Entanglement Enabled Spin Interference Between $\gamma A \to \pi^+\pi^-$ and $\gamma\gamma \to \pi^+\pi^-$

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Motivation

- In Ultraperipheral Collisions (UPCs), $\pi^+\pi^-$ pairs are produced via the **dominant $\gamma A \to \pi^+\pi^-$** and **subtle $\gamma\gamma \to \pi^+\pi^-$** channels.
- Hadronic light-by-light scattering, $\gamma\gamma \to \pi^+\pi^-$, **has never been observed in UPCs and contributes one of the two dominant uncertainties on a_μ**, the anomalous magnetic moment of the muon [1].
- Interference between the **spin-1** γA and **spin-2** $\gamma\gamma$ channels is expected to produce a **distinct $cos(1\Delta\phi)$ and $cos(3\Delta\phi)$ anisotropy in the final state**– an effect known as Entanglement Enabled Spin Interference (EESI).

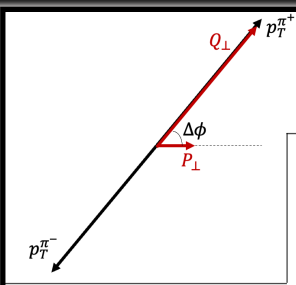
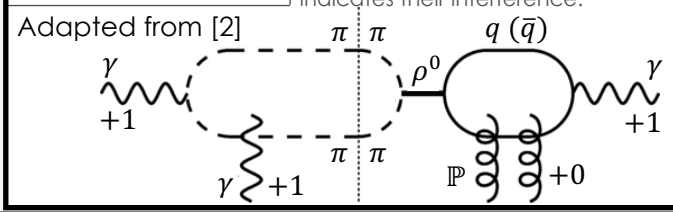


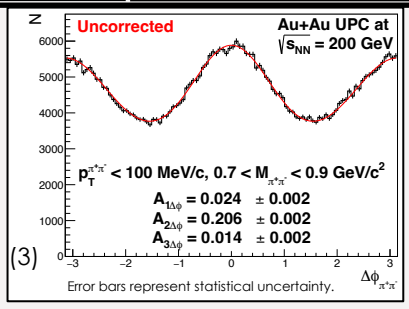
Figure 1: Illustration of $\Delta\phi$, the primary observable of this analysis. $\Delta\phi$ is defined as the angle between $P_\perp = p_T^{\pi^+} + p_T^{\pi^-}$ and $Q_\perp = \frac{1}{2}(p_T^{\pi^+} - p_T^{\pi^-})$.

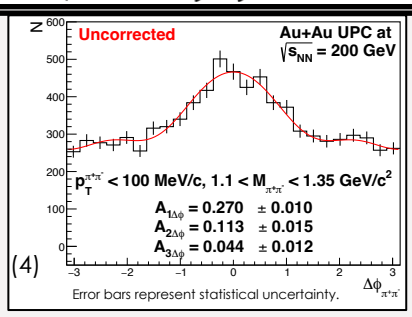
Figure 2: Diagram of interference leading to $cos(1\Delta\phi)$ and $cos(3\Delta\phi)$ anisotropy. Numbers represent the spin carried by incoming particles. The dotted line separates the $\gamma\gamma$ and γA diagrams and indicates their interference.



Data and Analysis

- Events with exactly two pions are selected from Au+Au $\sqrt{s_{NN}} = 200\ GeV$ data (STAR runs 10, 11, 14).
- The $\Delta\phi$ distribution is fit with a Fourier series in different mass ranges.
- Fit Function: $C(1 + \sum_{n=1}^{3} A_{n\Delta\phi}\cos(n\Delta\phi))$
- Even without any correction, the angular anisotropy is very clear and has significant mass dependence.

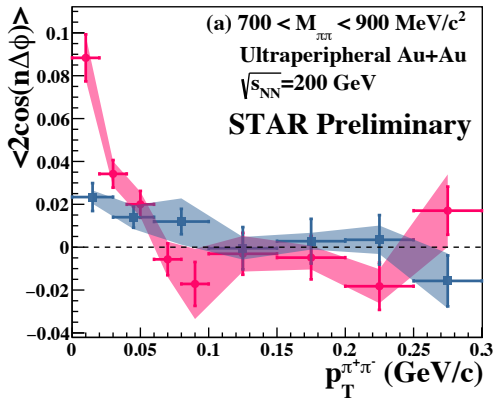




Figures 3 and 4: The $\Delta\phi$ distributions are fit with a Fourier series. $A_{2\Delta\phi}$ represents interference between $\gamma A \to \rho^0$ channels with alternate nuclei acting as the target [3] [4]. $A_{1,3\Delta\phi}$ represent interference between $\gamma\gamma$ and γA [2].

Results

- $A_{1\Delta\phi}$ and $A_{3\Delta\phi}$ are calculated as a function of $p_T, M_{\pi\pi}$ and corrected for acceptance effects.
- $A_{1\Delta\phi}$ and $A_{3\Delta\phi}$ are **non-zero** around the ρ^0 mass.
- The signal **peaks strongly around $M_{\pi\pi} \approx 1270\ MeV/c^2$**.



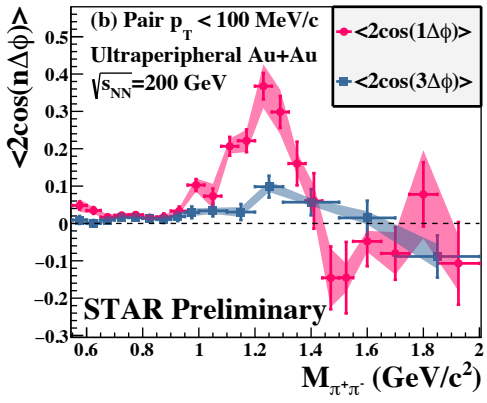


Figure 5: Fully corrected $A_{1\Delta\phi} = \langle 2\cos(1\Delta\phi)\rangle$ and $A_{3\Delta\phi} = \langle 2\cos(3\Delta\phi)\rangle$ as a function of p_T and $M_{\pi\pi}$. Error bars represent statistical uncertainty, and shaded regions represent systematic uncertainty.

References:

[1] Danilkin, Redmer, and Vanderhaeghen, Prog. Part. Nucl. Phys. 107, 20 (2019)

[2] Hagiwara, Zhang, Zhou, and Zhou, Phys. Rev. D 103, 074013 (2021)

[3] The STAR Collaboration, Sci.Adv.9,eabq3903 (2023)

[4] Brandenburg, Duan, Tu, Venugopalan, and Xu, Phys. Rev. Research 7, 013131 (2025)

- **The effect is largest at low p_T, roughly aligning with the peak of coherent production.**
- **Non-zero $A_{1\Delta\phi}$ and $A_{3\Delta\phi}$ around the ρ^0 mass at low p_T demonstrates interference between $\gamma A \to \rho^0 \to \pi^+\pi^-$ and non-resonant $\gamma\gamma \to \pi^+\pi^-$ in UPCs at STAR.**
- **$A_{1\Delta\phi}$ and $A_{3\Delta\phi}$ constrain the phase between $\gamma A \to \rho^0 \to \pi^+\pi^-$ and $\gamma\gamma \to \pi^+\pi^-$ [2].**
- **$A_{1\Delta\phi}$ and $A_{3\Delta\phi}$ at $M_{\pi\pi} \approx 1.27\ GeV/c^2$ indicates contribution from $\gamma\gamma \to f_2(1270) \to \pi^+\pi^-$.**

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