Onia Production and Spectroscopy at LHCb

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Outline

- Introduction to the LHCb experiment.
- Quarkonia production:
  - $J/\psi$ production cross-section.
  - $J/\psi$ polarization.
  - $\Upsilon(nS)$ production cross-section.
  - $\chi_c$ production cross-section.
- Spectroscopy: $X(3872)$ characterization.
- Conclusion.
The LHCb detector

Data samples:

- 2010: 0.037 fb\(^{-1}\) at \(\sqrt{s}=7\) TeV
- 2011: 1.1 fb\(^{-1}\) at \(\sqrt{s}=7\) TeV
- 2012: 2 fb\(^{-1}\) at \(\sqrt{s}=8\) TeV

results presented here are based on 2011 and 2012 data

tracking, ECAL, HCAL, counters lumi, muon, hadron PID
Abundantly produced in LHCb: \( \sim 60 \text{ Hz of } J/\psi \to \mu^+\mu^- @ 2012 \text{ conditions}. \)

Most of them are very well known resonances (width, mass peak, \( br \), ...).

Production mechanism not yet fully understood.

Active interest of theorists (Tevatron puzzle), several models of the production mechanism available:
- Color-Singlet (CS)
- Color-Octet (CO)
- FONLL (production from b-hadron decays)

For the LHC experiments, new computations are being performed: NLO, NNLO(*) corrections to CS and CO production.

LHCb studies quarkonium hadroproduction in a unique kinematic region:
- Forward rapidity range \( (2<y<4.5) \)
- Low \( p_T \) range \(<20 \text{ GeV/c} \)
J/ψ production

- Select decays of J/ψ into muon pairs:
  - opposite charged tracks from same vertex
  - good track quality and μID
  - minimum threshold on $p_T(μ)$

- Measurement of the double differential production cross-section in bins of $γ$ and $p_T$:
  - $0 < p_T < 14$ GeV/c
  - $2.0 < γ < 4.5$

- Prompt J/ψ and J/ψ from b decays components separated using pseudo-proper time:
  $$t_z = (z_{J/ψ} - z_{PV}) \times M_{J/ψ}/p_z$$

- Signal extraction by a simultaneous fit to $m_{μμ}$ and $t_z$ in each ($p_T, γ$) bin

2.6M J/ψ in 18 pb$^{-1}$ at $√s = 8$ TeV
Prompt $J/\psi$: results

- Prompt $J/\psi$ mesons assumed to be produced unpolarised

- $\sigma$(prompt $J/\psi$; $p_T < 14$ GeV/$c$, $2.0 < y < 4.5$) = 10.94 ± 0.02 (stat) ± 0.79 (sys) µb
- $\sigma$(J/ψ from b; $p_T < 14$ GeV/$c$, $2.0 < y < 4.5$) = 1.28 ± 0.01 (stat) ± 0.11 (sys) µb

- Systematic uncertainty ~ 7% (main contribution from luminosity and trigger efficiency)
- Predictions for direct $J/\psi$ meson production
- Experimental data include feed-down from higher charmonium states (20% from $\chi_c \rightarrow J/\psi \gamma$ and 8% from $\psi(2S) \rightarrow J/\psi \pi\pi$)
- Data in good agreement with NLO NRQCD

NLO CSM model:

NLO NRQCD model:
*Phys. Rev. D84 (2011) 051501
Phys. Rev. Lett. 106 (2011) 022003*

NNLO* model:
J/ψ from b: results

- Excellent agreement with theory
- 8 TeV data in *JHEP 06 (2013) 064*
- 2.76 TeV data in *JHEP 02 (2013) 041*
• Prompt charmonium production still puzzling: many theoretical models available describing well the cross section but not the polarization (NLO NRQCD).

• Prompt J/ψ cross-section depends on polarization (distortion in the decay product acceptance), may lead to large uncertainty on cross-section measurement.

• Status of experimental studies: previous measurements from CDF, PHENIX, HERA-B (PRL 99 (2007), 132001, PRD 82 (2010), 012001, EPJ C 60 (2009), 517)

• At LHC:
  ◦ Recent results from CMS arXiv:1307.6070.
J/ψ polarisation: strategy

- Data sample: 0.37 fb\(^{-1}\) integrated luminosity from 2011 run, in bins of \(p_T\) and \(y\)
- Extract polarization from angular distribution of the J/ψ -> \(μμ\) (feed-down included)
- Full angular analysis to determine the polarisation parameters (\(λ_0\), \(λ_\varphi\), \(λ_φ\)):

\[
\frac{d^2N}{d \cos \theta d \varphi} \propto 1 + λ_\theta \cos^2 \theta + λ_\varphi \sin 2\theta \cos \varphi + λ_φ \sin^2 \theta \cos 2\varphi
\]

