Studies of Onia & Strangeness Production in pp-collisions at LHCb

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(on behalf of the LHCb collaboration)

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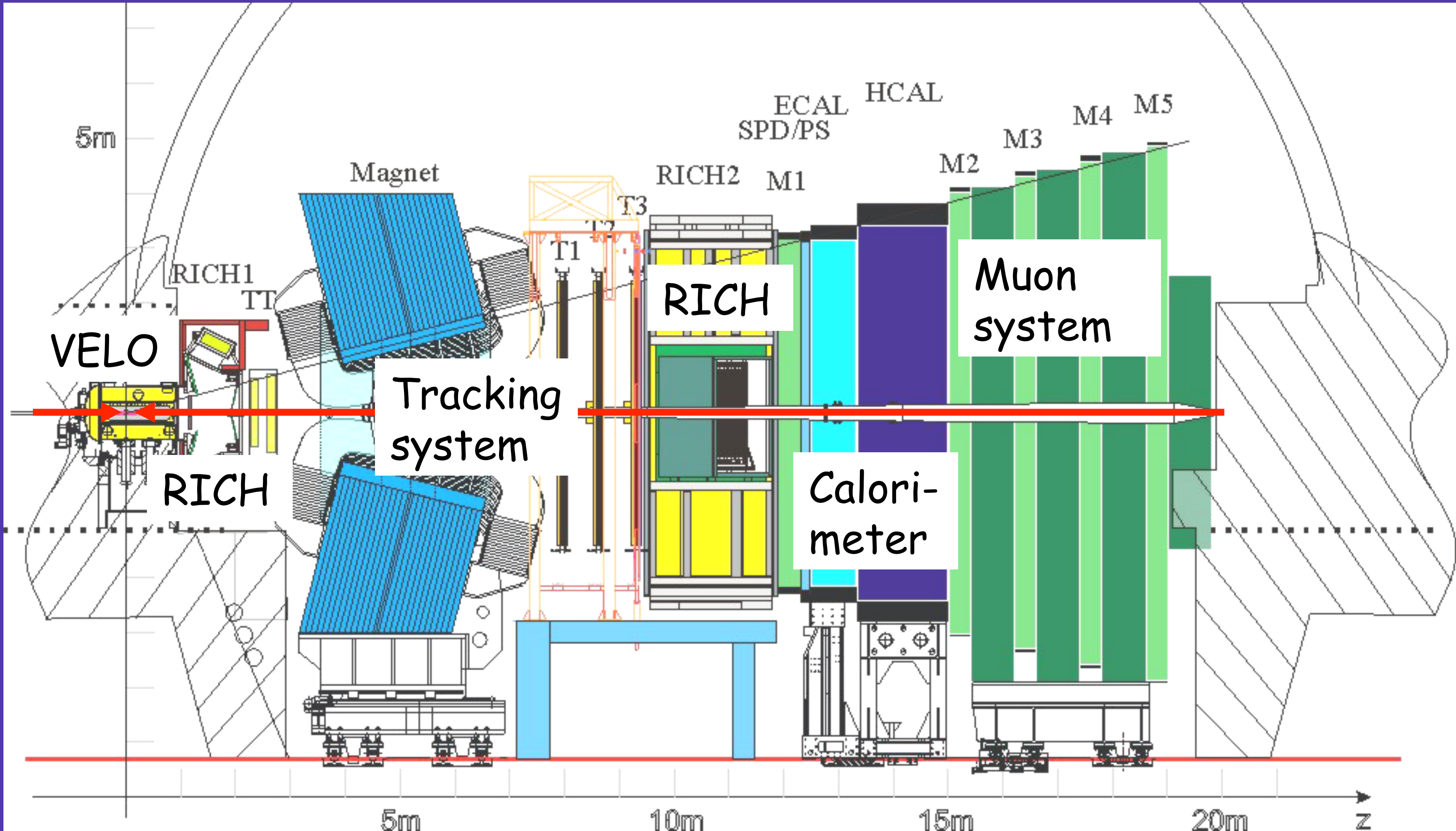
Outline

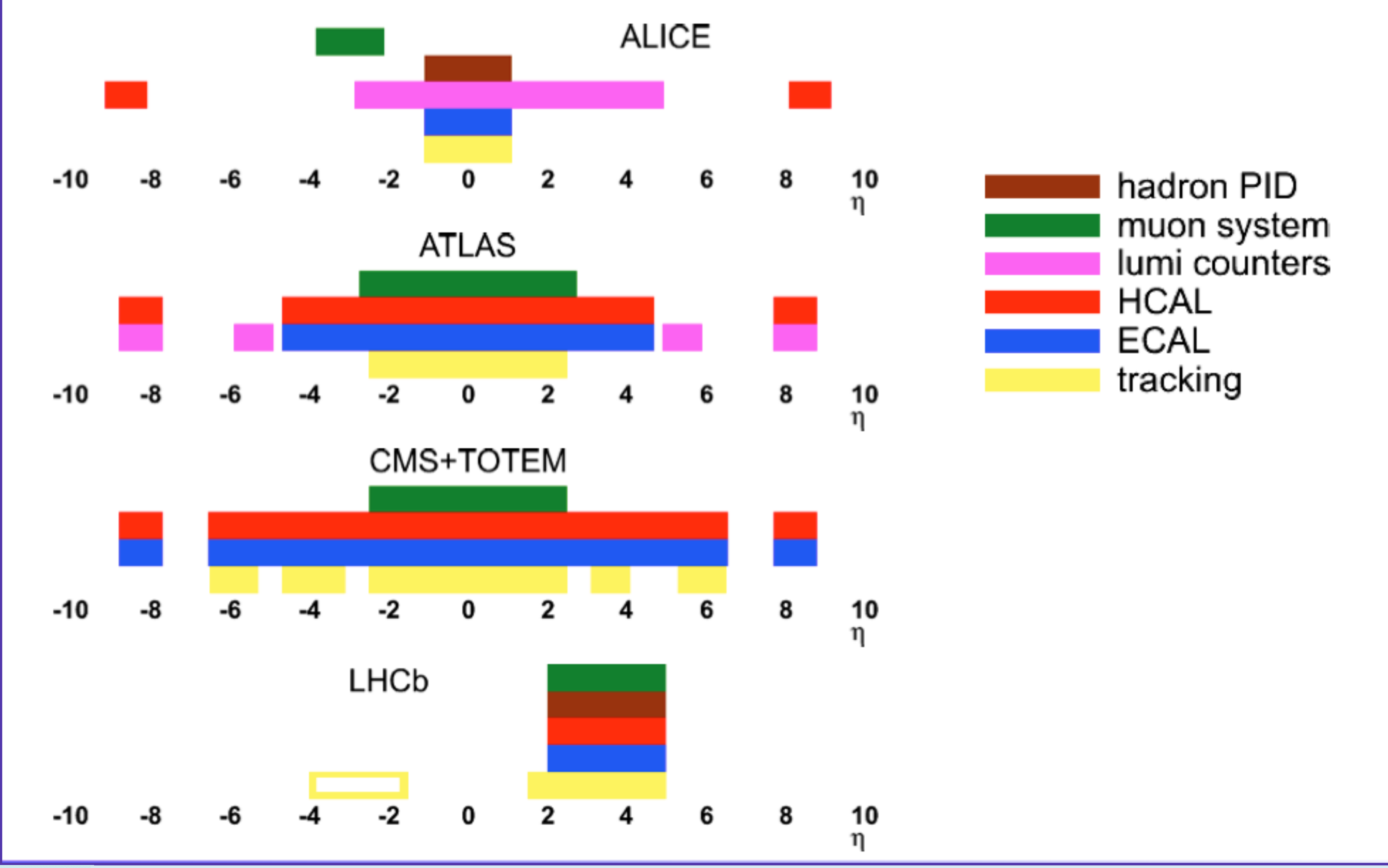
- LHCb detector
- Quarkonia Production
  - Charmonium,bottomonium, χ_c
  - Double charmonium & associated open charm
- Strangeness Production
  - Charged Particle ratios
  - V^0 production
  - Other strange baryon production

LHCb spectrometer

JINST 3 (2008) S08005



Acceptance of LHC Expts



Quarkonia Production

Motivation

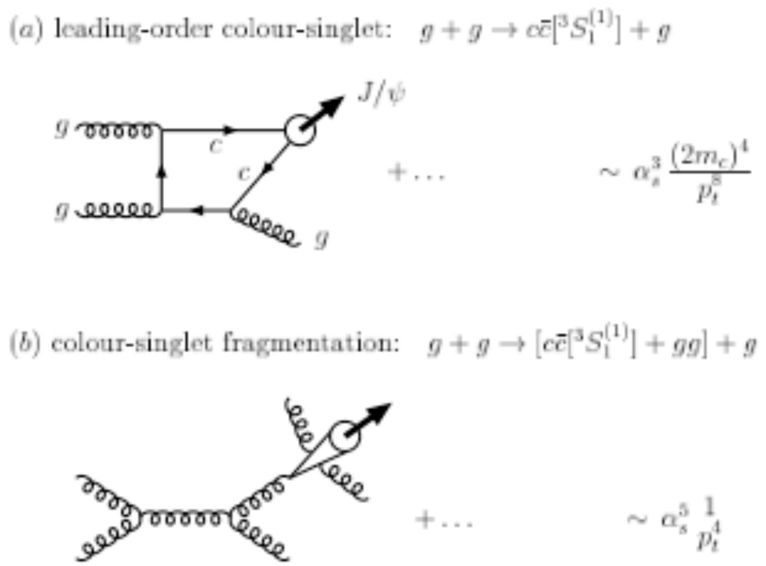
- Heavy $q\bar{q}$ simple applicaton of QCD(!)
  - Ideal testing ground for QCD
- Experimentally clean
  - Expt calibration
- Radial & orbital excitations
  - Good testing ground from QCD based models

Motivation

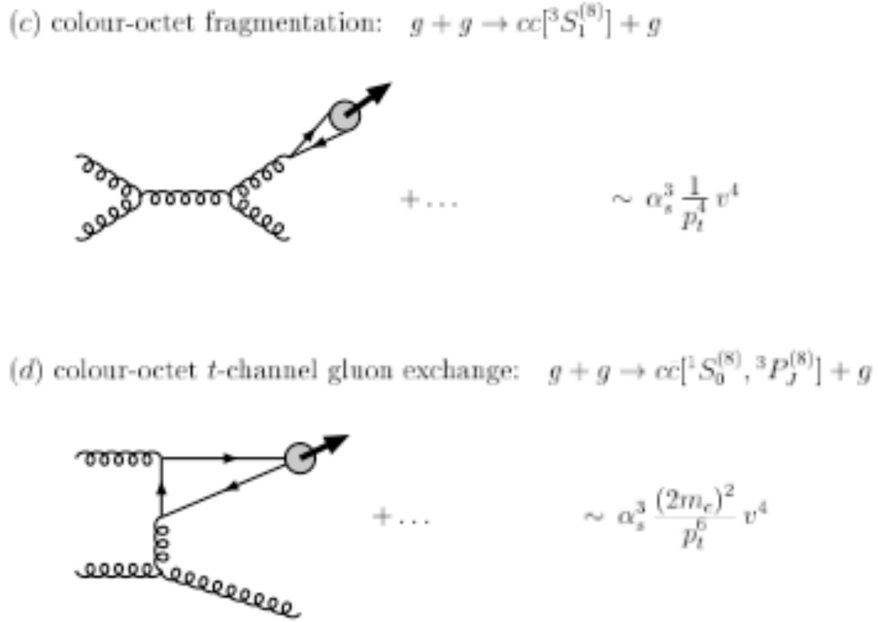
- Quarkonia usually described in framework of NRQCD
  - short distance (partonic calculations+PDF)
  - long distance matrix elements for quarkonia production
  - Colour octet(CO) + colour singlet(CS) models - kinematics
  - Problems in describing kinematics & polarisation in consistent manner
- Other 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

CSM vs COM

- CSM can be thought of as approx NRQCD
  - Only keep leading terms in *v*
- CSM & COM both also have "fragmentation" contributions
- In fact "fragmentation" is expected to dominate production
  - Colour octet fragmentation expected to dominate
  - BUT…

