NEW RESULTS ON VECTOR BOSON SCATTERING PROCESSES WITH THE ATLAS DETECTOR

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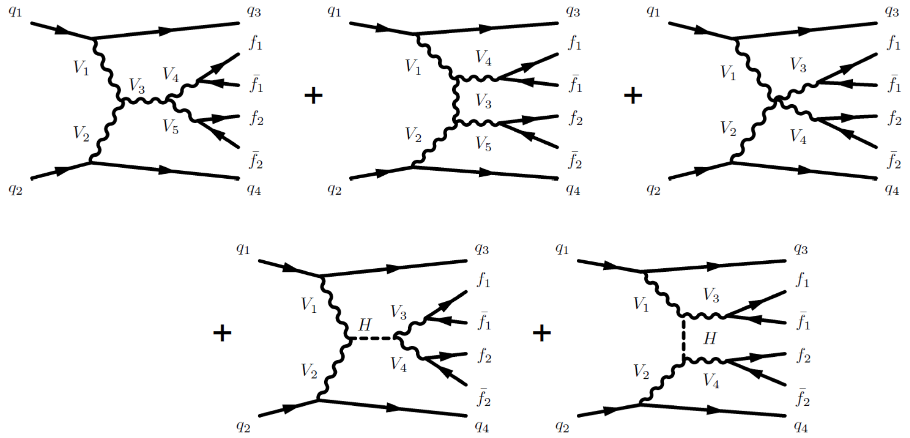
MOTIVATION

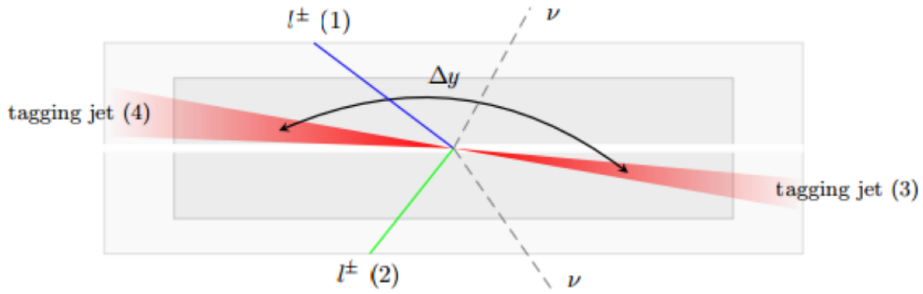
- Vector Boson Scattering is important for understanding EWK symmetry breaking
- Without the SM Higgs, longitudinal VV scattering cross section ($\sigma_{VV \rightarrow VV}$) increases as center-of-mass energy and violates unitarity at high energy
- Can be solved by adding contributions from Higgs



Representative Feynman diagrams of the VBS process at the LHC

- BSM Physics can alter the couplings of vector bosons, generating additional contribution to Quartic Gauge Couplings w.r.t the SM predictions.
- Same-Sign WW EWK ($W^{\pm}W^{\pm}jj \rightarrow \ell^{\pm}\nu\ell^{\pm}\nu jj$): WZ and fakes as major backgrounds
- WZ EWK ($W^{\pm}Zjj \rightarrow \ell^{\pm}\nu\ell^{\pm}\ell^{\mp}jj$): WZ-QCD as major background

EWK PRODUCTION OF SSWW VBS



ssWW Event Topology

Cuts in Inclusive Region

- Two same-sign ID Lepton with p_T>27GeV
- $|\eta|$<2.47(2.5) for Electron (Muon)
- $|\eta_e|$<1.37 in ee channel
  - Optimization. Suppress charge flip bkg
- Cut on unambiguous electron author
  - Reduce Chargflip by 25%-30%
- M_{ll} > 20GeV
- 3rd lepton veto
  - p_T>6GeV for veto leptons

