Implications of LHCb measurements and future prospects

17-19 Oct. 2018, CERN

Heavy flavor production at LHCb

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CERN

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Outline

- Introduction
- Production of open heavy flavor
- Production of heavy quarkonium
- Associated production
- Summary

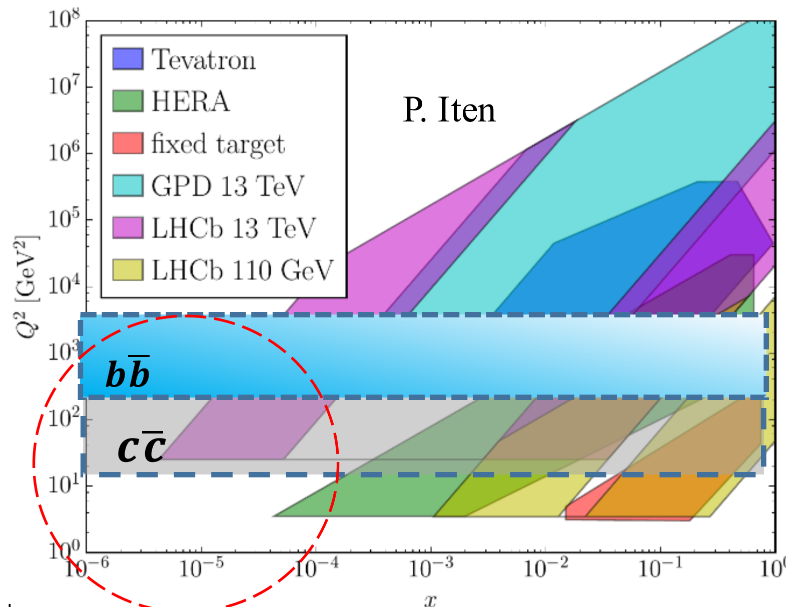
Introduction

- Heavy flavor productions probing QCD
  - m_Q provides scales for perturbative QCD calculations, down to low p_T

$$\sigma(Q) \longleftarrow f(x_1,\mu_F^2) \otimes f(x_2,\mu_F^2) \otimes d\sigma(x_1,x_2 \to Q+X,\mu_F^2,\mu_R^2) \otimes D(Q \to H_Q)$$

  - Sensitive to PDFs and fragmentation functions: non perturbative
  - Understanding QCD is fundamental and essential for new physics searches

- LHCb is optimized for precision measurements for b, c physics
  - Excellent tracking, vertexing, hardon and muon identification
  - Unique kinematic coverage: access to small Bjorken-x region not constrained by HERA
  - Large production/recording rate: $\sigma(c\bar{c}) \approx 8$ mb at $\sqrt{s} = 7$ TeV



$$x_{1,2} \sim \frac{\sqrt{m^2+p_T^2}}{\sqrt{s}} e^{\pm y}$$

Open heavy flavor production

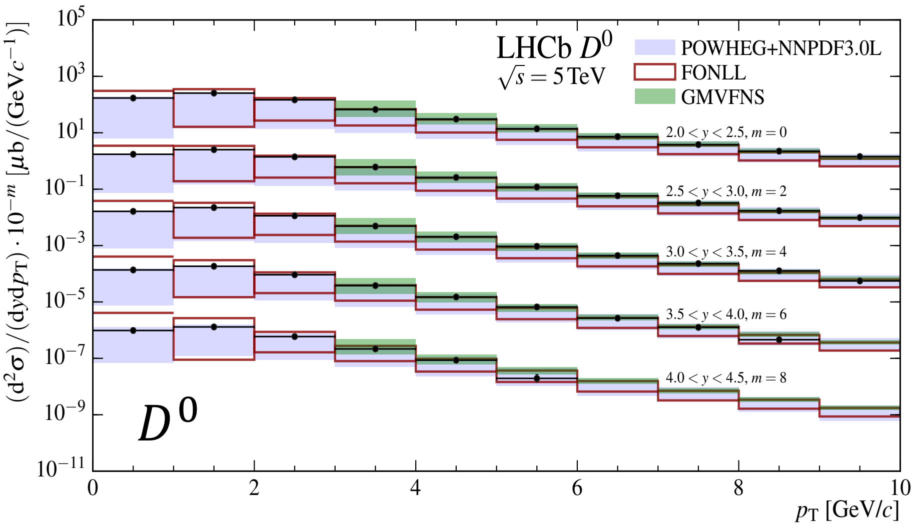
- ➢ Charm production at $\sqrt{s} = 5, 7, 13$ TeV
- ➢ Beauty production at $\sqrt{s} = 7, 13$ TeV
- ➢ Fragmentation functions

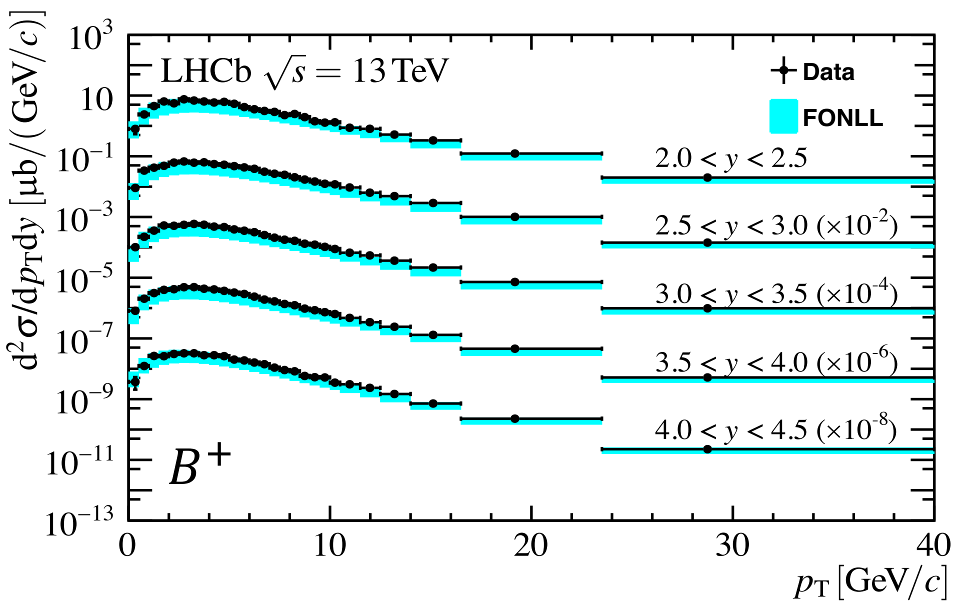
JHEP 03 (2016) 159
JHEP 09 (2016) 013
JHEP 05 (2017) 074
JHEP 06 (2017) 147
Nucl. Phys. B 871 (2013) 1

JHEP 12 (2017) 026
PRL 118 (2017) 052002

JHEP 08(2014) 143
JHEP 04 (2013) 001

Production cross-sections



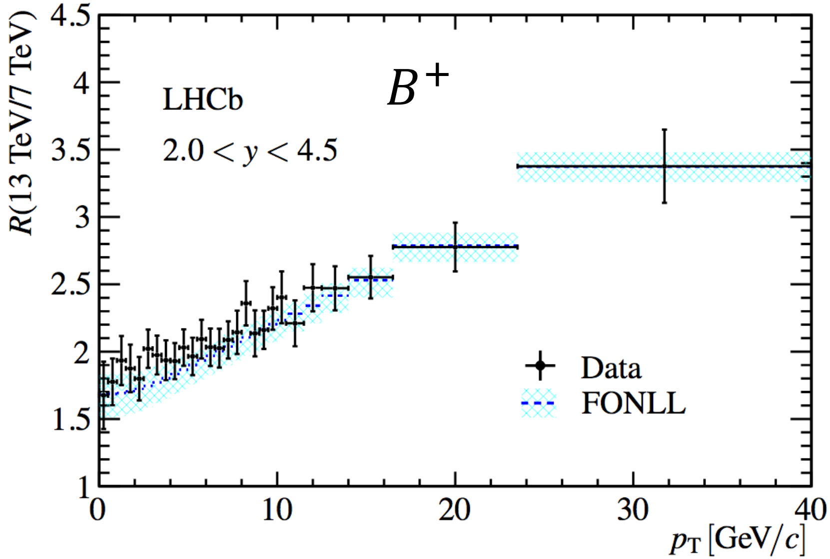


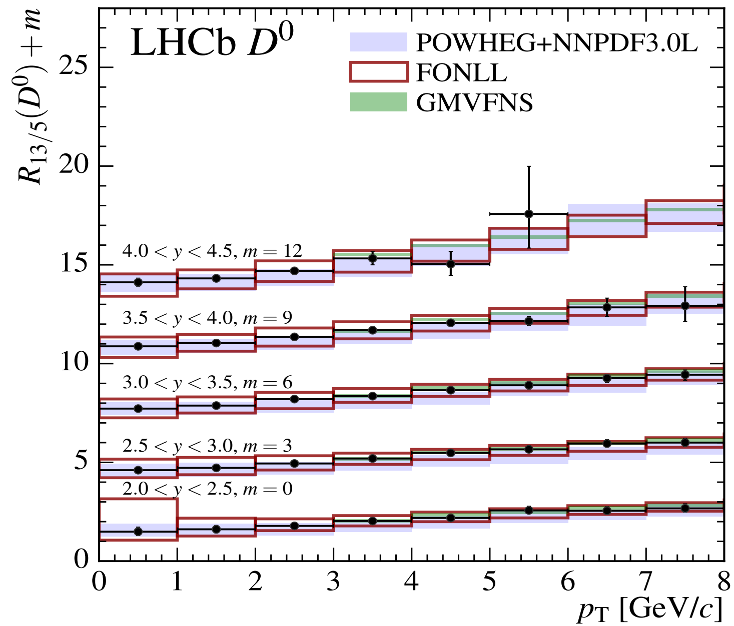
JHEP 06 (2017) 147
JHEP 12 (2017) 026

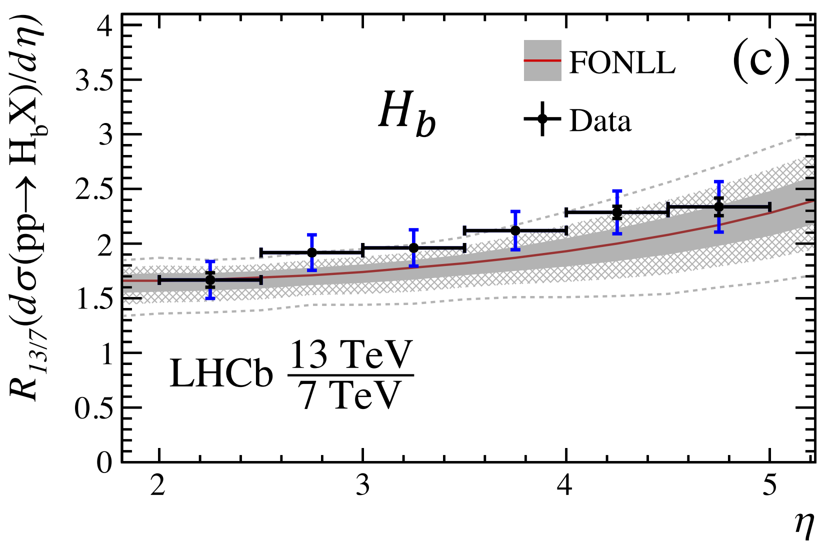
- Generally good agreement with theory predictions on p_T, y dependence in all LHCb acceptance
  - POWHEG, FONLL or GM-VFNS
  - Down to zero-p_T or low-x
- Large theoretical uncertainties from scales and PDFs. Smaller for beauty than charm:
  - $m_b > m_c$, smaller scale uncertainty for beauty
  - Charm reaching unconstrained low-x region

Cross-section ratios

JHEP 06 (2017) 147
JHEP 12 (2017) 026
JHEP 03 (2016) 159
JHEP 09 (2016) 013
JHEP 05 (2017) 074
PRL 118 (2017) 052002

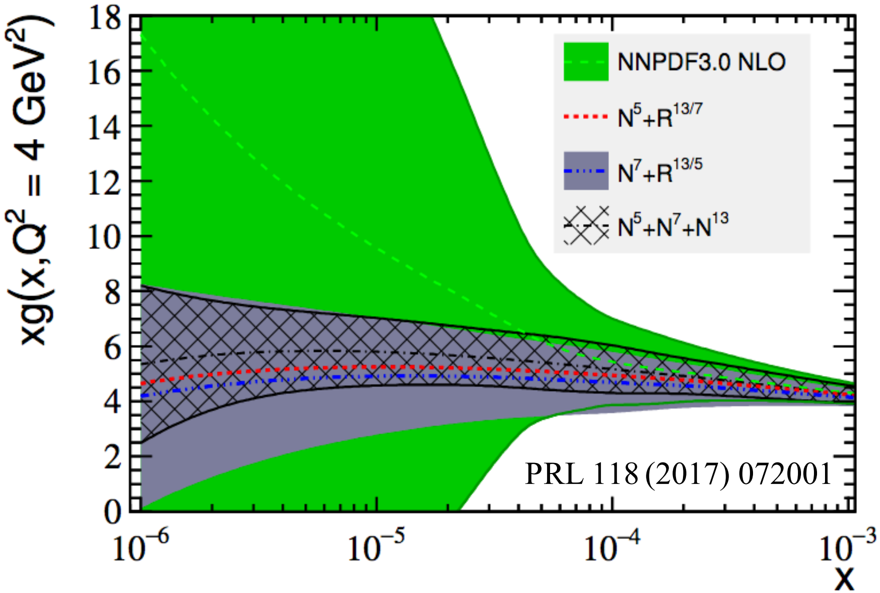


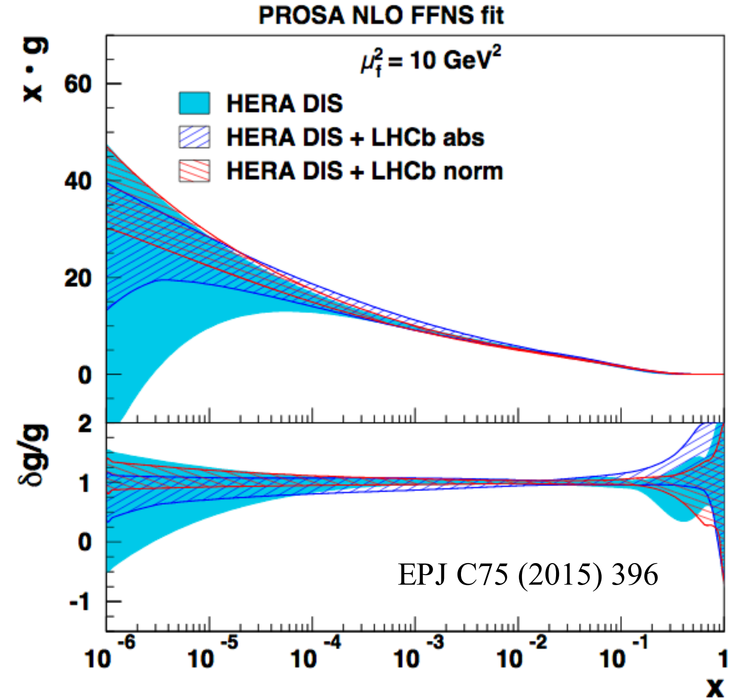


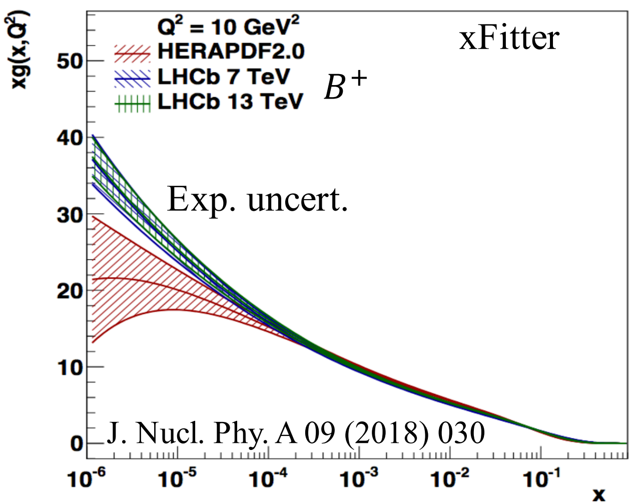


- Theoretical uncertainties from scales partially cancel
  - ➢ Still (some) sensitivity to PDFs
  - ➢ More sensitive to pQCD calculations
- Reasonably good agreement

