Modified NRQCD, Charmonium Production and the Resolution of the LHCb η_c anomaly

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September 4, 2023

NRQCD

- 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.
- NRQCD is derived from the QCD Lagrangian by neglecting all states of momenta much larger than the heavy quark mass, M_Q and to account for this exclusion by adding new interaction terms yielding the effective Lagrangian.

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.

NRQCD Factorisation

- In NRQCD, the following factorised form of the cross-section is obtained:

$$\sigma(J/\psi) \; = \sum_{n=\{\alpha,S,L,J\}} \frac{F_n}{M^{d_n-4}} \langle \mathcal{O}_n^{J/\psi}({}^{2S+1}L_J) \rangle, \qquad (1)$$

Where F_i's refer to the short-distance co-efficients and $\mathcal{O}$ refers to the non-perturbative matrix elements and M is the mass of the J/ψ.

Fock decomposition

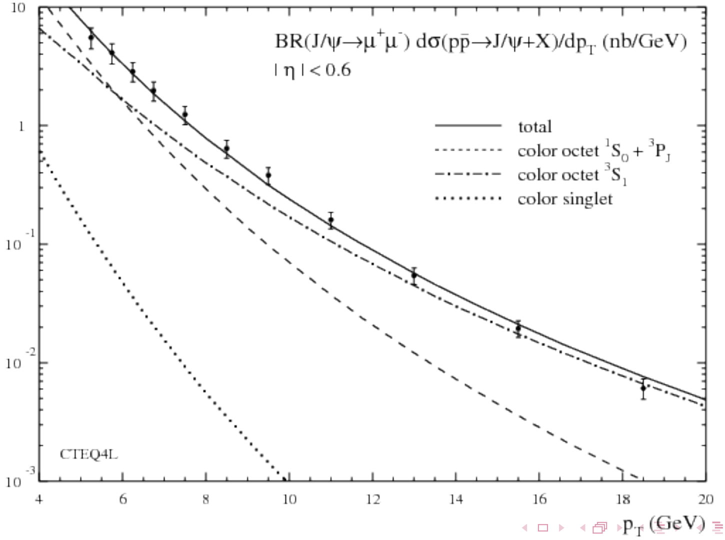
- The quarkonium state admits of a Fock-state expansion in orders of v.

$$|J/\psi\rangle = \mathcal{O}(1)\left|Q\bar{Q}[^3S_1^{[1]}]\right\rangle + \mathcal{O}(v^2)\left|Q\bar{Q}[^3P_J^{[8]}]\,g\right\rangle + \mathcal{O}(v^4)\left|Q\bar{Q}[^1S_0^{[8]}]\,g\right\rangle + \mathcal{O}(v^4)\left|Q\bar{Q}[^3S_1^{[8]}]\,gg\right\rangle + \cdots \quad (2)$$

The J/ψ cross section

$$
\begin{aligned}
\sigma_{J/\psi} &= \hat{F}_{{}^3S_1^{[1]}} \times \langle \mathcal{O}({}^3S_1)^{[1]}) \rangle \\
&+ \hat{F}_{{}^3S_1^{[8]}} \times \langle \mathcal{O}({}^3S_1)^{[8]}) \rangle \\
&+ \hat{F}_{{}^1S_0^{[8]}} \times \langle \mathcal{O}({}^1S_0)^{[8]}) \rangle \\
&+ \left[\hat{F}_{{}^3P_J^{[8]}} \times \langle \mathcal{O}({}^3P_J)^{[8]} \rangle \right] / M^2
\end{aligned} \tag{3}
$$

J/ψ at the Tevatron



The problems

- 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.

