Results on Breit-Wheeler Process in Heavy-Ion Collisions and its Application to Nuclear Charge Radius Measurements

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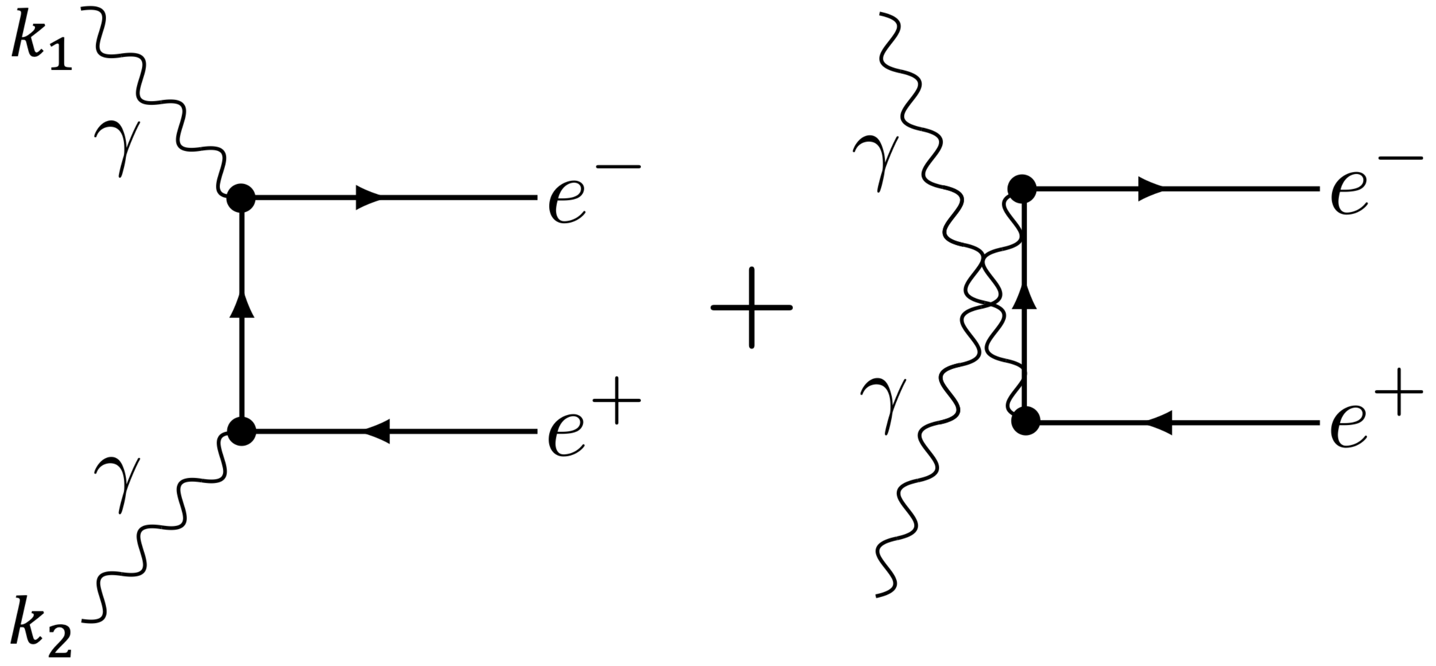
[1] Measurements at STAR

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

National Natural Science Foundation of China

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



◆**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?

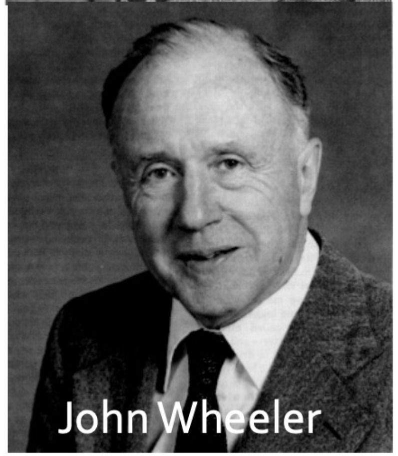
DECEMBER 15, 1934 PHYSICAL REVIEW VOLUME

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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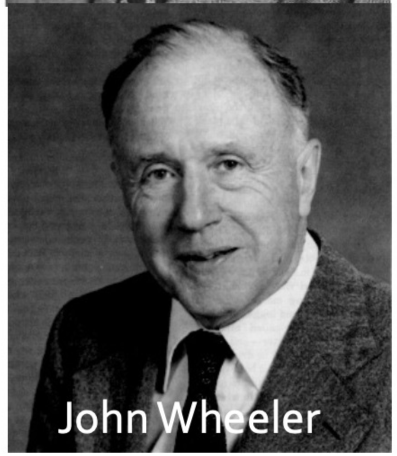
since the result is due to ... rather than exact relatio... try to observe the pair ... experiments with two be... meeting each other on a... of σ and the insufficiently... of quanta. In the considerations of Williams,

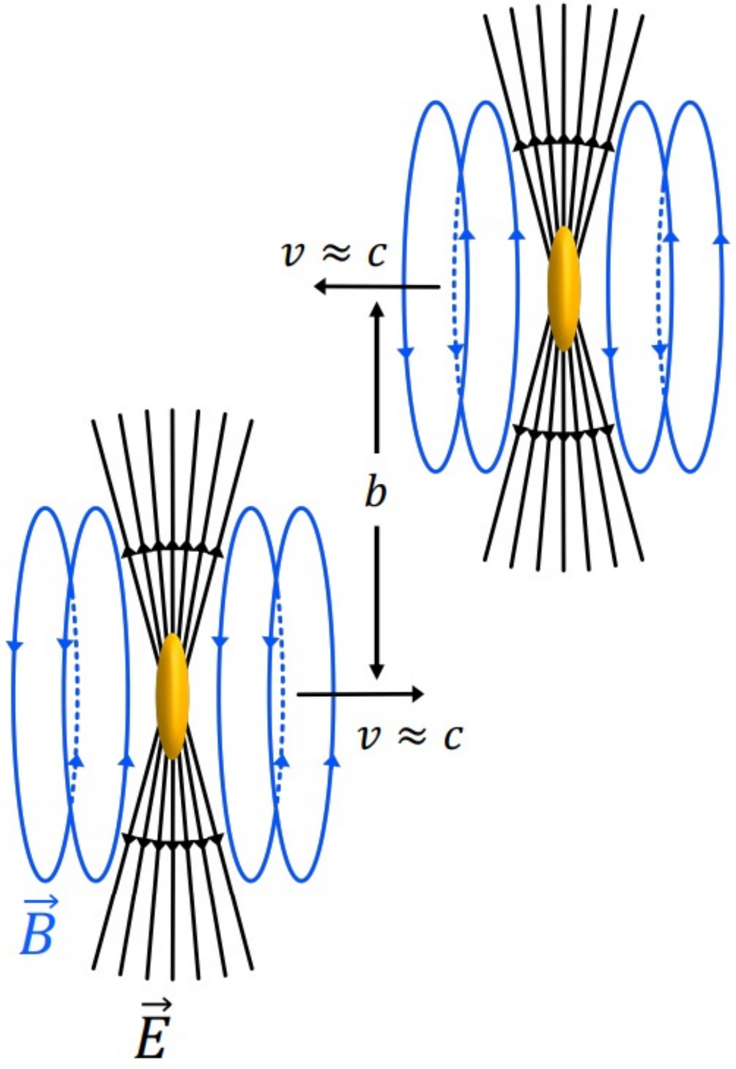
◆ Or maybe not impossible?

