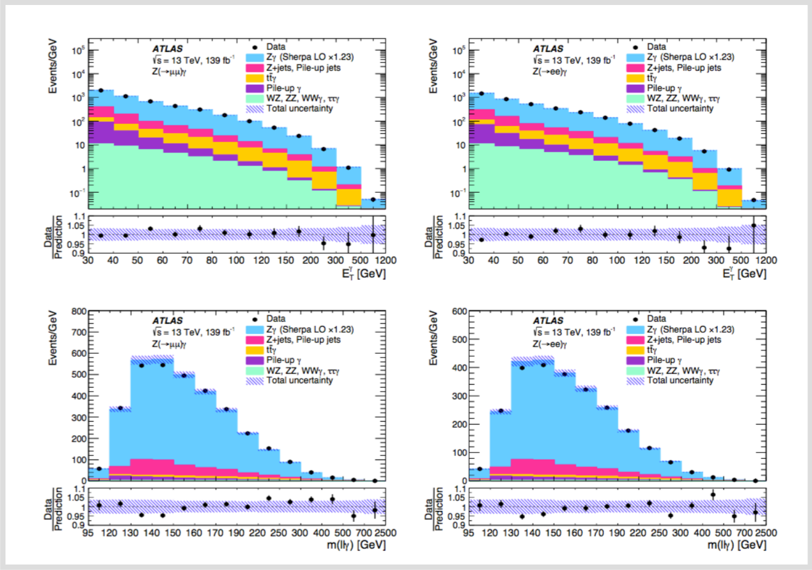
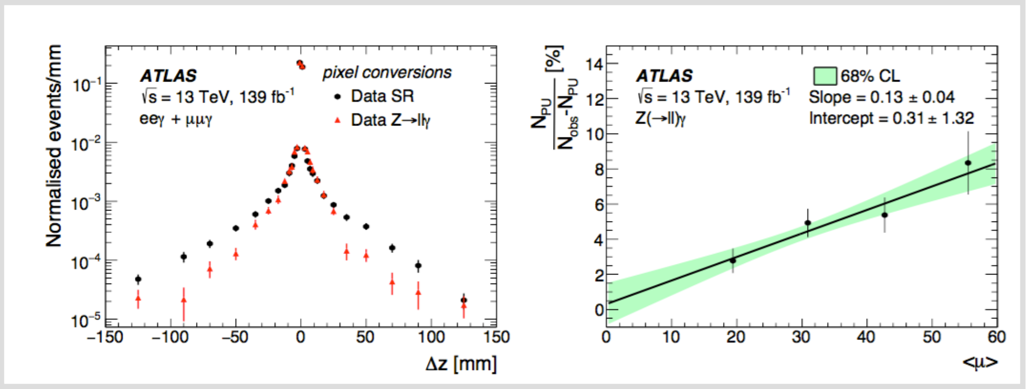
Z(→ l+l-)γ : Backgrounds



	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$
N_{obs}	41343	54413
$N_{Z+\text{jets}}$	4130 ± 440	5470 ± 580
(includes $N_{\text{PU,jets}}$	870 ± 170	1140 ± 230)
$N_{\text{PU},\gamma}$	1030 ± 210	1360 ± 270
$N_{t\bar{t}\gamma}$	1650 ± 250	1980 ± 300
N_{WZ}	254 ± 76	199 ± 60
N_{ZZ}	64 ± 19	102 ± 31
$N_{WW\gamma}$	92 ± 28	112 ± 34
$N_{\tau\tau\gamma}$	46 ± 15	39 ± 12
$N_{\text{obs}} - N_{\text{bkg}}$	34080 ± 590	45150 ± 750

- Main backgrounds [Data-driven estimates]:
  - Z+jets: 2-dim sideband method, considering probability that jet passes γ ID and isolation
  - Pile-up: Method based on estimated *z*-position of γ production vertex

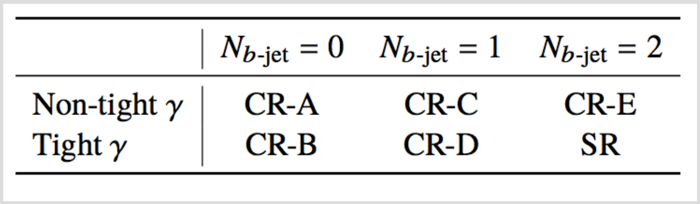




$$N_{\text{PU,pix-conv}} = \frac{N^{\text{high}\,|\Delta z|}_{\text{data, pix-conv}} - N^{\text{high}\,|\Delta z|}_{\text{single-}pp\text{, pix-conv}}}{\mathcal{P}^{\text{high}\,|\Delta z|}_{\text{PU, pix-conv}}},$$

