

# Associated $J/\psi$ and photon production in the Parton Reggeization Approach: SPS and DPS

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# Outline

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## Motivation

Numerous experimental studies on pair production indicate a significant contribution from double parton scattering (DPS). For example:

- ▶ Pair- $J/\psi(\Upsilon)$ ;  $J/\psi\Upsilon$  — [D0 (Phys.Rev.D 2014) (Phys.Rev.Lett. 2016) ] [ATLAS (Eur.Phys.J.C 2017)] [LHCb (JHEP 2017)(Phys.Let.B 2020)]
- ▶  $J/\psi Z(W)$  — [ATLAS (Eur.Phys.J. 2015) (J.High En.Phys. 2014) (JHEP 2020) ] [LHCb (JHEP 2016)(Phys.Lett.B 2018)]
- ▶  $J/\psi(\Upsilon)D$  — [LHCb (JHEP 2016)]

At similar energies, the effective DPS cross-sections are of close values:

- ▶ LHCb Pair- $J/\psi$ ,  $J/\psi\Upsilon$ ,  $\Upsilon\Upsilon$  fit  $\sigma_{eff} = 11.0 \pm 0.2$  mb
- ▶ ATLAS  $W+2$ -jet fit  $\sigma_{eff} = 15$  mb
- ▶ LHCb  $J/\psi D$ ,  $\Upsilon D$  fits  $\sigma_{eff} = 18.0 \pm 1.8$  mb and  $\sigma_{eff} = 15.8 \pm 2.4$  mb respectively.

we used  $\sigma_{eff} = 11$  mb for the associated  $J/\psi\gamma$  production.

## Existing $J/\psi\gamma$ studies

While no measurements of  $J/\psi\gamma$  production cross-sections exist yet, several theoretical predictions have been made:

- ▶ SPS LO CPM  $J/\psi\gamma$  [Drees, Kim (Z. Phys. C 1992)] [Doncheski, Kim (Phys.Rev.D 1994)]
- ▶ SPS LO CPM  $J/\psi\gamma$  [Mehen (Phys.Rev.D 1997)]
- ▶ SPS NLO CPM  $J/\psi\gamma$  [Li, Wang (Phys.Lett.B 2009) (Phys.Rev.D 2014)]
- ▶ SPS NLO CPM  $\Upsilon\gamma$  [Li, Wang (Phys.Rev.D 2019)]

At  $p_{T\psi} \leq m_\psi$  or  $p_{TJ/\psi\gamma} \leq m_\psi$  region, CPM predictions are not applicable. Also, NLO CPM predictions using the DPS are challenging.

- ▶ At high energies, an alternative approach for describing the cross-section over the entire  $p_T$ -range involves high-energy factorization with resummation of significant corrections using UPDFs. This method offers the advantage of employing LO  $2 \rightarrow 2$  processes in the NRQCD framework and  $2 \rightarrow 3$  processes in the ICM hadronization approach.

## Single Parton Scattering

In our previous paper, we presented LO PRA predictions for LHCb at SPS energies using both NRQCD and ICEM approaches. Our results demonstrated that the CSM provides a good approximation for associated  $RR \rightarrow J/\psi\gamma$  production at  $\sqrt{s} = 13 - 14$  TeV with  $p_T^{J/\psi,\gamma} < 20$  GeV. [Alimov, Karpishkov, Saleev (IMPLA 2025)]

- ▶ NRQCD — In this work, we take into account the production of  $J/\psi$  via color-octet states, which are small corrections. All subprocesses are  $2 \rightarrow 2$ . Contributions via the  $\chi_{cJ}, \psi(2S)$  decays are also taken into account:  
 $R^+R^- \rightarrow \chi_{cJ}(\rightarrow J/\psi X)\gamma, RR \rightarrow \psi(2S)(\rightarrow J/\psi X)\gamma.$
- ▶ ICEM —  $RR \rightarrow c\bar{c}\gamma$  according to [Alimov, Karpishkov, Saleev (IMPLA 2025)].

The processes via quark-antiquark annihilation are negligible.

