Implications of LHCb measurements and future prospects

12-14 Oct. 2016, CERN

Production measurements at LHCb

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Outline

- Introduction
- Production cross-sections
- Polarization ($J/\psi, \psi(2S)$)
- Associated production
- Future prospects
- Summary

Biased selection on quarkonia

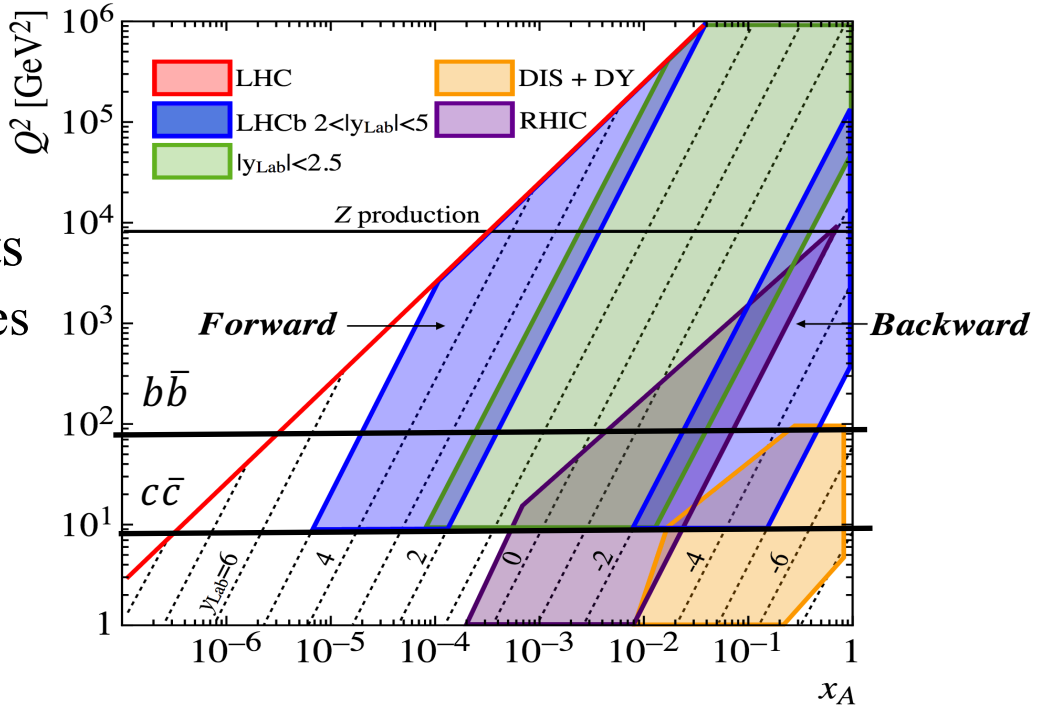
Introduction

- Heavy flavor productions are tools to understand QCD
  - Polarization measurements put further constraints to QCD-based models
  - Better understanding of QCD is fundamental and essential for new physics searches

- LHCb is optimized for precision measurements in b, c quark sectors
  - Excellent tracking, vertexing, hardon and muon identification
  - Kinematic coverage is unique: $2 < y < 4.5$, down to zero p_T

- Brief review of LHCb measurements
  - Including comparisons with theories

List of LHCb measurements on quarkonia



Productions in pp collisions

- J/ψ @ 2.76, 7, 8, 13 TeV
- $\psi(2S)$ @ 7 TeV
- $\Upsilon(nS)$ @ 7, 8 TeV
- χ_c @ 7 TeV
- χ_b @ 7/8TeV

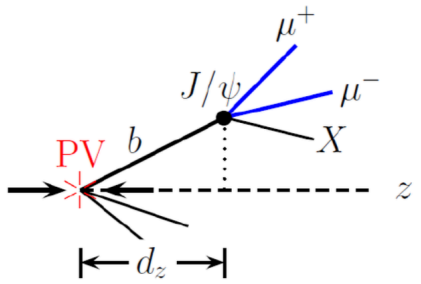
EPJC71 (2011) 1645
EPJC72 (2012) 2025
EPJC72 (2012) 2100
JHEP 02 (2013) 41
JHEP 06 (2013) 64
JHEP 11 (2015) 103
JHEP 10 (2015) 172

JHEP 11 (2012) 31
PLB718 (2012) 431
JHEP 10 (2013) 115
EPJC74 (2014) 3092

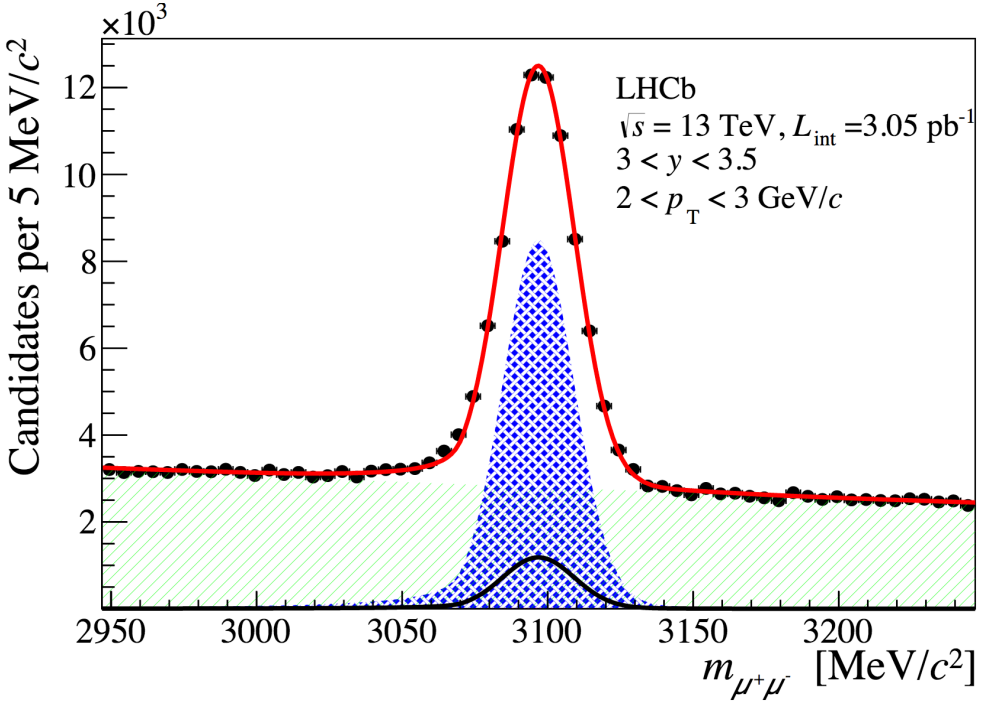
Quarkonia production at LHCb

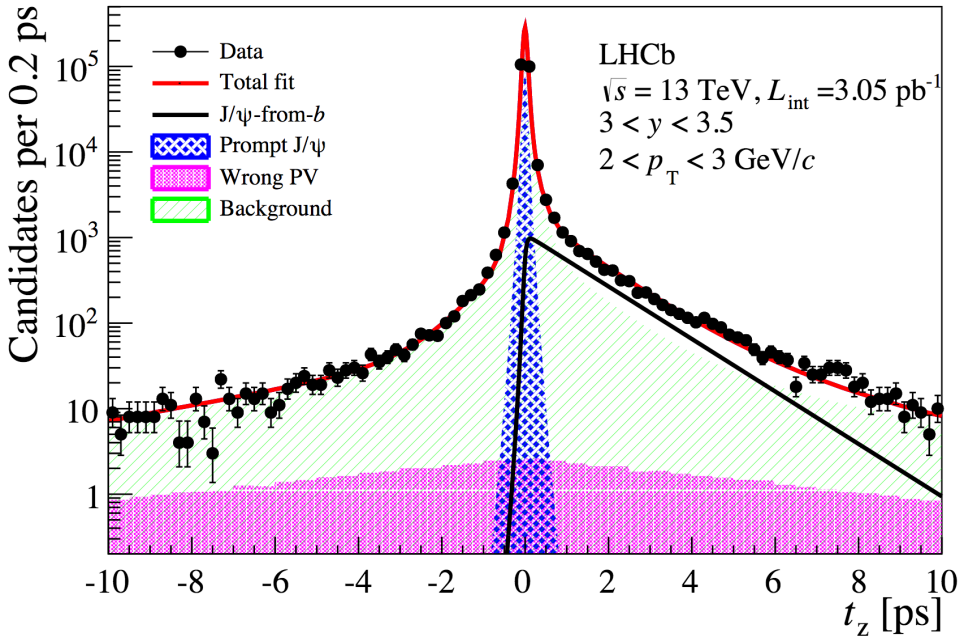
- Measurements are mostly performed in $\mu^+\mu^-$ final states, clean and easy to trigger
- Prompt ψ and ψ from b decays are separated using pseudo decay time, t_z
  - Thanks to LHCb vertex detector
  - ψ from b is indirect probe of $b\bar{b}$ hadron production

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

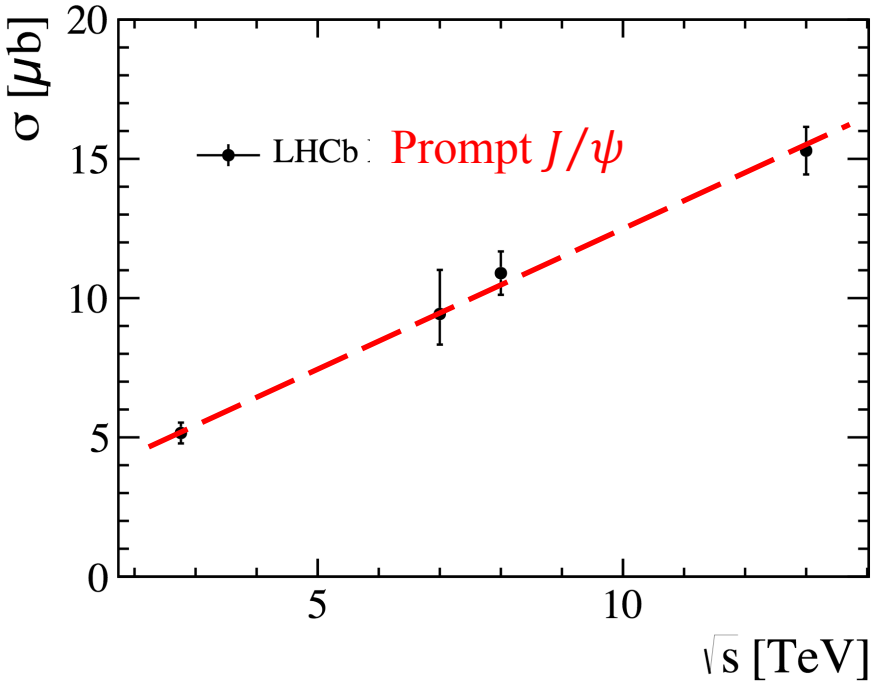


JHEP 10 (2015) 172

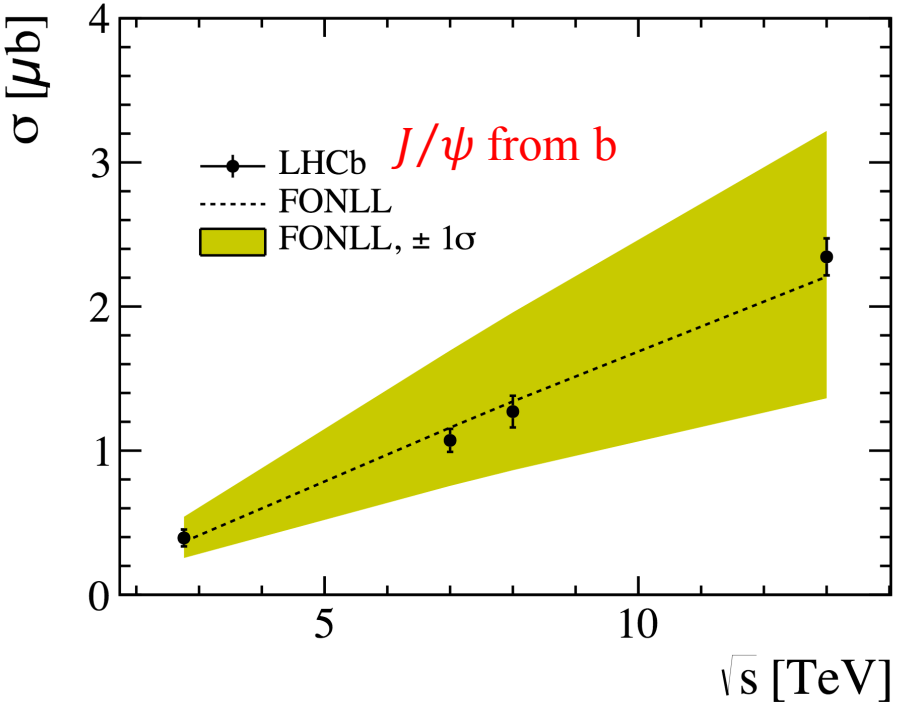




$\sigma(J/\psi)$ as a function of $\sqrt{s}$



JHEP 10 (2015) 172

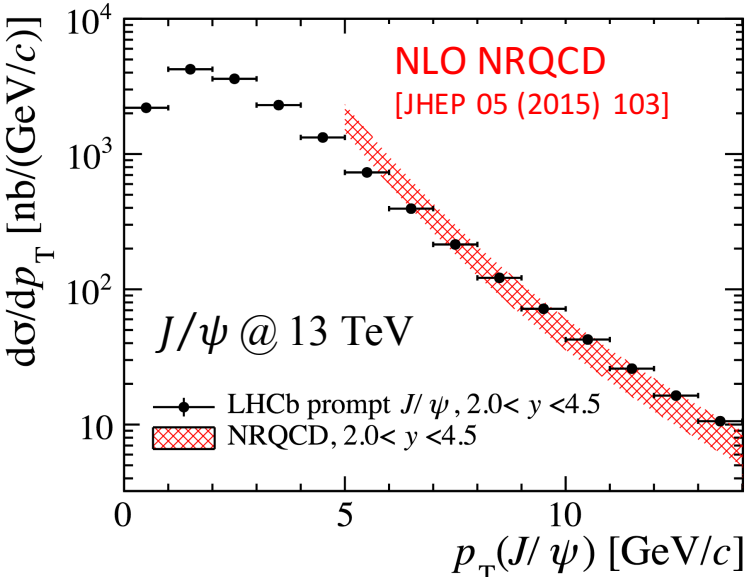


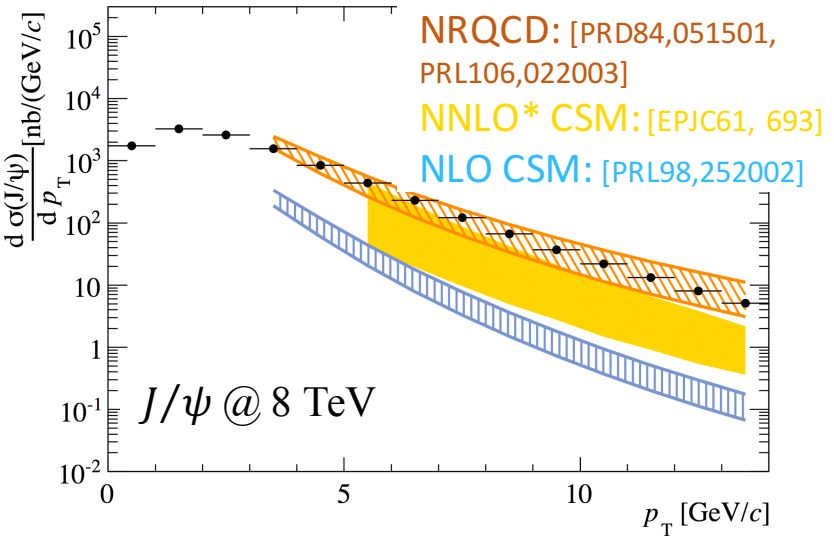
$\sigma(J/\psi$, prompt) scales almost linearly with $\sqrt{s}$ in range 2.76-13 TeV

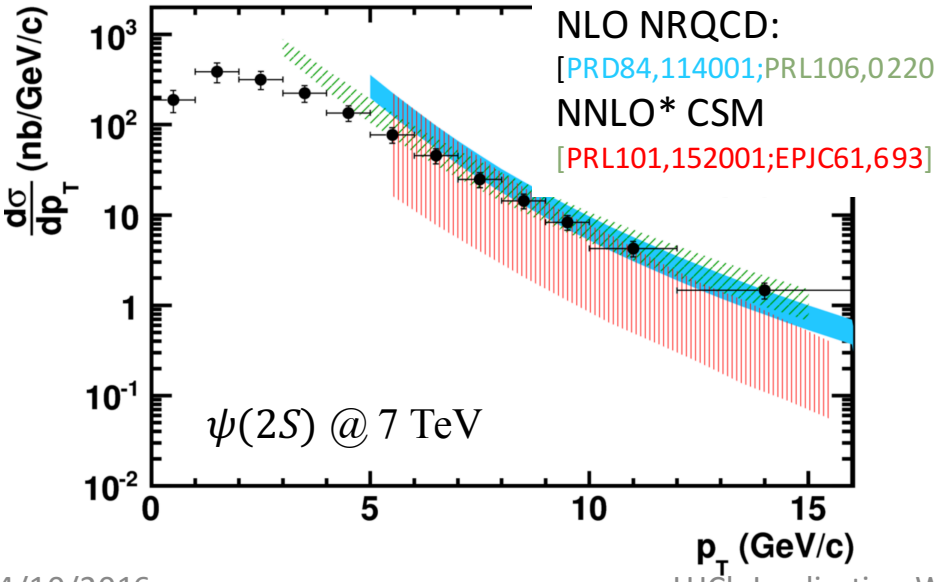
$\sigma(J/\psi$, from b) well described by FONLL prediction [JHEP 05 (1998) 007]

