Center for Frontiers in Nuclear Science

Measurement of the $\gamma\gamma \rightarrow e^+e^-$ Process and its Angular Correlations

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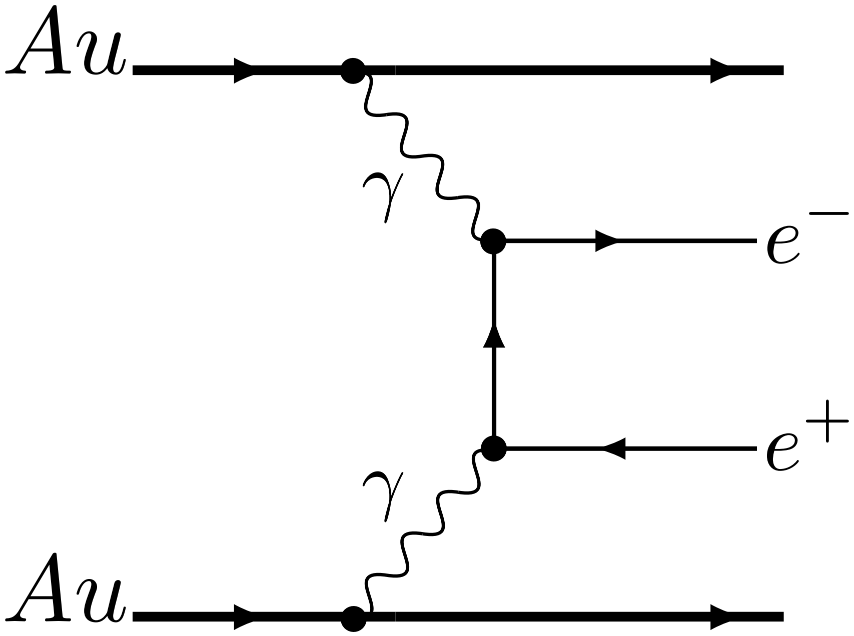
CFNS Annual Review, December 5-6, 2019

BROOKHAVEN NATIONAL LABORATORY

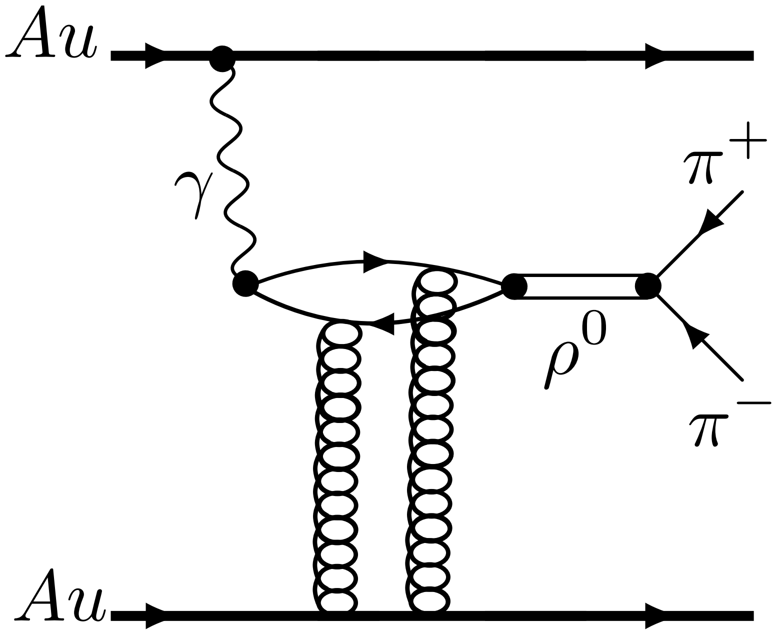
SHANDONG UNIVERSITY 1901

Discoveries in QED and their Application to Nuclear Physics

Part 1 : The Breit-Wheeler process ($\gamma\gamma \rightarrow e^{+}e^{-}$)



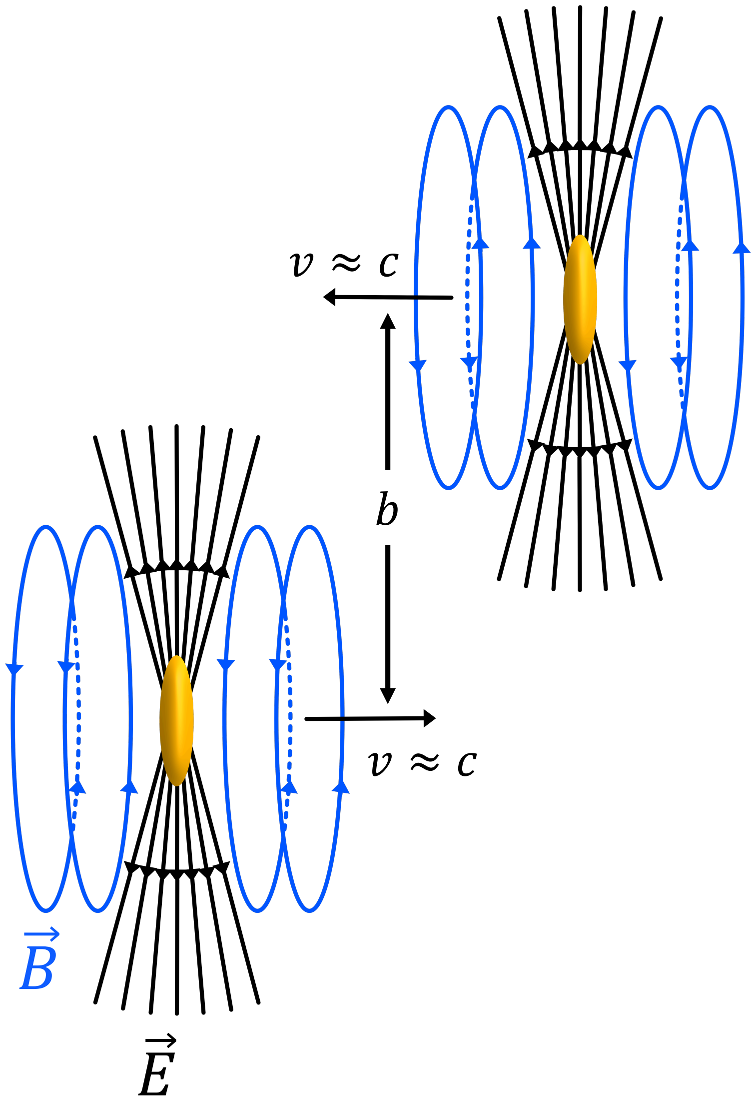
Part 2 : Diffractive Photoproduction of the ρ^0 Meson



Discovery of vacuum birefringence through $\gamma\gamma \rightarrow e^{+}e^{-}$ process provides a new observable for studying the nucleus now and at a future EIC

→ **New observable that may be sensitive to gluon GTMD / saturation scale**

Ultra-Peripheral Collisions



Ultra-relativistic charged nuclei produce highly Lorentz contracted electromagnetic field

Weizäcker-Williams Equivalent Photon Approximation (EPA):
→ In a specific phase space, EM fields can be quantized as a flux of **real photons**
Weizsäcker, C. F. v. *Zeitschrift für Physik* 88 (1934): 612

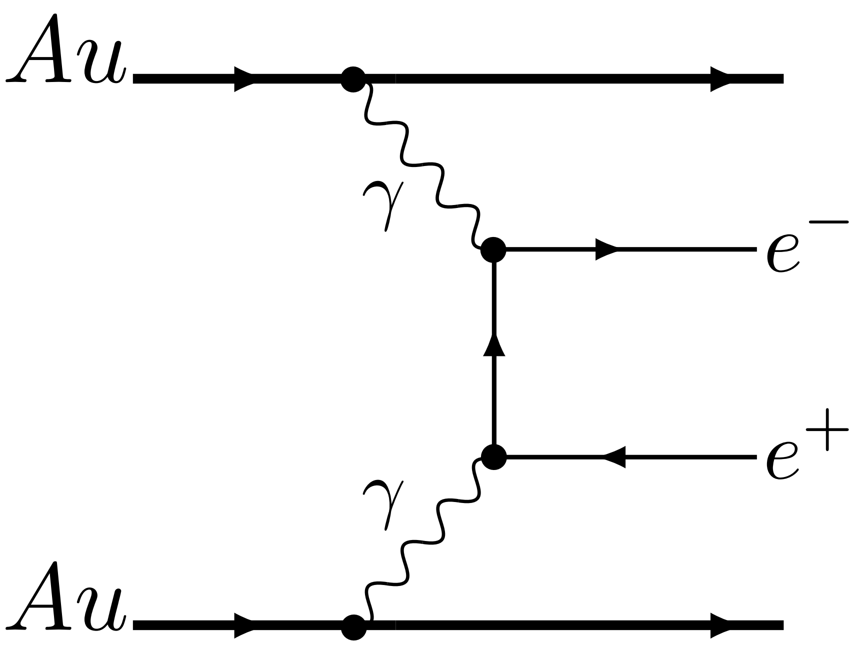
$Z\alpha \approx 1$ → High photon density
Magnetic field strength $\vec{\mathrm{B}} \approx 10^{14} - 10^{16}$ T
Skokov, V., et. al. *Int. J. Mod. Phys. A* 24 (2009): 5925–32

Test QED under extreme conditions

$\gamma\gamma \rightarrow e^+e^-$ Process

1934 Breit & Wheeler : “Collision of two Light Quanta”

G. Breit and J. A. Wheeler. *Physical Review* 46 (1934): 1087



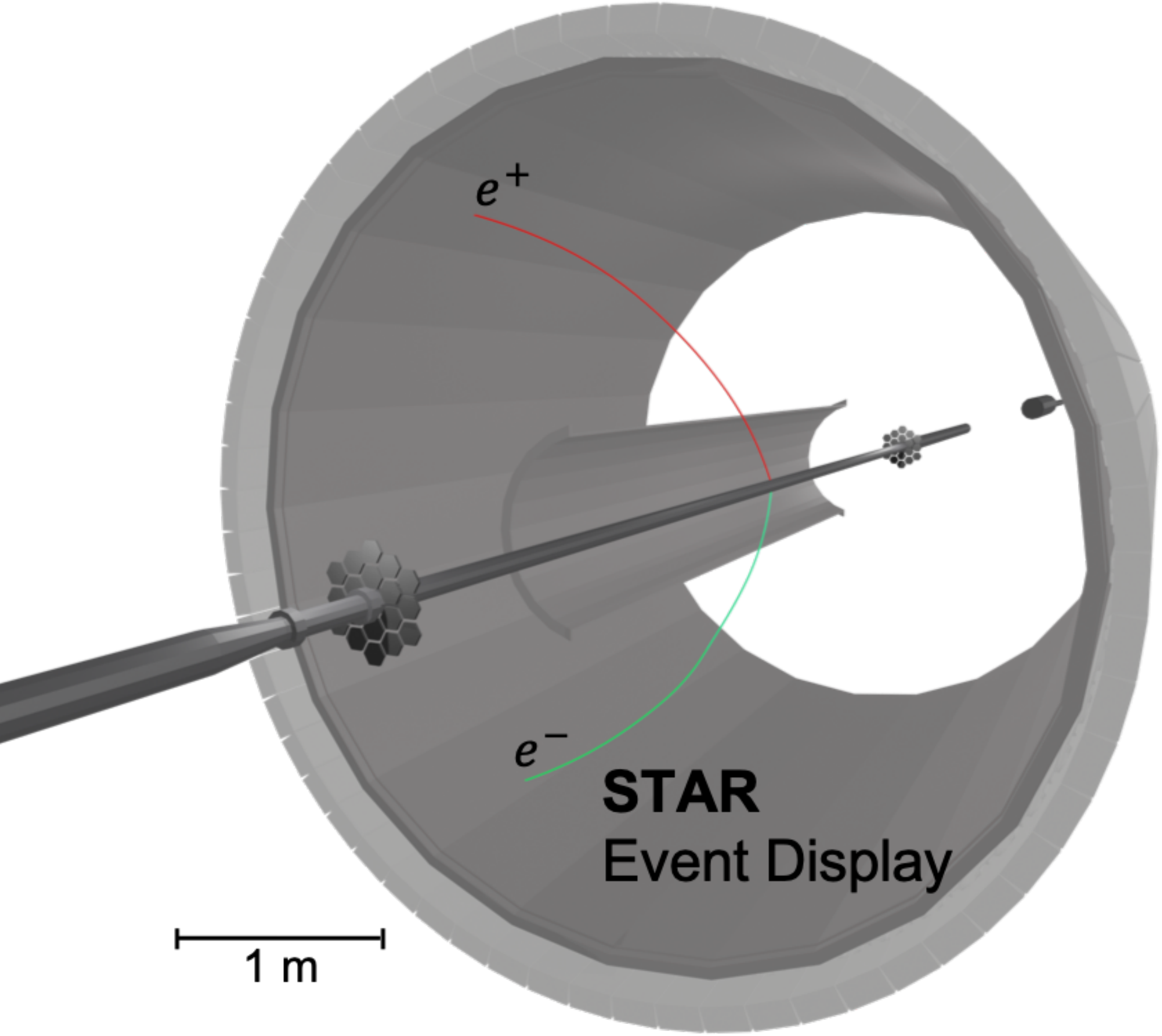
1. Identifying $\gamma\gamma \rightarrow e^+e^-$ process in ultra-peripheral heavy-ion collisions

