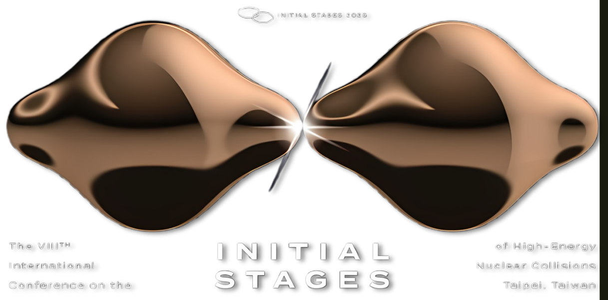
INVESTIGATING NUCLEAR STRUCTURE VIA THE BREIT-WHEELER PROCESS IN UPCS AT STAR

Nicholas Jindal, for the STAR Collaboration

Initial Stages Sept. 07 - 12, 2025



STAR

OHIO STATE

Supported in part by U.S. DEPARTMENT of ENERGY

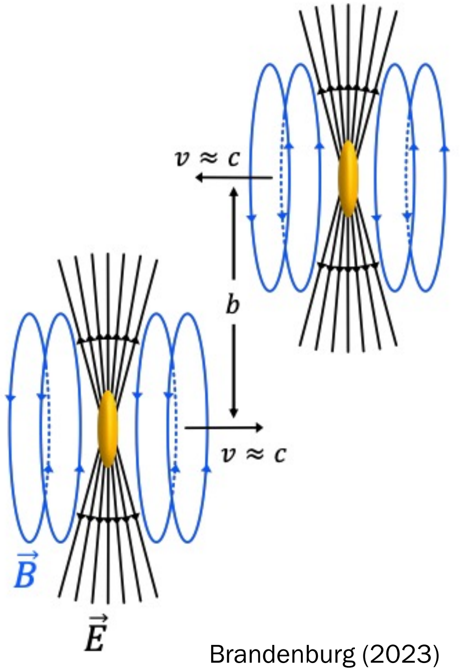
Outline

- UPCs and the Breit-Wheeler Process
- Motivation
- Accessing Nuclear Structure
- Sudakov Radiation
- Summary and Outlook

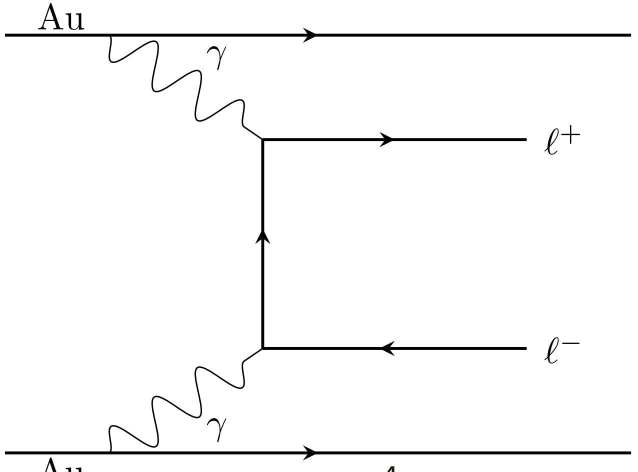
UPCS AND THE BREIT-WHEELER PROCESS

Ultra-Peripheral Collisions and the Breit-Wheeler Process

- Charged nuclei moving near the speed of light produce intense Lorentz-contracted electromagnetic fields→ **behaves like a flux of quasi-real photons**
- The fields are strong enough for dielectron production via the Breit-Wheeler process, providing a probe into the correlations between photon k_T and pair momentum
- The Wigner formalism encodes an **important connection between the spatial charge distribution and the photon momenta**



Brandenburg (2023)



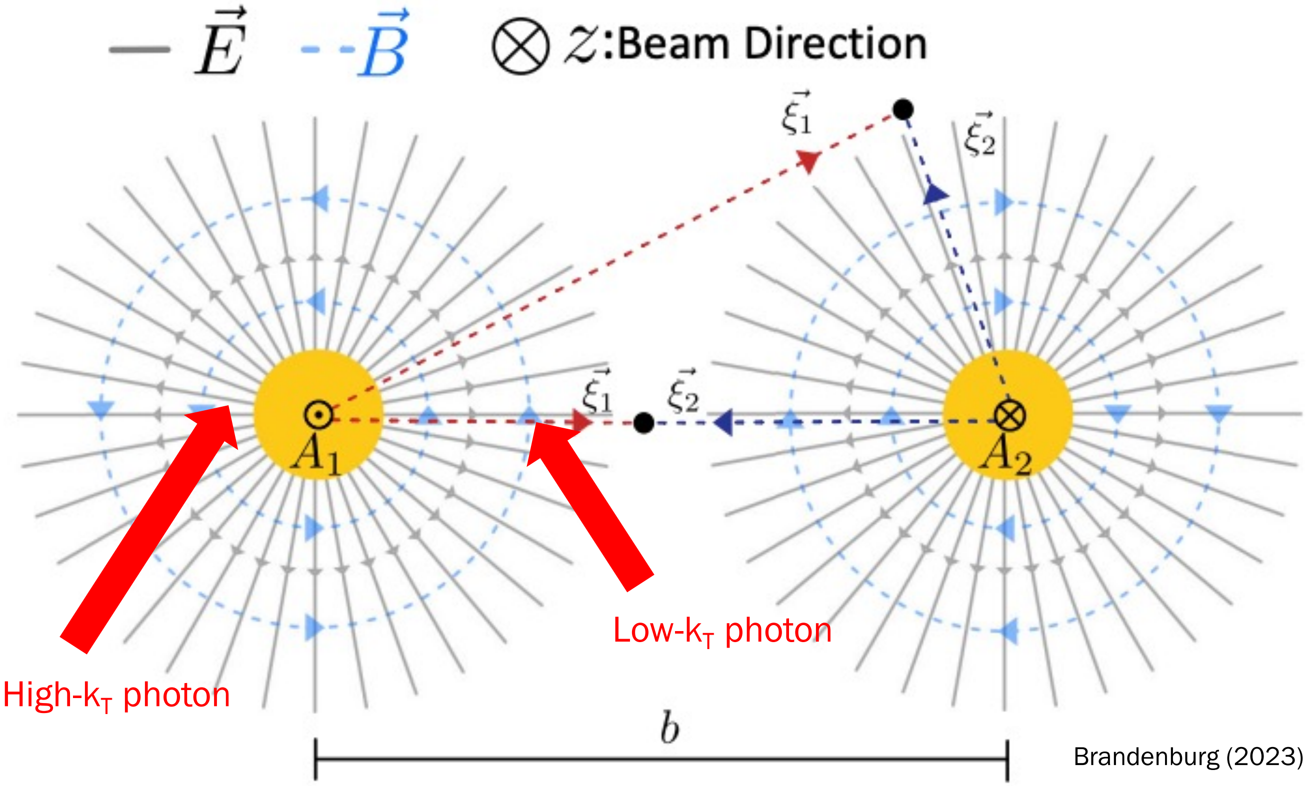
$$N_{ij}(\omega, \boldsymbol{b}, \boldsymbol{q}) = \int \frac{d^2\boldsymbol{Q}}{(2\pi)^2} \exp[-i\boldsymbol{b}\boldsymbol{Q}] E_i\left(\omega, \boldsymbol{q} + \frac{\boldsymbol{Q}}{2}\right) E_j^*\left(\omega, \boldsymbol{q} - \frac{\boldsymbol{Q}}{2}\right)$$

Schäfer, *et al, Phys. Proc. Ultra-Peripheral Collisions*, **1**, 009 (2024)
Brandenburg, *et al, Eur. Phys. J. A* **57**, 299 2021
Weizsäcker, C. F. v. *Zeitschrift für Physik* 88 (1934): 612
Yu Shi *et al.*, *Phys. Lett. B* 862 (2025) 139317

MOTIVATION

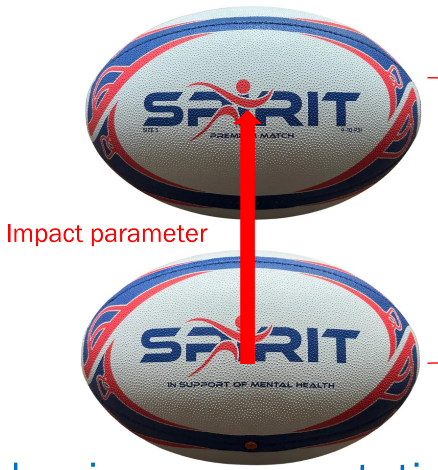
Motivation

- Nuclear shape of uranium (prolate) may **permit impact parameters that gold does not**
- Dielectron pair transverse momentum distribution shape can **encode this spatial subtlety**

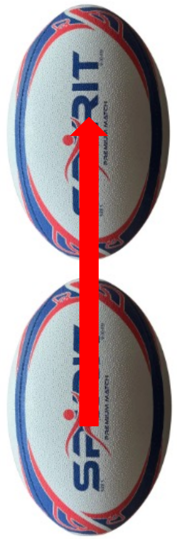


Brandenburg (2023)

Wigner formalism tells us that **both** the momentum and impact parameter influence the photon flux



Small impact parameter, orientation does not exist for a spherical nucleus



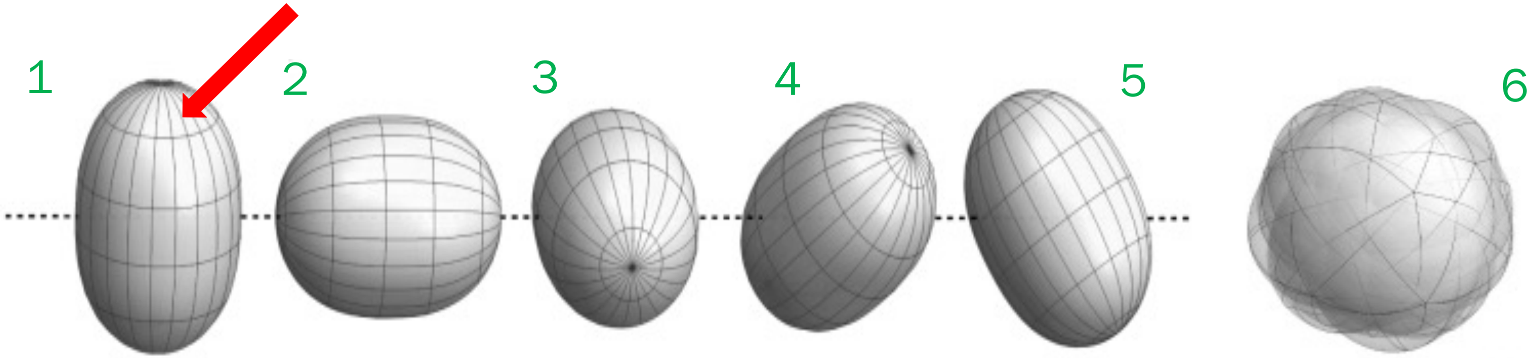
Large impact parameter for end-to-end orientation

