Production and polarization measurements at LHCb

heavy quarkonium and double charm production in pp collisions at √s = 7 TeV

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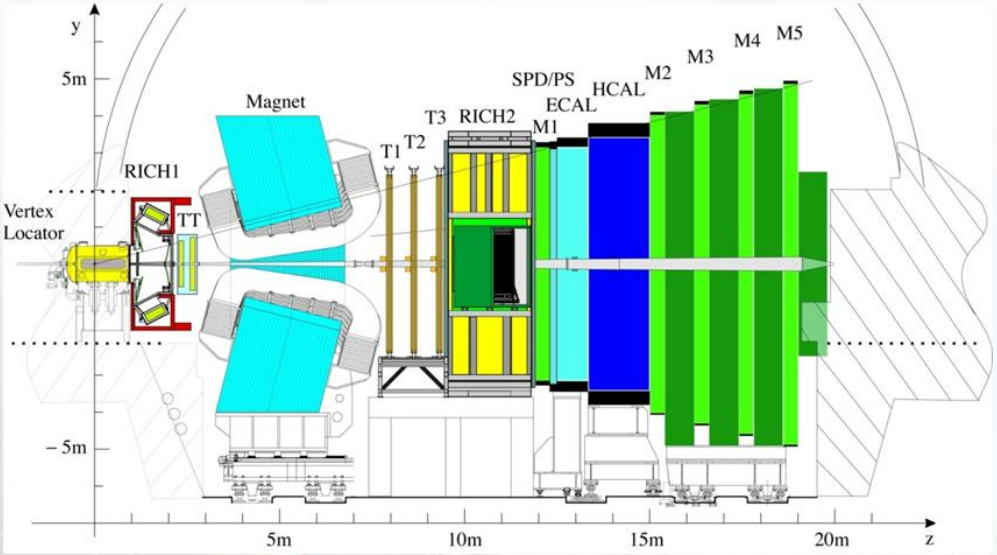
on behalf of the LHCb collaboration

SPIN-Praha-2012, July 1-8, 2012, Prague

LHCb experiment

LHCb experiment: heavy-flavour sector studies with main focus on the searches of the physics beyond Standard Model in CP-violation and rare decays of beauty and charm hadrons

- large $b\bar{b}$ (~300 μb) and $c\bar{c}$ (~6 mb) production cross-sections
- high luminosity
  - LHCb-2010: $L=1.6\times10^{32}\ cm^{-2}\ s^{-1}$
  - LHCb-2011: $L=3.5\times10^{32}\ cm^{-2}\ s^{-1}$
- forward single arm spectrometer with solid angle coverage $2 < \eta < 5$ ← complementary to other LHC experiments



Heavy quarkonium states are copiously produced

- Precise measurement of differential cross-sections, production ratios, polarization, etc
- Large J/Ψ and open charm cross-sections → multiple production studies

LHCb review talk: given by Giovanny (2 July)

Overview

- The mechanisms of heavy quarkonium production are not well understood. Several competing theoretical models, including:
  - Colour Singlet with LO + NLO + NNLO*
  - NLO Colour Singlet + Colour Octet (CS + CO) in the nonrelativistic quantum chromodynamics (NRQCD) framework
  - Colour Evaporation Model (CEM)
  + FONLL (Fixed-Order-Next-to-Leading-Log, charmonium from b-decays only)
- **<u>In this presentation:</u>**

2010
37.5 pb^{-1}

- **Heavy quarkonium**
  - J/Ψ, Ψ(2S), Υ(1S), Υ(2S), Υ(3S) production and prod. ratios
  - χ_c / J/Ψ ratio of production cross-sections and χ_{c2} / χ_{c1} cross-sections ratio
  - J/Ψ polarization studies (ongoing)

2011
335 pb^{-1}

- **J/Ψ pair**
  J/Ψ + associated open charm
  double open charm hadron production
  - important probe for heavy quarkonium production mechanism
  - other contributions are possible, like Double Parton Scattering or intrinsic charm content of the proton
  - searches for possible tetraquark states of four c-quarks

Heavy quarkonium studies

Analysis features (1)

Decay channels

- J/Ψ: $J/\Psi \to \mu^+\mu^-$
- Ψ(2S): $\Psi(2S) \to \mu^+\mu^-$ and $\Psi(2S) \to J/\Psi\pi^+\pi^-$, $J/\Psi \to \mu^+\mu^-$
- $\chi_{cJ}(1P)$ states, J=1,2: radiative decay $\chi_c \to J/\Psi\gamma$, $J/\Psi \to \mu^+\mu^-$
- Υ(nS), n=1,2,3 : $\Upsilon(nS) \to \mu^+\mu^-$

Trigger settings (2010)

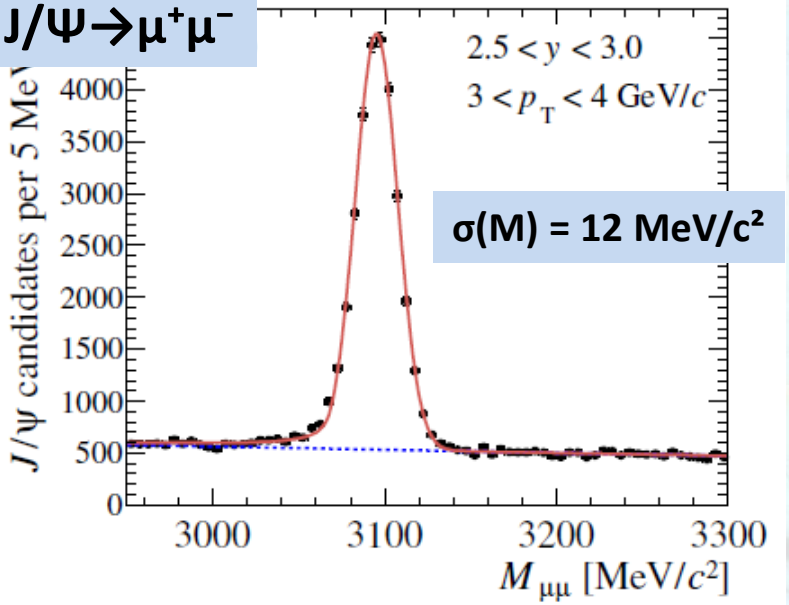
- **Level-0 trigger**: synchronous 40 MHz, hardware-based
  - Single-muon line: 1 candidate with $p_T > 1.4$ GeV/c
  - Di-muon line: 2 candidates with $p_T > 0.56$ GeV/c and $p_T > 0.48$ GeV/c
- **High Level Trigger**: asynchronous, software, 2 subfarms
  - HLT1 [partial event reconstruction]: confirms L0 + →
    - Single-muon: $p_T > 1.8$ GeV/c
    - Di-muon: di-muon pair with $M > 2.5$ GeV/c^2
  - HLT2 [full event reconstruction]: common vertex

