Observation and measurements of vector-boson scattering with ATLAS

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DIS 2019

Vector Boson Scattering: Motivation

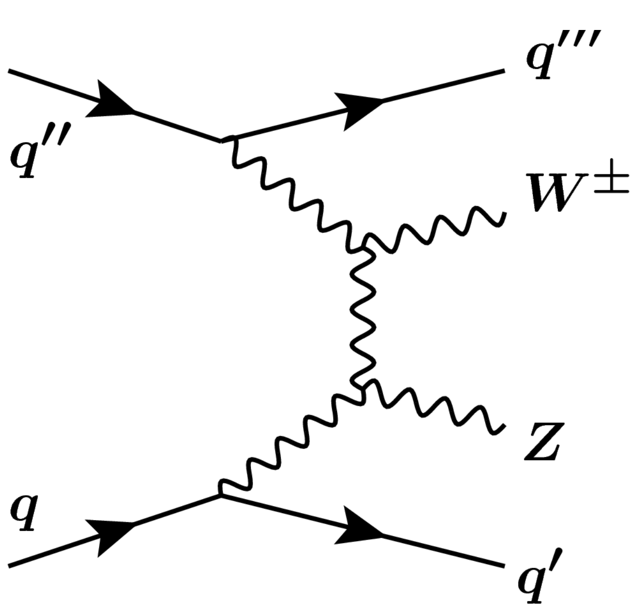
- Vector Boson Scattering is important for understanding EWK symmetry breaking

- Without the SM Higgs, longitudinal VV scattering cross section ($\sigma_{VV \to VV}$) increases as center-of-mass energy and violates unitarity at high energy

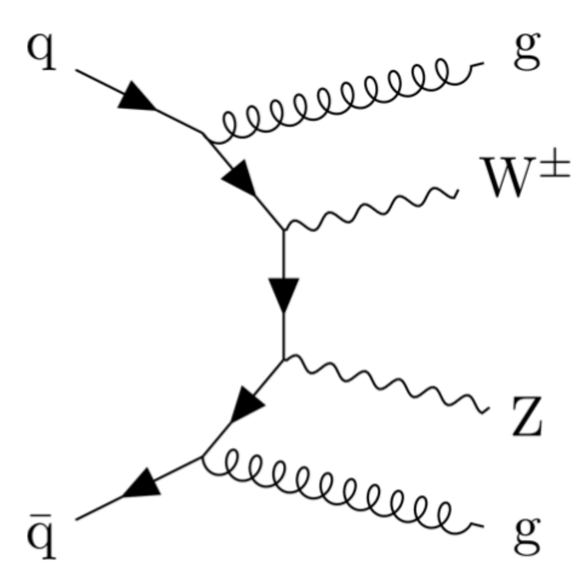
- Can be solved by adding contributions from Higgs

- VBS allows indirect search of New Physics by studying anomalous quartic gauge couplings (aQGC)

EW production $\mathcal{O}(\alpha^4)$



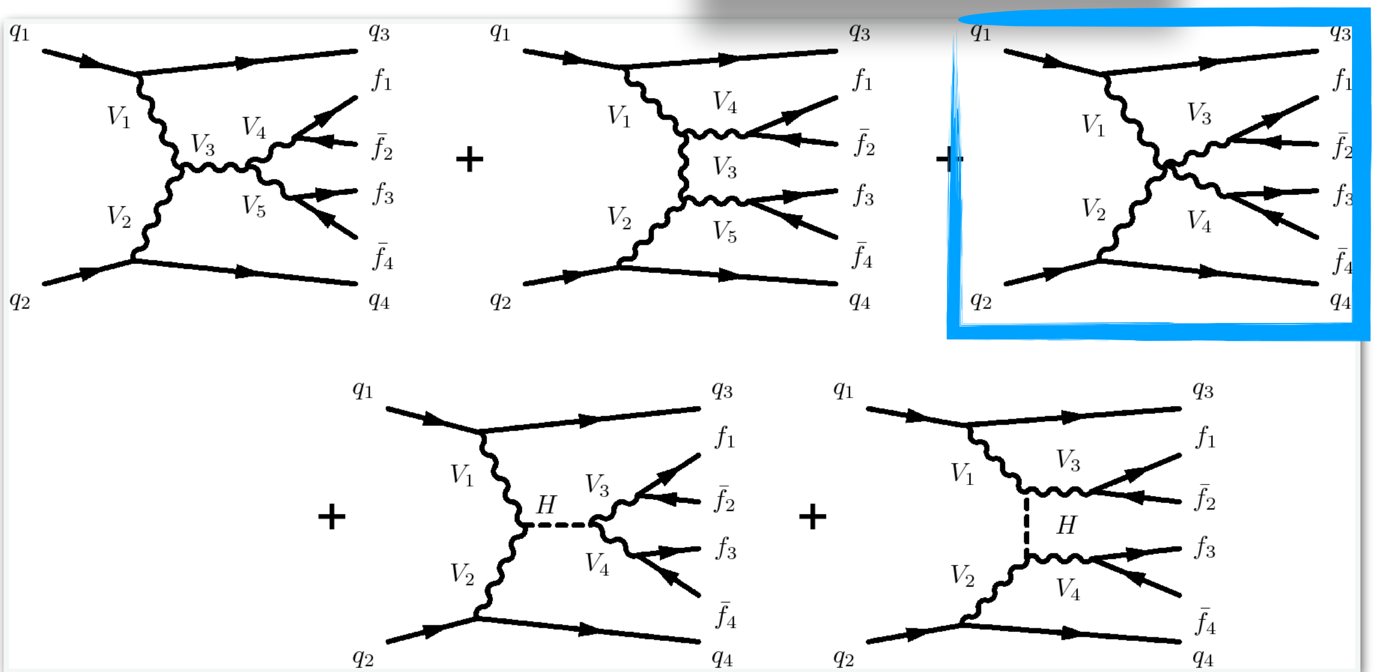
QCD-induced production $\mathcal{O}(\alpha^2\alpha_S^2)$



