重离子超边缘对撞(UPC)物理近期进展

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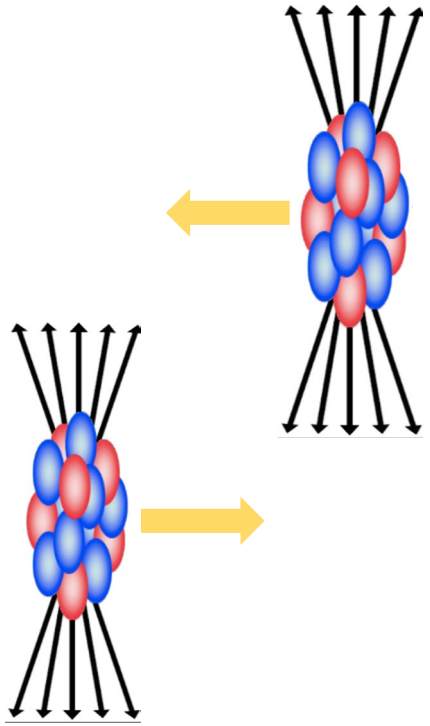
Outline：

- Background
- Photon-photon interactions in UPCs
- Photon-nuclear interactions in UPCs
- Summary

Focus on theory side, for experimental side, Wangmei's talk

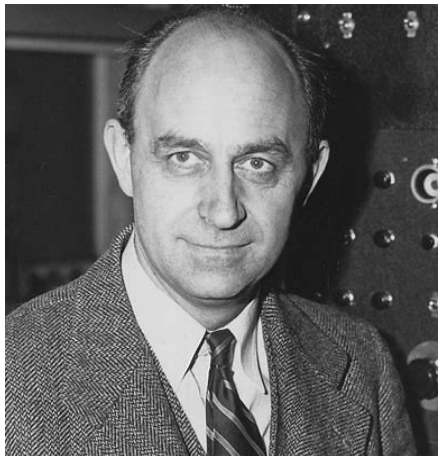
Relativistic heavy ion is extremely bright!



Time evolution of EM field
Deng-Huang, 2012

◆ Treated as a flux of quasi-photons

E. Fermi, 1924
Weizascker--Williams 1934



□ Photon wave length > R, i.e. k_t<30MeV, enhanced by Z^2

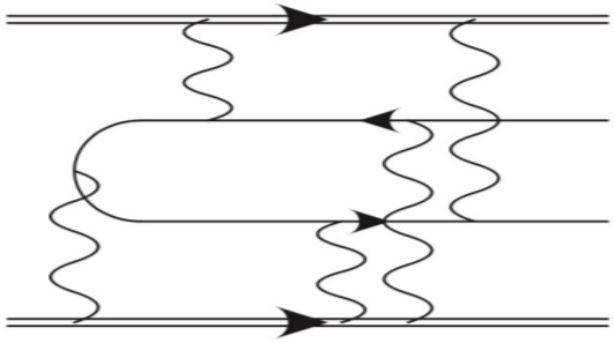
Two type interactions:

- photon-photon collisions
- photon-nuclear interactions

Photon-photon interactions

BSM & strong field QED

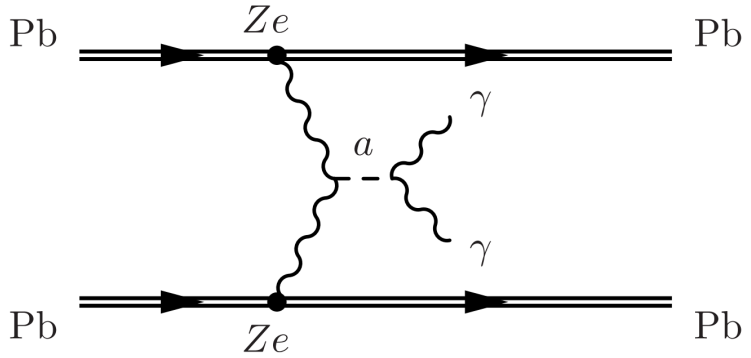
➢ Strong field QED Coulomb correction, vacuum birefringence, light by light scattering….



Zα ~0.6 for Au and Pb, significant effect?

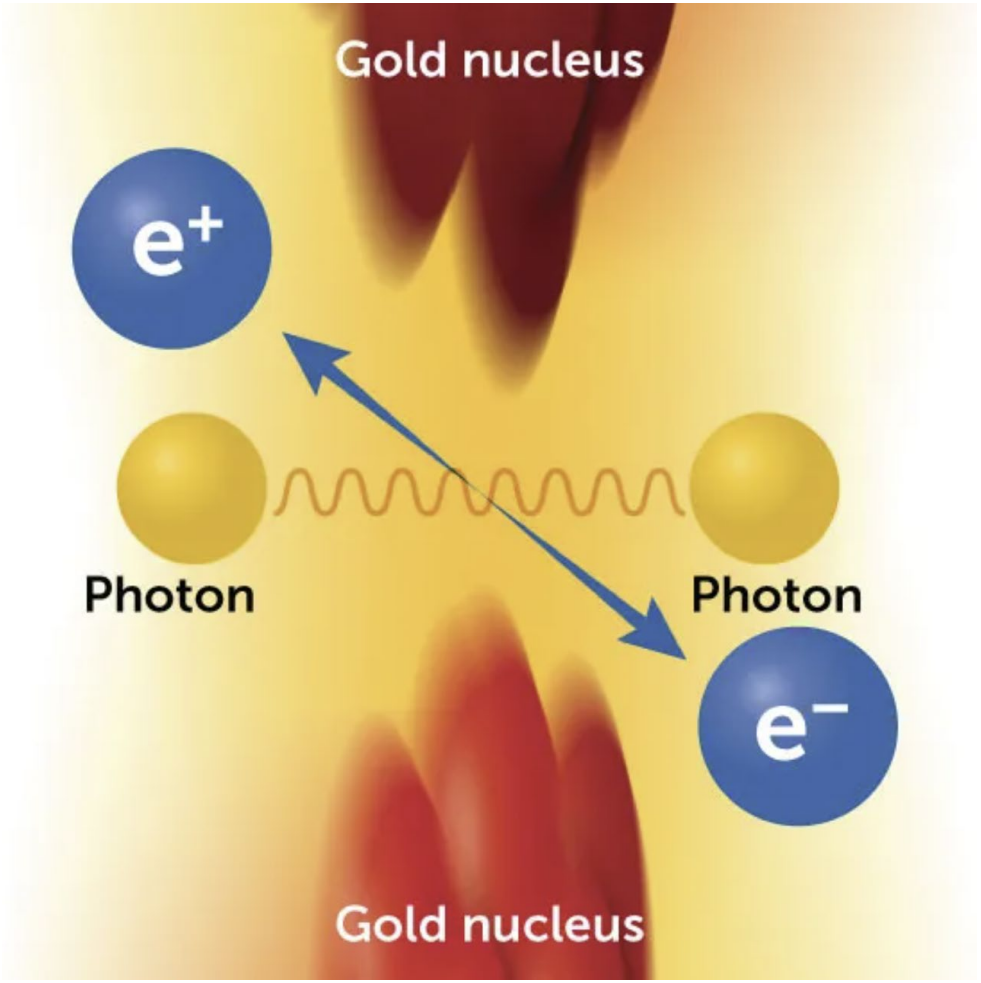
➢BSM physics axion search, tau anomalous magnetic moment, dark photons…

v.s. pp collisions, 截面大**4千万倍**。



Knapen-Lin-Lou-Melia, 2017

光生物质



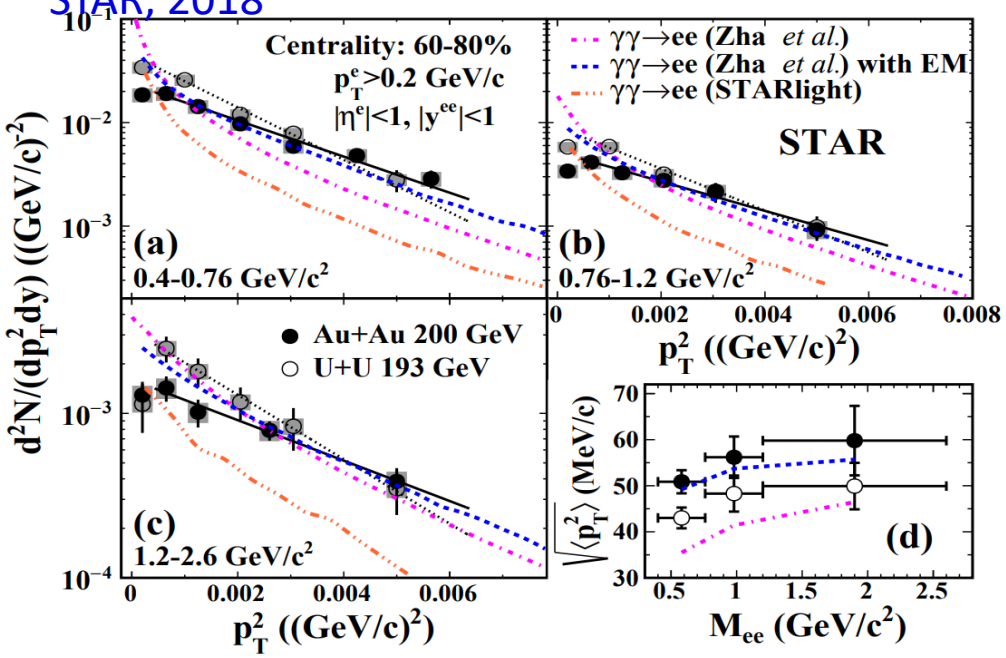
Lepton pair production via photon fusion

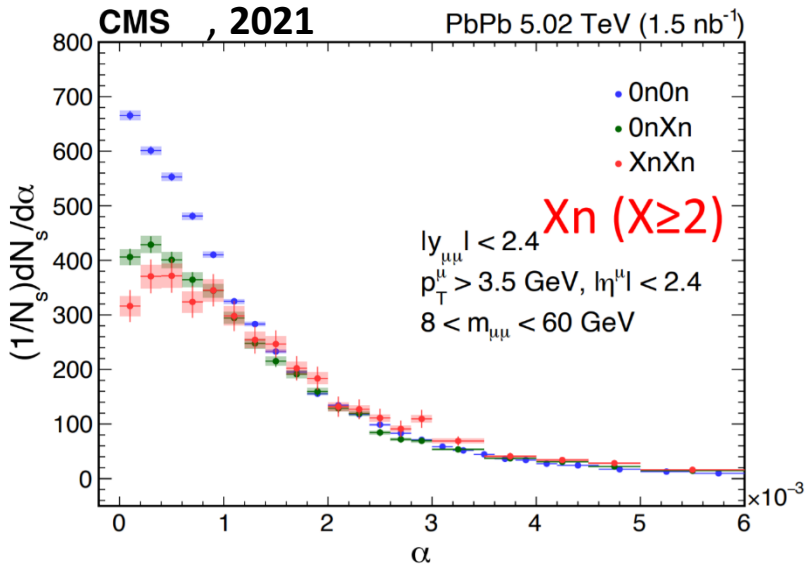
- Dip structure at very low qt
- Mean transverse momentum of pair increases for more central collisions

New wave of theory and experiment activities!

