Recent heavy flavour results from ATLAS

Lake Louise Winter Institute 2016

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9th February 2016

Introduction

Recent **ATLAS** heavy flavour results based on both **Run 1** and early **Run 2** data:

- **Charmonium / Open Charm Production**

  "Measurement of the differential cross-sections of prompt and non-prompt production of J/ψ and $\psi(2S)$ in pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS detector", **arXiv:1512.03657** (Submitted to EPJC)

  "Measurement of the differential non-prompt J/ψ production fraction $\sqrt{s} = 13$ TeV pp collisions at the ATLAS experiment", **ATLAS-CONF-2015-030**

  "Measurement of $D^{*\pm}$, $D^{\pm}$ and $D_s^{\pm}$ meson production cross sections in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector", **arXiv:1512.02913** (Submitted to Nucl. Phys. B.)

- **B Meson Properties**

  "Measurement of the CP-violating phase ϕ_s and the B_s^0 meson decay width difference with $B_s^0 \to J/\psi\,\phi$ decays in ATLAS", **arXiv:1601.03297** (Submitted to JHEP)

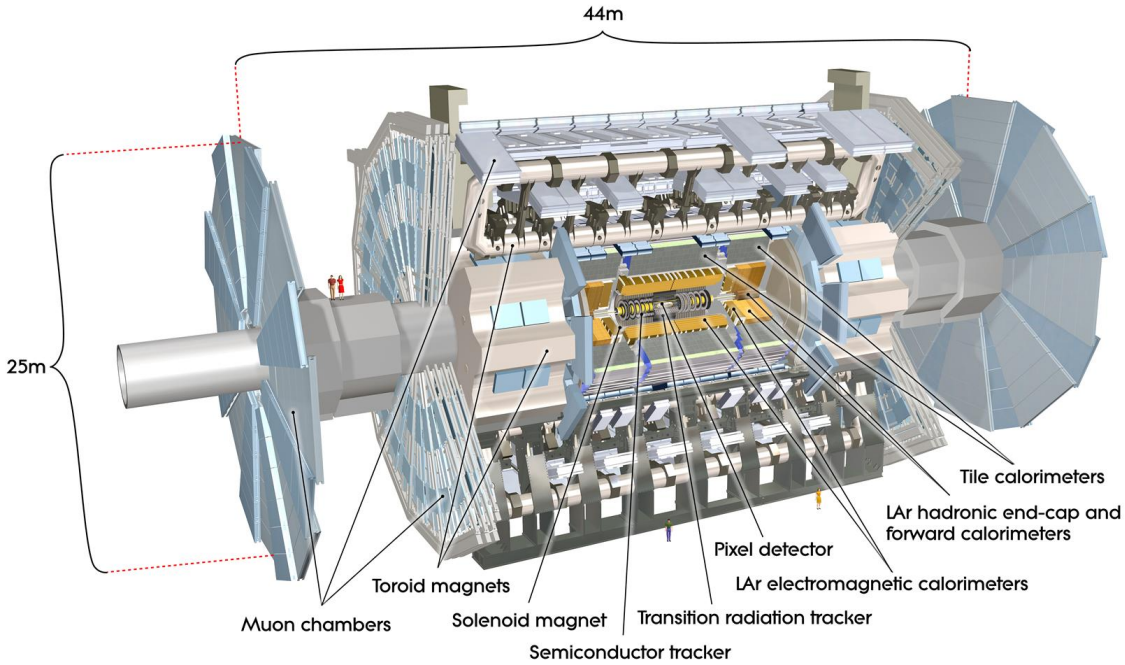
  "$B^{\pm}$ mass reconstruction in $B^{\pm} \to J/\psi\,K^{\pm}$ decay at ATLAS at 13 TeV pp collisions at the LHC", **ATLAS-CONF-2015-064**

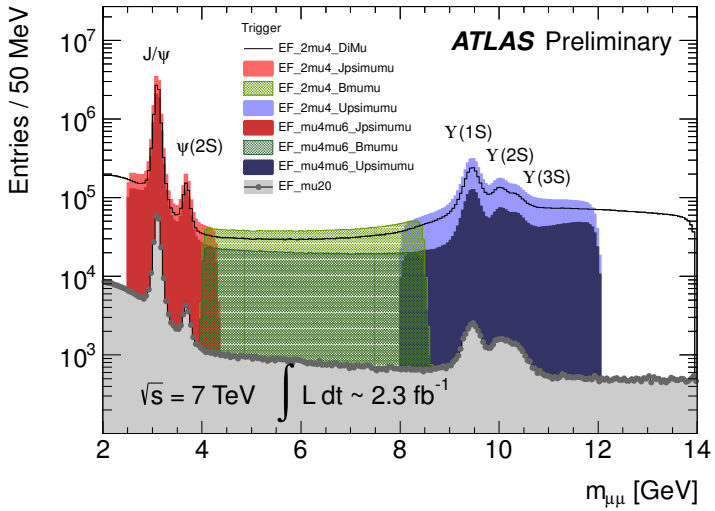
All ATLAS Heavy Flavour results can be found here:

`https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults`

Introduction - **The ATLAS Detector**

General purpose detector, well suited to studying heavy flavour production





Dedicated di-muon triggers for quarkonium

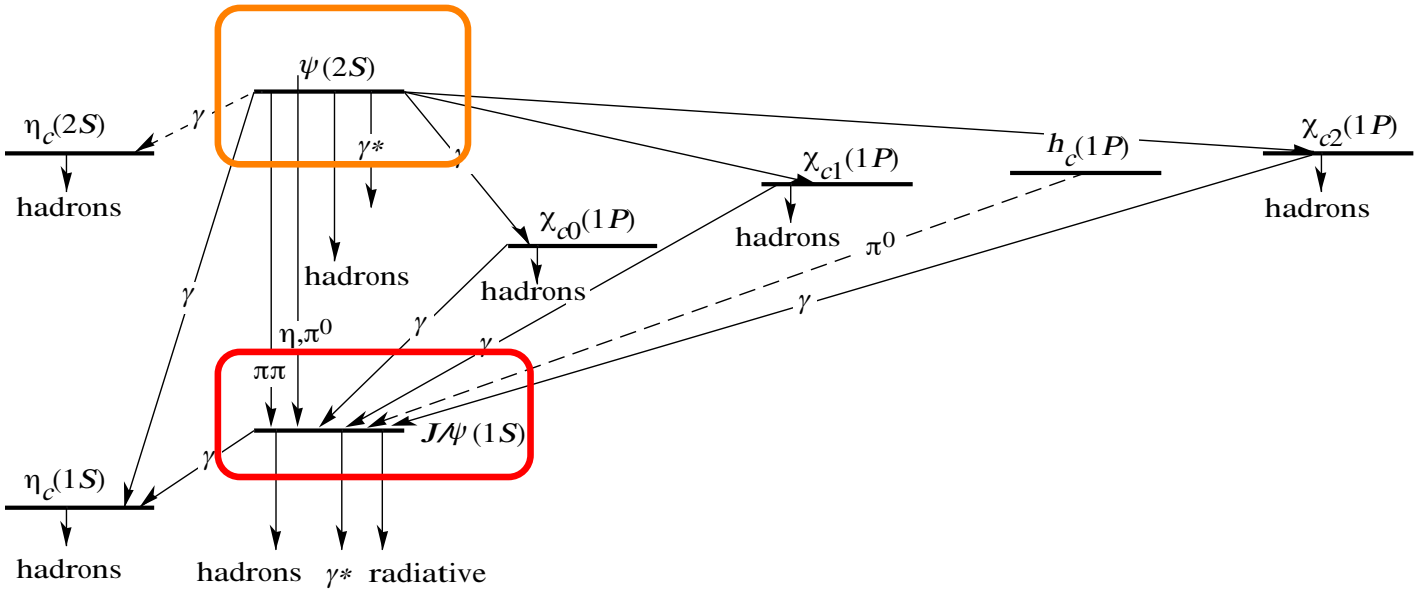
$\mathcal{Q} \to \mu^+\mu^-$ **decays - huge gain in yields w.r.t.**

single muon triggers

- **Muon Spectrometer (MS):** Triggering $|\eta| < 2.4$ and Precision Tracking $|\eta| < 2.7$
- **Inner Detector (ID):** Silicon Pixels and Strips (SCT) with Transition Radiation Tracker (TRT) $|\eta| < 2.5$
- **New for Run 2!** - "Insertable B-Layer" (IBL) - additional inner-most pixel layer ($r = 33$ mm) and lower x/X_0 beam pipe
- **Resolution in $m_{\mu^+\mu^-}$:** Around 50 MeV at J/ψ and 150 MeV at $\Upsilon(nS)$

Charmonium Production at the LHC

Measurements of quarkonium production at the LHC can offer unique windows on our understanding of the strong interaction!



