Czech Technical University in Prague
Faculty of Nuclear Sciences and Physical Engineering
Department of Physics

The $\cos(2\phi)$ azimuthal asymmetry in ρ^0 meson production in ultraperipheral heavy ion collisions

Hongxi Xing, Cheng Zhang, Jian Zhou and Ya-Jin Zhou, arxiv:2006.06206v2

Jan Cepila

Miniworkshop on Diffraction and Ultraperipheral Collisions, Decin 15.9.2020

What is it good for..

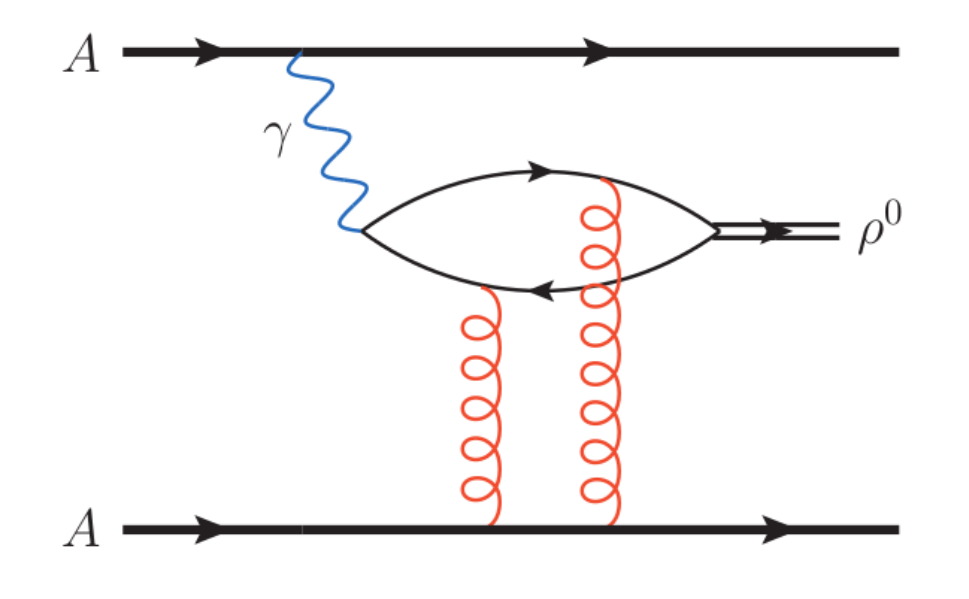
- **They want to study the spin of the meson wrt. photon in vector meson production**
- They do it by studying ρ_0 transverse momentum and, subsequently, the decay product transverse momentum in diffractive meson production
- Let's assume ϕ is the angle between the transverse momentum of ϕ and one of the produced pions from $\rho^0 \to \pi^+\pi^-$
- Angular distribution of decayed pions contains information about polarization of ρ^0, so observing angular correlation between π and ρ transverse momentum converts into correlation between transverse momentum and spin of ρ
- The incident photon is linearly polarized along the transverse momentum
- The correlation between polarization of photon and its transverse momentum in preserved through the rescattering to that of a vector meson. So, analyzing the vector meson polarization we get an information about original photon spin structure

Description of the scattering

- An almost real photon develops into a quark-antiquark pair, that after scattering off the hadron forms a vector meson
- We presume that at high energies the transverse positions of quark and antiquark is not altered during the scattering
- Scattering amplitude is

$$A(\Delta) = i \int d^2b e^{ib\Delta} \int \frac{d^2r}{4\pi} \int_0^1 dz \psi^{\gamma \to q\bar{q}}(r,z,\varepsilon^\gamma) N(r,b) \psi^{*,V \to q\bar{q}}(r,z,\varepsilon^V)$$

$\Delta = \sqrt{-t} = p_T^V$ is the nucleus recoil transverse momentum, ε^γ and ε^V are polarization vectors of a photon and a vector meson



