New Results on W Boson Production and Multi-lepton Cross Sections with the ATLAS Detector

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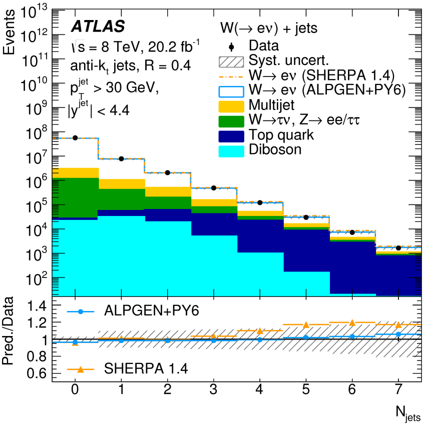
Inclusive W+jets production at 8 TeV

JHEP 05 (2018) 077

- $W \to e\nu$ channel
- Veto events with additional electrons
- Veto events with one of more b-jets - new cut suppresses top
- $E_T^{miss} > 25$ GeV
- $m_T > 40$ GeV



Transverse Mass

$$\mathbf{m_T = \sqrt{2p_T^{\ell}p_T^{\nu}(1-\cos(\phi^{\ell}-\phi^{\nu}))}}$$

- Complimentary to other W measurements -
  - Inclusive production: EPJC 77 (2017) 367,PLB 759 (2016) 601
  - Electroweak production: EPJC 77 (2017) 474
  - Collinear emission: PLB 765 (2017) 132

Inclusive W+jets production at 8 TeV

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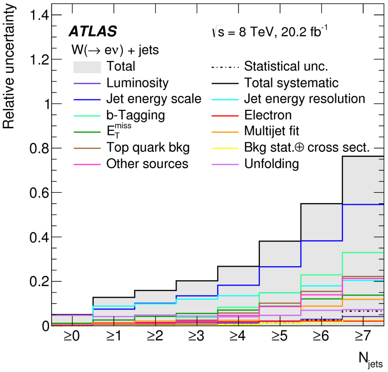
- Focus on probing events with additional jets;
    - Probe perturbative QCD effects
    - Improve modelling for key background to many ATLAS analyses
    - Large jet energies and rapidities probe EWK effects
    - Sensitive to valence quark and gluon PDFs at high x

Signal and background contributions

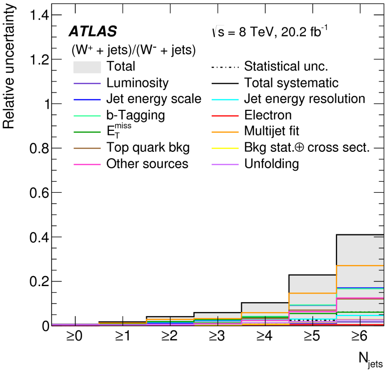
N_{jets}	0	1	2	3	4	5	6	7
$W \to e\nu$	94 %	86 %	75 %	67 %	57 %	47 %	40 %	35 %
Multijet	3 %	8 %	15 %	16 %	16 %	16 %	14 %	14 %
$t\bar{t}$	<1 %	<1 %	1 %	6 %	16 %	27 %	36 %	43 %
Single t	<1 %	<1 %	1 %	1 %	2 %	2 %	2 %	1 %
$W \to \tau\nu$	2 %	2 %	2 %	2 %	2 %	1 %	1 %	1 %
Diboson	<1 %	<1 %	1 %	1 %	1 %	1 %	<1 %	<1 %
$Z \to ee$	<1 %	3 %	5 %	6 %	6 %	6 %	5 %	5 %
$Z \to \tau\tau$	<1 %	<1 %	<1 %	<1 %	<1 %	<1 %	<1 %	<1 %
Total predicted	54 310 000 ±22 000	7 611 700 ±4000	2 038 000 ±1700	478 640 ±720	120 190 ±320	30 450 ±150	7430 ±63	1735 ±20
Data observed	56 342 232	7 735 501	2 070 776	486 158	120 943	29 901	7204	1641

Inclusive W+jets production at 8 TeV

Total W



W^+/W^-



- Jet energy systematic uncertainties increasingly dominate at higher jet multiplicities
- Zero jets region has largest contribution from uncertainty in the detector correction procedure
- Total syst. uncertainty from 5% inclusive - 76% for $\geq$7 jets
- Lots of sources cancel in W^+/W^- ratio
- Multijet background fit estimate becomes dominant, increasing with increasing jets

