Probing Extreme Electromagnetic Fields with the Breit-Wheeler Process

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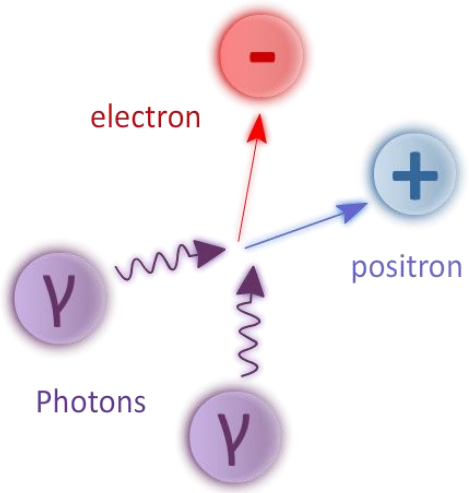
arXiv:1910.12400v1 [nucl-ex] 28 Oct 2019

2020/09/15

Workshop supported by grant SVK30/19/F4

What is a Breit-Wheeler process?

- Breit and Wheeler, 1934
- A positron-electron pair is created from the collision of two photons
- Fundamental process in astrophysics
  - Photons + microwave background



years after its prediction. The original Breit-Wheeler study (*4*) realized the near impossibility of achieving γ ray collisions in the existing Earth-based experiments and proposed an alternative approach with photon collisions originating from highly charged nuclei passing each other at ultra-relativistic speeds. Breit and Wheeler derived the cross-section for photon-photon fusion

Motivation

such that no strong interactions can take place (*12*). The photons generated by highly Lorentz-boosted Coulomb fields are expected to be linearly polarized. It has recently been realized that an experimental signature for the collision of polarized photons is a 4th-order modulation in azimuth (the angle in the plane perpendicular to the beam) between the pair momentum and the $e^{\pm}$ momentum (*13*).

Conventionally, photon-induced interactions between nuclei are expected to arise only in UPC. However, in the last few years, both photo-nuclear production (*19, 20*) and photon-photon collisions (*21–23*) have been observed in hadronic heavy-ion collisions (HHICs). Experiments have demonstrated that it is possible to identify and measure the photo-processes accompanying the creation of a Quark-Gluon Plasma (QGP). Theoretical models, motivated by the ex-

How to identify B-W process?

collision of two photons in the simplest Feynman diagram. Different processes are defined depending on the virtuality of the photons and whether the consideration of higher-order processes is necessary. Photons may carry a virtual non-zero mass in their role as an intermediate propagator of the electromagnetic force. For two photons there are three possible interactions: the collisions of two virtual photons, of one virtual and one real photon, or of two real photons. It is important to note that all three processes could be identified in particle colliders at specific kinematics (*35*). Landau and Lifshitz calculated the total cross-section for e^+e^- pro-

While two-photon processes have been studied in UPCs for some time, there has been significant confusion and uncertainty about how to distinguish between the different possible processes (*31, 39, 40*) and to determine if high photon virtuality or higher-order corrections (*19, 41*) are present. The lack of precise experimental measurements and the lack of kinematic

How to identify B-W process

production. Observation of the exclusive Breit-Wheeler process in ultra-relativistic heavy-ion collisions should have the following distinct features:

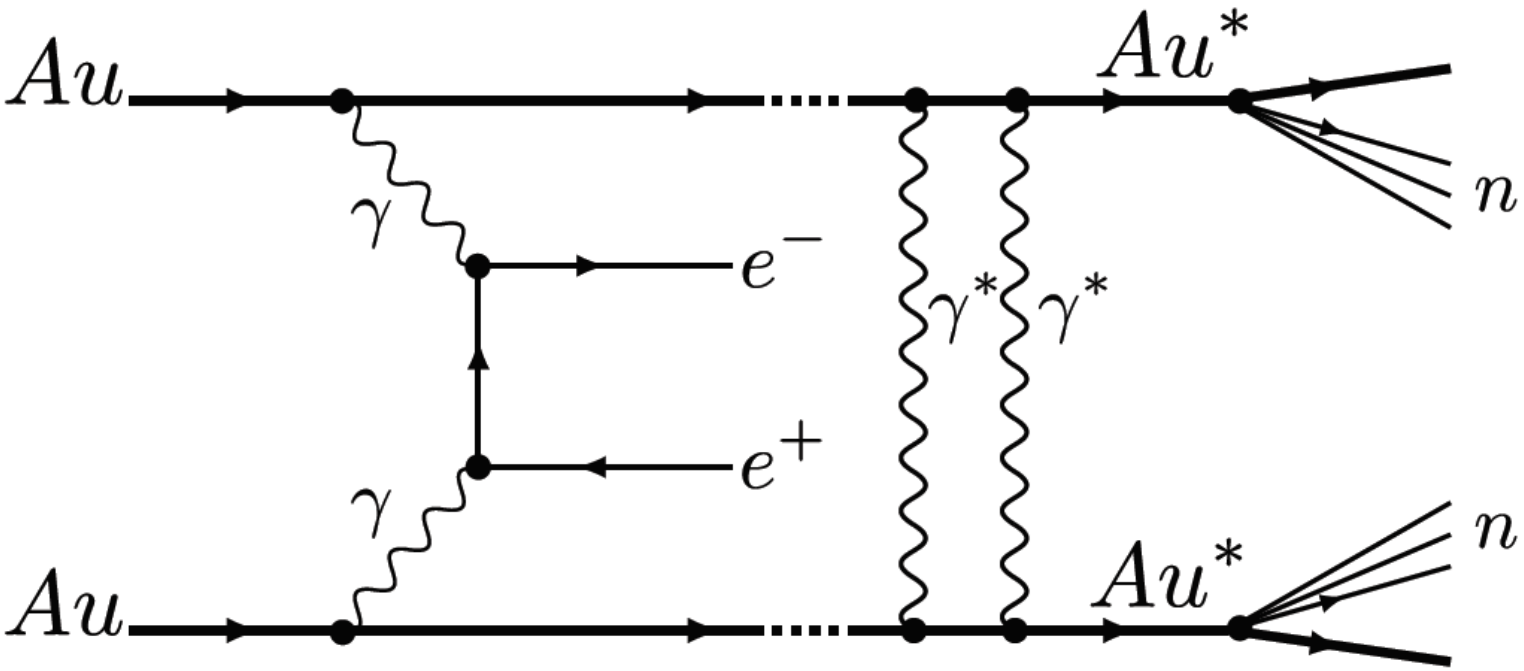
- Detection of e^+e^- pairs without accompanying background particles.
- Observation of a smooth e^+e^- invariant mass distribution without structure even in the mass range of known vector meson particles since the quantum numbers of two real photons (helicity state of 0 is disallowed) forbid the formation of a vector meson while highly virtual photons allow such a production channel.
- The slope of the invariant mass distribution should be consistent with QED two-body scattering falling off as a function of mass with the characteristic E^{-4} ($E \simeq M$, where E is the total energy of the pair and M its invariant mass) (*42*).
- Observation that the production rate peaks at low pair transverse momentum ($P_\perp$) characteristic of photon collisions generated by the Lorentz-boosted Coulomb field.
- The individual $e^\pm$ particles should be preferentially aligned longitudinally and the azimuthal angle between the e^+e^- pair momentum and the individual $e^\pm$ momenta should display modulations (*13*) due to the spin states for real photons.
- The measured kinematic distributions should match a theory calculation of the exclusive Breit-Wheeler process without explicit photon virtuality and without employing any higher order corrections.

Data from STAR

- Measured at RHIC using Au-Au collisions at a $\sqrt{s_{NN}} = 200\ GeV$
- Trigger to select UPC + neutron tagging using ZDC
- Sample with 1n1n and XnXn neutrons (total cross section scaled using STARlight)
- $\sim 23 \times 10^6$ recorded events
- Integrated luminosity $697 \pm 70\ \mu b^{-1}$
- Breit-Wheeler process requires high (99%) electron purity

