Quarkonia in dimuon final states
and exclusive dimuon decays at LHCb

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Outline

- The LHCb experiment
  - Detector description
- Quarkonia cross-section measurements: J/ψ, double J/ψ, ψ(2S), Y
  - Selection criteria, efficiencies, systematic errors
  - Results and comparison to theory
- Exclusive dimuon production
- Prospects for polarisation measurements at LHCb
- Conclusions
The LHCb experiment

- An experiment at LHC dedicated to $b$ ($c$) quark physics

- $b$ and $\bar{b}$ are both forward (backward) produced: detector geometry imposed by the kinematics
- 3 trigger levels reduce the event rate from 40 MHz to 2 kHz
- Stable data taking runs at $\sqrt{s} = 7$ TeV
- Instantaneous $L = 10^{31} - 10^{32}$ cm$^{-2}$s$^{-1}$

Angular acceptance $1.9 < \eta < 4.9$
Quarkonia cross-section measurements: J/ψ

- Double differential cross-section, as a function of $p_T$ and $y$:
  - $p_T < 14$ GeV/$c$ (14 bins), $2<y<4.5$ (5 bins)
  - separately for prompt J/ψ and for J/ψ from $b$
  - data sample: $(5.2\pm0.5)$ pb$^{-1}$ collected during 2010, $\sqrt{s}=7$ TeV
  - J/ψ reconstructed in the $\mu\mu$ decay mode

- **Trigger and selection criteria**
  - single muon OR dimuon trigger: muon $p_T$ cuts
  - off-line cuts:
    - muon track quality ($\chi^2$/nDoF < 4)
    - muon $p_T > 700$ MeV/$c$
    - common vertex fit quality ($p(\chi^2)>0.5\%$)
    - N primary vertices $\geq 1$
Quarkonia cross-section measurements: \( J/\psi \)

- Total number of \( J/\psi \): \( 564603 \pm 924 \)
- Fit: Crystal Ball (signal) + Exponential (bg)
- Separation prompt/from \( b \) \( J/\psi \)

Signal: prompt + from \( b \) + tail
Background (shape from sidebands)
Convolved by a resolution function: \( \sigma(t_z)=53 \) fs

\[
t_z(J/\psi) = \frac{d_z \times M_{J/\psi}}{p_z}
\]
Quarkonia cross-section measurements: J/ψ

- Efficiencies were computed from MC and were checked on data
- J/ψ polarisation (unknown) affects the efficiency. Polarisation scenarios simulated:
  - unpolarised J/ψ (figure)
  - fully transverse polarised J/ψ
  - fully longitudinal polarised J/ψ
- results were given in each of the three cases

- Many systematic error sources have been studied mostly through MC-data comparison:
  - tracking efficiency: 4% per track (2010 runs, now improved at 1%)
  - luminosity: 10% (2010 runs, now improved at 3.5%)
  - trigger efficiency: 1.7-4.5%
Quarkonia cross-section measurements: $J/\psi$

$$
\frac{d^2 \sigma}{dy dp_T} = \frac{N (J/\psi \rightarrow \mu^+\mu^-)}{\mathcal{L} \times \epsilon_{\text{tot}} \times \mathcal{B} (J/\psi \rightarrow \mu^+\mu^-) \times \Delta y \times \Delta p_T}
$$

Unpolarized $J/\psi$

- Integrated over the acceptance:

$$
\sigma (\text{prompt } J/\psi, p_T < 14 \text{ GeV}/c, 2.0 < y < 4.5) = 10.52 \pm 0.04 \pm 1.40_{-2.20}^{+1.64} \mu\text{b}
$$

$$
\sigma (J/\psi \text{ from } b, p_T < 14 \text{ GeV}/c, 2.0 < y < 4.5) = 1.14 \pm 0.01 \pm 0.16 \mu\text{b}
$$
Quarkonia cross-section measurements: $J/\psi$

