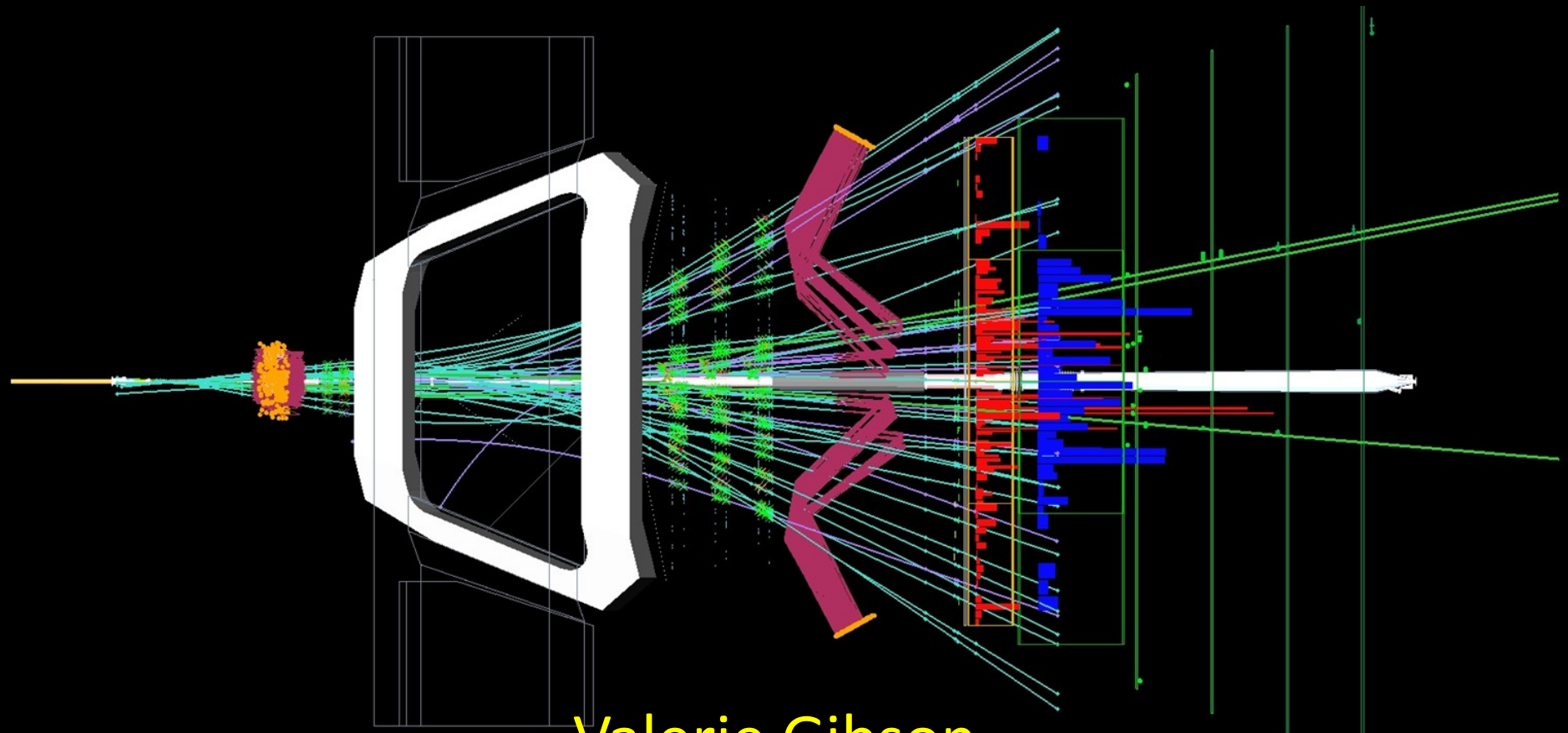
Quarkonia at LHCb



Valerie Gibson

on behalf of the LHCb Collaboration

University of Cambridge

Motivation

Quarkonia production provides a powerful test of perturbative and non-perturbative QCD models.

NRQCD

$$\sigma(pp \to Q + X) = \sum_n \sigma\left(pp \to q\bar{q}[n]\right) \bullet \left\langle \mathcal{O}^{Q}[n] \right\rangle$$

Perturbative — Non-perturbative

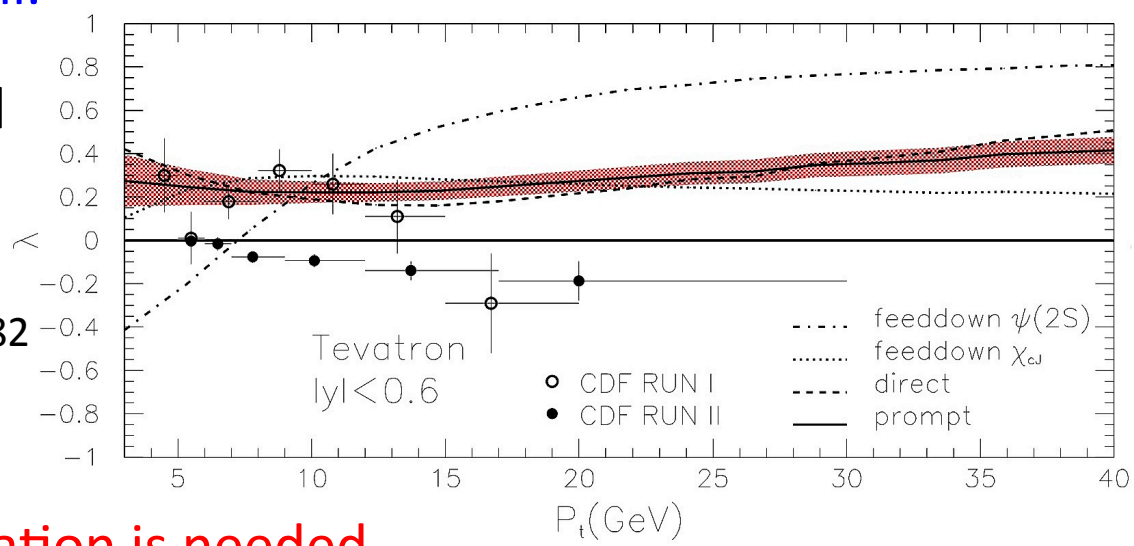
Short distance, partonic + pdf — Long distance matrix elements

A combination of colour octet and colour singlet contributions describe all cross-section and p_T spectra well.

Butenschoen & Kniehl, arXiv:1201.3862

Polarisation predictions fall well short of data, even including contributions from feed-down.

Gong, Wan, Wang & Zhang, arXiv:1205.6682



More input from the LHC on quarkonia production & polarisation is needed

The LHCb Experiment

LHCb is particularly suited to the study of onia.

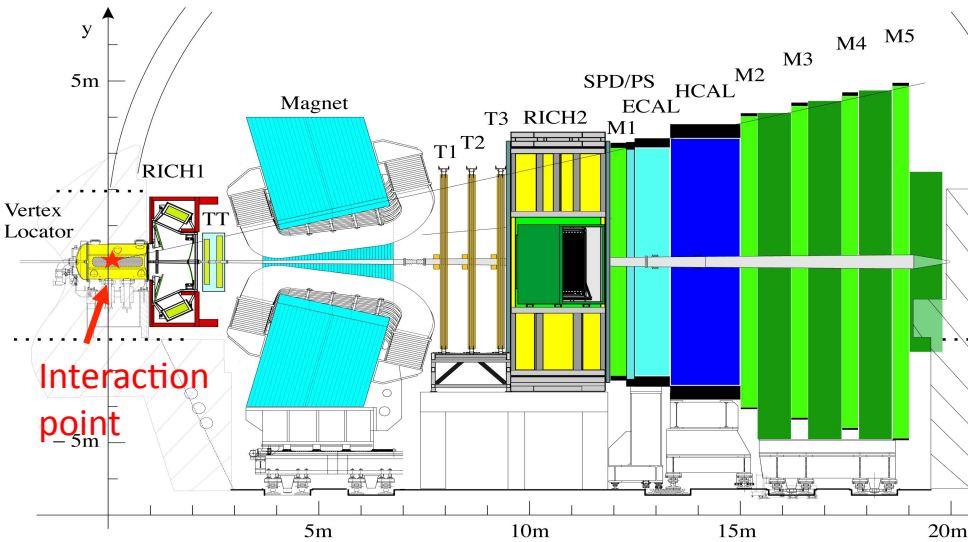
Large production cross-sections

$$\sigma\left(c\bar{c}\right) = 1742 \pm 267\ \mu\text{b}$$

$$\sigma\left(b\bar{b}\right) = 75.3 \pm 5.4 \pm 13\ \mu\text{b}$$

7 TeV
in acceptance

LHCb-CONF-2010-013, LHCb: PLB 694 (2010) 209



Analysis rapidity range : 2 < y < 4.5

Precision tracking and muon system, ECAL and RICH PID

Low p_T trigger (typical thresholds):

1μ : $p_T > 1.8$ GeV/c

2μ: $p_T > 0.56$ GeV/c

> 0.48 GeV/c

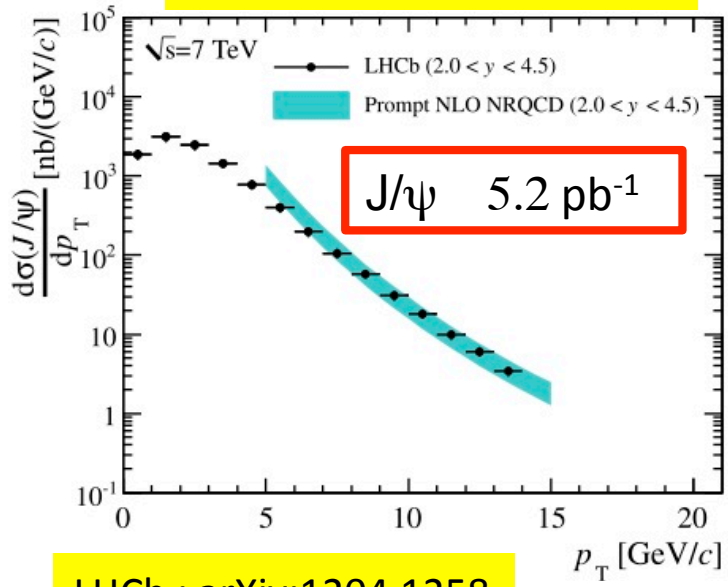
Year	√s (TeV)	Int. Lumi.
2010	7	36 pb^{-1}
2011	2.76	71 nb^{-1}
2011	7	1 fb^{-1}
2012	8	0.6 fb^{-1} (exp. ~1.5 fb^{-1})