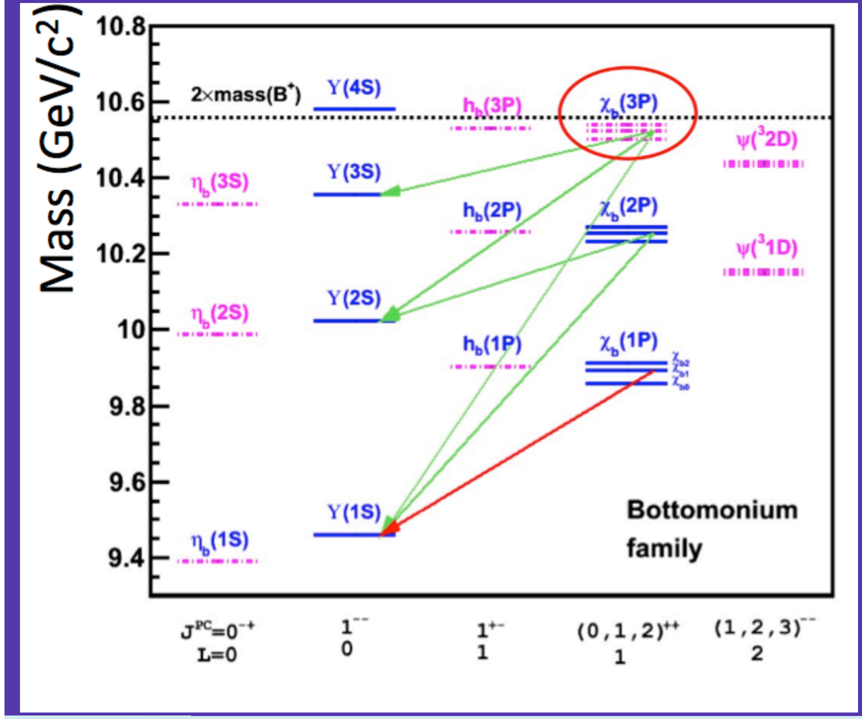


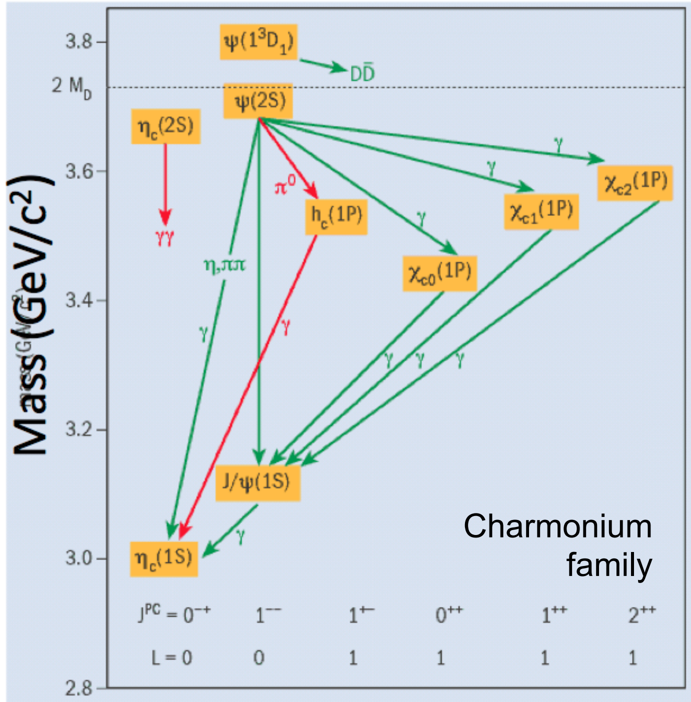
M. Kramer, Prog.Part.Nucl.Phys.47(2001) 141-201



Heavy Onia

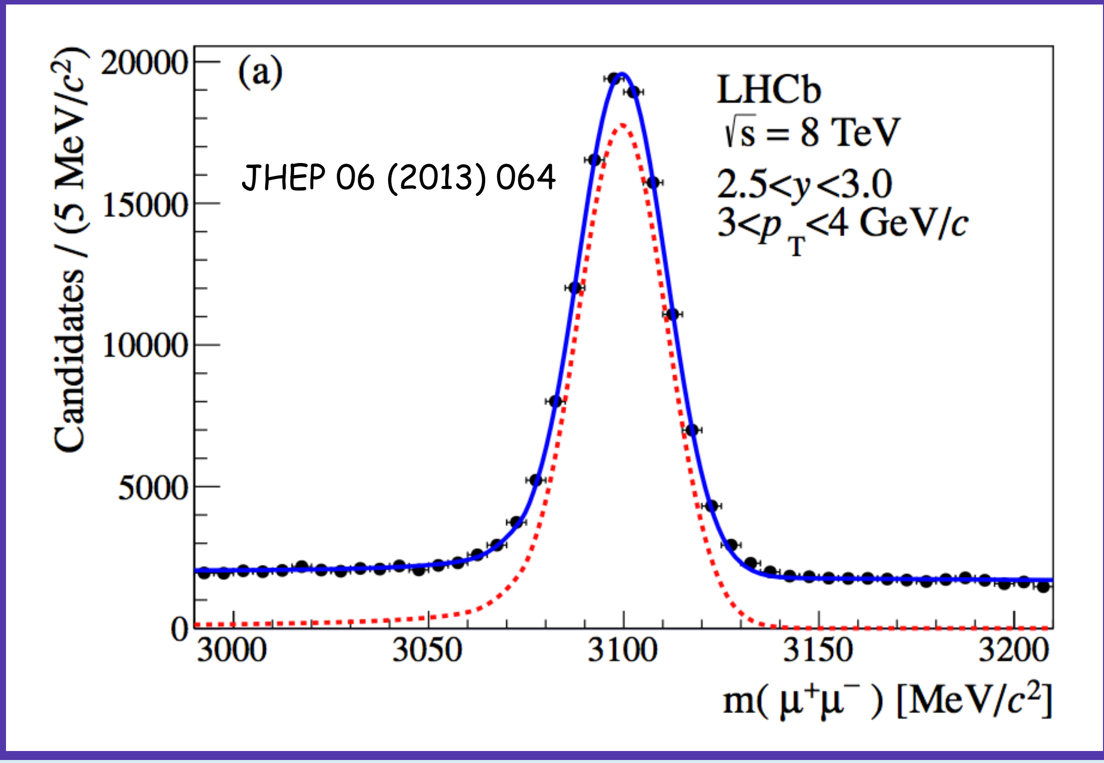
- Measurements also important tests of CS & CO production mechanism
  - Feed down fractions
  - Ratio of spin states
- Needed for polarisation measurements





LHCb measurements

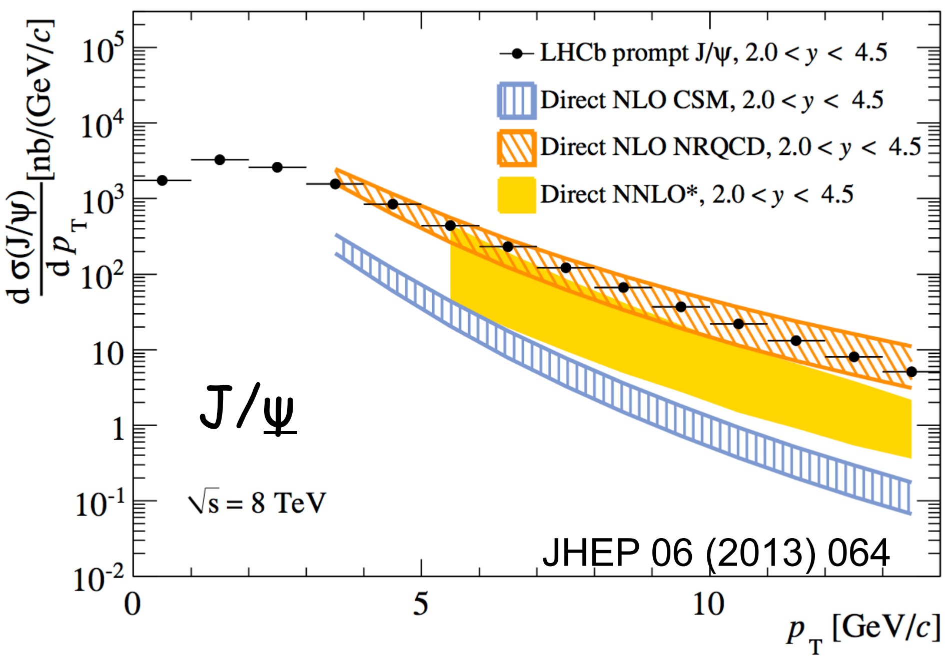
- Analysis rapidity range: $2 < y < 4.5$
- Low p_T triggers
  - Track p_T typically ~0.5 GeV/c^2

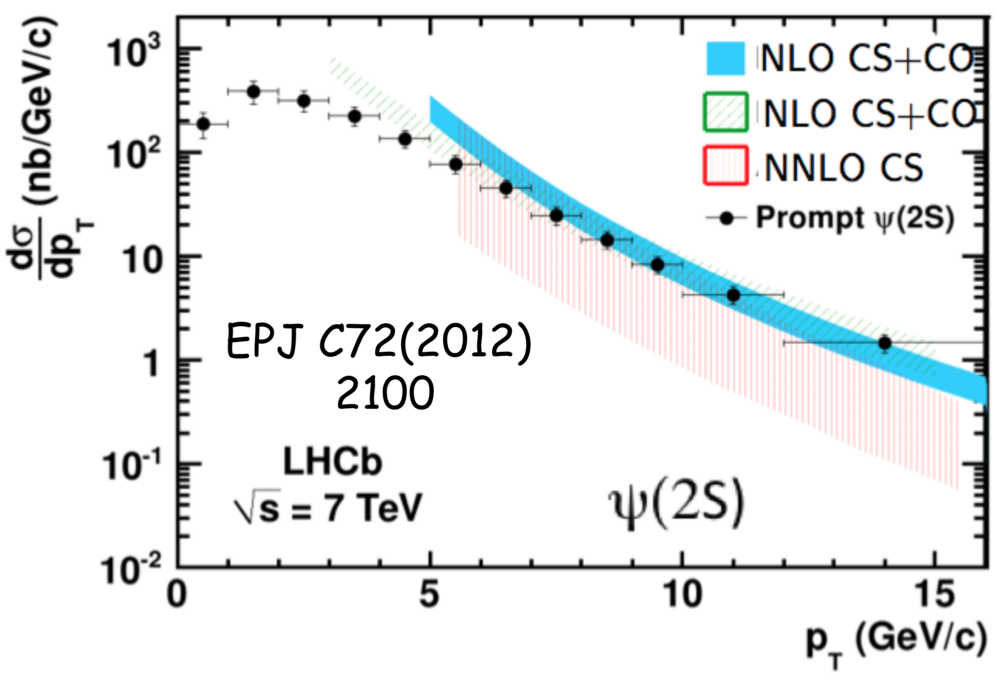


Quarkonia – prompt charmonia

J.M. Campbell et al. PRL 98 (2007) 252002
M. Butenschoen et al. PRL 106 (2011) 022003
M. Butenschoen et al. PRD 84 (2011) 051501
J.-P. Lansberg, EPJ C61 (2009) 693.

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.