K. T. Chao et al.

J.-P. Lansberg

R. Vogt

Quarkonia cross-section measurements: double $J/\psi$

- LO QCD makes predictions of $\sigma(pp \rightarrow J/\psi J/\psi + X)$ at the LHC energies

- Analysis performed in the range
  - $p_T < 10 \text{ GeV}/c$
  - $2 < y < 4.5$

with the full 2010 dataset

- Strategy
  - 4 muons from the same vertex
  - fit $M(\mu^+\mu^-)_1$ in bin of $M(\mu^+\mu^-)_2$
  - $140 \pm 18$ double $J/\psi$
Quarkonia cross-section measurements: double $J/\psi$

- Events are weighted with the inverse of tot. eff: $1/\varepsilon_{J/\psi J/\psi}^{\text{tot}}$

- Systematic errors (most important):
  - trigger efficiency: 8%
  - tracking efficiency: 4% per track (now improved at 1%)
  - luminosity: 10% (now improved at 3.5%)

\[
\sigma_{J/\psi J/\psi} = \frac{1}{\mathcal{L} \times \mathcal{B}_{\mu^+\mu^-}^2} \times N_{J/\psi J/\psi}^{\text{corr}} = 5.6 \pm 1.1 \pm 1.2 \text{ nb}
\]

- To compare with QCD calculation:
  - $\sigma(pp \rightarrow J/\psi \ J/\psi + X) = 4.15 - 4.34 \text{ nb}$

- Theoretical calculation does not include non-direct $J/\psi \ J/\psi$

Quarkonia cross-section measurements: $\psi(2S)$

- $\psi(2S) \rightarrow \mu^+\mu^-$  \hspace{1cm} B.R. = $7.7 \pm 0.8 \times 10^{-3}$
- Measured also in $\psi(2S) \rightarrow J/\psi(\mu^+\mu^-) \pi^+\pi^-$  
  (see Bo Liu's talk at quarkonia session on thursday)

- Selection similar to the $J/\psi \rightarrow \mu^+\mu^-$ one
  - harder cut on muon $p_T$ ($p_T > 1200$ MeV/c)
- Fit: CB + exponential

$N$ of $\psi(2S) = 89374 \pm 718$
Quarkonia cross-section measurements: $\psi(2S)$

- Efficiencies estimated from MC and checked (trigger) with real data
- Systematic errors: luminosity, trigger, tracking, polarisation, ...

Our preliminary measurement includes $\psi(2S)$ from $b$ also: $b$ fraction expected to be 10% at low $p_T$ and 40% at large $p_T$

Quarkonia cross-section measurements: Y(1S)

- Measurement of the Y cross-section: same strategy already discussed for J/ψ
- Selection:
  - 2 muon tracks
  - muon $p_T$ cut (>1 GeV/c)
  - track fit quality cut ($\chi^2$/nDoF < 4)
  - vertex fit quality cut (p($\chi^2$)>0.01%)

- Fit: three CB for signal + exponential for background
- 2S, 3S masses and widths fixed
- Only Y(1S) is considered for cross-section measurement
Quarkonia cross-section measurements: $Y(1S)$

- Efficiencies computed from Monte Carlo
- Polarisation effect evaluated

Integrated value over $p_T < 15$ GeV/$c$ and $2 < y < 4.5$

$$\sigma = 108.3 \pm 0.7^{+30.9}_{-25.8} \text{ nb}$$
Exclusive dimuon production

- two muons in the final state: non resonant or resonant through $J/\psi$, $\psi(2S)$ or $\chi_c$
- pomeron (gg) and odderon (ggg) predicted by QCD can be studied in a clean environment

**Selection**

- 36 pb$^{-1}$
- No backward tracks (from VeLo)
- Only two forward muons
- $p_T(\mu\mu)<900$ MeV/c to reduce contamination from inelastic (diffractive) prod.
- No photons (one photon for $\chi_c$)
Exclusive dimuon production