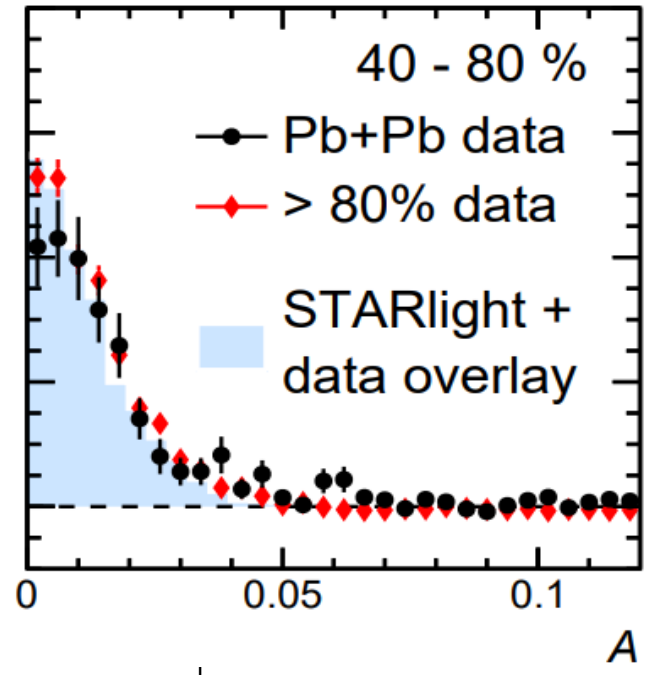
The beauty of experimental data

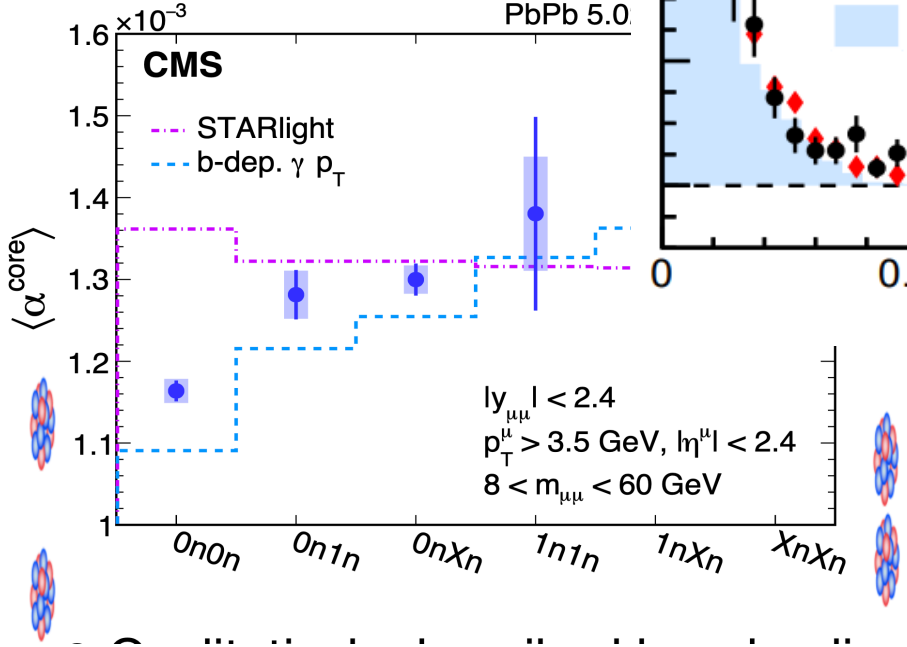
STAR, 2018





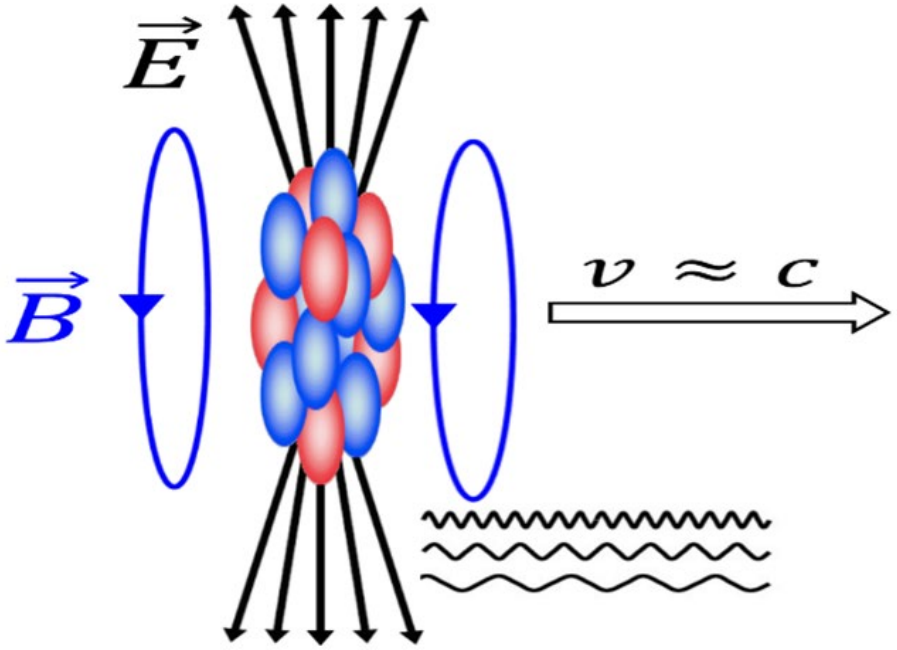
ATLAS 2018



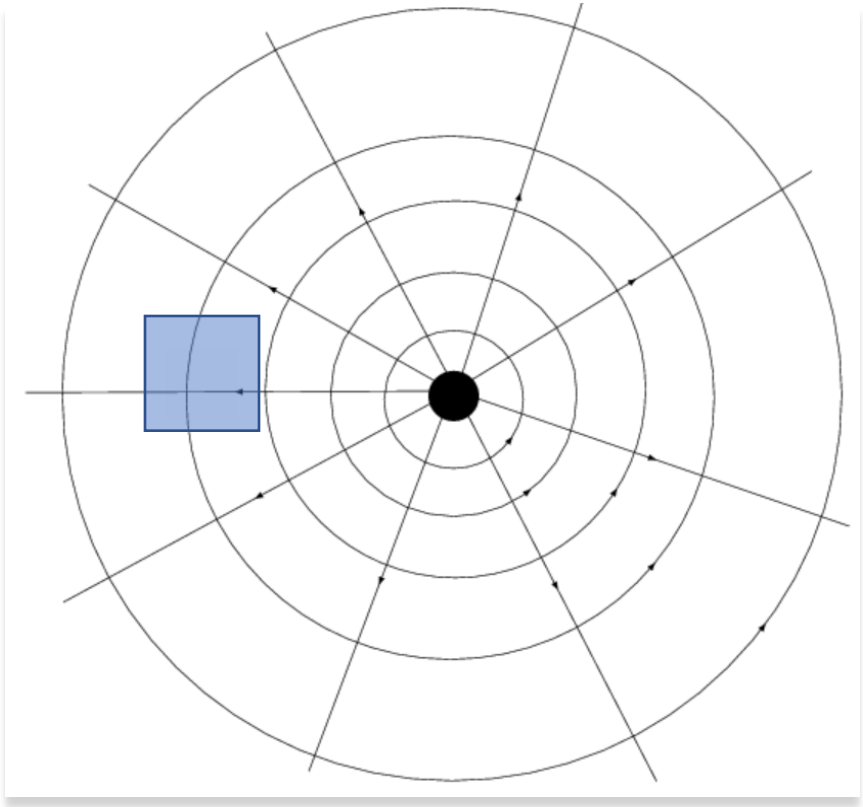


Mysterious dip in more central collisions
can not be reproduced using the WW approximation.

The boosted Coulomb potential



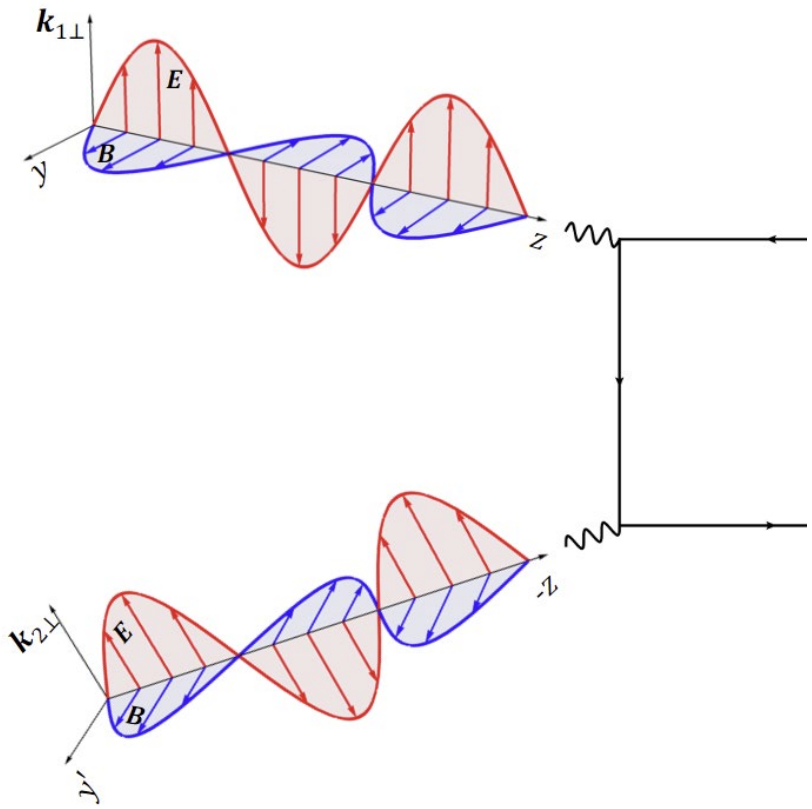
Side view



Head on view

Li-JZ-Zhou, 2019

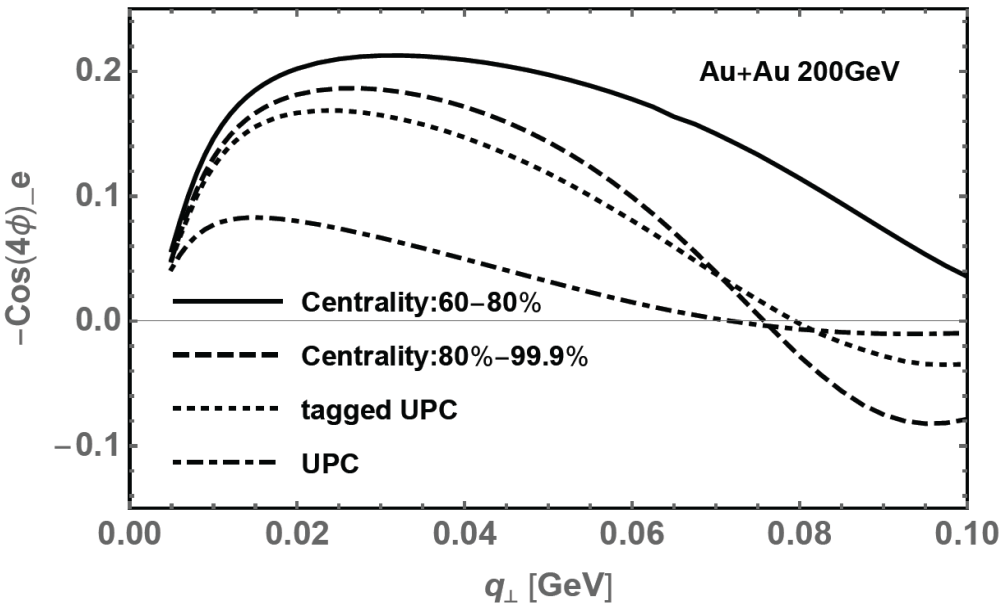
The cos4ϕ modulation in di-lepton production



Li-JZ-Zhou, 2019

Linear polarization of photons: induce cos4ϕ modulation in di-lepton production.

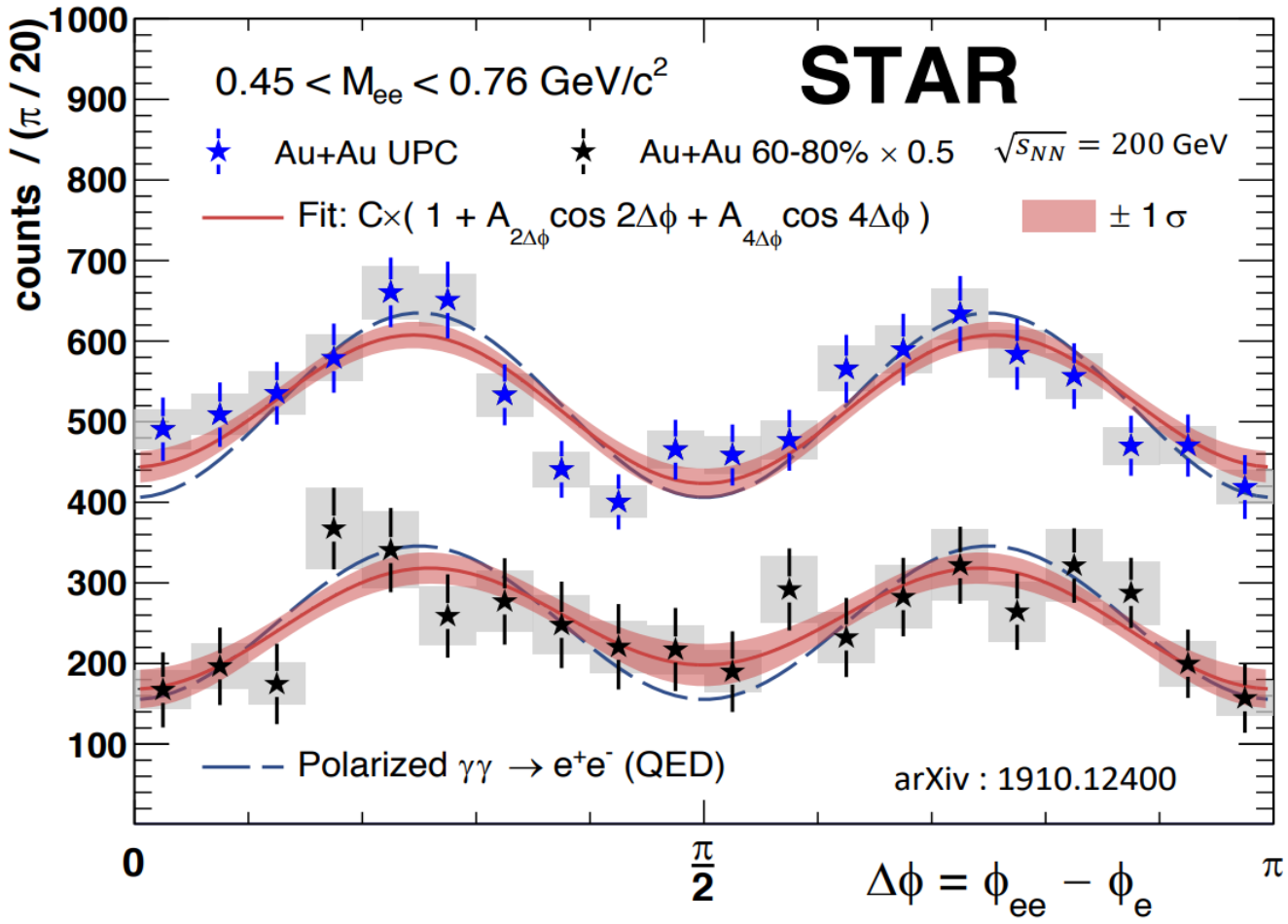
Verified by STAR experiment



Li-JZ-Zhou, 2020

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

STAR collaboration, PRL, 2021



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

cross section in helicity amplitude form with linealy polarized photon:

贾宇，周剑，周雅瑾, PRL, 2025

$$\frac{d\sigma}{d^2p_{1\perp}d^2p_{2\perp}dy_1dy_2} = \frac{1}{16\pi^2Q^4}\int d^2k_{1\perp}d^2k_{2\perp}$$

$$\times \quad \delta^2(q_\perp - k_{1\perp} - k_{2\perp})x_1x_2$$

$$\times \quad \left\{\frac{1}{2}\left(|M_{+-}|^2 + |M_{++}|^2\right) f(x_1, k_{1\perp}^2)f(x_2, k_{2\perp}^2)\right.$$

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

$$- \quad \cos(2\phi_1)\mathrm{Re}[M_{++}M_{+-}^*]\, f(x_2, k_{2\perp}^2)h_1^\perp(x_1, k_{1\perp}^2)$$

$$- \quad \cos(2\phi_2)\mathrm{Re}[M_{++}M_{+-}^*]\, f(x_1, k_{1\perp}^2)h_1^\perp(x_2, k_{2\perp}^2)$$

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

$$+ \quad \frac{1}{2}\left[\cos 2(\phi_1 - \phi_2)|M_{++}|^2 + \cos 2(\phi_1 + \phi_2)|M_{+-}|^2\right]$$

$$\times \quad \left. h_1^\perp(x_1, k_{1\perp}^2)h_1^\perp(x_2, k_{2\perp}^2)\right\}$$

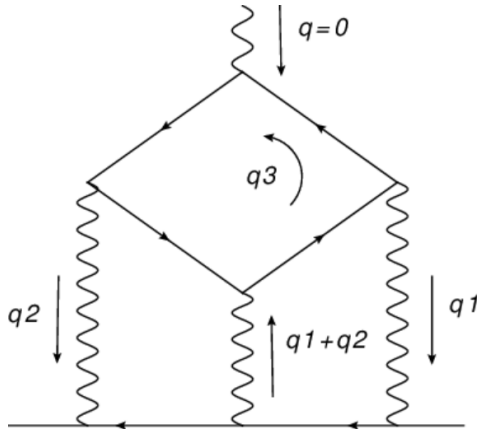
Contribute *to* $\cos(4\phi)$ azim. Assym.

Phenomenological impact

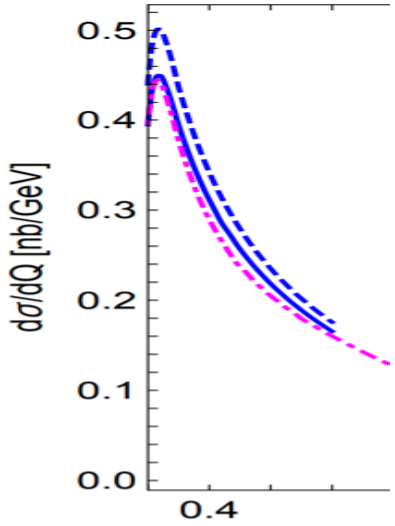
➢直接抽取相因子!

