Entanglement Enabled Intensity Interferometry (E^2I^2): A New Perspective on Vector Meson Production in UPC

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Work in preparation, with Sanjin Benić, Adrian Dumitru, Raju Venugopalan

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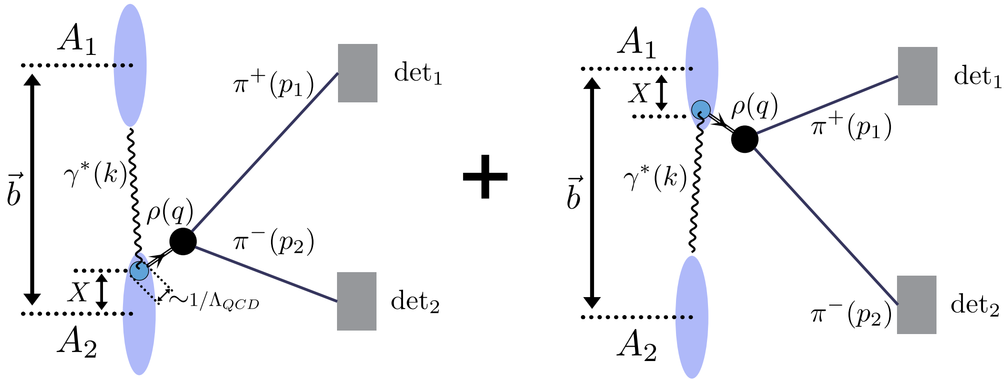
ρ^0 production in UPC



linearly polarized(Weizsacker-Williams) photon + nuclear target $\rightarrow \rho$ in **mid-rapidity**

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Angular correlation of $\pi^+\pi^-$

- $\boldsymbol{p}_1, \boldsymbol{p}_2$ are $\pi^+\pi^-$ **transverse momenta**

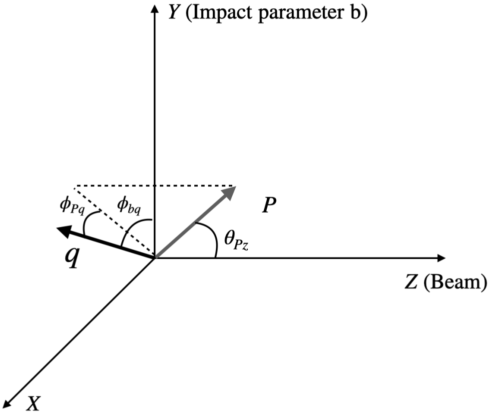
$$\begin{aligned} \boldsymbol{q} &= \boldsymbol{p}_1 + \boldsymbol{p}_2 \\ \boldsymbol{P} &= (\boldsymbol{p}_1 - \boldsymbol{p}_2)/2 \end{aligned}$$

-

$$\frac{dN}{d\boldsymbol{P}^2 d\boldsymbol{q}^2 d\phi_{Pq}} \propto C_0(|\boldsymbol{p}|, |\boldsymbol{P}|) + C_2(|\boldsymbol{p}|, |\boldsymbol{P}|) \cos(2\phi_{Pq})$$

- **The observable**:

$$2\langle \cos(2\phi_{Pq}) \rangle = \frac{C_2(|\boldsymbol{q}|)}{C_0(|\boldsymbol{q}|)}$$



Decay axis and definition of angles

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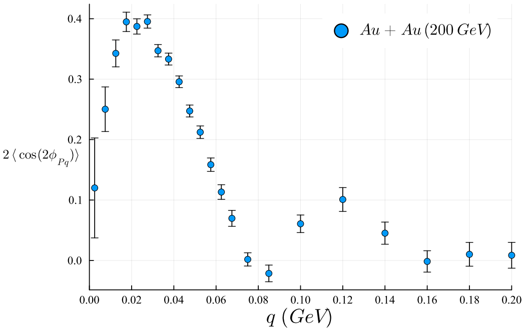
Goals

