Heavy-Hadrons Photoproduction at LHC Energies

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Abstract

Heavy-quarkonium systems provide a fertile ground for testing effective field Theories of Quantum Chromodynamics (QCD), with Non-Relativistic Quantum Chromodynamics (NRQCD) playing a crucial role in factorizing short-distance dynamics coefficients (SDC) from long-distance matrix elements (LDME). The recent observation of new structures in the $J/\psi J/\psi$ invariant mass spectrum [2], raises the question: Can these states be efficiently produced in photon-mediated interactions at the LHC? This work investigates the inclusive photoproduction of fully charmed tetraquark state T_{4c} treated as compact bound systems within the NRQCD framework, and explore the experimental feasibility in ultraperipheral collisions.

Background

In ultraperipheral collisions, the cross section for T_{4c} production can be factorized as the product of the equivalent photon flux of the nuclear Pb projectile and the γp cross section (a diagram can be seen in Figure 1). The minimum momentum fraction of the photon is given by $x_\gamma^{\text{min}} = \frac{M_T^2 - zM_{T_{4c}}^2}{sz(1-z)}$, within the photon flux determined within the framework of the Equivalent Photon Approximation (EPA)[1]:

$$f_{\gamma/Pb}(x_\gamma) = \frac{Z^2\alpha_{\text{em}}}{\pi x_\gamma}\left[2\eta K_0(\eta)K_1(\eta) + -\eta^2\left(K_1^2(\eta) - K_0^2(\eta)\right)\right], \quad (1)$$

where $\eta = x_\gamma m_p b$ depends on the proton mass, m_p and the impact parameter b. Using the EPA, one can express the inclusive production rate of the T_{4c} as

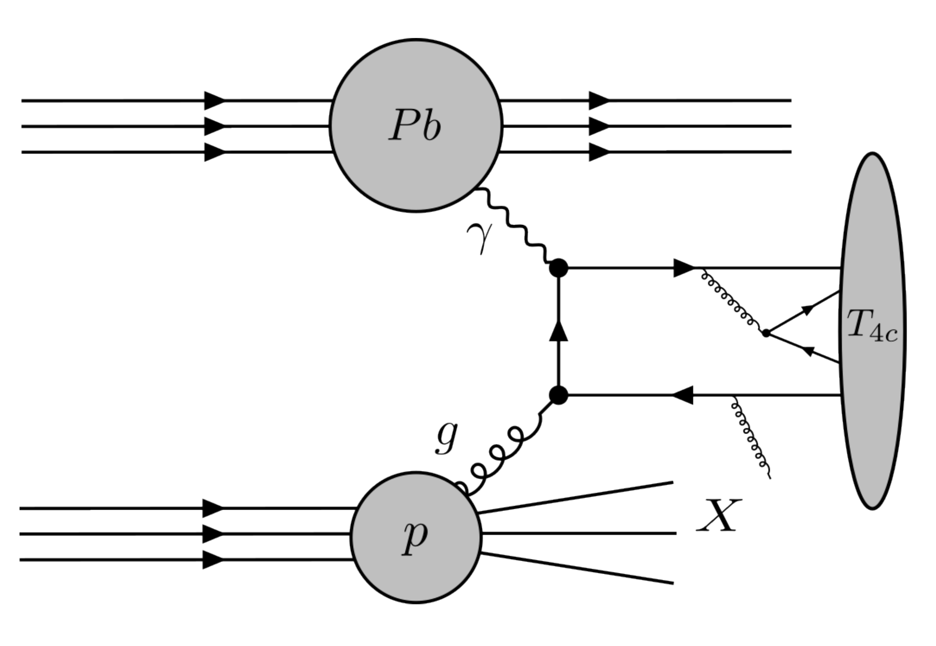
$$\frac{\mathrm{d}\sigma}{\mathrm{d}z\,\mathrm{d}p_T} = \sum_i \int_{x_\gamma^{\text{min}}}^{1} \mathrm{d}x_\gamma \, \frac{2x_i p_T}{z(1-z)} f_{\gamma/Pb}(x_\gamma) \times \times f_{i/p}(x_i,\mu)\frac{\mathrm{d}\hat{\sigma}^{(\gamma+i\to T_{4c}+X,\mu)}}{\mathrm{d}\hat{t}}, \quad (2)$$

