ρ^0 production and pion pair production by linearly polarized photons in UPCs and e^+e^- collisions

周雅瑾 (山东大学)

based on: arxiv:2406.09381 (贾宇，周剑，YZ)，JHEP10(2020)064 (邢宏喜，张成，周剑，YZ)，PRD104, 094021 (2021), PRD103, 074013 (2021) (Yoshikazu Hagiwara，张成，周剑，YZ)

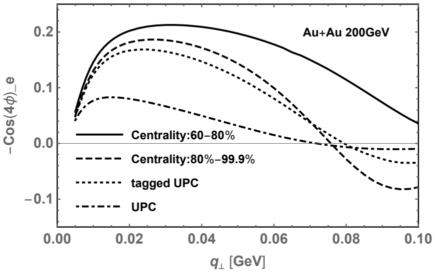
SHANDONG UNIVERSITY, QINGDAO

Outline

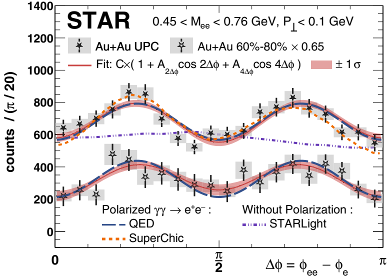
1. EPA, UPC, linearly polarized photon, motivations
2. diffractive vector meson (ρ^0) production in UPCs
3. Pion pair production in e^+e^- collisions and UPCs
4. Summary

Linearly polarized photon in UPCs verified by STAR collaboration

Azimuthal asymmetries in $\gamma\gamma \to e^+e^-$



C. Li, J. Zhou and YZ, 2020



STAR collaboration, PRL127, 052302 (2021)

	Measured	QED calculation
Tagged UPC	16.8%±2.5%	16.5%
60%-80%	27%±6%	34.5%

VERIFIED!

Equivalent photon approximation(EPA), Ultraperipheral collisions (UPCs)

relativistically moving ions will introduce electromagnetic field.

Equivalent photon approximation(EPA)
1924, Fermi;
Weizäscker and Williams, 1930's;

$$xf_1^\gamma(x, k_\perp^2) = \frac{Z^2\alpha_e}{\pi^2} k_\perp^2 \left[\frac{F(k_\perp^2 + x^2M_p^2)}{(k_\perp^2 + x^2M_p^2)}\right]^2$$

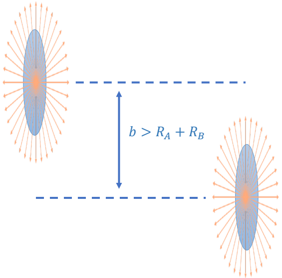
Woods-Saxon form factor,

$$F(\vec{k}^2) = \int d^3r e^{i\vec{k}\cdot\vec{r}} \frac{\rho^0}{1 + \exp\left[(r - R_{WS})/d\right]}$$

$\gamma - \gamma$: $d\sigma \propto Z^4$, e.g., $79^4 \approx 4$ 千万
$\gamma - A$: $d\sigma \propto Z^2$

But! strong interaction dominant in center collisions

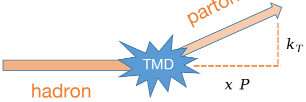
UPC:
Two nuclei physically miss each other, interact (only) electromagnetically

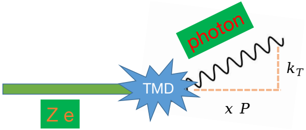


clean background

Linearly polarized photon

relativistically moving charged particles will introduce electromagnetic field
the photons are linearly polarized due to their transverse momentum





gluon/photon TMD (transverse-momentum-dependent) factorization:

$$\int \frac{2dy^- d^2y_\perp}{xP^+(2\pi)^3} e^{ik\cdot y} \langle P|F_+^\mu(0)F_+^\nu(y)|P\rangle\Big|_{y^+=0} = \delta_\perp^{\mu\nu} f_1(x, k_\perp^2) + \left(\frac{2k_\perp^\mu k_\perp^\nu}{k_\perp^2} - \delta_\perp^{\mu\nu}\right) h_1^\perp(x, k_\perp^2),$$

Mulders, Rodrigues, PRD63(2001)

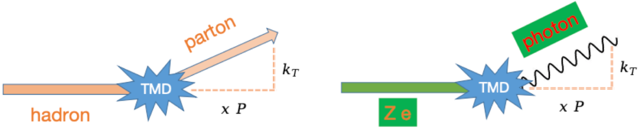
$\boxed{f_1(x, k_\perp^2) = h_1^\perp(x, k_\perp^2)}$, small-x gluons/photons are highly linearly polarized.