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**

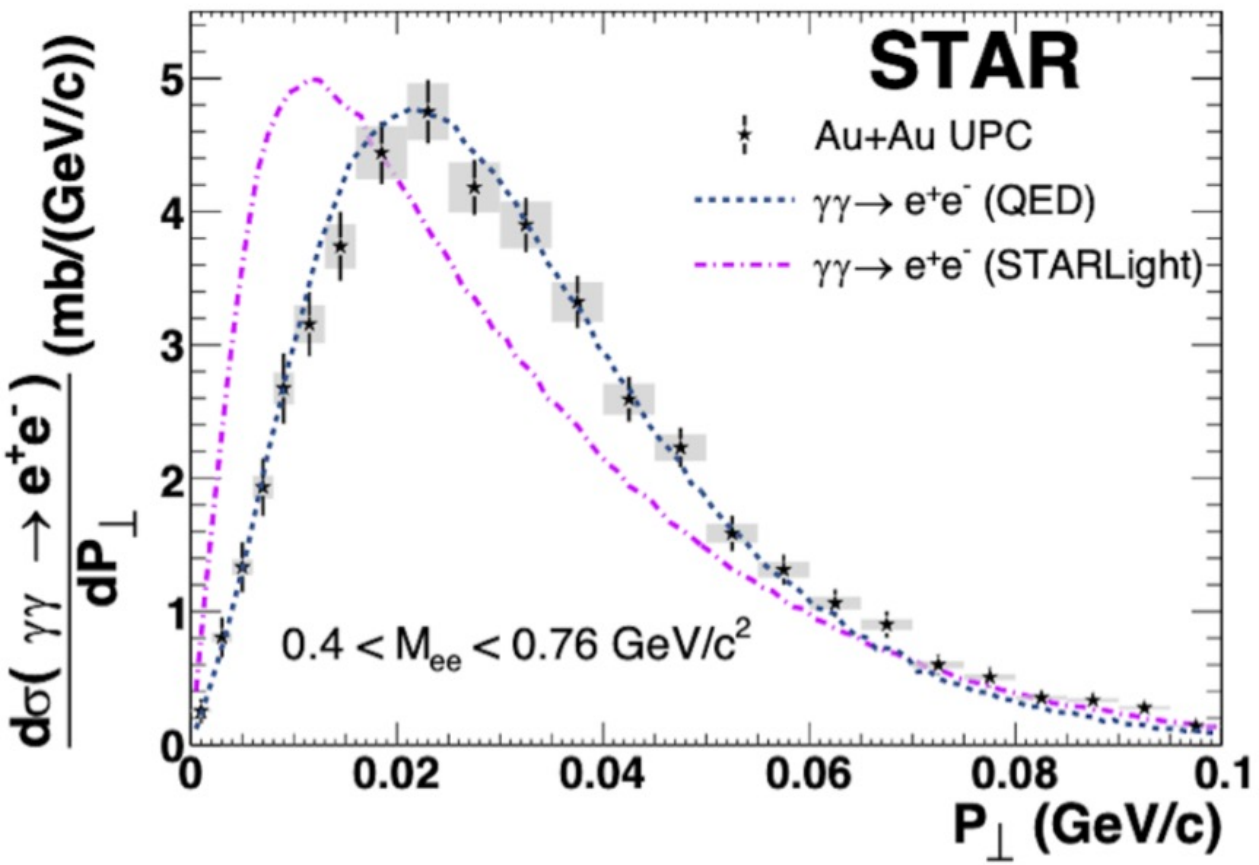
  Weizsäcker, C. F. v. Zeitschrift für Physik 88 (1934): 612
- High photon density from highly charged nuclei ($\propto Z^2$)
- Virtuality $Q^2 \lesssim (\hbar/R_A)^2$ in UPCs $\Longrightarrow$ **almost real**

  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 in UPCs

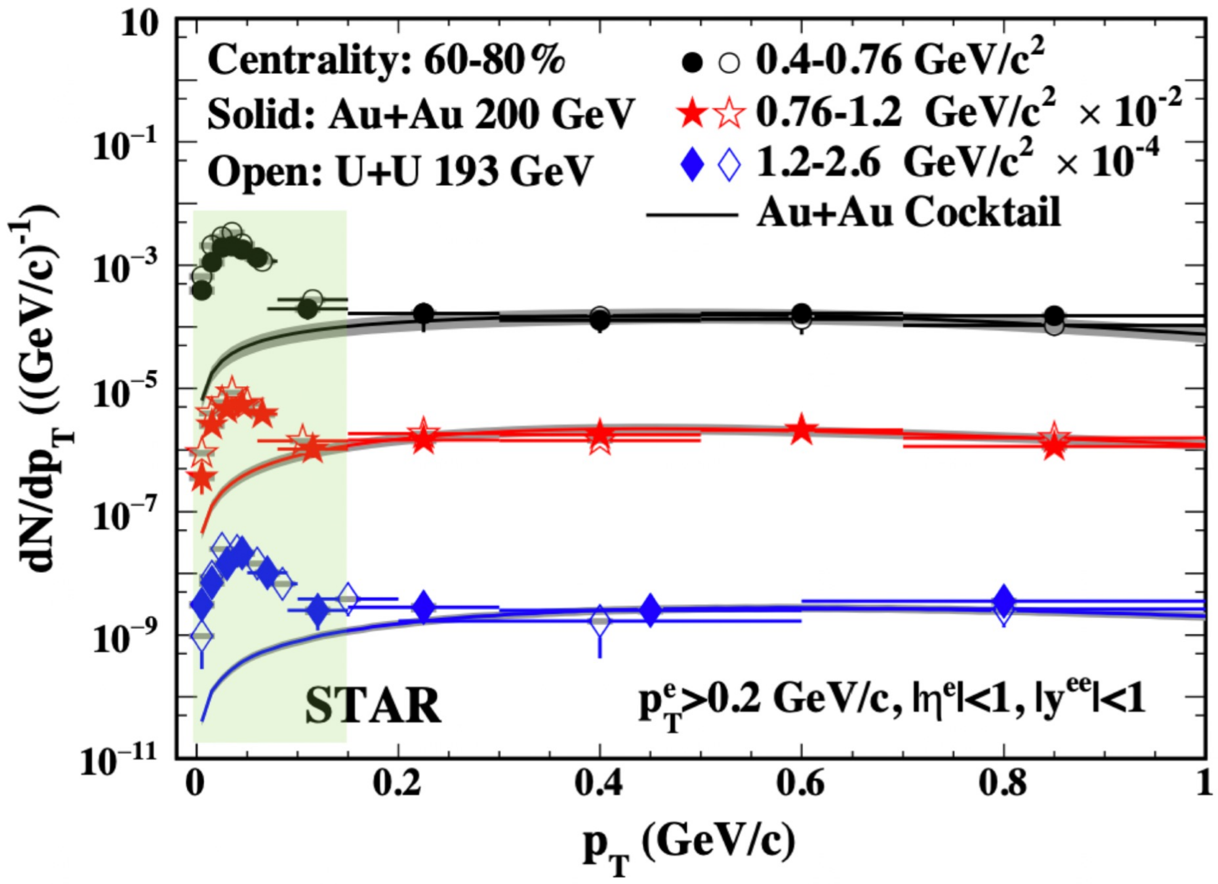
STAR, PRL 127 (2021) 052302

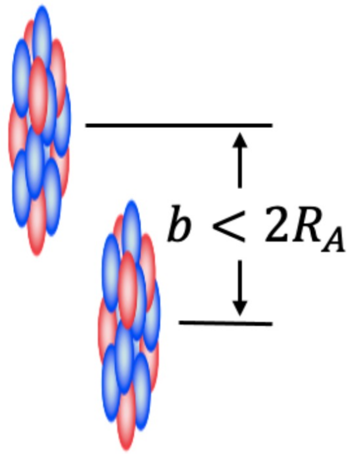


- Exclusive production of e^+e^- pair
- Smooth invariant mass spectra
- Individual l^+/l^- preferentially aligned along beam direction
- **Concentrated at low p_T**
  - **Back to back in transverse plane**

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

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





Observation of $\gamma\gamma \rightarrow e^{+}e^{-}$ in hadronic heavy ion collisions at STAR

