Results on Breit-Wheeler Process and Vacuum Birefringence

Xiaofeng Wang (王晓凤) for the STAR Collaboration

Shandong University (山东大学)

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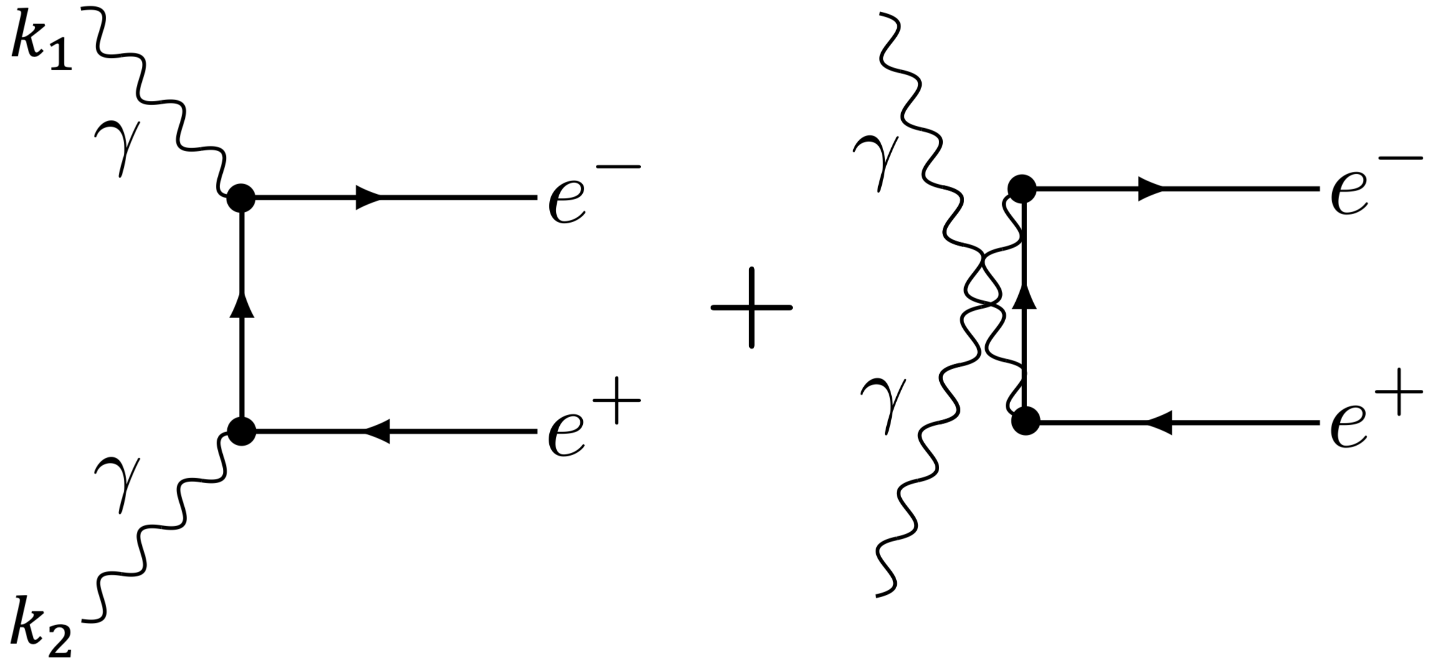
NSFC National Natural Science Foundation of China

Outline

- What is the Breit-Wheeler Process?
- Breit-Wheeler Process in Heavy Ion Collisions
- Vacuum Birefringence in Heavy Ion Collisions
- Summary & Outlook

The Breit-Wheeler Process : $\gamma\gamma \rightarrow e^+e^-$



◆**Breit-Wheeler process:** converting **real** photon into e^+e^-

Breit & Wheeler, Phys. Rev. 46 (1934) 1087

Breit-Wheeler Process, Why So Elusive ?

◆Already in 1934 Breit and Wheeler knew it was hard, maybe impossible?

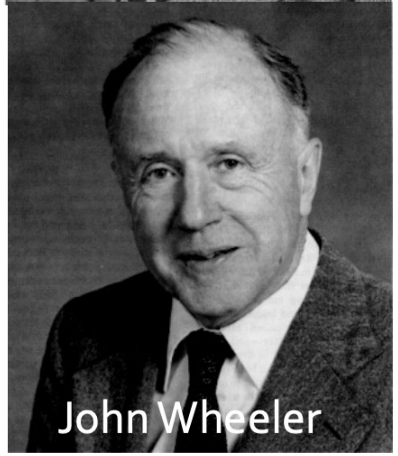
DECEMBER 15, 1934 PHYSICAL REVIEW VOLUME

Collision of Two Light Quanta

G. BREIT* AND JOHN A. WHEELER,** *Department of Physics, New York University*

(Received October 23, 1934)

As has been reported at the Washington meeting, pair production due to collisions of cosmic rays with the temperature radiation of interstellar space is much too small to be of any interest. We do not give the explicit calculations, since the result is due to the orders of magnitude rather than exact relations. It is also hopeless to try to observe the pair formation in laboratory experiments with two beams of x-rays or γ-rays meeting each other on account of the smallness of σ and the insufficiently large available densities of quanta. In the considerations of Williams,



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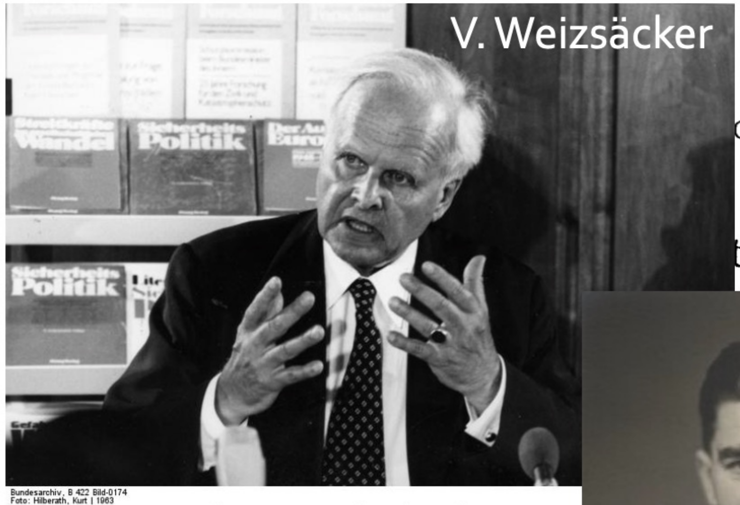

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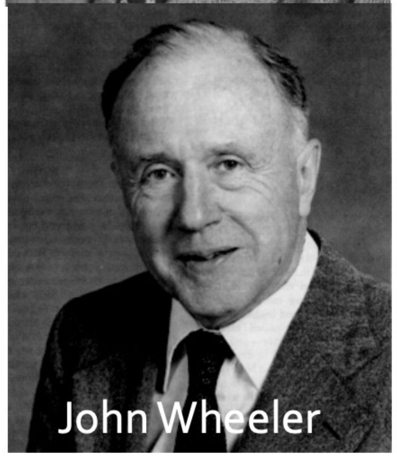
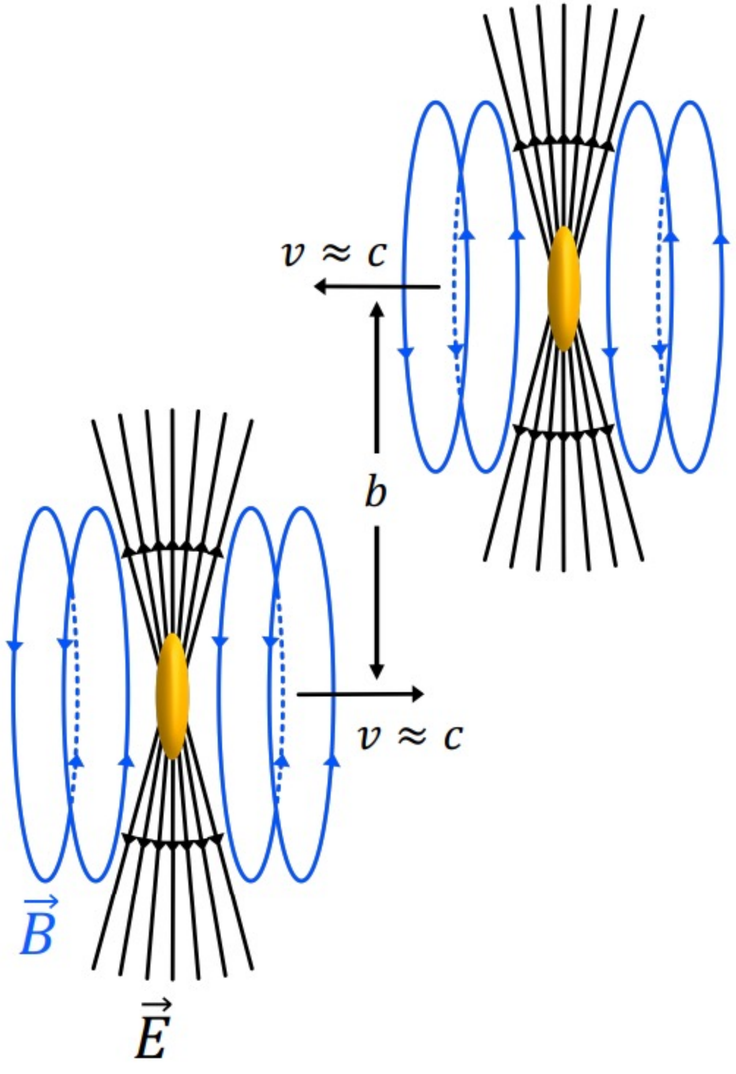
◆ Or maybe not impossible?

of quanta. In the considerations of Williams, however, the large nuclear electric fields lead to large densities of quanta in moving frames of reference. This, together with the large number of nucleii available in unit volume of ordinary materials, increases the effect to observable amounts. Analyzing the field of the nucleus into quanta by a procedure similar to that of v. Weizsäcker,[4] he finds that if one quantum $h\nu$

E. J. Williams, Phys. Rev. 45, 729(1934)
K. F. Weizsacker, Z. Physik, 612 (1934)



Ultra-Peripheral Heavy Ion Collisions (UPCs)



- Highly Lorentz-contracted charged nuclei produce electromagnetic fields (EM)
- Equivalent Photon Approximation (EPA): EM fields → a flux of **quasi-real photons**

  Weizsäcker, C. F. v. Zeitschrift für Physik 88 (1934): 612
- High photon density from highly charged nuclei ($\propto Z^2$)
- Virtuality $Q^2 \lesssim (\hbar/R_A)^2$ in UPCs ⟹ **almost real**

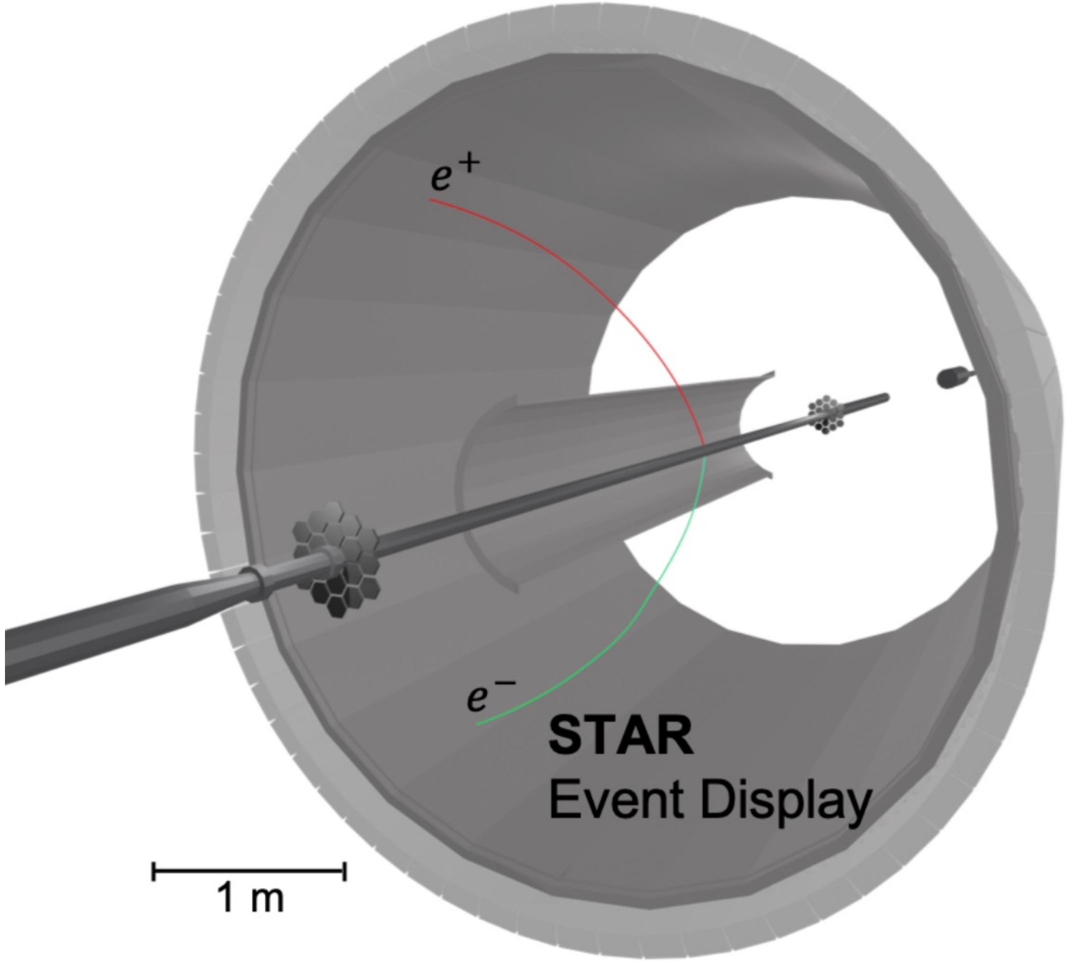
  Ann.Rev.Nucl.Part.Sci. 55 (2005) 271-310
- Virtuality cancels at low photon transverse momentum