## Double Parton Scattering

The DPS production cross section is expressed as follows:

$$\sigma(pp \rightarrow J/\psi\gamma) = \frac{\sigma^{SPS}(pp \rightarrow J/\psi X) \times \sigma^{SPS}(pp \rightarrow \gamma X)}{\sigma^{eff}}$$

[Ryskin, Snigirev (Phys. Rev. D 2011)]

- ▶ NRQCD –  $\sigma^{SPS}(pp \rightarrow J/\psi X)$  is the production cross-section of prompt- $J/\psi$  using the NRQCD.
- ▶ ICEM –  $\sigma^{SPS}(pp \rightarrow J/\psi X)$  is the production cross-section of prompt- $J/\psi$  using the ICEM.

$\sigma^{SPS}(pp \rightarrow \gamma X)$  include only  $QR \rightarrow \gamma q$  subprocess. The experimental requirement for photon isolation  $R > 0.4$  allows discarding the contribution from fragmentation production. [e.g. ATLAS (J. High Energy Phys. 2016)]  
[Chernyshev, Saleev (Phys.Rev.D 2024)]

The processes through quark-antiquark annihilation are negligible.

## Parton Reggeization approach

Parton Reggeization approach (PRA) is a scheme of  $k_T$ -factorization, which is based on the modified multi-Regge kinematics (mMRK) approximation of the QCD. [Nefedov, Saleev, Shipilova (Phys.Rev.D 2013)] [Karpishkov, Nefedov, Saleev (EPJ Web Conf. 2017)] [Nefedov, Saleev (Phys.Rev.D 2020)]

The Reggeized parton amplitudes are described by Lipatov's gauge invariant effective field theory (EFT). [Lipatov (Nucl.Phys.B 1995)]

The cross section is written as a convolution:

$$d\sigma(pp \rightarrow J/\psi\gamma) = \Phi_a(x_1, q_{1T}^2, \mu^2) \otimes \Phi_b(x_2, q_{2T}^2, \mu^2) \otimes d\hat{\sigma}(ab \rightarrow J/\psi\gamma)$$

where  $a, b$  are parton types in parton sub-processes  $a = g, s, u, d; b = g, \bar{s}, \bar{u}, \bar{d}$ .  $\Phi_{a,b}(x, q_T^2, \mu^2)$  is modified Kimber-Martin-Ryskin-Watt (mKMRW) PDFs with exact normalization.

The PRA has demonstrated its effectiveness in describing various pair production processes.

- ▶ Pair- $J/\psi, J/\psi\Upsilon, \Upsilon\Upsilon$  [Saleev, Chernyshev (Phys.Part.Nucl. 2025) (Mod.Phys.Lett.A 2025) (Phys.Part.Nucl.Lett. 2023) (Phys.Rev.D 2022)] [He, Kniehl, Nefedov, Saleev (Phys.Rev.Lett. 2019)] [Karpishkov, Nefedov, Saleev (Phys.Rev.D 2019)] [Karpishkov, Nefedov, Saleev (Phys.Part.Nucl.Lett. 2019)]
- ▶  $J/\psi(\Upsilon)$  and  $D$  [Saleev, Chernyshev (Phys.Part.Nucl. 2024) (Phys.Rev.D 2024)]
- ▶  $J/\psi(\Upsilon)$  and  $Z(W)$  [Saleev, Chernyshev (Int.J.Mod.Phys.A 2023)]

## NRQCD

- ▶ The quarkonium wave function can be written as a series expansion in terms of the relative velocity of quarks  $v^2 \sim 0.2 - 0.3$  using orthogonal color-singlet/octet states wavefunctions.

[Bodwin, Braaten, Lepage (Phys.Rev.D 1997)]

$$|J/\psi\rangle = \mathcal{O}(v^0)|c\bar{c}[{}^3S_1^{(1)}]\rangle + \mathcal{O}(v)|c\bar{c}[{}^3P_J^{(8)}]g\rangle + \mathcal{O}(v^2)|c\bar{c}[{}^1S_0^8]g\rangle + \dots$$

