Quarkonia production and polarisation at LHCb

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Outline

- Detector and data sample
- $J/\psi$, $Y(nS)$ production at $\sqrt{s}=8$ TeV
- $\chi_{cj}$ production
- $J/\psi$ polarisation
- $\Lambda_b$ polarisation
The LHCb experiment

Designed for CP violation and rare decays of heavy mesons
Single arm spectrometer, 40% of bb pairs produced in the acceptance.
Unique kinematic region:
high rapidity \(2.0 < y < 4.5\) and low pT

In total 3 fb\(^{-1}\) available for analyses
1 fb\(^{-1}\) @ 3.5TeV, 2 fb\(^{-1}\) @4TeV
Detector efficiency > 95%
Motivation

- Measurements of heavy-quark and quarkonia provide powerful tests on QCD models
- Current models (NRQCD, CSM, COM, $k_T$ factorization) have very different predictions, not always in agreement with experimental measurements
  - production of prompt $J/\psi$, $\psi(2S)$, $Y$, $\chi_c$
  - their polarisations
- LHCb can provide essential and unique contribution

![Graph showing $J/\psi$ polarisation at CDF](PRL 99 (2007) 132001 arXiv:0704.0638)
Measurement of the double differential production cross-section: bin in $y$ and $p_T$

About 2.6 M signals in $p_T < 14$ GeV/c and $2.0 < y < 4.5$

Prompt and from $b$ decays components separated using pseudo-decay time $t_z$

Simultaneous fit of the mass and the pseudo-decay time

Efficiency evaluated with MC simulation and validated on data

Systematic uncertainty ~ 7% dominated by luminosity and trigger efficiency
**Prompt J/ψ in good agreement with NLO NRQCD**

**J/ψ from b: in good agreement with FONLL**
Y(nS) production at $\sqrt{s} = 8$ TeV

→ previous measurements at 7 TeV

Measurement of the double differential cross-sections for the three Y states

NNLO is necessary
Better agreement with Y(3S), less feed-down contributions
\( \chi_{cj}(1P) \) production ratio

→ previous measurements without converted photons

\( \chi_c \) identified through the decay \( \chi_c \rightarrow J/\psi \rightarrow \mu\mu \gamma \)

Measurement using photons that convert in the detector and applying bremsstrahlung correction

Measurement with 1 fb\(^{-1} \) integrated luminosity (2011) in bin of pT and integrating on rapidity \( 2.0 < y < 4.5 \)

The use of the converted photons allows to clearly separate \( \chi_{c1} \) and \( \chi_{c2} \): lower statistics but better mass resolution
**$\chi_{cj}(1P)$ production ratio**

\[ \sigma(\chi_{c2})/\sigma(\chi_{c1}) \] decreases with \( J/\psi \) pT

Good agreement with (N)LO NRQCD predictions for pT > 4 GeV/c

Systematic uncertainty (~6%) dominated by photon efficiency

Large uncertainty (not included) from the unknown polarisation of the two $\chi$ states

**First evidence of the $\chi_{c0}$ state at hadron collider with a significance of 4.3\(\sigma\)**


LO: arXiv:1305.2389
J/ψ polarisation at $\sqrt{s} = 7$ TeV

Motivation

NLO NRQCD predicts J/ψ (Y) production cross section very well, but not polarisation. Important input to validate different models

Large uncertainty of cross-section measurement due to unknown polarisation

Strategy

Full angular analysis to determine polarisation parameters ($\lambda_\theta$, $\lambda_{\theta\phi}$, $\lambda_\phi$)

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

The angular distribution of the positive decay lepton is reported in one of the two following systems of axes, differing in the definition of the polarization axis (z):

- Helicity frame (HX)
- Collins-Soper (CS)
J/ψ polarisation at $\sqrt{s} = 7$ TeV

analysis key points

Crucial ingredient of the analysis is the knowledge of the **detector angular efficiency**. Angular efficiency distortion can result in artificial polarisation.