  Vidovic, M. and Greiner, M. and Best, C. Phys.Rev.C 47 (1993) 2308-2319

Breit-Wheeler Process in UPCs

- Exclusive production of l^+l^- pair

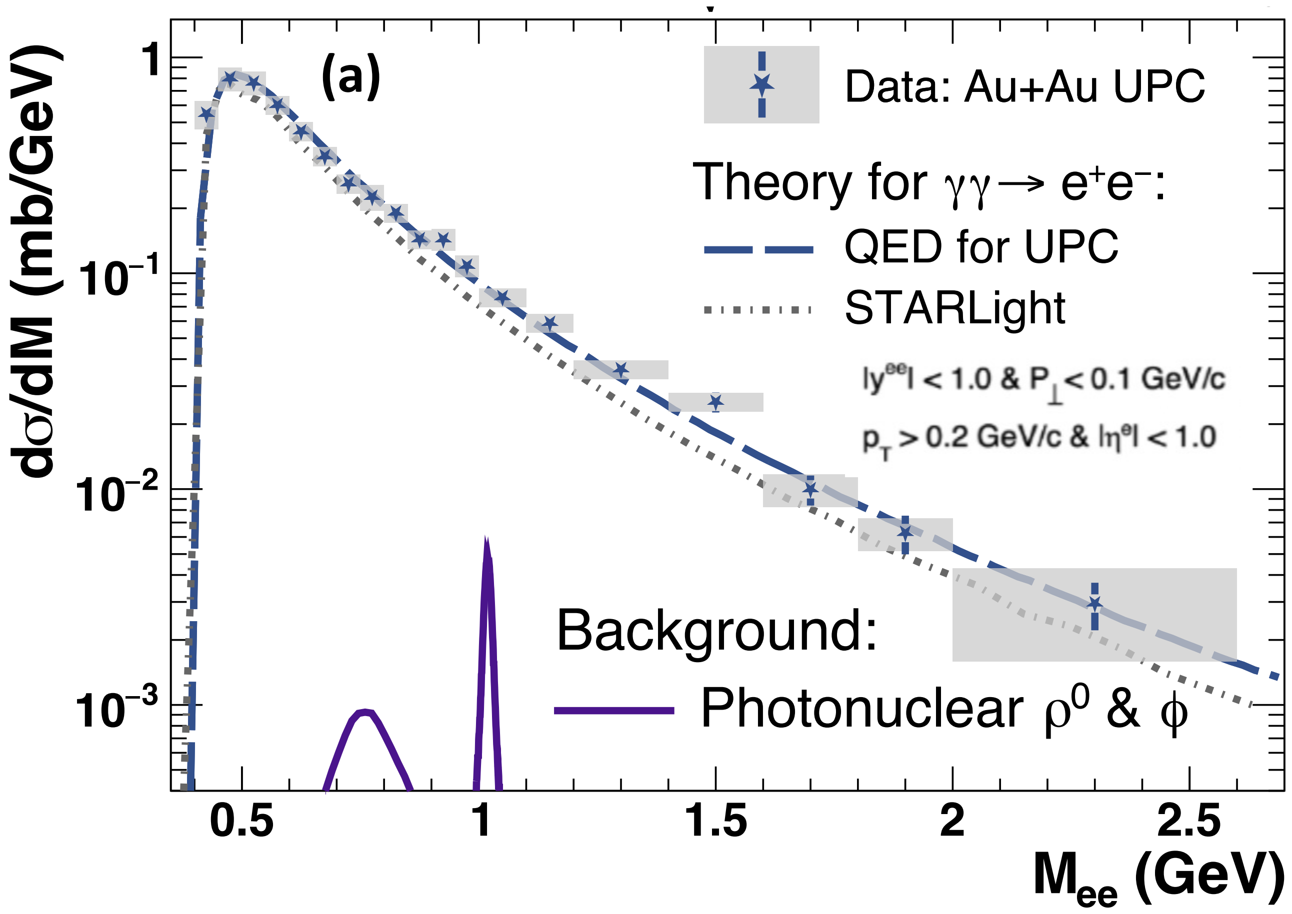
STAR, PRL 127 (2021) 052302



Breit-Wheeler Process in UPCs

- Exclusive production of l^+l^- pair
- Smooth invariant mass spectra

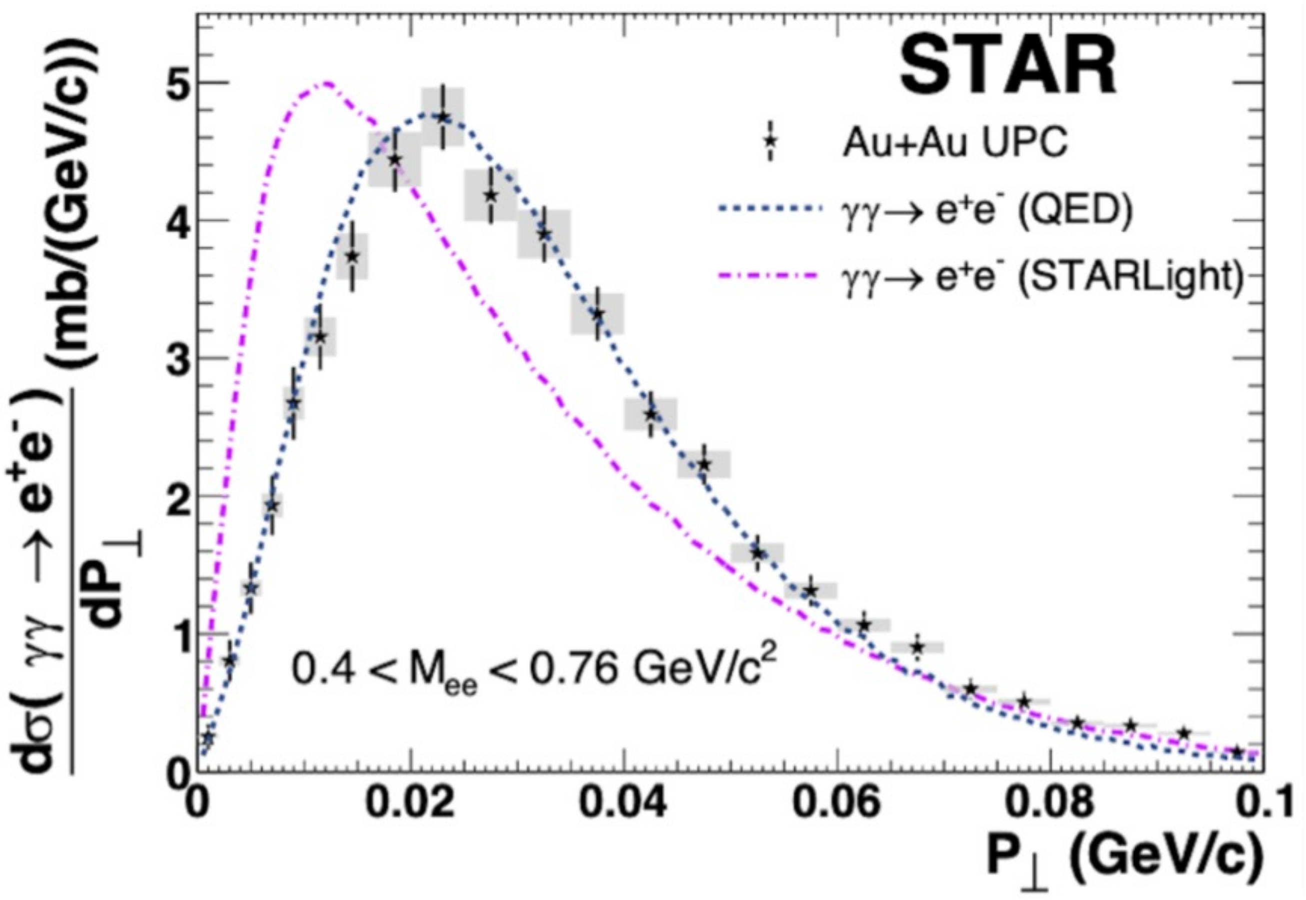
STAR, PRL 127 (2021) 052302



Breit-Wheeler Process in UPCs

- Exclusive production of l^+l^- pair
- Smooth invariant mass spectra
- Concentrated at low p_T
  - Back to back in transverse plane

STAR, PRL 127 (2021) 052302



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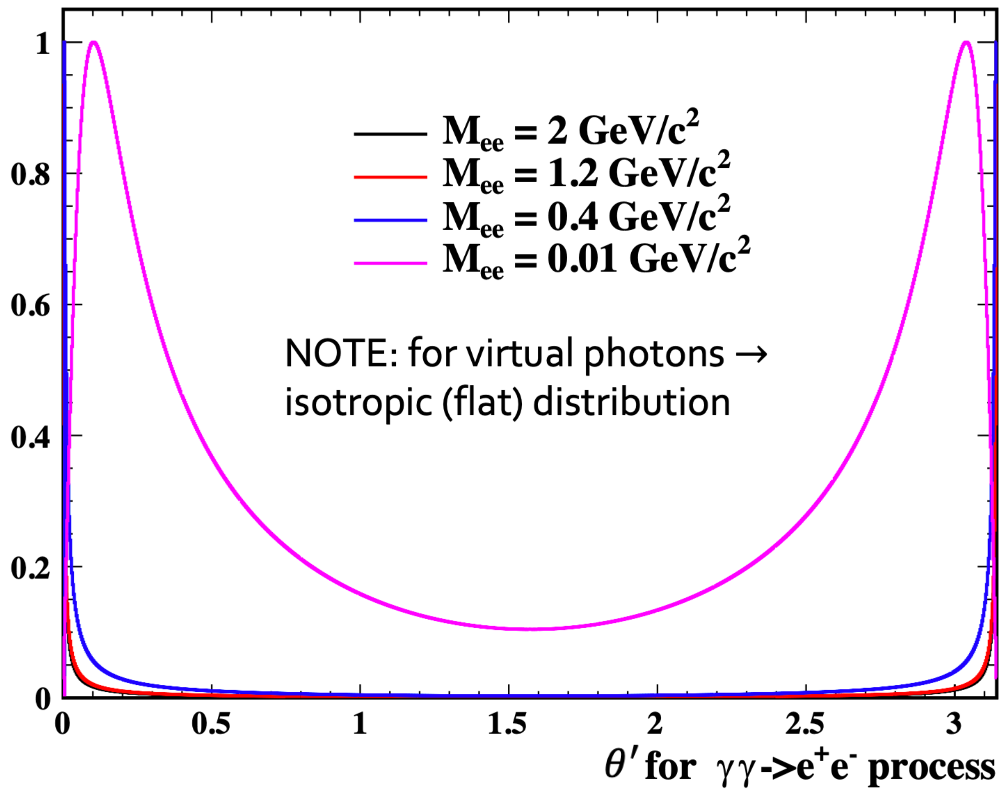
S. Brodsky, T. Kinoshita and H. Terazawa, Phys. Rev. D4, 1532 (1971)

  - Highly virtual photon interactions should have an isotropic distribution
  - θ': angle between l^+ and beam axis in pair rest frame