2. Ultra-peripheral vs. peripheral

3. First Earth-based observation of vacuum birefringence

4. Applications & connection to EIC

Signatures of the $\gamma\gamma \rightarrow e^{+}e^{-}$ Process



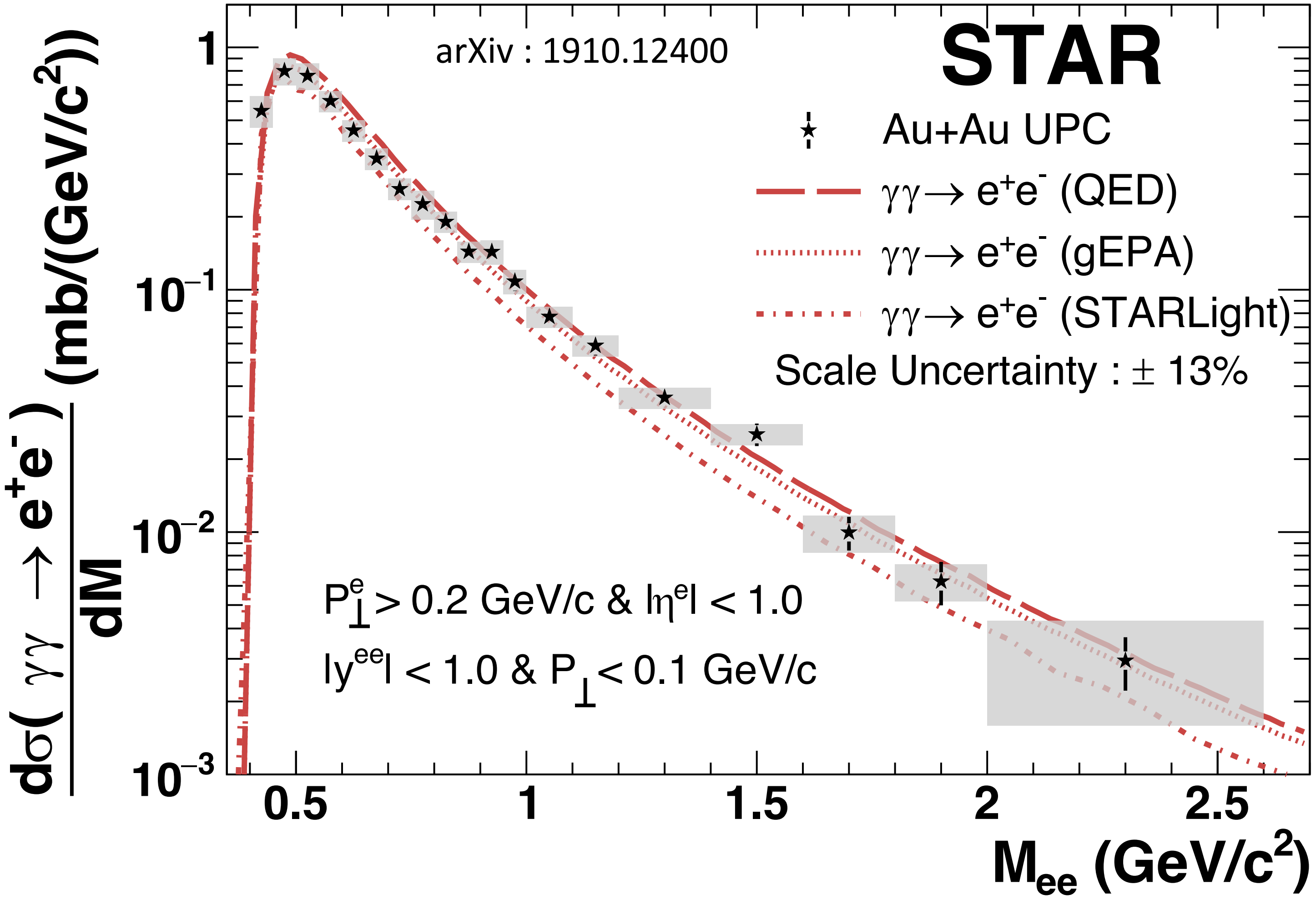
1. Exclusive production of $e^{+}e^{-}$ pair

2. Smooth invariant mass spectra
   (No vector mesons)

3. Individual e^{+}/e^{-} preferentially
   aligned in beam direction

4. Production peaked at very low $P_{\perp}$
   (pair transverse momentum)

Total $\gamma\gamma \rightarrow e^+e^-$ cross-section in STAR Acceptance



STARLight: S. R. Klein, et. al. *Comput. Phys. Commun.* 212 (2017) 258

gEPA & QED : W. Zha, J.D.B., Z. Tang, Z. Xu arXiv:1812.02820 [nucl-th]

Pure QED 2 → 2 scattering :

$$d\sigma/dM \propto E^{-4} \approx M^{-4}$$

No vector meson production

→ Forbidden for real photons with helicity ± 1 (i.e. 0 is forbidden)

$\sigma(\gamma\gamma \rightarrow e^+e^-)$ in STAR Acceptance:

Data : 0.261$\pm$0.004 (stat.) $\pm$ 0.013 (sys.) $\pm$ 0.034 (scale) mb

STARLight	gEPA	QED
0.22 mb	0.26 mb	0.29 mb

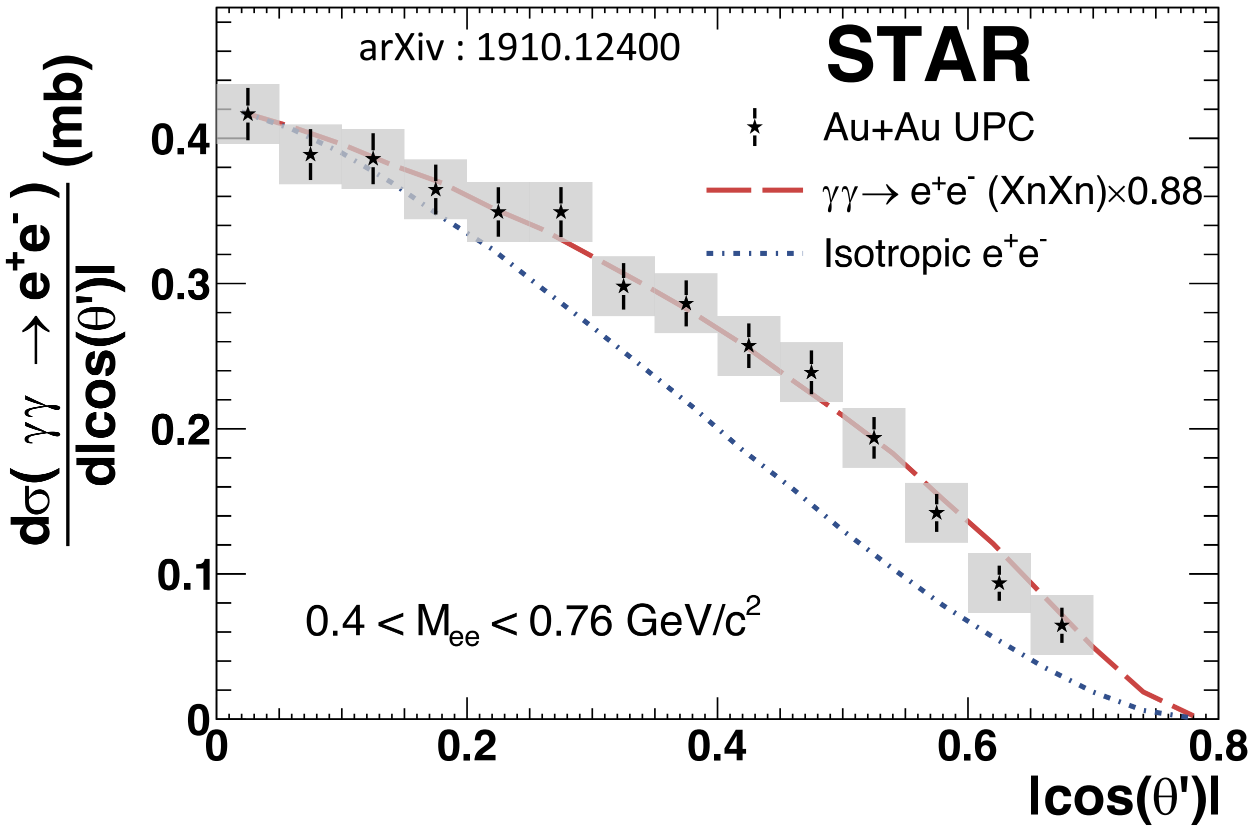
Measurement of total cross section agrees with theory calculations at $\pm 1\sigma$ level

$d\sigma(\gamma\gamma \to e^+e^-)/d\cos\theta'$

$\gamma\gamma \to e^+e^-$: Individual e^+/e^- preferentially aligned along beam axis [1]:

$$G(\theta) = 2 + 4\left(1 - \frac{4m^2}{W^2}\right)\frac{\left(1 - \frac{4m^2}{W^2}\right)\sin^2\theta\cos^2\theta + \frac{4m^2}{W^2}}{\left(1 - \left(1 - \frac{4m^2}{W^2}\right)\cos^2\theta\right)^2}$$

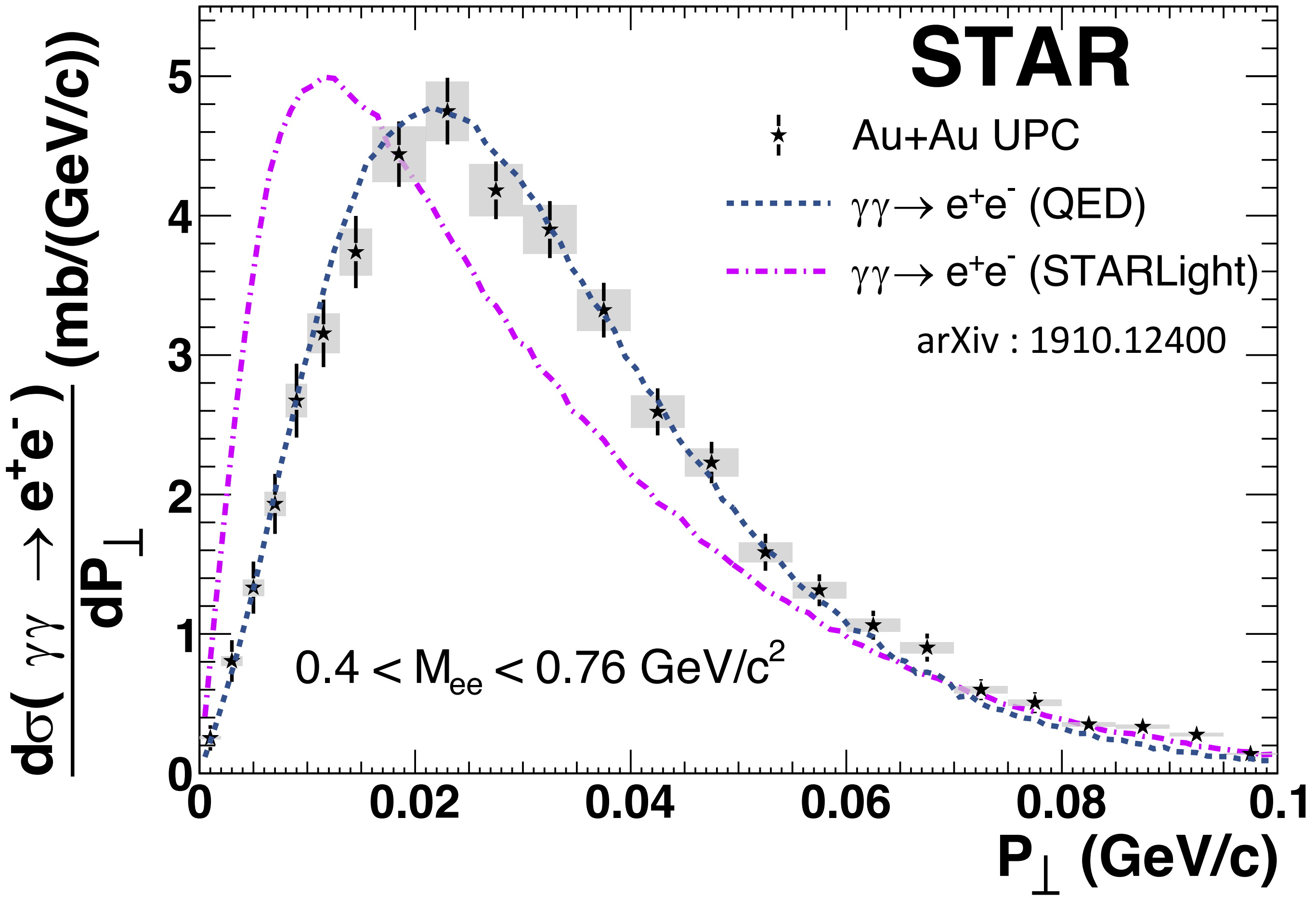
- Highly virtual photon interactions should have an isotropic distribution
- Measure θ', the angle between the e^+ and the beam axis in the pair rest frame.



