MANCHESTER 1824
The University of Manchester

LHCb

19th International Symposium on
Particles, Strings and Cosmology

Onia Production and Spectroscopy at LHCb

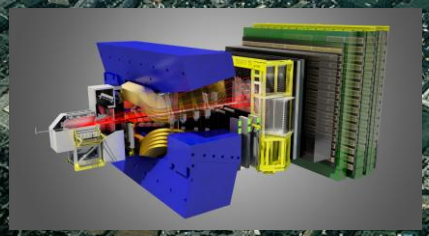
Stefano de Capua
on behalf of the LHCb collaboration

PASCOS 2013

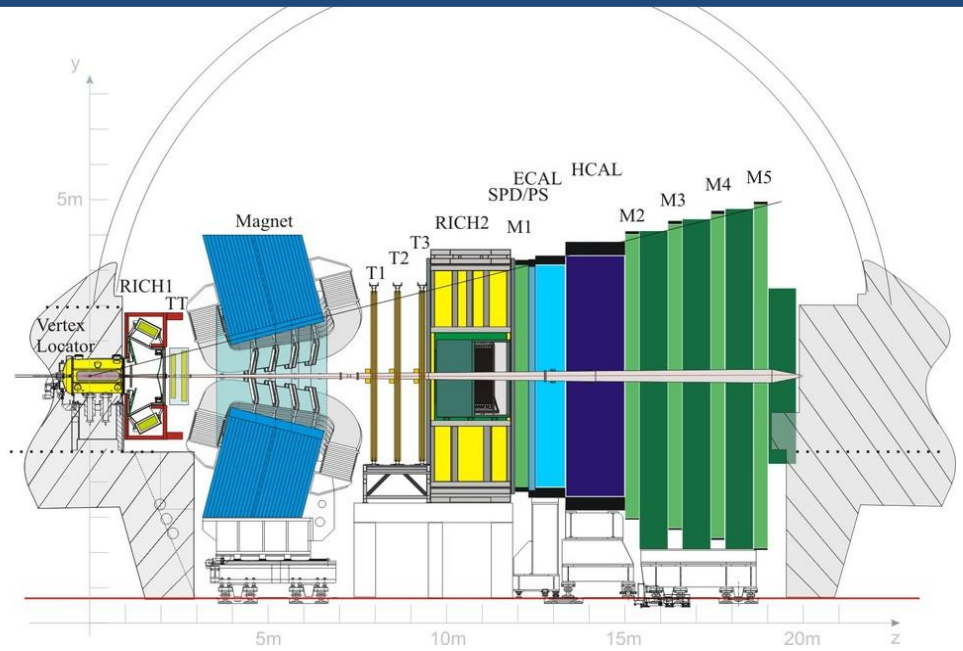
Outline

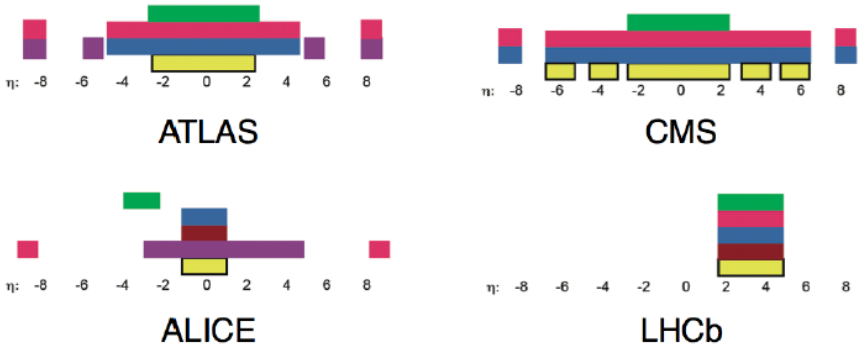
- Introduction to the LHCb experiment.
- Quarkonia production:
  - J/ψ production cross-section.
  - J/ψ polarization.
  - Υ(nS) production cross-section.
  - χ_c production cross-section.
- Spectroscopy: X(3872) characterization.
- Conclusion.

LHCb



The LHCb detector





tracking, ECAL, HCAL, counters lumi, muon, hadron PID

Data samples:

- 2010: 0.037 fb^{-1} at $\sqrt{s}$=7 TeV
- 2011: 1.1 fb^{-1} at $\sqrt{s}$=7 TeV
- 2012: 2 fb^{-1} at $\sqrt{s}$=8 TeV

results presented here are based on 2011 and 2012 data

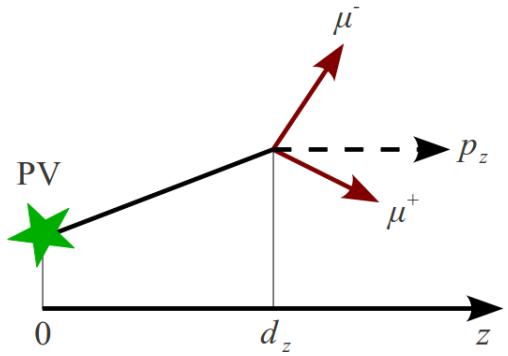
Quarkonia

- Abundantly produced in LHCb: ~60 Hz of $J/\psi \to \mu^+\mu^-$ @ 2012 conditions.
- Most of them are very well known resonances (width, mass peak, br, …).
- Production mechanism not yet fully understood.
- Active interest of theorists (Tevatron puzzle), several models of the production mechanism available:
  - Color-Singlet (CS)
  - Color-Octet (CO)
  - FONLL (production from b-hadron decays)
- For the LHC experiments, new computations are being performed:
  NLO, NNLO$^{(*)}$ corrections to CS and CO production.
- LHCb studies quarkonium hadroproduction in a unique kinematic region:
  - Forward rapidity range ($2<y<4.5$)
  - Low p_T range (<20 GeV/c)

J/ψ production

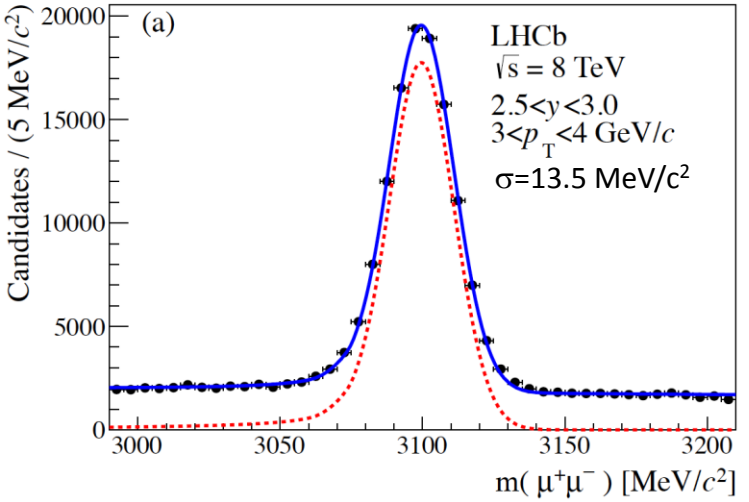
- Select decays of J/ψ into muon pairs:
  - opposite charged tracks from same vertex
  - good track quality and μID
  - minimum threshold on $p_T(\mu)$
- Measurement of the double differential production cross-section in bins of y and p_T:
  - $0 < p_T < 14$ GeV/c
  - $2.0 < y < 4.5$
- Prompt J/ψ and J/ψ from b decays components separated using pseudo-proper time:

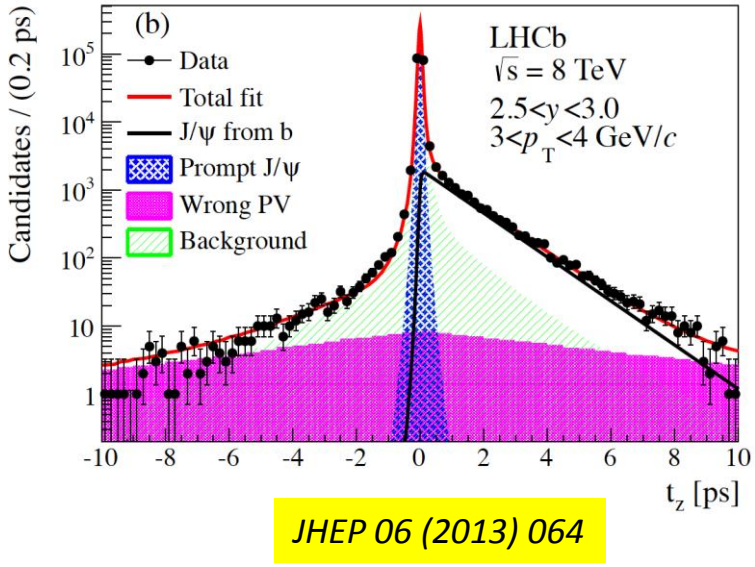
$$t_z = (z_{J/\psi} - z_{PV}) \times M_{J/\psi}/p_z$$



- Signal extraction by a simultaneous fit to $m_{\mu\mu}$ and t_z in each (p_T,y) bin