Quarkonia at 7 TeV

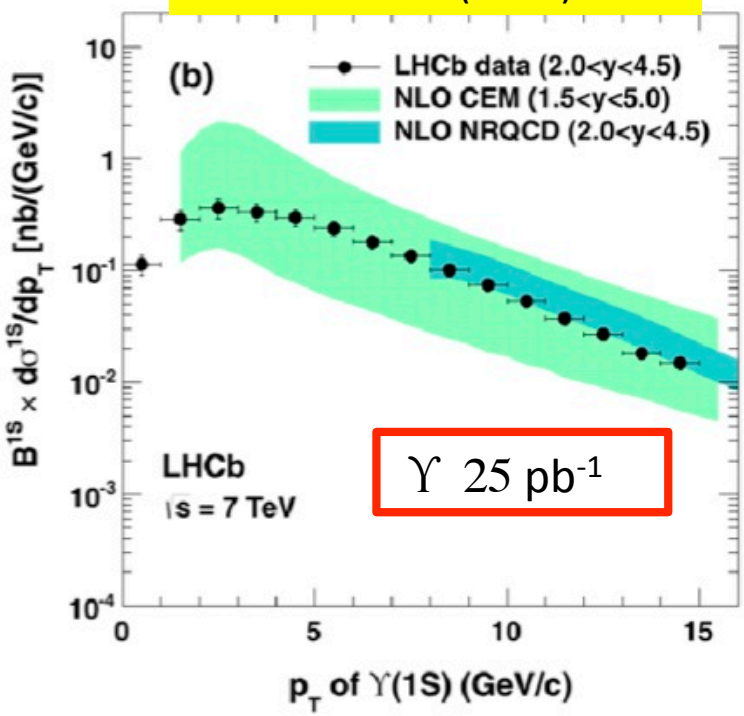
LHCb has published measurements of prompt quarkonia (J/ψ, ψ(2S) and ϒ) production at 7 TeV.

All consistent with NRQCD predictions

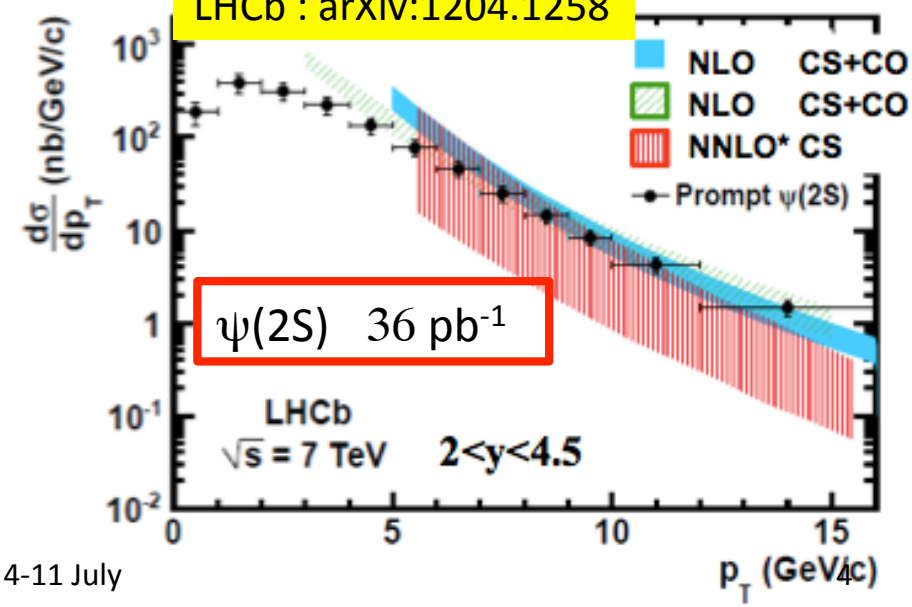
LHCb : EPJC 71 (2011) 1645



LHCb : EPJC 72 (2012) 2025



LHCb : arXiv:1204.1258

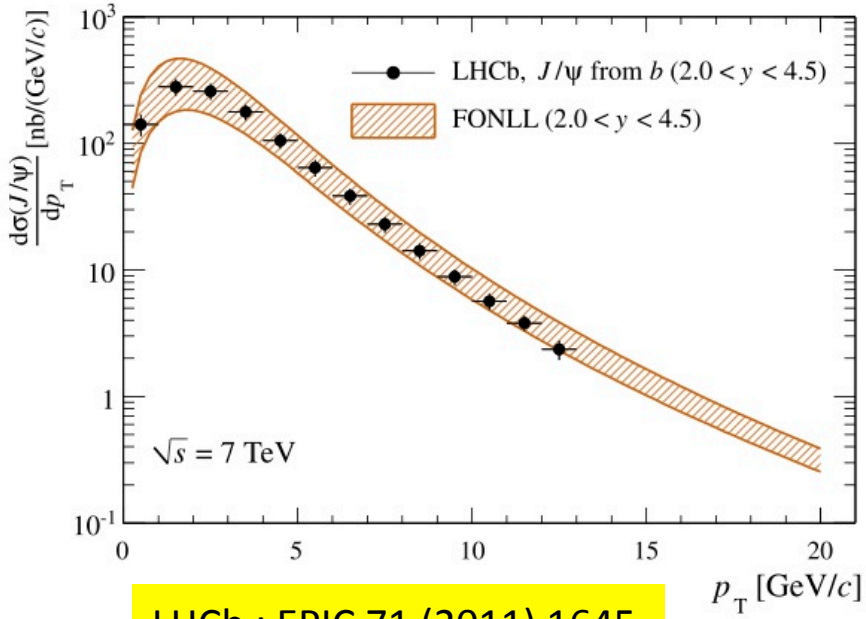


Quarkonia at 7 TeV

Non-prompt (from b-hadrons) J/ψ and ψ(2S) measurements are also consistent with FONLL predictions

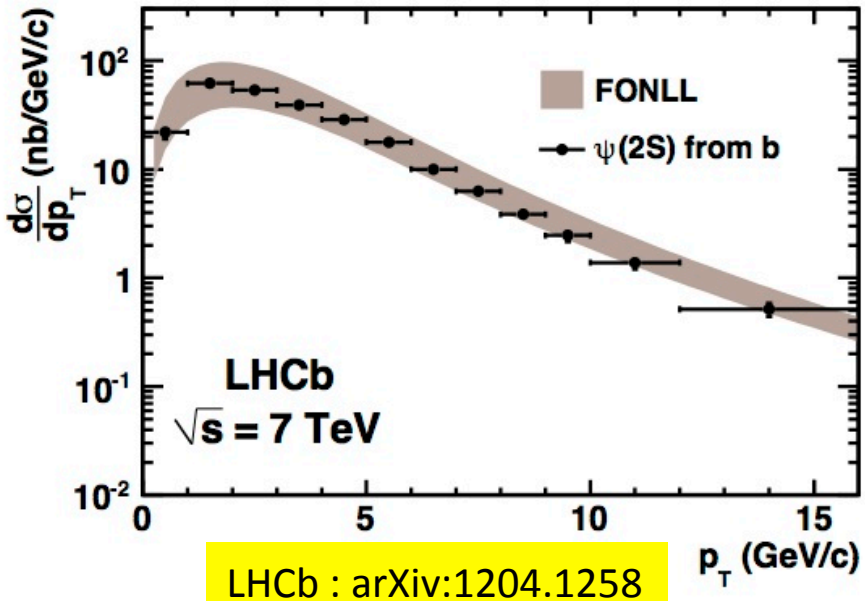
M.Cacciari et al; JHEP 05 (1998) 007
M.Cacciari et al; CERN-PH-TH/2011-227.

J/ψ 5.2 pb^{-1}



LHCb : EPJC 71 (2011) 1645

ψ(2S) 36 pb^{-1}



LHCb : arXiv:1204.1258

Quarkonia at 8 TeV

LHCb is performing extremely well at 8 TeV

Mass resolutions :

