Meeting of the American Physical Society
Division of Particles and Fields
August 13 - August 17, 2013

Quarkonia production and polarisation at LHCb

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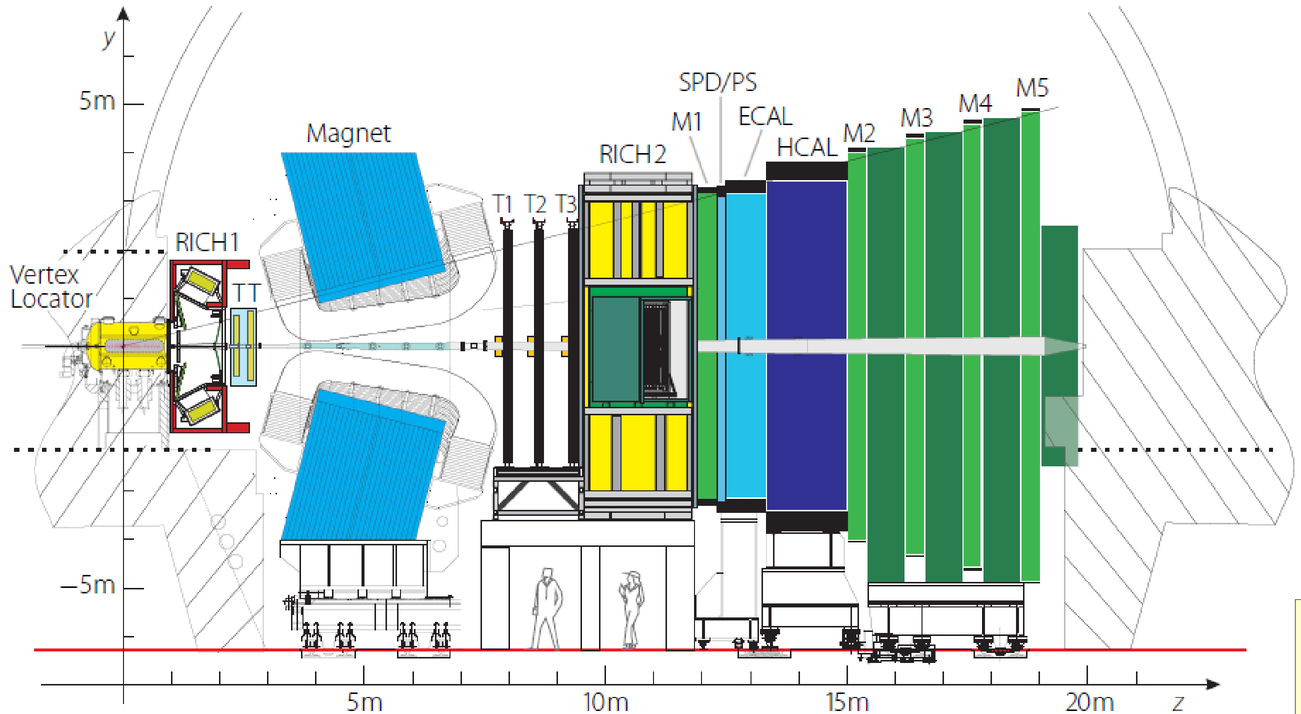
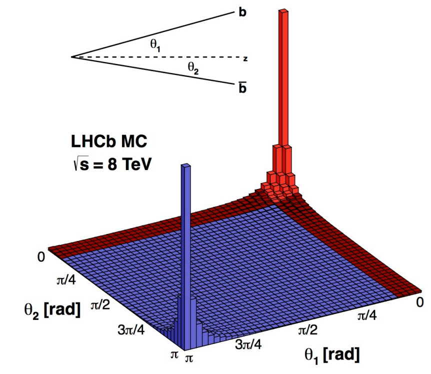
on behalf of the LHCb Collaboration

Outline

- Detector and data sample
- J/ψ, $\Upsilon(nS)$ production at $\sqrt{s}=8$ TeV
- χ_{cj} production
- J/ψ polarisation
- Λ_b polarisation

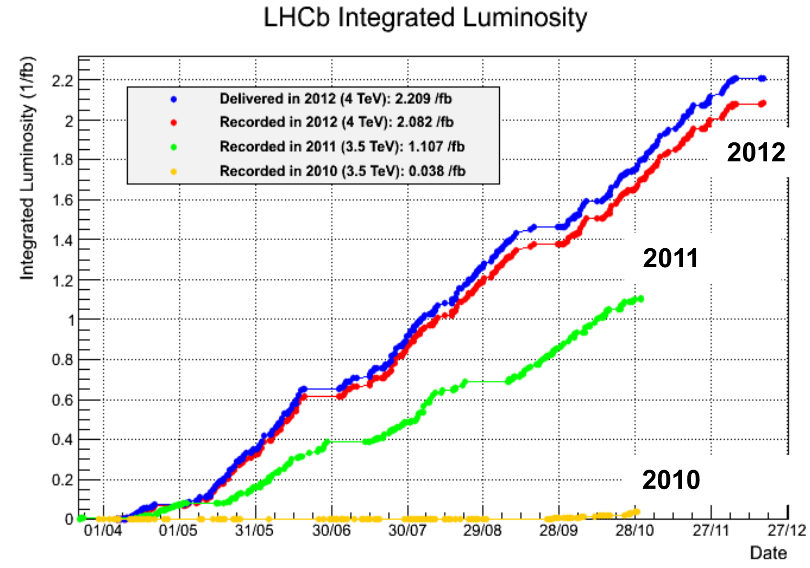
The LHCb experiment





bb production angles

In total 3 fb^{-1} available for analyses
1 fb^{-1} @ 3.5TeV, 2 fb^{-1} @4TeV
Detector efficiency > 95%



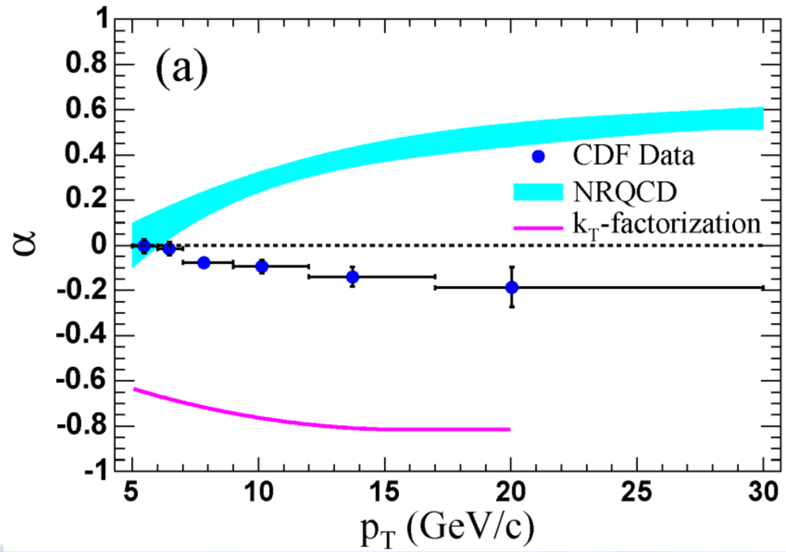
Designed for CP violation and rare decays of heavy mesons

Single arm spectrometer, 40% of bb pairs produced in the acceptance.

