Quarkonium Production @ LHCb

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The LHCb Experiment

conceived for CP violation and rare decays in the heavy flavour sector

single–armed forward spectrometer covering the rapidity range where most $b\bar{b}$ pairs are produced

Can study quarkonia production in unique rapidity range at the LHC energy frontier
The LHCb Detector

optimized for B meson decays: emphasis on vertexing, p resolution, PID, trigger

Muon ID eff: ~ 97 %
Mis-ID ($\pi\rightarrow\mu$) 1-3 %

J/ψ Mass
$\sigma=14.6$ MeV/c$^2$

Momentum resolution:
$\sigma(p)/p \sim 0.4\%$ (5 GeV/c)
$0.6\%$ (100 GeV/c)

Vertex resolution for average mult. (25 tracks):
$\sigma_{x,y} \sim 15 \mu$m
$\sigma_z \sim 70 \mu$m
robust and flexible design
very low $p_T$ cuts!
Half of bandwidth for (di)muon lines!
bandwidth increase in 2012 thanks to farm upgrade and deferred trigger
A Quarkonium Mine

Dimuon mass spectrum after 48 hours of data taking at the current luminosity

\[ \mathcal{L} = 4 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1} \]

LHCb Preliminary 70 pb\(^{-1}\) \(\sqrt{s} = 7 \text{ TeV}\)
**LHCb data samples**

2010: 37 pb$^{-1}$, low luminosity, Minimum Bias triggers

2011: 1100 pb$^{-1}$

2012: $\sqrt{s} = 8$ TeV
currently 400 pb$^{-1}$, aim at 1500
Measuring production (and soon polarization) of $c\bar{c}$ and $b\bar{b}$ states

- tests QCD production models:
  - Color Singlet (CS) model vs Color Octet (CO) contributions
  - $J/\psi$, $\psi(2S)$
  - $\chi_c/J/\psi$
  - $\Upsilon(nS)$

- the $B_c$ meson
  - test QCD in unique meson made from 2 pairs of heavy quarks

- double $J/\psi$ and double charm production
  - probe of double parton scattering, possible contributions from tetraquarks, . . .

- unpredicted $X$ states: $X(3872)$ and the mysterious $X(4140)$
Charmonium/Bottomonium to $\mu^+\mu^-$

- Production rates of $J/\psi$, $\psi(2S)$, $\Upsilon(nS)$ ($n=1,2,3$) measured from the 2010 data.

- High efficiency of dimuon channels: $\epsilon_{tot} > 40\%$ (including acceptance, trigger, reconstruction and selection) for high $p_T (> 10\text{ GeV}/c)$ and $2 < \eta < 4.5$.

- Mass resolution: $\sim 15\text{ MeV}/c^2$ for $J/\psi$, $\sim 50\text{ MeV}/c^2$ for $\Upsilon(1S)$.

- For charmonium, prompt production separated from $b$ decays using pseudo proper time:

$$t_z = \frac{(z_{J/\psi} - z_{PV}) m_{J/\psi}}{p_z}$$

- Limited by systematics: largest error from the unknown polarizations (10 – 20\%).
Production cross sections assuming unpolarized states

\[ \frac{d^2 \sigma (J/\psi)}{dp_T dy} \]

\[ \psi(2S) \]

\[ J/\psi \]

\[ \Upsilon(1S) \]

\[ \Upsilon(2, 3S) / \Upsilon(1S) \]

\[ LHCb: \text{arXiv:1202.6579} \]

\[ CMS: \text{Phys.Rev.D83:112004,2011} \]
Comparison with theory

- as already seen by Tevatron, production is larger by 2 orders of magnitude than LO CSM predictions.
- better agreement with N(N)LO CSM calculations
- remarkable agreements with NRQDC calculations including CO, and FONLL formalism for $b \to Q$
χc Production