Uranium representation

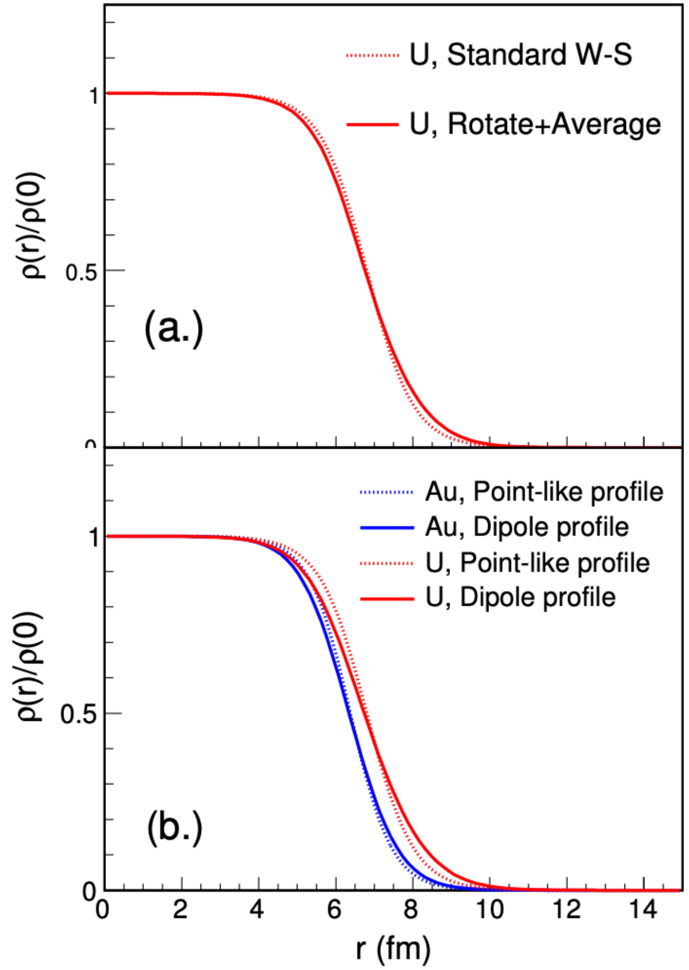
STAR Collaboration. *Nature* **635**, 67–72 (2024)

Uranium Charge Distribution

- Photon k_T spectrum depends on the nuclear form factor $F(\vec{k}) \equiv \int \vec{r}^2 d\vec{r} e^{i\vec{k}\cdot\vec{r}} \rho(\vec{r})$
- Spherical form factor **does not describe uranium accurately**



- Photon momenta distributions should be different due to the impact parameters
- Models have used a sphere with radius from averaging over all axes
- Compare with a quadrapole profile (1) and a point-like profile (3) and profile averaged over all angles (6)
- Note: the one-dimensional density distribution obtained via averaging over all angles is only approximately equivalent to a Woods-Saxon 1D profile



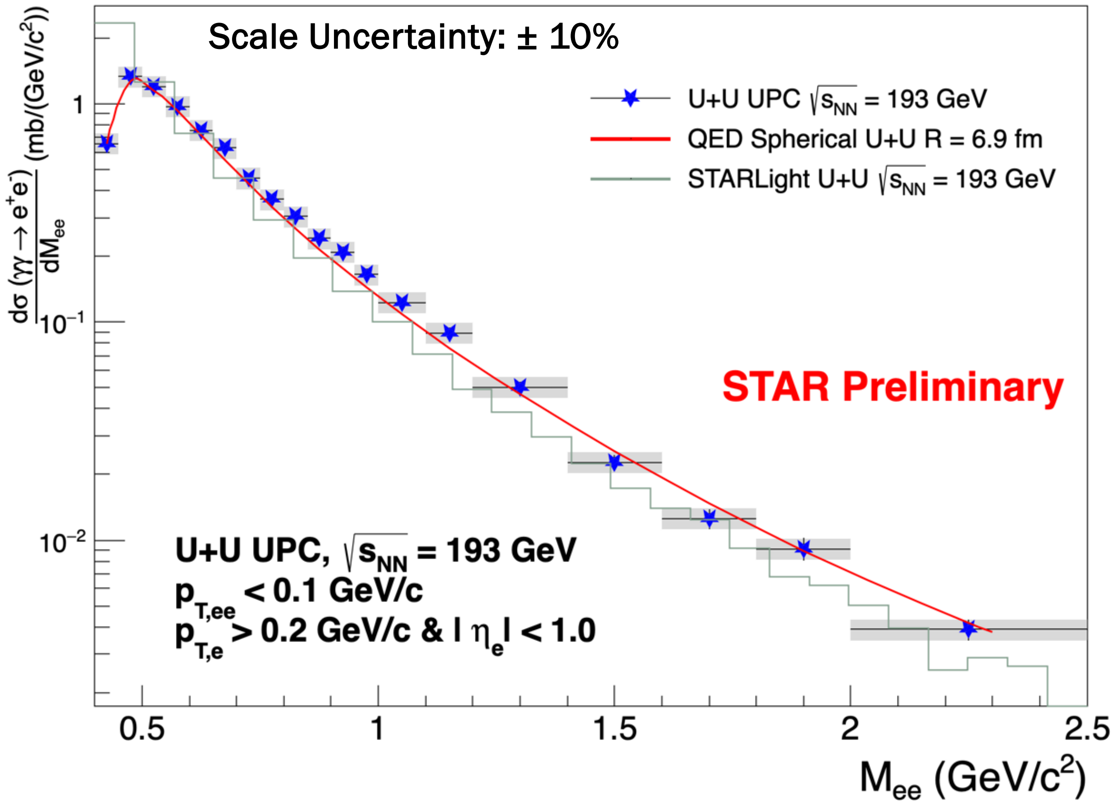
$$\rho(r,\theta) = \frac{\rho_0}{1 + \exp\left(\frac{r - R_{WS}(1 + \beta_2 Y_{20}(\theta))}{a_0}\right)}$$

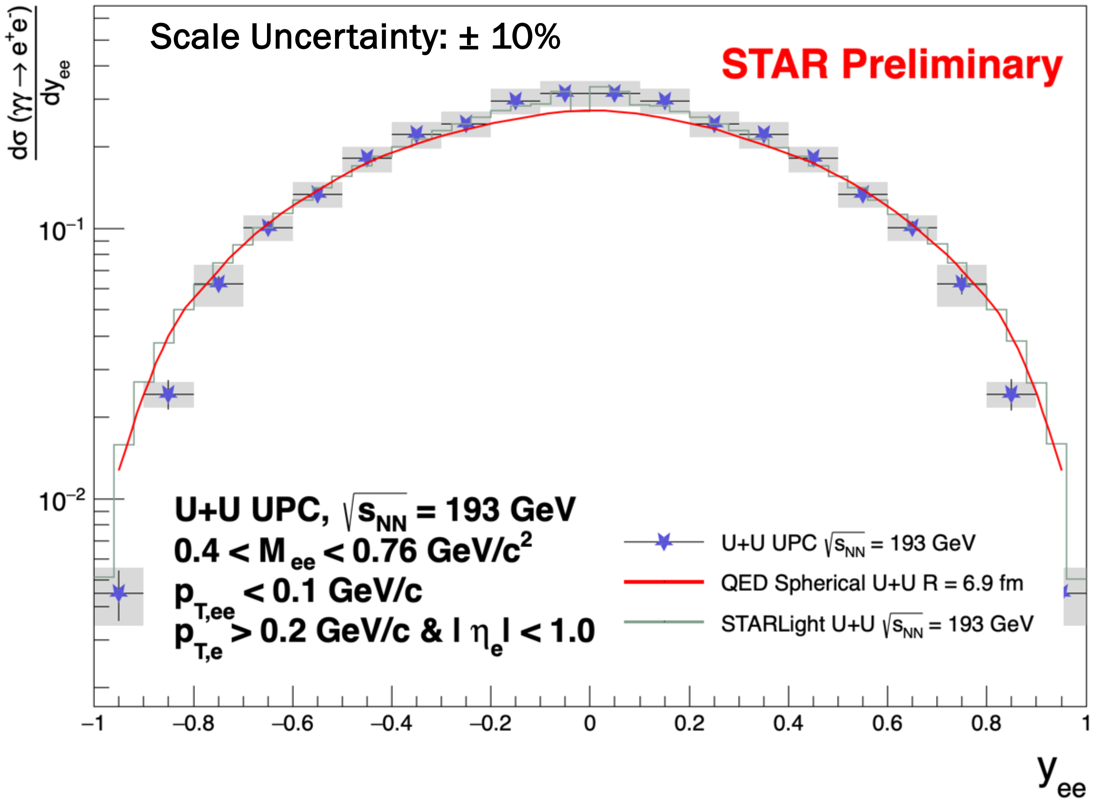
Q.Y. Shou *et al.*, Phys. Lett. B 749 (2015) 215–220.
Shi et al., Phys. Lett. B 862 (2025) 139317
STAR Collaboration. *Nature* **635**, 67–72 (2024)

ACCESSING NUCLEAR STRUCTURE

Cross Sections

- First measurement of the Breit-Wheeler ($\gamma\gamma \rightarrow e^+e^-$) process in collisions of deformed nuclei (U+U UPC at $\sqrt{s_{NN}} = 193\ GeV$)
- Leading-order QED reproduces dσ/dM and dσ/dy well
- By default, STARLight does not include production inside the nucleus, giving a 5-10% reduction in cross section