Unique kinematic region:
high rapidity (2.0 < y < 4.5) and low pT

Motivation

- Measurements of heavy-quark and quarkonia provide powerful tests on QCD models
- Current models (NRQCD, CSM, COM, k_T factorization) have very different predictions, not always in agreement with experimental measurements
  - production of prompt J/ψ, ψ(2S), Υ, χ_c
  - their polarisations
- LHCb can provide essential and unique contribution



J/ψ polarisation at CDF
PRL 99 (2007) 132001
arXiv:0704.0638

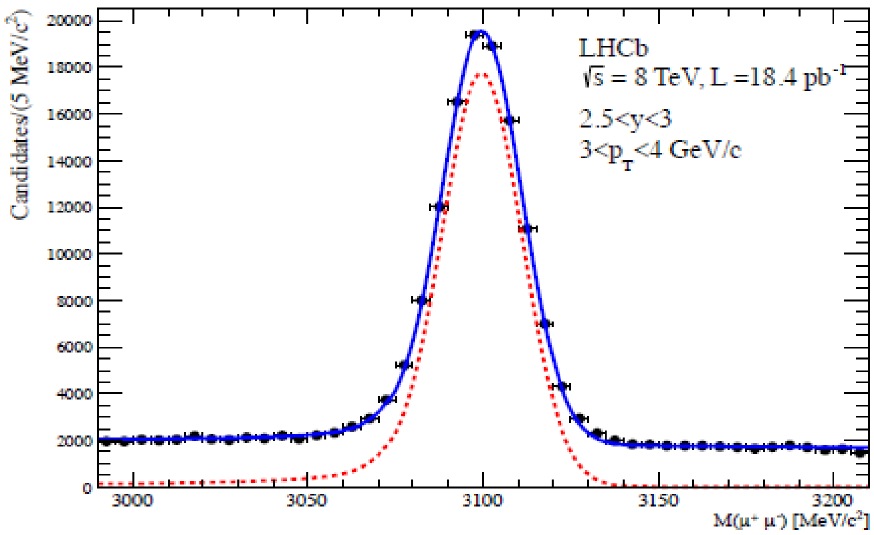
J/ψ production at √s = 8 TeV

JHEP 06 (2013) 064

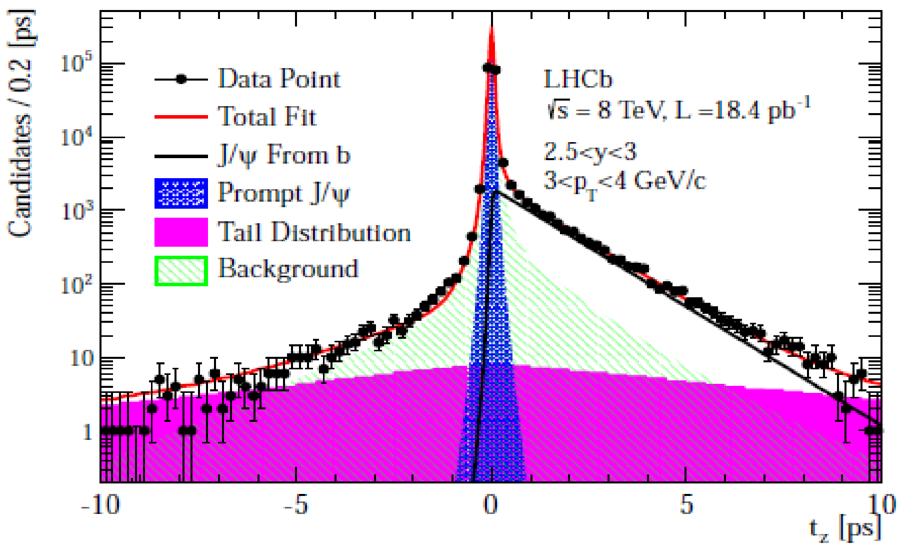
→ Previous measurements at 7 TeV and 2.76 TeV EPJC71 (2011) 1645; JHEP 02 (2013) 041

- Measurement of the double differential production cross-section: bin in y and pT
- About 2.6 M signals in pT < 14 GeV/c and 2.0 < y < 4.5
- Prompt and from *b* decays components separated using pseudo-decay time t_z
- Simultaneous fit of the mass and the pseudo-decay time
- Efficiency evaluated with MC simulation and validated on data
- Systematic uncertainty ~ 7% dominated by luminosity and trigger efficiency

