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Guilin, China

Quantum Entanglement of Particles With Zero Lifetime in Photoproduction Process

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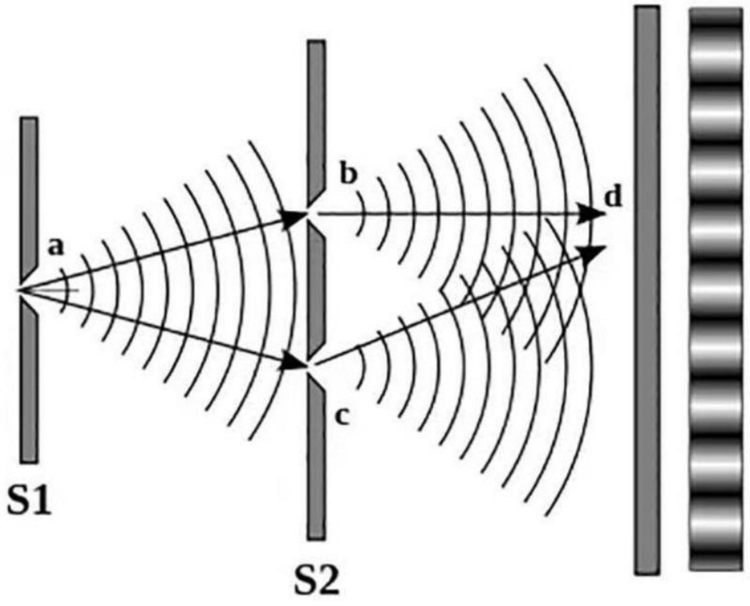
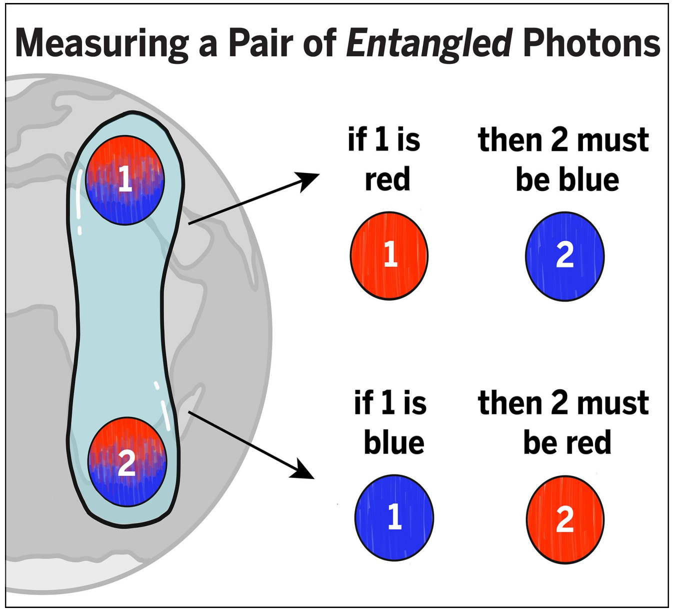
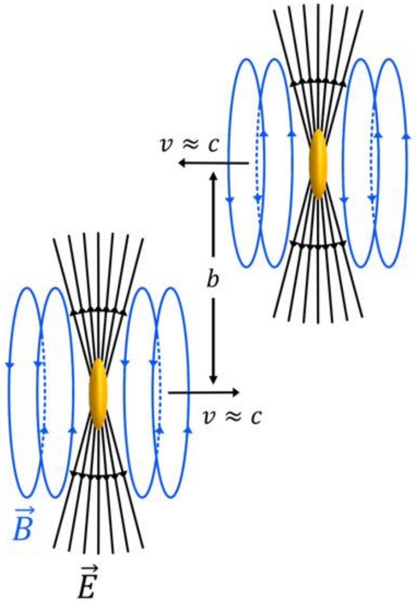
Quantum Interference and Entanglement



