Charm and Charmonia Production at LHCb

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(on behalf of LHCb)
Charmonium production mechanism is not well understood. Many theoretical models have been proposed but the agreement with experimental results is not yet satisfactory. This talk will give the most recent experimental results of the LHCb collaboration.

- Single arm spectrometer; ~25% of $b\bar{b}$ pairs produced in the acceptance (~20% for $c\bar{c}$ pairs)
- Unique kinematic region: high rapidity
Measurement of the relative rate of prompt $\chi_{c0}$, $\chi_{c1}$ and $\chi_{c2}$ production at $\sqrt{s} = 7$ TeV
Motivation and Selection

A $c\bar{c}$ pair is produced in gluon-gluon interactions, followed by the formation of bound charmonium states. This formation can be governed by purely perturbative Color Singlet Model or perturbative\(\otimes\)non-perturbative Color Octet Model.

Moreover, $\chi_c \rightarrow J/\psi \gamma$ can have a significant impact to the $J/\psi$ polarisation measurement.

Example of possible production diagrams in Color Octet model:

In this analysis, $\chi_c \rightarrow J/\psi \gamma$ decay is reconstructed. We select only the converted photons and $J/\psi \rightarrow \mu\mu$.

The photons converted in the detector material before the magnet reconstructed with new technique allow us to distinguish two peaks in data.
We fix the shape of the background distribution to the “fake” photons: the energy for them is set to twice that of $e^+$ or $e^-$. We than subtract this distribution and then perform the fit to the data using Crystal Ball functions to describe the $\chi_c$ signal.

We measure

$$\frac{\sigma(\chi_{c0})}{\sigma(\chi_{c2})} = 1.19 \pm 0.27 \text{ (stat)} \pm 0.29 \text{ (syst)} \pm 0.16 \text{ (p}_T\text{ model)} \pm 0.09 \text{ (B)}$$

the uncertainties are: statistical, systematics, $p_T$ modeling, branching fraction.

This gives the first evidence of $\chi_{c0}$ production at the hadron collider at $4.3\sigma$ significance.

For comparison, we obtain

$$\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})} = 0.787 \pm 0.014 \text{ (stat)} \pm 0.034 \text{ (syst)} \pm 0.051 \text{ (p}_T\text{ model)} \pm 0.047 \text{ (B)}$$
Results in transverse momentum bins

To compare to theory, we also measure $\sigma(\chi_{c1})/\sigma(\chi_{c2})$ as a function of transverse momentum.

The statistical and systematic uncertainties are not correlated to our previous analysis.

the uncertainties are: statistical, systematics, branching fraction and unknown polarisation
Measurement of $J/\psi$ polarization in pp collisions at $\sqrt{s} = 7$ TeV

$L = 0.37 \text{ fb}^{-1}$
The angular decay distribution is described by:

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

\(\theta\) is the polar angle between the direction of the positive lepton and the chosen polarization axis, 
\(\phi\) is the azimuthal angle, measured with respect to the production plane

In this formalism:

\((\lambda_\theta; \lambda_{\theta\phi}; \lambda_\phi) = (+1;0;0)\) - polarisation completely longitudinal
\((\lambda_\theta; \lambda_{\theta\phi}; \lambda_\phi) = (-1;0;0)\) - polarisation completely transverse
\((\lambda_\theta; \lambda_{\theta\phi}; \lambda_\phi) = (0;0;0)\) - unpolarised

Generally, the values of \(\lambda\) depend on the choice of the spin quantization frame.

We perform the analysis in the helicity frame (polarization axis coincides with the flight direction) and, as a cross-check, in the Collins-Soper frame (the polarization axis is the direction of the relative velocity of the colliding beams). The study is done in bins of rapidity and transverse momentum.
Candidate $J/\psi$ mesons are formed from pairs of opposite-sign muons reconstructed in the tracking system passing fiducial selection criteria on transverse momentum. We then study invariant mass and (pseudo) decay time distribution, $\tau$, which includes also the decay time resolution.

Example of distribution in the kinematic bin $5 < p_T < 7$ GeV/c and $3.0 < y < 3.5$

From these fits we define “signal region”: $\text{mass} \in [\mu-3\sigma;\mu+3\sigma]$, $|S_\tau|<4$.