+ global event cuts to avoid high multiplicity events

Overall L0xHLT trigger efficiency for di-muon channels: ~90%

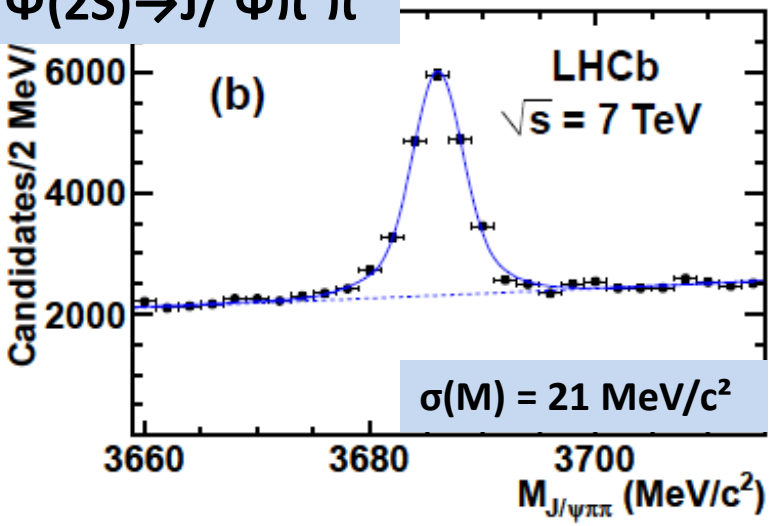
Invariant mass distributions

$J/\Psi \to \mu^+\mu^-$



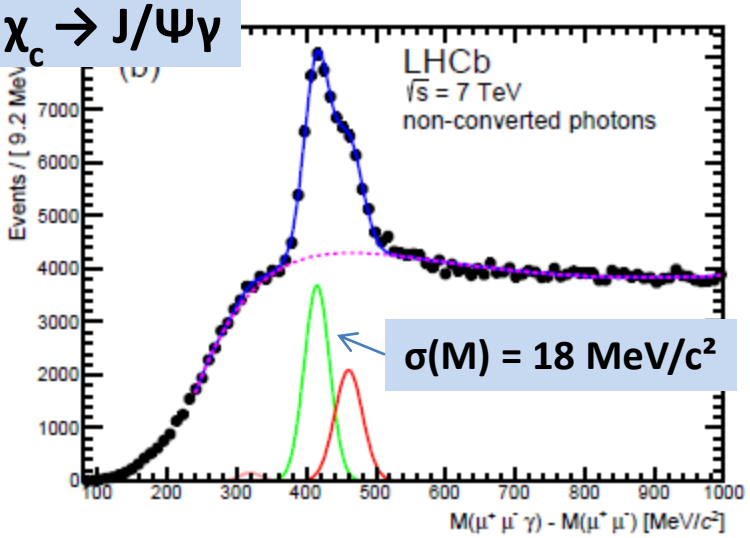
$\sigma(M) = 12$ MeV/c²

$\Psi(2S) \to J/\Psi\pi^+\pi^-$



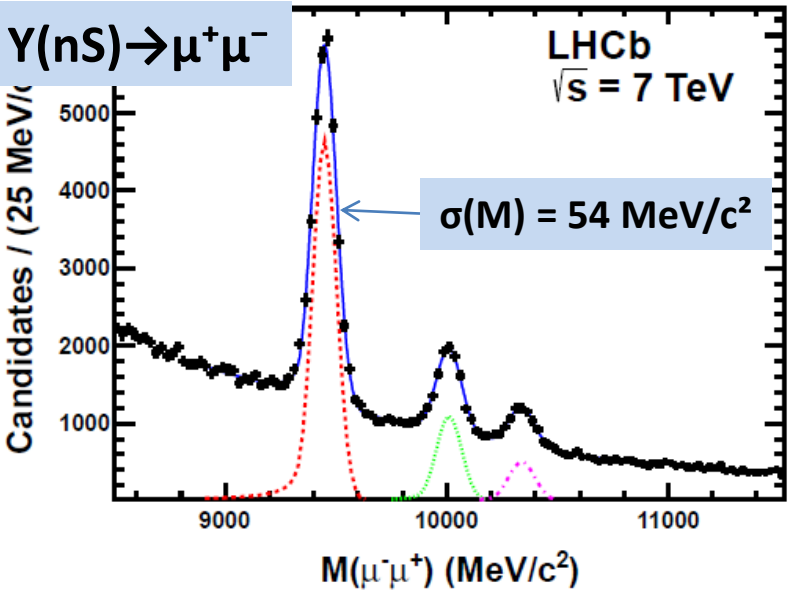
$\sigma(M) = 21$ MeV/c²

$\chi_c \to J/\Psi\gamma$



$\sigma(M) = 18$ MeV/c²

$\Upsilon(nS) \to \mu^+\mu^-$



$\sigma(M) = 54$ MeV/c²

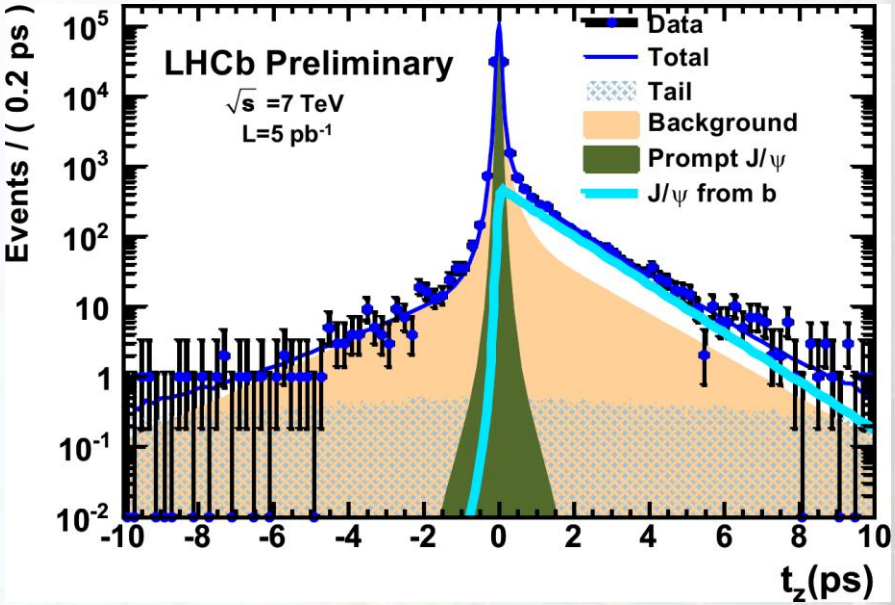
Analysis features (2)

- Three contributions (polarization might be different):
  - direct production
  - feed-down production
  - production via b-decay chain

} **prompt**

- Prompt and b-produced contributions are separated using pseudo-proper time variable t_z
- Prompt : large systematic error comes from unknown polarization
  - can strongly affect efficiencies obtained from MC (up to 40% in case of double-differential cross-sections).
  - uncertainty is estimated by comparing marginal cases of full transverse, full longitudinal and no polarization

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



J/Ψ production: results (1)

- Double-differential cross-sections (p_T, y) for 5 rapidity bins in $2 \le y \le 4.5$ and 14 transverse momentum bins in $0 \le p_T \le 14$ GeV/c :
  - prompt J/Ψ (3 sets: assuming no polarization / longitudinal polarization / full transverse polarization)
  - J/Ψ from b-decays
- Differential cross-sections as a functions of p_T : comparison with theory (unpolarized prompt J/Ψ, J/Ψ from b)
- Fraction of J/Ψ from b (5 y-bins and 14 p_T -bins)
- Integrated cross-sections:

Uncertainty due to unknown polarization

$$\sigma\,(\text{prompt } J/\psi, p_T < 14\ \text{GeV}/c, 2.0 < y < 4.5) = 10.52 \pm 0.04 \pm 1.40^{+1.64}_{-2.20}\ \mu\text{b}$$

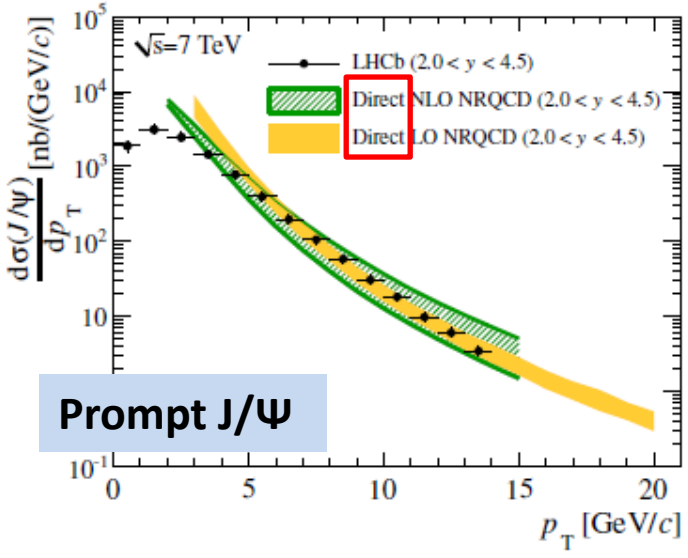
$$\sigma\,(J/\psi \text{ from } b, p_T < 14\ \text{GeV}/c, 2.0 < y < 4.5) = 1.14 \pm 0.01 \pm 0.16\ \mu\text{b}$$

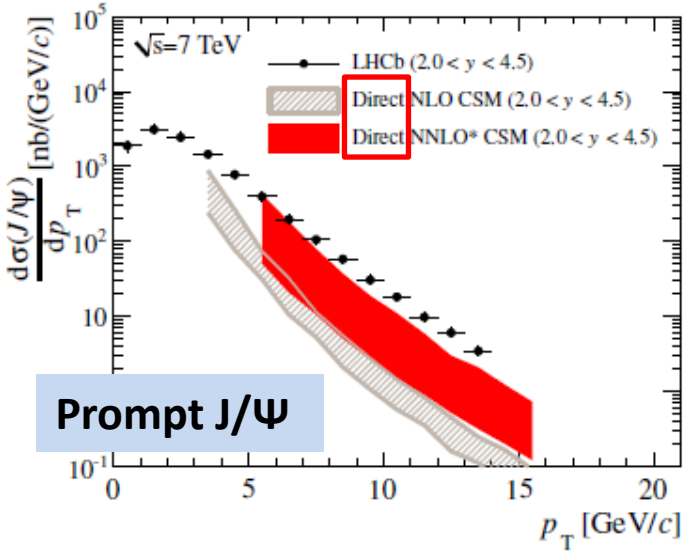
- Extrapolation to 4π using LEP branching fraction b→J/ΨX:

$$\sigma(pp \to b\bar{b}X) = 288 \pm 4 \pm 48\ \mu\text{b}$$

Published in ***Eur. Phys. J. C* 71 (2011) 1645**

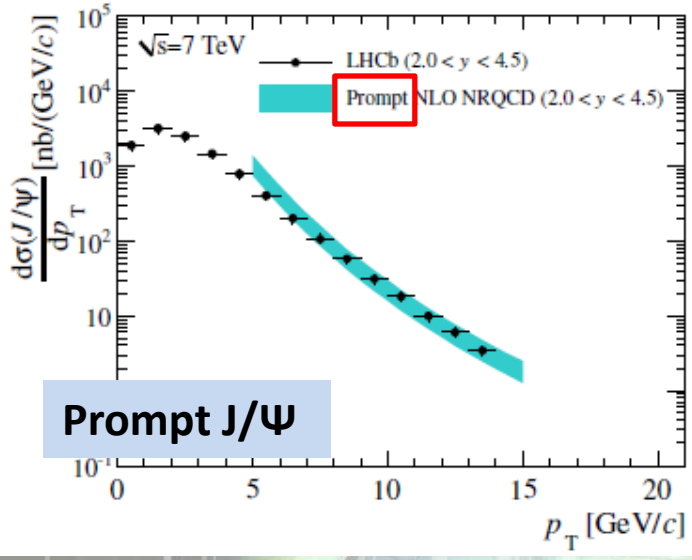
J/Ψ production: results(2)

