W/Z + HEAVY FLAVOR AT ATLAS

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INTRODUCTION

- W/Z production presents a standard candle to test the SM and to tune QCD models, MC and PDFs
- Productions including heavy flavor known with limited precision
  - Large uncertainties from both the theoretical and the experimental sides
- All results shown for 4.6 fb^{-1} of data collected in 2011 at $\sqrt{s} = 7$ TeV
- In this talk:
  - Quick reminder of the W+b cross section results
  - Present in more details the recent W+c measurements (and the sensitivity for the s-PDF)
- New Z+b measurement in preparation (not public yet)

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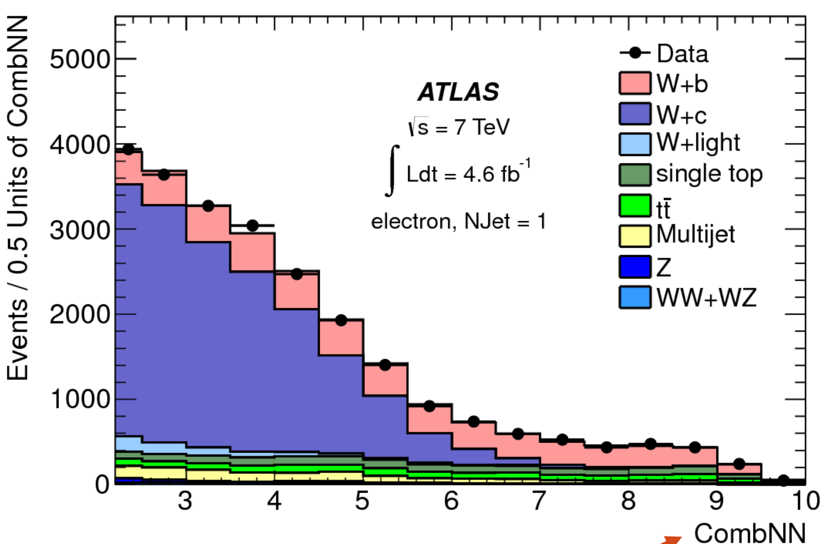
W PRODUCTION WITH B-QUARKS

JHEP 06 (2013) 084

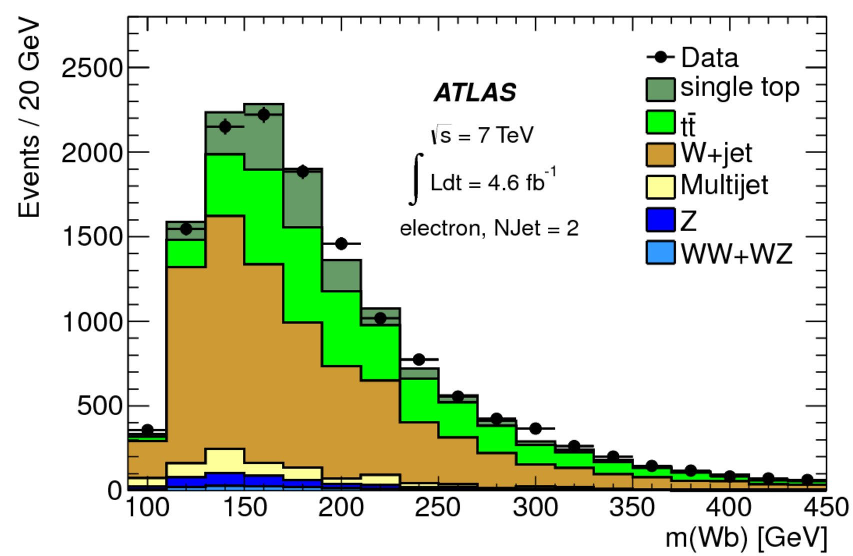
arXiv:1302.2929

W + B-JETS PRODUCTION

- Important measurement to constrain QCD with HF
  - Also an important background for many analyses namely WH(H→bb)
- Measurement based on a template fit of the b-tag weight of jets
  - Exactly one b-tag jet required (reject t-tbar)
- Main backgrounds
  - Top production; very hard to separate single top events
  - W+light or c-jets
  - Multijet production
  - Z and diboson production

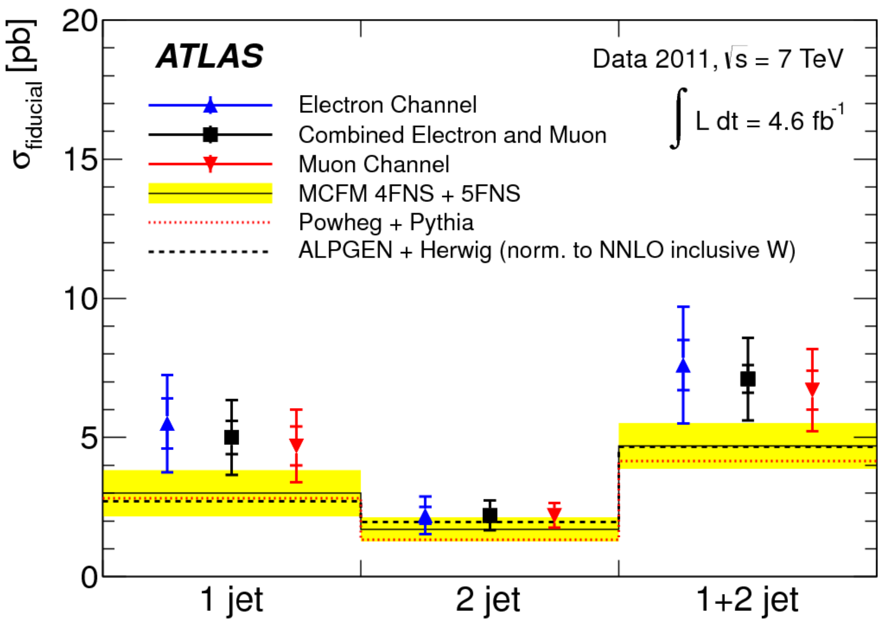


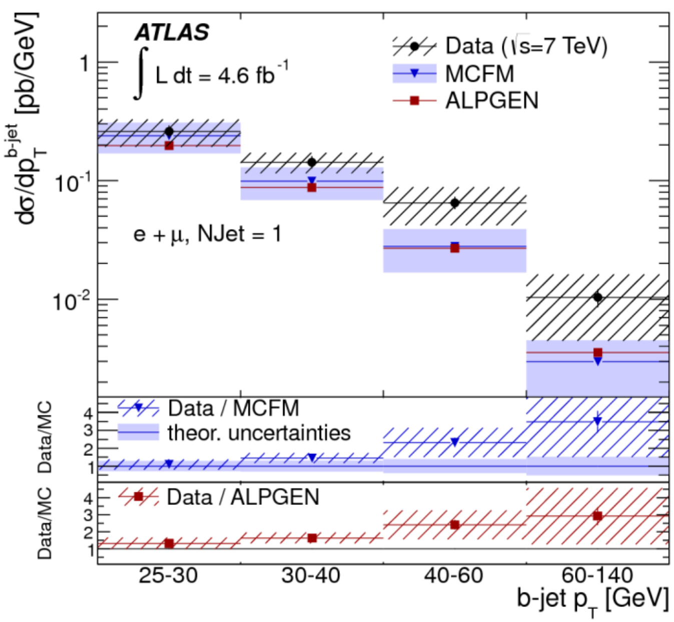
b-tag weight



W + B-JETS RESULTS

- Measurement corrected to a fiducial region with at least one b-jet
  - No separation between topologies with one or two b-jets
- Compatible with predictions in the one and two jets bins
- Also differential in jet p_T
  - Small tension at high p_T
    - to be confirmed with larger statistics





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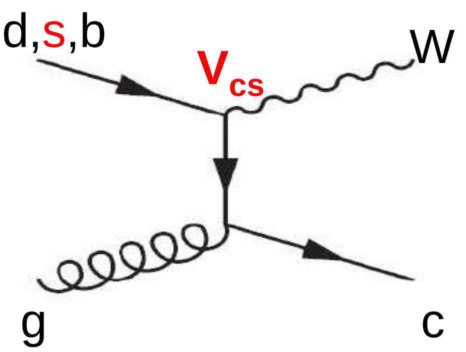
W PRODUCTION WITH A SINGLE C-QUARK

arXiv:1402.6263

Accepted in JHEP

W+C PRODUCTION

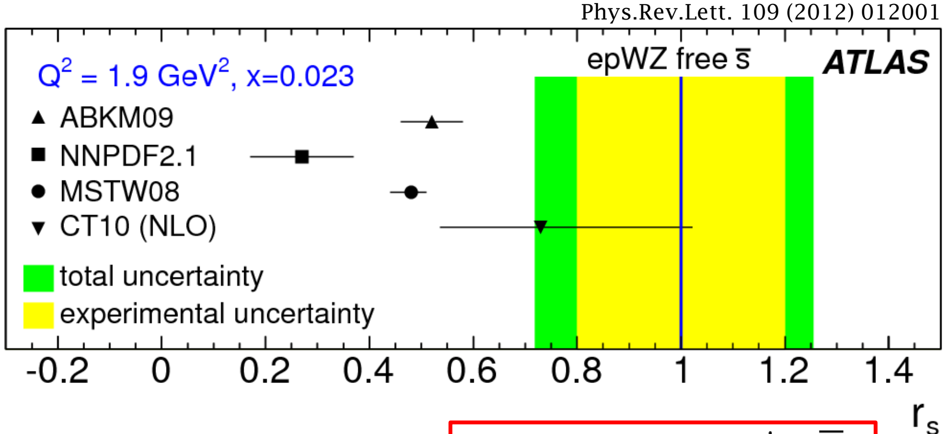


- Production of a W boson in association with a single c-quark
  - Measurement directly sensitive to the s-quark PDF
  - Also large background for many processes with a lepton and heavy flavor jets in the final state
- Carried out at Tevatron and CMS
  - PDF interpretation not straightforward (need to control c fragmentation, scale, …)
  - Only recently included in PDF fits
- s-quark PDF not well constrained in the phase space relevant for the LHC ($Q^2 \approx 100^2$ GeV^2 and $x \approx [0.001 - 0.1]$)
  - Constraints from low energy fix target experiments
- ATLAS measurements
  - Cross sections
  - Differential cross sections in lepton $|\eta|$, jet multiplicity and D meson p_T
  - Ratio of W^+ and W^- cross sections produced with a c-quark