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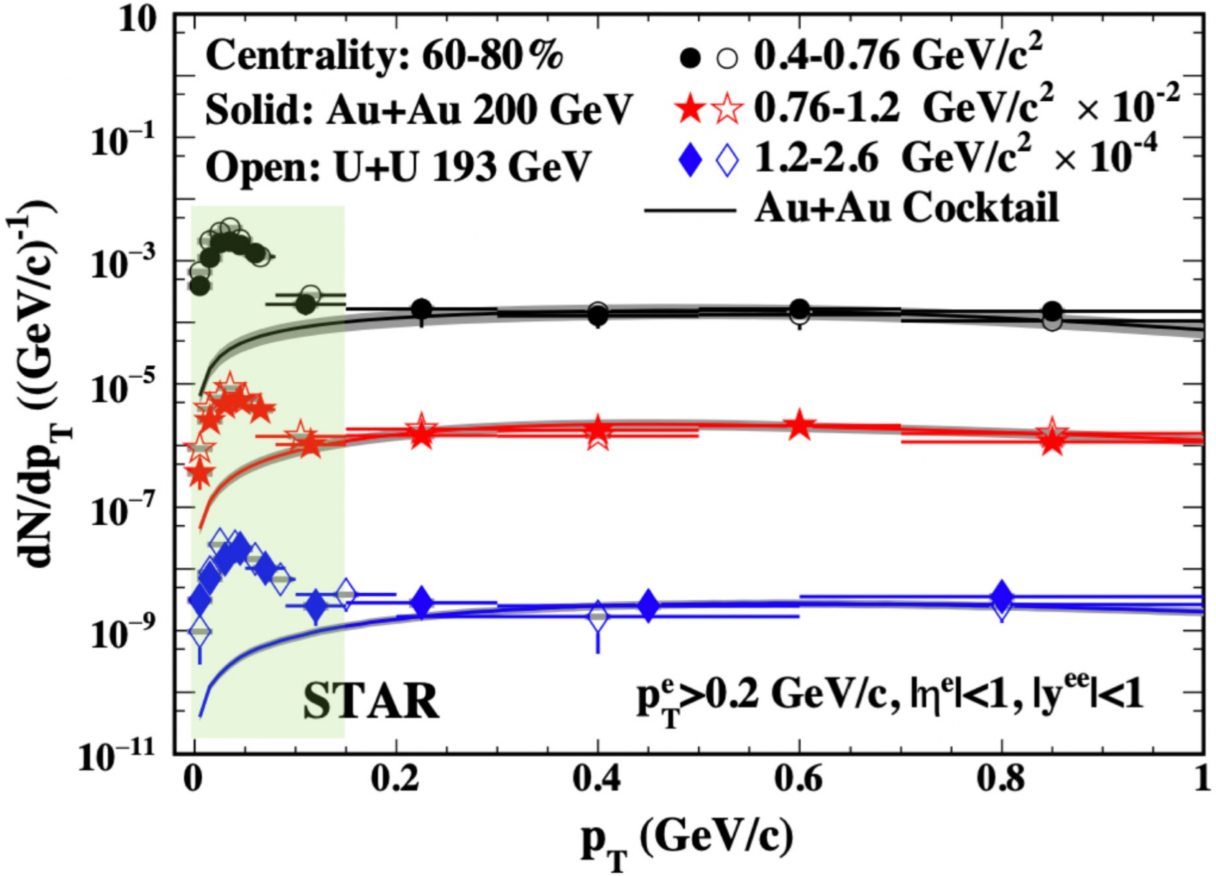
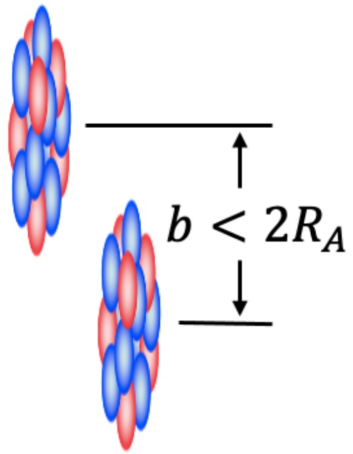




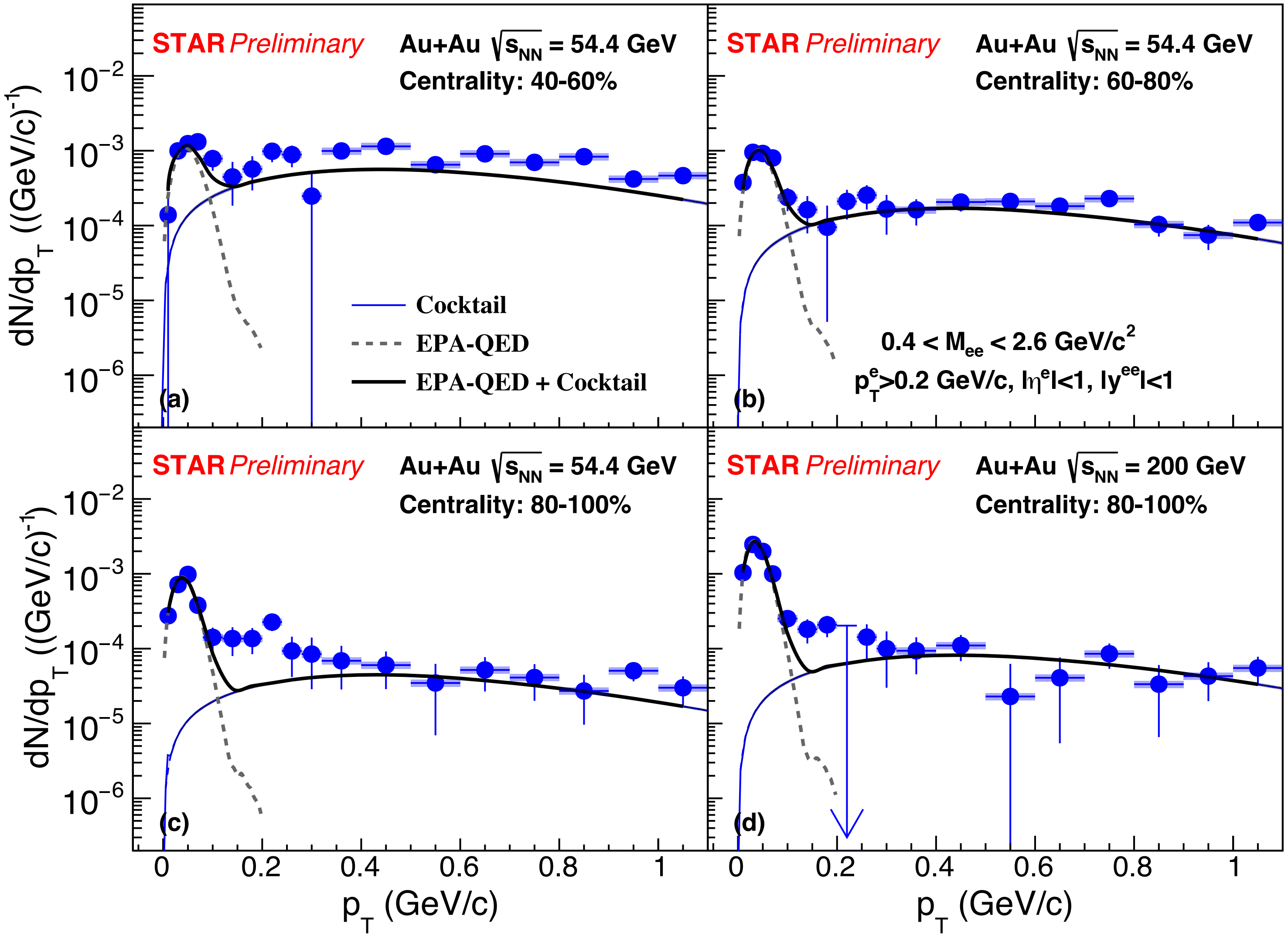
Energy dependence?

Centrality dependence?

Final state effect?

Observation of $\gamma\gamma \rightarrow e^+e^-$ in hadronic heavy ion collisions at STAR

Transverse Momentum Distribution



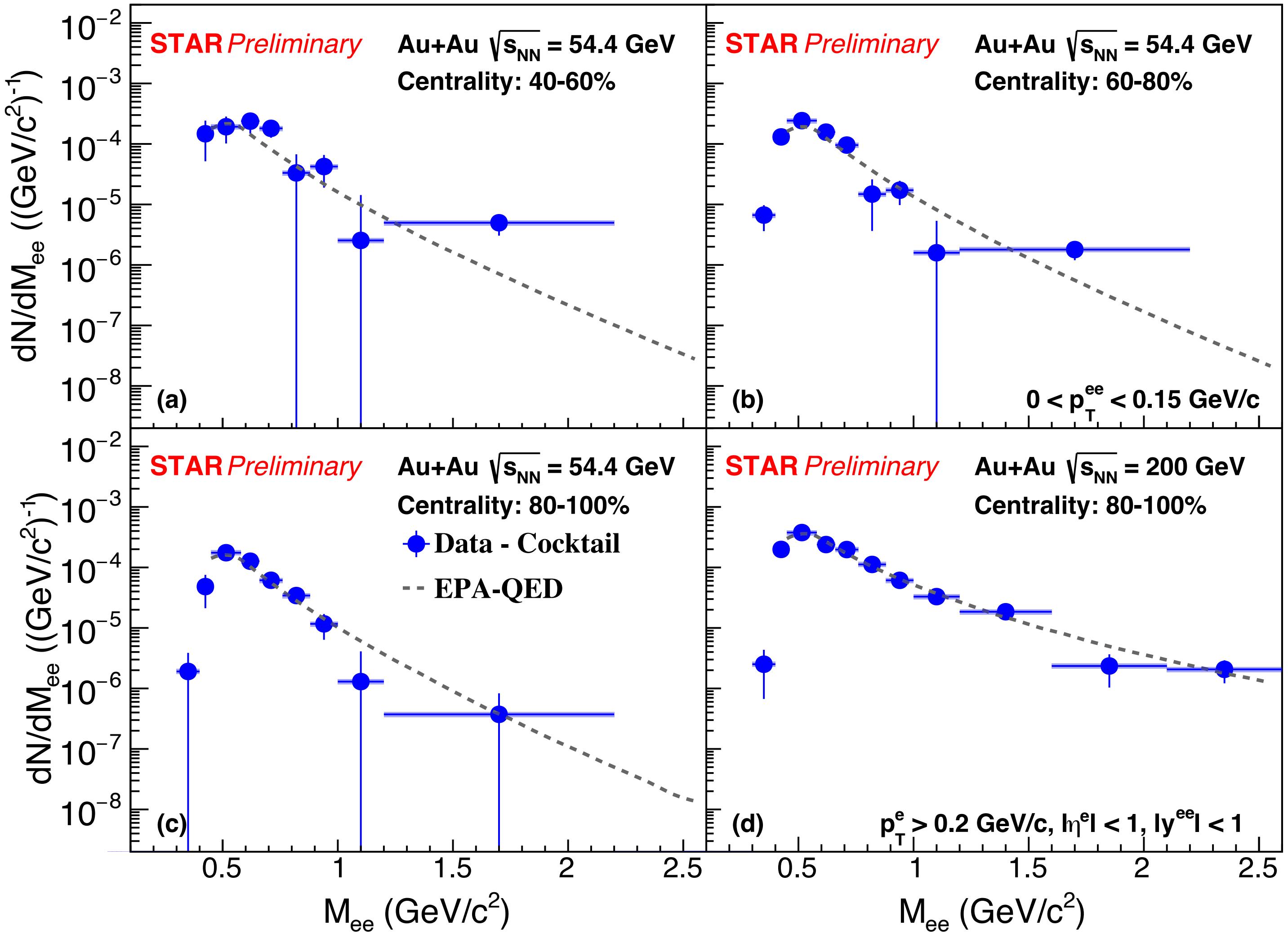
Excesses above hadronic production are observed at low-p_T

