Probing the linear polarization of coherent photons in heavy ion collisions

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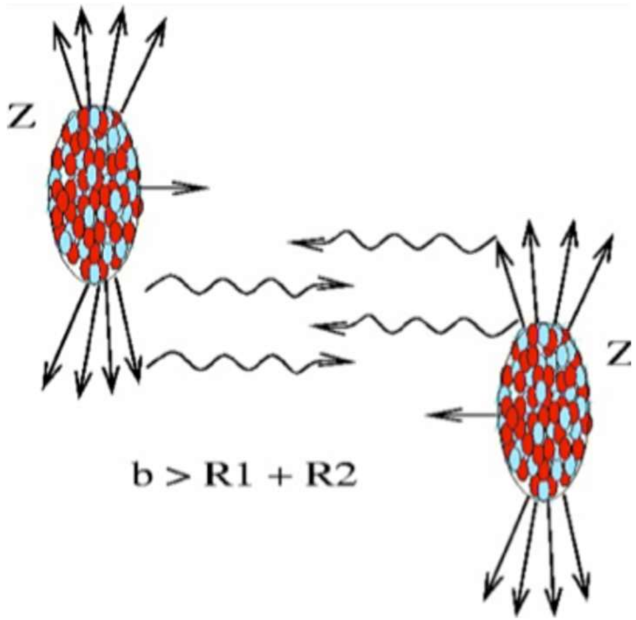
Based on papers: arXiv:1903.10084
arXiv:1911.00237
Cong Li, ZJ and Y. J. Zhou

Outline

- Background
- Cos 4ϕ asymmetry in EM dilepton production
- Summary and Outlook

Coherent photon distributions



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

$$n(\omega) = \frac{4Z^2\alpha_e}{\omega} \int \frac{d^2k_\perp}{(2\pi)^2} k_\perp^2 \left[\frac{F(k_\perp^2 + \omega^2/\gamma^2)}{(k_\perp^2 + \omega^2/\gamma^2)} \right]^2$$

$$\sigma^{WW}_{A_1A_2 \to A_1A_2X} = \int d\omega_1 d\omega_2 n_{A_1}(\omega_1) n_{A_2}(\omega_2) \sigma_{\gamma\gamma \to X}(\omega_1, \omega_2)$$

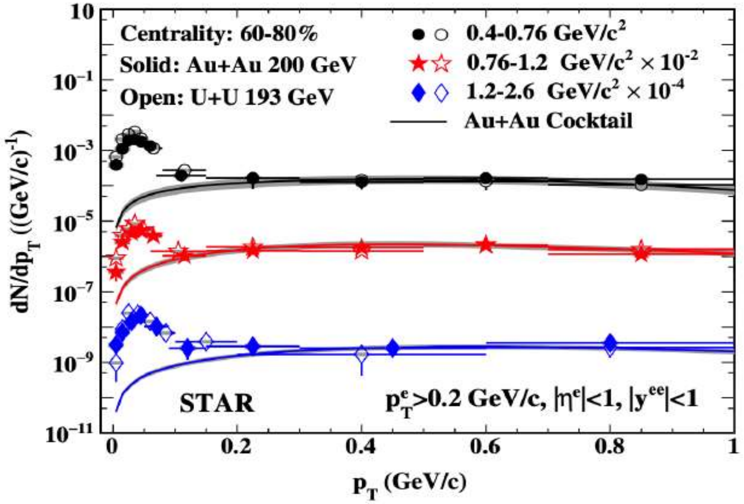
$K_T \leq 1/R_A$

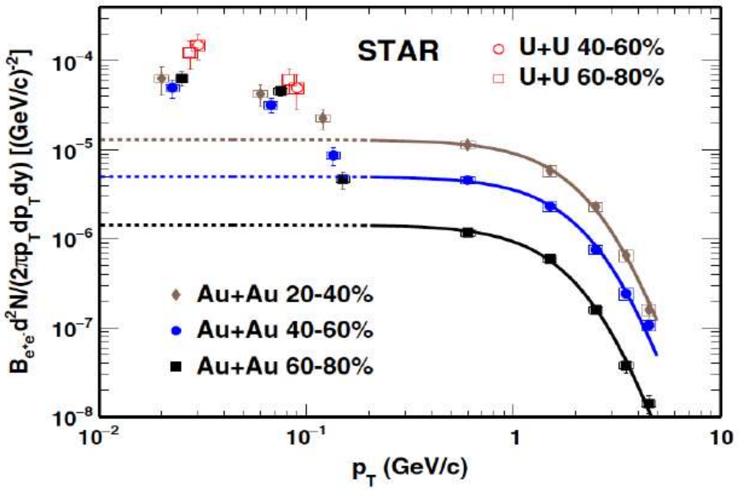
$d\sigma \propto Z^4$
clean background

$\gamma - \gamma$
$\gamma - \mathbf{A}$

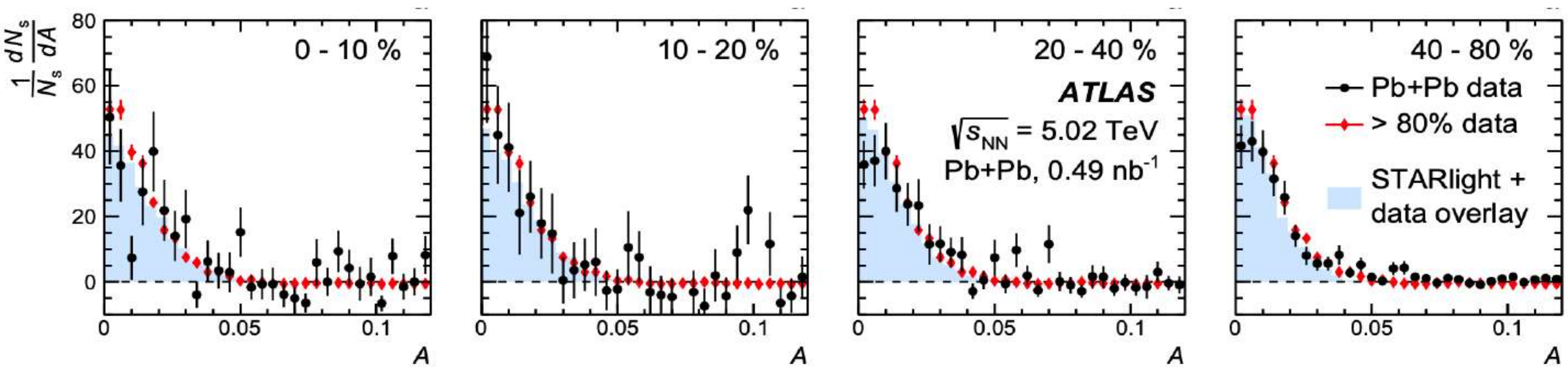
Coherent photon initiated processes in PCs and UPCs