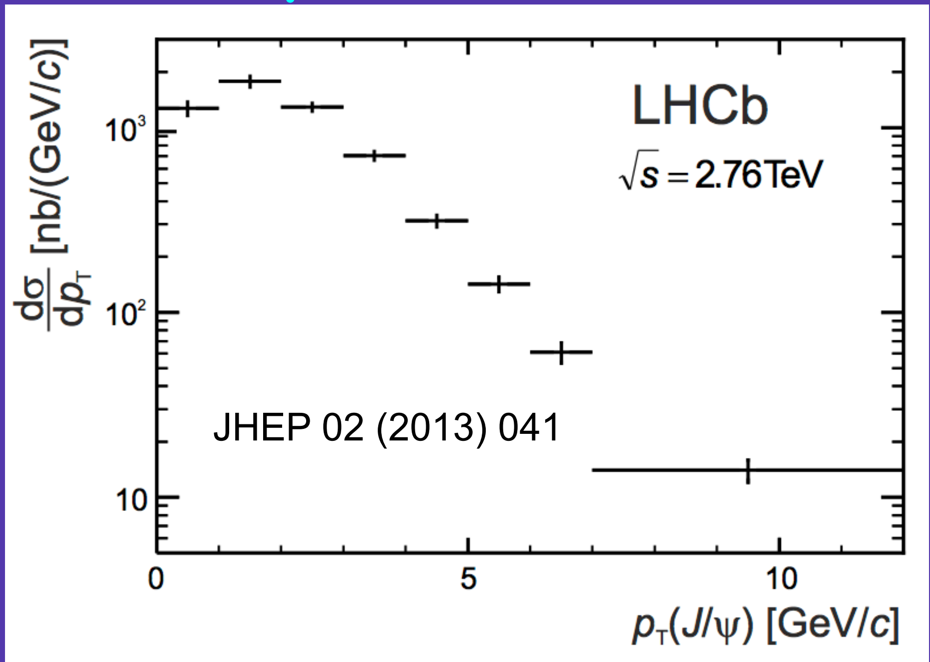




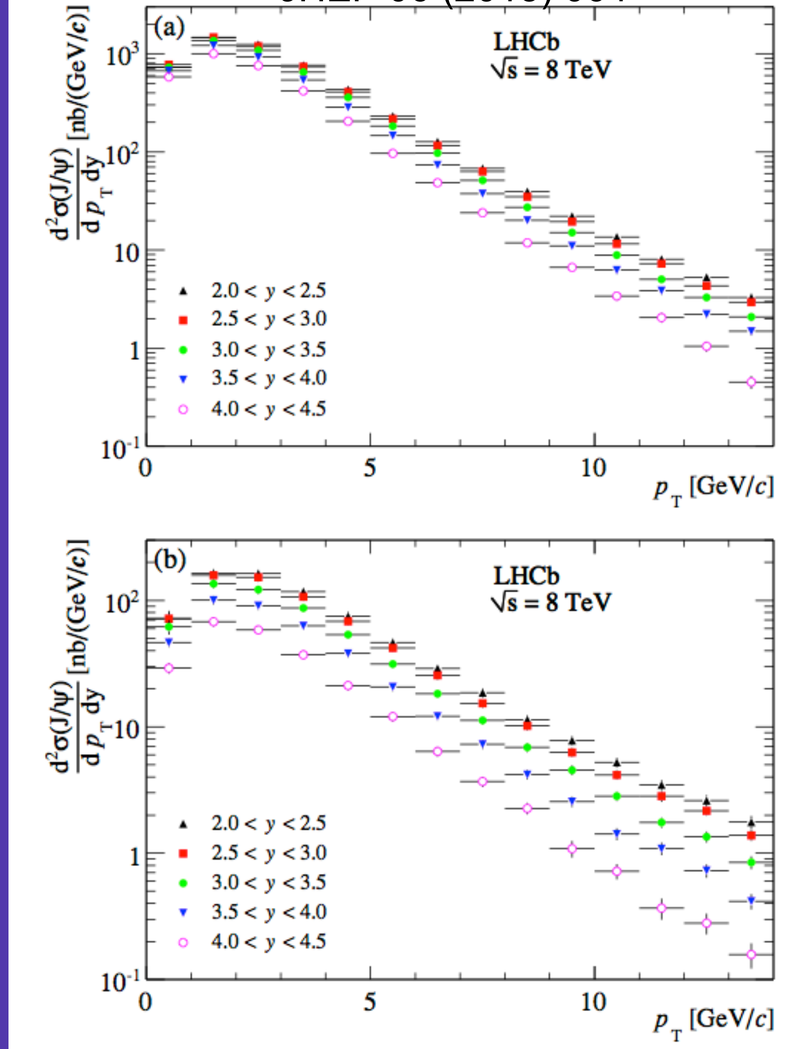
- Large p_T tails well reproduced especially in CO models

Quarkonia

- Prompt J/ψ



JHEP 06 (2013) 064

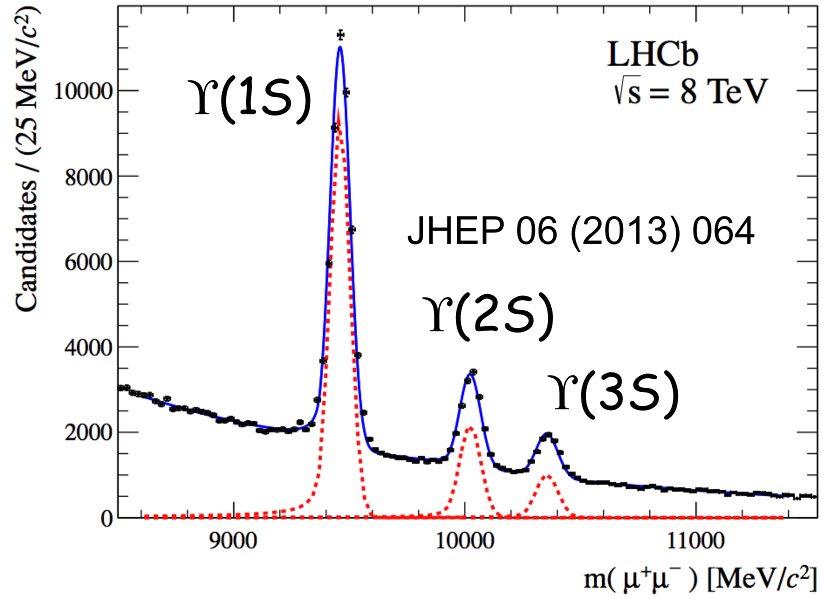


$$\sigma(\text{prompt } J/\psi,\ p_T < 14 \text{ GeV/c}, 2.0 < y < 4.5, \sqrt{s} = 8 \text{ TeV}) = 10.94 \pm 0.02 \pm 0.79\ \mu\text{b}$$

$$\sigma(\text{prompt } J/\psi,\ p_T < 12 \text{ GeV/c}, 2.0 < y < 4.5, \sqrt{s} = 2.76 \text{ TeV}) = 5.6 \pm 0.1 \pm 0.4\ \mu\text{b}$$

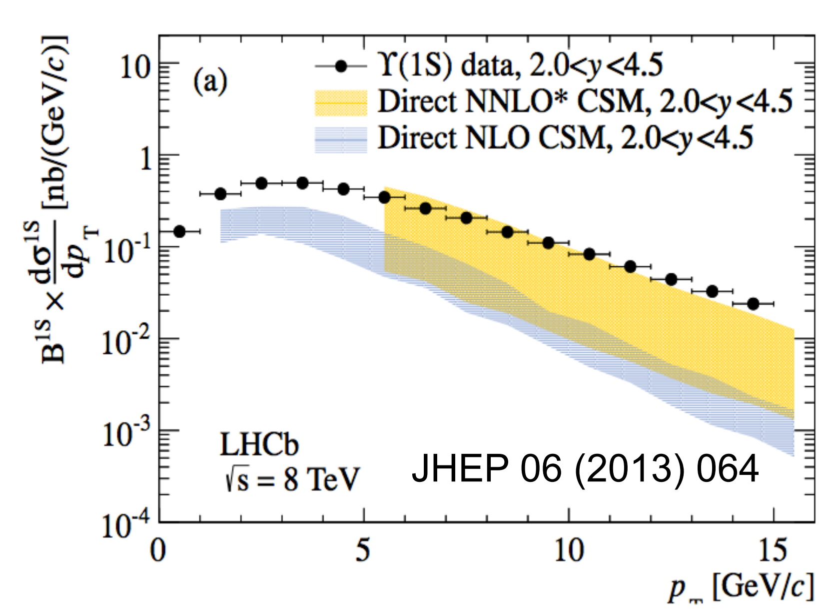
Quarkonia - Prompt bottomonium

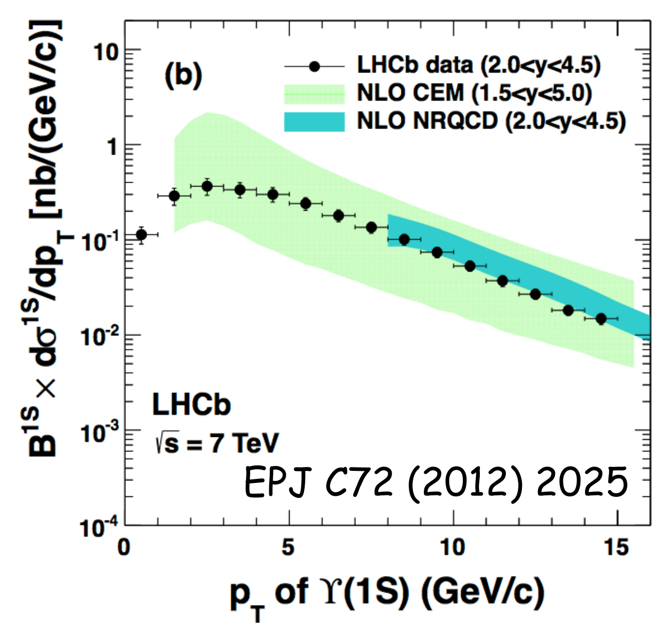
- Discrimination of theoretical models not yet feasible with differential dist^{bn}
  - except NLO CSM out by order of magnitude



J.M. Campbell et al PRL 98 (2007) 252002
P. Artoisenet et al PRL 101 (2008) 152001

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

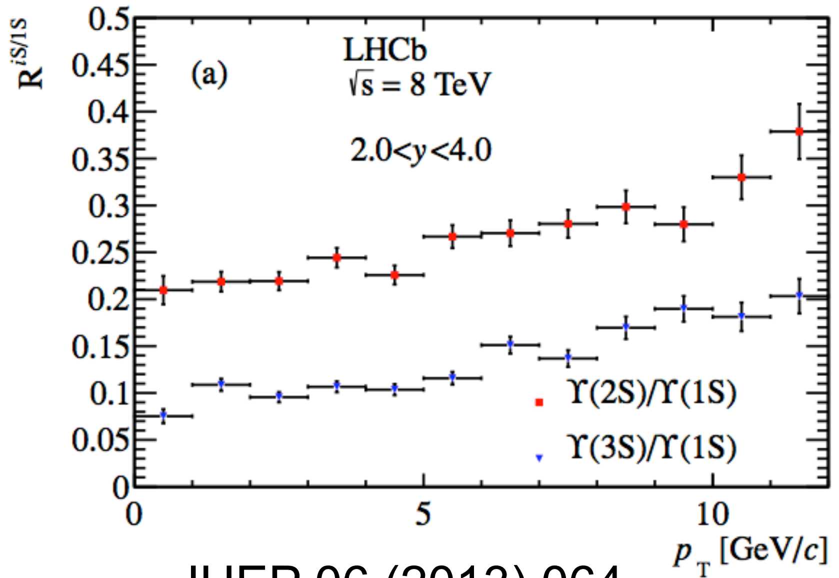




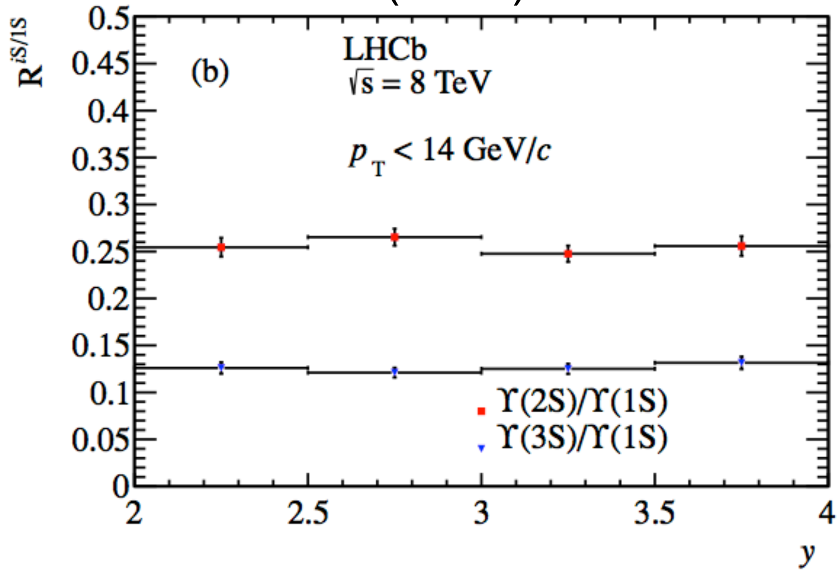
Quarkonia @ 8TeV

Ratio of Upsilon production flat as a function of y & increases as a function of p_T

