Doubly heavy hadron production in ultraperipheral collision

Jun Jiang (蒋军)
Shandong University

Collaborators: Hao yang, Xiao Liang, Zongguo Si, Congfeng Qiao, Bingwei Long, Yanrui Liu, Shiyuan Li

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  - Heavy quarkonium production in UPC
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- ✓ Summary and prospects

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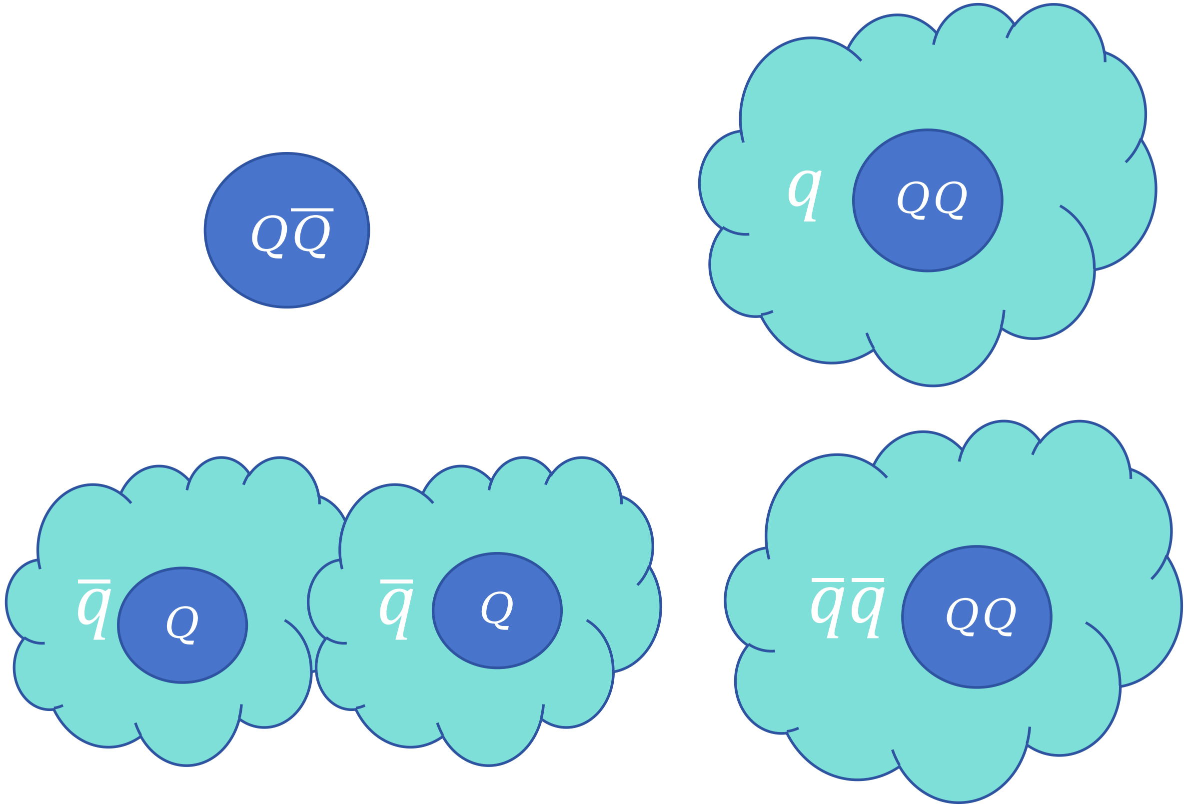
Why doubly heavy hadrons?

Perturbative creation of heavy quarks

$m_Q \gg \Lambda_{QCD}$

Non-perturbative transiton into hadrons

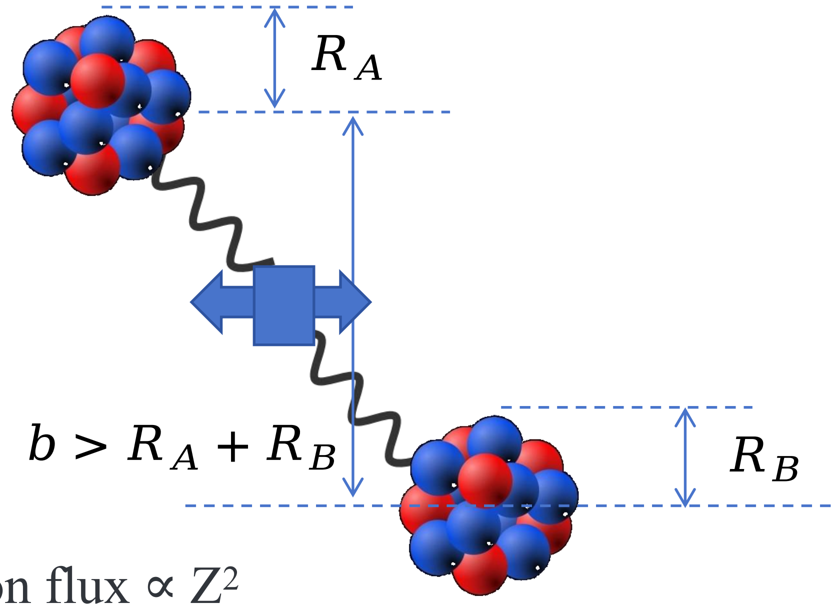
$\mu \ll \Lambda_{QCD}$



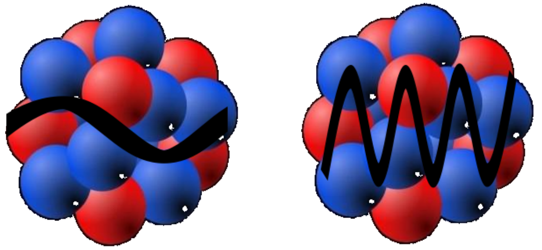
- heavy quarks have much smaller size
- soft gluons and light quarks will also contribute spin and mass via color interaction

Why ultraperipheral collision (UPC)?

