Heavy Quarkonia Studies at LHCb

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(for the LHCb collaboration)

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ReteQuarkonii Thematic Day @ IPN (Orsay), 09/02/2010
1. The LHC and LHCb experiment

2. Charmonium
   - $J/\psi$ production
   - $\psi(2S)$, $\chi_c$, $h_c(1P)$, $X(3872)$ and $Z(4430)^\pm$ studies

3. $B_c^\pm$

4. Bottomonium
The Large Hadron Collider (LHC)

- **The LHC experiments**
  - ALICE: dedicated heavy-ion experiment
  - ATLAS and CMS: general purpose detectors
  - LHCb: dedicated $b$-physics experiment
  - LHCf and TOTEM: Forward production of neutral particles & Total Cross Section, Elastic Scattering and Diffraction Dissociation

- **The LHC status**
  - 23/11/2009, first $pp$ collision at $\sqrt{s} = 900$ GeV
  - 30/11/2009, 2 circulating $p$-beams, each at 1.18 TeV
The $b$ production at the LHC

- Correlated production of $b$ and $\bar{b}$, $\sigma_{b\bar{b}} \sim 500 \mu b$

Different momenta of the participating partons: $x_1 \neq x_2$

- $b$, $\bar{b}$ boosted and in same "cone"

⇒ Forward detector (NOT a fixed-target experiment!)
The pileup and the LHCb luminosity

- **Pileup**
  - Inelastic $pp$ interactions in a bunch crossing are Poisson-distributed with mean $n_{pp} = \frac{\sigma_{pp}^{\text{inel}} \cdot L}{\nu_{bx}}$
  - $\sigma_{pp}^{\text{inel}} = 80 \text{ mb}$ for $\sqrt{s} = 14 \text{ TeV}$; $L$ - instantaneous luminosity; $\nu_{bx}$ - bunch crossing rate

- **ATLAS/CMS**
  - Nominal $L = 10^{34} \text{ cm}^{-2} \text{s}^{-1}$, $n_{pp} = 25$

- **LHCb**
  - Low luminosity: $2 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1}$ by not focusing the beam as much as ATLAS/CMS, $n_{pp} = 0.7$
  - $\sim 10^{12} \ b\bar{b}$ per year ($10^7 \text{ s}$)

- **Startup phase**
  - Lower $\sqrt{s}$, low $L$ and very low $\nu_{bx}$
  - $\Rightarrow$ significant pileup
  - similar $L_{\text{int}}$ to each experiment
The LHCb detector

**Geometry acceptance**
(15 - 300) mrad; 1.9 < η < 4.9

**Vertex Locator**
σ_{PV,x/y} ~ 10 µm, σ_{PV,z} ~ 60 µm; σ_{L} ~ 250 µm

**Magnet**
Warm magnet, ~ 4 Tm.

**Tracking system** (TT, T1-T3)
∆ρ/ρ: 0.35%-0.55%, σ_{m}: 12-25 MeV/c^2
The LHCb detector (cont.)

**RICH1 & RICH2**
- $\epsilon(K \rightarrow K) \sim 95\%$, mis-ID rate $(\pi \rightarrow K) \sim 5\%$

**Muon system (M1-M5)**
- $\epsilon(\mu \rightarrow \mu) \sim 94\%$, mis-ID rate $(\pi \rightarrow \mu) \sim 3\%$

**ECAL**
- $\sigma_{E}/E = 10\%/\sqrt{E} \pm 1\% \ (E \text{ in GeV})$

**HCAL**
- $\sigma_{E}/E = (69 \pm 5\%)/\sqrt{E} \pm (9 \pm 2\%) \ (E \text{ in GeV})$
The LHCb trigger system

- **Level-0 Trigger (Hardware)**
  - High $p_T$ $\mu, e, \gamma$, hadron candidates
  - Table:
    | $p_T$ (GeV) | had | $\mu$ | $\mu\mu$ | $e^\pm$ | $\gamma$ | $\pi^0$ |
    |------------|-----|-------|--------|-------|--------|--------|
    | >3.5       | 3.5 | 1     | $\sum > 1.5$ | 2.6   | 2.3    | 4.5    |
  - Efficiency: Muon (90%), Electromagnetic (70%), Hadronic (50%)

- **High Level Trigger (Software)**
  - HLT1: Check L0 candidate with more complete info, add impact parameters and lifetime cuts
  - HLT2: Global event reconstruction + selections (inclusive or exclusive)
  - Efficiency: Muon (80%), Electromagnetic (60%), Hadronic (80%)
The LHCb status

