10th International Conference On New Frontier In Physics (ICNFP 2021)

Vector-boson Scattering, Diboson And Triboson Production at ATLAS

VALLARY BHOPATKAR
On behalf of ATLAS Collaboration

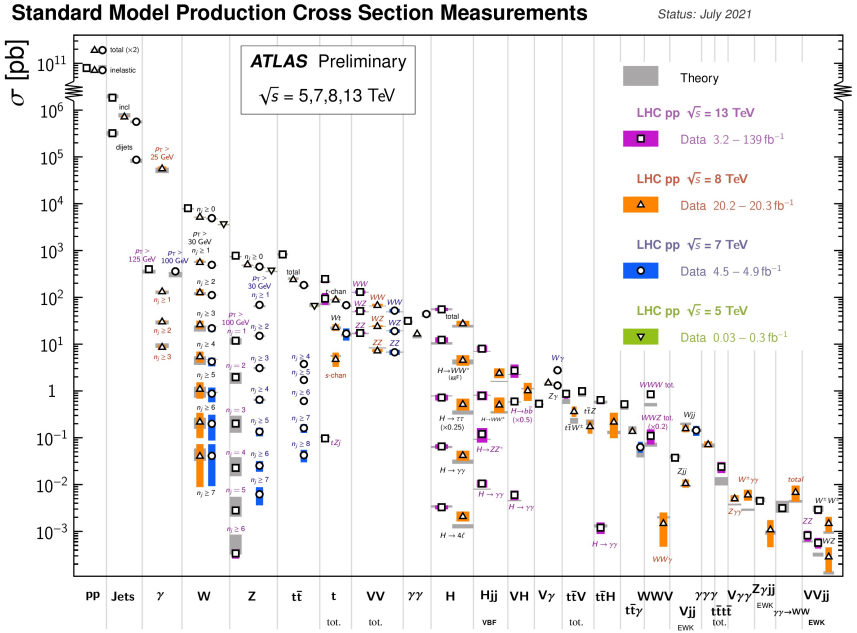
U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

Argonne NATIONAL LABORATORY 75 1946–2021

Motivation

ATL-PHYS-PUB-2021-032

- Through electroweak Boson self-interaction multi-boson can provide unique probe of standard model
- Precious test of higher order prediction
  - Higher order corrections important at higher center of mass energy
- Search for the Beyond Standard Model
  - Many process acts as a background for many direct BMS searches
  - Important to measure them precisely
- Differential Fiducial cross-section measurements
  - W^+W^- + ≥ 1 Jets Production JHEP 06 (2021) 003
- Observation and cross-section measurements
  - $Z(\rightarrow \ell\ell)\gamma jj$ Production ATLAS-CONF-2021-038
  - $Z(\rightarrow \nu\bar{\nu})\gamma jj$ Production EXOT-2021-17