Lowest order EPA-QED predictions are consistent with observed excesses

Energy dependence
54.4 GeV, 200 GeV

Centrality dependence
40-60%, 60-80%, 80-100%

Invariant Mass Distribution at Low-p_T

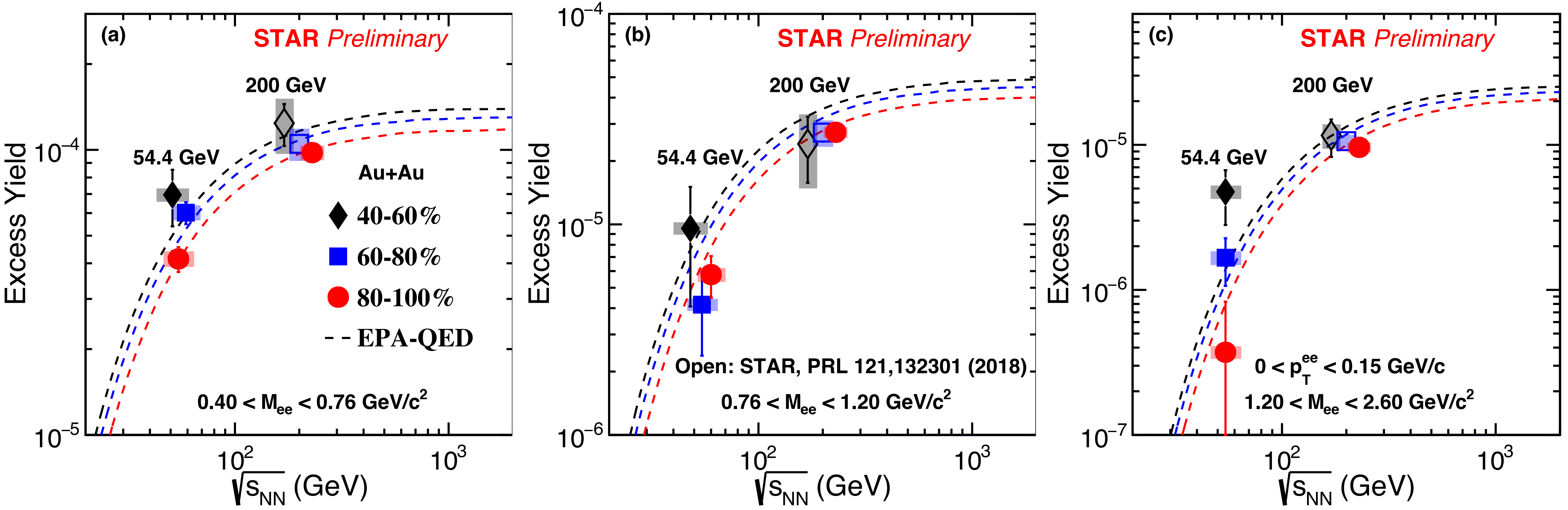


Excesses (Data - Cocktail) are extracted

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

Excesses are well described by lowest order EPA-QED predictions

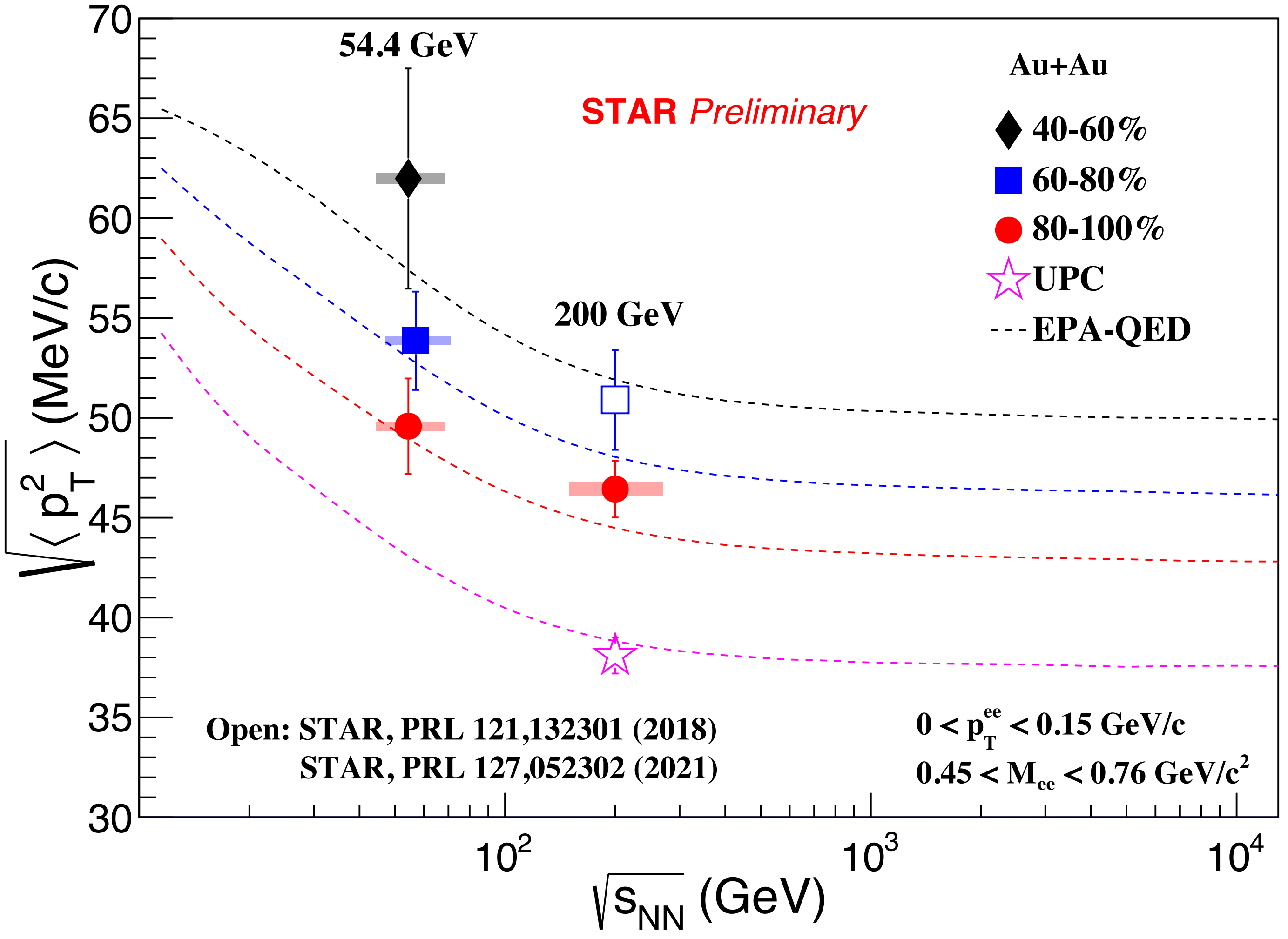
Energy Dependence of Excess Yield



Excess yield increase with beam energy

