广州大学

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Exclusive $J/\psi + \gamma$ production in ultraperipheral ion collisions

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In collaboration with Long-Bin Chen,

Phy. Rev. D 112, 056013 (2025) [2508.06946]

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OutLine

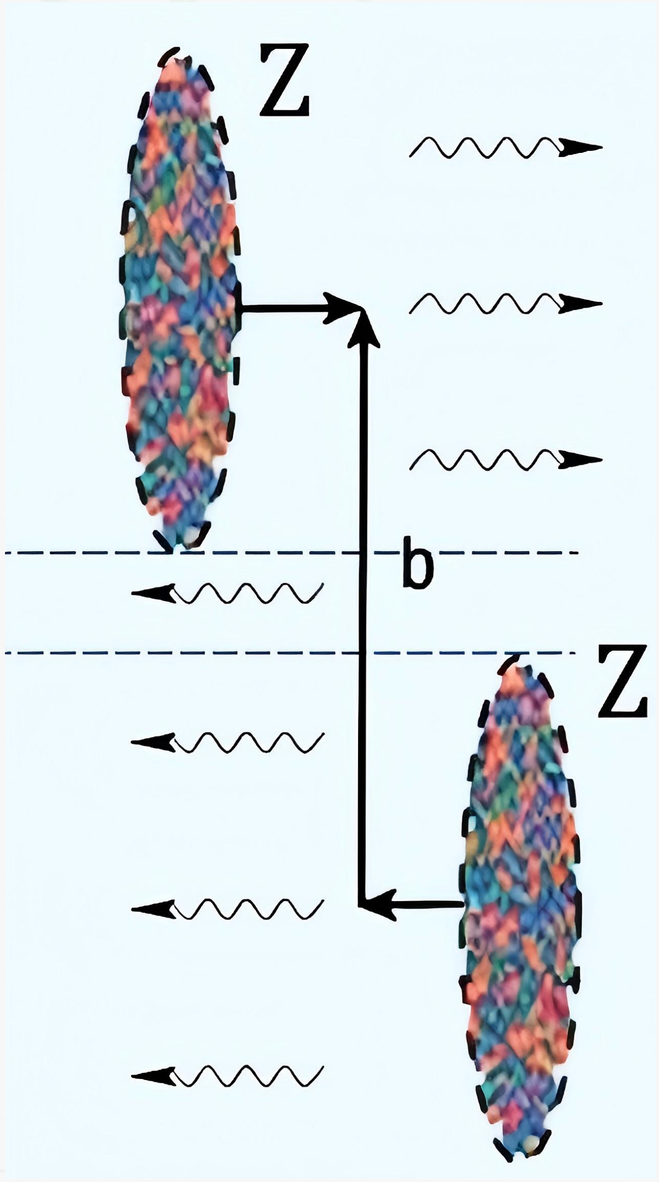
- Introduction
- Some technical details
- Numerical results
- Summary

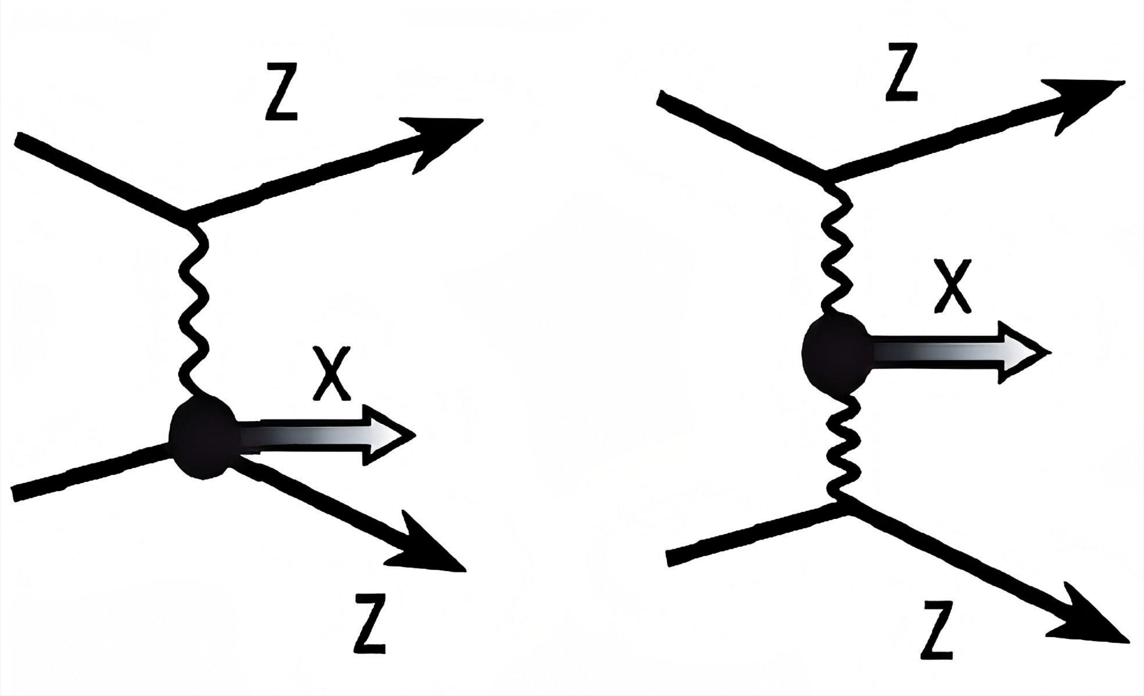
01

Introduction

- Ultraperipheral collisions
- Inclusive J/ψ production in $\gamma\gamma$ scattering
- Exclusive processes in $\gamma\gamma$ scattering