Inclusive W+jets production at 8 TeV

Program	Order in α_S	$N_{\text{partons}}^{\text{max}}$ at highest order	PDF set	NPC	PS	Comments
N_{jetti}	NNLO	1	CT14	✓		Not shown for N_{jets}, $\Delta R_{\text{jet1,jet2}}$ and $m_{\text{jet1,jet2}}$
BLACKHAT+SHERPA	NLO	1, 2 or 3	CT10	✓		
MCFM 6.8	NLO	1	CT10 + 3 more	✓		Figure 7 only
POWHEG+PYTHIA 8	NLO	1	CT14		✓	Figure 7 only
SHERPA 2.2.1	NLO	2	CT10		✓	Including NLO EW corrections in Figure 7
SHERPA 2.2.1	LO	2 (3)	NNPDF 3.0		✓	
ALPGEN+PYTHIA 6	LO	5	CTEQ6L1 (LO)		✓	
ALPGEN+HERWIG	LO	5	CTEQ6L1 (LO)		✓	
SHERPA 1.4.1	LO	4	CT10		✓	

Inclusive W+jets production at 8 TeV

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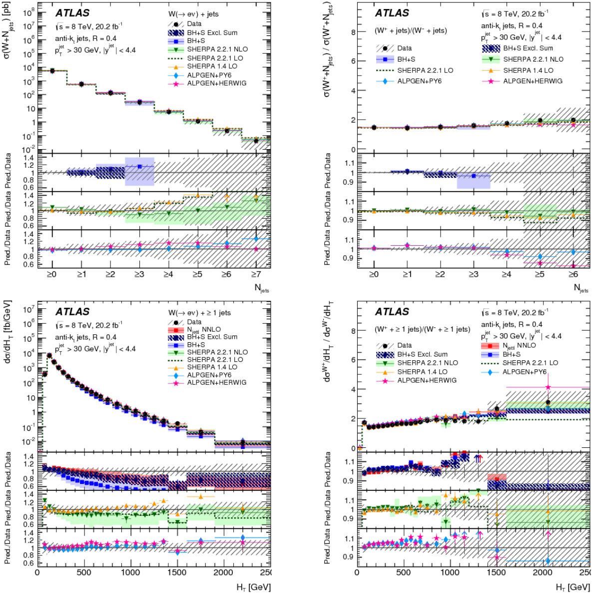

- Improved agreement in ratio suggests cancellation of jet mis-modelling
- $H_T = \Sigma p_T^l + p_T^\nu + p_T^{jets}$ is an important test of QCD
- Generally LO Alpgen with more jets in ME does better than higher fixed order generators
- BlackHat and N_{jetti} give much better agreement in H_T ratio

Inclusive W+jets production at 8 TeV

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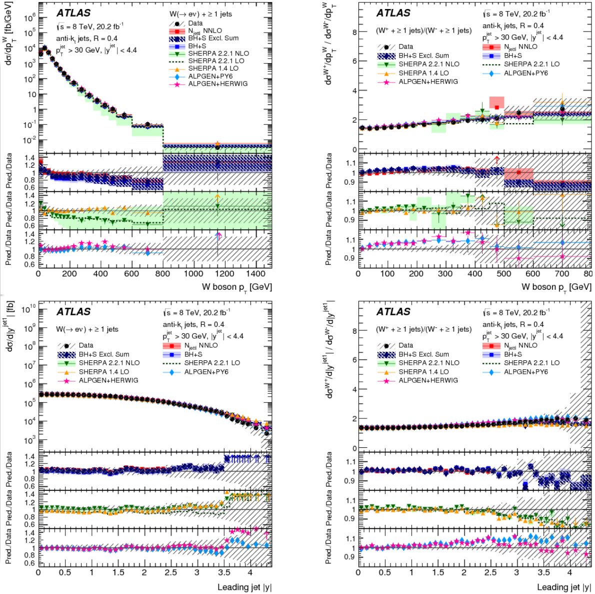
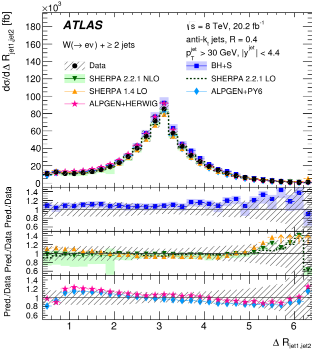
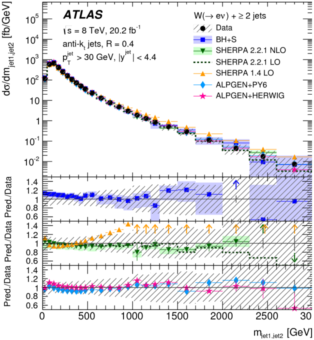
- W boson p_T sensitive to parton distributions in proton
- Jets in forward region can be sensitive to UE tuning
- At reconstructed leading jet $|y|$ of ∼3.6 the data drops below predictions - covered by uncertainty and cancels in ratio
- Effected by choice of parton showering and less so the PDF set



