Vector bosons and jet production in ATLAS

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on behalf of the ATLAS Collaboration

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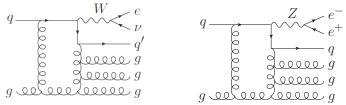
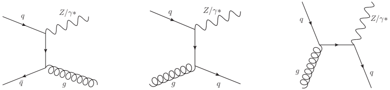
Motivations

- Powerful test of perturbative QCD (pQCD) and higher order effects over many orders of magnitude in cross section



- Overall it is away to explore corners of the phase space and search for deviations in clean signatures
- Measurements needed to re-assess the accuracy of the theoretical tools (MCs and PDFs) at this new energy regime
- Sensitive to the gluon PDF $\rightarrow$ Cross section $>$ 80% dominated by gq scattering



- Important background for studies of the Higgs boson and also searches for new phenomena where the signals can be tiny $\rightarrow$ Need to understand the backgrounds to be able to claim a discovery!
- The multiplicity and kinematics of the jets in V + jet events can be exploited to achieve a good separation between signal and background

State-of-the-art generators/calculations

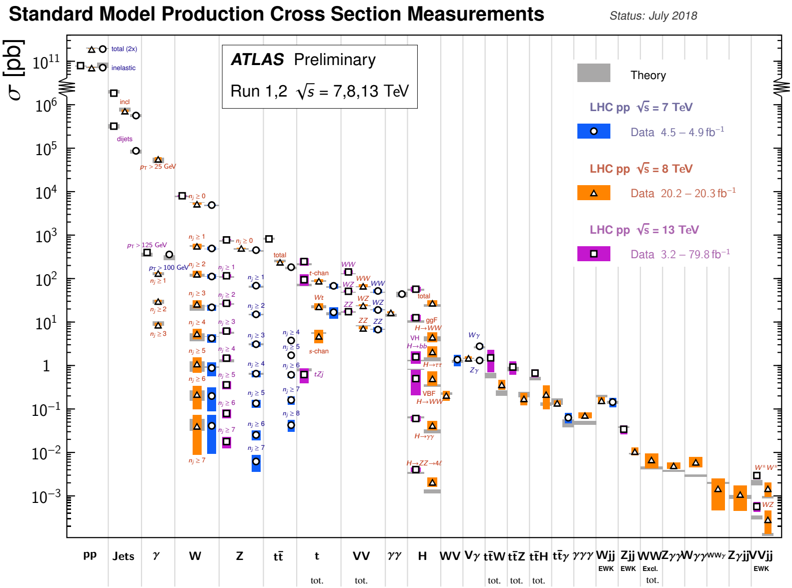
Monte Carlo event samples are used to:

- Determine background contributions
- Correct the measurements for detector effects (efficiency, resolution, acceptance)
- Estimate systematic uncertainties on the final results
- Correct the theory calculations for non-perturbative effects

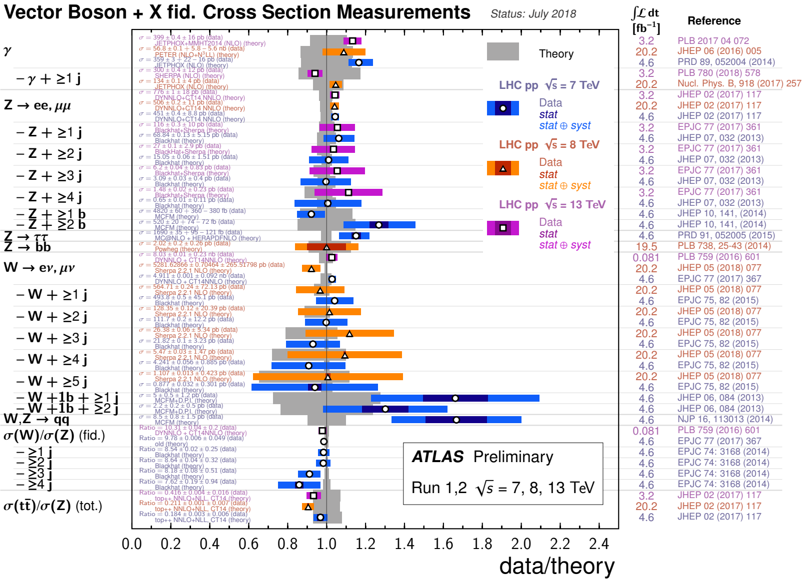
Results compared to the SM predictions, great progress/improvements in the generators/calculations over the last years:

- Multi-partons LO ME+PS (Alpgen, Sherpa 1.X, MadGraph 5)
- Multi-partons NLO and LO ME+PS (Sherpa 2.X, MadGraph 5 aMC@NLO, Powheg)
- Fixed-order NLO calculations (BlackHat+Sherpa)
- Fixed-order NNLO calculations (N_{jetti})

Recent measurements from ATLAS



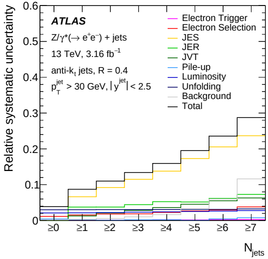
Recent measurements from ATLAS



V + jets analysis overview

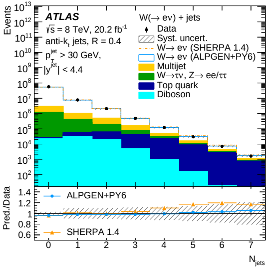
Z + jets production:

- Experimental clean signature
- Purity from $> 99\%$ (≥ 0 jets) to $\sim 80\%$ (≥ 7 jets)
- Main backgrounds:
    - Top and dibosons are the dominant backgrounds
    - Multijet background typically $< 1\%$
- Main uncertainty is the jet energy scale