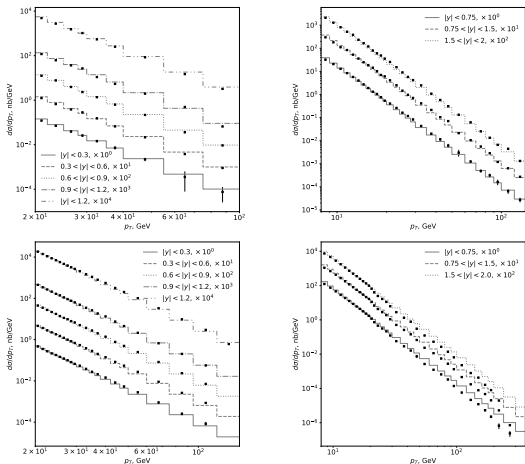
- ▶ Then, the heavy quarkonium production cross section can be written as the sum of the subprocess cross sections multiplied by a Long-Distance Matrix Elements (LDMEs).  $N_{col} = 2N_c, N_c^2 - 1$  for color-singlet and color-octet states accordingly;  $N_{pol} = 2J + 1$  with  $B = X$  or  $\gamma$ .

$$d\hat{\sigma}(ab \rightarrow J/\psi B) = \sum_n d\hat{\sigma}(ab \rightarrow c\bar{c}[{}^{2S+1}L_J^{(1,8)}]B) \times \frac{\langle \mathcal{O}^{J/\psi}[{}^{2S+1}L_J^{(1,8)}] \rangle}{N_{col}N_{pol}}$$

- ▶ The color-singlet LDMEs are determined either through the potential model or by extraction from decay widths, while the color-octet LDMEs, being model-dependent, were constrained in this work by fits to CMS-2018 and ATLAS-2024 data. [CMS (Phys.Lett.B 2018)] [ATLAS (Eur.Phys.J.C 2024)]

$\langle \mathcal{O}^{\psi(2S)}[{}^3S_1^{(1)}] \rangle / GeV^3$	$6.5 \times 10^{-1}$	$\langle \mathcal{O}^{J/\psi}[{}^3S_1^{(1)}] \rangle / GeV^3$	1.3
$\langle \mathcal{O}^{\psi(2S)}[{}^1S_0^{(8)}] \rangle / GeV^3$	0	$\langle \mathcal{O}^{J/\psi}[{}^1S_0^{(8)}] \rangle$	0
$\langle \mathcal{O}^{\psi(2S)}[{}^3S_1^{(8)}] \rangle / GeV^3$	$(9.0 \pm 1.4) \times 10^{-4}$	$\langle \mathcal{O}^{J/\psi}[{}^3S_1^{(8)}] \rangle / GeV^3$	$(0 \pm 10^{-4})$
$\langle \mathcal{O}^{\psi(2S)}[{}^3P_0^{(8)}] \rangle / GeV^5$	$(1.0 \pm 0.3) \times 10^{-2}$	$\langle \mathcal{O}^{J/\psi}[{}^3P_0^{(8)}] \rangle / GeV^5$	$(2.27 \pm 0.48) \times 10^{-2}$
		$\langle \mathcal{O}^{Xc0}[{}^3P_0^{(8)}] \rangle / GeV^5$	$(0 \pm 8.3) \times 10^{-2}$
		$\langle \mathcal{O}^{Xc0}[{}^3S_1^{(8)}] \rangle / GeV^3$	$(1.28 \pm 0.17) \times 10^{-3}$

# Prompt- $J/\psi$ LDME fit result



prompt- $J/\psi$  (left-bottom) and  $\psi(2S)$  (left-top) production at  $\sqrt{s} = 13$  TeV,  $|y| < 1.2$   
[\[CMS \(Phys.Lett.B 2018\)\]](#)

prompt- $J/\psi$  (right-bottom) and  $\psi(2S)$  (right-top) production at  $\sqrt{s} = 13$  TeV,  $|y| < 2$   
[\[ATLAS \(Eur.Phys.J.C 2024\)\]](#)

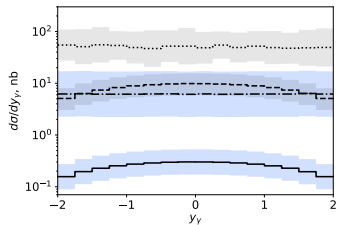
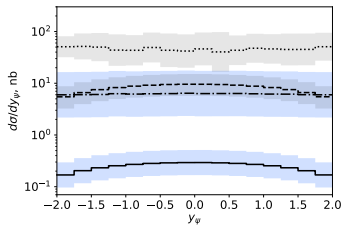
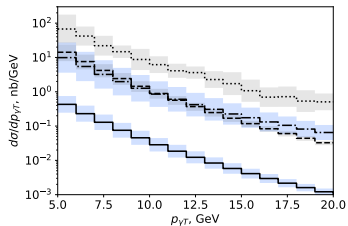
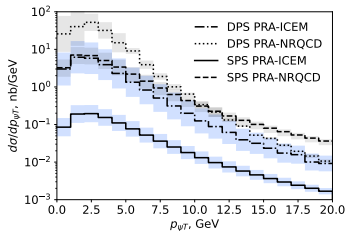
## ICEM

