Energy Dependence of Breit-Wheeler Process in Heavy-Ion Collisions and Its Application to Nuclear Charge Radius Measurements

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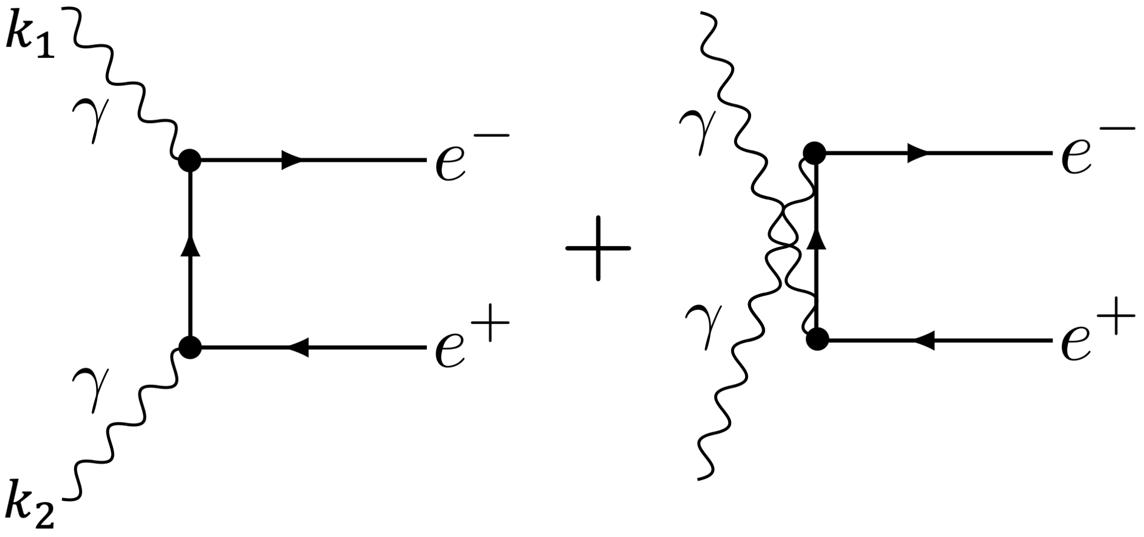
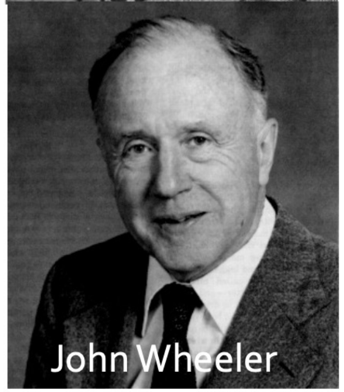
Outline

- ◆Breit-Wheeler Process in Heavy Ion Collisions
- ◆Application of Breit-Wheeler Process
  - ✓Study the properties of QGP
  - ✓Map the magnetic field
  - ✓Constrain nuclear charge radii
  - ✓Search for dark photon
- ◆Summary

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

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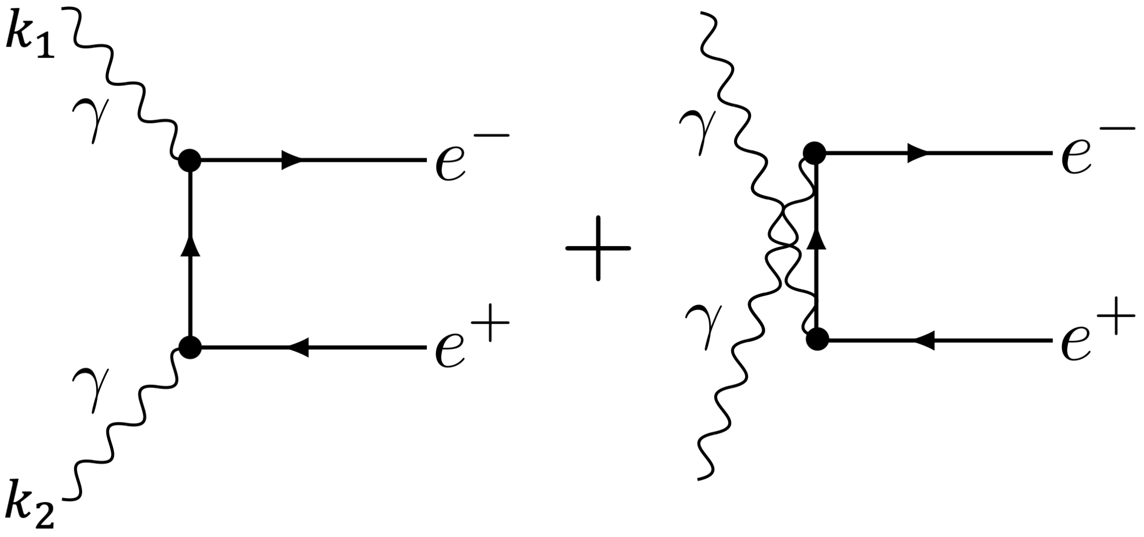
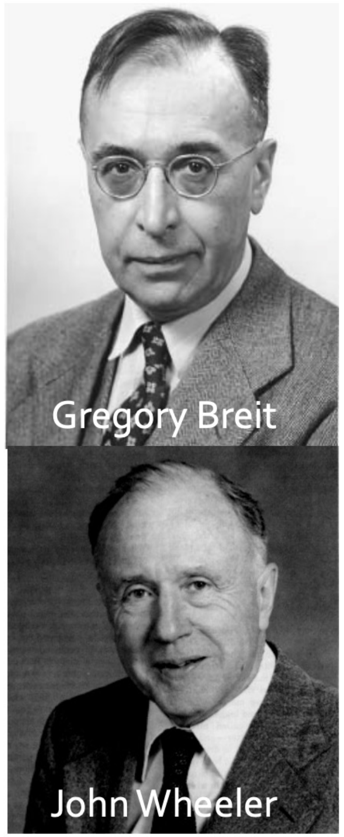


Hard to observe

- ☐ The cross section is small
- ☐ The insufficiently large available densities of photon



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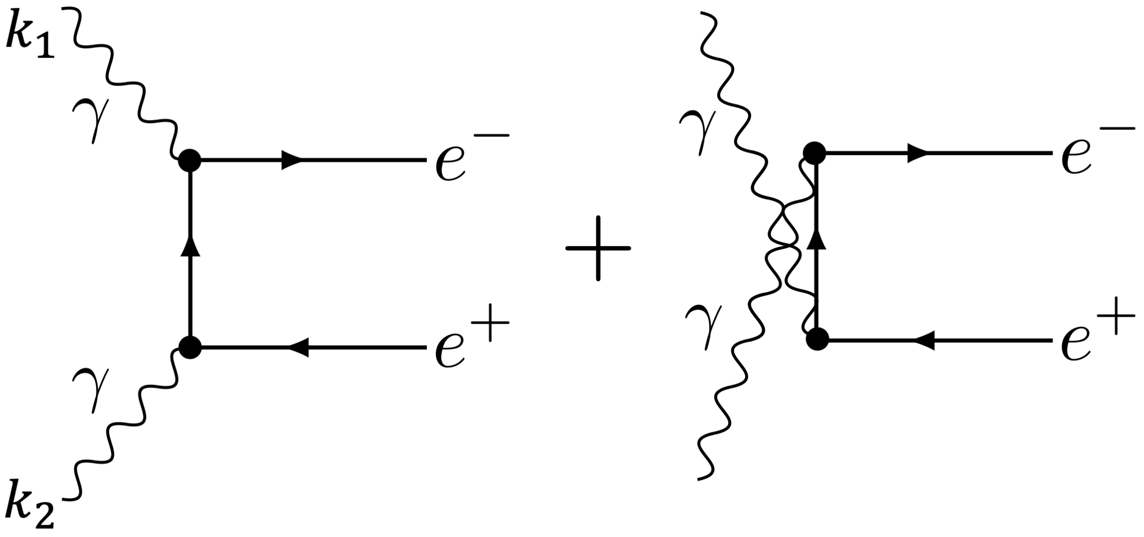

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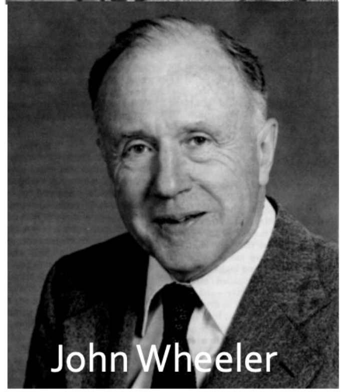

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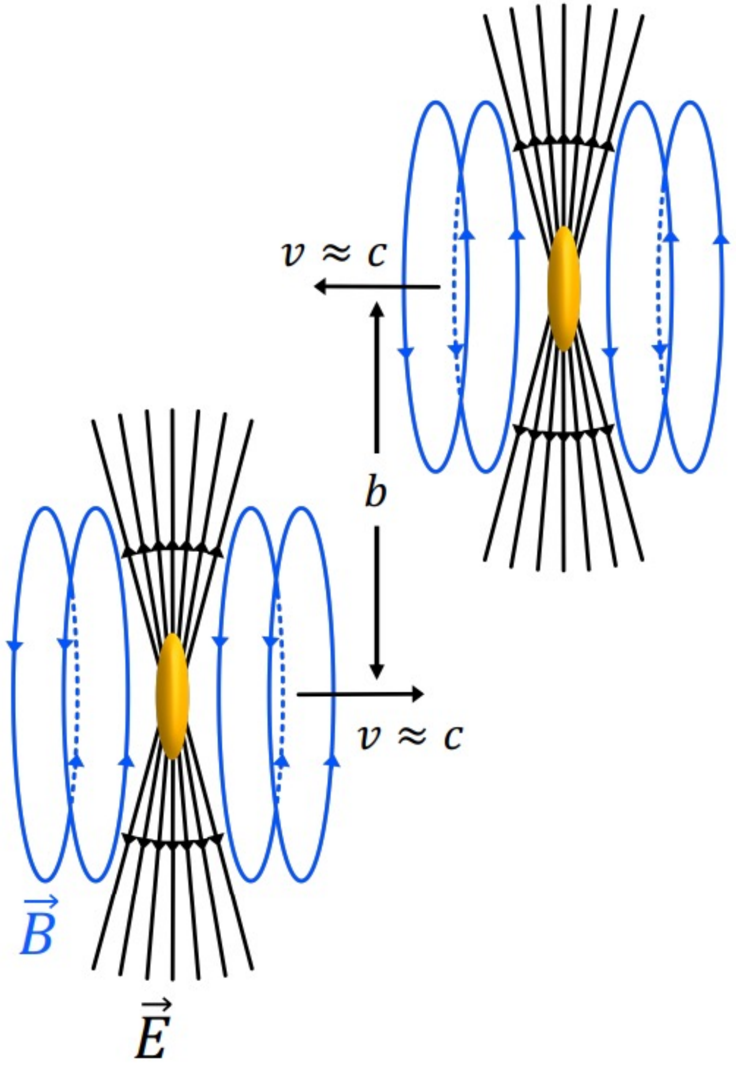
of quanta. In the considerations of Williams, however, the large nuclear electric fields lead to large densities of quanta in moving frames of reference. This, together with the large number

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 $\Longrightarrow$ **almost real**