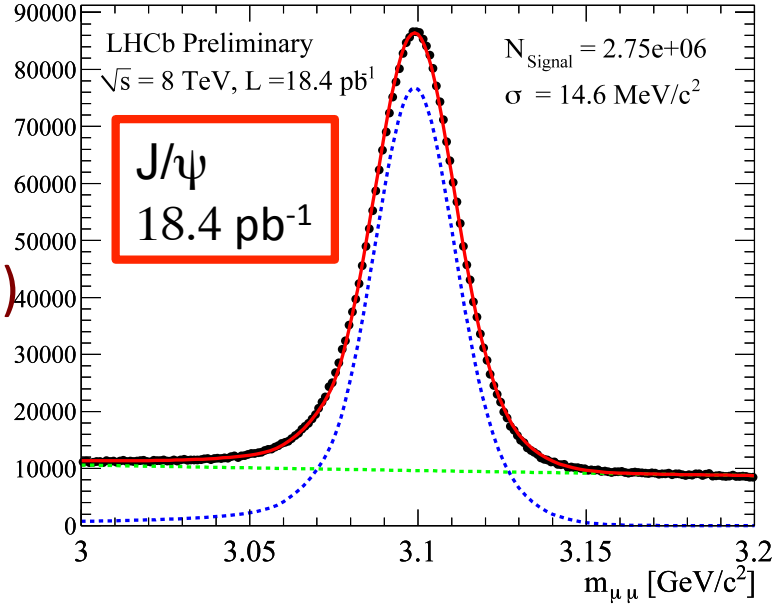
LHCb-CONF-2012-025

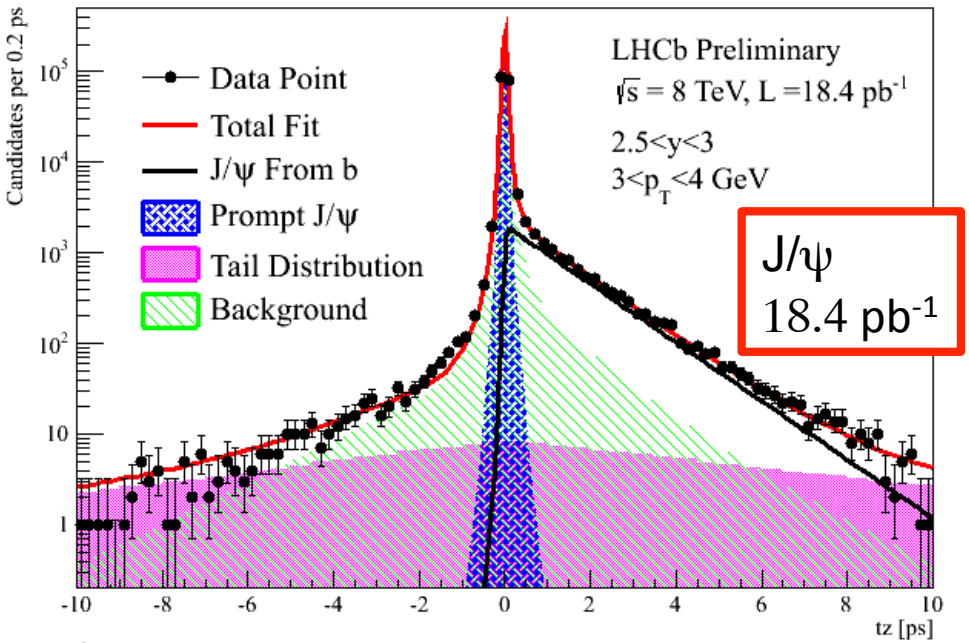
J/ψ 14.5 MeV/c^2

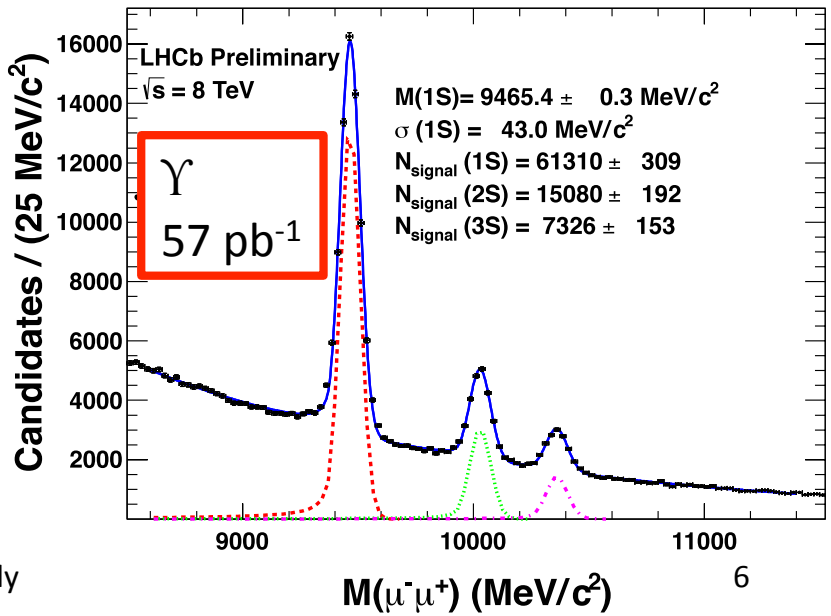
ϒ 43 MeV/c^2 (was 47 MeV/c^2 in 2011)

Proper time resolution : 61 fs

Cross-sections expected to increase by ~15%





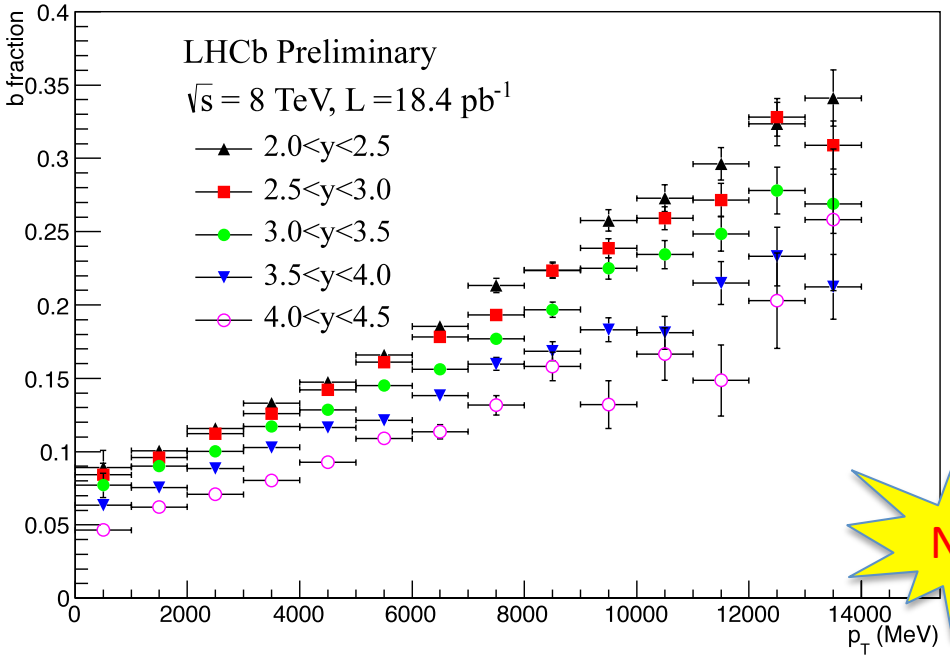


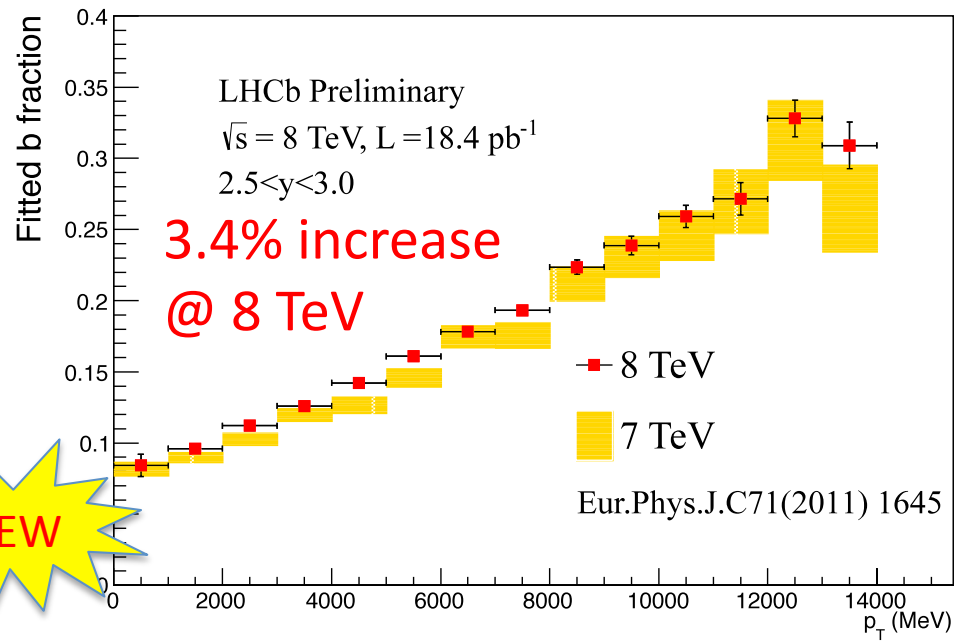
Quarkonia at 8 TeV

Fraction of J/ψ from b extracted from fit to mass and pseudo proper time

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

LHCb-CONF-2012-025



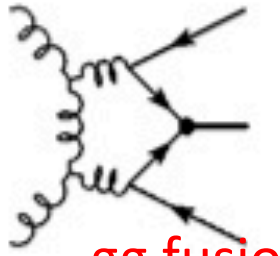


NEW

Expect more results at 8 (and 2.76) TeV very soon !

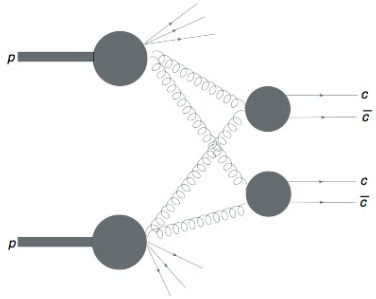
Multiple Quarkonia

Production of multiple heavy flavour states tests



gg fusion

- gluon fusion
- Double Parton Scattering (DPS)
- Intrinsic charm content of the proton



DPS

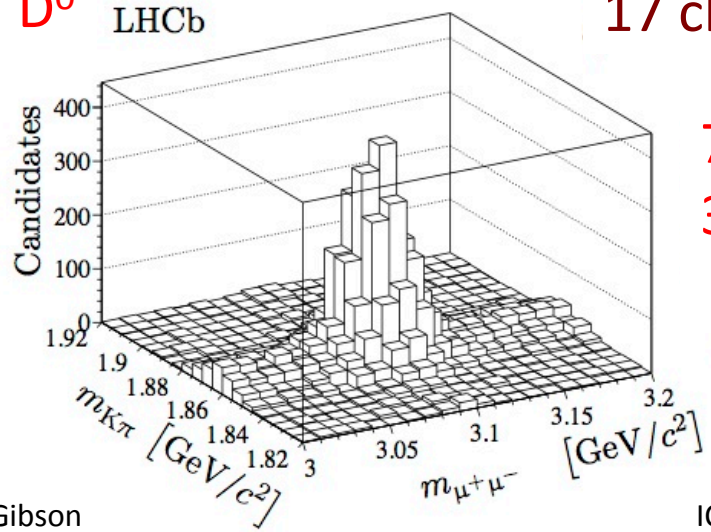
LHCb published first observation of double J/ψ production at hadron colliders

