

Exclusive and Inclusive quarkonia production in the forward acceptance at the LHC

J. Blouw, on behalf of the LHCb collaboration

Max-Planck-Institut für Kernphysik, Heidelberg

XXX-th International Workshop on High Energy Physics: Particle and Astroparticle Physics, Gravitation and Cosmology: Predictions, Observations and New Projects

- Motivation
- The LHCb spectrometer
- χ_c production, cross section ratios
- Exclusive χ_c , J/Ψ & $\Psi(2S)$ production
- Inclusive J/Ψ , $\Psi(2S)$ & Υ production
- Measurement of J/Ψ & $\Psi(2S)$ polarization
- Conclusions & Outlook

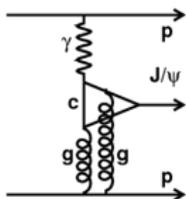
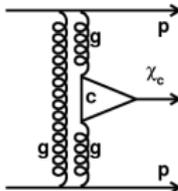
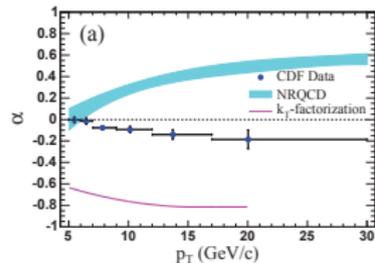


Photo production



Double pomeron exchange

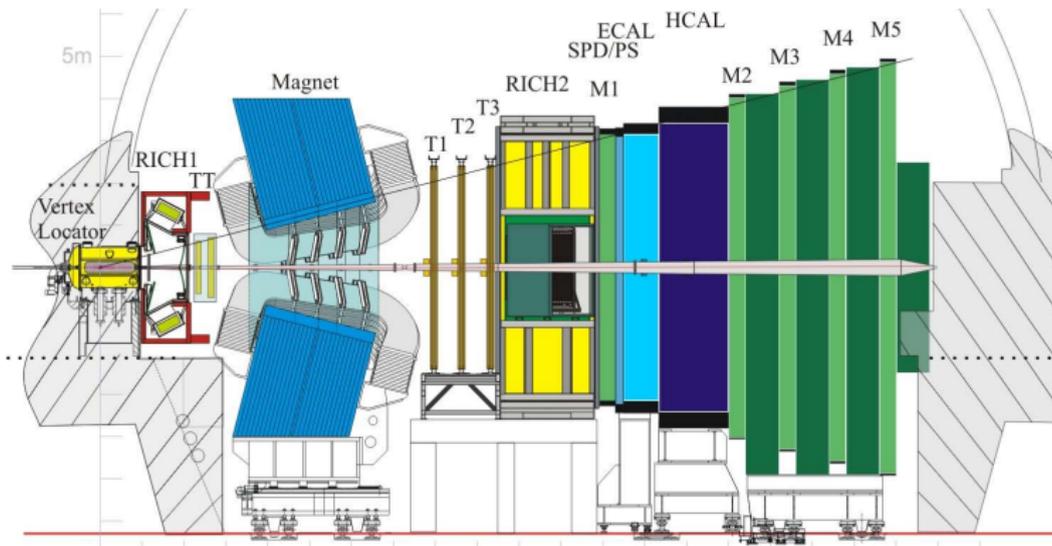


PRL 99:132001, 2007

(arXiv:0704.0638)

- Probe non-perturbative, soft QCD
- Quarkonia production mechanism not well understood
- Test predictions by various models
- Exclusive production: sensitive to pomeron/odderon
- Inclusive quarkonium production: p_T behavior of prompt production and polarization not well described

- Exclusive J/Ψ & χ_c production:
 - Understanding of diffraction (pomeron/odderon)
 - Sensitive to saturation effects
 - Provide constraints on gluon parton density function
- Inclusive J/Ψ & Υ production;
 - High and low p_T J/Ψ cross sections described by different models
 - Discrepancies in description of J/Ψ cross sections and J/Ψ polarization
 - Υ less affected by feed-through
 - $\chi_{c0,1,2}$ production ratios: distinguish CO from CSM models