Inclusive W+jets production at 8 TeV

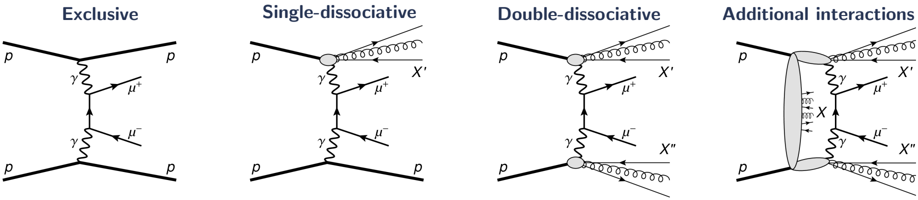




- Dijet angular separation and invariant mass test hard parton radiation at large angles and ME/PS matching
- Jets in forward region can be sensitive to UE tuning
- No single prediction models data well everywhere
- NNLO and NLO do describe data, but sometimes LO with many partons in ME are better
- Overall, worst disagreement for H_T, y_{jet}, and m_{jj} - need better modelling for high energy and large rapidity jets

Exclusive di-muon production at 13 TeV

PLB 777 (2018) 303



- In exclusive muon production protons remain intact, rather than dissociating
- Opportunity to study high energy electroweak effects
- Di-lepton channel is clean and has high cross-section - look for opposite charge muon pairs
- Distinguish signal with;
  - Muon pair from 2 track vertex with 1mm isolation
  - $m_{\mu^+\mu^-} < 70$ GeV
  - $p_T^{\mu^+\mu^-}$ <1.5 GeV

Exclusive di-muon production at 13 TeV

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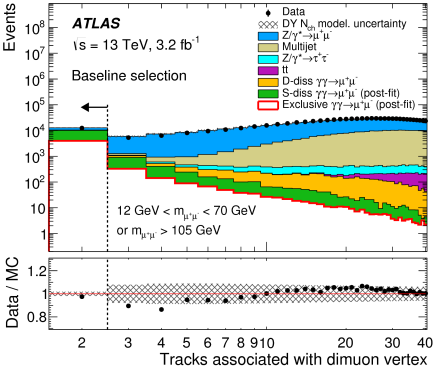
	Data	Signal	Total background	S-diss	D-diss	$Z/\gamma^* \to \mu^+\mu^-$	$Z/\gamma^* \to \tau^+\tau^-$	Multijet	$t\bar{t}$
Baseline selection	2 933 384	5740	2 897 000	8640	8000	2 268 000	10 900	590 000	12 200
1 mm vertex isolation	14 759	4560	11 100	6840	300	3900	30	50	0
$m_{\mu^+\mu^-} < 70$ GeV	12 395	4420	8800	6420	300	2000	30	50	0
$p_T^{\mu^+\mu^-} < 1.5$ GeV	7952	4370	4300	3550	60	670	7	10	0



Dominant background processes

- D-diss: Pythia8, absorptive effects included
- S-diss: Lpair4.0 - data-driven constraint for absorptive effects with signal
- Z→ $\mu\mu$ and Z→ $\tau\tau$ -PowhegBox+Pythia8
- Multijet - data-driven estimate, normalised against data in $m_{\mu\mu}$
- $t\bar{t}$ - PowhegBox+Pythia6

