Experimental results in heavy flavour and onia production.

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On behalf of the LHC Collaborations

5 June 2012 / PLHC 2012
Outline

1. Introduction
2. $J/\psi$ and $\Psi(2S)$
3. $\Upsilon(nS)$
4. Higher mass onia
5. B mesons
6. b-Baryons
7. Double charm
8. Conclusions
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Quarkonium production at hadron colliders has represented a tough challenge since its first evidence. A combination of Color Octect and Color Singlet mechanisms describe the $p_T$ spectrum and cross-sections measured at Tevatron, but the polarization remains elusive.

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

The production cross-section and possibly the polarization of states such as $\chi_c$, $\chi_b$ might also become available.

More in general the study of heavy flavour production processes:
- 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.
The LHC detectors

ATLAS

CMS

ALICE

LHCb

Introduction  $J/\psi$ and $\Psi(2S)$  $\Upsilon(nS)$  Higher mass onia  B mesons  b-Baryons  Double charm  Conclusions
Rapidity range

LHCb

CMS

ATLAS

ALICE

tracking, ECAL, HCAL, counters lumi, muon, hadron PID
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J/ψ production 101

- J/ψ produced in different ways:
  - Prompt production;
  - Feed down from heavier states: χ_c, Ψ(2S);
  - Secondary production from b-hadrons decays.
- Separation of the feed down component, ~ 30-40%, not trivial.

b component separated exploiting the long lifetime of the b-hadrons, selecting on J/ψ proper time.
**J/ψ production cross-section**

- A wealth of results already available
- All results in good agreement with NRQCD calculations.

**ATLAS data vs. CS**

![ATLAS data vs. CS](image1)


**CMS data vs. CS+CO**

![CMS data vs. CS+CO](image2)

LHCb data (5.2 pb\(^{-1}\)) vs. CS+CO

![LHCb data vs. CS+CO](image3)

- The dominant error is the uncertainty on the J/ψ polarization.

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**J/ψ polarization**

ALICE has measured the J/ψ polarization by means of an angular analysis of the muon decay polar and azimuthal angle distribution.

The analysis is carried out both in the Helicity and Collins-Soper frames.

\[
W(\cos \theta) \propto \frac{1}{3 + \lambda_\theta} (\lambda_\theta \cos^2 \theta) \quad W(\Phi) \propto 1 + \frac{2\lambda_\Phi}{3 + \lambda_\theta} \cos 2\Phi
\]
Almost no polarization for inclusive J/ψ

The $\lambda_\theta$ difference between prompt and inclusive J/ψ polarization estimated to be less than 0.05.
Recent result from ALICE: arXiv 1202.2816

The J/ψ yields appear to increase linearly as function of charged particles multiplicity.

Simulation carried out with PYTHIA 6.4.25 and Perugia 2011 tunes does not reproduce the results.
**Ψ(2S) production**

- Ψ(2S) does not suffer from feed-down from higher mass states, all prompt is direct.
- Reconstructed by LHCb (arXiv:1204.1258) and CMS (JHEP 02 (2012) 011) as:
  - Ψ(2S) → μ⁺μ⁻
  - Ψ(2S) → J/ψπ⁺π⁻
The $\Psi(2S)$ cross-section has been measured both at LHC and Tevatron.

Reasonable agreement between data and theory predictions.
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Three states $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ decay to $\mu^+\mu^-$ pairs.

$\Upsilon(1S)$ and $\Upsilon(2S)$ also produced through feed-down from higher mass states.
Reasonable agreement with theory found at LHCb for the 3 \( \Upsilon \) states.

ATLAS measures the production of \( \Upsilon(1S) \) in different \( y \) regions.
First measurement for $\Upsilon(3S)$.

Full angular analysis recently performed at CDF, PRL 108 151802 (2012), in both Helicity and Collins-Soper frame.

No strong longitudinal or transverse polarization in any state.

PRD 63 071501(R) (2001)
PRD 81 111502(R) (2010)
Production of $\chi_c$

- Detected as $\chi_c \rightarrow J/\psi \gamma$
- Energy resolution crucial to resolve the $\chi_{c1}$ and $\chi_{c2}$ states.