Results consistent with 7 TeV observation



JHEP 06 (2013) 064



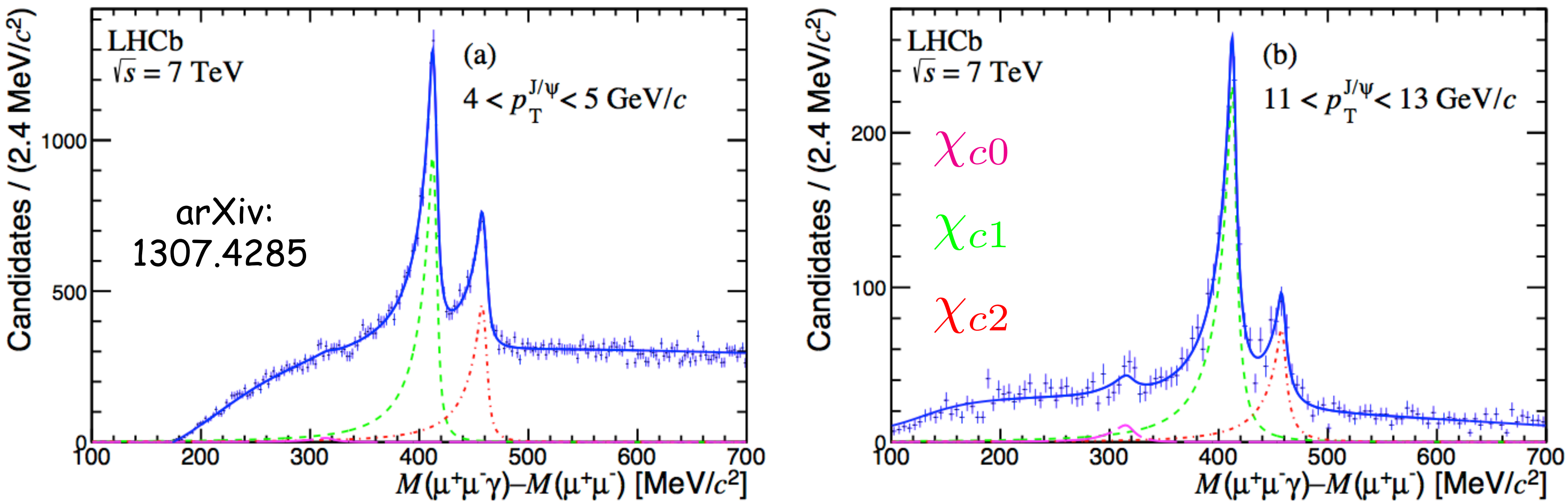
Higher Excited Onia

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

- Photons can be identified
  - Directly in ECAL
  - Converted before magnet

Phys.Lett. B714 (2012) 215
Phys.Lett.B718 (2012) 431
arXiv:1307.4285

First evidence of χ_{c0} at a hadron collider

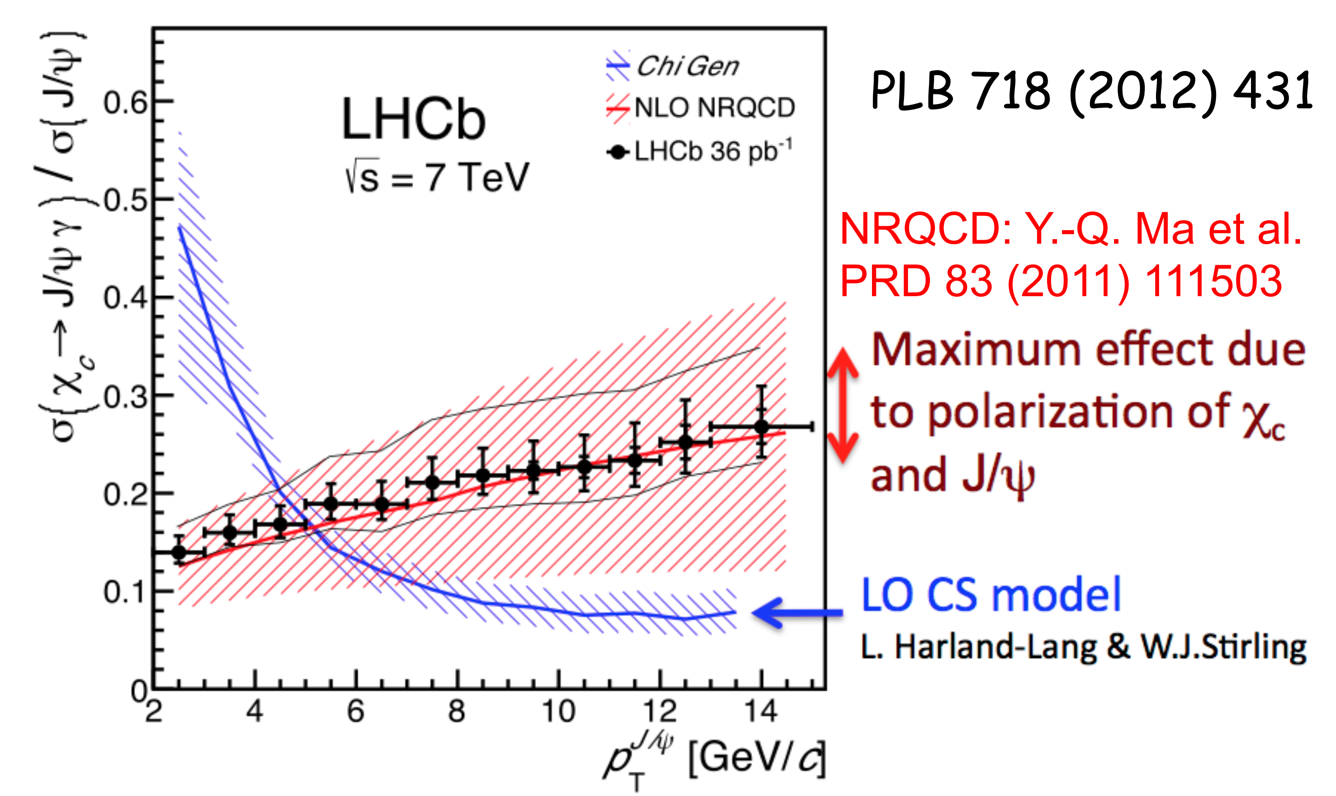


Heavy Onia: χ_c

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

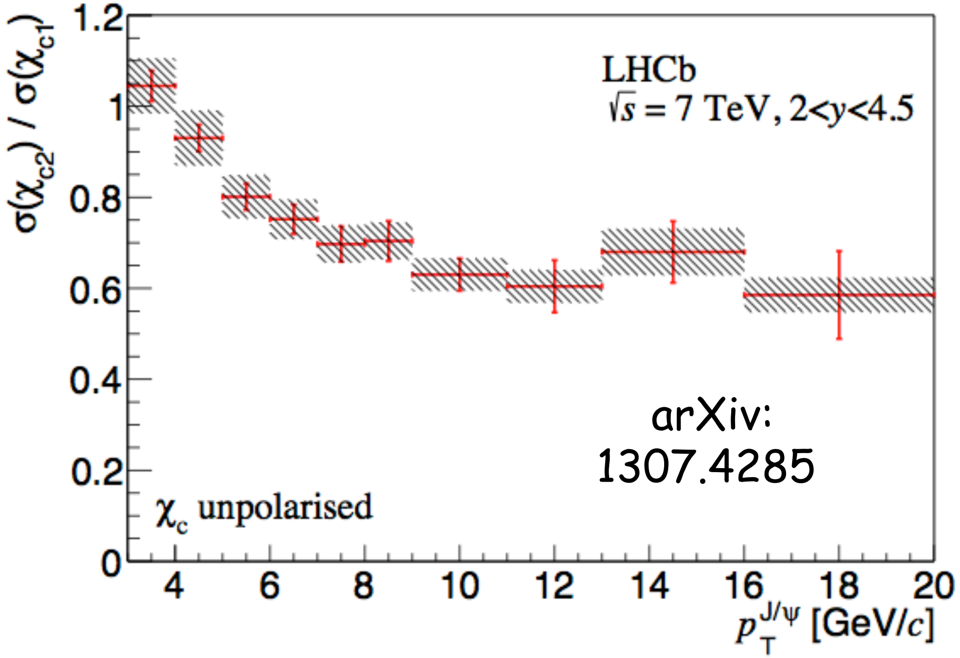
$$\frac{\sigma(\chi_c \to J/\Psi\gamma)}{\sigma(J\Psi)} \approx \frac{\sigma(\chi_c \to J/\Psi\gamma)}{\sigma^{\mathrm{dir}}(J\Psi) + \sigma(\Psi(2S) \to J/\Psi X) + \sigma(\chi_c(\to J/\Psi\gamma)}$$

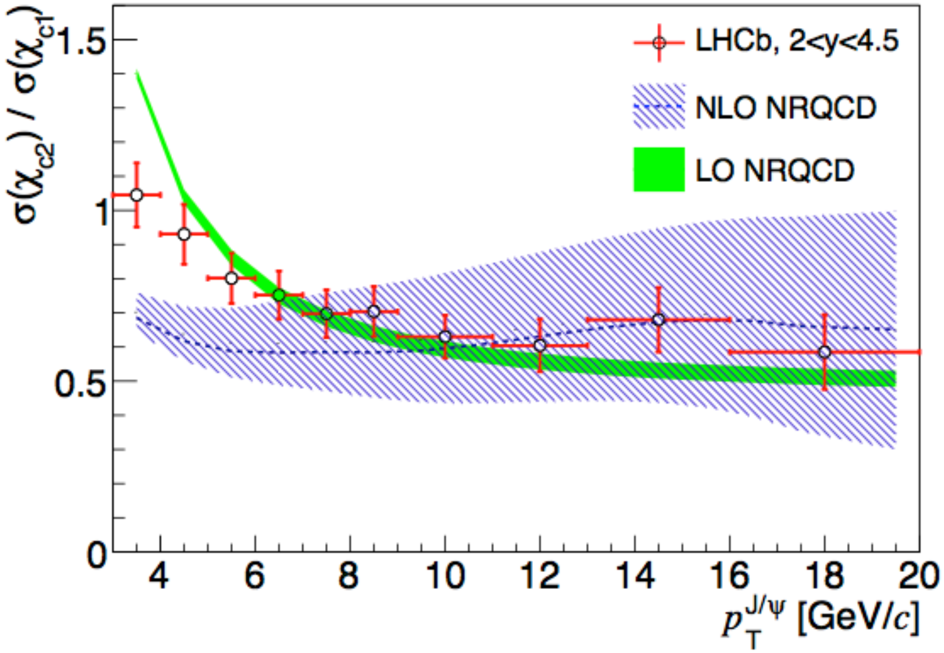
$2 < y_{J/\psi} < 4.5 \quad 2 < p_{T\,J/\psi} < 15$ GeV/c



LO CS model fails to describe data

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





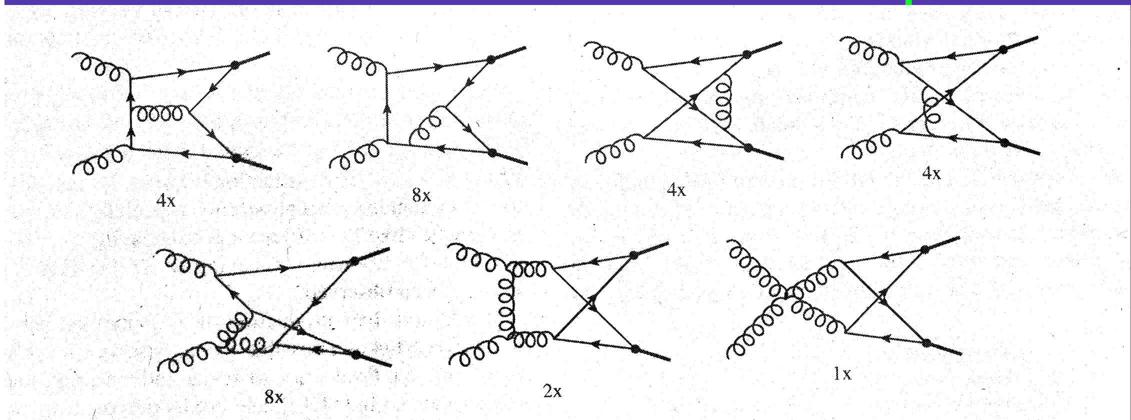
NLO NRQCD: Y.-Q. Ma et al. PRD 83 (2011) 111503
LO NRQCD: A. Likhoded et al. arXiv:1305.2389

Good agreement with NLO NRQCD prediction

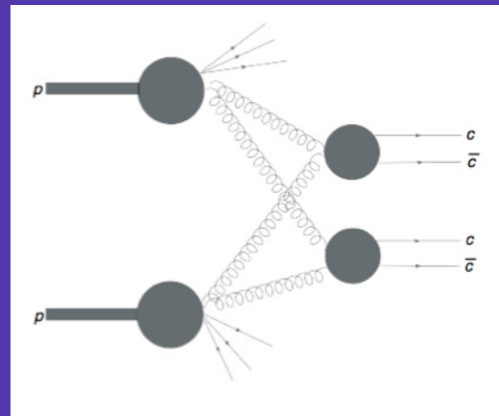
Multiple Quarkonia Production & associated open charm

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

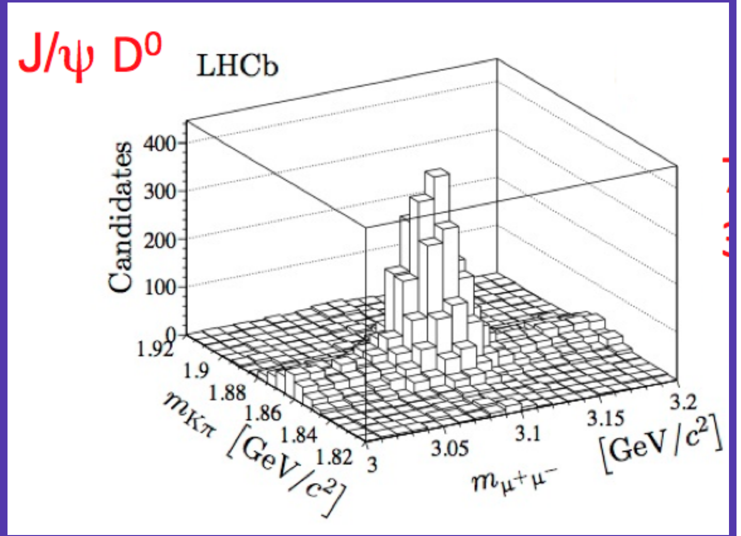
Phys.Lett. B707 (2012) 52

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

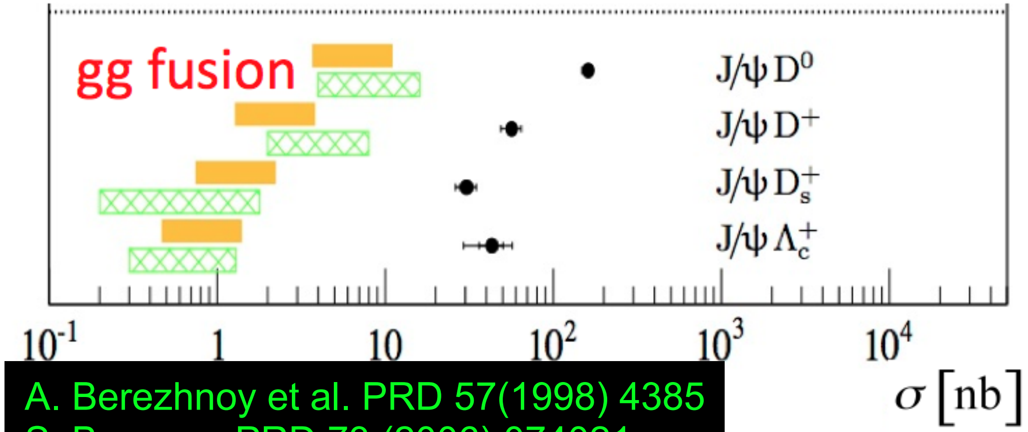
$$\frac{\sigma^{J/\psi J/\psi}}{\sigma^{J/\psi}} = (5.1 \pm 1.0(\mathrm{stat}) \pm 0.6(\mathrm{syst})^{+1.2}_{-1.0}(\mathrm{pol})) \times 10^{-4}$$

