Heavy Flavour Production at LHCb

Nick Brook

(on behalf of the LHCb collaboration)

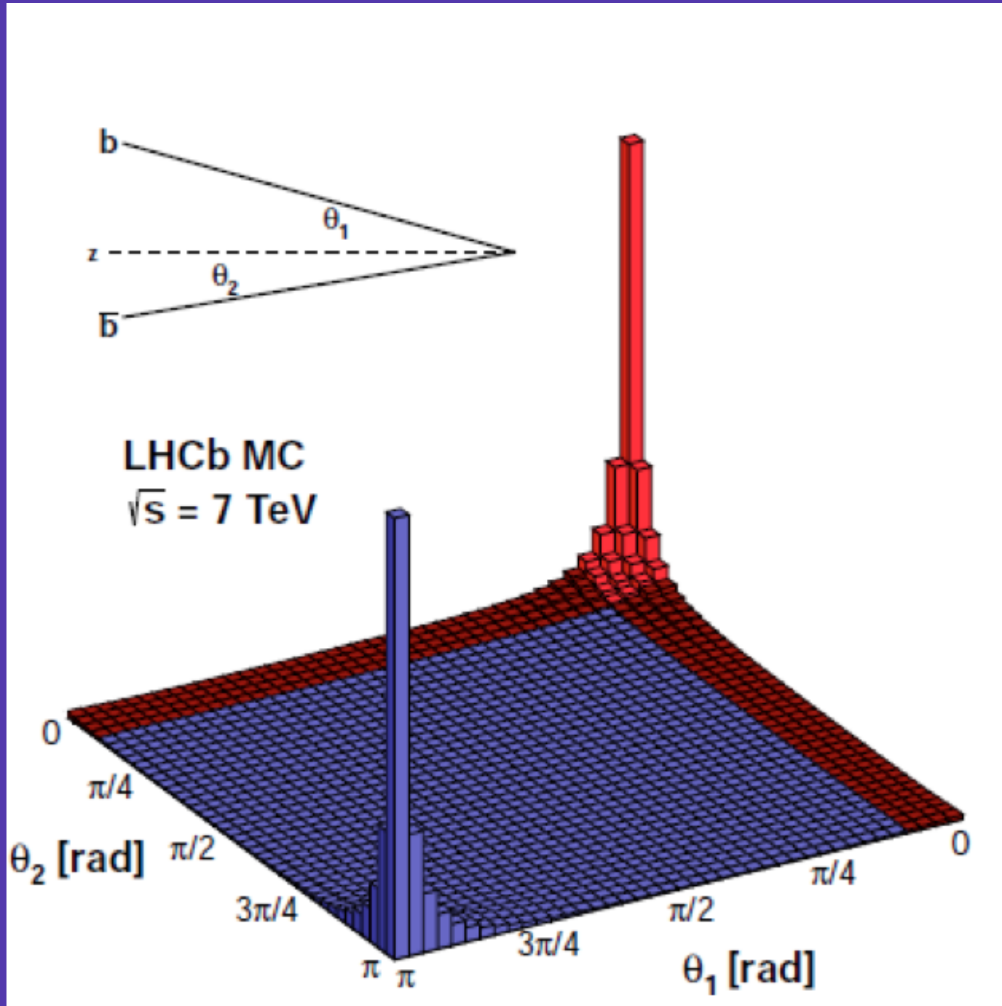
University of Bristol

Outline

- LHCb detector
- Quarkonia Production
  - Charmonium,bottomonium, χ_c, χ_b
  - Double charmonium & associated open charm
- Open Charm & Beauty
  - Production asymmetries
  - Double charm production

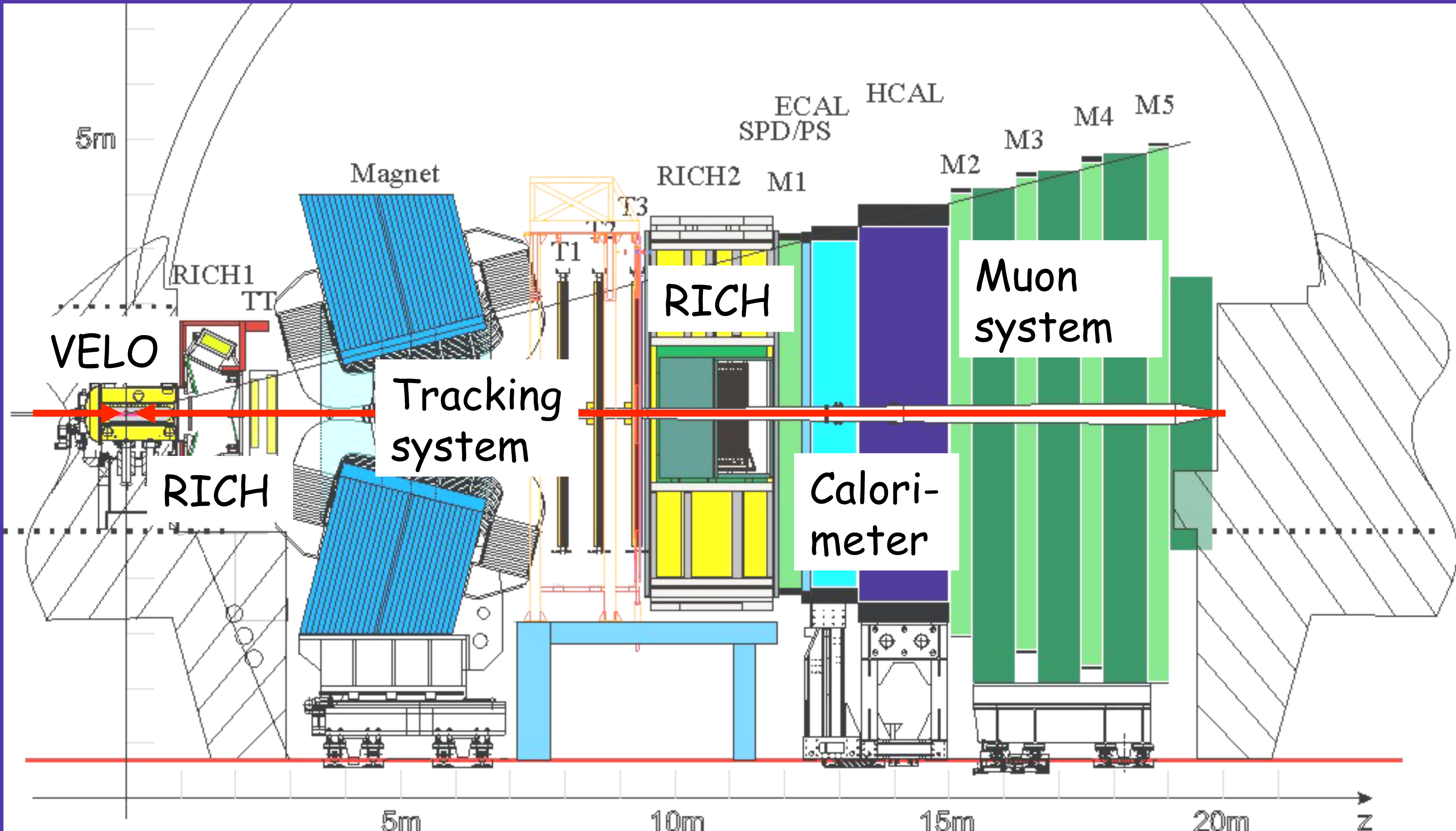
Production of B-hadrons at LHC

- >100k bb/sec are expected and all B-Hadron species are produced:
  - B^0, B^+, B_S, B_C, b-baryons
- B-hadrons are produced in the forward (beam) region:
  - LHCb - single arm forward spectrometer has been chosen which covers 12 mrad< θ < 300mrad

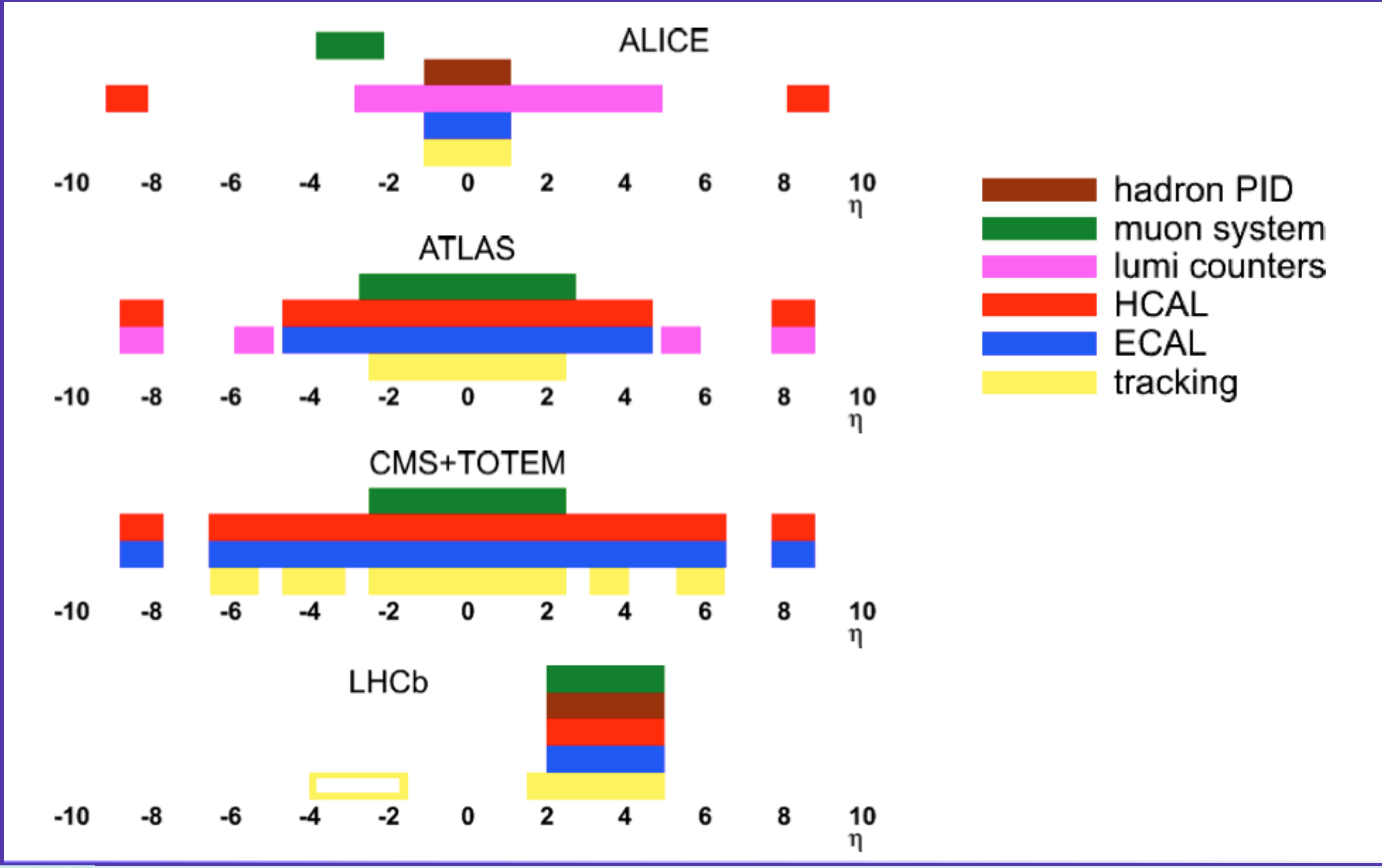


LHCb spectrometer

JINST 3 (2008) S08005



Acceptance of LHC Expts



Quarkonia Production

Motivation

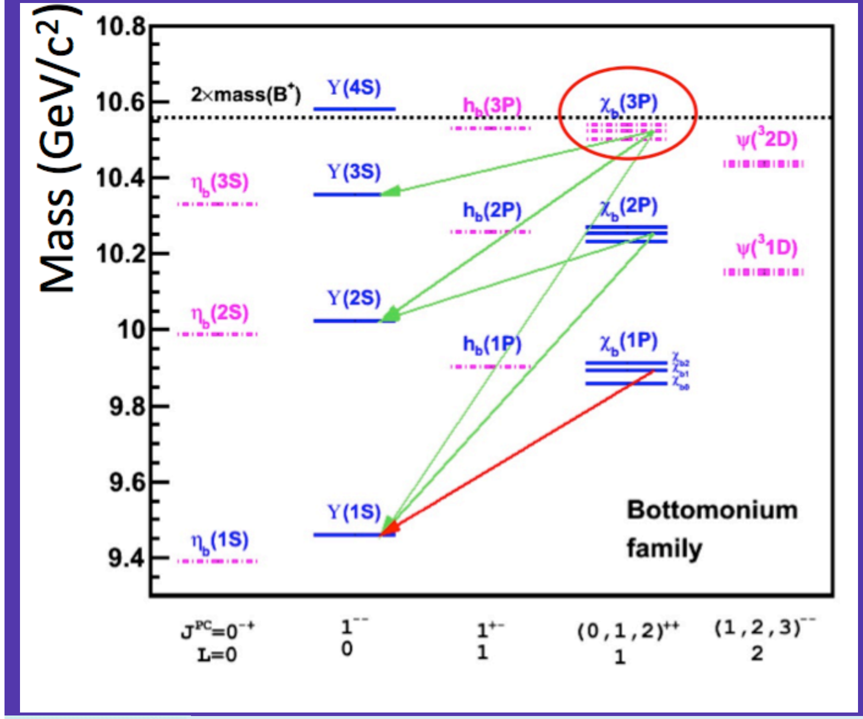
- Heavy $q\bar{q}$ simple applicaton of QCD(!)
  - Ideal testing ground for QCD
- Experimentally clean
  - Expt calibration
- Radial & orbital excitations
  - Good testing ground from QCD based models

