Interferences effect in UPCs

周剑

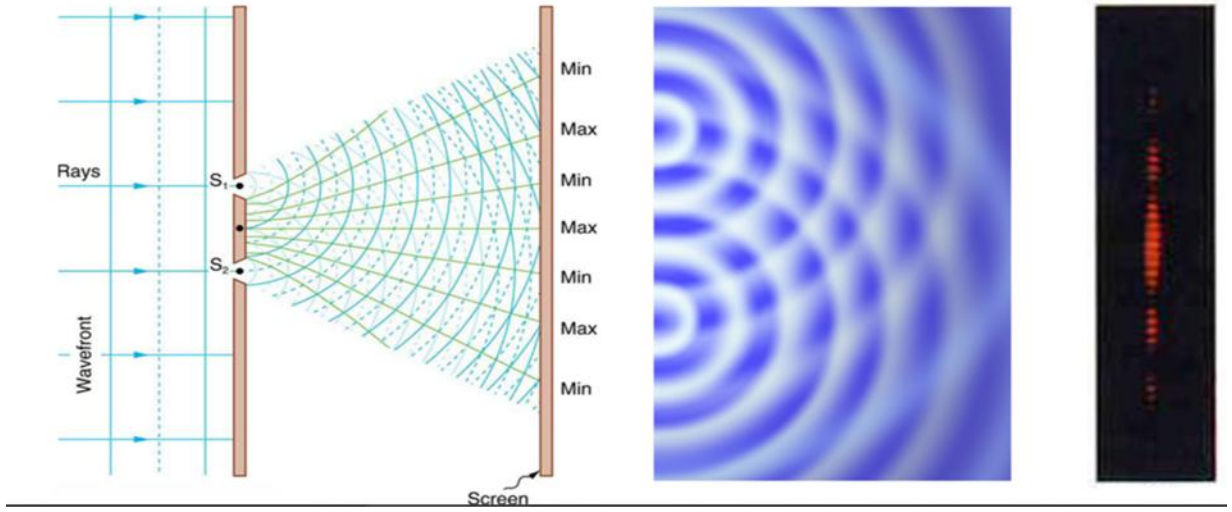
山东大学（青岛）
SHANDONG UNIVERSITY, QINGDAO

Quantum Entanglement Studies in Nuclear and Particle Physics 复旦 · 2026年10月24–26日

Outline：

- A brief introduction to UPC physics
- Double slit experiment in UPCs
- Spin interference effects in UPCs
- Summary

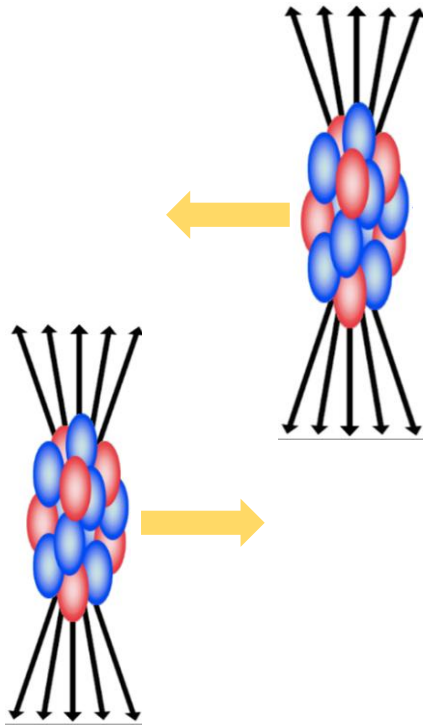
Young's double-slit experiment:



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



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

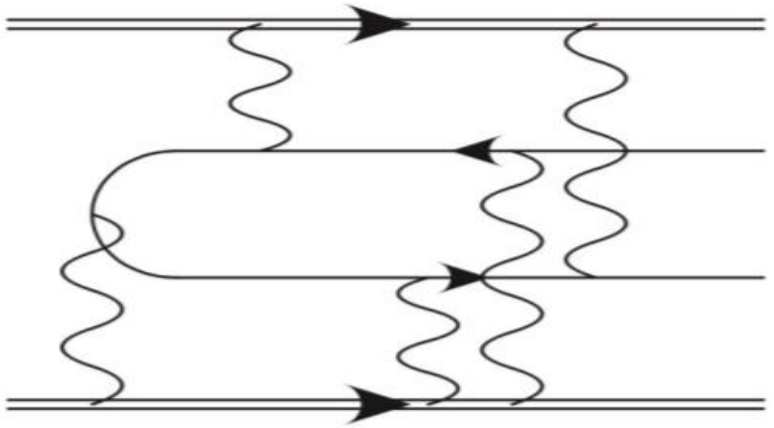
□ Photon wave length > R, i.e. k_t<30MeV, enhanced by Z^2

Two type interactions:

- photon-photon collisions
- photon-nuclear interactions

BSM & strong field QED

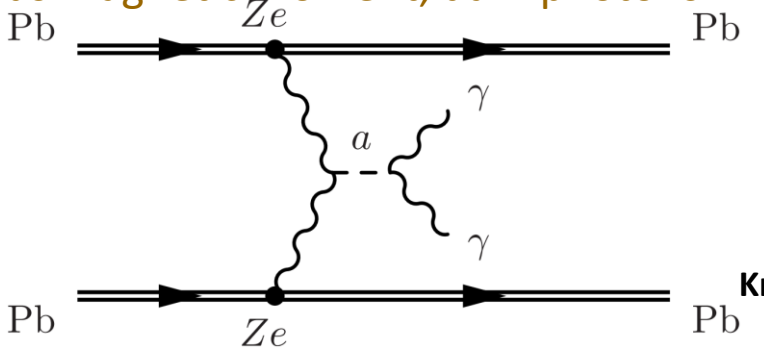
➢ Strong field QED Coulomb correction, vacuum birefringence, light by light scattering….



Zα ~0.6 for Au and Pb, significant effect?

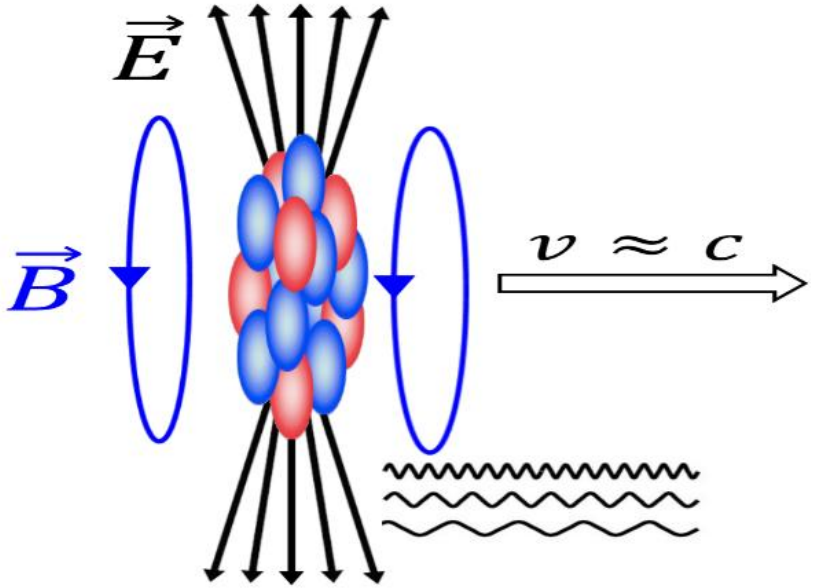
➢BSM physics axion search, tau anomalous magnetic moment, dark photons…