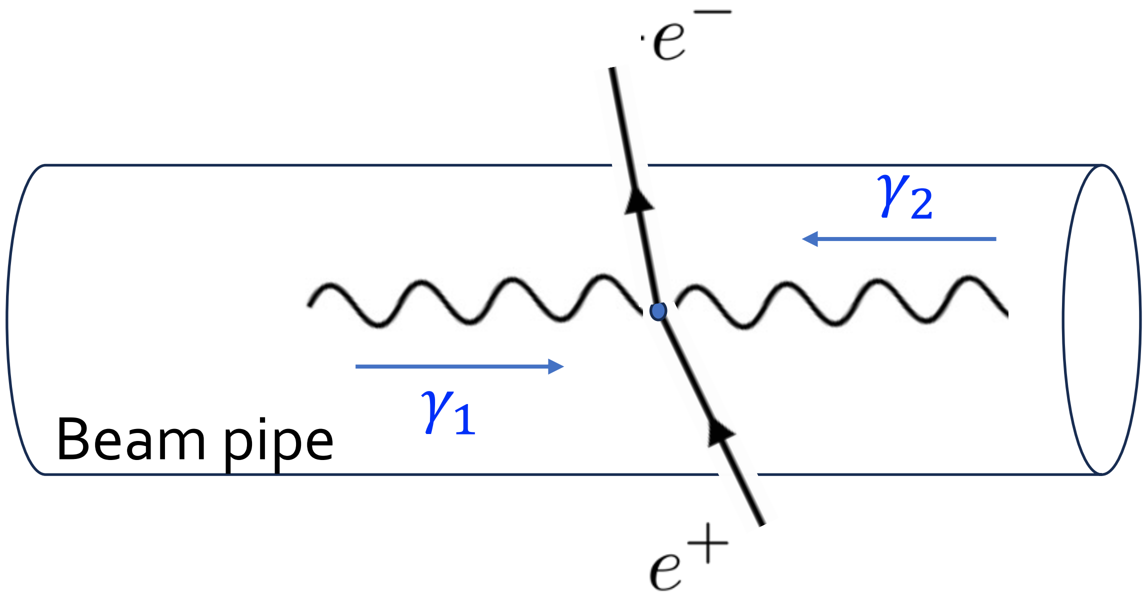
  Ann.Rev.Nucl.Part.Sci. 55 (2005) 271-310

- 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 Was Observed in UPCs at STAR

STAR, PRL 127 (2021) 052302



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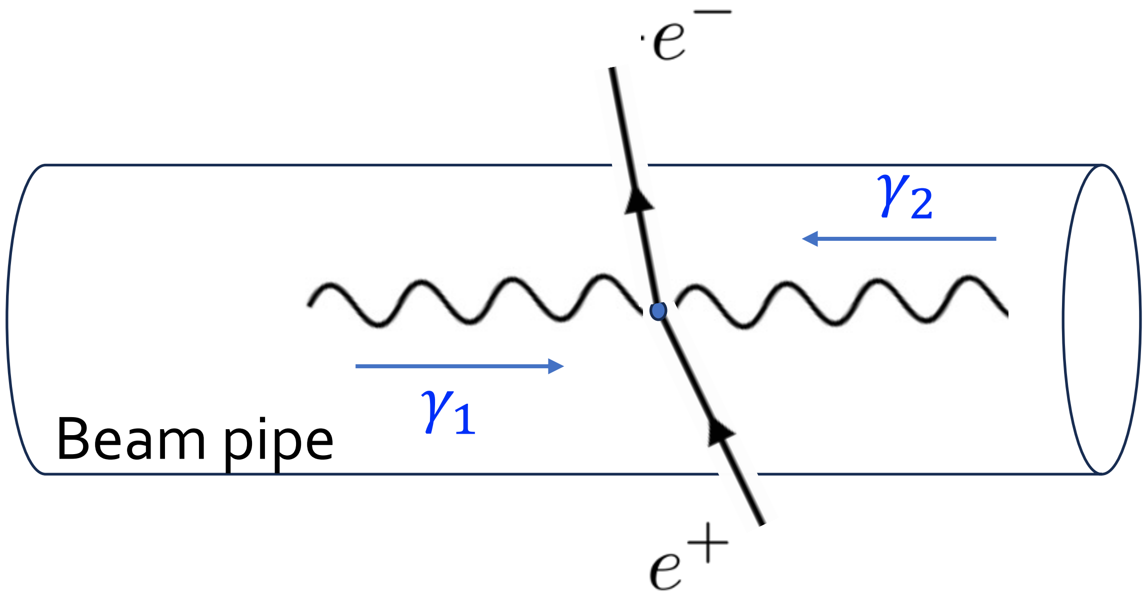

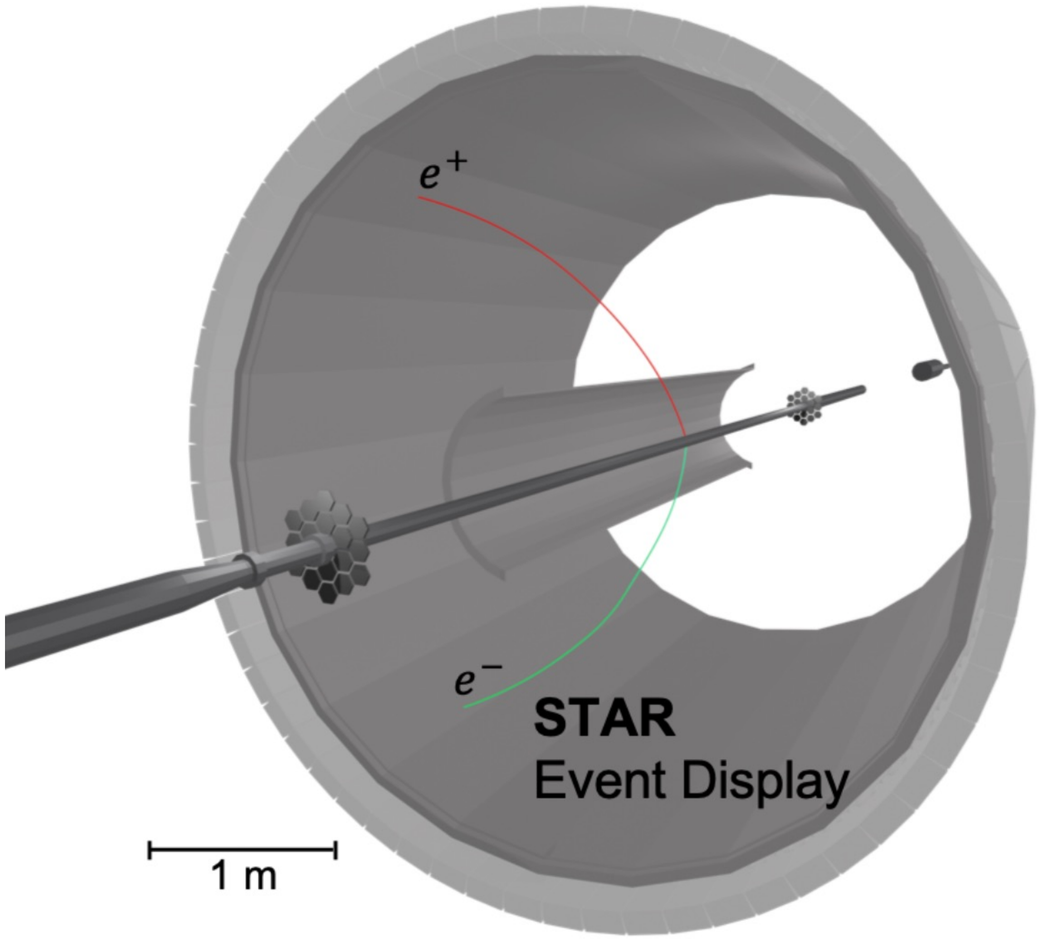

Distinctive features of BW process

- Exclusive production of e^+e^- pair

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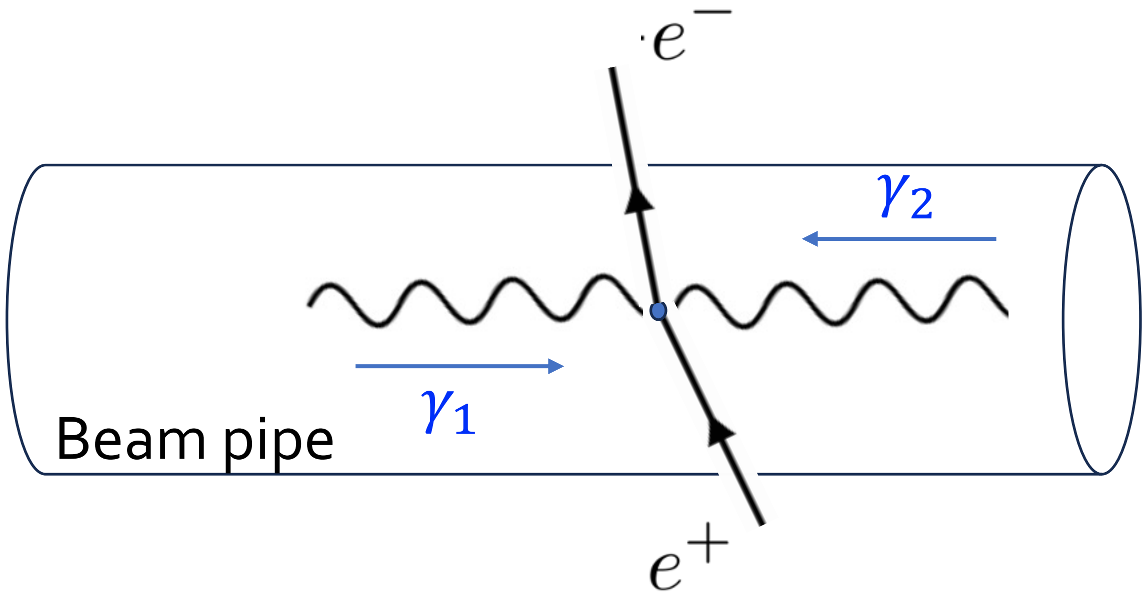

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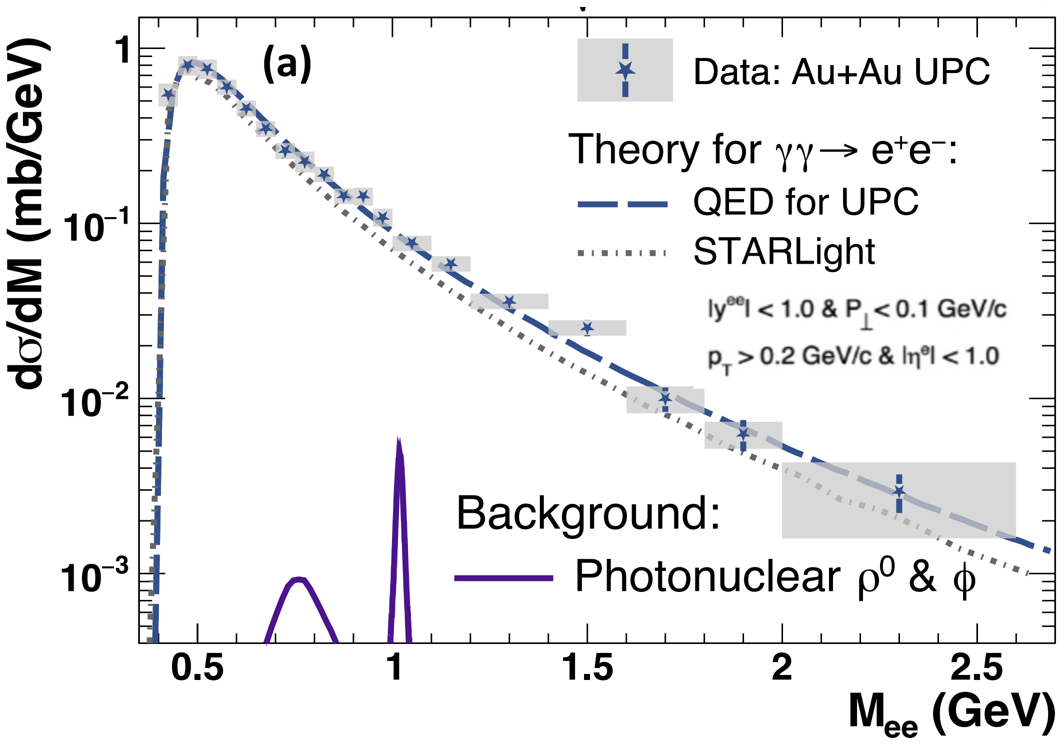

