Multi-boson production including vector-boson scattering and photon-photon fusion at ATLAS

WIN2021

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DESY

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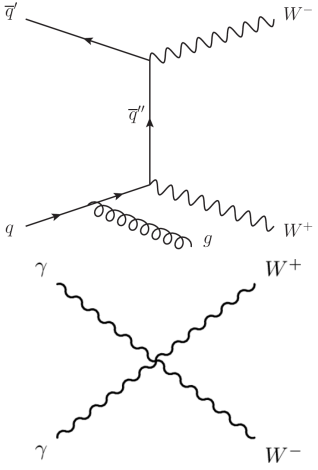
HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

Multiboson production

- Tests of the electroweak sector
- Tests calculations in perturbative QCD
- Search for new physics at the TeV scale



Plethora of ATLAS measurements:

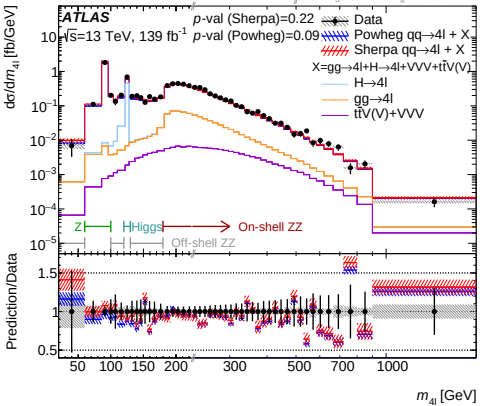
- Regular $p-p$ events:
  - $(ZZ/H/Z \rightarrow)\ 4l$ differential measurement [arXiv:2103.01918]
  - $WW(\rightarrow e\mu)+\geq 1$ jet differential measurement [arXiv:2103.10319]
  - $Z\gamma$ differential measurement [JHEP 03 (2020) 054]
  - ZZ+2 jets observation [arXiv:2004.10612]
- Photon-photon interaction:
  - $\gamma\gamma \rightarrow W^+W^-$ observation [Phys. Lett. B 816 (2021) 136190]
  - Forward proton scattering in $\gamma\gamma \rightarrow l^+l^-$ observation [Phys. Rev. Lett. 125, 261801 (2020)]

Analysis presented today:

Combination of SM searches and precision measurements with few BSM interpretations

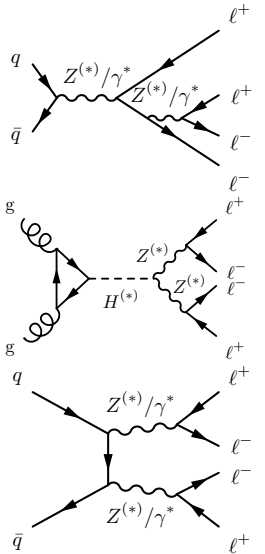
4l differential measurement: Introduction [arXiv:2103.019189]

- 4l Final state dominated by 3 main processes based on the m_{4l}:
  - Single Z production [60-100 GeV]
  - Higgs production [120-130 GeV]
  - ZZ on-shell production [180+ GeV]
- Remaining m_{4l} dominated by ZZ off-shell



← Four regions based on the m_{4l}

- Large number of differential distributions, e.g.:
  - $m_{12}, m_{34}, p_{\mathrm{T}}^{12}, p_{\mathrm{T}}^{34}$
  - $\Delta y_{pairs}, \Delta\phi_{pairs}$
- Vast majority dominated by statistical uncertainties



4l differential measurement: Results [arXiv:2103.019189]

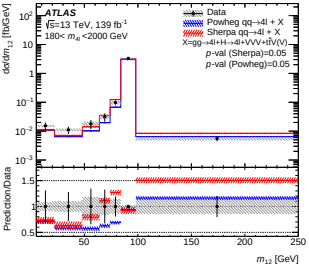
- Bayesian unfolding to particle level,
  pre-unfolding efficiency correction for each of the four leptons
  (minimizes dependence on SM description of lepton kinematics)
- Measured fiducial cross-section in agreement with predictions

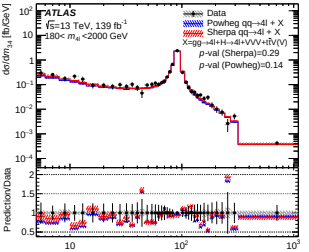
		Region			
	Full	$Z \to 4\ell$	$H \to 4\ell$	Off-shell ZZ	On-shell ZZ
Measured	88.9	22.1	4.76	12.4	49.3
fiducial	±1.1 (stat.)	±0.7 (stat.)	±0.29 (stat.)	±0.5 (stat.)	±0.8 (stat.)
cross-section	±2.3 (syst.)	±1.1 (syst.)	±0.18 (syst.)	±0.6 (syst.)	±0.8 (syst.)
[fb]	±1.5 (lumi.)	±0.4 (lumi.)	±0.08 (lumi.)	±0.2 (lumi.)	±0.8 (lumi.)
	±3.0 (total)	±1.3 (total)	±0.35 (total)	±0.8 (total)	±1.3 (total)
SHERPA	86±5	23.6±1.5	4.57±0.21	11.5±0.7	46.0±2.9
POWHEG + PYTHIA8	83±5	21.2±1.3	4.38±0.20	10.7±0.7	46.4±3.0