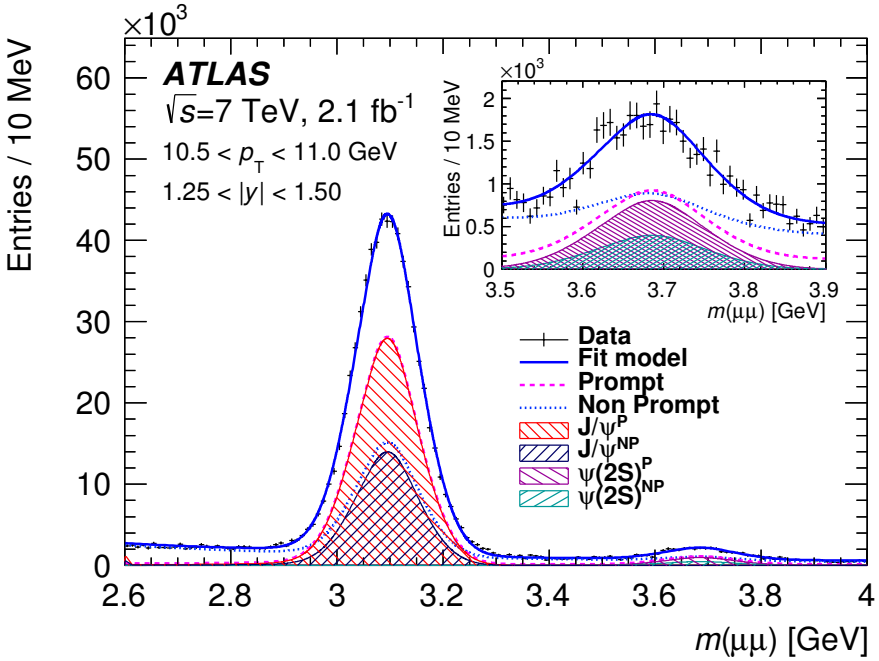
There are two important (distinct) charmonium production mechanisms at the LHC:

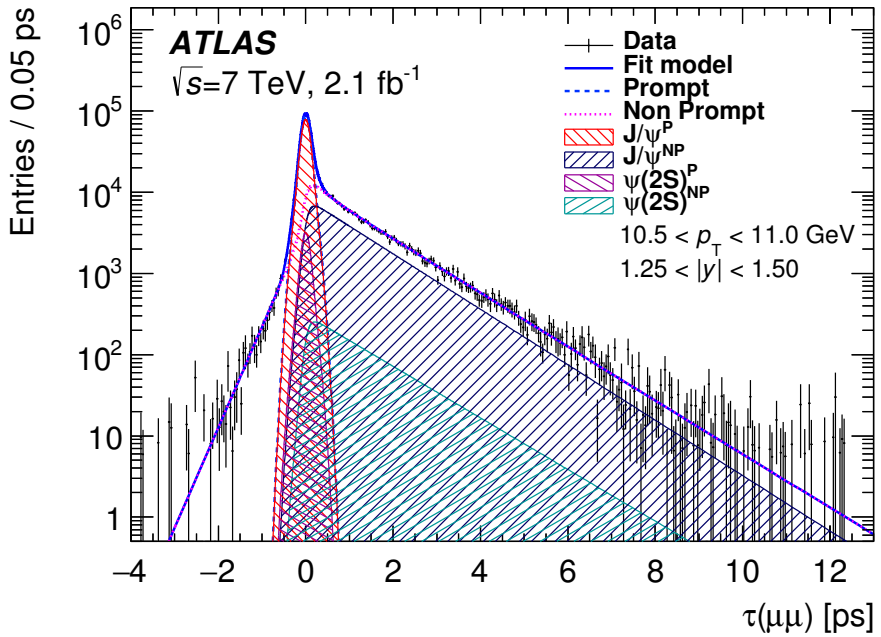
- **Prompt:** Produced *directly* in the primary *pp* interaction or through *feed-down* from decays of a heavier (directly produced) state
- **Non-prompt:** Produced in the decays of *b*-hadrons, can be separated experimentally (exploiting the "long" *b*-hadron lifetime)

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

$\psi(nS) \to \mu^+\mu^-$ production at 7 and 8 TeV - Method

Data (2.1 fb^{-1} at 7 TeV, 11.4 fb^{-1} at 8 TeV) collected with dimuon trigger, basic dimuon selection ($p_T^\mu > 4$ GeV and $|\eta^\mu| < 2.3$) and vertex fit performed:





- Each dimuon candidate is weighted to correct for trigger efficiency, muon identification and reconstruction 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

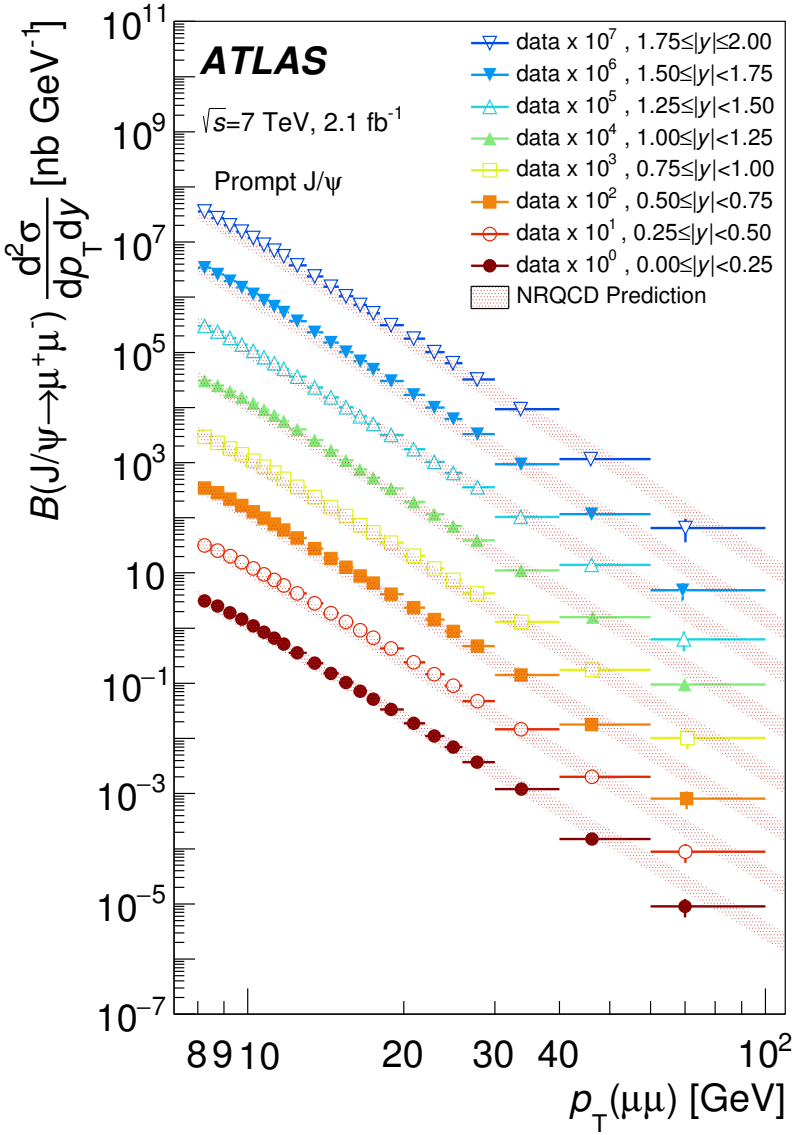
2D fits performed in up to 22 $p_T(\mu^+\mu^-)$ × 8 $y(\mu^+\mu^-)$ bins!