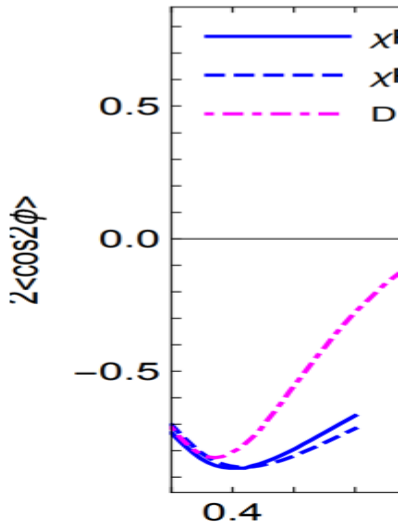
$$\cos(2\phi_1)\mathrm{Re}[M_{++}M_{+-}^*]$$

提供重要的色散关系输入:
hadronic LbL contribution to g_2

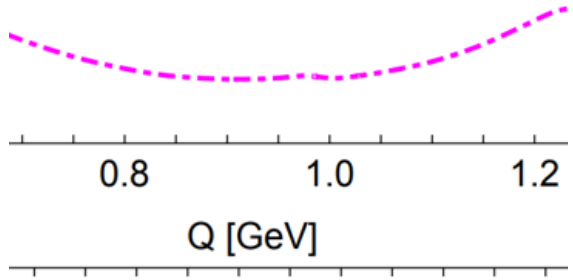


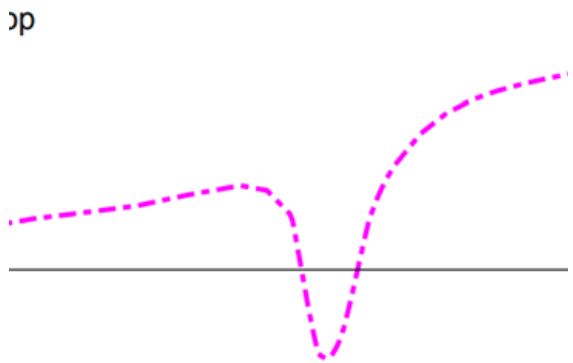
➢ 测试手征微扰论适用范围



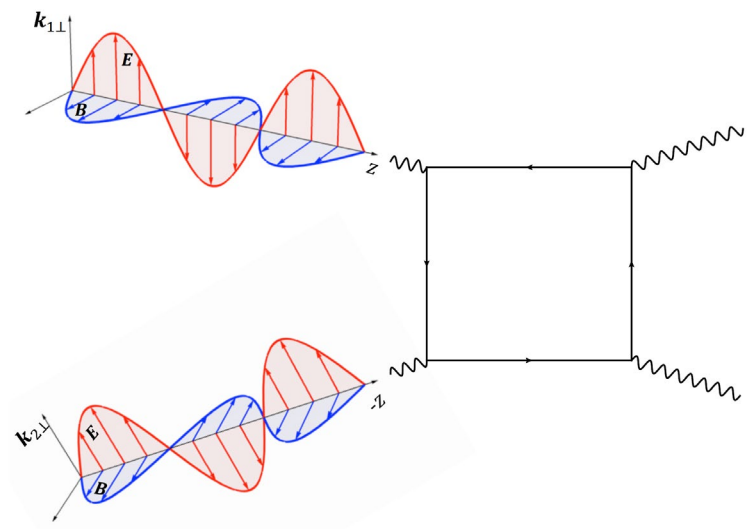


➢ 研究共振态结构





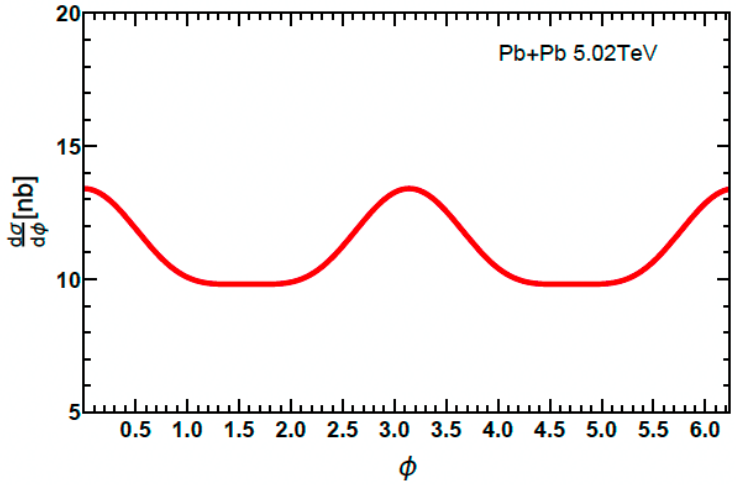
LHC上超边缘碰撞的光光散射中的方位角不对称性



贾宇，林硕，周剑，周雅瑾，arXiv:2410.13781

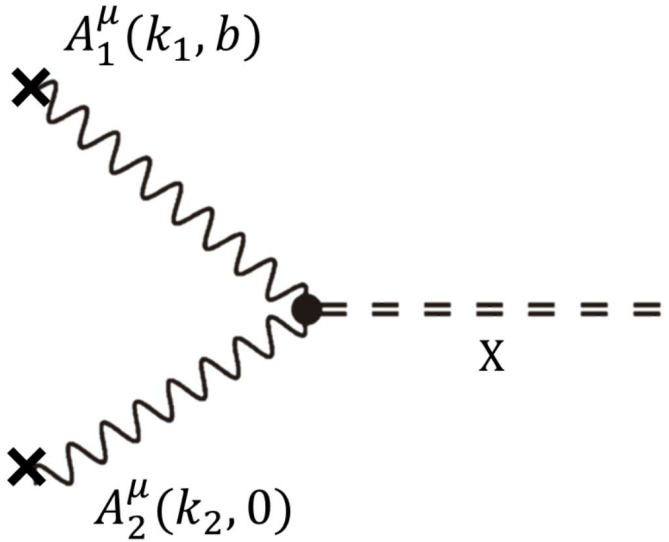
- 作为真空极化和量子非线性的直接表现，弹性光光散射(LbL)被认为是标准模型最迷人的基本过程之一；
- 强光光散射(HLbL)是缪子反常磁矩理论不确定性的主要来源；
- LHC上最近测量了超边缘碰撞上光光散射过程，但是与理论计算有一定的偏差。考虑光子的线性极化，我们重新研究了这个过程。
- 首次在光光散射中研究方位角不对称性。

Numerical results:



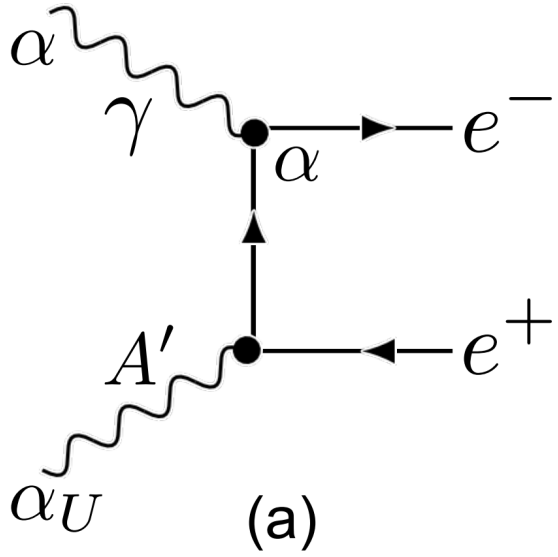
Linearly polarized photons: new experimental tool

➢ Hadron spectrum: determine the quantum numbers of X(6900) from photon-photon fusion in UPCs



SCNU team： Niu-Wang-Wang-Yang, 2022

➢ BSM: search for dark photons in UPCs

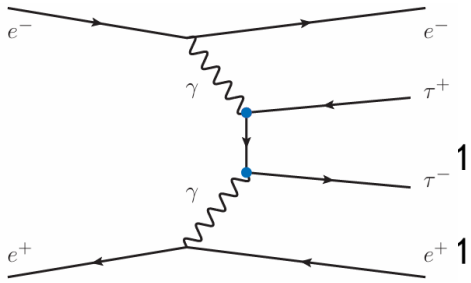


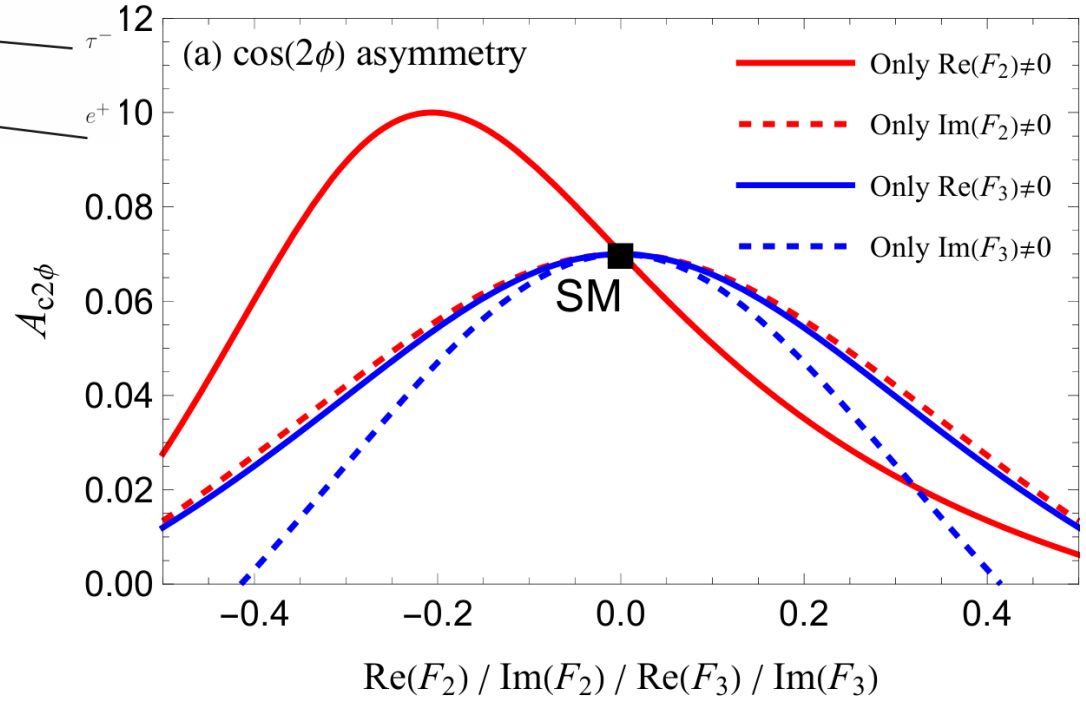
Xu-Lewis-Wang-Brandenburg-Ruan, 2022

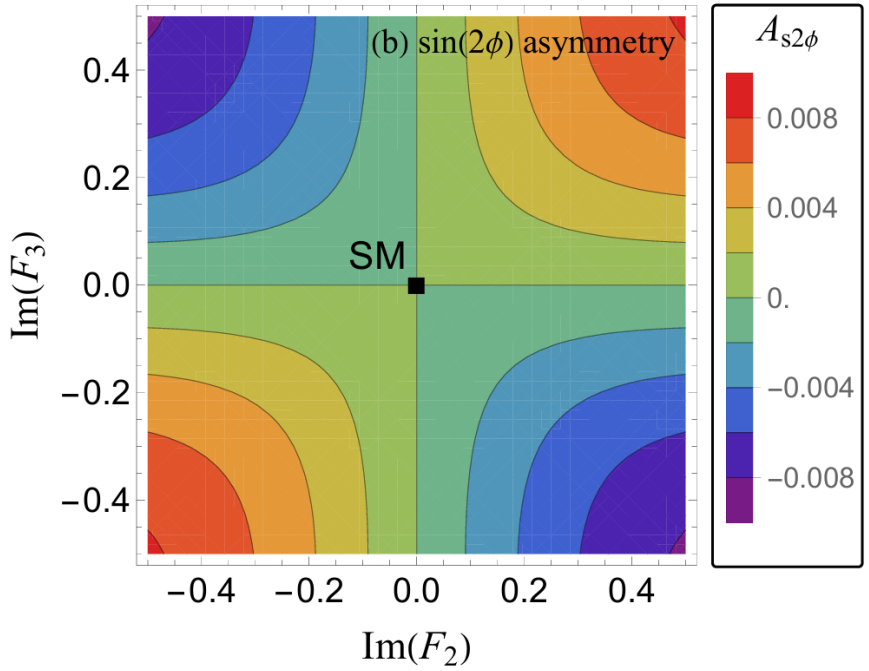
e^+e^-对撞机上双光子过程另外一个有趣应用

Linearly Polarized Photon Fusion as a Precision Probe of the Tau Lepton Dipole Moments at Lepton Colliders

Ding Yu Shao,[1,2,3,*] Hao Xiang,[1] Fang Xu,[1,†] Bin Yan,[4,5,‡] and Cheng Zhang[6,§]





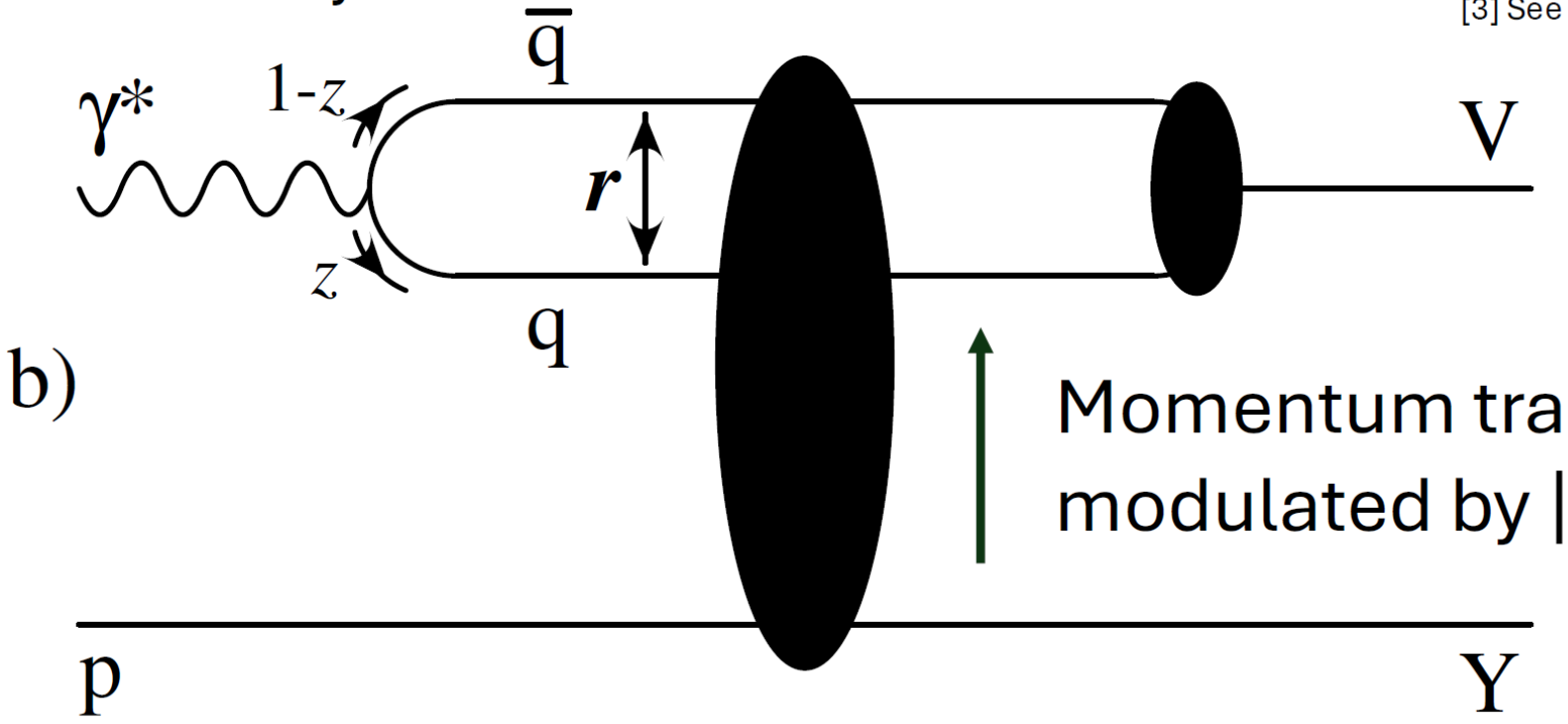


Photon-nuclear reactions

Shining light on Gluons

- Photo-nuclear measurements have been used to study QCD matter already for decades[1-3]