Exclusive di-muon production at 13 TeV

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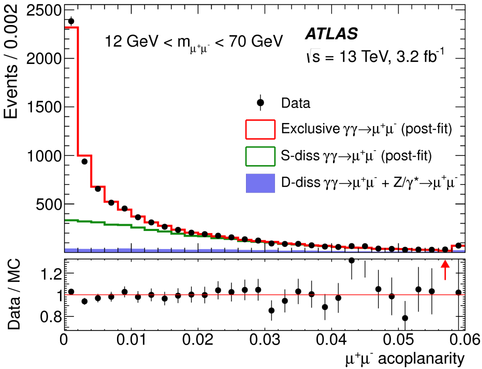
Acoplanarity: $\left(1 - \frac{|\Delta\phi_{\mu^+\mu^-}|}{\pi}\right)$

- Binned maximum likelihood fit
- Good separation from background
- Unaffected by muon momentum and scale uncertainties
- Fit determines expected number of signal and S-diss events



- Total fiducial cross-section then measured by dividing by luminosity and a correction factor for efficiency and reconstruction effects
- $\sigma^{\text{excl.fid.}}_{\gamma\gamma\to\mu^+\mu^-}$ **= 3.12 ± 0.07 (stat) ± 0.14 (syst) pb**
- Also measure differential cross-section for four di-muon mass bins
- Unfold detector effects using a bin-by-bin correction

Exclusive di-muon production at 13 TeV

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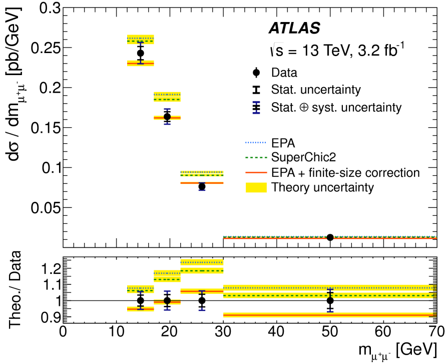

- *Equivalent Photon Association* assumes EM fields produced by colliding protons are quasi-real photons with small virtuality
- Finite size correction accounts for size of protons (r_p=0.064) and scales two-photon luminosity for smaller impact parameters
- Only photons produced outside the proton can participate
- SuperChic applies absorptive corrections at amplitude level differentially with momenta of the scattered protons - results in less suppression of $\sigma_{\gamma\gamma\to\mu\mu}$ towards lower muon pair masses

Exclusive di-muon production at 13 TeV

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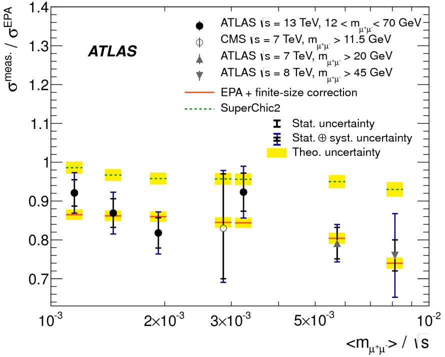

- Survival factor gives the ratio of measured cross-section to bare EPA prediction
- Can consider as a function of average di-muon mass: $\frac{<m_{\mu^+\mu^-}>}{\sqrt{s}}$
- Equivalent to the average proton energy fraction $< x >$
- Other measurements made by previous exclusive muon production and exclusive $\gamma\gamma \to W^+W^-$ measurement
- Uncertainty dominated by shape modelling - could reduce in future by tagging outgoing protons with forward detectors

Summary

- Inclusive W+jets at 8 TeV
  - Compare many generators using differential W and W^+/W^- ratio cross-sections
  - Variables test range of theoretical and modelling aspects
  - Require better modelling for high energy and large angle jets

- Exclusive muon production at 13 TeV
  - Measure fiducial cross-section for exclusive di-photon to di-muon production
  - Also measure differentially as a function of the di-muon mass
  - Compared to theoretical predictions with corrections for absorptive effects
  - The finite-size parametrisation has good agreement with the data

Thank you for listening

Backup

BACKUP

Inclusive W+jets production at 8 TeV

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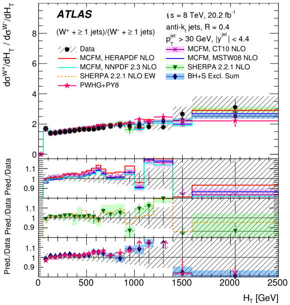