STARLight: Comput. Phys. Commun. 212 (2017) 258



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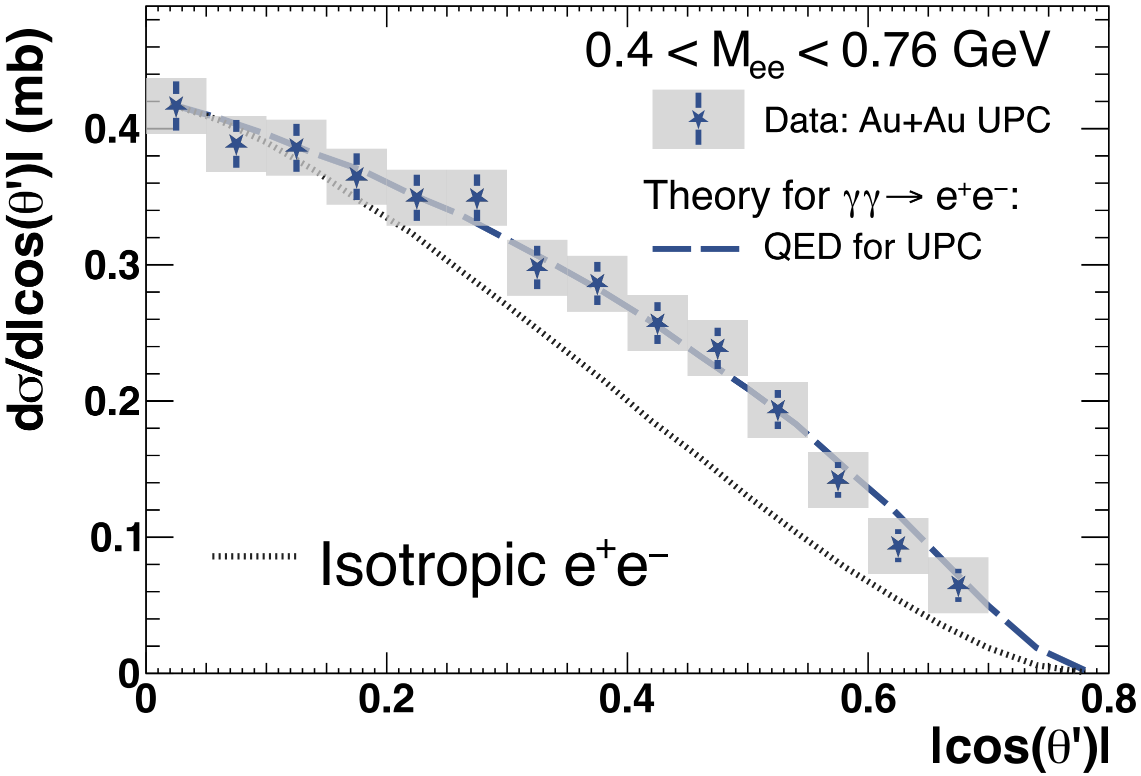
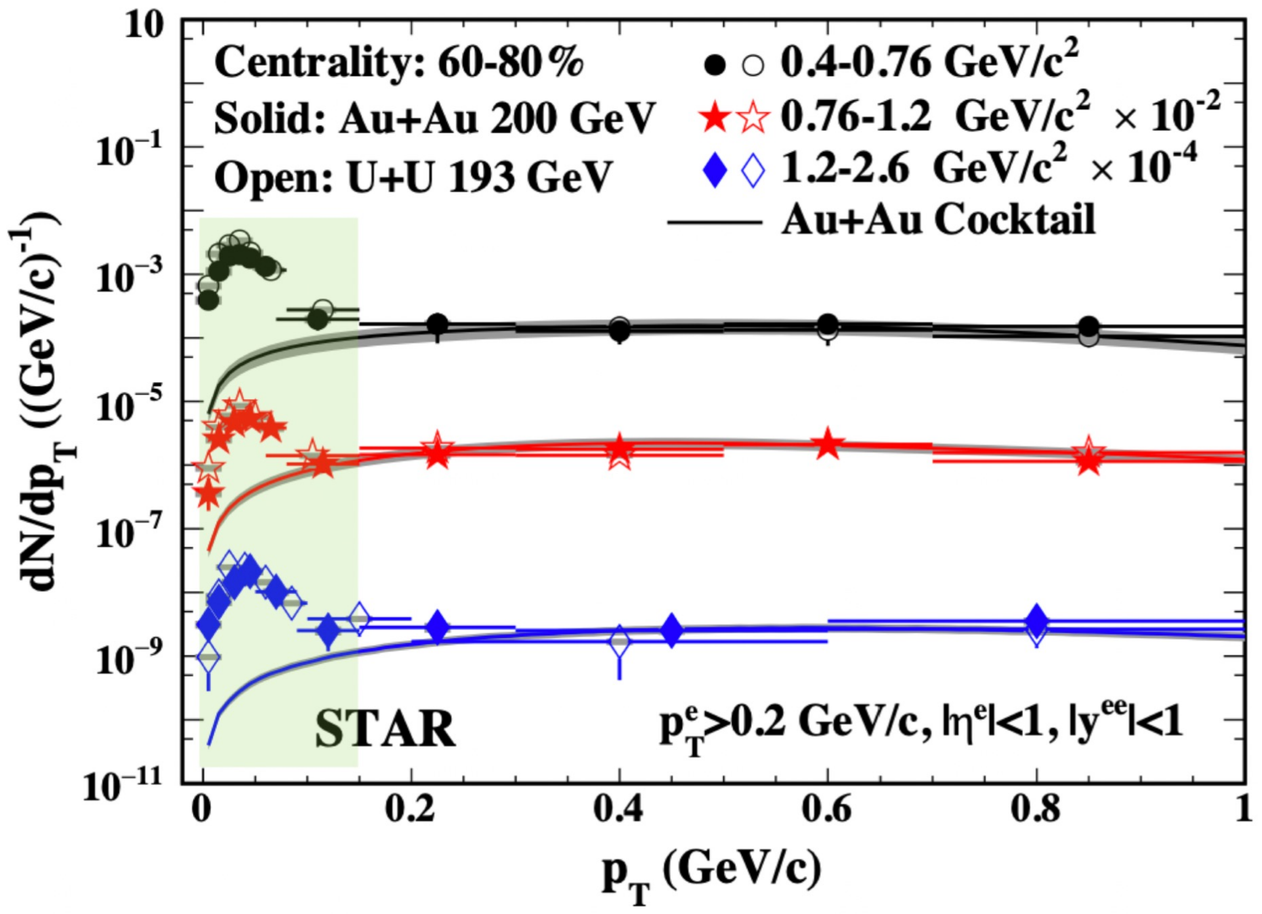
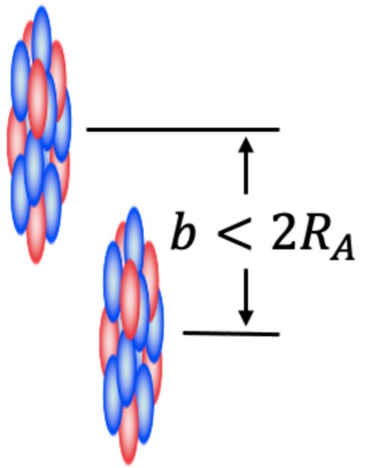


Breit-Wheeler Process in Hadronic Heavy Ion Collisions (HHICs)

STAR, PRL 121 (2018) 132301

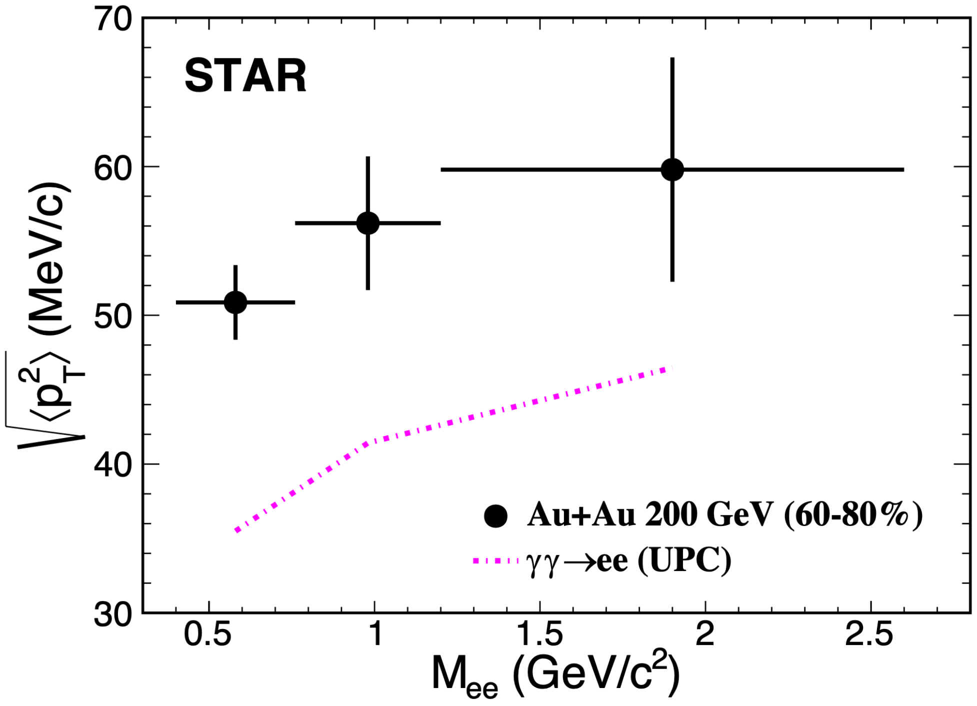




Observation of $\gamma\gamma \to e^+e^-$ in HHICs at STAR

p_T Broadening in HHICs

STAR, PRL 121 (2018) 132301



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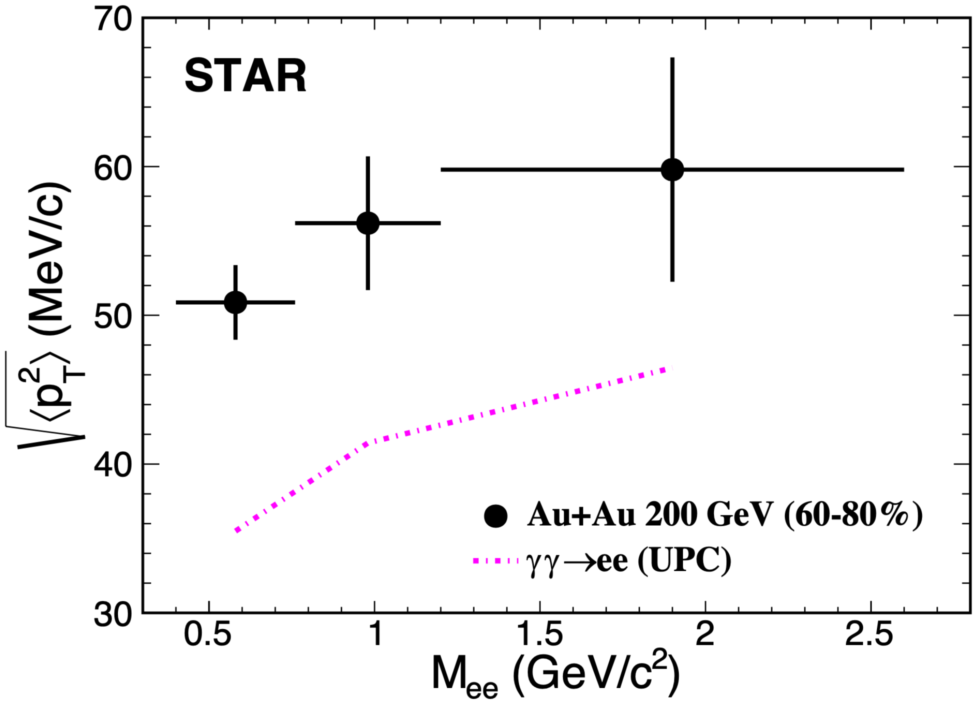
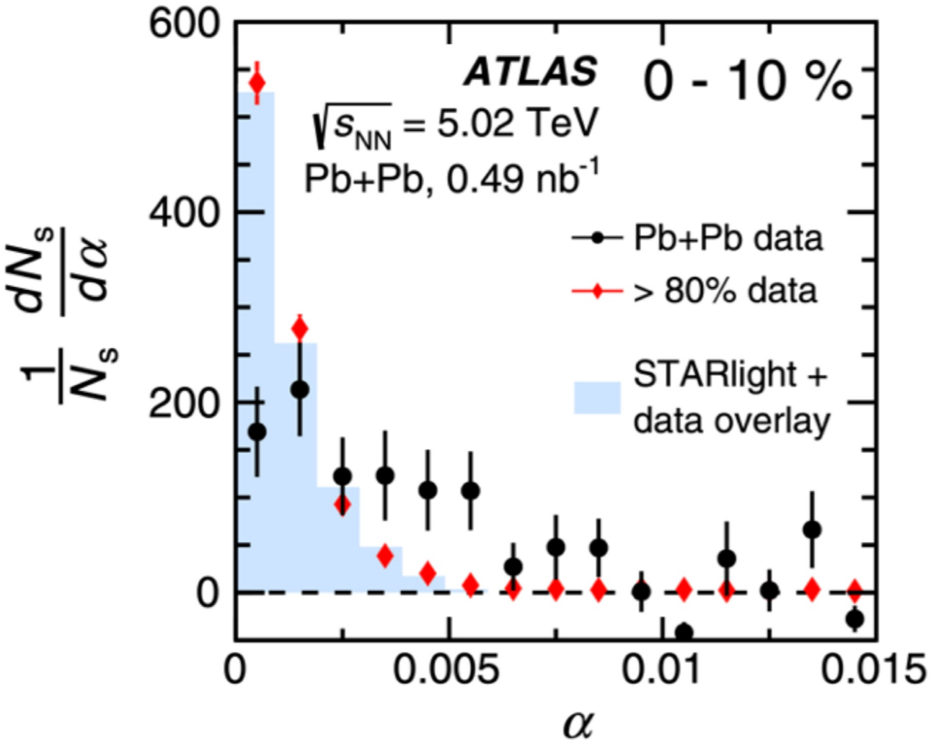
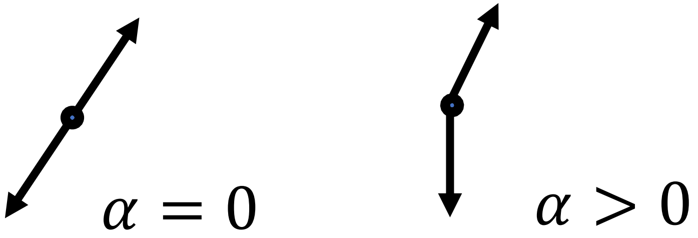


ATLAS, PRL 121 (2018) 212301



$$\alpha = 1 - \frac{|\phi^+ - \phi^-|}{\pi}, \ \alpha \propto p_T^{ll}/M_{ll}$$



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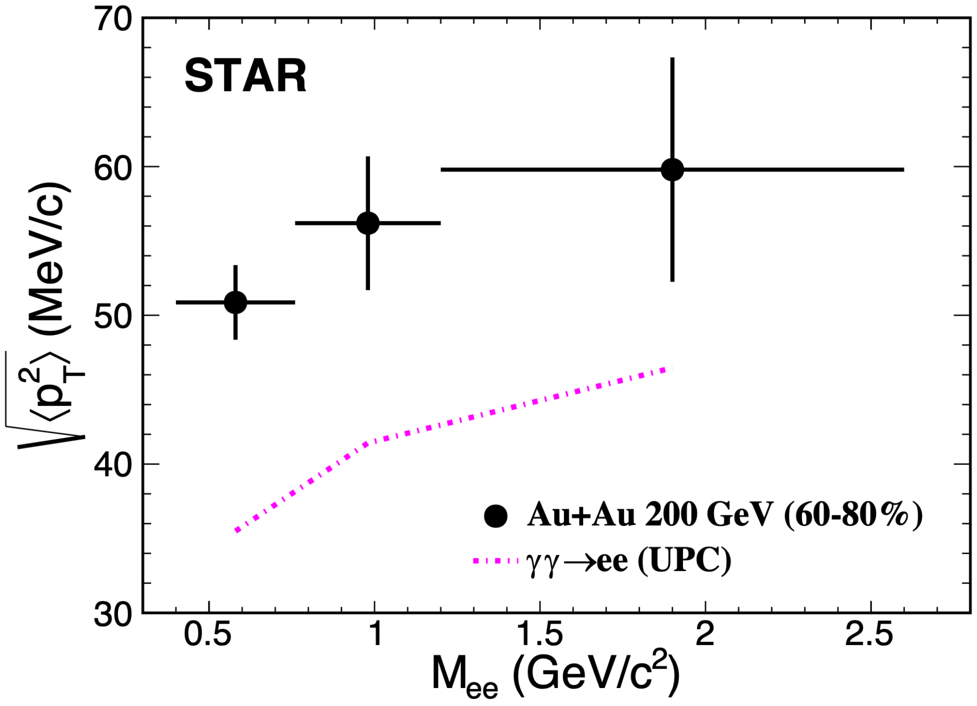

