Heavy Flavour production and spectroscopy at LHCb

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Outline

- Physical motivation for studying heavy flavour physics.
- About charm:
  - J/ψ production cross section results.
  - χ_c studies: χ_c to J/ψ cross section ratio and χ_{c2} to χ_{c1} cross section ratio.
  - Double charm production, double J/ψ, J/ψ + open charm production.
  - Open charm production cross section.
- About b:
  - $b\overline{b}$ production cross section.
  - Λ_b^0 and excited states.
- Conclusion and prospect.

Charmonium production at LHCb

Charmonium production mechanism is not well understood. Many theoretical models have been proposed but the agreement with experimental results is not yet satisfactory.
LHCb contributions (presented in this talk):

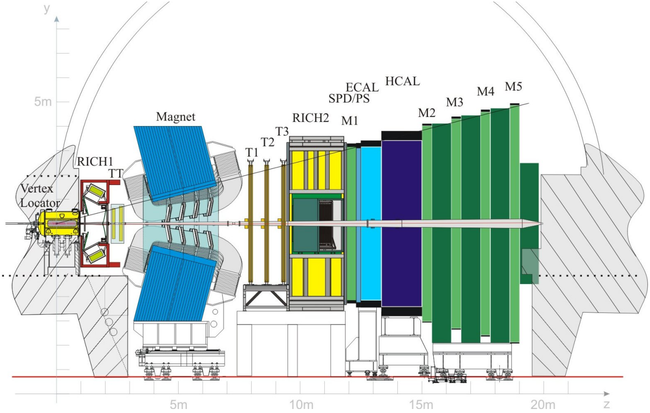
- J/ψ cross section and polarization, χ_c production: provide an important test for Color Singlet Model vs Color Octet Model.
- Measurements of production cross section of double J/ψ and J/ψ + open charm:
  - extremely rare processes (as predicted by QCD);
  - at LHC energies the main contribution is expected from the gluon-gluon fusion;
  - important test for Double Parton Scattering vs Single Parton Scattering.

Contributions at high energy to charmonium production are

1. Direct production in *pp* collisions prompt
2. Feed down from excited states ($\psi(2S)$, χ_c ...) prompt
3. Production from *b*-hadrons decays delayed

The LHCb experiment

- Single-arm forward spectrometer. Pseudorapidity range: $2 < \eta < 5$.
- Characteristics and performances:
  - Vertexing: proper time resolution 30-50 fs
  - MuonId: $\epsilon(\mu \to \mu) = 97\%$ $\epsilon(\pi \to \mu) = 2\%$
  - Charged tracks $\Delta p/p < 0.4\% - 0.6\%$

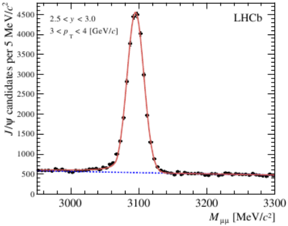


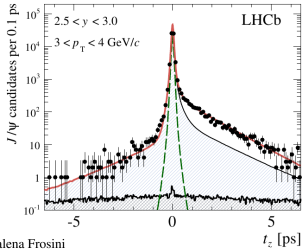
Year	L
2010	**37** pb^{-1} at 7 TeV
2011	**1.1** fb^{-1} at 7 TeV
2012	**2.1** fb^{-1} at 8 TeV

J/ψ cross section measurement at $\sqrt{s} = 7$ TeV

J/ψ production cross section: $$\frac{d^2\sigma}{dp_T dy} = \frac{N(J/\psi \to \mu^+\mu^-)}{L \times \varepsilon_{tot} \times Br(J/\psi \to \mu^+\mu^-)\Delta p_T \Delta y}$$

- Data sample $L = 5.1\ \text{pb}^{-1}$.
- Rapidity range $2.0 < y < 4.5$.
- Signal selection: good muon tracks and vertexing, muons $p_T > 700$ MeV/c.
- Efficiency ε_{tot}: simulated with an unpolarized Monte Carlo sample and cross-checked with data.