Distinctive features of BW process

- Exclusive production of e^+e^- pair
- Smooth invariant mass spectra
  - Quantum number conservation

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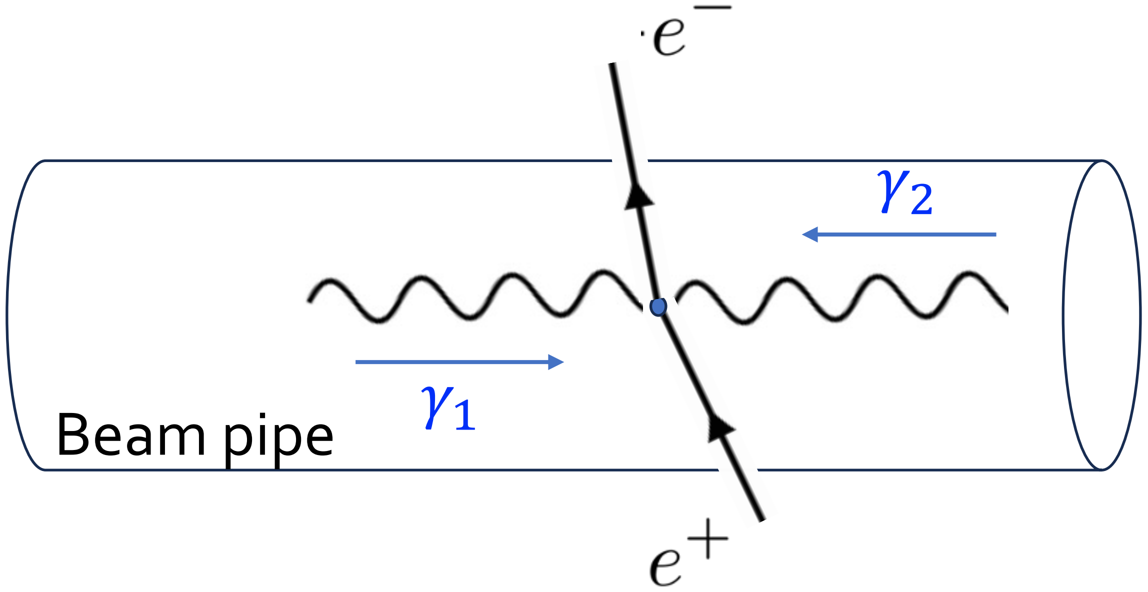

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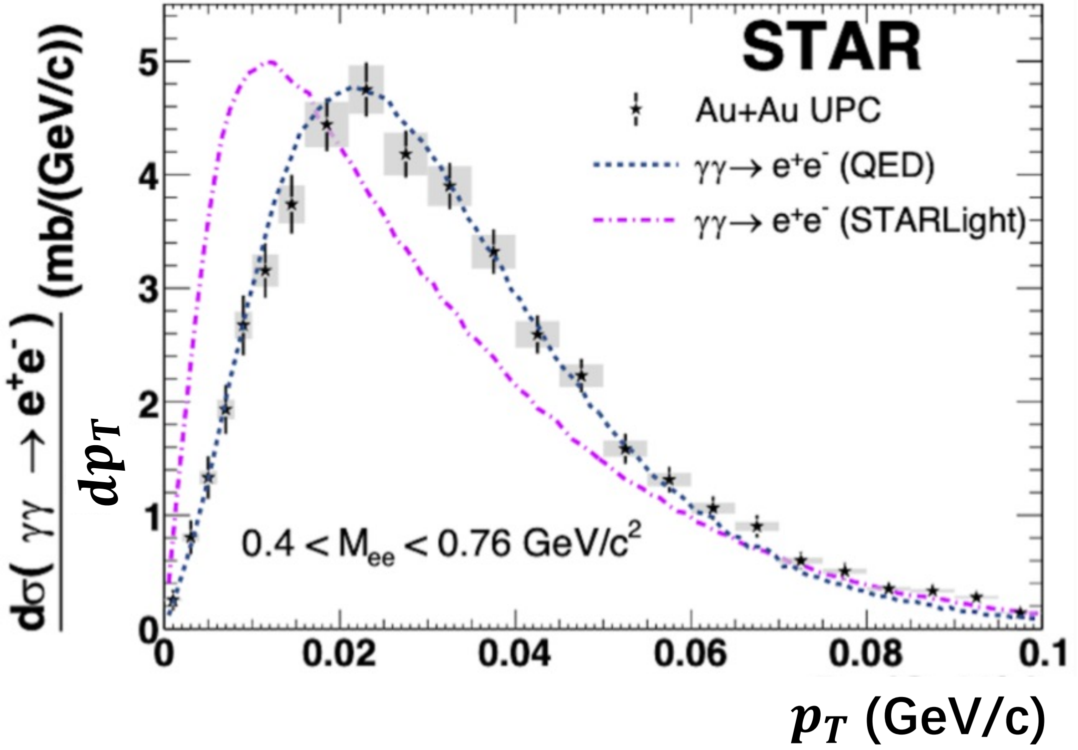
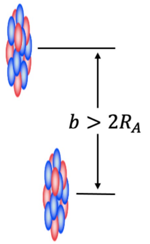


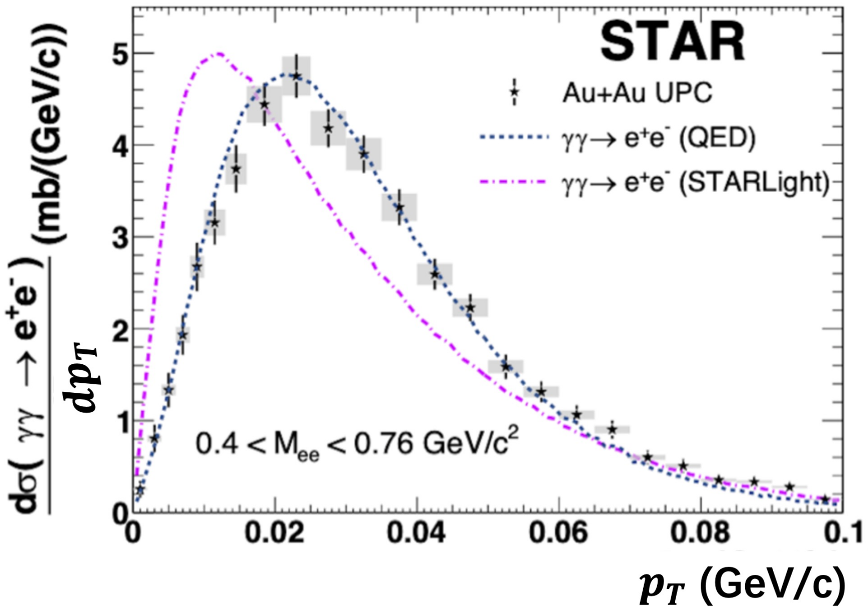
Distinctive features of BW process

- Exclusive production of e^+e^- pair
- Smooth invariant mass spectra
  - Quantum number conservation
- **Concentrated at low transverse momentum(p_T)**
  - **Back to back in transverse plane**

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



UPC



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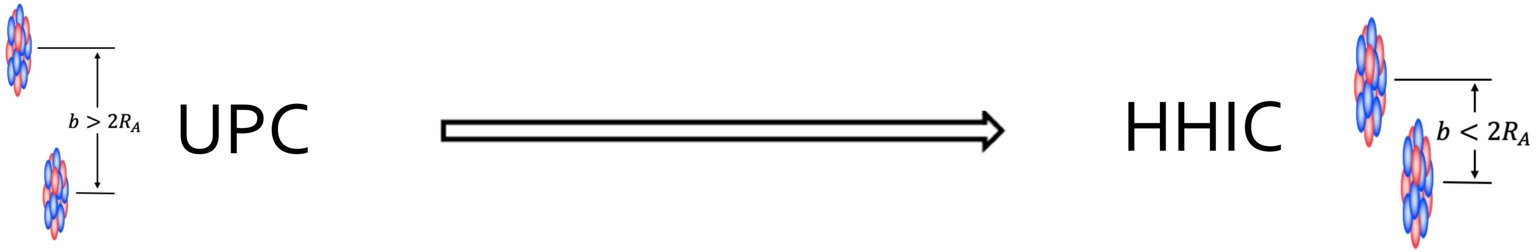

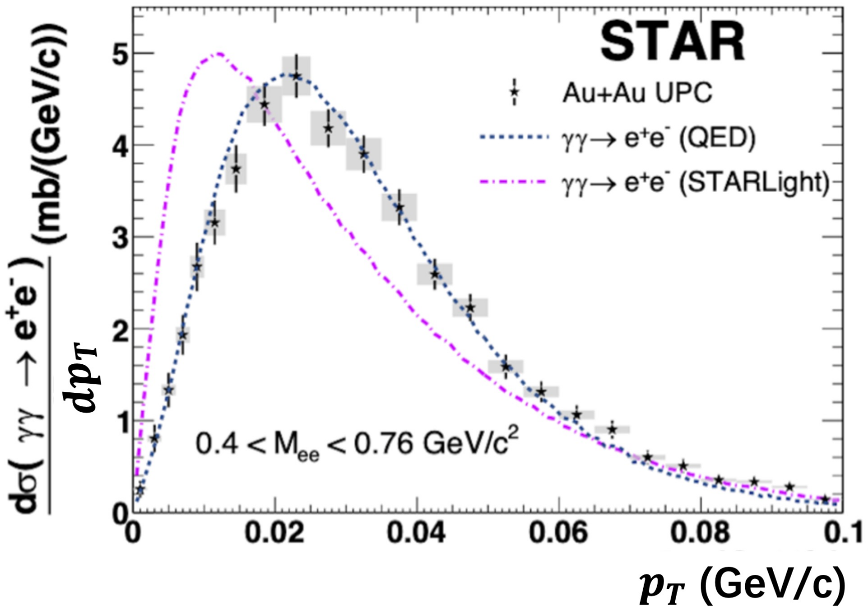

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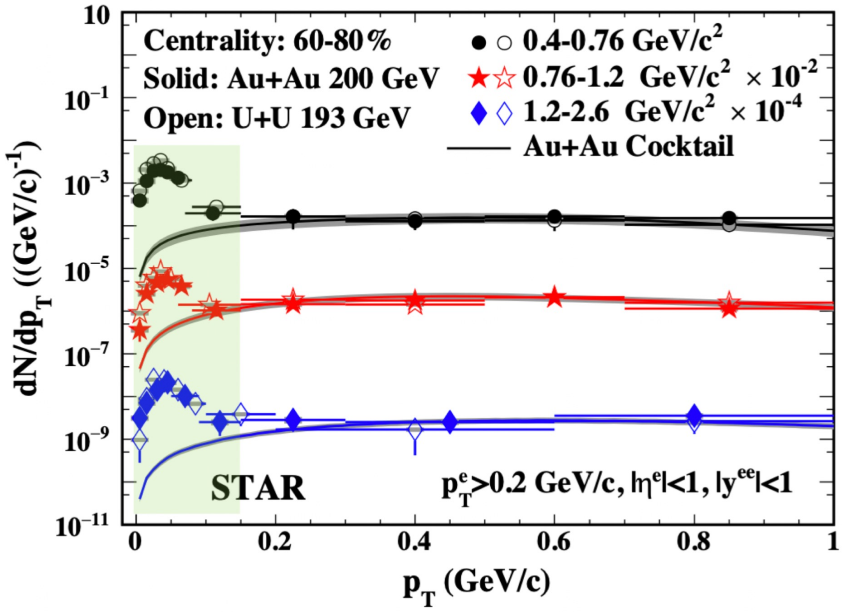

STAR: Phys.Rev.Lett. 121, 132301 (2018)

