Quarkonium production at LHCb

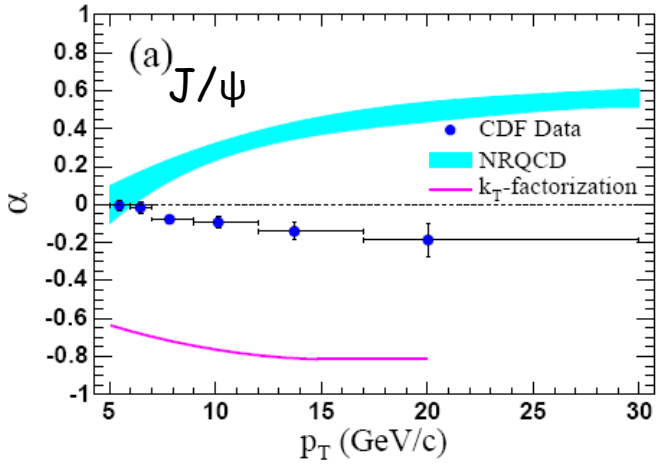
ZHANG Yanxi
On behalf of the LHCb collaboration

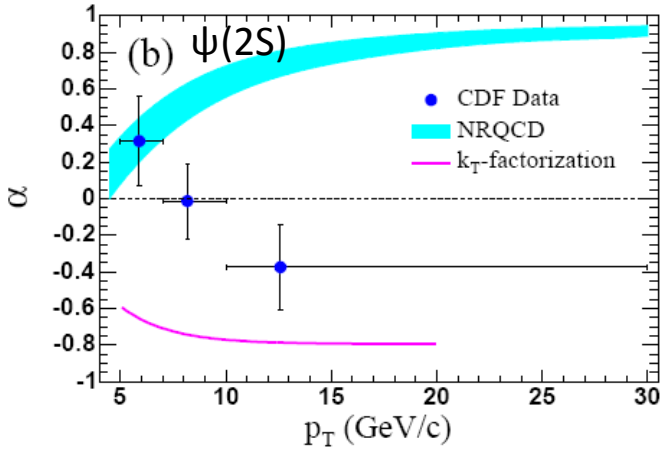
Outline

- Motivation
- Detector and operation
- Selected quarkonium results
  - ✓ J/ψ,ϒ(nS) production at $\sqrt{s} = 8$ TeV
  - ✓ χ_b states
  - ✓ Exclusive J/ψ and ψ(2S)
  - ✓ χ_c production
- Conclusions and outlook

Motivation

- Quarkonia production provides powerful test of perturbative and non-perturbative aspects of QCD
- Production mechanism in hadron colliders still uncertain
  - ✓ NRQCD mechanism including color singlet (CS) and color octet (CO) contributions describes the p_T dependent cross section of J/ψ as measured by Tevatron, but not the polarization
  - ✓ Color evaporation model (CEM), k_T factorization etc. cannot describe the cross section and polarization data simultaneously either
- Results from LHC experiments will be helpful to understand the issue

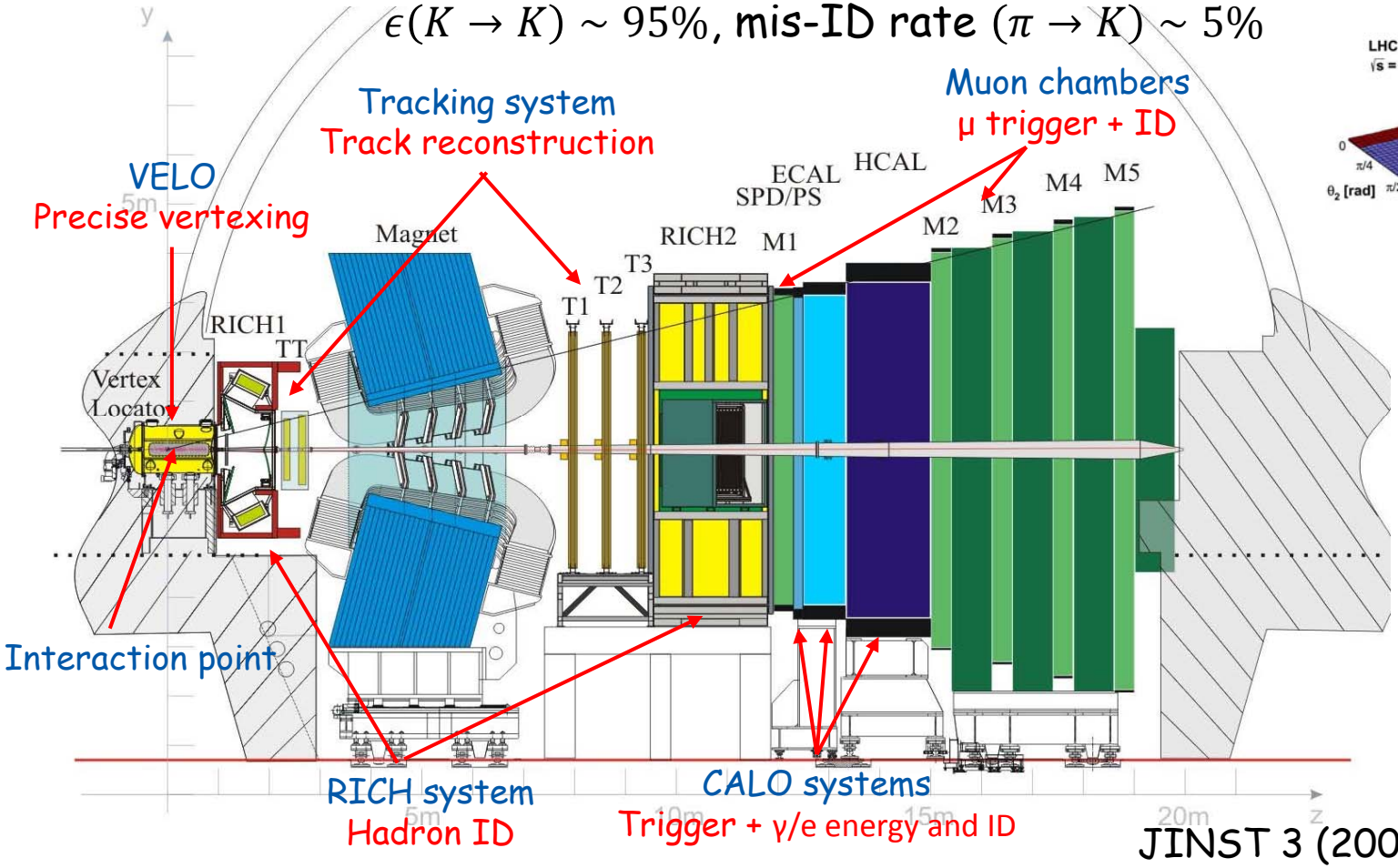


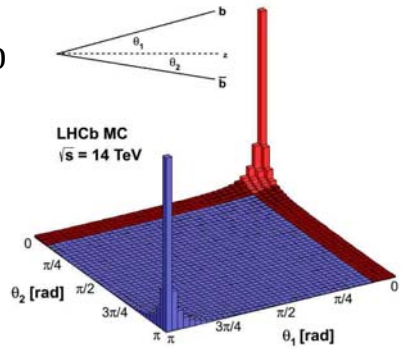


CDF: PRL 99 132001 (2007)