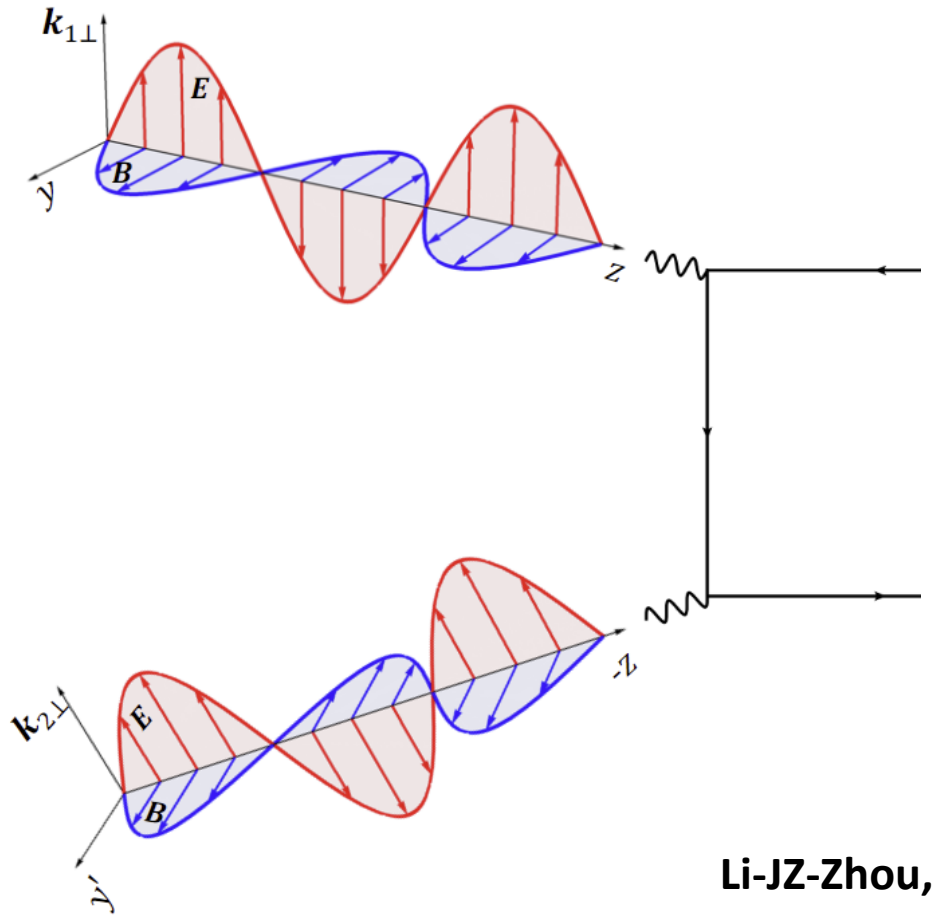
v.s. pp collisions, 截面大**4千万倍。**



Knapen-Lin-Lou-Melia, 2017

The boosted Coulomb potential

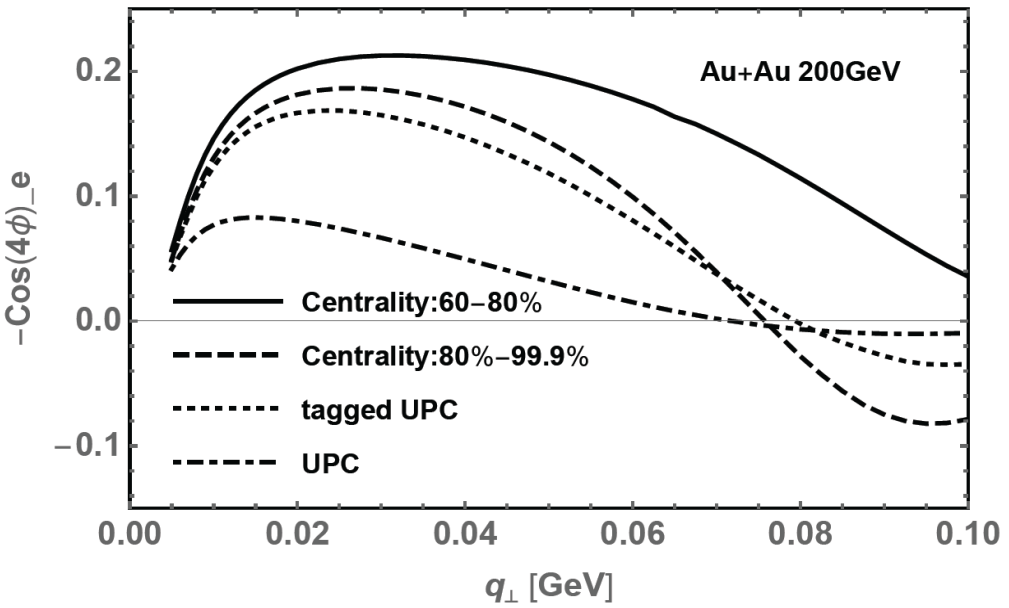




Li-JZ-Zhou, 2019

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

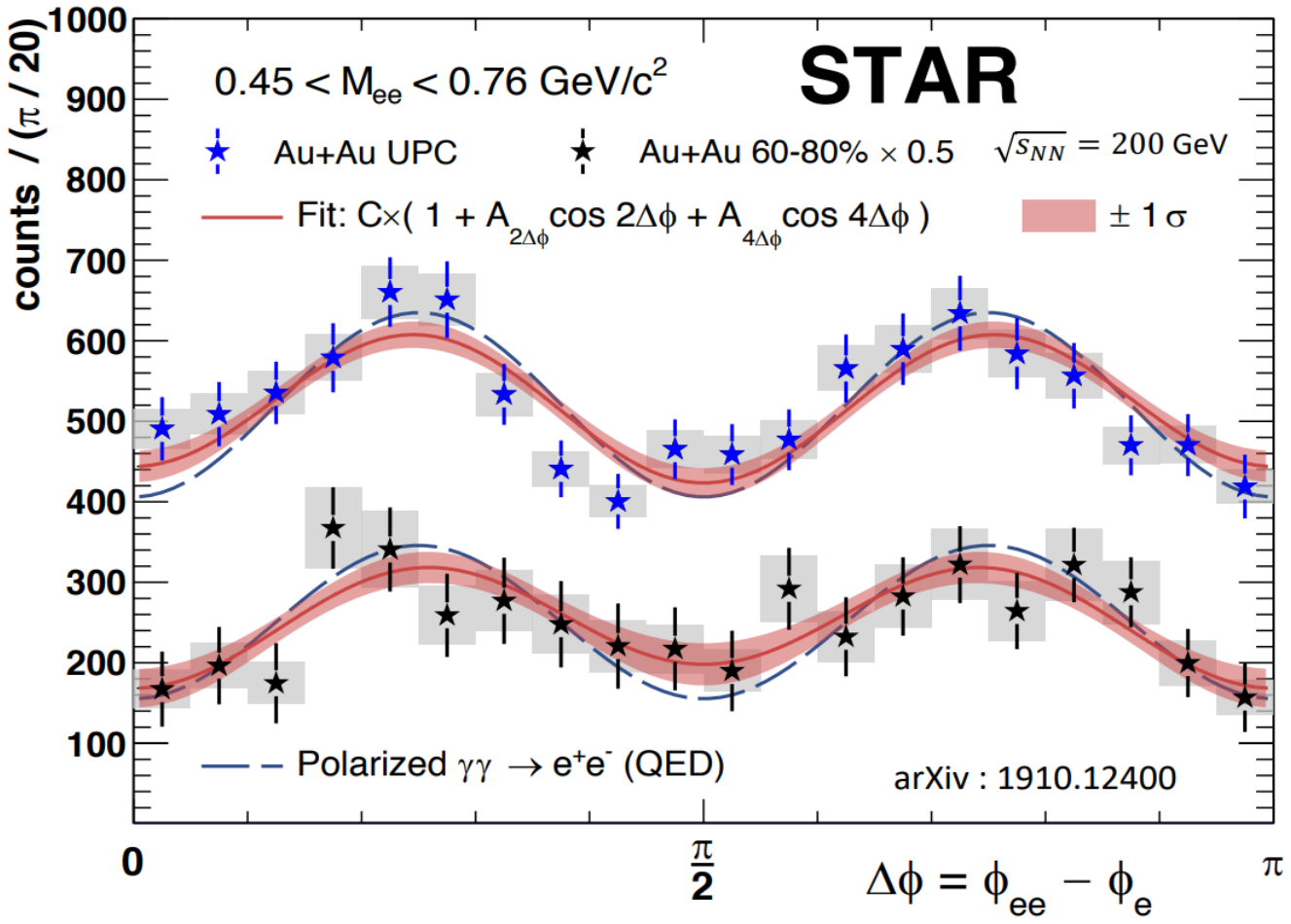
Verified by STAR experiment



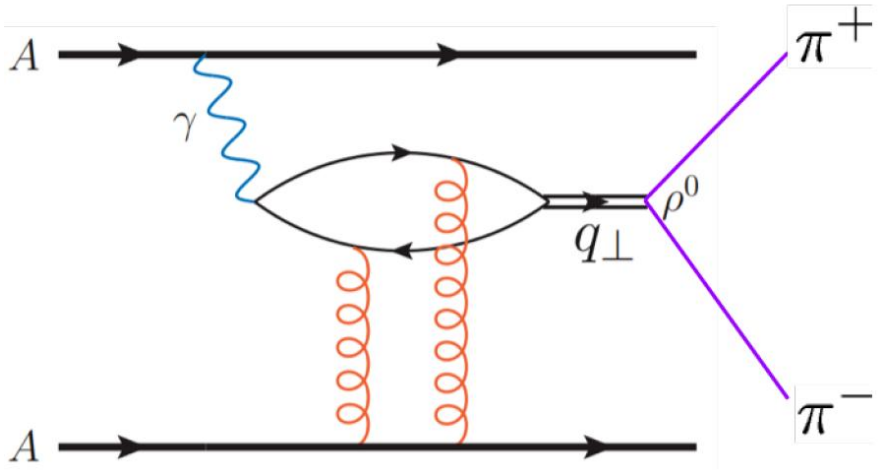
Li-JZ-Zhou, 2020

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

STAR collaboration, PRL, 2021

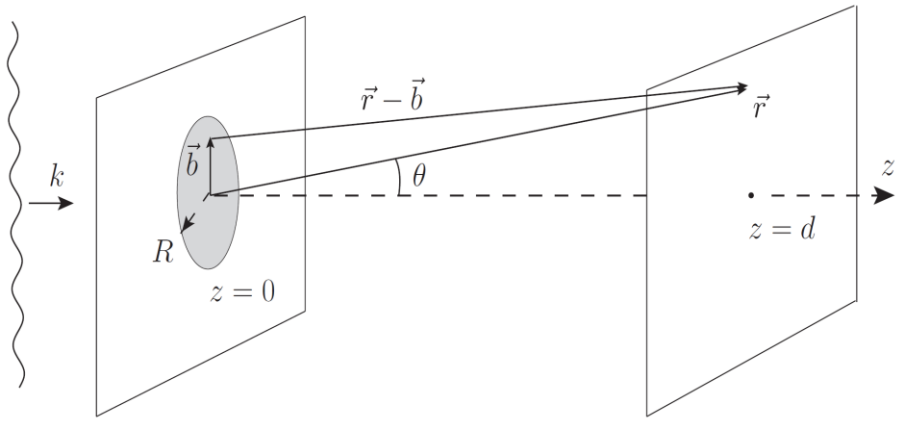


