Measurement of multiboson production in ATLAS

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On behalf of the ATLAS Collaboration

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Multiboson Physics

- Multiboson physics provides a unique probe of the Standard Model through electroweak-boson self-interactions
  - Precision tests of Standard Model theory predictions
  - Search for Beyond Standard Model physics
    - Anomalous gauge boson couplings

- This talk shows recent multiboson results from ATLAS Collaboration

- Di-boson production
  - Precision measurement in WW compared to previous measurements

WW : ATLAS-CONF-2023-012

- Tri-boson production
  - Differential measurements of $Z\gamma\gamma$ production to look deeper into the production mechanism
  - Observation of some most rare processes measured to date : $W\gamma\gamma$ and $WZ\gamma$

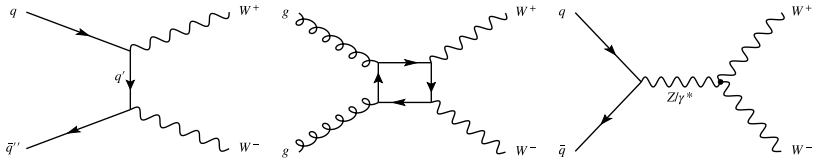
Zγγ : Eur. Phys. J. C 83 (2023) 539

Wγγ : ATLAS-CONF-2023-005

WZγ : arXiv:2305.16994

WW - Overview

ATLAS-CONF-2023-012



- W boson pair production is a key process to test self-couplings predicted by the Electron Weak sector of the Standard Model
- Stringent test for QCD corrections

- Most precise WW cross-section measurement in hadron-hadron collisions : 3.2% uncertainty after fitting compared to 6% (CMS) and 7% (ATLAS)
  - Fully leptonic final states : $e + \mu$
  - Better (top and fake) background estimates
  - **Jet-inclusive phase space** with high precision (**New**)
    - Extrapolation uncertainties reduced
- Measurement new observables based on lepton/*jet*/*met* kinematics

- **Fiducial cross section** :
  - σ_{fid} = 707 ± 7 (stat) ± 20 (syst) fb
- **Total cross section** :
  - σ_{total} = 127 ± 1 (stat) ± 4 (syst) pb

MC Samples and Event Selection

- **State-of-the-art** prediction model for on- and off-shell WW production

Process	Generator	Parton shower	Matrix element $\mathcal{O}(\alpha_S)$	Normalization
$q\bar{q} \to WW$	MiNNLO	Pythia8	NNLO	Generator
$gg \to WW$	Sherpa2.2.2	Sherpa	LO (0–1 jet)	NLO
$t\bar{t}$	Powheg Boxv2	Pythia8	NLO	NNLO+NNLL
Wt	Powheg Boxv2	Pythia8	NLO	NLO+NNLL
Z+jets	Sherpa2.2.1	Sherpa	NLO (0–2 jets), LO (3–4 jets)	NNLO
WZ, ZZ	Sherpa2.2.2	Sherpa	NLO (0–1 jet), LO (2–3 jets)	Generator†
$W\gamma, Z\gamma$	Sherpa2.2.8	Sherpa	NLO (0–1 jet), LO (2–3 jets)	Generator†

†: The cross-section calculated by Sherpa is found to be in good agreement with the NNLO result

- MiNNLO+Pythia8 (particle level, NNLO-QCD)
- MATRIX (Fixed-order NNLO-QCD$\times$NLO-EW ($q\bar{q}$) $\times$ NLO-QCD(gg) + γ-induced WW)

Selection	Criteria
Lepton p_T	> 27 GeV
Lepton η	$\lvert\eta\rvert < 2.47$ and not $1.37 < \lvert\eta\rvert < 1.52$ (electron) $\lvert\eta\rvert < 2.5$ (muon)
Lepton identification	`TightLH` (electron), `Medium` (muon)
Lepton isolation	`Gradient` (electron), `Tight_FixedRad` (muon)
Lepton impact parameter	$\lvert d_0/\sigma_{d_0}\rvert < 5, 3$ (electron, muon) $\lvert z_0 \cdot \sin\theta\rvert < 0.5$ mm
b-jet selection	$p_T > 20$ GeV, $\lvert\eta\rvert < 2.5$, DL1r (85% eff. WP)
Jet selection	$p_T > 30$ GeV, $\lvert\eta\rvert < 4.5$
Lepton selection	1 electron and 1 muon of opposite charge, no additional lepton with $p_T > 10$ GeV, `Loose` isolation, and `LooseLH` (electron) / `Loose` (muon) identification
Number of b-jets	0
Dilepton invariant mass	> 85 GeV

Theory Predictions

- $q\bar{q} \rightarrow WW$
  - Powheg MiNNLO + NNPDF3.0nnlo is 7% smaller than the fixed-order NNLO prediction using NNPDF3.1nnlo
  - Sherpa2.2.12 predicts a fiducial cross-section similar to Powheg MiNNLO

- $gg \rightarrow WW$
  - The Sherpa2.2.2 LO is significantly smaller than the MATRIX NLO QCD
  - A ***k*-factor** of **1.7** is applied(ratio of NLO and Sherpa cross-section in the total phase space)

Process	Code	PDF	Perturbative order	Fid. cross-section	
$q\bar{q} \rightarrow WW$	MATRIX2.0.1	NNPDF3.1	NNLO QCD	674 fb	±1.8 %
$q\bar{q} \rightarrow WW$	MiNNLO + Pythia8	NNPDF3.0	NNLO QCD + PS	624 fb	±1.1 %
$q\bar{q} \rightarrow WW$	Sherpa2.2.12	NNPDF3.0	NLO QCD + PS †	630 fb	±7.2 %
$gg \rightarrow WW$	MATRIX2.0.1	NNPDF3.1	NLO QCD	32 fb	±13 %
$gg \rightarrow WW$	Sherpa2.2.2	NNPDF3.0	LO QCD + PS †	15 fb	±30 %
$\gamma\gamma \rightarrow WW$	MATRIX 2.0.1	NNPDF3.1	LO	5 fb	±2.3 %
$\gamma\gamma \rightarrow WW$	MATRIX 2.0.1	NNPDF3.1	NLO EW	11 fb	±2.3 %
$q\bar{q} \rightarrow WWjj$ (EW)	Sherpa2.2.12	NNPDF3.0	LO + PS	4 fb	±7.0 %
For calculation of NLO EW correction:					
$q\bar{q} \rightarrow WW$	MATRIX2.0.1	NNPDF3.1	LO	436 fb	±5.1 %
$q\bar{q} \rightarrow WW$	MATRIX2.0.1	NNPDF3.1	NLO EW	418 fb	±5.1 %

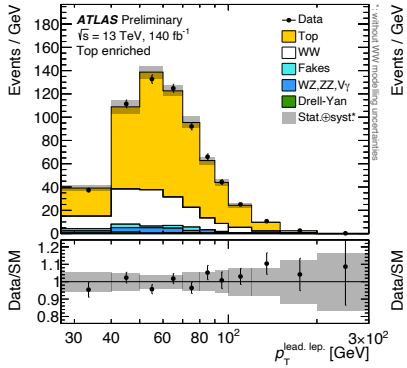
†: Includes matrix elements with additional parton emissions, matched and merged with the parton shower, which increases the accuracy of the simulation of high jet multiplicity events but also increases the nominal scale uncertainty.

Background Estimate

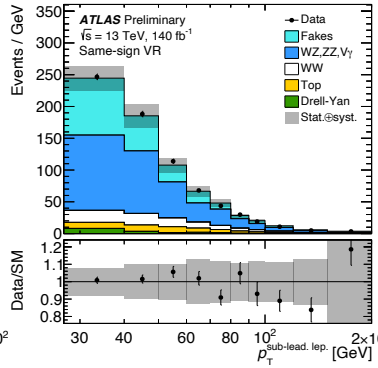
- Top-quark background : **b-tag counting method** (inspired by a $t\bar{t}$ cross-section measurement arx:1910.08819) and transfer factor method
- Fake/Non-prompt background data-driven estimate : Fake factor method
- Drell–Yan *Z+jets*, WZ, ZZ, $W\gamma$ and $Z\gamma$ background estimate : MC simulation
- Good behavior of background estimates in VRs!