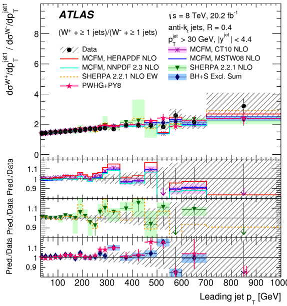

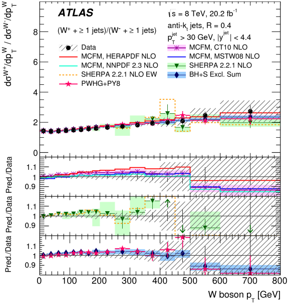

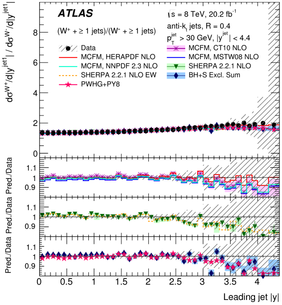

Exclusive di-muon production at 13 TeV

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$m_{\mu^+\mu^-}$ [GeV]	$N^i_{\text{excl.}}$	C_i	$d\sigma/dm_{\mu^+\mu^-}$ [pb/GeV]	$\delta^{\text{stat.}}$ [%]	$\delta^{\text{syst.}}$ [%]
12–17	1290± 60	0.333±0.007	0.243 ± 0.013	3.4	4.3
17–22	1040± 50	0.398±0.008	0.164 ± 0.010	3.7	4.5
22–30	830± 40	0.428±0.009	0.076 ± 0.005	3.9	4.6
30–70	690± 40	0.416±0.008	0.013 ± 0.001	4.9	4.9
12–70	3850±160	0.387±0.008	0.054 ± 0.003	2.1	4.5

Dominated by shape uncertainties from likelihood fit

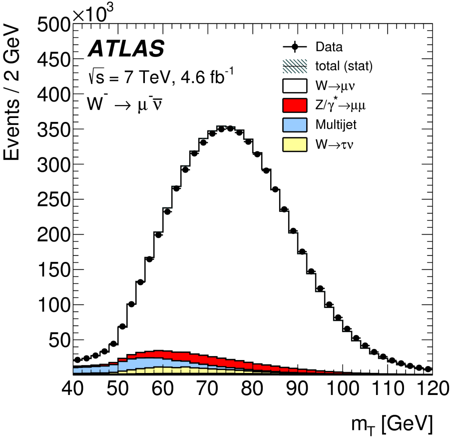
$m_{\mu^+\mu^-}$ [GeV]	Uncorrelated		Correlated							
	$\delta^{\text{trig.}}_{\text{stat.}}$ [%]	$\delta^{\text{reco.}}_{\text{stat.}}$ [%]	$\delta^{\text{trig.}}_{\text{syst.}}$ [%]	$\delta^{\text{reco.}}_{\text{syst.}}$ [%]	$\delta^{\text{sc./res.}}$ [%]	δ^{veto} [%]	δ^{PU} [%]	$\delta^{\text{bkg.}}$ [%]	δ^{shapes} [%]	$\delta^{\text{lumi.}}$ [%]
12–17	0.3	0.1	0.9	0.9	-0.4	-1.2	-0.5	0.8	3.0	2.1
17–22	0.3	0.1	0.9	1.0	-0.4	-1.2	-0.5	0.8	3.3	2.1
22–30	0.2	0.1	0.9	1.0	-0.2	-1.2	-0.5	0.6	3.5	2.1
30–70	0.3	0.1	1.0	1.1	-0.3	-1.2	-0.5	0.4	4.0	2.1
12–70	0.3	0.1	0.9	1.0	-0.3	-1.2	-0.5	0.8	3.3	2.1

Inclusive W production at 7 TeV

- One lepton (e/μ) p_T >25/18 GeV
- E_T^{miss} >25 GeV
- $m_T > 40$ GeV

Transverse Mass

$$\mathbf{m_T} = \sqrt{2 p_T^{\ell} p_T^{\nu}(1 - \cos(\phi^{\ell} - \phi^{\nu}))}$$

