Heavy Hadron Production and Spectroscopy at ATLAS

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on behalf of the ATLAS Collaboration

Hadron 2011, Heavy Hadron session - Munich

Outline

1. Introduction
2. Quarkonium production measurement
3. Exclusive B meson observation
4. Exclusive D meson production measurement
5. Summary

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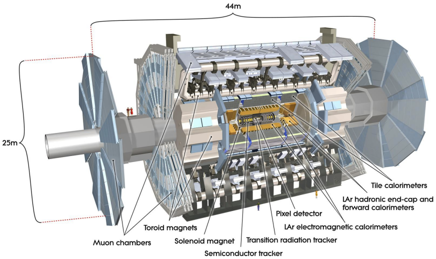
The ATLAS Detector

The ATLAS experiment is equipped with the following sub-systems:

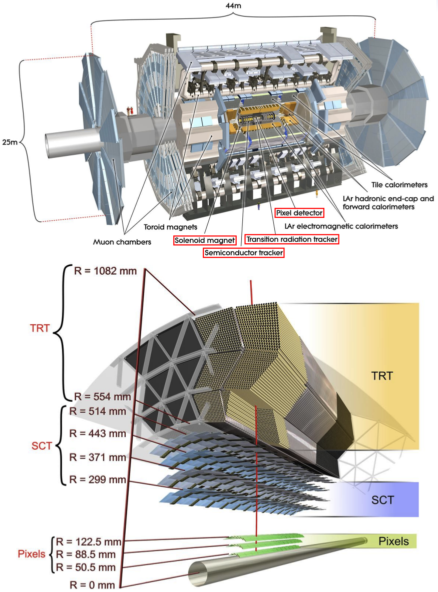
- Inner Detector Tracking
- EM and Hadronic Calorimeters
- Muon Spectrometer



The ATLAS Detector

The ATLAS experiment is equipped with the following sub-systems:

- Inner Detector Tracking
  - → 2 T solenoidal field
  - → Coverage: $|\eta| < 2.5$
  - → Momentum scale: ~0.1% at low energy, ~1% up to ~100 GeV
  - → Design σ/p_T: $3.4\times10^{-4}\cdot p_T/\text{GeV}\oplus 0.015$
  - → Impact parameter resolution: ~30 μm at 5 GeV ($r\phi$)
- EM and Hadronic Calorimeters
- Muon Spectrometer

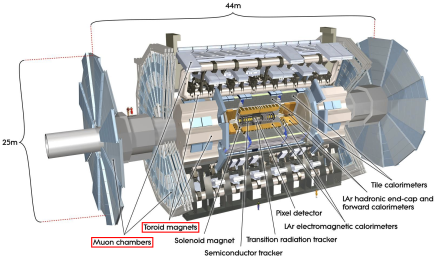


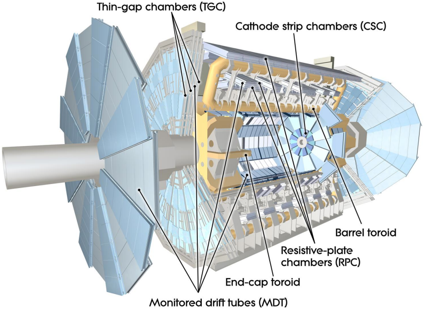
The ATLAS Detector

The ATLAS experiment is equipped with the following sub-systems:

- Inner Detector Tracking
- EM and Hadronic Calorimeters
- Muon Spectrometer

→ Toroidal field: $\int B \cdot dl$ =1-7.5 Tm
→ Coverage: $|\eta| <$2.7
→ Momentum scale: measured at less than 1%
→ Design σ/p_T: $\sim$3% for most range and $<$ 10% up to 1 TeV





The ATLAS Experiment: trigger selection basics

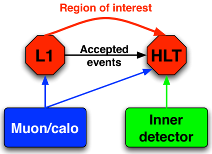
The ATLAS trigger scheme is made of three consecutive selection levels:

→ Level1: hardware processing

  → data from the muon and calorimeter systems
  → identifies "regions of interest" (RoI)

→ Level2 and EventFilter (HLT): software processing

  → data coming from all detectors, including ID
  → can process entire event or L1 RoI



