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

Nicholas Jindal, for the STAR Collaboration

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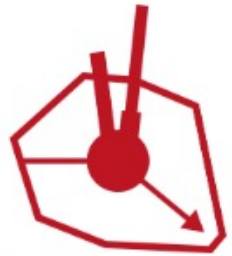
U.S. DEPARTMENT of ENERGY



DIS2026

Outline

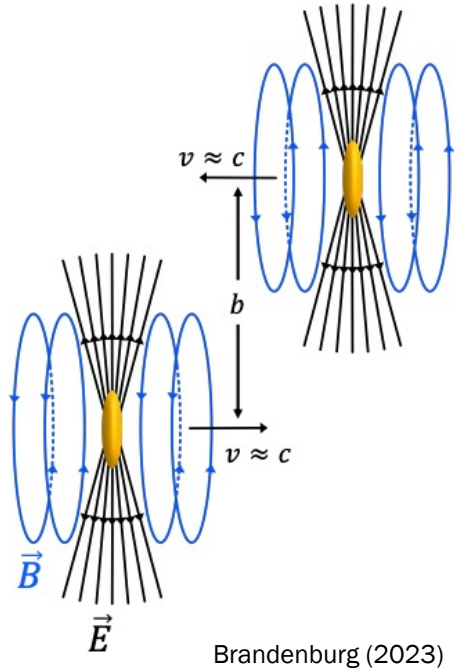
- UPCs and the Breit-Wheeler Process
- Motivation
- Accessing Nuclear Structure
- Extending the Framework
- Summary and Outlook

UPCS AND THE BREIT-WHEELER PROCESS

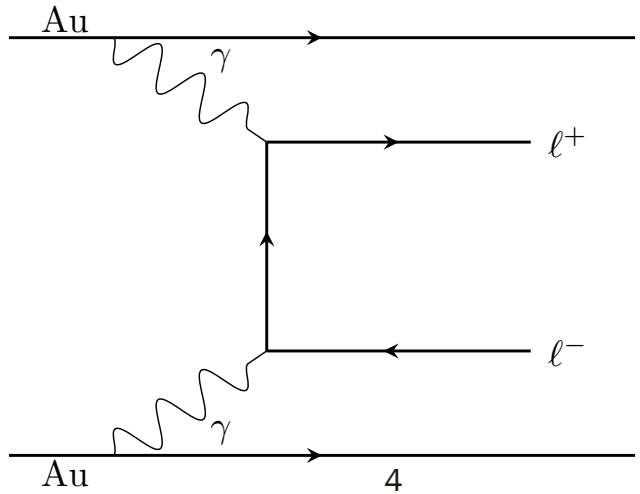
Ultra-Peripheral Collisions and the Breit-Wheeler Process

- 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**

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



Brandenburg (2023)

