Measurements of vector boson plus heavy flavours in ATLAS

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Run 1 measurements of vector boson plus jets

Covered by Sofia C. https://indico.cern.ch/event/366801/contribution/232

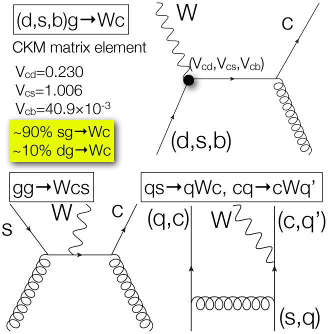
Inclusive measurements of vector bosons plus jets		
Analysis	Goal	Reference
W+jets	Validation of Monte Carlo event generators	Eur. Phys. J. C (2015) 75:82
Z+jets	Validation of Monte Carlo event generators	JHEP 07 (2013) 032
R_{jets}	Validation of Monte Carlo event generators	Eur. Phys. J. C (2014) 74: 3168

Highlighted by Sofia C., main focus of this talk

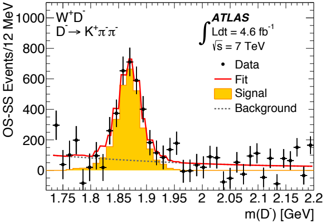
Measurements of vector bosons plus heavy flavours		
Analysis	Goal	Reference
W+charm	Constrain strange–quark PDF	JHEP 05 (2014) 068
W+b-jets	Validation of Monte Carlo event generators	JHEP 06 (2013) 084
Z+b–jets	Validation of Monte Carlo event generators	JHEP 10 (2014) 141

W+charm analysis: overview

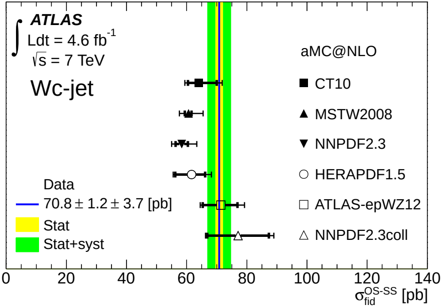
- Measure W+single–charm production
- Sensitivity to strange–quark PDF, testing suppressed/unsuppressed scenarios
  - Suppressed strange PDFs: $r_s = 0.5 \times [s(x) + \bar{s}(x)]/\bar{d}(x) \sim 0.5$
  - Unsuppressed strange PDFs: $r_s = 0.5 \times [s(x) + \bar{s}(x)]/\bar{d}(x) \sim 1$
- Exploiting the charge correlation between the W boson and the charm–quark for suppressing the backgrounds
  - Presenting Opposite Sign (OS) subtracting the Same Sign (SS) W+charm cross section
- Using two analysis strategies
  - Soft–lepton tagging: identify inclusively semi–leptonic decays of charmed hadrons
  - C–hadron reconstruction: reconstruct the decay modes $D^+ \to K^-\pi^+\pi^+$, $D^{*+} \to D^0\pi^+$ ($D^0 \to K^-\pi^+$), $D^0 \to K^-\pi^+\pi^0$, $D^0 \to K^-\pi^+\pi^-\pi^+$ and charge conjugates

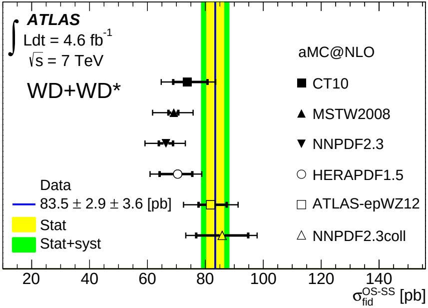


Dominant systematic uncertainties		
Cross section	Syst. error type	Syst. error [%]
$\sigma(W+D)$	Tracking efficiency	2.1
	Branching ratio	2.1
$\sigma(W+D^*)$	Tracking efficiency	2.2
	Signal modeling	1.9
σ(W+c–jets)	Background	3
	c–hadrons decays	2.9