Data are fully consistent with $G(\theta)$ distribution expected for $\gamma\gamma \to e^+e^-$

[1] S. Brodsky, T. Kinoshita and H. Terazawa, Phys. Rev. **D4**, 1532 (1971)
STARLight: S. R. Klein, et. al. *Comput. Phys. Commun.* 212 (2017) 258

$d\sigma(\gamma\gamma \to e^+e^-)/dP_\perp$



QED and STARLight are scaled to match measured $\sigma(\gamma\gamma \to e^+e^-)$

STARLight: S. R. Klein, et. al. *Comput. Phys. Commun.* 212 (2017) 258

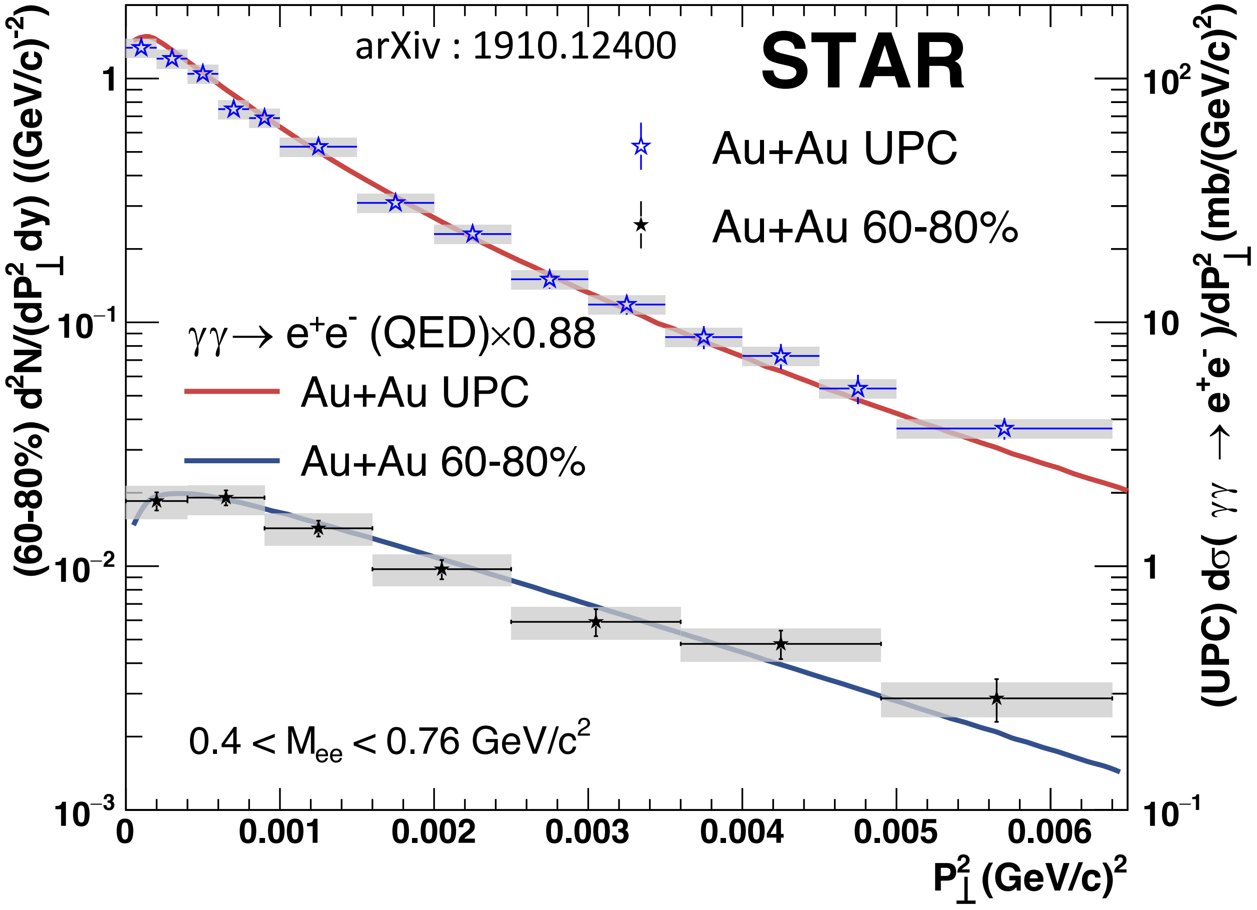
QED : W. Zha, J.D.B., Z. Tang, Z. Xu arXiv:1812.02820 [nucl-th]

- Cross-section peaks at low $P_\perp$, as expected for real photon collisions
- **Data are well described by leading order QED calculation ($\gamma\gamma \to e^+e^-$)**
- STARLight predicts significantly lower $\langle P_\perp \rangle$ than seen in data
  - STARLight calculations do not have centrality dependent $P_\perp$ distribution
- Experimentally investigate impact parameter dependence :

→**Compare UPC vs. peripheral collisions**

[1] STAR, Phys. Rev. Lett. 121 (2018) 132301

$\gamma\gamma \rightarrow e^+e^-$: UPC vs. Peripheral



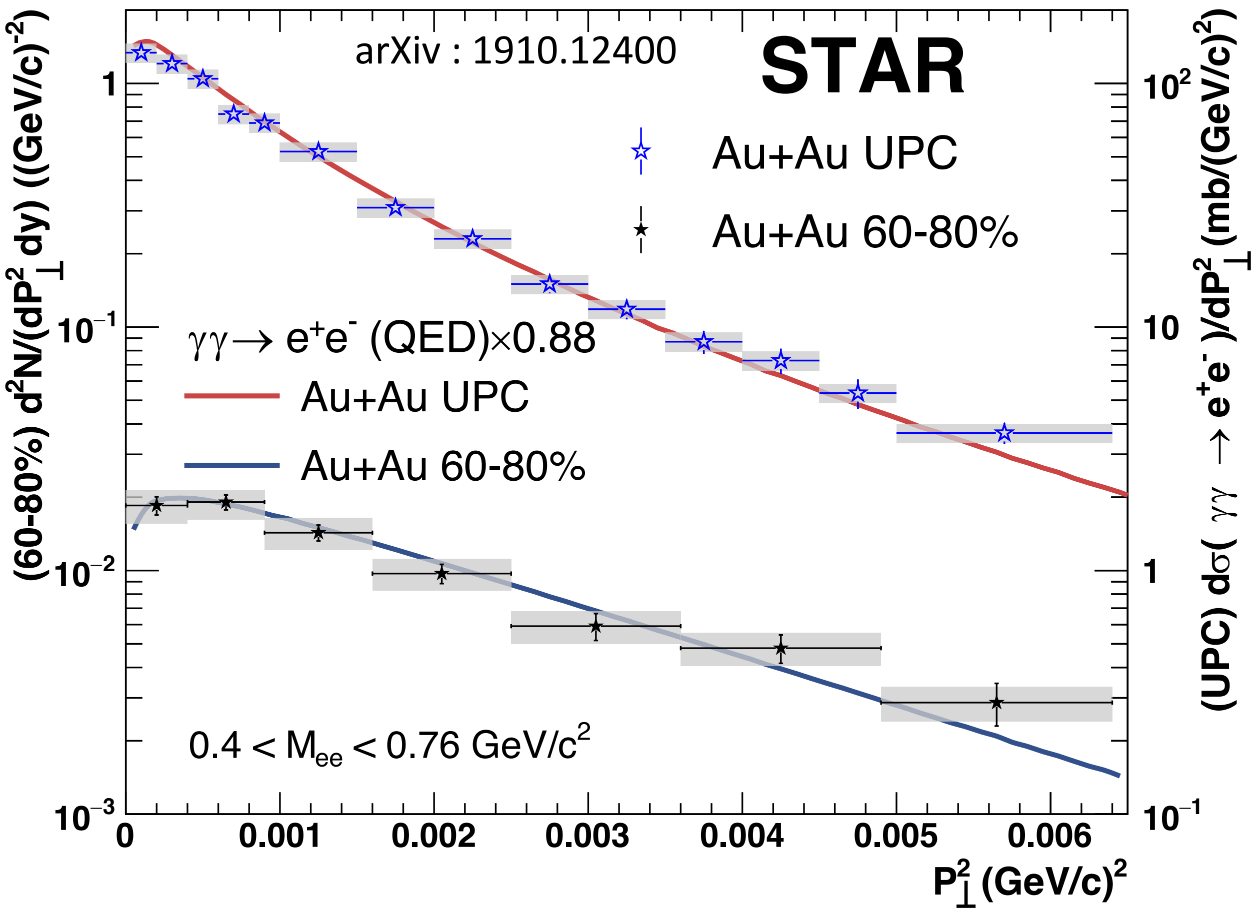
Characterize difference in spectra via $\sqrt{\langle P_\perp^2 \rangle}$

$\sqrt{\langle P_\perp^2 \rangle}$ **(MeV/c)**	**UPC Au+Au**	**60-80% Au+Au**
Measured	38.1 ± 0.9	50.9 ± 2.5
QED	37.6	48.5
***b* range (fm)**	≈ 20	$\approx 11.5 - 13.5$

- Leading order QED calculation of $\gamma\gamma \rightarrow e^+e^-$ describes both spectra ($\pm 1\sigma$)

$\gamma\gamma \rightarrow e^+e^-$: UPC vs. Peripheral

[1] STAR, Phys. Rev. Lett. 121 (2018) 132301
[2] S. R. Klein, et. al, Phys. Rev. Lett. 122, (2019), 132301
[3] ATLAS Phys. Rev. Lett. 121 (2018) , 212301



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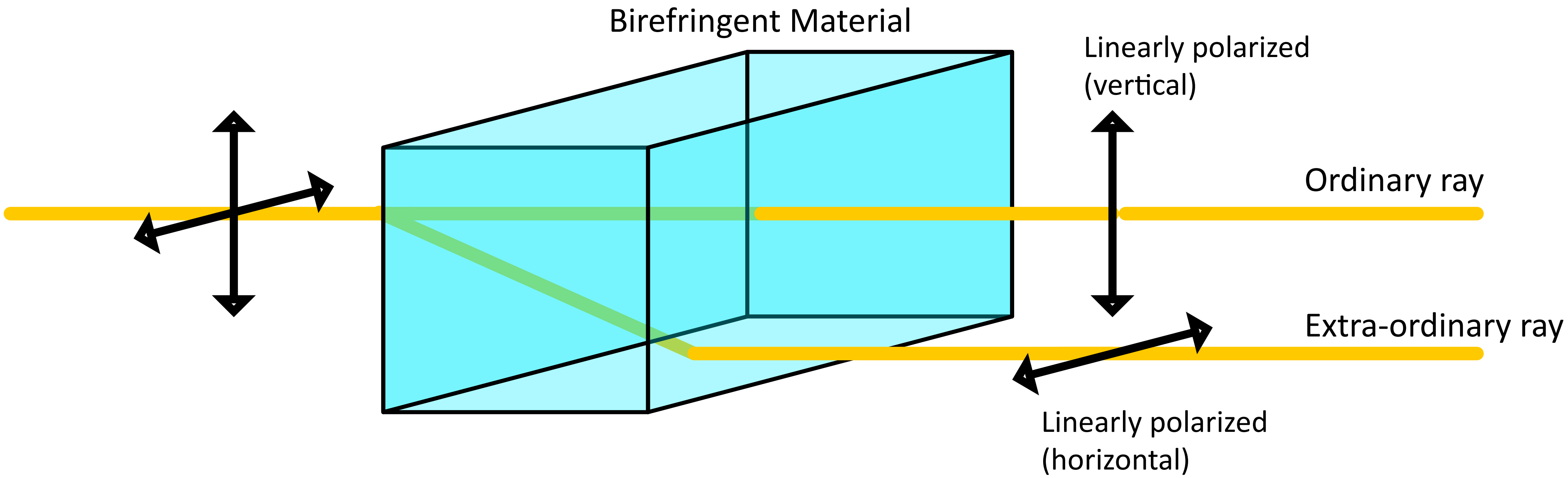
- Leading order QED calculation of $\gamma\gamma \rightarrow e^+e^-$ describes both spectra ($\pm 1\sigma$)
- Best fit for spectra in 60-80% collisions found for QED shape plus 14 ± 4 (stat.)± 4 (syst.) MeV/c broadening
- Proposed as a probe of trapped magnetic field or Coulomb scattering in QGP [1-3]

STAR observes 4.8σ difference between UPC and 60-80% Au+Au collisions

Optical Birefringence

Birefringent material: Different index of refraction for light polarized parallel ($n_{\parallel}$) vs. perpendicular ($n_{\perp}$) to material's ordinary axis

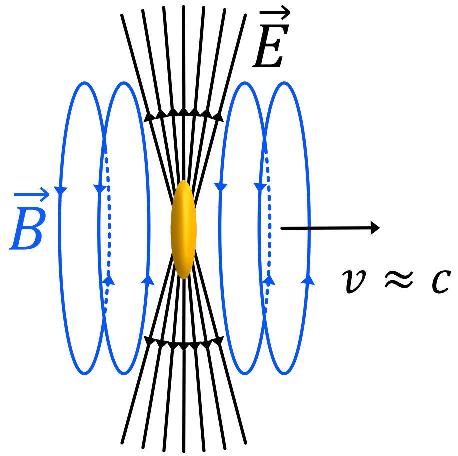
→ **splitting of wave function when $\Delta n = n_{\parallel} - n_{\perp} \neq 0$**