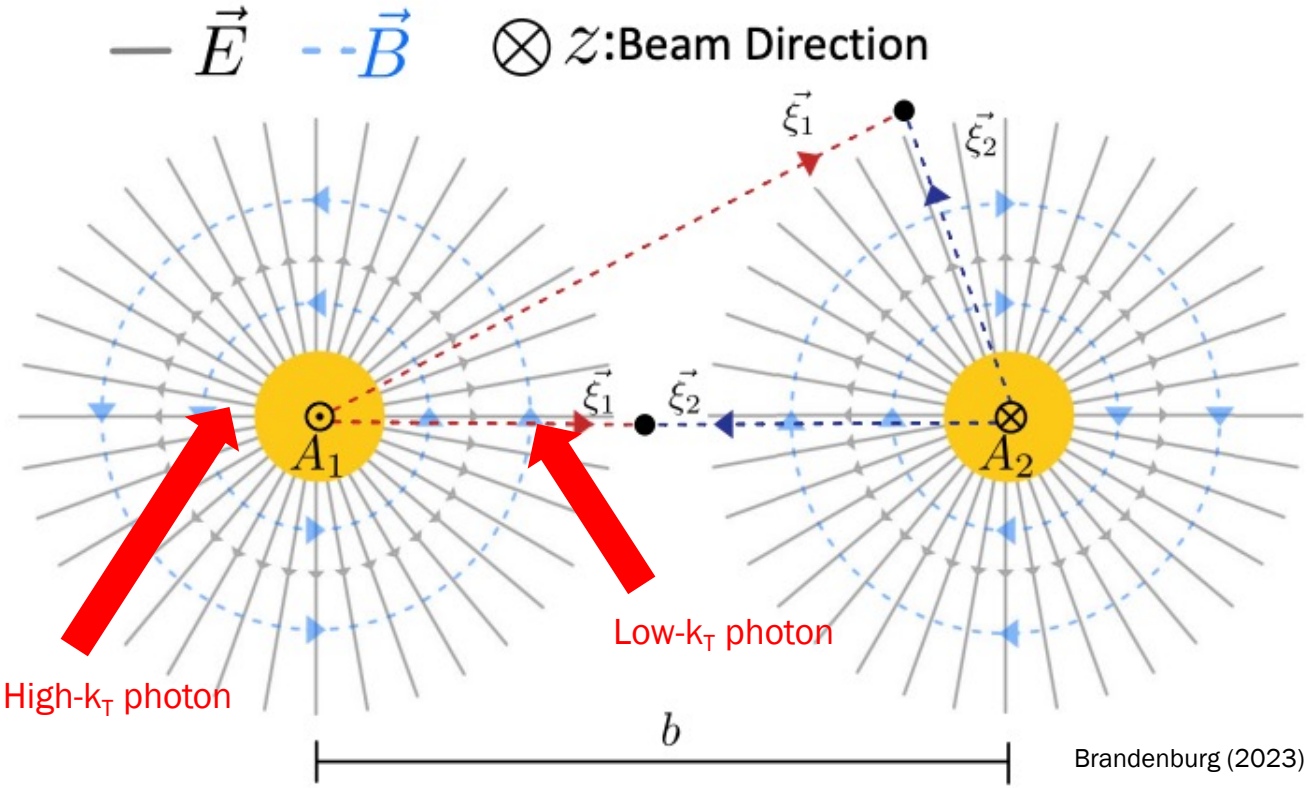


Schäfer, *et al, Phys. Proc. Ultra-Peripheral Collisions*, **1**, 009 (2024)
Brandenburg, *et al, Eur. Phys. J. A* **57**, 299 2021
Weizsäcker, C. F. v. *Zeitschrift für Physik* 88 (1934): 612
Yu Shi *et al.*, *Phys. Lett. B* 862 (2025) 139317

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**



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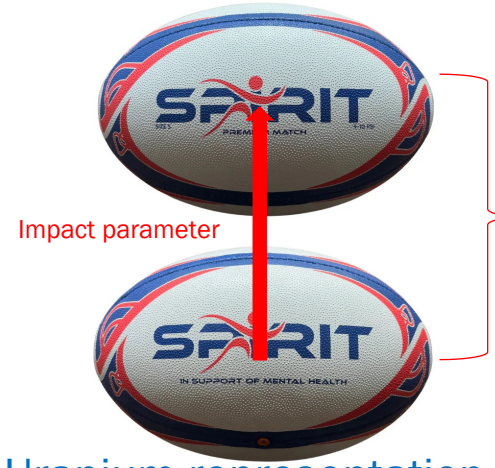


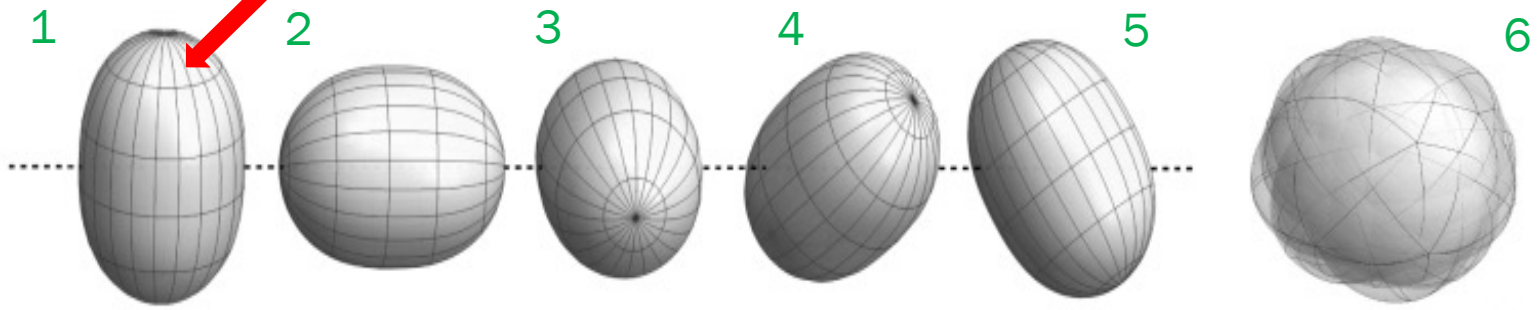
Wigner formalism tells us that **both** the momentum and impact parameter influence the photon flux

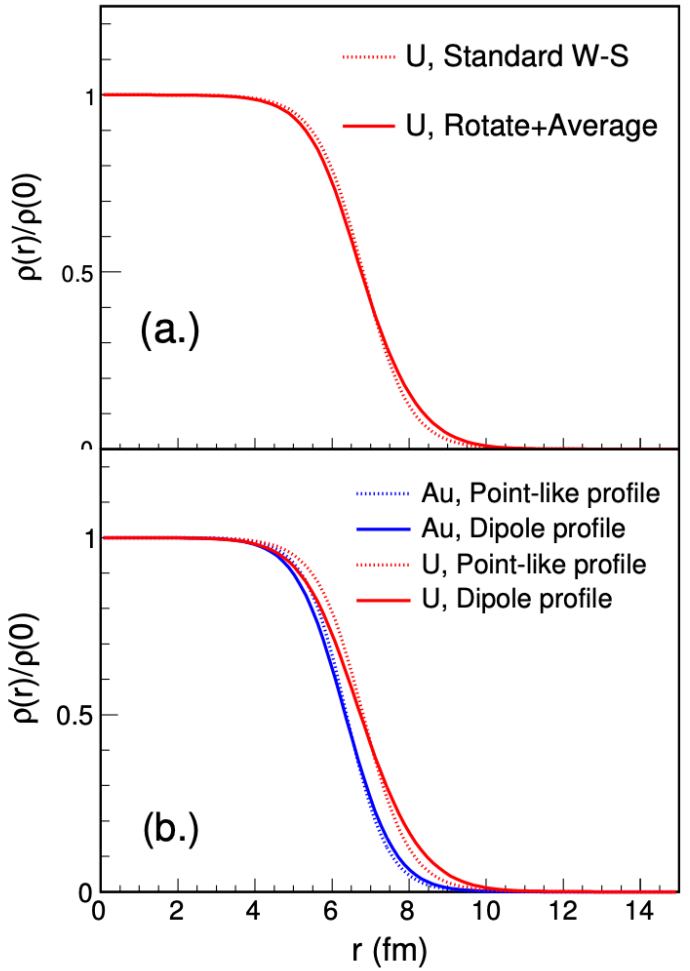
STAR Collaboration. *Nature* **635**, 67–72 (2024)

