Quarkonium Production at LHCb

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Outline

1. Introduction
2. $J/\psi$ and $\Psi(2S)$
3. $\Upsilon(nS)$
4. Double charmonium and open charm production
5. Conclusions
Why do we care about quarkonium?

- Since the first measurements at Tevatron the production of quarkonium states has proved a tough challenge.
- Various models have been proposed at different times and a combination of **Color Octet** and **Color Singlet** mechanisms appear to describe the $p_T$ spectrum and cross-sections measured at Tevatron.
- However the a satisfactory description of polarization remains elusive.

Other observables, **double-charm production**, production in p-Pb interactions etc., have been proposed to solve the puzzle.

- With its high luminosity the production cross-section and possibly the polarization of states such as $\chi_c$, $\chi_b$ might also become available at the LHC.

The interest in the study of heavy flavour production processes is not limited to its theoretical value but it also:

- provides excellent test of p-QCD and MC generators at new energies;
- improves the understanding of heavy flavour background in many searches;
- is an important test of the understanding of the detector.
Good separation of primary and secondary vertices.
Good momentum resolution $\sim 0.5\%$ with $J/\psi$ mass resolution of $\sim 13 \text{ MeV}/c^2$.
Good muon identification: pion $\rightarrow$ muon misidentification $\sim 0.7\%$.
Low $p_T$ triggers:
- $1\mu: p_T > 1.8 \text{ GeV}/c$;
- $2\mu: p_T > 0.56 \text{ GeV}/c$ and $p_T > 0.48 \text{ GeV}/c$.
Rapidity region $2 < y < 4.5$ complementary to the GPD.

Unless mentioned, results presented in this talk are based on the 2010 and/or 2011 7 TeV datasets.
The Analysis Strategy

- Define a fiducial volume in the LHCb acceptance: $2.0 < y < 4.5$ and a maximum for $p_T$ typically between $10 \text{ GeV}/c$ and $20 \text{ GeV}/c$ depending on the analysis.
- Reconstruct the quarkonium decay usually $\rightarrow \mu^+ \mu^-$
- Remove background as much as possible with cuts on the usual kinematic and reconstruction variables.
- Require the decay products triggered the event.
- Subtract the remaining background.
- Apply per-event efficiency corrections, with efficiency determined as much as possible from data.
  - Geometric acceptance;
  - Reconstruction efficiency;
  - Muon identification efficiency.
  - Trigger efficiency;
Prompt $J/\psi$ and $\Psi(2S)$

- **EPJ C71(2011) 1645**
  - $J/\psi \rightarrow \mu^+ \mu^-$
  - 5.2 pb$^{-1}$ from 2010 data

- **EPJ C72(2012) 2100**
  - $\Psi(2S) \rightarrow \mu^+ \mu^-$
  - $\Psi(2S) \rightarrow J/\psi \pi^+ \pi^-$
  - 36 pb$^{-1}$ from 2010 data

$J/\psi$ and $\Psi(2S)$ produced from primary vertex and in secondary decays.

$J/\psi$ also produced from feed-down from higher states.

Secondary decays component removed exploiting pseudo propertime:

$$t_z = \frac{z_{J/\psi} - z_{PV} \times M_{J/\psi}}{p_z}$$
Prompt $J/\psi$ and $\Psi(2S)$ 7 TeV results

- Dominant uncertainty is the unknown polarization affecting efficiency determination.
- Measurement performed in 3 cases assuming unpolarized, fully longitudinal and fully transversal polarization.
  - $\sigma_{prompt}(J/\psi) = 10.52 \pm 0.04 (\text{stat}) \pm 1.30 (\text{sys}^{+1.64}_{-2.20} (\text{pol}) \, \mu\text{b}$ EPJ C71(2011) 1645
  - $\sigma_{prompt}(\Psi(2S)) = 1.44 \pm 0.01 (\text{stat}) \pm 0.12 (\text{sys}^{+0.20}_{-0.40} (\text{pol}) \, \mu\text{b}$ EPJ C72(2012) 2100
- Models describe well the transverse momentum distribution.

<diagram>

NNLO CS: PRL (2008) 152001

NNLO CS (AL): EPJ C61 (2009) 693
NNLO CS+CO (MWC): PRD 84 (2011) 114001
NNLO CS+CO (KB): PRL 106(2011) 022003

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A sample of $0.071 \text{ pb}^{-1}$ collected in 2011 and used to measure the $J/\psi$ cross-section [1].