EPA-QED predicts similar energy dependence

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



$\sqrt{\langle p_T^2 \rangle}$ is sensitive to p_T broadening

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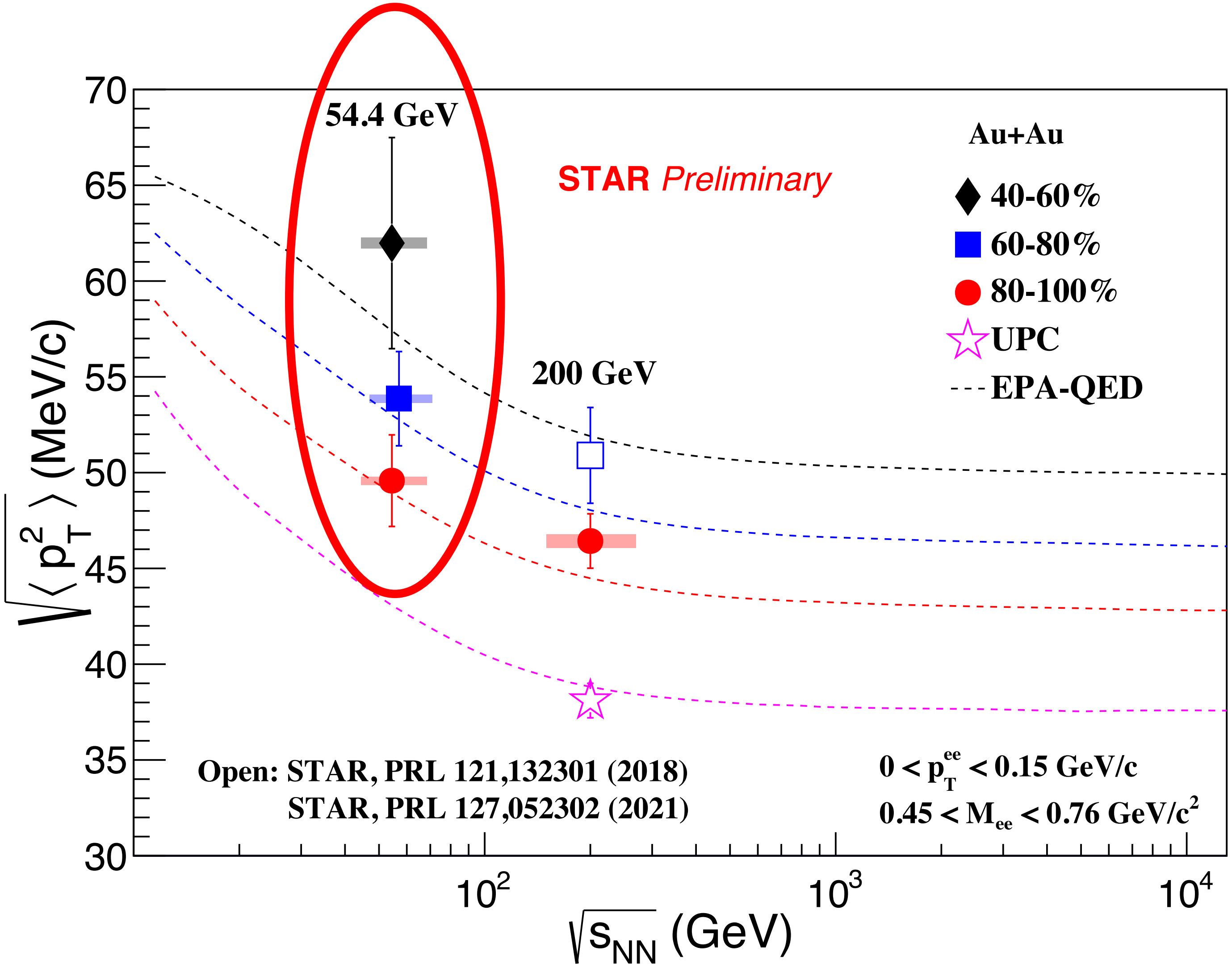

$\sqrt{\langle p_T^2 \rangle}$ is sensitive to p_T broadening

$\sqrt{\langle p_T^2 \rangle}$ decreases from semi-peripheral to peripheral collisions

Initial state effect: Impact parameter dependence

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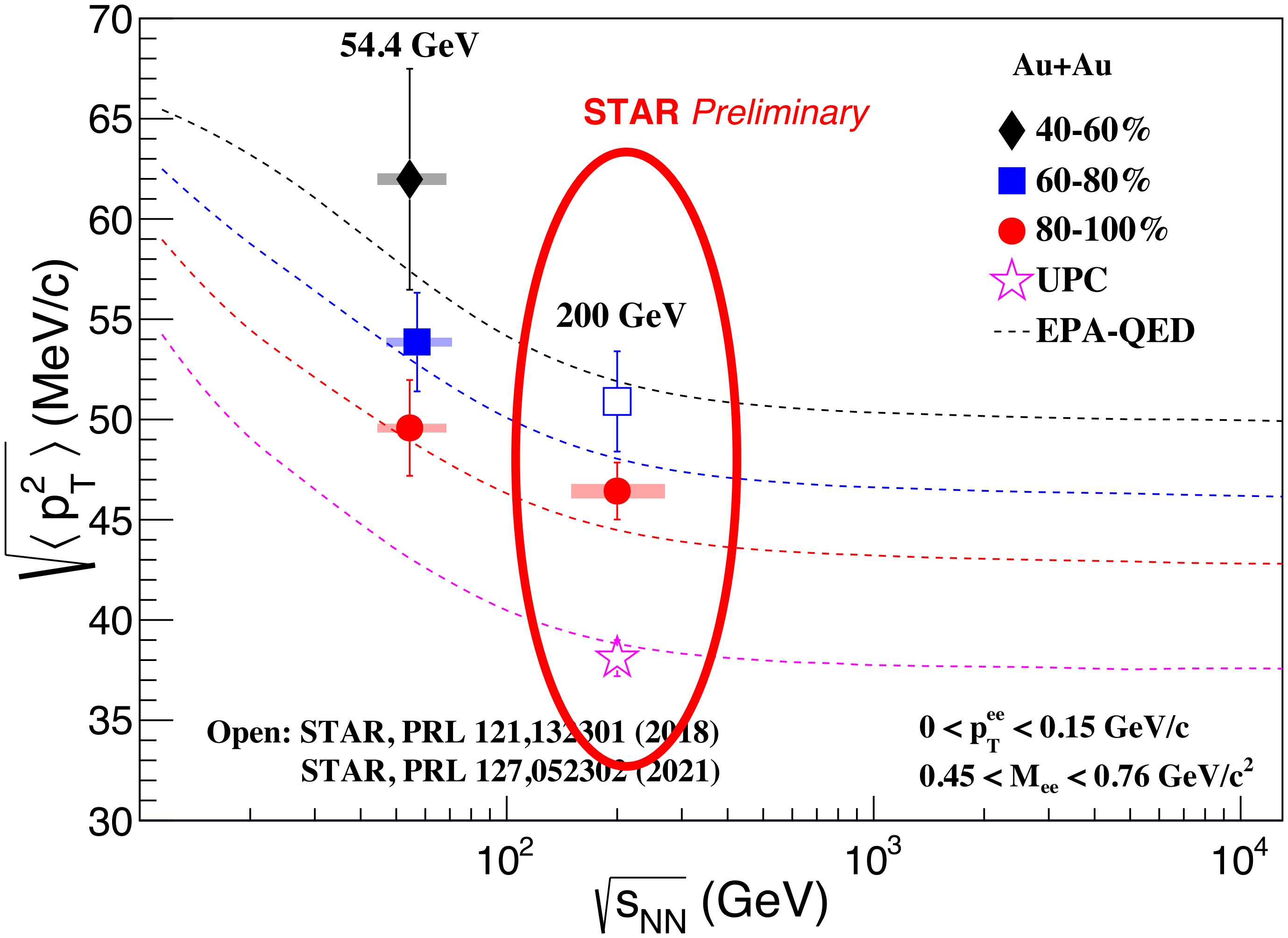