A. Metz and J. Zhou, 2011, C. Li, J. Zhou and YZ, 2019

Collinear factorization: $\sigma \sim$ PDFs(x) $\otimes$ hard part
TMD factorization: $\sigma \sim$ TMDs(x,k_T) $\otimes$ hard part

Linearly polarized photon

relativistically moving charged particles will introduce electromagnetic field
the photons are linearly polarized due to their transverse momentum



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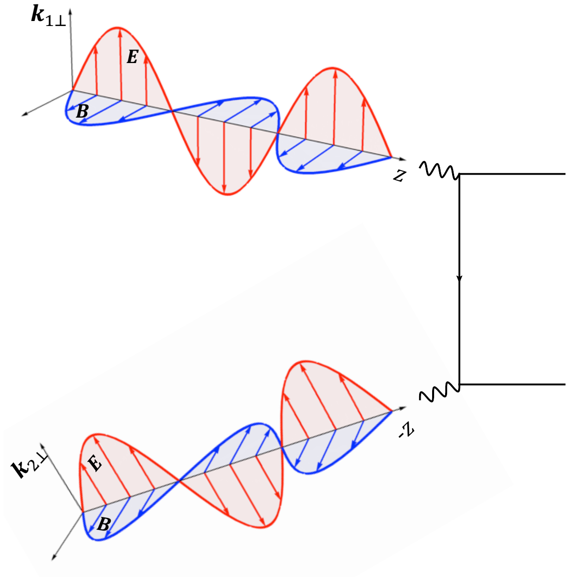
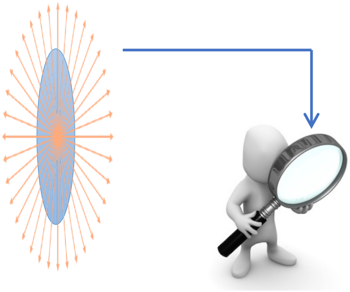
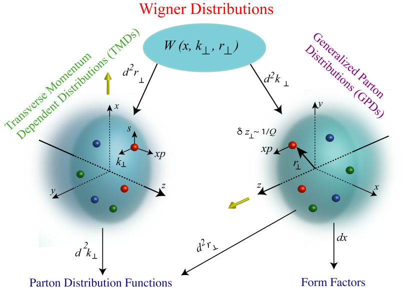

$k_{1\perp}$
E
B
z
$k_{2\perp}$
E
B
-z

UPC: an ideal platform to "see" nucleus

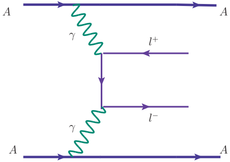


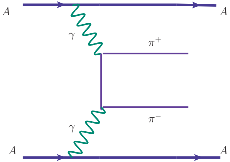


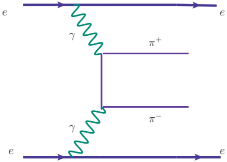
- linearly polarized photon
- high luminosity
- clean background
- ...

How? photo-nuclear diffractive production of vector mesons, di-jets...

Direct vector meson pair photoproduction in UPCs, e^+e^- colliders





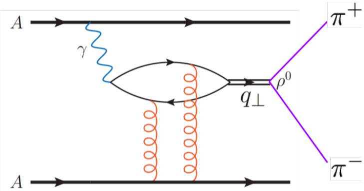


similar to $\gamma\gamma \to \mathrm{l}^+\mathrm{l}^-$, we can also study $\gamma\gamma \to \mathrm{M}\bar{\mathrm{M}}$ process either in UPCs or at $\mathrm{e}^+\mathrm{e}-$ colliders, more complicated.

I will talk about

- Topic I: diffractive vector meson (ρ^0) production in UPCs
- Topic II: pion pair production in e^+e^- collisions and UPCs

vector meson production in UPCs



$\phi = p_\perp^\pi \wedge q_\perp$ (ρ^0 and π's transverse momentum)
observable induced by polarized photon:

$$\langle \cos(n\phi) \rangle = \frac{\int \frac{d\sigma}{d\mathcal{P}.\mathcal{S}.} \cos(n\phi)\, d\mathcal{P}.\mathcal{S}.}{\int \frac{d\sigma}{d\mathcal{P}.\mathcal{S}.} d\mathcal{P}.\mathcal{S}.}$$

$$\mathcal{A}(\Delta_\perp) = i \int d^2 b_\perp e^{i\Delta_\perp \cdot b_\perp} \int \frac{d^2 r_\perp}{4\pi} \int_0^1 dz\, \Psi^{\gamma \to q\bar{q}}(r_\perp, z, \epsilon_\perp^\gamma) N(r_\perp, b_\perp) \Psi^{V \to q\bar{q}*}(r_\perp, z, \epsilon_\perp^V),$$