Cuts in Signal Region

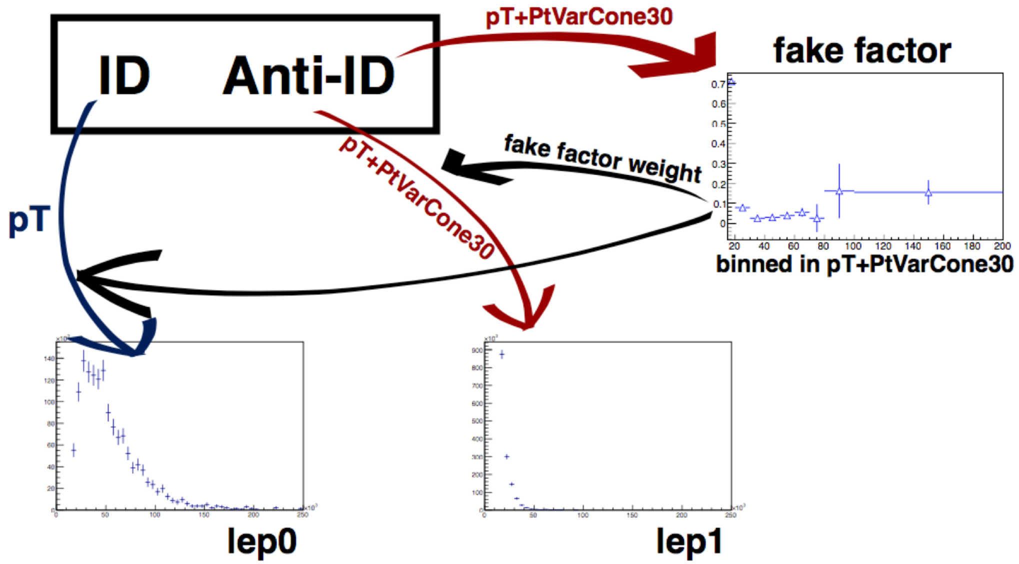
- nJet >= 2, (Sub)leading jet p_T>65(35)GeV
- Jet $|\eta|$<4.5
- Z veto in ee @ 15GeV of Z mass window
- MET >30GeV
- nbJet ==0
- ΔY_{jj} > 2
- M_{jj} > 500 GeV
- **Low M_{jj} Control region**
  - 500GeV > M_{jj} > 200GeV

BACKGROUND SUMMARY

$$N_{bkg}^{charge-flip} = N_{OC}^{data} \cdot weight$$

$$weight = \frac{\epsilon_1(1-\epsilon_2)+\epsilon_2(1-\epsilon_1)}{(1-\epsilon_1)(1-\epsilon_2)+\epsilon_1\epsilon_2}$$

- **Charge Flip Background** (Data-Driven Method)
  - Important only for electron due to bremsstrahlung
  - One electron charge is misidentified
  - Mainly from $t\bar{t}, W^{\pm}W^{\mp}jj, Z/\gamma^{*}$ + jets
  - Charge-flip rate(ϵ) is calculated by maximizing likelihood function from $Z \rightarrow ee$ sample
  - Apply a weight to OS samples to estimate the contribution in SS
- **Non-prompt Background** (Data-Driven Method, **Dominant Background**)
  - One jet is mis-reconstructed as an isolated lepton
  - Mainly from W+jets and $t\bar{t}$
  - Fake factor = $\frac{ID_{dijetData} - ID_{promptMC}}{AntiID_{dijetData} - AntiID_{promptMC}}$
  - $N_{bkg}^{fake} = (N_{ID+AntiID}^{Data} - N_{ID+AntiID}^{prompt\ MC}) \cdot fake\ factor$
- **Wγ+jets, Zγ+jets** (MC Estimation)
  - The photon is mis-reconstructed as an isolated electron
- **Prompt Background** (MC Estimation)
  - One or two leptons are not reconstructed
  - Mainly WZ+jets, ZZ+jets, $t\bar{t}V$ (V=W or Z), triboson
  - Use WZ CR to constrain WZ bkg and **WZ is one of dominant backgrounds**



LIKELIHOOD FIT

- Summary of the event yield before fitting
  - WZ background is normalized to data in WZ CR

	e^+e^+	e^-e^-	$e^+\mu^+$	$e^-\mu^-$	$\mu^+\mu^+$	$\mu^-\mu^-$	combined
WZ	1.7 ± 0.6	1.2 ± 0.4	13 ± 4	8.1 ± 2.5	5.0 ± 1.6	3.3 ± 1.1	32 ± 9
Non-prompt	4.1 ± 2.4	2.3 ± 1.8	9 ± 6	6 ± 4	0.57 ± 0.16	0.67 ± 0.26	23 ± 12
e/γ conversions	1.74 ± 0.31	1.8 ± 0.4	6.1 ± 2.4	3.7 ± 1.0	-	-	13.4 ± 3.5
Other prompt	0.17 ± 0.06	0.14 ± 0.05	0.90 ± 0.24	0.60 ± 0.25	0.36 ± 0.12	0.19 ± 0.07	2.4 ± 0.5
$W^\pm W^\pm jj$ strong	0.38 ± 0.13	0.16 ± 0.06	3.0 ± 1.0	1.2 ± 0.4	1.8 ± 0.6	0.76 ± 0.26	7.3 ± 2.5
Expected background	8.1 ± 2.4	5.6 ± 1.9	32 ± 7	20 ± 5	7.7 ± 1.7	4.9 ± 1.1	78 ± 15
$W^\pm W^\pm jj$ electroweak	3.80 ± 0.30	1.49 ± 0.13	16.5 ± 1.2	6.5 ± 0.5	9.1 ± 0.7	3.50 ± 0.29	40.9 ± 2.9
Data	10	4	44	28	25	11	122