Gluon PDFs







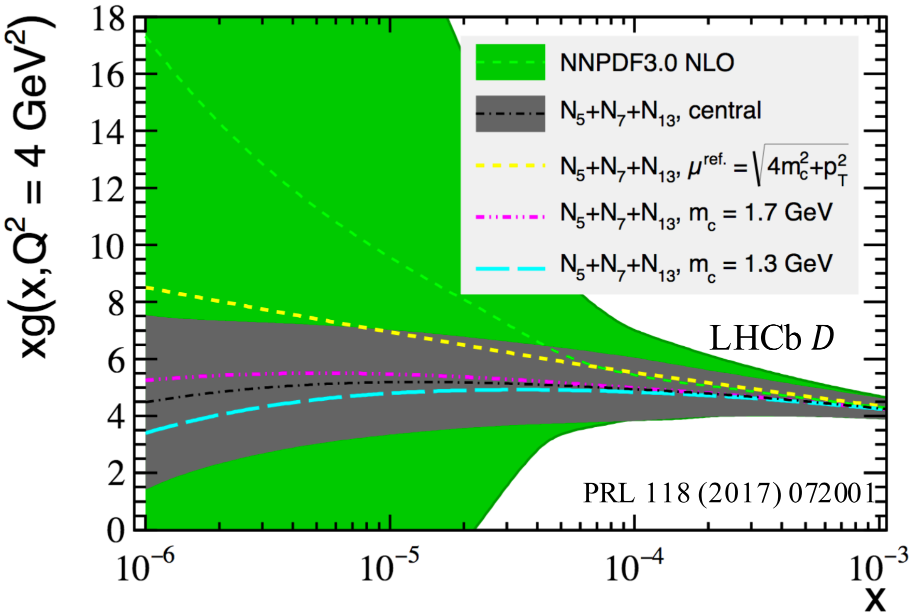
- LHCb charm production significantly reduces gluon PDF at low-x ($x < 10^{-4}$)
- Simultaneous description of at different energies imposes further constraints
- Beauty production (ratios) also sensitive to low-x region

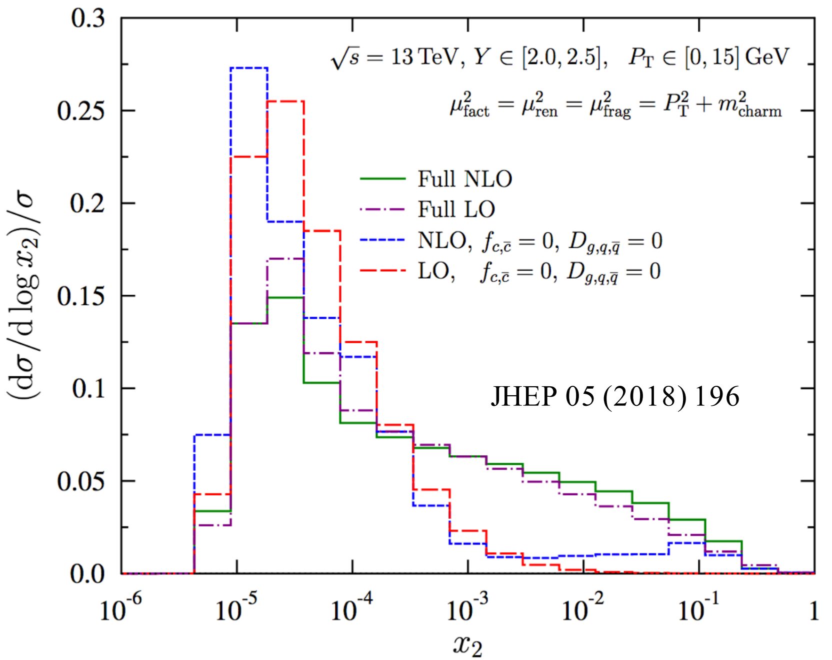
Gluon PDF Fits

- Theoretical uncertainties
  - Scales, heavy quark mass. Larger for charm calculations, especially at low-p_T
  - PDF parameterizations and fitting

$$xf(x, Q_0^2) = A_f x^{a_f} (1-x)^{b_f} I_f(x) \qquad I_f(x) = 1 + c_f\sqrt{x} + d_f x + \ldots$$

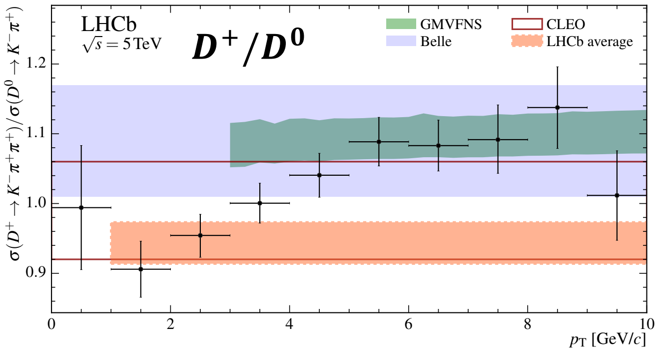
  - Perturbative calculations: flavor schemes …
  - Non-perturbative effects: fragmentation function …

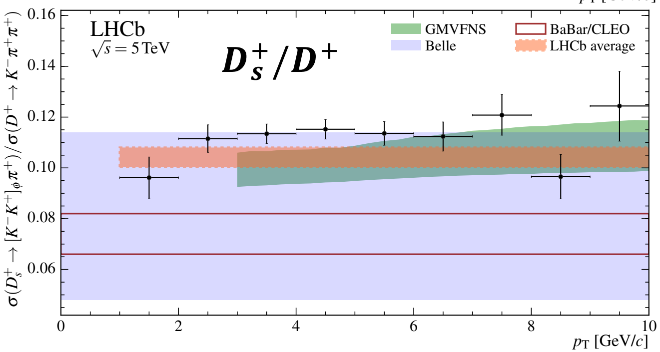


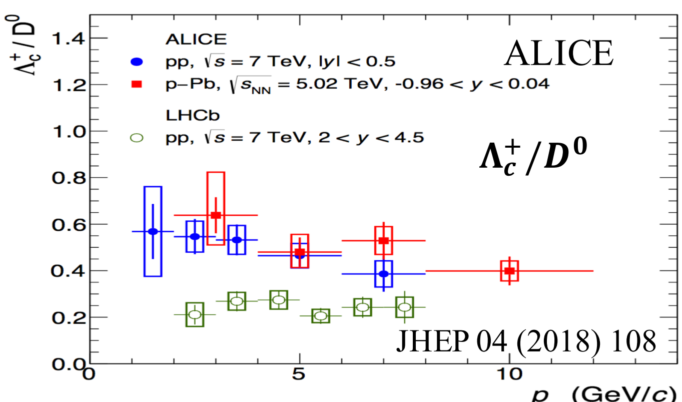


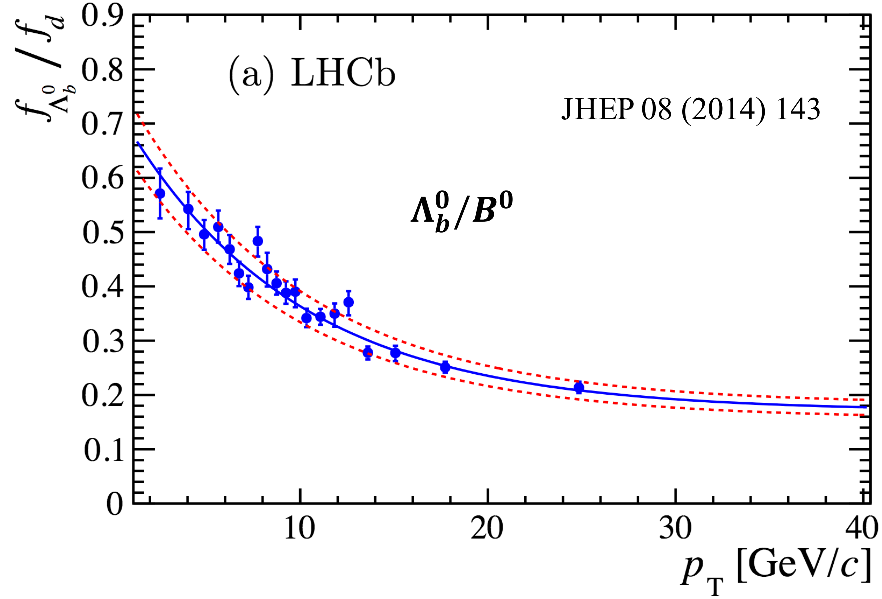
Fragmentation fraction

JHEP 1706 (2017) 147









- Different bottom FF between LHCb and previous measurements
  - ➢ $f_{\Lambda_b^0} \approx 8.9 \pm 1.2\%$ (PDG), $\approx 15\%$ (LHCb)
- $f_{\Lambda_c^+}$: large spread within literature
  - ➢ $f_{\Lambda_c^+}/f_{D^0} \approx 25\%$ (LHCb), $\approx 50\%$ (ALICE), $\approx 10 \pm 2\%$ in 2015 average [EPJ C76 (2016) 397]
- Fragmentation also kinematic dependent
  - ➢ f_{D^0}, f_{B^+} varies by up to 10%-15% from low p_T to high p_T

Taken into account properly in PDF fit?

Heavy quarkonium production

- $J/\psi, \Upsilon$ production at $\sqrt{s} = 13$ TeV
- $J/\psi, \Upsilon$ polarisation at $\sqrt{s} = 13$ TeV
- η_c production at $\sqrt{s} = 7, 8$ TeV

JHEP 10 (2015) 172
JHEP 07 (2018) 134

EPJ C73 (2013) 11
JHEP 12 (2017) 110

EPJ C75 (2015) 7

Heavy quarkonia production

- Factorization

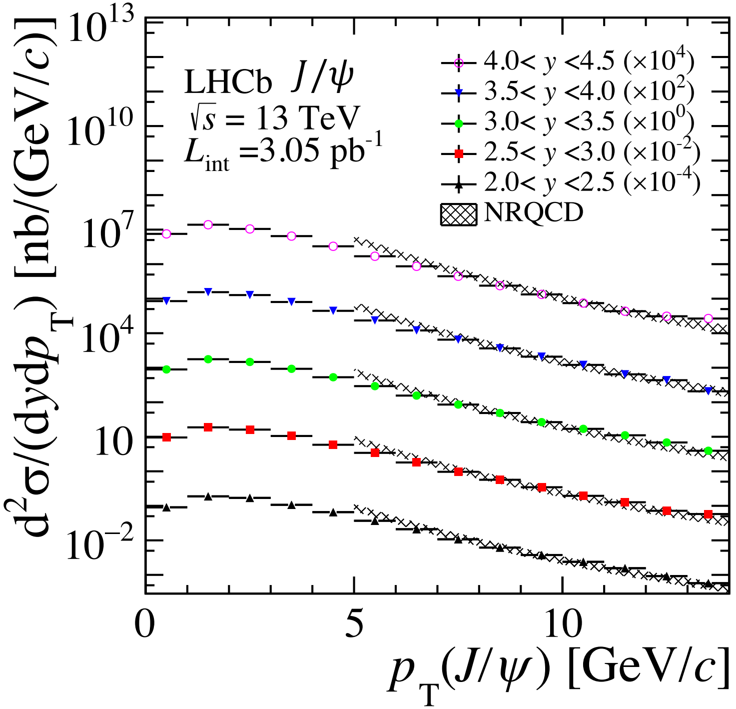
$$\sigma(AB \to H + X) \Leftarrow \sum_n \underbrace{\sigma(AB \to Q\bar{Q}[n]X)}_{\text{Perturbative}} \underbrace{< Q\bar{Q}[n] \to H >}_{\text{Non-perturbative}}$$

n: spin, parity, color indices

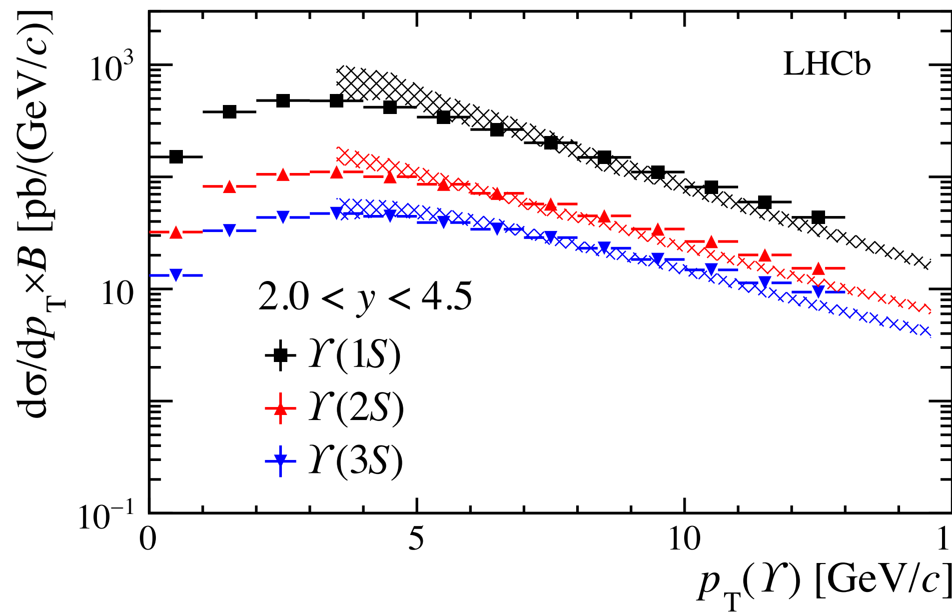
- Fragmentation of $Q\bar{Q}[n]$: heavy quarkonia production models
  - Color singlet mechanism (CSM): intermediate $Q\bar{Q}[n]$ in color singlet state and coincides with final state quarkonium H **spin-parity quantum number**
  - Non-relativistic QCD approach (NRQCD): **Both color singlet and octet** states allowed with varying probabilities (long distance matrix elements, LDME)
    - Double expansion: v (heavy quark velocity) for long distance, α_s and v for short distance. $v^2 \sim 0.3$ for $c\bar{c}$, $v^2 \sim 0.1$ for $b\bar{b}$
    - LDME obtained by fitting data: different p_{T} dependence for associated hard part
    - LDME absorbs non-perturbative effects, e.g. emissions of soft gluon
    - Leading LDMEs for J/ψ production: ${}^3S_1^{[1]}$, ${}^3S_1^{[8]}$, ${}^1S_0^{[8]}$, ${}^3P_J^{[8]}$
  - Color evaporation model: fixed probability for all $Q\bar{Q}$ pairs with $m_{Q\bar{Q}} < 2m_{H_Q}$
    - Improved version: $m_{H_{QQ}} < m_{Q\bar{Q}} < 2m_{H_Q}$