STAR measurement:

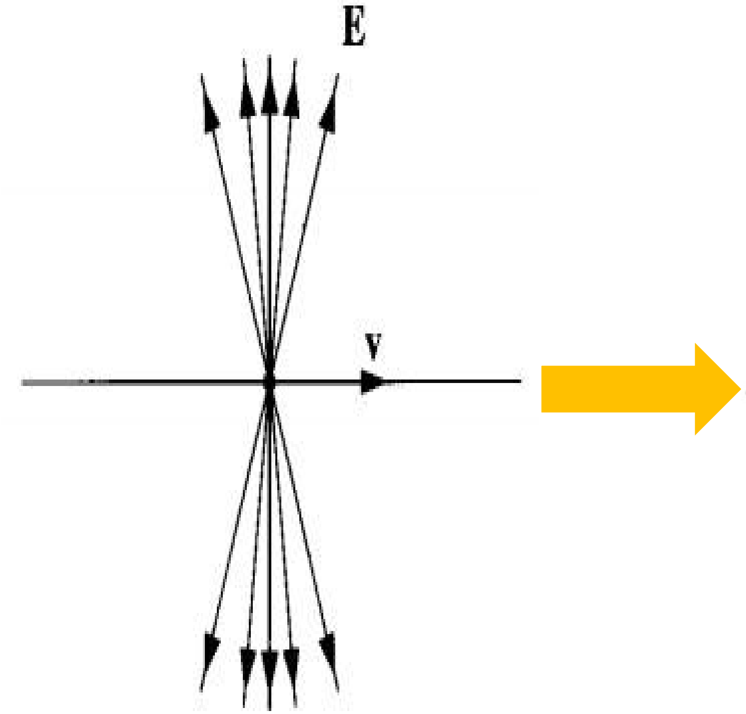




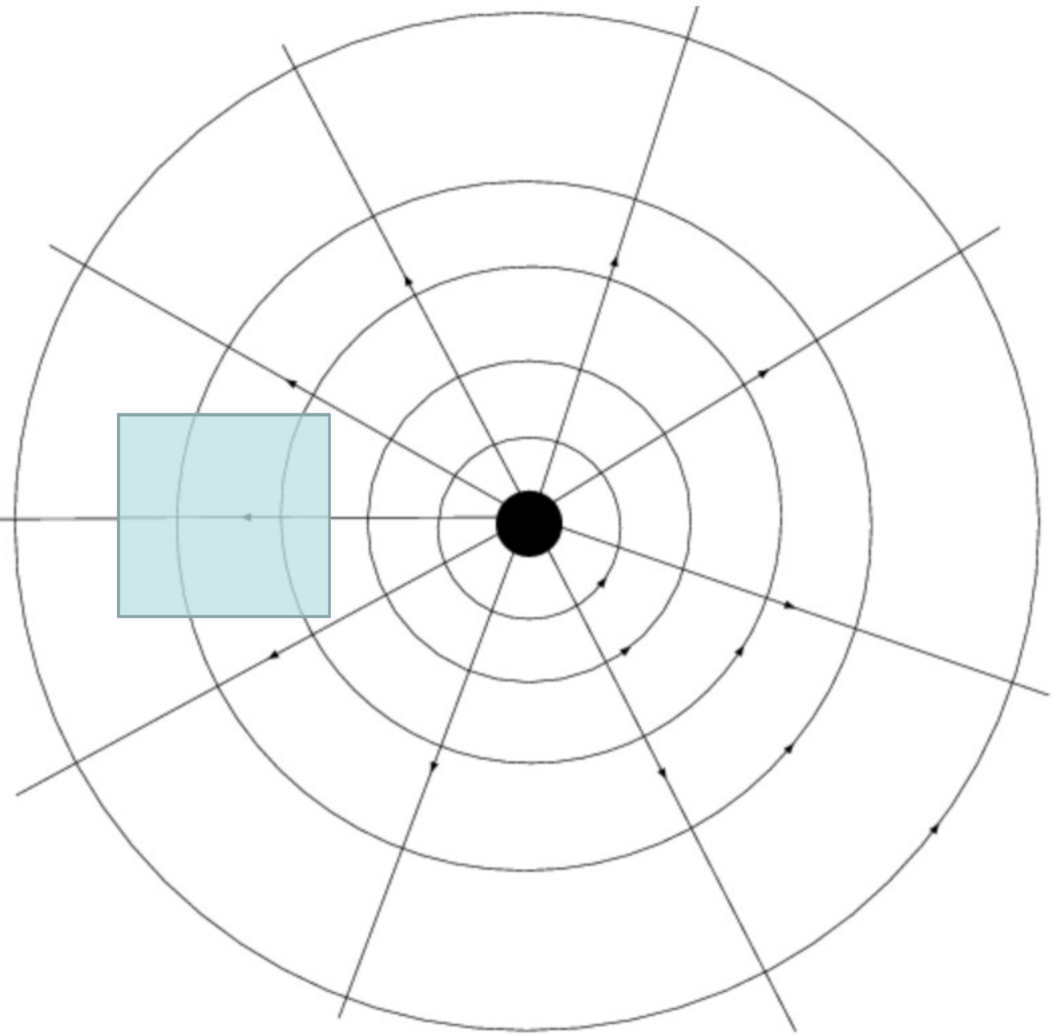
ATLAS measurement



The boosted Coulomb potential

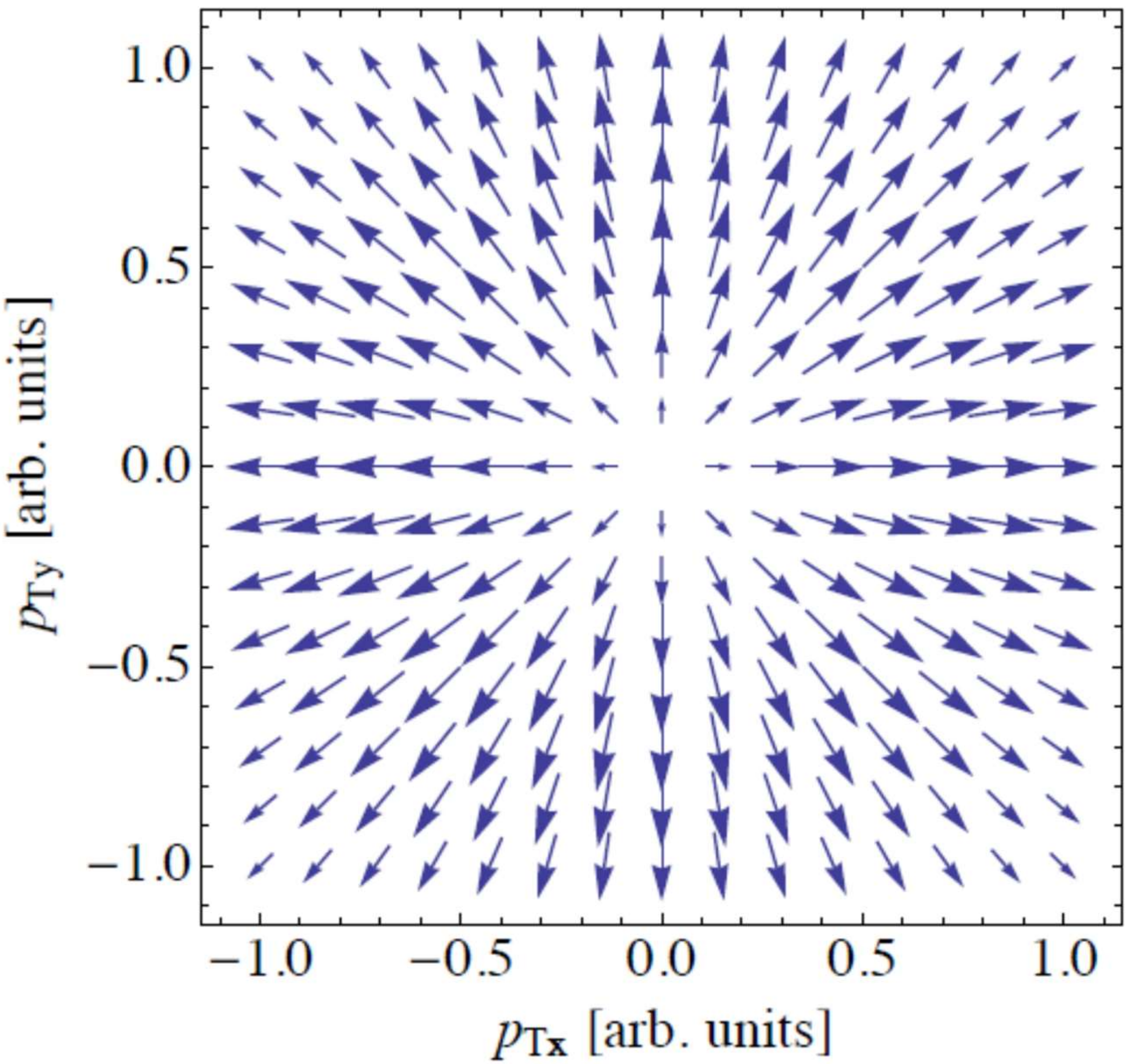


Side view



Head on view

Transverse momentum phase space



Linearly polarized photon TMD

Can be formulated in the context of TMD factorization:

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

similar to gluon TMD but no need to add gauge link ($F_{\mu\nu}$ is U(1) invariant)

A nucleus moves along P^+, A^+ dominant, $F^{\mu}_{+\perp} \propto k^\mu_\perp A^+$,