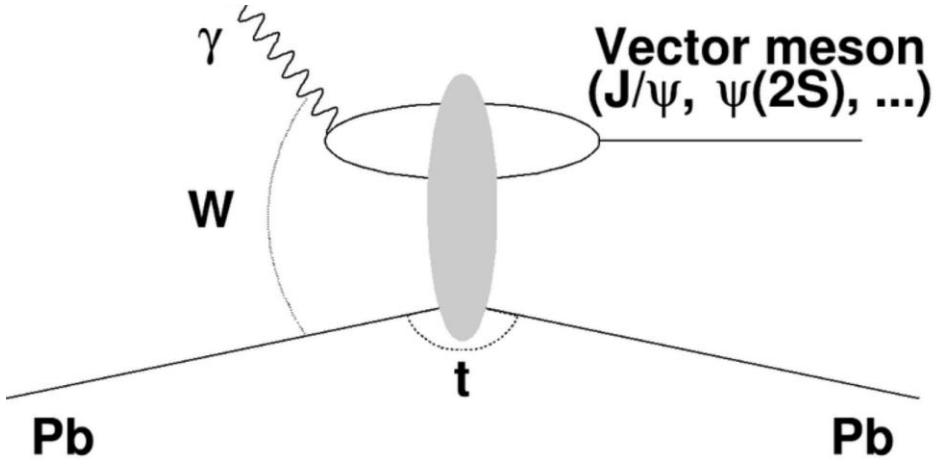
Photon-nuclear reactions

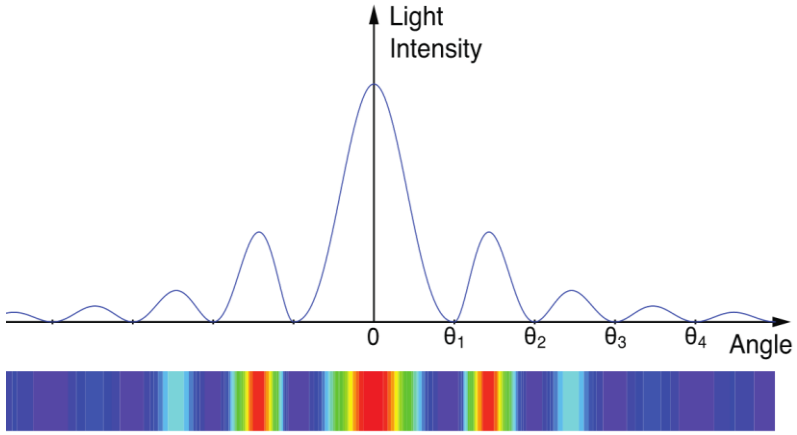


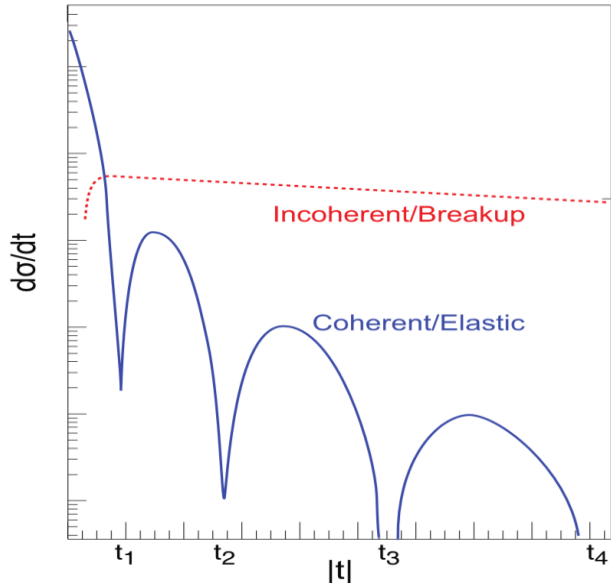
diffractive vector meson

Optical Analogy



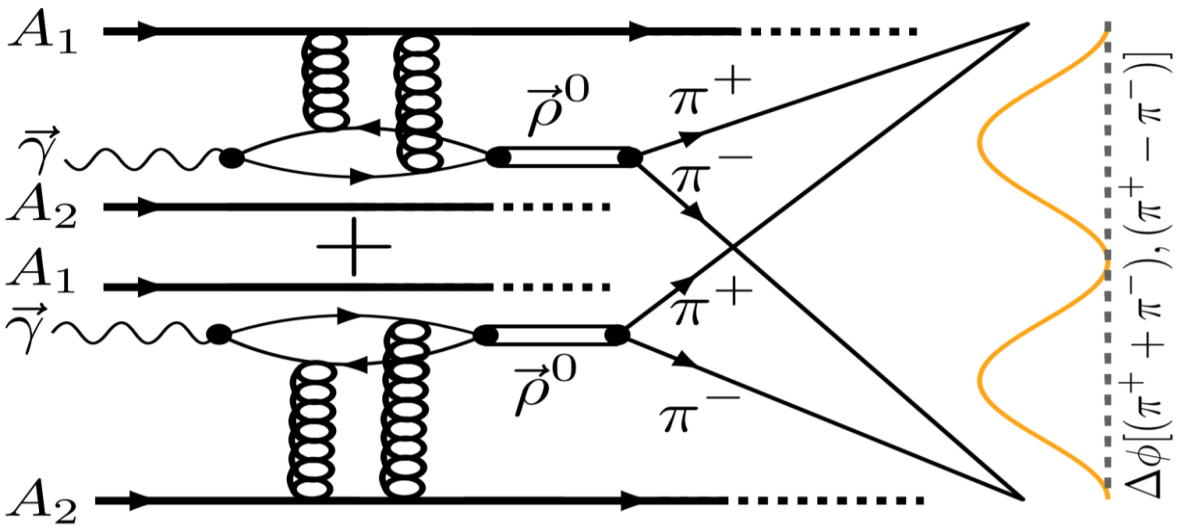




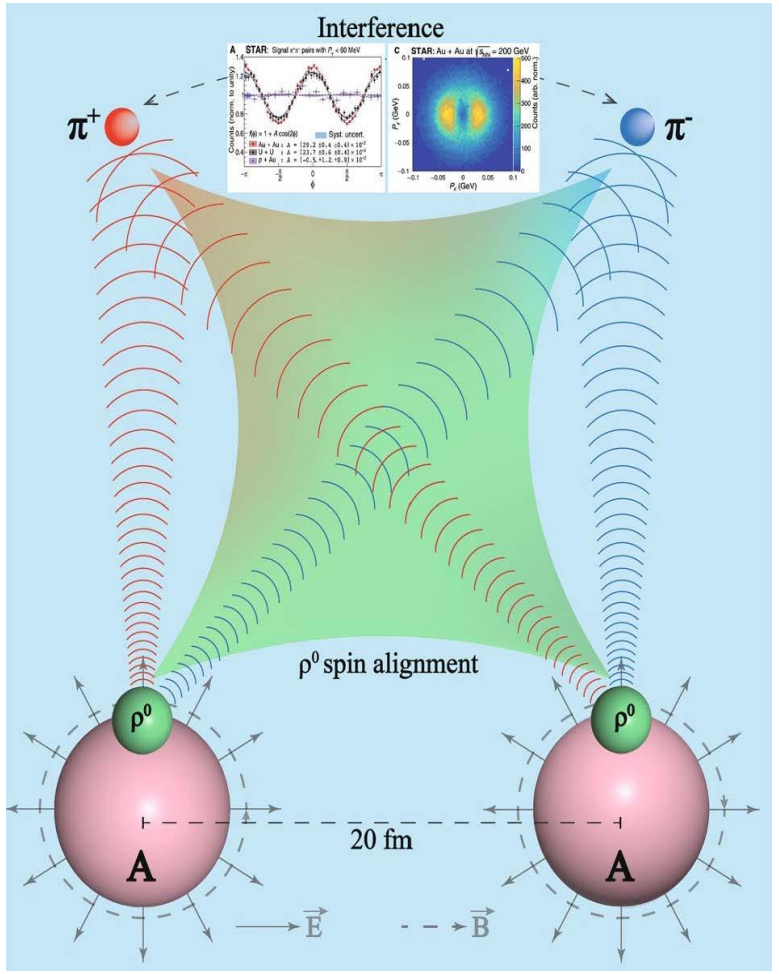


- Reconstruct the size R of the obstacle and the optical “blackness” of the obstacle from the diffractive pattern.

Double-slit effect in UPCs



Klein-Nystrand, 1999



- Remark: two different photons