Category	Event yield	
Data	144221	
Total SM	139700 ± 2400	
WW	56900 ± 1100	41%
Total bkg.	82600 ± 2100	59%
Top	66500 ± 1900	48%
Drell-Yan	6500 ± 400	5%
Fakes	5000 ± 1300	4%
WZ,ZZ,$V\gamma$	4500 ± 600	3%

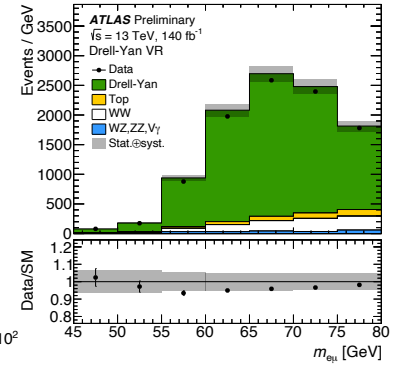
Top-enriched VR
≥ 1*jet*, m_{lj} < 140 GeV
Δϕ(e, μ) < π/2



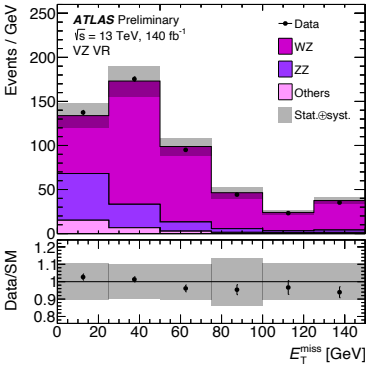
Same-sign VR
same-charge dilepton



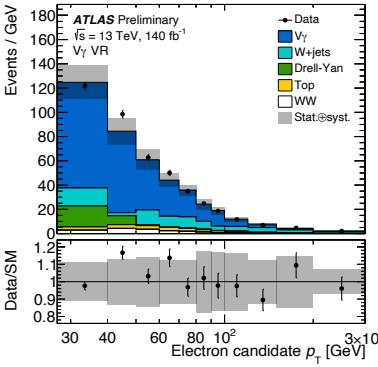
Drell-Yan
45 < $m_{e\mu}$< 80 GeV
E_T^{miss} < 20 GeV or
$P_T^{e\mu}$< 30 GeV



WZ*,ZZ
3l, $m_{e\mu}$ > 45 GeV
80 < m_{ll}^{SF} < 100 GeV

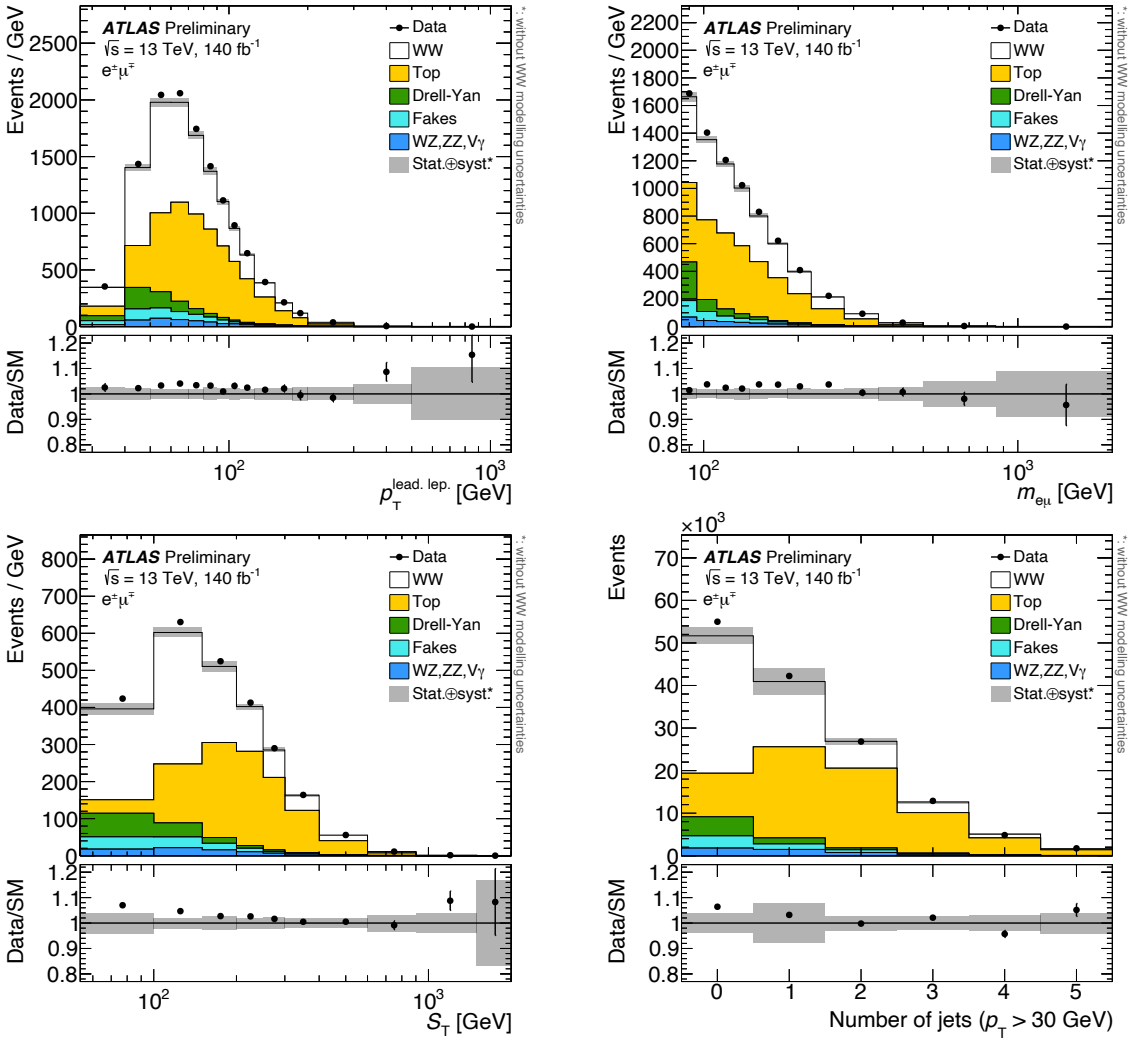


Vγ
***LooseLH* electron ID**
fail *b*-layer requirement



Kinematic Distributions at Detector Level

- Good agreement between data and Monte Carlo simulation



S_T : the scalar sum of all *jet* and lepton transverse momentum

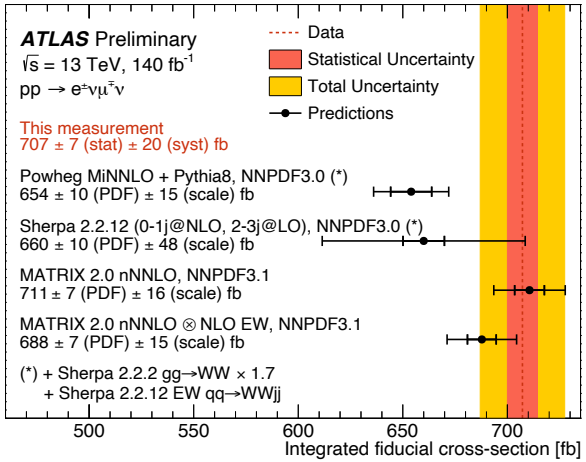
Integrated Cross Sections

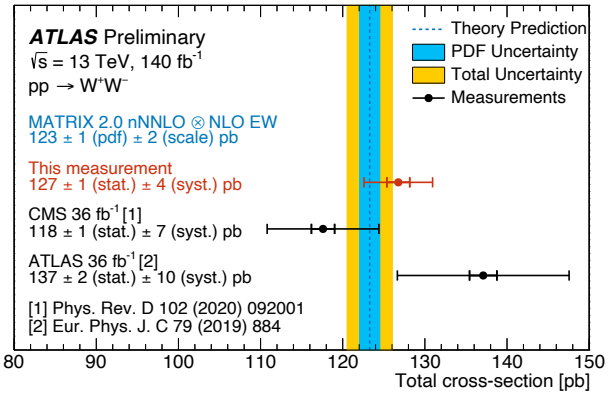
- Signal model, top background (theoretical model and *b*-tagging) and fake lepton are dominant uncertainties

- **Fiducial cross section**
  - σ_{fid} = 707 ± 7 (stat) ± 20 (syst) fb
  - Sherpa 2.2.2 llvvjj EW included to all prediction