$F^{\mu}_{+\perp} F^{\nu}_{+\perp} \propto k^\mu_\perp k^\nu_\perp A^+ A^+$, implies,

$$f_1^\gamma(x,k_\perp^2) = h_1^{\perp\gamma}(x,k_\perp^2)$$

How to probe it?

Cos 4ϕ asymmetry in EM dilepton production

$$\gamma(x_1 P + k_{1\perp}) + \gamma(x_2 \bar{P} + k_{2\perp}) \to l^+(p_1) + l^-(p_2)$$

$$\langle \cos(4\phi) \rangle \qquad \phi = P_\perp \wedge q_\perp$$

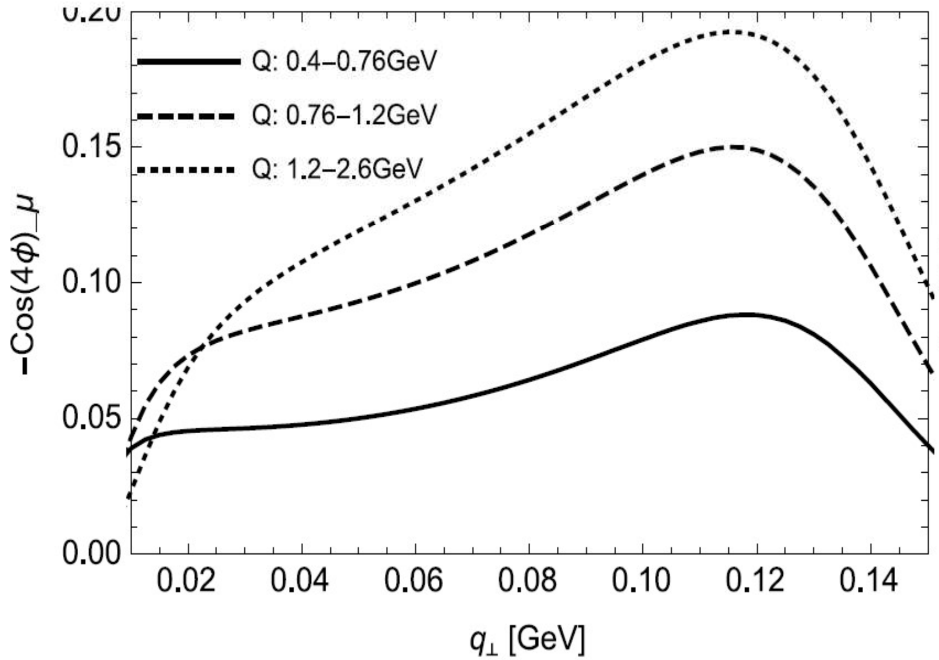
$$P_\perp \equiv (p_{1\perp} - p_{2\perp})/2 \qquad q_\perp \equiv p_{1\perp} + p_{2\perp}$$