The first theoretical formulation

- Full cross section in CGC effective theory:

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

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

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

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

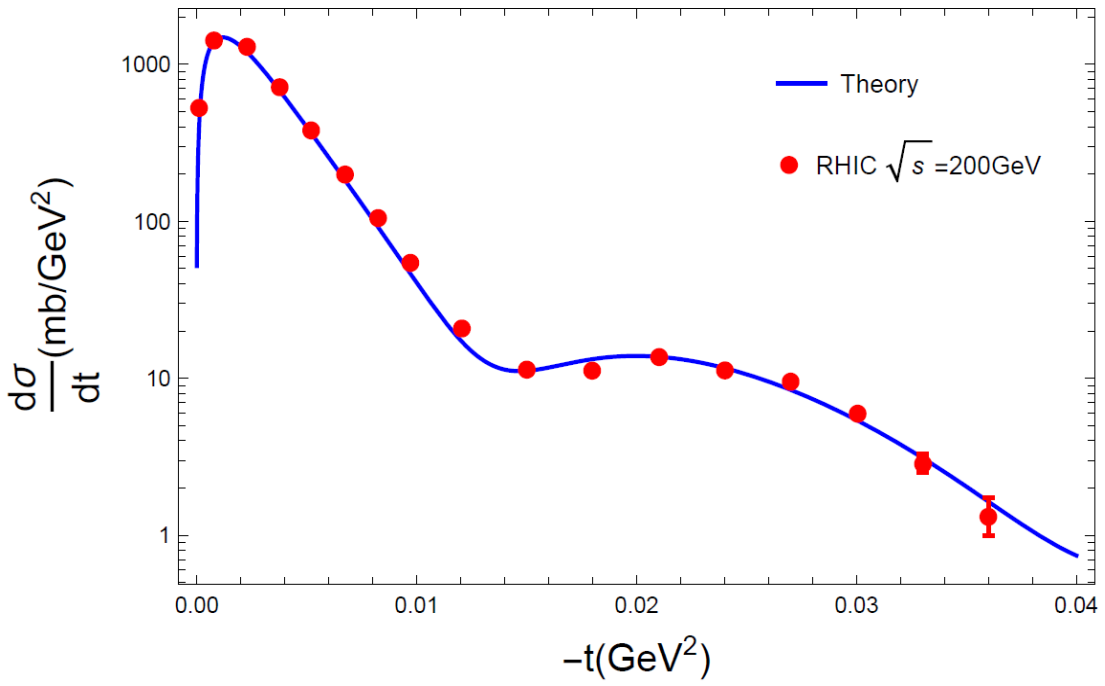
$$+\left[e^{i\tilde{b}_\perp\cdot(\Delta'_\perp-k_\perp)}\mathcal{A}_{co}(Y,\Delta_\perp)\mathcal{A}^*_{co}(-Y,\Delta'_\perp)\mathcal{F}(Y,k_\perp)\mathcal{F}(-Y,k'_\perp)\right]$$