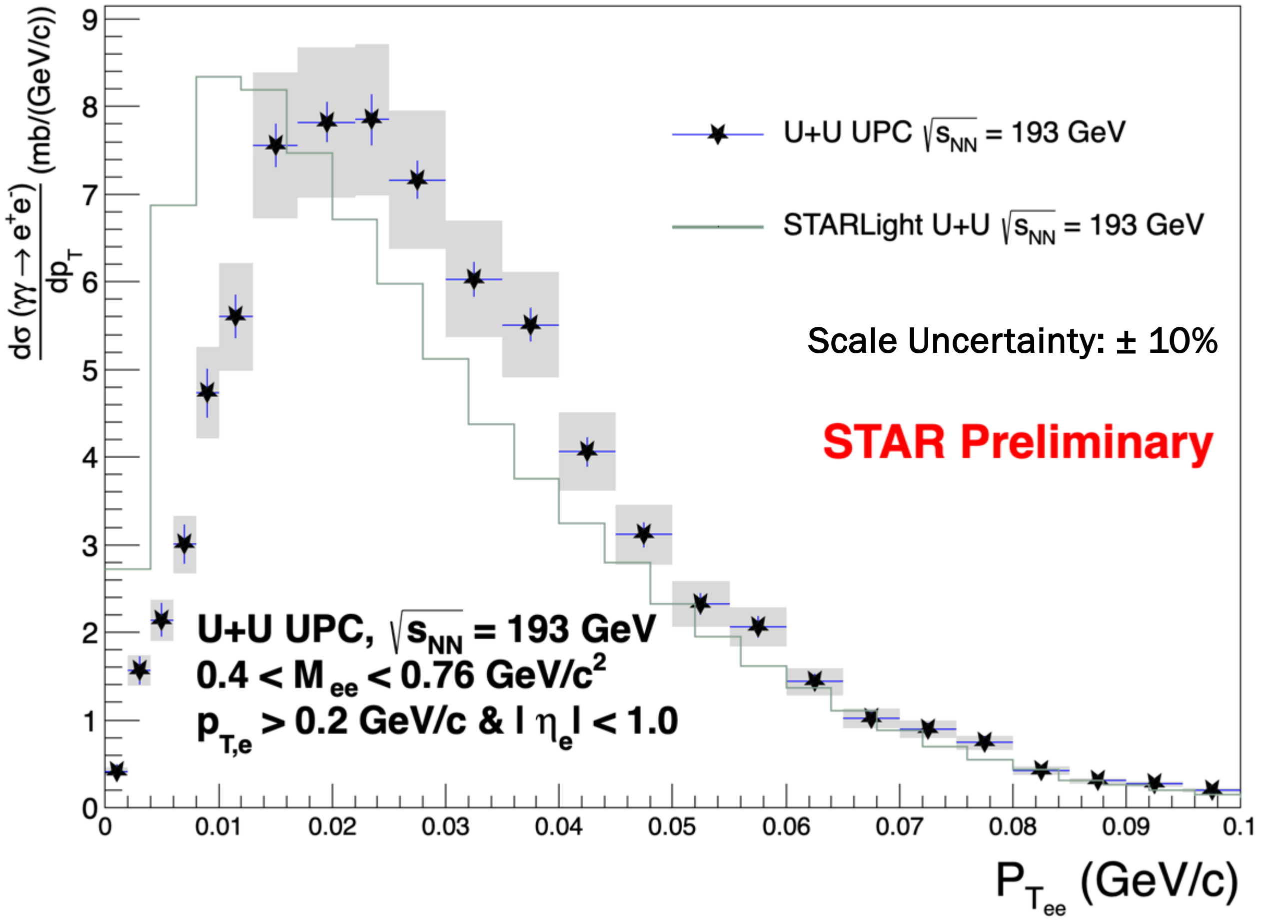


S. R. Klein, *Phys. Rev. C* 97 (2018) 054903.

$$STARLight: \frac{dN(k,p_T)}{dp_T} = \frac{2F^2(Q^2 = p_T^2)p_T^3}{(2\pi)^2\left(\left(\frac{k}{\gamma}\right)^2 + p_T^2\right)^2}$$

Cross Sections

- STARLight uses 1.2 fm * $A^{1/3}$ =7.4 fm for nuclear charge radius which is inaccurate for uranium (orientation-averaged charge radius R = 6.9 fm)
- STARlight also uses a k_T factorization approach which does not depend on the impact parameter (see equation above)
- STARlight predicts a significantly lower $\langle p_T \rangle$



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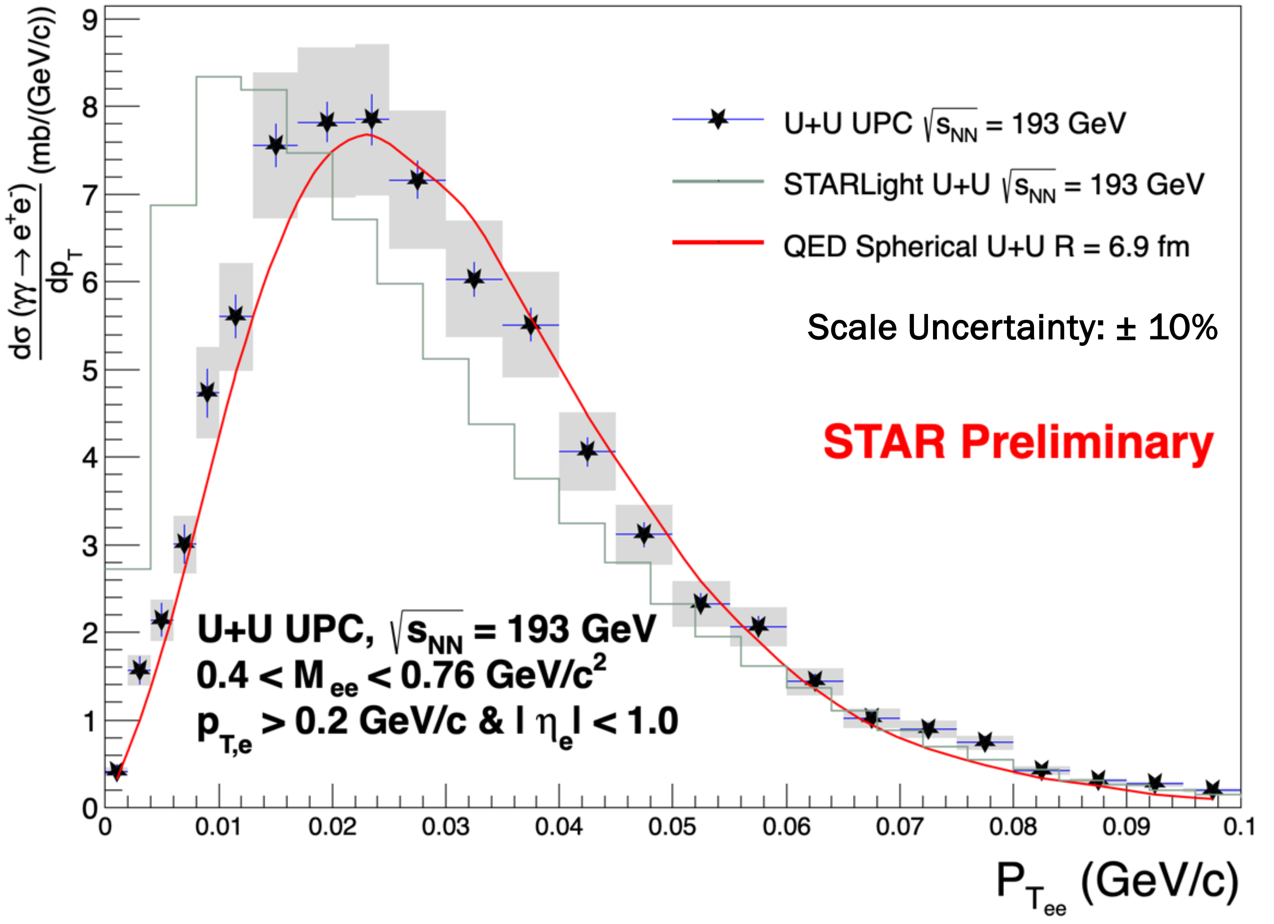
- STARlight predicts a significantly lower <p_T>
- QED calculation accounts for the quantum correlation between position and momentum as in the Wigner formalism, unlike STARLight



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

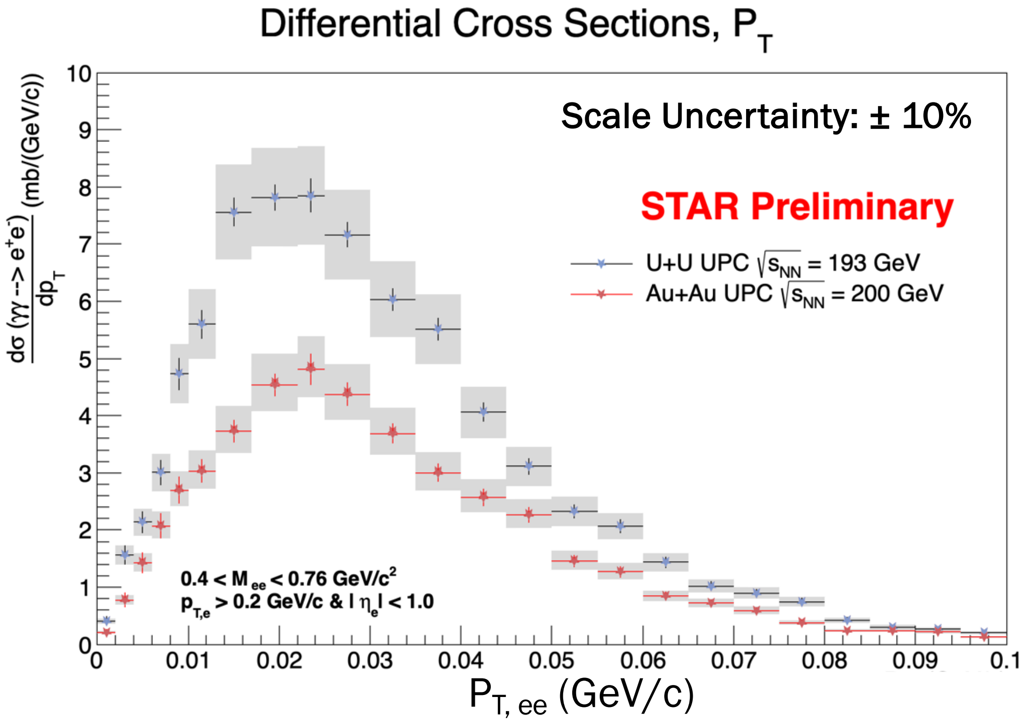
σ_{data} = 0.305 +- 0.003 (stat.) +- 0.009 (syst.) (mb)

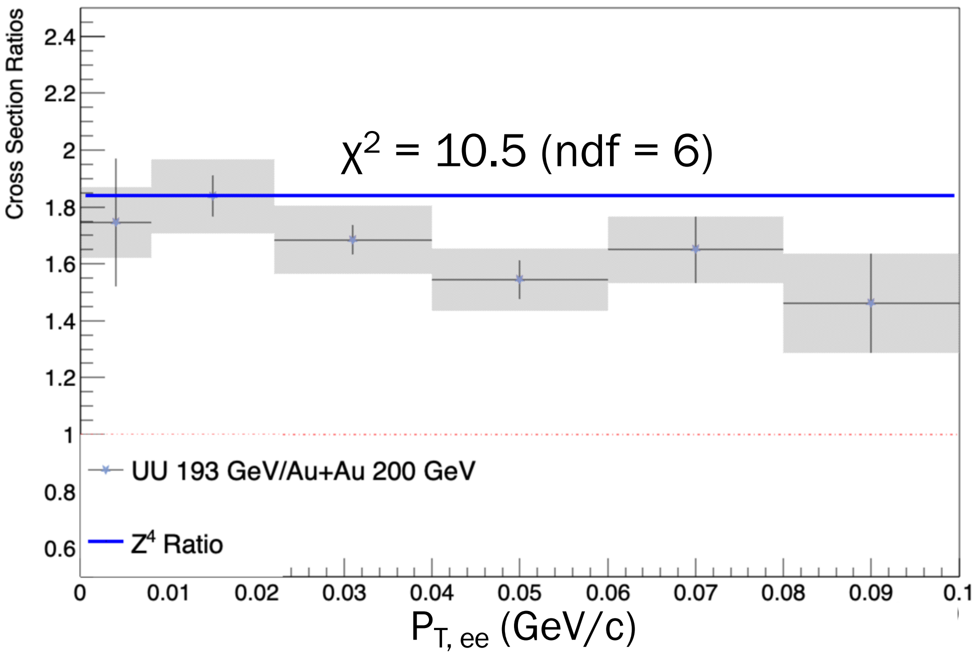
σ_{QED} = 0.301 +- 0.116 (mb)

Q.Y. Shou *et al.*, Phys. Lett. B 749 (2015) 215–220.