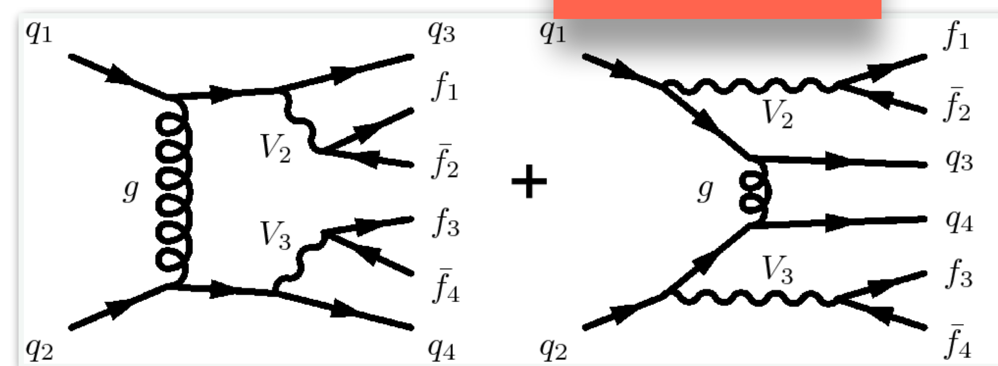
Vector Boson Scattering: Motivation

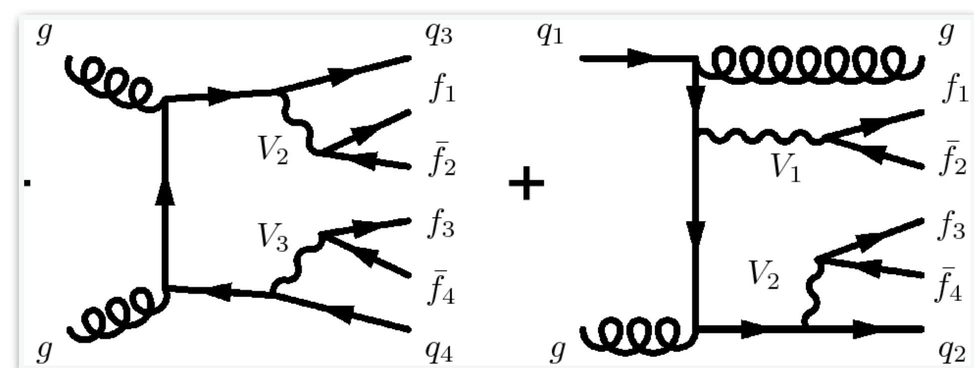
VVjj EWK VBS

QGC

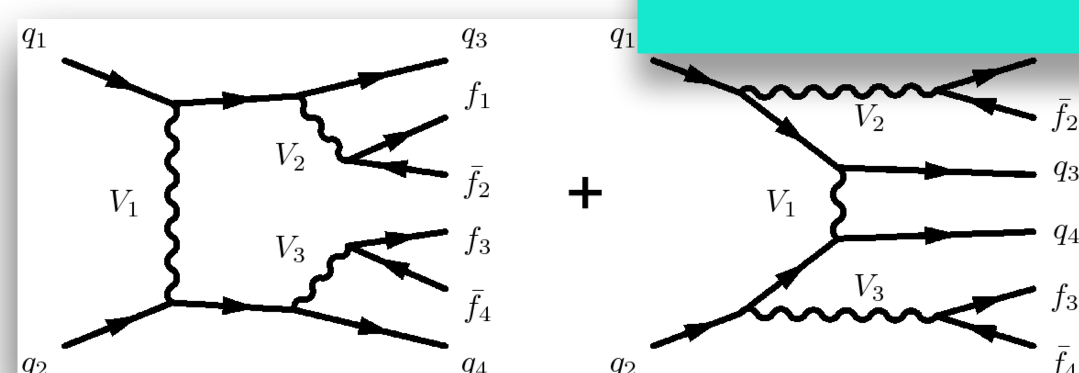


VVjj QCD





VVjj EWK non VBS

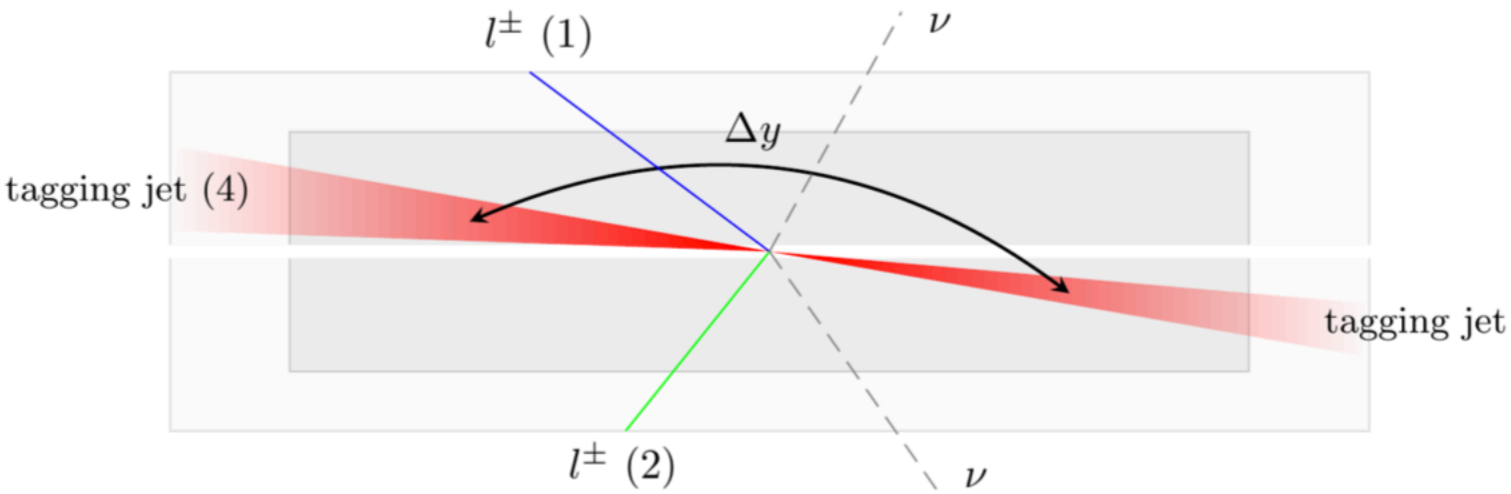


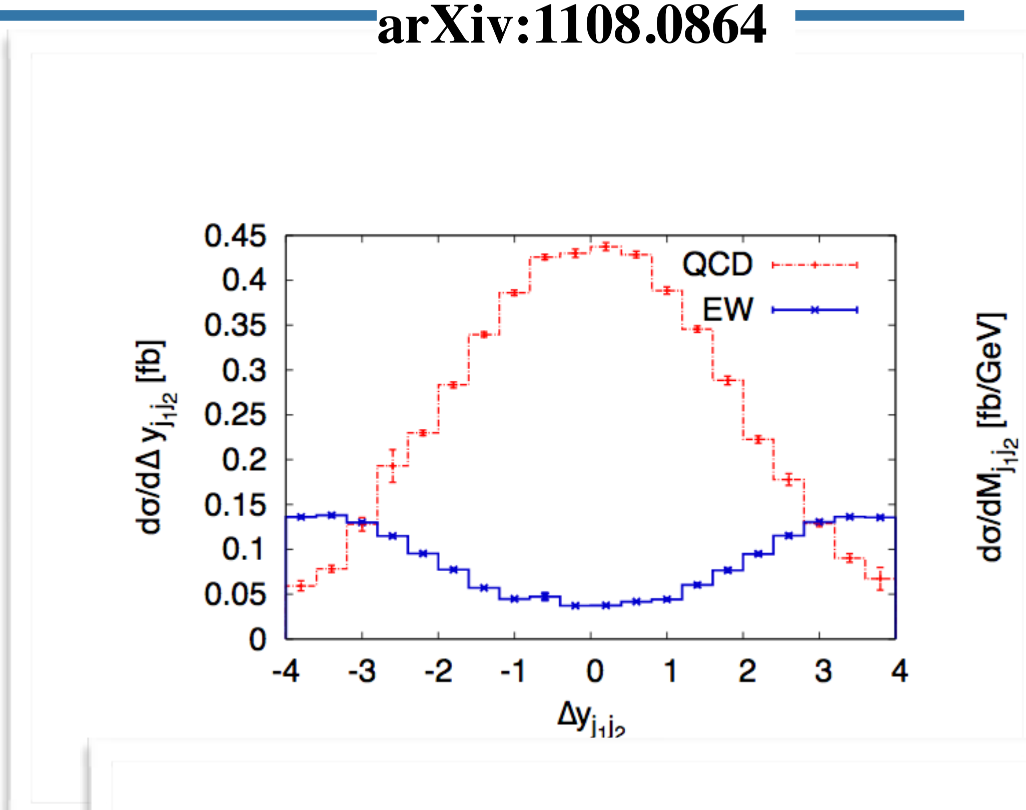
All EW-induced processes (only EW interaction vertices) treated as signal

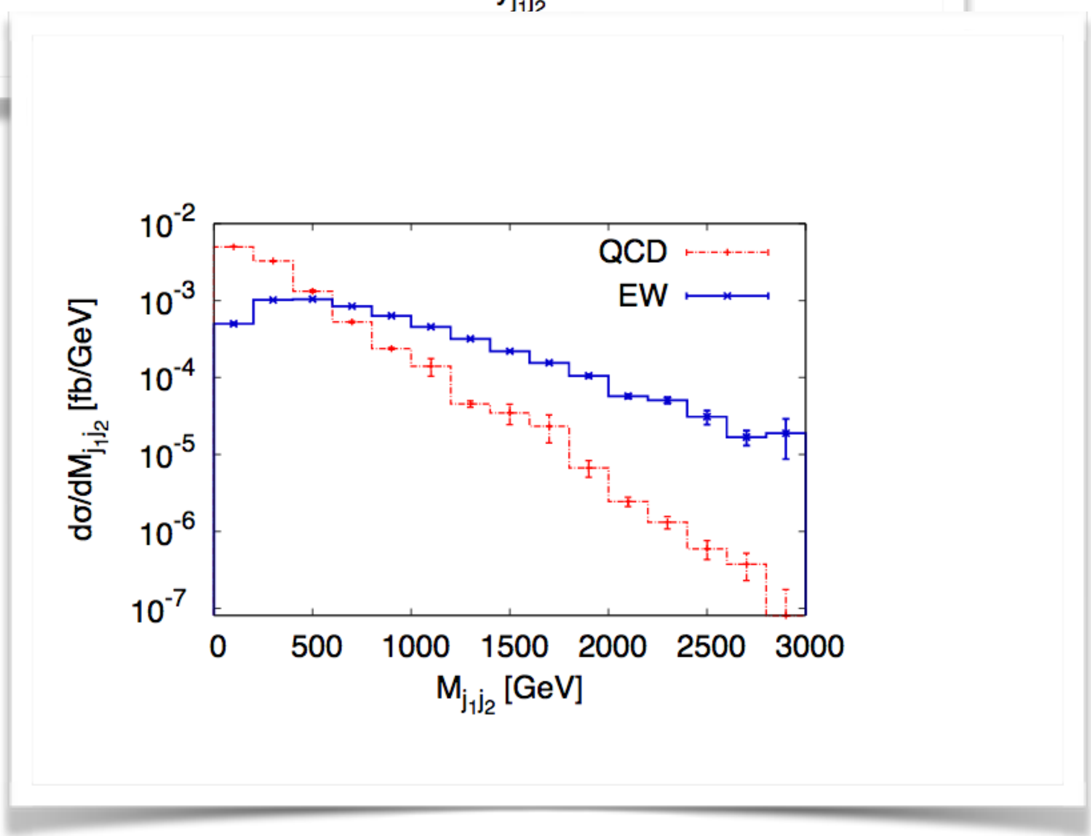
An interference occurs between electroweak and QCD production

Vector Boson Scattering: Phenomenology

arXiv:1108.0864







VBS has distinctive final states topology

- Two hadronic jets in forward and backward regions with very high energy (tagging jets)
- Hadronic activity suppressed between the two jets (rapidity gap) due to absence of color flow between interacting partons.
- Boson pair more central than in non-EWK processes

Vector Boson Scattering: WZjj @ 13 TeV

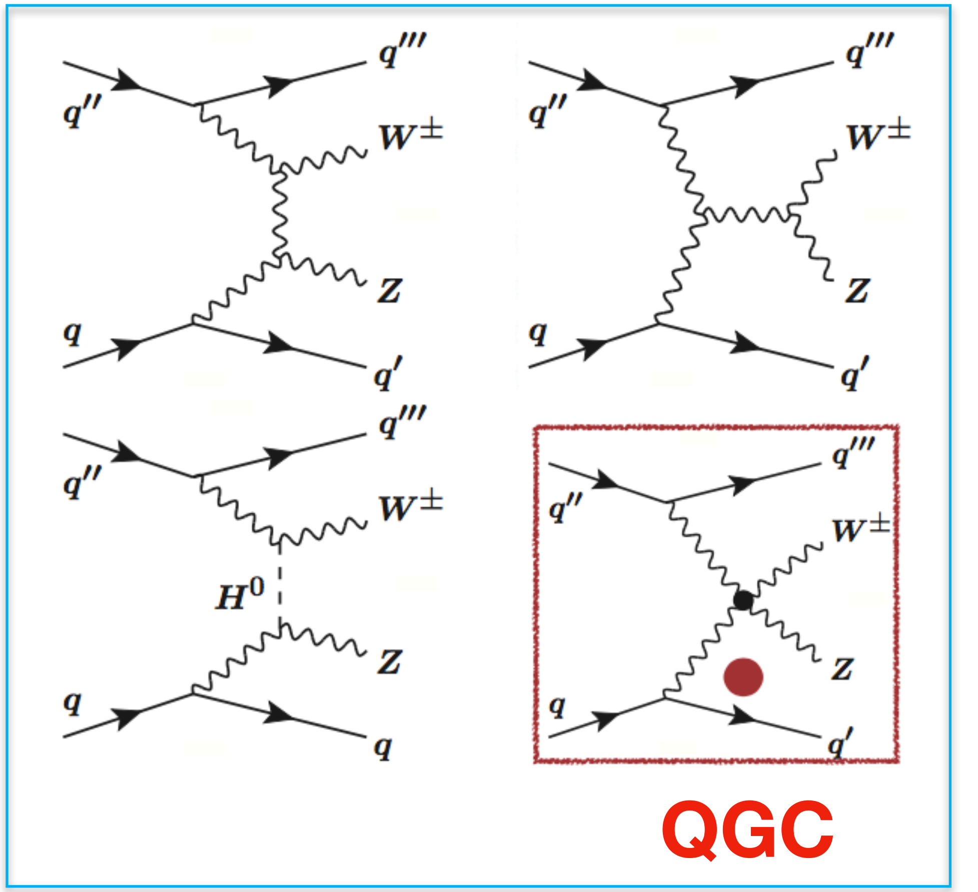
Study the electroweak WZjj production cross section measurement with 2015+2016 data @ ATLAS, 36.1 fb-1