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

Xing-Zhang-ZJ-Zhou, 2020

ρ^0 diffractive pattern

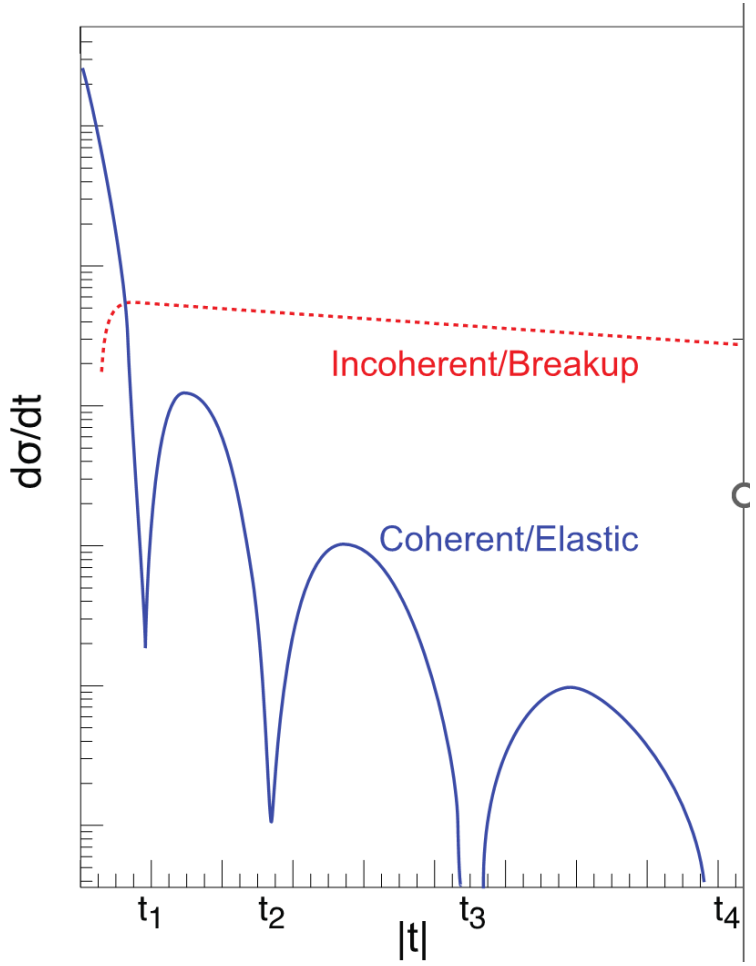
Diffractive VM production in UPC



Xing-Zhang-ZJ-Zhou 2020

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

Diffractive VM production in eA

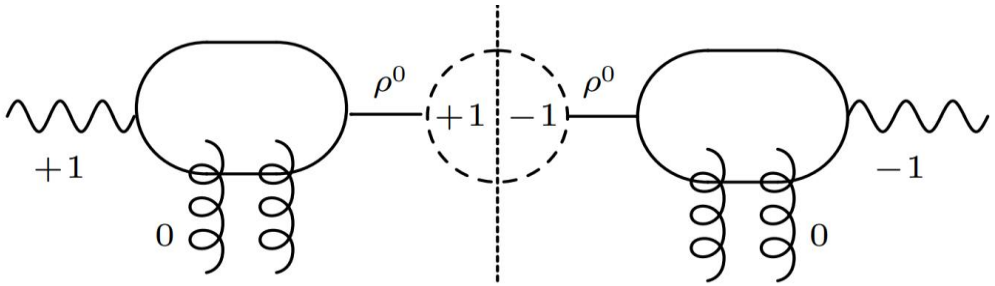


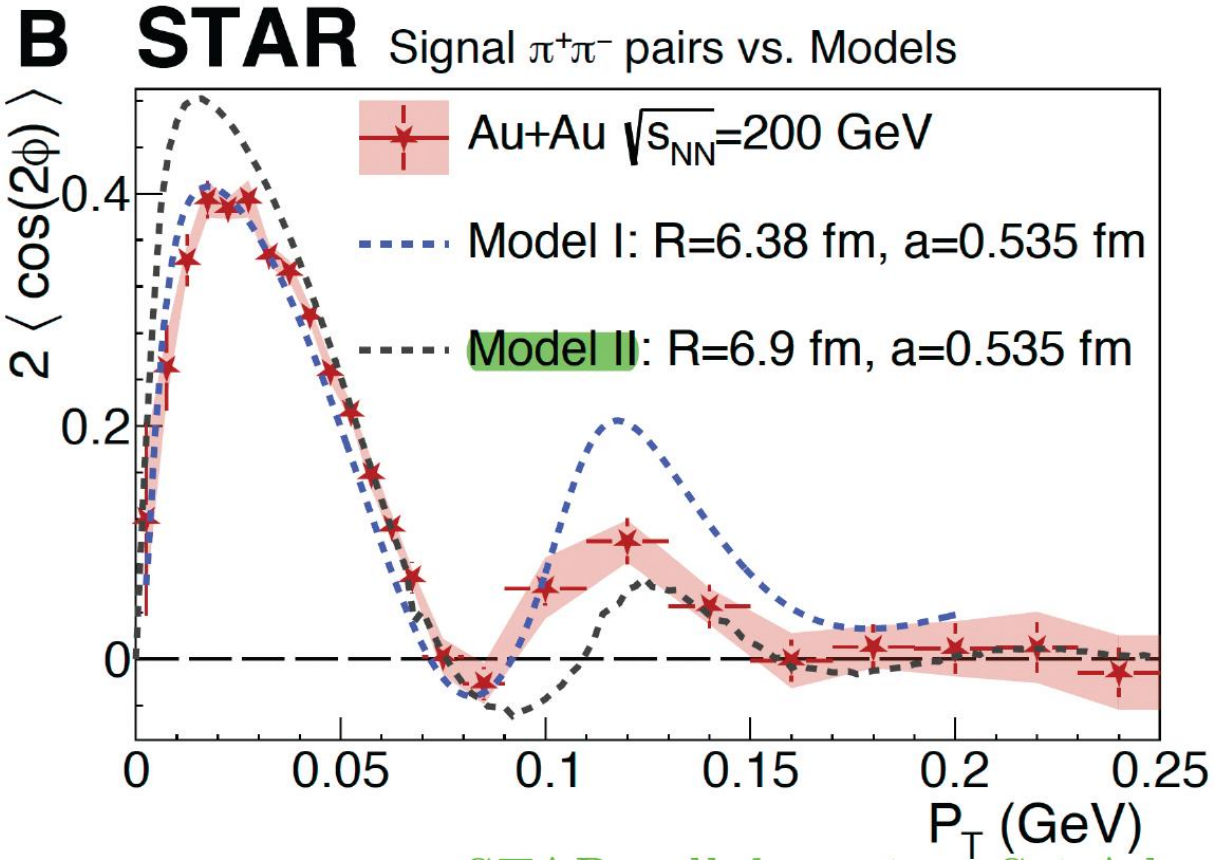
- One slit interference

Cos2ϕ in ρ^0 production

- Interference between two p waves

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



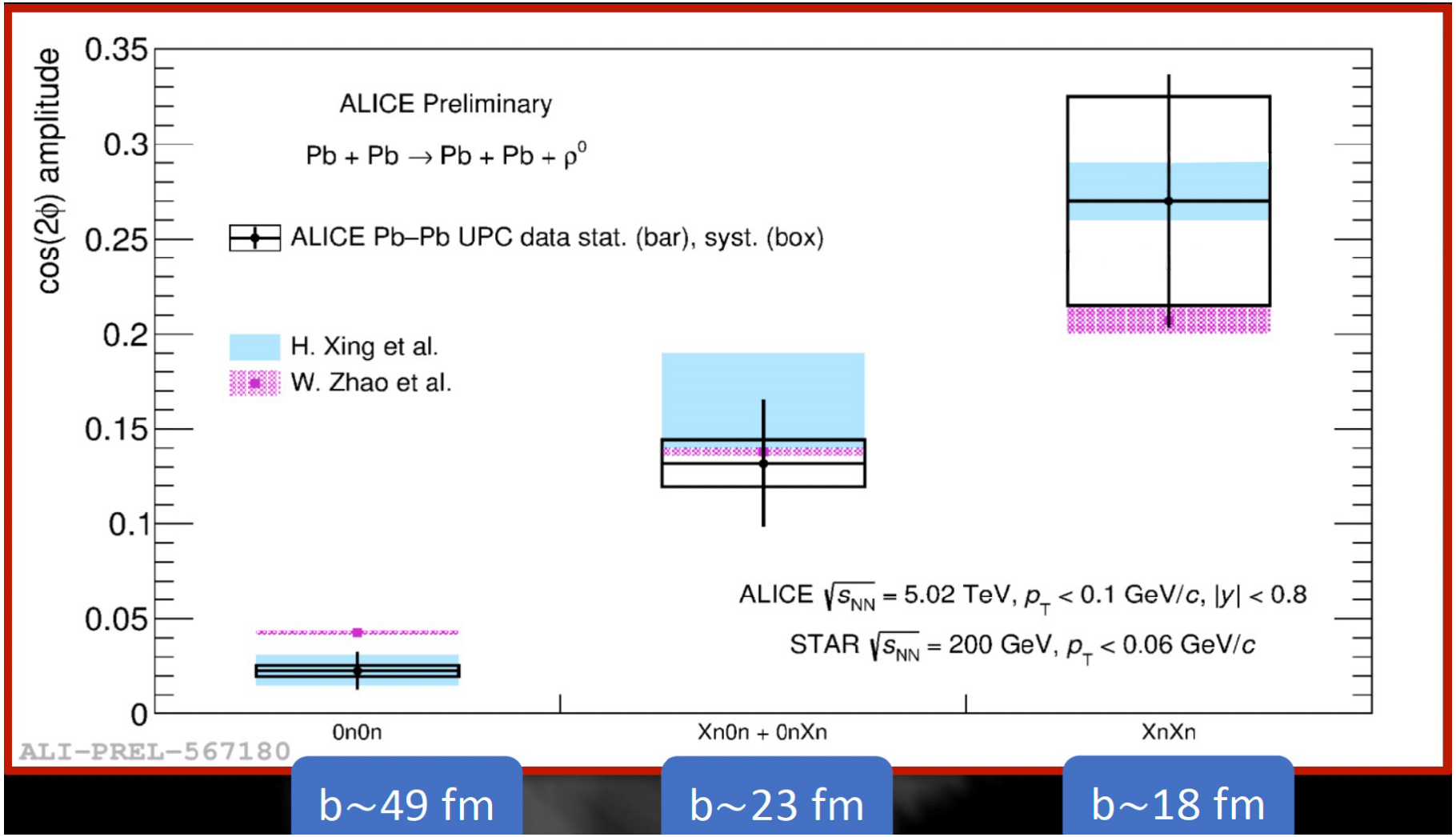


Theory curve II taken from