- Most precise $Z \to 4l$ BR measurement:

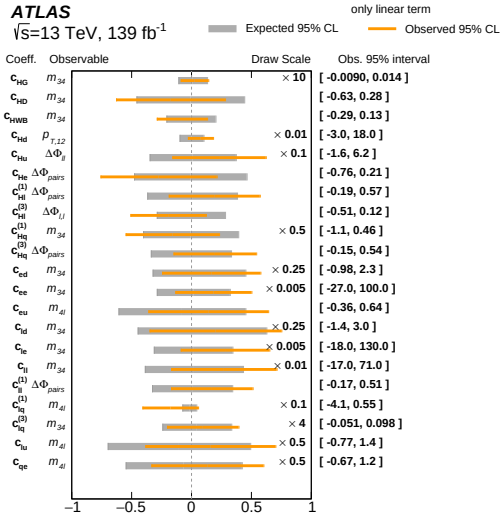
$$B(Z \to 4l) = 4.41 \pm 0.13(stat.) \pm 0.23(syst) \pm 0.09(theory) \pm 0.12(lumi) \times 10^{-6}$$

ZZ on shell dilepton masses:



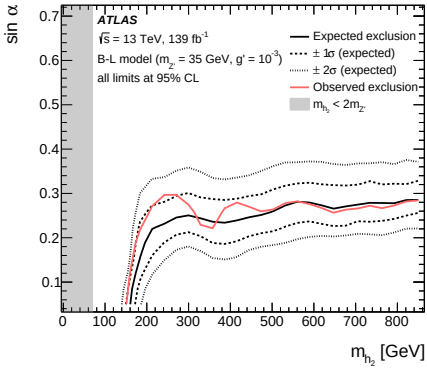


4/ differential measurement: BSM interpretation [arXiv:2103.019189]



← Limits on 22 Wilson coefficients of 6-dim SMEFT (both linear and full model, give vastly different limits!)

B-L spont. breaking, predicts exotic Higgs h_2 and Z', limits on masses ↓

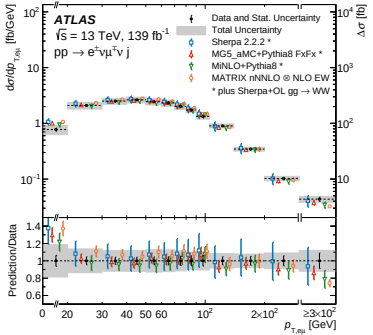


$WW+ \geq 1$ jet measurement [arXiv:2103.10319]

- First detailed study of WW+jets!
- Sensitive to NLO EW corrections
- Dominated by $qq \to WW$, $t\bar{t}$ dominant background
- Paper provides large number of differential quantities and comparison to various generators (MATRIX, SHERPA, ...)

Phase-space

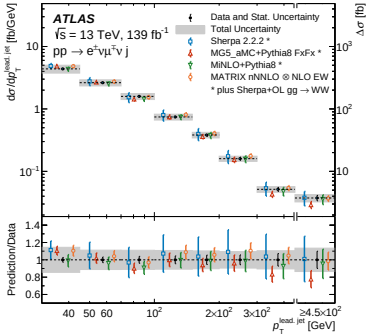
- $e\mu$, $m_{e\mu} > 85$ GeV (suppresses DY and Higgs)
- 1 jet $pt > 30$ GeV, $|\eta| < 4.5$ (no b-tag)



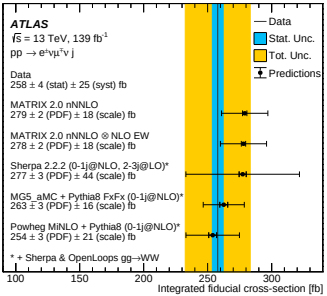
- Data-driven $t\bar{t}$ based on yield in 1/2 b-jet control regions:

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

- Unf. of many kinematic variables, e.g.:
  - p_{T} of the two leptons, $p_{\mathrm{T}}^{e\mu}$, $m_{e\mu}$
  - $p_{\mathrm{T}}^{lead.jet}$, N_{jet}, H_T



$WW+ \geq 1$ jet measurement: Cross-section and BSM interpretation [arXiv:2103.10319]



Measured cross-section:

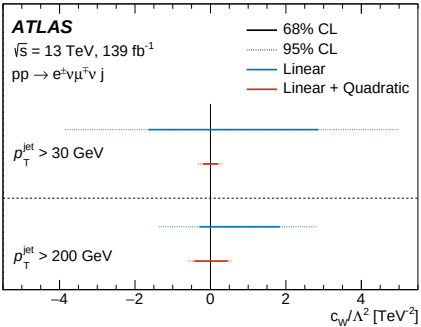
$258 \pm 4(\text{stat.}) \pm 25(\text{syst.})$ fb