$\psi(nS) \to \mu^+\mu^-$ production at 7 and 8 TeV - Results and Theory

Measurements compared to theoretical models of prompt and non-prompt charmonium production:

- **Prompt: Non-relativistic QCD (NRQCD)** - Factorise the hard production of $c\bar{c}$ pair with *any* colour and spin quantum numbers (pertubative QCD) and soft evolution into a quarkonium state (data derived) **(arXiv:1009.3655)**
- **Non-prompt: Fixed Order Next-to-Leading Logarithm (FONLL)** - Combine perturbative description of $b\bar{b}$ production with data driven fragmentation and $b-$hadron decay model **(arXiv:1205.6344)**

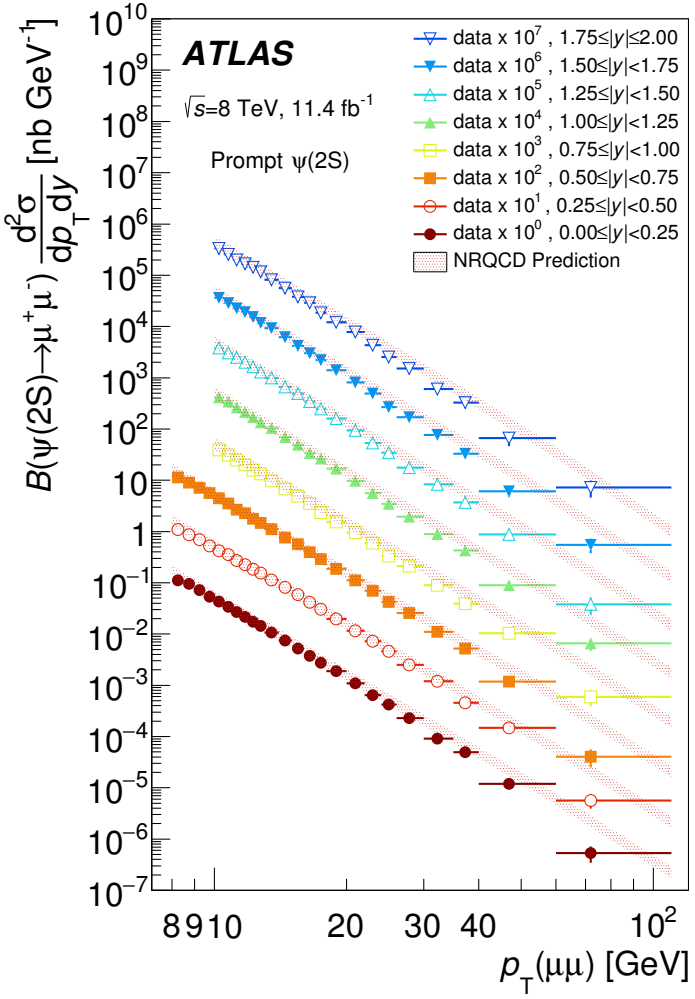
Prompt J/ψ production $\to$ well described by NRQCD

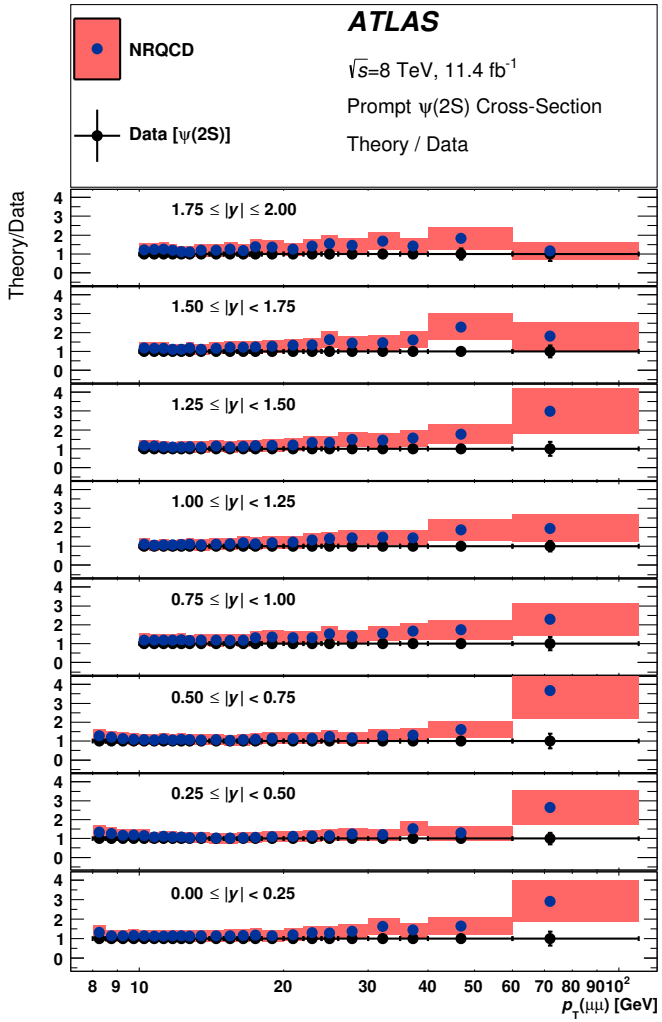


Study includes many detailed and comprehensive measurements, far too many for a short talk, please take a look at the paper!

$\psi(nS) \to \mu^+\mu^-$ production at 7 and 8 TeV - Prompt $\psi(2S)$ results

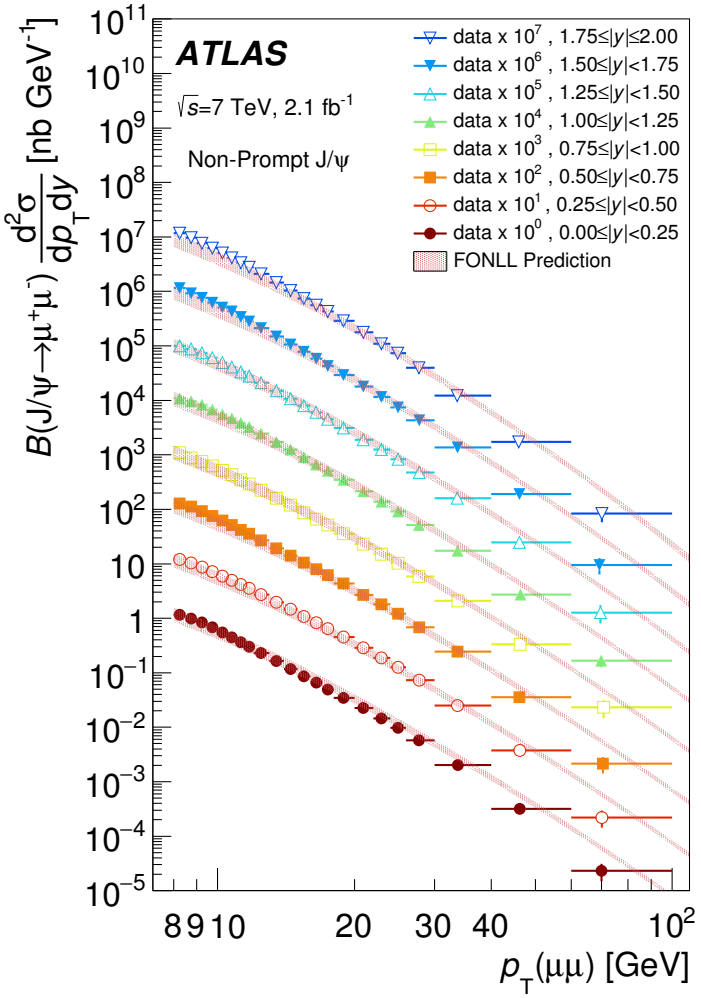
$\psi(2S)$ production represents a direct probe of prompt production mechanism, free from significant feed-down!