- Signal is extracted in a binned likelihood fit of M_{jj} distribution
- Use the signal and background shape information and constrain WZ and fake background using events with low M_{jj} and WZ CR
- Perform fitting in 3 regions:
  - Low M_{jj} control region: 1 M_{jj} bin: [200,500]GeV, 6 channels
  - WZ Control region: 1 M_{jj} bin: [200,500]GeV, 1 channel
  - Signal region: 4 M_{jj} bins: [500,700,1000,1500,3000]GeV, 6 channels(ee, em, mm with charge split)

OBSERVED RESULTS

- Observed Significance:
  6.9σ (4.6σ expected)
- Signal strength (Sherpa):

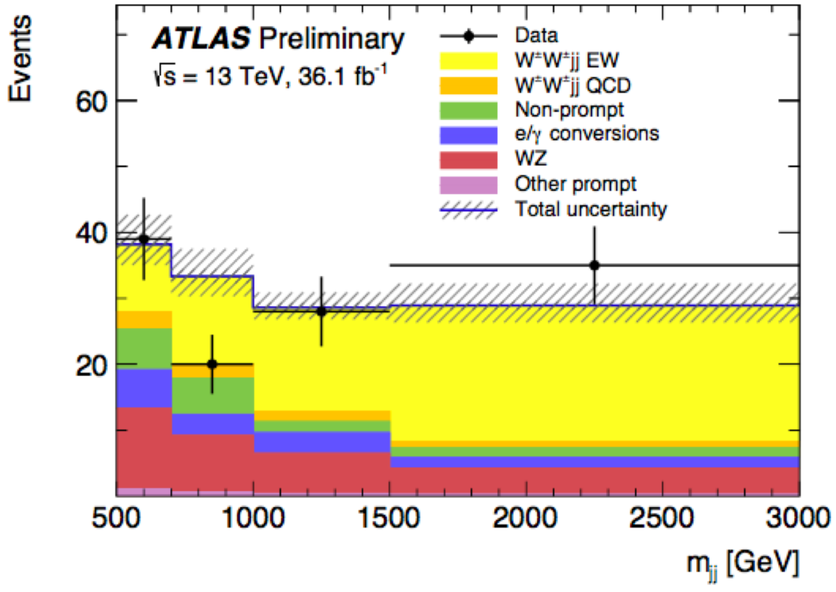
$$\mu_{obs} = 1.45^{+0.25}_{-0.24}\ (\text{stat.})^{+0.13}_{-0.14}\ (\text{sys.})$$

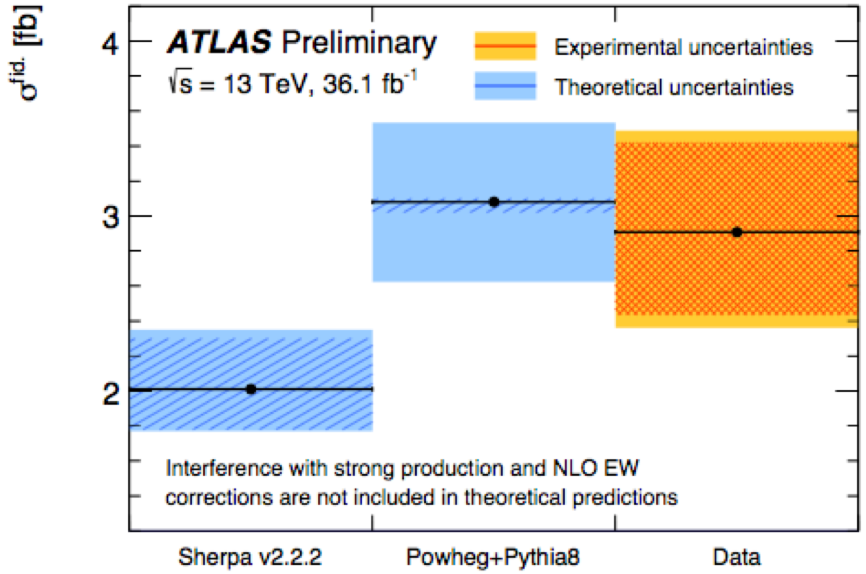
- Observed $W^{\pm}W^{\pm}jj$ EWK production fiducial cross section (including interference):

$$\sigma^{\text{fid}} = 2.91^{+0.51}_{-0.47}\ (\text{stat.}) \pm 0.27\ (\text{sys.})\ \text{fb}$$