η_c at the LHCb

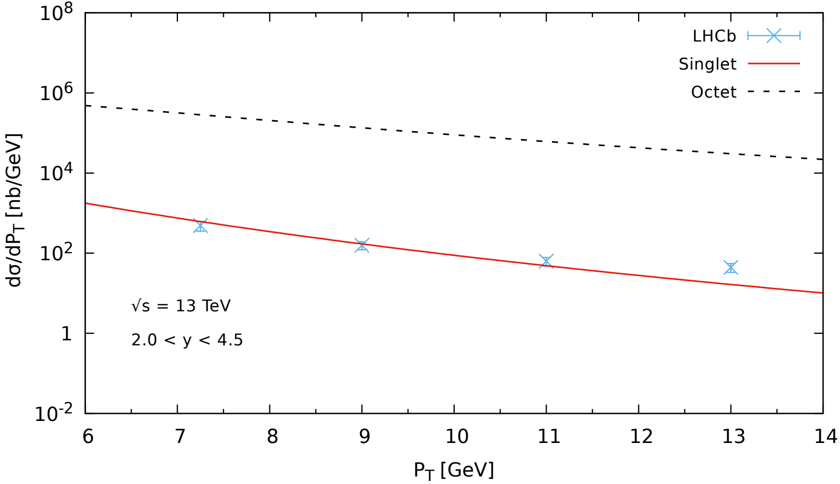


Figure: *The LHCb η_c anomaly*

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

$$\begin{aligned}\sigma_{J/\psi} &= \left[\hat{F}_{{}^3S_1^{[1]}} \times \langle \mathcal{O}({}^3S_1)^{[1]})\rangle\right] \\ &+ \left[\hat{F}_{{}^3S_1^{[8]}} + \hat{F}_{{}^1P_1^{[8]}} + \hat{F}_{{}^1S_0^{[8]}} + (\hat{F}_{{}^3P_J^{[8]}})\right] \times (\frac{\langle \mathcal{O}({}^3S_1)^{[1]}}{8}))\rangle \\ &+ \left[\hat{F}_{{}^3S_1^{[8]}} + \hat{F}_{{}^1P_1^{[8]}} + \hat{F}_{{}^1S_0^{[8]}} + (\hat{F}_{{}^3P_J^{[8]}})\right] \times \langle \mathcal{O}\rangle, \end{aligned} \quad (4)$$

- 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

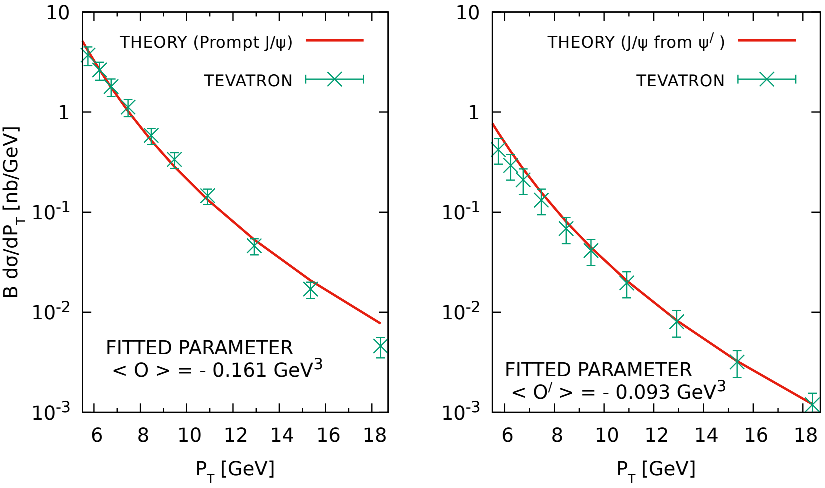
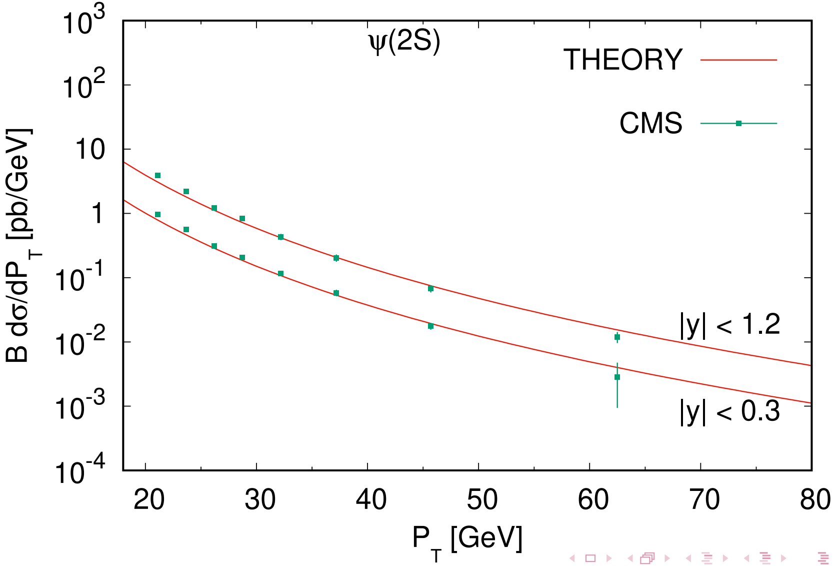