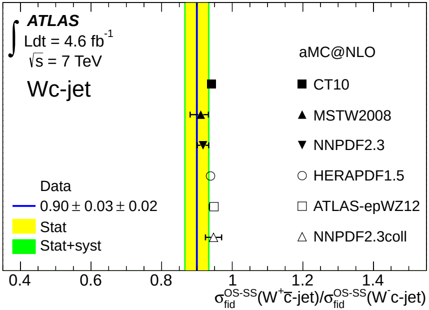
W+charm fiducial cross sections

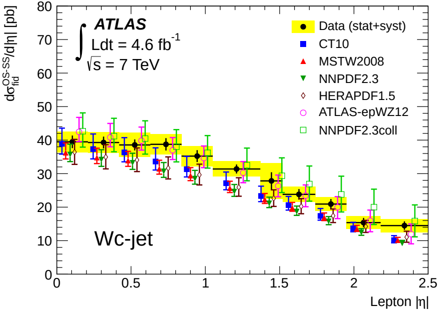




PDF set	Data	Strange–quark
CT10	DIS+Collider (no LHC)	-
MSTW2008	DIS+Collider (no LHC)	Suppressed
NNPDF2.3	DIS+Collider (no LHC)	Suppressed
HERAPDF1.5	HERA	Suppressed
ATLAS-epWZ12	HERA+2010 W/Z ATLAS data	Unsuppressed
NNPDF2.3coll	DIS+Collider	Enhanced

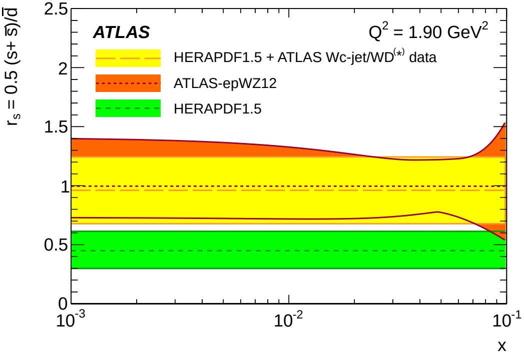
W+charm cross sections

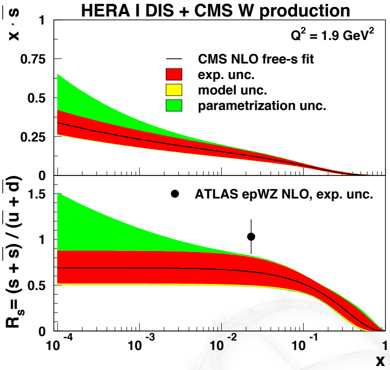




- Physics motivations for the $\sigma_{\text{fid}}^{\text{OS-SS}}(W^{+}c\text{-jet})/\sigma_{\text{fid}}^{\text{OS-SS}}(W^{-}c\text{-jet})$ asymmetry
  - Production modes induced by down–quark in the initial state
  - Intrinsic asymmetry in $s(x) - \bar{s}(x)$ as favored by neutrino data (taken into account NNPDF2.3 and MSTW2008)
- Distribution of lepton $|\eta|$ is well predicted (PDF sets differ in normalisation)

Constraint on the strange quark PDF



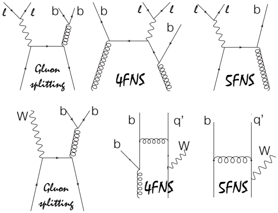


CMS ref. Phys.Rev. D90 (2014) 3, 032004

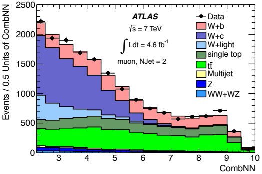
- CMS data favor a suppressed strange−quark PDF, within uncertainties still consistent with ATLAS data
- QCD analyses using high statistics W/Z and W+charm samples will help to clarify the current picture

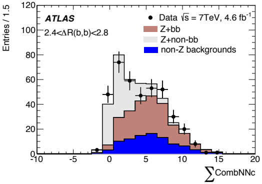
Overview of the W/Z+b–jets analyses

- The bulk of the Z+b(b) rate is driven by gluon–gluon (4 flavours scheme) bottom–gluon (5 flavours scheme) scattering
  - Gluon splitting is relevant at small bb opening angles
- A leading production mode for W+bb and W+b is provided by gluons splitting
- Two strategies for the backgrounds estimation
  - Data driven methods or MC predictions for the non–V+jets backgrounds
  - Fit to a neural–network (NN) distribution for the V+light–jets and V+charm backgrounds



Dominant systematic uncertainties		
Cross section	Syst. error type	Syst. error [%]
$\sigma(W+b)$ $(N_{jets}=1)$	jet energy	21
	MC modeling	8
$\sigma(W+b)$ $(N_{jets}=2)$	jet energy	16
	MC modeling	14
$\sigma(Z+b)$	b–jets eff.	3.4
	NN output shape	4.8
$\sigma(Z+bb)$	b–jets eff.	9.8
	NN output shape	4.8