W + jets production:

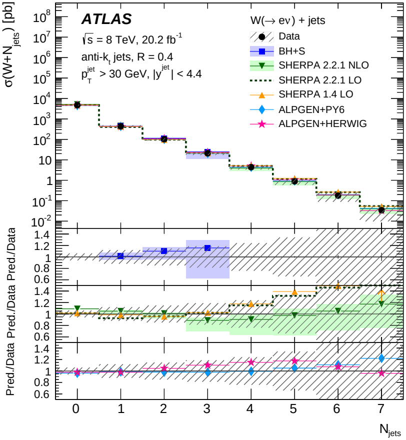
- Signature affected by larger backgrounds
- Main backgrounds:
    - Z/γ^*+jets and multijet are the dominant backgrounds for ≤ 2 jets
    - $t\bar{t}$ background dominates at high jet multiplicities
- Main uncertainties is the jet energy scale and jet energy resolution



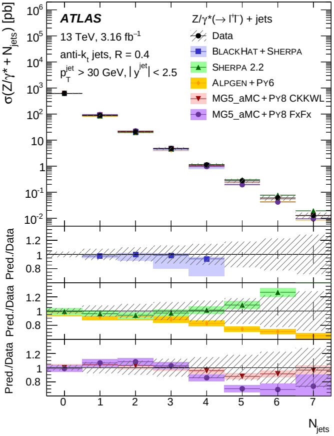
V + jet production: exclusive jet multiplicity

- For V production, each time we add one jet, we add one order more in α_s
- Discrepancies at high jet multiplicities where the generators just rely on the PS

[JHEP 05 (2018) 077]



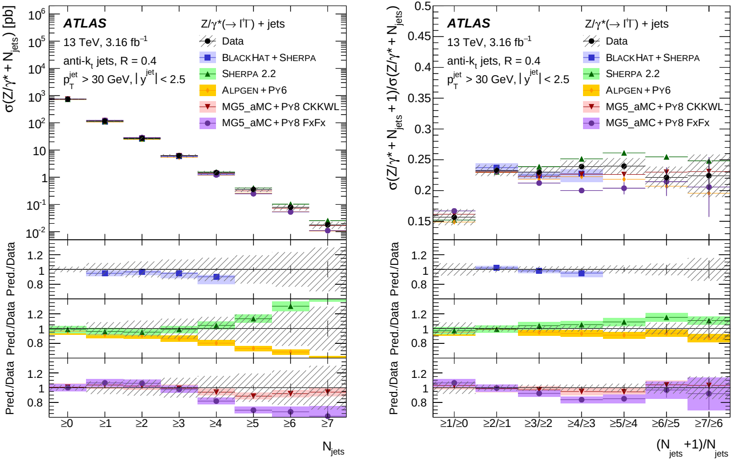
[EPJC 77 (2017) 361]



V + jet production: inclusive jet multiplicity and ratio

- Higher precision due to the cancellation of part of the systematic in the ratio
- First parton emission more suppressed than the subsequent parton emissions

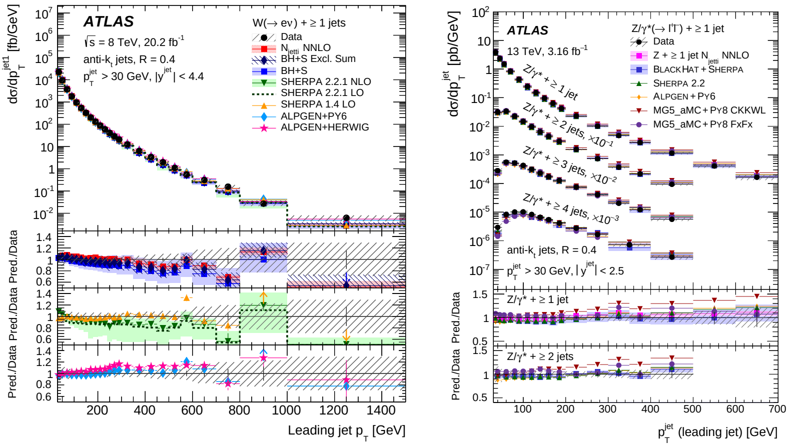
[EPJC 77 (2017) 361]



V + jet production: leading jet p_T

- The mass of the W/Z boson provides itself a well-defined scale
- When p_T^{jet} exceeds the scale given by the W/Z boson mass, NLO/LO K-factors can be large due to the presence of QCD corrections of $O(\alpha_s \ln^2(p_T^{\text{jet}}/m_{W/Z}))$

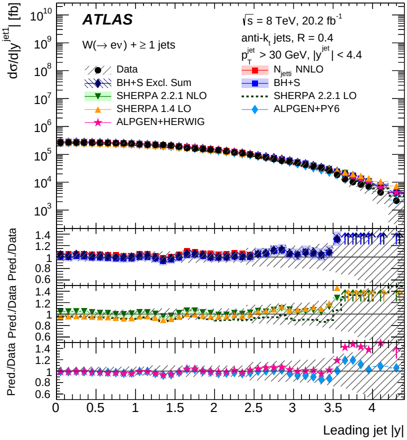
[JHEP 05 (2018) 077] [EPJC 77 (2017) 361]



V + jet production: leading jet rapidity

- Leading jet rapidity in good agreement with predictions

[JHEP 05 (2018) 077]