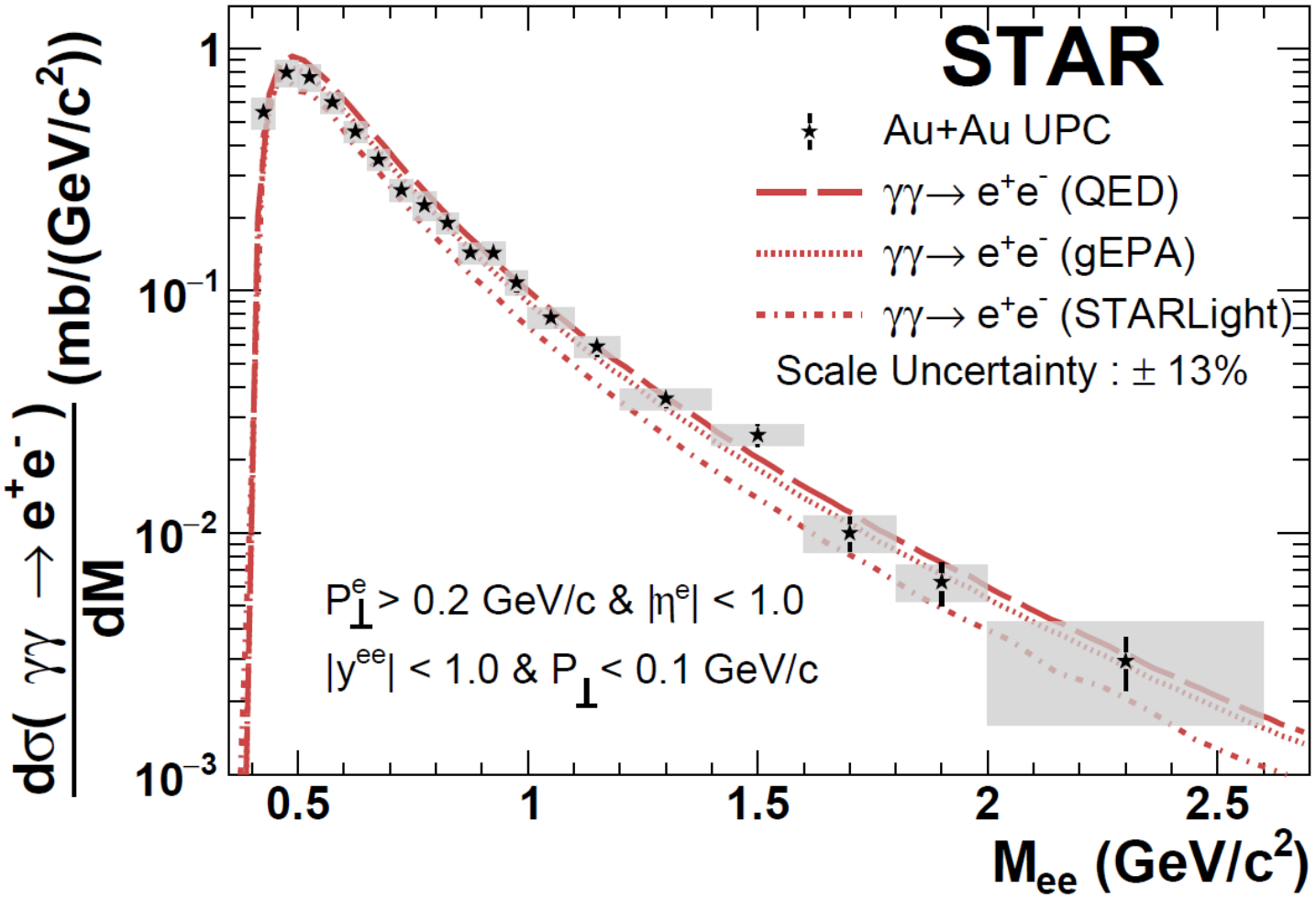
candidate $\gamma\gamma \rightarrow e^+e^-$ event inside the STAR detector is shown in Fig. 1C. In addition to the measurements of exclusive e^+e^- pairs produced in UPC collisions, we also present measurements from $60 - 80\%$ central (0% is head-on, 100% is a glancing collision) HHICs in which the nuclei undergo a collision with an impact parameter between approximately 11.5 and 13.5 fm.

