Onia and onia-like states at LHCb

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On behalf of the LHCb Collaboration
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Outline

• $J/\psi$ production in pp collisions
• $\Upsilon(nS)$ production
• $J/\psi$ production in pPb/Pbp collisions
• $J/\psi$ polarisation
• $\chi_c$ production
• Conclusions and outlook
Heavy quarkonium production models

Heavy quarkonium states provide powerful tests on QCD models both at perturbative and non-perturbative level
Several models available for the description of production mechanisms:

- **Colour Singlet (CS) Model**
  - Quarkonia are produced as observable color-neutral QQ pairs
  - Poor description of production rates at high \( p_T \)
  - Including large corrections at NLO and NNLO* (subset of NNLO) gives better agreement

- **NRQCD** (non relativistic QCD) model
  - Factorizes the short distance coefficients (calculated perturbatively) from long-distance matrix elements (assumed to be process independent) which include CS and Colour Octet (CO) amplitudes.
  - Good description of data on cross-sections but not of polarization

- **FONLL** (Fixed Order Next to Leading Log) formalism
  - Used in this context to describe quarkonium production from b-hadron decays
  - Combines Fixed Order Calculation (FO) with all order resummation of Leading and NL Logs (NLL)
J/ψ and Y(nS) production in pp collisions

- Select decays of J/ψ and Y(nS) into muon pairs

- Measurement of the double differential production cross-section in bins of $y$ and $p_T$
  - $0 < p_T < 14$ GeV/c; $2.0 < y < 4.5$ (J/ψ)
  - $0 < p_T < 15$ GeV/c; $2.0 < y < 4.5$ (Y(nS))

- Prompt J/ψ and J/ψ from b decays components separated using pseudo-proper time:
  $$ t_z = (z_{J/ψ} - z_{PV}) \times M_{J/ψ}/p_Z $$

- Signal extraction:
  - Simultaneous fit to $m_{μμ}$ and $t_z$ in each ($p_T, y$) bin for J/ψ
  - Fit to $m_{μμ}$ in each ($p_T, y$) bin for Y(nS)
J/ψ production at √s = 8 TeV

• Large selected sample: 2.6x10^6 J/ψ in 18 pb^{-1} at √s = 8 TeV

Also published this year:
• Results at √s = 2.76 TeV (JHEP 06 (2013) 064, JHEP 02(2013) 041)
• Updated cross-section measurement at √s = 7 TeV including polarization results
  ★ arXiv:1307.6379
**J/ψ production at √s = 8 TeV: results**

- Results at √s = 8 TeV
- Assume zero polarization

\[
\sigma(\text{prompt } J/\psi, p_T < 14 \text{ GeV}/c; 2.0 < y < 4.5) = 10.94 \pm 0.02 \pm 0.79 \text{ µb}
\]

\[
\sigma(\text{J/ψ from } b, p_T < 14 \text{ GeV}/c; 2.0 < y < 4.5) = 1.28 \pm 0.01 \pm 0.11 \text{ µb}
\]

Systematic uncertainty ~ 7% dominated by luminosity and trigger efficiency

\[
\sigma(pp \rightarrow b\bar{b}X) = \frac{\sigma(J/\psi \text{ from } b, p_T < 14 \text{ GeV}/c, 2.0 < y < 4.5)}{2B(b \rightarrow J/\psi X)}
\]

\[
\sigma(pp \rightarrow bbX) = 298 \pm 2 \pm 36 \text{ µb}; \quad \alpha_{4\pi} = 5.4
\]
Prompt $J/\psi$ signal include feed down from higher quarkonium states (e.g. $\sim20\%$ from $\chi_c \to J/\psi \gamma$; $\sim8\%$ from $\psi(2S) \to J/\psi \pi\pi$)

- Feed down not included in theory
- Prompt $J/\psi$ in good agreement with NLO NRQCD

NLO CSM:
Campbell, Maltoni, Tramontano
PRL98(2007)252002

NLO NRQCD:
Butenschoen, Kniehl
PRD 84 (2011) 05150,
PRL 106 (2011) 022003

NNLO* CSM:
Artoisenet, Campbell, Lansberg, Maltoni, Tramontano
EPJC61(2008)693
J/ψ production at $\sqrt{s} = 8$ TeV: results

Results at $\sqrt{s} = 8$ TeV

Excellent agreement with theory for J/ψ from b

FONLL CSM:
Cacciari et al. PLB 718 (2012) 431
Nason and Greco JHEP 05 (1998) 007
Y(nS) production at √s = 8 TeV

- previous measurements at 7 TeV (EPJ C72 (2012) 2025)
- measure double differential cross sections $x B^{iS} \equiv B(\Upsilon(iS) \rightarrow \mu\mu)$, $i=1,2,3$

\[
\begin{align*}
\sigma(p\bar{p} \rightarrow \Upsilon(1S)X) \times B^{1S} & = 3.241 \pm 0.018 \pm 0.231 \text{ nb}, \\
\sigma(p\bar{p} \rightarrow \Upsilon(2S)X) \times B^{2S} & = 0.761 \pm 0.008 \pm 0.055 \text{ nb}, \\
\sigma(p\bar{p} \rightarrow \Upsilon(3S)X) \times B^{3S} & = 0.369 \pm 0.005 \pm 0.027 \text{ nb},
\end{align*}
\]
Y(nS) production at $\sqrt{s} = 8$ TeV: results