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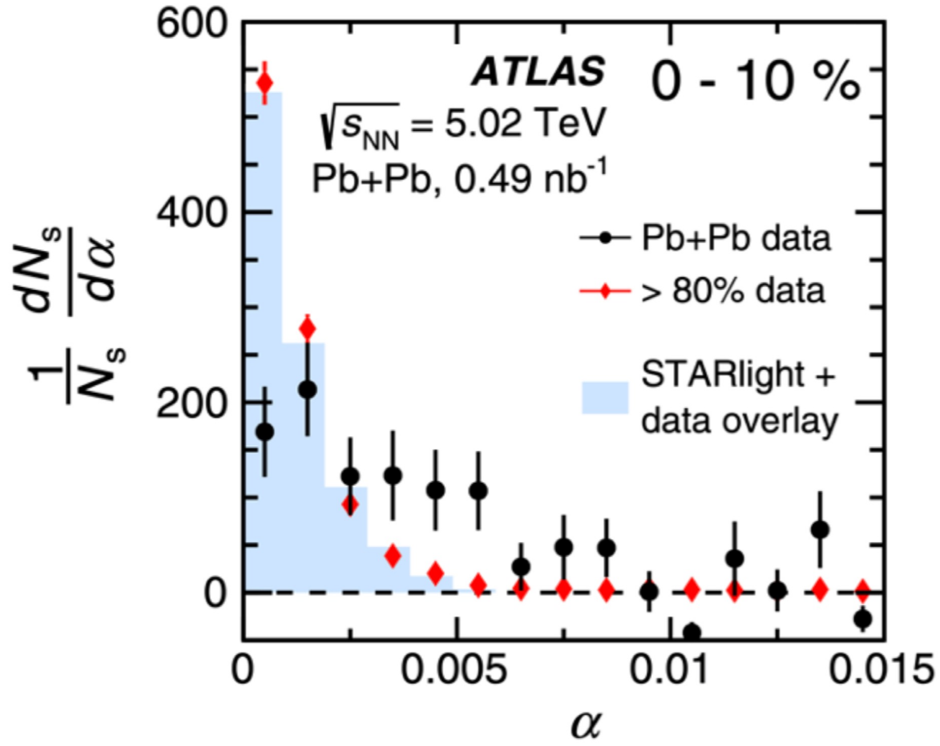

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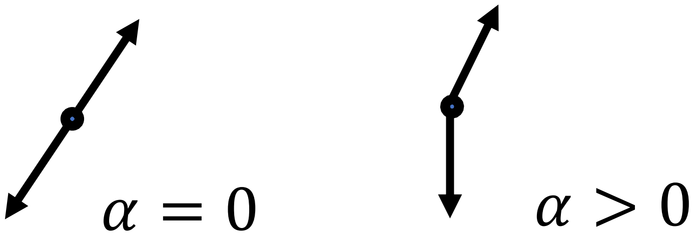
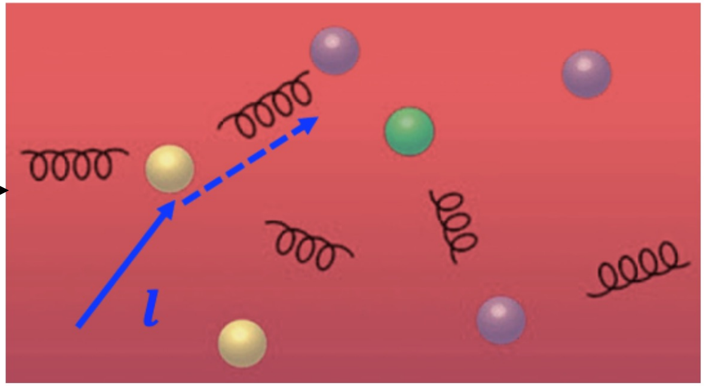


Back-to-back correlation becomes weaker towards central collisions

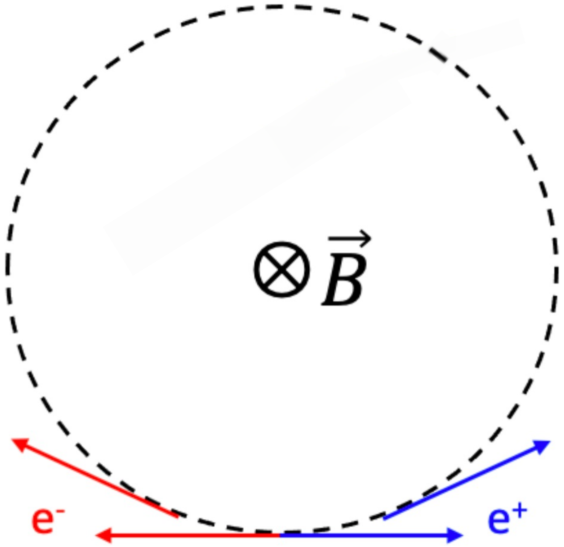
Origin of p_T Broadening in HHICs

Final-state effect?

Coulomb Scattering



Lorentz Force



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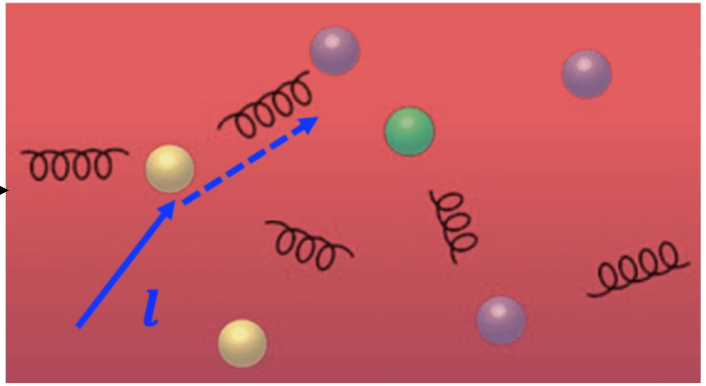

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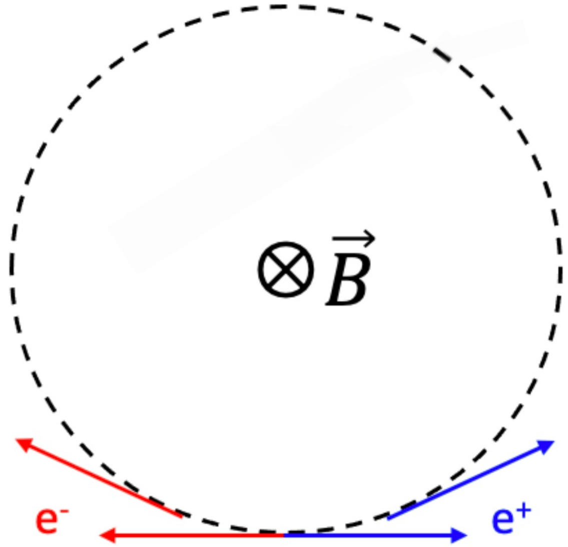
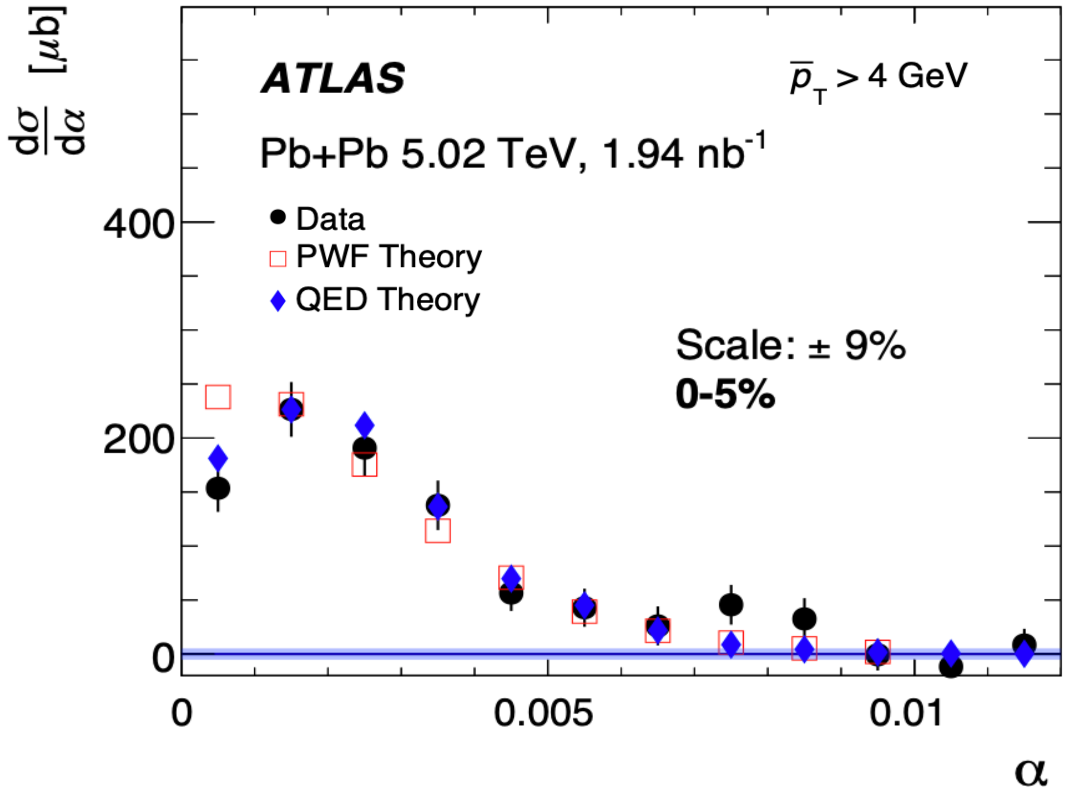


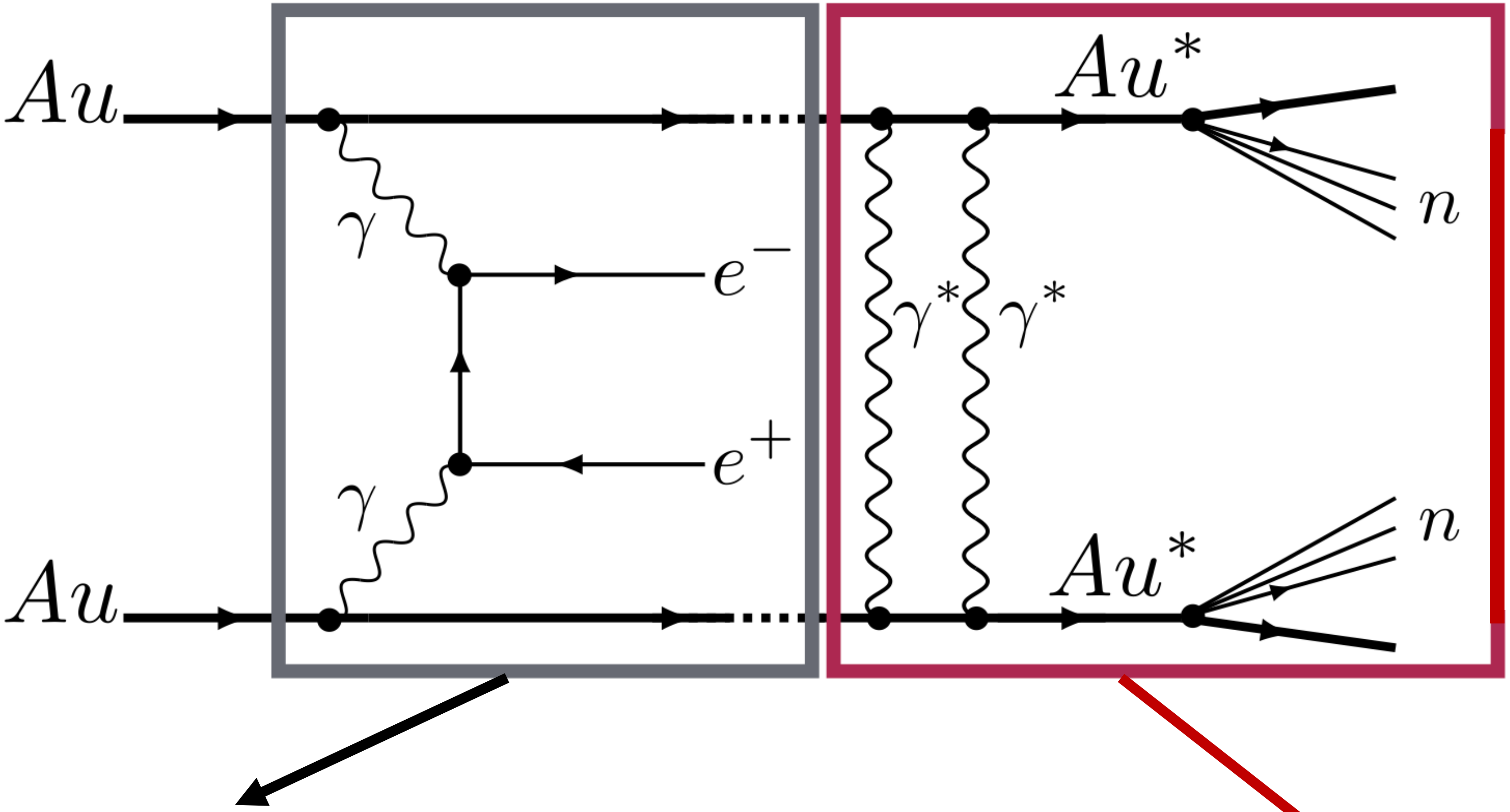
ATLAS, arXiv: 2206.12594

Initial-state effect?