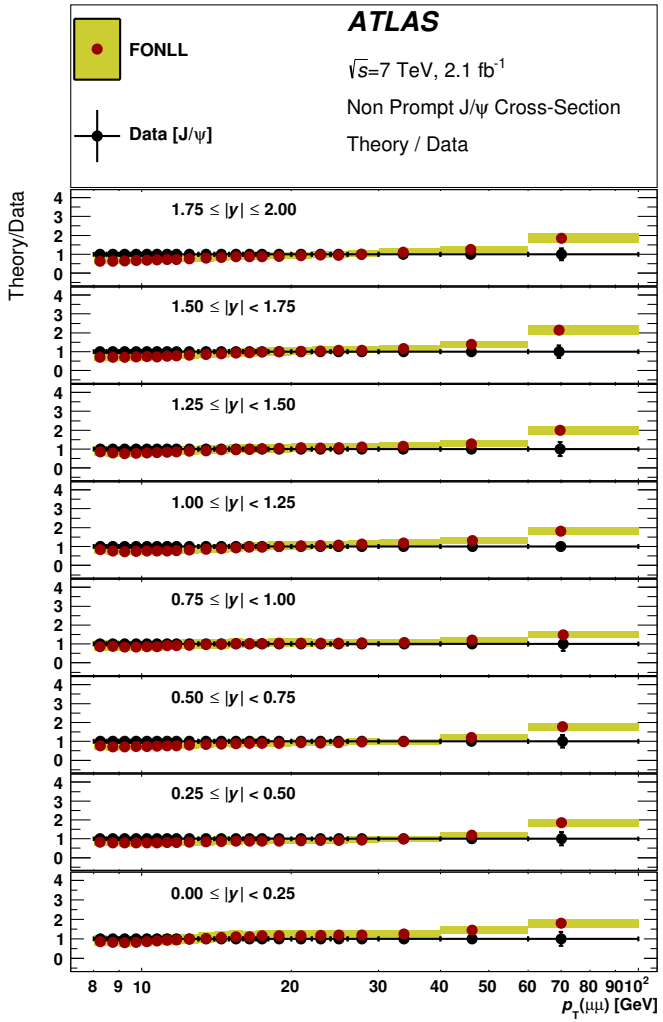




NRQCD generally describes data well, but agreement deteriorates at higher p_T...

Measurements of non-prompt J/ψ production compared to FONLL prediction:

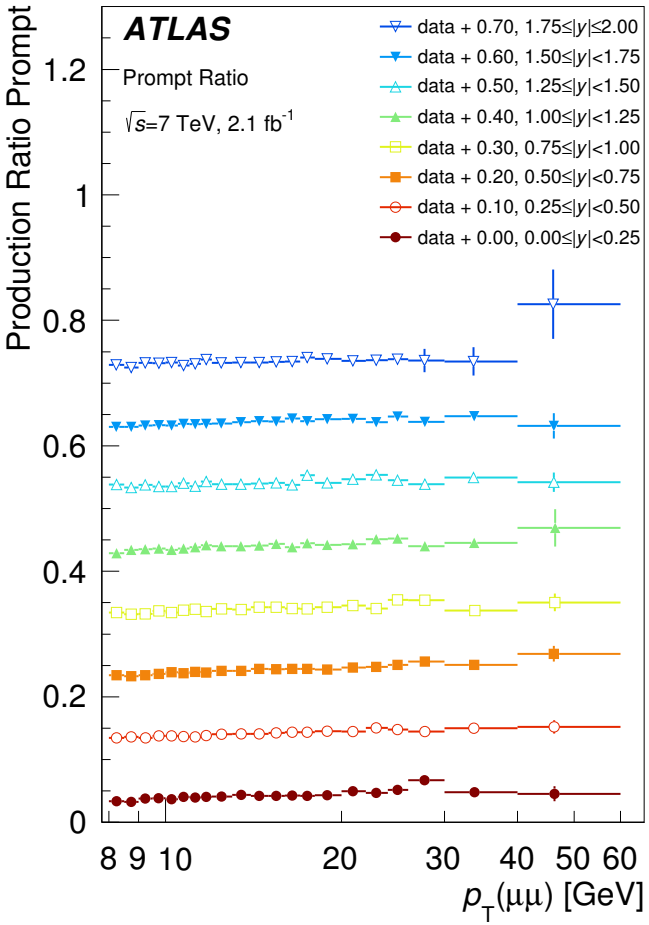


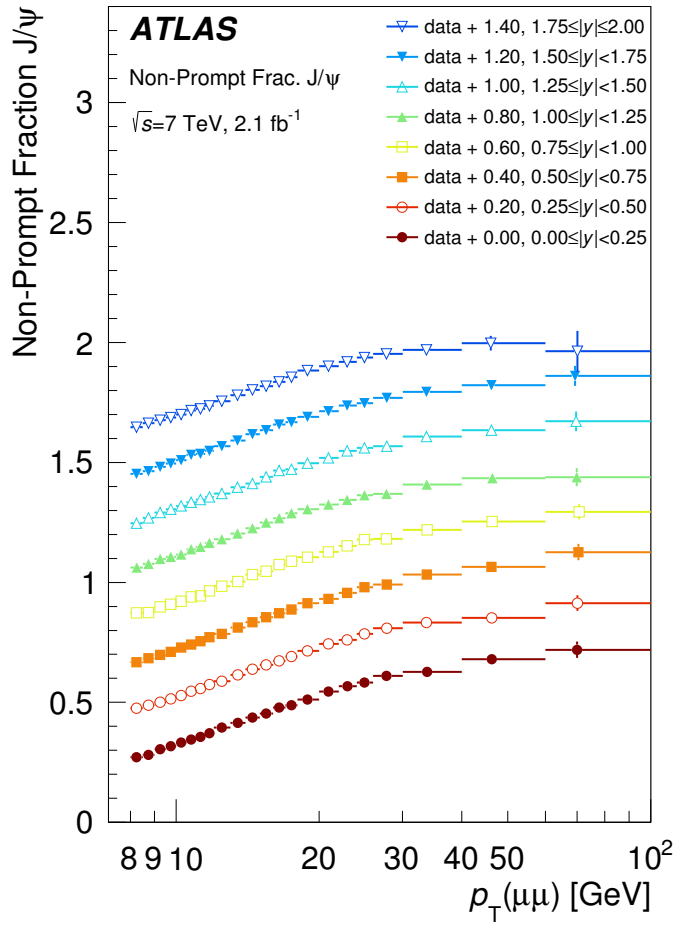


FONLL generally describes data well, but predicts a slightly harder p_T spectrum

$\psi(nS) \to \mu^+\mu^-$ production at 7 and 8 TeV - Production ratio results

← Left: Ratio of prompt $\psi(2S)$ to J/ψ production, consistent with flat across the broad p_T range studied!

