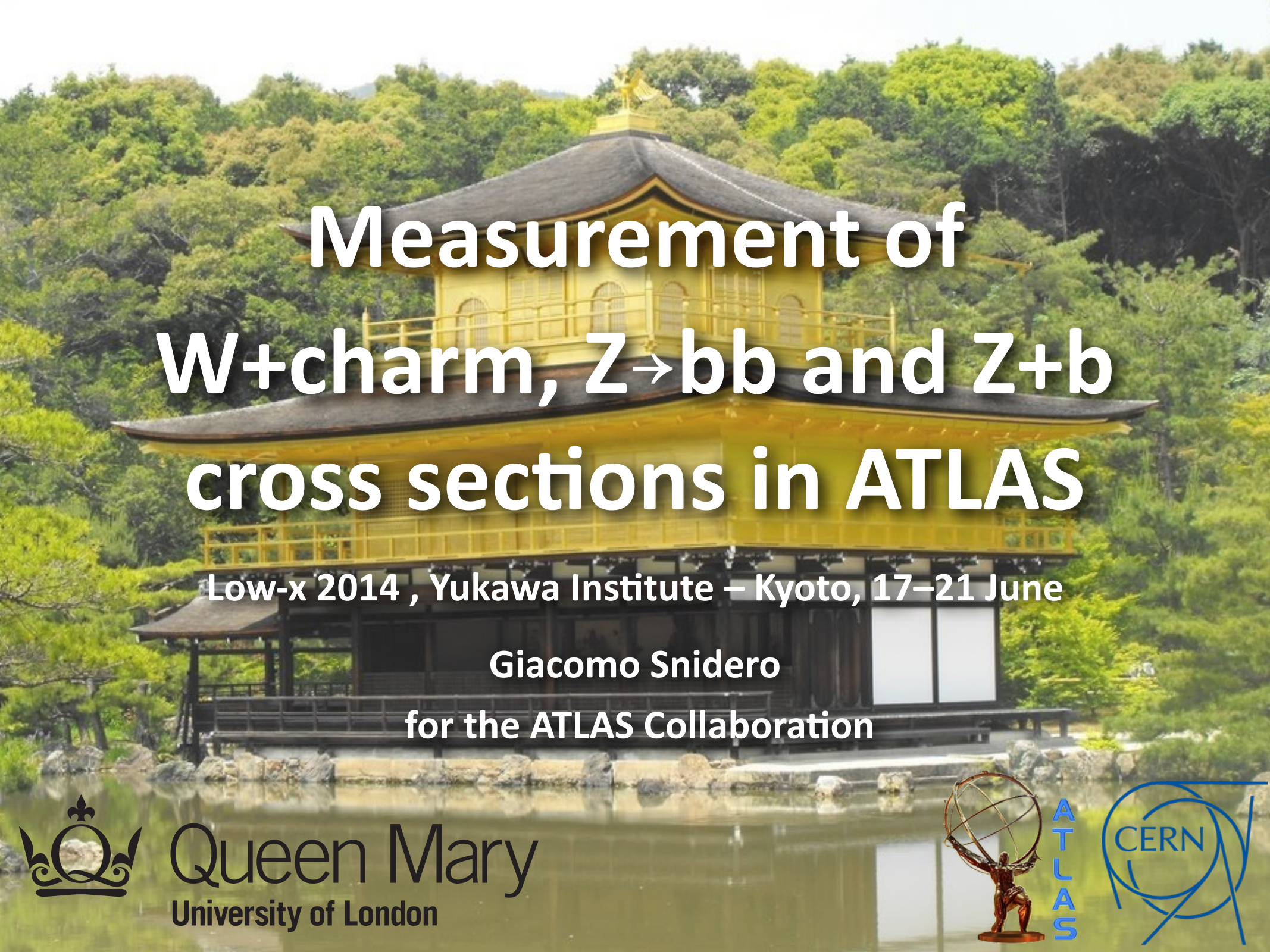


Measurement of W+charm, Z→bb and Z+b cross sections in ATLAS

Low-x 2014 , Yukawa Institute – Kyoto, 17–21 June

Giacomo Snidero

for the ATLAS Collaboration

Queen Mary
University of London

ATLAS

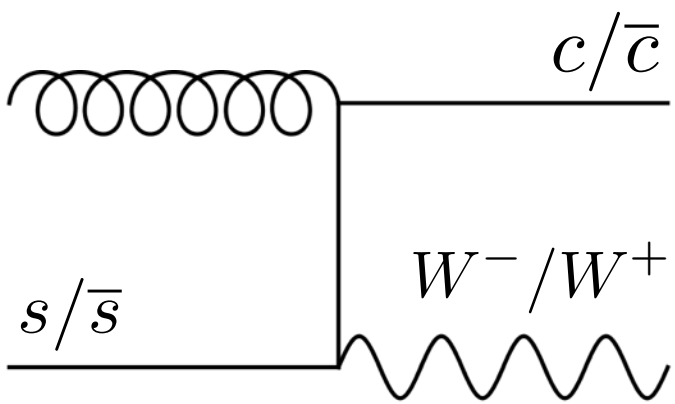
CERN

Measurement of the production of a W boson in association with a charm quark in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector

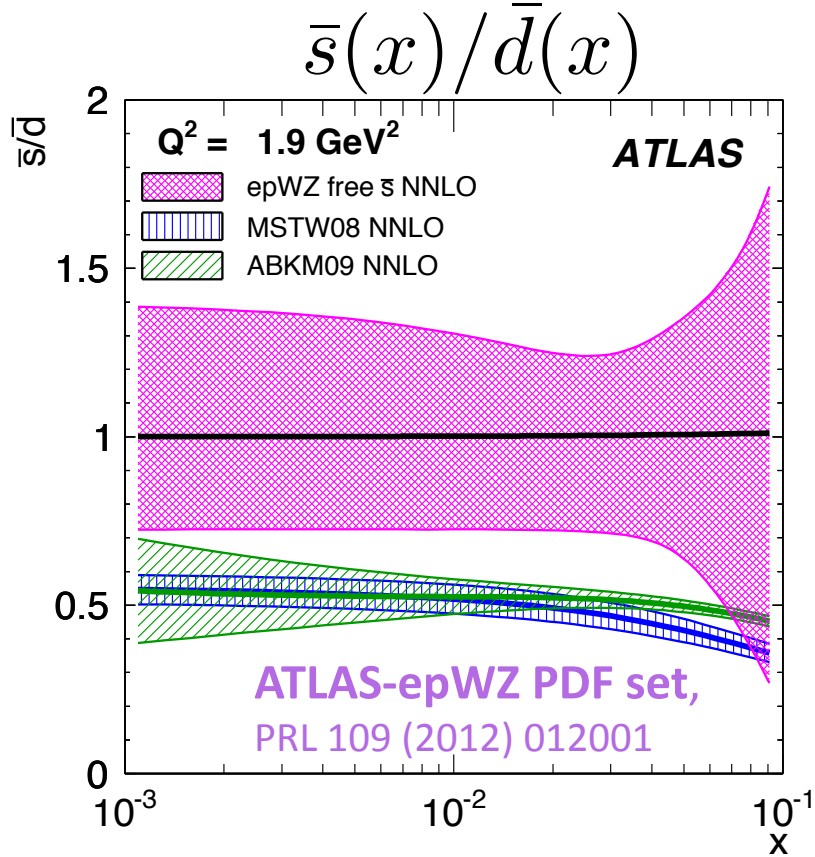
JHEP 05 (2014) 068

W+charm

- Production of a W boson with a *single* charm quark
- LO process is $gq \to Wc$, where q= u, s, b.
  The s-quark initiated scatterings are ≈ 80% in pp collisions at 7 TeV
- **W+charm probes the s-quark PDF**
  - Loosely constrained by existing data
  - Strange density is typically suppressed but e.g. an ATLAS QCD analysis of W, Z data suggests $s, \bar{s}/\bar{d} \sim 1$



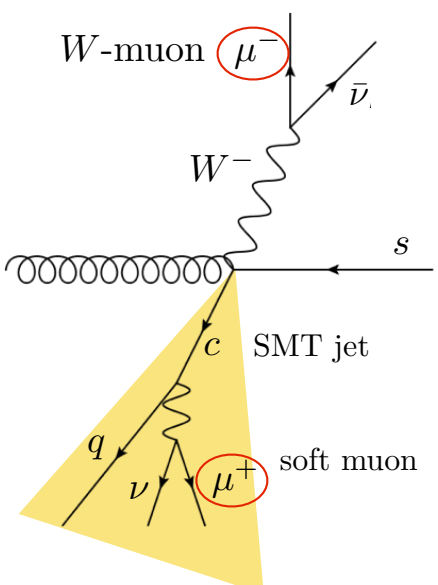
Leading W+charm diagram



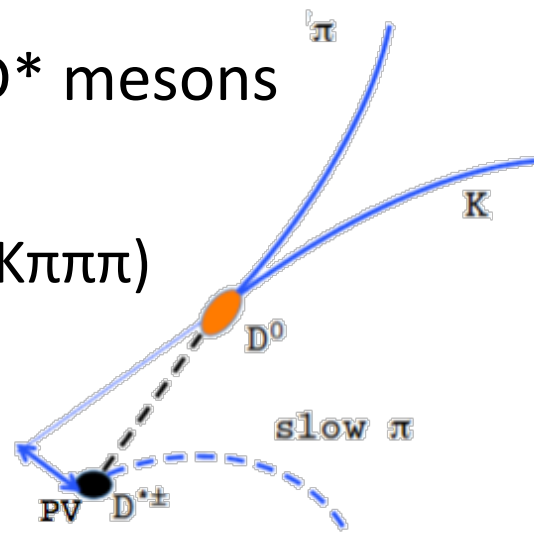
Measurement Strategy (1/2)

- Reconstruct W → eν / μν
- *Two independent methods for the c-quark tagging*
  - Different kinematic regions ⟹ two fiducial cross section:

$$\sigma_{\text{fid}}^{\text{OS}-\text{SS}}(W c\text{-jet}) \, , \sigma_{\text{fid}}^{\text{OS}-\text{SS}}(\text{WD}^{(*)})$$



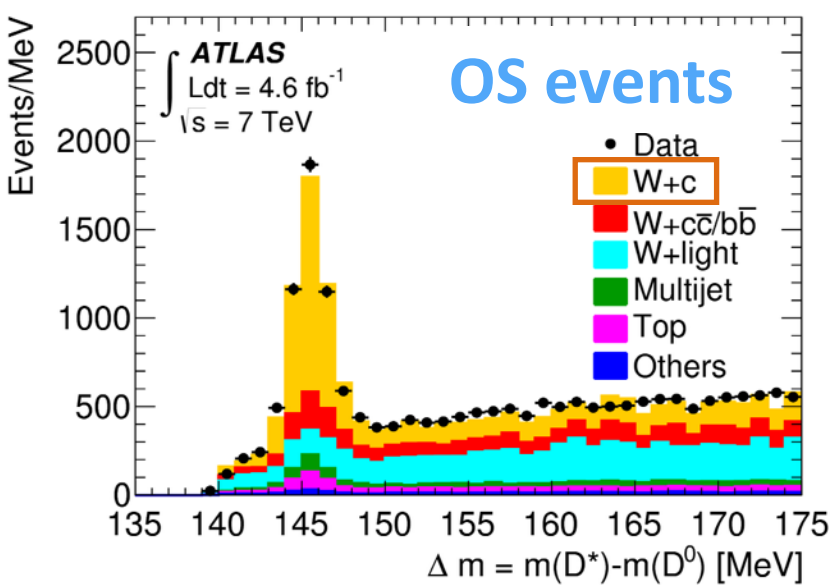
- **Wc-jet**: c-quark semileptonic decay to a muon within a jet – "soft muon tagging"
  (p_T(c-jet) > 25 GeV, |η|< 2.5)
- **WD$^{(*)}$**: hadronic decays of D and D* mesons in the tracker (p_T(D) > 8 GeV, |η|< 2.2)
  - D → Kππ ; D* → D^{0}π (D^0 → Kπ, Kππ^0, Kπππ)

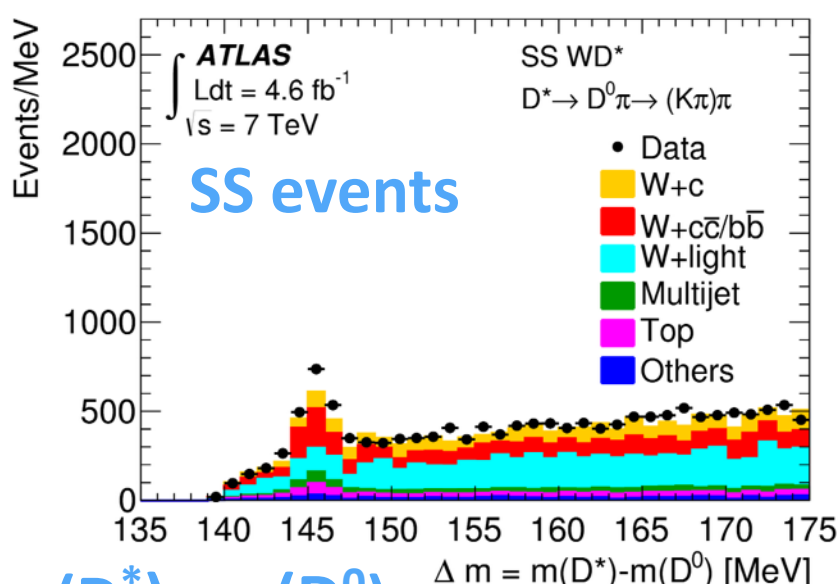


- Data analysed: √s = 7 TeV , ∫Ldt = 4.6 fb^{-1} (2011)

