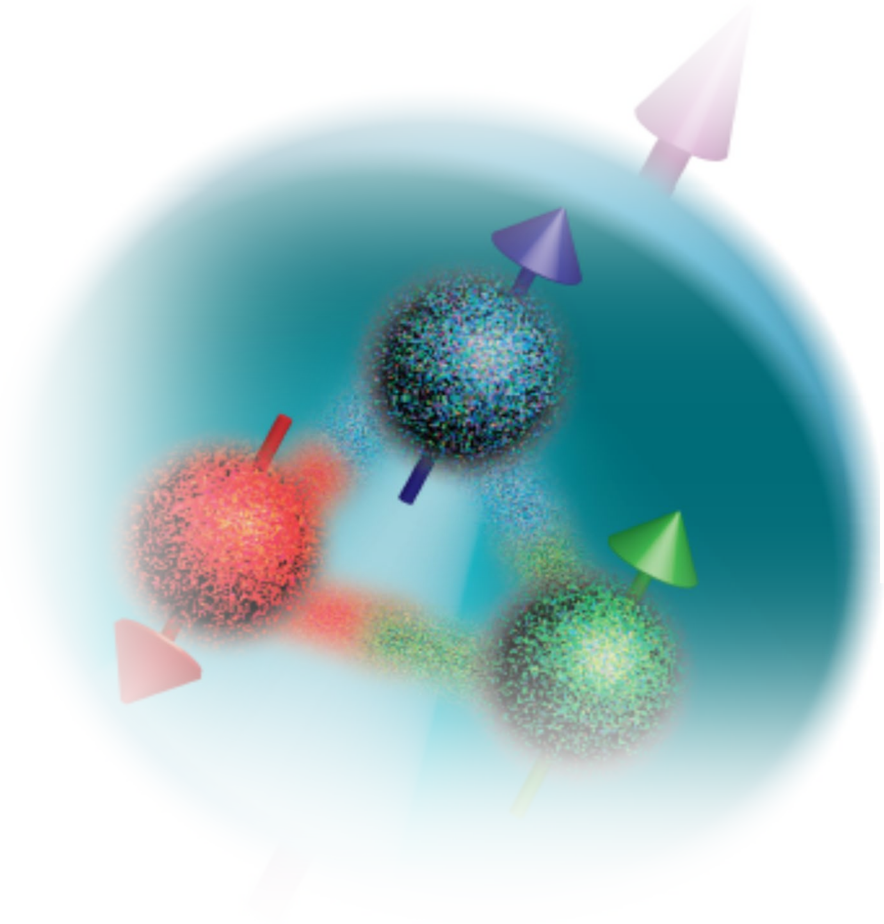
自旋物理研究的一些近期进展



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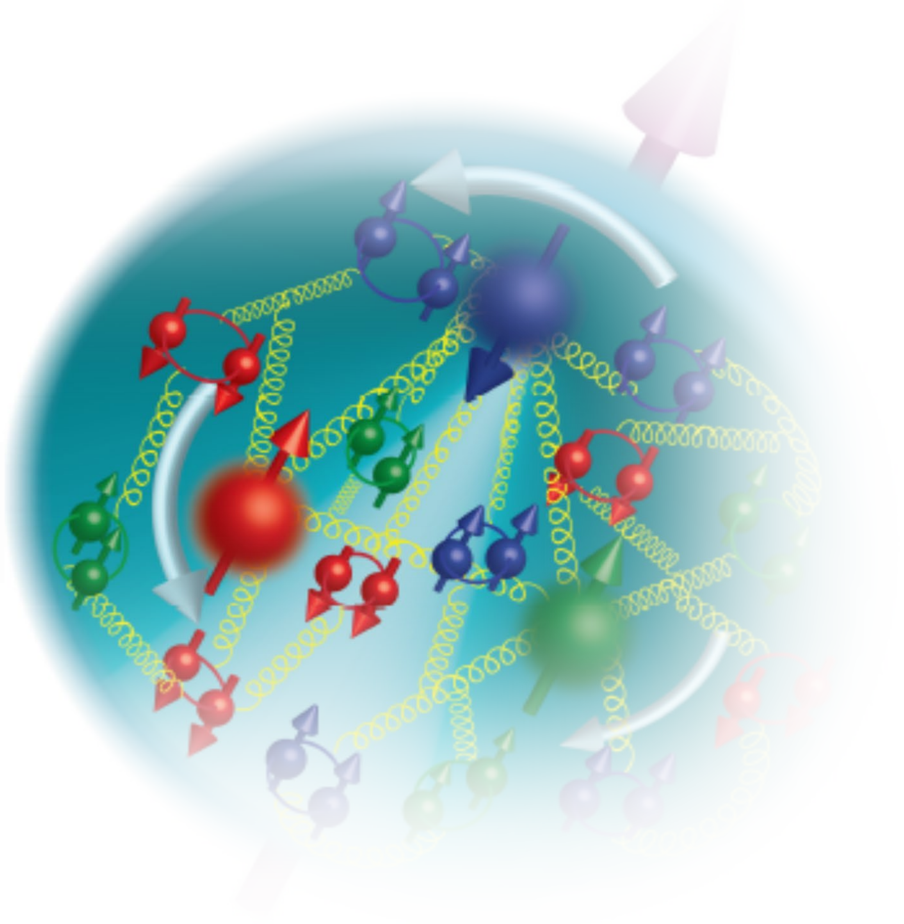


强子物理在线论坛第108期， 2024年12月6日

Outline:

- Introduction
- Nucleon spin structure
- Spin physics in UPCs
- Conclusions

研究背景介绍

The dawn of EIC era

EIC物理

- 质子质量起源，质子自旋起源
- 质子内部结构的三维成像
- 色玻璃凝聚物质研究

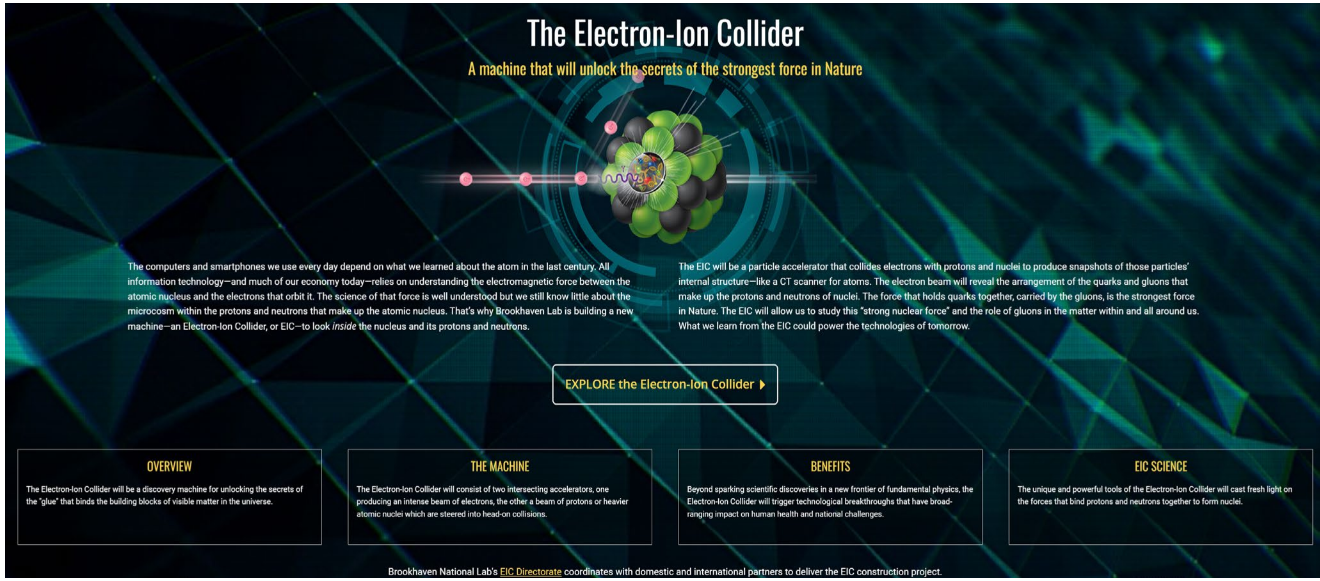
EIC项目

- 2015年美国核物理长期规划确定为最高优先级
- 2018年美国国家科学院最优先推荐核物理项目
- 明年开工建设
- 2030 年代中期运行取数
- 2022年发表的黄皮书目前引用已超过1000次

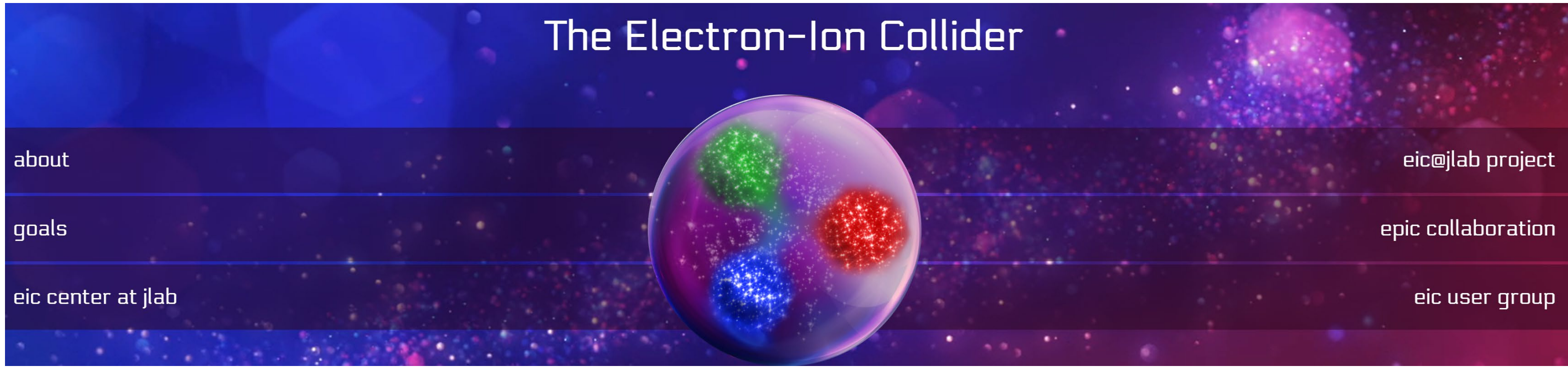
Science Requirements and Detector Concepts for the Electron-Ion Collider : EIC Yellow Report #1
R. Abdul Khalek (Vrije U., Amsterdam and Nikhef, Amsterdam), A. Accardi (Hampton U. and Jefferson Lab), J. Adam (Brookhaven), D. Adamiak (Ohio State U.), W. Akers (Jefferson Lab) et al. (Mar 8, 2021)
Published in: *Nucl.Phys.A* 1026 (2022) 122447 • e-Print: 2103.05419 [physics.ins-det]
pdf DOI cite claim reference search 1,008 citations

◆ 美国未来唯一的高能对撞机设施。

◆ 布鲁克海文国家实验室网站：



◆ JLab实验室网站：



EicC项目

EicC

Conceptual Design Report

Luis Albino[1], Daniele P. Anderle[2,3], Chentao Bao[4], Daniele Binosi[5], Xiong-Hui Cao[6], Xu Cao[7,8], Chao-Hsi Chang[6], Lei Chang[9], Mingxuan Chang[7,8], Ning-Bo Chang[10], Wan Chang[11], Kuang-Ta Chao[12], Hai Chen[4], Jinhui Chen[13,14], Kai Chen[15], Long Chen[16], Long-Bin Chen[17], Xurong Chen[7,8], Xuan Chen[16], Shan Cheng[18], Zhu-Fang Cui[19,20], Ling-Yun Dai[18], Maxime Defurne[21], Yongjie Deng[22], Heng-Tong Ding[23], Minghui Ding[19,20], Hongxin Dong[24], Liang Dong[25], Meng-Lin Du[26], Yi-Lun Du[27], Yong Du[28], Zhen Fang[18], Xu Feng[12], Jun Gao[29,30], S. V. Goloskokov[31], Li Gong[32], Boxing Gou[7,8], Xingrui Gou[22], Aiqiang Guo[7,8], Feng-Kun Guo[6,33,34], Jiacheng Guo[35], Zhi-Hui Guo[36], Qinghua He[37], Tie-Jiun Hou[38], Qipeng Hu[25], Zhengguo Hu[7,8], Zhi Hu[39], Jun Hua[2,3], Bowen Huang[4], Guangshun Huang[25], Hui Huang[40], Xu-Guang Huang[41,13,14], Yuan-Yuan Huang[42], Shihai Jia[35], Jun Jiang[16], Daekyoung Kang[13], Xiaoshen Kang[32], Leonid Kaptari[43], Weiyao Ke[15], Krešimir Kumerički[44], Jiangshan Lan[7,8], Cheng Li[25], De-Min Li[45], Hai Tao Li[16], Hengne Li[2,3], Minxiang Li[7,8], Peiyu Li[35], Shi-Yuan Li[16], Xiaomei Li[35], Xiaqing Li[22], Xin Li[7,8], Yang Li[25], Jian Liang[2,3], Yutie Liang[7,8], Ze-Rui Liang[36], Zuotang Liang[22], Dexu Lin[7,8], Ting Lin[22], ChongYang Liu[29,30], Guoming Liu[2,3], Jianbei Liu[25], Jie Liu[7,8], Liuming Liu[7,8], Tianbo Liu[22], Xiaohui Liu[46,47], Yan-Rui Liu[16], Yanwen Liu[25], Yubin Liu[9], Zheng Liu[40], Peng-Cheng Lu[16], Ya Lu[48], Yu Lu[33], Zhun Lu[49], Zongyang Lu[22], Tan Luo[18], Xiaofeng Luo[15], Mengjiao Lyu[50], Bo-Qiang Ma[12], Fu Ma[7,8], Jian-Ping Ma[6], Teng Ma[51], Weihu Ma[13], Yugang Ma[13,14], Yuming Ma[7,8], Souvik Maity[7,8], Lijun Mao[7,8], Víctor Martínez-Fernández[52], Cědric Mezrag[21], Chandan Mondal[7,8], Josě Manuel Morgado Chăvez[21], Maowu Nie[22], Haiping Peng[25], B. Pire[53], Jiajia Qin[39], Ning Ren[40], Craig Roberts[19,20], Peng Ru[2,3], Jorge Segovia[1], Kirill M. Semenov-Tian-Shansky[54,55], Ding-Yu Shao[41,13,14], Guodong Shen[7,8], Jian-Ming Shen[18], XiaoMin Shen[29,30], Chao Shi[37], Pan-Pan Shi[56], Shusu Shi[15], Zong-Guo Si[16], Jinxing Song[35], Qin-Tao Song[45], Ze Song[32], Feliciano De Soto[1], Hao Sun[57], Peng Sun[7,8], Pengfei Sun[35], Xu Sun[7,8], Zhiyu Sun[7,8], Paweł Sznajder[52], Chentao Tan[49], Liang Tang[36], Meitang Tang[7,8], Ye Tian[7,8], Jakub Wagner[52], Chenyang Wang[2,3], Enke Wang[2,3], Haozhen Wang[35], Jian Wang[16], Lei Wang[7,8], Wei Wang[29,30], Xiaoyu Wang[45], Xue Wang[22], Yao-Guang Wang[16], Yaping Wang[15], Yi Wang[58], Zhen Wang[22], Shu-yi Wei[22], Jia-Jun Wu[33], Qun Wu[16], Xing-Gang Wu[59], Jiawen Xia[7,8], Lei Xia[25], Bo-Wen Xiao[60], Hao Xiao[38], Jujun Xie[7,8], Yaping Xie[7,8], Hongxi Xing[2,3], Weizhi Xiong[22], Hushan Xu[7,8], Nu Xu[7,8], Qinghua Xu[22], Shu-Sheng Xu[61], Siqi Xu[7,8], Bin Yan[62], Wenbiao Yan[25], Wen-Cheng Yan[45], Chi Yang[22], Haijun Yang[29,30], Jiancheng Yang[7,8], Ke Yang[12], Qian Yang[22], Shuai Yang[2,3], Yi-Bo Yang[6,33], Zhi Yang[26], De-Liang Yao[18], Zaochen Ye[2,3], Zhi-Hong Ye[58], Li Yi[22], Peilin Yin[61], Yi Yin[60], Jie-Sheng Yu[18], Zihan Yu[22], Bilgai Almeida-Zamora[1], Chunhua Zeng[7,8], Jun Zeng[29,30], Wangmei Zha[25], Congyue Zhang[63], Dingwei Zhang[2,3], Jian-Hui Zhang[60], Jielei Zhang[64], Jinlong Zhang[22], Shu-Lei Zhang[18], Xiaoming Zhang[15], Xu Zhang[6], Yifei Zhang[25], Yu Zhang[65], Yu Zhang[38], Zeyu Zhang[58], Zhe Zhang[7,8], Zhen-Huang Zhang[38], Zhenyu Zhang[66], Ziqi Zhang[7,8], Chengxin Zhao[7,8], He Zhao[7,8], Hongwei Zhao[7,8], Jie Zhao[13,14], Jing Zhao[22], Xiaoyan Zhao[22], Xingbo Zhao[7,8], Yuxiang Zhao[7,8], Zhengguo Zhao[25], Bo Zheng[38], Duxin Zheng[27], Liang Zheng[67], Daicui Zhou[15], Jian Zhou[22], Jing Zhou[35], Kai Zhou[60], Xiang Zhou[66], Xiaorong Zhou[25], Ya-jin Zhou[22], Ruilin Zhu[24], Senjie Zhu[25], Yingchun Zhu[25], Zhimin Zhu[7,8], Xiao Zhuang[35], and Bing-Song Zou[6,33,34,5]

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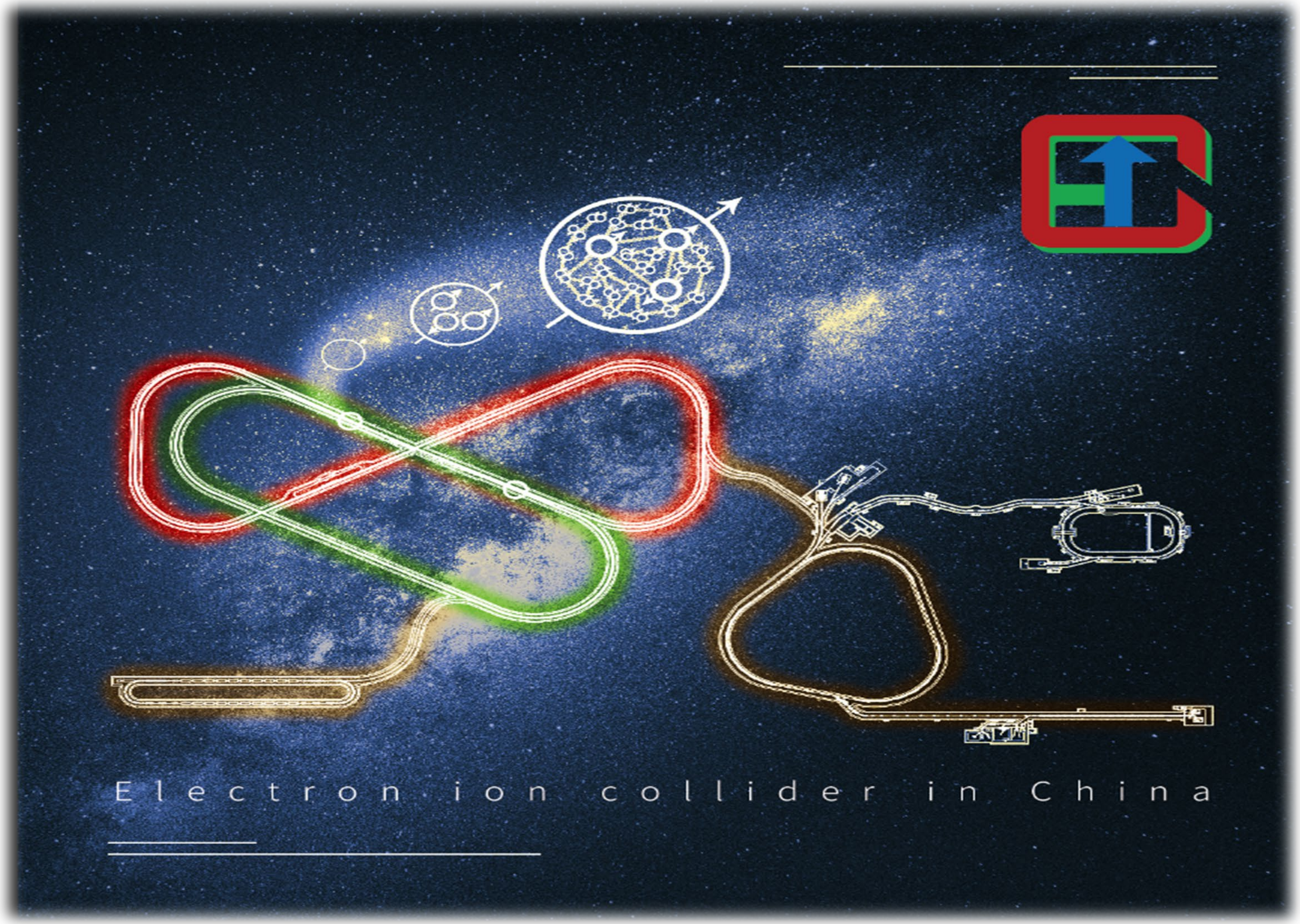
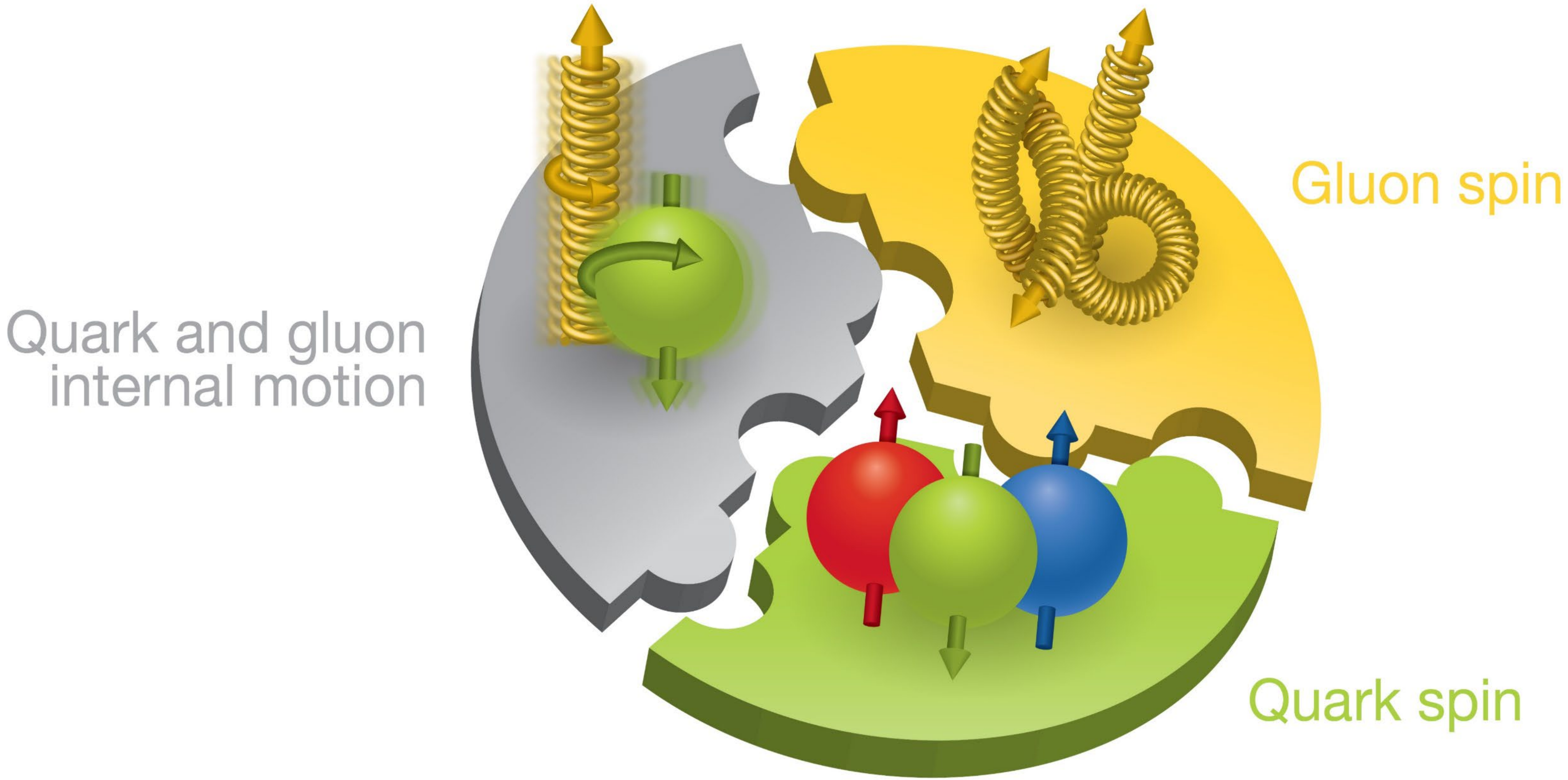