The studies presented here use the following trigger selections:

→ $J/\Psi \to \mu^+\mu^-$ channels: single muon trigger
  → different p_T thresholds (0, 4, 6 or 10 GeV) for different luminosities

→ D meson decays: minimum bias trigger
  → triggers on "collision activity"
  → jet triggers will be used for higher luminosities

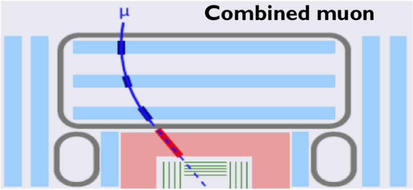
The ATLAS Experiment: muon reconstruction basics

To access different efficiency vs. fake fraction working points, the ATLAS muon reconstruction can adopt complementary strategies, among which:

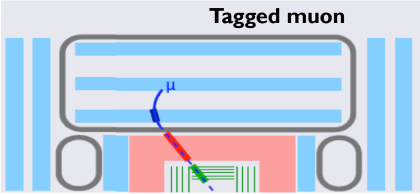
→ combined muon reconstruction:
full tracks reconstructed in both the Muon Spectrometer and the Inner Detector are combined

→ segment-tagged muon reconstruction:
full tracks in the Inner Detector are extrapolated to the Muon Spectrometer and associated with at least one muon track segment

→ in both cases energy loss estimated with the use of calorimeter data



Muon spectrometer Calorimeters Inner Detector



Inclusive $J/\Psi \to \mu^+\mu^-$: selection of candidates

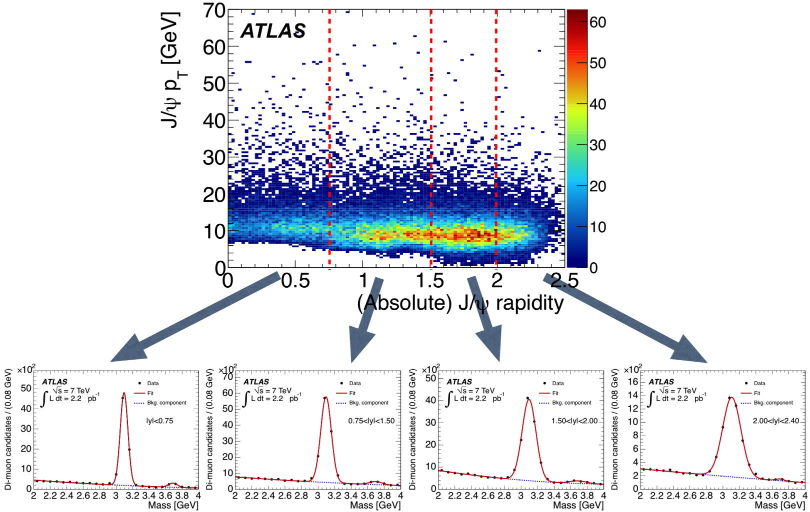
Candidate selection (2.2 pb^{-1}):

- → both muon candidates must be associated to an Inner Detector track
- → muon ID tracks must must have 1 pixel hit and 6 SCT hits
- → both muons must satisfy $p_T > 1$ GeV and $p > 3$ GeV
- → primary vertex must exist and must have been built with at least two tracks
- → at least one muon must be a combined muon
- → one of the muons must match the object firing the muon trigger

Selected candidates are then grouped into four rapidity slices and their number is extracted fitting the $\mu^+\mu^-$ mass histogram:

- → binned χ^2 fit is adopted
- → signal is modeled by a single Gaussian
- → linear background is assumed
- → $\Psi(2S)$ included in the fit procedure, but not counted

Inclusive $J/\Psi \rightarrow \mu^+\mu^-$: binned candidates



Inclusive $J/\Psi \to \mu^+\mu^-$: extrapolating the candidates

Each reconstructed candidate must be corrected, through a weight (w_i), for all the possible sources of inefficiency in the selection and reconstruction process