LHCb spectrometer

$\Delta p/p$: 0.4% @5 GeV/c, to 0.6% @100 GeV/c
$\Delta\tau = 40$ fs for $B_s \to J/\psi\,\varphi$ and $B_s \to D_s\,\pi$
$\epsilon(\mu \to \mu) \sim 97\%$, mis-ID rate $(\pi \to \mu) \sim 1 \sim 3\%$
$\epsilon(K \to K) \sim 95\%$, mis-ID rate $(\pi \to K) \sim 5\%$



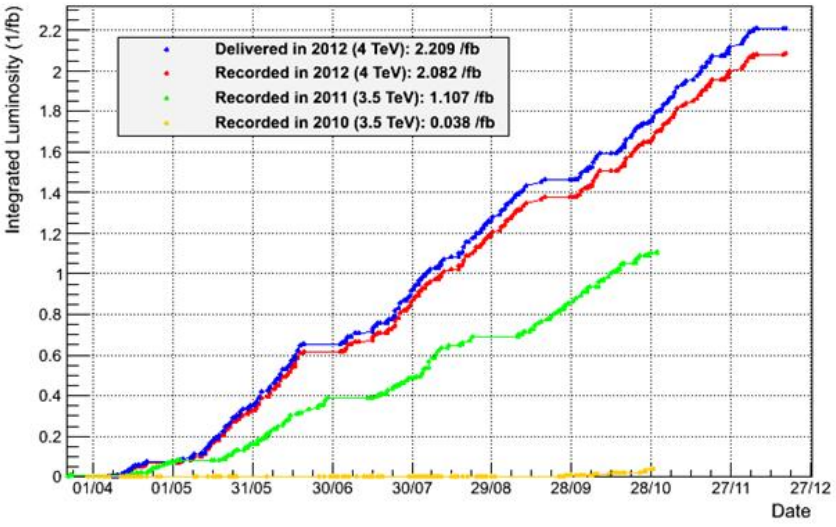


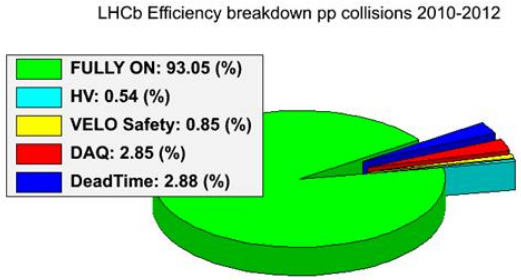
$2 < \eta < 5$

JINST 3 (2008) S08005

LHCb Operation

pp collisions with integrated luminosity 2010-2012





2010 37 pb^{-1} @ 7 TeV

2011 1.0 fb^{-1} @ 7 TeV

2012 2.0 fb^{-1} @ 8 TeV

Data taking efficiency:
> 90 %

Working detector channels:
~ 99 % for all sub-detectors

Trigger efficiencies:
~ 90 % for dimuon channels

Track reconstruction efficiency:
> 96 % for tracks traversing LHCb

Quarkonium @ 8 TeV

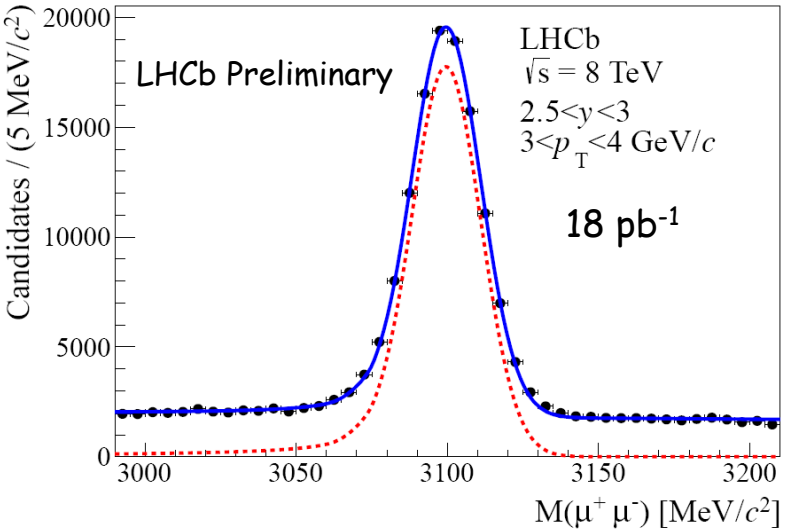
- J/ψ and ϒ(nS) production in 2012 data
  - ✓ pp collisions with $\sqrt{s} = 8$ TeV
- Signal reconstructed in $\mu^+\mu^-$ channel
  - ✓ $p_T(\mu^\pm) > 0.7\ (1.0)$ GeV/c for J/ψ (ϒ)
  - ✓ Prob(vertex χ^2/ndof) > 0.5 %
- Inclusive double differential cross section:

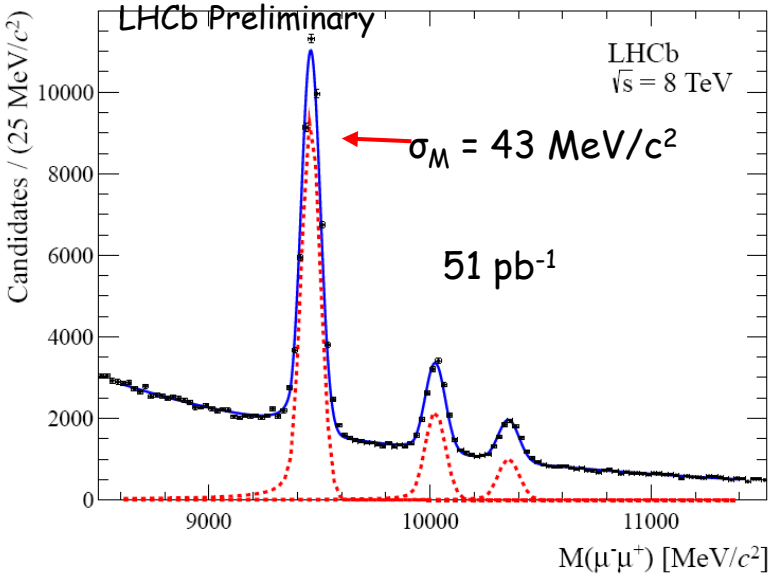
$$\frac{d^2\sigma}{dydp_T}(pp \to VX) = \frac{N(V \to \mu^+\mu^-)}{L \times \varepsilon \times \mathrm{Br}(V \to \mu^+\mu^-) \times \Delta y \times \Delta p_T}$$

V : J/ψ or ϒ(nS)
L : integrated luminosity
N: number of events determined by fitting invariant mass distribution

