Recent results on vector boson production in association with jets

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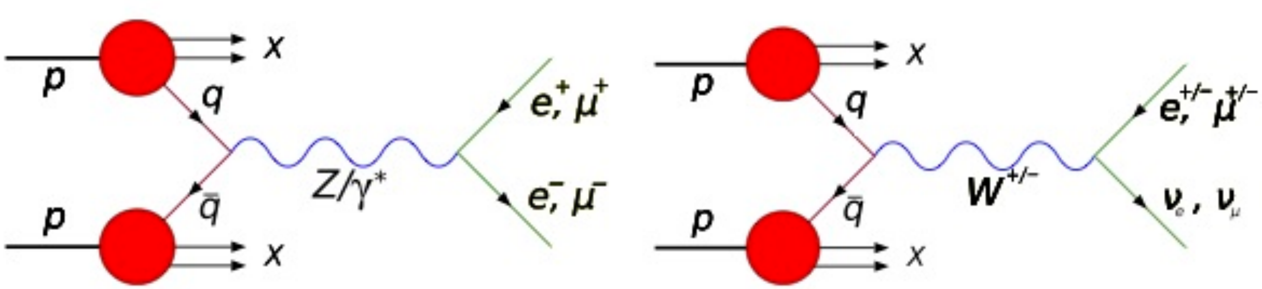
Outline:

- Motivation and overview
- ATLAS experiment
- Z+jets – event and scaling factors, based on 2011 data analysis
- W+jets – event properties, based on 2010 data analysis
- W/Z event ratio
- Z+jets VBF analysis
- W + ≥ 1 b-jets cross section
- W + charm hadron cross section
- Conclusions

Motivation and overview

- Drell-Yan production of W and Z bosons can be used to test perturbative QCD calculations
  - Inclusive analysis, integrated and rapidity dependent cross-sections
    - **Test Parton Distribution Functions (PDFs)**
  - Boson P_T and φ measurements, in boosted W/Z analysis
    - **Understanding interplay between High Order QCD and re-summation**
  - Analysis with jet reconstruction – Z+jets, W+jets, W/Z in association with Heavy Flavor jets
    - **Probe High Order QCD and constrain Parton Densities**

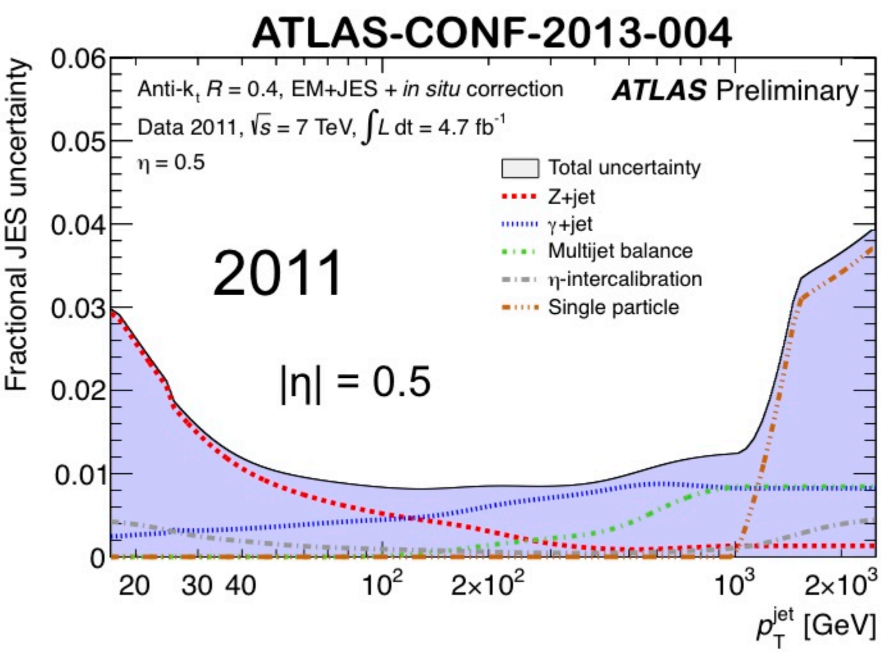
- Monte-Carlo modeling
  - Parton Shower and Matrix Element approaches need test and tuning
- Measurements
  - Major background to precision SM measurements and searches for new physics

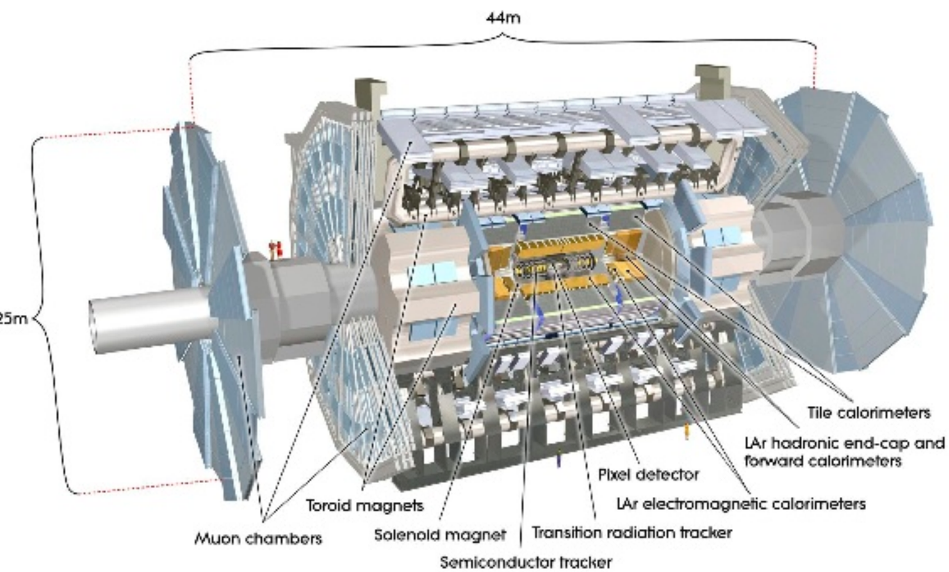


The ATLAS experiment

Excellent level of performance of ATLAS experiment, during years 2010 (36pb-1) and 2011 (4.66fb-1)

- Allowed precise SM measurements





- **Electrons**: EM calorimeter and tracking up to |eta|<2.5
- **Muons**: Muon spectrometer up to |eta|<2.7
- **Jets, MET, forward electrons**: Calorimetric coverage up to |eta|<4.9

Z+jets: jet multiplicity and jet P_T

Increased statistics allow an extension of 2010 measurements

- Jet multiplicities up to 7 jets
- Jet P_T up to 700 GeV

Event selection:

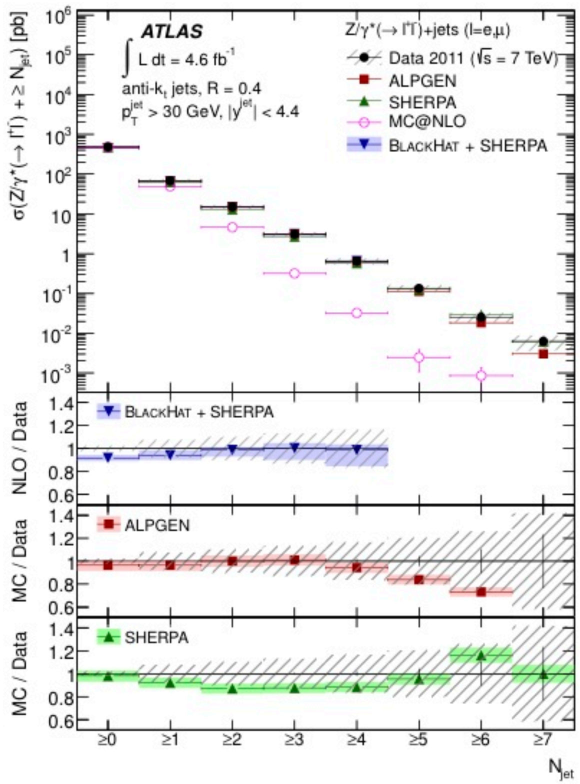
- Lepton P_T > 25 GeV
- Z->ee or Z->mumu + jets (PT>30GeV, |y| < 4.4)
- 66GeV < m(*ll*) < 116GeV