Ultraperipheral collisions (UPCs)





1. impact parameter $b > 2R$
2. equivalent photon approximation, $\gamma\gamma$ or γN scattering
3. photon number density $\propto Z^2$

Ultraperipheral collisions (UPCs)

Photon-photon collisions in UPCs at HL-LHC and FCC
(cited from JHEP 09 (2022) 248) :

System	$\sqrt{s_{\mathrm{NN}}}$	$\mathcal{L}_{\mathrm{int}}$	$E_{\mathrm{beam1}} + E_{\mathrm{beam2}}$	γ_{L}	R_{A}	$E_{\gamma}^{\mathrm{max}}$	$\sqrt{s_{\gamma\gamma}^{\mathrm{max}}}$
Pb-Pb	5.52 TeV	5 nb^{-1}	2.76 + 2.76 TeV	2960	7.1 fm	80 GeV	160 GeV
Xe-Xe	5.86 TeV	30 nb^{-1}	2.93 + 2.93 TeV	3150	6.1 fm	100 GeV	200 GeV
Kr-Kr	6.46 TeV	120 nb^{-1}	3.23 + 3.23 TeV	3470	5.1 fm	136 GeV	272 GeV
Ar-Ar	6.3 TeV	1.1 pb^{-1}	3.15 + 3.15 TeV	3390	4.1 fm	165 GeV	330 GeV
Ca-Ca	7.0 TeV	0.8 pb^{-1}	3.5 + 3.5 TeV	3760	4.1 fm	165 GeV	330 GeV
O-O	7.0 TeV	12.0 pb^{-1}	3.5 + 3.5 TeV	3760	3.1 fm	240 GeV	490 GeV
p-Pb	8.8 TeV	1 pb^{-1}	7.0 + 2.76 TeV	7450, 2960	0.7, 7.1 fm	2.45 TeV, 130 GeV	2.6 TeV
p-p	14 TeV	150 fb^{-1}	7.0 + 7.0 TeV	7450	0.7 fm	2.45 TeV	4.5 TeV
Pb-Pb	39.4 TeV	110 nb^{-1}	19.7 + 19.7 TeV	21 100	7.1 fm	600 GeV	1.2 TeV
p-Pb	62.8 TeV	29 pb^{-1}	50. + 19.7 TeV	53 300, 21 100	0.7,7.1 fm	15.2 TeV, 600 GeV	15.8 TeV
p-p	100 TeV	1 ab^{-1}	50. + 50. TeV	53 300	0.7 fm	15.2 TeV	30.5 TeV

Inclusive J/ψ production in $\gamma\gamma$ scattering

$\gamma + \gamma \to J/\psi + X$ @ $e^- e^+$ collider

LEP II experiment:

Phys. Lett. B 565, 76-86 (2003)

NRQCD predictions:

Phys. Rev. Lett. 89, 032001 (2002)
Phys. Rev. D 69, 014015 (2004)
Phys. Rev. D 79, 114020 (2009)
Phys. Rev. D 95, 036001 (2017)
Phys. Rev.D 84,051501 (2011)
Phys. Rev. D 112, 1, L011902 (2025)

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Inclusive J/ψ production in $\gamma\gamma$ scattering

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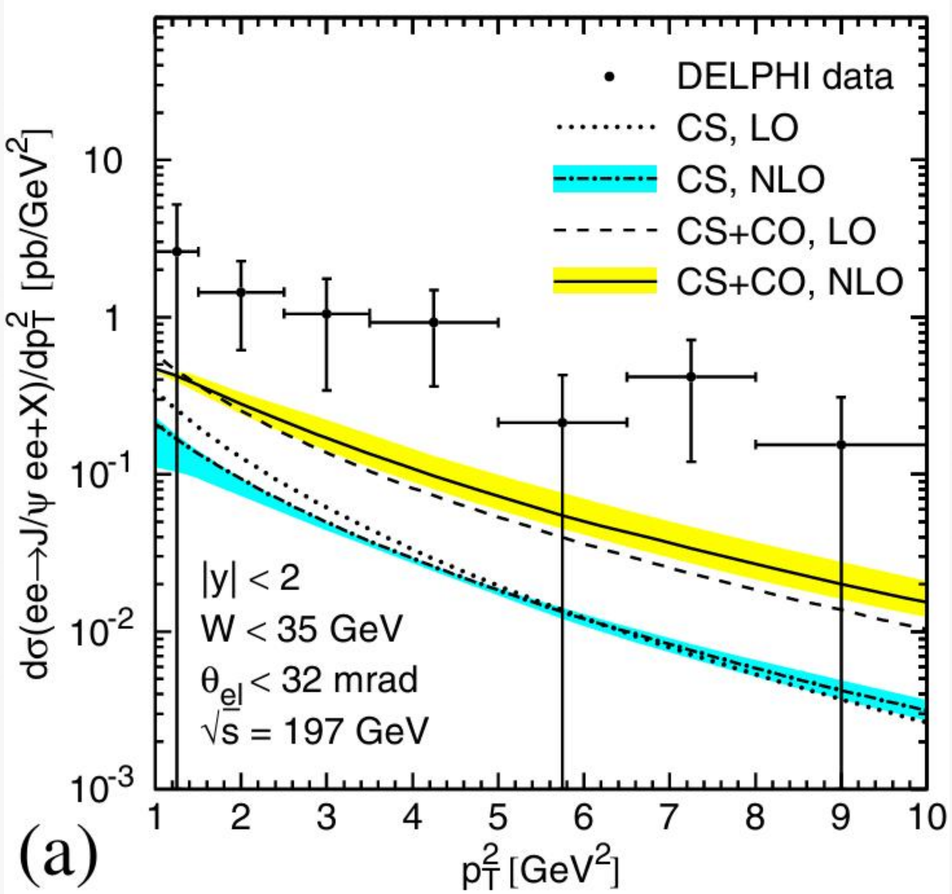