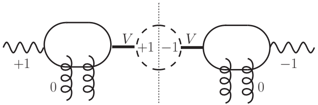
- dipole amplitude calculation:

$$N(b_\perp, r_\perp) = 1 - e^{-2\pi B_p A T_A(b_\perp) \mathcal{N}(r_\perp)}$$

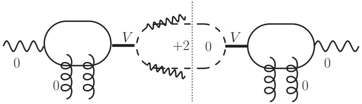
$\mathcal{N}(r_\perp) = 1 - \exp\left[-r_\perp^2 G(x_g, r_\perp)\right]$: dipole-nucleon scattering amplitude
$G(x_g) = \frac{1}{4} Q_s^2(x_g)$: gluon distribution (GBW model),

cartoon illustrations of the azimuthal asymmetries in vector boson production in UPCs

- $\cos 2\phi$ asymmetry

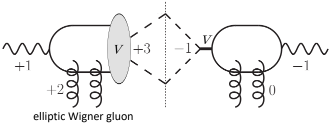


$\langle +1|-1\rangle \sim \cos 2\phi$

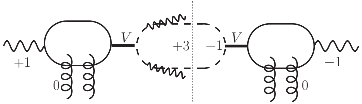


$\langle +2|0\rangle \sim \cos 2\phi$

- $\cos 4\phi$ asymmetry

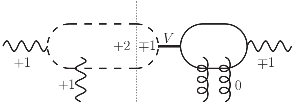


$\langle +3|-1\rangle \sim \cos 4\phi$



$\langle +3|-1\rangle \sim \cos 4\phi$

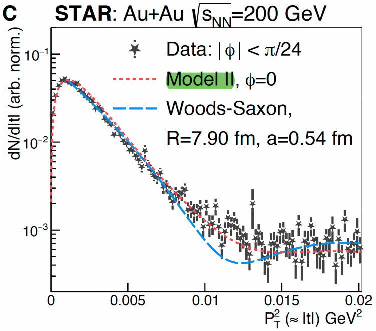
- $\cos\phi$ and $\cos 3\phi$ asymmetries

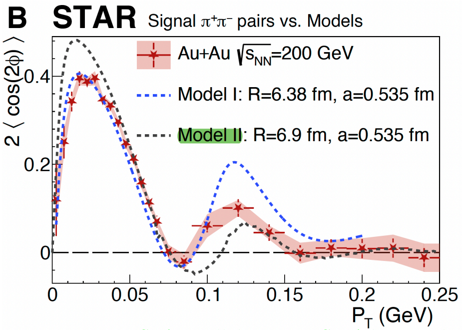


$\langle +2|\mp 1\rangle \sim \cos 3\phi/\cos\phi$

for azimuthal asymmetries in ρ^0 production see:
H.X. Xing, C. Zhang, J. Zhou and YZ, JHEP10(2020)064,
Y. Hagiwara, C. Zhang, J. Zhou and YZ, PRD103, 074013 (2021) and PRD104, 094021 (2021)

- $\cos(2\phi)$ azimuthal asymmetry in $\rho^0 \to \pi\pi$ photoproduction,



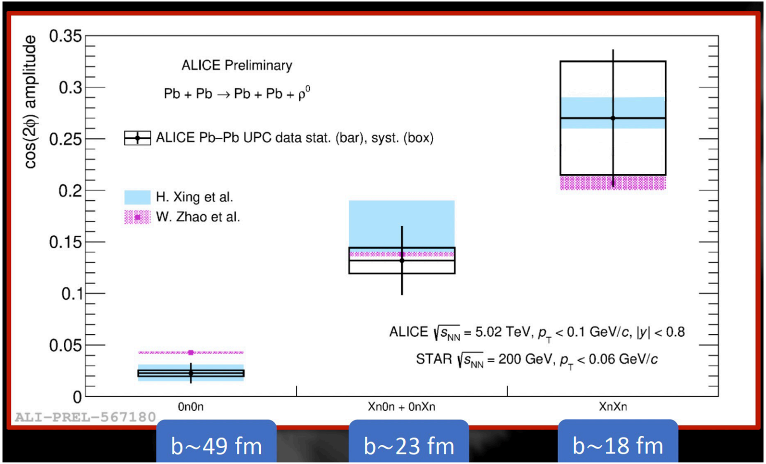


STAR collaboration, Sci.Adv. 9, eabq3903 (2023)