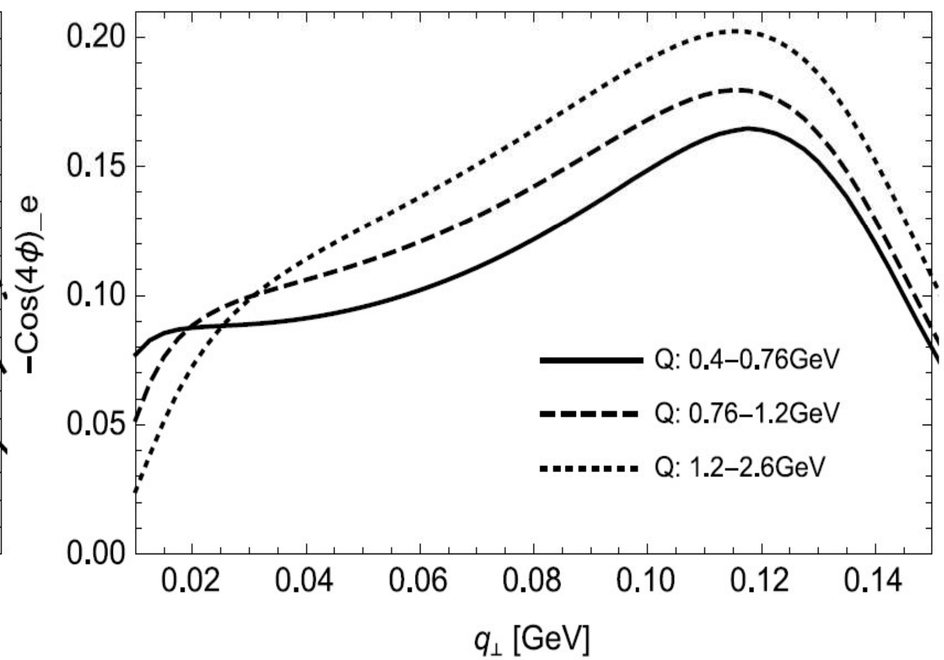
correlation limit: $P_\perp \gg q_\perp$

$\langle\cos(4\phi)\rangle$ **in the EPA: b_T [0, ∞]**

Numerical results for $b_T[0, \infty]$

RHIC : $\sqrt{s} = 200$ GeV, Au-Au, Z=79,
lepton rapidity integrate from -1 to 1





C. Li, ZJ, and Y. J. Zhou

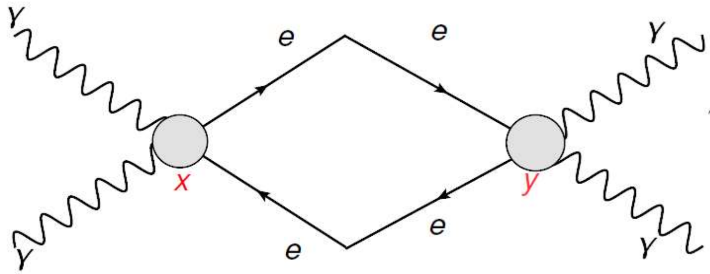
To incorporate experimental conditions

Various centrality classes and the tagged UPC

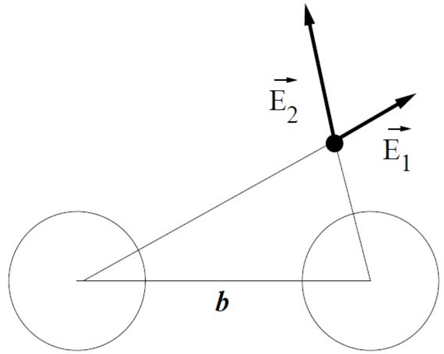
Take into account b_T dependence in theoretical calculations

Go beyond the EPA!

Impact parameter dependence



$$\gamma(x_1 P + k_{1\perp}) + \gamma(x_2 \bar{P} + k_{2\perp}) \rightarrow l^+(p_1) + l^-(p_2)$$



$$|\mathcal{M}|^2 \propto \int d^4x \, d^4y \, \langle \mathcal{P} | \bar{\psi}(x) \Gamma^{\mu\nu} \psi(x) A_\mu(x) A_\nu(x + b_\perp)$$

$$\bar{\psi}(y) \Gamma^{\mu'\nu'} \psi(y) A_{\mu'}(y) A_{\nu'}(y + b_\perp) | \mathcal{P} \rangle$$

$$\propto \int d^4x \, e^{-ik_1 \cdot x} e^{-ik_2 \cdot (x + b_\perp)} e^{ip_1 \cdot x} e^{ip_2 \cdot x} \int d^4y \, e^{ik_1' \cdot y} e^{ik_2' \cdot (y + b_\perp)} e^{-ip_1 \cdot y} e^{-ip_2 \cdot y}$$

$$\propto \delta^4(k_1 + k_2 - p_1 - p_2) \, \delta^4(k_1' + k_2' - p_1 - p_2) e^{-ik_{2\perp} \cdot b_\perp} e^{ik_{2\perp}' \cdot b_\perp}$$

$$\propto \delta^2(k_{1\perp} + k_{2\perp} - p_{1\perp} - p_{2\perp}) \, \delta^2(k_{1\perp}' + k_{2\perp}' - p_{1\perp} - p_{2\perp}) e^{i(k_{2\perp}' - k_{2\perp}) \cdot b_\perp}$$

M. Vidovic, M. Greiner, C. Best and G. Soff; 93

Successfully describes dilepton kt broadening

W. Zha, J. D. Brandenburg, Z. Tang and Z. Xu, 2019

b_T&azimuthal dependent cross section

$$\frac{d\sigma_0}{d^2p_{1\perp}d^2p_{2\perp}dy_1dy_2d^2b_\perp} = \frac{2\alpha_e^2}{Q^4}\frac{1}{(2\pi)^2}[\mathcal{A} + \mathcal{B}\cos 2\phi + C\cos 4\phi]$$

$$\mathcal{A} = \frac{Q^2 - 2P_\perp^2}{P_\perp^2}\frac{Z^4\alpha_e^2}{\pi^4}\int d^2k_{1\perp}d^2k_{2\perp}d^2\Delta_\perp\delta^2(q_\perp - k_{1\perp} - k_{2\perp})e^{i\Delta_\perp\cdot b_\perp}$$
$$\times\left[(k_{1\perp}\cdot k'_{1\perp})(k_{2\perp}\cdot k'_{2\perp}) + (k_{1\perp}\cdot k_{2\perp})\Delta_\perp^2 - (k_{1\perp}\cdot\Delta_\perp)(k_{2\perp}\cdot\Delta_\perp)\right]$$
$$\times\mathcal{F}\left(x_1, k_{1\perp}^2\right)\mathcal{F}^*\left(x_1, k_{1\perp}'^2\right)\mathcal{F}\left(x_2, k_{2\perp}^2\right)\mathcal{F}^*\left(x_2, k_{2\perp}'^2\right)$$