Xing-Zhang-ZJ-Zhou, 2020

Theory curve II taken from
Wangmei Zha et.al. 2021

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

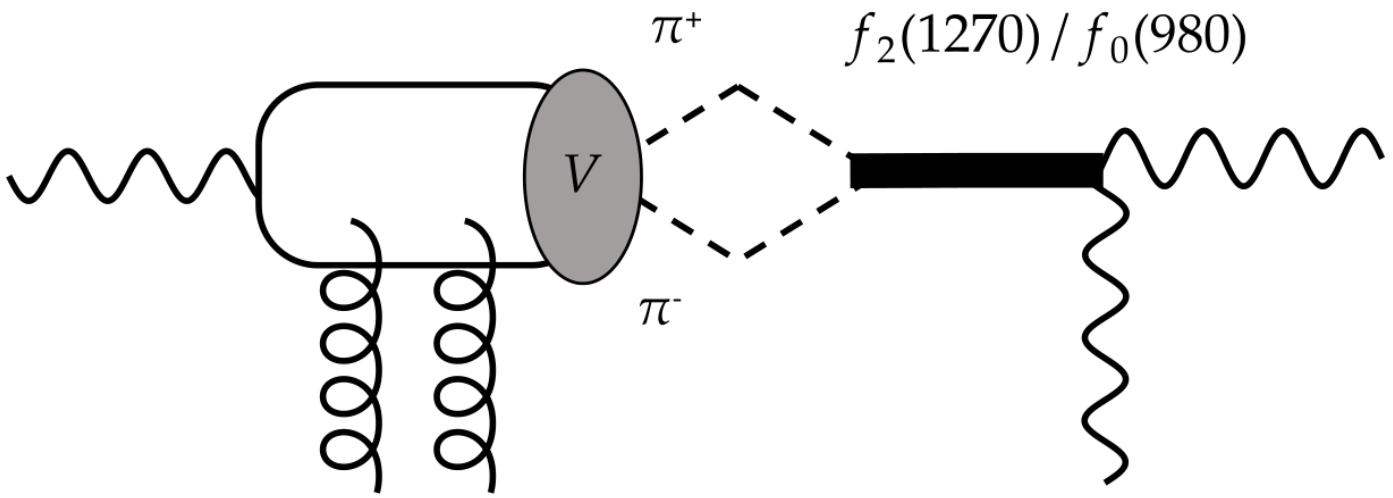
A different type Interference in UPCs

Coherent photonuclear

C-odd P wave

Two-photon fusion

C-even S wave



ρ^0–f_0 cross term + complex conjugate (c.c.)

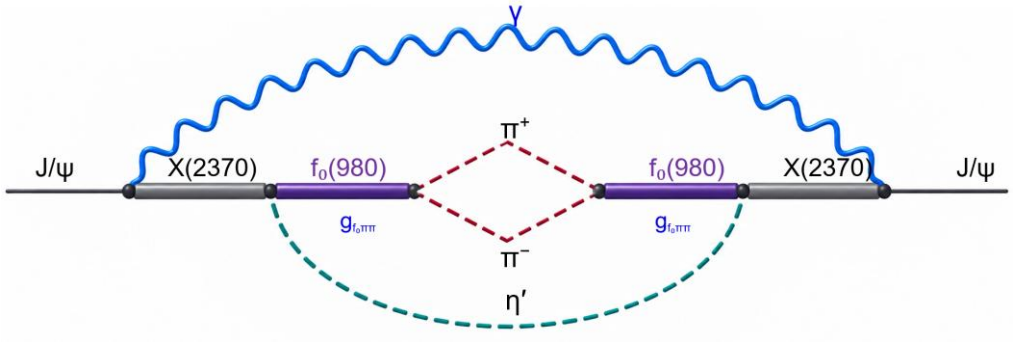
- Same final state, coherent amplitudes

J. D. Brandenburg, S. Corey, S. Lin, ZJ, Y. j. Zhou, 2026

Resonance phase interferometry

- f_2（1270） 是一个标准的（最轻的）张量介子，由轻夸克对组成，其参数实验约束较多。
- f_0 （980）是一个标量介子，（四夸克态？），混合了多少strange quark pair 贡献?