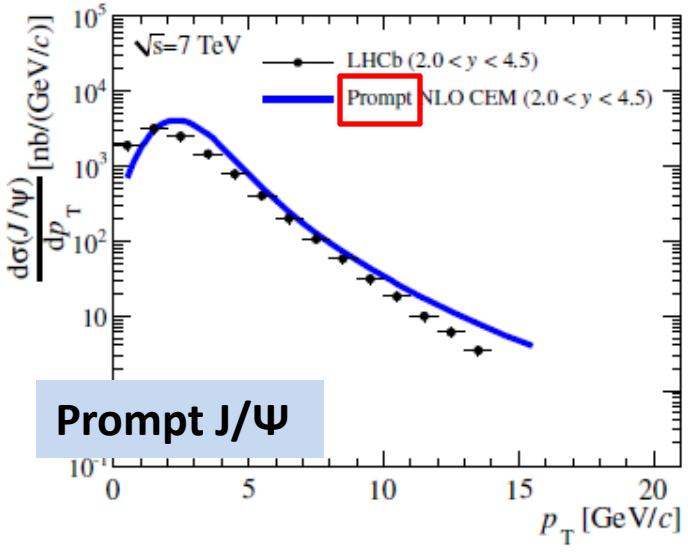




Direct J/Ψ production:

- COM: arXiv:1009.5662
- CSM: arXiv:0811.4005

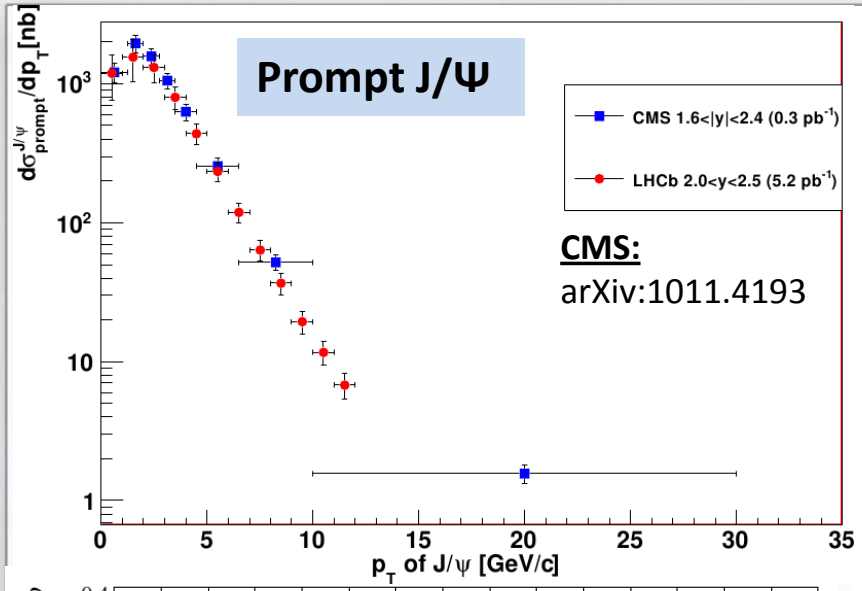


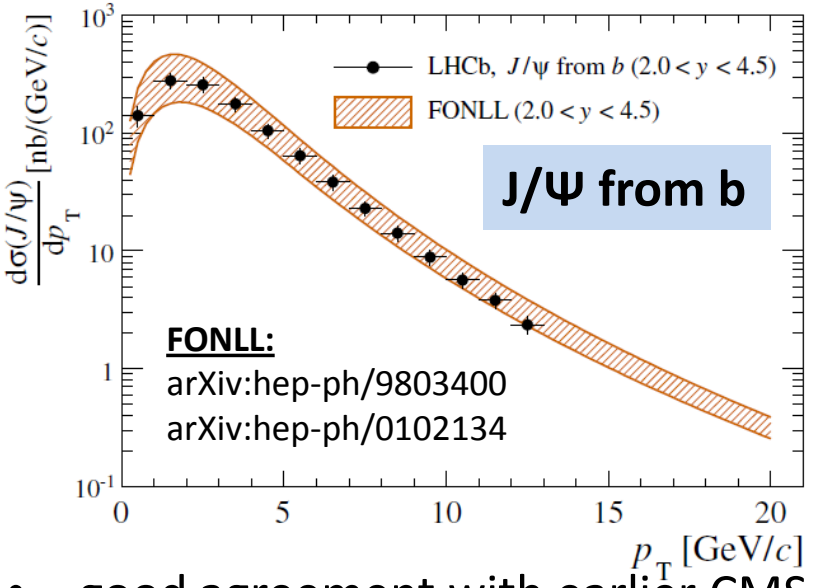


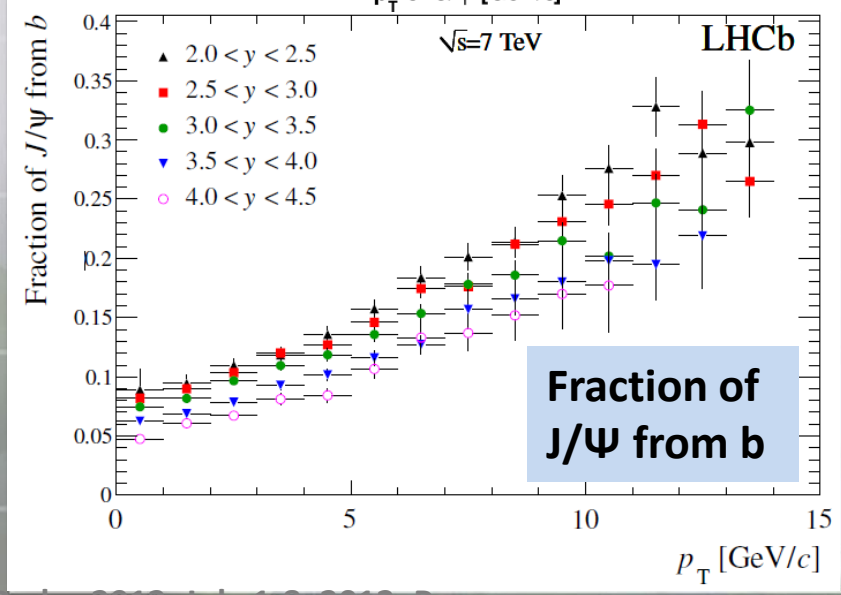
Prompt J/Ψ production:

- COM: direct + χ_c , Ψ(2S) arXiv:1009.3655
- CEM: direct + χ_c , Ψ(2S) arXiv:0806.1013

J/Ψ production: results(3)



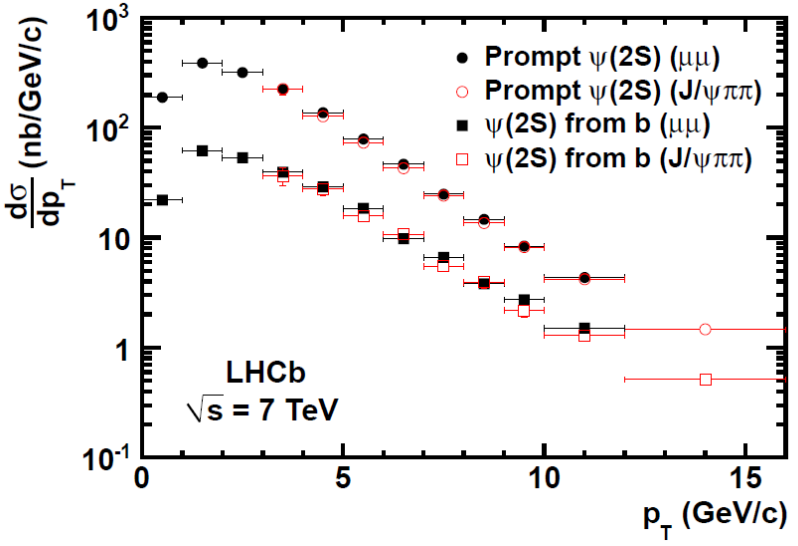




- good agreement with earlier CMS measurements
- prompt J/Ψ: a satisfactory agreement with theoretical predictions at high p_T (feed-down contribution estimate: ~30%)
- J/ Ψ from b-decays: very good agreement with FONLL-based calculations

Ψ(2S) production: results(1)

- Differential cross-sections as a function of pt for full y range $2 < y < 4.5$ and $p_T \leq 16$ GeV/c:
  - Weighted average for two decay modes
    - Prompt Ψ(2S)
    - Ψ(2S) from b-decays
  - Comparison with theory (prompt Ψ(2S), Ψ(2S) from b-decays)