- **Total cross section**
  - σ_{total} = 127 ± 1 (stat) ± 4 (syst) pb
  - Extrapolation using MATRIX with **2.4%** uncertainties (From scale variations and NLO EW correction differences)
  - Improvement in previous ATLAS measurement
    - Better background estimates (top and fake)
    - **Inclusive** measurement : Extrapolation uncertainties also reduced

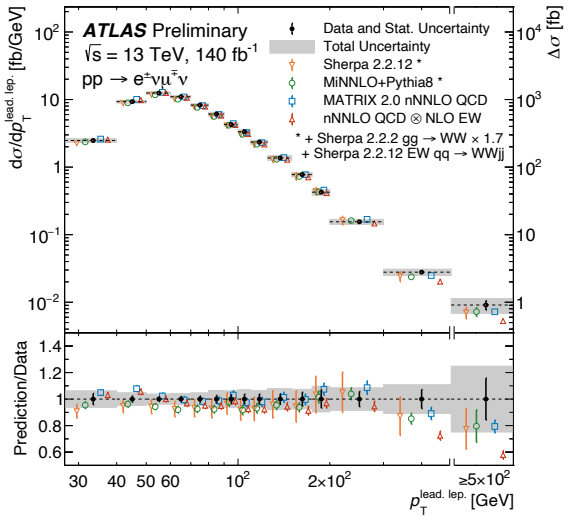
Uncertainty source	Effect
Total uncertainty	3.1%
Stat. uncertainty	1.1%
Top modelling	1.6%
Fake lepton background	1.5%
Flavour tagging	0.7%
Other background	0.9%
Signal modelling	1.0%
Jet calibration	0.6%
Luminosity	0.8%
Other systematic uncertainties	0.9%

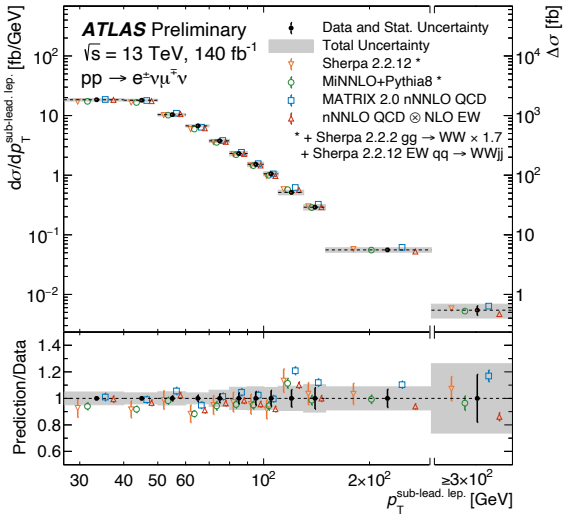


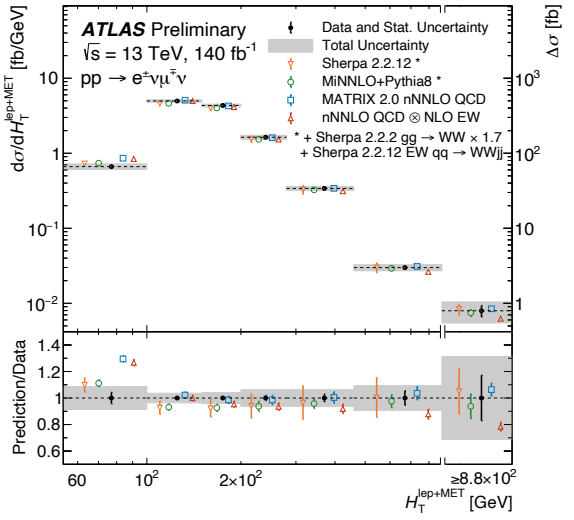


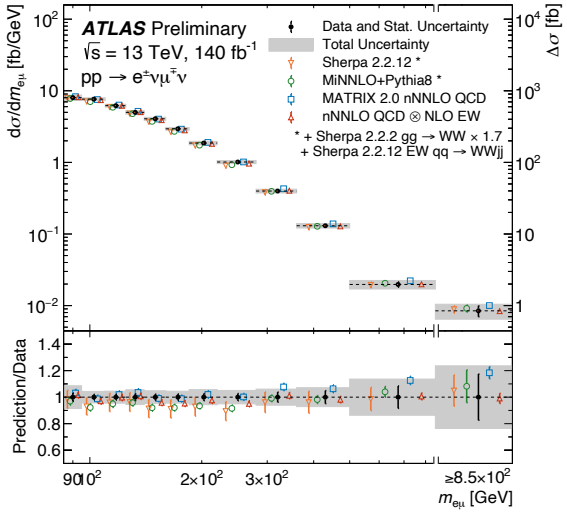
Differential Cross-section at Particle Level

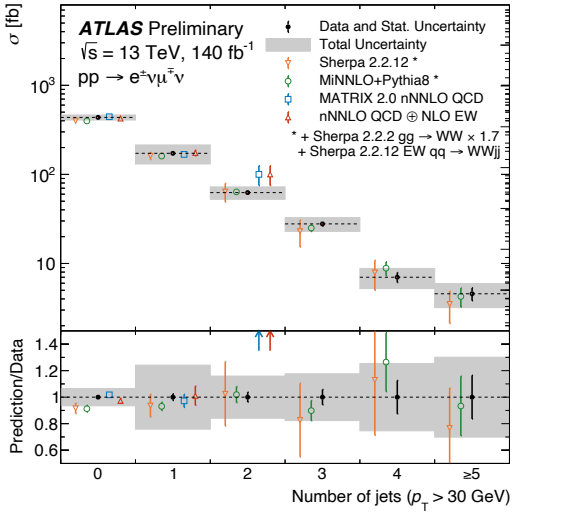
- Good agreement with predictions observed

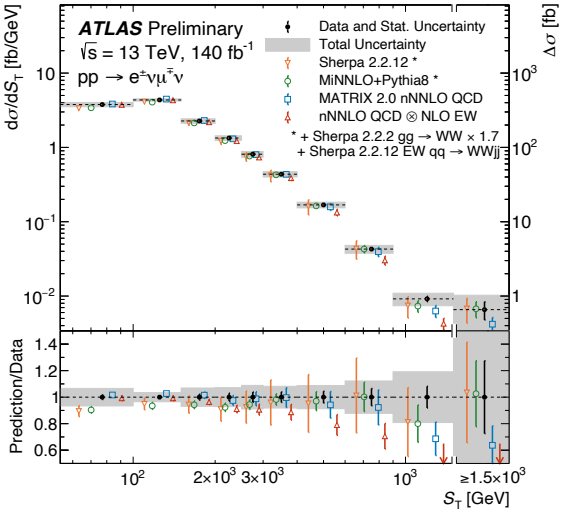




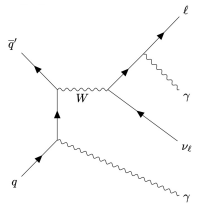


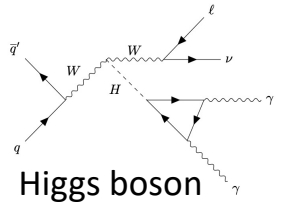




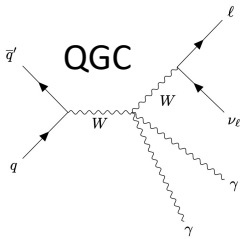


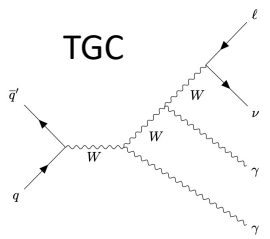
Wγγ - Overview





- **First** observation of $W\gamma\gamma$ process! ATLAS-CONF-2023-005
  - Leptonic final states of W decay, l = e, μ





- Signal Region Event Selection :
  - Single lepton + di-photon trigger
  - lepton p_T > 25 GeV and photons p_T > 20 GeV
  - W-boson : m_T^W > 40 GeV and E_T^{miss} > 25 GeV
  - Z veto : veto additional leptons
  - *b-jet* veto : reduce top quark background($tt/tt\gamma/tq\gamma/tW\gamma$)
  - $Z\gamma$ veto : Cuts on $p_T^{l\gamma\gamma}$, $m_{l\gamma\gamma}, m_{l\gamma1}, m_{l\gamma2}$ to reduce $e\rightarrow\gamma$ background
- Top Control Region Selection : at least one *b-jet* to fit $tt\gamma$ scale factor
- Top Validation Region Selection : Fail m_T^W and *met* cuts

