# Measurement of associated production of vector bosons with b-jets, with a charm quark, and with a J/ψ meson in ATLAS

Miriam Watson
University of Birmingham

**Beauty 2014**

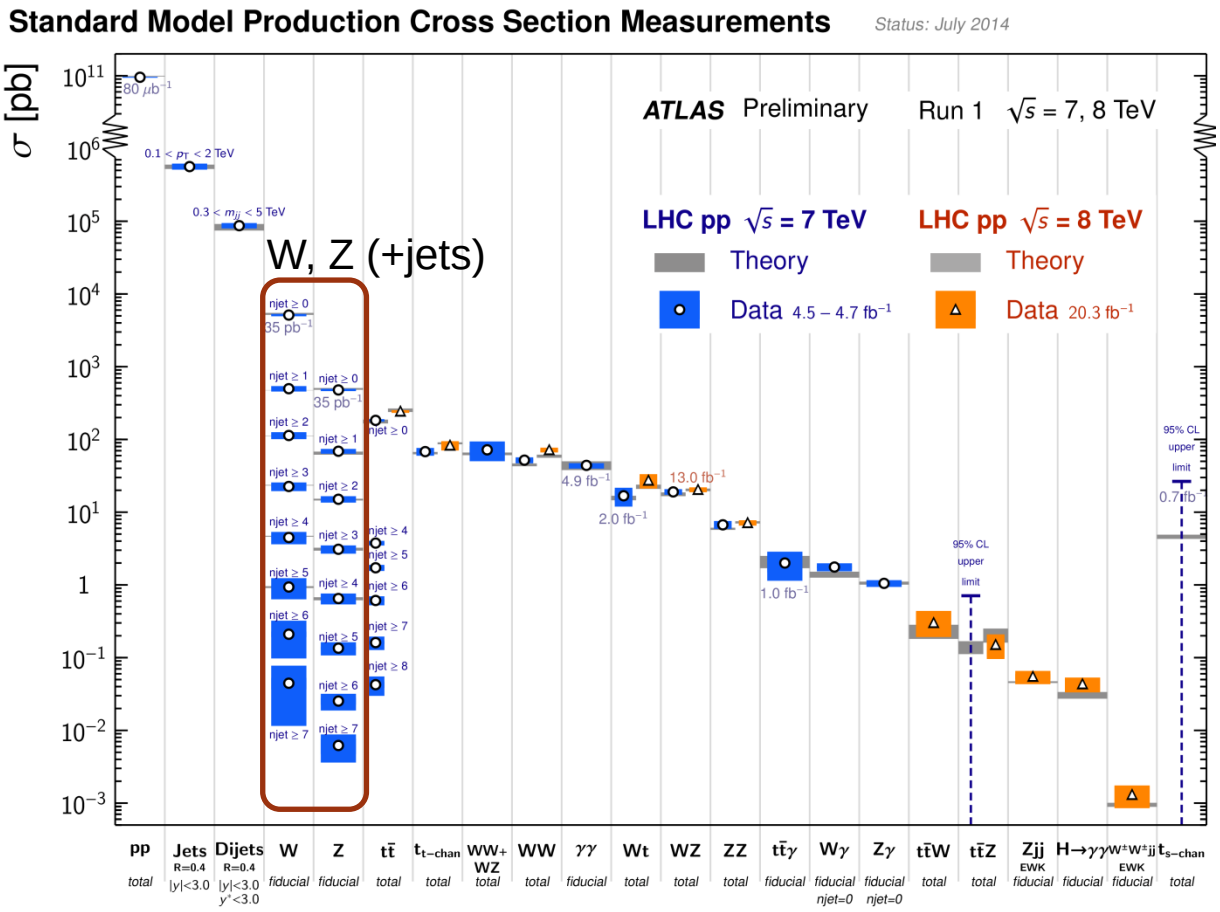
The 15th International Conference on B-Physics at Frontier Machines at the University of Edinburgh

14th - 18th July 2014


UNIVERSITY OF BIRMINGHAM

THE ROYAL SOCIETY

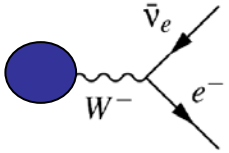
# ATLAS vector boson + X measurements

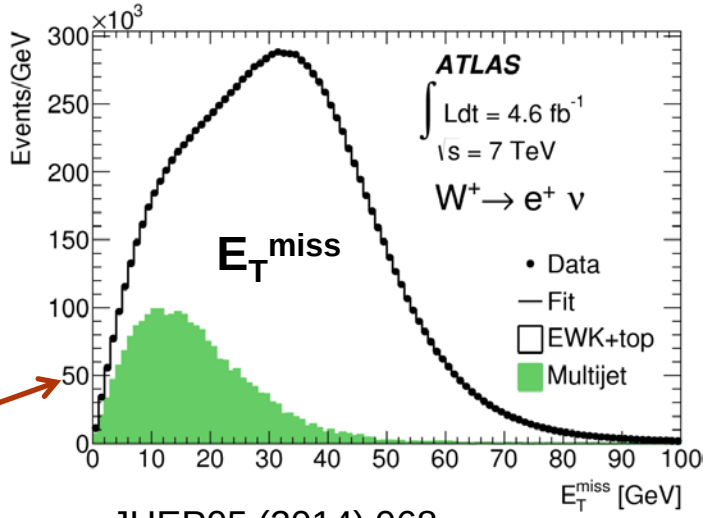



- Will cover V+ heavy flavour (HF) measurements today:
  - **W+b**
  - **W+c**
  - **Z+b(b)**
  - **W+J/ψ**
- V+HF production is a crucial test of pQCD
- Essential for H→bb and BSM searches
- V+b/c has unique sensitivity to heavy quark density of proton
- V+J/ψ probes quarkonium production mechanism