$M(\mu^+\mu^-)$



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

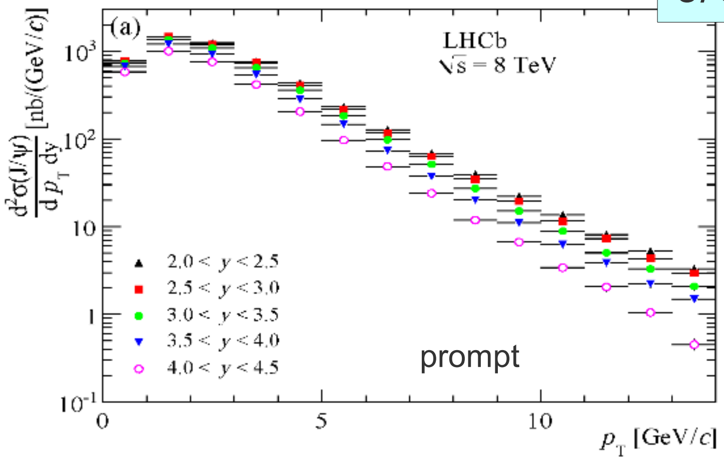


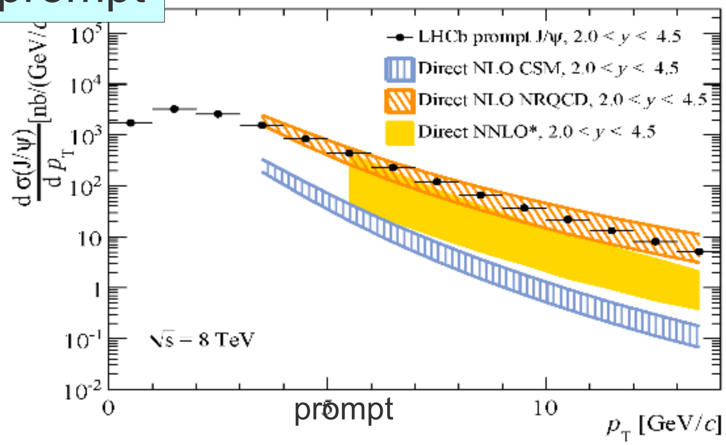
J/ψ production at √s = 8 TeV

JHEP 06 (2013) 064

Results

J/ψ prompt



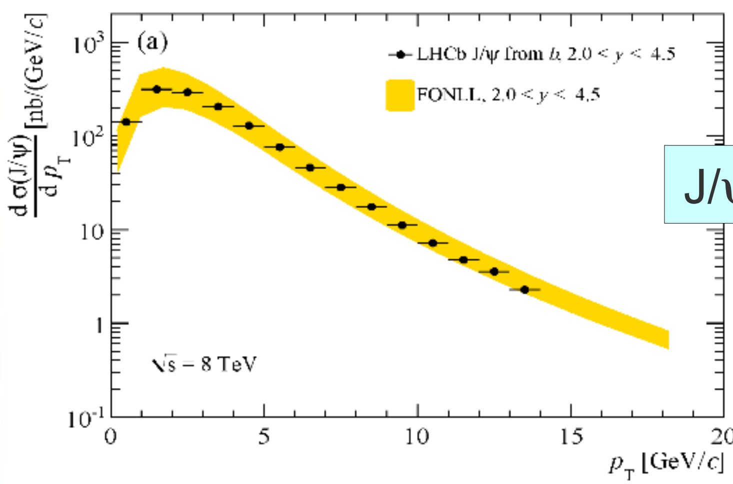


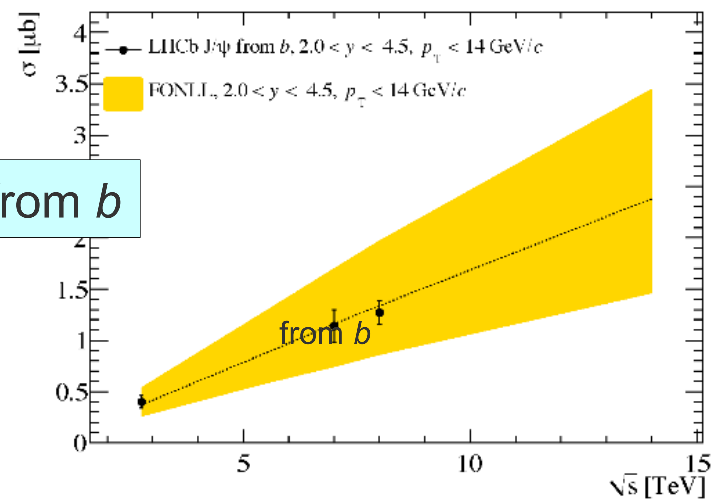
NLO CSM:
PRL98(2007)252002

NLO NRQCD:
PRD84(2011)05150,
PRL106(2011)022003

NNLO* CSM:
EPJC61(2008)693

J/ψ from *b*





FONLL CSM:
PLB 718 (2012) 431,
JHEP 05 (1998) 007

Prompt J/ψ in good agreement with NLO NRQCD

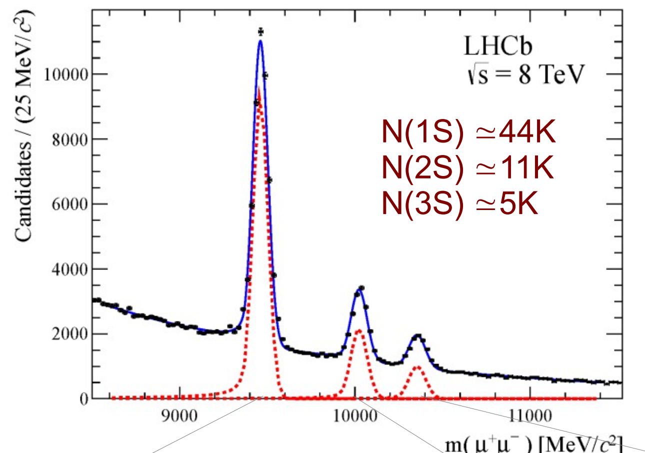
J/ψ from *b*: in good agreement with FONLL

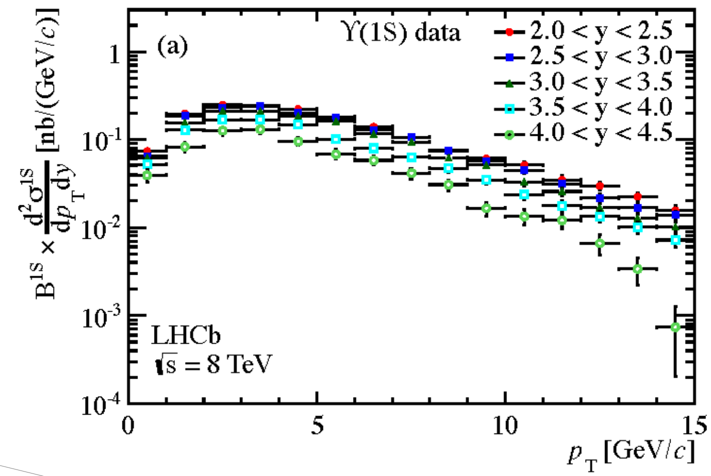
Υ(nS) production at √s = 8 TeV

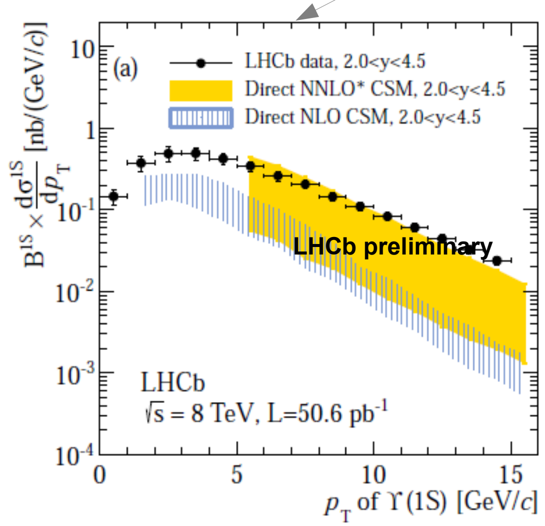
JHEP 06 (2013) 064

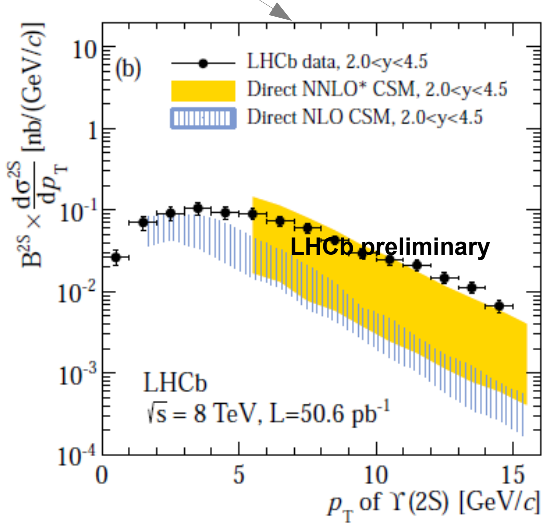
→ previous measurements at 7 TeV EPJC72 (2012) 2025

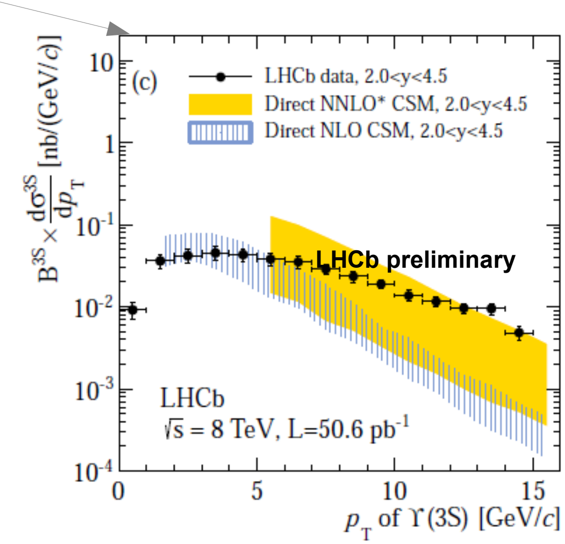
Measurement of the double differential cross-sections for the three Υ states