Measurement Strategy (2/2)

- Cross section measured
  - $\sigma_{\mathrm{fid}}^{\mathrm{OS-SS}}(W^+\bar{c})$, $\sigma_{\mathrm{fid}}^{\mathrm{OS-SS}}(W^-c)$ and their ratio
  - Differentially in: W-decay lepton $|\eta|$, jet multiplicity, p_T(D meson)
- **Signal yield from difference of OS and SS events (OS-SS)**
  - W and c-quark produced with opposite charges: signal is mainly OS
  - Backgrounds largely OS/SS symmetric: for most processes OS ≈ SS

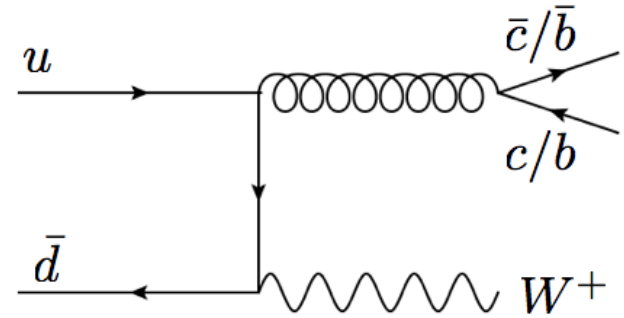




m(D*) - m(D⁰)

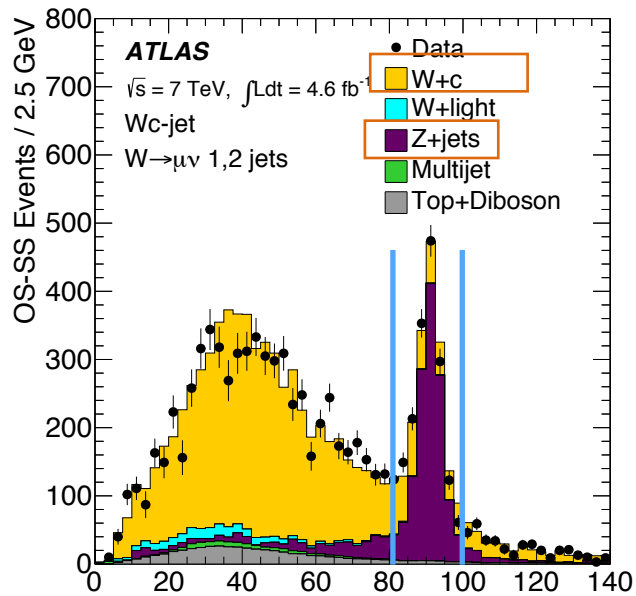
Signal and Backgrounds

- *Signal purity ≈ 80%, owing to OS-SS event yields*
- Signal events yield
  - $WD^{(*)}$: template fits to $D^{(*)}$ mass distributions
  - Wc-jet: cut-and-count
- Backgrounds
  - *W+bb/W+cc: cancel out in OS-SS events*
  - *W+light-jets*: similar diagram signal, slightly OS/SS asymmetric
  - Z+jets: Wc-jet , μ channel only
  - Multijet: QCD cc/bb events, slight OS/SS asym.
  - Top quark, Diboson: small



W+bb/cc production

W(→μν) + c-jet



m(W-decay μ, soft μ)

Systematic Uncertainties

Wc-jet

Relative systematic uncertainty in %	$W(e\nu)c$-jet	$W(\mu\nu)c$-jet
Lepton trigger and reconstruction*	0.7	0.8
Lepton momentum scale and resolution*	0.5	0.6
Lepton charge misidentification	0.2	-
Jet energy resolution*	0.1	0.1
Jet energy scale	2.4	2.1
$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction*	0.8	0.3
Background yields	4.0	1.9
Soft-muon tagging	1.4	1.4
c-quark fragmentation	2.0	1.6
c-hadron decays	2.8	3.0
Signal modelling	0.9	0.2
Statistical uncertainty on response	1.4	1.4
Integrated luminosity*	1.8	1.8
Total	6.5	5.3

WD(*)

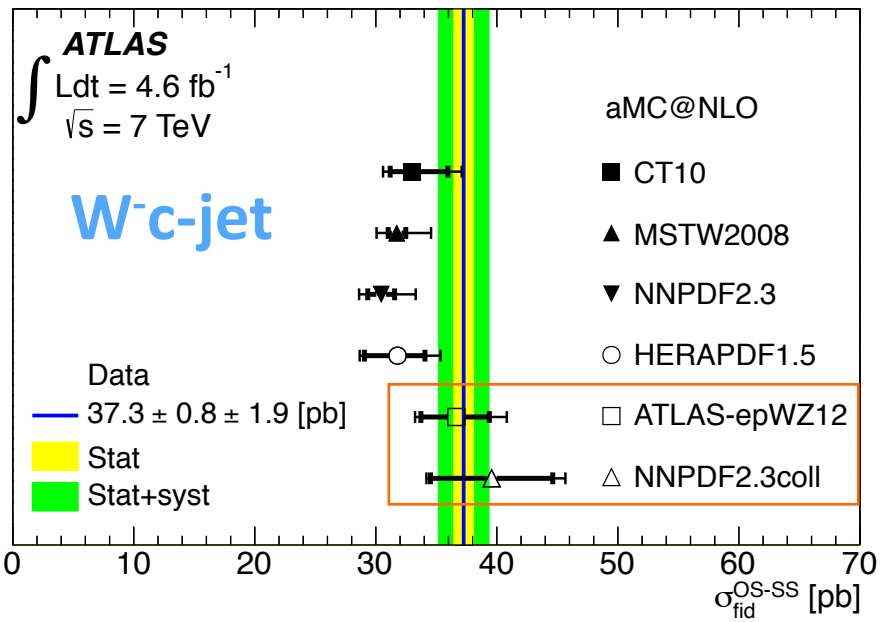
Relative systematic uncertainty in %	WD	WD^*
Lepton trigger and reconstruction*	0.4	0.4
Lepton momentum scale and resolution*	0.2	0.2
Lepton charge misidentification	0.1	0.1
$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction*	0.4	0.4
W background estimation	1.3	1.3
Background in $WD^{(*)}$ events	0.7	0.6
W efficiency correction	0.6	0.6
Tracking efficiency	2.1	2.2
Secondary vertex reconstruction efficiency	0.4	0.4
D^* isolation efficiency	-	2
Fitting procedure	0.8	0.5
Signal modelling	1.4	1.9
Statistical uncertainty on response	0.2	0.2
Branching ratio	2.1	1.5
Extrapolation to fiducial region	0.8	0.8
Integrated luminosity*	1.8	1.8
Total	4.3	4.8

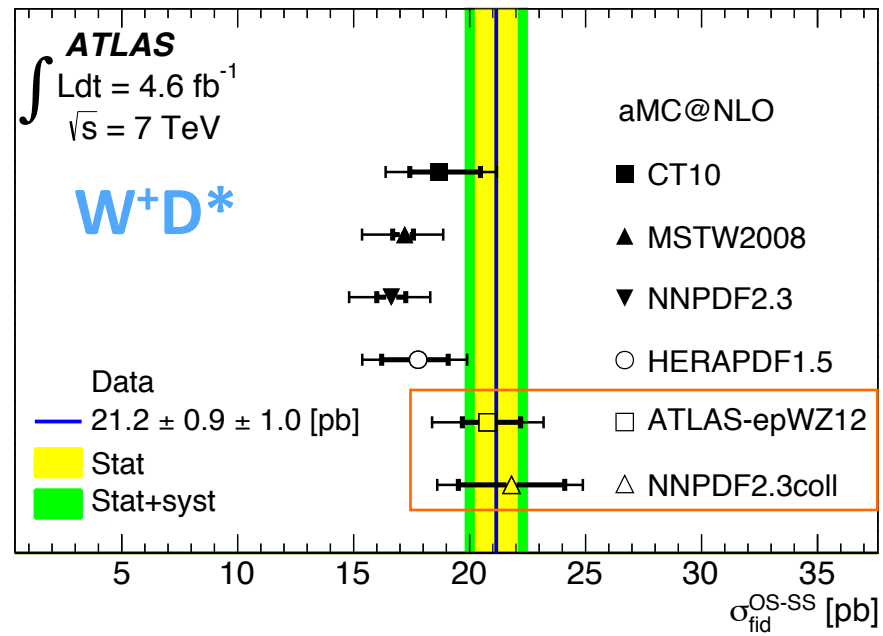
- Leading uncertainties: modelling of the c-quark decay (acceptance)
- W+D$^{(*)}$ slightly smaller systematics (but larger data statistical unc.)

W+charm – Results (1/2)

- Measured cross sections compared to aMC@NLO+Herwig++ with 6 PDF sets
  - CT10, MSTW2008, NNPDF2.3, HERAPDF1.5: $s, \bar{s}/\bar{d} < 1$
  - NNPDFcoll2.3, ATLAS-epWZ12: $s, \bar{s}/\bar{d} \sim 1$
- **W+charm data favours PDF sets with non-suppressed strange density**
  - Wc-jet and WD$^{(*)}$ results are consistent

	$\sigma_{\text{fid}}^{\text{OS-SS}}$ [pb]
$W^+\bar{c}$-jet	$33.6 \pm 0.9\,(\text{stat}) \pm 1.8\,(\text{syst})$
W^-c-jet	$37.3 \pm 0.8\,(\text{stat}) \pm 1.9\,(\text{syst})$
W^+D^-	$17.8 \pm 1.9\,(\text{stat}) \pm 0.8\,(\text{syst})$
W^-D^+	$22.4 \pm 1.8\,(\text{stat}) \pm 1.0\,(\text{syst})$
W^+D^{*-}	$21.2 \pm 0.9\,(\text{stat}) \pm 1.0\,(\text{syst})$
W^-D^{*+}	$22.1 \pm 0.8\,(\text{stat}) \pm 1.0\,(\text{syst})$

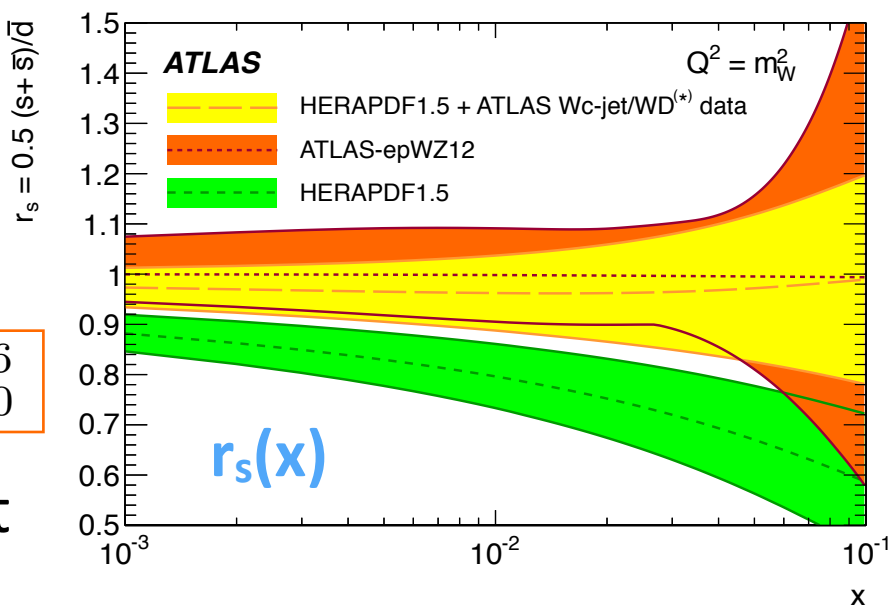




W+charm – Results (2/2)