Photon-induced dielectrons as probes to study the properties of QGP in HHIC

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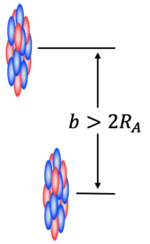
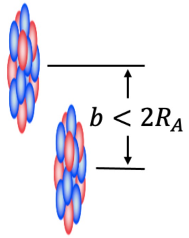
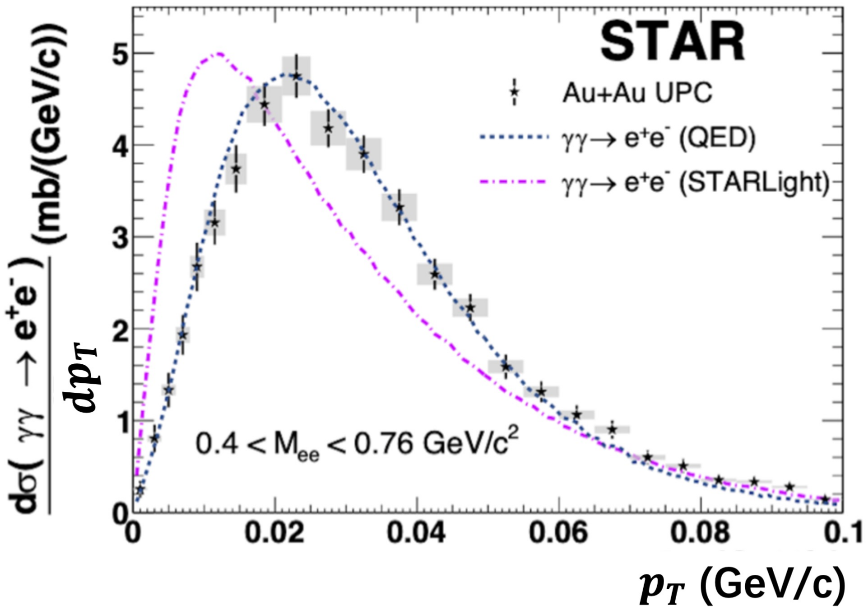


UPC ⟹ HHIC





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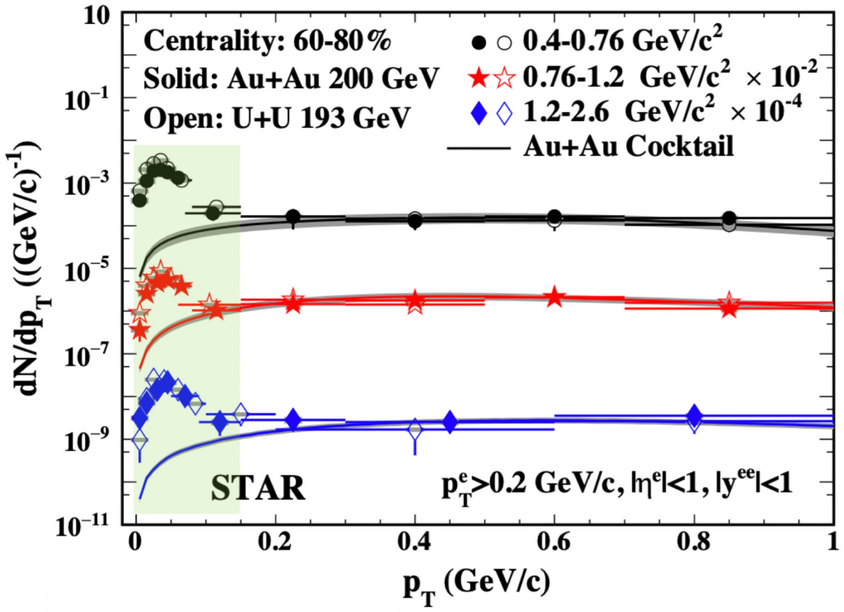

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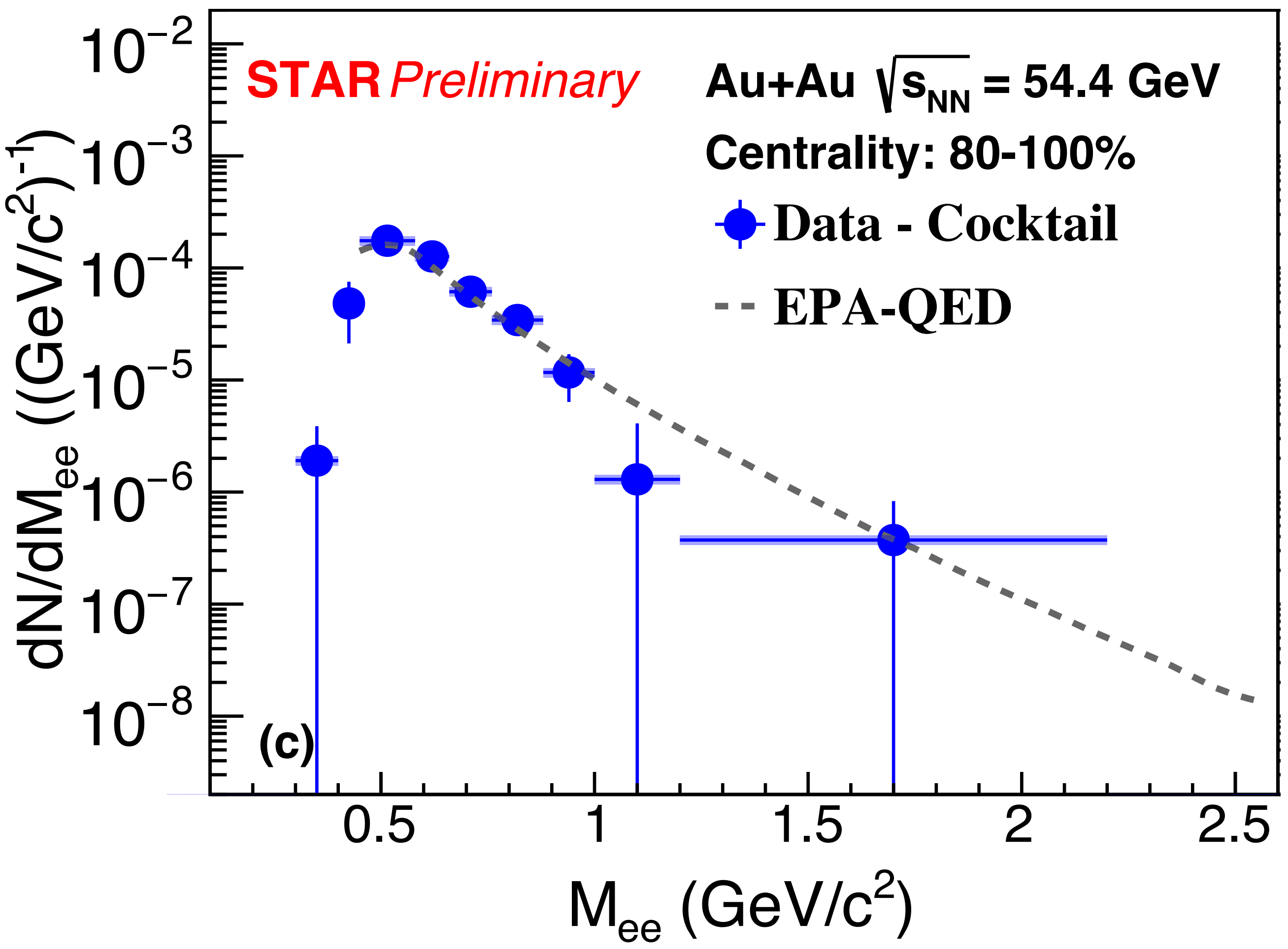
Data samples of 54 GeV and BES-I program

Energy	27 GeV	39 GeV	54 GeV	62 GeV
Used MB events	68M	132M	875M	62M

Photon-induced dielectrons as probes to study the properties of QGP in HHIC

Invariant Mass Distribution at Low-p_T

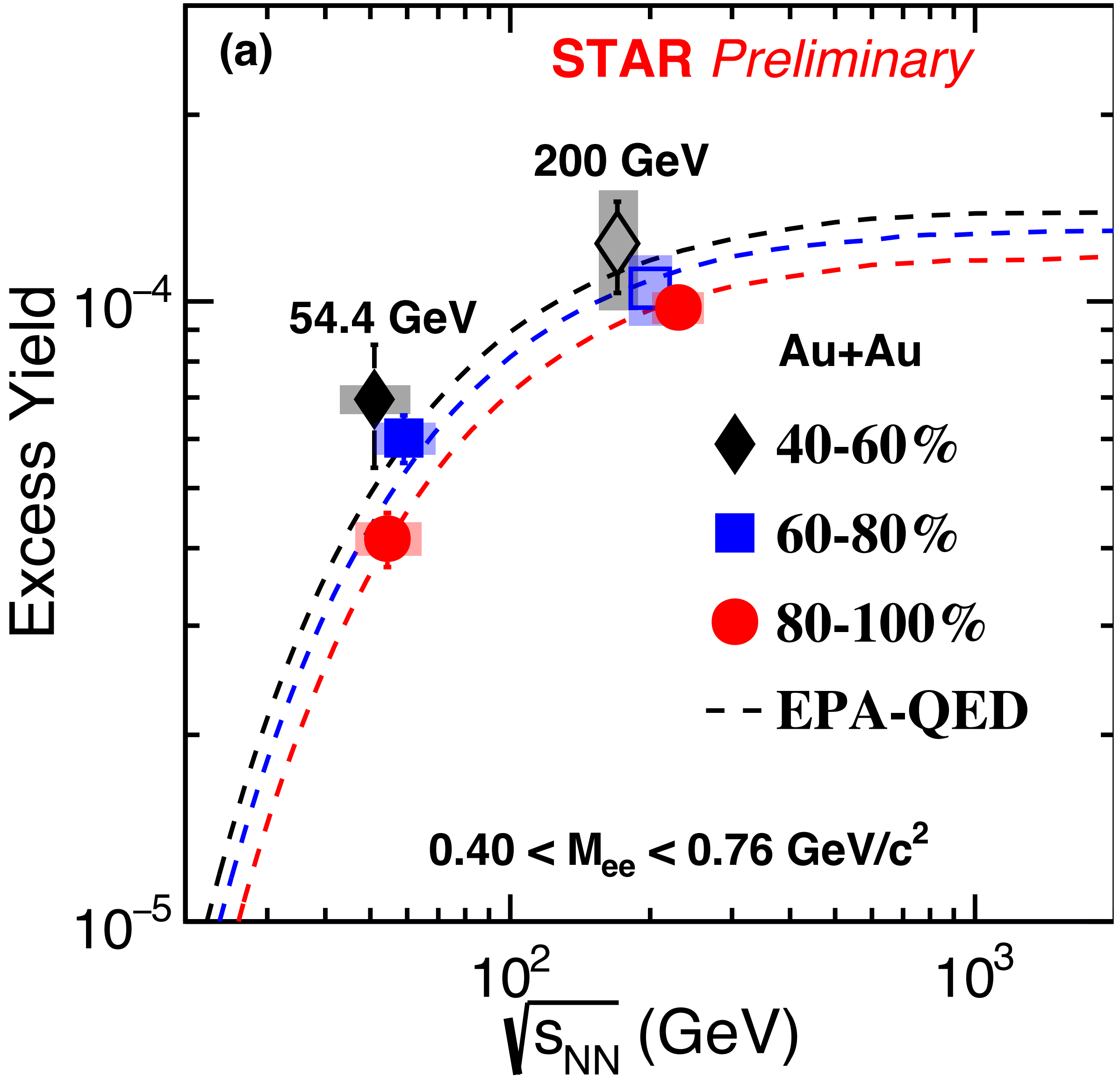


Excesses (Data - Cocktail) are extracted

No vector meson observed ($\gamma\gamma \nrightarrow$ vector meson)