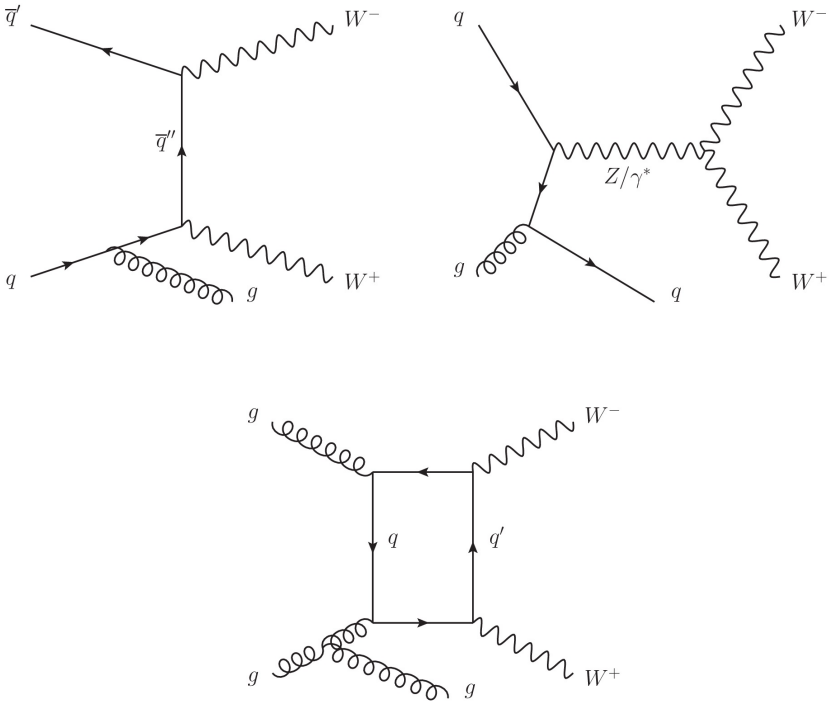


- Triboson Measurements
  - WWW results ATLAS-CONF-2021-039

Measurements of W^+W^- + ≥ 1 Jets Production

W^+W^- + ≥ 1 Jets Inclusive Measurements

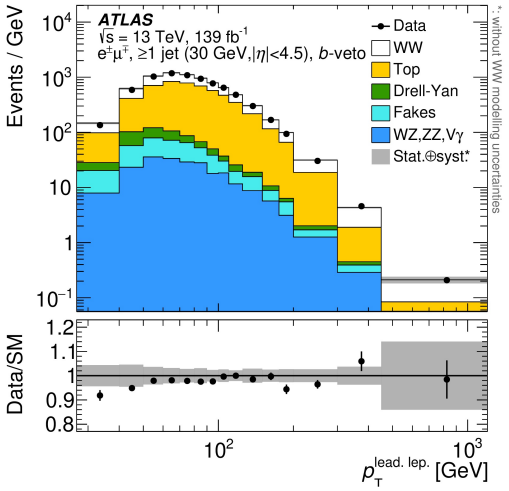
- The fiducial and differential cross-section measurements
  - First time at LHC, differential measurements performed in jet-inclusive phase space
- Provides stringent test of theoretical prediction
  - Perturbative QCD
  - Higher order EWK corrections
- Measurements are performed by selecting on opposite sign eμ pair along with at least one hadronic jet
- Sensitivity to triple gauge coupling vertex

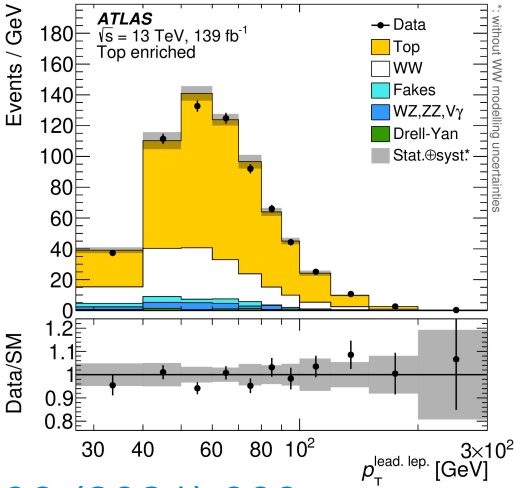


JHEP 06 (2021) 003

W^+W^- + ≥ 1 Jets Analysis Strategies

- Event selection criteria
  - Considered eμ channel only
  - Kinematic cuts selected to match the fiducial region
  - b-jet veto to reduced large top background
  - $m_{e\mu}$ > 85 MeV to suppress Drell-Yan background as well as H→WW resonance
- Background Estimation
  - Dominated by Top background
    - $t\bar{t}$ is estimated with data-driven method
    - Consider 2 control region with 1btag and 2btag
  - Drell-Yan background is estimated using the MC samples
  - Fake leptons also estimated using the data-driven method
  - Single top and diboson background estimated using MC (Sherpa) Samples