LHCb : PLB 707 (2012) 52

J/ψ + open charm (D^0, D^+, D_s^+, Λ_c^+) and double open charm production

LHCb : arXiv:1205.0975

J/ψ D^0

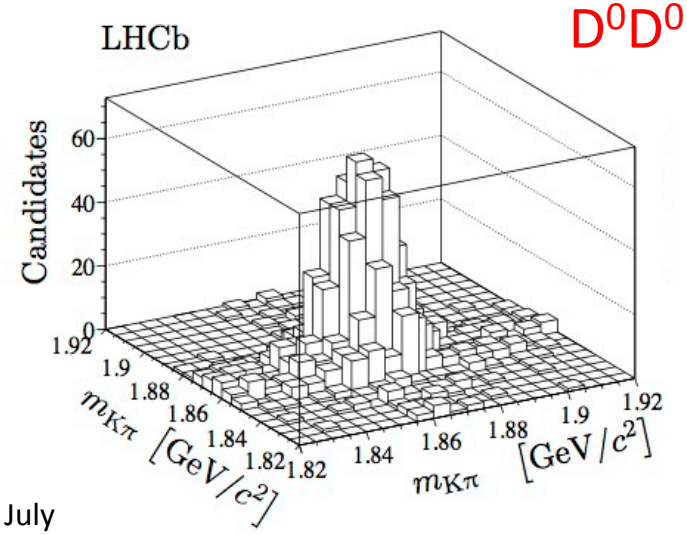


17 channels

7 TeV

355 pb^{-1}

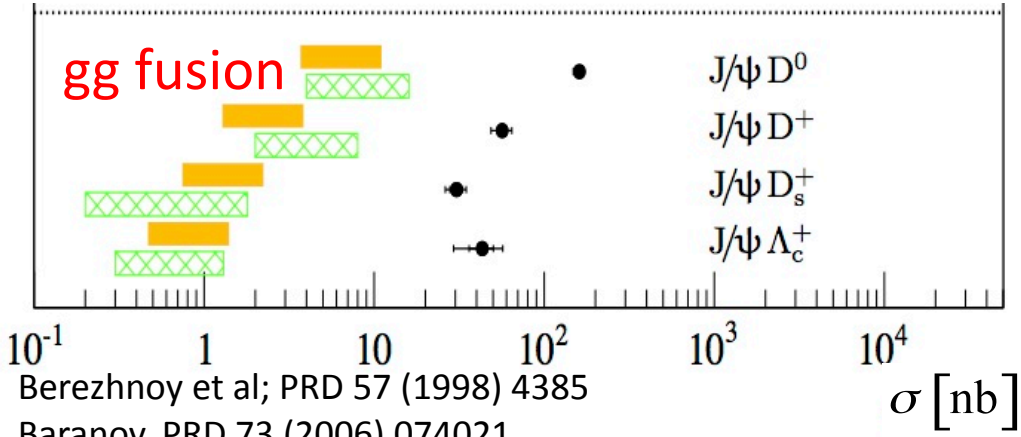
D^0D^0

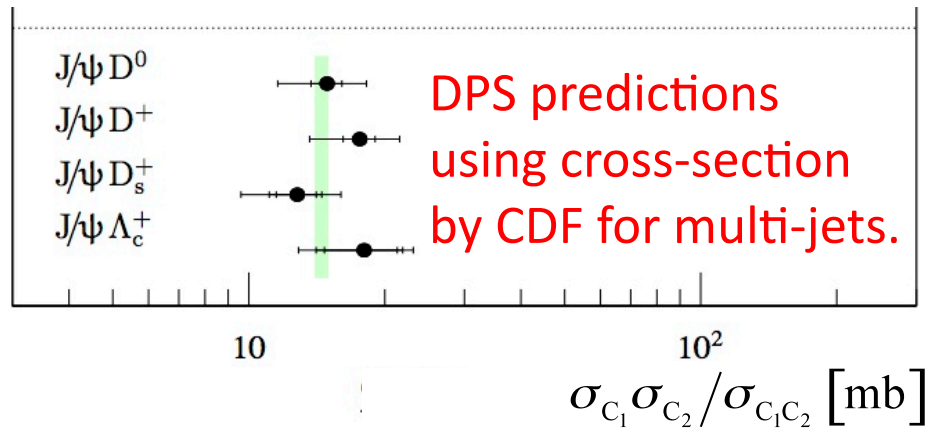


Multiple Quarkonia

Measured cross-sections suggest DPS needed

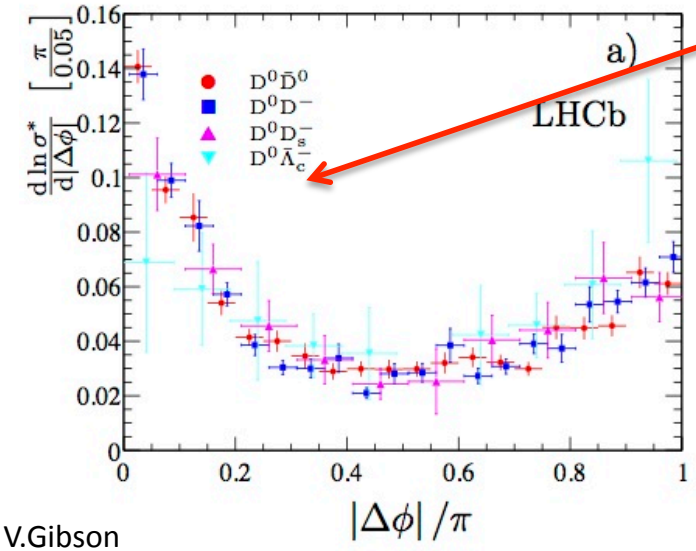
LHCb : arXiv:1205.0975



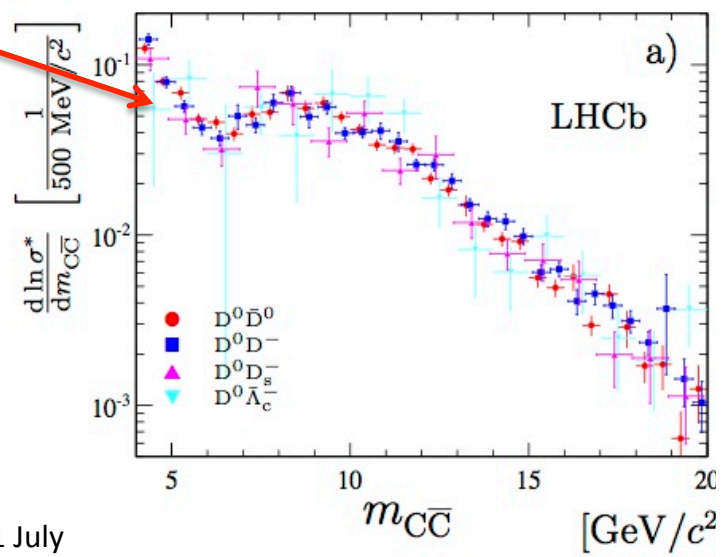


Berezhnoy et al; PRD 57 (1998) 4385
Baranov, PRD 73 (2006) 074021
Lansberg, EPJC 61 (2009) 693

Kinematic distributions suggest sizeable gluon-splitting contributions



$g \to c\bar{c}$



Heavy Onia

Measurements of heavy quarkonia provide important tests of the colour singlet and colour octet production mechanisms

- Feed-down fractions ($\chi_c \rightarrow J/\psi$; $\chi_b \rightarrow \Upsilon$)
- Ratios of $\chi_{c,bJ}$ (J=0,1,2) spin states

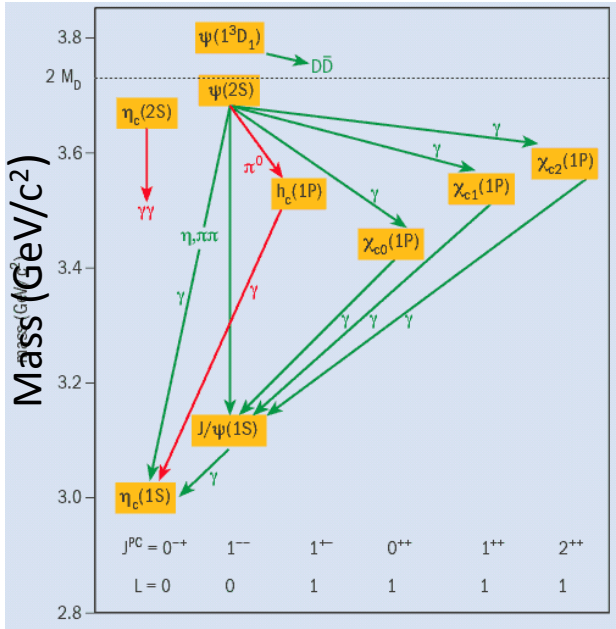
and are crucial for the measurement of polarization.

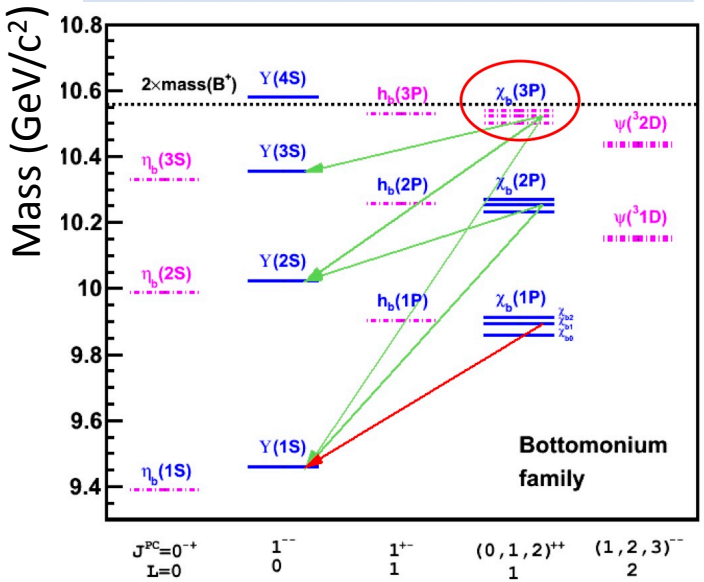
Studies of heavy bottomonia states are relatively new.

LHCb measurements in unique region

$2 < y < 4.5$; $p_T(J/\psi) > 2$ GeV/c

$p_T(\Upsilon) > 6$ GeV/c





Heavy Onia : χ_c

LHCb reconstructs χ_c via the radiative decay

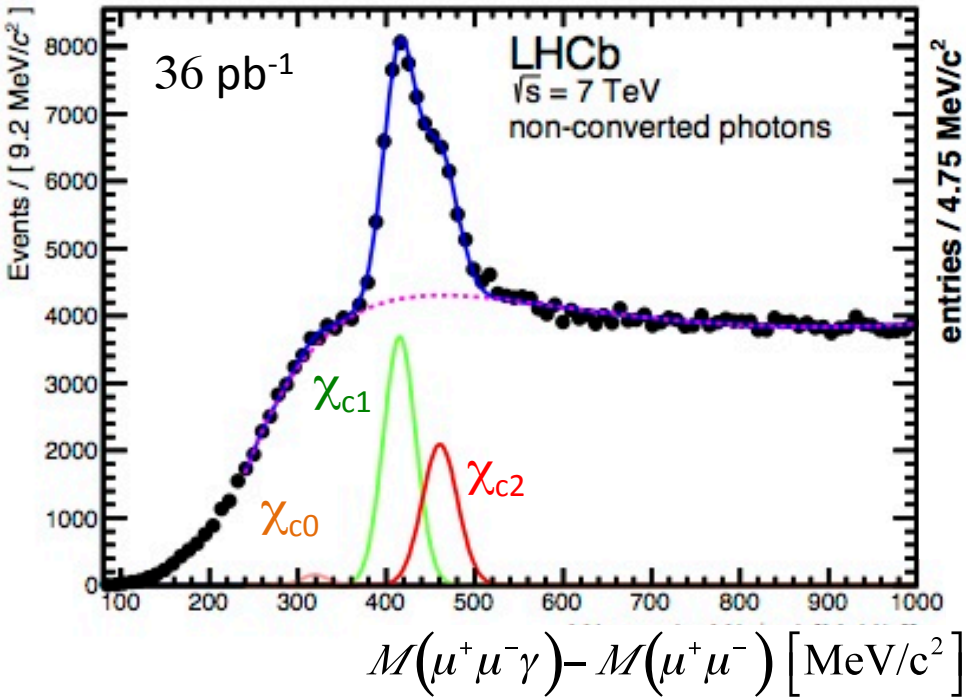
$$\chi_{cJ}(nP) \rightarrow J/\psi\,\gamma$$

