Heavy flavour production at ATLAS: open beauty and onia

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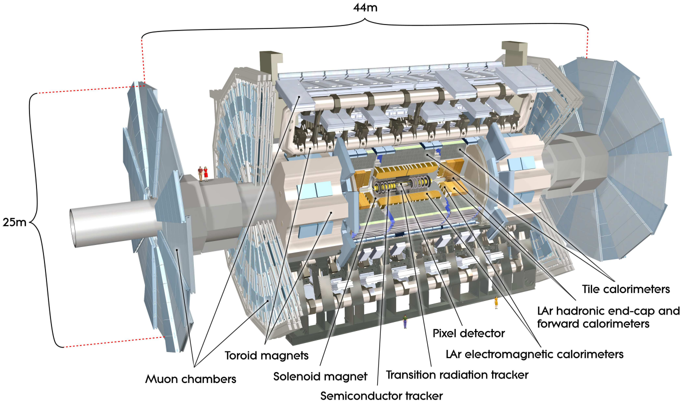
Introduction

- The ATLAS detector
- Open beauty production:
  - b-hadron production cross-section from $D^{\star}\mu X$ final states
  - B^{+} production cross-section from $J/\psi K$ final states
- Onia production:
  - J/ψ differential cross section, and prompt/non-prompt separation.
  - Inclusive $\Upsilon(nS)$ differential cross sections and ratios.
- Conclusions

Detector overview

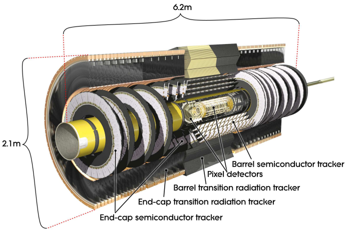


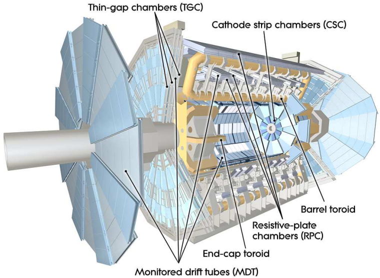
ATLAS is a general purpose detector, designed to be sensitive to a wide range of physical phenomena: SM rediscovery, Higgs, SUSY, BSM,... also flavour physics (high precision in tracking, muon and trigger systems)

Inner Detector and Muon Spectrometer

Inner Detector

- 2 T solenoidal magnetic field
- Pixel detector ($|\eta| < 2.5$): resolution 10/115 μm in $R\phi/z$
- SemiConductorTracker ($|\eta| < 2.5$): resolution 17/580 μm in $R\phi/z$
- TransitionRadiationTracker ($|\eta| < 2$): resolution 130 μm in $R\phi$
- $\sigma(p_T)/p_T \sim 0.05\% p_T(GeV) \oplus 1\%$





Muon Spectrometer

- Toroidal magnetic field: bending power 1.5-5.5 Tm (barrel) and 1-7.5 Tm (end-cap)
- Precision chambers (Monitored Drift Tubes MDT, Cathode Strip Chambers CSC)
- Fast Trigger layers (Resistive Plate Chambers RPC, Thin Gap Chambers TGC)
- $|\eta| < 2.7$, $\sigma(p_T)/p_T \sim 10\%$ up to 1 TeV

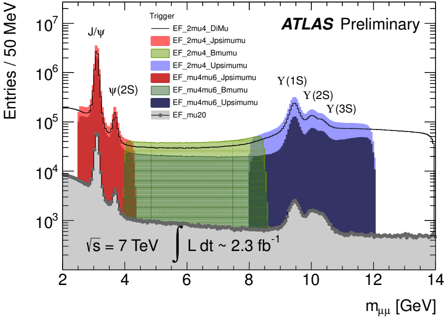
B-physics triggers

ATLAS has a 3-level trigger system (L1 - hardware, L2/EF - software) to reduce the rate from 40 MHz to $\mathcal{O}(200)$ Hz.