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

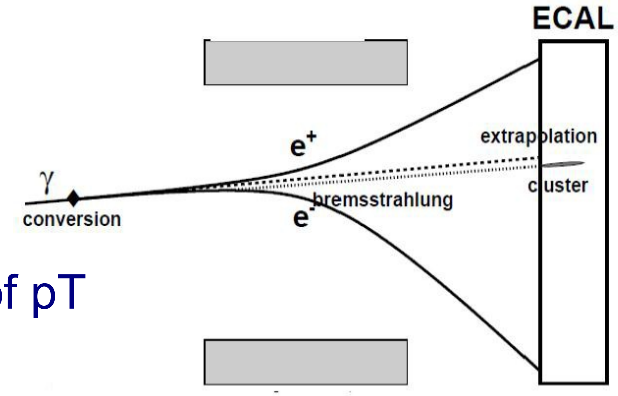
NNLO is necessary

Better agreement with Υ(3S), less feed-down contributions

χ_{cj}(1P) production ratio

→ previous measurements without converted photons

LHCb-PAPER-2013-028
ArXiv:1307.4285



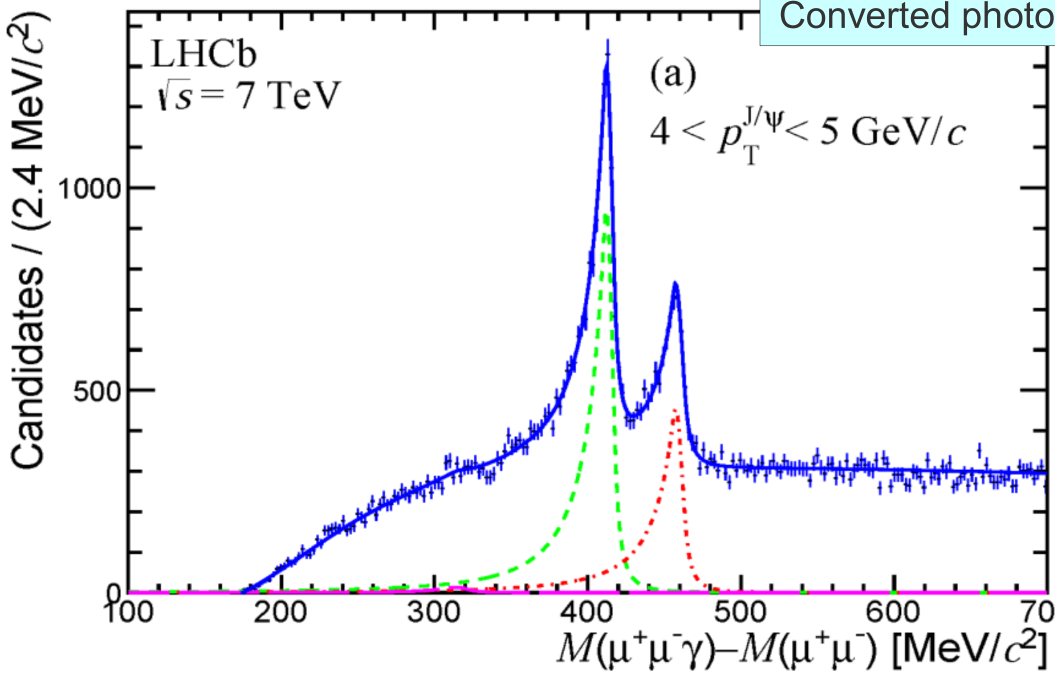
χ_c identified through the decay $\chi_c \to J/\psi\ (\to \mu\mu)\ \gamma$

Measurement using photons that convert in the detector and applying bremsstrahlung correction

Measurement with 1 fb^{-1} integrated luminosity (2011) in bin of pT and integrating on rapidity $2.0 < y < 4.5$

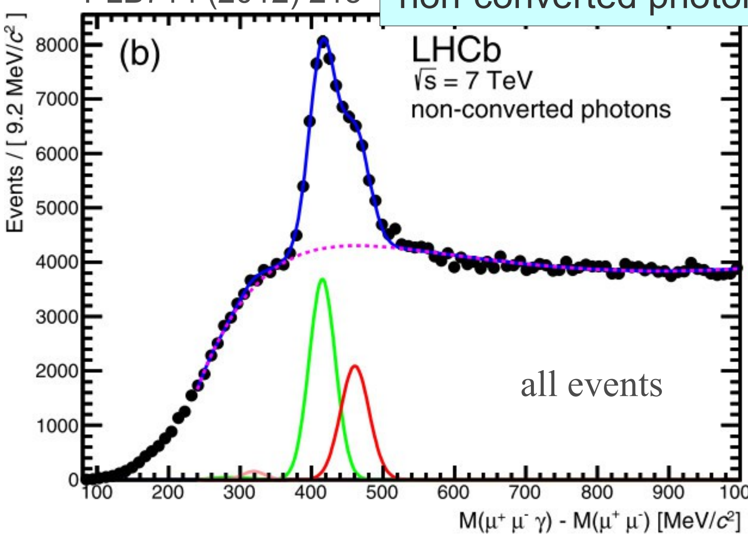
The use of the converted photons allows to clearly separate χ_{c1} and χ_{c2}: lower statistics but better mass resolution

Converted photons



PLB714 (2012) 215

non-converted photons

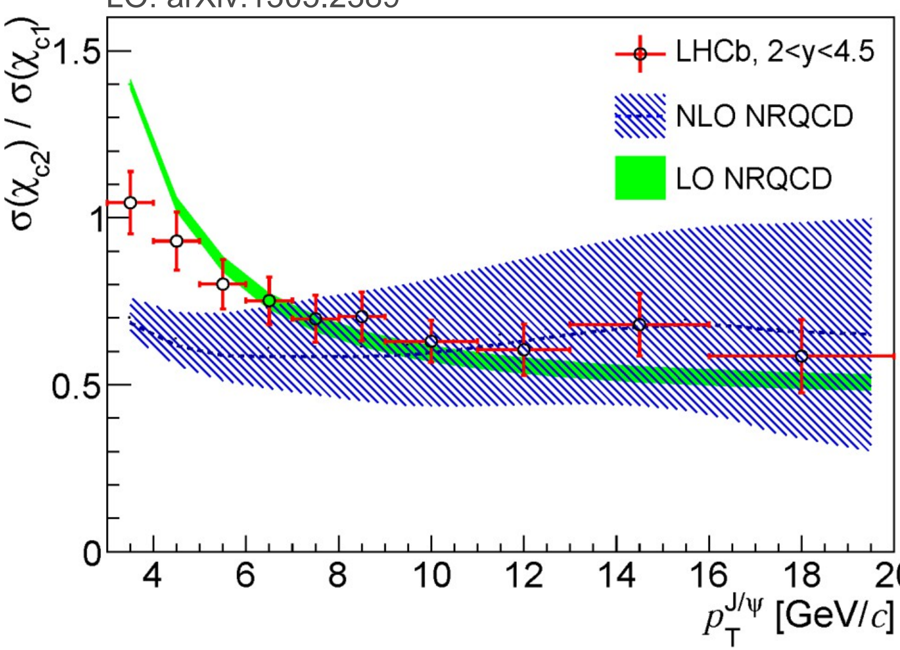


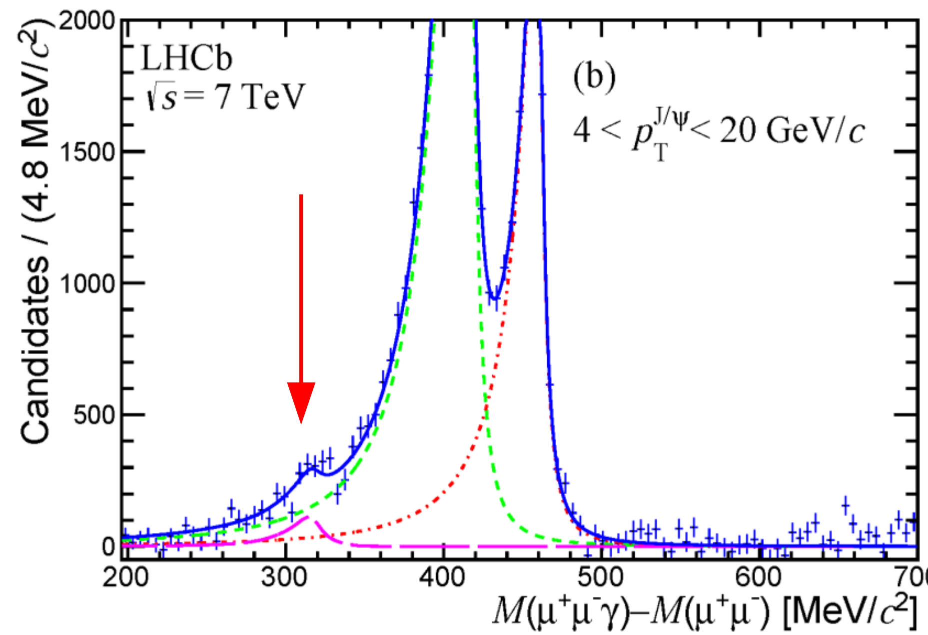
χ_{cj}(1P) production ratio

LHCb-PAPER-2013-028
ArXiv:1307.4285

- $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ decreases with J/ψ pT
- Good agreement with (N)LO NRQCD predictions for pT > 4 GeV/c
- Systematic uncertainty (~ 6%) dominated by photon efficiency
- Large uncertainty (not included) from the unknown polarisation of the two χ states
- **First evidence of the χ_{c0} state at hadron collider with a significance of 4.3σ**