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**

$\beta_2 > 0$ quantifies prolate deformation





- 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

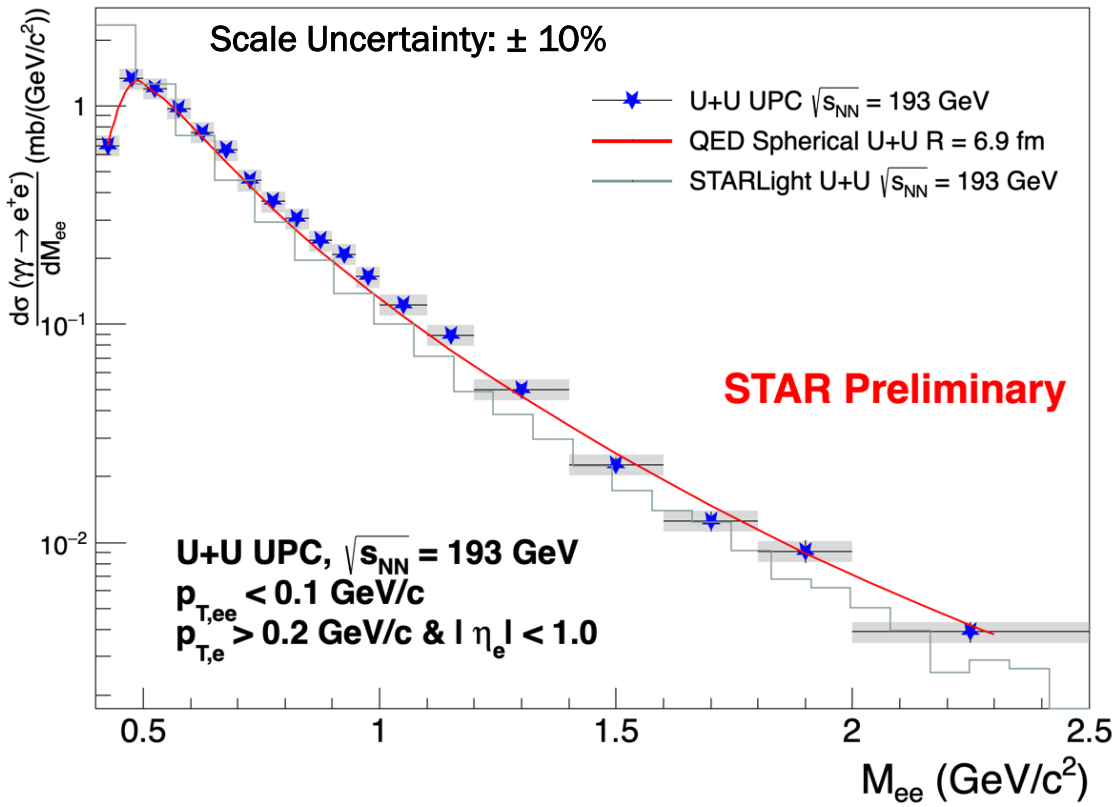
$$\rho(r,\theta) = \frac{\rho_0}{1+\exp\left(\frac{r - R_{WS}(1+\beta_2 Y_{20}(\theta))}{a_0}\right)}$$

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



$$\frac{d\sigma}{dm} = \frac{N^{e^+e^-}(m)}{dm * \mathcal{L} * \mathcal{E}}$$

- The raw yields are corrected for particle ID, tracking, and trigger efficiencies
- A combination of simulation and data-driven methods are used to obtain these corrections
- 10% uncertainty on luminosity