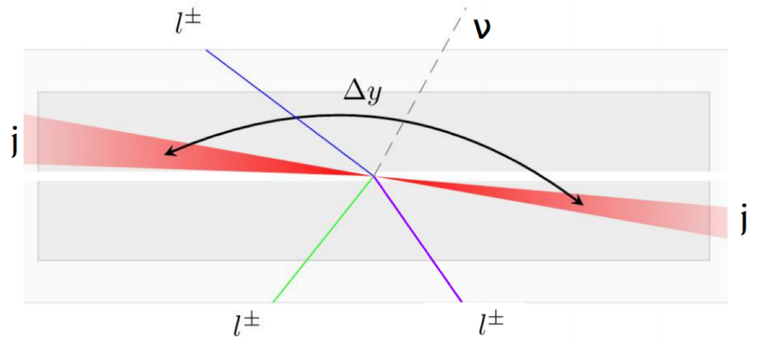
  with the predicted fiducial cross section
  (without interference and NLO EW correction)
  by Sherpa 2.2.2:
  $\sigma = 2.01^{+0.33}_{-0.23}$(sys.+stat.) fb

  by Powheg+Pythia8:
  $\sigma = 3.08^{+0.45}_{-0.46}$(sys.+stat.) fb
- Dominant uncertainty: non-prompt background 40%-90%



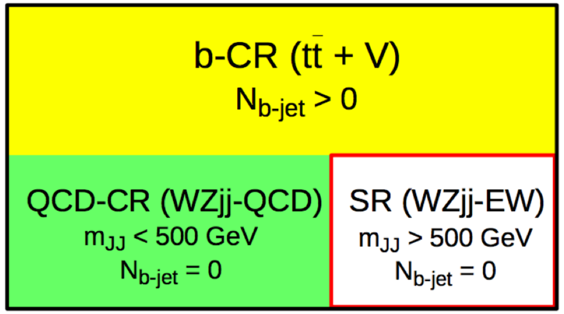


EWK PRODUCTION OF WZJJ VBS



WZjj VBS Event Topology

- Inclusive Event Selection
  - ZZ Veto: Less than 4 baseline leptons
    - p_T > 5 GeV & |η|<2.47 (2.7 for muon)
  - Number of Z selection leptons == 3
    - p_T>15GeV &|η| exclude 1.37-1.52 (|η| < 2.5 for muon)
  - p_T^{lead} > 27GeV
  - 2 SFOS Z selection leptons
  - $|M_{ll}-M_Z|<10$GeV
  - 1 W selection lepton
    - p_T>20GeV & Unambigious author for electron
  - m_T^W>30GeV
- WZjj EWK selection is on top of the inclusive selection
- Additional control regions are defined to constrain those irreducible backgrounds
  - WZjj QCD-CR
  - WZjj b-CR: $t\bar{t}$+V



- ZZ-CR
  - Inverting ZZ Veto by requiring at least 4 loose leptons
  - No b-jet

WZjj **Event selection**	
Jet multiplicity	≥ 2
p_T of two tagging jets	> 40 GeV
$\|\eta\|$ of two tagging jets	< 4.5
η of two tagging jets	opposite sign
m_{jj}	> 150 GeV
WZjj **b-CR**	
$N_{b-\text{jet}}$	> 0
WZjj **QCD-CR**	
$N_{b-\text{jet}}$	= 0
m_{jj}	< 500 GeV
WZjj **SR**	
$N_{b-\text{jet}}$	= 0
m_{jj}	> 500 GeV