Uranium vs. Gold Expectation

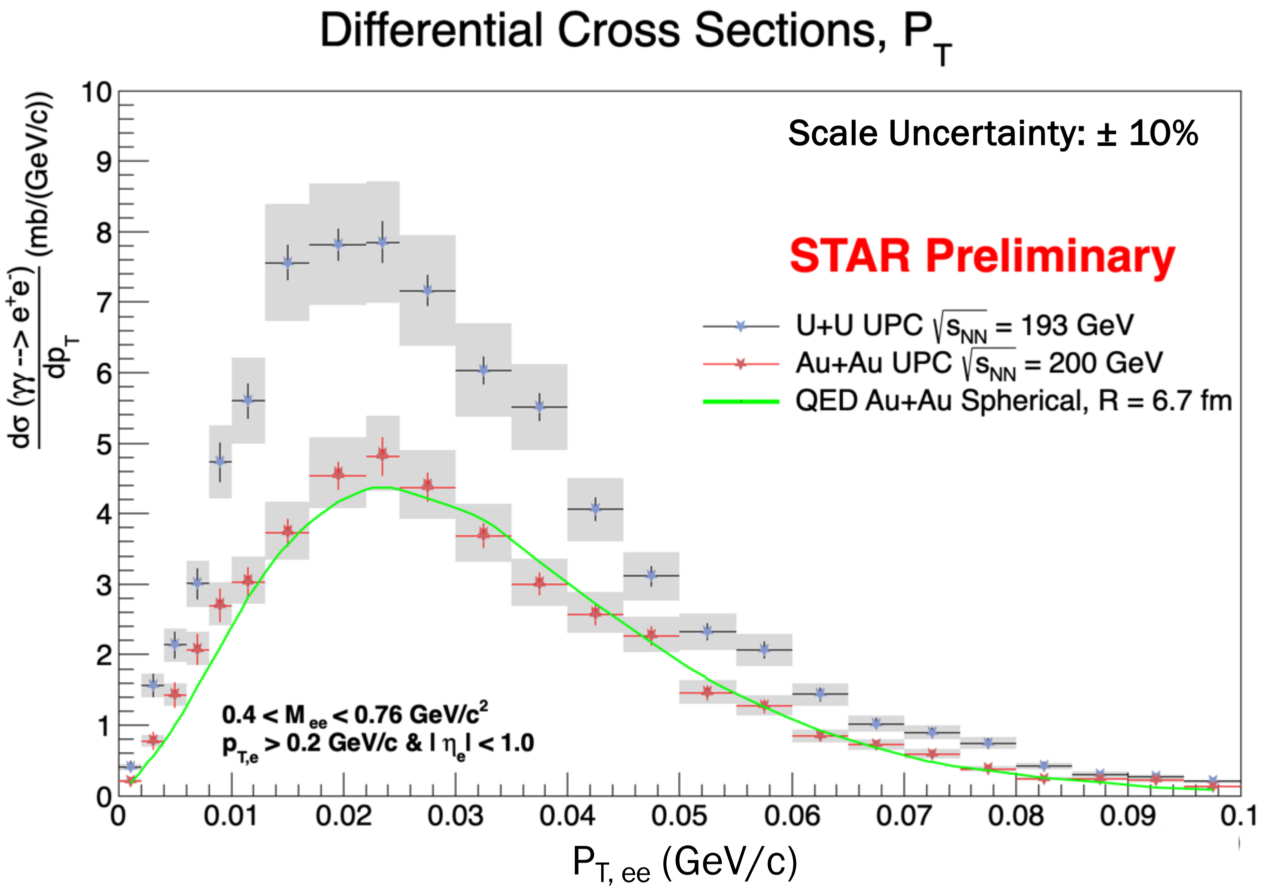
- The naïve expectation is a simple Z^4 scaling between U+U and Au+Au cross sections
- Can we model this better with QED?





Comparisons with Au and QED

- Au+Au data is in good agreement with a QED calculation using a spherically-symmetric charge density distribution with R = 6.7 fm and a_0 = 0.42 fm (χ^2/ndf = 25.3/24)



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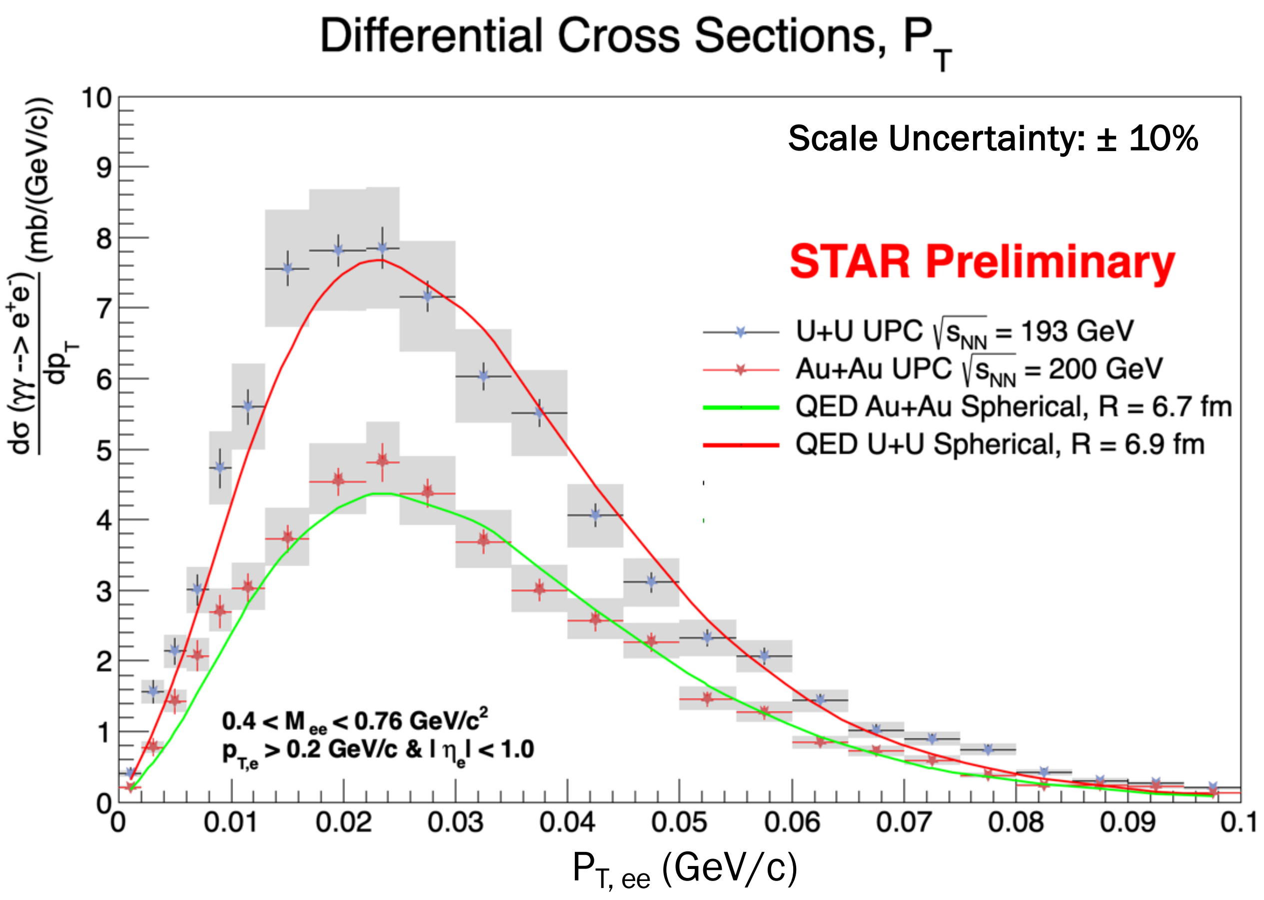

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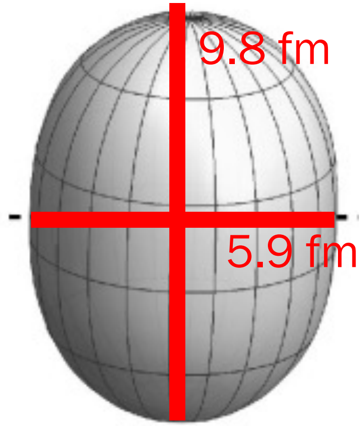