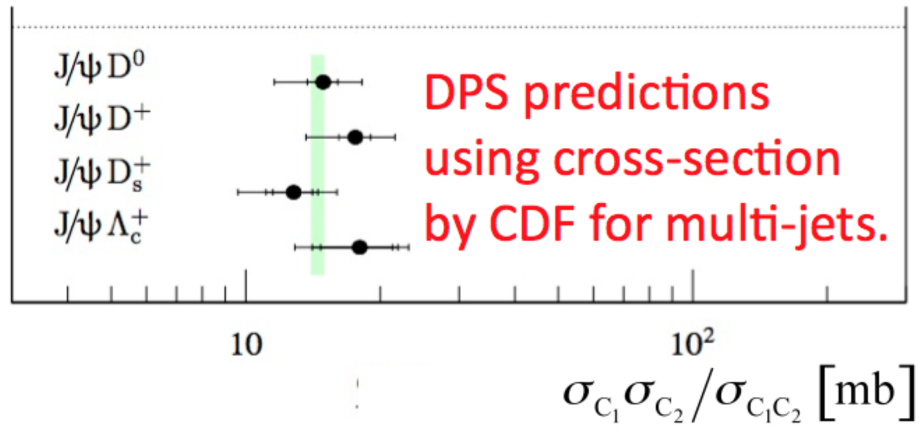
J/ψ production & associated charm

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





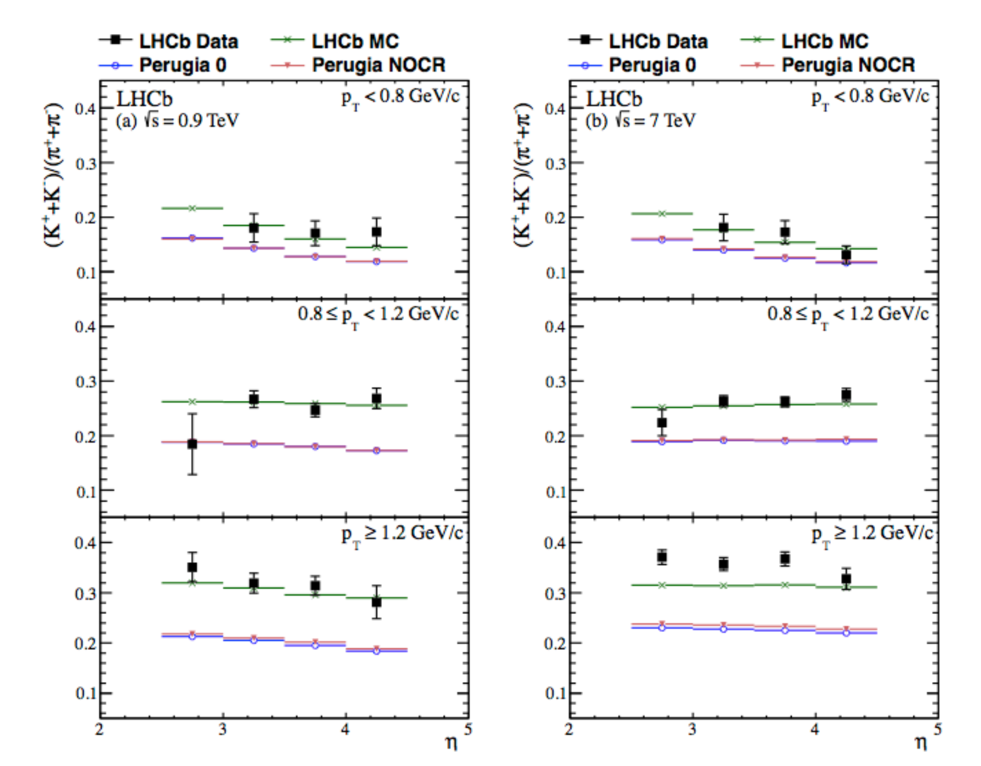
A. Berezhnoy et al. PRD 57(1998) 4385
S. Baranow PRD 73 (2006) 074021
J-.P. Landsberg EPJ C61 (2009) 693

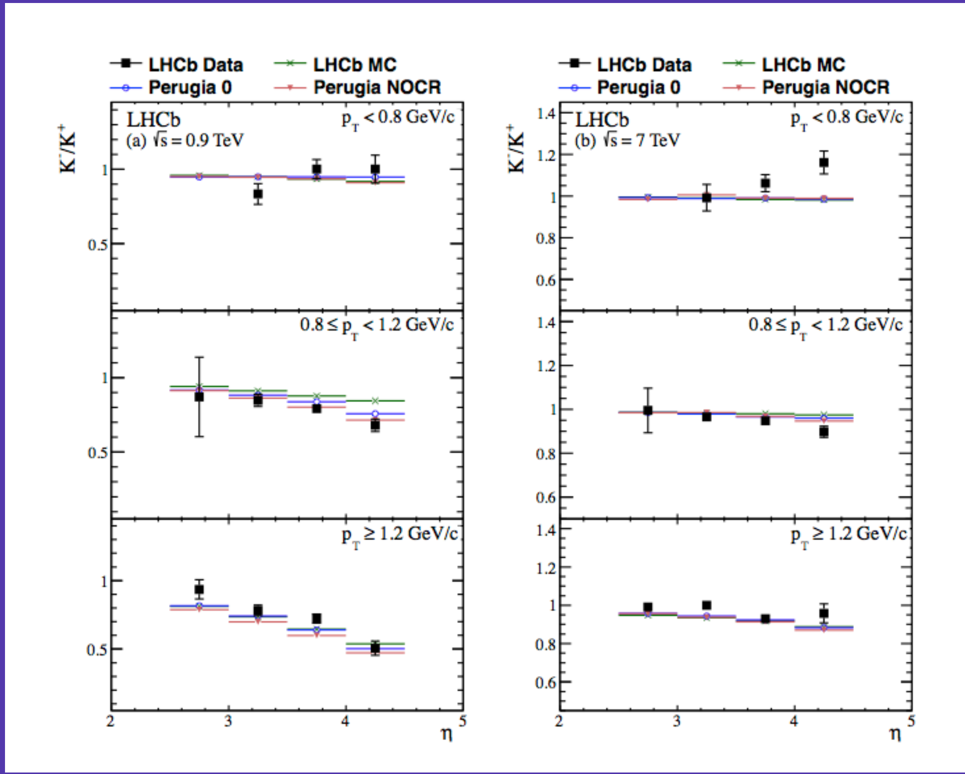
- Measured X-sections suggest DPS needed

Strange Particle Production

Charged kaon production

Eur.Phys.J. C72 (2012) 2168



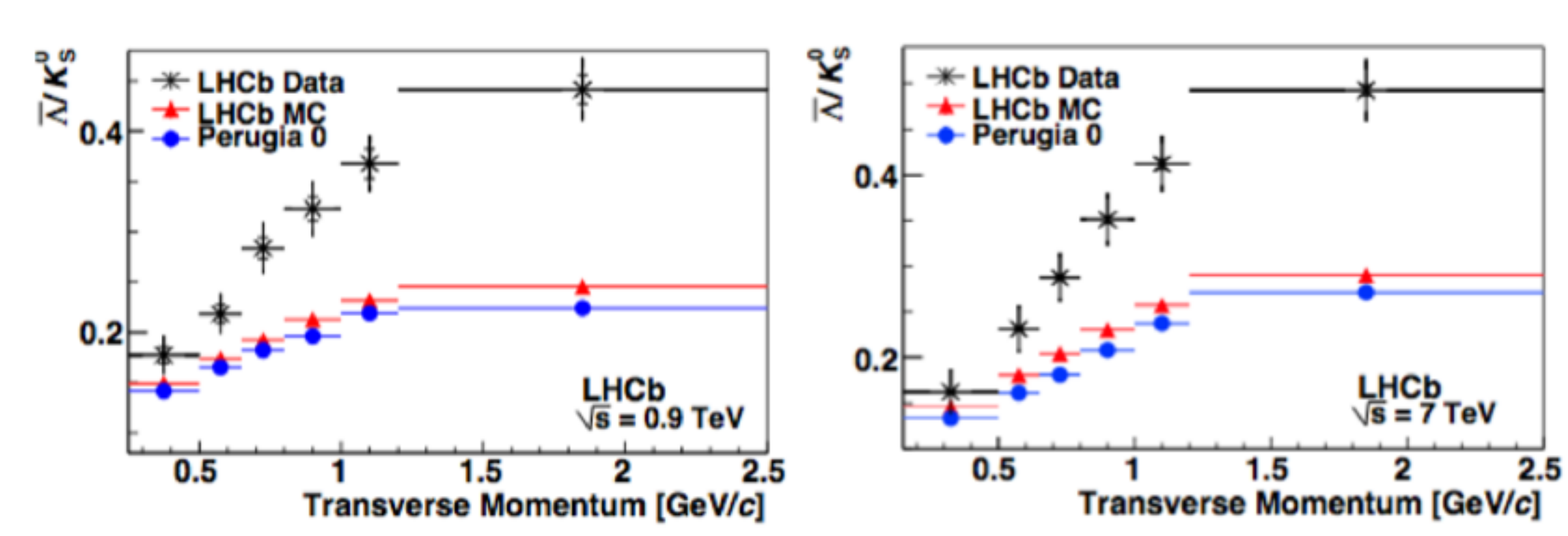


K/π ratio best described by LHCb tune (I. Belyaev et al IEEE Nucl.Sci.Symp.Conf.Rec. (2010) 1155)

Clear rise as p_T ↑

+/- ratio not unity. In general well described by MC models.