Proton spin decomposition



Spin decompositions of proton

- "Spin crisis" $\Delta\Sigma(Q^2 = 10.7GeV^2) = 0.060 \pm 0.047 \pm 0.069$ 1988, EMC

- Jaffe-Manohar decomposition

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + l_q + \Delta g + l_g$$

Jaffe, Manohar, 1990

$\Delta\Sigma \approx 0.3$ $\Delta g \approx 0.2$

Canonical OAM

- Ji decomposition

$$\frac{1}{2} = J_q + J_g = \frac{1}{2}\Delta\Sigma + \mathrm{L}_q + J_g$$

X.D. Ji, 1996

Kinematic OAM

Jaffe-Manohr decomposition v.s. Ji decomposition

Canonical V.S. Kinematical

$\vec{r} \times (\vec{p} - e\vec{A})$ $\vec{r} \times \vec{p}$

	JM decomposition	Ji decomposition
分解完全	是	否
角动量算子对易关系	是	否
规范不变性	否	是

◆ Gauge invariant extension

$\vec{S}^e_{\text{Ji}}$	$\vec{L}^e_{\text{Ji}}$	$\vec{J}^\gamma_{\text{Ji}}$	
$\vec{S}^e_{\text{gik}}$	$\vec{L}^e_{\text{gik}}$	$\vec{L}^\gamma_{\text{gik}}$	$\vec{S}^\gamma_{\text{gik}}$
$\vec{S}^e_{\text{gic}}$	$\vec{L}^e_{\text{gic}}$	$\vec{L}^\gamma_{\text{gic}}$	$\vec{S}^\gamma_{\text{gic}}$

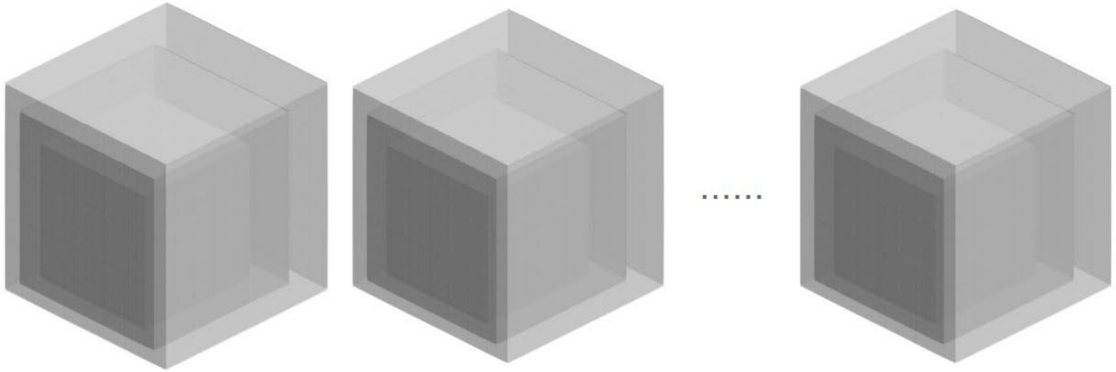
and commented on their advantages and disadvantages. There have been many very interesting theoretical developments, but we have concluded that they contain no new important physical implications, and for that reason we have concentrated on experimental tests and measurements only with regard to the canonical and Belinfante versions of the angular momentum.

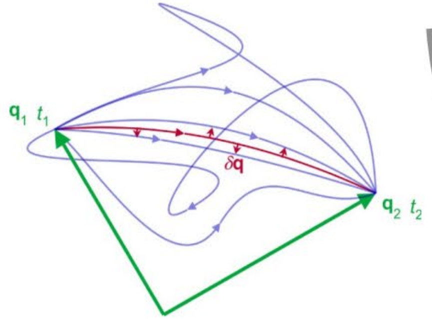
E. Leader & C. Lorce, 2014

Lattice QCD

Borrowed from Yibo's slides

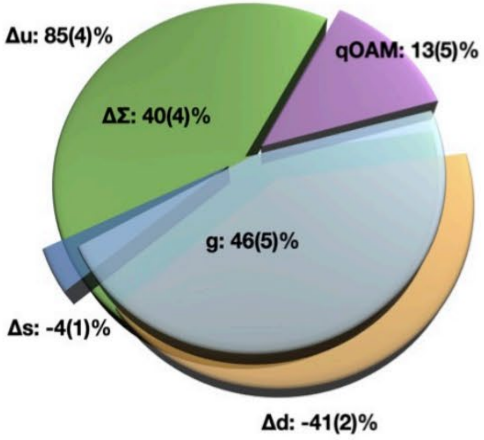
and QCD



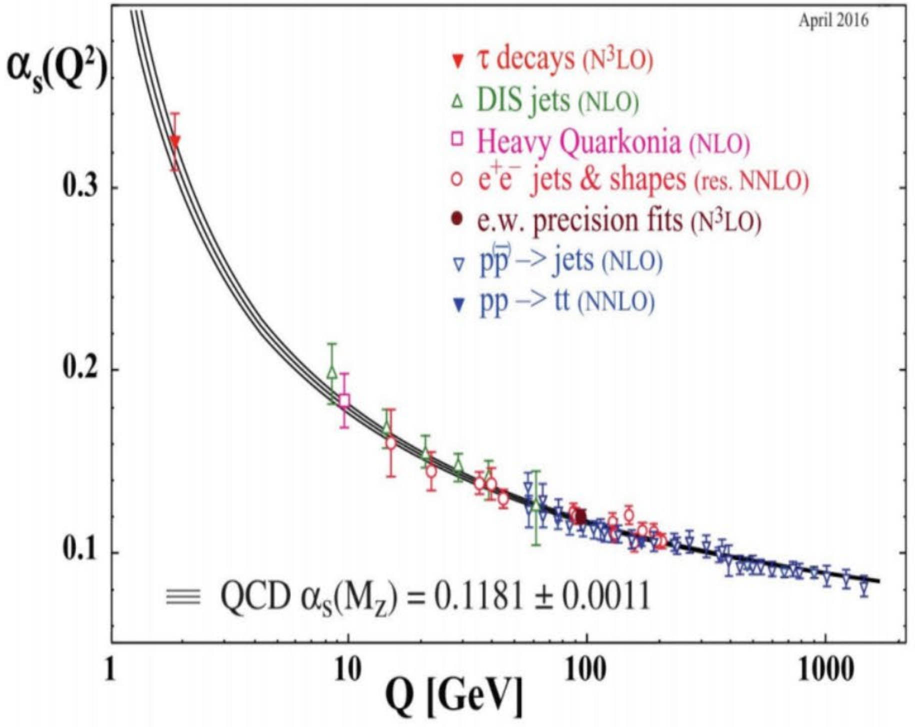


$$\langle \mathcal{O} \rangle = \frac{\int [\mathrm{d}A\mathrm{d}\psi]\mathcal{O}(A,\psi)e^{-\int \mathrm{d}^4x \mathcal{L}(A(x),\psi(x))}}{\int [\mathrm{d}A\mathrm{d}\psi]e^{-\int \mathrm{d}^4x \mathcal{L}(A(x),\psi(x))}}$$

$$= \frac{\sum_{i=1}^{N} \mathcal{O}(A_i, S_\psi(A_i))}{N} + \mathcal{O}(\frac{1}{\sqrt{N}})$$



G. Wang, et.al., χQCD, PRD106(2022) 014512



- QCD is non-perturbative at the hadron scale;
- Lattice QCD can provide first principle predictions on the hadron spin decomposition, **as functions of quark mass**.

Parton orbital angular momentum

- The total angular momentum is related to the GPDs:

$$J_q = \lim_{t \to 0} \frac{1}{2} \int_0^1 dx x [H_q(x,t,\xi) + E_q(x,t,\xi)]$$

Ji, 1997

Some properties of GPDs

- Form factors

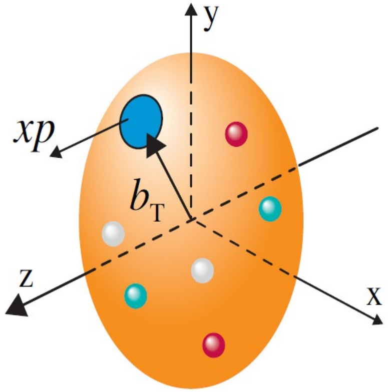
$$\sum_q e_q \int dx\, H^q(x,\xi,t) = F_1^p(t)\,, \qquad \sum_q e_q \int dx\, E^q(x,\xi,t) = F_2^p(t)$$

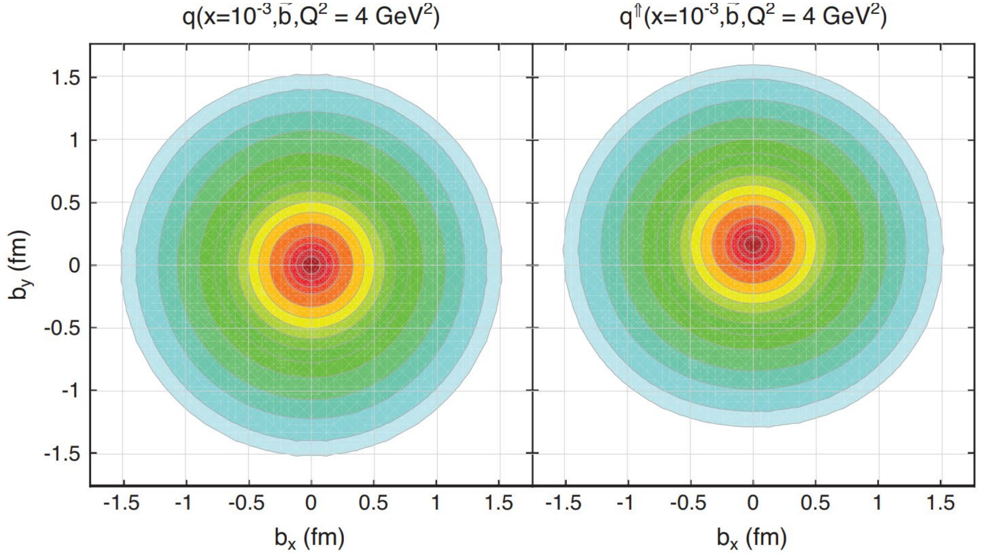
- Transverse spatial distribution

Soper 77 & Burkardt 2000

$$\mathcal{H}^q(x,\vec{b}_T^2) = \int \frac{d^2\vec{\Delta}_T}{(2\pi)^2}\, e^{-i\vec{\Delta}_T\cdot\vec{b}_T}\, H^q(x,0,-\vec{\Delta}_T^2)$$

$$f_q(z,b_{\perp,q}) = \mathcal{H}_q(z,b_{\perp,q}^2) + \frac{1}{M}\epsilon_\perp^{ij} b_{\perp,q}^i S_\perp^j \frac{\partial \mathcal{E}_q(z,b_{\perp,q}^2)}{\partial b_{\perp,q}^2}$$

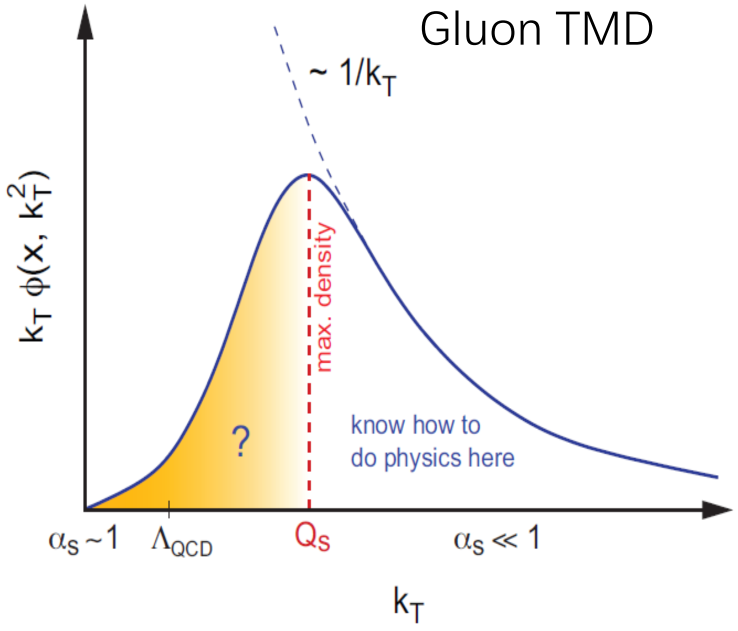




Small x evolution equations

- DGLAP $\ln\frac{Q^2}{\mu^2}$
- BFKL(CCFM) $\ln\frac{1}{x}$
- BK(JIMWLK, GLR-MQ) $\ln\frac{1}{x}$

take into account the saturation effect $\frac{1}{N_c}\mathrm{Tr}U(b_\perp + r_\perp/2)U^\dagger(b_\perp - r_\perp/2)$



$$\partial_Y \mathcal{N}(\mathbf{x},\mathbf{y}) = \frac{\bar{\alpha}}{2\pi}\int d^2z \frac{(\mathbf{x}-\mathbf{y})^2}{(\mathbf{x}-\mathbf{z})^2(\mathbf{z}-\mathbf{y})^2}\left[\mathcal{N}(\mathbf{x},\mathbf{z}) + \mathcal{N}(\mathbf{z},\mathbf{y}) - \mathcal{N}(\mathbf{x},\mathbf{y}) - \mathcal{N}(\mathbf{x},\mathbf{z})\mathcal{N}(\mathbf{z},\mathbf{y})\right]$$

Balitsky, 1996
Kovchegov, 1997

$$\bar{\alpha}_s = \frac{\alpha_s N_c}{\pi}$$

- BK equation in momentum space:

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

$$-\frac{\bar{\alpha}_s}{2\pi}\int d^2\Delta'_\perp \mathcal{N}(k_\perp + \frac{\Delta'_\perp}{2},\Delta_\perp - \Delta'_\perp)\mathcal{N}(k_\perp + \frac{\Delta'_\perp - \Delta_\perp}{2},\Delta'_\perp)$$

Generalized TMDs

➢ Parametrization

$$\mathcal{N}(k_\perp, \Delta_\perp, S_\perp) \approx \frac{\pi g^2}{2N_c} \Big\{ \mathcal{F}_{1,1}(k_\perp, \Delta_\perp) - i k_\perp \times S_\perp \frac{k_\perp \cdot \Delta_\perp}{M^4} \mathcal{F}_{1,2}(k_\perp, \Delta_\perp) - i \frac{\Delta_\perp \times S_\perp}{2M^2} \left[2\mathcal{F}_{1,3}(k_\perp, \Delta_\perp) - \mathcal{F}_{1,1}(k_\perp, \Delta_\perp) \right] \Big\}$$

$$\mathcal{N}(k_\perp, \Delta_\perp) = \frac{1}{(2\pi)^2} \int d^2 r_\perp e^{i k_\perp \cdot r_\perp} \frac{N(r_\perp, \Delta_\perp)}{r_\perp^2}$$

Assuming target transversely polarized.

◆ Typical nucleon recoiled transverse momentum is reversely proportional to the radius of nucleon,

$$\mathcal{F}_{1,1}(k_\perp, \Delta_\perp) = \overline{\mathcal{F}}_{1,1}(k)(2\pi)^2 \delta^{(2)}(\Delta_\perp)$$

◆ The forward BK(for the unpolarized gluon TMD) reads,

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

Spin-dependent small x evolution equation

- Project to the different spin correlation structures,

$$\partial_Y\left(k_\perp\times S_\perp\frac{k_\perp^i}{M^2}\mathcal{F}_{12}(k_\perp)+\epsilon^{ij}S_\perp^j(\mathcal{F}_{13}(k_\perp)-\frac{1}{2}\mathcal{F}_{11}(k_\perp))\right)=\frac{\bar{\alpha}_s}{\pi}\int\frac{d^2k'_\perp}{(k_\perp-k'_\perp)^2}\Big[k'_\perp\times S_\perp\frac{k'^i_\perp}{M^2}\mathcal{F}_{12}(k'_\perp)$$
$$+\frac{\epsilon^{ij}S_\perp^j}{2}(2\mathcal{F}_{13}(k'_\perp)-\mathcal{F}_{11}(k'_\perp))-\frac{k_\perp^2}{2k'^2_\perp}\left(k_\perp\times S_\perp\frac{k_\perp^i}{M^2}\mathcal{F}_{12}(k_\perp)+\frac{\epsilon^{ij}S_\perp^j}{2}(2\mathcal{F}_{13}(k_\perp)-\mathcal{F}_{11}(k_\perp))\right)\Big]$$
$$-4\pi^2\alpha_s^2\left(k_\perp\times S_\perp\frac{k_\perp^i}{M^2}\mathcal{F}_{1,2}(k_\perp)+\frac{\epsilon^{ij}S_\perp^j}{2}(2\mathcal{F}_{1,3}(k_\perp)-\mathcal{F}_{1,1}(k_\perp))\right)\overline{\mathcal{F}}_{1,1}(k_\perp),$$

- Read off the coefficients of $k_\perp\times S_\perp$ $\frac{\epsilon^{ij}S_\perp^j}{2}$

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

and,

$$\partial_Y\mathcal{F}_{1,3}(k_\perp)=\frac{\bar{\alpha}_s}{\pi}\int\frac{d^2k'_\perp}{(k_\perp-k'_\perp)^2}\left[-\frac{k_\perp^2}{2k'^2_\perp}\mathcal{F}_{1,3}(k_\perp)+\frac{k_\perp^2k'^2_\perp-(k_\perp\cdot k'_\perp)^2}{k_\perp^2}\frac{\mathcal{F}_{1,2}(k'_\perp)}{M^2}+\mathcal{F}_{1,3}(k'_\perp)\right]-4\pi^2\alpha_s^2\overline{\mathcal{F}}_{1,1}(k_\perp)\mathcal{F}_{1,3}(k_\perp)$$