Fiducial Cross-Section

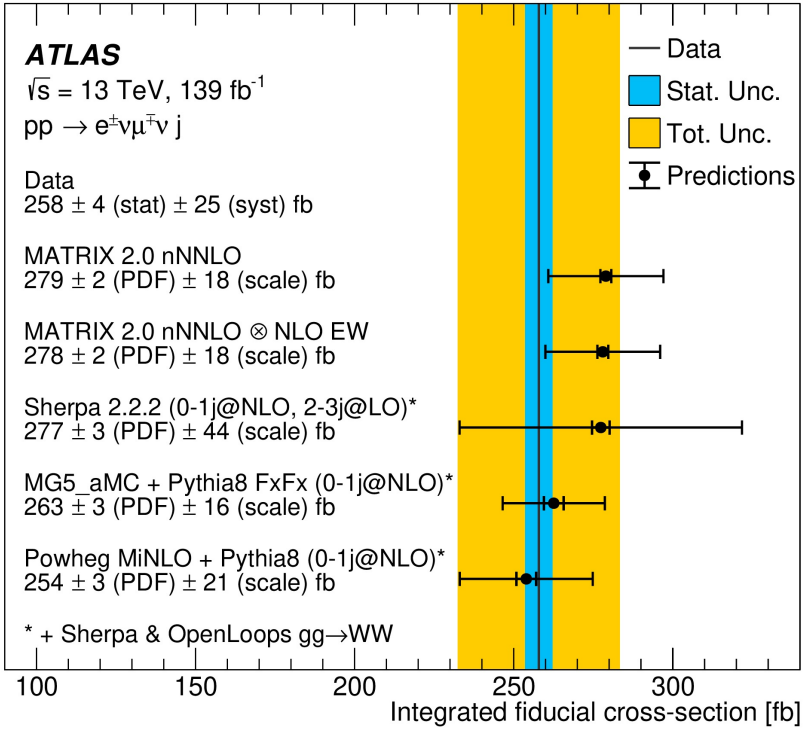
JHEP 06 (2021) 003

$\sigma_{fid} = 258 \pm 4\ (stat.) \pm 25\ (syst.)$ fb

10% total uncertainty

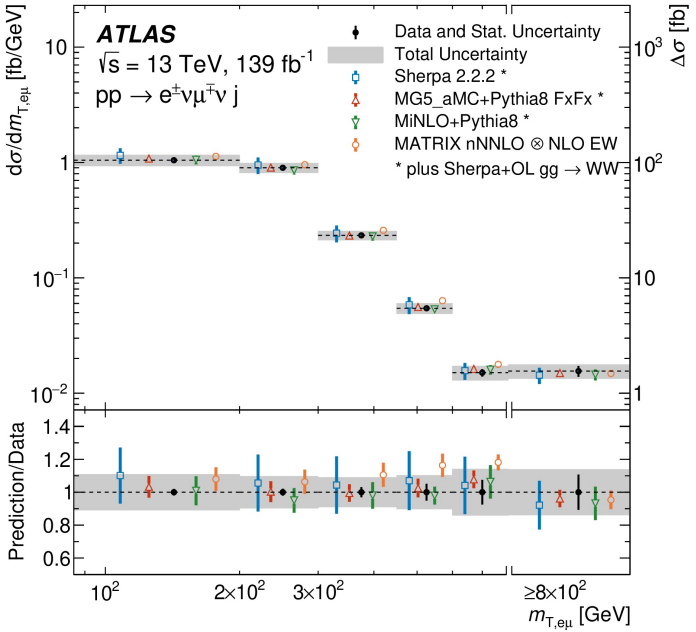
- Fix-order NLO prediction with Sherpa, Madgraph and Powheg generators are consistent with theory prediction

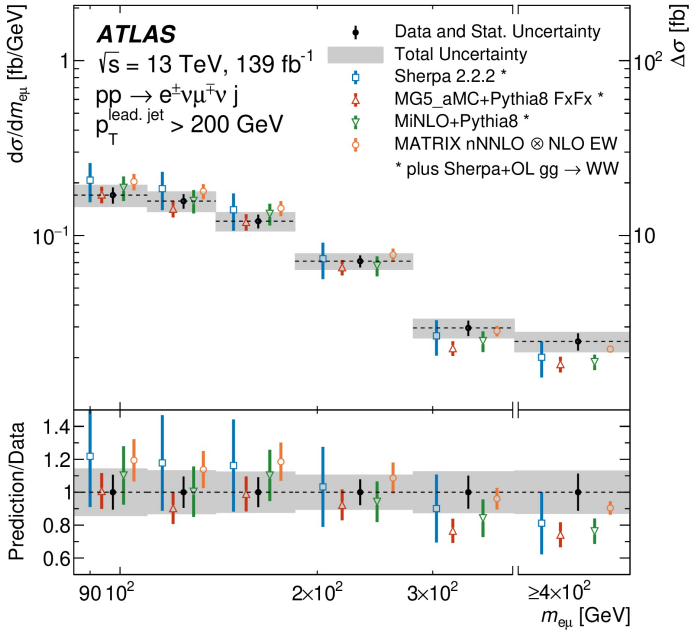
Fiducial selection requirements		
p_T^{ℓ}	>	27 GeV
$\lvert\eta^{\ell}\rvert$	<	2.5
$m_{e\mu}$	>	85 GeV
p_T^{j}	>	30 GeV
$\lvert y^{j}\rvert$	<	4.5



Differential Cross-section

JHEP 06 (2021) 003





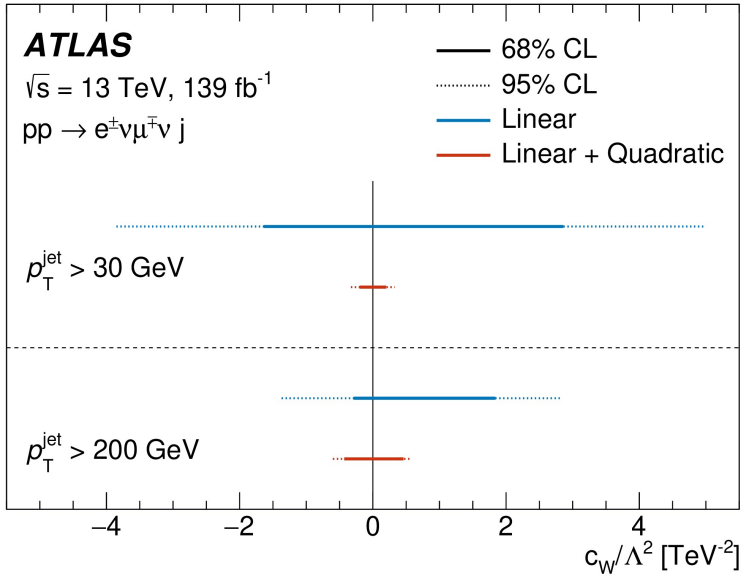
- Differential cross-section is measured with different kinematic variables
- Good agreement with MC prediction and Data
- Measurements with higher momentum for NLO EW correction
- Higher sensitivity to aTGCs

EFT in W^+W^- + ≥ 1 Jets: dim-6 operators

JHEP 06 (2021) 003

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i C_i^{(6)} \mathcal{O}_i^{(6)} + \sum_i C_i^{(8)} \mathcal{O}_i^{(8)} + \cdots$$

- Final state sensitive to dim-6 Q_w variable
- $m_{e\mu}$ used as a discriminant in an enhanced $p_T > 200$ GeV jet phase space
- C_w coefficient is constraint
- In addition to these studies ATLAS has published combined EFT interpretation results of differential cross-section measurements of WW, WZ, 4l, and Z+ jj production ATL-PHYS-PUB-2021-022



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]