B-physics triggers based on single and di-muons:

- Topological triggers: two L1 muons refined at HLT (good vertex and mas cut)
- TrigDiMuon triggers: require one L1 muon and the search for a second muon in ID tracks

In 2011 and 2012 lower threshold, on both muons, at 4 GeV.



b-hadron production at LHC

Motivation:

- The production of heavy quarks at hadron colliders provides a challenging test of QCD predictions.
- b-hadron production cross section has been predicted at NLO accuracy for long time.
- b-hadrons are important backgrounds for many new physics searches, therefore a better understanding of their production is crucial.

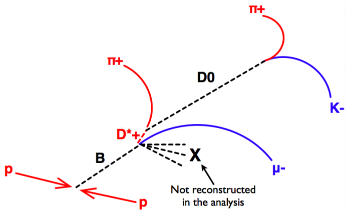
$H_b \to D^\star\mu$: candidates selection

Nucl. Phys. B864 (2012) 341-381

Data sample: $\int \mathcal{L}dt = 3.3\ pb^{-1}$ (2010, 7 TeV)

Selection:

- Trigger on muons with $p_T > 6\ GeV$.
- Fit oppositely charged tracks pairs with $p_T > 1\ GeV$ to common vertex to form the D^0 candidate
- Combine D^0 candidate with a track of opposite charge to the kaon candidate track with $p_T > 250\ MeV$ to form the $D^\star$ candidate.
- Select the $D^\star$ candidate
  - $p_T(D^\star) > 4.5\ GeV$
  - $|m(K\pi) - m(D^0)| < 64(40)\ MeV$ if $|\eta| > 1.3$ and $p_T(D^\star) > 12\ GeV$(elsewhere)
- Fit D^0-vertex and b-vertex simultaneously.
- Select the B candidate if $2.5\ GeV < m(D^\star\mu) < 5.4\ GeV$.



$H_b \to D^\star\mu$: analysis method

$$\frac{d\sigma(pp \to H_b X \to D^\star \mu X')}{dp_T(dy)} = \frac{f_b N^{D^\star\mu}}{2\epsilon \mathcal{B} \mathcal{L} \Delta p_T (\Delta y)}$$

- $N^{D^\star\mu}$: number of reconstructed $D^\star\mu$ pairs
- f_b: fraction of $D^\star\mu$ candidates from a single b decay (MC)
- ϵ: reconstruction, trigger and selection efficiency
- $\mathcal{L}$: integrated luminosity of the collected data sample
- $\mathcal{B}$: total branching ratio $\mathcal{B}(D^\star \to D^0\pi)\mathcal{B}(D^0 \to K\pi)$
- factor 2: $N^{D^\star\mu}$ counts both $D^{\star+}\mu^-$ and $D^{\star-}\mu^+$

Unfolding is used to account for kinematics of the missing particles and obtain:

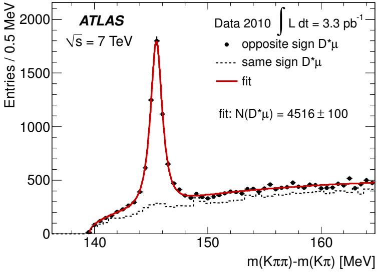
$$\frac{d\sigma(pp \to H_b X \to D^\star \mu X')}{dp_T(dy)}$$

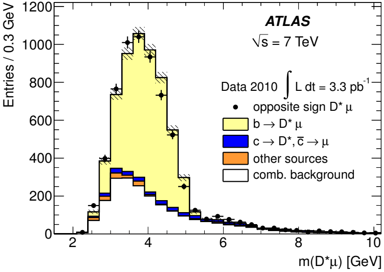
Acceptance corrections and branching ratio $\mathcal{B}(b \to D^\star \mu X)$ are used to obtain:

$$\frac{d\sigma(pp \to H_b X)}{dp_T(dy)}$$

$H_b \to D^\star\mu$: reconstructed candidates

B candidates identified as opposite sign $D^\star\mu$ excess in the $D^\star$ invariant mass distribution.