← consistent with SM prediction

- Limited by jet calibration and background modeling

BSM interp. for $p_{\mathrm{T}}^{\text{lead. jet}} > 200$ GeV

- 6-dim SMEFT for the anomalous triple gauge coupling (aTGC)
- Limits on the Wilson parameters c_W ⟶ (both linear and quadratic interpretation, quadratic terms have sizeable effect ⟹ higher orders and the dim-8 interference terms cannot be ignored)

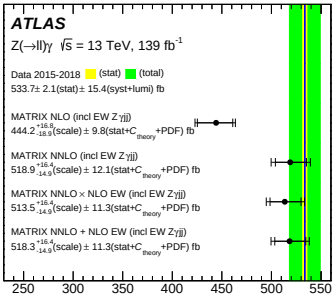


$Z\gamma$ measurement [JHEP 03 (2020) 054]

- Goal: measure $Z(ll)\gamma$ with initial state photon
  $\implies$ $m_{ll} + m_{ll\gamma} \geq 182$ GeV excludes $Z \to ll \to ll\gamma$
- Background from **pile-up**:
  - γ and ll from different $p - p$ interaction
  - estimate through data-driven method, several %
- Limited by instrumental uncertainties and by background from mis-identified jets

Phase-space

- $ee/\mu\mu$, $m_{ll} > 40$ GeV
- $m_{ll} + m_{ll\gamma} \geq 182$ GeV

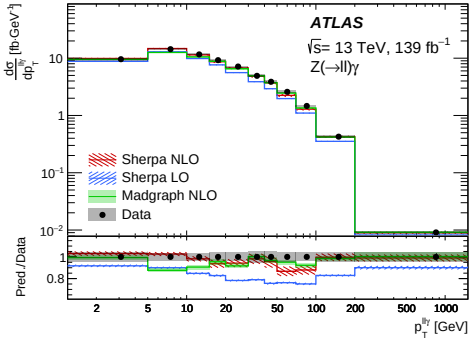


Several kinematic variables unfolded to particle level:

- E_T^{γ}, $|\eta_{\gamma}|$, $m(ll\gamma)$
- $p_{\mathrm{T}}(ll\gamma)$, $\Delta\phi(ll, \gamma)$

Measured cross-section:

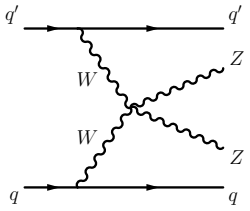
$533.7 \pm 2.1(\mathrm{stat})$
$\pm\ 12.4(\mathrm{syst}) \pm 9.1(\mathrm{lumi})$ fb



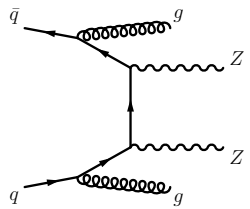
Vector boson scattering (VBS in) $ZZ + 2$ jets

- Presence of Higgs cancels out VBS divergences in the SM: fundamental test of electroweak symmetry breaking
- Also sensitive to anomalous $ZZ \to ZZ$ coupling
- Pure **EW** (no color-flow between protons/quarks)
- Background from **QCD** production
- EW VBS large rapidity separation and invariant mass of the two jets
- Showing today $ZZ + 2$ jets observation
- Older $Z\gamma + 2$ jets VBS measurement [arXiv:1910.09503]

EW:



QCD:



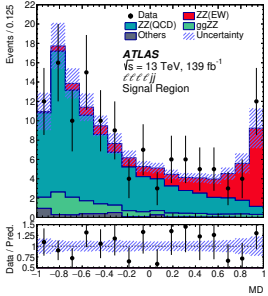
$ZZ + 2$ jets observation [arXiv:2004.10612]

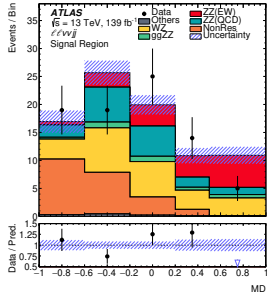
- Measured in *lllljj* and *llvvjj* final states
- *lllljj* allows full kinematic reconstruction

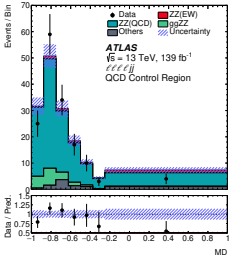
Main selection to separate EW from QCD

- $m_{jj} > 300(400)$ GeV for llll (llvv)
- $\Delta y_{jj} > 2$

- QCD background: data driven normalization
  ↓ from control region with reversed m_{jj}/y_{jj} selection