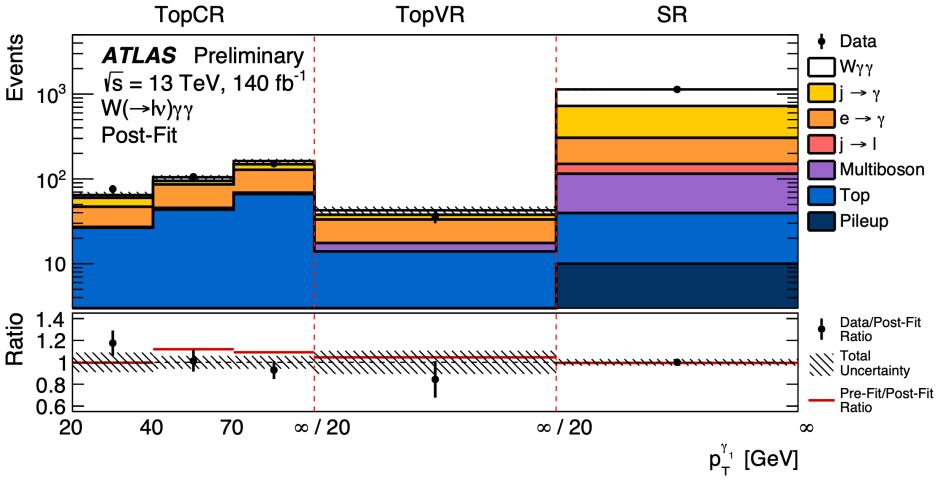
- Background estimate
  - MC simulated to estimate $Z\gamma\gamma$, $Z\gamma$, WH($\gamma\gamma$), $WW\gamma$, $tq\gamma$, $tW\gamma$
    - $tt\gamma$ (constrained in TopCR) : $\boldsymbol{\alpha(tt\gamma) = 0.83^{+0.21}_{-0.25}}$
  - Data-driven estimates :
    - Non-prompt photons ($j \rightarrow \gamma$)(37% of events in SR) : 2D Template fit method
    - Electrons reconstructed as photons (e $\rightarrow \gamma$)(14% of events in SR) : Fake factor method
    - Non-prompt leptons ($j \rightarrow l$)($j \rightarrow e$: 2% and $j \rightarrow \mu$: 1% of events in SR) : Fake factor method
    - Background from pileup (1% of events in SR) : Tails of converted photon ΔZ distribution

Uncertainties and Result

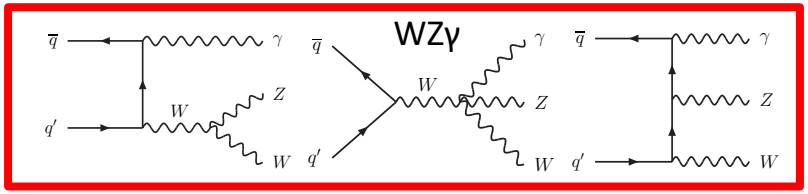
- Total uncertainty is **17%**, dominated by data-driven background estimate (13%) and photon efficiency (4.5%)

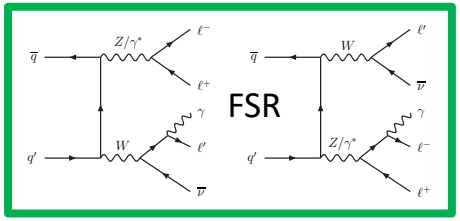
Source	SR	TopCR
$W\gamma\gamma$	410 ± 60	28 ± 5
Non-prompt $j \to \gamma$	420 ± 50	42 ± 20
Misidentified $e \to \gamma$	155 ± 11	120 ± 9
Multiboson ($WH(\gamma\gamma)$, $WW\gamma$, $Z\gamma\gamma$)	76 ± 13	5.2 ± 1.7
Non-prompt $j \to \ell$	35 ± 10	–
Top ($tt\gamma$, $tW\gamma$, $tq\gamma$)	30 ± 7	136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

- Binned profile likelihood fit with Signal Region and Top Control Region
  - **Observed**(expected) **significance :**
    - **5.6σ** (5.6σ)
  - **Signal strength :**
    - $\mu_{\text{signal}} = 1.01^{+0.17}_{-0.16}$
  - **Measured fiducial cross-section :**
    - $\sigma_{\text{fid}} = 12.2^{+2.1}_{-2.0}$ **fb**

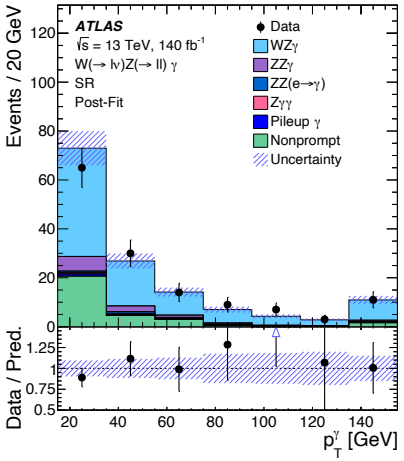


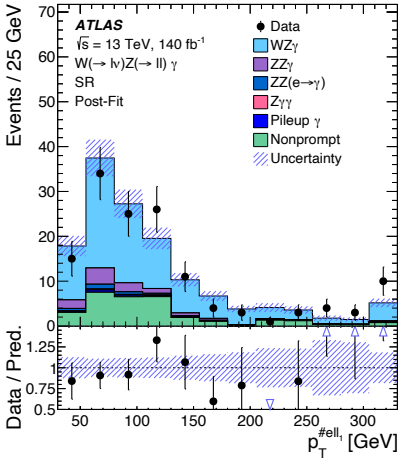
WZγ - Overview





- **First** observation of $WZ\gamma$ process!
  - Fully leptonic final states, l = e, μ arXiv:2305.16994
- Signal Region Event Selection :
  - Vetoed if pass 4th lepton
  - E_T^{miss} > 20 GeV to suppress backgrounds ($ZZ\gamma$, ZZ (e→γ))
  - $m_{(eW,\gamma)}$ away from Z to suppress $ZZ(e\rightarrow\gamma)$ background
  - m_{ll} > 81 GeV and ΔR(l, γ)>0.4 to suppress FSR contribution
- Also define $ZZ\gamma$ CR and ZZ CR to estimate background
- Observation of $WZ\gamma$ with **6.3σ** (5.0σ expected)
  - σ_{fid} **= 2.01±0.30 (stat)±0.16 (syst) fb**
  - σ_{pre} **= 1.50±0.01 (stat)±0.02 (PDF+αs) ± 0.06 (scale) fb**

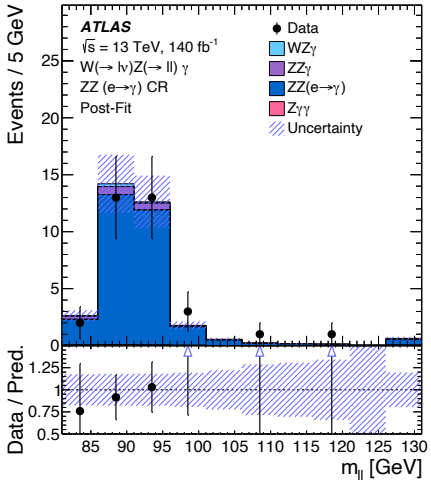


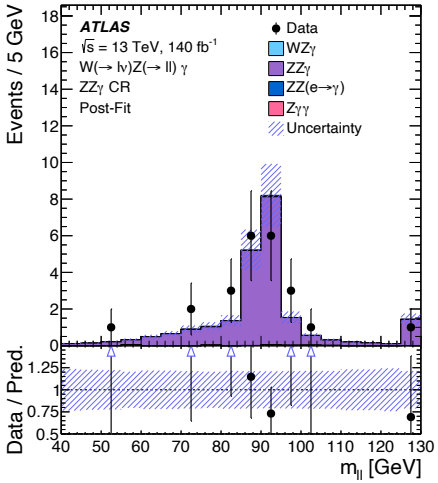


	Photons	Leptons (e, μ)	Neutrino
$\lvert\eta\rvert$	$\lvert\eta^{\gamma}\rvert < 2.37$	$\lvert\eta^{\ell}\rvert < 2.5$	–
p_{T}	$p_{\mathrm{T}}^{\gamma} > 15\,GeV$	$p_{\mathrm{T}}^{\ell_1,\ell_2,\ell_3} > 30, 20, 20\,GeV$	$p_{\mathrm{T}}^{\nu} > 20\,GeV$
Isolation	$E_{\mathrm{T}}^{\mathrm{cone0.2}}/p_{\mathrm{T}}^{\gamma} < 0.07$	–	–
ℓ_Z assignment	for $eee/\mu\mu\mu$ channels, choose smallest $\lvert m_{\ell\ell} - m_Z\rvert$		
ΔR	$\Delta R(\ell, \gamma) > 0.4$		
Z invariant mass	$m_{\ell\ell} > 81\,GeV$		