BACKGROUND SUMMARY

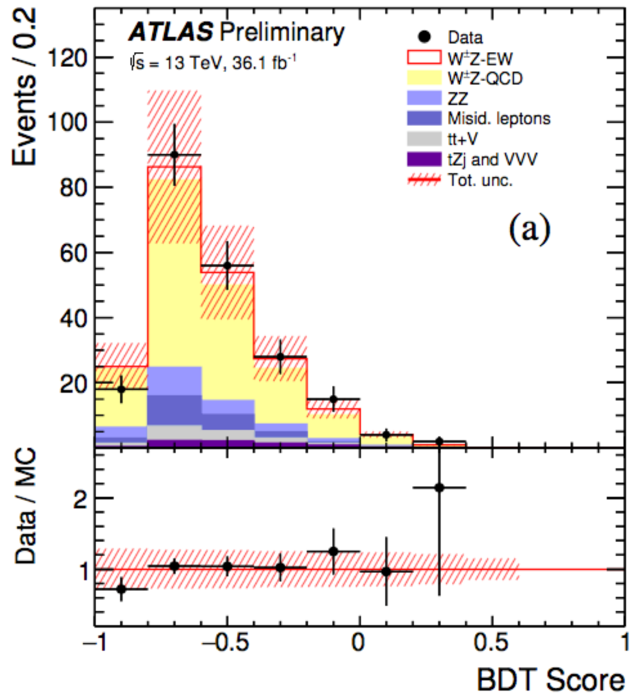
- **Irreducible background**: All candidates are prompt leptons or produced in the decay of tau
  - WZjj-QCD: Sherpa 2.2.2 (0,1j@NLO; 2,3j@LO), **Dominate Background**
  - ZZ: Sherpa 2.2.2(0,1j), Sherpa 2.1.1 ($gg \rightarrow ZZ$)
  - $t\bar{t}$+V (V= Z or W): Madgraph5+aMC@NLO+Pythia8
  - tZj: Madgraph5+aMC@NLO+Pythia8
  - VVV: Sherpa 2.1.1
- **Reducible background**: At least one of the candidate leptons is not a prompt lepton
  - Z+j, Zγ, $t\bar{t}$, Wt and WW
  - Data driven matrix method
    - Determine the probability matrix that a fake lepton is misidentified as a loose or tight lepton in a CR enriched in misidentified leptons.
    - Apply the matrix to the data samples of WZjj candidate events where at lease one lepton is loose.
    - Then the number of events with at least one misidentified tight lepton is obtained
  - Cross-checked with MC simulations scaled to data
- **WZjj-EW Signal**: Sherpa 2.2.2

	SR	QCD-CR	b-CR	ZZ-CR
Data	161	213	141	52
Total MC	199.2 ± 1.4	289.4 ± 1.9	159.2 ± 1.8	44.7 ± 6.4
$WZjj$-EW (signal)	24.93 ± 0.18	8.46 ± 0.10	1.36 ± 0.05	0.21 ± 0.12
$WZjj$-QCD	144.17 ± 0.85	231.2 ± 1.1	24.44 ± 0.29	1.43 ± 0.69
Misid. leptons	9.2 ± 1.1	17.7 ± 1.5	29.7 ± 1.6	0.50 ± 0.32
ZZ-QCD	8.10 ± 0.19	14.98 ± 0.34	1.96 ± 0.08	35.0 ± 5.9
tZ	6.46 ± 0.18	6.56 ± 0.19	36.19 ± 0.45	0.18 ± 0.09
$t\bar{t}+V$	4.21 ± 0.18	9.11 ± 0.23	65.36 ± 0.64	2.8 ± 1.3
ZZ-EW	1.50 ± 0.10	0.44 ± 0.05	0.10 ± 0.08	3.4 ± 1.6
VVV	0.59 ± 0.03	0.93 ± 0.04	0.13 ± 0.01	1.0 ± 1.0

Number of observed and expected events in SR and CRs before fitting. Only Stats Uncert.

BDT TRAINING

- A BDT is trained in signal region to separate WZjj-EW signal from WZjj-QCD and other backgrounds
- A total of 15 variable is used as input
  - Variables related to the kinematics of tagging jets
    - $m_{jj}, N_{jets}, p_T^{j1}, p_T^{j2}, \eta_{j1}, \Delta\eta(j1,j2), \Delta\phi(j1,j2)$
  - Variables related to the kinematics of vector bosons:
    - $|y_Z - y_{l,W}|, m_T^{WZ}, p_T^W, p_T^Z, \eta_W$
  - Variables related to both leptons and jets kinematics:
    - $\Delta R(j1, Z)$: Distance in the pseudorapidity-azimuth plane between Z and j1
    - Event balance R_{pT}^{hard}: transverse component of the vectorial sum of the momenta of the 3 leptons+2jets, divided by the scalar sum of their pT
    - Centrality $\zeta_{lep} = \min(\Delta\eta_-, \Delta\eta_+)$ with $\Delta\eta_- = \min(\eta_l^W, \eta_{l1}^Z, \eta_{l2}^Z) - \min(\eta_{j1}, \eta_{j2})$ and $\Delta\eta_+ = max(\eta_{j1}, \eta_{j2}) - max(\eta_l^W, \eta_{l1}^Z, \eta_{l2}^Z)$
- BDT training has been verified in WZjj-QCD CR, by good description of the BDT score distribution in data