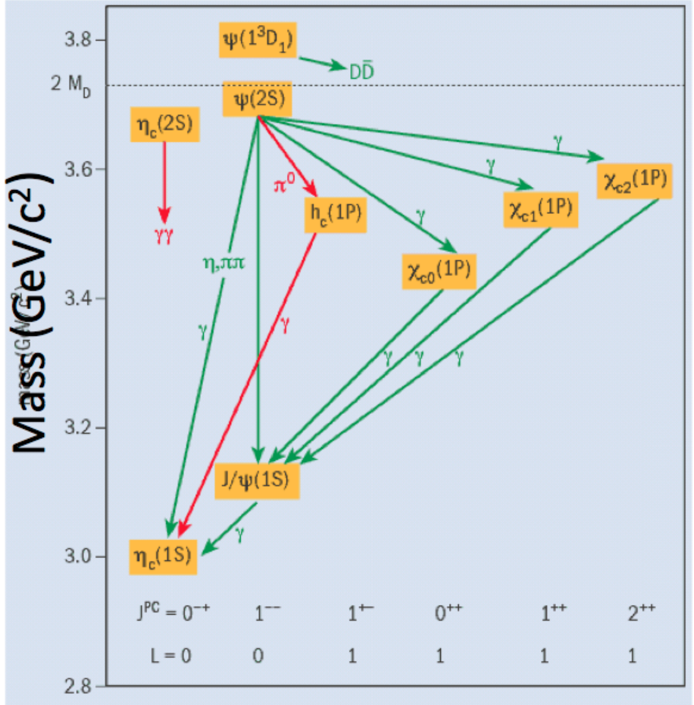
Motivation

- Quarkonia usually described in framework of NRQCD
  - short distance (partonic calculations+PDF)
  - long distance matrix elements for quarkonia production
  - Colour octet(CO) + colour singlet(CS) models - kinematics
  - Problems in describing kinematics & polarisation in consistent manner
- Other models:
  - Colour evaporation model (CEM)
    - heavy quark pair in pQCD not in colour-singlet state
    - Colour & spin of state is "randomized" by soft interactions after production
    - Production of $^3S_1$ state is now possible via a single gluon

Heavy Onia

- Measurements also important tests of CS & CO production mechanism
  - Feed down fractions
  - Ratio of spin states
- Needed for polarisation measurements





LHCb measurements

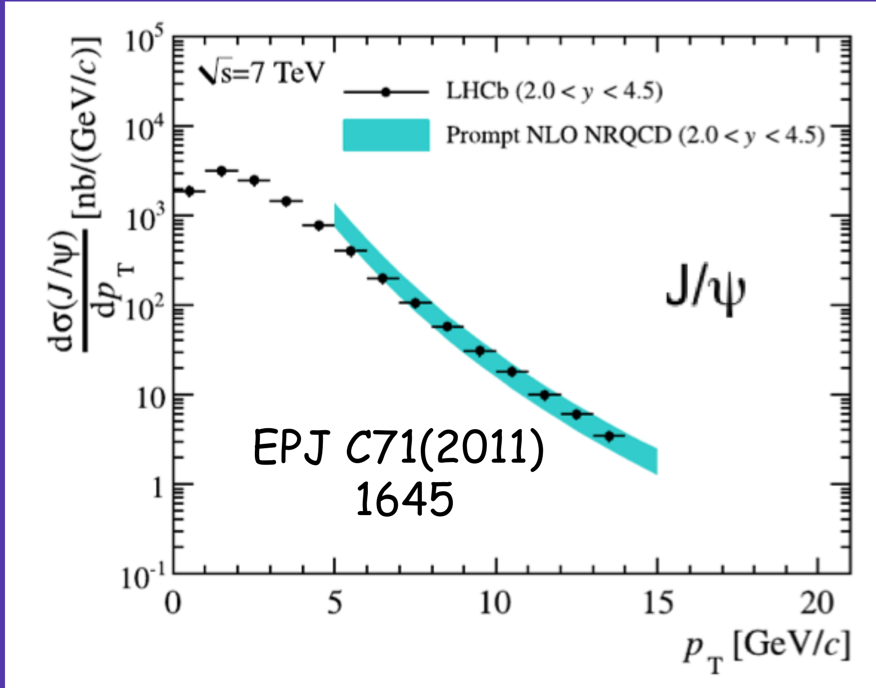
- Analysis rapidity range: $2 < y < 4.5$
- Low p_T triggers
  - Typical thresholds:
    - 1μ: $p_T > 1.8$ GeV/c
    - 2μ: $p_T > 0.56$ GeV/c; $p_T > 0.48$ GeV/c
- All measurements presented are at $\sqrt{s} = 7$ TeV

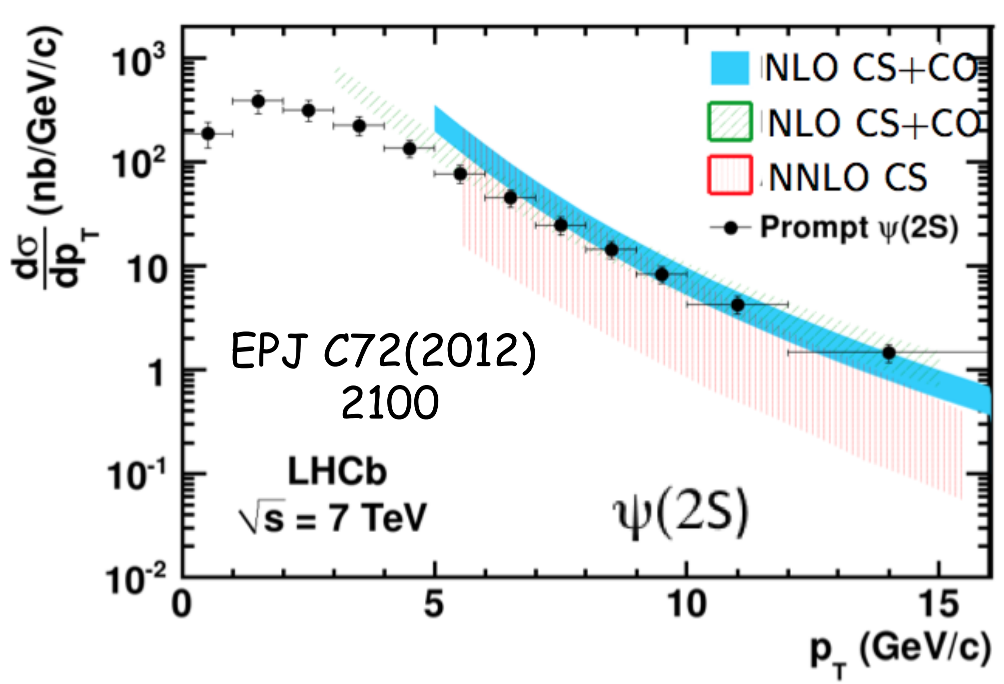
Quarkonia @ 7TeV

- Prompt charmonia

Y.-Q. Ma et al. PRL 106 (2011) 042002

Y.-Q. Ma et al. PRD 84 (2011) 114001
B. Kniehl et al. PRL 106 (2011) 022003
P. Artoisenet et al. PRL (2008) 152001
J.-P. Lansberg, EPJ C61 (2009) 693.

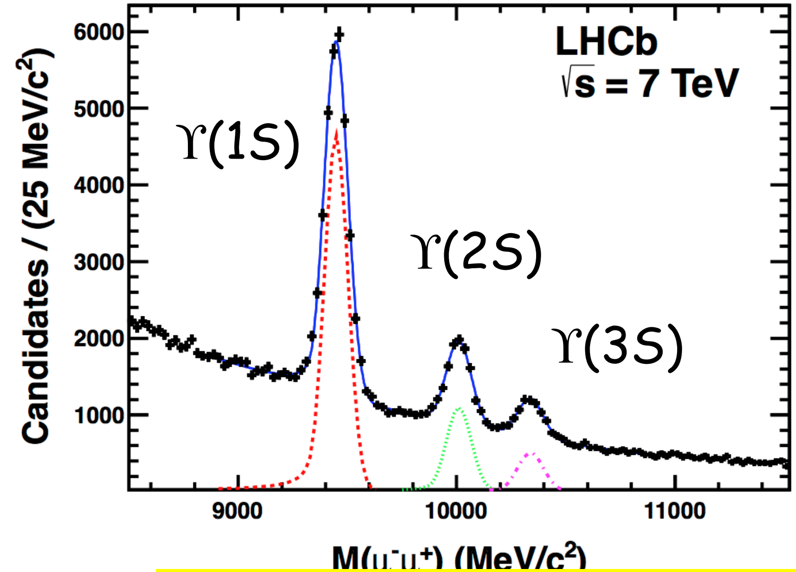




- All consistent with predictions
  - Large p_T tails well reproduced especially in CO models

Quarkonia @ 7TeV

- Prompt bottomonium
  - Good agreement of theory with measured X-section
  - Discrimination of theoretical models not yet feasible with differential dist^{bn}



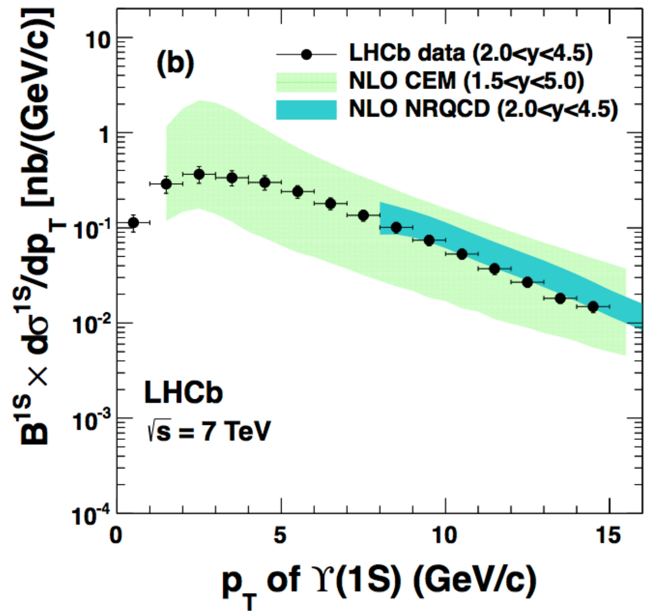
EPJ C72 (2012) 2025

CEM: Y.-Q. Ma et al. PRD 84 (2011) 114001
NRQCD: A.D. Frawley et al. Phys.Rep. 462 (208) 125

$$\sigma(pp \to \Upsilon(1S)) \times \mathcal{B}^{1S} = (2.29 \pm 0.01(\text{stat}) \pm 0.10(\text{syst})^{+0.19}_{-0.37}(\text{pol}))\ \text{nb}$$

$$\sigma(pp \to \Upsilon(2S)) \times \mathcal{B}^{2S} = (0.562 \pm 0.007(\text{stat}) \pm 0.023(\text{syst})^{+0.048}_{-0.092}(\text{pol}))\ \text{nb}$$

$$\sigma(pp \to \Upsilon(3S)) \times \mathcal{B}^{3S} = (0.283 \pm 0.005(\text{stat}) \pm 0.012(\text{syst})^{+0.025}_{-0.048}(\text{pol}))\ \text{nb}$$