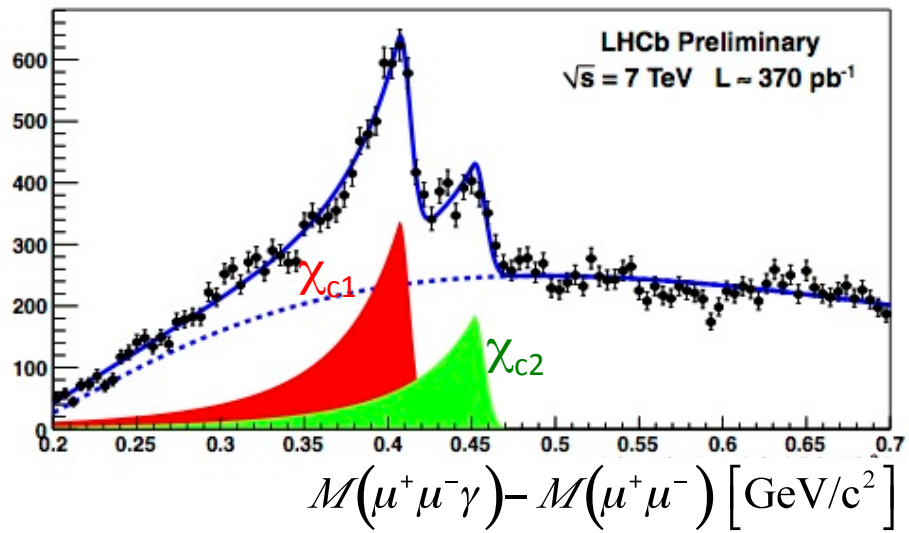
LHCb : arXiv:1202.1080
LHCb : arXiv:1204.1462
LHCb-CONF-2011-062

Photons identified in the ECAL

$p_T^\gamma > 650$ MeV/c; $p^\gamma > 5$ GeV/c

Photons converted before the magnet





Heavy Onia : χ_c

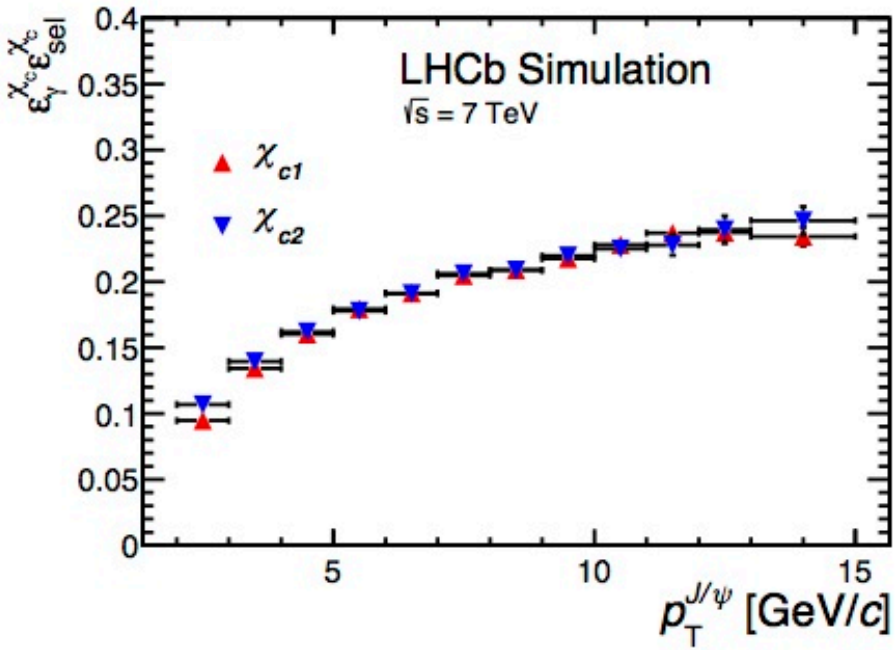
LHCb : arXiv:1204.1462

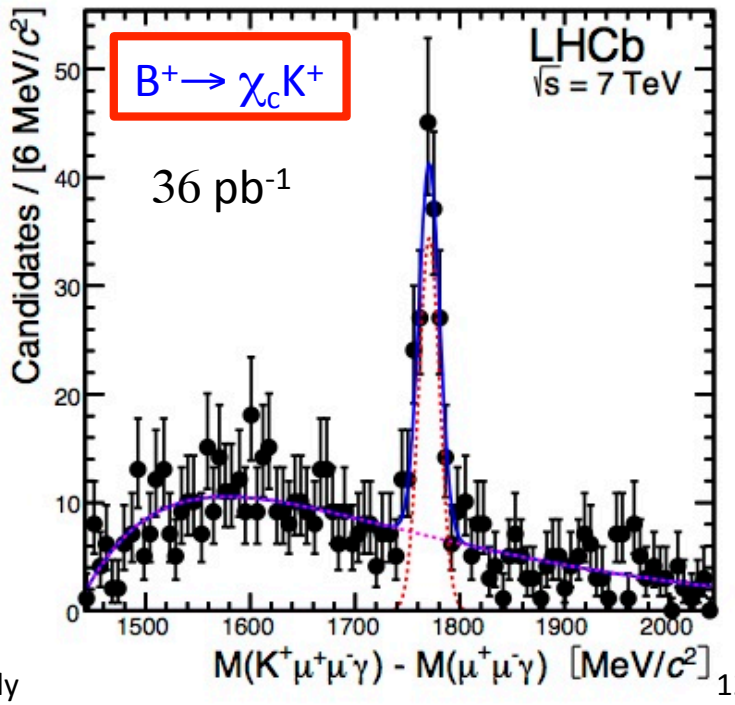
Fraction of J/ψ from χ_c states

$$\frac{\sigma(\chi_c \to J/\psi\gamma)}{\sigma(J/\psi)} \approx \frac{\sigma(\chi_c \to J/\psi\gamma)}{\sigma^{\rm dir}(J/\psi) + \sigma(\psi(2S) \to J/\psi X) + \sigma(\chi_c \to J/\psi\gamma)}$$

depends on signal yields (χ_c and J/ψ) and efficiencies (J/ψ, γ and χ_c).

Photon efficiency checked using $B^+ \to \chi_c K^+$ and $B^+ \to J/\psi K^+$ decays

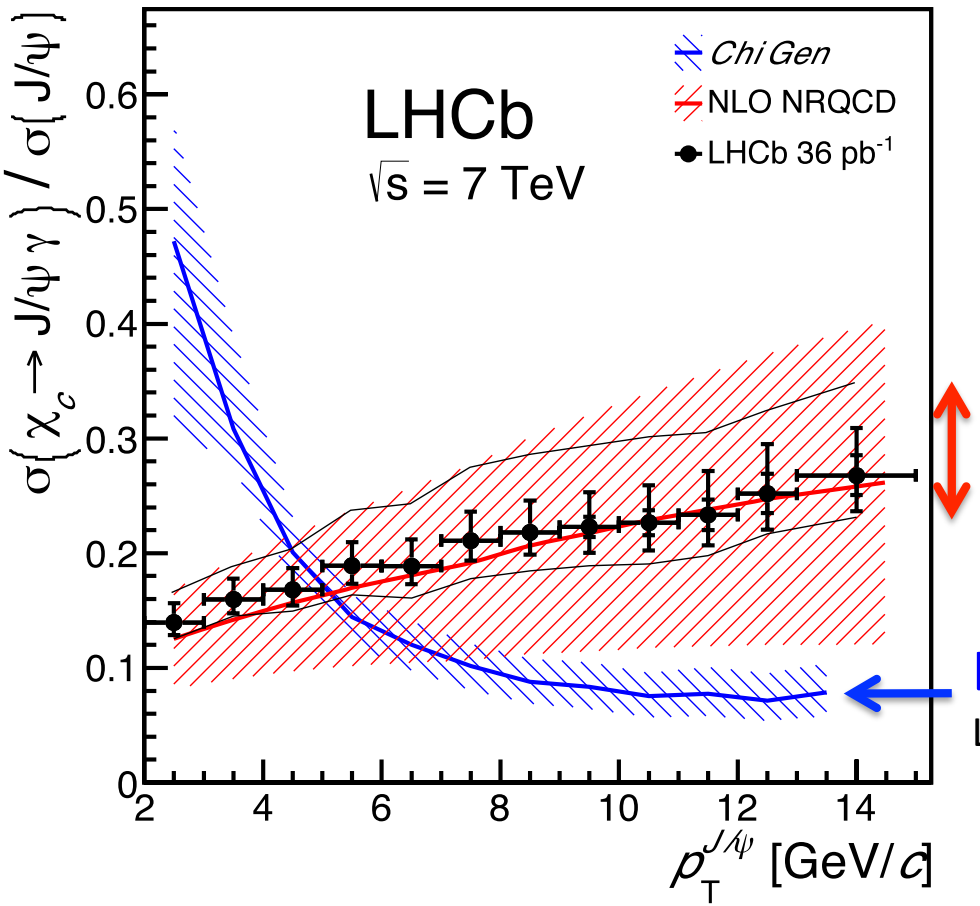




Heavy Onia : χ_c

LHCb : arXiv:1204.1462

Fraction of J/ψ from χ_c states:



Maximum effect due to polarization of χ_c and J/ψ

LO CS model

L. Harland-Lang & W.J.Stirling

Results in remarkable agreement with NLO NRQCD prediction

Ma, Wang & Chao, PRD 83 (2011) 111503

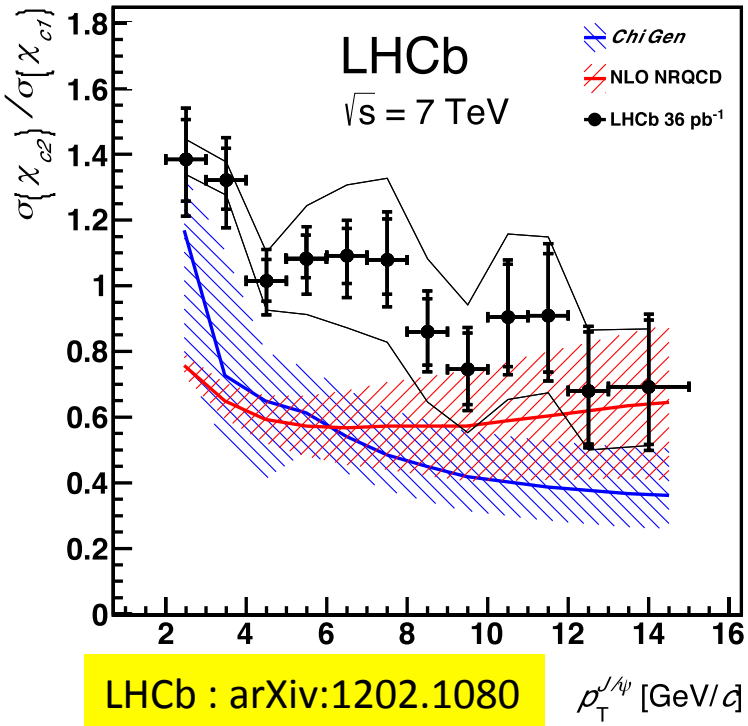
Heavy Onia : χ_c

Ratio of χ_c spin states

$$\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})} = \frac{N_{\chi_{c2}}}{N_{\chi_{c1}}} \cdot \frac{\epsilon^{\chi_{c1}}}{\epsilon^{\chi_{c2}}} \cdot \frac{\mathcal{B}(\chi_{c1} \to J/\psi\,\gamma)}{\mathcal{B}(\chi_{c2} \to J/\psi\,\gamma)},$$

