Studies with onia at LHCb

Luigi Li Gioi - for the LHCb collaboration
CNRS/IN2P3 - Laboratoire de Physique Corpusculaire de Clermont Ferrand
LHCb results of production of $c\bar{c}$ and $b\bar{b}$ states and comparison with theoretical models

Few results from exotic states

- $\psi(2S)$ production cross section
- $Y(1S)$ production cross section
- $\chi_{c2}$ and $\chi_{c1}$ cross section ratio
- $\chi_b$ observation
- $X(3872)$ mass measurement
- $X(3872)$ production cross section
- Search of $X(4140)$
- Exclusive dimuon production

Most of the analysis based on 2010 data = 35 pb$^{-1}$
564 pb$^{-1}$ recorded so far
LHCb detector

Forward region spectrometer (1.9 < $\eta$ < 4.9), 4% solid angle, 40% b-hadron cross section
$\psi(2S)$ production cross section (I)

- Two decay modes: $\psi(2S) \rightarrow J/\psi \pi \pi$, $\psi(2S) \rightarrow \mu \mu$
- Data include also $\psi(2S)$ from b: from 10% (low PT) to 40% (high PT)

\[
d\sigma(p_T) = \frac{N_{\psi(2S)}(p_T)}{L_{\text{int}} \epsilon(p_T) \mathcal{B}(\psi(2S) \rightarrow J/\psi \pi^+\pi^-) \mathcal{B}(J/\psi \rightarrow \mu^+\mu^-) \Delta p_T}
\]

\[
\sigma(3 < p_T \leq 16 \text{ GeV}/c, 2 < y \leq 4.5) = 0.62 \pm 0.04 \pm 0.12^{+0.07}_{-0.14} \mu b
\]

\[
N(\psi(2S)) = 11234 \pm 174
\]
ψ(2S) production cross section (II)

\[
\frac{d^3\sigma}{dp_T dy}(p_T, y) = \frac{N_{\psi(2S)}(p_T, y)}{\mathcal{L}_{\text{int}} \epsilon(p_T, y) \mathcal{B}(\psi(2S) \rightarrow e^+ e^-) \Delta p_T \Delta y}
\]

- Lepton universality assumed
- Smaller error respect to B(ψ(2S) → μ μ)

\[N(\psi(2S)) = 89374 \pm 718\]

\[\sigma(\text{inclusive } \psi(2S); 0 < p_T \leq 12 \text{ GeV}/c, 2 < y \leq 4.5) = 1.88 \pm 0.02 \pm 0.31_{-0.48}^{+0.25} \text{ µb}\]

Good agreement with NLO: CSM + COM

Unknown polarization

Theory predictions: Y.Q Ma, K. Wang and K. T. Chao, B. Kniehl, M. Butenschoen
Y(1S) production cross section (I)

Y(1S), Y(2S), Y(3S) reconstructed

Result of Y(1S)

Cross section of Y(2S) and Y(3S) soon

\[ \frac{d^2\sigma}{dp_Tdy} = \frac{N(Y(1S) \rightarrow \mu^+\mu^-)}{\mathcal{L} \times \varepsilon \times \mathcal{B}(Y(1S) \rightarrow \mu^+\mu^-) \times \Delta y \times \Delta p_T} \]

\[ \sigma(pp \rightarrow Y(1S) X; 0 < p_T < 15 \text{ GeV}/c, 2 < y < 4.5) = 108.3 \pm 0.7^{+30.9}_{-25.8} \text{ nb} \]

Unknown polarization and luminosity uncertainty
Y(1S) production cross section (II)

Comparison with theory (P. Artoisenet, K.T. Chao, J.P. Lansberg and R. Vogt)

Comparison with CMS results (arXiv:1012.5545)
\( \chi_{c2} \) and \( \chi_{c1} \) cross section ratio (I)

\[
\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})} = \frac{N_{\chi_{c2}}}{N_{\chi_{c1}}} \cdot \frac{\epsilon_{\chi_{c1}}^{J/\psi} \epsilon_{\chi_{c1}}^{\gamma}}{\epsilon_{\chi_{c2}}^{J/\psi} \epsilon_{\chi_{c2}}^{\gamma}} \cdot \frac{\epsilon_{\chi_{c1}}^{sel}}{\epsilon_{\chi_{c2}}^{sel}} \cdot \frac{Br(\chi_{c1} \rightarrow J/\psi \gamma)}{Br(\chi_{c2} \rightarrow J/\psi \gamma)}
\]