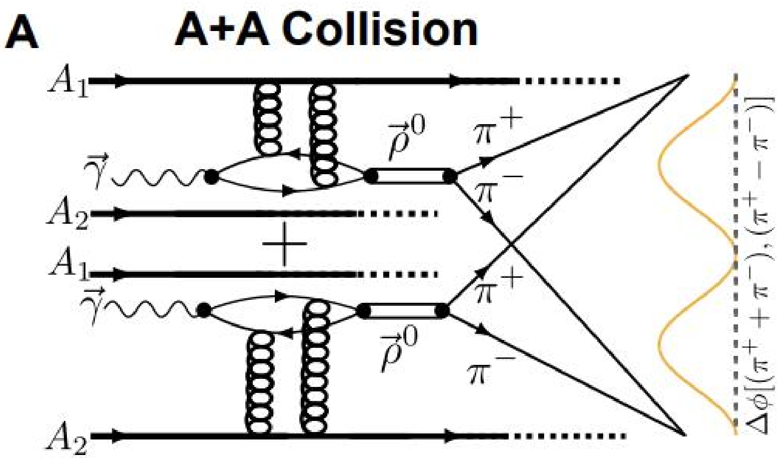


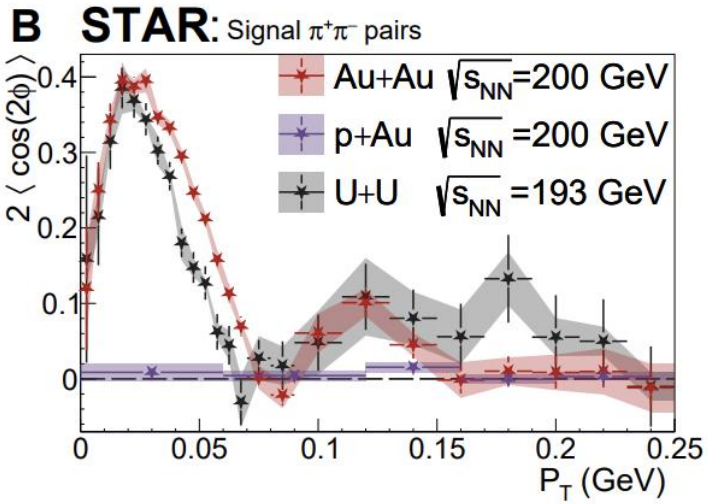
- Interference: The manifestation of the linear superposition of probablity amplutudes upon obseravtion.
- Entanglement: Entangled subsystems exhibit nonlocal correlations.
- How can these effects be studied in relativistic heavy-ion collisions?

Photoproduction Process



$$\vec{E} \perp \vec{B} \perp \vec{v}, \quad |\vec{E}| = |\vec{B}|$$

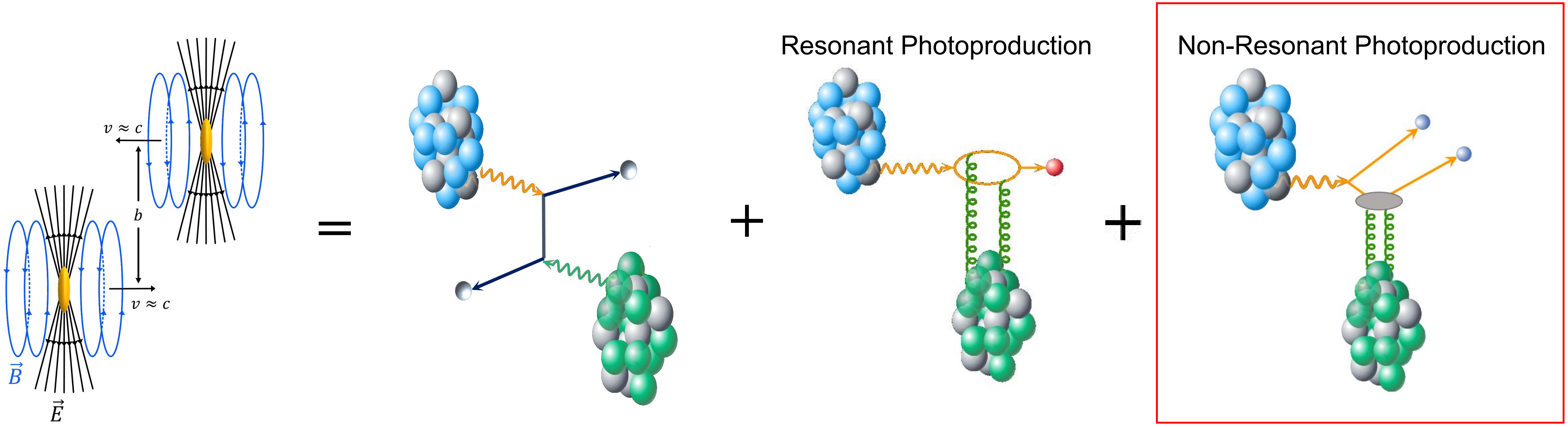




STAR, Sci.Adv. 9 (2023) 1, eabq3903

- Relativistic Heavy Ion Collider: A novel linearly polarized photon collider.
- Photoproduction in relativistic heavy-ion collisions: Fermi-scale double slit interfence.
- Polarized photon $\longrightarrow$ Entangled final products.