$$C = -2\frac{Z^4\alpha_e^2}{\pi^4}\int d^2k_{1\perp}d^2k_{2\perp}d^2\Delta_\perp\delta^2(q_\perp - k_{1\perp} - k_{2\perp})e^{i\Delta_\perp\cdot b_\perp}$$
$$\times\{2[2(k_{2\perp}\cdot\hat{q}_\perp)(k_{1\perp}\cdot\hat{q}_\perp) - k_{1\perp}\cdot k_{2\perp}][2(k'_{2\perp}\cdot\hat{q}_\perp)(k'_{1\perp}\cdot\hat{q}_\perp) - k'_{1\perp}\cdot k'_{2\perp}]$$
$$-\left[(k_{1\perp}\cdot k'_{1\perp})(k_{2\perp}\cdot k'_{2\perp}) + (k_{1\perp}\cdot k_{2\perp})\Delta_\perp^2 - (k_{1\perp}\cdot\Delta_\perp)(k_{2\perp}\cdot\Delta_\perp)\right]\}$$
$$\times\mathcal{F}\left(x_1, k_{1\perp}^2\right)\mathcal{F}^*\left(x_1, k_{1\perp}'^2\right)\mathcal{F}\left(x_2, k_{2\perp}^2\right)\mathcal{F}^*\left(x_2, k_{2\perp}'^2\right)$$

where $\mathcal{F}\left(x, k_\perp^2\right) = \frac{F(k_\perp^2 + x^2M_p^2)}{(k_1^2 + x^2M_p^2)}$, $\Delta_\perp = k_{1\perp} - k'_{1\perp} = k'_{2\perp} - k_{2\perp}$

C. Li, JZ and Y. Zhou,2019

Resummed cross section

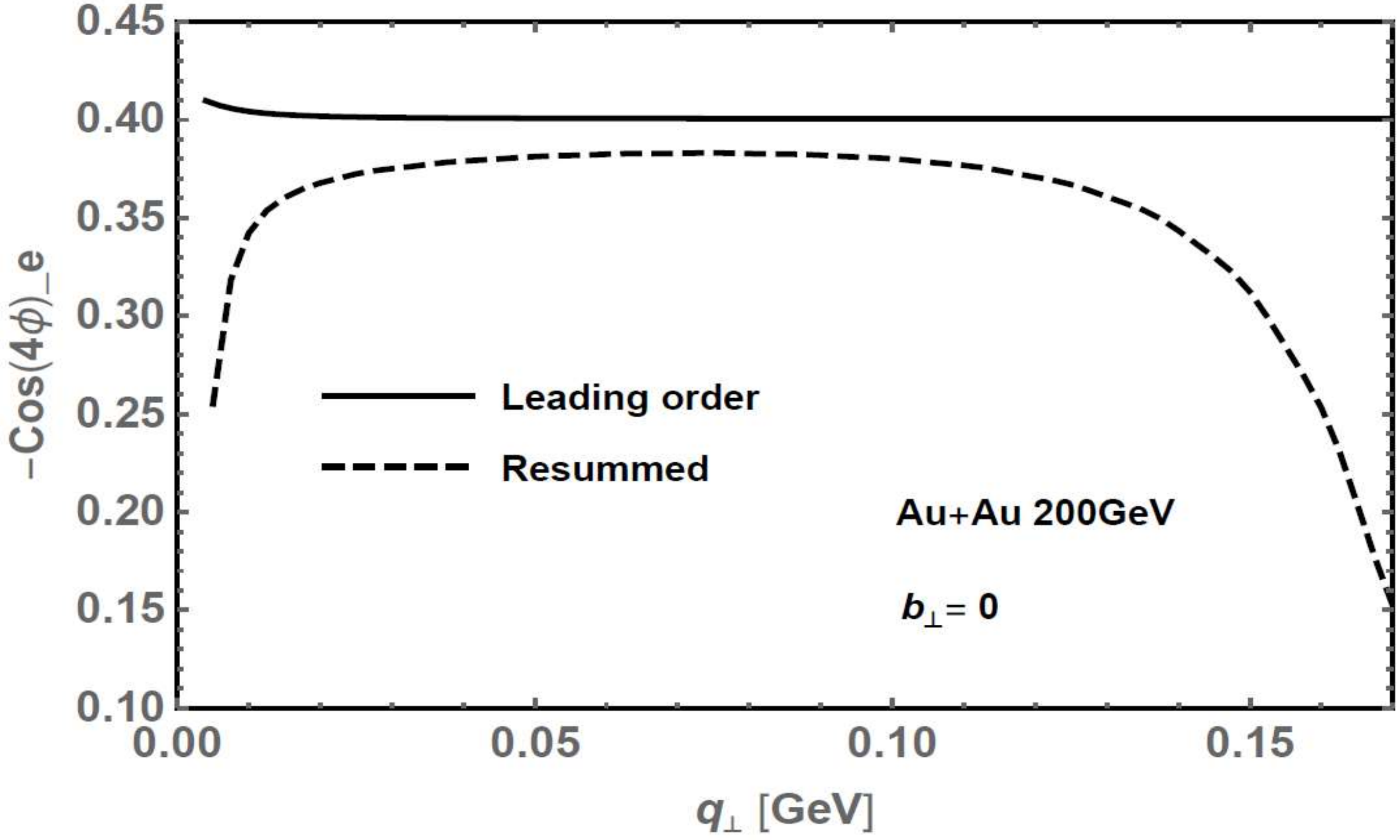
$$q_\perp \ll Q \qquad \alpha_e^n \ln^{2n} \frac{Q^2}{q_\perp^2}$$

$$\frac{d\sigma}{d^2p_{1\perp}d^2p_{2\perp}dy_1dy_2d^2b_\perp} = \int \frac{d^2r_\perp}{(2\pi)^2} e^{ir_\perp\cdot(q_\perp - k_{1\perp} - k_{2\perp})} e^{-S(Q,r_\perp)} \frac{d\sigma_0}{d^2p_{1\perp}d^2p_{2\perp}dy_1dy_2d^2b_\perp}$$