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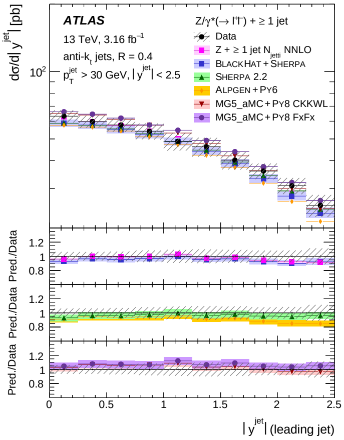
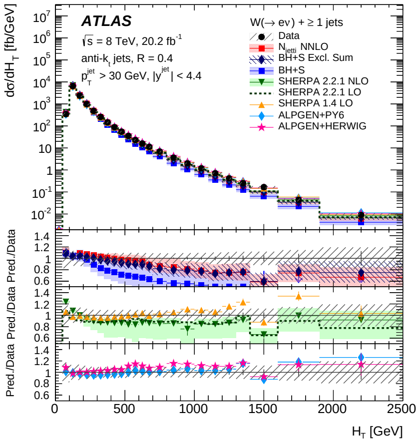


V + jet production: H_T

- Inclusive quantity used to set the scale, discriminant in BSM searches
- BlackHat+SHERPA $V + \geq 1$ jet (NLO estimate for the respective parton multiplicity, including the real emission of one additional parton) → For $H_T \sim 350$ GeV, NLO deviate where the average jet multiplicity exceeds two

[JHEP 05 (2018) 077]



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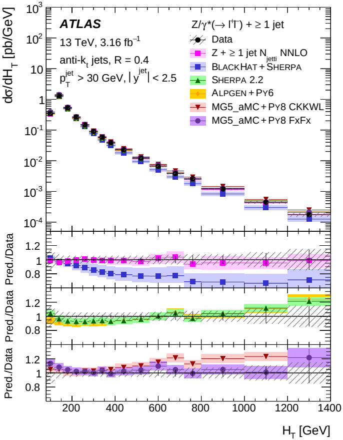
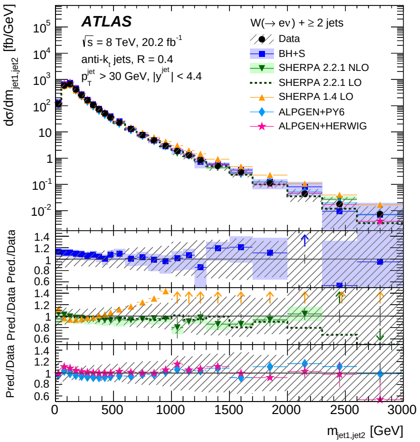


V + jet production: angular distributions

- Important variables for searches
- Angular relations between the two leading jets and the dijet mass often used to separate heavy SM particles or beyond-SM physics from the V+jets process

[JHEP 05 (2018) 077]



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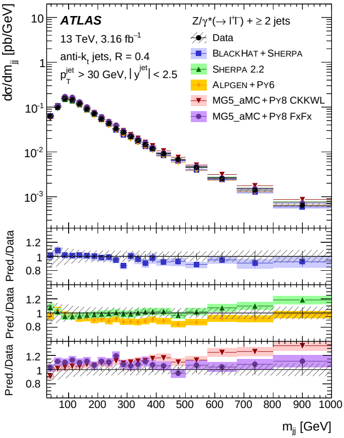
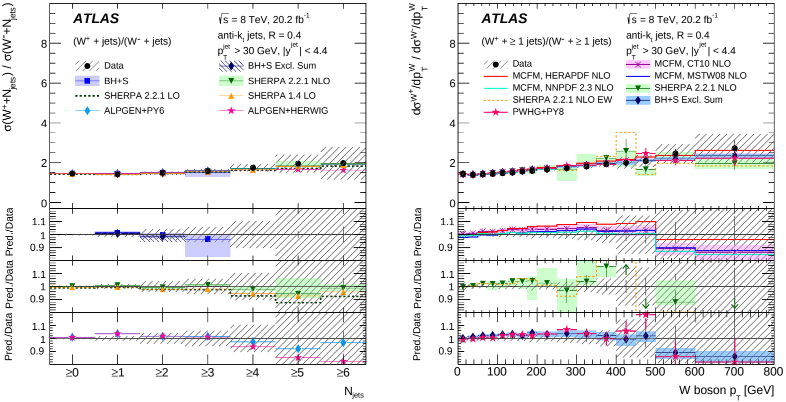


V + jet production: W^+/W^- cross section ratios

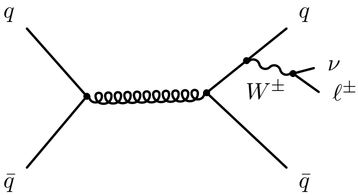
- Many experimental and theoretical uncertainties cancel out, making it a more precise test of the theoretical predictions
- Valuable input for the up quark, down quark, and gluon PDFs of the proton

[JHEP 05 (2018) 077]

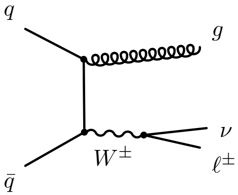


Collinear W emission off high p_T jets [PLB 765 (2017) 132]

- Test of models, including novel NNLO predictions, in an extreme phase space
- First direct measurement of the process of W emission from light partons, explores corners of the phase space accessible with the LHC
- Back-to-back dijet topology, where a soft collinear W is emitted from one of the legs (requiring a high-p_T jet)
- Process logarithmically enhanced as the p_T of the leading jet increases over the W mass
- Background for searches and top-tagging