- Combine the evolution equations for F1,2 and F1,3

Note: $\mathcal{E}\equiv-\mathcal{F}_{1,1}+\mathcal{J}$

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

Small x evolution of Eg

- The forward BK(for the unpolarized gluon TMD) reads,

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

- Small x evolution equation for kt dependent Eg,

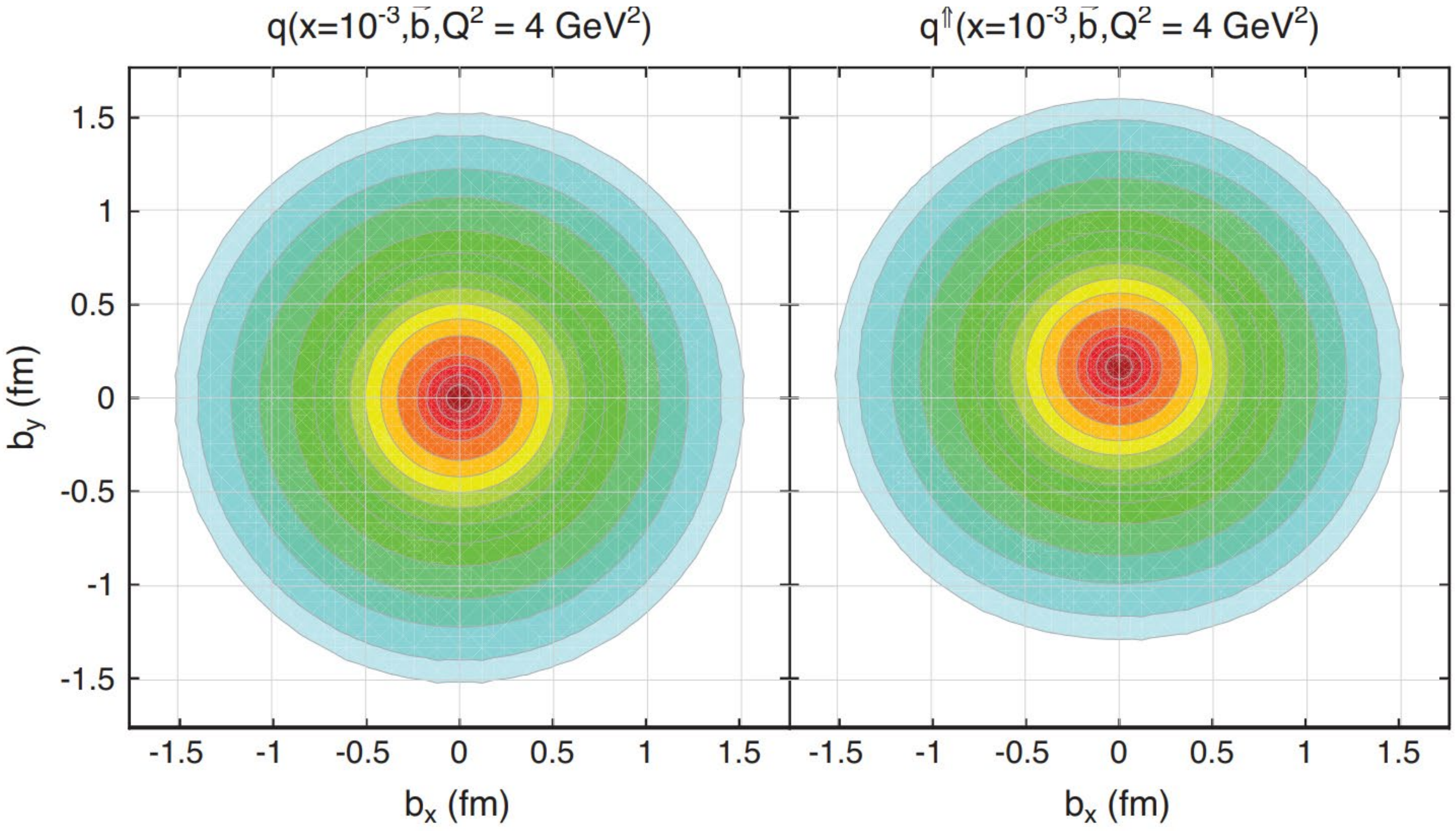
$$\partial_Y \mathcal{E}(k_\perp) = \frac{\bar{\alpha}_s}{\pi} \int \frac{d^2k'_\perp}{(k_\perp - k'_\perp)^2} \left[\mathcal{E}(k'_\perp) - \frac{k_\perp^2}{2k'^2_\perp} \mathcal{E}(k_\perp) \right] - 4\pi^2 \alpha_s^2 \overline{\mathcal{F}}_{1,1}(k_\perp) \mathcal{E}(k_\perp)$$

Hatta, ZJ, PRL, 2022

- In the dilute limit:

$$xE_g(x) \sim xG(x) \propto \left(\frac{1}{x}\right)^{\bar{\alpha}_s 4 \ln 2}$$

Energy dependent behavior of distorted proton



$$f_q(z, b_{\perp,q}) \;=\; \mathcal{H}_q(z, b_{\perp,q}^2) + \frac{1}{M}\epsilon_\perp^{ij} b_{\perp,q}^i S_\perp^j \frac{\partial \mathcal{E}_q(z, b_{\perp,q}^2)}{\partial b_{\perp,q}^2}$$

Numerical results

- The MV model (x_0=0.01) $Y = \ln \frac{x_0}{x}$

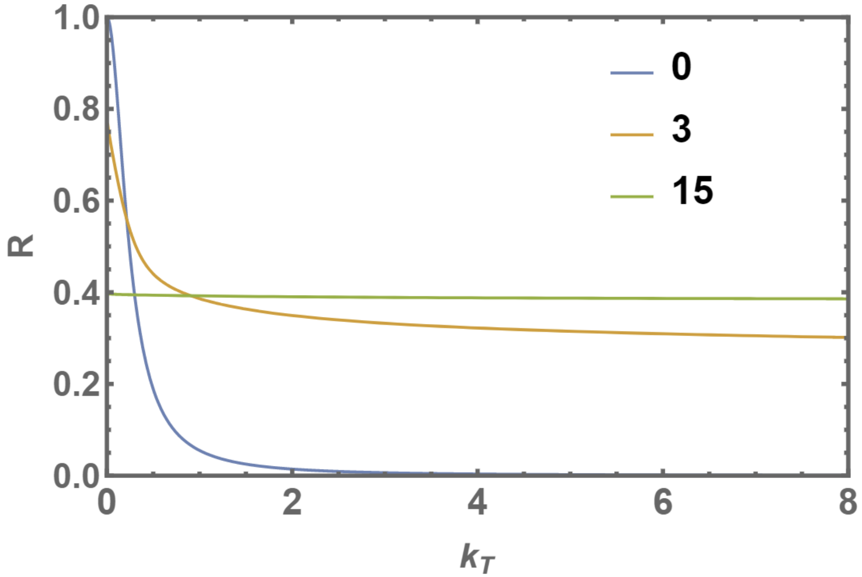
$$\mathcal{F}_{1,1}(Y=0,k_\perp) = \frac{N_c \mathcal{A}_\perp}{2\pi^2 \alpha_s} \int \frac{d^2 r_\perp}{(2\pi)^2 r_\perp^2} e^{-ik_\perp \cdot r_\perp} \left\{ 1 - \exp\left[-\frac{r_\perp^2 Q_{s0}^2}{4} \ln\left(\frac{1}{r_\perp \Lambda_{\rm mv}} + e \right) \right] \right\}$$

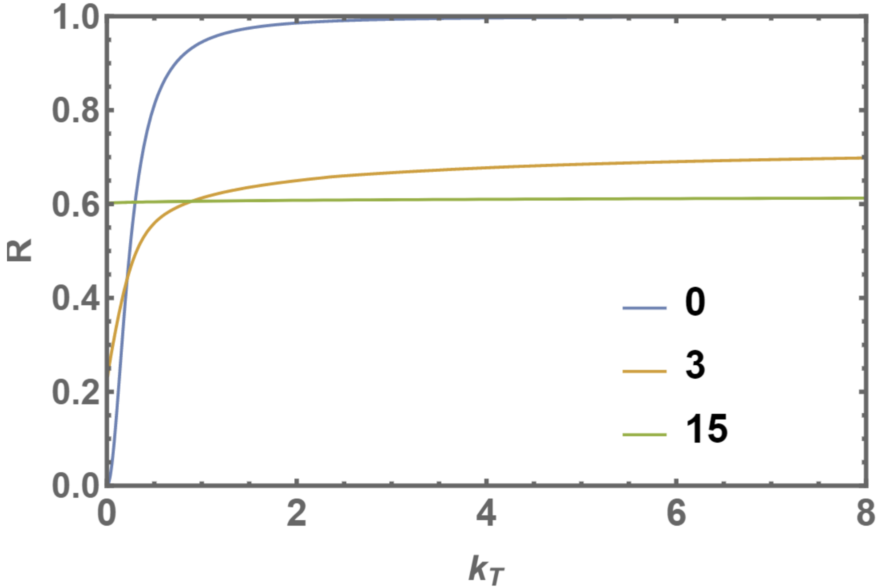
- Two toy models:

$$\mathcal{E}(Y=0,k_\perp) = \frac{\Lambda_{\rm mv}^2}{k_\perp^2 + \Lambda_{\rm mv}^2} \mathcal{F}_{1,1}(Y=0,k_\perp)$$

$$\mathcal{E}(Y=0,k_\perp) = \frac{k_\perp^2}{k_\perp^2 + \Lambda_{\rm mv}^2} \mathcal{F}_{1,1}(Y=0,k_\perp)$$

$$R \equiv \frac{\mathcal{E}(x,k_\perp)}{\mathcal{F}_{1,1}(x,k_\perp)}$$



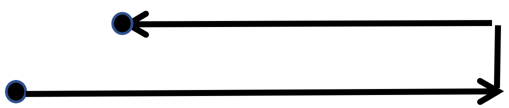


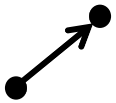
Probe quark OAM

Canonical parton OAM and the GTMD

- Canonical OAM and GTMD: $L^q(x,\xi) = -\int d^2k_\perp \frac{k_\perp^2}{M^2} F_{1,4}^q(x,k_\perp,\xi,\Delta_\perp=0)$

C. Lorce, B. Pasquini, 2011; Y. Hatta, 2012



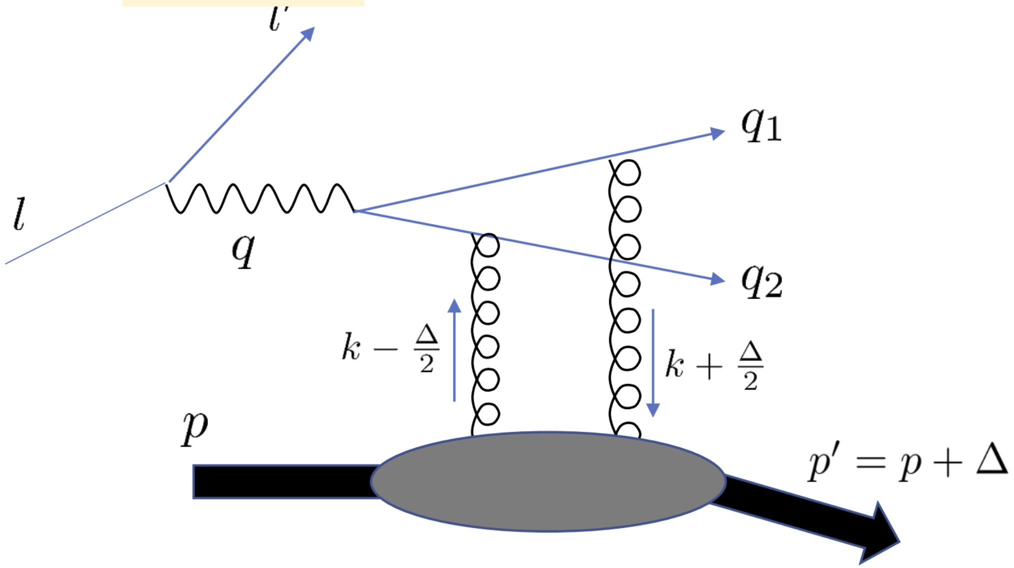


Canonical V.S. Kinematical

$\vec{r}\times(\vec{p}-e\vec{A})$ $\vec{r}\times\vec{p}$

- Probe F 1,4 in diffractive di-jet production

X. Ji, F. Yuan, and Y. Zhao, 2017; Y. Hatta, Y. Nakagawa, F. Yuan, Y. Zhao, and B. Xiao, 2017; S. Bhattacharya, R. Boussarie, and Y. Hatta 2022



Generalized TMDs

$$W^{q\,[\Gamma]}_{\lambda,\lambda'}(P,\Delta,x,\vec{k}_\perp) = \int \frac{dz^-\,d^2\vec{z}_\perp}{2(2\pi)^3}\, e^{ik\cdot z}\,\langle p',\lambda'|\,\bar{q}(-\tfrac{z}{2})\,\Gamma\,\mathcal{W}(-\tfrac{z}{2},\tfrac{z}{2})\,q(\tfrac{z}{2})\,|p,\lambda\rangle\Big|_{z^+=0}$$

A. Belitisky, X. D. Ji and F. Yuan, 2003
S. Meissner, A. Metz, M. Schlegel and K. Goeke, 2008

- which is the Fourier transform of Wigner distribution:

$$\rho^{[\Gamma]}(\vec{b}_\perp,\vec{k}_\perp,x,\vec{S}) = \int \frac{\mathrm{d}^2\Delta_\perp}{(2\pi)^2}\, e^{-i\vec{\Delta}_\perp\cdot\vec{b}_\perp}\, W^{[\Gamma]}(\vec{\Delta}_\perp,\vec{k}_\perp,x,\vec{S})$$

Parametrization:

$$W^{q\,[\gamma^+]}_{\lambda,\lambda'} = \frac{1}{2M}\,\bar{u}(p',\lambda')\left[F^q_{1,1} + \frac{i\sigma^{i+}k^i_\perp}{P^+}F^q_{1,2} + \frac{i\,\sigma^{i+}\Delta^i_\perp}{P^+}F^q_{1,3} + \frac{i\sigma^{ij}k^i_\perp\Delta^j_\perp}{M^2}F^q_{1,4}\right]u(p,\lambda)$$

$b_\perp \times k_\perp$ Orbital angular momentum

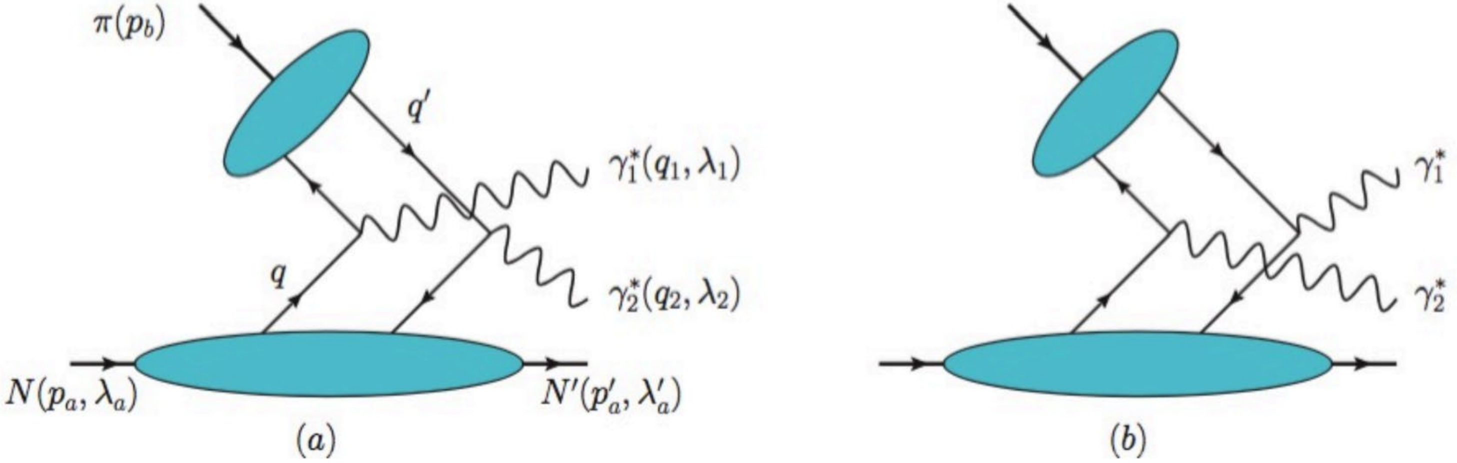
$$W^{q\,[\gamma^+\gamma_5]}_{\lambda,\lambda'} = \frac{1}{2M}\,\bar{u}(p',\lambda')\left[-\frac{i\varepsilon^{ij}_\perp k^i_\perp\Delta^j_\perp}{M^2}G^q_{1,1} + \frac{i\sigma^{i+}\gamma_5 k^i_\perp}{P^+}G^q_{1,2} + \frac{i\sigma^{i+}\gamma_5\Delta^i_\perp}{P^+}G^q_{1,3} + i\sigma^{+-}\gamma_5\,G^q_{1,4}\right]u(p,\lambda)$$

Are Parton Wigner distributions measurable?

Exclusive double Drell-Yan process

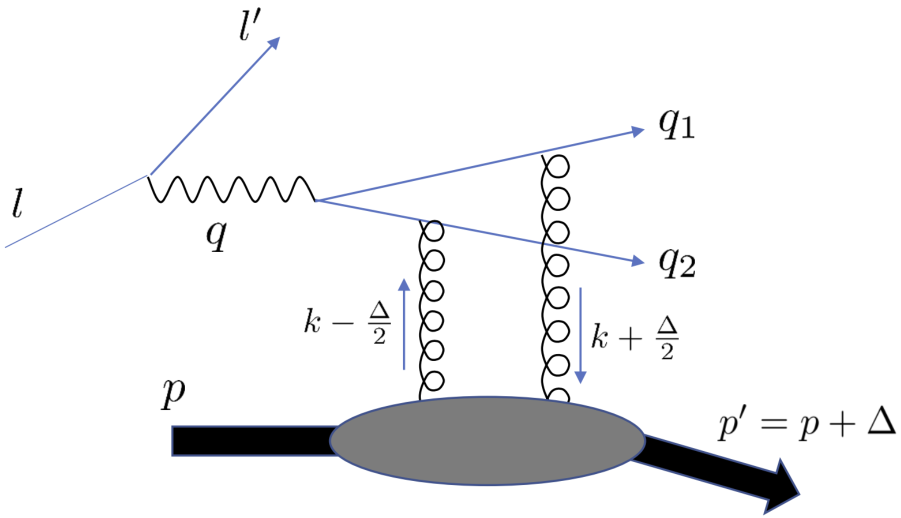
Quark case: exclusive double DY proces

Only ERBL region!



Bhattacharya, Metz, ZJ 2017

Gluon case: diffractive di-jet production



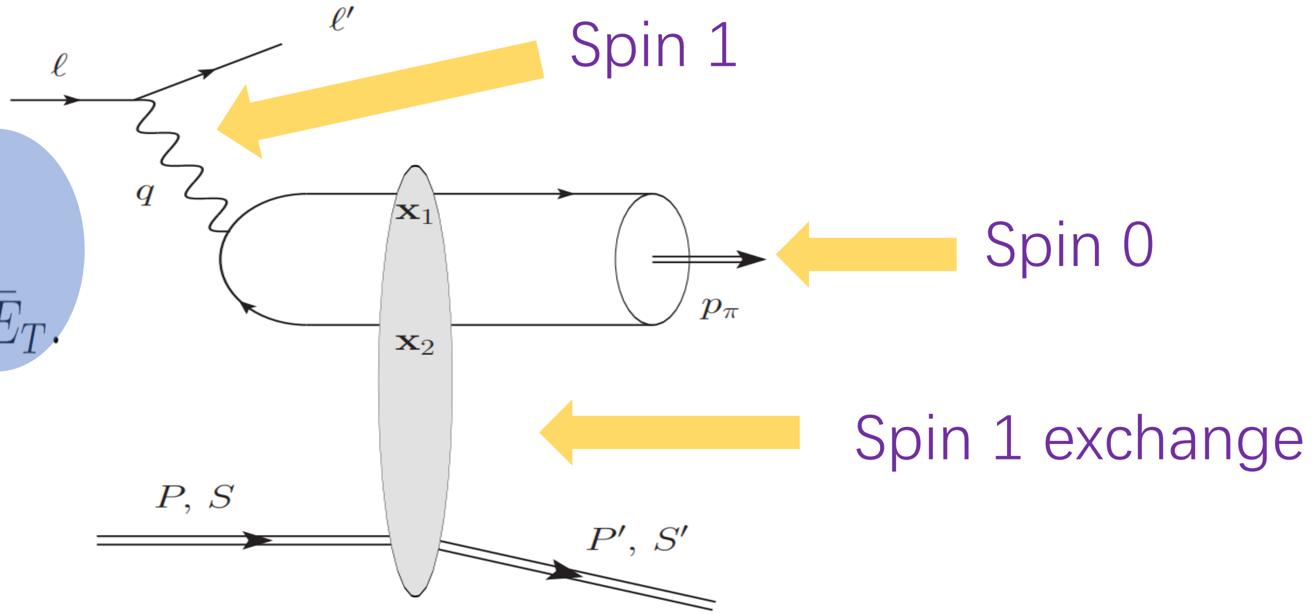
Hatta-Nakagawa-Yuan-Zhao-Xiao, 2017

Exclusive π^0 production in ep collisions

- In the forward limit, helicity flip process!

$$M_{0-,++} = \langle H_T \rangle \propto \int_{-1}^{1} d\bar{x} \mathcal{H}_{0-,++}(\bar{x}, ...) H_T;$$

$$M_{0+,++} = \langle \bar{E}_T \rangle \propto \frac{\sqrt{-t'}}{4m} \int_{-1}^{1} d\bar{x} \mathcal{H}_{0-,++}(\bar{x}, ...) \bar{E}_T.$$



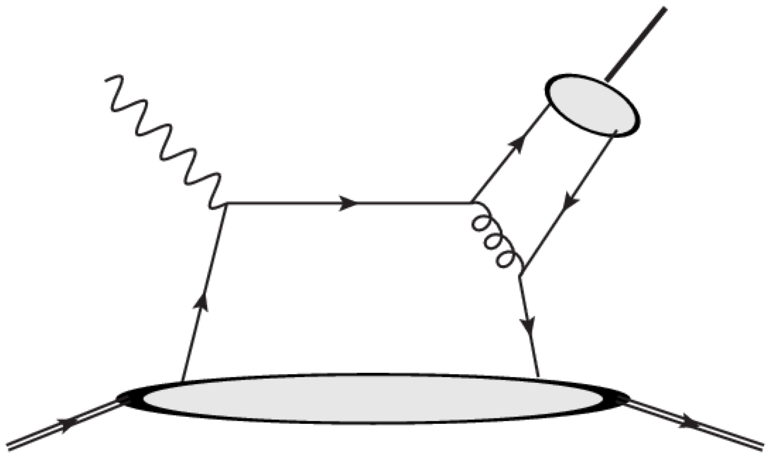
Give access to the chiral odd GPDs

L. Frankfurt, P. Pobylitsa, M. Polyakov, and M. Strikman, 1999
S. Goloskokov, Y. p. Xie, X. r. Chen, 2022

Twist-3 correction to DA, G. Duplančić, P. Kroll, K. Passek-K., and L. Szymanowski, 2024

Helicity non-flip production: quark channel

- Vanishes at leading twist!



