Measurements of Dibosons+Jets Production

Multi-Boson Interactions, 24.08.2021

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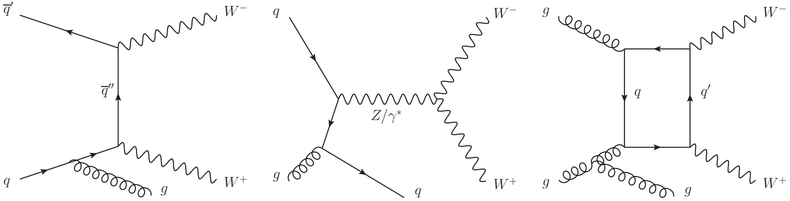
Introduction

- Presenting LHC Run 2 results of diboson+jets production
- Measurements of diboson-plus-jets production:
  - Test of perturbative QCD and event generation tools
  - Test of interplay of QCD and electroweak corrections
  - Allow to constrain new physics and background to searches
- Large Run 2 dataset, improved analysis methods, and precise theoretical predictions enable fairly precise measurements
- Measurements of jets exists for *WW*, *WZ*, and *ZZ* production
  - CMS *WW*: Phys. Rev. D 102 (2020) 092001, 2015–2016 data NEW
  - ATLAS $WW+\geq 1$ jet: JHEP 06 (2021) 003, 2015–2018 data NEW
  - CMS *WZ*: CMS-PAS-SMP-20-014 (preliminary), 2015–2018 data NEW
  - ATLAS *WZ*: Eur. Phys. J. C 79 (2019) 535, 2015–2016 data
  - ATLAS *WZjj*: Phys. Lett. B 793 (2019) 469, 2015–2016 data
  - CMS *ZZ*: Phys. Lett. B 789 (2019) 19, 2015–2016 data
  - ATLAS *ZZ*: Phys. Rev. D 97 (2018) 032005, 2015–2016 data
- Publications contain comprehensive analyses of diboson production, will only highlight parts relevant for diboson-plus-jet

Common Features of Analyses

- Analyses share many common features
  - Event selection: identify prompt leptons from W/Z decays, veto additional leptons
  - Increase signal-to-background ratio with few simple kinematic cuts (more elaborate methods for CMS *WW*)
  - Non-prompt and mis-id. lepton-background (a.k.a. fake-lepton background) estimated with data-driven methods
  - Prompt lepton backgrounds estimated with mixture of MC simulation and data-driven methods
  - Control and validation regions for important background processes
  - Data unfolded to correct for detector effects
- All analyses use anti-k_T jets with $R = 0.4$, but kinematic cuts vary and will be indicated
- Dominant uncertainties of jet measurements due to uncertainties in jet-energy scale, theoretical signal model, and, especially in case of *WW* production, background modelling

WW Production

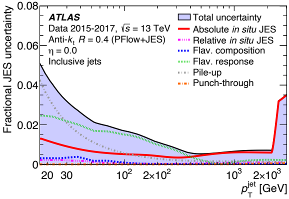


- Measurements of *WW* production suffer from large $t\bar{t}$ background
- Background can be reduced by application of *b*-veto
- Jet vetoes typically used to further reduce $t\bar{t}$ yield

Jet Vetoes

- Jet veto introduces jet-energy scale uncertainties, uncertainty increases for more stringent vetoes
- Jet vetoes also theoretically challenging
  - Large logarithmic terms $\propto \log(m_{WW}/p_{\mathrm{T}}^{\mathrm{jet}})$ limit accuracy of predictions for jet-vetoed cross section
  - Availability of NNLO and NNLO+NNLL predictions improve situation
- Latest *WW* measurements improve accuracy by also measuring events with jets
  - Reduce $t\bar{t}$ background with sophisticated methods that don't rely on jet veto (CMS)
  - Employ precise data-driven $t\bar{t}$ background prediction method

Eur. Phys. J. C 81 (2021) 689



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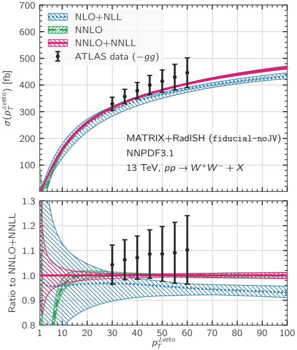


CMS *WW*: Event Selection

CMS *WW*: Phys. Rev. D 102 (2020) 092001, 2015–2016 dataset

- Two analyses: sequential cuts and MVA ("random forest")
- Different flavour (DF) and same-flavour (SF) categories

Event selection:

Quantity	Sequential Cut		Random Forest	
	DF	SF	DF	SF
Number of leptons	Strictly 2		Strictly 2	
Lepton charges	Opposite		Opposite	
$p_T^{\ell\,\max}$	>25		>25	
$p_T^{\ell\,\min}$	>20		>20	
$m_{\ell\ell}$	>20	>40	>30	>30
Additional leptons	0		0	
$\lvert m_{\ell\ell} - m_Z \rvert$	—	>15	—	>15
$p_T^{\ell\ell}$	>30	>30	—	—
p_T^{miss}	>20	>55	—	—
$p_T^{\text{miss,proj}}$, $p_T^{\text{miss,track proj}}$	>20	>20	—	—
Number of jets	≤1		—	—
Number of b-tagged jets	0		0	
DYMVA score	—	>0.9	—	—
Drell–Yan RF score S_{DY}	—	—	>0.96	
$t\bar{t}$ RF score $S_{t\bar{t}}$	—	—	>0.6	

CMS *WW*: Total Cross Section Measurement

- Main result on total cross section from sequential cut analysis
- Data-driven method to estimate fake lepton background
- Normalization of top and DY backgrounds determined in CRs
- Other backgrounds estimated using theory predictions
- Fit performed in four SRs and four top CRs: 0 and 1 jet as well as same-flavour and different flavour

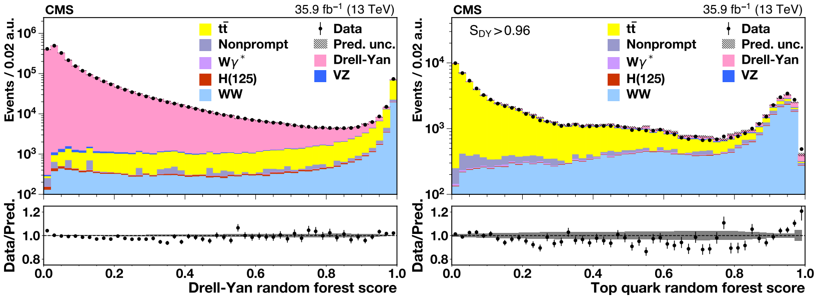
Category		Signal strength	Cross section [pb]
0-jet	DF	1.054 ± 0.083	125.2 ± 9.9
0-jet	SF	1.01 ± 0.16	120 ± 19
1-jet	DF	0.93 ± 0.12	110 ± 15
1-jet	SF	0.76 ± 0.20	89 ± 24
0-jet & 1-jet	DF	1.027 ± 0.071	122.0 ± 8.4
0-jet & 1-jet	SF	0.89 ± 0.16	106 ± 19
0-jet & 1-jet	DF & SF	0.990 ± 0.057	117.6 ± 6.8

- Addition of 1-jet region reduces both experimental uncertainties and sensitivity on signal modelling uncertainties
- Measurement of 117.6±6.8 fb in excellent agreement with NNLO prediction of 118.8±3.6 fb

CMS *WW*: Random Forest

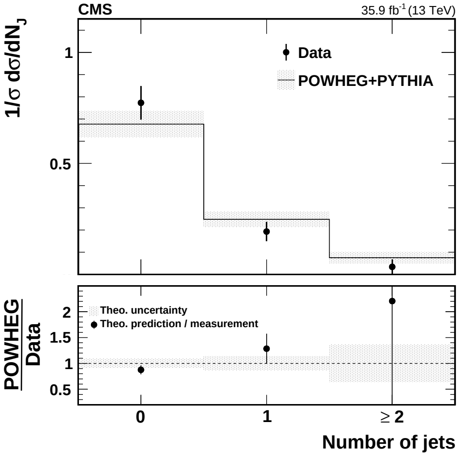
- Measurement of jet multiplicity based on random forest selection
- Two classifiers S, against DY and top background, cut $S_{DY} > 0.96$ and $S_{top} > 0.2$
- Relatively small dependence of selection efficiency on N_{jets}

Feature	Classifier	
	Drell–Yan	Top quark
Lepton flavor	✓	
Number of jets		✓
$p_T^{\ell\,min}$	✓	
p_T^{miss}	✓	✓
$p_T^{miss,proj}$	✓	
$p_T^{\ell\ell}$	✓	✓
$m_{\ell\ell}$	✓	
$m_{\ell\ell p_T^{miss}}$	✓	
$\Delta\phi_{\ell\ell p_T^{miss}}$	✓	✓
$\Delta\phi_{\ell J}$		✓
$\Delta\phi_{p_T^{miss} J}$		✓
$\Delta\phi_{\ell\ell}$	✓	
H_T		✓
Recoil	✓	✓



CMS *WW*: Results

- Measurement of fraction on 0, 1, and ≥2 jet events
- Background-subtracted data unfolded using matrix inversion and corrected for inefficiency
- Compared to Powheg NLO+PS prediction that is reweighted to match p_T^{WW} spectrum of NNLL+NNLO calculation