- NNLO* CSM gives reasonable agreement
- No feed-down included in theory

NLO CSM: Campbell, Maltoni, Tramontano PRL 98 (2007) 252002
NNLO* CSM: Artoisenet, Campbell, Lansberg, Maltoni, Tramontano PRL 101 (2008) 152001
Summary of production cross-sections at $\sqrt{s} = 7$ TeV

- Impressive amount of results
- Nice complementarity in acceptance among GPDs and LHCb

$\sqrt{s} = 7$ TeV

ALICE: 5.6 nb$^{-1}$
ATLAS: 2.2 pb$^{-1}$
CMS: 37, 36 pb$^{-1}$
LHCb: 5.2, 36, 25 pb$^{-1}$

Note: the lines do not represent any theoretical model; they are added to help guiding the eye through the points
\(J/\psi\) production in pPb/Pbp collisions

- \(\sqrt{s_{\text{NN}}} = 5\ \text{TeV}\)
- \(1.5 < y < 4\ \text{(pA)};\ -5 < y < -2.5\ \text{(Ap)}\)
- \(L \sim 2\ \text{nb}^{-1}\)

A real challenge for LHCb!

arXiv:1308.6729
Prompt $J/\psi$ production suppressed at large $y$; modest suppression seen in $J/\psi$ from $b$

- Reasonable agreement with theoretical models
- Good agreement with ALICE results (arXiv:1308.6726)
J/ψ polarisation: introduction

- Charmonium production still puzzling: many theoretical models available describing well the cross section but not the polarization.

- Experimental results pre-LHC difficult to interpret
J/ψ polarisation: analysis

- Perform full angular analysis to determine polarisation parameters \( \lambda_\theta, \lambda_\phi, \lambda_{\theta\phi} \).

- Data presented in two different polarization frames:
  - Helicity frame (HX)
  - Collin-Soper frame (CS)

- Reference frame invariant parameter \( \lambda_{\text{inv}} = (\lambda_\theta + 3\lambda_\phi) / (\lambda_\theta - \lambda_\phi) \) is also measured.
**J/ψ polarisation: analysis**

- Select $J/ψ → \mu \mu$ decays; selected events include $J/ψ$ from feed-down by higher charmonium states.

- The measurement is performed in bins of $p_T$ and pseudo-rapidity ($y$):
  - $p_T$ bins: 2, 3, 4, 5, 7, 10, 15 GeV/c; $y$ bins: 2.0, 2.5, 3.0, 3.5, 4.0, 4.5

- Prompt $J/ψ$ are separated from those coming from $B$ decays using the pseudo-proper time significance:
  $$S_τ = t_z/\delta t_z < 4,$$
  where $t_z = (z_{J/ψ \text{ vertex}} - z_{J/ψ \text{ PV}}) \times M(J/ψ)/p_Z$

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![Graph 1](LHCb s = 7 TeV)

- $L=0.37 \text{ fb}^{-1}$

![Graph 2](JHEP 06 (2013) 064)

- $L=0.37 \text{ fb}^{-1}$
J/ψ polarisation: results

- Parameters $\lambda_\phi, \lambda_{\phi\phi}$ consistent with $0 \Rightarrow \lambda_{\text{inv}} = \lambda_\theta$

- A small longitudinal polarization is observed. Results in HX and CS are consistent

arXiv:1307.6379
J/ψ polarisation: results

- LHCb results are compatible with NLO NRQCD calculations that include feed down
- Good agreement is also observed with recent measurements from ALICE and CMS (although in a different kinematic region)
- Measurements of ψ(2S) and Υ(nS) polarization to be released soon

\[ \text{arXiv:1307.6379} \]

NLO NRQCD (2): PRL110(2013) 042002

P. Faccioli - QCD @ LHC 2013, 2–6 Sept., DESY, Hamburg
**χ_C production at √s = 7 TeV**

- Ratio $\sigma(\chi_C^2)/\sigma(\chi_C^1)$ sensitive to production models
- Select prompt $\chi_C^j$ in the decay $\chi_C^j \to J/\psi (\to \mu\mu)\gamma$
- Measurement using photons that convert in the detector and applying bremsstrahlung correction
- Measurement with 1 fb$^{-1}$, at $\sqrt{s} = 7$ TeV, in bins of $p_T$ and integrating on rapidity $2.0 < y < 4.5$
- Converted photons allows to resolve $\chi_C^1$ and $\chi_C^2$: lower statistics but better mass resolution

converted photons

non converted photons
χ_c production: results

ArXiv:1307.4285

- First evidence of the χ_c^0 state at a hadron collider with a significance of 4.3σ
- Reasonable agreement with (N)LO NRQCD predictions for p_T > 4 GeV/c
- Systematic uncertainty (~6%) dominated by photon efficiency
- Large uncertainty (not included) from the unknown polarisation of the two χ_c states
Conclusions and outlook

- LHCb is producing a large number of results on heavy quarkonia
- Precise tests of theoretical models
- Complementarity with other LHC experiments makes these results even more valuable
- Many new results in preparation:
  - $\psi(2S)$, $\Upsilon(nS)$, $\chi_c$ polarization
  - $X_b$ cross section
  - Onia pair production;
  - Onia exclusive production and associate production
  - Onia production in pA/Ap
  - Exotic states
  - ...

01.10.13  MeNu 2013  G. Passaleva
Thank you!