- Non-forward region, allowing pion to carry 1 unit OAM, twist-3 effect.

- Collinear expansion to isolate twist-3 contribution:

$$H(k_\perp, \Delta_\perp) = H(k_\perp = 0, \Delta_\perp = 0) + \frac{\partial H(k_\perp, \Delta_\perp = 0)}{\partial k_\perp^\mu}\Big|_{k_\perp = 0} k_\perp^\mu + \frac{\partial H(k_\perp = 0, \Delta_\perp)}{\partial \Delta_\perp^\mu}\Big|_{\Delta_\perp = 0} \Delta_\perp^\mu + \dots$$

Angular correlations

➢ Scattering amplitudes depending on different correlations

$$\mathcal{M}_1 = \frac{g_s^2 e f_\pi}{2\sqrt{2}} \frac{(N_c^2-1)2\xi}{N_c^2\sqrt{1-\xi^2}} \delta_{\lambda\lambda'} \frac{\epsilon_\perp \times \Delta_\perp}{Q^2} \{\mathcal{F}_{1,1} + \mathcal{G}_{1,1}\},$$

$$\mathcal{M}_2 = \frac{g_s^2 e f_\pi}{2\sqrt{2}} \frac{(N_c^2-1)2\xi}{N_c^2\sqrt{1-\xi^2}} \delta_{\lambda,-\lambda'} \frac{M\epsilon_\perp \cdot S_\perp}{Q^2} \{\mathcal{F}_{1,2} + \mathcal{G}_{1,2}\}$$

$$\mathcal{M}_4 = \frac{i g_s^2 e f_\pi}{2\sqrt{2}} \frac{(N_c^2-1)2\xi}{N_c^2\sqrt{1-\xi^2}} \lambda\delta_{\lambda\lambda'} \frac{\epsilon_\perp \cdot \Delta_\perp}{Q^2} \{\mathcal{F}_{1,4} + \mathcal{G}_{1,4}\} ($$

$$S_\perp^\mu = (0^+, 0^-, -i, \lambda)$$

Bhattacharya, Zheng, ZJ, PRL, 2024

$$\mathcal{F}_{1,1} = \int_{-1}^{1} dx \frac{x^2 \int d^2k_\perp F_{1,1}^{u+d}(x,\xi,\Delta_\perp,k_\perp)}{(x+\xi-i\epsilon)^2(x-\xi+i\epsilon)^2} \times \int_0^1 dz \frac{\phi_\pi(z)(1+z^2-z)}{z^2(1-z)^2}, \quad (8)$$

$$\mathcal{G}_{1,1} = \int_{-1}^{1} dx \int_0^1 dz \frac{\phi_\pi(z)(x^2+2x^2z+\xi^2)}{z^2(x+\xi-i\epsilon)^2(x-\xi+i\epsilon)^2} \times \int d^2k_\perp \frac{k_\perp^2}{M^2} G_{1,1}^{u+d}(x,\xi,\Delta_\perp,k_\perp), \quad (9)$$

$$\mathcal{F}_{1,2} = \int_{-1}^{1} dx x \frac{\xi(1-\xi^2)\int d^2k_\perp k_\perp^2 F_{1,2}^{u+d}(x,\xi,\Delta_\perp,k_\perp)}{M^2(x+\xi-i\epsilon)^2(x-\xi+i\epsilon)^2} \times \int_0^1 dz \frac{\phi_\pi(z)(1+z^2-z)}{z^2(1-z)^2}, \quad (10)$$

$$\mathcal{G}_{1,2} = \int_{-1}^{1} dx \int_0^1 dz \frac{\phi_\pi(z)(x^2+2x^2z+\xi^2)(1-\xi^2)}{z^2(x+\xi-i\epsilon)^2(x-\xi+i\epsilon)^2} \times \int d^2k_\perp \frac{k_\perp^2}{M^2} G_{1,2}^{u+d}(x,\xi,\Delta_\perp,k_\perp), \quad (11)$$

$$\mathcal{F}_{1,4} = \int_{-1}^{1} dx \frac{x\xi \int d^2k_\perp k_\perp^2 F_{1,4}^{u+d}(x,\xi,\Delta_\perp,k_\perp)}{M^2(x+\xi-i\epsilon)^2(x-\xi+i\epsilon)^2} \times \int_0^1 dz \frac{\phi_\pi(z)(1+z^2-z)}{z^2(1-z)^2}, \quad (12)$$

$$\mathcal{G}_{1,4} = \int_{-1}^{1} dx \int_0^1 dz \frac{x(4\xi^2 z+\xi^2-2x^2z+x^2)}{z^2\xi(x+\xi-i\epsilon)^2(x-\xi+i\epsilon)^2}\phi_\pi(z) \times \int d^2k_\perp G_{1,4}^{u+d}(x,\xi,\Delta_\perp,k_\perp). \quad (13)$$

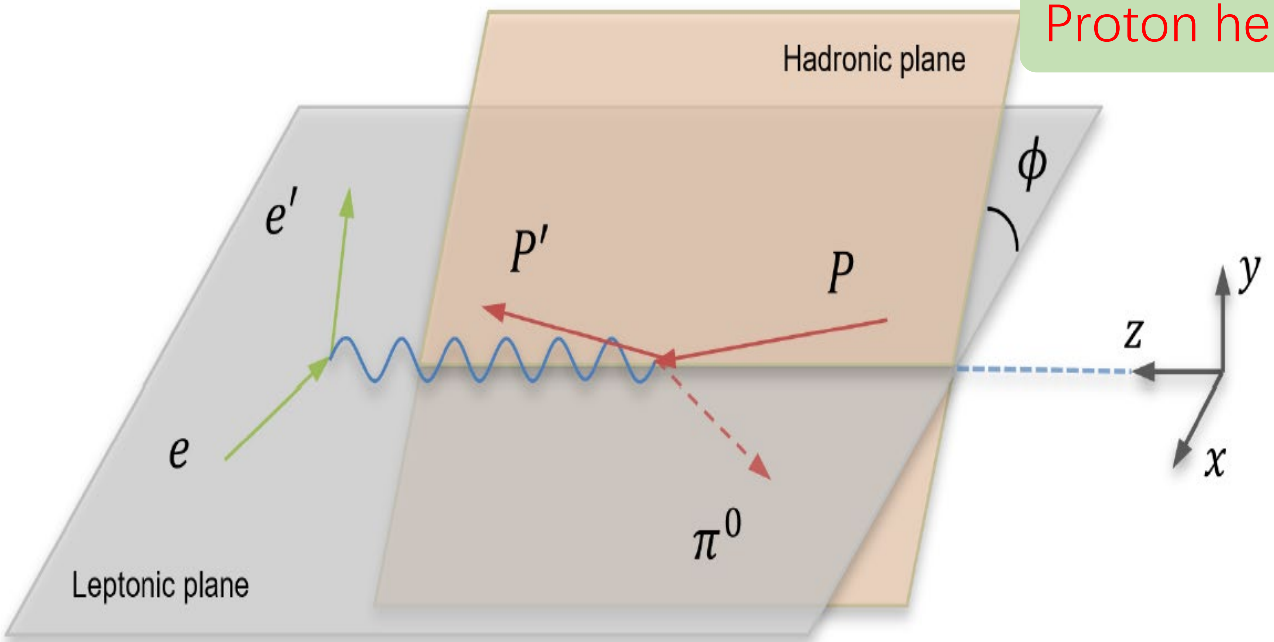
Azimuthal dependent cross section

$$\frac{d\sigma}{dt dQ^2 dx_B d\phi} = \frac{(N_c^2-1)^2\alpha_{em}^2\alpha_s^2 f_\pi^2 \xi^3 \Delta_\perp^2}{2N_c^4(1-\xi^2)Q^{10}(1+\xi)}[1+(1-y)^2]\times\left\{\left[|\mathcal{F}_{1,1}+\mathcal{G}_{1,1}|^2+|\mathcal{F}_{1,4}+\mathcal{G}_{1,4}|^2+2\frac{M^2}{\Delta_\perp^2}|\mathcal{F}_{1,2}+\mathcal{G}_{1,2}|^2\right]\right.$$

$$\left.+\cos(2\phi)a\left[-|\mathcal{F}_{1,1}+\mathcal{G}_{1,1}|^2+|\mathcal{F}_{1,4}+\mathcal{G}_{1,4}|^2\right]+\lambda\sin(2\phi)\,2a\,\mathrm{Re}\left[(i\mathcal{F}_{1,4}+i\mathcal{G}_{1,4})\left(\mathcal{F}_{1,1}^*+\mathcal{G}_{1,1}^*\right)\right]\right\}$$

Proton helicity

Distinguished experimental signature of $F_{1,4}$



$$\phi = \phi_{l_\perp} - \phi_{\Delta_\perp}$$

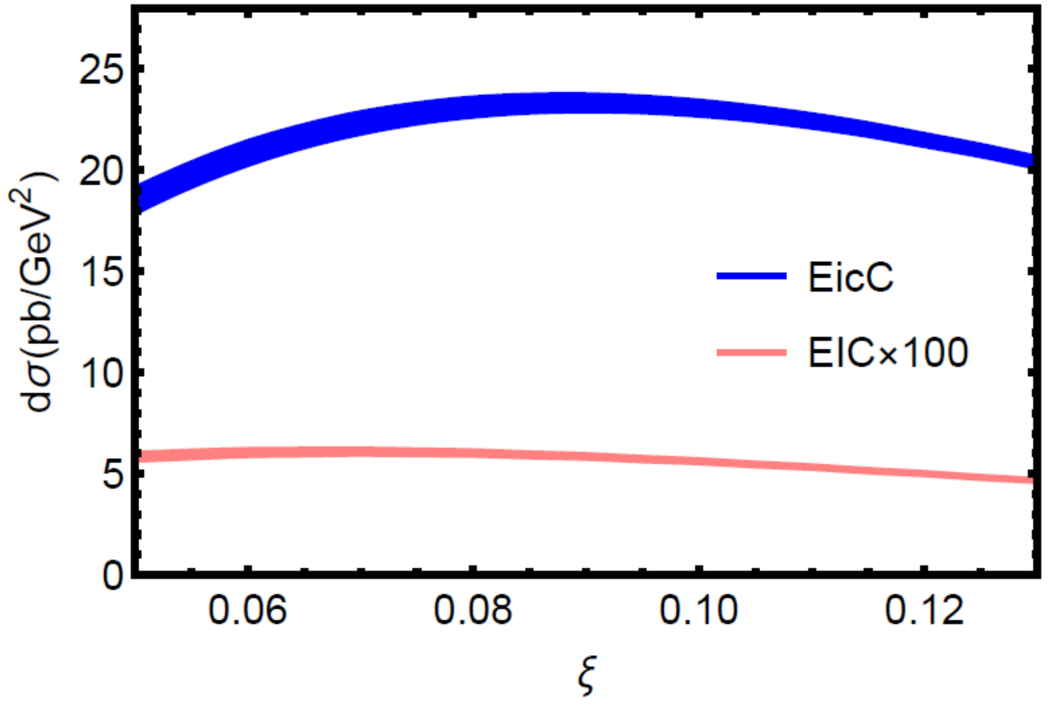
$$\int d^2k_\perp \mathrm{Re}[F_{1,1}(x,\xi,\Delta_\perp,k_\perp)] \approx H(x,\xi,\Delta_\perp)$$

$$\int d^2k_\perp \mathrm{Re}[G_{1,4}(x,\xi,\Delta_\perp,k_\perp)] \approx \tilde{H}(x,\xi,\Delta_\perp)$$

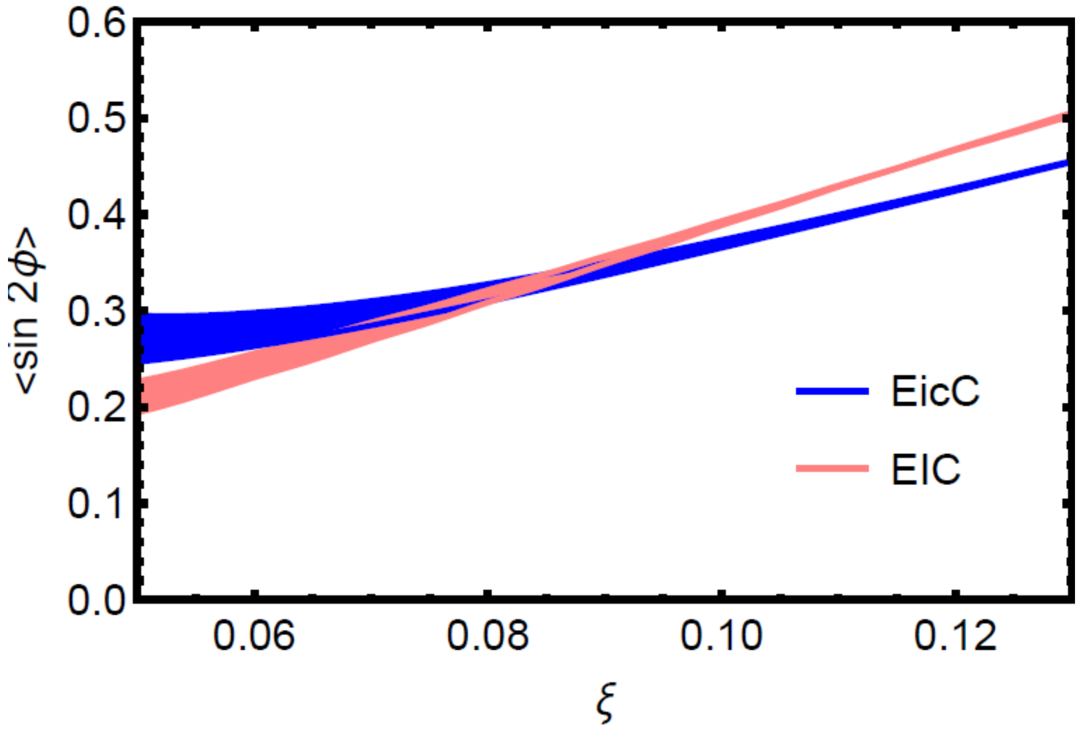
Bhattacharya, Zheng, ZJ, PRL, 2024

Numerical results

Unpolarized cross section:



sin2Φ azimuthal asymmetry

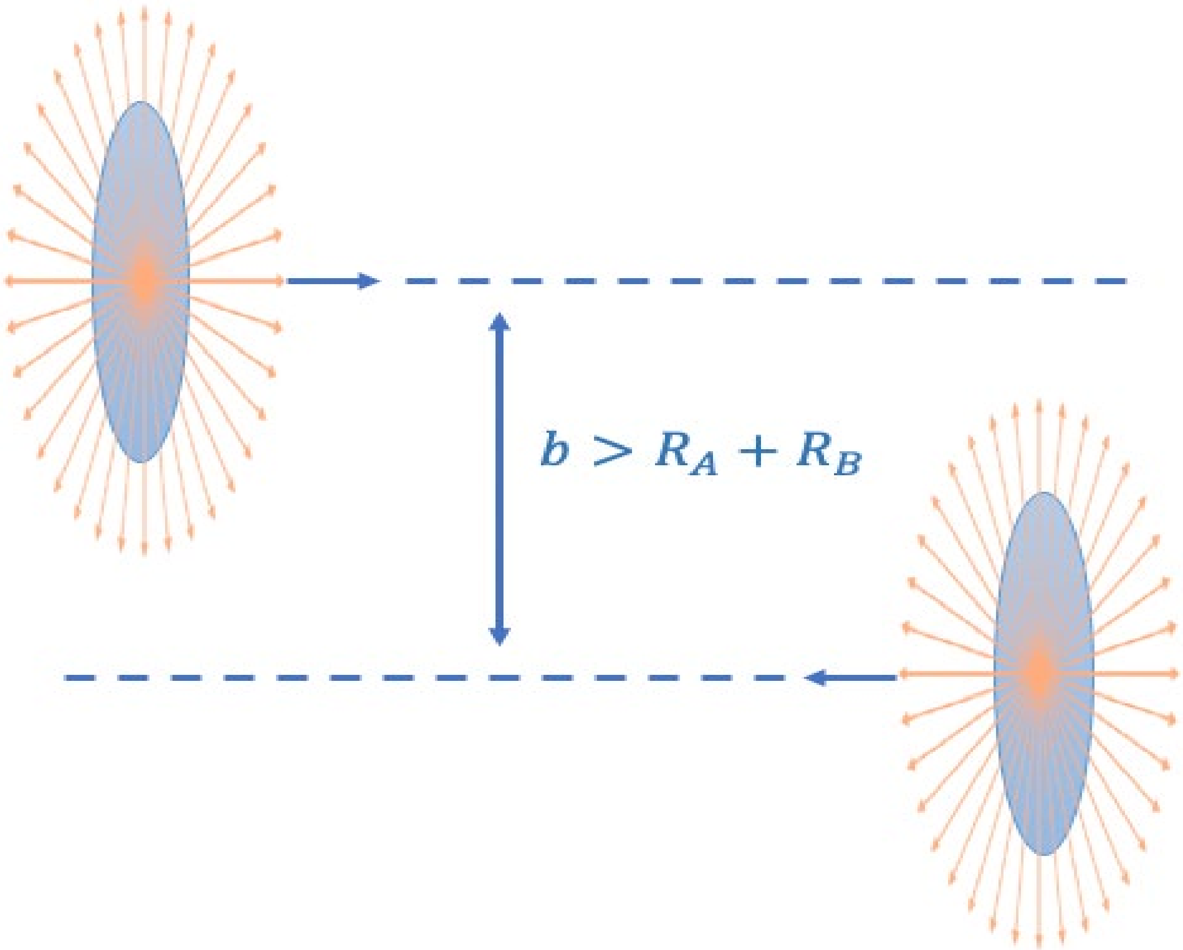


EIC: $Q^2=10$, EicC: $Q^2=3$

$$\xi = \frac{p^+ - p'^+}{p^+ + p'^+}$$

- We focus on the large zeta region to suppress gluon contribution.

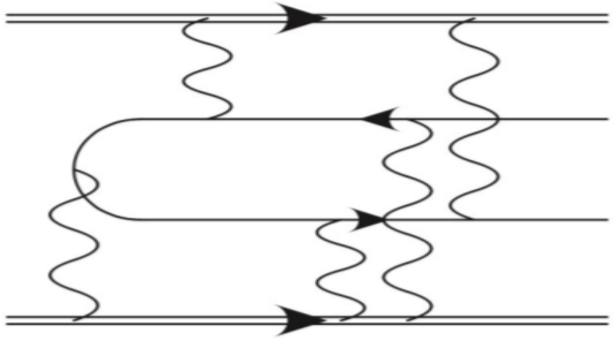
重离子超边缘碰撞的自旋物理研究



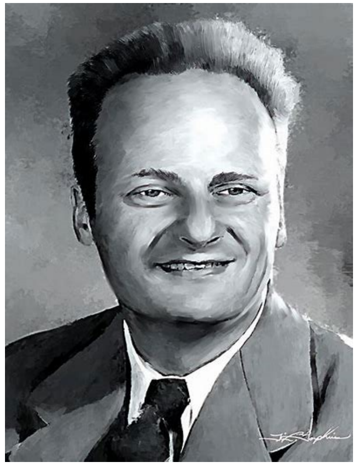
一次金核-金核对撞相当于4000万次质子-质子对撞！

Strong field QED & BSM

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

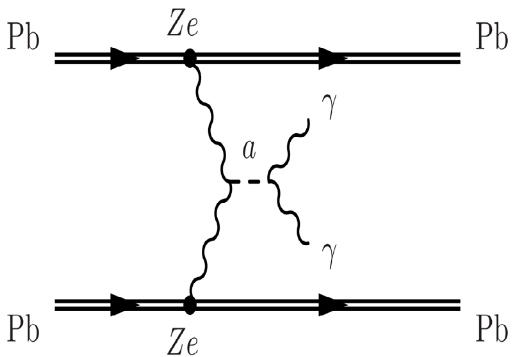


Zα ~0.6 for Au and Pb, significant effect?