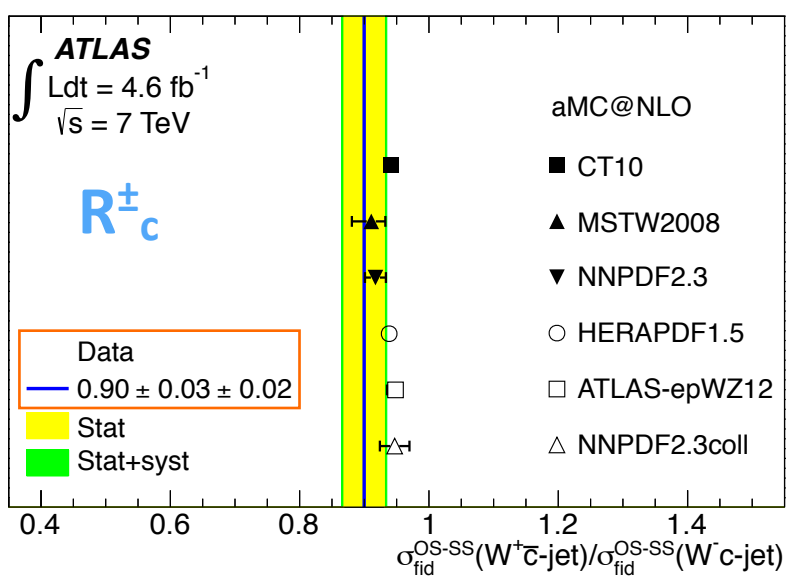
- **Strange-to-down sea PDF ratio, $r_s(x)$,** constrained from W+charm data exclusively in the HERA1.5 PDF set
  - The x-averaged result **consistent with no suppression**

$$r_s \equiv \frac{s+\bar{s}}{2\bar{d}} = 0.96^{+0.26}_{-0.30}$$



- Cross section W-charge ratio consistent with $s = \bar{s}$ (stat. unc. limited)

$$R_c^{\pm} \equiv \frac{\sigma_{\text{fid}}^{\text{OS-SS}}(W^+\bar{c})}{\sigma_{\text{fid}}^{\text{OS-SS}}(W^-c)} \sim \frac{\bar{s} + V_{cd}^2 \cdot \bar{d}}{s + V_{cd}^2 \cdot d}$$



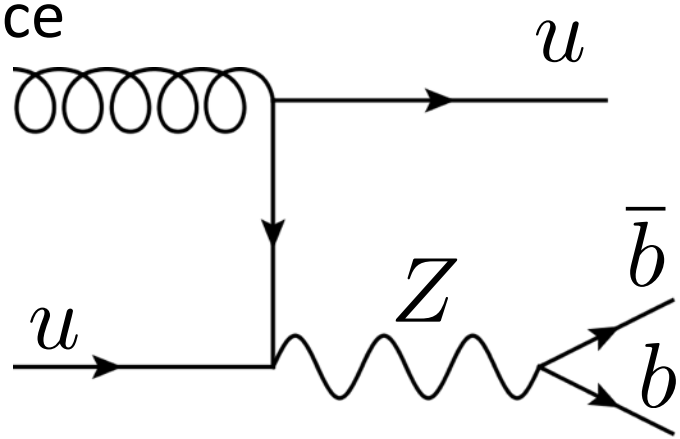
- Differential cross sections in W-decay lepton$|\eta|$, jet multiplicity and $p_T(D)$ in agreement with shapes from all PDF sets

Measurement of the cross section of high transverse momentum $Z \to bb$ production in proton-proton collisions at $\sqrt{s}$ = 8 TeV with the ATLAS Detector

Submitted to PLB – arXiv:1404.7042

$Z \to bb$

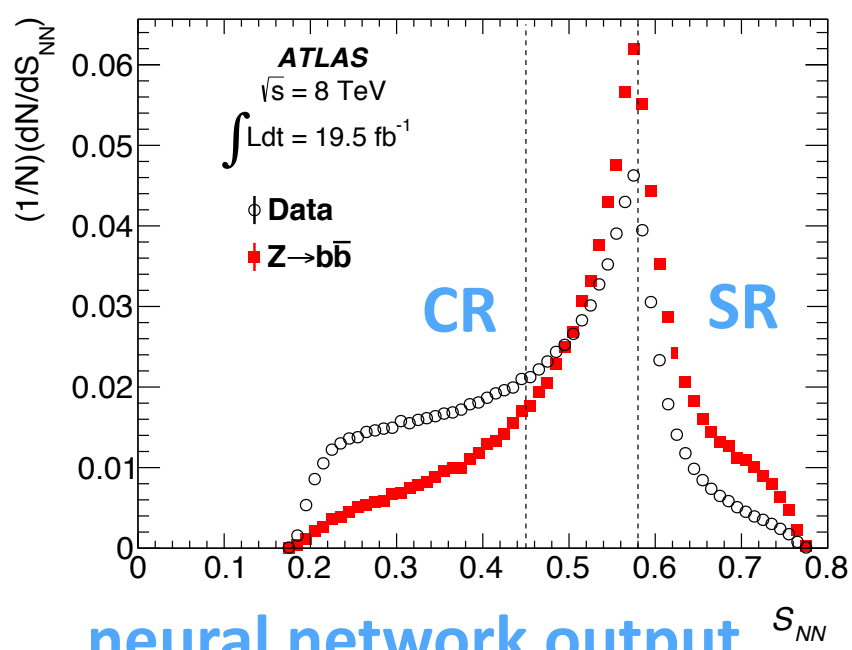
- Z boson decay to a b-quark pair in the **"boosted" regime** (p_T>200 GeV)
  - First LHC measurement of a high-p_T Z boson + jets from **fully hadronic final state**
- Demonstrates the validity of
  - NLO + parton shower predictions for high-p_T Z boson + jets
  - Analysis techniques for hadronic decays of boosted objects, relevant for
    - $H \to bb$ and Searches of BSM resonances
- Can provide benchmark for ATLAS performance
  - e.g. $Z \to bb$ peak to constrain b-jet energy scale
- Data analysed
  - $\sqrt{s}$ = 8 TeV , $\int L dt$ = 19.5 fb^{-1} (2012)



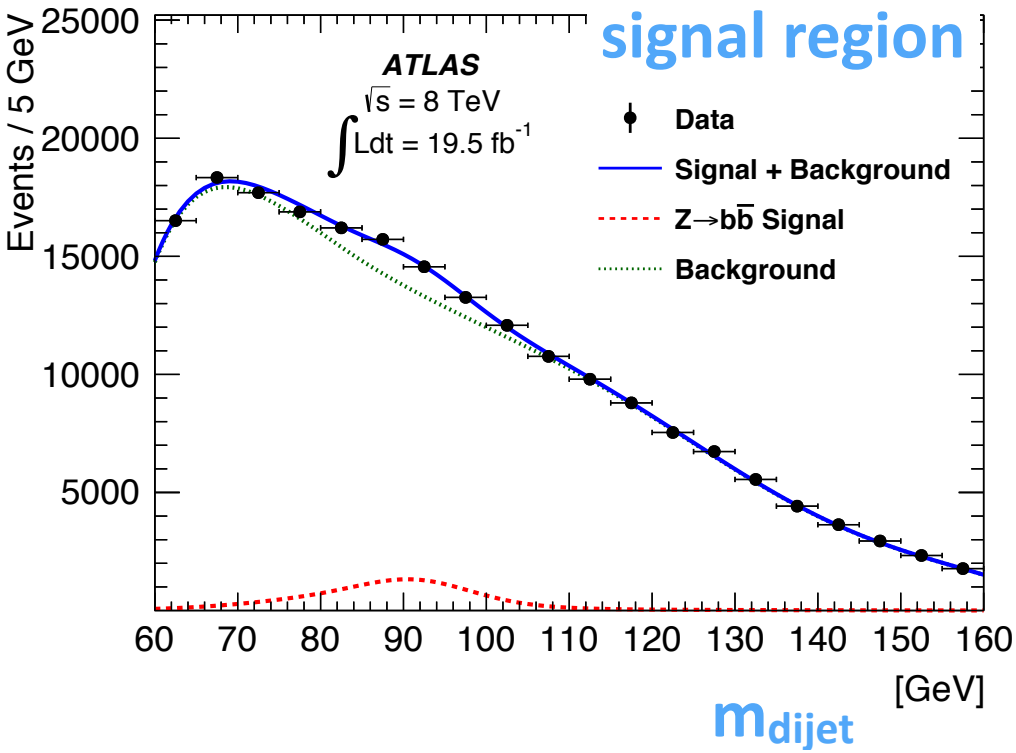
Leading $Z \to bb$ diagram at the LHC

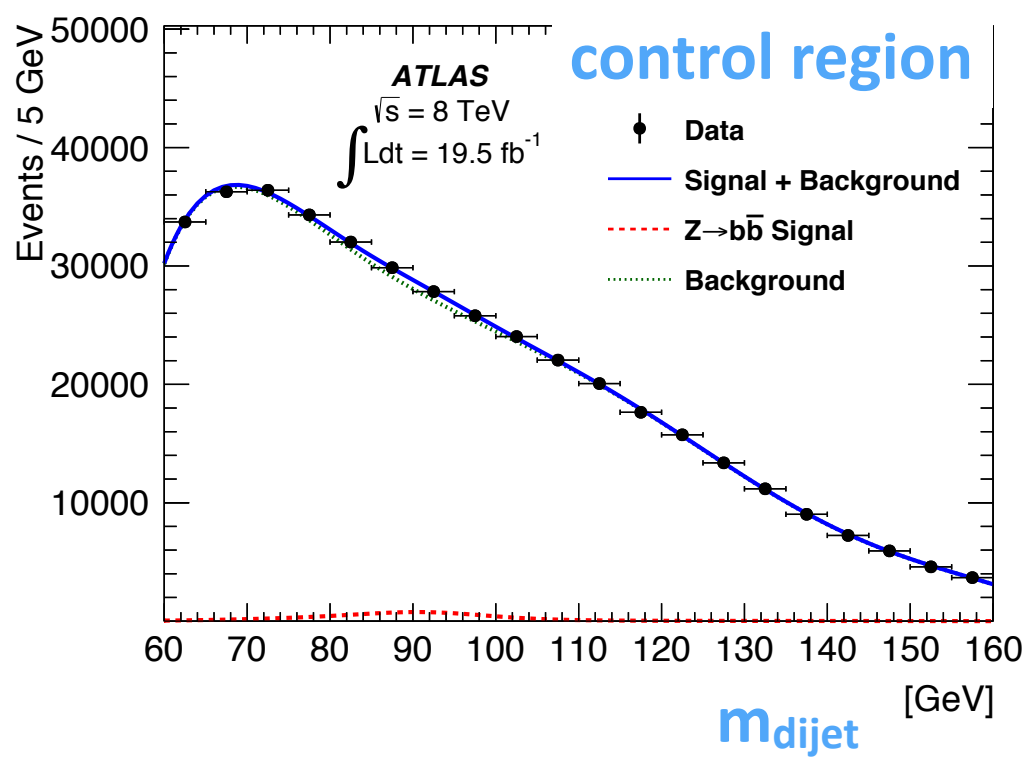
Measurement Strategy

- Select data with 2 b-tagged jets (dijet) in 3 to 5 total jets
  - *S/B of few % due to overwhelming QCD multijet background*
- Quantities $|\eta_{dijet}|$ and $\Delta\eta$(dijet, balancing-jet) discriminate signal and background
  - Signal (*qg* scattering) more central η w.r.t. background (mainly *gg*)
  - Combined in neural network to define in the data *signal region (SR)* and *control region (CR)*
- *Signal yield:* **simultaneous fit** to $\mathbf{m_{dijet}}$ **distributions** in **CR** and **SR**
- Fit to signal-depleted CR determines m_{dijet} shape of multijet background



Fit (1/2)





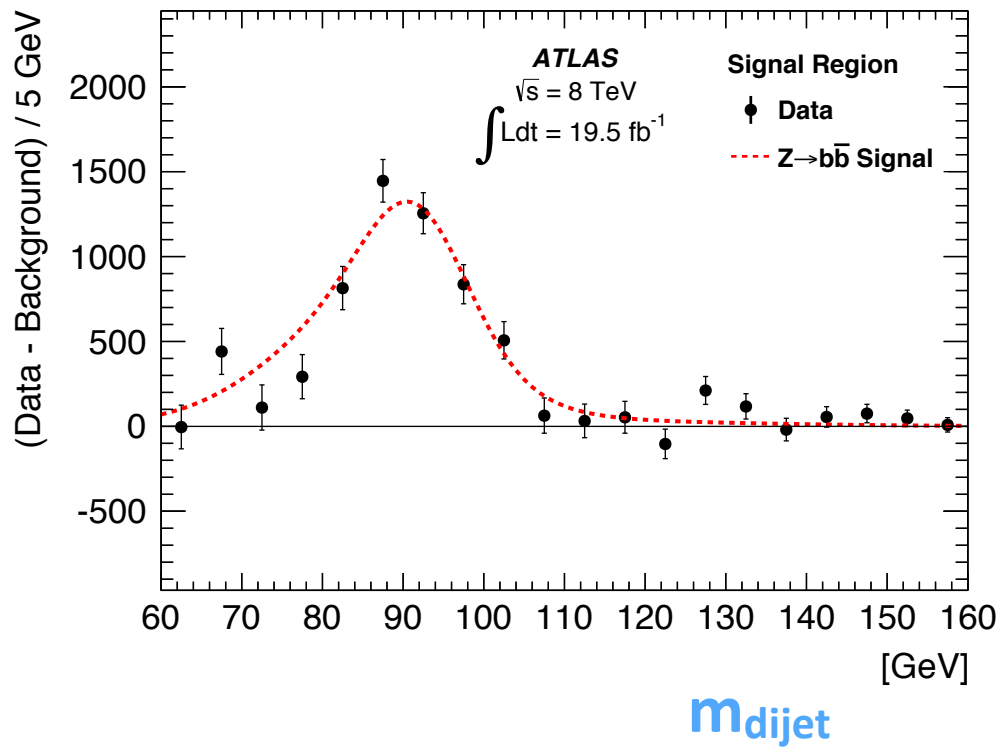
- *Signal m_{dijet} distribution*: sum of 3 gaussians (empirically)
  - 2 free parameters: normalisation in SR and first gaussian peak position
  - Other params fixed from separate fit to signal MC m_{dijet} distribution
  - In the CR, signal yield fraction fixed from MC