Model II: H.X. Xing, C. Zhang, J. Zhou and YZ, JHEP10(2020)064

Fermi-scale interference effect, linearly polarized photon

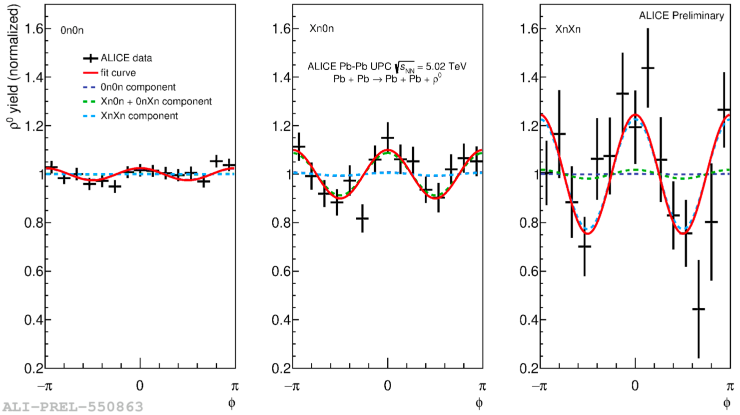
The prediction for the impact parameter dependence is verified by ALICE



SDU-SCNU组: Hongxi Xing, Cheng Zhang, Jian Zhou, Ya-Jin Zhou *JHEP* 10 (2020) 064

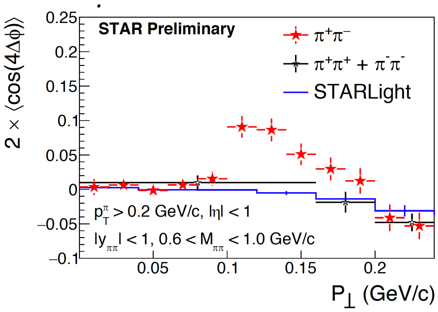
BNL组: Heikki Mäntysaari, Farid Salazar, Björn Schenke, Chun Shen, Wenbin Zhao *Phys.Rev.C* 109 (2024) 2, 024908

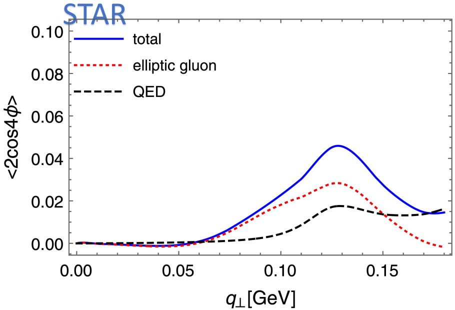
ALICE data



ALICE Collaboration, talk by A. G. Riffero on UPC 2023 (Mexico)

- $\cos(4\phi)$ azimuthal asymmetry in $\rho^0 \to \pi\pi$ photoproduction





Daniel Brandenburg, QM 2019

elliptic gluon Wigner distribution is important to describe the STAR data

Y. Hagiwara, C. Zhang, J. Zhou and YZ, PRD104, 094021 (2021)

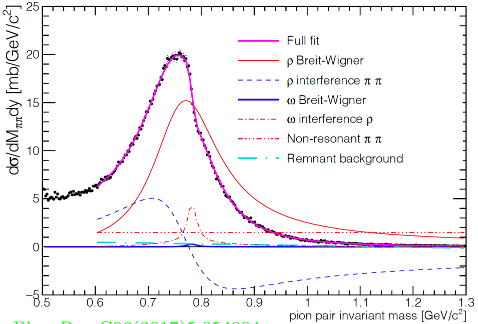
Pion pair production in e^+e^- collisions and UPCs

Motivations:

- $\gamma\gamma \to \mathrm{M\bar{M}}$ is important
- at $p_{\mathrm{M\bar{M}}} \ll p_{\mathrm{M}}$, transverse momenta non-negligible, TMD factorization
- the first attempt to study the azimuthal asymmetry in heavy composite particles
- $\gamma\gamma \to \pi\pi$ is the cleanest and most important one
- may shed light on Light-by-Light (LbL) scattering process mediated by the pion loop
- interdisciplinary study among TMD physics & Chpt & dispersion relation