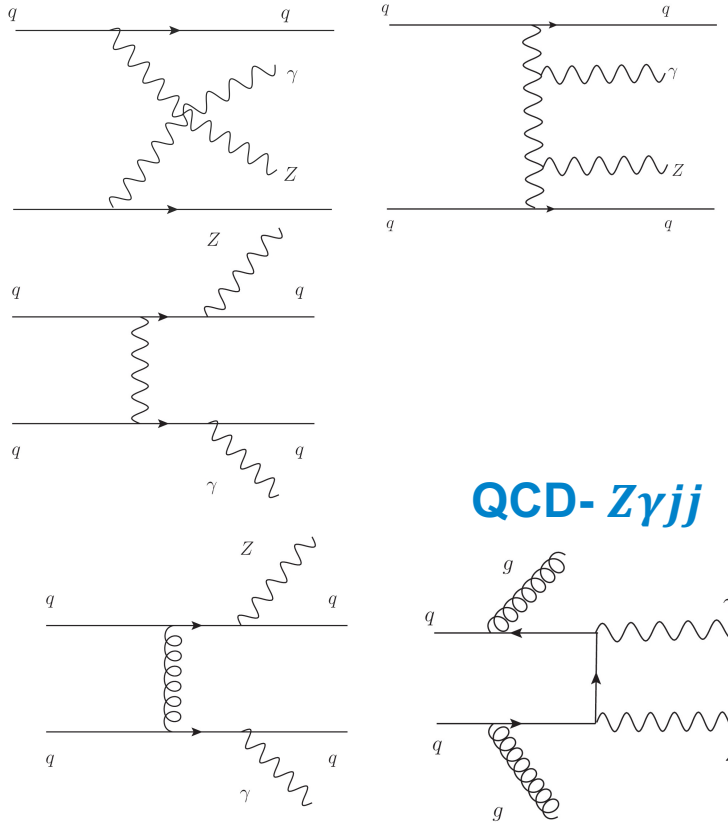
Vector Boson Scattering

Production $Z(\rightarrow \ell\ell)\gamma jj$

ATLAS-CONF-2021-038

- Powerful test to the standard model (SM) for its sensitivity to the gauge self-interaction
- Provides opportunity to explore vector boson scattering (VBS), which directly probe the electroweak symmetry breaking of the SM as well as can extract the constraints on anomalous gauge coupling
- Electroweak production of the Zγjj final state contains both VBS and non-VBS process
- When initial and final states of the Zγ production are same then the production mechanism with EWK and QCD interference
- Observation and cross-section measurements of EW-Zγjj with 139 fb^{-1} Run-II data is presented
  - Z boson decays to wither e^-e^+ or $\mu^-\mu^+$

EW- $Z\gamma jj$



QCD- $Z\gamma jj$

ATLAS-CONF-2021-038

EWK Production $Z(\rightarrow \ell\ell)\gamma jj$

Analysis Strategy

- Events selection by defining phase is applied at particle level

Lepton	$p_{\mathrm{T}}^{\ell} > 20, 30(\text{leading})\ \text{GeV}, \quad \lvert\eta_{\ell}\rvert < 2.47$ $N_{\ell} \geq 2$
Photon	$E_{\mathrm{T}}^{\gamma} > 25\ \text{GeV}, \quad \lvert\eta_{\gamma}\rvert < 2.37$ $E_{\mathrm{T}}^{cone20} < 0.07 E_{\mathrm{T}}^{\gamma}$ $\Delta R(\ell, \gamma) > 0.4$
Jet	$p_{\mathrm{T}}^{jet} > 50\ \text{GeV}, \quad \lvert y_{jet}\rvert < 4.4$ $\lvert\Delta y\rvert > 1.0$ $m_{jj} > 150\ \text{GeV}$ remove jets if $\Delta R(\gamma, j) < 0.4$ or if $\Delta R(\ell, j) < 0.3$
Event	$m_{\ell\ell} > 40\ \text{GeV}$ $m_{\ell\ell} + m_{\ell\ell\gamma} > 182\ \text{GeV}$ $\zeta(\ell\ell\gamma) < 0.4$ $N_{jets}^{gap} = 0$

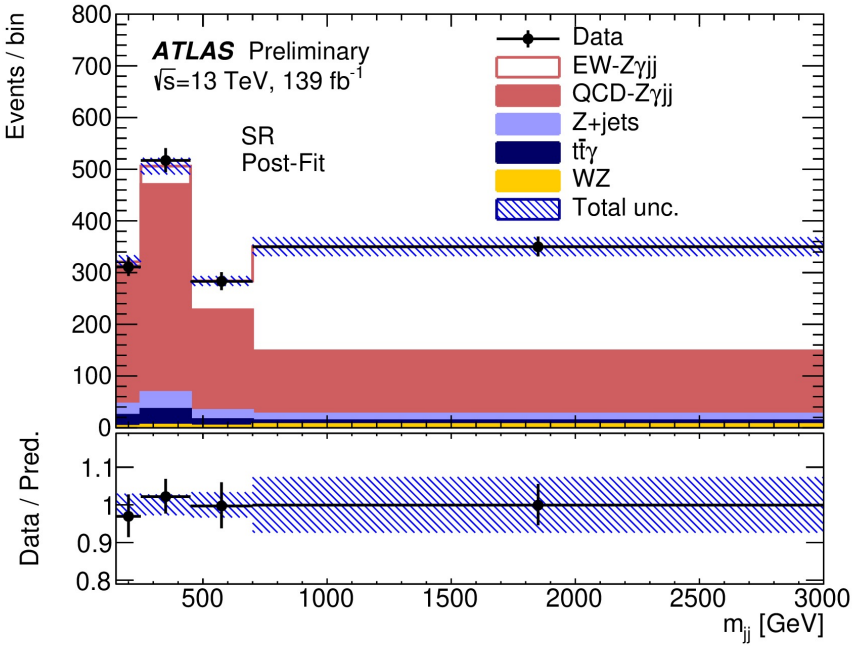
- Cuts on the centrality (ζ) of the $\ell^{+}\ell^{-}\gamma$ system defines the Signal and Control Regions
  - **SR (ζ <0.4) and QCD CR (ζ >0.4)**