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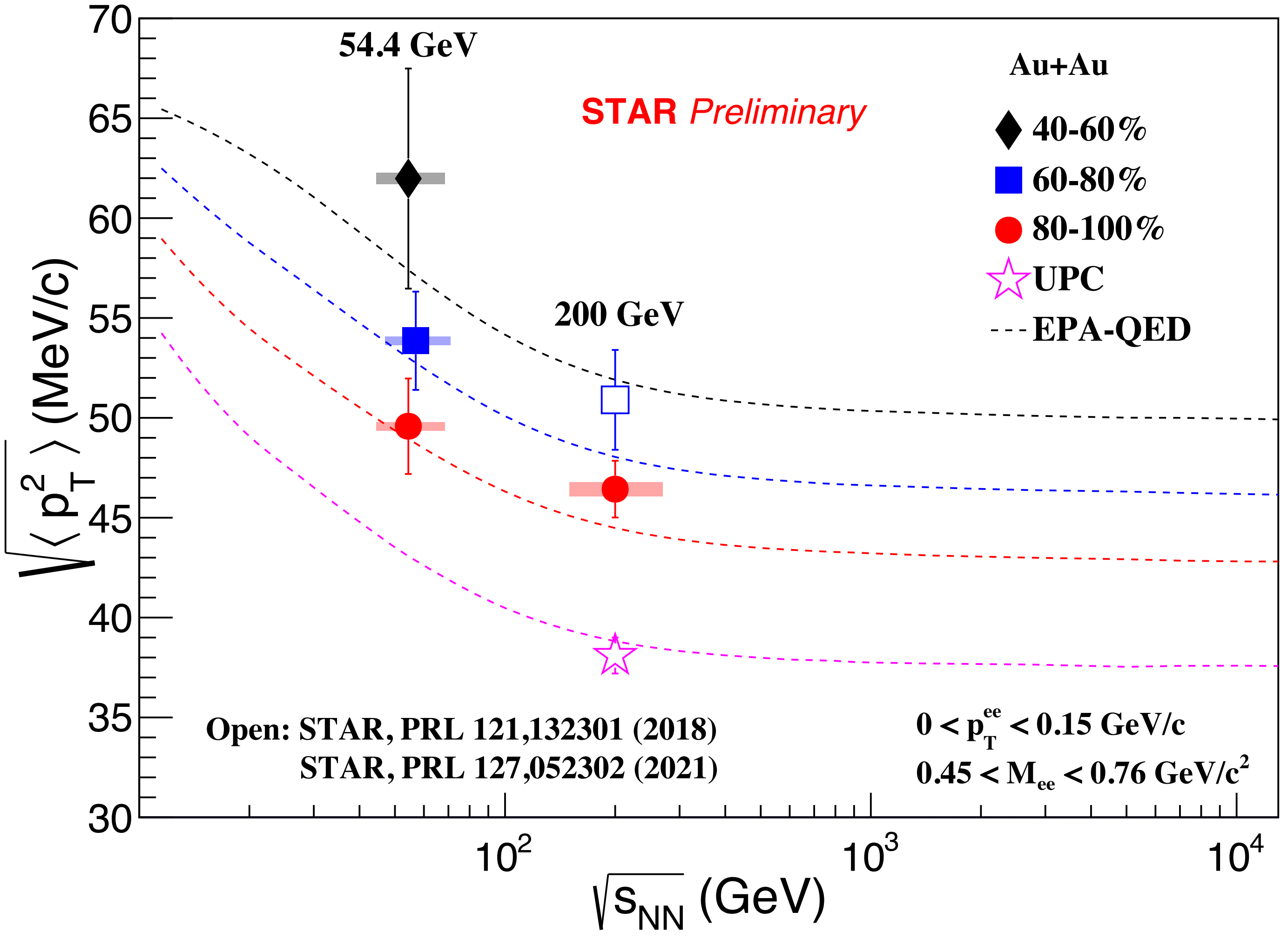

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Impact parameter dependence

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

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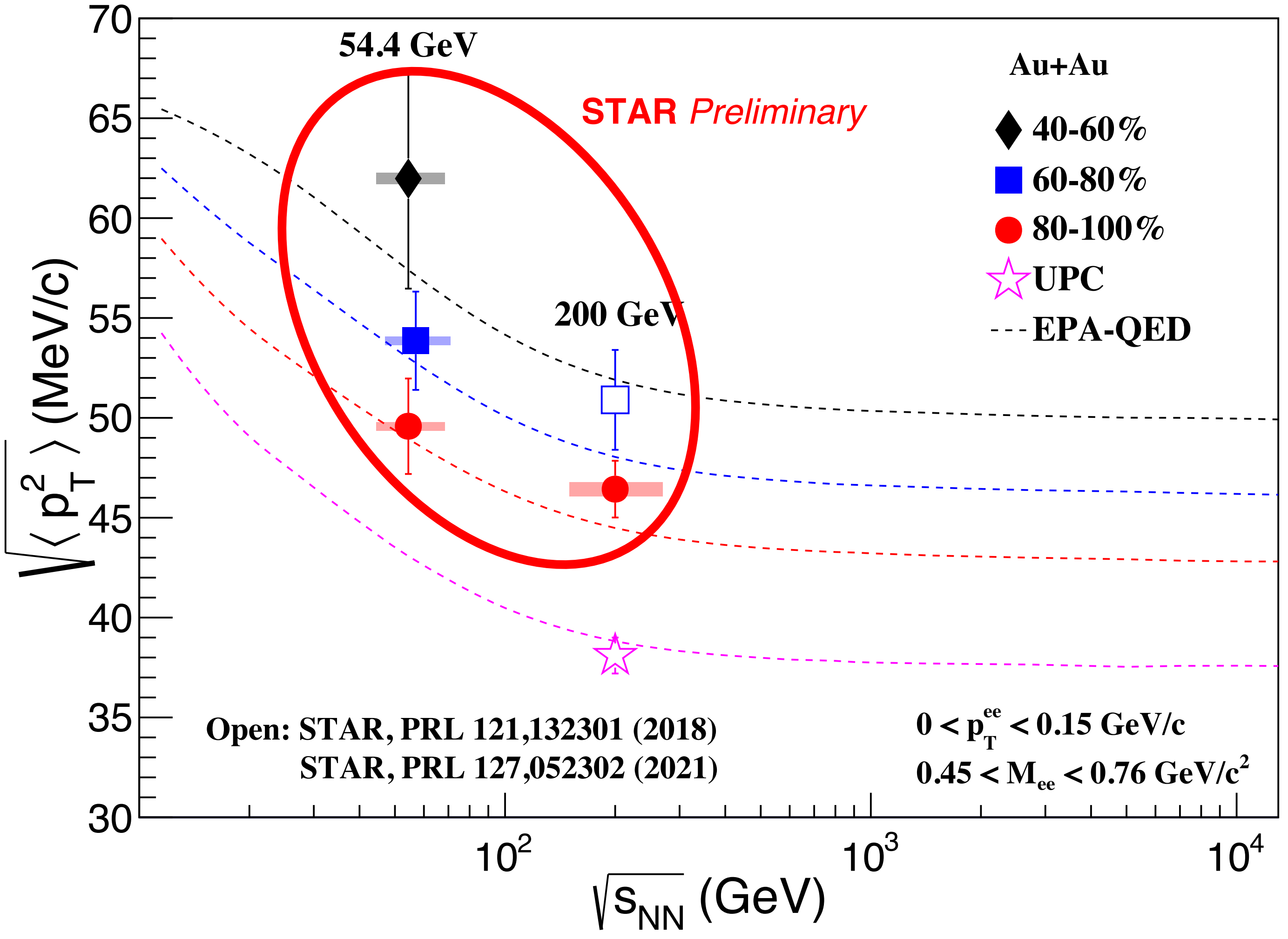

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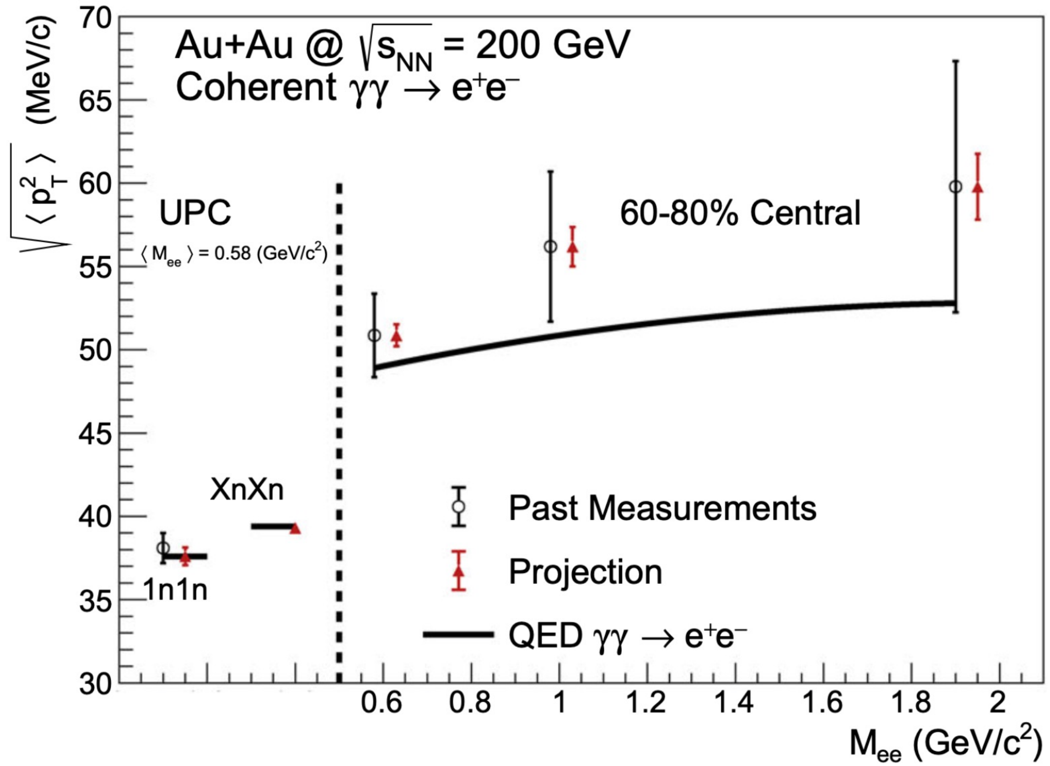
Indication of final state effect