where $i = g$, represents the parton in standard QCD, p_T denotes the T_{4c} transverse momentum and $f_{i/p}$ is the parton distribution function (PDF) that describes the probability of finding a parton i with a given momentum fraction of the proton. The PDF will be evaluated using CTEQ6LO parametrization, assuming $\mu = M_T$. Due to charm quark mass ($m_c = 1.5$ GeV), the partonic cross section $\mathrm{d}\hat{\sigma}\,/\,\mathrm{d}\hat{t}$ in (2) factorizes into perturbative SDC coefficients and an LDME matrix elements associated with hadronization, these matrix elements must be estimated through a phenomenological potential model. The NRQCD factorization is expressed as (3)

$$\frac{\mathrm{d}\hat{\sigma}(\gamma g \to T_{4c}^{(1)} + X, \mu)}{\mathrm{d}\hat{t}} = \frac{2M_{T_{4c}}}{m_c^{14}} F_{3,3}^{(1)}(\hat{s},\hat{t}) \left\langle O_{3,3}^{(1)} \right\rangle. \quad (3)$$

Here, the perturbative SDC coefficients $F_{3,3}^{(1)}(\hat{s},\hat{t})$ are provided in an asymptotic form, and the LDME matrix elements $\left\langle O_{3,3}^{(1)} \right\rangle$ have been estimated for two models given by [3]: **Model-I** $= 0.078\text{GeV}^9$ and **Model-II** $= 0.011\text{GeV}^9$.

Figure-1: Diagram for T_{4c}



Results

- In Figure 2, we observe high T_{4c} production in low transverse momentum.
- For comparison, we plot the p_T distribution of the T_{4c} for the LHC and HERA (Figure 3), where the LHC curve is an order of magnitude higher, reflecting the stronger photon flux from Pb and the higher center-of-mass energy, which enhance the photoproduction cross section.
- In Figure 4, we presents our results for the rapidity distribution of T_{4c} production in proton-lead collisions at LHC energies. As expected, we have an asymmetric distribution around $Y = 0$. By integrating these distribution, we obtain the total cross section and event rates per year, as show in Table 1.
- We also estimated the integrated production rates and obtained a substantial event yield for the T_{4c} (shown in Table 1), indicating that its production is significant in the considered energy regime.