CDF PRL 98 (2007) 232001

ATLAS Preliminary

$\sqrt{s} = 7$ TeV

- $2.90 < M(\mu^+\mu^-) < 3.25$ GeV
- $p_T(\gamma) > 10$ GeV, $|y(\gamma)| < 2.4$

$N(\chi_c) = 2960 \pm 120$

$\alpha = 0.962 \pm 0.062$

$\delta = 2.7 \pm 1.9$ MeV

J/$\psi + \gamma$ mass distribution

CMS Preliminary

$\sigma = 9.6 \pm 0.2$ MeV/c$^2$

$m_{\gamma\mu\mu} = 3.502 \pm 0.001$ GeV/c$^2$

$\Delta m_{\text{had}} = 45.6$ MeV/c$^2$

$\Delta m_{\text{det}} = 95.9$ MeV/c$^2$

ATLAS-CONF-2012-136

Entries per 10 MeV/c$^2$

Entries per 5 MeV/c$^2$

Entries / 10 MeV/c$^2$
**\( \chi_c \) cross-section**

- \( \sigma(\chi_c \rightarrow J/\psi \gamma)/\sigma(J/\psi) \) arXiv:1202.1462
- \( \sigma(\chi_{c2})/\sigma(\chi_{c1}) \) measured at LHCb arXiv:1202.1080
- Photons observed in the ECAL or as two converted electrons.
- Results in agreement with NLO CO+CS.
- **NEW** CMS results presented last week at Blois (PAS-BPH-11-010)
**χ_b production**

- Observed by ATLAS, PRL 108 (2012) 152001, as χ_b → Υ(nS) + γ
- First observation of the χ_b(3P) state.
- Photons reconstructed from calorimeter and from conversions.

Observed by LHCb in the 2010 data.
- Only using non converted photons.
- Measurement with converted photons and χ_b ratios coming shortly.
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First observation by CDF in the mode $B_c^+ \rightarrow J/\psi l^+ \nu$

Observed in the $B_c^+ \rightarrow J/\psi \pi^+$ mode by LHCb (LHCB-CONF-2011-027) and ATLAS (ATLAS-CONF-2012-028)

In this mode LHCb measures its mass as

$$M(B_c^+) = 6268.0 \pm 4.0 \pm 0.6 \text{ MeV}/c^2$$

LHCb also observes the mode $B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$ (LHCB-PAPER-2011-044)

The relative branching ratio is measured:

$$\frac{\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)} = 2.41 \pm 0.30 \pm 0.33$$

consistent with theoretical predictions.
Observation of $B_{(s)}^{**}$ mesons

- Observed by LHCb (LHCB-CONF-2011-053)
- Searched in the $B^+\pi^-$, $B^+K^-$ and $B^0\pi^-$ channels.
- The photon from the $B^* \rightarrow B \gamma$ is not reconstructed.
- First direct observation of the $B_1^+$ and $B_2^{**}$ states.

\[
\begin{align*}
M_{B_{s1}^0} &= (5828.99 \pm 0.08)_{\text{stat}} \pm 0.13_{\text{syst}} \pm 0.45_{B\text{mass}} \text{ MeV/c}^2, \\
M_{B_{s2}^0} &= (5839.67 \pm 0.13)_{\text{stat}} \pm 0.17_{\text{syst}} \pm 0.29_{B\text{mass}} \text{ MeV/c}^2, \\
M_{B_1^0} &= (5724.1 \pm 1.7)_{\text{stat}} \pm 2.0_{\text{syst}} \pm 0.5_{B\text{mass}} \text{ MeV/c}^2, \\
M_{B_1^+} &= (5726.3 \pm 1.9)_{\text{stat}} \pm 3.0_{\text{syst}} \pm 0.5_{B\text{mass}} \text{ MeV/c}^2, \\
M_{B_2^0} &= (5738.6 \pm 1.2)_{\text{stat}} \pm 1.2_{\text{syst}} \pm 0.3_{B\text{mass}} \text{ MeV/c}^2, \\
M_{B_2^+} &= (5739.0 \pm 3.3)_{\text{stat}} \pm 1.6_{\text{syst}} \pm 0.3_{B\text{mass}} \text{ MeV/c}^2, \\
Q &= M(B_{(s)0}) - M(B_{(s)}) - M(h) \text{ [MeV/c}^2].
\end{align*}
\]
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**Λ_b cross-section**

- Λ_b differential cross-section \(\sigma(pp \rightarrow \Lambda_b)BR(\Lambda_b \rightarrow J/\psi \Lambda^0)\) recently measured by CMS (arXiv:1205.0594)
- Dependence on \(p_T\) and \(y\) studied, as well as the \(\bar{\Lambda}_b/\Lambda_b\) ratio

![Graphs and plots showing data and theory predictions for Λ_b cross-sections](image-url)
Two narrow states observed at LHCb in the \( \Lambda_b \pi^+ \pi^- \) spectrum (arXiv:1205.3452).