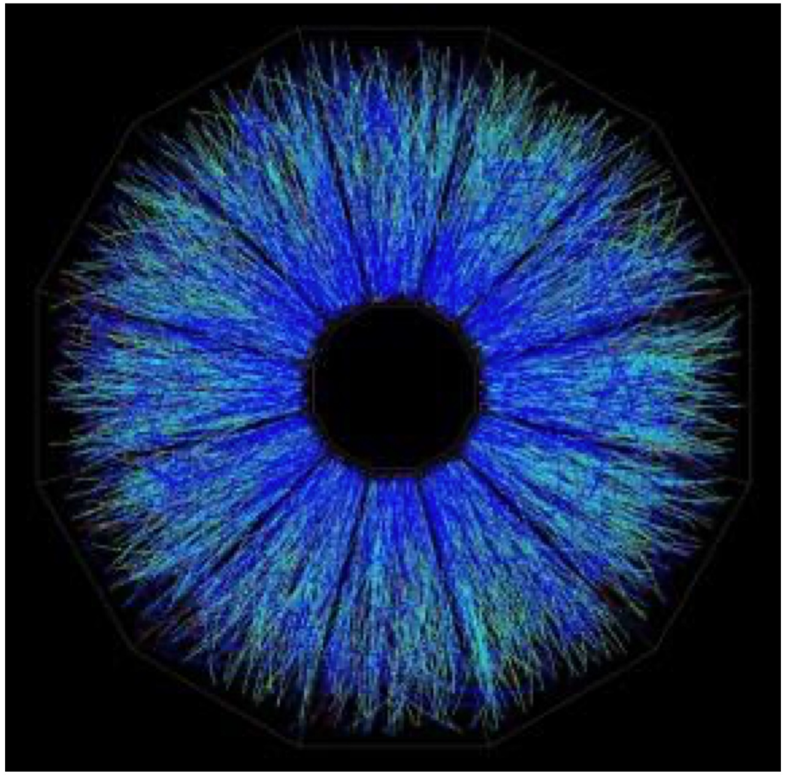
Are there final-state QED effect?