- BDT used to separate EW from QCD ↑
- EW+interf. generated using MadGraph 2.6.1, QCD with Sherpa 2.2.2
- $ZZ + 2$ jets observed with 5.5σ significance, statistically limited!
- Measured cross-section consistent with SM:

	Measured fiducial σ [fb]	Predicted fiducial σ [fb]
$\ell\ell\ell\ell jj$	$1.27 \pm 0.12(\text{stat}) \pm 0.02(\text{theo}) \pm 0.07(\text{exp}) \pm 0.01(\text{bkg}) \pm 0.03(\text{lumi})$	$1.14 \pm 0.04(\text{stat}) \pm 0.20(\text{theo})$
$\ell\ell\nu\nu jj$	$1.22 \pm 0.30(\text{stat}) \pm 0.04(\text{theo}) \pm 0.06(\text{exp}) \pm 0.16(\text{bkg}) \pm 0.03(\text{lumi})$	$1.07 \pm 0.01(\text{stat}) \pm 0.12(\text{theo})$

Photon induced processes

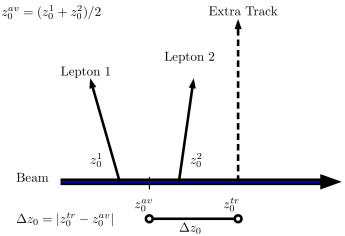
- Photon-photon interactions: Rare processes, great way to study the EW part of the Standard Model
- Proton/heavy ions charged particles $\Longrightarrow$ boosted EM field behaves as a field of quasi-real photons
  $\Longrightarrow$ photon-photon interactions!
- Pure *EW* interaction = low particle activity
  $\Longrightarrow$ *exclusive selection* to find such events:

Exclusive selection for $\gamma\gamma \to W^+W^-(\to ll)$ and $\gamma\gamma \to l^+l^-$

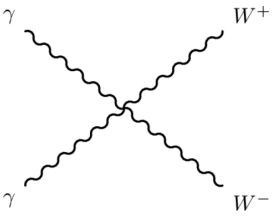
- **Signal**: Only two leptons in the final state
- **Background** (e.g. $Z \to ll, WW \to ll\nu\nu$):
  Extra tracks from underlying event, ISR

$\Longrightarrow$ reject events with additional activity near the dilepton vertex

For following analyses activity =
= extra tracks of charged particles in central detector ($|\eta| < 2.5$)



$\gamma\gamma \to W^+W^-$ observation [Phys. Lett. B 816 (2021) 136190]



- $\gamma\gamma \to W^+W^-$: a unique probe into the EW sector ($\gamma\gamma WW$ quartic vertex!)
- Studied in events with low multiplicity of tracks
- Multiplicity of tracks badly modeled in background $\Longrightarrow$ various data driven correction:
  - Underlying event correction
  - Pile-up correction

Signal region

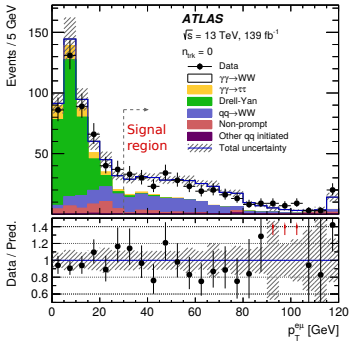
- $p_{\mathrm{T}}^{ll} > 30$ GeV
- No extra central particles

- Simultaneous fit of the signal region and several control regions
- $\gamma\gamma \to W^+W^-$ observed with 8.4 sigma significance!

Measured cross-section:

$3.13 \pm 0.31(\mathrm{stat.}) \pm 0.28(\mathrm{syst.})$ fb

- Result consistent with the Standard Model
- Limiting factors:
  - Modeling of the inclusive WW
  - Statistical uncertainty of data-driven background



Forward proton scattering in $\gamma\gamma \to l^+l^-$ observation [Phys. Rev. Lett. 125, 261801 (2020)]

- Photon-photon processes:
  uncertainty from modeling of interaction between scattered protons
- Proton-tagging offers direct probe
  $\Longrightarrow$ take advantage of ATLAS Forward Proton (AFP) spectrometer

Energy loss of proton

- Energy loss of proton measured by the AFP: $\xi_{AFP} = 1 - E_{scattered}/E_{beam}$
- Central detector estimation: $\xi_{ll}^{\pm} = m_{ll}e^{\pm y_{ll}}/2E_{beam}$
- Difference $|\xi_{AFP} - \xi_{ll}^{\pm}| < 0.005$ used to match dilepton pair with scattered proton

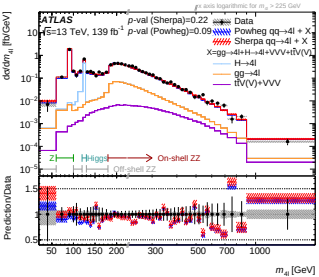
- Results consistent with the SM prediction
- Ability to measure the scattered proton $\Longrightarrow$ can be used in future $\gamma\gamma \to W^+W^-$ measurement