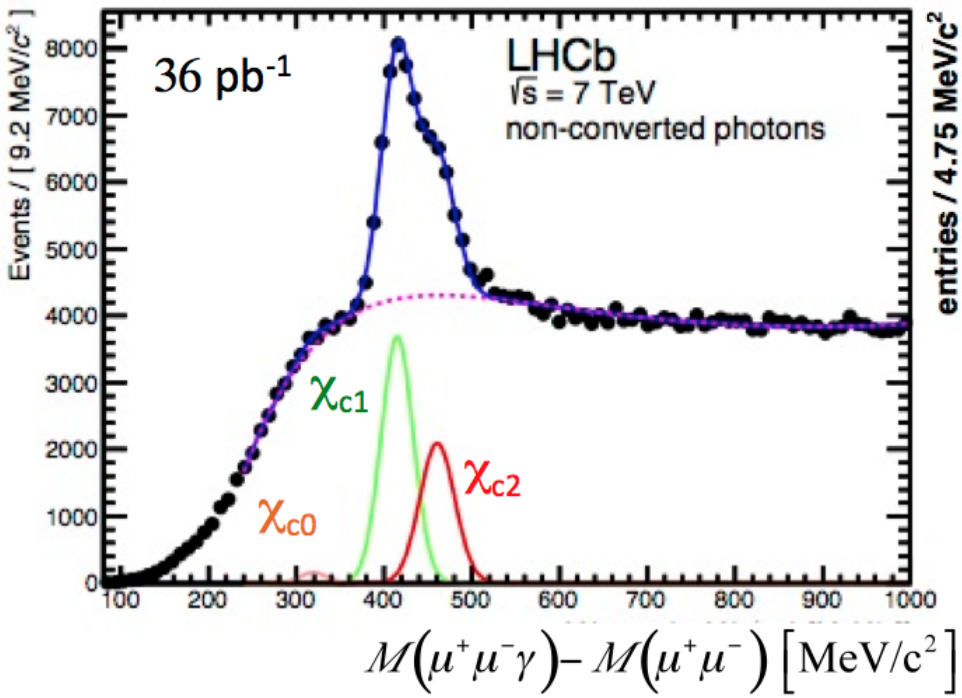
Heavy Onia: χ_c

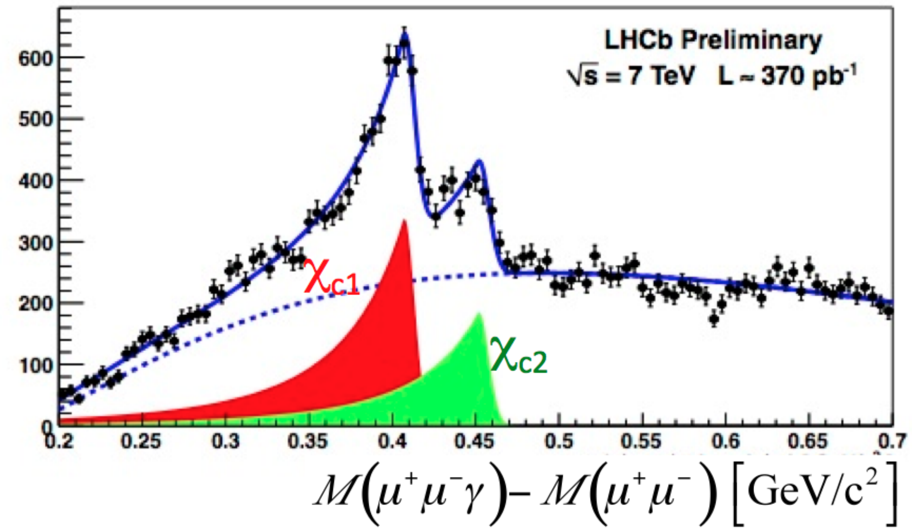
$$\chi_{cJ}(nP) \rightarrow J/\Psi\gamma$$

Phys.Lett. B714 (2012) 215
arXiv:1204.1462
LHCb-CONF-2011-062

- Photons identified
  - Directly in ECAL
  - Converted before magnet

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



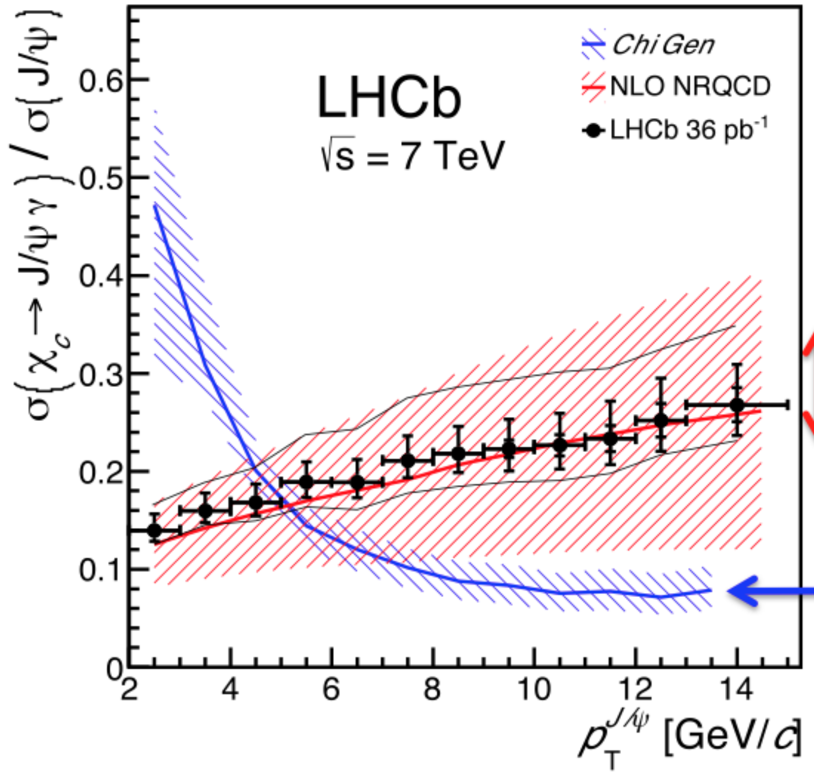


Heavy Onia: χ_c

$$\chi_{cJ}(nP) \to J/\Psi\gamma$$

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

$2 < y_{J/\psi} < 4.5 \quad 2 < p_{T\,J/\psi} < 15$ GeV/c



arXiv:1204.1462

NRQCD: Y.-Q. Ma et al. PRD 83 (2011) 111503

Maximum effect due to polarization of χ_c and J/ψ

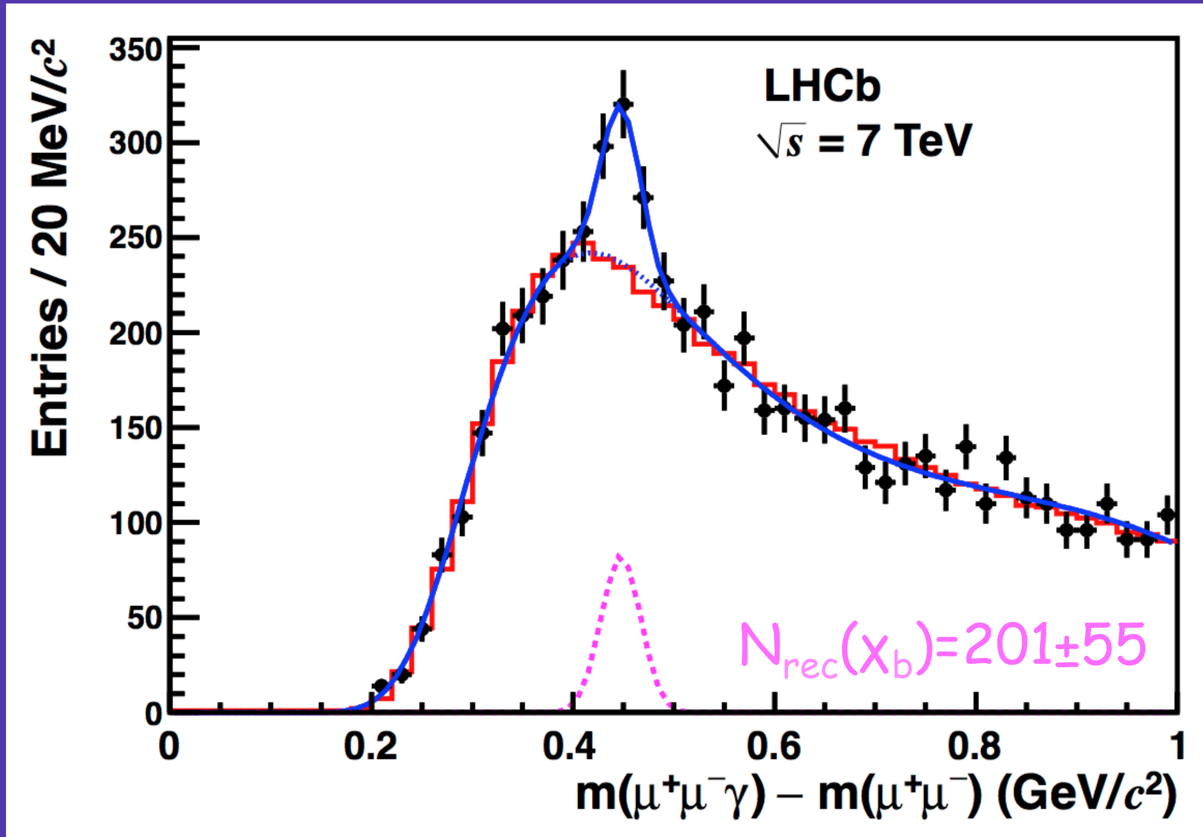
LO CS model
L. Harland-Lang & W.J.Stirling

Good agreement with NLO NRQCD prediction

Heavy Onia: χ_b $\chi_b(1P) \to \Upsilon(1S)\gamma \to \mu^+\mu^-\gamma$

arXiv:1209.0282

$2 < y_\Upsilon < 4.5 \quad 6 < p_\Upsilon < 15$ GeV/c

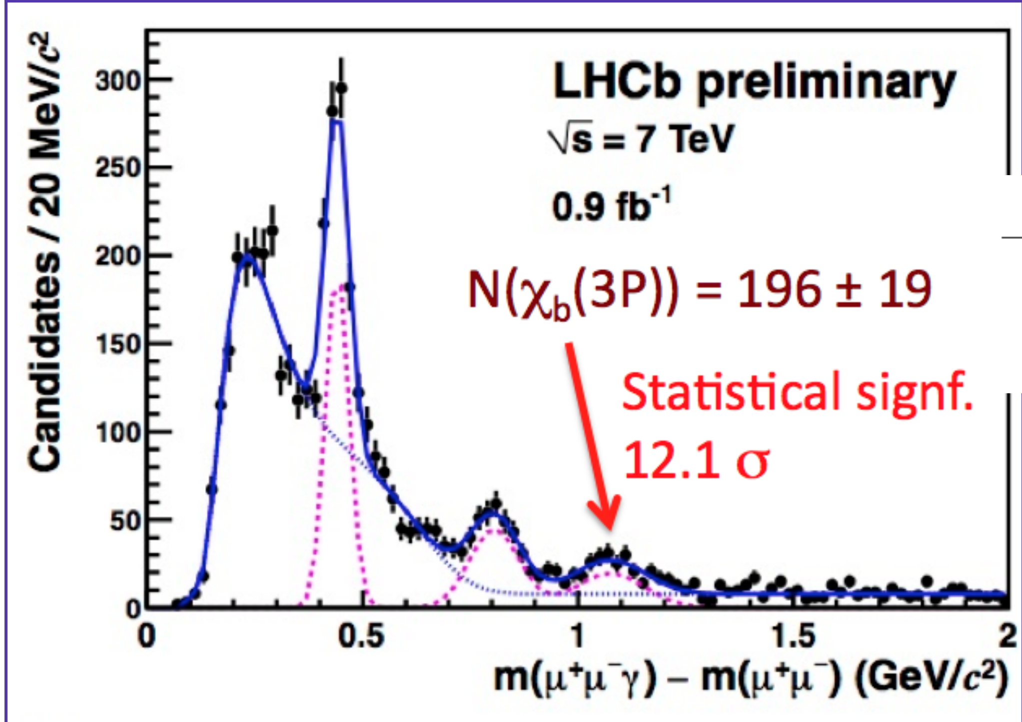


$$f_{\chi_b(1P)\to\Upsilon(1S)} = (20.7 \pm 5.7(stat) \pm 2.1(syst)^{+2.7}_{-5.4}(pol))\%$$

Consistent with CDF (PRL 84 (2000) 2094): (27.1± 6.9±4.4)%

Heavy Onia: χ_b $\chi_b(3P) \to \Upsilon(1S)\gamma \to \mu^+\mu^-\gamma$

LHCb-CONF-2012-020



	Yield	Mass (MeV/c^2)	Width (MeV/c^2)
$\chi_b(1P)$	652 ± 50	9901 ± 2	25 ± 2
$\chi_b(2P)$	323 ± 32	10266 ± 6	57 ± 6
$\chi_b(3P)$	196 ± 19	10535 ± 10	80 ± 10

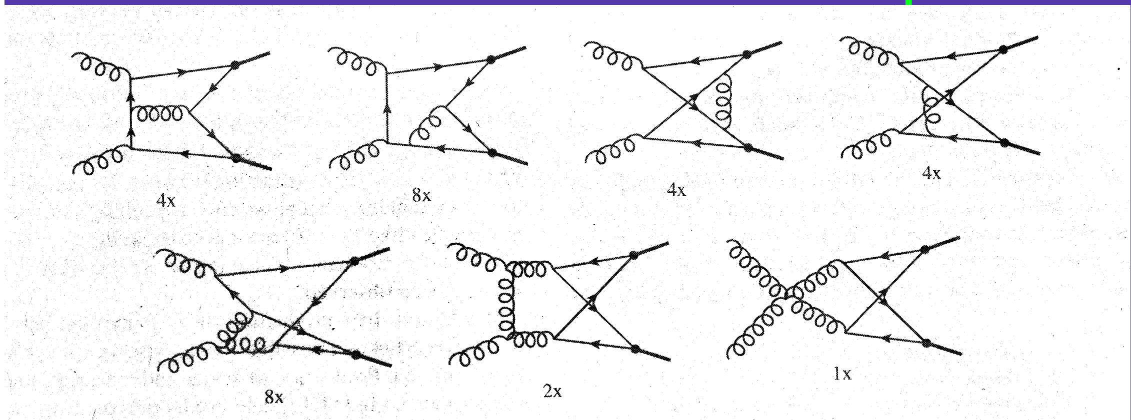
$$m(\chi_b(3P)) = 10.535 \pm 0.010 \text{GeV}/c^2$$