For each momentum and rapidity slice we will thus have:

$$\frac{d^2\sigma(J/\Psi)}{dp_T\, dy} \cdot Br(J/\Psi \to \mu^+\mu^-) = \frac{N_{corr}}{\mathcal{L} \cdot \Delta p_T \Delta y}$$

$$N_{corr} = \sum_i w_i N_{reco}$$

where each candidate weight can be decomposed into

Bin migration **Muon reconstruction efficiency**

$$w^{-1} = \mathcal{A} \cdot \mathcal{M} \cdot \epsilon^2_{trk} \cdot \epsilon^+_\mu\left(p^+_T, \eta^+\right) \cdot \epsilon^-_\mu\left(p^-_T, \eta^-\right) \cdot \epsilon_{trig}$$

Acceptance **Muon ID track efficiency** **Trigger efficiency**

and the acceptance correction is model dependent on the J/Ψ polarization, which is an unknown parameter

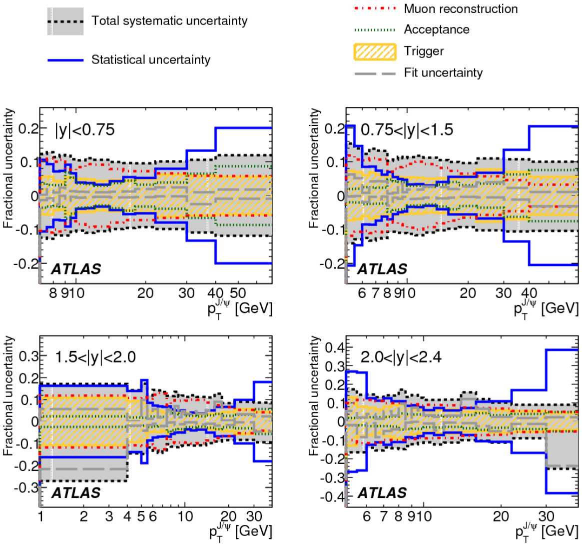
Inclusive $J/\Psi \rightarrow \mu^+\mu^-$: systematics discussion

The adopted unfolding method is affected by a variety of systematic uncertainties:

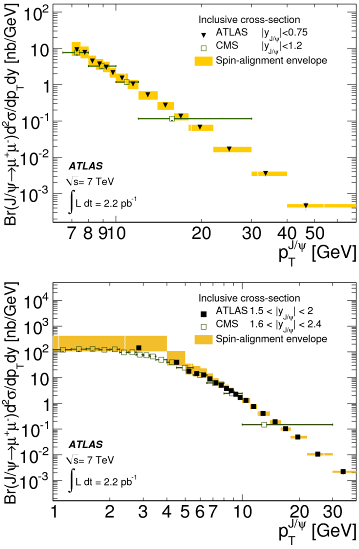
- → spin-alignment uncertainty due to different possible models
  five extreme cases, including: isotropic, full longitudinal, transverse
- → acceptance correction evaluated with finite MC datasets
- → differences between prompt and non-prompt components
- → efficiency determination for: trigger selection, Inner Detector track reconstruction and muon reconstruction, primary vertex finding
- → luminosity determination
- → bin migration effects
- → final state radiation
- → fit uncertainty

... resulting in ...
(spin-alignment and luminosity excluded)

Inclusive $J/\Psi \to \mu^+\mu^-$: systematics



Inclusive $J/\Psi \to \mu^+\mu^-$: differential results



Inclusive $J/\Psi \to \mu^+\mu^-$: integrated results

Integrated results can also be obtained in two regions:

→ the maximum rapidity range, $|y| < 2.4$, which requires $p_T > 7$ GeV

$$Br(J/\Psi \to \mu^+\mu^-) \cdot \sigma(pp \to J/\Psi X) =$$

$$81 \pm 1\,(\text{stat}) \pm 10\,(\text{syst}) \pm^{25}_{20}\,(\text{spin}) \pm 3\,(\text{lumi})\ \text{nb}$$

→ the maximum momentum range, $p_T > 1$ GeV, which requires $1.5 \leq |y| < 2.0$

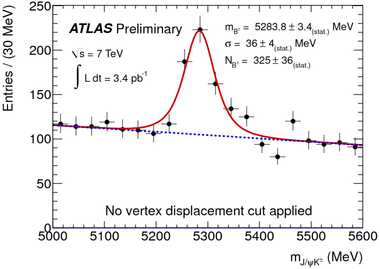
$$Br(J/\Psi \to \mu^+\mu^-) \cdot \sigma(pp \to J/\Psi X) =$$

$$510 \pm 70\,(\text{stat}) \pm^{84}_{123}\,(\text{syst}) \pm^{919}_{134}\,(\text{spin}) \pm 17\,(\text{lumi})\ \text{nb}$$

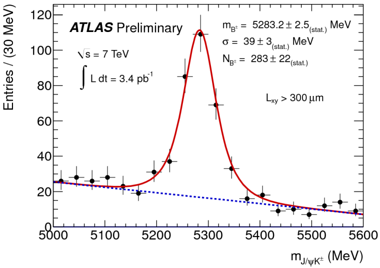
Exclusive beauty: $B^{\pm} \rightarrow J/\Psi + K^{\pm}$ observation

Candidate selection (3.4 pb^{-1}):

- → $J/\Psi \rightarrow \mu^+\mu^-$: two muons required, at least one combined
- → $K^{\pm}$: a third track is selected
- → $B^{\pm}$: combined vertexing performed; $\mu^+\mu^-$ mass constrained to the J/Ψ
- → signal-to-background can be enhanced cutting on the transverse decay length
- → mass spectrum parameters estimated with unbinned maximum likelihood fit, assuming Gaussian signal and linear background



Without decay length cut

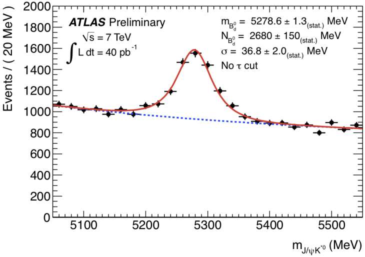


With decay length cut

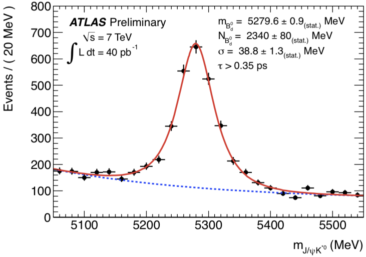
Exclusive beauty: $B_d^0 \to J/\Psi + K^{\star 0}$ observation

Candidate selection (40 pb^{-1}):

- → $J/\Psi \to \mu^+\mu^-$: two muons required, at least one combined
- → $K^{\star 0} \to K^+\pi^-$: two more tracks required; invariant mass cut at $M_{K^{\star 0}}$
- → B_d^0: combined vertexing performed; $\mu^+\mu^-$ mass constrained to the J/Ψ
- → signal-to-background can be enhanced cutting on the pseudo-proper time
- → mass spectrum parameters estimated with unbinned maximum likelihood fit, assuming Gaussian signal and exponential plus constant background



Without pseudo-proper time cut

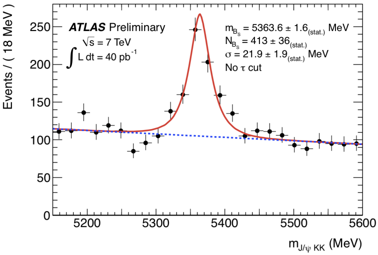


With pseudo-proper time cut

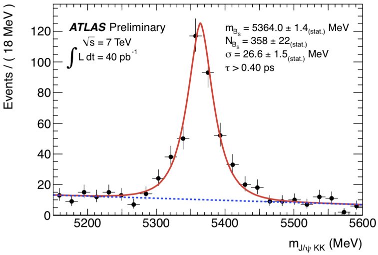
Exclusive beauty: $B_s^0 \rightarrow J/\Psi + \phi$ observation

Candidate selection (40 pb^{-1}):

- → $J/\Psi \rightarrow \mu^+\mu^-$: two muons required, at least one combined
- → $\phi \rightarrow K^+K^-$: two more tracks required; invariant mass cut at M_ϕ
- → B_s^0: combined vertexing performed; $\mu^+\mu^-$ mass constrained to the J/Ψ
- → signal-to-background can be enhanced cutting on the pseudo-proper time
- → mass spectrum parameters estimated with unbinned maximum likelihood fit, assuming Gaussian signal and exponential plus constant background



Without pseudo-proper time cut



With pseudo-proper time cut

Exclusive beauty: summary

The overall exclusive B meson observation results are summarized as follows (with statistical errors only)

		m_B (MeV)	σ_m (MeV)	N_{sig}
$B^{\pm}$	no L_{xy} cut	5283.8±3.4	36±4	325±36
$B^{\pm}$	with L_{xy} cut	5283.2±2.5	39±3	283±22
B_d^0	no τ cut	5278.6±1.3	36.8±2.0	2680±150
B_d^0	with τ cut	5279.6±0.9	38.8±1.3	2340±80
B_s^0	no τ cut	5363.6±1.6	21.9±1.9	413±36
B_s^0	with τ cut	5364.0±1.4	26.6±1.5	358±22

All results are in agreement with P.D.G. values and, where applicable, consistency between opposite sign decay chains is observed

Exclusive charm: selection of D meson candidates

Multiple decay chains have been investigated:

$$D^{\star+} \to D^0 \pi_s^+ \quad \text{with} \quad D^0 \to K^- \pi^+$$
$$D_s^+ \to \phi \pi^+ \quad \text{with} \quad \phi \to K^- K^+$$
$$D^+ \to K^- \pi^+ \pi^+$$

Candidate selection (1.1 nb^{-1}):

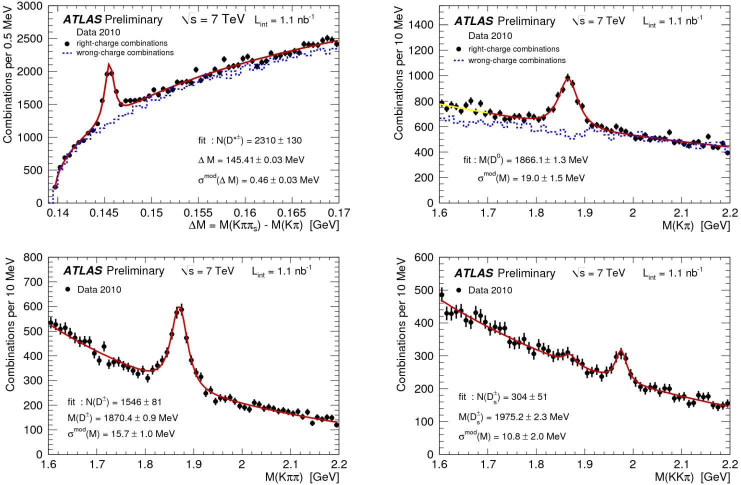
- → three charged particles in the ID passing minimum quality and p_T cuts
- → intermediate invariant mass cuts where applicable
- → additional p_T cuts on reconstructed objects (e.g. D^0, $D^\star$)
- → vertex reconstruction and lifetime cuts

The yield of selected candidates is extracted fitting their mass histogram:

- → binned χ^2 fit is adopted
- → signal is modeled by a single modified Gaussian ($\propto \exp[-0.5 \cdot pull^{1+1/(1+0.5 \cdot pull)}]$)
- → power function multiplied by exponential adopted for background

Exclusive charm: distribution of candidates

$D^{\star +} \to D^0 \pi_s^+$ $D^0 \to K^- \pi^+$



$D^+ \to K^- \pi^+ \pi^+$ $D_s^+ \to \phi \pi^+$

Exclusive charm: systematics discussion

As done for the $J/\Psi \rightarrow \mu^+\mu^-$ case discussed before, the cross-section measurement is extracted by unfolding the observed candidate yield

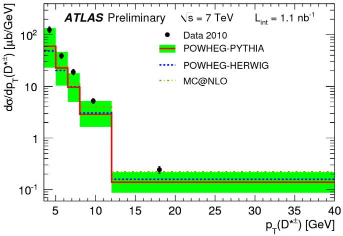
This measurement is thus affected by similar systematic uncertainties:

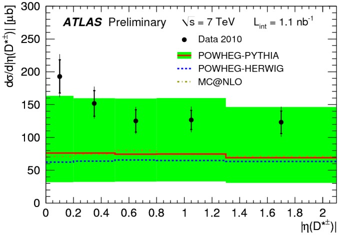
- $\rightarrow$ acceptance correction evaluated with finite MC datasets
- $\rightarrow$ model dependence of the acceptance
- $\rightarrow$ efficiency determination for: trigger selection, Inner Detector track reconstruction and vertexing
- $\rightarrow$ efficiency of kinematical cuts
- $\rightarrow$ luminosity determination
- $\rightarrow$ bin migration effects
- $\rightarrow$ branching ratios
- $\rightarrow$ fit uncertainty
- $\rightarrow$ compared with theory dominated by scale uncertainty

... resulting in ...
(luminosity excluded)

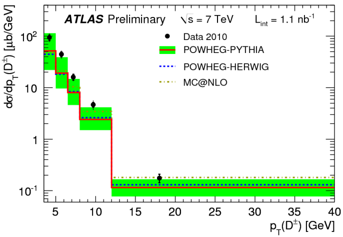
Exclusive charm: differential results

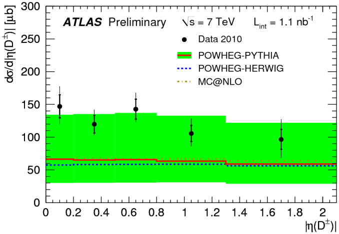
→ Differential cross-section for $D^{\star\pm}$ mesons as a function of p_T and $|\eta|$





→ Differential cross-section for $D^{\pm}$ mesons as a function of p_T and $|\eta|$





Exclusive charm: integrated results

Integrated results can also be obtained in the following region:

→ D meson pseudo-rapidity $|\eta(D)| < 2.1$

→ D meson transverse momentum $|p_T(D)| > 3.5$ GeV

$$\sigma^{vis}(D^{\star\pm}) = 285 \pm 16(\text{stat})\,^{+32}_{-27}(\text{syst}) \pm 31(\text{lumi}) \pm 4(\text{br})\,\mu\text{b}$$

$$\sigma^{vis}(D^{\pm}) = 238 \pm 13(\text{stat})\,^{+35}_{-23}(\text{syst}) \pm 26(\text{lumi}) \pm 10(\text{br})\,\mu\text{b}$$

$$\sigma^{vis}(D_s^{\pm}) = 168 \pm 34(\text{stat})\,^{+27}_{-25}(\text{syst}) \pm 18(\text{lumi}) \pm 10(\text{br})\,\mu\text{b}$$

Summary

Many ATLAS results from the analysis of the first year of data:

- → integrated and differential inclusive $J/\Psi \rightarrow \mu^+\mu^-$ cross-section
  arXiv:1104.3038
- → integrated and differential $D^{(*)}$ mesons cross-section
  ATLAS-CONF-2011-017
- → observation of B mesons in exclusive decays
  ATLAS-CONF-2010-098 and ATLAS-CONF-2011-050

But this was just a small selection of the results ATLAS has performed or is about to perform in the heavy flavour sector:

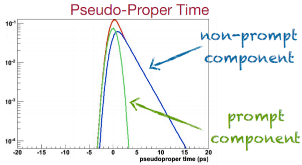
- → prompt and non-prompt J/Ψ fraction
  arXiv:1104.3038, see backup
- → inclusive b-jet cross-sections
  ATLAS-CONF-2011-056 and ATLAS-CONF-2011-057
- → Υ cross-section and J/Ψ and Υ spin alignment
- → $\Psi(2s)$ and double onia production
- → measurements at 2.76 TeV
- → ...

Inclusive $J/\Psi \to \mu^+\mu^-$: prompt/non-prompt fraction

Another currently available measurement on inclusive $J/\Psi \to \mu^+\mu^-$ is the prompt/non-promt fraction

This fraction is extracted from data, based on the pseudo-proper lifetime dicriminating variable, defined as

$$\tau = \frac{L_{xy} \cdot m(J/\Psi)}{p_T(J/\Psi)}$$

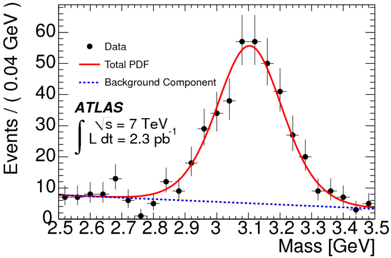


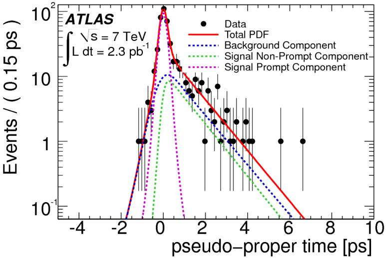
- → a simultaneous invariant mass and pseudo-proper lifetime fit is performed, to extract the non-prompt fraction in each J/Ψ signal slice
- → once both the inclusive cross section and the non-prompt fraction are available, they can be combined to extract prompt and non-prompt cross sections

Inclusive $J/\Psi \to \mu^+\mu^-$: prompt fraction example

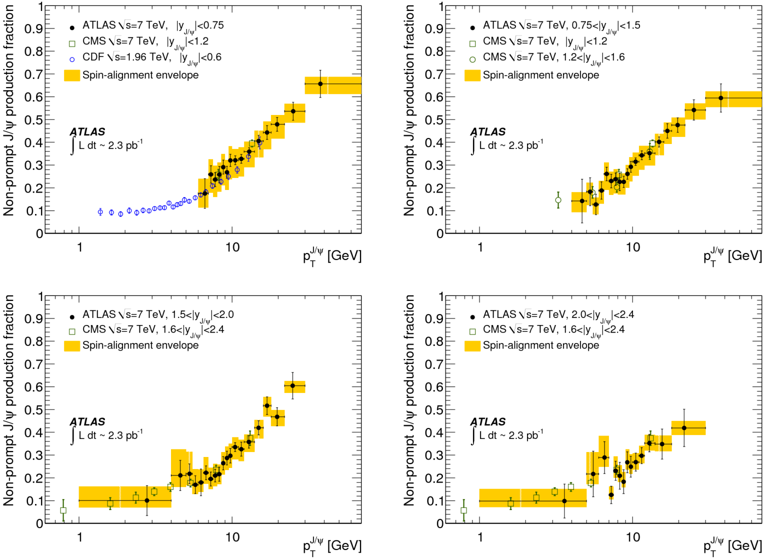
As an example, below are shown plots obtained in the simultaneous fitting procedure for the $J/\Psi \to \mu^+\mu^-$ bin with

- $\to$ transverse momentum: $9.5 < p_T < 10.0$ GeV
- $\to$ rapidity: $2 \leq |y| < 2.4$

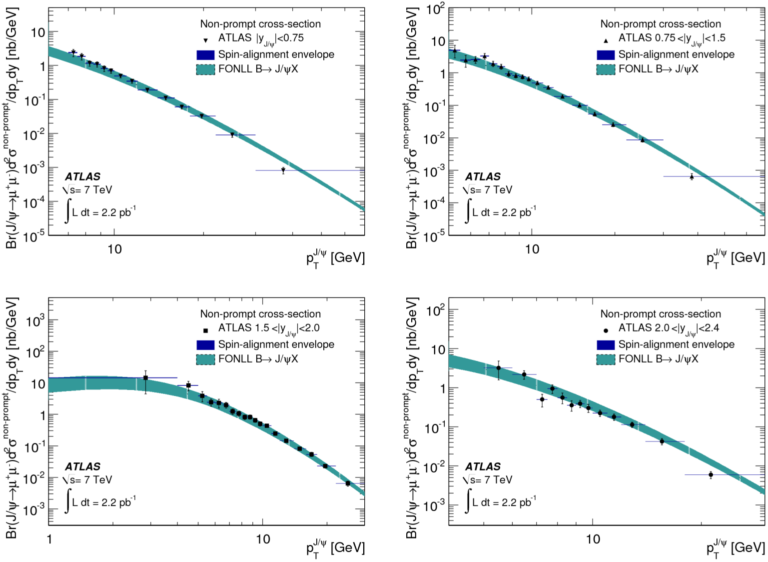




Inclusive $J/\Psi \to \mu^+\mu^-$: prompt fraction results



Inclusive $J/\Psi \to \mu^+\mu^-$: non-prompt cross section



Inclusive $J/\Psi \to \mu^+\mu^-$: prompt cross section