p_T distributions: prompt ψ

LHCb: EPJC72 (2012) 2100, JHEP 06 (2013) 64, JHEP 10 (2015) 172



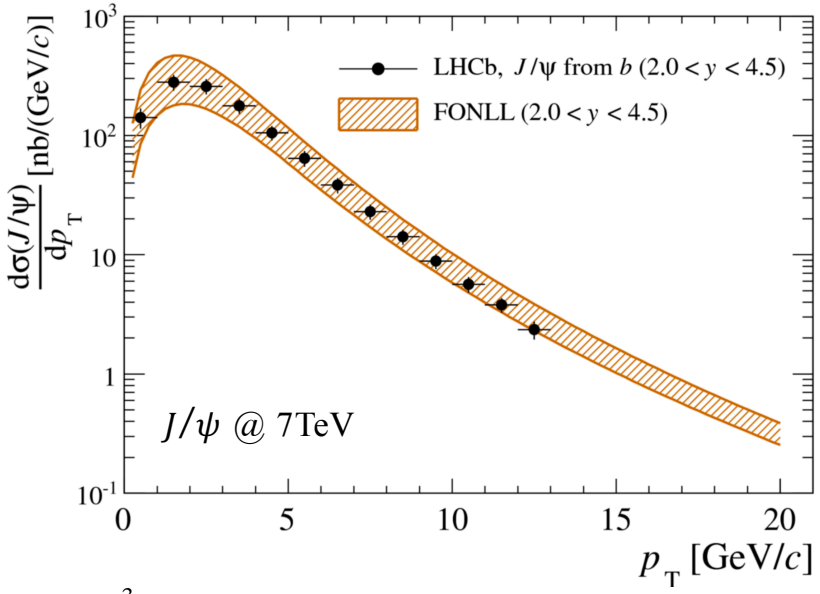


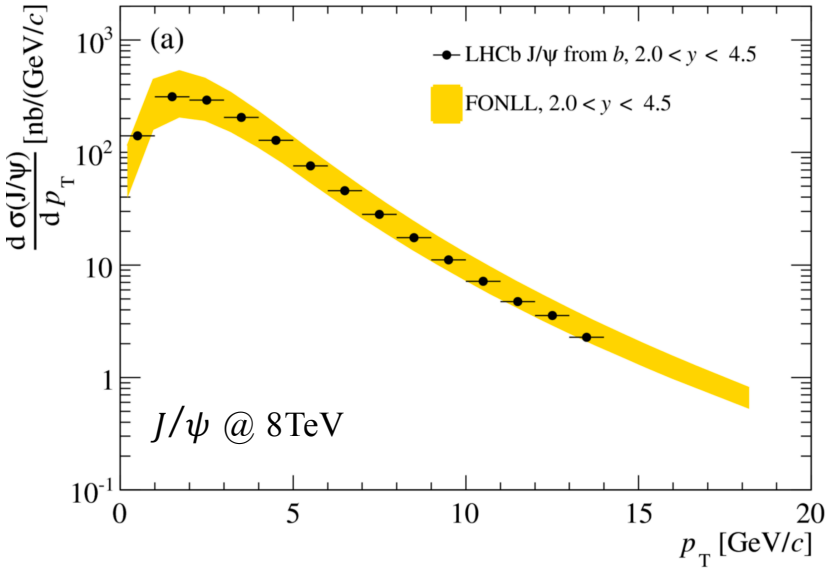


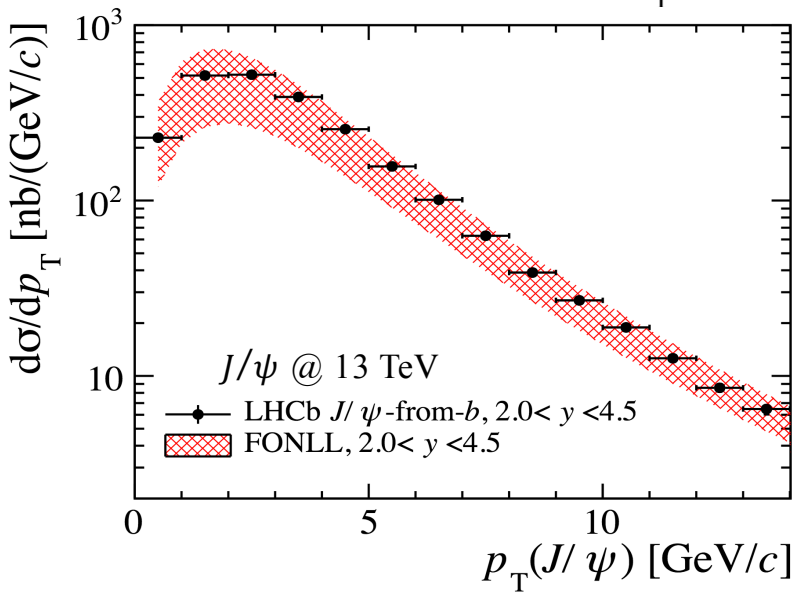
- In good agreement with NLO NRQCD predictions
- NLO or NNLO* CSM calculations underestimates data

p_T distributions: ψ from b

LHCb: EPJC71 (2011) 1645 , JHEP 06 (2013) 64, JHEP 10 (2015) 172





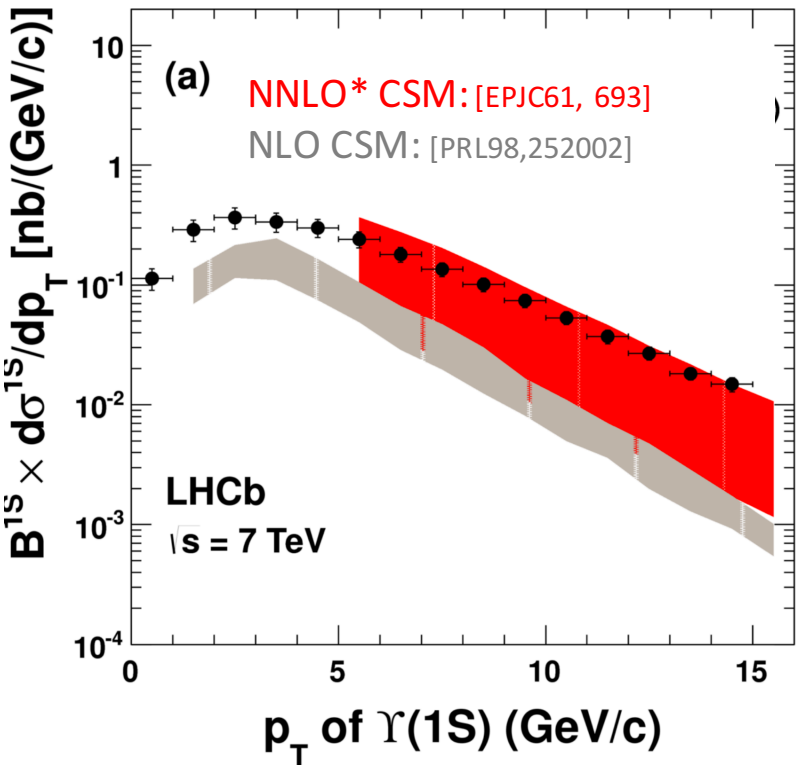


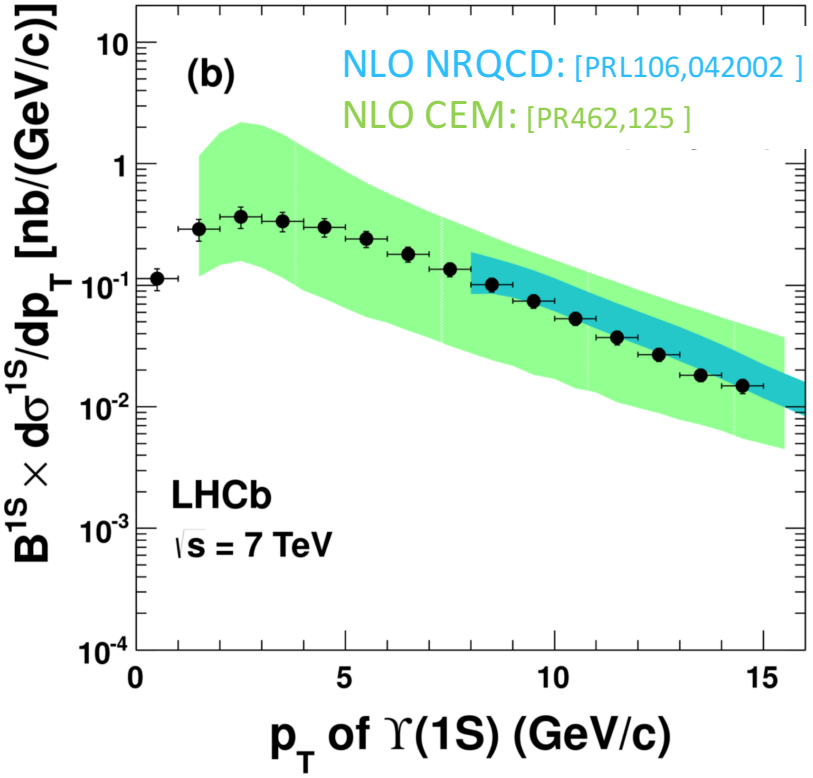
FONLL: [JHEP 05 (1998) 007]

See backup slide for $\psi(2S)$ from b
Data consistent with FONLL calculations

p_T distributions: Υ @7 TeV

LHCb: EPJC72 (2012) 2025



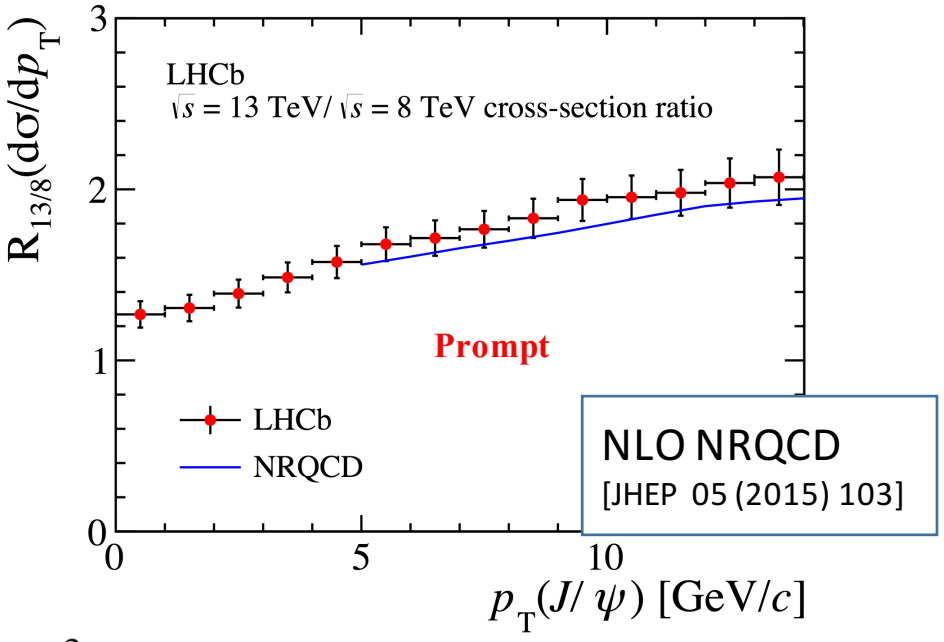


- p_T distributions consistent with NRQCD and CEM, but not with CSM
- NLO (NNLO*) CSM calculations underestimate p_T differential cross-section
- Agreement with NRQCD and CEM are better

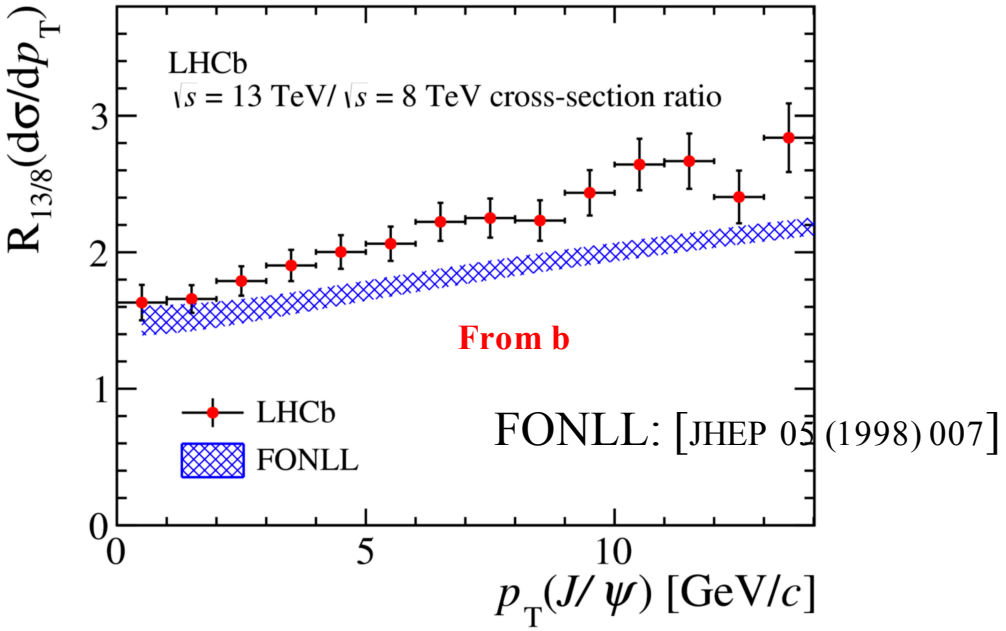
Ratio of $\sigma(J/\psi)$ at 13, 8 TeV

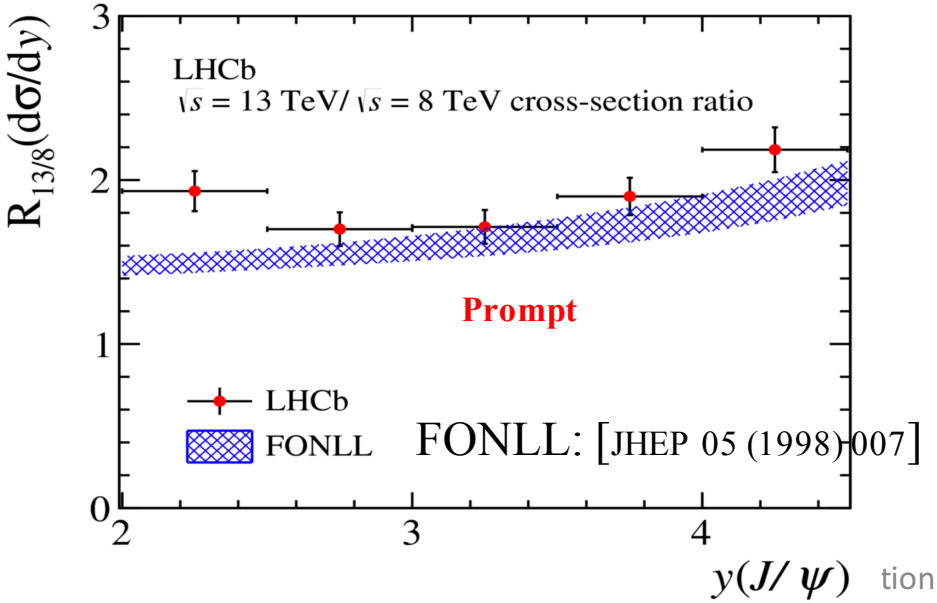
Uncertainties largely cancel

LHCb: JHEP 10 (2015) 172



NLO NRQCD
[JHEP 05 (2015) 103]

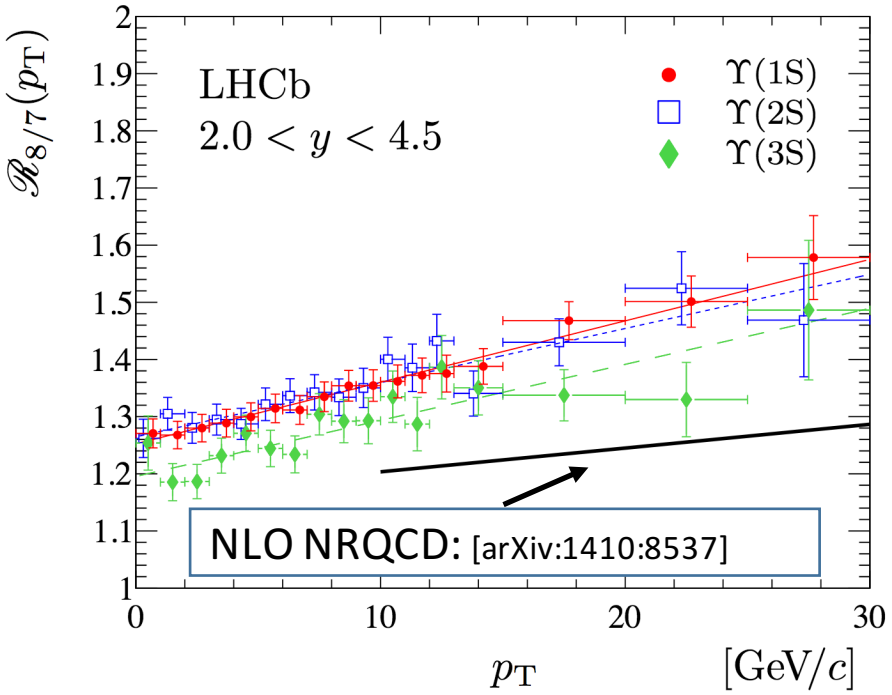


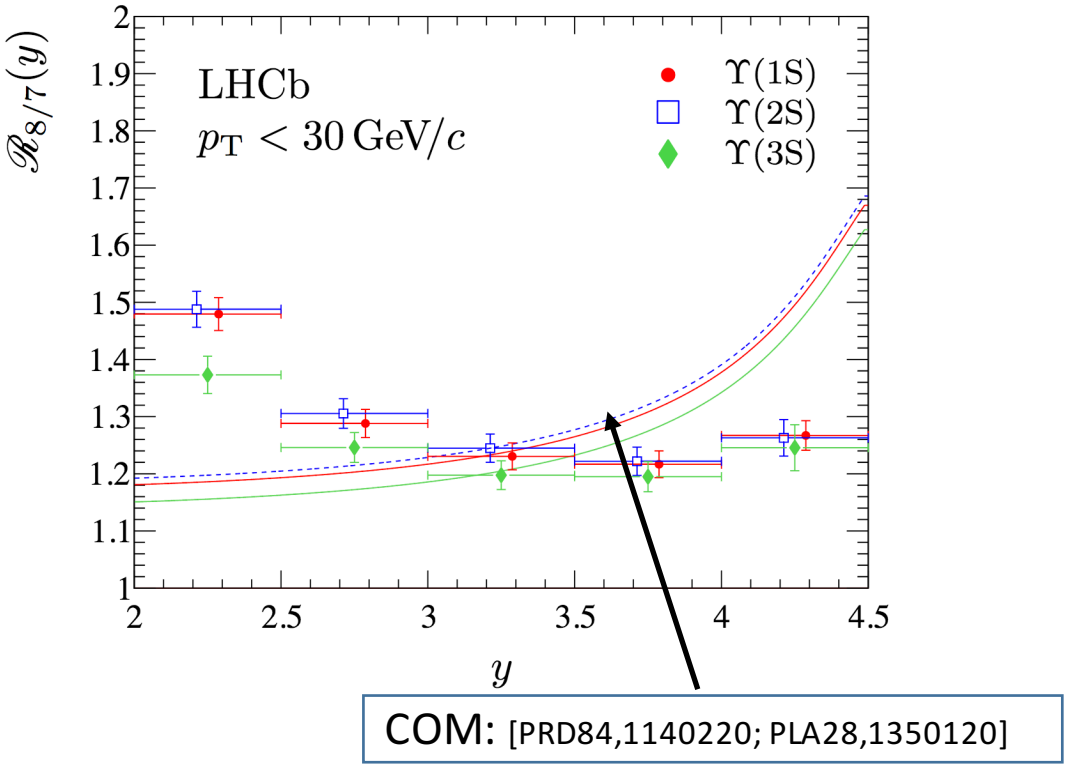


- Cross-section ratio between 13 and 8 TeV increases with p_T
- Ratio for prompt J/ψ is consistent with NLO NRQCD predictions
- Agreement with FONLL also not bad

