Review of LHCb heavy-quark and quarkonia results

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on behalf of the LHCb collaboration

20 July, 2013

HEP 2013
Stockholm
18-24 July 2013

Outline

- The LHCb detector and data taking
- J/ψ and $\Upsilon(\mathrm{nS})$ productions at $\sqrt{s} = 8\ \mathrm{TeV}$
- χ_{cJ} production using converted photons at $\sqrt{s} = 7\ \mathrm{TeV}$
- J/ψ polarisation at $\sqrt{s} = 7\ \mathrm{TeV}$ 

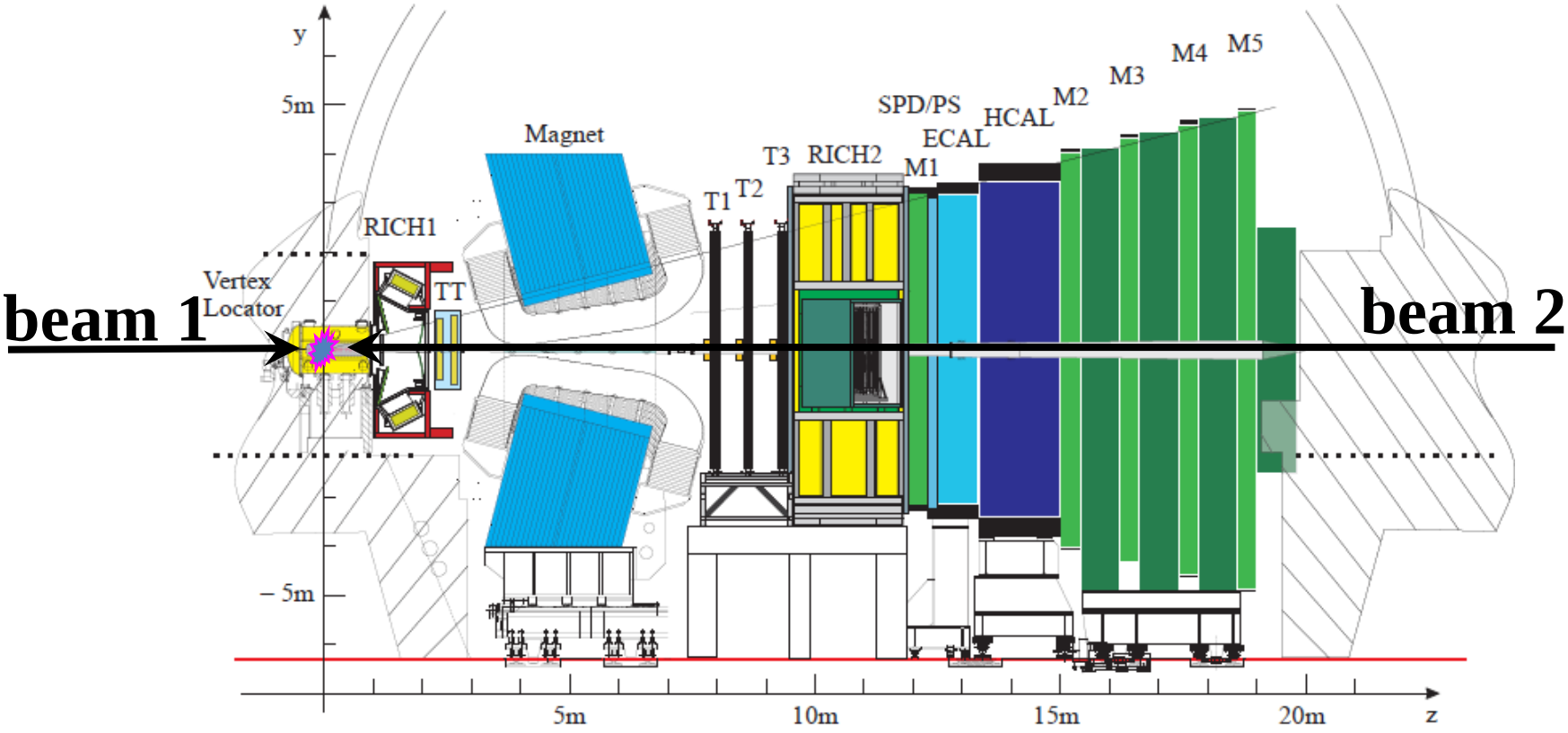
- Other results
- Summary and prospects

LHCb detector

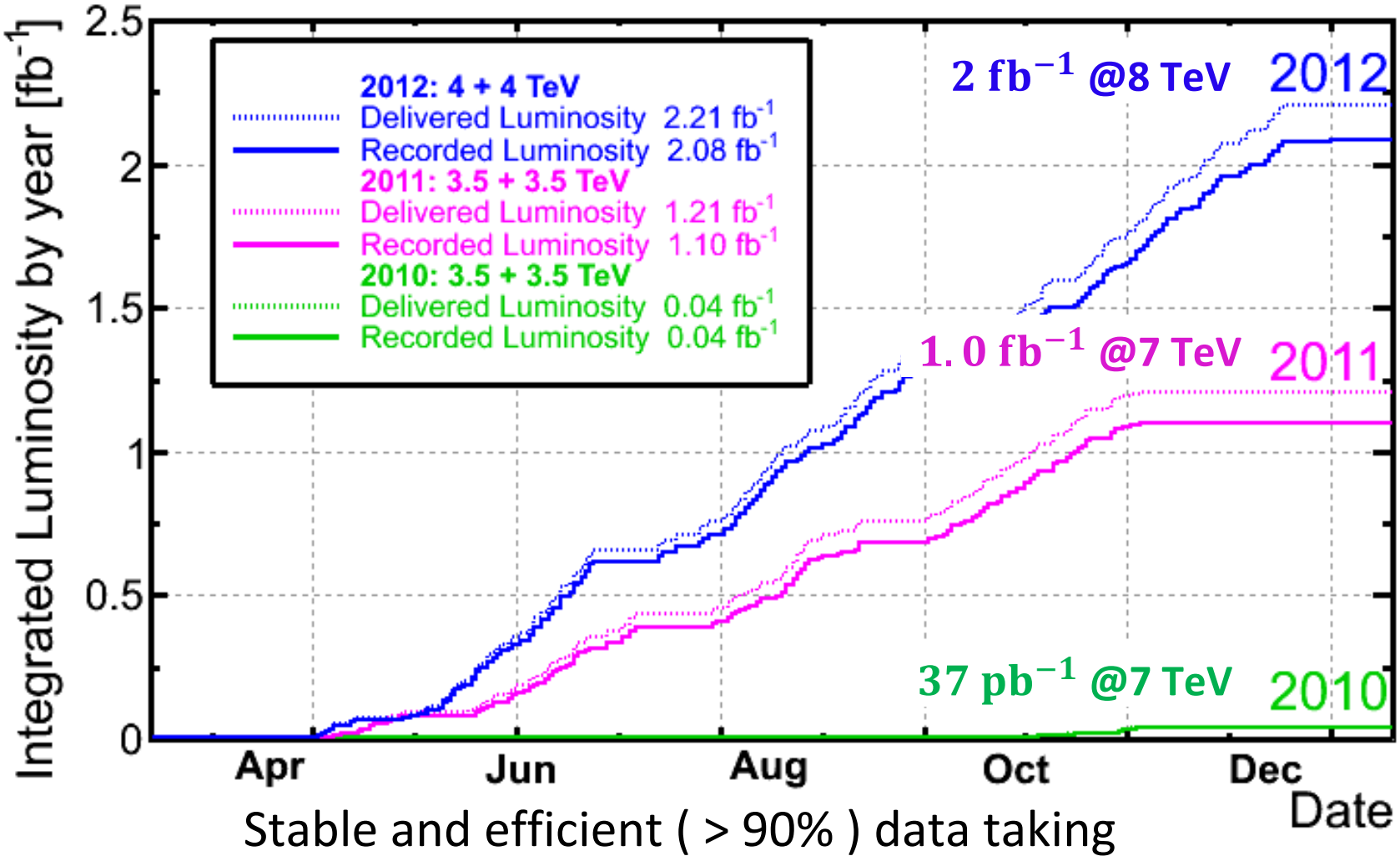
JINST 3 (2008) S08005

Dedicated to beauty and charm physics

Pseudorapidity acceptance
$2 < \eta < 5$



LHCb data taking

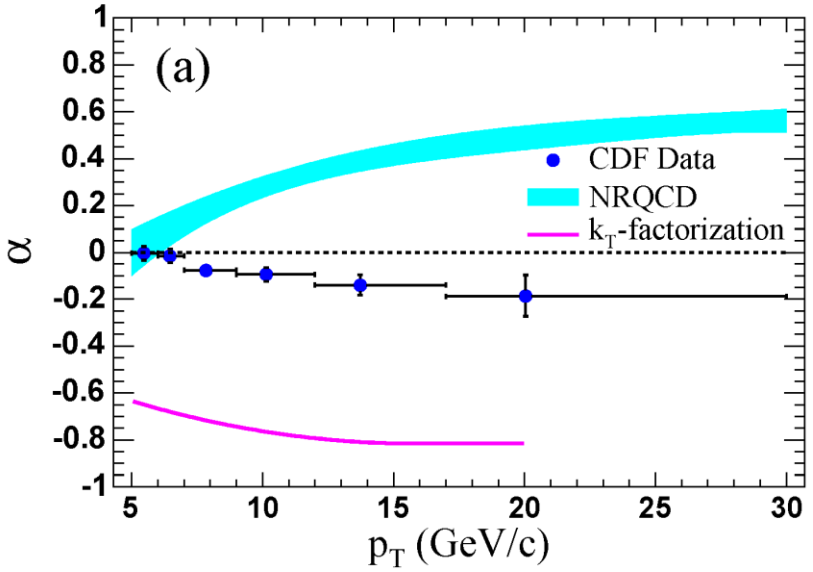


Stable and efficient (> 90%) data taking

Most results based on 2011 data at 7 TeV

Motivation

- Measurements of heavy-quark and quarkonia provide powerful tests on QCD models
- Current models (NRQCD, CSM, COM, k_{T} factorization, et al) can not describe all experimental measurements
  - ✓ production of prompt J/ψ, $\psi(2S)$, Υ, χ_c, and
  - ✓ their polarisations
- LHCb can provide essential and unique contributions