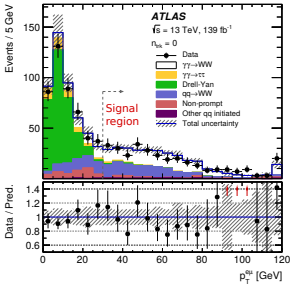
Summary

ATLAS has a rich multi-boson program:

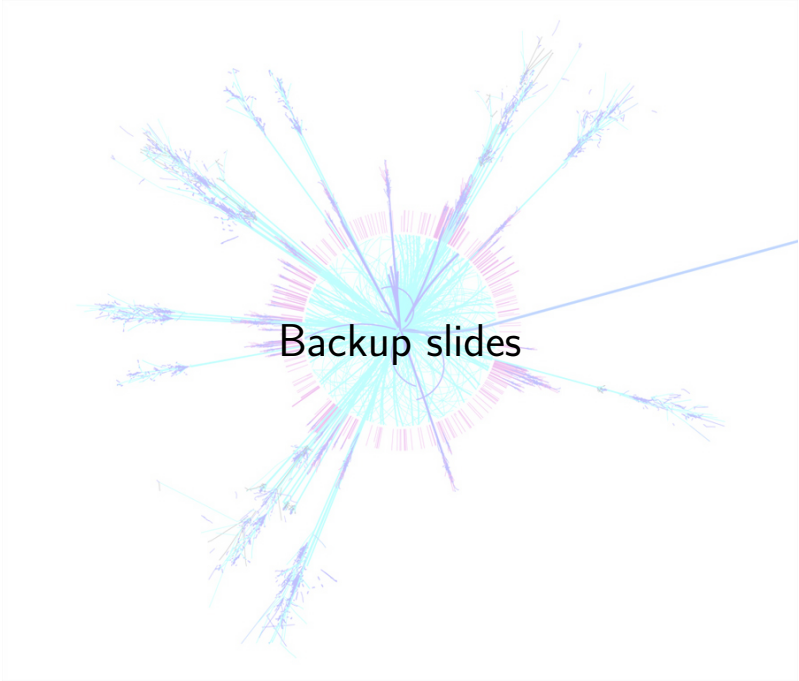
- Precision measurements
- Observations of new processes
- BSM limits

Great way to probe the EW part of the standard model!

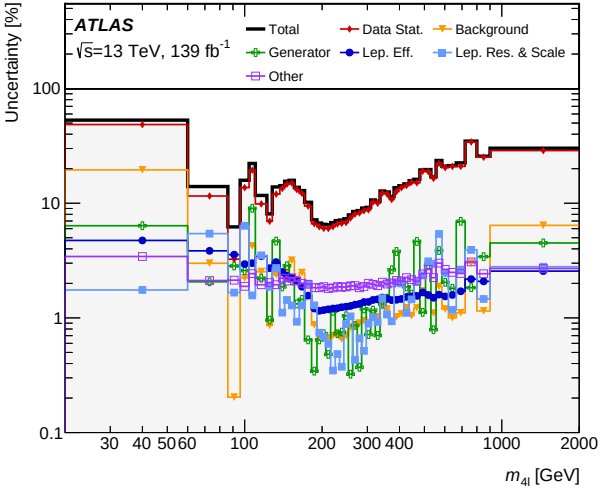




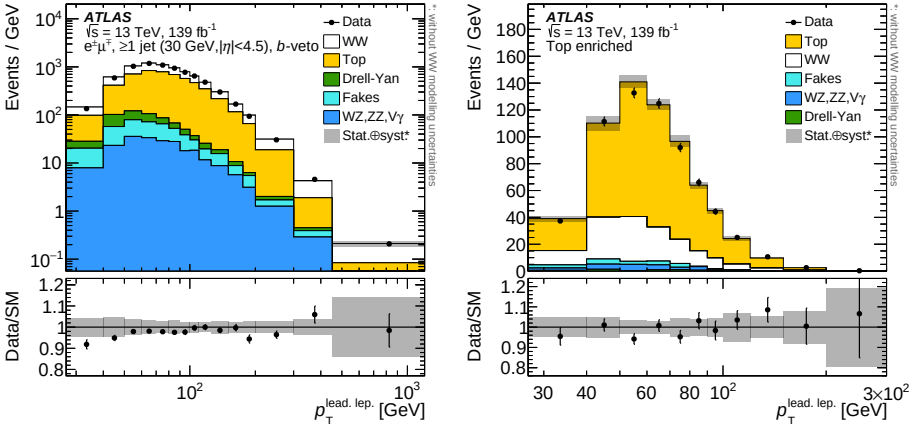
- $4l$ and WW+jet differential measurement, with BSM interpretation (SMEFT, B-L symmetry breaking)
- $Z\gamma$ measurement, with non-negligible contribution of Z and γ from different $p-p$ collisions
- Vector boson scattering measured in ZZ+2jet final state, large invariant mass and rapidity difference compared to QCD
- New photon-photon processes observed recently!
  - $\gamma\gamma \to WW$ final state
  - Proton scattering associated with $\gamma\gamma \to ll$