- Integrated cross-sections:

$$\sigma_{\text{prompt}}(\psi(2S)) = 1.44 \pm 0.01\ (\text{stat}) \pm 0.12\ (\text{syst})^{+0.20}_{-0.40}\ (\text{pol})\ \mu\text{b},$$
$$\sigma_b(\psi(2S)) = 0.25 \pm 0.01\ (\text{stat}) \pm 0.02\ (\text{syst})\ \mu\text{b},$$

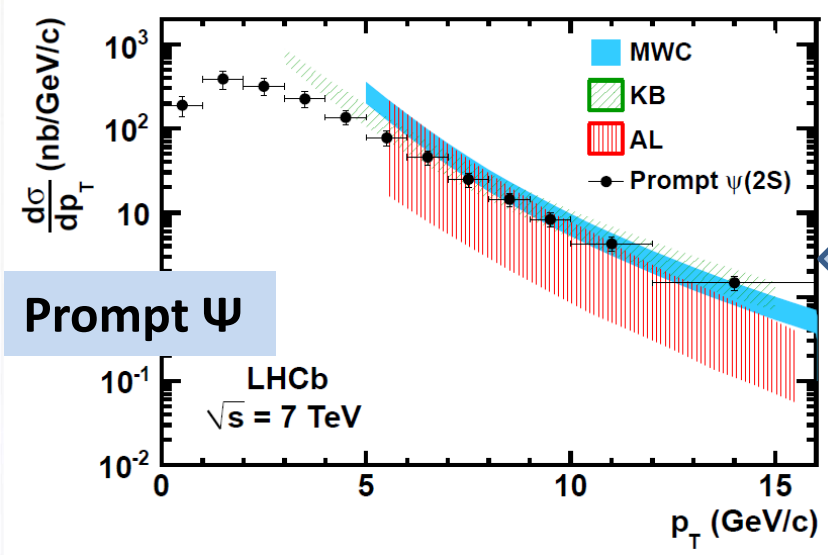
- Inclusive b→Ψ(2S)X branching fraction:

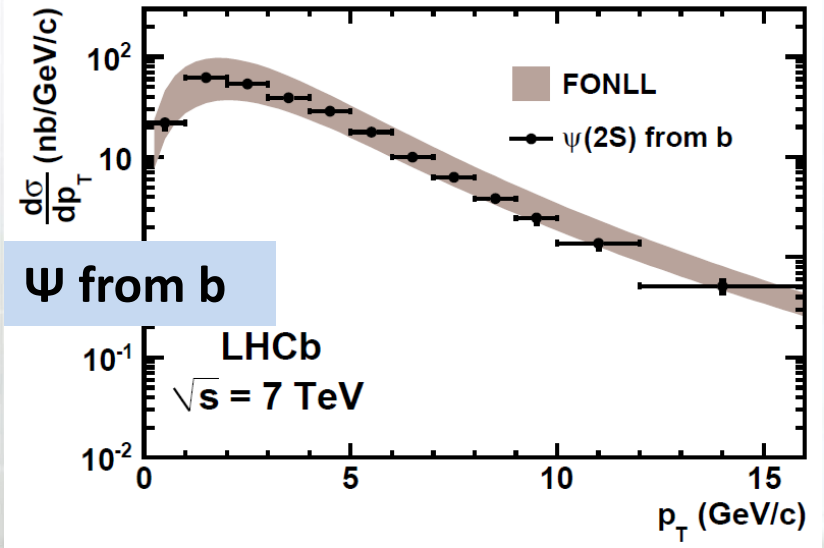
$$\mathcal{B}(b \to \psi(2S)X) = (2.73 \pm 0.06\ (\text{stat}) \pm 0.16\ (\text{syst}) \pm 0.24\ (\text{BF})) \times 10^{-3}$$

CMS: (3.08 ± 0.12 (stat+sys) ± 0.13(theor) ± 0.42(BF)) x 10^{-3} JHEP 02 (2011) 11
World average (LEP+Tevatron): (4.2 ± 2.4) x 10^{-3} J. Phys. G 37 (2010) 075021

Preprint: **arXiv:1204.1258**

Ψ(2S) production: results (2)





Direct Ψ(2S) production:

- MWC: NLO CS + CO
  arXiv:hep-ph/1012.1030
- KB: NLO CS + CO
  Phys. Rev. Lett. 106 (2011) 022003 + pc
- AL: CS LO+NLO+NNLO*
  Phys. Rev. Lett. 101 (2008) 152001
  Eur. Phys. J. C61 (2009) 693

- good agreement between two decay modes (within 0.5σ)
- prompt Ψ(2S): good agreement with theory at high transverse momenta
- Ψ(2S) from b-decays: very good agreement with FONLL
- more precise measurement of the branching fraction (PDG value(2010): 50% accuracy). Good agreement with recent CMS measurements

χ_c studies: results(1)

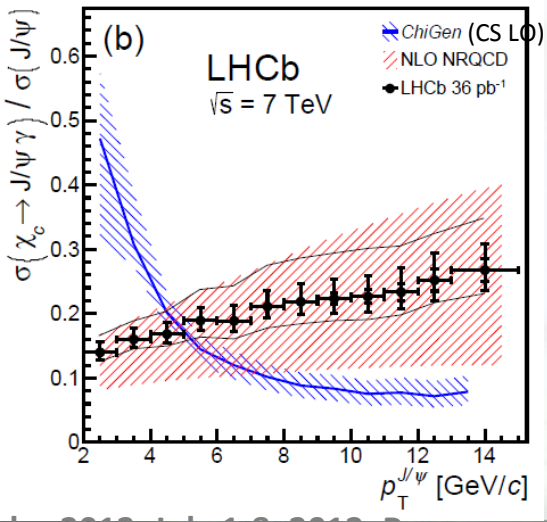
Two complementary measurements, both in form of dependence on $p_T(J/\Psi)$ in full y-range $2 < y < 4.5$ and in $p_T(J/\Psi)$ range $2 < p_T(J/\Psi) < 15$ GeV/c:

– Ratio of prompt production cross-sections

Vital for the estimation of feed-down contribution in J/Ψ prod.

$\sigma(\chi_c \to J/\Psi\gamma) / \sigma(J/\Psi)$, $\chi_c = \chi_{cJ}(1P)$, J = 0,1,2

- on the basis of 37 pb^{-1} (2010) **[arXiv:1204.1462]**
  - γ, reconstructed in calorimeter (converted/non-coverted)



- significant statistical improvement wrt to previous measurements
- HERA-*B* measurement:

$$\sigma(\chi_c \to J/\psi\gamma) / \sigma(J/\psi) = 0.188 \pm 0.013^{+0.024}_{-0.022}$$

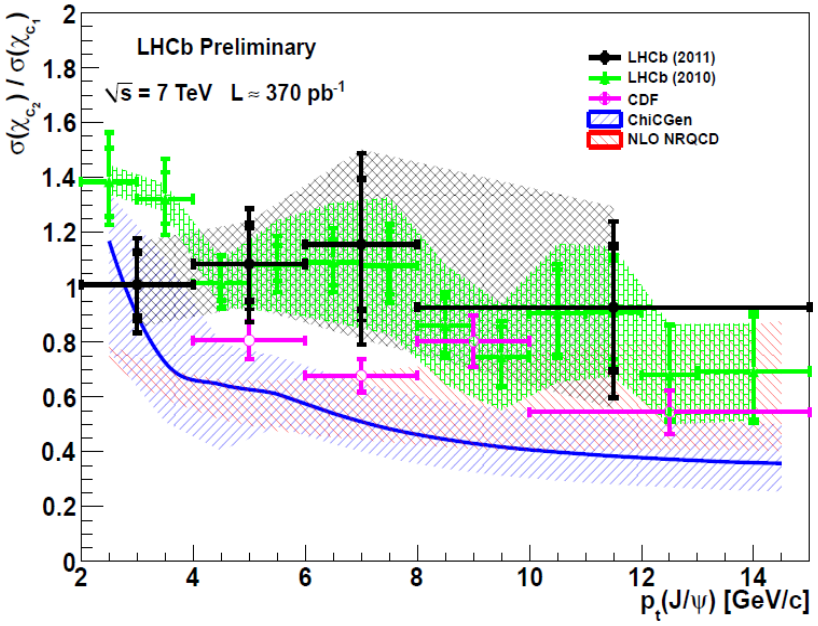
($p_T(J/\Psi) < 5$ GeV/c, Phys. Rev. D 79, 012001 (2009))

- in agreement with NLO NRQCD model over the full range of p_T

χ_c studies: results(2)

- Ratio of prompt production cross-sections $\sigma(\chi_{c2}) / \sigma(\chi_{c1})$
  - on the basis of 37 pb^{-1} (2010) **[arXiv:1202.1080]**
    - γ, reconstructed in calorimeter
  - on the basis of 370 pb^{-1} (2011) **[LHCb-CONF-2011-062]**
    - converted γ, reconstructed via tracker (**preliminary**)
      - advantage: tracker has better resolution than calorimeter
      - disadvantage: low statistics