Production cross-sections

JHEP 10 (2015) 172
JHEP 12 (2017) 110



NRQCD: JHEP 05 (2015) 103



- p_T-differential cross-section described by NRQCD calculations, hint of harder p_T spectrum for Υ data? Note that p_T/m_Q is relatively small for Υ at LHCb.
- Also in good agreement for different rapidity bins
- Divergence at low-p_T between data and NRQCD. Total cross-section however well described by CSM [EPJ C75 (2015) 7]

Note: non-perturbative LDMEs obtained by fitting to CDF data → LDMEs universal

Production cross-sections

JHEP 10 (2015) 172
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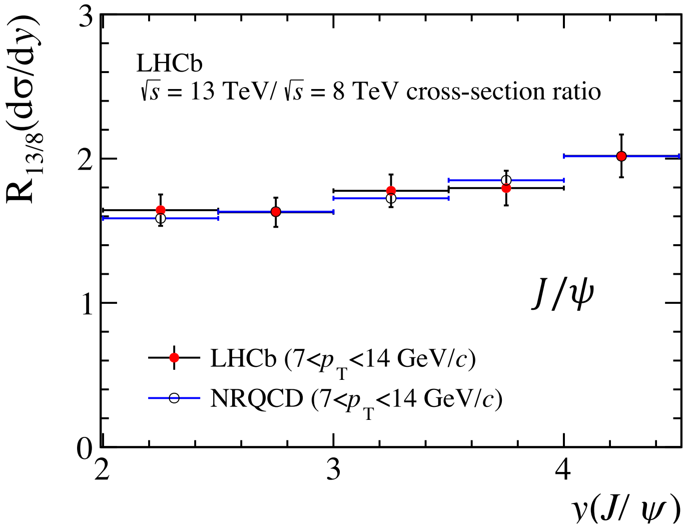
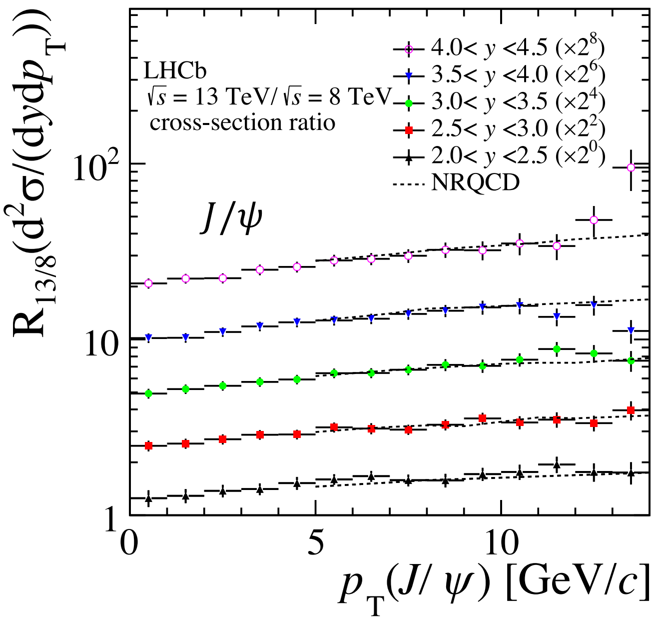
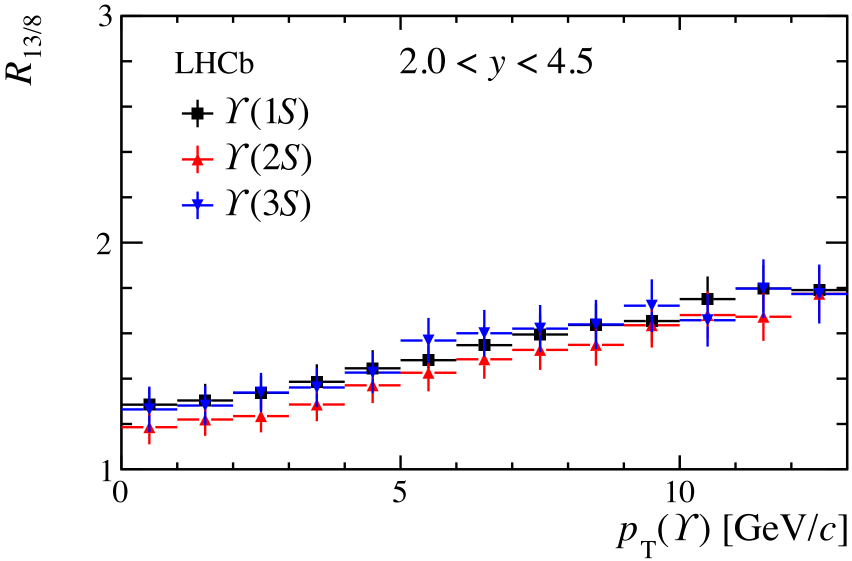




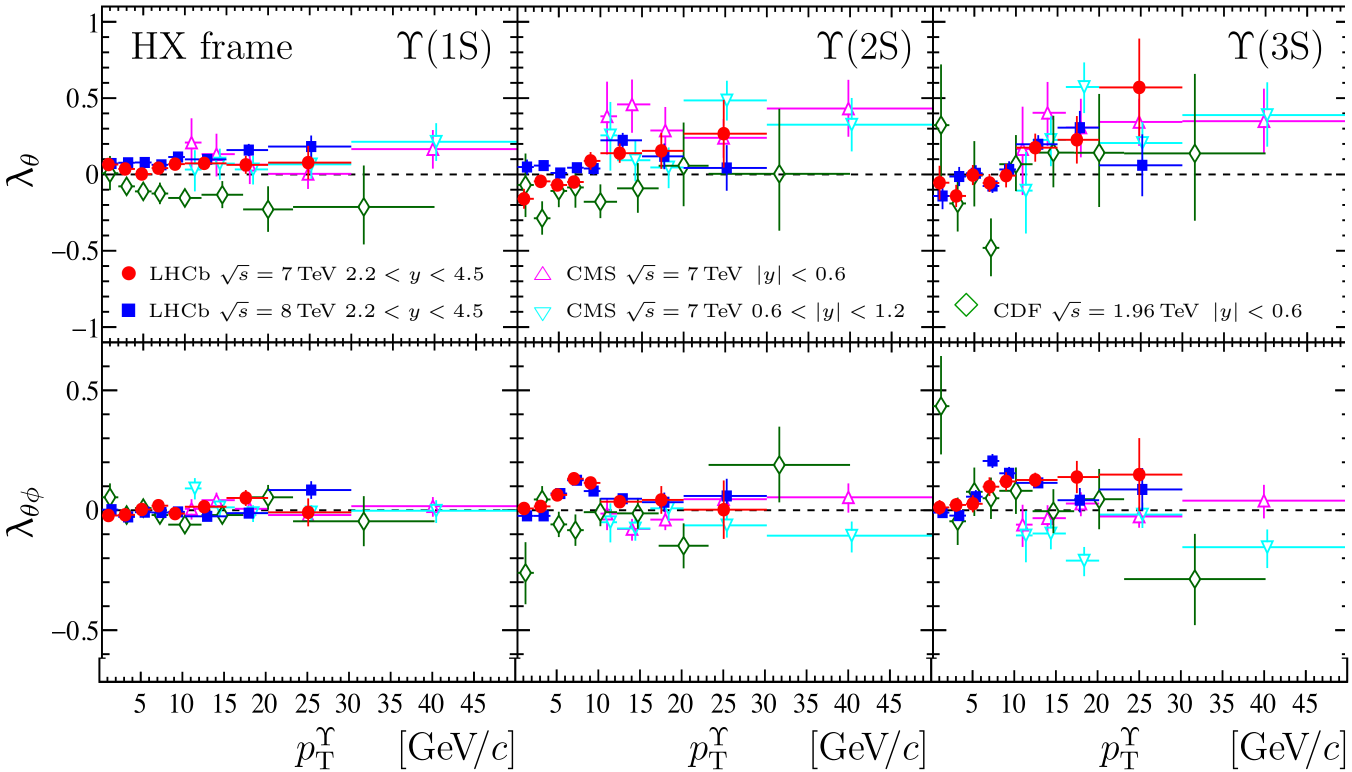


- Remarkable agreement between data and NRQCD for cross-section ratios
- Likely also agree at low-p_T, despite divergence in absolute cross-sections
    - ➢ Is it fully understood?
- Can be tested for Υ production

Υ polarisations

JHEP 12 (2017) 110

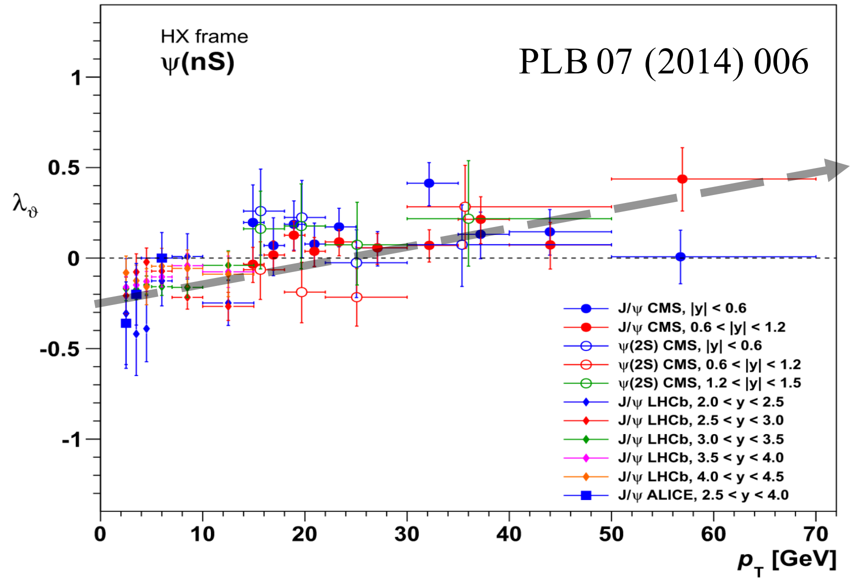
$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi}\frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta\cos^2\theta+\lambda_{\theta\phi}\sin 2\theta\cos\phi+\lambda_\phi\sin^2\theta\cos 2\phi\right)$$

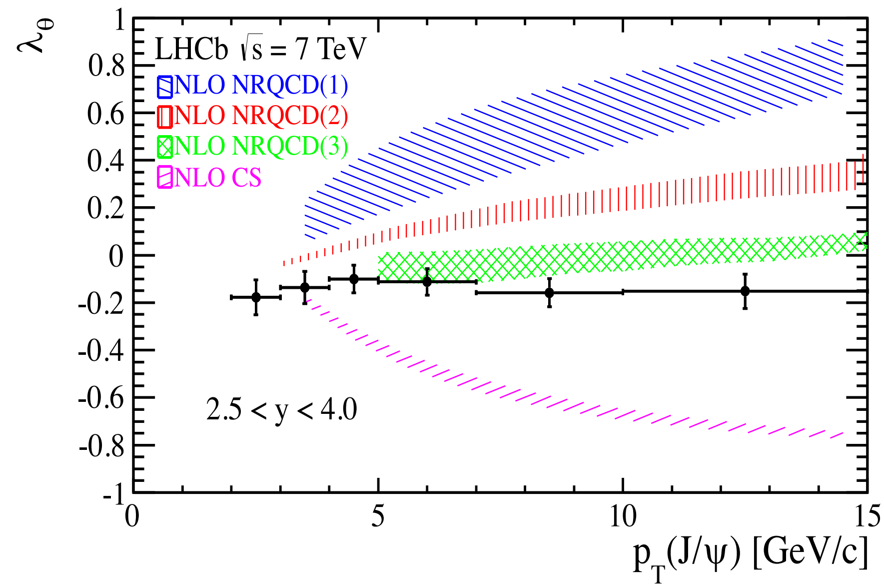


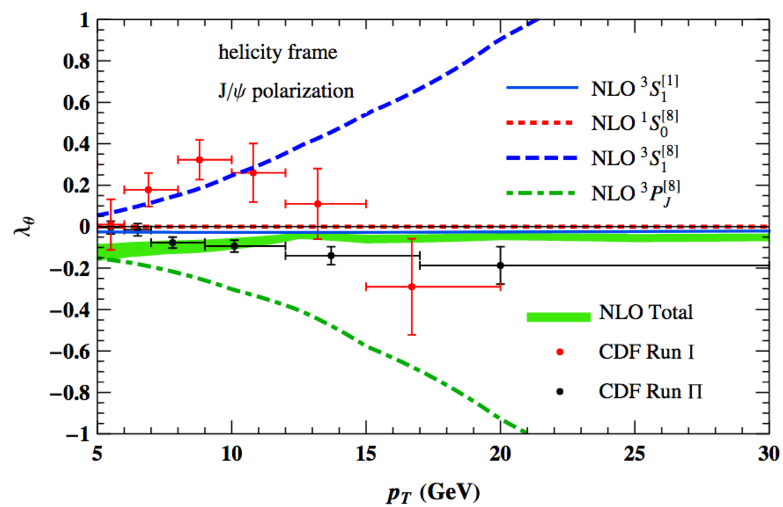
- Small quarkonium polarisation confirmed in Υ data, consistent with CMS measurements
- Sizable transverse polarisation (λ_θ) at high p_T, hint of increasing trend with p_T as predicted by NRQCD: (LO) gluon fragmentation ($^3S_1^{[8]}$) dominates at "**large p_T**"
  - ➢ At which magnitude of p_T? Does it hold at higher order?

Polarisations

EPJ C73 (2013) 11

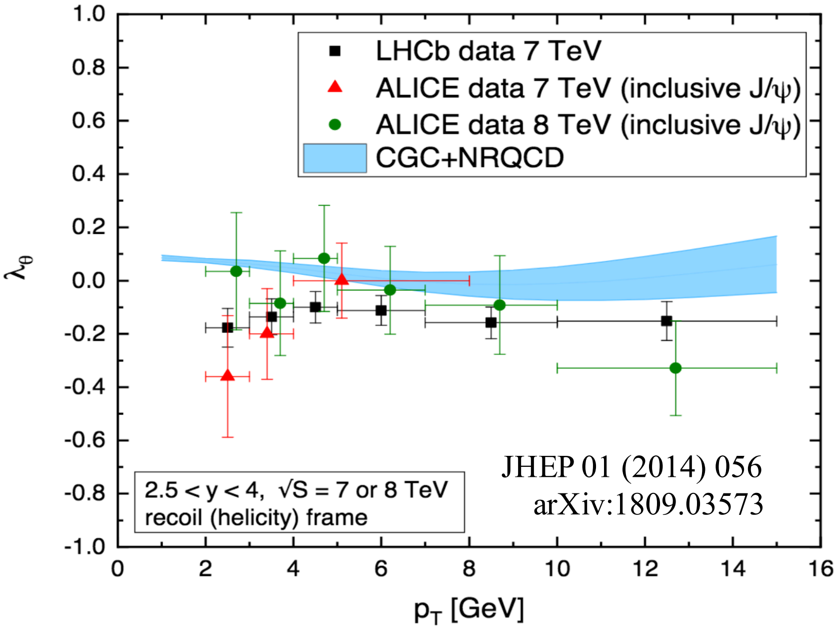


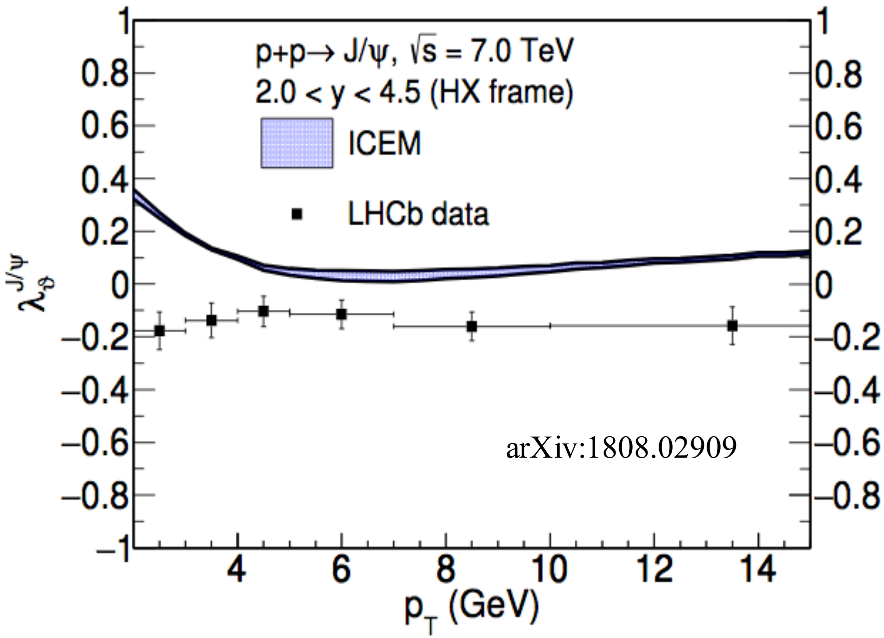




- Similar trend for J/ψ polarisation from LHCb and ALICE (low p_T) to CMS (high p_T)
- Overall small polarization up to $p_T \sim 70$ GeV
- LDMEs tuned to predict both prediction and small polarisation, two solutions:
  i. Large $^1S_0^{[8]}$ contribution [PRL 113 (2014) 022001]
  ii. Cancellation of $^3S_1^{[8]}$ using $^3P_J^{[8]}$ component [PRL 208 (2012) 242004]

Polarisations

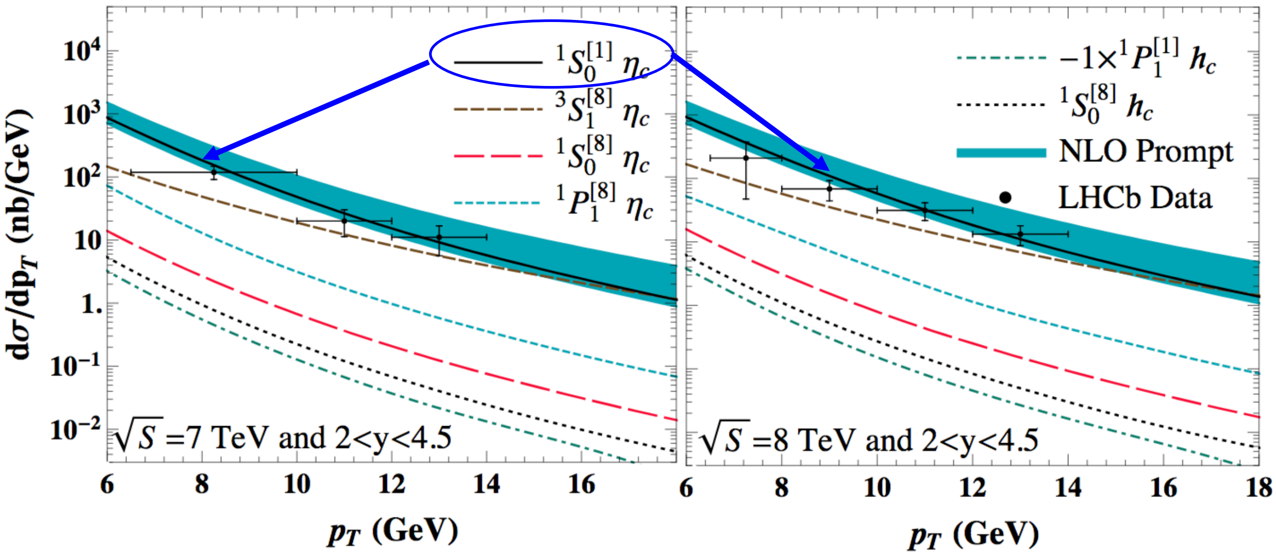




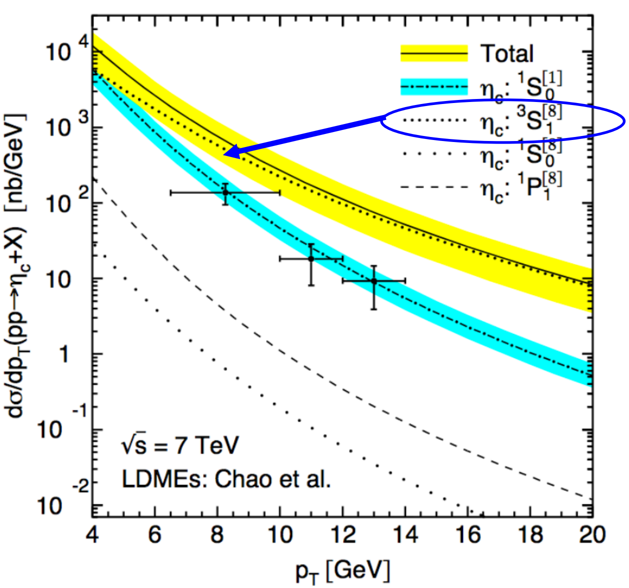
- NRQCD extended to very low p_{T} using CGC calculation, describing both J/ψ cross-section and polarisation
- ICEM calculation gives small polarization at Tevatron and LHC
  - ➢ Almost absence of rapidity dependence

η_c production

EPJ C75 (2015) 7



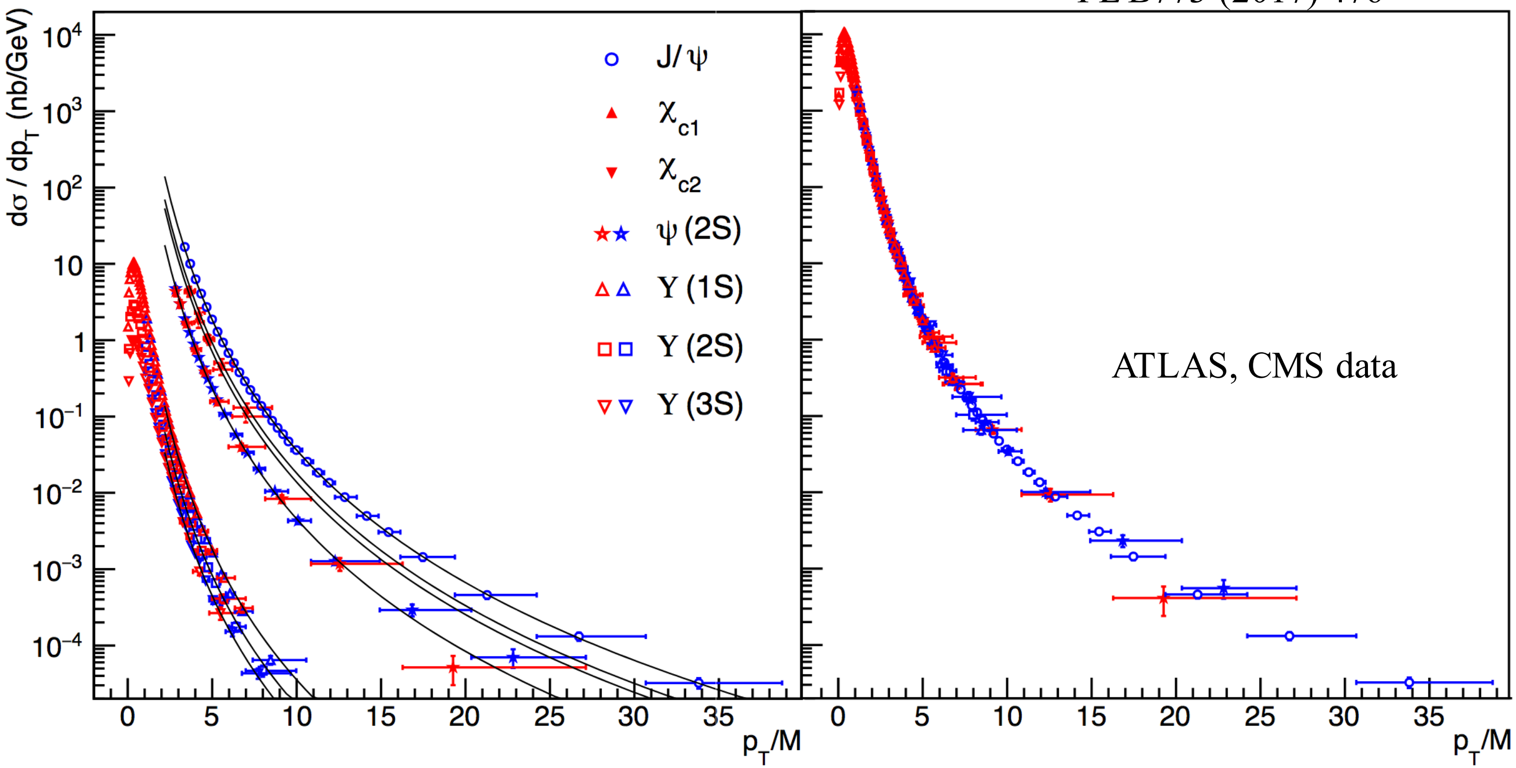
PRL 114 (2015) 092004
PRL 114 (2015) 092005
PRL 114 (2015) 092006



- Data saturated by color singlet $O^{\eta_c}(^1S_0^{[8]})$ contribution, little room for $O^{\eta_c}(^3S_1^{[8]})$ component
- Heavy quark spin symmetry: $O^{\eta_c}(^3S_1^{[8]}) \approx O^{J/\psi}(^1S_0^{[8]})$
- However large $O^{J/\psi}(^1S_0^{[8]})$ contribution for J/ψ, required to describe cross-section and polarisation
  - ➢ LDMEs from J/ψ analysis strongly overshoot η_c data
  - ➢ Confirming cancellation between two LDMEs ($^3S_1^{[8]}$ and $^3P_J^{[8]}$) for J/ψ ? or LDMEs not universal?
- Studying other systems [Talk by J.-P. Lansberg]

Production p_T-scaling

PL B773 (2017) 476



- Differential production as a function of p_T/m has similar shape (within the same y)
  - Charmonium and bottomonium; ground states and excited states
  - Implying similar short distance dynamics?
- Explanation from first principles? Recent progress on NNLO CSM shows missing contributions in NNLO* don't change the magnitude [arXiv: 1809.02369]

Associated production

- Double propmt J/ψ production at $\sqrt{s} = 13$ TeV

JHEP 10 (2017) 068
JHEP 06 (2017) 047

- Υ + charm production at $\sqrt{s} = 7{,}8$ TeV

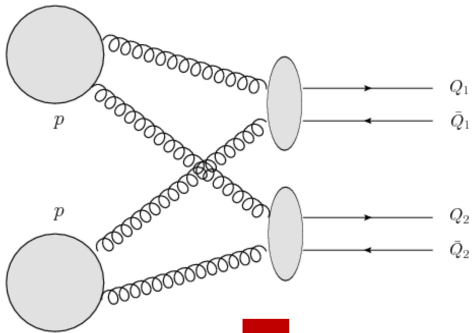
JHEP 07 (2016) 052

- Double charm production at $\sqrt{s} = 7, 8$ TeV

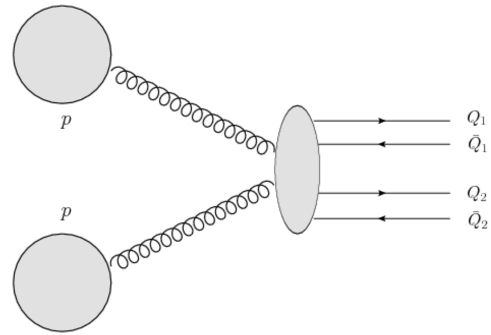
JHEP 06 (2012) 141

Double parton scattering

Double-parton scattering (DPS)

