Modified NRQCD and Charmonia

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Introduction

- Non-Relativistic QCD (NRQCD) (Bodwin, Braaaten and Lepage, Phys. Rev. D **51**, 1125 (1995)), as an effective theory approach to the study of quarkonia, met with considerable success in predicting production cross-sections.
- The predictions that exploit the heavy-quark symmetry of the NRQCD Lagrangian viz. polarization of the quarkonium state produced at high-p_T and the η_c cross-section, are both in serious conflict with the experimental results.
- This suggests that a modification of NRQCD is called for.

Colour-octet states

- The precursor to NRQCD was the colour-singlet model (Baier, Rückl, Z. Phys. C **19**, 251 (1983)) where from the short-distance amplitude of the production of the $Q\bar{Q}$ pair, a colour-singlet state with the correct ${}^{2S+1}L_J$ quantum numbers is projected out.
- A similar deployment of projection-operators in NRQCD yields both colour-singlet and colour-octet quarkonium states.
- The colour-singlet or colour-octet state then makes the appropriate non-perturbative transition to the physical quarkonium state.

Perturbative soft gluons

- The colour-octet $c\bar{c}$ state can radiate several soft *perturbative* gluons.
- In the multiple emissions that the colour-octet state can make before it makes the final NRQCD transition to a quarkonium state, the angular momentum and spin assignments of the $c\bar{c}$ state changes constantly.
- We make the assumption that the soft gluon transitions mix only the S and P states. We neglect the higher angular momentum states.
- We also asumme that all the transition probabilities are equal.
- We also note that in the process of making these transitions an octet state can sometimes also transition to a singlet state.

The modified formula

- The formula for the production cross-section of a quarkonium state is then given by

$$\begin{aligned}\sigma_{J/\psi} &= \left[\hat{F}_{^3S_1^{[1]}} \times \langle\mathcal{O}(^3S_1)^{[1]})\rangle\right] \\ &+ \left[\hat{F}_{^3S_1^{[8]}} + \hat{F}_{^1P_1^{[8]}} + \hat{F}_{^1S_0^{[8]}} + (\hat{F}_{^3P_J^{[8]}})\right] \times (\frac{\langle\mathcal{O}(^3S_1)^{[1]}}{8})\rangle \\ &+ \left[\hat{F}_{^3S_1^{[8]}} + \hat{F}_{^1P_1^{[8]}} + \hat{F}_{^1S_0^{[8]}} + (\hat{F}_{^3P_J^{[8]}})\right] \times \langle\mathcal{O}\rangle, \qquad (1)\end{aligned}$$

- Armed with the above formula, we will try to first check what predictions result for the cross-sections of the J/ψ, ψ' and χ_c states.