- Described by lowest-order QED without medium effect
  - b dependence of initial photon p_T

Control b in UPCs



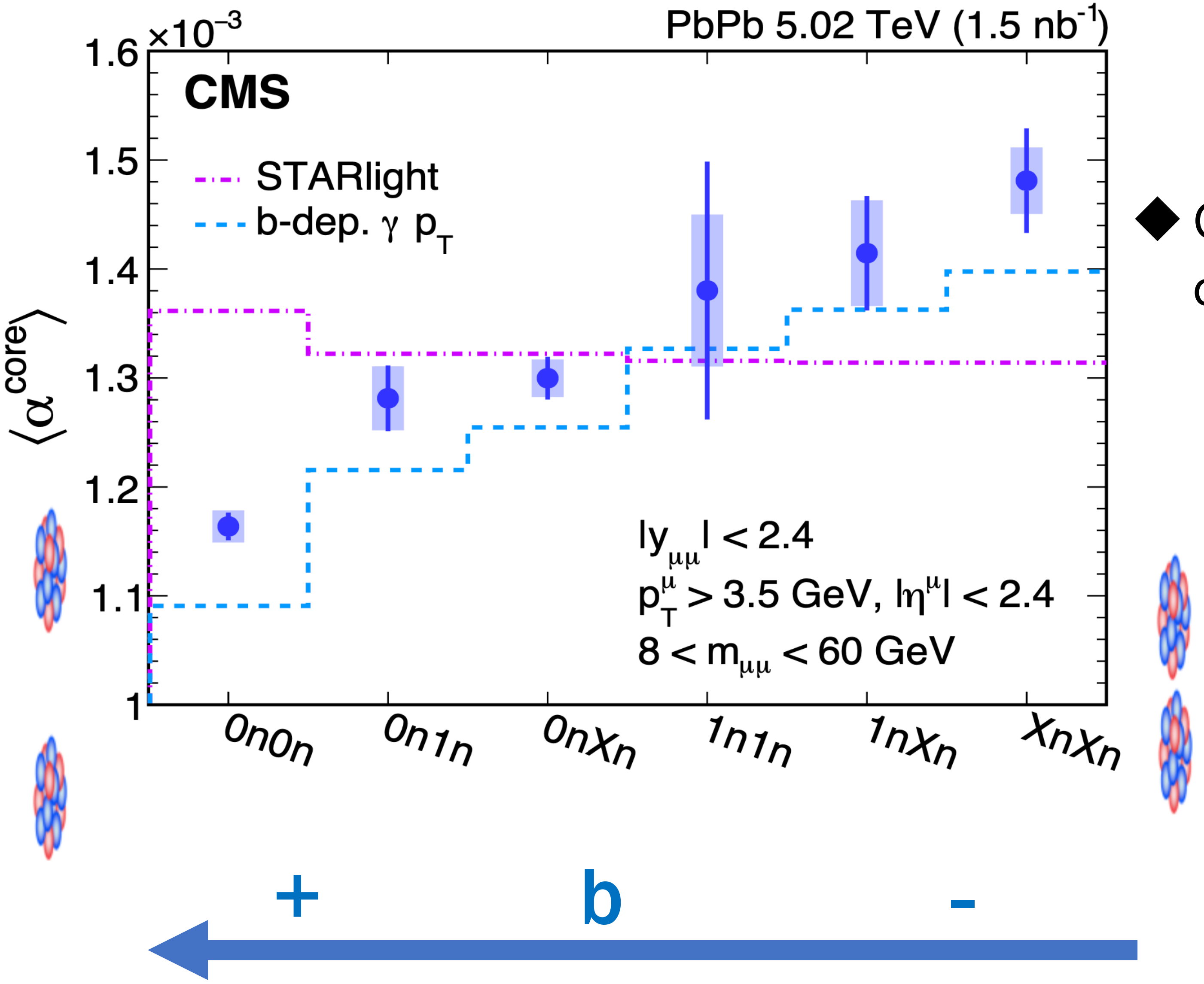
Breit-Wheeler $\gamma\gamma \to e^{+}e^{-}$ pair production process

Mutual Coulomb excitation and nuclear dissociation

- Control b in UPCs

Control *b* in UPCs

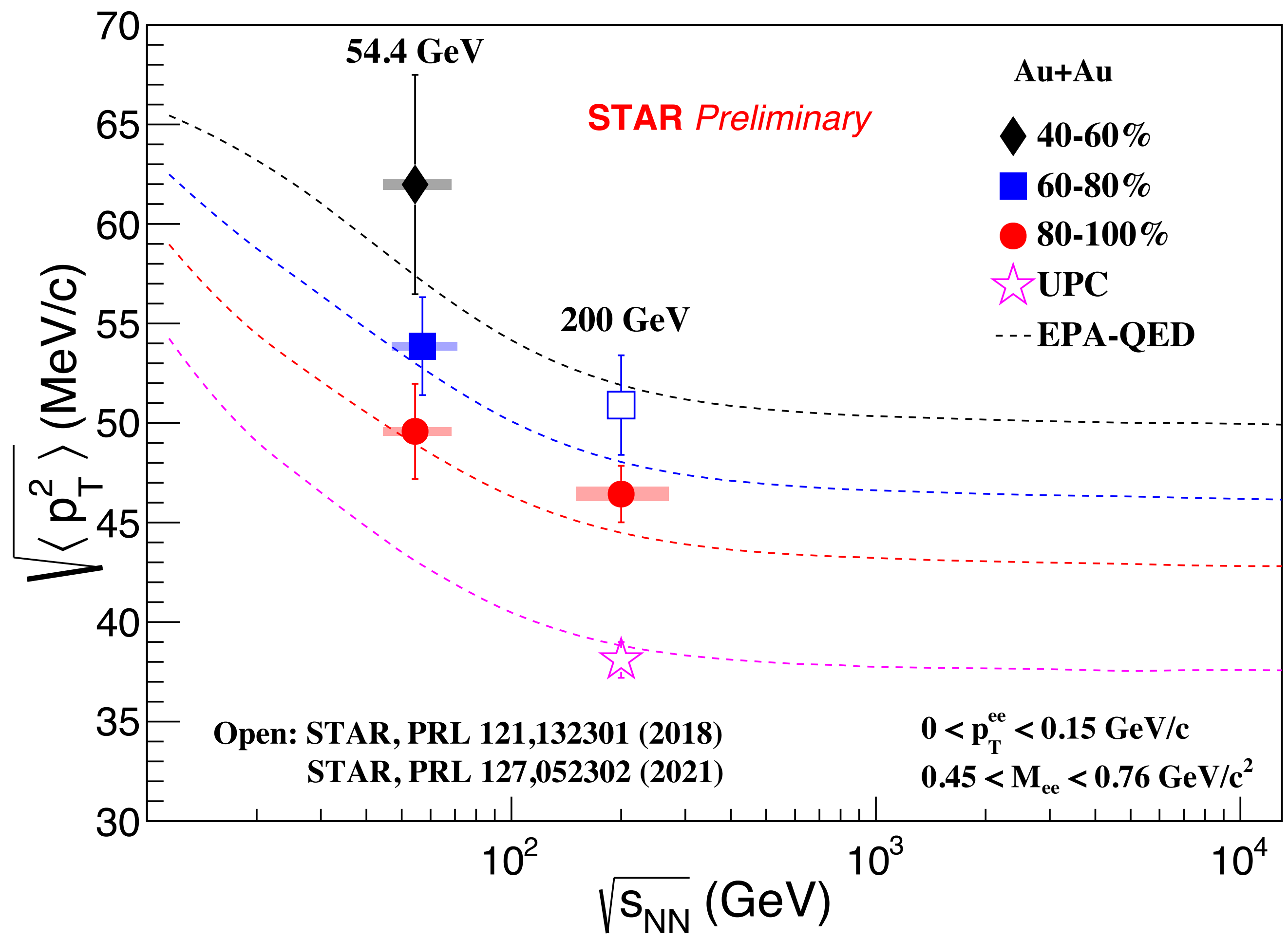
CMS, PRL 127 (2021) 122001



- Qualitatively described by a leading order QED model
  - Initial photon p_T has *b* dependence
  - Systematically lower than data, which could be caused by lacking high order corrections

Impact to Explore QGP EM Properties

QED: Zha et al., Phys.Lett.B 800 (2020) 135089



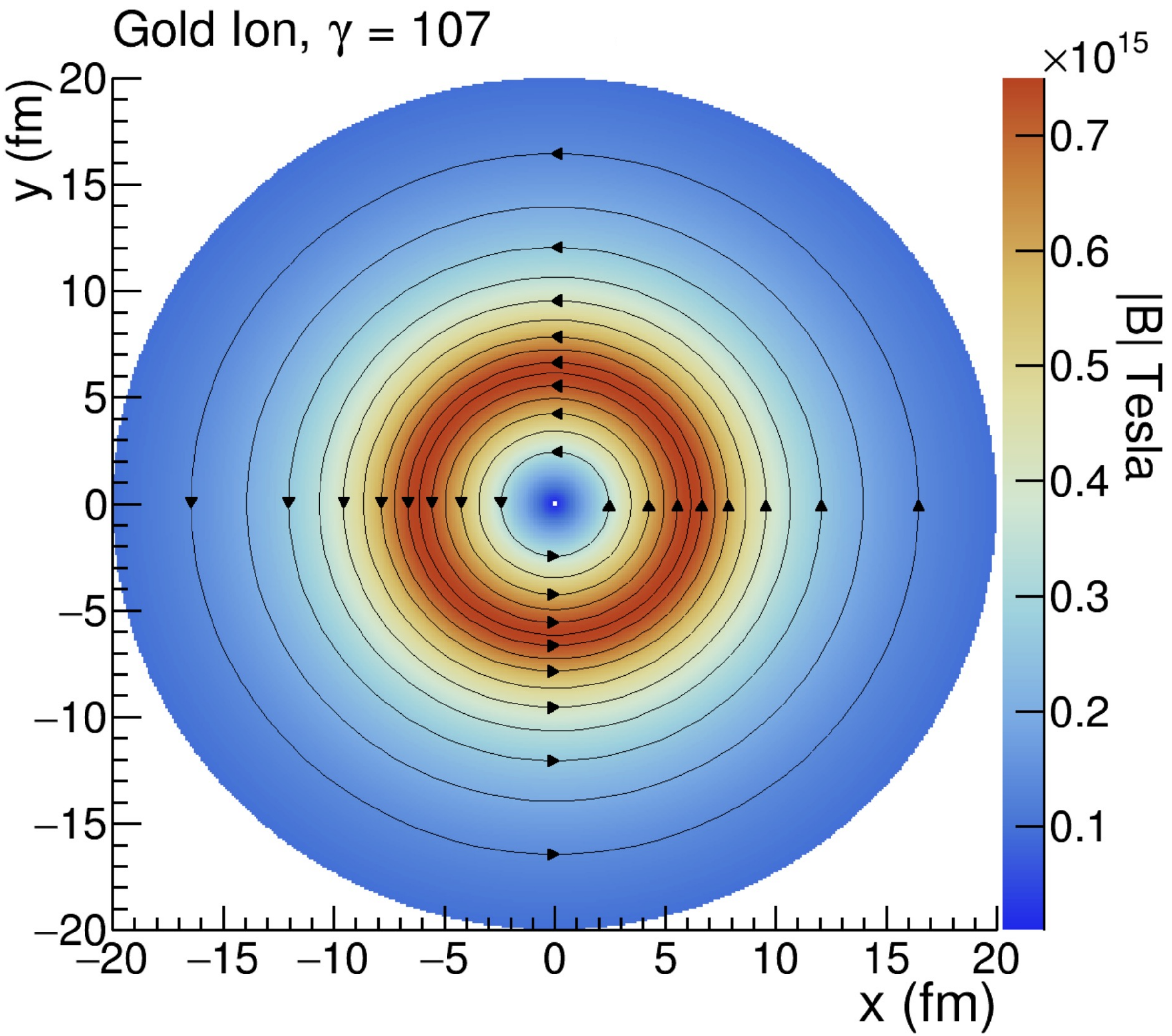
- $\sqrt{\langle p_T^2 \rangle}$ decreases from semi-peripheral to peripheral collisions
- Non-UPCs slightly higher than QED model: final state effect?
  - The b dependence of photon p_T should be considered to explore QGP EM properties

Application: Mapping the Magnetic Field

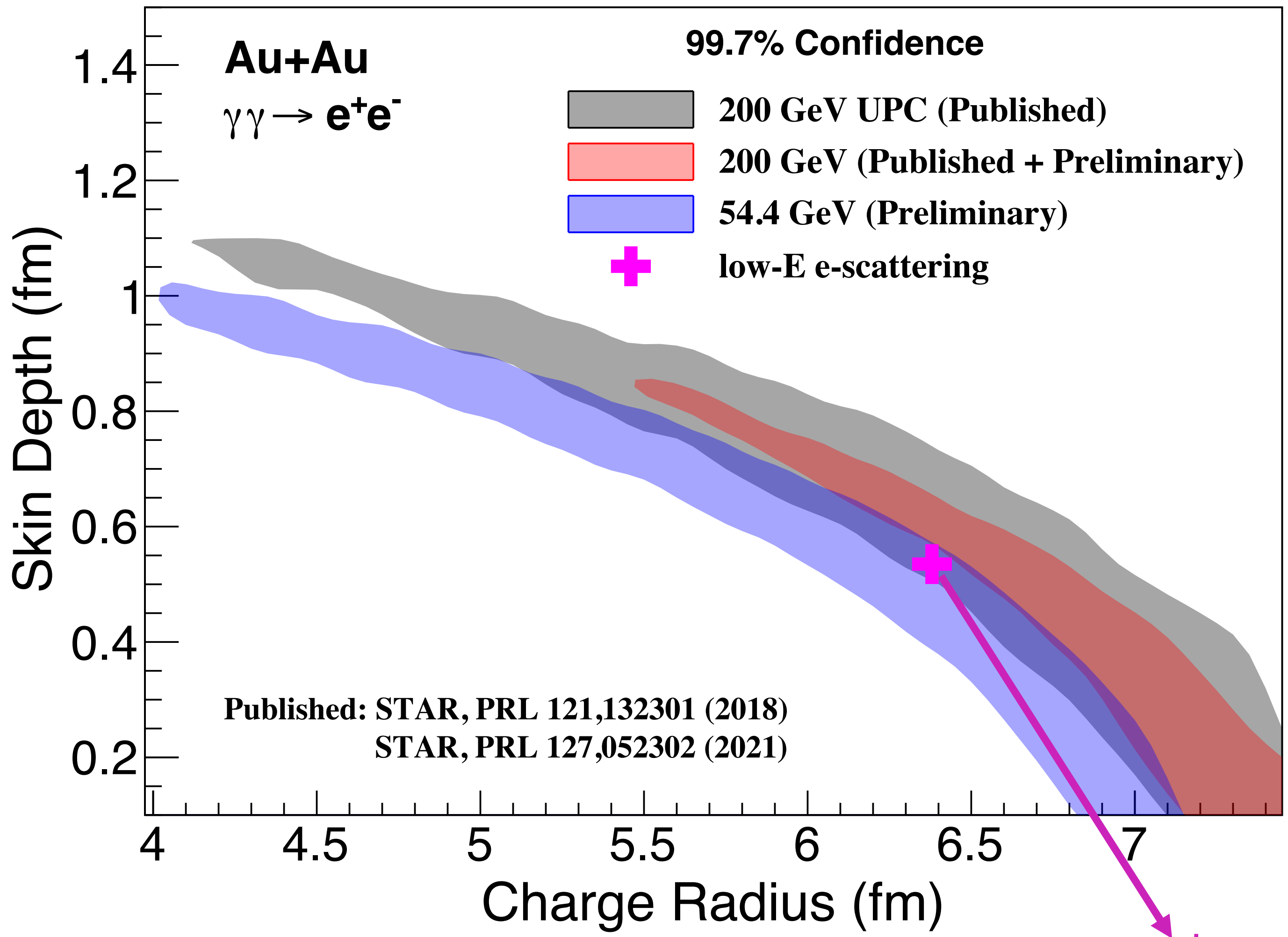
- Total and differential cross-sections (e.g. $d\sigma/dP_{\perp}$) for $\gamma\gamma \rightarrow e^{+}e^{-}$ are related to field strength and configuration
  - **Photon density is related to energy flux of the electromagnetic fields** $n \propto \vec{S} = \frac{1}{\mu_0}\vec{E}\times\vec{B}$