Mass consistent with ATLAS (PRL 108 (2012) 152001) & D0 (PRD 86(2012) 031103)

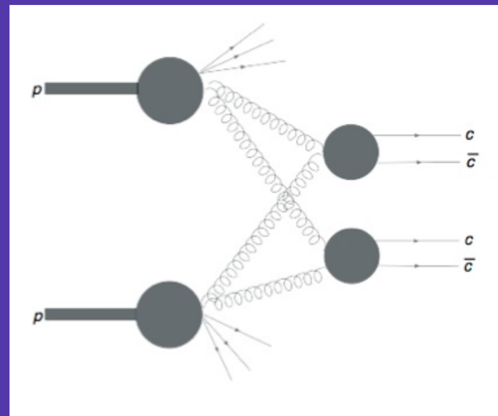
Multiple Quarkonia Production & associated open charm

Double J/ψ production

- Production of multiple heavy flavour states tests
  - pQCD (dominantly gluon fusion @ LHC)
  - Double parton scattering (DPS)
  - Intrinsic charm of the proton



gg fusion



DPS

LHCb: $2 < y_{J/\psi} < 4.5$ $p_{T\,J/\psi} < 10$ GeV/c

Phys.Lett. B707 (2012) 52

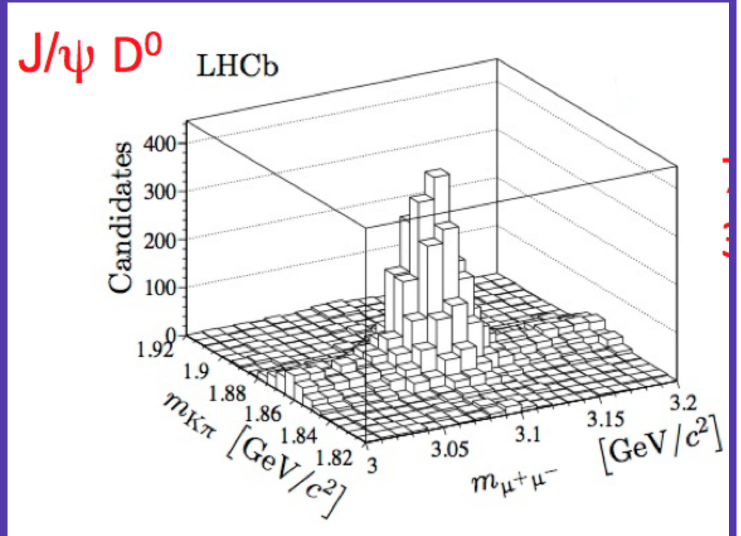
$$\sigma^{J/\psi J/\psi} = 5.1 \pm 1.01 \pm 1.1\,\mathrm{nb}$$

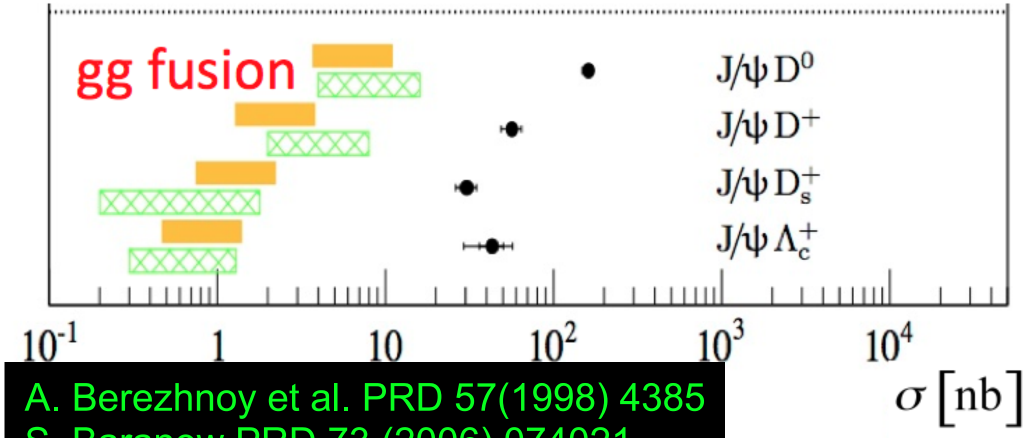
$$\frac{\sigma^{J/\psi J/\psi}}{\sigma^{J/\psi}} = (5.1 \pm 1.0(\mathrm{stat}) \pm 0.6(\mathrm{syst})^{+1.2}_{-1.0}(\mathrm{pol})) \times 10^{-4}$$

J/ψ production & associated charm

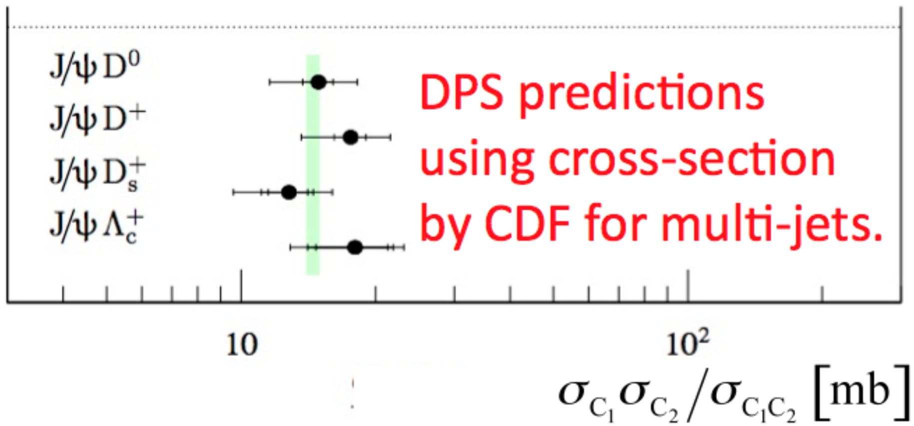
LHCb: $2 < y_{J/\psi} < 4$ $p_{T\,J/\psi} < 12$ GeV/c;
$2 < y_{charm} < 4$ $3 < p_{T\,charm} < 12$ GeV/c

JHEP 06 (2012) 141





A. Berezhnoy et al. PRD 57(1998) 4385
S. Baranow PRD 73 (2006) 074021
J-.P. Landsberg EPJ C61 (2009) 693

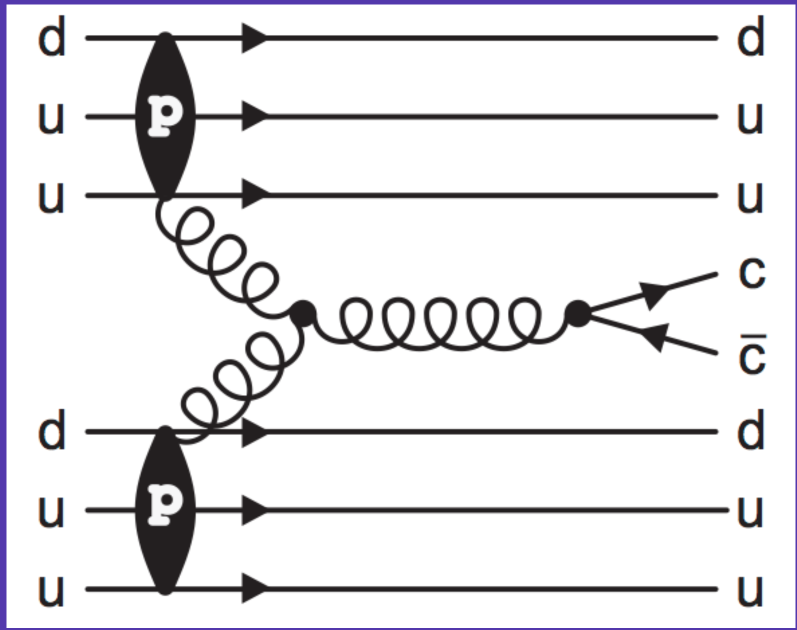


- Measured X-sections suggest DPS needed

Open charm and bottom production

Production Asymmetries

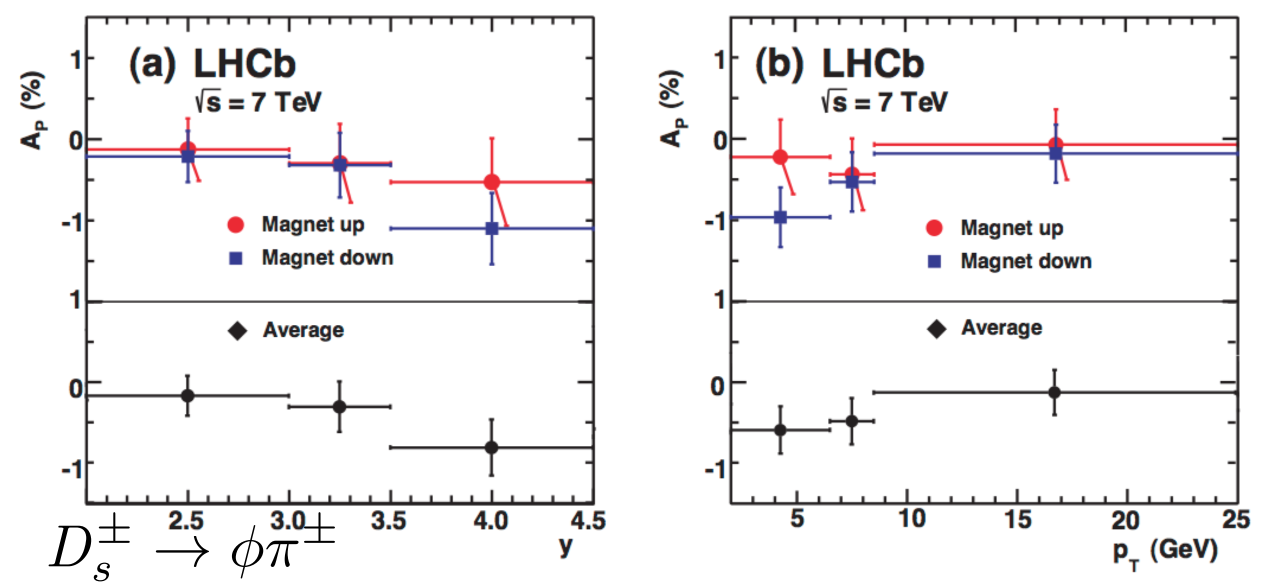
- Production diagrams asymmetric
  - beam drag
  - other fragmentation effects



$$A_P = \frac{\sigma(D^+_{d,s}) - \sigma(D^-_{d,s})}{\sigma(D^+_{d,s}) + \sigma(D^-_{d,s})}$$

Production Asymmetries

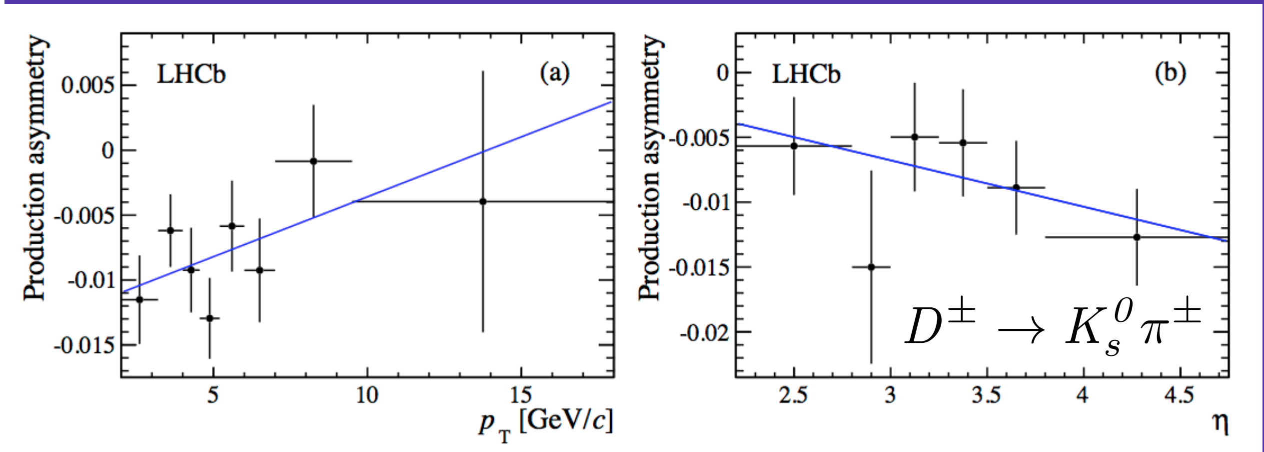
Phys.Lett. B713 (2012) 186



$A_P(D_s)$ = (-0.33±0.22±0.10)%

2 < y < 4.5 p_T> 2GeV

No obvious p_T or y dependence



$A_P(D_d)$ = (-0.96±0.26±0.18)%

No obvious p_T or η dependence

2 < y < 4.75 2.0 < p_T< 18 GeV/c
(excluding 2.20 < y < 2.80 2.0 < p_T< 3.2 GeV/c)