Backup slides

4l extra: Uncertainties breakdown



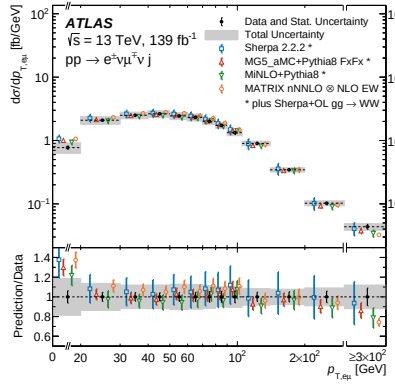
WW+jet extra: detector level



Leading jet p_{T} in:

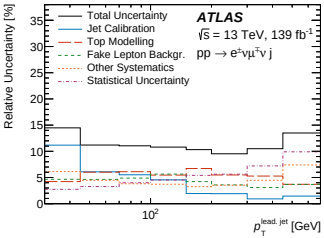
- Left: Signal region
- Right: Top control region (top - data-driven normalization)

WW+jet extra: particle level

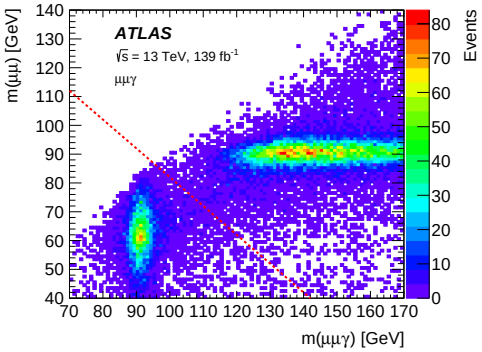


Process	Generator	Parton shower	PDF	Matrix element $O(\alpha_S)$
$q\bar{q} \to WW$	MATRIX 2.0	–	NNPDF3.1	NNLO
$gg \to WW$	MATRIX 2.0	–	NNPDF3.1	NLO
$q\bar{q} \to WW$	Sherpa 2.2.2	Sherpa	NNPDF3.0	NLO (0–1 jet), LO (2–3 jets)
$q\bar{q} \to WW$	Powheg MiNLO	Pythia 8	NNPDF3.0	NLO (0–1 jet)
$q\bar{q} \to WW$	MadGraph 2.3.3	Pythia 8	NNPDF3.0	NLO (0–1 jet)
$gg \to WW$	Sherpa 2.2.2 + OpenLoops	Sherpa	NNPDF3.0	LO (0–1 jet)

- Left: Unfolded $p_{\mathrm{T}}^{e\mu}$
- Top right : Summary of $qq \to WW$ generators
- Bottom right: Uncertanties

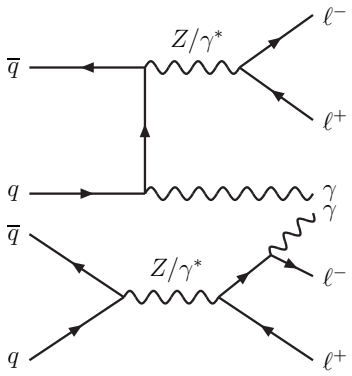


$Z\gamma$ extra: Selection

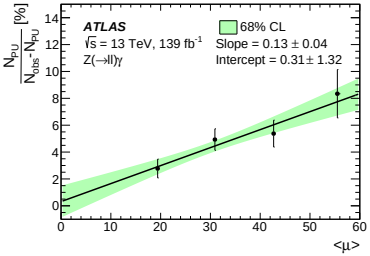


Photons	Electrons/Muons
$E_{\mathrm{T}}^{\gamma} > 30$ GeV	$p_{\mathrm{T}}^{\ell} > 30,25$ GeV
$\lvert\eta^{\gamma}\rvert < 2.37$	$\lvert\eta^{\ell}\rvert < 2.47$
$E_{\mathrm{T}}^{\mathrm{cone0.2}}/E_{\mathrm{T}}^{\gamma} < 0.07$	dressed leptons
$\Delta R(\ell,\gamma) > 0.4$	
Event selection	
$m(\ell\ell)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

$\leftarrow m_{ll} + m_{ll\gamma} \geq 182$ GeV
to separate ISR/FSR photons:



$Z\gamma$ extra: PU contribution and XS



	Cross-section [fb]		
$e^+e^-\gamma$	530.4	$\pm$ 9.0 (uncorr)	$\pm$ 11.7 (corr) $\pm$ 9.0 (lumi)
$\mu^+\mu^-\gamma$	535.0	$\pm$ 6.1 (uncorr)	$\pm$ 11.5 (corr) $\pm$ 9.1 (lumi)
$\ell^+\ell^-\gamma$	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)