1. **Understand data**
   - Dip at $q = 0$, Peaks around $q = 20$ and $120\,\mathrm{Mev}$
2. **Universal, model independent formulation**
   - Phase information are model independent $\Rightarrow$ signal exists or not
   - Matrix elements are model dependent $\Rightarrow$ shape of the signal
   - For model dependent formulation, see:
     H. Mäntysaari et al., PRC (2024)
     Y. Hagiwara et al., PRD(2021)
     H. Xing et al., JHEP(2020)
3. **Easy to generalize to other process/channels.**
4. **Inspired by Hanbury Brown and Twiss intensity Interferometry**



Sci.Adv. 9 (2023) 1, eabq3903
arxiv.2204.01625

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HBT Intensity Interferometry (I): Classical formulation

- **Stochastic source**: $\langle A_i \rangle = 0 \ (i = 1, 2)$

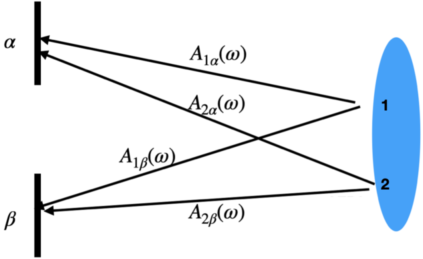
$$\langle A_{1\alpha} \rangle \propto \int_0^{2\pi} \frac{d\theta_1}{2\pi} e^{i\theta_1} = 0$$

- **No amplitude interference**
  $\langle A_i A_j \rangle = \langle A_i \rangle \langle A_j \rangle = 0 \ (i \neq j)$
-

$$A_\alpha = A_{1\alpha} + A_{2\alpha}$$
$$A_\beta = A_{1\beta} + A_{2\beta}$$
$$I_{\alpha/\beta} = |A_{\alpha/\beta}|^2$$

- **Density-density correlation**:

$$\langle I_\alpha I_\beta \rangle - \langle I_\alpha \rangle \langle I_\beta \rangle = 2\,\mathrm{Re}\Big\{ \langle A_{1\alpha} A^*_{2\alpha} A^*_{1\beta} A_{2\beta} \rangle \Big\}$$



Random locations at **stochastic** source emit photon with **same frequency** detected by two detector α and β

more details see hep-ph/9804026 by Gordon Baym

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HBT Intensity Interferometry (II): Quantum formulation

- **Final state $|\phi\rangle$**

$$|\phi\rangle = \Big(A_{1\alpha}A_{2\beta} + A_{2\alpha}A_{1\beta}\Big)|\omega^{\alpha}, \omega^{\beta}\rangle$$

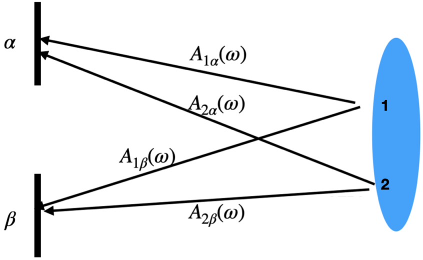
- **$\langle\phi|\phi\rangle$ contains the same correlation**

$$\langle\phi|\phi\rangle - |A_{1\alpha}|^2|A_{2\beta}|^2 - |A_{2\alpha}|^2|A_{1\beta}|^2$$
$$= 2\,\mathrm{Re}\Big\{\langle A_{1\alpha}A^*_{2\alpha}A^*_{1\beta}A_{2\beta}\rangle\Big\}$$

- **If $\omega_1 \neq \omega_2$,**

$$|\psi\rangle = A_{1\alpha}A_{2\beta}|\omega_1\rangle^{\alpha} \otimes |\omega_2\rangle^{\beta} + A_{2\alpha}A_{1\beta}|\omega_2\rangle^{\alpha} \otimes |\omega_1\rangle^{\beta}$$

$\langle\psi|\psi\rangle$ contains no such correlation term due to orthogonality of two possible final states.