Z(→ bb)ɣ : Backgrounds

- Background templates from MC/ from Data are fitted to the observed jet mass spectrum
- Dominant backgrounds:
  - y + jets with gluon to *bb* splitting [data-driven templates: MC not reliable]
    - Calculate transfer factors from Control Regions with modified $N_{\text{b-jet}}$ and inverted photon ID/isolation requirements
  - tty, Wy [templates from MC]
  - Multijet / V+jets / Hy (negligible)



	$N_{b\text{-jet}} = 0$	$N_{b\text{-jet}} = 1$	$N_{b\text{-jet}} = 2$
Non-tight γ	CR-A	CR-C	CR-E
Tight γ	CR-B	CR-D	SR

$$N^{\gamma+\text{jets}}_{\text{CR},i} = N_{\text{CR},i} - N^{t\bar{t}+\gamma}_{\text{CR},i} - N^{W\gamma}_{\text{CR},i}$$

$$N^{\gamma+\text{jets}}_{\text{SR},i} = \left(\frac{N^{\gamma+\text{jets}}_{\text{CR-D},i}}{N^{\gamma+\text{jets}}_{\text{CR-C},i}} \right) N^{\gamma+\text{jets}}_{\text{CR-E},i} ,$$

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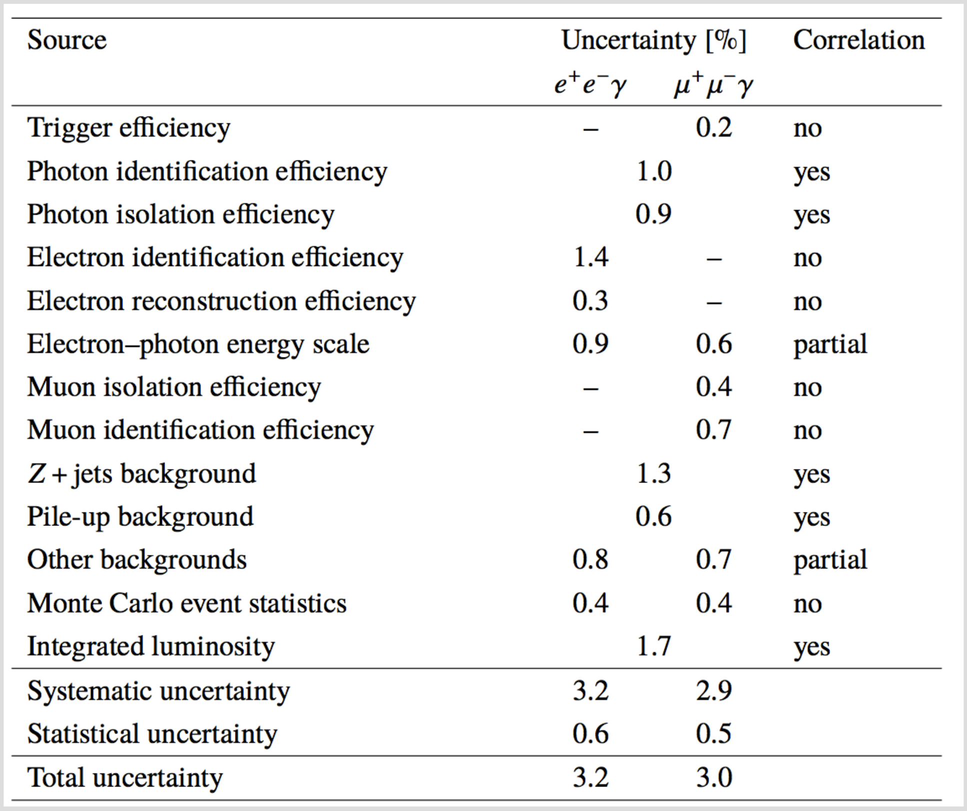
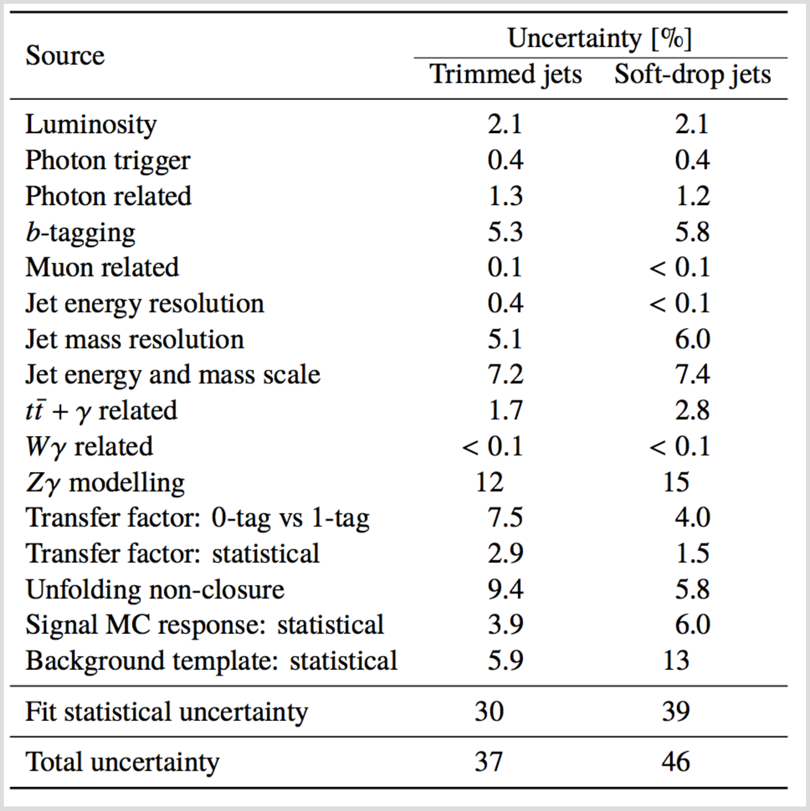
Z(→ l^+l^-)ɣ and Z(→ bb)ɣ : Uncertainties