PRL 99 (2007) 132001;
arXiv:0704.0638

J/ψ and $\Upsilon(\mathrm{nS})$ productions at $\sqrt{s} = 8\ \mathrm{TeV}$

[JHEP 06 (2013) 064; arXiv:1302.5578]

J/ψ production measurement

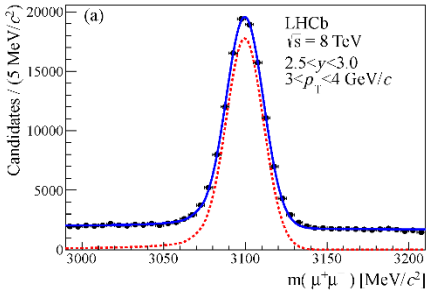
JHEP 06 (2013) 064

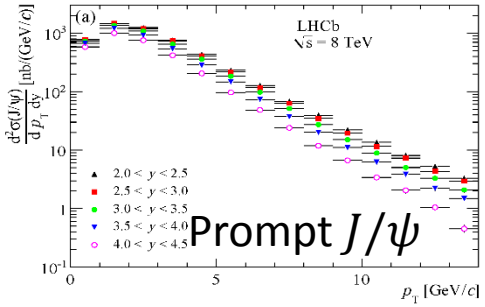
- J/ψ cross-section measured at $\sqrt{s} = 8$ TeV

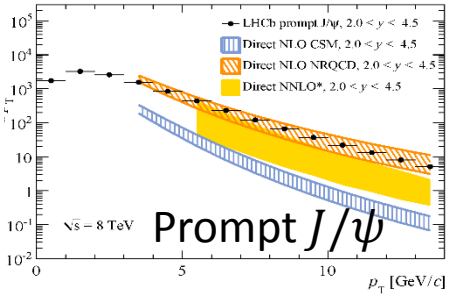
  [Previous measurements at 7 TeV and 2.76 TeV: EPJC71 (2011) 1645; JHEP 02 (2013) 041]

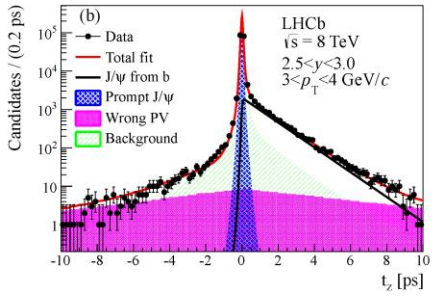
  - High efficiency for dimuon trigger; excellent muon identification; excellent J/ψ mass resolution: 14 MeV/c^2 (28-40 MeV/c^2 at CMS)

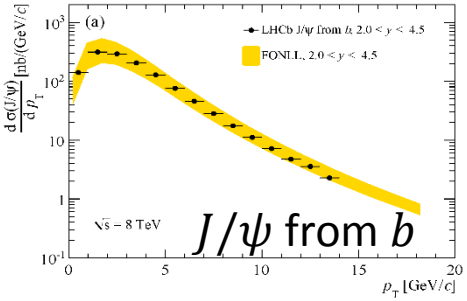
About 2.6 M signals in $p_{\mathrm{T}} < 14$ GeV/c and $2.0 < y < 4.5$

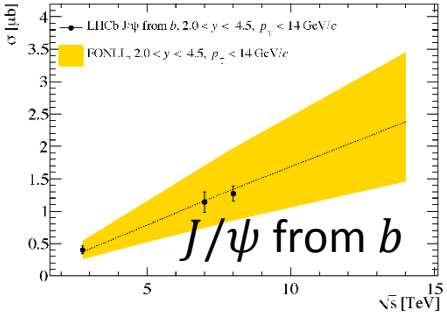












NLO CSM:
PRL98(2007)252002
NLO NRQCD:
PRD84(2011)051501
PRL106(2011)022003
NNLO* CSM:
EPJC61(2008)693

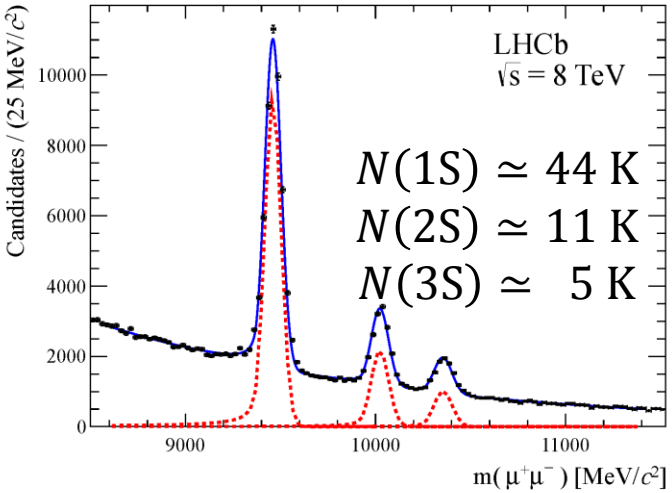
- Prompt J/ψ: in good agreement with NLO NRQCD
- J/ψ from b : in good agreement with FONLL
- Integrated cross-sections at different energies well agree with theory

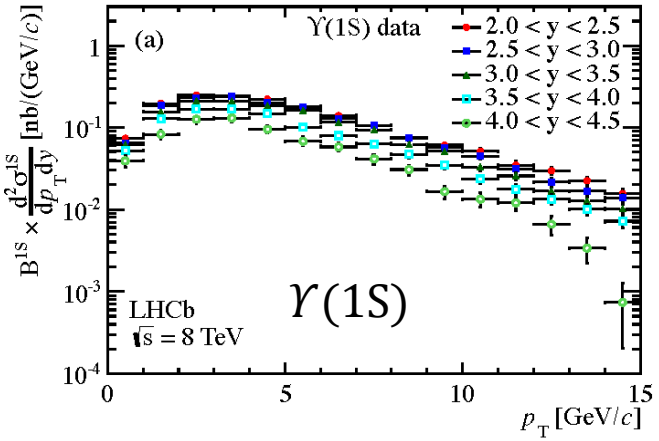
Υ(nS) production measurement

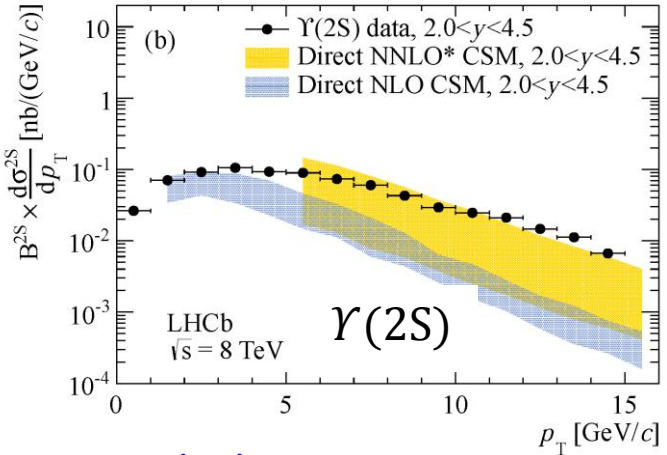
JHEP 06 (2013) 064

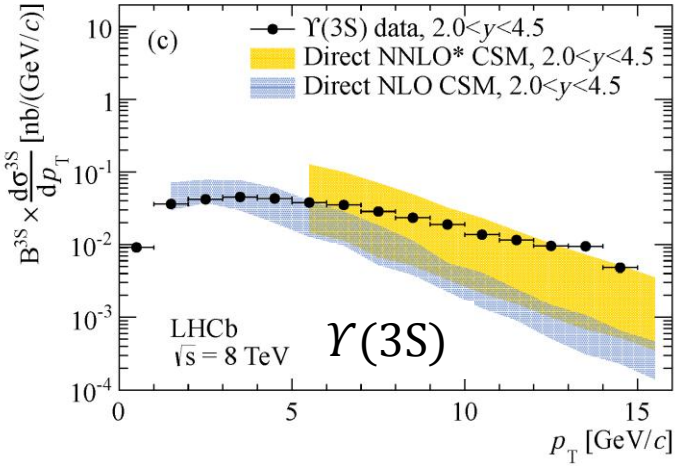
- Differential cross-sections measured at $\sqrt{s} = 8$ TeV
  [Previous measurement at 7 TeV: EPJC72 (2012) 2025]

Assuming Υ unpolarised









- NNLO calculation is necessary
- Better agreement for Υ(3S) (less affected by feed-down)

NLO CSM: PRL98 (2007)252002
NNLO* CSM: PRL101(2008)152001

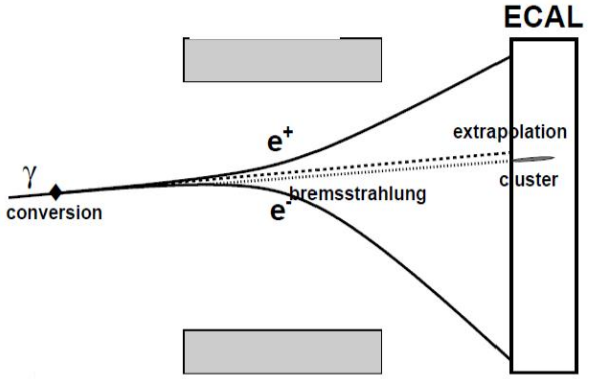
χ_{c0}, χ_{c1} and χ_{c2} production ratio using converted photons