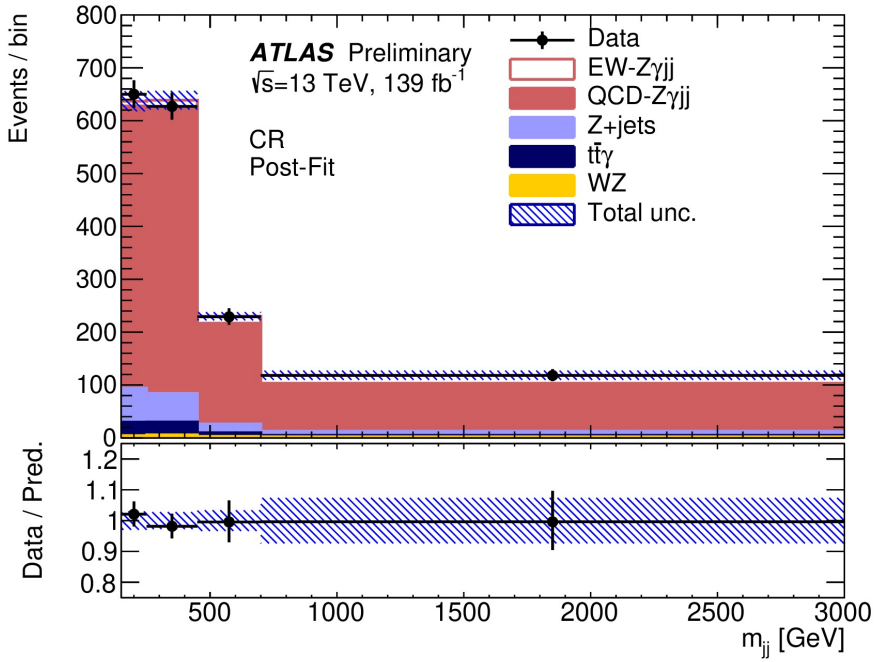
Background Estimation

- Main source of background: Zγjj events from QCD induced process i.e. QCD- Zγjj
  - Shape estimated from MC and normalization factor determined from the final fit
- Second largest background comes form Z+jet
  - Estimated with data driven method
- $t\bar{t}\gamma$ events estimated using MC samples
  - scaled factor is derived by comparing the prediction with the data using an eμγ events
- Other small backgrounds estimated using MC

m_{jj} Distribution in SR and CR

ATLAS-CONF-2021-038



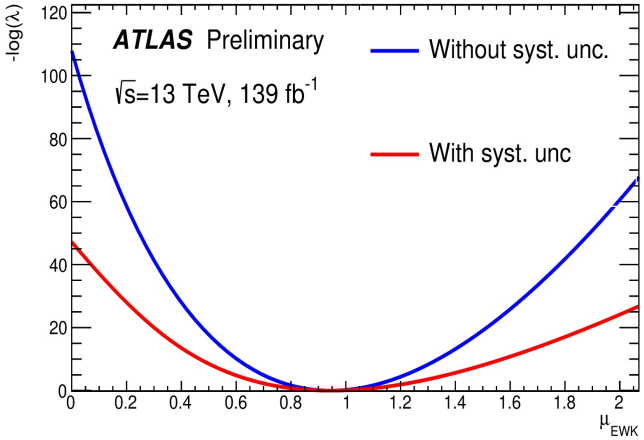


Events beyond the upper limit of the histogram are included in the last bin

Cross-section of Production $Z(\rightarrow \ell\ell)\gamma jj$

- Measured signal strength
  - $\mu_{EW} = 0.95 \pm 0.08\,(\mathrm{stat}) \pm 0.11(\mathrm{syst})$
- Observed significance of 10σ, whereas expected is 11σ
- Fiducial cross-section in the EWK $pp \rightarrow Z\gamma jj$ in the phase space
  - $\sigma_{EW} = 4.49 \pm 0.40\,(\mathrm{stat}) \pm 0.42(\mathrm{syst})$ fb with overall 13% uncertainty
  - Results are consistent with the predicated cross-section using the MadGraph5 interfaced with Pythia8
- The total cross-section of $(EW + QCD) - Z\gamma jj$ is obtained with the precision of 7%
  - $\sigma_{EW+QCD} = 20.6 \pm 0.6(stat)^{+1.2}_{-1.0}(syst)$ fb