arXiv:1210.4112

Double Charm Production

- Handle on DPS and sea charm quarks

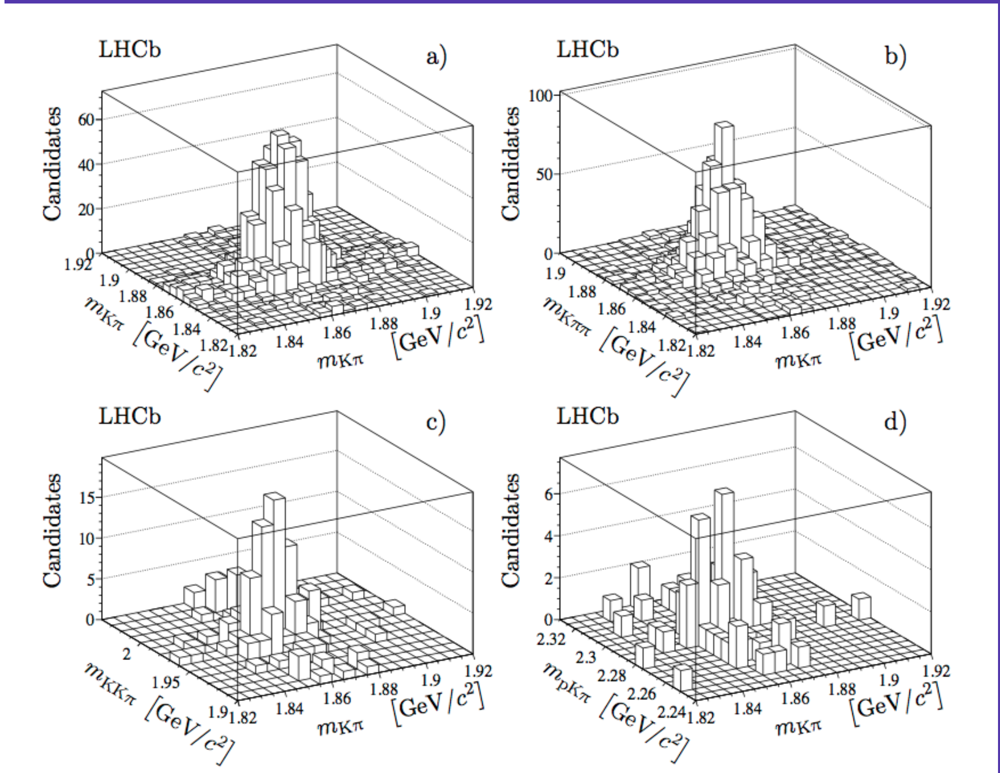
[μb]		σ_{DPS}	σ_{sea}
D^0D^0		2.0 ± 0.5	1.5
D^0D^+		1.7 ± 0.4	1.4
$D^0D_s^+$	predictions	0.65 ± 0.15	0.4
$D^0\Lambda_c^+$		1.5 ± 0.5	
D^+D^+		0.34 ± 0.09	0.3
$D^+D_s^+$		0.27 ± 0.07	0.2
$D^+\Lambda_c^+$		0.64 ± 0.23	

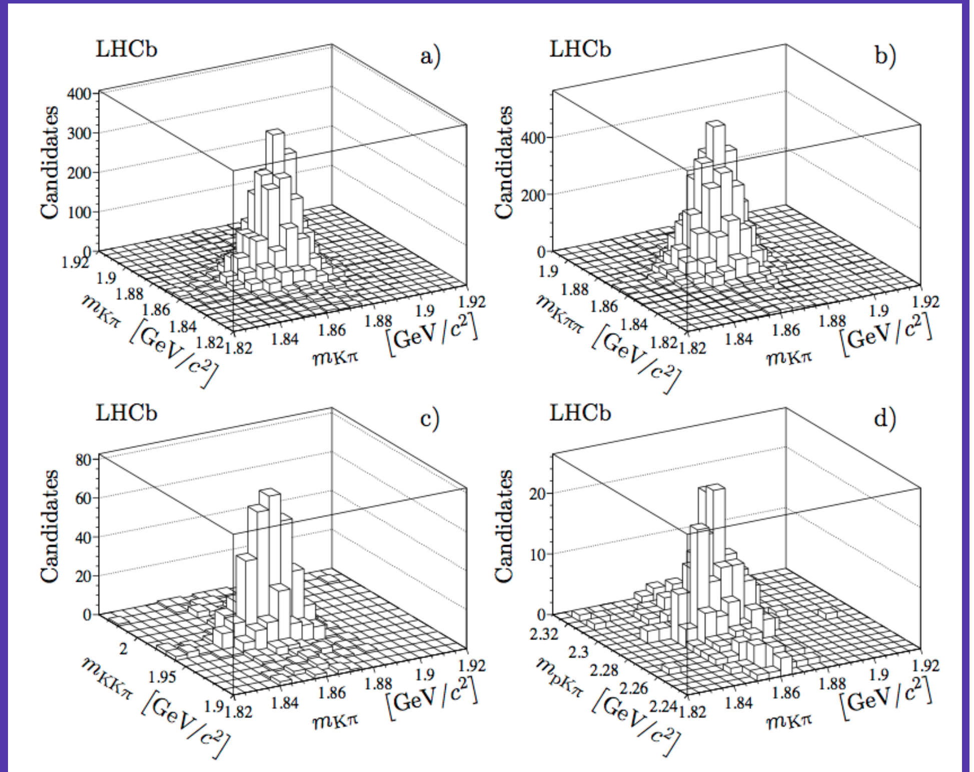
DPS:
C. Kom et al. PRL 107 (2011) 082002
S. Baranov et al. PLB 705 (2011) 116
A. Novoselov arXiv:1106.2184
M. Luszczak PRD 85 (2012) 094034

sea:
S. Brodsky et al. PLB 93 (1980) 451.

Double Charm Production

$D^0\,D^0$ $D^0\,D^+$ $D^0\,\bar{D}^0$ $D^0\,D^-$





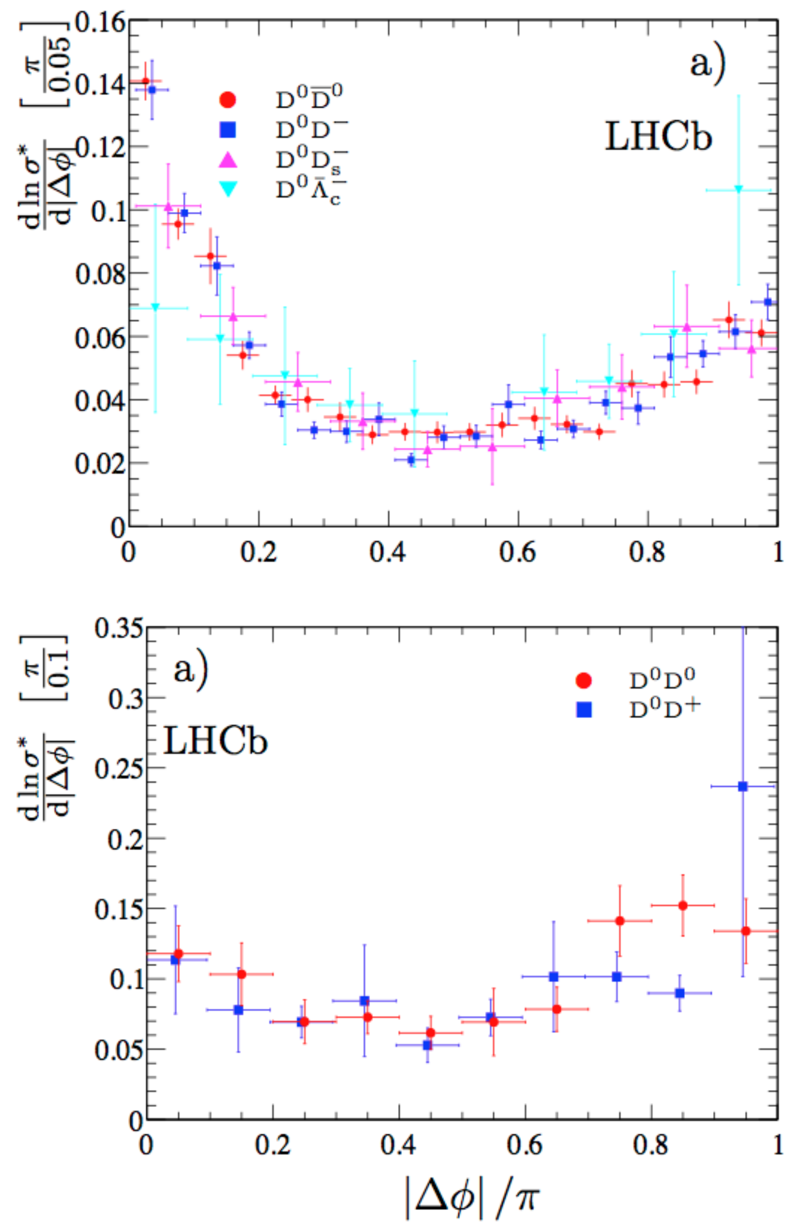
$D^0\,D_s^+$ $D^0\,\bar{\Lambda}_c^-$ $D^0\,D_s^-$ $D^0\,\Lambda_c^+$

Same sign charm

Opposite sign charm

Double Charm Production

JHEP 06 (2012) 141



Opposite sign:
Δϕ→0 peak indicates g->ccbar splitting contribution and/or non-collinear contribution

Same sign:
Δϕ flat indicates no production correlation

Summary & Prospects

- LHCb has very many important production results
  - First observations
  - X-section measurements
  - Evidence for the importance of DPS
  - Heavy quarkonia
- Polarisation measurements on the way
- Analysis of 8 TeV data under way
- More detailed studies of kinematic distribution of double charm production
- Production measurements planned from pA runs

Backups

Onia x-sections @ 7 TeV

Charmonia and Bottomonium at √s = 7 TeV

- LHCb has published the production rates of prompt and non-prompt quarkonia ***at 7 TeV***

EPJC 71 (2011) 1645

$$\sigma_{prompt}(J/\psi) = 10.52 \pm 0.04(stat) \pm 1.40(syst)^{+1.64}_{-2.20}(pol)\mu b$$

$$\sigma_{b}(J/\psi) = 1.14 \pm 0.01(stat) \pm 0.16(syst)\mu b$$

data sample of 5.2 pb^{-1}
use $J/\psi \to \mu^+\mu^-$
cross sections integrated over the ranges
p_T < 14. GeV/c and 2.0 < y < 4.5

arXiv: 1204.1258

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

$$\sigma_{b}(\psi(2S)) = 0.25 \pm 0.01(stat) \pm 0.02(syst)\mu b$$

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

data sample of 36. pb^{-1}
use $\psi(2S) \to \mu^+\mu^-$ and
$\psi(2S) \to J/\psi\,(\mu^+\mu^-)\pi^+\pi^-$
cross sections integrated over the ranges
p_T < 16. GeV/c and 2.0 < y < 4.5

EPJC 72 (2012) 2025

$$\sigma_{prompt}(\Upsilon(1S)) \times Br(\Upsilon(1S) \to \mu^+\mu^-) = 2.29 \pm 0.01(stat) \pm 0.10(syst)^{+0.19}_{-0.37}(pol)nb$$

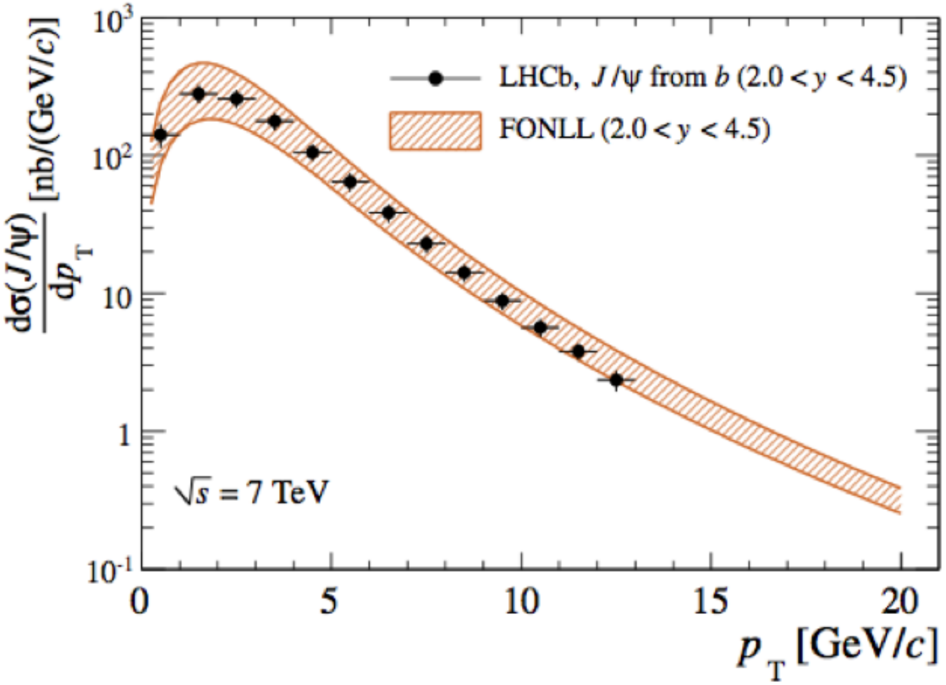
$$\sigma_{prompt}(\Upsilon(2S)) \times Br(\Upsilon(2S) \to \mu^+\mu^-) = 0.562 \pm 0.007(stat) \pm 0.023(syst)^{+0.048}_{-0.092}(pol)nb$$