Figure: *Fit to the J/ψ and ψ' cross-sections at the Tevatron - CDF.*

ψ' at the LHC



χ_c at the Tevatron

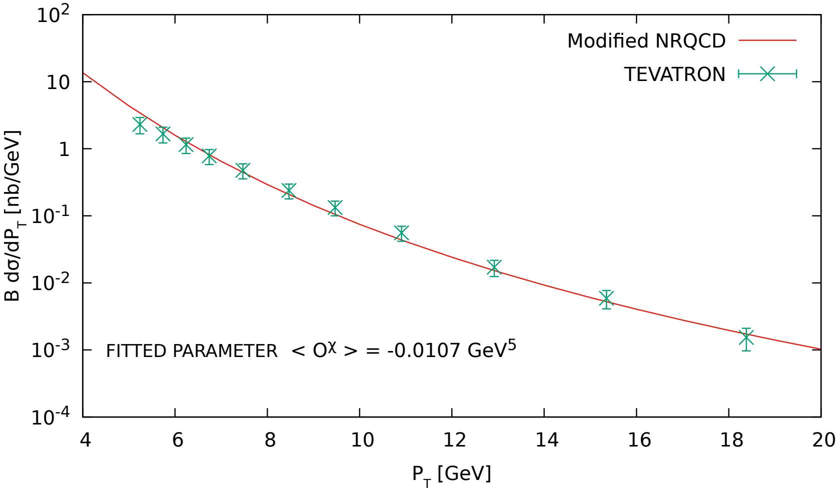


Figure: *Fit to the χ_c cross-section at the Tevatron - CDF.*

J/ψ at the LHC

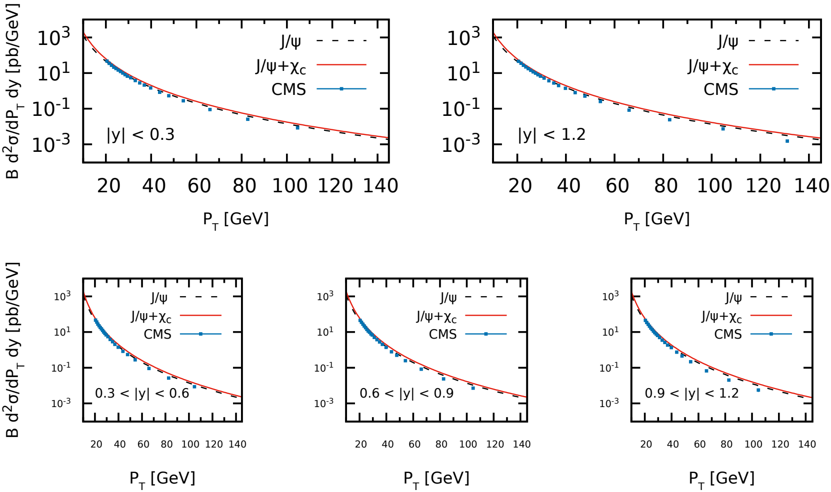


Figure: *Prediction for the J/ψ cross-section at the LHC - CMS.*