ATLAS-CONF-2021-038



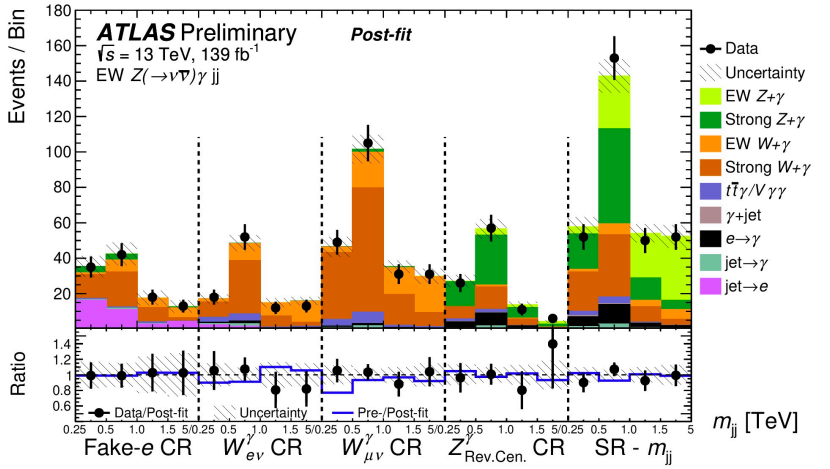
Production of $Z(\rightarrow \nu\bar{\nu})\gamma jj$

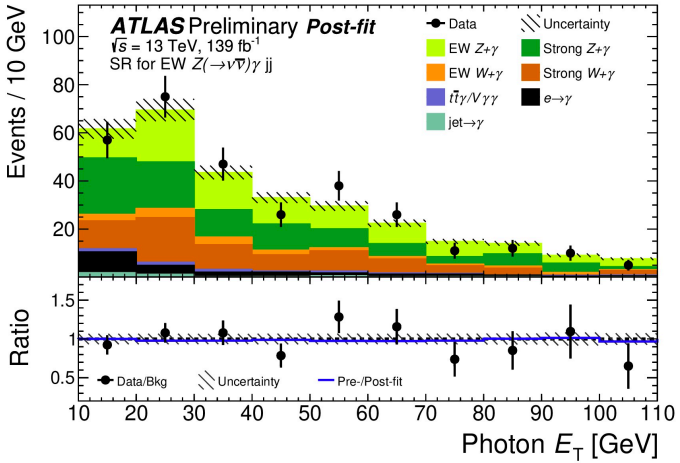
- The first observation measurement of production of $Z(\rightarrow \nu\bar{\nu})\gamma jj$ with 5.2(5.1) σ significance
- Backgrounds are constraint during the final fit with defining the multiple control regions
- In the signal regions all events with leptons are vetoed
- Measured signal strength

  $\mu_{EW} = 1.03 \pm 0.25$
- Measured fiducial cross-section:

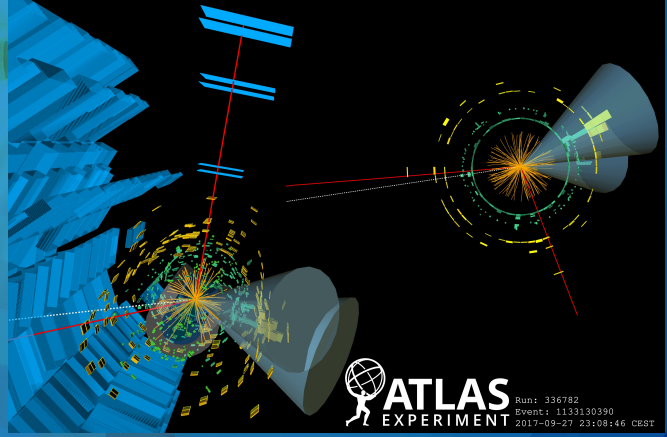
  $\sigma^{fid}_{Z(\rightarrow\nu\bar{\nu})\gamma EW} = 1.31 \pm 0.2\ (stat) \pm 0.2\ (syst)\ fb$
- Analysis also set limits on the invisible Higgs decay