Klein, Mueller, Xiao, Yuan, 2019

Central collisions

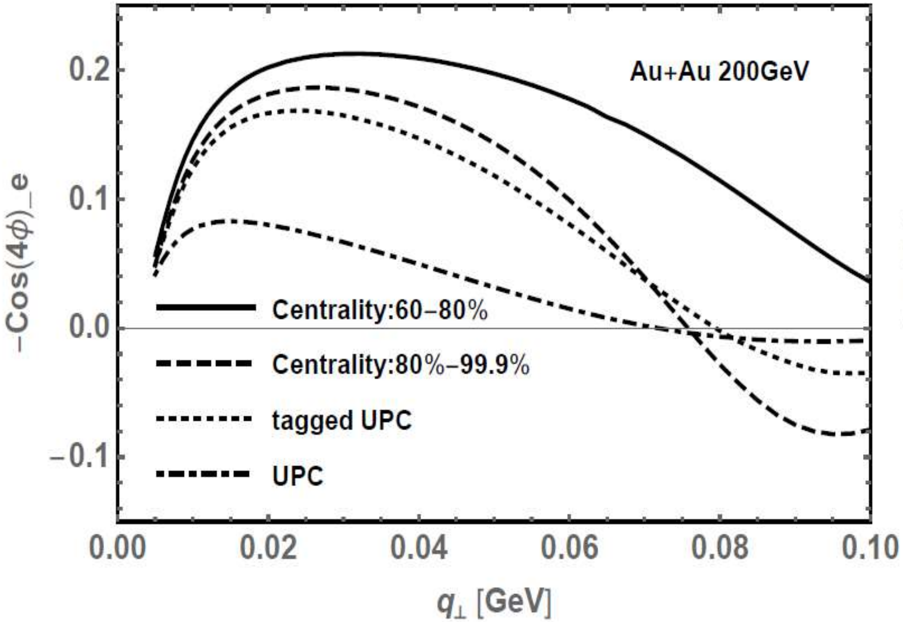
$$\frac{C\,(b_\perp = 0)}{2\mathcal{A}\,(b_\perp = 0)} = \frac{-2P_\perp^2}{2\left(Q^2 - 2P_\perp^2\right)}$$

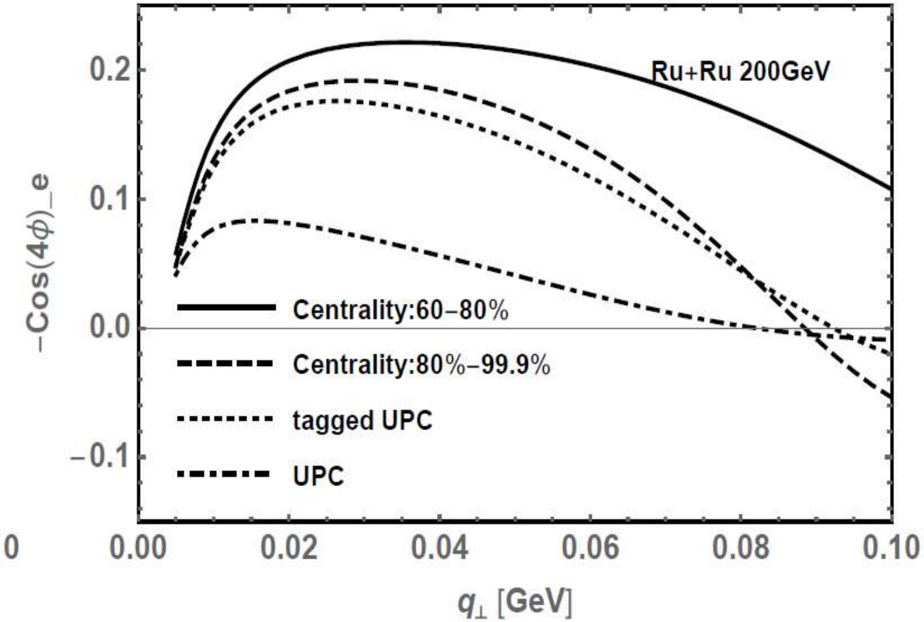


Numerical results I

RHIC : $\sqrt{s} = 200$ GeV: Au-Au, Z=79, A=197,   Ru-Ru, Z=44, A=101

y integrate over[-1,1], $P_\perp$ integrate over [0.2GeV,0.4GeV]

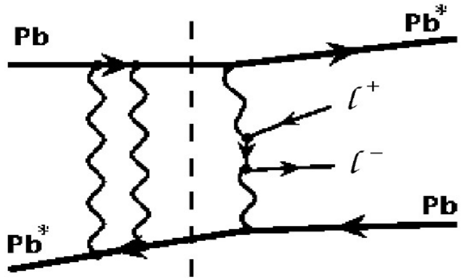




UPCs: $b > 2R_A$

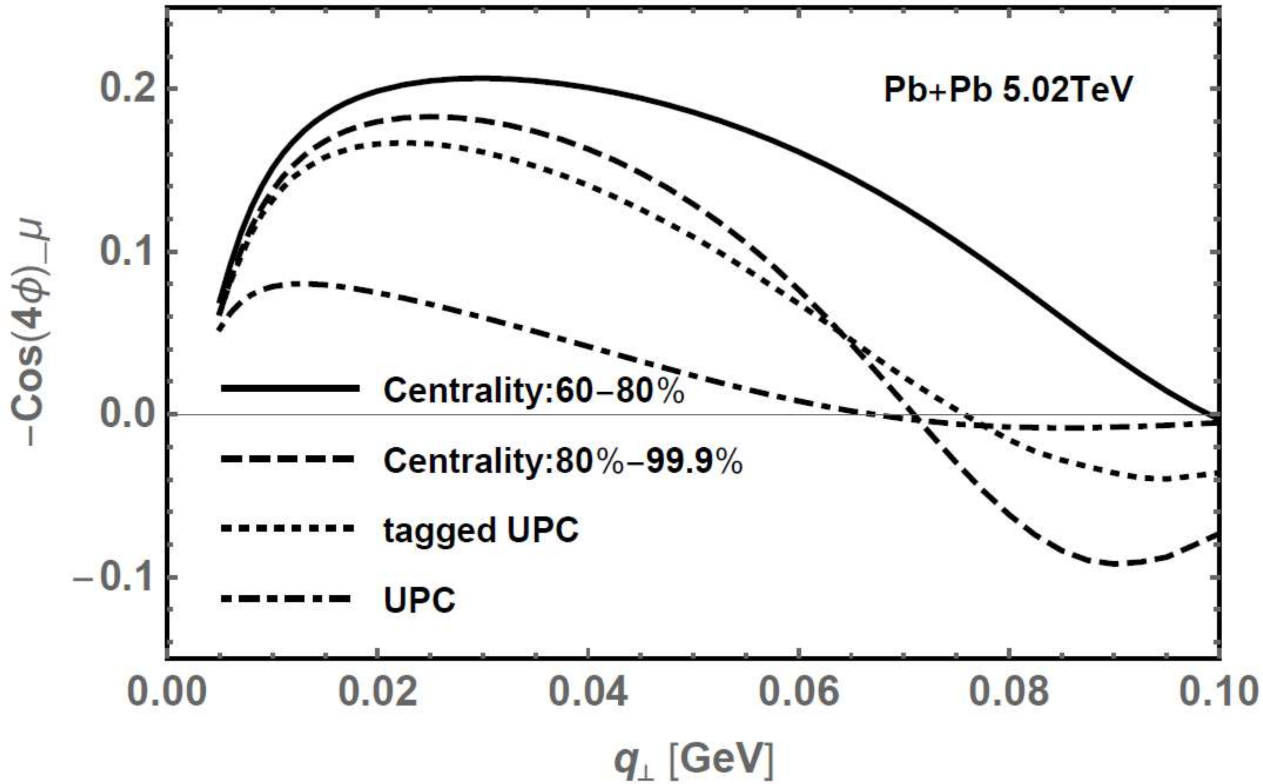
Tagged UPCs:

$$2\pi \int_{2R_A}^{\infty} b_\perp db_\perp P^2(b_\perp)\, d\sigma(b_\perp, \dots)$$