Breit-Wheeler process at STAR



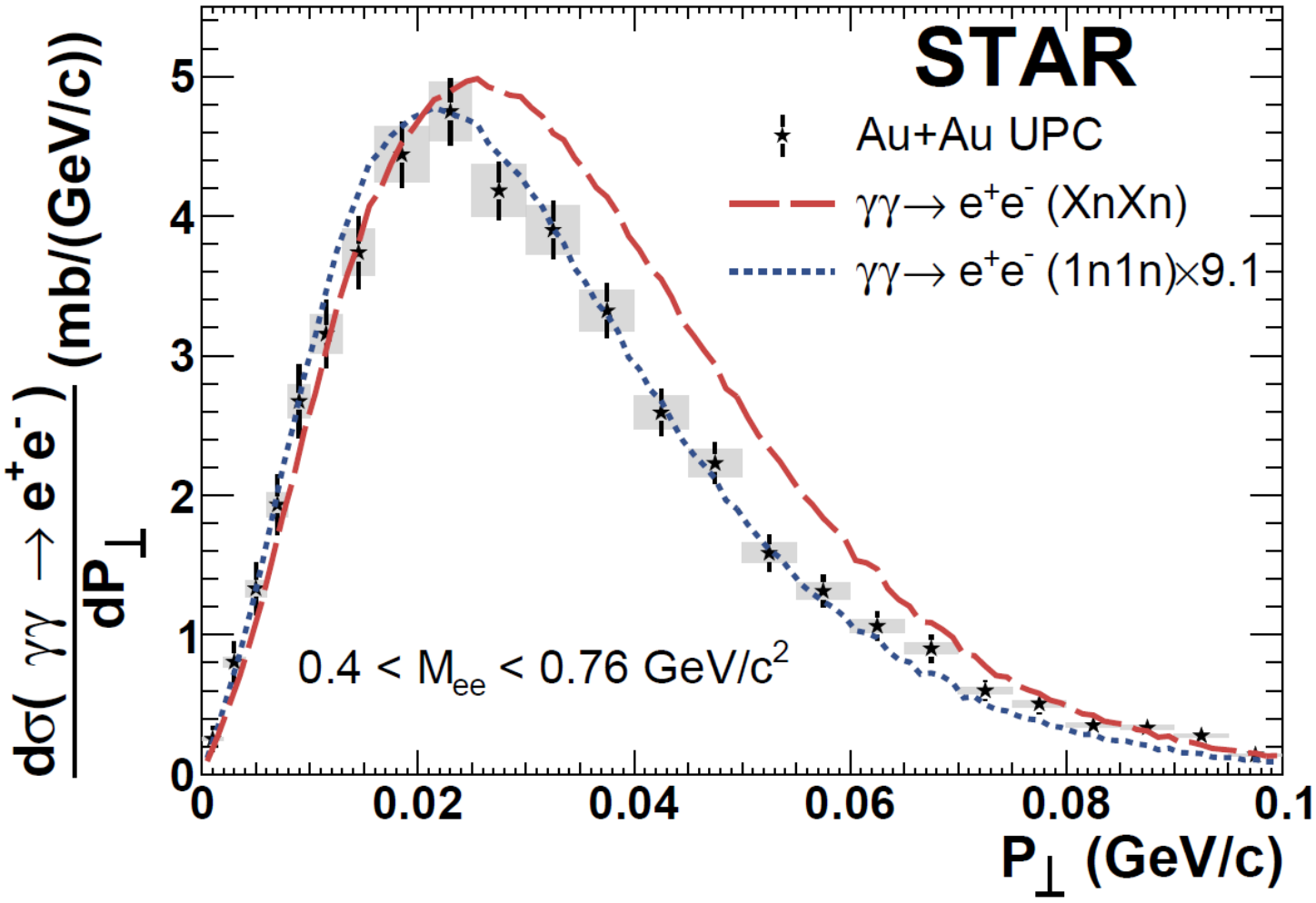
Invariant mass

- Smoothness of the spectrum – evidence of the purity of the event selection and PID
- Comparison to models:
  - Agrees with all three models at the 1 sigma level