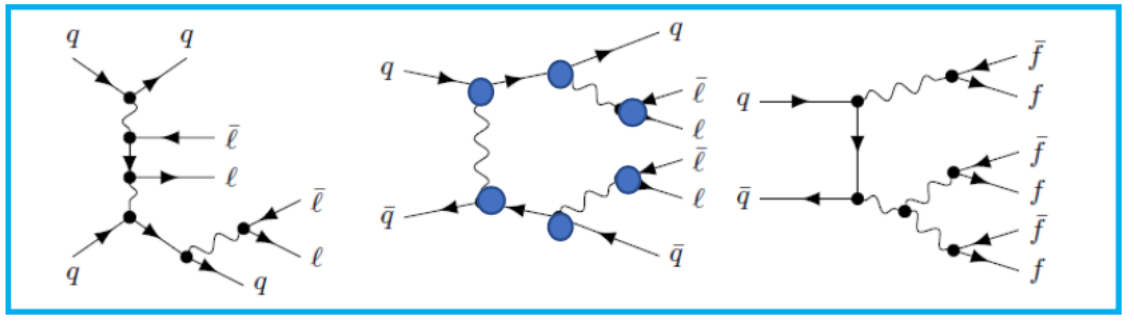
Access to vector boson scattering and QGC

but also many other electroweak diagrams

Leptonic decay: clear signature

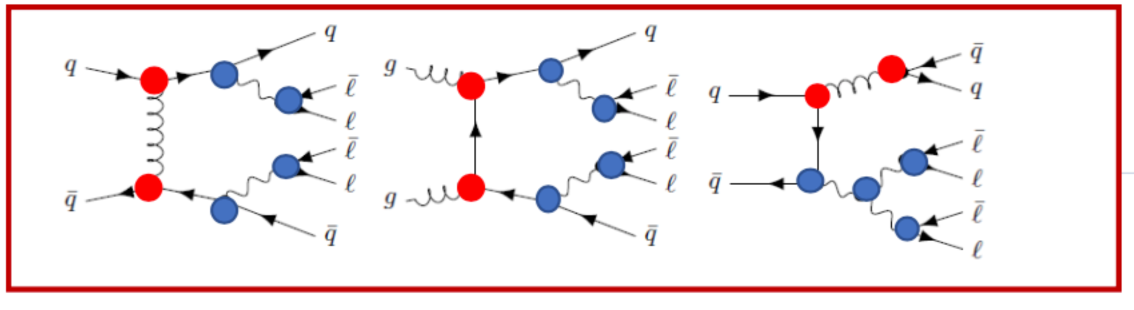
Main irreducible background: QCD-induced WZjj





α_{EW} order: 6

α_s order: 0



α_{EW} order: 4

α_s order: 2

arXiv:1812.09740 [hep-ex]: in pub Phys.Lett.B

WZjj @ 13 TeV :Background and signal models

Signal W±Zjj EWK:

Sherpa 2.2.2 0,1j@ NLO, 2,3 j @ LO, order 6 at α_{EW}, order 0 at α_S

13% purity in SR

W±Zjj QCD: **Normalized in CR**

Largest background contribution

Sherpa 2.2.2 0,1j@ NLO, 2,3 j @ LO, order up to 4 at α_{EW}

ZZjj QCD, ZZjjEW: **Normalized in CR**

Sherpa 2.2.2 and VVV: Sherpa 2.1

tt+V and tZ: **Normalized in CR**

MadGraph5+aMC@NLO+Pythia8

Interference: MadGraph5 aMC@NLO2.2

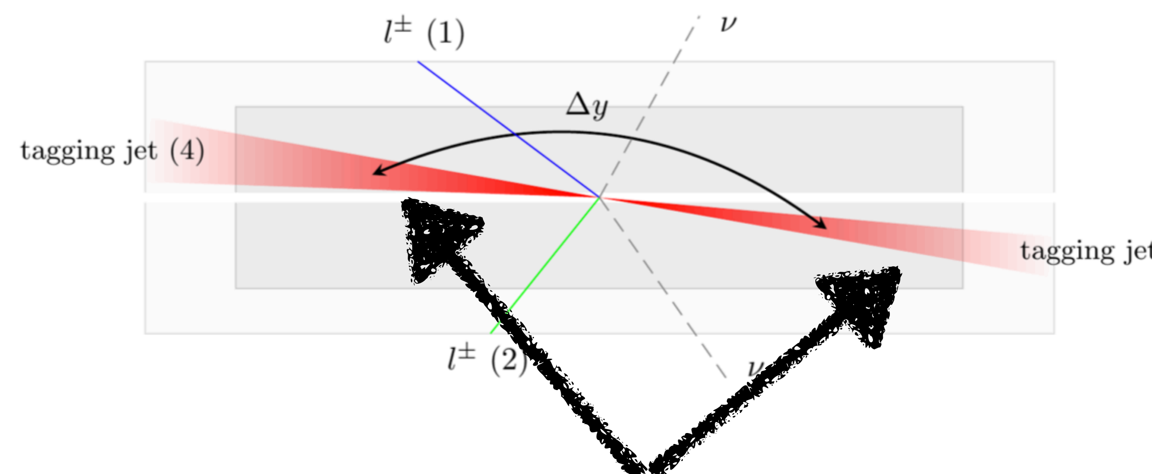
WZjj @ 13 TeV: Event Selection

Trigger: *single lepton trigger*

***Lepton selection and ZZ veto**: number of leptons == 3 with pT > 15 GeV and |η| < 2.5 (leading lepton with pT > 25 GeV (27 for 2016 data)*

Z selection: Two same-flavor opposite-charge lepton such that |Mll−MZPDG| <10GeV

W selection: 3rd lepton with pT>20 GeV and MT(W) > 30 GeV



***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

Control regions

	#leptons	#bjets	mjj (GeV)
ZZ CR	**4**	0	>500
QCD CR	3	0	**<500**
b CR	3	**1**	>500
WZjj SR	3	0	>500

WZjj @ 13 TeV: Background Summary

Irreducible background: All candidates are prompt leptons or produced in the decay of tau (Main sources of backgrounds)

- ✦ W±Zjj QCD, ZZ, tt + V, tZj, VVV

Reducible background: At least one of the candidate leptons is not a prompt lepton

- ✦ Z+j, Zγ, tt, Wt and WW
- ✦ Data driven matrix method

	SR	$WZjj$–QCD CR	b-CR	ZZ-CR
Data	161	213	141	52
Total predicted	200 ± 41	290 ± 61	160 ± 14	45.2 ± 7.5
$WZjj$–EW (signal)	24.9 ± 1.4	8.45 ± 0.37	1.36 ± 0.10	0.21 ± 0.12
$WZjj$–QCD	144 ± 41	231 ± 60	24.4 ± 1.7	1.43 ± 0.22
Misid. leptons	9.8 ± 3.9	17.7 ± 7.1	30 ± 12	0.47 ± 0.21
$ZZjj$–QCD	8.1 ± 2.2	15.0 ± 3.9	1.96 ± 0.49	35 ± 11
tZj	6.5 ± 1.2	6.6 ± 1.1	36.2 ± 5.7	0.18 ± 0.04
$t\bar{t}+V$	4.21 ± 0.76	9.11 ± 1.40	65.4 ± 10.3	2.8 ± 0.61
$ZZjj$–EW	1.80 ± 0.45	0.53 ± 0.14	0.12 ± 0.09	4.1 ± 1.4
VVV	0.59 ± 0.15	0.93 ± 0.23	0.13 ± 0.03	1.05 ± 0.30

Number of observed and expected events in SR and CRs before any normalisation or fit

WZjj @ 13 TeV: Multivariate analysis

A BDT is trained in signal region to separate WZjj-EW signal from WZjj-QCD and other backgrounds

BDT build from 15 discriminative variables

$\Delta y(\ell_W, Z)$	m_{jj}	η_W
ζ	$\Delta R(j1, Z)$	p_T^{j2}
$R_{p_T^{hard}}$	$\Delta\eta(j1, j2)$	p_T^{j1}
N_{jets}	p_T^W	m_T^{WZ}
$\Delta\phi(j1, j2)$	η_{j1}	p_T^Z

Top 5 of relevance in BDT training

- Variables related to the kinematics of tagging jets

  $$m_{jj}, N_{jets}, p_T^{j}1, p_T^{j}2, \eta_{j1}, \Delta\eta_{j1,j2}, \Delta\phi_{j1,j2}$$

- Variables related to the kinematics of vector bosons:

  $$|y_Z - y_{l,W}|\; m_T^{WZ}, p_T^W, p_T^Z, \eta_W$$

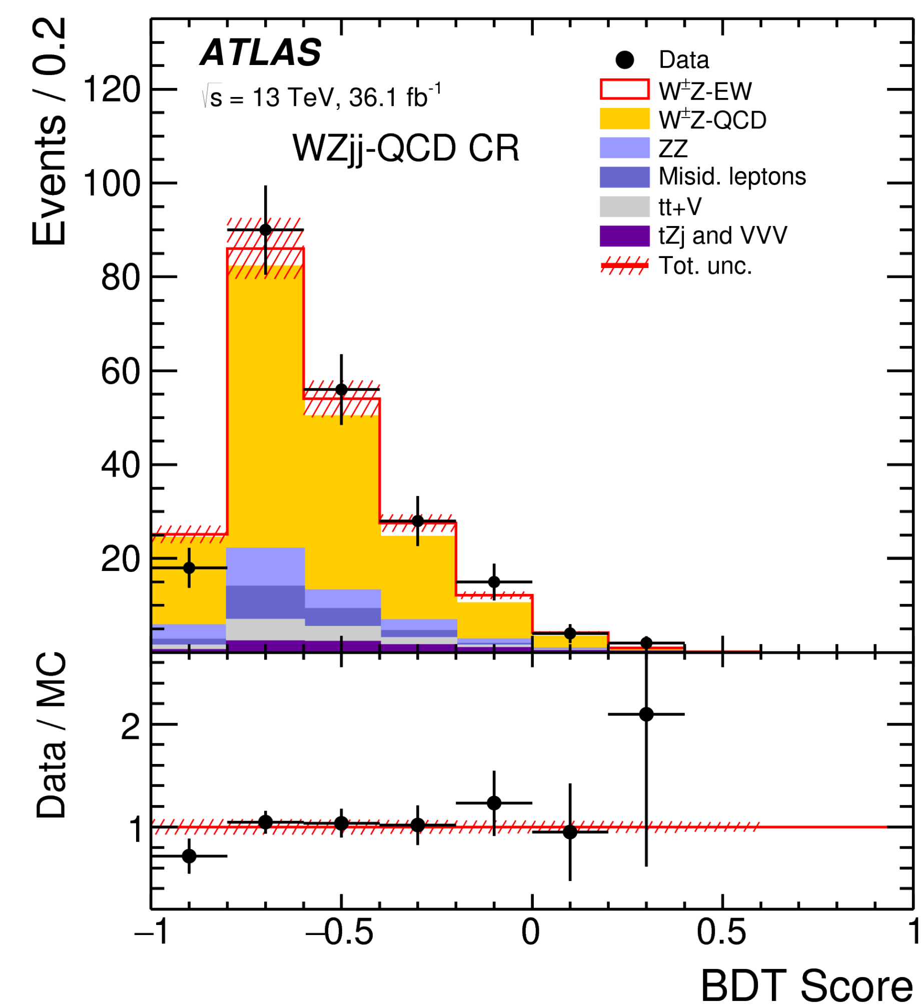
- Variables related to both leptons and jets kinematics:

$$\Delta R(j1, Z)$$

$$R_{pT}^{hard} = (\sum_{i,j)} p)_T / \sum_{i,j)} p_T$$

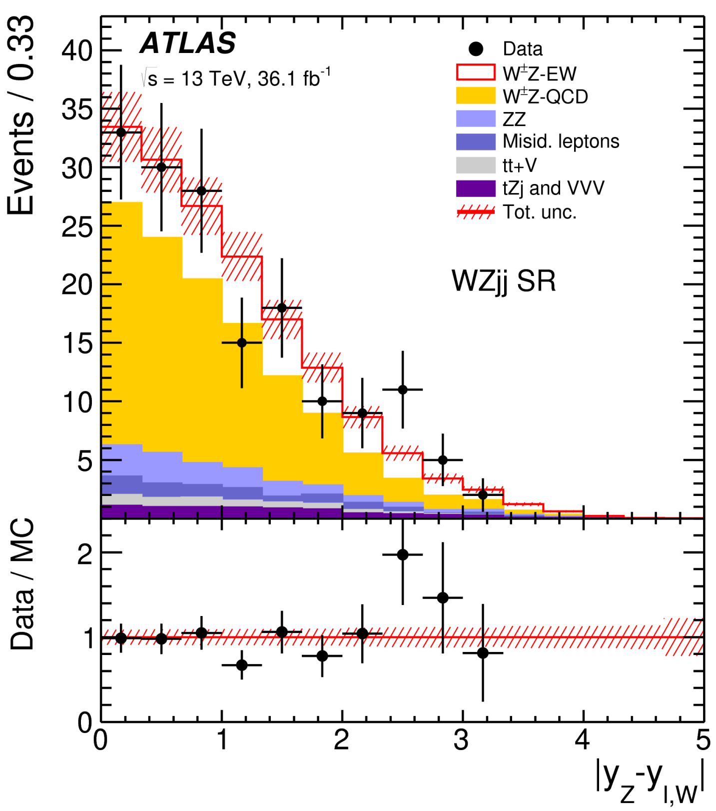
$$min(\Delta\eta_-, \Delta\eta_+)$$

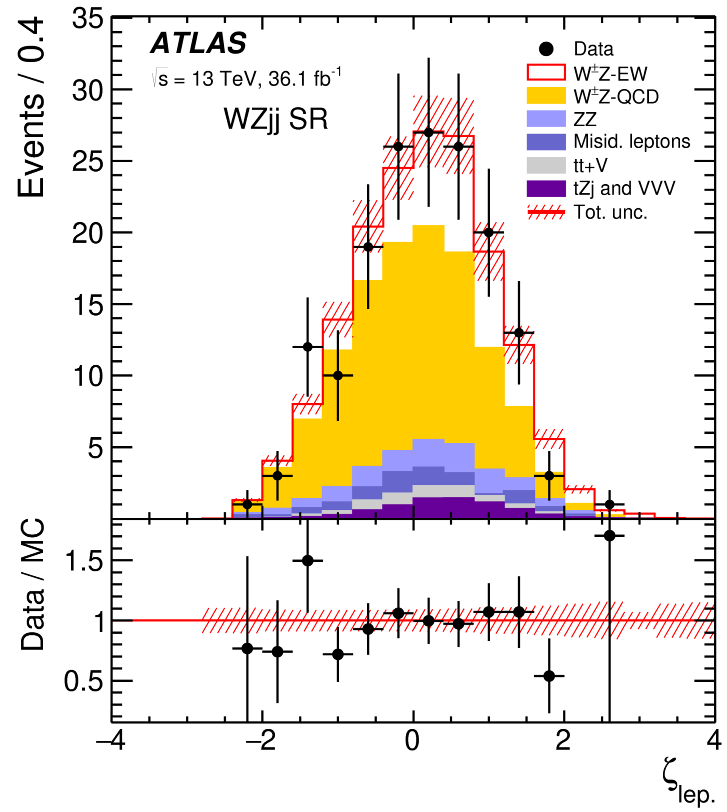
$$\zeta = min(\Delta\eta_-, \Delta\eta_+)$$
$$\Delta\eta_- = min(\eta_l^W, \eta_{l1}^Z, \eta_{l2}^Z) - min(\eta_{j1}, \eta_{j2})$$
$$\Delta\eta_+ = max(\eta_{j1}, \eta_{j2}) - max(\eta_l^W, \eta_{l1}^Z, \eta_{l2}^Z)$$

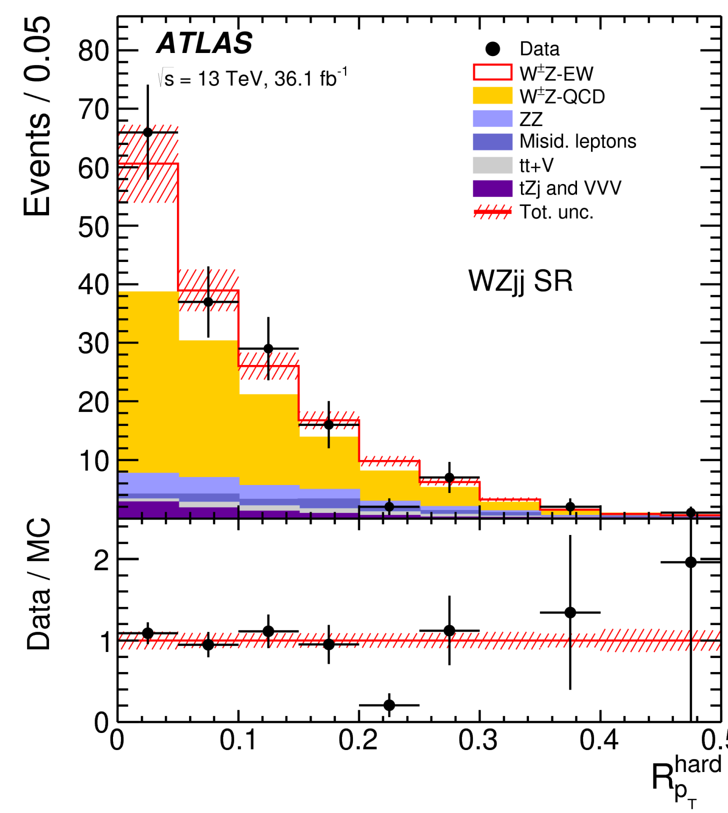


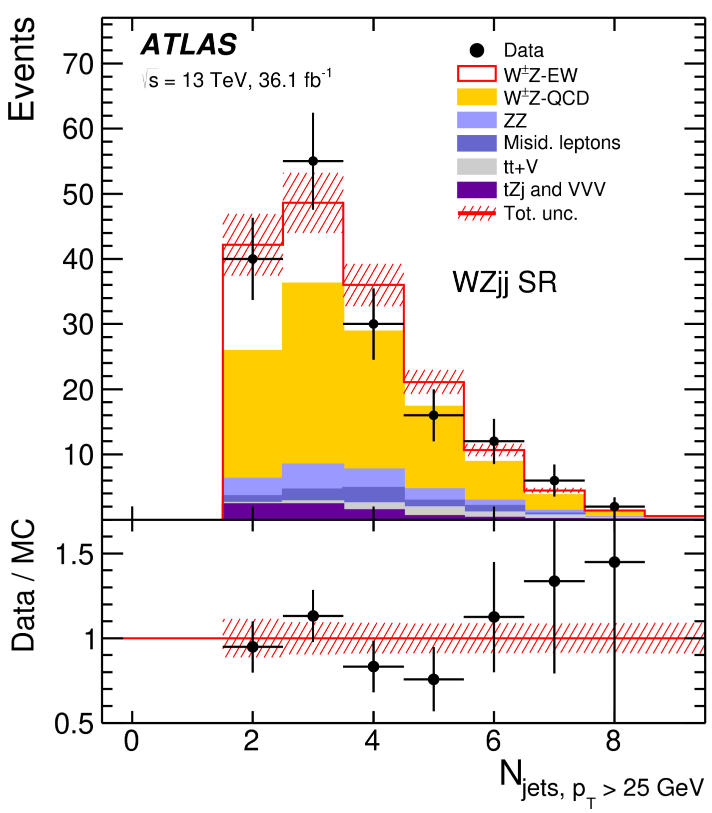
Description of BDT score distribution for background and of all BDT input variables controlled in QCD-CR: good agreement observed with data.

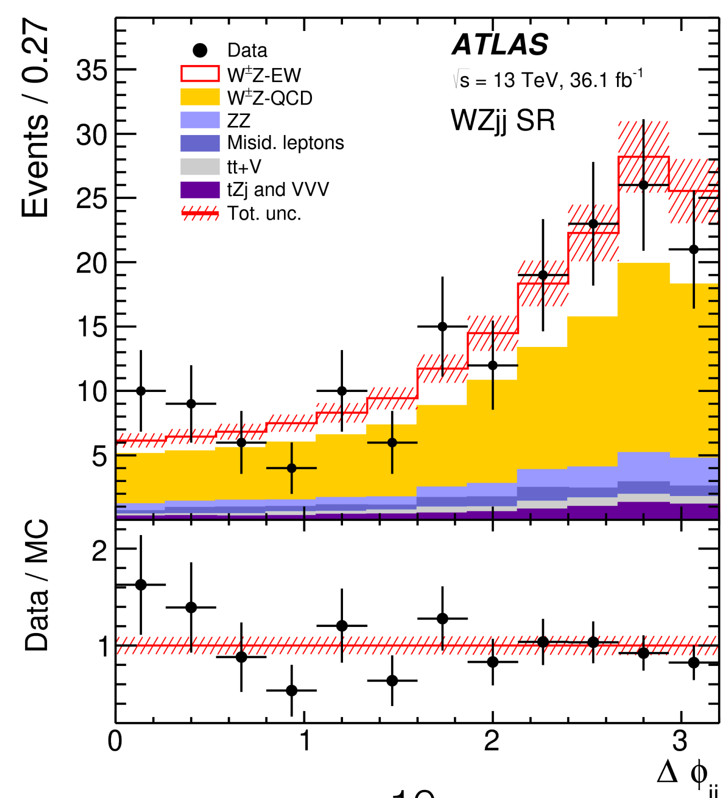
WZjj @ 13 TeV: Multivariate analysis











Top 5 of relevance in BDT training

Modelling of 5 most important variables in BDT checked in SR and QCD-CR.