Background Estimate

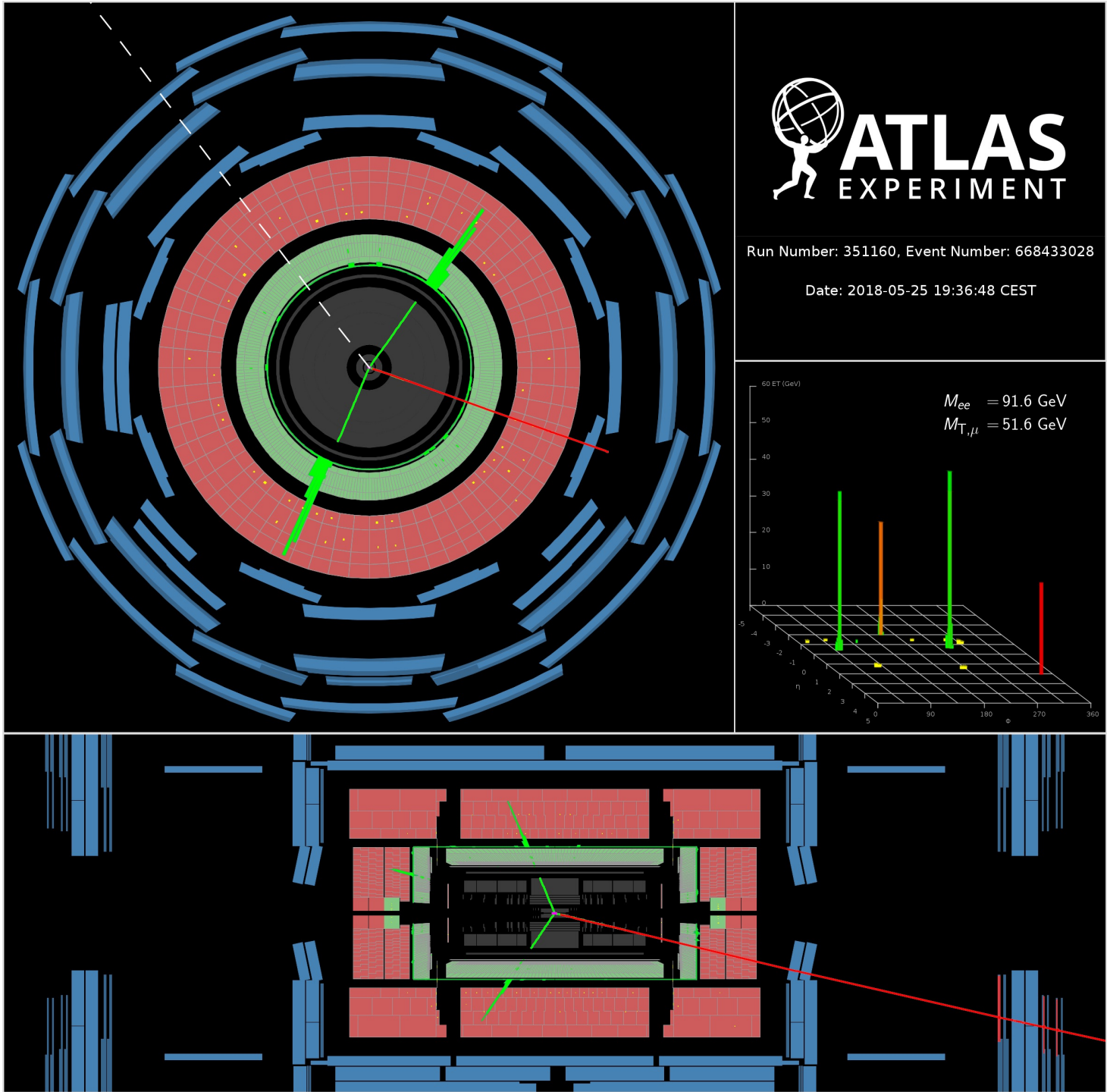
- Non-prompt lepton ($j \to l$) or photon ($j \to \gamma$) background
  - Data driven estimation based on fake factor of lepton-like/photon-like *jet*
- $ZZ\gamma$ (including ZZ with FSR γ) and ZZ with electron faking photon ($e \to \gamma$)
  - MC estimation with dedicated CRs
- WZ+pileup γ
  - Overlay MC
- $Z\gamma\gamma$ ($\gamma \to e$)
  - MC estimation





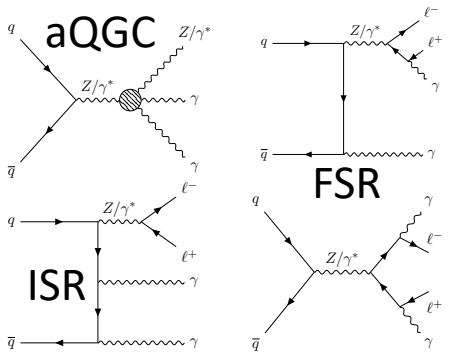
Process	SR	$ZZ\gamma$ CR	$ZZ(e \to \gamma)$ CR
$WZ\gamma$	92 ± 15	0.21 ± 0.07	0.56 ± 0.14
$ZZ\gamma$	10.7 ± 2.3	23 ± 5	1.8 ± 0.4
$ZZ(e \to \gamma)$	3.0 ± 0.6	0.028 ± 0.020	30 ± 6
$Z\gamma\gamma$	1.05 ± 0.32	0.15 ± 0.06	0.29 ± 0.10
Nonprompt background	30 ± 6	-	-
Pileup γ	1.9 ± 0.7	-	-
Total yield	139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

	SR definition	$ZZ\gamma$ CR definition	$ZZ(e \to \gamma)$ CR definition
Lepton veto	no additional leptons with $p_{\mathrm{T}}^{\ell_4} > 10\ GeV$	one additional lepton with $p_{\mathrm{T}}^{\ell_4} > 10\ GeV$	same as SR
Z-leptons assignment	smallest $\lvert m_{\ell\ell} - m_Z \rvert$	same as SR	same as SR
ΔR	$\Delta R(\ell,\gamma) > 0.4, \quad \Delta R(\mu, e) > 0.2$	same as SR	same as SR
$ZZ(e \to \gamma)$ rejection	$\lvert m(e_W,\gamma) - m_Z \rvert > 10\ GeV$	same as SR	$\lvert m(e_W,\gamma) - m_Z \rvert < 10\,GeV$
Missing p_{T}	$E_{\mathrm{T}}^{\mathrm{miss}} > 20\ GeV$	no requirement	$E_{\mathrm{T}}^{\mathrm{miss}} < 20\ GeV$
Z candidate mass	$m_{\ell\ell} > 81\,GeV$	$m_{\ell\ell} > 40\,GeV$	same as SR

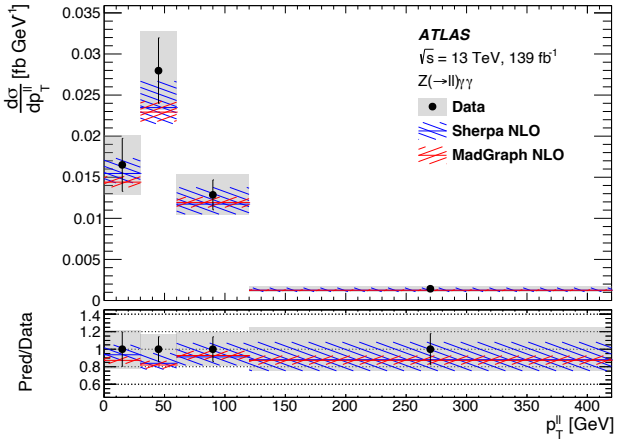

ATLAS
EXPERIMENT
Run Number: 351160, Event Number: 668433028
Date: 2018-05-25 19:36:48 CEST
M_{ee} = 91.6 GeV
$M_{T,\mu}$ = 51.6 GeV
60 ET (GeV)