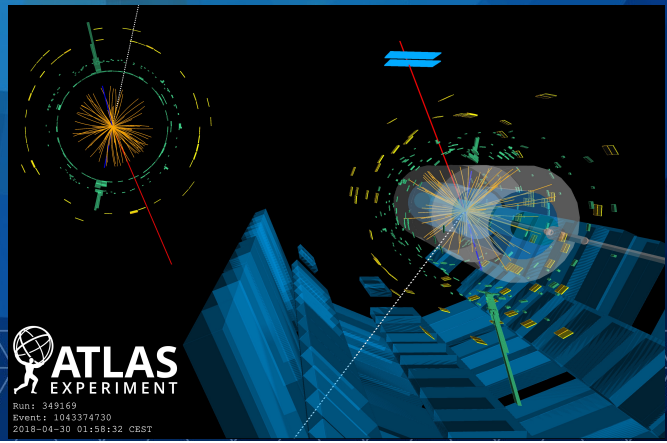
EXOT-2021-17





Triboson Production





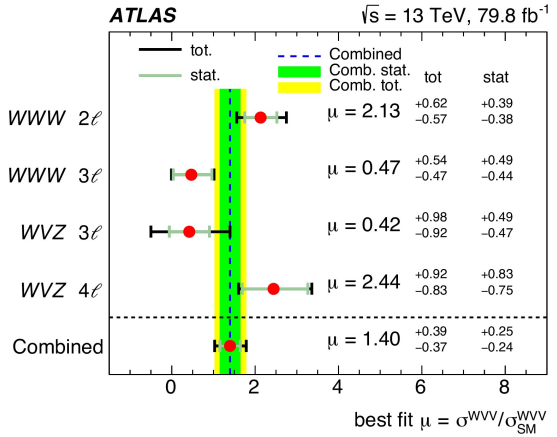
Triboson Production at LHC

- Evidence and observations of the combined triboson channels are reported by ATLAS and CMS experiments
  - Evidence for production of massive vector boson with ATLAS detector
    - ATLAS 80 fb^{-1} : WVV 4.1σ, WWW 3.2σ
    - CMS 137 fb^{-1} : VVV 5.7σ, WWW 3.3σ
- Now with full Run II 139 fb^{-1} data ATLAS experiment achieved observation results in stand alone WWW channel