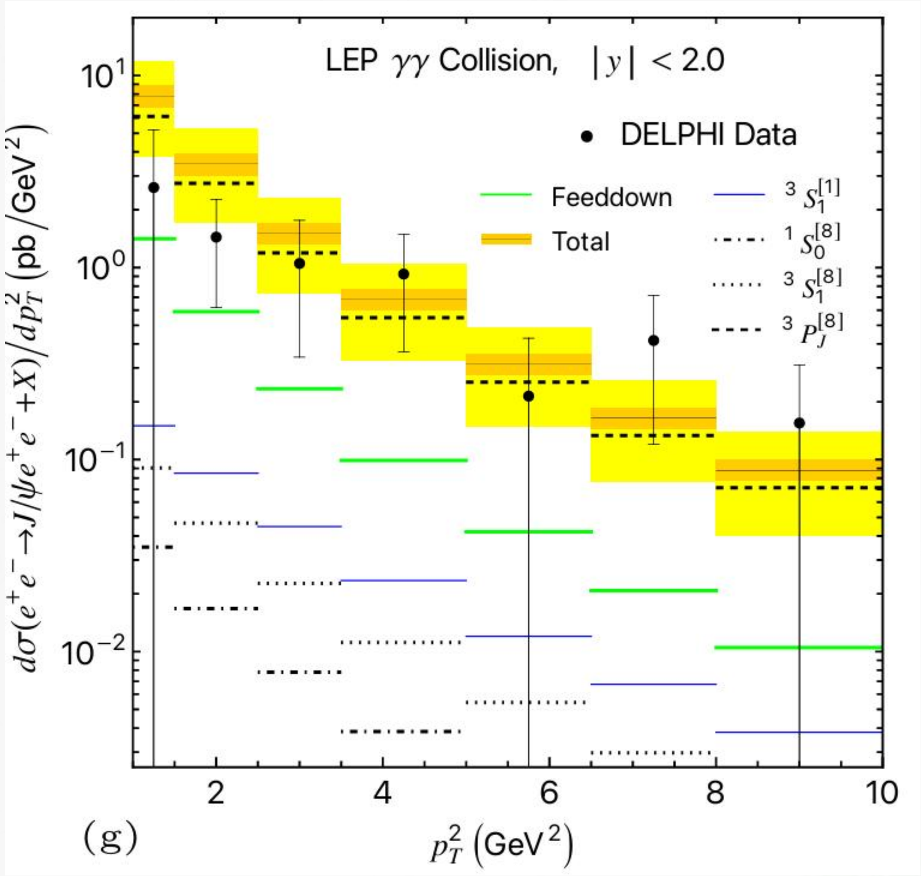

M.Butenschoen, B.A.Kniehl,
Phys.Rev.D 84,051501 (2011)

N. Brambilla, M. Butenschoen, X. P. Wang,
Phys.Rev.D 112, 1, L011902 (2025)

different CO LDMEs

Inclusive J/ψ production in $\gamma\gamma$ scattering

$\gamma + \gamma \to J/\psi + X$ @ $e^- e^+$ collider

Difficulties:

- Sizable experimental errors
- CO vs CS
- Direct photon vs resolved photon (photons interact either directly or via their quark and gluon content)

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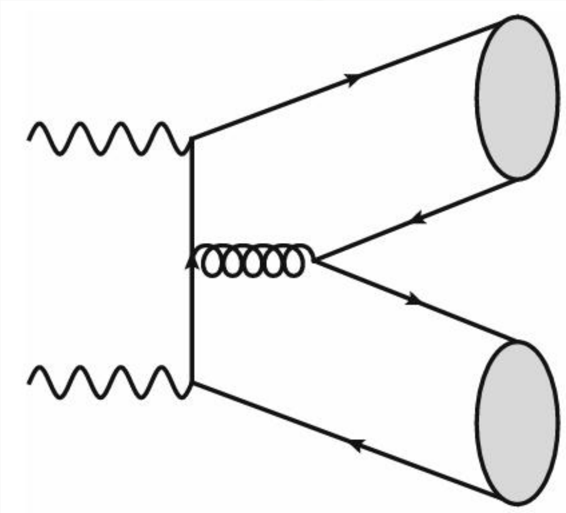
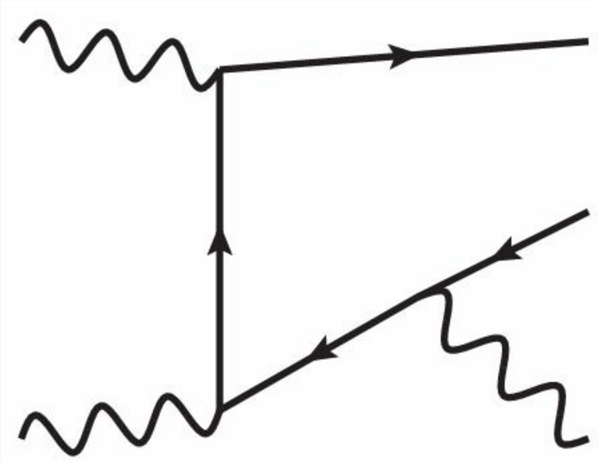
Investigating specific subprocesses separately may help to clarify the situation. UPCs at the LHC provide new opportunities... With the luminosity upgrade, both inclusive and exclusive processes can be measured.