higher statistics

STAR collaboration BUR for Run-23-25



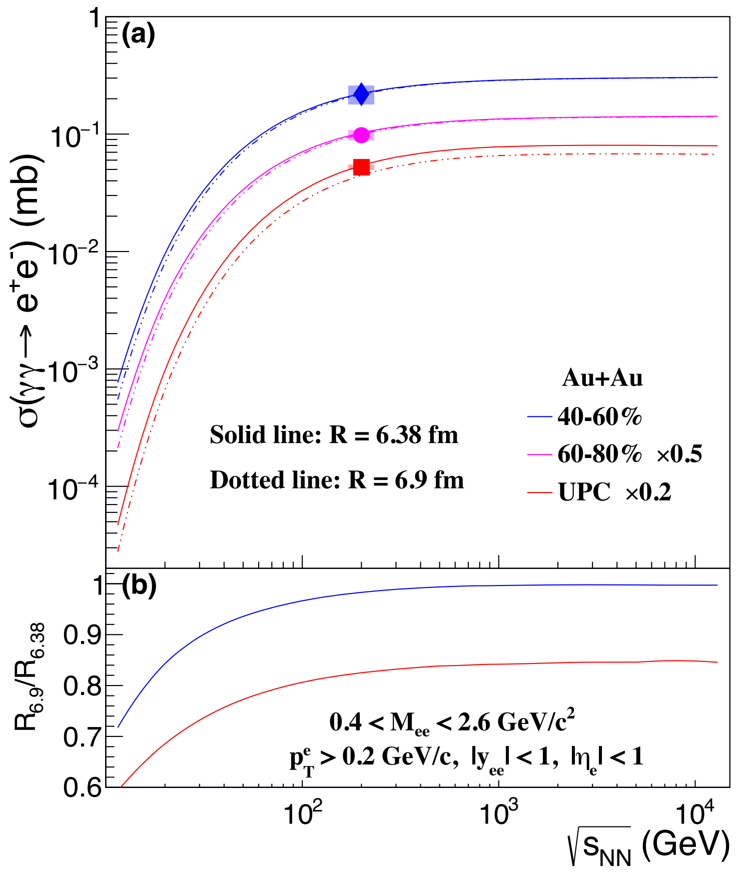
iTPC upgrade

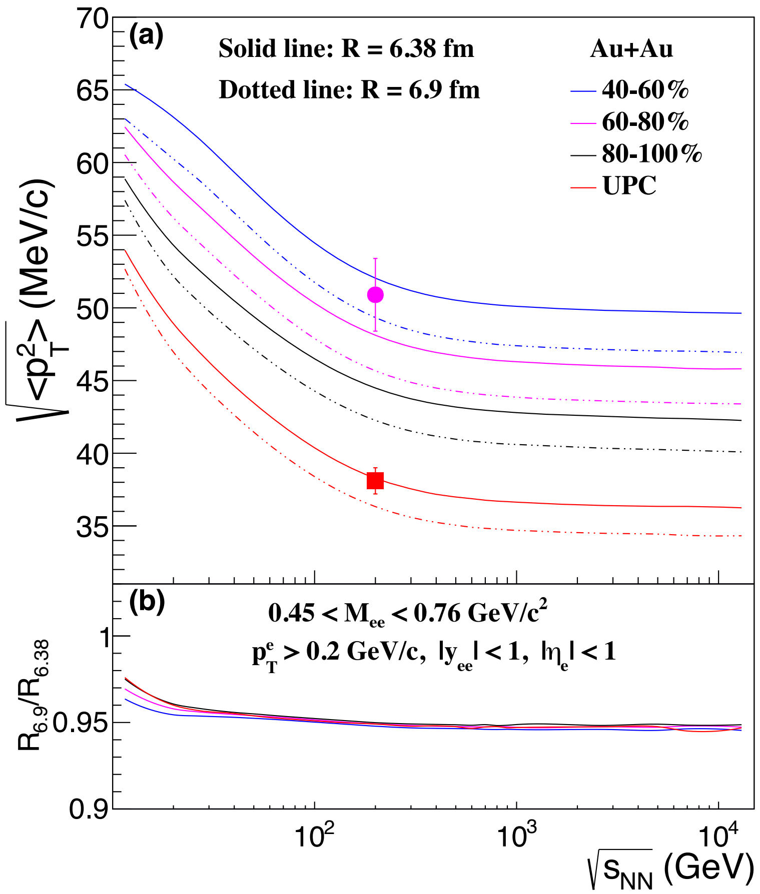


lower p_T,

lower systematic uncertainty

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





Cross section increases with beam energy

$\sqrt{\langle p_T^2 \rangle}$ decreases with increasing beam energy

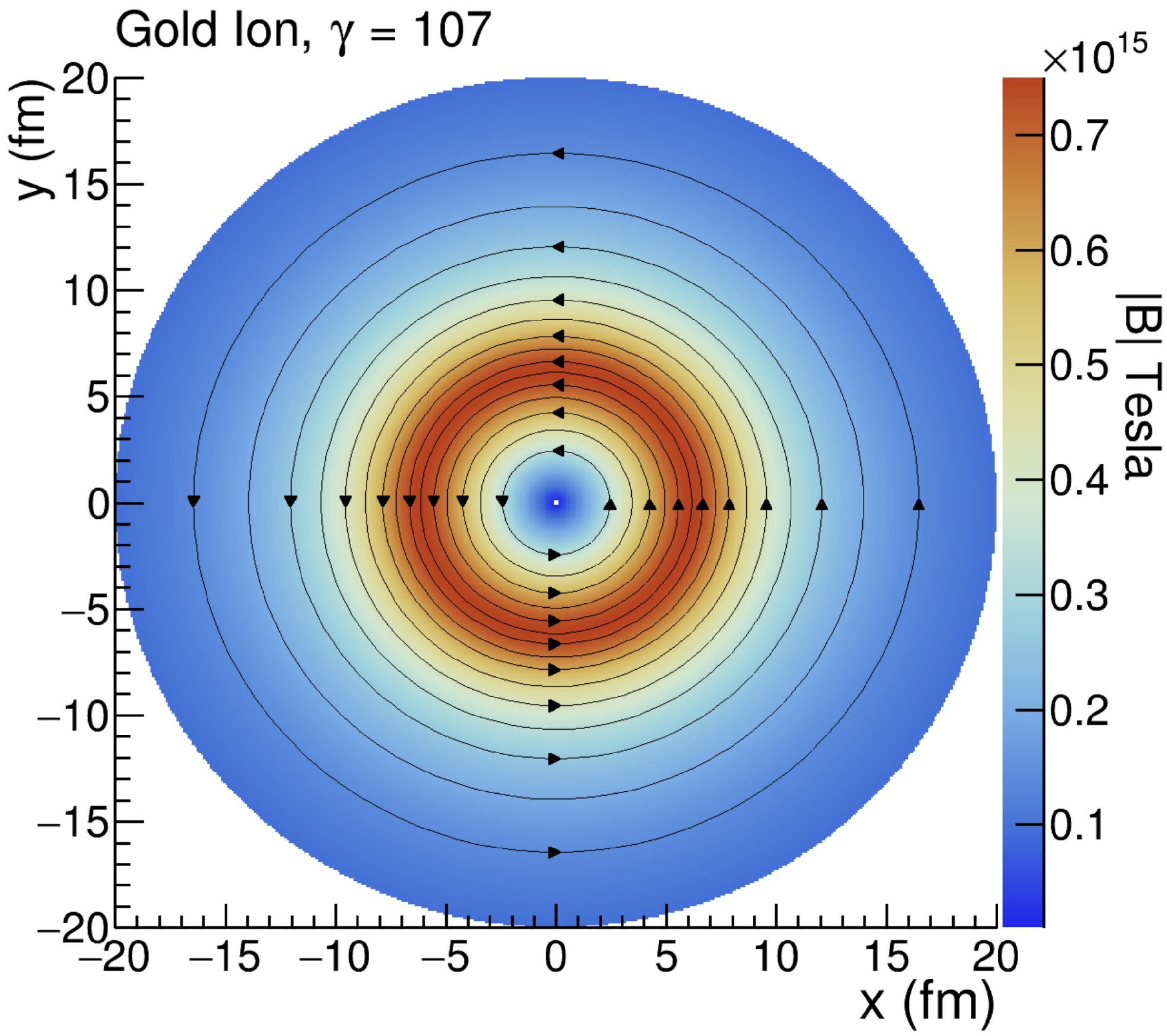
The kinematics of the Breit-Wheeler process are **sensitive** to the details of the **nuclear charge distribution**

Application: Mapping the Magnetic Field

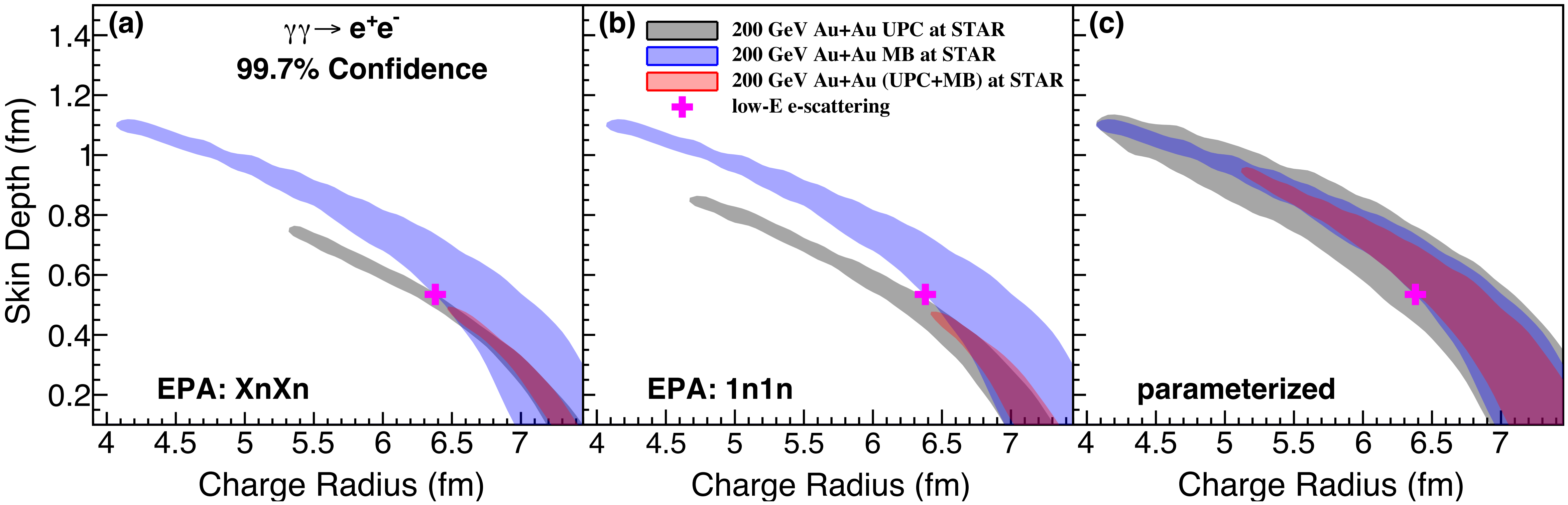
- Total and differential cross-sections (e.g. $d\sigma/dP_{\perp}$) for $\gamma\gamma \rightarrow e^{+}e^{-}$ are related to field strength and configuration
  - **Photon density is related to energy flux of the electromagnetic fields** $n \propto \vec{S} = \frac{1}{\mu_0}\vec{E}\times\vec{B}$

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

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



Application: Constrain Charge Distribution with Precision



Using LO QED to calculate Breit-Wheeler process to match data with least-χ^2

UPC consistent with nominal nuclear geometry

Peripheral collisions systematically larger

Application: Constrain Charge Distribution with Precision

TABLE I. RMS of radius ($\sqrt{\langle r^2 \rangle}$) at minimum χ^2 (χ^2_{min}) and uncertainties within $\chi^2_{min}+1$ with different σ_{NN} and with different neutron selection conditions in ZDC and parameterized probability. UPC and MB respectively represent ultra-peripheral collision and minibias collision data are used, which is same as Fig. 5. A default $\sigma_{NN} = 41.6$ mb has been used in all other calculations. These are to be compared to the default value of nuclear charge radius RMS of $\sqrt{\langle r^2 \rangle} = 5.33$ fm at $R = 6.38$ fm and $d = 0.535$ fm.

condition	σ_{NN} (mb)	UPC	MB	UPC+MB
1n1n	35.0	5.55 + 0.03 - 0.30	5.66 + 0.09 - 0.12	5.55 + 0.03 - 0.03
	40.0	5.32 + 0.26 - 0.21	5.67 + 0.08 - 0.10	5.58 + 0.01 - 0.04
	41.6	5.39 + 0.14 - 0.21	5.67 + 0.08 - 0.12	5.53 + 0.10 - 0.02
	45.0	5.47 + 0.02 - 0.21	5.66 + 0.09 - 0.11	5.54 + 0.08 - 0.03
XnXn	35.0	5.70 + 0.01 - 0.29	5.66 + 0.09 - 0.12	5.64 + 0.07 - 0.07
	40.0	5.70 + 0.01 - 0.30	5.67 + 0.08 - 0.10	5.70 + 0.01 - 0.12
	41.6	5.67 + 0.03 - 0.17	5.67 + 0.08 - 0.12	5.67 + 0.03 - 0.09
	45.0	5.54 + 0.17 - 0.16	5.66 + 0.09 - 0.11	5.64 + 0.06 - 0.11
Parameterized	35.0	5.51 + 0.15 - 0.18	5.66 + 0.09 - 0.12	5.61 + 0.13 - 0.11
	40.0	5.43 + 0.22 - 0.08	5.67 + 0.08 - 0.10	5.67 + 0.04 - 0.16
	41.6	5.41 + 0.25 - 0.09	5.67 + 0.08 - 0.12	5.62 + 0.12 - 0.11
	45.0	5.40 + 0.23 - 0.17	5.66 + 0.09 - 0.11	5.62 + 0.09 - 0.11

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Summary

- Beam energy and centrality dependences of $\gamma\gamma \rightarrow \mathrm{e}^{+}e^{-}$ have been measured at STAR
  - ✓ Excess yield: **Increases with beam energy**
  - ✓ $\sqrt{\langle p_T^2 \rangle}$: Decreases with increasing impact parameter
  - ✓ $\sqrt{\langle p_T^2 \rangle}$: **Decreases with increasing beam energy**
  - ✓ $\sqrt{\langle p_T^2 \rangle}$: Indication of final state effect

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Thanks for your attention!