REMINDER

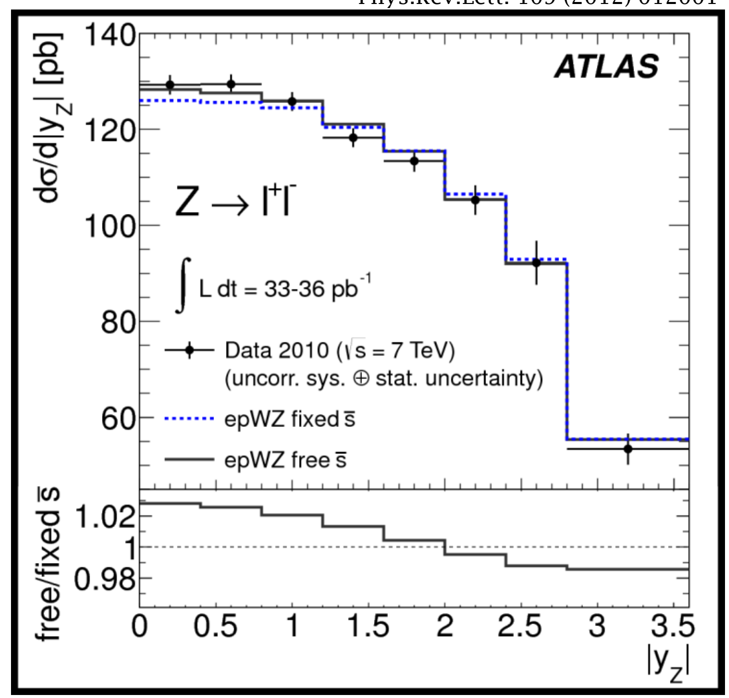
- ATLAS already performed a PDF fit which is indirectly sensitive to the s-quark PDF
  - Fit using W/Z differential cross section measurements
  - Fit suggesting high s-density compared to "usual" PDF values
  - s-quark density comparable to the d-quark sea density
- See P. Newman's first talk today

Phys.Rev.Lett. 109 (2012) 012001

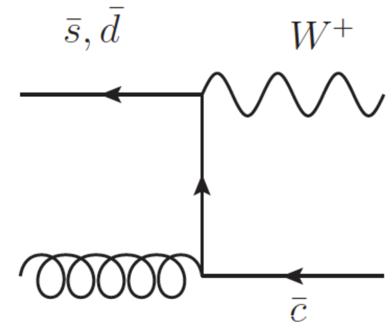


$$r_s = 0.5\frac{s+\bar{s}}{\bar{d}}$$

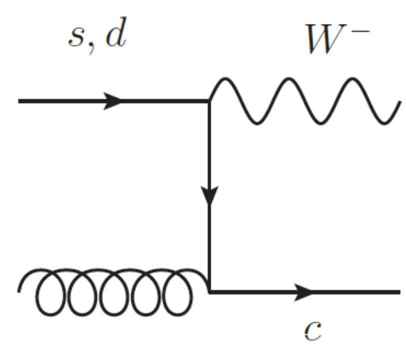
Phys.Rev.Lett. 109 (2012) 012001

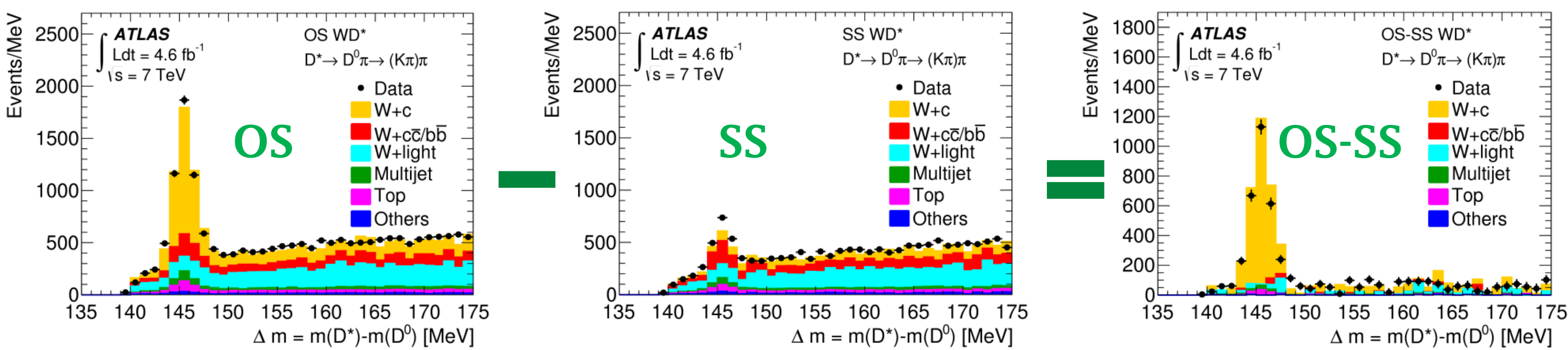


ANALYSIS OVERVIEW



- Analysis based on the charge correlation between the c-quark and the W boson to suppress backgrounds
- Tag c-quark production with 2 methods
  - Soft muon decay in a c-jet
  - Reconstruction of D(*) charged mesons (no jets required)
- Both methods have access to the c-quark charge
- SS events subtracted from OS events to select a relatively pure Wc sample



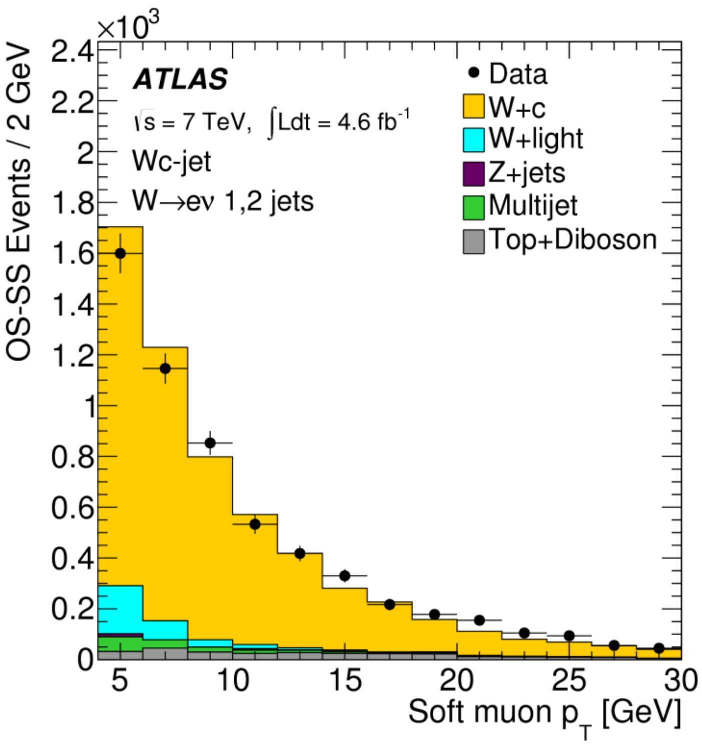


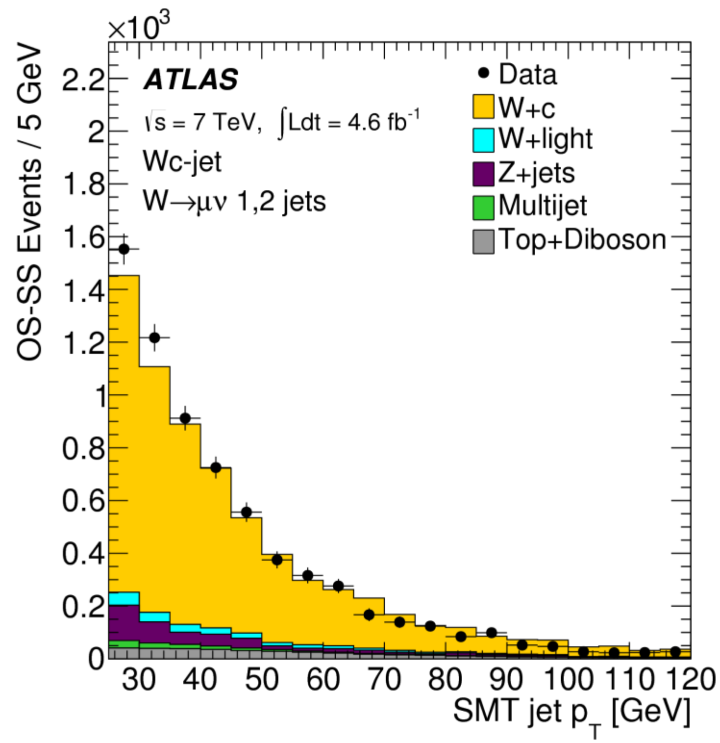
SELECTION AND BACKGROUNDS

- The W side selection
  - High-p_T isolated lepton
  - MET and W transverse mass cuts
- The c-quark side selection
  - Wc-jet
    - Exactly one c-jet in the event tagged by the presence of a soft muon
    - p_T(jet)>25 GeV, $|\eta$(jet)$|$<2.5
  - WD(*)
    - Reconstruct secondary vertices and fit the invariant mass
    - p_T(D(*))>8 GeV, $|\eta$(D(*))$|$<2.2
- Backgrounds
  - W+light-jet and Multijet (especially c-cbar) → Main backgrounds
  - Wcc and Wbb → totally cancel in OS-SS
  - t-tbar → nearly OS/SS symmetric (largely cancels in OS-SS)
  - Single top and diboson → (OS/SS asymmetric but small)
  - Z production → only relevant in the Wc-jet muon channel