Ratio of $\sigma(\Upsilon)$ at 8, 7 TeV

LHCb: JHEP 06 (2013) 64

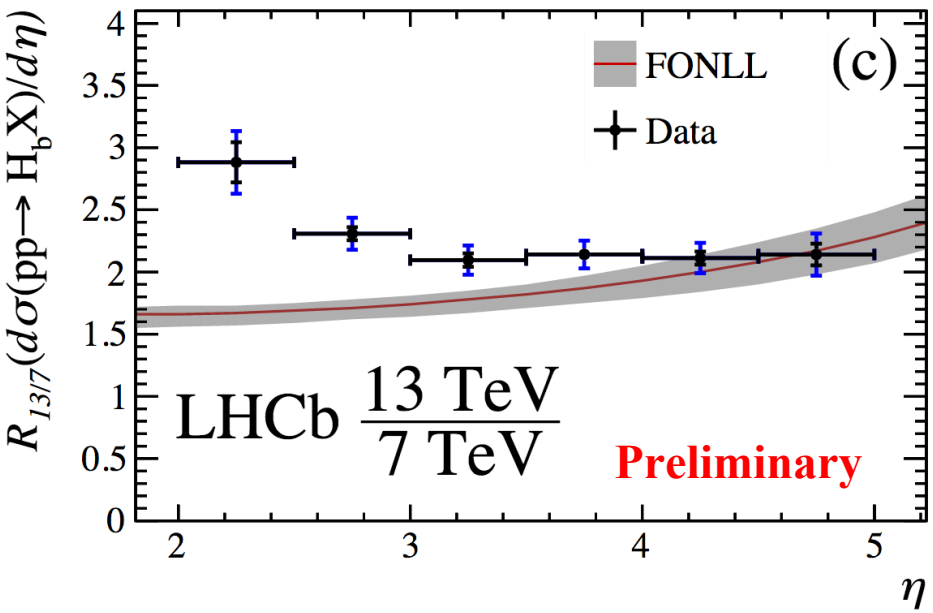




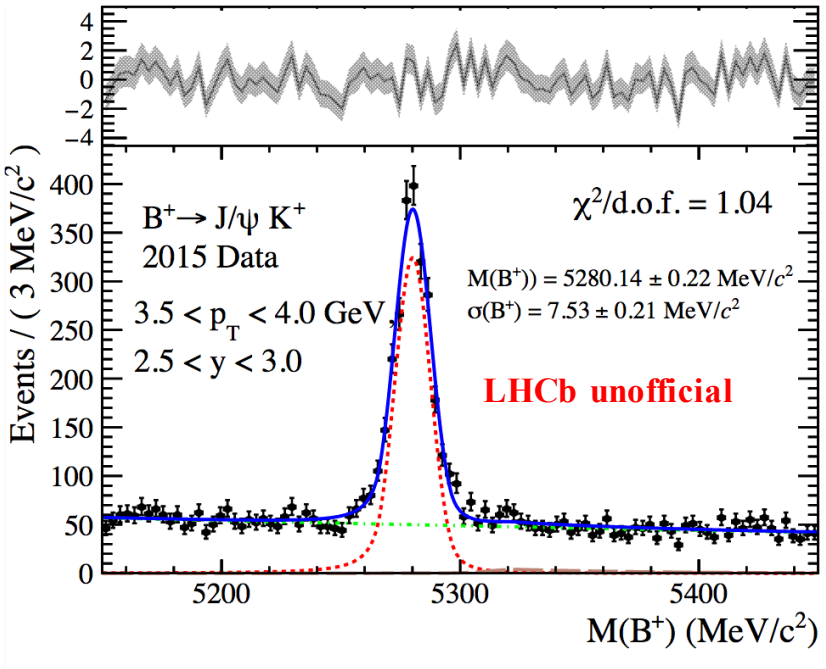
- Cross-section increases by 30% from 7 to 8 TeV on average
- The ratio increases with p_T, magnitude not quite predicted by NRQCD
- The ratio has unexpected trend at small y
- Not compatible with COM calculations

Ratio of $\sigma(b)$ at $\sqrt{S} = 13/7(8)$

$b\bar{b}$ cross-section with semileptonic decays



B^+ cross-section using $B^+ \to J/\psi\, K^+$

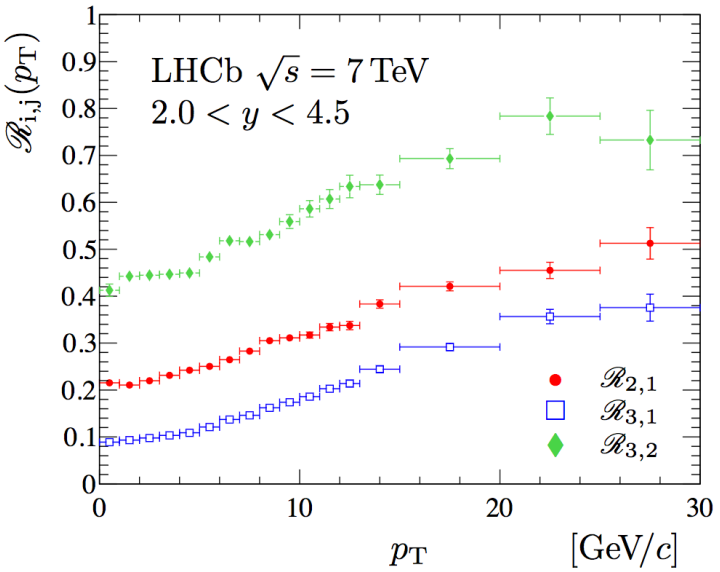


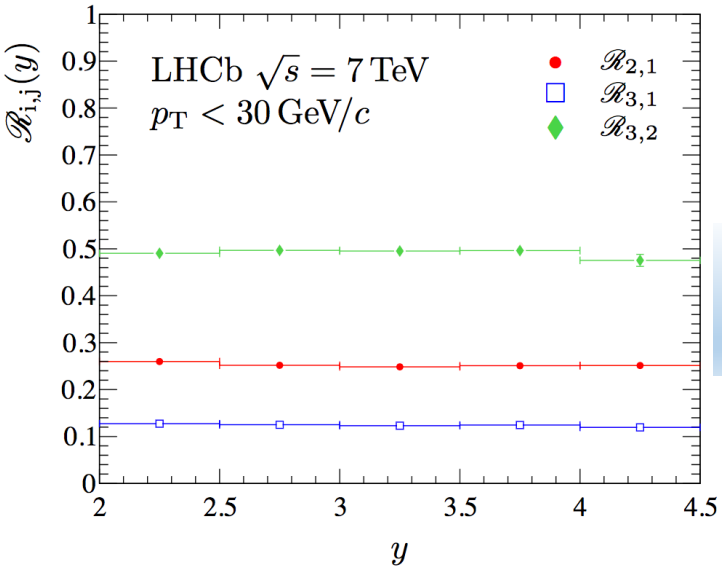
Cross-section ratio measurements using semileptonic decays and exclusive decay are consistent. Behavior not predicted by FONLL.

Production for excited states

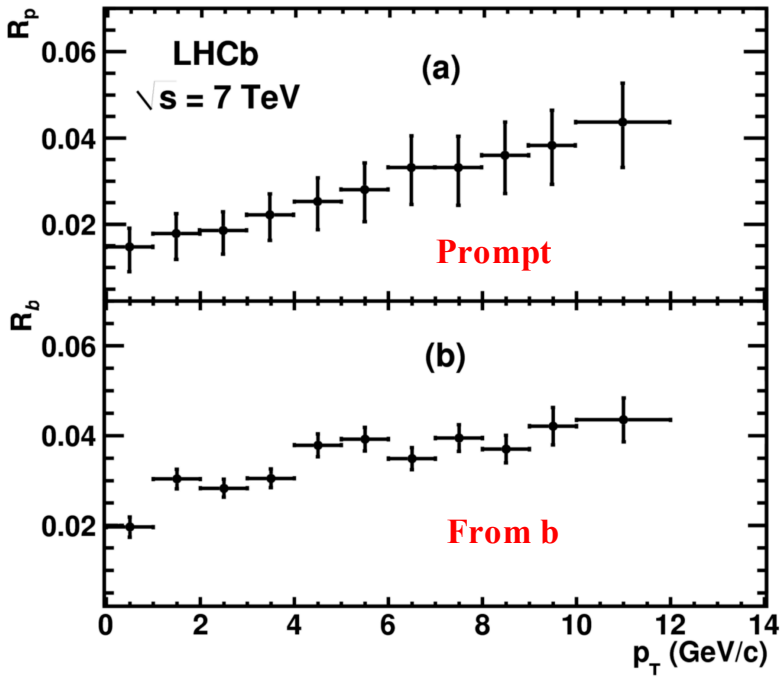
$\sigma(\Upsilon(nS))/\sigma(\Upsilon(1S))$ @ 7 TeV

LHCb: JHEP 06 (2013) 64, EPJC72 (2012) 2100





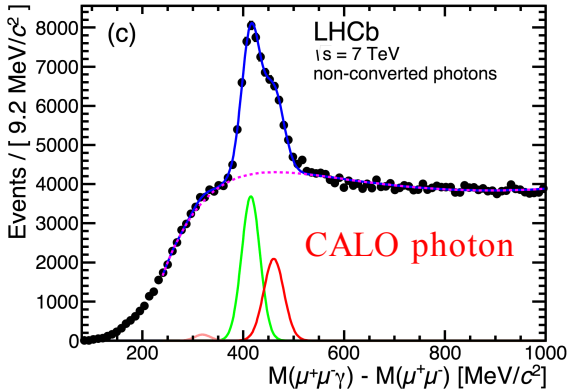
$\sigma(\psi(2S))/\sigma(J/\psi)$ @ 7 TeV

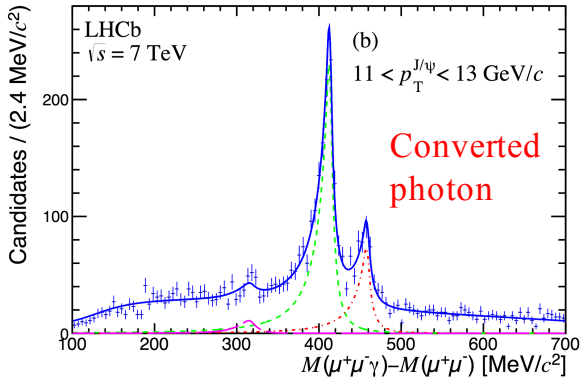


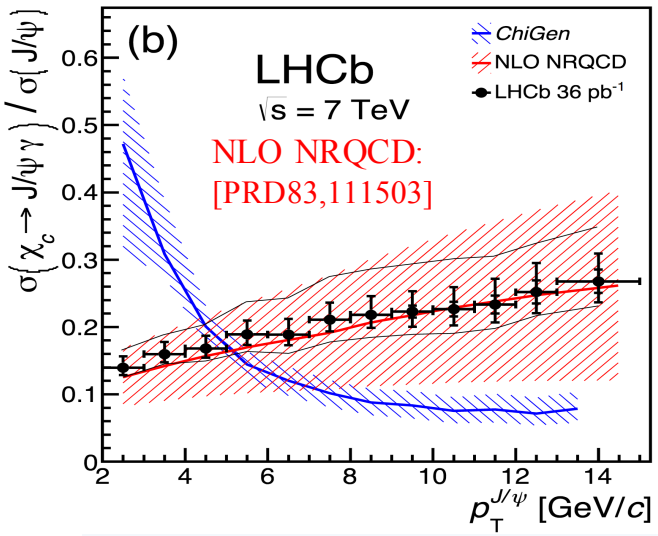
Ratios increase with p_T, constant as a function of y
Results are important to determine feed-down fractions

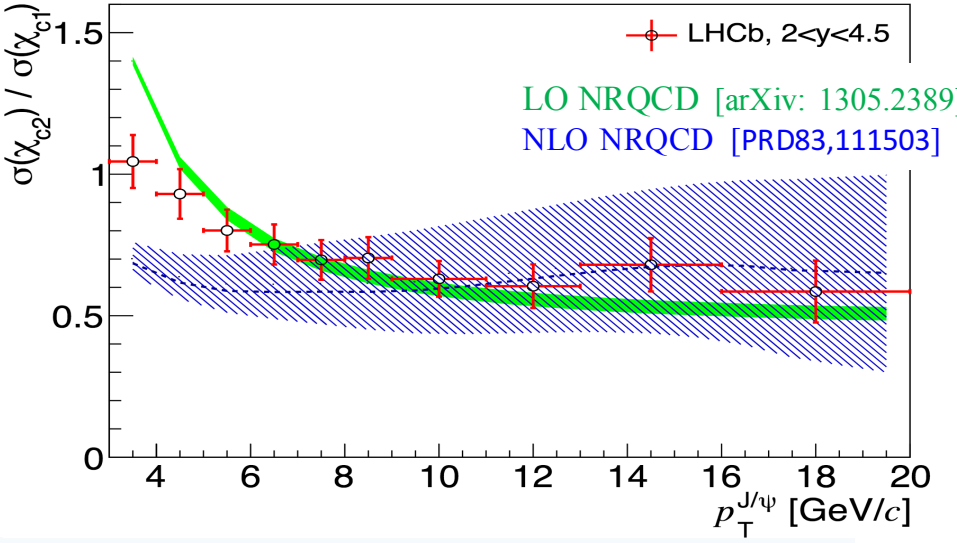
χ_c production

LHCb: PLB718 (2012) 431, JHEP 10 (2013) 115





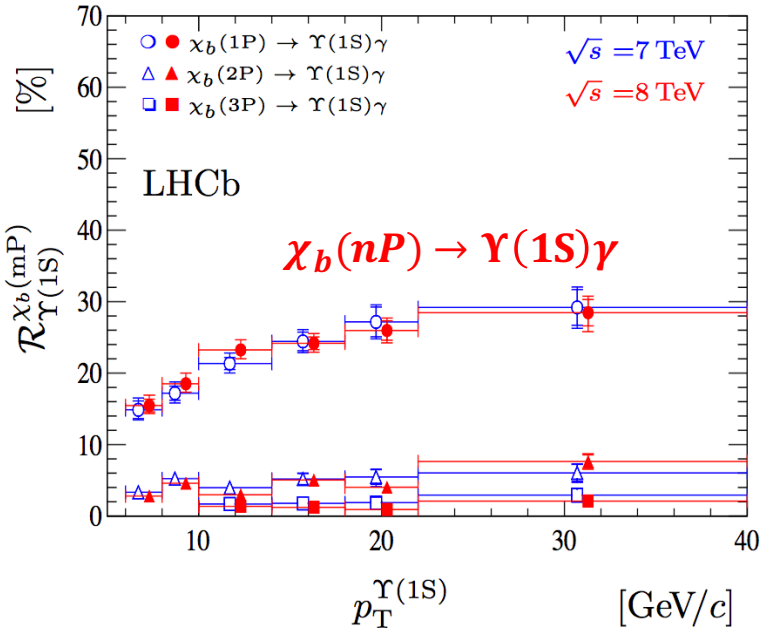


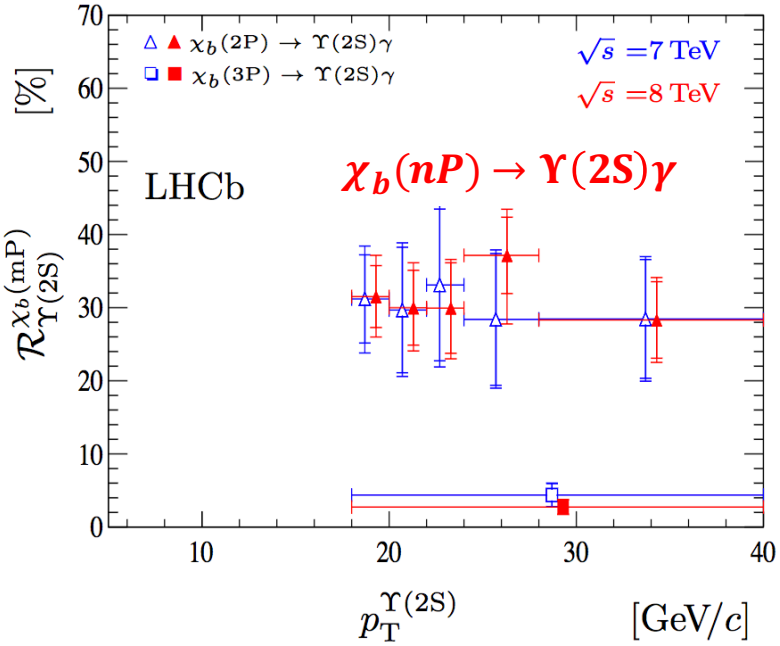


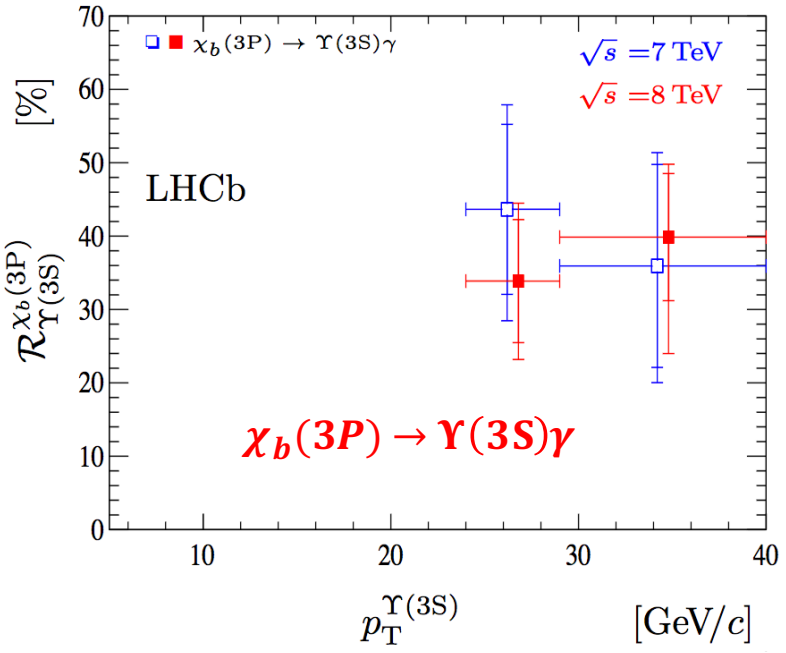
- $\frac{\sigma(\chi_c)}{\sigma(J/\psi)}$ increases with p_T
- $\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})}$ decreases with p_T at low p_T then becomes flat at mid p_T
- Data well predicted by NRQCD models