WZjj @ 13 TeV: Systematic uncertainties

Object-related systematics mostly coming from jet reconstruction and calibration.

Conservative normalisation uncertainties applied on non-dominant background:

- 40% for reducible (misid. Leptons) background, 20% for VVV, 15% for tZj

Source	Uncertainty [%]
$WZjj$-EW theory modelling	5.0
$WZjj$-QCD theory modelling	2.3
$WZjj$-EW and $WZjj$-QCD interference	1.9
Jets	6.7
Pileup	2.2
Electrons	1.6
Muons	0.7
b-tagging	0.3
MC statistics	2.1
Misid. lepton background	1.0
Other backgrounds	0.1
Luminosity	2.1

Theory-related sources come from:

QCD scale and PDF uncertainties for both WZjj-EW and WZjj-QCD

Signal modeling: MadGraph VS Sherpa2.2.2

WZjj QCD modeling: Powheg+Pythia VS Powheg+Herwig.

Interference is included as a shape uncertainty on signal.

QCD/EW interference is part of the measured signal
Interference impact included as shape uncertainty on signal
Estimated at LO using MadGraph5_aMC@NLO 2.2

Size of interference: +10% of EW WZjj

- 10-5% uncertainty (low-high BDT values)

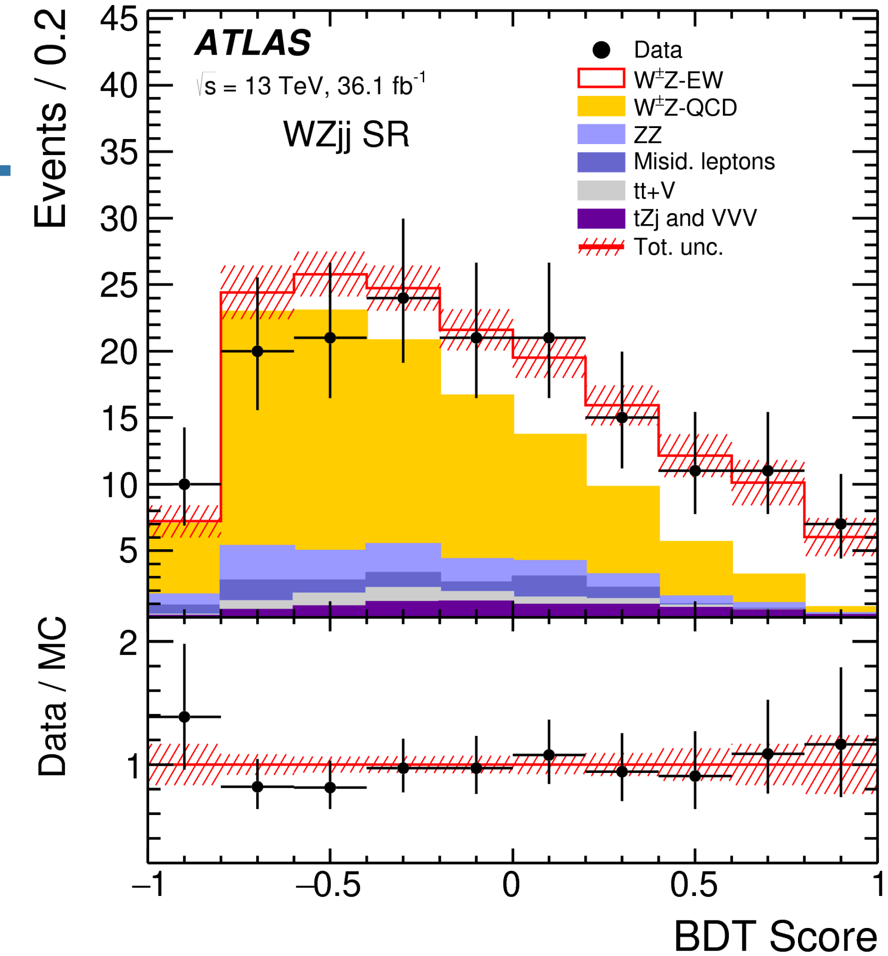
WZjj @ 13 TeV: Signal extraction

Signal is extracted in a maximum-likelihood fit of BDT score distribution in **SR**

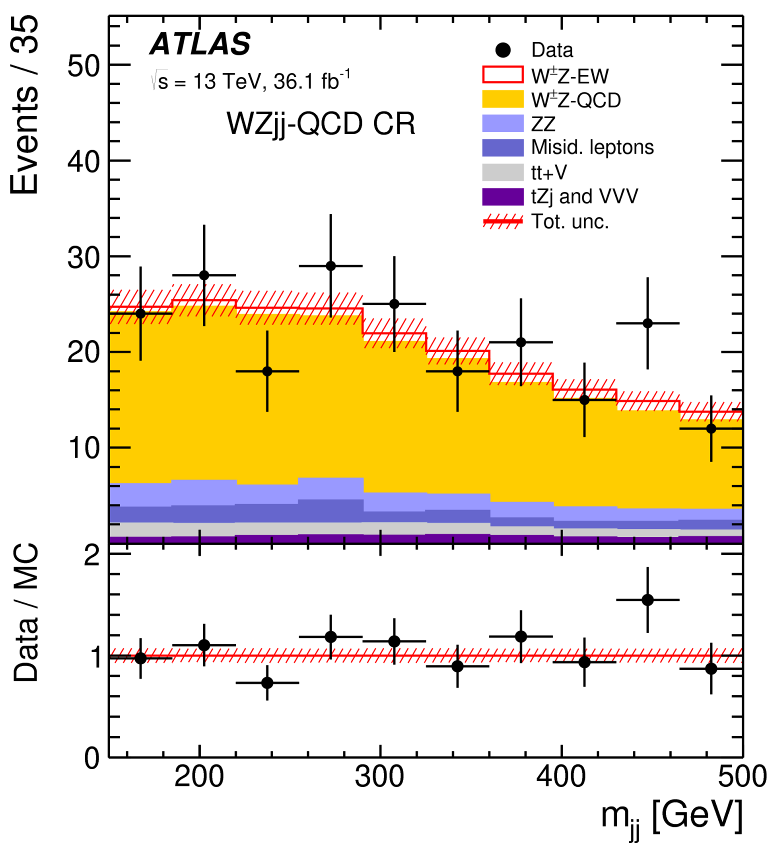
- M_{jj} distribution in WZjj QCD-CR
- b-jets multiplicity in b-CR:
- M_{jj} distribution in ZZ-CR:
- BDT score distribution in SR

signal strength parameter

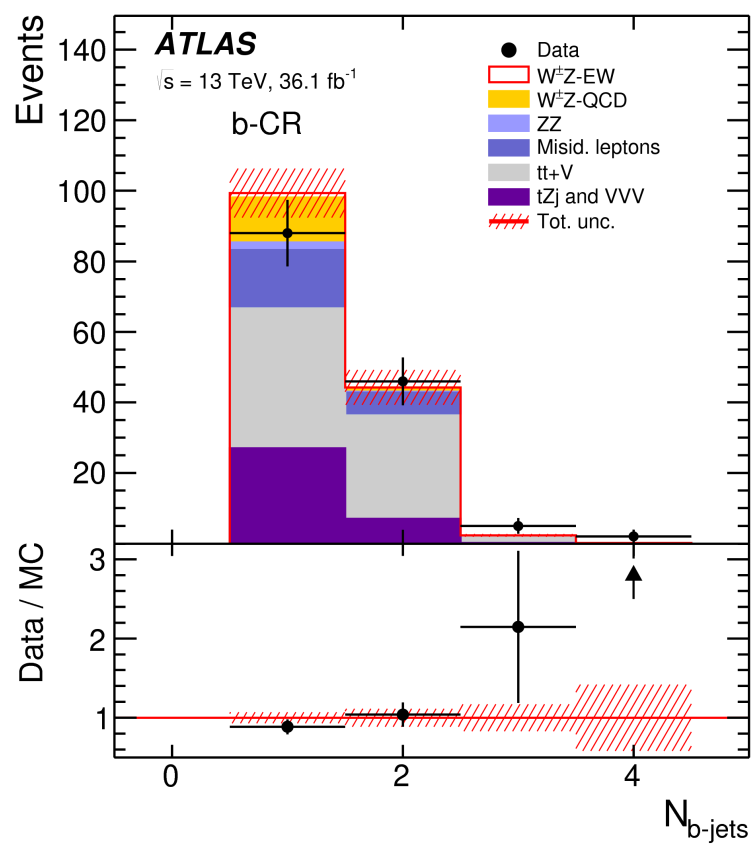
$\mu_{WZjj-EW}$



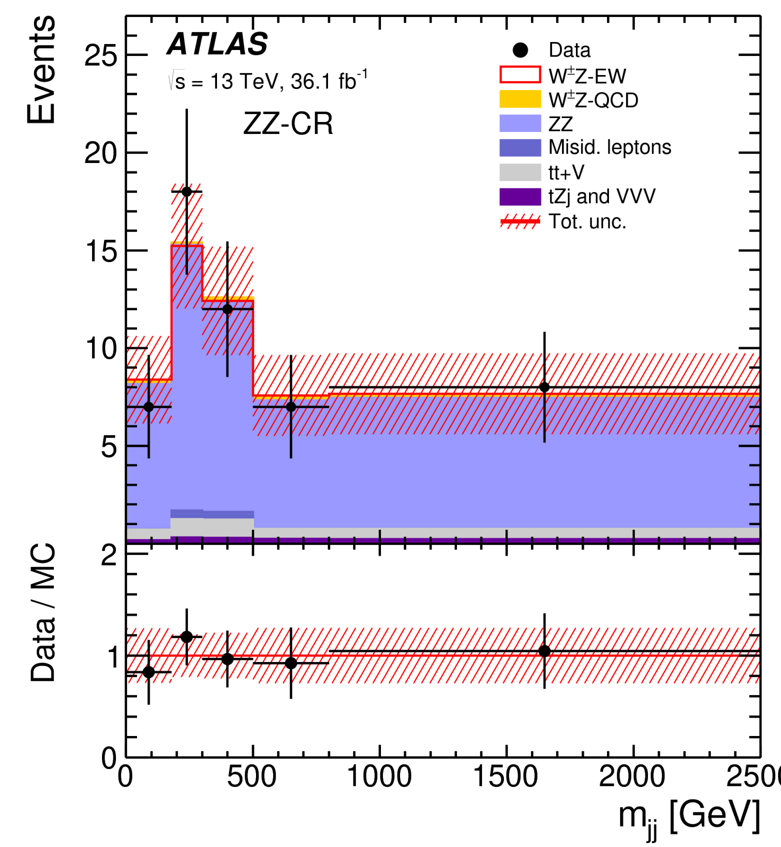
constrain WZjj-QCD



constrain tt +V



constrain ZZ



WZjj @ 13 TeV: Signal extraction

All uncertainty sources implemented as nuisance parameters, affecting shape and/or normalisation

