Quarkonia and double charm

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Outline

1. Introduction
2. J/ψ and $\Psi(2S)$
3. $\Upsilon(\mathrm{nS})$
4. Production cross sections at LHC at 7 TeV
5. Higher mass onia
6. Double J/ψ production
7. J/ψ + open charm and open charm + open charm
8. Conclusions

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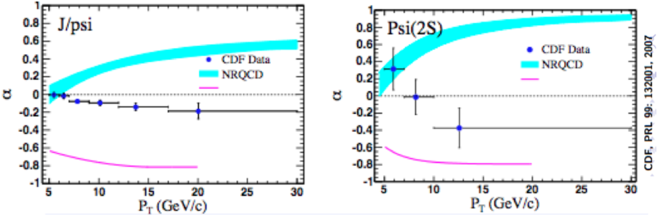
Why do we care about quarkonium?

- Since the first measurements at Tevatron the production of quarkonium states has proved a tough challenge.
- Various models have been proposed at different times and a combination of Color Octet and Color Singlet mechanisms appear to describe the p_T spectrum and cross-sections measured at Tevatron.
- However the a satisfactory description of polarization remains elusive.



- Other observables, double-charm production, production in p-Pb interactions etc.. have been proposed to solve the puzzle.
- With its high luminosity the production cross-section and possibly the polarization of states such as χ_c, χ_b might also become available at the LHC.
- The interest in the study of heavy flavour production processes is not limited to its theoretical value but it also:
  - provides excellent test of p-QCD and MC generators at new energies;
  - improves the understanding of heavy flavour background in many searches;
  - is an important test of the understanding of the detector.

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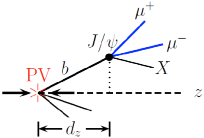
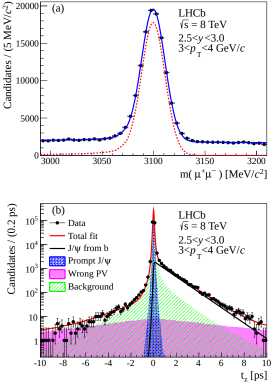
J/ψ production

- Select decays of J/ψ into muon pairs
  - Opposite charged tracks from the same vertex
  - Good track quality and muon id.
  - Require minimum muon p_T.
- Measure the double differential cross section in bins of p_T and y.
  - $p_T < 14$ GeV/c
  - $2.0 < y < 4.5$
- Measure the cross section separately for prompt J/ψ (includind feed-down) and J/ψ from b-decays.
- Two sample separated using pseudo propertime: $t_z = (z_{J/\psi} - z_{PV}) \times \frac{M_{J/\psi}}{p_z}$



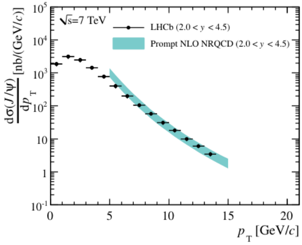
- Yields extracted from simultaneous fit of mass and t_z.



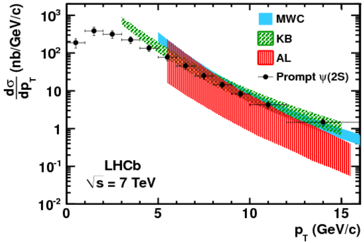
JHEP 06 (2013) 064

Prompt J/ψ and $\Psi(2S)$ 7 TeV results

- Dominant uncertainty is the unknown polarization affecting efficiency determination.
- Measurement performed in 3 cases assuming unpolarized, fully longitudinal and fully transversal polarization.
- $\sigma_{prompt}(J/\psi) = 10.52 \pm 0.04(stat) \pm 1.30(sys)^{+1.64}_{-2.20}(pol)\ \mu b$ EPJ C71(2011) 1645
- $\sigma_{prompt}(\Psi(2S)) = 1.44 \pm 0.01(stat) \pm 0.12(sys)^{+0.20}_{-0.40}(pol)\ \mu b$ EPJ C72(2012) 2100
- Models describe well the transverse momentum distribution.