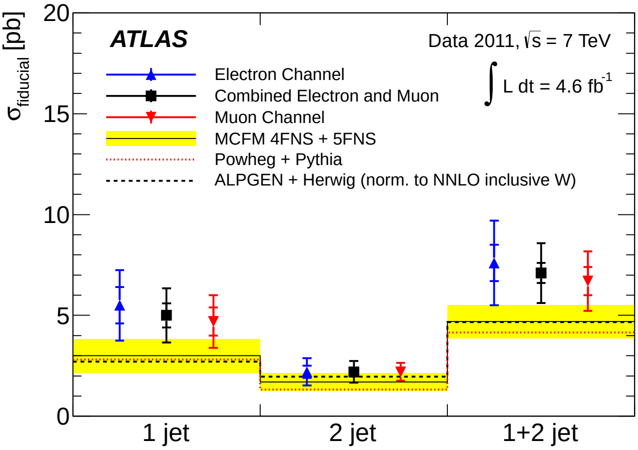


W/Z+b–jets theoretical predictions

Program	Max number of partons at NLO ($\alpha_s^{N_{jets}+1}$)	LO ($\alpha_s^{N_{jets}}$)	Cross section	H.f. scheme
ALPGEN	-	5	$\sigma(W/Z+\geq 1\,b)$, $\sigma(W/Z+\geq 2\,b)$	4FNS
SHERPA	-	4	$\sigma(Z+\geq 1\,b)$, $\sigma(Z+\geq 2\,b)$	5FNS
MCFM (Z+b)	1	2	$\sigma(Z+\geq 1\,b)$	5FNS
MCFM (Z+bb)	2	3	$\sigma(Z+\geq 2\,b)$	5FNS
MCFM (W+b)	2	3	$\sigma(W+\geq 1\,b)$, $\sigma(W+\geq 2\,b)$	4FNS+5FNS
aMC@NLO	1	2	$\sigma(Z+\geq 1\,b)$	5FNS
aMC@NLO	2	3	$\sigma(Z+\geq 2\,b)$	4FNS
PowHeg	2	3	$\sigma(W+\geq 1\,b)$, $\sigma(W+\geq 2\,b)$	4FNS

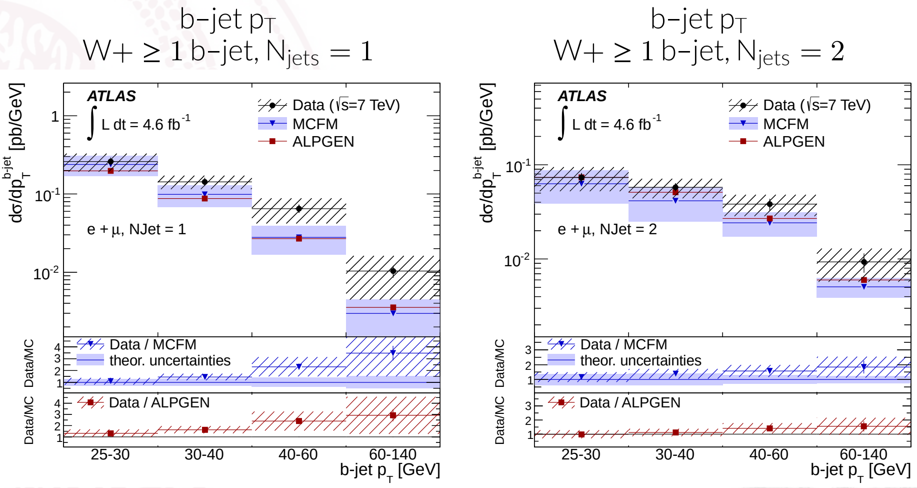
- MCFM predictions are corrected for non–perturbative effects, all other calculations are at particle level
- ALPGEN prediction for $\sigma(W+\geq 1/2\,b)$ is normalised according to the NNLO k–factor ($\sim$1.2) for inclusive W cross section