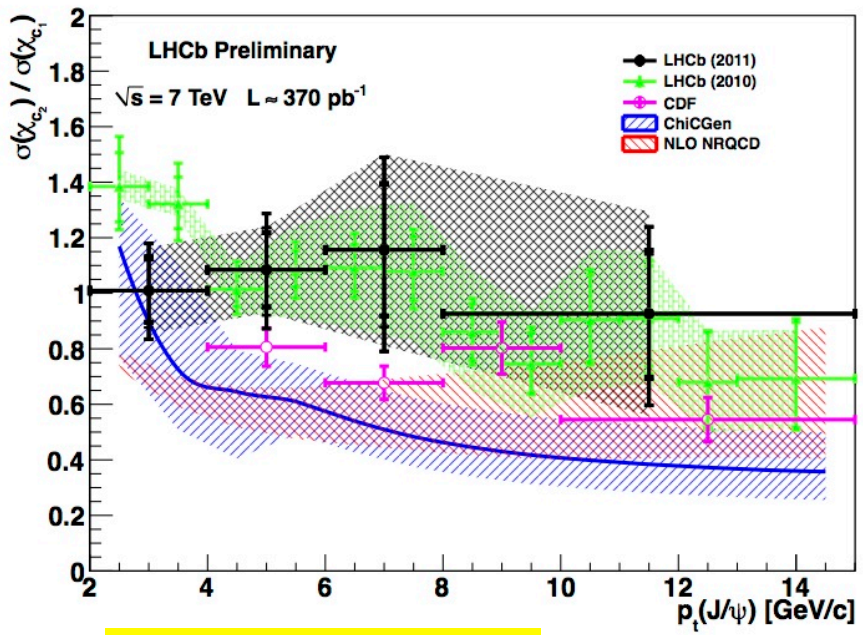
depends on χ_c signal yields and ratios of efficiencies.

ECAL photons



LHCb : arXiv:1202.1080

Conversion photons



LHCb-CONF-2011-062

R[illegible]dels at low J/ψ p_T

Heavy Onia : χ_b

LHCb-PAPER-2012-015

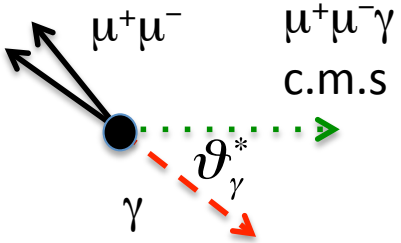
LHCb reconstructs χ_b via the radiative decay

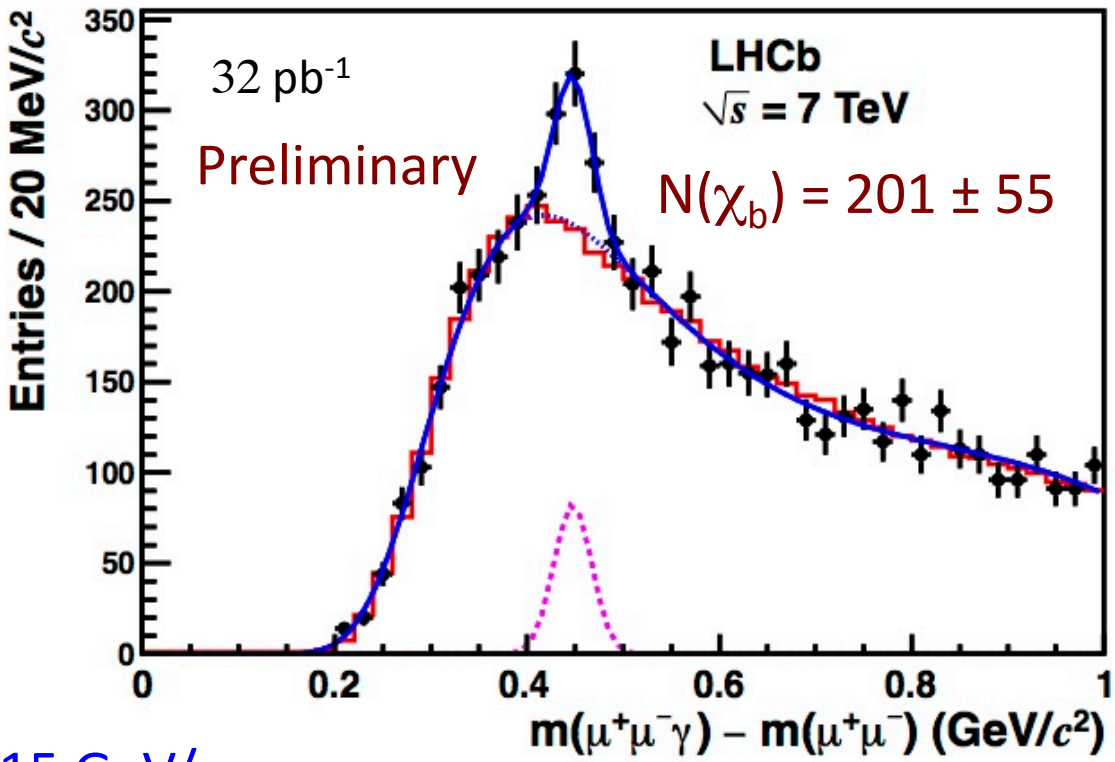
$$\chi_{bJ}(nP) \rightarrow \Upsilon(1S)\gamma$$

Photons identified in the ECAL :

$p_T^\gamma > 600\ \mathrm{MeV/c^2}$

$\cos\vartheta_\gamma^* > 0$





Select $\Upsilon(1S)$ and $6 < p_T(\mu^+\mu^-\gamma) < 15$ GeV/c

χ_b (J=0,1,2) mass differences comparable with experimental resolution.

Heavy Onia : χ_b

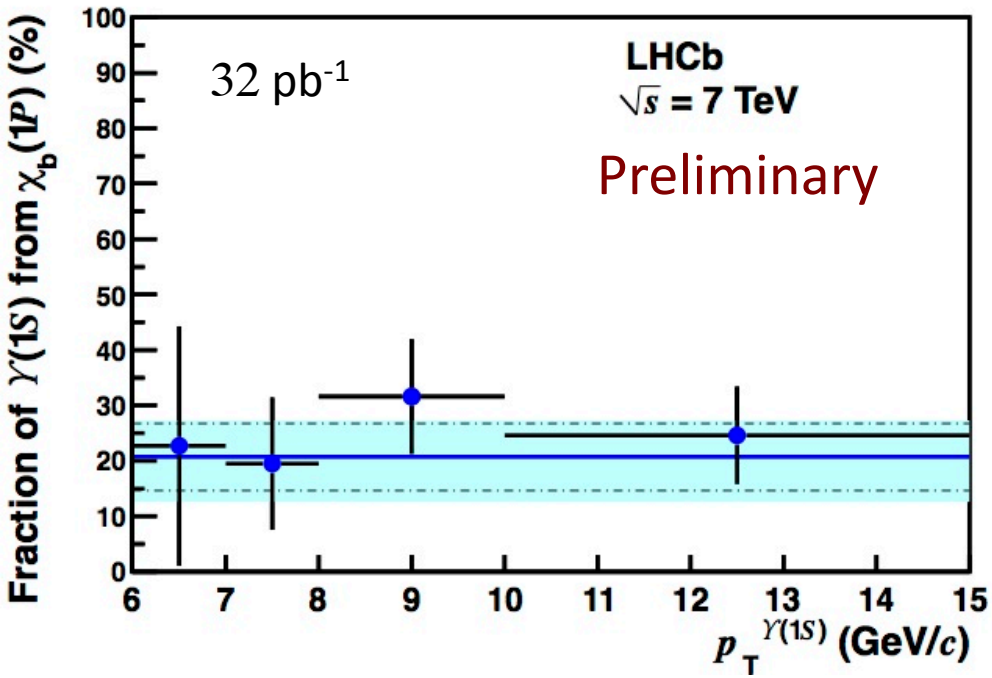
LHCb-PAPER-2012-015

Fraction of Υ(1S) from χ_b(1P) decays $f_{\chi_b \to \Upsilon} = \frac{N_{\chi_b}}{N_\Upsilon} \times \frac{1}{\varepsilon_{\chi_b}}$

depends on signal yields and efficiency to reconstruct and select χ_b after Υ(1S) candidate is selected $\varepsilon_{\chi_b} = (9.4 \pm 0.08)\%$

$$f_{\chi_b \to \Upsilon} = \left(20.7 \pm 5.7\,(stat.) \pm 2.1\,(syst.)\ {}^{+2.7}_{-5.4}\,(pol.)\right)\%$$