M. Vidović, et al., Phys. Rev. C 47 (1993), 2308

→ Extract $\vec{B}$ (single ion) based on measured cross-section



Application: Constrain Charge Distribution

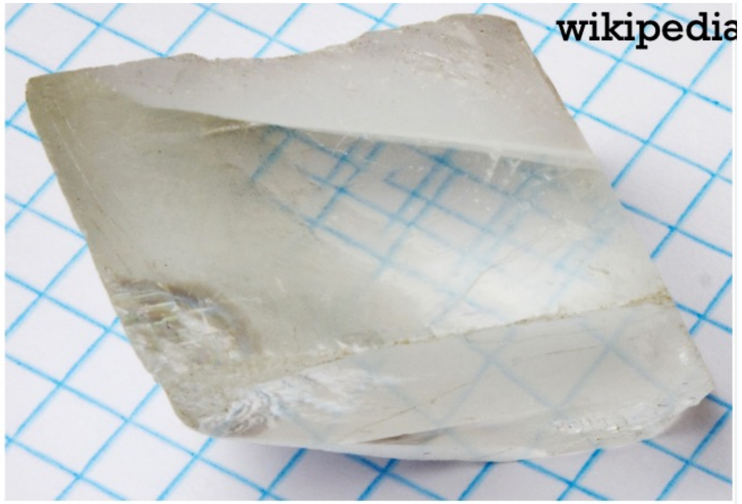


EPA-QED: Daniel Brandenburg et al.
Eur. Phys. J. A 57 (2021) 299

- $\gamma\gamma \rightarrow l^+l^-$ can be used to constrain nucleus charge distribution at RHIC energy (STAR data compared to EPA-QED)
- 200 GeV vs 54.4 GeV / low energy scattering: a potential indication of charge fluctuation and/or final-state effect

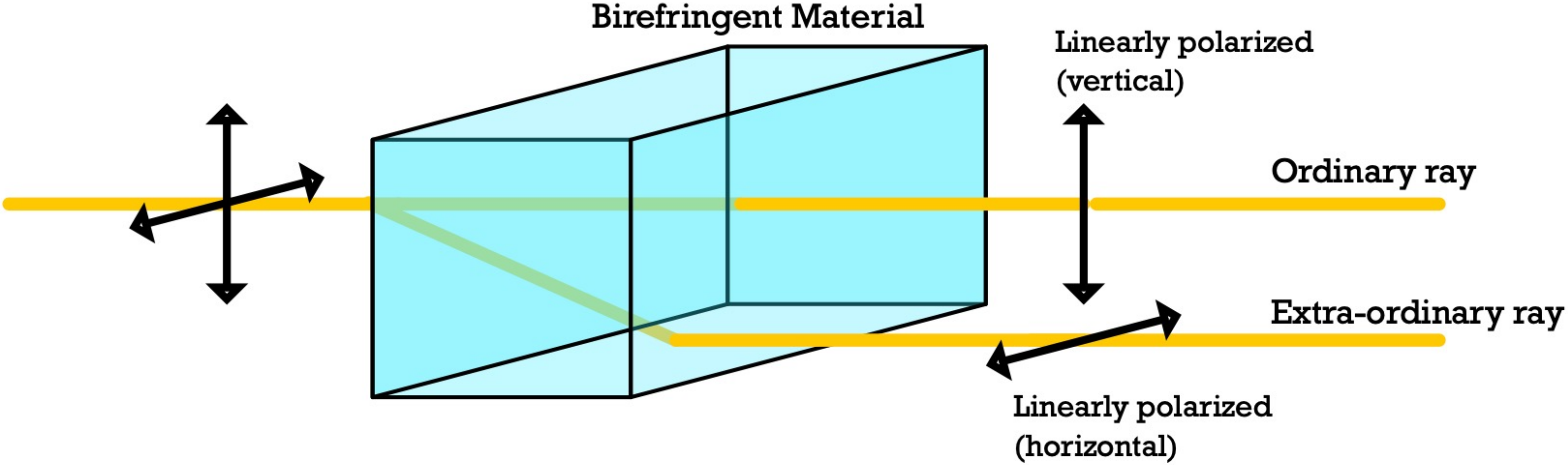
Low energy scattering: R=6.38 fm, d=0.535 fm
Nuclear Sizes and Structure (Oxford University Press, 1977)

Optical Birefringence



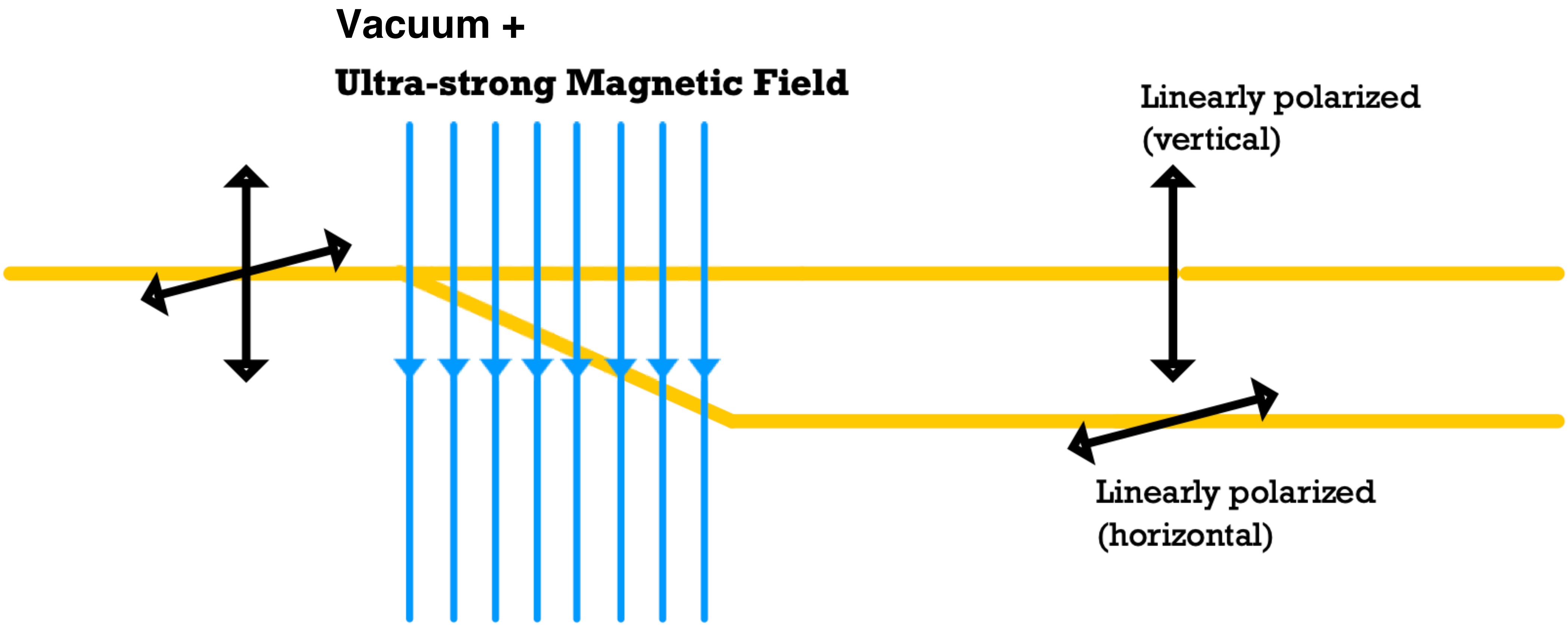
Birefringent material: Different index of refraction for light polarized parallel ($n_{\parallel}$) vs. perpendicular ($n_{\perp}$) to optical axis of material

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



Vacuum Birefringence

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. $\Delta\sigma = \sigma_{\parallel} - \sigma_{\perp} \neq 0$



Birefringence of the QED Vacuum

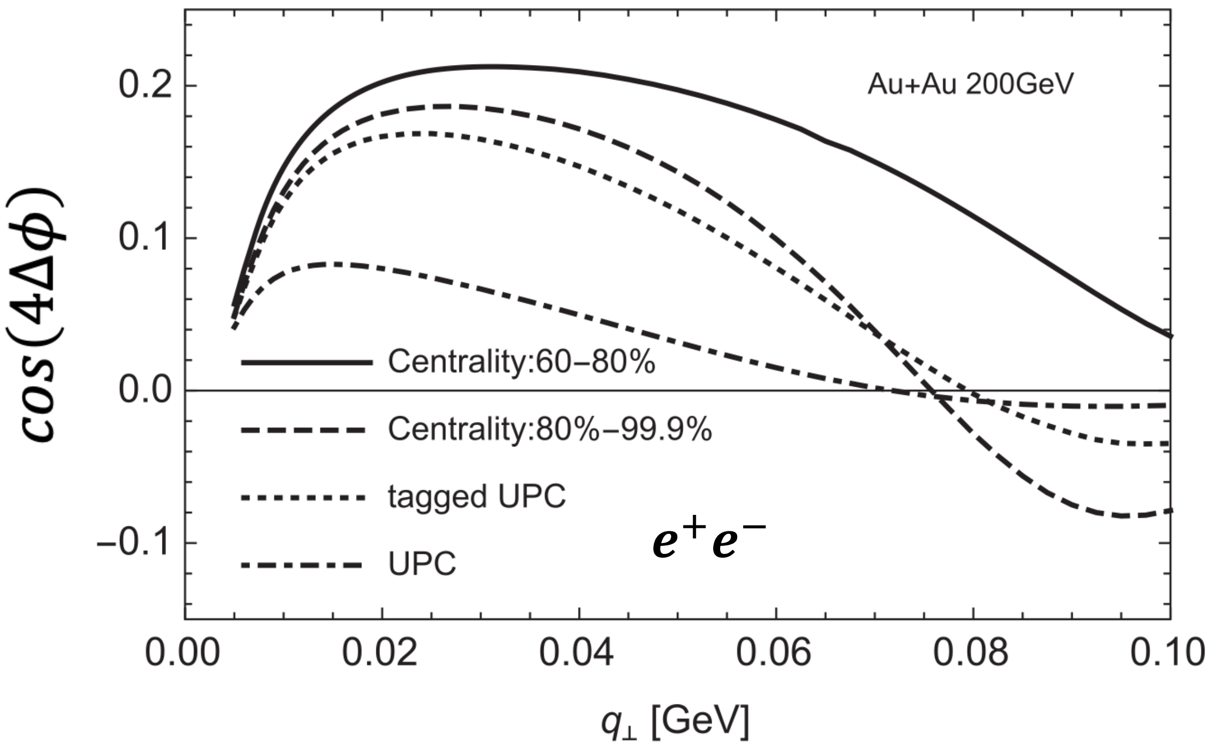
Vacuum birefringence: Predicted in 1936 by Heisenberg & Euuler. Index of refraction for γ interaction with $\vec{B}$ field depends on relative polarization angle i.e. $\Delta\sigma = \sigma_{\parallel} - \sigma_{\perp} \neq 0$

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

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

C. Li, J. Zhou, Y.-j. Zhou, Phys. Lett. B 795, 576 (2019)

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



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STAR, PRL 127 (2021) 052302

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Ultra-Peripheral

Quantity	Measured	QED	χ^2/ndf
$-A_{4\Delta\phi}(\%)$	16.8 $\pm$ 2.5	16.5	18.8 / 16

Peripheral (60−80%)