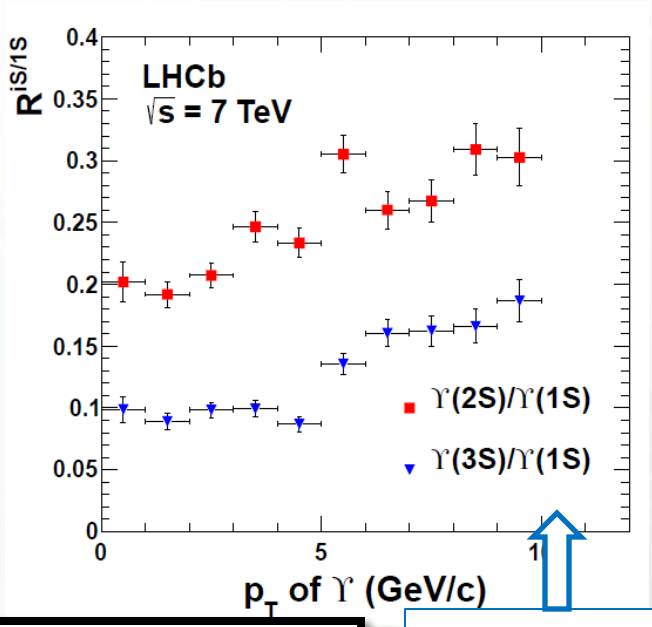
Sensitive to CS and CO production mechanisms



- 2010 and 2011 results [!complementary approaches!] are in good agreement
- LHCb ratio seems to be systematically above NLO NRQCD predictions for $p_T < 8$ GeV/c, but…
- uncertainties are large → more data are needed to make conclusive statement

Υ(nS) production: results(1)

- Inclusive double-differential cross-sections for 5 rapidity bins $2 < y < 4.5$ and 15 transverse momentum bins $0 < p_T < 15$ GeV/c
  - separately for Υ(1S), Υ(2S), Υ(3S)
  - comparison with theoretical predictions
- Ratios of cross-sections Υ(2S)→μμ and Υ(3S)→μμ wrt Υ(1S)→μμ as a function of p_T in full y-range
- Integrated cross-sections:



$$\sigma(pp \to \Upsilon(1S)\,X) \times \mathcal{B}^{1S} = 2.29 \pm 0.01 \pm 0.10\ ^{+0.19}_{-0.37}\ \text{nb},$$
$$\sigma(pp \to \Upsilon(2S)\,X) \times \mathcal{B}^{2S} = 0.562 \pm 0.007 \pm 0.023\ ^{+0.048}_{-0.092}\ \text{nb},$$
$$\sigma(pp \to \Upsilon(3S)\,X) \times \mathcal{B}^{3S} = 0.283 \pm 0.005 \pm 0.012\ ^{+0.025}_{-0.048}\ \text{nb},$$

Polarization uncertainties are not included (15-26%)

Uncertainty due to unknown polarization

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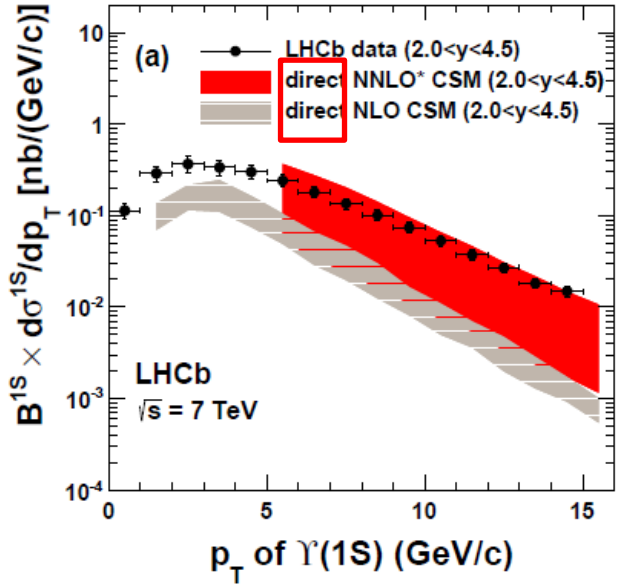
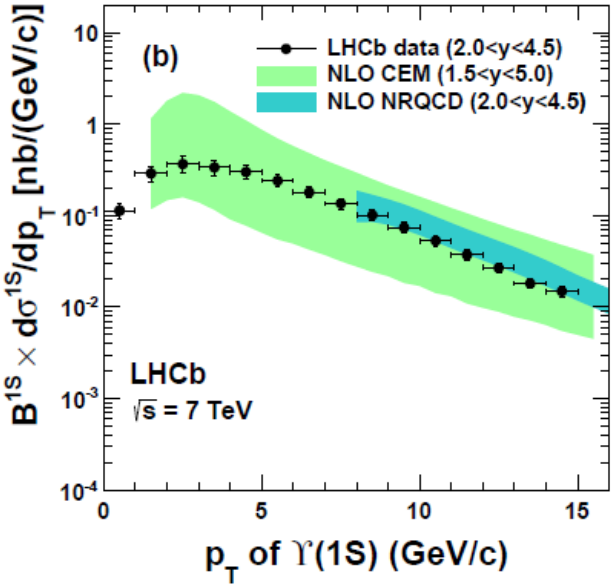
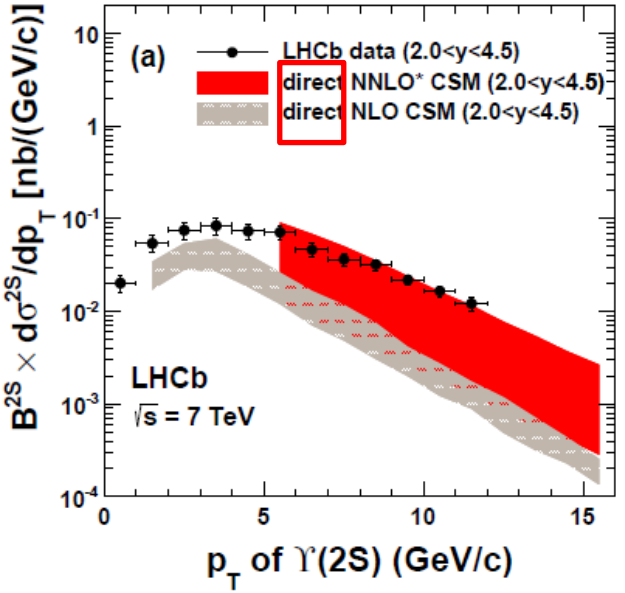
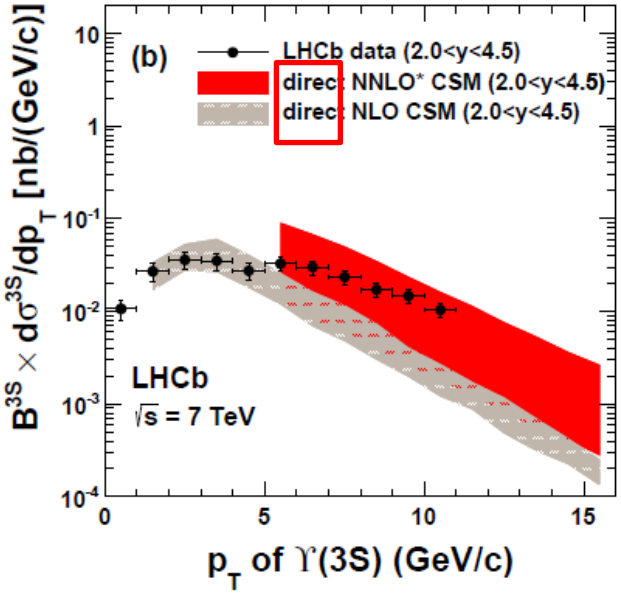
Υ(nS) production: results(2)









Υ(nS) production:

- NNLO* CSM: direct arXiv:0806.3282.
  CEM: direct + χ_b, Υ arXiv:0806.1013
  NLO NRQCD: direct + χ_b, Υ arXiv:1009.3655

- Satisfactory agreement with theoretical predictions (feed-down contribution estimate: up to ~50%)
- Better agreement for Υ(3S) (expected to be less affected by feed-down)
- Nice overlap with recent CMS results [arXiv:1012.5545], CERN PH seminar (26 June 2012)