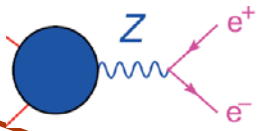
# W and Z candidates

- 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

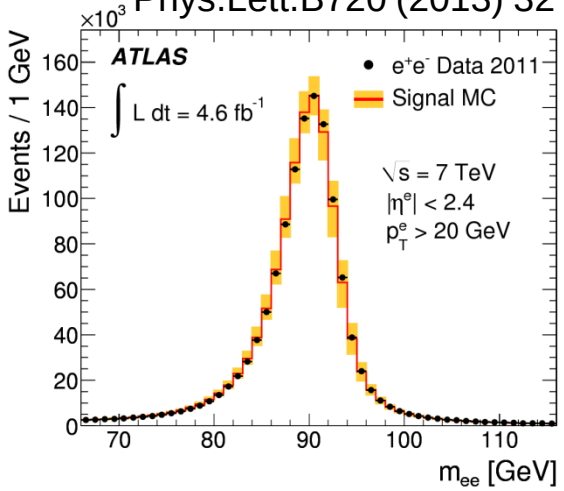


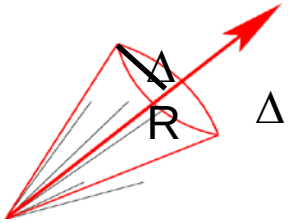




JHEP05 (2014) 068




Phys.Lett.B720 (2013) 32



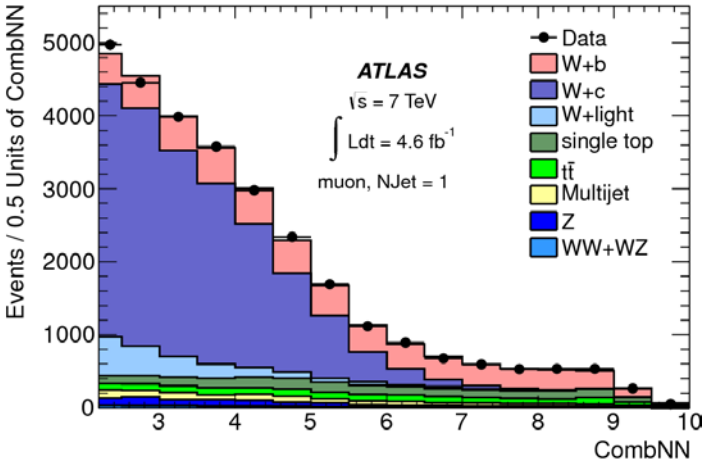



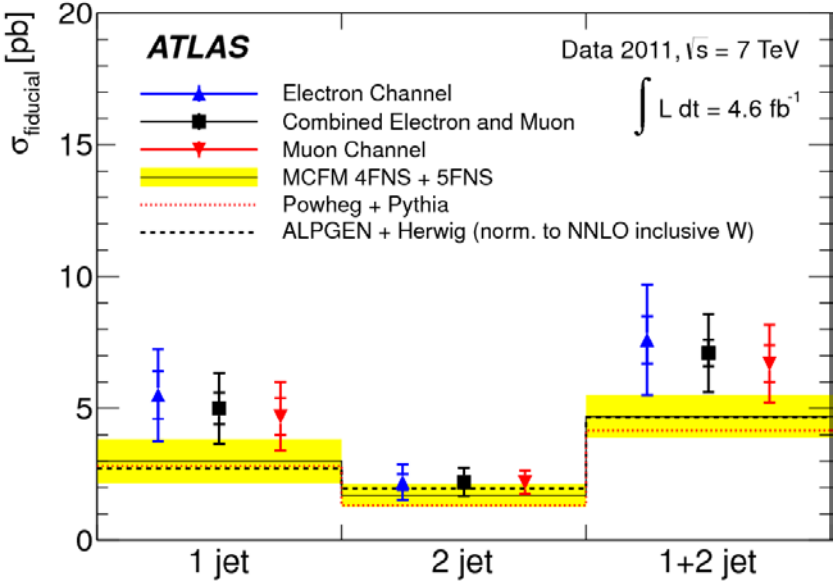

$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$

# W+b

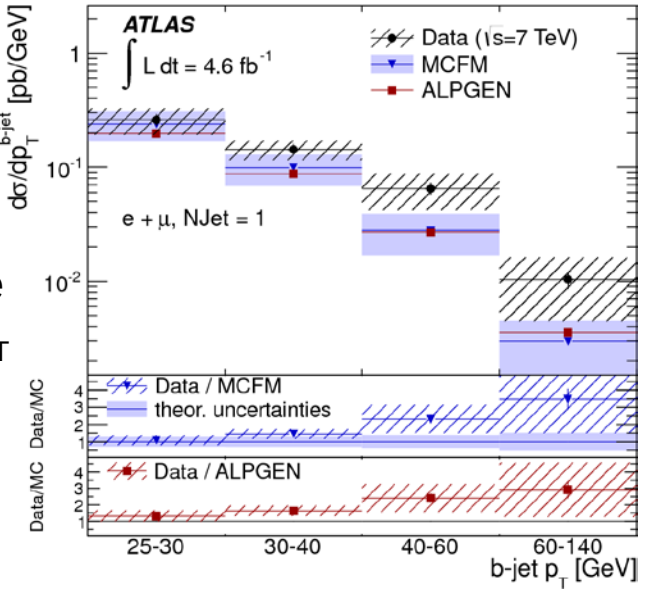
arXiv:1302.2929,
JHEP 06 (2013) 084

- 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



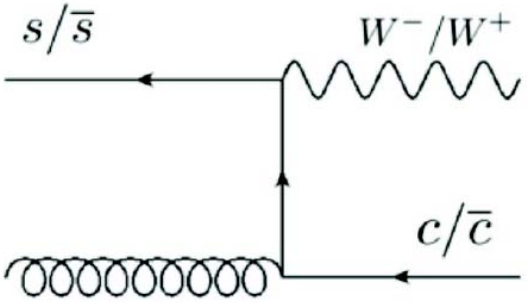

Predictions slightly underestimate data at high $p_T$ for 1-jet case

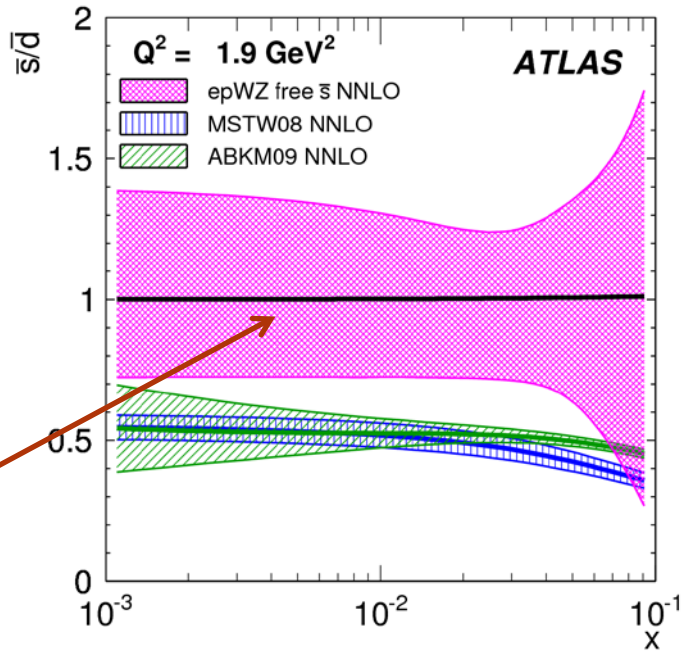


# W+c

arXiv:1402.6263,
JHEP 05 (2014) 068