Non-Resonant Photoproduction

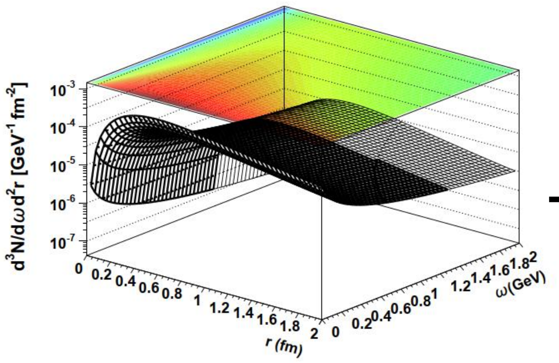


$\gamma\gamma$ process

γA process

- Drell-Soding mechanism: polarized photon fluctuate to a non-resonant particle pairs.
- Pronounced mass shape modulation: $\frac{d\sigma}{dM_{\pi^+\pi^-}} = \left| A_\rho \frac{\sqrt{M_{\pi\pi} M_\rho \Gamma_\rho}}{M_{\pi\pi}^2 - M_\rho^2 + i M_\rho \Gamma_\rho} + A_{non-res}(M_{\pi\pi}) \right|^2.$
- Zero lifetime entangled pair.

Theoretical Framework



Z. Cao and et al.,
Chin.Phys.C 43 (2019) 6, 064103

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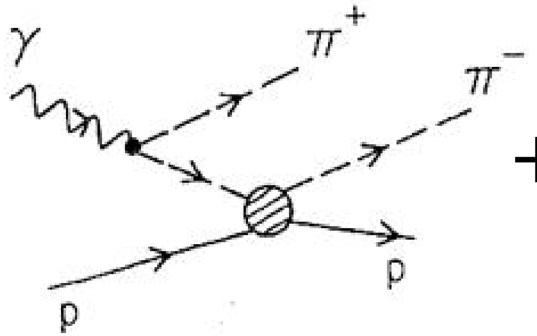

S. D. Drell,
Phys.Rev.Lett. 5 (1960) 278-281

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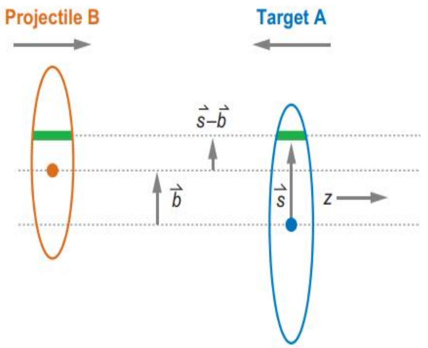
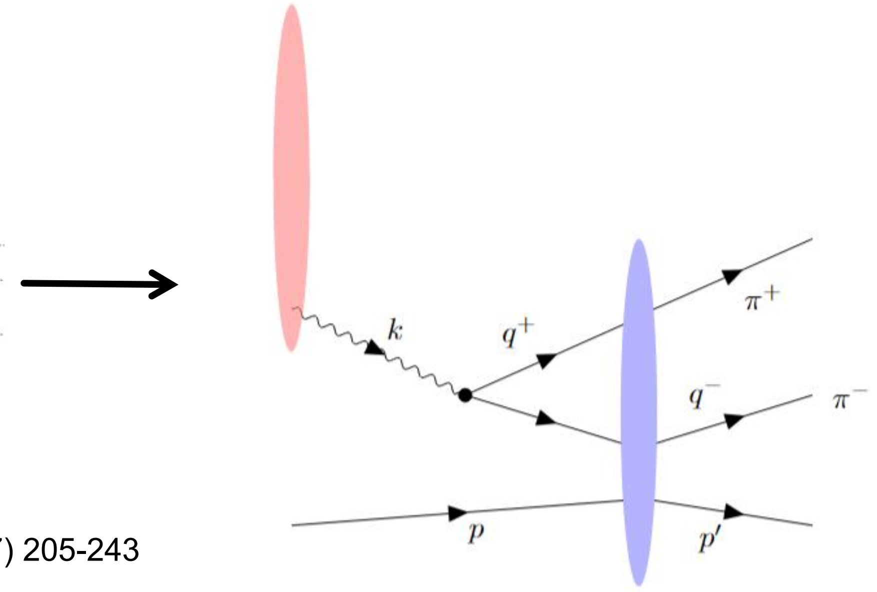
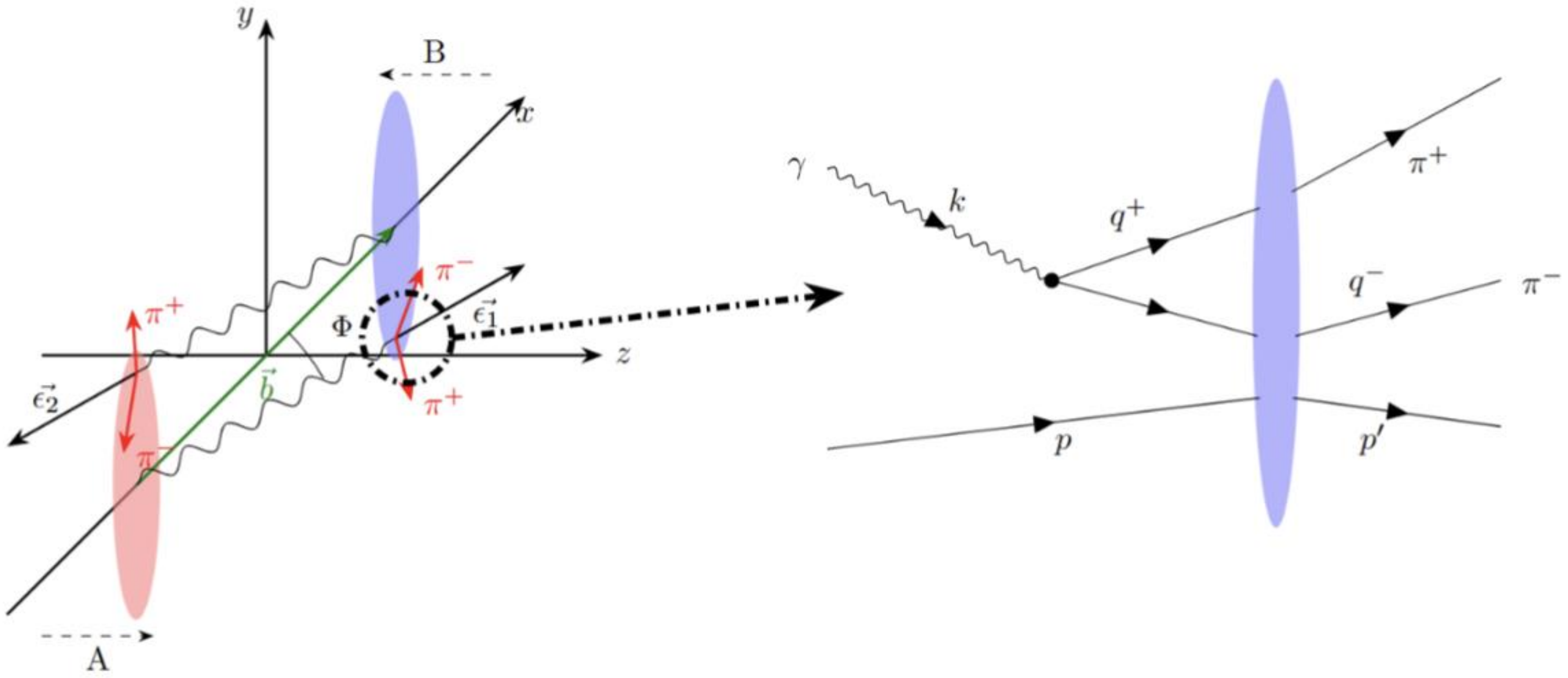