Figure-2: p_T Distribution

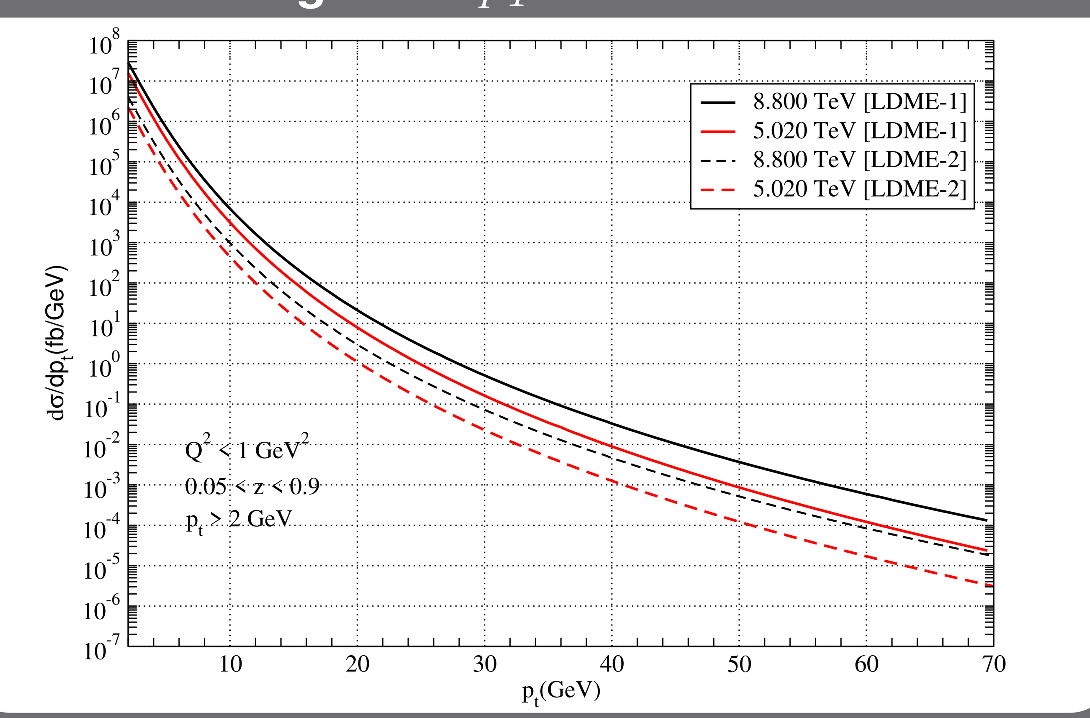


Figure-3: HERA Comparison

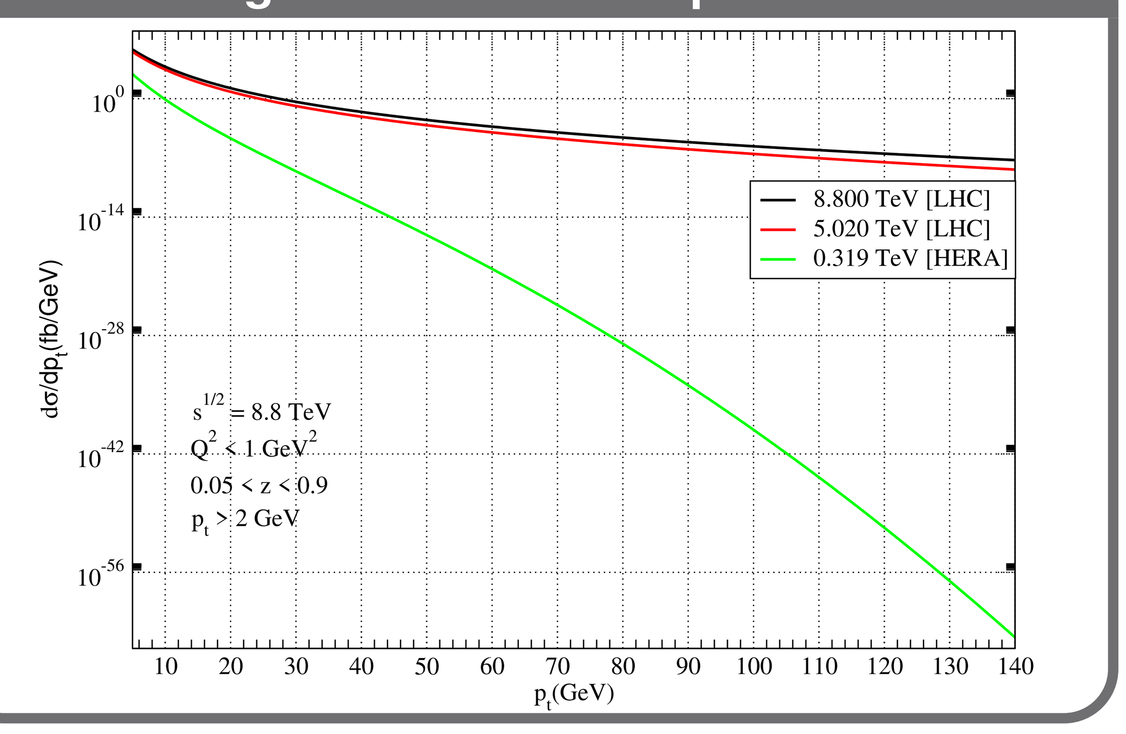


Figure-4: Y Distribution

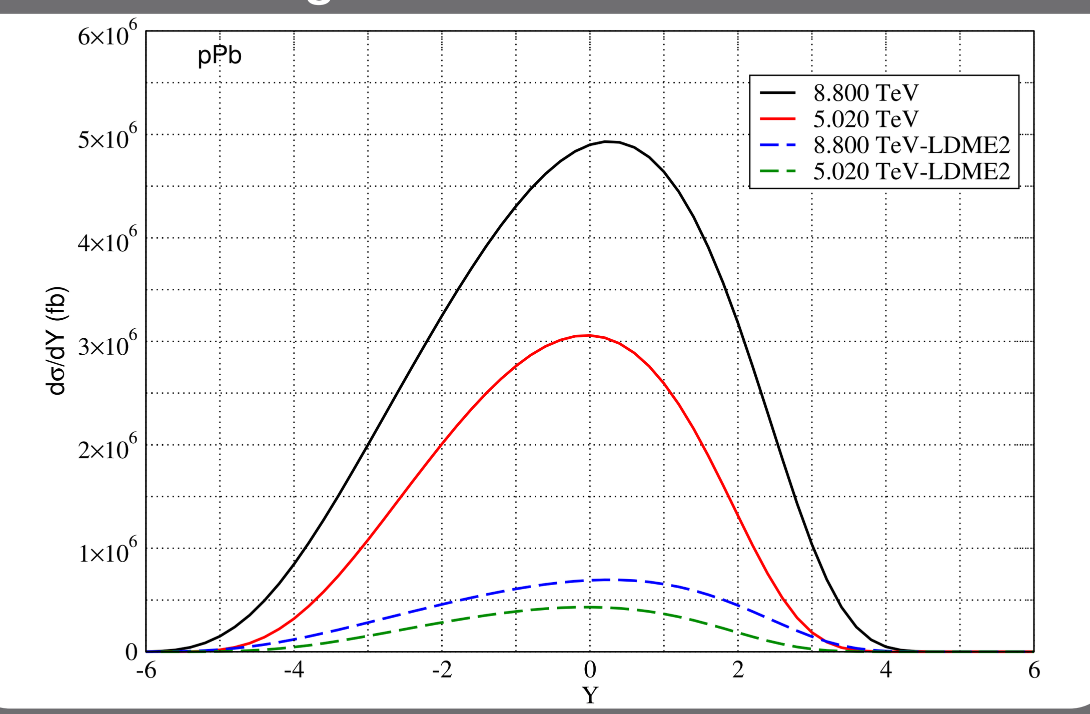


Table-1: Event Rates N

			Model I		Model II	
	$\sqrt{s}$ [TeV]	$\mathcal{L}$	σ [fb]	N	σ [fb]	N
LHC	5,020	10 nb^{-1}	$1,335 \times 10^7$	$1,335 \times 10^2$	$1,882 \times 10^6$	$18,82$
	8,800	1 pb^{-1}	$2,435 \times 10^7$	$2,435 \times 10^4$	$3,4341 \times 10^6$	$3,4341 \times 10^3$

Conclusion

The T_{4c} photoproduction mechanism in ultraperipheral collisions at LHC energies can be studied within the NRQCD framework, with significant production rates enabled by the collider high luminosity. These results show that the experimental study of T_{4c} at LHC energies is, in principle, feasible.

Ongoing Efforts

For a more comprehensive analysis, we plan to incorporate the lead nuclear PDF (nCTEQ) in future studies to achieve a complete analysis of T_{4c} production.

KEY REFERENCES

[1] V P Gonçalves et al. In: *Journal of Physics G: Nuclear and Particle Physics* 32.3 (Jan. 2006), pp. 295–308.

[2] CMS collaboration et al. In: *Phys. Rev. Lett.* 132 (11 Mar. 2024), p. 111901.

[3] Feng Feng et al. In: *Phys. Rev. D* 110 (5 Sept. 2024), p. 054007.

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