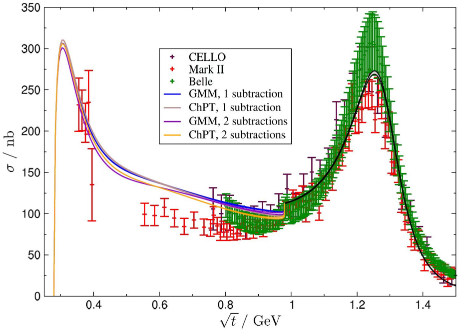
direct pion pair production, e^+e^- collider vs. UPC

UPC : only low invariant mass is possible



STAR, Phys.Rev.C96(2017)5,054904

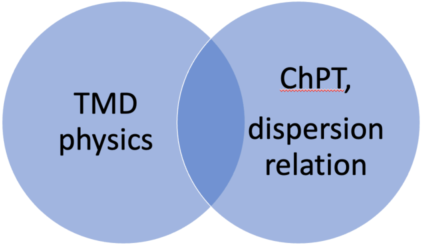
e^+e^- collider, not effected by ρ resonance



Conclusion: to study the polarization effect of poin pair production from $\gamma\gamma$ fusion,

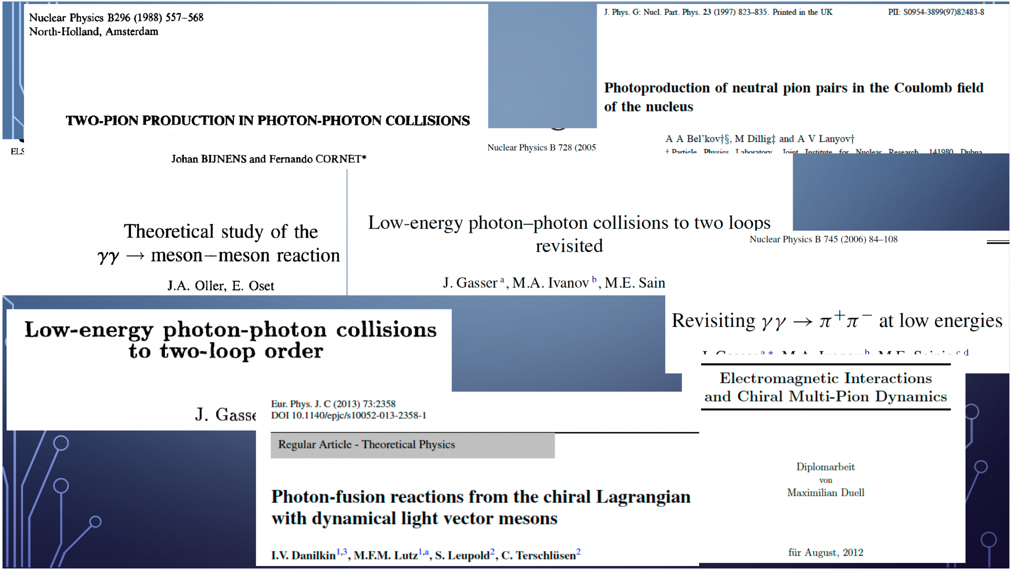
e^+e^- collider is better

Theoretical setup:



Some ChPT calculations for $\gamma\gamma \to \pi\pi$

e.g.,



Nuclear Physics B296 (1988) 557–568
North-Holland, Amsterdam

TWO-PION PRODUCTION IN PHOTON-PHOTON COLLISIONS

Johan BIJNENS and Fernando CORNET*

J. Phys. G: Nucl. Part. Phys. 23 (1997) 823–835. Printed in the UK PII: S0954-3899(97)82483-8

Photoproduction of neutral pion pairs in the Coulomb field of the nucleus

A A Bel'kov†§, M Dillig‡ and A V Lanyov†

Nuclear Physics B 728 (2005

Theoretical study of the
$\gamma\gamma \to$ meson–meson reaction

J.A. Oller, E. Oset

Low-energy photon–photon collisions to two loops revisited

J. Gasser [a], M.A. Ivanov [b], M.E. Sain

Nuclear Physics B 745 (2006) 84–108

Revisiting $\gamma\gamma \to \pi^+\pi^-$ at low energies

Low-energy photon-photon collisions to two-loop order

J. Gasse

Eur. Phys. J. C (2013) 73:2358
DOI 10.1140/epjc/s10052-013-2358-1

Regular Article - Theoretical Physics

Photon-fusion reactions from the chiral Lagrangian with dynamical light vector mesons