Post-fit BDT score distributions in WZ-QCD CR

SIGNAL EXTRACTION

- Signal is extracted in a maximum-likelihood fit of BDT score distribution in SR
- Perform fitting in 4 regions
  - M_{jj} distribution in WZjj QCD-CR: constrain WZjj-QCD → $\mu_{WZ-QCD} = 0.60 \pm 0.25$
  - b-jets multiplicity in b-CR: constrain $t\bar{t}$+V → $\mu_{t\bar{t}+V} = 1.18 \pm 0.19$
  - M_{jj} distribution in ZZ-CR: constrain ZZ → $\mu_{ZZ} = 1.34 \pm 0.29$
  - BDT score distribution in SR
- Observed results
  - Observed significance: **5.6σ** (3.3σ expected)
  - Signal strength (Sherpa): $\mu_{EW} = 1.77 \pm 0.41(\text{stat.}) \pm 0.17(\text{syst.})$
  - Observed WZjj-EW production cross section(including interference):

$$\sigma^{\text{fid., EW}}_{\text{meas.}} = 0.57\ ^{+0.14}_{-0.13}\ (\text{stat.})\ ^{+0.05}_{-0.04}\ (\text{syst.})\ ^{+0.04}_{-0.03}\ (\text{th.})\ \text{fb}$$

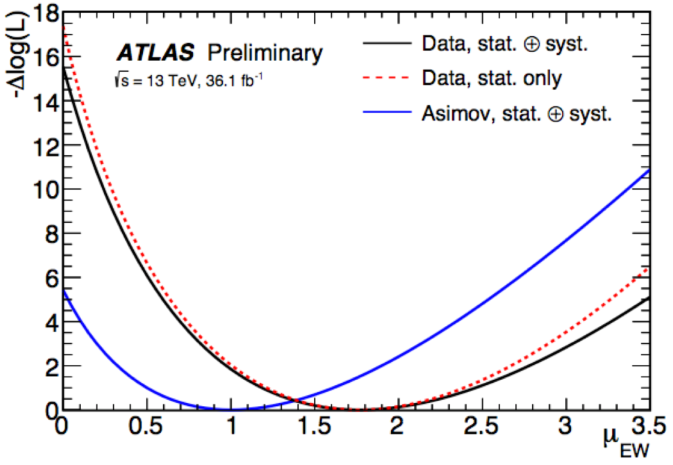
with SM LO prediction (without interference) from Sherpa:

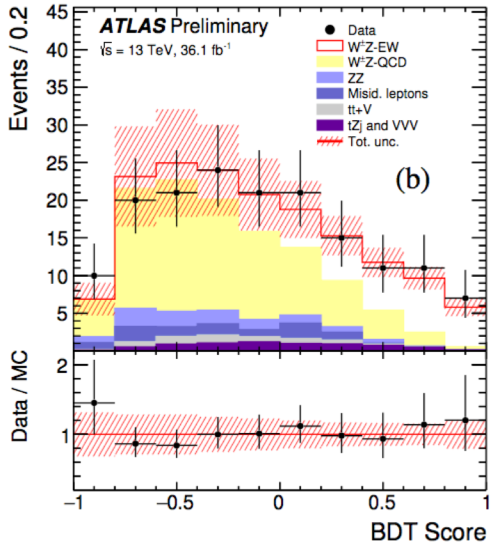
$$\sigma^{\text{fid., EW th.}}_{\text{Sherpa}} = 0.321 \pm 0.002\ (\text{stat.}) \pm 0.005\ (\text{PDF})^{+0.027}_{-0.023}\ (\text{scale})\ \text{fb}$$

from Madgraph:

$$\sigma^{\text{fid., EW th.}}_{\text{MadGraph}} = 0.366 \pm 0.004\ (\text{stat.})\ \text{fb}$$