χ_b production

LHCb: EPJC74 (2014) 3092

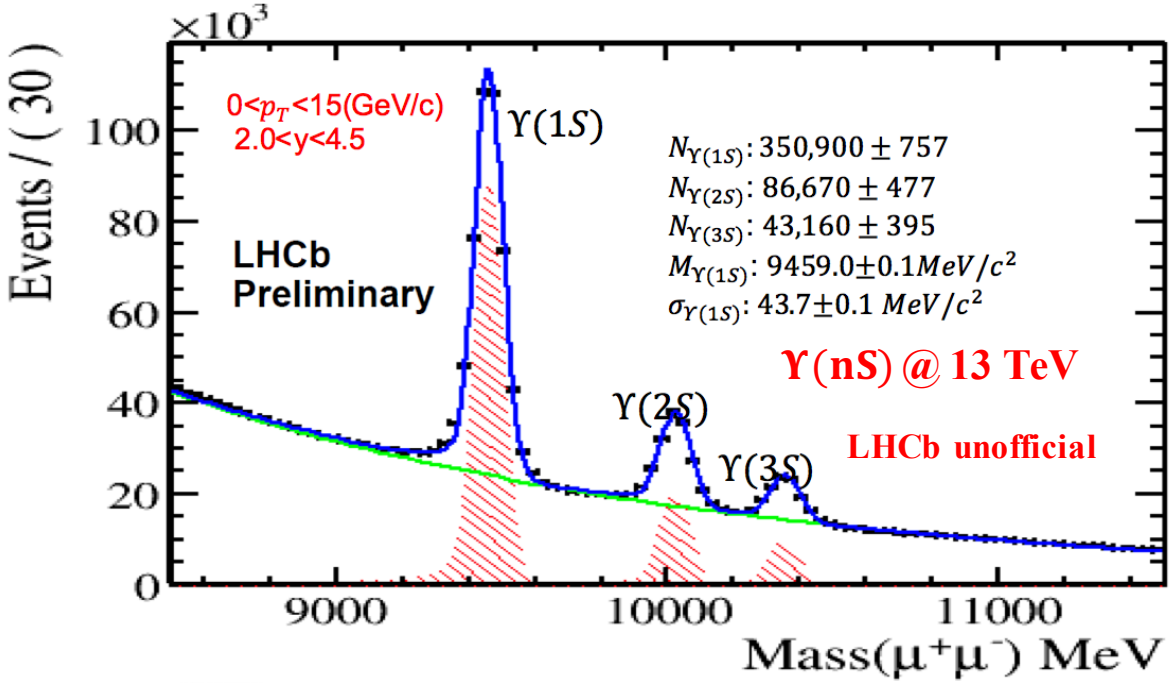


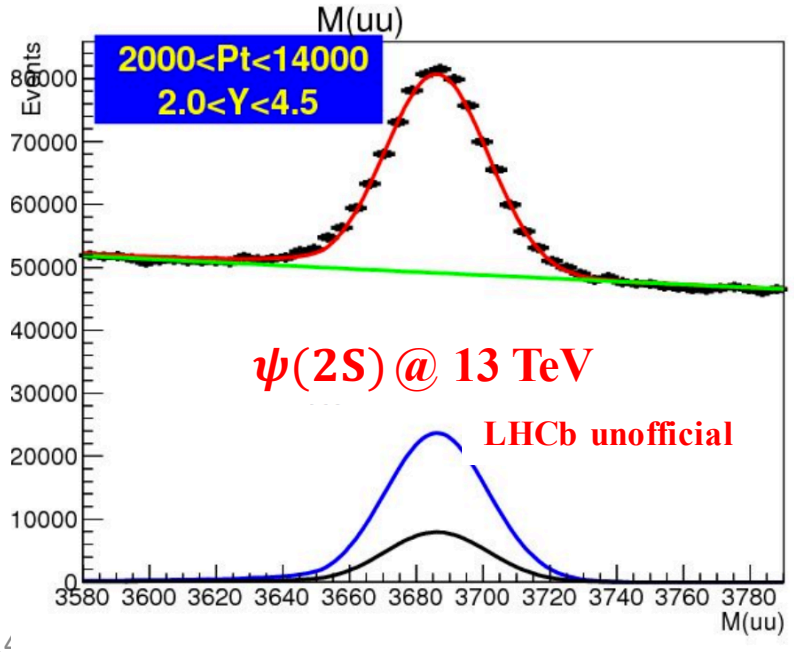




- $\Upsilon(nS)$ has a large and similar fraction from decays of $\chi_b(nP)$ states, 30-40%
- No evidence of dependence on pp colliding energy

Prospects





- Several analyses of quarkonia cross-section @ 13 TeV finalizing
- Cross-section measurements using 5 TeV pp special run data
- More will follow

Differential production cross-section of B_c^+ in pp collisions

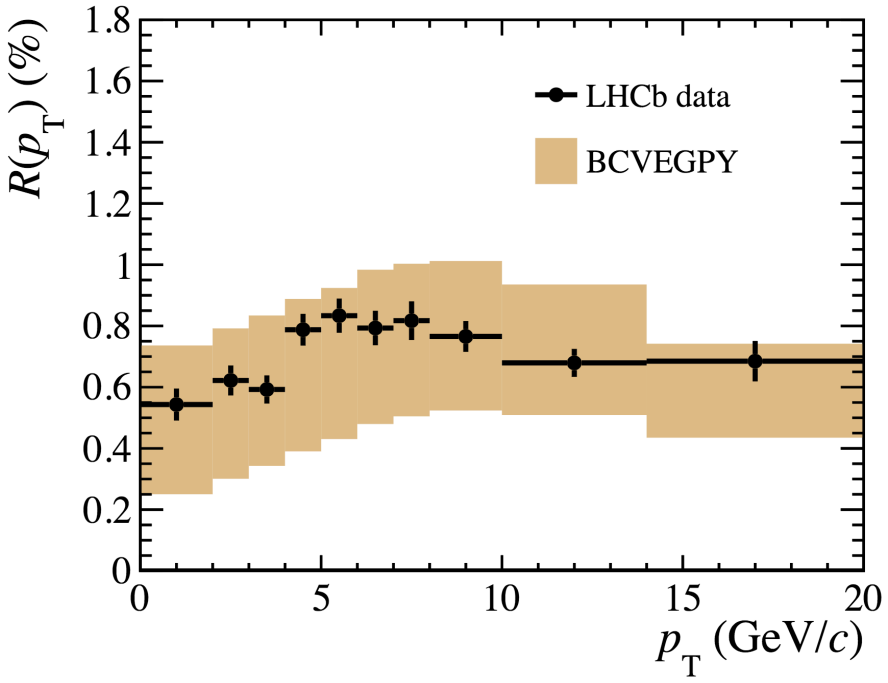
PRL 114 (2015) 132001

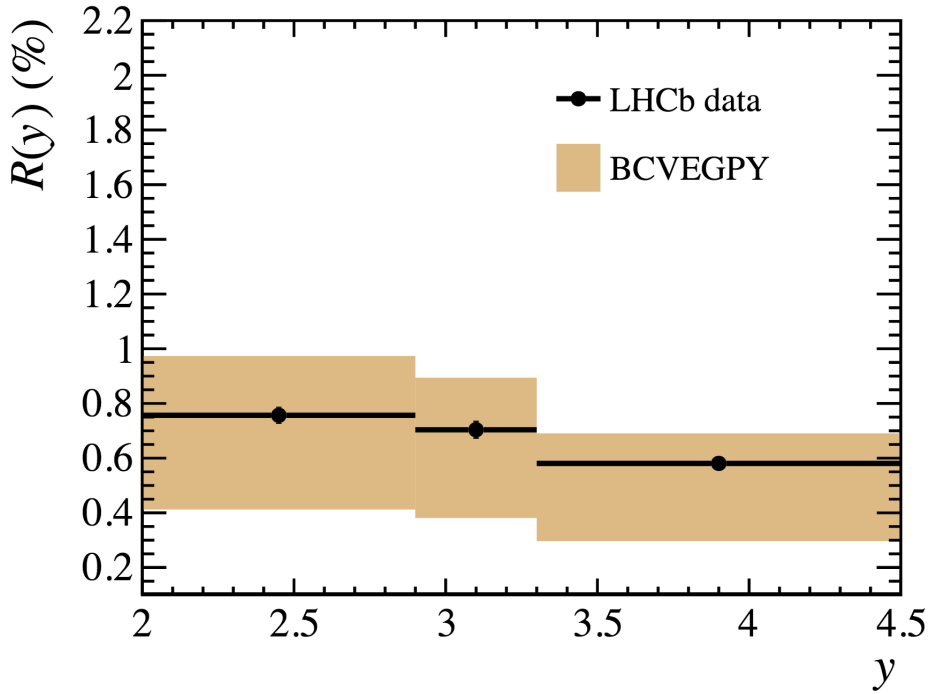
B_c^+ production

LHCb: PRL 114 (2015) 132001

- LHC is a factory of B_c^+ meson, decays extensively studied at LHCb
- B_c^+ differential cross-section precisely measured at LHCb

$$R(p_{\mathrm{T}}, y) \equiv \frac{\mathrm{d}\sigma_{B_c^+}(p_{\mathrm{T}}, y)\ \mathcal{B}(B_c^+ \to J/\psi\,\pi^+)}{\mathrm{d}\sigma_{B^+}(p_{\mathrm{T}}, y)\ \mathcal{B}(B^+ \to J/\psi\,K^+)}$$





Kinematic spectrum surprisingly consistent with BCVEGPY predictions, normalized to FONLL for B+. [Comput. Phys. Commun. 174, 241, JHEP 10(2012) 137].

Polarization of quarkonia in pp collisions

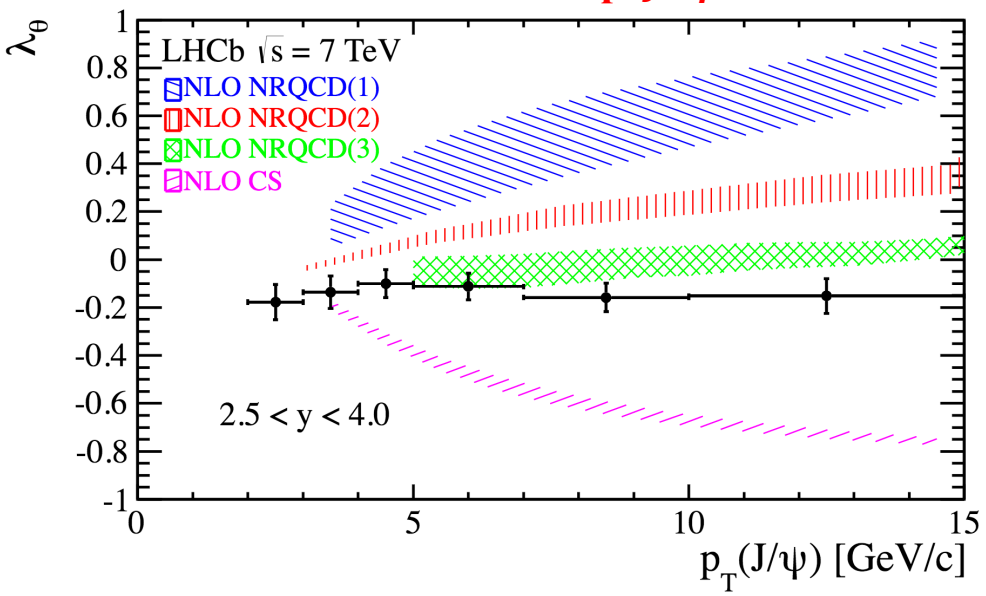
- J/ψ and $\psi(2S)$ polarisation

EPJC73 (2013) 2631
EPJC74 (2014) 2872

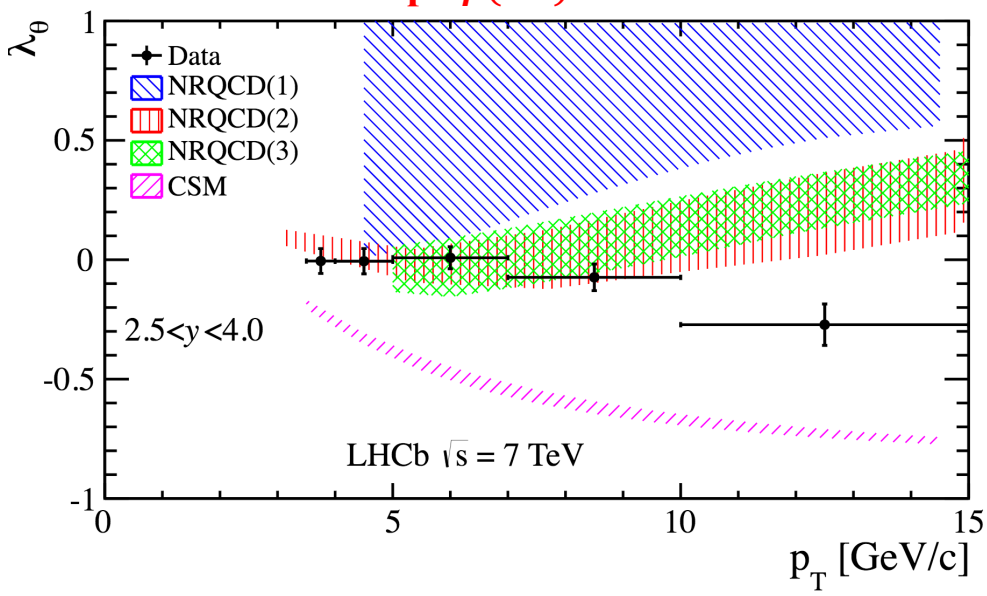
Polarisation results

LHCb: EPJC73 (2013) 2631, EPJC74 (2014) 2872

Prompt J/ψ



Prompt $\psi(2S)$

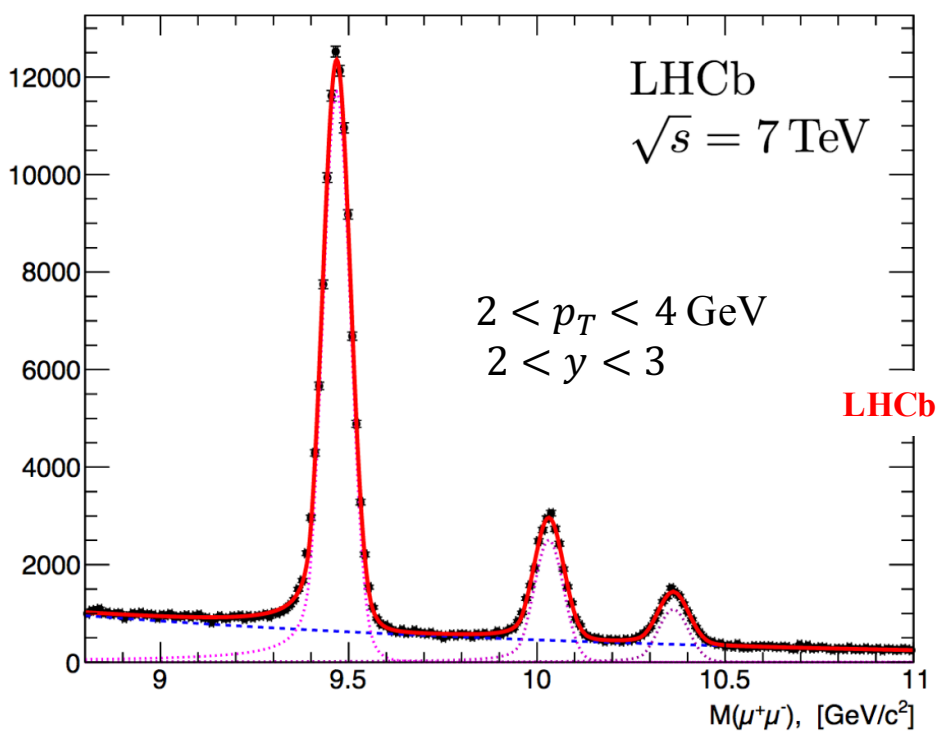


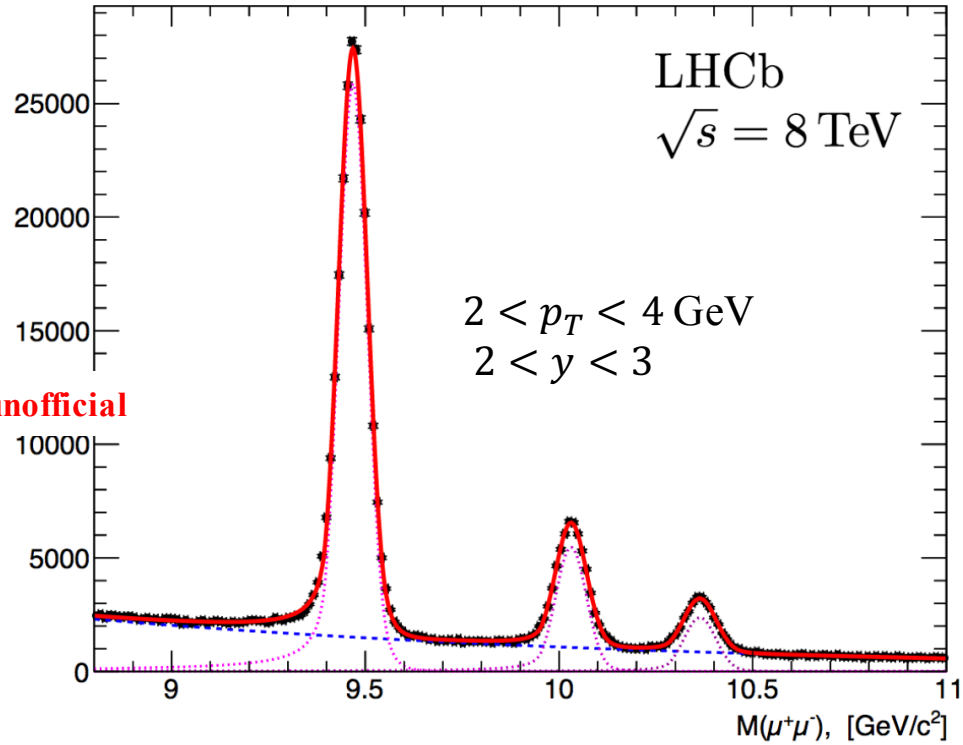
NLO NRQCD
PRL 108 (2012) 172002
PRL 110 (2013) 042002
PRL 108 (2012) 242004
NLO CSM
PRL 108 (2012) 172002

- Data consistent with no/small polarization
- No strong p_T dependence
- Rule out NLO CSM predictions
- NLO NRQCD calculations also not satisfactory

Prospects

- Υ(nS) polarization measurement finalizing: preliminary results suggests tiny polarization, no evidence of p_T dependence up to 20 GeV





Associated production

- J/ψ + open charm
- Υ + open charm
- Double J/ψ

JHEP 06 (2012) 141
JHEP 07 (2016) 052
PLB707 (2012) 52

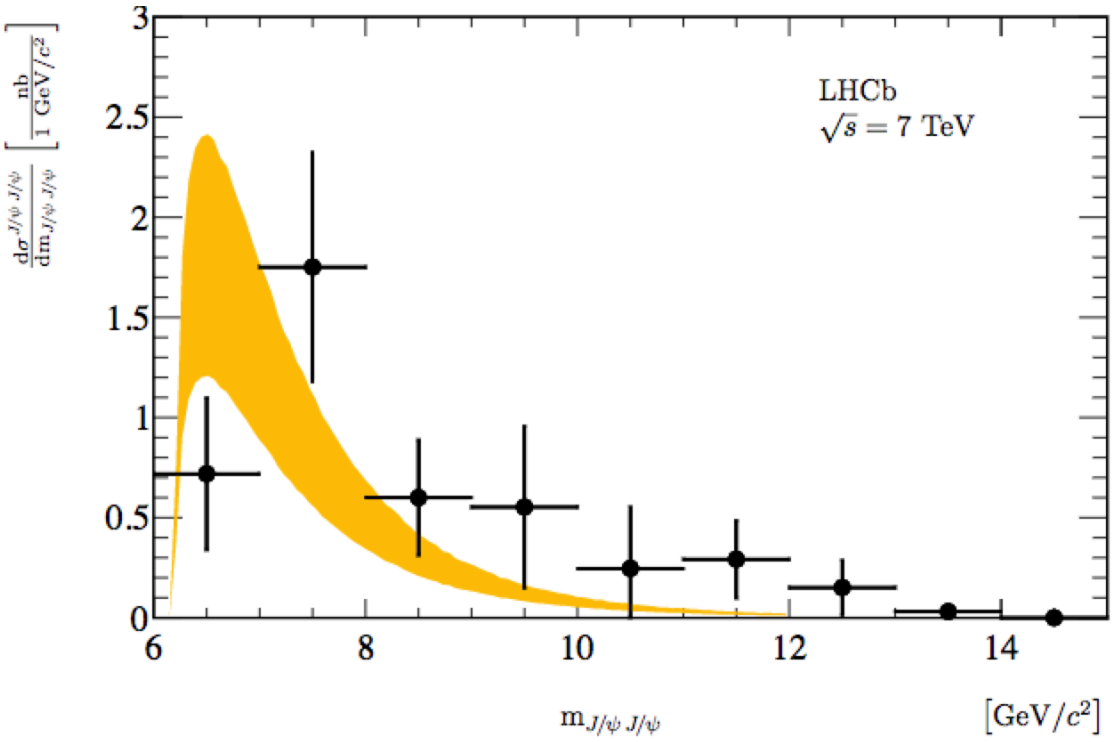
Double J/ψ @ 7 TeV

Measured with a small amount of data

LHCb: PLB707 (2012) 52

$$\sigma^{J/\psi J/\psi} = 5.1 \pm 1.5 \text{ nb}$$

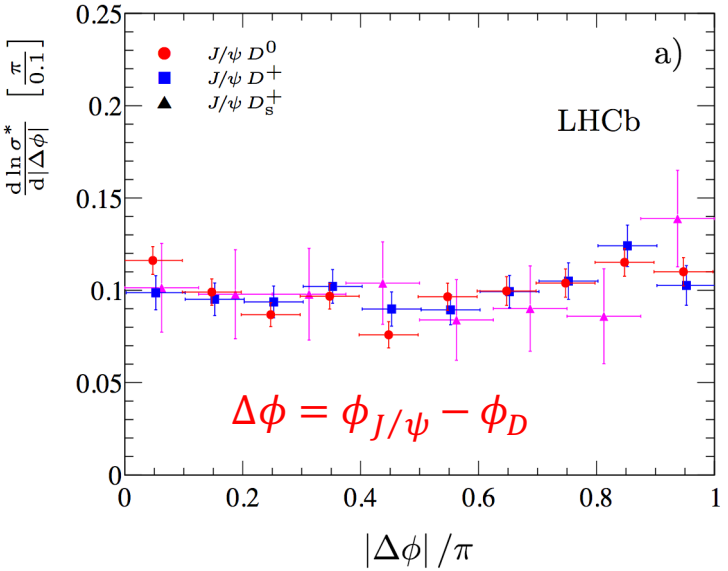
$$\frac{\sigma^{J/\psi J/\psi}}{\sigma^{J/\psi}} = (5.1 \pm 1.0 \pm 0.6^{+1.2}_{-1.0}) \times 10^{-4}$$