Important also to reject the combinatorial **background** contamination.

Weighted log likelihood used to extract the polarisation parameters and to subtract the background

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

$\omega_i$ from a sWeight-like technique

Efficiency $\epsilon(\cos \theta, \phi)$ estimated with simulation and corrected using $B^{\pm} \rightarrow J/\psi K^{\pm}$

Norm(): normalization function, evaluated with the unpolarised MC sample

Data sample: 370 pb$^{-1}$ at 7 TeV
**J/ψ polarisation at $\sqrt{s} = 7$ TeV**

**Results**

Measurement performed in bins of J/ψ pT and rapidity

Since in HX frame $\lambda_\phi \approx 0$, $\lambda_\theta$(HX) = $\lambda_{\text{inv}} = (\lambda_\theta - 3\lambda_\phi)/(\lambda_\theta - \lambda_\phi)$ is a unambiguous indicator of the polarisation

J/ψ meson results to have a weak longitudinal polarization

Uncertainty dominated by the systematic associated with efficiency correction
**J/ψ polarisation at $\sqrt{s} = 7$ TeV**

**Comparison with theory**

Measured $\lambda_\theta$ contradicts the CSM predictions for direct J/$\psi$ production, both in size of the polarization parameters and pT dependence.

Concerning the NRQCD models, predictions can result in a better agreement with LHCb results (it depends on the scheme used to evaluate the non-perturbative matrix elements).

Agreement with ALICE’s results with large uncertainty in ALICE

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**Graphs and References**

- NLO NRQCD (2): PRL110(2013) 042002
- ALICE: PRL108(2012)082001
Polarisation affects the efficiency (acceptance) in cross-section measurement. The measurement of the J/Ψ production cross-section has been updated, in light of the polarisation measurement.

\[
\sigma(\text{prompt } J/\psi; \ p_T < 14 \text{ GeV/c}, \ 2.0 < y < 4.5) = 9.46 \pm 0.04 \pm 0.53^{+0.86}_{-1.10} \mu b
\]

previous measurement:
\[
\sigma(\text{prompt } J/\psi; \ p_T < 14 \text{ GeV/c}, \ 2.0 < y < 4.5) = 10.52 \pm 0.04 \pm 1.40^{+1.64}_{-2.20} \mu b
\]
$\Lambda^0_b \rightarrow J/\psi \Lambda$ decay amplitudes and $\Lambda^0_b$ polarization

$\Lambda^0_b$ in $pp$ collisions expected to be transversally polarized (HQET)

**Not yet measured** at a hadron collider

$\Lambda^0_b \rightarrow \Lambda J/\psi (1/2 \rightarrow 1/2 + 1)$ with $\Lambda \rightarrow p\pi$ and $J/\psi \rightarrow \mu^+\mu^-$

Decay dynamics is completely described looking at 5 angles

Integrating over azimuthal $\phi_1$ and $\phi_2$, we simplify the decay distribution and we still are sensitive to polarization and squared amplitudes
\[ \Lambda^0_b \rightarrow J/\psi \Lambda \text{ decay formalism} \]

three angles differential decay rate

\[ \frac{d\Gamma}{d\Omega_3} = \frac{1}{16\pi} \sum_{i=0}^{7} f_i (|M_{1/2,0}|^2, |M_{-1/2,0}|^2, |M_{-1/2,-1}|^2, |M_{1/2,+1}|^2) \ g_i (P_b, \alpha_\Lambda) \ h_i (\cos \theta, \cos \theta_1, \cos \theta_2) \]

\[ M_{\lambda_1,\lambda_2} \text{ helicity amplitudes (4)} \]

\[ |M_{1/2,0}|^2 + |M_{-1/2,0}|^2 + |M_{-1/2,-1}|^2 + |M_{1/2,+1}|^2 = 1 \]