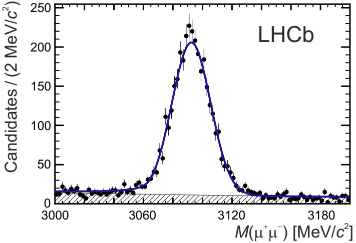
NNLO CS: PRL (2008) 152001

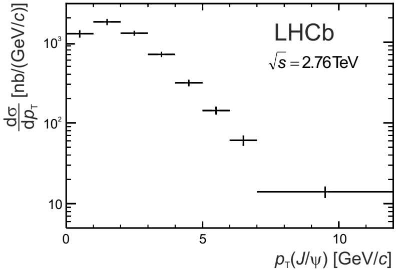


NNLO CS (AL): EPJ C61 (2009) 693
NNLO CS+CO (MWC): PRD 84 (2011) 114001
NNLO CS+CO (KB): PRL 106(2011) 022003

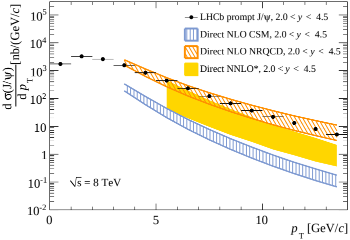
Prompt J/ψ 2.76 TeV results

- A sample of $0.071\,\mathrm{pb}^{-1}$ collected in 2011 and used to measure the J/ψ cross-section JHEP 02 (2013) 041.
- Measurement carried out in the kinematic region $p_{\mathrm{T}} < 12\,\mathrm{GeV}/c$, $2 < y < 4.5$.
- $\sigma_{inclusive}(J/\psi) = 5.6 \pm 0.1(stat) \pm 0.4(sys)\,\mu\mathrm{b}$
- Uncertainty from unknown polarization estimated to be as large as an extra 20%.





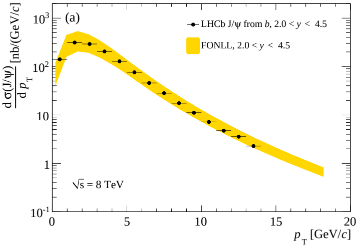
Prompt J/ψ at 8 TeV

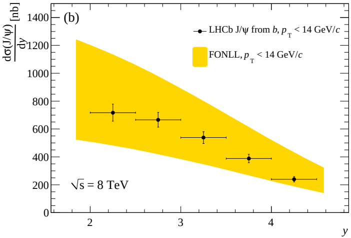


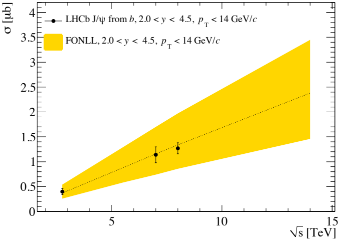
- NLO CSM model:
  - Phys. Rev. Lett. 98 (2007)
- NLO NRQCD model:
  - Phys. Rev. D84 (2011) 051501
  - Phys. Rev. Lett. 106 (2011) 022003
- NNLO* model:
  - Phys. Rev. Lett. 101 (2008) 152001
  - Eur. Phy. J. C 61 (2008) 693

- 8 TeV measurement using 18 pb^{-1} 2012 data.
- Prompt J/ψ assumed unpolarized.
- $\sigma_{prompt}(J/\psi) = 10.94 \pm 0.02(stat) \pm 0.79(sys)\ \mu b$
- $\sigma_{from\ b}(J/\psi) = 1.28 \pm 0.01(stat) \pm 0.11(sys)\ \mu b$
- Systematic uncertainty ∼7% mainly from luminosity and trigger efficiency.
- Experimental data include feed down ∼20% from χ_c and ∼8% from $\psi(2S)$.
- Data in good agreement with NLOQCD.