Color dipole parametrizations

- Dipole cross section on nucleus is

$$N^A(r,b) = 1 - e^{-2\pi B_p A T_A(b) N(r)}$$

$$N^{GBW}(r) = 1 - e^{-\frac{1}{4}Q_s^2(x) r^2}$$

- Incoherent (diffractive) vector meson production is

$$\sigma \sim \langle |A|^2 \rangle_N - |\langle A \rangle_N|^2$$

- Expanding Glauber to binomial series and integrating out IPSat impact parameter component one gets

$$|A(\Delta)|^2 \sim A(2\pi B_p)^2 e^{-B_p \Delta^2} \int d^2 b T_A(b) \left| \int \frac{d^2 r}{4\pi} \int_0^1 dz \psi^{\gamma \to q\bar{q}}(r,z,\varepsilon^\gamma) \right.$$
$$\left. \psi^{*,V \to q\bar{q}}(r,z,\varepsilon^V) N(r) e^{-2\pi(A-1) B_p T_A(b) N(r)} \right|^2$$

The polarized wave function

- The photon wave function is

$$\Psi^{\gamma\to q\bar{q}}(r_\perp, z, \epsilon_\perp^\gamma) = \frac{ee_q}{2\pi}\delta_{aa'}\Bigg\{\delta_{\sigma,-\sigma'}\left[(1-2z)i\epsilon_\perp^\gamma\cdot r_\perp + \sigma\epsilon_\perp^\gamma\times r_\perp\right]\frac{-1}{|r_\perp|}\frac{\partial}{\partial|r_\perp|} + \delta_{\sigma\sigma'}m_q(\epsilon_\perp^{\gamma,1} + i\sigma\epsilon_\perp^{\gamma,2})\Bigg\}K_0(|r_\perp|e_f),$$

where $\varepsilon^\gamma = \vec{k}_T/|\vec{k}_T|$ - polarization of a photon is in transverse momentum, σ are q and $\bar{q}$ helicities, a,a' are color indices

- Transversely polarized vector meson wave function (Gauss-LC) is

$$\Psi^{V\to q\bar{q}}(r_\perp, z, \epsilon_\perp^V) = \delta_{aa'}\Bigg\{\delta_{\sigma,-\sigma'}\left[(2z-1)i\epsilon_\perp^V\cdot r_\perp + \sigma\epsilon_\perp^V\times r_\perp\right]\frac{-1}{|r_\perp|}\frac{\partial}{\partial|r_\perp|} + \delta_{\sigma\sigma'}m_q(\epsilon_\perp^{V,1} + i\sigma\epsilon_\perp^{V,2})\Bigg\}\Phi(|r_\perp|, z)$$

The unpolarized wave function

- After the convolution we get

$$\sum_{a,a',\sigma,\sigma'} \Psi^{\gamma\to q\bar{q}}\Psi^{V\to q\bar{q}*} = \frac{ee_q}{\pi} N_c e^{i(z-\frac{1}{2})\Delta_\perp\cdot r_\perp}\left\{\frac{1}{r_\perp^2}\left[\frac{\partial}{\partial|r_\perp|}\Phi^*(|r_\perp|,z)\right]\left[\frac{\partial}{\partial|r_\perp|}K_0(|r_\perp|e_f)\right]\right.$$
$$\times\left[(2z-1)^2(\epsilon_\perp^{V*}\cdot r_\perp)(\epsilon_\perp^\gamma\cdot r_\perp)+(\epsilon_\perp^{V*}\times r_\perp)(\epsilon_\perp^\gamma\times r_\perp)\right]$$
$$\left.+m_q^2(\epsilon_\perp^\gamma\cdot\epsilon_\perp^{V*})\Phi^*(|r_\perp|,z)K_0(|r_\perp|e_f)\right\}.$$

- and doing some algebra we finally get

$$\sum_{a,a',\sigma,\sigma'} \Psi^{\gamma\to q\bar{q}}\Psi^{V\to q\bar{q}*} = (\epsilon_\perp^{V*}\cdot\epsilon_\perp^\gamma)\frac{ee_q}{2\pi}2N_c\int\frac{d^2r_\perp}{4\pi}\,N(r_\perp,b_\perp)\left\{\left[z^2+(1-z)^2\right]\right.$$
$$\left.\times\frac{\partial\Phi^*(|r_\perp|,z)}{\partial|r_\perp|}\frac{\partial K_0(|r_\perp|e_f)}{\partial|r_\perp|}+m_q^2\Phi^*(|r_\perp|,z)K_0(|r_\perp|e_f)\right\},$$