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

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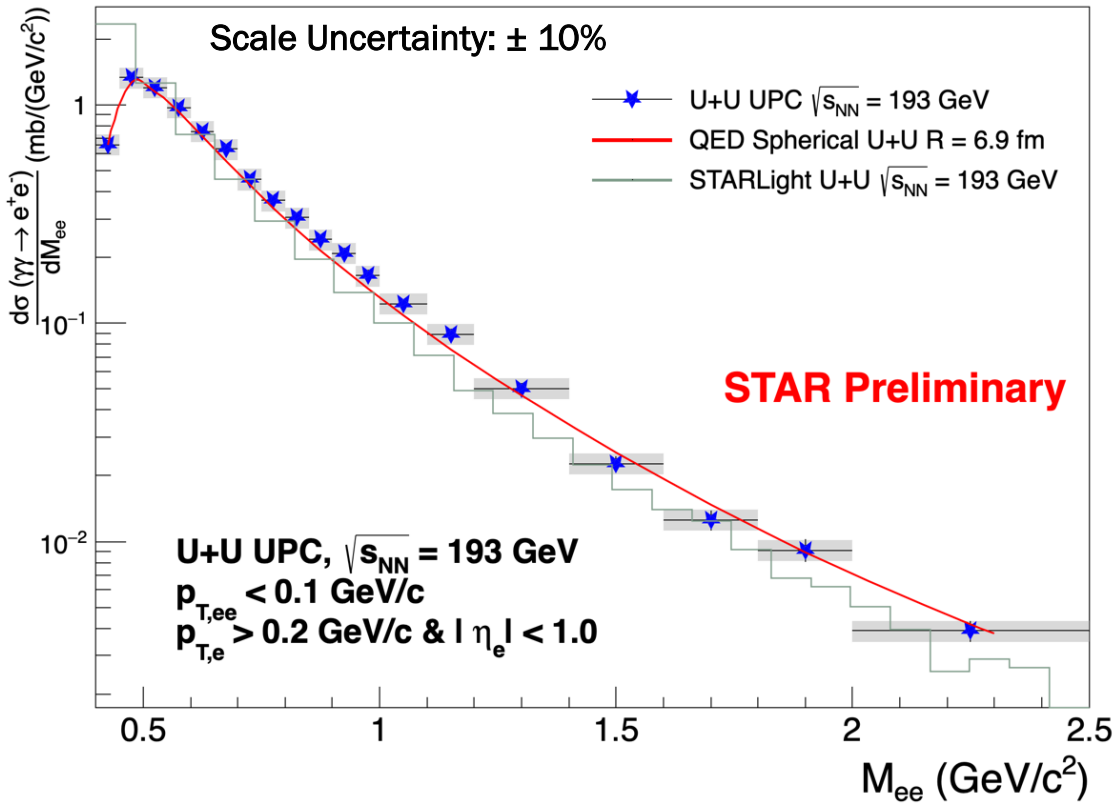