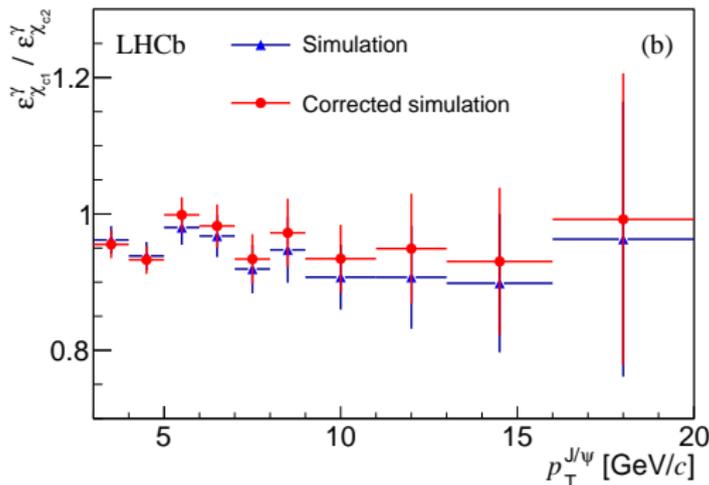


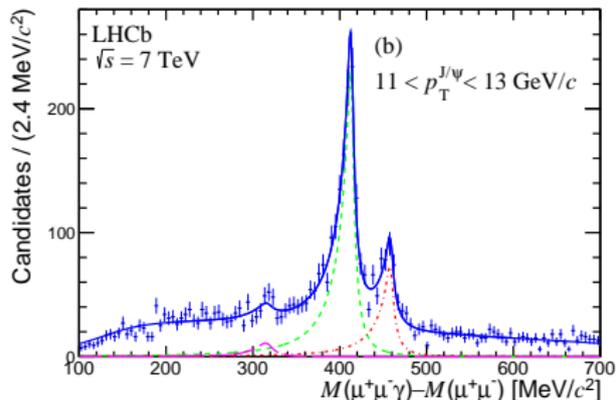
- Design luminosity ($2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$)
- Acceptance from $2 < \eta < 5$
- Probes down to $x_F \approx 5 \times 10^{-6}$
- Maximum rapidity gap: 3.5 units
- Good IP measurement: $\langle \delta \text{IP} \rangle = 20 \mu\text{m}$ for $p_T > 2 \text{ GeV}$:
 - excellent vertex reconstruction to select e.g. J/Ψ mesons
 - separation of prompt from secondary J/Ψ 's
- μ ID efficiency: $\sim 97\%$ for $< 3\% \pi \rightarrow \mu$ mis-id probability from $p = 2 - 100 \text{ GeV}$

Cross section ratio:

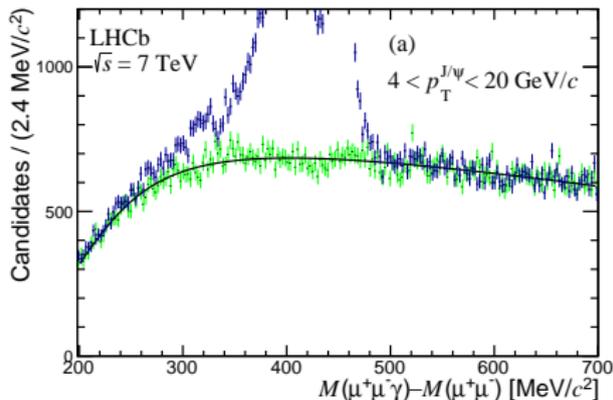
$$\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})} = \frac{N_{\chi_{c2}} \epsilon_{\chi_{c1}} \mathcal{B}(\chi_{c1} \rightarrow J/\Psi \gamma)}{N_{\chi_{c1}} \epsilon_{\chi_{c2}} \mathcal{B}(\chi_{c2} \rightarrow J/\Psi \gamma)}$$

- Different p_T^γ spectra for γ 's from χ_{c2} vs. χ_{c1}
- Reconstruction efficiency for converted photons decreases with decreasing p_T^γ
- Taken from simulation (cross checked using reconstructed π^0)



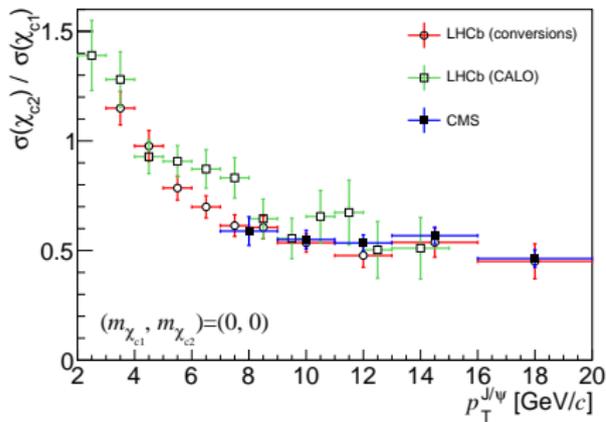
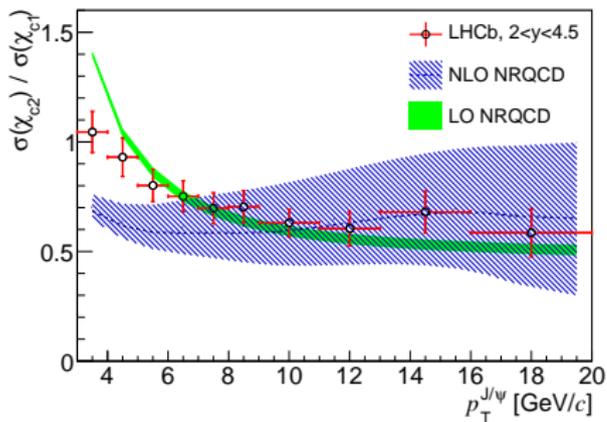
Mass spectrum for $11 < p_T^{J/\Psi} < 13$ GeV