Collinear W emission from a light quark



W + jets production where the W boson is balanced by a hadronic recoil

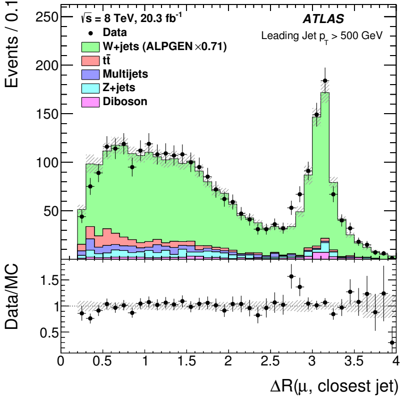
Collinear W emission off high p_T jets

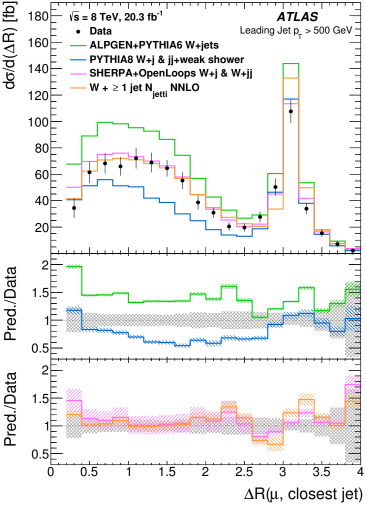
[PLB 765 (2017) 132]

- ALPGEN+PYTHIA6 overestimates the total cross-section
- PYTHIA8 (modified to include the W emission) disagrees in the collinear region ($\Delta R < 2.4$)
- SHERPA+OpenLoops NLO QCD+EW calculation agrees well within the uncertainties
- $W+\geq 1$ jet N_{jetti} NNLO calculation agrees well within the uncertainties

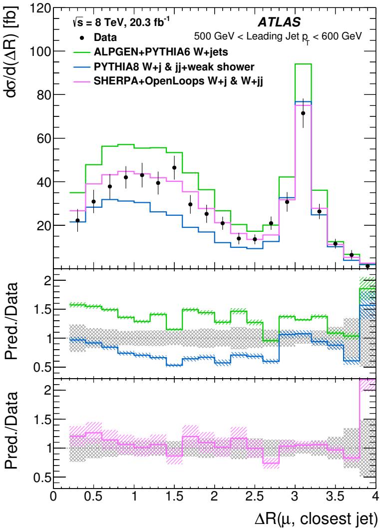
Collinear region: $0.2 < \Delta R < 2.4$

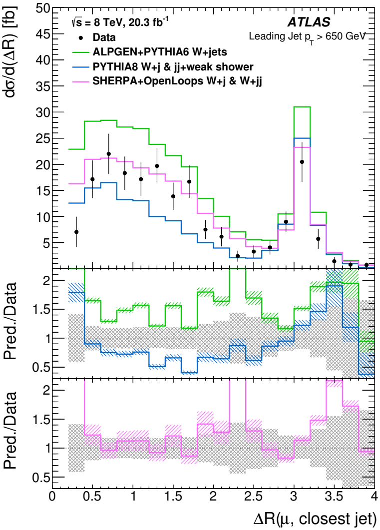
Back-to-back region: $\Delta R > 2.4$





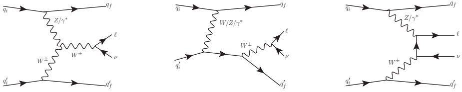
Collinear *W* emission off high p_T jets [PLB 765 (2017) 132]





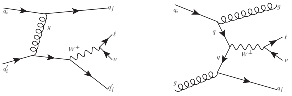
EW *Wjj* production @ 7, 8 TeV

LO diagrams for electroweak *Wjj* production:

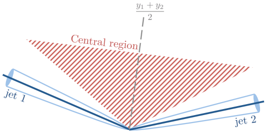


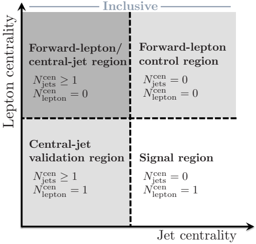
Vector boson fusion | *W* bremsstrahlung | Non-resonant

LO diagrams for strong *Wjj* production:



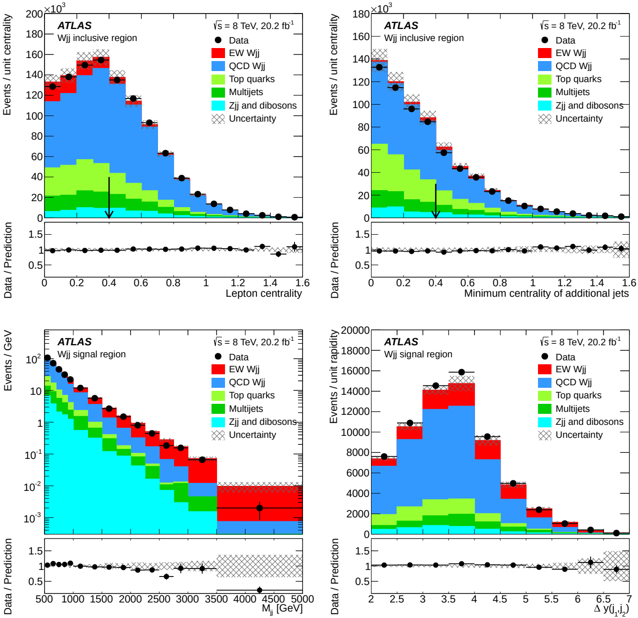
Region name	Requirements
Preselection	Lepton $p_T > 25$ GeV Lepton $\|\eta\| < 2.5$ $E_T^{miss} > 20$ GeV $m_T > 40$ GeV $p_T^{j_1} > 80$ GeV $p_T^{j_2} > 60$ GeV Jet $\|y\| < 4.4$ $M_{jj} > 500$ GeV $\Delta y(j_1, j_2) > 2$ $\Delta R(j, \ell) > 0.3$
Fiducial and differential measurements	
Signal region	$N^{cen}_{lepton} = 1, N^{cen}_{jets} = 0$
Forward-lepton control region	$N^{cen}_{lepton} = 0, N^{cen}_{jets} = 0$
Central-jet validation region	$N^{cen}_{lepton} = 1, N^{cen}_{jets} \geq 1$
Differential measurements only	
Inclusive regions	$M_{jj} > 0.5$ TeV, 1 TeV, 1.5 TeV, or 2 TeV
Forward-lepton/central-jet region	$N^{cen}_{lepton} = 0, N^{cen}_{jets} \geq 1$
High-mass signal region	$M_{jj} > 1$ TeV, $N^{cen}_{lepton} = 1, N^{cen}_{jets} = 0$
Anomalous coupling measurements only	
High-q^2 region	$M_{jj} > 1$ TeV, $N^{cen}_{lepton} = 1, N^{cen}_{jets} = 0, p_T^{j_1} > 600$ GeV