[1] H1 Collaboration. *J. High Energ. Phys.* **2010**, 32 (2010).
[2] ZEUS Collaboration. *Eur. Phys. J. C* **2**, 247–267 (1998).
[3] See refs 1-25 in [2]

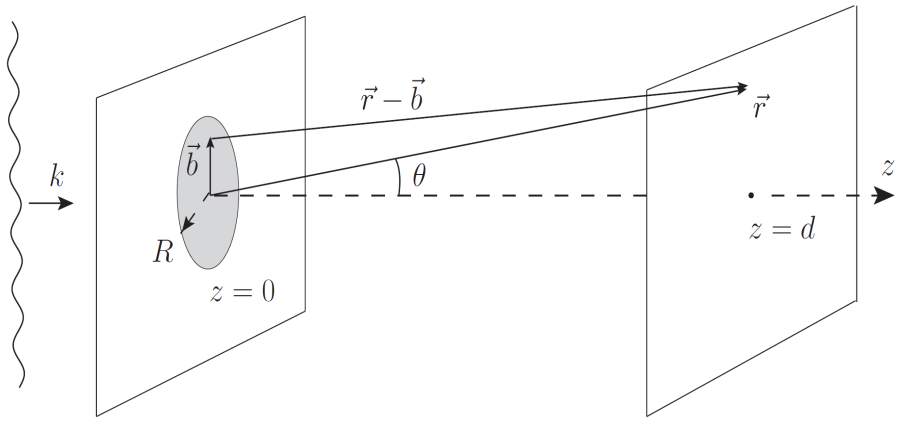


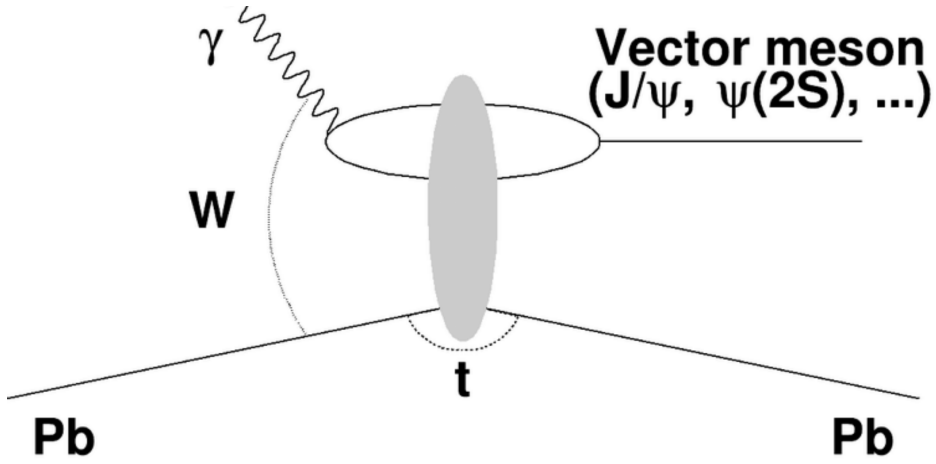
Vector Meson ('heavy photon')

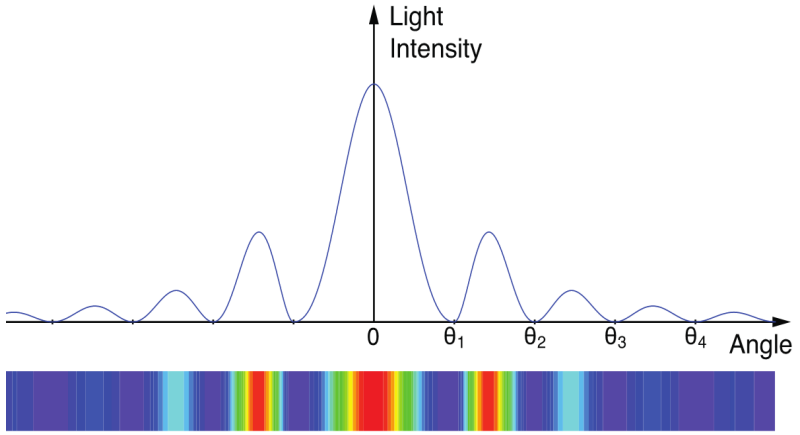
Momentum transfer (t) modulated by $|F(t)|^2$

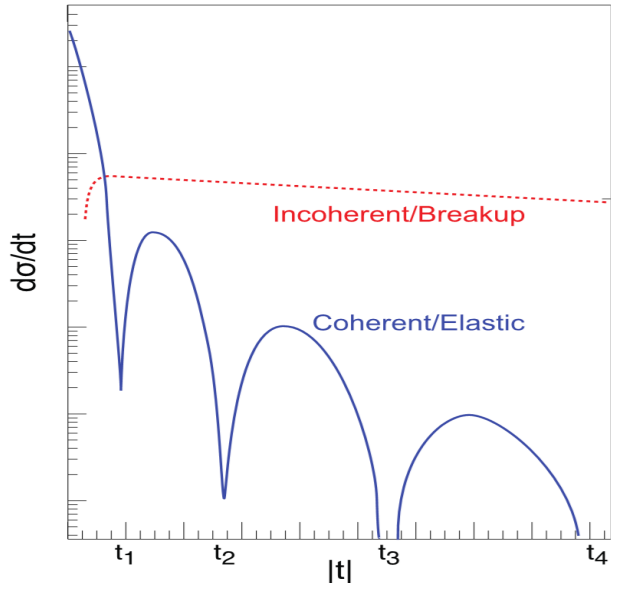
Well known process for probing the **hadronic structure** of the photon and matter distribution of nucleon (nuclear) target

Optical Analogy







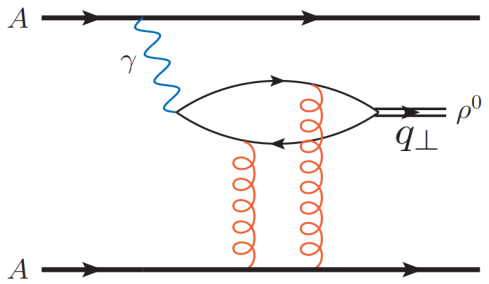


- Reconstruct the size R of the obstacle and the optical “blackness” of the obstacle from the diffractive pattern.

Diffractive vector meson production

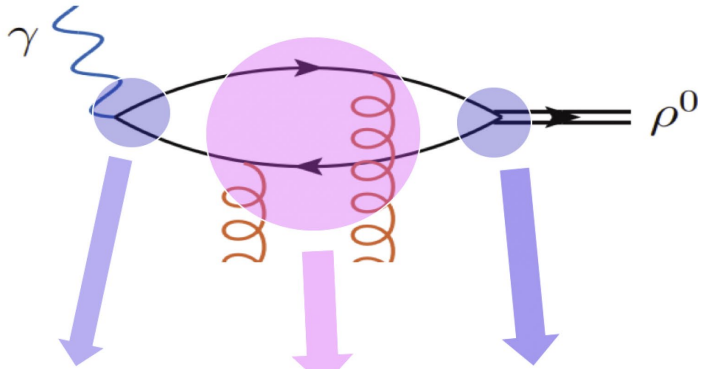
Motivations:

- Studying the saturation effect
- Transverse spatial imaging of gluons



$$\frac{\sigma_{el}^{q\bar{q}A}}{\sigma_{tot}^{q\bar{q}A}} = \frac{\int d^2b\, N^2}{2\int d^2b\, N} \longrightarrow \frac{1}{2}$$

- Small x formalism:
  dipole model, CGC, Glauber model…

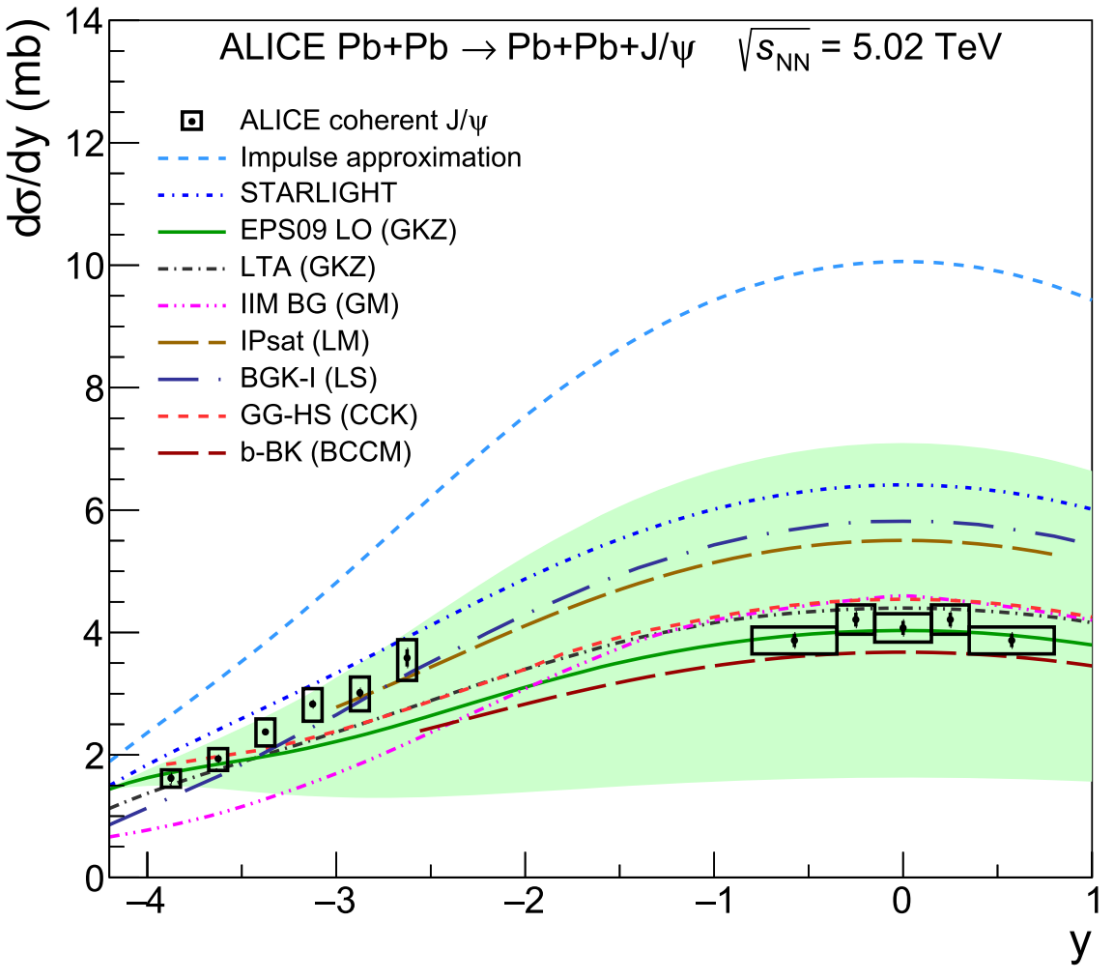


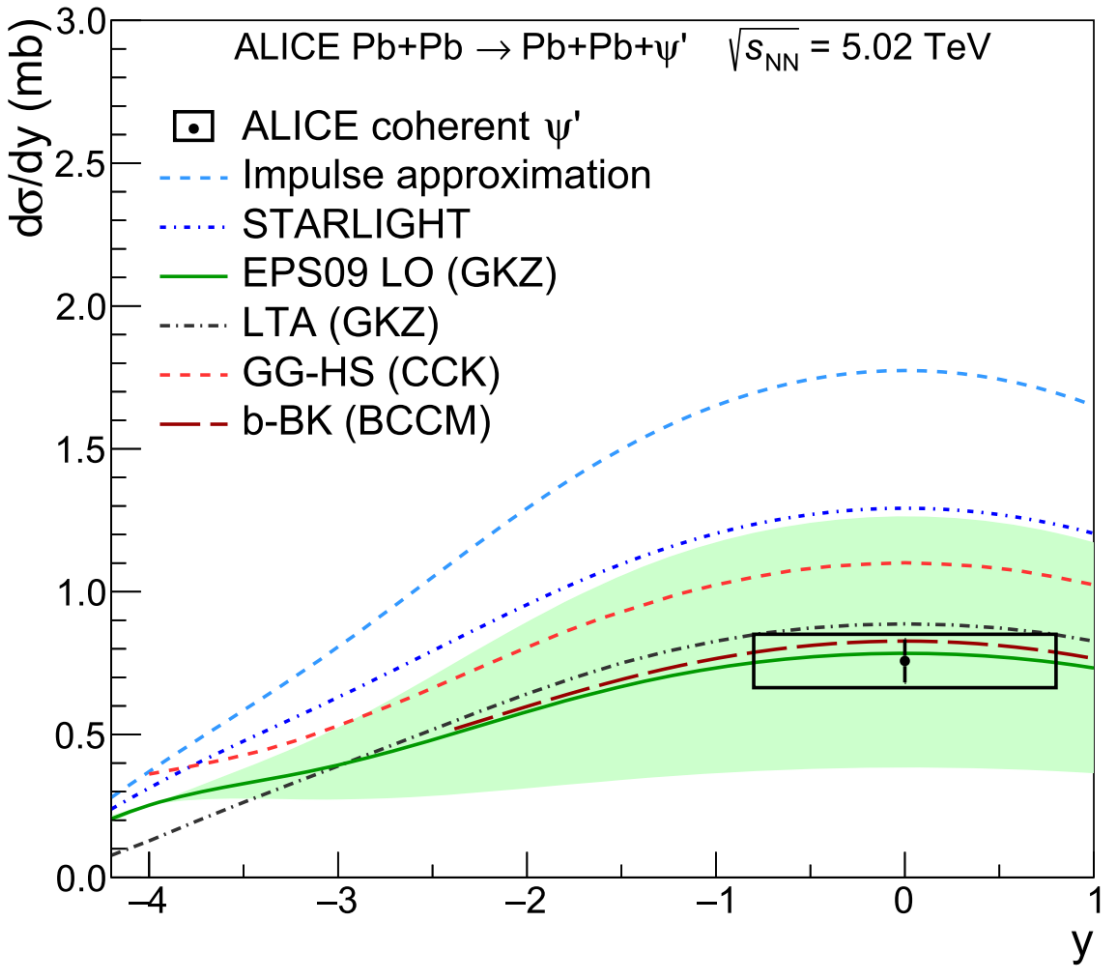
$$\mathcal{A}(\Delta_\perp) = i\int d^2b_\perp e^{i\Delta_\perp\cdot b_\perp}\int\frac{d^2r_\perp}{4\pi}\int_0^1 dz\, \Psi^{\gamma\to q\bar{q}}(r_\perp,z,\epsilon_\perp^\gamma)N(r_\perp,b_\perp)\Psi^{V\to q\bar{q}*}(r_\perp,z,\epsilon_\perp^V)$$