- This is what we know from regular unpolarized VM case except for factor $\varepsilon^\gamma\cdot\varepsilon^V=\cos\phi$ - this says that the polarization state survives after eikonal rescattering

The cross section

- Now we embed the amplitude into the cross section formula. Note that the delta function means the conservation of transverse momentum in VM vertex

$$\frac{d\sigma}{d^2q_\perp dY} = \frac{1}{4\pi^2}\int d^2\Delta_\perp d^2k_\perp x f(x,k_\perp)\delta^2(k_\perp+\Delta_\perp-q_\perp)\langle|\mathcal{A}|^2\rangle_N,$$

- k_T is the momentum of a photon, Δ is the recoil of the hadron and q_T is the momentum of the meson
- $f(x,k_T)$ is the TMD of a photon within equivalent photon approximation
- Variation if over positions of nucleons inside nucleus (no idea how they do it)
- We substitute for the variation (somehow) and we get

The cross section

$$\frac{d\sigma}{d^2q_\perp dY} = \frac{\mathcal{C}}{4\pi^2}\int d^2\Delta_\perp d^2k_\perp x f(x,k_\perp)\delta^2(k_\perp+\Delta_\perp-q_\perp)(\epsilon_\perp^{V*}\cdot\hat{k}_\perp)^2$$
$$\times\left[|\mathcal{A}_{co}(\Delta_\perp)|^2+\int d^2b_\perp T_A(b_\perp)|\mathcal{A}_{in}(\Delta_\perp)|^2\right]$$
$$=\frac{\mathcal{C}}{8\pi^2}\int d^2\Delta_\perp x f(x,q_\perp-\Delta_\perp)\left\{1+\cos 2\phi\left[2(\hat{q}_\perp\cdot\hat{k}_\perp)^2-1\right]\right\}$$

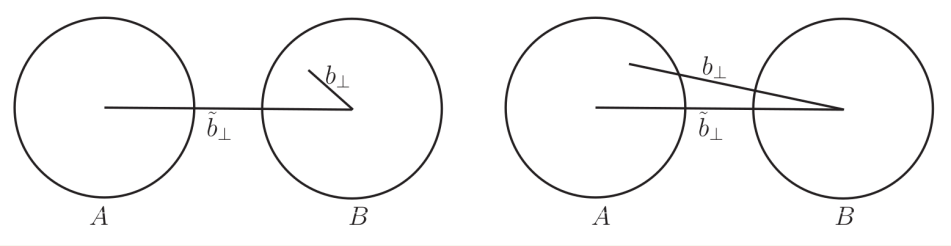
$$\times\left[|\mathcal{A}_{co}(\Delta_\perp)|^2+\int d^2b_\perp T_A(b_\perp)|\mathcal{A}_{in}(\Delta_\perp)|^2\right],$$

$$\mathcal{A}_{co}(\Delta_\perp)=\int d^2b_\perp e^{-i\Delta_\perp\cdot b_\perp}\int\frac{d^2r_\perp}{4\pi}\,N(r_\perp,b_\perp)[\Phi^*K](r_\perp),$$
$$\mathcal{A}_{in}(\Delta_\perp)=\sqrt{A}2\pi B_p e^{-B_p\Delta_\perp^2/2}\left[\int\frac{d^2r_\perp}{4\pi}\mathcal{N}(r_\perp)e^{-2\pi(A-1)B_pT_A(b_\perp)\mathcal{N}(r_\perp)}[\Phi^*K](r_\perp)\right]$$

$$[\Phi^*K](r_\perp)=\frac{N_c e e_q}{\pi}\int_0^1 dz\left\{m_q^2\Phi^*(|r_\perp|,z)K_0(|r_\perp|e_f)+\left[z^2+(1-z)^2\right]\right.$$
$$\left.\times\frac{\partial\Phi^*(|r_\perp|,z)}{\partial|r_\perp|}\frac{\partial K_0(|r_\perp|e_f)}{\partial|r_\perp|}\right\}.$$

The cross section

- Now we have the total cross section for γA collision. We have to convolute it with the flux of photons F from the other nucleus



$$\mathcal{M}(Y,\tilde{b}_\perp,b_\perp) \propto \left[F_A(Y,b_\perp-\tilde{b}_\perp)N_B(Y,b_\perp)+N_A(-Y,b_\perp-\tilde{b}_\perp)F_B(-Y,b_\perp)\right],$$