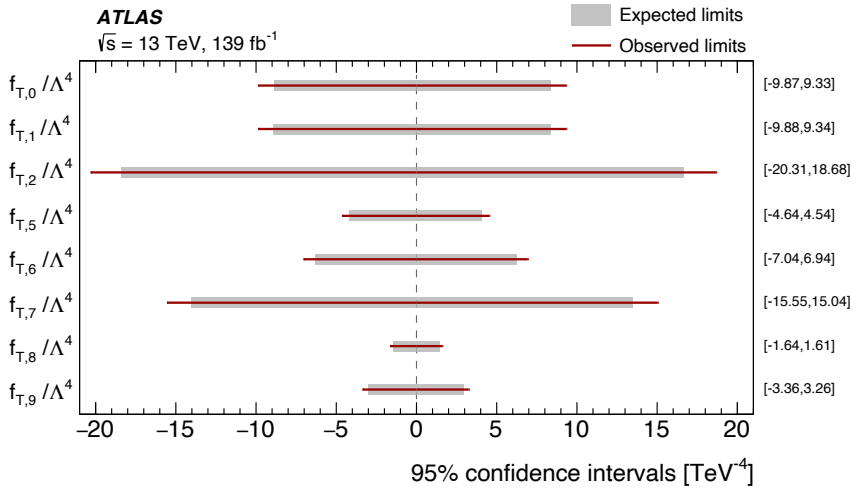
Zγγ - Overview

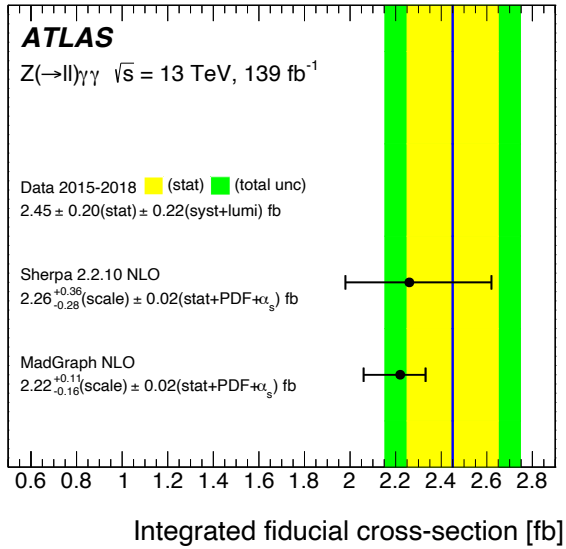
Eur. Phys. J. C 83 (2023) 539



- First ATLAS measurement on ***Zγγ*** at 13 TeV with full Run-2 dataset (**purely ISR $Z(ll)\gamma\gamma$ production**)
  - ATLAS 8TeV and CMS 13TeV with no FSR rejection
- **First differential cross-section measurements** of $Z(ll)\gamma\gamma$
  - Well described by NLO predictions
- **Integrated cross-sections:**
  - **σ_{fid} = 2.45 ± 0.20(stat) ± 0.22(syst) ± 0.04(lumi) fb**
- **EFT operator limits**
  - EFT contributions simulated with MadGraph LO
  - Limits set on dimension-8 EFT operators vastly improved wrt ATLAS 8 TeV analysis





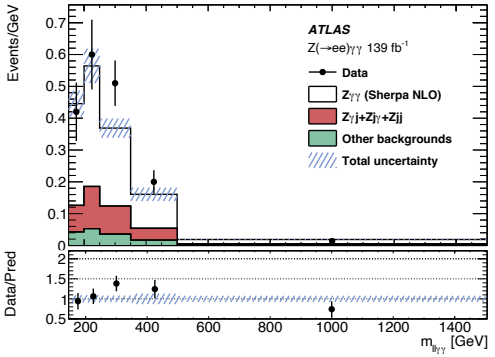


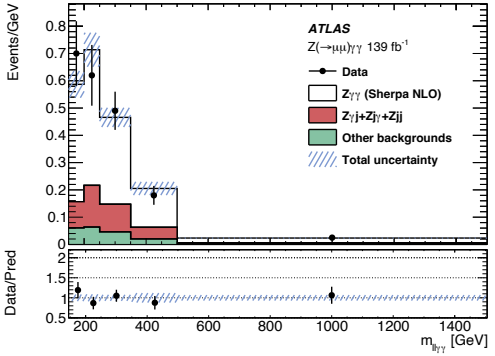
MC Samples and Event Selection

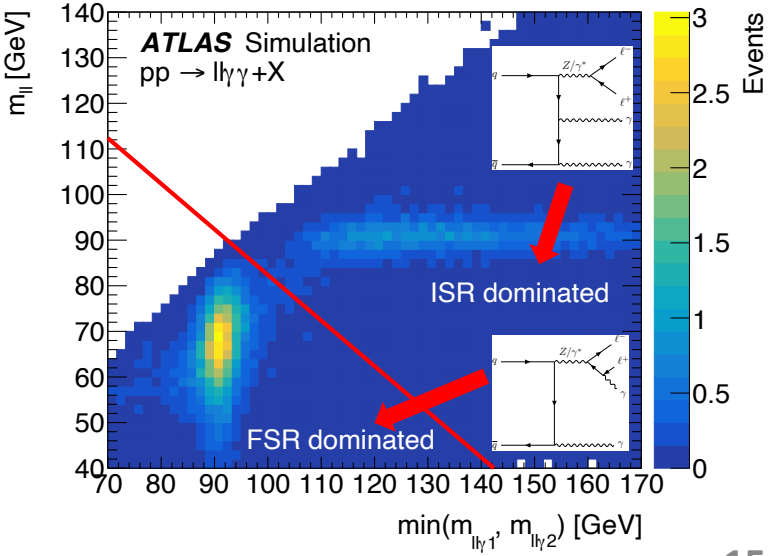
- Signal Region Event Selection :
  - Leading SFOS lepton pair
  - $m_{ll} > 40$ GeV
  - $m_{ll} + \min\{m_{ll\gamma 1}, m_{ll\gamma 2}\} > 2m_Z$
- Fiducial selection is as close as possible to detector-level selection

Photons	Leptons
$p_{\mathrm{T}}^{\gamma} > 20$ GeV	$p_{\mathrm{T}}^{\ell 1} > 30$ GeV, $p_{\mathrm{T}}^{\ell 2} > 20$ GeV
$\lvert\eta^{\gamma}\rvert < 2.37$	$\lvert\eta^{\ell}\rvert < 2.47$
$E_{\mathrm{T}}^{\mathrm{iso}}/p_{\mathrm{T}}^{\gamma} < 0.07$	dressed leptons
Event	
$\Delta R(\gamma,\ell) > 0.4, \Delta R(\gamma,\gamma) > 0.4$	
$m_{\ell\ell} > 40$ GeV	
$m_{\ell\ell} + \min(m_{\ell\ell\gamma_1}, m_{\ell\ell\gamma_2}) > 2m_Z$	

	Process	Generator	Order	PDF Set	PS/UE/MPI
Signal	$\ell\ell\gamma\gamma$	Sherpa 2.2.10	NLO	NNPDF3.0nnlo	Sherpa 2.2.10
	$\ell\ell\gamma\gamma$	MadGraph5_aMC@NLO 2.7.3	NLO	NNPDF3.0nlo	Pythia 8.244
Background	$Z\gamma$ + jets	Sherpa 2.2.4	LO	NNPDF3.0nnlo	Sherpa 2.2.4
	Z + jets	Powheg Box v1	NLO	CT10nlo	Pythia 8.186
	$t\bar{t}\gamma$	MadGraph5_aMC@NLO 2.3.3	LO	NNPDF2.3lo	Pythia 8.212
	$ZZ \to \ell\ell\ell\ell$	Sherpa 2.2.2	NLO	NNPDF3.0nnlo	Sherpa 2.2.2
	$WZ\gamma \to \ell\nu\ell\ell\gamma$	Sherpa 2.2.5	NLO	NNPDF3.0nnlo	Sherpa 2.2.5
	$Z(\to \ell\ell)H(\to \gamma\gamma)$	Powheg Box v2	NLO	NNPDF3.0nlo	Pythia 8.212
	γ + jets	Sherpa 2.2.2	NLO	NNPDF3.0nnlo	Sherpa 2.2.2
	$\gamma\gamma$ + jets	Sherpa 2.2.2	NLO	NNPDF3.0nnlo	Sherpa 2.2.2