I.V. Danilkin[1,3], M.F.M. Lutz[1,a], S. Leupold[2], C. Terschlüsen[2]

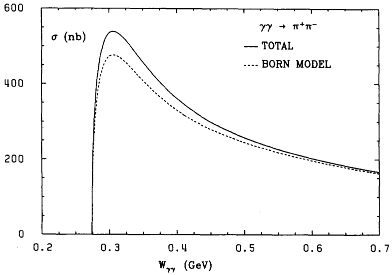
Electromagnetic Interactions and Chiral Multi-Pion Dynamics

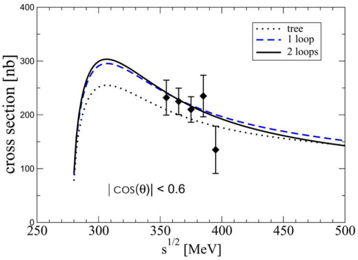
Diplomarbeit
von
Maximilian Duell

für August, 2012

Some ChPT calculations for $\gamma\gamma \to \pi\pi$

e.g.,





J.BIJNENS and F. CORNET, NPB296(1988)557-568

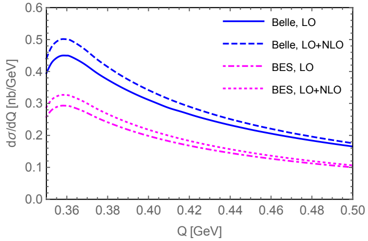
J. Gasser et al., NPB745(2006)84–108

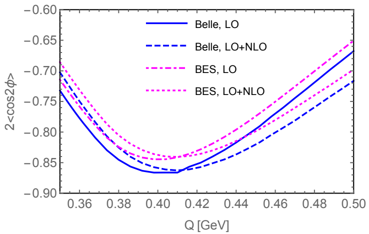
$$A_{\gamma\gamma\to\pi^+\pi^-} = 2ie^2\left\{C\varepsilon_1\cdot\varepsilon_2 - \frac{p_1\cdot\varepsilon_1 p_2\cdot\varepsilon_2}{p_1\cdot k_1} - \frac{p_1\cdot\varepsilon_2 p_2\cdot\varepsilon_1}{p_1\cdot k_2}\right\}$$

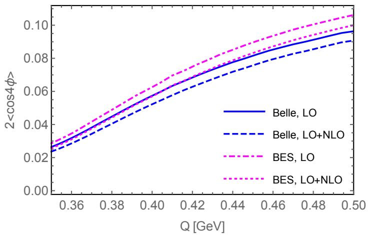
$$C = 1 + \frac{4Q^2}{f_\pi^2}(L_9^r + L_{10}^r) - \frac{1}{16\pi^2 f_\pi^2}\left(\frac{3}{2}Q^2 + \frac{1}{2}m_\pi^2 \ln^2 g_\pi(Q^2) + m_K^2 \ln^2 g_K(Q^2)\right)$$

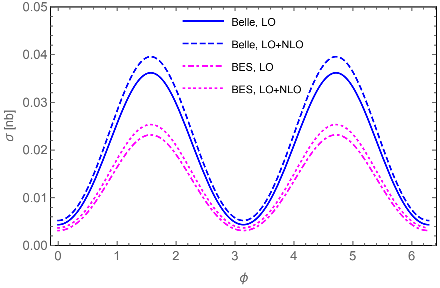
Dipoin production in e^+e^- collider, ChPT

Numerical results:









Dipoin production in e^+e^- collider, data-driven method

Ling-Yun Dai and M.R. Pennington, "Comprehensive Amplitude Analysis of $\gamma\gamma \to \pi^+\pi^-, \pi^0\pi^0$ and $\overline{K}K$ below 1.5 GeV", PRD90, 036004 (2014)

$$\frac{d\sigma}{d\Omega} = \frac{\rho(s)}{128\pi^2 s}[|M_{+-}|^2 + |M_{++}|^2],$$

isospin decomposition of the amplitudes:

$$\mathcal{F}_\pi^{+-}(s) = -\sqrt{\frac{2}{3}}\mathcal{F}_\pi^{I=0}(s) - \sqrt{\frac{1}{3}}\mathcal{F}_\pi^{I=2}(s),$$

$$\mathcal{F}_\pi^{00}(s) = -\sqrt{\frac{1}{3}}\mathcal{F}_\pi^{I=0}(s) + \sqrt{\frac{2}{3}}\mathcal{F}_\pi^{I=2}(s),$$