Random locations at **stochastic** source emit photon with **same frequency** detected by two detector α and β

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Entanglement Enabled Intensity Interferometry

$$|\psi\rangle = A_{1\alpha}A_{2\beta}|\omega_1\rangle^{\alpha} \otimes |\omega_2\rangle^{\beta} + A_{2\alpha}A_{1\beta}|\omega_2\rangle^{\alpha} \otimes |\omega_1\rangle^{\beta}$$

If we apply an **unitary transformation** that mix the two frequencies, $U = U_1 \otimes U_2$

$$U_1|\omega_1\rangle = \cos(\theta)|\omega_1\rangle + \sin(\theta)e^{i\omega_0}|\omega_2\rangle\ ,$$
$$U_2|\omega_2\rangle = \sin(\theta)e^{-i\omega_0}|\omega_1\rangle + \cos(\theta)|\omega_2\rangle$$

Then use a filter (**projection operator** $\Pi = |\omega_1\rangle^{\alpha}\langle\omega_1|^{\alpha} \otimes |\omega_1\rangle^{\beta}\langle\omega_1|^{\beta}$), to rotate the two distinct final states into one common state,

$$\Pi U|\psi\rangle = \cos(\theta)\sin(\theta)e^{-i\omega_0}\Big(A_{1\alpha}A_{2\beta} + A_{2\alpha}A_{1\beta}\Big)|\omega_1\rangle^{\alpha} \otimes |\omega_1\rangle^{\beta}$$

Now its standard HBT, and interference term has been recovered in $\Big|\Big(A_{1\alpha}A_{2\beta} + A_{2\alpha}A_{1\beta}\Big)\Big|^2$

J.Cotler, F. Wilczek, arXiv:1502.02477

J. Cotler, F. Wilczek, V. Borish, arXiv:1607.05719v2, Annals of Physics, 424 (2021) 168346

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E^2I^2 in UPC

- **Source $\Rightarrow$ nuclear target excited by photon**
- **Final state (linearly polarized ρ)**

$$|\pi^+(\boldsymbol{p}_1)\pi^-(\boldsymbol{p}_2)\rangle = M_{\lambda_\rho=1}(\boldsymbol{p}_1,\boldsymbol{p}_2)|\lambda=1\rangle + M_{\lambda_\rho=-1}(\boldsymbol{p}_1,\boldsymbol{p}_2)|\lambda=-1\rangle + \cancel{M_{\lambda_\rho=0}(\boldsymbol{p}_1,\boldsymbol{p}_2)|\lambda=-1\rangle}$$

- **Combine unitary transformation and projection into $\Pi U = \hat{T}_{\rho\to\pi^+\pi^-}$,**

$$\langle\rho(\boldsymbol{q})|\hat{T}_{\rho\to\pi^+\pi^-}|\psi\rangle \propto M_{\lambda_\rho=1}(\boldsymbol{p}_1,\boldsymbol{p}_2) + M_{\lambda_\rho=-1}(\boldsymbol{p}_1,\boldsymbol{p}_2)$$

This interference is the key to the signal!

- **Why formulate in this way instead of taking a model and do the calculation?**
  - Perturbative models might not be reliable in non-perturbative kinematic region
  - Physics is more transparent

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Coordinate Space ($\boldsymbol{x}_1 = \boldsymbol{b}$, $\boldsymbol{x}_2 = \boldsymbol{0}$)