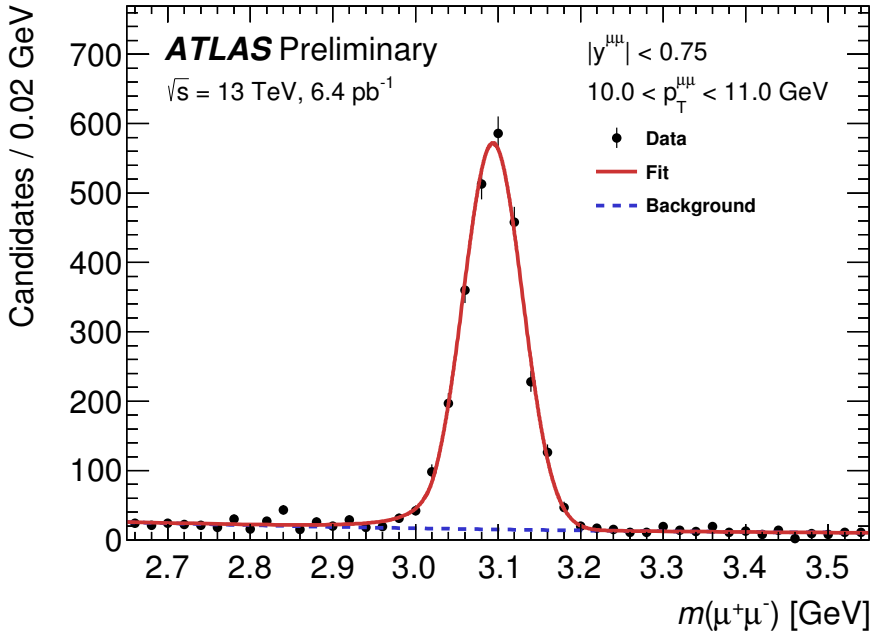


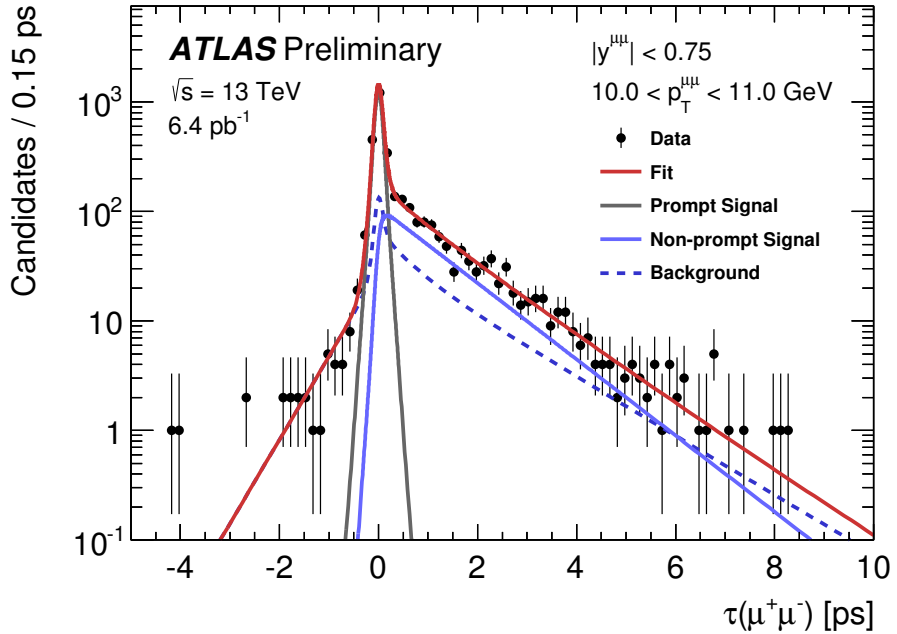


Right →: Non-prompt J/ψ fraction, data dominated by prompt production at low p_T, but non-prompt production exceeds prompt by $p_T > 20$ GeV!

Fraction of non-prompt J/ψ at 13 TeV - Introduction

First ATLAS quarkonium production measurement at 13 TeV, fraction of non-prompt J/ψ production, very similar analysis to comprehensive Run 1 study!



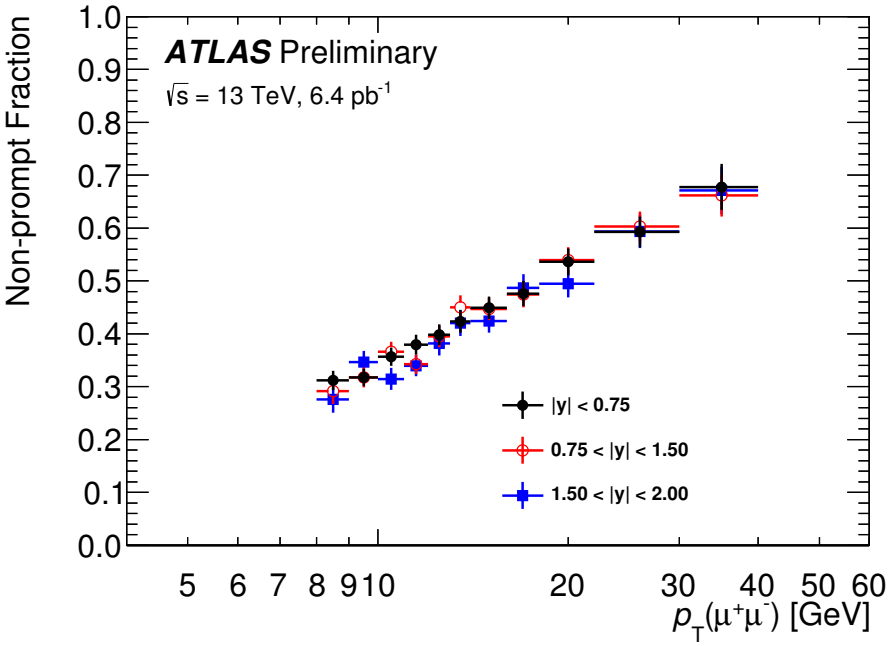


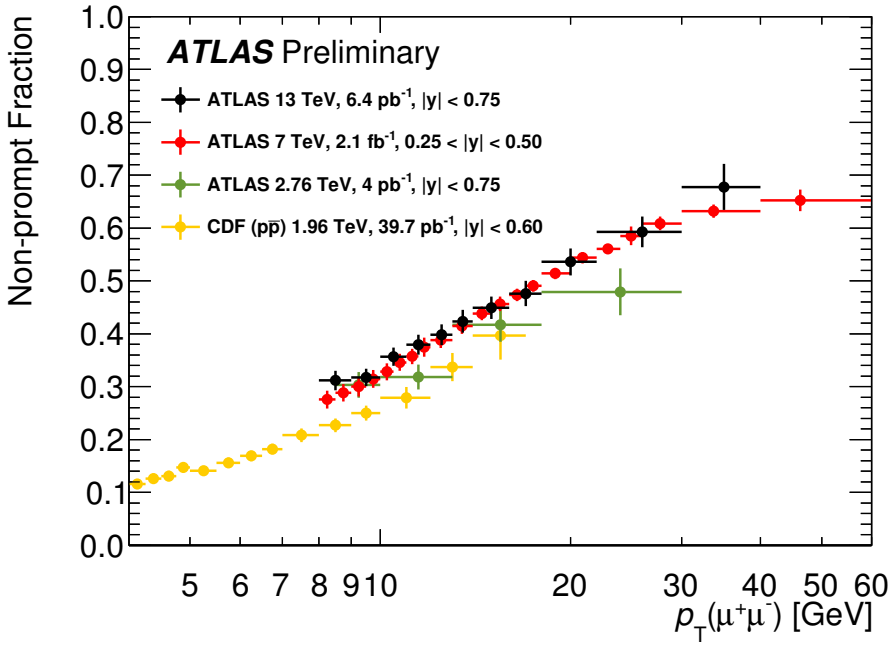
Early data sample of 6.4 pb^{-1}, collected with dimuon and high-p_T muon triggers

- **Prompt** and **non-prompt** J/ψ yields are determined from an un-weighted unbinned fit to the 2D dimuon mass and pseudo-proper decay time distribution
- Efficiencies and acceptance cancel to a good approximation in non-prompt fraction, assign small systematic uncertainty (3%)