- Data presented in two different polarisation frames: Helicity frame (HX) and Collin-Soper frame (CS)
- Prompt J/ψ and J/ψ from b decays components separated by using pseudo-proper time

\[5<p_T<7\text{ GeV/c},
3.0<y<3.5\]


Parameters \( \lambda_{\theta\phi} \) and \( \lambda_{\phi} \) consistent with 0, so \( \lambda_{\text{inv}} = (\lambda_{\theta} + 3\lambda_{\phi})/(1 - \lambda_{\phi}) = \lambda_{\theta} \)

A small longitudinal polarization is observed.

Results in HX and CS are consistent.

LHCb results are compatible with NLO NRQCD calculations that include feed-down contributions.

Good agreement is also observed with recent measurements from ALICE and CMS (although in a different kinematic region).
Y(nS) production

\[ \sigma(pp \rightarrow Y(1S) X) \times B^{1S} = 3.241 \pm 0.018 \text{ (stat)} \pm 0.231 \text{ (sys)} \text{ nb} \]
\[ \sigma(pp \rightarrow Y(2S) X) \times B^{2S} = 0.761 \pm 0.008 \text{ (stat)} \pm 0.055 \text{ (sys)} \text{ nb} \]
\[ \sigma(pp \rightarrow Y(3S) X) \times B^{3S} = 0.369 \pm 0.005 \text{ (stat)} \pm 0.027 \text{ (sys)} \text{ nb} \]

\[ B^{iS} = Br[ Y(iS) \rightarrow \mu \mu ], \ i=1,2,3 \]

JHEP 06 (2013) 064
Y(nS) production: data vs. theory

- reasonable agreement with NNLO* CSM
- no feed-down included in theory
- NLO NRQCD not yet available

NLO CSM: PRL 98 (2007) 252002
NNLO* CSM: PRL 101 (2008) 152001
Summary of production cross-section at $\sqrt{s} = 7$ TeV

Presented by H.K. Woehri at LHCP 2013, Barcelona, 13-18 May 2013

- impressive amount of results
- nice complementarity in acceptance among GPDs and LHCb

Note: the lines do not represent any theoretical model; they are added to help guiding the eye through the points
Studies on $\chi_c$ production provide an important test for understanding quarkonium production.

- substantial feed-down contribution to prompt $J/\psi$ from $\chi_c$ states impact on $J/\psi$ polarization measurements.
- $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ is sensitive to CS and CO models.

Select prompt $\chi_{cj} \rightarrow (J/\psi \rightarrow \mu \mu) \gamma$

- photons reconstructed in the calorimeter:
  - high statistics
  - poor resolution

- photons converted in the detector material before the magnet ($\gamma \rightarrow e^+e^-$):
  - improve mass resolution (tracker)
  - lower statistics (light material budget in the vertex locator)
**$\chi_c$ production at $\sqrt{s} = 7$ TeV**

- Measurement with 1 fb$^{-1}$ at $\sqrt{s} = 7$ TeV, in bins of $p_T$ and integrated over rapidity in the range $2.0 < y < 4.5$, using converted photons.

- First evidence of the $\chi_{c0}$ state at a hadron collider with a significance of 4.3$\sigma$!

- $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ in reasonable agreement with (N)LO NRQCD predictions for $p_T > 4$ GeV/c

- Systematic uncertainty (~6$\%$) dominated by photon efficiency

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

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NLO: PRD 83 (2011) 111503
New exotic mesons have been observed by different experiments: X(3872), X(4140), Z±(4430), which don't fit into the ccbar conventional picture.

X(3872) discovered by Belle (2003) in B± -> X(3872)K± [PRL 91 (2003) 262001] and confirmed by CDF, D0 and BaBar. Also LHCb measured production cross-section and mass with 34.7 pb⁻¹ at √s = 7 TeV [EPJ C72, 1972 (2012)]

After 10 years, its nature still uncertain (conventional charmonium, bound D⁰D* molecule, tetraquark state,...)