Fit (2/2)

- *Background m_{dijet} distributions*:
  - Multijet: 7th order polynomial shape (CR fit)
    - 9 free params: polynomial coefficients and normalisations in CR & SR
  - ttbar, W → qq', Z → cc: small, gaussians fitted in MC m_{dijet} distributions

- Binned maximum likelihood fit
  - Total of 11 parameters
  - Simultaneously fit in SR and CR
  - *Signal yield extracted*
    6400 ± 600 (stat. unc.)
    from ≈ 3M events

signal region: data - bkg



Systematic Uncertainties

Source of uncertainty	$\Delta\sigma^{\text{fid}}_{Z\to b\bar{b}}(\%)$
Jet Energy Scale	+6.5/-5.0
Jet Energy Resolution	±5.1
b-tagging	±3.6
Trigger Modelling	±6
Control Region Bias	+4.9/-5.5
Signal $\mathcal{S}_{\mathcal{NN}}$ Modelling	±2.9
Signal m_{dijet} Shape	±2.2
$Z \to c\bar{c}$ Normalisation	±0.4
$t\bar{t}$ Normalisation	±1.1
$W \to q\bar{q}'$ Normalisation	±1.0

Jet energy calibration affects both fit and acceptance

Modelling of the jet triggers efficiency (acceptance)

CR definition changes multijet m_{dijet} distribution

Z→bb – Result

- Measured cross section

$$\sigma^{\text{fid}}_{Z\to b\bar{b}} = 2.02 \pm 0.20\ (\text{stat.}) \pm 0.25\ (\text{syst.}) \pm 0.06\ (\text{lumi.}) = 2.02 \pm 0.33\ \text{pb}$$

- **Data in agreement with two NLO + Parton Shower predictions**

POWHEG + PYTHIA 8: $\sigma_{Z\to b\bar{b}} = 2.02^{+0.25}_{-0.19}\ (\text{scales})\ ^{+0.03}_{-0.04}\ (\text{PDF})\ \text{pb}$

aMC@NLO + Herwig++: $\sigma_{Z\to b\bar{b}} = 1.98^{+0.16}_{-0.08}\ (\text{scales}) \pm 0.03\ (\text{PDF})\ \text{pb}$

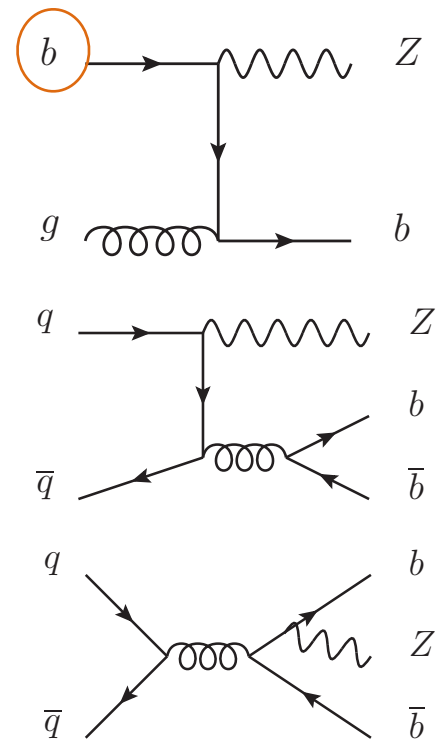
  - Independent ME generator and PS simulation
  - CT10 PDF set

Measurement of differential production cross sections for a Z boson in association with at least one or two b-jets in 7 TeV proton-proton collisions with the ATLAS detector

To be submitted to JHEP

Z+b

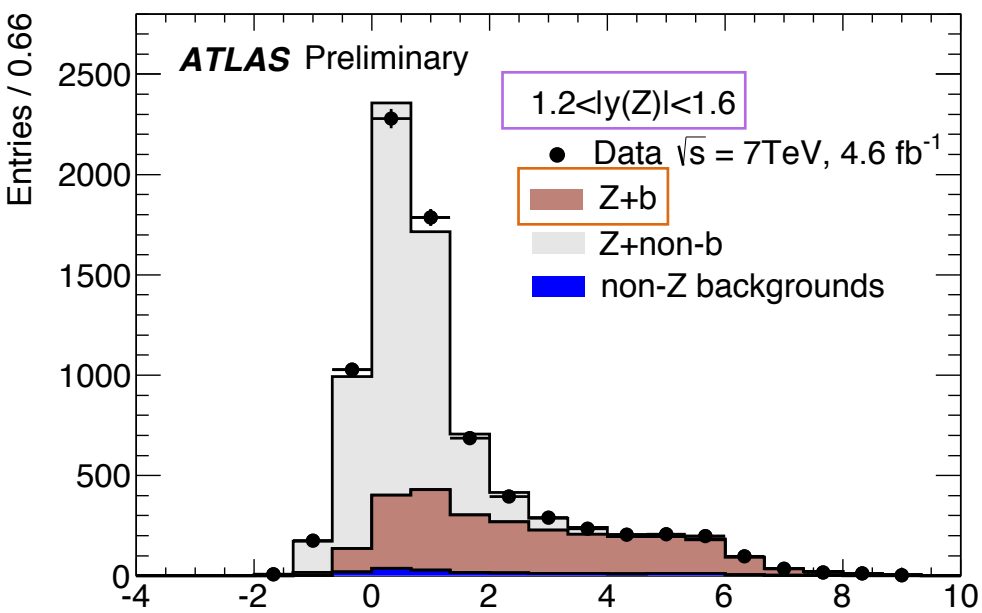
- Production of a $Z/\gamma^* \to ee/\mu\mu$ decay in association with b-jets
- Test predictions of pQCD for **heavy-flavour quark** production
  - 4FNS vs 5FNS **flavour number schemes** and b-quark PDFs
  - **NLO** (MCFM, aMC@NLO) vs **LO** multi-leg (Algen, Sherpa)
- Background for
  - $(ZH) \to bb$ and BSM searches
- Measured **unfolded differential** cross sections **in 12 kinematic variables**
  - Z boson with ≥1 or ≥2 b-jets
  - e.g. ΔR(b-jet,b-jet), y(Z), p_T(Z), …
- Data analysed: $\sqrt{s}$ = 7 TeV, $\int L dt$ = 4.6 fb^{-1} (2011)

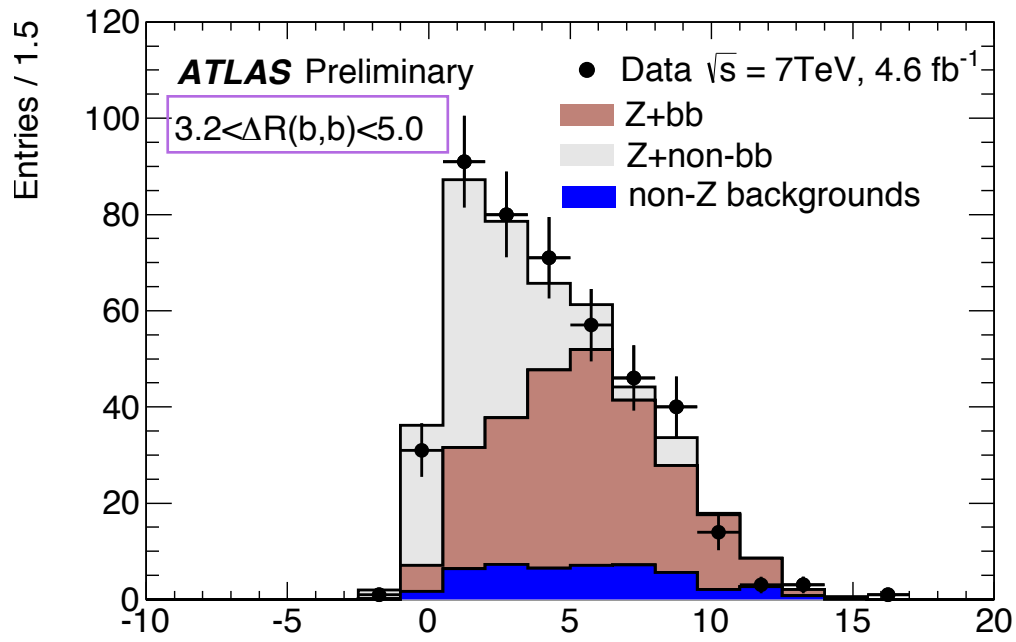


examples of Z+b diagrams

Strategy

- Major backgrounds are Z+c-jets and Z+light-jets
- *Template fits to distribution discriminating the "jet-flavour"*
  - Neural network with input secondary vertices and displaced tracks information discriminates "real" and fake b-tagged jets selected in data
  - Signal and Z+non-b background shapes from MC
    - non-Z background (top quark, multijet, diboson) are fixed





neural network output

fit data in each bin of σ(Z+b)

Systematic Uncertainties

Source of uncertainty	$\sigma(Zb)[\%]$	$\sigma(Zbb)[\%]$
b-jet tagging efficiency	3.4	9.8
c-jet mistag rate	0.2	2.3
light-jet mistag rate	0.4	0.0
JES	2.9	4.7
JER	0.3	0.7
b-jet template shape	4.8	4.8
c-jet template shape	0.2	0.6
light-jet template shape	0.9	0.9
b-jet template scale factor	N/A	2.3
MPI	2.5	0.8
gluon splitting	1.2	1.5
background normalisation	1.1	3.6
$t\bar{t}$ modelling	0.0	2.9
MC sample size	1.0	1.4
lepton scale and resolution	1.2	1.2
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.0	0.6
luminosity	1.8	1.8
total	7.7	14.0

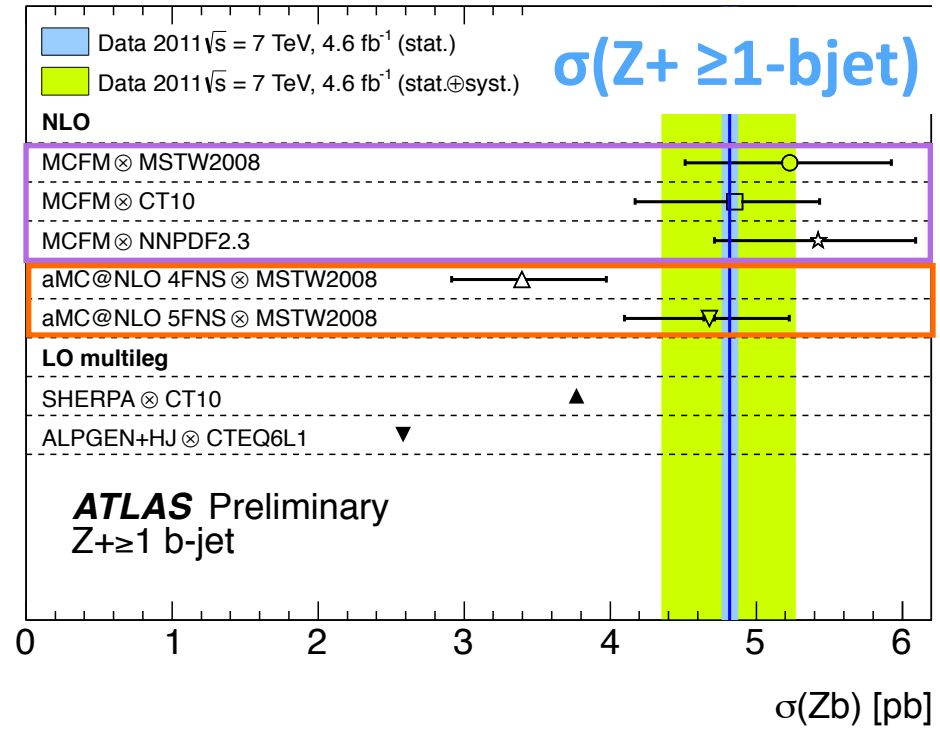
MC corrected for b-tagging efficiency measured in data

