Exotic spectroscopy and Quarkonia at LHCb

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(On behalf of the LHCb collaboration)
Tsinghua, Beijing & LAL, Orsay
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Outline

• Introduction
• Exotic measurement and prospects
  – $X(3872)$ mass measurement;
  – XYZ prospects.
• Quarkonia measurements and prospects
  – $\psi(2S)$ production;
  – $\chi_{c1}, \chi_{c2}$ cross-section ratio.
• Summary
Introduction: LHCb detector

- Characteristics relevant for these analysis:
  - Proper time resolution: 30-50 fs;
  - $\mu$ identification efficiency: $\sim 95\%$;
  - $\Delta p/p : 0.35 - 0.55 \%$. 

- 37 $pb^{-1}$ of data collected at $\sqrt{s} = 7$TeV in 2010.
Exotic mesons

• In recent years, new exotic mesons have been observed by different experiments:
  – X(3872), X(4140), Z(4430)...
• Many models, all with limited success:
  – Tetraquark: Tightly bound four quark.
  – Molecular state: Loosely bound mesons with a quark/color exchange (short distance) or π exchange (large distance).
  – Charmonium hybrids: States with a excited gluonic degree of freedom.
Motivation
- Measure X mass using $X \rightarrow J/\psi \, \pi^+ \, \pi^-$. 

Introduction
- First observed by Belle, confirmed by CDF and Babar;
- Quantum numbers constrained to be $J^{PC} = 1^{++}$ or $2^{-+}$. 

Analysis strategy
- Using the inclusive production;
- Based on $L=34.8 \, \text{pb}^{-1}$ of data;
- $\psi(2S) \rightarrow J/\psi \, \pi^+ \, \pi^-$ as control channel.
Fit functions and calibration

- **Fit functions:**
  - Background (*from same sign background shape*):
    \[
    F_{bg}(M; m_r, c_0, c_1, c_2) = \frac{1}{a} (M - m_r)^{c_0} e^{-Mc_1 - M^2c_2}
    \]
  - Signal Voigt function (*convolution of BW with Gaussian*):
    \[
    V(M; \mu, \sigma, \Gamma) = \int_{-\infty}^{\infty} G(M - M'; \sigma)L(M'; \mu, \Gamma) \, dM'
    \]

- **Calibration**
  - $J/\psi$ mass is constant over the whole data-taking.
Systematics

• Systematics under control:
  – \( M_{\psi(2S)} = 3686.12 \pm 0.06 \) (stat) MeV/c\(^2\)
    consistent with world average
    (3686.09 ± 0.04 MeV/c\(^2\));
  – The \( \psi(2S) \) mass does not depend on
    any kinematic variables.

<table>
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<tr>
<th>Source of uncertainty</th>
<th>Value [MeV/c(^2)]</th>
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<td>Background model</td>
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<td>Momentum calibration:</td>
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<td>( \eta ) dependence of momentum scale</td>
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<td>Tracking stations (TT information)</td>
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<td>Vertex detector (track slopes)</td>
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<tr>
<td>Quadratic sum</td>
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</table>
Mass spectrum

- Results
  - \( M_{\chi(3872)} = 3871.96 \pm 0.46 \text{ (stat)} \pm 0.10 \text{ (syst)} \text{ MeV/c}^2 \)
  - \( N_{\chi(3872)} = 585 \pm 74, \sigma = 2.75 \pm 0.54 \text{ MeV/c}^2 \)

Exotic spectroscopy and Quarkonia at LHCb
Comparison with other experiments

- $X(3872)$ mass is compatible with other measurements;
- New average: $3871.63 \pm 0.20$ MeV/c$^2$, indistinguishable from the $D^{*0}D^0$ threshold ($3871.79 \pm 0.29$ MeV/c$^2$);
- A statistical error of 0.12 MeV/c$^2$ is expected with 500 pb$^{-1}$;
- A measurement of the $X(3872)$ mass respect to the $D^{*0}D^0$ threshold to reduce systematics will be done too.
X(3872) prospects

- Production cross section measurement, for both of the prompt and b meson component;
  - Studies are underway with 2010 data.

- Determination of the quantum numbers using
  \[ B^+ \rightarrow X(3872) \left( J/\psi \; \pi^+ \pi^- \right) K^+; \]
  - \( \sim 1000 \) reconstructed \( X(3872) \) events are expected with \( 2 \) fb\(^{-1} \).

- Study of the \( M_{\pi\pi} \);
  - Understand the \( X(3872) \) decay mechanism and constrain models.

- \( X(3872) \) width;
  - Now (PDG): \( \Gamma < 2.3 \) MeV/c\(^2\), CL = 90%
Other exotic prospects

- **Z(4430) confirmation**
  - Discovered by Belle in the $\psi(2S)\pi$ system, Babar found no evidence.
  - $Z(4430)$ yield at LHCb:
    - $\sim 860 / 1$ fb$^{-1}$ expected.  
      (CERN-THESIS-2009-129)  
      
- **X(4140) confirmation**
  - Discovered by CDF in $B^+ \rightarrow K^+[J/\psi\phi]$;
  - Not seen at Belle with larger yield.

- **Exotic bottomonium**
  - $X \rightarrow (Y(nS) \rightarrow \mu^+\mu^-)\pi^+\pi^-$.  

*Many other exotic studies are on-going!*
\( \Psi(2S) \) production

LHCb-CONF-2011-026

**Motivation**
- Testing NRQCD CS and CO mechanisms.

**Introduction**
- No appreciable feed-down from higher mass states, directly compared with the theory;
- Two decay modes:
  - \( \Psi(2S) \to J/\psi \pi^+\pi^- \): larger BR, lower efficiency;
  - \( \Psi(2S) \to \mu^+\mu^- \): more statistics.

**Analysis strategy**
- \[ \frac{d^2\sigma}{dp_T dy}(p_T, y) = \frac{N_{\psi(2S)}(p_T, y)}{L_{int} \varepsilon(p_T, y) B(\psi(2S) \to e^+e^-) \Delta p_T \Delta y} \]
- \[ \frac{d\sigma}{dp_T}(p_T) = \frac{N_{\psi(2S)}(p_T)}{L_{int} \varepsilon(p_T) B(\psi(2S) \to J/\psi\pi^+\pi^-) B(J/\psi \to \mu^+\mu^-) \Delta p_T} \]
- Samples in bins of \( p_T \) and \( y \).
- Based on \( L \sim 35 \text{ pb}^{-1} \) of data.
Extraction of $N(\psi(2S))$

- **Mass Spectra**

  ![Mass Spectra](image)

  - $\psi(2S) \rightarrow \mu^+ \mu^-$

  ![Mass Spectra](image)

  - $\psi(2S) \rightarrow J/\psi(\mu\mu)\pi^+ \pi^-$

- **The number of $\psi(2S)$ extracted from mass fit.**

- **Efficiencies extracted from Monte Carlo, and corrected by comparing data and MC.**
Efficiencies

\[ \varepsilon_{\text{total}} = \varepsilon_{\text{geo}} \times \varepsilon_{\text{rec}} \times \varepsilon_{\text{tri}} \]

\[ \psi(2S) \rightarrow \mu^+ \mu^- \]

\[ \psi(2S) \rightarrow \mu^+ \mu^- \]

\[ \psi(2S) \rightarrow J/\psi (\mu\mu)\pi^+\pi^- \]

\[ \psi(2S) \rightarrow J/\psi (\mu\mu)\pi^+\pi^- \]

\[ \psi(2S) \rightarrow J/\psi (\mu\mu)\pi^+\pi^- \]

Exotic spectroscopy and Quarkonia at LHCb
Systematics and results

- **Dominant systematics**
  - Trigger efficiency;
  - Tracking efficiency;
  - Polarization;
  - Luminosity.

- **Results**
  \[ \sigma(\psi_{2S}; 0 < p_T \leq 12\text{GeV}/c, 2 < y < 4.5) = 1.88 \pm 0.02 \pm 0.31^{+0.25}_{-0.48} \mu\text{b} \]
  \[ \sigma(\psi_{2S}; 3 < p_T \leq 16\text{GeV}/c, 2 < y < 4.5) = 0.62 \pm 0.04 \pm 0.12^{+0.07}_{-0.14} \mu\text{b} \]
  - This measurement includes also non-prompt \( \psi(2S) \): a more accurate comparison will be carried out by separating prompt from non-prompt components.

_Y.-Q. Ma et al. PRL 106 042002 (2011) and private communication._

*Only uncorrelated errors are shown*

Exotic spectroscopy and Quarkonia at LHCb
\( \chi_{c1} \chi_{c2} \) cross section ratio

**Motivation**
- Testing NRQCD CS and CO mechanisms.

**Introduction**
- 30% of J/\( \psi \) from \( \chi_c \) (1,2) \( \to \) J/\( \psi \) \( \gamma \) : Tevatron;
- \( \chi_{c1} \) and \( \chi_{c2} \) very close : two peaks impossible;
- Very few \( \chi_{c0} \) events expected.

**Analysis strategy**
- Separate data in converted and not converted photons, and then combine the results (all photons reconstructed in the calorimeter);
- Final results in bins of J/\( \psi \) \( p_T \) in the range \([3, 15]\) GeV/c.
- Based on L=35.6 pb\(^{-1}\) of data.
Extraction of $N(\chi_{c1})$ & $N(\chi_{c2})$


- The number of $\chi_c$ extracted from the mass fit.
- Efficiencies extracted from Monte Carlo.
Ratio of efficiencies

- Ratio of $J/\psi$ efficiencies

\[ \frac{\chi_{c2}^{J/\psi}}{\chi_{c1}^{J/\psi}} = \frac{N_X^{\chi_{c2}^{J/\psi \, \text{rec}}}}{N_X^{\chi_{c1}^{J/\psi \, \text{rec}}}} \cdot \frac{N_X^{\chi_{c1}^{J/\psi \, \text{gen}}}}{N_X^{\chi_{c2}^{J/\psi \, \text{gen}}}}. \]

- Consistent with unity for all $p_T$ bins.

- Calculated separately for converted and not converted photons.

- Ratio of $[3, 4]$ bin is different from 1 but the effect is negligible.
Systematics and results

**Systematics:**
- Fit;
- Efficiencies;
- MC statistics;
- $\text{Br}(\chi_c(1,2) \rightarrow J/\psi \gamma)$;
- Polarization.

**Results**
- Significant statistical improvement than previous hadron colliders;
- Agreement with CS and CO in high $p_T$ region.

**Plan to measure** $\sigma(\chi_c \rightarrow J/\psi \gamma) / \sigma(J/\psi)$
Summary

• XYZ spectroscopy is an exciting field
  – X(3872) mass has been measured and more studies will be done;
  – On-going studies:
    • Confirmation of discoveries: Z(4430), X(4140), etc;
    • More exotic states in the J/ψππ, J/ψφ, J/ψJ/ψ spectra, or bottomonium states.

• Quarkonia production
  – ψ(2S) and χ_c production are measured and more studies are on-going.
backup
Abstract

• The last ten years have seen a resurgence of interest in exotic spectroscopy driven by the discovery of the X(3872) in the J/ψ ππ spectrum. Searches and studies of exoticonia form an important part of LHCb’s physics program. We present results for the production of ψ(2s) and χc(1,2) in the dimuon plus pions or photon channels, as well as the first results for X(3872) production using the dataset collected in 2010, which corresponds to about 34 pb$^{-1}$. A measurement of the X(3872) mass in the J/ψ ππ mode together with production properties will be presented. The ψ(2s) production in the same decay channel and the χc2 to χc1 cross section ratio will also be discussed, together with future prospects on these measurements at LHCb.
Systematics

<table>
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<th>Error source</th>
<th>$\mu\mu$ mode</th>
<th>$J/\psi\pi\pi$ mode</th>
<th>Comment</th>
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<td>0-18%</td>
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<td>GEC</td>
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<td>Muon ID</td>
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* dielectron
# Systematics

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</table>
\( \gamma \) reconstruction

- \( \pi_0 \) mass fit: \( \pi_0 \) mass peak is symmetric in all cases.

- With new Calorimeter conditions and correction \( p_0 \) mass peak is symmetric in all cases.