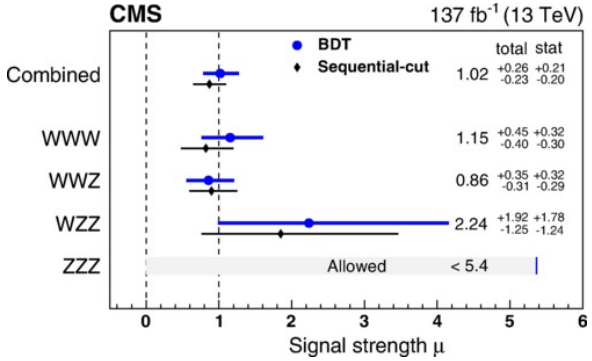
New Results: ATLAS 139 fb^{-1} WWW 8.2σ

ATLAS-CONF-2021-039

J. Physics Letter B .2019.134913



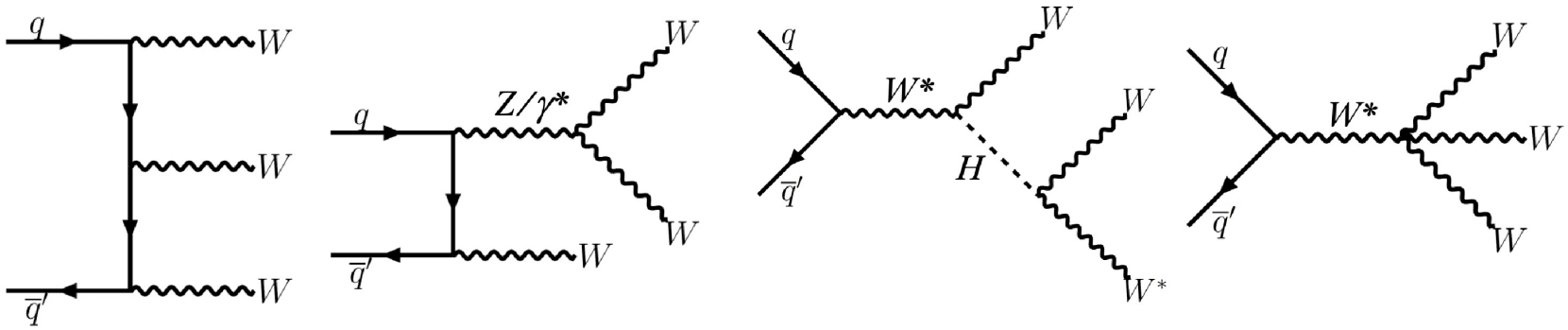
Phys. Rev. Lett. 125, 151802



WWW Production

ATLAS-CONF-2021-039

Using Run II ATLAS Data: $W^{\pm}W^{\mp}W^{\mp} \rightarrow lvlvjj$ $(lvlvlv)$

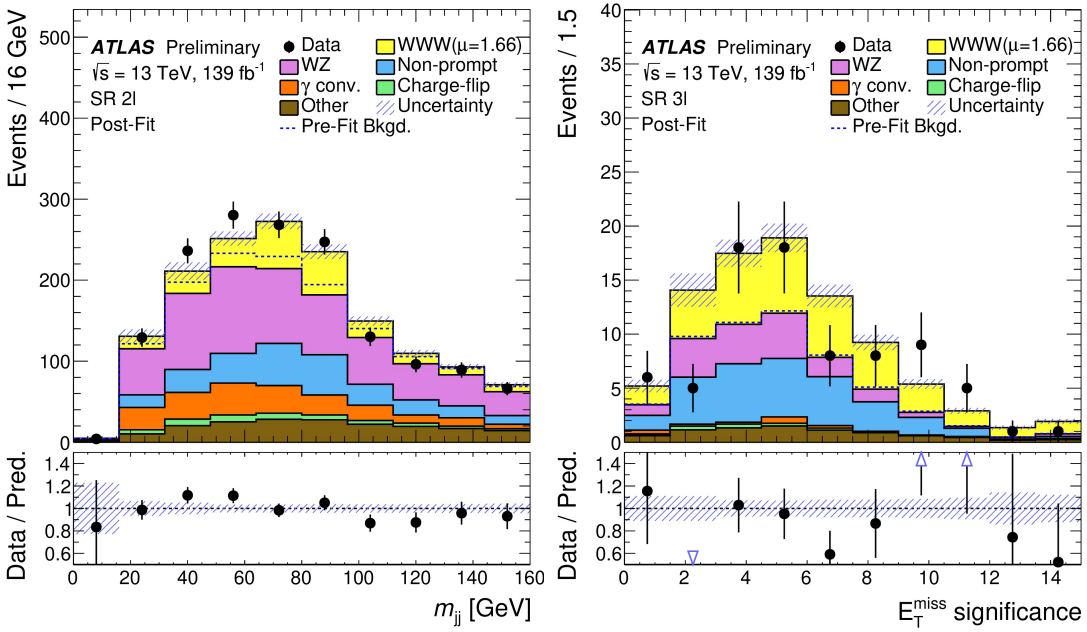


- During Run II analysis, WWW production is measured using two final states:
  - Two lepton channel: $W^{\pm}W^{\mp}W^{\mp} \rightarrow l^{\pm}\nu l^{\pm}\nu jj$
    - It only includes same-sign leptons (ee, eμ, μμ) and two jets from the third W bosons
  - Three lepton channel: $W^{\pm}W^{\mp}W^{\mp} \rightarrow l^{\pm}\nu l^{\mp}\nu l^{\mp}\nu$
    - It includes zero same flavor opposite sign lepton pairs

WWW Signal and Backgrounds

ATLAS-CONF-2021-039

- The signal events includes events from WWW along with WH events contributing from the 3rd Feynman diagram

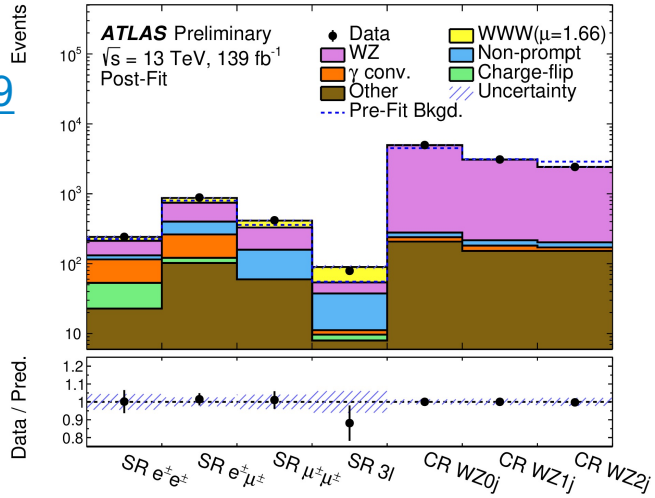


- Background includes WZ, Non-prompt, γ- conversion, and charge flip
- 2 lepton channel: More statistics but also large background
  - Dominated by WZ, γ- conversion and followed by other backgrounds
- 3 lepton channel: Relatively small background but is statistically limited
  - Dominated by non-prompt background

Analysis Strategy

ATLAS-CONF-2021-039

- Analysis is dominated by the WZ background
  - Data-driven method is used to estimated the WZ normalization scale factors
  - There are three WZ control region based on the jet multiplicity i.e. 0j, 1j and ≥ 2j
  - Separate normalization factor used for each control region
- Machine learning techniques are used to increased the signal sensitivity
  - Boosted Decision Trees (BDT) is used to fit the signal and control region simultaneously
  - For BDT training:
    - 2 lepton channel: includes 12 variables
    - 3 lepton channel: includes 11 variables



BDT variables (ordered by importance)

2ℓ	3ℓ
$\lvert m_{jj} - m_W \rvert$	$E_{\mathrm{T}}^{\mathrm{miss}}$ significance $\times 10/E_{\mathrm{T}}^{\mathrm{miss}}$
p_{T} (forward jet)	$p_T(\ell_2)$
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	N(jets)
$p_T(j_2)$	same flavor $m_{\ell\ell}$
minimum $m(\ell, j)$	$m_T(\ell\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}})$
$m(\ell_2, j_1)$	$m(\ell_2, \ell_3)$
N(jets)	$\Delta\phi(\ell\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}})$
p_{T} (ℓ_2)	minimum $\Delta R(\ell, \ell)$
$m_{\ell\ell}$	p_{T} (ℓ_3)
$\lvert\eta(\ell_1)\rvert$	$m_T(\ell_2, E_{\mathrm{T}}^{\mathrm{miss}})$
N(leptons in jets)	$E_{\mathrm{T}}^{\mathrm{miss}}$ significance
$m(\ell_1, j_1)$	

WWW Measurements

ATLAS-CONF-2021-039

Signal Strength

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

Measured Cross-Section of WWW production

850 ± 100 (stat.) ± 80 (sys.) fb

- SM expected cross-section from MC samples is used to estimate the μ
  - Cross-section from MC: WWW + WH: 511 ± 42 fb

Summary

- ATLAS Run-II measurements with integrated luminosity 139 fb^{-1} are presented
  - W^+W^- + ≥ 1 Jets, $Z(\rightarrow \ell\ell)\gamma jj$, $Z(\rightarrow \nu\bar{\nu})\gamma jj$, and WWW production
- Cross-section measurements are studied in detail
- Observation results in stand-alone WWW channel are achieved with 8.2σ

Thank You!!