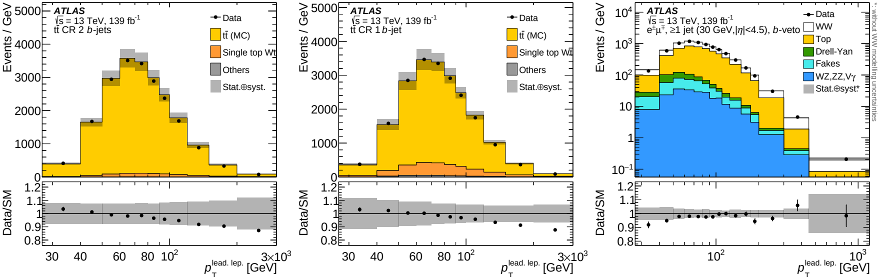
Jets: $p_T > 30$ GeV, $|\eta| < 2.5$

ATLAS *WWj*: Overview

ATLAS $WW+\geq 1$ jet: JHEP 06 (2021) 003, 2015−2018 dataset

1. Selection
   - $=2$ opposite-sing different-flavour leptons: $e^{\pm}\mu^{\mp}$ ($p_T > 27$ GeV)
   - ≥ 1 jet ($p_T > 30$ GeV, $\eta < 4.5$)
   - 0 b-jets ($p_T > 20$ GeV, $\eta < 2.5$, 85% tagging efficiency)
   - $m_{e\mu} > 85$ GeV
2. Subtraction of backgrounds
   - Data-driven estimates for top and fake lepton background
   - Minor backgrounds from MC simulation
3. Fiducial cross-section measurement and unfolding of 18 observables (in a phase space requiring at least one jet)
   - Involving only leptons: $p_{\mathrm{T}}^{\mathrm{lead.\ lep.}}$, $p_{\mathrm{T}}^{\mathrm{sub-lead.\ lep.}}$, $m_{e\mu}$, $p_{\mathrm{T},e\mu}$, $y_{e\mu}$, $\Delta\phi_{e\mu}$, $\cos\theta^*$
   - Also involving jets and MET: $m_{\mathrm{T},e\mu}$, $p_{\mathrm{T}}^{\mathrm{lead.\ jet}}$, H_{T}, S_{T}, and N_{jet}
   - Additional measurements at $p_{\mathrm{T}}^{\mathrm{lead.\ jet}} > 200$ GeV and $p_{\mathrm{T}}^{\mathrm{lead.\ lep.}} > 200$ GeV

ATLAS *WWj*: Top Background Estimate (1/2)



- $t\bar{t}$ estimate based on technique of Eur. Phys. J. C 80 (2020) 528
- Two clean control regions with $=1, =2$ b-jets
- Allows to estimate both number of $t\bar{t}$ events for any b-jet multiplicity, $\mathcal{L}\sigma_{t\bar{t}}\varepsilon_{e\mu}$, and efficiency for identifying a b-jet, ε_b
- Only information from $t\bar{t}$ simulation: b-jet correlation factor C_b

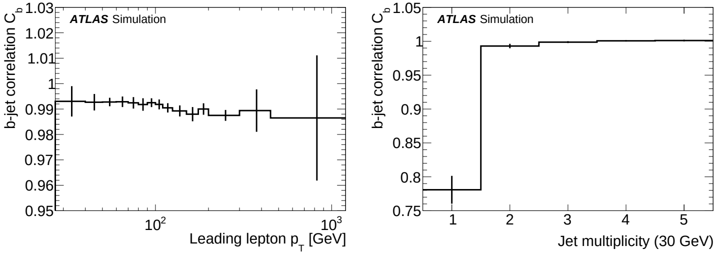
$$N_{2b} = \mathcal{L}\sigma_{t\bar{t}}\varepsilon_{e\mu} \cdot C_b\varepsilon_b^2 + N_{2b}^{\text{others,MC}} ,$$

$$N_{1b} = \mathcal{L}\sigma_{t\bar{t}}\varepsilon_{e\mu} \cdot 2\varepsilon_b \left(1 - C_b\varepsilon_b\right) + N_{1b}^{\text{others,MC}} ,$$

$$\Rightarrow N_{0b}^{t\bar{t}} = \mathcal{L}\sigma_{t\bar{t}}\varepsilon_{e\mu} \cdot \left(1 - 2\varepsilon_b + C_b\varepsilon_b^2\right)$$

ATLAS *WWj*: Top Background Estimate (2/2)

- Estimate performed differentially, in each analysis bins
- Strongly reduces both $t\bar{t}$ modelling and b-tagging uncertainties