Excesses are well described by lowest order EPA-QED predictions

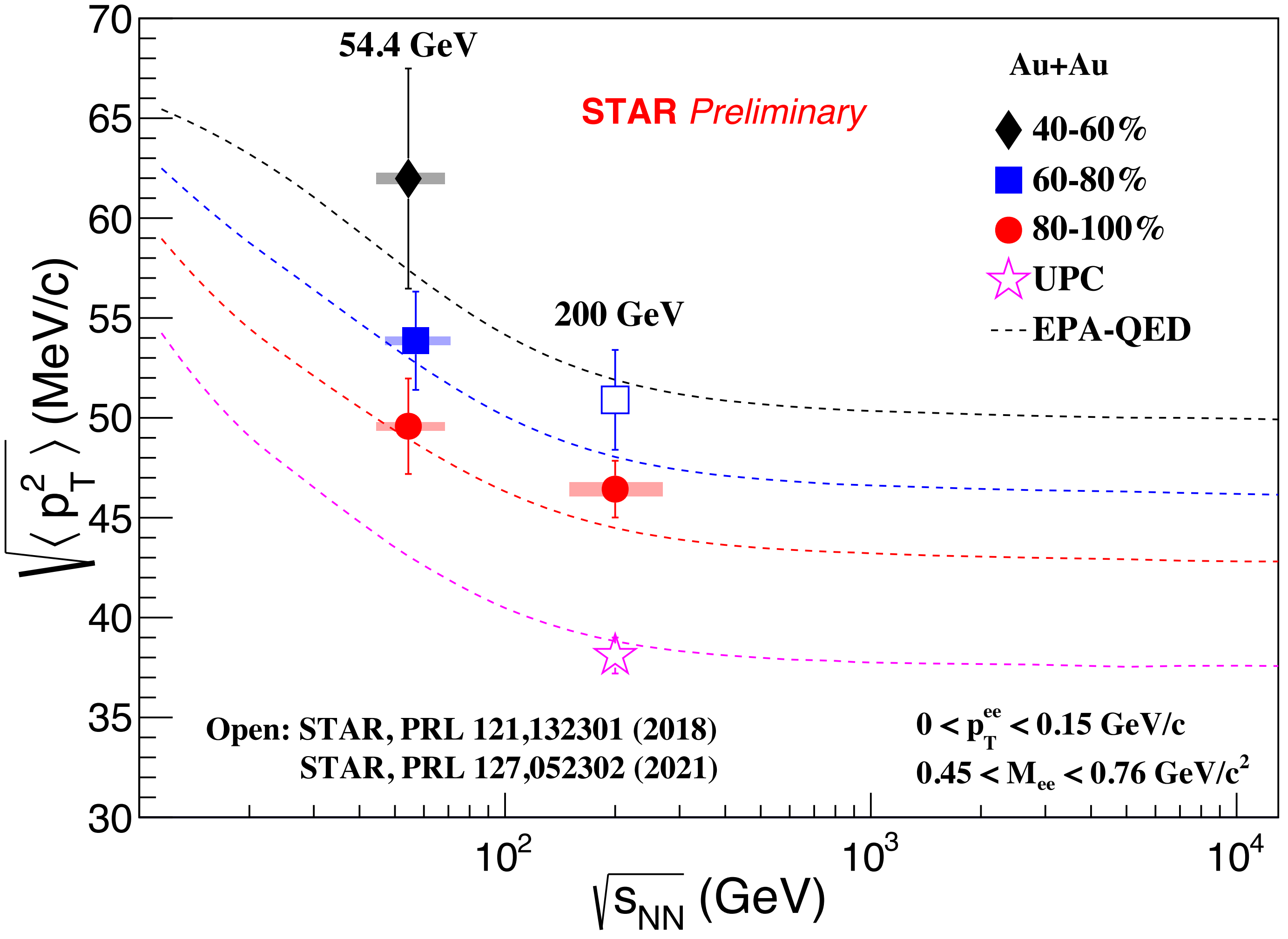
Energy Dependence of Excess Yield



Excess yield increase with beam energy

EPA-QED predicts similar energy dependence

Energy Dependence of $\sqrt{\langle p_T^2 \rangle}$



- The $\sqrt{\langle p_T^2 \rangle}$ of e^+e^- pairs decreases with increasing beam energy

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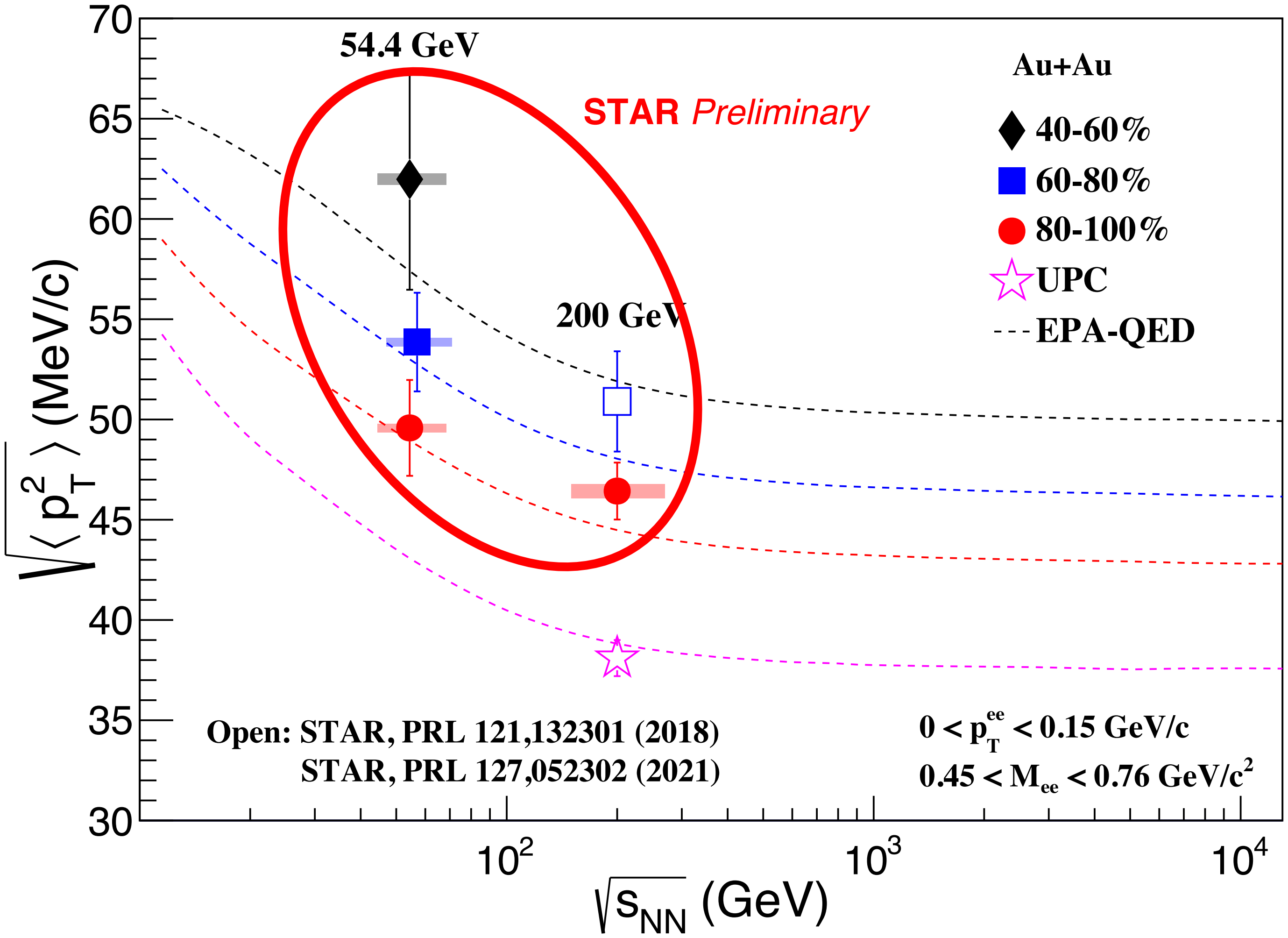
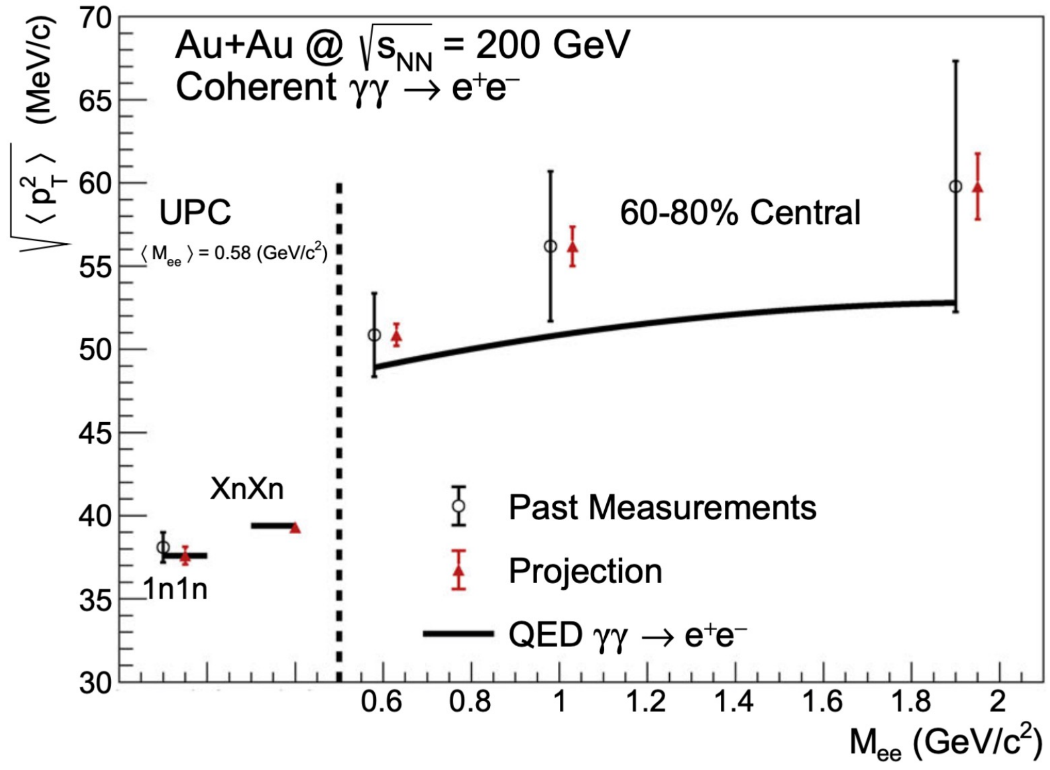


- The $\sqrt{\langle p_T^2 \rangle}$ of e^+e^- pairs decreases with increasing beam energy
- Indication of final state effect

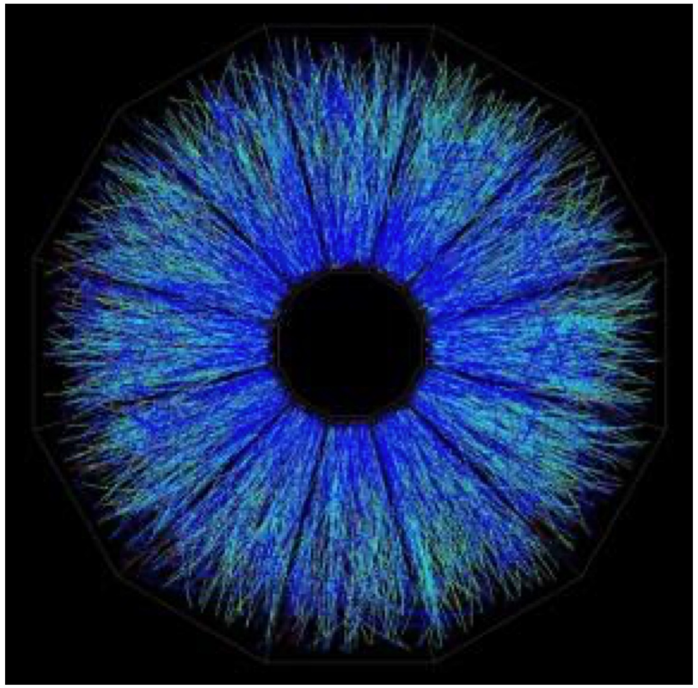
Are There Final-State QED Effect?