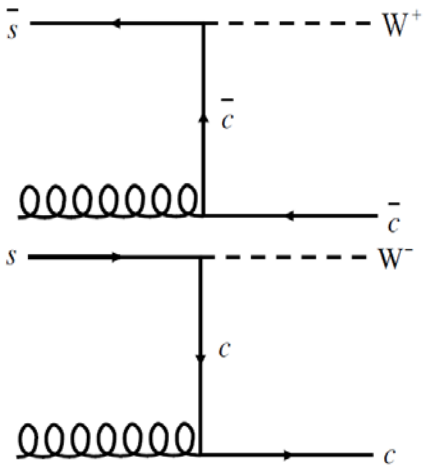
- Production of W in association with a single charm quark
- LO process: $gq \rightarrow Wc$; q=d, s, b
  - d quark ≈ 10%
  - s quark dominates
  - Directly sensitive to s-quark PDF at x~0.01
- Experimental measurements mixed:
  - Some analyses favour s-quark sea suppression w.r.t. d-quark sea
  - ATLAS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

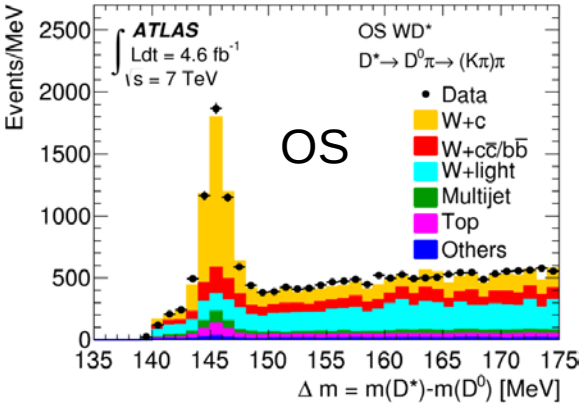


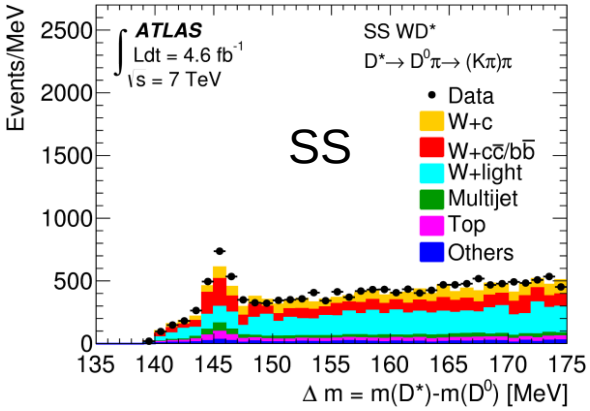



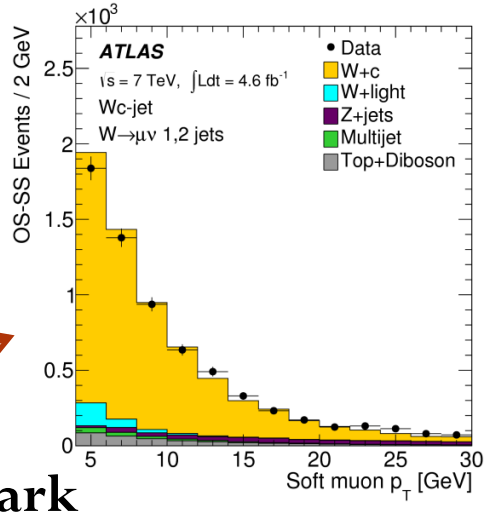

Phys.Rev.Lett. 109 (2012) 012001

# W+c measurement overview




- 4.6 fb$^{-1}$ of data collected in 2011 at $\sqrt{s} = 7$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 + $c\bar{c}, b\bar{b}$

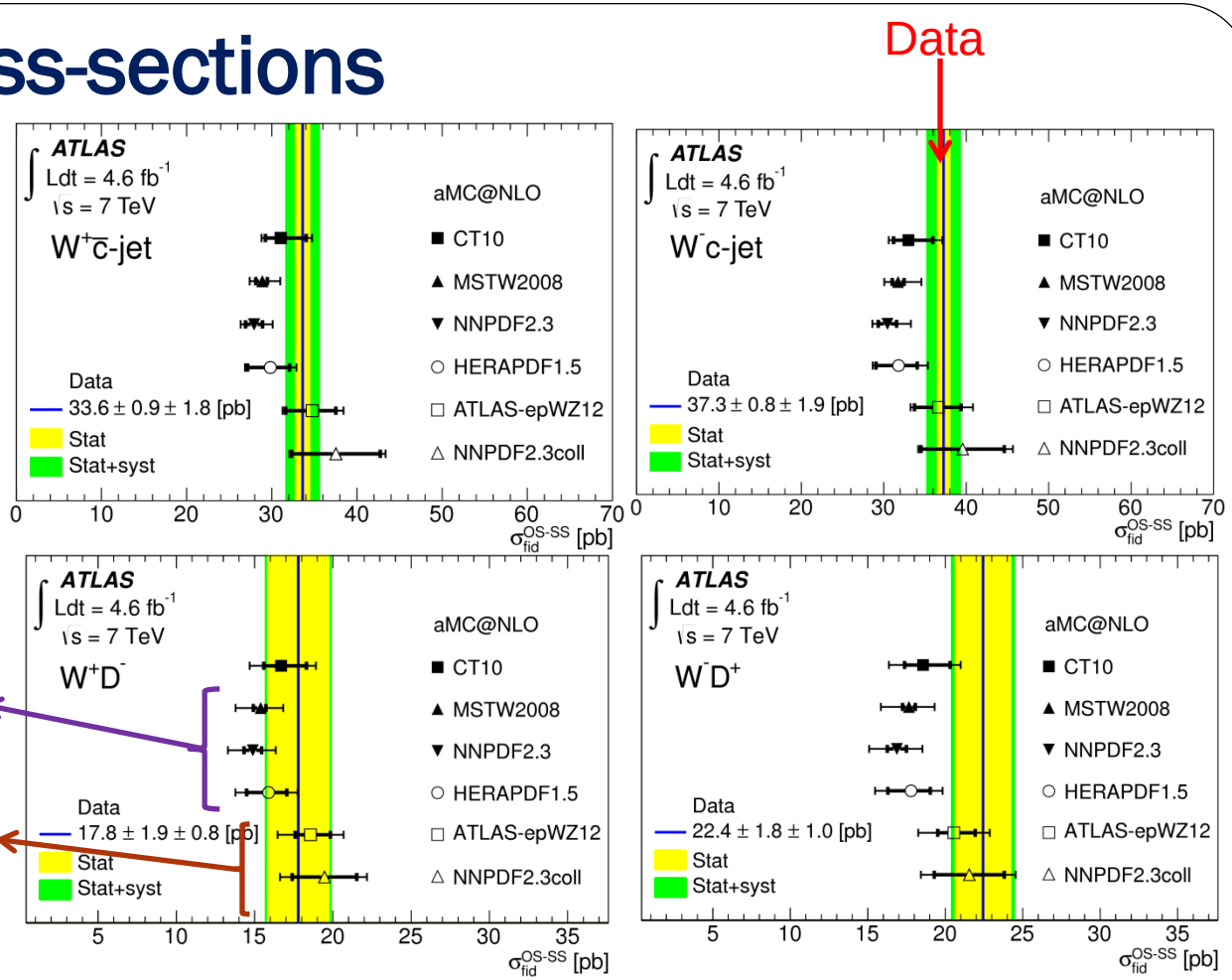
# Fiducial W+c cross-sections

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

s-quark suppressed cf. d-quark

s-quark ~ d-quark

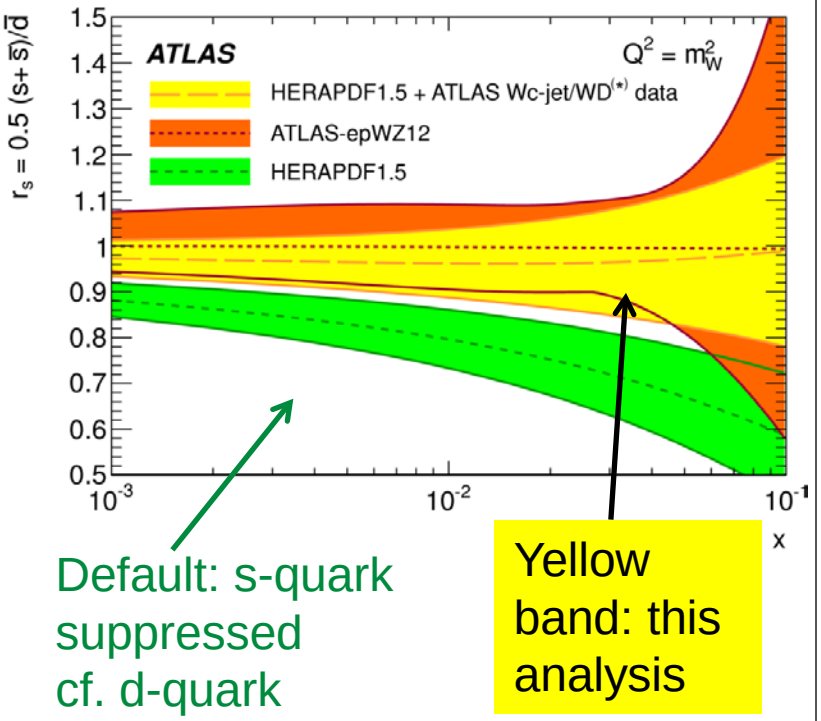
- Data consistent with wide range of predictions
- Favour symmetric light-quark sea at x~0.01



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

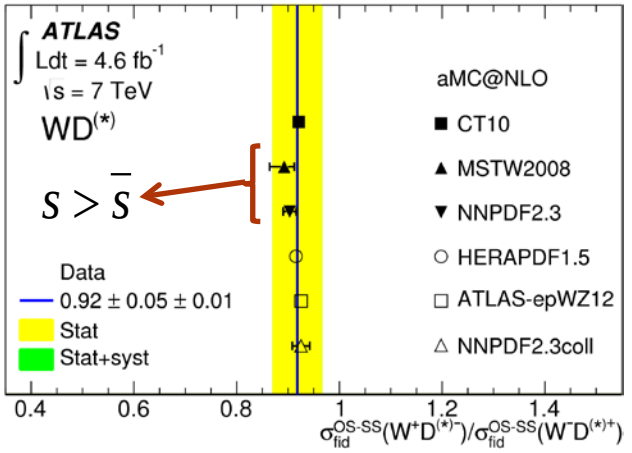
- Ratio of strange to down sea quarks is regulated in HERA PDF by a single parameter (eigenvector $f_s$)
- Free fit of strange to down sea content of proton in ATLAS data (within this model)

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



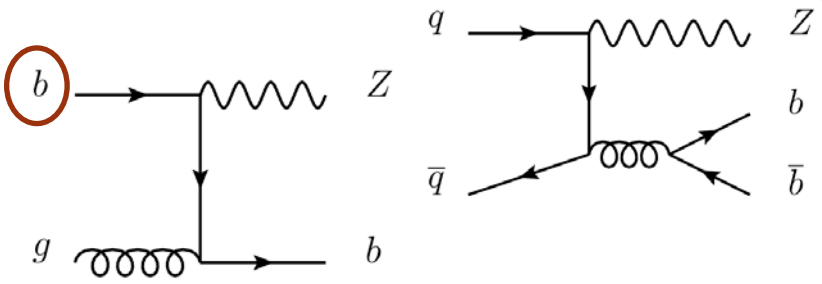

- Results compatible with the ATLAS-epWZPDF (includes W/Z data)
- Consistent with SU(3) flavour symmetry in the proton

- Charge asymmetry is consistent with symmetric $s = \bar{s}$ and with PDF sets with a small asymmetry, $s > \bar{s}$

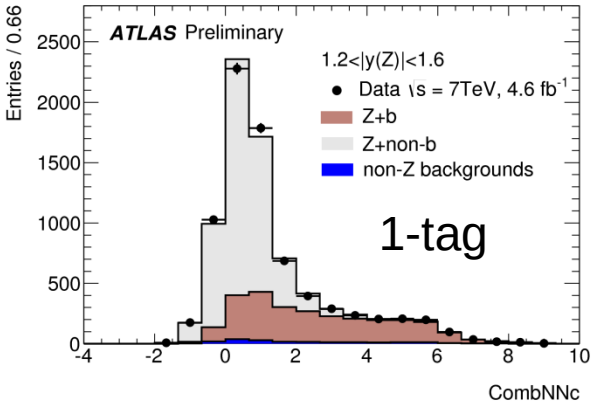


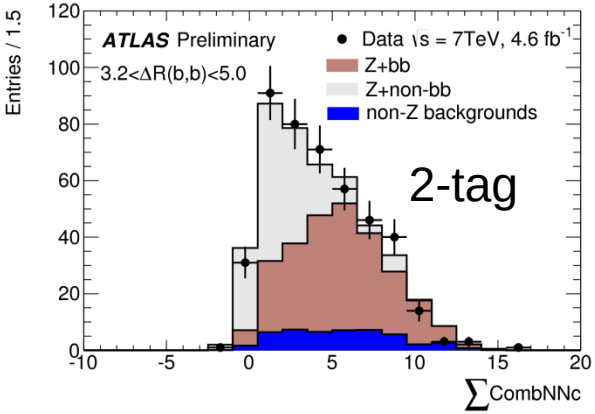
# Z + b(b)

To be 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




Neural net with secondary vertices and displaced tracks

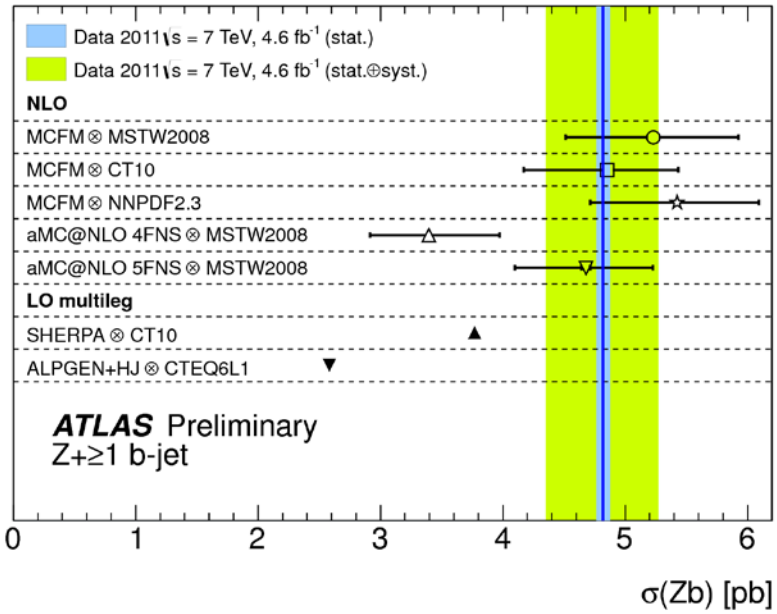
- 4.6 $fb^{-1}$ of data collected in 2011 at $\sqrt{s} = 7$ TeV
- Template fits to b-jet tagging distributions
- Main backgrounds from Z+c-jets,light-jets

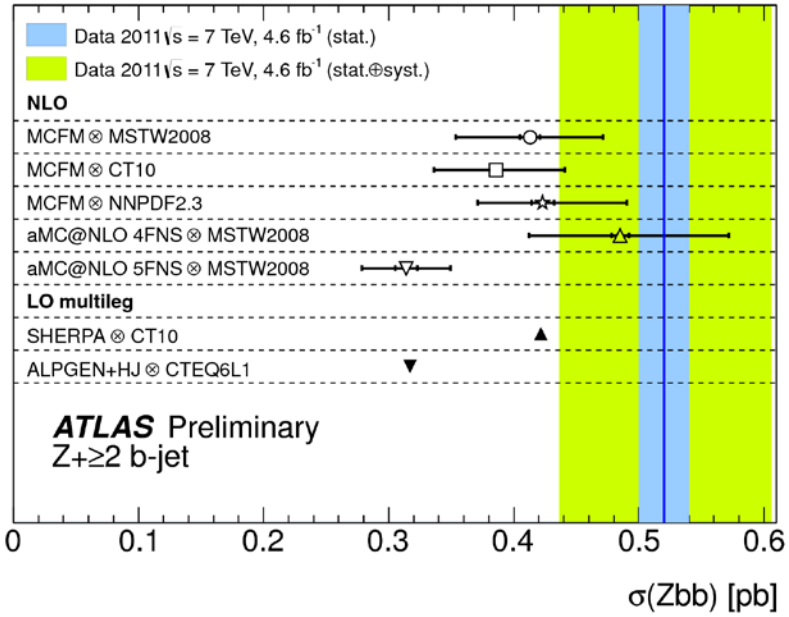
# Z + b(b) cross-sections

- 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+≥1 b-jet:
    - Main difference is 4FNS vs. 5FNS (both NLO)
    - 4FNS underestimates data
  - For Z+≥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

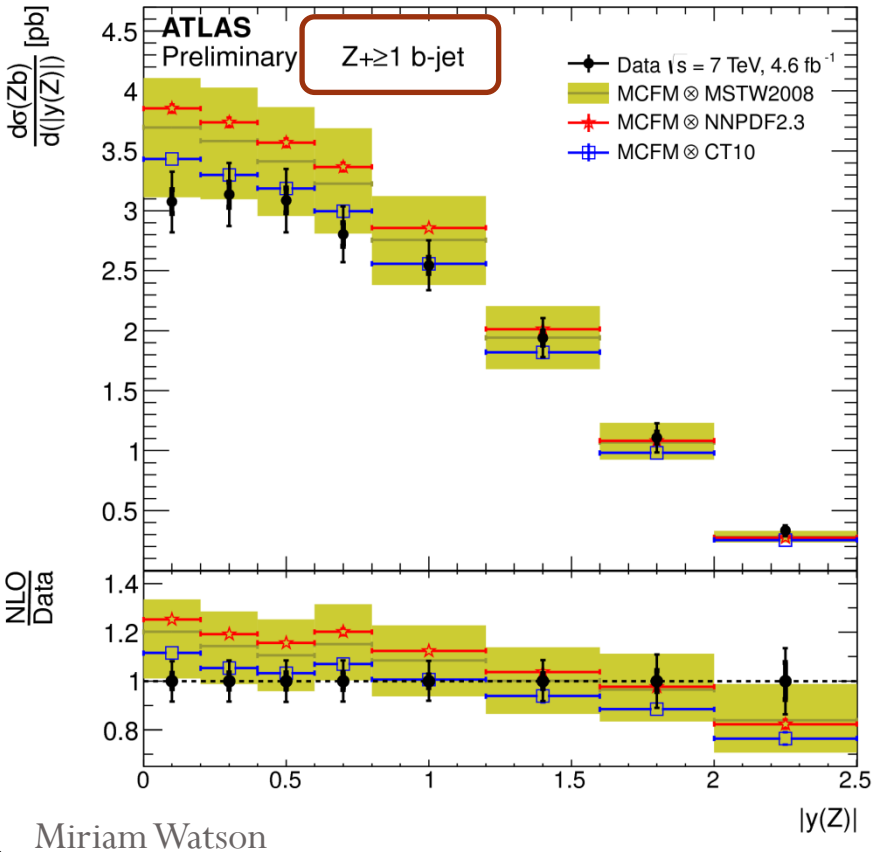


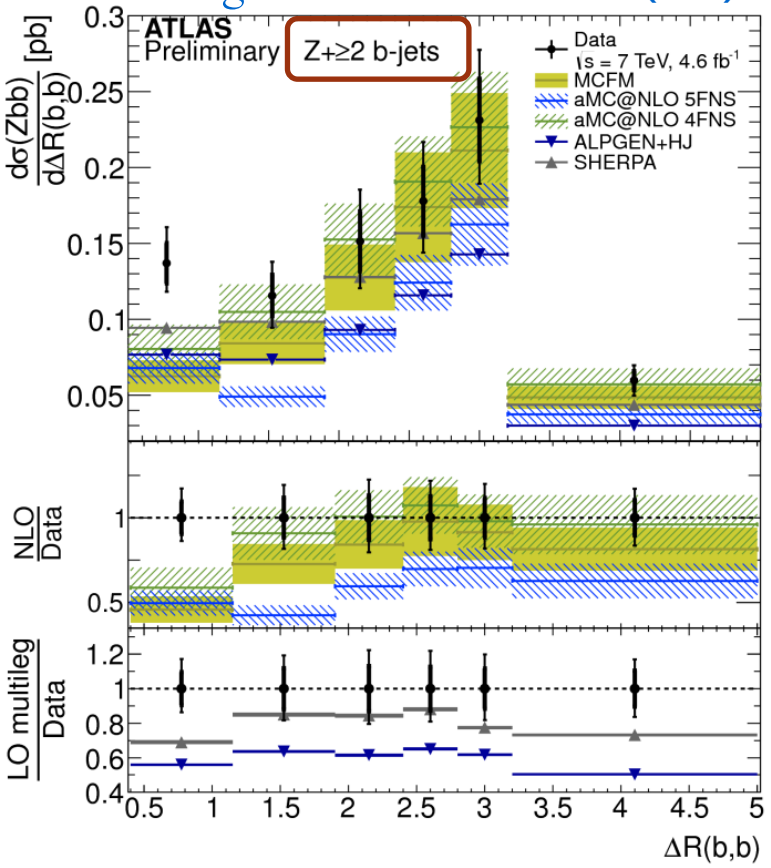
# Z + b(b) differential cross-sections

- Unfolded differential distributions measured in 12 kinematic variables

- dσ(Z+≥1 b-jet) / d|y(Z)|
- Alternative PDF sets show similar trends
- Differences small c.f. scale uncertainties



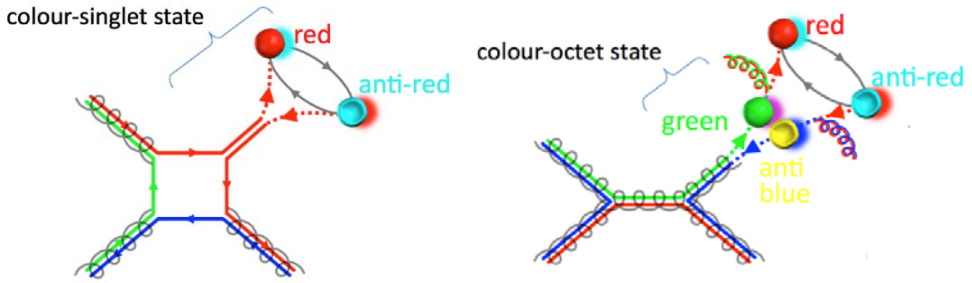

- dσ(Z+≥2 b-jets) / dΔR(b,b)
- Reasonable description within uncertainties
- Some disagreement at small ΔR(b,b)

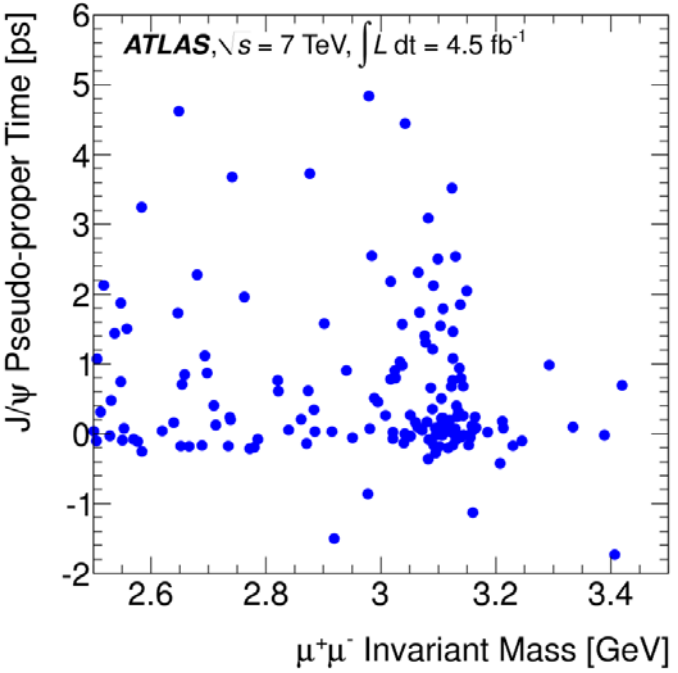


# W+prompt J/ψ measurement

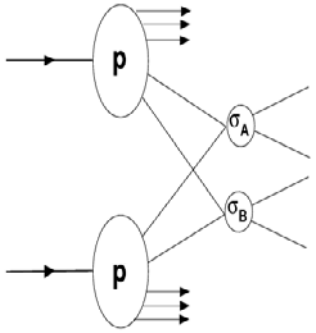
arXiv:1401.2831,
JHEP 04 (2014) 172

- Search for associated production of W(→μν) and prompt J/ψ (→$\mu^+\mu^-$)
- 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



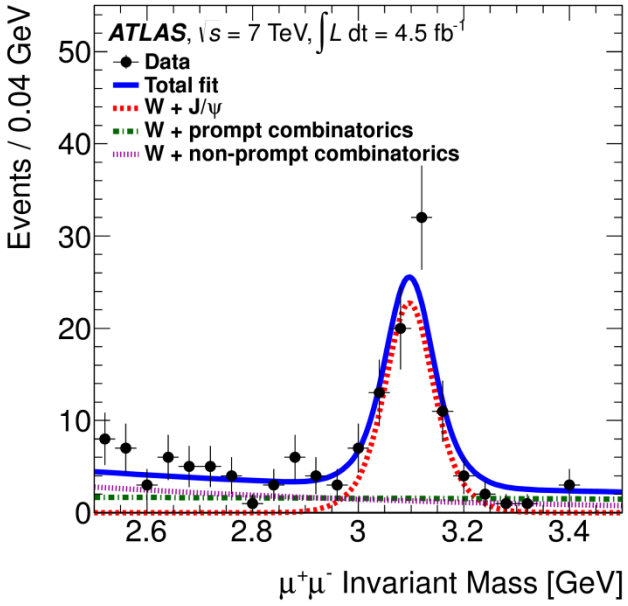

- Use 4.6 $fb^{-1}$ at 7 TeV (2011)
- Sensitive to multiple parton interactions
- Include double parton scattering (DPS) in signal, and estimate contribution

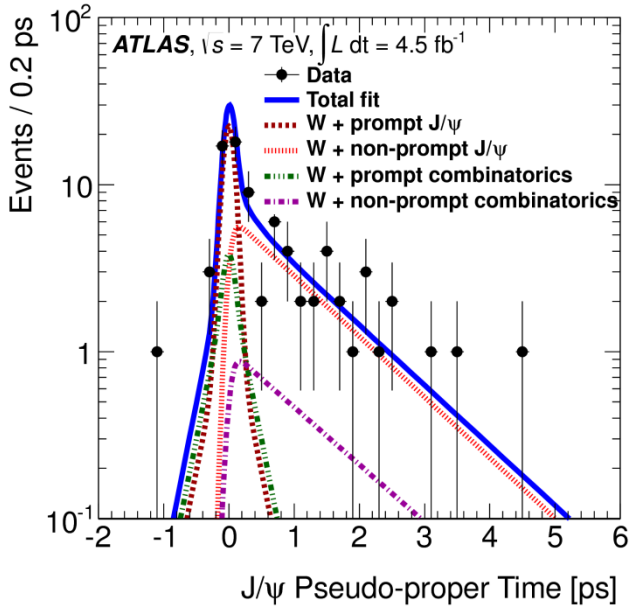


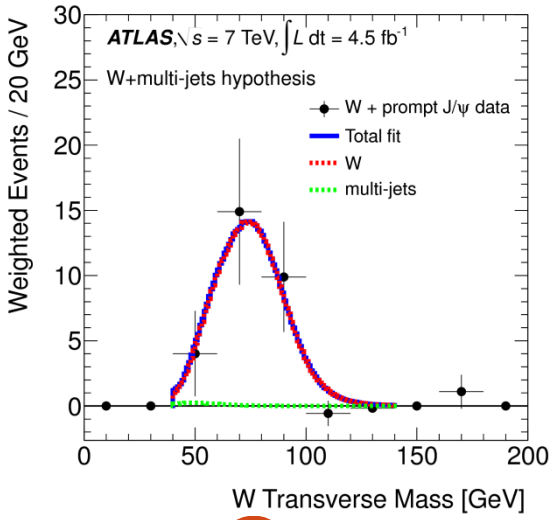

DPS: two independent pairs of partons yield a W and a J/ψ (single pp)

# Prompt J/ψ fits and W verification

- Unbinned maximum likelihood fit to J/ψ mass and pseudo-proper time → 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

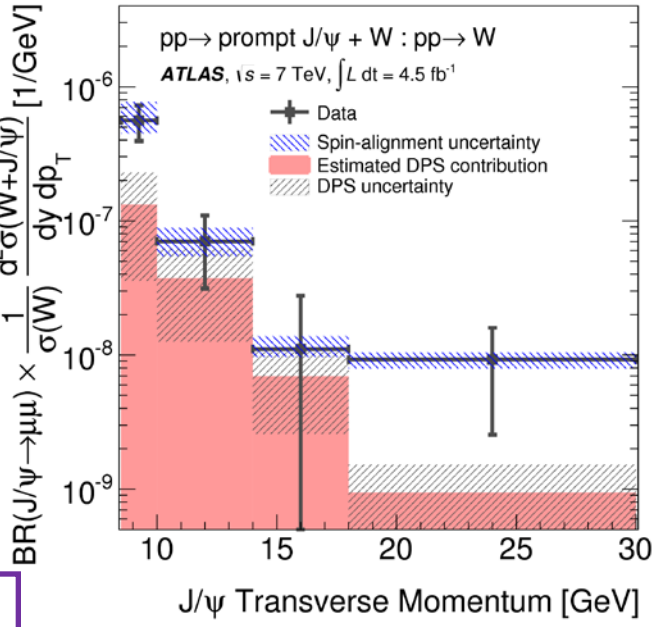
# SPS and DPS contributions

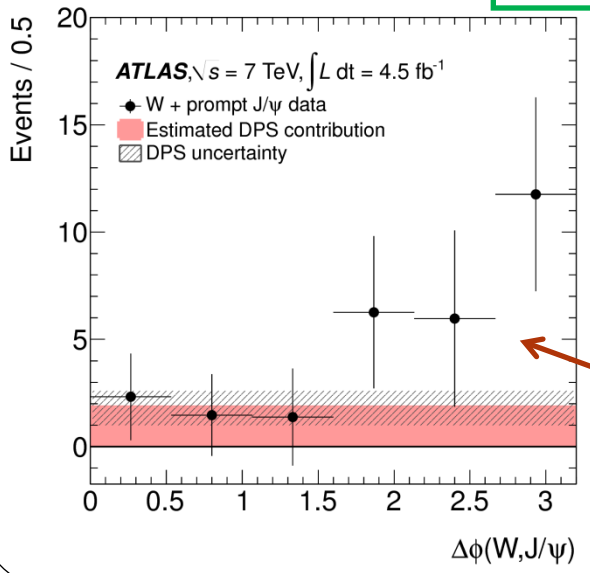
- Measure $(W^{\pm} + J/\psi)$ production cross-section relative to inclusive $W^{\pm}$ cross-section
- Estimate DPS contribution from:
  - $d\sigma(W+J/\psi) = d\sigma(W) \otimes d\sigma(J/\psi) / \sigma_{eff}$

Measured in this analysis

From ATLAS prompt $J/\psi$ arXiv:1104.3038

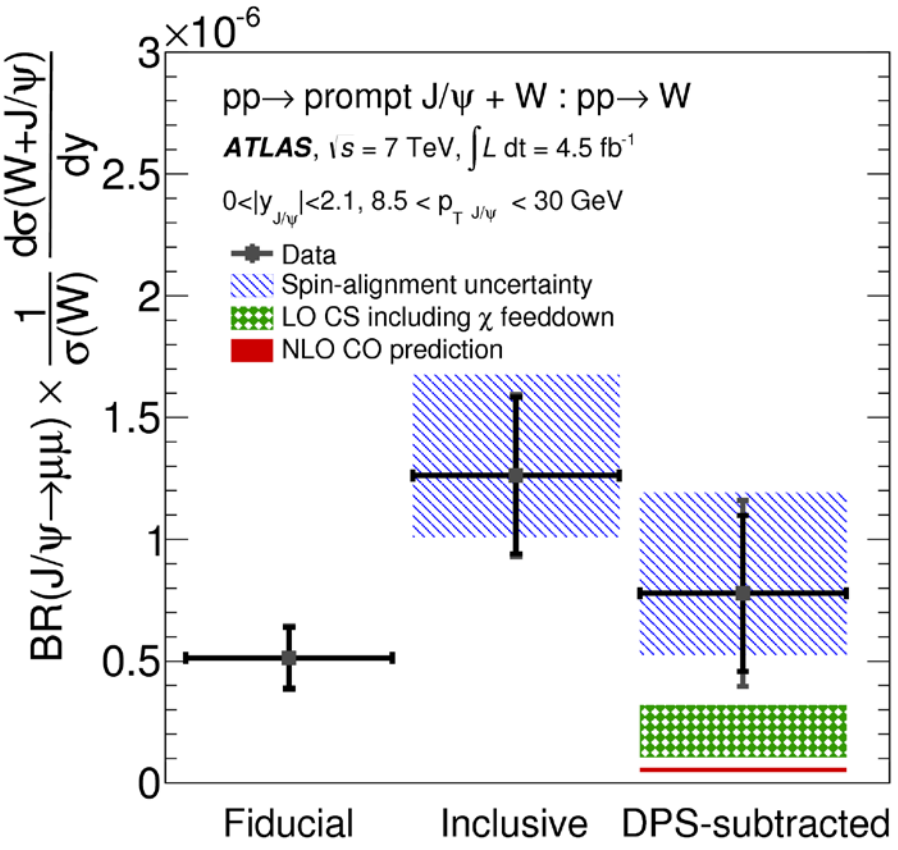
From ATLAS W+2jets arXiv:1301.6872




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

# Prompt J/ψ+W compared to theory




CS: arXiv:1303.5327
CO:arXiv:1012.3798

- Summary of fiducial, corrected and DPS-subtracted cross-section ratios
- Colour singlet model (CS): LO, includes feed-down from ψ(2S) and $\chi_c$
- 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

# 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+ prompt J/ψ
  - 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)⟶ estimate of sensitivity

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

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