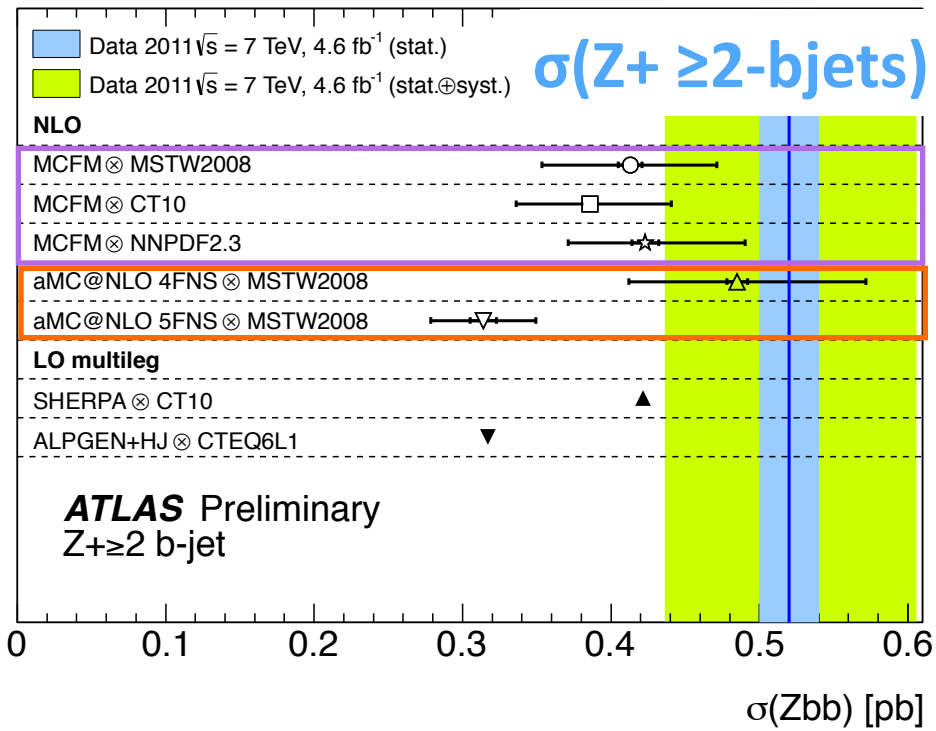
Jet energy scale modifies jet-flavour discriminant shapes and unfolding

Signal MC shape is checked in b-jets from ttbar-enriched control data sample

Z+b – Results (1/3)

- **MCFM** with various 5FNS PDF sets
  - *All in agreement with data*
  - used MSTW2008, CT10, NNPDF2.3
  - Corrected to particle level with Pythia and Sherpa
- **aMC@NLO + Herwig++** with 4FNS or 5FNS PDFs (MSTW2008)
  - *Z+ ≥1 b-jet*: 5FNS favoured, 4FNS underestimates data
  - *Z+ ≥2 b-jets*: opposite of the above
- LO multi-leg Alpgen, Sherpa
  - underestimate data, but theory uncertainties not included

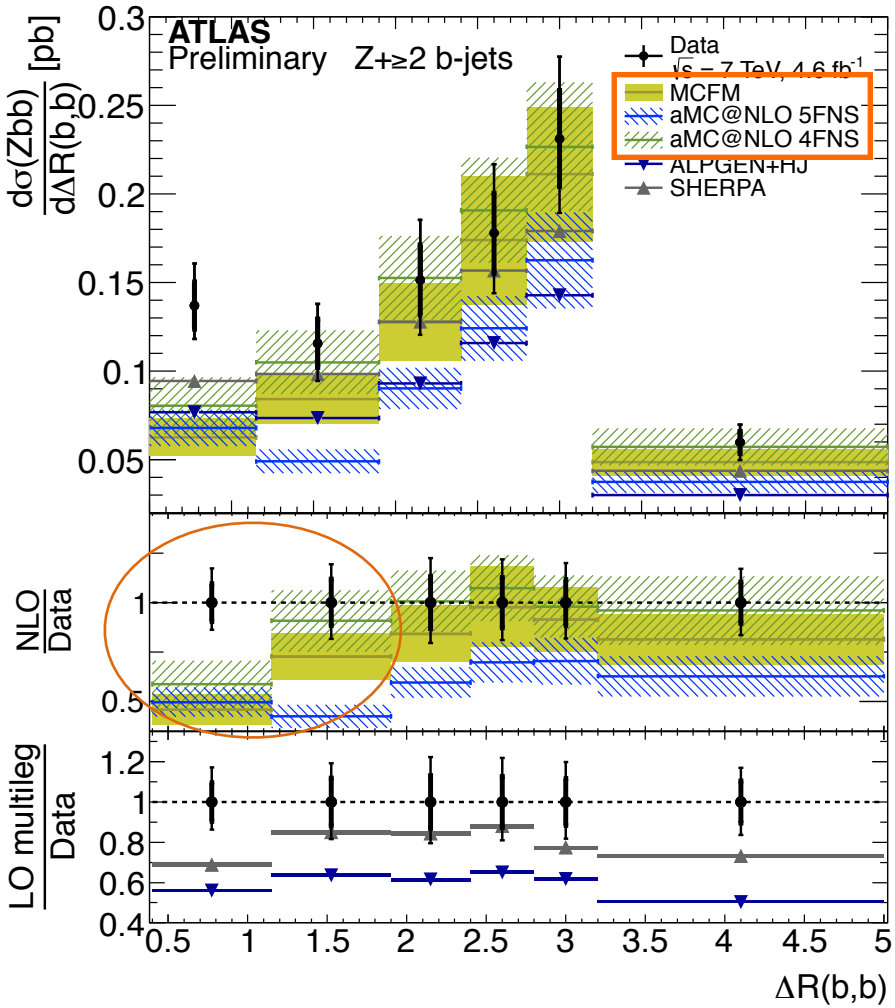




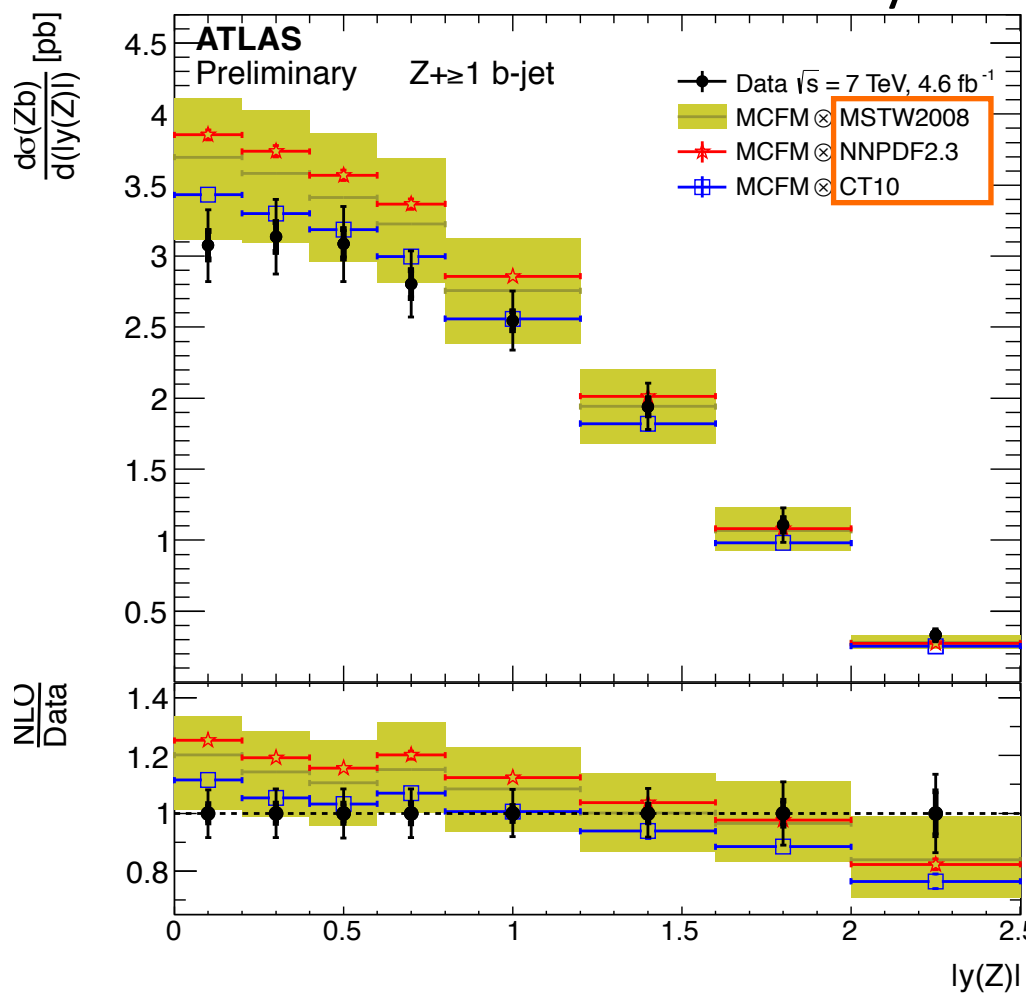
Z+b – Results (2/3)

4 examples of differential σ(Z+b)