- Left: Contribution of PU as function of average number of int. vertices
- Right: Measured cross-section vs. various generators

ZZ+ 2 jet extra: Detailed selection

	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
Electrons	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.47$ $\lvert d_0/\sigma_{d_0}\rvert < 5$ and $\lvert z_0 \times \sin\theta\rvert < 0.5$ mm	
Muons	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.7$ $\lvert d_0/\sigma_{d_0}\rvert < 3$ and $\lvert z_0 \times \sin\theta\rvert < 0.5$ mm	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.5$
Jets	$p_{\mathrm{T}} > 30$ (40) GeV for $\lvert\eta\rvert < 2.4$ ($2.4 < \lvert\eta\rvert < 4.5$)	$p_{\mathrm{T}} > 60$ (40) GeV for the leading (sub-leading) jet
ZZ selection	$p_{\mathrm{T}} > 20$, 20, 10 GeV for the leading, sub-leading and third leptons Two OSSF lepton pairs with smallest $\lvert m_{\ell^+\ell^-} - m_Z\rvert + \lvert m_{\ell'^+\ell'^-} - m_Z\rvert$ $m_{\ell^+\ell^-} > 10$ GeV for lepton pairs $\Delta R(\ell, \ell') > 0.2$ $66 < m_{\ell^+\ell^-} < 116$ GeV	$p_{\mathrm{T}} > 30$ (20) GeV for the leading (sub-leading) lepton One OSSF lepton pair and no third leptons $80 < m_{\ell^+\ell^-} < 100$ GeV No b-tagged jets $E_{\mathrm{T}}^{\mathrm{miss}}$-significance > 12
Dijet selection	Two most energetic jets with $y_{j_1} \times y_{j_2} < 0$ $m_{jj} > 300$ GeV and $\Delta y(jj) > 2$	$m_{jj} > 400$ GeV and $\Delta y(jj) > 2$

- …

$Z\gamma$+2 jets extra:

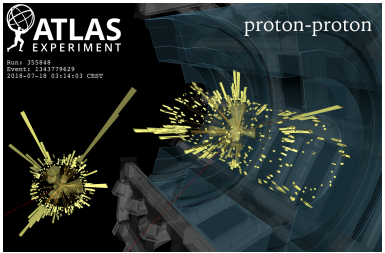
Variable used in the BDT
m_{jj}
$\Delta\eta_{jj}$
$\zeta(\ell\ell\gamma)$
$m_{\ell\ell\gamma}$
$p_T^{\ell\ell\gamma}$
$m_{\ell\ell}$
$p_T^{\ell\ell}$
$p_T^{\text{lead lep}}$
$p_T^{\text{lead jet}}$
$\eta^{\text{lead jet}}$
$min\Delta R(\gamma, j)$
$\Delta\phi(\ell\ell\gamma, jj)$
$\Delta R(\ell\ell\gamma, jj)$

	$\ell^+\ell^-\gamma jj$ preselection
Lepton	$p_T^\ell > 20$ GeV
	$\lvert\eta_\ell\rvert < 2.5$
	remove e if $\Delta R(e,\mu) < 0.1$
	$N_\ell \geq 2$
Boson	$m_{\ell^+\ell^-} > 40$ GeV
	$m_{\ell^+\ell^-} + m_{\ell^+\ell^-\gamma} > 182$ GeV
Photon	$E_T^\gamma > 15$ GeV
	$\lvert\eta_\gamma\rvert < 2.37$
	remove γ if $\Delta R(\ell,\gamma) < 0.4$
	$N_\gamma \geq 1$
Jet	$p_T^{\text{jet}} > 50$ GeV , $\lvert\eta_{\text{jet}}\rvert < 4.5$
	$N_{\text{Jets}} \geq 2$
	remove jets if $\Delta R(\ell, \text{jet}) < 0.3$ OR $\Delta R(\gamma, \text{jet}) < 0.4$
	$\lvert\Delta\eta_{jj}\rvert > 1.0$
	$m_{jj} > 150$ GeV
Signal Region	$\ell^+\ell^-\gamma jj$ preselection
	$\zeta(\ell\ell\gamma) < 5$

Source	Uncertainty [%]
Statistical	$^{+19}_{-18}$
$Z\gamma jj$–EW theory modelling	$^{+10}_{-6}$
$Z\gamma jj$–QCD theory modelling	± 6
$t\bar{t}+\gamma$ theory modelling	± 2
$Z\gamma jj$–EW and $Z\gamma jj$–QCD interference	$^{+3}_{-2}$
Jets	± 8
Pile-up	± 5
Electrons	± 1
Muons	$^{+3}_{-2}$
Photons	± 1
Electrons/photons energy scale	± 1
b-tagging	± 2
MC statistical uncertainties	± 8
Other backgrounds normalisation (including Z+jets)	$^{+9}_{-8}$
Luminosity	± 2
Total uncertainty	± 26

