Associated J/ψ and photon production in the Parton Reggeization approach at high energy

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ICPPA-2024

Introduction

The experimental study of associated production of $J/\psi\gamma$ in pp collisions is of considerable interest

- for verifying predictions of perturbative quantum chromodinamics (QCD) and various models of heavy quark hadronization into heavy quarkonium;
- to obtain information about the gluon parton distribution function (PDF), including the transverse momentum dependent (TMD) gluon PDF.

At the high transverse momentum, $p_{T\psi} \gg m_\psi$

- the initial parton transverse momentum may be neglected, is able to use collinear parton model CPM.

At the low transverse momentum $p_{T\psi} \ll m_\psi$

- the approach must be depended on a non-perturbative transverse momenta of initial partons. It is able to use the TMD factorization approach, well-know as TMD parton model.

At the intermediate range of transverse momenta $p_{T\psi} \simeq m_\psi$

- It is able to use different methods of CPM and TMD predictions merging.

  There is another way at high energy — Parton Reggeization Approach (PRA)

PRA

- Parton Reggeization approach (PRA) is a scheme of k_T-factorization, which is based on modified multi-Regge kinematic's (mMRK) approximation of the QCD. The Reggeized parton amplitudes are described by the Lipatov's gauge invariant effective field theory (EFT). [L.N. Lipatov (1995)].
  The cross section is written as a convolution:

$$d\sigma(pp \to J/\psi\gamma) = \sum_{a,b} \int_0^1 \frac{dx_1}{x_1} \int \frac{d^2 q_{1T}}{\pi} \Phi_a(x_1, q_{1T}^2, \mu^2) \int_0^1 \frac{dx_2}{x_2} \int \frac{d^2 q_{2T}}{\pi} \Phi_b(x_2, q_{2T}^2, \mu^2) \times d\hat{\sigma}(ab \to J/\psi\gamma)$$

where a, b are parton types in parton sub-processes $a = g, s, u, d$; $b = g, \bar{s}, \bar{u}, \bar{d}$.

- The parton cross section of the sub-process $a(q_1) + b(q_2) \to J/\psi(p) + \gamma(k)$ is written in a standard way

$$d\hat{\sigma}(ab \to J/\psi\gamma) = (2\pi)^4 \delta^{(4)}(q_1 + q_2 - p - k) \frac{\overline{|M|^2}_{PRA}}{2x_1 x_2 s} \frac{d^3 p}{(2\pi)^3 2p^0} \frac{d^3 k}{(2\pi)^3 2k^0}$$

- $\Phi_{a,b}(x, q_T^2, \mu^2)$ is modified Kimber-Martin-Ryskin-Watt (mKMRW) PDFs with exact normalization.
  [M. A. Nefedov, V. A. Saleev (2020)]

$$\int_0^{\mu^2} dq_T^2 \Phi_{a,b}(x, q_T^2, \mu^2) = x f_{a,b}(x, \mu^2)$$

NRQCD

- The quarkonium wave function can be written as a series expansion in terms of the relative velocity of quarks $\upsilon^2 \sim 0.2 - -0.3$ using orthogonal color-singlet/octet states wavefunctions.
[G. T. Bodwin, E. Braaten, G. P. Lepage (1995)]
$$|J/\psi\rangle = \mathcal{O}(\upsilon^0)|c\bar{c}[^3S_1^{(1)}]\rangle + \mathcal{O}(\upsilon)|c\bar{c}[^3P_J^{(8)}]g\rangle + \mathcal{O}(\upsilon^2)|c\bar{c}[^1S_0^8]g\rangle + \ldots$$
- Then, the heavy quarkonium production cross section can be written as the sum of the subprocess cross sections multiplied by a Long-Distance Matrix Elements (LDMEs). $N_{col} = 2N_c, N_c^2 - 1$ for color-singlet and color-octet states accordingly; $N_{pol} = 2J + 1$.
$$d\hat{\sigma}(ab \to J/\psi\gamma) = \sum_n d\hat{\sigma}(ab \to c\bar{c}[^{2S+1}L_J^{(1,8)}]\gamma) \times \frac{\langle \mathcal{O}^{J/\psi}[^{2S+1}L_J^{(1,8)}]\rangle}{N_{col}N_{pol}}$$
- A special case is the Color Singlet Model (CSM), which takes into account only the general contribution from the color singlet state
$$d\hat{\sigma}(ab \to J/\psi\gamma) = d\hat{\sigma}(ab \to c\bar{c}[^3S_1^{(1)}]\gamma) \times \frac{\langle \mathcal{O}^{J/\psi}[^3S_1^{(1)}]\rangle}{6N_c}$$
- $\langle \mathcal{O}^{J/\psi}[^3S_1^{(1)}]\rangle = 1.3\ GeV^3$ is calculated in the potential model or extracted from decay width $\Gamma(J/\psi \to \mu^+\mu^-)$, but color-octet LDMEs are model dependent. Color-octet LDMEs were extracted from single J/ψ production data in the PRA.
[M. A. Nefedov, V. A. Saleev, A. V. Shipilova (2013)]