Prospects on prompt J/Ψ polarization

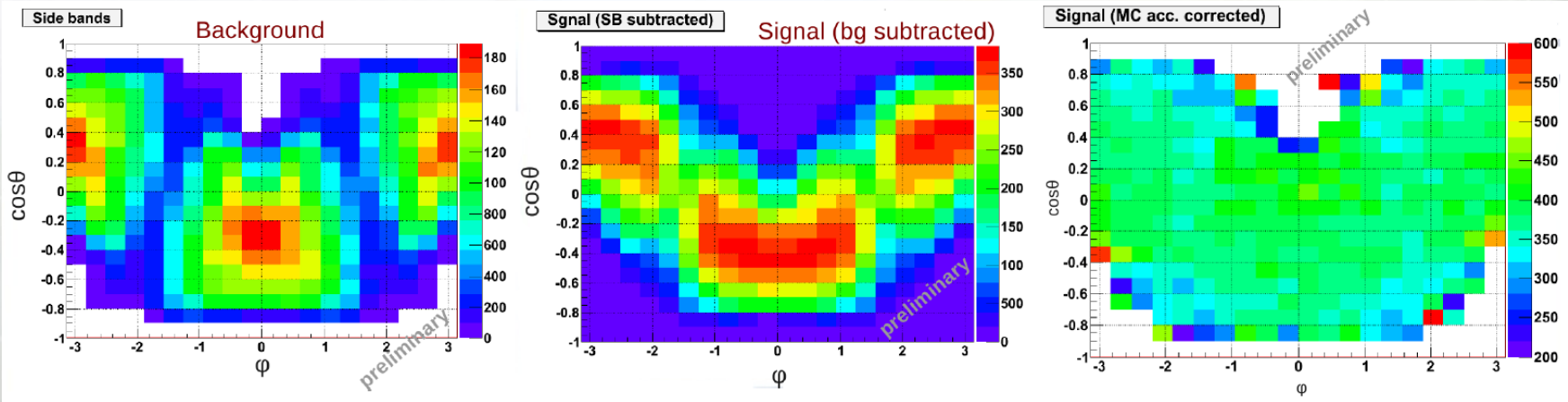
- The information about polarization can be extracted from angular distribution of decay muons: two angles, three real parameters

$$\frac{d^2N}{d\cos\theta d\phi} = 1 + \lambda_\theta \cos^2\theta + \lambda_{\theta\phi} \sin 2\theta \cos\phi + \lambda_\phi \sin^2\theta \cos 2\phi$$

$$\frac{dN}{d\cos\theta} = 2\pi(1 + \lambda_\theta \cos^2\theta)$$

$$\frac{dN}{d\phi} = (2 + \frac{2}{3}\lambda_\theta) + \frac{4}{3}\lambda_\phi \cos(2\phi)$$

- World data: several definitions of the polarization frame (HX, CS, GJ). Values of λ-parameters depend on the choice of reference, but it is possible to construct their combinations which are invariant, like $\lambda = (\lambda_\theta + 3\lambda_\phi) / (1 - \lambda_\phi)$
- Analysis is ongoing. The strategy is:
  - to study both two-angle distribution and integrated one-angle distributions, then compare results
  - try to obtain results for more than one frame to cross-check invariant combinations



Double charm production

J/Ψ J/Ψ production

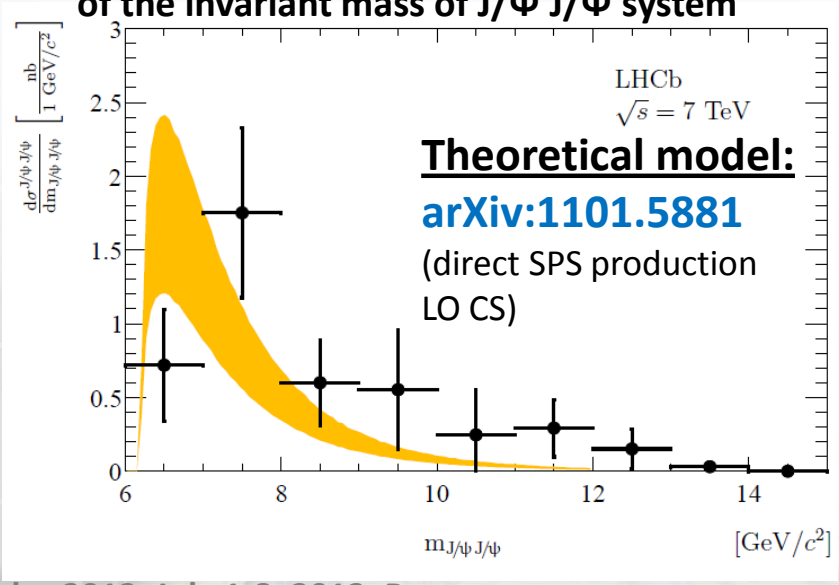
- Production cross-section in full rapidity range 2 < y < 4.5 and transverse momentum range $p_T(J/\Psi) < 10$ GeV/c

$$\sigma^{J/\psi\, J/\psi} = 5.1 \pm 1.0 \pm 1.1 \text{ nb}$$

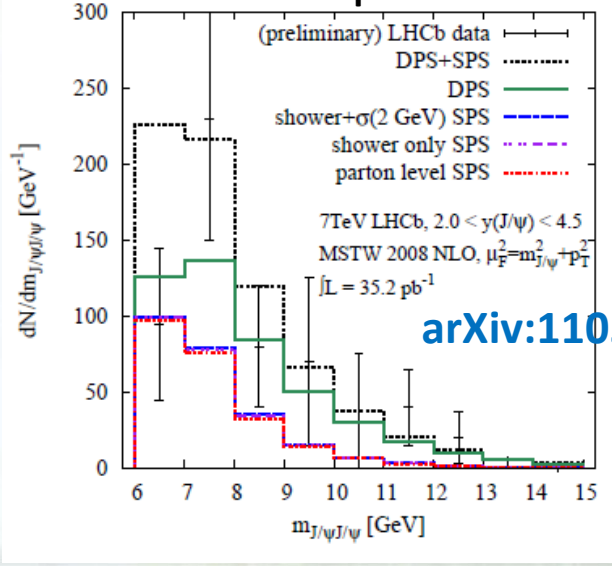
Published in ***Phys. Lett. B* 707 (2012) 52–59**

  - Theoretical prediction from SPS: 4.1±1.2 nb [arXiv:1101.5881], expected DPS contribution: 2±1 nb [arXiv:1106.2184]
  - Previously observed in hadronic collisions only by NA3 experiment (Phys. Lett. B 114, 457 (1982))

Differential production cross-section as a function of the invariant mass of J/Ψ J/Ψ system



LHCb results might indicate a significant contribution from the DPS production mechanism.