Fraction of non-prompt J/ψ at 13 TeV - Results

Non-prompt fraction measurements at 13 TeV compared to *pp* measurements at lower $\sqrt{s}$ and measurements in $p\bar{p}$ collisions:

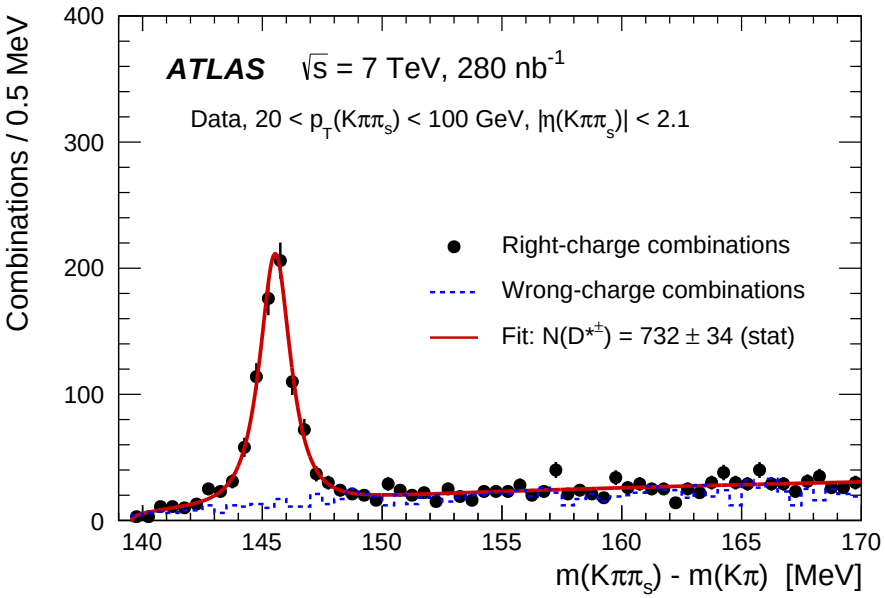


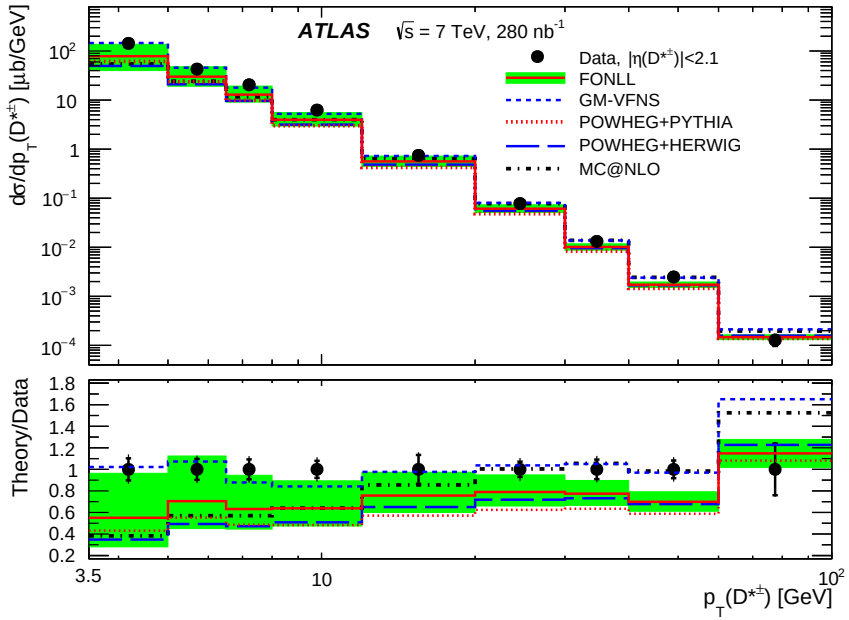


- Comparison exhibits interesting trends, though little change in non-prompt fraction is seen when moving from 7 TeV to 13 TeV!
- Similarly minimal dependence on rapidity observed, as per Run 1 results...

Measurements of $D_{(s)}^{(*)\pm}$ production at 7 TeV

Charm production studied through the reconstruction of exclusive D meson decays





- Total and differential cross sections compared to a range of theory predictions and MC generators - several charm fragmentation observables also extracted
- Results within fiducial phase space extrapolated to a measurement of the total charm cross section

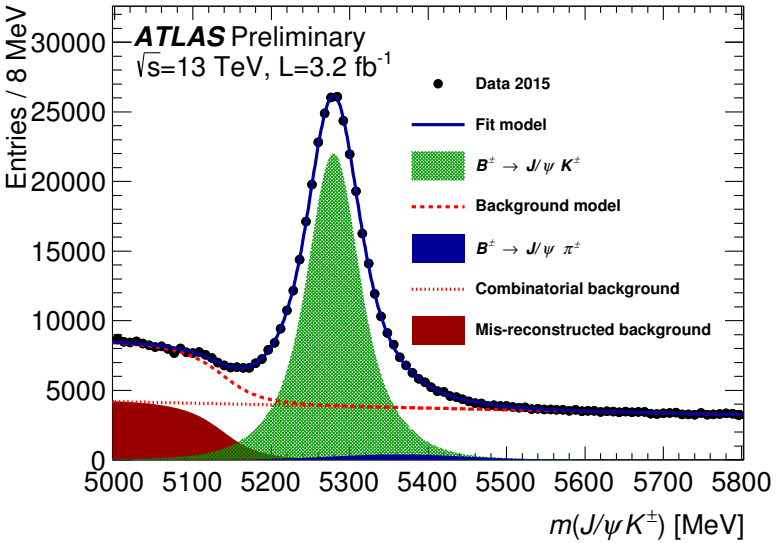
$$\sigma_{c\bar{c}}^{\text{tot}} = 8.6 \pm 0.3\,(stat.) \pm 0.7\,(syst.) \pm 0.3\,(lum.) \pm 0.2\,(ff.)^{+3.8}_{-3.4}\,(extr.)\ \text{mb}$$

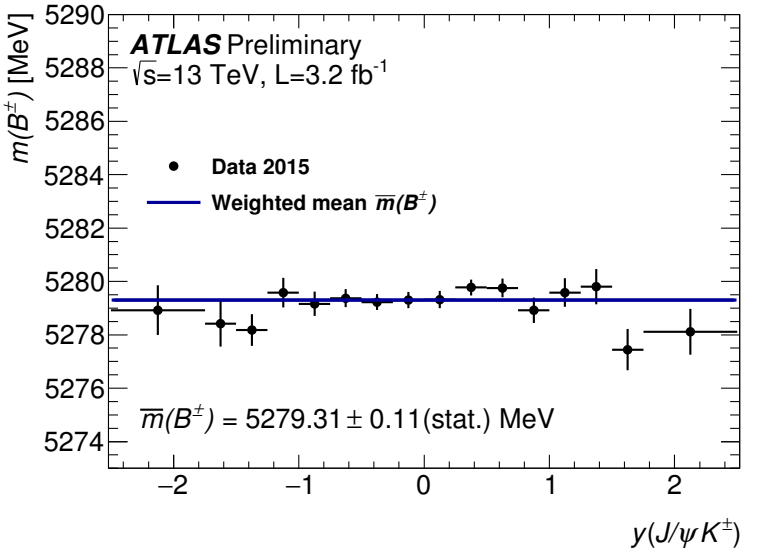
Valuable tool for tuning and validation of MC generators used across LHC physics!

Measurement of $B^{\pm}$ meson mass with 13 TeV data

Initial performance study using full (3.2 fb^{-1}) 2015 *pp* dataset at $\sqrt{s} = 13$ TeV, in preparation for further detailed *b*-hadron measurements!