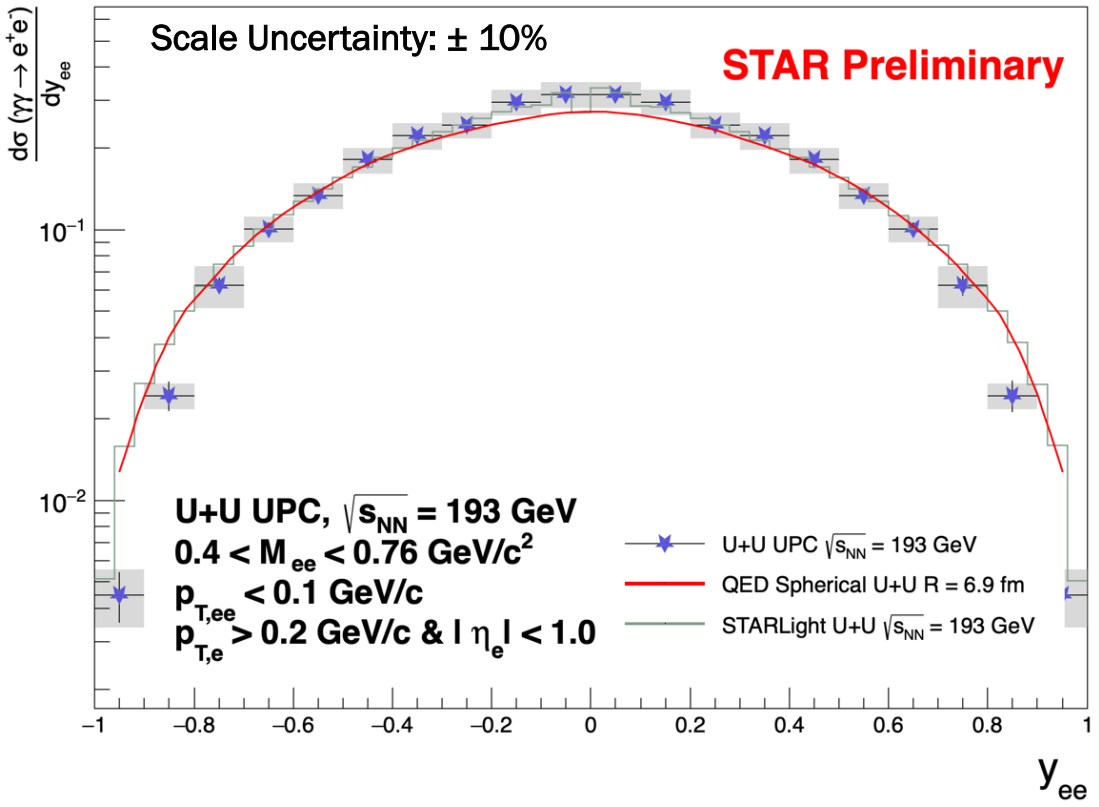

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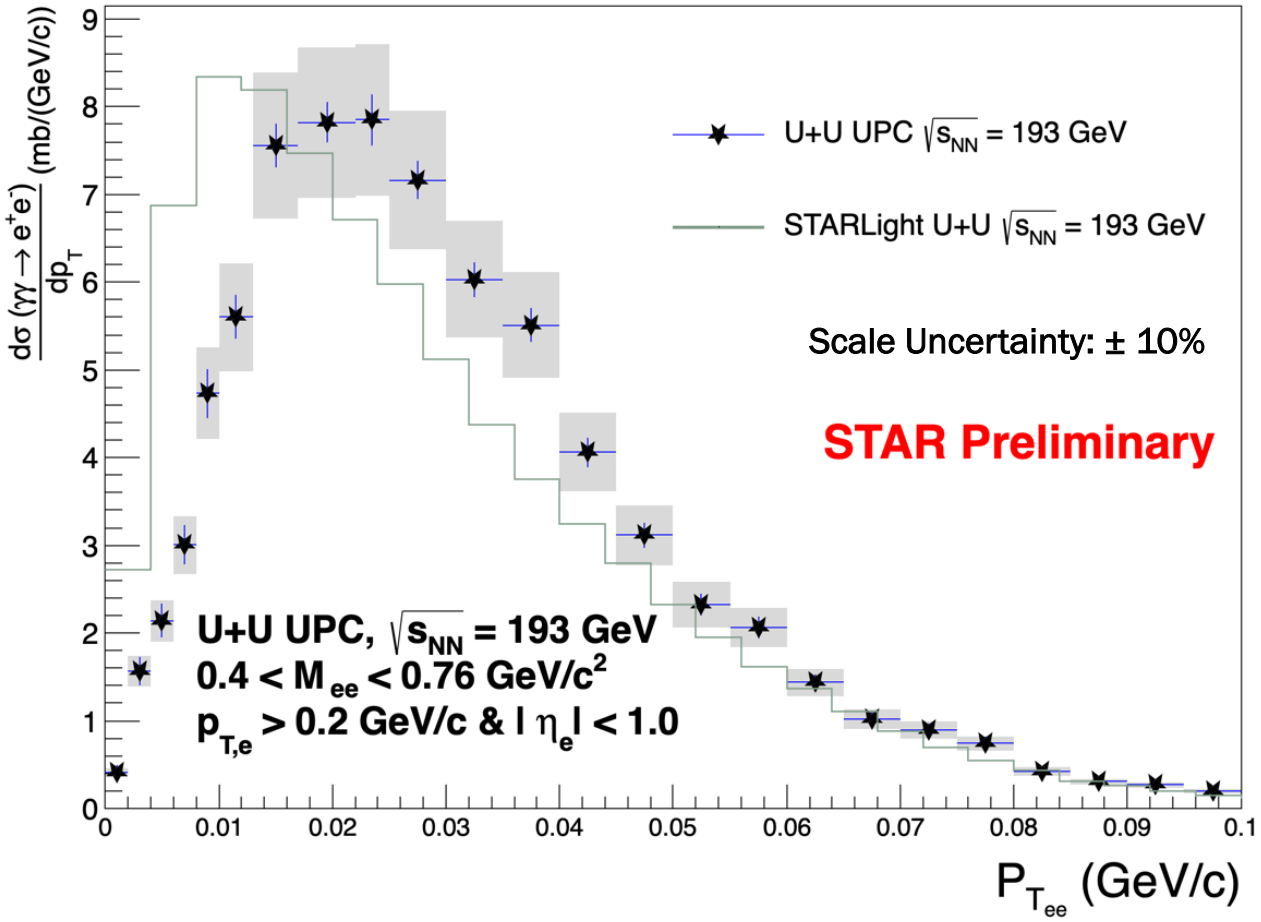
Cross Sections