Fiducial W+b–jets cross sections

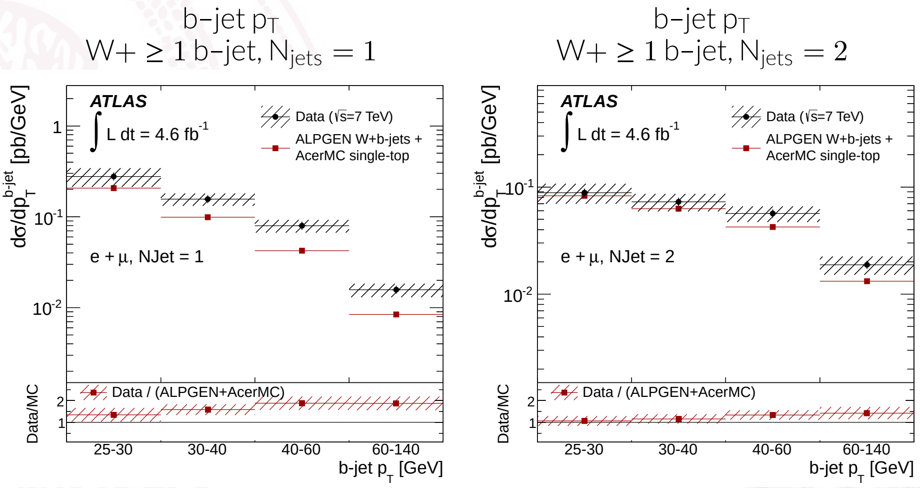


Contribution from DPI, 35%–20% depending on the jet multiplicity, is relevant for the fiducial cross section interpretation

W+b–jets differential cross sections

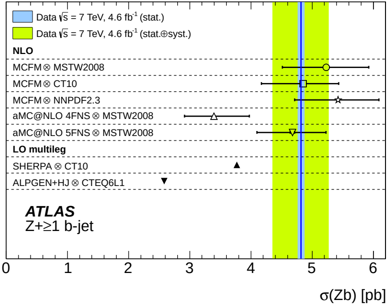


W+b–jets + single top differential cross sections

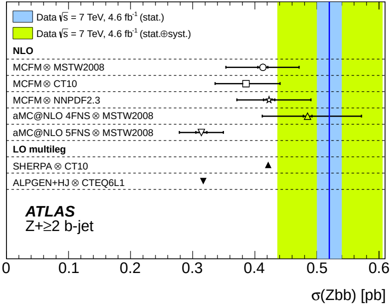


Fiducial Z+b–jets cross sections

$\sigma(Z+\geq 1\ b)$



$\sigma(Z+\geq 2\ b)$

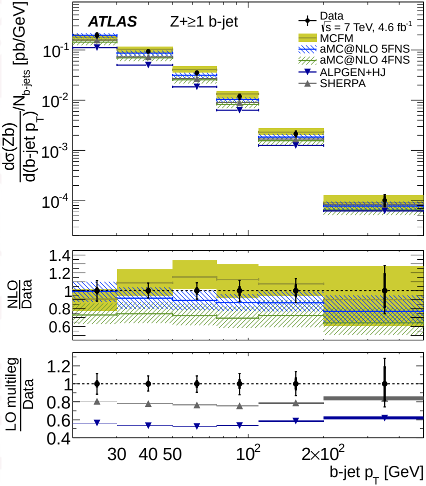


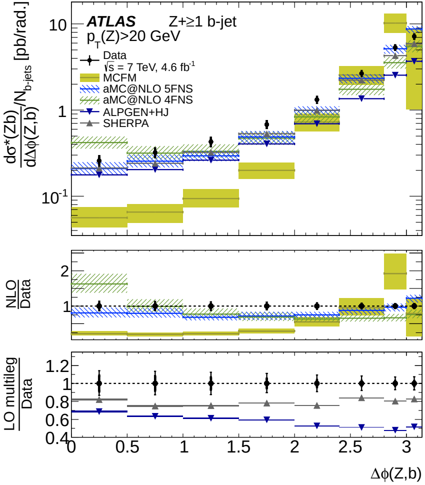
- NLO predictions provide a different description of the data depending on the b–jet multiplicity
  - Very interesting to test how this feature evolves at at 13 TeV

$\sigma(Zbb)/\sigma(Zb)$

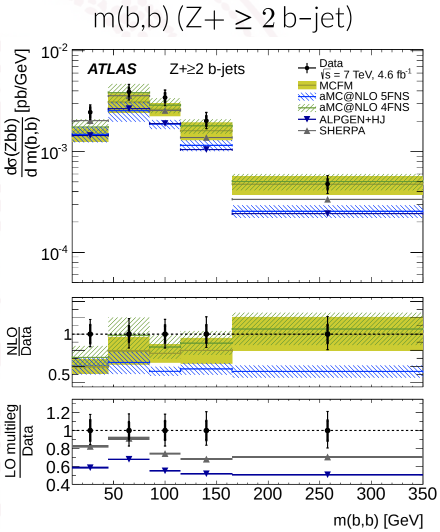
Data	MCFM	aMC@NLO (4FNS)	aMC@NLO (5FNS)	Sherpa	Alpgen
0.108	0.078	0.143	0.067	0.112	0.123

Z+b differential cross sections





Z+bb differential cross sections



Summary

Summary of Run 1 results and Run 2 preparation

- Comprehensive set of particle level cross section measurements have been provided
- All results are based on 7 TeV data
  - Ongoing analyses of 8 TeV data expected to converge by the end of this year
- Available data have been used to define the baseline generators to be used in Run 2
- Many improvements are foreseen
  - New generators: MEPS@NLO, automated NLO, ..
  - New tunings, Monte Carlo settings

Analyses wish list for Run 2

- Fast measurements for validating the new Monte Carlo generators at 13 TeV
- Repeat all Run 1 analyses with the full Run 2 dataset
- Study in detail the gluon splitting process $g \rightarrow bb$
- More ”exotic” measurements..