\( \Lambda_b \) reconstructed as \( \Lambda_c^+ \pi^- \)

Masses:

\[
M_{\Lambda_b^0*(5912)} = 5911.05 \pm 0.12 \pm 0.03 \pm 0.66 \text{ MeV}/c^2
\]

\[
M_{\Lambda_b^0*(5920)} = 5919.76 \pm 0.07 \pm 0.02 \pm 0.66 \text{ MeV}/c^2
\]

Width limits at 95% CL:

\[
\Gamma_{\Lambda_b^0*(5912)} < 0.82 \text{ MeV}
\]

\[
\Gamma_{\Lambda_b^0*(5920)} < 0.71 \text{ MeV}
\]

Expected to be \( J^P = 1/2^- \) and \( 3/2^- \) states.
**observation**

- Recently observed at CMS (arXiv:1204.5955)
- First observation of the $\Xi^*_b^+ \rightarrow \Xi_b \pi^+$ decay.
- $M(\Xi^*_b^+) - M(\Xi_b \pi) = 14.84 \pm 0.74 \pm 0.26$ MeV
- Consistent with the theoretical prediction for $\Xi^*_b^+$ and expected to have $J^P = 3/2^+$
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Double charm observation

- $J/\psi + C$ and CC production studied at LHCb in 16 channels (arXiv:1205.0975)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi D^0$</td>
<td>4875 ± 86</td>
</tr>
<tr>
<td>$J/\psi D^+$</td>
<td>3323 ± 71</td>
</tr>
<tr>
<td>$J/\psi D_s^+$</td>
<td>328 ± 22</td>
</tr>
<tr>
<td>$J/\psi \Lambda_c^+$</td>
<td>116 ± 14</td>
</tr>
<tr>
<td>$D^0 D^0$</td>
<td>1087 ± 37</td>
</tr>
<tr>
<td>$D^0 D^+$</td>
<td>10080 ± 105</td>
</tr>
<tr>
<td>$D^0 D^-$</td>
<td>1177 ± 39</td>
</tr>
<tr>
<td>$D^0 D_s^+$</td>
<td>11224 ± 112</td>
</tr>
<tr>
<td>$D^0 D_s^-$</td>
<td>111 ± 12</td>
</tr>
<tr>
<td>$D^0 \Lambda_c^+$</td>
<td>859 ± 31</td>
</tr>
<tr>
<td>$D^0 \Lambda_c^-$</td>
<td>41 ± 8</td>
</tr>
<tr>
<td>$D^0 \Lambda_c^+$</td>
<td>308 ± 19</td>
</tr>
<tr>
<td>$D^+ D^+$</td>
<td>249 ± 19</td>
</tr>
<tr>
<td>$D^+ D^-$</td>
<td>3236 ± 61</td>
</tr>
<tr>
<td>$D^+ D_s^+$</td>
<td>52 ± 9</td>
</tr>
<tr>
<td>$D^+ D_s^-$</td>
<td>419 ± 22</td>
</tr>
<tr>
<td>$D^+ \Lambda_c^+$</td>
<td>21 ± 5</td>
</tr>
<tr>
<td>$D^+ \Lambda_c^-$</td>
<td>137 ± 14</td>
</tr>
</tbody>
</table>

LHCb

Candidates

$J/\psi D^0$
Double charm production

- The \( J/\psi \) \( p_T \) distribution appears to be the same for all species of open charm hadrons.
- Analogously the \( p_T \) distribution of the open charm appear to be the same.
- Fit to the distribution yields results that agree within errors.
- The azimuthal angle and rapidity correlations have been studied too.

Compared to \( gg \rightarrow J/\psi c\bar{c} \) computations

Compared to Double Parton Scattering computations

PRD 57 (1998) 4385
PRD 73 (2006) 074021

arXiv:1105.4105
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Many new results and updates of old results produced since PLHC 2011
My apologies to all those that did not fit in because of time constraints.
Several measurements will be repeated at 8 TeV
Still much to explore:
  - Exotic spectroscopy
  - Polarization measurements
  - $B_c$ physics
  - Double quarkonium
  - Precision measurements
  - ...
Stay tuned for PLHC 2013