1 Two-photon Physics



- ✓ Energy frontier
- ✓ Low multiplicity and rapidity gap
- ✓ Cross sections enhanced by Z^4 because photon flux ∝ Z^2
- ✓ Coherent photon virtuality $Q^2 < R_A^{-2}$ → Equivalent Photon Approximation

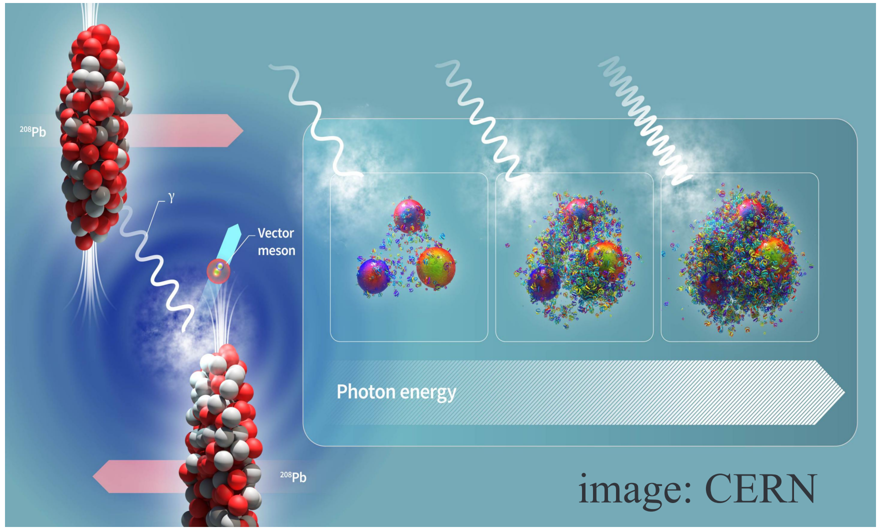


Coherent: $\lambda > R_A$

Incoherent: $\lambda < R_A$

2 One Photon: γp, γA interaction

- ✓ Diffractive preocesses
- ✓ Probe PDF in proton and nuclear down to small x at moderate Q^2
- ✓ Probe saturation phenomena and nuclear gluon shadowing



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Heavy quarkonium production in UPC

Two-photon distribution

$$\sigma(\mathrm{A\,B} \xrightarrow{\gamma\gamma} \mathrm{A}\;X\;\mathrm{B}) = \int \frac{dE_{\gamma_1}}{E_{\gamma_1}} \frac{dE_{\gamma_2}}{E_{\gamma_2}} \frac{\mathrm{d}^2 N^{(\mathrm{AB})}_{\gamma_1/\mathrm{Z}_1,\gamma_2/\mathrm{Z}_2}}{\mathrm{d}E_{\gamma_1}\,\mathrm{d}E_{\gamma_2}} \sigma_{\gamma\gamma\to X}(W_{\gamma\gamma})$$

where $$\frac{\mathrm{d}^2 N^{(\mathrm{AB})}_{\gamma_1/\mathrm{Z}_1,\gamma_2/\mathrm{Z}_2}}{\mathrm{d}E_{\gamma_1}\,\mathrm{d}E_{\gamma_2}} = \int \mathrm{d}^2\boldsymbol{b}_1\,\mathrm{d}^2\boldsymbol{b}_2 P_{\text{no inel}}\left(|\boldsymbol{b}_1-\boldsymbol{b}_2|\right) N_{\gamma_1/\mathrm{Z}_1}(E_{\gamma_1},\boldsymbol{b}_1) N_{\gamma_2/\mathrm{Z}_2}(E_{\gamma_2},\boldsymbol{b}_2)\theta(b_1-\epsilon R_A)\theta(b_2-\epsilon R_B)$$

And the no inelastic/ hadronic interaction probability density:

$$P_{\text{no inel}}(b) = \begin{cases} e^{-\sigma^{\mathrm{NN}}_{\mathrm{inel}}\cdot T_{\mathrm{AB}}(b)}, & \text{for nucleus-nucleus UPCs} \\ e^{-\sigma^{\mathrm{NN}}_{\mathrm{inel}}\cdot T_{\mathrm{A}}(b)}, & \text{for proton-nucleus UPCs} \\ |1-\Gamma(s_{\mathrm{NN}},b)|^2 \text{ with } \Gamma(s_{\mathrm{NN}},b)\propto e^{-b^2/(2b_0)} & \text{for proton-proton UPCs} \end{cases}$$

Photon flux:

$$N^{\mathrm{EDFF}}_{\gamma/\mathrm{Z}}(E_\gamma,b) = \frac{Z^2\alpha}{\pi^2}\frac{\xi^2}{b^2}\left[K_1^2(\xi)+\frac{1}{\gamma_{\mathrm{L}}^2}K_0^2(\xi)\right]$$

$$N^{\mathrm{ChFF}}_{\gamma/\mathrm{Z}}(E_\gamma,b) = \frac{Z^2\alpha}{\pi^2}\left|\int_0^{+\infty}\frac{dk_\perp k_\perp^2}{k_\perp^2+E_\gamma^2/\gamma_{\mathrm{L}}^2}F_{\mathrm{ch,\,A}}\left(\sqrt{k_\perp^2+E_\gamma^2/\gamma_{\mathrm{L}}^2}\right)J_1(bk_\perp)\right|^2$$

H.-S. Shao and D. d'Enterria, JHEP 09 (2022) 248

Heavy quarkonium production in UPC

Two-photon distribution can be factored into two PDF-like photon fluxes by assuming $P_{\text{no inel}}$ =1 and integrating over b:

$$\sigma(\mathrm{A\,B} \xrightarrow{\gamma\gamma} \mathrm{A}\ X\ \mathrm{B}) = \int \frac{dx_1}{x_1}\frac{dx_2}{x_2} f(x_1) f(x_2) \times \mathrm{d}\hat{\sigma}(\gamma\gamma \to X)$$

where

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

$$x_i = E_i / E_{\text{beam}} \qquad \chi \equiv x m_N b_{\min} \qquad \gamma_L = E_{\text{beam}} / m_N$$

The dissociation effect ($P_{\text{no inel}} < 1$) might bring up to 20% corrections. S. Knapen, *et al.*, PRL118, 171801 (2017).