Backup

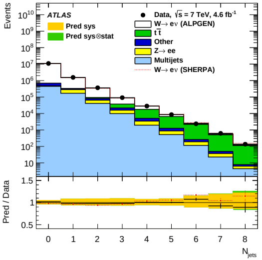
Overview of inclusive V+jets analyses

- Comprehensive test of Monte Carlo event generators
- Plenty of differential cross sections measurements in W+jets and Z+jets events: ~50 distributions were provided
- Measuring also $R_{\text{jets}} = \sigma(W + \text{jets})/\sigma(Z + \text{jets})$

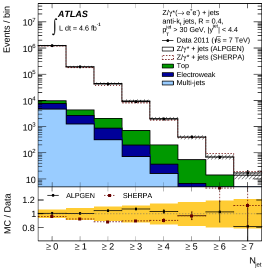
Dominant systematic uncertainties		
Cross section	$N_{\text{jets}} \geq 1$	$N_{\text{jets}} \geq 4$
$\sigma(W + \text{jets})$	jet energy (8.5%)	jet energy (18%)
	Multijet background (1.5%)	$t\bar{t}$ background (14.5%)
$\sigma(Z + \text{jets})$	jet energy (7.5%)	jet energy (16.5%)
R_{jets}	jet energy (2.5%)	jet energy (6.4%)
	E_T^{miss} (1.4%)	$t\bar{t}$ background (13%)

- Jet energy calibration is the dominant systematic uncertainty for both W+jets and Z+jets measurements
  - Strongly correlated across W+jets and Z+jets analyses; reduced in R_{jets}
- The uncertainty on the $t\bar{t}$ data driven estimation limits the experimental precision at high jet multiplicity

W+jets (inclusive jet multiplicity)



Z+jets (inclusive jet multiplicity)

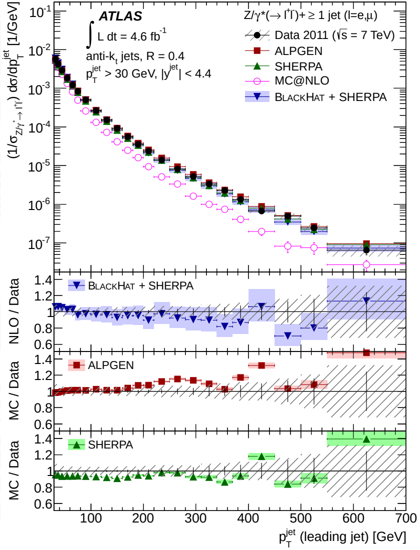


V+jets theory predictions

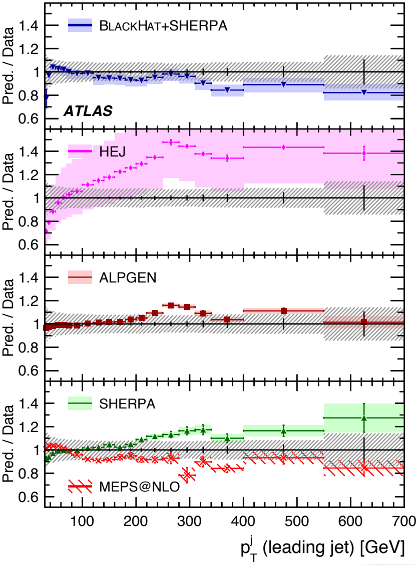
Program	Max number of partons at approx. NNLO ($\alpha_s^{N_{jets}+2}$)	NLO ($\alpha_s^{N_{jets}+1}$)	LO ($\alpha_s^{N_{jets}}$)	Parton/particle level
	W+jets predictions			
LoopSim	1	2	3	parton level with corrections
BlackHat+SHERPA	-	5	6	parton level with corrections
BlackHat+SHERPA (excl. sums)	1	2	3	parton level with corrections
HEJ	All orders resummation			parton level
MEPS@NLO	-	2	4	particle level
ALPGEN	-	-	5	particle level
SHERPA	-	-	4	particle level
	Z+jets predictions			
BlackHat+SHERPA	-	4	5	parton level with corrections
ALPGEN	-	-	5	particle level
SHERPA	-	-	4	particle level