- The LHCb detector is fully installed. First data at $\sqrt{s} = 900$ GeV recorded, analysis ongoing.
- Very preliminary $K^0_S$ and $\Lambda$ mass distributions, real data!

\[ M_{K^0_S} = 497.3 \pm 0.2 \text{ (stat.) MeV/c}^2 \]
\[ \sigma_m = 4.3 \pm 0.1 \text{ (stat.) MeV/c}^2 \]
\[ M_{K^0_S}^{\text{PDG}} = 497.7 \text{ MeV/c}^2 \]

\[ M_{\Lambda} = 1115.6 \pm 0.1 \text{ (stat.) MeV/c}^2 \]
\[ \sigma_m = 1.4 \pm 0.1 \text{ (stat.) MeV/c}^2 \]
\[ M_{\Lambda}^{\text{PDG}} = 1115.7 \text{ MeV/c}^2 \]
The $J/\psi$ was discovered more than 30 years ago, but we still do not understand the underlying production mechanism:

- LO color octet mechanism (COM) can describe the $p_T$ spectrum and cross section of the $J/\psi$ produced at Tevatron, but cannot explain the polarization, NLO doesn’t help.
- The other models, e.g., color evaporation model, $k_T$ factorization, soft color interaction model cannot describe the cross section and polarization simultaneously, either.
- New measurements at the LHCb experiment (higher energy, special $\eta$ coverage) will help resolve this issue.

Large cross section and clear $J/\psi \rightarrow \mu^+ \mu^-$ signal

- $J/\psi$ crucial for detector alignment, calibration, $\mu$-ID and tracking efficiencies measurements, and so on.
- The measurements of the cross sections of the prompt $J/\psi$ and the $J/\psi$ from $b$ decays are important for later analysis in LHCb, e.g., absolute branching fraction measurements, assess event yields.
**J/ψ selection**

- Selection studied with the simulated minimum bias events
  - Loose μ ID selection, loose cuts on $p_T(\mu^\pm)$, $\mu^+$ and $\mu^-$ coming from a common vertex, at least one reconstructed primary vertex
- Expect about $2.8 \times 10^6$ reconstructed $J/\psi$ for 5 pb$^{-1}$ of data at $\sqrt{s} = 7$ TeV
- Very good mass resolution: $\sim 11$ MeV/$c^2$
Separation of prompt $J/\psi$ from $b \rightarrow J/\psi$

- Pseudo-lifetime $t_z$

$$t_z = \frac{dz}{\rho_z^{J/\psi}} m^{J/\psi}$$

- Simple approximation of $b$ lifetime
$t_z$ distribution

- $t_z$ distribution has four components
  - **Prompt $J/\psi$**, peak at 0, Gaussian
  - $J/\psi$ from $b$ decays, Exponential convoluted with Gaussian
  - Background distribution, estimated from mass sidebands
  - Long tail due to association to wrong primary vertex, measured using the $J/\psi$ vertex and the PV in different event

![Graph showing distribution of $t_z$](image)

- LHCb MC
- Tail part
- Prompt $J/\psi$ part
- $J/\psi$ from $b$ component
- All $J/\psi$
$J/\psi$ cross section measurement

- Measurement in bins of $p_T$ and $\eta$
  - 7 bins for $p_T$ 0-7 GeV/c, 4 bins for $\eta$ 3-5
- Combined mass and lifetime fit used to extract number of prompt $J/\psi$ and $J/\psi$ from $b$ decays
- Tests of fitting procedure on sample corresponding to 0.145 pb$^{-1}$ @ 14 TeV ⇒ Good agreements between fit result and MC input

Only binning in $p_T$, because of small Monte Carlo statistics
Reconstruction, selection and trigger efficiencies required to obtain the cross sections, estimated using Monte Carlo

\[
\sigma(\text{prompt } J/\psi) \times \mathcal{B}(J/\psi \rightarrow \mu^+\mu^-) = 3104.2 \pm 2.2 (\text{fit}) \pm 7.3 (\text{efficiency}) \text{ nb (input: 3102.0 nb)}
\]

\[
\sigma(J/\psi \text{ from } b) \times \mathcal{B}(J/\psi \rightarrow \mu^+\mu^-) = 233.6 \pm 1.7 (\text{fit}) \pm 2.0 (\text{efficiency}) \text{ nb (input: 235.7 nb)}
\]
Systematics by $J/\psi$ polarization

- Polarization, using helicity frame. Will also use Gottfried-Jackson (GJ) and Collins-Soper (CS) frames, as suggested.
  \[ \frac{dN}{d\cos\theta} \propto 1 + \alpha \cos^2 \theta; \quad (\alpha = 1, \text{Transverse}; \alpha = -1, \text{Longitudinal}) \]

- LHCb acceptance generates an artificial polarization

![Graphs showing distribution of $\cos\theta$ in different conditions: Full, Both mu>10mrad, Both mu<400mrad, Both mu in LHCb acceptance, with LHCb MC data.]
Tevatron measurements disagree with theoretical predictions

- Not possible to put correct polarization in Monte Carlo

Systematic error up to 25% if ignoring polarization

<table>
<thead>
<tr>
<th>Input $\alpha$</th>
<th>Input $\sigma$ [nb]</th>
<th>Measured $\sigma$ [nb] assuming $\alpha = 0$</th>
<th>Discrepancy</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4340</td>
<td>$4337.3 \pm 7.7$</td>
<td>—</td>
</tr>
<tr>
<td>+1 (T)</td>
<td>4909</td>
<td>$4305.4 \pm 7.7$</td>
<td>-12%</td>
</tr>
<tr>
<td>-1 (L)</td>
<td>3518</td>
<td>$4383.0 \pm 7.9$</td>
<td>+25%</td>
</tr>
</tbody>
</table>

Working on measuring polarization and cross section simultaneously
$\psi(2S)$

- $\psi(2S) \rightarrow \mu^+\mu^-$ similar to $J/\psi \rightarrow \mu^+\mu^-$, yield about 2-4% of the $J/\psi$ yield, lower $S/B$ (1-2), similar mass resolution: 13 MeV/$c^2$.
- Goal is to measure $\sigma(\psi(2S))/\sigma(J/\psi)$, as a function of $p_T$, with separation of prompt $\psi(2S)$ from non-prompt $\psi(2S)$.
- Early measurement (most systematics cancelled), with precision of about 10%: $\frac{\varepsilon_{\text{rec} & \text{sel} & L0}(\psi(2S))}{\varepsilon_{\text{rec} & \text{sel} & L0}(J/\psi)} = 1.01 \pm 0.07(\text{stat.})$

- Also complicated by the unknown polarization (systematics up to 22% on $\sigma(\psi(2S))/\sigma(J/\psi)$).
$\chi_c$

- $\sim 30\%$ of $J/\psi$ come from $\chi_{c1,2} \rightarrow J/\psi \gamma$ [Tevatron measurements]. Important observables: fraction of $J/\psi$ from $\chi_{c1,2}$, $R_{\chi_c} = \sigma(\chi_{c2})/\sigma(\chi_{c1})$.
- $J/\psi$ selection + $E_T(\gamma)>500$ MeV for $\chi_{c1,2} \rightarrow J/\psi \gamma$.
- Plot $\Delta M = m(J/\psi \gamma) - m(J/\psi)$
  - Signal modelled as two Gaussians
  - Background: $P(\Delta M) = (\Delta M)^{c0} \cdot \exp(-c1 \cdot \Delta M - c2 \cdot \Delta M^2)$
- $\sigma_m \sim 27$ MeV/$c^2$ [$M(\chi_{c2}) - M(\chi_{c1}) = 55$ MeV], some sensitivity to $\sigma(\chi_{c2})/\sigma(\chi_{c1})$. 

![Plot $\Delta M$ vs # Events](image)
Very limited experimental studies of the $h_c$ decays.

- Only $h_c \to \eta_c \gamma$ and $h_c \to 2(\pi^+ \pi^-)\pi^0$ observed.

At LHCb, $h_c \to \eta_c \gamma$ ($\eta_c \to \phi \phi$) is difficult ($E_\gamma \sim 500$ MeV in the $h_c$ rest frame)

- will be covered in the nominal running

Ongoing studies of hadronic channels, e.g., $h_c \to p\bar{p}$, $h_c \to \phi K^+ K^-$, $h_c \to \phi \pi^+ \pi^-$, ...

- $h_c \to p\bar{p}$ probably accessible in 2010, improving trigger efficiency

Simultaneous measurements of the $[J/\psi, \chi_{c0,1,2}, h_c] \to p\bar{p}$

ongoing:

- Mass resolutions are about 10 MeV/$c^2$.
- Will measure

$$\frac{\sigma(h_c) \times \mathcal{B}(h_c \to p\bar{p})}{\sigma(J/\psi) \times \mathcal{B}(J/\psi \to p\bar{p})}$$

cross check from the measurements of

$$\frac{\sigma(\chi_{ci}) \times \mathcal{B}(\chi_{ci} \to p\bar{p})}{\sigma(J/\psi) \times \mathcal{B}(J/\psi \to p\bar{p})}.$$ 

Would be interesting to measure $\mathcal{B}(B^+ \to h_c K^+)$
**X(3872) and Z(4430)±**

- At LHCb, large sample of prompt \( X(3872) \rightarrow J/\psi \pi^+ \pi^- \) (and the control channel \( \psi(2S) \rightarrow J/\psi \pi^+ \pi^- \)) and \( X(3872) \) from \( b \) decays make it possible to study \( X(3872) \) systematically
  - About 1.8K \( B^\pm \rightarrow X(3872)(\rightarrow J/\psi \pi^+ \pi^-)K^\pm \) signal events can be selected from 2 fb\(^{-1} \) of data at \( \sqrt{s} = 14 \) TeV. Possible to disentangle unknown \( J^{PC} \): \( 1^{++} / 2^{--} \)

Expected distributions for \( 1^{++} \) and \( 2^{--} \) hypotheses for 2 fb\(^{-1} \) of data. Generator level only, no detector simulation, no acceptance corrections yet!

- Similar studies for \( B^0 \rightarrow Z(4430)\pm(\rightarrow \psi(2S)\pi^\pm)K^\mp \)
  - About 6.2K signal events can be selected from 2 fb\(^{-1} \) of data at \( \sqrt{s} = 14 \) TeV assuming \( \mathcal{B}(B^0 \rightarrow Z(4430)\pm K^\mp) \times \mathcal{B}(Z(4430)\pm \rightarrow \psi(2S)\pi^\pm) = 4.1 \times 10^{-5} \)
  - Possible to confirm the Belle discovery with about 100 pb\(^{-1} \) of data at \( \sqrt{s} = 7 \) TeV if the \( Z(4430)\pm \) exists
\[ \sigma(B_c^+)_{LHC}/\sigma(B_c^+)_{Tevatron} \sim O(10) \]

\[ B_c^\pm \rightarrow J/\psi(\mu^+\mu^-)\pi^\pm \]

- About 310 signal events can be selected from 1 fb\(^{-1}\) of data at \(\sqrt{s} = 14\) TeV assuming \(\sigma_{\text{tot}}(B_c^\pm) = 0.4\) \(\mu\)b and \(\mathcal{B}(B_c^\pm \rightarrow J/\psi\pi^\pm) = 0.13\%

- Mass: \(\pm 1.7\) (stat.) MeV/c\(^2\) (CDF: 2.9 (stat.) \(\pm 2.5\) (syst.) MeV/c\(^2\))

- Lifetime: \(\pm 27\) (stat.) fs. (D0: 38 (stat.) \(\pm 32\) (syst.) fs)

\[ B_c^\pm \rightarrow J/\psi(\mu^+\mu^-)\mu^\pm X \]

- Signal yield one order of magnitude higher
- Lifetime and production cross section measurements possible with 2010 data
About 50% $\Upsilon(1S)$ produced directly, 40% $\Upsilon(1S)$ from the feed-down of $\chi_{b2}(1P)$.

$\Upsilon(1S) \rightarrow \mu^+\mu^-$ selection
- Loose muon particle ID
- $p_T(\mu) > 1.5$ GeV/c

$\varepsilon(L0) \sim 96\%$

Mass resolution, about 37 MeV/c$^2$
$\chi_{b2}(1P)$

- About 40% of $\Upsilon(1S)$ is from the feed-down of $\chi_{b2}(1P) \rightarrow \Upsilon(1S)\gamma$.
- $\Upsilon(1S)$ selection + $E_T(\gamma) > 500$ MeV

![Graph showing the distribution of $\Delta M/GeV$ with #Events on the y-axis and $\Delta M/GeV$ on the x-axis. The graph compares LHCb MC data with inclusive $\Upsilon(1S)$ MC data. The parameters $c0 = 5.3 \pm 0.1$, $c1 = 8.5 \pm 0.3$, $c2 = -1.259 \pm 0.07$, mean = 0.465 $\pm$ 0.003, sig = 0.035 $\pm$ 0.003, sigma = 0.047 $\pm$ 0.004 are displayed on the graph.]}
Many analysis of heavy quarkonia ongoing at the LHCb experiment.

About 2.8M $J/\psi \rightarrow \mu^+\mu^-$ events can be selected from 5 pb$^{-1}$ of data in the coming run ($\sqrt{s} = 7$ TeV), the production cross sections of prompt $J/\psi$ and the $J/\psi$ from $b$ decays will be measured.

Other studies will also be possible with 2010 data

- $\psi(2S) \rightarrow \mu^+\mu^-$
- $B^0 \rightarrow Z(4430)^\pm (\rightarrow \psi(2S)\pi^\pm)K^\mp$
- $B_c^\pm \rightarrow J/\psi \mu^\pm X$
- $\Upsilon(1S) \rightarrow \mu^+\mu^-$
- ...