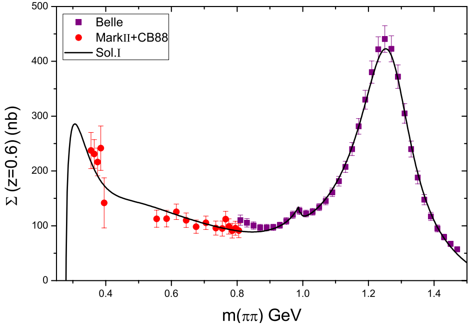
$$\mathcal{F}_K^{+-}(s) = -\sqrt{\frac{1}{2}}\mathcal{F}_K^{I=0}(s) - \sqrt{\frac{1}{2}}\mathcal{F}_K^{I=1}(s),$$

$$\mathcal{F}_K^{00}(s) = -\sqrt{\frac{1}{2}}\mathcal{F}_K^{I=0}(s) + \sqrt{\frac{1}{2}}\mathcal{F}_K^{I=1}(s).$$

partial wave expansions of the amplitudes:

$$M_{++}(s,\theta,\phi) = e^2\sqrt{16\pi}\sum_{J\geq 0} F_{J0}(s) Y_{J0}(\theta,\phi),$$

$$M_{+-}(s,\theta,\phi) = e^2\sqrt{16\pi}\sum_{J\geq 2} F_{J2}(s) Y_{J2}(\theta,\phi).$$



Dipoin production in e^+e^- collider, data-driven method

cross section in helicity amplitude form with linealy polarized photon:

$$
\begin{aligned}
\frac{d\sigma}{d^2p_{1\perp}d^2p_{2\perp}dy_1dy_2} &= \frac{1}{16\pi^2Q^4}\int d^2k_{1\perp}d^2k_{2\perp} \\
\times\ & \delta^2(q_\perp - k_{1\perp} - k_{2\perp})x_1x_2 \\
\times\ & \Big\{\frac{1}{2}\left(|M_{+-}|^2 + |M_{++}|^2\right) f(x_1,k_{1\perp}^2)f(x_2,k_{2\perp}^2) \\
-\ & \cos(2\phi_1)\mathrm{Re}[M_{++}M_{+-}^*]\, f(x_2,k_{2\perp}^2)h_1^\perp(x_1,k_{1\perp}^2) \\
-\ & \cos(2\phi_2)\mathrm{Re}[M_{++}M_{+-}^*]\, f(x_1,k_{1\perp}^2)h_1^\perp(x_2,k_{2\perp}^2) \\
+\ & \frac{1}{2}\Big[\cos 2(\phi_1-\phi_2)|M_{++}|^2 + \cos 2(\phi_1+\phi_2)|M_{+-}|^2\Big] \\
\times\ & h_1^\perp(x_1,k_{1\perp}^2)h_1^\perp(x_2,k_{2\perp}^2)\Big\}
\end{aligned}
$$

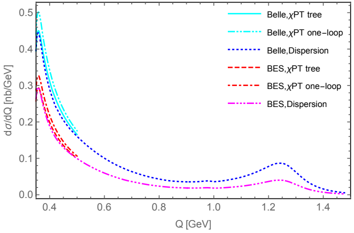
→ Reduce to collinear factorization after integrating over $k_{1,2\perp}$, → $\frac{1}{2}(|M_{++}|^2 + |M_{+-}|^2)ff$

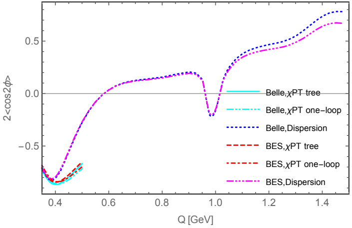
→ Contribute *to* $\cos(2\phi)$ azim. Assym., induced by linearly polarized photon, Involve the relative phase between M_{++} and M_{+-}

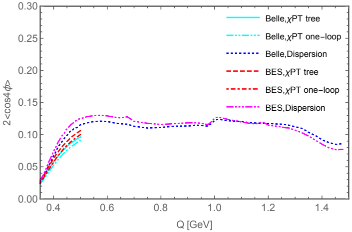
→ Contribute *to* $\cos(4\phi)$ azim. Assym.