$\Lambda(\Lambda\text{bar})/K_S^0$ production ratios



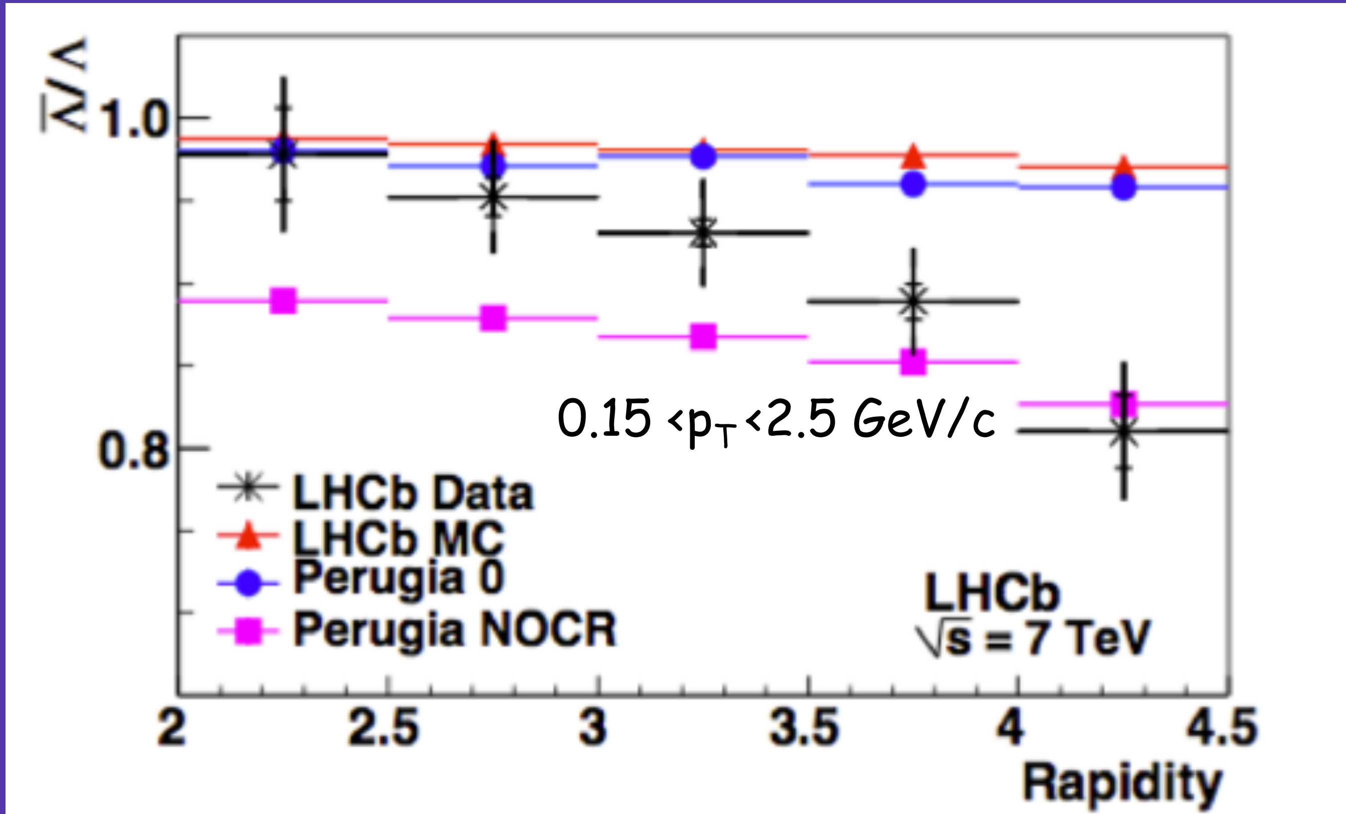
Ratio rises at p_T raises as expected

Rise in forward region greater than MC predictions

JHEP 08 (2011) 034

Λ production ratios

JHEP 08 (2011) 034



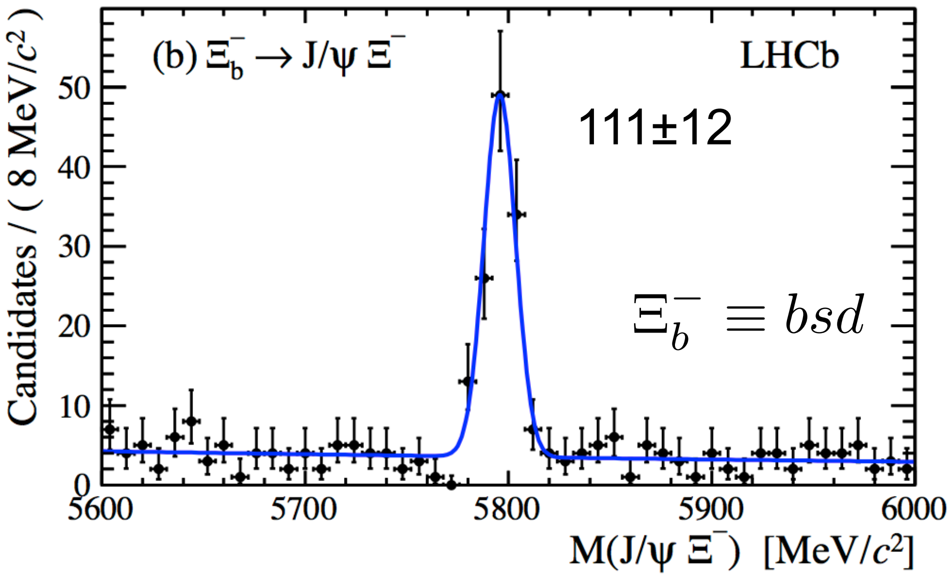
AntiParticle/particle ratio flat (~1) in central region

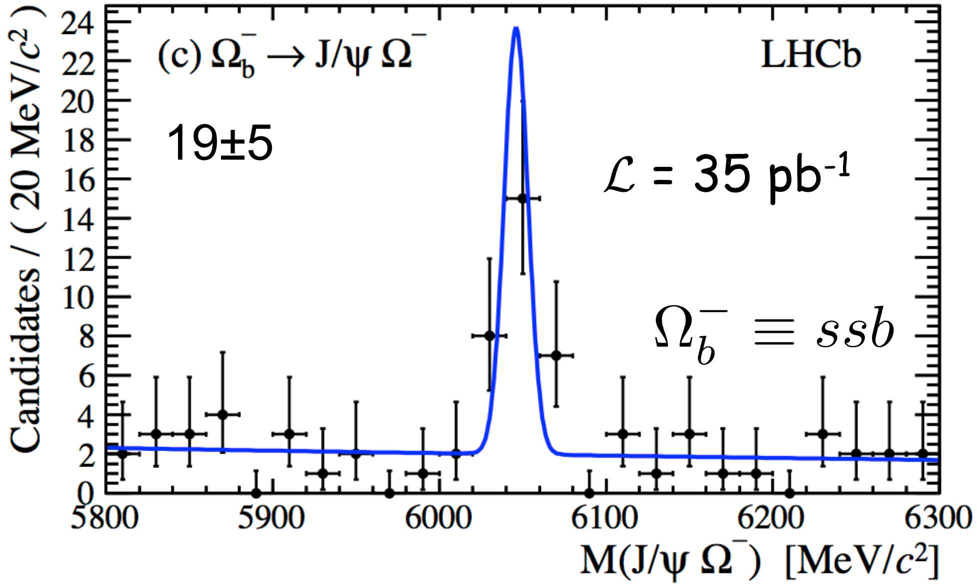
Ratio falls off go to forward region

MC predictions remain essentially flat

Ω^-_b & Ξ^-_b production

PRL 110 (2013) 182001





	M(Ξ^-_b) (MeV/c²)	M(Ω^-_b) (MeV/c²)
CDF	5790.9±2.7	6054.4±6.9
D0	5774±19	6165±16
PDG	5791.1±2.2	6071±40
LHCb	5795.8±1.0	6046.0±2.3

Test of constituent quark models/ lattice QCD

World's most precise mass measurements

Summary & Prospects

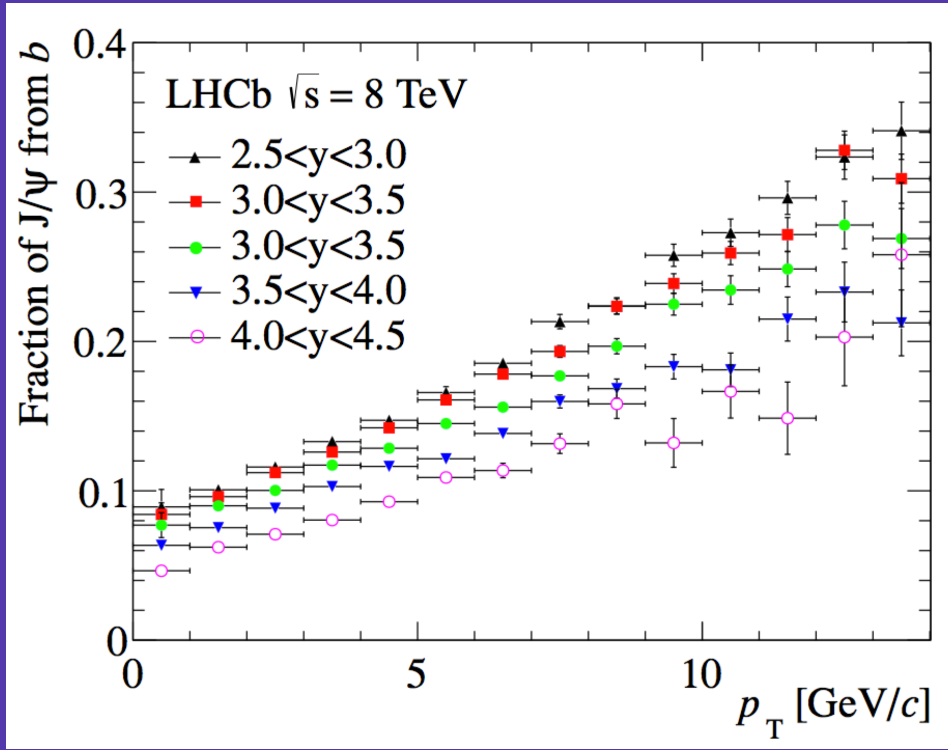
- LHCb has very many important production results
  - First observations
  - X-section measurements
  - Evidence for the importance of DPS
  - Excited quarkonia
- Polarisation measurements on the way
- More detailed studies of kinematic distribution of double J/ψ production
- Unique measurements on the forward rapidity region
- Much data still to analyse
  - $\mathcal{L}$ = 2.08 fb^{-1} (2012); $\mathcal{L}$ = 1.1 fb^{-1} (2010-11)

