J/ψ production cross section and polarization with LHCb

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Outline

- Physical motivation for studying charmonium physics.
- LHCb detector and condition data taking in 2010 and 2011.
- J/ψ production cross section results and ongoing polarization measurement.
- 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 and J/ψ + open charm production.
- 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):

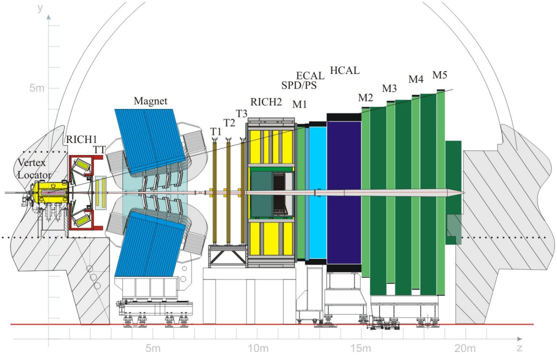
- J/ψ cross section and polarization, χ_c production: provide an important test for Color Singlet Model vs Color Octet Model.
- Measurements of production cross section of double J/ψ and J/ψ + open charm:
  - extremely rare processes (as predicted by QCD);
  - at LHC energies the main contribution is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

Contributions at high energy to charmonium production are

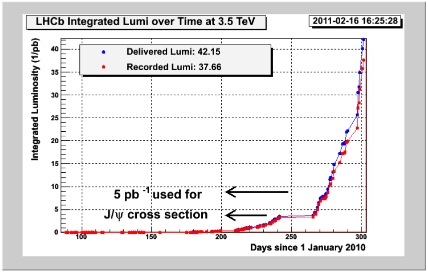
1. Direct production in *pp* collisions prompt
2. Feed down from excited states ($\psi(2S)$, χ_c ...) prompt
3. Production from *b*-hadrons decays delayed

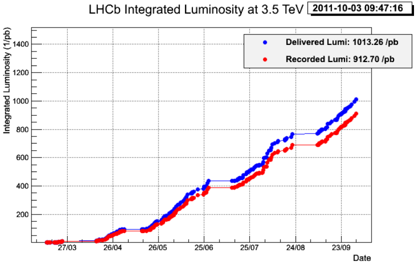
The LHCb experiment

- 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 $\Delta p/p < 0.4\% - 0.6\%$



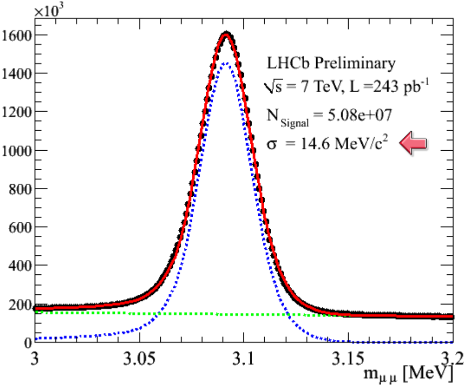
High efficiency 2010-2011 data taking





- 2010 data sample: 37 pb^{-1} recorded by LHCb at $\sqrt{s} = 7$ TeV.
  - 5 pb^{-1} used for J/ψ cross section measurement
  - Full 2010 data sample used for double J/ψ and χ_c production.
- 1 fb^{-1} recorded in 2011.
- 355 pb^{-1} used for J/ψ + open charm production.
- 370 pb^{-1} used for χ_{c2} to χ_{c1} ratio.
- In 2010 working at instantaneous luminosity of $1.6 \cdot 10^{32}$ cm^{-2} s^{-1}, in 2011 mostly at $3.5 \cdot 10^{32}$ cm^{-2} s^{-1}.
- 2012 collisions at $\sqrt{s} = 8$ TeV.

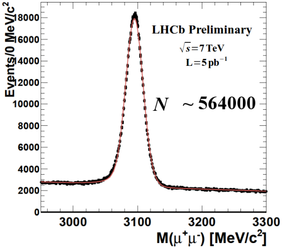
J/ψ collection at LHCb



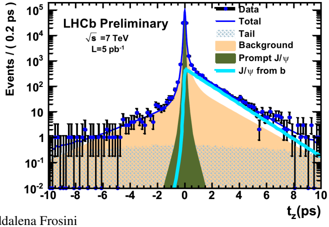
- $\sim 10^5$ reconstructed J/ψ per 1 pb^{-1}.
- Mass resolution of 14.6 MeV/c^2, close to MC expectation (resolution from MC $\sim$ 13 MeV/c^2).

J/ψ cross section measurement

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



- 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.

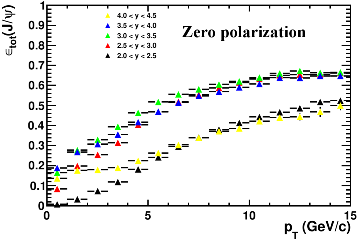
$$t_z = \frac{(z_{J/\psi} - z_{PV})m_{J/\psi}}{p_z}$$

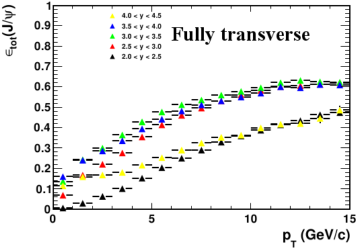
- Eur. Phys. J. C 71 (2011) 1645.

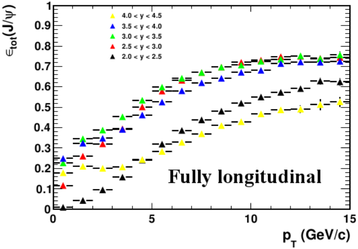
Efficiency

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.

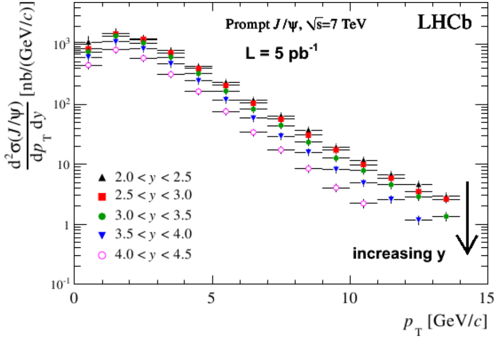






- Deviation from zero polarization is taken as systematic uncertainty.

Results: prompt J/ψ

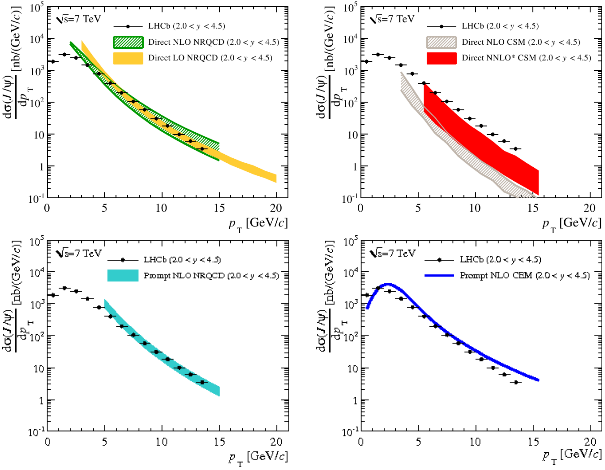


Total cross section is estimated summing over each analysis bin ($p_T < 14$ GeV/c and $2 < y < 4.5$).

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

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

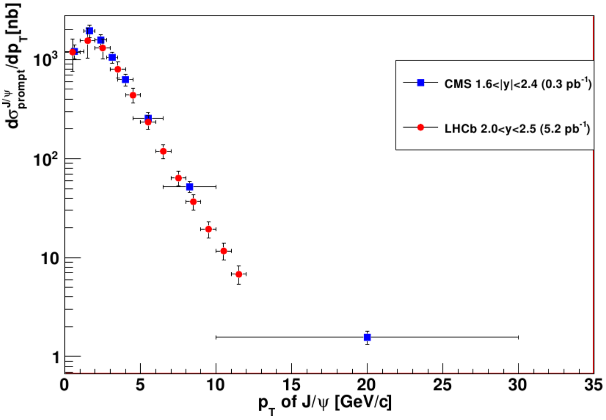
Comparison with theory: prompt J/ψ



- 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.

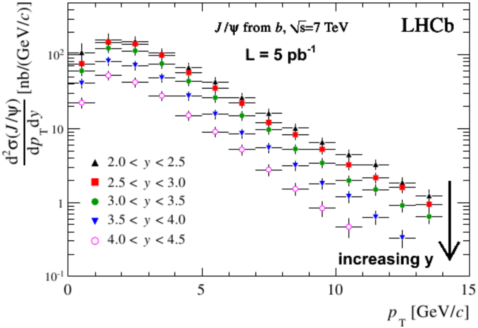
Comparison with CMS results: prompt J/ψ



- Good agreement with CMS results (arXiv:1011.4193).

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

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



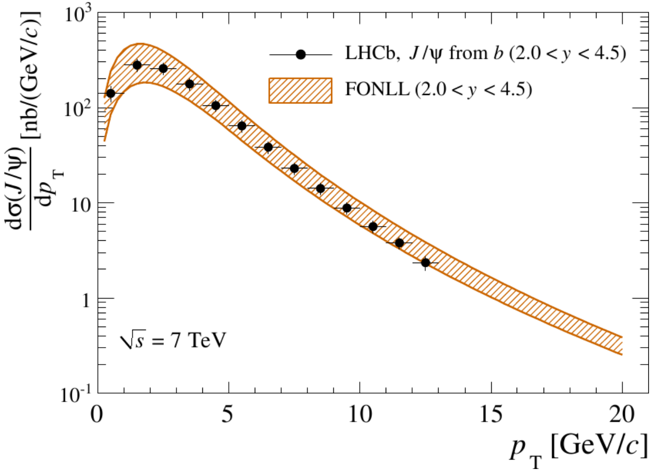
- $\sigma_{J/\psi \text{ from } b} = [1.14 \pm 0.01(\text{stat}) \pm 0.16(\text{sys})]\ \mu\text{b}$
- $\sigma(pp \to b\bar{b}X) = \alpha_{4\pi} \dfrac{\sigma_{J/\psi \text{ from } b}}{2\mathcal{B}(b \to J/\psi X)} = [288 \pm 4(\text{stat}) \pm 48(\text{sys})]\ \mu\text{b}$

to be compared with

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

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

Comparison with theory: J/ψ from b

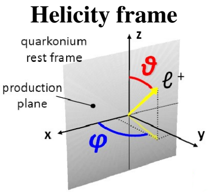


- Good agreement with FONLL (Fixed Order plus Next Leading Logarithm, arXiv:hep-ph/9803400v1, arXiv:hep-ph/0102134v1)

Polarization measurement of prompt J/ψ

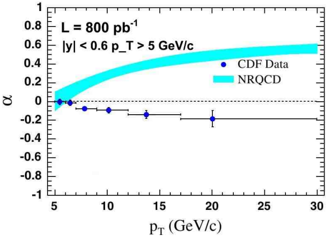
- Prompt J/ψ polarization in the **helicity frame**

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



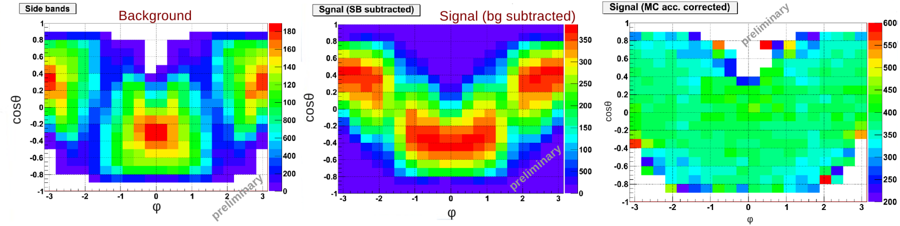
  - θ: polar angle between μ^+ in J/ψ rest frame and J/ψ flight direction.
  - ϕ: azimuthal angle between J/ψ production plane (beam axis and J/ψ momentum) and the μ^+ plane (beam axis and μ^+ momentum).

- Polarization measurement needed together with the cross section to better understand the production mechanism. COM failed to predict polarization (CDF data, Phys. Rev. Lett. 99, 132001 (2007))
- Reduce the systematic uncertainty on the cross section.



Strategy for the measurement

- Analysis window: J/ψ rapidity $2 < y < 4.5$ and transverse momentum 2 GeV/c $< p_T <$ 15 GeV/c.
- Results will be given in J/ψ p_T and y bins.
- Polarization measured by extracting λ_θ, λ_ϕ, $\lambda_{\theta\phi}$ parameters extracted with an unbinned maximum likelihood fit to muons angular distribution.
- Results out soon.



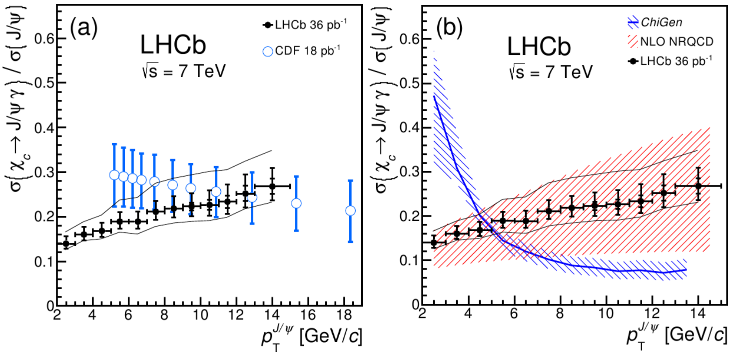
χ_c production and decay to J/ψ

- 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 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 arXiv:1202.1080) and converted photons (2011 preliminary results LHCb-CONF-2011-062).
- Ratio of prompt χ_c to J/ψ production cross section through the radiative decay $\chi_c \to J/\psi\gamma$ with $J/\psi \to \mu^+\mu^-$ (arXiv:1109.0963).

χ_c to J/ψ ratio

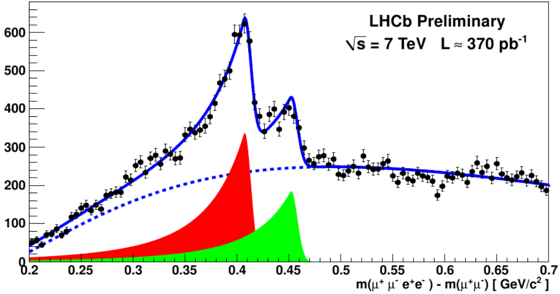


- **ChiGen → CSM** (http://projects.hepforge.org/superchic/chigen.html)
- **NRQCD → COM** (Phys. Rev. D 83 111503 R, 2011)

- Main systematic coming from the photon efficiency.
- Good agreement with theoretical expectation from NRQCD models.
- arXiv:1109.0963, submitted to Phys. Lett. B.

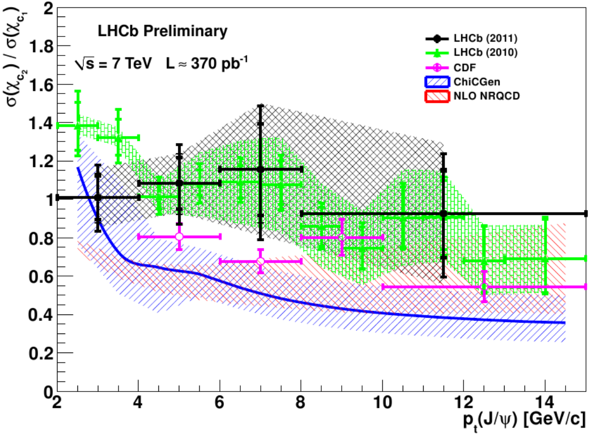
χ_{c2} and χ_{c1} signal yields

- 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 $\gamma \rightarrow e^+e^-$: possibility to resolve the individual χ_{cJ} states (take advantage of the tracker resolution) but low statistics (light material budget in the vertex detector).



- Efficiency determined from the Monte Carlo sample.

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 (arXiv:1202.1080).

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.

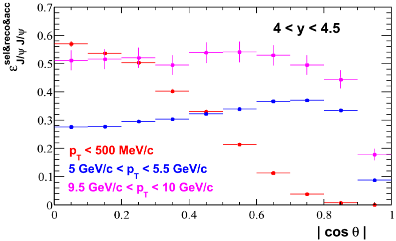
At LHCb

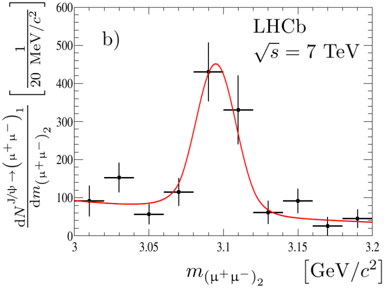
- Measurement of J/ψ-J/ψ production cross section with both J/ψ $2 < y < 4.5$ and $p_T < 10$ GeV/c (arXiv:1109.0963 , submitted to Phys. Lett. B).
- J/ψ production with associated open charm (arXiv:1205.0975 where D is D^0, D^+, D_s^+ and Λ_c^+ reconstructed from $J/\psi \to \mu^+\mu^-$, $D^0 \to \pi^+K^-$, $D^+ \to \pi^+\pi^+K^-$, $D_s^+ \to \pi^+K^+K^-$, $\Lambda_c^+ \to p\pi^+K^-$.

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 $\mathcal{L} = 37.5 \pm 1.3\ \text{pb}^{-1}$

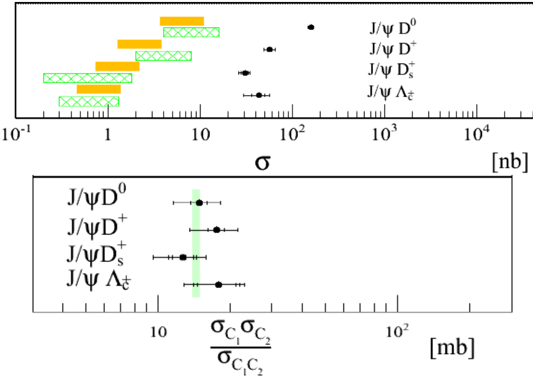
$$\sigma_{J/\psi J/\psi} = \frac{N^{corr}_{J/\psi J/\psi}}{\mathcal{L}\,\mathcal{B}^2_{\mu^+\mu^-}} = (5.1 \pm 1.0|_{stat} \pm 1.1|_{syst})\ \text{nb}$$

- 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.

$J/\psi C$ cross sections



- Cross section results compared with gluon-gluon fusion (Phys. Rev. D57 (1998) 4385, Phys. Rev. D73 (2006) 074021, Eur. Phys. J. C61 (2009) 693) .
- Cross section ratio compared with theoretical calculation from DPS approach (Phys. Rev. Lett. 107 (2011) 082002, Phys. Lett. B705 (2011) 116, arXiv:1106.2184) .

- Main systematic errors coming from tracking and trigger efficiency, unknown J/ψ polarization and luminosity.

Conclusion

- LHCb performed provides lots of contributions in understanding the charmonium production mechanism.
- J/ψ production cross section has been measured with 5 pb^{-1} for prompt and from b J/ψ.
- J/ψ polarization measurement ongoing (critical test for Color Octet Model).
- 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 and J/ψ + open charm. Experimental results show an agreement with theoretical expectation from Double Parton Scattering.
- Outlook: measurement of J/ψ production cross section at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 8$ TeV.

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