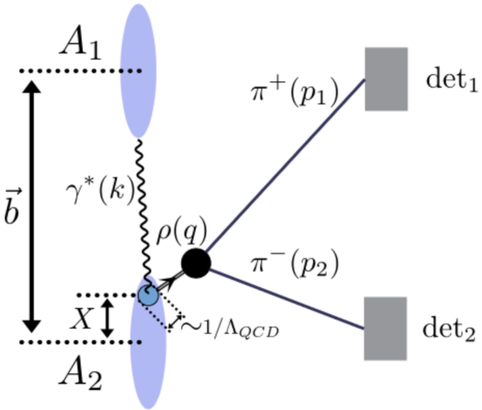

Figure: M_{12}

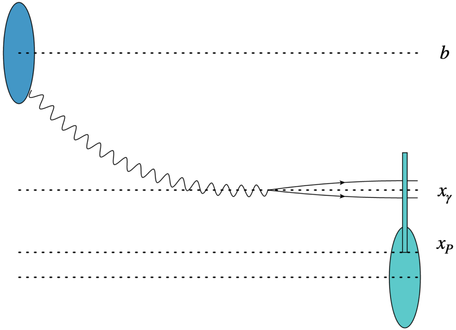

Figure: M_{12} in coordinate space

$$M^{\lambda_\rho}_{12\to\rho}(\boldsymbol{q},\boldsymbol{b}) = \int d^2\boldsymbol{x}_p \int d^2\boldsymbol{x}_\gamma \int d^2\boldsymbol{r}\; e^{i\boldsymbol{q}\cdot\boldsymbol{x}_\gamma}\,\mathcal{F}(\boldsymbol{x}_\gamma - \boldsymbol{b})\,P(\boldsymbol{x}_p, -\boldsymbol{r})\,\bar{M}^{\lambda_\rho}_{\gamma\mathbb{P}\to\rho}(\boldsymbol{x}_\gamma - \boldsymbol{x}_p, \boldsymbol{r})$$

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Photon-Pomeron fusion

Our convention has $\boldsymbol{x}_1 = \boldsymbol{b}$, $\boldsymbol{x}_2 = \boldsymbol{0}$.

$$M^{\lambda\rho}_{12\to\rho}(\boldsymbol{q},\boldsymbol{b}) = \int d^2\boldsymbol{x}_p \int d^2\boldsymbol{x}_\gamma \int d^2\boldsymbol{r}\; e^{i\boldsymbol{q}\cdot\boldsymbol{x}_\gamma} \mathcal{F}(\boldsymbol{x}_\gamma - \boldsymbol{b}) \bar{M}^{\lambda\rho}_{\gamma\mathbb{P}\to\rho}(\boldsymbol{x}_\gamma - \boldsymbol{x}_p, \boldsymbol{r}) P(\boldsymbol{x}_p, -\boldsymbol{r})$$
$$= \int \frac{d^2\boldsymbol{k}}{(2\pi)^2} e^{i\boldsymbol{k}\cdot\boldsymbol{b}} \frac{d^2\boldsymbol{\Delta}}{(2\pi)^2} \frac{d^2\boldsymbol{K}}{(2\pi)^2} (2\pi)^2 \delta^{(2)}(\boldsymbol{q} - \boldsymbol{\Delta} - \boldsymbol{k}) \mathcal{F}(\boldsymbol{k}) \bar{M}^{\lambda\rho}_{\gamma\mathbb{P}\to\rho}(\boldsymbol{\Delta}, \boldsymbol{K}) P(\boldsymbol{\Delta}, \boldsymbol{K})$$

where the photon is originated from $\boldsymbol{x}_1 = \boldsymbol{b}$

$$\mathcal{F}(\boldsymbol{x}_\gamma - \boldsymbol{b}) = \int \frac{d^2\boldsymbol{k}}{(2\pi)^2} e^{-i(\boldsymbol{x}_\gamma - \boldsymbol{b})\cdot\boldsymbol{k}} \mathcal{F}(\boldsymbol{k})$$