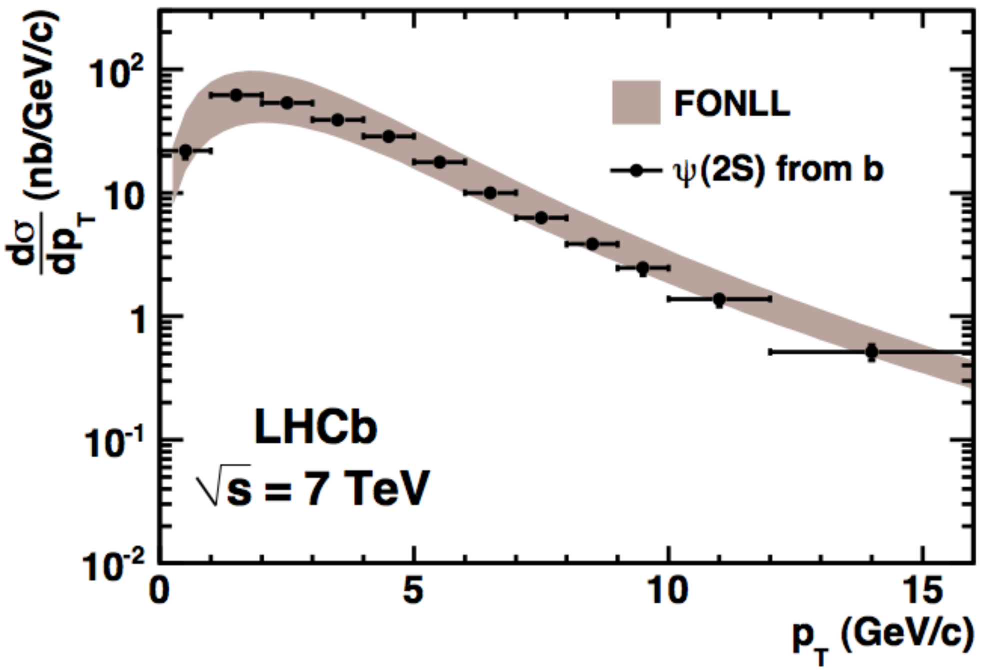
$$\sigma_{prompt}(\Upsilon(3S)) \times Br(\Upsilon(3S) \to \mu^+\mu^-) = 0.283 \pm 0.005(stat) \pm 0.012(syst)^{+0.025}_{-0.048}(pol)nb$$

data sample of 25. pb^{-1}
use $\Upsilon(iS) \to \mu^+\mu^-$ (i=1,2,3)
cross sections integrated over the ranges
p_T < 15. GeV/c and
2.0 < y < 4.5

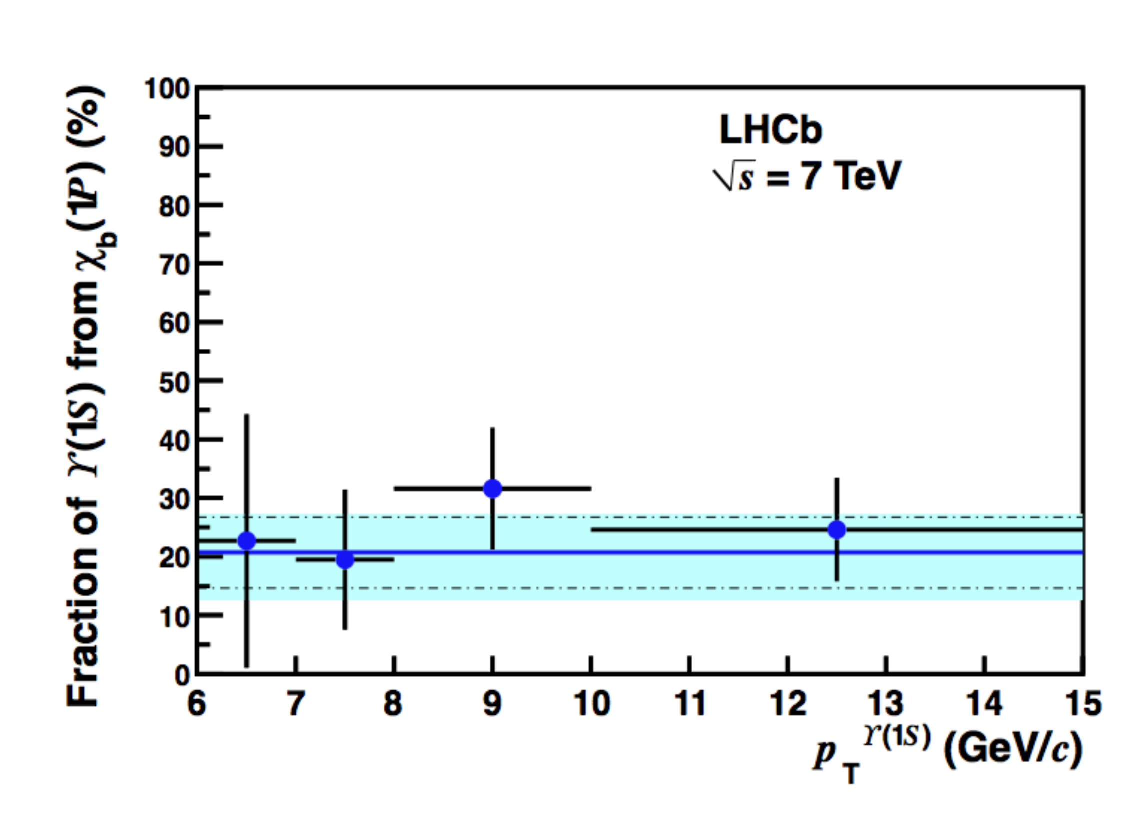
- the largest error on the prompt cross sections is due to the unknown quarkonia states polarizations
- differential cross sections have been measured as a function of p_T and y of the quarkonia states
- the inclusive BR(b -> ψ(2S)X) has been obtained combining $\sigma_b(\psi(2S))$ and $\sigma_b(J/\psi)$, and the last error is due to the uncertainty on BR(b -> J/ψX) [*PDG*]

Onia from B-decays





Bottomonium



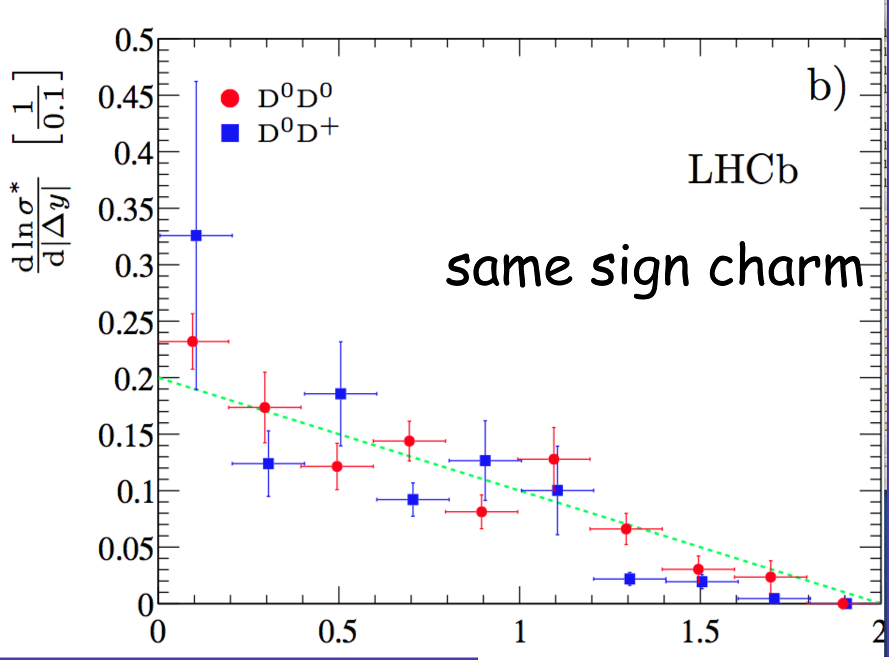
$$\epsilon_{\rm cond}(\chi_b) = \frac{\epsilon(\chi_b)_{tot}}{\epsilon(\Upsilon)_{tot}}$$

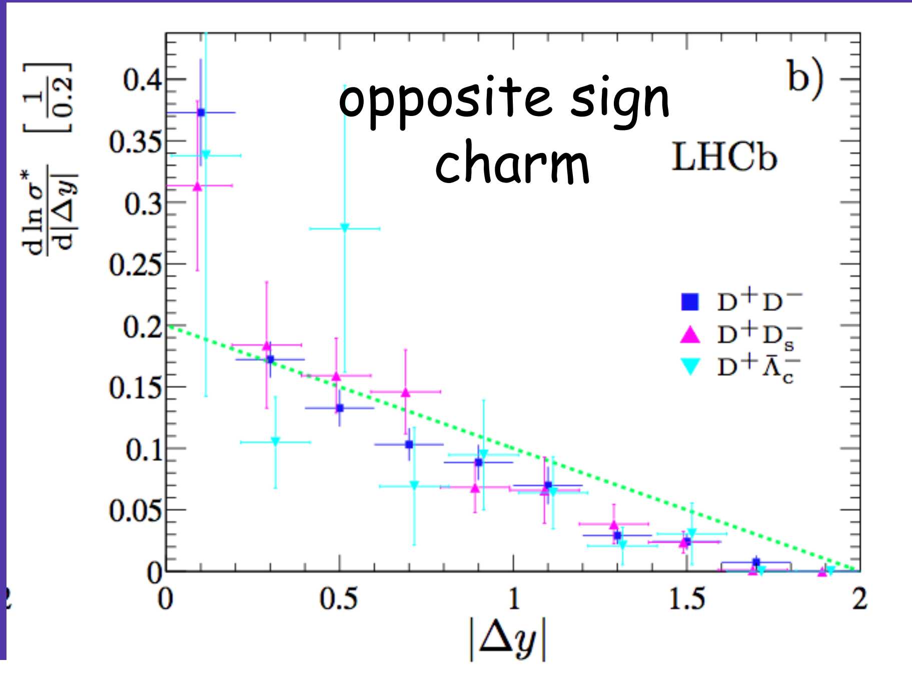
$p_T^{\Upsilon(1S)}$ (GeV/c)	$6-7$	$7-8$	$8-10$	$10-15$	$6-15$
$N_{\rm rec}(\chi_b)$	41 ± 39	35 ± 22	91 ± 30	82 ± 29	201 ± 55
$N_{\rm rec}(\Upsilon)$	2730 ± 64	2193 ± 57	2866 ± 64	2627 ± 59	$10\,345 \pm 123$
$\epsilon_{\rm cond}(\chi_b)$ in %	6.7 ± 0.2	8.3 ± 0.2	10.0 ± 0.2	12.8 ± 0.2	9.4 ± 0.1
Fraction in %	23 ± 22	20 ± 12	32 ± 10	25 ± 9	21 ± 6

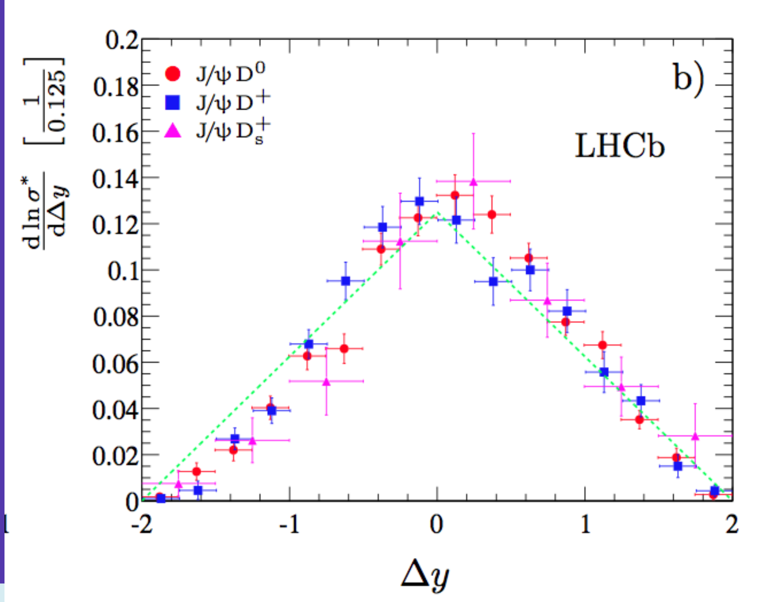
Charmonium & associated charm

Mode	σ [nb]	$\sigma_{CC}/\sigma_{C\bar{C}}$ [%]	$\sigma_{C_1}\sigma_{C_2}/\sigma_{C_1C_2}$ [mb]
D^0D^0	$690 \pm 40 \pm 70$	10.9 ± 0.8	$2 \times (42 \pm 3 \pm 4)$
$D^0\bar{D}^0$	$6230 \pm 120 \pm 630$		$2 \times (4.7 \pm 0.1 \pm 0.4)$
D^0D^+	$520 \pm 80 \pm 70$	12.8 ± 2.1	$47 \pm 7 \pm 4$
D^0D^-	$3990 \pm 90 \pm 500$		$6.0 \pm 0.2 \pm 0.5$
$D^0D_s^+$	$270 \pm 50 \pm 40$	15.7 ± 3.4	$36 \pm 8 \pm 4$
$D^0D_s^-$	$1680 \pm 110 \pm 240$		$5.6 \pm 0.5 \pm 0.6$
$D^0\bar{\Lambda}_c^-$	$2010 \pm 280 \pm 600$	—	$9 \pm 2 \pm 1$
D^+D^+	$80 \pm 10 \pm 10$	9.6 ± 1.6	$2 \times (66 \pm 11 \pm 7)$
D^+D^-	$780 \pm 40 \pm 130$		$2 \times (6.4 \pm 0.4 \pm 0.7)$
$D^+D_s^+$	$70 \pm 15 \pm 10$	12.1 ± 3.3	$59 \pm 15 \pm 6$
$D^+D_s^-$	$550 \pm 60 \pm 90$		$7 \pm 1 \pm 1$
$D^+\Lambda_c^+$	$60 \pm 30 \pm 20$	10.7 ± 5.9	$140 \pm 70 \pm 20$
$D^+\bar{\Lambda}_c^-$	$530 \pm 130 \pm 170$		$15 \pm 4 \pm 2$