Background:

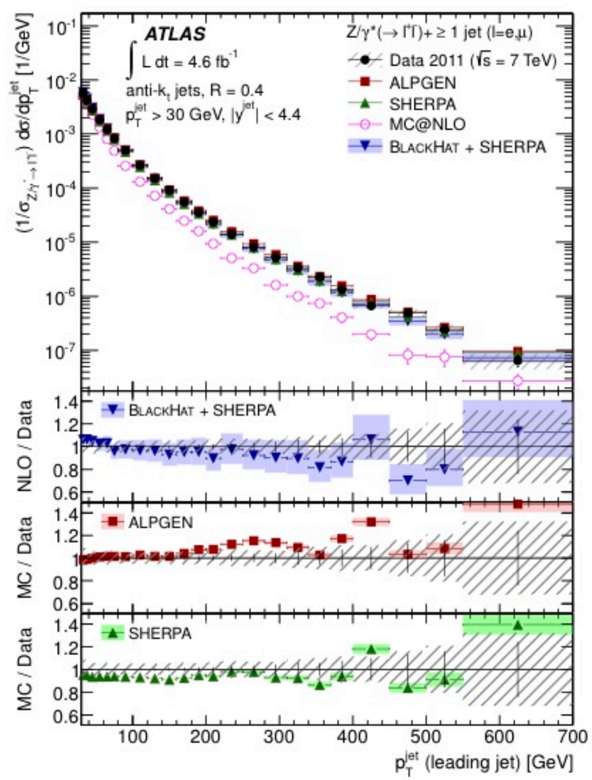
- $N_{jet} \leq 1$: multi-jet(QCD), di-boson
- $N_{jet} > 1$: top-pair production

Good agreement with BlackHat +Sherpa calculations and with predictions from ALPGEN, SHERPA

The MC@NLO parton shower underestimates observed rate for additional jet emission by a factor of two



Cross section for inclusive jet multiplicities

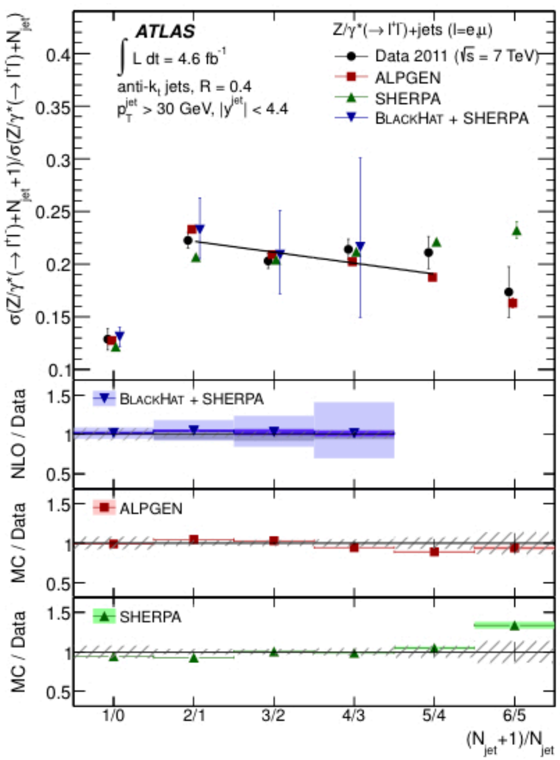


Cross section as a function of *lead jet PT*

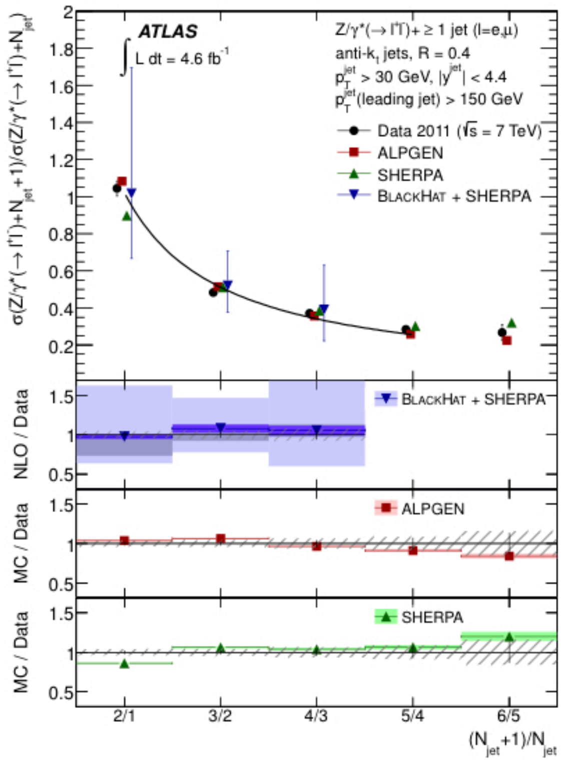
Z+jets: scaling properties

Scaling properties are useful in analysis that employ jet vetoes and separate signal from W/Z+jets backgrounds

Ratio of cross sections for successive jet multiplicities



Staircase scaling, with standard event selection



Poisson scaling, with at least one jet with P_T > 150GeV

Data compared to NLO pQCD predictions from BlackHat+Sherpa, and ALPGEN and Sherpa event generators

Exclusive ratios: $R_{(n+1)/n} = N_{Z+(n+1)}/N_{Z+n}$

Exclusive jet multiplicities with two benchmark patterns, both well reproduced by the theory predictions:

- Staircase scaling: $R_{(n+1)/n}$ constant, linear fit from $R_{2/1} - R_{5/4}$ describes

$$R_{(n+1)/n} = R_0 + \frac{dR}{dn} * n$$

- Poisson scaling, with asymmetric jet PT follows:

$$R_{(n+1)/n} \sim \frac{1}{n}$$

Z+jets: P_T of recoiled Z boson

NLO fixed order Z+≥1 jet underestimate cross section above P_T ≈ 80GeV

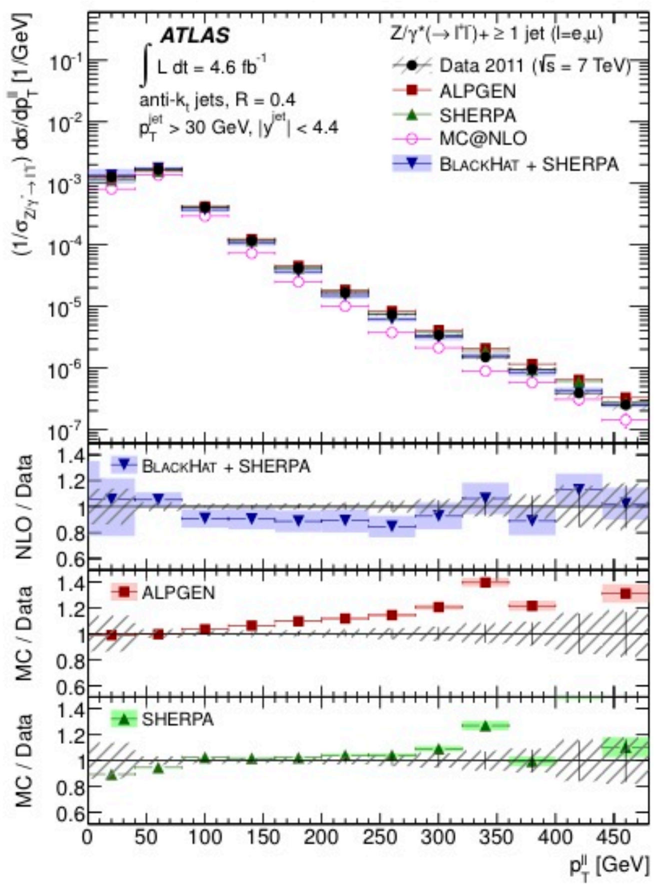
- At large P_T 2-jet events contribute
- Use exclusive sum of NLO calculations to have better agreement