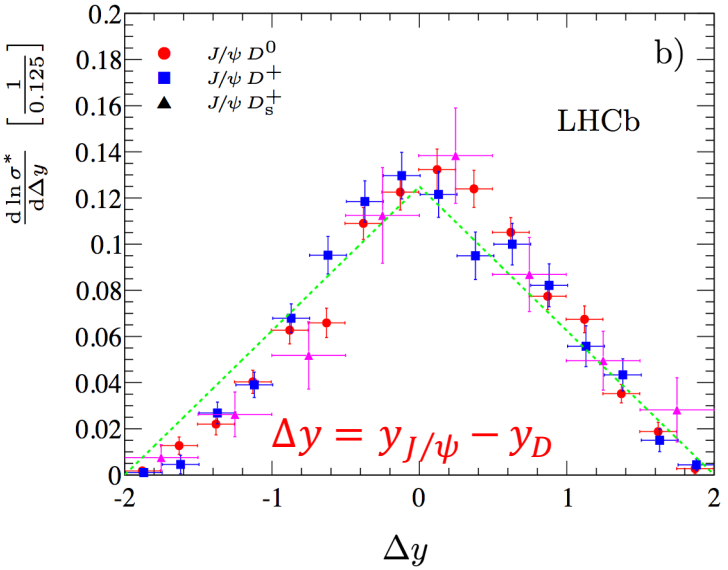


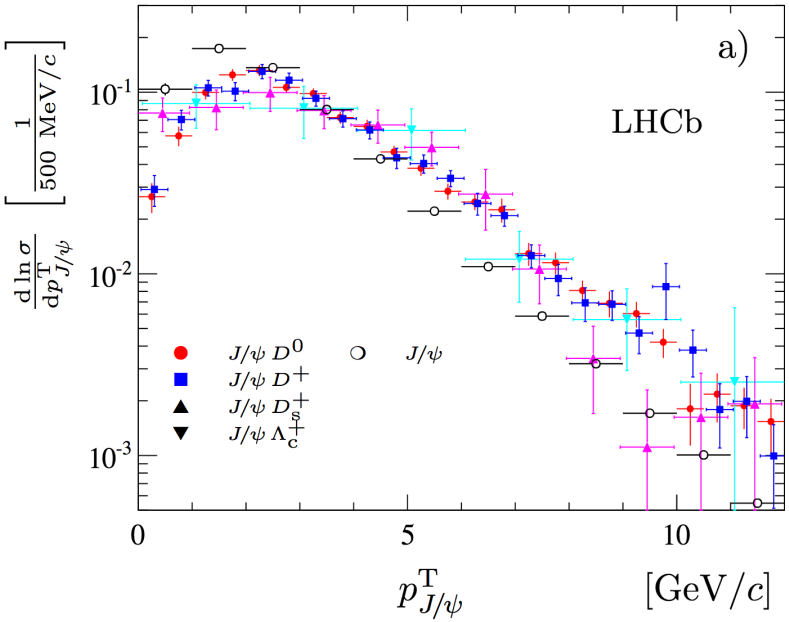
- Data agree with theoretical calculations [PRD 84 (2001) 094023] within uncertainty
- Analyses with full 7 TeV dataset, and 13 TeV data @ 2015 are ongoing

J/ψ + open charm

LHCb: JHEP 06 (2012) 141







Mode	σ [nb]
$J/\psi\, D^0$	$161.0 \pm 3.7 \pm 12.2$
$J/\psi\, D^+$	$56.6 \pm 1.7 \pm 5.9$
$J/\psi\, D_s^+$	$30.5 \pm 2.6 \pm 3.4$
$J/\psi\, \Lambda_c^+$	$43.2 \pm 7.0 \pm 12.0$

- Correlation between J/ψ and D^0 is small
- J/ψ p_T distribution is harder than inclusive

Υ + open charm

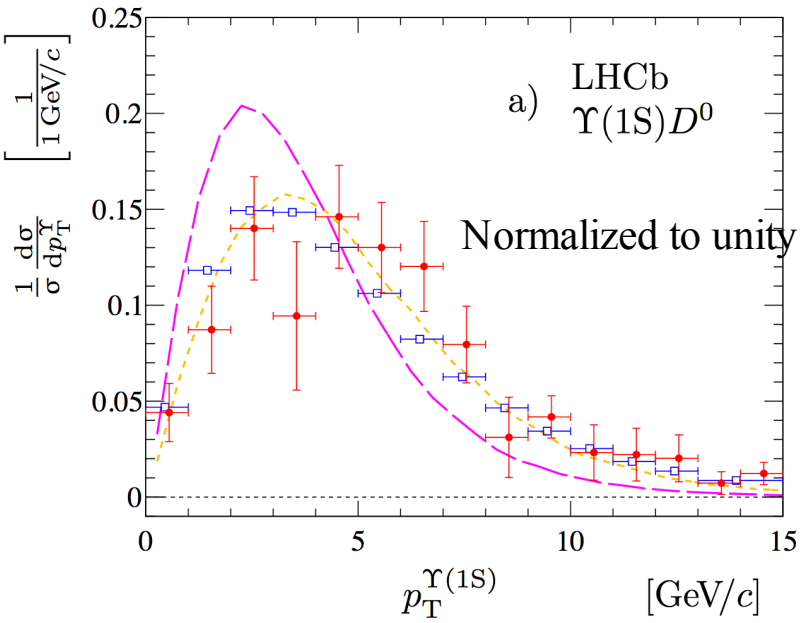
$$\mathscr{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^0}_{\sqrt{s}=7\,\mathrm{TeV}} = 155 \pm 21\,(\mathrm{stat}) \pm 7\,(\mathrm{syst})\,\mathrm{pb}$$

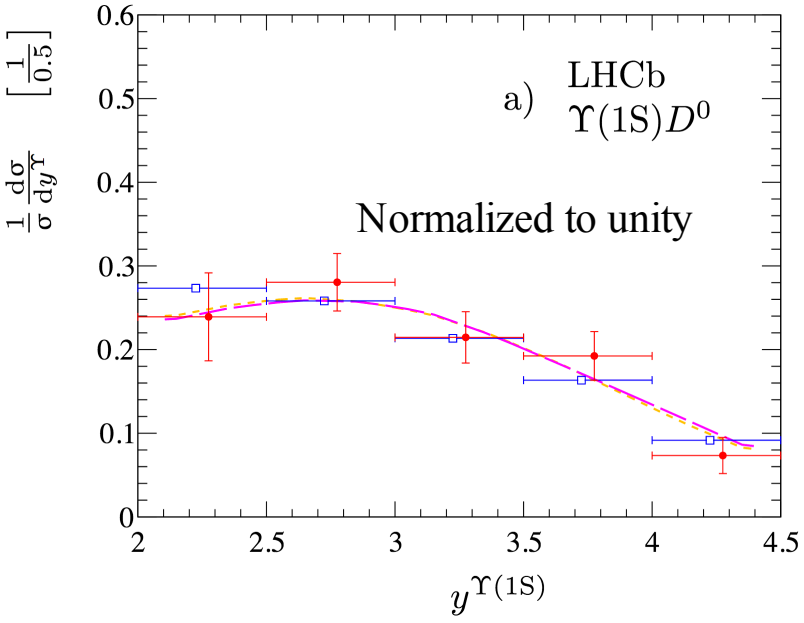
$$\mathscr{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^+}_{\sqrt{s}=7\,\mathrm{TeV}} = 82 \pm 19\,(\mathrm{stat}) \pm 5\,(\mathrm{syst})\,\mathrm{pb}$$

$$\mathscr{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^0}_{\sqrt{s}=8\,\mathrm{TeV}} = 250 \pm 28\,(\mathrm{stat}) \pm 11\,(\mathrm{syst})\,\mathrm{pb}$$

$$\mathscr{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^+}_{\sqrt{s}=8\,\mathrm{TeV}} = 80 \pm 16\,(\mathrm{stat}) \pm 5\,(\mathrm{syst})\,\mathrm{pb}$$

LHCb: JHEP 07 (2016) 052

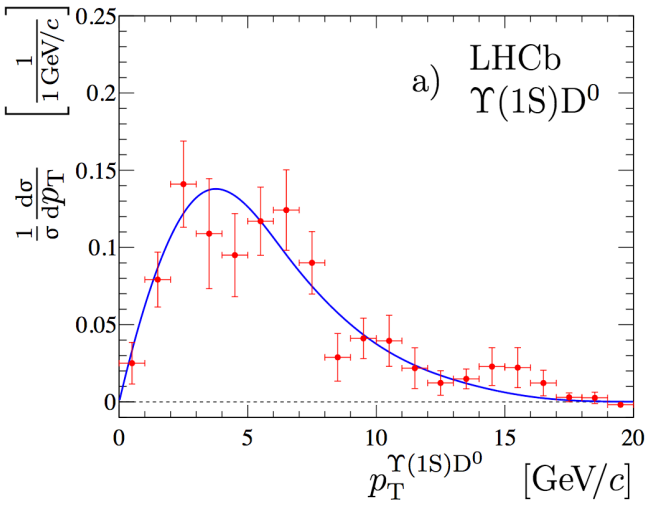


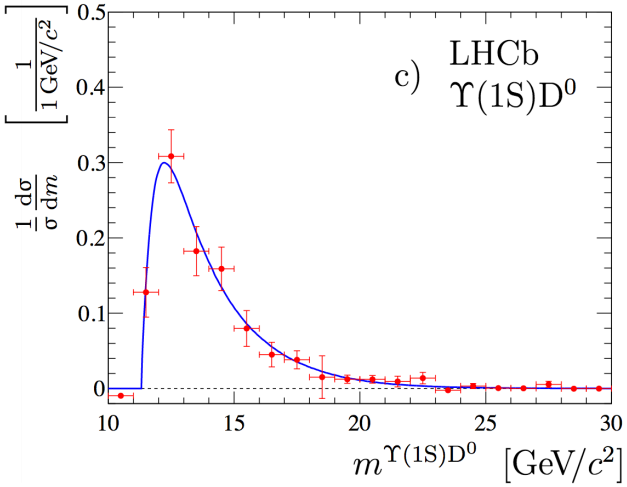


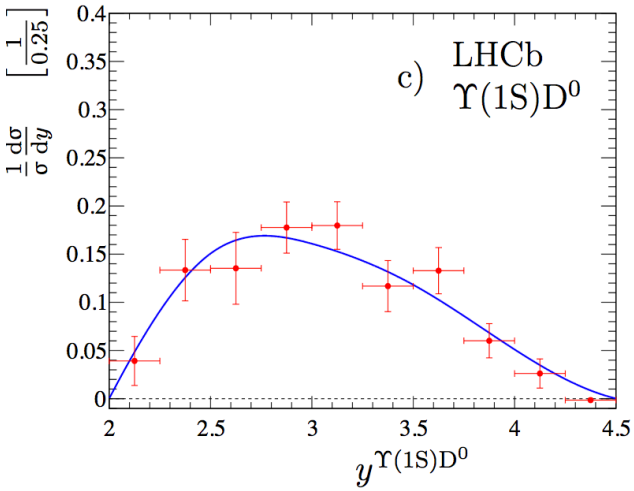
- Υ p_T and y distributions compatible with inclusive productions (as DPS)
- Data are consistent with theoretical calculations [SPS from S. P. Barano: k_T-factorization and collinear approximation]

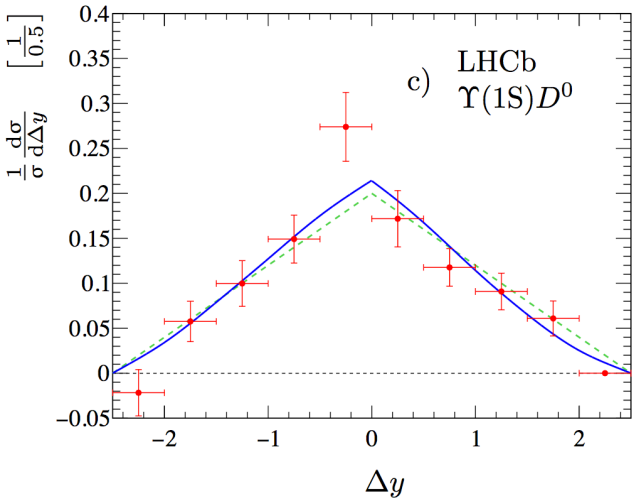
Υ + open charm

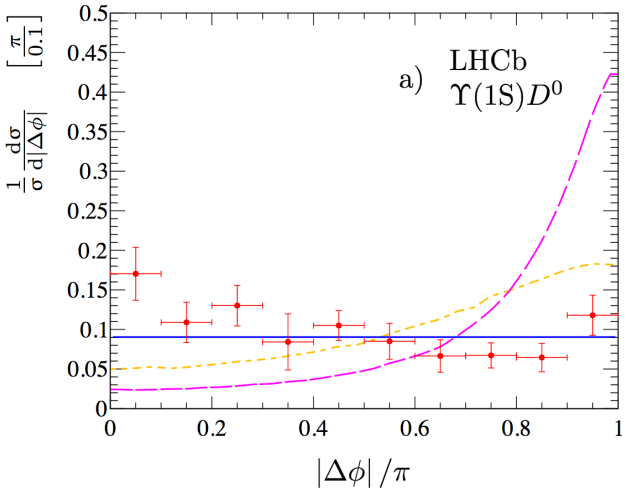
LHCb: JHEP 07 (2016) 052











Assume Υ and D produced independently (as DPS)

SPS: [S. P. Barano: k_T-factorization and collinear approximation]

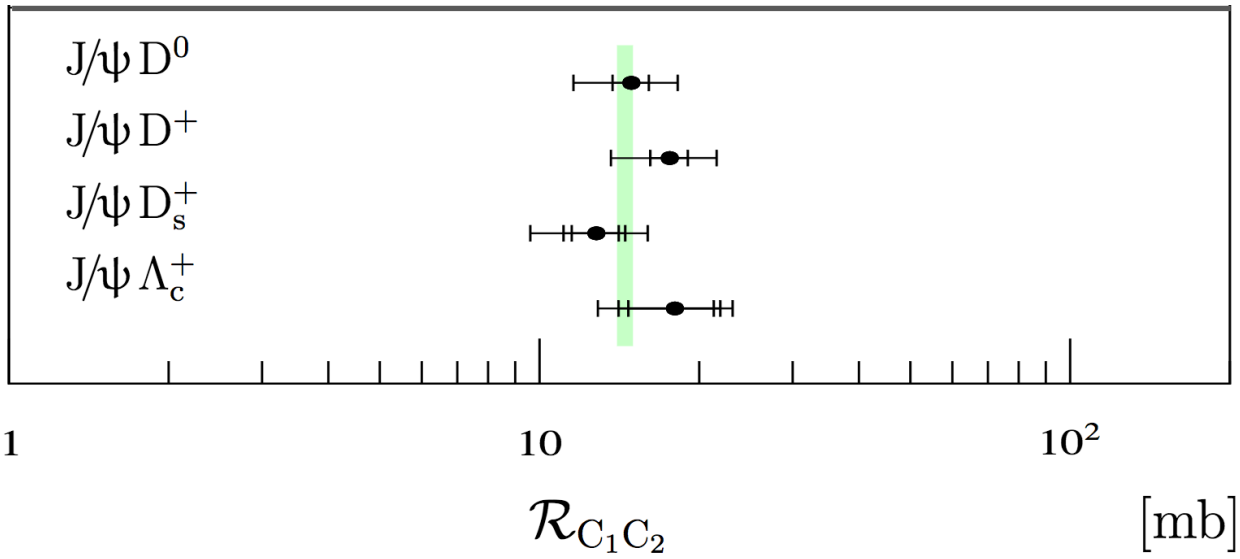
Data suggest Υ and D are not correlated, favor DPS production

Effective cross-section: σ_{eff}

- Assume associated production is purely from Double Parton Scattering:

$$\sigma_{\mathrm{eff}}^{\mathrm{DPS}} = \alpha \frac{\sigma_{c_1} \times \sigma_{c_2}}{\sigma_{c_1 c_2}^{\mathrm{DPS=asso.}}}$$

LHCb: JHEP 06 (2012) 141
JHEP 07 (2016) 052



$$\sigma_{\mathrm{eff}}|_{\Upsilon(1S)\mathrm{D}^{0,+},\sqrt{s}=7\,\mathrm{TeV}} = 18.0 \pm 2.1\,(\mathrm{stat}) \pm 1.2\,(\mathrm{syst}) = 18.0 \pm 2.4\,\mathrm{mb}$$

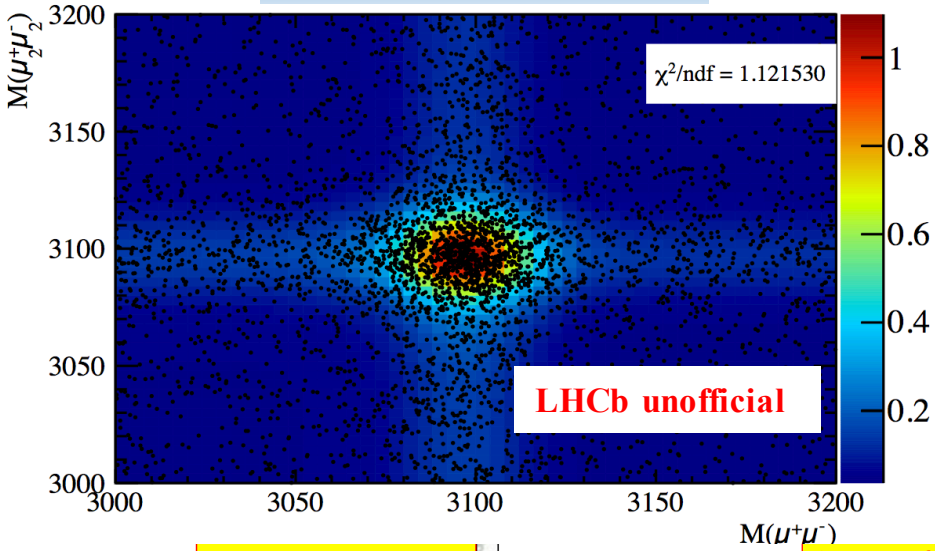
$$\sigma_{\mathrm{eff}}|_{\Upsilon(1S)\mathrm{D}^{0,+},\sqrt{s}=8\,\mathrm{TeV}} = 17.9 \pm 1.8\,(\mathrm{stat}) \pm 1.2\,(\mathrm{syst}) = 17.9 \pm 2.1\,\mathrm{mb}$$

Consistent with **Tevatron (jets)**: $\sigma_{\mathrm{eff}}^{\mathrm{DPS}} = 14.5 \pm 1.7^{+1.7}_{-2.3}$ mb [PRD56 (1997) 3811]

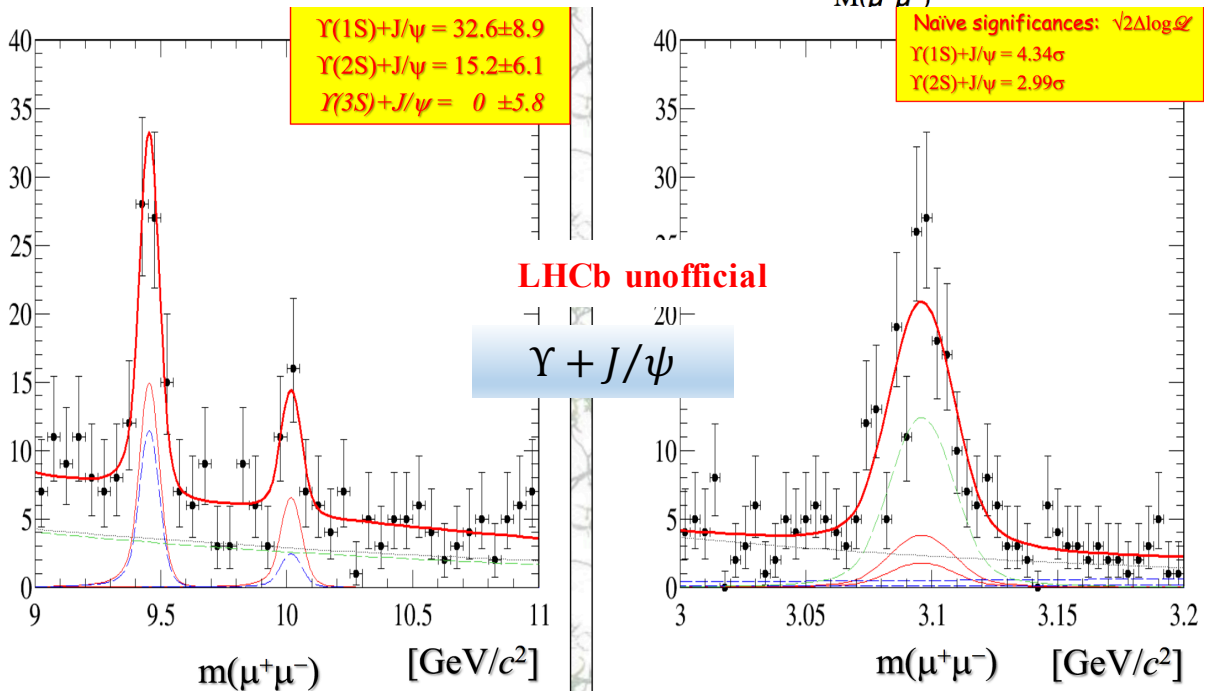
Dominated by DPS? Or σ_{eff} is not universal?

Prospects

Double J/ψ @ 13 TeV



~1K signals in 0.3 fb^{-1}
Analysis to be public soon



Evidence of $\Upsilon + J/\psi$ in LHCb RunI data

$\Upsilon(1S) + J/\psi \sim 4\ \sigma$
$\Upsilon(2S) + J/\psi \sim 3\sigma$

Production prospects with 100× more data

Analyses with 300 fb^{-1}

- Inclusive productions already in good precision with RunI and early RunII data, however with many more data we make precise measurements of
  - ➢ $\chi_b(nP)$ production and decay
  - ➢ Associated production including bottom quark
    - ✓ $\psi+\psi$: ~1M double J/ψ and ~1K $\psi(2S)+\psi(2S)$
    - ✓ $\Upsilon(nS)+\psi$: ~5K for $\Upsilon(1S)+J/\psi$
    - ✓ $\Upsilon(nS)+\Upsilon(nS)$: ~50 $\Upsilon(1S)+\Upsilon(1S)$
    - ✓ Double open B: expect ~100 double fully reconstructed $B^+ \to J/\psi\, K^+$ decays, many more if studying detached J/ψ
    - ✓ $\Upsilon(nS)+B$: could explore $\Upsilon(nS)$ + detached J/ψ (~1000), or $\Upsilon(nS)$+exclusive B decay (~100)

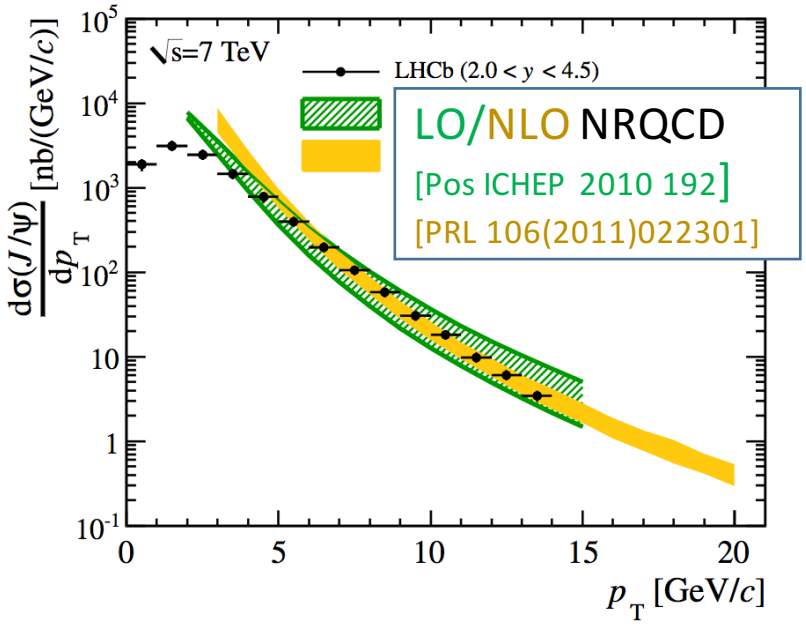
Summary

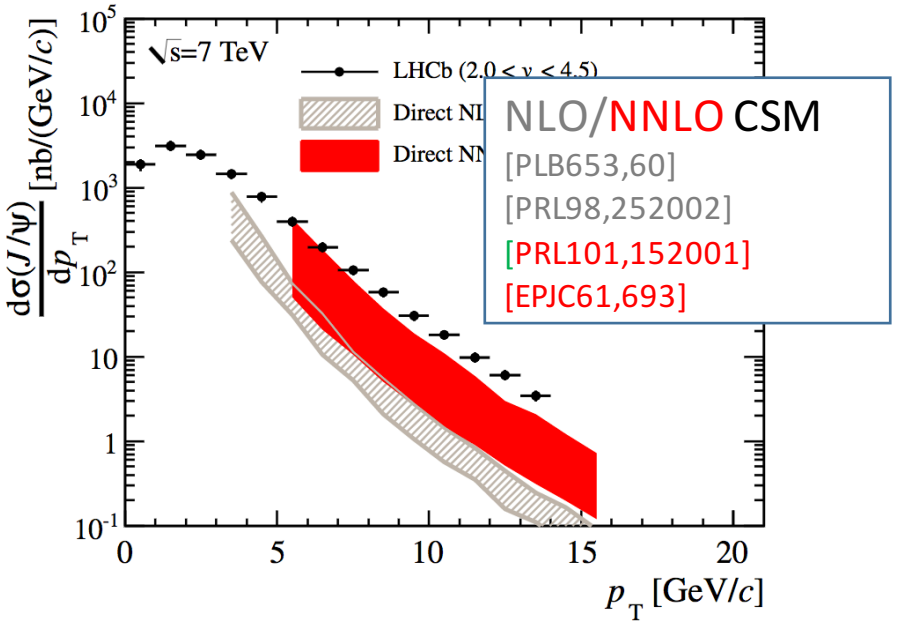
- LHCb studied productions using RunI data for
  - Charmonia: J/ψ (also RunII), $\psi(2S)$, $\chi_c(1P)$, η_c …
  - Bottomonia: $\Upsilon(nS)$, $\chi_b(nP)$, …
  - B_c^+ state
  - $J/\psi + D$, $\Upsilon + D$, $J/\psi + J/\psi$, …
- Also measured the polarization for
  - J/ψ and $\psi(2S)$
- More measurements using RunI and early RunII data will come out soon
  - $\psi(2S)$ and $\Upsilon(nS)$ productions at 5 and13 TeV
  - $\Upsilon(nS)$ polarization measurements
- With 300/fb data, we could explore more (precise) associated production, especially $\Upsilon(nS)$+...

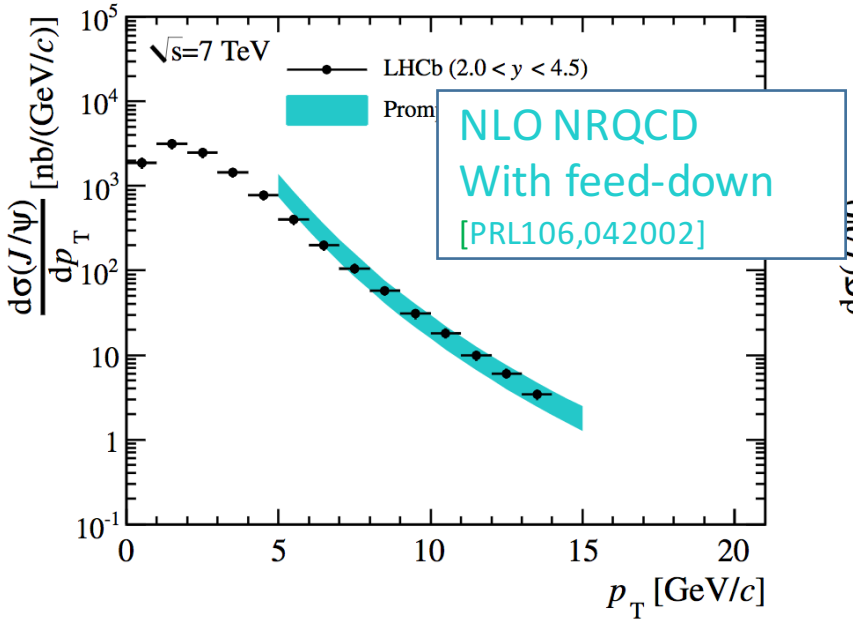
Thank you for your attention

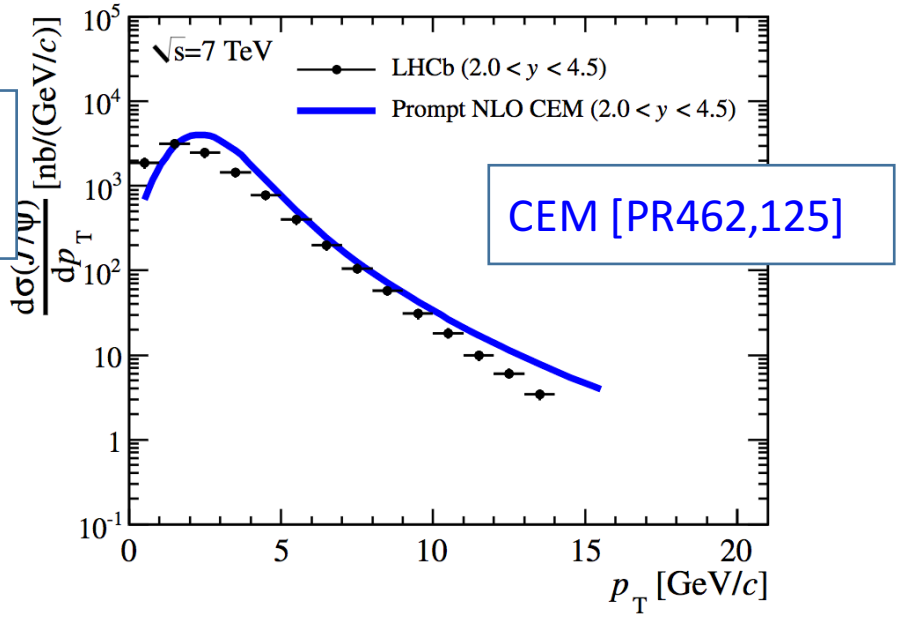
Backups

p_T distributions (prompt J/ψ @ 7 TeV)

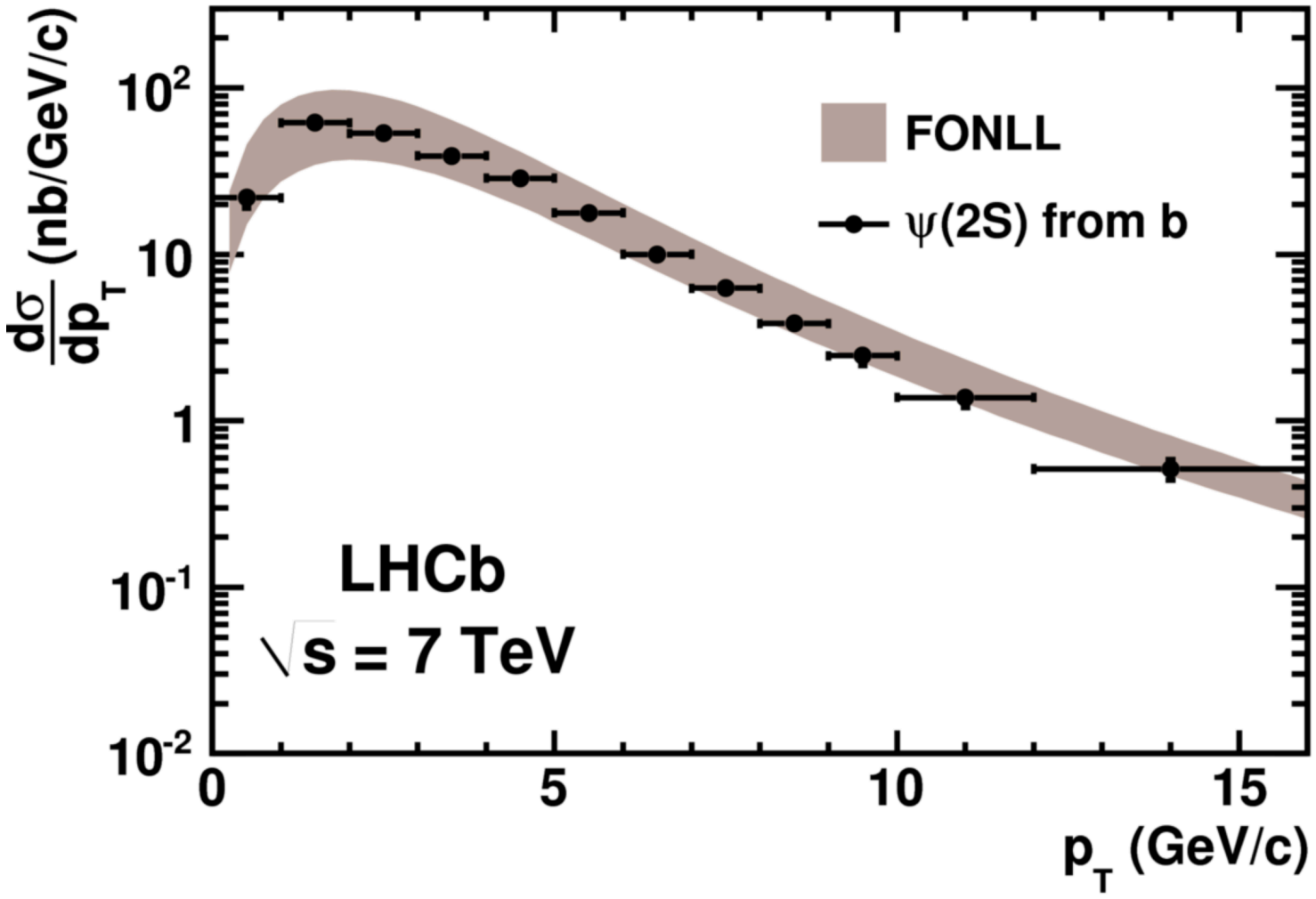




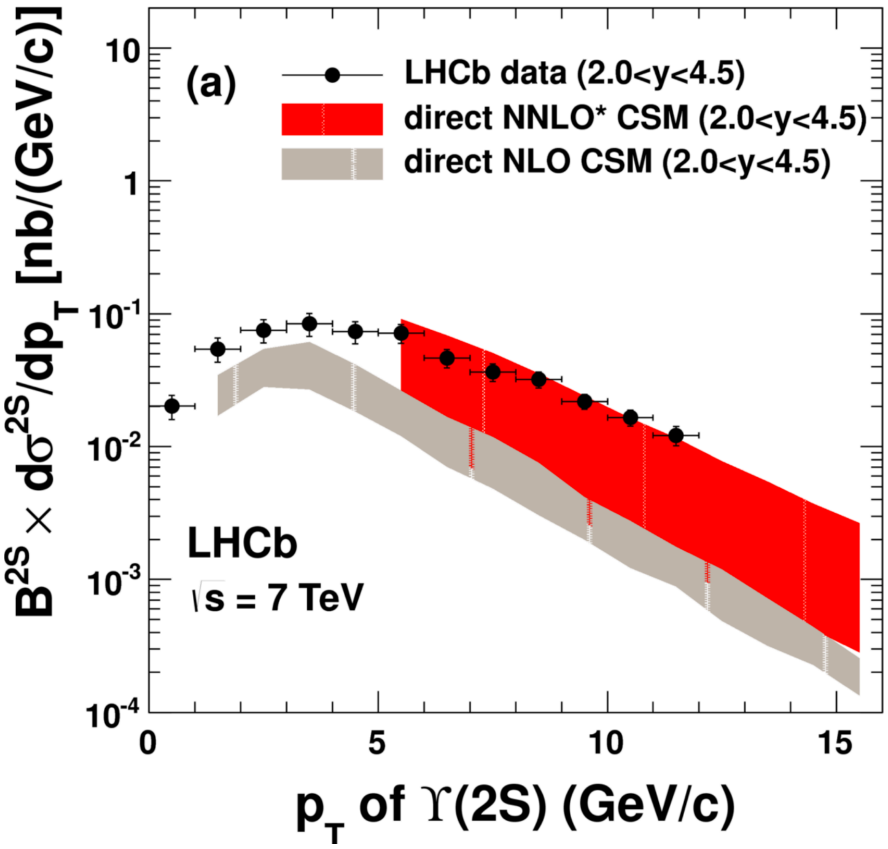


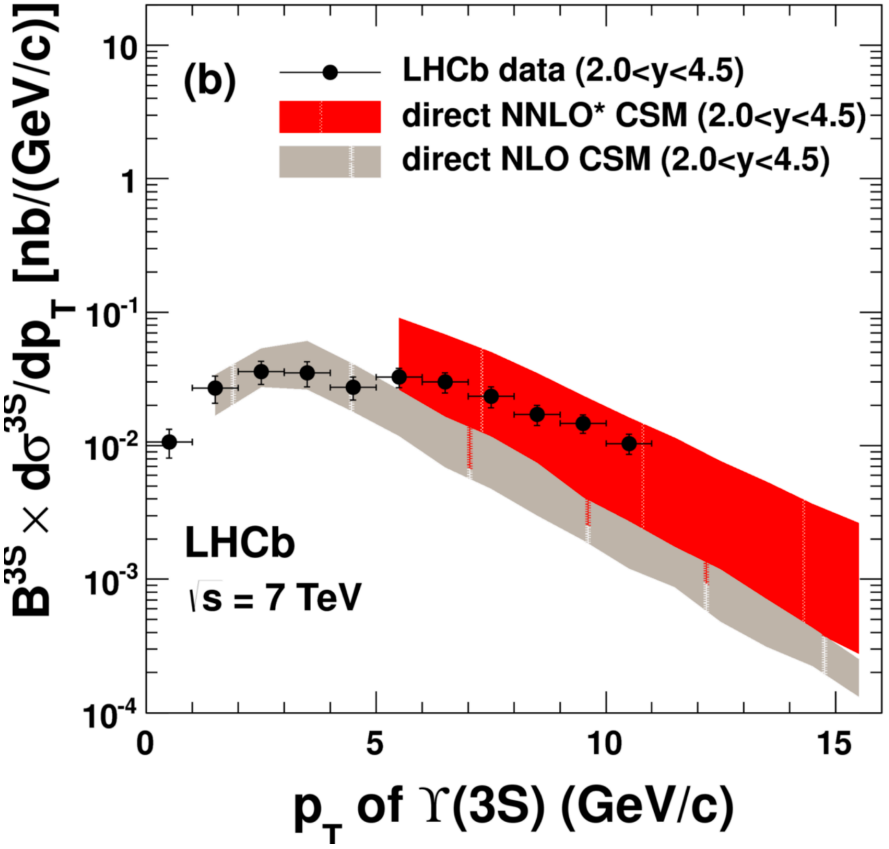


p_T distributions ($\psi(2S)$ from b)



p_T distributions (Υ @7 TeV)