χ_c at the LHC

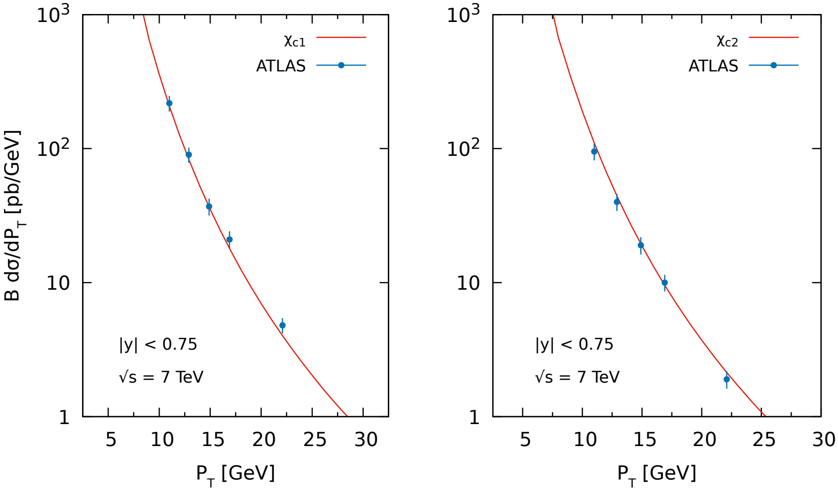


Figure: *Prediction for the χ_c cross-section at the LHC - ATLAS.*

η_c at the LHC - I

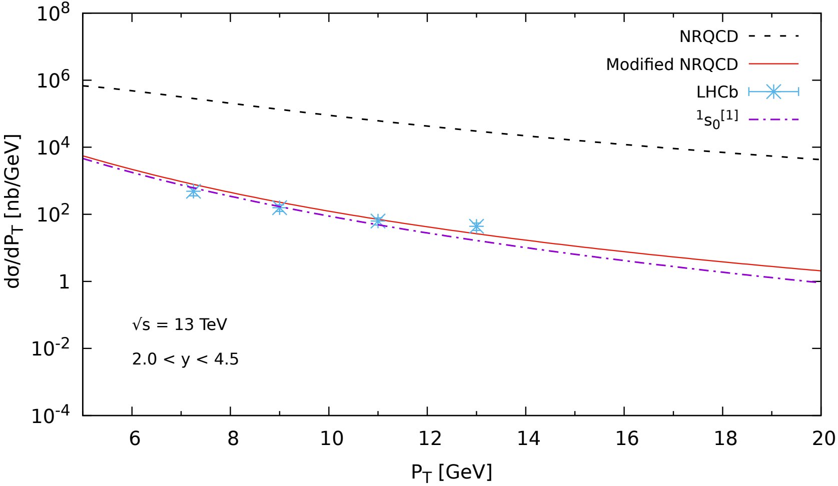


Figure: *Prediction for the η_c cross-section at the LHC - LHCb 13 TeV.*

η_c at the LHC - II

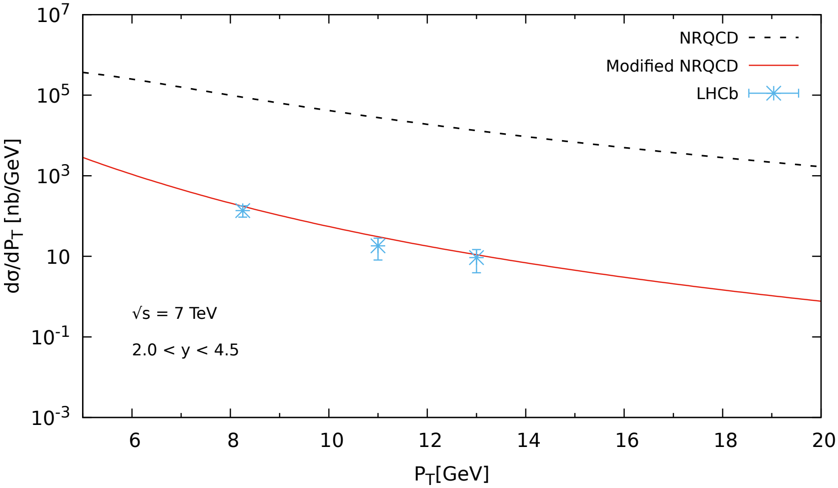