- Dominant Uncertainty: Jet related uncertainty 6.7%to μ_{EW}





Post-fit BDT score distributions in SR

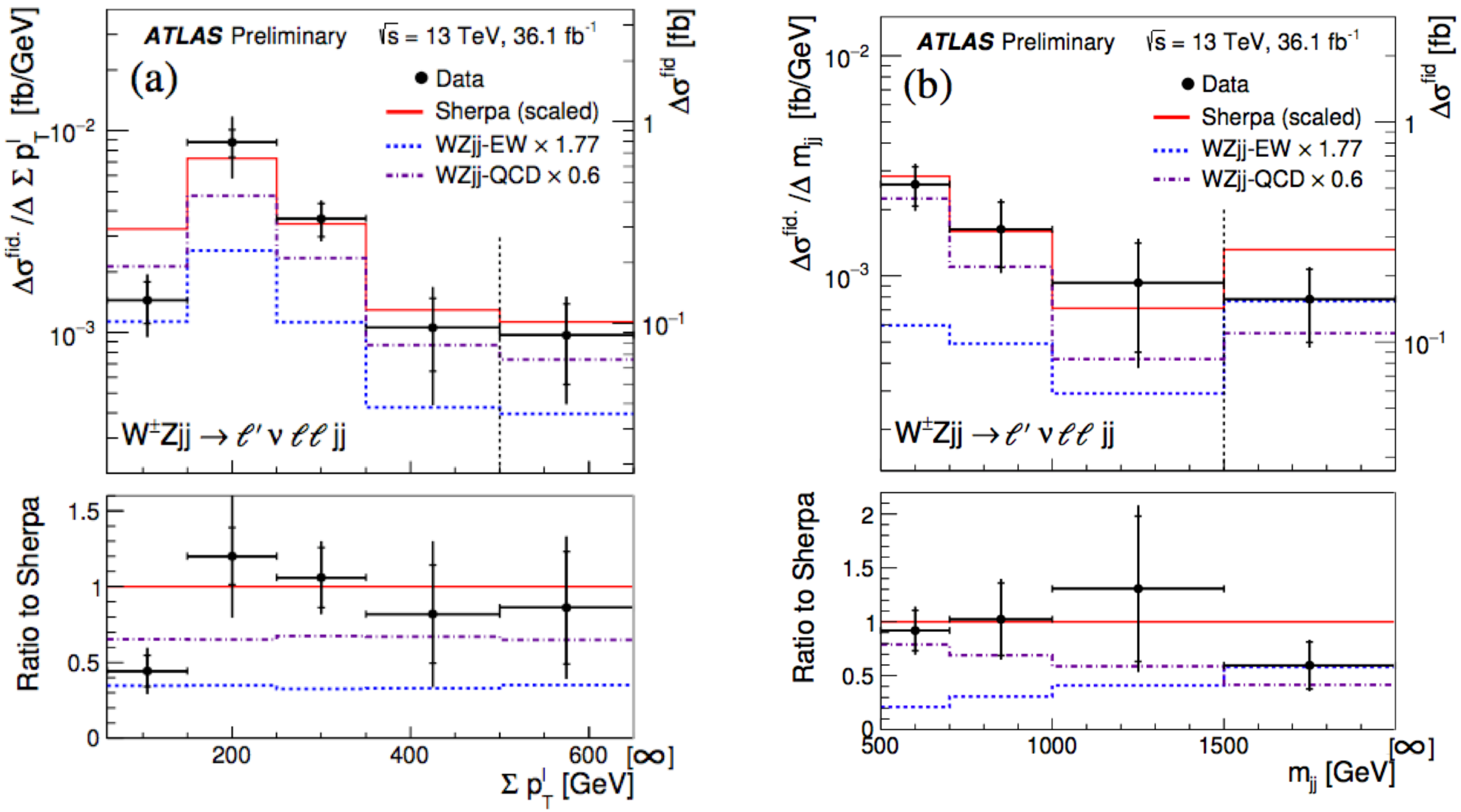
DIFFERENTIAL CROSS SECTIONS

- Interesting distributions are unfolded from WZjj-EW SR to VBS fiducial phase space
- Two types of variables:
  - Variables sensitive to aQGCs:

$$m_T^{WZ}$$
$$\sum p_T^l$$
$$\Delta\phi(W,Z)$$

  - Variables for model constrains:

$$N_{jets}(p_T > 40\,GeV)$$
$$N_{jets}^{gap}(p_T > 25\,GeV)$$
$$m_{jj}$$
$$\Delta\phi(j1,j2)$$
$$\Delta y(j1,j2)$$