NLO: Phys. Rev. **D83** (2011) 111503
LO: arXiv:1305.2389





J/ψ polarisation at √s = 7 TeV

LHCb-PAPER-2013-008
arXiv:1307.6379v2

Motivation

NLO NRQCD predicts J/ψ (Υ) production cross section very well, but not polarisation.
Important input to validate different models

Large uncertainty of cross-section measurement due to unknown polarisation

Strategy

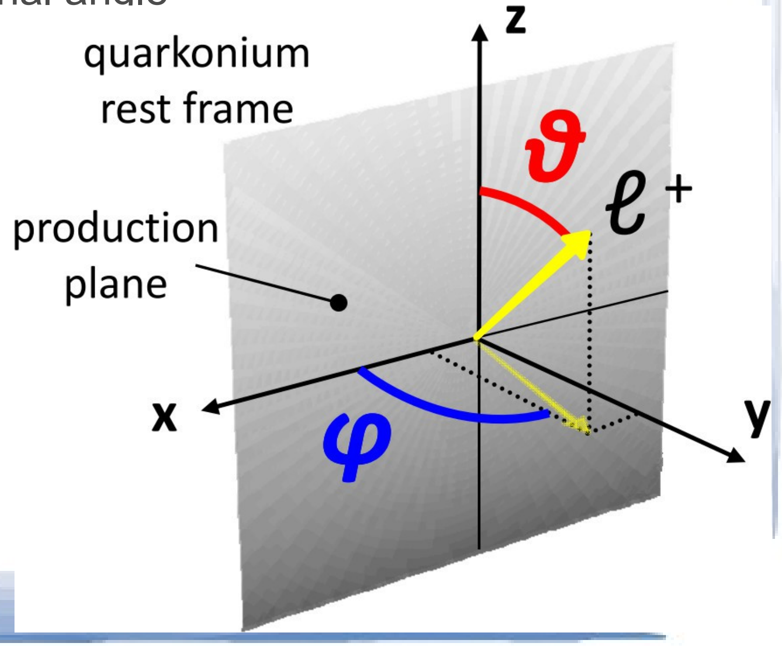
Full angular analysis to determine polarisation parameters (λ_θ, $\lambda_{\theta\varphi}$, λ_φ)

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

polar angle (θ) — azimuthal angle (ϕ)

The angular distribution of the positive decay lepton is reported in one of the two following systems of axes, differing in the definition of the **polarization axis(z)**:

- Helicity frame (HX)
- Collins-Soper (CS)



J/ψ polarisation at √s = 7 TeV

LHCb-PAPER-2013-008
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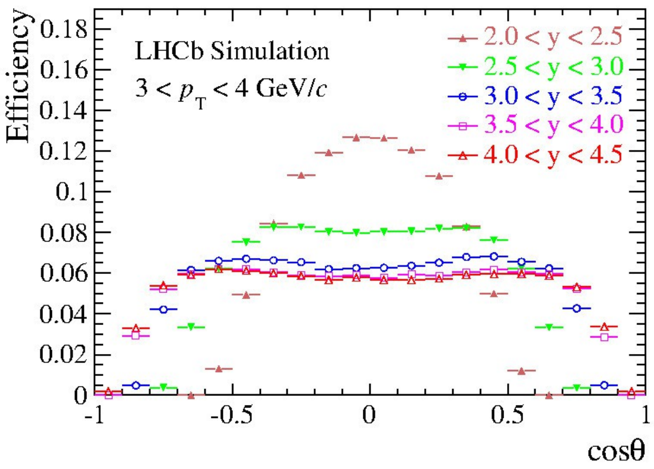
analysis key points

Crucial ingredient of the analysis is the knowledge of the **detector angular efficiency.** Angular efficiency distortion can result in artificial polarisation



Important also to reject the combinatorial **background** contamination

Weighted log likelihood used to extract the polarisation parameters and to subtract the background

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

ω_i from a sWeight-like technique

efficiency ε(cosθ,φ) estimated with simulation and corrected using $B^\pm \rightarrow J/\Psi K^\pm$

Norm(): normalization function, evaluated with the unpolarised MC sample

Data sample: 370 pb^{-1} at 7 TeV

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

LHCb-PAPER-2013-008
arXiv:1307.6379v2

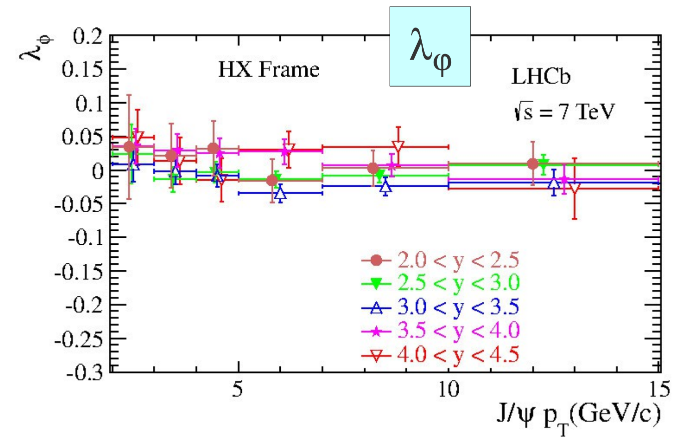
Results

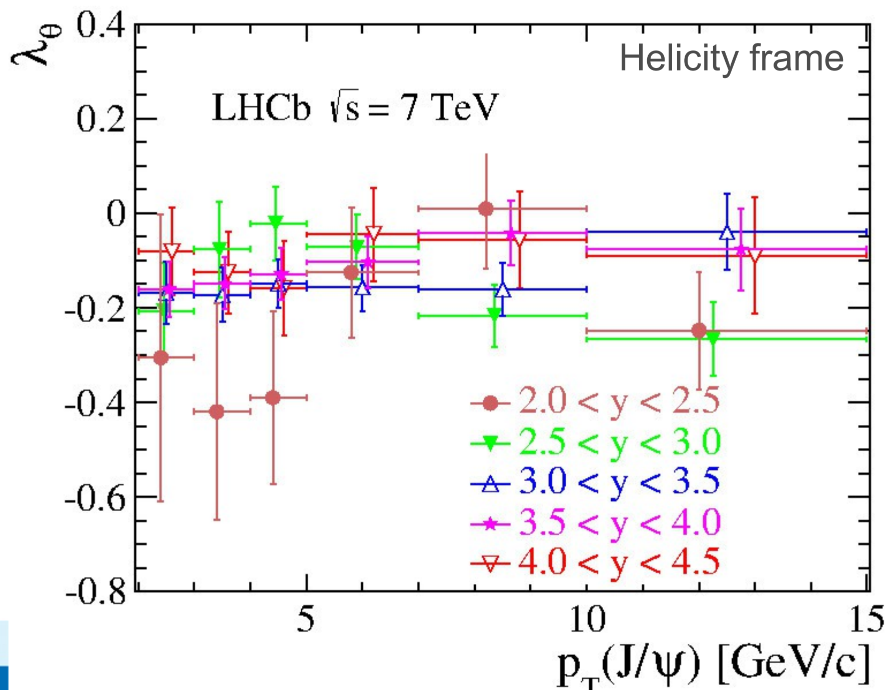
Measurement performed in bins of J/ψ pT and rapidity