Transverse momentum

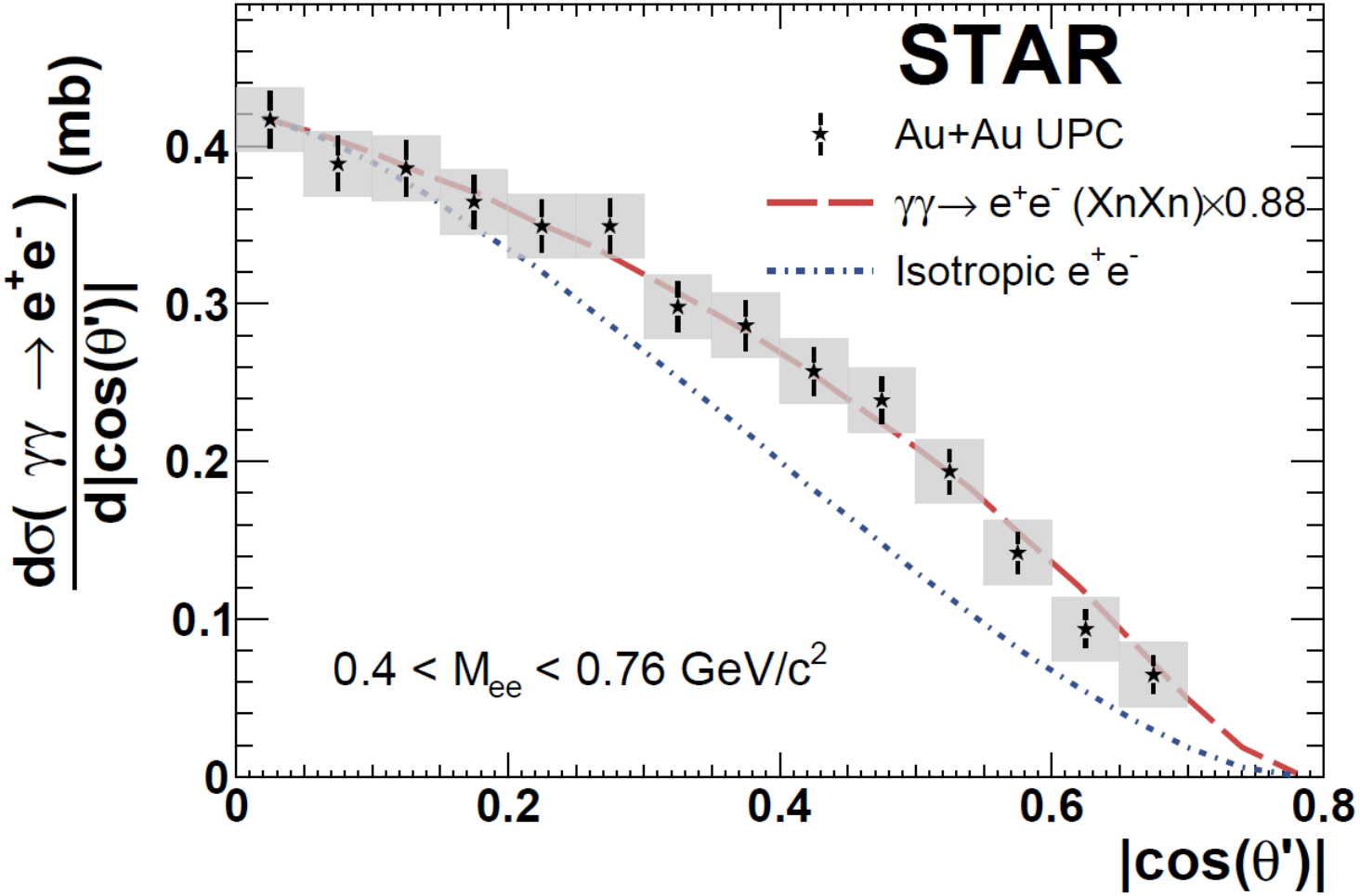
- The pT distribution shows a clear peak at 20 MeV/c as expected
- Matching to 1n1n predictions due to trigger selection