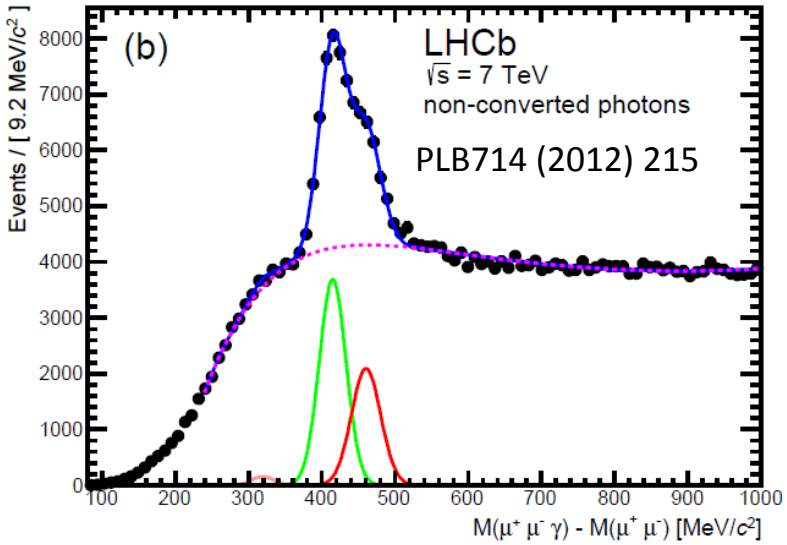
[LHCb-PAPER-2013-028; arXiv:1307.4285]

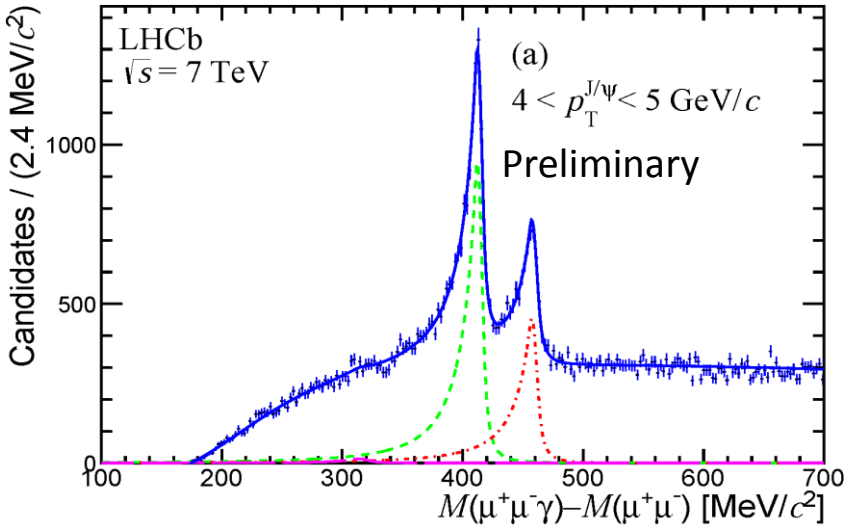
$\chi_{cJ}(1P)$ production ratio

arXiv:1307.4285
LHCb-PAPER-2013-028

- Previous measurements using unconverted photons
  - χ_{c1} and χ_{c2} not well separated
- $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ measured as a function of p_{T} at $\sqrt{s} = 7$ TeV
- $\chi_{cJ} \to J/\psi\gamma$ channel used, with γ converted into e^+e^- in the detector
  - First measurement using converted γ in LHCb [LHCb-CONF-2011-062]
  - good resolution but low efficiency
  - χ_{c1} and χ_{c2} well separated







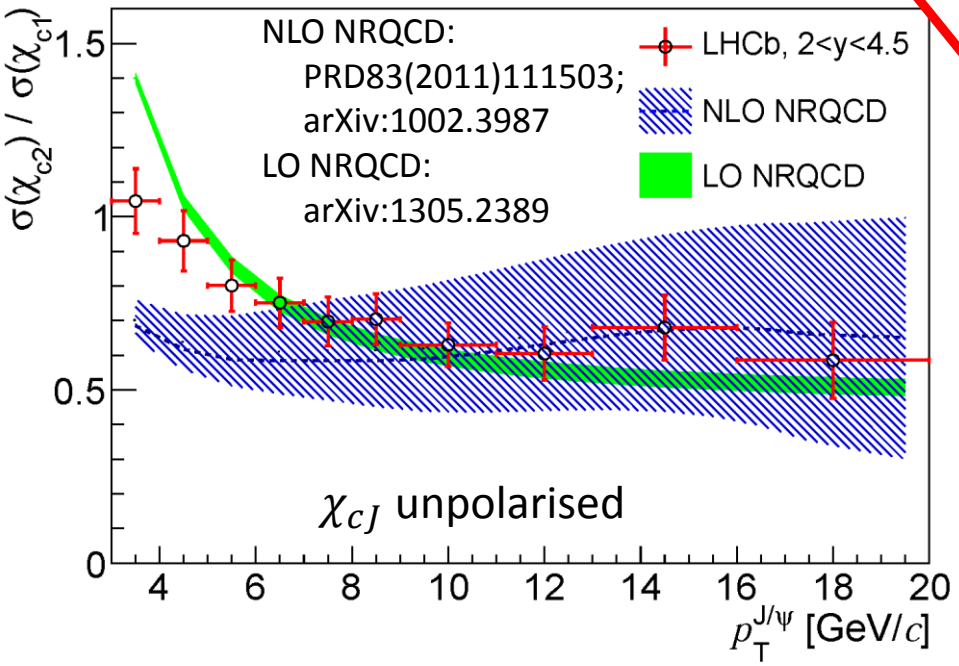
$\chi_{cJ}(1P)$ production ratio: results

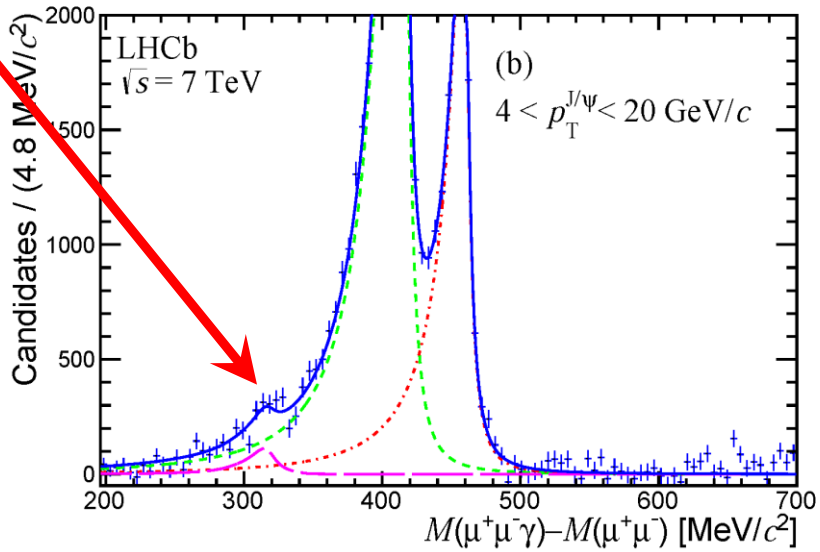
arXiv:1307.4285
LHCb-PAPER-2013-028

- $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ decreases with $p_{\mathrm{T}}^{J/\psi}$
- In agreement with (N)LO NRQCD calculations for high p_{T}
- First evidence of χ_{c0} at hadron collider with statistical significance of $4.4\,\sigma$

$$\sigma(\chi_{c0})/\sigma(\chi_{c2}) = 1.19 \pm 0.27(\mathrm{stat}) \pm 0.29(\mathrm{syst}) \pm \underline{0.16(p_{\mathrm{T}}\ \mathrm{model})} \pm 0.09(\mathcal{B})$$

Due to difference choices of p_T spectrum





J/ψ polarisation at $\sqrt{s} = 7$ TeV

[LHCb-PAPER-2013-008]

Motivation and strategy

LHCb-PAPER-2013-008

- NLO NRQCD describes J/ψ (Υ) production very well, but not for polarisation
- Large uncertainty of cross-section measurement due to unknown polarisation

- Full angular analysis to determine polarisation parameters ($\boldsymbol{\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}}$)

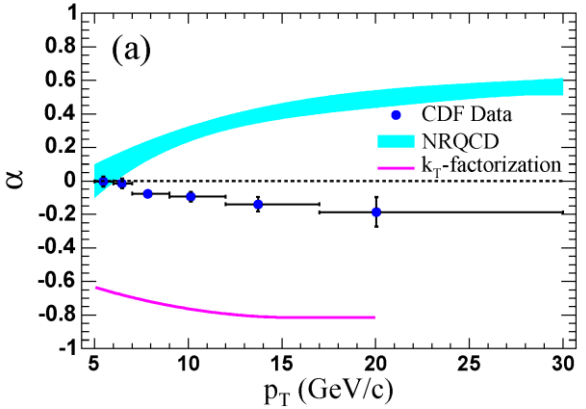
$$\frac{\mathrm{d}^2N}{\mathrm{d}\cos\theta \mathrm{d}\phi} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos^2 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi$$

- Weighted logarithm likelihood

$$\log L = \alpha \sum_{i=1}^{N_{\mathrm{tot}}} \omega_i \times \log\left[\frac{P(\cos\theta_i, \varphi_i | \lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) \times \varepsilon(\cos\theta_i, \varphi_i)}{\mathrm{Norm}(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi})}\right]$$

  - ✓ $\varepsilon(\cos\theta_i, \varphi_i)$: estimated from MC and corrected with $B^+ \to J/\psi\, K^+$ sample
  - ✓ $\mathrm{Norm}(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi})$: normalization of numerator
  - ✓ ω_i: sWeight from sPlot technique
  - ✓ $\alpha = \sum_{i=1}^{N_{\mathrm{tot}}} \omega_i \,/\, \sum_{i=1}^{N_{\mathrm{tot}}} \omega_i^2$: constant factor to correctly account for statistical uncertainties