Good Theory-Data agreement in exclusive sample (=1jet)

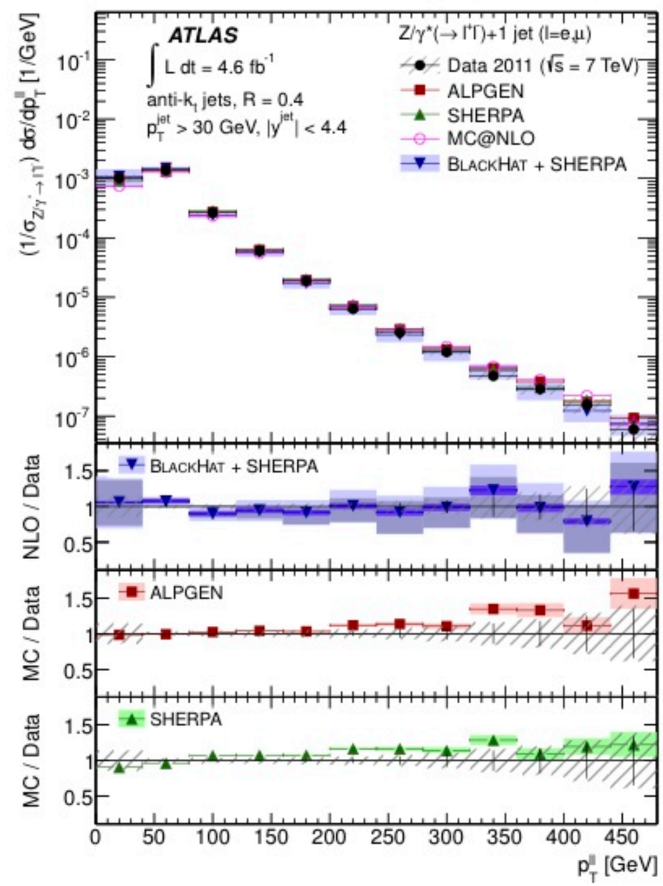
- 2 jet events are vetoed

Both ALPGEN and SHERPA predict harder Z P_T spectrum

Inclusive



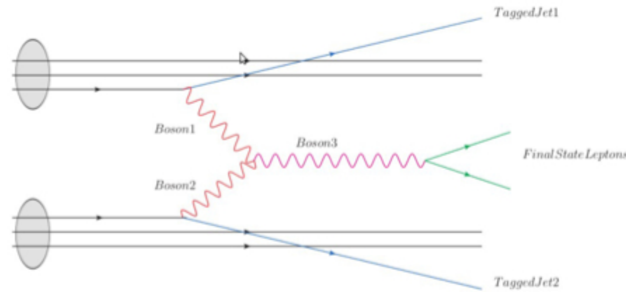
Exclusive

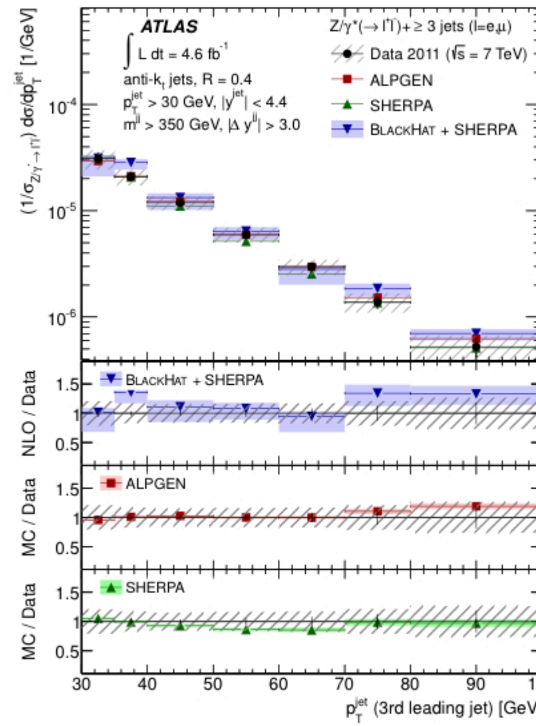


Z+jets: Vector Boson Fusion (VBF)

- A veto on a third jet is used to reject Z+jets background in VBF Higgs analysis
- Study of Z+jets events with VBF selection allows to estimate 3[rd] jet veto efficiency

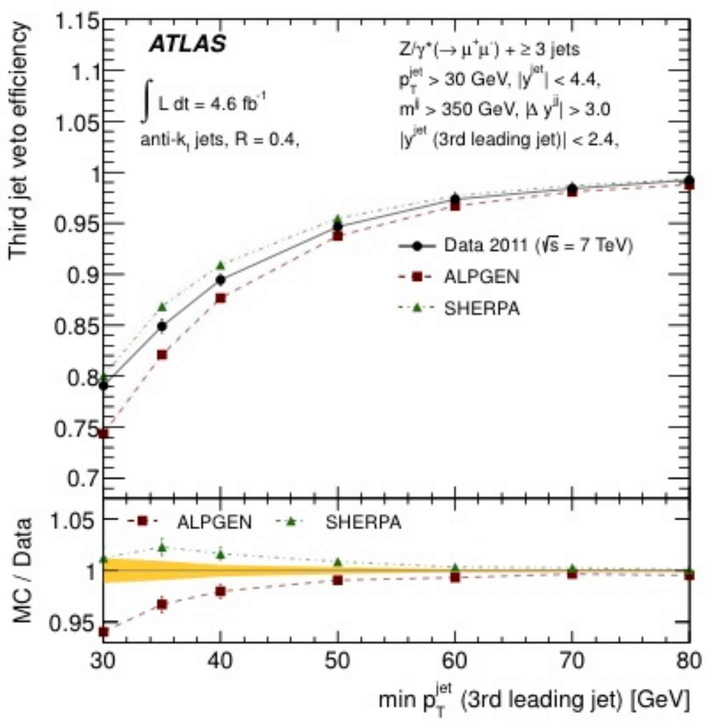
VBF signature:
- Two forward jets (large Δy(j,j) separation)
- High di-jet mass
- Central jet gap





PT distribution of the 3[rd] jet after VBF-like selection ->

Predictions are consistent with data



<- Fraction of events passing veto requirements on 3[rd] jet in central region, as function of veto scale

The overestimate of $R_{2/3}$ in ALPGEN leads to an underestimation of the efficiency (in the low PT regime), SHERPA prediction agrees better with the data

W+jets: jet multiplicity and P_T

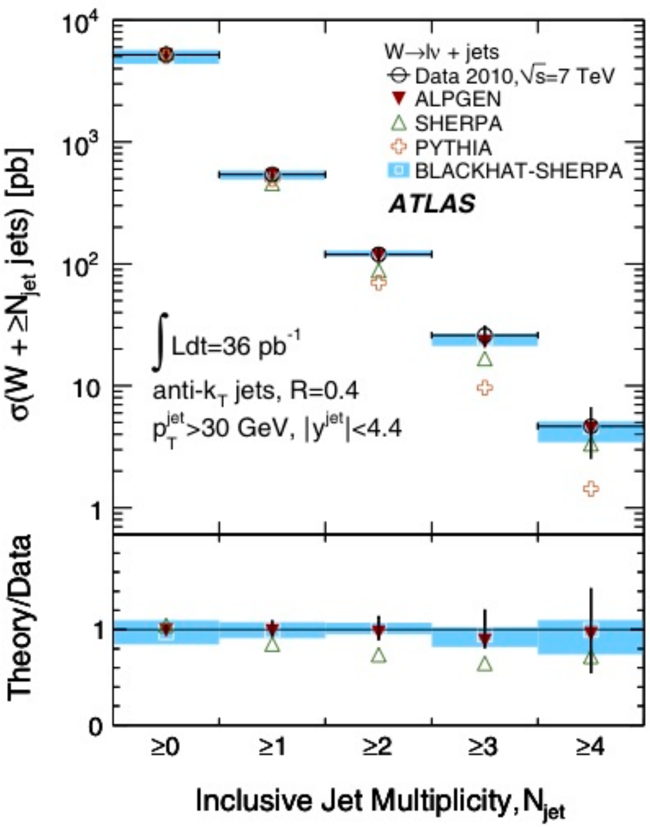
W+jets complementary to Z+jets

Background to:

- SM processes: ttbar, single-top production
- Higgs searches and searches beyond SM

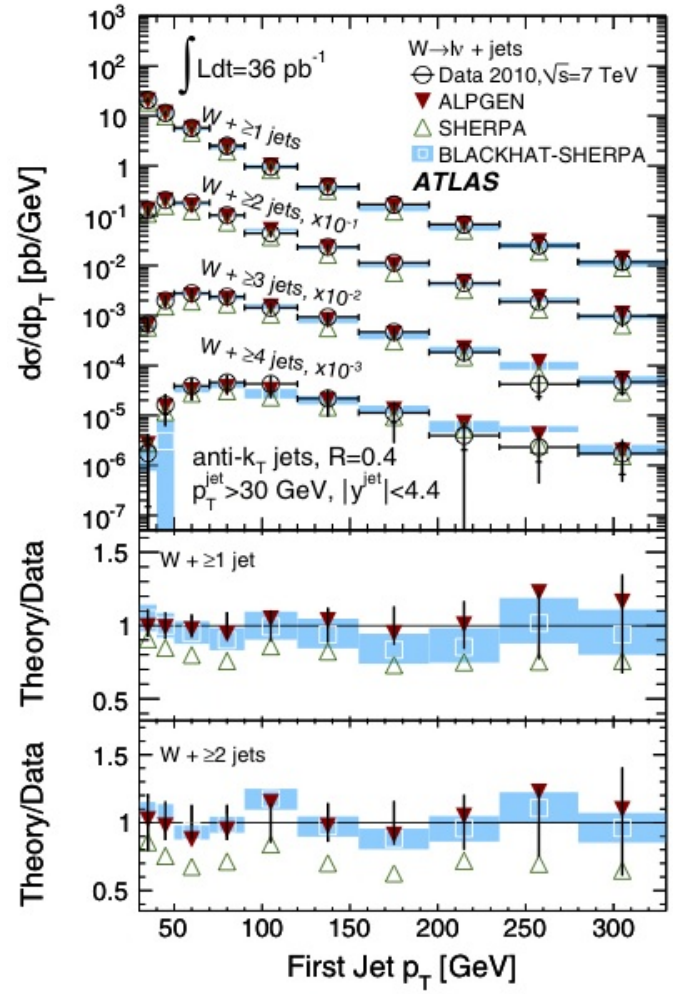
Event selection:

- Lepton PT > 20GeV
- W->enu or W->munu + jets (PT>30GeV, |y| < 4.4)
- MET>25GeV, MT>40GeV



Good agreement with ALPGEN and BLACKHAT+SHERPA

Worse with SHERPA



W+jets / Z+jets event ratio

- Allows to exploit the cancellation of theoretical and experimental uncertainties
  - Common systematic uncertainties, such as JES uncertainty, reduces systematics of the V+jets measurement

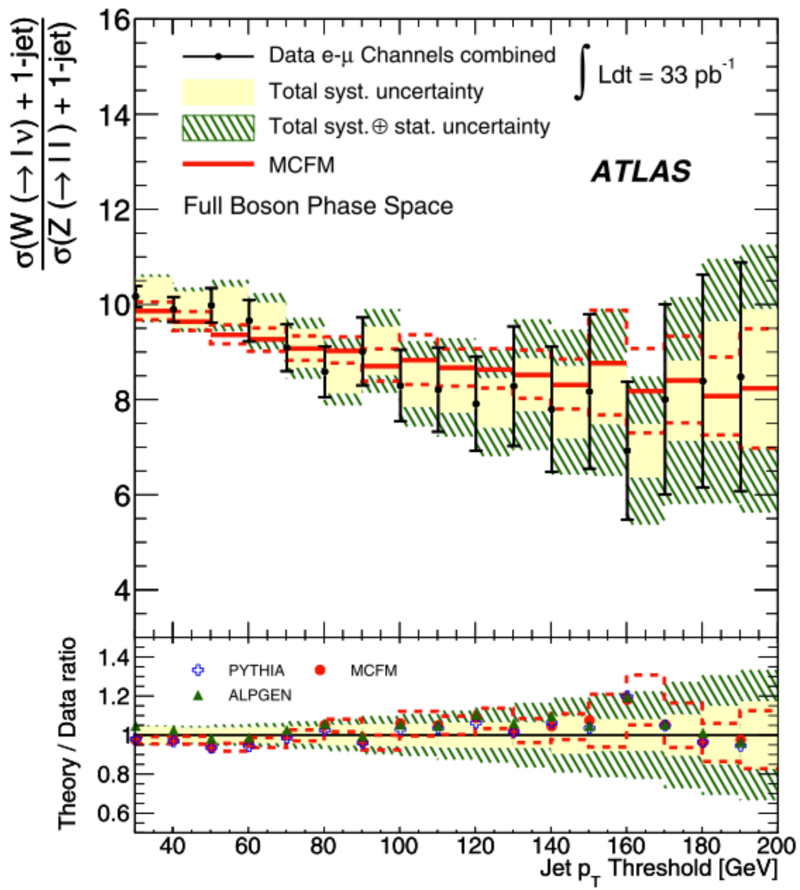
- Provides model independent sensitivity to the physics coupling to leptons and jets

- Ratio of W+jets / Z+jets as a function of jet P_T threshold in exclusive 1 jet bin

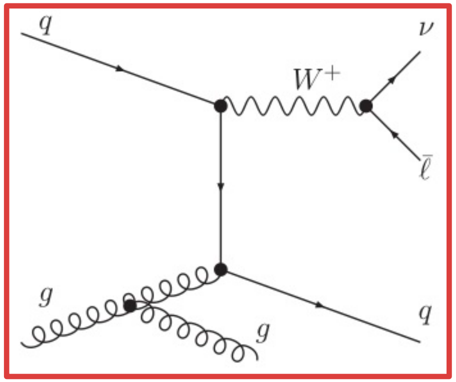
$$R_{jet}(X) = \frac{W + jets(X)}{Z + jets(X)}$$

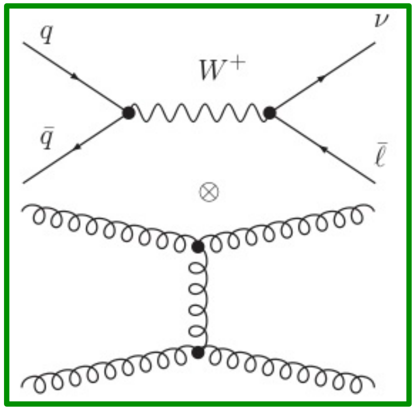
- Comparison with LO and NLO predictions shows agreement with the data

- With larger data samples from 2011and 2012 will become very precise measurement