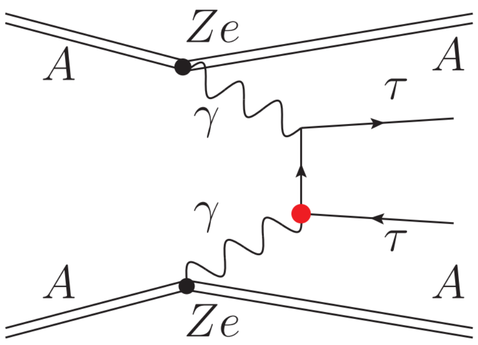


- BSM physics axion search, tau anomalous magnetic moment, dark photons…

Knapen-Lin-Lou-Melia, 2017

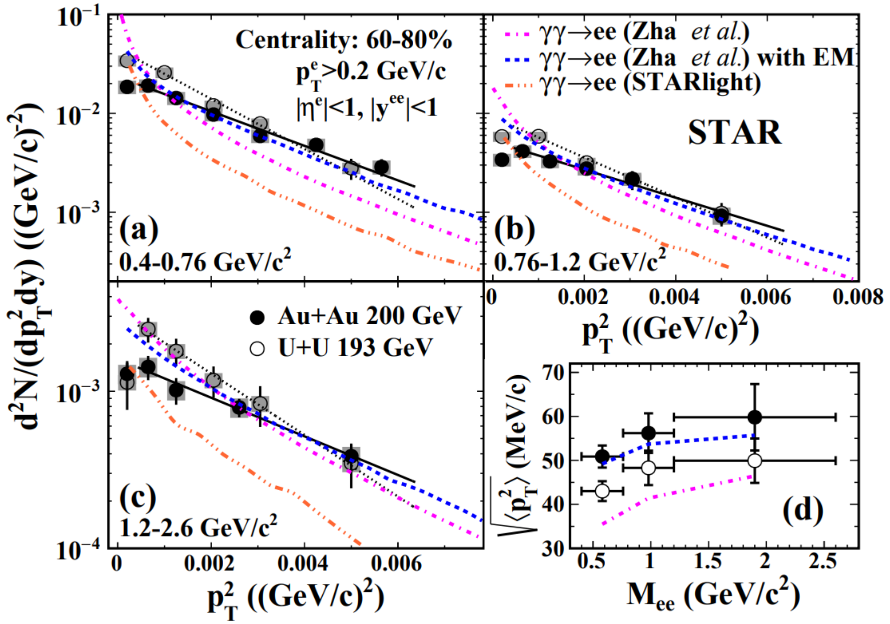


Shao-Yan-Yuan-Zhang, 2023

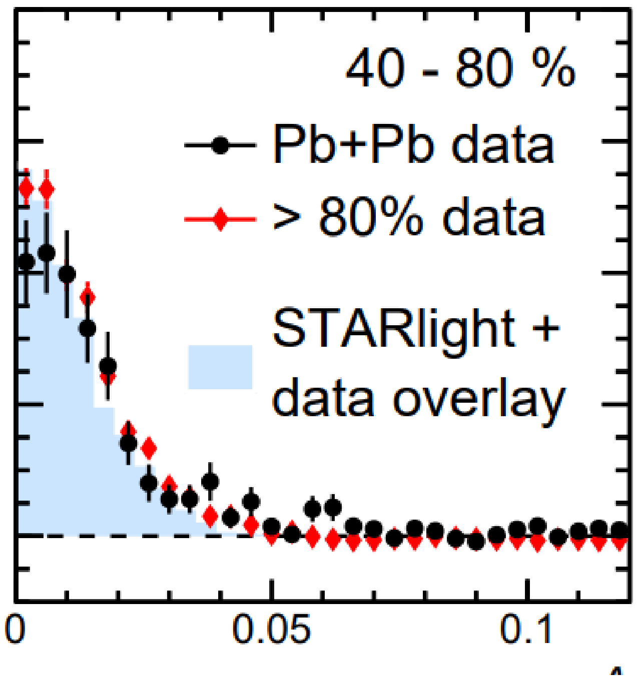


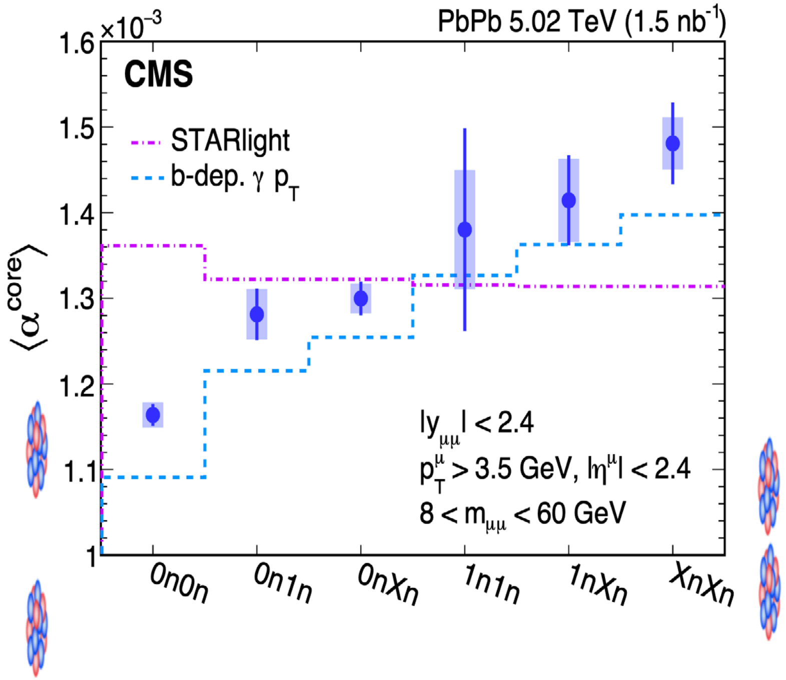
Dip structure and bt dependent qt distribution

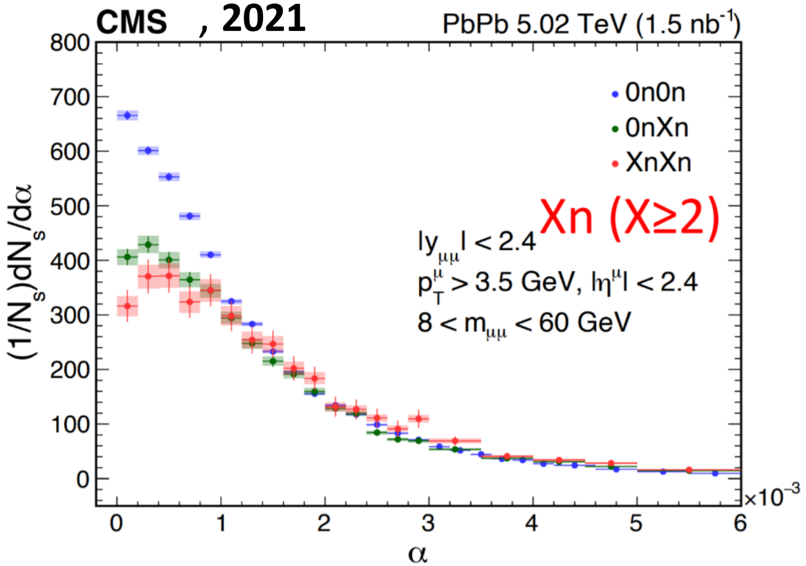
STAR, 2018

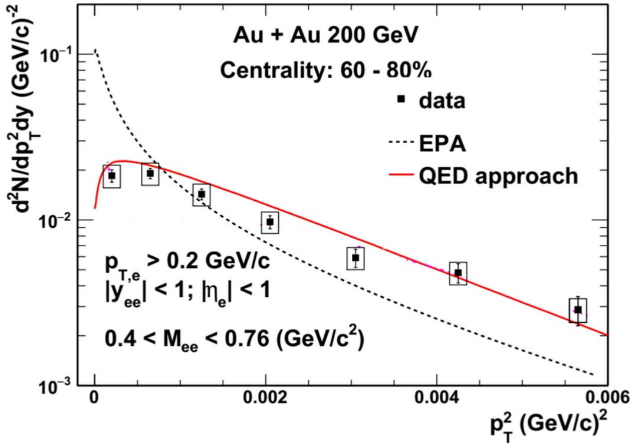


ATLAS 2018





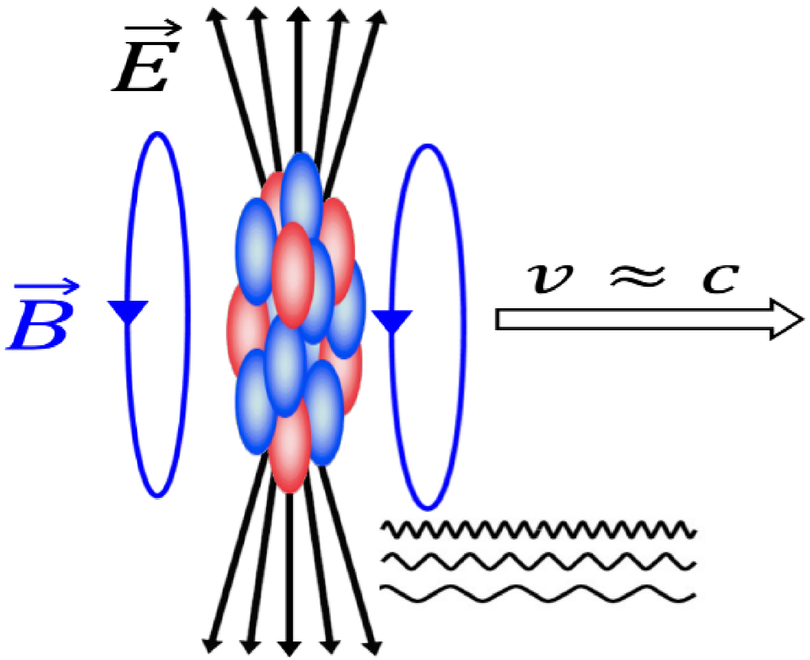




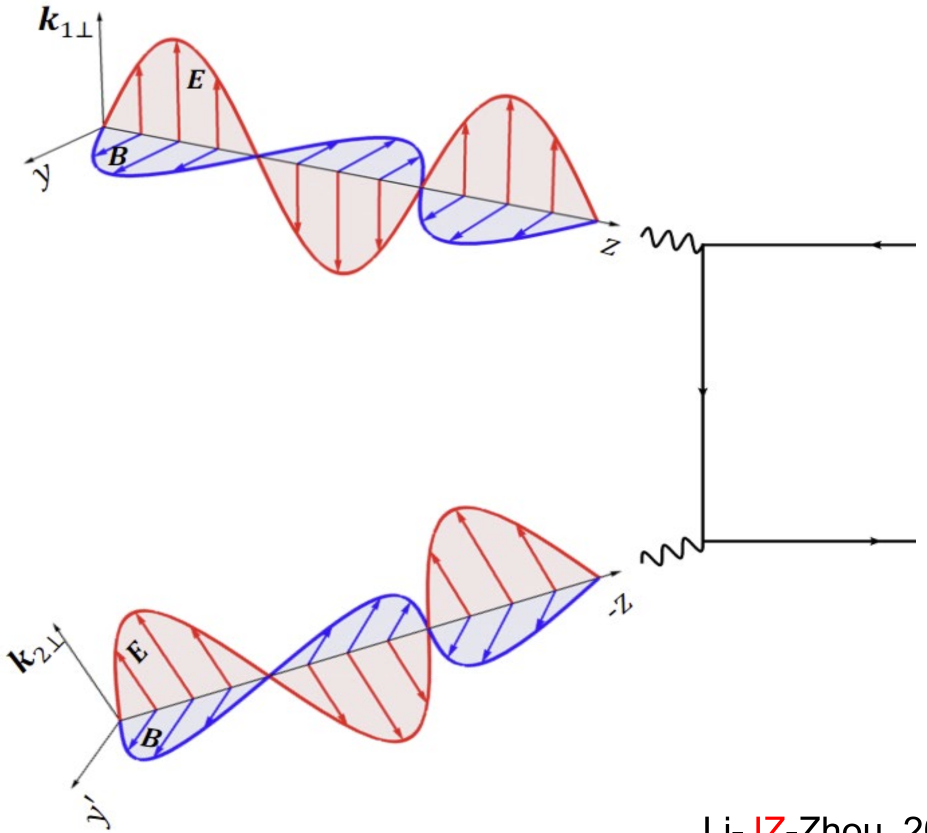
◆ WW approximation is not sufficient!

Chi Yang, Shuai Yang, Zebo Tang, Wangmei Zha, Daniel Brandenberg, Zhangbu Xu, et.al.

The boosted Coulomb potential



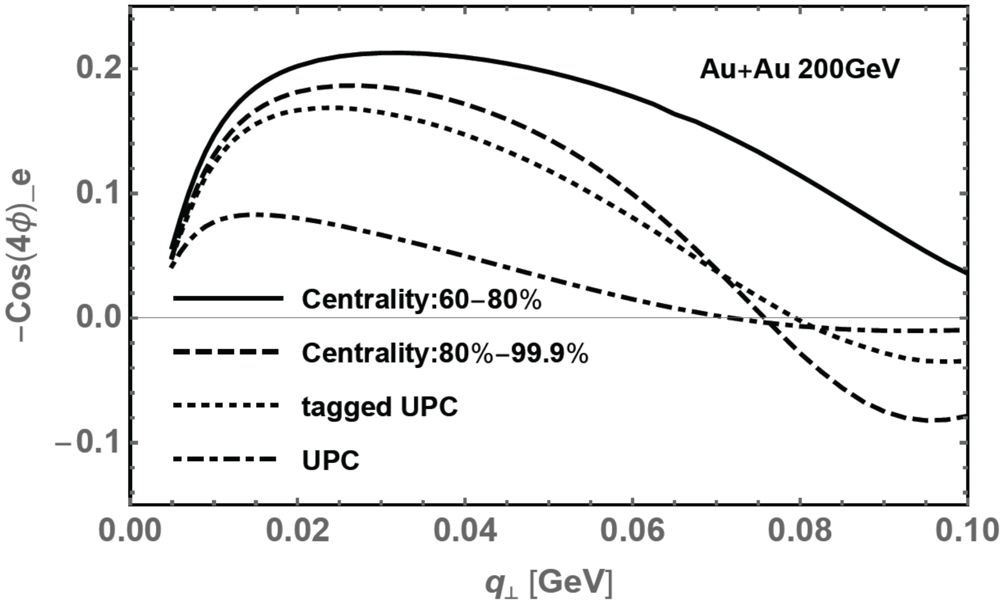
E. Fermi, 1924
Weizascker--Williams 1934



Li-JZ-Zhou, 2019

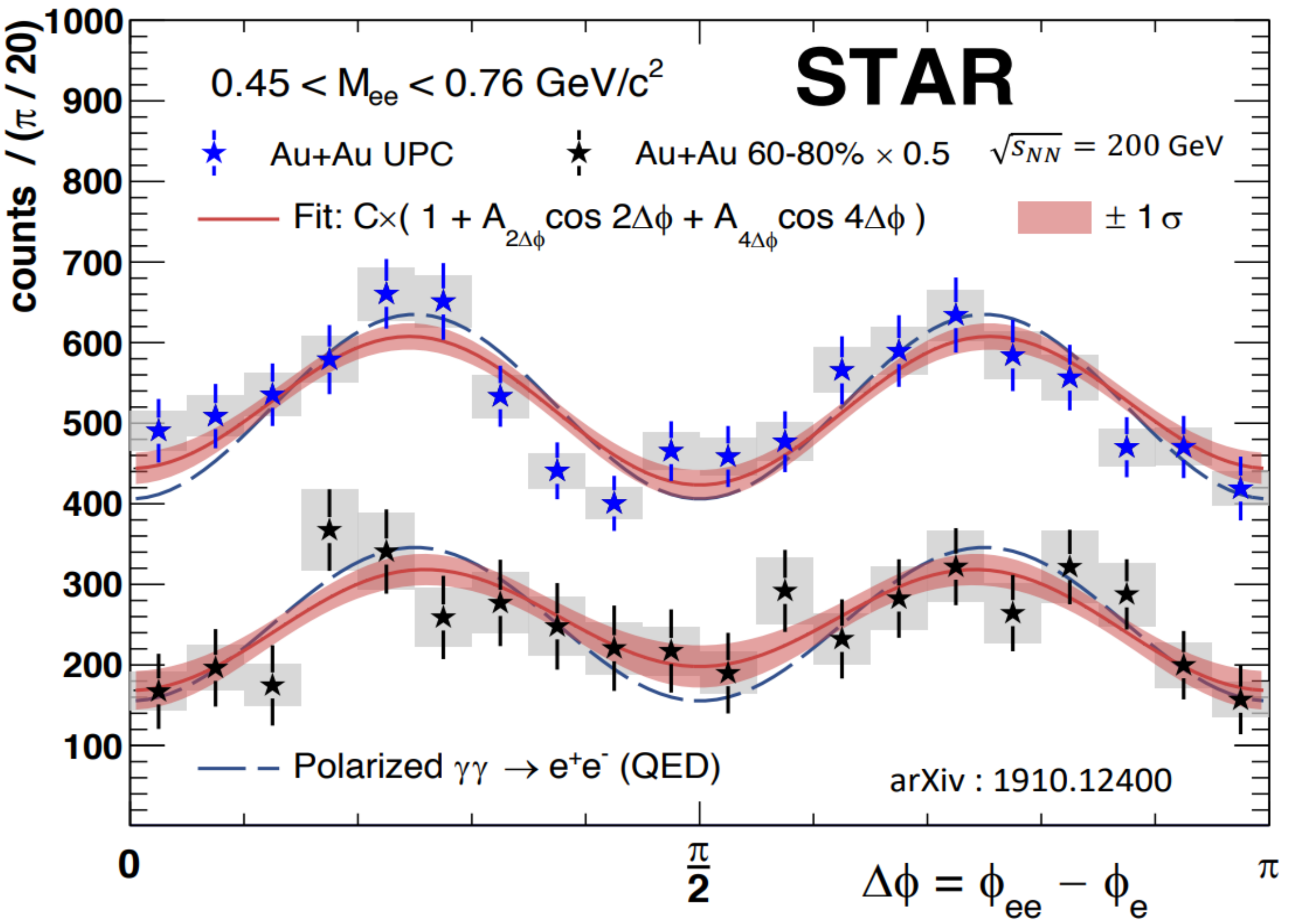
Linear polarization of photons: induce cos4ϕ modulation in di-lepton production.

Verified by STAR experiment



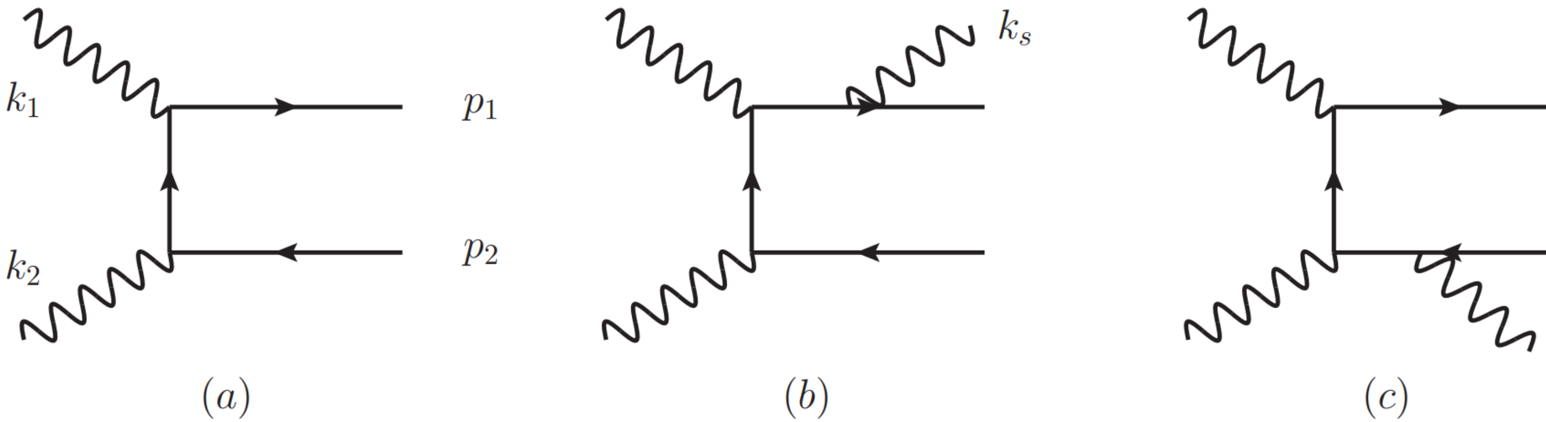
Li-JZ-Zhou, 2020

STAR collaboration, PRL, 2021



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

Resummation for qt distribution



◆Primordial coherent photon distribution: $$e^{-\frac{q_\perp^2}{(30\mathrm{Mev})^2}}$$

◆Perturbative tail from the soft photon reoil effect: $$\frac{\alpha}{\pi^2}\frac{1}{q_\perp^2}\ln\frac{Q^2}{m^2}$$

Resummation 是量子场论的精华。

---李重生，2009年TEV物理研讨会，南开，天津

Double & Single leading logarithms

- The resumed cross section:

$$\frac{d\sigma}{d^2p_{1\perp}d^2p_{2\perp}dy_1dy_2d^2b_\perp} = \int \frac{d^2r_\perp}{(2\pi)^2} e^{ir_\perp\cdot q_\perp} e^{-\mathrm{Sud}(r_\perp)} \int d^2q'_\perp e^{-ir_\perp\cdot q'_\perp} \frac{d\sigma_0(q'_\perp)}{d\mathcal{P}.\mathcal{S}.}$$

Born cross section

Leading double logarithm: $\frac{\alpha_e}{\pi}\ln\frac{M^2}{m^2}\ln\frac{P_\perp^2}{\mu_r^2}$

Hatta-Xiao-Yuan-ZJ, PRL 2021

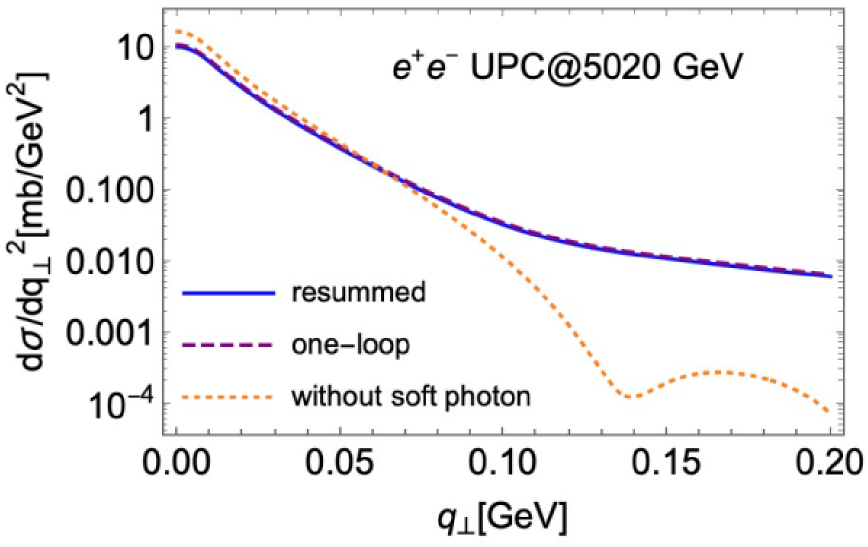
≈**0.75** for LHC kinematics

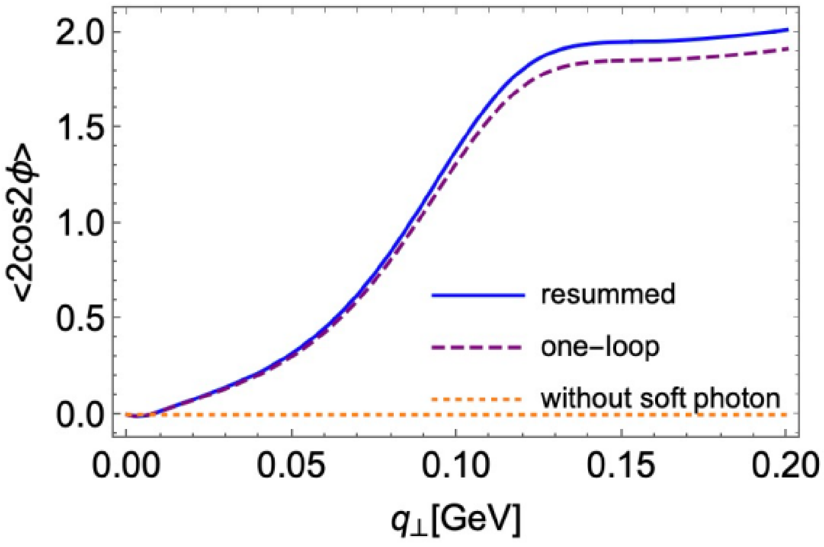
- Double+Single leading logarithm: $\frac{\alpha_e}{\pi}\ln\frac{M^2}{m^2}\ln\frac{P_\perp^2}{\mu_r^2} + \frac{\alpha_e}{\pi}\ln\frac{M^2}{m^2}\ln 4\cos^2\phi_r$