NEW



CDF pp collisions
$\sqrt{s}$=1.8 TeV, p_T>8 GeV/c

$f_{\chi_b \to \Upsilon} = (27.1 \pm 6.9 \pm 4.4)\%$

CDF: PRL 84 (2000) 2094

Total uncertainty incl. polarization

Heavy Onia : χ_b

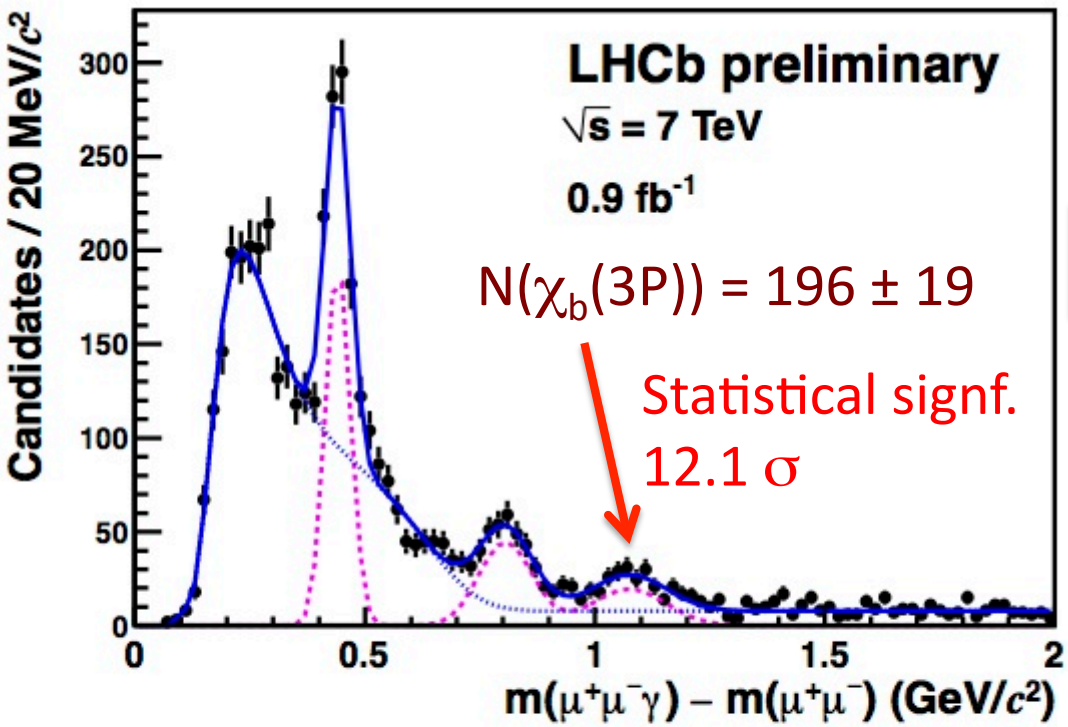
LHCb-CONF-2012-020

Observation of $\chi_b(3P)$

$$\chi_{bJ}(nP) \to \Upsilon(1S)\gamma$$

NEW

Select $\Upsilon(1S)$ and $p_T(\mu^+\mu^-\gamma) > 20$ GeV/c



Preliminary

$$m(\chi_b[1P]) = 9.901 \pm 0.002 \quad \text{GeV/c}^2$$

$$m(\chi_b[2P]) = 10.266 \pm 0.006 \text{ GeV/c}^2$$

$$\boxed{m(\chi_b[3P]) = 10.535 \pm 0.010 \text{ GeV/c}^2}$$

Consistent with ATLAS/D0

ATLAS : arXiv:1112.5154
D0 : arXiv:1203.6034

More detailed studies to come

Summary

LHCb is producing many important quarkonia results:

- Cross-section measurements, signal for Double Parton Scattering and heavy quarkonia

Short –medium term expect new measurements:

- Cross-sections (@ 2.76, 8, 14 TeV), polarisations, double onia ($J/\psi\ \psi(2S)$, $J/\psi\Upsilon$, $\Upsilon\Upsilon$) and χ_b

An upgraded LHCb detector (from 2018) opens up new & exciting possibilities:

- Precision studies of Double Parton Scattering, search for Triple Parton scattering
- Production studies with hadronic decays of quarkonia ($p\bar{p},\ \phi\phi$)

LHCb has a world class quarkonia program !

Questions ?

Quarkonia at 7 TeV

Theory references for quarkonia production

J/ψ and ϒ

Ma, Wang and Chao; PRL 106 (2011) 042002

ψ(2S)

Ma, Wang and Chao; arXiv:hep-ph/1012.1030

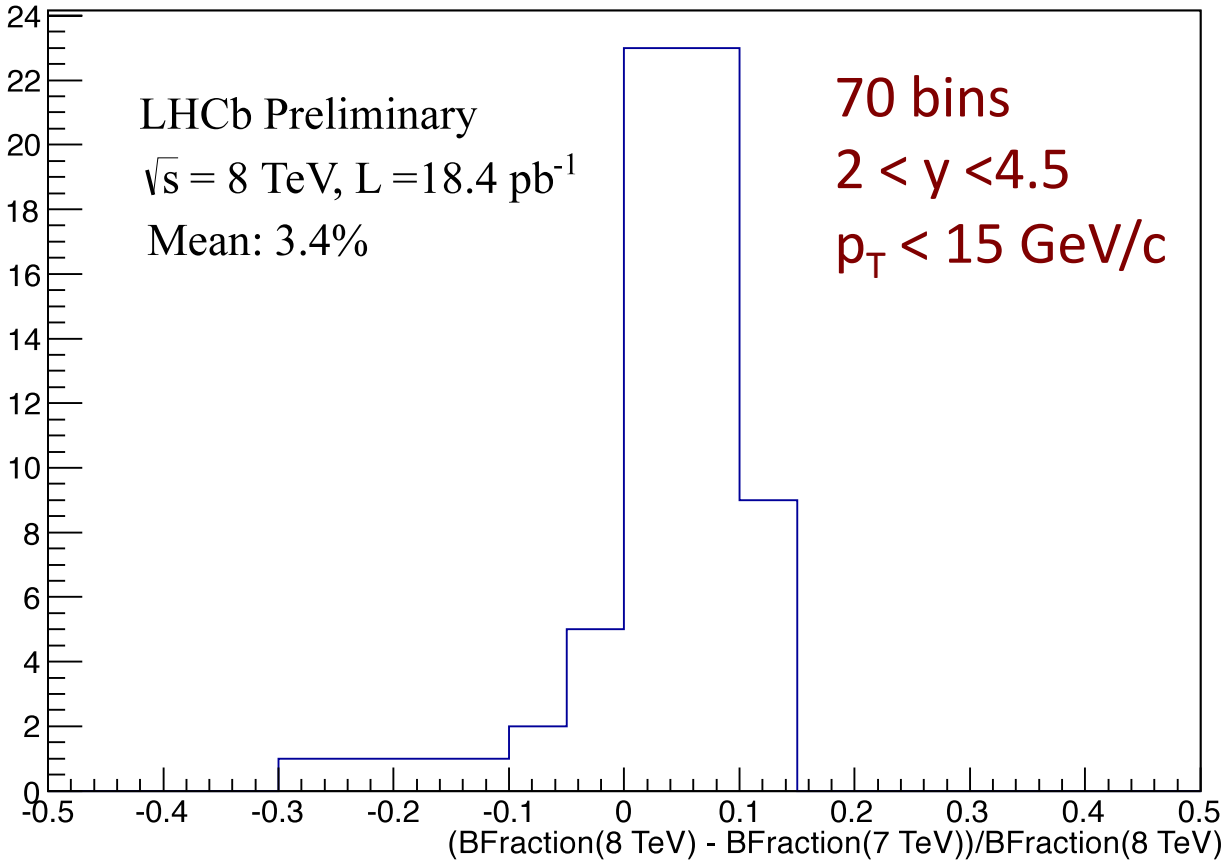
Kniehl and Butenschoen; PRL 106 (2011) 022003 and private comm.

Artoisenet et al; PRL 101 (2008) 152001

Lansberg; EPJC 61 (2009) 693

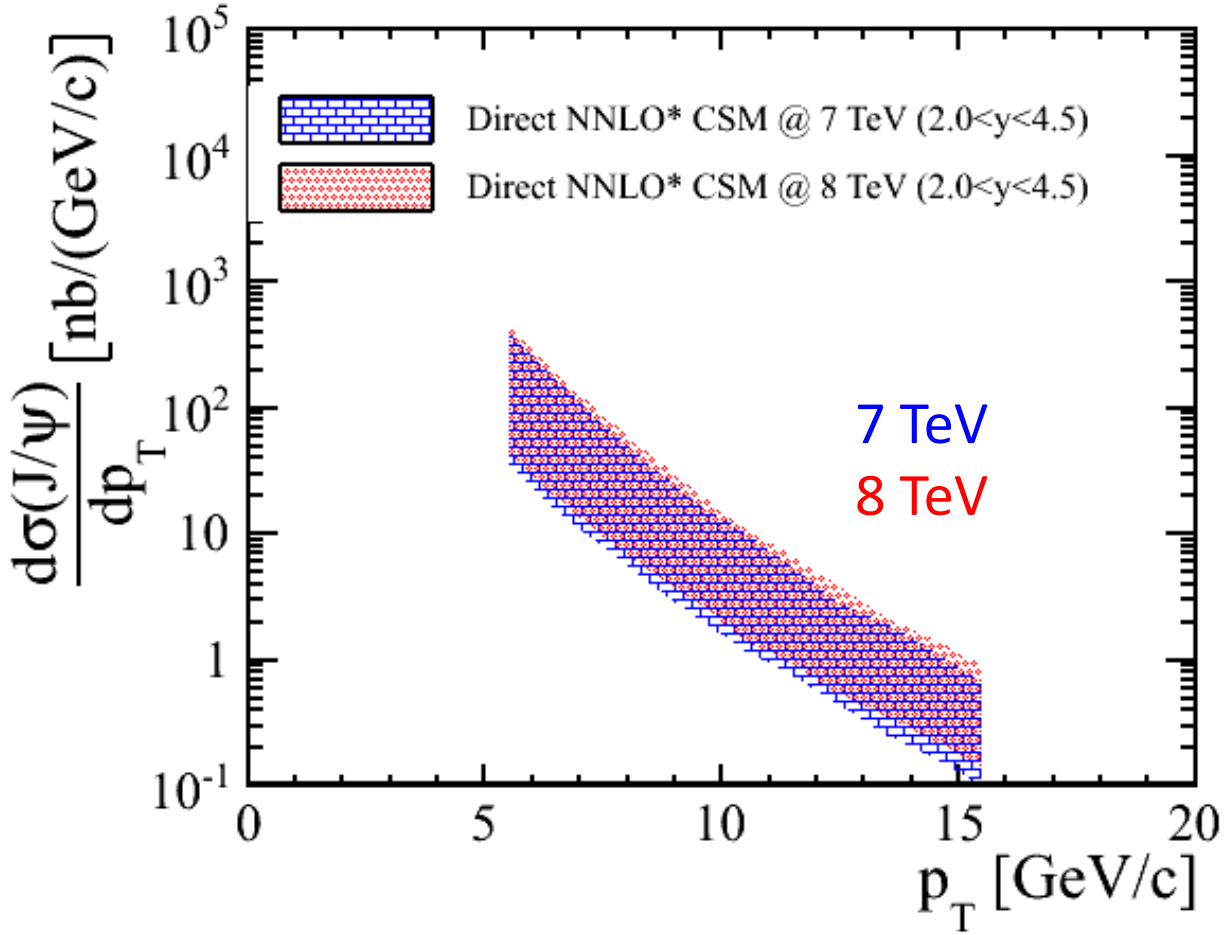
Quarkonia at 8 TeV

B fractions



Quarkonia at 8 TeV

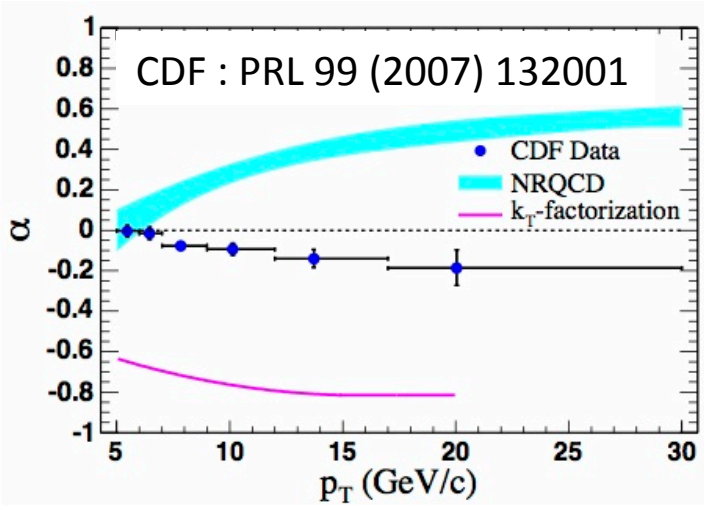
Comparison of expected J/ψ cross-sections in LHCb at 7 and 8 TeV