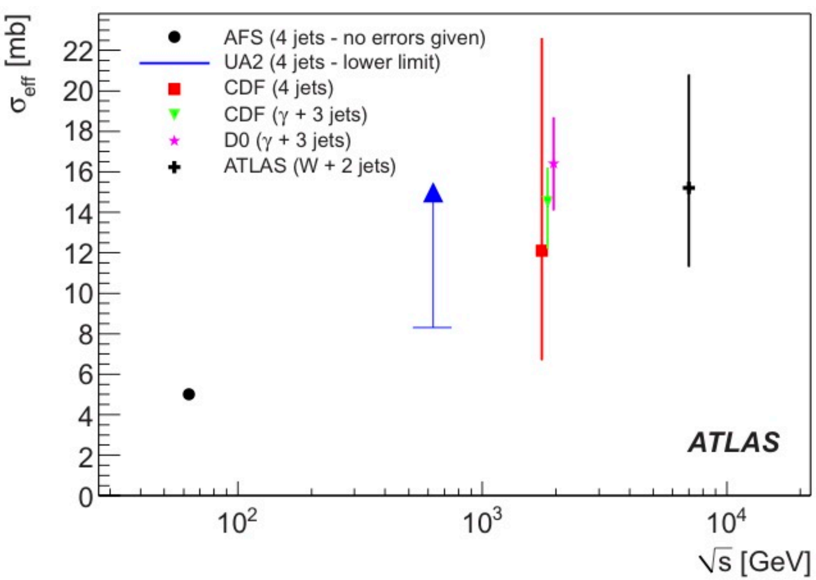
W+jets: double-parton interactions

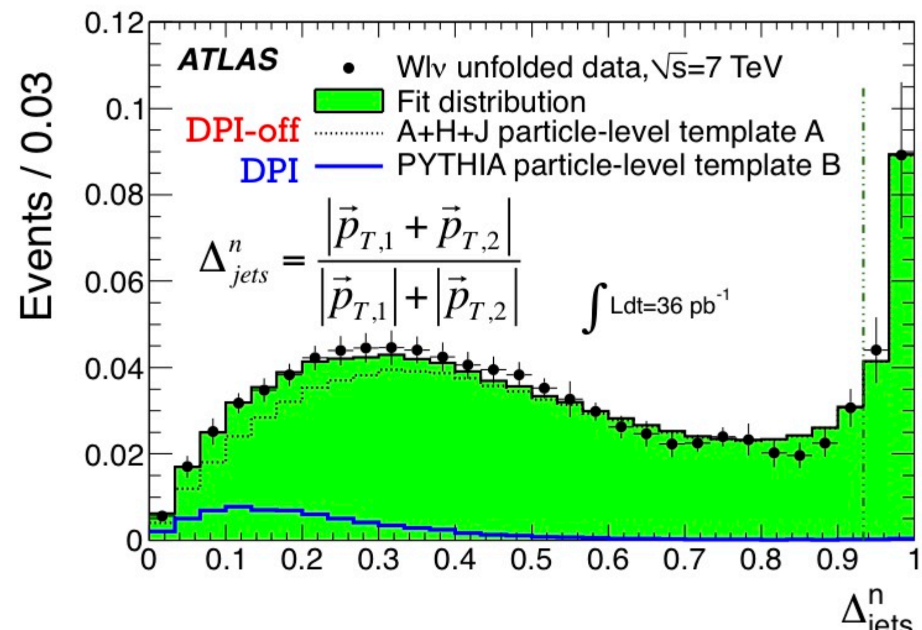




$$d\sigma_{Y+Z}^{(tot)} = d\sigma_{Y+Z}^{(SPI)} + \frac{d\sigma_Y \times d\sigma_Z}{\sigma_{eff}}$$

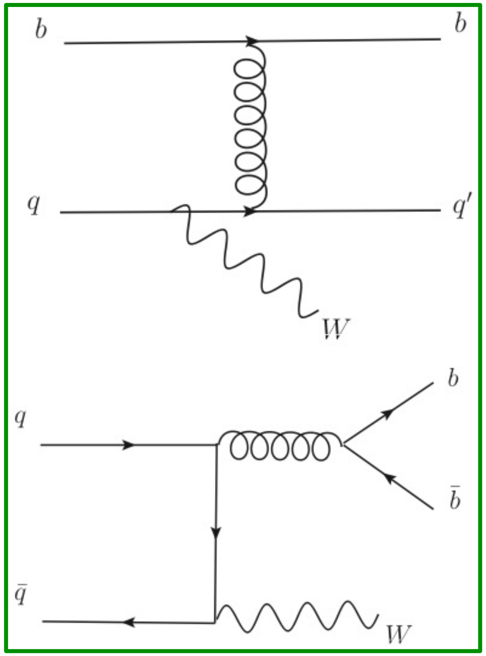
- Two parton scatterings in the same pp-collision, experimentally measured as W +2jets
- Fraction of DPI events in W+2jets data extracted from template fit to normalized transverse momentum balance of two jets
  - jets PT>20GeV, |y|<2.8
- Rate and kinematics in good agreement with predictions of MC models and with previous measurements at lower energies

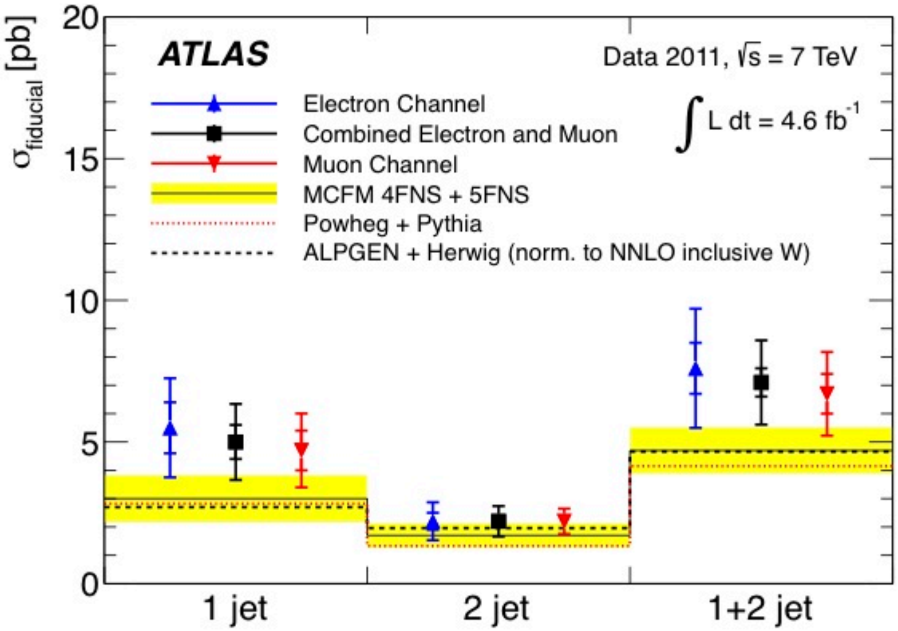




W+b-jets

- Important test for pQCD in presence of HF quarks
  - Modeling HF production in initial state (PDF) and final state (gluon splitting)
- Competing flavor schemes:
  - **Single b final states**, require heavy flavor in initial state, modeled by 5FNS
  - **Two b final states** modeled by 4FNS (u, d, c, s)
- Background to *Higgs* (WH, ZH), *Single-top* measurements and to new physics Searches





Measurements with a single b-jet requirement in the W+1 jet and W+2 jets

Compared with NLO (MCFM and Powheg)
- MCFM corrected for hadronization and DPI effects
- Powheg corrected for DPI effects