Background spectrum from fake photons



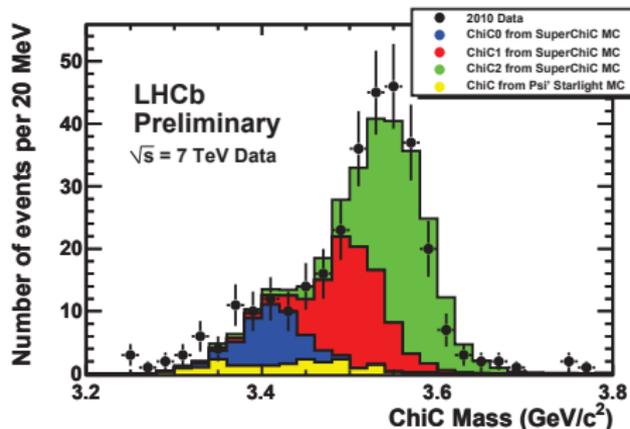
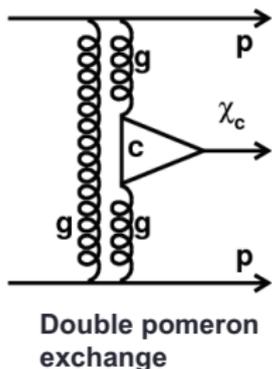
- Signal fit with double-sided Crystal Ball
- χ_{c0} fit with Crystal Ball convoluted with Breit-Wigner
 - $N(\chi_{c0}) = 705 \pm 163$
 - Signal with 4.3σ significance
- Empirical function with 3 parameters for background shape
- Background shape determined from χ_c 's reconstructed with fake photons
- Normalization of background determined from fit to signal

- Compare LHCb results to (N)LO NRQCD calculations (PR. D83:111503,2011 (arXiv:1002.3987), arXiv:1305.2389)
- Compare LHCb results to LHCb (γ_{ECAL}) (PL B 714 (2012), pp. 215-223 (arXiv:1202.1080) & CMS EPJ C 72 (2012) 2251 (arXiv:1210.0875))



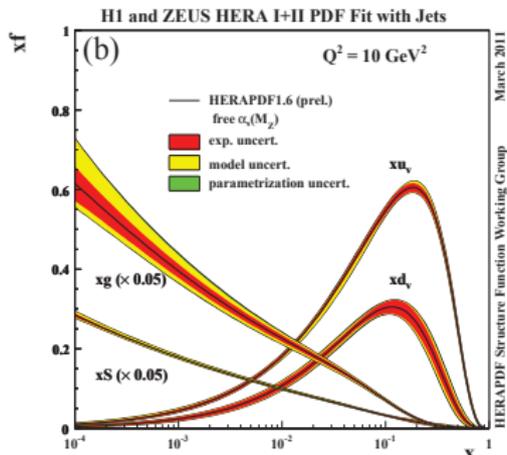
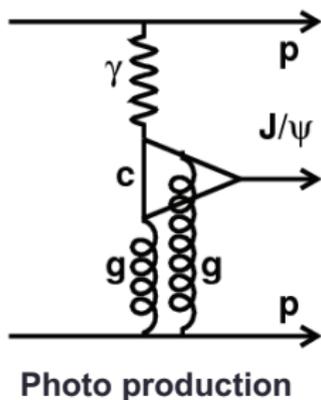
- Small discrepancies at low p_T
- New data provide better comparison to CMS at high p_T

Exclusive χ_c production:



- CEP of χ_c s only possible through double-pomeron exchange
- Select J/Ψ s with: $M(J/\Psi) - M_{J/\Psi}(\text{PDG}) < 65 \text{ MeV}/c$
- Only two muon tracks and one photon
- No tracks in backward region
- Use SuperChiC generator for χ_c simulations (Comput.Phys.Commun.144:104-110,2002 (arXiv:hep-ph/0010303))
- Result: $(39 \pm 13)\%$ estimated to originate from exclusive production