- Data sample: 0.37 fb^{-1} at 7 TeV



PRL 99 (2007) 132001;
arXiv:0704.0638

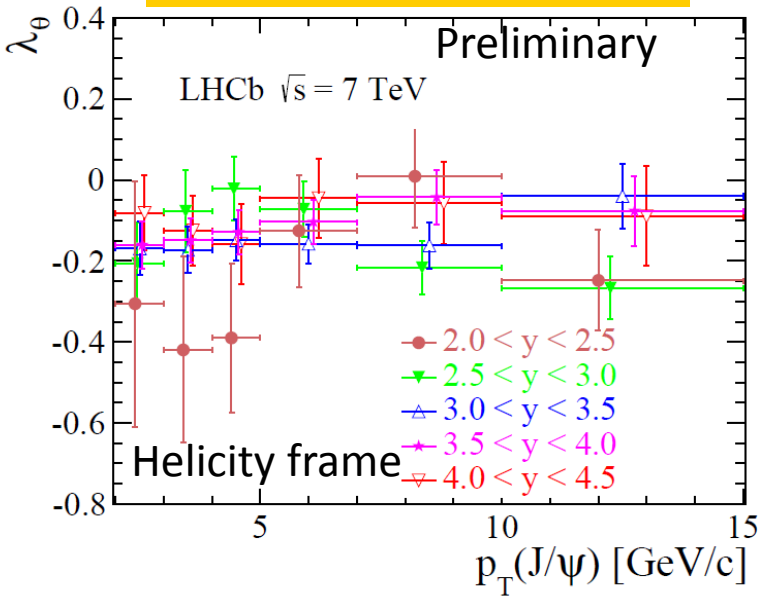
J/ψ polarisation: results

LHCb-PAPER-2013-008

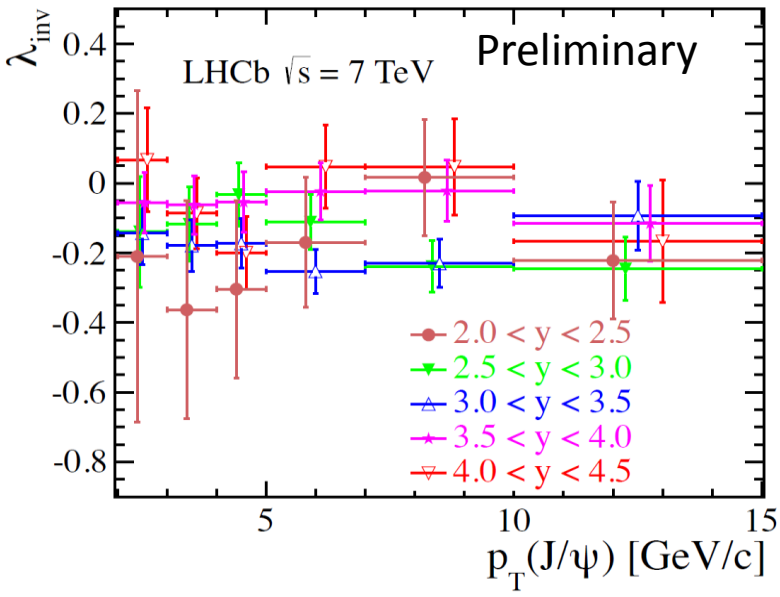
- $(\lambda_\theta, \lambda_{\theta\varphi}, \lambda_\varphi)$ measured in (p_{T}, y) bins in different frame
- Polarisation measured to be small
- The only J/ψ polarisation measurements for prompt J/ψ in pp collisions at 7 TeV

$$\lambda_{\mathrm{inv}} = \frac{\lambda_\theta - 3\lambda_\varphi}{1 - \lambda_\varphi} \quad : \text{ independent of frame choice}$$

λ_θ in helicity frame



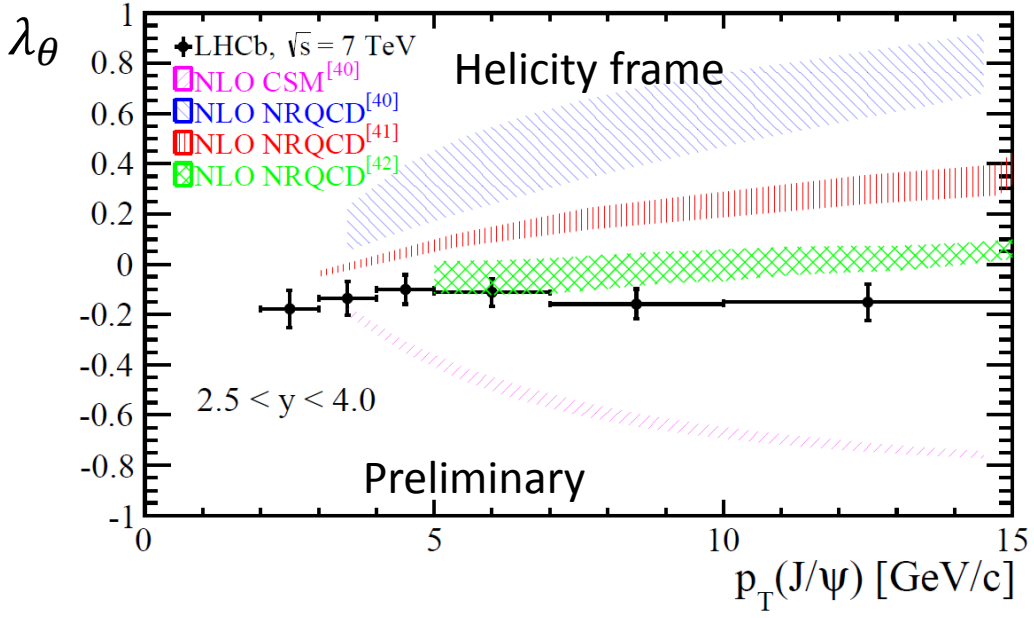
λ_{inv}

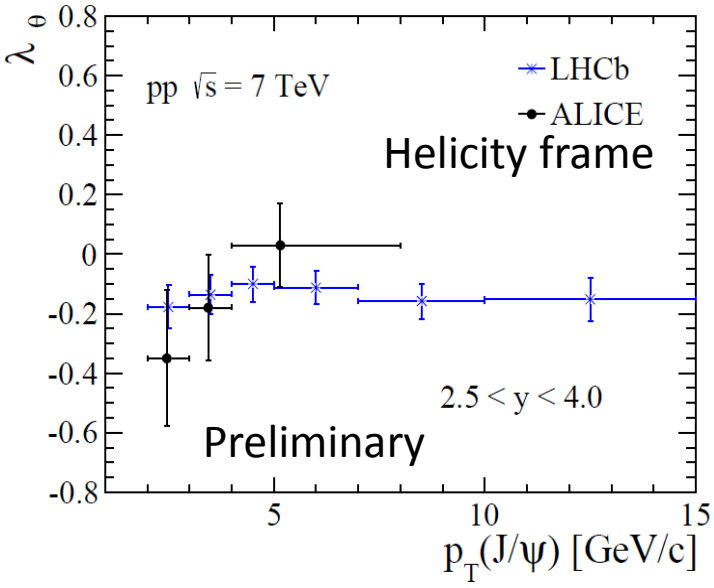


J/ψ polarisation: comparisons

LHCb-PAPER-2013-008

- Measured λ_θ agrees with neither theoretical prediction
- Agree with ALICE's result with large uncertainty in ALICE





NLO CSM: NPB 151(2012) 222-224 (Proc. Suppl.)
NLO NRQCD: NPB 151(2012) 222-224 (Proc. Suppl.)
NLO NRQCD: PRL110(2013)042002
NLO NRQCD: PRL108(2012)242004

ALICE: PRL108(2012)082001

J/ψ cross-section at 7 TeV updated

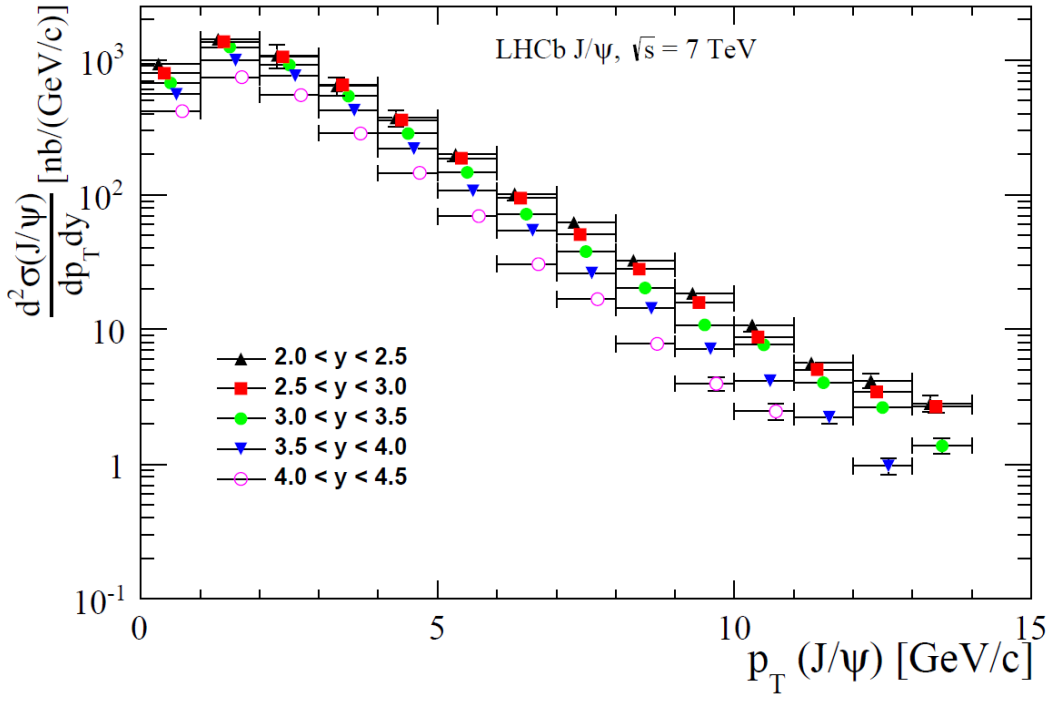
LHCb-PAPER-2013-008

- Polarisation affects the efficiencies in cross-section measurements
- J/ψ cross-section measurement updated by taking into account polarisation

$$\sigma(\text{prompt } J/\psi; p_{\mathrm{T}} < 14\ \mathrm{GeV}/c, 2.0 < y < 4.5) = 9.46 \pm 0.04 \pm 0.53^{+0.86}_{-1.10}\ \mu\mathrm{b}$$