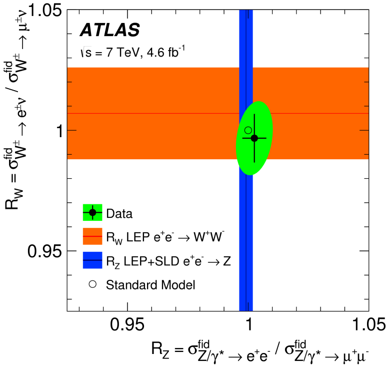


Backgrounds

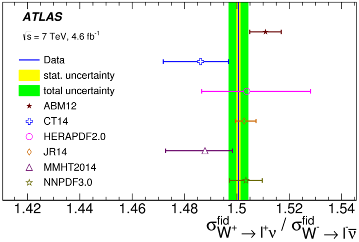
- $W \to \tau\nu$ ~1-2%
- $Z/\gamma^* \to \ell^+\ell^-$ ~1-6%
- $Z/\gamma^* \to \tau^+\tau^-$, $\bar{t}t$, top, VV all ~0.1-1%
- Multijet ~2-7% - fake leptons → data-driven estimation
  - Estimated for each lepton flavour
  - Multiple methods including template fits and extrapolating from control region
  - Lepton quality selections inverted

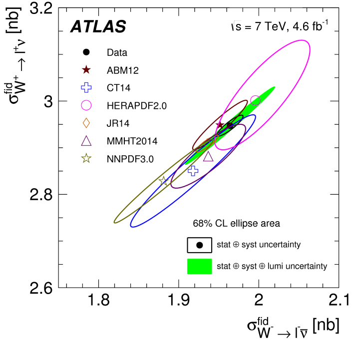
Inclusive W production at 7 TeV

Lepton Universality



Process	σ^{fid}[pb]
$W^+ \to e^+\nu$	2939$\pm$1 (stat) $\pm$28 (syst) $\pm$53 (lumi)
$W^- \to e^-\nu$	1957$\pm$1 (stat) $\pm$21 (syst) $\pm$35 (lumi)
$W^+ \to \mu^+\nu$	2948$\pm$1 (stat) $\pm$21 (syst) $\pm$53 (lumi)
$W^- \to \mu^-\nu$	1964$\pm$1 (stat) $\pm$13 (syst) $\pm$35 (lumi)
$W^+ \to \ell^+\nu$	2947$\pm$1 (stat) $\pm$15 (syst) $\pm$53 (lumi)
$W^- \to \ell^-\nu$	1964$\pm$1 (stat) $\pm$11 (syst) $\pm$53 (lumi)
$W \to \ell\nu$	4911$\pm$1 (stat) $\pm$26 (syst) $\pm$88 (lumi)





Inclusive W production at 7 TeV

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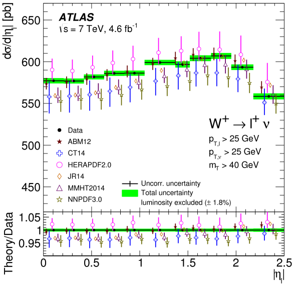
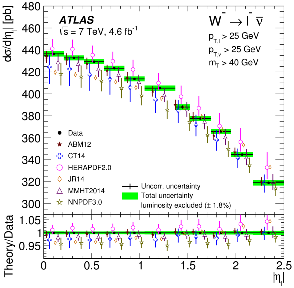
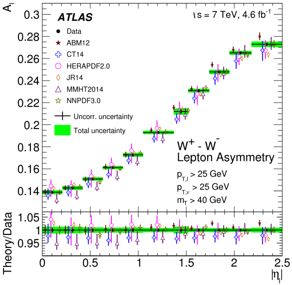
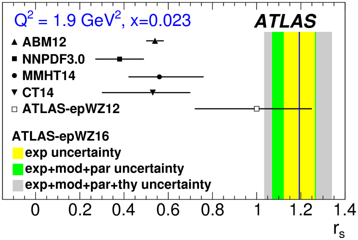






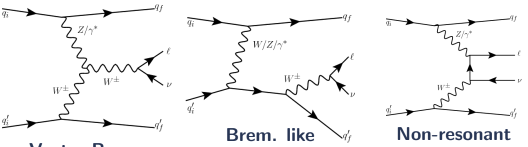


- Inputs to asymmetry and correlations provided
- Detailed profiling of all PDF sets shown
- QCD fit determining new set of PDF's - ATLAS-epWZ16
- Strange quark density supports unsuppressed strange sea $r_S = \frac{s+\bar{s}}{2\bar{d}}$

