

Summary of ATLAS Heavy Flavour Production Measurements

First meeting of the LHC Heavy Flavour Working Group

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10th November 2015



Introduction

Introduction

- ▶ During LHC Run 1 (and already in Run 2) ATLAS has produced a wealth of diverse heavy flavour production measurements
- ▶ This summary will focus on the main results and what we've learnt rather than the details of the individual analyses

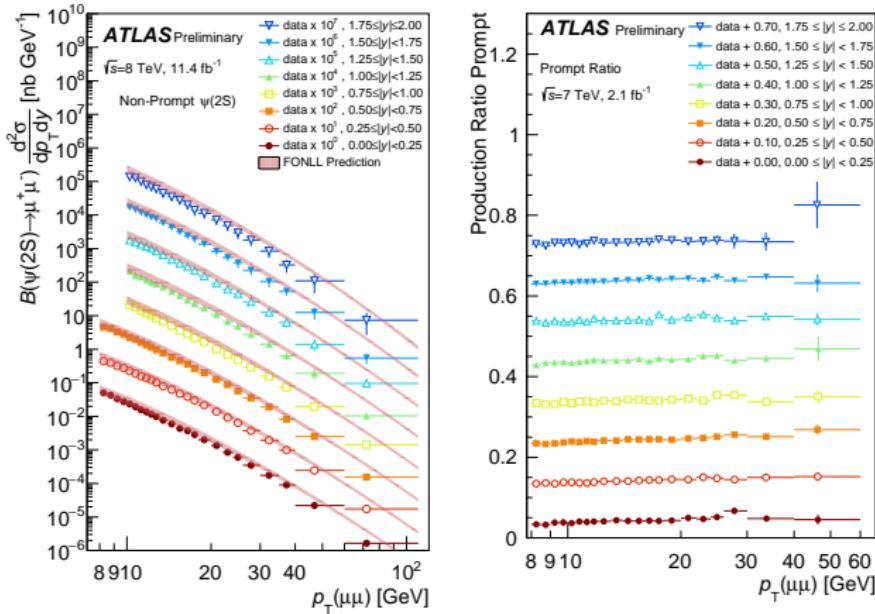
Overview

- ▶ **Quarkonium Production** - Measurements of prompt and non-prompt charmonium (J/ψ , χ_{cJ} and $\psi(2S)$) and bottomonium ($\Upsilon(nS)$)
- ▶ **Associated Production** - Measurements of prompt (and non-prompt) charmonium produced in association with W^\pm and Z bosons
- ▶ **Open Heavy Flavour Production** - Measurements of B^\pm and $D^{(*)}$ meson production

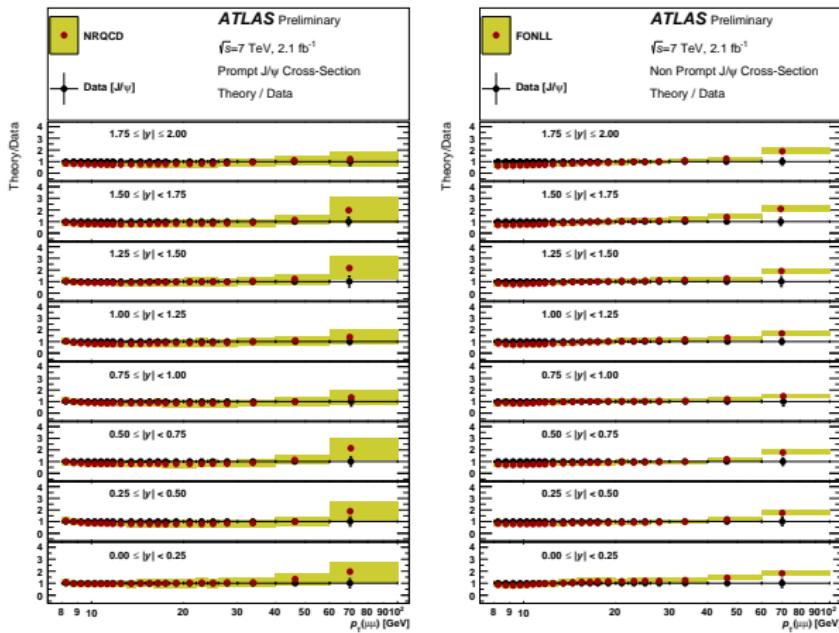
All ATLAS Heavy Flavour results can be found here:

<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults>

J/ψ and $\psi(2S)$ production at $\sqrt{s} = 7$ and 8 TeV - ATLAS-CONF-2015-024

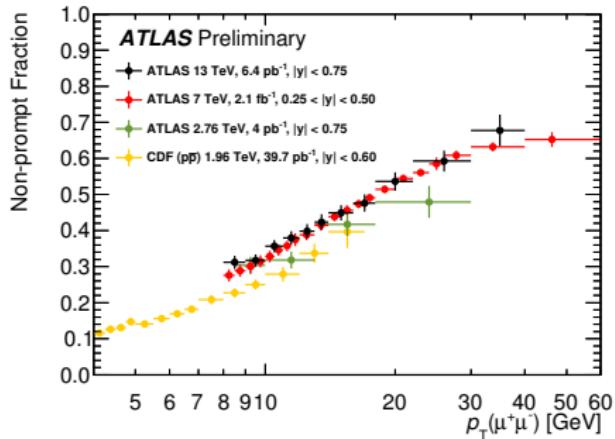
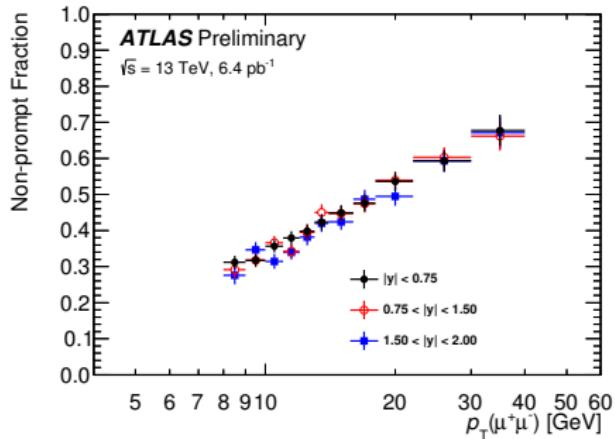


- **Comprehensive** set of J/ψ and $\psi(2S)$ differential cross section measurements
- Measured in 8 $|y|$ bins and up to 22 bins in p_T , for both prompt and non-prompt production and all associated cross section ratios and fractions



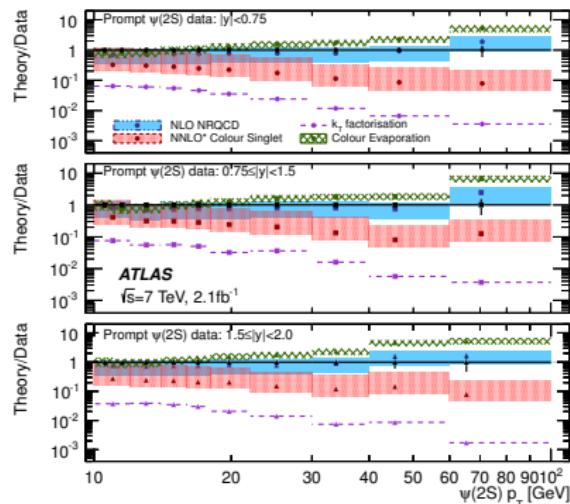
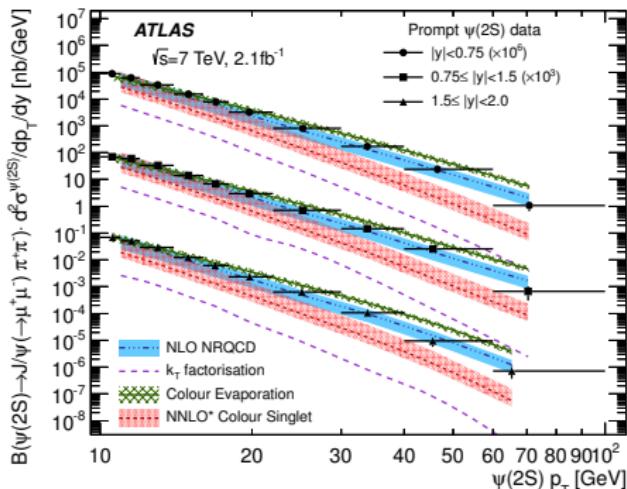
- ▶ Theoretical predictions for prompt (NRQCD) and non-prompt (FONLL) $\psi(nS)$ production scrutinised at an **impressive level of detail**
- ▶ Generally good agreement observed, though hints of discrepancies towards high p_T

Beginning of an exciting programme of HF production measurements in Run 2!



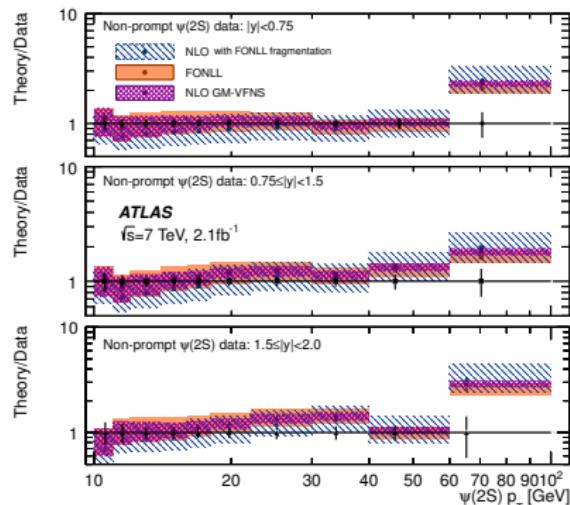
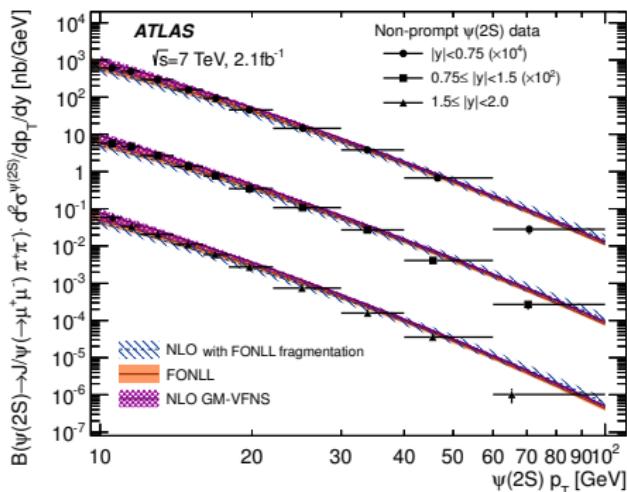
- ▶ First ATLAS heavy flavour measurement with Run 2 $\sqrt{s} = 13$ TeV data
- ▶ Very little change in fraction of non-prompt J/ψ w.r.t. $\sqrt{s} = 7$ TeV
- ▶ Only the first $\sim 6 \text{ pb}^{-1}$ analysed, scope for much more detailed measurement with the full 2015 dataset of $\sim 4 \text{ fb}^{-1}$

Prompt $\psi(2S)$ differential cross sections



- The $J/\psi(\mu^+ \mu^-) \pi^+ \pi^-$ channel offers higher yields and improved resolution w.r.t. $\psi(2S) \rightarrow \mu^+ \mu^-$, high precision measurements probe out to 100 GeV in p_T !
- Predictions of NLO NRQCD provide best description of data across p_T and y

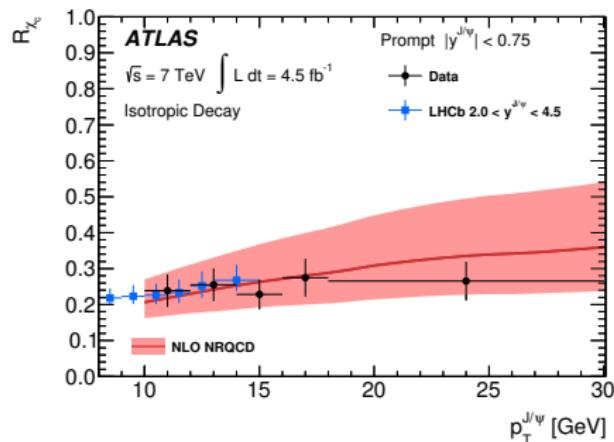
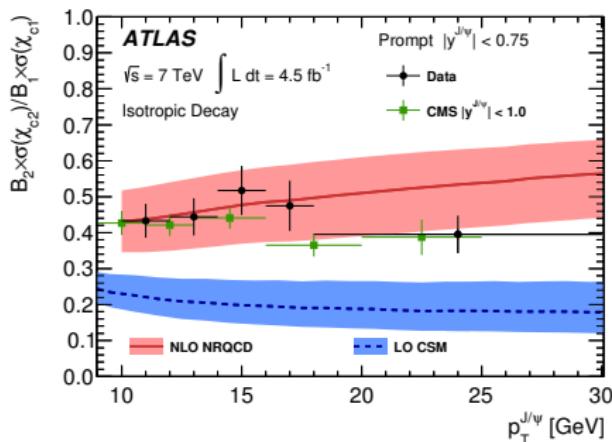
Non-prompt $\psi(2S)$ differential cross sections



- ▶ All predictions shown provide good description of data, though agreement deteriorates at very high p_T
- ▶ Hint for some small scale discrepancy in FONLL model? (FONLL/Data ratio has nearly constant non-zero gradient)

(←) Ratio of prompt χ_{c2}/χ_{c1} cross sections

- More χ_{c1} produced than χ_{c2} , contrary to spin counting expectation
- NLO NRQCD describes ratio well at low $p_T^{J/\psi}$, change in behavior at high $p_T^{J/\psi}$

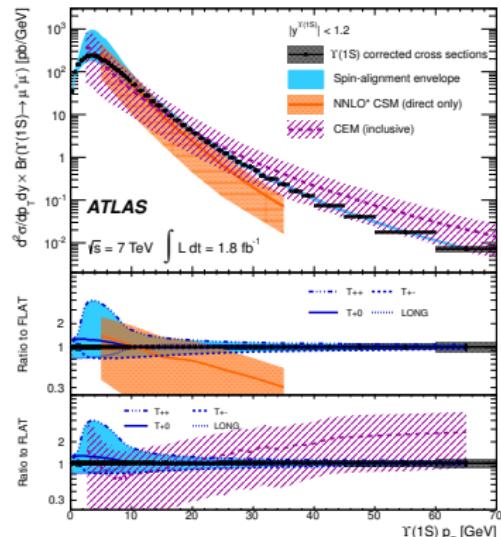
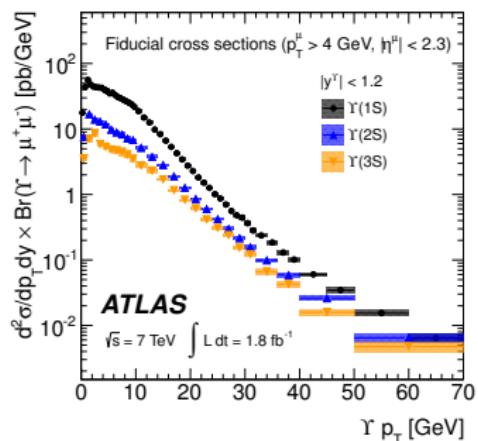


(→) Fraction of prompt J/ψ produced in feed-down from χ_c decays

- Between 20 – 30% of prompt J/ψ are produced in feed-down from the decays of χ_{c1} and χ_{c2}

Acceptance Corrected $\Upsilon(1S)$ cross-section \rightarrow

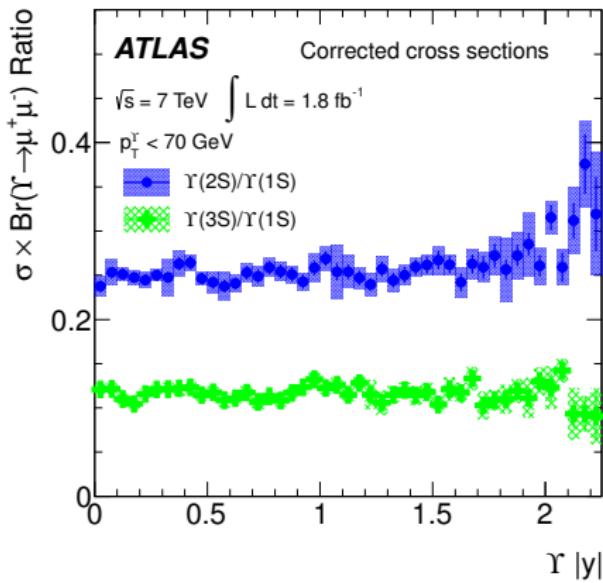
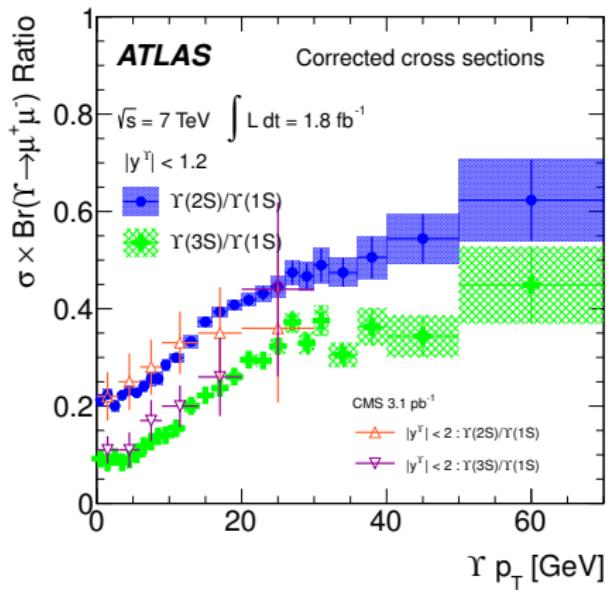
- ▶ Corrected cross sections also measured for $\Upsilon(2S)$ and $\Upsilon(3S)$
- ▶ Acceptance sensitive to Υ polarisation - blue uncertainty band
- ▶ Colour Evaporation Model does not reproduce shape of data well
- ▶ NNLO* Colour Singlet Model generally underestimates data, though doesn't include (large) feed-down contributions



← Fiducial $\Upsilon(nS)$ cross-sections

- ▶ No sensitivity to Υ polarisation
- ▶ More precise test for predictions calculated within fiducial volume

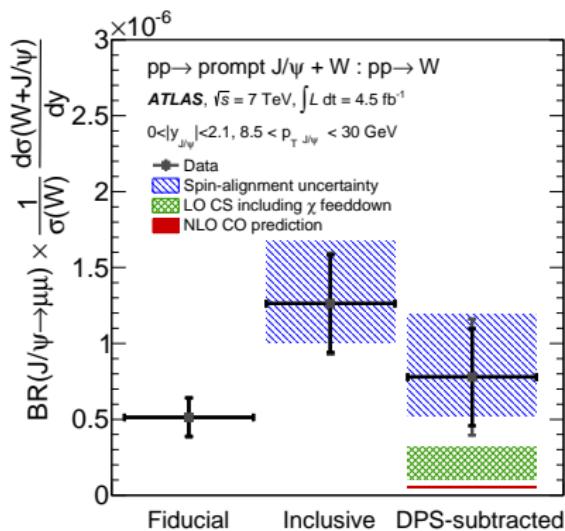
$\Upsilon(3S)$ and $\Upsilon(2S)$ production relative to $\Upsilon(1S)$



Evidence for beginning of plateau at high p_T ? Behavior of ratios as a function of p_T sensitive to feed-down contributions from $\chi_b(mP)$...

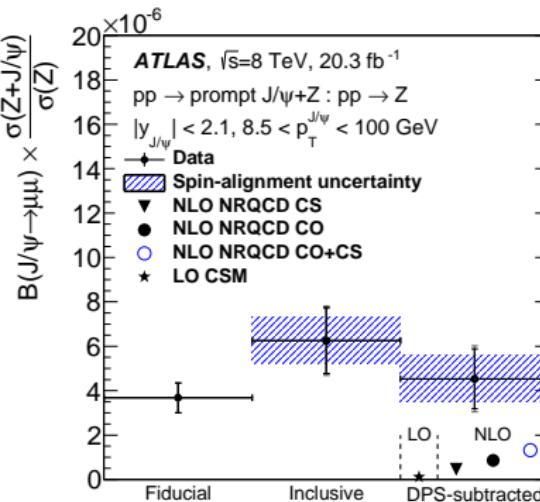
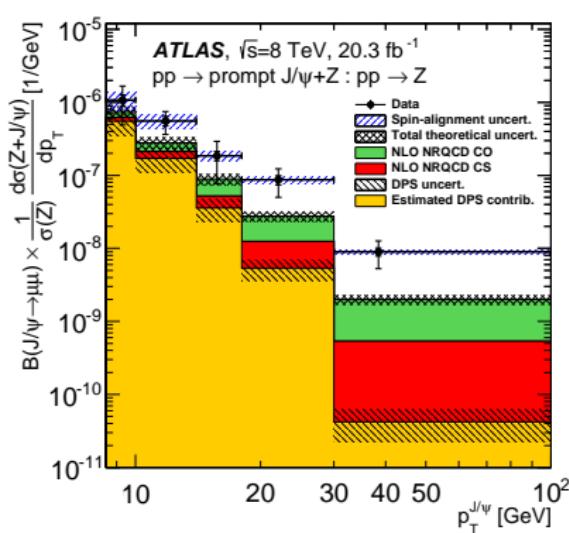
Novel probe of the quarkonium production mechanism, sensitive to a different mixture of colour octet/singlet processes w.r.t. inclusive production

- ▶ Measured relative to $W \rightarrow \mu\nu$, reduced systematic and theory uncertainties
- ▶ Inclusive production rate also contains a DPS contribution, complements “traditional” DPS probes (jet based)
- ▶ SPS production rate not well described by existing CO or CO+CS predictions

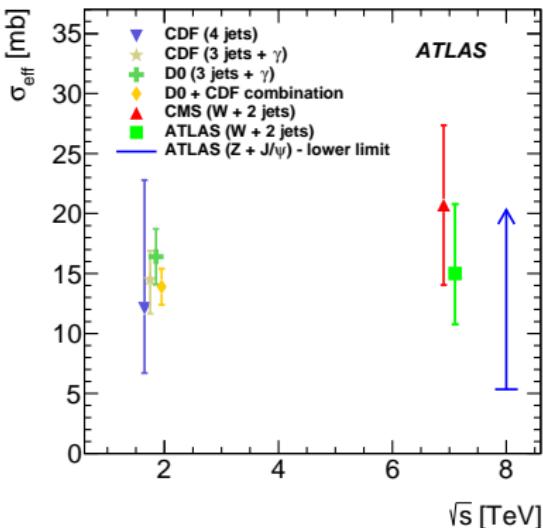
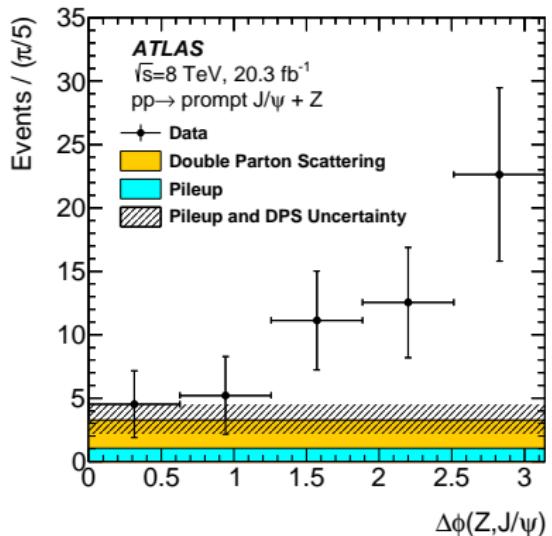


Pioneering measurement, perfectly suited to GPDs (ATLAS and CMS) - prospects scale well with future LHC conditions!

Studies initiated in $W^\pm + J/\psi$ analysis substantially extended with proceeding study of $Z + J/\psi$ associated production



- Same philosophy as preceding measurement, measured relative to inclusive $Z \rightarrow \ell\ell$ production, both prompt and non-prompt J/ψ
- Similarly large excess observed w.r.t. CO and CO+CS predictions, as in $W^\pm + J/\psi$

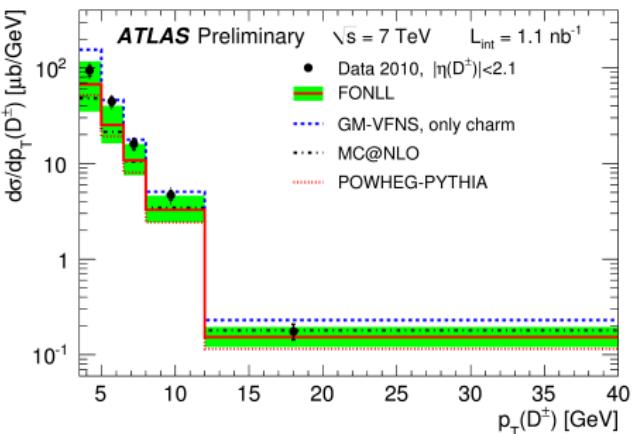
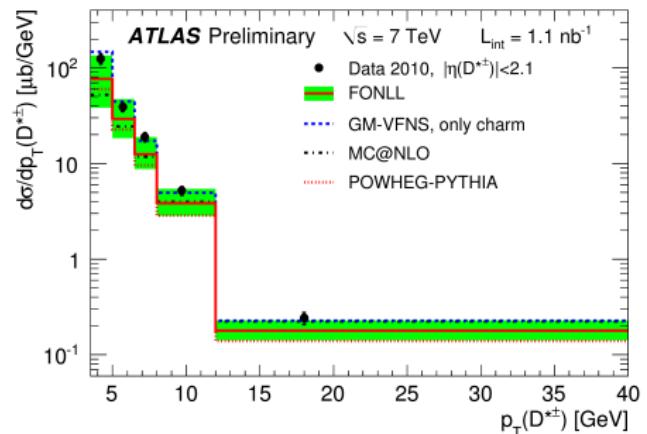


- ▶ Larger data sample allows more detailed study of DPS contribution using $\Delta\phi(Z, J/\psi)$ distribution to discriminate DPS vs. SPS
- ▶ Lower limit set on effective cross-section regulating DPS interactions, $\sigma_{\text{eff}} > 5.3 \text{ mb}$ at 68% CL

Together, these studies open a new window on quarkonium production at the LHC!

Measurements of $D^{(*)\pm}$ production - ATLAS-CONF-2011-017 and ATL-PHYS-PUB-2011-012

Charm production studied through the reconstruction of exclusive D meson decays



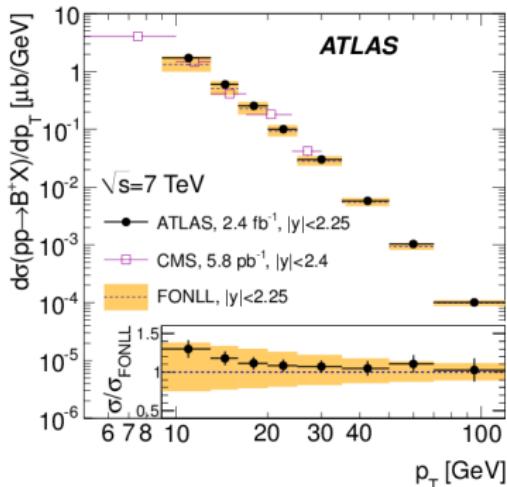
- ▶ Several charm fragmentation observables extracted in addition to the total charm production cross section
- ▶ D_s also measured, allowing strangeness suppression in fragmentation to be studied
- ▶ Total and differential cross sections compared to a range of theory predictions and MC generators - measurements differential in $|\eta(D)|$ also made

Valuable tool for tuning and validation of MC generators used across LHC physics!

Complementary to measurements of non-prompt J/ψ , directly probing exclusive $b \rightarrow B$ fragmentation, both total and differential cross sections measured

Compared to FONLL prediction

- ▶ b -quark production calculated in fixed order next-to-leading logarithm (FONLL) approach
- ▶ b fragmentation function fitted from LEP data
- ▶ Use world average value $f_{\bar{b} \rightarrow B^+} = (40.1 \pm 0.8)\%$
- ▶ Good agreement with data!



Extrapolated Total Cross-section

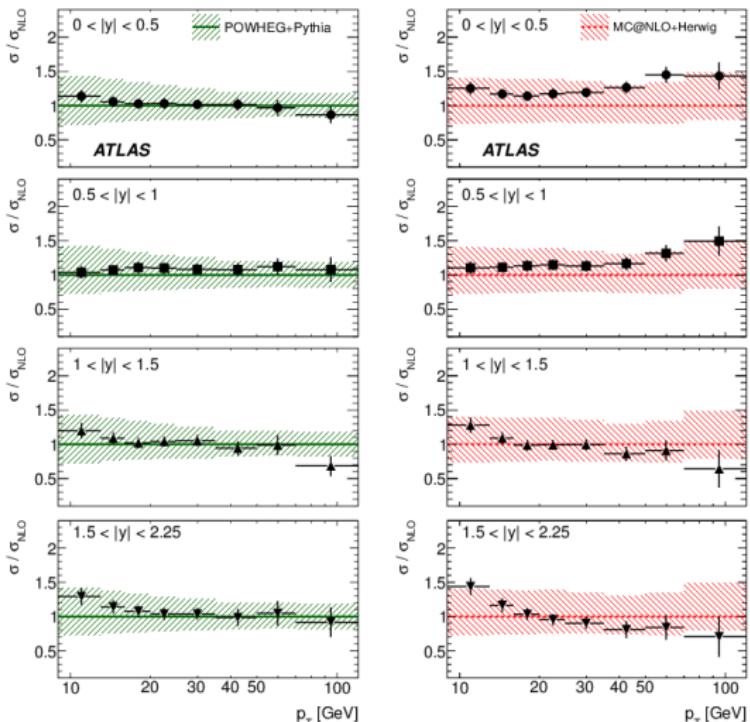
$$\sigma(pp \rightarrow B^+ + X) = 10.6 \pm 0.3 \text{ (stat.)} \pm 0.7 \text{ (syst.)} \pm 0.2 (\mathcal{L}) \pm 0.4 (\mathcal{B}) \mu\text{b}$$

$$\sigma^{\text{FONLL}}(pp \rightarrow b + X) \cdot f_{\bar{b} \rightarrow B^+} = 8.6^{+3.0}_{-1.9} \text{ (scale)} \pm 0.6 (m_b) \mu\text{b}$$

Comparison with MC generators

- ▶ Compare to two combinations of MC b -quark production (**POWHEG** and **MC@NLO**) + parton showering (**Pythia** and **Herwig**)
- ▶ Good agreement in both cases - though both tend to underestimate data at low p_T
- ▶ Systematic change in Data w.r.t. **MC@NLO+Herwig** as a function of $|y|$

Wealth of precise data can help inform modelling of b -quark production and fragmentation



POWHEG+Pythia

MC@NLO+Herwig

Conclusion

Summary

- ▶ During LHC Run 1 ATLAS has produced a wealth of diverse heavy flavour production measurements
- ▶ Several examples of unique contributions to LHC HF community, strong synergy with other experiments
- ▶ Many precise measurements, all archived in HEPDATA: hepdata.cedar.ac.uk
- ▶ Several exciting Run 1 results in the pipeline that will broaden the scope of the ATLAS HF production measurement programme
- ▶ Heavy Flavour production measurements now underway with Run 2 data, can look forward to many interesting results soon!

All ATLAS Heavy Flavour results can be found here:

<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults>