First Photonuclear Measurements in Asymmetric Heavy Ion Collisions

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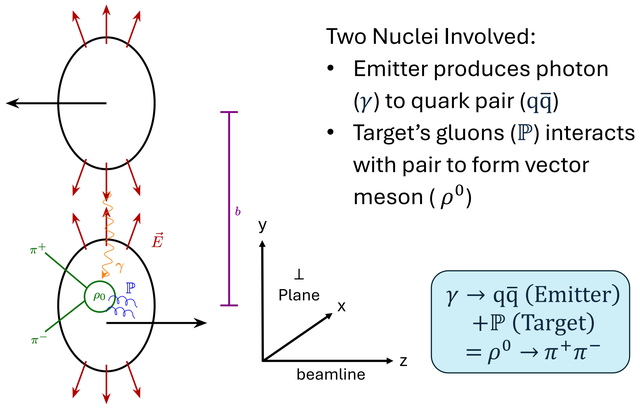
Abstract

In an ultra-peripheral collision (UPC), two ions interact at $v \approx c$ with their centers separated by $|\vec{b}| \geq 2$ radii. At relativistic speeds, ions' electromagnetic fields become Lorentz-boosted and can be quantized as linearly polarized photons. A photon from one nucleus can fluctuate into a quark-antiquark pair and interact with gluons from the other nucleus to produce a vector meson, such as a ρ_0, via diffractive photoproduction. A spin interference pattern between the ρ_0 wavefunctions manifests in ϕ - the angle between the ρ^0momentum and its daughter π^+momentum. The diffractive photoproduction enables measurements of the nucleus's strong-interaction radii, and the interference can fine-tune these results. Such methods have previously been used on symmetrical collisions. Uniquely, In this study the colliding nuclei are ^{63}Cu and ^{197}Au, establishing it as the first UPC analysis on asymmetrical collisions.

Introduction

Background: UPCs and the Photonuclear Process



Two Nuclei Involved:

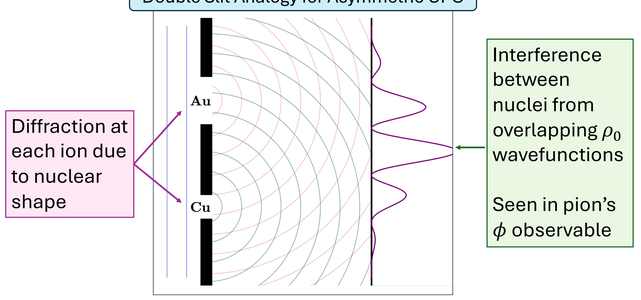
- Emitter produces photon (γ) to quark pair ($q\bar{q}$)
- Target's gluons ($\mathbb{P}$) interacts with pair to form vector meson (ρ^0)

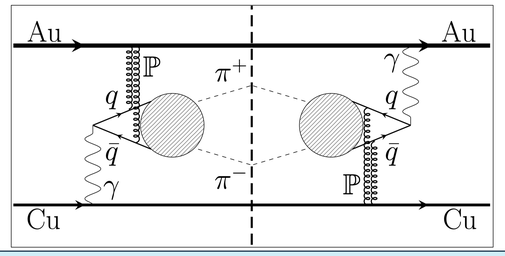
$\gamma \rightarrow q\bar{q}$ (Emitter) $+\mathbb{P}$ (Target) $= \rho^0 \rightarrow \pi^+\pi^-$

Diffractive + Interference Effects

Within UPCs, there are two notable processes that enable geometric measurements: diffraction from the target nuclei and interference between the two.

Double Slit Analogy for Asymmetric UPC





Feynman-like diagram representing one of the interference terms for a Cu+Au collision. Indistinguishable in observables.

Motivation & Pathway

Analysis and measurements have been successfully extracted from symmetrical UPCs. **Never has the same been done for an asymmetric collision, offering a unique opportunity to study inference between colliding nuclei.**

$\pi^+ + \pi^- = \rho_0 \Rightarrow P^2_{\perp,\rho_0} = |t| \Rightarrow [F_{Au}(t) + F_{Cu}(t)]^2 + F_{in}(t)$

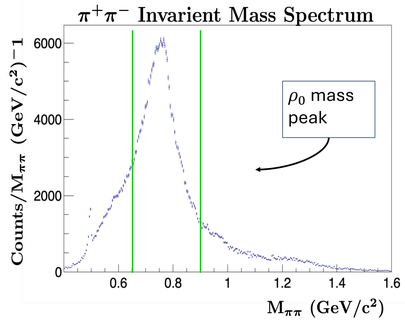
Reconstruct ρ_0 | Form t-spectrum | Fit for radii

Data Analysis

Signal Selection: $\rho_0 \rightarrow \pi^+\pi^-$

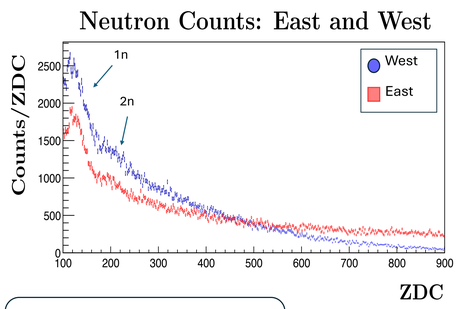
ρ^0's mass is around .770 GeV/c^2.

Selecting for a parent mass is one of the main method to root out the signal.



Copper versus Gold Beam

The Zero Detector Calorimeter (ZDC) measures neutral particles.



Neutrons
- ^{197}Au: 118
- ^{63}Cu: 34

Cu beam travels West.

Au beam travels East.

Fitting for Radii

Equations: t $\propto {}^1/_R$

Coherent: photon + entire nucleus. Uses Wood-Saxon

$$\mathcal{F}_c(t) = \frac{4\pi\hbar}{\sqrt{|t|}} \int r\rho_A(R_A, r)\sin\left(\frac{r\sqrt{|t|}}{\hbar}\right)dr$$

Incoherent: photon + single nucleon. Uses dipole model.

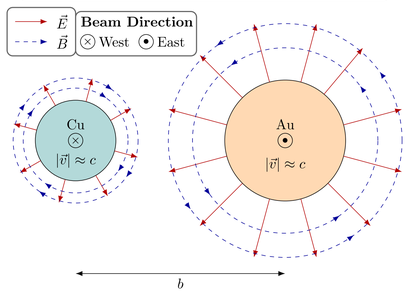
$$\mathcal{F}_i(t) = \frac{1}{Q_0^2\left(1 + \frac{t}{Q_0^2}\right)^2}$$

Add together and incorporate asymmetry

Full Equation: $(A_{Cu}\mathcal{F}_{Cu} + A_{Au}\mathcal{F}_{Au})^2 + A_i\mathcal{F}_i$

Free Parameters: $(A_{Cu}, A_{Au}, R_{Au}, R_{Cu})$

UPC between Au+Cu in Transverse Plane



Probability of being :

- Emitter $\propto$ (# Protons)^2
- Target $\propto$ (# Nucleons)^2

Protons & Nucleons:

- ^{197}Au: 79 & 197
- ^{63}Cu: 29 & 63

Results

Extracting Nuclear Radii

Full equation fitted to dN/dt as a function of $P_\perp^2$ to extract nuclear radii

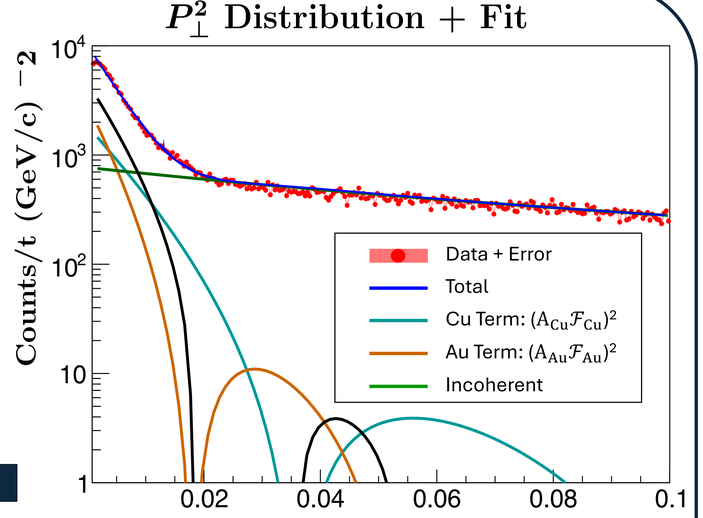
Fit Results

$R_{Au} = 6.46 \pm$ 3e-4 fm	$(\chi^2/ndf)_{coh} = 5.20$
$R_{Cu} = 4.49 \pm$ 1e-3 fm	$(\chi^2/ndf)_{incoh} = 3.55$

Gold Peaks: skinnier, further left (lower t)

Copper Peaks : wider, further right (higher t)

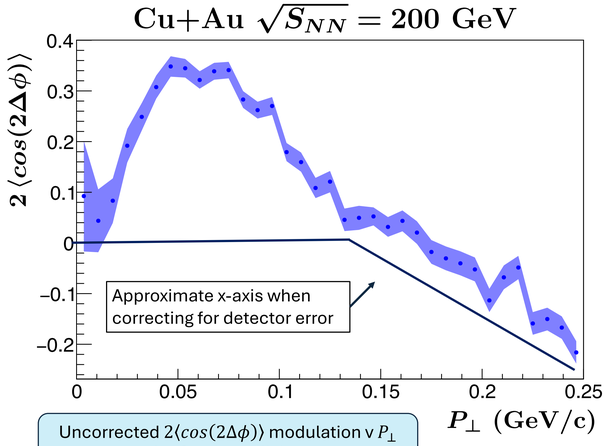
Incoherent dominates at t > .02 (GeV/c)^2



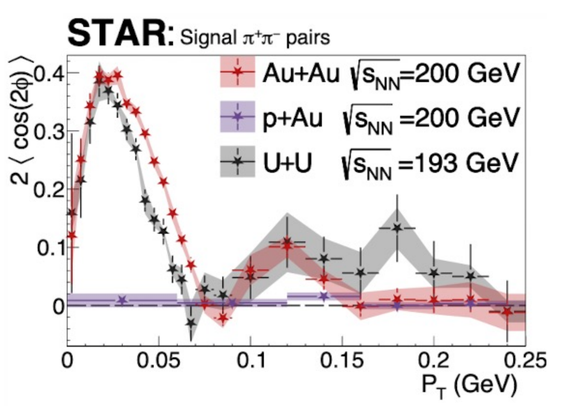
$P_\perp^2 \approx |t|$ (GeV/c)^2

Asymmetric vs. Symmetric Interference

Cu+Au modulation notably wider than Au+Au as diffractive peaks extend to higher $P_\perp$ due to copper nuclei as possible target.



Uncorrected $2\langle cos(2\Delta\phi)\rangle$ modulation v $P_\perp$ for Cu+Au collision



Corrected $2\langle cos(2\Delta\phi)\rangle$ modulation v $P_\perp$ for symmetrical Au+Au and U+U collisions [1]

Conclusion

Discussion

- Good fit quality – closely matches predicted nuclear radii
  - Commonly used scaling model $R_A = 1.2A^{1/3}$ fm: ($R_{Au} \approx 6.98$, $R_{Cu} \approx 4.77$)
  - Measurement from symmetrical UPC: ($R_{Au} = 6.38$ [1])
- Clear evidence of copper's effect in diffractive coherent production in $2\langle cos(2\Delta\phi)\rangle$ modulation

Future Work

- Further analyze spin interference in asymmetrical collision to improve understanding of quantum effects
- Improve accuracy of incoherent term to more confidentially remove from t-distribution
- Correct kinematic distribution for detector and cut efficiencies to reconstruct physical data

Acknowledgements

I would like to thank my research advisor, Dr. Brandenburg, for his continuous guidance and support through out this project. I also express my gratitude to the Ohio State University Department of Physics and The Bunny C. Clark Student Support Fund who provided funding for the summer to enable this research

References

[1] James Daniel Brandenburg, Spencer R. Klein, Zhangbu Xu, Shuai Yang, Wangmei Zha, Jian Zhou. (2025).Probing quantum phenomena through photoproduction in relativistic heavy-ion collisions. Progress in Particle and Nuclear Physics, 143(3).