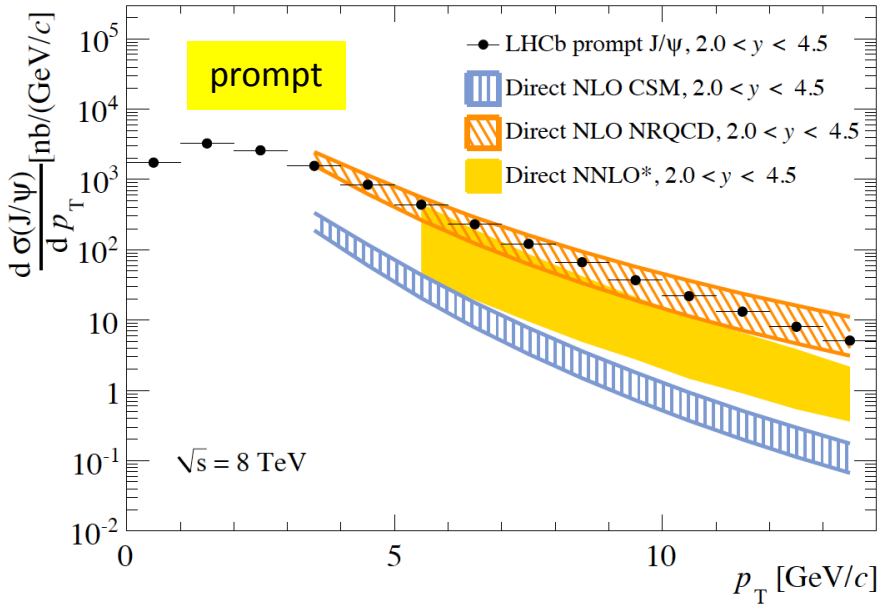
2.6M J/ψ in 18 pb^{-1} at √s = 8 TeV





JHEP 06 (2013) 064

Prompt J/ψ: results



NLO CSM model:
Phys. Rev. Lett. 98 (2007)

NLO NRQCD model:
Phys. Rev. D84 (2011) 051501
Phys. Rev. Lett. 106 (2011) 022003

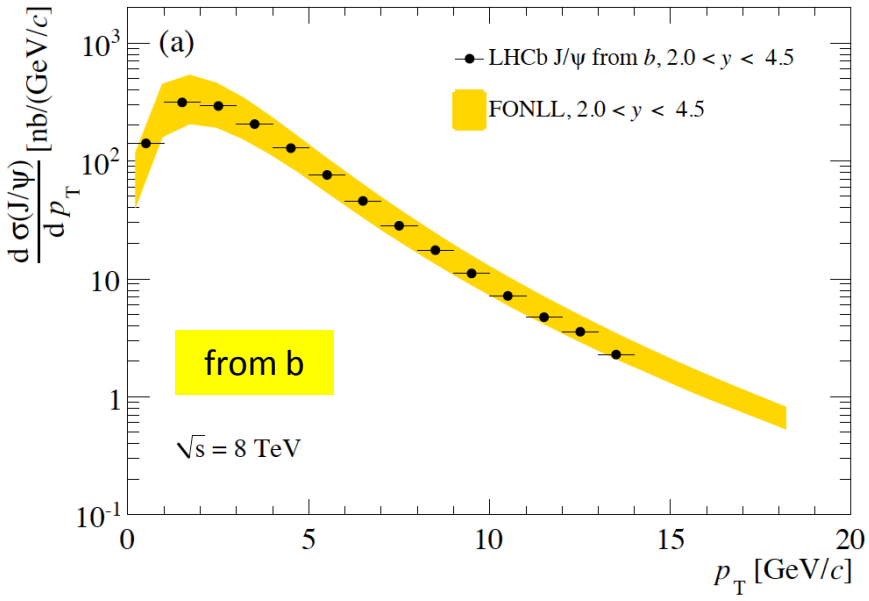
NNLO* model:
Phys. Rev. Lett. 101 (2008) 152001
Eur. Phy. J. C 61 (2008) 693

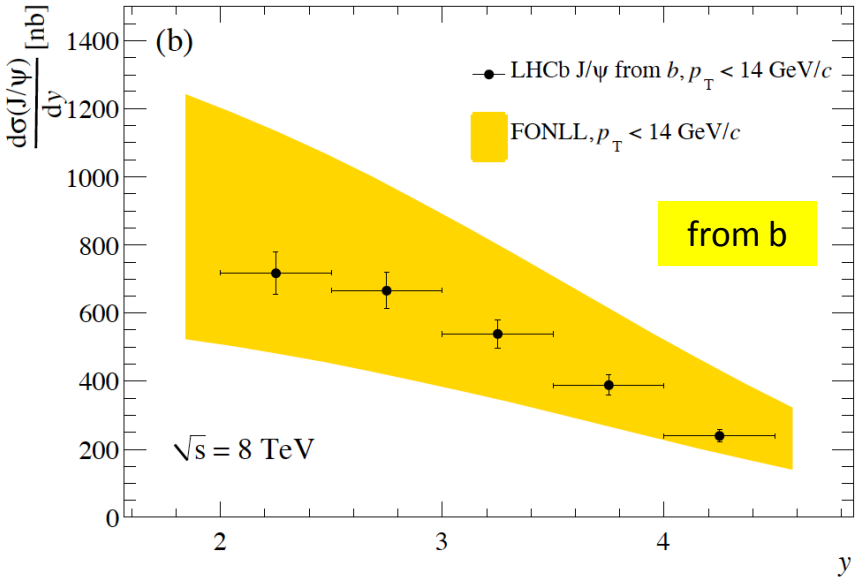
- Prompt J/ψ mesons assumed to be produced unpolarised

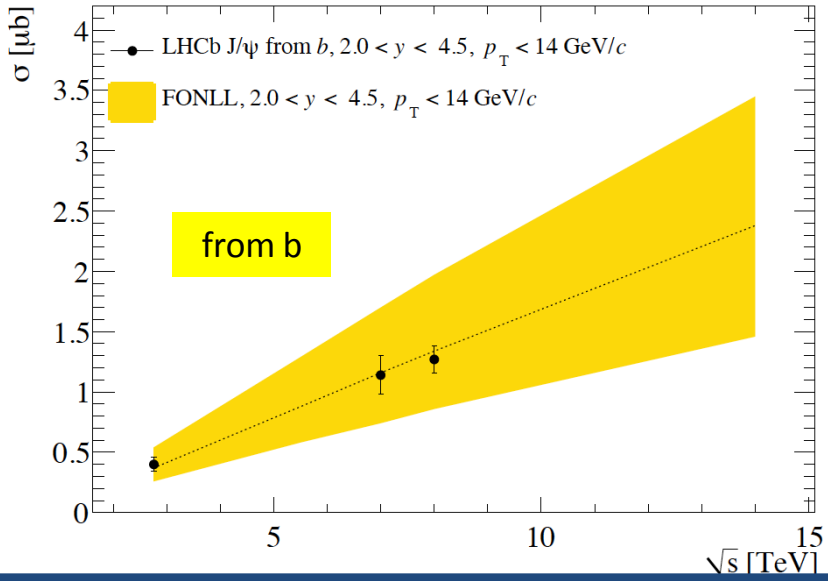
- σ(prompt J/ψ; p_T < 14 GeV/c; 2.0 < y < 4.5) = 10.94 ± 0.02 (stat) ± 0.79 (sys) μb
- σ(J/ψ from b; p_T < 14 GeV/c; 2.0 < y < 4.5) = 1.28 ± 0.01 (stat) ± 0.11 (sys) μb

- Systematic uncertainty ~ 7% (main contribution from luminosity and trigger efficiency)
- Predictions for direct J/ψ meson production
- Experimental data include feed-down from higher charmonium states (20% from χ_c -> J/ψ γ and 8% from ψ(2S) -> J/ψ ππ)
- Data in good agreement with NLO NRQCD

J/ψ from b: results







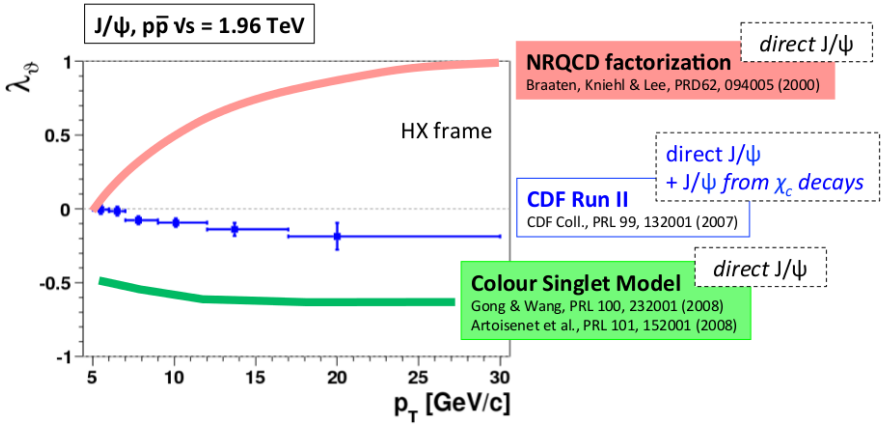
FONLL model:
JHEP 10 (12) 137
JHEP 05 (1998) 007

- Excellent agreement with theory

- 8 TeV data in *JHEP 06 (2013) 064*
- 7 TeV data in *Eur. Phys. J. C71 (2011) 1645*
- 2.76 TeV data in *JHEP 02 (2013) 041*

J/ψ polarisation

- Prompt charmonium production still puzzling: many theoretical models available describing well the cross section but not the polarization (NLO NRQCD).
- Prompt J/ψ cross-section depends on polarization (distortion in the decay product acceptance), may lead to large uncertainty on cross-section measurement.