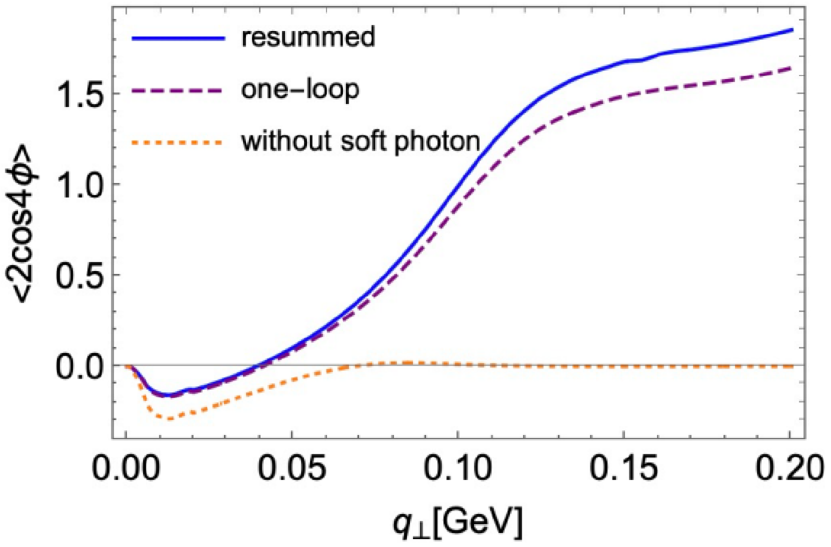
Shao-Zhang-ZJ-Zhou, 2023

Cos2ϕ, Cos4ϕ azimuthal asymmetries

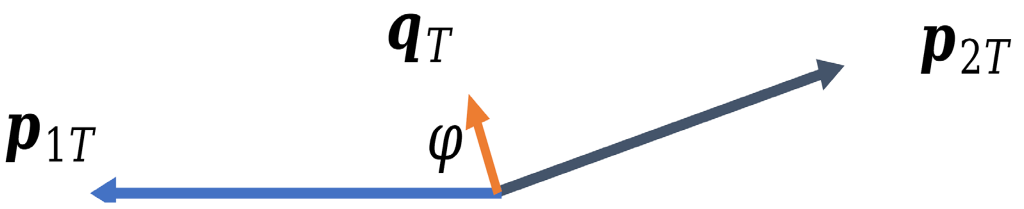
Numerical results



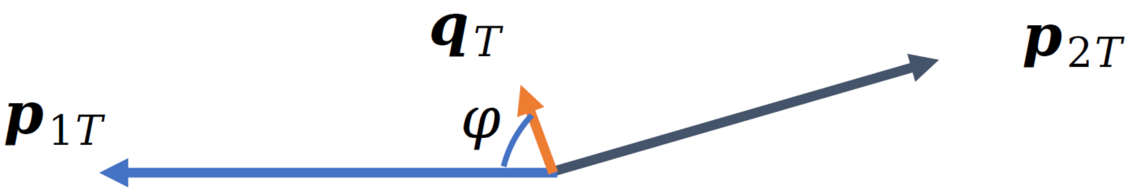


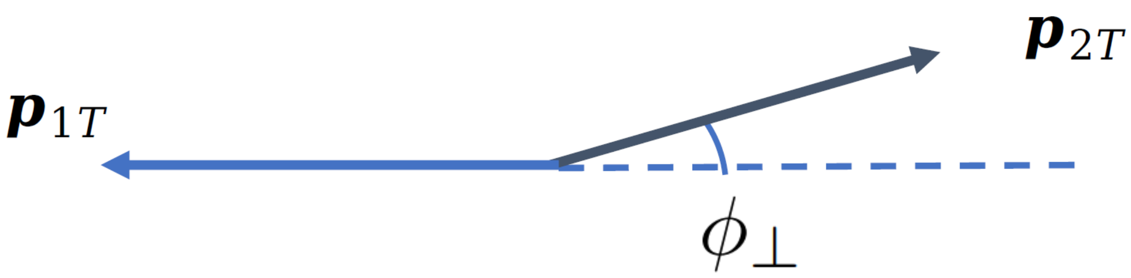


- At high qt, perturbative contribution dominates,
- Soft photon radiations give rise to huge cos2ϕ, cos4ϕ asymmetries
- Leading single logarithm contribution is small



Resummation formular at low α





Acoplanartiy: $\alpha = |\phi_\perp|/\pi$ $\quad \alpha \propto \frac{q_{\perp x}}{P_\perp}$

Can one first derive a resumed qt distribution, and then re-construct α distribution? No!

- One dimensional resummation formula:

$$\frac{d\sigma}{dq_x d^2P_\perp dy_1 dy_2 d^2b_\perp} = \int \frac{dr_x}{2\pi} e^{ir_x q_x} e^{-\mathrm{Sud_a}(r_x, r_y=0)} \int dq'_x dq'_y \; e^{-ir_x q'_x} \frac{d\sigma_0(q'_\perp)}{d\mathcal{P}.\mathcal{S}.}$$

Double&Single leading logarithm

- Double leading logarithm:

$$\mathrm{Sud_a}(r_x) = \frac{\alpha_e}{2\pi}\left[\ln^2\frac{M^2}{\mu_{rx}^2} - \ln^2\frac{m^2}{\mu_{rx}^2}\theta(m-\mu_{rx})\right]$$

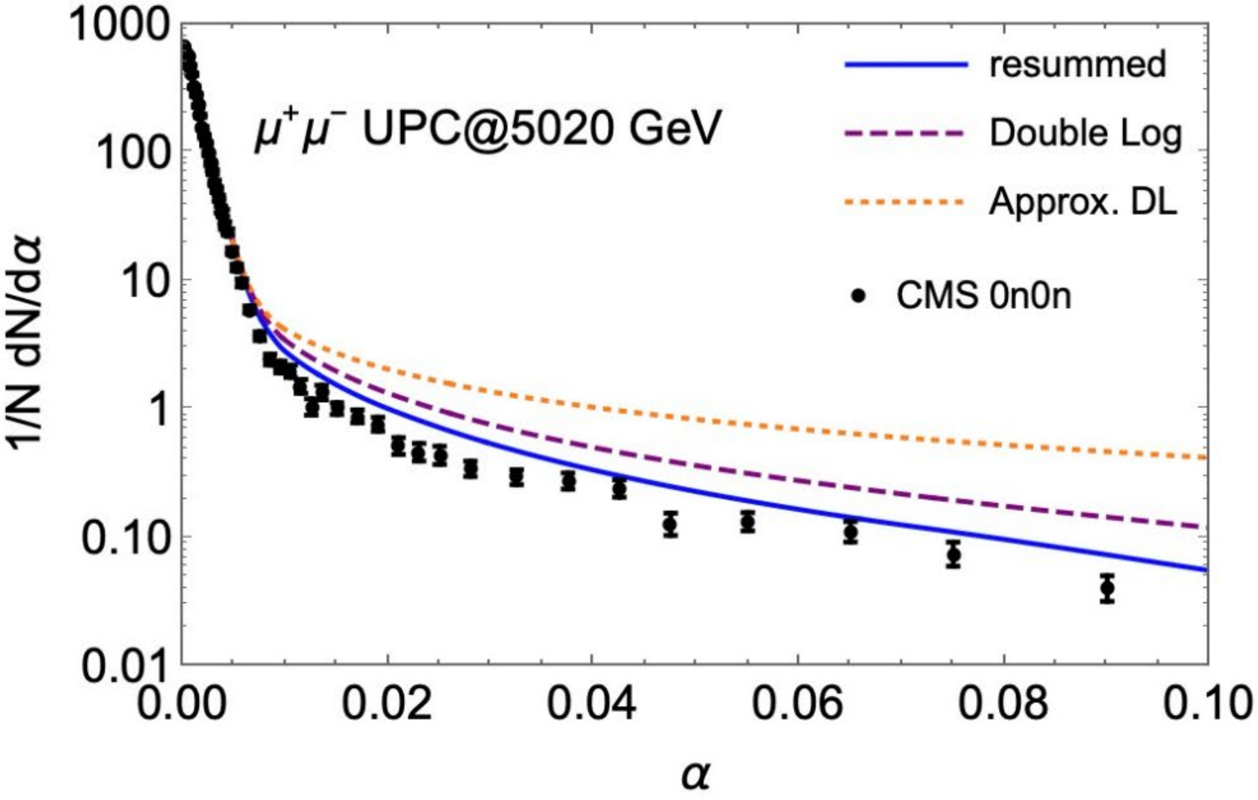
Klein-Mueller-Xiao-Yuan,2018

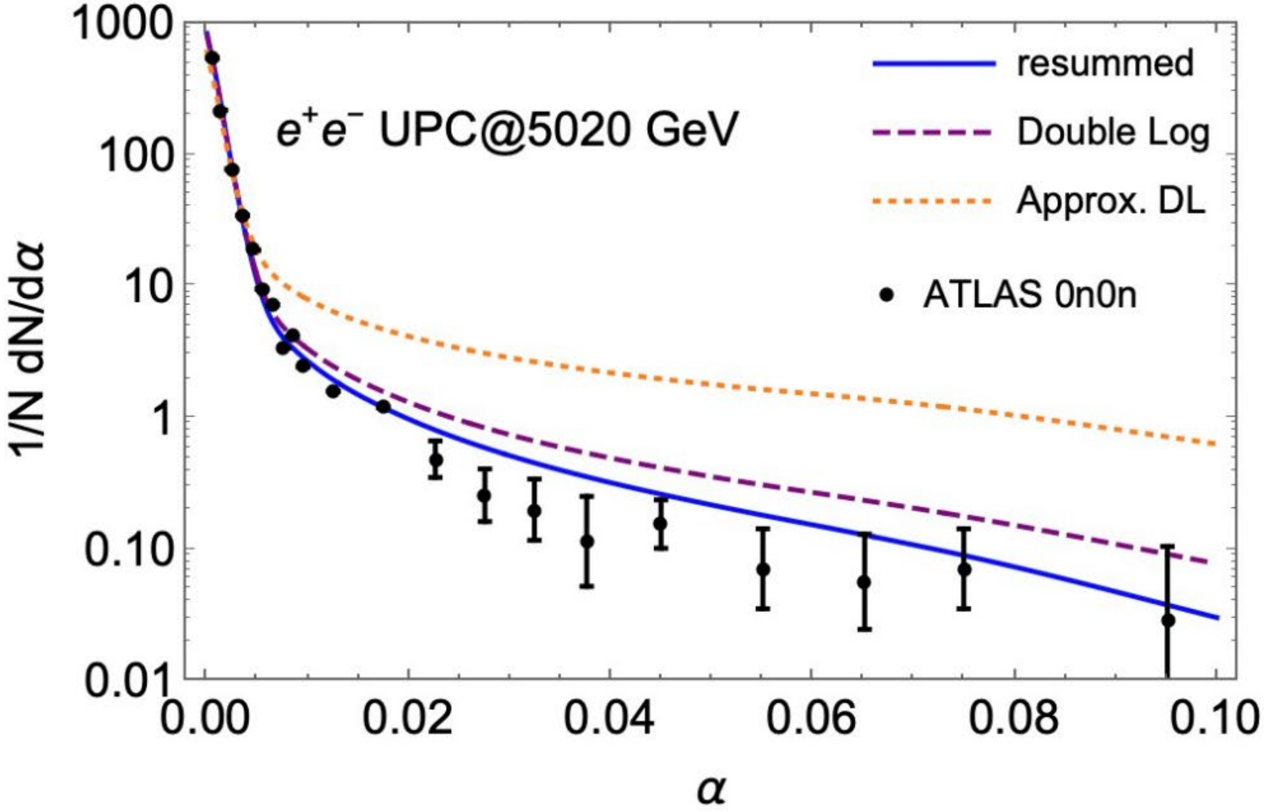
- Double+Single leading logarithm

$$\frac{\alpha_e}{2\pi}\left[\left(\ln^2\frac{M^2}{\mu_{rx}^2} - 3\ln\frac{M^2}{\mu_{rx}^2}\right) - \left(\ln^2\frac{m^2}{\mu_{rx}^2} - \ln\frac{m^2}{\mu_{rx}^2}\right)\theta(m-\mu_{rx})\right]$$

Shao-Zhang-ZJ-Zhou, 2023

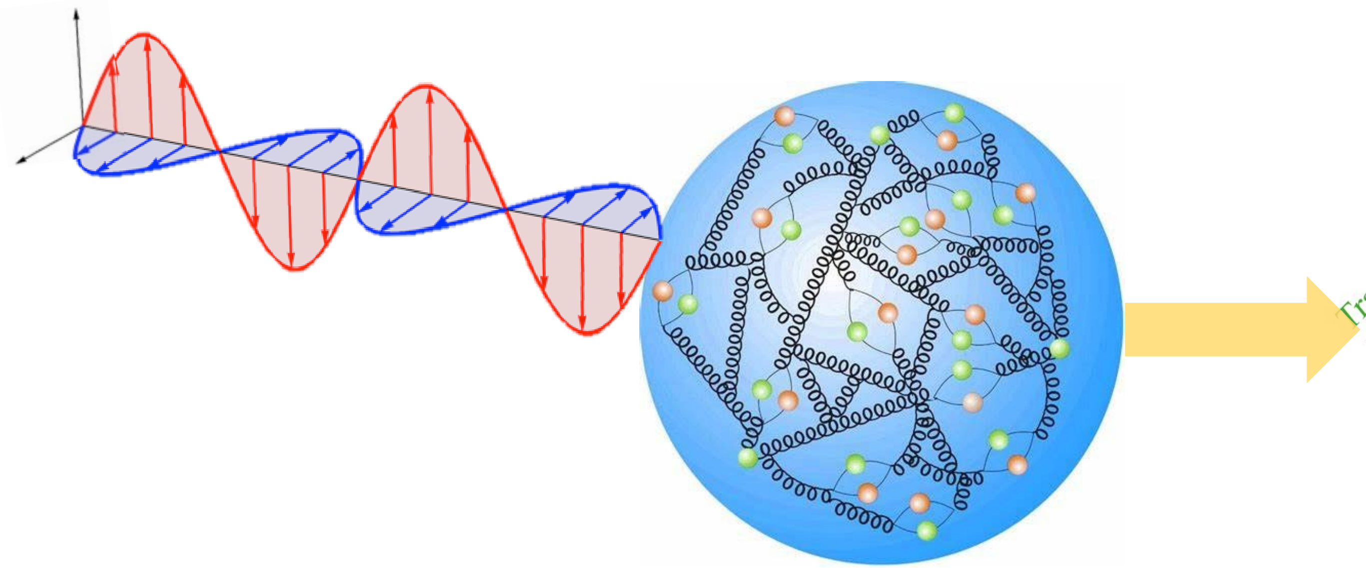
Numerical results

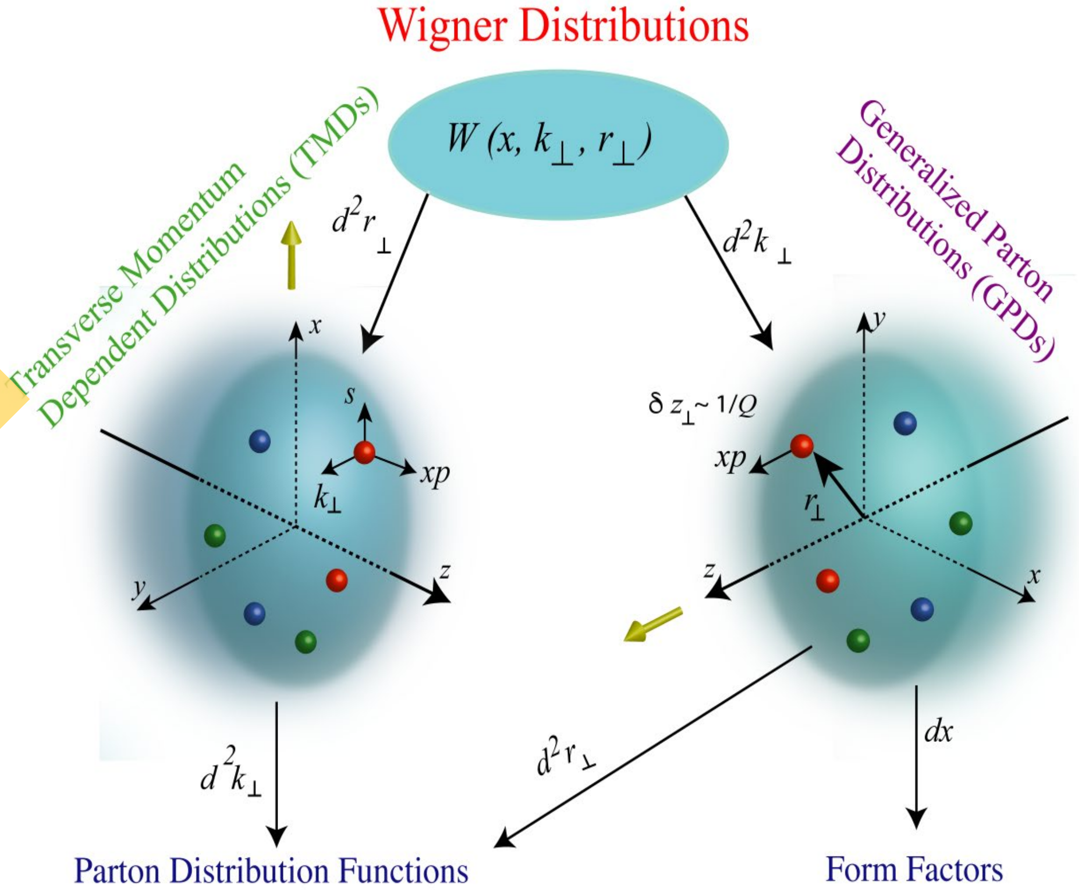




- Exclude incoherent events by selecting 0n0n events.
- The difference between qt double log and α double is sizable
- Single log contribution is sizable
- Something missing in our resummation formular?