- Use J/ψ pseudo proper time to disentangle prompt J/ψ and J/ψ from b.

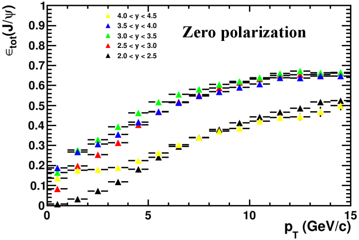
$$t_z = \frac{(z_{J/\psi} - z_{PV})m_{J/\psi}}{p_z}$$

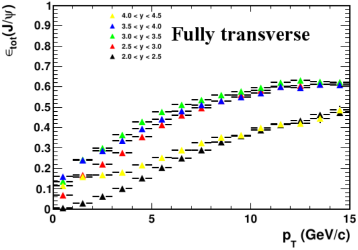
- Eur. Phys. J. C 71 (2011) 1645.

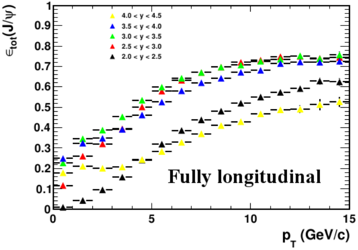
Efficiency

Total efficiency ε_{tot} includes detector acceptance, reconstruction, trigger.

- J/ψ **polarization** (acceptance and reconstruction efficiency): ε_{tot} built with non-zero polarization MC sample.

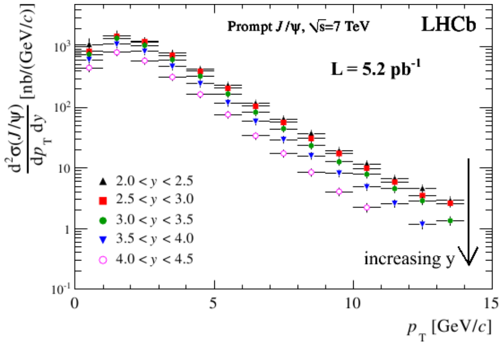






- Deviation from zero polarization is taken as systematic uncertainty.

Results: prompt J/ψ



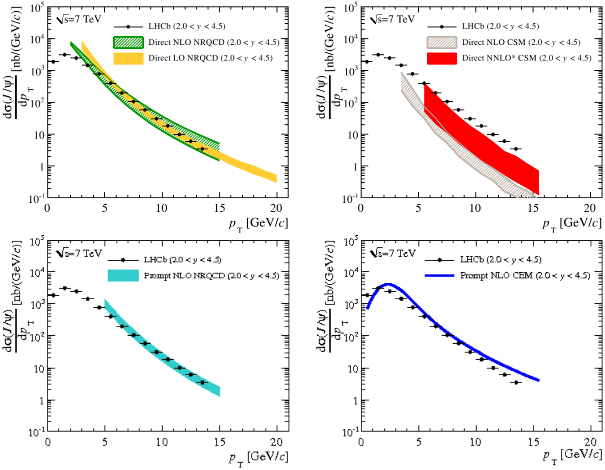
Eur. Phys. J. C 71 (2011) 1645

Total cross section is estimated summing over each analysis bin ($p_T < 14$ GeV/c and $2 < y < 4.5$)

$$\sigma_{\text{prompt } J/\psi} = \left[10.52 \pm 0.04(\text{stat}) \pm 1.40(\text{syst})^{+1.64}_{-2.20}(\text{pol})\right] \mu\text{b}$$

- Main systematics from luminosity, tracking, trigger efficiency.
- Prospect: aim to reduce luminosity and tracking uncertainties.

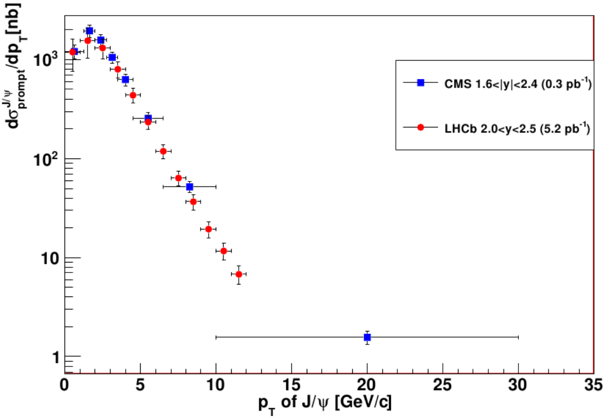
Comparison with theory: prompt J/ψ



- direct J/ψ production with COM and CSM (arXiv:1009.5662v3, arXiv:0811.4005v1);
- direct J/ψ production + contribution from χ_c decay with COM and CEM (arXiv:1009.3655v2, arXiv:0806.1013v2).

- Good agreement with NRQCD models.

Comparison with CMS results: prompt J/ψ

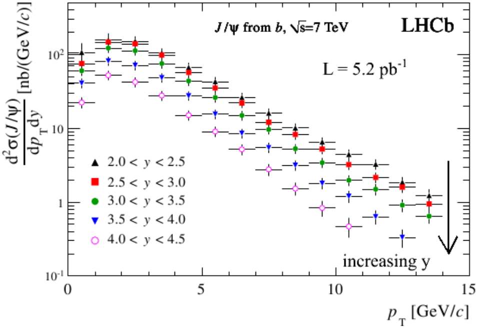


- Good agreement with CMS results (Eur. Phys. J. C 71 (2011) 1575).

Results: J/ψ from b and $b\bar{b}$ cross section

Eur. Phys. J. C 71 (2011) 1645

Total cross section in $p_T < 14$ GeV/c and $2 < y < 4.5$.



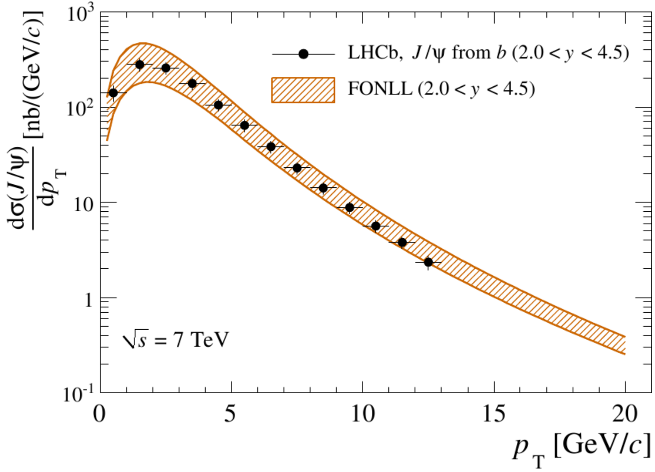
- $\sigma_{J/\psi \text{ from } b} = [1.14 \pm 0.01(\text{stat}) \pm 0.16(\text{sys})]\ \mu\text{b}$
- $\sigma(pp \to b\bar{b}X) = \alpha_{4\pi} \dfrac{\sigma_{J/\psi \text{ from } b}}{2\mathcal{B}(b \to J/\psi X)} = [288 \pm 4(\text{stat}) \pm 48(\text{syst})]\ \mu\text{b}$

to be compared with

$$\sigma(pp \to b\bar{b}X) = (284 \pm 20(\text{stat}) \pm 49\text{syst})\ \mu\text{b}$$ 14 nb^{-1}

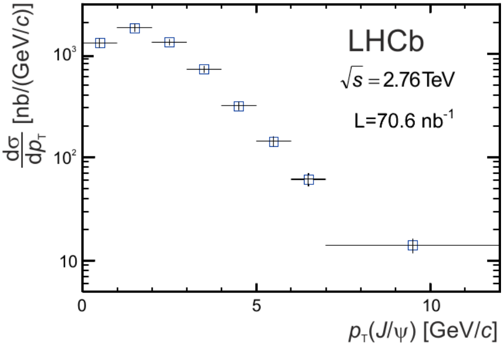
obtained from $b \to D^0 \mu\nu X$ decays in LHCb (Phys. Lett. B694 (2010) 209).

Comparison with theory: J/ψ from b



- Good agreeement with FONLL (Fixed Order plus Next Leading Logarithm, arXiv:hep-ph/9803400v1, arXiv:hep-ph/0102134v1)

Inclusive J/ψ cross section at $\sqrt{s}$ =2.76 TeV



arXiv:1212.1045

- Special run at $\sqrt{s}$ =2.76 TeV to provide reference for Pb-Pb collisions.
- Data sample $L = 70.6\ \text{nb}^{-1}$.

Total cross section is estimated summing over each analysis bin ($p_T < 12$ GeV/c and $2 < y < 4.5$)

$$\sigma_{J/\psi} = [5.6 \pm 0.1(\text{stat}) \pm 0.4(\text{syst})]\ \mu\text{b}$$

- Assuming unpolarized J/ψ.
- Main systematic coming efficiency calculation with Monte Carlo and luminosity.

χ_c production and decay to J/ψ

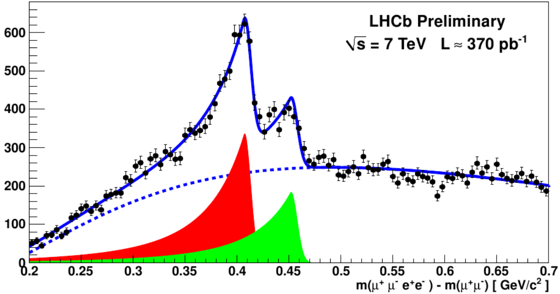
- Studies on χ_c production provide an important test for understanding quarkonium production.
- Production rate of χ_{c2} to χ_1 sensitive to the Color Singlet and Color Octet approach.
- Feed down contribution to prompt J/ψ from χ_c states has consequences on polarization measurement:
  - polarization measured for prompt component, including directly produced + feed from intermediate charmonium states (such as χ_c);
  - polarization of J/ψ from radiative decays from χ_c can be different from directly produced $J/\psi \Rightarrow$ possible source of uncertainty;
  - amount of J/ψ from χ_c decays can quantify the uncertainty.

LHCb contributions:

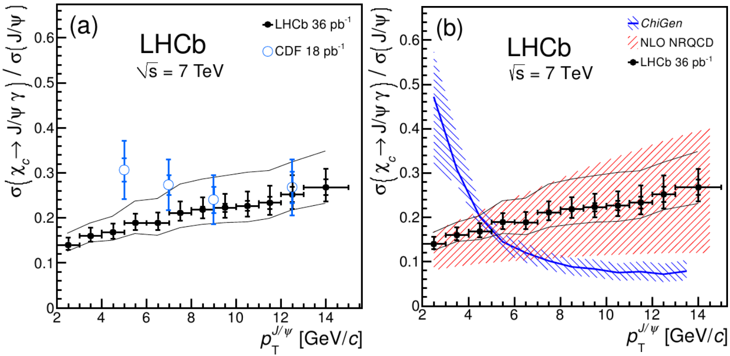
- Ratio of prompt χ_c to J/ψ production cross section through the radiative decay $\chi_c \to J/\psi\gamma$ with $J/\psi \to \mu^+\mu^-$ (PLB 718 (2012), 431).
- Ratio of χ_{c2} to χ_{c1} production cross sections with $\chi_c \to J/\psi\gamma$, $J/\psi \to \mu^+\mu^-$, photons reconstructed in the calorimeter (2010 results PLB 714 (2012), 215) and converted photons (2011 preliminary results LHCb-CONF-2011-062).

χ_{c2} and χ_{c1} signal yields

- Number of signal events extracted with fit in bins of J/ψ momentum.
- Two kinds of photons used
  - **photons reconstructed in the calorimeter**: high statistics but poor resolution to separate the χ_{cJ} states;
  - **photons converted** in the detector material before the magnet $\gamma \to e^+e^-$: possibility to resolve the individual χ_{cJ} states (take advantage of the tracker resolution) but low statistics (light material budget in the vertex detector).



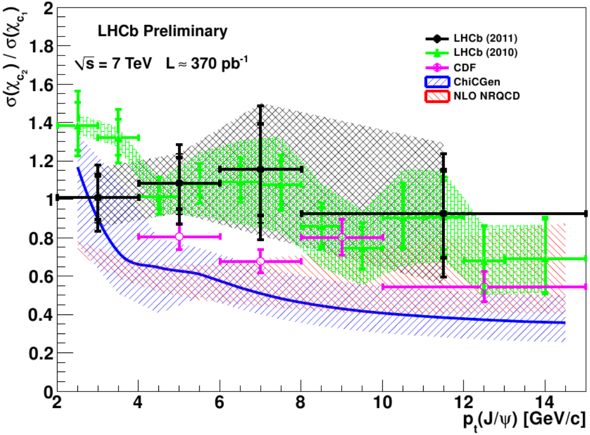
χ_c to J/ψ ratio



- **ChiGen → CSM** (http://projects.hepforge.org/superchic/chigen.html)
- **NRQCD → COM** (Phys. Rev. D 83 111503 R, 2011)

- Main systematic coming from the photon efficiency.
- Good agreement with theoretical expectation from NRQCD models.
- PLB 718 (2012), 431.

χ_{c2} to χ_{c1} ratio



- **ChicGen → CSM** (http://projects.hepforge.org/superchic/chigen.html)
- **NRQCD → COM** (Phys. Rev. D 83 111503 R, 2011)

Good agreement between

- 2011 results with converted photons (LHCb-CONF-2011-062);
- 2010 results, based on 36 pb^{-1} 2010 statistics, using photon detected in the calorimeters (PLB 714 (2012), 215).

Double charm production

- Double J/ψ events observed in $p-\pi$ collisions at 150 GeV/c and 280 GeV/c by N-3 (Phys. Lett. B 114, 457 (1982), Phys Lett B 158, 85 (1985)).
- Provide a test for Color Octet vs Color Singlet models and for DPS (Double Parton scattering) vs SPS (Single Parton scattering)
  - Color Singlet + SPS gives consistent results with experimental value in LHCb acceptance for double J/ψ production;
  - need to investigate other channels (as J/ψ + open charm).
- Look for charmed tetraquark.

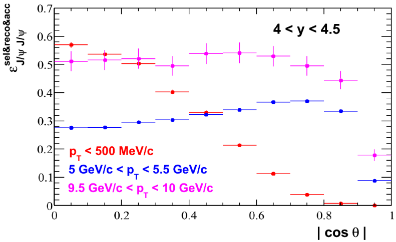
At LHCb

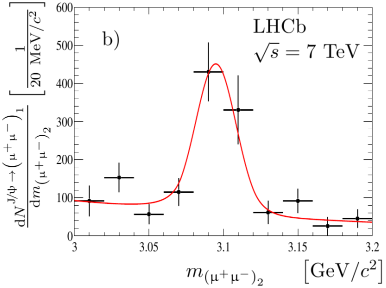
- Measurement of J/ψ-J/ψ production cross section with both J/ψ $2 < y < 4.5$ and $p_T < 10$ GeV/c (PLB 707 (2012), 52).
- J/ψ with associated open charm and double charm production (arXiv:1205.0975) where D is D^0, D^+, D_s^+ and Λ_c^+ reconstructed from $J/\psi \to \mu^+\mu^-$, $D^0 \to \pi^+K^-$, $D^+ \to \pi^+\pi^+K^-$, $D_s^+ \to \pi^+K^+K^-$, $\Lambda_c^+ \to p\pi^+K^-$.

Double J/ψ signal yield

- Build the invariant mass distribution of the first muon pairs in bins of second muon pairs.
- Event per event total efficiency

$$\varepsilon^{tot}_{J/\psi J/\psi} = \varepsilon^{sel\&reco\&acc}_{J/\psi J/\psi} \times \varepsilon^{\mu ID}_{J/\psi J/\psi} \times \varepsilon^{trg}_{J/\psi J/\psi}$$





- Polarization effect: binning in J/ψ $\cos\theta$.
- Efficiency correction: weight each event with $\omega = \left(\varepsilon^{tot}_{J/\psi J/\psi}\right)^{-1}$
- $J/\psi \to (\mu^+\mu^-)_1$ events efficiency corrected distribution in bins of $(\mu^+\mu^-)_2$ pair.

Double J/ψ cross section

With $L = 37.5 \pm 1.3\ \text{pb}^{-1}$ (PLB 707 (2012), 52)

$$\sigma_{J/\psi J/\psi} = \frac{N^{corr}_{J/\psi J/\psi}}{\mathcal{L}\,\mathcal{B}^2_{\mu^+\mu^-}} = [5.1 \pm 1.0(\text{stat}) \pm 1.1(\text{syst})]\ \text{nb}$$

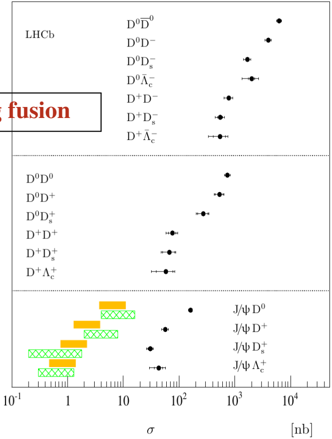
- Main systematics: tracking, trigger efficiency, J/ψ polarization.

Theoretical expectation (arXiv:1101.5881, arXiv:1106.2184):

- CSM at LO with Single Parton Scattering in LHCb acceptance: 4.15 nb with $\sim 30\%$ error;
- contribution from Double Parton Scattering in LHCb acceptance: 2 nb with $\sim 50\%$ error;
- sum of the two contributions is in agreement with experimental value.

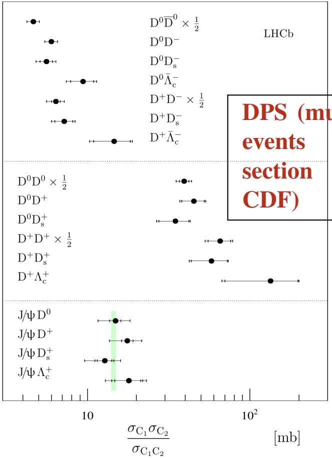
Double charm cross sections

Double-charm cross section



gg fusion

Ratio of single- over double-charm cross sections



DPS (multi-jet events cross section from CDF)

- Good agreement with DPS calculation.

Open charm cross section

- Measurement based on 15 nb^{-1} data sample acquired in May 2010. Supercedes LHCb-CONF-2010-013
- Differential cross sections

$$\frac{d\sigma_i(H_c)}{p_T} = \frac{N_i(H_c \to f + \text{c.c.})}{\varepsilon(H_c \to f) \cdot \mathcal{B}(H_c \to f) \cdot L \cdot \Delta p_T}$$

measured for eight p_T bins, $p_T < 8$ GeV/c, and five y bins, $2.0 < y < 4.5$

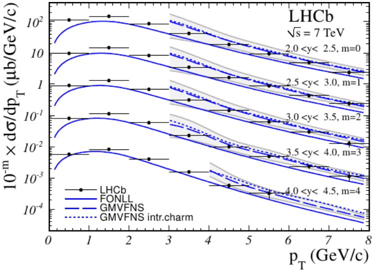
- 1-D y bin for Λ_c^+

$\sigma(pp \to c\bar{c}X)$ is obtained combining the five D^0, D^+, D^{*+}, D_s^+ and Λ_c^+ states decaying in the following modes (LHCb-PAPER-2012-041):

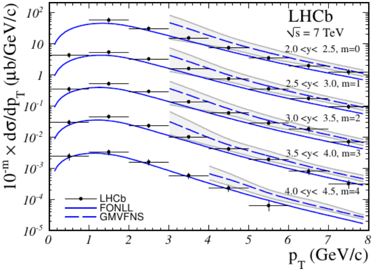
- $D^0 \to \pi^+ K^-$
- $D^+ \to \pi^+ \pi^+ K^-$
- $D_s^+ \to \phi(K^+ K^-)\pi^+$
- $D^{*+} \to D^0 \pi^+$
- $\Lambda_c^+ \to p\pi^+ K^-$

D^0, D^+ cross section

D^0 production



D^+ production



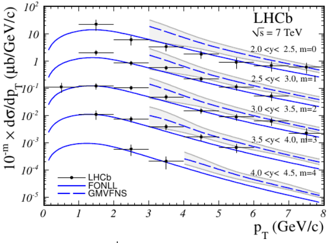
Experimental results compared with FONLL [1] and GMVFNS [2]

[1] Fixed-Order-Next-to-Leading-Logarithm, JHEP 1210 (2012) 137

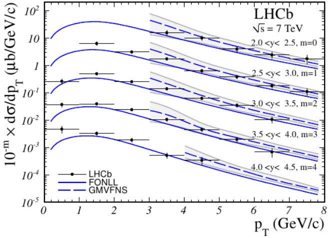
[2] Generalized Mass Variable Flavour Number Scheme, Eur. Phys. J. C 72 (2012) 2082

D_s^+, D^{*+}, Λ_c^+ cross section

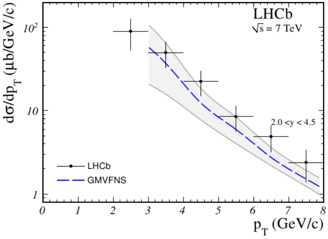
D_s^+ production



D^{*+} production

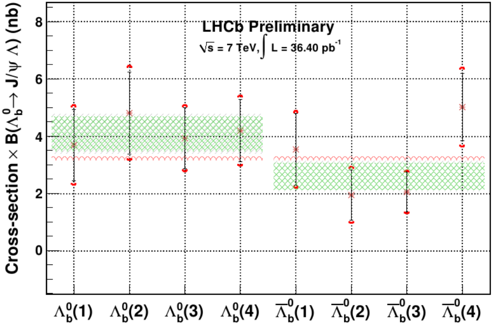


Λ_c^+ production



Λ_b production

- Λ_b^0 production cross section measured in the decay mode $\Lambda_b^0 \to \Lambda^0 J/\psi$ with $\Lambda^0 \to p\pi^-$ and $J/\psi \to \mu^+\mu^-$ (sample divided into 8 categories according to the b quark content, magnet polarity and track type).



- Integrated results (LHCb-CONF-2012-031):

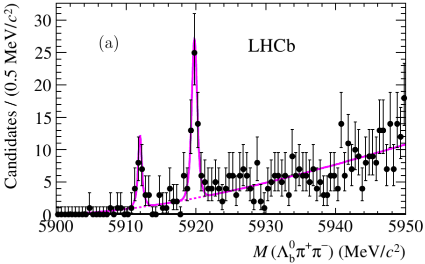
$$\sigma_{\Lambda_b^0} \times \mathcal{B}(\Lambda_b \to \Lambda^0 J/\psi) = [4.08 \pm 0.59(\text{stat}) \pm 0.36(\text{sys})]\ \mu\text{b}$$

$$\sigma_{\overline{\Lambda_b}^0} \times \mathcal{B}(\overline{\Lambda_b} \to \overline{\Lambda^0} J/\psi) = [2.60 \pm 0.46(\text{stat}) \pm 0.26(\text{sys})]\ \mu\text{b}$$

Observation of excited Λ_b states

Two new excited states observed in the $\Lambda_b^0\pi^+\pi^-$ decay mode (PRL 109, 172003 (2012)) with masses

- $M_{\Lambda_b^{0*}(5912)} = \left[5911.97 \pm 0.12(\mathrm{stat}) \pm 0.02(\mathrm{sys}) \pm 0.66(\Lambda_b^0\mathrm{mass})\right]$ MeV/c^2 with 5.2σ significance.
- $M_{\Lambda_b^{0*}(5920)} = \left[5919.77 \pm 0.08(\mathrm{stat}) \pm 0.02(\mathrm{sys}) \pm 0.66(\Lambda_b^0\mathrm{mass})\right]$ MeV/c^2 with 10.2σ significance



Mass difference w.r.t. Λ_b^0

- $\Delta M_{\Lambda_b^{0*}(5912)} = [292.60 \pm 0.12(\mathrm{stat}) \pm 0.04(\mathrm{syst})]$ MeV/c^2
- $\Delta M_{\Lambda_b^{0*}(5920)} = [300.40 \pm 0.08(\mathrm{stat}) \pm 0.04(\mathrm{sys})]$ MeV/c^2

Conclusion

- LHCb performed provides lots of contributions in the heavy flavour sector.
- J/ψ production cross section has been measured at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 2.76$ TeV for prompt and from b J/ψ. $b\bar{b}$ cross section extrapolated from the latter. Ongoing: measurement of J/ψ and Υ production at $\sqrt{s} = 8$ TeV, J/ψ polarization.
- Measurement of χ_{c2} to χ_{c1} production cross section and study of relative χ_c to J/ψ production using radiative decays (important also for J/ψ polarization measurement).
- Production cross section of double J/ψ, J/ψ + open charm and double charm production. Experimental results show an agreement with theoretical expectation from Double Parton Scattering.
- Measurement of open charm cross section.
- Study of the Λ_b^0 and excited states.
- More: Ξ_b^-, Ω_b^- masses, Υ production (Eur.Phys. J. C 72 6 (2012), 2025)...

Back up slides

Luminosity measurements

1. Van der Meer scan method.
2. Beam profile method: beam overlap integral term of luminosity is determined studying each beam shape. The position, angle and size of bunches are measured from the collisions between the beam and the residual gas in the interaction region. Ref: NIM A 553 (2005) 388, arXiv:1008.3105v2 [hep-ex]

Results consistent within the 10 % error.

Theoretical models

1. **Colour Singlet Model (CSM)**
   - production of $c\bar{c}$ on-shell pair.
   - binding the $c\bar{c}$ pair to form the meson, assuming colour and spin don't change. Since the physical state is colourless $c\bar{c}$ pair must be produced in colour singlet state.
2. **Colour Octet Model (COM)**: NRQCD approach. Charmonium production is possible also through colour octet states.

Prompt J/ψ:

- Direct J/ψ production with Color Octet Model: arXiv:1009.5662v3 [hep-ph]
- Direct J/ψ production with Color Singlet Model: arXiv:0811.4005v1 [hep-ph]
- Prompt J/ψ production with Color Octet Model: arXiv:1009.3655v2 [hep-ph]
- Prompt J/ψ production with Color Evaporation Model: arXiv:0806.1013v2 [nucl-ex]

J/ψ from b:

- FONLL Fixed Order plus Next Leading Logarithm: arXiv:hep-ph/9803400v1, arXiv:hep-ph/0102134v1

Theory reference for double charm production

- *gg* fusion: Phys. Rev. D57 (1998) 4385, Phys. Rev. D73 (2006) 074021, Eur. Phys. J. C61 (2009) 693.
- DPS calculation: Phys. Rev. Lett. 107 (2011) 082002, Phys. Lett. B705 (2011) 116, arXiv:1106.2184.