Exclusive processes in $\gamma\gamma$ scattering

Exclusive processes: $\gamma + \gamma \to J/\psi + J/\psi$, $\gamma + \gamma \to J/\psi + \gamma$





Clear production mechanism:
both CO and resolved contributions are suppressed.

Exclusive processes in $\gamma\gamma$ scattering

Study on $\gamma + \gamma \to J/\psi + J/\psi$: Hao Yang, Zi-Qiang Chen, Bingwei Long, Eur. Phys. J. C 85, 802 (2025), up to NLO

- NLO QCD correction is negative and significant.
- Near-threshold-region requires further investigation (Fully charm tetraquark).

This report is about our research on $\gamma + \gamma \to J/\psi + \gamma$.

02

Some technical details

- Factorization formula
- Perturbative calculation

Factorization formula

- Equivalent photon approximation framework

Final cross section = subprocess cross section ⊗ equivalent photon spectral functions:

$$\sigma^{A+B\to A+B+J/\psi+\gamma} = \int \frac{\mathrm{d}x_1}{x_1}\frac{\mathrm{d}x_2}{x_2} n_1(x_1) n_2(x_2) \hat{\sigma}^{\gamma+\gamma\to J/\psi+\gamma}$$

Equivalent photon spectral function:

$$n(x) = \frac{2Z^2\alpha}{\pi}\left\{\chi K_0(\chi)K_1(\chi) - (1-\gamma_{\mathrm{L}}^{-2})\frac{\chi^2}{2}\left[K_1^2(\chi) - K_0^2(\chi)\right]\right\}$$

Factorization formula

- NRQCD factorization formula up to $\mathcal{O}(v^2)$

Amplitude for $\gamma+\gamma\to J/\psi+\gamma$:

$$\mathcal{M}^{\gamma+\gamma\to J/\psi+\gamma}=\sqrt{2M}\left[c_0\,\langle J/\psi|\psi^\dagger\boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}\chi|0\rangle+\frac{c_2}{m^2}\,\langle J/\psi|\psi^\dagger(-\tfrac{i}{2}\overleftrightarrow{\boldsymbol{D}})^2\boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}\chi|0\rangle\right]$$

short distance coefficients

NRQCD matrix elements

Short distance coefficients: matching procedure

NRQCD matrix elements: input parameters

Factorization formula

- NRQCD factorization formula up to $\mathcal{O}(v^2)$

Matching procedure: considering $\gamma+\gamma\to c\bar{c}({}^3S_1^{[1]})+\gamma$ process

$$\mathcal{M}^{\gamma+\gamma\to c\bar{c}({}^3S_1^{[1]})+\gamma}\Big|_{\text{pert QCD}} = c_0\,\langle c\bar{c}({}^3S_1^{[1]})|\psi^\dagger\boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}\chi|0\rangle\Big|_{\text{pert NRQCD}} + \frac{c_2}{m^2}\,\langle c\bar{c}({}^3S_1^{[1]})|\psi^\dagger(-\tfrac{i}{2}\overleftrightarrow{\boldsymbol{D}})^2\boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}\chi|0\rangle\Big|_{\text{pert NRQCD}}$$

right side:

$$\langle c\bar{c}({}^3S_1^{[1]})|\psi^\dagger\boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}\chi|0\rangle\Big|_{\text{pert NRQCD}} = \sqrt{2N_c}2E_{\boldsymbol{q}}\left[1+\frac{2C_F}{3}\frac{\boldsymbol{q}^2}{m^2}\frac{\alpha_s}{\pi}\left(\frac{\mu_{\mathrm{R}}^2}{\mu_{\mathrm{F}}^2}\right)^{\epsilon}\times\left(\frac{1}{\epsilon_{\mathrm{IR}}}-\gamma_{\mathrm{E}}+\ln(4\pi)\right)\right],$$

$$\langle c\bar{c}({}^3S_1^{[1]})|\psi^\dagger(-\tfrac{i}{2}\overleftrightarrow{\boldsymbol{D}})^2\boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}\chi|0\rangle\Big|_{\text{pert NRQCD}} = \sqrt{2N_c}2E_{\boldsymbol{q}}\boldsymbol{q}^2,$$

Factorization formula

- NRQCD factorization formula up to $\mathcal{O}(v^2)$

Matching procedure: considering $\gamma+\gamma\to c\bar{c}({}^3S_1^{[1]})+\gamma$ process