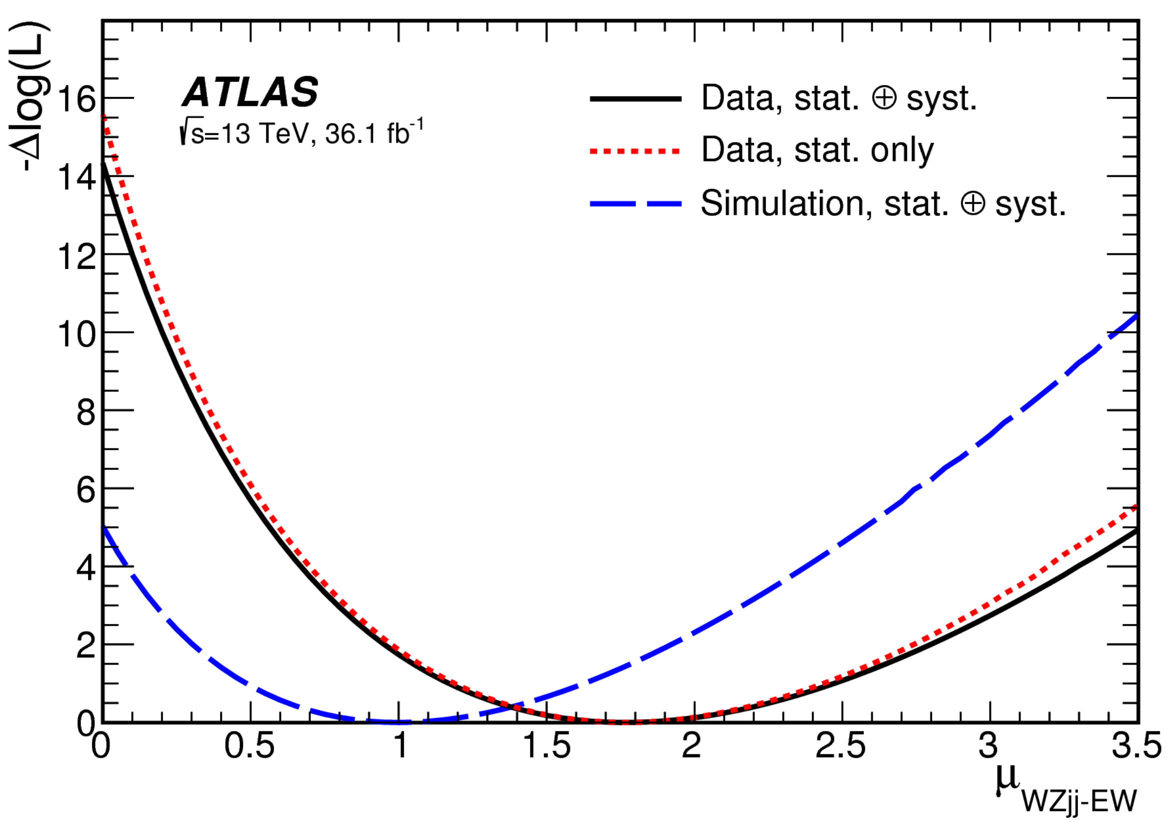
Parameter of Interest is the WZjj-EW signal normalisation:

Observed results

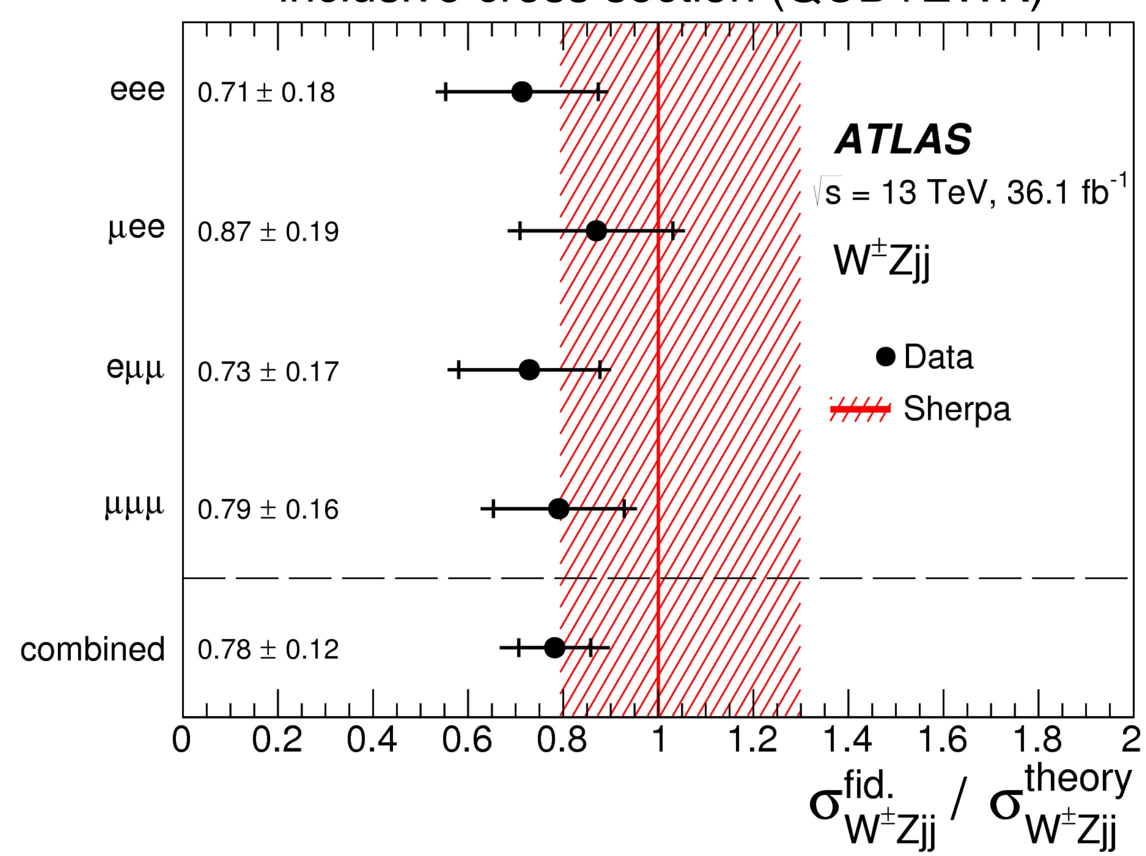
- Observed significance: **5.6σ** (3.3σ expected)
- Signal strength (Sherpa): $\mu_{WZjj} = 1.77 \pm 0.41(stat) \pm 0.17(syst)$
- Observed WZjj-EW production cross section(including interference): $\sigma^{fid.}_{meas} = 0.57^{+0.14}_{-0.13}(stat.)^{+0.05}_{-0.04}(syst)^{+0.04}_{-0.03}(th.)fb$

Background normalisation

Process	Fitted normalisation
$WZjj$-QCD	0.56 ± 0.16
$t\bar{t} + V$	1.07 ± 0.23
ZZ-QCD	1.34 ± 0.24



inclusive cross section (QCD+EWK)



WZjj @ 13 TeV: Differential cross section

The measured WZjj cross-section in the fiducial phase space is

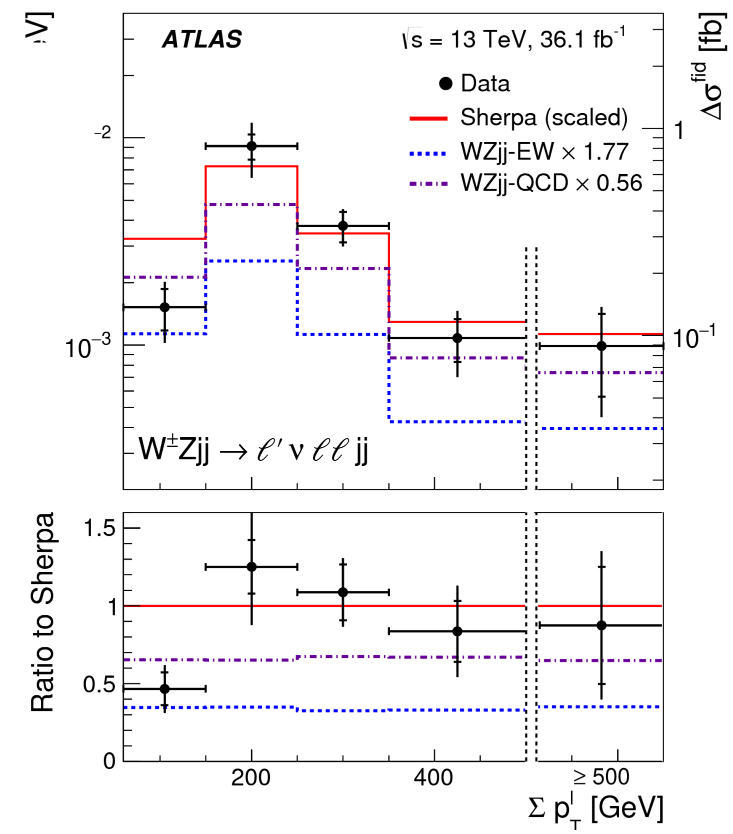
$$\sigma^{\text{fid.}}_{W^{\pm}Zjj} = 1.68 \pm 0.16\,(\text{stat.}) \pm 0.12\,(\text{exp. syst.}) \pm 0.13\,(\text{mod. syst.}) \pm 0.044\,(\text{lumi.})\text{ fb},$$
$$= 1.68 \pm 0.25\text{ fb},$$

Interesting distributions are unfolded from WZjj-EW SR to VBS fiducial phase space using iterative Bayesian unfolding method:

Two types of variables:

- Variables sensitive to aQGCs: $m_T^{WZ}, \sum p_T^l, \Delta\phi(W,Z)$
- Variables for model constrains:

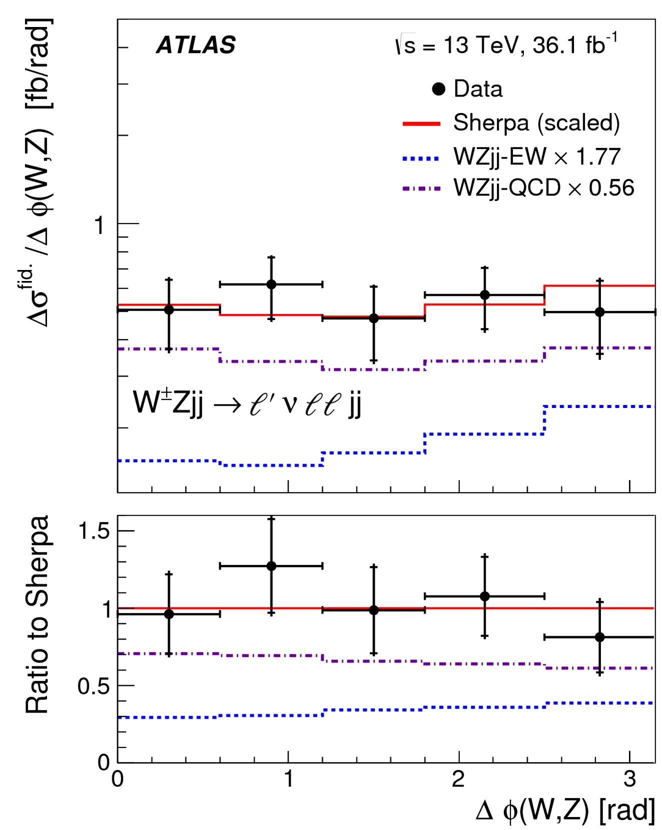
$N_{jets}(p_T > 40GeV), m_{jj}, \Delta\phi(j_1,j_2), \Delta y(j_1,j_2)$

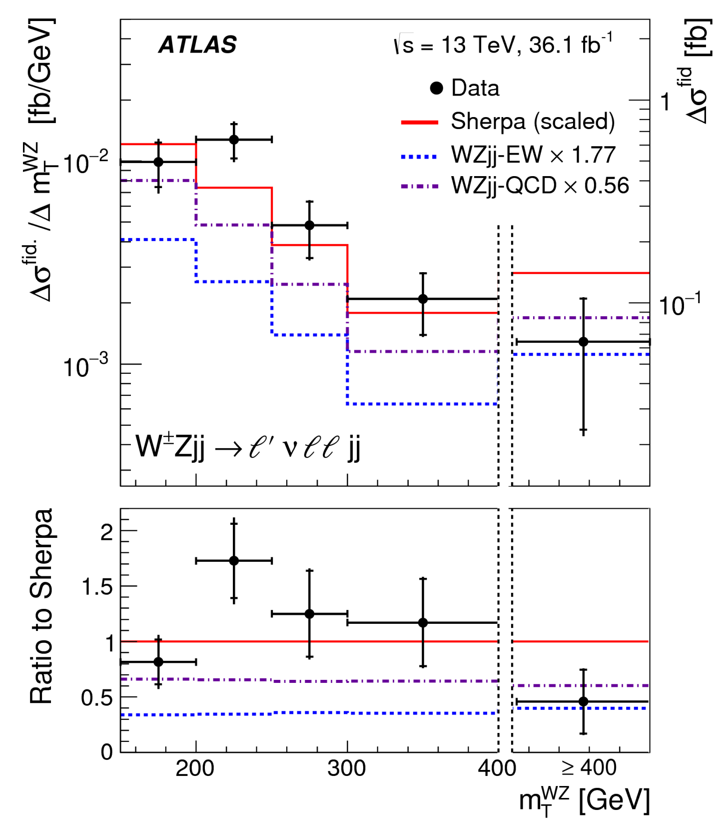


The Sherpa QCD and EW

prediction are normalised by their

corresponding normalisation factor





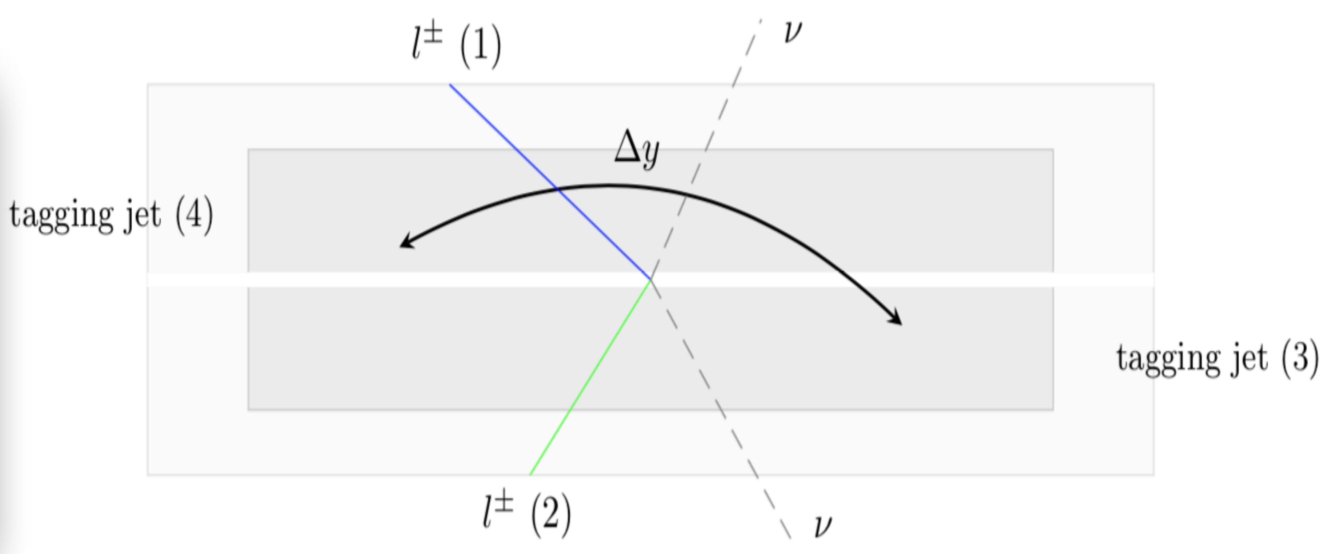
A good description of the measured cross sections within uncertainties by Sherpa is observed after the rescaling

W^+W^+jj @ 13 TeV: Major backgrounds and experimental selection

ATLAS publication with Run-2 data (2015+2016, $\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}): ATLAS-CONF-2018-030

Fiducial selection:

Cut	2 leptons	jet$_1$	jet$_2$	$\nu\nu$-system
$W^{\pm}W^{\pm}jj$ final state	same-charge (e or μ)	anti-k_T ($R = 0.4$)		
$p_T >$	27 GeV	65 GeV	35 GeV	30 GeV
$\|\eta\| <$	2.5	4.5	4.5	
	$m_{ll} > 20$ GeV			
VBS selection		$m_{jj} > 500$ GeV , $\Delta y_{jj} > 2.0$		



Main background contributions:

1. Processes with two real prompt same-charge leptons ==> Mainly **$W^{\pm}Z$+jets**
2. Experimental backgrounds:
   - ✦ Processes with **non-prompt ("fake") leptons** from mis-identified jets, or leptons from hadron decays
   - ✦ Processes with **electron charge mis-identification**

Suppression via additional experimental cuts:

- Third lepton veto (p^{l3} > 6 GeV)
- Tight reconstruction and isolation requirements on lepton candidates
- B-jet veto
- Z veto in ee channel ($|m_{ee} - m_Z| > 15$ GeV)

W^+W^+jj @ 13 TeV: Background

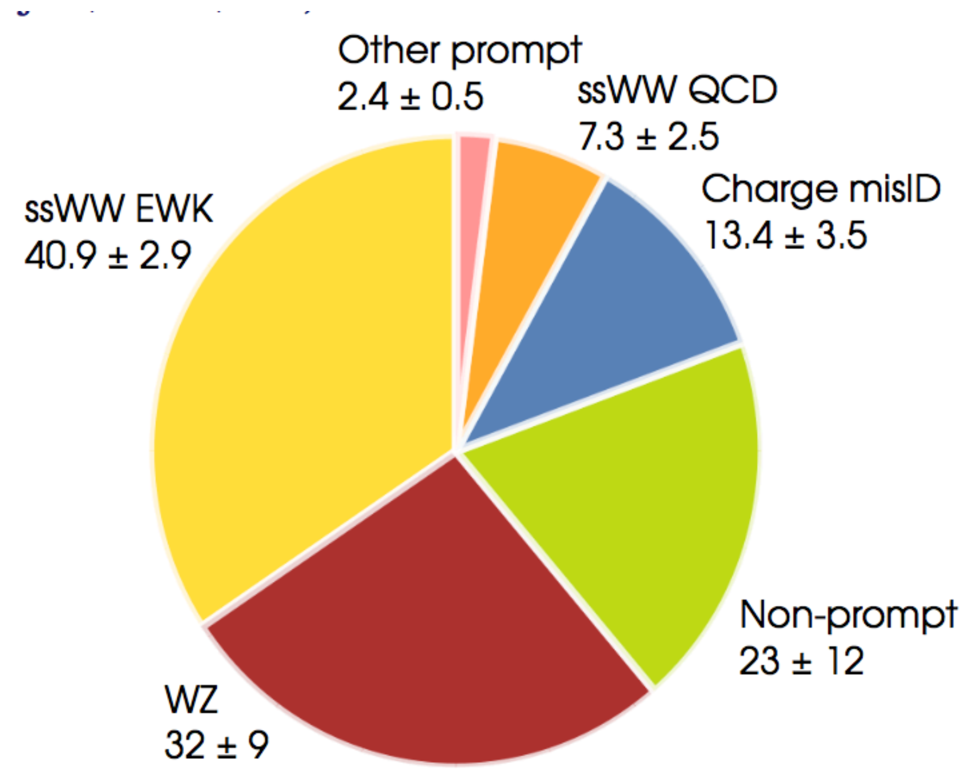
Background estimate methods and event yields in signal region

$W^{\pm}Z$ +jets: Shape MC modelled and normalised from data in tri-lepton control region ⇒ Reduction of uncertainties (dominantly theoretical pQCD scale uncertainties) to 8%

Non-prompt leptons estimate:
Scale factor from di-jet control region ⇒ Dominant experimental uncertainty (40-90%). low Mjj region helps to constrain this background uncertainty