Previous measurement for comparison

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



Other results

Earlier heavy quarkonia results

- J/ψ cross-sections at 7 TeV

  EPJC71 (2011) 1645; arXiv:1103.0423
- J/ψ cross-sections at 2.76 TeV

  JHEP 02 (2013) 041; arXiv:1212.1045
- $\Upsilon(nS)$ cross-sections at 7 TeV

  EPJC72 (2012) 2025; arXiv:1202.6579
- χ_c production at 7 TeV (unconverted γ)

  PLB714 (2012) 215; arXiv:1202.1080

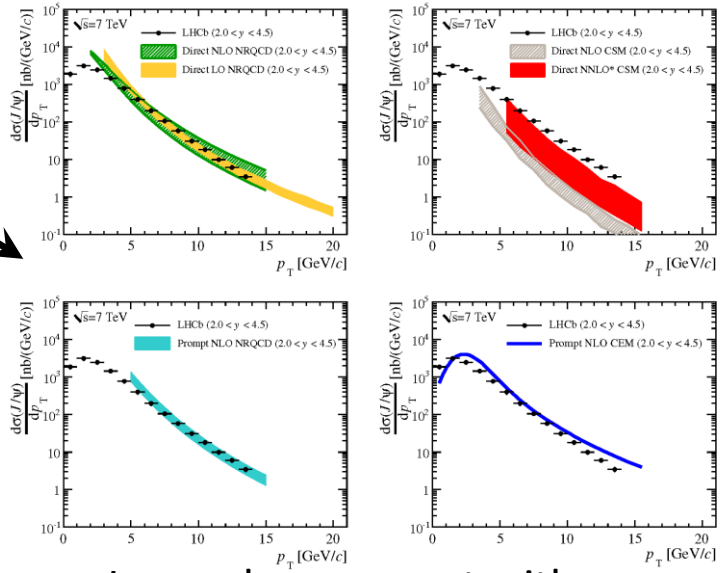
  PLB718 (2012) 431; arXiv:1204.1463
- J/ψ pair production at 7 TeV

  PLB707 (2012) 52; arXiv:1109.0963
- Υ from χ_b decay at 7 TeV

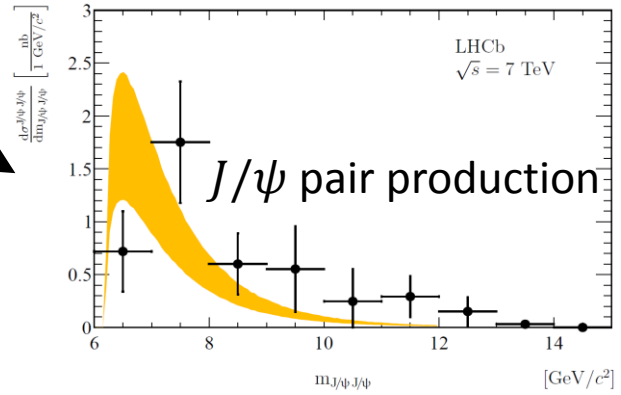
  JHEP 11 (2012) 031; arXiv:1209.0282
- $\psi(2S)$ cross-sections at 7 TeV

  Eur.Phys.J. C72 (2012) 2100
- J/ψ + open charm production at 7 TeV

  JHEP 06 (2012) 141; arXiv:1205.0975



In good agreement with (N)LO NRQCD calculations



Agree with theoretical prediction within uncertainty

PRD84 (2011) 094023; arXiv:1101.5881

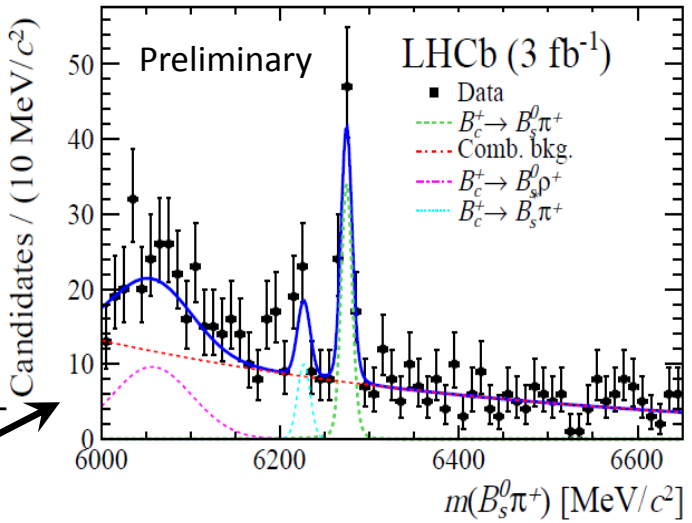
B_c measurements at LHCb

see Niels Tuning's talk
On Thursday morning

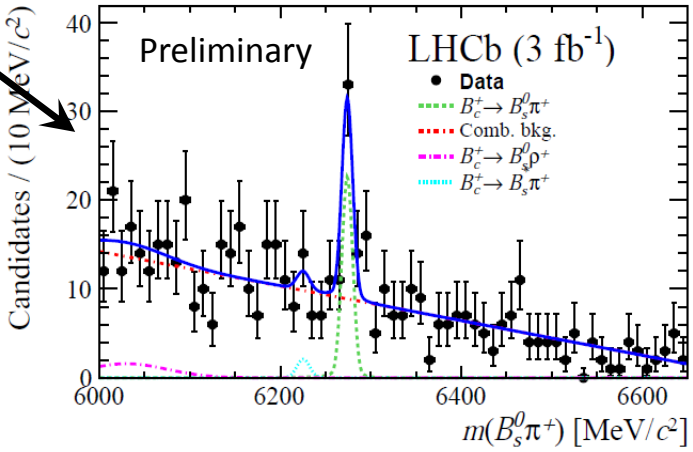
- Before LHCb, only two decay modes observed
- LHCb provided six new decay channels
  - ✓ $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$
    PRL108(2012)251802; arXiv:1204.0079
  - ✓ $B_c^+ \to \psi(2S)\pi^+$
    PRD87(2013)071103(R); arXiv:1303.1737
  - ✓ $B_c^+ \to J/\psi D_s^{(*)+}$
    PRD87(2013)112012; arXiv:1304.4530
  - ✓ $B_c^+ \to J/\psi K^+$
    arXiv:1306.6723; LHCb-PAPER-2013-021
  - ✓ $B_c^+ \to B_s^0(\to D_s^-\pi^+ \text{ or } J/\psi\phi)\pi^+$
    - First channel with $\bar{b}$ as spectator!

    LHCb-PAPER-2013-044

$D_s^-\pi^+$



$J/\psi\phi$



- precise measurements of mass, production, …
  PRL109(2012)232001; arXiv:1209.5634

(selected) Highlight of recent b-hadron results

- Precise cross-sections of B mesons at 7 TeV

  [arXiv:1306.3663; LHCb-PAPER-2013-004]

  $\sigma(pp \to B^+X) = 38.9 \pm 0.3_{\text{stat}} \pm 2.5_{\text{syst}} \pm 1.3_{\text{norm}}$ μb

  $\sigma(pp \to B^0X) = 38.1 \pm 0.6_{\text{stat}} \pm 3.7_{\text{syst}} \pm 4.7_{\text{norm}}$ μb

  $\sigma(pp \to B_s^0X) = 10.5 \pm 0.2_{\text{stat}} \pm 0.8_{\text{syst}} \pm 1.0_{\text{norm}}$ μb