- b-jet correlation factor C_b typically close to 1, small dependence on most measured observables, small dependence on simulation
- Method works for 1-jet events as b-jet p_T cut lower than light-jet p_T cut ($\Rightarrow$ 2 and b-tag 1-jet CR exists) – but larger dependence on C_b prediction
- Precision of method improves with jet-multiplicity and for jet-inclusive measurements

ATLAS *WWj*: Theory Predictions

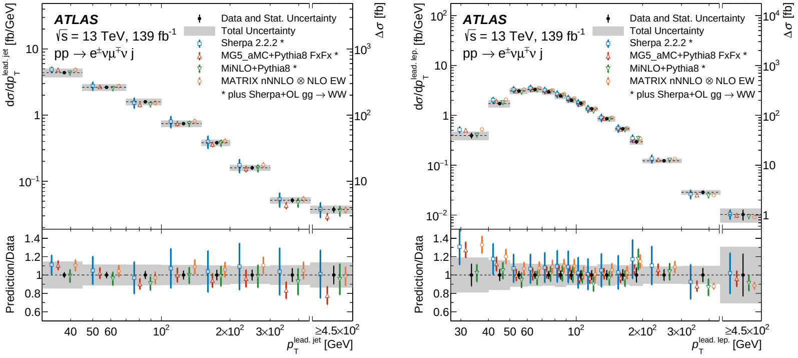
- ATLAS *WWj* result compared to large number of theory predictions

Process	Generator	Parton shower	PDF	Matrix element $\mathcal{O}(\alpha_S)$
$q\bar{q} \to WW$	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)

- Fixed order: MATRIX nNNLO
  - NNLO for $qq \to WW$ (only NLO accurate in 1-jet phase space)
  - Combined with NLO prediction for $gg \to WW$ (only LO in 1-jet phase space) and NLO EW correction to $qq \to WWj$
- Three NLO+PS predictions
  - All include NLO QCD corrections to $qq \to WWj$
  - Combined with $gg \to WW(j)$ at LO

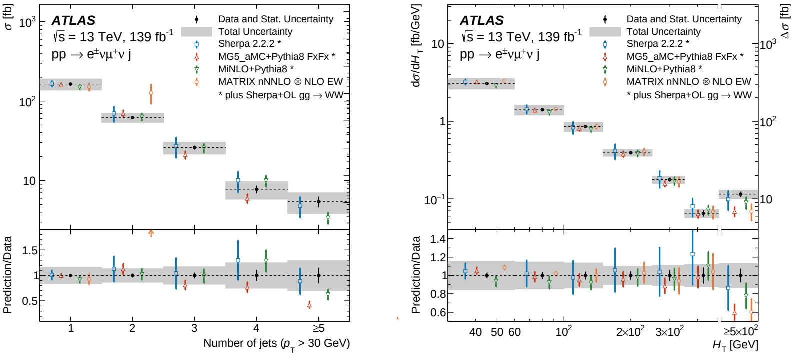
ATLAS *WWj*: Results (1/2)

- Background-subtracted data unfolded with iterative Bayesian method and corrected for inefficiencies
- Fiducial differential cross sections compared to predictions in phase space close to detector acceptance



- Excellent agreement for leading jet and lepton p_T (in 1-jet events) over more than an order of magnitude

ATLAS *WWj*: Results (2/2)

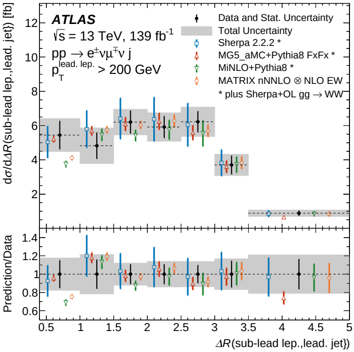


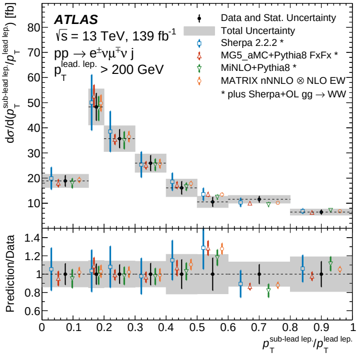
Jets: $p_T > 30$ GeV, $|\eta| < 4.5$

- Fiducial differential cross section as a function of jet multiplicity and $H_T = \sum p_T^{jet}$
- Good measurement precision even for $N_{jet} \geq 5$ and $H_T > 500$ GeV
- Good agreement with prediction

ATLAS WWj: Measurements at High Lepton p_{T}

- Additional measurements performed in a phase space requiring leading lepton $p_{\mathrm{T}} > 200$ GeV
- Targeting V+jet-like topologies, with a relatively soft V radiated from a hard jet – interesting interplay of QCD and EW corrections