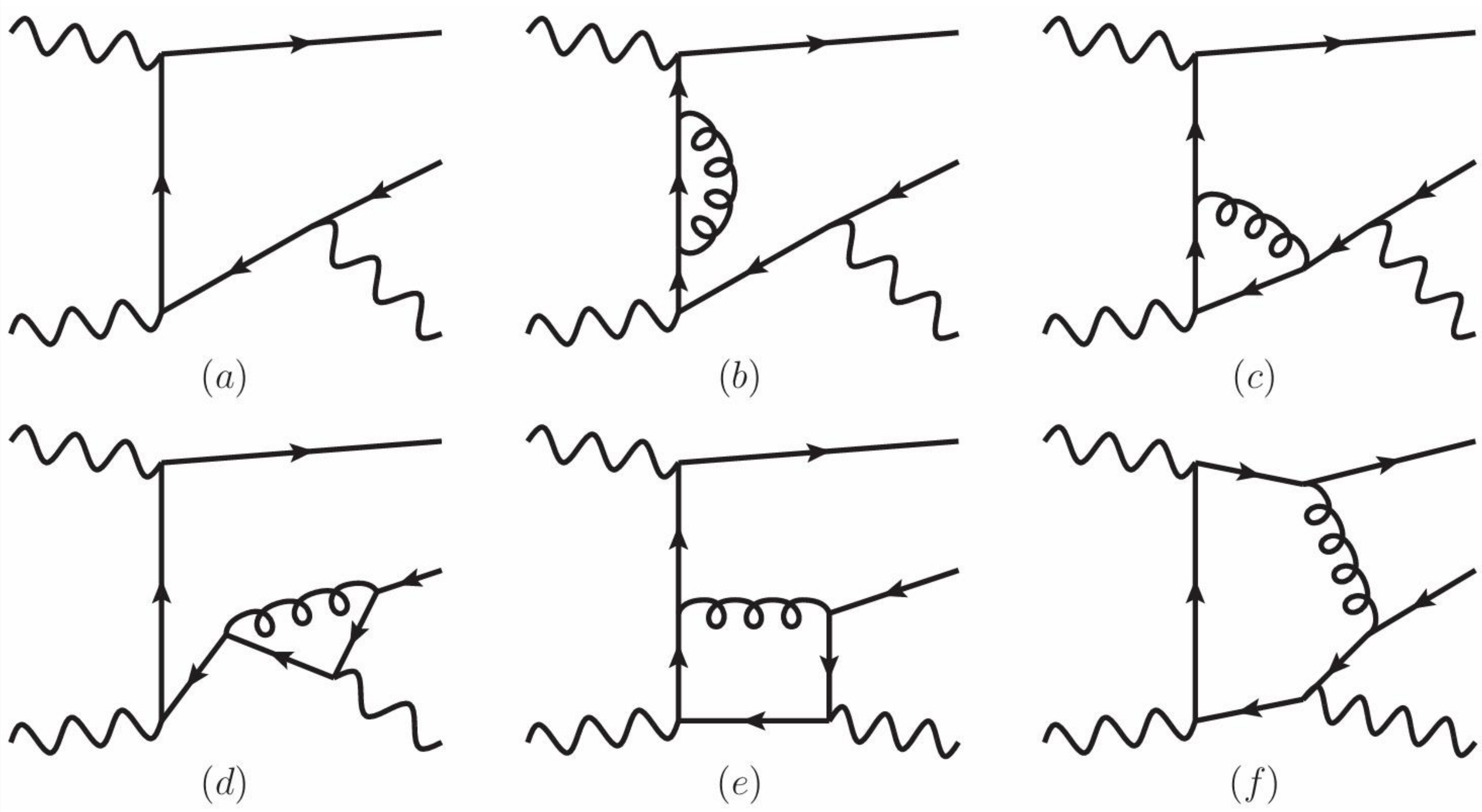
$$\mathcal{M}^{\gamma+\gamma\to c\bar{c}({}^3S_1^{[1]})+\gamma}\Big|_{\text{pert QCD}} = c_0\,\langle c\bar{c}({}^3S_1^{[1]})|\psi^\dagger\boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}\chi|0\rangle\Big|_{\text{pert NRQCD}} + \frac{c_2}{m^2}\,\langle c\bar{c}({}^3S_1^{[1]})|\psi^\dagger(-\tfrac{i}{2}\overleftrightarrow{\boldsymbol{D}})^2\boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}\chi|0\rangle\Big|_{\text{pert NRQCD}}$$

left side: $$\mathcal{M}^{\gamma+\gamma\to c\bar{c}({}^3S_1^{[1]})+\gamma}\Big|_{\text{pert QCD}} = \mathcal{M}_{00}+\frac{\alpha_s}{\pi}\mathcal{M}_{01}+\frac{\boldsymbol{q}^2}{m^2}\mathcal{M}_{10}+\frac{\boldsymbol{q}^2}{m^2}\frac{\alpha_s}{\pi}\mathcal{M}_{11}$$

we then elucidate some points in the calculation of $\mathcal{M}^{\gamma+\gamma\to c\bar{c}({}^3S_1^{[1]})+\gamma}$.

Perturbative calculation

$$\gamma(p_1) + \gamma(p_2) \to c\left(\frac{k}{2}+q\right)\bar{c}\left(\frac{k}{2}-q\right) + \gamma(p_3)$$



Perturbative calculation

$$\gamma(p_1) + \gamma(p_2) \to c\left(\frac{k}{2} + q\right)\bar{c}\left(\frac{k}{2} - q\right) + \gamma(p_3)$$

Kinematic:

$$p_1^2 = p_2^2 = p_3^2 = 0,$$

$$\left(\frac{k}{2} + q\right)^2 = \left(\frac{k}{2} + q\right)^2 = m^2,$$

$$k^2 = 4(m^2 + \boldsymbol{q}^2) = 4E_{\boldsymbol{q}}^2;$$

$$t = (p_2 - p_3)^2,$$

$$u = (p_1 - p_3)^2.$$

Introduce $\tilde{t} = t/(4E_{\boldsymbol{q}}^2)$, $\tilde{u} = u/(4E_{\boldsymbol{q}}^2)$, which are independent of $\boldsymbol{q}^2$ (facilitate the $\boldsymbol{q}^2$ expansion).