- Left: variables used to train the BDT
- Middle: Selection
- Right: Uncertainties

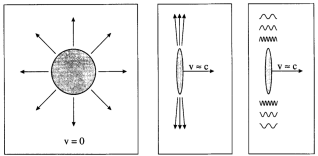
LHC as a photon collider



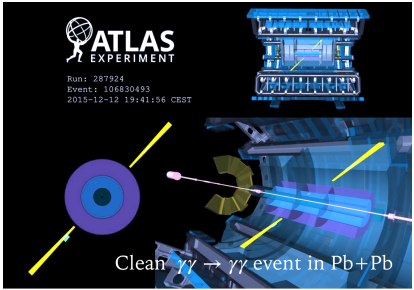
- Regular LHC event: interaction of constituent partons
  $\Longrightarrow$ large activity due to presence of strong interaction
  (parton shower, hadronization, underlying event ...)

(Event displays taken from
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/EventDisplayRun2Physics)

- Proton/heavy ions charged particles:
  boosted EM field behaves as a field of quasi-real photons
  $\Longrightarrow$ photon-photon interactions!

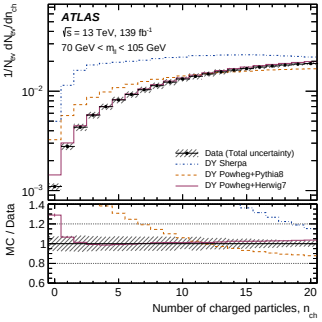


- No color flow between protons = no extra particle activity

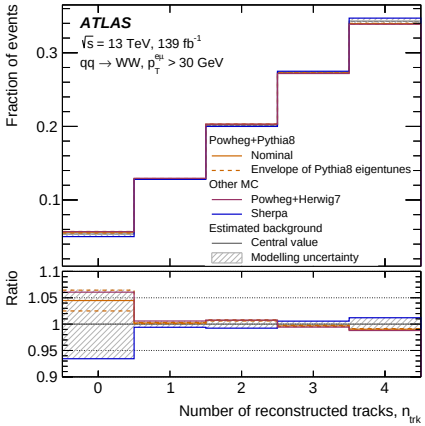


$\gamma\gamma \to W^+W^-$ extra: Modeling of inclusive WW

- Data driven correction from unfolded Drell-Yan:



- Numerous samples available
  1. Powheg+Pythia 8 + parameter variations
  2. Sherpa
  3. Powheg+Herwig 7 (last minute addition)
- HS and PU corrections applied on all of them
- Remaining mismodelling taken as a systematic (PP8/Sherpa mean value +- envelope)



[arXiv:2010.04019]

$\gamma\gamma \to W^+W^-$ extra: uncertainties theoretical prediction

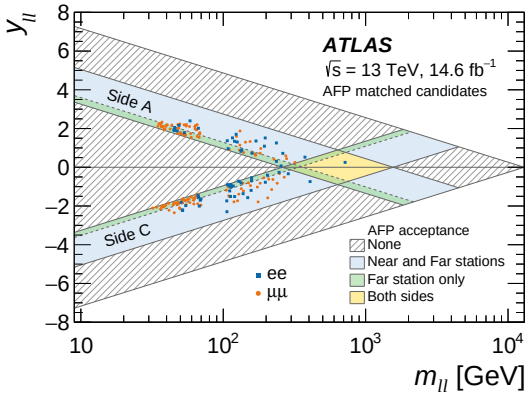
Measured cross-section:

3.13±0.31(stat.)±0.28(syst.) fb

Source of uncertainty	Impact [% of the fitted cross section]
Experimental	
Track reconstruction	1.1
Electron energy scale and resolution, and efficiency	0.4
Muon momentum scale and resolution, and efficiency	0.5
Misidentified leptons, systematic	1.5
Misidentified leptons, statistical	5.9
Other background, statistical	3.2
Modelling	
Pile-up modelling	1.1
Underlying-event modelling	1.4
Signal modelling	2.1
WW modelling	4.0
Other background modelling	1.7
Luminosity	1.7
Total	8.9

- 2.34 ± 0.27 fb (HERWIG7+data driven modeling correction)
- 2.8 ± 0.8 fb or 3.5 ± 1.0 fb MG5_aMC@NLO with two estimates of the survival probability

$\sigma_{\text{HERWIG+LPAIR}} \times S_{\text{surv}}$	$\sigma^{\text{fid.}}_{ee+p}$ [fb]	$\sigma^{\text{fid.}}_{\mu\mu+p}$ [fb]
$S_{\text{surv}} = 1$	15.5 ± 1.2	13.5 ± 1.1
S_{surv} using Refs. [31,30]	10.9 ± 0.8	9.4 ± 0.7
SUPERCHIC 4 [94]	12.2 ± 0.9	10.4 ± 0.7
Measurement	11.0 ± 2.9	7.2 ± 1.8



- Left: Prediction of survival factor vs measurement
- Right: Distribution of measure events