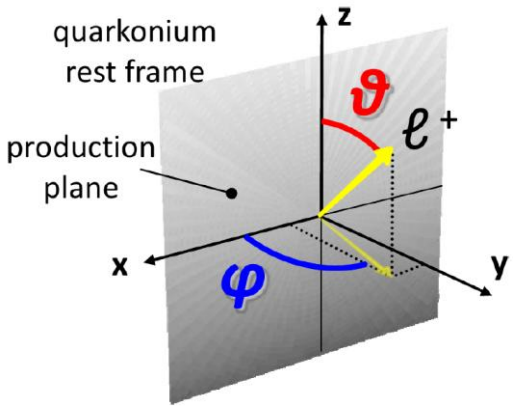
- Status of experimental studies: previous measurements from CDF, PHENIX, HERA-B (PRL 99 (2007), 132001, PRD 82 (2010), 012001, EPJ C 60 (2009), 517)
- At LHC:
  - ALICE PRL 108 (2012) 082001: overlapping kinematic region with LHCb (possible direct comparison).
  - Recent results from CMS arXiv:1307.6070.

J/ψ polarisation: strategy

- Data sample: 0.37 fb^{-1} integrated luminosity from 2011 run, in bins of p_T and y
- Extract polarization from angular distribution of the J/ψ -> μμ (feed-down included)
- Full angular analysis to determine the polarisation parameters (λ_θ, $\lambda_{\theta\phi}$,λ_ϕ):

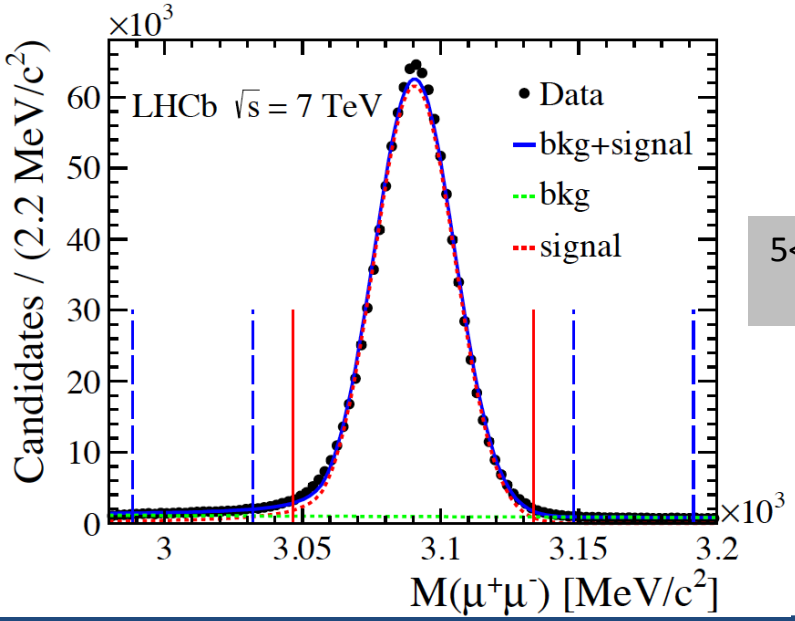
$$\frac{d^2N}{d\cos\theta d\varphi} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi + \lambda_\varphi \sin^2\theta \cos 2\varphi$$

polar angle — azimuthal angle



- Data presented in two different polarisation frames: Helicity frame (HX) and Collin-Soper frame (CS)

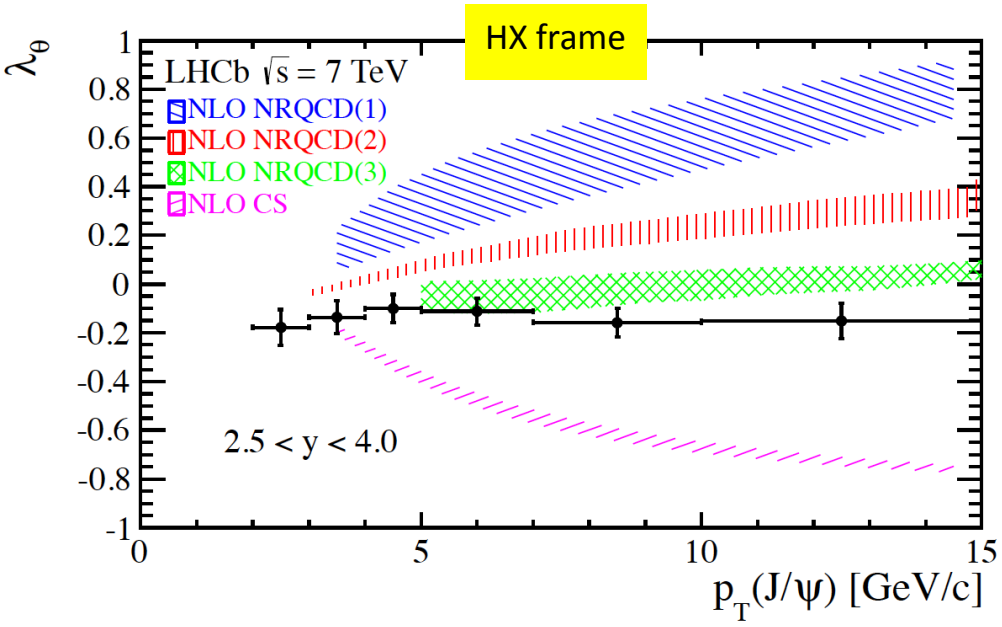
- Prompt J/ψ and J/ψ from b decays components separated by using pseudo-proper time

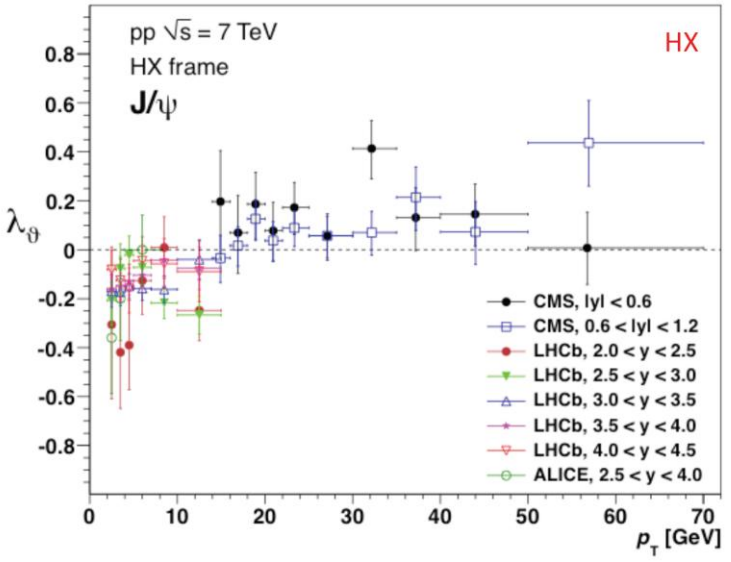


5<p_T<7 GeV/c, 3.0<y<3.5

Eur. Phys. J. C (2013) 73:2631

J/ψ polarisation: results





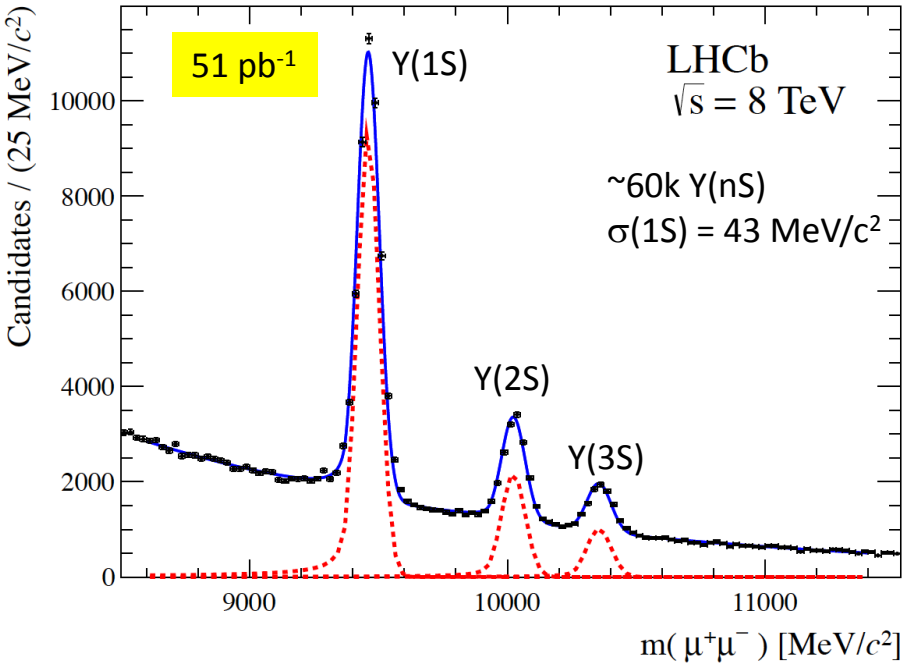
NLO NRQCD (1): NPB 222-224 (2012) 151 (Proc. Suppl.)
NLO NRQCD (2): PRL 110 (2013) 042002.
NLO NRQCD (3): PRL 108 (2012) 242004.
NLO CS: NPB 222-224 (2012) 151 (Proc. Suppl.)