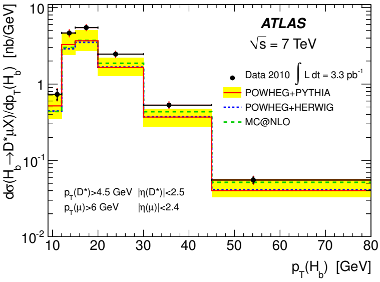


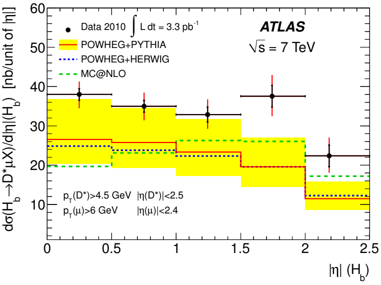
Signal composition shown in the $D^\star\mu$ invariant mass distribution.

Measured cross section $\sigma(pp \to H_b X \to D^\star \mu X)$

$\sigma(H_b \to D^\star \mu X)$ measured in the kinematic intervals:

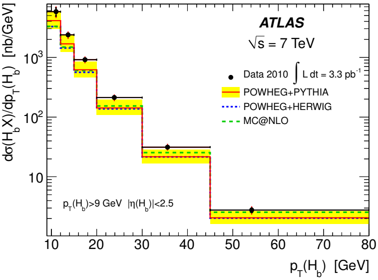
$p_T(D^\star\mu) > 4.5\ GeV\ |\eta|(D^\star\mu) < 2.5$
$p_T(\mu) > 6\ GeV\ |\eta|(\mu) < 2.4$

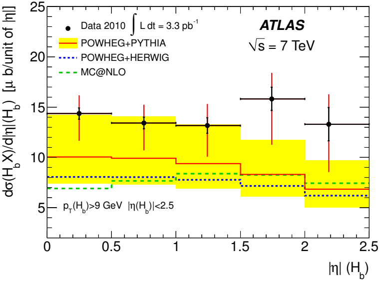




Unfolded cross section $\sigma(pp \rightarrow H_b X)$

- Unfolded distributions: correct p_T and η distributions with MC to account for the kinematics of X.
- Correct with branching fraction $\mathcal{B}(H_b \rightarrow D^\star \mu)$.
- Decay acceptance evaluated with POWHEG+PYTHIA NLO.





$p_T(H_b) > 9\ GeV\ |\eta|(H_b) < 2.5$

Hint of underestimation by NLO QCD predictions (though covered by theoretical uncertainties).

Total cross section $\sigma(pp \rightarrow H_b X)$

Extrapolate to full phase space

ATLAS

$\sigma(pp \rightarrow H_b X) = 360 \pm 9(stat) \pm 34(syst) \pm 25(Br) \pm 12(Lumi) \pm 77(ext.+acc.)\mu b$

LHCb[1]

$\sigma(pp \rightarrow H_b X) = 284 \pm 20(stat) \pm 49(syst)\mu b$

(LHCb result doesn't include extrapolation uncertainty)

Results are compatible.

[1] [Phys. Lett. B694 (2010) 209]

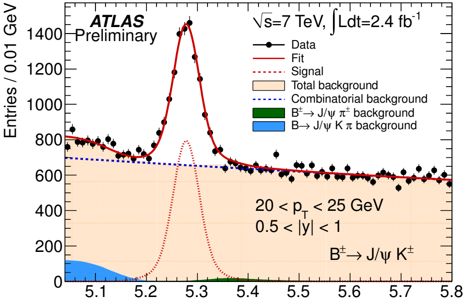
$B^\pm \to J/\psi K^\pm$: candidates selection

ATLAS-CONF-2013-008

Data sample: $\int \mathcal{L}dt = 2.4\ fb^{-1}$ (2011, 7 TeV)

Selection:

- Muon tracks of a selected J/ψ candidate with mass in the range [2.7,3.5] GeV are fitted to a common vertex with an additional charged track of $p_T > 1$ GeV.
- Retain $B^\pm$ candidate if $p_T > 9$ GeV and $|y| < 2.3$.