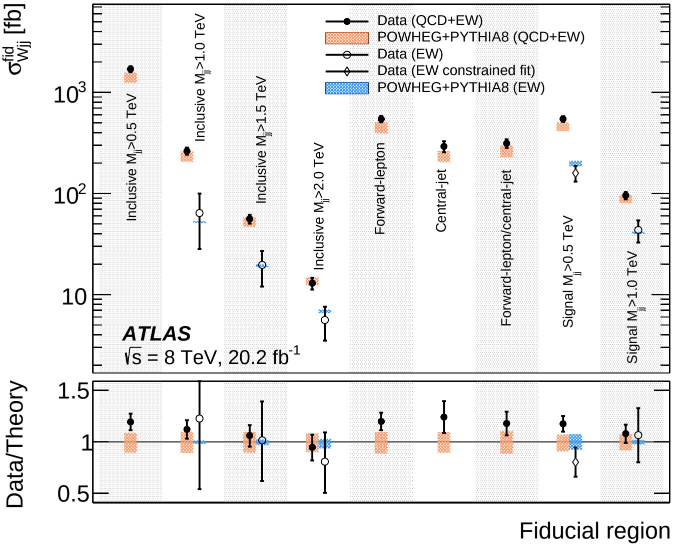
EW *Wjj* production @ 7, 8 TeV

[EPJC 77 (2017) 474]



EW *Wjj* production @ 7, 8 TeV

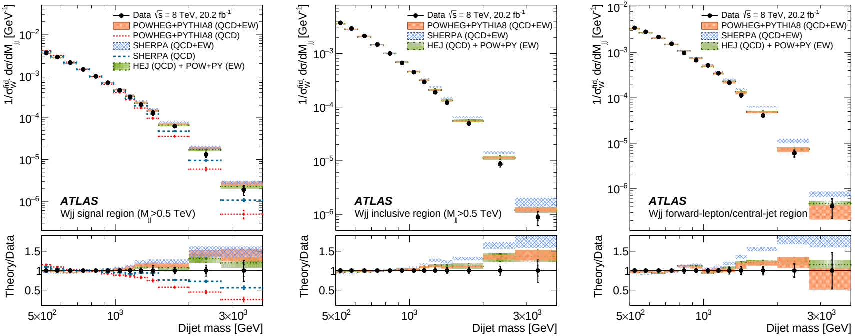
[EPJC 77 (2017) 474]



EW *Wjj* production @ 7, 8 TeV

[EPJC 77 (2017) 474]

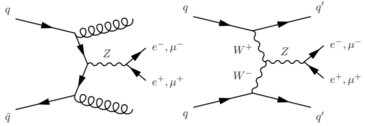
- Differential measurements performed in distributions that provide discrimination between QCD and EW *Wjj* production
  - Using the dijet system to distinguish the t-channel VBF topology from the background (M_{jj} and $\Delta y(j_1, j_2)$)
  - Using the rapidity of other objects relative to the dijet rapidity gap, exploiting the colourless gauge boson exchange (lepton centrality, jet centrality and the number of jets in the rapidity gap)
- The best discrimination between QCD and EW *Wjj* is provided by the dijet mass distribution



EW Zjj production @ 13 TeV

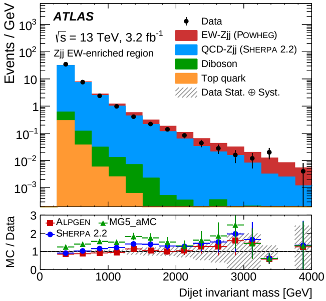
[PLB 775 (2017) 206]

- EW Zjj is a much rarer process than QCD Zjj



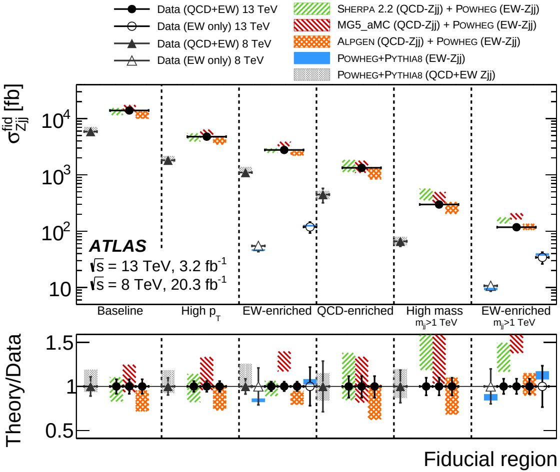
QCD Zjj EW Zjj

- Discrimination between QCD and EW production:
  - Two high-p_T jets with large Δy and m_{jj}
  - No colour connection → No hadronic activity in Δy
- Different fiducial regions defined