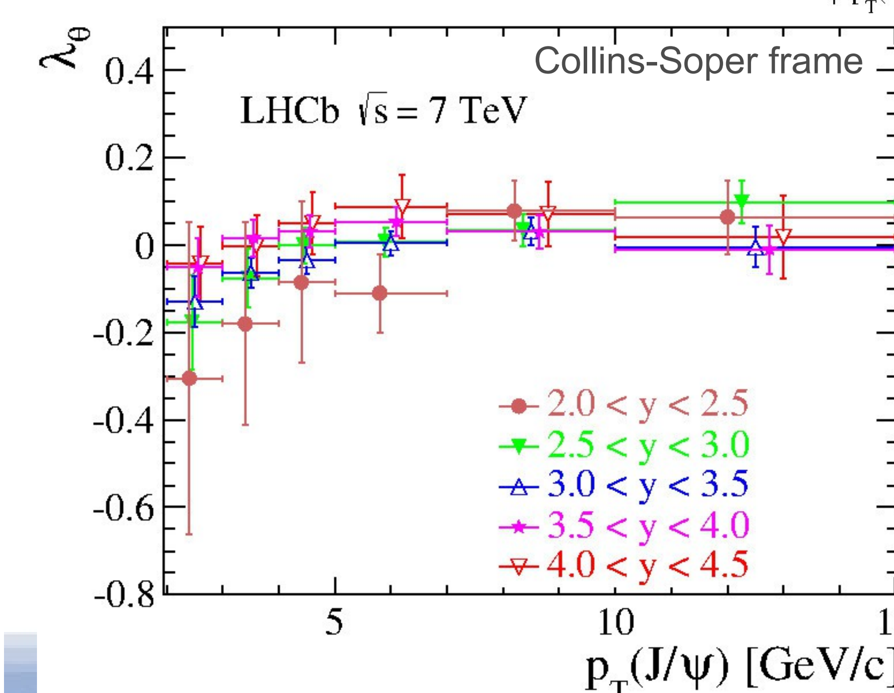
Since in HX frame $\lambda_\varphi \approx 0$, $\lambda_\theta(HX) \approx \lambda_{inv} = (\lambda_\theta - 3\lambda_\varphi)/(\lambda_\theta - \lambda_\varphi)$ is a unambiguous indicator of the polarisation

J/ψ meson results to have a weak longitudinal polarization

Uncertainty dominated by the systematic associated with efficiency correction







J/ψ polarisation at √s = 7 TeV

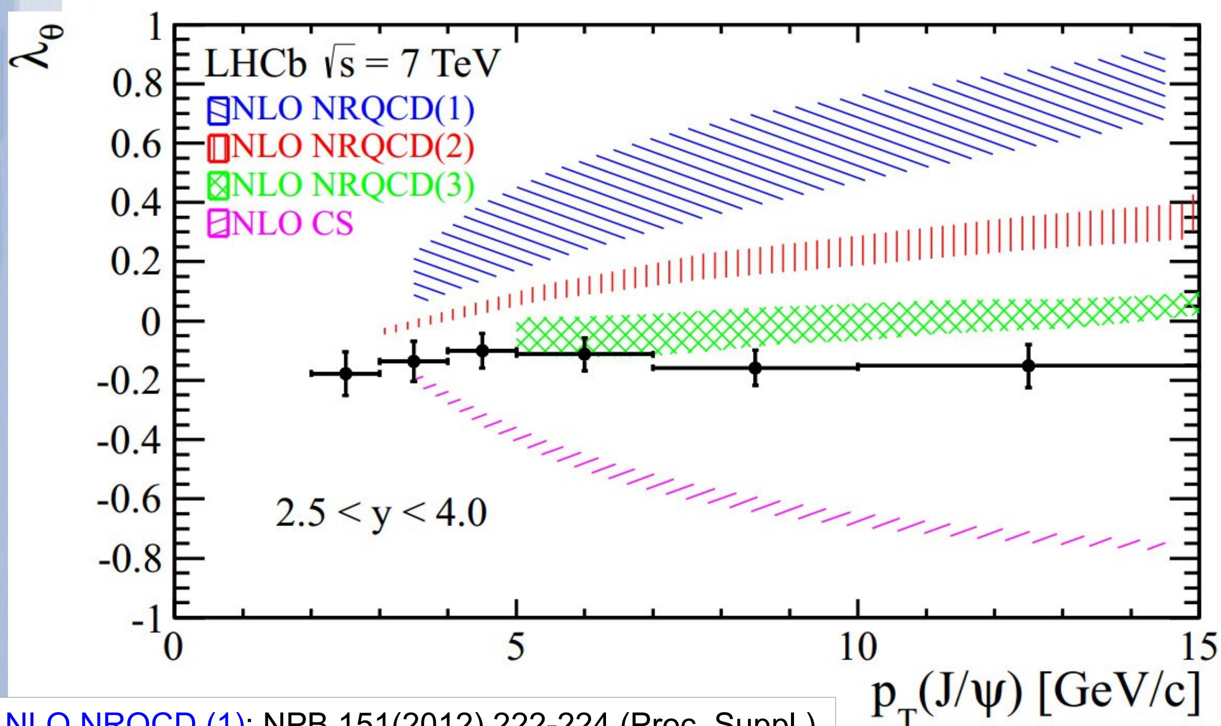
LHCb-PAPER-2013-008
arXiv:1307.6379v2

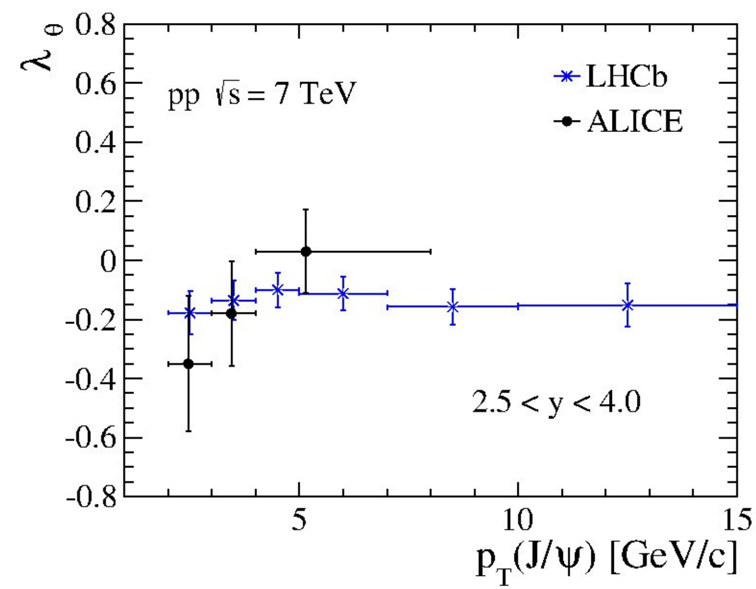
Comparison with theory

Measured λ_θ contradicts the **CSM** predictions for direct J/ψ production, both in size of the polarization parameters and pT dependence.

Concerning the **NRQCD** models, predictions can result in a better agreement with LHCb results (it depends on the **scheme** used to evaluate the non-perturbative matrix elements)

Agreement with ALICE's results with large uncertainty in ALICE





ALICE: PRL108(2012)082001

NLO NRQCD (1): NPB 151(2012) 222-224 (Proc. Suppl.)
NLO NRQCD (2): PRL110(2013) 042002
NLO NRQCD (3): PRL108(2012) 242004
NLO CSM: NPB 151(2012) 222-224 (Proc. Suppl.)