Z(→ l^+l^-)ɣ



Source	Uncertainty [%]		Correlation
	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$	
Trigger efficiency	–	0.2	no
Photon identification efficiency	1.0		yes
Photon isolation efficiency	0.9		yes
Electron identification efficiency	1.4	–	no
Electron reconstruction efficiency	0.3	–	no
Electron–photon energy scale	0.9	0.6	partial
Muon isolation efficiency	–	0.4	no
Muon identification efficiency	–	0.7	no
Z + jets background	1.3		yes
Pile-up background	0.6		yes
Other backgrounds	0.8	0.7	partial
Monte Carlo event statistics	0.4	0.4	no
Integrated luminosity	1.7		yes
Systematic uncertainty	3.2	2.9	
Statistical uncertainty	0.6	0.5	
Total uncertainty	3.2	3.0	

Z(→ bb)ɣ



Source	Uncertainty [%]	
	Trimmed jets	Soft-drop jets
Luminosity	2.1	2.1
Photon trigger	0.4	0.4
Photon related	1.3	1.2
b-tagging	5.3	5.8
Muon related	0.1	< 0.1
Jet energy resolution	0.4	< 0.1
Jet mass resolution	5.1	6.0
Jet energy and mass scale	7.2	7.4
$t\bar{t} + \gamma$ related	1.7	2.8
$W\gamma$ related	< 0.1	< 0.1
$Z\gamma$ modelling	12	15
Transfer factor: 0-tag vs 1-tag	7.5	4.0
Transfer factor: statistical	2.9	1.5
Unfolding non-closure	9.4	5.8
Signal MC response: statistical	3.9	6.0
Background template: statistical	5.9	13
Fit statistical uncertainty	30	39
Total uncertainty	37	46

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WW production EFT interpretation

- Self-coupling of EW bosons can be probed by WWZ when Ws are produced in s-channel
- New physics at scale Λ can alter WW production, and can be described by an EFT with dimension 6 -> anomalous TGC
- Constraints on EFT coeffs determined one at a time using leading l pT unfolded fiducial cross-section (most sensitive observable)
- Alternative pT distributions generated at LO for each Ci (SM, BSM + interference) in MG_aMC@NLO
- Construct likelihood function, and calculate 95%CL intervals
- Improvements wrt previous results due to increase CoM

Parameter	Observed 95% CL [TeV^{-2}]	Expected 95% CL [TeV^{-2}]
c_{WWW}/Λ^2	[−3.4 , 3.3]	[−3.0 , 3.0]
c_W/Λ^2	[−7.4 , 4.1]	[−6.4 , 5.1]
c_B/Λ^2	[−21 , 18]	[−18 , 17]
$c_{\tilde{W}WW}/\Lambda^2$	[−1.6 , 1.6]	[−1.5 , 1.5]
$c_{\tilde{W}}/\Lambda^2$	[−76 , 76]	[−91 , 91]

c_{WWW}, c_W, c_B, $c_{\tilde{W}WW}$ and $c_{\tilde{W}}$

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i \, .$$

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