$|V_{CS}|$ =0.969±0.013(exp)$^{+0.006}_{-0.003}$(mod)$^{+0.003}_{-0.027}$(par)$^{+0.011}_{-0.005}$(thy)

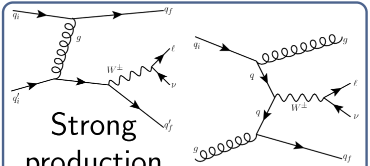
Electroweak W production at 7 and 8 TeV

EPJC 77 (2017) 474

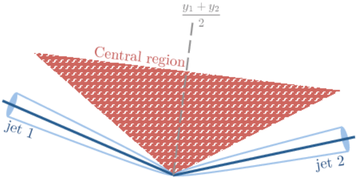


Vector Boson Fusion — **Brem. like** — **Non-resonant**

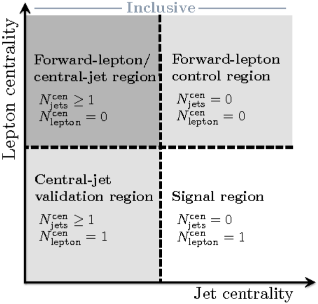
EWK production



Strong production



- One lepton + E_T^{miss}
- m_T >40 GeV
- Two high p_T jets with high m_{jj}



Distinguish electroweak process using centrality

$$C_l = \left| \frac{y_l - \frac{y_1+y_2}{2}}{y_1 - y_2} \right|$$

Backgrounds similar to inclusive, multijet fit simultaneously to strong W

Electroweak W production at 7 and 8 TeV

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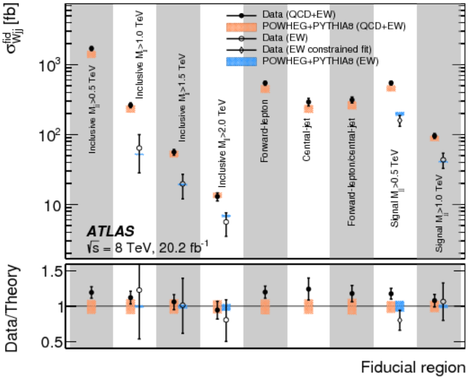
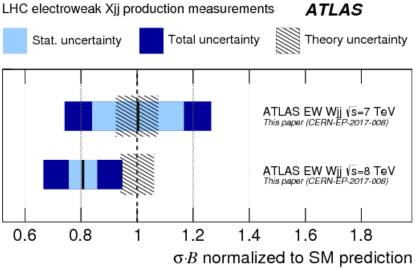
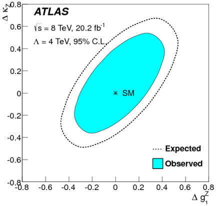
Fiducial cross-sections





- Integrated QCD+EW Wjj cross-sections in all regions
- EW-only Wjj production in high m_{jj} regions
- EW Wjj fraction uses binned likelihood fit of mjj spectrum - constraint in CR reduces uncertainty

aTGC Limits



- 3 anomalous WWW coupling constants
- use m_{jj} >1 TeV and p_T^{jet1} >600 GeV

Electroweak W production at 7 and 8 TeV

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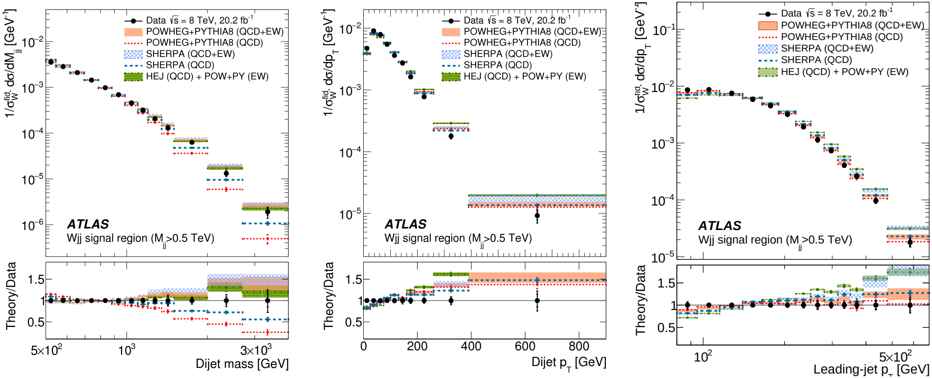
Dijet mass | **Dijet p_T** | **Leading jet p_T**