2.6m J/ψ, 60 k ϒ(nS) in total

LHCb-PAPER-2013-016

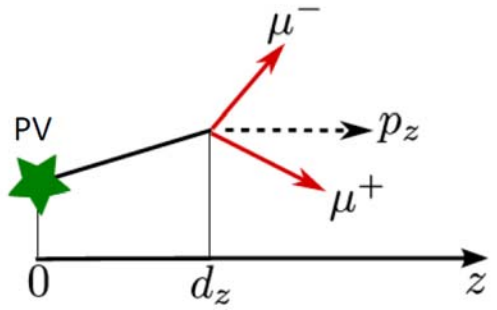




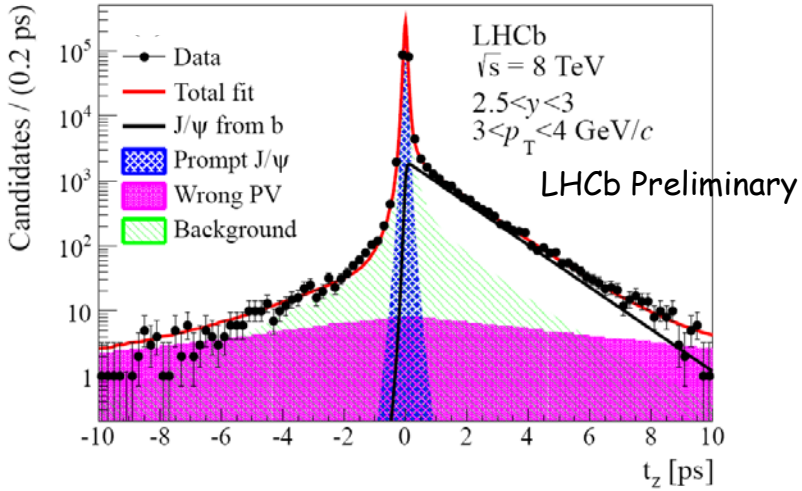
Quarkonium @ 8 TeV

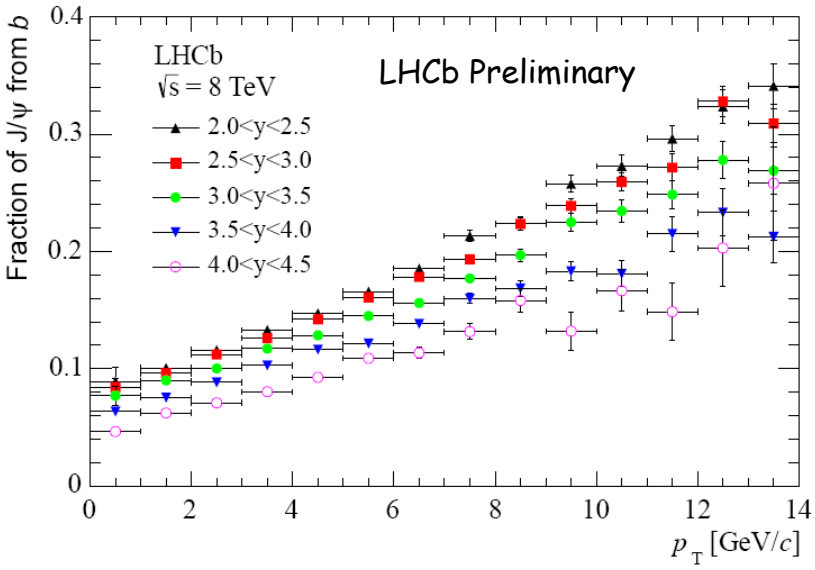
- Prompt J/ψ and J/ψ from *b*-hadron decays discriminated by pseudo decay time t_z:

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



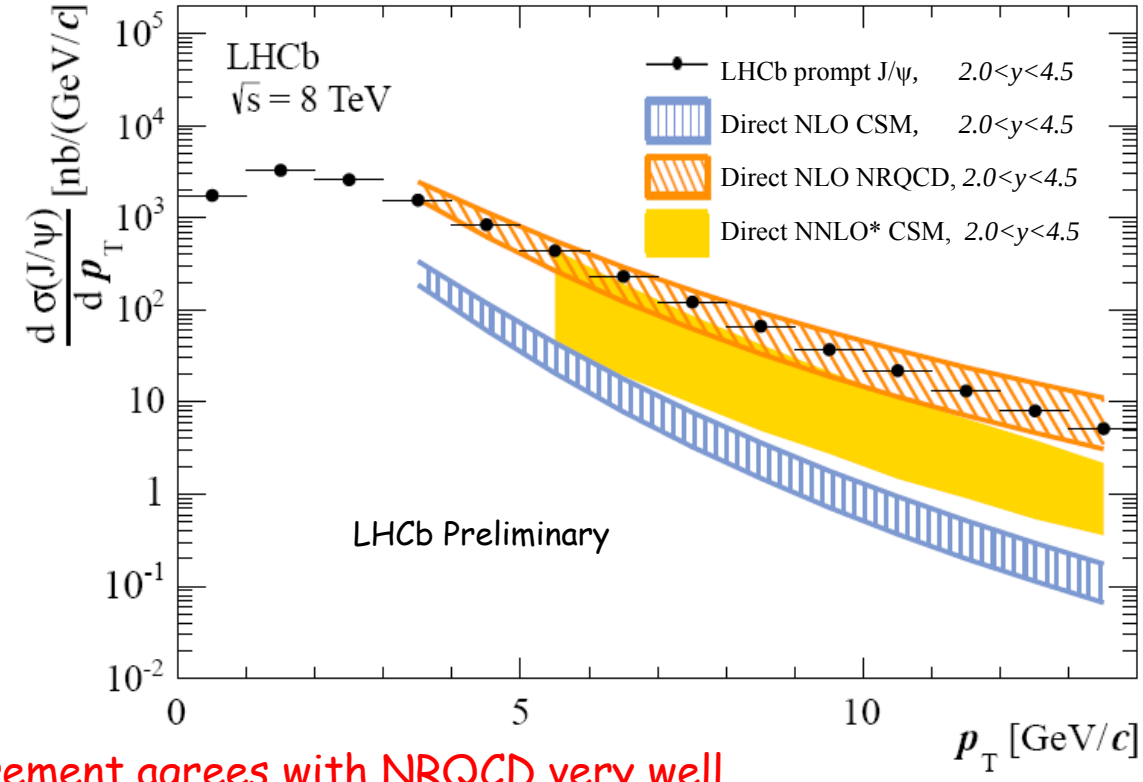
- ✓ Empirical function for backgrounds based on mass sidebands
- ✓ δ-function for prompt
- ✓ Exponential function of J/ψ from *b*
- ✓ Resolution included for each component





Quarkonium @ 8 TeV

Prompt J/ψ differential cross section as a function of p_T integrated over y range [2.0,4.5]



PRL 98 252002 (2007)
PRL 106 022003 (2011)
PRL 101 152001 (2008)

Measurement agrees with NRQCD very well.