Birefringence of the QED Vacuum

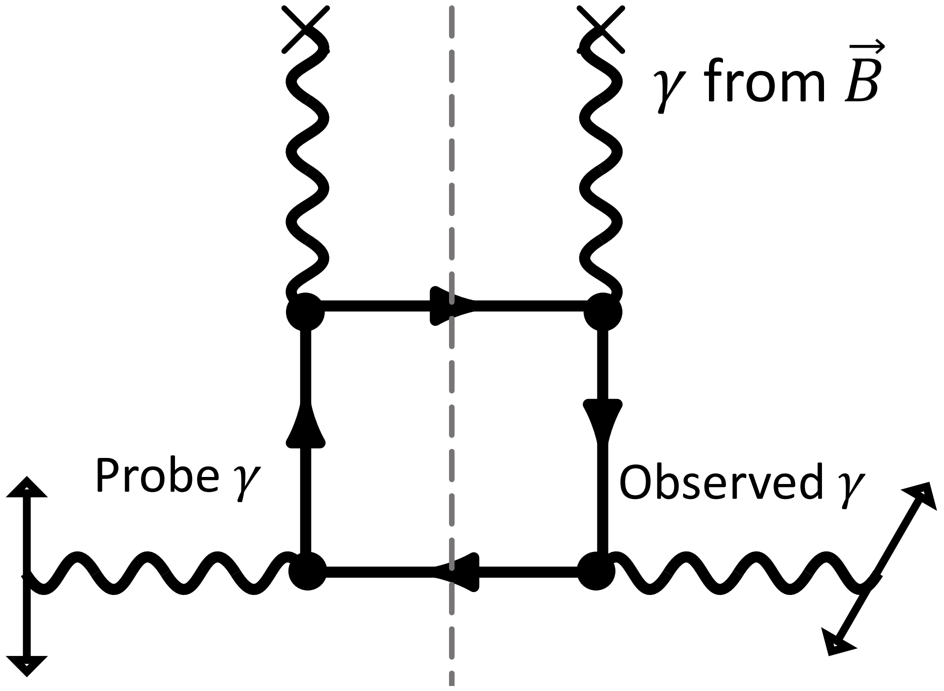
Vacuum birefringence : Predicted in 1936 by Heisenberg & Euler. Index of refraction for γ interaction with $\vec{B}$ field depends on relative polarization angle i.e. $\boldsymbol{\Delta\sigma = \sigma_{\parallel} - \sigma_{\perp} \neq 0}$

Lorentz contraction of EM fields →
Quasi-real photons should be linearly polarized ($\vec{E} \perp \vec{B} \perp \vec{k}$)



Can we observe vacuum birefringence in ultra-peripheral collisions?

Feynman Diagram for Vacuum Birefringence



$Real(n)$ = transmission process $\gamma\gamma \to \gamma\gamma$
$Imag(n)$ = absorption process $\gamma\gamma \to e^{+}e^{-}$ (diagram cut)

S. Bragin, et. al., *Phys. Rev. Lett.* 119 (2017), 250403
R. P. Mignani, *et al.*, *Mon. Not. Roy. Astron. Soc.* 465 (2017), 492

Birefringence of the QED Vacuum

[1] C. Li, J. Zhou, Y.-j. Zhou, Phys. Lett. B 795, 576 (2019)
QED calculation: arxiv : 1911.00237

Recently realized, $\Delta\sigma = \sigma_{\parallel} - \sigma_{\perp} \neq 0$ leads to **$\cos(n\Delta\phi)$ modulations** in polarized $\gamma\gamma \rightarrow e^{+}e^{-}$ [1]

$$\Delta\phi = \Delta\phi[(e^{+} + e^{-}), (e^{+} - e^{-})]$$
$$\approx \Delta\phi[(e^{+} + e^{-}), e^{+}]$$

Ultra-Peripheral

Quantity	Measured	QED	χ^2/ndf
$-A_{4\Delta\phi}(\%)$	16.8 ± 2.5	22	18.8 / 16

Peripheral (60−80%)

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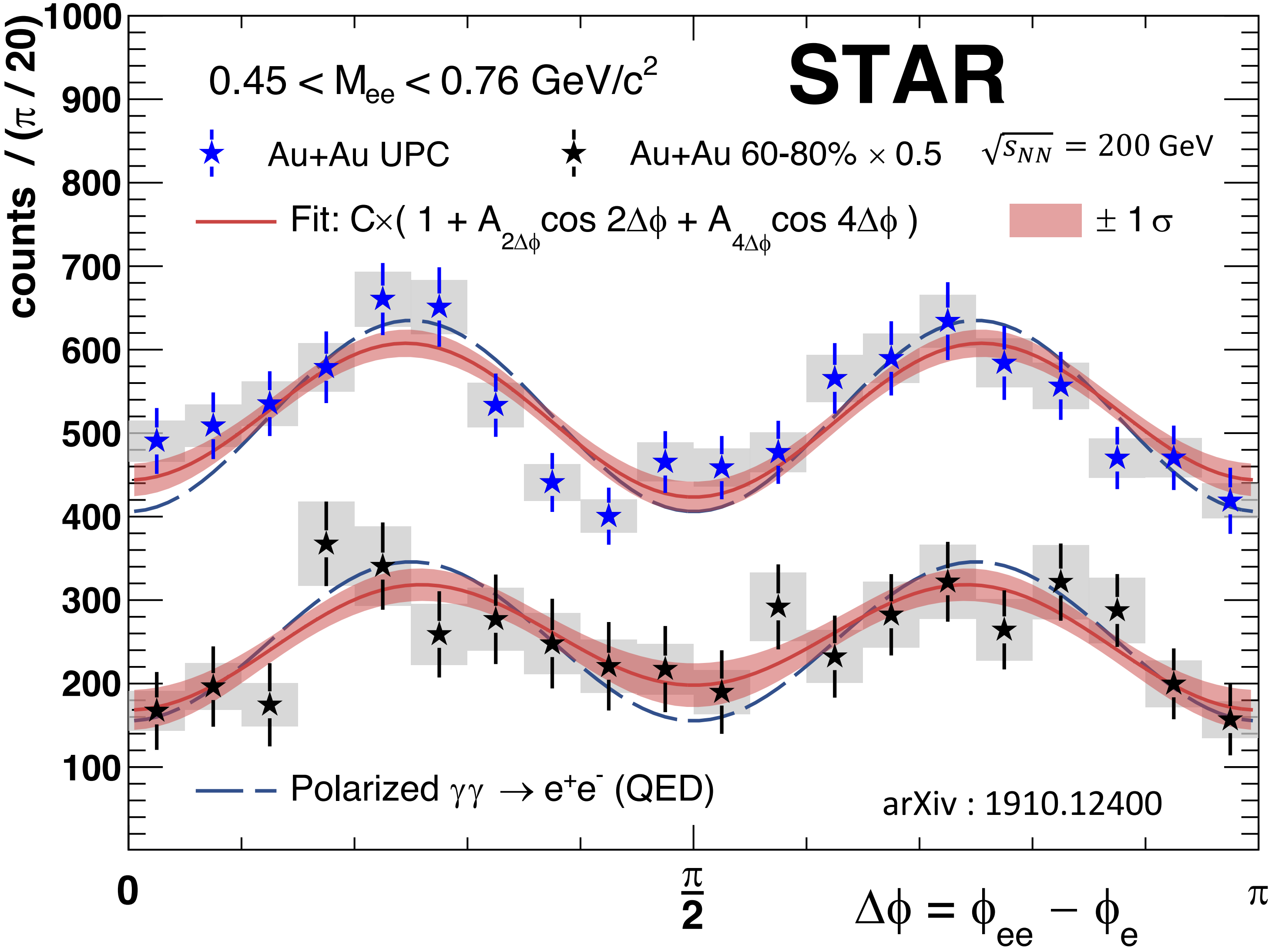

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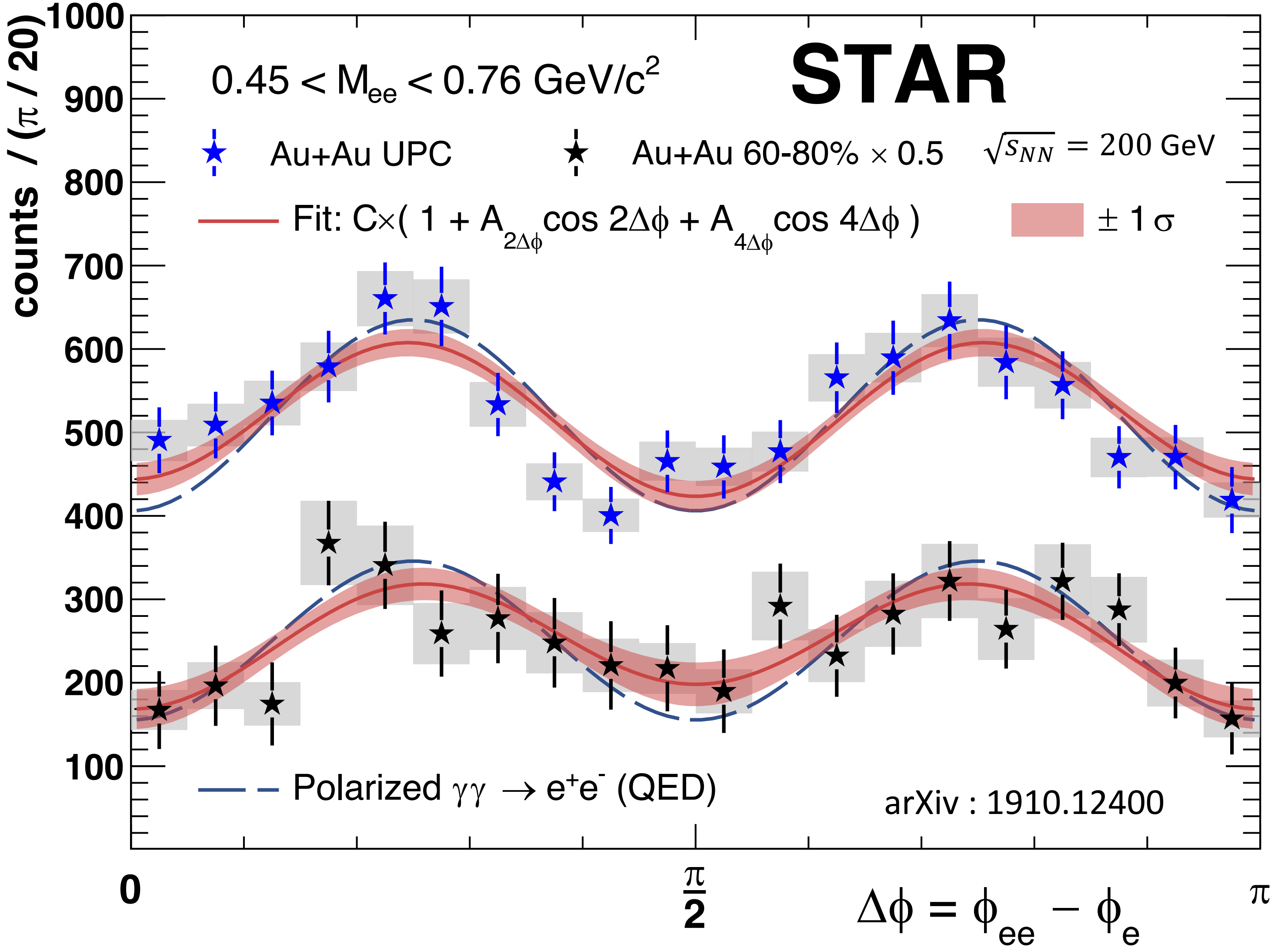