Cos theta

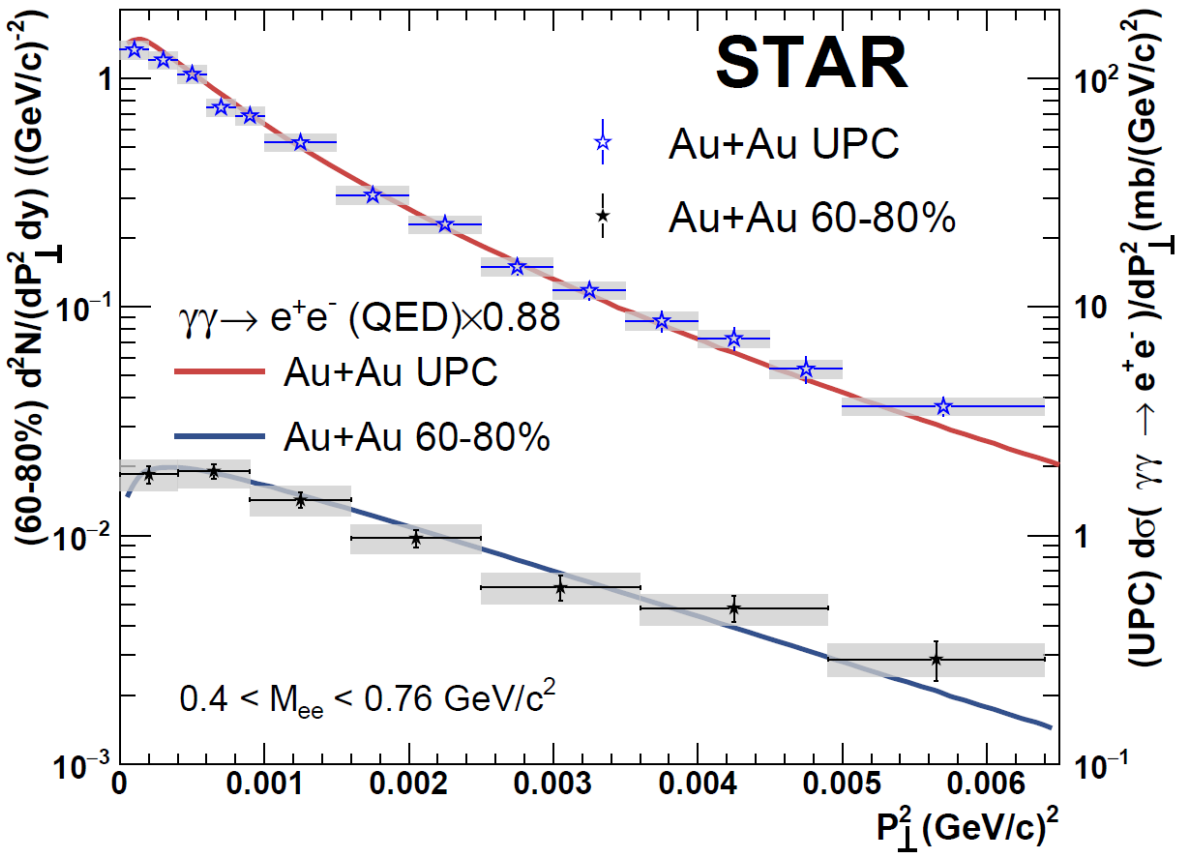
- Theta – polar angle of the e+ momentum vector with respect to the beam measured in e+e- centre-of-mass frame