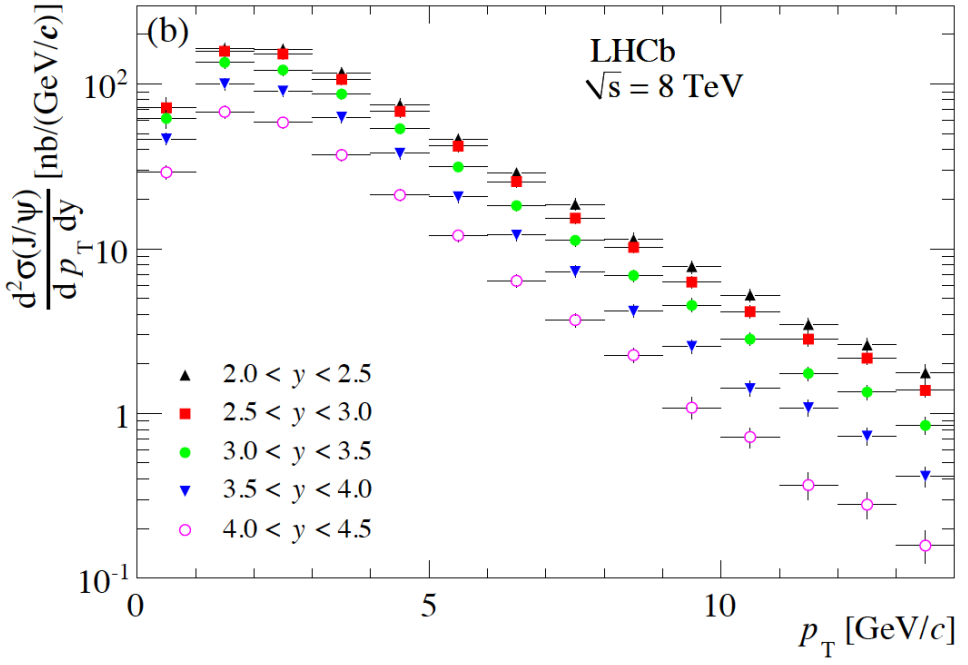
ALICE: PRL108(2012)082001
CMS: arXiv:1307.6070
LHCb: arXiv:1307.6379
(P. Faccioli, QCD@LHC 2013, DESY, Hamburg)

- Parameters $\lambda_{\theta\phi}$ and λ_{ϕ}consistent with 0, so $\lambda_{inv} = (\lambda_\theta+3\lambda_\phi)/(1-\lambda_\phi) = \lambda_\theta$
- A small longitudinal polarization is observed.
- Results in HX and CS are consistent.

- LHCb results are compatible with NLO NRQCD calculations that include feed-down contributions.
- Good agreement is also observed with recent measurements from ALICE and CMS (although in a different kinematic region).

Y(nS) production





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

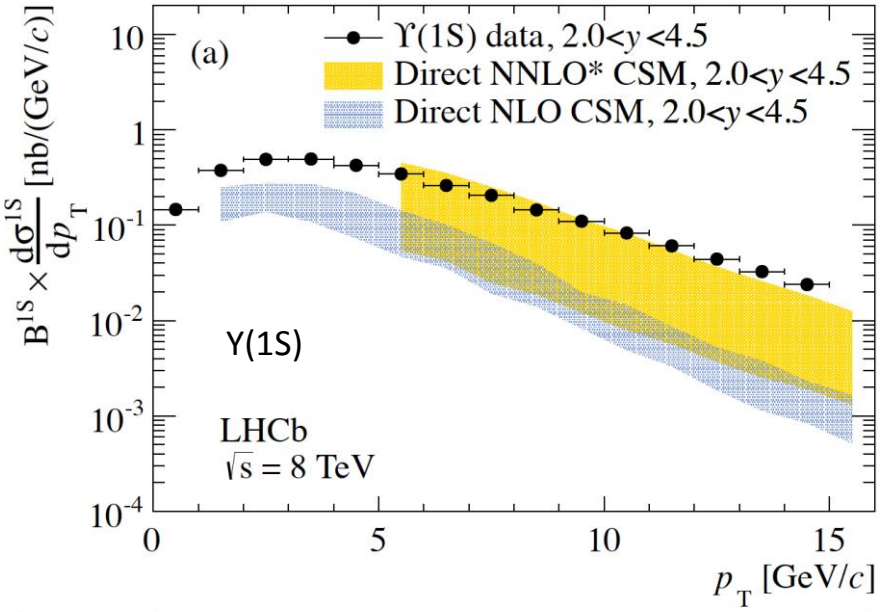
$\sigma(pp \to Y(2S)\,X) \times B^{2S} = 0.761 \pm 0.008\,(stat) \pm 0.055\,(sys)$ nb

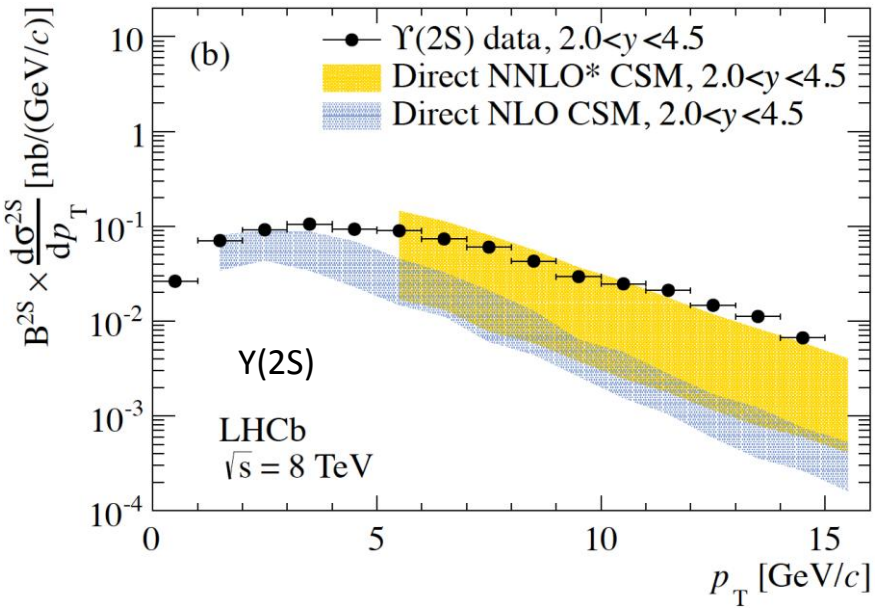
$\sigma(pp \to Y(3S)\,X) \times B^{3S} = 0.369 \pm 0.005\,(stat) \pm 0.027\,(sys)$ nb