M. L. Miller and et al.,
Ann.Rev.Nucl.Part.Sci. 57 (2007) 205-243



- Calculating photon flux according to Equivalent photon approximation (EPA) model.
- Following Drell and Soding's methodology to calculate the cross section for $\gamma \mathrm{p} \to \pi^+\pi^-\mathrm{p}$.
- Calculating the cross section in γA case using the Glauber model.

The Amplitude for Drell-Soding Process



- Establish a right-handed coordinate system with the impact parameter as the x-axis and the beam direction as the z-axis.

- The amplitude:

$$\boxed{A(\vec{x}_\perp, M_{\pi^+\pi^-}) = |\vec{a}(\omega, \vec{x}_\perp)| \Gamma_{\gamma A \to \pi^+\pi^- A}(M_{\pi^+\pi^-}, \vec{x}_\perp)}$$

Equivalent Photon Approximation

$$\boxed{A(\vec{x}_\perp, M_{\pi^+\pi^-}) = |\vec{a}(\omega,\vec{x}_\perp)| \Gamma_{\gamma A\to\pi^+\pi^- A}(M_{\pi^+\pi^-},\vec{x}_\perp)}$$

- The equation for the electromagnetic vector potential:

$$\partial_\mu \partial^\mu A^\nu(x) = j^\nu(x) \longrightarrow A^\nu(k) = -\frac{1}{k^2} j^\nu(k) = -2\pi\delta(k\cdot u)\frac{\rho(\sqrt{-k^2})}{k^2}u^\nu = Zr(k)u^\nu$$

$$\begin{aligned} \overrightarrow{E_T}(k) &= -iA^0(k)\overrightarrow{k_T} \\ \overrightarrow{B_T}(k) &= \vec{v}\times\overrightarrow{E_T}(k) = -ivA^0(k)(-k_y, k_x, 0)^T \end{aligned} \longrightarrow \int_{-\infty}^{\infty} dt \int d\overrightarrow{x_\perp}\cdot\vec{S}(\vec{r},t) = \int_0^\infty d\omega\omega\cdot n(\omega)$$