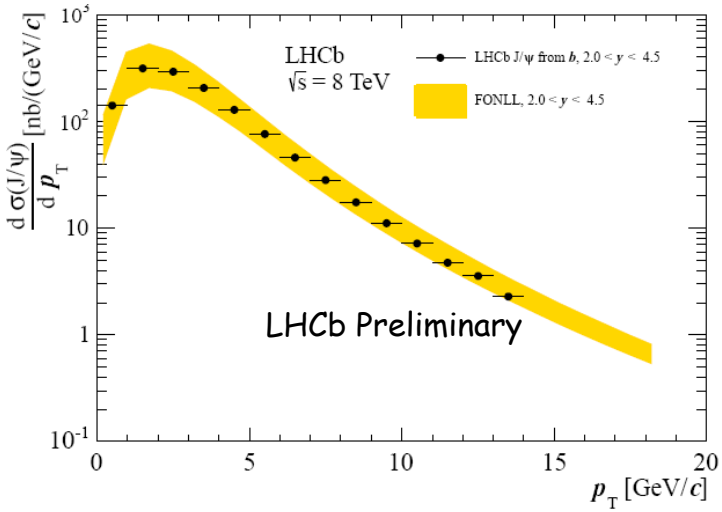
Prompt J/ψ cross section integrated over LHCb fiducial region:

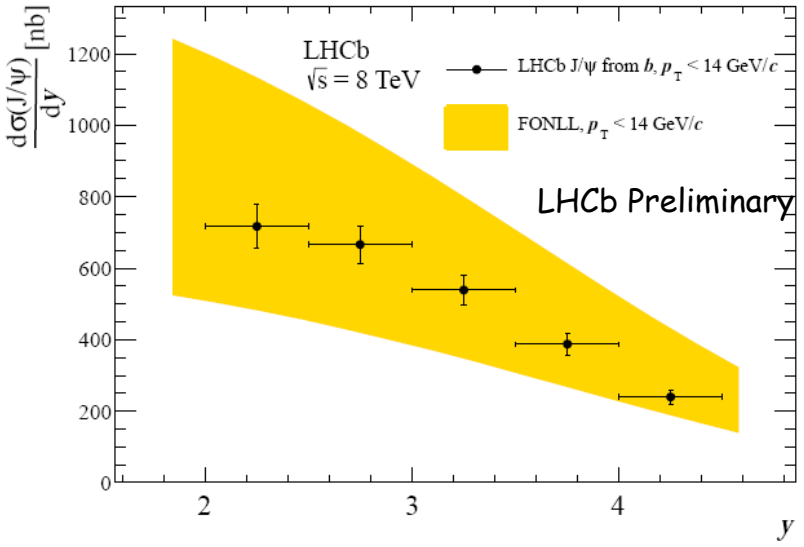
$$\sigma(\text{prompt } J/\psi, p_T < 14\,\text{GeV}/c, 2.0 < y < 4.5) = 10.94 \pm 0.02 \pm \boxed{0.79}\,\text{ub}$$

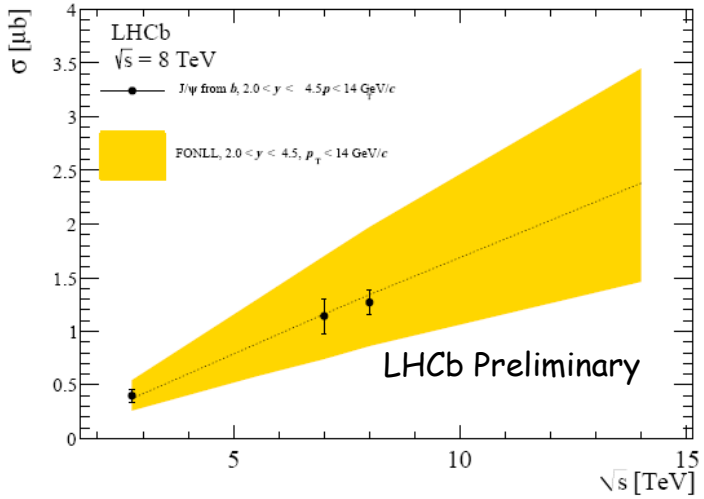
main syst.: trigger efficiency & luminosity

Quarkonium @ 8 TeV

cross section of J/ψ from *b* hadron decay







Consistent with FONLL predictions

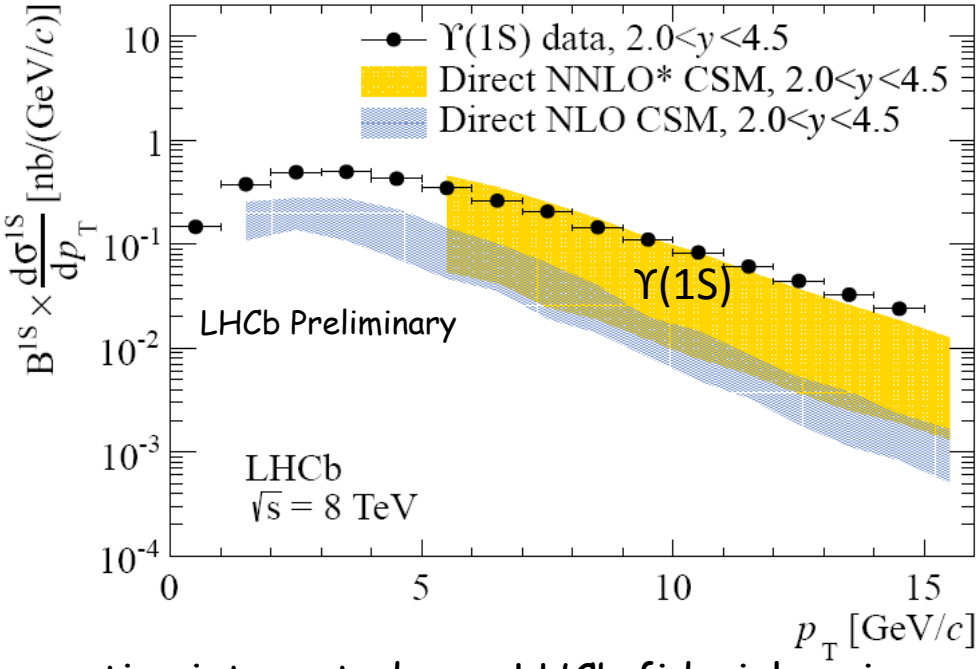
FONLL:JHEP 05 (1998) 007, JHEP 1210 (2012) 137

Quarkonium @ 8 TeV

Large uncertainties on Br(ϒ(nS)→ $\mu^+\mu^-$)

Presents cross section times branching fraction

ϒ(1S) differential cross section as a function of p_T integrated over y range [2.0,4.5]



PRL 101 152001 (2008)

PRL 98 252002 (2007)