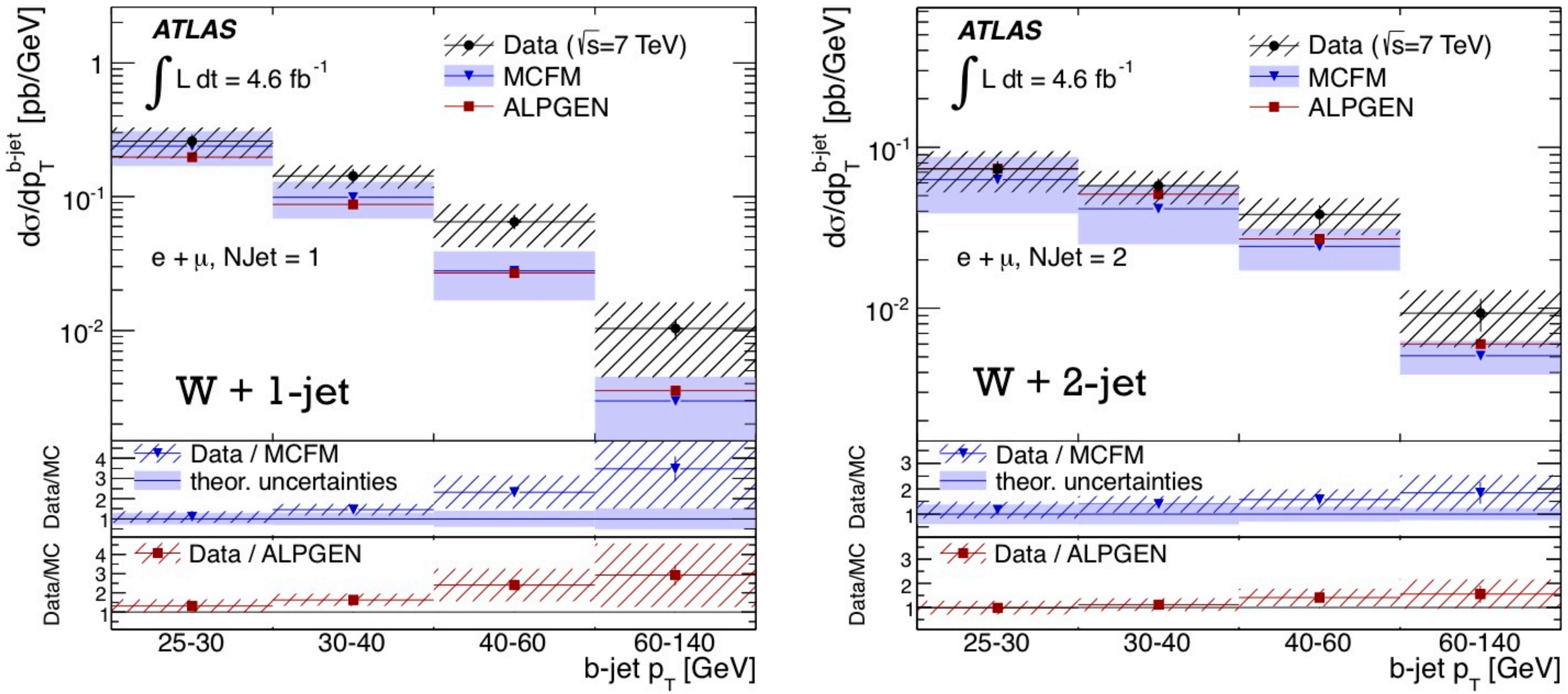
Compared with LO (Alpgen)
- Scaled to NNLO inclusive W

Total uncertainty in prediction (yellow bars)
- From variations of the normalization and factorization scales, PDF set, DPI model and non-perturbative corrections

Measurements are consistent within 1.5 σ with NLO predictions in 1 -jet and 1+2 -jet bins

W+b-jets: b-jet P_T

Large data-sets allowed measurement of differential cross-section as a function of the b-jet PT, for the first time

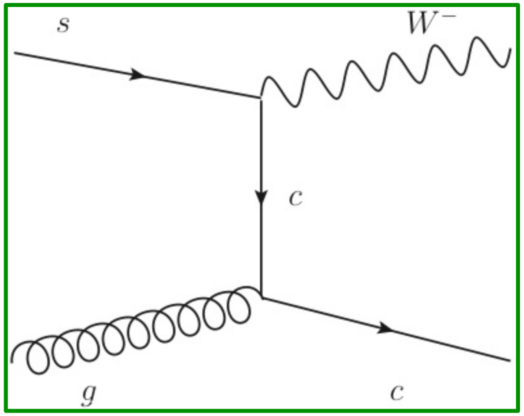


- Single-top and other backgrounds are subtracted
- Predictions are in agreement with data, within their uncertainties
  - Disagreement larger at high b-jet PT

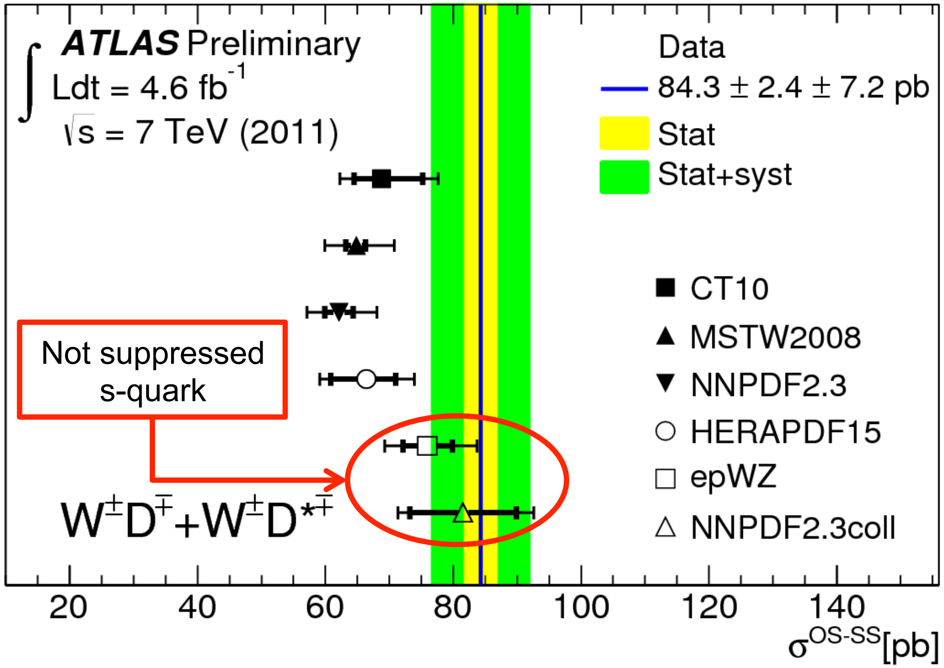
W + charm hadron cross section

- s-quark is poorly known compared to light quarks, W+c can be used as probe
- Maximum correlation in W+c for s(x) at x ~0.02
  - Large sensitivity to s(x) for 0.0001 <= x <= 0.1

Event selection:
W -> eν or μν + charm hadron (D)
D meson reconstructed in $D^+ \to K^-\pi^+\pi^+$ and $D^{*+} \to D^0\pi^+$ with:
- $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^0$ or $D^0 \to K^-\pi^+\pi^-\pi^+$



$D^\pm/D^{*\pm}$ decays reconstructed in tracker
Charge correlation between the leptons from W and D(*) used to extract single-charm component: subtracted same-sign contribution (OS – SS)
Yield extracted by fitting the $D^\pm$ mass or D^*-D^0 mass diff. in OS-SS



Measured cross sections compared to a MC@NLO predictions, based on different PDF predictions
- Inner error bar is PDF uncertainty
- Outer error is quadratic sum: PDF +scale+frag

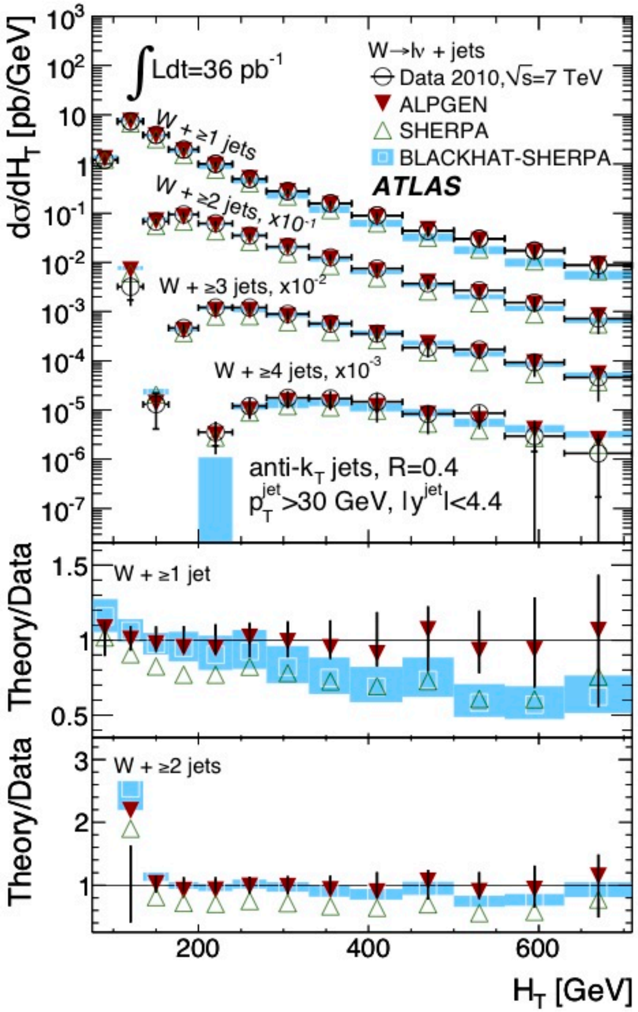
Good agreement with epWZ and NNPDF2.3coll sets
- S-quark enhanced PDFs are favored
- Confirms preference for SU(3) symmetric sea