Double open charm production

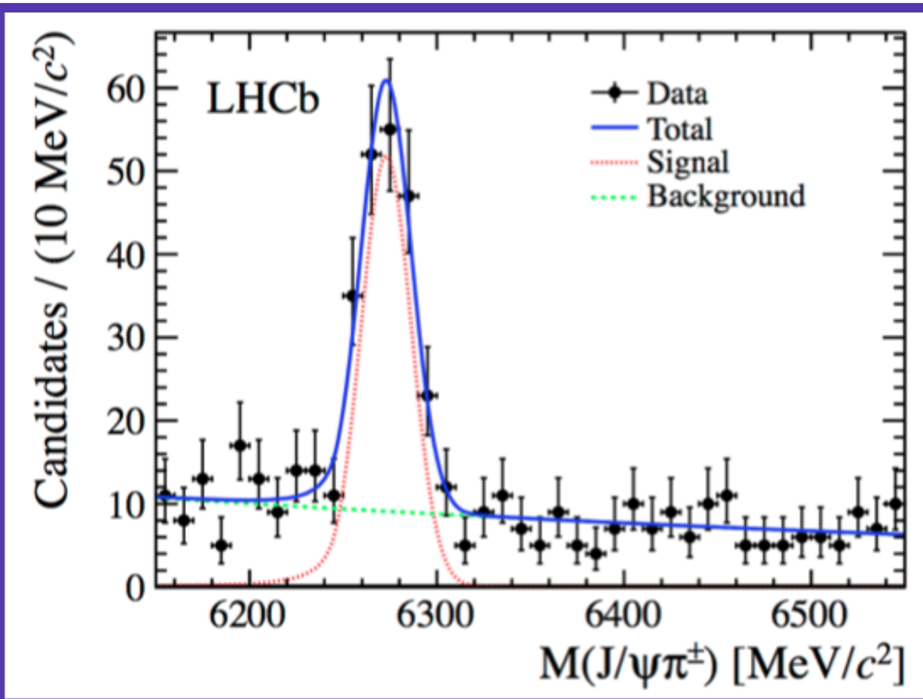






B^+_c production

- Unique in SM
  - Meson containing 2 different heavy flavour quarks
  - Mass measurement test predictions of potential models & lattice QCD



arXiv:1209.5634

$$R_{c/u} = \frac{\sigma(B_c^+)\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+)\mathcal{B}(B^+ \to J/\psi K^+)}$$

$$= (0.68 \pm 0.10(\text{stat}) \pm 0.03(\text{syst}) \pm 0.05(\text{lifetime}))\%$$

$$m(B_c^+) = 6273.7 \pm 1.3(stat) \pm 1.6(syst) MeV/c^2$$

$$m(B_c^+) - m(B^+) = 994.6 \pm 1.3(stat) \pm 0.6(syst) MeV/c^2$$

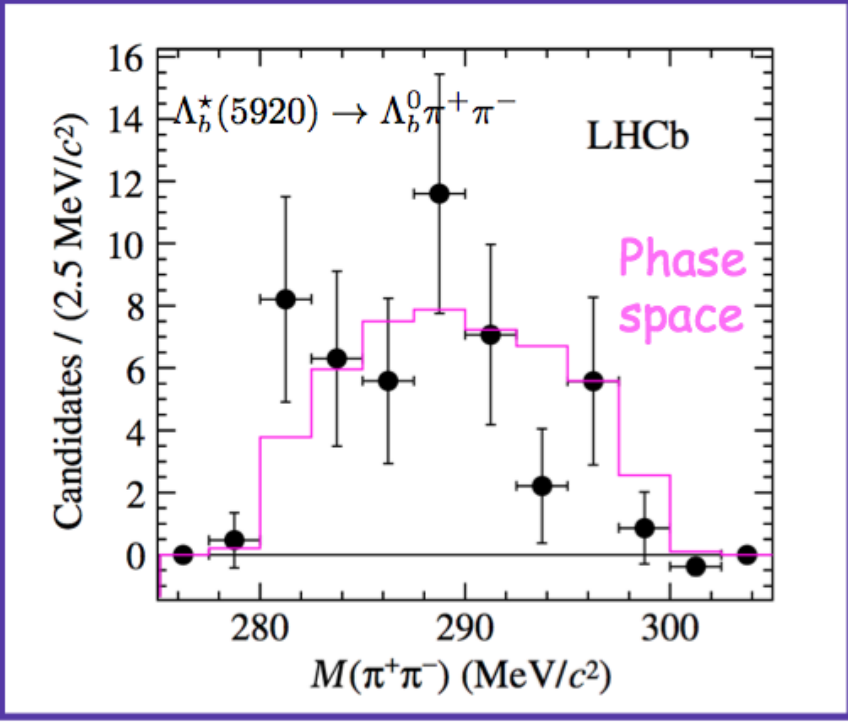
World's most precise measurement
in agreement with CDF & D0 (& lattice QCD)

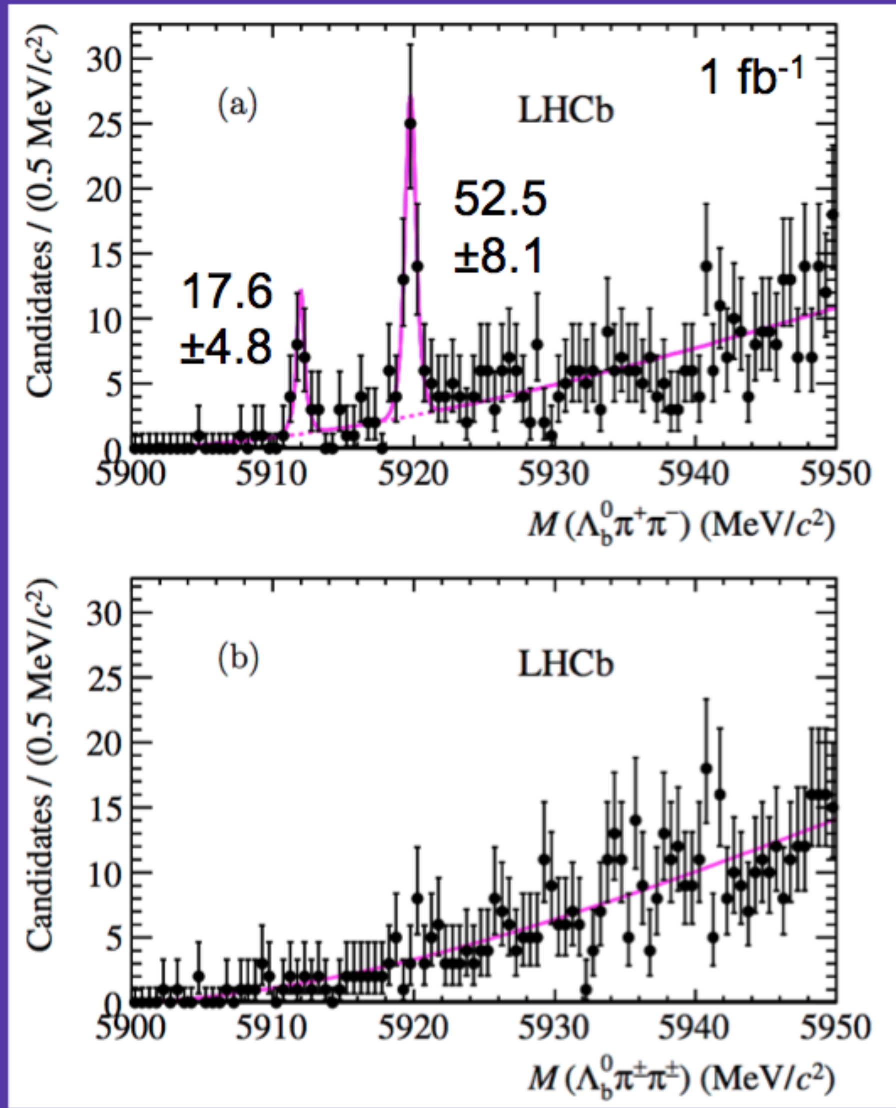
PRL 109 (2012) 172003

b-baryon production

- 1st observation of excited Λ_b production

$$\Lambda_b^* \rightarrow \Lambda_b^0 \pi^+ \pi^-$$





$$M_{\Lambda_b^{*0}(5912)} = 5911.97 \pm 0.12 \pm 0.02 \pm 0.66\ \mathrm{MeV}/c^2,$$
$$M_{\Lambda_b^{*0}(5920)} = 5919.77 \pm 0.08 \pm 0.02 \pm 0.66\ \mathrm{MeV}/c^2,$$

LHCb-CONF-2012-031

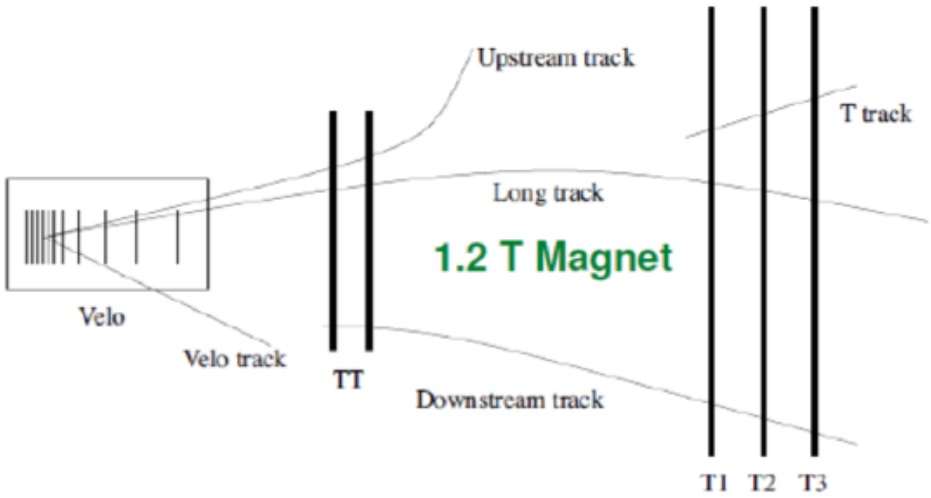
b-baryon production

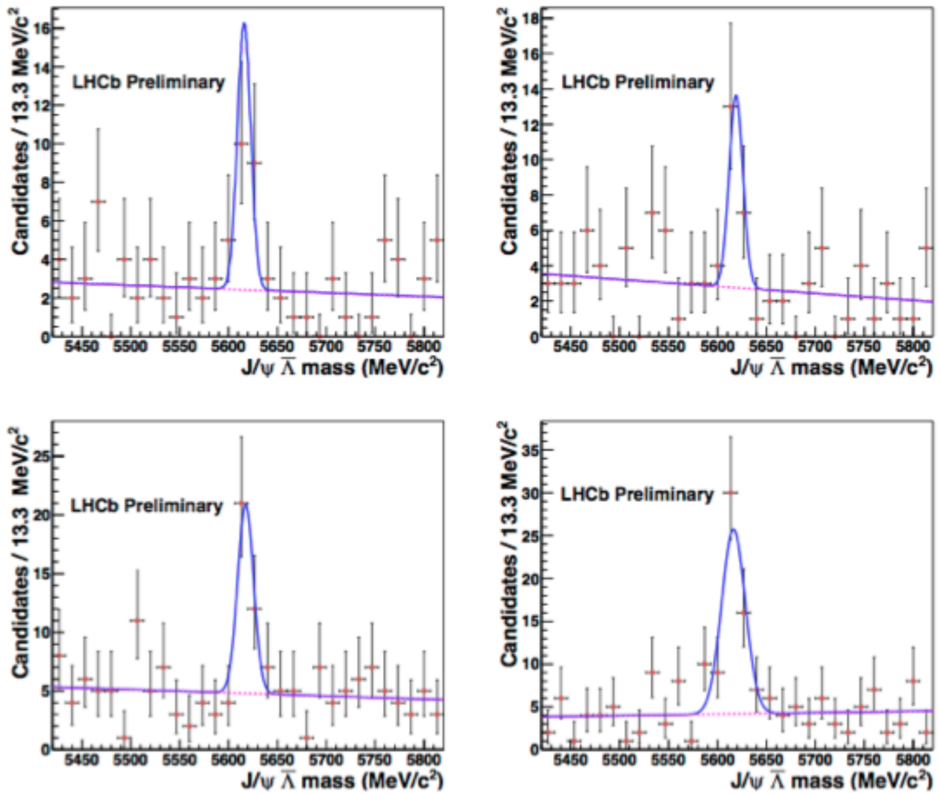
- Λ_b production X-section

$2.2 < y < 4.5$

$p_T < 13.0\ GeV/c^2$

$$\sigma(pp \to \Lambda_b^0 X)\mathcal{B}(\Lambda_b^0 \to J/\Psi\Lambda) = 4.08 \pm 0.59_{stat} \pm 0.36_{syst}\ \text{nb},$$
$$\sigma(pp \to \bar{\Lambda}_b^0 X)\mathcal{B}(\bar{\Lambda}_b^0 \to J/\Psi\bar{\Lambda}) = 2.60 \pm 0.46_{stat} \pm 0.26_{syst}\ \text{nb}.$$