Background Estimate and Uncertainties

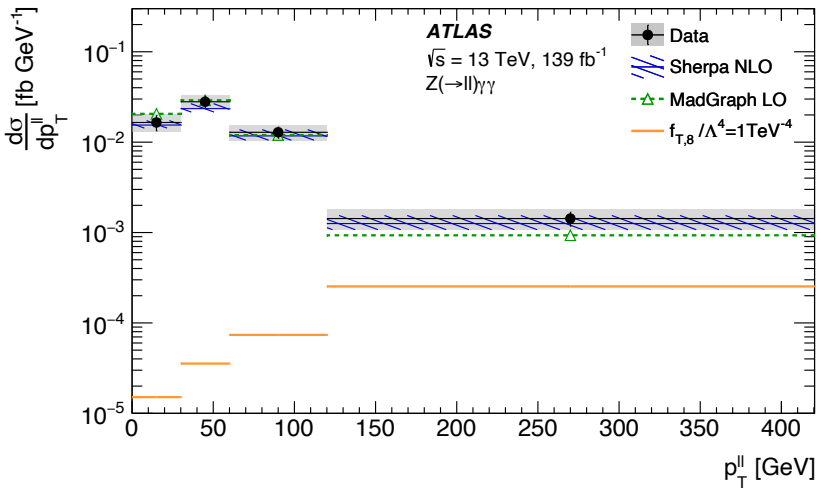
- Non-prompt photon background
  - Data-driven matrix method to determine $Z\gamma\gamma$, $Zj\gamma$ and Zjj normalization
- Top ($t\bar{t}\gamma\gamma$)
  - Normalisation factor from $e\mu$ CR
  - Shape from simulation
- Pile-up ($Z\gamma$+γ, Z+$\gamma\gamma$)
  - Overlay MC events at particle level
  - Correct to detector level with bin-by-bin factors from signal MC
- $e\rightarrow\gamma$ fakes
  - From simulation
  - Conservative uncertainty to cover potential mismodelling
- $Z(\rightarrow ll)$H($\rightarrow\gamma\gamma$)
  - From simulation

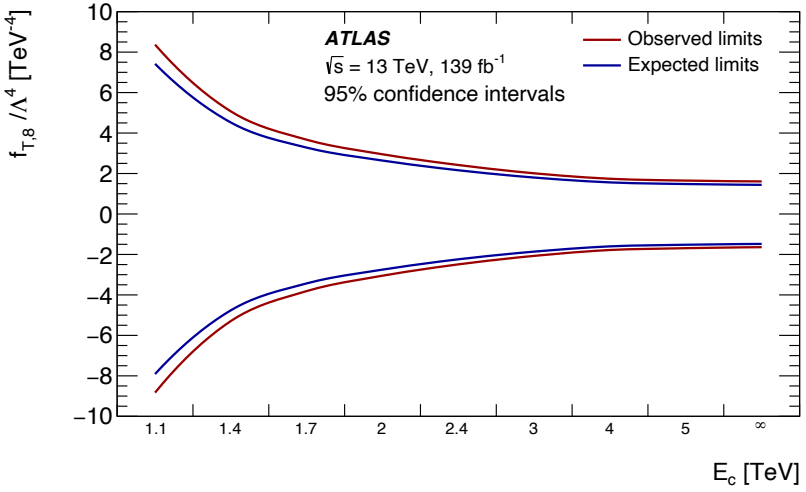
	$e^+e^-\gamma\gamma$	$\mu^+\mu^-\gamma\gamma$
Data	148	171
	Background predictions	
$Z\gamma j + Zj\gamma + Zjj$	29.8±5.7 (stat.)±5.5 (sys.)	34.4±6.6 (stat.)±6.3 (sys.)
$t\bar{t}\gamma\gamma$	6.4±0.4 (stat.)±1.4 (sys.)	8.4±0.5 (stat.)±1.8 (sys.)
$ZZ \rightarrow \ell\ell\ell\ell$	1.03±0.10 (stat.)±0.51 (sys.)	1.24±0.11 (stat.)±0.62 (sys.)
$WZ\gamma \rightarrow \ell\nu\ell\ell\gamma$	0.69±0.06 (stat.)±0.35 (sys.)	0.52±0.05 (stat.)±0.26 (sys.)
$Z(\rightarrow \ell\ell)H(\rightarrow \gamma\gamma)$	1.08±0.01 (stat.)±0.22 (sys.)	1.38±0.01 (stat.)±0.28 (sys.)
$Z\gamma + \gamma$	2.07±0.16 (stat.)±0.72 (sys.)	2.74±0.21 (stat.)±0.96 (sys.)
$Z + \gamma\gamma$	1.44±0.04 (stat.)±0.39 (sys.)	1.90±0.05 (stat.)±0.51 (sys.)
Data – background	105.5±12.2 (stat.)±8.1 (sys.)	120.4±13.1 (stat.)±9.4 (sys.)
	Signal predictions	
Sherpa NLO	91.5±0.9 (stat.)	119.5±1.0 (stat.)
MadGraph5_aMC@NLO	91.0±1.0 (stat.)	118.1±1.2 (stat.)

Source	Relative uncertainty [%]	
	$e^+e^-\gamma\gamma$	$\mu^+\mu^-\gamma\gamma$
Photon identification efficiency	2.5	2.6
Photon isolation efficiency	2.0	2.0
Electron–photon energy resolution	0.2	0.1
Electron–photon energy scale	0.8	0.6
Electron identification efficiency	2.0	-
Electron reconstruction efficiency	0.3	-
Muon isolation efficiency	-	0.4
Muon reconstruction efficiency	-	0.4
Muon trigger efficiency	-	0.3
Muon momentum scale	-	0.2
Pile-up reweighting	2.8	2.9
Monte Carlo signal statistics	1.1	1.0
Signal modelling	1.1	1.1
Integrated luminosity	1.7	1.7
$j \rightarrow \gamma$ backgrounds	7.5	7.6
Other backgrounds	1.7	1.9
Total systematic uncertainty	8.6	7.5
Data statistical uncertainty	11.5	10.9
Total uncertainty	14.5	13.3

EFT Interpretation

- Dimension-8 EFT operators allow for the existence of aQGCs
  - $Z\gamma\gamma$ sensitive to transverse operators involving neutral aQGCs ($ZZ\gamma\gamma$, $Z\gamma\gamma\gamma$)
- Limits are set using unfolded p_T^{ll} distribution
  - Most sensitive to NP effects
- Limits extracted through profile likelihood ratio
  - Also provided as a function of energy scale cut-off





Summary

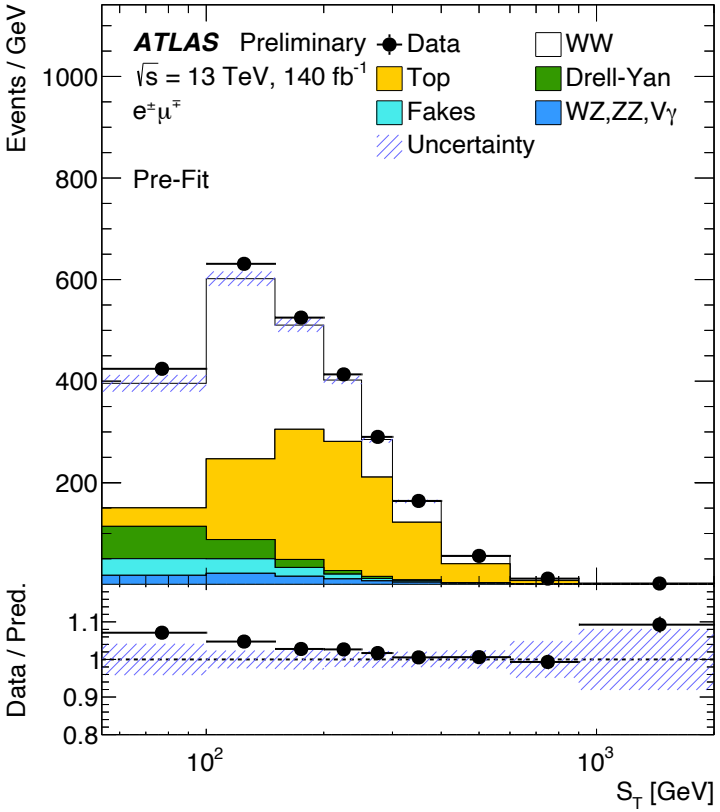
- **Most** precise WW cross section measurement in hadron-hadron collisions
  - **First** time using **fully jet-inclusive phase space**
  - Accurate data-driven background estimates
  - Differential cross-section based on new observables