Figure: *Prediction for the η_c cross-section at the LHC - LHCb 7 TeV.*

η_c at the LHC - III

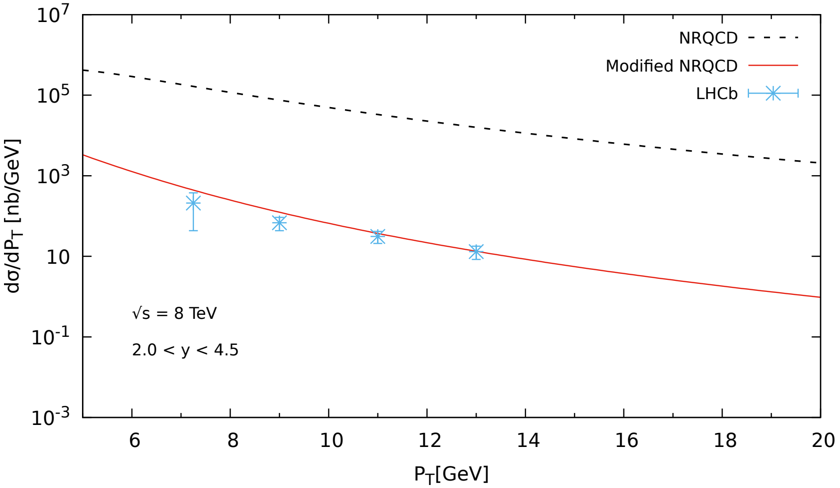


Figure: *Prediction for the η_c cross-section at the LHC - LHCb 8 TeV.*

η_c to J/ψ ratio at the LHC

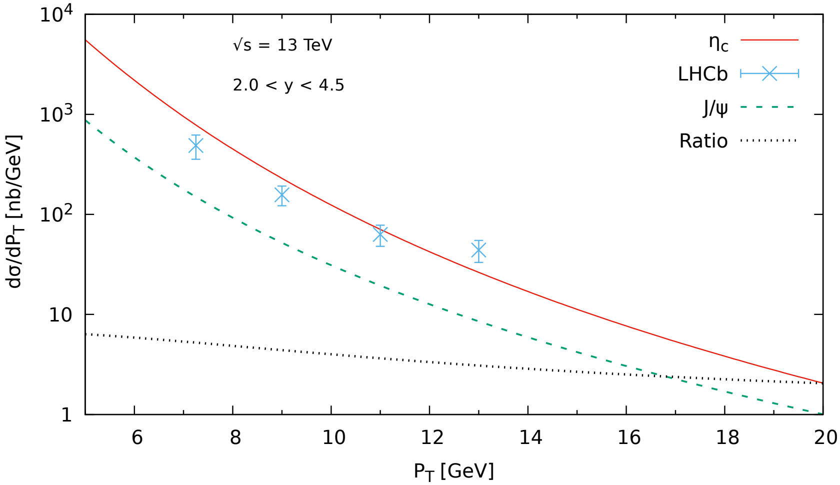


Figure: *Prediction for the η_c to J/ψ cross-section ratio at the LHC - LHCb 13 TeV.*