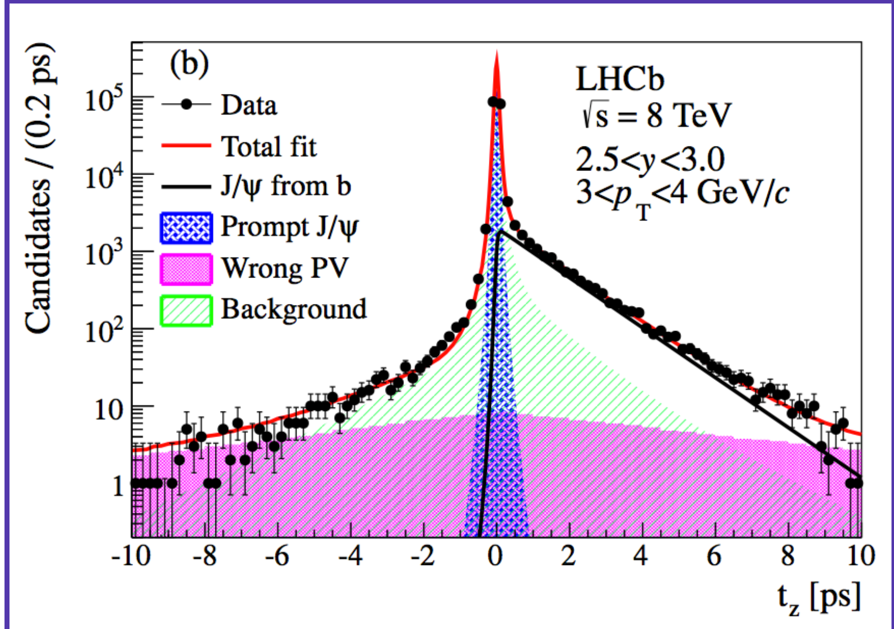
Backups

Charmonium from b

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

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

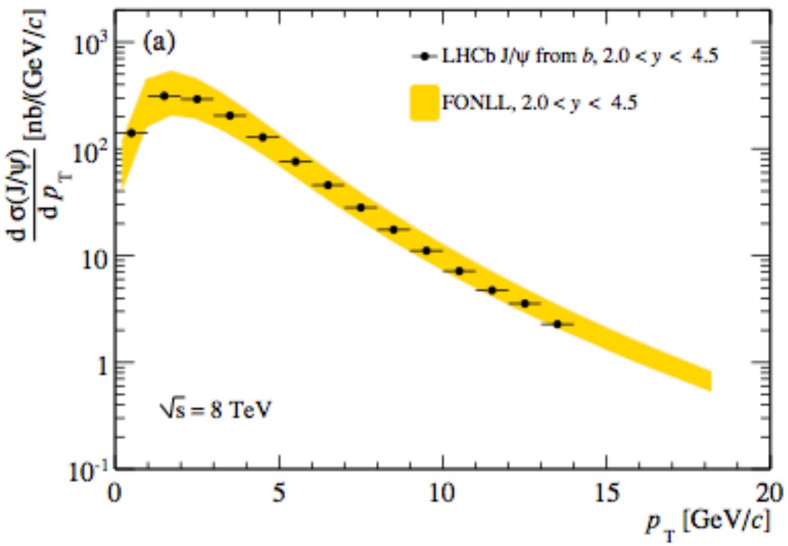


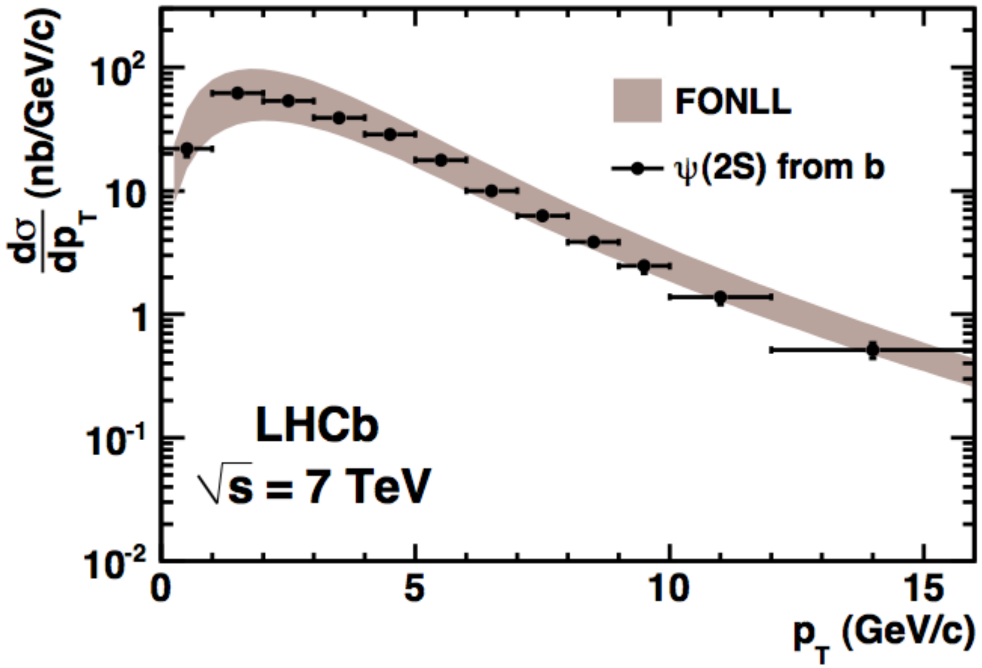


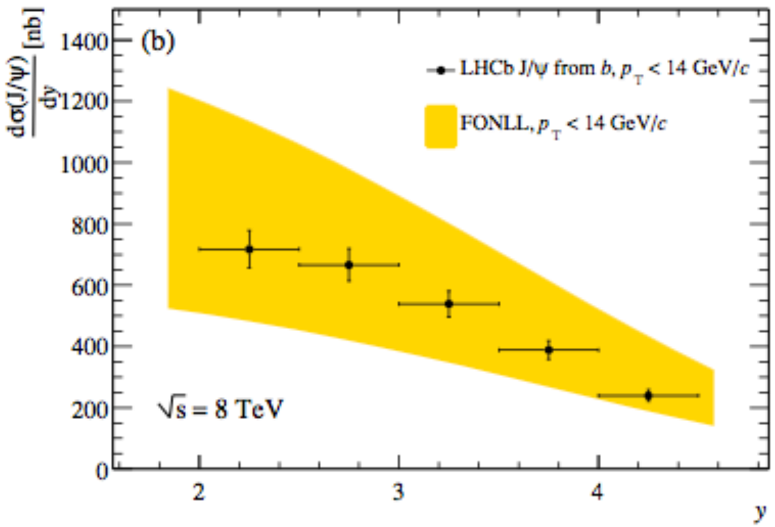
Fraction of J/ψ from b increases as p_T ↑

Fraction of J/ψ from b decreases as y ↑

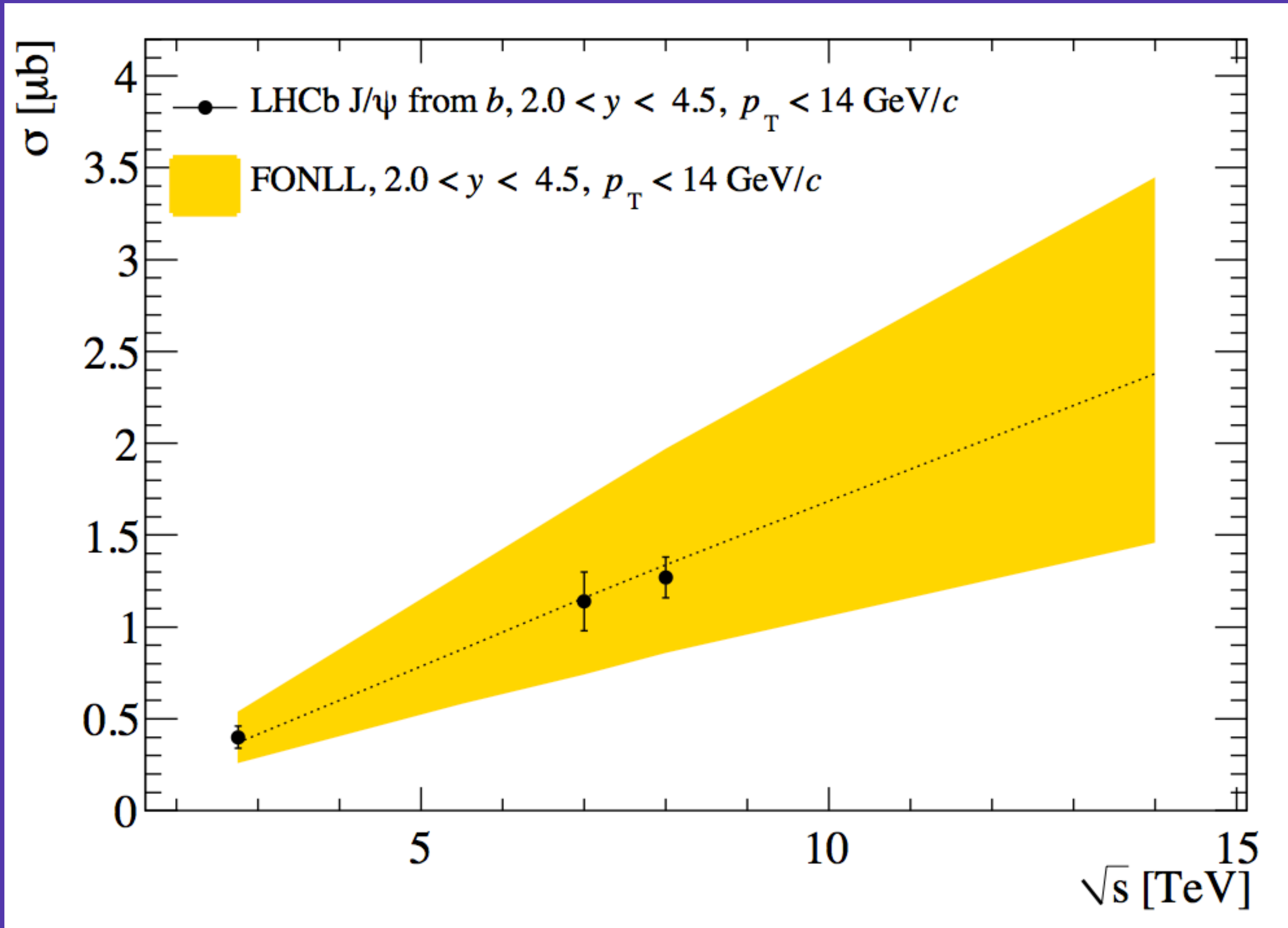
Onia from B-decays







Charmonium from B-decays



Charmonium & associated charm

Mode	σ [nb]	$\sigma_{CC}/\sigma_{C\overline{C}}$ [%]	$\sigma_{C_1}\sigma_{C_2}/\sigma_{C_1C_2}$ [mb]
D^0D^0	$690 \pm 40 \pm 70$	10.9 ± 0.8	$2 \times (42 \pm 3 \pm 4)$
$D^0\overline{D}^0$	$6230 \pm 120 \pm 630$		$2 \times (4.7 \pm 0.1 \pm 0.4)$
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 Charm Production

- Handle on DPS and sea charm quarks

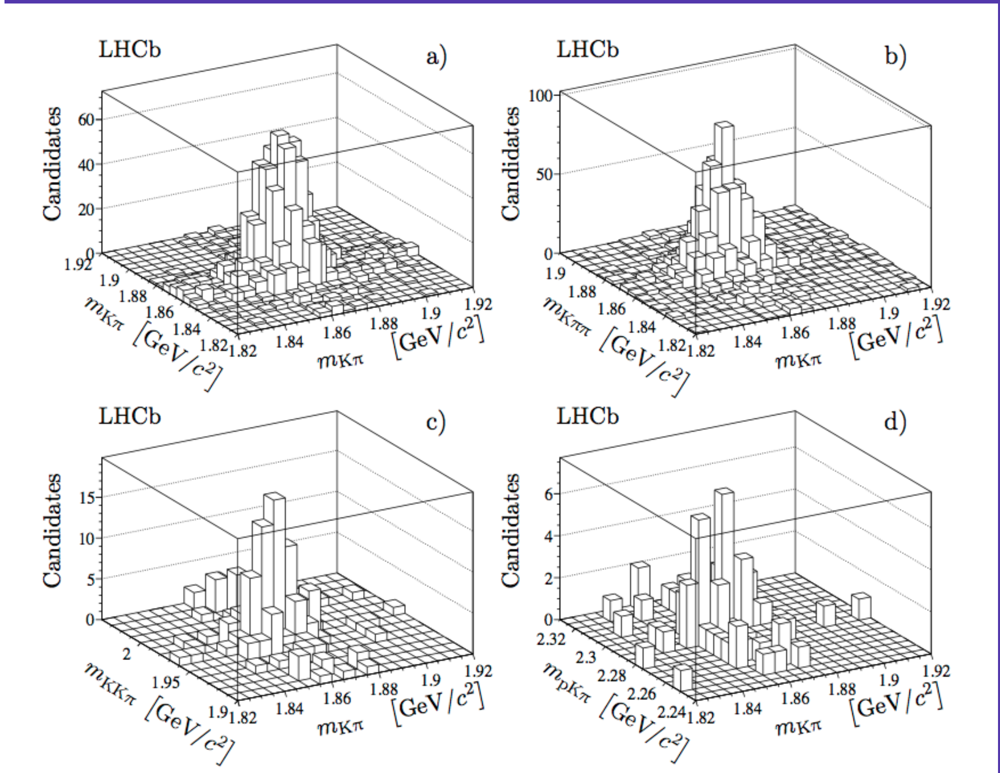
[μb]		σ_{DPS}	σ_{sea}
D^0D^0		2.0 ± 0.5	1.5
D^0D^+		1.7 ± 0.4	1.4
$D^0D_s^+$	predictions	0.65 ± 0.15	0.4
$D^0\Lambda_c^+$		1.5 ± 0.5	
D^+D^+		0.34 ± 0.09	0.3
$D^+D_s^+$		0.27 ± 0.07	0.2
$D^+\Lambda_c^+$		0.64 ± 0.23	

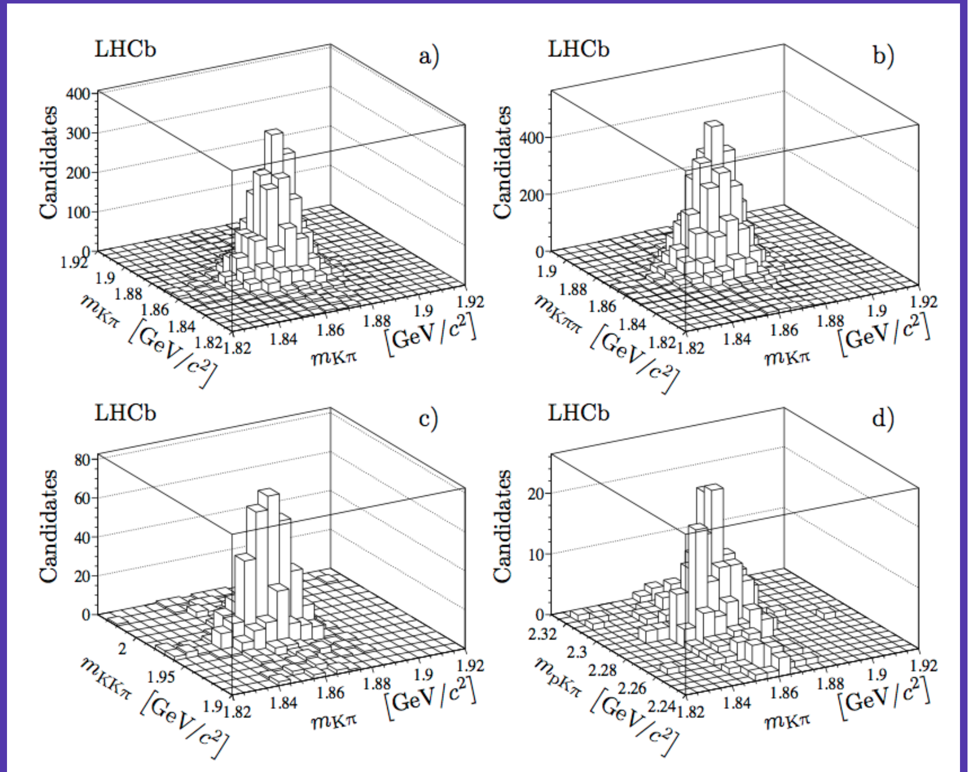
DPS:
C. Kom et al. PRL 107 (2011) 082002
S. Baranov et al. PLB 705 (2011) 116
A. Novoselov arXiv:1106.2184
M. Luszczak PRD 85 (2012) 094034

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

Double Charm Production

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





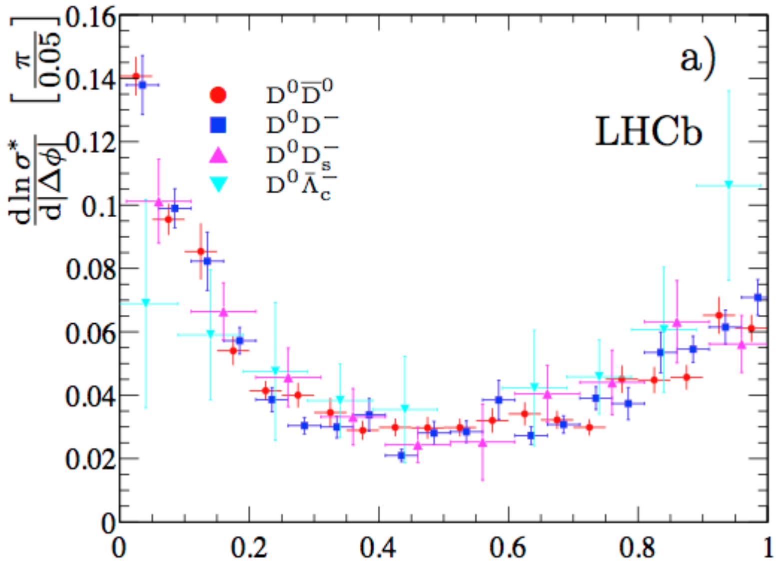
$D^0 D_s^+$ $D^0 \bar{\Lambda}_c^-$ $D^0 D_s^-$ $D^0 \Lambda_c^+$