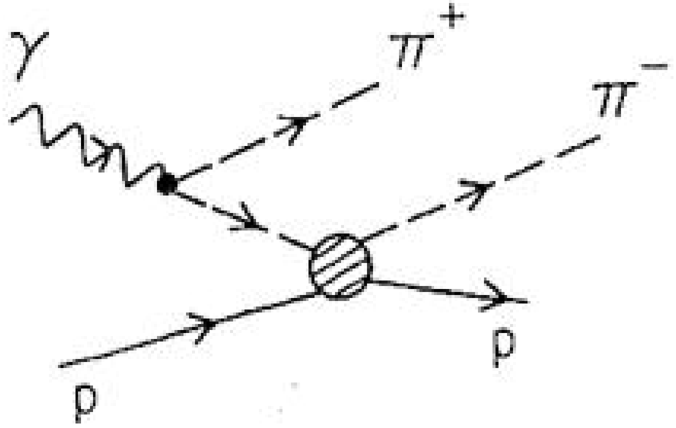
- $\vec{a}(\omega,\vec{x}_\perp)$ is the photon flux amplitude:

$$\vec{a}(\omega,\vec{x}_\perp) = \sqrt{n(\omega,\vec{x}_\perp)} = \sqrt{\frac{4Z^2\alpha}{\omega_\gamma}} \int \frac{d^2\vec{k}_{\gamma\perp}}{(2\pi)^2}\vec{k}_{\gamma\perp}\frac{F_\gamma(\vec{k}_{\gamma\perp})}{|\vec{k}_{\gamma\perp}|^2} e^{i\vec{x}_\perp\cdot\vec{k}_{\gamma\perp}}$$

$$\vec{k}_\gamma = \left(\vec{k}_{\gamma\perp}, \frac{\omega_\gamma}{\gamma_c}\right), \quad \omega_\gamma = \frac{1}{2}M_{\pi^+\pi^-}e^{\pm y}$$

F. Kruass and et al.
Prog.Part.Nucl.Phys. 39 (1997) 503-564

The scattering amplitude $\Gamma_{\gamma p\to\pi^+\pi^- p}(M_{\pi^+\pi^-})$



- The Jackson frame:

$$k = (0,0,k;k) \qquad p = (p_x,0,p_z;E) \qquad p' = (p_x,0,p_z';E')$$
$$q_\pm = (\pm q\sin\theta\cos\phi, \pm q\sin\theta\sin\phi, \pm q\cos\theta; \omega)$$

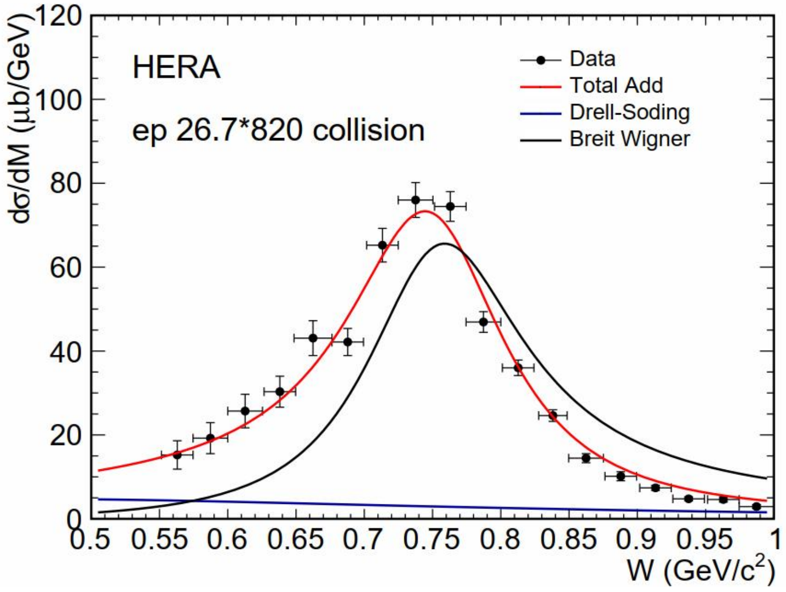
k: photon; $p(p')$: proton before (after) scattering; $q_\pm$: $\pi^\pm$.

- The cross section can be writen as:

$$\frac{d\sigma}{dt dM_{\pi^+\pi^-} d\Omega} = \frac{q}{256\pi^4 \left(s-m_p^2\right)^2}|M|^2$$

$$M = e\left[\left(\frac{\varepsilon\cdot q_+}{k\cdot q_+}\right)T_- - \left(\frac{\varepsilon\cdot q_-}{k\cdot q_-}\right)T_+ + \frac{\varepsilon\cdot(p+p')}{k\cdot(p+p')}(T_+ - T_-)\right]$$

$$T_\pm = 2i\left[(q_\pm\cdot p')^2 - m_\pi^2 m_p^2\right]^2 \sigma_{\pi p} e^{B_\pm t/2}$$



HERA, Z.Phys.C 69 (1995) 39-54

The scattering amplitude $\Gamma_{\gamma A \to \pi^+\pi^- A}(M_{\pi^+\pi^-}, \vec{x}_\perp)$