$J/\psi$ 

$\psi(2S)$ 

$\text{inv mass} > 100 \text{ MeV}/c^2$ away from $J/\psi$ and $\psi(2S)$

14/06/2011
Exclusive dimuon production

\[
\sigma_{J/\psi \rightarrow \mu^+\mu^-}(2 < \eta_{\mu^+}, \eta_{\mu^-} < 4.5) = 474 \pm 12 \pm 51 \pm 92 \text{ pb}
\]

\[
\sigma_{\psi(2S) \rightarrow \mu^+\mu^-}(2 < \eta_{\mu^+}, \eta_{\mu^-} < 4.5) = 12.2 \pm 1.8 \pm 1.3 \pm 2.4 \text{ pb}
\]

\[
\sigma_{\chi_{c0} \rightarrow J/\psi \gamma \rightarrow \mu^+\mu^-\gamma}(2 < \eta_{\mu^+}, \eta_{\mu^-}, \eta_{\gamma} < 4.5) = 9.3 \pm 2.2 \pm 3.5 \pm 1.8 \text{ pb}
\]

\[
\sigma_{\chi_{c1} \rightarrow J/\psi \gamma \rightarrow \mu^+\mu^-\gamma}(2 < \eta_{\mu^+}, \eta_{\mu^-}, \eta_{\gamma} < 4.5) = 16.4 \pm 5.3 \pm 5.8 \pm 3.2 \text{ pb}
\]

\[
\sigma_{\chi_{c2} \rightarrow J/\psi \gamma \rightarrow \mu^+\mu^-\gamma}(2 < \eta_{\mu^+}, \eta_{\mu^-}, \eta_{\gamma} < 4.5) = 28.0 \pm 5.4 \pm 9.7 \pm 5.4 \text{ pb}
\]

\[
\sigma_{pp \rightarrow p\mu^+\mu^-p}(2 < \eta_{\mu^+}, \eta_{\mu^-} < 4.5; m_{\mu^+\mu^-} > 2.5 \text{ GeV/c}^2) = 67 \pm 10 \pm 7 \pm 15 \text{ pb}
\]

- Predictions are rather uncertain and vary a lot
- Exclusive J/ψ
  - Starlight generator: 292 pb
  - SuperChic generator: 330 pb
  - L. Motyka et al., PR D78 (2008) 014023: 330 pb
  - W. Schäfer et al., PR D76 (2007) 094014: 710 pb
- Exclusive ψ(2S)
  - Starlight generator: 6.1 pb
  - W. Schäfer: 17 pb
Prospects for polarisation measurements

- Theories give clear predictions of prompt $J/\psi$ polarisation
- Polarisation knowledge helps to decrease the error on the cross-sections measured

$$\frac{d^2N}{d\cos \theta d\phi} \propto 1 + \lambda_\theta \cos^2 \theta + \lambda_{\theta\phi} \sin 2\theta \cos \phi + \lambda_\phi \sin^2 \theta \cos 2\phi$$

**Coming soon**: polarisation measurement ($\lambda_\theta$, $\lambda_{\theta\phi}$, $\lambda_\phi$) in the helicity frame, in 15 $p_T$ bins, $0<p_T<15$ GeV/c

<table>
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<tr>
<th>Parameter</th>
<th>min</th>
<th>max</th>
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<tr>
<td>$\lambda_\theta$</td>
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<td>$\lambda_{\theta\phi}$</td>
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<tr>
<td>$\lambda_\phi$</td>
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</tbody>
</table>

Expected statistical sensitivity

Challenge: systematic due to the detector effect on the angular distributions
Conclusions

- Quarkonia results have been presented: cross-sections for
  - J/ψ (separately prompt and non-prompt)
  - double J/ψ
  - ψ(2S) (not yet separated prompt from non-prompt)
  - Y(1S)
  - Exclusive dimuon

- Comparison with the theoretical models: experimental error is lower than the theoretical one

- Other interesting informations will come from quarkonium polarisation measurements: results expected soon