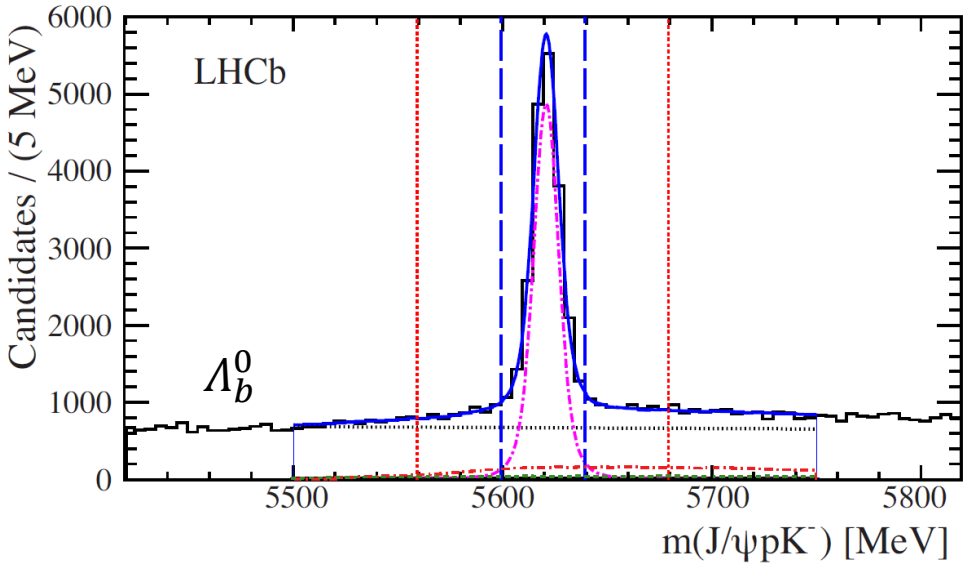
- Precise Λ_b^0 lifetime measurement

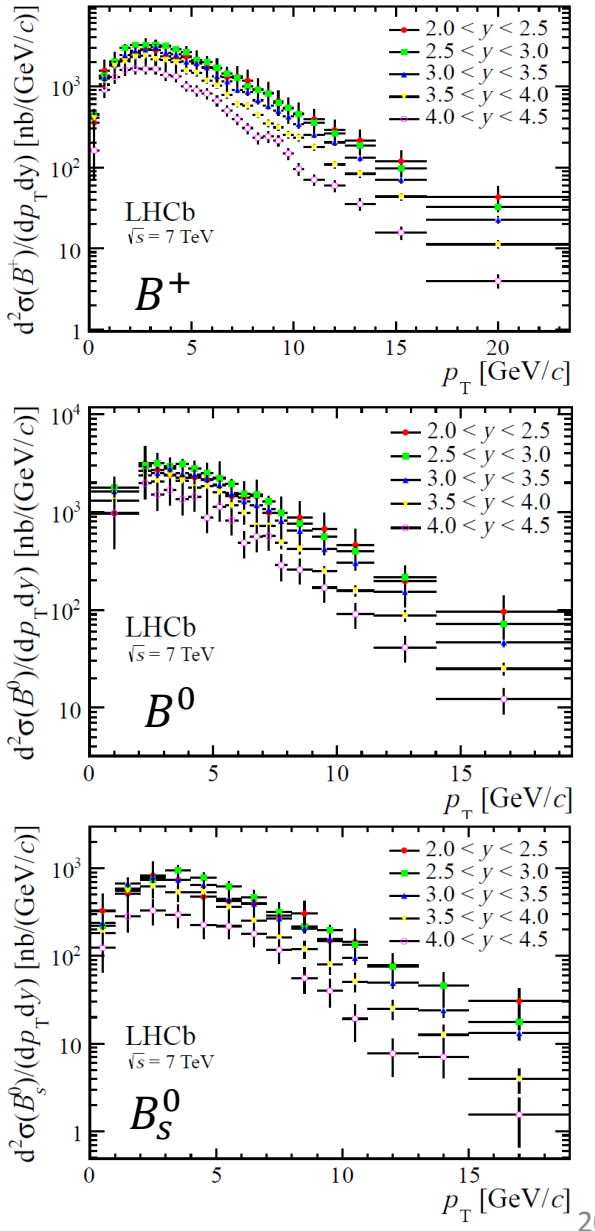
  [arXiv:1307.2476; LHCb-PAPER-2013-032]

  $\tau_{\Lambda_b^0}/\tau_{\bar{B}^0} = 0.976 \pm 0.012 \pm 0.006$ ps

  $\tau_{\Lambda_b^0} = 1.482 \pm 0.018 \pm 0.012$ ps

  See Lars Eklund's talk on Saturday morning





Summary and prospects

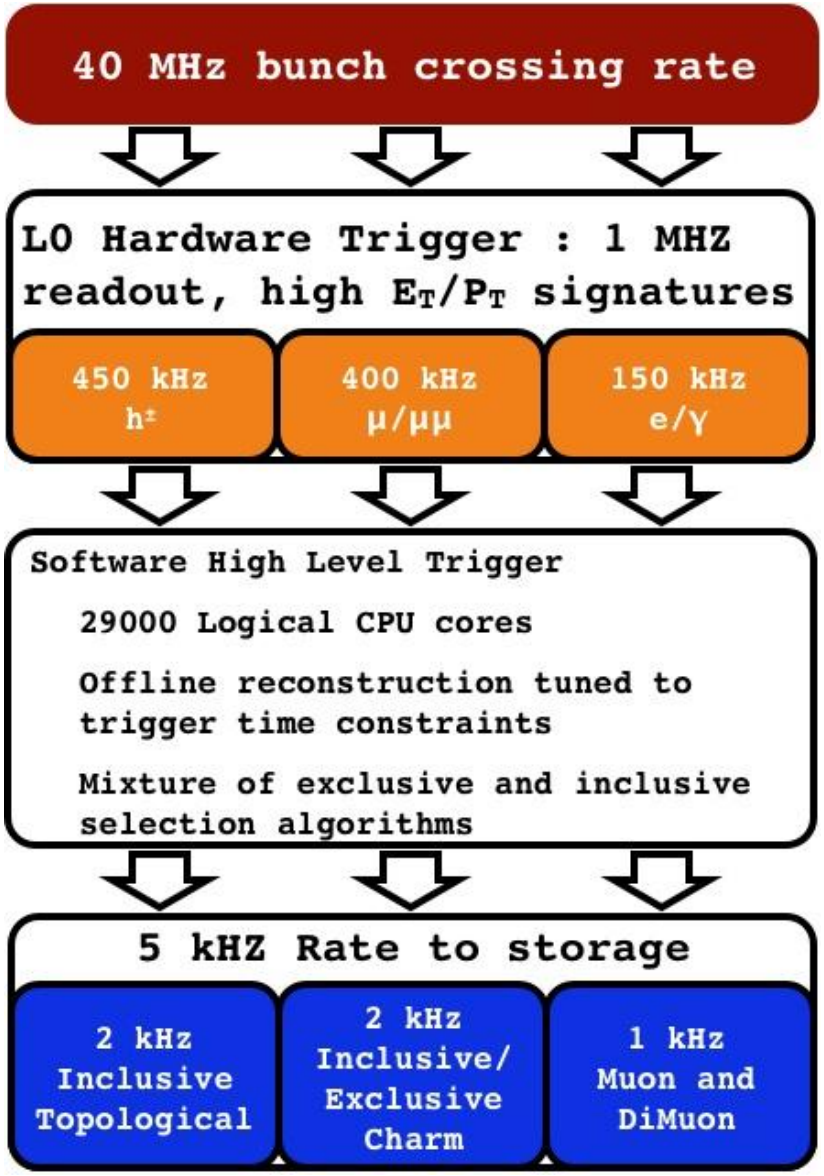
- LHCb presented prosperous measurements of heavy-quark and quarkonia
- Cross-sections of J/ψ and Υ measured at various energy
- χ_{cJ} production ratio using converted/unconverted photons
  - First evidence of χ_{c0} at hadron collider
- J/ψ polarisation measurement at $7\ \mathrm{TeV}$
- Excellent B_c studies in LHCb
  - Six new decay channels including $B_c^+ \to B_s^0 \pi^+$ (weakly $B \to B$ decay)
  - Precise B_c mass/production measurements
- Exciting results of b-hadrons
  - Precise B cross-section measurements
  - Precise Λ_b^0 lifetime measurement
- More analyses in progress with 2011+2012 data sets
- Important contribution to heavy-ion physics
  - Cold Nuclear Matter effects on J/ψ production in pPb collisions presented, and more analysis ongoing

see Fanfan Jing's talk on Thurday morning

Thank you!

Backup slides

LHCb trigger

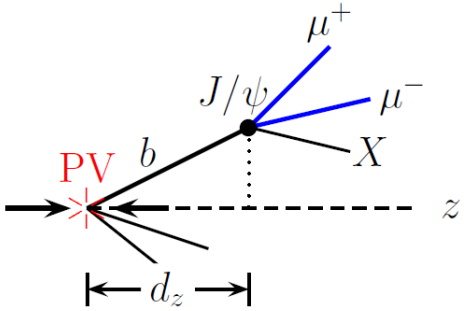


J/ψ production: signal extraction

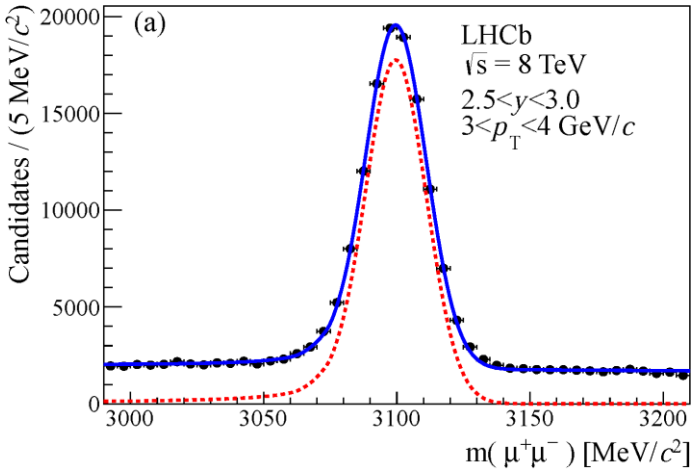
JHEP 06 (2013) 064

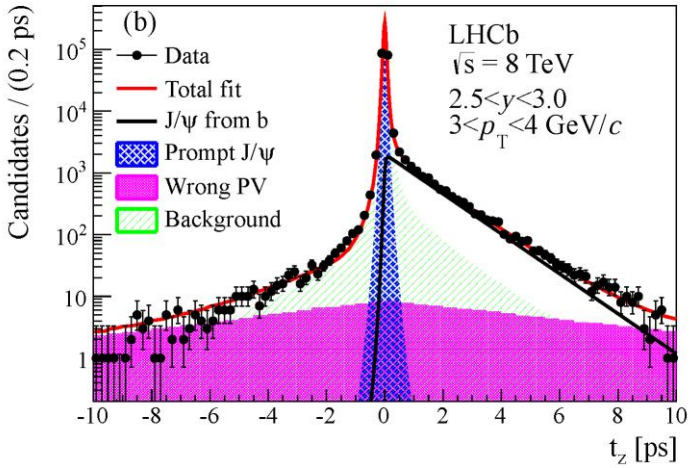
- J/ψ cross-section measured as a function of p_{T} and y at $\sqrt{s} = 8$ TeV
  [Previous measurements at 7 TeV and 2.76 TeV: EPJC71 (2011) 1645; JHEP 02 (2013) 041]
  - High efficiency for dimuon trigger
  - Excellent muon identification
  - Excellent J/ψ mass resolution: 14 MeV/c^2 (28-40 MeV/c^2 at CMS)
- Prompt J/ψ and J/ψ from b separated by combined fits to dimuon invariant mass and t_z distributions in each (p_{T}, y)