  - A good description of the measured cross sections within uncertainties by Sherpa is observed after the rescaling

CONCLUSION

- The electroweak productions of $W^{\pm}W^{\pm}jj$ and $W^{\pm}Zjj$ are observed in 36.1 fb^{-1} of pp collision data recorded at $\sqrt{s} = 13$ TeV by the ATLAS detector at the LHC
- Observed Significance
  - $W^{\pm}W^{\pm}jj$ EWK: 6.9σ (4.6σ expected)
  - $W^{\pm}Zjj$ EWK: 5.6σ (3.3σ expected)
- Measured fiducial cross section
  - $W^{\pm}W^{\pm}jj$ EWK: $\sigma_{obs}(W^{\pm}W^{\pm}jj \to \ell^{\pm}\nu\ell^{\pm}\nu jj) = 2.91^{+0.51}_{-0.47}$ (stat.) ± 0.27 (sys.) fb ($2.01^{+0.33}_{-0.23}$ (sys.+stat.) fb predicted by sherpa)
  - $W^{\pm}Zjj$ EWK: $\sigma_{obs}(W^{\pm}Zjj \to \ell^{\pm}\nu\ell^{\pm}\ell^{\mp}jj) = 0.57\ ^{+0.14}_{-0.13}$ (stat.) $^{+0.05}_{-0.04}$ (syst.) $^{+0.04}_{-0.03}$ (th.) fb (0.321 ± 0.002 (stat.) ± 0.005 (PDF)$^{+0.027}_{-0.023}$ (scale) fb predicted by Sherpa)
- Conference notes
  - $W^{\pm}W^{\pm}jj$ EWK
  - $W^{\pm}Zjj$ EWK

Thanks for listening!

BACK UP

OBJECT DEFINITION

- ID Electron
  - p_T > 27GeV & |η|<2.47 exclude 1.37-1.52
  - Tight LH+ Isolation
  - Coming from primary vertex
- AntiID Electron
  - $p_T + p_{Tcone30}$> 27GeV & |η|<2.47 exclude 1.37-1.52, p_T>20GeV
  - Medium LH
  - Coming from primary vertex
  - Fail ID Electron
- Veto Electron
  - p_T>6GeV & |η|<2.47 (exclude crack region)
  - Loose LH + Blayer
  - Coming from primary vertex

- ID Muon
  - p_T > 27GeV & |η|<2.5
  - Medium Muon Quality & Isolation
  - Coming from primary vertex
- AntiID Muon
  - $p_T + p_{Tcone30}$> 27GeV & |η|<2.5, p_T>15GeV
  - Medium Muon Quality
  - Coming from primary vertex (looser)
  - Fail ID Muon
- Veto Muon
  - p_T>6GeV & |η|<2.5
  - Coming from primary vertex (looser)
  - Loose Muon Quality

- Jets
  - |η|<4.5: if |η|<2.4, p_T > 25GeV; otherwise, p_T > 30GeV
  - If 60GeV>p_T>20GeV & |η|<2.4, apply JVT>0.59
  - Anti-k_t algorithm R=0.4

OBJECT DEFINITION

- Baseline Electron
  - p_T > 5 GeV & |η|<2.47
  - Loose LH+ Blayer + Isolation
  - Coming from primary vertex
  - Overlap removal (e-to-μ & e-to-e)
- Z selection Electron(including baseline)
  - Overlap removal (e-to-jets)
  - p_T>15GeV &|η| exclude 1.37-1.52
  - Medium LH + Isolation (tighter)
- W selection Electron (including baseline+Z)
  - p_T>20GeV
  - Tight LH
  - Unambigious author

- MET reconstruction
  - Negative vector sum of p_T
    - Identified hard physics objects
    - Track-based additional soft terms

- Baseline Muon
  - p_T > 5 GeV & |η|<2.7
  - Loose quality + Isolation
  - Coming from primary vertex
- Z selection Muon(including baseline)
  - Overlap removal (μ-to-jets)
  - p_T>15GeV & |η| < 2.5
  - Medium Quality
- W selection Muon (including baseline+Z)
  - p_T>20GeV
  - Tight Quality + Isolation(tighter)

- Jet
  - Anti-k_t algorithm with R=0.4
  - p_T>25GeV
  - $|\eta|$<4.5
  - JVT>0.59 if pT<60GeV && $|\eta|$<2.4
  - b-tagged (77% WP) using MV2v10