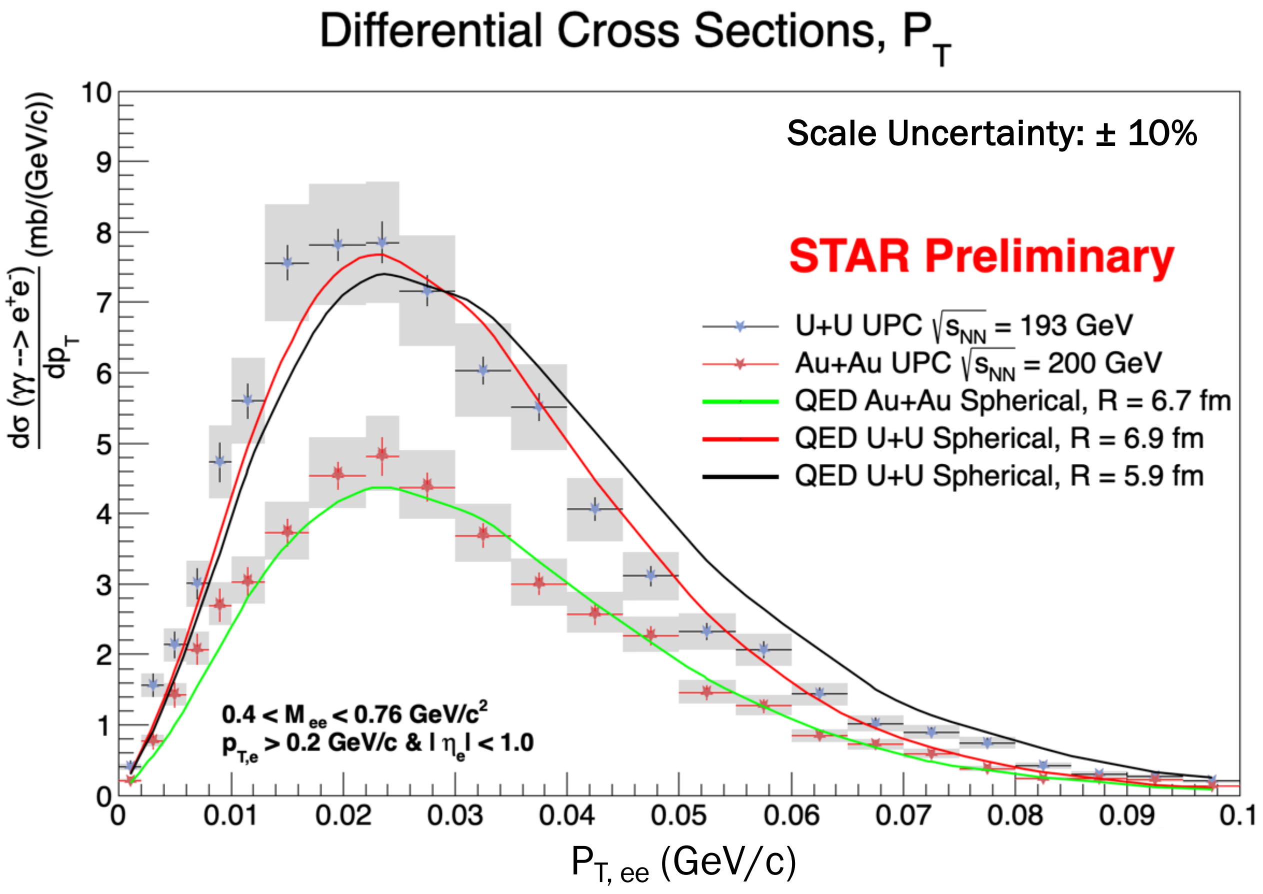

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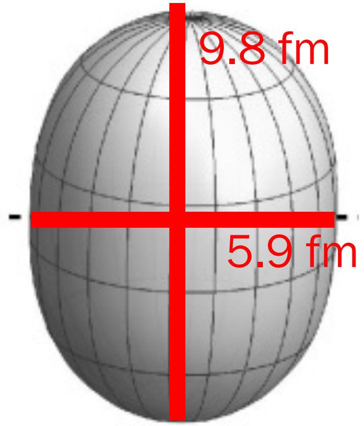
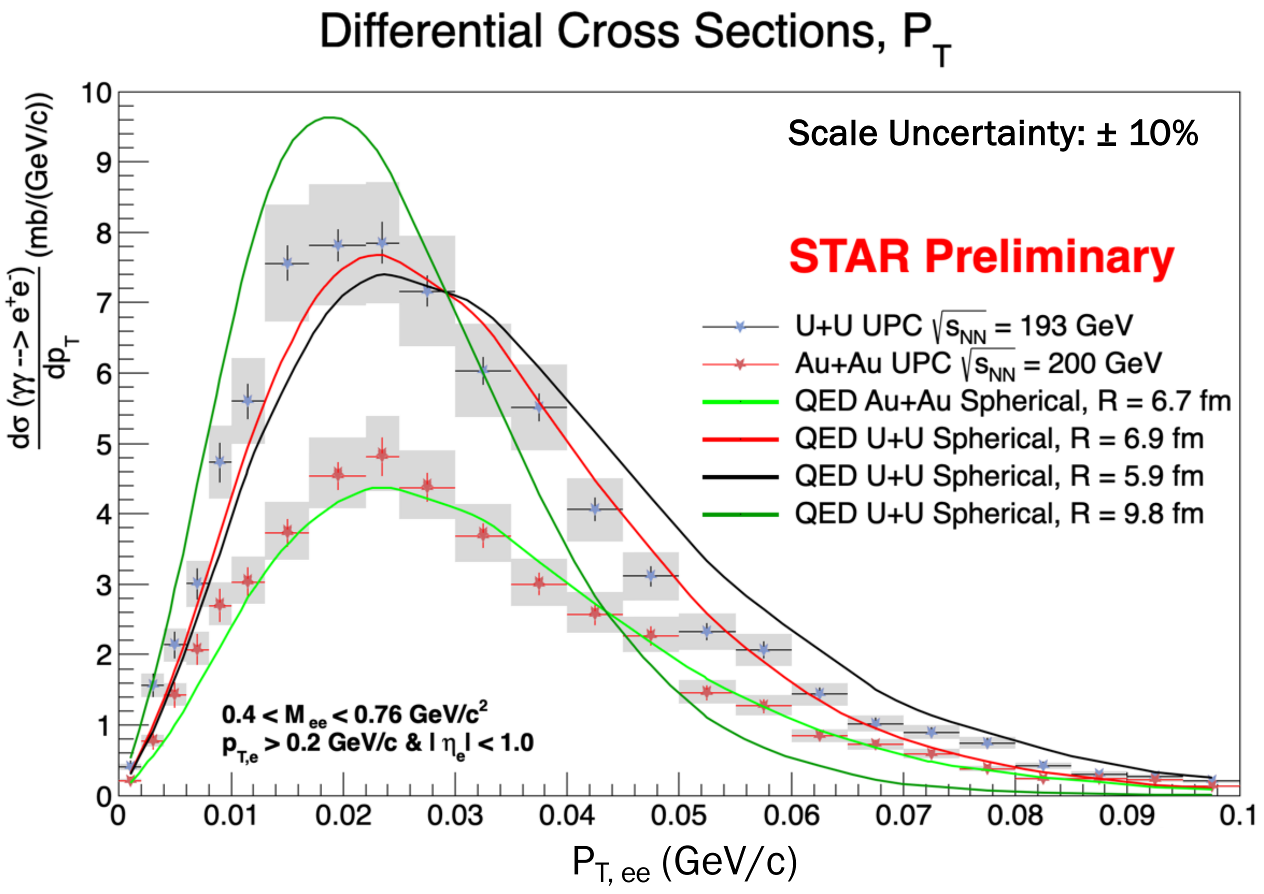
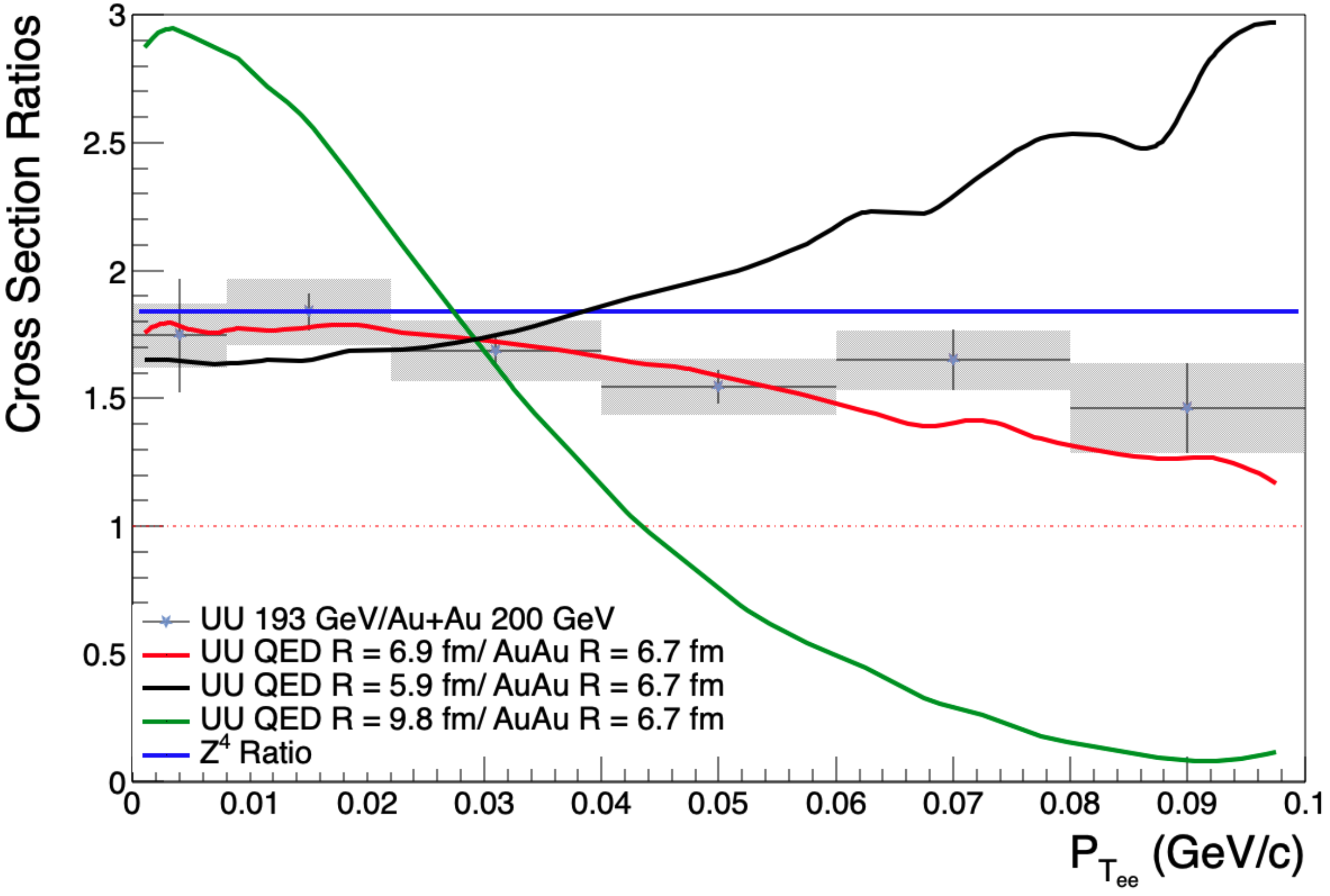
- A smaller radius shifts the peak to higher p_T
- A larger radius does the opposite





Cross Section Ratio

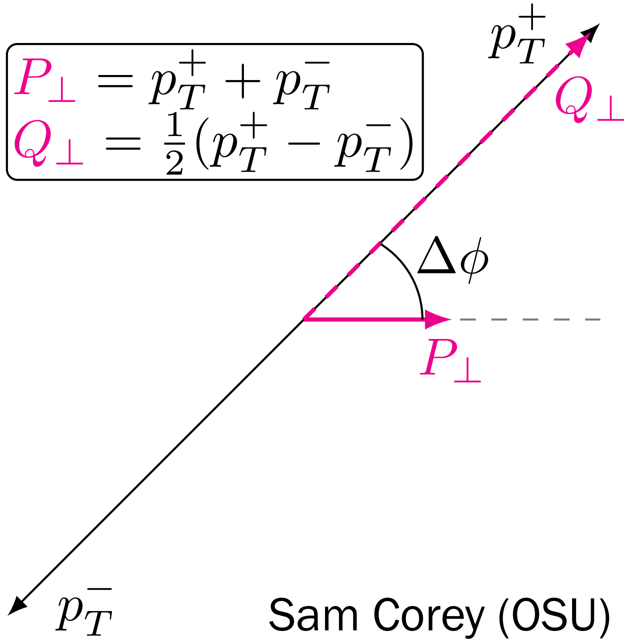
Comparison with Data Ratio	X^2 / (ndf = 6)
UU QED R = 6.9 fm/ AuAu QED R = 6.7 fm	2.9 / 6 = 0.5
UU QED R = 5.9 fm/ AuAu QED R = 6.7 fm	66.7 / 6 = 11.1
UU QED R = 9.8 fm/ AuAu QED R = 6.7 fm	197.0 / 6 = 32.8
Z^4 Ratio	10.5 / 6 = 1.8