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



About 2.6 M signals in $p_{\mathrm{T}} < 14$ GeV/c and $2.0 < y < 4.5$

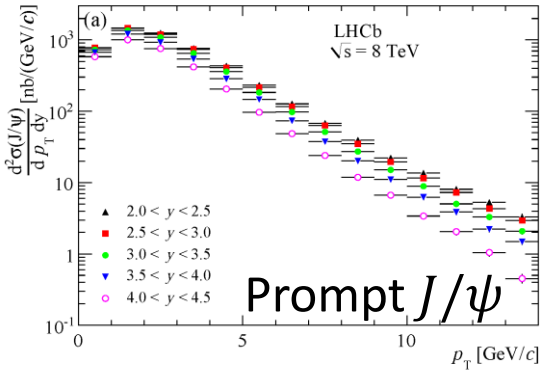


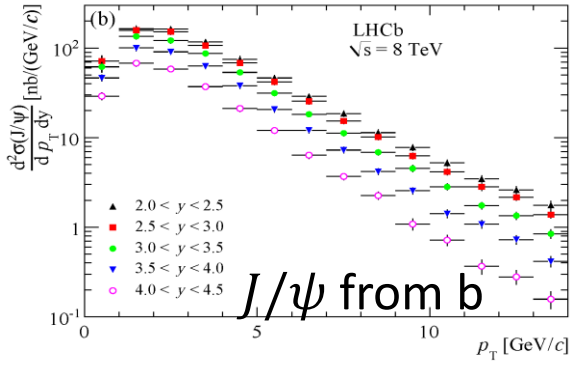


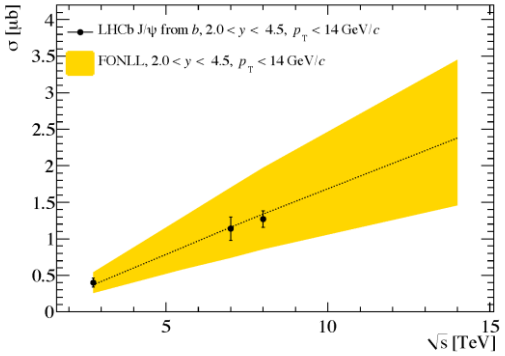
J/ψ production: results and comparisons

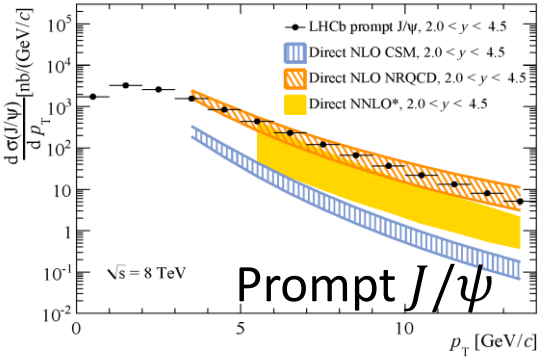
JHEP 06 (2013) 064

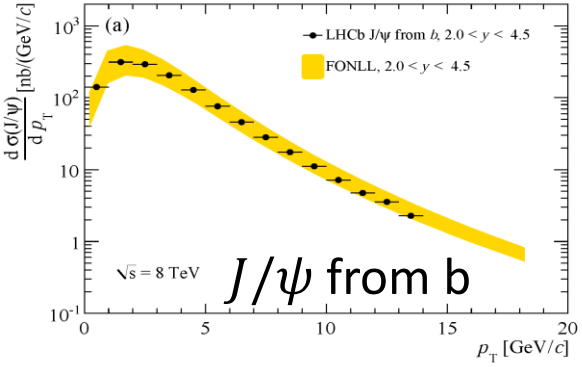
- Differential cross-sections of prompt J/ψ and J/ψ from b
- Assuming J/ψ unpolarised











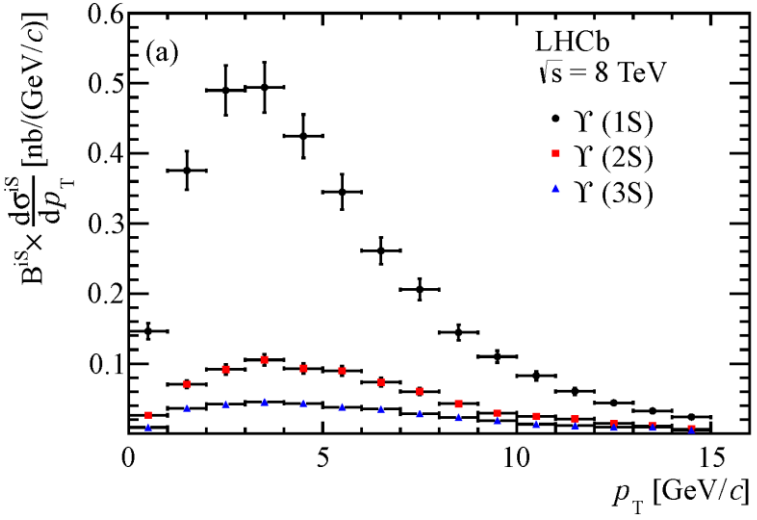
NLO CSM:
PRL98(2007)252002
NLO NRQCD:
PRD84(2011)051501
PRL106(2011)022003
NNLO* CSM:
EPJC61(2008)693

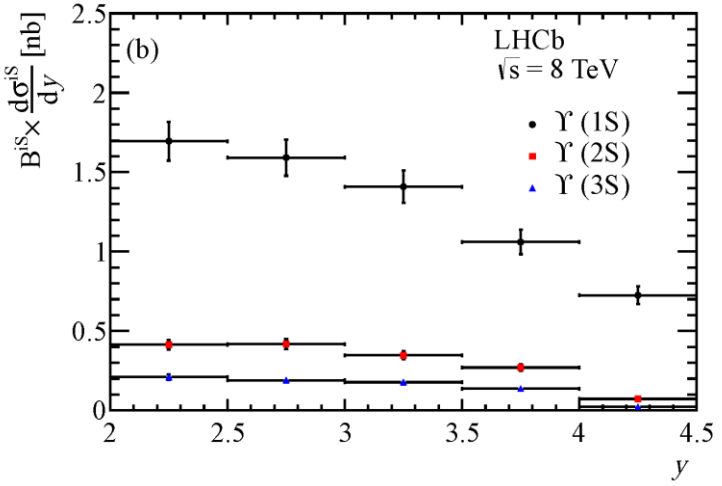
- Prompt J/ψ: in good agreement with NLO NRQCD
- J/ψ from b : in good agreement with FONLL
- Integrated cross-sections at different energies well agree with theory

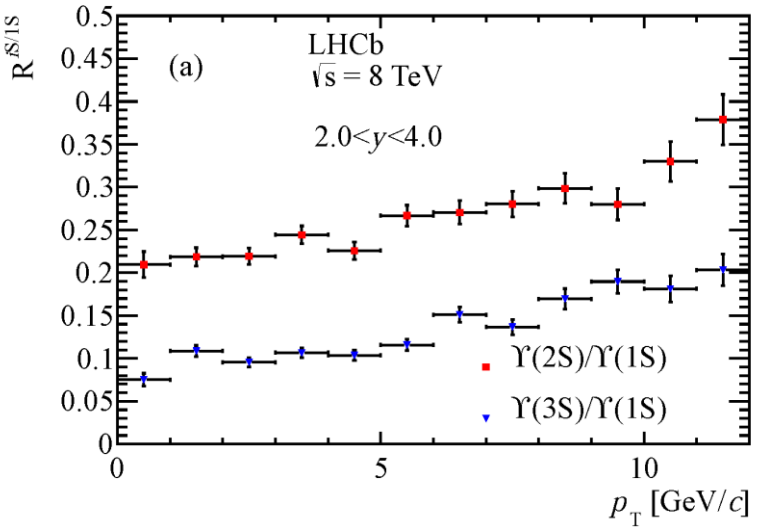
Υ(nS) production measurement

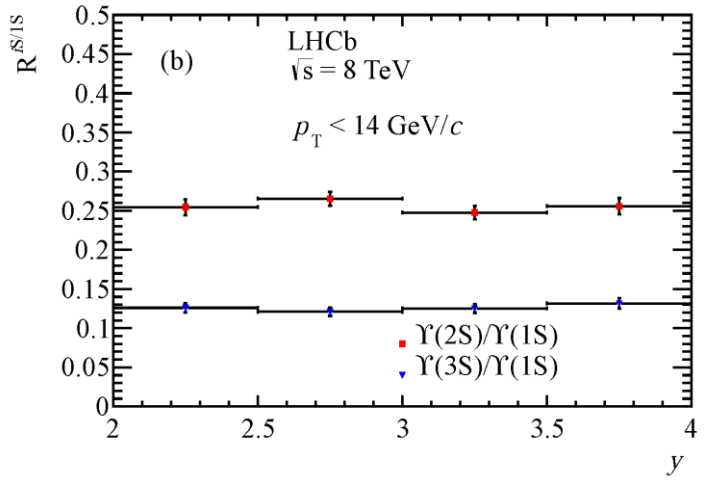
JHEP 06 (2013) 064

- Υ(nS) production cross-sections measured as a function of p_{T} and y at $\sqrt{s} = 8$ TeV