Cross sections as functions of a ratio *x* and the center-of-mass energy of two photons $W_{\gamma\gamma}$

$$\sigma(\mathrm{A\,B} \xrightarrow{\gamma\gamma} \mathrm{A}\ X\ \mathrm{B}) = 2\int \frac{\mathrm{d}x}{x}\frac{\mathrm{d}W_{\gamma\gamma}}{W_{\gamma\gamma}} f(x) f\left(\frac{W_{\gamma\gamma}^2}{x S_{\mathrm{NN}}}\right) \times \mathrm{d}\hat{\sigma}(\gamma\gamma \to X)$$

Heavy quarkonium production in UPC

Results: total cross sections

TABLE I: The LO and NLO total cross sections (in nb) for $\eta_c + c + \bar{c}$, $\eta_b + b + \bar{b}$ and $B_c + b + \bar{c}$ production via photon-photon fusion in ultraperipheral Pb-Pb collision at $\sqrt{S_{\rm NN}} = 5.52$ and 39.4 TeV. Here, scale $\mu = \sqrt{m_H^2 + p_t^2}$ with m_H being the mass of heavy quarkonia, and the transverse momentum cut 1 GeV $\leq p_t \leq 50$ GeV is employed.

processes	$\eta_c + c\bar{c}$	$\eta_b + b\bar{b}$	$B_c + b\bar{c}$
$\sigma_{\rm LO}$ (5.52 TeV)	1.7×10^2	0.034	0.57
$\sigma_{\rm NLO}$ (5.52 TeV)	1.9×10^2	0.027	0.47
K-factor	1.2	0.78	0.83
$\sigma_{\rm LO}$ (39.4 TeV)	1.1×10^3	0.46	6.5
$\sigma_{\rm NLO}$ (39.4 TeV)	1.3×10^3	0.30	5.8
K-factor	1.2	0.66	0.90

B_c^* at LO: 7.0 nb at 5.52 TeV and 65 nb at 39.4TeV

HL-LHC with $\mathcal{L}_{int} = 5\ nb^{-1}$ and $\sqrt{S} = 5.52\ TeV$: $970^{+500}_{-320}\ \eta_c$ events

FCC with $\mathcal{L}_{int} = 110\ nb^{-1}$ and $\sqrt{S} = 39.4\ TeV$: $(1.4^{+0.65}_{-0.43}) \times 10^5\ \eta_c$, 30 η_b, and 640 B_c.

Heavy quarkonium production in UPC

Results: uncertainties

Scale dependence

TABLE II. The LO and NLO total cross sections (in nb) under typical renormalization scale values for $\eta_c + c + \bar{c}$ production via photon-photon fusion in ultraperipheral Pb-Pb collision at $\sqrt{S_{\rm NN}} = 5.52$ and 39.4 TeV. Here, the transverse momentum cut $1\ \text{GeV} \leq p_t \leq 50\ \text{GeV}$ is employed. And the scale $\mu = r\sqrt{4m_c^2 + p_t^2}$ varies by a factor of $r = \{0.5, 1, 2\}$.

r	0.5	1	2
$\sigma_{\rm LO}$ (5.52 TeV)	3.2×10^2	1.7×10^2	1.0×10^2
$\sigma_{\rm NLO}$ (5.52 TeV)	3.2×10^2	1.9×10^2	1.3×10^2
K-factor	1.0	1.2	1.3
$\sigma_{\rm LO}$ (39.4 TeV)	2.0×10^3	1.1×10^3	0.65×10^3
$\sigma_{\rm NLO}$ (39.4 TeV)	2.1×10^3	1.3×10^3	0.86×10^3
K-factor	1.1	1.2	1.3

Mass uncertainties

TABLE III. The LO and NLO total cross sections (in nb) under typical charm quark masses for $\eta_c + c + \bar{c}$ production via photon-photon fusion in ultraperipheral Pb-Pb collision at $\sqrt{S_{\rm NN}} = 5.52$ and 39.4 TeV. Here, $\mu = \sqrt{4m_c^2 + p_t^2}$ and the transverse momentum cut $1\ \text{GeV} \leq p_t \leq 50\ \text{GeV}$ is employed. And the charm quark masses are $m_c = \{1.4, 1.5, 1.6\}$ GeV.

m_c (GeV)	1.4	1.5	1.6
$\sigma_{\rm LO}$ (5.52 TeV)	2.6×10^2	1.7×10^2	1.1×10^2
$\sigma_{\rm NLO}$ (5.52 TeV)	2.9×10^2	1.9×10^2	1.3×10^2
K-factor	1.1	1.2	1.2
$\sigma_{\rm LO}$ (39.4 TeV)	1.6×10^3	1.1×10^3	0.72×10^3
$\sigma_{\rm NLO}$ (39.4 TeV)	1.9×10^3	1.3×10^3	0.88×10^3
K-factor	1.2	1.2	1.2

Heavy quarkonium production in UPC

Results: cross sections in different collision systems and transverse momentum distribution

Cross sections in different collision systems

TABLE IV. The LO and NLO total cross sections (in nb) for $\eta_c + c + \bar{c}$ production via photon-photon fusion in various ultraperipheral nucleon-nucleon colliding systems. Here $\mu = \sqrt{4m_c^2 + p_t^2}$, and transverse momentum cut 1 GeV $\leq p_t \leq$ 50 GeV is employed for η_c. Note, different colliding systems have different nucleon-nucleon c.m. energies, see texts for details.