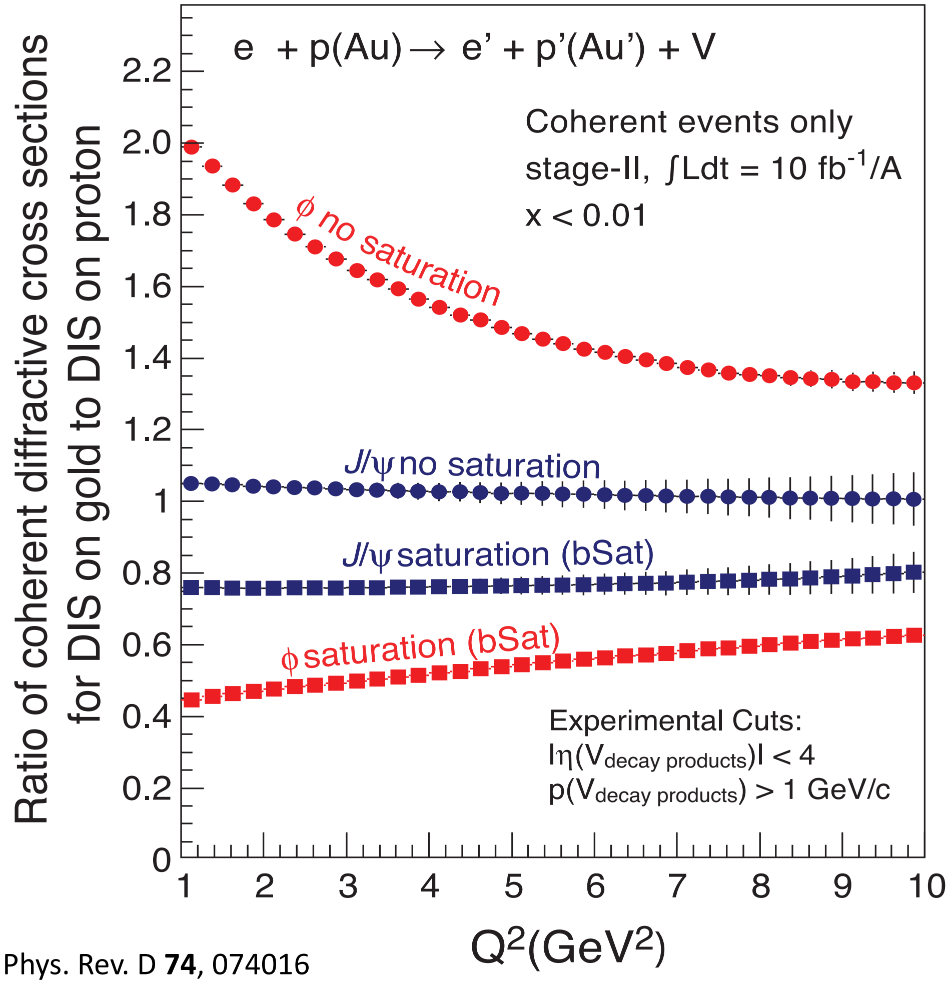
→ **First Earth-based observation** **(6.7σ level) of vacuum birefringence**

Probing Saturation at the EIC

➢ **Where does the saturation of gluon densities set in?**

One of three "most intellectually pressing questions that an **EIC** will address…"

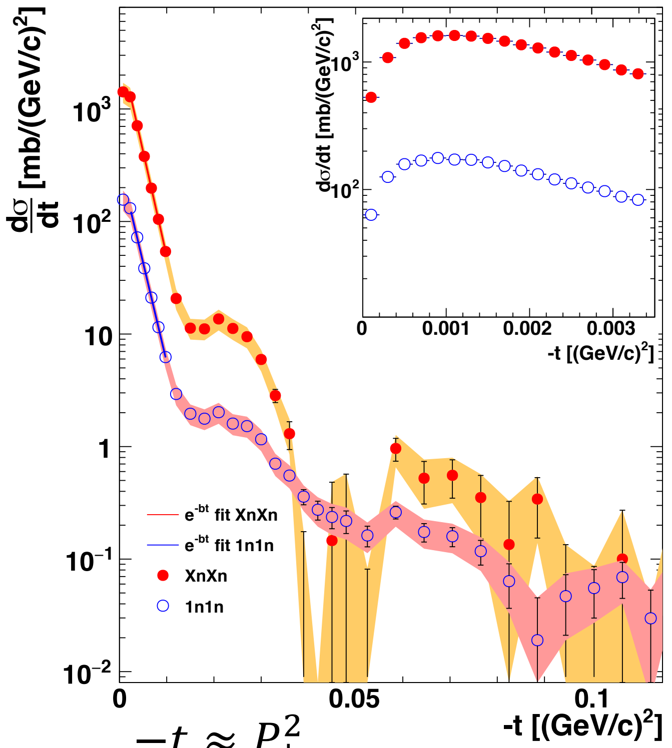
[EIC White Paper https://www.bnl.gov/npp/docs/EIC_White_Paper_Final.pdf]



Phys. Rev. D **74**, 074016

Experimentally accessible through diffractive photoproduction process

Diffractive ρ^0 photoproduction at STAR



$-t \approx P_\perp^2$

[STAR, Phys. Rev. C **96,** (2017) , 054904]

Diffraction peaks are the characteristic feature for coherent diffractive events

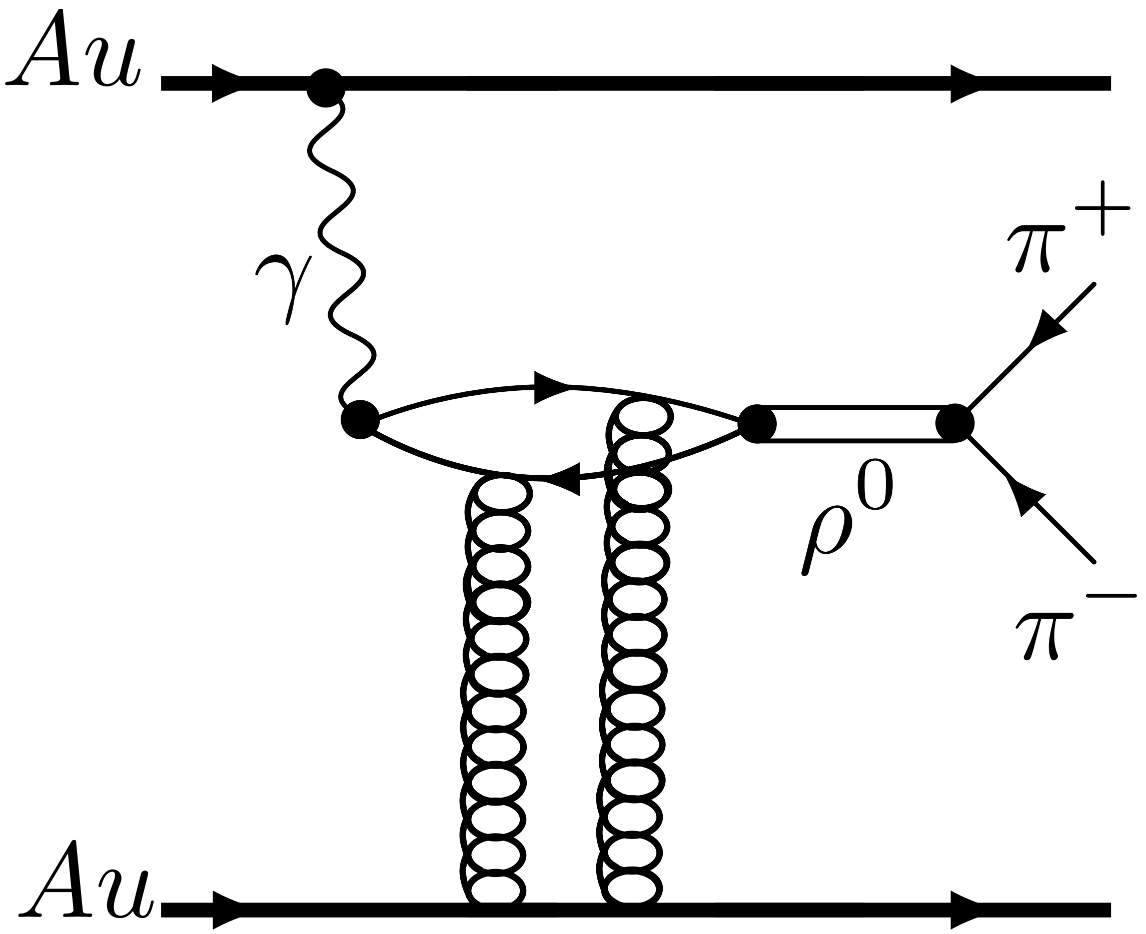
Experimentally, separation of coherent and incoherent process can be difficult (model dependent) with large uncertainties

Photoproduction of the ρ^0 Meson

Employ the same observable for $\rho^0 \to \pi^+\pi^-$ (and direct $\pi^+\pi^-$)

- **Use the <u>polarized</u> γ as a probe of the nucleus**
- Calculate coefficients $\langle \cos(n\Delta\phi) \rangle$

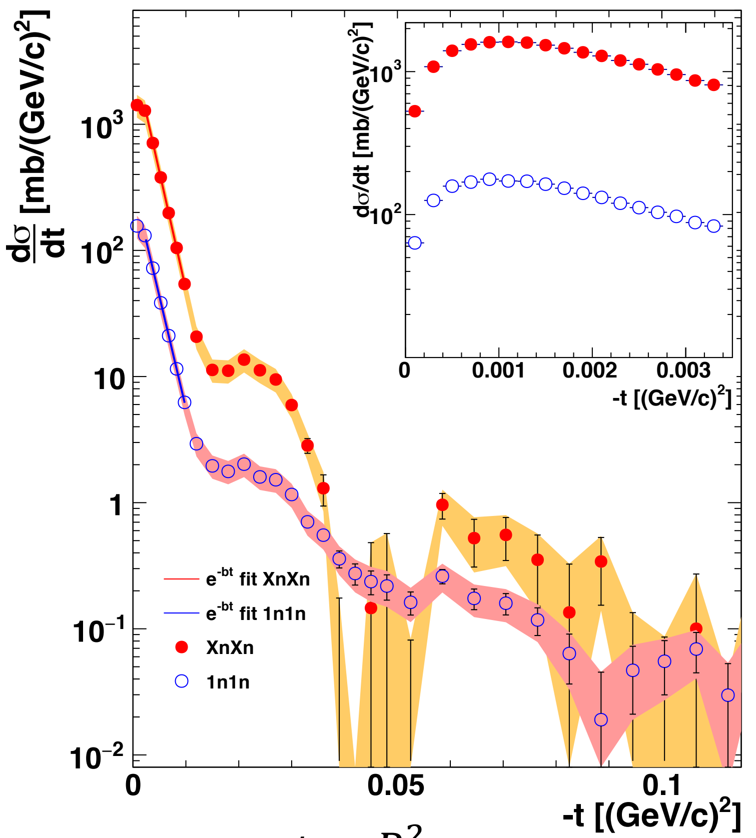
$$\Delta\phi = \Delta\phi[(\pi^+ + \pi^-), (\pi^+ - \pi^-)]$$



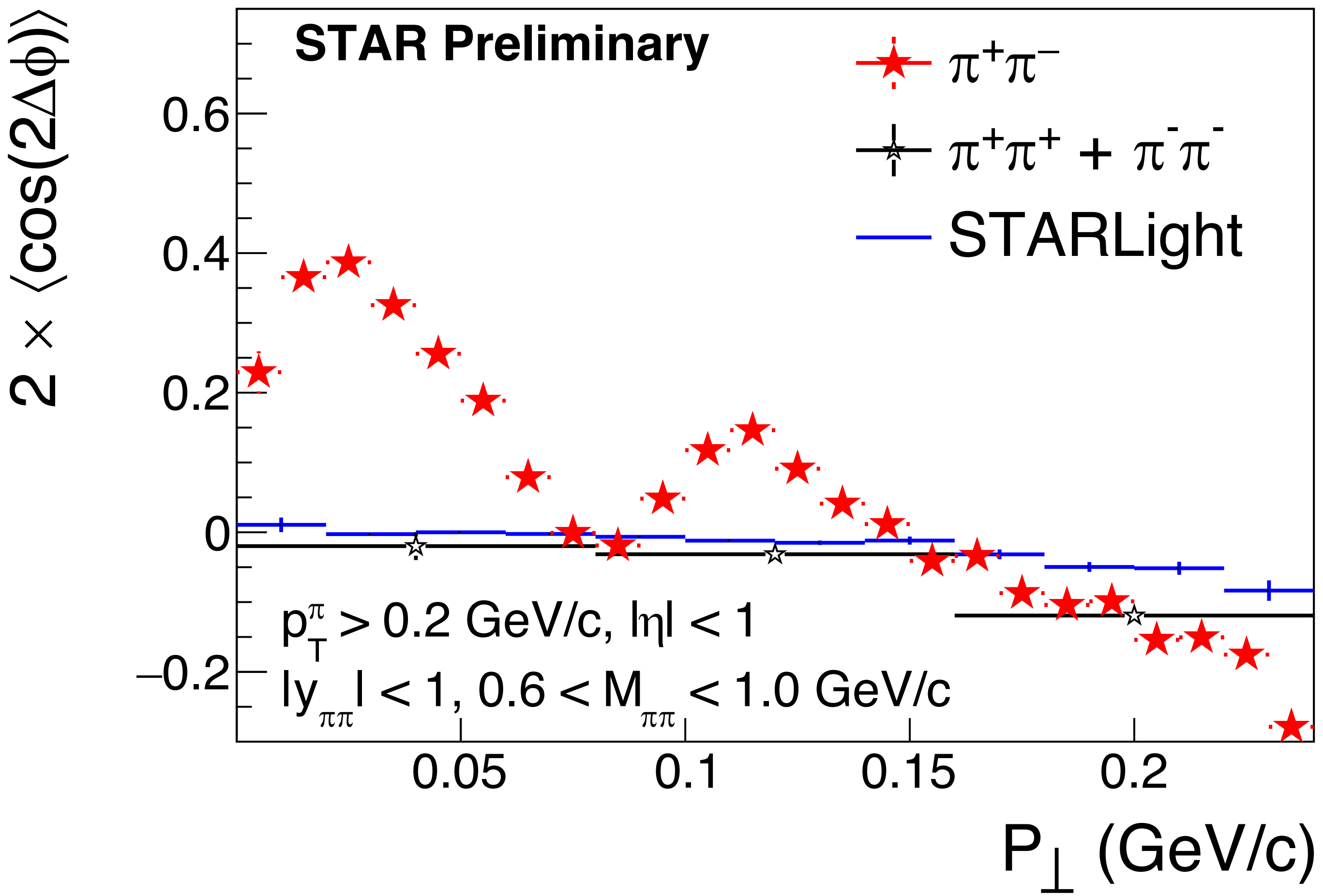
J. Zhou Phys. Rev. D **94** (2016), 114017