- Measurement carried out in the kinematic region $p_T < 12 \text{ GeV/c}$, $2 < y < 4.5$.
- $\sigma_{\text{inclusive}}(J/\psi) = 5.6 \pm 0.1(\text{stat}) \pm 0.4(\text{sys}) \mu\text{b}$
- Uncertainty from unknown polarization estimated to be as large as an extra 20%.

![Graph showing $p_T(J/\psi)$ vs.Candidates/(2 MeV/c²)](image1)

![Graph showing $d\sigma/dp_T$ vs. $p_T(J/\psi)$ in nb/(GeV/c)](image2)
Non-prompt $J/\psi$ and $\Psi(2S)$

- The 7 TeV data analysis provides a measurement of the cross-section of $J/\psi$ and $\Psi(2S)$ from B hadrons.
- Transverse momentum distributions in good agreement with FONLL predictions.

$\sqrt{s} = 7$ TeV

$\frac{d\sigma}{dp_T}$ [nb/(GeV/c)]

FONLL: JHEP 05 (1998) 007

$J/\psi$ from B hadrons cross-section is measured at 2.76 TeV:

$$\sigma_{secondary}(J/\psi) = 400 \pm 35(stat) \pm 49(sys)\text{nb}$$

Good agreement with theoretical prediction: $370^{+120}_{-110}$ nb JHEP 05 (2021) 137.
$\Upsilon(nS)$ at 7 TeV

- $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ reconstructed in the $\mu^+\mu^-$ channel from a 25 pb$^{-1}$ sample EPJC 72 (2012) 2025.
- Cross-sections measured in the range: $p_T < 15$ GeV/$c$, $2 < y < 4.5$.
Analysis carried out on the 36 pb$^{-1}$ collected in 2010 PLB 707 (2012) 52-59.

Cross section measured in the region $p_T < 10$ GeV/c, $2 < y < 4.5$.

First observation of double $J/\psi$ production at hadronic collider.

Cross-section measured to be $\sigma = 5.1 \pm 1.0 \pm 1.1$ nb.

In agreement with theoretical prediction of $\sigma = 4$ nb PRD 84 (2011) 094023.
Double $J/\psi$ + open charm

$J/\psi$ + one of: $D^0$, $D^+$, $D_s^+$, or $\Lambda_c$
reconstructed in 355 pb$^{-1}$ collected in 2011 JHEP 02 (2012) 141.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield</th>
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<tbody>
<tr>
<td>a)</td>
<td>$J/\psi \ D^0$</td>
</tr>
<tr>
<td>b)</td>
<td>$J/\psi \ D^+$</td>
</tr>
<tr>
<td>c)</td>
<td>$J/\psi \ D_s^+$</td>
</tr>
<tr>
<td>d)</td>
<td>$J/\psi \ \Lambda_c^+$</td>
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$J/\psi + D^0$. 
Open charm + open charm

- Any pair of $D^0$, $D^+$, $D_s^+$, $\Lambda_c$ reconstructed in 355 pb$^{-1}$ collected in 2011 JHEP 02 (2012) 141.
- Both same sign and opposite sign considered.
- Opposite sign yields between $\sim 10^4$ and $\sim 200$ events.
- Same sign yields between $\sim 10^3$ and $\sim 50$ events.

Cross-section ratios compared to Double Parton Scattering expectations based on Tevatron results.
The $J/\psi$ $p_T$ spectrum appears to be harder when accompanied by another charm.

On the contrary the single open charm spectrum is harder than the double open charm one.
The azimuthal angle difference between the $J/\psi$ and the open charm or between two same sign open charm does not show a correlation.

On the contrary the distribution for opposite sign OC+OC shows a peak at $\Delta \Phi \to 0$ suggesting a $g \to c\bar{c}$ splitting contribution.
Conclusions

- LHCb has successfully run during the first data taking collecting a wealth of $c\bar{c}$ and $b\bar{b}$ candidates.
- Many interesting results have already been produced including:
  - Cross-section measurements;
  - First observations;
  - First suggestions of the relevance of DPS.
- Work is currently ongoing to provide measurement of
  - Production cross-sections of other states;
  - Quarkonium polarization;
  - Differential cross-sections of double $J/\psi$ states.
- So don’t miss this workshop in 2014!