higher statistics

STAR collaboration Beam Use Requests for Run-23-25

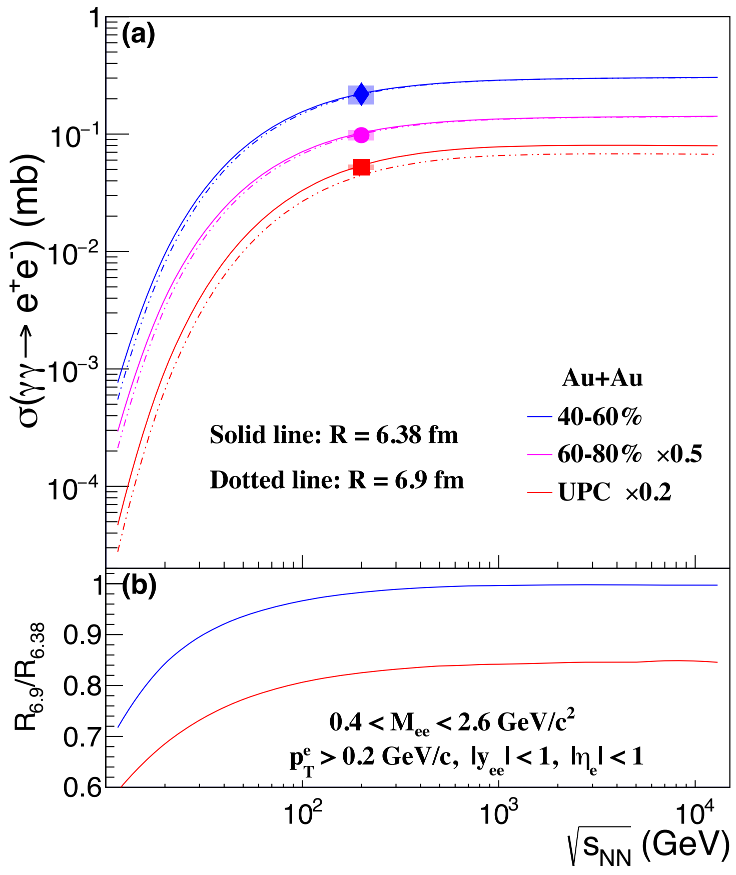


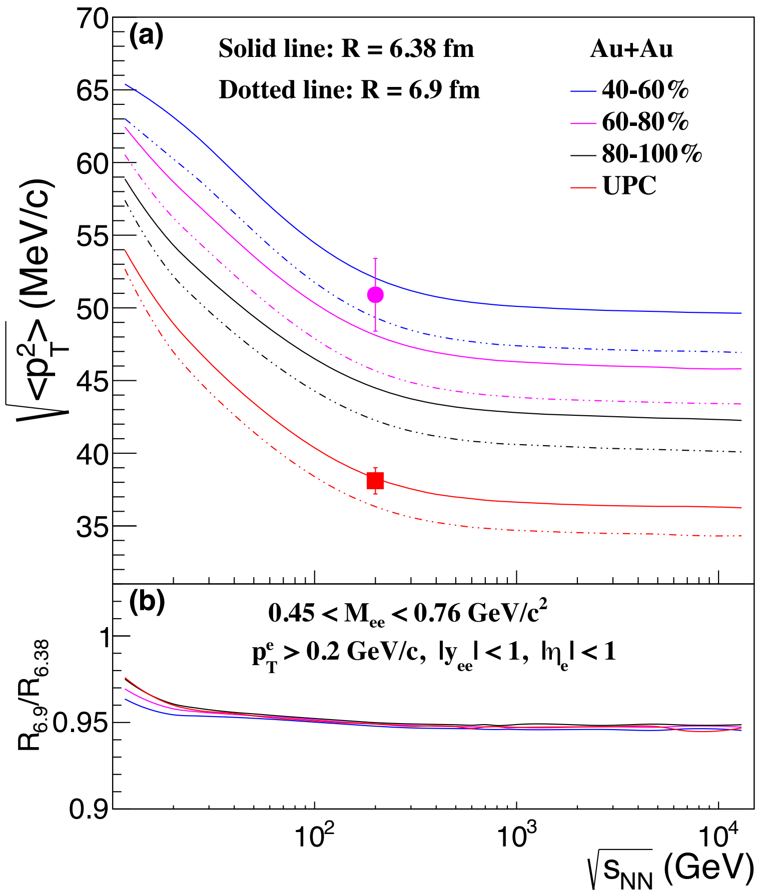
Upgrade of inner Time Projection Chamber



lower p_T, lower systematic uncertainty

Energy Dependence of Cross Section and $\sqrt{\langle p_T^2 \rangle}$





The kinematics of the Breit-Wheeler process are **sensitive** to the details of the **nuclear charge distribution**

X. W, J.D. Brandenburg, L. Ruan, F. Shao, Z. Xu, C. Yang, and W. Zha. Phys. Rev. C 107, 044906 (2023)

Application: Mapping the Magnetic Field

R. D. Woods and D. S. Saxon, Phys. Rev. 95, 577–578 (1954)

Woods-Saxon: $$\rho_A(r) = \frac{\rho^0}{1 + \exp[(r - R)/d]}$$

R: charge radius, d: skin depth

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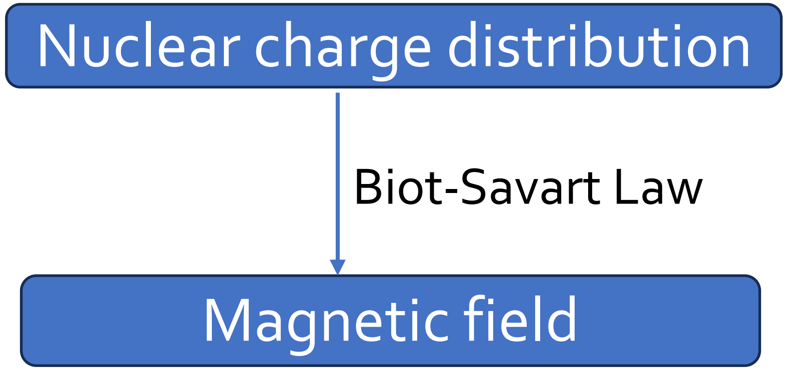