J/ψ from b



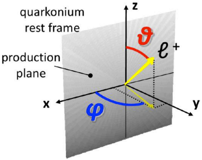




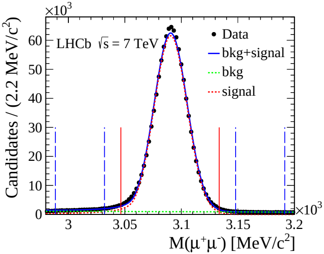
- Excellent agreement with theory
- 8 TeV: JHEP 06 (2013) 064
- 7 TeV: Eur. Phys. J. C71 (2011) 1645
- 2.76 TeV: JHEP 02 (2013) 041

J/ψ polarization strategy

- $371\,\mathrm{pb}^{-1}$ 7 TeV data from 2011, divided in bins of p_T and rapidity.
- Extract polarization from angular distribution of $J/\psi \to \mu^+\mu^-$ (feed down included).
- Full angular analysis to determine the polarization parameters $(\lambda_\theta, \lambda_{\theta\phi}, \lambda_\phi)$



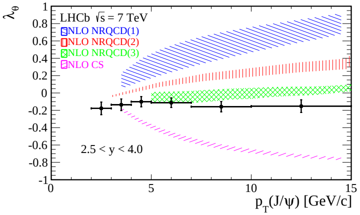
$$\frac{dN^2}{d\cos\theta d\phi} \propto 1 + \cos^2\theta + \lambda_{\theta\phi}\sin 2\theta\phi + \lambda_\phi \sin^2\theta\cos 2\phi$$



$5\,\mathrm{GeV}/c < p_T < 7\,\mathrm{GeV}/c$ and $3.0 < y < 3.5$

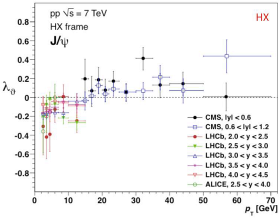
- Data presented in both Helicity frame (HX) and Collins-Soper frame (CS)
- Prompt J/ψ and J/ψ from b separated using pseudo propertime
- $\lambda_{inv} = (\lambda_\theta + 3\lambda_\phi)/(1 - \lambda_\phi)$ also measured (independent of the frame)
- Eur. Phys. J. C (2013) 73:2631

J/ψ polarization results



HX frame

- CSM no feed down: Nucl. Phys. Proc. Suppl. B222-224 (2012) 151
- NRQCD: no feed-down: Nucl. Phys. Proc. Suppl. B222-224 (2012) 151
- NRQCD: feed-down from $\chi_c(^3P_J^1, ^3S_J^8)$ and $\psi(2S)$ Phys. Rev. Lett. 110 (2013) 042002
- NRQCD: feed-down from $^3P^{[8]}$ Phys.Rev. Lett. 108 (2012) 242004



HX frame

- ALICE: PRL108(2012)082001
- CMS: arXiv:1307.6070
- LHCb: arXiv:1307.6379
- (P. Faccioli, QCD at LHC 2013, DESY, Hamburg)

- $\lambda_{\theta\phi}$ and λ_ϕ consistent with 0 $\Rightarrow \lambda_\theta = \lambda_{inv}$
- Small longitudinal polarization observed $\lambda_\theta = -0.145 \pm 0.027$
- Results in HX and CS frame consistent.
- LHCb results are compatible with NLO NRQCD calculations that include feed-down contributions.
- Good agreement with ALICE.

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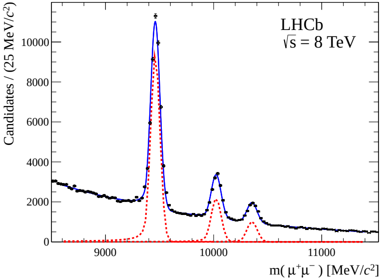
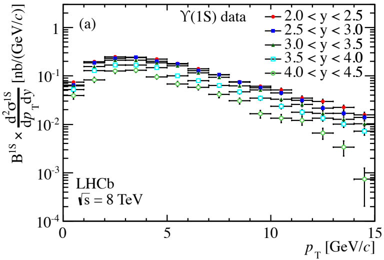
$\Upsilon(nS)$ production