- radiative decays with low–pT γ: challenging!
- measure $\sigma(\chi_c \rightarrow J/\psi \gamma)/\sigma(J/\psi)$, mostly due to $\chi_{c1,2}$, using calorimeter system for γ identification and energy reconstruction
- $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ seems larger than any prediction
- result confirmed using photons converted in tracker (lower statistics, better mass resolution)
Polarization

- polarization in helicity frame

\[
\frac{dN}{dcos\theta d\phi} \propto 1 + \lambda_\theta \cos^2 \theta + \lambda_\phi \sin^2 \theta \cos 2\phi + \lambda_\theta\phi \sin^2 \theta \cos \phi
\]

- improve accuracy on cross sections, but also
critical test for production models: sizeable \(J/\psi\) polarization predicted by COM not observed by CDF!

- strategy: extract \(\lambda_\theta, \lambda_\phi, \lambda_\theta\phi\) from unbinned ML fit in bins of \(\eta, p_T\)

\(J/\psi\) result expected soon
The $B_c$ meson

- Quarkonium-like state made of $b\bar{c}$ (or c.c.)
- Only ground state observed so far, a rich spectroscopy to be started
- LHCb already provided the world best mass measurement from 2010 data in $B_c^+ \rightarrow J/\psi \pi^+$

![Graph showing $M(J/\psi \pi^+)$ vs. $M(J/\psi \pi^+)$ for LHCb Preliminary data.](image1)

![Graph showing $B_c$ mass spectrum.](image2)
**B_c production**

- **J/ψ π⁺ channel**: preliminary result from 2010 data (CERN-LHCb-CONF-2011-017)

\[
\frac{\sigma(B_c^+ \times B(B_c^+ \rightarrow J/\psi \pi^+))}{\sigma(B^+ \times B(B^+ \rightarrow J/\psi K^+))} = (2.2 \pm 0.8_{\text{stat}} \pm 0.2_{\text{syst}})\% \quad (P_T > 4 \text{ GeV/c, } 2.5 < \eta < 4.5)
\]

to be improved using 2011 data and more precise lifetime measurement (largest systematic)

- **First Observation of B_c^+ → J/ψ π⁺π⁻ π⁺**

using 2011 data  (arXiv:1204.0079)

\[
\frac{\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)} = 2.41 \pm 0.30_{\text{stat}} \pm 0.33_{\text{syst}}
\]

Systematics dominated by uncertainty on decay model

Predictions were ranging from 1.5 to 2.3
**Double J/ψ production**

- Production of double $c\bar{c}$ pair is expected from high order gluon-gluon diagrams, with strong sensitivity to possible CO contributions.

- Could be enhanced by double parton scattering (DPS) and charm content of the proton (IC).

![Graph showing dN(J/ψ J/ψ)/dμ±μ∓ vs m(μ±μ∓)2](image)

- $\sigma(J/ψ J/ψ)$ measured from 2010 data (37.5 pb$^{-1}$) requiring 2 J/ψ from common vertex.

- 141 ± 19 events observed, with average efficiency of 21%
Cross-section result for \( p_T < 10 \text{ GeV/c} \), \( 2 < \eta < 4.5 \)

\[
\sigma(J/\psi J/\psi) = 5.1 \pm 1.0_{\text{stat}} \pm 1.1_{\text{syst}} \text{ nb}
\]

Theoretical predictions:

4.1 \pm 1.2 \text{ nb} from LO CSM

(including feed–down from \( \psi(2S) \))

2 \pm 1 \text{ nb} from double parton scattering

(Berezhnoy et al., Phys.Rev.D84 (2011))

(Novoselov, arXiv:1106.2184)

Look at invariant mass to test production model and possible feed–down from charm tetraquark (low mass) or \( \chi_b \)