Photoproduction of the ρ^0 Meson

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



$-t \approx P_{\perp}^{2}$



- Amplitude of the $\cos(2\Delta\phi)$ modulation appears to be related to diffraction peaks
- <u>Theory input needed</u> for quantitative description of data

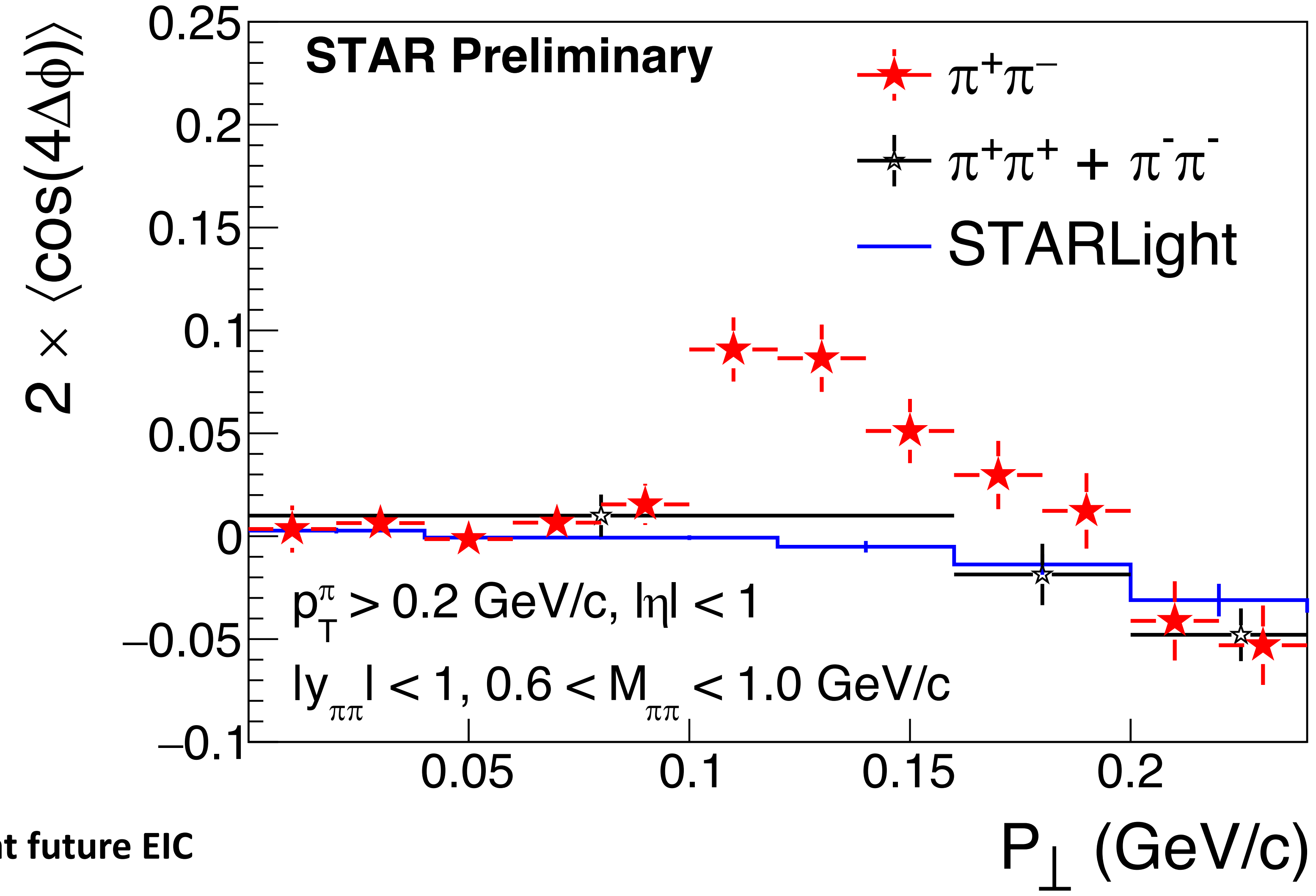
Photoproduction of the ρ^0 Meson

Observation of significant $\cos(4\Delta\phi)$ modulation with respect to background

Predicted to be sensitive to the gluon Generalized Transverse Momentum Dependent (GTMD) Distribution [1]

"…offers direct access to the second derivative of the saturation scale with respect to $b_\perp^2$" [1]

Tensor Pomeron model may also lead to $\cos 4\Delta\phi$ modulations



Same analysis possible for J/ψ and ϕ at future EIC

- Theory input needed for quantitative description of data

[1] J. Zhou Phys. Rev. D **94** (2016), 114017

Summary 1

1. Measurements of exclusive $\gamma\gamma \rightarrow e^+e^-$ process

2. Experimental demonstration that the $\sqrt{\langle P_\perp^2 \rangle}$ spectra from $\gamma\gamma \rightarrow l^+l^-$ **depends on impact parameter** (4.8σ observation)

3. **First Earth-based observation of Vacuum Birefringence :**
   Observed (6.7σ) via angular modulations in linear polarized $\gamma\gamma \rightarrow e^+e^-$ process

Summary 2 (Applications)

New observable measured for photoproduced ρ^0 Meson

- Significant $\cos 2\Delta\phi$ and $\cos 4\Delta\phi$ modulations observed at STAR
- May be sensitive to gluon Generalized Transverse Momentum Dependent (GTMD) Distribution
- May be related to the spin of Pomeron (in Pomeron model)
- Theory input still needed for quantitative description of data
- Even more opportunities at the EIC with J/ψ, ϕ, etc.

Thank you for your attention

Awards, Talks and Papers

Awards:

- Nuclear Physics A Young Scientist Award, Quark Matter 2019

Selected Talks:

- Seminar, “Energy Dependence of Jet Quenching Signatures”, Brookhaven National Laboratory, Jan 18, 2019
- Lecture, “Machine Learning Opportunities in STAR”, STAR Collaboration Meeting Student Day, March 29, 2019
- Seminar, “Machine Learning for Heavy Ion Collisions”, Shandong University, May 10, 2019
- Lecture, “Exploring QCD Matter at High Baryon Density”, FAIRNESS, May 24, 2019
- Plenary, “STAR Upgrades”, RHIC & AGS User’s Meeting, June 4, 2019
- Parallel, “STAR Upgrades”, Initial Stages, June 24, 2019
- Parallel, “Measurement of the $\gamma\gamma \rightarrow e^{+}e^{-}$ Process and its Angular Correlations”, Quark Matter, Nov 5, 2019

Papers:

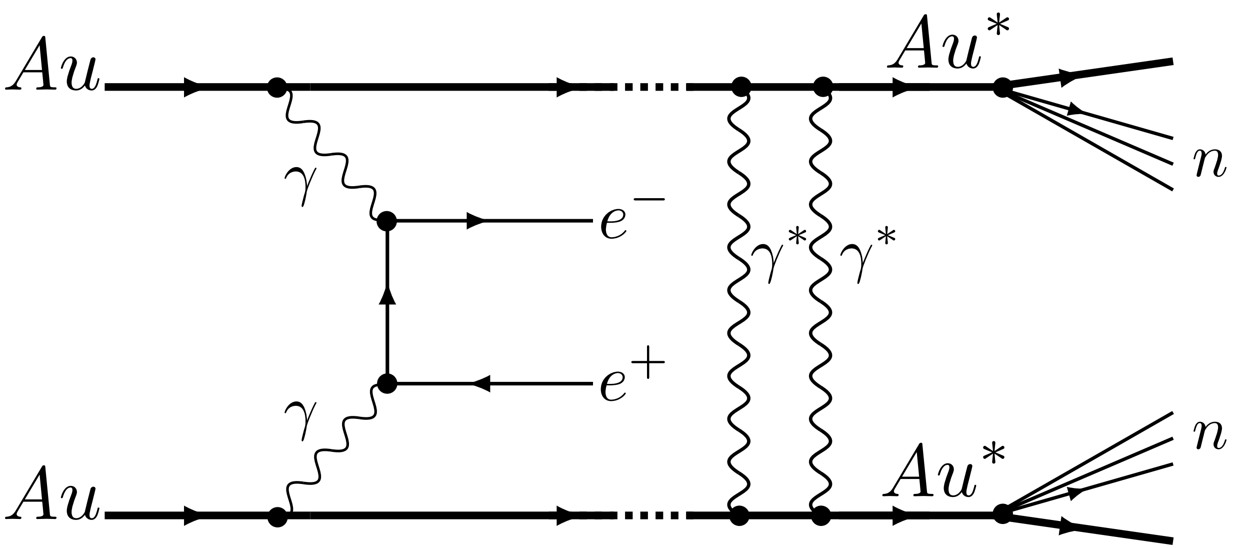
- (Principle Author), “J/ψ suppression in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV through the dimuon channel at STAR”, Physics Letters B, (2019)
- W. Zha, JDB, et al., “Initial transverse-momentum broadening of Breit-Wheeler process in relativistic heavy-ion collisions”, Physics Letters B (2019)
- (Corresponding Author), “Probing Extreme Electromagnetic Fields with the Breit-Wheeler process”, arxiv:1910.12400