	Fiducial region					
Object	Baseline	High-mass	High-p_T	EW-enriched	EW-enriched, $m_{jj} > 1$ TeV	QCD-enriched
Leptons	$\lvert\eta\rvert < 2.47$, $p_T > 25$ GeV, $\Delta R_{j,\ell} > 0.4$					
Dilepton pair	$81 < m_{\ell\ell} < 101$ GeV					
	—			$p_T^{\ell\ell} > 20$ GeV		
Jets	$\lvert y\rvert < 4.4$					
	$p_T^{j_1} > 55$ GeV		$p_T^{j_1} > 85$ GeV	$p_T^{j_1} > 55$ GeV		
	$p_T^{j_2} > 45$ GeV		$p_T^{j_2} > 75$ GeV	$p_T^{j_2} > 45$ GeV		
Dijet system	—	$m_{jj} > 1$ TeV	—	$m_{jj} > 250$ GeV	$m_{jj} > 1$ TeV	$m_{jj} > 250$ GeV
Interval jets	—			$N_{\text{jet } (p_T>25 \text{ GeV})}^{\text{interval}} = 0$		$N_{\text{jet } (p_T>25 \text{ GeV})}^{\text{interval}} \geq 1$
Zjj system	—			$p_T^{\text{balance}} < 0.15$		$p_T^{\text{balance},3} < 0.15$

The EW-*Zjj* cross-sections at 13 TeV are in agreement with the predictions from POWHEG+PYTHIA for both $m_{jj} > 250$ GeV and $m_{jj} > 1$ TeV



EW *Zjj* production @ 13 TeV

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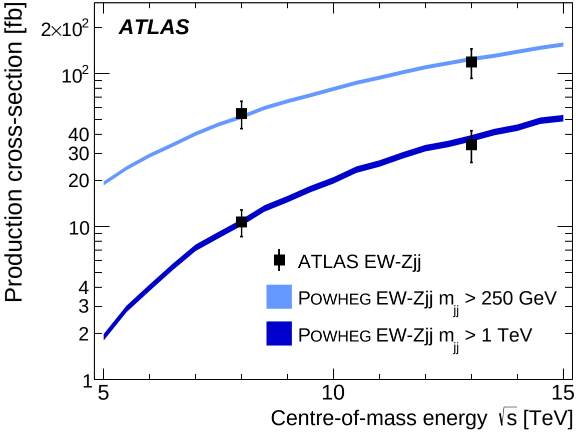


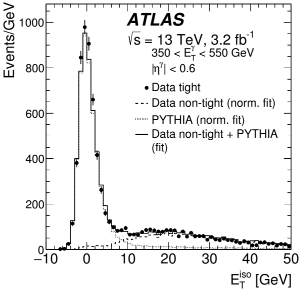
$\gamma +$ jet production @ 13 TeV

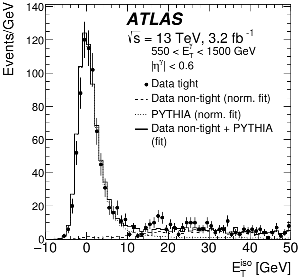
[PLB 780 (2018) 578]

- Test of the pQCD, MC tuning, etc.
- Background subtracted bin-by-bin using a data-driven technique based on a two-dimensional sideband method (“Isolated”, “Non-isolated”, “Tight”, “Non-tight”)
- Fiducial phase-space region:

Requirements on photons
$E_T^\gamma > 125$ GeV, $\lvert\eta^\gamma\rvert < 2.37$ (excluding $1.37 < \lvert\eta^\gamma\rvert < 1.56$)
$E_T^{\rm iso} < 4.2 \cdot 10^{-3} \cdot E_T^\gamma + 10$ GeV
Requirements on jets
anti-k_t algorithm with $R = 0.4$
the leading jet within $\lvert y^{\rm jet}\rvert < 2.37$ and $\Delta R^{\gamma-{\rm jet}} > 0.8$ is selected
$p_T^{\rm jet\text{-}lead} > 100$ GeV
UE subtraction using $k_\perp$ algorithm with $R = 0.5$ (cf. Section ??)
Additional requirements for $d\sigma/dm^{\gamma-{\rm jet}}$ and $d\sigma/d\lvert\cos\theta^*\rvert$
$\lvert\eta^\gamma + y^{\rm jet\text{-}lead}\rvert < 2.37$, $\lvert\cos\theta^*\rvert < 0.83$ and $m^{\gamma-{\rm jet}} > 450$ GeV

- Distributions unfolded to the particle level using a bin-by-bin technique which corrects for resolution effects and the efficiency of the photon and jet reconstruction
- Cross sections measured as a function of: E_T^γ, $p_T^{\rm jet\text{-}lead}$, $\Delta\phi^{\gamma-{\rm jet}}$, $m^{\gamma-{\rm jet}}$ and $\lvert\cos\theta^*\rvert$
- Results compared to:
  - NLO QCD predictions from JETPHOX and SHERPA
  - Tree-level predictions of PYTHIA and SHERPA