SUDAKOV RADIATION

Sudakov Radiation

- Sudakov radiation occurs when one or both of the dielectron pair emit a ”soft” (low-energy) photon
- This photon “steals” momentum from electron
- The low p_T electron pair, typically decaying nearly back-to-back, are not reconstructed as such
- We observe a characteristic p_T “broadening” due to Sudakov radiation
- We also become sensitive to the reconstructed angle, denoted as **Δϕ**
  - *Defined as the angle between the pair in the lab frame and the difference in transverse momenta of the tracks in the pair rest frame*

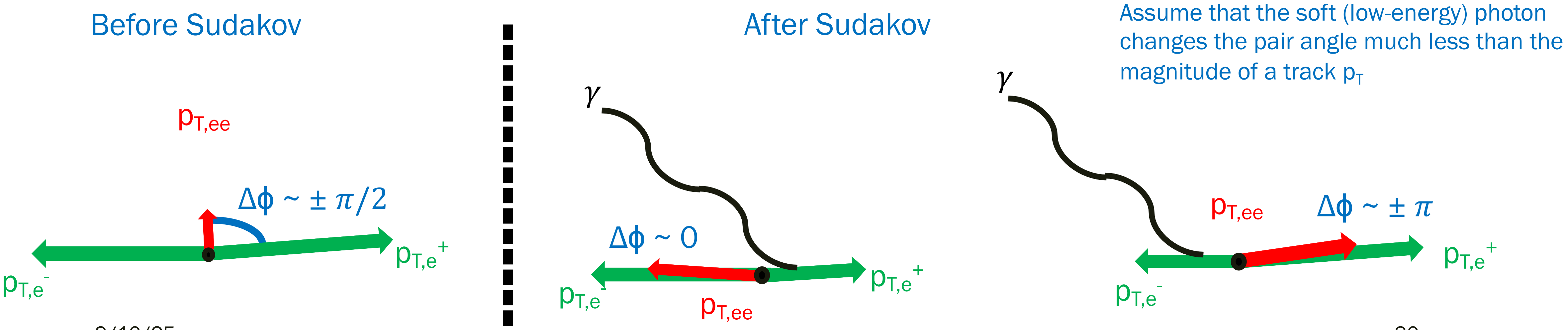


Sam Corey (OSU)

How Nuclear Shape is Relevant

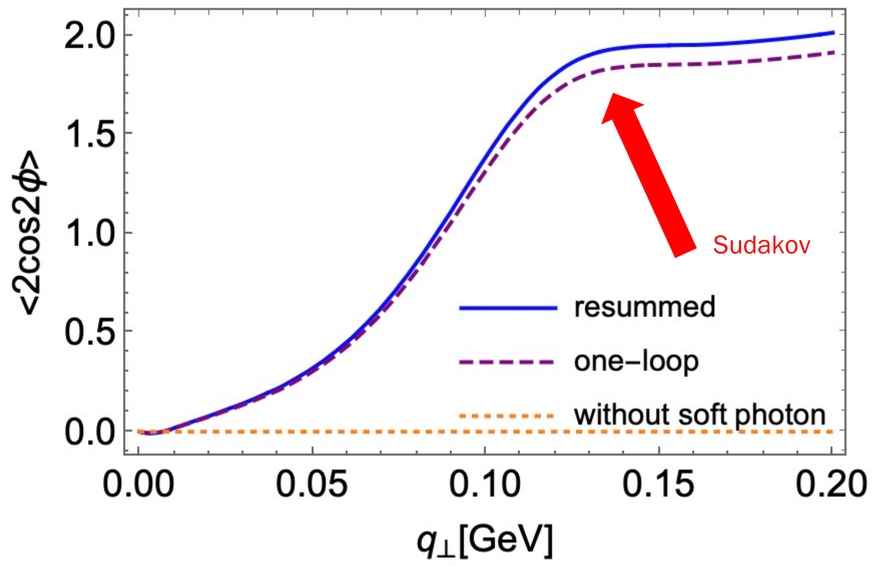
- Sudakov radiation leading logarithm factor in the cross section is dependent on the difference in the track transverse momenta, defined as $P_\perp$
- Higher p_T pairs → larger Sudakov factor
- Expect uranium to have excess production at higher p_T due to access to smaller impact parameters than gold
- **Despite a lower beam energy in U+U, we expect stronger Sudakov strength at high p_T as compared to Au+Au due to this excess production**

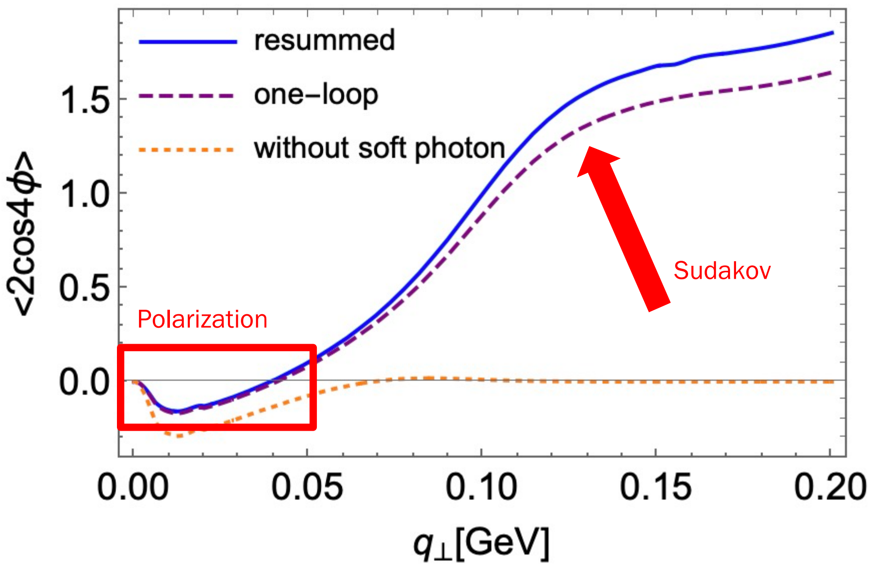
$$Sud(r_\perp) \propto \ln(P_\perp^2)$$



Expected Effect from EPA Calculations

- Without Sudakov radiation, there is no expected modulation in **Δϕ**, and this is demonstrated via the even Fourier harmonics of the distribution as a function of pair p_T
- The cos(4**Δϕ**) modulation goes negative at low p_T due to photon polarization



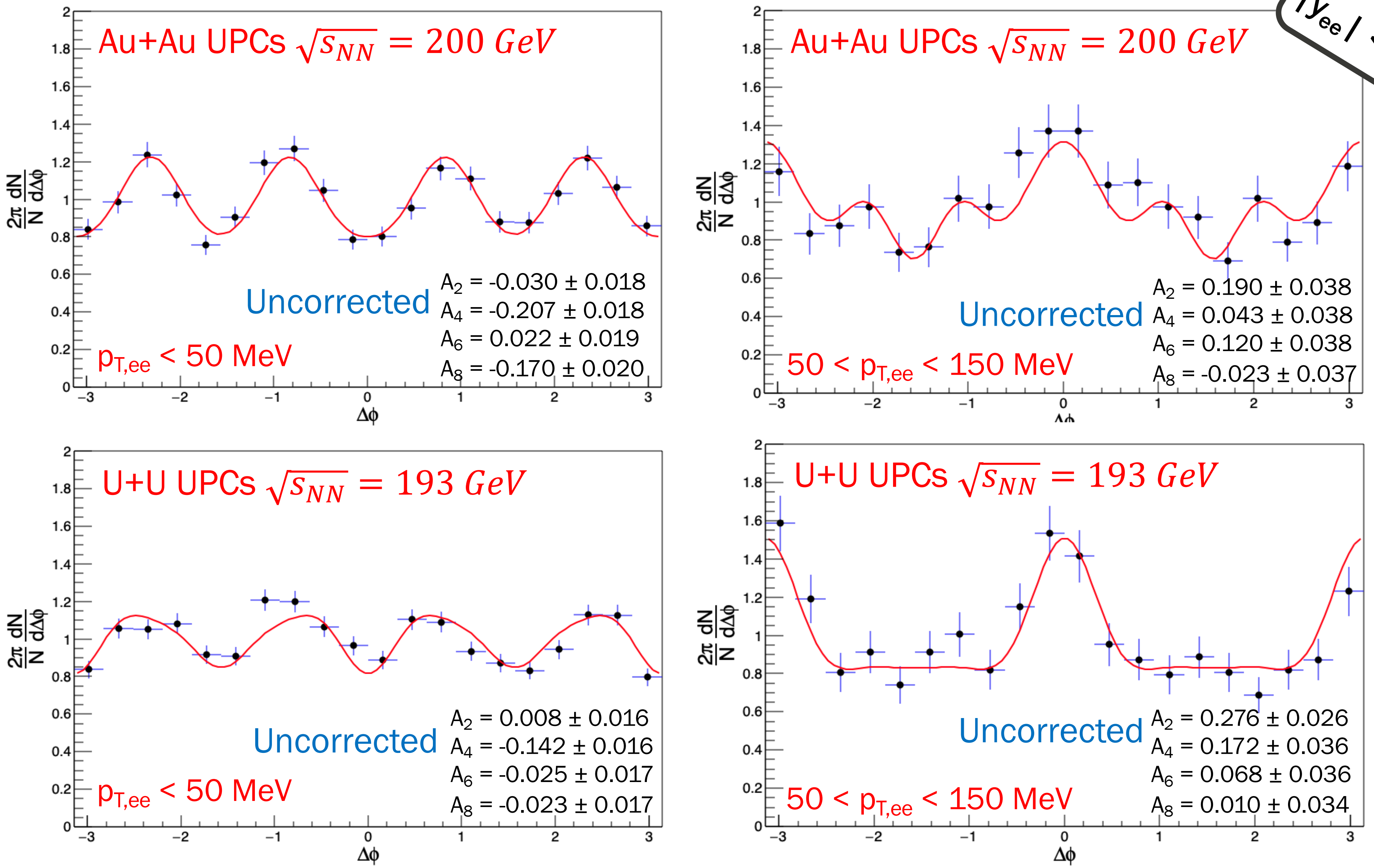


D. Y. Shao, C. Zhang, J. Zhou & Y.-j. Zhou, *Phys. Rev. D* 108 (2023) 116015.

Δϕ Distributions

$$f(\varphi) = A * (1 + A_2\cos(2\Delta\varphi) + A_4\cos(4\Delta\varphi) + A_6\cos(6\Delta\varphi) + A_8\cos(8\Delta\varphi))$$