- The problem is that this formula for the probability amplitude for producing a meson at the position b_T inside two nuclei is in position space and our cross section is in momentum space
- We transform it first to the momentum space

$$\mathcal{M}(Y,\tilde{b}_\perp,q_\perp) = \int d^2b_\perp e^{-ib_\perp\cdot q_\perp}\mathcal{M}(Y,\tilde{b}_\perp,b_\perp) \propto \int \frac{d^2k_\perp}{(2\pi)^2}\frac{d^2\Delta_\perp}{(2\pi)^2}(2\pi)^2\delta^2(q_\perp-\Delta_\perp-k_\perp)$$
$$\times\left\{F_A(Y,k_\perp)N_B(Y,\Delta_\perp)e^{-i\tilde{b}_\perp\cdot k_\perp}+F_B(-Y,k_\perp)N_A(-Y,\Delta_\perp)e^{-i\tilde{b}_\perp\cdot\Delta_\perp}\right\},$$

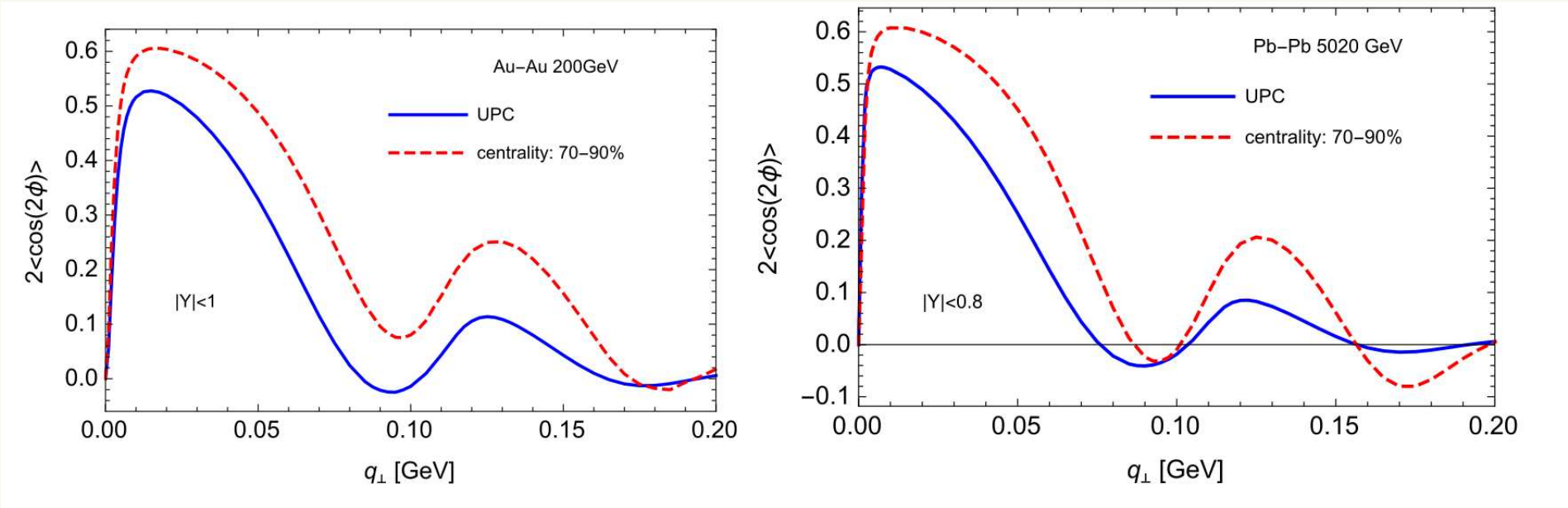
- This we insert into the master formula to get

Nuclear dipole cross section

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

$$|F(Y,k_T)|^2 = xf(x,k_T)$$

Results


Au−Au 200GeV
UPC
centrality: 70−90%
|Y|<1
2<cos(2ϕ)>
q⊥ [GeV]
Pb−Pb 5020 GeV
UPC
centrality: 70−90%
|Y|<0.8
2<cos(2ϕ)>
q⊥ [GeV]