Nucleon	Pb-Pb	Xe-Xe	Kr-Kr	Ca-Ca	Ar-Ar	O-O
$\sigma_{\rm LO}$	1.7×10^2	41	11	1.4	0.83	0.046
$\sigma_{\rm NLO}$	1.9×10^2	46	12	1.6	0.94	0.052
K-factor	1.2	1.1	1.1	1.1	1.1	1.1

Ratios of cross sections for different ions are mainly determined by the quartic ion charge Z^4

p_t distribution

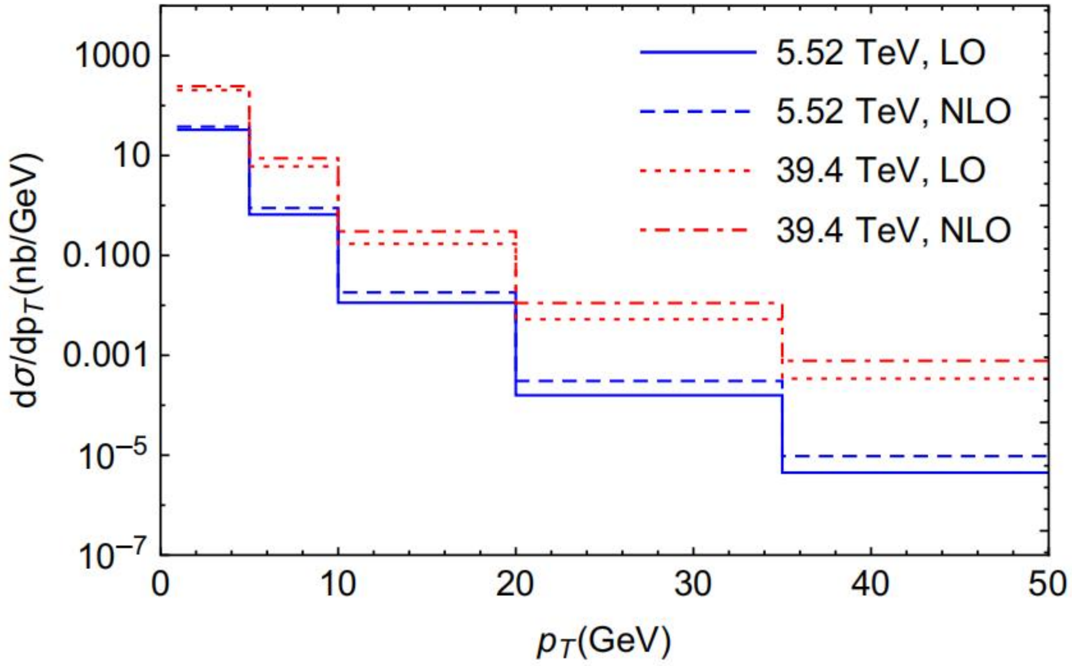

FIG. 1. The differential transverse momentum distribution $d\sigma/dp_t$ of η_c for the $\eta_c + c + \bar{c}$ production via photon-photon fusion in ultraperipheral Pb-Pb collision at $\sqrt{S_{\rm NN}} = 5.52$ and 39.4 TeV. Here, $\mu = \sqrt{4m_c^2 + p_t^2}$ and the transverse momentum cut 1 GeV $\leq p_t \leq$ 50 GeV is employed.

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Doubly heavy baryon and tetraquark production in UPC

NRQCD

- The NRQCD factorization framework is developed to study the production and decay of heavy quarkonia, which are factored into perturbative short-distance coefficients and non-perturbative matrix elements.
- The double expansion are over the QCD runing coupling and the relative velocity between heavy constituent quarks.

G. T. Bodwin, E. Braaten and G. P. Lepage, PRD 51, 1125 (1995) [erratum: PRD 55, 5853 (1997)];
A. Petrelli, *et al.*, NPB 514, 245 (1998);
P. L. Cho, A. K. Leibovich, PRD 53 (1996) 150.

Extension of NRQCD

✓ Zhang and Ma extend the NRQCD framework to explore the fully heavy tetraquak states for both compact and molecule configurations.

$$a_{T_C}^{\dagger}(P,J,J_z,a) = \sqrt{\frac{2}{M}}\left(\sqrt{\frac{2}{m_{cc}}}\frac{1}{\sqrt{2}}\right)\left(\sqrt{\frac{2}{m_{\bar{c}\bar{c}}}}\frac{1}{\sqrt{2}}\right)\Psi_C^{Ja}(\mathbf{0}) \times \sum_{\lambda_1\lambda_2} C_{JJ_z}^{\lambda_2\lambda_2} \sum_{\sigma_1\sigma_2\sigma_3\sigma_4} C_{\lambda\lambda_1}^{\sigma_1\sigma_2} C_{\lambda\lambda_2}^{\sigma_3\sigma_4} \sum_{ijkl} G_{ijkl}^{a} \times a_c^{\dagger}\left(\frac{P}{4},\sigma_1,i\right) a_c^{\dagger}\left(\frac{P}{4},\sigma_2,j\right) a_{\bar{c}}^{\dagger}\left(\frac{P}{4},\sigma_3,k\right) a_{\bar{c}}^{\dagger}\left(\frac{P}{4},\sigma_4,l\right)$$

$$a_{T_M}^{\dagger}(P,J,J_z) = \sum_{\lambda_1\lambda_2} C_{JJ_z}^{\lambda_1\lambda_2} \int \frac{\mathrm{d}^3q}{(2\pi)^3} \frac{2P^0}{(P^0)^2-4(q^0)^2} \times \tilde{\psi}_M(q) a_{J/\psi}^{\dagger}\left(\frac{P}{2}+q,\lambda_1\right) a_{J/\psi}^{\dagger}\left(\frac{P}{2}-q,\lambda_2\right)$$

H.-F. Zhang, X.-M. Mo, Y.-P. Yan, PRD 110 (2024), 096021;
H.-F. Zhang, Y.-Q. Ma, arXiv:2009.08376.

Doubly heavy baryon and tetraquark production in UPC

Diquark fragmentation model

- In some literatures, also named extension of NRQCD framework, which is also used to study the production of doubly heavy baryon and doubly heavy tetraquark.