- \( N(\chi_{c}) \) : from fit on data sample
- Efficiencies (\( \epsilon \)) : from Monte Carlo
  - \( \epsilon_{J/\psi}^{\chi_{c}} \) is the total detection efficiency for \( J/\psi \) from \( \chi_{c} \)
  - \( \epsilon_{\gamma}^{\chi_{c}} \epsilon_{\chi_{c}}^{\gamma} \epsilon_{\chi_{c}}^{sel} \) is the photon total detection efficiency times the \( \chi_{c} \) selection efficiency

Photons reconstruction:
- Unconverted photons
- Converted photons (\( \gamma \rightarrow e^{+}e^{-} \)) after the magnet are identified by requiring a signal in the Scintillating Pad Detector (SPD). We cannot reconstruct converted photons before the magnet.
- Particle identification using a “confidence level likelihood”
  - Calorimeter information
  - Tracking information
  - Ratio of track seed energy to ECAL cluster energy

Luigi Li Gioi
\(\chi_{c2}\) and \(\chi_{c1}\) cross section ratio (II)

- Data sample separated in converted (after the magnet) and non converted photons. Extraction From each sub-sample of \(N(\chi_{ci})\) from a fit in \(M(J/\psi \gamma) - M(J/\psi)\) in bin of \(J/\psi P_T\)

- Combination of the two results

- Evaluate the largest uncertainty due to the unknown polarization on the combined results
\( \chi_{c2} \) and \( \chi_{c1} \) cross section ratio (III)

- Result in bins of \( J/\psi \) PT
- NLO NRQCD: same model used for the \( \psi(2S) \) analysis
- Results: statistical and statistical + systematic errors
- Shaded black area: uncertainty due to the unknown polarization
- Some differences respect to the theory predictions: Kuang-Ta Chao, Lucian Harland-Lang
\( \chi_b \) observation

- \( \chi_b \) reconstructed from Y(1S) and a photon
- Clear signal. The 3 \( \chi_b \) states cannot be resolved
- Plan to measure cross section

LHCb Preliminary
\[ \sqrt{s} = 7 \text{ TeV Data 2010} \]

\[ \begin{align*}
\chi^2 / \text{ndf} & \quad 30.43 / 34 \\
N & \quad 349.9 \pm 58.6 \\
\Delta M & \quad 0.4433 \pm 0.0034 \\
\sigma & \quad 0.0276 \pm 0.0043 \\
A & \quad 5.253e+007 \pm 34381126 \\
\alpha & \quad 18.69 \pm 3.76 \\
a0 & \quad -26.75 \pm 8.82 \\
a1 & \quad 71.8 \pm 21.7 \\
a2 & \quad -42.17 \pm 19.71 \\
a3 & \quad 10.72 \pm 7.57
\end{align*} \]
**X(3872) mass measurement (I)**

- Exotic meson, internal structure unclear
- Most X of prompt. The b fraction is $8 \pm 3$ (stat) %

**Momentum scale**
- Accounts effects related imperfections in the knowledge of the magnetic field map and of the alignment of the tracking system
- Average overall scale factor to be applied on all raw measurements of the track momenta
- Detailed studies with $J/\psi$ and other resonances
  - Stability versus time
  - Variation with decay kinematics
- Calibration checked with $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$ decay: $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$ mass becomes $3686.12 \pm 0.06$ (stat) MeV/$c^2$, in good agreement with the PDG value of $3686.09 \pm 0.04$ MeV/$c^2$

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Upsilon(1S) \rightarrow \mu^+\mu^-$</td>
<td>9459.90 ± 0.54</td>
<td>9460.30 ± 0.26</td>
</tr>
<tr>
<td>$J/\psi \rightarrow \mu^+\mu^-$</td>
<td>3096.97 ± 0.01</td>
<td>3096.916 ± 0.011</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^-\pi^+$</td>
<td>1864.75 ± 0.07</td>
<td>1864.83 ± 0.14</td>
</tr>
<tr>
<td>$K_{S}^0 \rightarrow \pi^+\pi^-$</td>
<td>497.62 ± 0.01</td>
<td>497.61 ± 0.02</td>
</tr>
</tbody>
</table>

**J/ψ mass stable in all 2010**
**X(3872) mass measurement (II)**

Unbinned maximum likelihood fit to \( M(\psi \pi^+ \pi^-) \)

- \( \psi(2S) \) described by Breit-Wigner convolved with Gaussian (Voigt profile)
- \( X(3872) \) also described by Voigt, width fixed to 1.3 MeV (CDF average from BaBar and Belle limits)
- Background described by threshold function (gives good description of same sign background: \( J/\psi \pi^\pm \pi^\pm \))

\[
\begin{align*}
\text{M}(J/\psi \pi^+ \pi^-) &= 3871.96 \pm 0.46 \text{ (stat)} \pm 0.10 \text{ (syst)} \text{ MeV/c}^2 \\
N(X(3872)) &= 585 \pm 74
\end{align*}
\]

**X(3872) observation in \( B^\pm \rightarrow X(3872) K^\pm \)**

\[
N(X(3872)) = 71 \pm 12
\]
X(3872) production cross section

\[ \sigma_{X(3872)} \times BR(X(3872) \rightarrow J/\psi \pi^+\pi^-) = \frac{N_{corr}^{X(3872)}}{L_{int} \times \eta_{tot} \times BR(J/\psi \rightarrow \mu^+\mu^-)} \]

The yield efficiency corrected \( N_{corr}^{X(3872)} = 9597 \pm 2217 \)

\[ \sigma_{X(3872)} \times BR(X(3872) \rightarrow J/\psi \pi^+\pi^-) = 4.74 \pm 1.10 \text{(stat)} \pm 1.01 \text{(syst)} \text{ nb} \]

**Systematics**

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X(3872) polarization</td>
<td>1.4</td>
</tr>
<tr>
<td>X(3872) decay model</td>
<td>negligible</td>
</tr>
<tr>
<td>X(3872) decay width</td>
<td>11.8</td>
</tr>
<tr>
<td>Mass resolution</td>
<td>1.3</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>16</td>
</tr>
<tr>
<td>Track ( \chi^2 ) cut</td>
<td>2</td>
</tr>
<tr>
<td>Trigger</td>
<td>5</td>
</tr>
<tr>
<td>Global event cuts</td>
<td>2.1</td>
</tr>
<tr>
<td>Vertex ( \chi^2 ) cut</td>
<td>3</td>
</tr>
<tr>
<td>Muon identification</td>
<td>1.1</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>3.5</td>
</tr>
<tr>
<td>( J/\psi \rightarrow \mu^+\mu^- ) branching fraction</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>21.3</strong></td>
</tr>
</tbody>
</table>
Search of X(4140) (I)

- Search of X(4140) in $B^+ \to J/\psi \phi K^+$, $\phi \to K^+ K^-$
- CDF observed a X(4140) structure with a significance of 5 $\sigma$
- If real these are candidates of exotic bound state

CDF observed a X(4140) structure with a significance of 5 $\sigma$

CDF: 115 ± 12 events in 6 fb$^{-1}$

LHCb observed 381 ± 22 events in 2010+2011: 0.4 fb$^{-1}$
Search of $X(4140)$ (II)

Fit of $M(J/\psi \phi) - M(J/\psi)$
- Signal: relativistic spin 0 Breit-Wigner smeared with the resolution
- Background: efficiency shaped 3 body phase space (smeared with the resolution), quadratic polynomial

3 body phase space

Expected events scaling with CDF results
- $39 \pm 9 \pm 6$
- $7 \pm 5$ events

quadratic polynomial

CDF: $0.149 \pm 0.039 \pm 0.024$

LHCb doesn’t confirm $X(4140)$

CDF: $0.149 \pm 0.039 \pm 0.024$

arXiv:1101.6058v1

LHCb preliminary
Exclusive dimuon (I)

QED used for indirect precise luminosity measurement

QCD can test prediction in a low multiplicity environment

$M(\mu\mu) > 2.5 \text{ GeV/c}^2$, resonances removed

Background estimation from data > 2 tracks

Reconstruct of forward and backward tracks

Exclusive = only 2 forward tracks in total
Exclusive dimuon (II)

\[ P_T(\mu\mu) < 900 \text{ MeV}/c, \text{ two tracks, 1 photon for } \chi_c \]

No background subtracted. ~80% exclusive events

Result and theory predictions

1) \( \sigma(\text{QED}) \): 67 ± 10 ± 5 ± 15 pb

2) \( \sigma(J/\psi) \): 474 ± 12 ± 45 ± 92 pb

3) \( \sigma(\psi(2S)) \): 12.2 ± 1.8 ± 1.2 ± 2.4 pb

4) \( \sigma(\psi(2S))/\sigma(J/\psi) \): 0.20 ± 0.03

5) \( \sigma(\chi_{c0}) \): 9.3 ± 2.2 ± 3.5 ± 1.8 pb

6) \( \sigma(\chi_{c1}) \): 16.4 ± 5.3 ± 5.8 ± 3.2 pb

7) \( \sigma(\chi_{c2}) \): 28.0 ± 5.4 ± 9.7 ± 5.4 pb

1) 42 pb (LPAIR)

2) 292 pb (Starlight) 330 pb (SuperChic) 330 pb (Motyka&Watt) 710 pb (Schafer&Szczurek)

3) 6.1 pb (Starlight) 17 pb (Schafer&Szczurek)

4) 0.16 (Starlight) 0.2 (Schafer&Szczurek) 0.166 ± 0.012 (HERA) 0.14 ± 0.05 (CDF)

5) 14 pb (SuperChic)

6) 10 pb (SuperChic)

7) 3 pb (SuperChic)
Summary

- LHCb performed many analysis of the quarkonium states using 2010 collected data
  - Good agreement of $\psi(2S)$ cross section measurement with NRQCD
  - These results are useful to test theoretical models
  - Good agreement of $Y(1S)$ cross section
  - Some disagreement of $\chi_{c2}$ and $\chi_{c1}$ cross section ratio with theory models
  - Comparison of different exclusive dimuon production cross sections with theory predictions

- Results from $X(...)$ states
  - Precise measurement of $X(3872)$ mass
  - $X(3872)$ production cross section measurement
  - LHCb doesn't confirm CDF $X(4140)$

- LHCb has a very high $J/\psi$ statistic in 2011 data
  - 564 pb$^{-1}$ recorded so far
  - 1 fb$^{-1}$ expected in 2011
  - A lot of new results expected in the future
Backup slides
$\chi_{c2}, \chi_{c1}$: comparison with CDF results
X(3872) mass average

Average according to the prescriptions of PDG 2010

CDF
BaBar $B^+$
BaBar $B^0$
D0
Belle
PDG Average $3871.56 \pm 0.22$
LHCb Preliminary
New average $3871.63 \pm 0.20$
X(3872) : mass measurement syst.

Signal Modeling
- Vary fit range
- Vary natural width from 0 – 2.6 MeV
- Embed MC in same-sign background and check for bias from background fit model

Calibration
- Vary momentum scale by ± 0.1 per mille [quoted uncertainty]
- Parameterize residual $\eta$ bias and make dependent scale factor
- Vary amount of material by 10 %

Alignment
- Drop TT hits and repeat procedure
- Scale track slopes in velo by per mille

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Value [MeV/c$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mass fitting:</strong></td>
<td></td>
</tr>
<tr>
<td>Natural width</td>
<td>0.02</td>
</tr>
<tr>
<td>Background model</td>
<td>0.02</td>
</tr>
<tr>
<td>Fit range</td>
<td>0.01</td>
</tr>
<tr>
<td><strong>Momentum calibration:</strong></td>
<td></td>
</tr>
<tr>
<td>Average momentum scale</td>
<td>0.05</td>
</tr>
<tr>
<td>$\eta$ dependence of momentum scale</td>
<td>0.03</td>
</tr>
<tr>
<td><strong>Detector description:</strong></td>
<td></td>
</tr>
<tr>
<td>Energy loss correction</td>
<td>0.05</td>
</tr>
<tr>
<td><strong>Detector alignment:</strong></td>
<td></td>
</tr>
<tr>
<td>Tracking stations (TT information)</td>
<td>0.05</td>
</tr>
<tr>
<td>Vertex detector (track slopes)</td>
<td>0.01</td>
</tr>
<tr>
<td>Quadratic sum</td>
<td>0.10</td>
</tr>
</tbody>
</table>
LHCb fit of X(4274)

22 ± 8 events

49 ± 18 events expected from CDF results assuming the same efficiency of X(4140) from CDF

\[ \text{BR}(B^+ \rightarrow \text{X}(4274)K^+, \text{X}(4274) \rightarrow J/\psi \phi) / \text{BR}(B^+ \rightarrow J/\psi K^+) < 0.08 \quad (90\% \text{ C.L.}) \]