“sidebands region”: $\text{mass} \in [\mu-3\sigma;\mu+3\sigma]$. 
We define the likelihood:

\[
\log L = \sum_{i=1}^{N_{\text{tot}}} w_i \times \log \left( \frac{P(\cos \theta_i, \phi_i | \lambda_\theta, \lambda_\theta, \lambda_\phi) \epsilon(\cos \theta_i, \phi_i)}{N(\lambda_\theta, \lambda_\theta, \lambda_\phi)} \right)
\]

\[
= \sum_{i=1}^{N_{\text{tot}}} w_i \times \log \left( \frac{P(\cos \theta_i, \phi_i | \lambda_\theta, \lambda_\theta, \lambda_\phi)}{N(\lambda_\theta, \lambda_\theta, \lambda_\phi)} \right) + \sum_{i=1}^{N_{\text{tot}}} w_i \times \log [\epsilon(\cos \theta_i, \phi_i)]
\]

with \( w_i = \)

\(+1 \) signal region

\(-1 \) sidebands region

Efficiency is taken from simulated events for each kinematical bin:

We cross-check the fitting model on the \( B \rightarrow J/\psi K \) decays, where \( J/\psi \) is completely polarised. This is confirmed by our fit.
We obtain the following results in the Helicity frame:

\[ \lambda_0 \]

\[ p_T(J/\psi) [\text{GeV}/c] \]

In addition, we update the cross-section results:

\[ \sigma_{\text{prompt}}(2 < y < 4.5, 2 < p_T < 14 \text{ GeV}/c) = 4.88 \pm 0.01 \pm 0.27 \pm 0.12 \mu\text{b} \]

\[ \sigma_{\text{prompt}}(2 < y < 4.5, p_T < 14 \text{ GeV}/c) = 9.46 \pm 0.04 \pm 0.53^{+0.86}_{-1.10} \mu\text{b} \]

Previously, results had high systematic uncertainty due to the unknown polarisation up to 20%.)
Study of the Quarkonia production at different energies
J/ψ production at $\sqrt{s} = 2.76$ TeV

The analysis is performed with 71 nb$^{-1}$ of data. 2D fit to extract the number of J/ψ.

$$\sigma (J/\psi, p_T < 12 \text{ GeV}/c, 2.0 < y < 4.5) = 5.6 \pm 0.1 \pm 0.4 \mu b.$$  
$$\sigma (J/\psi \text{ from } b, p_T < 12 \text{ GeV}/c, 2.0 < y < 4.5) = 400 \pm 35 \pm 49 \text{ nb}.$$  

J/ψ production at $\sqrt{s} = 8$ TeV

The analysis is performed with 51 pb$^{-1}$ of data.

$$\sigma (\text{prompt } J/\psi, p_T < 14 \text{ GeV}/c, 2.0 < y < 4.5) = 10.94 \pm 0.02 \pm 0.79 \mu b.$$  
$$\sigma (J/\psi \text{ from } b, p_T < 14 \text{ GeV}/c, 2.0 < y < 4.5) = 1.28 \pm 0.01 \pm 0.11 \mu b.$$  

Y(nS) results are also available (see backup)
Study of the J/ψ production cross-section in proton-lead collisions at $\sqrt{s_{NN}} = 5$ TeV
The analysis was performed using data collected in September 2012. A particular benefit of LHCb detector is again its coverage in rapidity.

The full study of production is performed, we extract the differential cross-section and the full cross-section.

\[
\sigma_{Ap}(\text{prompt } J/\psi; p_T < 14 \text{ GeV/c}, -5.0 < y < -2.5) = 1141.9 \pm 49.8 \text{ (stat.)} \pm 98.4 \text{ (syst.) } \mu\text{b},
\]
\[
\sigma_{Ap}(J/\psi \text{ from } b; p_T < 14 \text{ GeV/c}, -5.0 < y < -2.5) = 119.7 \pm 8.3 \text{ (stat.)} \pm 10.0 \text{ (syst.) } \mu\text{b}.
\]

\[
\sigma_{pA}(\text{prompt } J/\psi; p_T < 14 \text{ GeV/c}, 1.5 < y < 4.0) = 1028.2 \pm 13.6 \text{ (stat.)} \pm 88.6 \text{ (syst.) } \mu\text{b},
\]
\[
\sigma_{pA}(J/\psi \text{ from } b; p_T < 14 \text{ GeV/c}, 1.5 < y < 4.0) = 150.1 \pm 4.2 \text{ (stat.)} \pm 12.6 \text{ (syst.) } \mu\text{b}.
\]
LHCb has performed a set of analyses on quarkonia production and polarisation.