W/Z+jets results: transverse momentum of the leading jet

Z+jets

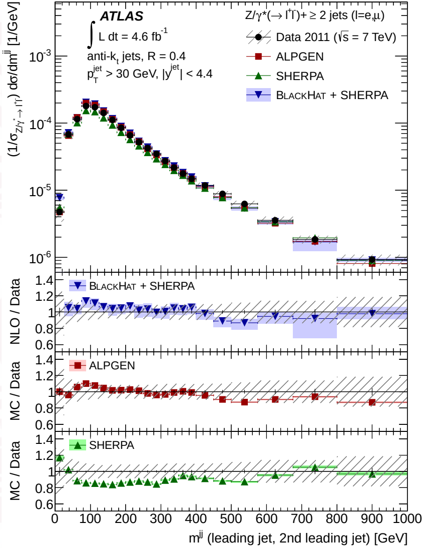


W+jets

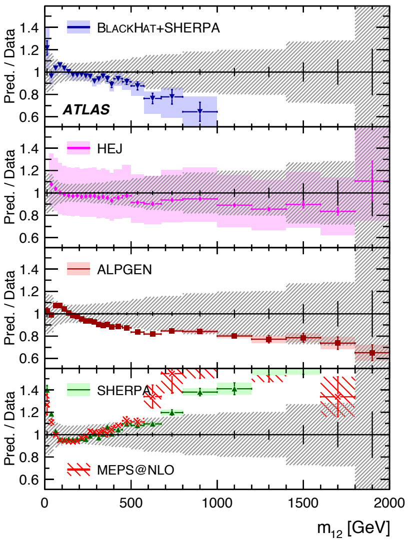


W/Z+jets results: invariant mass of the leading jets

Z+jets

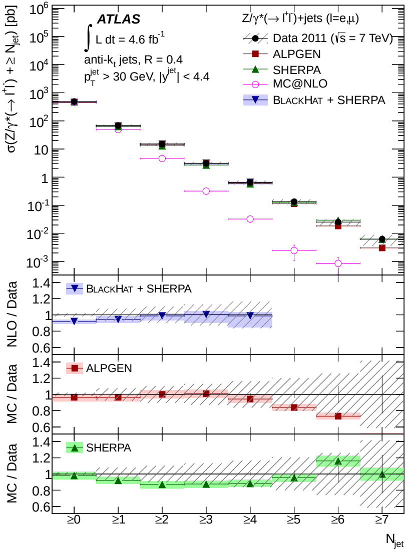


W+jets

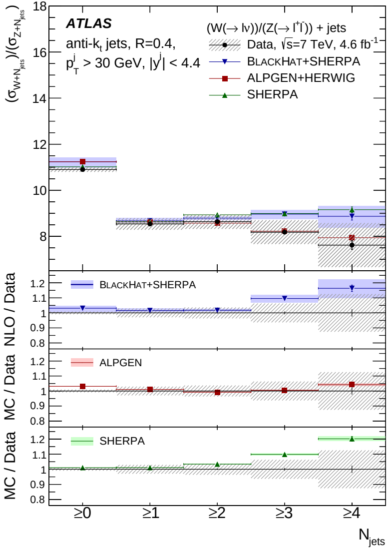


Inclusive jet multiplicity

Z+jets



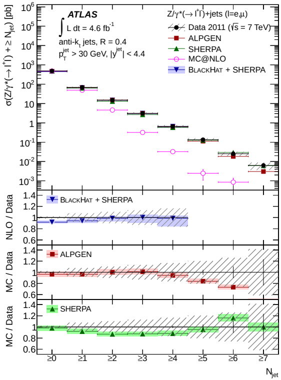
$R_{jets} = \sigma(W + jets)/\sigma(Z + jets)$



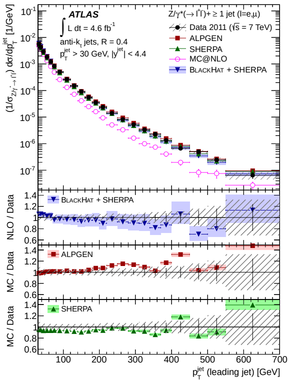
W/Z+jets

- Overall very good description of the data
- Jet multiplicity ratios are very well described too
  - Potentially useful for constraining the backgrounds with very early data
- Jet p_T has some features