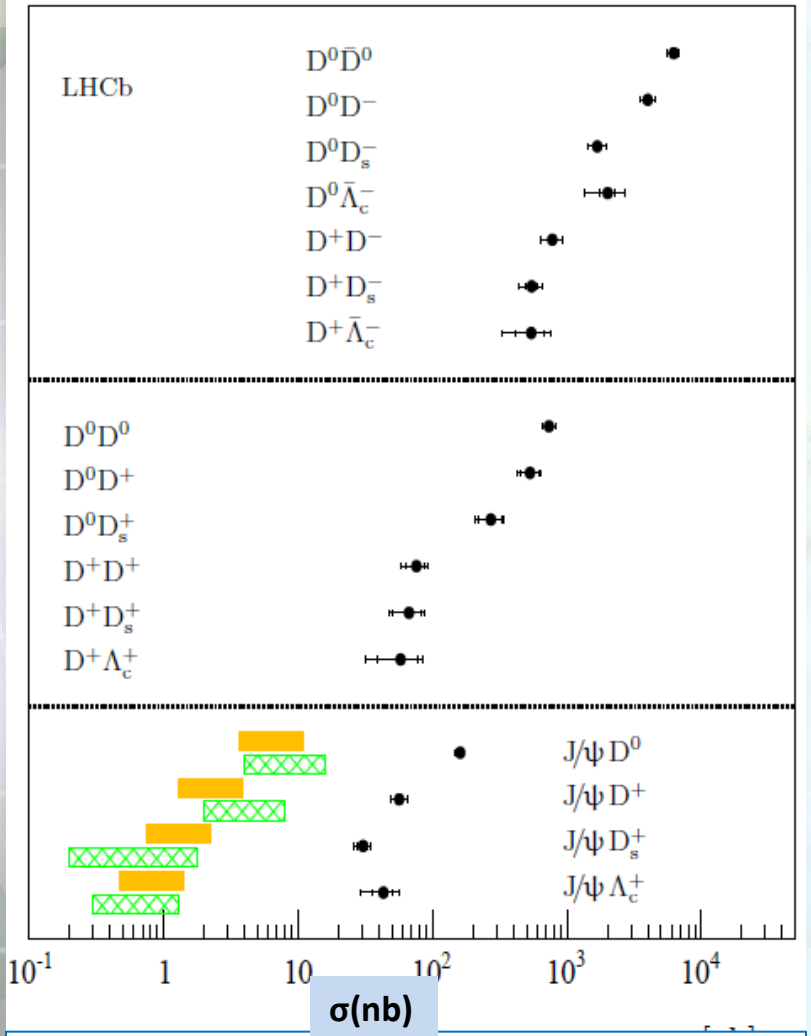
J/ΨC and CC production

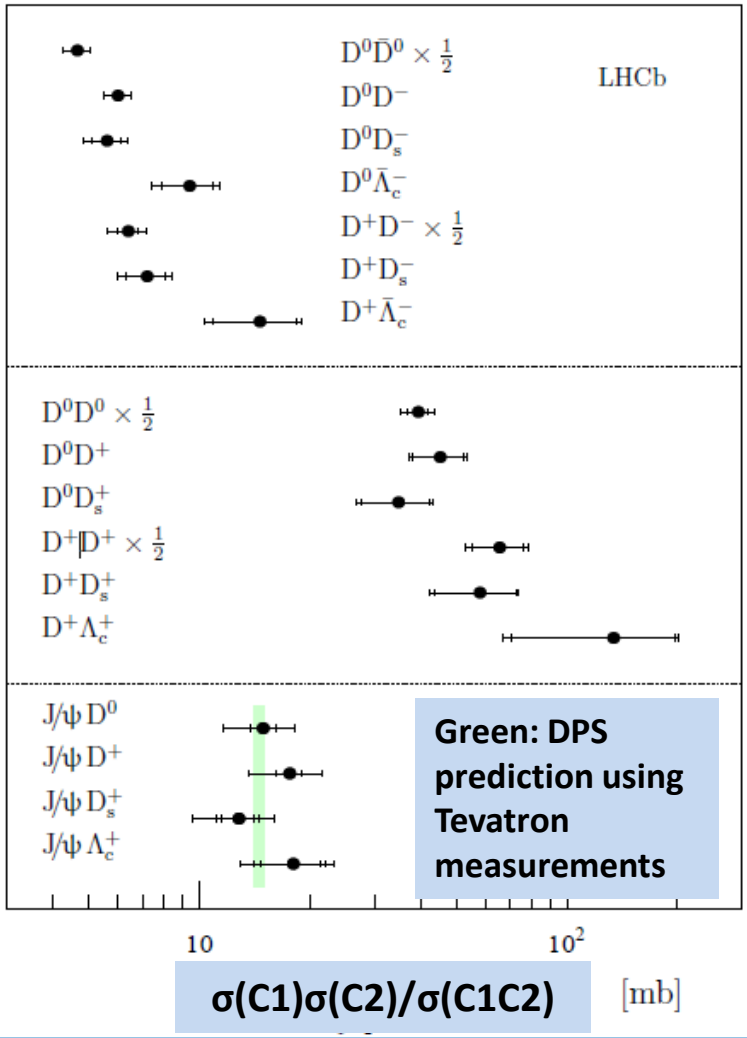
- Acceptance region:

  $2 < y_{J/\Psi}, y_C < 4$, p_T (J/Ψ) < 12 GeV/c, 3 < p_T (C) < 12 GeV/c
- Signals with a statistical significance in excess of 5σ have been observed for:
  - J/ΨC: $J/\Psi D^0$, $J/\Psi D^+$, $J/\Psi D_s^+$, $J/\Psi \Lambda_c^+$
  - CC $D^0 D^0$, $D^0 D^+$, $D^0 D_s^+$, $D^+ D^+$, $D^+ D_s^+$, $D^0 \Lambda_c^+$
  - $C\bar{C}$ (control) $D^0 \bar{D}^0$, $D^0 D^-$, $D^0 D_s^-$, $D^+ D^-$, $D^+ D_s^-$, $D^0 \bar{\Lambda}_c^-$, $D^+ \bar{\Lambda}_c^-$
- Measured values:
  - Production cross-sections
  - Ratios **σ(J/Ψ)σ(C)/σ(J/ΨC)** and **σ(C1)σ(C2)/σ(C1C2)**, where σ(J/Ψ) and σ(C) stay for J/Ψ and open charm prompt production
  - Ratios **$\sigma(CC)/\sigma(C\bar{C})$**
  - Properties of J/ΨC, CC, and $C\bar{C}$ events:
    - Slope parameters of transverse momentum spectra of individual particles
    - The correlations in azimuthal angle and rapidity
    - Invariant mass spectra

Preprint: **arXiv:1205.0975**

J/ ΨC and CC production: results(1)



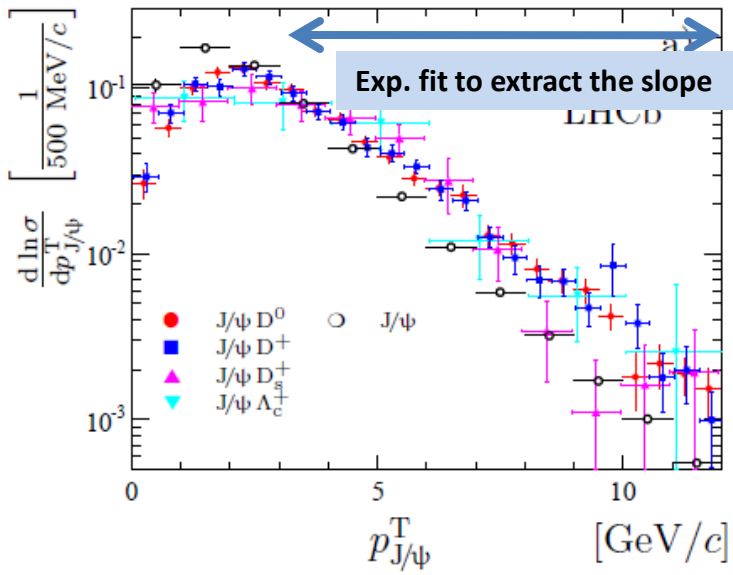


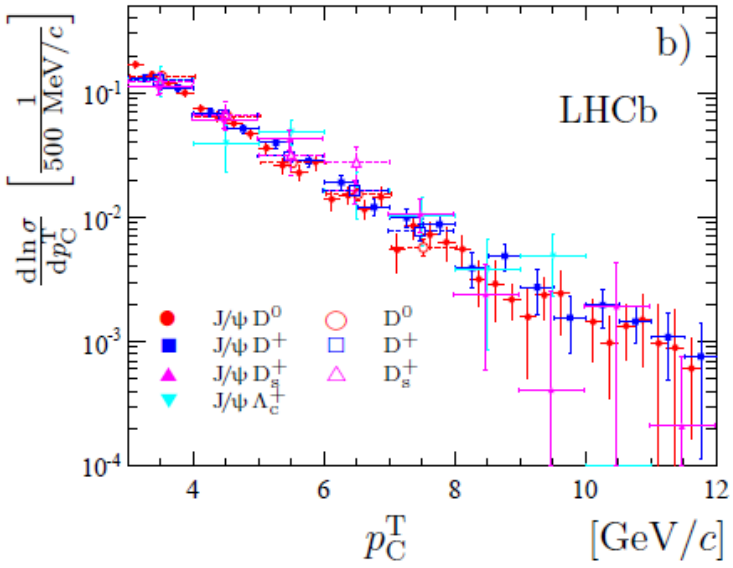
Green: DPS prediction using Tevatron measurements

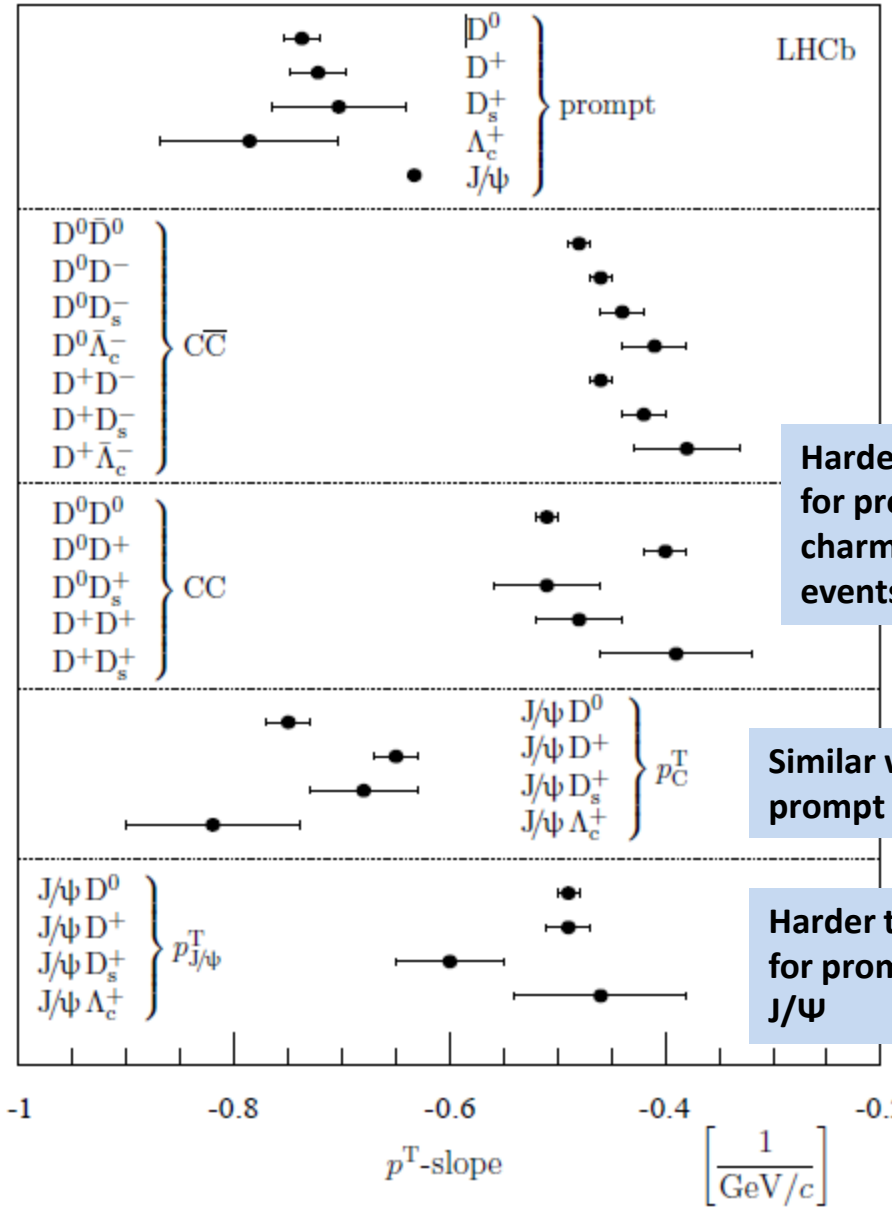
Theory predictions (gluon fusion processes):
- green hatched arXiv:hep-ph/9710339 and Rev. D73 (2006) 074021
- yellow: arXiv:0811.4005