J/ψ cross section at 7 TeV update

LHCb-PAPER-2013-008
arXiv:1307.6379v2

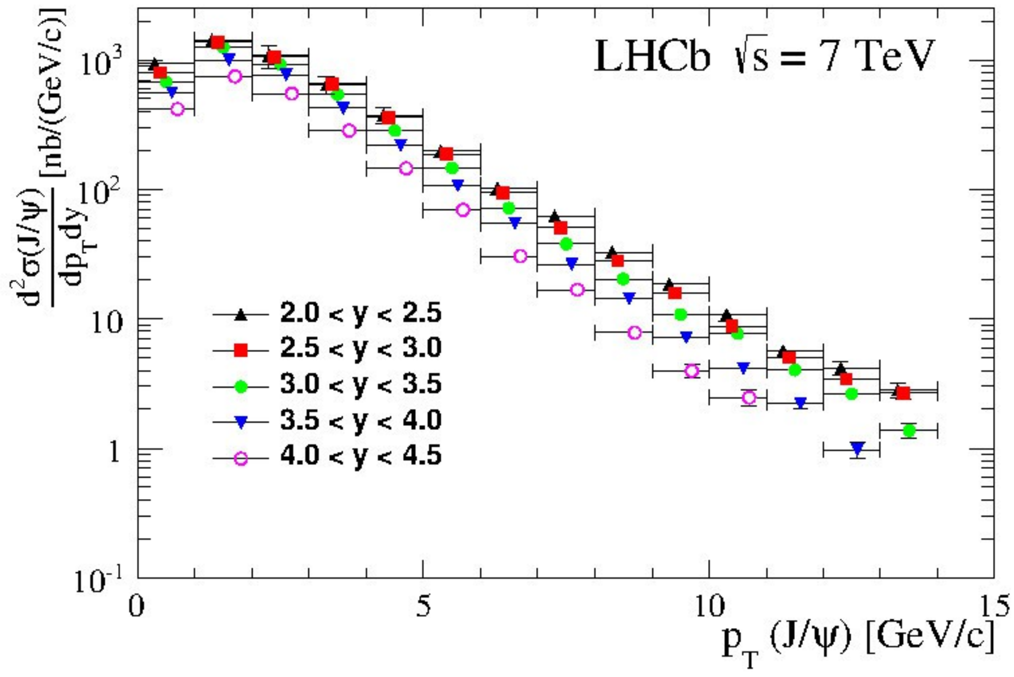
Polarisation affects the efficiency (acceptance) in cross-section measurement.

The measurement of the J/Ψ production cross-section has been **updated**, in light of the polarisation measurement.

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

previous measurement:

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



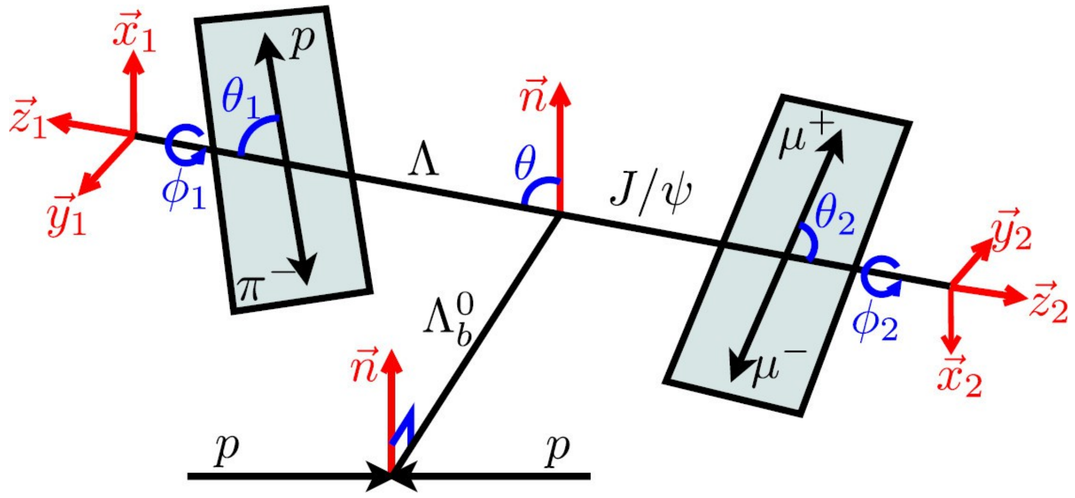
PLB 724 (2013) 27-35

$\Lambda^0_b \to J/\psi\, \Lambda$ decay amplitudes and Λ^0_b polarization

Λ^0_b in *pp* collisions expected to be transversally polarized (HQET)

Not yet measured at a hadron collider

$\Lambda^0_b \to \Lambda\, J/\psi$ ($\frac{1}{2} \to \frac{1}{2} + 1$) with $\Lambda \to p\pi$ and $J/\psi \to \mu^+\mu^-$



n normal to the production plane

θ angle between **p**(Λ)-**n** in the Λ_b rest frame

θ1, φ1 in the Λ rest frame

θ2, φ2 in the J/Ψ rest frame

Decay dynamics is completely described looking at 5 angles

Integrating over azimuthal ϕ_1 and ϕ_2, we simplify the decay distribution and we still are sensitive to polarization and squared amplitudes

PLB 724 (2013) 27-35

$\Lambda^0_b \to J/\psi\ \Lambda$ decay formalism

three angles differential decay rate

$$\frac{d\Gamma}{d\Omega_3} = \frac{1}{16\pi}\sum_{i=0}^{7} f_i(|\mathcal{M}_{\frac{1}{2},0}|^2, |\mathcal{M}_{-\frac{1}{2},0}|^2, |\mathcal{M}_{-\frac{1}{2},-1}|^2, |\mathcal{M}_{+\frac{1}{2},+1}|^2)\, g_i(P_b, \alpha_\Lambda)\, h_i(\cos\theta, \cos\theta_1, \cos\theta_2)$$

$\mathcal{M}_{\lambda_1,\lambda_2}$ helicity amplitudes (4) $\quad |\mathcal{M}_{\frac{1}{2},0}|^2 + |\mathcal{M}_{-\frac{1}{2},0}|^2 + |\mathcal{M}_{-\frac{1}{2},-1}|^2 + |\mathcal{M}_{+\frac{1}{2},+1}|^2 = 1$

i	$f_i(\alpha_b, r_0, r_1)$	$g_i(P_b, \alpha_\Lambda)$	$h_i(\cos\theta, \cos\theta_1, \cos\theta_2)$
0	1	1	1
1	α_b	P_b	$\cos\theta$
2	$2r_1 - \alpha_b$	α_Λ	$\cos\theta_1$
3	$2r_0 - 1$	$P_b\alpha_\Lambda$	$\cos\theta\cos\theta_1$
4	$\frac{1}{2}(1 - 3r_0)$	1	$\frac{1}{2}(3\cos^2\theta_2 - 1)$
5	$\frac{1}{2}(\alpha_b - 3r_1)$	P_b	$\frac{1}{2}(3\cos^2\theta_2 - 1)\cos\theta$
6	$-\frac{1}{2}(\alpha_b + r_1)$	α_Λ	$\frac{1}{2}(3\cos^2\theta_2 - 1)\cos\theta_1$
7	$-\frac{1}{2}(1 + r_0)$	$P_b\alpha_\Lambda$	$\frac{1}{2}(3\cos^2\theta_2 - 1)\cos\theta\cos\theta_1$

α_Λ known

$$\alpha_b \equiv |\mathcal{M}_{\frac{1}{2},0}|^2 - |\mathcal{M}_{-\frac{1}{2},0}|^2 + |\mathcal{M}_{-\frac{1}{2},-1}|^2 - |\mathcal{M}_{+\frac{1}{2},+1}|^2$$

amplitude asymmetry, predicted 15%*

$$r_0 \equiv |\mathcal{M}_{\frac{1}{2},0}|^2 + |\mathcal{M}_{-\frac{1}{2},0}|^2$$

$$r_1 \equiv |\mathcal{M}_{\frac{1}{2},0}|^2 - |\mathcal{M}_{-\frac{1}{2},0}|^2$$