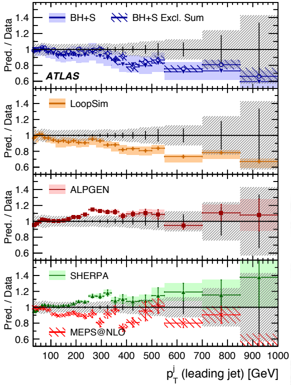
Inclusive jet multiplicity



leading–jet p_T (Z+jets)

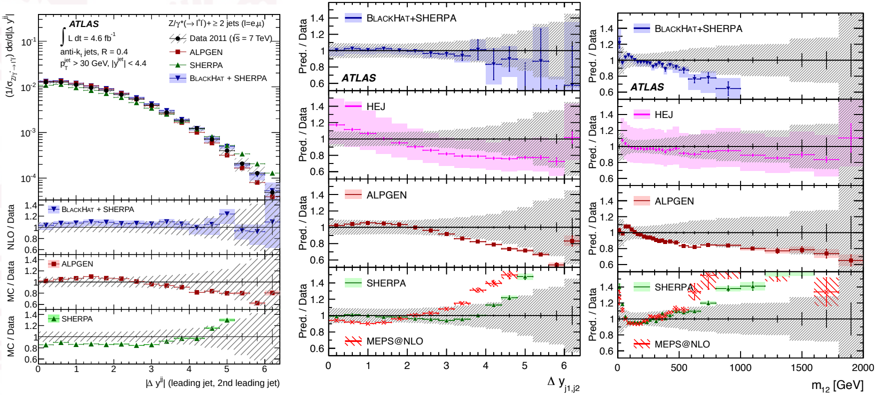


leading–jet p_T (W+jets)



W/Z+jets: di–jet system

- Angular correlation and invariant mass of the di–jet system are useful tools for constraining the backgrounds in searches
- The description of the data is not fully satisfactory
  - Would be interesting to check the effect of the MC tunes such data–MC comparisons (not explored in Run 1)



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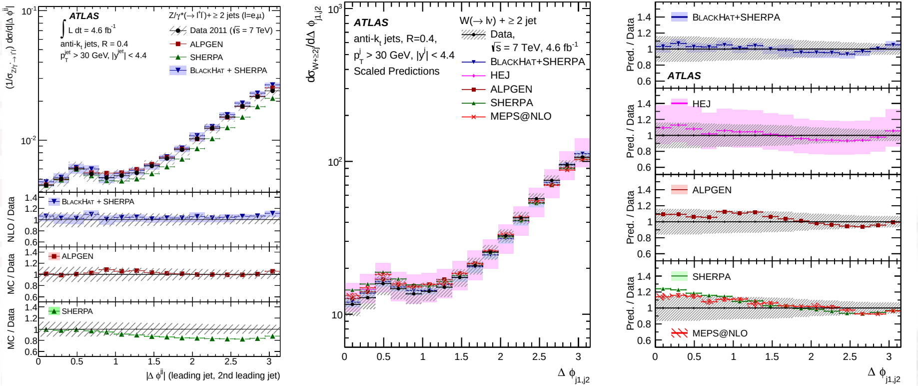
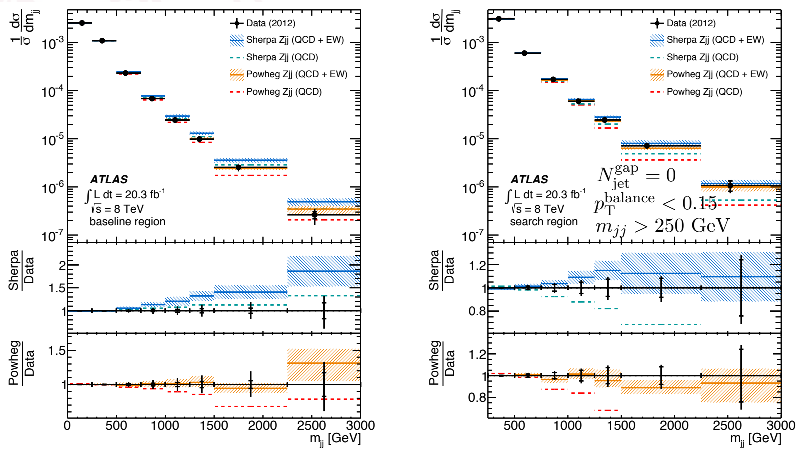


Z+jj production (VBF region)

- Still the only 8TeV V+jets measurements available from ATLAS
- Useful for validation of new Monte Carlo configurations