WC-JET ANALYSIS

- Cut and count OS-SS events
- A variety of background estimation methods
  - Multijet and W+light backgrounds estimated using data driven methods
  - Z+jets normalized to the Z peak in data for the muon channel
  - Other smaller backgrounds are estimated from MC

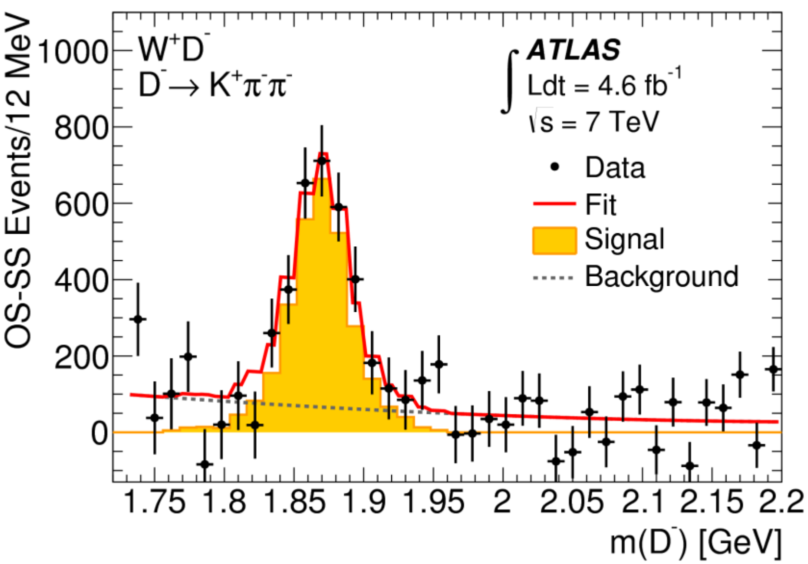


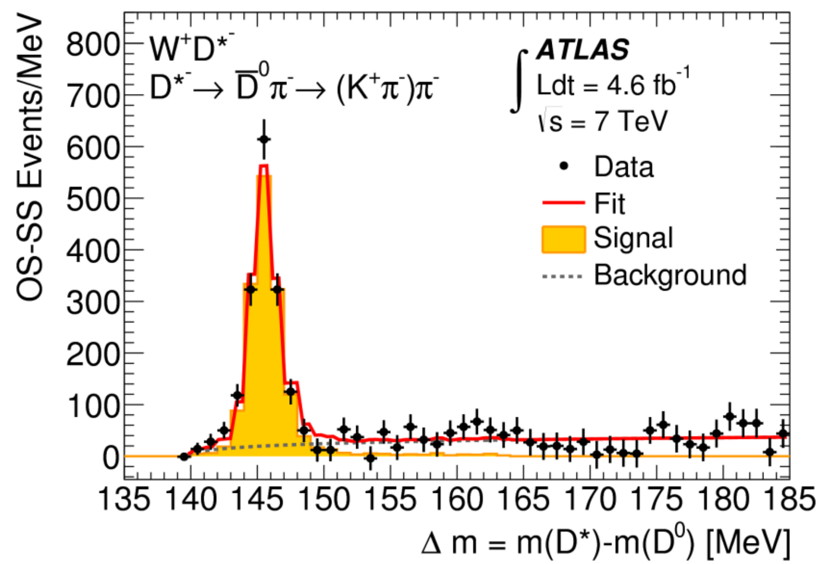


WD(*) ANALYSIS

- Exclusive reconstruction of D/D* mesons in different channels
  - $D^+ \rightarrow K\pi\pi$
  - $D^* \rightarrow D^0\pi \rightarrow (K\pi)\ \pi$
  - $D^* \rightarrow D^0\pi \rightarrow (K\pi\pi^0)$
  - $D^* \rightarrow D^0\pi \rightarrow (K\pi\pi\pi)\ \pi$

  Form vertices from charged tracks with correct charge combination and fit the invariant mass (in p_T bins)
- Signal templates from control region with semileptonic B decays
- Measure WD/W ratio and then multiply by the W cross section





CROSS SECTIONS

- Measurements corrected to particle level in a fiducial region
  - Extrapolation reduced as much as possible
- Special care taken to evaluate c-quark fragmentation and c-hadron decay related properties and their uncertainties
- Electron and muon channels averaged as well as the different decay channels for the D* analysis
- c-jet, D and D* cross sections kept separated
  - +/- ratio for D and D* are averaged (same phase space)

Requirement	Cut
Lepton transverse momentum	$p_T^\ell > 20$ GeV
Lepton pseudorapidity	$\|\eta^\ell\| < 2.5$
Neutrino transverse momentum	$p_T^\nu > 25$ GeV
W transverse mass	$m_T^W > 40$ GeV
D meson transverse momentum	$p_T^{D^{(*)}} > 8$ GeV
D meson pseudorapidity	$\|\eta^{D^{(*)}}\| < 2.2$
c-jet transverse momentum	$p_T^{jet} > 25$ GeV
c-jet pseudorapidity	$\|\eta^{jet}\| < 2.5$

Measurements corrected to a common fiducial region concerning the W-boson side

Different fiducial cuts for Wc-jet/D(*) on the c-side
Complementary analyses probing different regions of phase space

SYSTEMATICS WD(*)

Total systematics of the order of 4-5%

Tracking efficiency dominating the reco systematics

D/D* decay BR dominating the acceptance correction systematics

* Correlated with Wc-jet

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_T^{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

SYSTEMATICS WC-JET

Total systematics of the order of 5-6%

JES dominating the reco uncertainties

Largest systematics from background yields (mostly stat from data control regions and MC

Large systematics from c fragmentation and decay

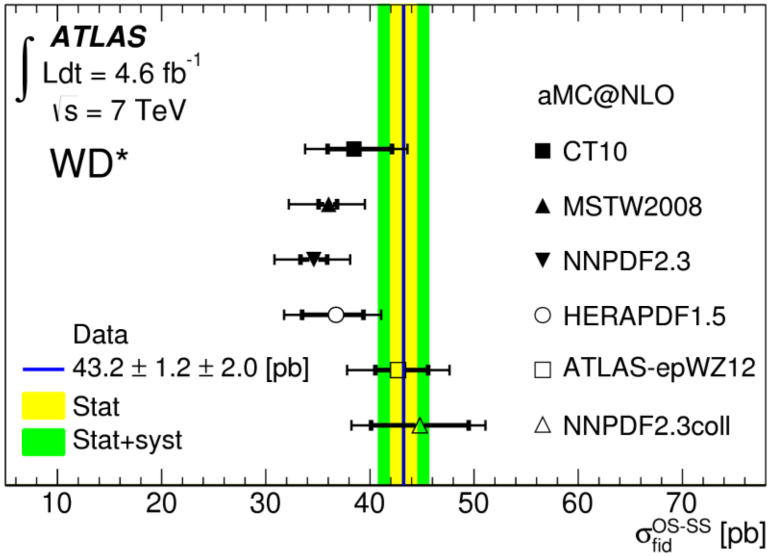
* Correlated with WD(*)

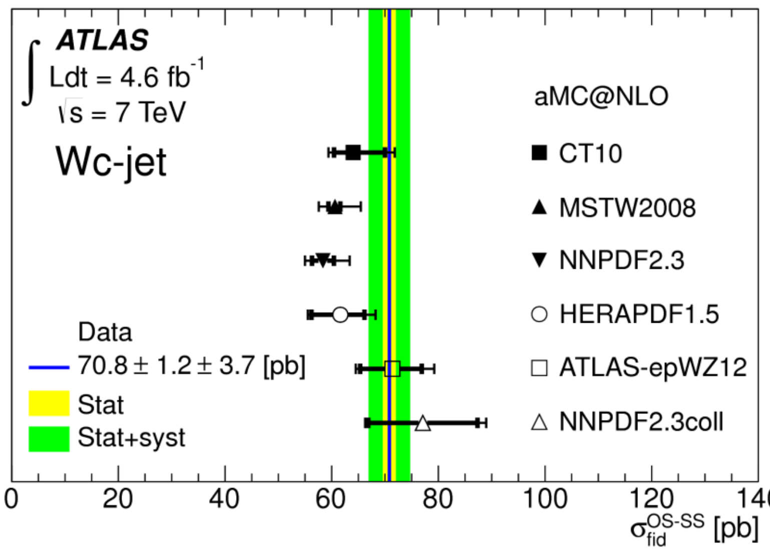
Relative systematic uncertainty in %	$W(e\nu)c$-jet	$W(\mu\nu)c$-jet
Lepton trigger and reconstruction*	0.7	0.8
Lepton momentum scale and resolution*	0.5	0.6
Lepton charge misidentification	0.2	-
Jet energy resolution*	0.1	0.1
Jet energy scale	2.4	2.1
$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction*	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

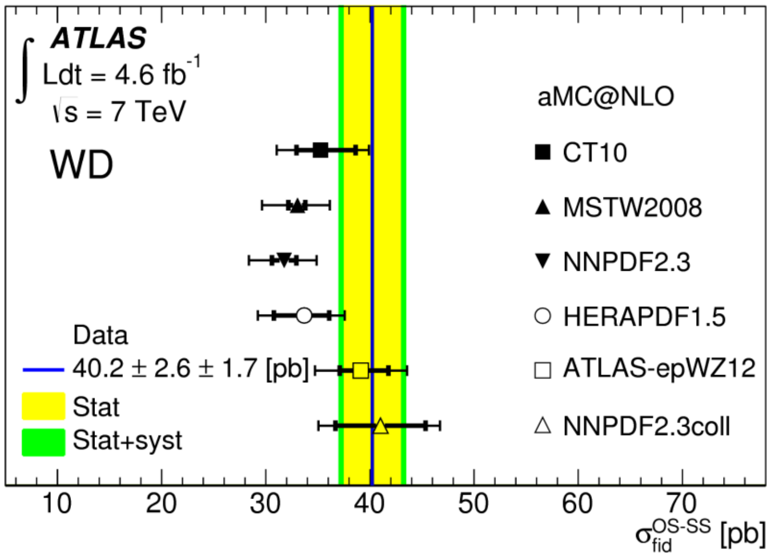
No large correlated systematics between the Wc-jet and the WD(*) analyses (mainly Lumi) → complementary; significant gain from combination