$0.45 < M_{ee} < 0.76$ GeV/c²
$|y_{ee}| < 1$



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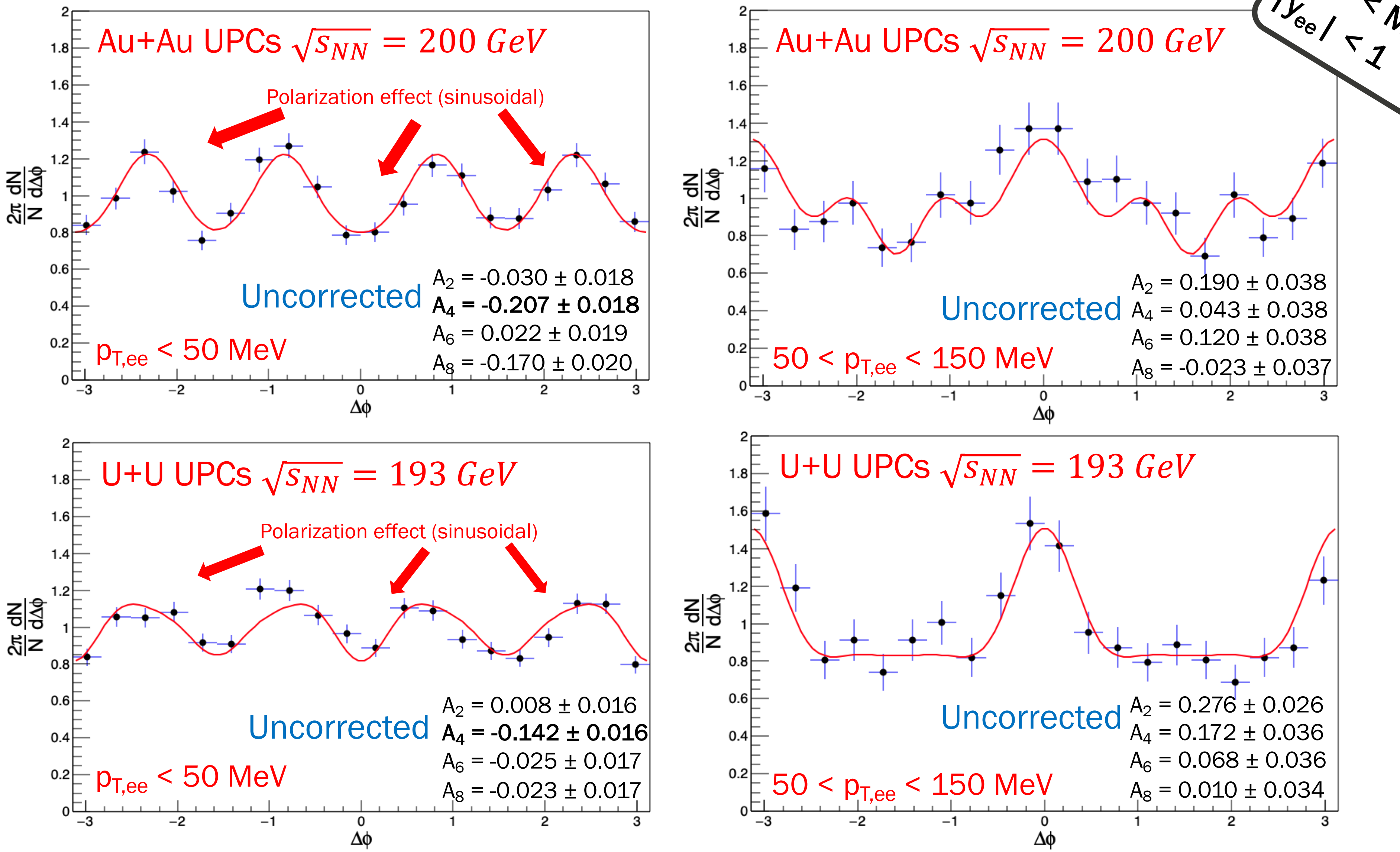

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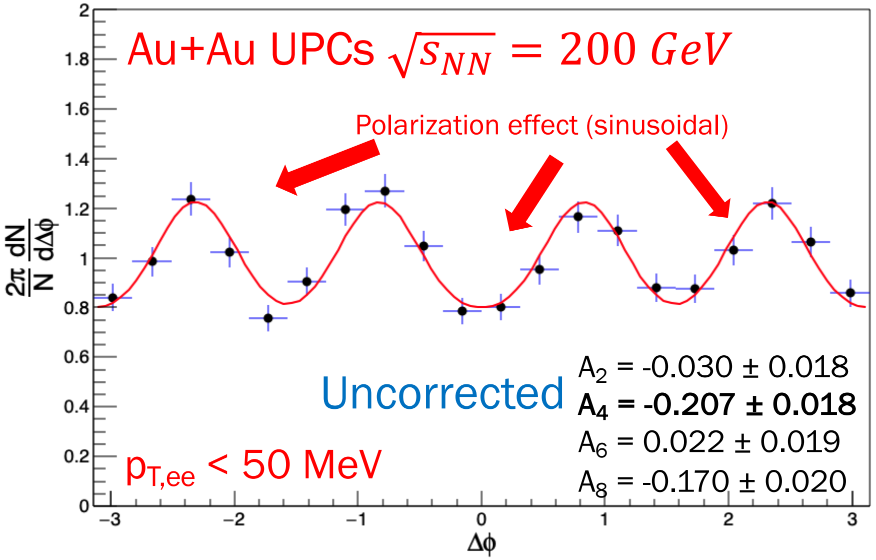
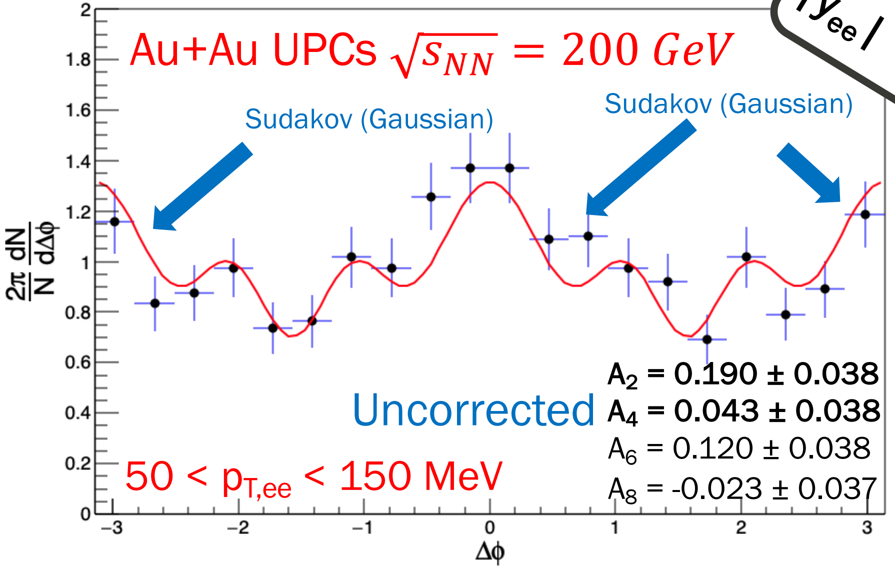
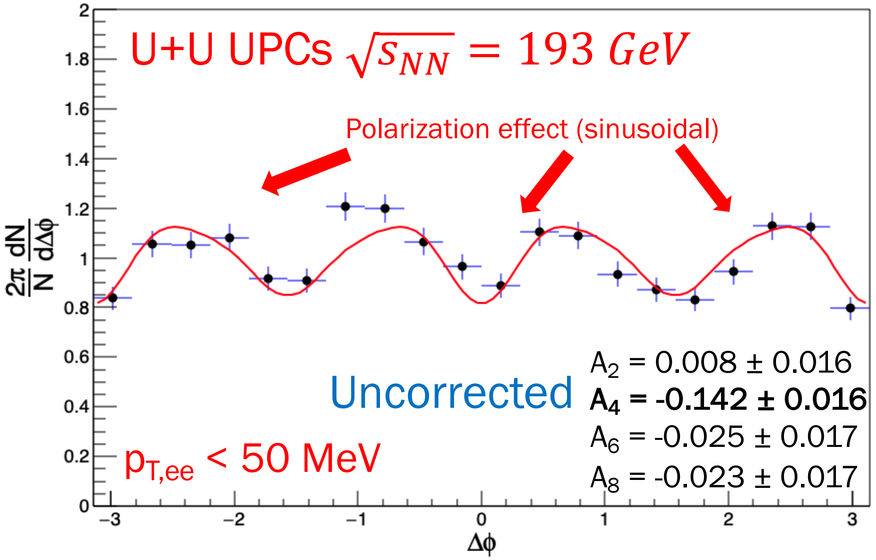
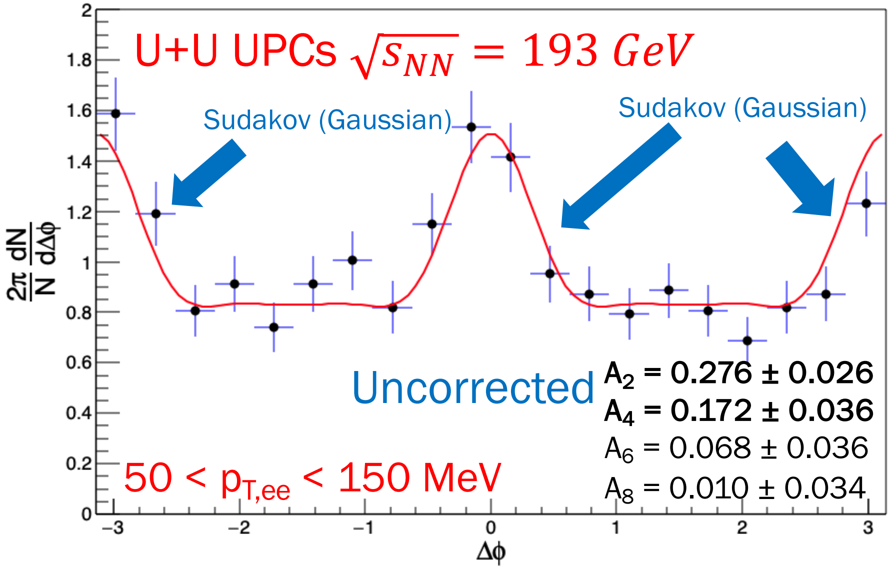