J/ψ and ψ' at the Tevatron

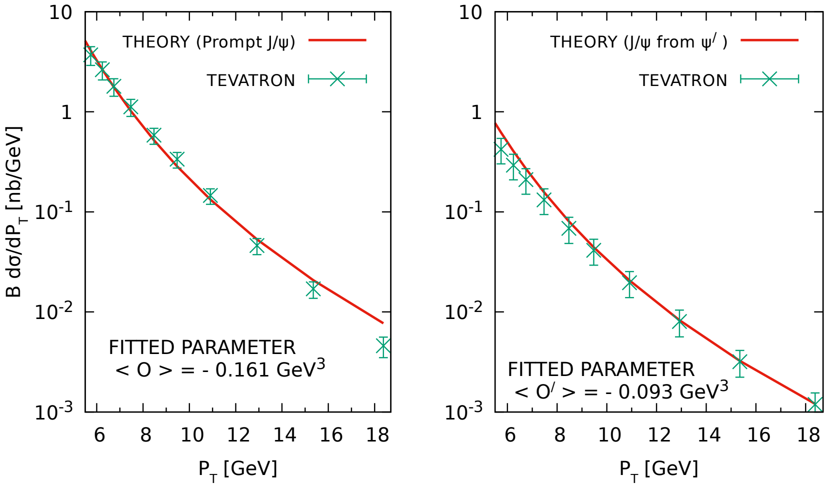
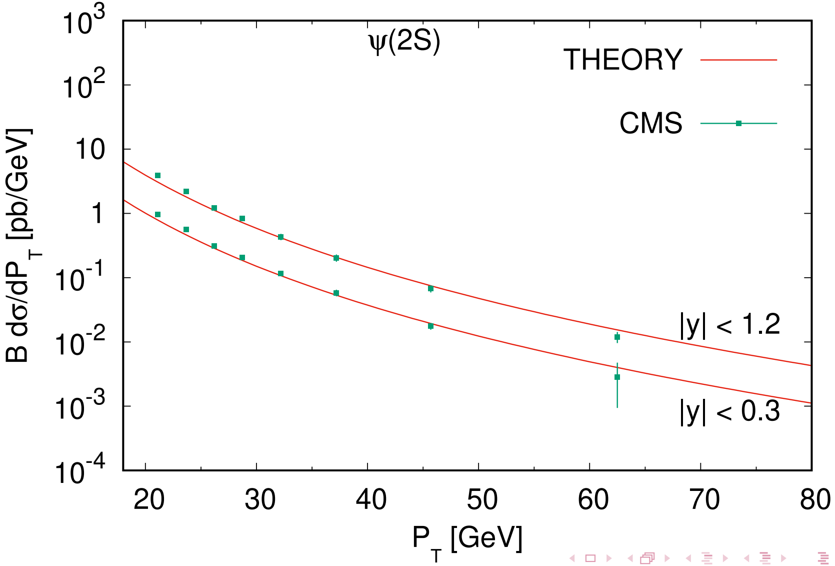