Step 1: **diquark** with definite quantum number and color

Relation of spin chains between diquark and quarkonium: $(-1)^{\rho+1}$

Colored objects: $\mathbf{3} \otimes \mathbf{3} = \bar{\mathbf{3}} \oplus \mathbf{6}$

Step 2: **hadronization of diquark**

Diquark-antiquark symmetry for anti-3 color: fragmentation function $(QQ)^{\bar{\mathbf{3}}} \longleftrightarrow \bar{Q}^{\bar{\mathbf{3}}}$

Other descriptions: potential models, experimantal fitting

J. P. Ma and Z. G. Si, PLB 568 (2003) 135;
Y. Jin, *et al.*, PRD 89 (2014) 094006;
J. Jiang, *et al.*, PRD 86 (2012), 054021;
T. Hyodo, *et al.*, PLB 721 (2013) 56;
J. Jiang, *et al.*, PLB 866 (2025) 1395435.
etc.

Born-Oppenheimer EFT

One Born–Oppenheimer Effective Theory to rule them all:
hybrids, tetraquarks, pentaquarks, doubly heavy baryons and quarkonium

M. Berwein, *et al.*, PRD 110 (2024), 094040.

Doubly heavy baryon and tetraquark production in UPC

Results: cross sections for $\gamma\gamma \to \Xi_{cc} + \overline{cc}$

TABLE II. The cross sections for $\gamma + \gamma \to \Xi_{cc}[cc, n] + \bar{c}\bar{c}$ through UPCs at the HL-LHC and FCC.

Collisions	$\sqrt{s_{NN}}$ (TeV)	$\Xi_{cc}[cc, {}^3S_1\text{-}\bar{\mathbf{3}}]$	$\Xi_{cc}[cc, {}^1S_0\text{-}\mathbf{6}]$	Total	$N_{\Xi_{cc}}$
Pb-Pb	5.52	270 nb	9.53 nb	279.5 nb	1.40×10^3
Xe-Xe	5.86	65.9 nb	2.38 nb	68.28 nb	2.05×10^3
Kr-Kr	6.46	17.8 nb	0.663 nb	18.46 nb	2.21×10^3
Ar-Ar	6.3	1.36 nb	0.0518 nb	1.411 nb	1.55×10^3
Ca-Ca	7.0	2.31 nb	0.0886 nb	2.398 nb	1.92×10^3
O-O	7.0	77.1 pb	3.03 pb	80.13 pb	9.61×10^2
p-Pb	8.8	203 pb	8.33 pb	211.33 pb	2.11×10^2
p-p	14	89.6 fb	3.99 fb	93.59 fb	1.43×10^4
Pb-Pb	39.4	1780 nb	74.5 nb	1854 nb	2.04×10^5
p-Pb	62.8	728 pb	32.8 pb	760.8 pb	2.20×10^4
p-p	100	233 fb	10.9 fb	243.9 fb	2.44×10^5

Probability for light quarks: $u : d : s = 1 : 1 : 0.3$
$Br(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+) \approx 10\%$
$Br(\Lambda_c^+ \to p K^- \pi^+) \approx 5\%$

Considering detection efficiencies, observation of Ξ_{cc}^{++} at FCC may be expected.

Doubly heavy baryon and tetraquark production in UPC

Results: uncertainties for $\gamma\gamma \rightarrow \Xi_{cc} + \overline{cc}$

TABLE III. The cross sections for $\Xi_{cc}[cc, {}^3S_1\text{-}\bar{\mathbf{3}}]$ ($\Xi_{cc}[cc, {}^1S_0\text{-}\mathbf{6}]$) (in unit of nanobarn) under different m_c and renormalization scales through ultraperipheral Pb-Pb collision at 5.52 TeV.

μ	m_c (GeV) 1.7	1.8	1.9
$\frac{1}{2}\sqrt{4m_c^2 + p_T^2}$	752 (25.8)	496 (16.9)	334 (11.4)
$\sqrt{4m_c^2 + p_T^2}$	404 (14.3)	271 (9.53)	185 (6.48)
$2\sqrt{4m_c^2 + p_T^2}$	252 (9.09)	170 (6.10)	117 (4.18)

Doubly heavy baryon and tetraquark production in UPC

Results: differential distributions for $\gamma\gamma \to \Xi_{cc} + \overline{cc}$