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

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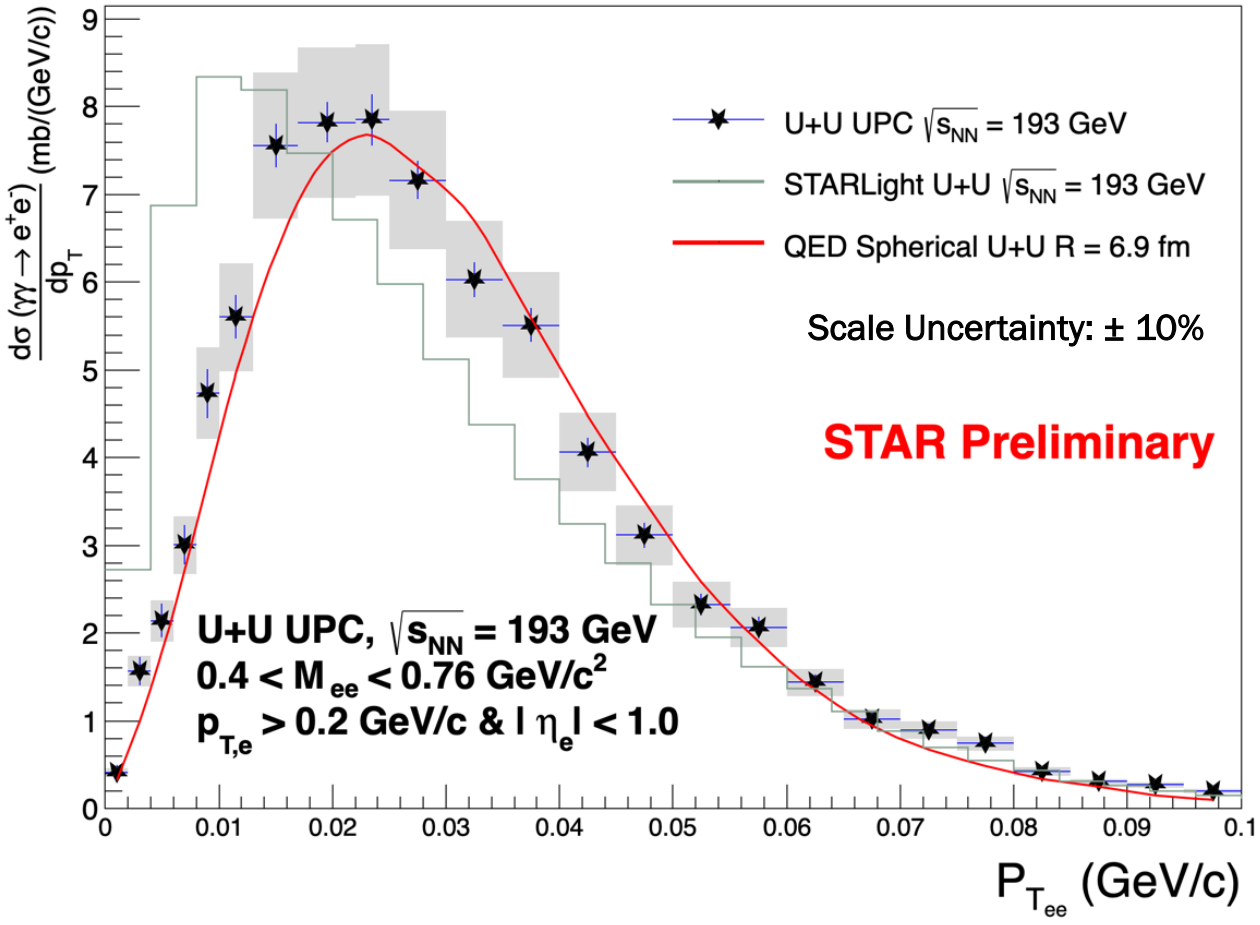
- STARlight predicts a significantly lower $<p_T>$
- QED calculation accounts for the quantum correlation between position and momentum as in the Wigner formalism, unlike STARLight

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

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

σ_{QED} = 0.301 +- 0.116 (mb)



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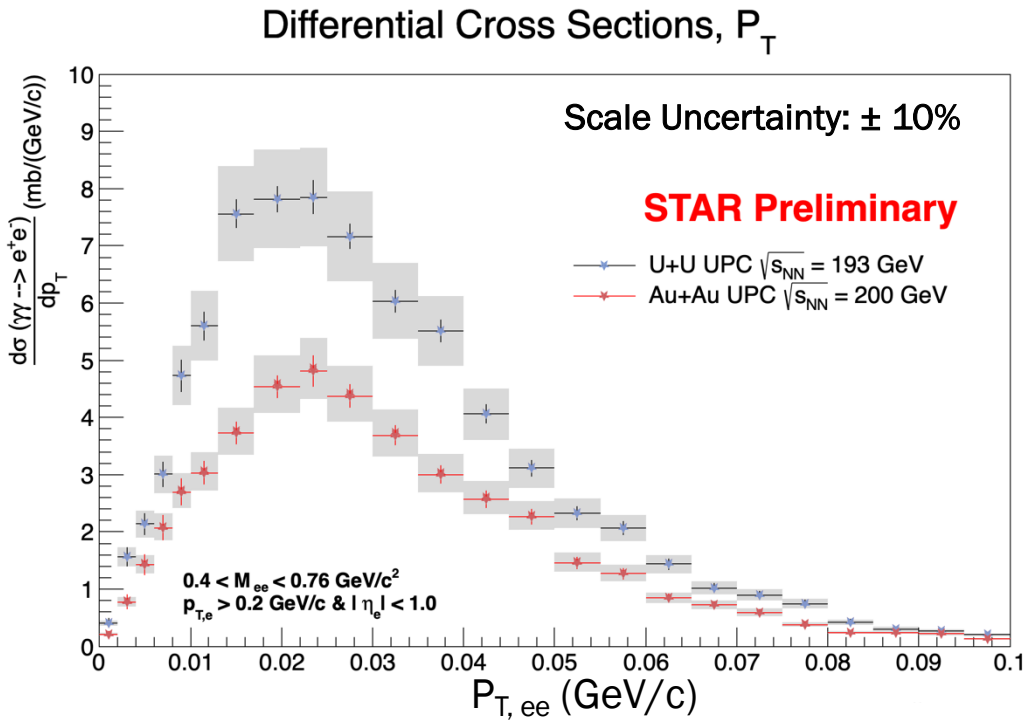
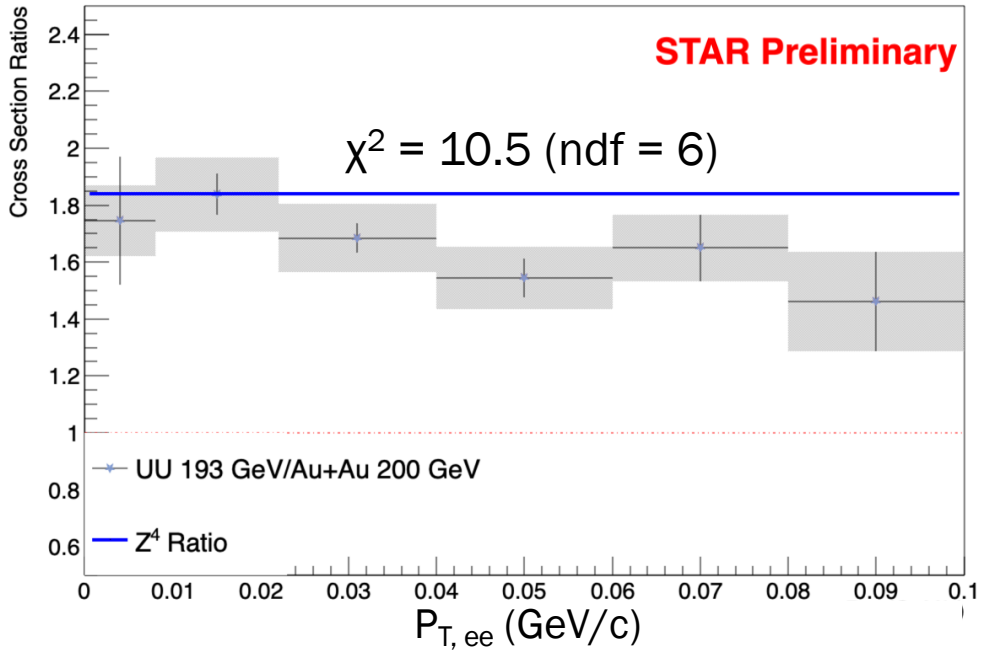
Uranium vs. Gold Expectation