Ryskin, 93; Brodsky, Frankfurt, Gunion, Mueller, Strikman, 94; Klein, Nystrand,1999; Munier, Stasto, Mueller, 2001, Kowalski, Teaney, 2003; Lappi, Mantysaari, 2011; Rezaeian, Siddikov, Klundert, Venugopalan，2013；Guzey, Strikman, Zhalov, 2014, Lansberg, Massacrier, Szymanowski, Wagner, 2019; Mäntysaari, Salazar, Schenke, 2022; and many more…

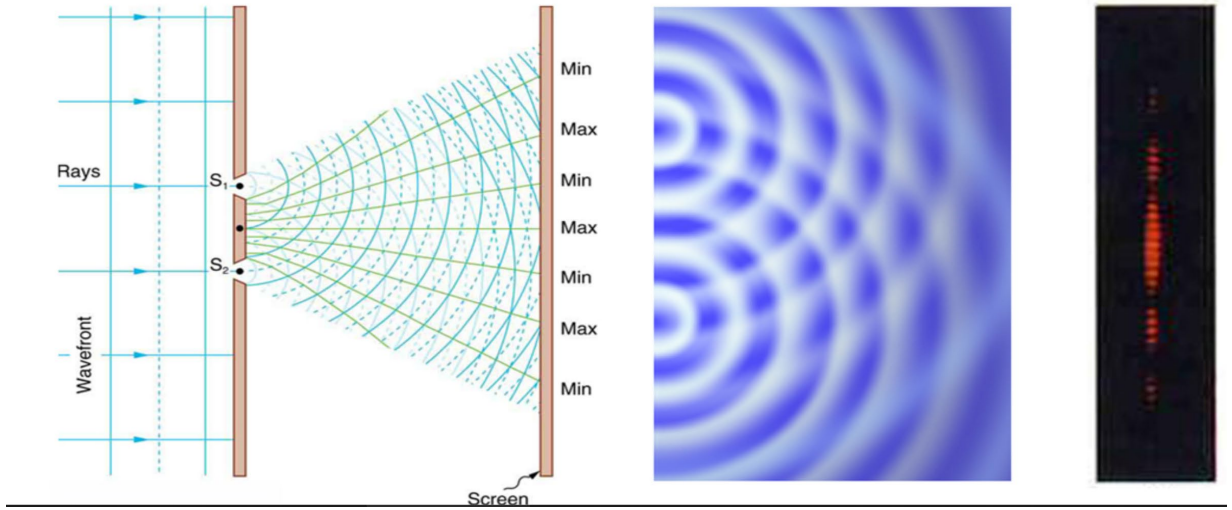
Test different saturation models

- One example:

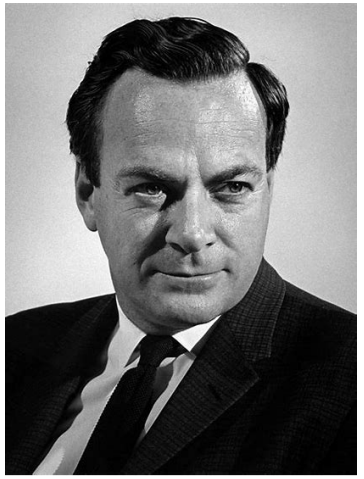




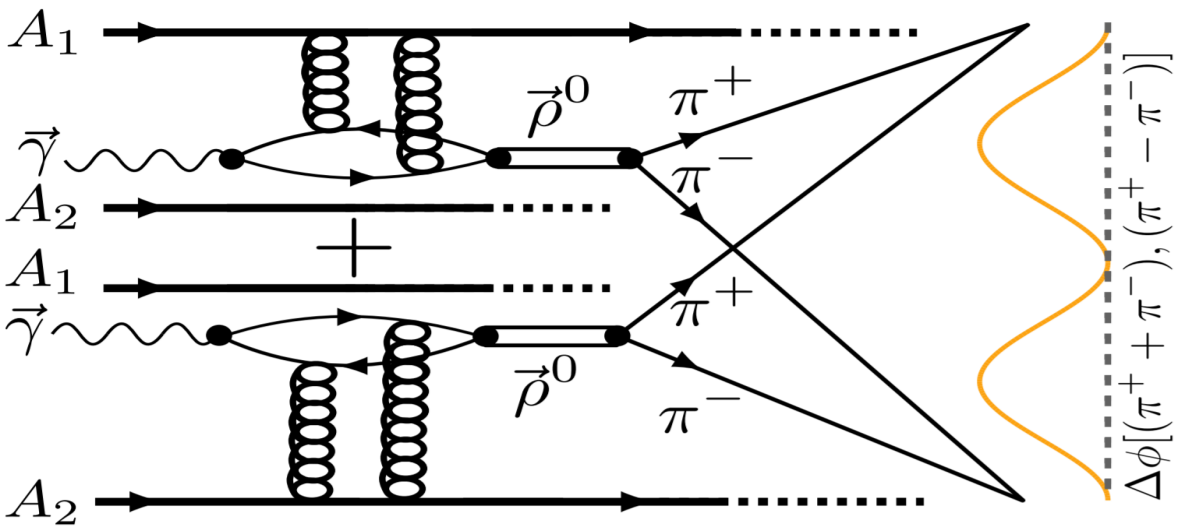
Young's double-slit experiment:



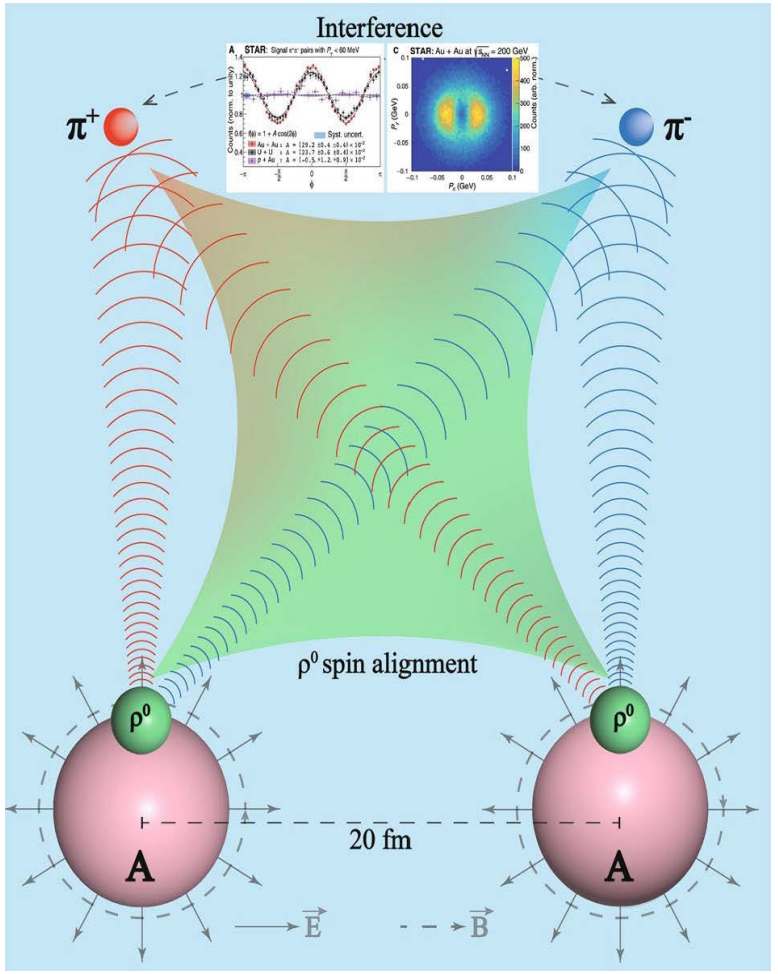
"I will take just this one experiment, which has been designed to contain all of the mystery of quantummechanics".



Double-slit effect in UPCs



Klein-Nystrand, 1999



摘自马余刚院士的评述文章

◆ Remark: two different photons

The first theoretical formulation

- Full cross section in CGC effective theory:

$$\frac{d\sigma}{d^2q_\perp dY d^2\tilde{b}_\perp} = \frac{1}{(2\pi)^4}\int d^2\Delta_\perp d^2k_\perp d^2k'_\perp \delta^2(k_\perp+\Delta_\perp-q_\perp)(\epsilon^{V*}_\perp\cdot\hat{k}_\perp)(\epsilon^V_\perp\cdot\hat{k}'_\perp)\Big\{\int d^2b_\perp$$

$$\times e^{i\tilde{b}_\perp\cdot(k'_\perp-k_\perp)}\left[T_A(b_\perp)\mathcal{A}_{in}(Y,\Delta_\perp)\mathcal{A}^*_{in}(Y,\Delta'_\perp)\mathcal{F}(Y,k_\perp)\mathcal{F}(Y,k'_\perp)+(A\leftrightarrow B)\right]$$

$$+\left[e^{i\tilde{b}_\perp\cdot(k'_\perp-k_\perp)}\mathcal{A}_{co}(Y,\Delta_\perp)\mathcal{A}^*_{co}(Y,\Delta'_\perp)\mathcal{F}(Y,k_\perp)\mathcal{F}(Y,k'_\perp)\right]$$

$$+\left[e^{i\tilde{b}_\perp\cdot(\Delta'_\perp-\Delta_\perp)}\mathcal{A}_{co}(-Y,\Delta_\perp)\mathcal{A}^*_{co}(-Y,\Delta'_\perp)\mathcal{F}(-Y,k_\perp)\mathcal{F}(-Y,k'_\perp)\right]$$

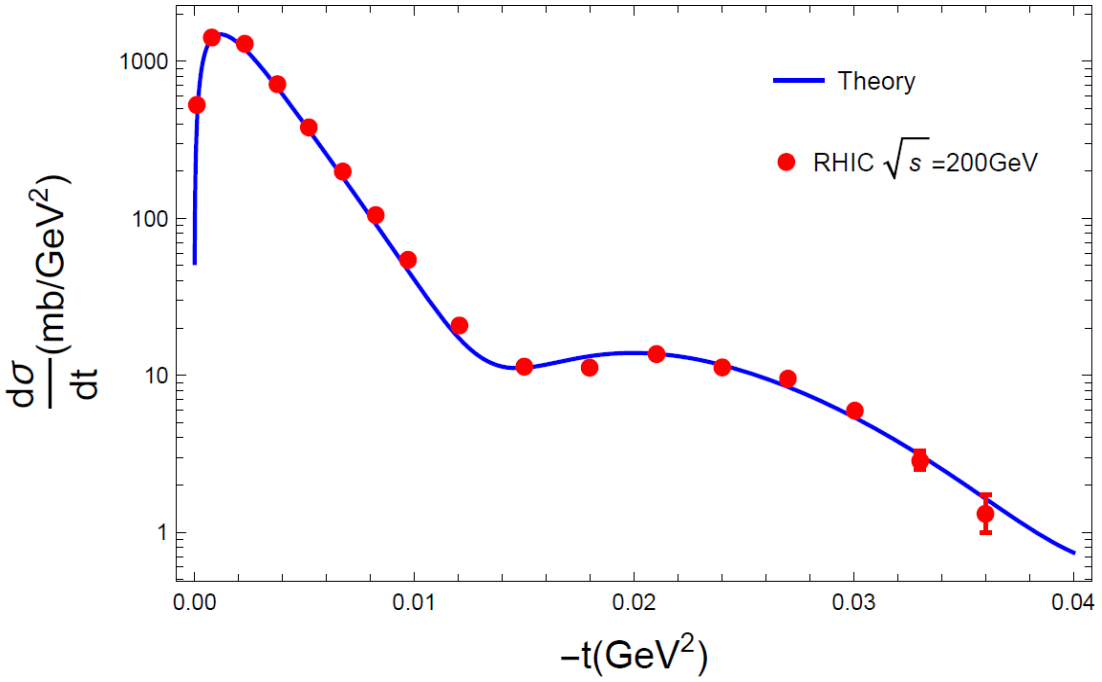
$$+\left[e^{i\tilde{b}_\perp\cdot(\Delta'_\perp-k_\perp)}\mathcal{A}_{co}(Y,\Delta_\perp)\mathcal{A}^*_{co}(-Y,\Delta'_\perp)\mathcal{F}(Y,k_\perp)\mathcal{F}(-Y,k'_\perp)\right]$$

$$+\left[e^{i\tilde{b}_\perp\cdot(k'_\perp-\Delta_\perp)}\mathcal{A}_{co}(-Y,\Delta_\perp)\mathcal{A}^*_{co}(Y,\Delta'_\perp)\mathcal{F}(-Y,k_\perp)\mathcal{F}(Y,k'_\perp)\right]\Big\}, \qquad (2.14)$$