Summary

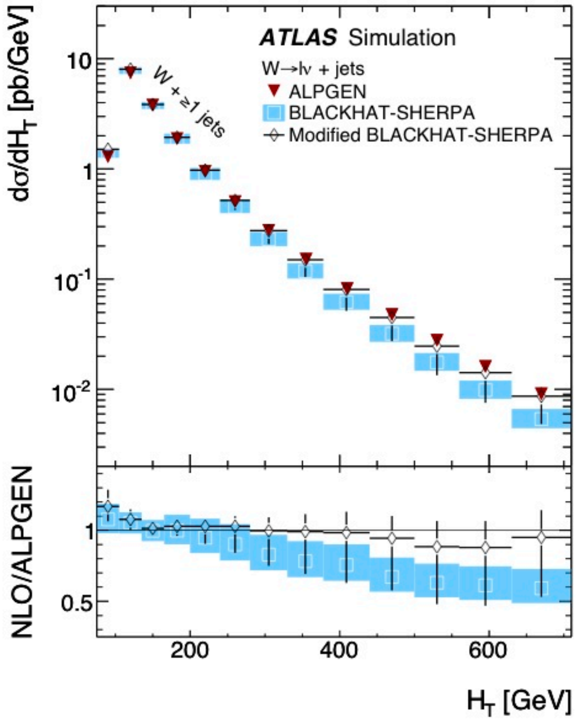
- Experimental uncertainties are becoming smaller than theoretical predictions, in large regions of phase space, with 2010-2011 data
  - Higher jet multiplicities and P_T ranges
- Experimental study provides insight on QCD models
  - Construction of PDF: flavor symmetric light quark sea favored (W+c studies)
  - Impact of missing higher jet multiplicity and modification by exclusive summation (W/Z+jets)
- Input to Higgs and new physics searches
  - Validation of 3^{rd} jet veto in VBF selection
- More high precision results will come with 2012 ATLAS data

Backup

W+jets: scalar P_T sum (HT)

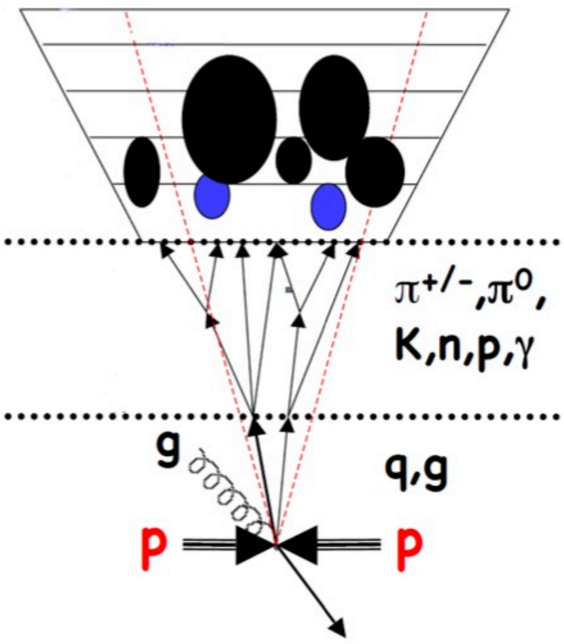


$$H_T = \sum_{\text{leptons, jets}} |p_T|$$



- HT is sensitive to factorization and normalization scales in fixed-order calculations
- Discrepancy at large HT (higher jet multiplicity) in BLACKHAT due to limited order of calculations
- Agreement improved on HT with BlackHat by replacing NLO W+≥1 jet with exclusive sum:
  - W+≥1 = (W+1) + (W+2) + (W+3) + (W+≥4)
  - Confirmed by Z+jets analysis

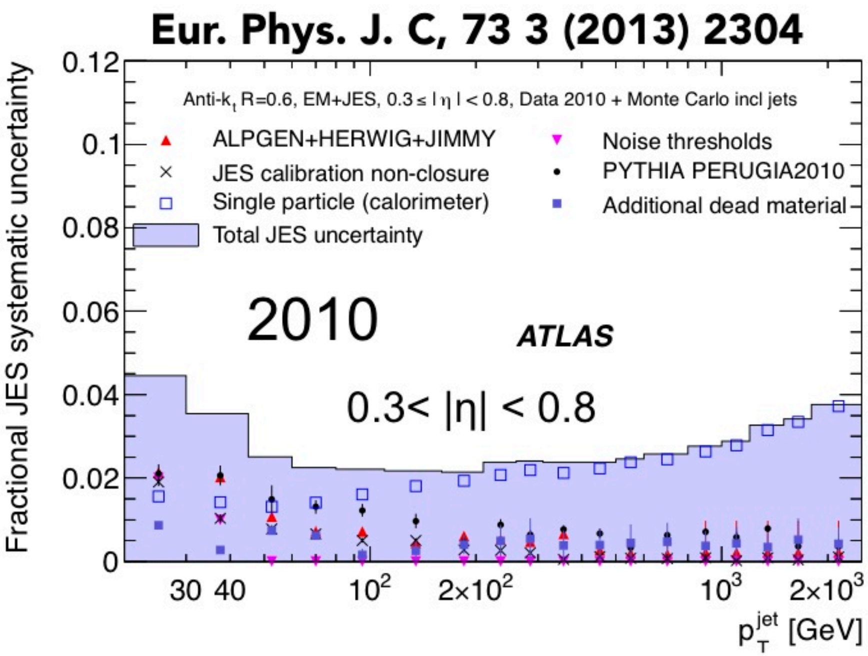
Jet Reconstruction

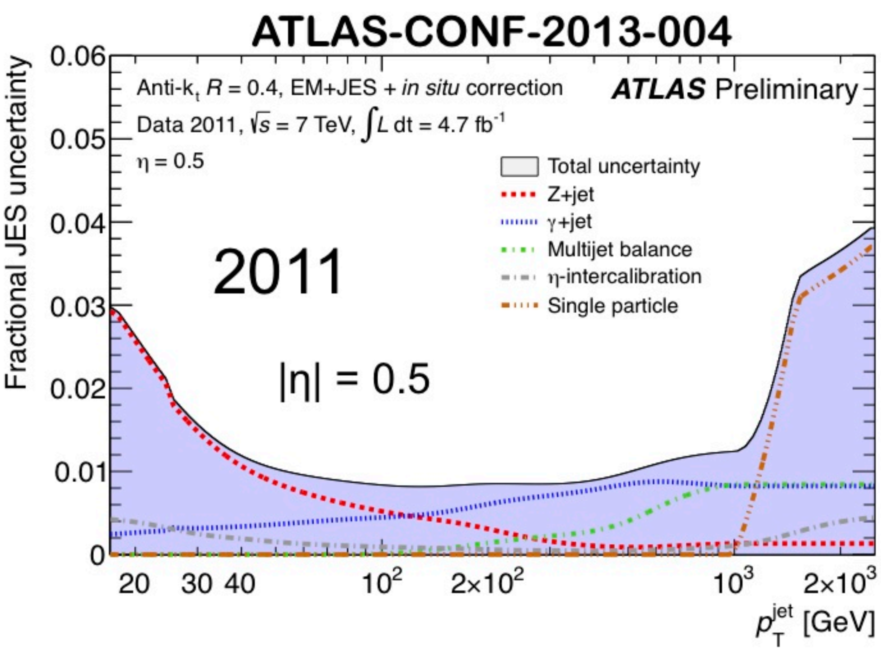


Calorimeter cells calibrated to electromagnetic (EM) scale

- Input to jet reconstruction
  - 3D topological clusters
    - Uses nearest neighbor energy significance to localize showers in calorimeter
    - Efficient noise suppression
- Jet reconstruction
  - Jets are reconstructed using the anti-Kt algorithm with size parameter R set at 0.4
- Jet Calibration
  - Energy and momentum of a jet measured in the calorimeter are corrected
    - For non-compensation, energy losses in dead material, shower leakage