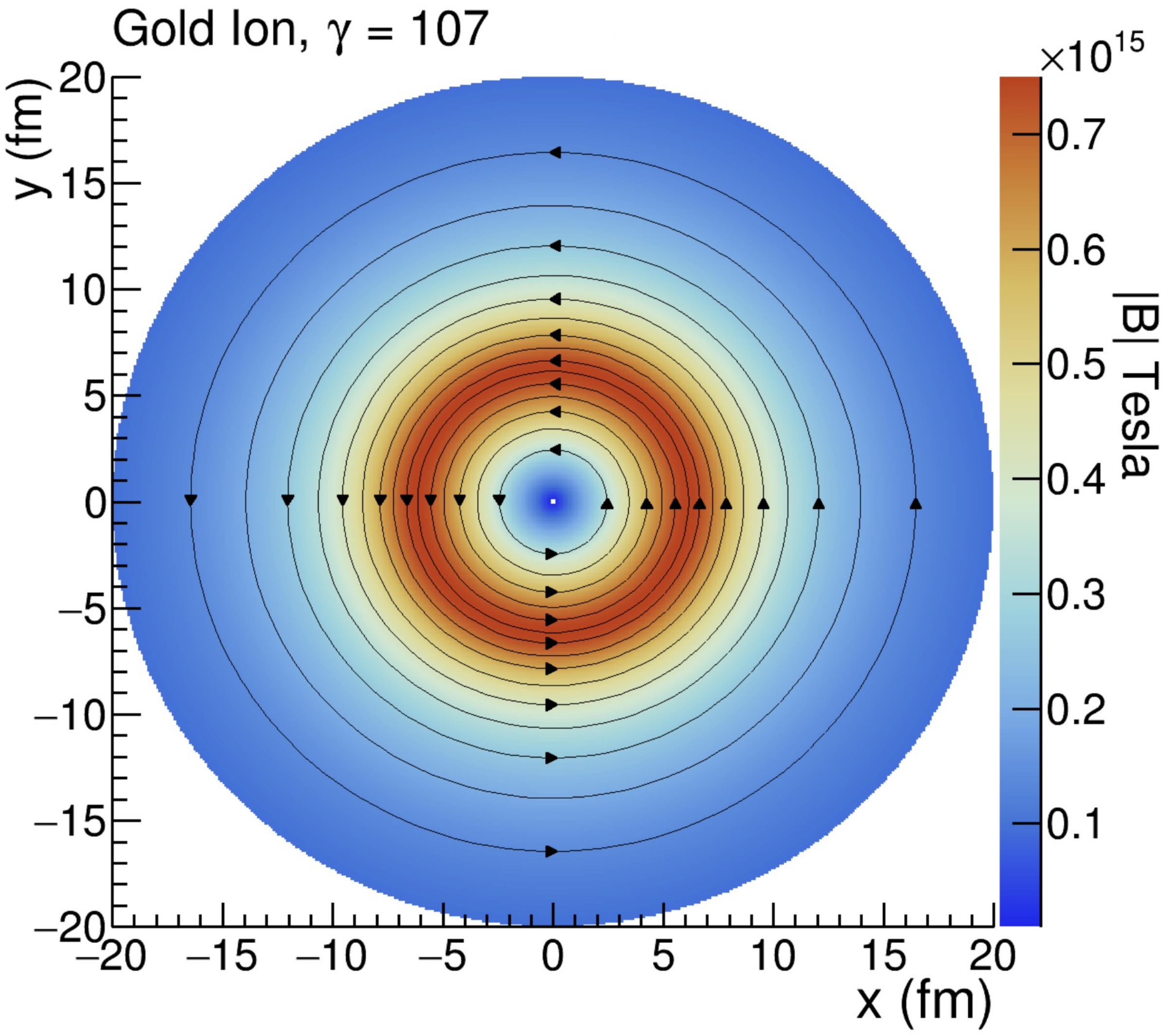

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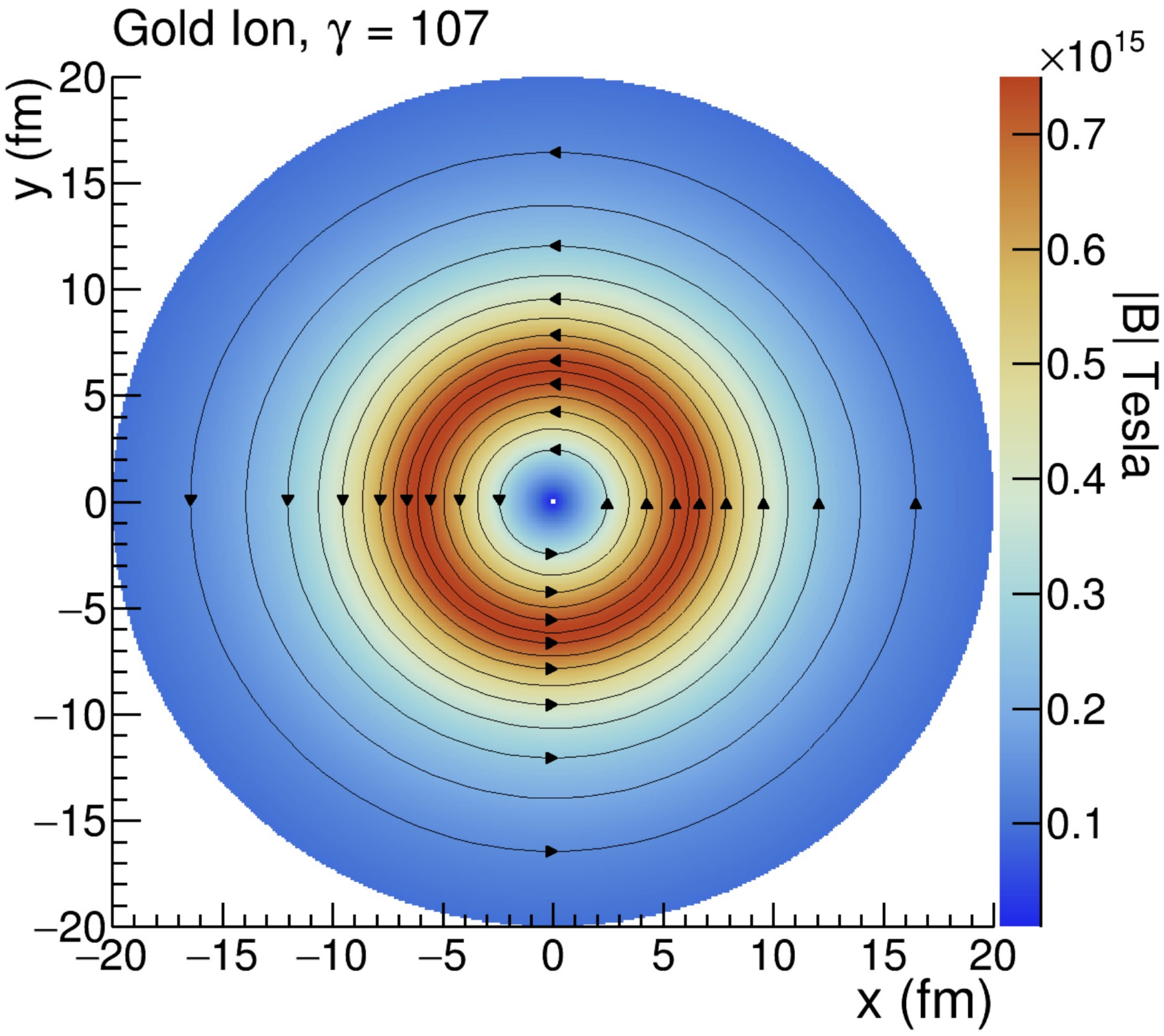
Nuclear charge distribution

↓ Biot-Savart Law

Magnetic field

↓ EPA

The kinematics of Breit-Wheeler process



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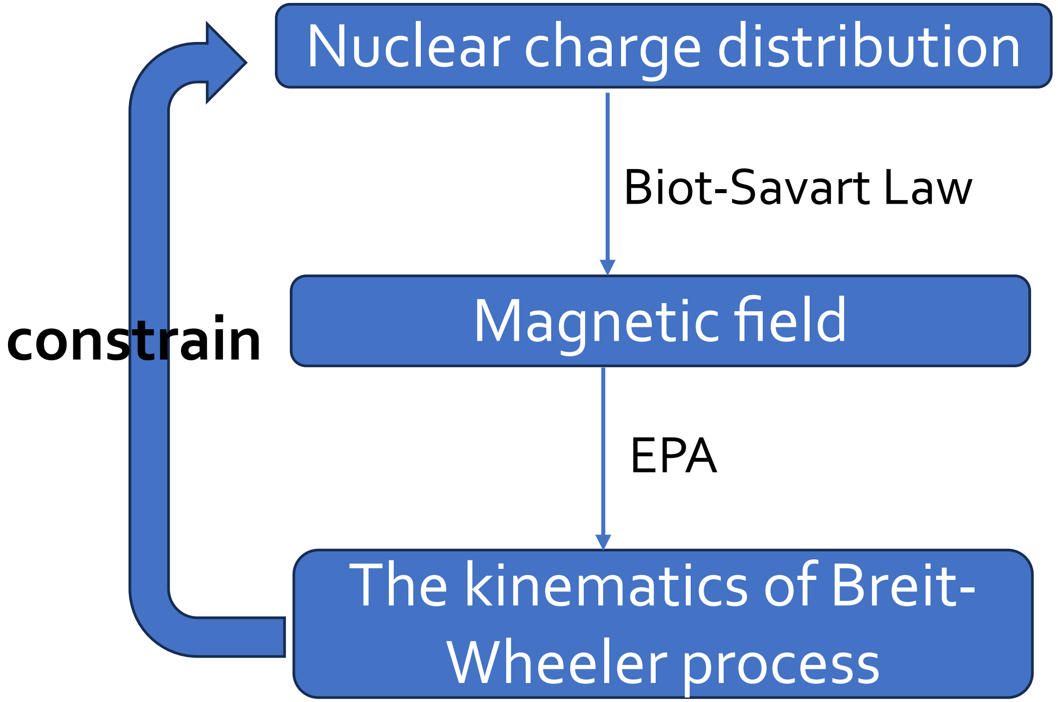
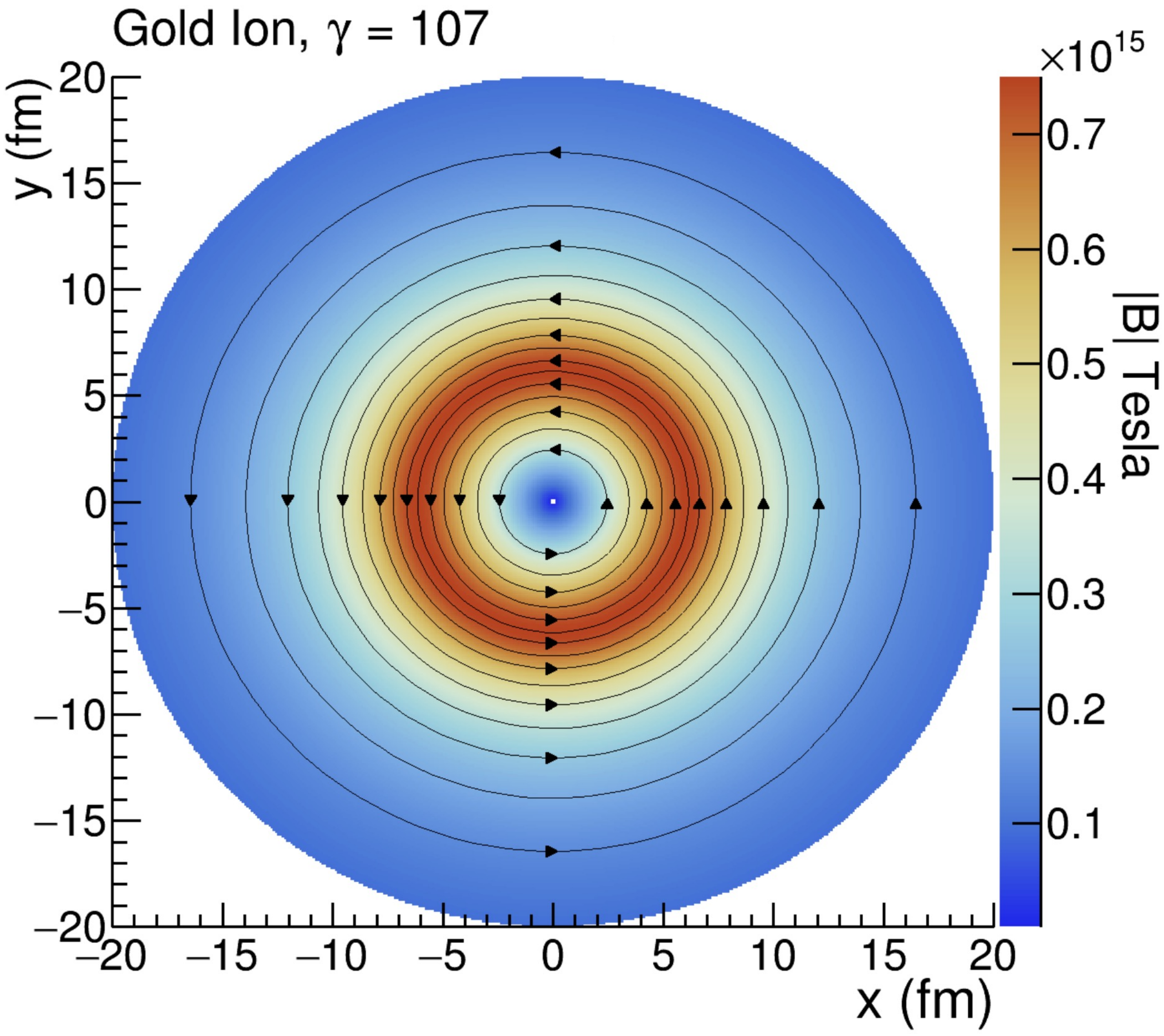
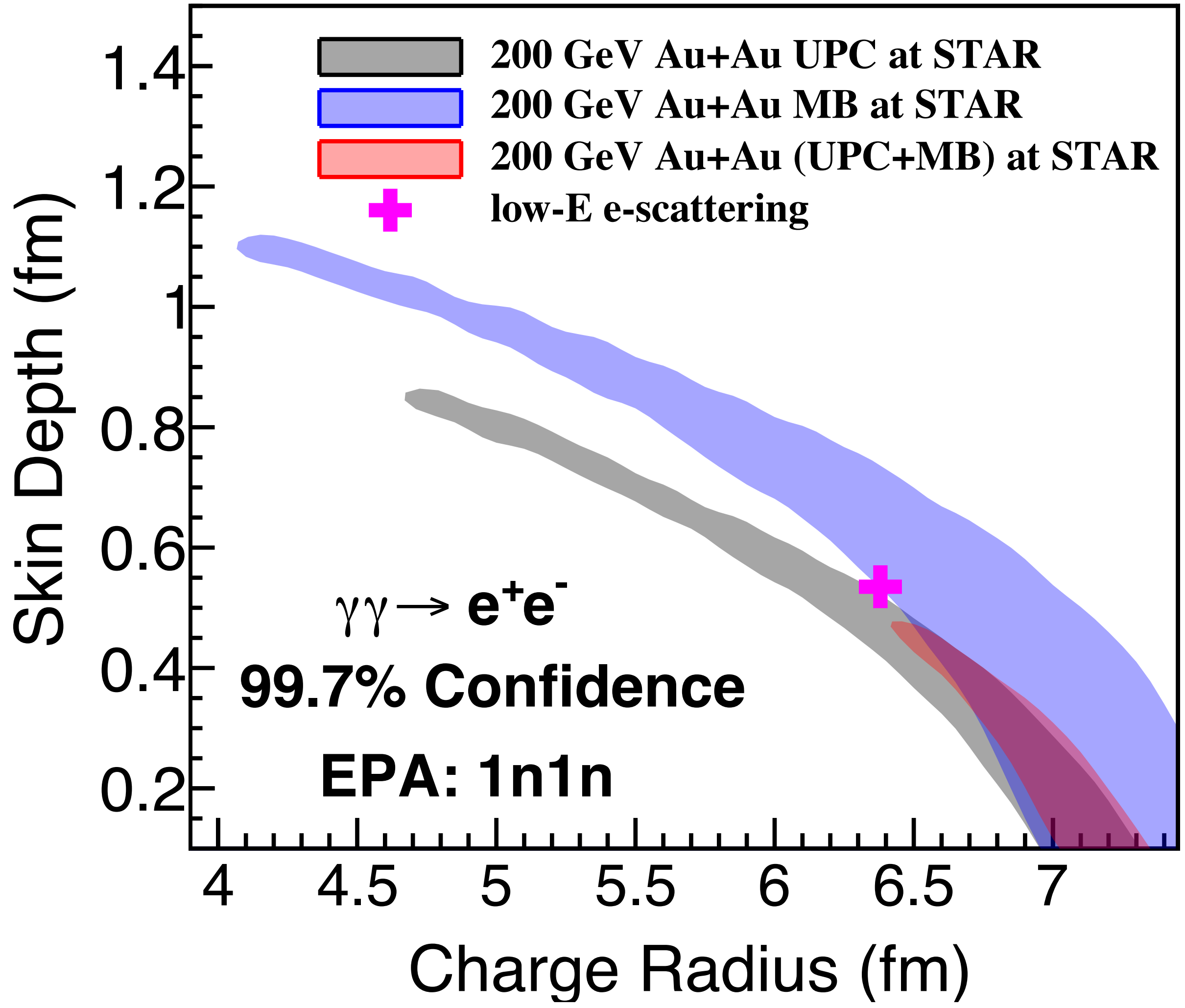