Quarkonia @ 8 TeV

LHCb is performing extremely well at 8 TeV

LHCb-CONF-2012-025

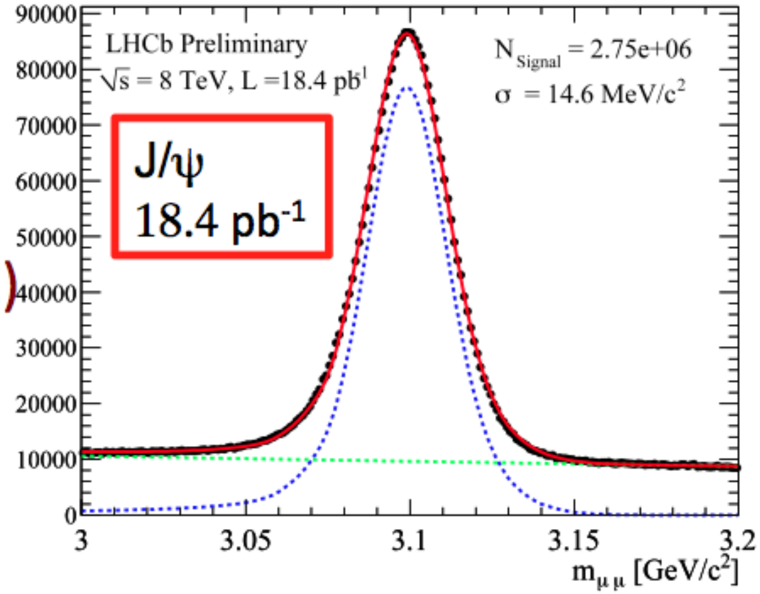
Mass resolutions :

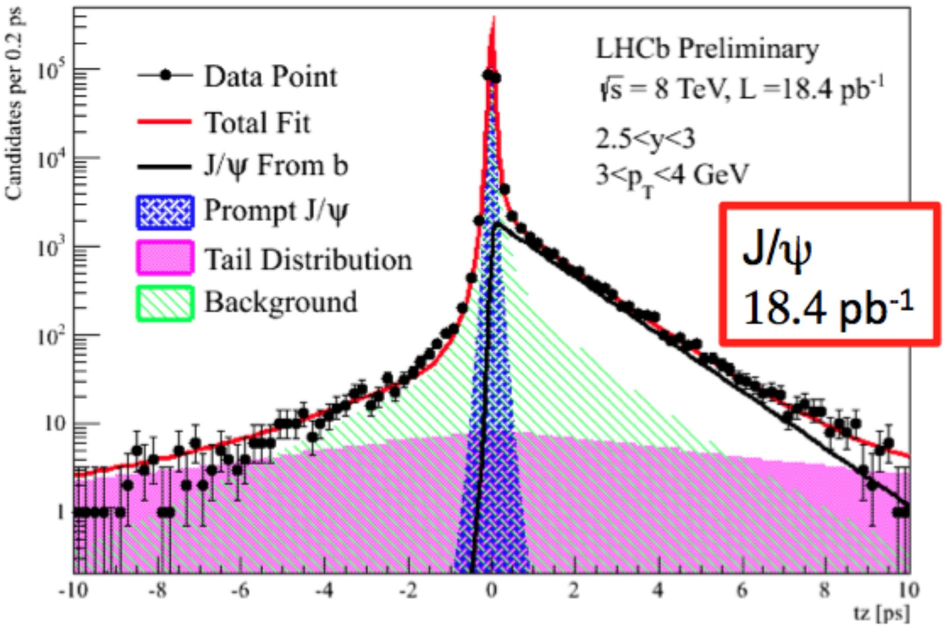
J/ψ 14.5 MeV/c^2

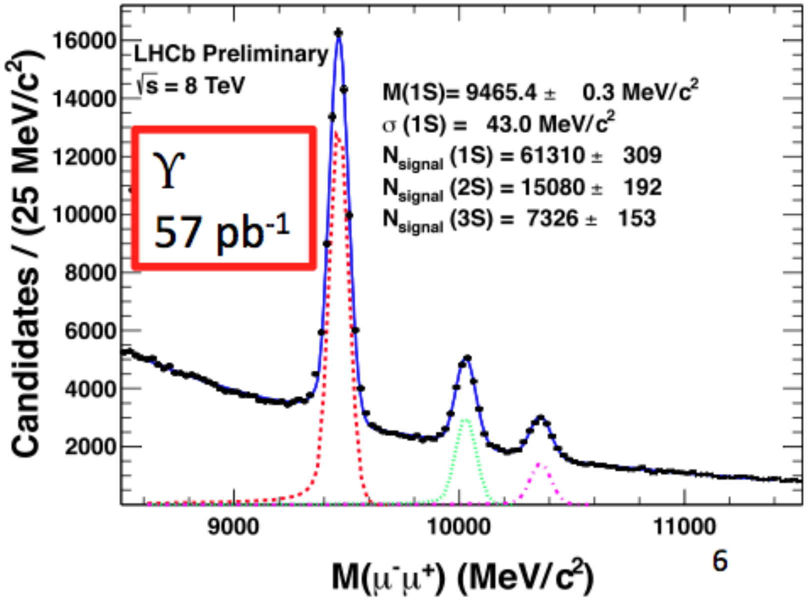
Υ 43 MeV/c^2 (was 47 MeV/c^2 in 2011)

Proper time resolution : 61 fs

Cross-sections expected to increase by ~15%







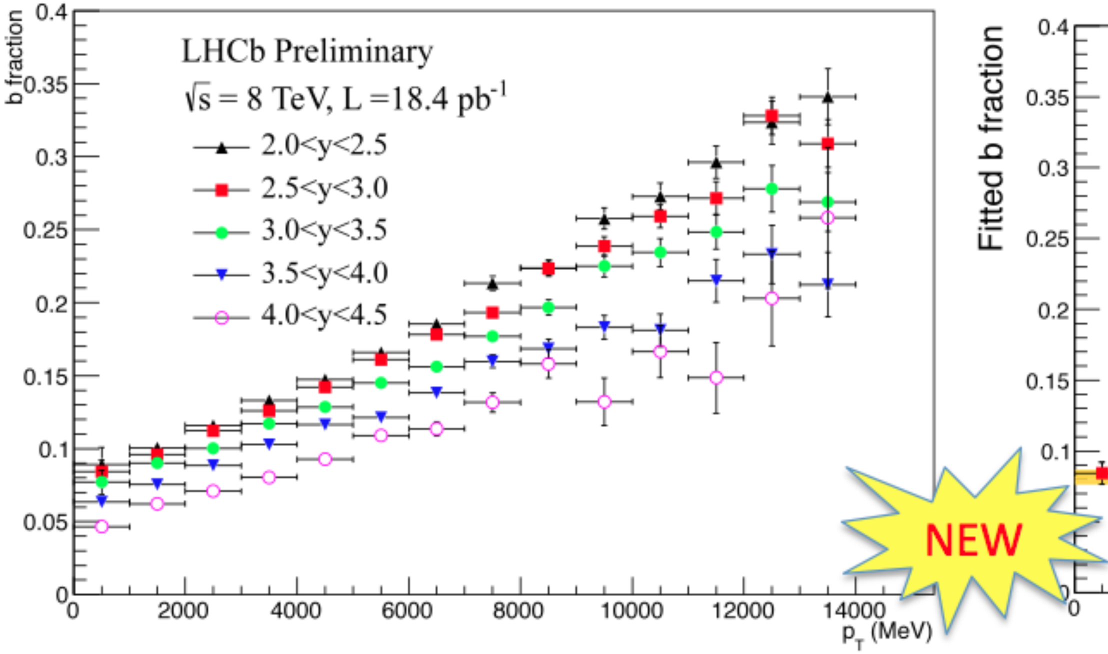
6

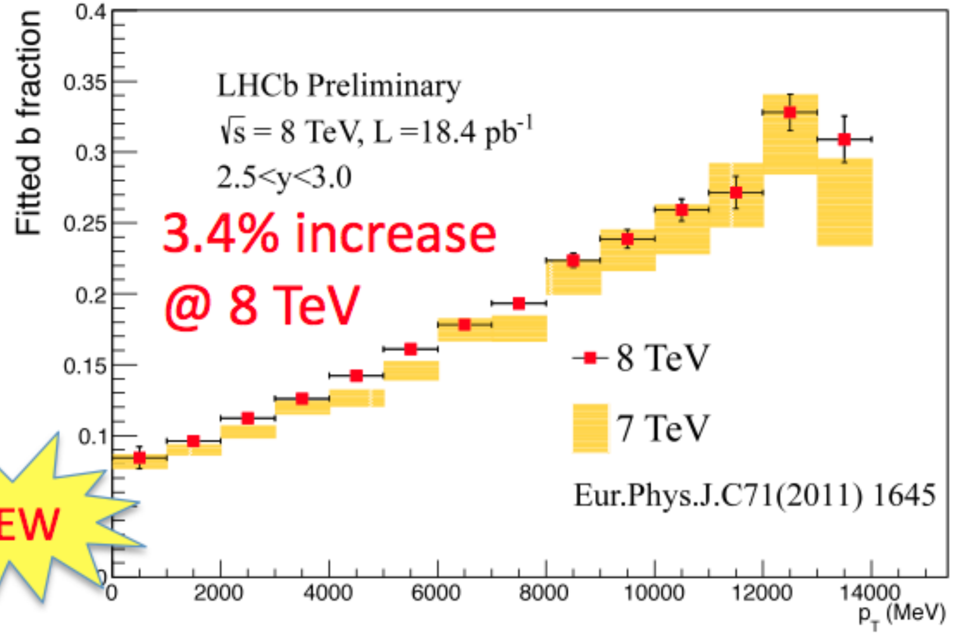
Quarkonia @ 8 TeV

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

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

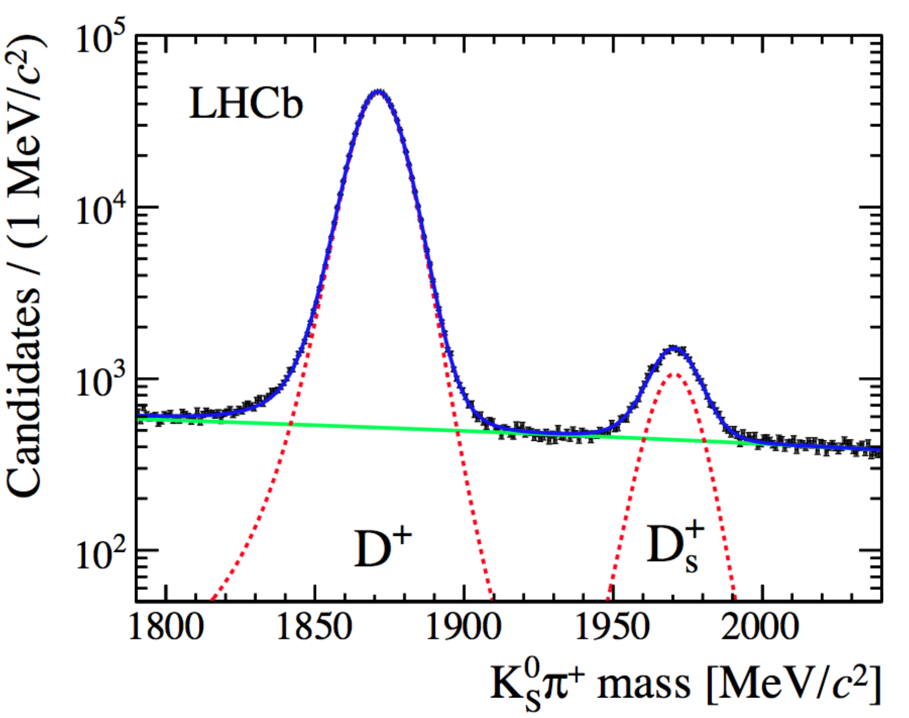
LHCb-CONF-2012-025





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

B production asymmetry



Peak fitted to Cruijff function

$$f(m) \propto \exp\left(\frac{-(m-\mu)^2}{2\sigma_{L,R}^2 + (m-\mu)^2\alpha_{L,R}}\right)$$

~1M D^+ candidates