Jet Energy Scale



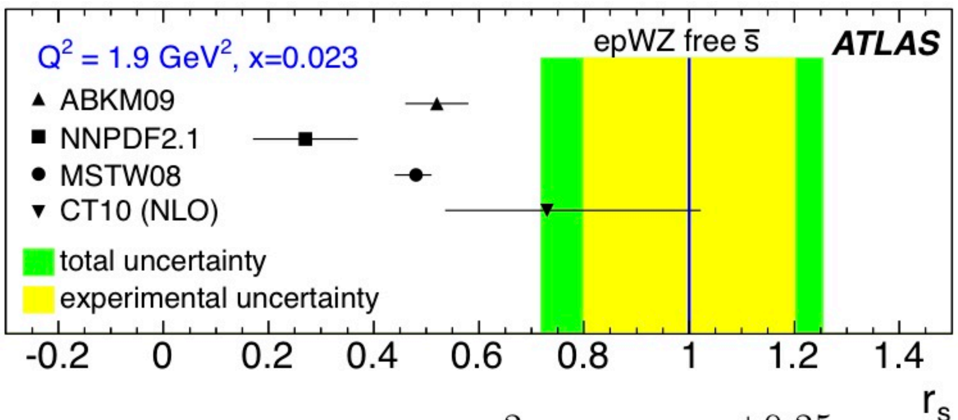


- 2010 JES calibration from MC
- Uncertainties from MC, single hadron response and dijet balance validated using in-situ techniques

- 2011 JES calibration from MC with corrections using in situ technique
  - Uncertainties from in-situ techniques

Impact of W, Z data on PDF

- Little is known about s-quark, current information from neutrino-nucleon scattering
- Flavor SU(3) symmetry suggest equal light sea quark distributions
- But strange quarks might be suppressed due to mass effect
- W, Z differential cross section measurements sensitive to s-PDF at Bjorken x ≈ 0.01
  - Use ATLAS W,Z and HERA ep data in HERAFitter (NNLO) -> epWZfit



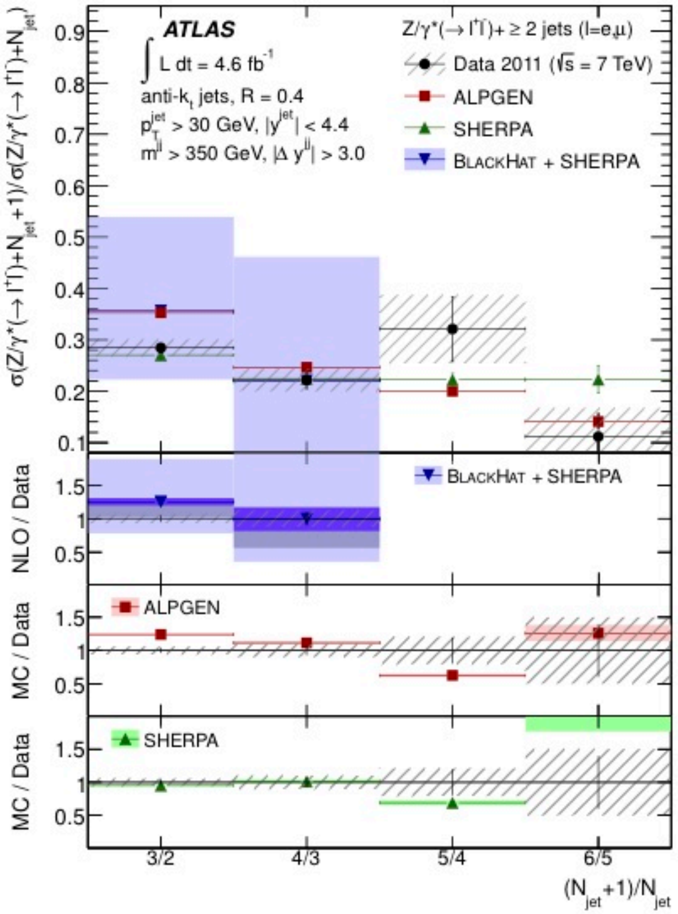
$$r_s(0.023, 1.9\text{GeV}^2) = 1.00^{+0.25}_{-0.28}$$

Z+jets scaling

- Poisson scaling, well known in FSR QED from e+e- colliders, when large difference between the scale of the process Q and the radiation cut-off scale Q0
  - For Q>>Q0 each emission is independent from previous one
- At hadron colliders, QCD jet radiation of the initial state partons has huge impact.
  - Poisson scaling ($R_{(n+1)/n} = \langle n\rangle/n+1$; $P_n = \langle n\rangle^n e^{-\langle n\rangle} / n!$) – Abelian
    - With large leading jet PT cut, we move to sufficiently high x, such that additional jet ratios are unaffected by the PDF
  - Staircase scaling ($R_{(n+1)/n} = e^{-b}$; $\sigma_n = \sigma_0\, e^{-bn}$) – non Abelian
    - Appears with democratic jet selection and no major scale separation
    - $R_{1/0}$ suppressed by PDF (by 60%)

Z+jets: ratio

- Ratio of the cross sections for two successive multiplicities, in events passing the VBF pre-selection



W, Z cross sections

- Uncertainties dominated by lepton reconstruction, identification efficiency and Missing ET for W

Electron channels (%)	$W^\pm$	W^+	W^-	Z
Trigger	0.4	0.4	0.4	<0.1
Electron reconstruction	0.8	0.8	0.8	1.6
Electron identification	0.9	0.8	1.1	1.8
Electron isolation	0.3	0.3	0.3	—
Electron energy scale and resol.	0.5	0.5	0.5	0.2
Non-operational LAr channels	0.4	0.4	0.4	0.8
Charge misidentification	0.0	0.1	0.1	0.6
QCD background	0.4	0.4	0.4	0.7
Electroweak+$t\bar{t}$ background	0.2	0.2	0.2	<0.1
E_T^{miss} scale and resolution	0.8	0.7	1.0	—
Pile-up modeling	0.3	0.3	0.3	0.3
Vertex position	0.1	0.1	0.1	0.1
$C_{W/Z}$ theoretical uncertainty	0.6	0.6	0.6	0.3
Total experimental uncertainty	**1.8**	**1.8**	**2.0**	**2.7**
$A_{W/Z}$ theoretical uncertainty	1.5	1.7	2.0	2.0
Total excluding luminosity	2.3	2.4	2.8	3.3
Luminosity	3.4			

Muon channels (%)	$W^\pm$	W^+	W^-	Z
Trigger	0.5	0.5	0.5	0.1
Muon reconstruction	0.3	0.3	0.3	0.6
Muon isolation	0.2	0.2	0.2	0.3
Muon p_{T} resolution	0.04	0.03	0.05	0.02
Muon p_{T} scale	0.4	0.6	0.6	0.2
QCD background	0.6	0.5	0.8	0.3
Electroweak+$t\bar{t}$ background	0.4	0.3	0.4	0.02
E_T^{miss} resolution and scale	0.5	0.4	0.6	-
Pile-up modeling	0.3	0.3	0.3	0.3
Vertex position	0.1	0.1	0.1	0.1
$C_{W/Z}$ theoretical uncertainty	0.8	0.8	0.7	0.3
Total experimental uncertainty	**1.6**	**1.7**	**1.7**	**0.9**
$A_{W/Z}$ theoretical uncertainty	1.5	1.6	2.1	2.0
Total excluding luminosity	2.1	2.3	2.6	2.2
Luminosity	3.4			