Same sign charm

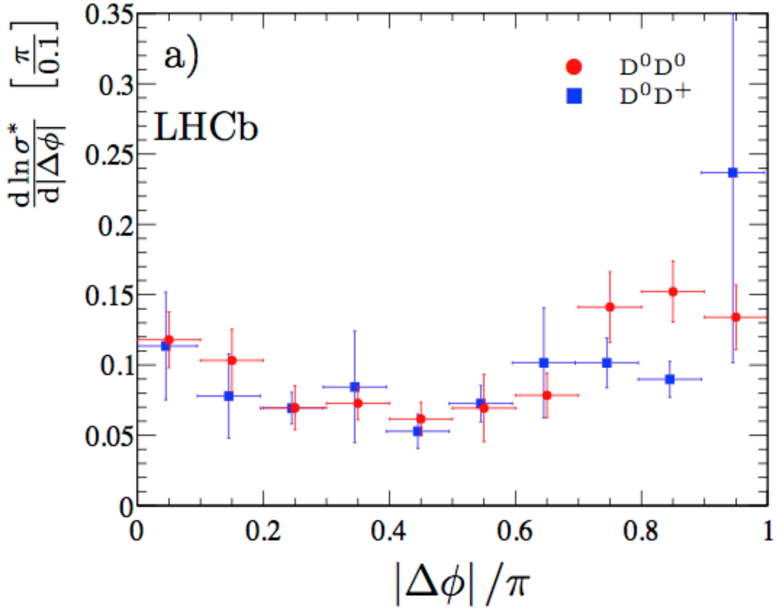
Opposite sign charm

Double Charm Production

JHEP 06 (2012) 141

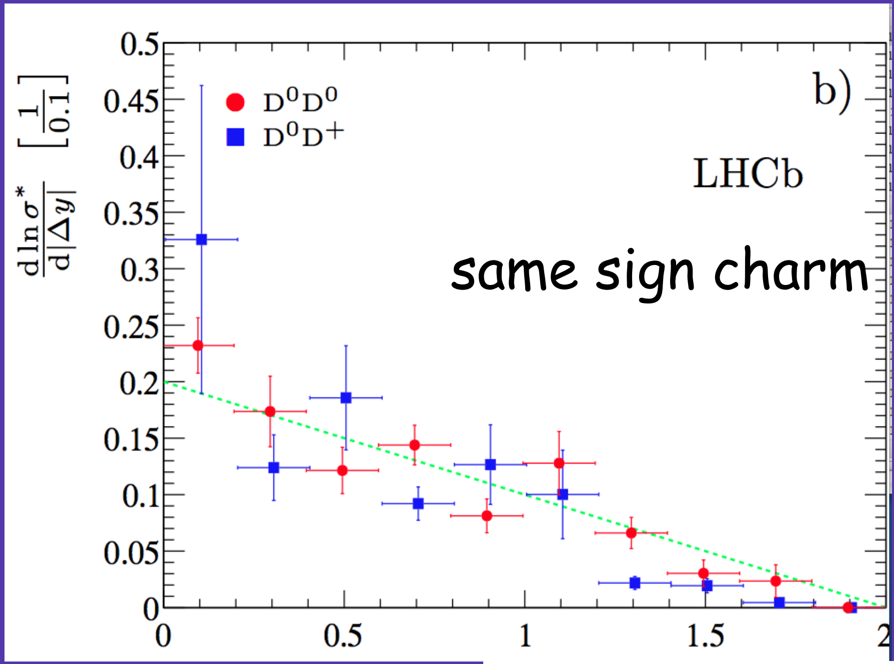


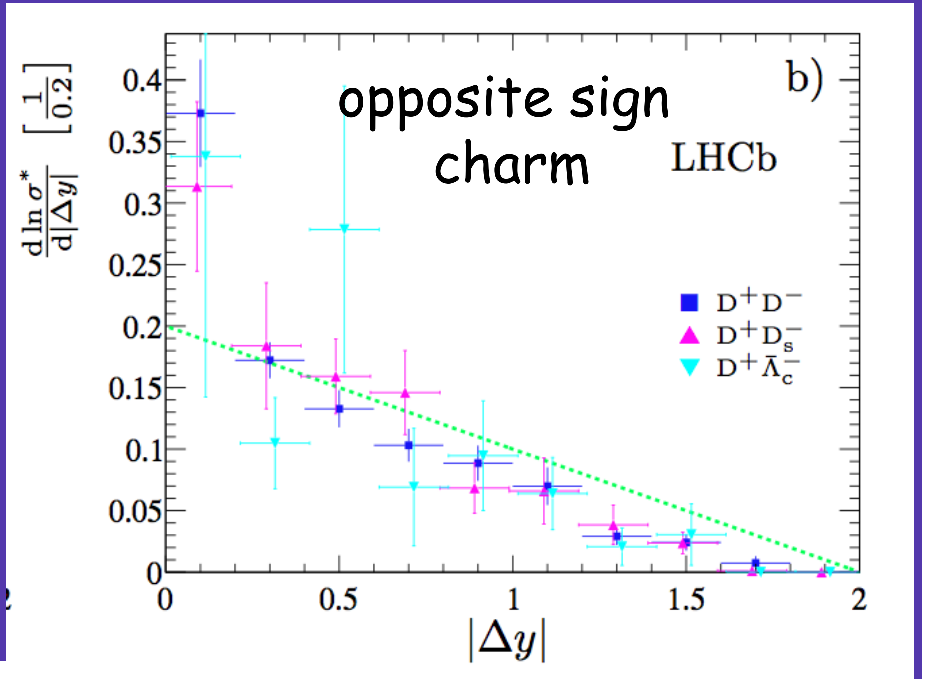
Opposite sign:
Δϕ→0 peak indicates g->ccbar splitting contribution and/or non-collinear contribution

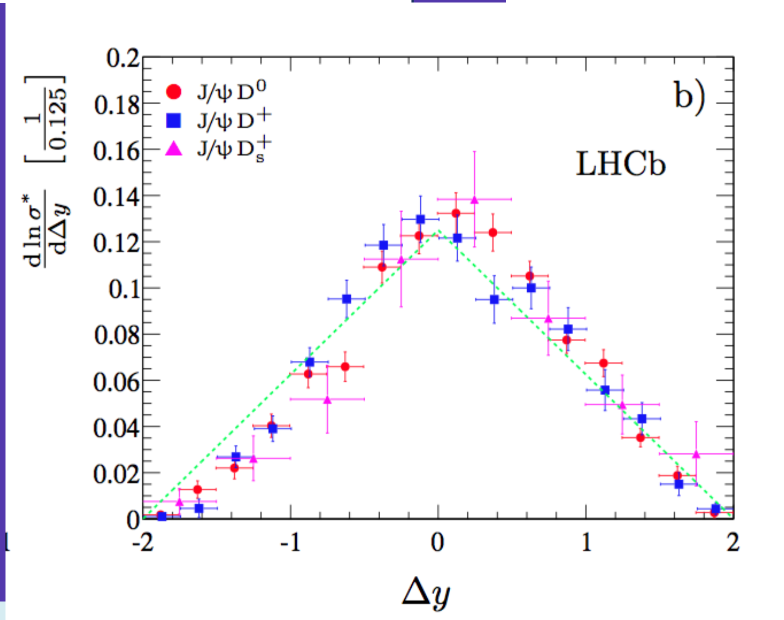


Same sign:
Δϕ flat indicates no production correlation

Double open charm production

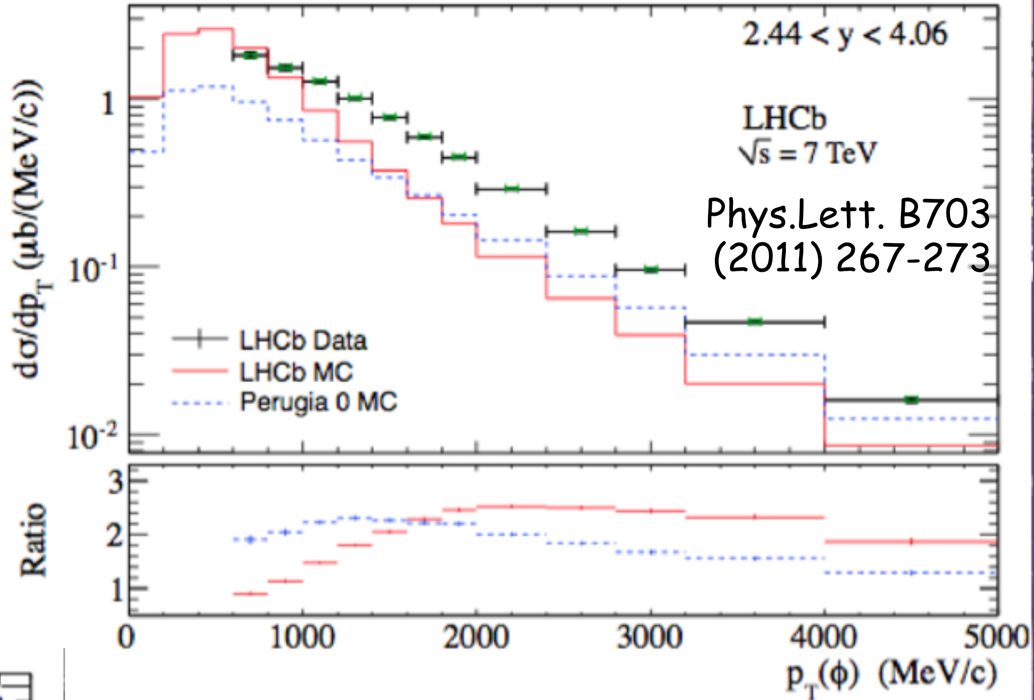


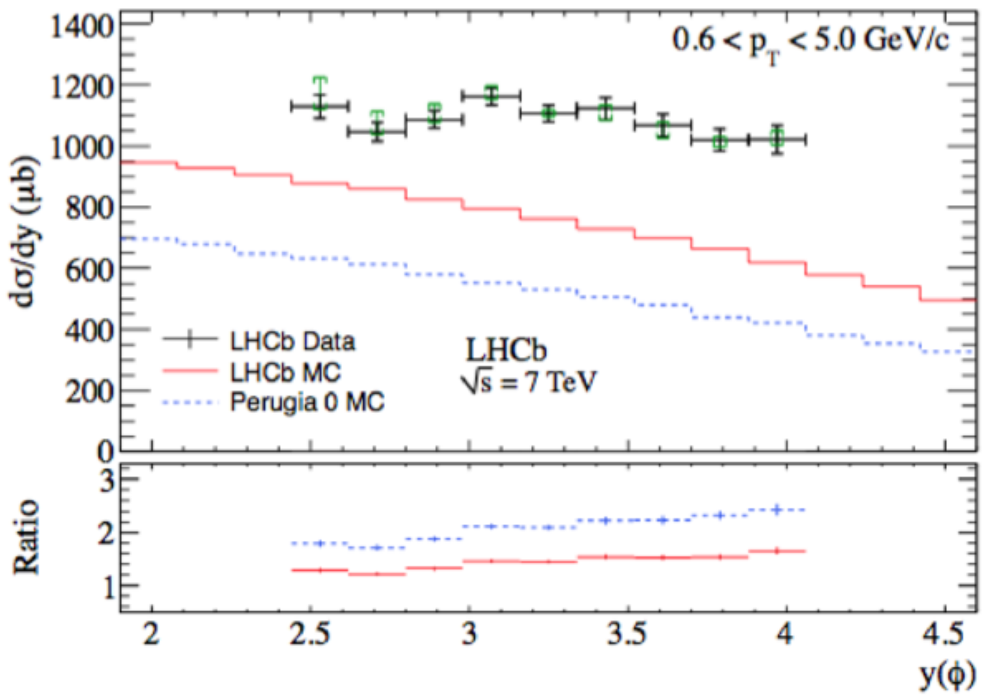




ϕ production

X-section underestimated by MC
Flatter rapidity distribution than MC
p_T spectra closer to P0 tune





$$\sigma_{pp\to\phi X} = 1758 \pm 19(\text{stat}) {}^{+43}_{-14}(\text{syst}) \pm 182(\text{scale})\mu b$$

$$p_T \in [0.6, 5.0 \text{ GeV}/c]$$

$$y \in [2.44, 4.06]$$