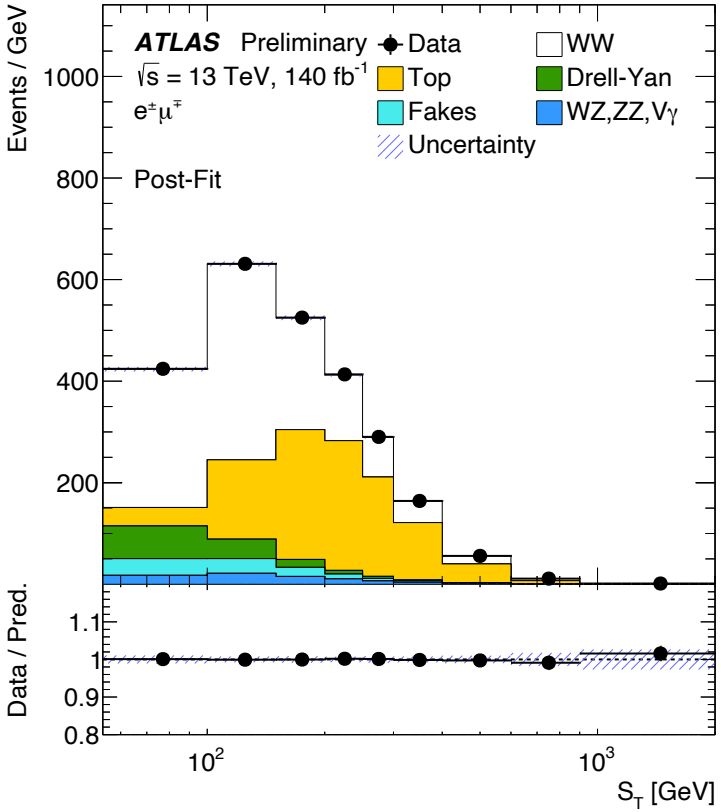
- **First** observation of $W\gamma\gamma$ and $WZ\gamma$ process
  - Fiducial cross-section measurement

- First ATLAS measurement on $Z\gamma\gamma$ at 13 TeV with full Run-2 dataset
  - **First** differential cross-section measurements
  - Limits are set using unfolded p_T^{ll} distribution

Backup - WW Fit

- Pre-fit(left) and post-fit(right) model for the profile likelihood fit in the S_T distribution.





Backup - WW B-tag counting method

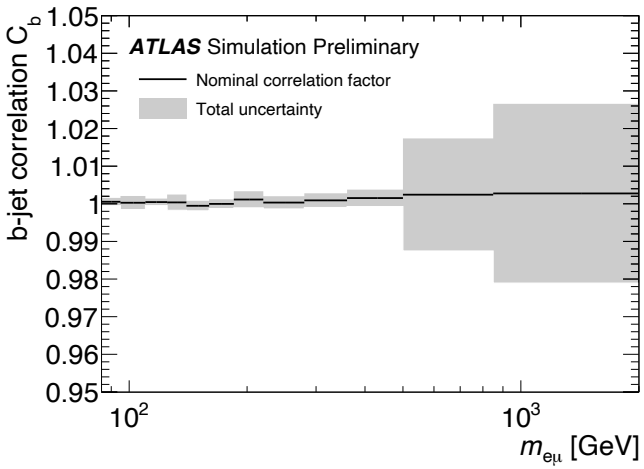
arx:1910.08819

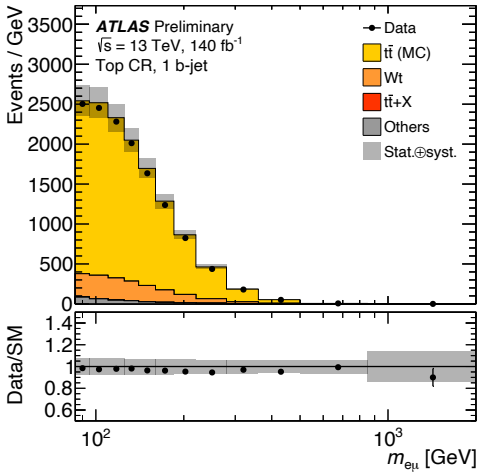
- Parametrized with 3 parameters :
  - Number of $t\bar{t}$ events without requirements on the b-jet multiplicity : $N_{\geq 0b}^{t\bar{t}}$
  - The efficiency of identifying and selecting a b-jet in a $t\bar{t}$ event : ε_b
  - The probability of identifying both b-jets in a $t\bar{t}$ events : C_b

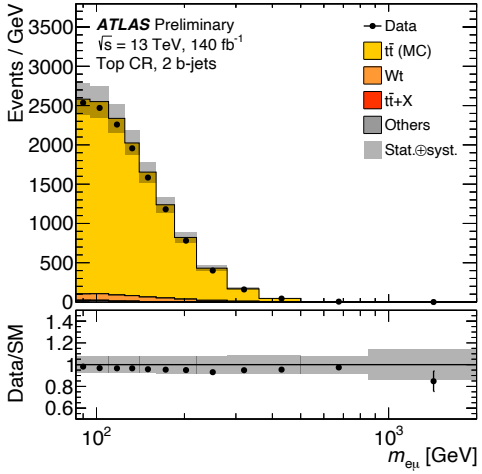
- Lower $t\bar{t}$ total uncertainty by a factor of ~5 (an uncertainty of about 3%)

$$N_{1b}^{t\bar{t}} = N_{1b} - N_{1b}^{\text{others}} = N_{\geq 0b}^{t\bar{t}} \cdot 2\varepsilon_b \left(1 - C_b\varepsilon_b\right)$$
$$N_{2b}^{t\bar{t}} = N_{2b} - N_{2b}^{\text{others}} = N_{\geq 0b}^{t\bar{t}} \cdot C_b\varepsilon_b^2$$
$$N_{0b}^{t\bar{t}} = N_{\geq 0b}^{t\bar{t}} \cdot \left(1 - 2\varepsilon_b + C_b\varepsilon_b^2\right)$$

$$N_{0b}^{t\bar{t}} = \frac{C_b}{4} \frac{\left(N_{1b}^{t\bar{t}} + 2N_{2b}^{t\bar{t}}\right)^2}{N_{2b}^{t\bar{t}}} - N_{1b}^{t\bar{t}} - N_{2b}^{t\bar{t}}$$







Backup - Wγγ Uncertainty

Source of uncertainty	Impact [%]
Data-driven background estimates	13
Photon efficiency	4.5
Signal MC theoretical modeling	3.5
Background MC theoretical modeling	3.0
Monte Carlo statistics	2.8
Jet efficiency and calibration	2.4
Top normalization	2.4
Pileup reweighting	1.6
$E_{\mathrm{T}}^{\mathrm{miss}}$ calibration	1.4
Muon efficiency and calibration	1.4
Luminosity	1.0
Electron and photon calibration	0.7
Flavor tagging efficiency	0.6
Systematic	15
Statistical	8.3
Total	17

- Major sources of uncertainty and their impacts on the measured fiducial cross-section, as calculated from the correlation matrix of the fiducial cross-section fit.

Backup - WZγ Uncertainty

- The impact of uncertainties on the measured fiducial cross-section in the fit.

Sources	Relative uncertainty [%]
Photon identification and isolation efficiency	2.5
Electron identification, isolation, reconstruction efficiency	0.3
Electron–photon resolution and energy scale	0.6
Muon identification, isolation, reconstruction, momentum resolution and scale	2.4
Missing E_{T} resolution and energy scale	0.3
Lepton fake factor	1.9
Photon fake factor	2.2
Prompt lepton modelling in loose-lepton region	2.2
Prompt photon leakage factor in loose-photon region	0.9
Pile-up γ background	0.9
Signal PDF and α_s, QCD Scales	1.1
Integrated luminosity	0.9
$Z\gamma\gamma$ cross-section	0.2
Signal MC statistics	1.2
Background MC statistics	0.4
Data statistics in loose-lepton and/or loose-photon region	5.4
Total systematic uncertainty	7.7
$ZZ\gamma$ and $ZZ(e \to \gamma)$ normalisation	2.6
Data statistics	14.8
Total statistical uncertainty	15.1