ICEM

- In the Improved Color Evaporation Model (ICEM) the cross section for the associated production of J/ψ and direct photon is related to the cross section for the associated production of $c\bar{c}$-pair and direct photon in the Single Parton Scattering (SPS) as follows:

$$d\hat{\sigma}(ab \to J/\psi\gamma) \simeq \mathcal{F}^{\psi} \int\limits_{m_\psi}^{2m_D} dM \frac{d\hat{\sigma}(ab \to c\bar{c}\gamma)}{dM}\Big|_{p_T=(M/m_\psi)p_{T\psi}}$$

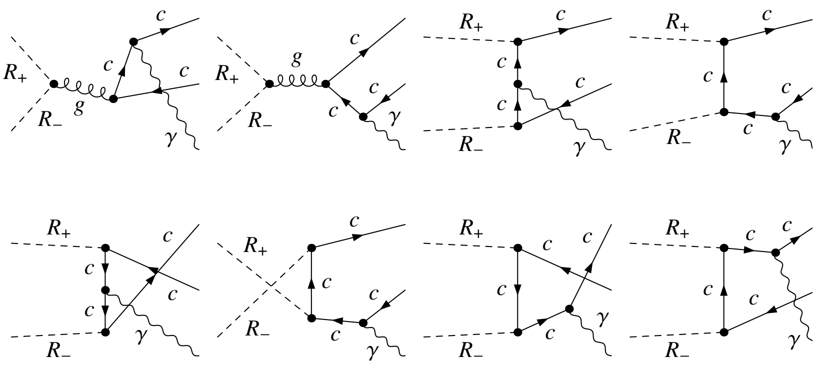
- The phenomenological coefficient $\mathcal{F}^{\psi}$ is associated with the hadronization probability.
  [Y.-Q. Ma, R. Vogt (2016)]

- On the LO PRA, we have only two parton sub-processes, but sub-processes with $q\bar{q}$ initial state is neglectable small then we take into account only $R^+R^- \to c\bar{c}\gamma$.

- $F^{J/\psi} = 0.02$ has been obtained by a fit of the prompt J/ψ production at the LHC.
  [V. A. Saleev, A. A. Chernyshev (2022)]

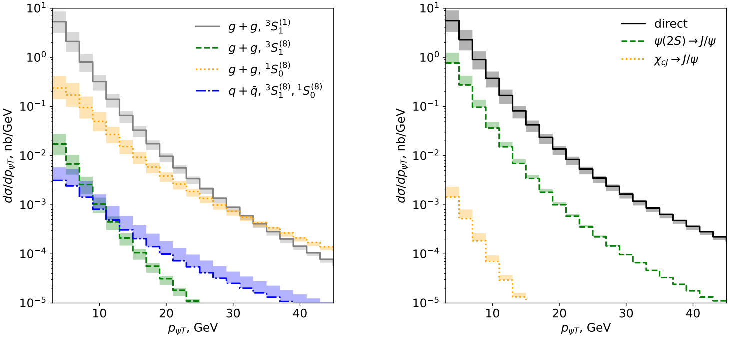
- Another way in the PRA-ICEM calculation is to use Monte-Karlo generator KaTie.
  [A. van Hameren]
  We have done cross check for all calculations in the PRA-ICEM within the KaTie, and find good agreement.

EFT's diagrams



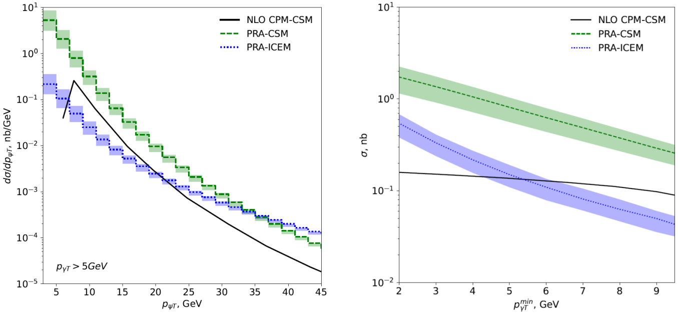
- Amplitudes include effective vertexes and Reggeized gluons in the initial state.
- Set of Feynman diagram are the same for both the NRQCD and the ICEM, but in the NRQCD the $c\bar{c}$ spinors are replaced by a projector with intermediate-state quantum numbers.