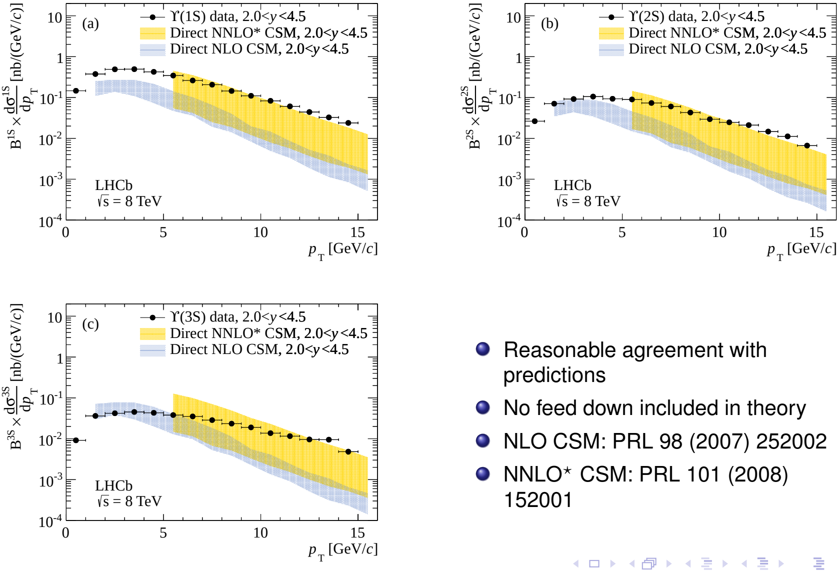
- 25 pb^{-1} 7 TeV 2010 data
- 51 pb^{-1} 8 TeV 2012 data
- Same procedure as for J/ψ
- $p_T < 15$ GeV/c
- $2.0 < y < 4.5$

$$\sigma\,(pp \to \Upsilon(1S)X) \times B^{1S} = 3.241 \pm 0.018(stat) \pm 0.231(sys)\ nb$$

$$\sigma\,(pp \to \Upsilon(2S)X) \times B^{2S} = 0.761 \pm 0.008(stat) \pm 0.055(sys)\ nb$$

$$\sigma\,(pp \to \Upsilon(3S)X) \times B^{3S} = 0.369 \pm 0.005(stat) \pm 0.027(sys)\ nb$$

$\Upsilon(nS)$ comparison with theory



- Reasonable agreement with predictions
- No feed down included in theory
- NLO CSM: PRL 98 (2007) 252002
- NNLO* CSM: PRL 101 (2008) 152001

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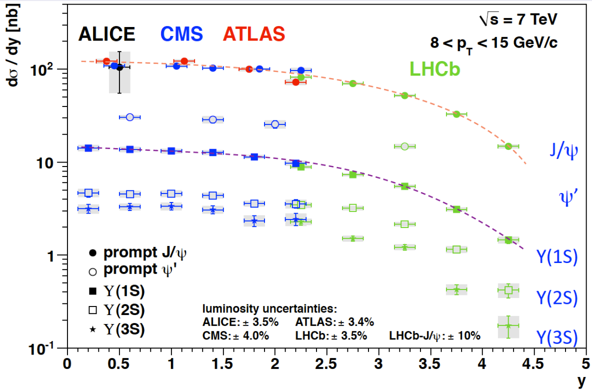
Production cross sections at LHC at 7 TeV

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



Note: the lines do not represent any theoretical model; they are added to help guiding the eye through the points

ALICE : 5.6 nb^{-1}
ATLAS : 2.2 pb^{-1}
CMS : 37, 36 pb^{-1}
LHCb : 5.2, 36, 25 pb^{-1}

ALICE: arXiv:1205.5880
ATLAS: NPB850 (2011) 387
CMS: JHEP02 (2012) 011
LHCb: EPJC71 (2011) 1645
LHCb: arXiv:1204.1258
CMS: BPH-11-001
LHCb: EPJC72 (2012) 2025