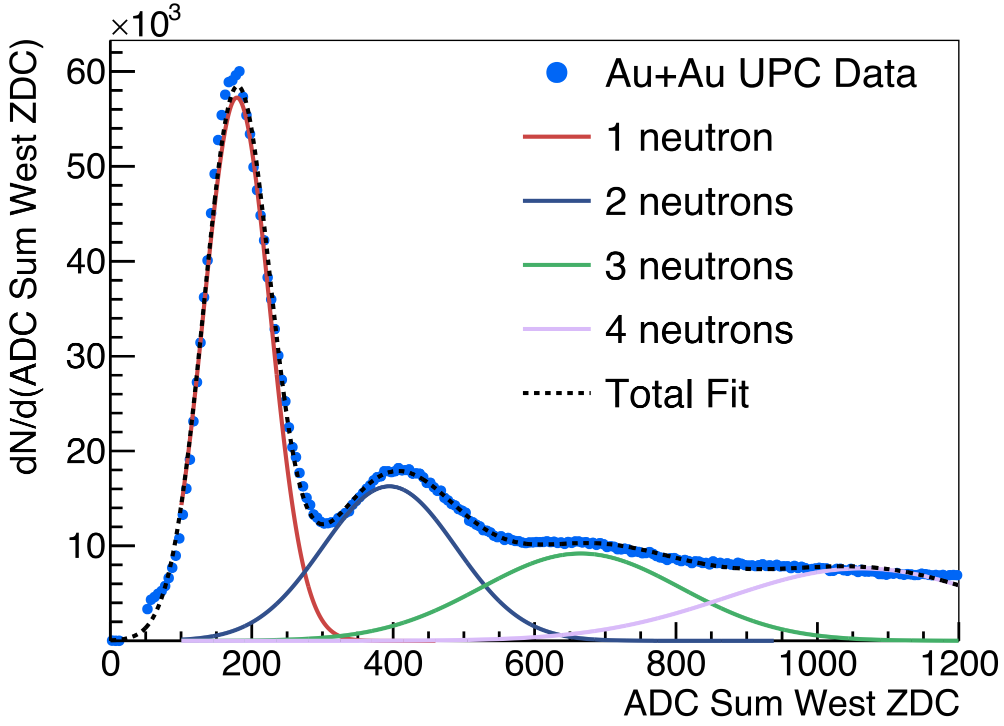
Backup

The $\gamma\gamma \to e^+e^-$ Process

1934 Breit & Wheeler : "Collision of two Light Quanta"

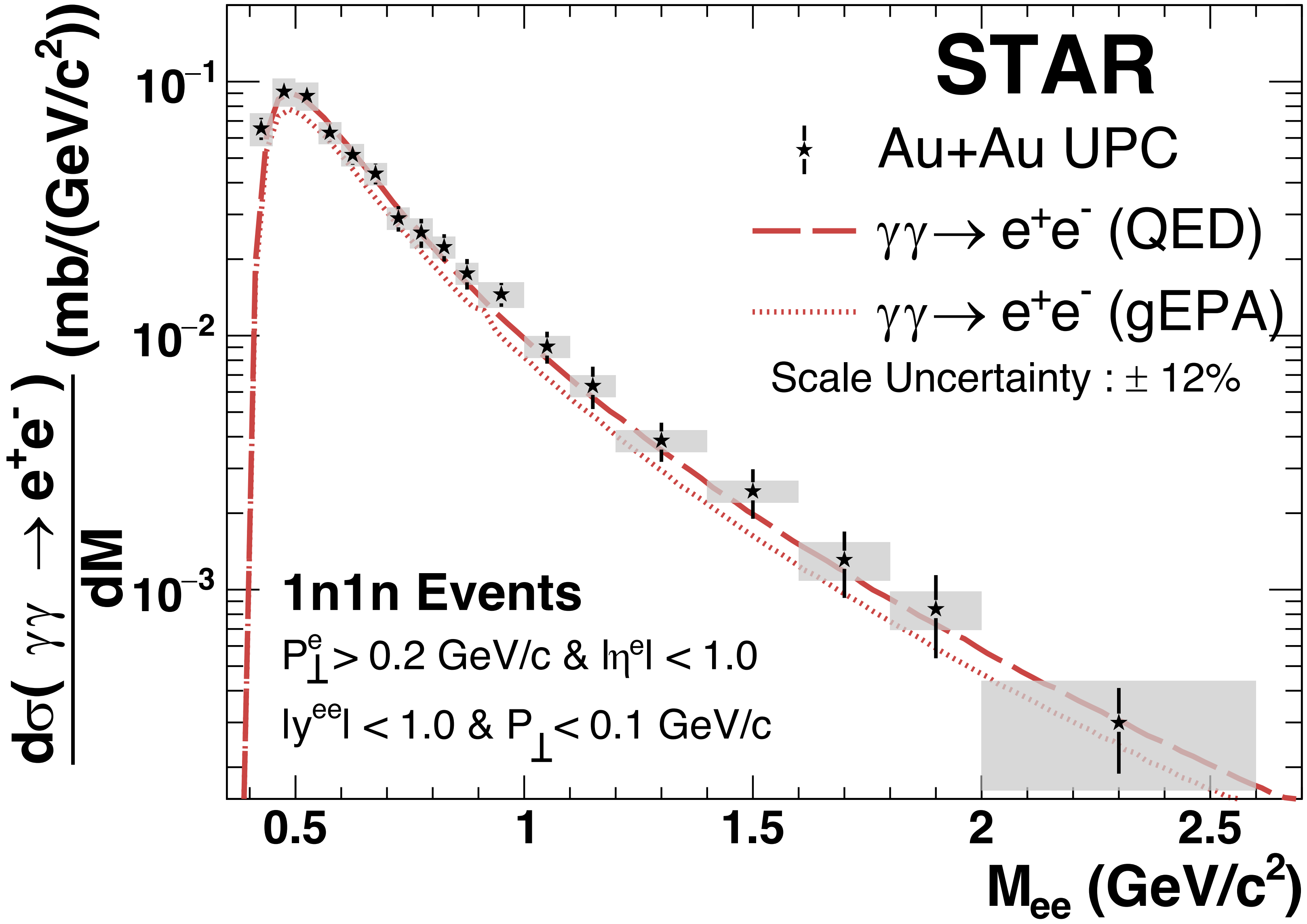
G. Breit and J. A. Wheeler. *Physical Review* 46 (1934): 1087





- Trigger on neutrons in ZDC → Select events with mutual Coulomb excitation followed by dissociation

$d\sigma/dM$ for events with 1n1n events



1n1n: events with 1 neutron in each ZDC

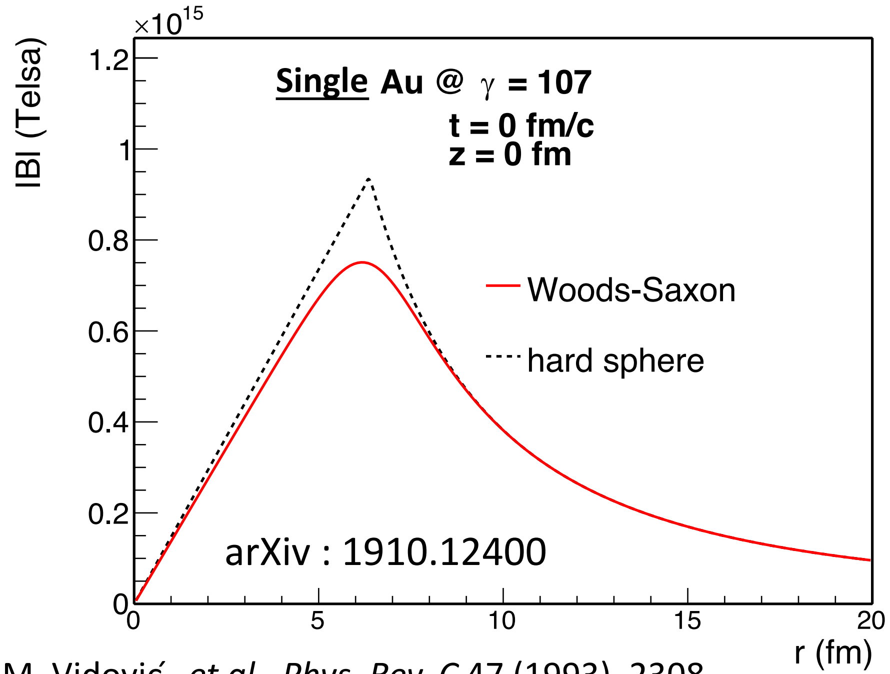
Application : Mapping the Magnetic Field

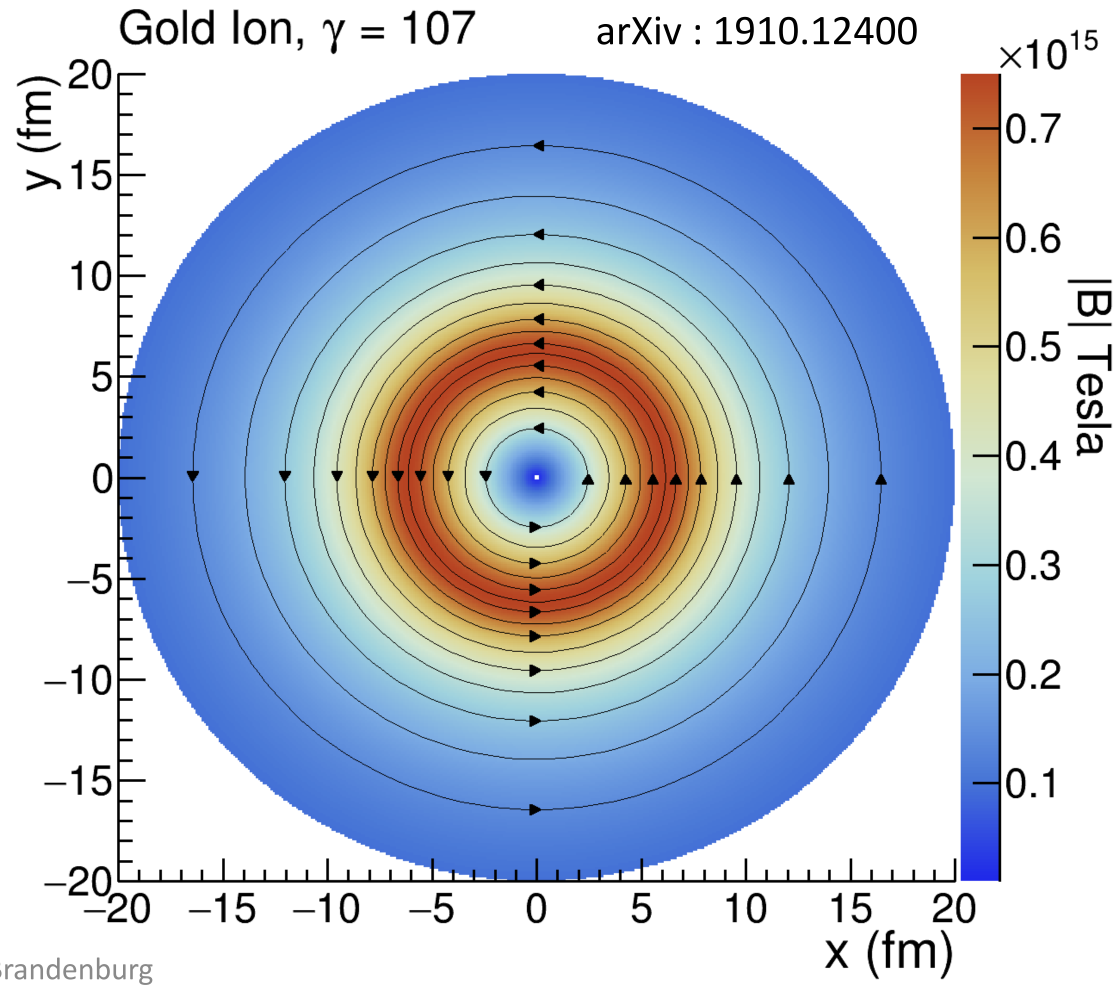
Total and differential cross-sections (e.g. $d\sigma/dP_{\perp}$) for $\gamma\gamma \rightarrow e^{+}e^{-}$ are related to <u>field strength and configuration</u>

photon density is related to energy flux of the electromagnetic fields [1]

$$n \propto \vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B}$$

→ Report $\vec{B}$ (single ion) that matches measured cross-section





[1] M. Vidović, *et al.*, *Phys. Rev. C* 47 (1993), 2308

Application : Mapping the Magnetic Field

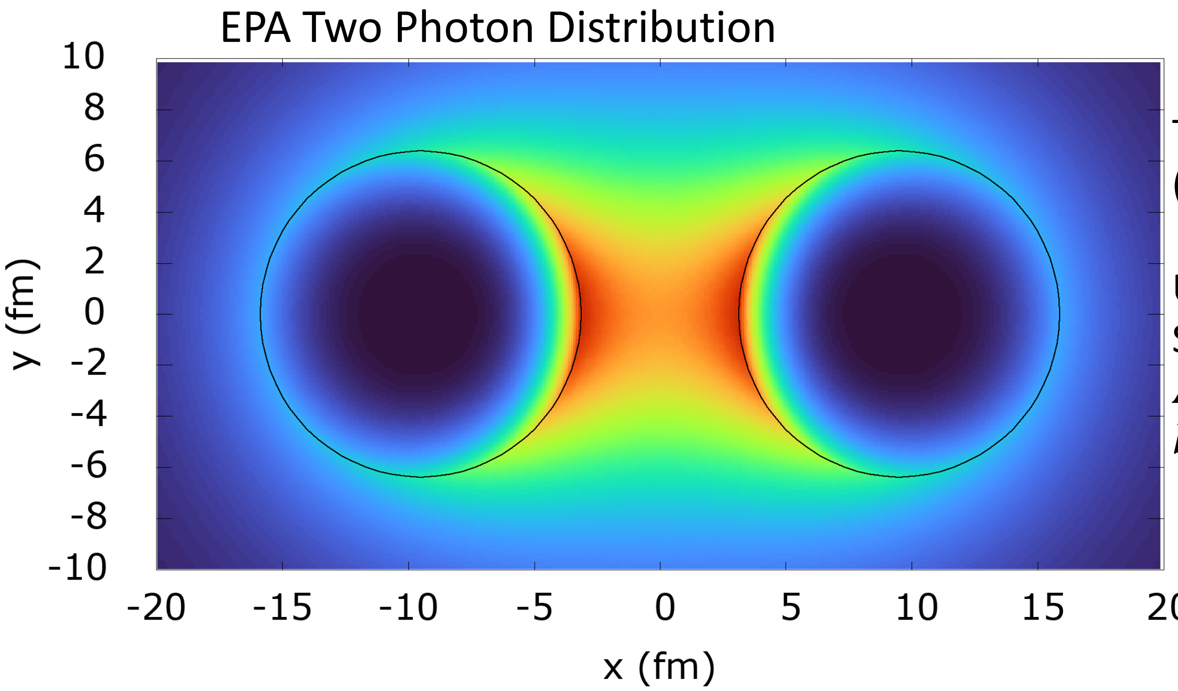
The colliding photons in the $\gamma\gamma \rightarrow e^+e^-$ process <u>originate from the Lorentz-contracted Electromagnetic fields</u>

photon density is related to energy flux of the electromagnetic fields

$$n \propto \vec{S} = \frac{1}{\mu_0}\ \vec{E} \times \vec{B}$$

For highly Lorentz contracted fields

$|E| \approx |B|$ with $\vec{E} \perp \vec{B}$ and $\vec{S} \propto |E|^2 \approx |B|^2$



Two-photon density (arb. norm.)