BESIII: glue ball candidate X(2370)



Coherent photonuclear ρ⁰ P wave provides the reference

$$|T_\rho + T_R|^2 = |T_\rho|^2 + |T_R|^2 + 2\,\mathrm{Re}(T_\rho T_R^*)$$

R = f_0, f_2

Interference probes the relative resonance phase

J. D. Brandenburg, S. Corey, S. Lin, ZJ, Y. j. Zhou, 2026

Pion interchange and odd harmonics

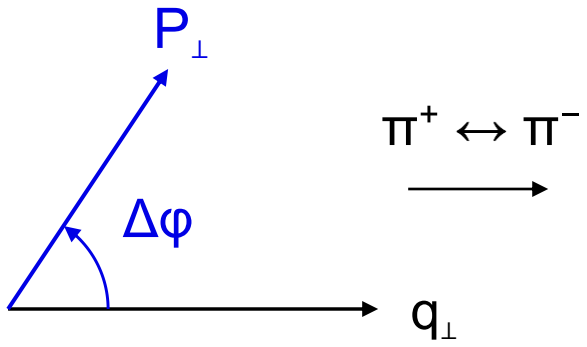
$q_\perp = p_{1\perp} + p_{2\perp}$ $\quad P_\perp = (p_{1\perp} - p_{2\perp})/2$

$\Delta\varphi = \varphi_{P\perp} - \varphi_{q\perp}$ $\quad Q^2 = (p_1 + p_2)^2$

Odd under $\pi^+ \leftrightarrow \pi^-$

P wave × C-even wave

Resonant contributions



$\pi^+ \leftrightarrow \pi^-$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Delta\phi} = \frac{\sigma_0}{2\pi}\left[1 + A_1\cos(\Delta\phi) + A_3\cos(3\Delta\phi) + \cdots\right]$$

A_1: $f_0 + f_2$ $\quad A_3$: f_2 helicity-2

Coherent two-source amplitudes

“单缝衍射”与Color dipole 散射振幅：

$$\frac{d\sigma_{\rm int}^{(R)}}{d^2p_{1\perp}d^2p_{2\perp}dy_1dy_2d^2\tilde{b}_\perp} = -\frac{1}{Q^2(2\pi)^5}\frac{|P_\perp|f_{\rho\pi\pi}}{\sqrt{4\pi}}\mathcal{K}_{\rho R}(Q)$$
$$\times\int d^2k_\perp\, d^2\Delta_\perp\, d^2k'_\perp\, \delta^2(q_\perp-k_\perp-\Delta_\perp)(\hat{P}_\perp\cdot\hat{k}'_\perp)$$
$$\times\Big\{-(\hat{k}_\perp\cdot\hat{\Delta}_\perp)D_R(Q)\mathcal{M}^R_{++}+\Big[2(\hat{k}_\perp\cdot\hat{P}_\perp)(\hat{\Delta}_\perp\cdot\hat{P}_\perp)-\hat{k}_\perp\cdot\hat{\Delta}_\perp\Big]D_R(Q)\mathcal{M}^R_{+-}\Big\}$$
$$\times\Big\{e^{i\tilde{b}_\perp\cdot(k'_\perp-k_\perp)}\mathcal{F}(x_1,k_\perp)\mathcal{F}(x_2,\Delta_\perp)\mathcal{F}^*(x_1,k'_\perp)\mathcal{A}^*_{\rm co}(x_2,\Delta'_\perp)$$
$$+e^{i\tilde{b}_\perp\cdot(\Delta'_\perp-k_\perp)}\mathcal{F}(x_1,k_\perp)\mathcal{F}(x_2,\Delta_\perp)\mathcal{F}^*(x_2,k'_\perp)\mathcal{A}^*_{\rm co}(x_1,\Delta'_\perp)\Big\},\qquad R=f_0,f_2.$$

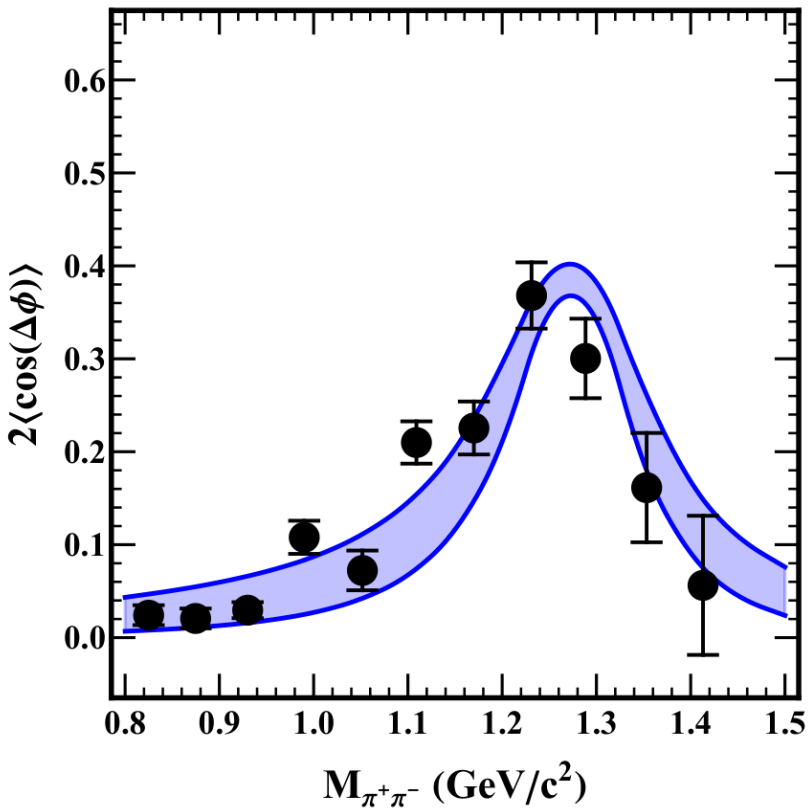
方位角不对称对共振态传播子虚部非常敏感：

$$\mathcal{K}_{\rho R}(Q)={\rm Im}\left[\frac{1}{D_\rho(Q)D_R^*(Q)}\right],\qquad R=f_0,f_2,\qquad (6)$$