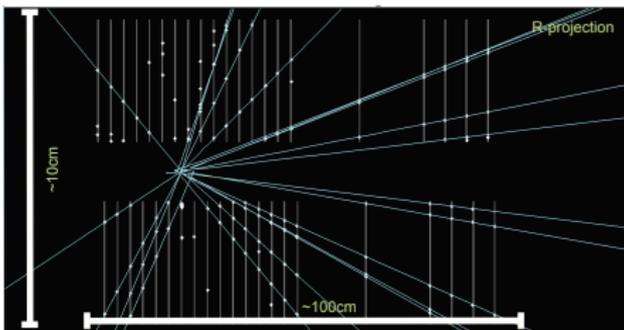
Photoproduction of J/Ψ and $\Psi(2S)$, parameterization by H1/ZEUS (AIP Conf.Proc. 1441 (2012) 225-228 (arXiv:1112.0224))



$$\sigma(\gamma p \rightarrow J/\Psi p) \propto (xg(x, Q^2))^2$$

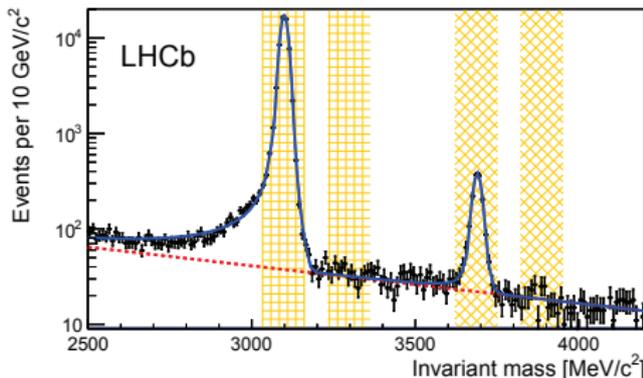
- Photoproduction sensitive to gluon parton distribution
- Probes gluon pdf down to $x \approx 5 \cdot 10^{-6}$
- Sensitive to gluon-saturation effects
- Sensitive to pomeron/odderon

LHCb: JPG: Nucl. Part. Phys. 41 (2014) 055002 (arXiv:1401.3288)



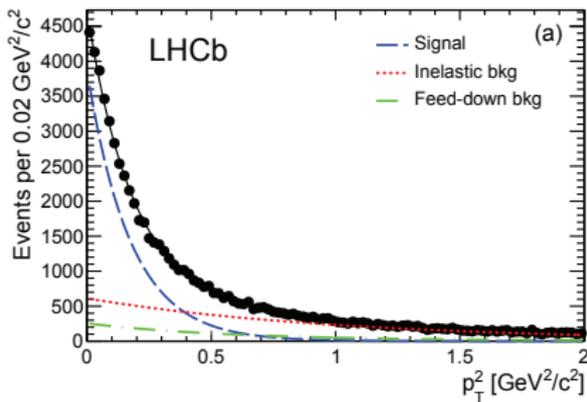
Selection:

- $p_{\mu^+, \mu^-} > 6$ GeV for each μ
- $p_T > 0.4$ GeV for each μ
- Rapidity gap of 3.5 units in forward region
- Rapidity gap of 1.7 ± 0.5 units in backward region

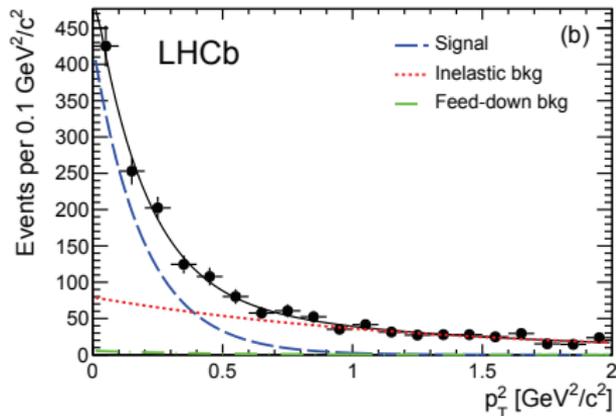


Inelastic background for J/Ψ and $\Psi(2S)$:

For J/Ψ :



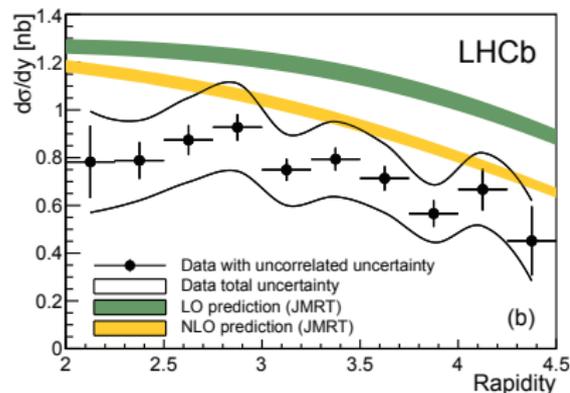
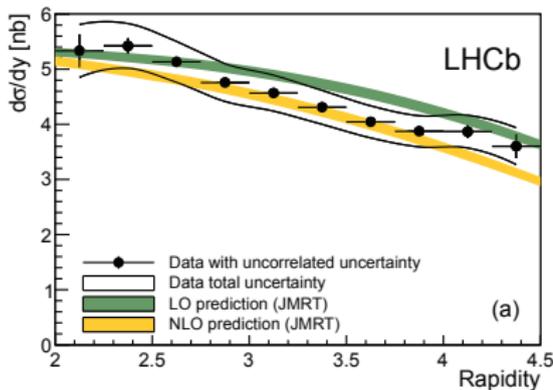
For $\Psi(2S)$:



- Use Regge theory ($\frac{d\sigma}{dt} \propto e^{bt}$) to model signal and background
- Use fit to determine fractions of background (inelastic and feed-down)
- Expectations for LHCb well matched by results from fit

Comparison to theory:

- Predictions by JMRT at LO and NLO (extrapolation to LHC energies)
- LO: power-law photoproduction from HERA with photon flux function and gap-survival factor



- NLO predictions compare well with J/Ψ data
- Not so good comparison to $\Upsilon(2S)$ data

Jones, Martin, Ryskin & Teubner, JHEP 1311 (2013) 085 (arXiv:1307.7099)

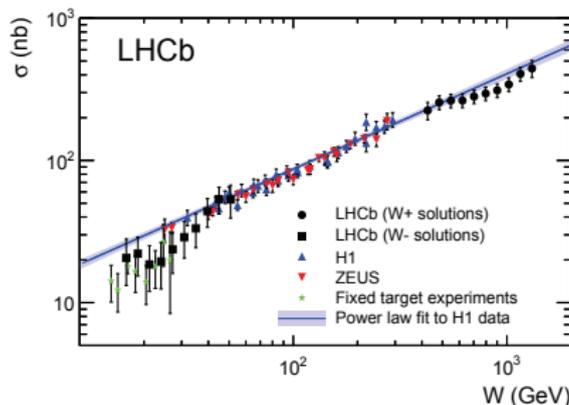
LHCb: JPG: Nucl. Part. Phys. 41 (2014) 055002 (arXiv:1401.3288)

Relation between exclusive J/Ψ production and photoproduction:

$$\frac{d\sigma}{dy}_{pp \rightarrow pJ/\Psi p} = r_+ k_+ \frac{dn}{dk_+} \sigma_{\gamma p \rightarrow J/\Psi p}(W_+) + r_- k_- \frac{dn}{dk_-} \sigma_{\gamma p \rightarrow J/\Psi p}(W_-)$$

- W_{\pm} and r_{\pm} absorptive corrections
- $\frac{dn}{dk}$ photon flux factor for photon with energy k_{\pm}
- Derive W_{\pm} from data using power-law results for W_{\mp} by H1 (Eur.Phys.J. C73 (2013) 2466 (arXiv:1304.5162))

$$\sigma_{\gamma p \rightarrow J/\Psi p}(W) = 81(W/90 \text{ GeV})^{0.67} \text{ nb}$$

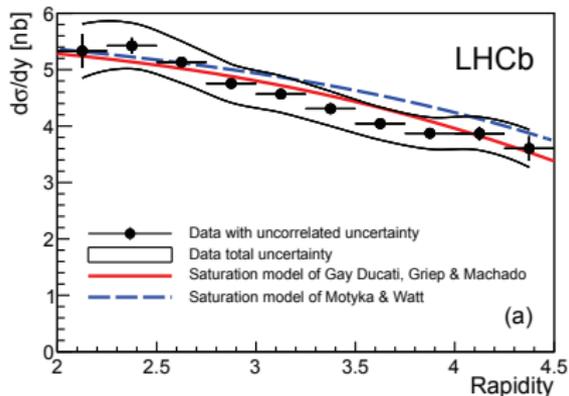


Only marginal agreement of H1 power-law fit with LHCb data

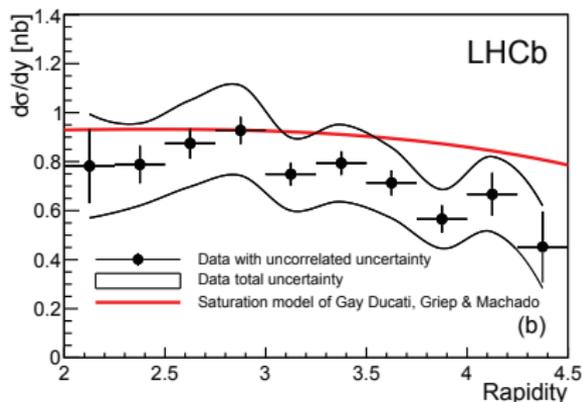
LHCb: JPG: Nucl. Part. Phys. 41 (2014) 055002 (arXiv:1401.3288)

Comparison of LHCb data with saturation models by Gay, Ducati Griep & Machado, and Motyka & Watt:

J/Ψ :



idem dito for $\Psi(2S)$:



Good agreement found with both saturation models.