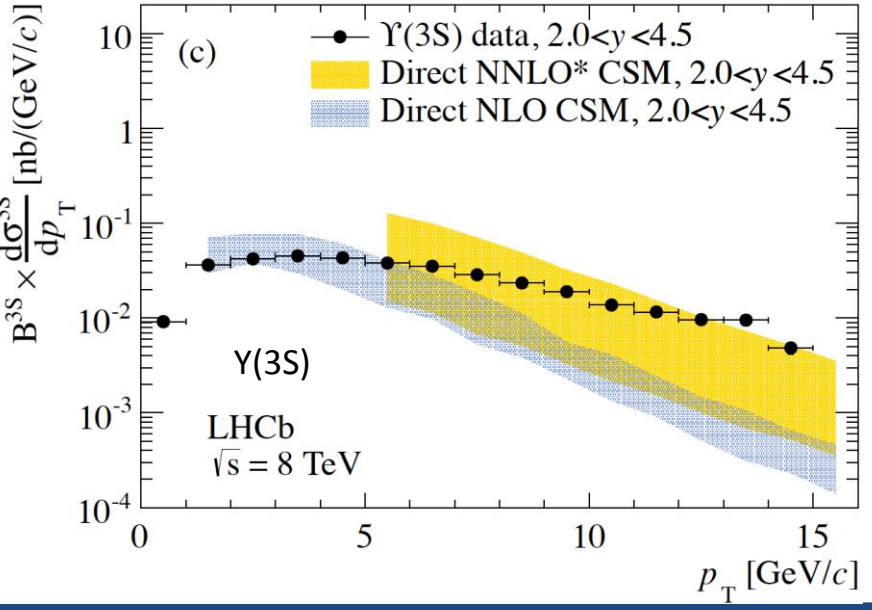
B^{iS} = Br[Y(iS) -> μμ], i=1,2,3

JHEP 06 (2013) 064

Υ(nS) production: data vs. theory







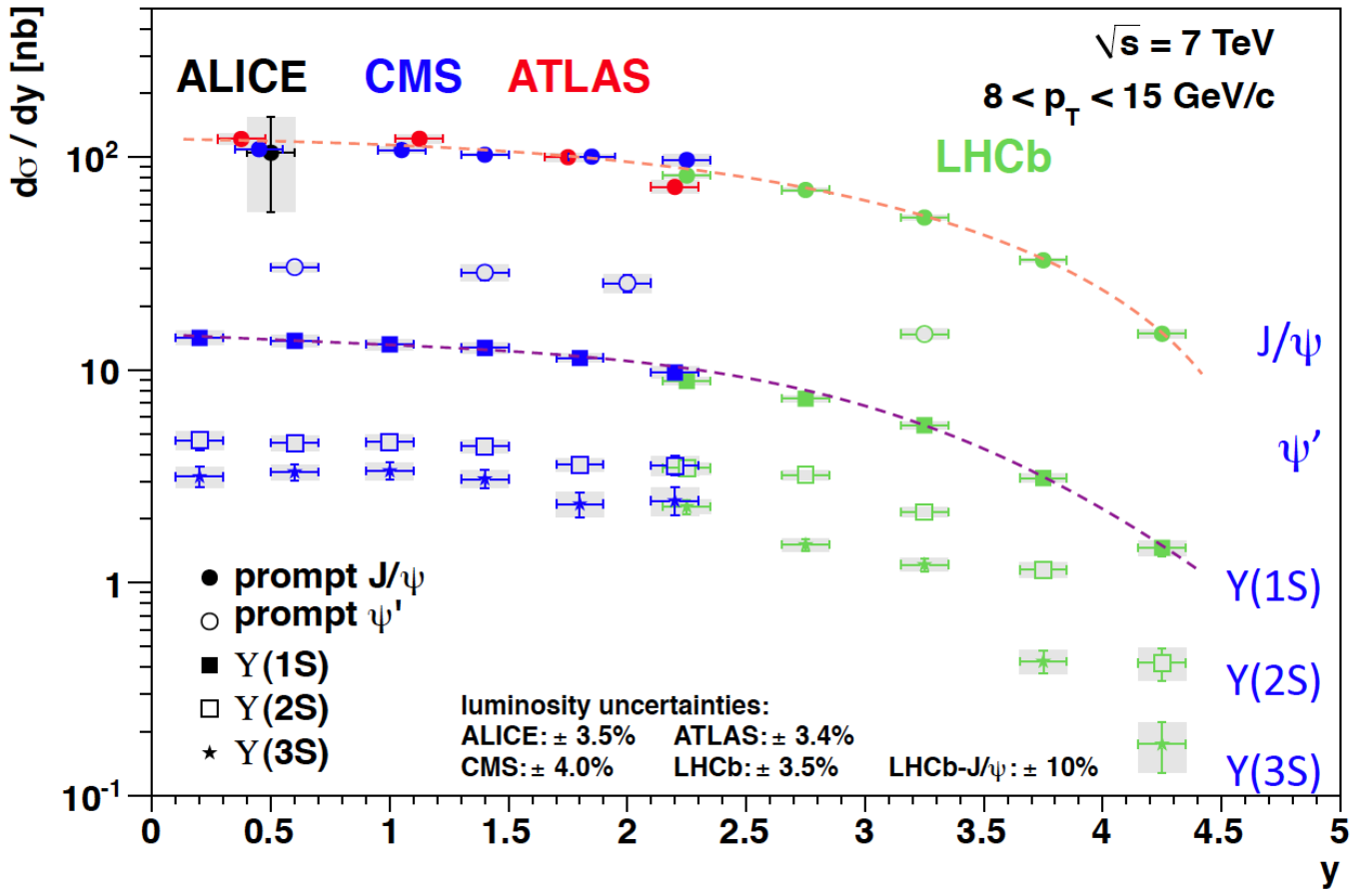
- reasonable agreement with NNLO* CSM
- no feed-down included in theory
- NLO NRQCD not yet available

NLO CSM: PRL 98 (2007) 252002

NNLO* CSM: PRL 101 (2008) 152001

Summary of production cross-section at √s = 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

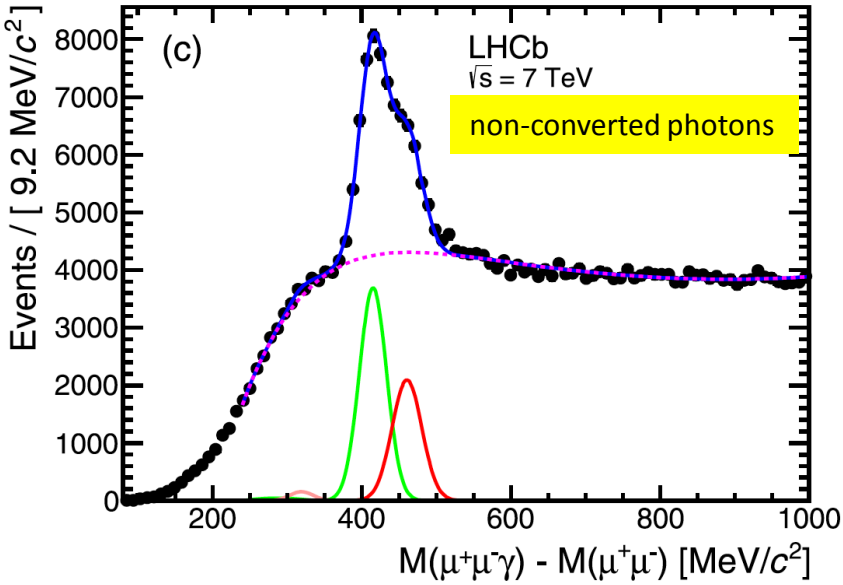
- impressive amount of results
- nice complementarity in acceptance among GPDs and LHCb

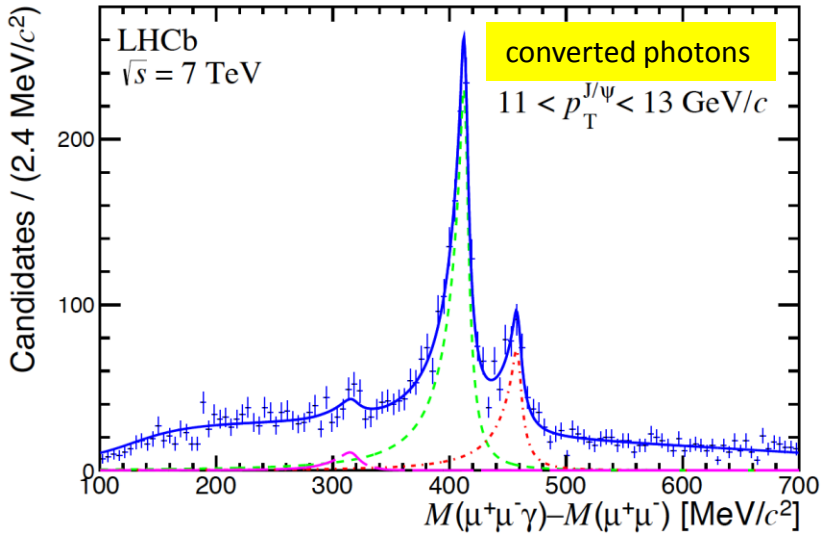
ALICE : 5.6 nb^{-1}
ATLAS : 2.2 pb^{-1}
CMS : 37, 36 pb^{-1}
LHCb : 5.2, 36, 25 pb^{-1}

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

χ_c production at $\sqrt{s}$ = 7 TeV

- Studies on χ_c production provide an important test for understanding quarkonium production.
  - substantial feed-down contribution to prompt J/ψ from χ_c states impact on J/ψ polarization measurements.
  - $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ is sensitive to CS and CO models.
- Select prompt χ_{cj} -> (J/ψ->$\mu\mu$) γ
- photons reconstructed in the calorimeter:
  - high statistics
  - poor resolution
- photons converted in the detector material before the magnet (γ->e^+e^-):
  - improve mass resolution (tracker)
  - lower statistics (light material budget in the vertex locator)