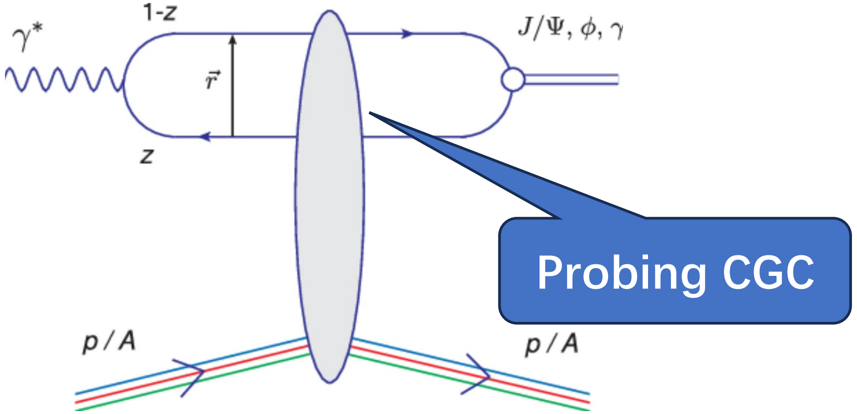
如何用线偏振光探测核子/原子核结构

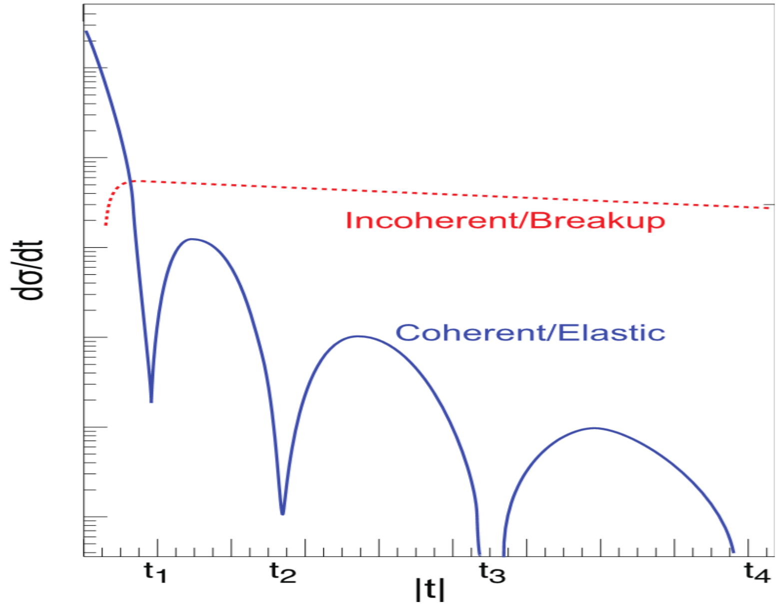




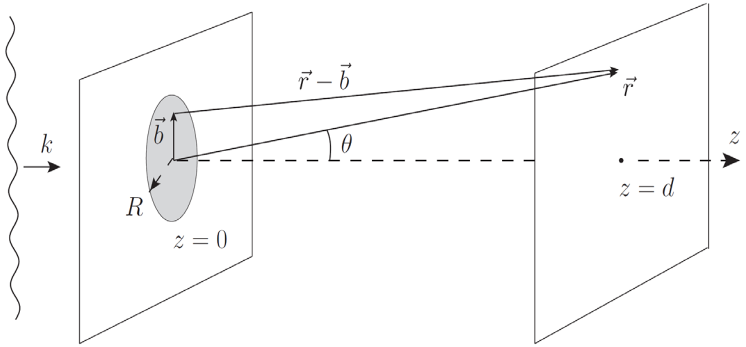
Diffractive production and Optical Analogy

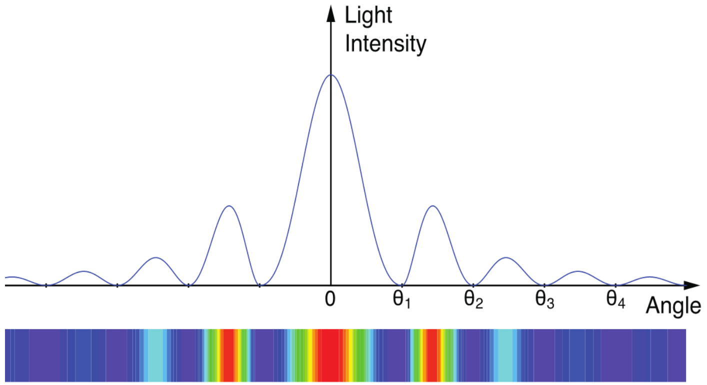
◆ 矢量介子产生：探测色玻璃凝聚态的理想实验渠道





◆ 光学类比：

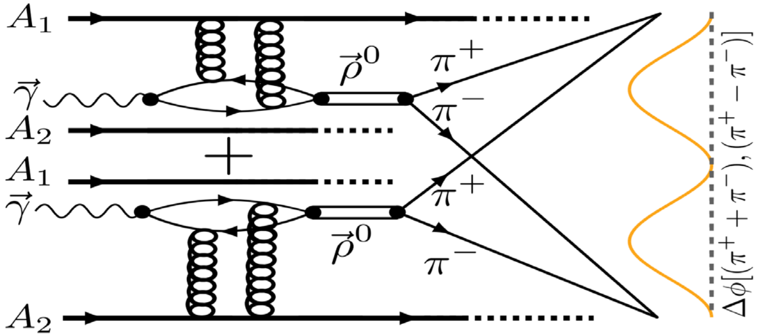




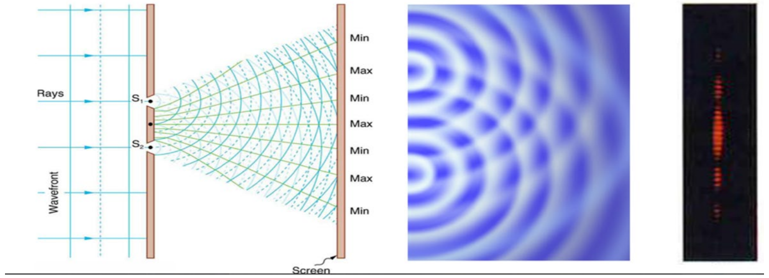
➢ Reconstruct the size R of the obstacle and the optical “blackness” of the obstacle from the diffractive pattern.

Theoretical formulation of quantum interference effect

➢ Full cross section:



$$
\begin{aligned}
\frac{d\sigma}{d^2q_\perp dY d^2\tilde{b}_\perp} =& \frac{1}{(2\pi)^4}\int d^2\Delta_\perp d^2k_\perp d^2k'_\perp \delta^2(k_\perp + \Delta_\perp - q_\perp)(\epsilon_\perp^{V*}\cdot\hat{k}_\perp)(\epsilon_\perp^{V}\cdot\hat{k}'_\perp)\Big\{\int d^2b_\perp \\
&\times e^{i\tilde{b}_\perp\cdot(k'_\perp - k_\perp)}\left[T_A(b_\perp)\mathcal{A}_{in}(Y,\Delta_\perp)\mathcal{A}^*_{in}(Y,\Delta'_\perp)\mathcal{F}(Y,k_\perp)\mathcal{F}(Y,k'_\perp) + (A\leftrightarrow B)\right] \\
&+\left[e^{i\tilde{b}_\perp\cdot(k'_\perp - k_\perp)}\mathcal{A}_{co}(Y,\Delta_\perp)\mathcal{A}^*_{co}(Y,\Delta'_\perp)\mathcal{F}(Y,k_\perp)\mathcal{F}(Y,k'_\perp)\right] \\
&+\left[e^{i\tilde{b}_\perp\cdot(\Delta'_\perp - \Delta_\perp)}\mathcal{A}_{co}(-Y,\Delta_\perp)\mathcal{A}^*_{co}(-Y,\Delta'_\perp)\mathcal{F}(-Y,k_\perp)\mathcal{F}(-Y,k'_\perp)\right] \\
&+\left[e^{i\tilde{b}_\perp\cdot(\Delta'_\perp - k_\perp)}\mathcal{A}_{co}(Y,\Delta_\perp)\mathcal{A}^*_{co}(-Y,\Delta'_\perp)\mathcal{F}(Y,k_\perp)\mathcal{F}(-Y,k'_\perp)\right] \\
&+\left[e^{i\tilde{b}_\perp\cdot(k'_\perp - \Delta_\perp)}\mathcal{A}_{co}(-Y,\Delta_\perp)\mathcal{A}^*_{co}(Y,\Delta'_\perp)\mathcal{F}(-Y,k_\perp)\mathcal{F}(Y,k'_\perp)\right]\Big\}, \qquad (2.14)
\end{aligned}
$$



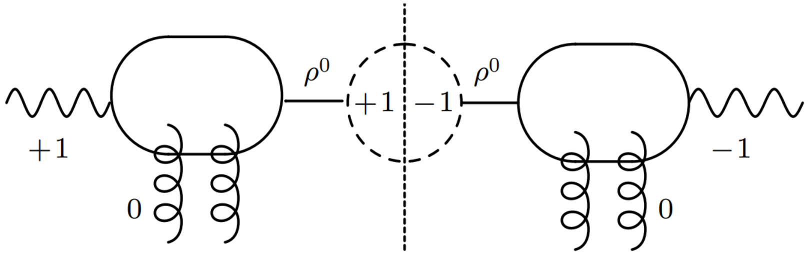
Interference effect encoded in these phases

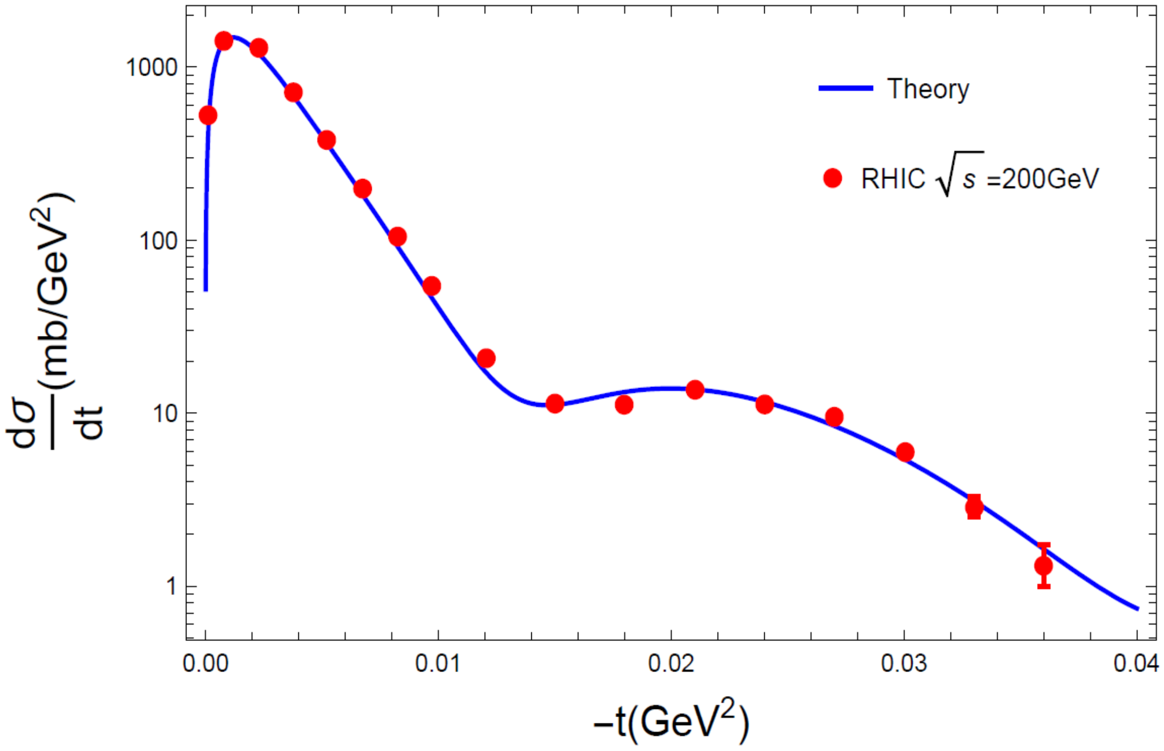
Xing-Zhang-ZJ-Zhou, 2020

The manifestation of quantum interference effect in ρ0 production

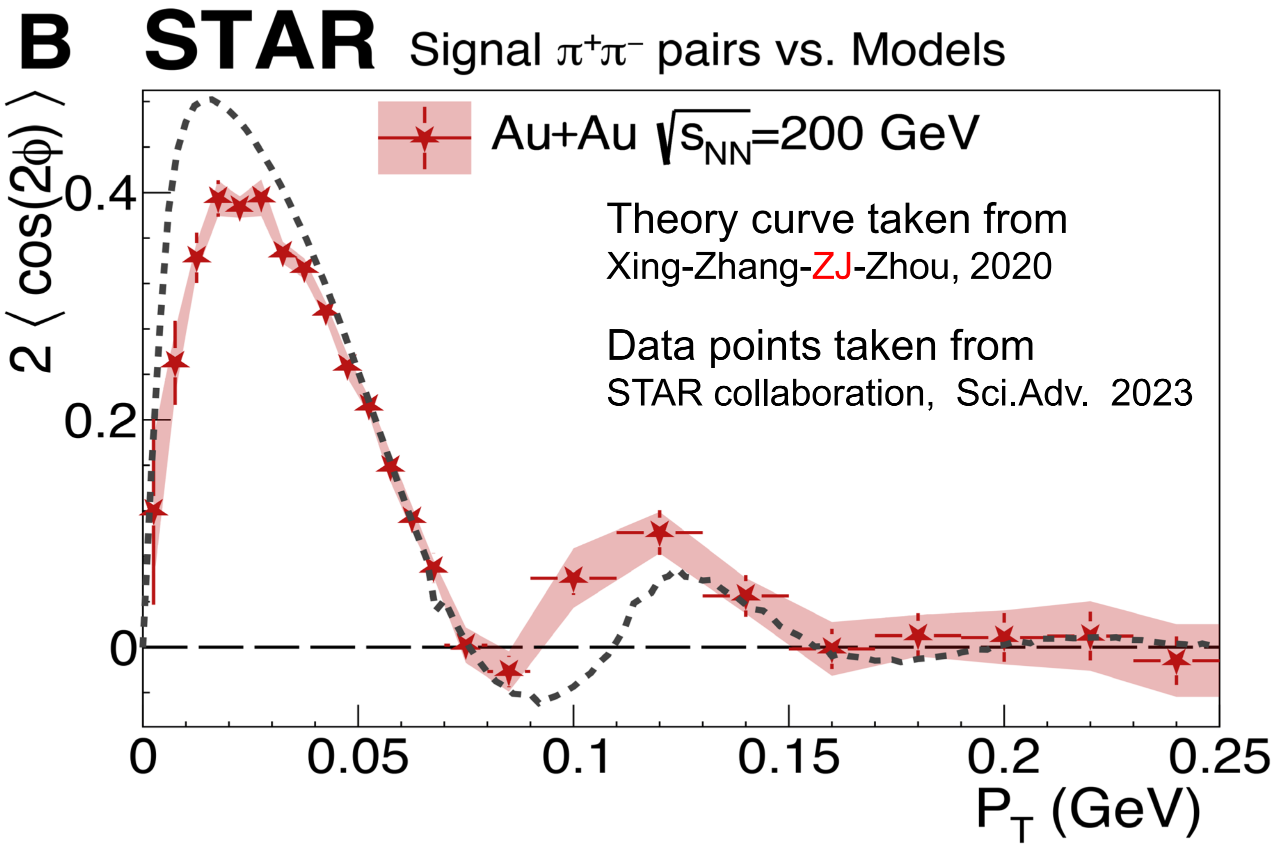
- Interference between two p waves

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



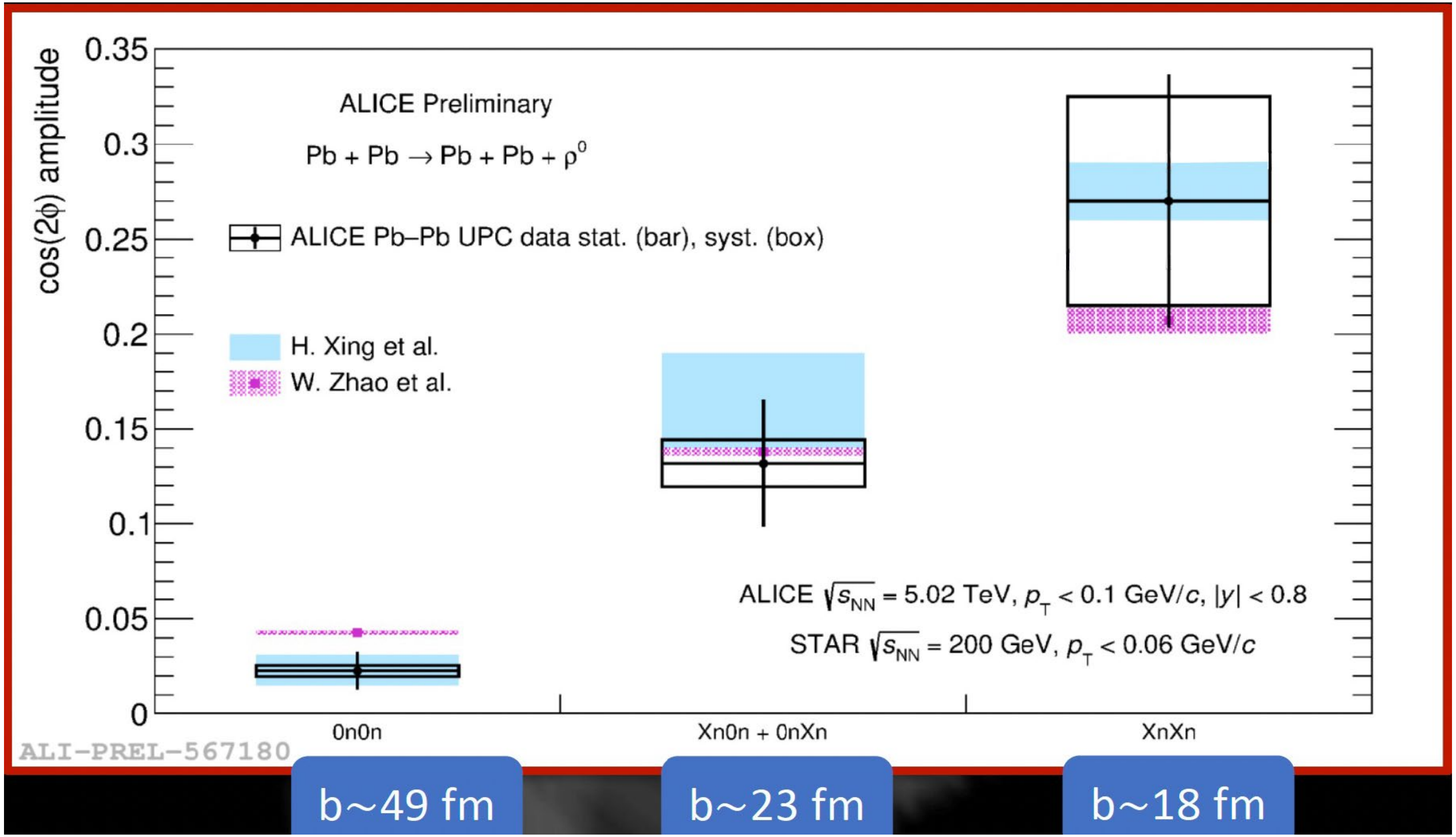


Xing-Zhang-ZJ-Zhou 2020



A Glauber model calculation: Zha, Brandenburg, Ruan,Tang, 2021

ALICE measurement of Cos2ϕ asymmetry

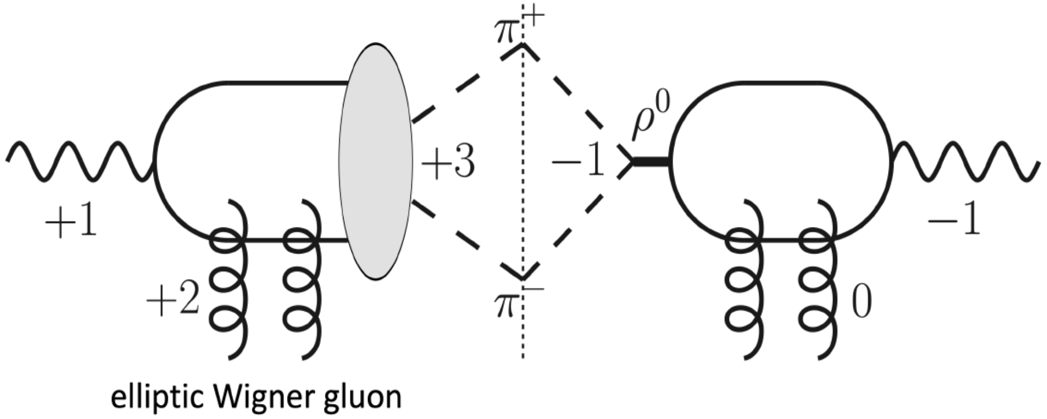


SDU-SCNU组： Hongxi Xing, Cheng Zhang, Jian Zhou, Ya-Jin Zhou *JHEP* 10 (2020) 064

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

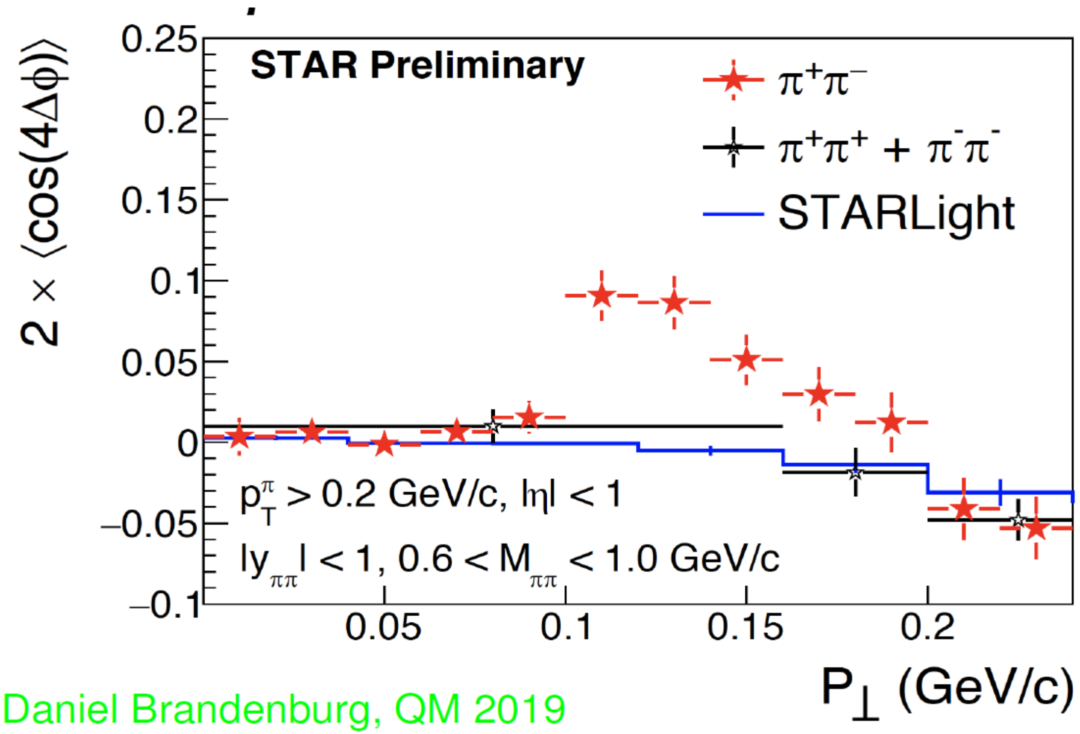
Cos4ϕ in dipion production Ⅰ

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



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

◆ STAR measurement:



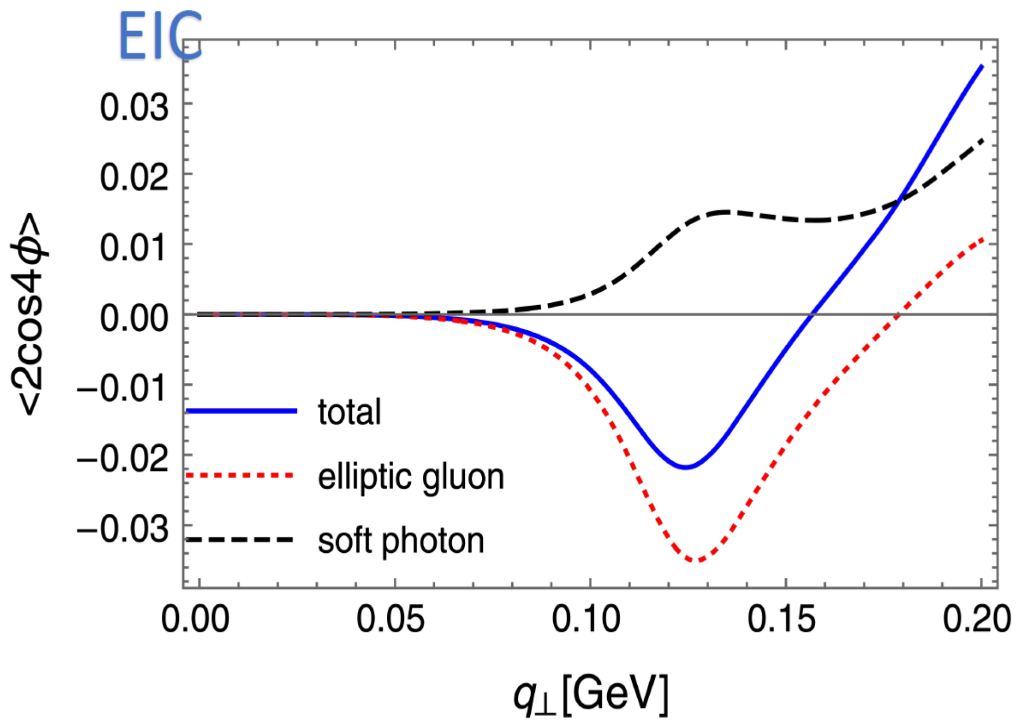
Daniel Brandenburg, QM 2019

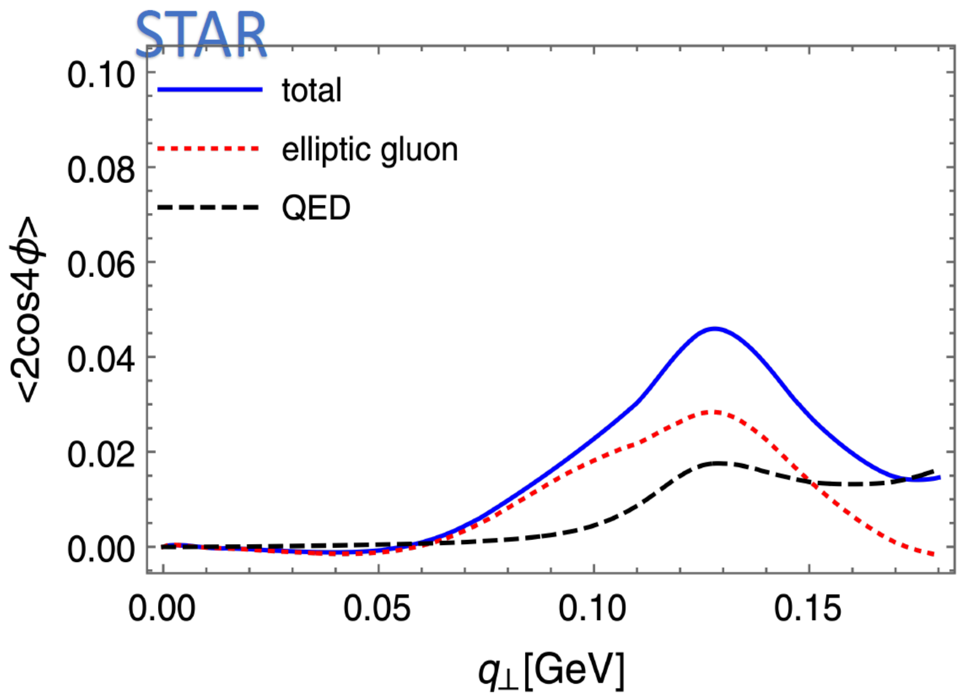
Cos4ϕ in dipion production II

QED contribution alone not adequate

↓

contribution from elliptic gluon distribution



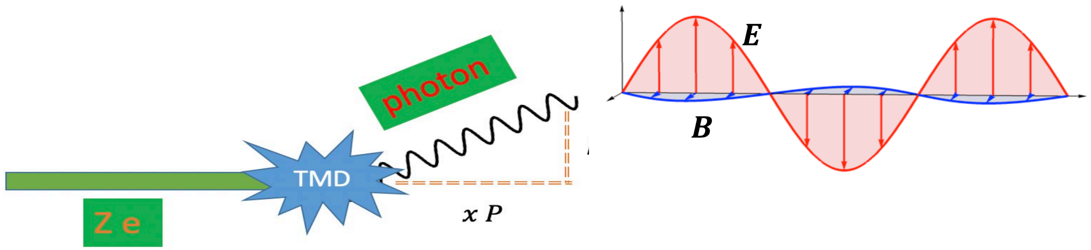


- The asymmetry flip sign at EIC

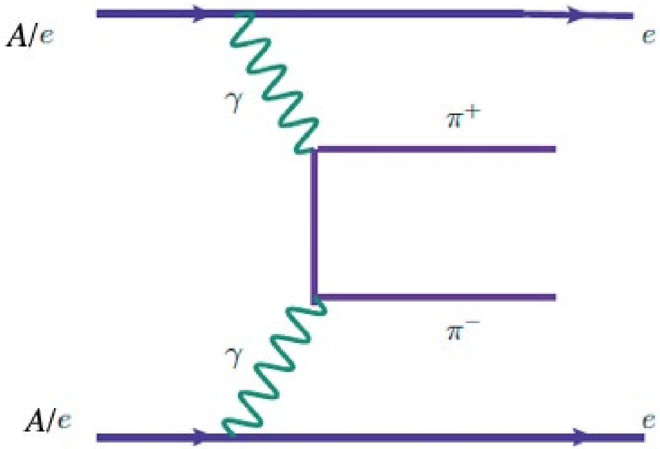
Hagiwara-Zhang-ZJ-Zhou, 2021

正负电子对撞机上双光子对撞的新奇方位角测量

贾宇，周剑，周雅瑾，arXiv:2406.09381

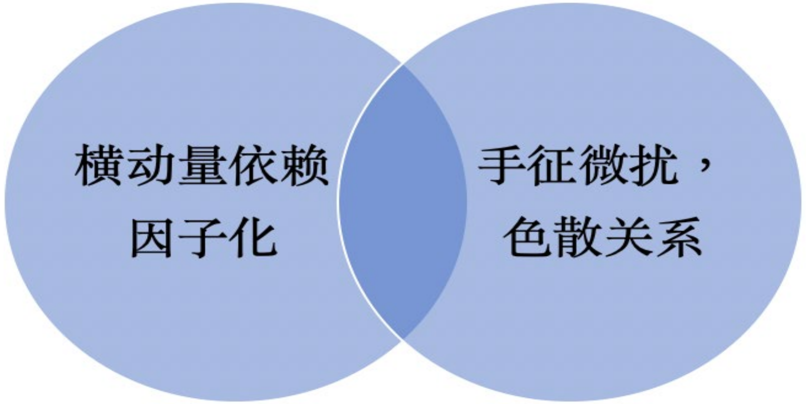


光子有横动量，是线性极化的



- 双光子产生重子对过程对于揭示C-even共振结构和理解介子内部结构非常重要，$\gamma\gamma \to \pi\pi$ 是其中最干净最重要的；
- 介子对横动量远小于单个介子横动量时，需TMD因子化；
- 首次尝试在重的复合粒子产生中研究方位角不对称性；
- 对于由π介子圈贡献的光光散射(Light-by-Light, LbL)过程有重要意义；
- 多方向交叉研究，横动量依赖物理& 手征微扰论 & 实验数据驱动方法。

理论框架：



High Energy Physics - Phenomenology

[Submitted on 29 Apr 2014 (v1), last revised 22 Jul 2014 (this version, v2)]

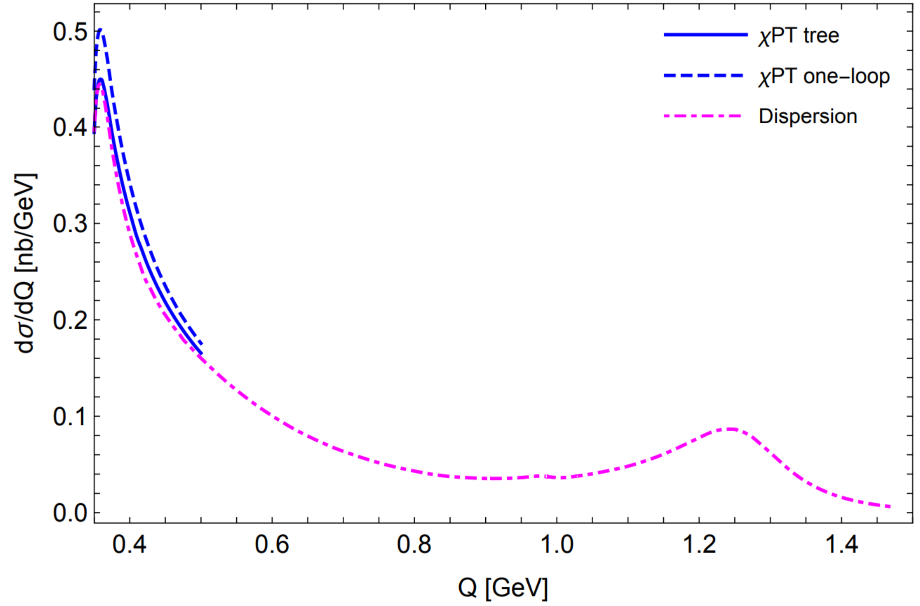
Comprehensive Amplitude Analysis of $\gamma\gamma \to \pi^+\pi^-, \pi^0\pi^0$ and $\overline{K}K$ below 1.5 GeV

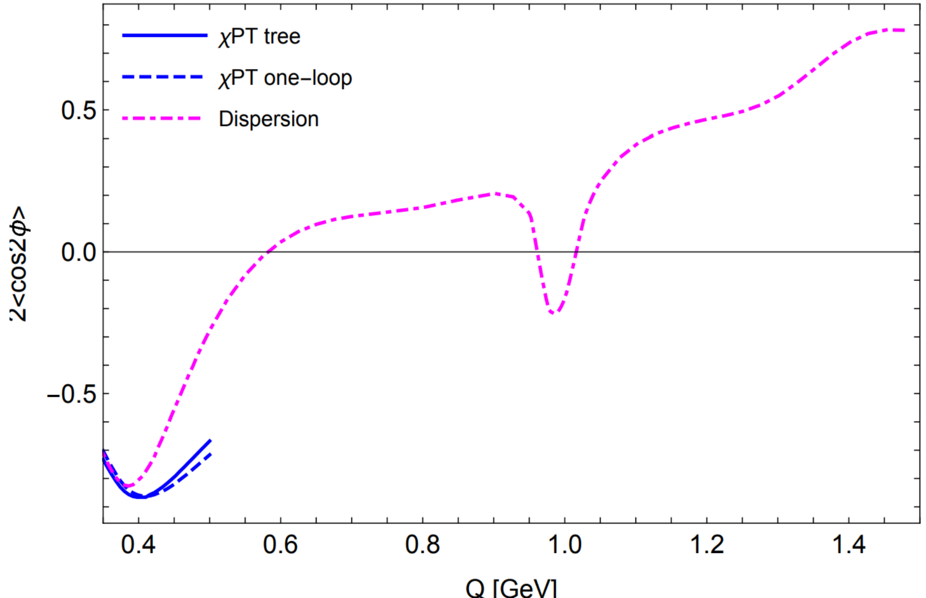
Ling-Yun Dai, Michael R. Pennington

➢直接抽取相因子！

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

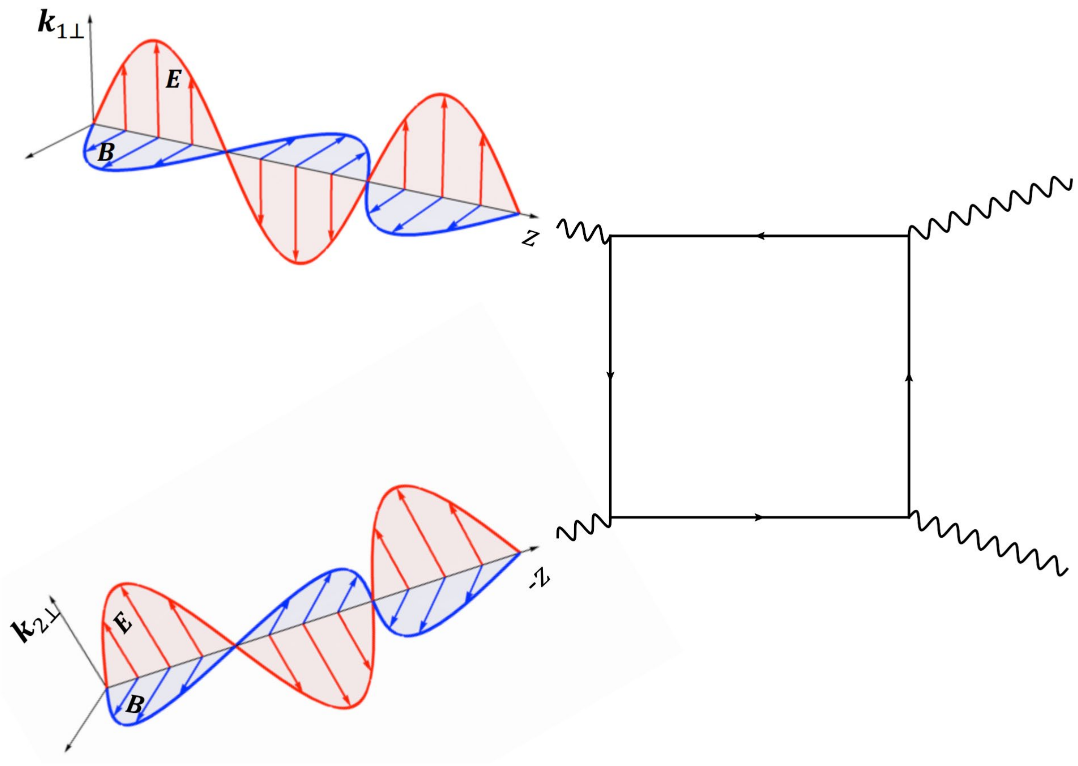
数值结果：





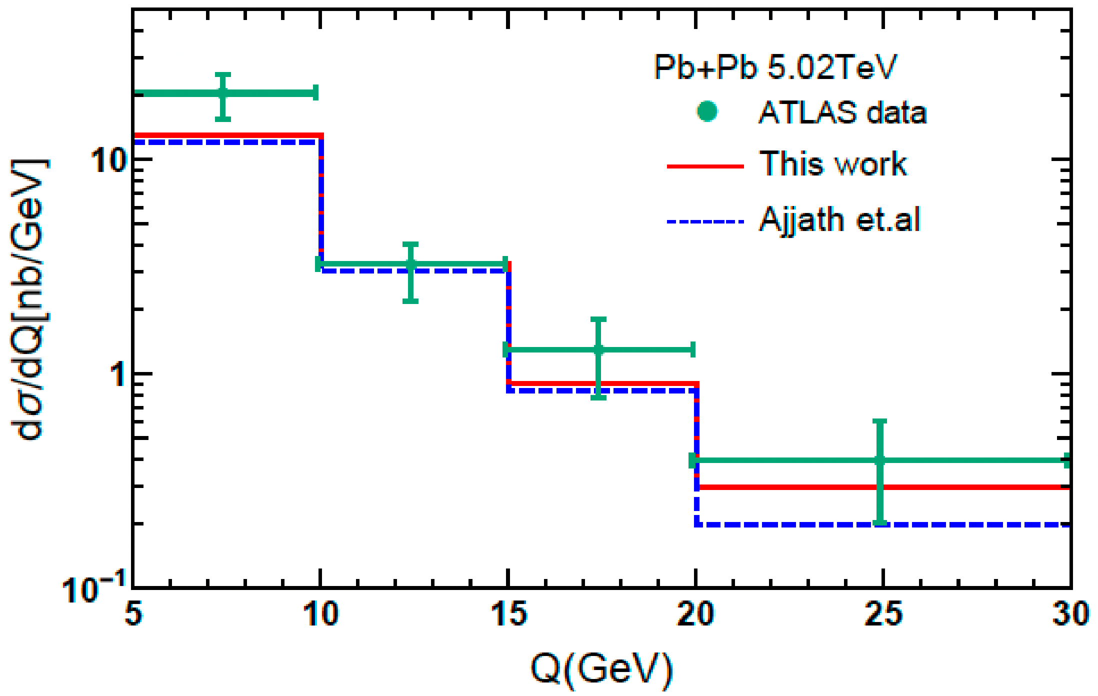
LHC上超边缘碰撞的光光散射中的方位角不对称性

贾宇，林硕，周剑，周雅瑾，arXiv:2410.13781

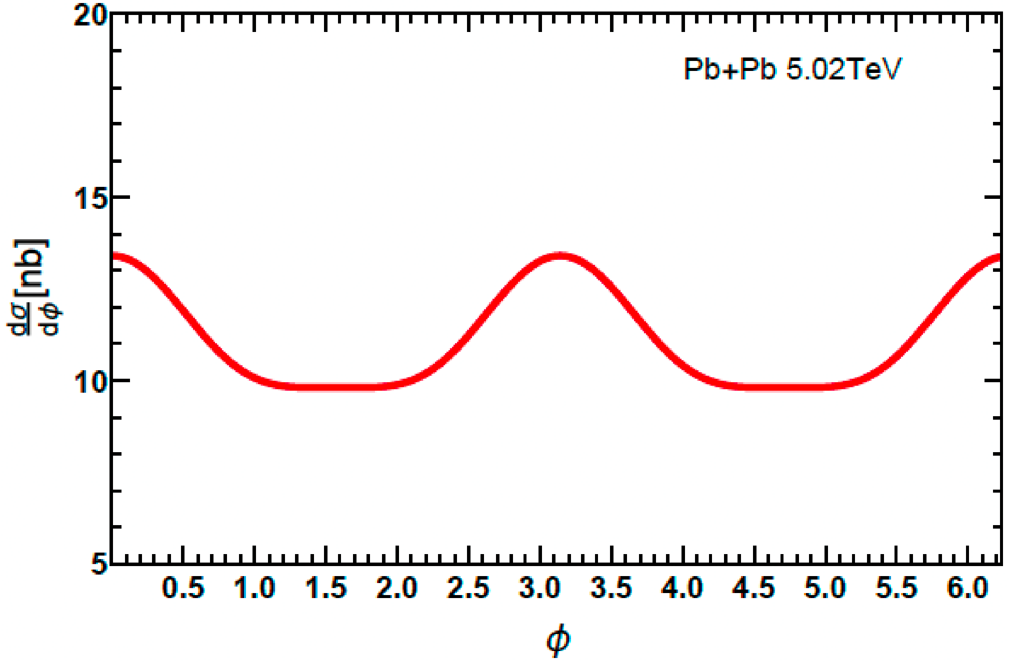


- 作为真空极化和量子非线性的直接表现，弹性光光散射(LbL)被认为是标准模型最迷人的基本过程之一；
- 强光光散射(HLbL)是缪子反常磁矩理论不确定性的主要来源；
- LHC上最近测量了超边缘碰撞上光光散射过程，但是与理论计算有一定的偏差。考虑光子的线性极化，我们重新研究了这个过程。
- 首次在光光散射中研究方位角不对称性。

Numerical results



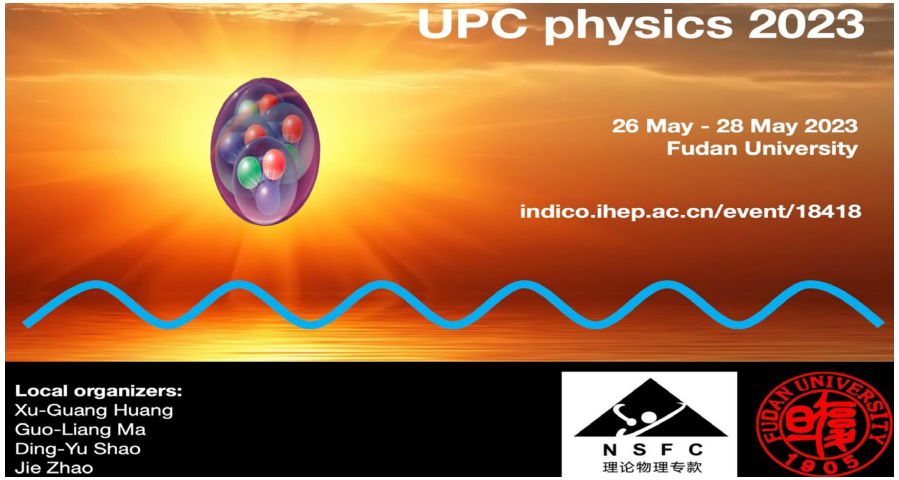
Unpolarized cross section



azimuthal modulation

UPC专题会议系列

第一届中国UPC会议



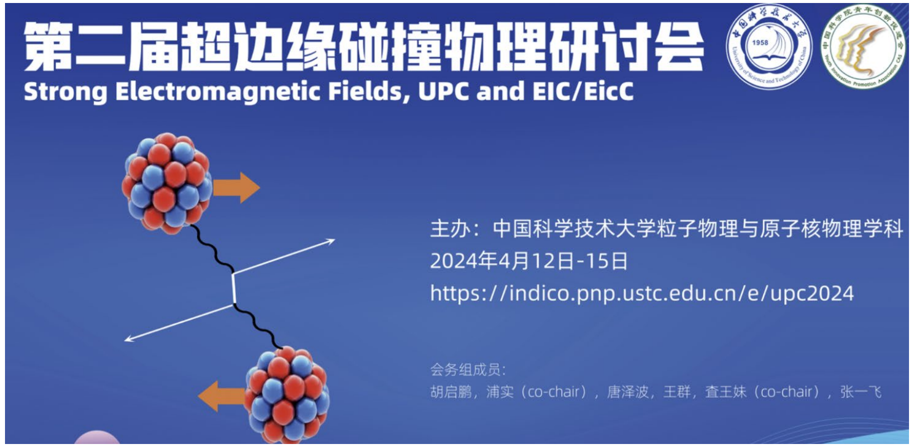
第一届国际UPC会议

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

UPC2025: The second international workshop on the physics of Ultra Peripheral Collisions

9–13 Jun 2025
Saariselkä, Finland
Europe/Helsinki timezone

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Summary:

- 核子自旋结构 研究近年来稳步取得进展，但仍有许多谜题；
- UPC有丰富的极化依赖物理

EIC era---The Renaissance of nucleon structure study