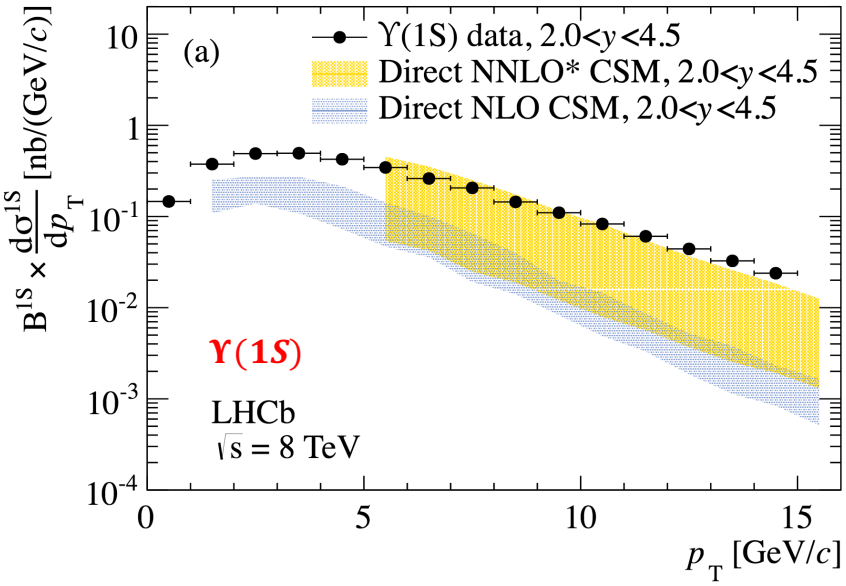


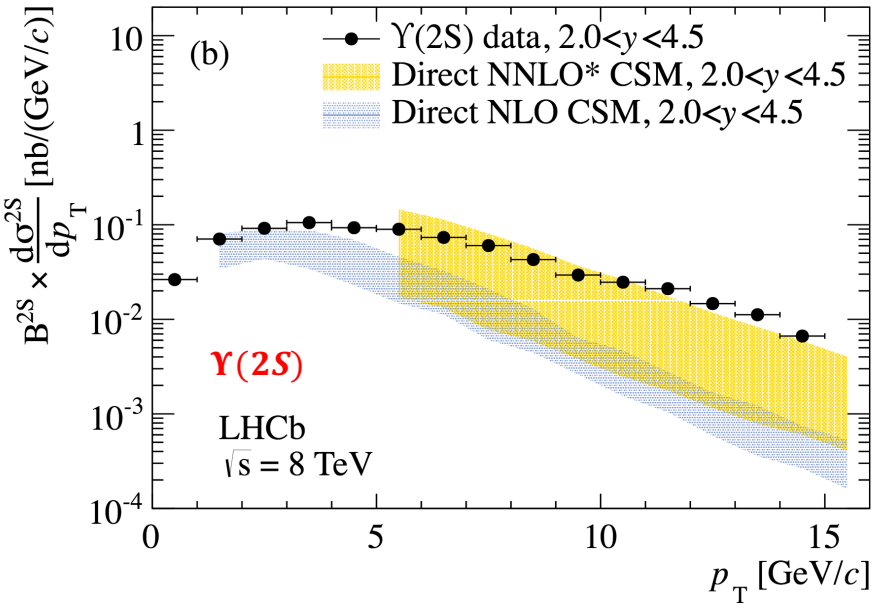


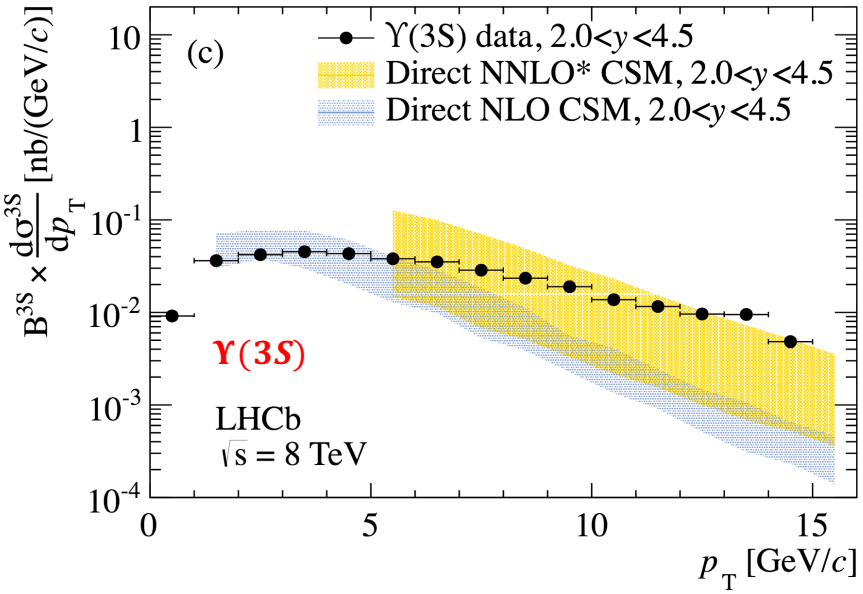
NLO/NNLO* CSM

[PRL101,152001,PRL98,252002]

p_T distributions for Υ(nS)





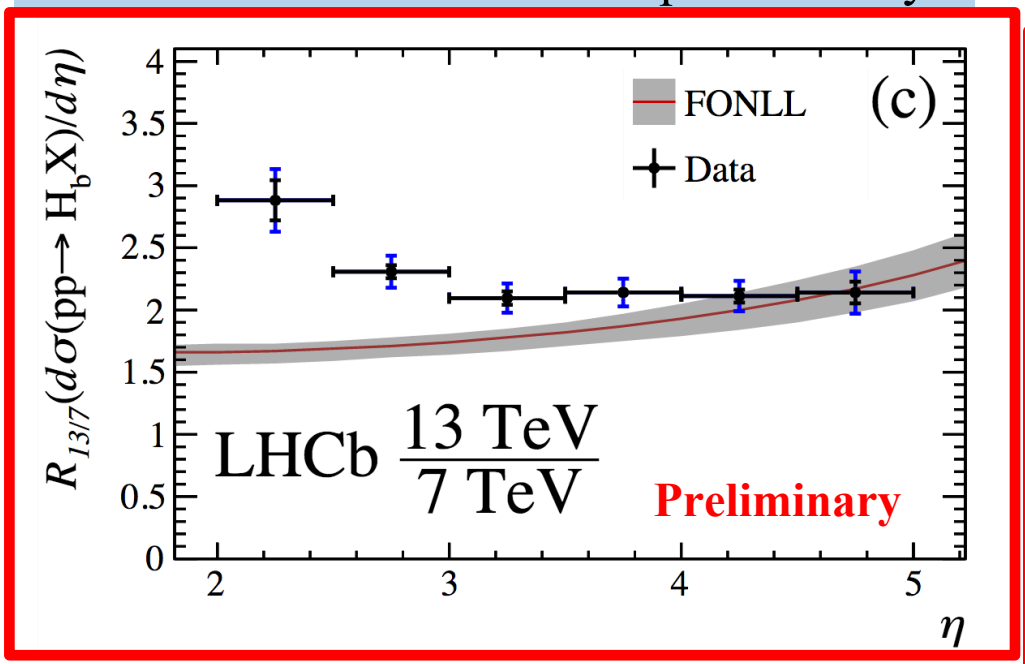


NNLO* CSM: [EPJC61, 693]
NLO CSM: [PRL98,252002]

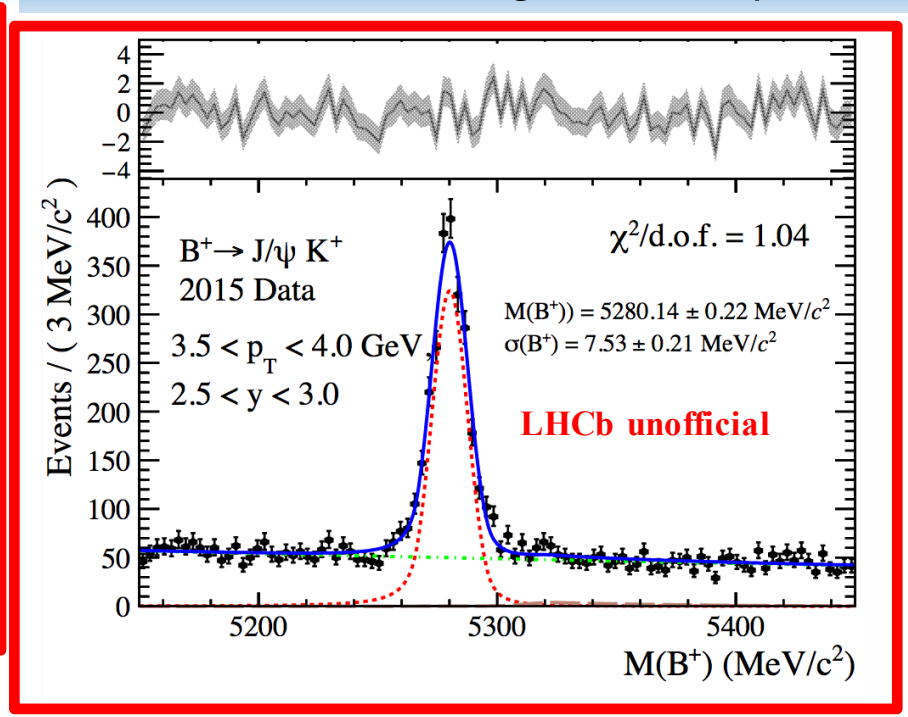
NLO (NNLO*) CSM calculations underestimates Υ data and p_T distributions not predicted

Ratio of $\sigma(b)$ at $\sqrt{S} = 13/7(8)$

$b\bar{b}$ cross-section with semileptonic decays



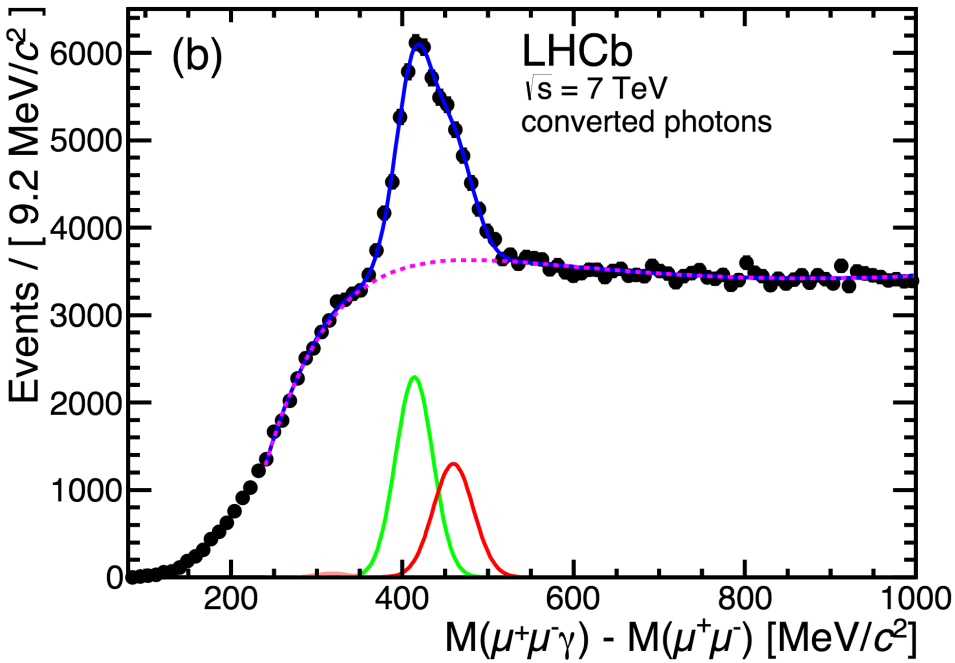
B^+ cross-section using $B^+ \to J/\psi\, K^+$

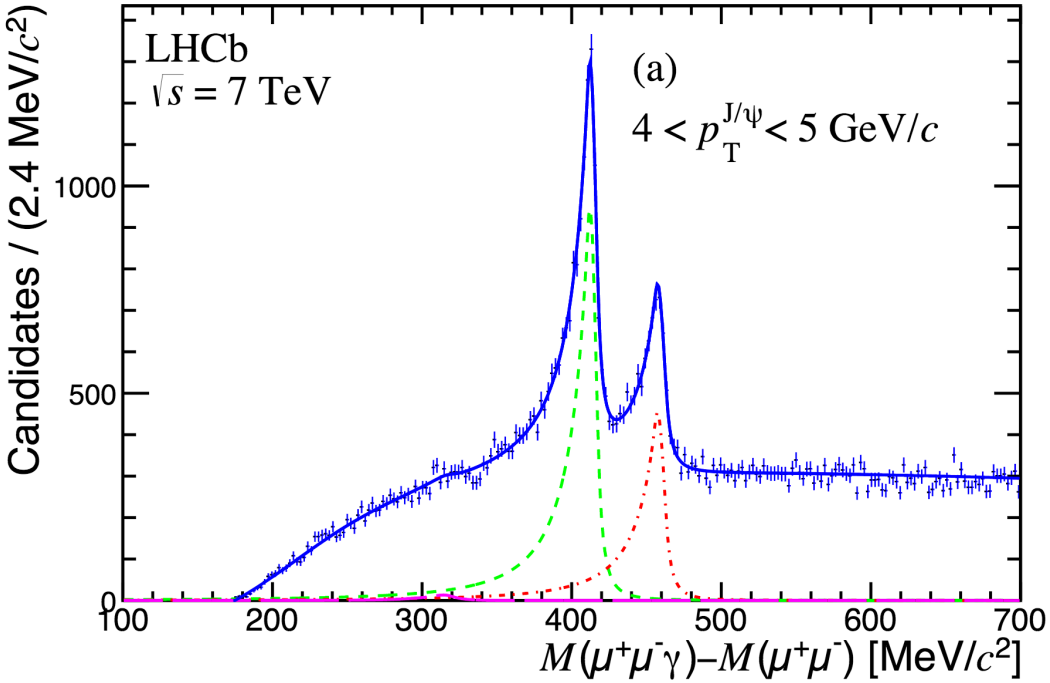


Cross-section ratio measurements using semileptonic decays and exclusive decay are consistent. Behavior not predicted by FONLL.

χ_c reconstruction

- Converted photon v.s. CALO photon





η_c production

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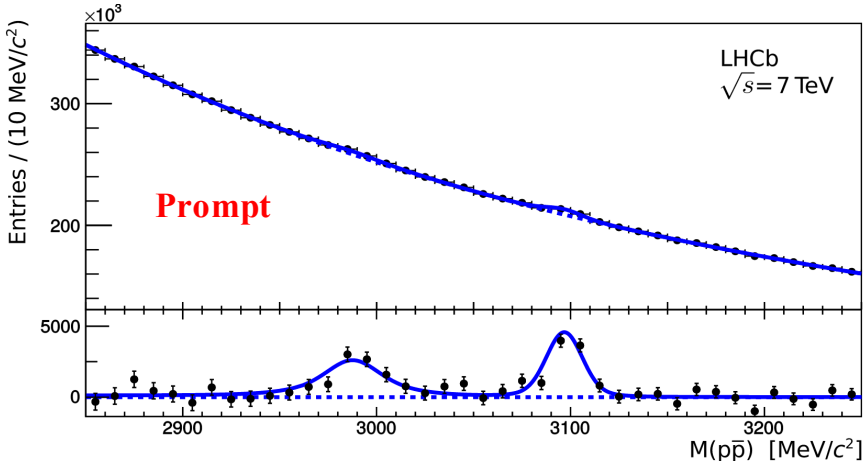
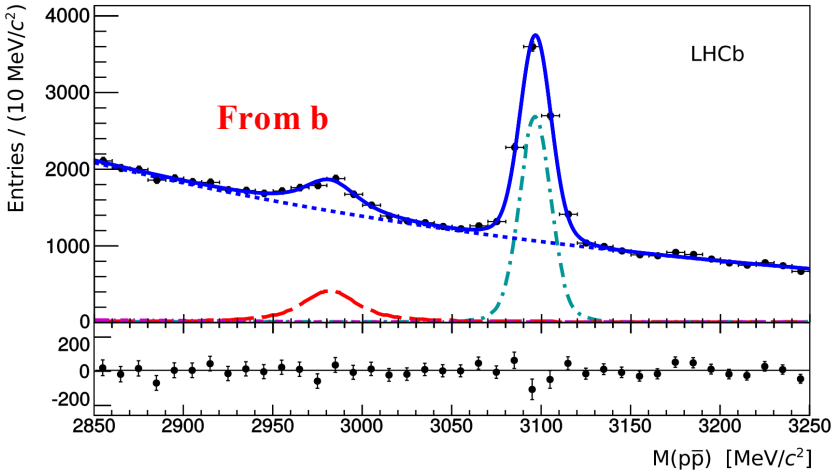
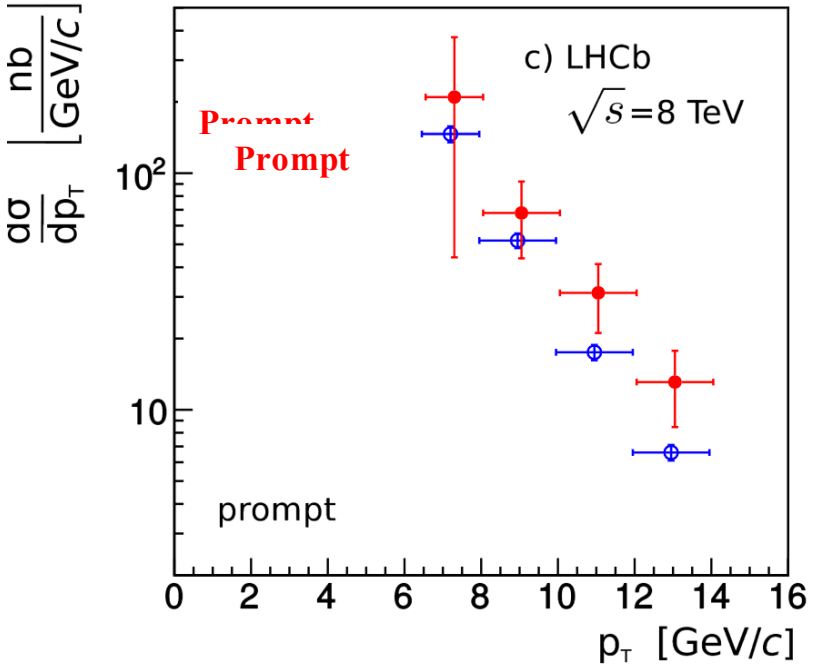
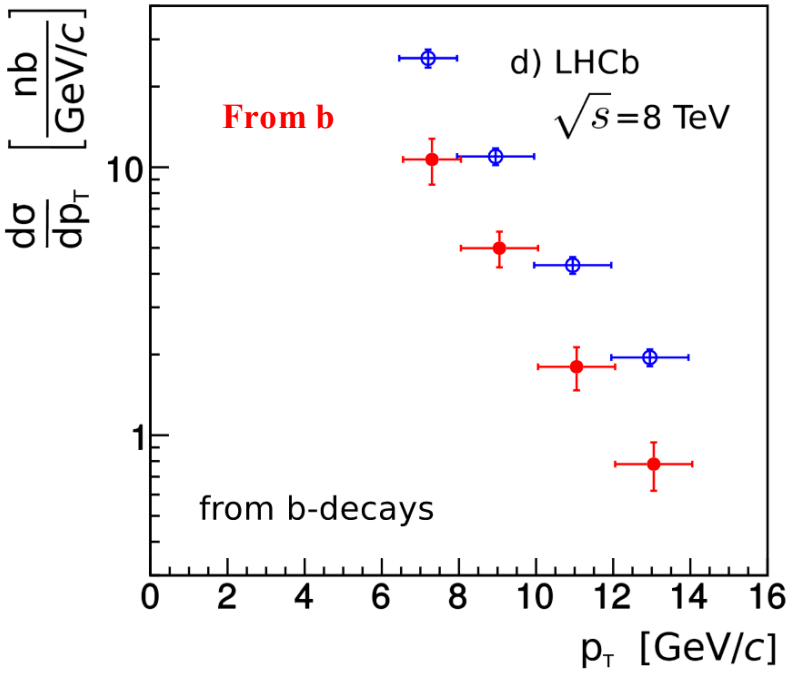
- Prompt and secondary η_c prodction