by the same logic,

$$M^{\lambda\rho}_{21\to\rho}(\boldsymbol{q},\boldsymbol{b}) = -\int d^2\boldsymbol{x}_p \int d^2\boldsymbol{x}_\gamma \int d^2\boldsymbol{r}\; e^{i\boldsymbol{q}\cdot\boldsymbol{x}_\gamma} \mathcal{F}(\boldsymbol{x}_\gamma) \bar{M}^{\lambda\rho}_{\gamma\mathbb{P}\to\rho}(\boldsymbol{x}_\gamma - \boldsymbol{x}_p, \boldsymbol{r}) P(\boldsymbol{x}_p - \boldsymbol{b}, -\boldsymbol{r})$$
$$= -\int \frac{d^2\boldsymbol{k}}{(2\pi)^2} e^{i\boldsymbol{\Delta}\cdot\boldsymbol{b}} \frac{d^2\boldsymbol{\Delta}}{(2\pi)^2} \frac{d^2\boldsymbol{K}}{(2\pi)^2} (2\pi)^2 \delta^{(2)}(\boldsymbol{q} - \boldsymbol{\Delta} - \boldsymbol{k}) \mathcal{F}(\boldsymbol{k}) \bar{M}^{\lambda\rho}_{\gamma\mathbb{P}\to\rho}(\boldsymbol{\Delta}, \boldsymbol{K}) P(\boldsymbol{\Delta}, \boldsymbol{K})$$

where $P(\boldsymbol{\Delta}, \boldsymbol{K})$ is the **Pomeron Form Factor**. More details, see arxiv:1808.02501

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ρ decay

- **Linearly polarized ρ along the photon polarization (S-channel helicity conservation)**: $\boldsymbol{\varepsilon}^{\rho} = \boldsymbol{\varepsilon}^{\gamma} = \boldsymbol{b}$

$$|\varepsilon^{\rho}\rangle = \frac{1}{\sqrt{2}}\left(e^{i\phi_{\boldsymbol{b}}}|\lambda = -1\rangle - e^{-i\phi_{\boldsymbol{b}}}|\lambda = +1\rangle\right)$$

- **The decay pattern of helicity states are,**

$$\langle\theta_P, \phi_P|T_{V\to\pi\pi}|\lambda\rangle = Y_1^{\lambda}(\theta_P, \phi_P)$$

where we have spherical harmonics $Y_1^{\pm 1}(\theta, \phi) = \mp\frac{1}{2}\sqrt{\frac{3}{2\pi}}\sin(\theta)e^{i\pm\phi}$

- **Interference between the two helicity state will give rise to**

$$e^{i\phi_{\boldsymbol{b}}}\sin(\theta_P)e^{-i\phi_{\boldsymbol{P}}} + e^{-i\phi_{\boldsymbol{b}}}\sin(\theta)e^{i\phi_{\boldsymbol{P}}} = 2\sin(\theta_P)\cos(\phi_{\boldsymbol{b}} - \phi_{\boldsymbol{P}})$$

In experiment, we take the ρ and $\pi^+\pi^-$ to be at central rapidity so $\theta_P = \frac{\pi}{2}$.

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The first peak

Interference around 20 Mev ($\boldsymbol{k} \sim \boldsymbol{q}$ or $\Delta \approx 0$)

$$M^{\lambda_\rho}_{12\to\rho}(\boldsymbol{q},\boldsymbol{b}) + M^{\lambda_\rho}_{21\to\rho}(\boldsymbol{q},\boldsymbol{b}) = \int \frac{d^2\boldsymbol{k}}{(2\pi)^2}(e^{i\boldsymbol{k}\cdot\boldsymbol{b}} - e^{i\boldsymbol{\Delta}\cdot\boldsymbol{b}})\frac{d^2\boldsymbol{\Delta}}{(2\pi)^2}\frac{d^2\boldsymbol{K}}{(2\pi)^2}(2\pi)^2\delta^{(2)}(\boldsymbol{q}-\boldsymbol{\Delta}-\boldsymbol{k})\mathcal{F}(\boldsymbol{k})\bar{M}^{\lambda_\rho}_{\gamma\mathbb{P}\to\rho}(\boldsymbol{\Delta},\boldsymbol{K})P(\boldsymbol{\Delta},\boldsymbol{K})$$