- dσ(Z+ ≥2-bjets) / dΔR(b-jet,b-jet) : NLO underestimate small ΔR

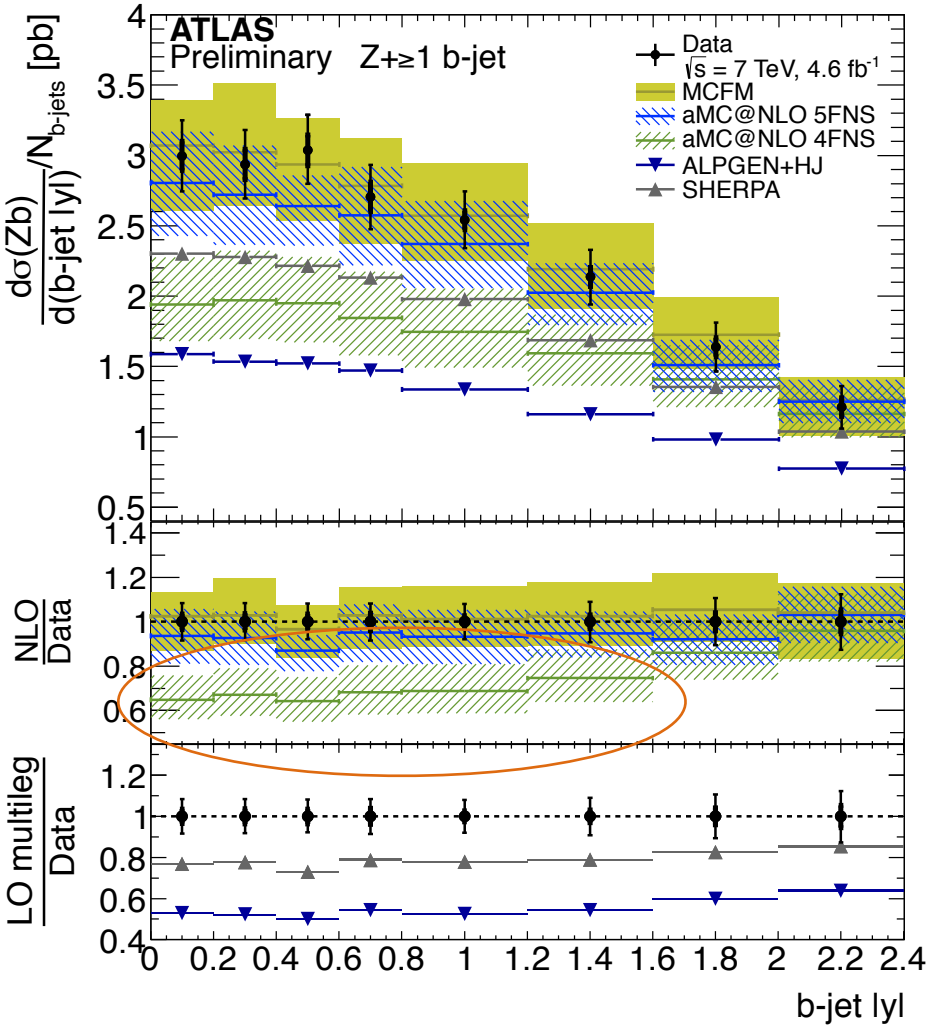


- dσ(Z+ ≥1-bjets) / dy(Z) : PDFs differences small w.r.t. scale uncertainty

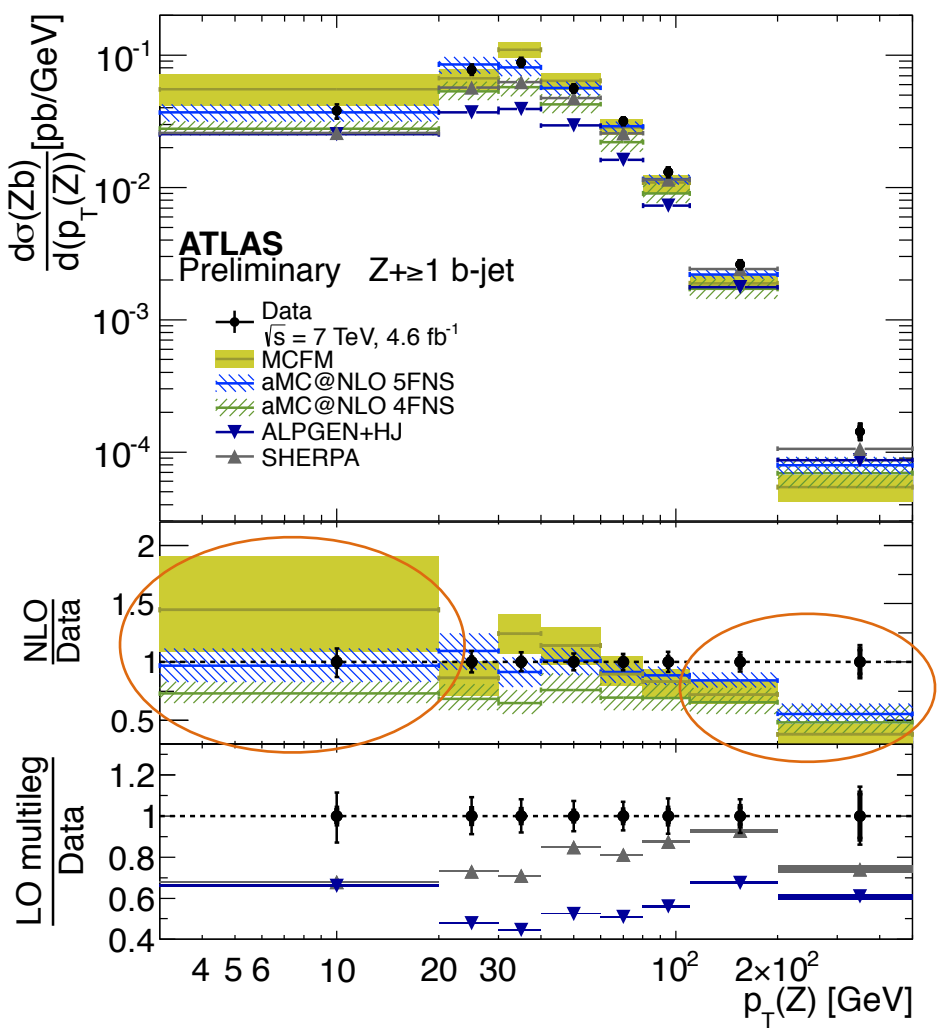


Z+b – Results (3/3)

- dσ(Z+ ≥1-bjet) / dy(b-jet) :
  4FNS underestimate central rapidity



- dσ(Z+ ≥1-bjet) / dp$_T$(Z) :
  discrepancies at high/low Z-p$_T$



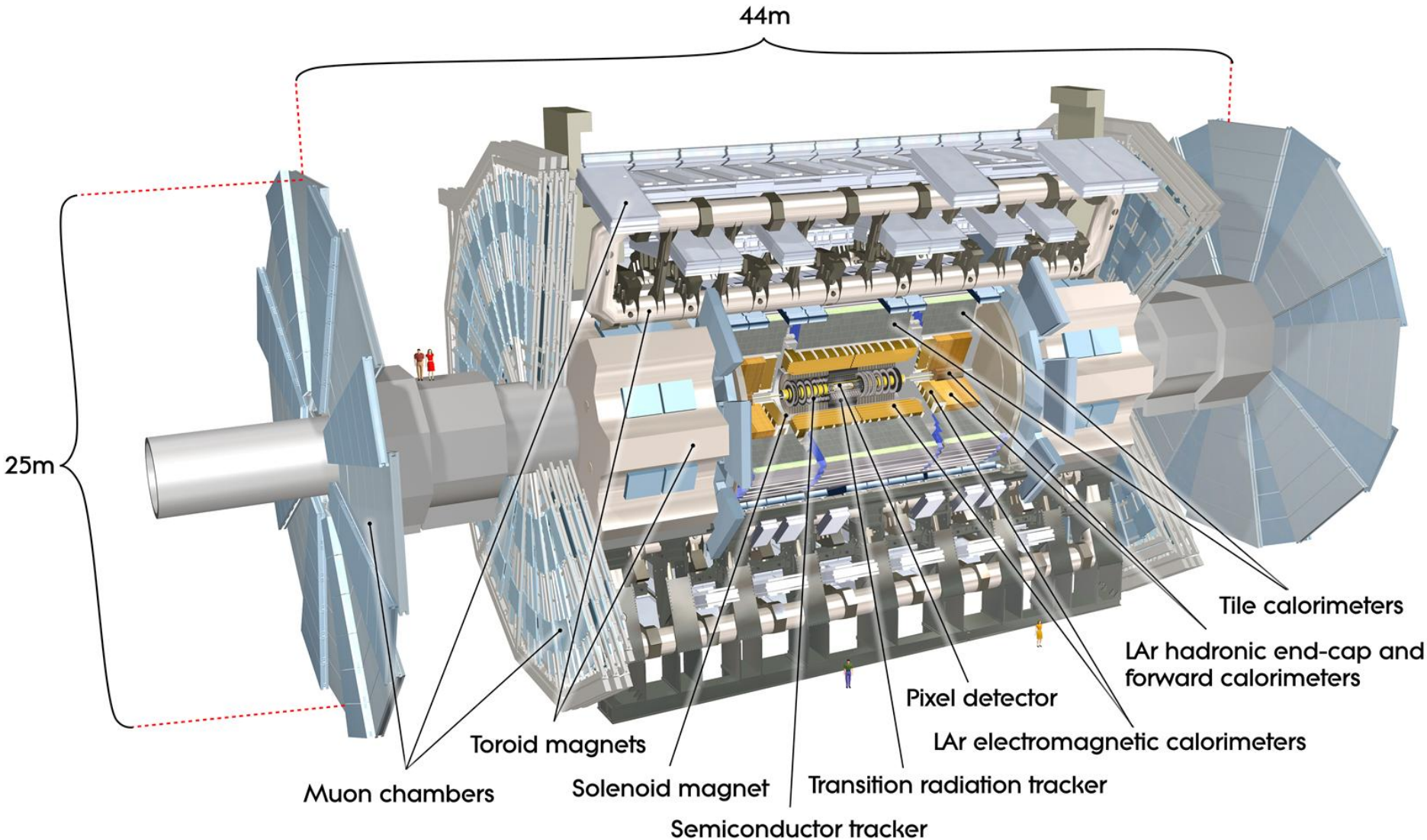
Conclusions

Presented **ATLAS measurements** for the production cross section of

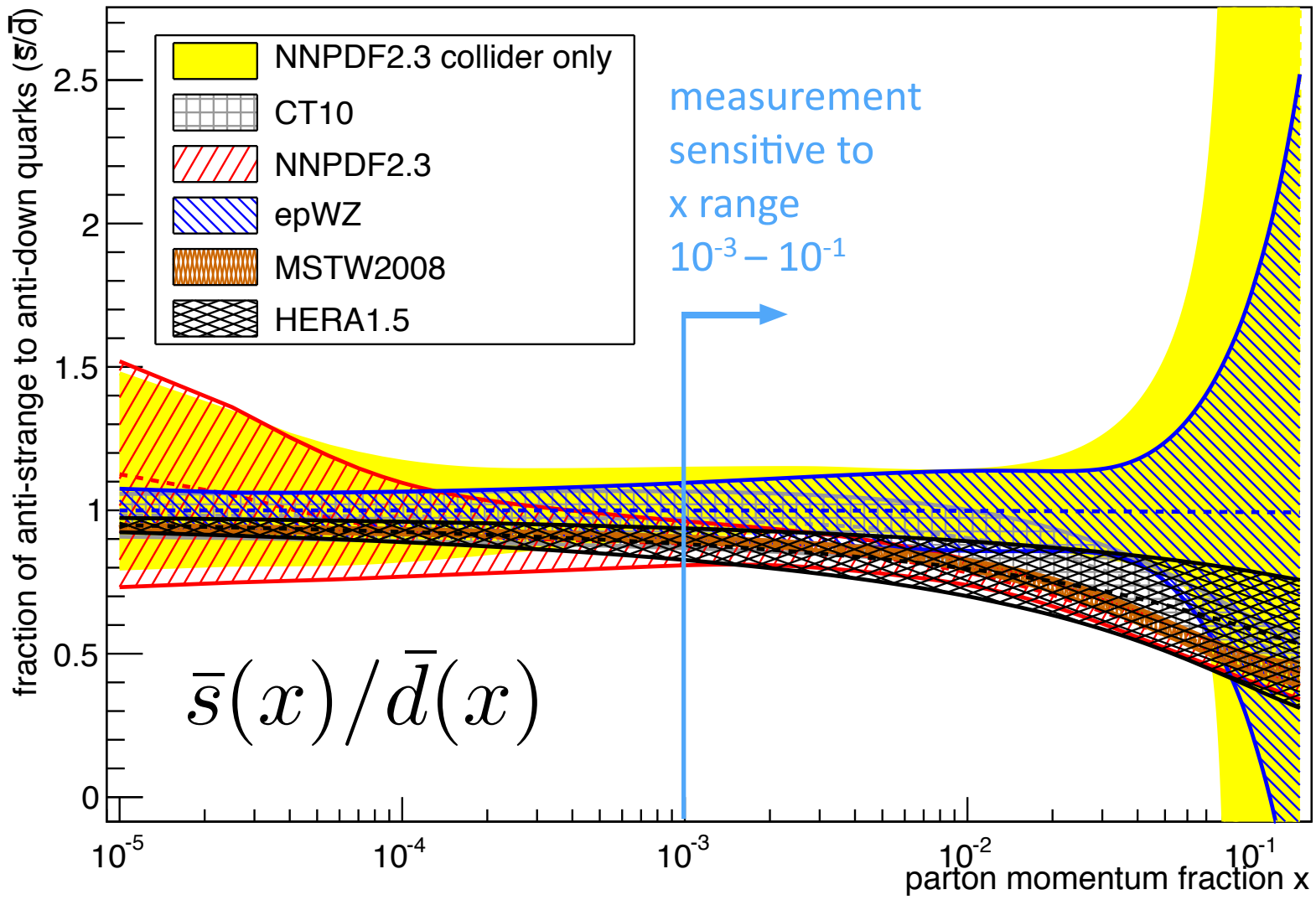
- ***W+charm***
  - Data favours PDF sets with non-suppressed s-quark density
  - Consistent results using two complementary c-quark tagging methods
- ***Z→bb***
  - Measured high-p_T Z boson + jets in fully hadronic final state
  - NLO + parton shower predictions in agreement with data
- ***Z+b***
  - Measured unfolded cross sections in 12 kinematic variables
  - Various NLO and LO predictions in overall agreement with data, exceptions is selected regions

Extra

ATLAS detector



W+charm: s-quark densities



W+charm : fiducial cross section

- Fiducial cross section from measured signal yield

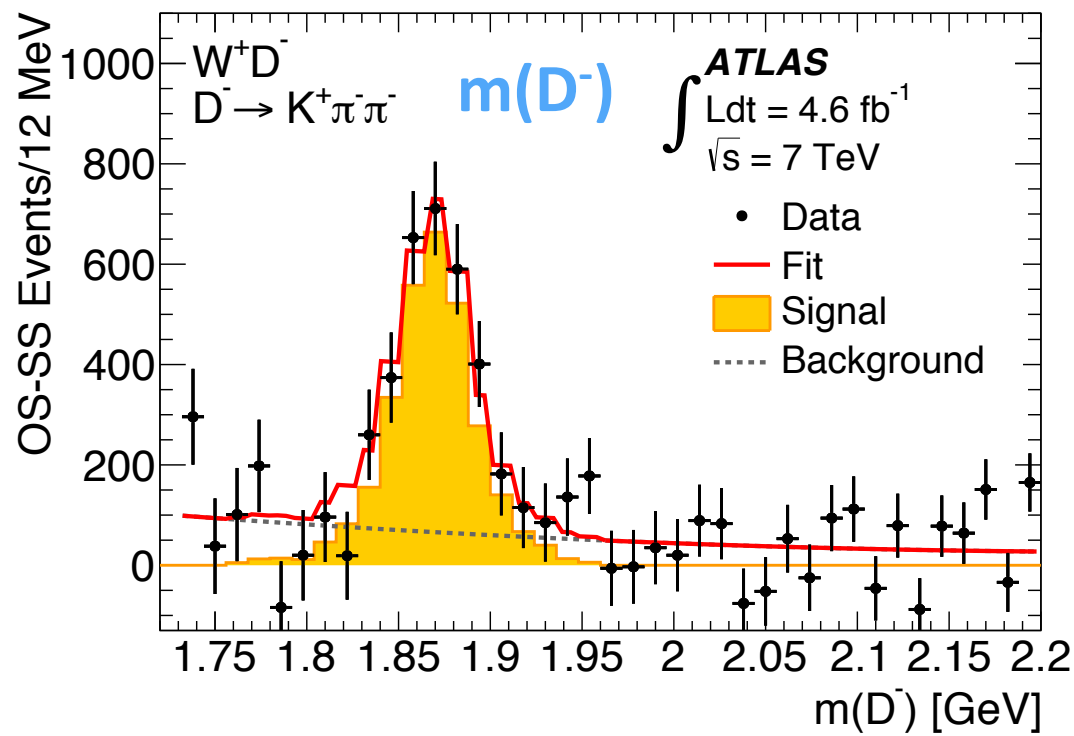
$$\sigma_{\text{fid}}^{\text{OS}-\text{SS}} = \frac{N_{\text{data}}^{\text{OS}-\text{SS}} - N_{\text{bkg}}^{\text{OS}-\text{SS}}}{\mathcal{L} \cdot C}$$