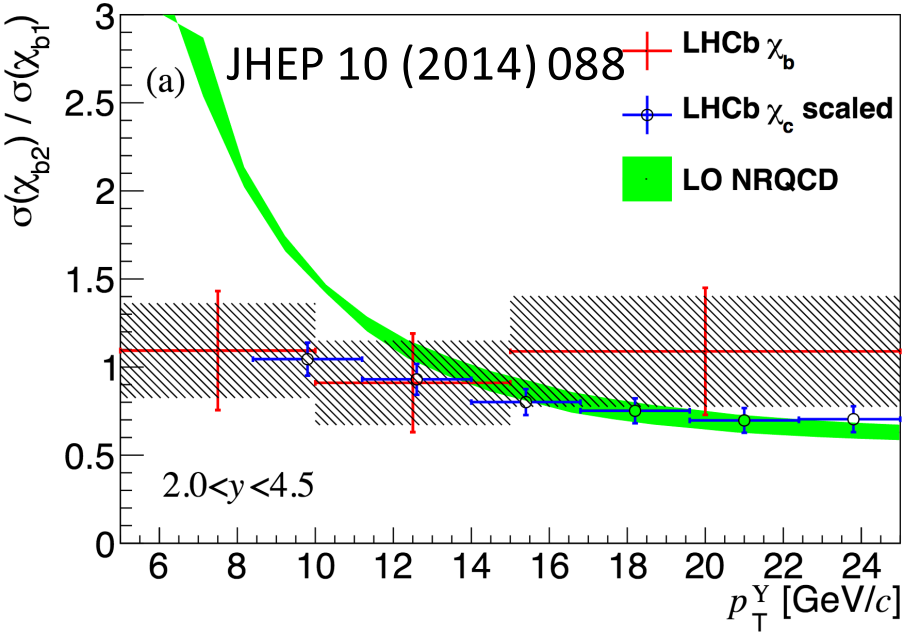


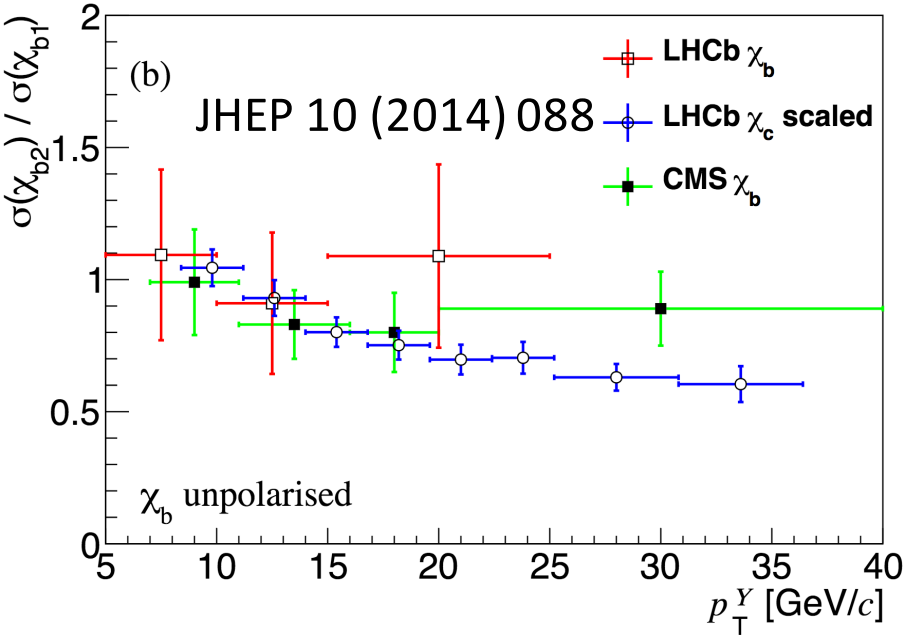


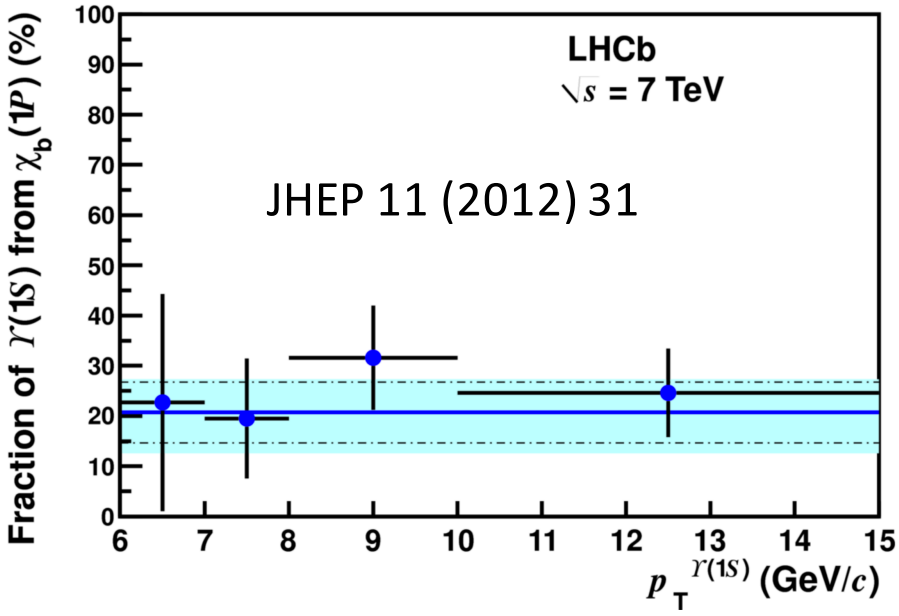




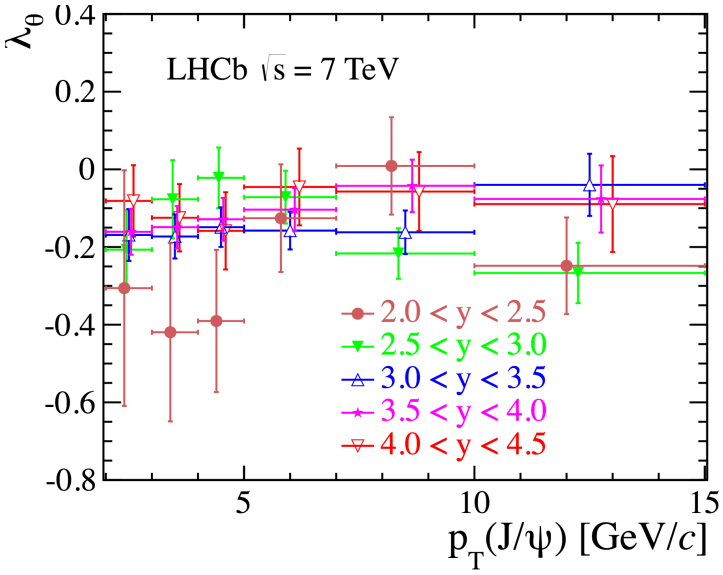
$\chi_b(1P)$ production

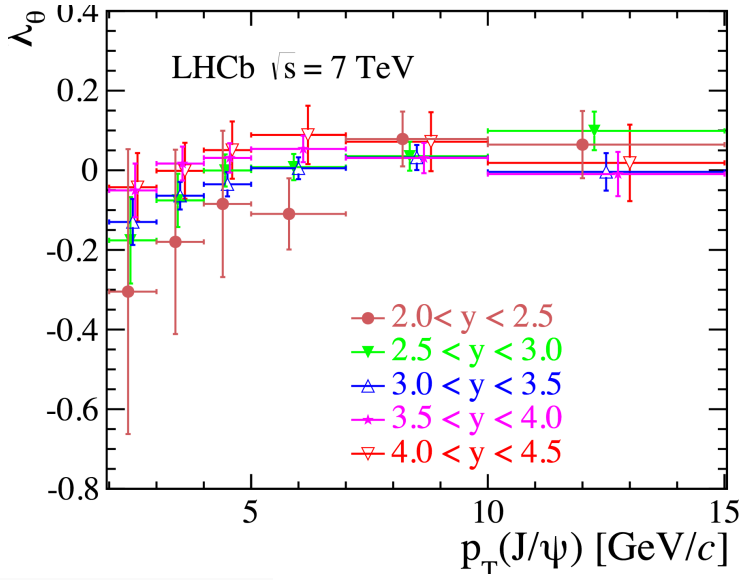


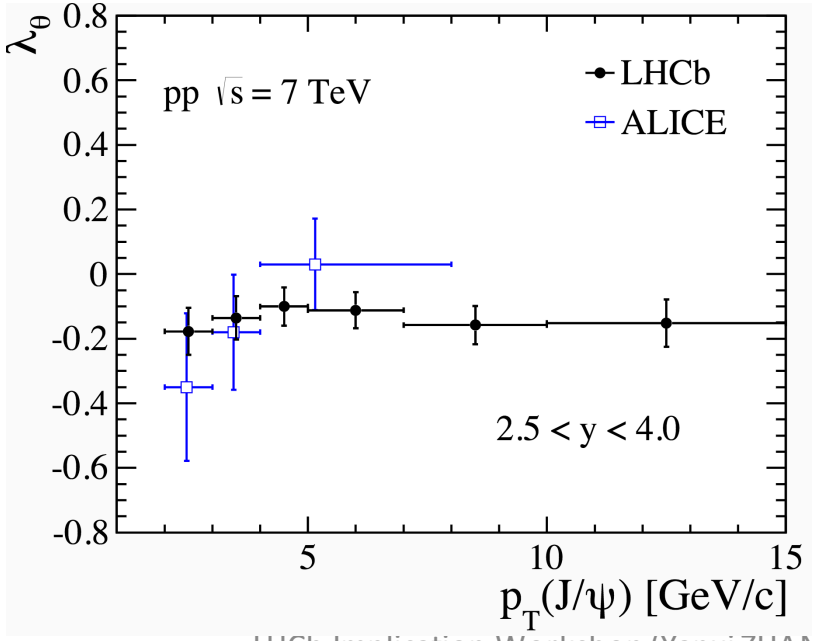




Polarization analysis

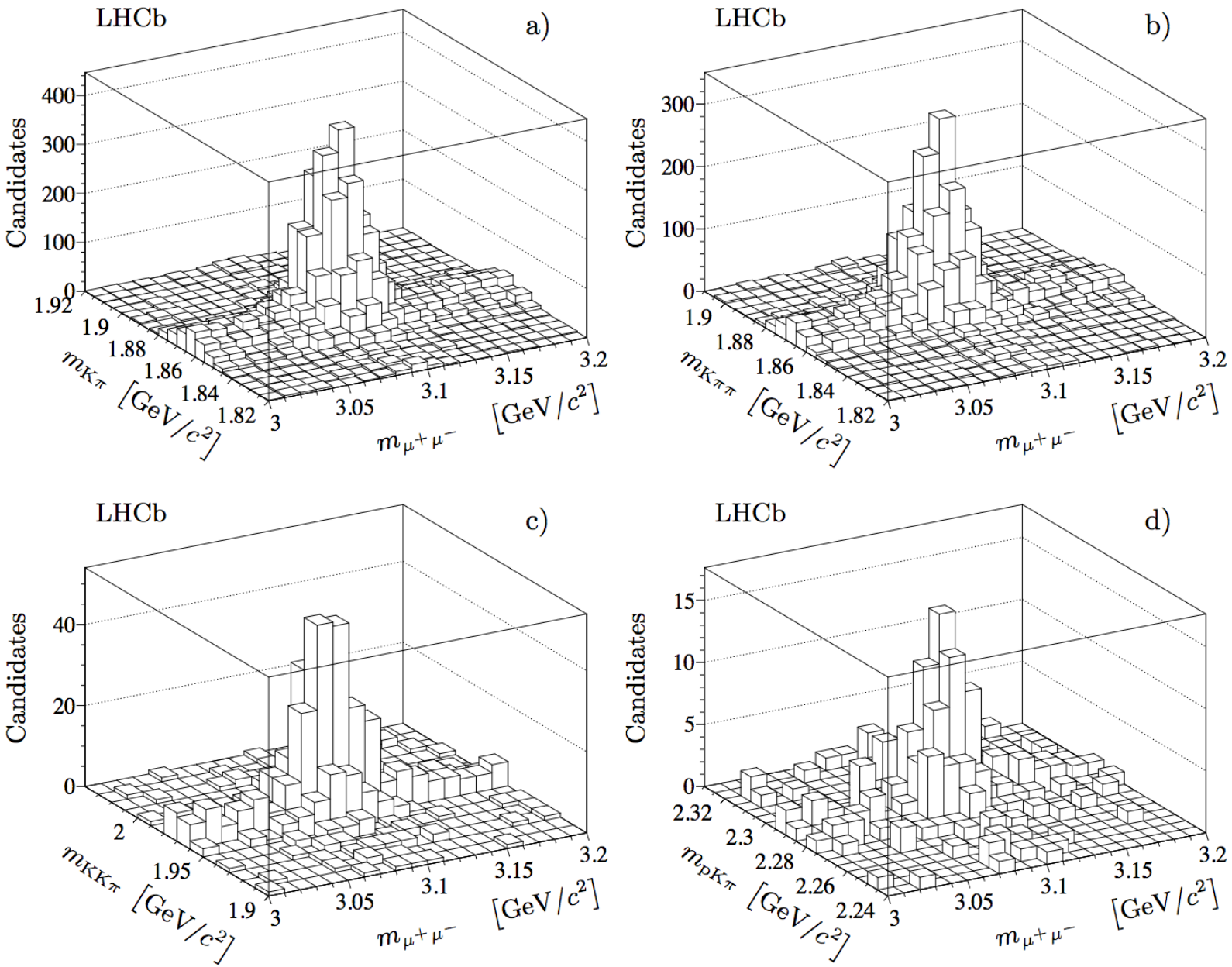






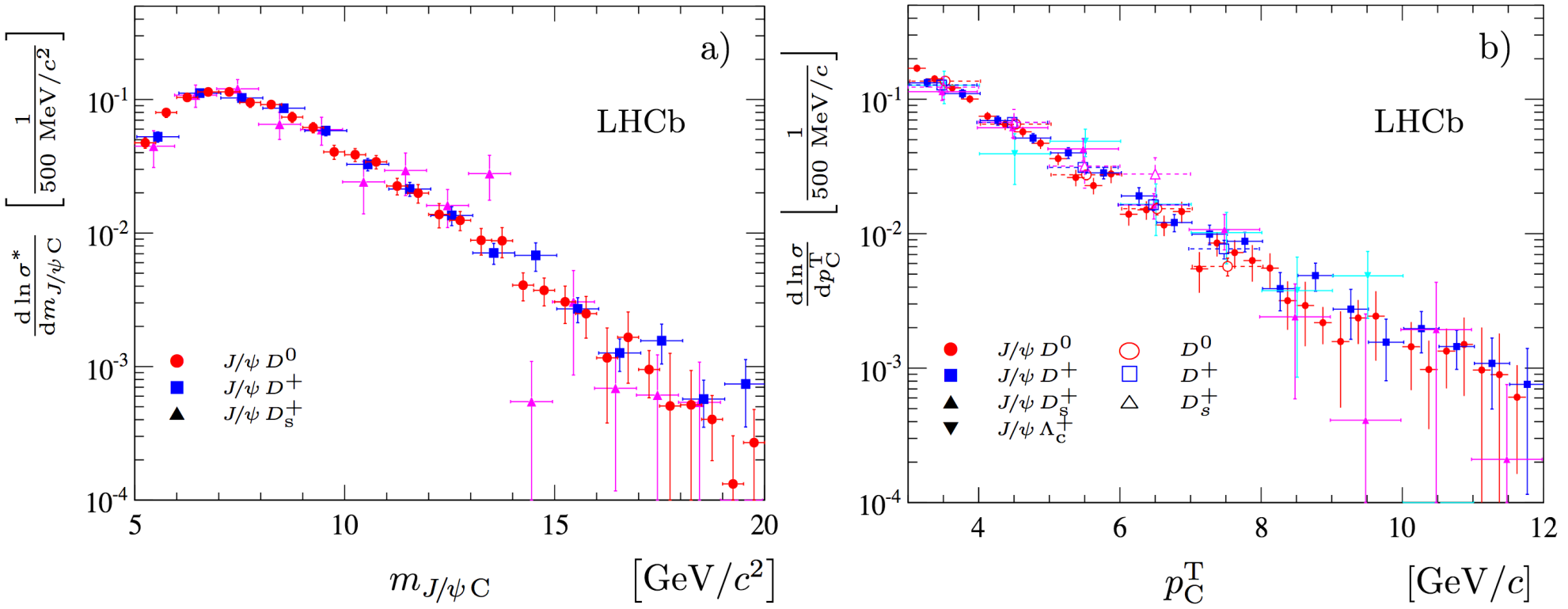
J/ψ + open charm mass

- 2D mass plots



J/ψ + open charm

- Invariant mass and charm p_T



Charm p_T distributions similar to inclusive ones

*p*Pb data taking (2013)

- pPb x