B^{nS} : $\mathrm{Br}\left(\Upsilon(\mathrm{nS}) \to \mu^+\mu^-\right)$

ϒ(nS) cross section integrated over LHCb fiducial region:

$$\sigma(pp \to \Upsilon(1S)X) \times B^{1S} = 3.241 \pm 0.018 \pm 0.231\ \mathrm{nb}$$

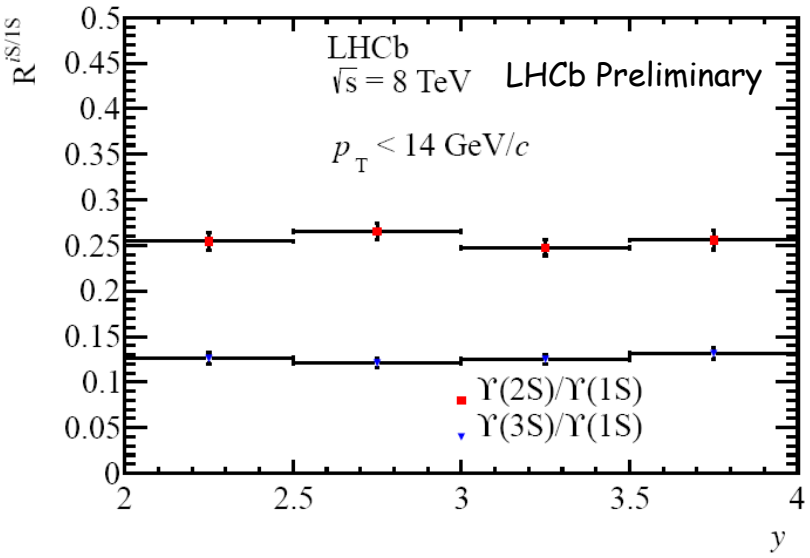
$$\sigma(pp \to \Upsilon(2S)X) \times B^{2S} = 0.761 \pm 0.008 \pm 0.055\ \mathrm{nb}$$

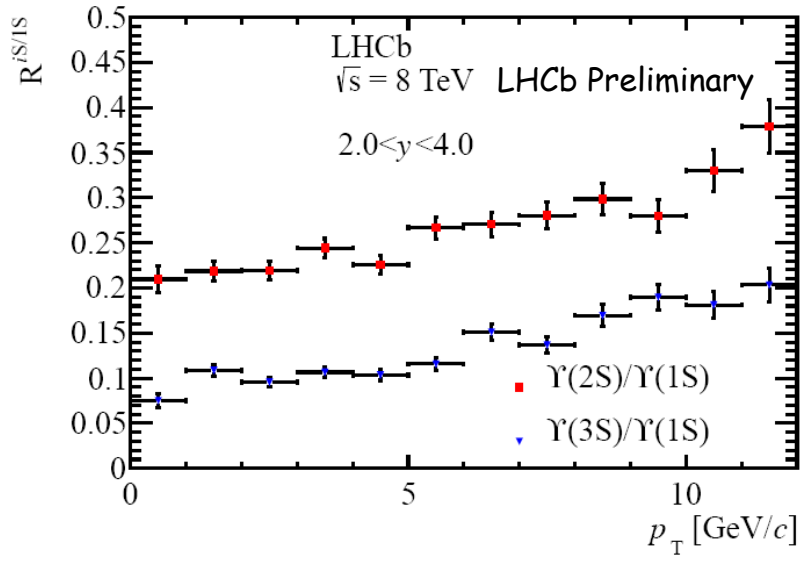
$$\sigma(pp \to \Upsilon(3S)X) \times B^{3S} = 0.369 \pm 0.005 \pm 0.027\ \mathrm{nb}$$

$p_T < 15\ \mathrm{GeV}/c, 2.0 < y < 4.5$

main syst.: trigger eff. & luminosity

Quarkonium @ 8 TeV





Υ(nS) cross section ratio:

$\sigma(\Upsilon(2S))/\sigma(\Upsilon(1S))$

$\sigma(\Upsilon(3S))/\sigma(\Upsilon(1S))$

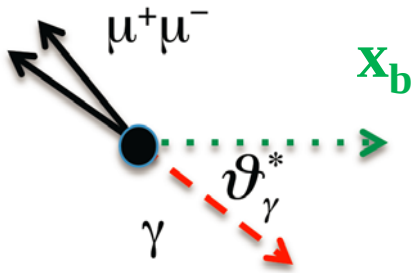
~ constant as a function of y

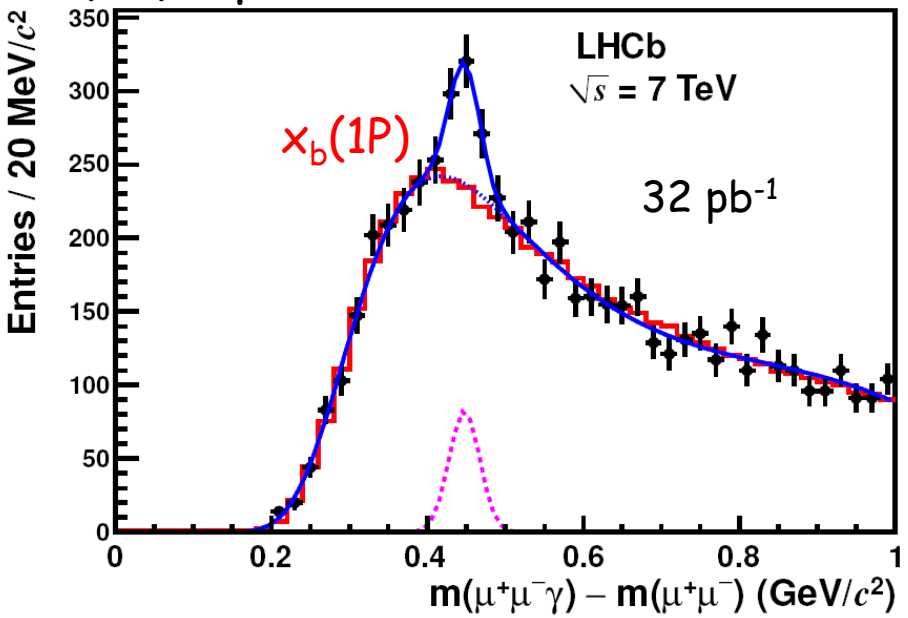
Increasing with p_T, due to feed down?