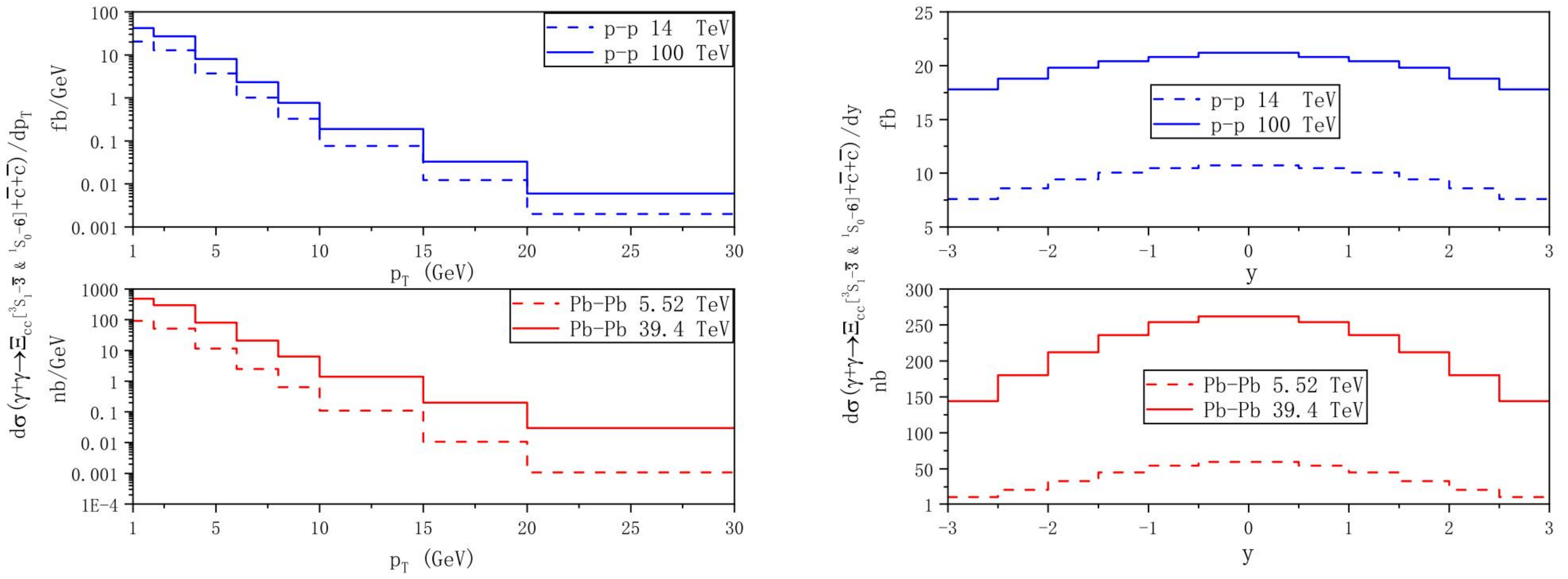


FIG. 5. The transverse momentum p_T and rapidity y distributions for Ξ_{cc} production via ultraperipheral collisions. Here, for the p_T distribution, y is cut to be $[-3, 3]$; for the y distribution, p_T is cut to be 1–30 GeV.

Doubly heavy baryon and tetraquark production in UPC

Results: cross sections $\gamma\gamma \to \Xi_{bc} + \overline{bc}$

TABLE IV. The cross sections for $\gamma + \gamma \to \Xi_{bc}[bc, n] + \bar{b}\bar{c}$ through UPCs at the HL-LHC and FCC.

Collisions	$\sqrt{s_{NN}}$ (TeV)	$\Xi_{bc}[bc, {}^3S_1\text{-}\bar{\mathbf{3}}]$	$\Xi_{bc}[bc, {}^3S_1\text{-}\mathbf{6}]$	$\Xi_{bc}[bc, {}^1S_0\text{-}\bar{\mathbf{3}}]$	$\Xi_{bc}[bc, {}^1S_0\text{-}\mathbf{6}]$	Total
Pb-Pb	5.52	850 pb	425 pb	335 pb	167.5 pb	1777 pb
Xe-Xe	5.86	221 pb	110 pb	88 pb	44 pb	463 pb
Kr-Kr	6.46	64.3 pb	32.1 pb	25.8 pb	12.9 pb	135.1 pb
Ar-Ar	6.3	5.16 pb	2.58 pb	2.08 pb	1.04 pb	10.86 pb
Ca-Ca	7.0	8.94 pb	4.47 pb	3.62 pb	1.81 pb	18.84 pb
O-O	7.0	315 fb	157 fb	128 fb	64 fb	664 fb
p-Pb	8.8	910 fb	455 fb	374 fb	187 fb	1926 fb
p-p	14	0.472 fb	0.236 fb	0.197 fb	0.098 fb	1.003 fb
Pb-Pb	39.4	8.32 nb	4.16 nb	3.44 nb	1.72 nb	17.64 nb
p-Pb	62.8	3.92 pb	1.96 pb	1.65 pb	0.825 pb	8.355 pb
p-p	100	1.36 fb	0.68 fb	0.58 fb	0.29 fb	2.91 fb

Doubly heavy baryon and tetraquark production in UPC

Results: cross sections for $\gamma\gamma \to \Xi_{bb} + \overline{bb}$

Not feasible for Ξ_{bc}/Ξ_{bb}.

TABLE V. The cross sections for $\gamma + \gamma \to \Xi_{bb}[bb, n] + \bar{b}\bar{b}$ through UPCs at the LHC and FCC.

Collisions	$\sqrt{s_{NN}}$ (TeV)	$\sigma(\gamma\gamma \to \Xi_{bb}[bb, {}^3S_1\text{-}\bar{\mathbf{3}}] + \bar{b}\bar{b})$	$\sigma(\gamma\gamma \to \Xi_{bb}[bb, {}^1S_0\text{-}\mathbf{6}] + \bar{b}\bar{b})$	Total
Pb-Pb	5.52	37.0 pb	1.12 pb	38.12 pb
Xe-Xe	5.86	10.2 pb	0.323 pb	10.52 pb
Kr-Kr	6.46	3.18 pb	0.105 pb	3.285 pb
Ar-Ar	6.3	265 fb	9.09 fb	274.1 fb
Ca-Ca	7.0	470 fb	16.3 fb	486.3 fb
O-O	7.0	17.4 fb	0.629 fb	18.02 fb
p-Pb	8.8	54.1 fb	2.08 fb	56.18 fb
p-p	14	32 ab	1.4 ab	33.4 ab
Pb-Pb	39.4	514 pb	20.4 pb	534.4 nb
p-Pb	62.8	273 fb	12 fb	285 fb
p-p	100	101 ab	4.74 ab	105.7 ab

Doubly heavy baryon and tetraquark production in UPC

Results: cross sections for $g\gamma \to \Xi_{cc} + \overline{cc}$ Nuclear gluon PDFs: NNPDF

TABLE VI. The cross sections for $g + \gamma \to \Xi_{cc}[cc, n] + \bar{c}\,\bar{c}$ through elastic photoproduction at the HL-LHC and FCC. The cross sections in brackets are the contributions from $\gamma + g$ channel, which are different from $g + \gamma$ channel in the p-Pb collision; while the two contributions are absolutely equal for same ions collision, e.g., Pb-Pb. The total cross sections contain all the $g + \gamma$ and $\gamma + g$ channels.