- Good agreement between data and simulations

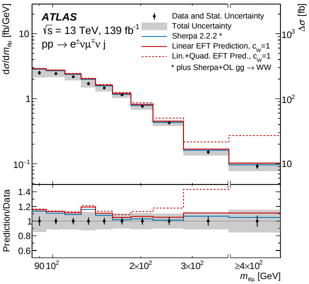
VV+jets and Anomalous Triple Gauge Couplings

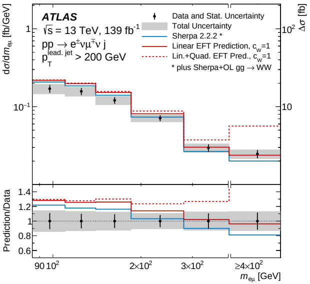
Two effects in VV+jet topologies that affect predictions of effect of anomalous triple gauge couplings (aTGCs)

1. Effect of aTGCs diluted in VV+jets
   - V+jet-like topologies, with a relatively soft V radiated from a hard jet, important at high invariant mass
   - No triple gauge coupling effect as V+jets-like diagrams dominate
   - Effect In principle also relevant for jet-inclusive measurements
2. Enhanced interference of aTGC and SM amplitude in VV+jets
   - Without jet, aTGC amplitude (in particular the one corresponding to O_W operator of Warsaw basis) different helicity compared to SM $\Rightarrow$ interference suppressed
   - Different helicities possible in VV+jets, recovers some of the interference $\Rightarrow$ improves sensitivity to aTGC
   - ATLAS WW+jets measurement tried to take advantage of effect $\rightarrow$ measure aTGC in events with hard jet

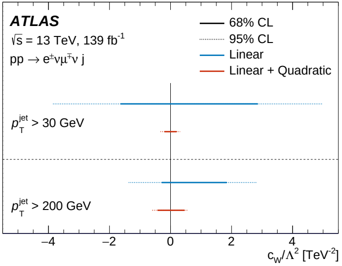
ATLAS *WWj*: EFT Interpretation

- $m_{\ell\ell}$ distribution in events with $\geq$ 30 GeV (left) and $\geq$ 200 GeV jet (right)
- Interference (“linear EFT”) increases with jet p_T

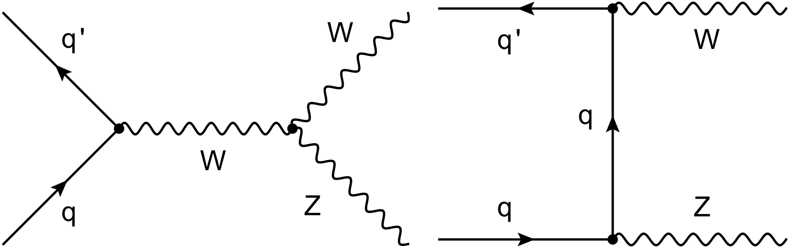




- Comparing limits for
  - $\geq$ 30 GeV jet vs $\geq$ 200 GeV jet
  - Term linear in c_W (interference with SM) only versus linear+quadratic model
  - Sensitivity to linear term indeed improved for higher jet p_T cut but quadratic term still dominant



WZ Production



- *WZ* production: smaller cross section and leptonic branching ratio compared to *WW*
- Advantage: no $t\bar{t}$ background, small background contributions from ZZ, $t(\bar{t})Z$, and lepton fakes

CMS *WZ*: Overview

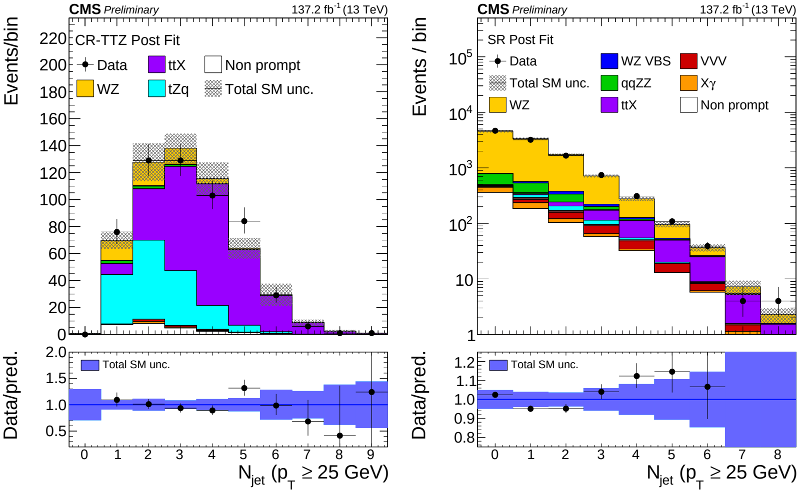
CMS *WZ*: CMS-PAS-SMP-20-014, 2015–2018 dataset (preliminary)