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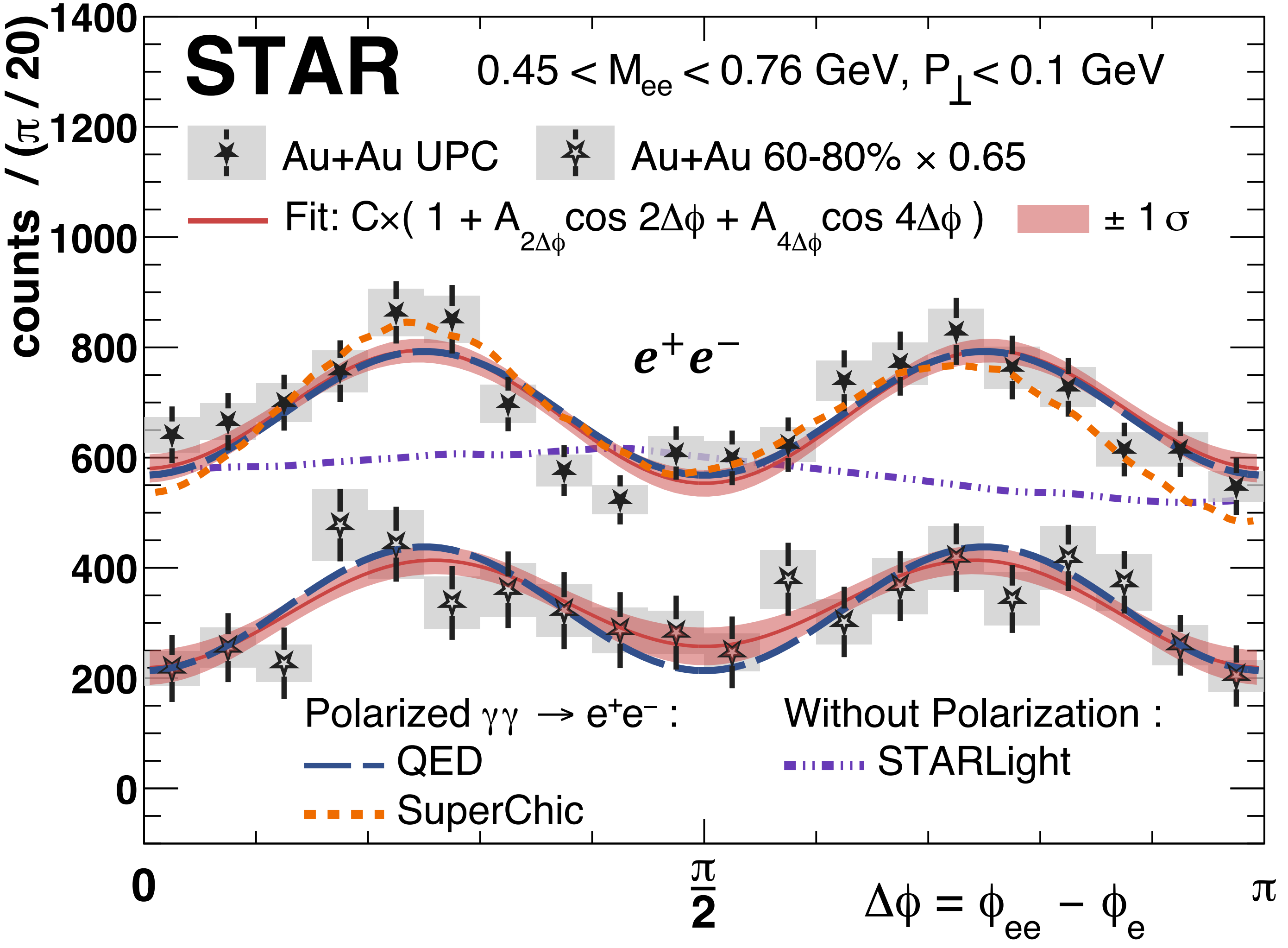

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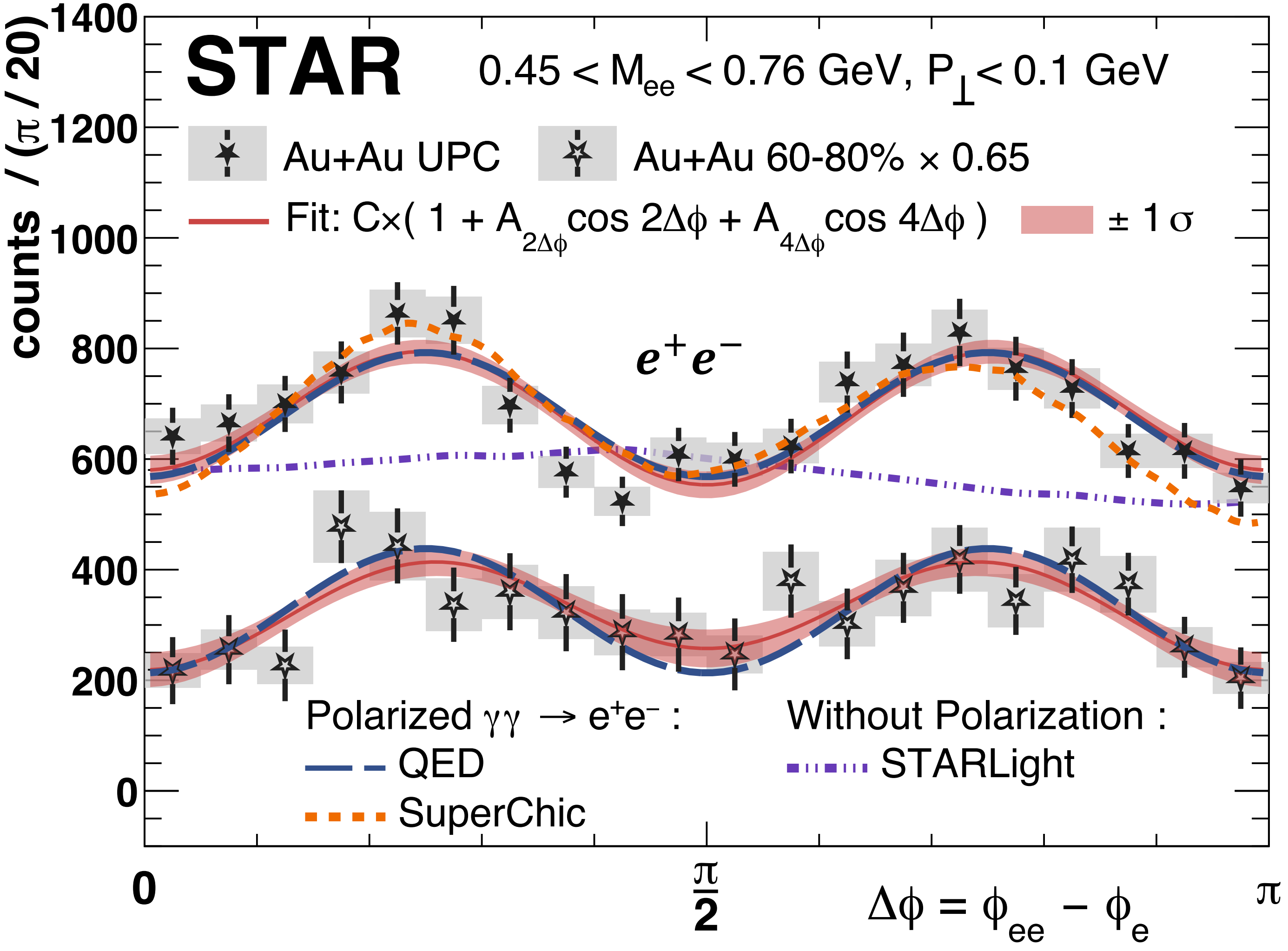
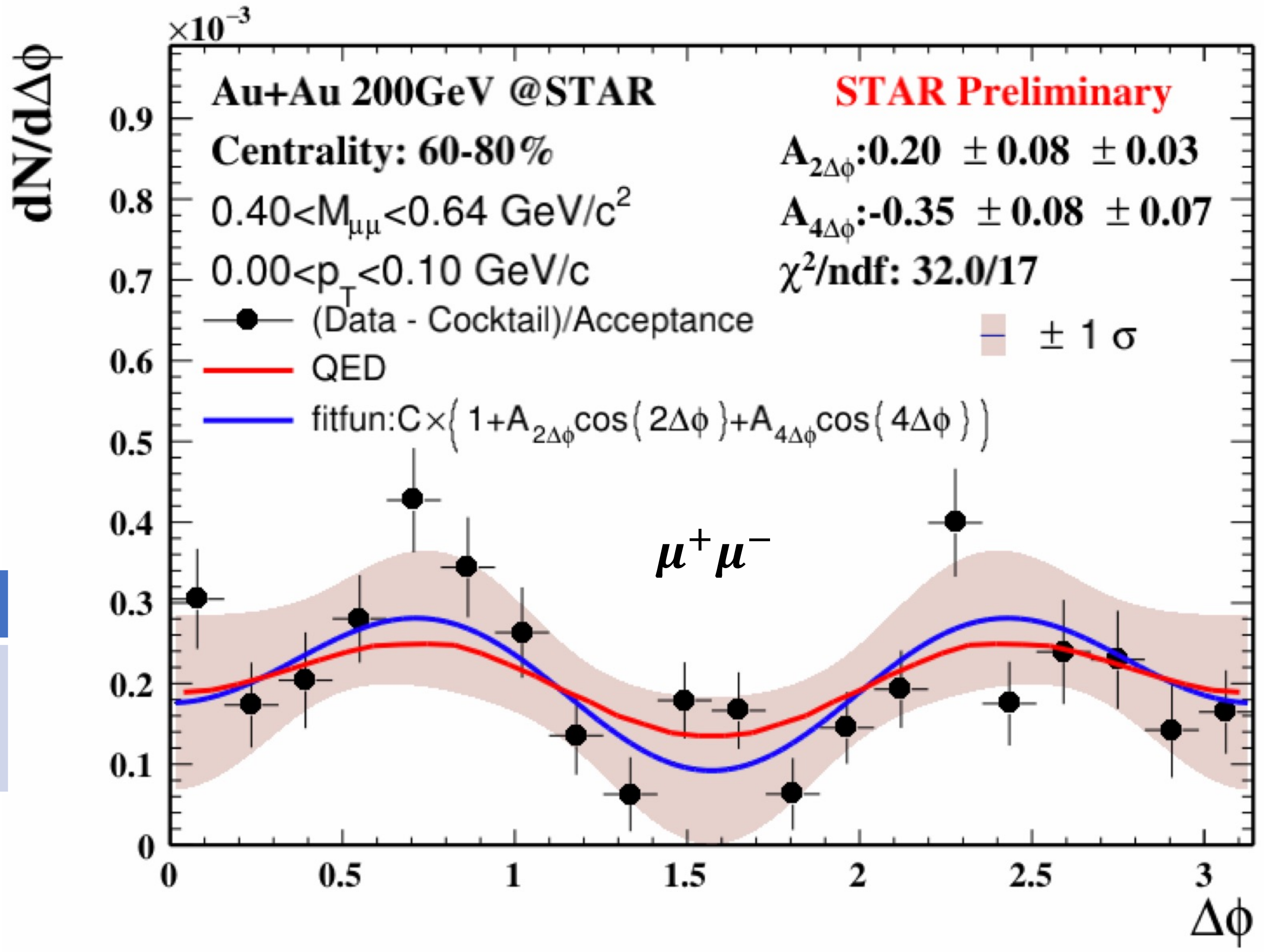


→ First earth-based observation (6.7 σ level) of vacuum birefringence

Birefringence of the QED Vacuum

- $cos(2\Delta\phi)$ **modulation** is proportional to m^2/p_T^2:
  Only measurable for $\mu^+\mu^-$ pairs at STAR
  - $cos(4\Delta\phi)$: 3.3σ
  - $cos(2\Delta\phi)$: 2.3σ

Quantity	Measured	QED	χ^2/ndf
$A_{2\Delta\phi}(\%)$	$20 \pm 8 \pm 3$	13	32/17
$-A_{4\Delta\phi}(\%)$	$35 \pm 8 \pm 7$	22	



QED: Zha et al., Phys.Lett.B 800 (2020) 135089

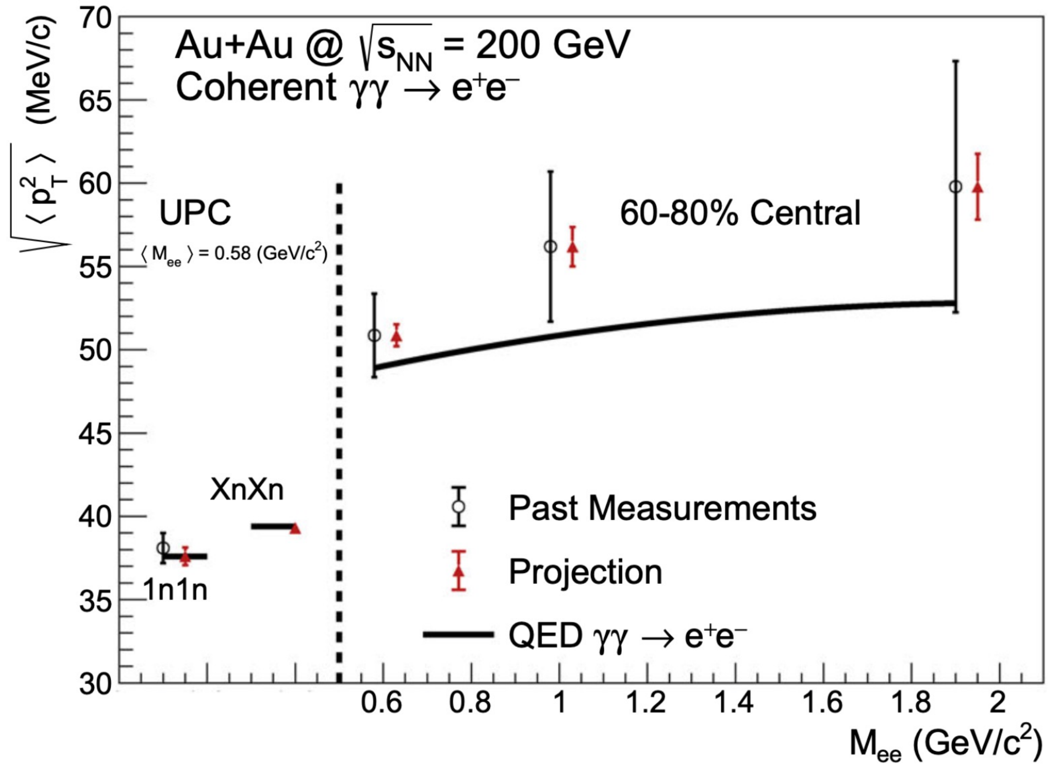
Summary

1. Measurements of exclusive Breit-Wheeler process
2. Experimental demonstration that the $\sqrt{\langle p_T^2 \rangle}$ spectra from $\gamma\gamma \rightarrow l^+ l^-$ **depends on impact parameter**
3. Higher precision data needed to conclusively determine if there are medium effects
4. Breit-Wheeler process in HICs provides a new tool to **constrain nuclear charge distribution**
5. **First earth-based observation of vacuum birefringence** : Observed (6.7σ) via angular modulations in linearly polarized $\gamma\gamma \rightarrow l^+ l^-$ process

