Quarkonium results from LHCb

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on behalf of the LHCb collaboration

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Outline

• LHCb detector description
• Motivations for studying quarkonium
• Selected quarkonium results:
  • $\psi(2S)$
  • $\chi_c$
  • $Y(nS)$
  • $J/\psi +$ open charm
  • $X(3872), X(4140)$
• Prospects and conclusions
The LHCb experiment

- An experiment at the LHC designed to study CP violating and rare decays of $b(c)$-hadrons

- $b$ and $\bar{b}$ are forward(backward) produced: $\sigma_{bb} \sim 300 \mu b$ at 7 TeV

- 3 trigger levels reduce the frequency of accepted events to 3 kHz (Max)
Luminosity during 2011

- LHCb peak luminosity per fill: $3-4 \times 10^{32} / \text{cm}^2 \text{s (2011)}$

- Instantaneous luminosity levelling
  - Obtained through vertical beam displacements

- 91% data taking efficiency
- 99% of data taken are good for physics

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Motivations for studying quarkonium

- The production mechanisms are not yet fully understood
- Many theoretical approaches proposed in the last years:
  - NLO Colour Singlet + Colour Octet (CS + CO) in the Non-Relativistic QCD framework
  - NNLO Colour Singlet
  - Colour Evaporation Model
  - FONLL (Fixed-Order-Next-to-Leading-Log), only for charmonium from $b$-decays
- Theory makes predictions of cross-section and polarization
- LHCb can study quarkonium hadroproduction in a unique kinematic region:
  - Large rapidity ($2<y<4.5$)
  - Down to low $p_T$
Prompt $\psi(2S)$ cross-section

- The $\psi(2S)$ prompt component has not appreciable feed-down from higher mass states: prompt $\psi(2S) = \text{direct } \psi(2S)$

- This facilitates the cross-section interpretation

- Reconstructed in the decay channels $\psi(2S) \rightarrow \mu^+\mu^- \ (90k \text{ events})$ and $\psi(2S) \rightarrow J/\psi(\mu^+\mu^-) \pi^+\pi^- \ (12k \text{ events})$ and the results have been averaged

$$\sigma_{\text{prompt}} = 1.44 \pm 0.01 \ \text{(stat)} \pm 0.12 \ \text{(syst)}^{+0.20}_{-0.40} \ \text{(pol)} \ \mu\text{b}$$

- In the range $p_T < 16 \text{ GeV/c}$ and $2 < y < 4.5$

- Dominant syst. errors from luminosity, trigger and tracking: can be reduced

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Separation between prompt $\psi(2S)$ and those originating from $b$-hadron decays: study of the pseudo decay time

\[ \sigma_b = 0.25 \pm 0.01 \text{ (stat)} \pm 0.02 \text{ (syst)} \mu b \]

- In the range $p_T < 16$ GeV/c and $2 < y < 4.5$
- Dominant syst. errors from luminosity, trigger and tracking: can be reduced

Combining the last result with the LHCb $J/\psi$ measurements [Eur.Phys. J.C 71 (2011) 1645] we determine the inclusive $B(b \rightarrow \psi(2S)X)$, currently known at 50% level [PDG].

Good agreement with a recent measurement from CMS

$B(b \rightarrow \psi(2S)X) = 2.73 \pm 0.17 \text{(stat)} \pm 0.24 \text{ (BF)} \cdot 10^{-3}$

$B(b \rightarrow \psi(2S)X) = 3.08 \pm 0.18 \text{(stat)} \pm 0.42 \text{ (BF)} \cdot 10^{-3}$

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[CMS-BPH-10-014]
$\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})}$

- $\chi_c J$ provides substantial feed-down to the prompt $J/\psi$ through $\chi_c J \rightarrow J/\psi \gamma$
- Impact on the $J/\psi$ polarization and cross-section measurements
- $\chi_c J \rightarrow J/\psi \gamma$ with $J/\psi \rightarrow \mu^+ \mu^-$ and $\gamma \rightarrow e^+ e^-$ using converted photons (2011) in the tracking system: good resolution $\rightarrow \chi_c$ states resolved, lower efficiency

$\chi_{c0}$: very few expected events
- Good agreement with LHCb 2010 analysis ($\gamma$ using calorimeter clusters only) and CDF.
- Agreement with NLO CS + CO above 8 GeV/c
\[ \sigma(\chi_c \rightarrow J/\psi \gamma)/\sigma(J/\psi) \]

- \( \gamma \) reconstruction using calorimeter clusters only (lower resolution)
- Prompt charmonium selection: requiring \( d_z \frac{M_{J/\psi}}{p_z} < 0.1 \text{ ps} \) (pseudo decay time)

Separate errors to take into account all possible polarization scenarios of \((\chi_{c1}, \chi_{c2}, J/\psi)\)

Results in agreement with NLO CS + CO Ma, Wang and Chao [PR D83 (2001) 111503]
ChiGen [hepforge.org/superchic/chigen.html]
[LHCb-PAPER-2011-030]
Bottomonium: Y(nS)

- Direct production or feed-down from higher bottomonium states
- Through the decay channel $Y(nS) \rightarrow \mu^+\mu^-$
- Signal fitted by Crystal Ball functions.
  Background fitted by an exponential
  - Yields: 26400 $Y(1S)$, 6700 $Y(2S)$, 3300 $Y(3S)$
- Unknown polarization taken as syst. error (last asymmetrical error)

\[
\begin{align*}
\sigma(pp \rightarrow Y(1S) X) \times B(Y(1S) \rightarrow \mu^+\mu^-) &= 2.29 \pm 0.01 \pm 0.10 ^{+0.19}_{-0.37} \text{ nb} \\
\sigma(pp \rightarrow Y(2S) X) \times B(Y(2S) \rightarrow \mu^+\mu^-) &= 0.562 \pm 0.007 \pm 0.023 ^{+0.048}_{-0.092} \text{ nb} \\
\sigma(pp \rightarrow Y(3S) X) \times B(Y(3S) \rightarrow \mu^+\mu^-) &= 0.283 \pm 0.005 \pm 0.012 ^{+0.025}_{-0.048} \text{ nb}
\end{align*}
\]
Double Charm(onium)

- $J/\psi C, \overline{C}C, CC$ where $C = D^0, D^+, D_s^+, \Lambda_c^+$
- Predictions for the production cross-sections are given by
  - **LO pQCD**: $gg \to J/\psi J/\psi$ excellent agreement with the LHCb measurements [PLB 707 52]
  - **Intrinsic Charm (IC)**: based on charm PDFs. Quite large uncertainties on the predictions
  - **Double Parton Scattering (DPS)**: two independent scattering processes. Assumes the factorization of the PDFs

LHCb performed the first observation of the modes $J/\psi C$ at hadron machines

- $3 < p_T^C < 12 \text{ GeV}/c$, $p_T^{J/\psi} < 12 \text{ GeV}/c$, $2 < y_{J/\psi}, y_C < 4$

Require both hadrons consistent with the same PV

Use *per-event* efficiency correction

- Efficiencies extracted from data (when possible) [LHCb-PAPER-2012-003]
Pileup is negligible (real data + MC)
Signal significance > 5σ

**Dominant systematic**
- Hadron track reconstruction: 2% per track

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<th>Fitted signal</th>
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<tr>
<td>J/ψ D⁰</td>
<td>4875±86</td>
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<tr>
<td>J/ψ D⁺</td>
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<td>J/ψ D⁺_s</td>
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<td>J/ψ Λ⁺_c</td>
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<tr>
<td>D⁰D⁺</td>
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<tr>
<td>D⁰ Λ⁺_c</td>
<td>41±8</td>
</tr>
</tbody>
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355 pb⁻¹

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Double Charm(onium)

Green line: expected distribution for uncorrelated events

[EPJ C61 (2009) 693]

[PR D57 (1998) 4385]

[PR D73 (2006) 074021]
X(3872)

- Observed for the first time by Belle (2003) in B decays. Confirmed by CDF, D0 and BaBar.
- Quantum numbers not yet established ($J^{PC}=2^{-+}$ or $1^{++}$). Its nature is still uncertain: conventional charmonium? Di-Charm molecule? Tetraquark state? → Mass is a crucial input to theories.

\[
\begin{align*}
M_{X(3872)} &= 3871.95 \pm 0.48 \text{ (stat)} \pm 0.12 \text{ (syst)} \text{ MeV/c}^2 \\
\sigma_{X(3872)} B_{J/\psi \pi^+ \pi^-} &= 4.7 \pm 1.1 \text{ (stat)} \pm 0.7 \text{ (syst)} \text{ nb}
\end{align*}
\]

- Dominant systematics (mass): 10% momentum calibration scale; 5% energy loss correction.
- Dominant systematics ($\sigma$): 7% tracking efficiency; 6% background model.

[28.03.2012]
Observed by CDF in $B^+ \rightarrow J/\psi \phi K^+$:
- $19 \pm 6 \ X(4140)$ and $22 \pm 8 \ X(4274)$.
- $J/\psi \phi$ close to the kinematic threshold: should be unobservable
- Its nature: molecule? Tetraquark? ...

Belle found no evidence for $X(4140)$ in $\gamma \gamma \rightarrow J/\psi \phi$

380 $B^+ \rightarrow J/\psi \phi K^+$ selected events at LHCb
No evidence for the $X(4140)$ nor for the $X(4274)$: upper limits at 90% CL

\[
\frac{\mathcal{B}(B^+ \rightarrow X(4140)K^+)}{\mathcal{B}(B^+ \rightarrow J/\psi \phi K^+)} < 0.07
\]

\[
\frac{\mathcal{B}(B^+ \rightarrow X(4274)K^+)}{\mathcal{B}(B^+ \rightarrow J/\psi \phi K^+)} < 0.08
\]
Prospects and conclusions

- LHCb is in good shape and performs better than expectations
- More than 1/fb recorded (about 50% analyzed)
- Very active quarkonium group working in close connection with theorists community
- Latest quarkonium analyses presented here. Many others in progress. Active plans for new measurements at $\sqrt{s}=8$ TeV

- Stay tuned for news!

Thank you for listening