- Event selection for SR and CRs

Region	N_ℓ	$p_T\{\ell_{Z1},\ell_{Z2},\ell_W,\ell_4\}$	N_{OSSF}	$\|M(\ell_{Z1},\ell_{Z2})-m_Z\|$	p_T^{miss}	N_{btag}	$\min(M(\ell\ell'))$	$M(\ell_{Z1},\ell_{Z2},\ell_W)$
SR	$=3$	$>\{25,10,25\}$ GeV	≥ 1	<15 GeV	>30 GeV	$=0$	>4 GeV	>100 GeV
CR-$t\bar{t}$Z	$=3$	$>\{25,10,25\}$ GeV	≥ 1	<15 GeV	>30 GeV	>0	>4 GeV	>100 GeV
CR-ZZ	$=4$	$>\{25,10,25,10\}$ GeV	≥ 1	<15 GeV	-	$=0$	>4 GeV	>100 GeV
CR-conv	$=3$	$>\{25,10,25\}$ GeV	≥ 1	-	≤ 30 GeV	$=0$	>4 GeV	<100 GeV

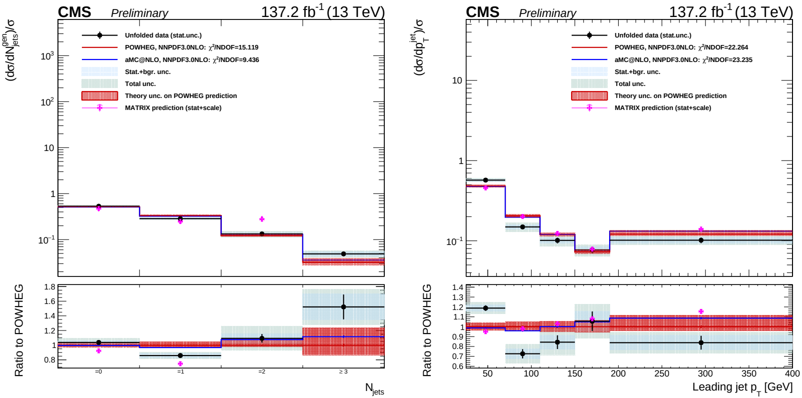
- $t(\bar{t})Z$, ZZ, and $V\gamma$ estimated from fit that includes control regions
- Data-driven estimate of fake lepton background
- Cross section measurement in combined fit of SR and CRs
- Additional features of analysis (charge asymmetry measurement, polarization measurement, limits on anomalous triple gauge couplings) not covered here

CMS *WZ*: Post-Fit in CR and SR



- Post-fit result for N_{jet} distribution in $t\bar{t}Z$ CR and SR

CMS WZ: Results



Jets: $p_T > 25$ GeV, $|\eta| < 2.5$

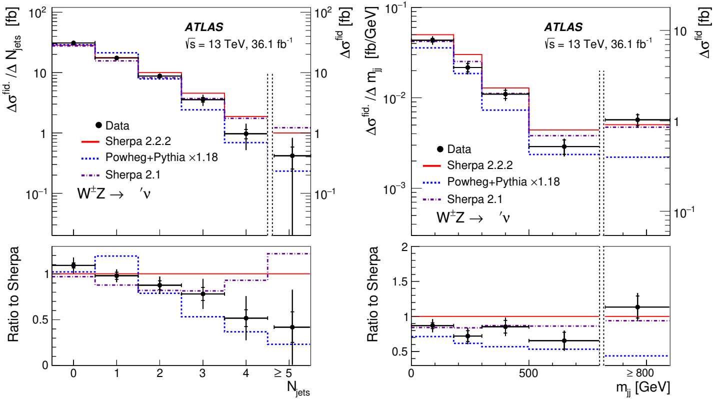
- Fiducial differential cross section as function of N_{jet} and jet p_T
- Bad description by all predictions, Powheg, aMC@NLO (includes 0 and 1 jet @NLO via FxFx), and MATRIX NNLO QCD

ATLAS WZ: Overview

ATLAS WZ: Eur. Phys. J. C 79 (2019) 535, 2015–2016 dataset

1. Fiducial phase space:
   - $=3$ leptons, at least on same-flavour opposite-charge pair
   - Z candidate with $|m_{\ell\ell} - m_Z| < 10$ GeV
   - $p_{\mathrm{T}}^{\ell} > 15$ GeV (20 GeV) for leptons from Z (W)
   - $m_{\mathrm{T}}^{W} > 30$ GeV
2. Subtraction of backgrounds
   - Data-driven estimates for fake lepton background
   - Other backgrounds from MC simulation, ZZ and $t\bar{t}V$ scaled to CR yield
3. Fiducial cross section and polarization measurement