to see it, taking the $c\bar{c}$ rest frame

$$k = 2E_{\boldsymbol{q}}(1,0,0,0), \quad q = (0, q_x, q_y, q_z),$$

$$p_3 = \frac{2E_{\boldsymbol{q}}\sin(\theta_1 + \theta_2)}{\sin\theta_1 + \sin\theta_2 - \sin(\theta_1 + \theta_2)}(1,0,0,1),$$

$$p_1 = \frac{2E_{\boldsymbol{q}}\sin\theta_2}{\sin\theta_1 + \sin\theta_2 - \sin(\theta_1 + \theta_2)}(1, \sin\theta_1, 0, \cos\theta_1),$$

$$p_2 = \frac{2E_{\boldsymbol{q}}\sin\theta_1}{\sin\theta_1 + \sin\theta_2 - \sin(\theta_1 + \theta_2)}(1, -\sin\theta_2, 0, \cos\theta_2),$$

Perturbative calculation

$$\gamma(p_1) + \gamma(p_2) \to c\left(\frac{k}{2}+q\right)\bar{c}\left(\frac{k}{2}-q\right) + \gamma(p_3)$$

Spin-color projector:

$$\Pi_3 = \frac{1}{4\sqrt{2}E_{\boldsymbol{q}}(E_{\boldsymbol{q}}+m)}\left(\frac{\not{k}}{2}-\not{q}-m\right)\not{\epsilon}^*\left(\not{k}+2E_{\boldsymbol{q}}\right)\left(\frac{\not{k}}{2}-\not{q}+m\right)\otimes\left(\frac{\mathbf{1_c}}{\sqrt{N_c}}\right)$$

Renormalization constants:

$$\delta Z_2^{\mathrm{OS}} = -C_F\frac{\alpha_s}{4\pi}\left[\frac{1}{\epsilon_{\mathrm{UV}}}+\frac{2}{\epsilon_{\mathrm{IR}}}-3\gamma_E+3\ln\frac{4\pi\mu_{\mathrm{R}}^2}{m^2}+4\right],$$
$$\delta Z_m^{\mathrm{OS}} = -C_F\frac{\alpha_s}{4\pi}\left[\frac{3}{\epsilon_{\mathrm{UV}}}-3\gamma_E+3\ln\frac{4\pi\mu_{\mathrm{R}}^2}{m^2}+4\right].$$

03

Numerical results

- Cross-check and input parameters
- Numerical results

Cross-check and input parameters

Cross-check

We reproduce the result of $\Gamma(J/\psi \to 3\gamma)$:

$$\Gamma(J/\psi \to 3\gamma) = \frac{8(\pi^2-9)e_c^6\alpha^3}{9m_c^2}\left|\langle 0|\chi^\dagger \boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}^*\psi|J/\psi(\boldsymbol{\epsilon})\rangle\right|^2 \left\{1 - 12.630\,\frac{\alpha_s}{\pi} + \left[\frac{132-19\pi^2}{12(\pi^2-9)} + \left(\frac{16}{9}\ln\frac{\mu_f^2}{m_c^2} + G\right)\frac{\alpha_s}{\pi}\right]\langle v^2\rangle_{J/\psi} + \cdots\right\}, \tag{1}$$

F. Feng, Y. Jia, W. L. Sang, Phys. Rev. D 87, 051501 (2013)

Cross-check and input parameters

Input parameters

M : physical J/ψ mass
m : charm quark mass

$$\alpha = 1/137.065, \quad M = 3.096 \text{ GeV}, \quad m_{\mathrm{p}} = 0.9315 \text{ GeV},$$

$$\langle \mathcal{O}_1 \rangle_{J/\psi} = 0.440^{+0.067}_{-0.055} \text{ GeV}^3, \quad \langle \boldsymbol{q}^2 \rangle = 0.441^{+0.140}_{-0.140} \text{ GeV}^2.$$

To maintain consistency, M, m, $\langle \boldsymbol{q}^2 \rangle$ are not treated as independent:

$$M = 2\sqrt{m^2 + \langle \boldsymbol{q}^2 \rangle} \Rightarrow m = 1.40^{+0.05}_{-0.05} \text{ GeV}.$$

mass scheme:

$$\hat{\sigma} = \int \mathrm{dPS}_2 \, |\mathcal{M}|^2$$

keep M

expand M in $\langle \boldsymbol{q}^2 \rangle$ series

Numerical results

Kinematic cuts:

$p_{\mathrm{T}} > 2$ GeV, $|y_{\psi,\gamma}| < 2.4$

suppress the background from the Pomeron exchange process and facilitate the exclusive event selection.

System	Term	Central	$\Delta\langle \boldsymbol{q}^2\rangle$	$\Delta\langle \mathcal{O}_1\rangle$	$\Delta\mu_{\mathrm{R}}$	$\Delta\mu_{\mathrm{F}}$
Pb-Pb, $\sqrt{s_{\mathrm{NN}}} =$ 5.52 TeV	LO (nb)	87.90	$^{+10.38}_{-8.62}$	$^{+13.38}_{-10.99}$	—	—
	$\mathcal{O}(\alpha_s)$ (nb)	-43.93	$^{-5.49}_{+4.59}$	$^{-6.69}_{+5.49}$	$^{+8.29}_{-13.72}$	—
	$\mathcal{O}(v^2)$ (nb)	-29.08	$^{-17.05}_{+12.38}$	$^{-4.43}_{+3.64}$	—	—
	$\mathcal{O}(\alpha_s v^2)$ (nb)	12.98	$^{+7.74}_{-5.57}$	$^{+1.98}_{-1.62}$	$^{-2.44}_{+4.04}$	$^{+1.78}_{-1.79}$
	NLO (nb)	27.88	$^{-4.42}_{+2.77}$	$^{+4.24}_{-3.48}$	$^{+5.85}_{-9.68}$	$^{+1.78}_{-1.78}$
p-p, $\sqrt{s_{\mathrm{NN}}} =$ 14 TeV	LO (fb)	10.970	$^{+1.292}_{-1.080}$	$^{+1.670}_{-1.371}$	—	—
	$\mathcal{O}(\alpha_s)$ (fb)	-5.462	$^{-0.683}_{+0.569}$	$^{-0.832}_{+0.683}$	$^{+1.025}_{-1.698}$	—
	$\mathcal{O}(v^2)$ (fb)	-3.646	$^{-2.136}_{+1.552}$	$^{-0.555}_{+0.456}$	—	—
	$\mathcal{O}(\alpha_s v^2)$ (fb)	1.627	$^{+0.970}_{-0.698}$	$^{+0.248}_{-0.203}$	$^{-0.304}_{+0.503}$	$^{+0.222}_{-0.222}$
	NLO (fb)	3.489	$^{-0.557}_{+0.342}$	$^{+0.531}_{-0.436}$	$^{+0.720}_{-1.194}$	$^{+0.222}_{-0.222}$