Application: Constrain Charge Distribution with Precision



RMS of radius, low-E e-scattering: 5.33 fm

	UPC	MB	UPC+MB
RMS	5.39+0.14-0.21	5.67+0.08-0.12	5.53+0.10-0.02

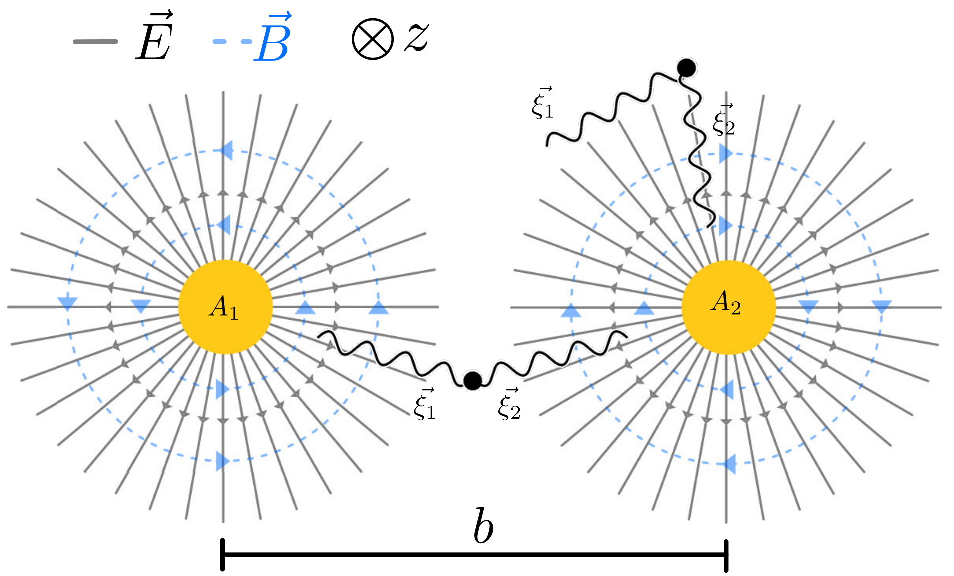
UPC consistent with nominal nuclear geometry

Peripheral collisions systematically larger

Indication of final state effect in HHIC

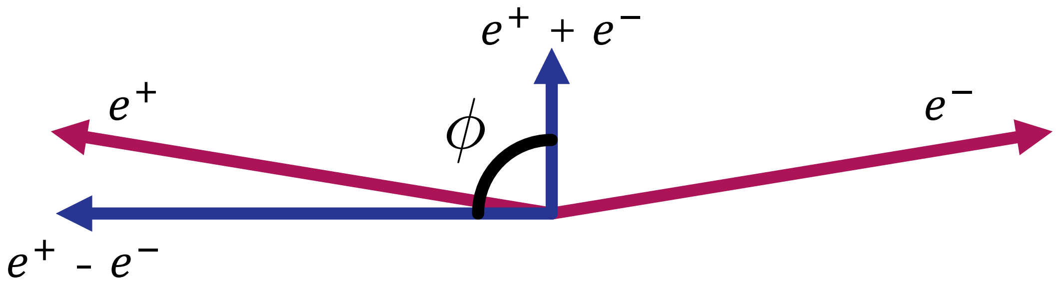
X. W, et al. Phys. Rev. C 107, 044906 (2023)

Polarization in the Breit-Wheeler Process

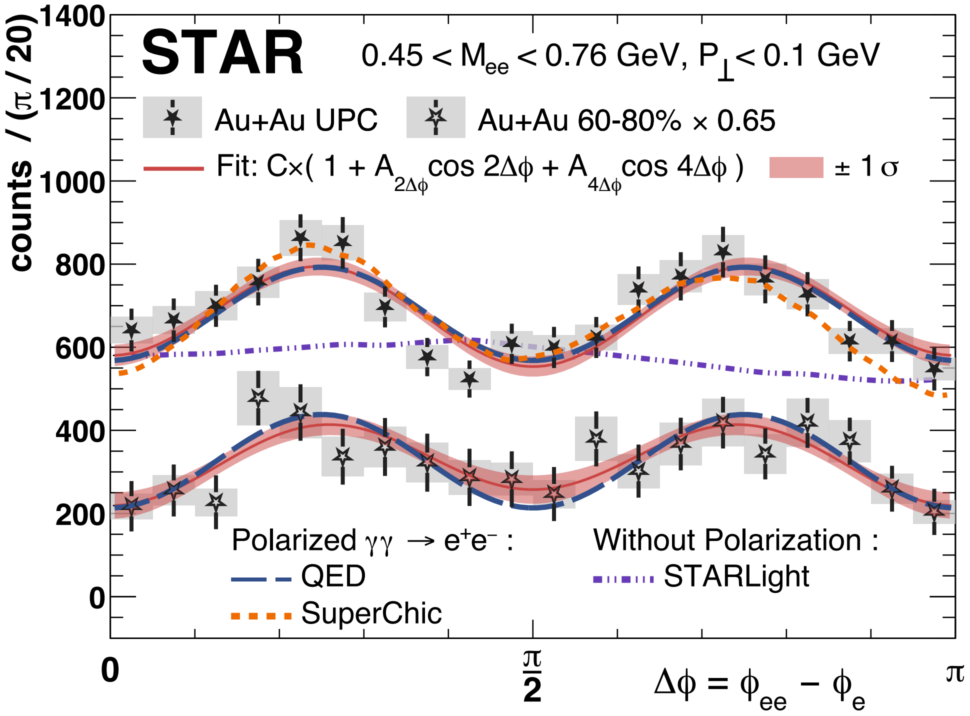


- The incoming photon polarization leads to vacuum birefringence [Toll, 1952], visible as a $\cos 4\phi$ modulation

[1]C. Li, et al. Phys. Lett. B 795, 576 (2019)
[2] J.Brandenburg, arXiv:2208.14943



STAR Collaboration, Phys. Rev. Lett. **127**, 052302 (2021).



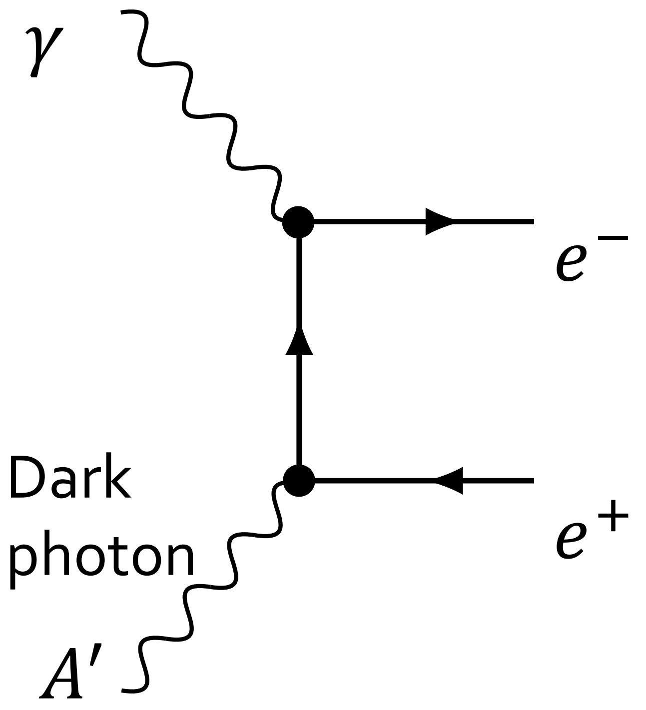
Spin 1 photon helicity a = (-,0,+)

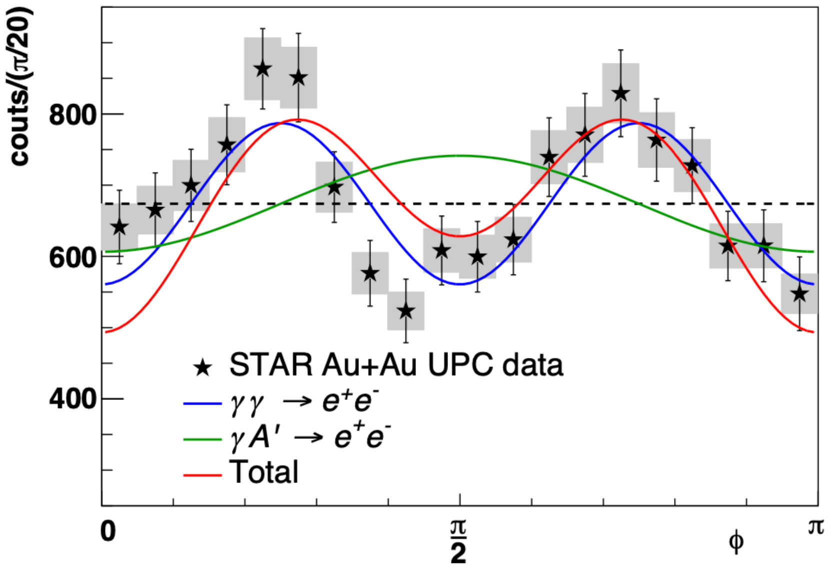
Helicity 0: Forbidden for real photon

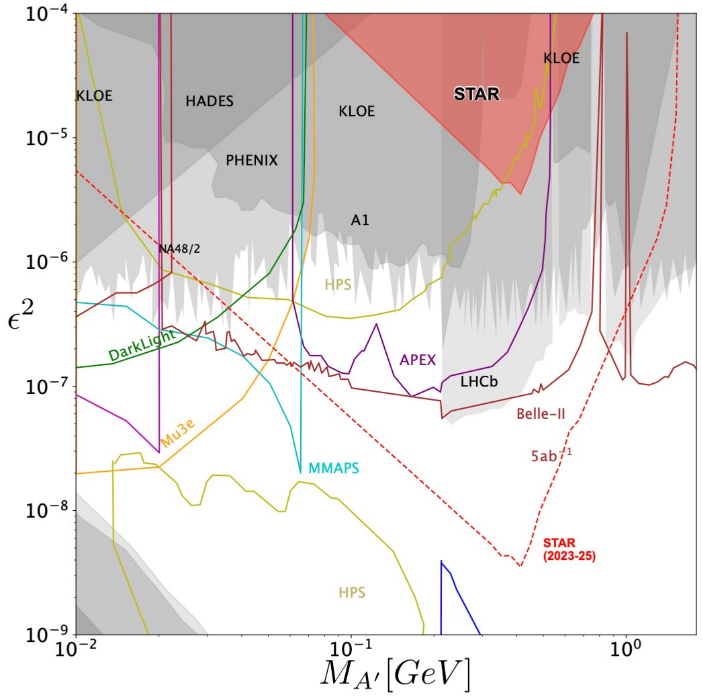
Real photon: Allowed J^P states: $2^\pm$, $0^\pm$

The $J_Z = 2$ states lead to $\pm\cos 4\phi$ azimuthal modulations

Application: Search for Dark Photon







In preparation, https://arxiv.org/abs/2211.02132

The $J_Z = 1$ states lead to $\pm \cos 2\phi$ azimuthal modulations

A coupling constant to charged standard model particles, $\alpha_U = \epsilon^2 \alpha$

Summary

- **The kinematics** of the Breit-Wheeler process have beam energy dependences
- $\sqrt{\langle p_T^2 \rangle}$ and nuclear charge radius: Indication of final state effect
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Thank you!