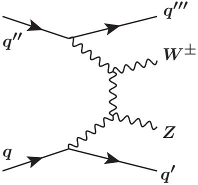
ATLAS *WZ*: Results



Jets: $p_T > 25$ GeV, $|\eta| < 4.5$

- N_{jet} and m_{jj} fiducial differential cross sections shown here
- Similar trend in Powheg+Pythia vs data as in CMS measurement
- Also compared to Sherpa 2.1 (extra jets at LO QCD) and Sherpa 2.2.2 (first jet at NLO QCD)

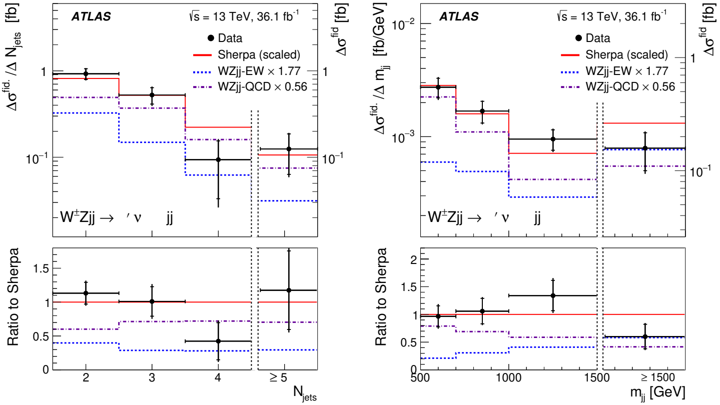
ATLAS *WZjj*: Overview



ATLAS measurement of *WZjj* in VBS-enhanced phase space: Phys. Lett. B 793 (2019) 469, 2015–2016 dataset

1. Fiducial phase space
   - Lepton selection similar to *WZ* measurement
   - Additionally: two jets in opposite hemispheres with $m_{jj} > 500$ GeV
2. Background estimates
   - Data-driven estimates for fake lepton background
   - Dedicated CRs for *ZZ*, $t\bar{t}V$, and QCD *WZjj* (*WZjj* with at least one QCD vertex)
   - Minor backgrounds from MC simulation
3. Fit for both EW *WZjj* and QCD *WZjj* signal strength
   - BDT used to separate processes in SR
   - Three CRs included in fit
4. Differential cross section measurement of QCD+EW *WZjj*, scaling EW and QCD contributions to fit result

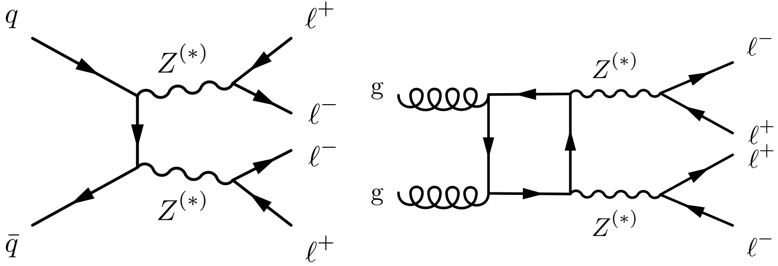
ATLAS *WZjj*: Differential cross sections



Jets: $p_{\mathrm{T}} > 40$ GeV, $|\eta| < 4.5$

- Fiducial differential cross section as function of jet multiplicity
- Compared to predictions from Sherpa 2.2.2 for QCD and EW *WZjj*, scaled to the fitted value

ZZ Production



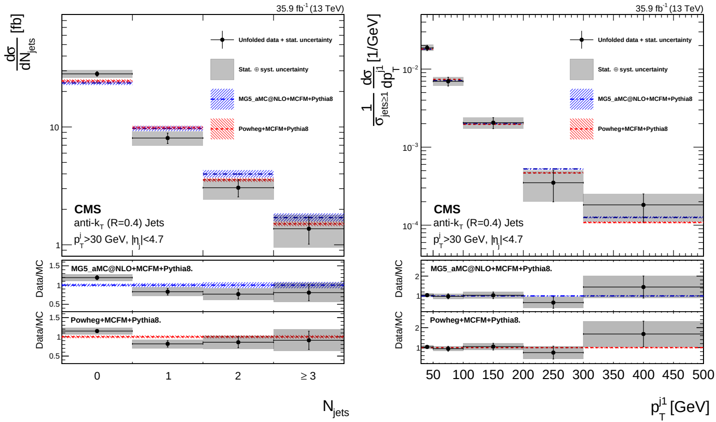
- Smallest cross section and leptonic branching ratio
- Only very small prompt and fake lepton background