Uniformly Charged Sphere

Au ion, $R = 6.38$ fm

$b = 19$ fm

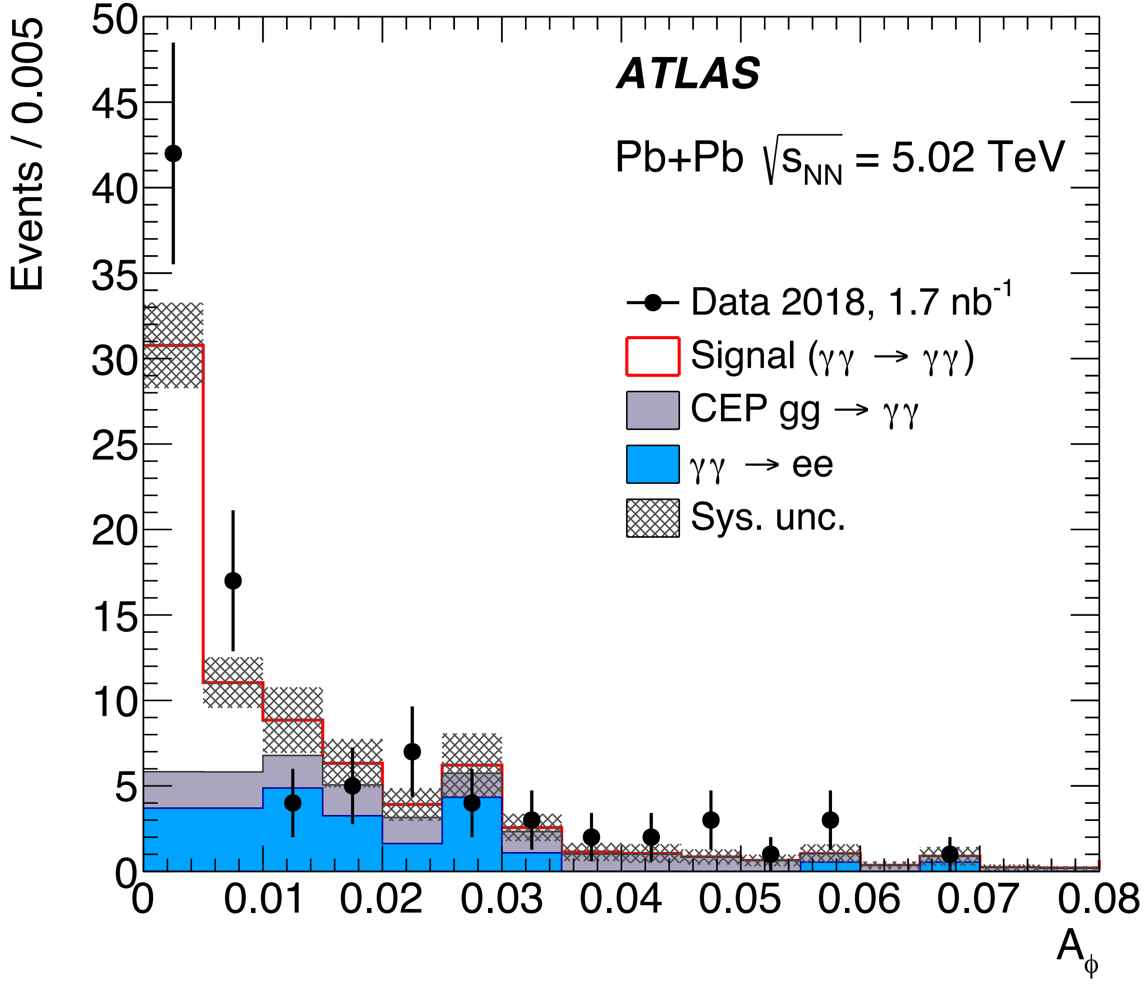
Equivalent Photon Approximation, photon density (single ion):

$$n(\omega; b) = \frac{1}{\pi\omega}|E_\perp(b,\omega)|^2 = \frac{1}{\pi\omega}|B_\perp(b,\omega)|^2 = \frac{4Z^2\alpha}{\omega}\left|\int \frac{d^2k_\perp}{(2\pi)^2} k_\perp \frac{F(k_\perp^2 + \omega^2/\gamma^2)}{k_\perp^2 + \omega^2/\gamma^2} e^{-i\, b\cdot k_\perp}\right|^2$$

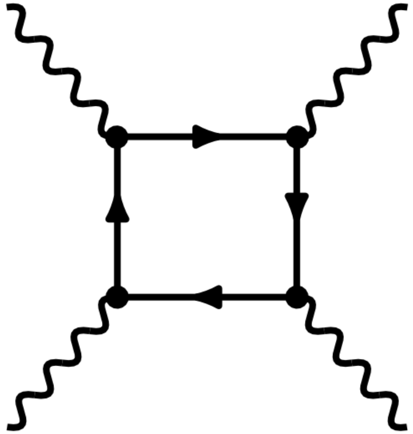
[1] M. Vidović, *et al.*, *Phys. Rev. C* 47, 2308 (1993).

[2] C. F. v. Weizsäcker, *Z. Phys.* 88, 612 (1934).

Example : Light-by-Light Scattering



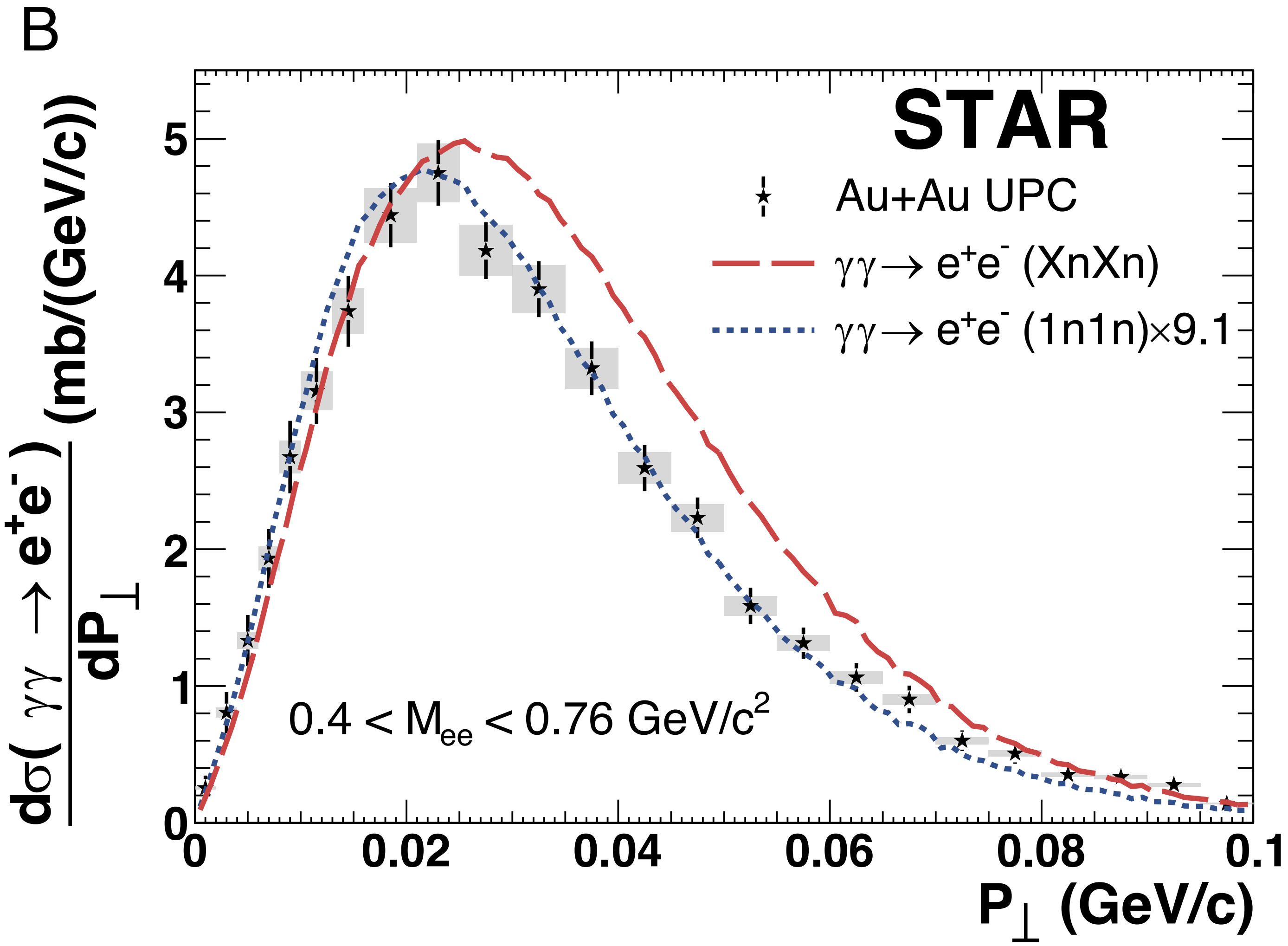
ATLAS Observed Light-by-Light Scattering in UPCs:



- Purely quantum mechanical process (α_{em}^4)
- Light-by-Light scattering involves real photons by definition

ATLAS, *Nature Physics* 13 (2017), 852

$d\sigma(\gamma\gamma \rightarrow e^+e^-)/dP_\perp$



- Cross-section peaks at low $P_\perp$, as expected for real photon collisions
- QED calculations predicts higher $\langle P_\perp \rangle$ at smaller impact paramters (b)

More neutrons in ZDC ⟷ Fewer neutrons in ZDC

Smaller $\langle b \rangle$ — Larger $\langle b \rangle$

- Total σ corrected to XnXn condition, but shape is not corrected.
- Data agrees well with QED calculation (scaled 1n1n condition)

QED Calculation: W. Zha, J.D.B., Z. Tang, Z. Xu arXiv:1812.02820 [nucl-th]

Photoproduction of the ρ^0 Meson

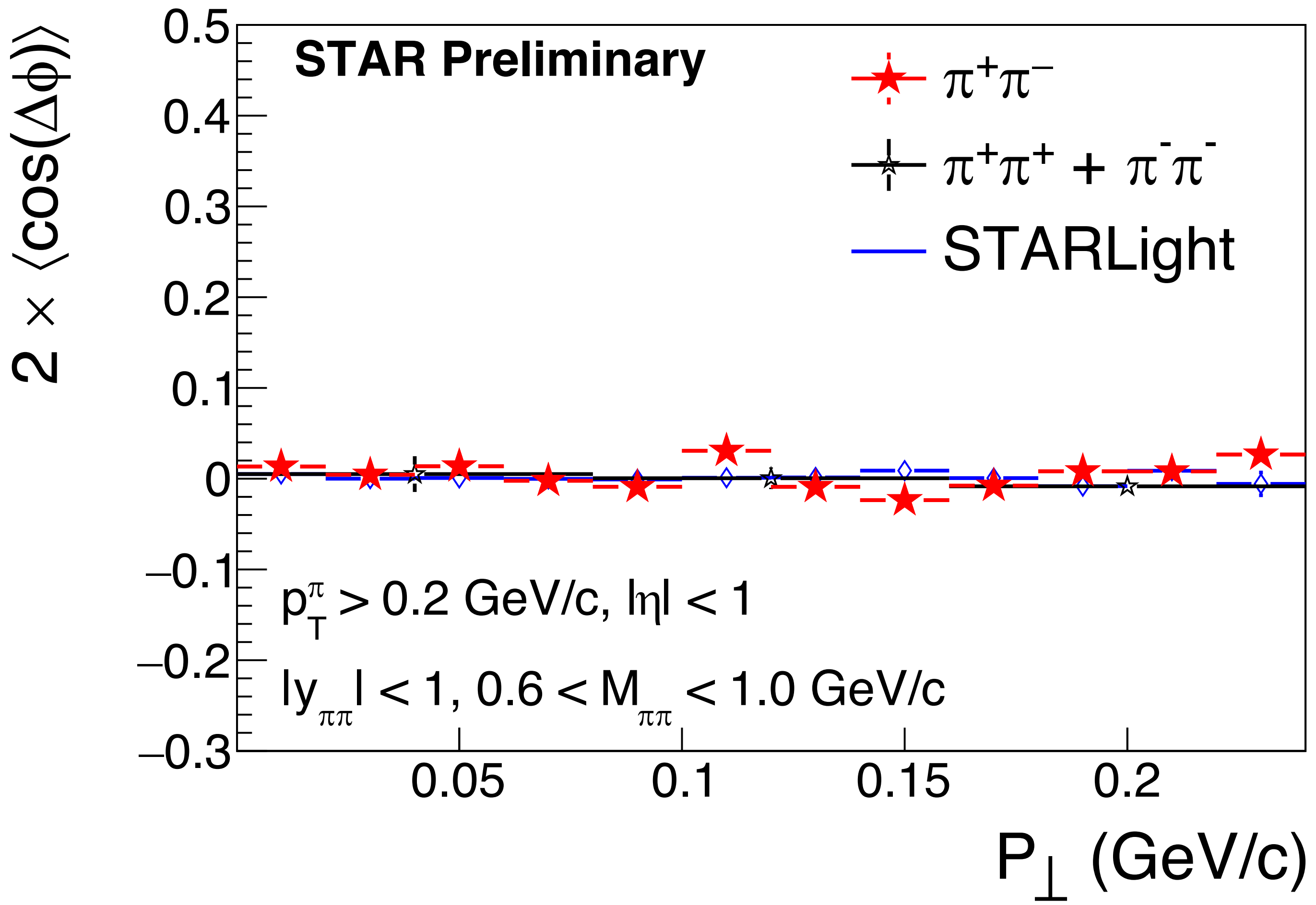
Use similar observable for $\rho^0 \rightarrow \pi^+\pi^-$

- Calculate coefficients $\langle\cos(n\Delta\phi)\rangle$
- Sensitive to gluon distribution and gradients

$n = 1$: Closure test, no modulation expected

Background estimates:

1. STARLight (does not include polarization effects)
2. Data-driven (like-sign pairs)



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J. Zhou Phys. Rev. D **94** (2016), 114017