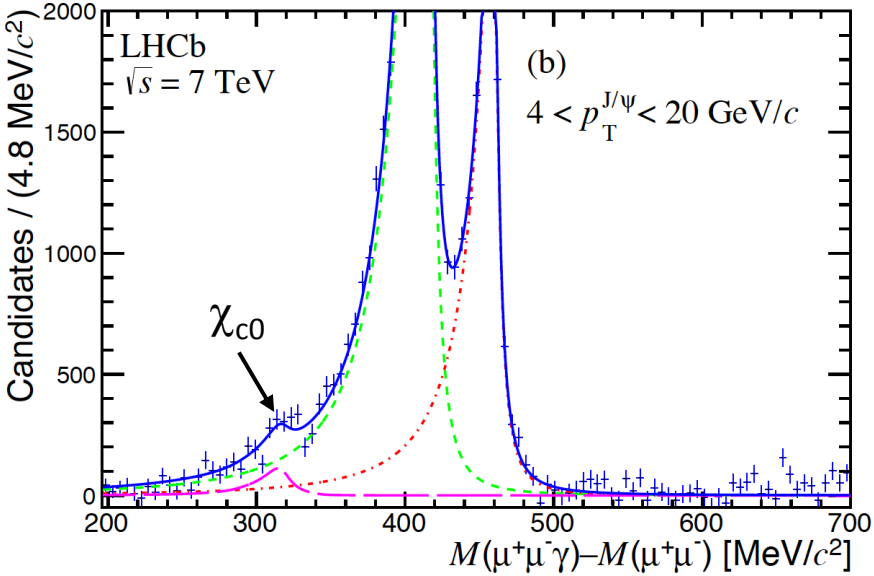


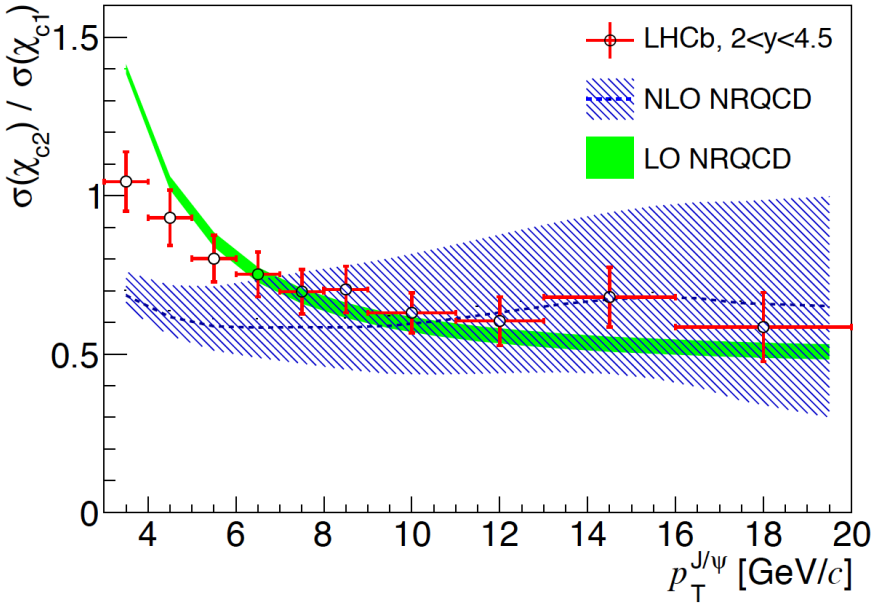


χ_c production at $\sqrt{s}$ = 7 TeV

JHEP 10 (2013) 115

- Measurement with 1 fb^{-1} at $\sqrt{s}$ = 7 TeV, in bins of p_T and integrated over rapidity in the range 2.0 < y < 4.5, using converted photons.
- First evidence of the χ_{c0} state at a hadron collider with a significance of 4.3σ!
- $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ in reasonable agreement with (N)LO NRQCD predictions for p_T > 4 GeV/c
- Systematic uncertainty (~6%) dominated by photon efficiency
- Large uncertainty (not included) from the unknown polarisation of the two χ_c states





NLO: PRD 83 (2011) 111503
LO: arXiv:1305.2389.

X(3872)

- New exotic mesons have been observed by different experiments: X(3872), X(4140), $Z^{\pm}(4430)$, which don't fit into the *ccbar* conventional picture.

- X(3872) discovered by Belle (2003) in $B^{\pm} \to X(3872)K^{\pm}$ [PRL 91 (2003) 262001] and confirmed by CDF, D0 and BaBar. Also LHCb measured production cross-section and mass with 34.7 pb^{-1} at $\sqrt{s}$ = 7 TeV [EPJ C72, 1972 (2012)]

- After 10 years, its nature still uncertain (conventional charmonium, bound D^0D^* molecule, tetraquark state,…)

- C-parity known to be positive as $X(3872) \to J/\psi\,\gamma$ observed by Belle [PRL 107 091803] and BaBar [PRD 74 071101 (R)]

- CDF helicity angle measurement [PRL 98 132002] excluded all J^{PC} except:
  - $J^{PC} = 2^{-+}$: $\eta_{c2}(1^1D_2)$
  - $J^{PC} = 1^{++}$: $\chi_{c1}(2^3P_1)$ or exotic D^0D^* bound state or tetraquark

- Belle data of $X(3872) \to J/\psi\,\pi\pi$ equally well described by 1^{++} and 2^{-+} [PRD 84 052004]

- BaBar analysis of $X(3872) \to J/\psi\,\omega$ prefers 2^{-+} but does not exclude 1^{++} [PRD 82, 011101(R)]

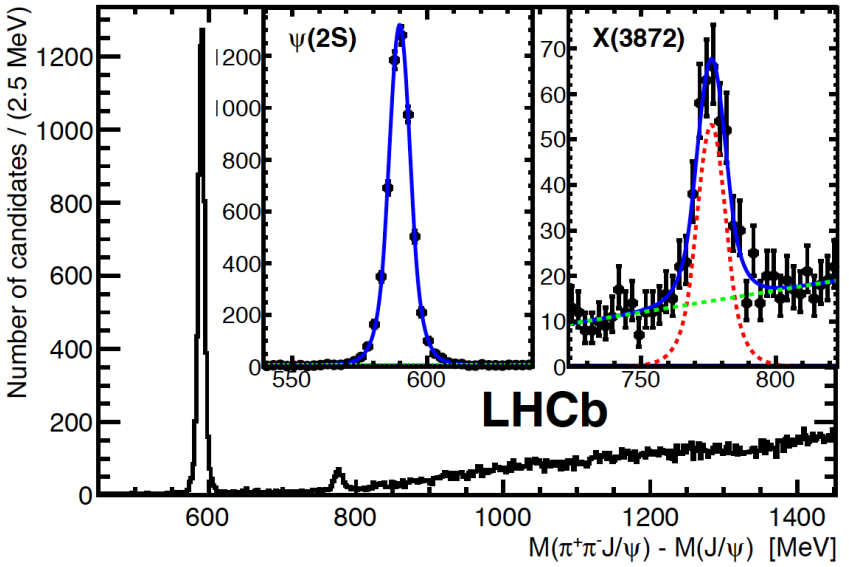
X(3872): analysis strategy

- Goal: measure the X(3872) J^{PC}

PRL 110 222001

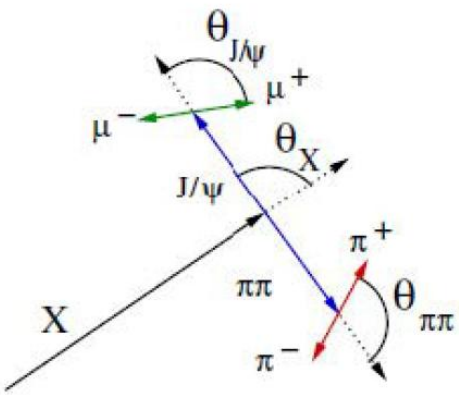
- 5-D angular correlations of decay products in $B^+ \to X(3872)\, K^+$ decay mode, with $X(3872) \to J/\psi\, \pi^+\pi^-$

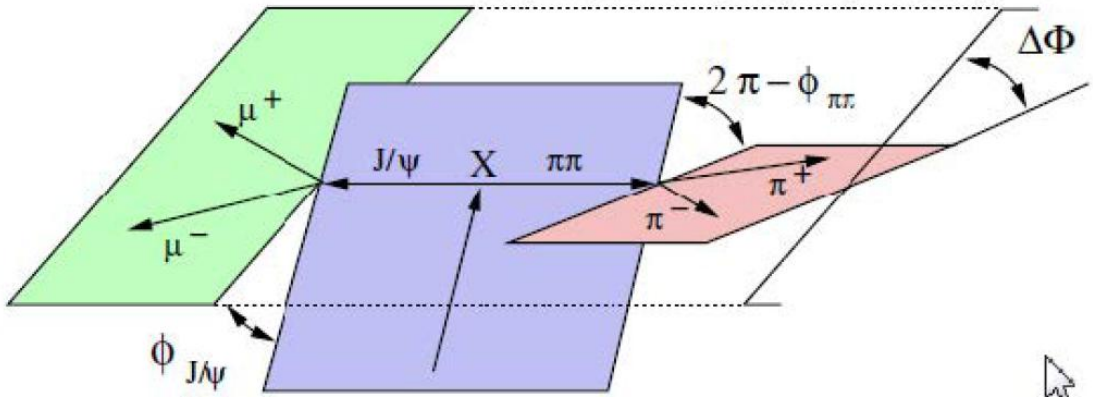
- Data sample: 1 fb^{-1} at $\sqrt{s}$ = 7 TeV (2011)
  - $B^+ \to \psi(2S)\, K^+$ as a control channel
  - 313±26 $B^+ \to X(3872)\, K^+$ (568±31 bkg events)
  - 68% signal purity in $\pm 2.5\sigma_X$ region
  - σ_X = 5.5 ± 0.5 MeV