The production cross-section have got a well pronounced dependence of energy.

More results to come.
Exclusive Charmonia Production $\sqrt{s} = 7$ TeV

$\mathcal{L} = 36$ pb$^{-1}$
We reconstruct only events with exactly two tracks. DiMuon transverse momentum is used to discriminate between signal and inelastic background component. Signal distribution is estimated with SuperChic event generator.

We obtain:

\[
\sigma_{pp\rightarrow J/\psi(\rightarrow \mu^+\mu^-)}(2.0 < \eta_{\mu^\pm} < 4.5) = 307 \pm 21 \pm 36 \text{ pb},
\]

\[
\sigma_{pp\rightarrow \psi(2S)(\rightarrow \mu^+\mu^-)}(2.0 < \eta_{\mu^\pm} < 4.5) = 7.8 \pm 1.3 \pm 1.0 \text{ pb},
\]

Moreover we were able to estimate the dependence of the J/Psi production on the centre-of-mass energy of the photon-proton system, W. The results are compatible to that of H1 and Zeus.
Prompt charm production in pp collisions at $\sqrt{s} = 7$ TeV (via open charm)

For D-meson production asymmetries see Hamish Gordon's talk.

$\mathcal{L} = 15$ nb$^{-1}$
The analysis is based on fully reconstructed decays of charmed hadrons in the following decay $D^0 \rightarrow K\pi$, $D^+ \rightarrow K\pi\pi\pi$, $D^* \rightarrow D^0(K\pi)\pi\pi$, $D_s \rightarrow \phi(KK)\pi\pi$, and $\Lambda \rightarrow pK\pi$. After kinematic selection, we perform a 2D fit to each channel, using invariant mass, $\log_{10}(IP\chi^2)$. In $D^*$ case we additional fit to $\Delta m = m_{D^*} - m_D$.

We then use the following formula to obtain the differential cross-section.

\[
\frac{d\sigma_i(H_c)}{dp_T} = \frac{1}{\Delta p_T} \cdot \frac{N_i(H_c \rightarrow f + c.c.)}{\varepsilon_{i,tot}(H_c \rightarrow f) \cdot B(H_c \rightarrow f) \cdot L_{int}}
\]

$\Delta p_T$ is the width in pT of bin i, $N_i(H_c \rightarrow f + c.c.)$ is the measured yield of $H_c$ and their charge conjugate decays, $B(H_c \rightarrow f)$ is the branching fraction of the decay, $\varepsilon_{i,tot}(H_c \rightarrow f)$ is the total efficiency for observing the signal decay in bin i, and $L_{int} = 15.0 \pm 0.5$ nb$^{-1}$ is the integrated luminosity of the sample.
Finally, using fragmentation function from PDG, we can obtain the total production cross-section

$$\sigma (c\bar{c}) \mid p_T < 8 \text{ GeV/c}, \ 2.0 < y < 4.5 = 1419 \pm 12 \text{ (stat)} \pm 116 \text{ (syst)} \pm 65 \text{ (frag)} \mu b$$
Conclusions

LHCb provides a good laboratory to study the quark-antiquark pair production.

The results of LHCb are different and complimentary to those of General Purpose Detectors.

The comparison of theoretical models can be performed using already set of results shown in this presentation.
Backup
Quarkonia production at $\sqrt{s} = 8$ TeV

We also perform the $Y(ns)$ production measurements with $Y(ns)$ reconstructed from the pair of muons

Here $B^{is}$ is the branching fraction of $Y(is) \rightarrow \mu\mu$