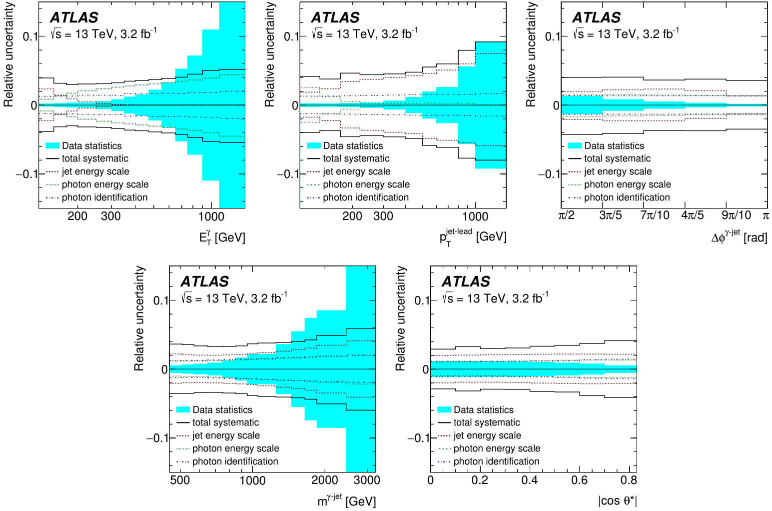




γ + jet production @ 13 TeV

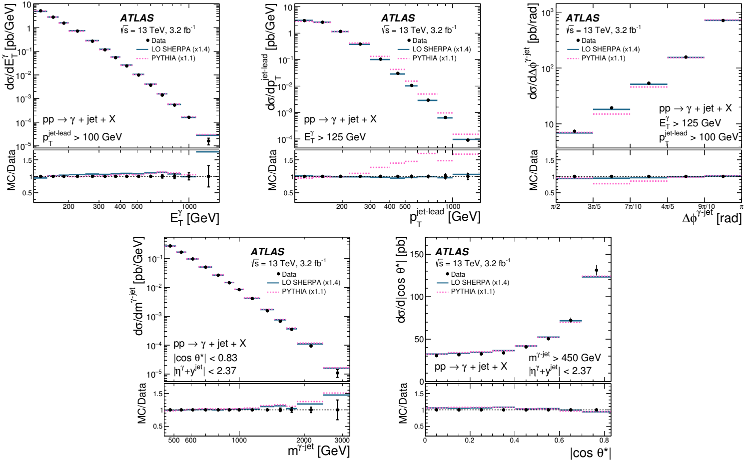
[PLB 780 (2018) 578]

- Dominant systematic uncertainties: jet energy scale, photon energy scale and photon identification

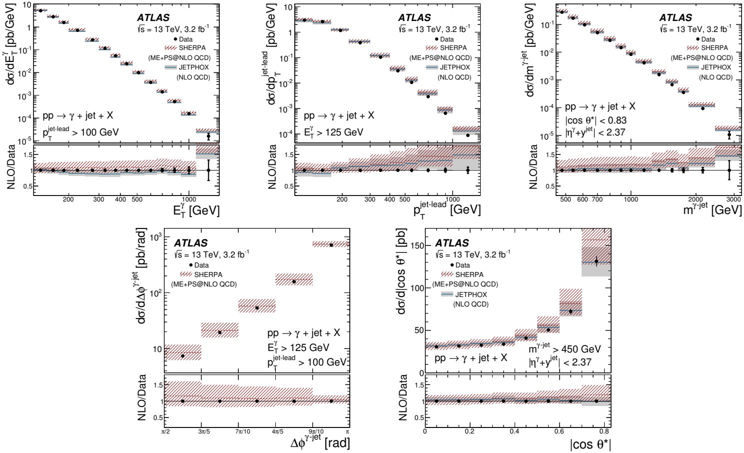


$\gamma +$ jet production @ 13 TeV

- The predictions of the tree-level plus parton-shower MC models by PYTHIA and LO SHERPA give a satisfactory description of the shape of the data distributions, except for $p_T^{\text{jet-lead}}$ in the case of PYTHIA
- Predictions normalised to the integrated measured cross sections



- The fixed-order NLO QCD calculations of JETPHOX, corrected for hadronisation and UE, and the multi-leg NLO QCD plus PS calculations of SHERPA in agreement within uncertainties
- NLO SHERPA is able to reproduce the data down to $\Delta\phi^{\gamma-\text{jet}} = \pi/2$ due to the inclusion of the matrix elements for $2 \rightarrow n$ processes with $n = 4$ and 5
- Experimental uncertainties much smaller than the uncertainties in the predictions $\rightarrow$ calculations with higher precision will allow stringent tests of the theory

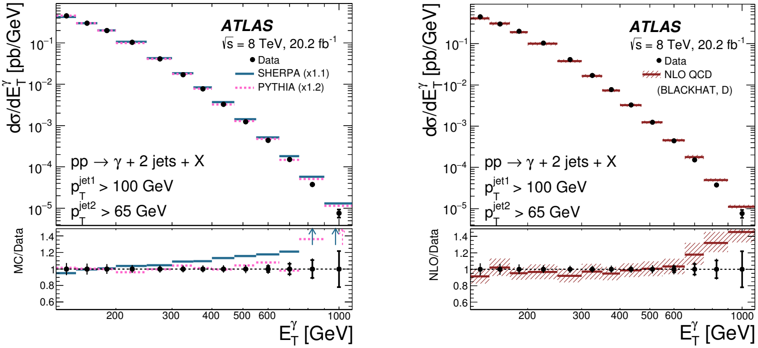


$\gamma + 2$ jet production @ 8 TeV

[Nucl. Phys. B 918 (2017) 257]

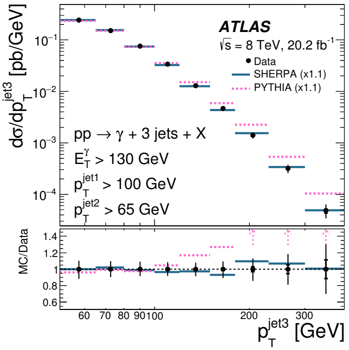
Photon plus two-jet production is investigated by measuring cross sections as functions of E_T^γ, p_T^{jet2} and angular correlations:

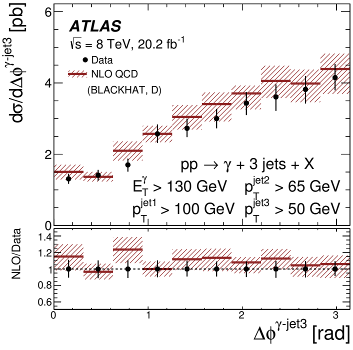
- PYTHIA gives a good description of the measured cross-section up to $E_T^\gamma \sim 750$ GeV
- SHERPA describes well the measurements as a function of p_T^{jet2}, $\Delta\phi^{\gamma-\text{jet2}}$ and $\Delta\phi^{\text{jet1}-\text{jet2}}$
- BLACKHAT gives a good description of the data within the experimental and theoretical uncertainties for $E_T^\gamma < 750$ GeV



Photon plus three-jet production is investigated by measuring cross sections as functions of E_T^γ, p_T^{jet3} and angular correlations:

- PYTHIA gives a good description of the measured cross-section as a function of E_T^γ
- SHERPA describes well the measured cross-section as a function of p_T^{jet3}
- BLACKHAT gives an adequate description of the data within the uncertainties, being systematically above the data





$\gamma +$ HF jet production @ 8 TeV

[PLB 776 (2018) 295]

- At the LHC, prompt photons arise mainly through the Compton process $qg \to q\gamma$
- HF quarks arise in the proton through either extrinsic (perturbative) or intrinsic (non-perturbative) mechanisms
- Currently global PDF fits show that HF quarks in the proton are almost entirely extrinsic
- However the hypothesis of the non-zero intrinsic (or valence-like) heavy quark component of the proton distribution functions has not been ruled out yet
- Measurements performed as a function of E_{T}^{γ} in the central ($|\eta^{\gamma}| < 1.37$) and forward ($1.56 < |\eta^{\gamma}| < 2.37$) regions
- Most sensitive region (large Bjorken-x): large $|\eta^{\gamma}|$ and high E_{T}^{γ}
- Results compared to LO calculations:
  - SHERPA: up to 3 partons, five-flavour CT10 PDF set, massive 5F scheme
  - PYTHIA: up to 2 partons, five-flavour LO CTEQ6L1 PDF set, standard 5F scheme
- $\gamma + b$ results compared to NLO calculations from MG5_aMC+PY8 using different PDF sets:
  - NNPDF3.0nlo 5F: u-, d-, s-, c- and b-quarks are treated as massless and used in the calculations
  - NNPDF3.0nlo 4F: u-, d-, s- and c-quarks are treated as massless and used in the calculations (b-quarks are treated as massive and generated in the ME through gluon splitting)
- $\gamma + c$ results compared to NLO calculations from MG5_aMC+PY8 using different PDF sets:
  - NNPDF3.1nlo PC: set with only perturbative charm
  - NNPDF3.1nlo FC: set with a charm contribution fitted to data in the global PDF fit (0.26% intrinsic)
  - CT14nnlo sets using the BHPS model (BHPS1: 0.6% intrinsic charm, BHPS2: 2.1% intrinsic charm)

$\gamma +$ HF jet production @ 8 TeV

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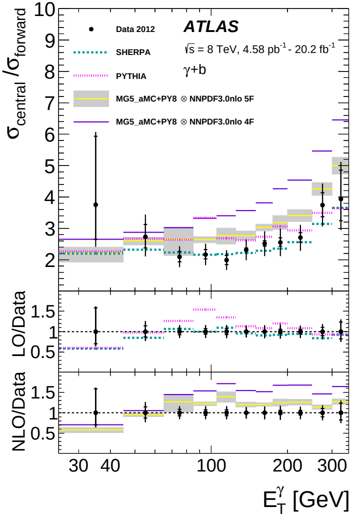
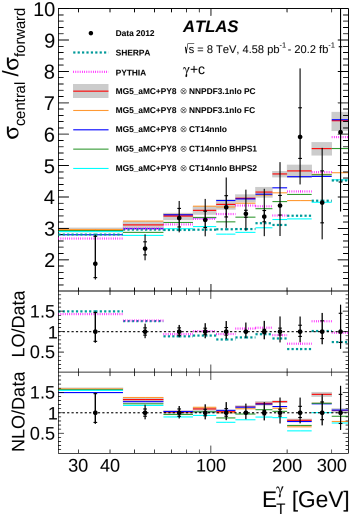
- For $\gamma + b$, the best description is provided by SHERPA
- For $\gamma + c$, all the predictions are in agreement with the data





Conclusions

- Vector boson production in association with jets:
  - Test of perturbative QCD and higher order effects over many orders of magnitude in cross section
  - Important background for searches for new physics
  - Sensitive to PDFs
- V+jets measurements needed to re-assess the accuracy of the theoretical tools (MCs and PDFs) in this new energy regime
- Recent measurements presented:
  - W + jets at 8 TeV [JHEP 05 (2018) 077]
  - Z + jets at 13 TeV [EPJC 77 (2017) 361]
  - Collinear W emission off high p_{T} jets at 8 TeV [Phys. Lett. B 765 (2017) 132]
  - EW Wjj at 7/8 TeV [EPJC 77 (2017) 474]
  - EW Zjj at 13 TeV [Phys. Lett. B 775 (2017) 206]
  - γ + jet at 13 TeV [Phys. Lett. B 780 (2018) 578]
  - γ + jets at 8 TeV [Nucl. Phys. B 918 (2017) 257]
  - γ + heavy flavour jet at 8 TeV [Phys. Lett. B 776 (2018) 295]
- Results:

  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults