Production of quarkonium and heavy flavour in ATLAS

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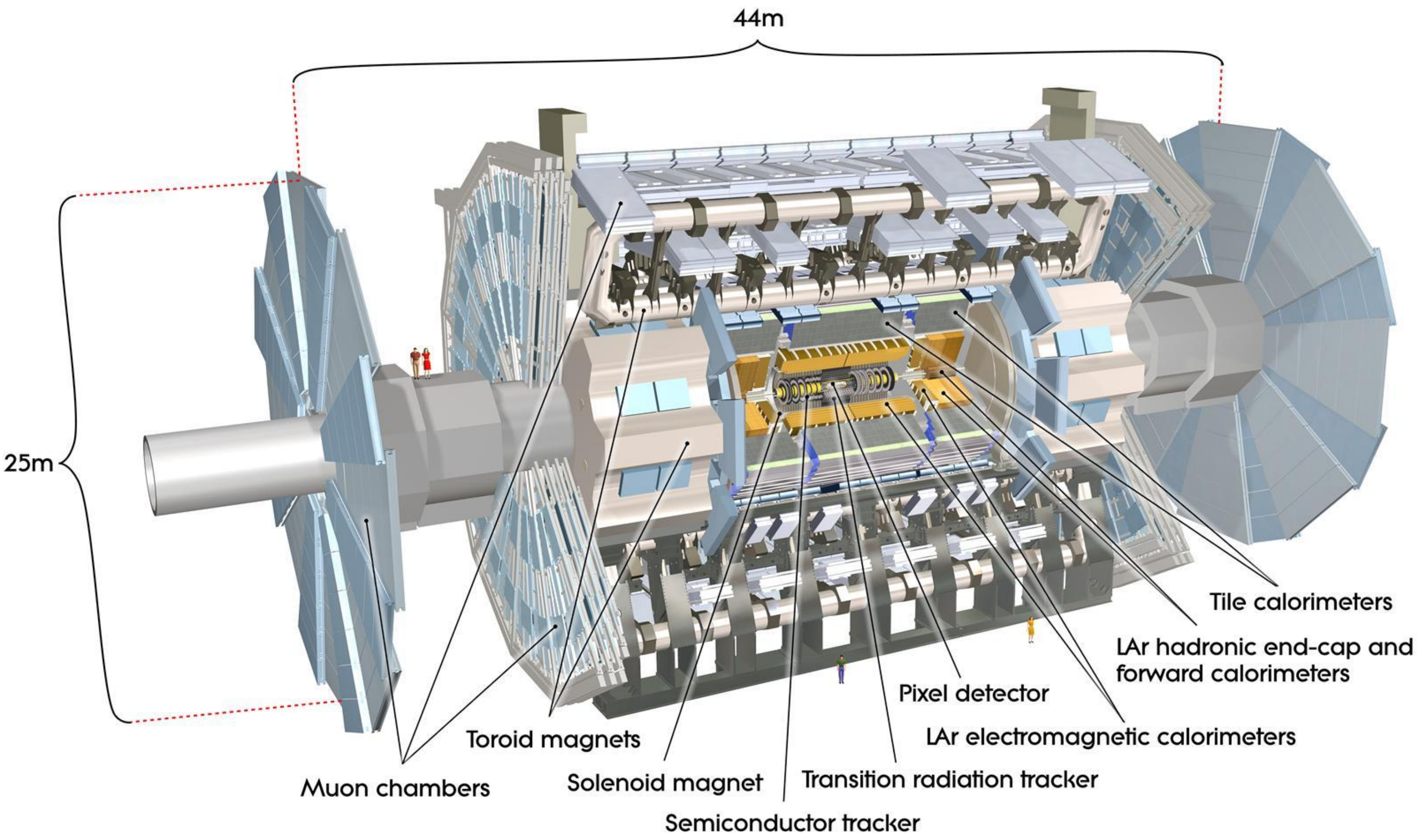
Outline

- The ATLAS detector
- Data taking and triggers
- Charmonium / open charm
  - J/ψ and ψ(2S) production at 7 and 8 TeV
  - Non-prompt J/ψ fraction at 13 TeV
  - $D_{(s)}^{(*)\pm}$ production at 7 TeV
- B meson production and properties
  - Ratio of *b* quark fragmentation fractions f_s/f_d at 7 TeV
  - $B^{\pm}$ meson reconstruction at 13 TeV
  - B_d and B_s mixing and CPV (*Evelina Bouhova-Thacker* talk)
  - $B_{(d/s)} \rightarrow \mu^+\mu^-$ in ATLAS (*Jaroslav Günther* talk)
- Conclusions

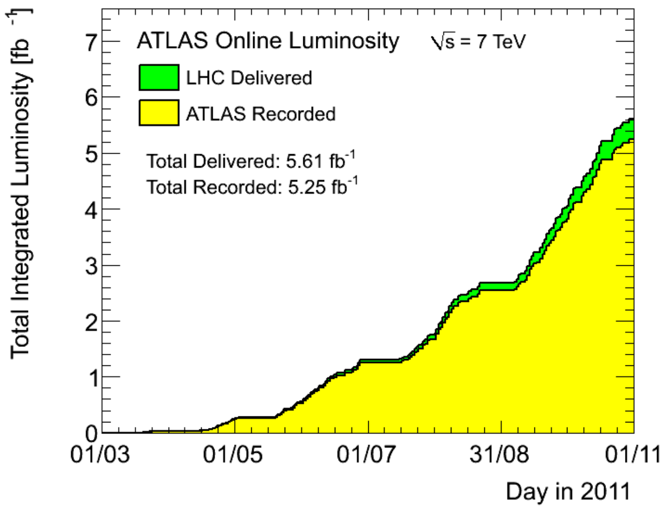
The ATLAS detector



- Inner Detector (ID)
  - 2 T solenoid magnet
  - Silicon Pixels and Silicon Strips
    →Precision tracking $p_T > 0.4$ GeV, $|\eta|<2.7$
  - Insertable B-Layer (IBL): additional inner-most pixel layer (r = 33 mm) and lower x/X_0 beam pipe
  - Transition Radiation Tracker
- Muon Spectrometer
  - 0.5 T toroid B-field
  - Monitored Drift Tubes and Cathode Strip Chambers
    →Precision tracking $|\eta|<2.7$
  - Resistive Plate Chambers and Thin Gas Chambers → Triggering $|\eta|<2.4$
- Combined μ performances
  - $\sigma_p/p < 10\%$ up to 1 TeV
  - Resolution in $m_{\mu+\mu-}$: ~50 MeV at J/ψ, ~150 MeV at Υ(nS)
  - Resolution in b-hadrons proper decay time ~100 fs (before IBL installation)

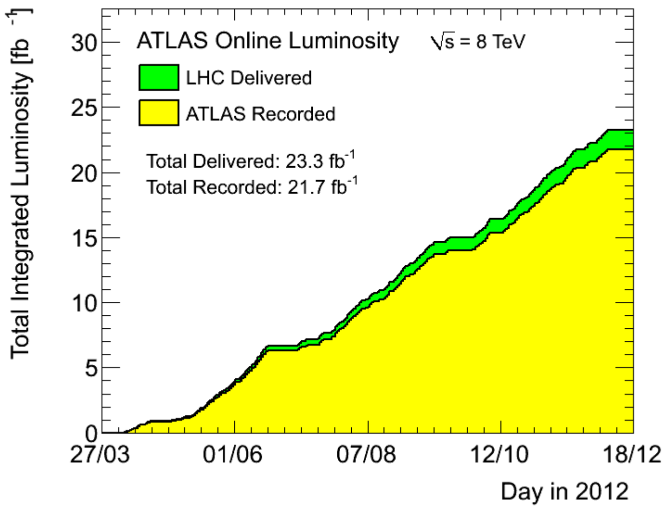
Data taking and datasets

2011



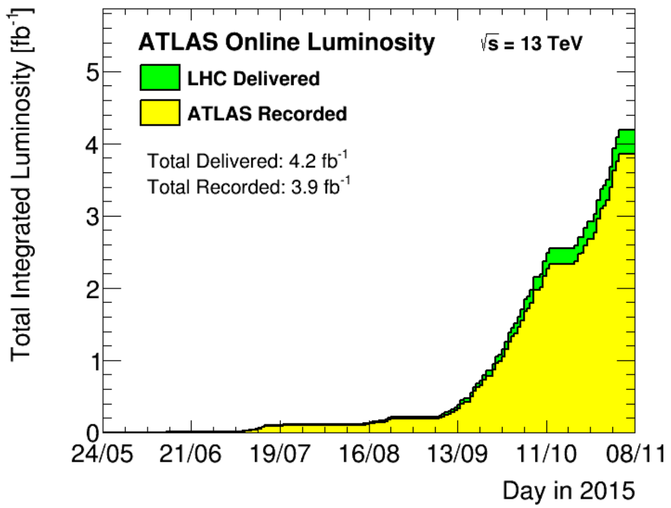
- $\sqrt{s} = 7$ TeV
- 4.57 fb^{-1} good for physics
- 50 ns bunch spacing
- Peak: 3.7×10^{33} $cm^{-2}s^{-1}$

2012



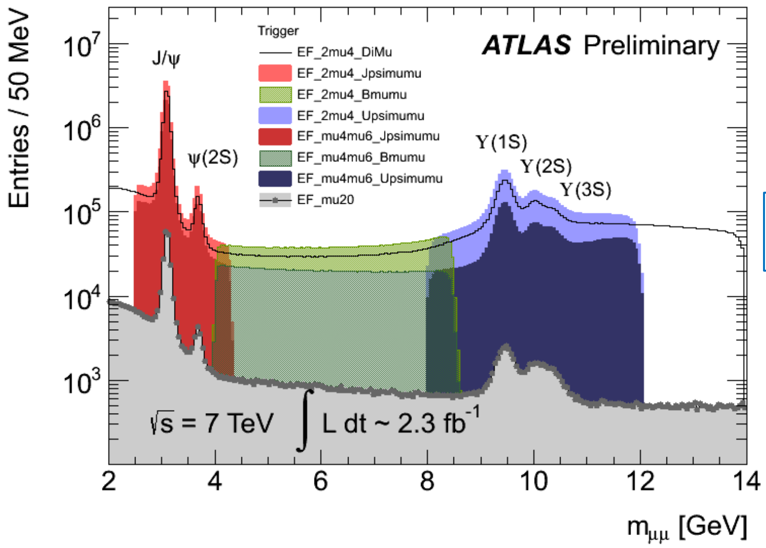
- $\sqrt{s} = 8$ TeV
- 20.3 fb^{-1} good for physics
- 50 ns bunch spacing
- Peak: 7.7×10^{33} $cm^{-2}s^{-1}$

2015

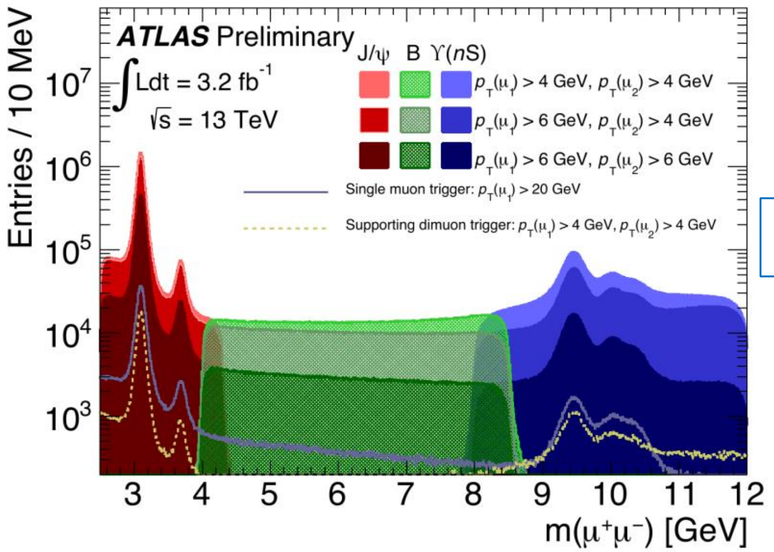


- $\sqrt{s} = 13$ TeV
- 3.2 fb^{-1} good for physics
- 50/25 ns bunch spacing
- Peak: 5.0×10^{33} $cm^{-2}s^{-1}$

Heavy Flavor Physics specific triggers



$\sqrt{s} = 7$ TeV



$\sqrt{s} = 13$ TeV

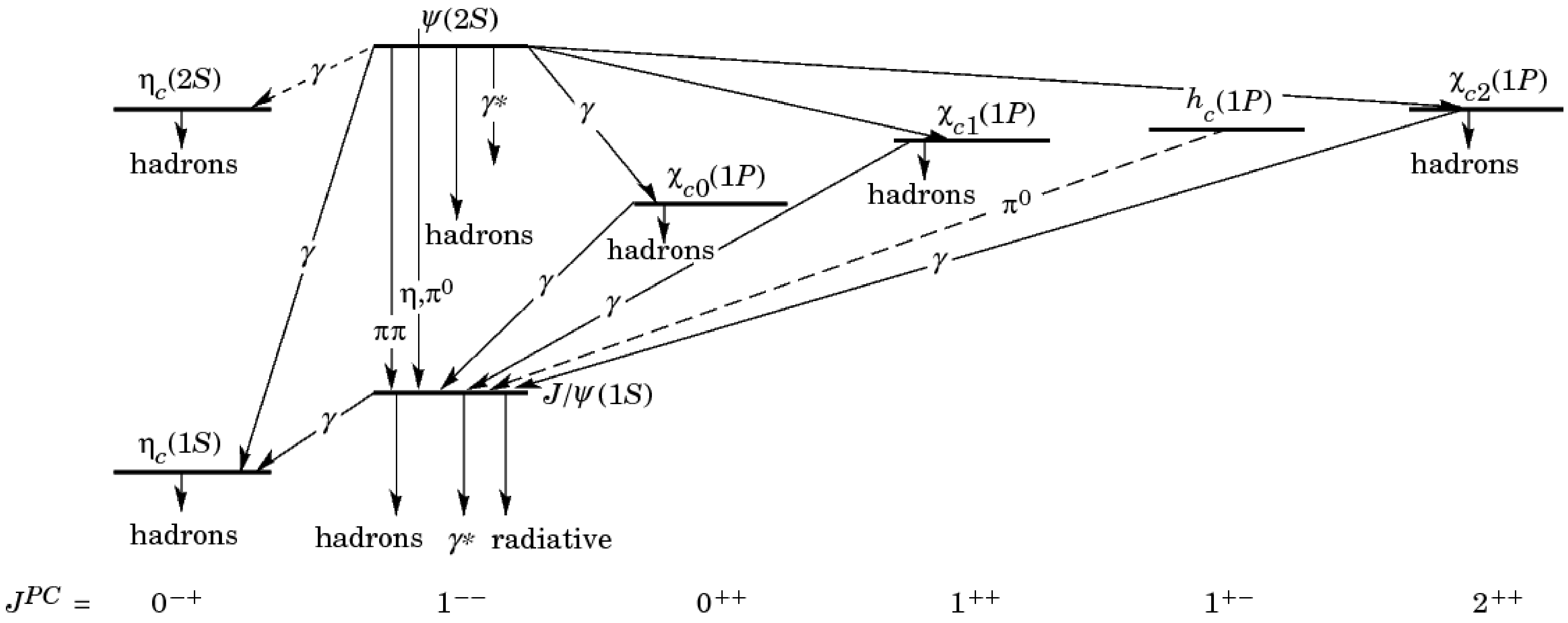
Quarkonia : $J/\psi \rightarrow \mu\mu$, $\Upsilon \rightarrow \mu\mu$

Exclusive: $B \rightarrow J/\psi(\mu\mu)\ X$ decays

Rare decays: $B \rightarrow \mu\mu(X)$ decays

- ►Trigger on low-p_T 4,6 GeV dimuons
- ►Large gain in yields w.r.t single higher p_T muon triggers
- ►20 MHz collision rate, ~400 Hz recorded
- ►HF physics concentrates on low p_T dimuon signatures

Charmonium production at 7 and 8 TeV



arXiv:1512.03657, to appear in EPJC

Two distinct charmonium production mechanisms at the LHC:

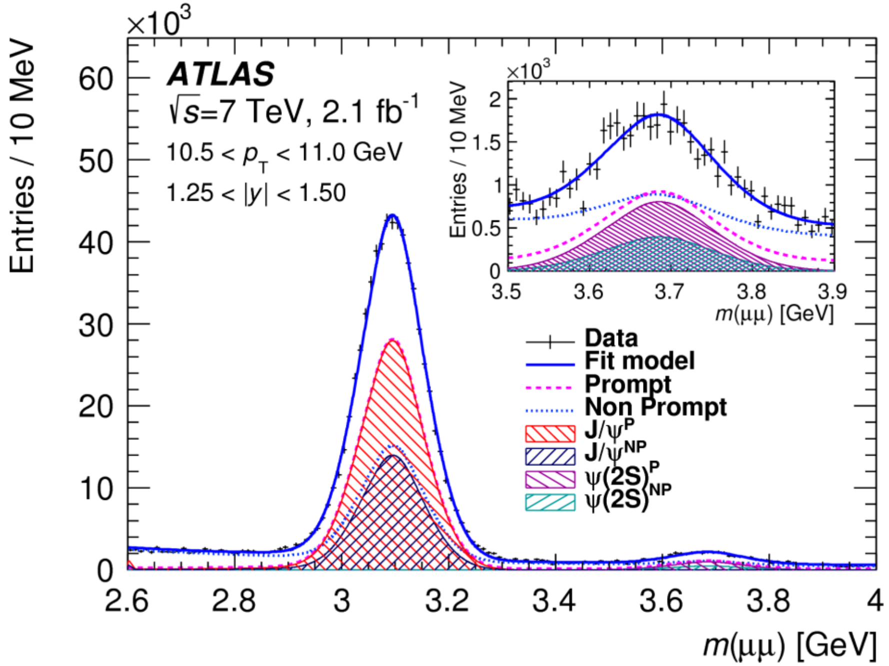
► Prompt component: produced directly in the *pp* interaction or through feed-down decays of heavier states

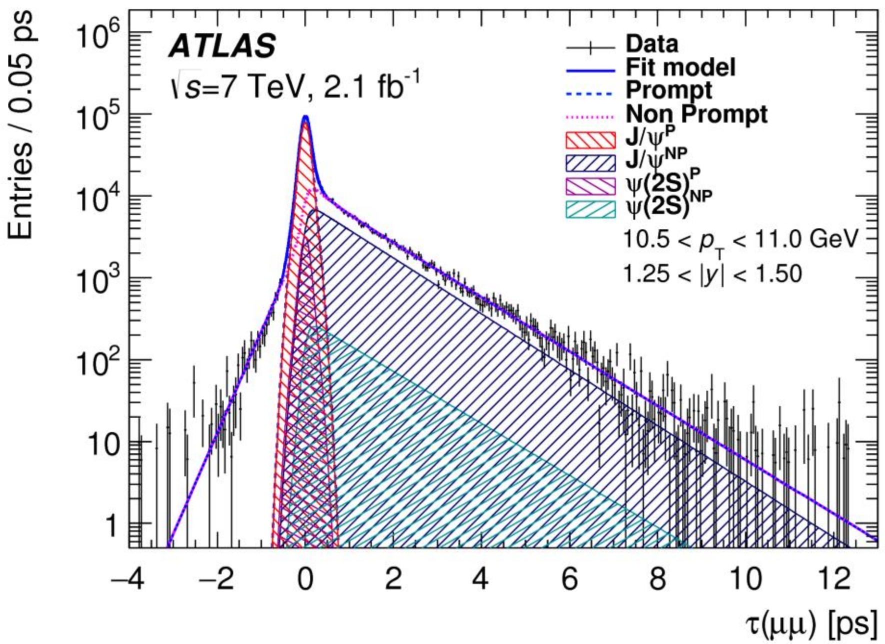
► Non-prompt component: produced in decays of *b*-hadrons, can be separated experimentally due to the "long" *b*-hadron lifetime

► Around 35% of prompt J/ψ come from feed-down, $\psi(2S)$ are almost all direct

Charmonium production - method

- ►Data (2.1 fb^{-1} at 7 TeV and 11.4 fb^{-1} at 8 TeV) collected with dimuon triggers
- ►Basic muon kinematic selection: $p_T(\mu_{1,2})$>4 GeV and $|\eta(\mu_{1,2})|$<2.3 and vertex fit of dimuon tracks
- ►Each dimuon candidate is weighted to correct for muon identification, trigger and reconstruction efficiencies and geometrical acceptance
- ►Corrected prompt and non-prompt J/ψ and $\psi(2S)$ yields are determined from an unbinned fit to the 2D dimuon mass and pseudo-proper decay time distribution → 22 × 8 (p_T, y) bins





$$\tau = \frac{L_{xy} m_{\mu\mu}}{p_{T\mu\mu}}$$

prompt decays

$$\delta(\tau) \otimes R(\tau)$$

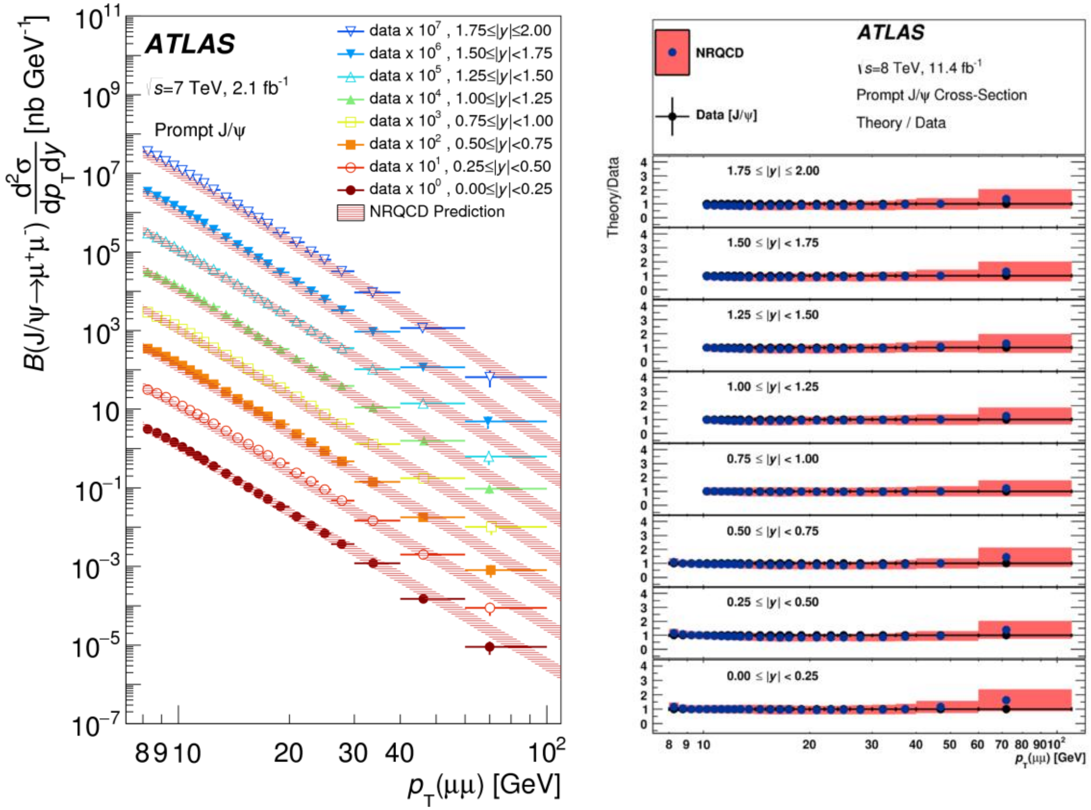
non-prompt decays

$$1/\tau_{\psi} \exp(\tau/\tau_{\psi}) \otimes R(\tau)$$

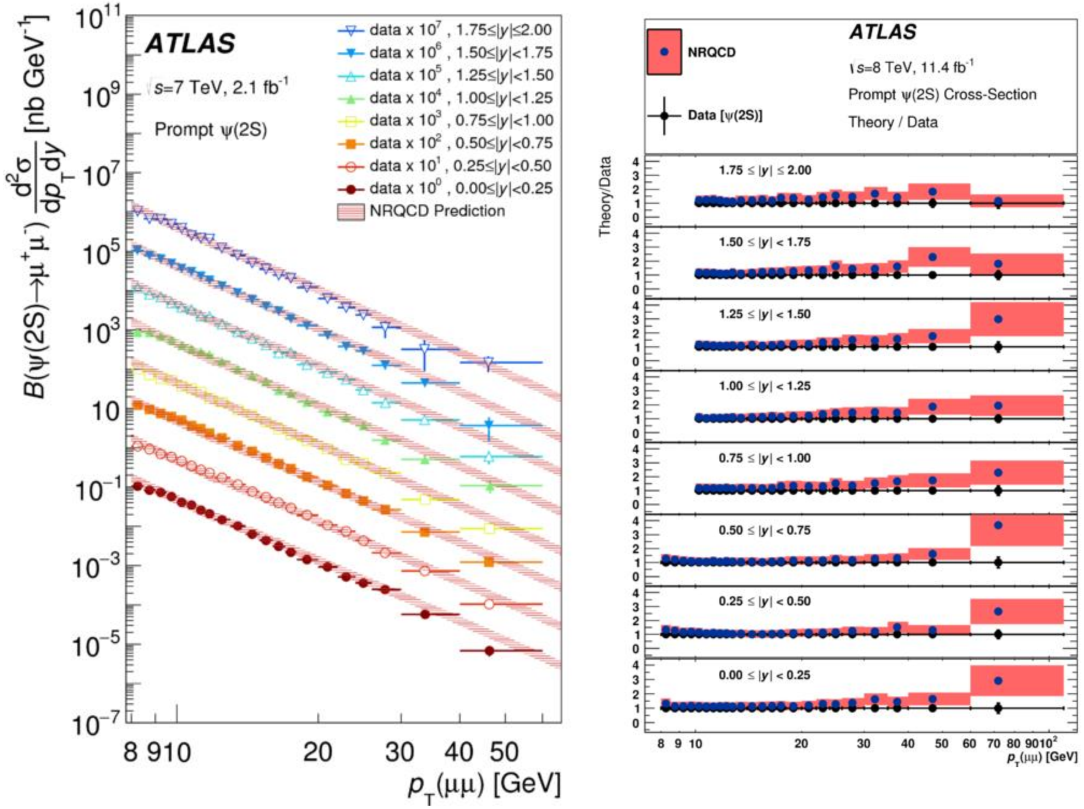
arXiv:1512.03657, to appear in EPJC

Charmonium production – prompt component

Prompt J/ψ compared to NRQCD.
Good agreement across range of p_T
No y dependence. Data spectra slightly softer.



Prompt $\psi(2S)$ compared to NRQCD.
Free from feed-down, direct probe of prompt production. Data spectra slightly softer.

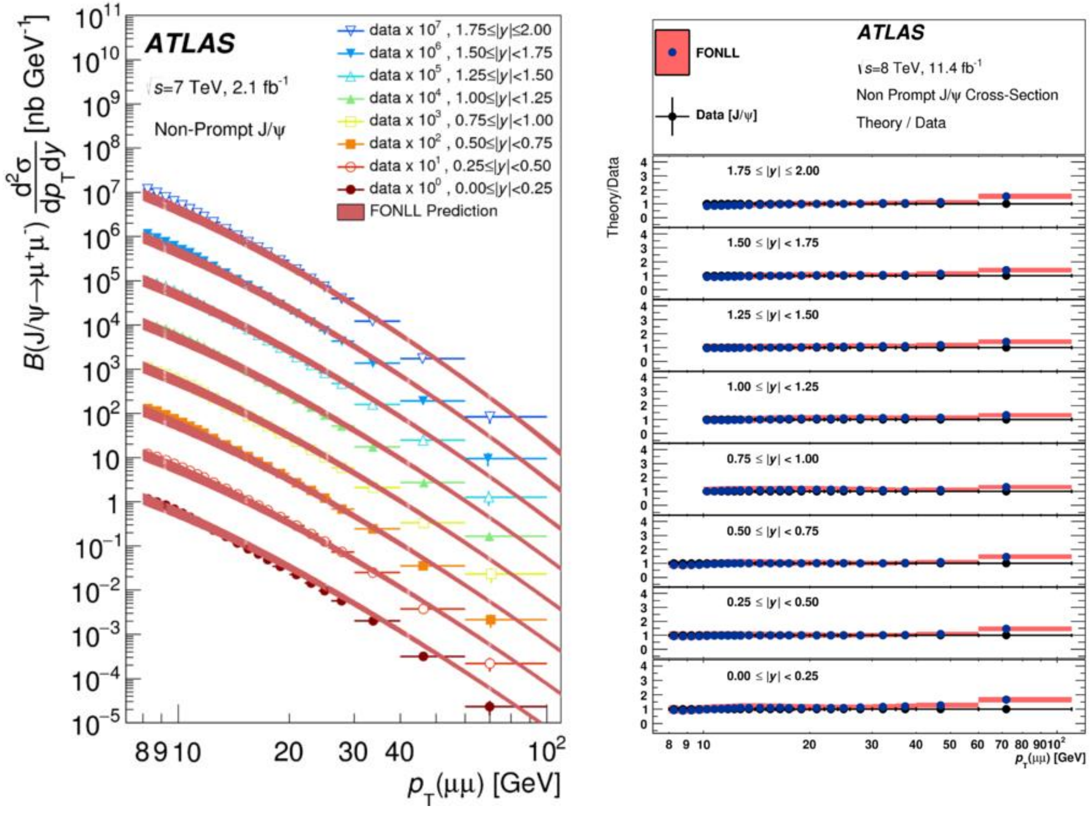


arXiv:1512.03657, to appear in EPJC

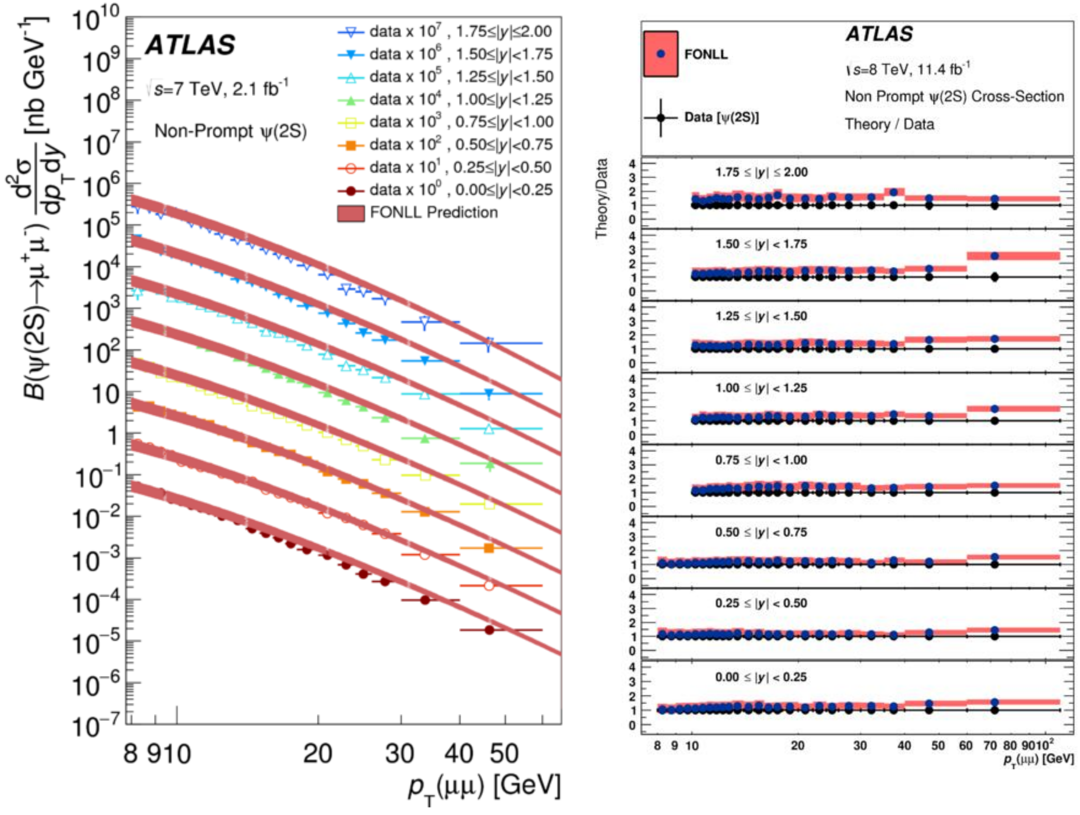
NRQCD = Non-Relativistic QCD. Factorize the hard production of $c\bar{c}$ pair with any colour and spin quantum numbers (pQCD)

Charmonium production – non-prompt component

Non-prompt J/ψ compared to FONLL.
Good agreement across but predicts slightly harder p_T spectra



Non-prompt ψ(2S) compared to FONLL.
Good agreement across but predicts slightly harder p_T spectra

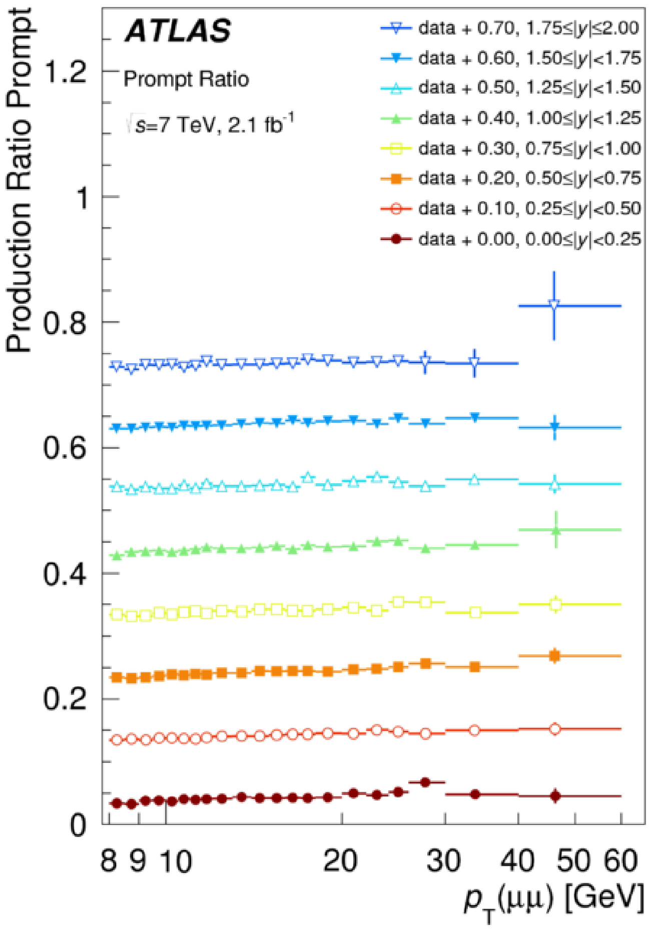


arXiv:1512.03657, to appear in EPJC

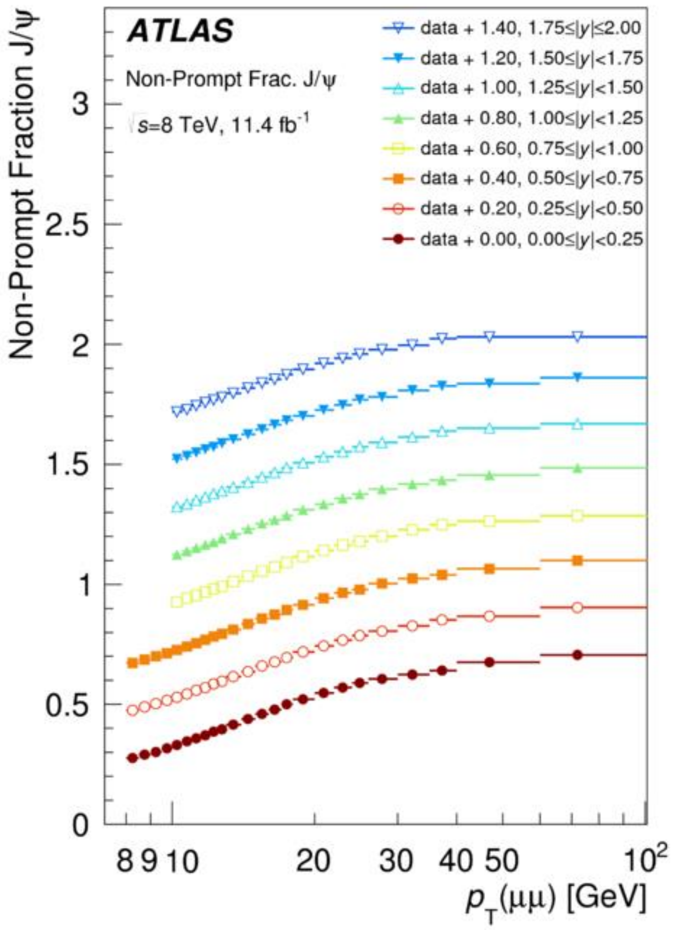
FONLL = Fixed Order Next-to-Leading Logarithm. Combine $b\bar{b}$ production with data driven fragmentation and decay models.

Charmonium production – production ratios

prompt ψ(2S) / prompt J/ψ
consistent with p_T independence



prompt J/ψ / non-prompt J/ψ
cross-over around 20 GeV



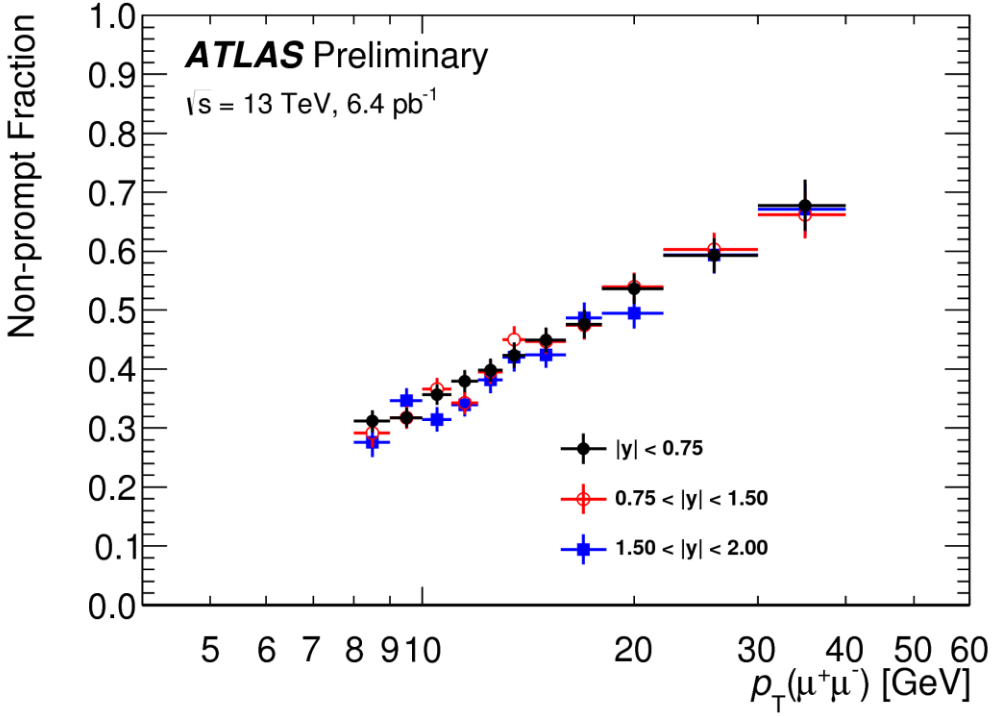
Efficiencies and acceptance cancel to a good approximation in the non-prompt fraction

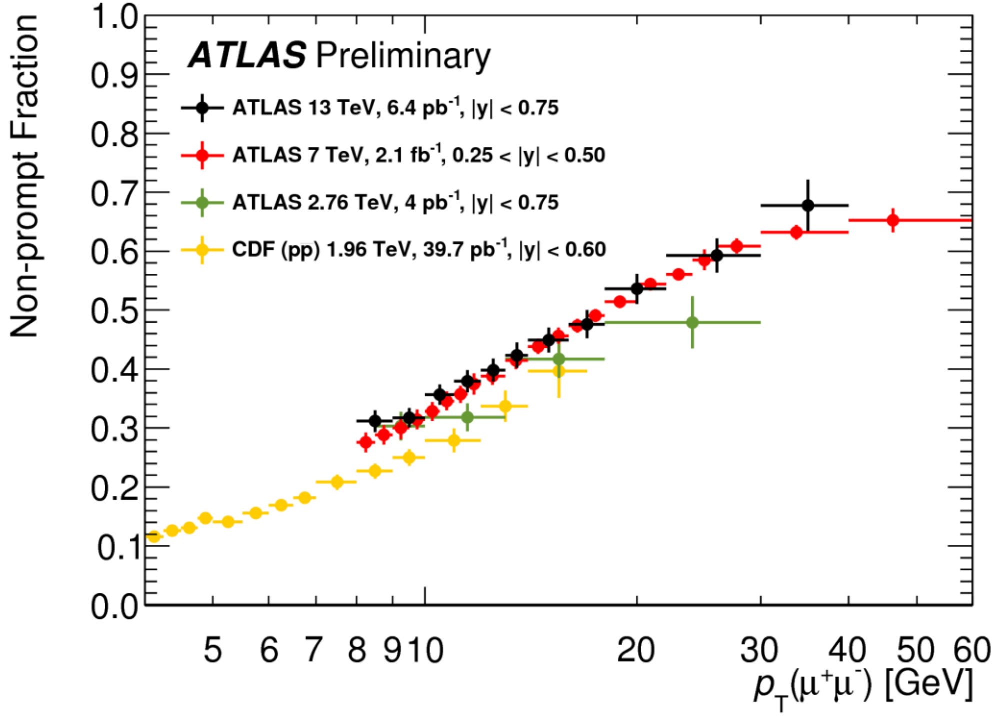
arXiv:1512.03657, to appear in EPJC

Non-prompt J/ψ fraction at 13 TeV

► Early data sample 6.4 pb^{-1} collected with dimuon triggers

► Same method as in Run 1



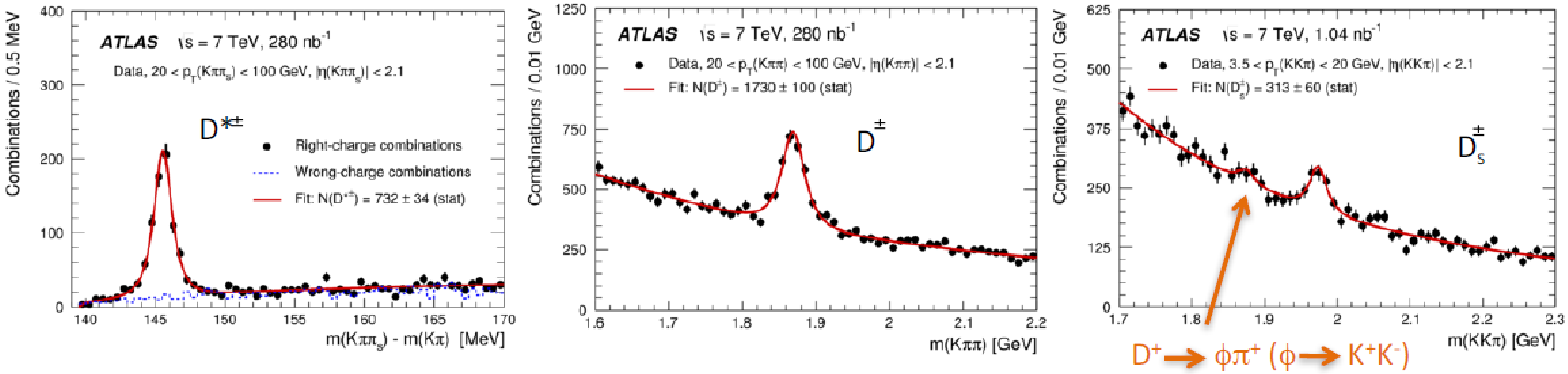


ATLAS-CONF-2015-030

► Minimal rapidity dependence but intriguing $\sqrt{s}$ dependence moving from 7 to 13 TeV

$D^{*\pm}$, $D^{\pm}$, $D_s^{\pm}$ production at 7 TeV

► Charm production studied through the reconstruction of exclusive D meson decays



arXiv:1512.02913, submitted to NPB

► Valuable tool for **tuning** and **validation** of MC generators used for LHC physics

► Total and differential cross sections compared to a range of theory predictions and MC generators

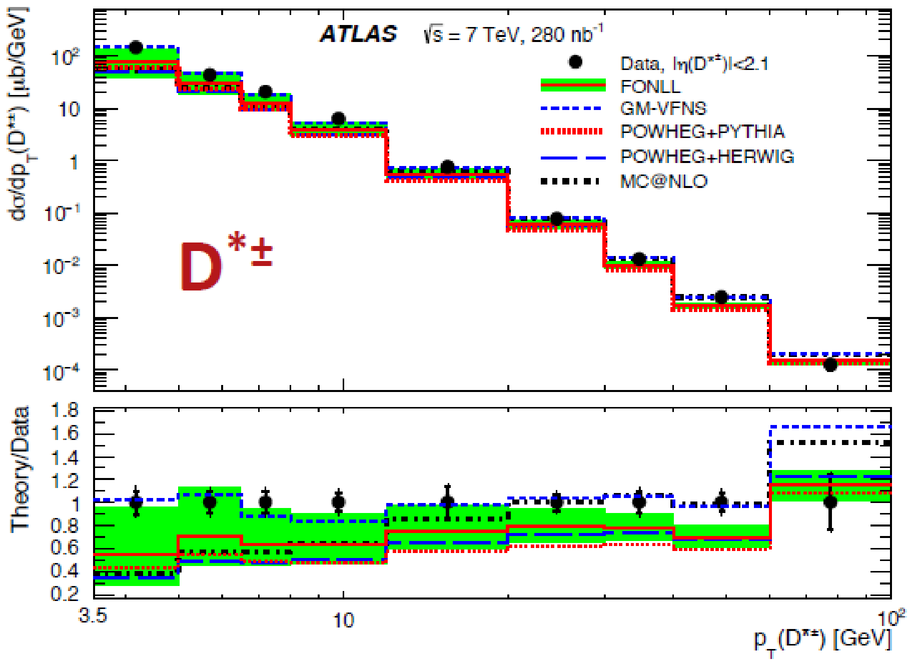
► Results within fiducial space (3.5<p_T<20 GeV, |η|<2.1) extrapolated to a measurement of the **total charm CS**:

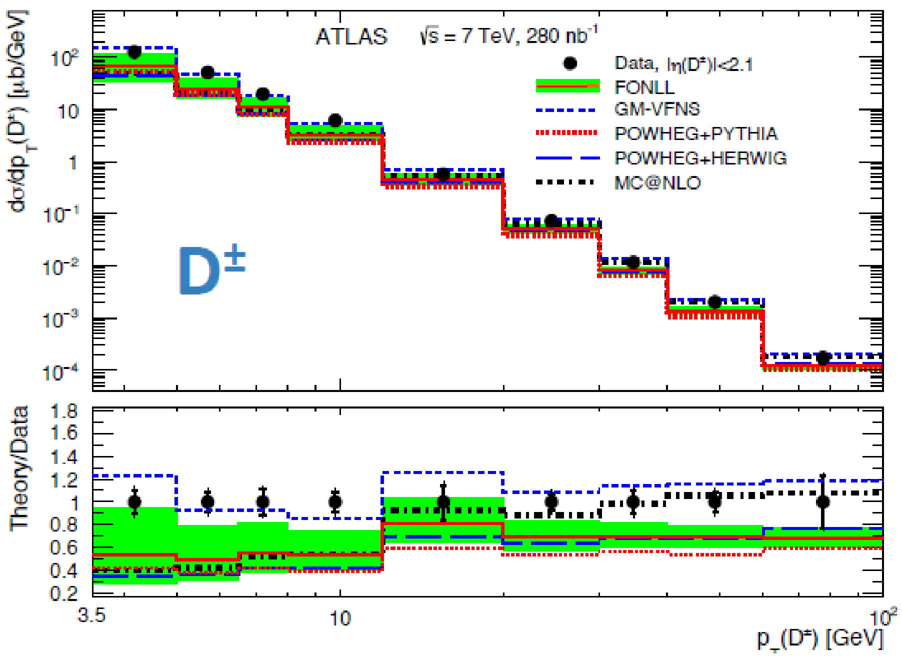
$$\sigma_{c\bar{c}}^{tot} = 8.6 \pm 0.3\ (stat) \pm 0.7\ (syst) \pm 0.3\ (lum) \pm 0.2\ (ff)\ ^{+3.8}_{-3.4}\ (extr)\ \text{mb}$$

Cfr a similar extrapolation from ALICE: $\sigma_{c\bar{c}}^{tot} = 8.5 \pm 0.3\ (stat)\ ^{+1.0}_{-2.4}\ (syst) \pm 0.3\ (lum) \pm 0.2\ (ff)\ ^{+5.0}_{-0.4}\ (extr)\ \text{mb}$ [JHEP 07 (2012) 191]

$D^{*\pm}$, $D^{\pm}$, $D_s^{\pm}$ production at 7 TeV

- ▶ Differential cross sections as a function of p_T
- ▶ Shapes well reproduced by FONLL and POWHEG
- ▶ Predicted overall normalization in general lower than data
- ▶ Differential cross sections in η shows similar trends





arXiv:1512.02913, submitted to NPB

Ratio of b quark fragmentation fractions f_s/f_d at 7 TeV

- Important for searches and rare decays, e.g. $B_s^0 \to \mu^+\mu^-$
- Extract from $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$
- 2.47 fb^{-1} of 7 TeV data used
- From experiment:

$$\frac{f_s}{f_d}\frac{B(B_s^0 \to J/\psi\phi)}{B(B_d^0 \to J/\psi K^{*0})} = 0.199 \pm 0.004(stat) \pm 0.008(syst)$$

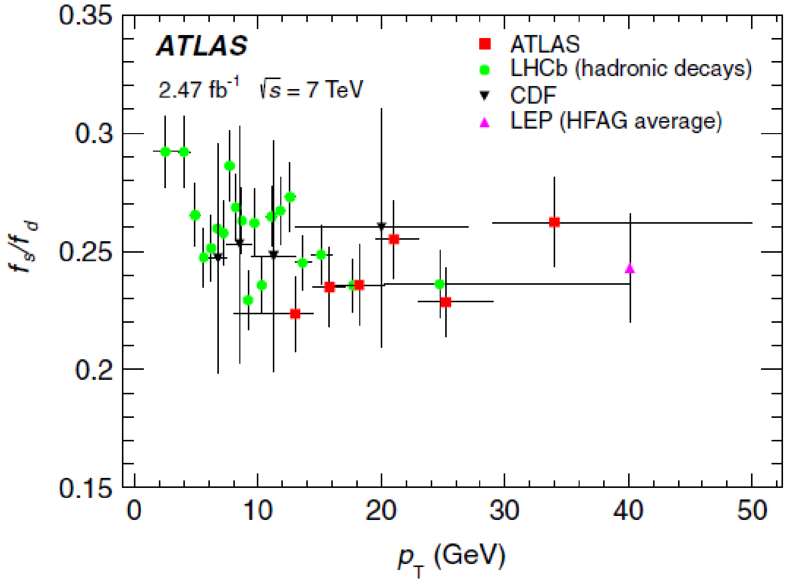
- Perturbative QCD predictions: Phys. Rev. D 89 (2014) 094010

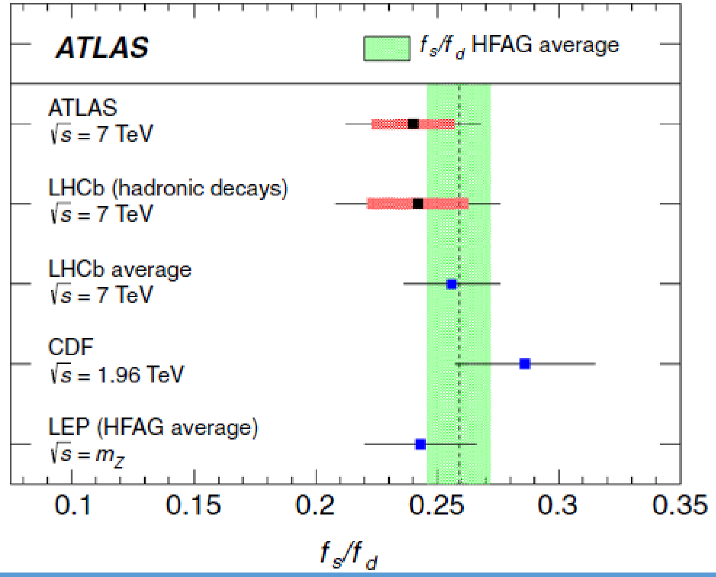
$$\frac{B(B_s^0 \to J/\psi\phi)}{B(B_d^0 \to J/\psi K^{*0})} = 0.83^{+0.03}_{-0.02}(\omega_B)^{+0.01}_{-0.01}(f_M)^{+0.01}_{-0.02}(a_i)^{+0.01}_{-0.02}(m_c)$$

- Resulting ratio:

$$\frac{f_s}{f_d} = 0.240 \pm 0.004\,(stat) \pm 0.010\,(syst) \pm 0.017\,(th)$$

- No p_T or η dependence in the measured kinematic range



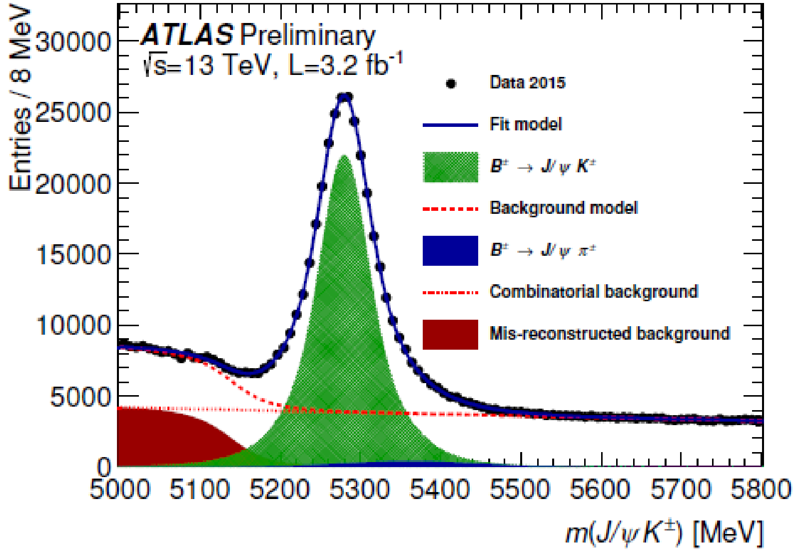


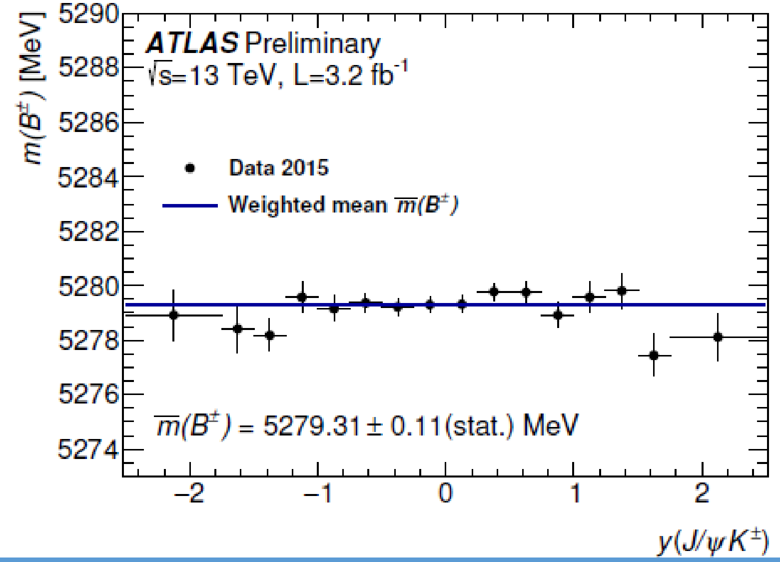
Phys. Rev. Lett. 115, 262001 (2015)

$B^{\pm} \rightarrow J/\psi K^{\pm}$ reconstruction at 13 TeV

- ▶ Good probe for detector performance at the new conditions (energy, pile-up, new IBL detector)
- ▶ Ancillary to future analyses
- ▶ Used full 2015 pp dataset (3.2 fb^{-1})
- ▶ Simple selection
  - Reconstruction in $B^{\pm} \rightarrow J/\psi K^{\pm}$
  - Selection: $p_T(\mu) > 4$ GeV, $p_T(K) > 3$ GeV
  - 3-track vertex fit (χ^2/NDF < 3)
  - Independent fit in 16 rapidity regions
- ▶ Systematic uncertainty dominated by fit model (0.25 MeV)
- ▶ p_T scale systematic uncertainty better than permill!
- ▶ Good agreement with world average

Fit	$B^{\pm}$ mass [MeV]	Fit error [MeV]
Default Fit	5279.31	0.11 (stat.)
$L_{xy} > 0.2$ mm	5279.34	0.09 (stat.)
World Average fit	5279.29	0.15
LHCb	5279.38	0.11 (stat.) $\pm$ 0.33 (syst.)

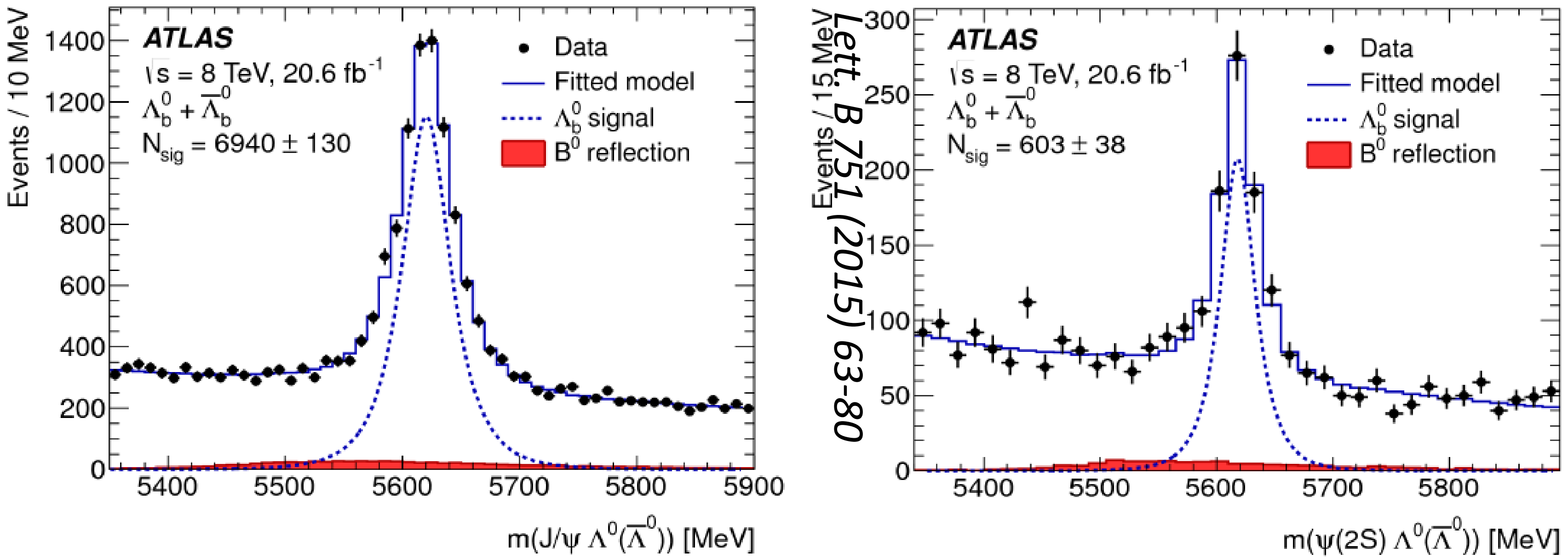




ATLAS-CONF-2015-064

Observation of $\Lambda_b^0 \rightarrow \psi(2S)\Lambda^0$ decay

- First observation of this decay mode (20.6 fb^{-1} at 8 TeV)
- BR predicted of the same order of $\Lambda_b^0 \rightarrow J/\psi\Lambda^0$ decay (ratio 0.8 ± 0.1) [Phys. Rev. D 88, 114018 (2013)]
- Analysis in kinematic range $p_T(\Lambda_b)$ > 10 GeV and $|\eta(\Lambda_b)|$ < 2.1
- Decay modes: J/ψ and ψ(2S) in μμ, Λ_0 in $p\pi^-$
- Simultaneous fit of $m_{J/\psi\Lambda^0}$ and $m_{J/\psi K_s^0}$
- Main source of systematic uncertainty is due to the signal extraction procedure (2.8%)
- Prediction exceed the measured value but within the typical ratios of B meson decays



Phys. Lett. B 751 (2015) 63-80

$$\frac{\Gamma(\Lambda_b^0 \rightarrow \psi(2S)\Lambda^0)}{\Gamma(\Lambda_b^0 \rightarrow J/\psi\Lambda^0)} = \mathbf{0.501 \pm 0.033\ (\mathit{stat}) \pm 0.016\ (\mathit{syst}) \pm 0.011\ (\mathfrak{B})}$$

$\mathfrak{B}$ = uncertainties related to the charmonium branching fractions

Conclusions

- ► Run 1 results provided a comprehensive set of results
  - ► Quarkonium production and decay
  - ► Useful for MC generator testing and tuning
  - ► Synergy with other LHC experiments
  - ► Further Run 1 results still to come
- ► First studies of 2015 *pp* collisions at 13 TeV
  - ► J/ψ production (prompt/non-prompt components)
  - ► *B*-hadron reconstruction
- ► ATLAS will continue on its *B*-physics program
  - ► Detector upgrade copes with challenging Run 2 conditions
  - ► Expect new interesting results to come!