\[
\begin{array}{|c|c|c|c|}
\hline
i & f_i (\alpha_b, r_0, r_1) & g_i (P_b, \alpha_\Lambda) & h_i (\cos \theta, \cos \theta_1, \cos \theta_2) \\
\hline
0 & 1 & 1 & 1 \\
1 & \alpha_b & P_b & \cos \theta \\
2 & 2r_1 - \alpha_b & \alpha_\Lambda & \cos \theta_1 \\
3 & 2r_0 - 1 & \bar{P}_b \alpha_\Lambda & \cos \theta \cos \theta_1 \\
4 & \frac{1}{2} (1 - 3r_0) & 1 & \frac{1}{2} (3 \cos^2 \theta_2 - 1) \\
5 & \frac{1}{2} (\alpha_b - 3r_1) & P_b & \frac{1}{2} (3 \cos^2 \theta_2 - 1) \cos \theta \\
6 & -\frac{1}{2} (\alpha_b + r_1) & \alpha_\Lambda & \frac{1}{2} (3 \cos^2 \theta_2 - 1) \cos \theta_1 \\
7 & -\frac{1}{2} (1 + r_0) & \bar{P}_b \alpha_\Lambda & \frac{1}{2} (3 \cos^2 \theta_2 - 1) \cos \theta \cos \theta_1 \\
\hline
\end{array}
\]

\( \alpha_\Lambda \text{ known} \)

Four parameters to be determined simultaneously from the angular distribution

\[ \alpha_b \equiv |M_{1/2,0}|^2 - |M_{-1/2,0}|^2 + |M_{-1/2,-1}|^2 - |M_{1/2,+1}|^2 \]

\[ r_0 \equiv |M_{1/2,0}|^2 + |M_{-1/2,0}|^2 \]

\[ r_1 \equiv |M_{1/2,0}|^2 - |M_{-1/2,0}|^2 \]

\[ P_b \rightarrow \text{tranverse polarisation, expected 0.1-0.2} \]

Amplitude asymmetry, predicted 15%*

PLB 614 (2005) 165
PLB 649 (2007) 1952
Λ^0_b \rightarrow J/\psi \Lambda \text{ signal selection}

Analysis based on 1 fb^{-1} at 7 TeV

Two different classes of events analysed separately: decay inside (LL) or outside (DD) the VELO

Weighted Likelihood implemented to subtract the background and correct for the detector efficiency:

\[ w_i = w(m) \times w(\cos \theta, \cos \theta_1, \cos \theta_2) \]

- \( w_i = w(m) \) → Mass term: from mass distribution
- \( w(\cos \theta, \cos \theta_1, \cos \theta_2) \) → detector acceptance term: from simulation

\[ \begin{align*}
\Lambda^0_b \rightarrow J/\psi \Lambda \\
\text{DD} & \quad 5346 \pm 96 \\
\text{LL} & \quad 1861 \pm 49
\end{align*} \]
$\Lambda^{0}_b \rightarrow J/\psi \Lambda$ angular distributions fit and results

Angular distribution, background subtracted and acceptance corrected

$P_b = 0.05 \pm 0.07 \pm 0.02$

$\alpha_b = -0.04 \pm 0.17 \pm 0.07$

$r_0 = 0.57 \pm 0.02 \pm 0.01$

$r_1 = -0.59 \pm 0.10 \pm 0.05$

cannot exclude T pol at 10%

compatible with 0.15 prediction

Systematic errors mostly due to the determination of the acceptance function from Monte Carlo: ~100% of $P_b$ error and ~60% of $a_b$ error
Conclusions

LHCb made several measurements of quarkonia production and polarisation and is contributing significantly to this sector.

Cross-sections of $J/\psi$ and $Y$ measured at various energy

$\chi_c$ production ratio using converted/unconverted photons and first evidence of $\chi_{c0}$ at hadron collider

$J/\psi$ and $\Lambda_b$ polarisation measured at 7 TeV

... many more analyses in progress with 2011+2012 data sets