$$\approx(e^{i\boldsymbol{q}\cdot\boldsymbol{b}} - 1)\int \frac{d^2\boldsymbol{k}}{(2\pi)^2}\frac{d^2\boldsymbol{\Delta}}{(2\pi)^2}\frac{d^2\boldsymbol{K}}{(2\pi)^2}(2\pi)^2\delta^{(2)}(\boldsymbol{q}-\boldsymbol{k})\mathcal{F}(\boldsymbol{k})\bar{M}^{\lambda_\rho}_{\gamma\mathbb{P}\to\rho}(\boldsymbol{\Delta},\boldsymbol{K})P(\boldsymbol{\Delta},\boldsymbol{K})$$

- Interference results in **maxima** at $\phi_{qb} = 0$ or $\pi \Rightarrow \rho$ production prefer to align $\boldsymbol{q}$ with **impact parameter direction $\boldsymbol{b}$**
- From ρ decay, we had $\cos(\phi_b - \phi_P)^2$, also **maxima** at $\phi_b - \phi_P = 0$ or π. $\Rightarrow$ **Decay prefers to align $\boldsymbol{P}$ with $\boldsymbol{b}$**

This combination give rise to $\cos(2\phi_{Pq})$ correlation.

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Coherent

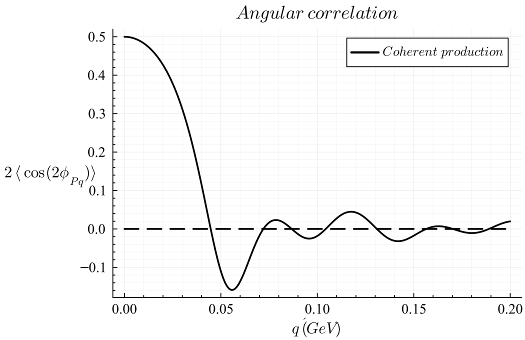

Figure: Angular correlation from coherent production alone

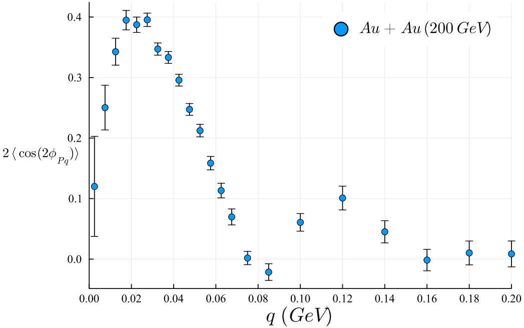

Figure: STAR data

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Coherent+incoherent (Toy model)

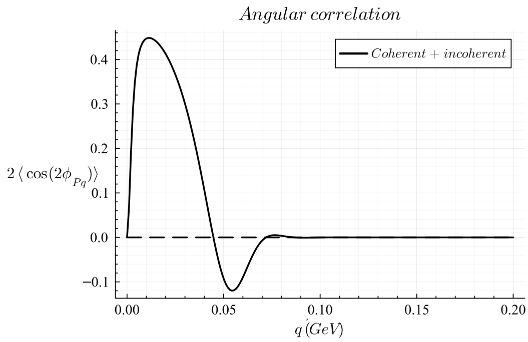

Figure: $\frac{d^2N_{\rm toy}^{\rm incoh.}}{dP_\perp^2\,dq_\perp^2\,d\phi_{\boldsymbol{P}_\perp\boldsymbol{q}_\perp}} = \frac{A_i/Q_0^2}{(1+q_\perp^2/Q_0^2)^2}$