- Angular correlations in the B^+ decay chain carry information on the J^{PC} of the X(3872)

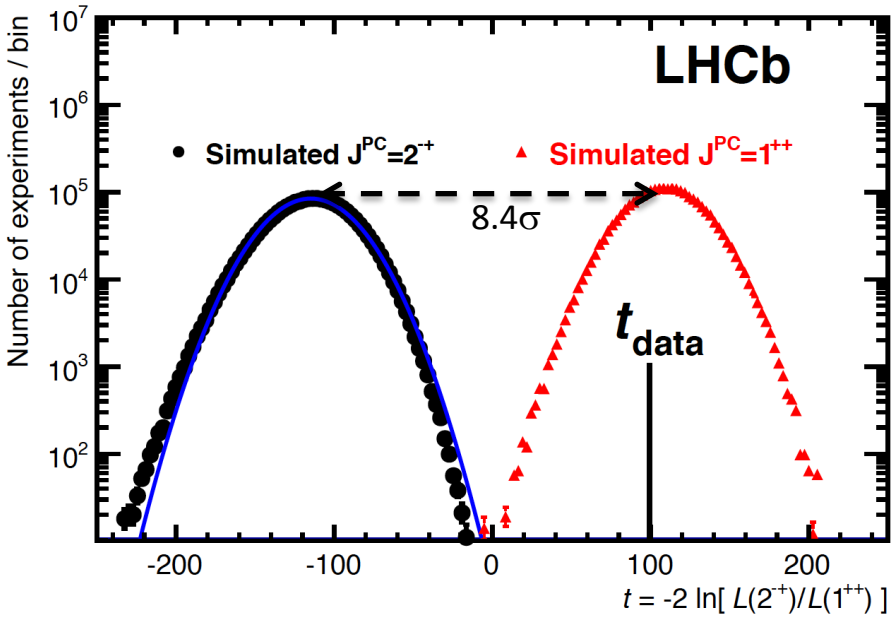
- 5-D angular space: $\Omega = (\cos\theta_X, \cos\theta_{\pi\pi}, \Delta\phi_{X,\pi\pi}, \cos\theta_{J/\psi}, \Delta\phi_{X,J/\psi})$





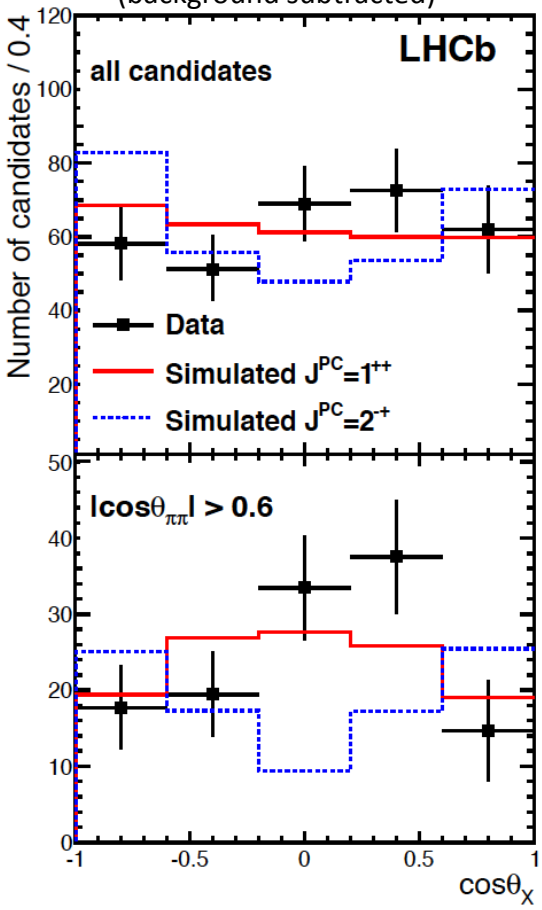
X(3872): results

- Likelihood ratio test to discriminate between the two J^{PC} hypotheses:
  - test statistic $t = -2 \ln[L(2^{-+})/L(1^{++})]$
  - $t > 0$ favors 1^{++}, $t < 0$ favors 2^{-+}
  - we observe t_{data}=99, which favours 1^{++} over 2^{-+} (rejected at >8σ)



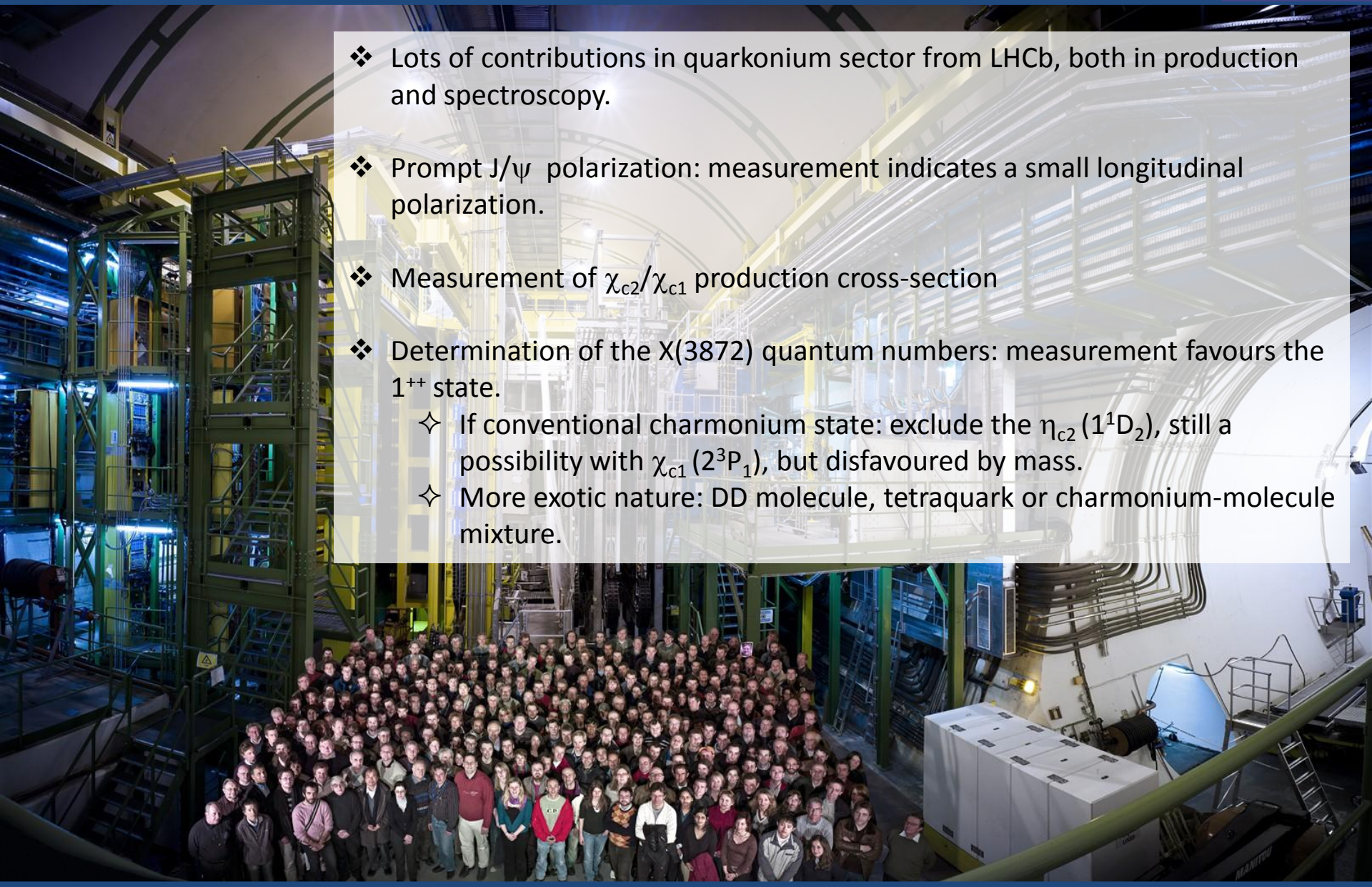
- Angular correlations in 5-D allow for very clear separation between the two J^{PC} hypotheses
- Conventional charmonium fading: only *ccbar* possibility is $\chi_{c1}(2^3P_1)$, but mass is off
- Stay tuned for more results in the exciting field!