Electron charge mis-identification and $\gamma \rightarrow e$ conversions probability and background estimate:
From $Z \rightarrow ee$ enriched region

Other irreducible backgrounds ($W^{\pm}W^{\pm}jj$ QCD, ZZ+jets, VVV, $t\bar{t}V$) —> **Monte-Carlo modelled**



Event yields in combined channel in signal region before the fit:

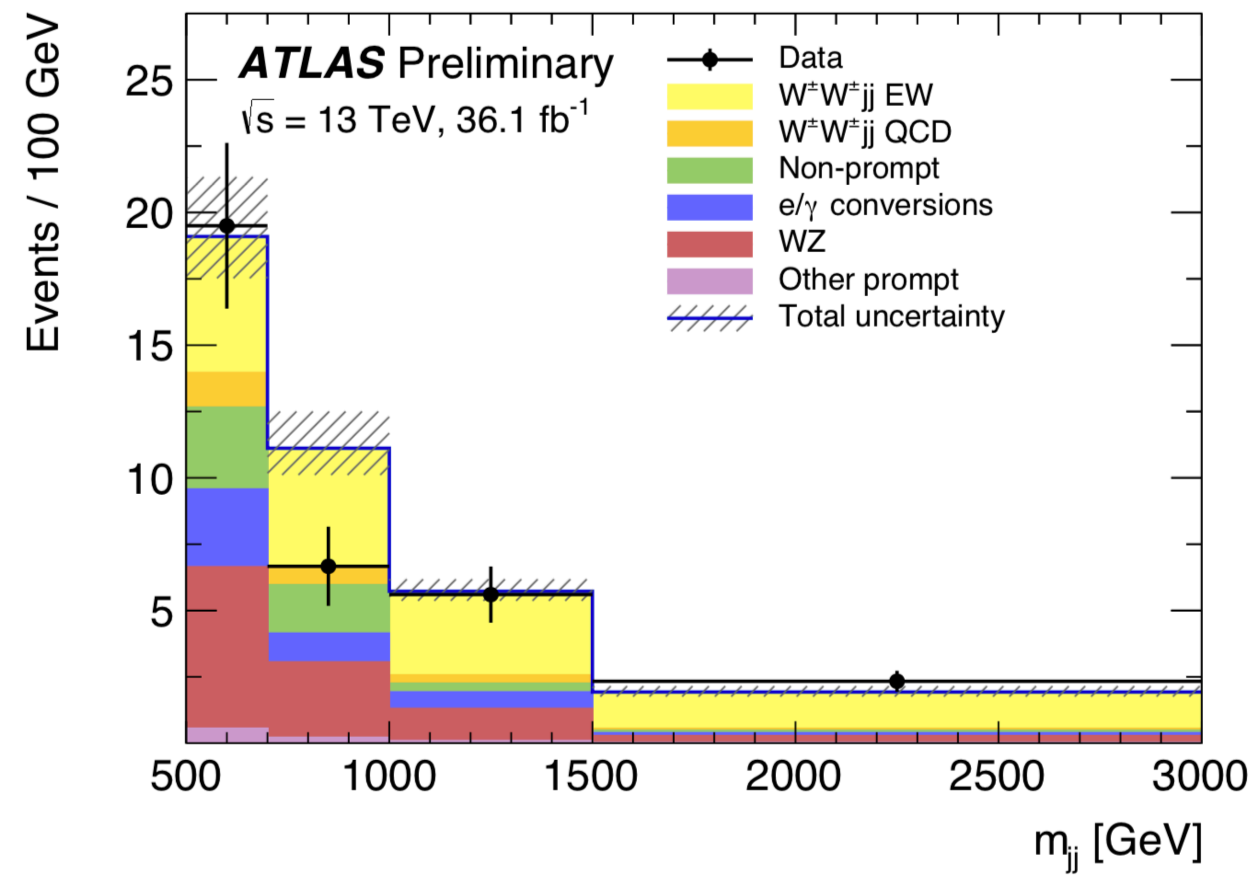
Total expected: 118.9 ± 15.3 events Data: 122 events

W^+W^+jj @ 13 TeV: Sensitivity estimate

Multi-bin likelihood fit:

- 4-bin m_{jj} distribution in signal region (m_{jj} > 500 GeV)
- 6 lepton flavour and charge split channels: $e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$ + $\mu^{\pm}e^{\pm}$, $\mu^{\pm}\mu^{\pm}$
- Background estimates constrained in two control regions:
  - ✓ $W^{\pm}Z$ CR: Require a third lepton with one OS SF pair
  - ✓ Low mjj CR: SR selection, mjj ∈ (200, 500) GeV
- $W^{\pm}Z$ normalisation reduced by ~ 12%

Di-jet invariant mass distribution in region mjj > 500 GeV after fit



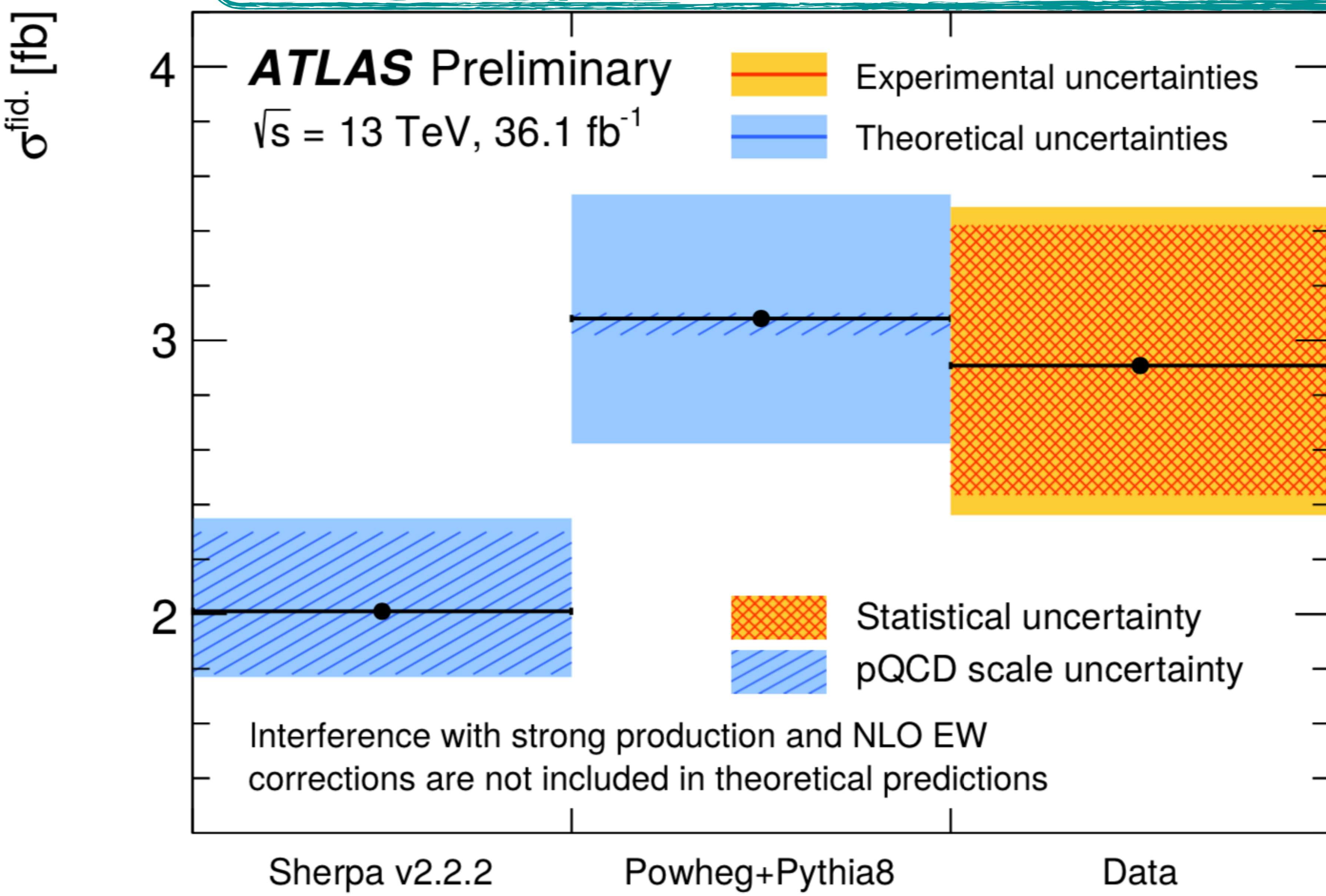
Results:

Observed (expected with Sherpa) significance is **6.9σ** (4.9σ)

W^+W^+jj @ 13 TeV: Measurement of fiducial cross section

Signal predictions do not include:

- ✦ Interference between EWK and QCD-induced production (+6%) [VBSCan 1803.07943]
- ✦ NLO EWK corrections (−16%) [A. Denner, M. Pellen et al. (1708.00268)]



(2,3j@ LO pQCD)

$\sigma^{fid} = 2.01\ ^{+0.33}_{-0.23}$ (sys.+stat.) fb

(@NLO pQCD)

$\sigma^{fid} = 3.08\ ^{+0.45}_{-0.46}$ (sys.+stat.) fb

Measured fiducial cross section: $\sigma^{fid} = 2.91^{+0.51}_{-0.47}$(stat.) ± 0.27(sys.) fb

Summary and Conclusions

ATLAS has published result on VBS measurements using 36.1 fb^{-1} of data collected in 2015+2016 at $\sqrt{s}$ = 13 TeV

- Run 2 of the LHC has revealed access to further exploration of final states in VBS
  - ✓ First observation of electro-weak $W^{\pm}Zjj$ production
  - ✓ Observation of electro-weak production of $W^{\pm}W^{\pm}jj$ final state
  - ✓ Observed Significance:

$W^{\pm}W^{\pm}jj$ **EWK:** 6.9σ (4.6σ expected)

$W^{\pm}Zjj$ **EWK:** 5.6σ (3.3σ expected)

with Sherpa signal

- Measurement of fiducial cross sections for these final states
- With more data being collected for the full Run2
  - ✓ Higher order theoretical computations are becoming more important
  - ✓ Improving sensitivity for BSM

VBS final states continue to be a playground for exciting physics to be explored!

Backup

Process	Remarks	sqrt(s)	Lumi	Reference
	this talk	13 Tev	36.1 fb^{-1}	
	this talk	13 Tev	36.1 fb^{-1}	
		8 TeV	20.2 fb^{-1}	JHEP07(2017)107
		8 TeV	20.2 fb^{-1}	Phys. Rev. D 95 (2017) 032001