J/ψ Polarization

Measurement of J/ψ polarization needed to

- Understand failure of NRQCD predictions
- Largest error on cross-section & feed-down

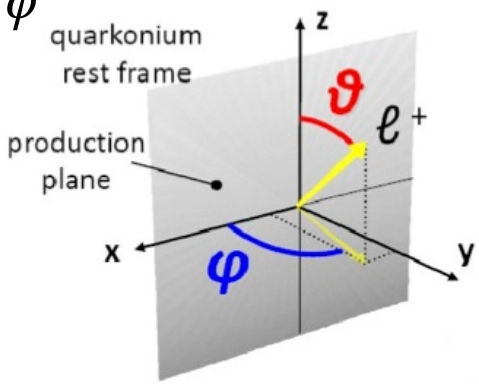


Polarization described by 3 parameters

$$\lambda_\vartheta,\ \lambda_\phi \text{ and } \lambda_{\vartheta\phi}$$

Extract from a fit to the angular distribution of the positive lepton

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

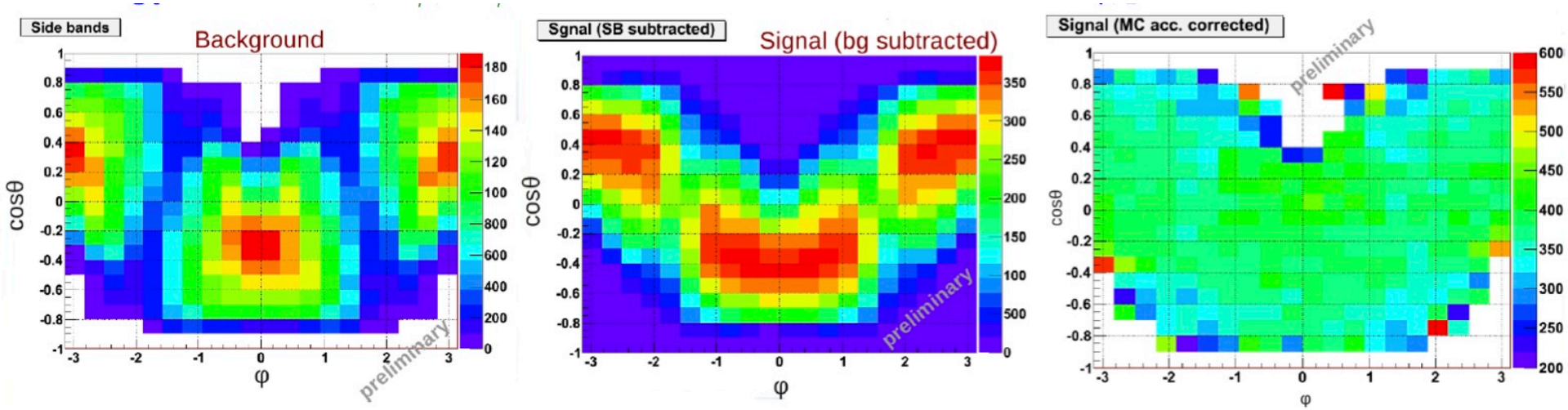


θ = polar angle between μ^+ in J/ψ rest frame & J/ψ flight direction
ϕ = azimuthal angle between J/ψ production plane and μ^+ plane

J/ψ Polarization

LHCb strategy:

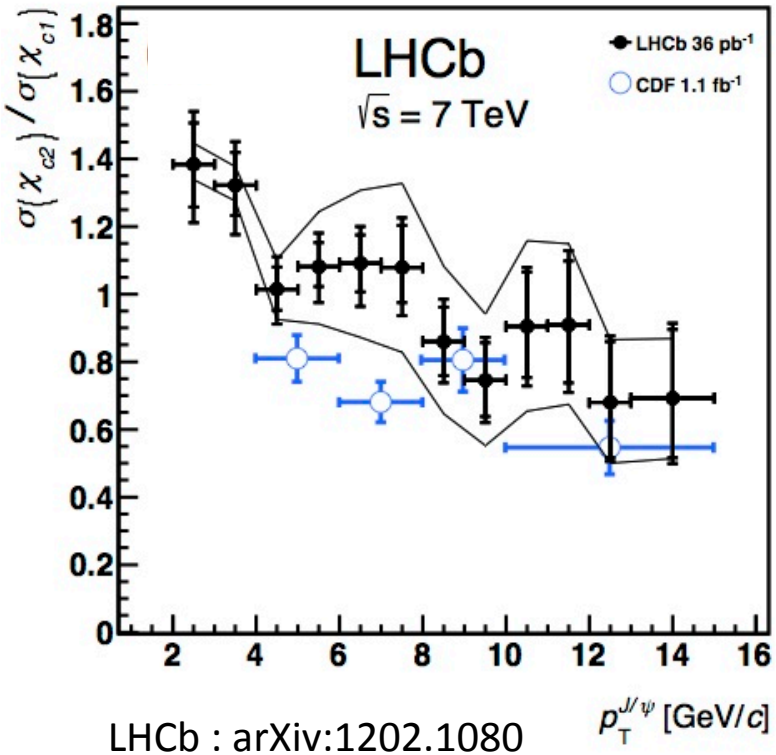
- Measure polarization by extracting λ_ϑ, λ_ϕ and $\lambda_{\vartheta\phi}$ using an unbinned maximum likelihood fit to the μ^+ angular distribution
- Results will be given in bins of J/ψ p_T and y (2 < p_T < 15 GeV/c)



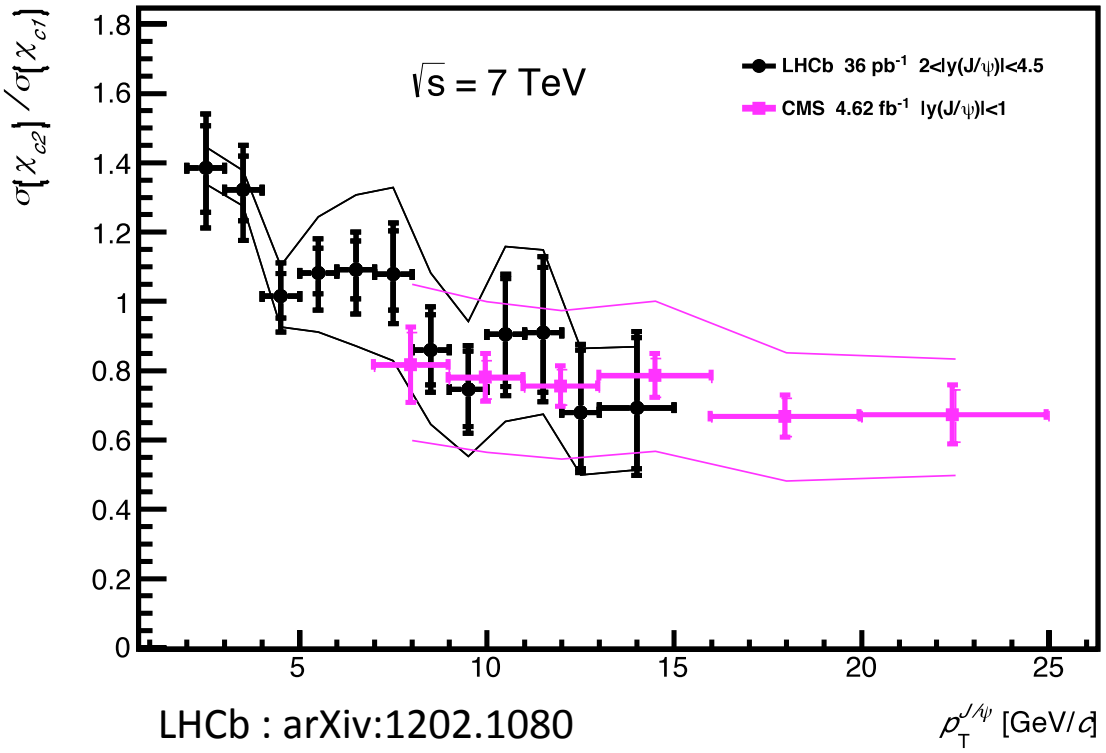
Polarization of prompt and non-prompt J/ψ available very soon.

Heavy Onia : χ_c

Ratio of χ_c spin states $\sigma(\chi_{c2}) / \sigma(\chi_{c1})$



LHCb : arXiv:1202.1080
CDF : PRL 98 (2007) 232001



LHCb : arXiv:1202.1080
CMS PAS BPH-11-010

Heavy Onia : χ_b

LHCb-PAPER-2012-015

Fraction of $\Upsilon(1S)$ from $\chi_b(1P)$ decays

Versus p_T

$p_T^{\Upsilon(1S)}$ (GeV/c)	$6-7$	$7-8$	$8-10$	$10-15$	$6-15$
$N_{\rm rec}(\chi_b)$	41.3 ± 39.4	35.2 ± 21.5	91.5 ± 30.0	82.7 ± 29.4	201.1 ± 55.2
$\epsilon_{\rm conditional}(\chi_b)$ in %	6.68 ± 0.15	8.28 ± 0.19	10.04 ± 0.15	12.78 ± 0.18	9.40 ± 0.08
Fraction in %	22.7 ± 21.6	19.5 ± 11.9	31.6 ± 10.4	24.6 ± 8.8	20.7 ± 5.7

Systematic Uncertainties

Source	Uncertainty
Unknown $\chi_{bJ}(1P)$ mixture	7%
Photon reconstruction efficiency	5.5%
Background description	5%
Quadratic sum of the above	10%
100% polarization of $\Upsilon(1S)$	$^{+13}_{-26}$%