Xing-Zhang-ZJ-Zhou, 2020

ρ^0 diffractive pattern

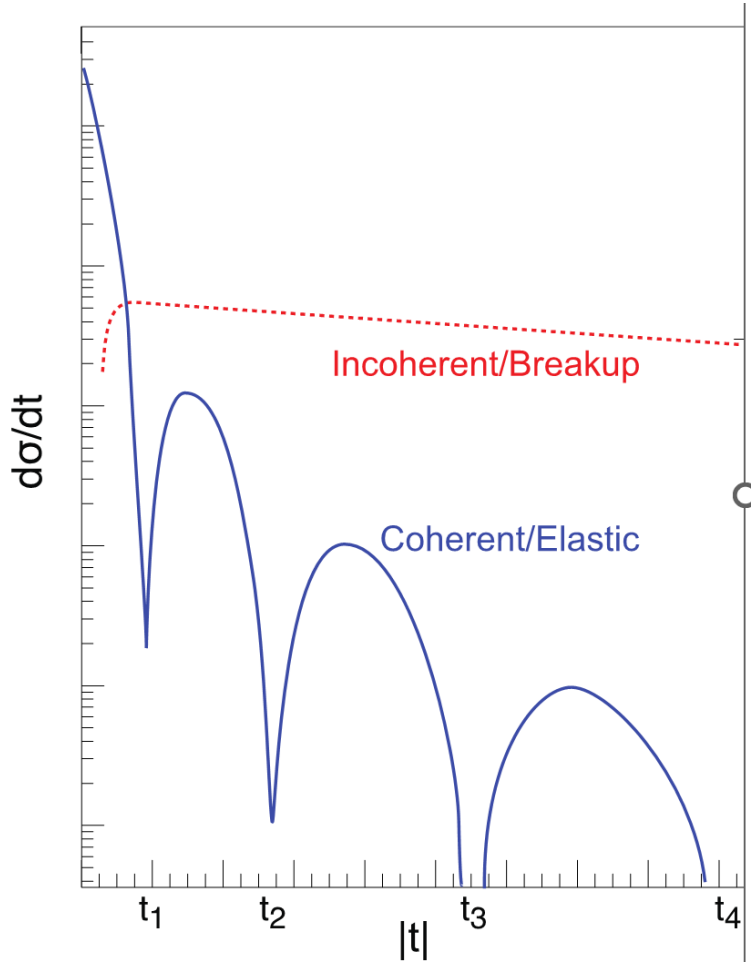
Diffractive VM production in UPC



Xing-Zhang-ZJ-Zhou 2020

- Double slit interference effect
- Smearing caused by finite photon kt

Diffractive VM production in eA

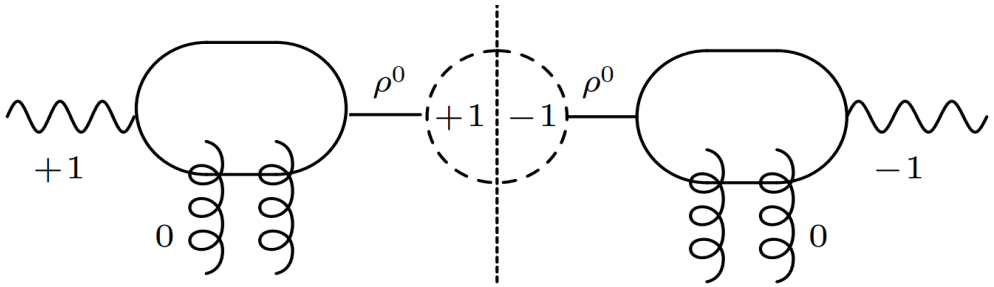


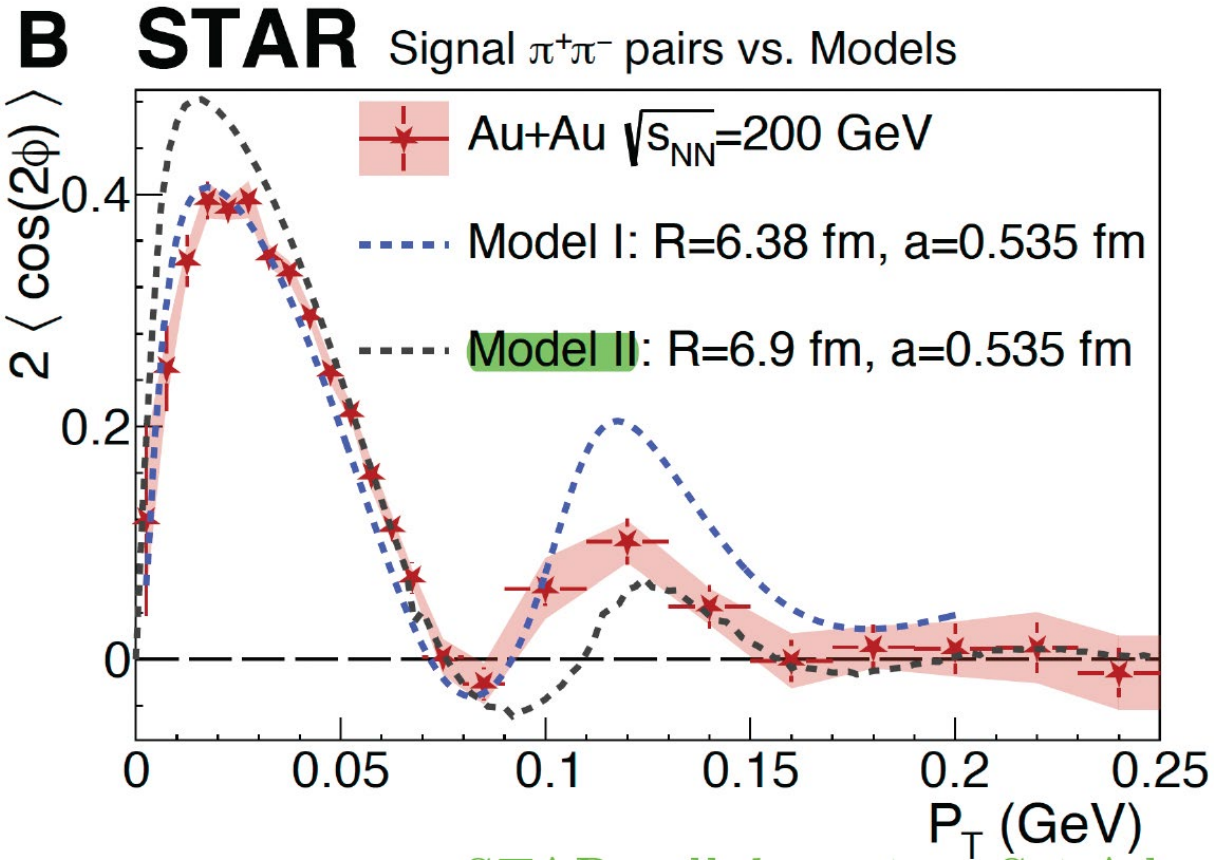
- One slit interference

Cos2ϕ in ρ^0 production

- Interference between two p waves

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

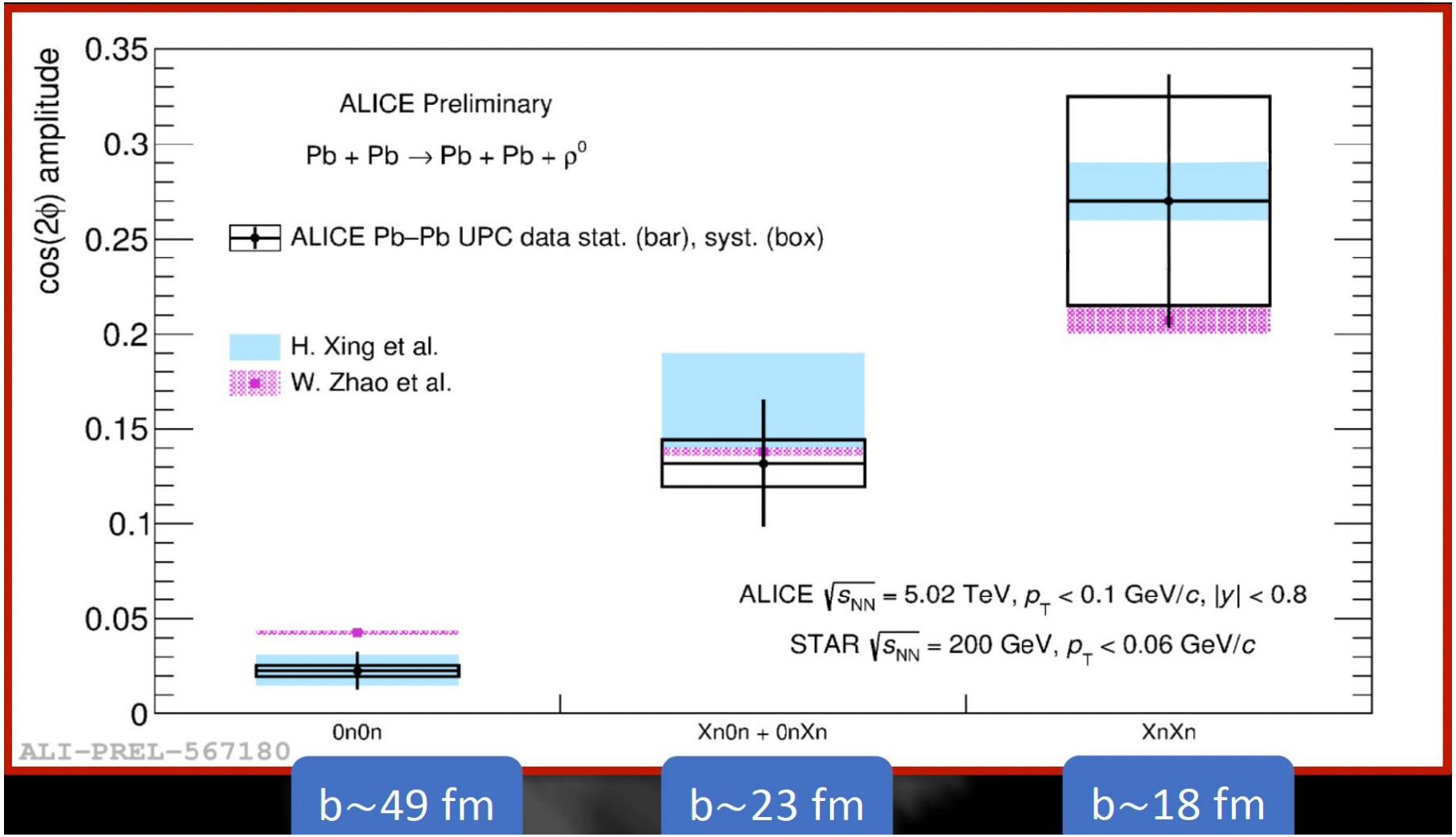




Theory curve II taken from
Xing-Zhang-ZJ-Zhou, 2020

Data points taken from
STAR collaboration, **Sci.Adv. 2023**

ALICE measurement of Cos2ϕ asymmetry

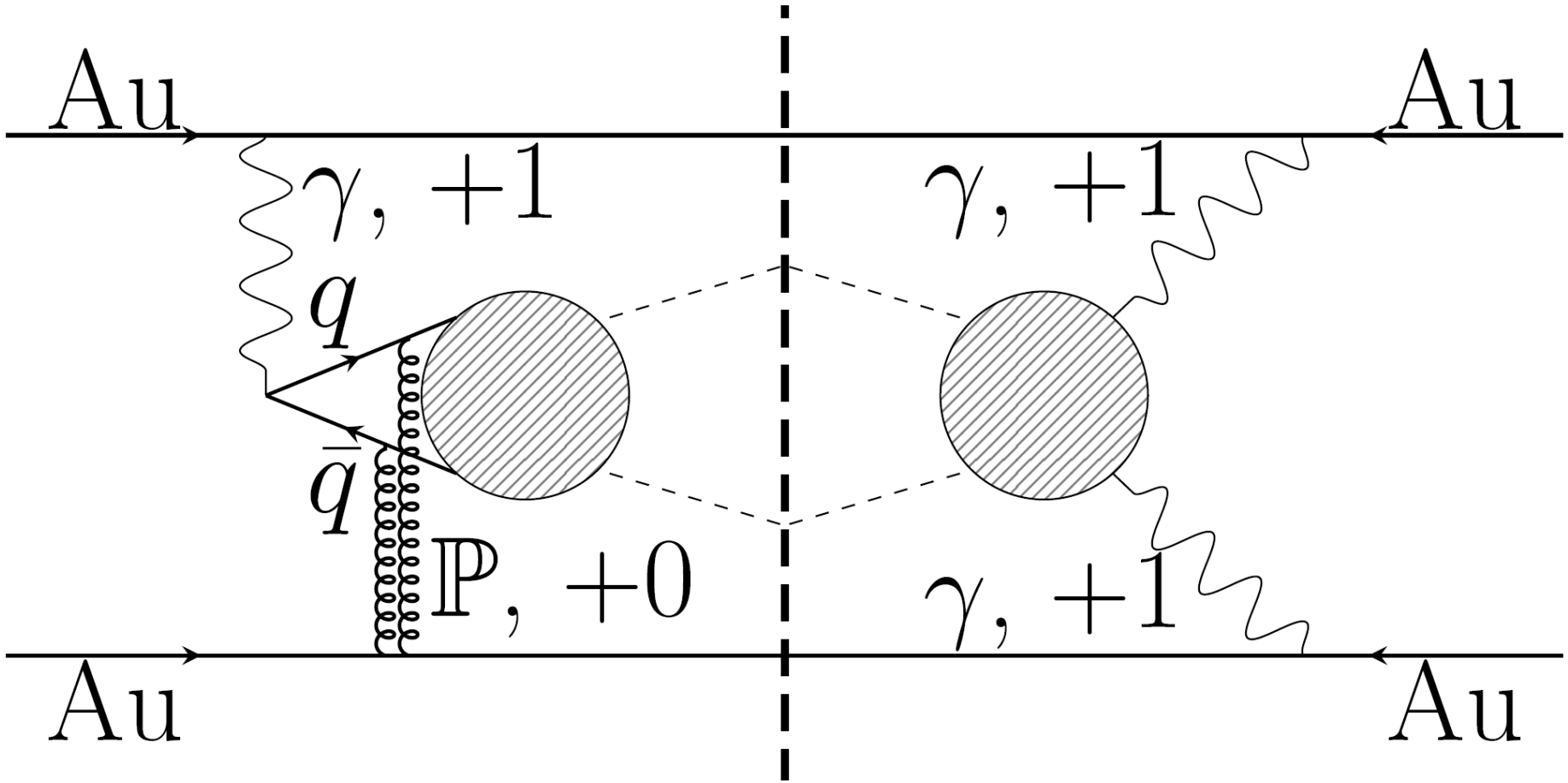


SDU-SCNU组: Hongxi Xing, Cheng Zhang, Jian Zhou, Ya-Jin Zhou *JHEP* 10 (2020) 064

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

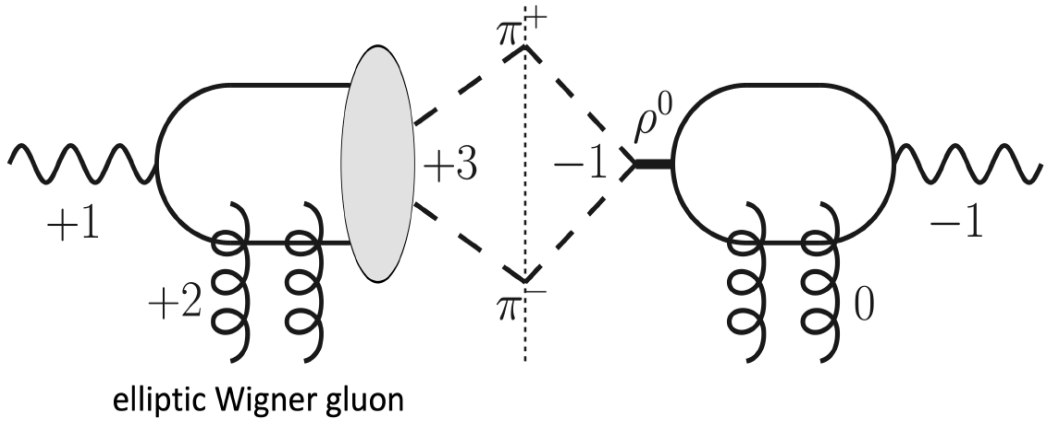
Spin Interference between γA and $\gamma\gamma$

- Interference between γA and $\gamma\gamma$ may also be present.
- This interference is expected to produce a $\cos(\Delta\phi)$ and $\cos(3\Delta\phi)$ anisotropy.