- Fiducial region for the W boson e/μ channel decays:
  - $p_T(l) > 20$ GeV; $p_T(\nu) > 25$ GeV; $m_T(W) > 40$ GeV
- Fiducial regions for the c-quark
  - *c-jet*: $p_T > 25$ GeV, $|\eta| < 2.5$, matched to c-hadron with $p_T > 5$ GeV and $\Delta R < 0.3$
  - *$D^{(*)}$ meson*: $p_T > 8$ GeV, $|\eta| < 2.2$

- *Soft muon Tagging selections:*
  - pT(soft μ)> 4 GeV; ΔR(soft μ, jet)< 0.5

W+charm: W+$D^{(*)}$ mass fit

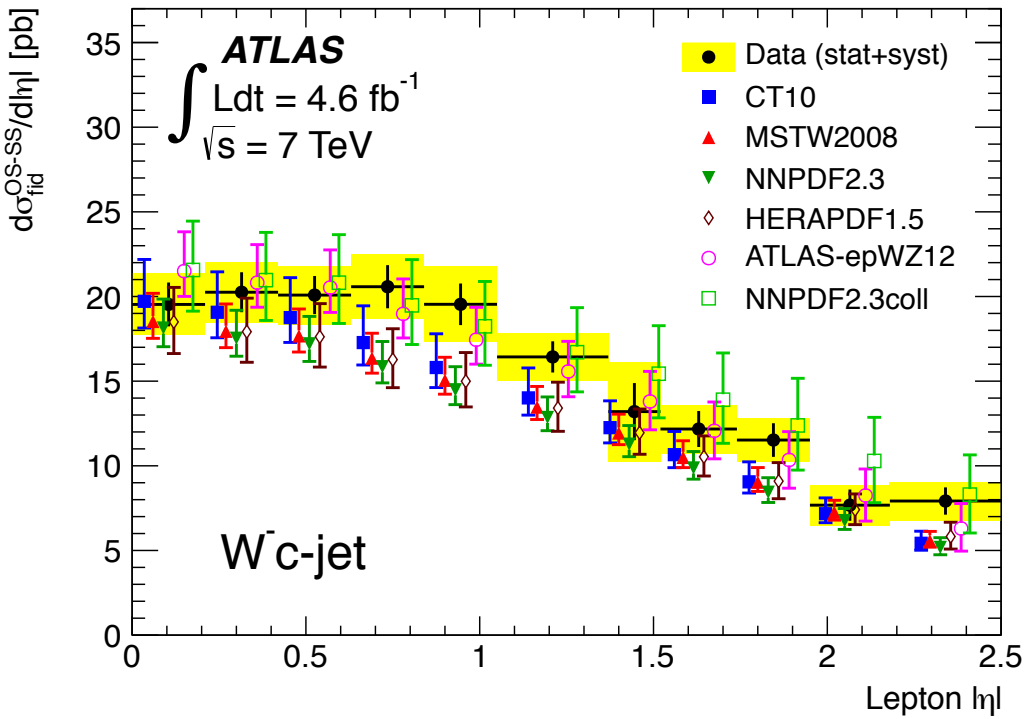
- Signal yield extracted from template fits to the mass distributions m(D) or $\Delta m = m(D^*)-m(D^0)$ in the 4 $D^{(*)}$ decay channels
  - Reconstruct decays with selections on tracks
  - Fit for the fraction of signal and background using OS-SS events
- *Signal shape*: data control sample with $D^{(*)}$ mesons from b-quark semileptonic decays
- *Background shape*: mainly W+light-jets, from data control region
- *Other backgrounds*: multijet, top, diboson, small, subtracted after the fit

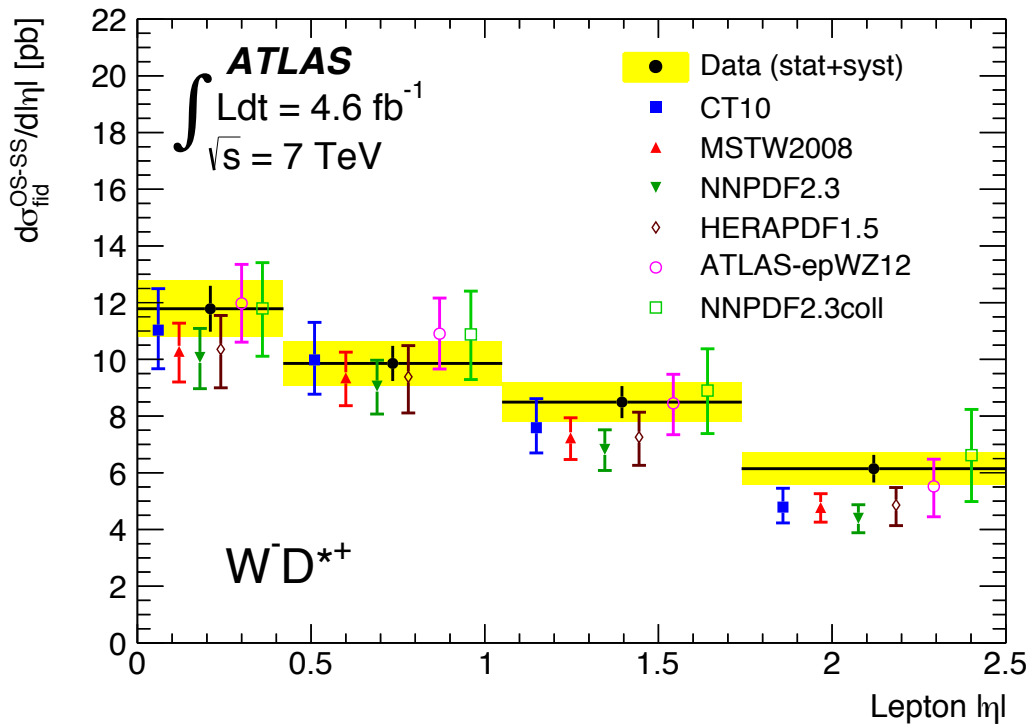


W+charm: theory predictions

- Predictions with aMC@NLO
  - Generated with CT10NLO, and reweigh to other PDF sets
  - PDF unc = 68%, according to prescriptions ofromeach analysis
- Showered with Herwig++
  - unc as the difference between Pythia and Herwig++
- Charm fragmentation fractions
  - Rescaled to LEP/HERA measurements (arXiv:1112.3757)
  - Charm fragmentation function validated by generating e+e- events and comparing to LEP/BELLE data
- Scale variation of μR and μF from 1⁄2μ to 2μ

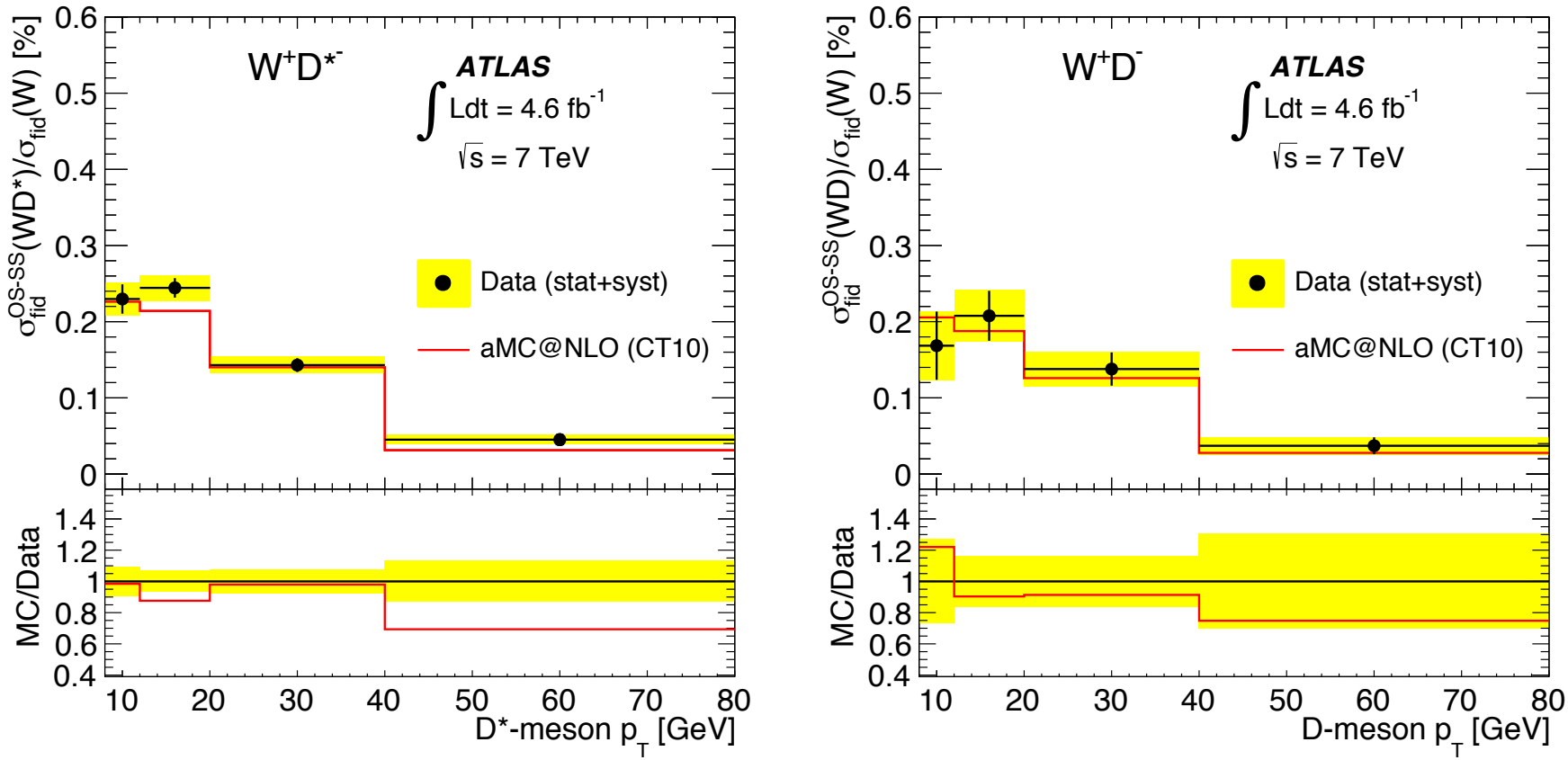
W+charm: differential in W-lepton |η|





Measured differential cross section as a function of lepton |η| compared to predictions obtained using various PDF sets: (left) W^{-}c-jet and (right) $W^{-}D^{*+}$. The measurements are shown by the filled circles. The error bars give the statistical uncertainty, while the sum in quadrature of the statistical and systematic uncertainties is shown as an error band. The theory predictions are based on the aMC@NLO simulation. The different markers correspond to the predictions obtained using various PDF sets and the corresponding error bars represent the total theoretical uncertainties (sum in quadrature of PDF, parton shower, fragmentation and scale uncertainties).

W+charm: differential in $p_T(D^{(*)})$



Measured cross-section ratio (left) $\sigma(W^+D^{(*)-})/\sigma(W^+)$ and (right) $\sigma(W^+D^-)/\sigma(W^-)$ differential in p_T of the D meson compared to theory predictions. The measurement is shown by the filled markers. The error bars give the statistical uncertainty, while the sum in quadrature of the statistical and systematic uncertainties is shown as an error band. The solid line shows the prediction of the aMC@NLO MC simulation obtained using the CT10 PDF set. The ratio of the simulated distribution to data is shown in the lower panels. Here, the error band corresponds to the sum in quadrature of the statistical and systematic uncertainties.