Numerical results

Resonable convergence behavior (in constrast to $J/\psi \to 3\gamma$ case):

$\mathcal{O}(\alpha_s)$: -50%

$\mathcal{O}(v^2)$: -33%

$\mathcal{O}(\alpha_s v^2)$: 15%

of the LO term.

System	Term	Central	$\Delta\langle \boldsymbol{q}^2 \rangle$	$\Delta\langle \mathcal{O}_1 \rangle$	$\Delta\mu_{\mathrm{R}}$	$\Delta\mu_{\mathrm{F}}$
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Numerical results

$$\sigma_{\mathrm{LO}} = 87.90^{+16.94}_{-13.97}\ \mathrm{nb}, \quad \sigma_{\mathrm{NLO}} = 27.88^{+7.94}_{-11.34}\ \mathrm{nb}, \quad \text{for Pb-Pb collision;}$$

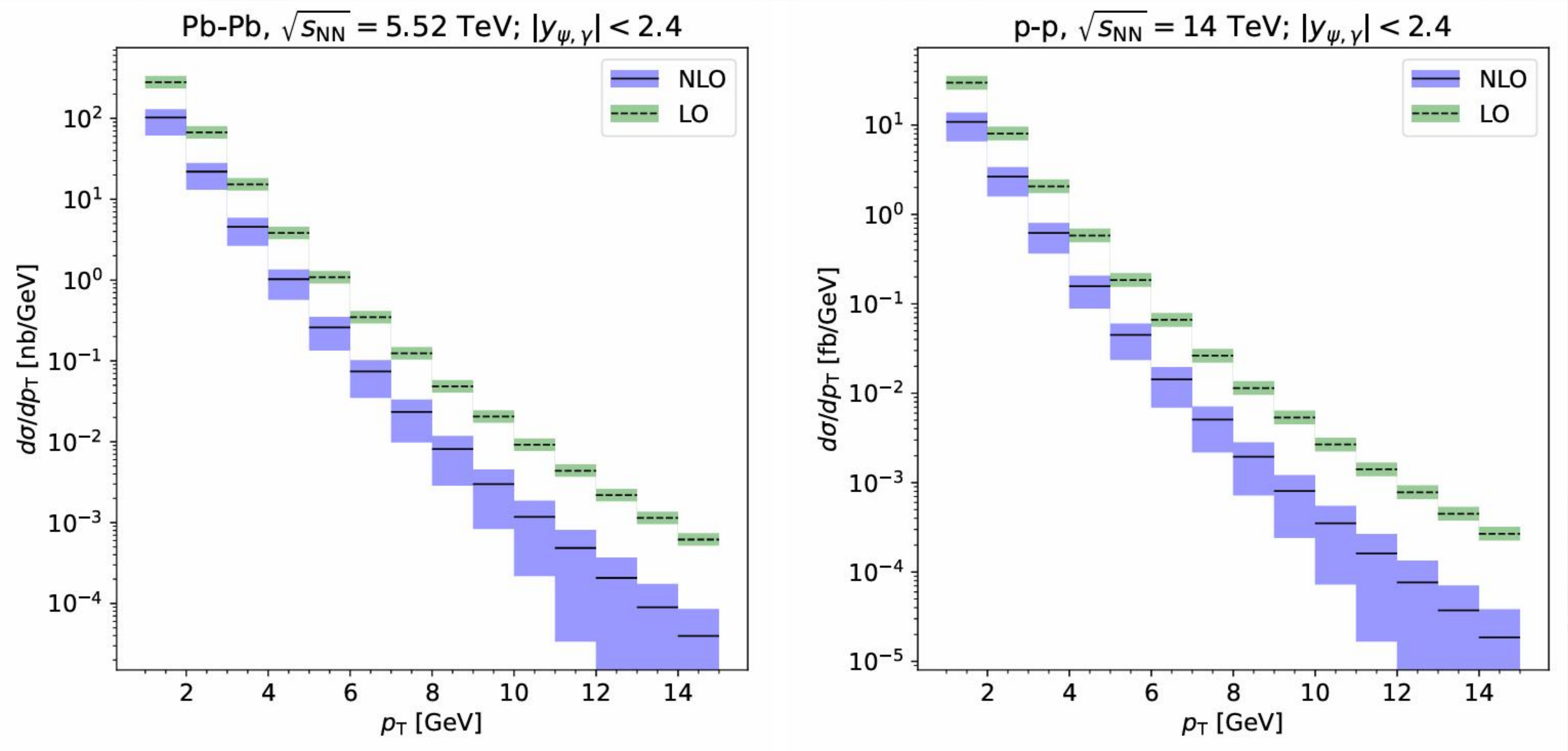
$$\sigma_{\mathrm{LO}} = 10.970^{+2.112}_{-1.746}\ \mathrm{fb}, \quad \sigma_{\mathrm{NLO}} = 3.489^{+0.984}_{-1.406}\ \mathrm{fb}, \quad \text{for p-p collision.}$$

	Typical integrated luminosity	Number of candidate ($\sigma \times \mathcal{L} \times \mathrm{Br}(J/\psi \to \ell^-\ell^+) \times \varepsilon_\gamma$)
Pb-Pb (1 month)	5 nb^{-1}	4-8
p-p (10 months)	150 fb^{-1}	15-32

Lowering the minimum transverse momentum cut to 1 GeV would quadruple the integrated cross sections.