GDG & M: PRD 88, 017504 (2013) (arXiv:1305.4611)

M & W: PRD 78:014023, 2008 (arXiv:0805.2113)

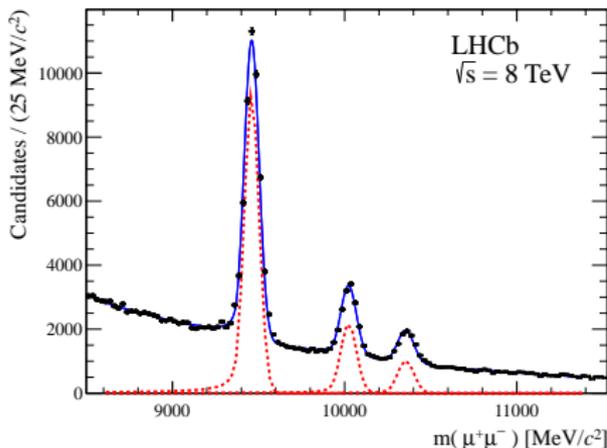
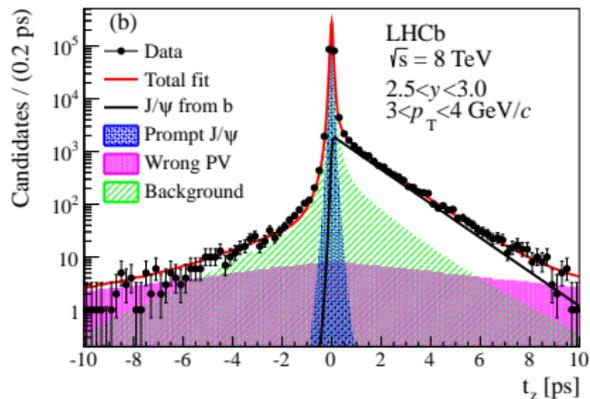
LHCb: JPG: Nucl. Part. Phys. 41 (2014) 055002 (arXiv:1401.3288)

- Use pseudo-proper time

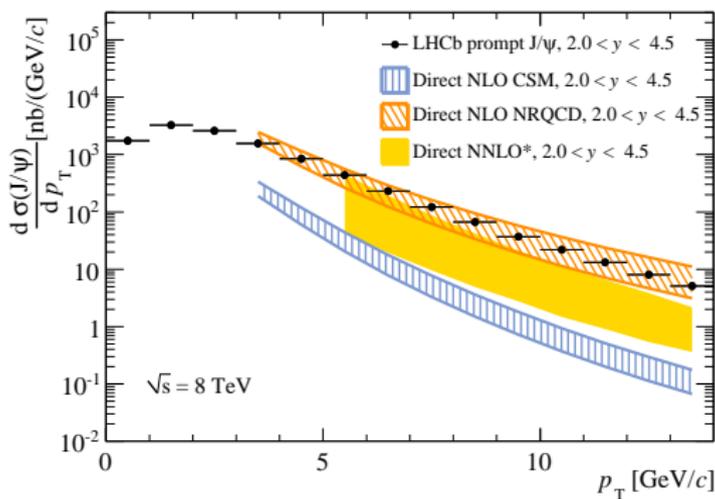
$$t_z = \frac{(z_{J/\Psi} - z_{PV}) \times M_{J/\Psi}}{p_z}$$

to differentiate prompt from secondaries (J/Ψ from b 's)

- Crystal Ball for J/Ψ & Υ signals and exponential for background



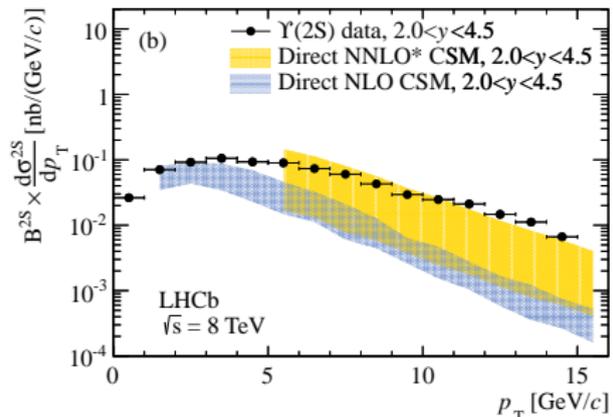
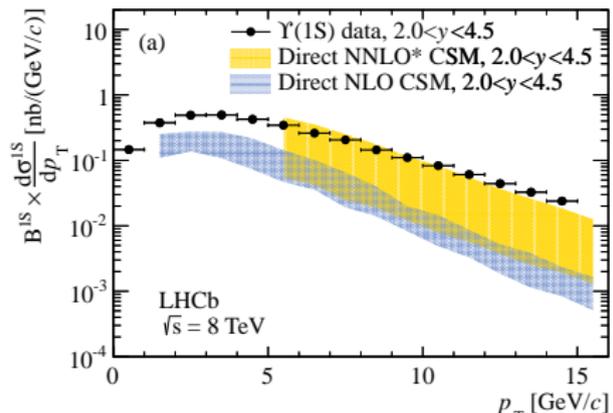
LHCb: JHEP 06 (2013) 064 [arXiv:1304.6977](https://arxiv.org/abs/1304.6977)