Collisions	$\sqrt{s_{NN}}$ (TeV)	$\Xi_{cc}[cc, {}^3S_1\text{-}\bar{\mathbf{3}}]$	$\Xi_{cc}[cc, {}^1S_0\text{-}\mathbf{6}]$	Total	$N_{\Xi_{cc}}$
Pb-Pb	5.52	82.9 μb	7.09 μb	179.98 μb	9.00×10^5
Xe-Xe	5.86	24.9 μb	2.14 μb	54.08 μb	1.62×10^6
Kr-Kr	6.46	8.34 μb	0.72 μb	18.12 μb	2.17×10^6
Ar-Ar	6.3	1.08 μb	0.094 μb	2.35 μb	2.58×10^6
Ca-Ca	7.0	1.46 μb	0.127 μb	3.17 μb	2.53×10^6
O-O	7.0	108 nb	9.44 nb	234.88 nb	2.81×10^6
p-Pb	8.8	628 (44.2) nb	54.2 (4.01) nb	730.41 nb	7.30×10^5
p-p	14	325 pb	29.6 pb	709.2 pb	1.06×10^8
Pb-Pb	39.4	374 μb	34.3 μb	816.6 μb	8.98×10^7
p-Pb	62.8	2.75(0.14) μb	0.25(0.013) μb	3.15 μb	9.13×10^7
p-p	100	1090 pb	103 pb	2386 pb	2.38×10^9

Feasible!

Doubly heavy baryon and tetraquark production in UPC

Results: differential distributions for $g\gamma \rightarrow \Xi_{cc} + \overline{cc}$

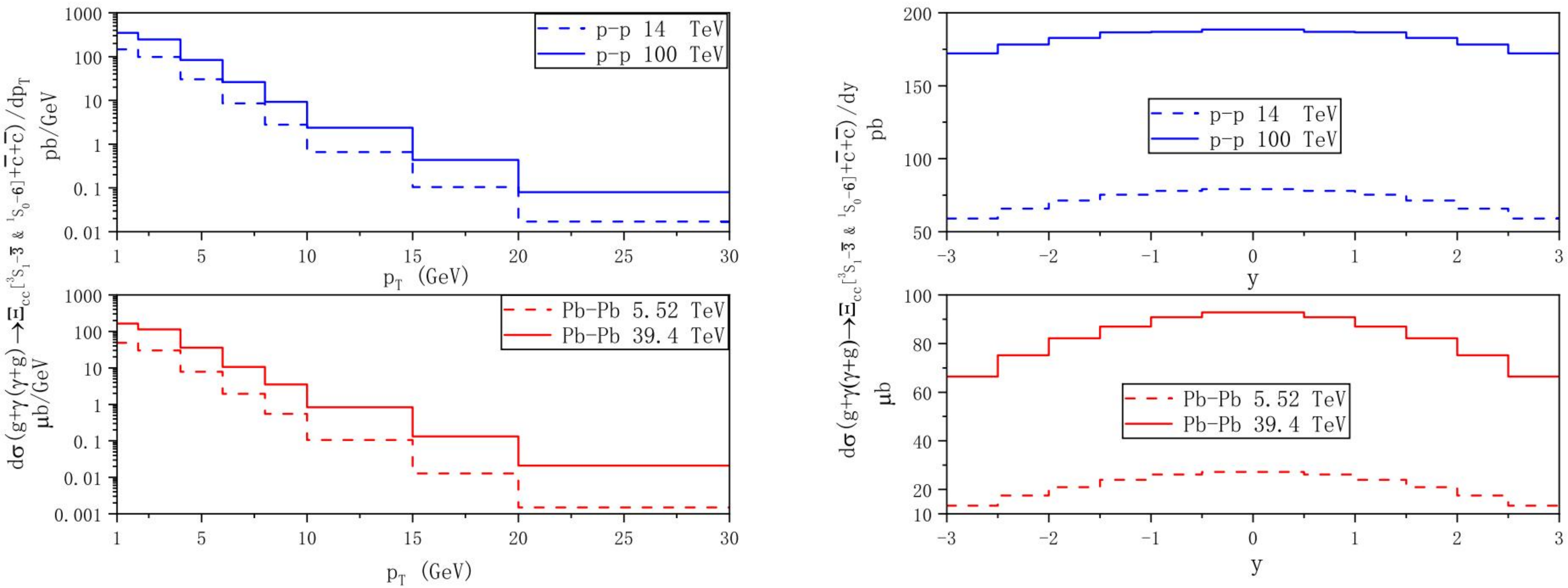


FIG. 6. The transverse momentum p_T and rapidity y distributions for Ξ_{cc} production via semielastic ion-ion collisions. Here, for the p_T distribution, y is cut to be $[-3, 3]$; for the y distribution, p_T is cut to be 1–30 GeV.

Doubly heavy baryon and tetraquark production in UPC

Results: cross sections for $g\gamma \to \Xi_{bc} + \overline{bc}$

Four spin-color states are comparable.

Open for Ξ_{bc}, especially at FCC.

TABLE VII. The cross sections for $g + \gamma \to \Xi_{bc}[bc, n] + \bar{b}\bar{c}$ through elastic photoproduction at the HL-LHC and FCC. The cross sections in brackets are the contributions from the $\gamma + g$ channel, which are different from the $g + \gamma$ channel in the p-Pb collision; while the two contributions are absolutely equal for the same ion collisions. The total cross sections contain all the $g + \gamma$ and $\gamma + g$ channels.

Collisions	$\sqrt{s_{NN}}$ (TeV)	$\Xi_{bc}[bc, {}^3S_1\text{-}\bar{\mathbf{3}}]$	$\Xi_{bc}[bc, {}^3S_1\text{-}\mathbf{6}]$	$\Xi_{bc}[bc, {}^1S_0\text{-}\bar{\mathbf{3}}]$	$\Xi_{bc}[bc, {}^1S_0\text{-}\mathbf{6}]$	Total
Pb-Pb	5.52	619 nb	530 nb	184 nb	129 nb	2924 nb
Xe-Xe	5.86	193 nb	165 nb	57.9 nb	40.3 nb	912.4 nb
Kr-Kr	6.46	67.8 nb	57.8 nb	20.4 nb	14.1 nb	320.2 nb
Ar-Ar	6.3	8.88 nb	7.57 nb	2.67 nb	1.85 nb	41.94 nb
Ca-Ca	7.0	12.3 nb	10.5 nb	3.72 nb	2.57 nb	58.18 nb
O-O	7.0	932 pb	792 fb	281 pb	194 pb	4398 pb
p-Pb	8.8	5.07 (0.48) nb	4.32 (0.40) nb	1.52 (0.15) nb	1.06 (0.10) nb	13.1 nb
p-p	14	3.64 pb	3.06 pb	1.12 pb	0.76 pb	17.16 pb
Pb-Pb	39.4	4334 nb	3635 nb	1338 nb	907 nb	20.4 μb
p-Pb	62.8	32.5 (2.10) nb	27.2 (1.75) nb	10.0 (0.65) nb	6.81 (0.44) nb	81.45 nb
p-p	100	15.7 pb	13.0 pb	4.91 pb	3.29 pb	73.8 pb