DPS approach:
J/ΨC and CC: the same for all modes
—
CC: should not depend on the final state

J/ ΨC and CC production : results(2)





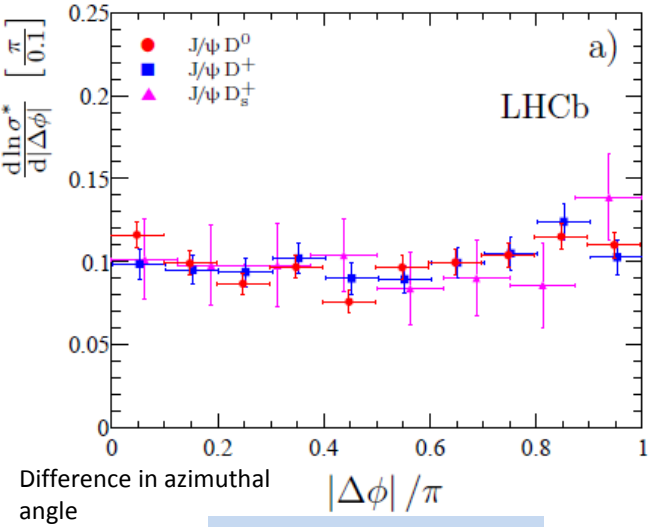


Harder than for prompt charm / J/Ψ events

Similar with prompt charm

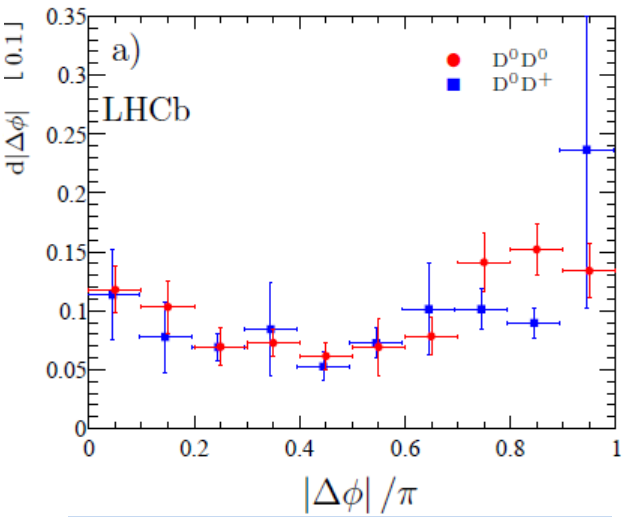
Harder than for prompt J/Ψ

J/ ΨC and CC production : results(3)

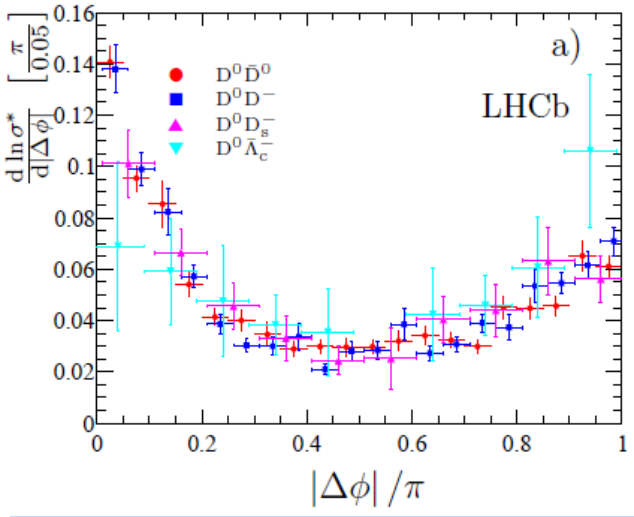


Difference in azimuthal angle

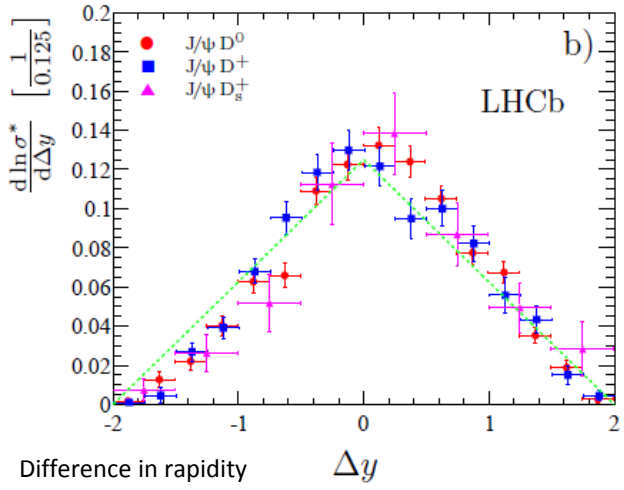
No correlations



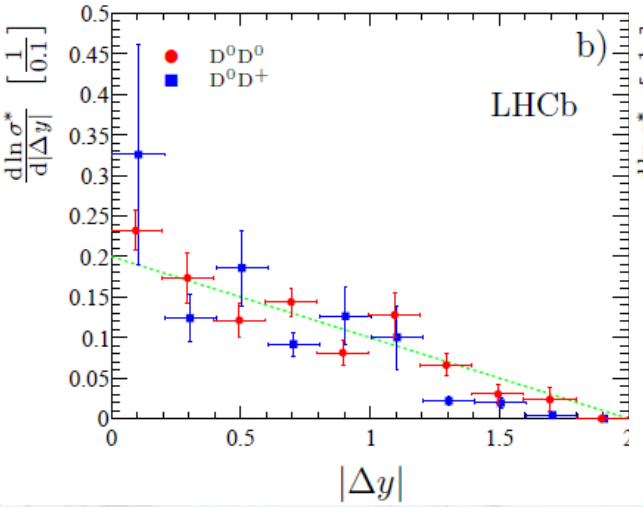
Consistent with no correlations

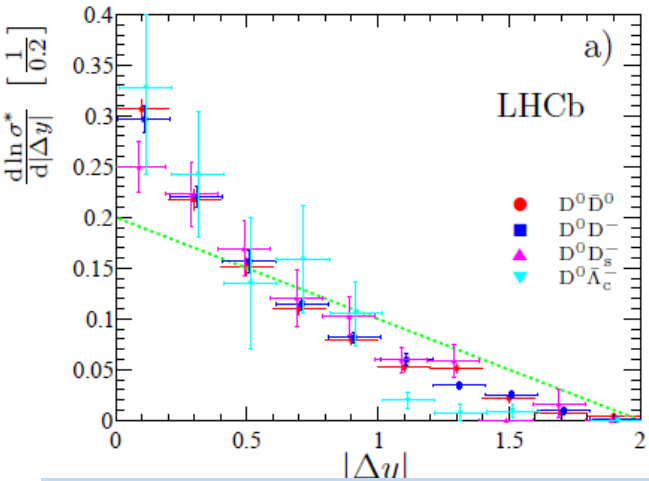


Clear enhancement for low Δϕ/Δy



Difference in rapidity

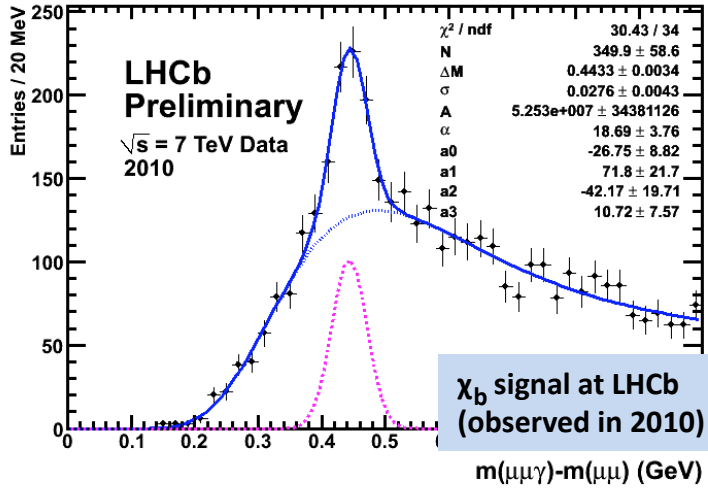




Suggest a sizeable contribution from the gluon splitting process to c-quark production (arXiv:hep-ph/0211096)

Future prospects

- Many results are being updated with more luminosity
- Some production measurements will be repeated at √s = 8 TeV energy
- Polarization for J/Ψ and other heavy quarkonium states
- χ_b studies. First results will be reported at ICHEP2012
- Update J/ΨJ/Ψ results with more statistics, explore other promising channels for charmonium pairs and double charm production studies: J/Ψ Ψ(2S), J/ΨY, YY



χ_b signal at LHCb (observed in 2010)

All preprints and conference reports: please check LHCb web-portal http://lhcb.web.cern.ch/lhcb/