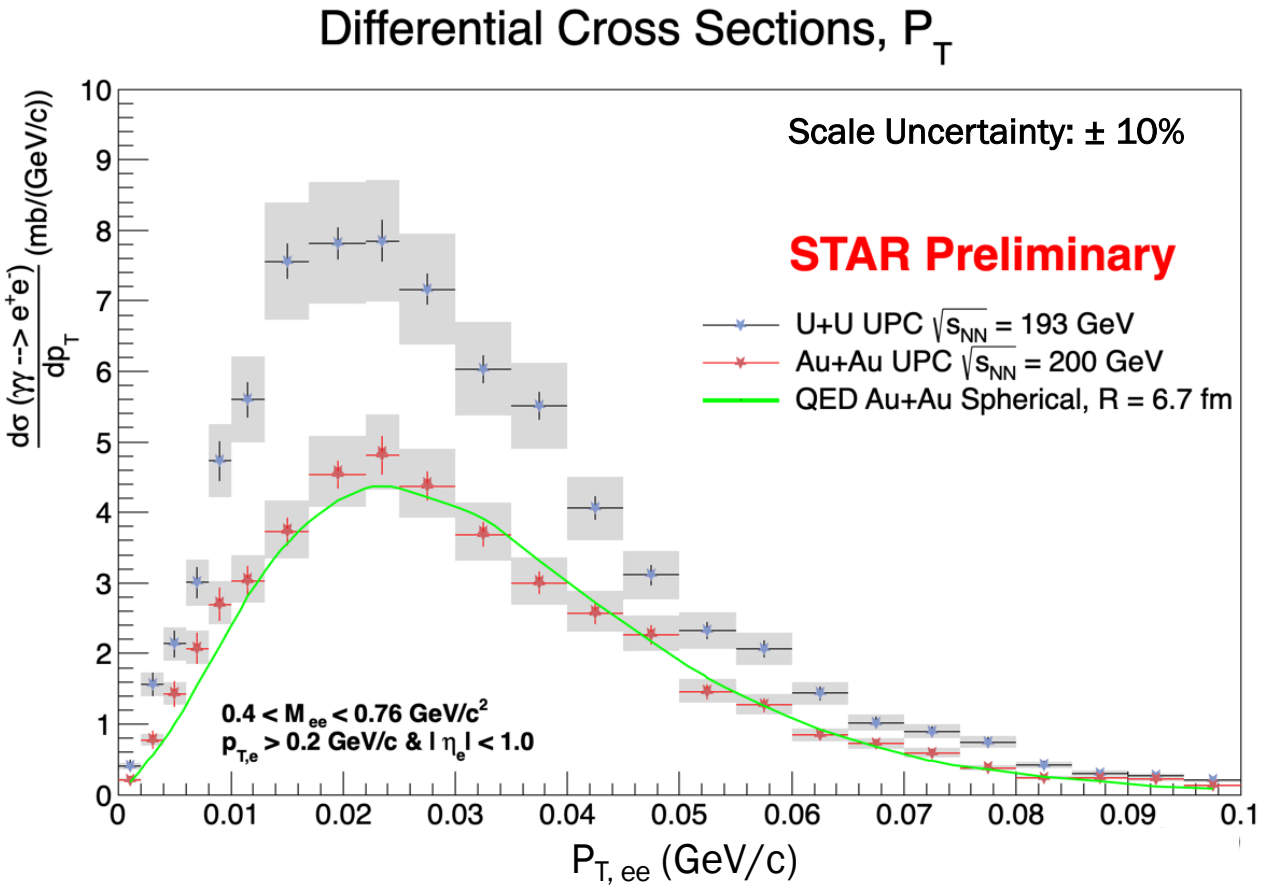
- Photon flux scales as Z^2, so for a two-photon process, $\sigma \propto Z^4$
- The naïve expectation for the ratio is a simple Z_U^4 / Z_{Au}^4 scaling between U+U and Au+Au cross sections
- Can we model this better with QED?