Doubly heavy baryon and tetraquark production in UPC

Results: cross sections for $g\gamma \rightarrow \Xi_{bb} + \overline{bb}$

TABLE VIII. The cross sections for $g+\gamma \rightarrow \Xi_{bb}[bb,n] + \bar{b}\bar{b}$ through elastic photoproduction at the HL-LHC and FCC. The cross sections in brackets are the contributions from $\gamma + g$ channel, which are different from $g+\gamma$ channel in the p-Pb collision; while the two contributions are absolutely equal for same ion collisions. The total cross sections contains all the $g+\gamma$ and $\gamma+g$ channels.

Collisions	$\sqrt{s_{NN}}$ (TeV)	$\sigma(g\gamma \rightarrow \Xi_{bb}[bb,{}^3S_1\text{-}\bar{\mathbf{3}}] + \bar{b}\bar{b})$	$\sigma(g\gamma \rightarrow \Xi_{bb}[bb,{}^1S_0\text{-}\mathbf{6}] + \bar{b}\bar{b})$	Total
Pb-Pb	5.52	60.0 nb	4.81 nb	129.62 nb
Xe-Xe	5.86	19.2 nb	1.56 nb	41.52 nb
Kr-Kr	6.46	6.96 nb	0.57 nb	15.06 nb
Ar-Ar	6.3	920 pb	75.6 pb	1991 pb
Ca-Ca	7.0	1299 pb	107 pb	2812 pb
O-O	7.0	99.5 pb	8.27 pb	215.5 pb
p-Pb	8.8	523 (58.8) pb	42.9 (5.11) pb	629.8 pb
p-p	14	454 fb	39.8 fb	987.6 fb
Pb-Pb	39.4	546 nb	48.1 nb	1188 nb
p-Pb	62.8	4.17 (0.30) nb	0.37 (0.027) nb	4.867 nb
p-p	100	2245 fb	206 fb	4902 fb

NOT Feasible.

Doubly heavy baryon and tetraquark production in UPC

Results: cross sections for T_{cc}

Diquark-antiquark symmetry $c \to \Lambda_c^+ \Leftrightarrow (cc) \to T_{cc}^+$

$$f(c \to \Lambda_c^+) \approx \frac{\sigma(T_{cc})}{\sigma(\Xi_{cc}) + \sigma(T_{cc})} = 20.4\%$$

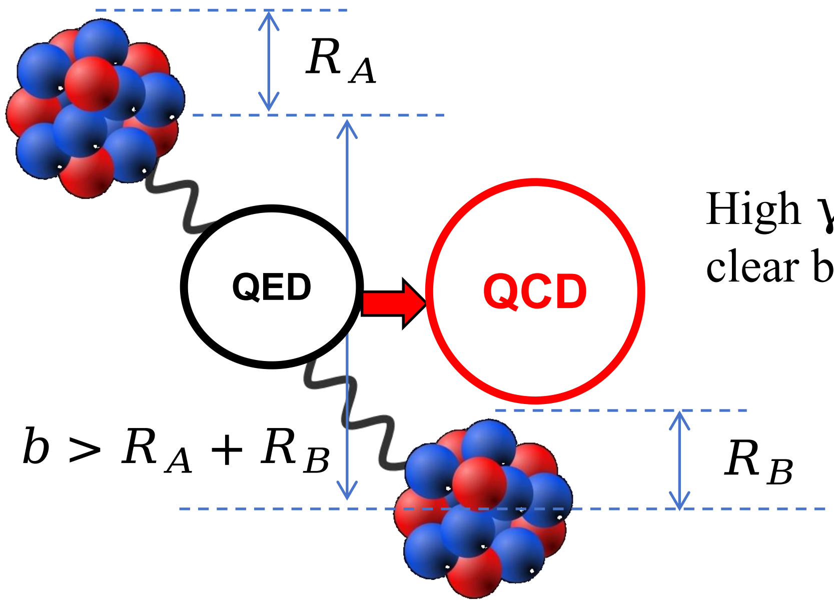
$$\sigma(T_{cc}) = \sigma(\Xi_{cc}) \times 25.6\%$$

$$Br(T_{cc} \to D^0 D^0 \pi^+) \approx 100\% \text{ and } Br(D^0 \to K^- \pi^+) \approx 3.94\%$$

For $\gamma\gamma$ interaction, 81 events for Pb-Pb UPC and 96 for pp UPC at FCC, unexpected at HL-LHC.
For γg interaction, 357 events for Pb-Pb UPC and 4×10^4 for pp UPC at HL-LHC, higher at FCC.

Contents

Summary and prospects



High $\gamma\gamma$ center of mass energy,
clear background for QCD final states

The heavy ion UPC opens another door of the study on the production of (exotic) doubly heavy hadrons at HL-LHC and FCC!

Backup slides

	Photon	vs	pomeron
J^{PC}	1^{--}		$0^{++}, 2^{++}$(two gluon model, but in Regge theory *J* increases with energy)

To distinguish between photon-Pomeron and photon-photon interactions in UPC,

- Photon-Photon: Particles are more centrally produced due to balanced photon energies from both nuclei.
- Photon-Pomeron: Produced particles may be skewed toward the rapidity region of the Pomeron-emitting nucleus.

- Photon-Photon: Cross-sections scale as Z^4 (photon flux squared).
- Photon-Pomeron: Cross-sections scale as $Z^2 \times A^{1/3}$ reflecting photon flux and nuclear gluon density.

- For exclusive processes, they may be distinguished by the quantum numbers.