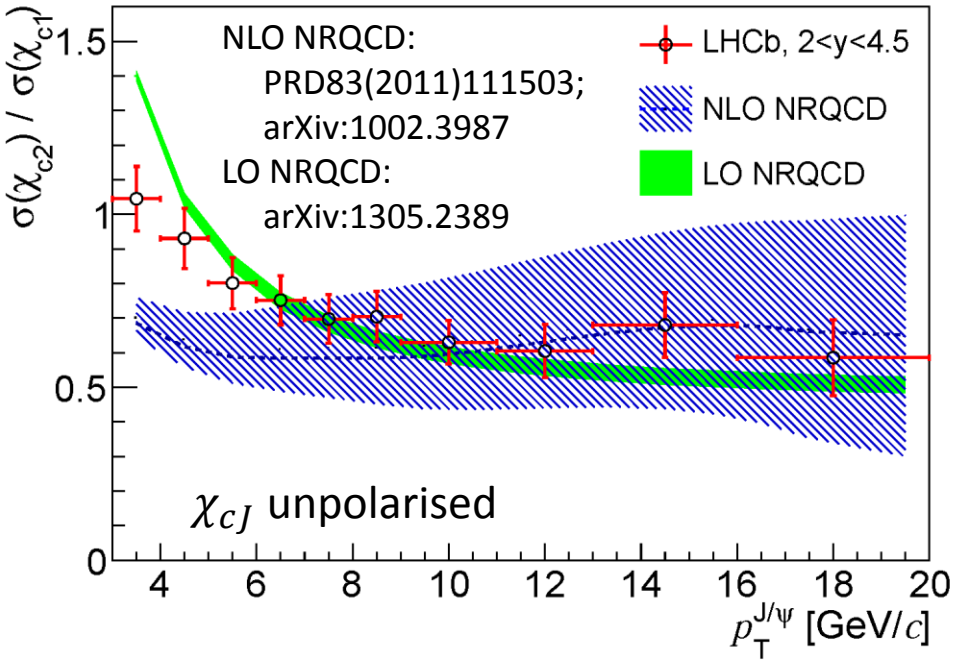




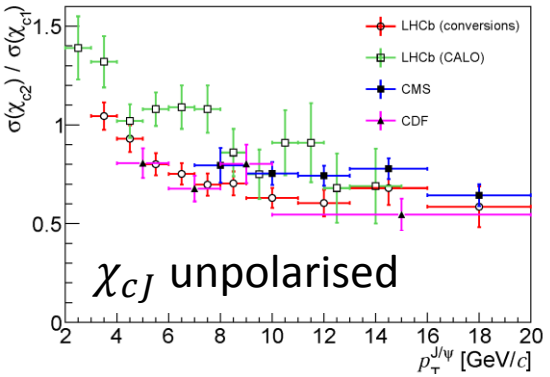
$\chi_{cJ}(1P)$ production ratio: results

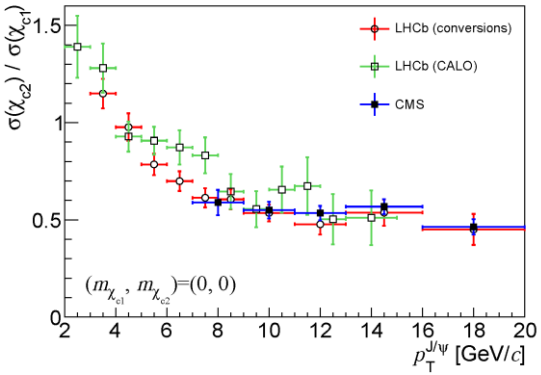
- $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ decreases with $p_{\mathrm{T}}^{J/\psi}$
- In agreement and more precise than previous measurements by LHCb unconverted γ, CMS and CDF
- First evidence of χ_{c0} at hadron collider

$$\sigma(\chi_{c0})/\sigma(\chi_{c2}) = 1.19 \pm 0.27(\mathrm{stat}) \pm 0.29(\mathrm{syst}) \pm 0.16(p_{\mathrm{T}}\ \mathrm{model}) \pm 0.09(\mathcal{B})$$



LHCb-PAPER-2013-028





m_{χ_c}: azimuthal angular momentum

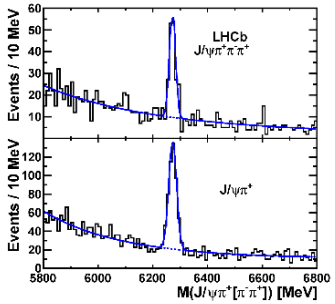
LHCb(CALO): PLB714(2012)215
CMS: EPJC72(2012)2251
CDF: PLB98(2007)232001

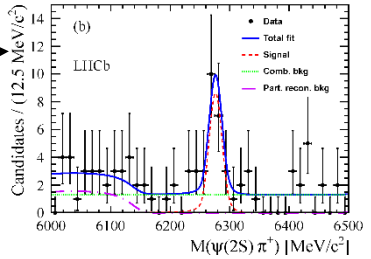
B_c measurements at LHCb

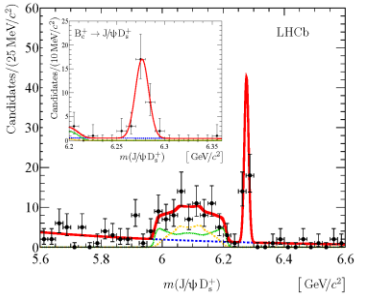
(see Niels Tune's talk)

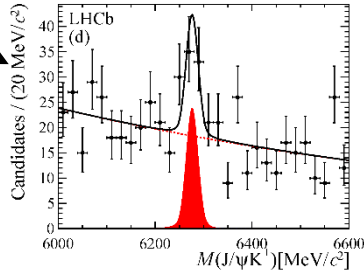
- Observation of new B_c decay channels and relative production measurements
  - ✓ $B_c^+ \to J/\psi \pi^+ \pi^- \pi^+$
    PRL108(2012)251802; arXiv:1204.0079
  - ✓ $B_c^+ \to \psi(2S)\pi^+$
    PRD87(2013)071103(R); arXiv:1303.1737
  - ✓ $B_c^+ \to J/\psi D_s^{(*)+}$
    PRD87(2013)112012; arXiv:1304.4530
  - ✓ $B_c^+ \to J/\psi K^+$
    arXiv:1306.6723; LHCb-PAPER-2013-021
  - ✓ $B_c^+ \to B_s^0 (\to D_s^- \pi^+ \text{ or } J/\psi \phi)\pi^+$
    - $\bar{b}$ as spectator!

    LHCb-PAPER-2013-044









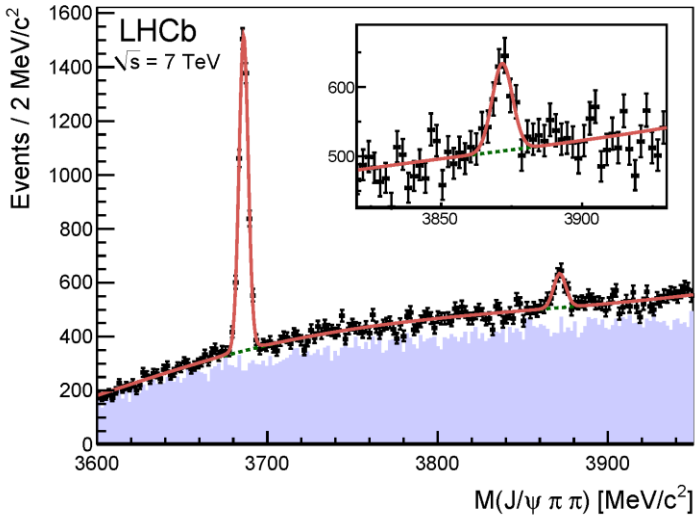
- precise measurements of mass, production …

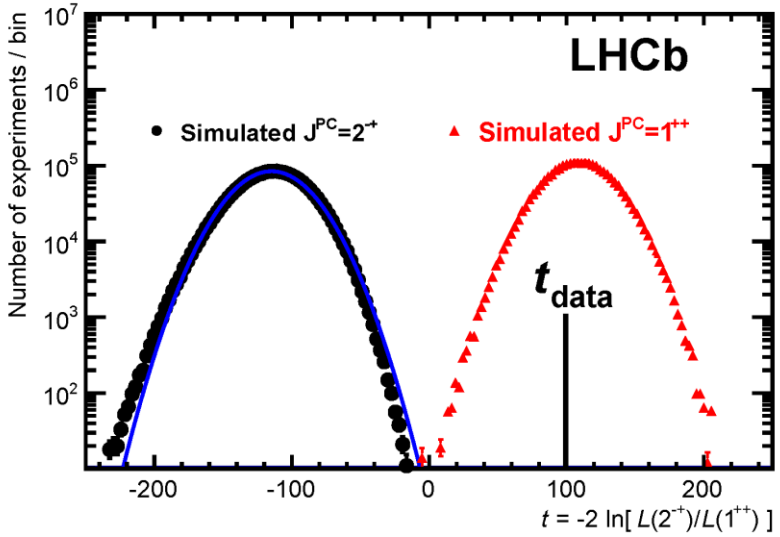
  PRL109(2012)232001; arXiv:1209.5634;
  LHCb-PAPER-2012-028

Exotics

- $X(3872)$ production and mass
  EPJC72 (2012) 1972; arXiv:1112.5310; LHCb-PAPER-2011-034

- J^{PC} determination of $X(3872)$
  PRL110 (2013) 222001; arXiv:1302.6269; LHCb-PAPER-2013-001





$$m_{X(3872)} = 3871.95 \pm 0.48\,(\text{stat}) \pm 0.12\,(\text{syst})\ \text{MeV}/c^2$$
$$m_{\psi(2S)} = 3686.12 \pm 0.06\,(\text{stat}) \pm 0.10\,(\text{syst})\ \text{MeV}/c^2$$

$$J^{PC} = 1^{++}$$