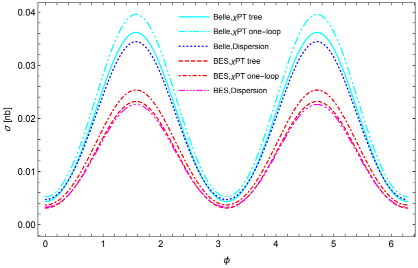
Dipoin production in e^+e^- collider, data-driven method

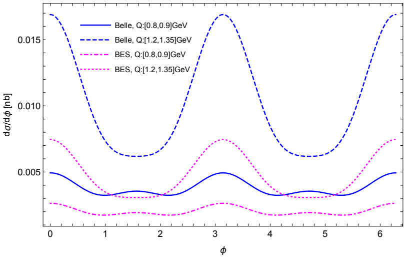
Numerical results: 可以用来直接抽取相因子









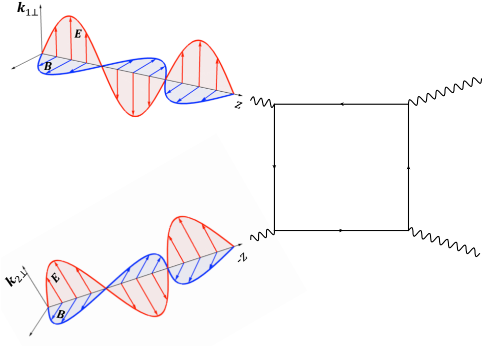


about the light-by-light scattering in UPCs

arXiv:2410.13781

Azimuthal modulation in light-by-light scattering from ultraperipheral collisions at LHC

Yu Jia *,[1] Shuo Lin †,[2] Jian Zhou ‡,[3,4] and Ya-jin Zhou §[3]



UPC物理研究现状及国际动态

- **国内UPC物理研究团队：** 中国科技大学，复旦大学，华南师范大学，山东大学...

- **UPC物理实验研究：** STAR, ALICE, ATLAS, CMS

- **综述文章：** Snowmass UPC 专题， 物理学报编辑推荐

EF07: Ultra-Peripheral Collisions in Heavy-Ion Physics

Jaroslav Adam[2], Carlos Bertulani[12], James D. Brandenburg[2], Frank Geurts[7], Victor P. Goncalves[5], Yoshitaka Hatta[2], Yongsun Kim[13], Spencer R. Klein[4], Cong Li[3], Wei Li[7], Michael Murray[6], Joakim Nystrand[9], Mariusz Przybycien[1,*], John P. Ralston[6], Christophe Royon[6], Lijuan Ruan[2], Bjoern Schenke[2], Janet Seger[10], Peter Steinberg[2], Daniel Tapia Takaki[6], Zebo Tang[11], Zhoudunming Tu[2], Ralf Ulrich[14], Ramona Vogt[4], Bowen Xiao[8], Zhangbu Xu[2,*], Shuai Yang[7], Wangmei Zha[11], Jian Zhou[3,*], and Ya-jin Zhou[3]

专题：高能重离子碰撞过程的自旋与手征效应 编辑推荐

高能重离子超边缘碰撞中极化光致反应

浦实, 肖博文, 周剑, 周雅瑾

物理学报, 2023, 72(7): 072503. doi: 10.7498/aps.72.20230074

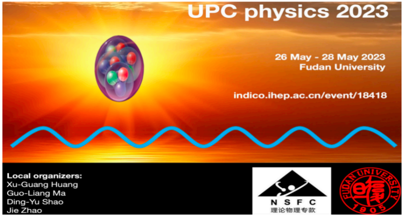
Coherent photons induced high energy reactions in ultraperipheral heavy ion collisions

Pu Shi, Xiao Bo-Wen, Zhou Jian, Zhou Ya-Jin

Acta Phys. Sin., 2023, 72(7): 072503. doi: 10.7498/aps.72.20230074

UPC专题会议系列

第一届中国UPC会议



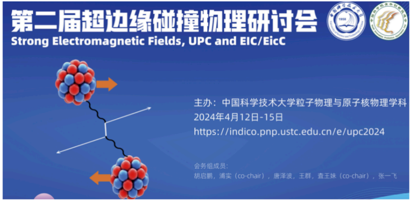
第一届国际UPC会议

UPC 2023: International workshop on the physics of Ultra Peripheral Collisions

11–15 Dec 2023
Playa del Carmen

Enter your search term

第二届中国UPC会议



第二届国际UPC会议将在芬兰University of Jyvaskyla举办

Summary

- UPC 光子是线性极化的，使之成为探索核子三维结构的优秀平台
- e^+e^- 光子融合直接产生 dipion，由于光子的线性极化，会有非常大的 cos2phi 效应，可以用来直接抽取相因子, 对理解 $f_2(1270)$ 这种 C even 共振态可能有用