- Differential measurements for QCD+EW Wjj production and EW-only Wjj production
- Distributions which discriminate between production modes:
  - m_{jj}, lepton centrality, jet centrality, $\delta y(jet_1, jet_2)$ and number of jets in rapidity gap
- Distributions which give sensitivity to anomalous triple gauge couplings
  - Leading jet p_T, di-jet p_T, $\delta\phi(jet_1, jet_2)$

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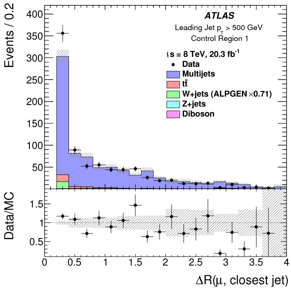
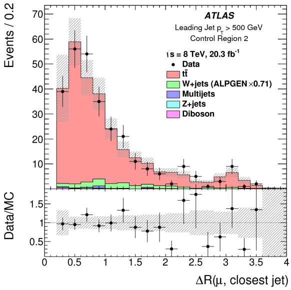
- Measure real W boson emission from initial or final state quarks
- Study region with small angular separation $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ between W boson and a jet
- Also has contributions from W+2 jets processes and corrections
- Select events with a muon, at least one jet with p_T >500 GeV and no b-jets or electrons
- Control region enriched for each of three main background processes - derive scale factors from data in these along with signal region to apply to background and signal processes
- Dijet: 1.134±0.054, $t\bar{t}$: 0.861±0.061, Z+jets: 0.705±, W+jets: 0.711±0.016

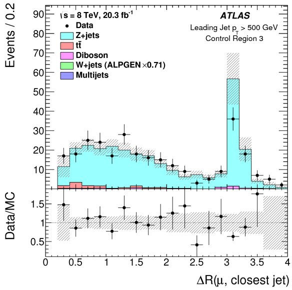
Multijet



$t\bar{t}$



Z+jets



Collinear production at 8 TeV

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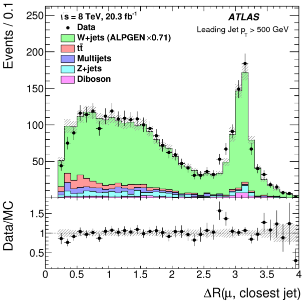

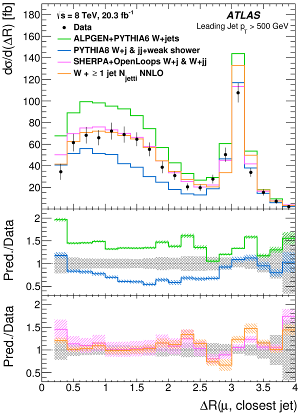

Collinear region - 0.2$< \Delta R <$2.4

Process	$\sigma\,(W(\rightarrow \mu\nu) + \geq 1$ jet, $0.2 < \Delta R < 2.4)$ [fb]
Data ($\sqrt{s}$ = 8 TeV, 20.3 fb^{-1})	116.2 ± 3.2 (stat.) ± 8.8 (syst.) ± 2.3 (lumi.)
ALPGEN+PYTHIA6 W+jets	167.1 ± 0.9 (stat.)
PYTHIA8 $W+j$ & jj+weak shower	83.4 ± 0.7 (stat.) ± 4.4 (pdf)
SHERPA+OpenLoops $W+j$ & $W+jj$	128 ± 20 (scale)
W + ≥ 1 jet N_{jetti} NNLO	123 ± 9 (scale)

- ALPGEN 2.14 generates W bosons in ME, with up to 5 additional partons
- Interfaced with Pythia6 and normalised to NNLO pQCD
- Pythia8 can produce W boson in ME or as EWK final state radiation of dijet events
- Sherpa+OpenLoops has NLO QCD and EWK corrections
- NNLO calculation from N_{jetti}
- Also enhance collinear by increasing jet p_T >650 GeV