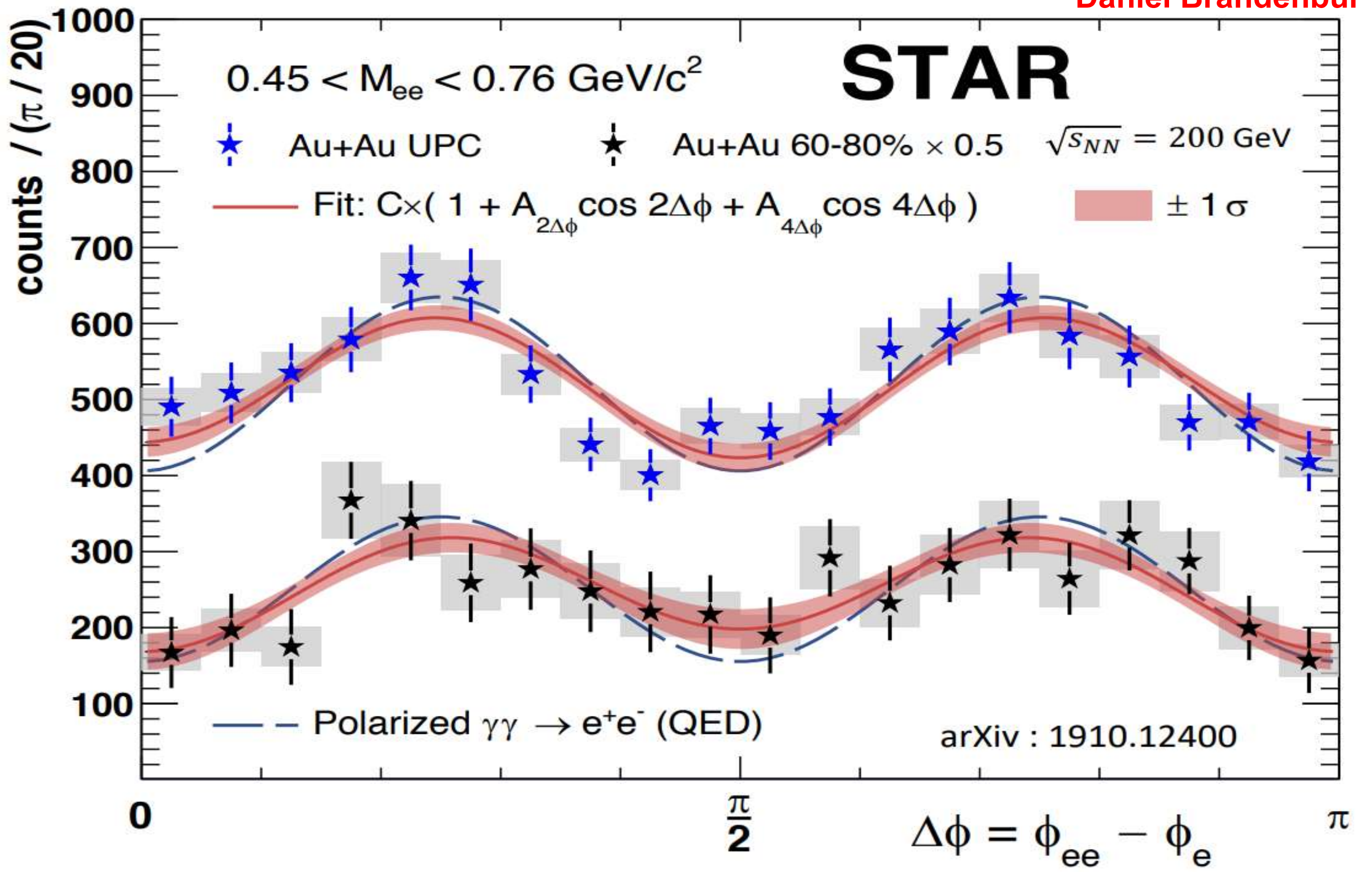
Numerical results II

LHC : $\sqrt{s} = 5.02$ TeV, Pb-Pb, Z=82, A=208
y integrate over[-1,1], $P_\perp$ integrate over [4GeV,45GeV]



Verified by STAR experiment

Daniel Brandenburg, QM 2019



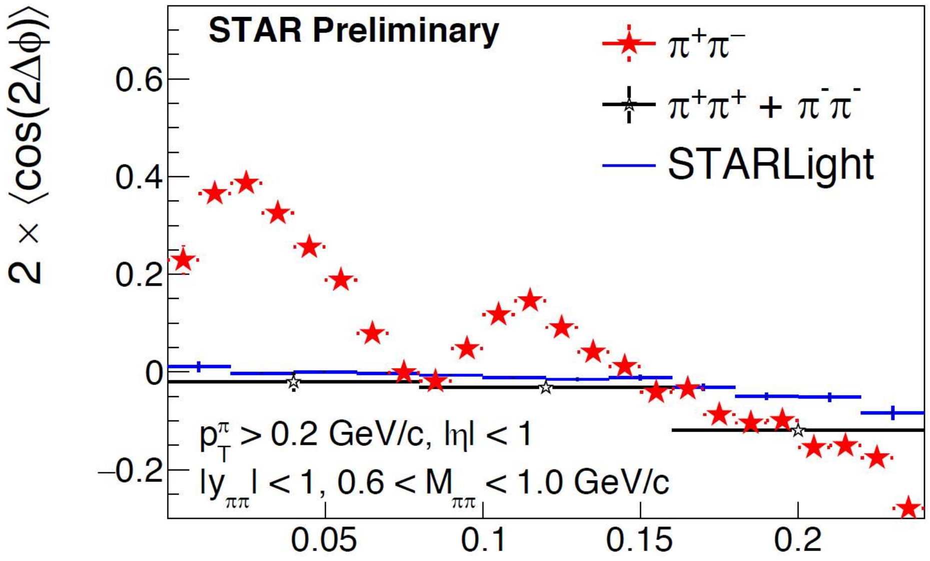
$0.45GeV^2<Q^2<0.76GeV^2$
$P_t>200MeV$
$|y|<1$
$q_t<100MeV$