Figure: *Fit to the J/ψ and ψ' cross-sections at the Tevatron - CDF.*

ψ' at the LHC



χ_c at the Tevatron

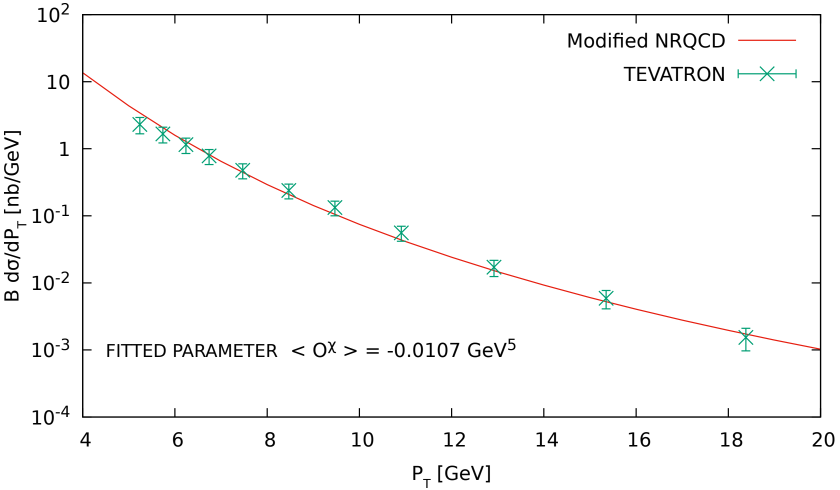


Figure: *Fit to the χ_c cross-section at the Tevatron - CDF.*

J/ψ at the LHC

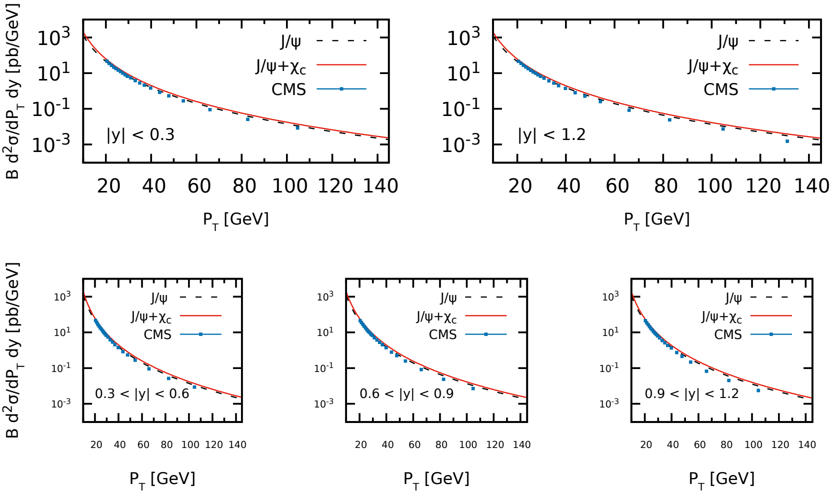


Figure: *Prediction for the J/ψ cross-section at the LHC - CMS.*

χ_c at the LHC

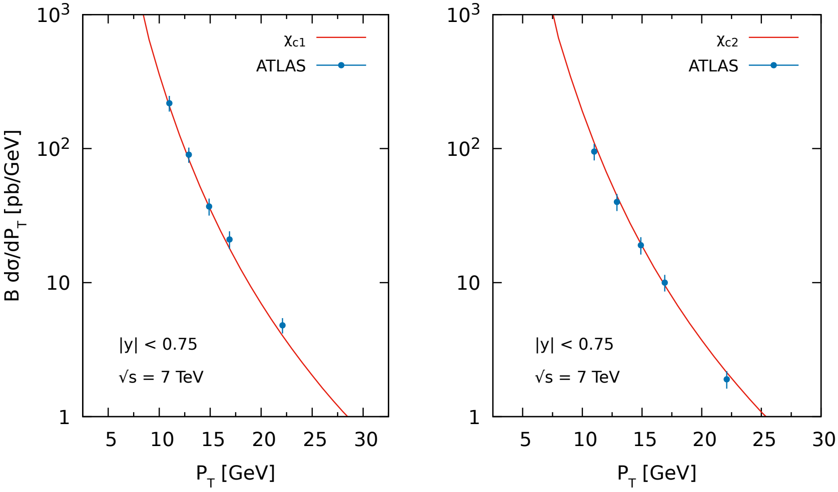


Figure: *Prediction for the χ_c cross-section at the LHC - ATLAS.*

η_c at the LHC - I

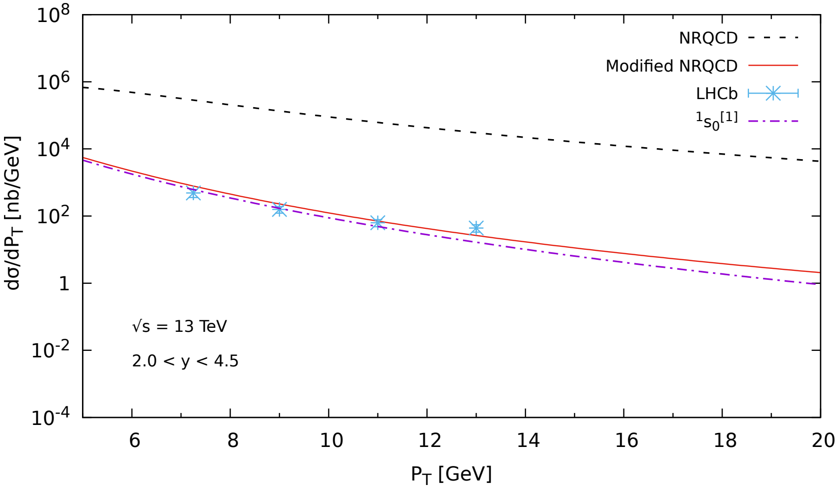


Figure: *Prediction for the η_c cross-section at the LHC - LHCb 13 TeV.*

η_c at the LHC - II

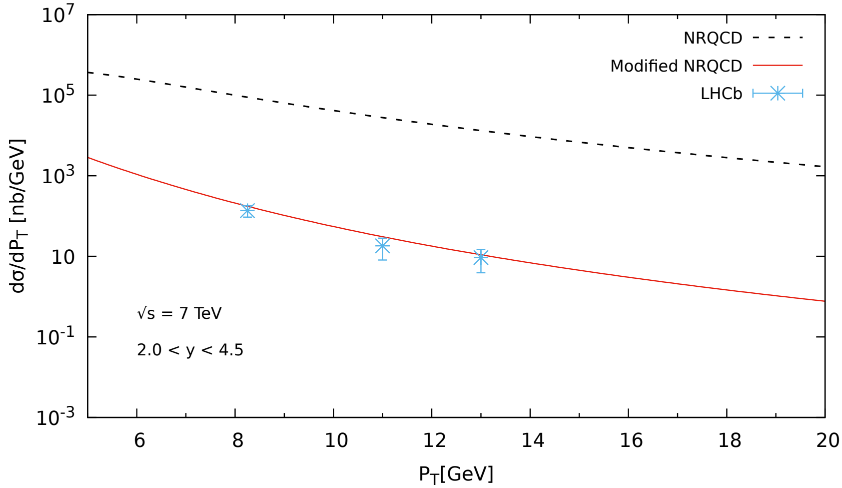


Figure: *Prediction for the η_c cross-section at the LHC - LHCb 7 TeV.*

η_c at the LHC - III

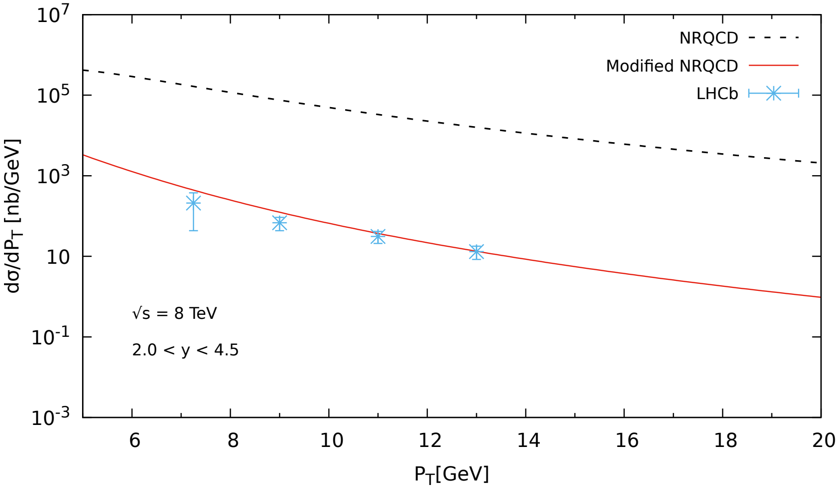


Figure: *Prediction for the η_c cross-section at the LHC - LHCb 8 TeV.*

η_c to J/ψ ratio at the LHC

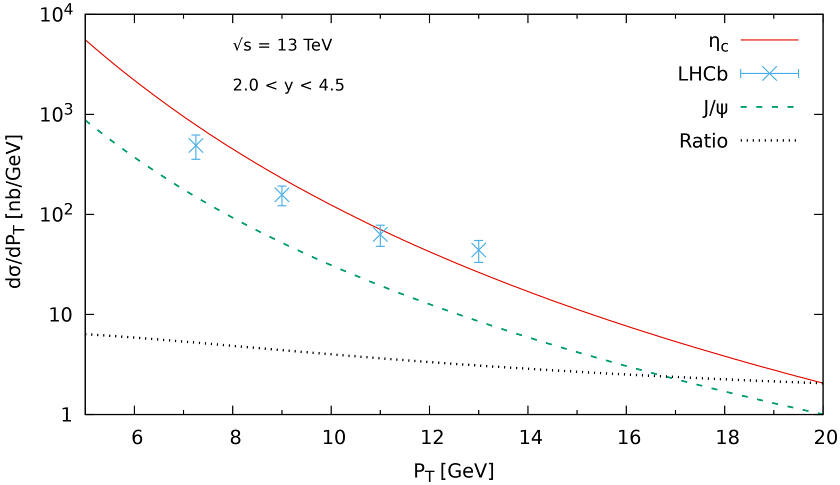


Figure: *Prediction for the η_c to J/ψ cross-section ratio at the LHC - LHCb 13 TeV.*

References

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- S. S. Biswal, S. S. Mishra and K. Sridhar, *χ_c production in modified NRQCD* [arXiv:2206.15252 [hep-ph]]. To be published.
- S. S. Biswal, S. S. Mishra and K. Sridhar, *Resolving the LHCb η_c anomaly using modified NRQCD*. Draft in preparaation.