X_b states

LHCb: JHEP 11 (2012) 031

- $x_b(nP)$ is reconstructed with $\Upsilon(1S)$ + photon in 7 TeV 2010 data
  - ✓ $\Upsilon(1S) \to \mu^+\mu^-$
  - ✓ $p_T^{\Upsilon(1S)} > 6.0$ GeV/c
  - ✓ $p_T^{\gamma} > 0.6$ GeV/c
  - ✓ $\cos\theta^*_{\gamma} > 0$



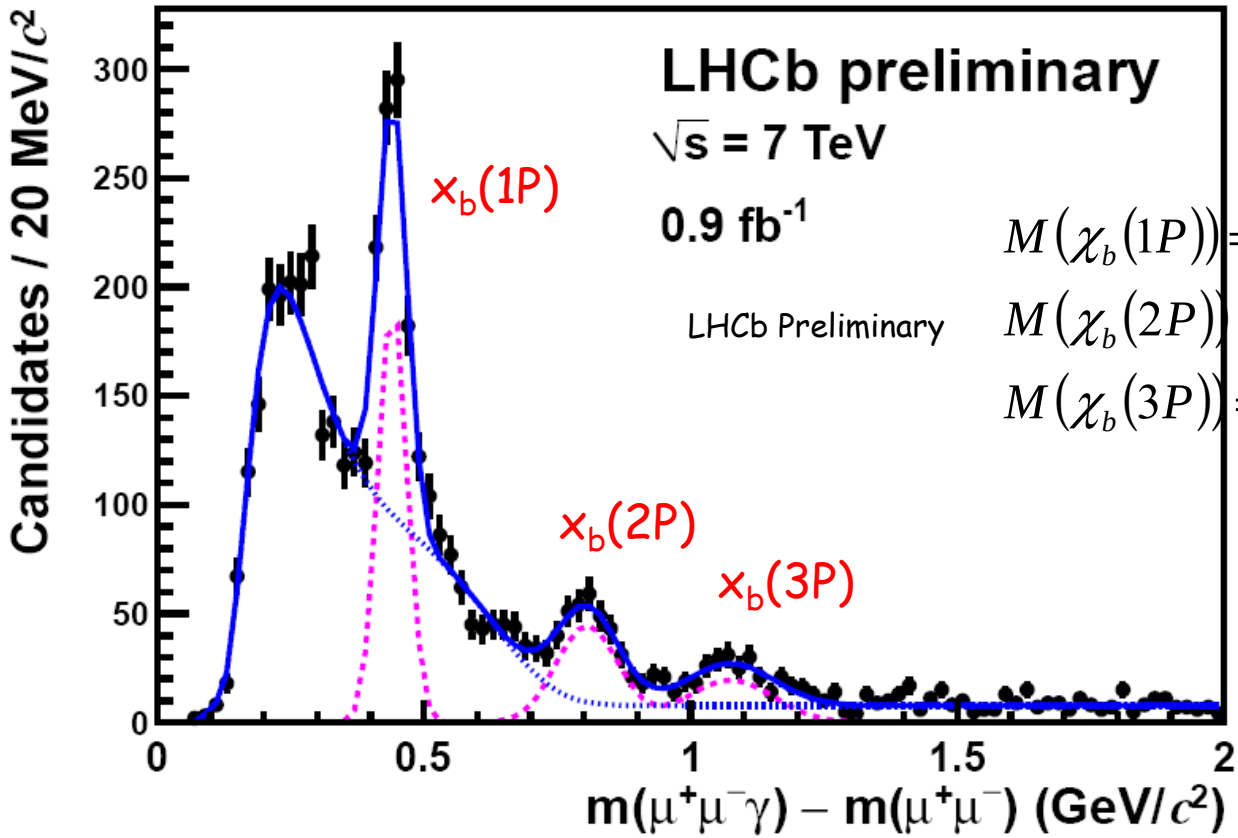


- Mass difference fitted with gaussian for signal + empirical function for background.
  - ✓ N ($x_b(1P)$) = 201±55, ΔM=447±4 MeV/c^2, σ=19±4 MeV/c^2
  - ✓ Three $x_{bJ}(1P)$ cannot be resolved
- Fraction of $\Upsilon(1S)$ from $x_{bJ}(1P)$ decay: $\left(20.7 \pm 5.7 \pm 2.1^{+2.7}_{-5.4}\right)\%$

stat. syst. unknown polarization

Observation of $X_b(3P)$

$\chi_b(nP) \to \Upsilon(1S)(\mu^+\mu^-)\gamma$ LHCb 2011 0.9 fb^{-1} data LHCb-CONF-2012-020



Fitted mass agree with PDG

$$M(\chi_b(1P)) = 9901 \pm 2\,\mathrm{MeV}/c^2$$
$$M(\chi_b(2P)) = 10266 \pm 6\,\mathrm{MeV}/c^2$$
$$M(\chi_b(3P)) = 10535 \pm 10\,\mathrm{MeV}/c^2$$

ΔM fitted with 3 Gaussian functions for signal peaks + empirical background

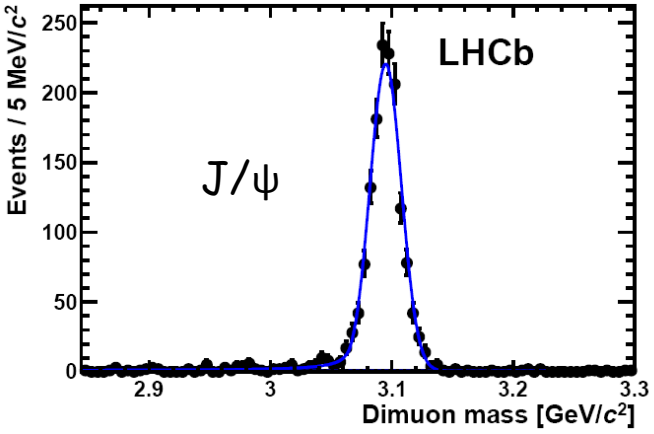
$x_b(3P)$: 196± 19 events, 12 standard deviations

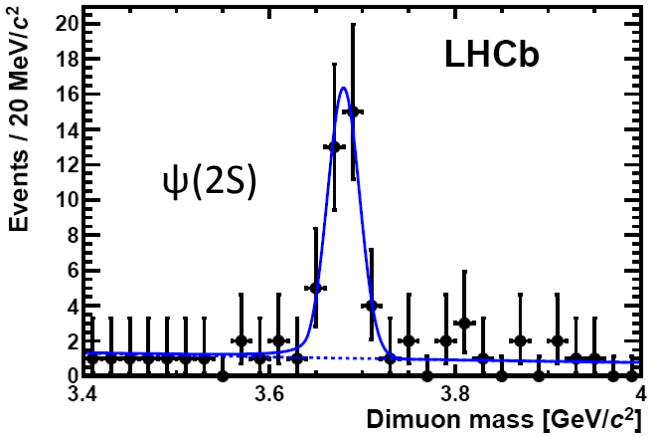
$x_b(3P)$ mass agrees with ATLAS (PRL 108 (2012) 152001) and CDF (PRD 86 (2012) 031103)

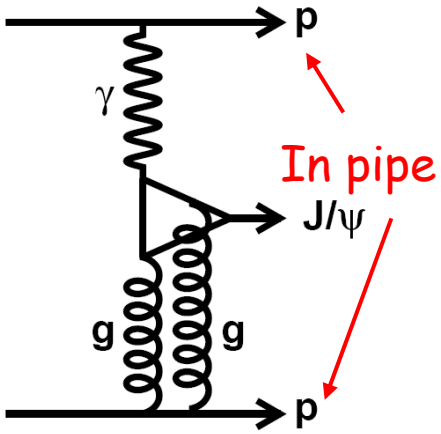
Exclusive ψ production

LHCB-PAPER-2012-044 (arXiv:1301.7084v1)