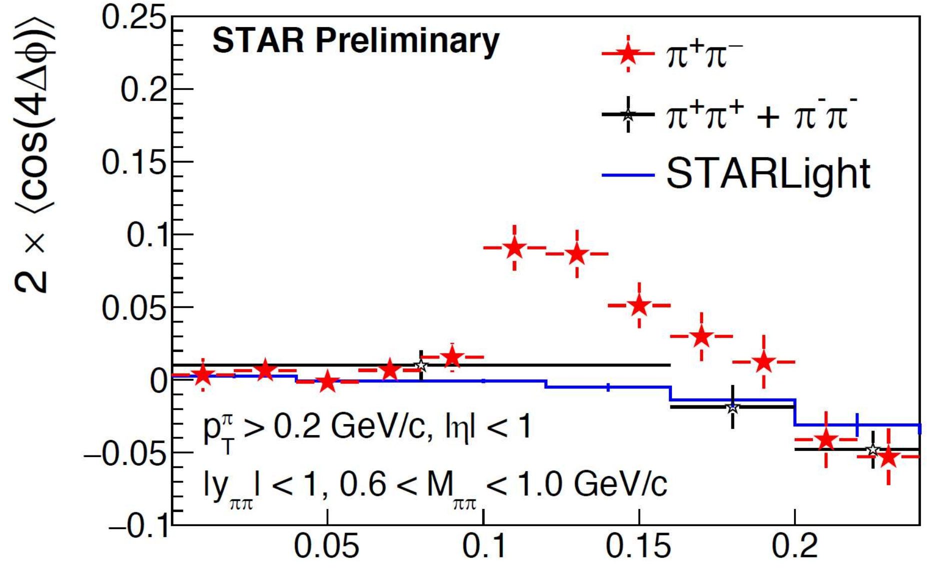
	Measured	QED calculation
Tagged UPC	16.8%±2.5%	16.5%
60%-80%	27%±6%	34.5%

As a probe to study QCD phenomenology

Photoproduction of the rho^0 production

Daniel Brandenburg, QM 2019





- linearly polarized photons
- coherent production

- Potential access to gluon Wigner distribution/GTMD **(for the first time)**

The same analysis applies to the QCD case.

Gluons are highly linearly polarized.

CGC is highly linearly polarized state

Metz & Zhou, 2011

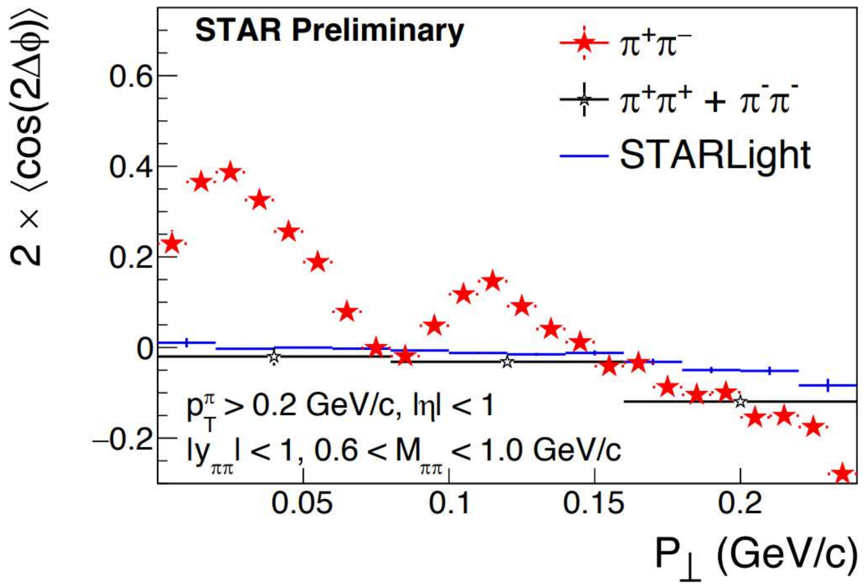
Summary

- QED problem is interesting in its own right.
- Set a baseline for QGP studies,

  e.g. v_4 from the initial state effect

Outlook

➢ Spin correlation: vector meson production mechanism



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➢ Use cos4ϕ asymmetry to study the Coulomb correction

Thank you for your attention.

Inputs for the photon TMDs

In the equivalent photon approximation (EPA),

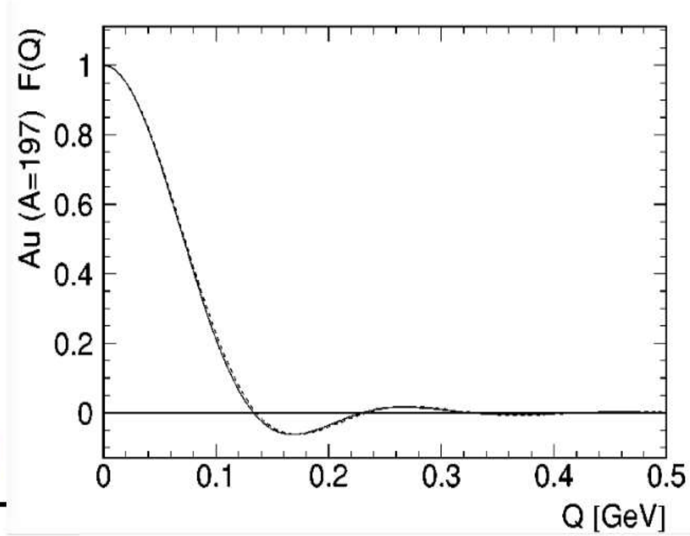
$$xf_1^{\gamma}(x,k_\perp^2) = xh_1^{\perp\gamma}(x,k_\perp^2) = \frac{Z^2\alpha_e}{\pi^2}k_\perp^2\left[\frac{F(k_\perp^2+x^2M_p^2)}{(k_\perp^2+x^2M_p^2)}\right]^2$$

Woods-Saxon form factor,

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

from STARlight MC,

$$F(|\vec{k}|) = \frac{4\pi\rho^0}{|\vec{k}|^3A}\left[\sin(|\vec{k}|R_A) - |\vec{k}|R_A\cos(|\vec{k}|R_A)\right]\frac{1}{a^2\vec{k}^2+1}$$



Klein, Nystrand,PRC60,014903