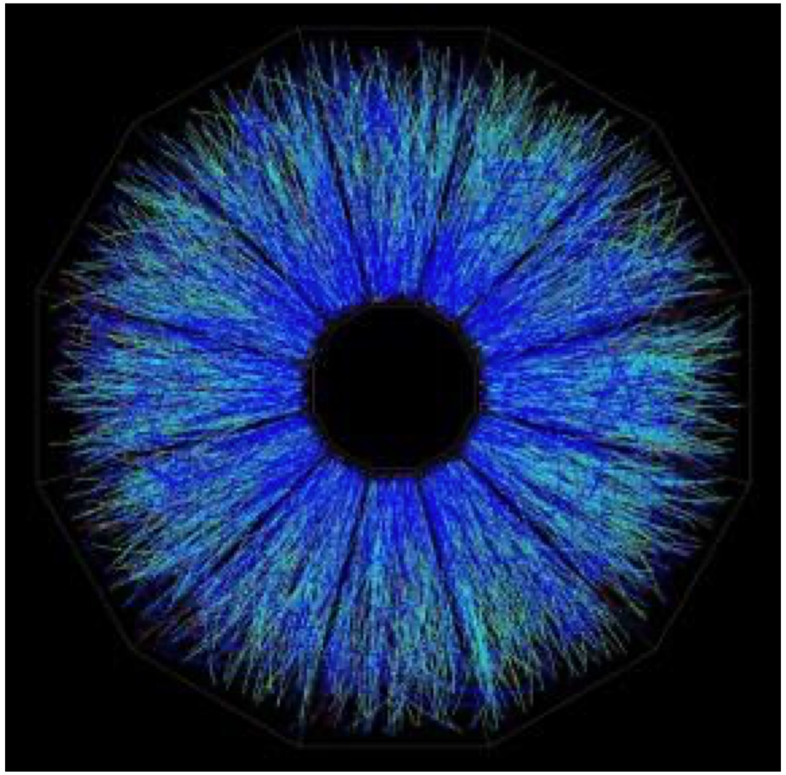
RHIC Run 2023-2025

higher statistics

STAR collaboration BUR for Run-23-25



iTPC upgrade



lower p_T,

lower systematic uncertainty

RHIC Run 2023-2025

higher statistics

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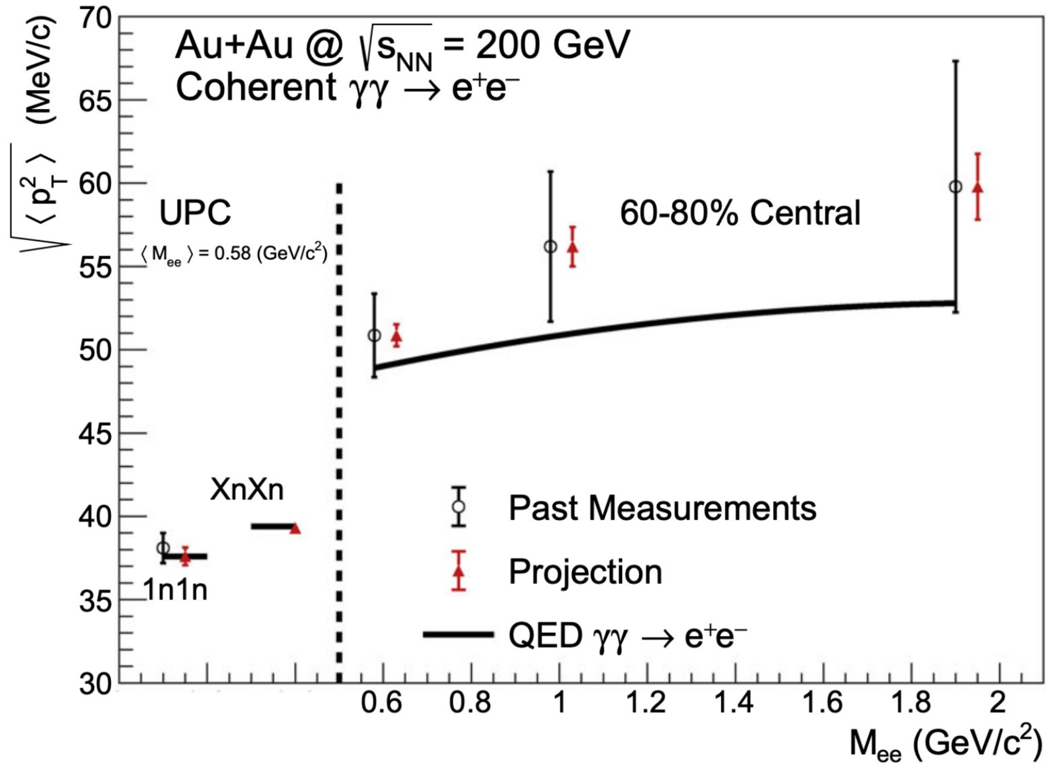

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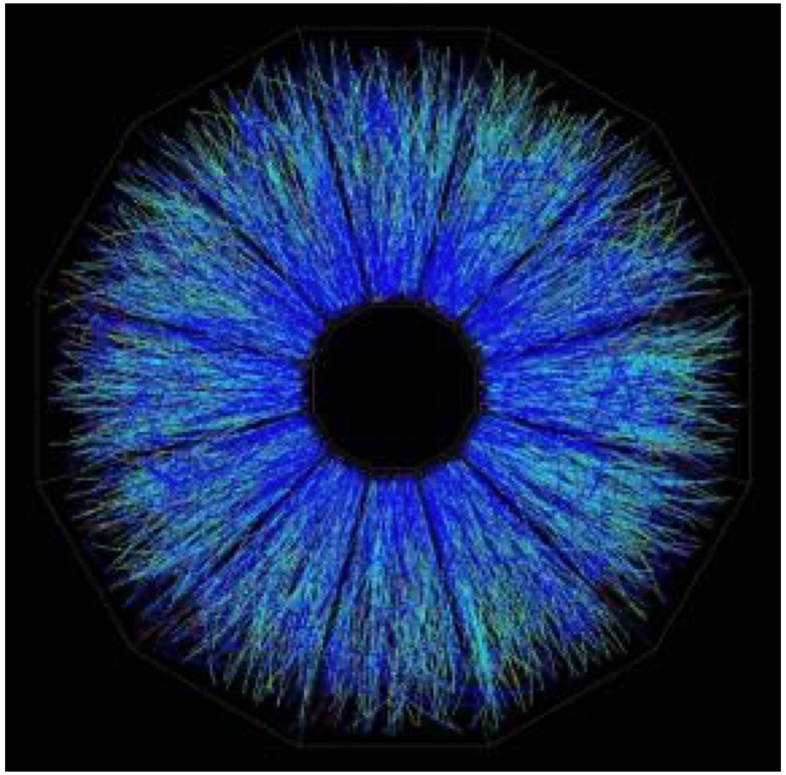

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Thanks for your attention !

backup

Vacuum Birefringence

Daniel Brandenburg, QM 2019 talk

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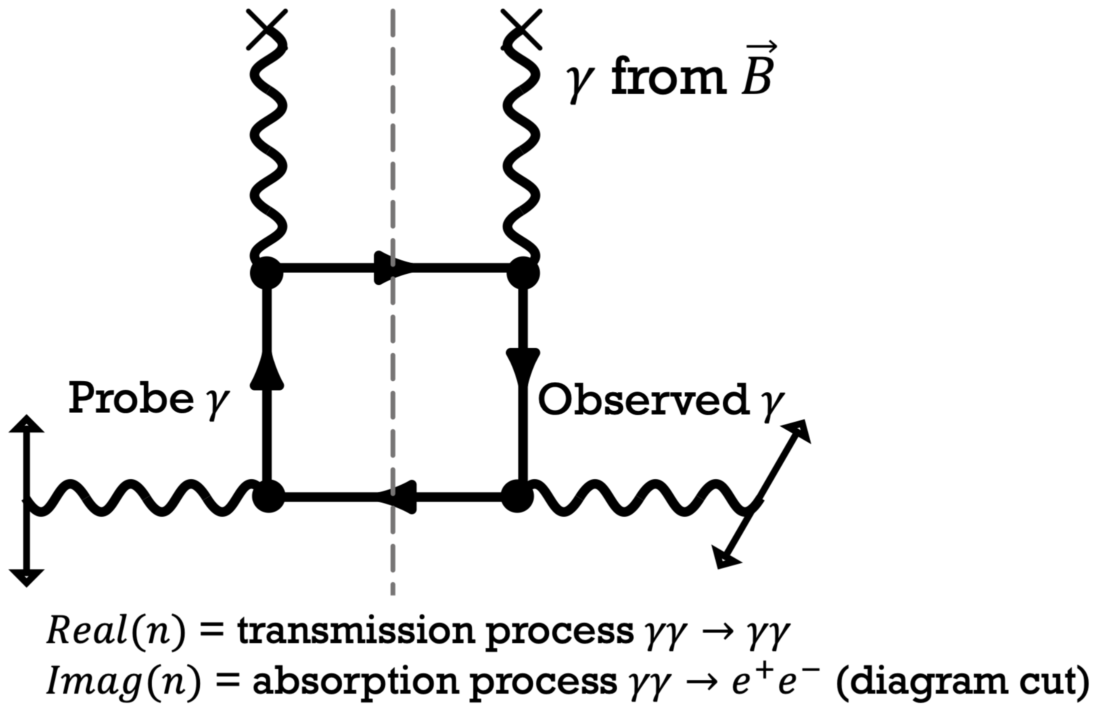

Feynman Diagram for Vacuum Birefringence

Distinctive Features of Breit-Wheeler Process

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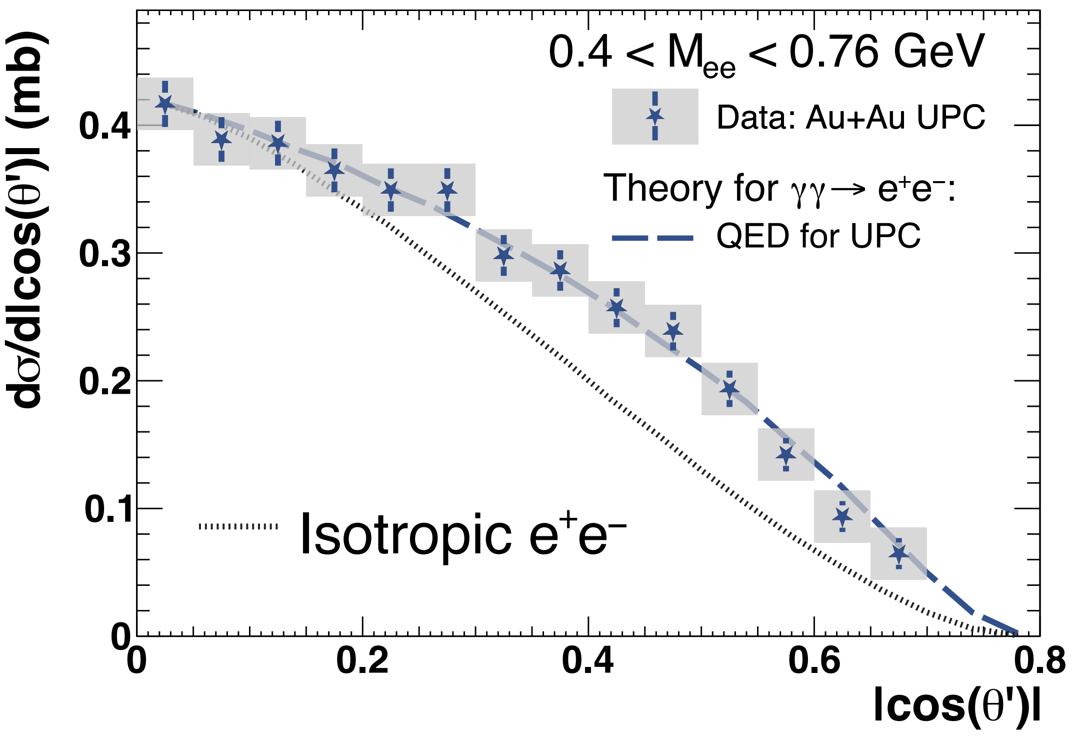
- Individual l^+/l^- preferentially aligned along beam direction

S. Brodsky, T. Kinoshita and H. Terazawa, Phys. Rev. D4, 1532 (1971)

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

  - Highly virtual photon interactions should have an isotropic distribution
  - θ': angle between l^+ and beam axis in pair rest frame

STAR, PRL 127 (2021) 052302



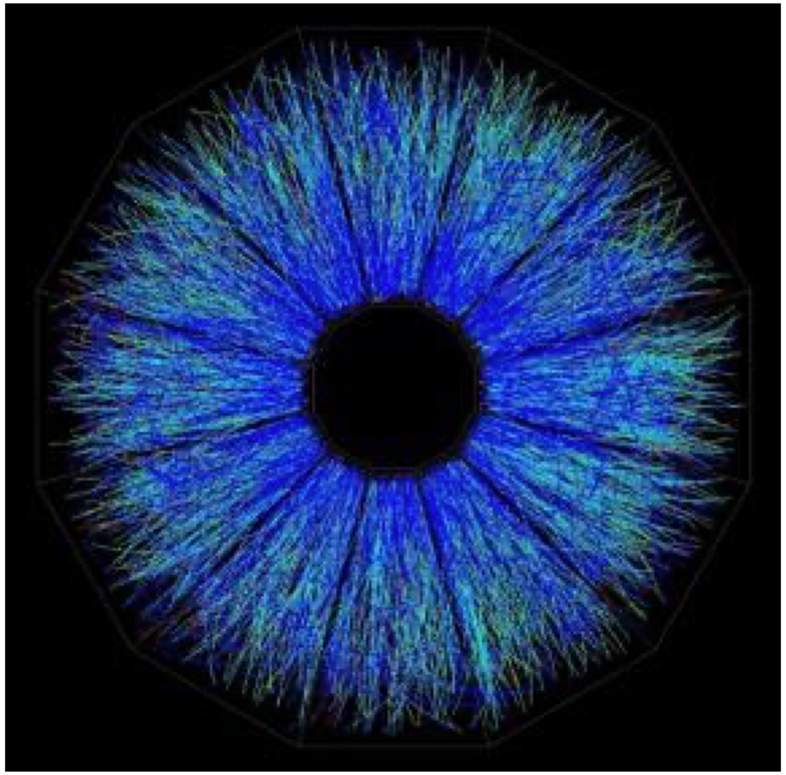
RHIC Run 2023-2025

higher statistics

STAR collaboration BUR for Run-23-25

year	minimum bias [$\times 10^9$ events]	high-p_T int. luminosity [nb^{-1}]		
		all vz	|vz|<70cm	|vz|<30cm
2014 2016	2	27	19	16
2023 2025	20	40	36	24

iTPC upgrade



lower p_T,
lower systematic uncertainty