- Reconstruct $B^{\pm} \to J/\psi\, K^{\pm}$ decay mode with simple selection ($p_T^{\mu} > 4$ GeV and $p_T^{K} > 3$ GeV)
- Perform three-track ($\mu^+\mu^- K^{\pm}$) vertex fit with $\chi^2/d.o.f < 3$ requirement
- $B^{\pm}$ mass extracted from 16 separate unbinned fits to $m(J/\psi K^{\pm})$ distributions, binned in $y(J/\psi K^{\pm})$
- Systematic uncertainty (0.25 MeV) dominated by fit model (mom. scale not yet included)





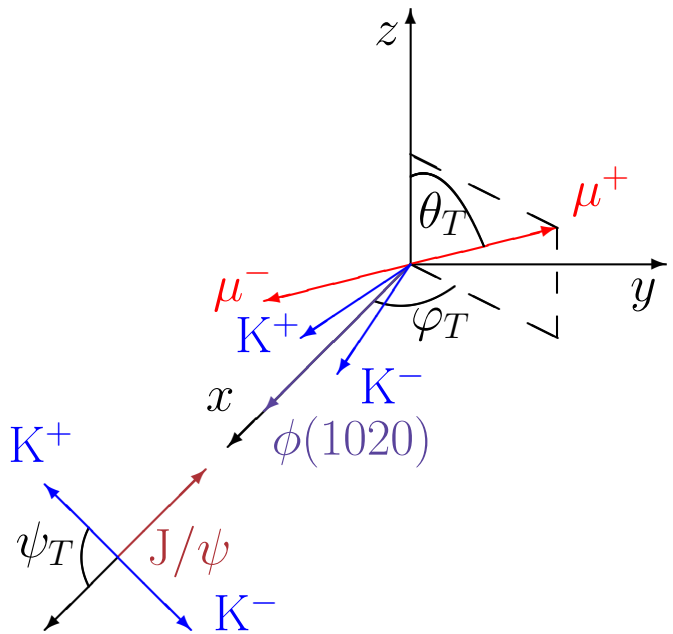
Fit	$B^{\pm}$ mass [MeV]	Fit error [MeV]
Default Fit	5279.31	0.11 (stat.)
$L_{xy} > 0.2$ mm	5279.34	0.09 (stat.)
World Average fit	5279.29	0.15
LHCb	5279.38	0.11 (stat.) ± 0.33 (syst.)

Good agreement with world average!

Measurement of $B_s^0 \to J/\psi\,\phi$ decay parameters - Introduction

BSM physics may affect CP violation in the $B_s^0 \to J/\psi\,\phi$ decays! Measurements of the CP violating phase ϕ_s provides sensitivity to potential new physics!

- CPV arises due to to interference between direct decays and decays with $B_s^0 - \bar{B}_s^0$ mixing
- $P \to VV$ transition, described by three angles in transversity basis
- Perform full time-dependent angular analysis, measure full set of decay parameters (ϕ_s, $\Delta\Gamma_s$ and 8 others)
- Latest analysis uses data sample of 14.3 fb^{-1} at $\sqrt{s} = 8$ TeV
- Search for deviation from small SM predicted value $\phi_s = 0.0363^{+0.0016}_{-0.0015}$ (arXiv:1106.4041)



Transversity Basis Angles: arXiv:1507.07527

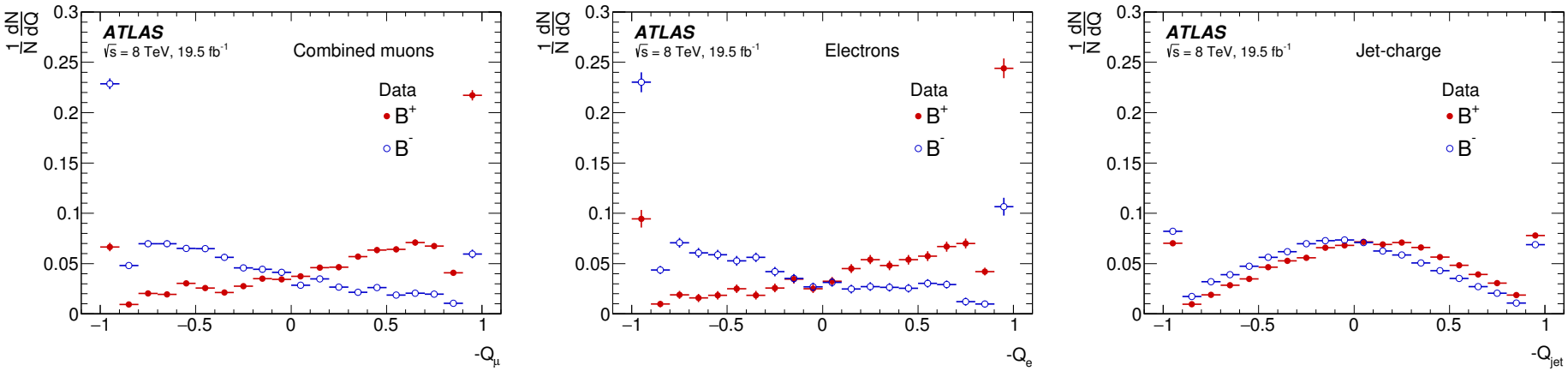
Full likelihood uses $m(\mu^+\mu^-K^+K^-)$, τ, $\delta\tau$, ϕ_T, $cos(\theta_T)$, $cos(\psi_T)$ and initial flavour probability used as input

Measurement of $B_s^0 \to J/\psi\,\phi$ decay parameters - Flavour Tagging

Analysis uses "opposite side tagging" to assign probability to initial flavour or B_s^0 system - improves sensitivity and resolves sign ambiguities:

- Method uses observables on the "opposite side" of the event to the B_s^0 candidate
- Observables include charge of tracks within a b tagged jet or cone around muon/electron on opposite side of event
- Distributions used to built per-candidate B_s tag probability (untagged events assigned probability of 0.5)

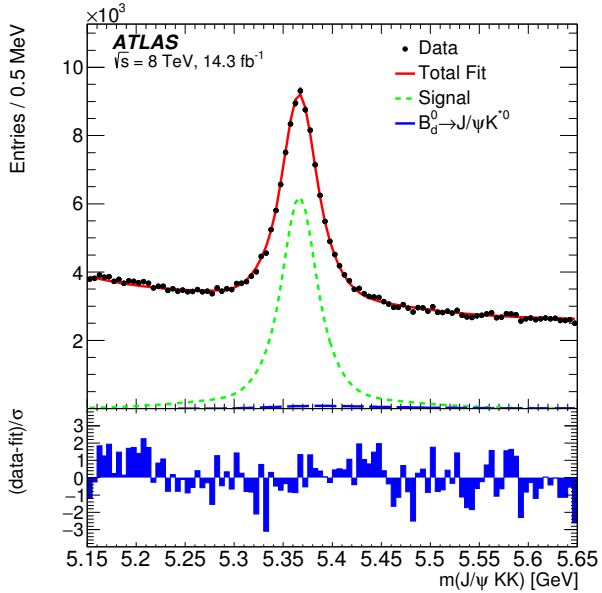
Method calibrated with reconstructed $B^\pm \to J/\psi\,K^\pm$ decays in data!

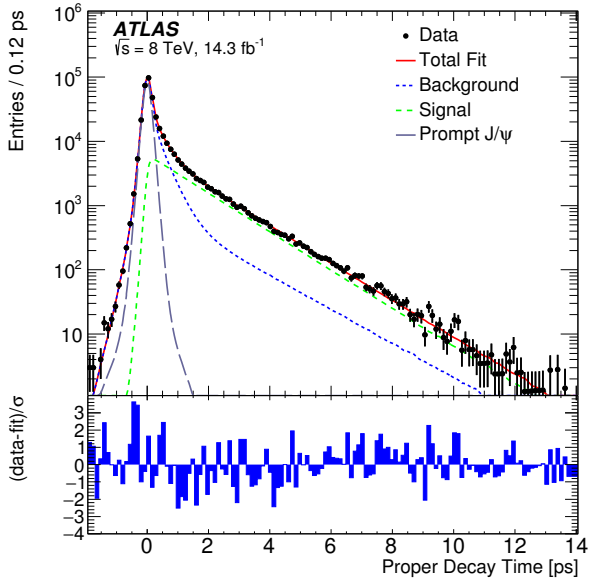


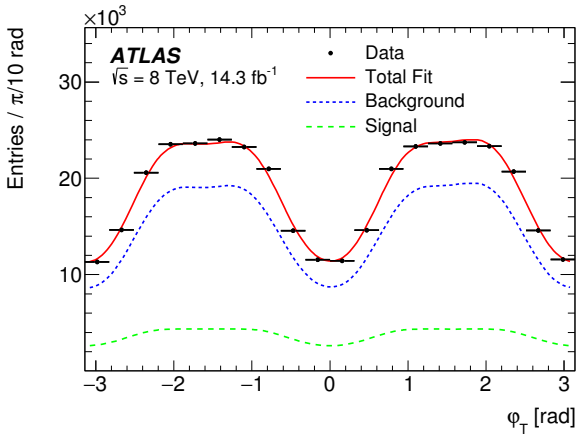
Muon cone charge ($\leftarrow$), electron cone charge ($\uparrow$) and $b-$tagged jet charge ($\rightarrow$)

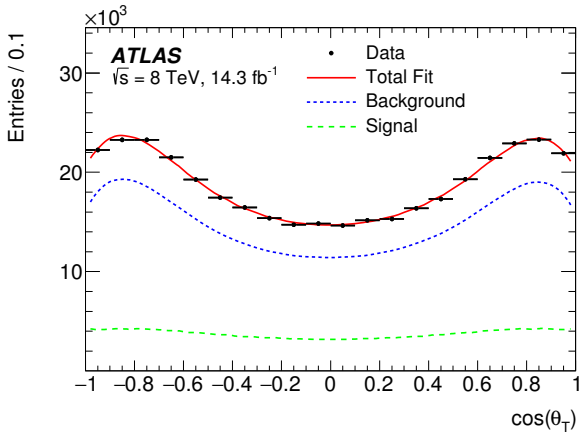
Measurement of $B_s^0 \to J/\psi\,\phi$ decay parameters - Fit Result

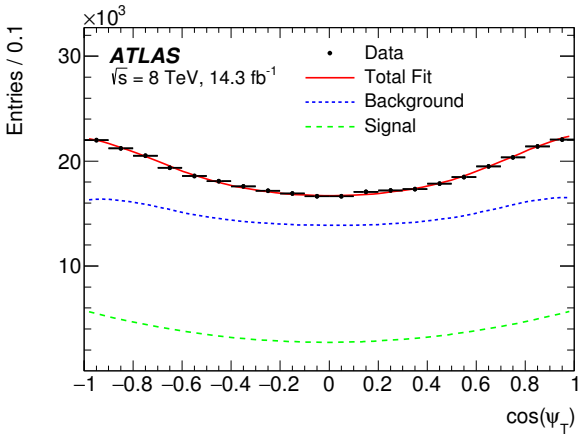
B_s^0 mass (left) and proper decay time (right) fit result projections







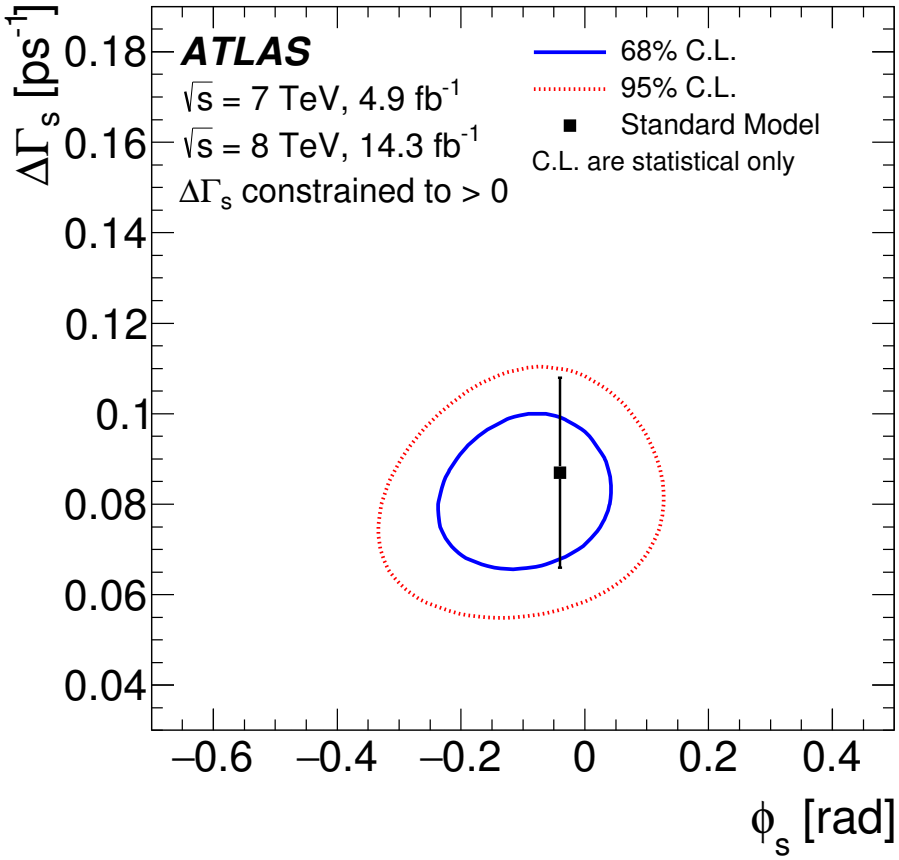




Projections of the transversity angles, ϕ_T ($\leftarrow$), $cos(\theta_T)$ ($\uparrow$) and $cos(\psi_T)$ ($\rightarrow$)

Measurement of $B_s^0 \to J/\psi\,\phi$ decay parameters - Results

New measurement (8 TeV) statistically combined with previous measurement (7 TeV, PRD 90 (2014) 052007), to yield comprehensive measurement exploiting full Run 1 dataset:



Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s[rad]	−0.123	0.089	0.041
$\Delta\Gamma_s$[ps^{-1}]	0.096	0.013	0.007
Γ_s[ps^{-1}]	0.678	0.004	0.004
$\lvert A_\parallel(0)\rvert^2$	0.230	0.005	0.006
$\lvert A_0(0)\rvert^2$	0.514	0.004	0.002
$\lvert A_S(0)\rvert^2$	0.090	0.008	0.020
$\delta_\perp$ [rad]	4.46	0.48	0.29
$\delta_\parallel$ [rad]	3.15	0.13	0.05
$\delta_\perp - \delta_S$ [rad]	−0.08	0.04	0.01

Simultaneous measurement of ϕ_s and $\Delta\Gamma_s$ consistent with Standard Model prediction, no evidence for new physics...

Summary

- **Charmonium / Open Charm Production**
- ATLAS have recent published their most comprehensive set of S-wave charmonium production measurements using full Run 1 dataset!
- Initial measurements of J/ψ production at 13 TeV have also been released, paving the way for more detailed measurements to come!
- Comprehensive set of open charm production measurements at 7 TeV published - important tool for MC generator tuning!

B Meson Properties

- Final Run 1 measurement of $B_s^0 \to J/\psi\,\phi$ decay parameters, significant improvement in sensitivity, though no evidence for deviations from SM prediction
- Initial performance studies on B meson reconstruction with 13 TeV data have concluded, prospects for further detailed studies in Run 2 are bright!

Expect many more exciting ATLAS heavy flavour results from both the Run 1 and Run 2 datasets soon!