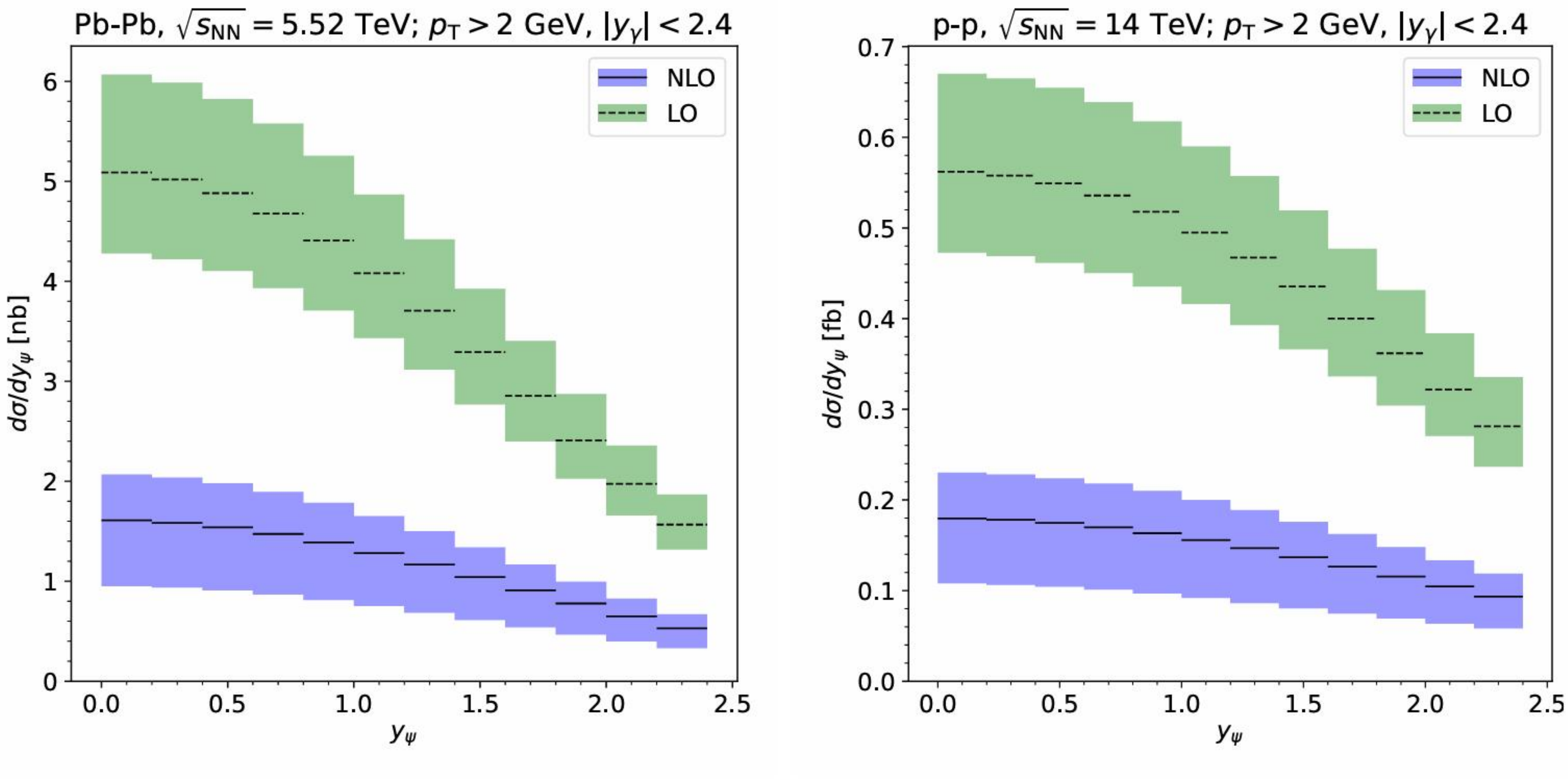
Numerical results

p_{T}-distribution



Numerical results

y_ψ-distribution



(a) (b)

04

Summary

- We investigate the exclusive process $\gamma + \gamma \to J/\psi + \gamma$ in UPCs at the HL-LHC, up to $\mathcal{O}(\alpha_s v^2)$.
- The $\mathcal{O}(\alpha_s)$, $\mathcal{O}(v^2)$, $\mathcal{O}(\alpha_s v^2)$ corrections represent approximately -50%, -33%, and 15% of the LO contribution, exhibiting reasonable convergence behavior.
- Total cross sections including all corrections are $25.18^{+7.18}_{-10.34}$ nb for Pb-Pb collision, and $3.053^{+0.865}_{-1.238}$ fb for p-p collision. These values suggest that a future experimental analysis is feasible.

Thank You!