P_b → tranverse polarisation, expected 0.1-0.2

PLB 614 (2005) 165
PLB 649 (2007) 1952

Four parameters to be determined simultaneously from the angular distribution

LHCb

PLB 724 (2013) 27-35

$\Lambda^0_b \rightarrow J/\psi\,\Lambda$ signal selection

Analysis based on 1 fb^{-1} at 7 TeV

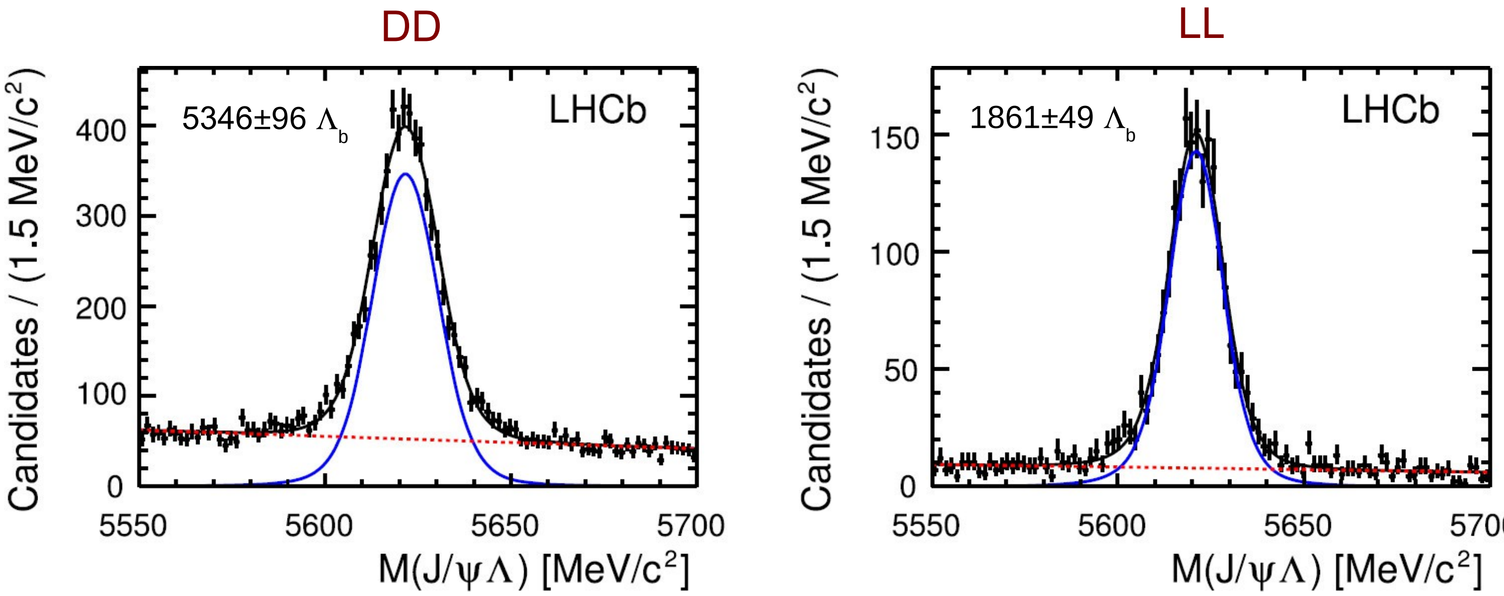
Two different classes of events analysed separately: decay inside (LL) or outside (DD) the VELO

Weighted Likelihood implemented to subtract the background and correct for the detector efficiency:

$$w_i = w(m) \times w(\cos\theta, \cos\theta_1, \cos\theta_2)$$

$w_i = w(m)$ → Mass term: from mass distribution

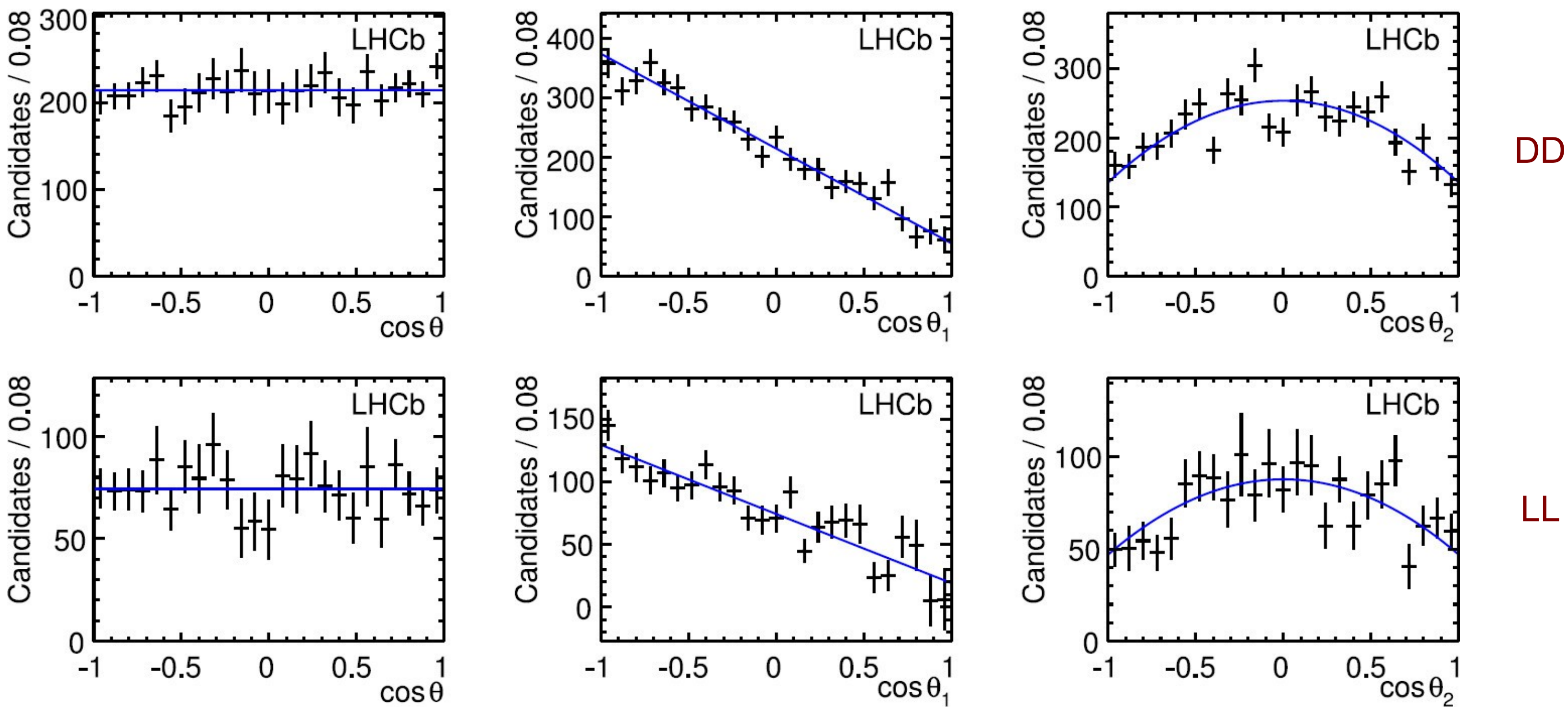
$w(\cos\theta, \cos\theta_1, \cos\theta_2)$ → detector acceptance term: from simulation



PLB 724 (2013) 27-35

$\Lambda^0_b \to J/\psi\ \Lambda$ angular distributions fit and results

Angular distribution, background subtracted and acceptance corrected



$$P_b = \quad 0.05 \pm 0.07 \pm 0.02$$ ► cannot exclude T pol at 10%

$$\alpha_b = -0.04 \pm 0.17 \pm 0.07$$ ► compatible with 0.15 prediction

$$r_0 = \quad 0.57 \pm 0.02 \pm 0.01$$

$$r_1 = -0.59 \pm 0.10 \pm 0.05$$

Systematic errors mostly due to the determination of the acceptance function from Monte Carlo: ~100% of P_b error and ~60% of a_b error

PLB 724 (2013) 27-35

Conclusions

LHCb made several measurements of quarkonia production and polarisation and is contributing significantly to this sector

Cross-sections of J/ψ and Υ measured at various energy

χ_c production ratio using converted/unconverted photons and first evidence of χ_{c0} at hadron collider

J/ψ and Λ_b polarisation measured at 7 TeV

… many more analyses in progress with 2011+2012 data sets

LHCb