

Measurements of vector bosons with charm and beauty at ATLAS

Miriam Watson
University of Birmingham

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Hyperons, Charm and Beauty Hadrons**

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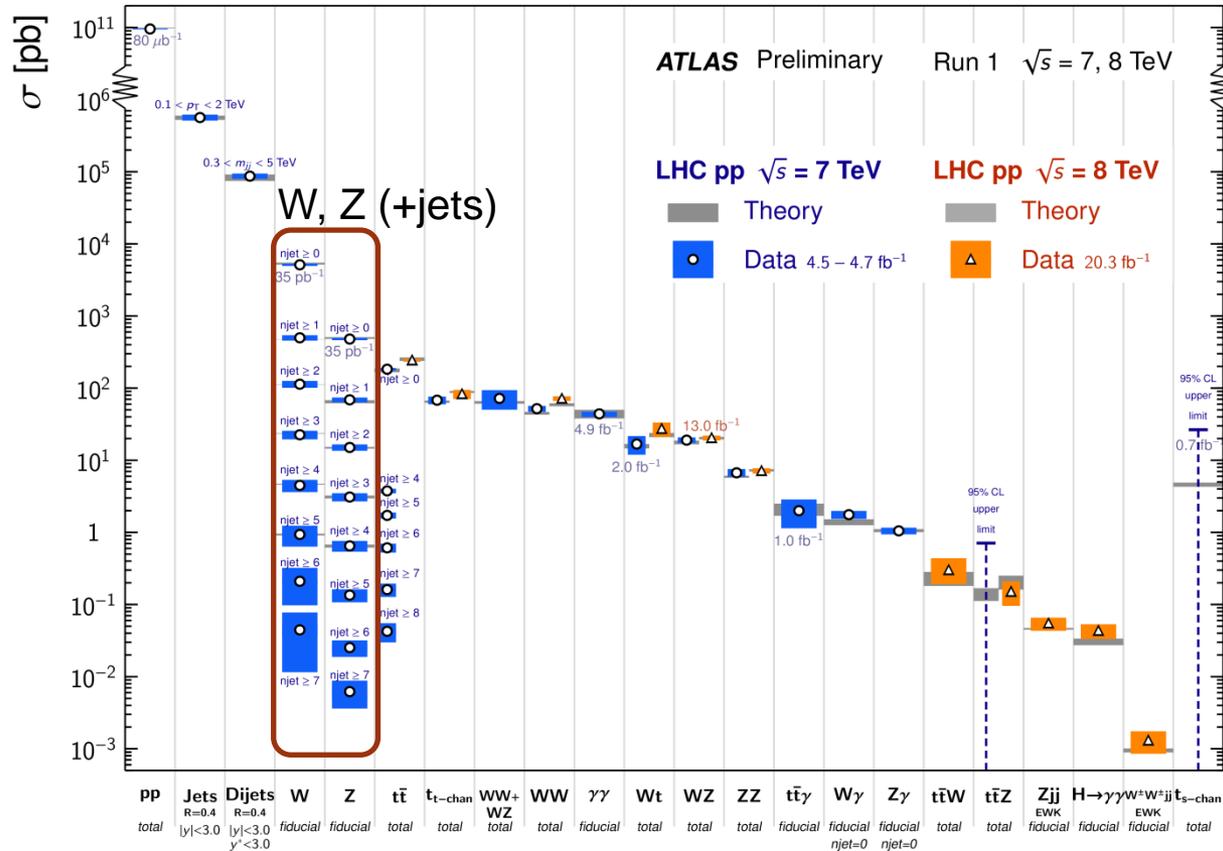


THE ROYAL
SOCIETY

ATLAS vector boson + X measurements

Standard Model Production Cross Section Measurements

Status: July 2014



- Will cover V+ heavy flavour (HF) measurements today:

- W+b
- W+c
- Z+b(b)
- W+J/psi

- V+HF production is a crucial test of pQCD
- Essential for H → bb and BSM searches
- V+b/c has unique sensitivity to heavy quark density of proton
- V+J/psi probes quarkonium production mechanism

W and Z candidates

- Selected in $W \rightarrow l\nu$, $Z \rightarrow l^+l^-$ modes; $l=e,\mu$

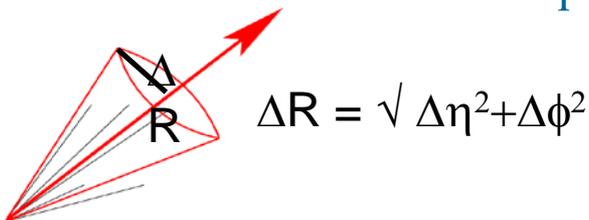
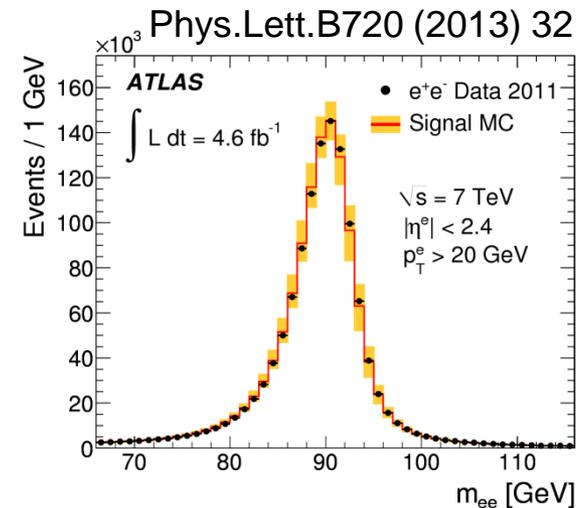
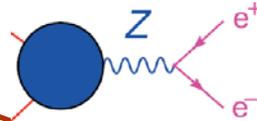
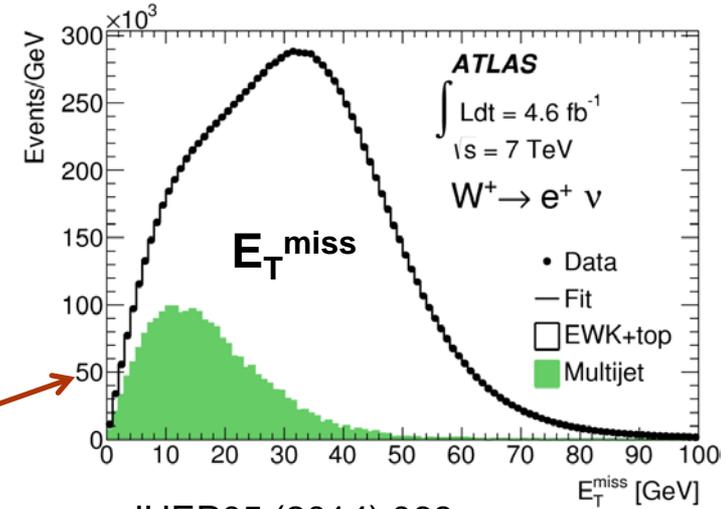
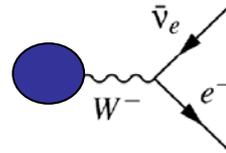
- General selection:

- High p_T lepton triggers
- p_T , $|\eta|$ cuts on lepton

- W**: significant missing E_T and transverse mass, M_T

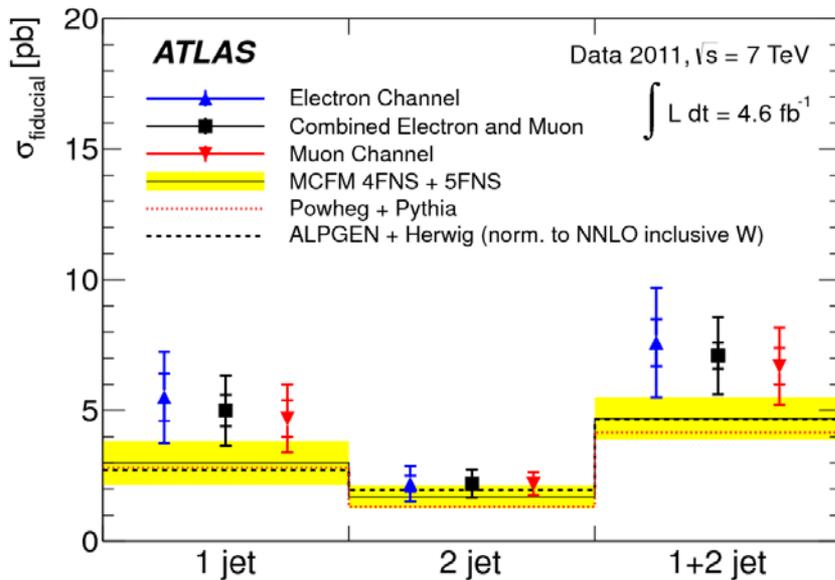
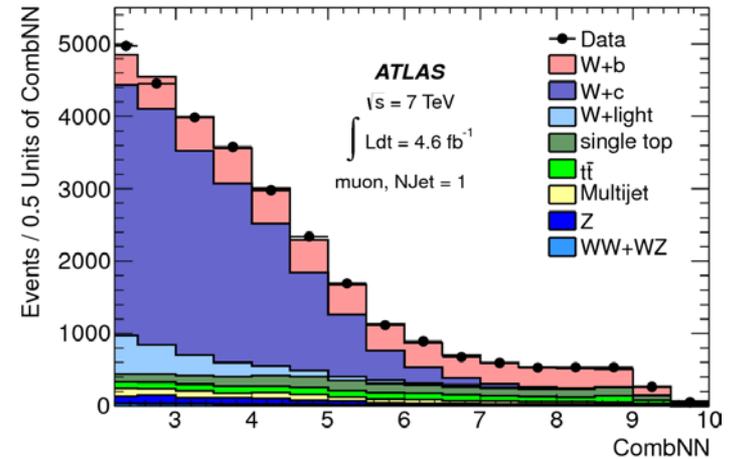
- Z**: dilepton mass close to M_Z

- Isolated lepton**: check track or cluster activity in a cone around the lepton to remove leptons in jets

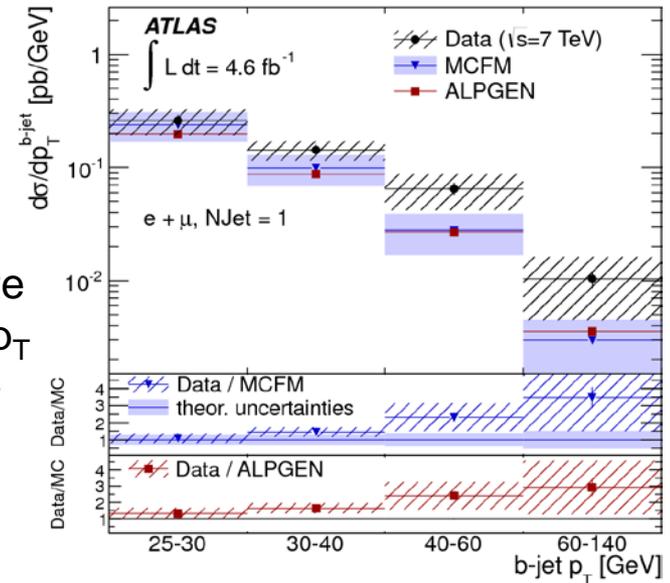


W+b

- Constrain pQCD with heavy flavours
- Background to e.g. WH(H→bb)
- Extract b-jet contribution using template fit to b-tag weights
- Compare with NLO MCFM, NLO+PS Powheg+Pythia, LO+PS Alpgen+Herwig
 - 1-jet bin: data consistent within 1.5σ with NLO predictions
 - 2-jet bin: good agreement of data with theory

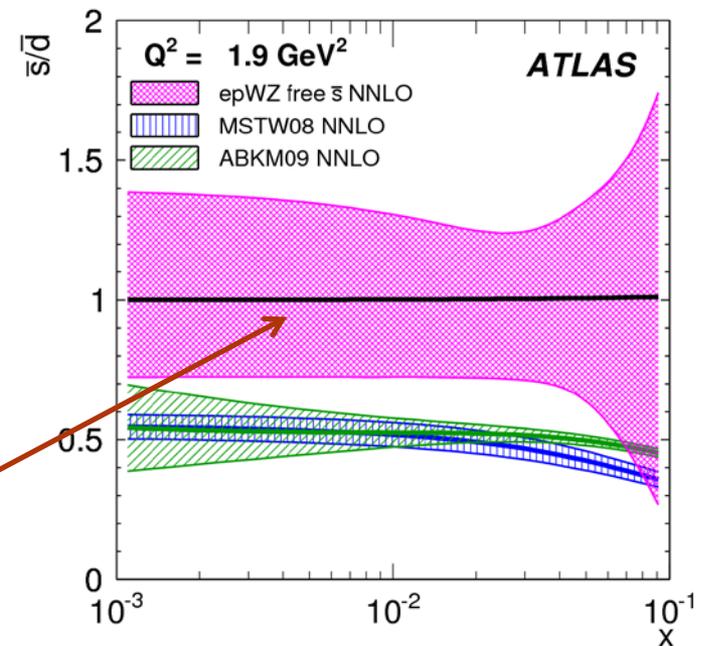
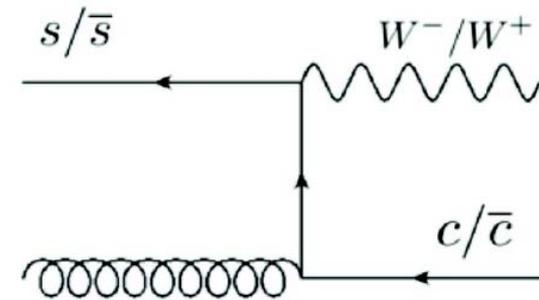


Predictions
slightly
underestimate
data at high p_T
for 1-jet case



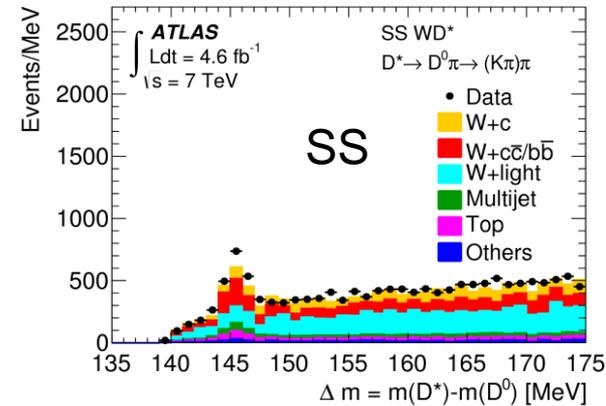
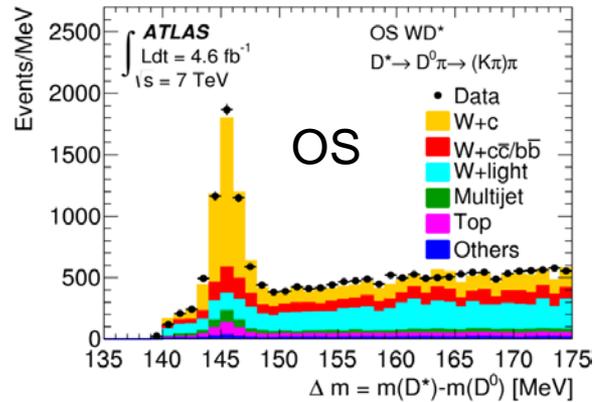
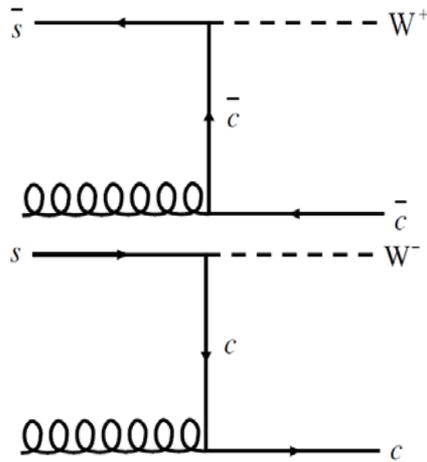
W+c

- Production of W in association with a single charm quark
- LO process: $gq \rightarrow Wc$; $q = d, s, b$
 - d quark $\approx 10\%$
 - s quark dominates
 - Directly sensitive to s-quark PDF at $x \sim 0.01$
- Experimental measurements mixed:
 - Some analyses favour s-quark sea suppression w.r.t. d-quark sea
 - ATLAS W/Z measurements favour SU(3) flavour symmetric sea

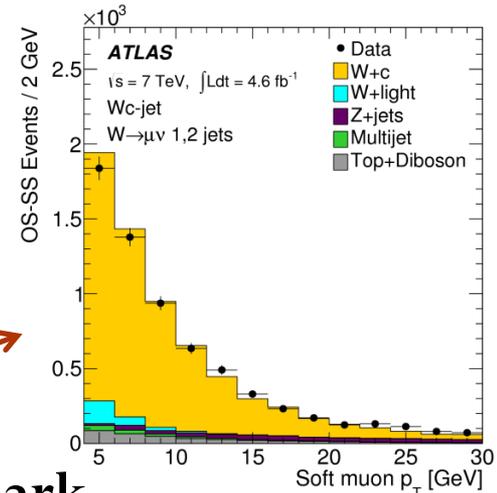


Phys.Rev.Lett. 109 (2012) 012001

W+c measurement overview

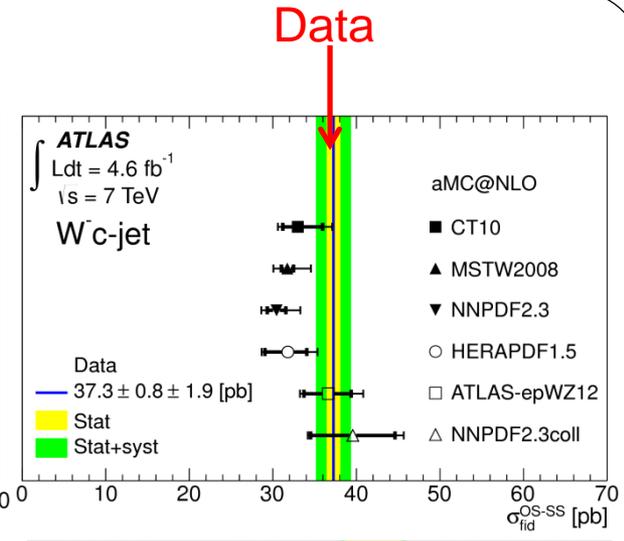
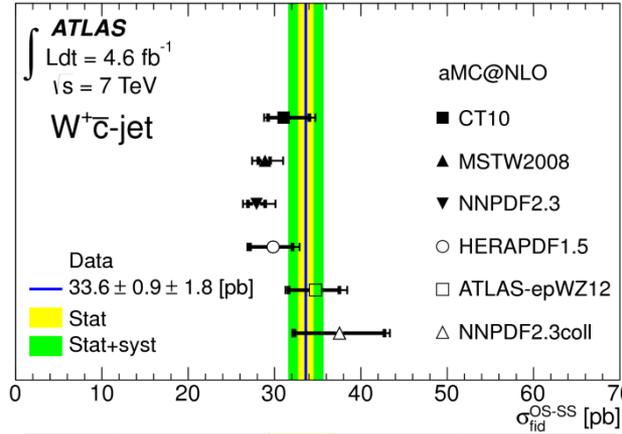


- 4.6 fb⁻¹ of data collected in 2011 at $\sqrt{s} = 7 \text{ TeV}$
- W boson selected via muon or electron decays
- Charm is tagged using either:
 - D^(*) decays ($D^- \rightarrow K^+ \pi^- \pi^-$, $D^{*+} \rightarrow D^0 \pi^+$); or
 - Semi-leptonic decays inside a jet (soft muons)
- Charge correlation between W boson and charm quark
 - Signal has opposite sign (OS)
 - Most backgrounds are charge symmetric (OS and SS)
- OS-SS enables isolation of the W + c final state from W + c \bar{c} , b \bar{b}



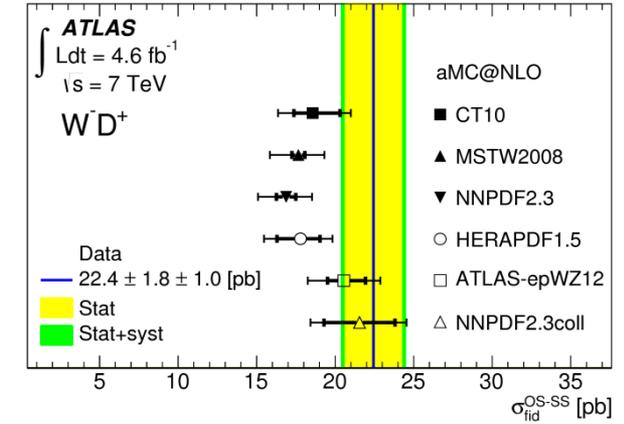
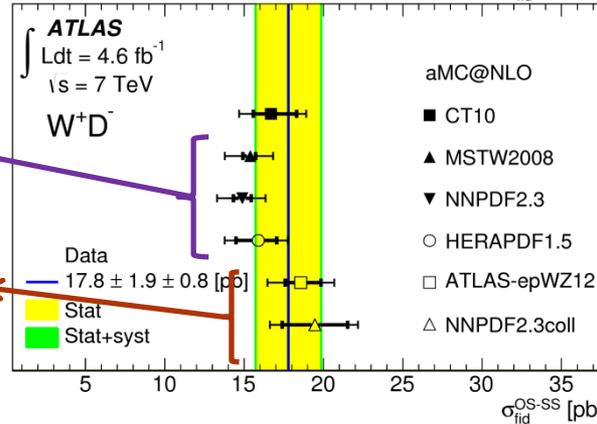
Fiducial W+c cross-sections

- Compare fiducial cross-sections with aMC@NLO plus various PDF sets
- Predicted values vary by $\sim 25\%$



s-quark suppressed
cf. d-quark

s-quark
~ d-quark



σ_{fid}^{OS-SS}

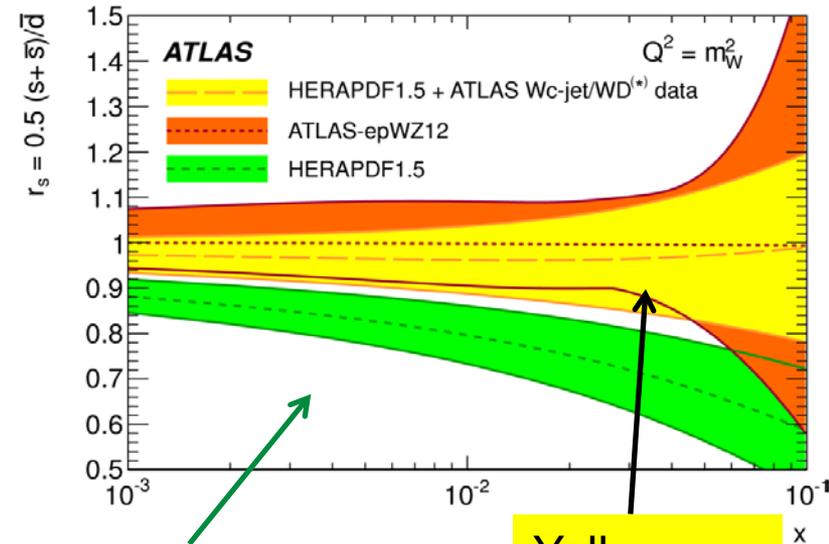
- Data consistent with wide range of predictions
- Favour symmetric light-quark sea at $x \sim 0.01$

Ratio of strange-to-down in sea and s quark asymmetry

- Ratio of strange to down sea quarks is regulated in HERA PDF by a single parameter (eigenvector f_s)
- Free fit of **strange to down** sea content of proton in ATLAS data (within this model)

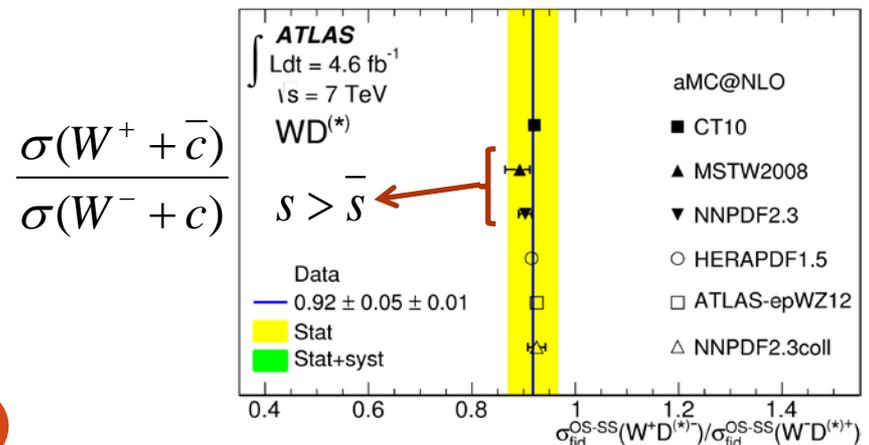
$$r_s \equiv 0.5(s + \bar{s})/\bar{d} = f_s/(1 - f_s) = 0.96^{+0.26}_{-0.30}$$

- Results compatible with the ATLAS-epWZPDF (includes W/Z data)
- Consistent with SU(3) flavour symmetry in the proton
- Charge asymmetry is consistent with symmetric $s = \bar{s}$ and with PDF sets with a small asymmetry, $s > \bar{s}$



Default: s-quark suppressed cf. d-quark

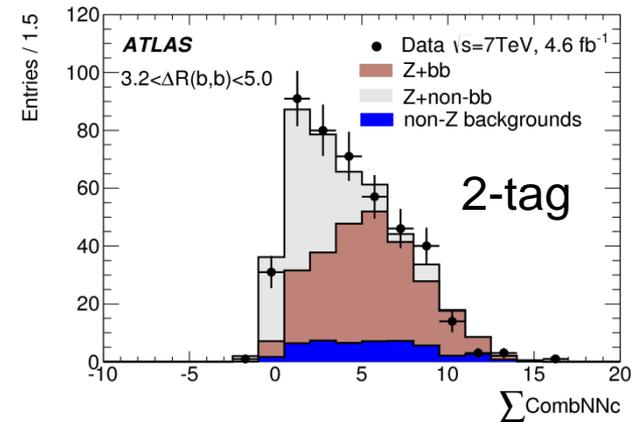
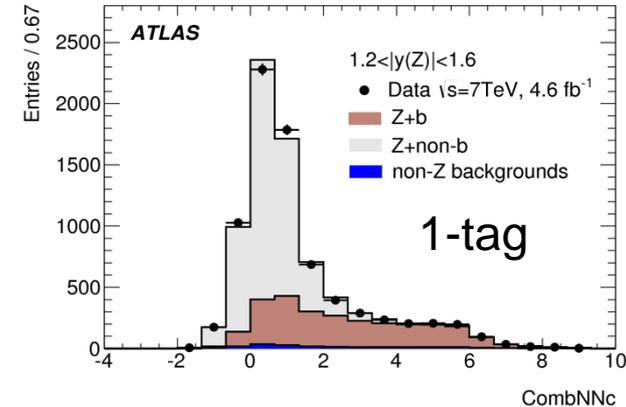
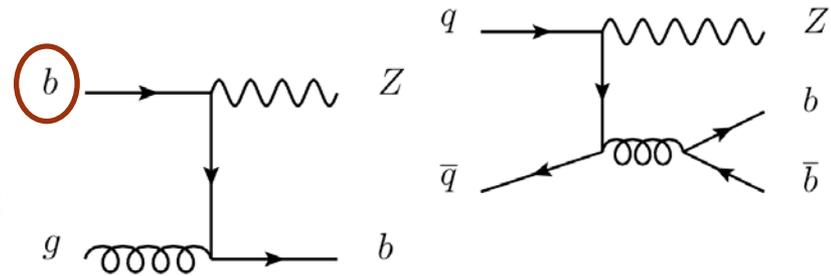
Yellow band: this analysis



Z + b(b)

arXiv:1407.3643,
submitted to JHEP

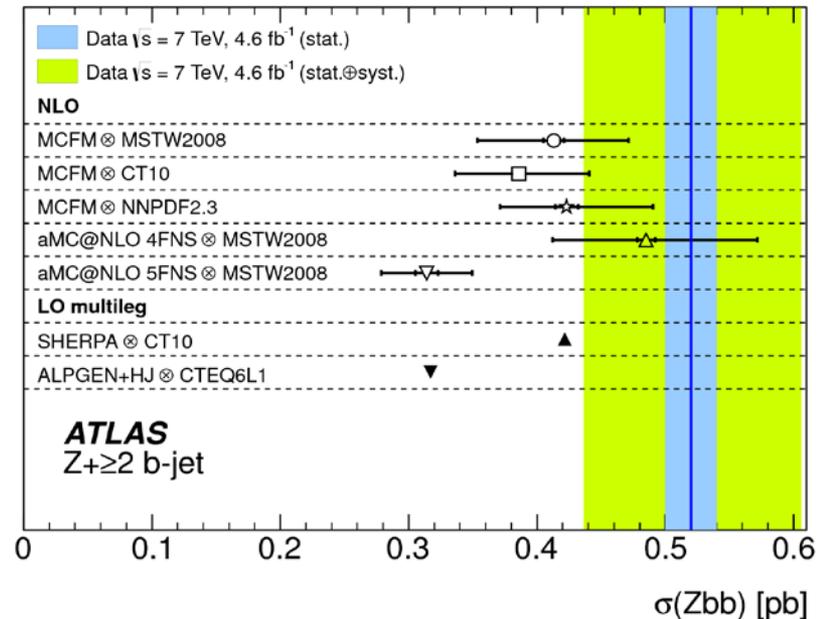
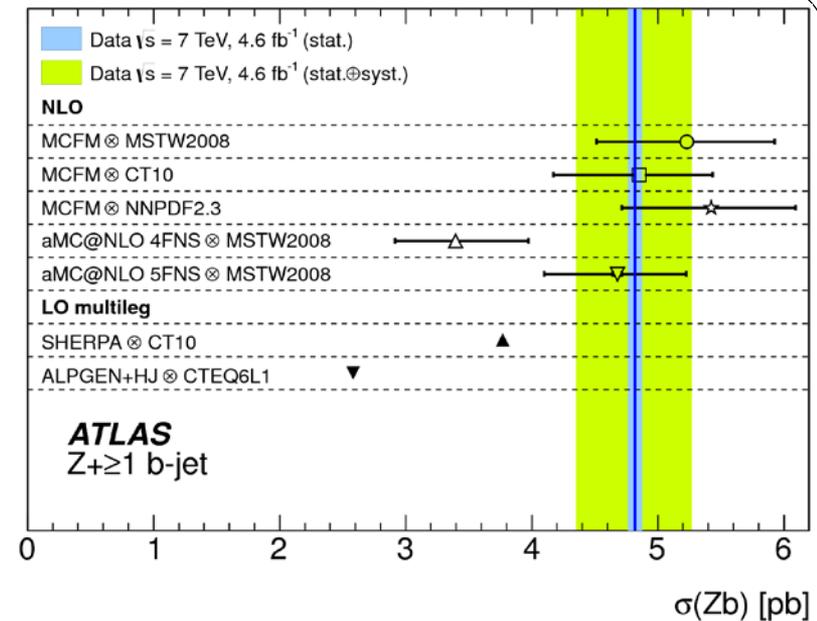
- Production of Z in association with b jets
- Test different approaches to heavy quark modelling:
 - 4-flavour vs. 5-flavour number scheme (nFNS)
 - use of b-quark vs. gluon+light initial partons
 - Use of b quark mass in calculations
 - Comparison of LO and NLO predictions
- Important background for Higgs and BSM searches
- 4.6 fb⁻¹ of data collected in 2011 at $\sqrt{s} = 7$ TeV
- Template fits to b-jet tagging distributions
- Main backgrounds from Z+c-jets, light-jets



Neural net with secondary vertices and displaced tracks

Z + b(b) cross-sections

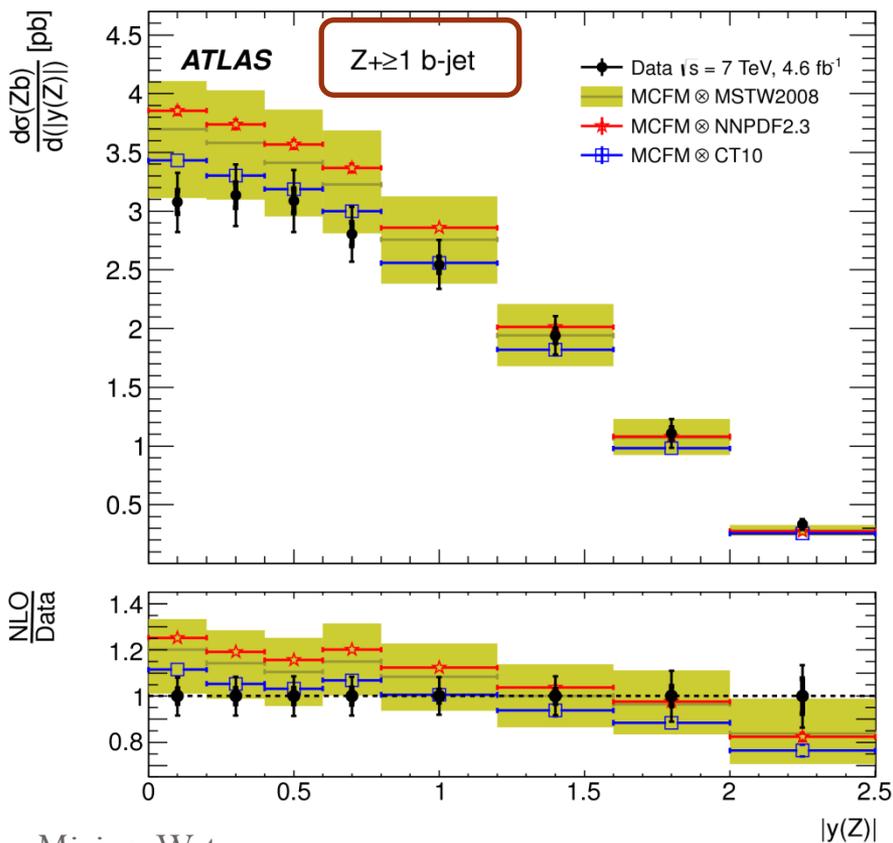
- MCFM agrees with data
 - NLO, 5FNS
 - Corrected to particle level
 - PDF sets: MSTW2008, CT10, NNPDF2.3
- aMC@NLO + HERWIG++ (MSTW2008)
 - Particle level
 - 1) NLO Z+b in 5FNS
 - 2) NLO Z+bb in 4FNS
 - For $Z+\geq 1$ b-jet:
 - Main difference is 4FNS vs. 5FNS (both NLO)
 - 4FNS underestimates data
 - For $Z+\geq 2$ b-jets:
 - 5FNS is a LO approximation, 4FNS is NLO
 - Dominant Z + bb diagrams do not involve initial state b-quarks, so FNS is less relevant
- Alpgen (4FNS), Sherpa (5FNS)
 - LO multi-leg
 - Underestimate the data
 - Theory uncertainties not included



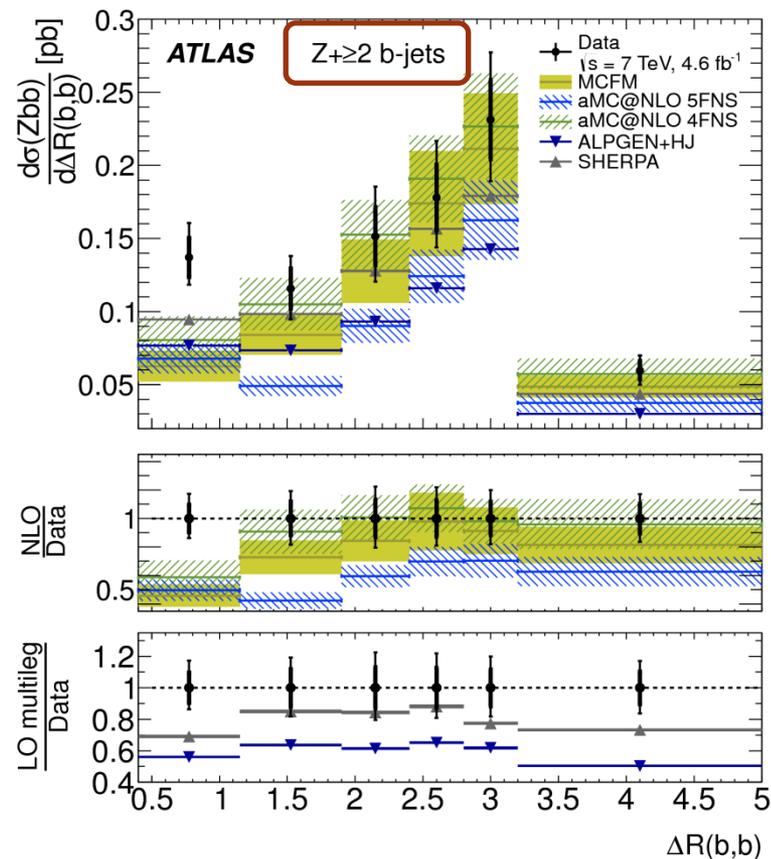
Z + b(b) differential cross-sections

- Unfolded differential distributions measured in 12 kinematic variables

- $d\sigma(Z+\geq 1 \text{ b-jet}) / d|y(Z)|$
- Alternative PDF sets show similar trends
- Differences small c.f. scale uncertainties

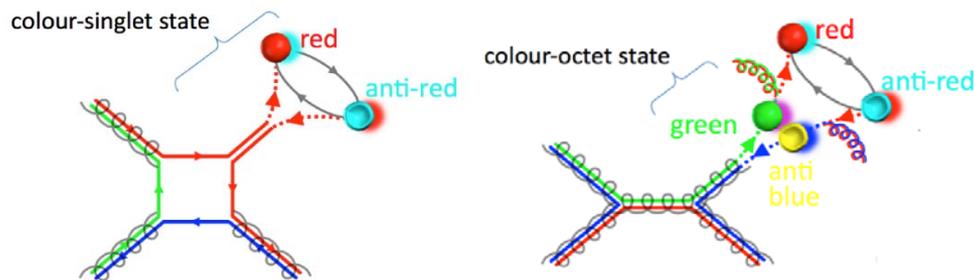


- $d\sigma(Z+\geq 2 \text{ b-jets}) / d\Delta R(b,b)$
- Reasonable description within uncertainties
- Some disagreement at small $\Delta R(b,b)$

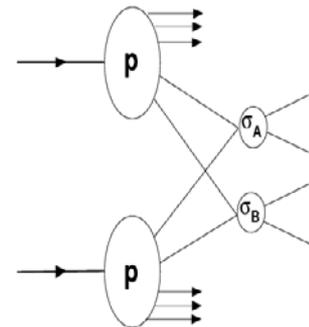
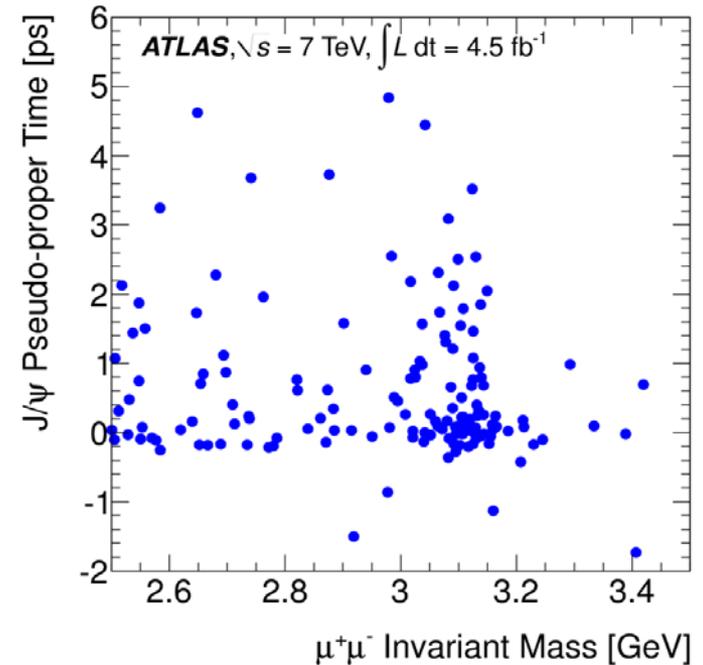


W+prompt J/ψ measurement

- Search for associated production of $W(\rightarrow\mu\nu)$ and **prompt J/ψ** ($\rightarrow\mu^+\mu^-$)
- Probes quarkonium production mechanism
 - **Colour singlet (CS)** mechanism cannot describe all measurements
 - **Colour octet (CO)**: initial coloured state decays into a singlet quarkonium bound state



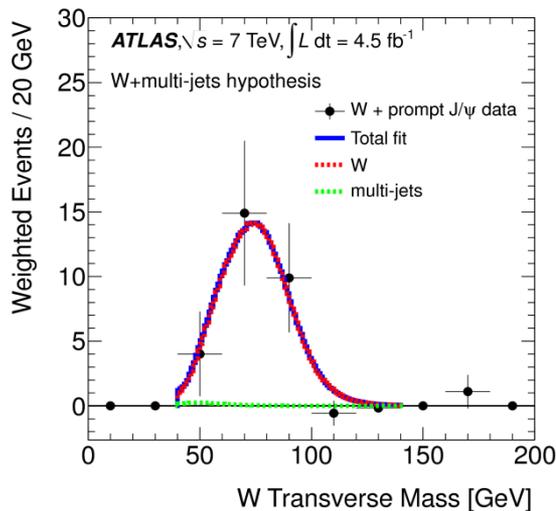
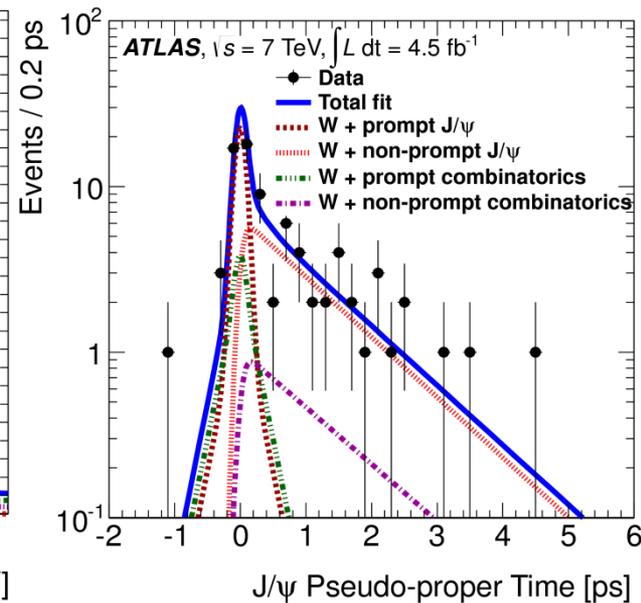
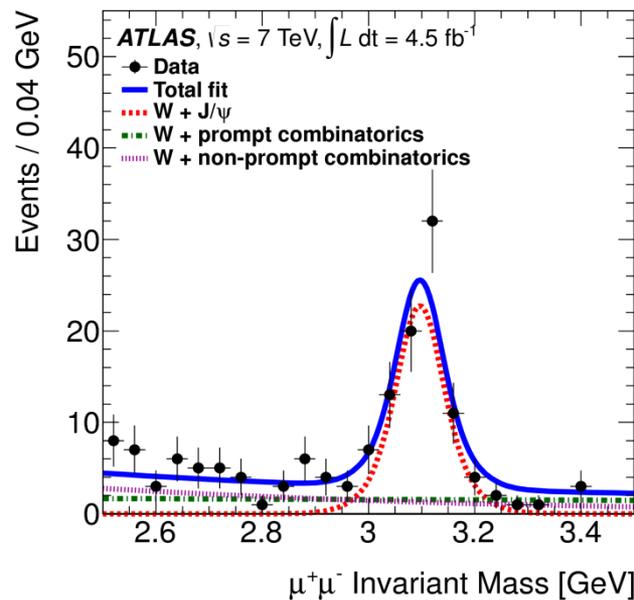
- Use 4.6 fb^{-1} at 7 TeV (2011)
- Sensitive to multiple parton interactions
- Include double parton scattering (DPS) in signal, and estimate contribution



DPS: two independent pairs of partons yield a W and a J/ψ (single pp)

Prompt J/ψ fits and W verification

- Unbinned maximum likelihood fit to J/ψ mass and pseudo-proper time \rightarrow extract prompt signal
- Fit weighted $m_T(W)$ distribution for prompt candidates: W signal and multi-jet background
- Jet bkd. 0.1 ± 4.6 events



Observe ~ 29 W+prompt J/ψ events

Background-only hypothesis rejected at 5.3σ level

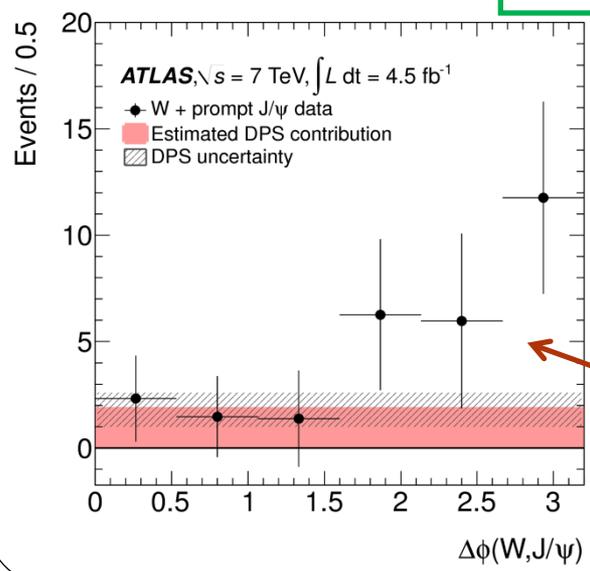
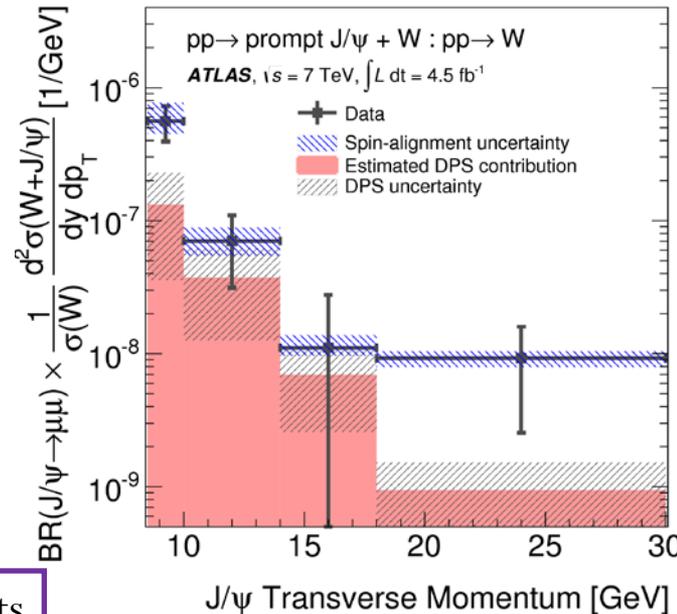
SPS and DPS contributions

- Measure $(W^\pm + J/\psi)$ production cross-section relative to inclusive W^\pm cross-section
- Estimate **DPS contribution** from:
 - $d\sigma(W+J/\psi) = d\sigma(W) \otimes d\sigma(J/\psi) / \sigma_{\text{eff}}$

Measured in this analysis

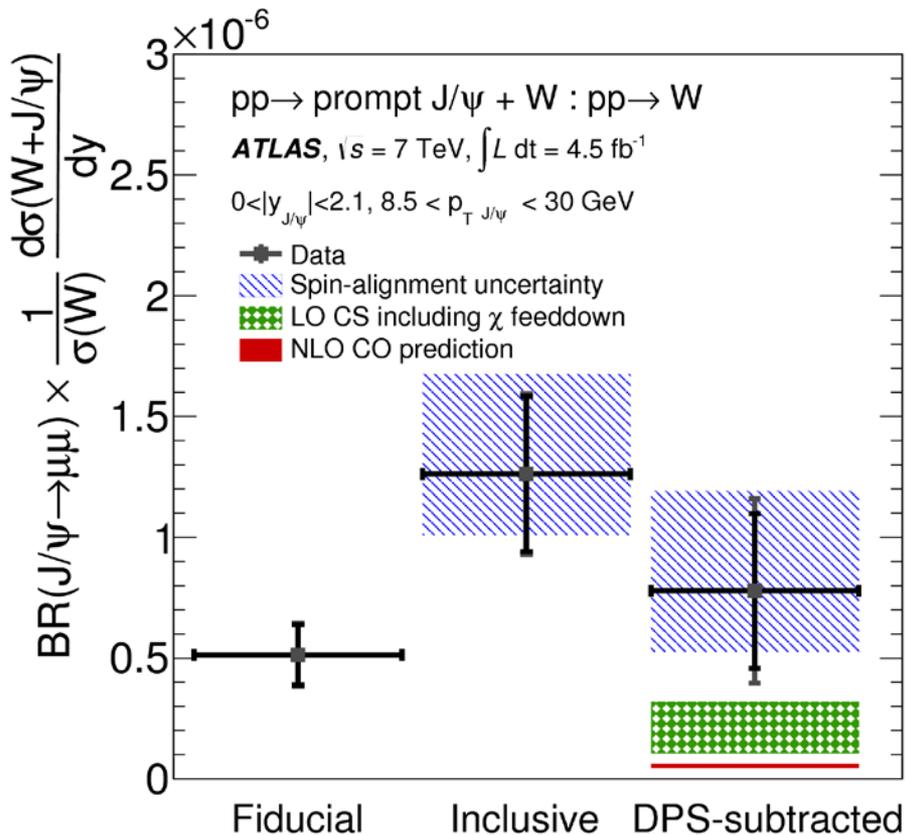
From ATLAS prompt J/ψ
arXiv:1104.3038

From ATLAS $W+2\text{jets}$
arXiv:1301.6872



- Note: this is a phenomenological approximation
- DPS estimate $\sim 40\%$
- Expect peak towards $\Delta\phi = \pi$ for **SPS contribution**

Prompt $J/\psi+W$ compared to theory



- Summary of fiducial, corrected and DPS-subtracted cross-section ratios
- **Colour singlet model (CS): LO**, includes feed-down from $\psi(2S)$ and χ_c
- **Colour octet model (CO) : NLO**
- Rate appears to be dominated by CS contributions (but could have large corrections to CO, or modified DPS formalism)
- Both compatible with measurement at 2σ

CS: arXiv:1303.5327

CO: arXiv:1012.3798

Summary

Full details of ATLAS heavy flavour results at <https://twiki.cern.ch/twiki/bin/view/AtlasPublic>

- Measurements of vector bosons + heavy flavour allow QCD predictions to be probed in new regions of phase space and at higher energies than before
- V + b/c measurements:
 - Probe the PDF of the proton
 - Challenge predictions in differential distributions
- V + quarkonia
 - First observation of associated $W + \text{prompt } J/\psi$
 - Confront data with models (e.g. colour-singlet, -octet) in new regime
 - Future measurements will provide important input to understanding multiple parton scattering

Backup slides

Cross-section ratio +/-

$$R_c^\pm = \frac{W^+ + \bar{c}}{W^- + c}$$

- Ratio W^+ / W^- is smaller than 1 due to **valence** down contribution
- Deviation of predicted value might be due to **strange sea asymmetry** $s : \bar{s}$
- Take CT10 prediction (no asymmetry) \rightarrow estimate of sensitivity

$$A_{s\bar{s}} = (2 \pm 3)\%$$

- $W+c$ analysis is dominated by statistical uncertainties: 2012 data will help