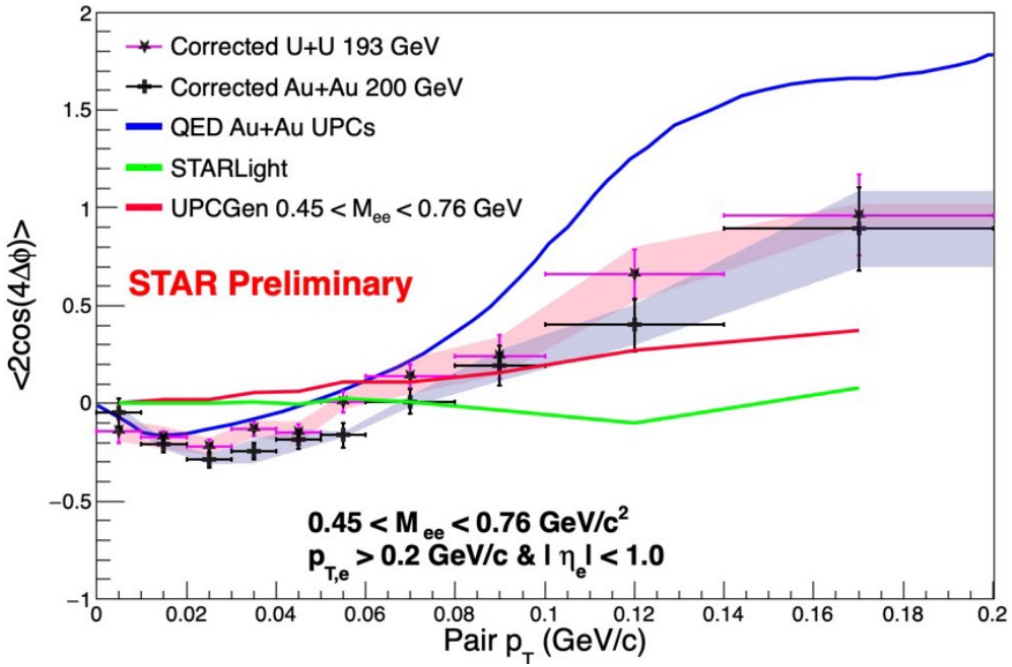
Cos4ϕ in dipion production I

- Elliptic gluon distribution:
Non-trivial correlation between bt and kt



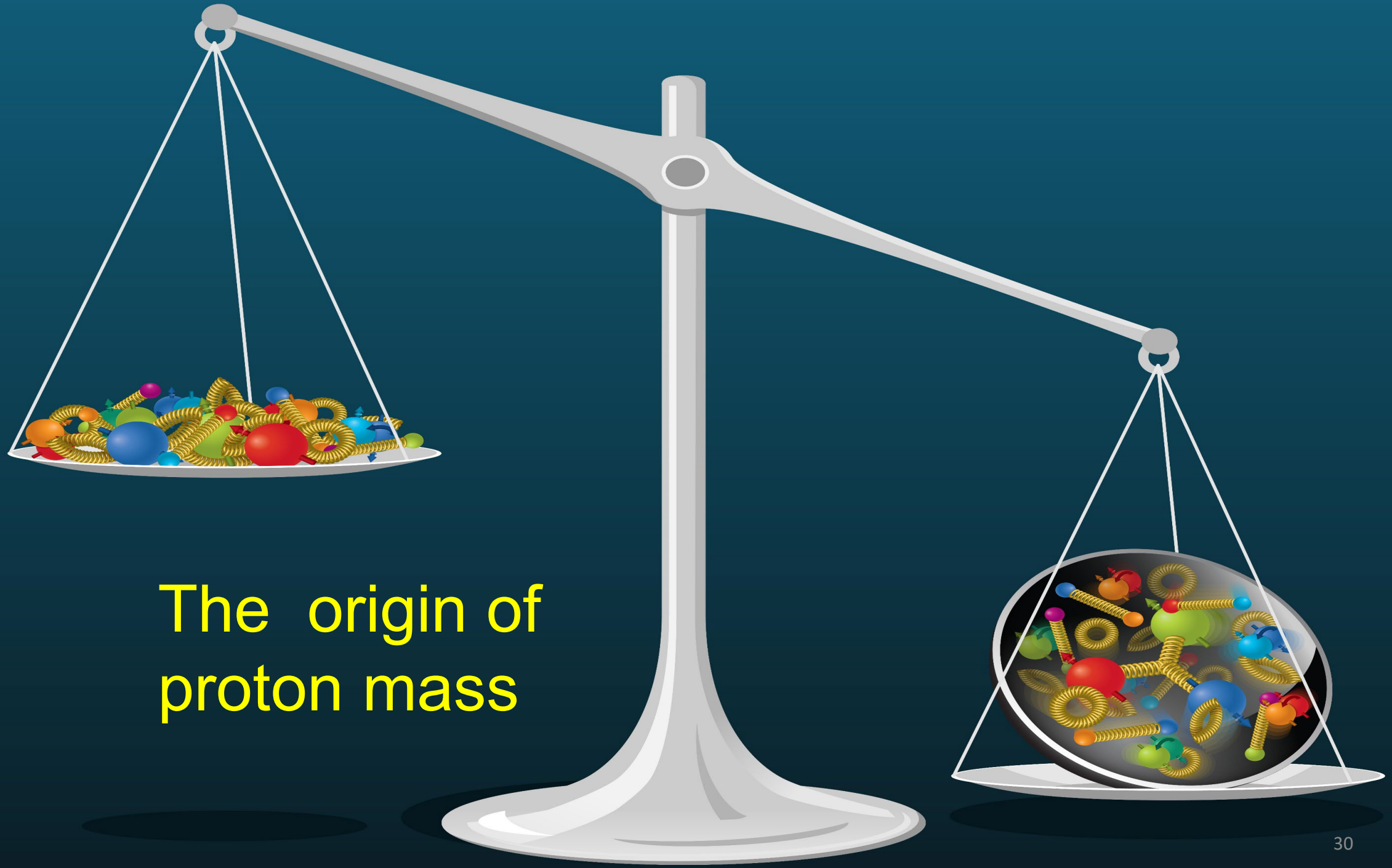
elliptic Wigner gluon

- STAR measurement:



Hatta-Xiao-Yuan, 2016
ZJ, 2016
Boussarie-Hatta-Xiao-Yuan, 2018
Mäntysaari-Mueller-Salazar-Schenke,2020
Mäntysaari-Roy-Salazar-Schenke,2021
……

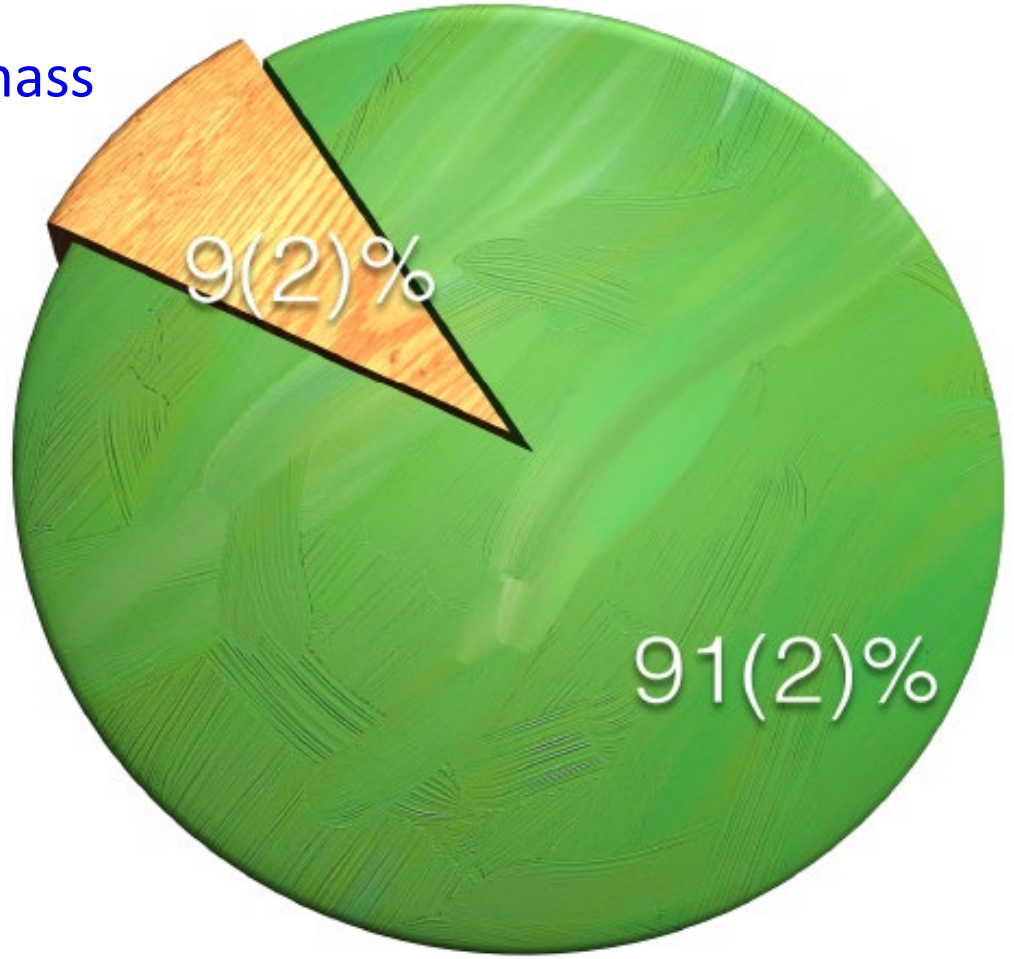
The dawn of EIC era



The origin of proton mass

Proton mass

Quark mass

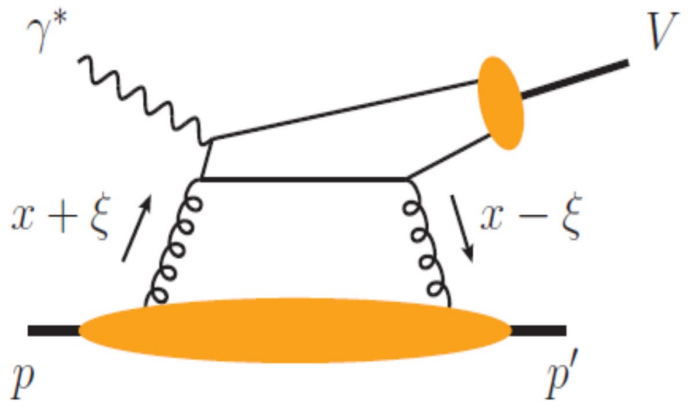


Kinematic & potential energies + Trace anomaly

How to measure trace anomaly

- Twist-4 operator: $\langle P'|F^{\mu\nu}F_{\mu\nu}|P\rangle$

  - Threshold J/psi production **Kharzeev,Satz,Syamtomov, 1998**



  - Threshold J/psi production in pA UPCs **Yoshitaka-Yang 2018, Yoshitaka-Rajan-Yang, 2019**

- Extractions: **Xu-Xie-Wang-Chen, 2020**
  Wang-Bu-Zeng, 2022

- Intense debates:
  Hatta, Ji, Ma, Sun, Tong, Yuan…..

Proton spin decomposition

Jaffe, Manohar 1990
Ji, 1997
Chen et.al. 2008
……

Quark and gluon internal motion

Gluon spin

Quark spin

Gluon OAM

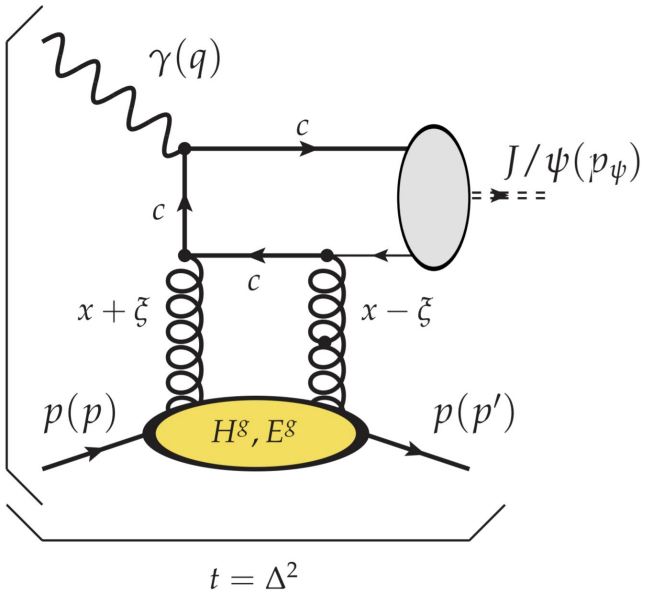
- Ji's sum rule

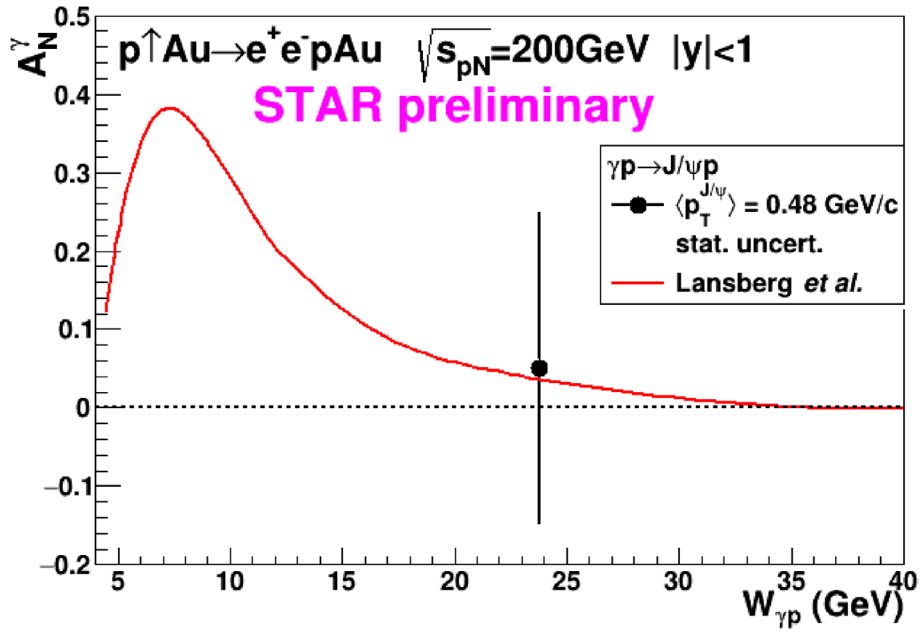
$$J_g = \frac{1}{2}\int_0^1 dx\; x\,[H_g(x,\xi) + E_g(x,\xi)]$$