Comparison to:

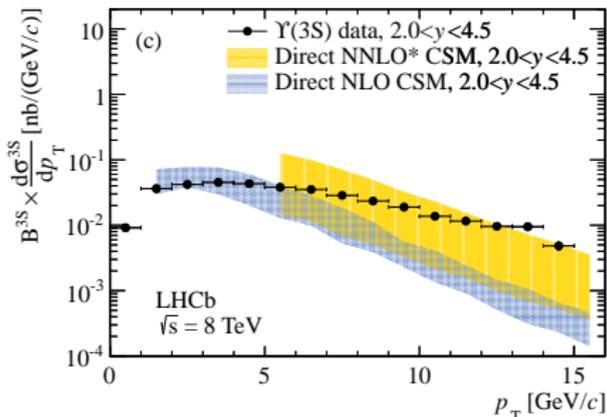
- Direct J/Ψ NLO NRQCD (PR D84 (2011) 051501 (arXiv:1105.820), PRL 106:022003, 2011 (arXiv:1009.5662))
- Direct J/Ψ NLO CSM (PRL 98 (2007) 252002 (arXiv:hep-ph/0703113))
- Direct J/Ψ NNLO CSM (PRL 101:152001,2008 (arXiv:0806.3282), EPJ C60:693-703,2009 (arXiv:0811.4005))

CSM at NLO underestimates LHCb data, even considering a 20% feed-down from higher states



Comparison of LHCb data to NLO & NNLO CSM calculations by

- Direct NLO CSM (Campbell, Maltoni & Tramontano, PRL 98 (2007) 252002 (arXiv:hep-ph/0703113))
 - Direct NNLO CSM (Artoisenet *et al.*, PRL 101:152001,2008 (arXiv:0806.3282))
- NLO CSM does not reproduce high- p_T data
- Incomplete NNLO compares much better to LHCb data.

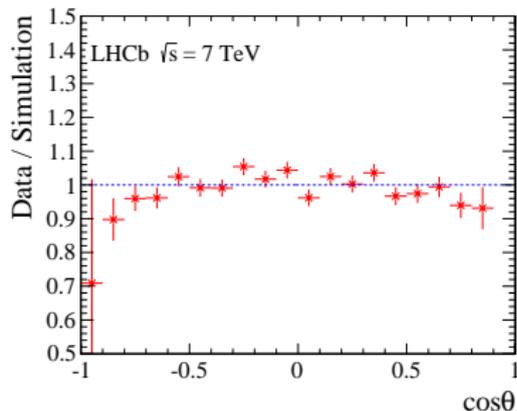
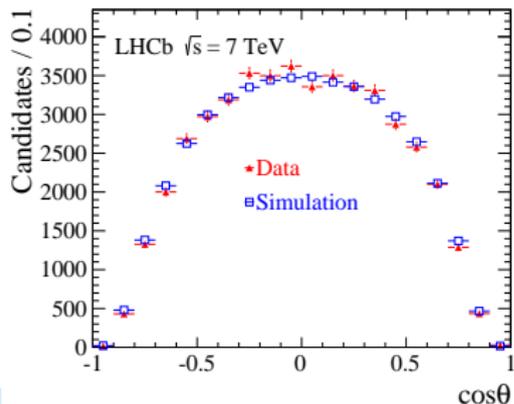


LHCb: JHEP 06 (2013) 064 (arXiv:1304.6977)

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

- Pseudo-decay time used to select prompt mesons
- Fit to angular distribution determines polarization parameters
- In helicity frame, $\lambda_\phi = \lambda_{\phi\theta} = 0$, $\lambda_\theta = \lambda_{\text{inv}}$
- Simulation used to determine efficiency in $(\cos\theta, \phi)$ plane
- Compare simulated angular distributions to $B \rightarrow J/\Psi K^+$ results:

$\cos\theta$ from $B \rightarrow J/\Psi K^+$ and simulation

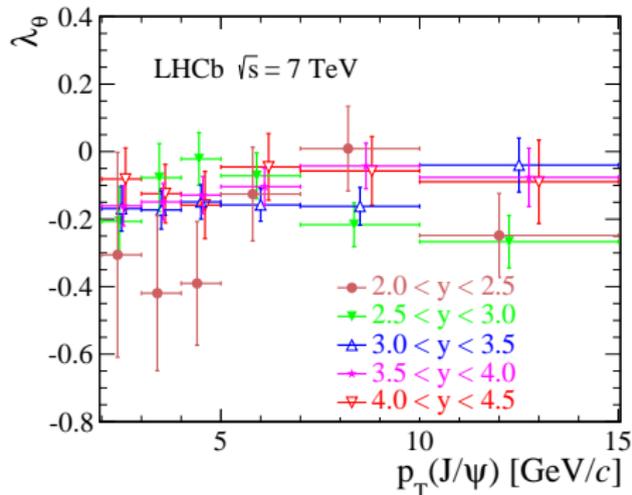


EPJ C (2013) 73:11 (arXiv:1307.6379), EPJ C (2014) 74:2872 (arXiv:1403.1339)