- Photo-production through double gluon exchange process: γp→ψp
- ψ reconstructed in $\mu^+\mu^-$ channel with 36 pb^{-1} 2011 data
  - ✓ no other tracks and photons in detector
  - ✓ dedicated trigger







$$\sigma_{pp\to J/\psi}\left(2.0<\eta_\mu<4.5\right)=307\pm21\pm36\ \text{pb}$$

$$\sigma_{pp\to\psi(2S)}\left(2.0<\eta_\mu<4.5\right)=7.8\pm1.3\pm1.0\ \text{pb}$$

$\sigma(\chi_{c2})/\sigma(\chi_{c1})$ ratio

LHCb: PLB 714 (2012) 215-223
CONF-2011-062

- Cross section ratio χ_{c2}/χ_{c1} sensitive to production mechanisms
  - ✓ spin counting yields 5/3
  - ✓ CDF (PRL 98, 232001 (2007)): ~0.7
- LHCb measures the X_c production ratio in channel $\chi_{cJ} \to J/\psi(\mu^+\mu^-)\gamma$
  - ✓ Three kinds of photons reconstructed
    - ➢ non-converted photons
    - ➢ photons converted after magnet
    - ➢ photons converted before magnet

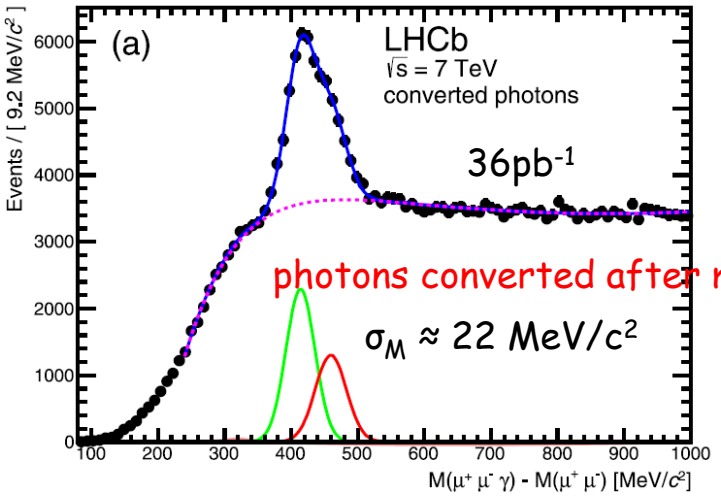
    by calorimeter 2010 $36pb^{-1}$

    by tracking for e^+e^- 2011 $370pb^{-1}$
  - ✓ Prompt χ_{cJ} selected with pseudo decay time
    - ➢ t_z<0.1 ps, χ_{cJ} from b < 0.1%
  - ✓ χ_{cJ} analyzed in bins of J/ψ p_T
  - ✓ Same selections for χ_{c2} and χ_{c1} : systematic uncertainties cancel significantly

$\sigma(X_{c2})/\sigma(X_{c1})$ ratio

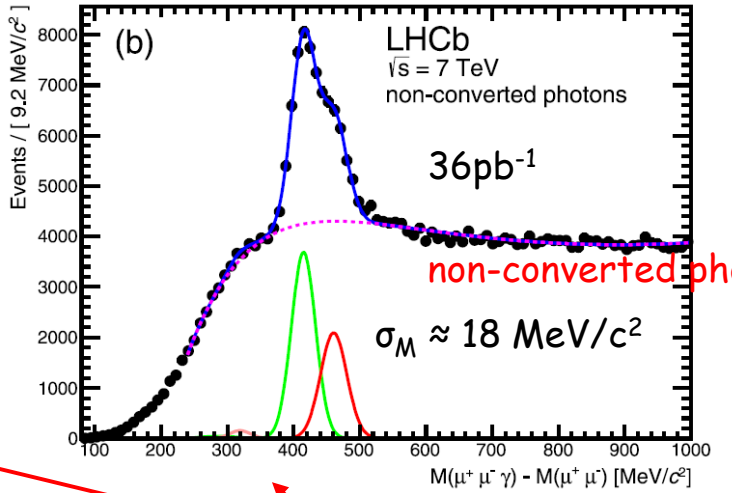
LHCb: PLB 714 (2012) 215-223
CONF-2011-062