- No evidence for deviations from predictions of B-W process is observed



Comparison to HHIC

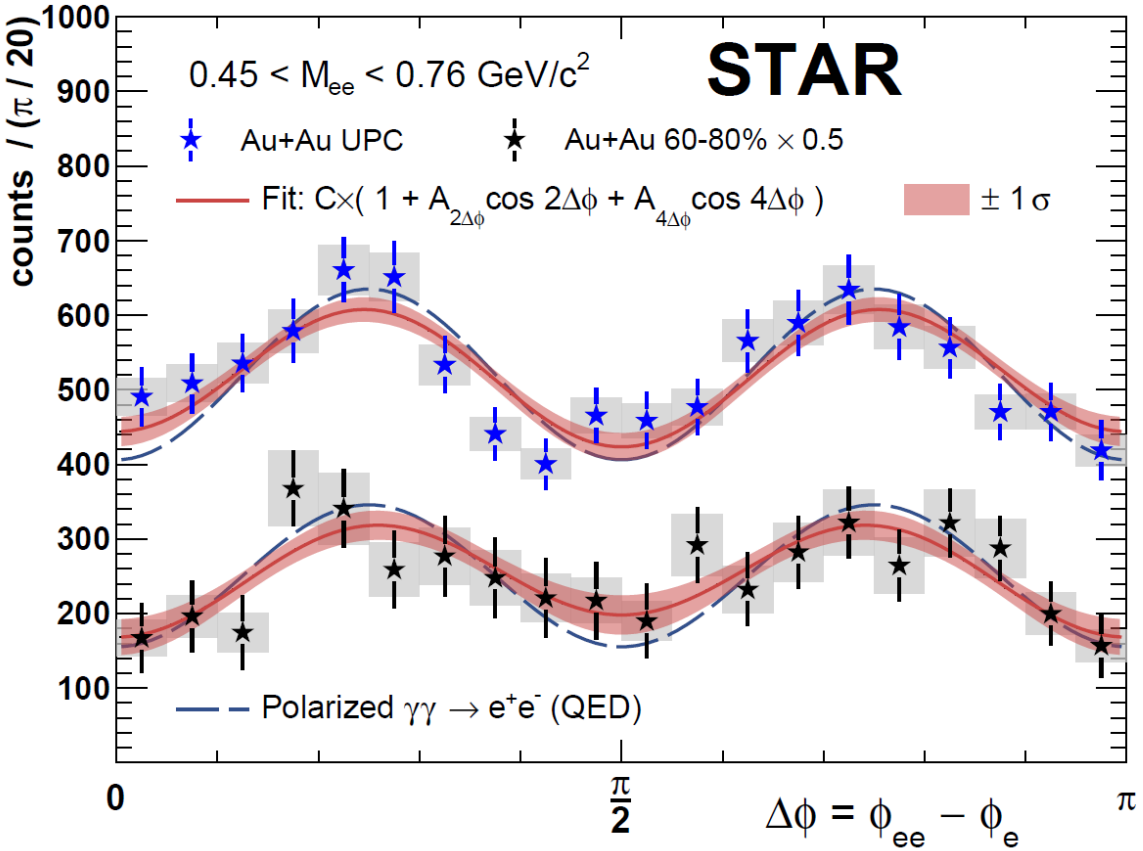
- Significantly different shape observed
- => sensitivity to initial collision geometry



estimate the additional contribution above the measured range. We observe a significant (4.8σ) increase in the $\sqrt{\langle P_\perp^2 \rangle}$ in $60-80\%$ central collisions compared to the same quantity in UPC.

Azimuthal distribution

Theoretical predictions suggest that the collision of linearly polarized photons from an unpolarized nucleus should lead to modulations in the azimuthal distribution of the produced pairs (*13*). The expected experimental signature of linearly polarized photon collisions is the modulation of the $\Delta\phi = \phi_{ee} - \phi_e$ distribution, where ϕ_{ee} and ϕ_e are the azimuthal angle of the momentum in the laboratory frame of the e^+e^- pair and of the e^+, respectively. The mea-



nitude of a $\cos 4\Delta\phi$ modulation. Considering the statistical and systematic uncertainties in both collision systems, a significant $\cos 4\Delta\phi$ modulation is observed. The observed magnitude

Conclusion

of values predicted for the Breit-Wheeler process in UPCs. The total measured cross-section agrees with all three calculations at the $\pm 1\sigma$ level. In Fig. 2C and Fig. 3, the QED theory curves are scaled down by $\sim 12\%$ to facilitate direct comparison of the differential distributions. The differential distributions presented in Figures 2, 3, and 4 are all, within uncertainties, consistent with the expectation from the Breit-Wheeler process alone. Deviations from the predictions for the Breit-Wheeler process due to non-zero photon virtuality, if present, are suppressed by $1/\gamma^2$ ($\gamma \approx 100$) (*53*). Within the current experimental uncertainties, no evidence for deviations from the predictions for the Breit-Wheeler process is observed.