NRQCD: color-singlet and color-octet contributions



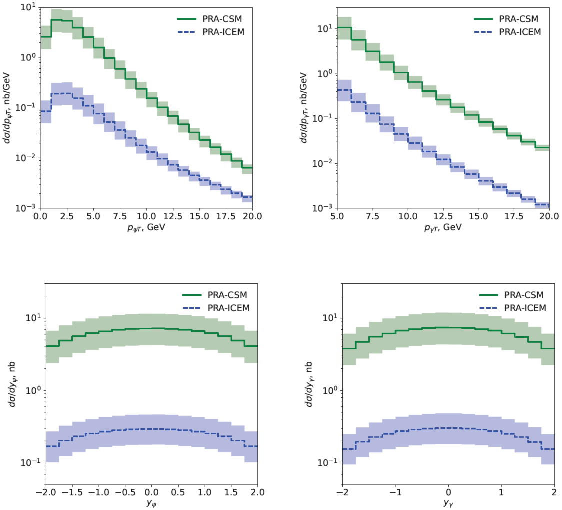
- $p_{T\gamma} > 5\ GeV$; $|y_{J/\psi}|, |y_\gamma| < 3$.
- Contributions from octet states becomes comparable to the singlet state contribution only at $p_{TJ/\psi} > 35\ GeV$ than we used CSM for prediction at $p_{TJ/\psi} < 35\ GeV$.
- The cascade decay are negligible.

NLO CPM vs. PRA



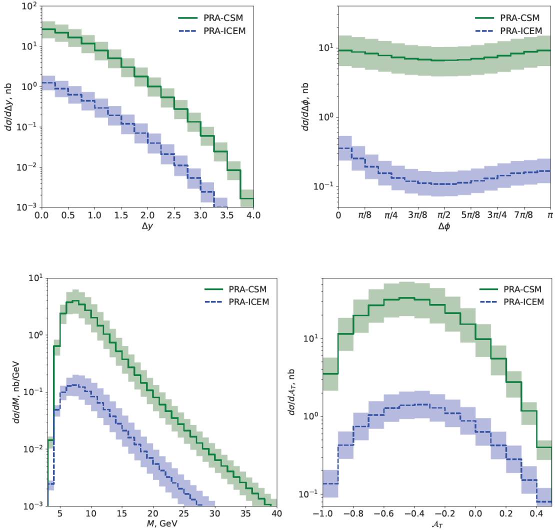
- $|y_{J/\psi}|, |y_\gamma| < 3$.
- NLO CPM-CSM computation [R. Li, J.-X. Wang (2009)]
- Our PRA-CSM calculation slightly overestimated the NLO CPM-CSM cross section. It is interesting because in the single J/ψ production the results obtained in the LO PRA and the NLO CPM using the NRQCD are approximately coincided.
  [A. Karpishkov, M. Nefedov, V. Saleev (2021)].

LHC $\sqrt{s} = 13\ TeV$ predictions



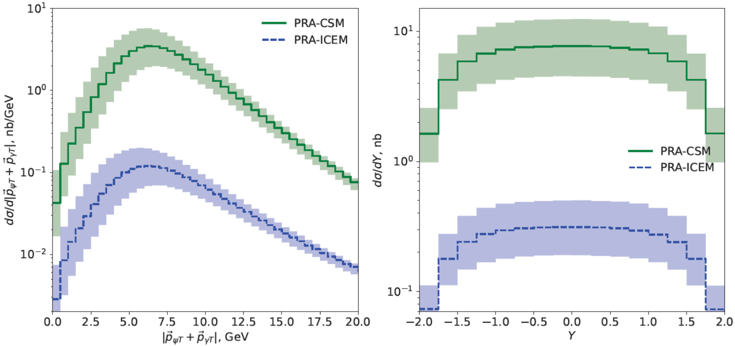
- $p_{T\gamma} > 5\ GeV$; $|y_{J/\psi}|, |y_\gamma| < 2$.
- There are significant disparity in the PRA predictions using different hadronization models.

LHC $\sqrt{s} = 13\ TeV$ predictions



- $p_{T\gamma} > 5\ GeV$; $|y_{J/\psi}|, |y_\gamma| < 2$.
- $\Delta y = |y_{J/\psi} - y_\gamma|$; $\Delta\phi = |\phi_{J/\psi} - \phi_\gamma|$; M is J/ψ and γ pair invariant mass; $\mathcal{A}_T = \frac{p_{TJ/\psi} - p_{T\gamma}}{p_{TJ/\psi} + p_{T\gamma}}$.

LHC $\sqrt{s} = 13\ TeV$ predictions



- $p_{T\gamma} > 5\ GeV$; $|y_{J/\psi}|, |y_\gamma| < 2$.
- Y is J/ψ and γ pair rapidity.

Summary

- We confirm previously obtained result that in the process of the associated J/ψ and direct photon production color-octet contributions can be neglected.
- We can neglect small contribution from the quark-antiquark annihilation processes at the energy $\sqrt{s} = 13 - 14\ TeV$, and the same way, the decay contributions to the associated J/ψ and the direct photon cross sections can be neglected as well.
- Was find surprising sufficient differences in the PRA-CSM and the PRA-ICEM predictions which become large when the $p_{T\gamma}$ increases. So experimental measurements of the J/ψ and large-$p_{T\gamma}$ photon production cross section can be potentially used to distinguish between the ICEM and the NRQCD.

Thank you for your attention!