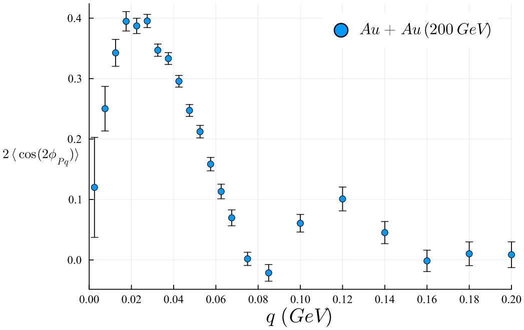

Figure: STAR data

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The second peak and more

In $\boldsymbol{\Delta} \sim \boldsymbol{q} \gg \boldsymbol{k}$ limit,

$$M^{\lambda\rho}_{12\to\rho}(\boldsymbol{q},\boldsymbol{b}) + M^{\lambda\rho}_{21\to\rho}(\boldsymbol{q},\boldsymbol{b}) = \int \frac{d^2\boldsymbol{k}}{(2\pi)^2}(e^{i\boldsymbol{k}\cdot\boldsymbol{b}} - e^{i\boldsymbol{\Delta}\cdot\boldsymbol{b}})\frac{d^2\boldsymbol{\Delta}}{(2\pi)^2}\frac{d^2\boldsymbol{K}}{(2\pi)^2}(2\pi)^2\delta^{(2)}(\boldsymbol{q}-\boldsymbol{\Delta}-\boldsymbol{k})\mathcal{F}(\boldsymbol{k})\bar{M}^{\lambda\rho}_{\gamma\mathbb{P}\to\rho}(\boldsymbol{\Delta},\boldsymbol{K})P(\boldsymbol{\Delta},\boldsymbol{K})$$

$$\approx(1 - e^{i\boldsymbol{q}\cdot\boldsymbol{b}})\int \frac{d^2\boldsymbol{k}}{(2\pi)^2}\frac{d^2\boldsymbol{\Delta}}{(2\pi)^2}\frac{d^2\boldsymbol{K}}{(2\pi)^2}(2\pi)^2\delta^{(2)}(\boldsymbol{q}-\boldsymbol{k})\mathcal{F}(\boldsymbol{k})\bar{M}^{\lambda\rho}_{\gamma\mathbb{P}\to\rho}(\boldsymbol{\Delta},\boldsymbol{K})P(\boldsymbol{\Delta},\boldsymbol{K})$$

However, for incoherent kinematics, it is not clear at this point whether the interference will survive. Furthermore:

1. Incoherent for nucleus but coherent at nucleon level.
2. Helicity flip:

$$\mathcal{M}_{\lambda\bar{\lambda}}(\boldsymbol{k},\boldsymbol{q}) = \delta_{\lambda,\bar{\lambda}}\widetilde{\mathcal{M}}^{nf}_{TT}(\boldsymbol{0},\boldsymbol{\Delta}) + \delta_{\lambda,-\bar{\lambda}}e^{i(\lambda-\bar{\lambda})\phi_\Delta}\widetilde{\mathcal{M}}^{f}_{TT}(\boldsymbol{0}_\perp,\boldsymbol{\Delta})$$

3. Spin dependent Pomeron: angular dependence in $P(\boldsymbol{\Delta},\boldsymbol{K})$.

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Generalizations and connection to EIC

- **One can also study through J/ψ. However, since J/ψ has multiple decay channels. It requires E^2I^2 analysis of different final states, with different unitary operator but same filter, which is the state of J/ψ.**

- **Study of Odderon through E^2I^2 of the decay product of $C = 1$ vector meson, for example χ_c. Pomeron form factor P with Odderon form factor iO. And change the coupling to $\gamma O \to \chi_c$**

- **In UPC, the interference effect between two nucleus was important, for $\epsilon_\gamma = \epsilon_V = b$ and correlate b with q. EIC has greater momentum transfer, which makes it ideal to study spin-dependent Pomeron and spin-flip process.**

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Thank you!

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