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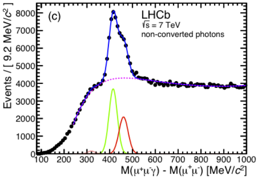
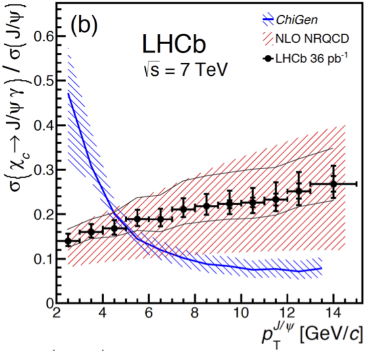
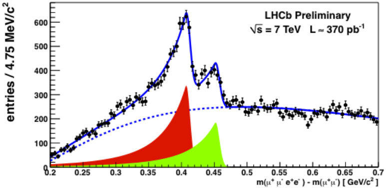
χ_c cross-section



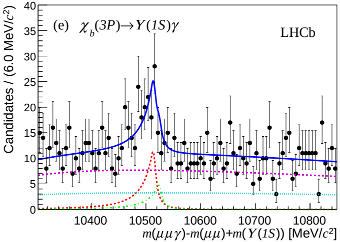


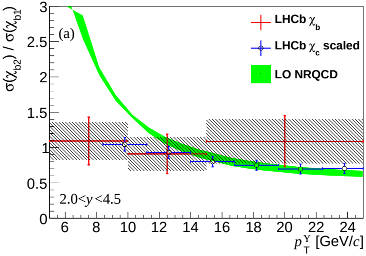
- Detected as $\chi_c \rightarrow J/\psi\ \gamma$
- $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ measured at LHCb arXiv:1202.1080
- Photons observed in the ECAL or as two converted electrons.
- Results in agreement with NLO CO+CS.

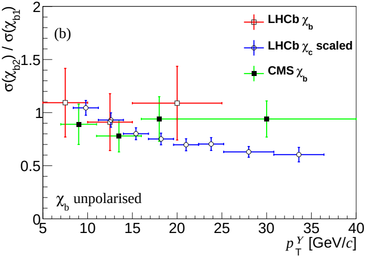


χ_b production

- Detected as $\chi_b \to \Upsilon(\mathrm{nS})\gamma$
- Measurement of the mass of $\chi_{b1}(3P)$ and $\Delta m_{12}(1P)$
- $\sigma(\chi_{b1})/\sigma(\chi_{b2})$ arXiv:1407.7734
- Photons observed in the ECAL or as two converted electrons.
- Results aree with theory expectations based on LHCb measurements of χ_c







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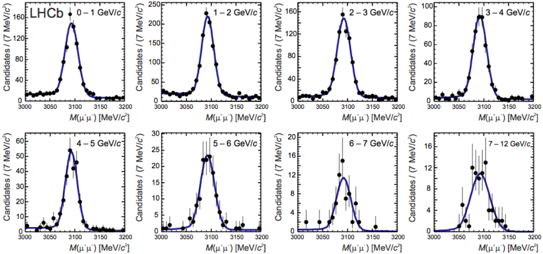
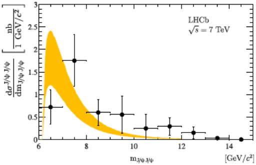
The Analysis Strategy

- Define a fiducial volume in the LHCb acceptance: $2.0 < y < 4.5$ and $p_T < 10\,\mathrm{GeV}/c$.
- Reconstruct $J/\psi \rightarrow \mu^+\mu^-$
- Remove background as much as possible:
  - Cuts on the usual kinematic and reconstruction variables.
  - Require that both J/ψ originate from the same interaction.
  - Require both J/ψ decay vertices are compatible with the primary vertex.
  - This removes the background from double $B \rightarrow J/\psi X$ decays.
- Require one of the J/ψ triggered the event.
- Subtract the remaining background.
- Apply per-event efficiency corrections, with efficiency determined as much as possible from data.

Double J/ψ

- Analysis carried out on the 36 pb^{-1} collected in 2010 PLB 707 (2012) 52-59.
- Cross section measured in the region $p_{\mathrm{T}} < 10\,\mathrm{GeV}/c$, $2 < y < 4.5$.
- First observation of double J/ψ production at hadronic collider.





- Cross-section measured to be $\sigma = 5.1 \pm 1.0 \pm 1.1$ nb.
- In agreement with theoretical prediction of $\sigma = 4$ nb PRD 84 (2011) 094023.

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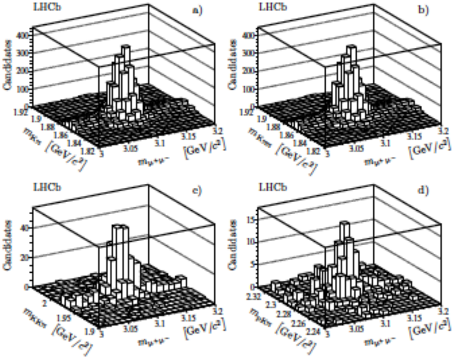
The Analysis Strategy

- Similar to the one for double charmonium.
- Define a fiducial volume in the LHCb acceptance: $2.0 < y < 4.0$ and $p_T < 12\,\mathrm{GeV}/c$.
- Reconstruct $J/\psi \to \mu^+\mu^-$
- Reconstruct $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D_s^+ \to (K^+K^-)_\Phi\pi^+$, and $\Lambda_c \to p^+K^-\pi^+$.
- Remove background as much as possible:
  - Cuts on the usual kinematic and reconstruction variables.
  - Require that both originate from the same interaction.
  - Require both decay vertices are compatible with the primary vertex.
- J/ψ +OC require the J/ψ to have triggered the event, OC+OC require one of the hadrons to have triggred the event.
- Subtract the remaining background.
- Apply per-event efficiency corrections, with efficiency determined as much as possible from data.

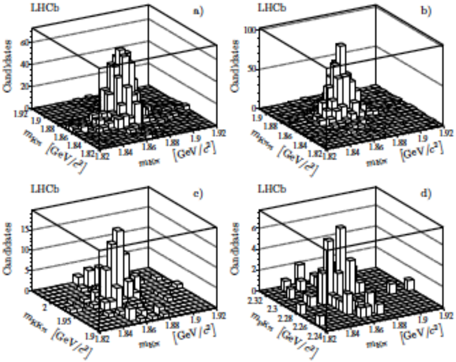
J/ψ + Open Charm



Clear $c\bar{c}c\bar{c}$ signals:

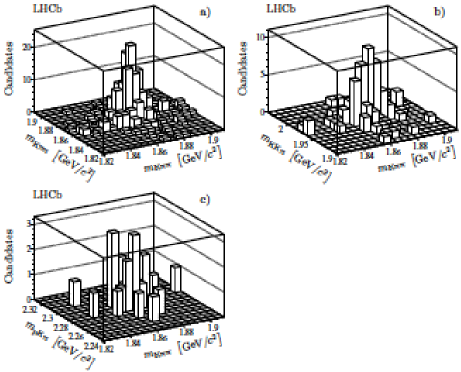
	Mode	Yield
a)	J/ψ D^0	4875 ± 86
b)	J/ψ D^+	3323 ± 71
c)	J/ψ D_s^+	328 ± 22
d)	J/ψ Λ_c^+	116 ± 14

Open Charm + Open Charm: D^0 channels



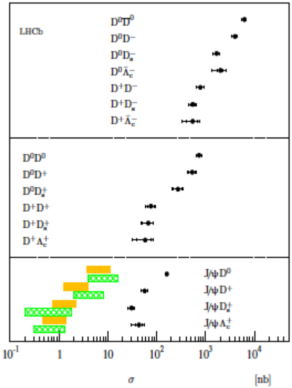
	Mode	Yield
a)	$D^0\ D^0$	1087 ± 37
b)	$D^0\ D^+$	1177 ± 39
c)	$D^0\ D_s^+$	111 ± 12
d)	$D^0\ \Lambda_c^+$	41 ± 8
	$D^0\ \bar{D}^0$	10080 ± 105
	$D^0\ D^-$	11224 ± 112
	$D^0\ D_s^-$	859 ± 31
	$D^0\ \Lambda_c^-$	208 ± 19

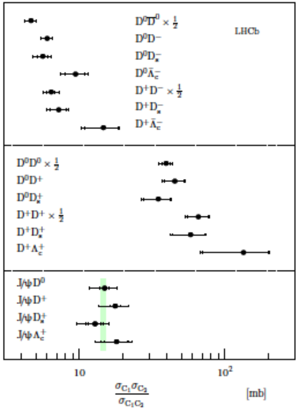
Open Charm + Open Charm: D^+ channels



	Mode	Yield
a)	$D^+ D^+$	249 ± 19
b)	$D^+ D_s^+$	52 ± 9
c)	$D^+ \Lambda_c^+$	21 ± 5
	$D^+ D^-$	3236 ± 61
	$D^+ D_s^-$	419 ± 22
	$D^+ \Lambda_c^-$	127 ± 14

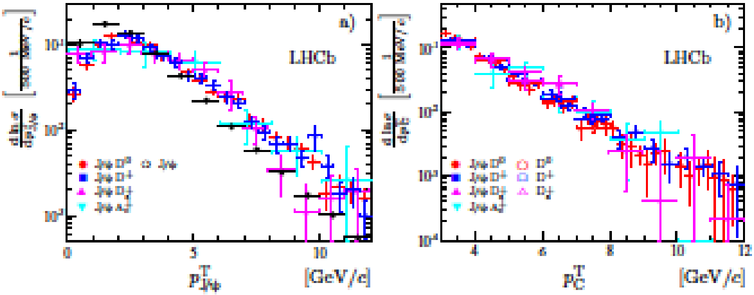
Cross Sections





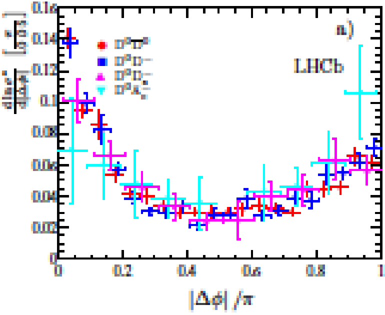
- J/ψ +OC cross section compared to $gg \rightarrow J/\psi\, c\bar{c}$ calculations (Berezhnoy et al. Phys. Rev. D 57 (1998) 4385, Baranov Phys. Rev. D73 (2006) and Lansberg Eur. Phys. J. C 61(2009) 693)
- Ratios compared to DPS extrapolation of Tevatron data.

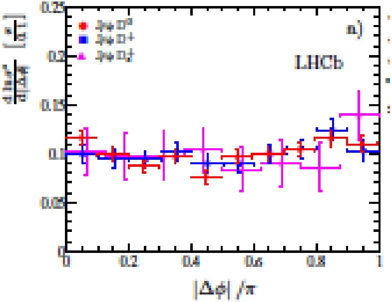
J/ψ p_T in J/ψ +OC events



- The J/ψ p_T spectrum appears to be harder than the one of the prompt J/ψ.
- This does not seem to be the case for the open charm hadron.

Azimuthal Angle Correlation





- There appears to be no correlation between the azimuthal angle of the J/ψ and the open charm.
- The same behaviour is observed in same sign OC+OC.
- On the other hand opposite sign OC+OC show a peak at $\Delta\Phi \to 0$ suggesting a $g \to c\bar{c}$ splitting contribution.

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Conclusions

- During Run I LHCb has collected a wealth of $c\bar{c}$ and $b\bar{b}$ candidates.
- Many interesting results have already been produced including
  1. differential spectra for 1S triplet and singlet state for charmonia
  2. spectra for 2S triplet charmonia
  3. polarization of 1S and 2S triplet charmonia states
  4. relative production of 1P and 1S charmonia states
  5. relative production of tensor and vector 1P charmonia states
  6. differential spectra for 1S,2S,3S bottomonia
  7. relative nP/nS bottomonia production
  8. energy dependence of charmonia 1S and bottomonia 1S,2S,3S cross-sections
- Work currently ongoing to provide measurements of polarization of 1S,2S,3S bottomonia state and more...