CMS ZZ: Overview

CMS ZZ: Phys. Lett. B 789 (2019) 19, 2015–2016 dataset

1. Fiducial phase space
   - 2 opposite-sign same-flavour lepton pairs ($p_T^{\ell} > 5$ GeV)
   - $p_T^{\ell_1} > 20$ GeV, $p_T^{\ell_2} > 10$ GeV,
   - Two Z candidates with $60 < m_Z < 120$ GeV
2. Subtraction of backgrounds
   - Data-driven estimates for fake lepton background
   - Minor prompt backgrounds from MC simulation ($< 2\%$)
3. Measurement of jet multiplicities (both incl forward jets and central jets only) and kinematics

CMS *ZZ*: Results



Jets: $p_T > 30$ GeV, $|\eta| < 4.7$

- Fid. diff. cross section as function of jet multiplicity and lead. jet p_T
- Statistical uncertainties dominant
- Again, under-prediction of 0-jet events, otherwise good agreement with Powheg+Pythia and MG5_aMC (0&1 jet @NLO)

ATLAS ZZ: Overview

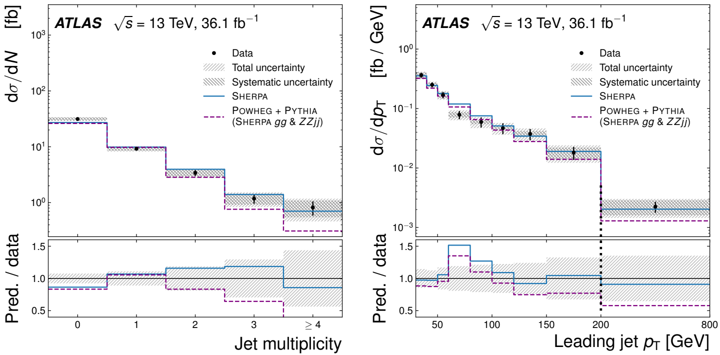
ATLAS ZZ: Phys. Rev. D 97 (2018) 032005, 2015−2016 dataset

Event selection:

Type	Input or requirement
Leptons (e, μ)	Prompt Dressed with prompt photons within $\Delta R = 0.1$ (added to closest prompt lepton) $p_{\mathrm{T}} > 5\ GeV$ $\lvert\eta\rvert < 2.7$
Quadruplets	Two same-flavor opposite-charge lepton pairs Three leading-p_{T} leptons satisfy $p_{\mathrm{T}} > 20$ GeV, 15 GeV, 10 GeV
Events	Only quadruplet minimizing $\lvert m^a_{\ell\ell} - m_Z\rvert + \lvert m^b_{\ell\ell} - m_Z\rvert$ is considered Any same-flavor opposite-charge dilepton has mass $m_{\ell\ell} > 5$ GeV $\Delta R > 0.1$ (0.2) between all same-flavor (different-flavor) leptons Dileptons minimizing $\lvert m^a_{\ell\ell} - m_Z\rvert + \lvert m^b_{\ell\ell} - m_Z\rvert$ are taken as Z boson candidates Z boson candidates have mass $66\ GeV < m_{\ell\ell} < 116$ GeV
Jets	Clustered from all non-prompt particles Anti-k_t algorithm with $R = 0.4$ $p_{\mathrm{T}} > 30\ GeV$ $\lvert\eta\rvert < 4.5$ Rejected if within $\Delta R = 0.4$ of a fiducial lepton

After subtraction of prompt and fake lepton backgrounds: measurements of lepton and jet kinematics (both incl forward jets and central jets only)

ATLAS ZZ: Results



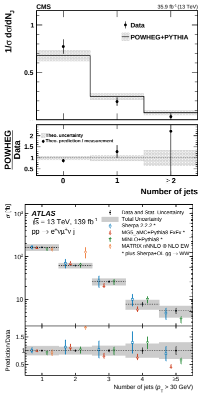
Jets: $p_T > 30$ GeV, $|\eta| < 4.5$

- Fid. diff. cross section as function of jet multiplicity and lead. jet p_T
- As for CMS, under-prediction of 0-jet events
- High jet multiplicity and p_T regions better modelled by Sherpa (0&1 jet @NLO, 2&3 jet at LO)

Conclusion

- Large Run 2 dataset, advanced analysis techniques, and precise theoretical prediction enable precision studies of *VV*+jets
- CMS and ATLAS both published measurements of jets in *WW*, *WZ*, and *ZZ* production
- Good agreement with NLO QCD predictions of *VV*+jet production

WW



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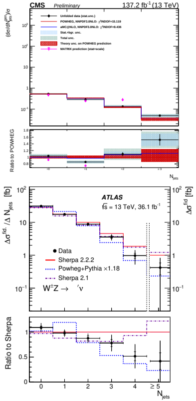

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