$f_2(1270)$: odd harmonics

Au+Au 200 GeV, XnXn; $|\eta_{1,2}| < 1$, $q\perp < 100$ MeV, $P\perp > 200$ MeV

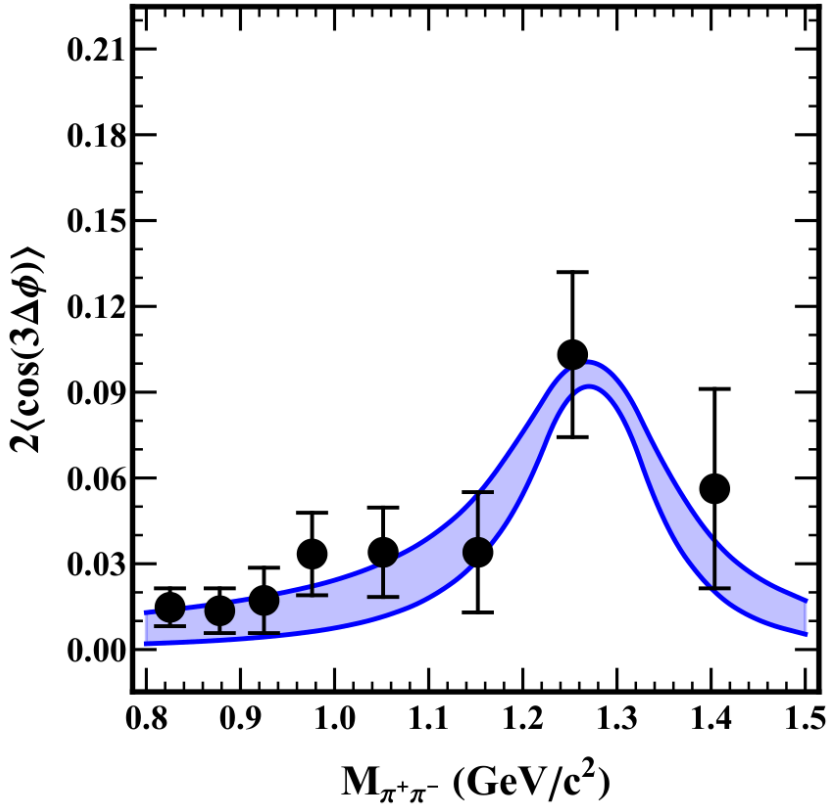
First harmonic



f_2-only: Λf_2 = 1–1.5 GeV

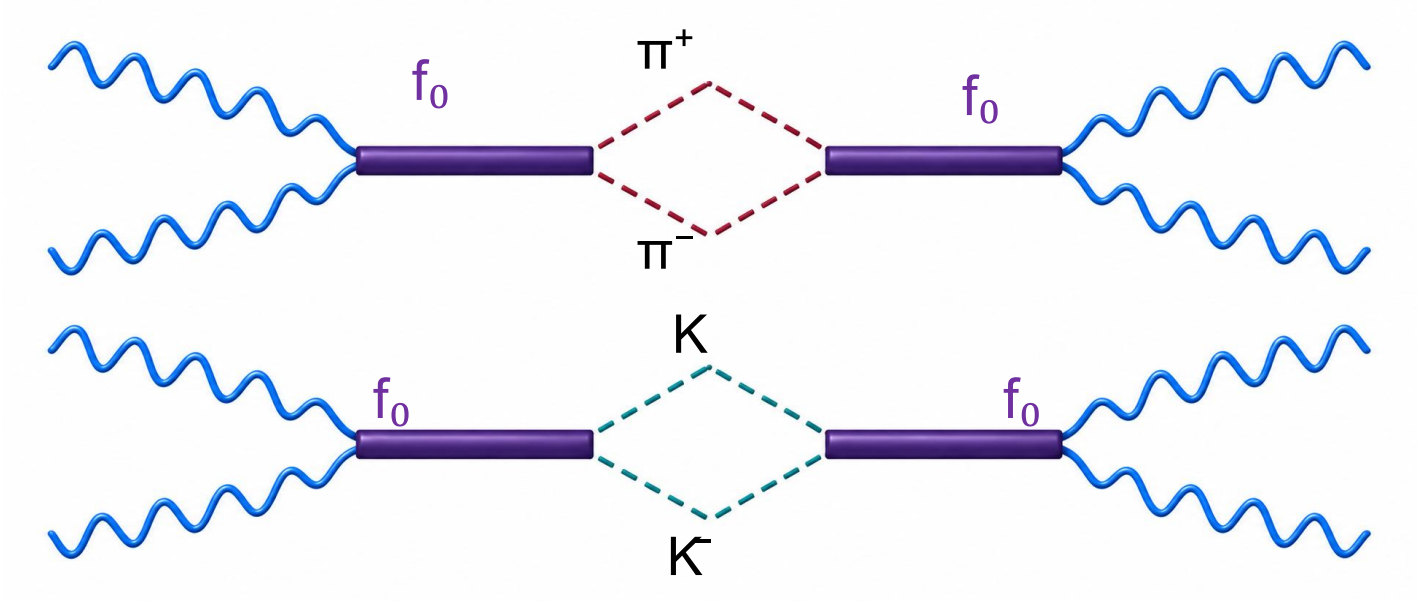
External input (no STAR fit)

Third harmonic



STAR preliminary: full moments

Coupled channels in $f_0(980)$



ππ channel

threshold $2m_\pi$

$\Gamma_\pi(Q)$

K \barK channel

threshold $2m_K$

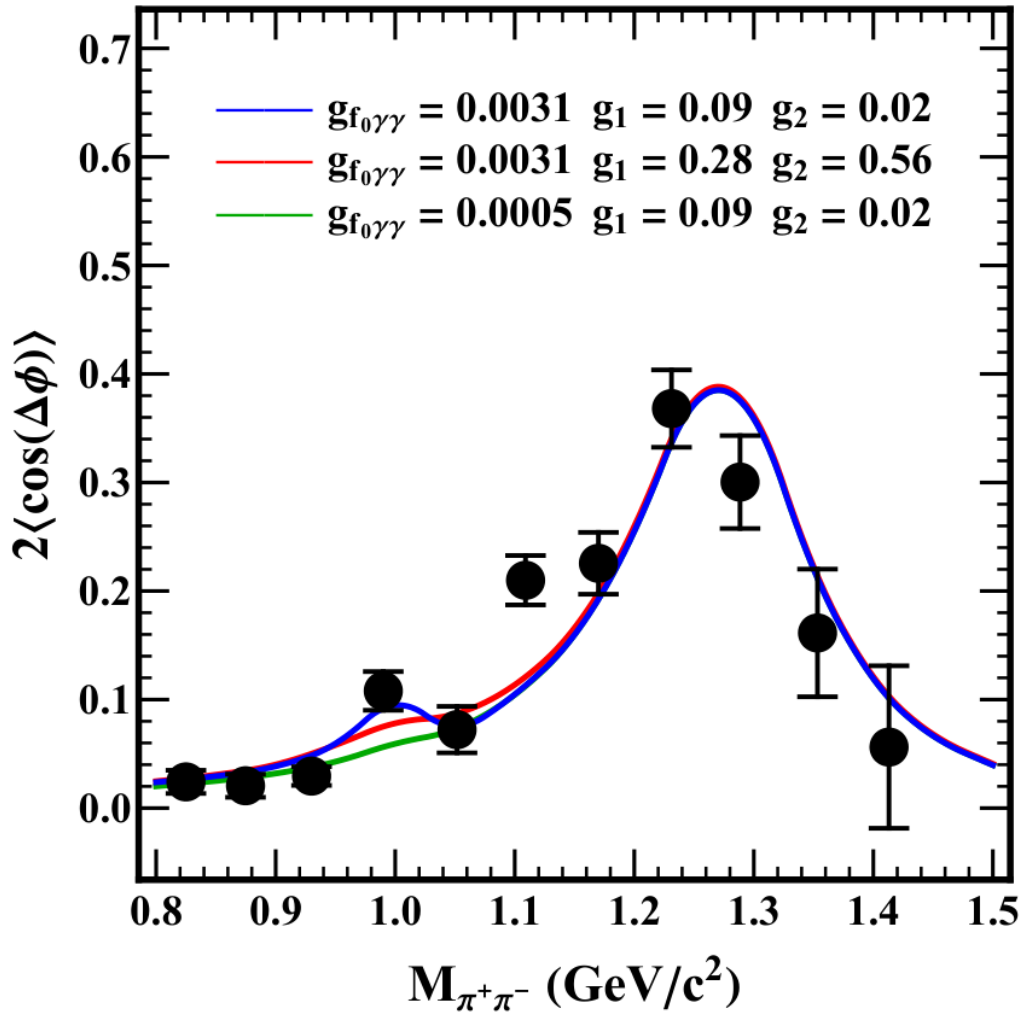
$\Gamma_K(Q)$

$$D_{f_0}(Q) = Q^2 - m_{f_0}^2 + \mathrm{i} m_{f_0} \left[\Gamma_\pi(Q) + \Gamma_K(Q)\right]. \qquad (9)$$

Threshold opening: magnitude and phase

Coupling scenarios for $f_0(980)$

- K \barK 阈值效应:



I (blue), II (red), III (green)

I vs II: coupled-channel shape
Same two-photon coupling

I vs III: normalization
Same g_1, g_2

Common f_2: Λ = 1.3 GeV

Data points: STAR preliminary
Scenarios, not a best-fit selection

Fig. 3

Summary:

- 强场QED与冷核物质研究 in UPCs
- 费米尺度的双缝干涉

  Diffractive vector meson production in UPCs
- 通过不同共振态的分波干涉约束相位

  间接提高测量 X(2370) 性质的精度

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