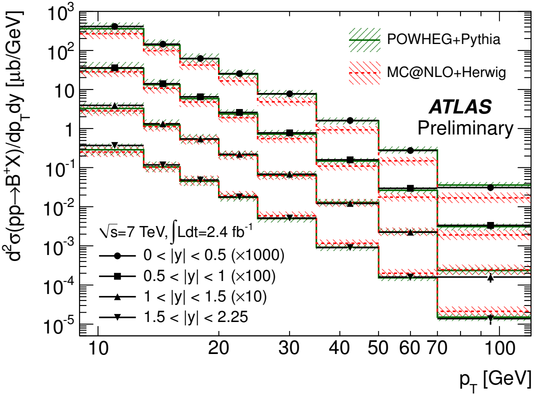
$B^{\pm} \to J/\psi K^{\pm}$: cross-section

Differential cross-section:

$$\frac{d\sigma(pp \to B^{+}X)}{dp_T dy} = \frac{N_{reco}^{B^{\pm}}}{A(\epsilon^{B^{+}} + \epsilon^{B^{-}})\mathcal{B}\mathcal{L}\Delta p_T \Delta y}$$

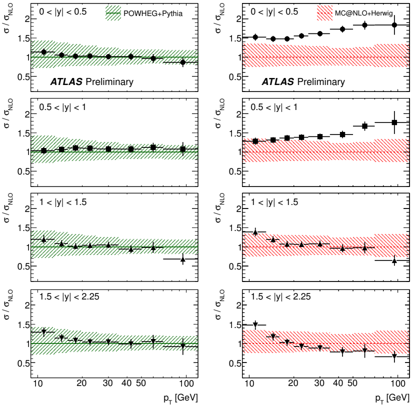
- $N_{reco}^{B^{\pm}}$:number of reconstructed signal events
- A: kinematic acceptance
- $\epsilon^{B^{\pm}}$: efficiency reconstruction for signal events
- $\mathcal{L}$: integrated luminosity of the collected data sample
- $\mathcal{B}$: total branching ratio

$B^{\pm} \to J/\psi K^{\pm}$: cross-section



POWHEG+PYTHIA: good agreement in absolute scale and in the dependence of p_T and y
MC@NLO+HERWIG: predicts lower production cross section and softer p_T spectrum than the one observes in data, which becomes harder for $|y| > 1$.

$B^\pm \to J/\psi K^\pm$: cross-section



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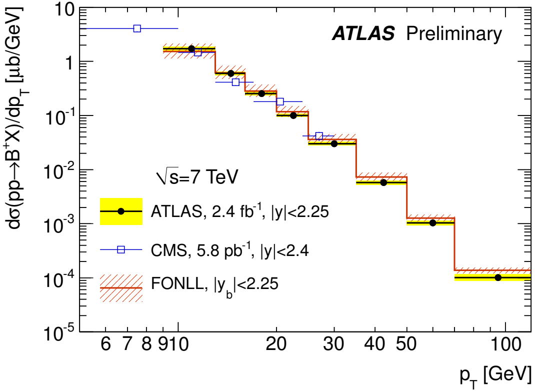


FONLL[2] (with $f_{b\to B^+} = (0.401 \pm 0.013)$) is in good agreement with the measured $d\sigma/dp_T$.

Results also in good agreement with CMS.

[2] Fixed-Order-Next-to-Leading Logarithm

Quarkonia production at LHC

- Test of perturbative QCD in a new energy region
- Production mechanism not well understood (*Color Singlet* vs *Color Octet*)
- Quarkonia production occurs through
    - Prompt production: direct production or feed-down from higher quarkonium states
    - Non-prompt production: from decays of B hadrons (J/ψ only)
- Di-muon decay channels are easy to reconstruct and trigger and hence constitute also an important tool for testing the detector performance.

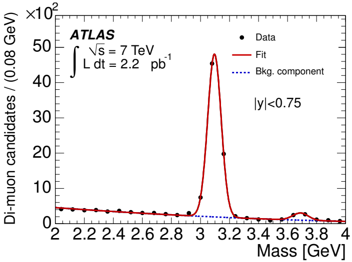
J/ψ inclusive cross-section

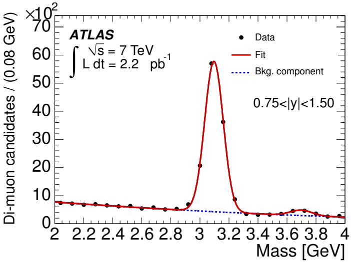
Nucl. Phys. B 850 (2011) 387-344

Data sample: $\int \mathcal{L}dt = 2.3\ pb^{-1}$ (2010, 7 TeV)

Event selection:

- Two reconstructed muons with ID track of opposite charges
- At least one of the muons had to be combined





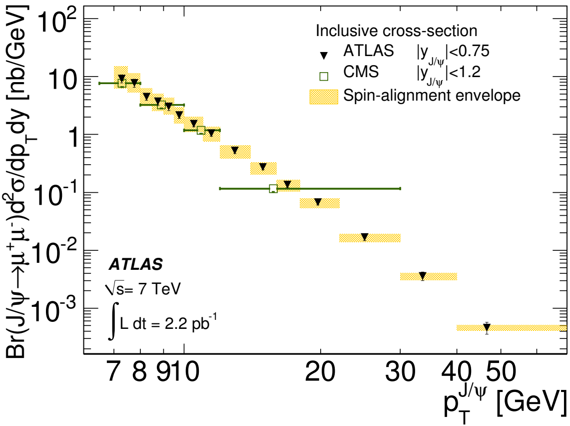
J/ψ inclusive cross-section

Differential cross-section:

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

- $N_{corr} = \sum w^{-1} N_{reco}$, $w^{-1} = AN\epsilon^2_{trk}\epsilon^+_\mu(p_T,\eta)\epsilon^-_\mu(p_T,\eta)\epsilon_{trig}$ where A is the detector acceptance, N takes into account bin migration effects, ϵ is the reconstruction efficiency (tag-and-probe) on data ϵ_{trig} is the trigger efficiency.
- $\mathcal{L}$: integrated luminosity of the collected data sample
- $\mathcal{B}$: total branching ratio

J/ψ inclusive cross-section



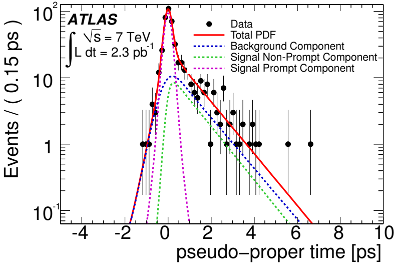
- Variation due to 5 extreme spin alignment scenarios
- Agreement with CMS [and also with their updated results on 37 pb^{-1} (JHEP 02 (2012) 011)]

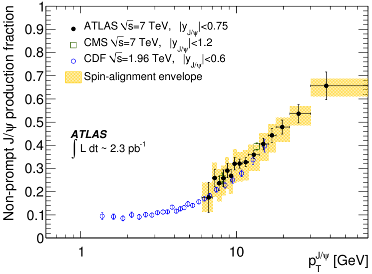
J/ψ measurement of non-prompt fraction

Pseudo-proper time:

$$\tau = \frac{L_{xy}\, m(J/\psi)}{p_T(J/\psi)}$$

- Simultaneous fit to mass and τ to extract the non-prompt fraction in each J/ψ signal slice.



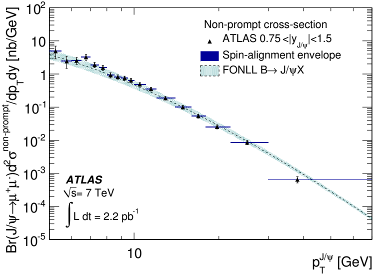


- No dependence on the centre of mass energy but strong dependence on p_T.

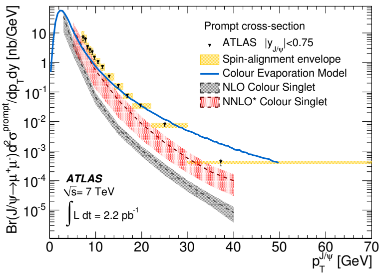
Measurement of non-prompt/prompt J/ψ cross-section

Once both inclusive cross section and the non-prompt fraction are available they can be combined to extract prompt and non-prompt cross sections.

Non-prompt J/ψ cross-section



Prompt J/ψ cross-section



- Non-prompt cross-section agrees well with FONLL predictions
- Color Evaporation Model shape not quite in agreement
- NLO Color Singlet Model (CSM) predictions disagree with data
- NNLO* CSM describe the data better but still underestimate the data at high p_T.

$\Upsilon(1S, 2S, 3S)$ candidate selection

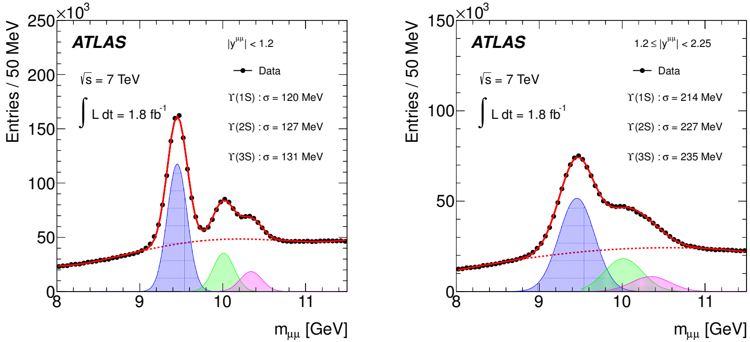
Phys. Rev. D 87 (2013) 052004

Data sample: $\int \mathcal{L}dt = 1.8\ pb^{-1}$ (2011, 7 TeV)

[improvement and extension of the studies on the $\Upsilon(1S)$ from earlier paper]

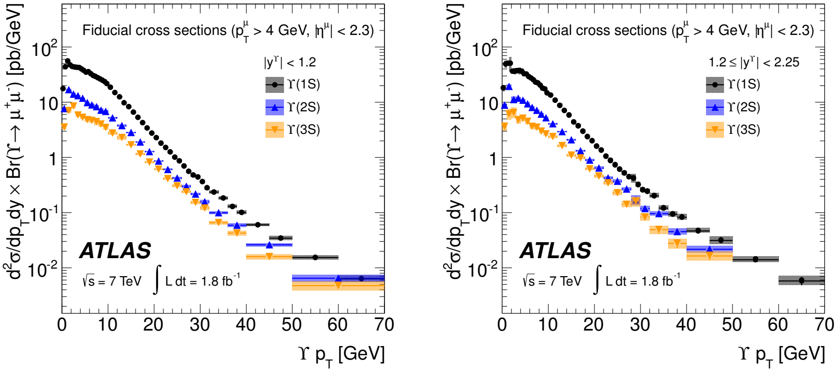
Selection:

- Two combined muons (ID track + Muon spectrometer track) with $p_T > 4$ GeV



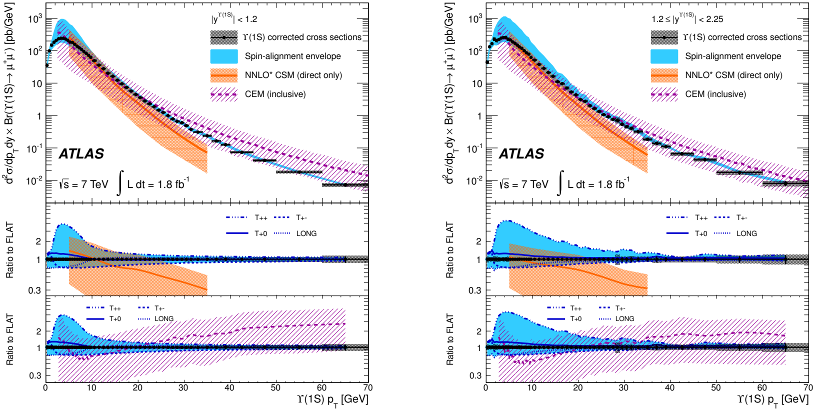
$\Upsilon(1S, 2S, 3S)$ cross-section

- Cross-section measured (with a method similar to one used for J/ψ cross-section) in the fiducial region of the ATLAS dector.



$\Upsilon(1S, 2S, 3S)$ cross-section

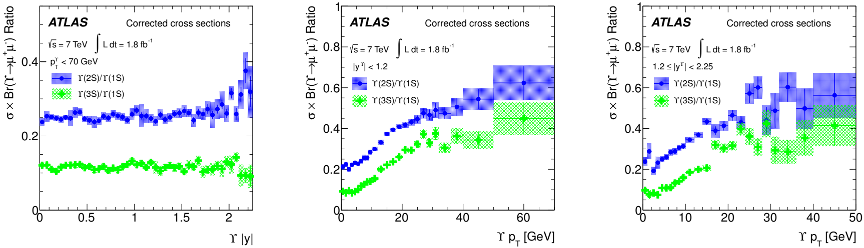
- Differential cross-sections corrected by the di-muon branching fraction and extrapolated to the full phase space



CSM: Color Singlet Mechanism (direct production), CEM: Color Evaporation Model (inclusive prediction)

$\Upsilon(1S, 2S, 3S)$ cross-section ratios

- Observed $\Upsilon(1S)$ cross-section is a sum of prompt production and feed-down from other states
- Ratio of cross-section flat across the rapidity range, relatively constant in the p_T interval $[0, 5]$ GeV, then steady increase up to 30-40 GeV (saturation)



In agreement with CMS [(Phys. Rev. D83 (2011)] and finer binning, extension to higher p_T's and reduced uncertainties.

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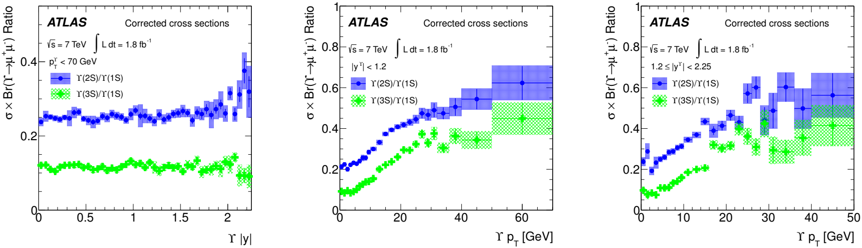

- The naive theoretical picture currently available in fixed order calculations is not able to describe the p_T dependence (CSM predicts $\Upsilon(2S)/\Upsilon(1S) \sim 36\%$ and $\Upsilon(3S)/\Upsilon(1S) \sim 29\%$ flat).
- The variation is expected to be due to the contribution to the total rate from prompt $\chi_b(nP) \to \Upsilon(nS) + \gamma$ decays which has (apparently) a non-trivial p_T dependence to the overall contribution to inclusive Υ production. These ratios offer an indirect way to study the production rate of the χ_b (very difficult to measure directly).

Conclusions

- Heavy flavor and quarkonia program at ATLAS has produced impressive and competitive results.
- Presented results in:
  - b-hadron production in $D^\star\mu$ final state
  - B^+-hadron production in $J/\psi K^+$ final state
  - J/ψ prompt/non-prompt production
  - $\Upsilon(nS)$ production and ratios
- Data/Theory comparison
  - Few production measurements in tension with the corresponding theory predictions, although in agreement within uncertainties.
  - Naive models (CSM) already failing to describe details of the measurements ($\Upsilon(nS)$ ratios).
- Aim at continuing improving the understanding of heavy flavor and quarkonia hadroproduction and theory-experiment convergence. Analyses in the pipeline:
  - New results on B, J/ψ and χ production.
  - Associated production of quarkonia and vector bosons.

Backup

Systematics on NLO QCD predictions for $\sigma(pp \to H_b)$ ($D^\star\mu$ analysis)

- Scale uncertainty, determined by varying μ_r and μ_f independently to $\mu/2$ and 2μ, with the additional constraint $1/2 < \mu_r/\mu_f < 2$, and selecting the largest positive and negative variations.
- m_b uncertainty, determined by varying the b-quark mass (4.75 GeV) by $\pm$ 0.25 GeV.
- PDF uncertainty, determined by using the CTEQ6.6 PDF error eigenvectors; the total uncertainty is obtained by varying each parameter independently within these errors and summing the resulting variations in quadrature
- Hadronisation uncertainty, determined in PYTHIA by using the Peterson fragmentation function instead of the Bowler one, with extreme choices of the b-quark fragmentation parameter: $b = 0.002$ and $b = 0.01$.