1D projection onto $\cos\theta_X$ (background subtracted)



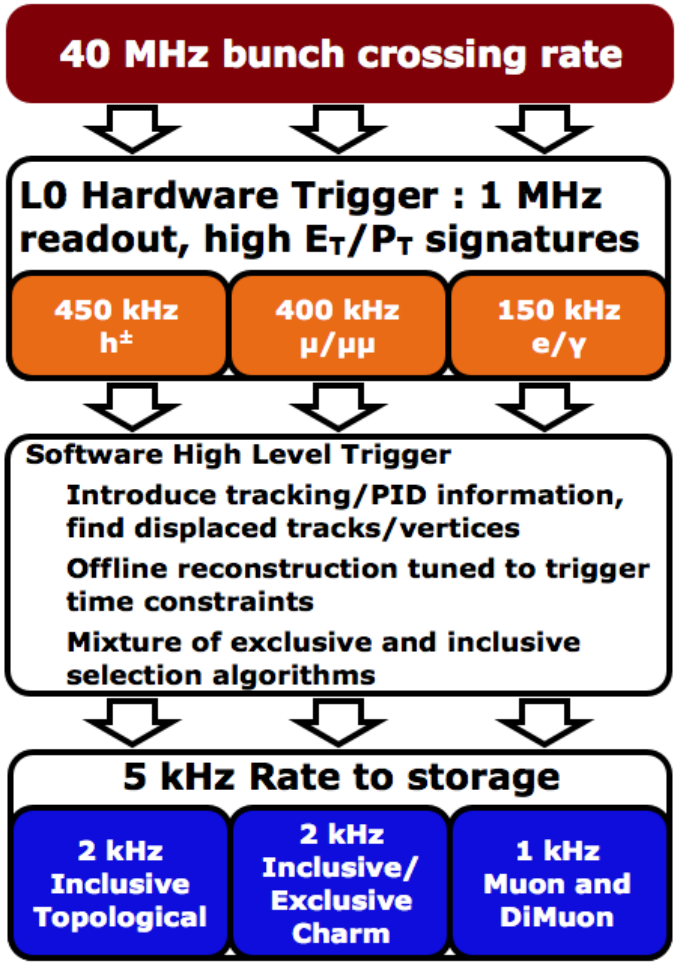
- Marginal differences in 1D distributions between 1^{++} and 2^{-+}
- Discrimination relies on correlations in specific phase-space regions

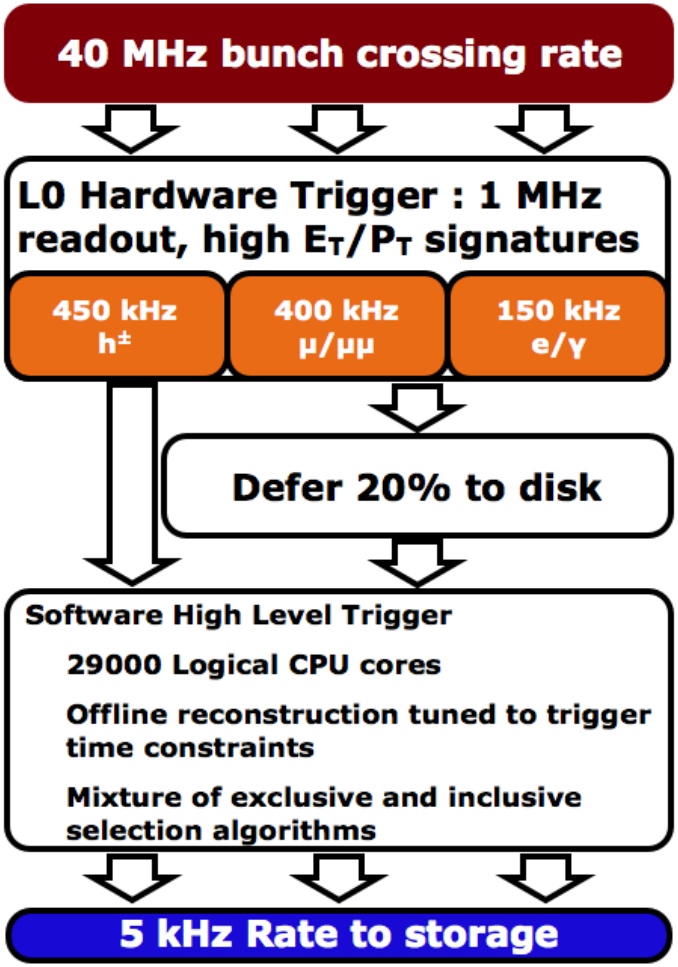
Conclusions



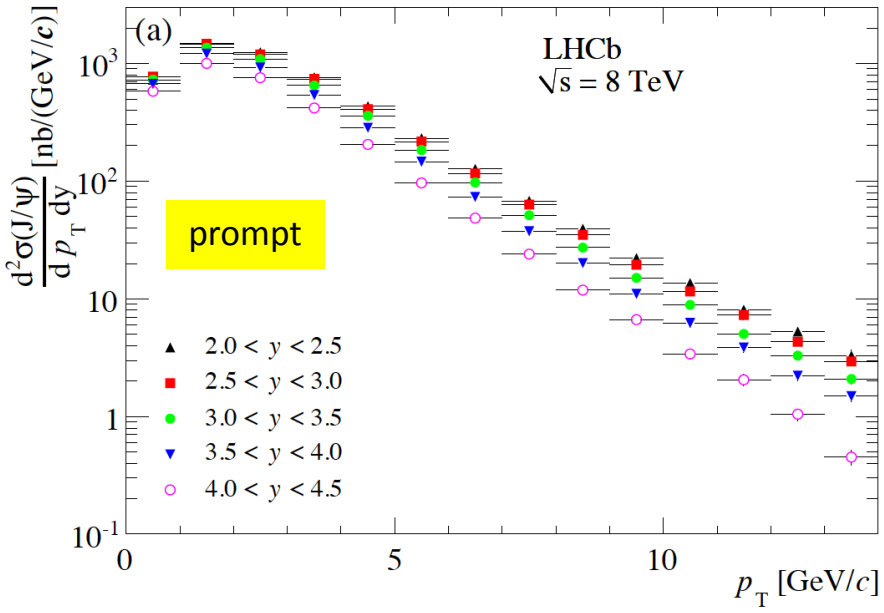
- Lots of contributions in quarkonium sector from LHCb, both in production and spectroscopy.
- Prompt J/ψ polarization: measurement indicates a small longitudinal polarization.
- Measurement of χ_{c2}/χ_{c1} production cross-section
- Determination of the X(3872) quantum numbers: measurement favours the 1^{++} state.
  - If conventional charmonium state: exclude the η_{c2} (1^1D_2), still a possibility with χ_{c1} (2^3P_1), but disfavoured by mass.
  - More exotic nature: DD molecule, tetraquark or charmonium-molecule mixture.

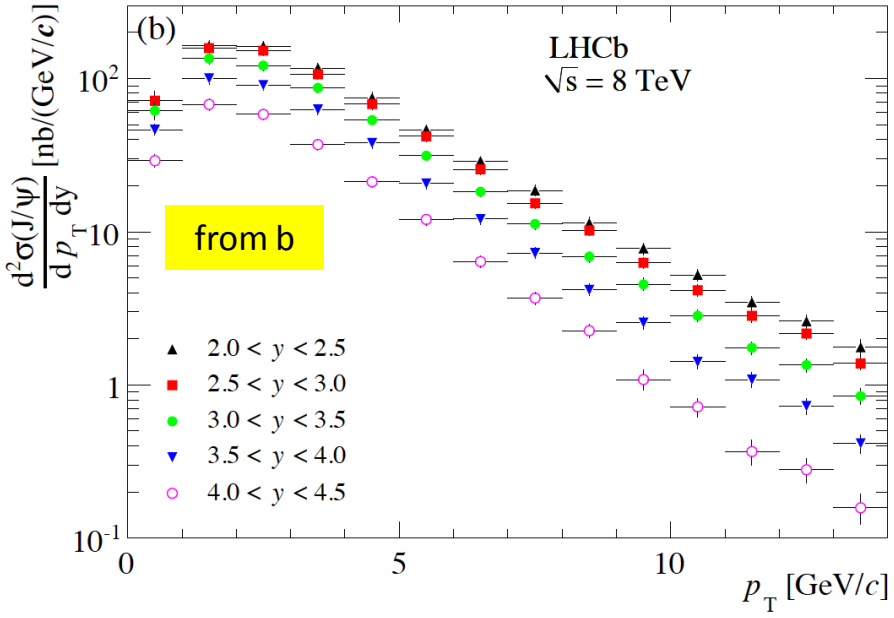
LHCb Trigger





J/ψ double differential cross-section





J/ψ polarisation: results