Yields determined by fitting the invariant mass differences



photons converted after magnet

$\sigma_M \approx 22$ MeV/c^2

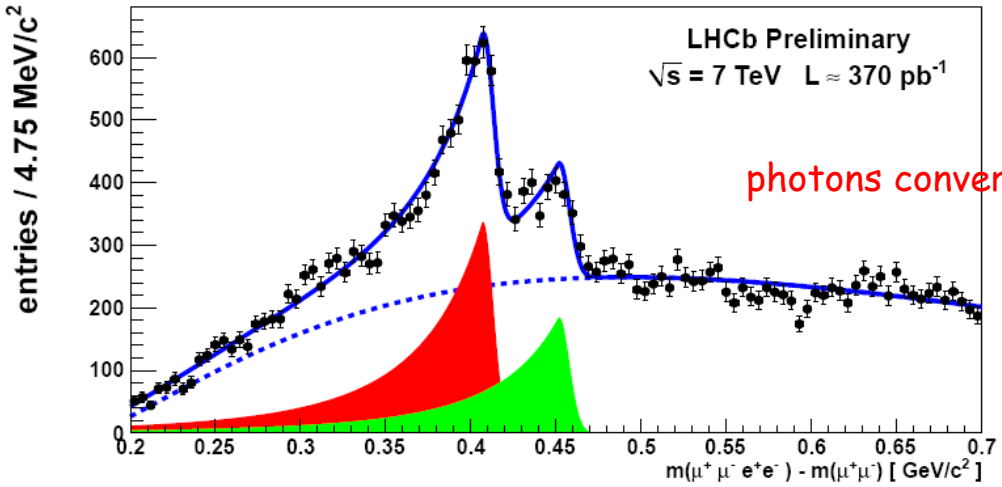


non-converted photons

$\sigma_M \approx 18$ MeV/c^2

LHCb 2010 data

2 Gaussian functions for X_{c1} & X_{c2}



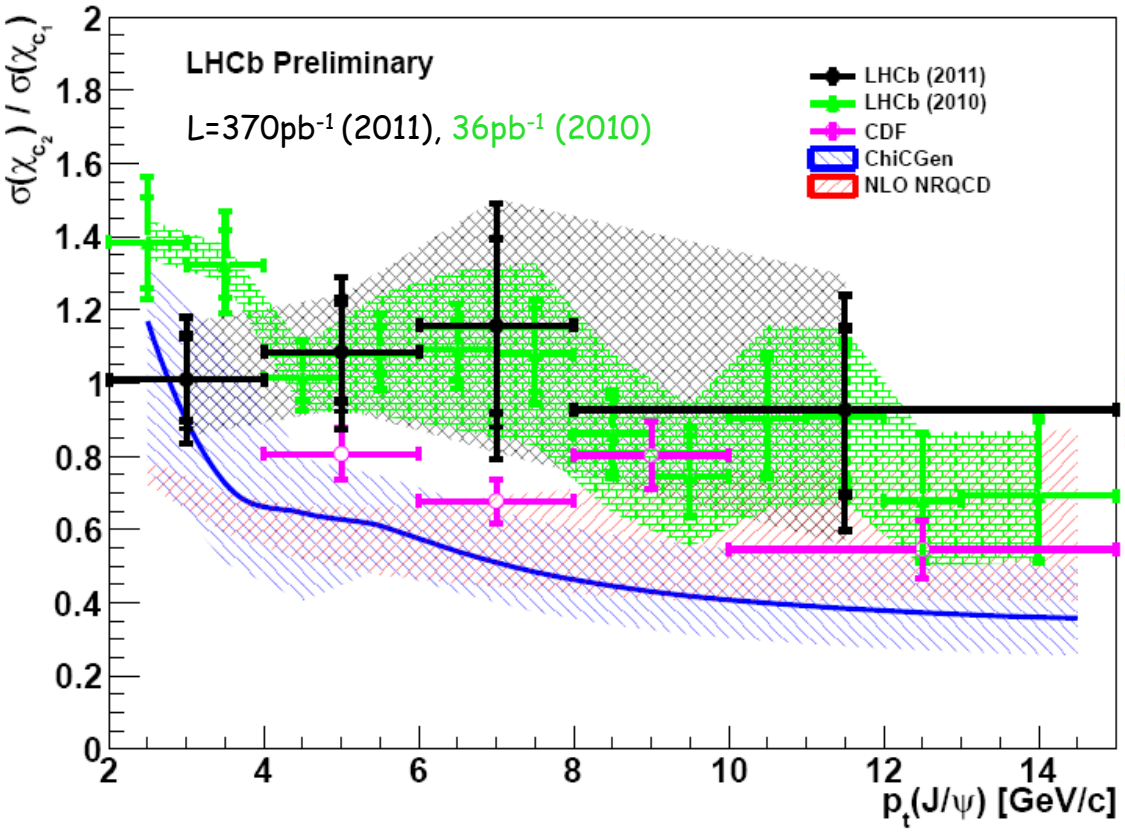
photons converted before magnet

LHCb 2011 data

2 Crystal Ball functions for X_{c1} & X_{c2}

Gaining resolution by losing efficiency

$\sigma(\chi_{c2})/\sigma(\chi_{c1})$ ratio



PRL 98, 232001 (2007)

Harland-Lang, et al LO CSM

PRD 83, (2011) 111503

ChiCGen predictions lie consistently below data, probably can be explained by not inclusion of higher order corrections and/or CO terms in the calculation.

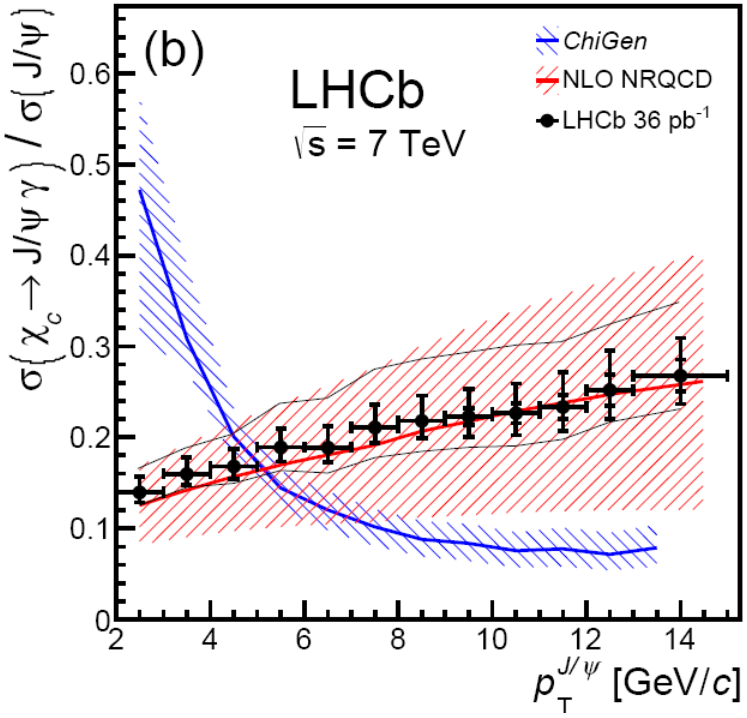
In high J/ψ p_T range, measurements agree with NLO NRQCD prediction.

$\sigma(X_c \to J/\psi\gamma)/\sigma(J/\psi)$ ratio

LHCb: PLB 718 (2012) 431-440

χ_{cJ} reconstructed with only calorimeter photons

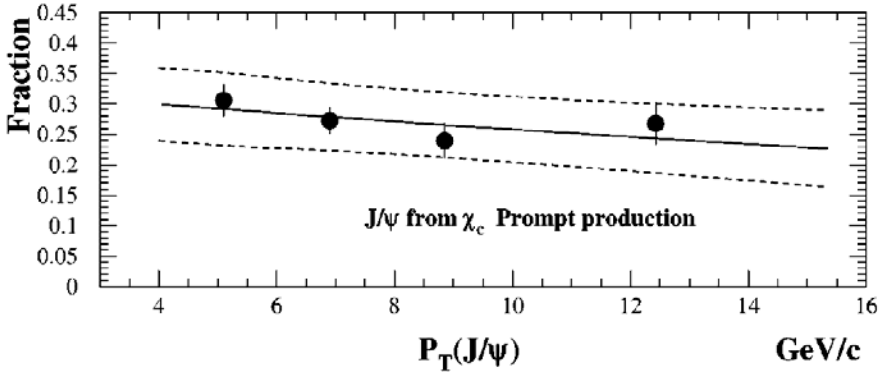
- ✓ selections similar as in $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ ratio analysis
- ✓ prompt χ_{cJ} and J/ψ analyzed



Harland-Lang, et al LO CSM

PRD 83, (2011) 111503

CDF,PRL 79 (1997) 579



Ratio increasing with J/ψ p_T, trend different from CDF result.

Results agree with NLO NRQCD prediction.

Conclusion

- Quarkonium production has provided ideal place to test QCD
  - ✓ Cross section and polarization both important in the test
  - ✓ High order corrections crucial in some phase space region
- LHCb has many important production results in quarkonim physics
  - ✓ J/ψ,ϒ(nS) production cross section measurement
  - ✓ Cross section ratio measurement
  - ✓ Observation of new quarkonium states
- Many more results in preparation
  - ✓ Polarizations of J/ψ, ψ(2S), ϒ(nS), χ_c, etc
  - ✓ Multi heavy quark(onium) production
  - ✓ Quarkonium in the A-p, p-A collisions in LHCb
  - ✓ Search for new states

Thanks for listening