CROSS SECTION RESULTS

- Inner error bars: PDF uncertainties
- Total error bars: total theory uncertainties
  - Scale uncertainties: 4-9%
- PDF sets with relatively large s-quark density describe better the different measurements

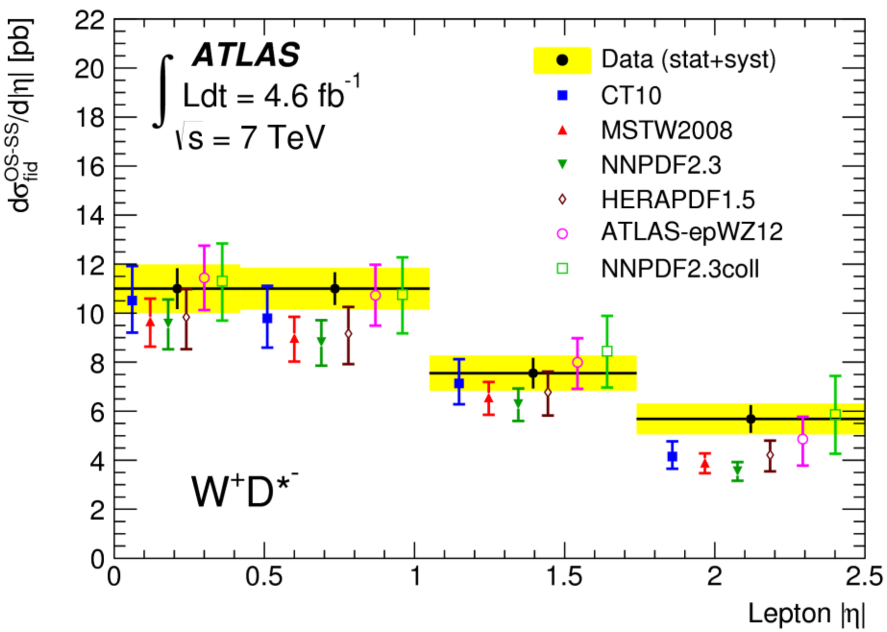


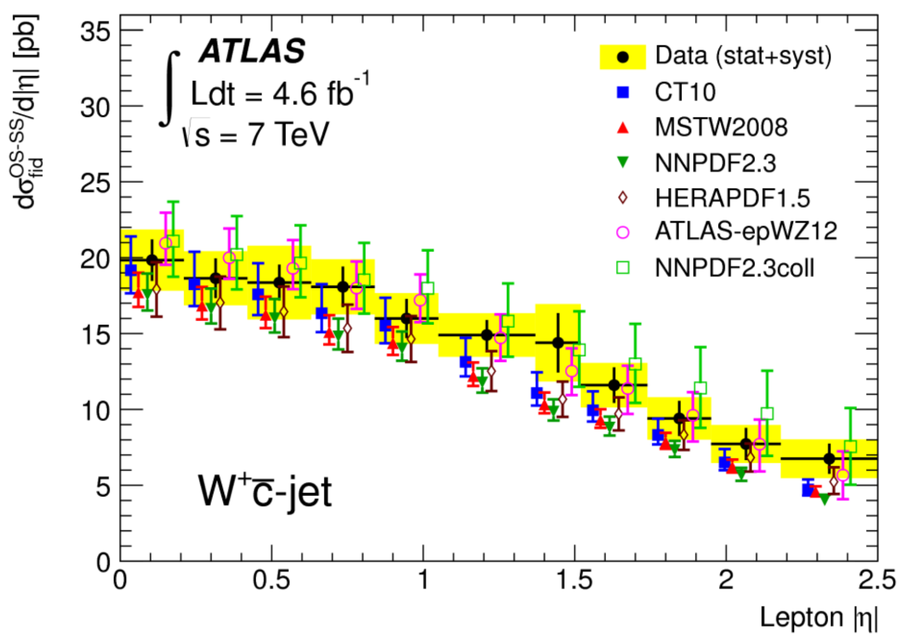




DIFFERENTIAL MEASUREMENTS

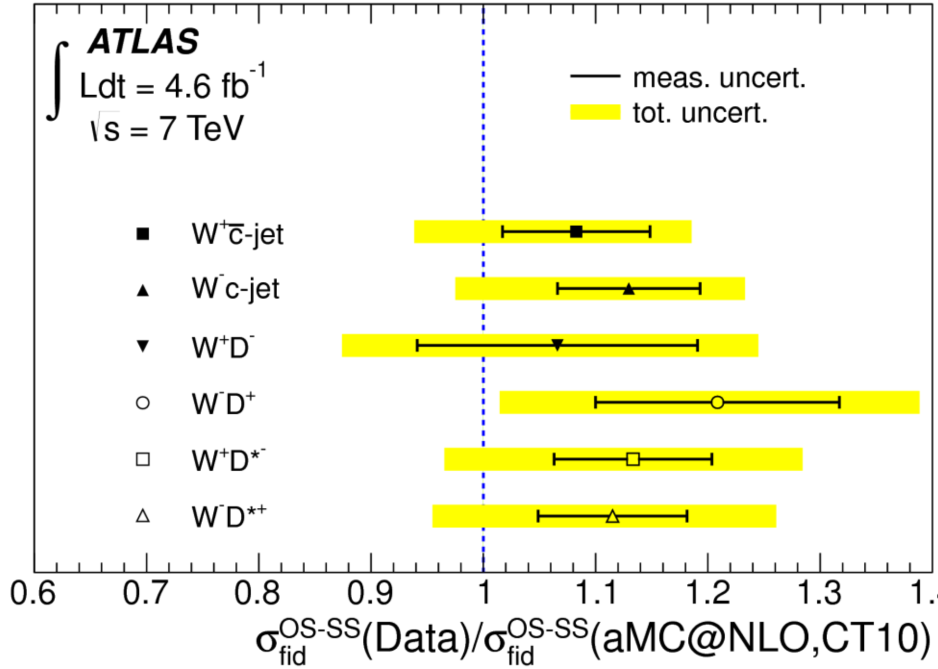
- Differential measurements in lepton pseudorapidity to increase sensitivity to different PDF sets
- Measurements limited by statistical uncertainties
- Could not discriminate between different shapes from different sets
  - Main discrimination from total normalization
  - Need additional statistics (8 TeV data)





RESULTS COMPATIBILITY

- Compatible results in the different channels
  - Assuming extrapolation using aMC@NLO(CT10)
- Quantify compatibility with different PDF sets (with aMC@NLO)
  - Chi2 fit with systematics as nuisance parameters
- Fit performed simultaneously for all channels
  - All correlations taken into account



$$\chi^2 = \sum_{k,i} w_k^i \frac{\left[\mu_k^i - m^i \left(1 + \sum_j \gamma_{j,k}^i b_j + \sum_j (\gamma^{\text{theo}})_{j,k}^i b_j^{\text{theo}}\right)\right]^2}{(\delta_{\text{sta},k}^i)^2 \Delta_i^k + (\delta_{\text{unc},k}^i m^i)^2} + \sum_j b_j^2 + \sum_j (b_j^{\text{theo}})^2$$

Method developed in Eur. Phys. J. C 63 (2009) 625-678, arXiv:0904.0929 [hep-ex] and implemented in HeraFitter

COMPARISON WITH PREDICTIONS

	CT10	MSTW2008	HERAPDF1.5	ATLAS-epWZ12	NNPDF2.3	NNPDF2.3coll
$W^+\bar{c}$-jet (χ^2/ndof)	3.8/11	6.1/11	3.5/11	3.1/11	8.5/11	2.9/11
W^-c-jet (χ^2/ndof)	9.0/11	10.3/11	8.3/11	6.3/11	10.5/11	6.1/11
W^+D^- (χ^2/ndof)	3.6/4	3.7/4	3.7/4	3.4/4	3.8/4	3.4/4
W^-D^+ (χ^2/ndof)	3.7/4	4.6/4	3.3/4	2.0/4	4.7/4	1.6/4
W^+D^{*-} (χ^2/ndof)	2.9/4	6.0/4	2.2/4	1.7/4	8.1/4	1.6/4
W^-D^{*+} (χ^2/ndof)	3.0/4	4.4/4	2.4/4	1.6/4	4.2/4	1.4/4
N_{exp}	114	114	114	114	114	114
N_{theo}	28	22	16	20	40	40
Correlated χ^2 (exp)	0.8	1.8	0.9	1.1	2.2	1.0
Correlated χ^2 (theo)	6.2	1.9	2.6	0.1	7.4	0.2
Correlated χ^2 (scale)	0.6	2.5	1.1	0.0	2.7	0.0
Total χ^2/ndof	33.6/38	41.3/38	28.0/38	19.2/38	52.1/38	18.2/38

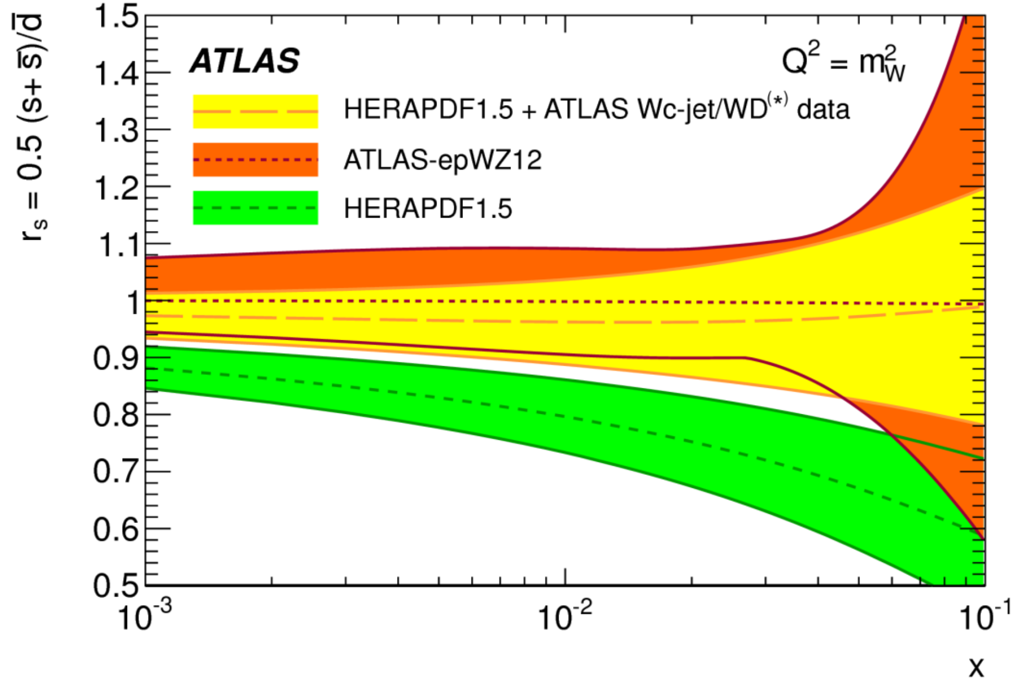
PDFs with small uncertainties and tension in the nominal values
Scale nuisance parameter shifted by more than 2 sigma (~20%) to compensate

PDFs with compatible nominal values and large uncertainties
Measurement helps constraining these PDFs

Reduced scale uncertainties needed to better discriminate PDF sets

S-QUARK PDF

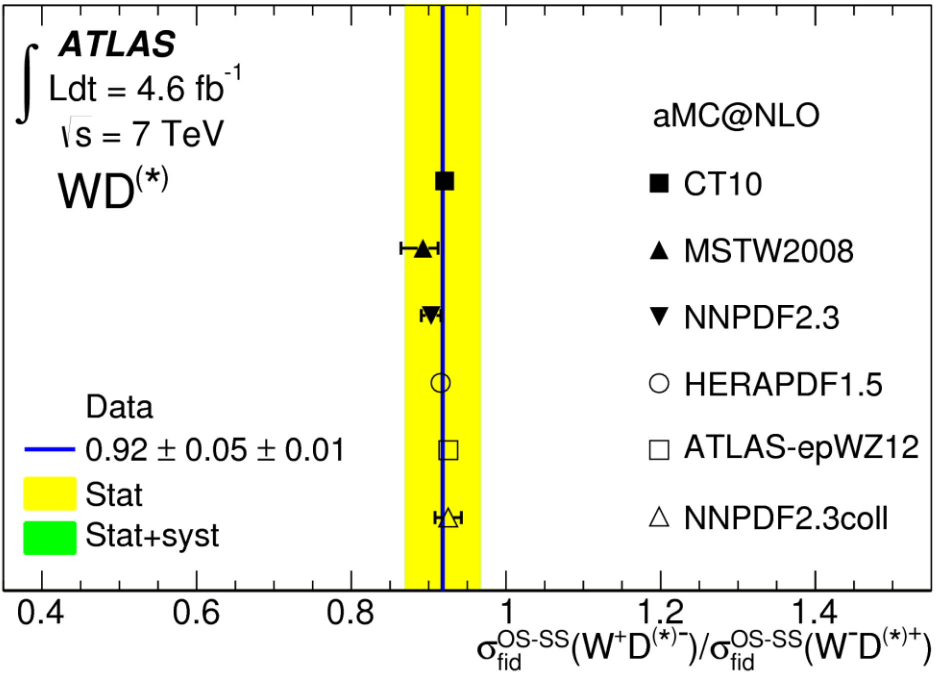
- Hera PDF implements the s-density as a single parameter with a single uncertainty
  - The actual parameter is the ratio to dbar-density
- Leave the corresponding nuisance parameter free in the fit
  - "pseudo-fit" of the s-density

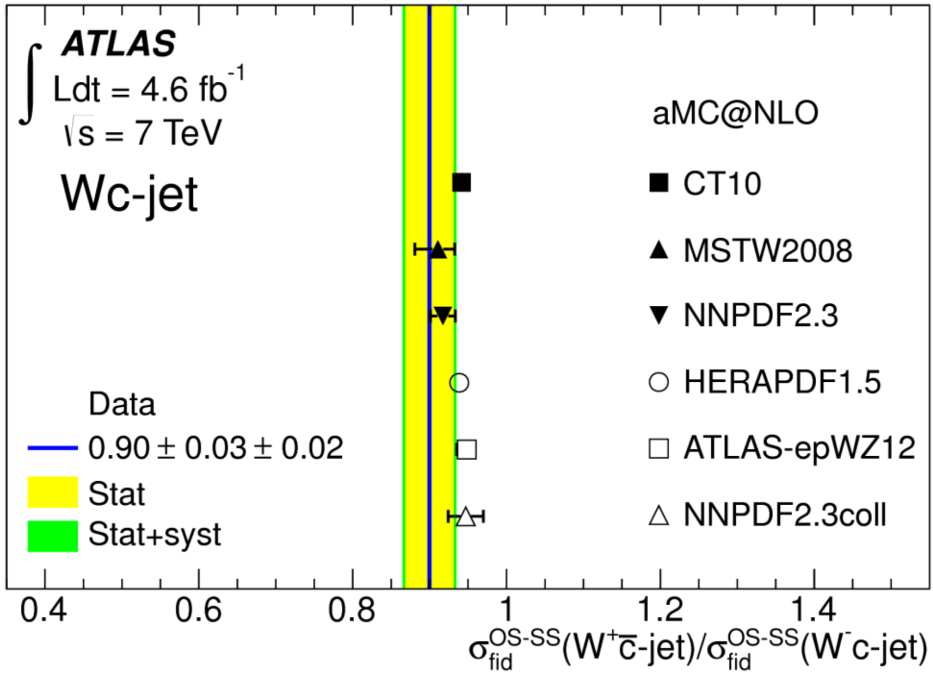


- Results fully compatible with the ATLAS-epWZ PDF which includes ATLAS W/Z data
- Results pointing to SU(3) flavor symmetry in the proton
  - No visible effect from the s-quark mass
- Tension with CMS data (next talk) but uncertainties are large
  - More data for a definitive conclusion

+/- RATIO RESULTS

- W^+cbar/W^-c ratio sensitive to s-sbar asymmetry (suggested by NuTeV data)
  - Also sensitive to s/d density fraction (expect more W^- due to the d valence)
- Systematics cancel in the ratio (statistically dominated)
  - Need more data (8 TeV?) to be sensitive to % level s-sbar asymmetry





CONCLUSION

- Wb measurements compatible with theory predictions
  - Small tension at high p_T to be confirmed
- ATLAS Wc analysis supports previously enhanced s-density suggested by ATLAS W/Z data
  - Independent cross section measurements using different techniques and covering different phase spaces (Wc-jet and WD(*)) in excellent agreement
- Wc measurements interpretation in terms of PDFs diluted by large theory uncertainties
  - Some work needed on this front as well
- Large statistical uncertainty for the +/- ratio and differential measurements for the Wc analysis
  - Need more data (8 TeV) to take advantage of shape differences
  - In addition, need a good control of s/dbar to be sensitive to the s-sbar asymmetry suggested by NuTeV data
- Tension between Wc ATLAS and CMS measurements
  - But uncertainties still large, still compatible

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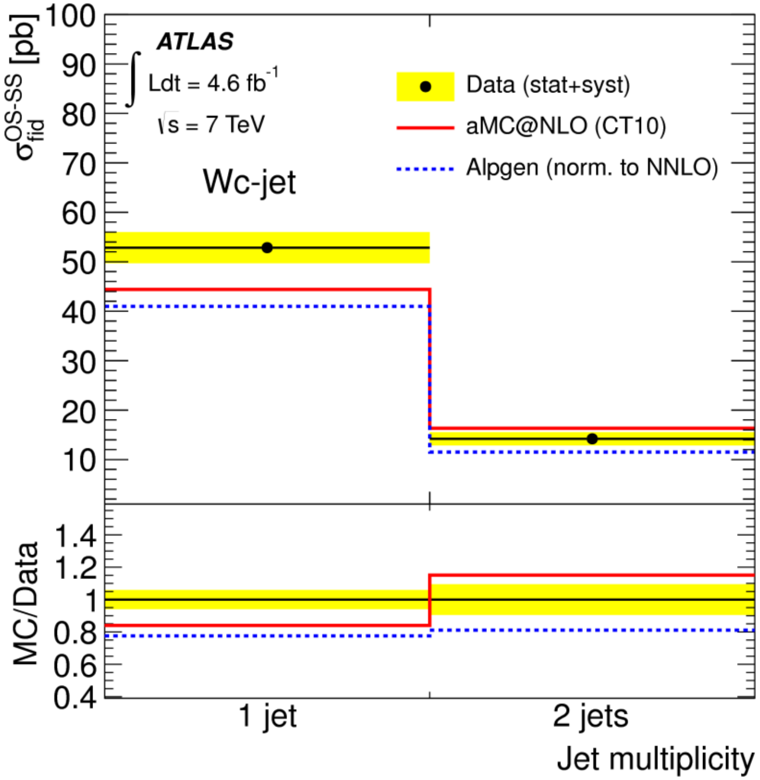
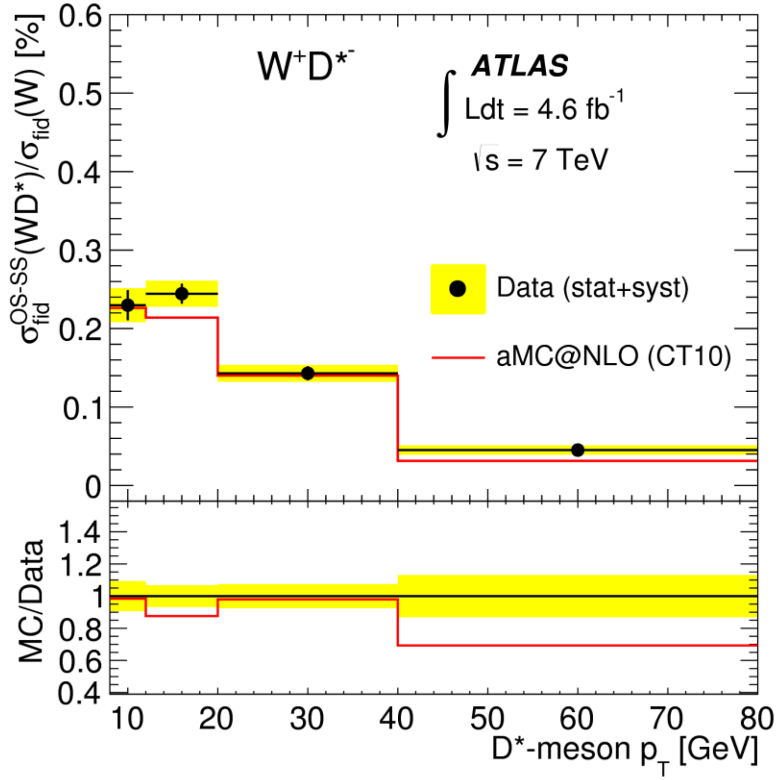
BACKUP

ADDITIONAL MEASUREMENTS

Disclaimer: no prediction uncertainties, qualitative comparison to MC nominal values

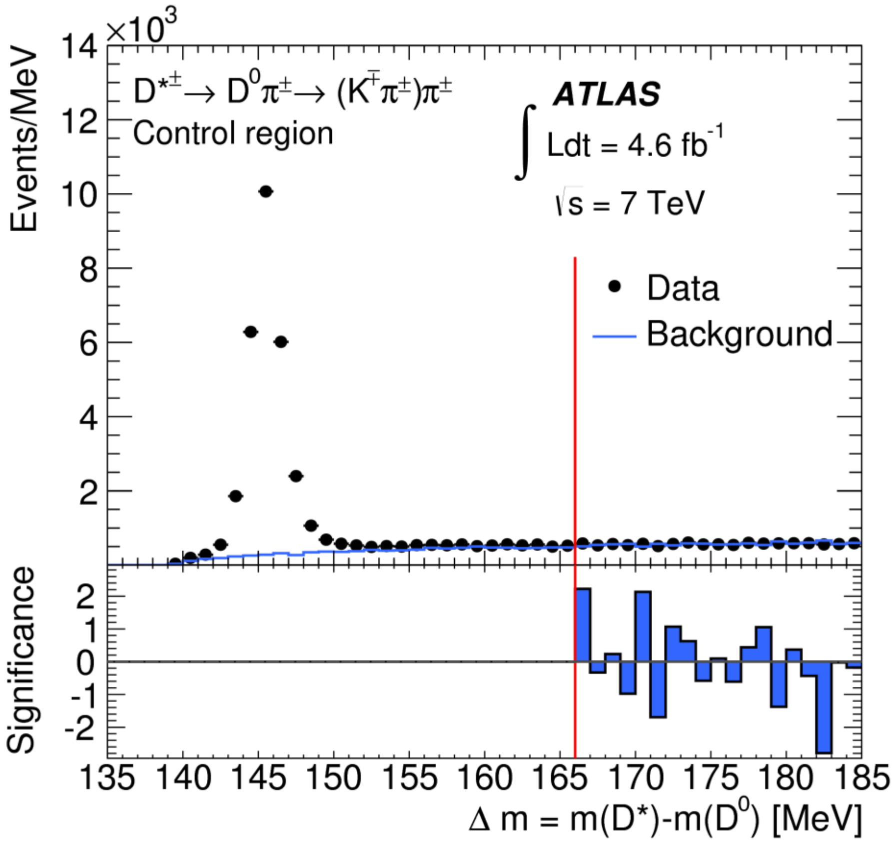


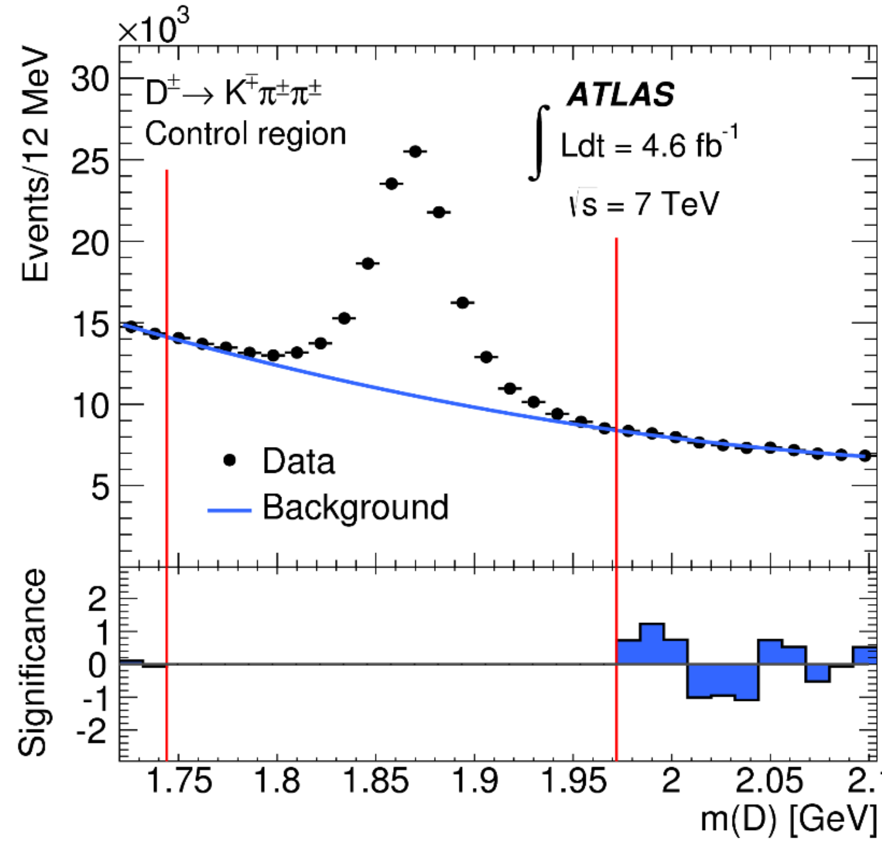


aMC@NLO+HERWIG++ does not seem to reproduce the jet multiplicity very well
Alpgen+Pythia doing much better

Small tension at high pT between data and aMC@NLO+HERWIG++
Need more data to confirm

WD(*) SIGNAL TEMPLATES

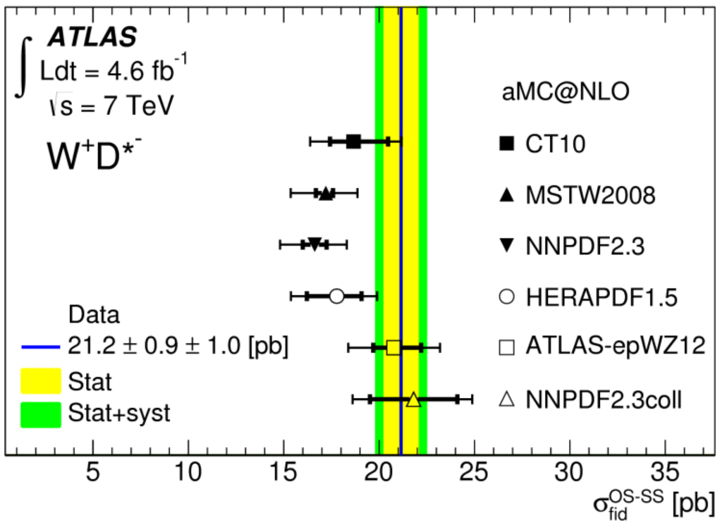


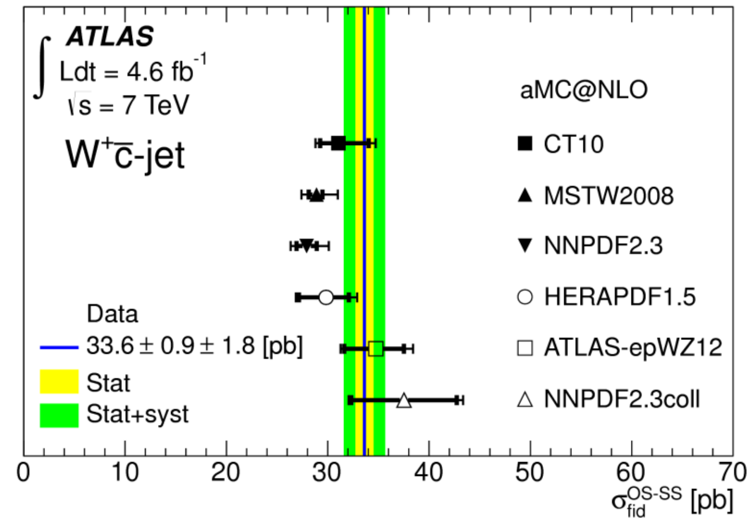


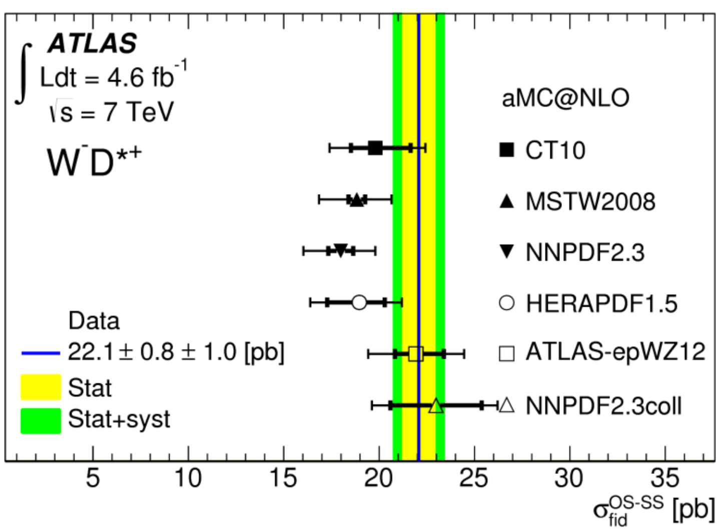
CROSS SECTIONS

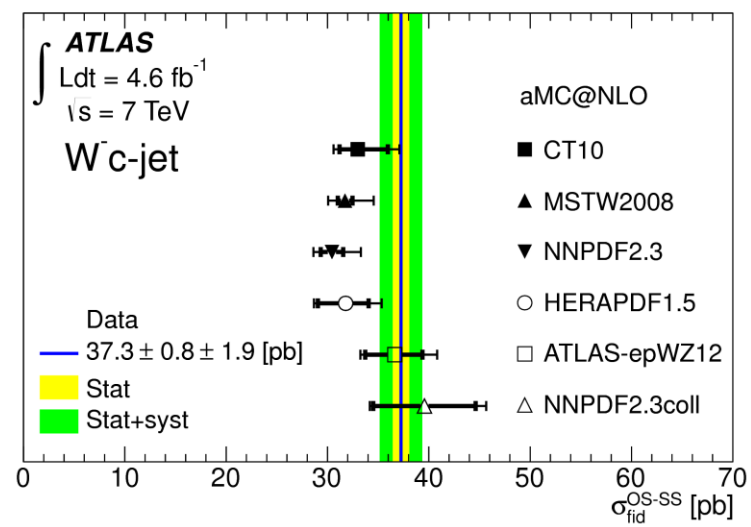
	$W^+\bar{c}$-jet	W^-c-jet	W^+D^-	W^-D^+	W^+D^{*-}	W^-D^{*+}
cross section [pb]	33.62	37.26	17.79	22.44	21.15	22.08
stat uncertainty [pb]	0.89	0.82	1.94	1.77	0.87	0.82
uncorr syst uncertainty[pb]	0.35	0.39	0.04	0.04	0.04	0.04
corr syst uncertainty[pb]	1.80	1.89	0.76	0.96	0.98	1.03
syst uncertainty[pb]	1.84	1.93	0.76	0.96	0.98	1.03
total uncertainty[pb]	2.04	2.10	2.08	2.02	1.31	1.31
Correlation matrix						
$W^+\bar{c}$-jet	1	0.76	0.05	0.06	0.09	0.10
W^-c-jet	0.76	1	0.05	0.07	0.10	0.10
W^+D^-	0.05	0.05	1	0.17	0.18	0.19
W^-D^+	0.06	0.07	0.17	1	0.24	0.25
W^+D^{*-}	0.09	0.10	0.18	0.24	1	0.58
W^-D^{*+}	0.10	0.10	0.19	0.25	0.58	1