Ji, 1997

- SSA in exlcusive J/psi production in polarized pA UPCs

Koempel-Kroll-Metz-ZJ, 2012
Lansberg-Massacrier-Szymanowski-Wagner, 2018





Small x asymptotic behavior of gluon OAM

- Never can reach x=0 at any experiment, how to extrapolate down to x=0

- Small x evolution equation for $E_g(x)$

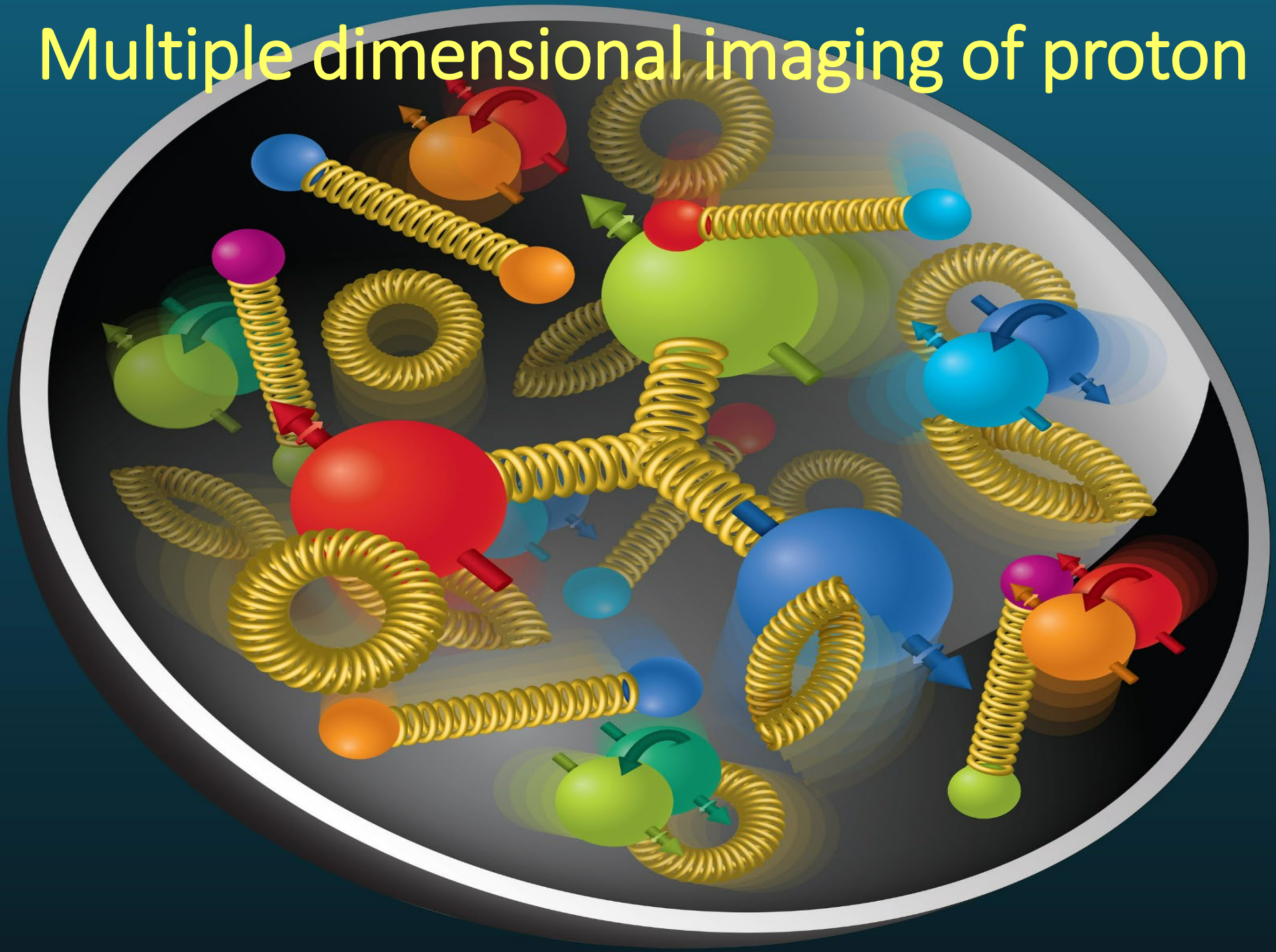
$$\partial_Y \mathcal{E}(k_\perp) = \frac{\bar{\alpha}_s}{\pi} \int \frac{d^2k'_\perp}{(k_\perp - k'_\perp)^2} \left[\mathcal{E}(k'_\perp) - \frac{k_\perp^2}{2k'^2_\perp} \mathcal{E}(k_\perp) \right] - 4\pi^2 \alpha_s^2 \overline{\mathcal{F}}_{1,1}(k_\perp) \mathcal{E}(k_\perp)$$

Hatta, ZJ, 2022

Conclusion: $E_g(x)$ rises as rapidly as the normal unpolarized gluon distribution!

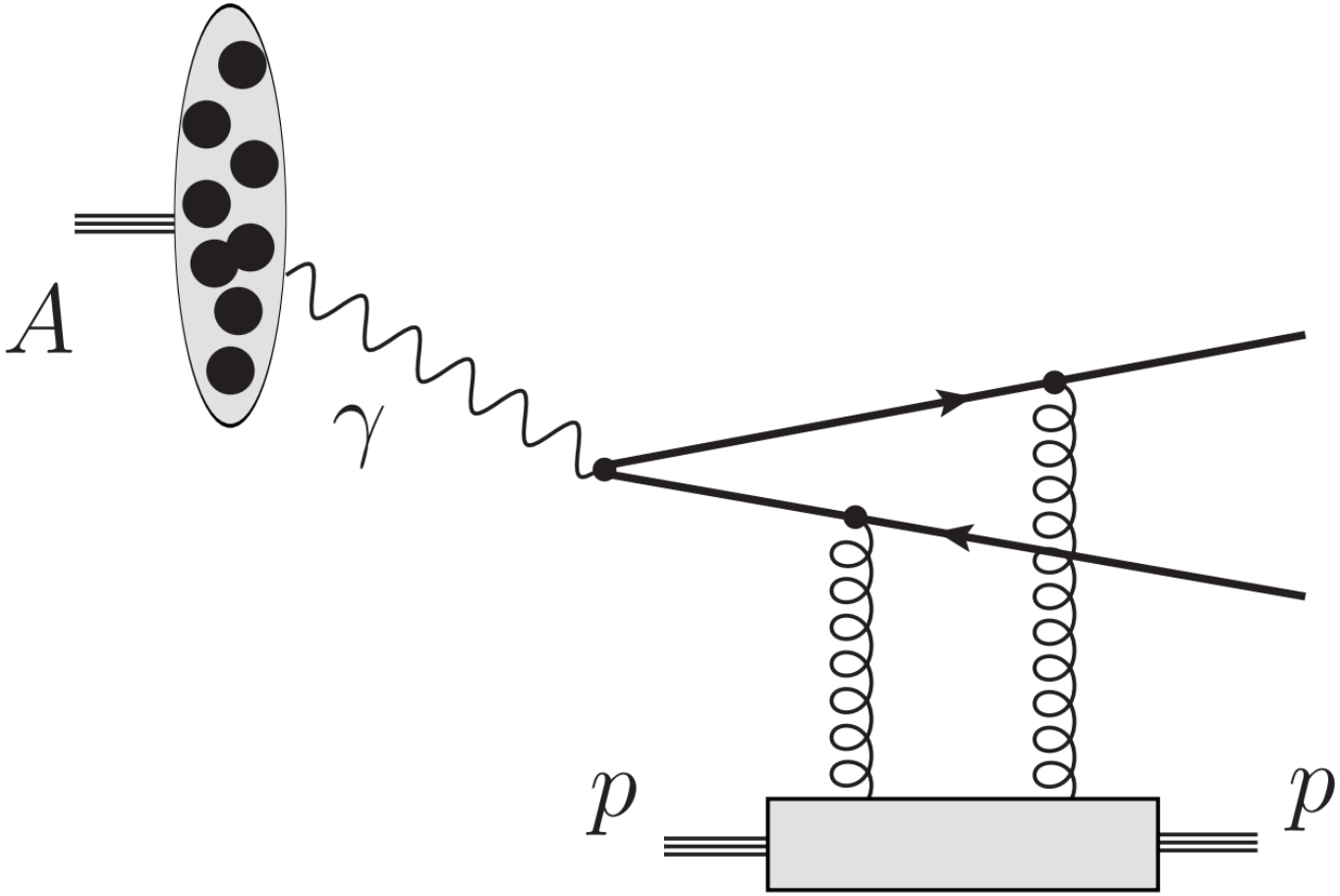
$$x^{-0.3}$$

Multiple dimensional imaging of proton



Gluon Tomography via diffractive di-jet

- 5D imaging of gluon tomography of proton



Braun-Ivanov, 2005
Hatta-Xiao-Yuan, 2016
Hagiwara-Hatta-Pasechnik-Tasevsky-Terayaev, 2017
Boer-Setyadi, 2021
Hatta-Xiao-Yuan-ZJ, 2021
Iancu-Mueller-Triantafyllopoulos-Wei, 2023
……..

Complementary to EIC&EicC

- Virtual photon
- Circularly polarized photons
- (Semi)-Inclusive process

More EIC&EicC physics: Hongxi's lecture

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

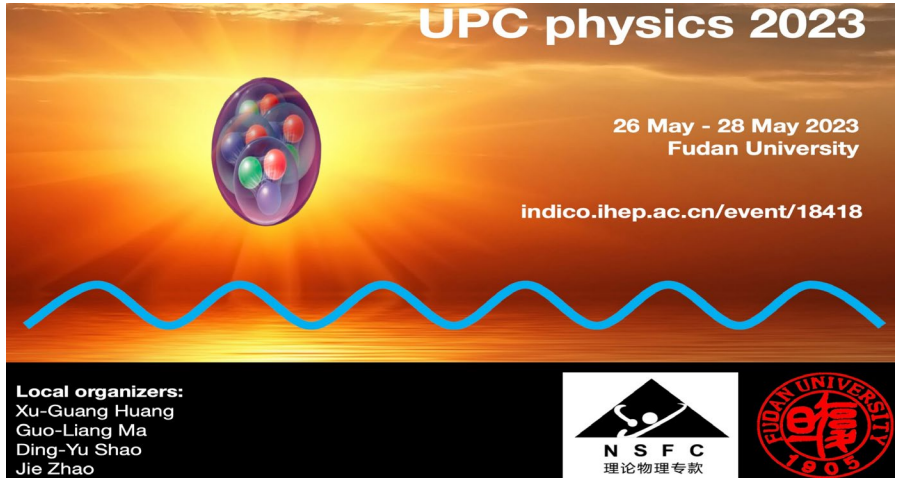
Coherent photons induced high energy reactions in ultraperipheral heavy ion collisions

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

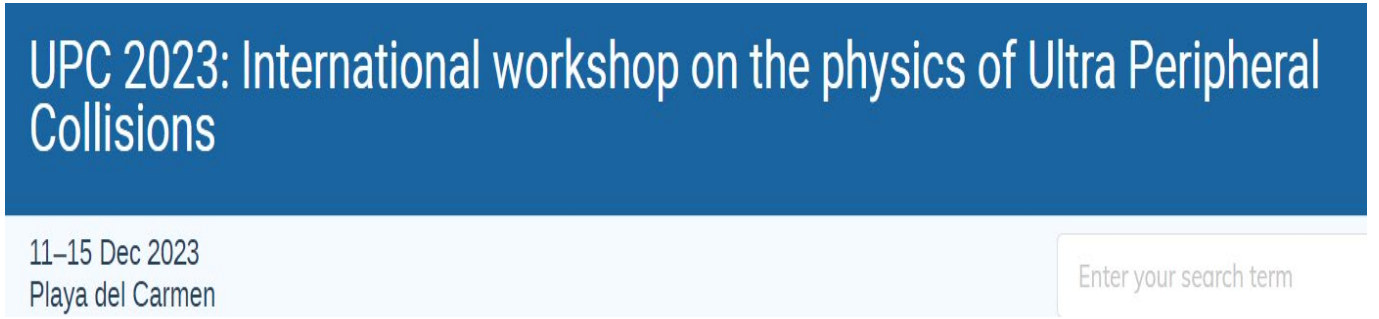
Acta Phys. Sin., 2023, 72(7): 072503. doi: 10.7498/aps.72.20230074

UPC专题会议系列

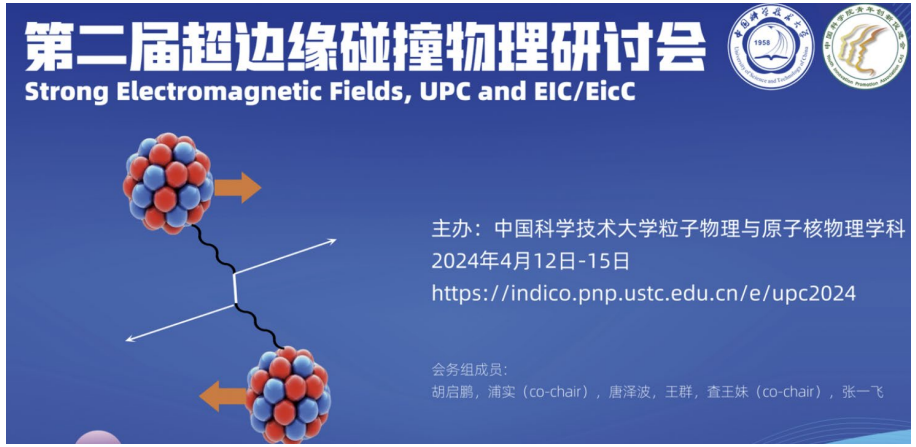
第一届中国UPC会议



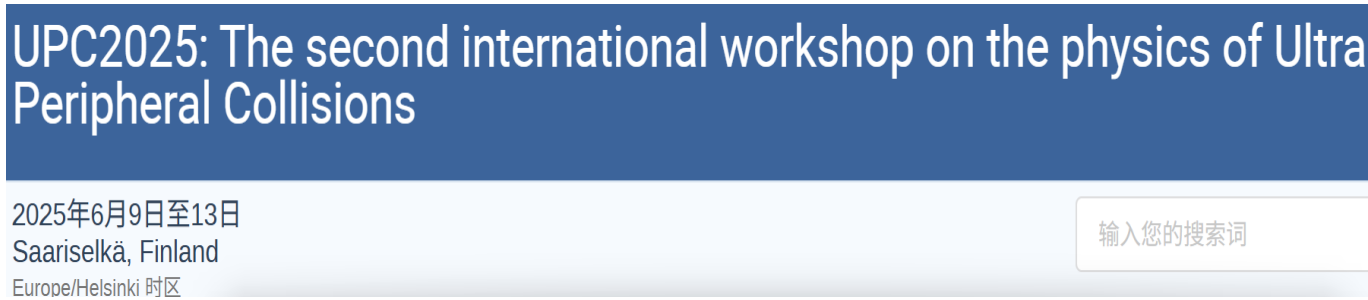
第一届国际UPC会议



第二届中国UPC会议



第二届国际UPC会议



Summary:

- 强场QED (光生物质，光光散射，库伦修正，真空双折射，施温格对产生)
- 寻找新物理
- 费米尺度上研究量子力学基本问题
- 冷核物质研究 (矢量介子，双喷注衍射产生)