Result to be updated with full statistics
Double charm production was also looked at in channels $J/\psi C$ (or $J/\psi \bar{C}$) and $CC$ ($\bar{C}C$)
where $C = D^0(\rightarrow K^-\pi^+)$, $D^+(\rightarrow K^-\pi^+\pi^+)$, $D_{s}^{+}(\rightarrow \phi\pi^+)$, $\Lambda_c^+(\rightarrow pK^-\pi^+)$,
measuring also $C\bar{C}$ states as a reference

predictions from DPS and IC larger by one order of magnitude than LO CSM calculations

if DPS dominates, one would expect

$$\frac{\sigma_{C_1}\sigma_{C_2}}{\sigma_{C_1C_2}} = \frac{\sigma_{DPS}}{\sigma_{eff}} \sim 15 \text{ mb}$$
(from Tevatron multi–jet events)

very clean and large samples obtained from $0.36 \text{ fb}^{-1}$

<table>
<thead>
<tr>
<th>Mode</th>
<th>$S$</th>
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<tbody>
<tr>
<td>$J/\psi D^0$</td>
<td>$4875 \pm 86$</td>
</tr>
<tr>
<td>$J/\psi D^+$</td>
<td>$3323 \pm 71$</td>
</tr>
<tr>
<td>$J/\psi D_{s}^+$</td>
<td>$328 \pm 22$</td>
</tr>
<tr>
<td>$J/\psi \Lambda_c^+$</td>
<td>$116 \pm 14$</td>
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</tbody>
</table>

and 6 $CC$ modes with $> 3\sigma$ SIG.
Cross–section results:

<table>
<thead>
<tr>
<th>LHCb</th>
<th>$D^0\bar{D}^0$</th>
<th>$D^0D^-$</th>
<th>$D^0D_s^-$</th>
<th>$D^0\Lambda_c^-$</th>
<th>$D^+D^-$</th>
<th>$D^+D_s^-$</th>
<th>$D^+\Lambda_c^-$</th>
</tr>
</thead>
</table>

Much larger than LO predictions:


DPS prediction works well for $J/\psi C$ modes!
while $CC$ modes are lower by factor 2 to 3

DPS prediction, Phys.Rev. D56 (1997) 3811
Looking for $X,Y,Z$ states

- $X(3872)$ production from 2010 data ($35 \text{ pb}^{-1}$):
  \[ \sigma (X(3872)) \times B(X(3872) \rightarrow J/\psi \pi^+\pi^-) = 5.4 \pm 1.3_{\text{stat}} \pm 0.8_{\text{syst}} \text{ nb} \]
  for $5 < p_T < 20\text{ GeV/c}$, $2.5 < \eta < 4.5$

- $m_{X(3872)} = 3871.95 \pm 0.48_{\text{stat}} \pm 0.12_{\text{syst}} \text{ MeV/c}^2$
  still unclear if above $DD^*$ threshold or not
  $(m(D^0)+m(D^{*0}) = 3871.79 \pm 0.29 \text{ MeV/c}^2)$

- search for the $X(4140)$ and $X(4274)$ states claimed by CDF (arXiv:1101.6058) with significance $> 5\sigma$ and $3.1\sigma$
- no evidence for such states is found from $0.37 \text{ fb}^{-1}$
  disagreement with CDF is estimated at the $2.4\sigma$ level

## Conclusions and Prospects

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<th>Achieved</th>
<th>much more to come</th>
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<td><strong>Quarkonia</strong></td>
<td>Accurate production measurements of main quarkonia states @7 TeV:</td>
<td>Polarization for J/ψ and others, studies @8 TeV, χb studies</td>
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<td></td>
<td>plenty of inputs for theorists!</td>
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<td><strong>B_c</strong></td>
<td>production in J/ψ π channel and first observation of J/ψ π π π, best mass</td>
<td>updated results, search in new decay modes</td>
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<td>measurement</td>
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<td><strong>Double c̅c̅</strong></td>
<td>Observation of double J/ψ, 4 J/ψ + C and 6 CC modes with high (&gt; 3σ)</td>
<td>updated J/ψ J/ψ result, search for double heavy baryons</td>
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<td>significance, strong hint for DPS!</td>
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<td><strong>New/exotic states</strong></td>
<td>X(3872) production and mass, search for X(4140)</td>
<td>X(3872) from B, search for claimed Z states and for tetra/pentaquarks</td>
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