C-parity known to be positive as X(3872) -> J/ψ γ observed by Belle [PRL 107 091803] and BaBar [PRD 74 071101 (R)]

CDF helicity angle measurement [PRL 98 132002] excluded all JPC except:
- JPC = 2⁺: ηc₂(1¹D₂)
- JPC = 1++: χc₁(2³P₁) or exotic D⁰D* bound state or tetraquark

Belle data of X(3872) -> J/ψ ππ equally well described by 1++ and 2⁺ [PRD 84 052004]

BaBar analysis of X(3872) -> J/ψ ω prefers 2⁺ but does not exclude 1++ [PRD 82, 011101(R)]
X(3872): analysis strategy

- Goal: measure the X(3872) $J^{PC}$

- 5-D angular correlations of decay products in $B^+ \rightarrow X(3872) K^+$ decay mode, with $X(3872) \rightarrow J/\psi \, \pi^+ \pi^-$

- Data sample: 1 fb$^{-1}$ at $\sqrt{s} = 7$ TeV (2011)
  - $B^+ \rightarrow \psi(2S) K^+$ as a control channel
  - $313\pm26$ $B^+ \rightarrow X(3872) K^+$ (568$\pm$31 bkg events)
  - 68% signal purity in $\pm 2.5\sigma_X$ region
  - $\sigma_X = 5.5 \pm 0.5$ MeV

- Angular correlations in the $B^+$ decay chain carry information on the $J^{PC}$ of the X(3872)

- 5-D angular space: $\Omega = (\cos\theta_X, \cos\theta_{\pi\pi}, \Delta\phi_{X,\pi\pi}, \cos\theta_{J/\psi}, \Delta\phi_{X,J/\psi})$
X(3872): results

- Likelihood ratio test to discriminate between the two $J^{PC}$ hypotheses:
  - test statistic $t = -2 \ln[L(2-+)/L(1++)]$  
  - $t > 0$ favors $1^{++}$, $t < 0$ favors $2^+$
  - we observe $t_{data} = 99$, which favours $1^{++}$ over $2^+$ (rejected at $>8\sigma$)

- Angular correlations in 5-D allow for very clear separation between the two $J^{PC}$ hypotheses
- Conventional charmonium fading: only $cc\bar{c}$ possibility is $\chi_{c1}(2^3P_1)$, but mass is off
- Stay tuned for more results in the exciting field!

- Marginal differences in 1D distributions between $1^{++}$ and $2^+$
- Discrimination relies on correlations in specific phase-space regions
Conclusions

- Lots of contributions in quarkonium sector from LHCb, both in production and spectroscopy.
- Prompt J/ψ polarization: measurement indicates a small longitudinal polarization.
- Measurement of $\chi_{c2}/\chi_{c1}$ production cross-section
- Determination of the X(3872) quantum numbers: measurement favours the $1^{++}$ state.
  - If conventional charmonium state: exclude the $\eta_{c2}(1^{1}D_{2})$, still a possibility with $\chi_{c1}(2^{3}P_{1})$, but disfavoured by mass.
  - More exotic nature: DD molecule, tetraquark or charmonium-molecule mixture.
LHCb Trigger

40 MHz bunch crossing rate

L0 Hardware Trigger: 1 MHz readout, high $E_T/P_T$ signatures

- 450 kHz $h^\pm$
- 400 kHz $\mu/\mu$ and $e/\gamma$

Software High Level Trigger
- Introduce tracking/PID information, find displaced tracks/vertices
- Offline reconstruction tuned to trigger time constraints
- Mixture of exclusive and inclusive selection algorithms

5 kHz Rate to storage
- 2 kHz Inclusive Topological
- 2 kHz Inclusive/Exclusive Charm
- 1 kHz Muon and DiMuon

40 MHz bunch crossing rate

L0 Hardware Trigger: 1 MHz readout, high $E_T/P_T$ signatures

- 450 kHz $h^\pm$
- 400 kHz $\mu/\mu$ and $e/\gamma$

Defer 20% to disk

Software High Level Trigger
- 29000 Logical CPU cores
- Offline reconstruction tuned to trigger time constraints
- Mixture of exclusive and inclusive selection algorithms

5 kHz Rate to storage
J/ψ double differential cross-section

(a) Prompt from b

(b) From b

LHCb √s = 8 TeV

\( \frac{d^2\sigma(J/\psi)}{dp_T dy} \) [nb/(GeV/c)]

\( p_T [GeV/c] \)

\( \sqrt{s} = 8 \) TeV

LHCb

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J/ψ polarisation: results

![Graph showing J/ψ polarisation results in the HX and CS frames.](image)

LHCb $\sqrt{s} = 7$ TeV

- HX frame
- CS frame

**Legend:**
- $2.0 < y < 2.5$
- $2.5 < y < 3.0$
- $3.0 < y < 3.5$
- $3.5 < y < 4.0$
- $4.0 < y < 4.5$