W+charm: differential N_{jets}

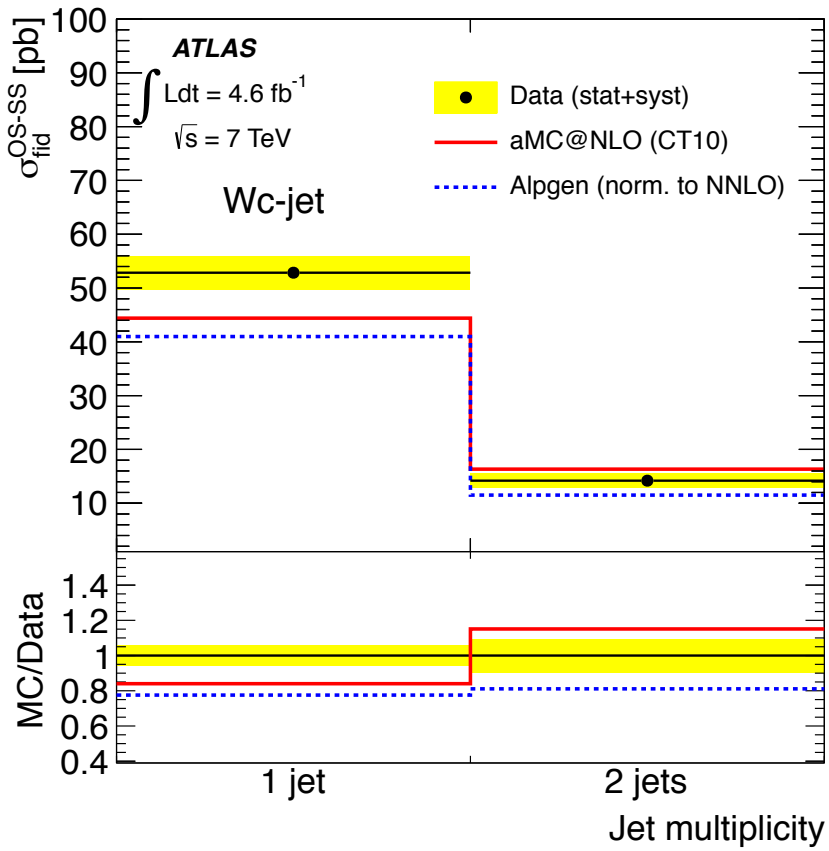


Figure 16. Measured cross sections as a function of the jet multiplicity compared to aMC@NLO produced using the CT10 NLO PDF set. The predictions from ALPGEN normalised to the inclusive W NNLO cross section are also shown for reference. In the lower panels, the ratio of the simulated distribution to data is shown.

Z → bb: Selections

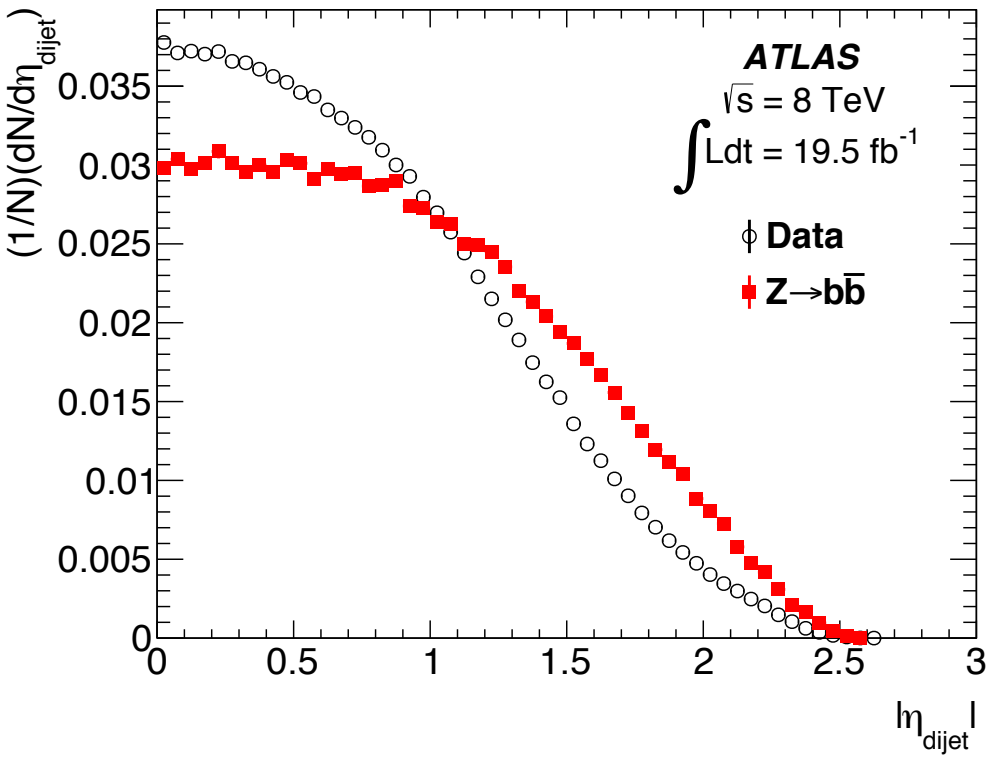
- Select two jets originating from Z → bb decay
  - Jets clustered using anti-kt with R = 0.4
  - dijet momentum pT(dijet) > 200 GeV (reduces bb multijet background)
  - dijet mass 60 < m_{dijet} < 160 GeV
  - Events with exactly 2 b-tagged jets in 3 to 5 total jets
- Fiducial cross section measured from signal event yield

$$\sigma^{\text{fid}}_{Z\to b\bar{b}} = \frac{N_{Z\to b\bar{b}}}{\mathcal{L}\cdot C_{Z\to b\bar{b}}}$$

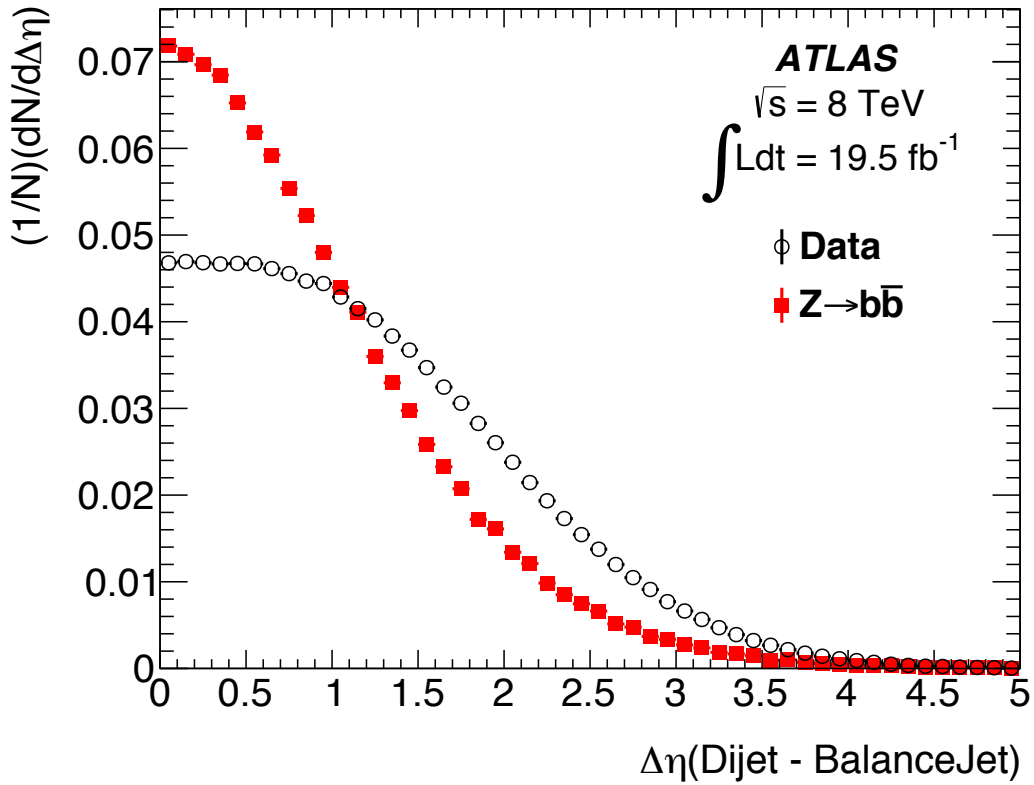
W+charm : s-to-d sea PDF ratio

- HERAPDF1.5 PDF set:
  - The fraction of strange-quarks in the sea is expressed as
    f_s = sbar/(dbar + sbar)
    The central value $f_s = 0.31$ at $Q^2 = 1.9$ GeV^2, consistent with N-ν data
- strange density fraction f_s extracted with χ2 fit:
  - χ2 function constructed with measured σ(W+charm) and HERAPDF1.5 predictions, including all experimental and theory uncertainties
  - Uncertainty on f_S is a nuisance parameter in the χ^2 minimisation; the baseline uncertainty (0.23-0.38) is artificially increased (100 times)
  - This procedure corresponds to a free fit of f_s to the W+charm data

Z → bb: $|\eta_{dijet}|$ $\Delta\eta$(dijet, balancing-jet)



(a)



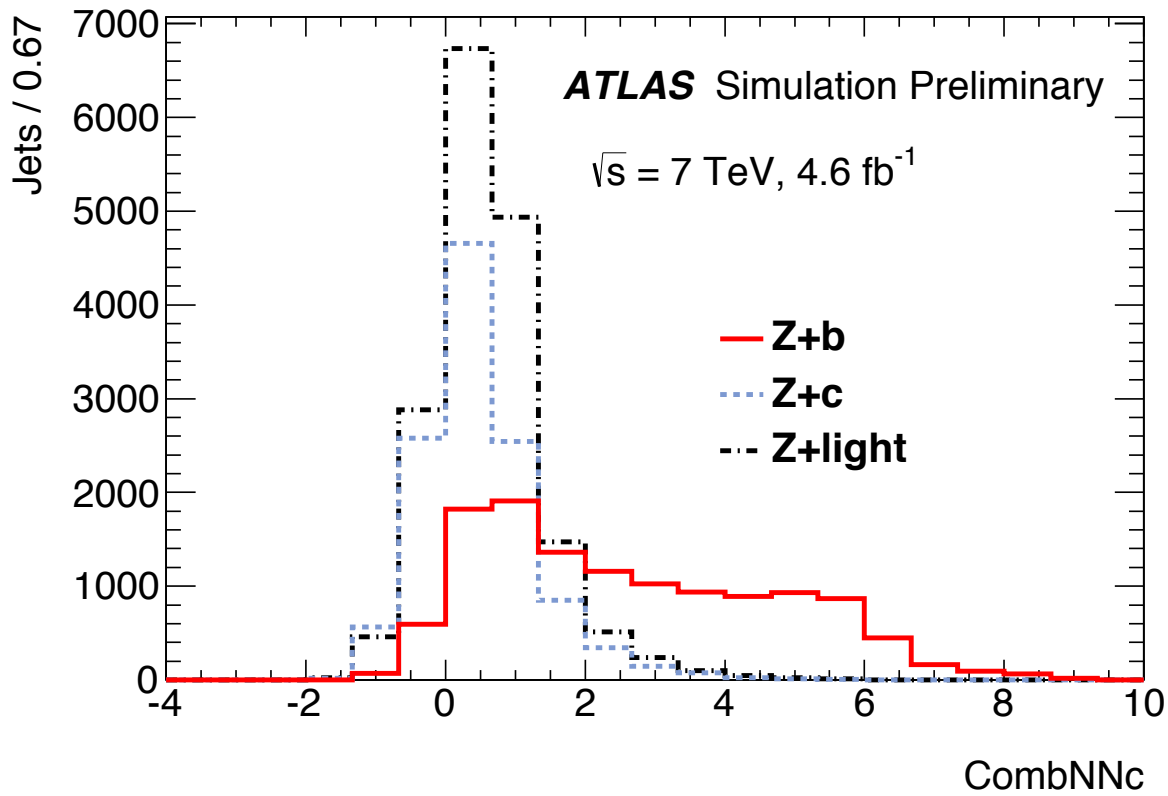
(b)

The distributions of (a) the dijet pseudorapidity and of (b) the pseudorapidity difference between the dijet and the balancing jet

Z + b : fiducial cross sections

- Select Z + b-jets events with
  - $Z \to ee/\mu\mu$: $p_T(l) > 20$ GeV, $76 < m(ll) < 106$ GeV
  - ≥1 or ≥2 b-tagged jets : anti-kt R = 0.4, $p_T > 20$ GeV, $|\eta| < 2.4$
- *12 differential cross section measurements*
  - *Z+ ≥1 b-jets*: Z boson p_T & $|y|$; b-jet p_T & $|y|$;
    $\Delta y(Z,b\text{-jet})$, $\Delta\phi(Z,b\text{-jet})$, $\Delta R(Z,b\text{-jet})$, $|y(Z) - y(b\text{-jet})|/2$
  - *Z+ ≥2 b-jets*: Z boson p_T & $|y|$; m(b-jet, b-jet); ΔR(b-jet, b-jet)

Z + b: NN output shapes



Jet flavour distributions for CombNNc in simulated Z+jets events for all selected tagged jets in events with at least one tagged jet. The $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ channels are combined and simulated data are normalised such that the predicted number of jets in 4.6 fb^{-1} are shown.