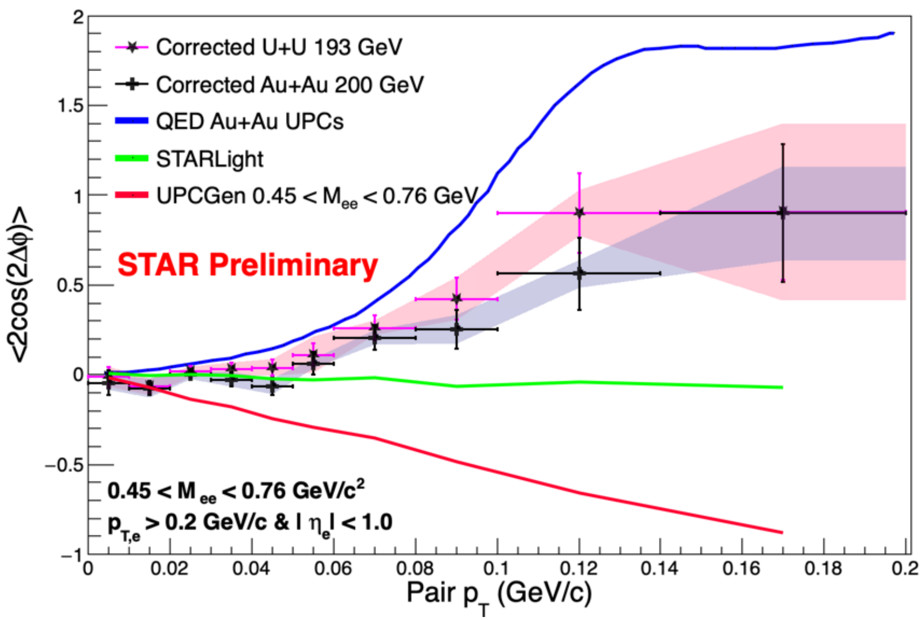


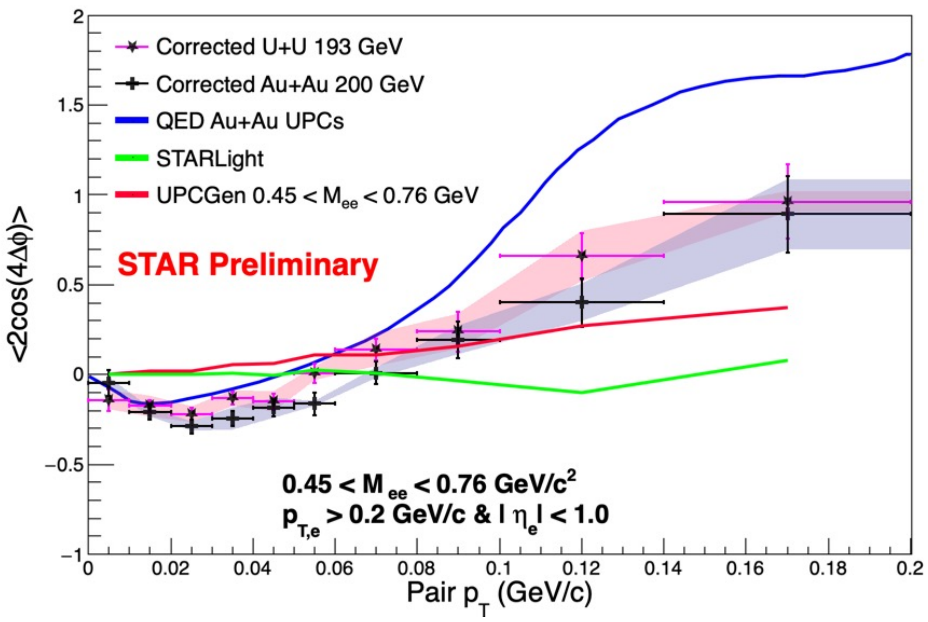




Cos(nΔϕ) vs. p_T

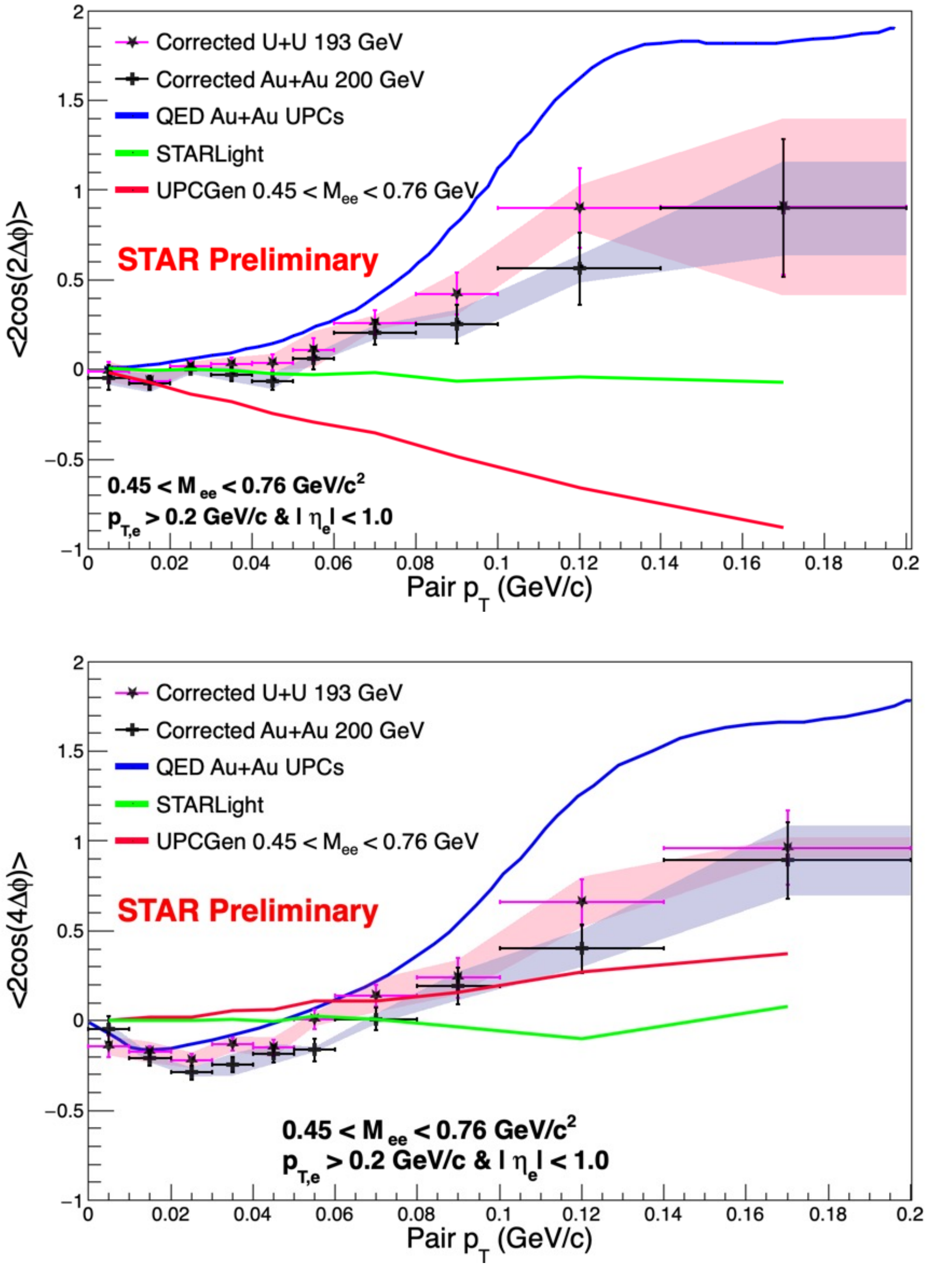
	Theory χ^2 (ndf = 10)	Zero χ^2 (ndf = 10)
UU A_2	28.7 / 10 = 2.9	36.2 /10 = 3.6 (3.8σ)
AuAu A_2	80.8 / 10 = 8.1	25.3 / 10 = 2.5 (2.6σ)
UU A_4	35.0 / 10 = 3.5	74.3 / 10 = 7.4 (6.8σ)
AuAu A_4	88.7 / 10 = 8.9	103.6 / 10 = 10.4 (8.5σ)





Cos(nΔϕ) vs. p_T

- Performed zeroth order polynomial fits at high pair p_T ($75 < p_T < 200$ MeV)
- U+U A_2: $p_0 = 0.550 \pm 0.099$ (5.55σ)
- Au+Au A_2: $p_0 = 0.355 \pm 0.092$ (3.86σ)
- U+U A_4: $p_0 = 0.496 \pm 0.077$ (6.44σ)
- Au+Au A_4: $p_0 = 0.350 \pm 0.076$ (4.61σ)
- In combination, these measurements constitute an **observation of Sudakov radiation with 10.4σ significance**

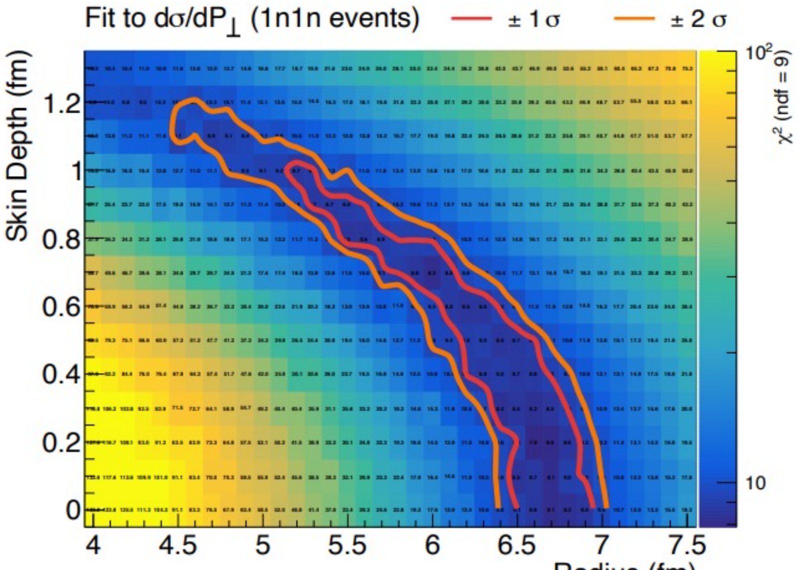


SUMMARY AND OUTLOOK

Summary and Outlook

- UPCs offer a novel tool for studying the electromagnetic field distributions from heavy ions
- First Breit-Wheeler cross section measurements in a deformed nucleus
- Strong evidence for Sudakov radiation in both Au+Au and U+U UPCs
- Both cross sections and azimuthal asymmetries are strong tools for probing nuclear shape
- Opportunity to employ our QED framework to determine the most likely deformation parameters for uranium

Parameter Scan for AuAu



Xiaofeng Wang (2023)

BACKUP

Quantifying the Curves

Curves Compared	X^2 (ndf = 24)
Au data and Au QED	25.3 / 24 = 1.05
UU data and UU QED R = 6.9 fm	42.8 / 24 = 1.78
UU data and UU QED R = 5.9 fm	112.8 / 24 = 4.70
UU data and UU QED R = 9.8 fm	350.6 / 24 = 14.61