CROSS SECTION RESULTS

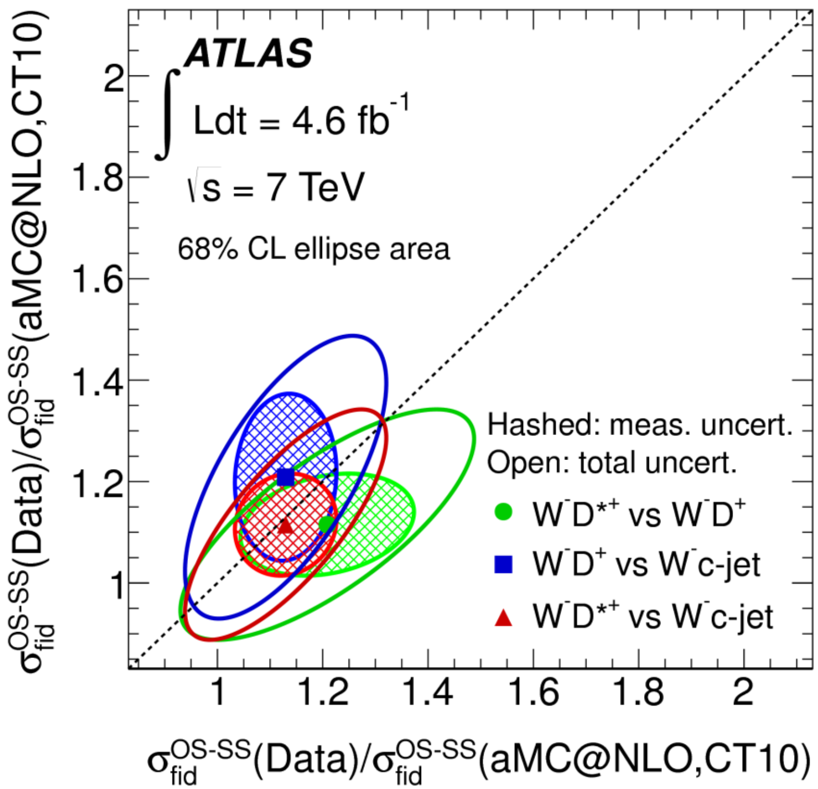


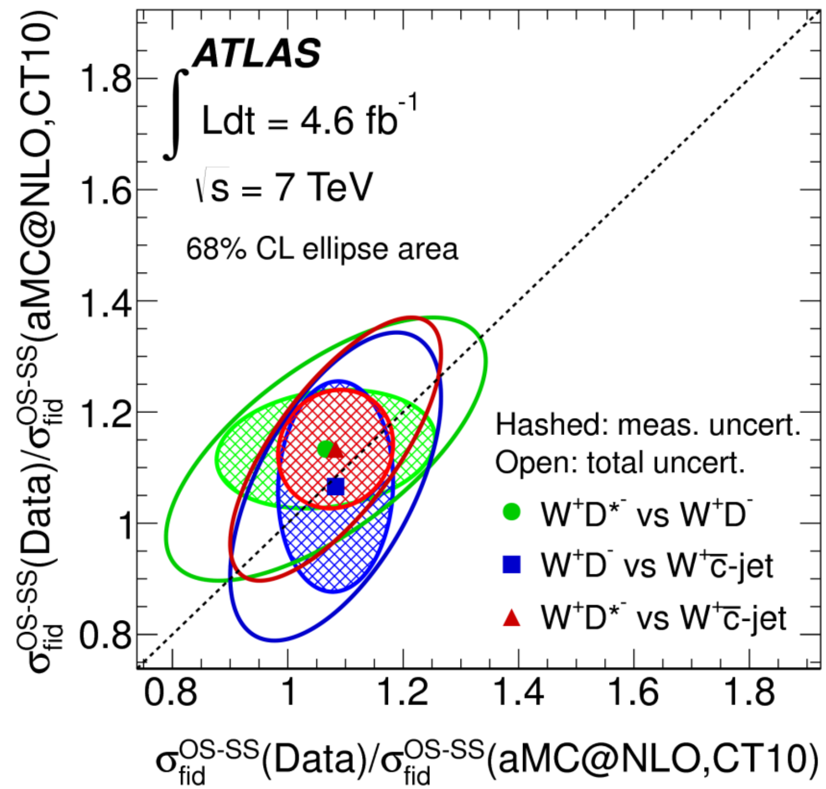




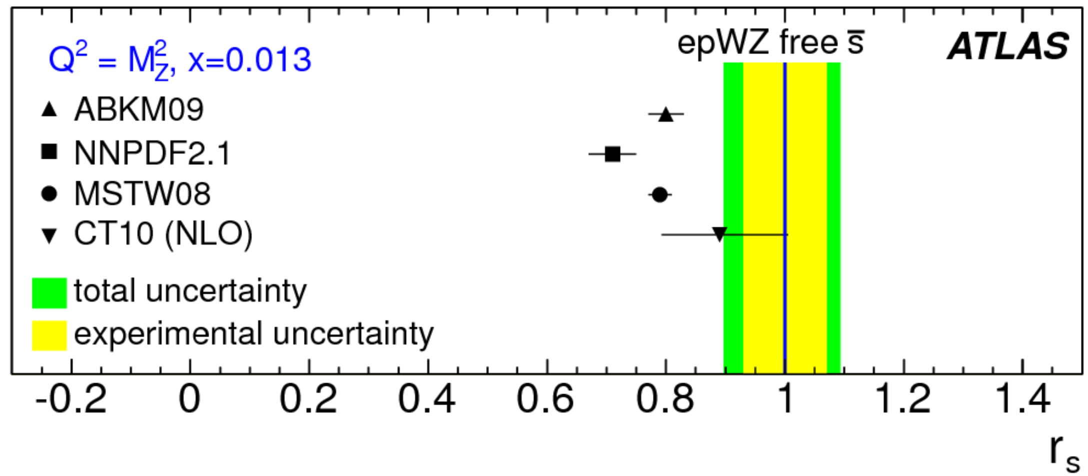


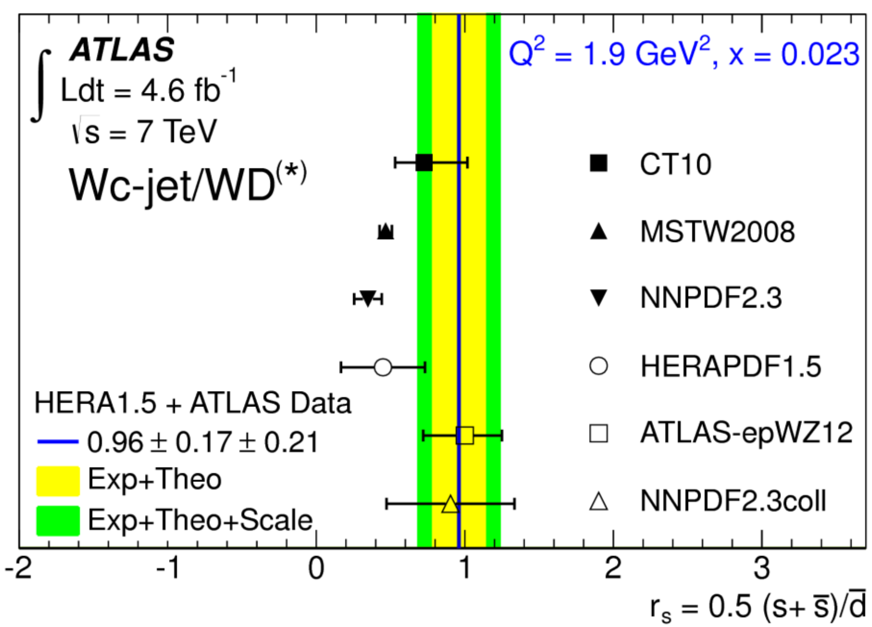
RESULTS COMPATIBILITY





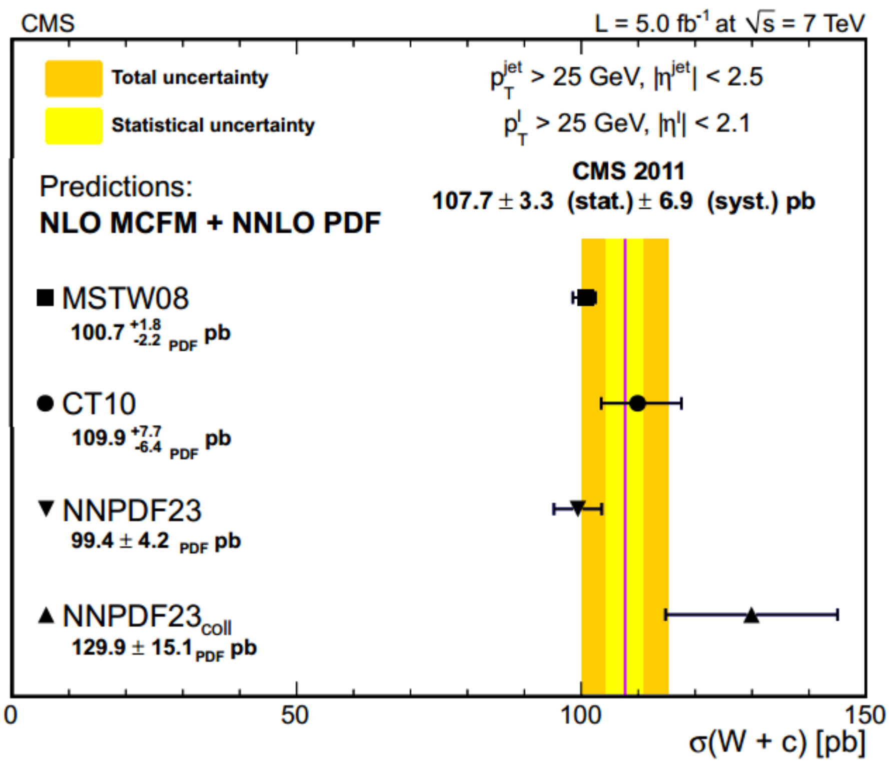
DIFFERENT ATLAS R_S RESULTS

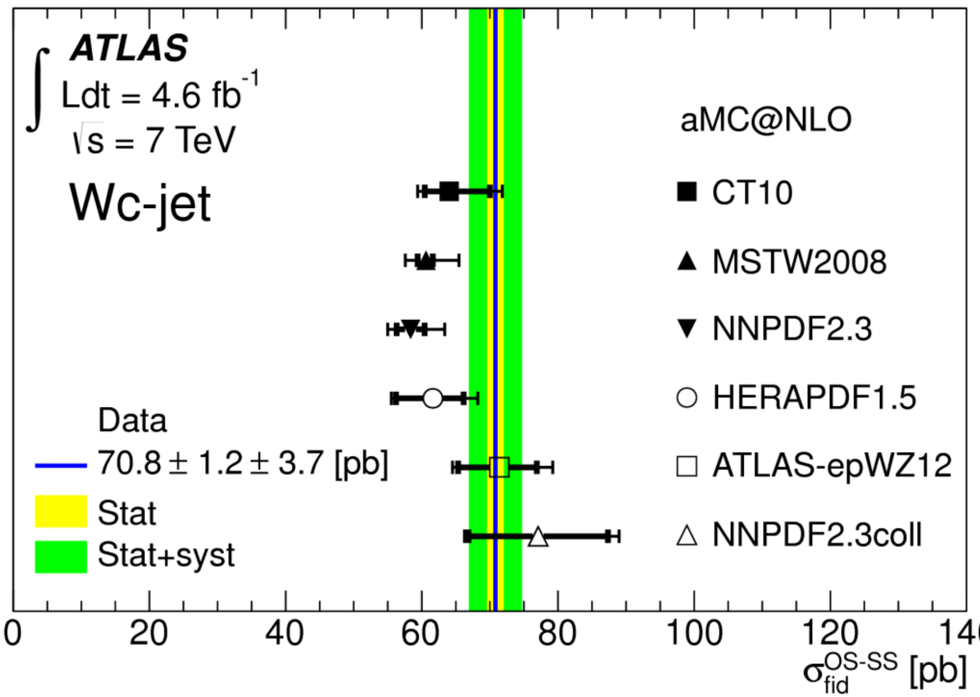




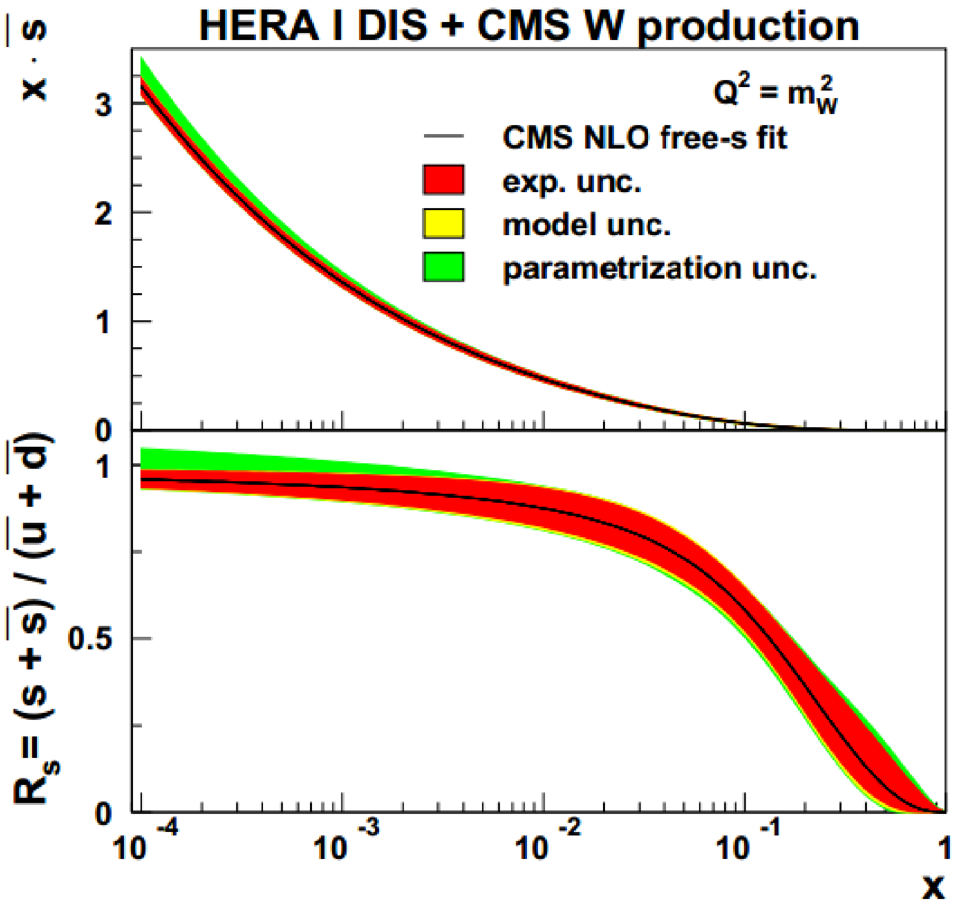
ATLAS VS CMS

arXiv: 1310.1138
JHEP 1402 (2014) 013





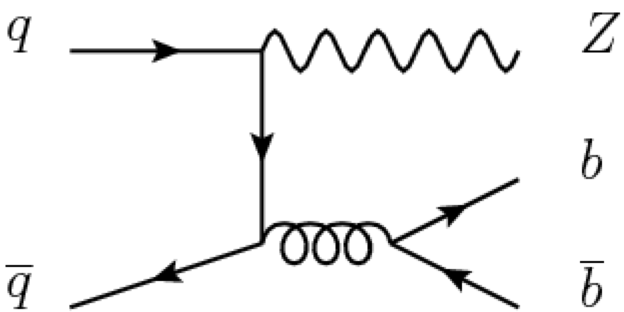
CMS FIT

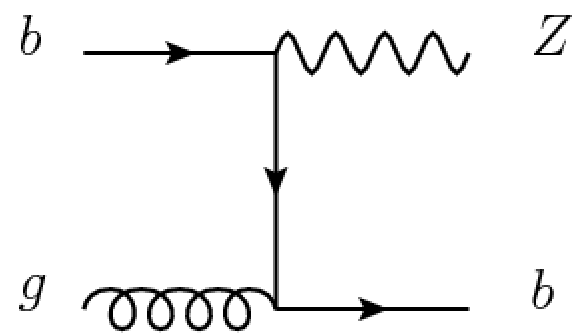


HERA I DIS + CMS W production
$Q^2 = m_W^2$
CMS NLO free-s fit
exp. unc.
model unc.
parametrization unc.
$x \cdot \bar{s}$
0
1
2
3
$R_s = (s + \bar{s}) / (\bar{u} + \bar{d})$
0
0.5
1
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x

Z+B-JETS

- Measurement performed with 2010 data at 7 TeV (36 pb^{-1})
- Per jet inclusive cross section measurement
- Statistically limited to be able to test different models





$$\sigma_b = \frac{N_b}{C_e \mathcal{L}_e + C_\mu \mathcal{L}_\mu}$$

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Experiment	$3.55^{+0.82}_{-0.74}(\text{stat})^{+0.73}_{-0.55}(\text{syst}) \pm 0.12(\text{lumi})$ pb
MCFM	3.88 ± 0.58 pb
ALPGEN	2.23 ± 0.01 (stat only) pb
SHERPA	3.29 ± 0.04 (stat only) pb

Normalized to Z inclusive NNLO cross section (ALPGEN, SHERPA)