PDFs parametrization

$$x\mathrm{u_v}(x) = A_{\mathrm{u_v}}\, x^{B_{\mathrm{u_v}}}\, (1-x)^{C_{\mathrm{u_v}}}\, (1+E_{\mathrm{u_v}} x^2),$$

$$x\mathrm{d_v}(x) = A_{\mathrm{d_v}}\, x^{B_{\mathrm{d_v}}}\, (1-x)^{C_{\mathrm{d_v}}},$$

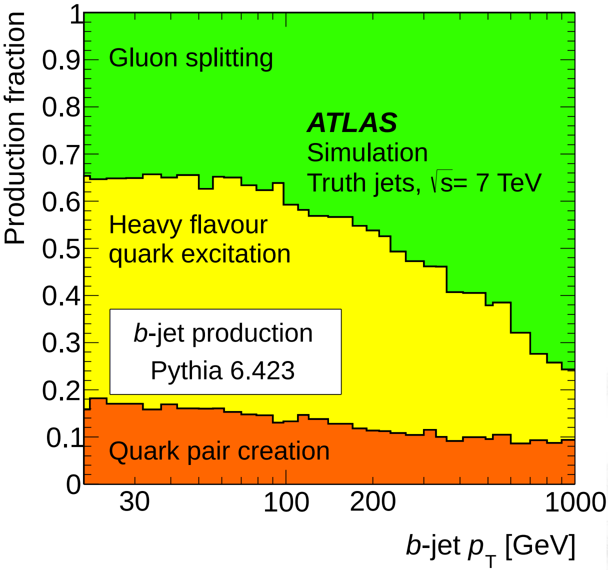
$$x\overline{\mathrm{U}}(x) = A_{\overline{\mathrm{U}}}\, x^{B_{\overline{\mathrm{U}}}}\, (1-x)^{C_{\overline{\mathrm{U}}}},$$

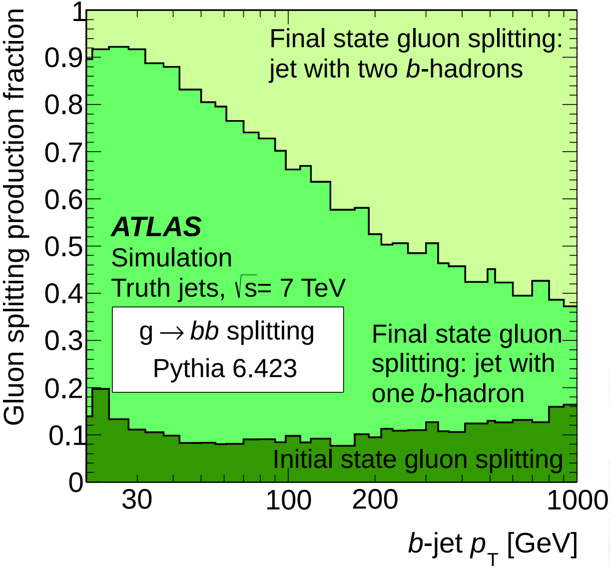
$$x\overline{\mathrm{D}}(x) = A_{\overline{\mathrm{D}}}\, x^{B_{\overline{\mathrm{D}}}}\, (1-x)^{C_{\overline{\mathrm{D}}}},$$

$$x\mathrm{g}(x) = A_{\mathrm{g}}\, x^{B_{\mathrm{g}}}\, (1-x)^{C_{\mathrm{g}}} + A'_{\mathrm{g}}\, x^{B'_{\mathrm{g}}}\, (1-x)^{C'_{\mathrm{g}}}$$

$$x\bar{\mathrm{d}}(x) = A_{\bar{\mathrm{d}}}\, x^{B_{\bar{\mathrm{d}}}}\, (1-x)^{C_{\bar{\mathrm{d}}}},$$

$$x\bar{\mathrm{s}}(x) = A_{\bar{\mathrm{s}}}\, x^{B_{\bar{\mathrm{s}}}}\, (1-x)^{C_{\bar{\mathrm{s}}}}.$$


Production fraction
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Gluon splitting
ATLAS
Simulation
Truth jets, √s= 7 TeV
Heavy flavour
quark excitation
b-jet production
Pythia 6.423
Quark pair creation
30
100
200
1000
b-jet p_T [GeV]


Gluon splitting production fraction
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
30
100
200
1000
b-jet p_T [GeV]
Final state gluon splitting:
jet with two b-hadrons
ATLAS
Simulation
Truth jets, $\sqrt{s}$= 7 TeV
g → bb splitting
Pythia 6.423
Final state gluon
splitting: jet with
one b-hadron
Initial state gluon splitting