- The scattering amplitude in coordinate space:

$$\frac{d\sigma}{dt dM_{\pi^+\pi^-} d\Omega} = \frac{q}{256\pi^4 \left(s - m_p^2\right)^2} |M|^2 \longrightarrow \frac{d\sigma}{dt dM_{\pi^+\pi^-}}|_{t=0} = \frac{1}{4\pi}\left(\int \Gamma(M_{\pi^+\pi^-}, \vec{x}_\perp) d^2\vec{x}_\perp\right)^2$$

- The free pion survived probability:

$$P_{survived} = \int \left(P_{no\ interaction}(\vec{x}_\perp) + P_{elastic}(\vec{x}_\perp)\right) d^2(\vec{x}_\perp)$$

$$P_{no\ interaction}(\vec{x}_\perp) = exp\left(-\sigma_{\pi p} * T(\vec{x}_\perp)\right), \quad P_{elastic}(\vec{x}_\perp) = \left(1 - exp\left(-\sigma_{\pi p} * T(\vec{x}_\perp)/2\right)\right)^2$$

- The virtual pion scattering amplitude:

$$T_\pm(\vec{x}_\perp) = 2i\left[(q_\pm \cdot p')^2 - m_\pi^2 m_p^2\right]^2 * 2\int \left(1 - exp\left(-\sigma_{\pi p} * T(\vec{x}_\perp)/2\right)\right) d^2(\vec{x}_\perp)$$

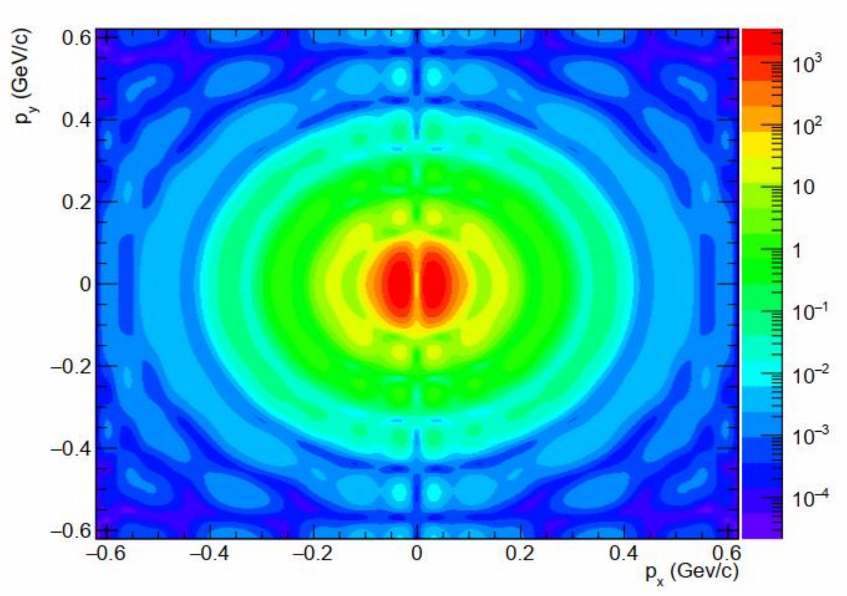
The p_T Distribution of Non-Resonant $\pi^+\pi^-$

$$A(\vec{x}_\perp, M_{\pi^+\pi^-}) = |\vec{a}(\omega,\vec{x}_\perp)|\Gamma_{\gamma A\to\pi^+\pi^- A}(M_{\pi^+\pi^-},\vec{x}_\perp)$$

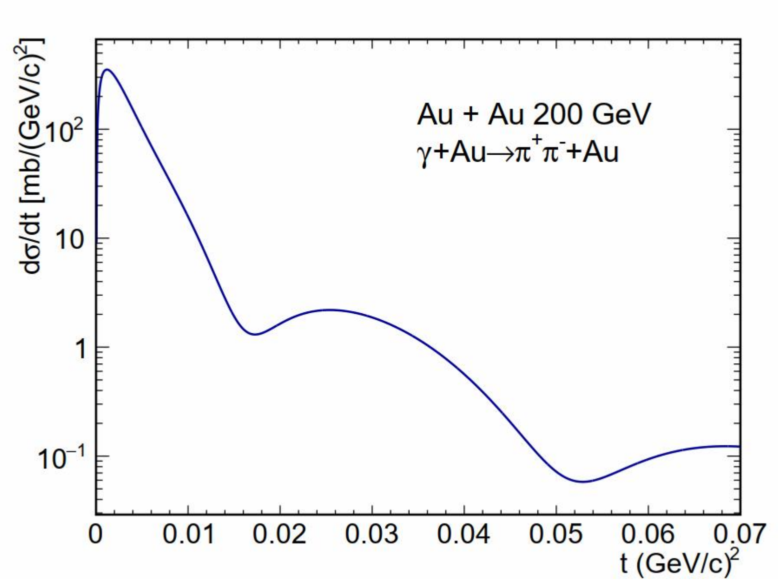
- The 2D-transverse momentum distribution:

$$\frac{d^3P}{dM_{\pi^+\pi^-}dp_x dp_y} = \left|\frac{1}{2\pi}\int d^2\vec{x}_\perp (A_1 + A_2)e^{i\vec{p}_\perp\cdot\vec{x}_\perp}\right|$$

$$\frac{d^3\sigma}{dM_{\pi^+\pi^-}dp_x dp_y} = \int \frac{d^3P}{dM_{\pi^+\pi^-}dp_x dp_y} P_{UPC}(b) d^2b$$

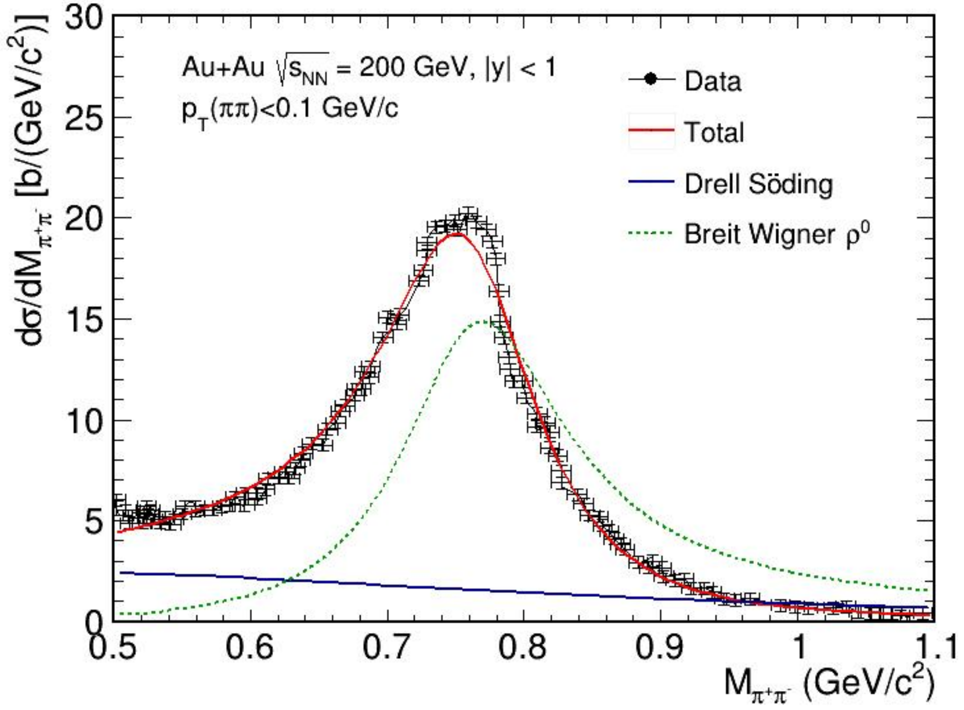


Interference and Diffraction pattern

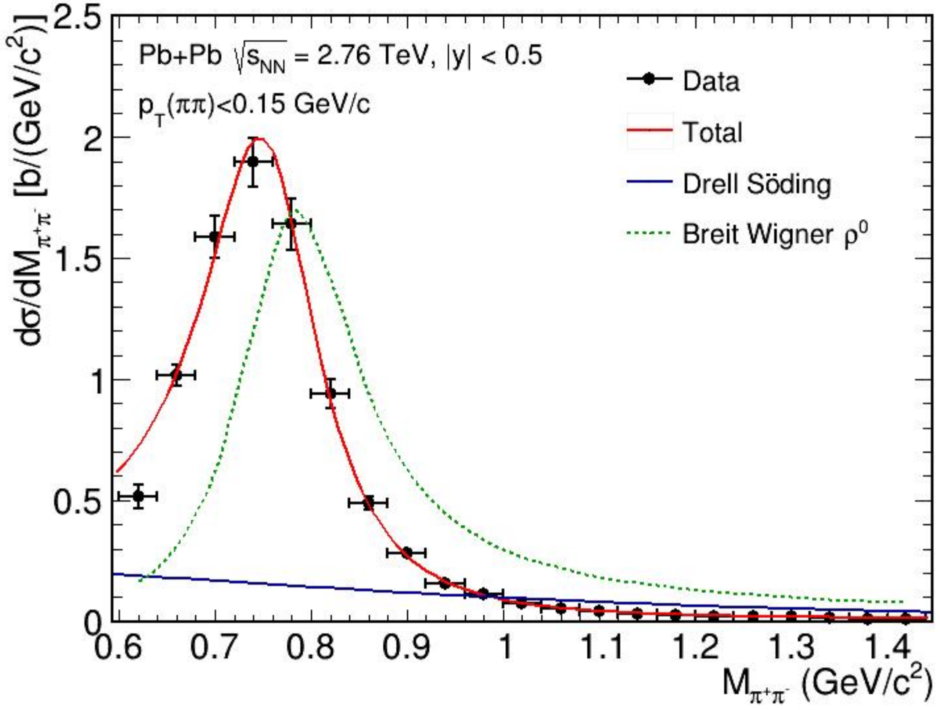


Clear peak-valley structure

The Mass Distribution of Non-Resonant $\pi^+\pi^-$



STAR, Phys.Rev.C 96 (2017) 5, 054904



ALICE, JHEP 09 (2015) 095

$$\frac{d\sigma}{dM_{\pi^+\pi^-}} = \left| A_\rho \frac{\sqrt{M_{\pi\pi} M_\rho \Gamma_\rho}}{M_{\pi\pi}^2 - M_\rho^2 + i M_\rho \Gamma_\rho} + A_{non-res}(M_{\pi\pi}) \right|^2$$

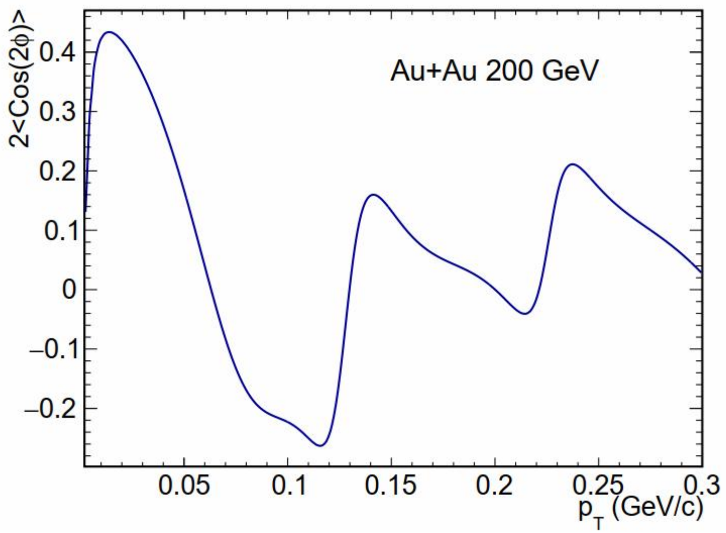
The A_2 modulation

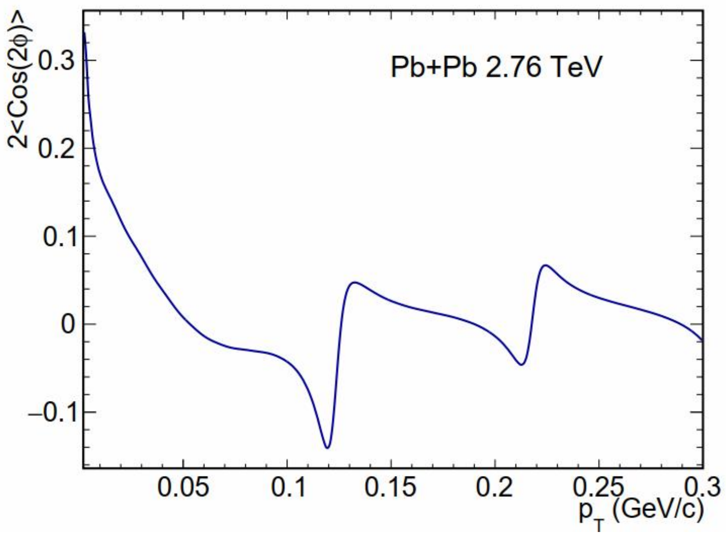
- The non-resonant $\pi^+\pi^-$ inherits the photon polarization state, the angular distribution of these two $\pi^+\pi^-$ is:

$$\frac{d^2N}{d\cos\theta\, d\phi} = \frac{3}{8\pi}\sin^2(\theta)\left[1+\cos\left(2(\phi-\Phi)\right)\right]$$

- The second-order modulation is given by:

$$2\langle\cos(2\phi)\rangle = \cos(2\Phi)$$





- The modulation strength shows a periodic oscillation with the transverse momentum.
- Shape has a certain dependence on the collision system.

Summary

- A theoretical framework was developed for Drell-Soding process calculations in heavy-ion UPCs.

- A clear quantum interference pattern can be observed in the p_T distribution.

- The spin entanglement of these non-resonant pairs has persisted since production and is manifested in the cosine modulation of the angular distribtuion of the final state.

Summary

- A theoretical framework was developed for Drell-Soding process calculations in heavy-ion UPCs.

- A clear quantum interference pattern can be observed in the p_T distribution.

- The spin entanglement of these non-resonant pairs has persisted since production and is manifested in the cosine modulation of the angular distribtuion of the final state.

Thank You !