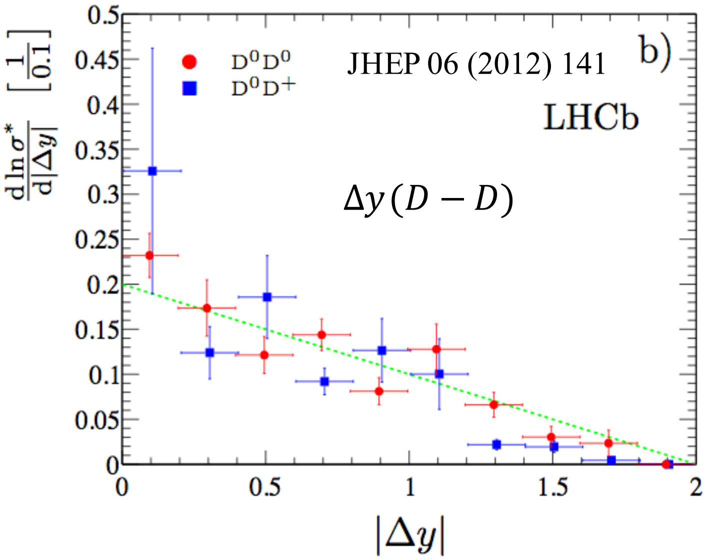


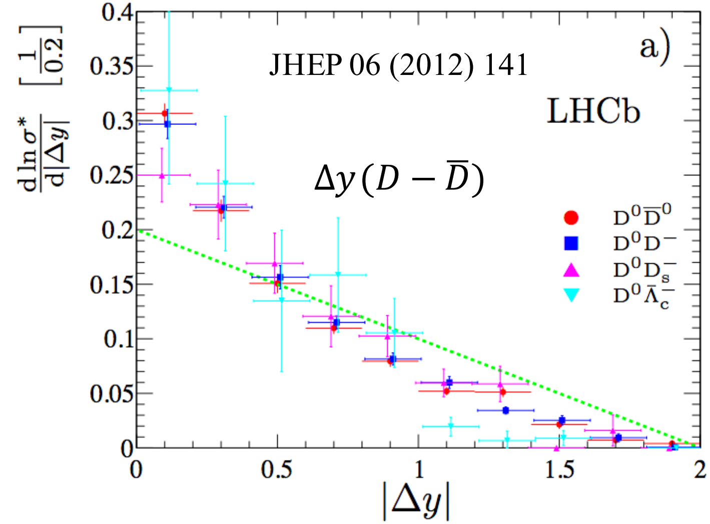
Single-parton scattering (SPS)

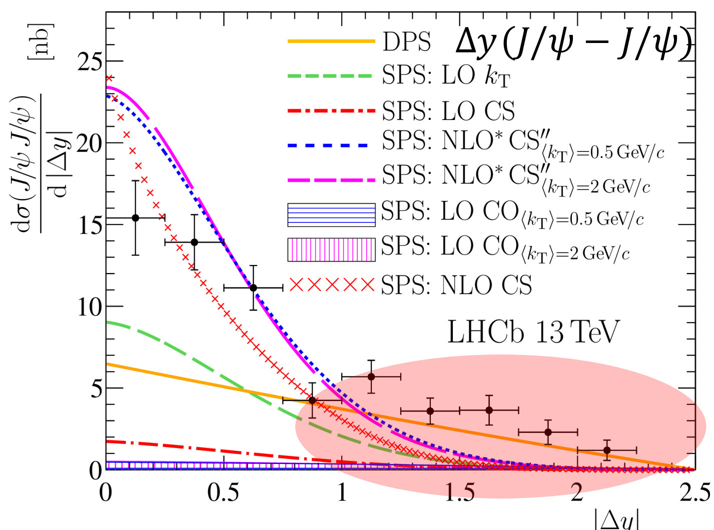


- Information on parton transverse profile and multi parton correlations
- DPS cross-section $\sigma_{Q_1 Q_2} = \alpha \frac{\sigma_{Q_1}\sigma_{Q_2}}{\sigma_{\mathrm{eff}}}$, α is a permutation number
  - Generalized Parton Distributions factorized into transverse and longitudinal components
  - Distributions of two partons uncorrelated
  - $\sigma_{\mathrm{eff}} = \int d^2 \boldsymbol{b} \boldsymbol{F}^2(\boldsymbol{b})$: integral of overlapping parton transverse profile, expected to be process independent → universal
  - DPS like two uncorrelated SPS processes
- Identifying DPS contribution and studying universality of σ_{eff}

Double heavy flavor production







JHEP 10 (2017) 068
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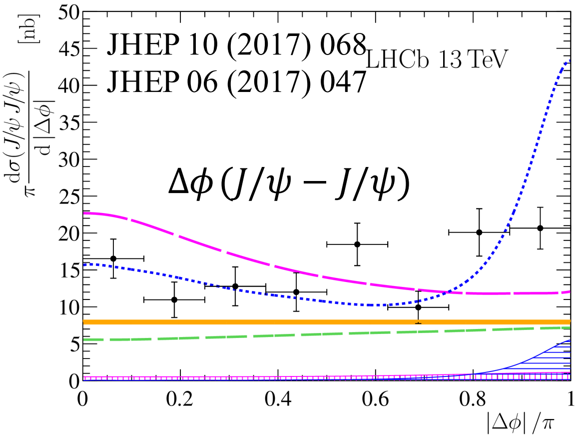
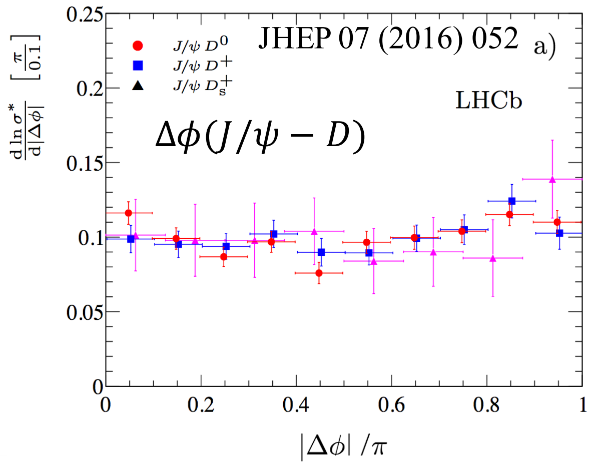
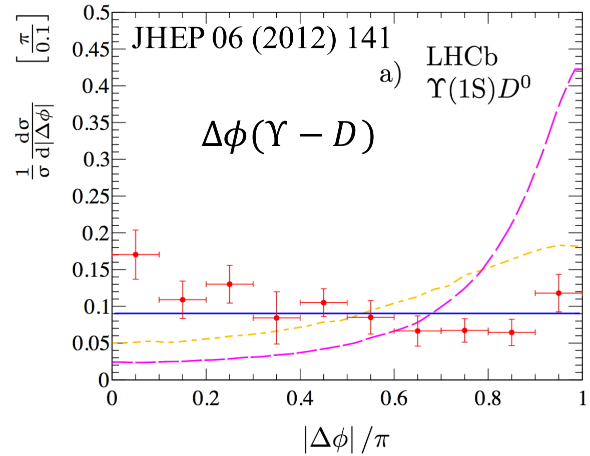
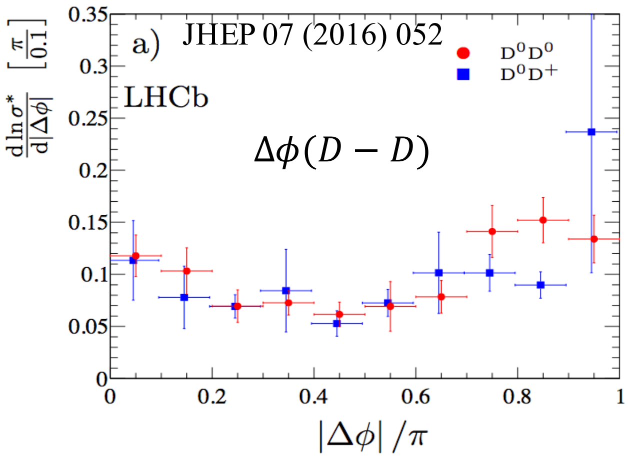
- Larger Δy in same sign charm compared with opposite charm, comparable with uncorrelated production
  - ➢ $D\bar{D}$ dominated by single $c\bar{c}$ pair production
- Δy between $J/\psi - J/\psi$ disfavors SPS-only production at LO/NLO*
- Wider Δy distribution requires DPS
  - ➢ Higher order effect?

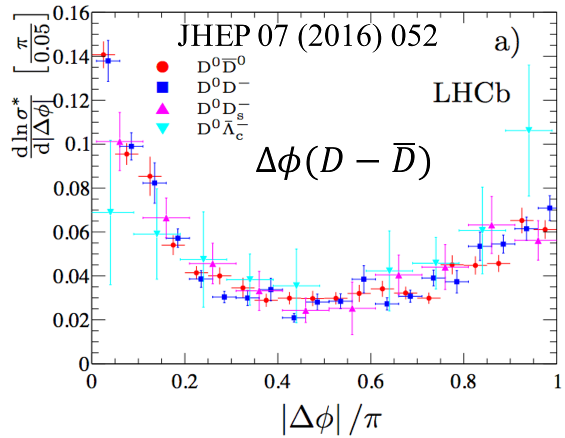
Double heavy flavor production





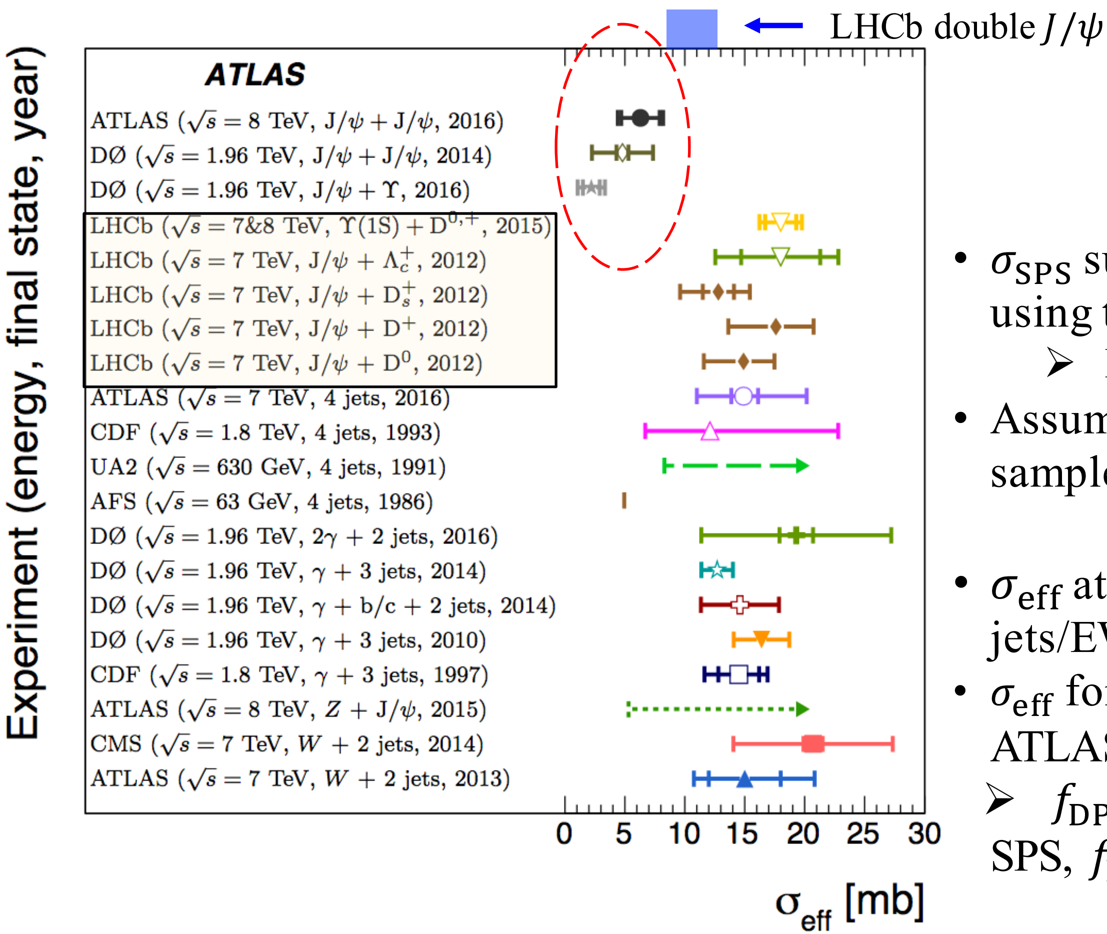






- Peaking at $\Delta\phi = 0$ for opposite-sign charm pairs → production with gluon splitting
- Approximately flat $\Delta\phi$ distribution between quarkonium-charm, same-sign charm→ uncorrelated production, consistent with DPS

Effective cross-section: σ_{eff}



$$\sigma_{\text{eff}} = \alpha \frac{\sigma_{Q_1}\sigma_{Q_2}}{\sigma_{Q_1Q_2}(\text{DPS})}$$

- σ_{SPS} subtracted for double J/ψ analysis using theory templates
  - ➢ DPS dominates over SPS
- Assuming SPS negligible for $DD, J/\psi, \Upsilon D$ samples, giving a lower limit on σ_{eff}

- σ_{eff} at LHCb consistent with data of jets/EW productions: ~ 15 mb
- σ_{eff} for (double) quarkonia measured by ATLAS/D0/CMS prefers a low value
  - ➢ f_{DPS} overestimated? Dominated by SPS, $f_{\text{DPS}} \approx 10\%$

DPS enhanced in heavy ion collisions, σ_{eff} studied in cleaner environment !

PRL 118 (2017) 122001

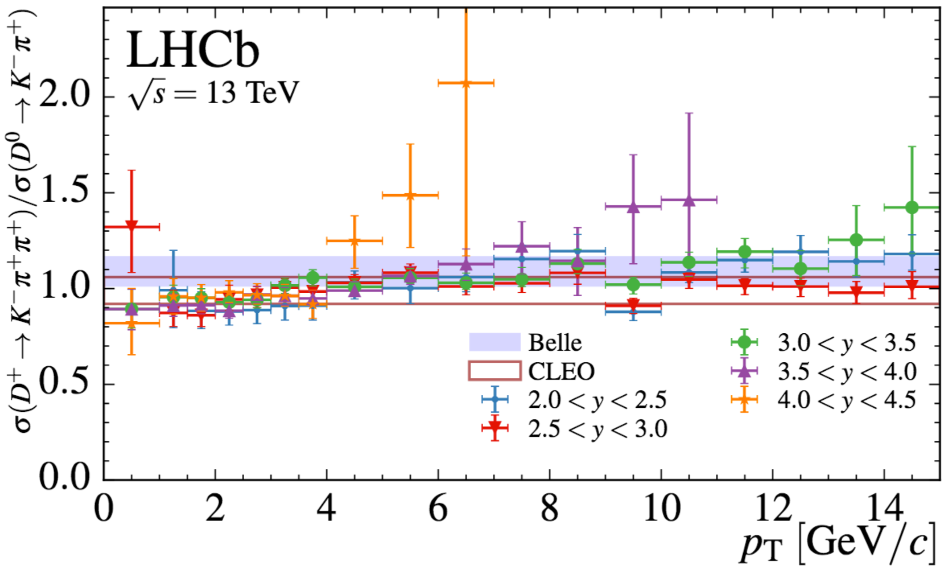
Summary

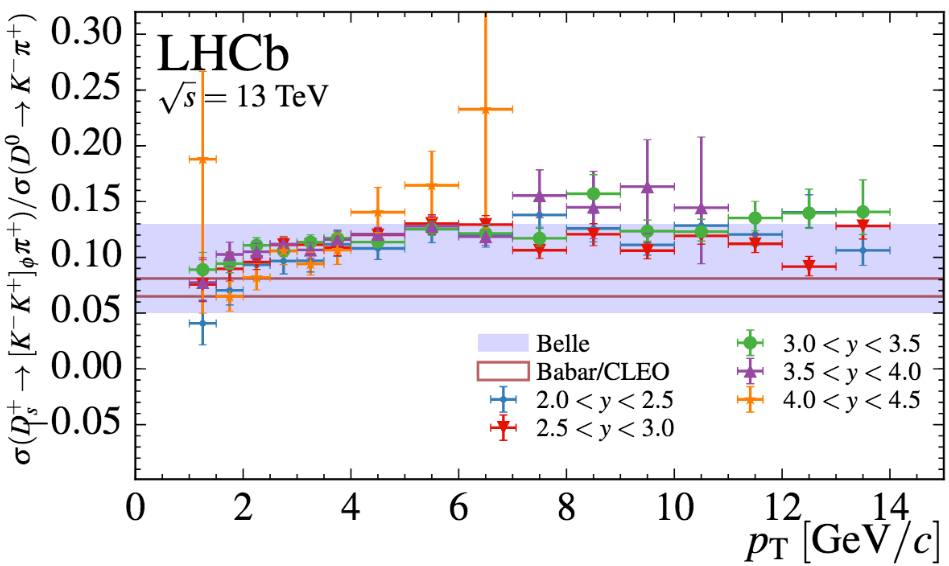
- A variety of measurements of heavy flavour production by LHCb
  - Studying pQCD calculations
  - Constraining PDF at low-x
  - Experimental data for heavy quark fragmentation
  - Quarkonium production testing NRQCD factorisation
  - Experimental evidence of DPS, studying factorisation of generalized parton distributions
- To be resolved
  - Large CO for J/ψ but CS dominating for η_c
  - NRQCD LDMEs can't describe η_c and J/ψ consistently? What about other systems?
  - Baryon fragmentation function, its kinematic dependence
  - σ_{eff} not universal? Process/Kinematic dependence

Thank you for your attention

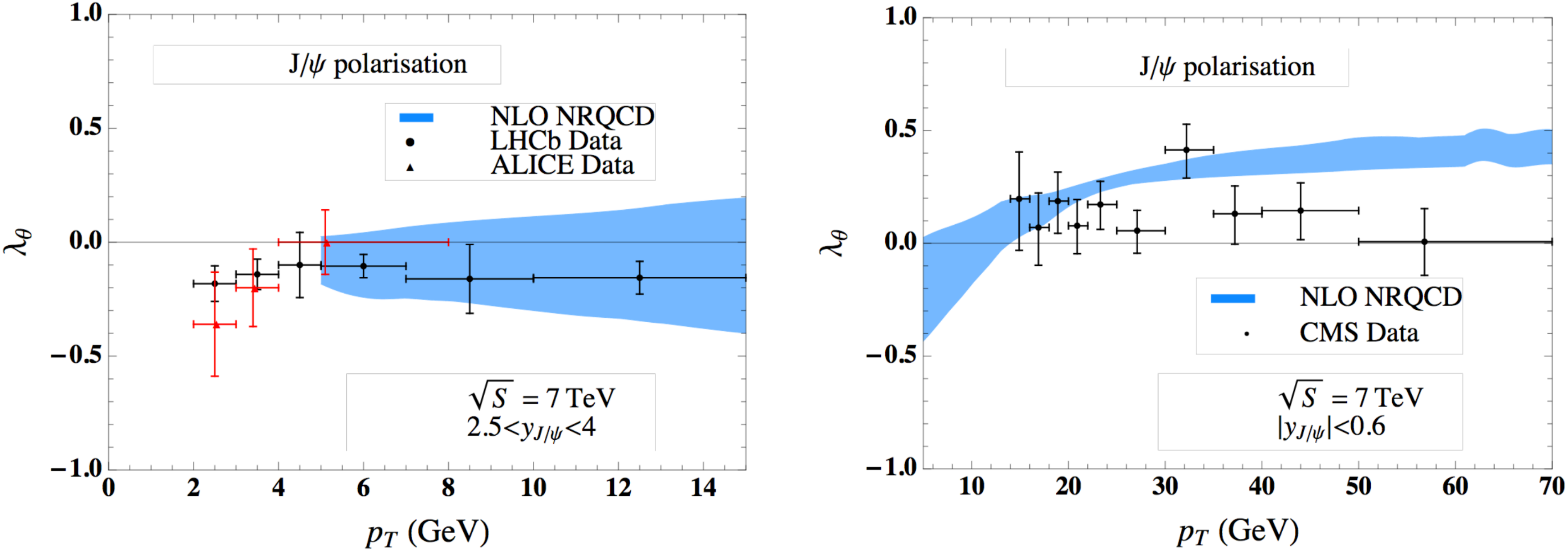
Backups

Charm production ratios



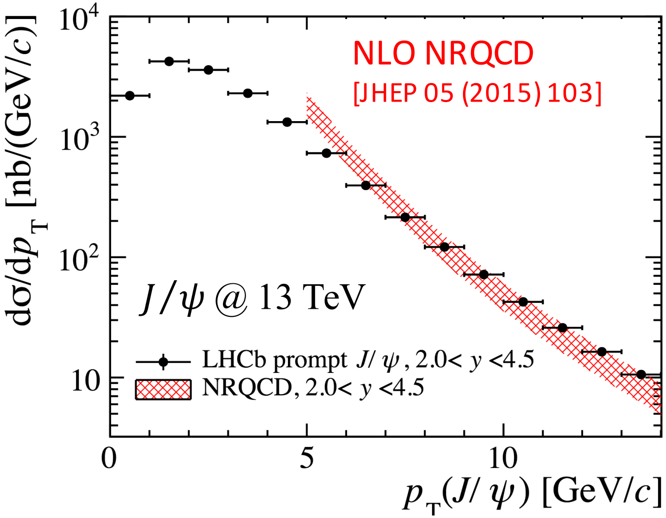


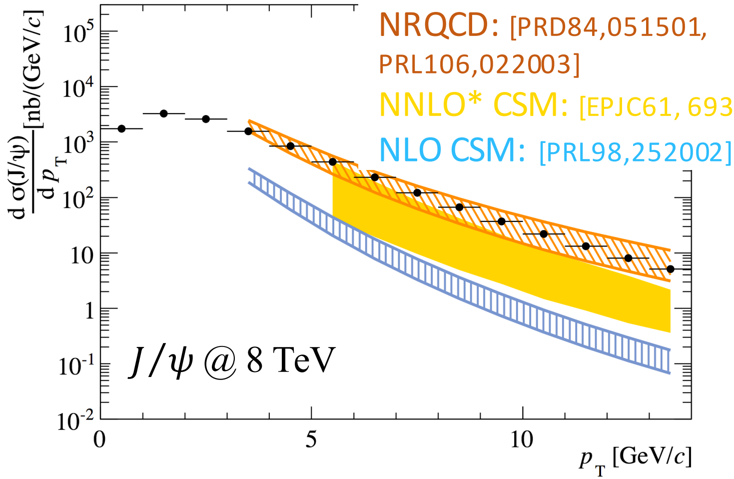
J/psi polarisation with NRQCD

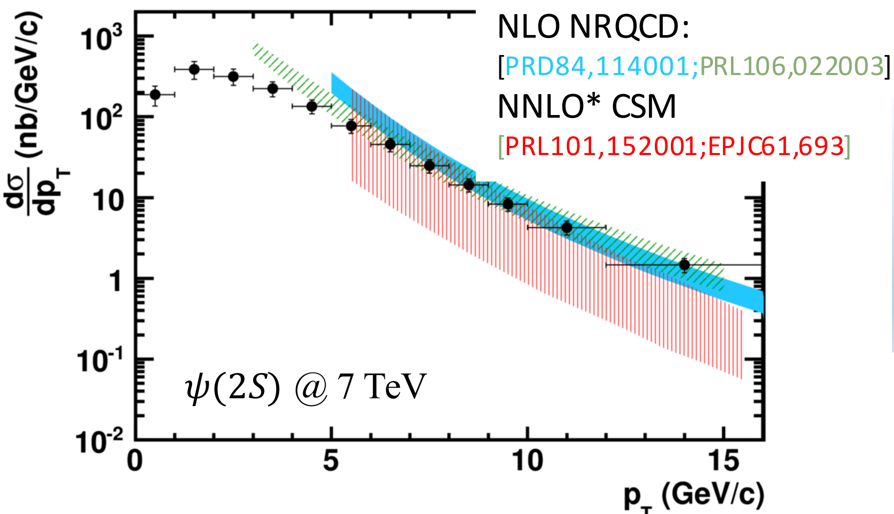


p_T distributions: prompt ψ

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



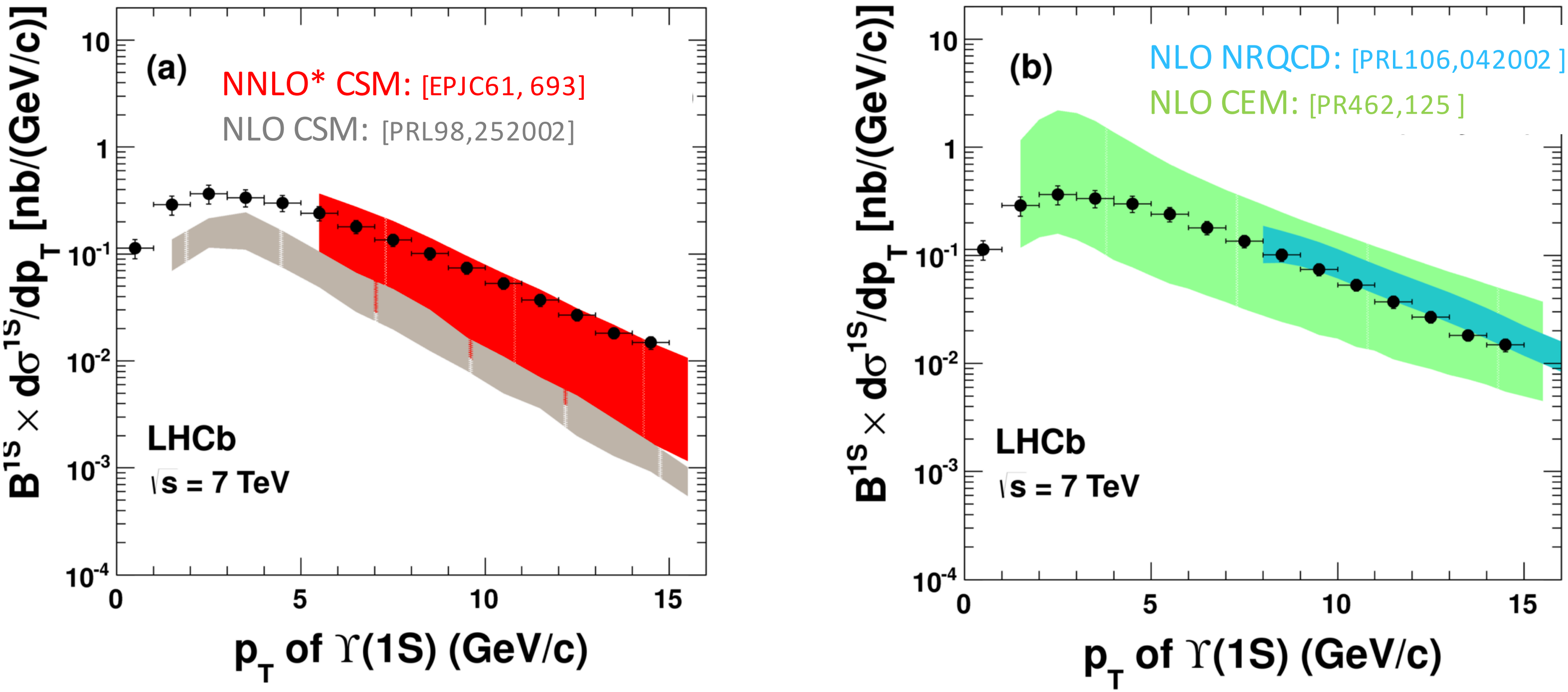




- In good agreement with NLO NRQCD predictions
- NLO or NNLO* CSM calculations underestimates data

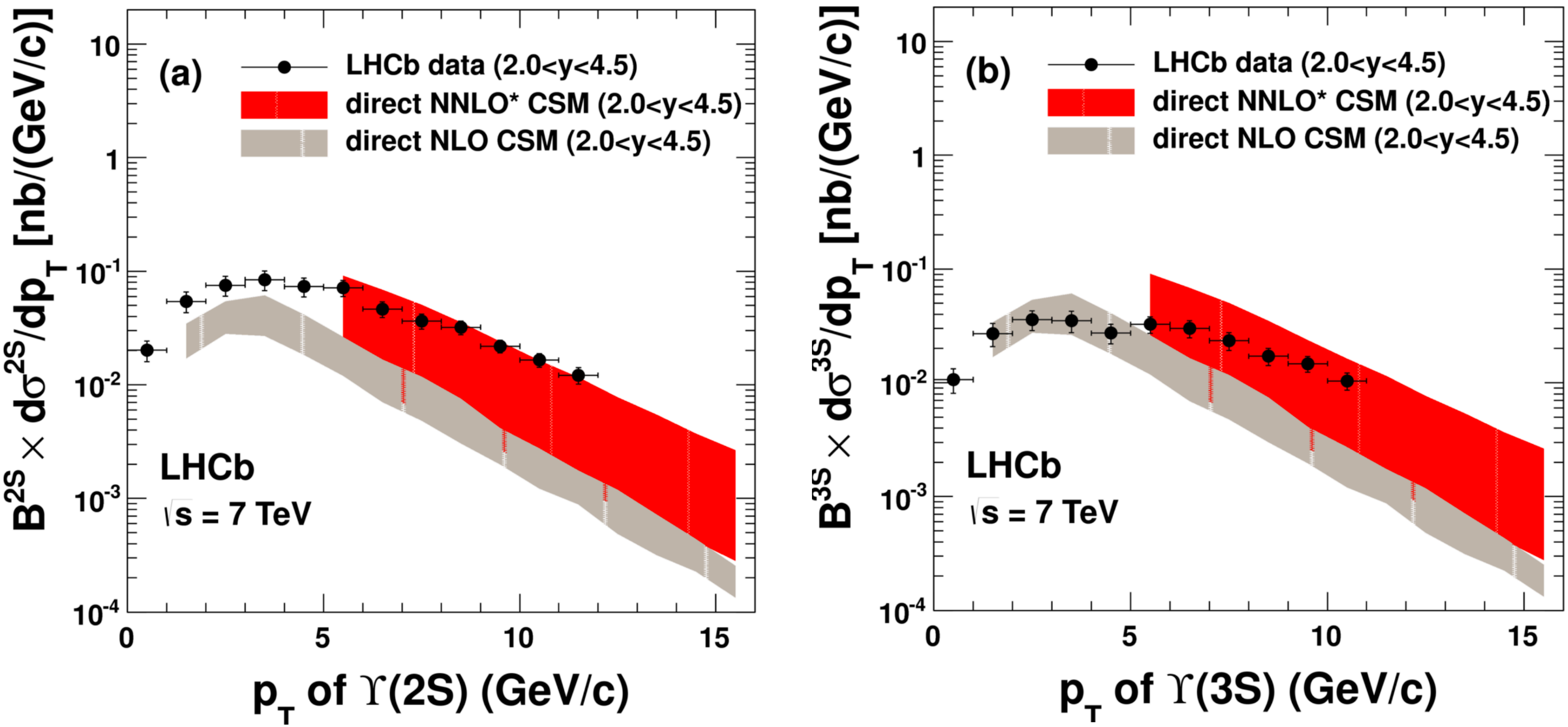
p_T distributions: Υ @7 TeV

LHCb: EPJC72 (2012) 2025



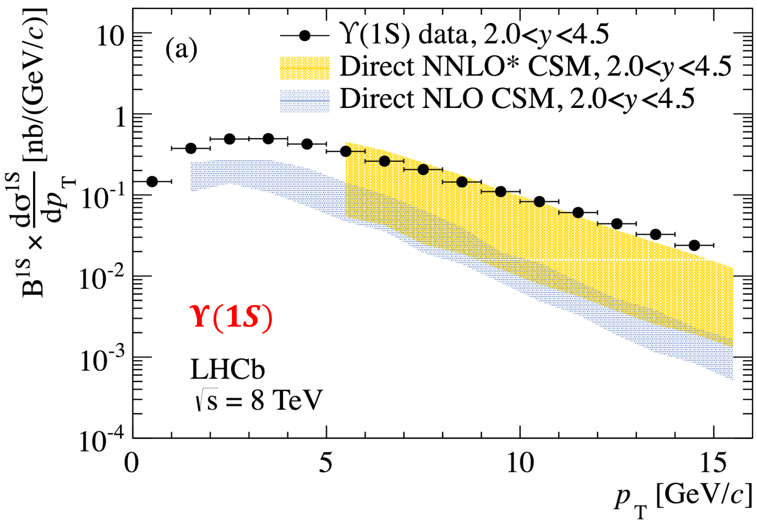
- p_T distributions consistent with NRQCD and CEM, but not with CSM
- NLO (NNLO*) CSM calculations underestimate p_T differential cross-section
- Agreement with NRQCD and CEM are better

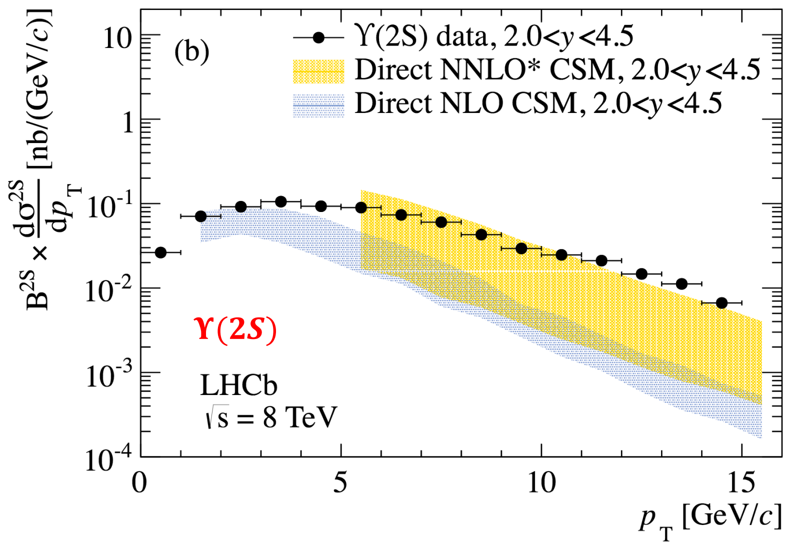
p_T distributions (Υ @7 TeV)

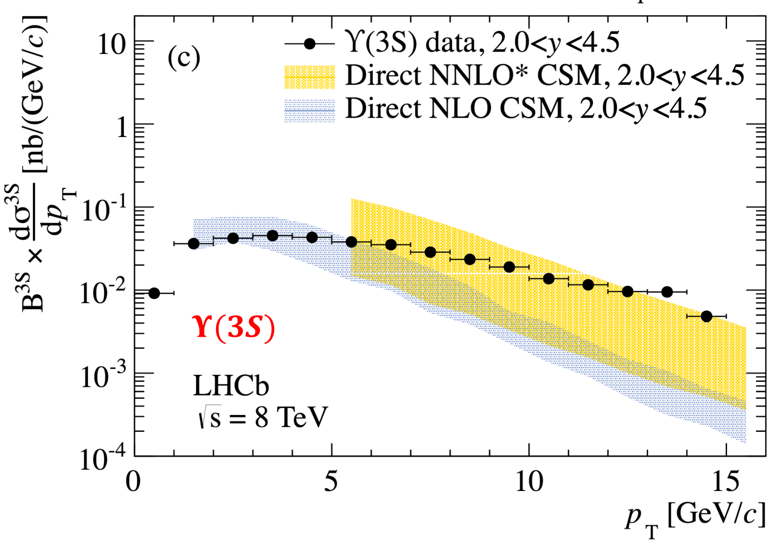


NLO/NNLO* CSM
[PRL101,152001,PRL98,252002]

p_T distributions for ϒ(nS)





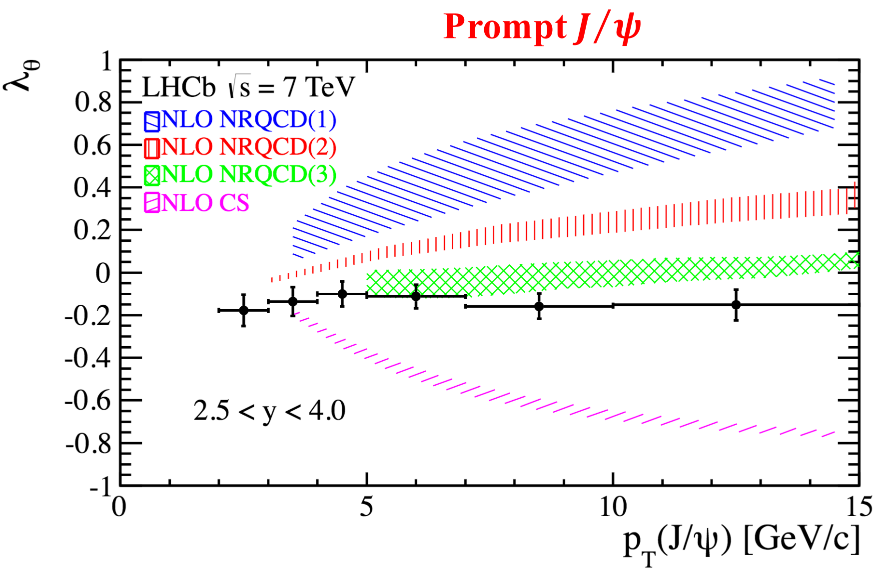


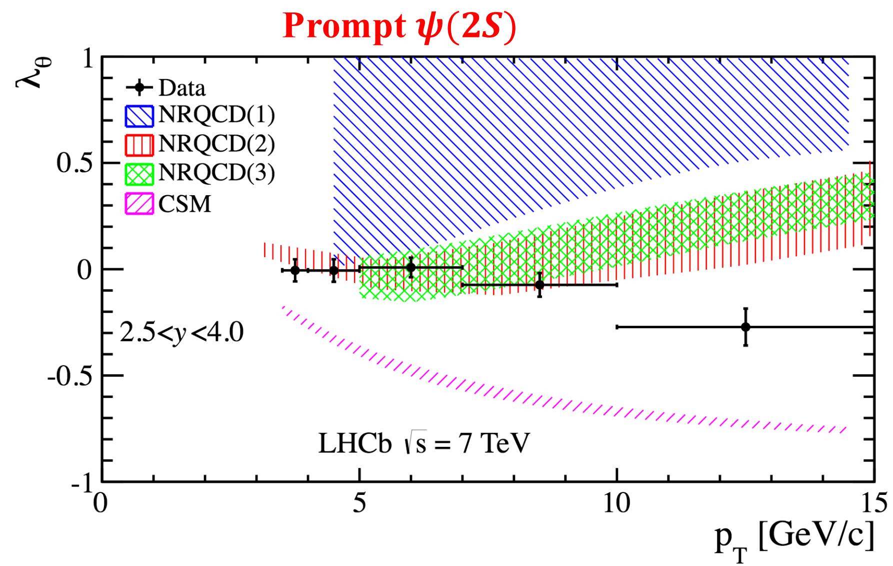
NNLO* CSM: [EPJC61, 693]
NLO CSM: [PRL98,252002]

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

Polarisation results

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

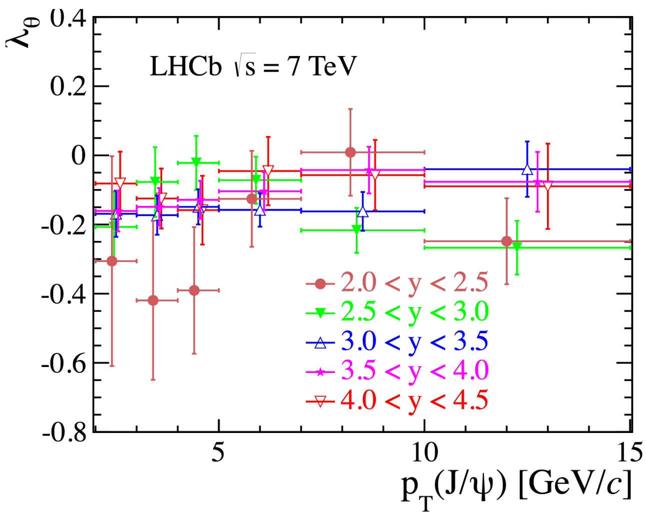


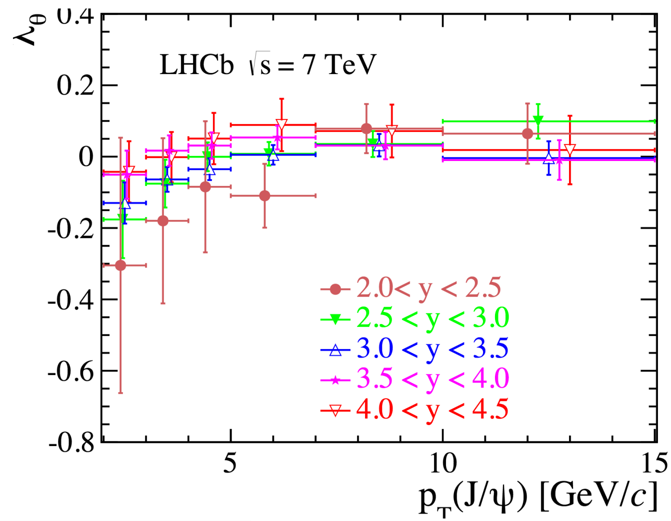


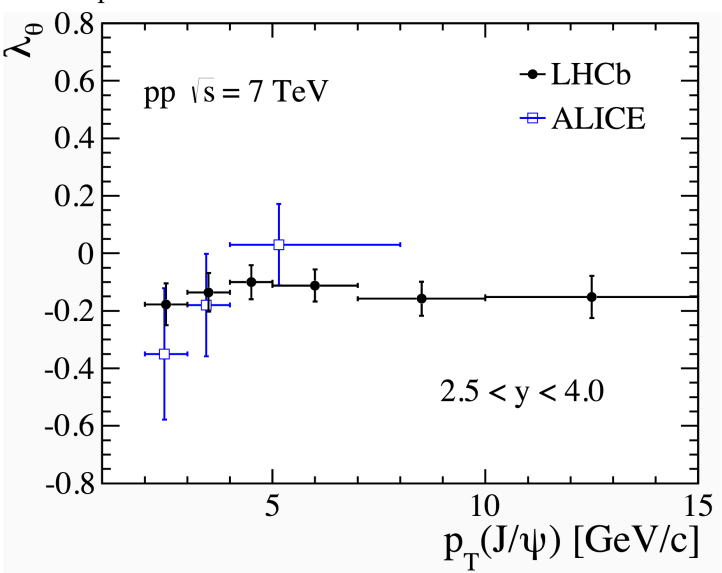
NLO NRQCD
PRL 108 (2012) 172002
PRL 110 (2013) 042002
PRL 108 (2012) 242004
NLO CSM
PRL 108 (2012) 172002

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

Polarization analysis

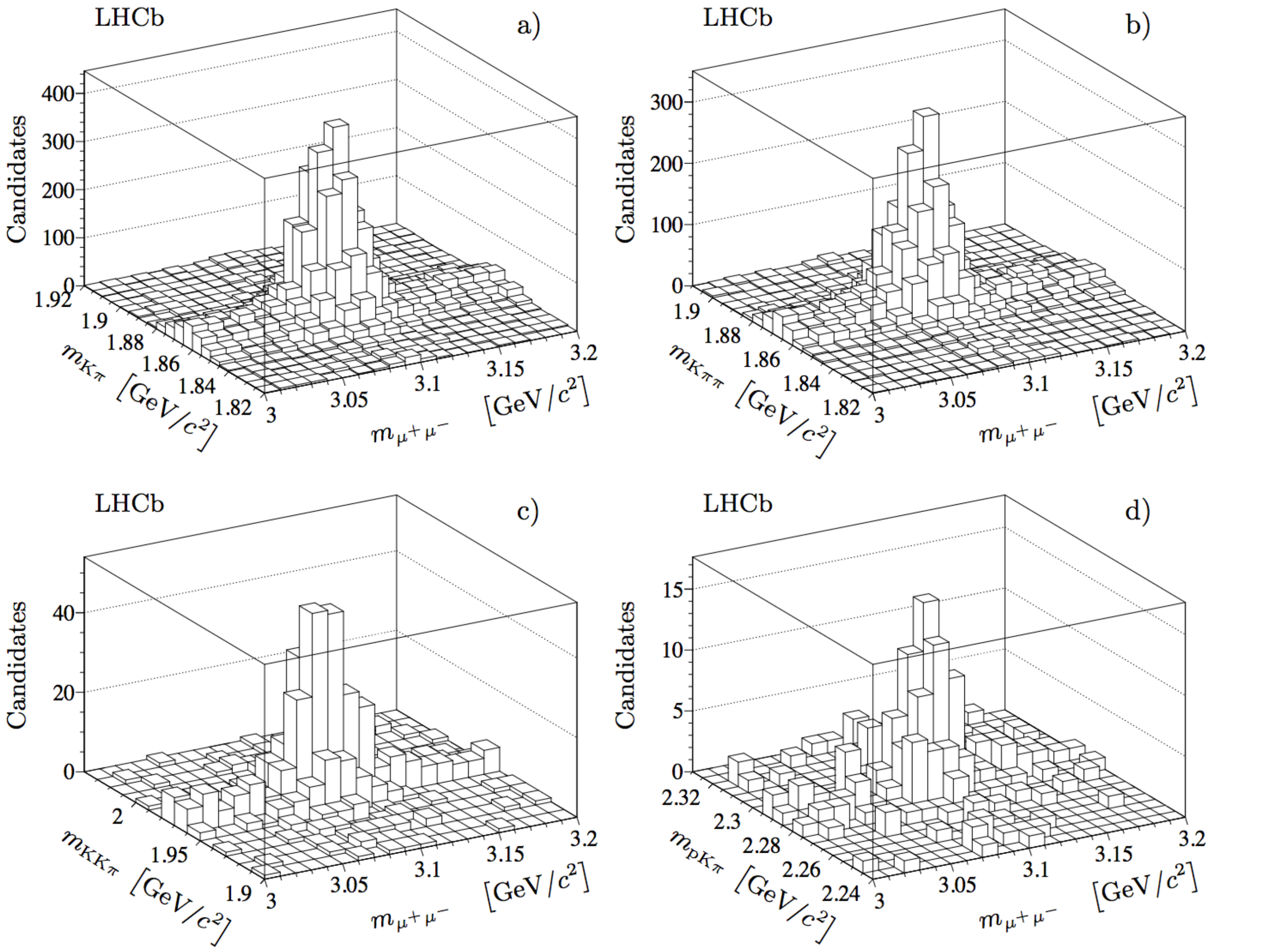






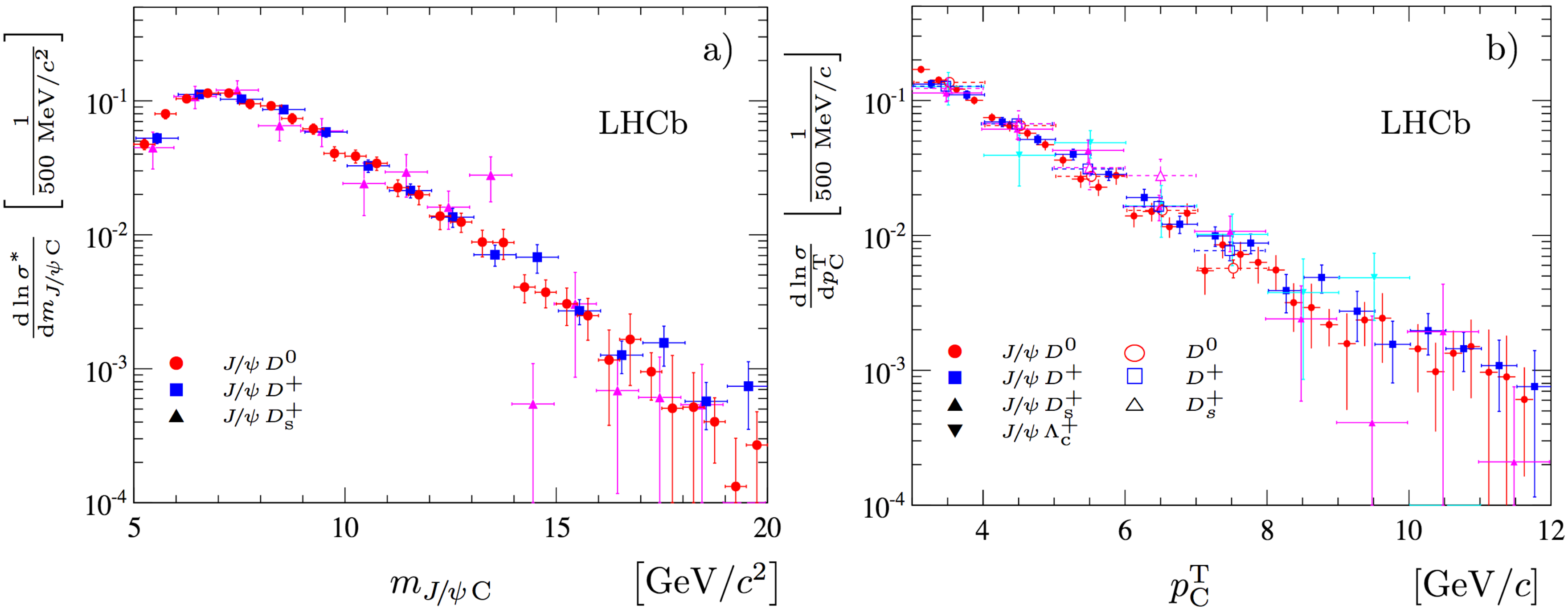
J/ψ + open charm mass

- 2D mass plots



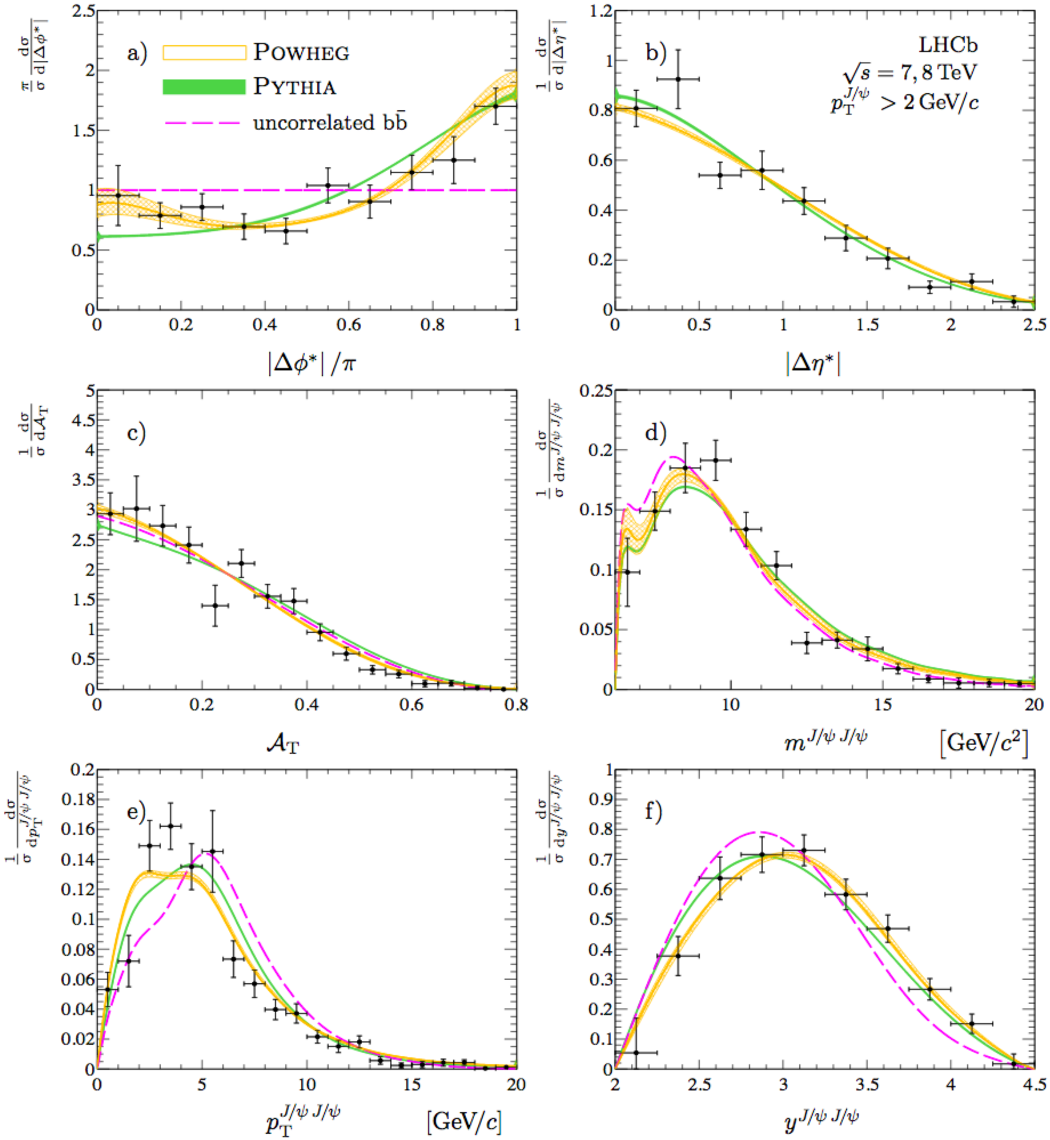
J/ψ + open charm

- Invariant mass and charm p_T



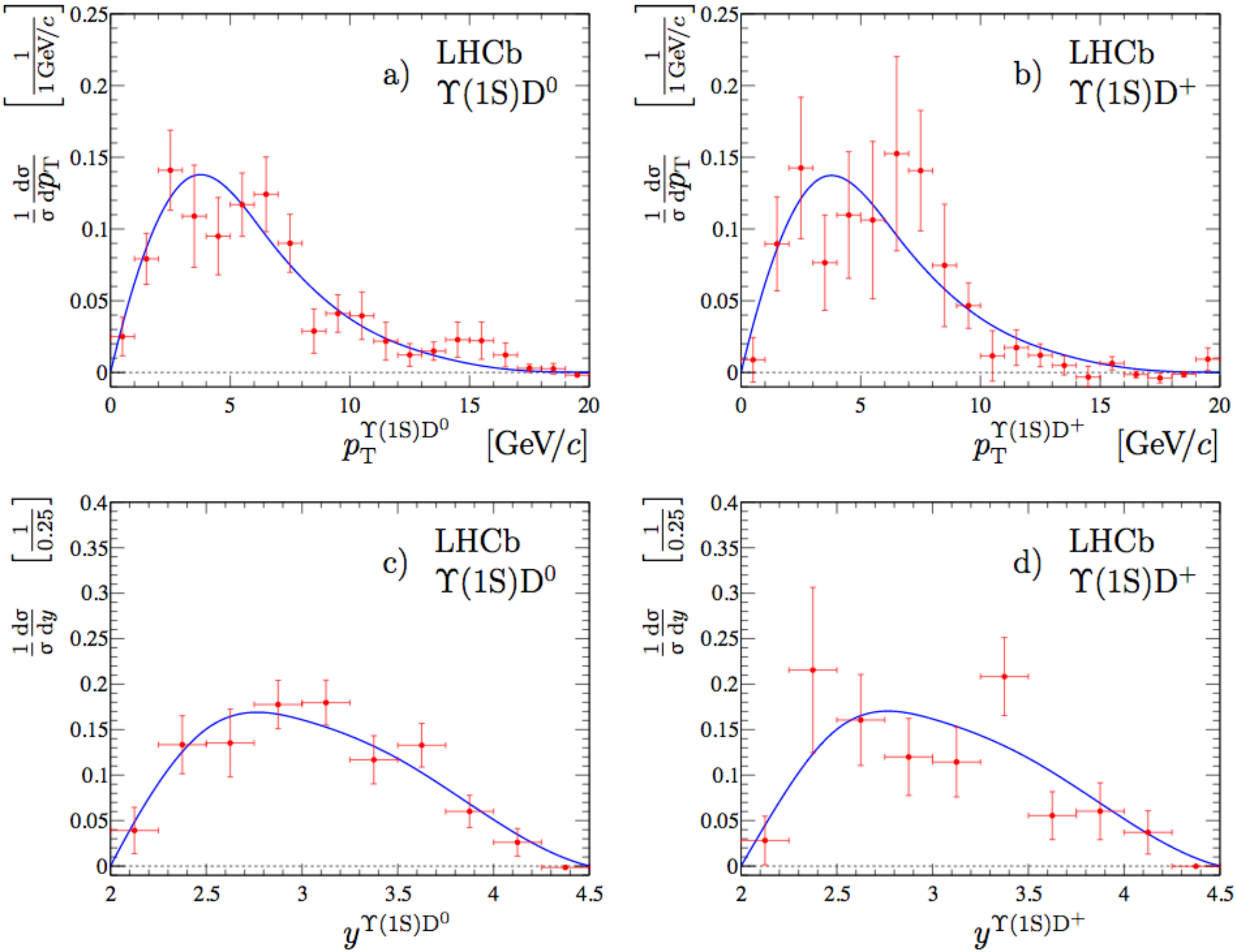
Charm p_T distributions similar to inclusive ones

Double detached J/ψ



- Two beauty hadrons are correlated
- Production from gluon splitting not large
- Consistent with Pythia and POWHEG

$\Upsilon + D$



- Distribution consistent with that produced from uncorrelated Υ and D production