$\Upsilon(1S)$ at the LHC

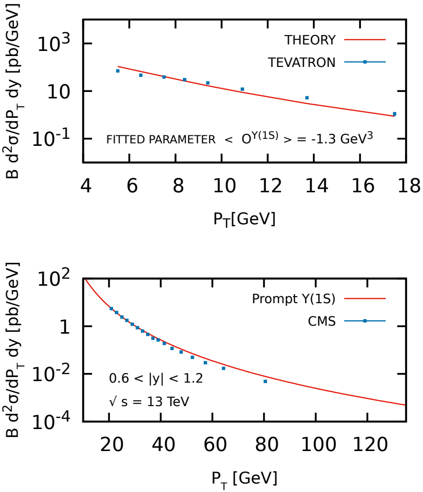


Figure: *Prediction for $\Upsilon(1S)$ production at the LHC - CMS 13 TeV.*

$\Upsilon(2S)$ at the LHC

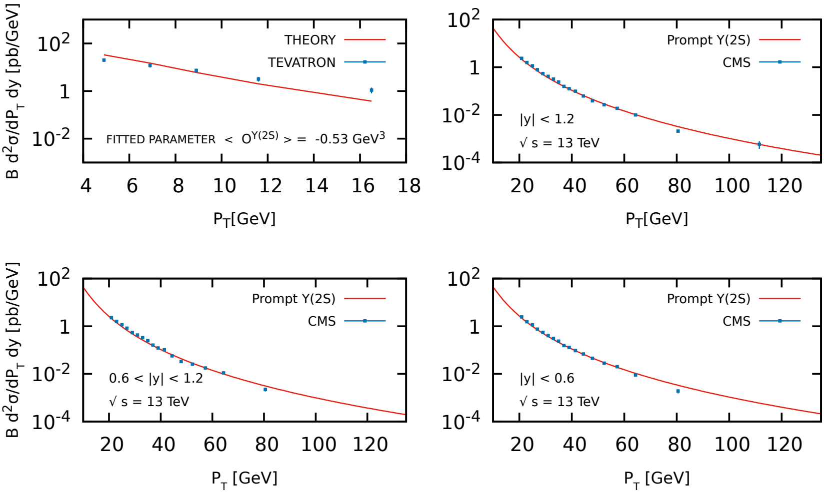


Figure: *Prediction for $\Upsilon(2S)$ production at the LHC - CMS 13 TeV.*

$\Upsilon(3S)$ at the LHC

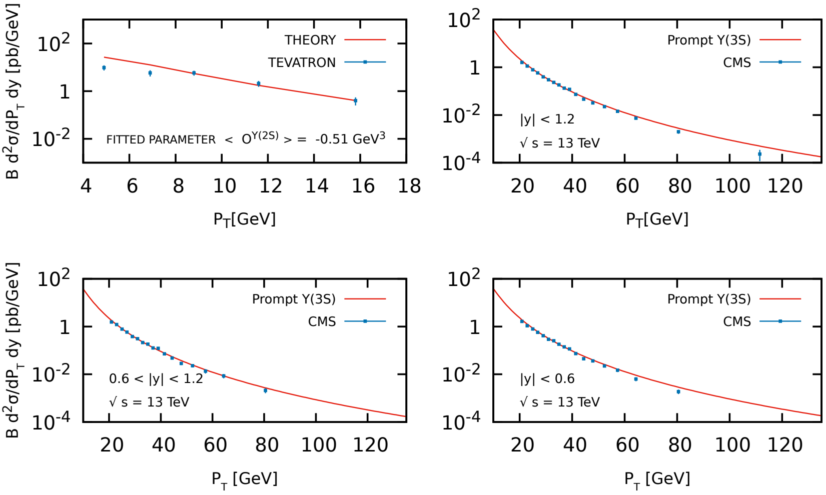


Figure: *Prediction for $\Upsilon(3S)$ production at the LHC - CMS 13 TeV.*

η_b at the LHC

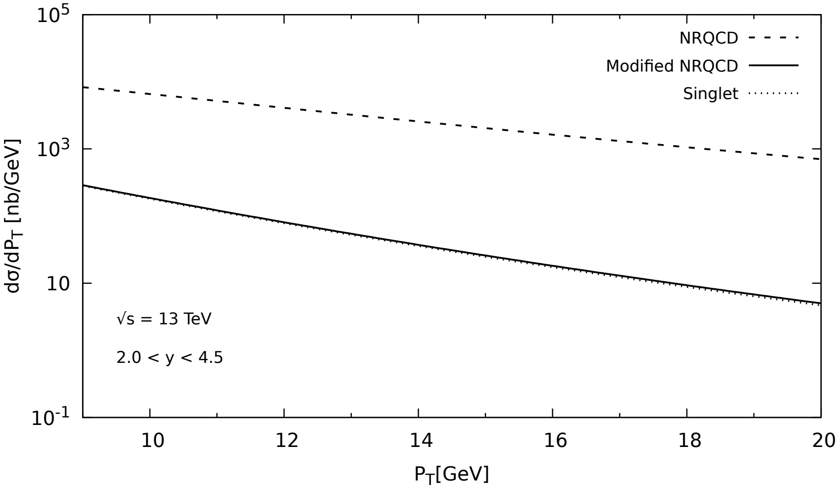


Figure: *Prediction for η_b production at the LHC 13 TeV.*

References

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