- ▶ In the Improved Color Evaporation Model (ICEM) the cross section for the associated production of  $J/\psi$  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:

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

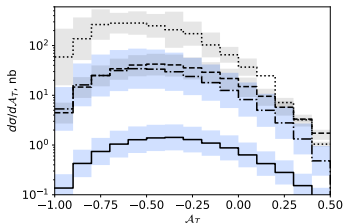
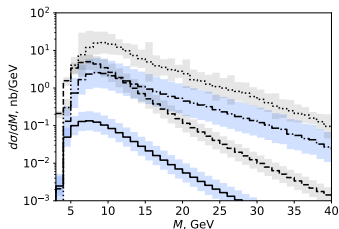
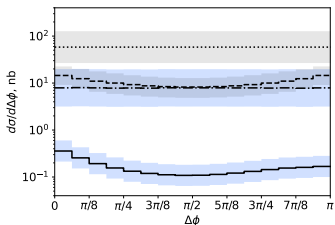
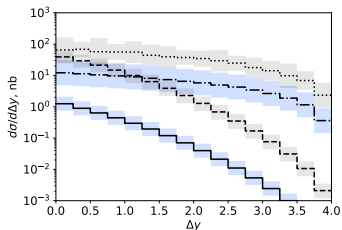
- ▶ The phenomenological coefficient  $\mathcal{F}^\psi$  is associated with the hadronization probability. [Ma, Vogt (Phys.Rev.D 2016)]
- ▶  $F^{J/\psi} = 0.02$  has been obtained by a fit of the prompt  $J/\psi$  production at the LHC. [Chernyshev, Saleev (Phys.Rev.D 2022)]
- ▶ Another way in the PRA-ICEM calculation is to use Monte-Karlo generator KaTie. [Hameren (Comp.Phys.Comm. 2017)]  
We have cross-checked all calculations in the PRA-ICEM framework using KaTie and found good agreement for both SPS and DPS predictions.

# Predictions at LHCb kinematics



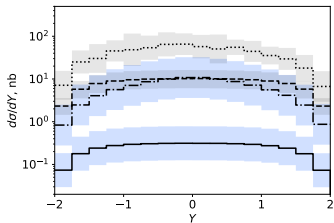
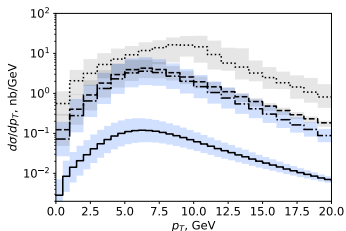
SPS PRA-ICEM (solid), SPS PRA-NRQCD (dashed),  
DPS PRA-ICEM (dash-dotted), DPS PRA-NRQCD (dotted)  
 $\sqrt{s} = 13$  TeV,  $|y_{J/\psi}|, |y_\gamma| < 2$  and  $p_{T,\gamma} > 5$  GeV

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 $\sqrt{s} = 13$  TeV,  $|y_{J/\psi}|, |y_\gamma| < 2$  and  $p_{T\gamma} > 5$  GeV

## Summary

- ▶ Various differential cross sections for the associated  $J/\psi\gamma$  production are predicted at  $\sqrt{s} = 13$  TeV,  $|y_{J/\psi}|, |y_\gamma| < 2$  and  $p_{T\gamma} > 5$  GeV.
- ▶ For associated  $J/\psi\gamma$  production, we find that, the DPS contribution dominates over SPS by a factor of  $\sim 6$ .
- ▶ Our analysis shows that when including DPS contributions, the PRA-NRQCD predictions remain significantly higher than those from PRA-ICEM.
- ▶ This confirms that the substantial discrepancy between PRA-NRQCD and PRA-ICEM predictions observed in [Alimov, Karpishkov, Saleev (IMPLA 2025)] stays even after DPS effects have been taken into account.
- ▶ Experimental measurements of the associated  $J/\psi\gamma$  production cross-sections can be used to discriminate between the ICEM and NRQCD hadronization models.

Thank you for your attention!