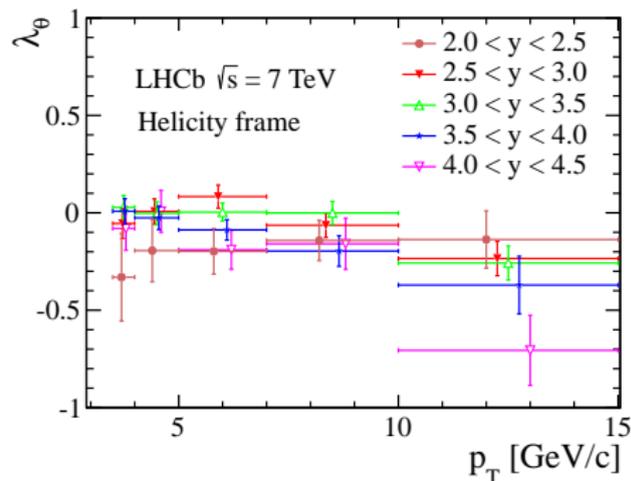
J/Ψ and $\Psi(2S)$ polarization

- J/Ψ polarization mostly negative across (y, p_T) -plane
- $\Psi(2S)$ polarization also mostly negative

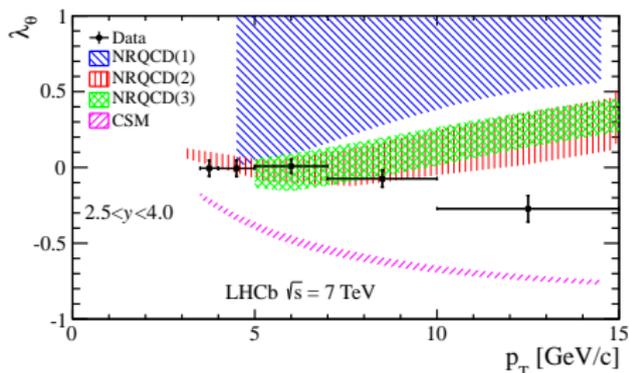
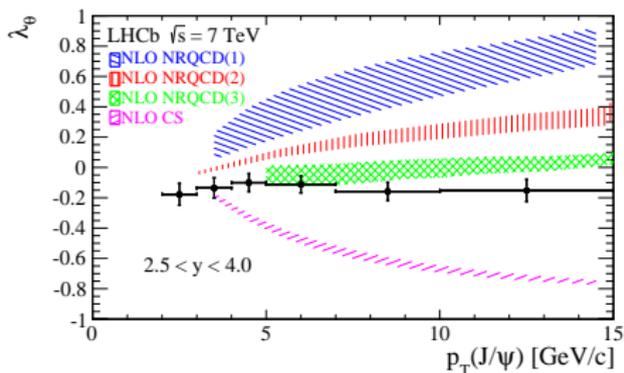
J/Ψ polarization:



$\Psi(2S)$ polarization:



- Color-Singlet models do not reproduce LHCb data
- LHCb results include contributions from feed-down (CSM model does not)
- High p_T behavior not described by any model



Butenschoen & Kniehl, PRL 108 (2012) 172002 (arXiv:1201.1872)

Gong, Wan, Wang & Zhang, PRL 110, 042002 (2013) (arXiv:1205.6682)

Chao *et al.*, PRL 108, 242004 (2012) (arXiv:1201.2675)

Shao & Chao, arXiv:1209.4610

EPJ C (2013) 73:11 (arXiv:1307.6379), EPJ C (2014) 74:2872 (arXiv:1403.1339)

- Unique kinematic regime accessed by LHCb ($x > 5 \cdot 10^{-6}$)
- Results on χ_c ratios, inclusive Υ , exclusive J/Ψ , $\Psi(2S)$ production
- χ_c cross section ratios from converted photons agree well with CMS data
- LO & NLO calculations only disagree at low p_T for χ_c cross section ratios
- Inclusive Υ production reasonable agreement with incomplete NNLO CSM calculations
- Exclusive and inclusive J/Ψ cross sections agree well with predictions
 - from phenomenology (NLO using power-law fits)
 - from saturation models by Gay *et al.*, & Motyka and Watt
- Polarization results disagree with theoretical models at high p_T