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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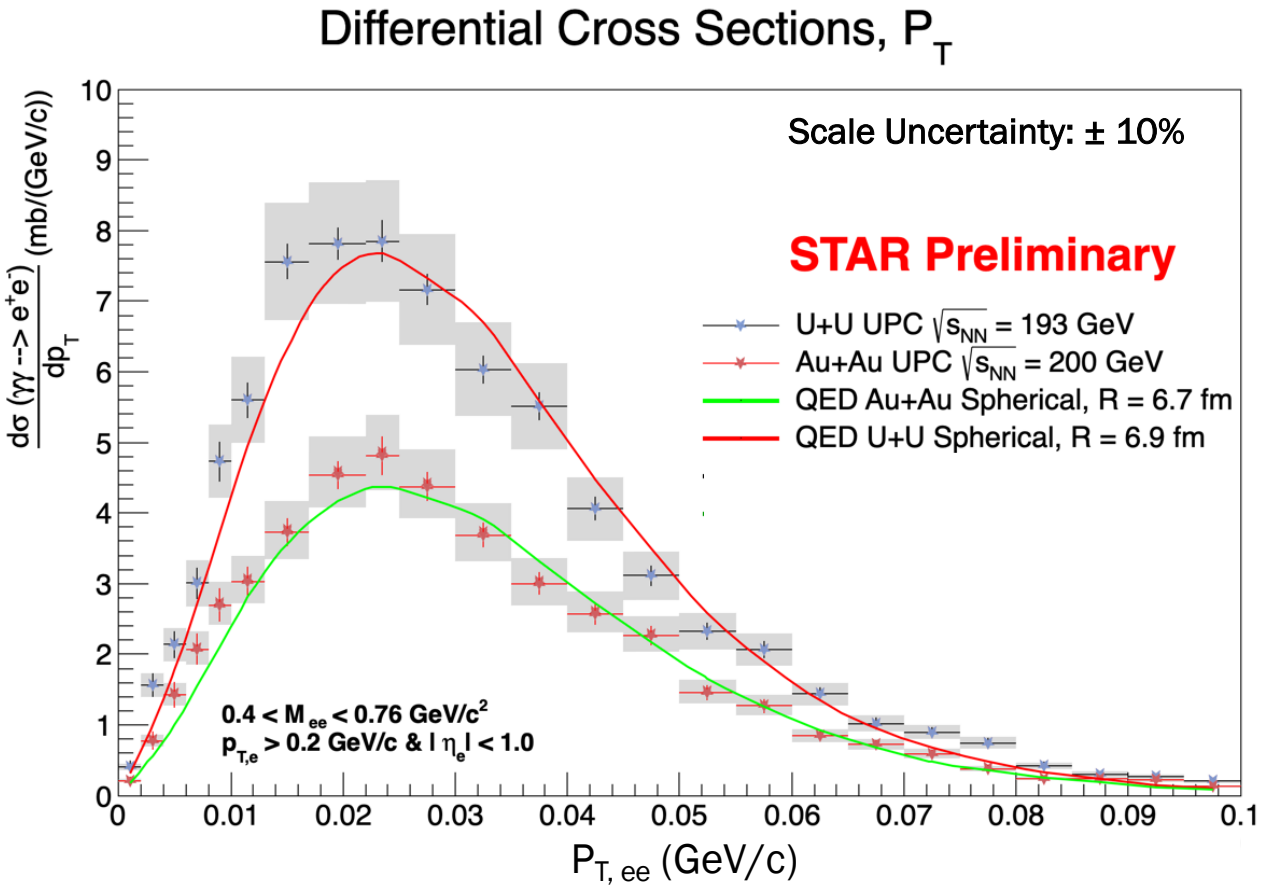

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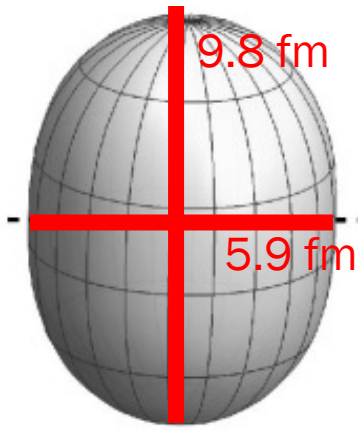
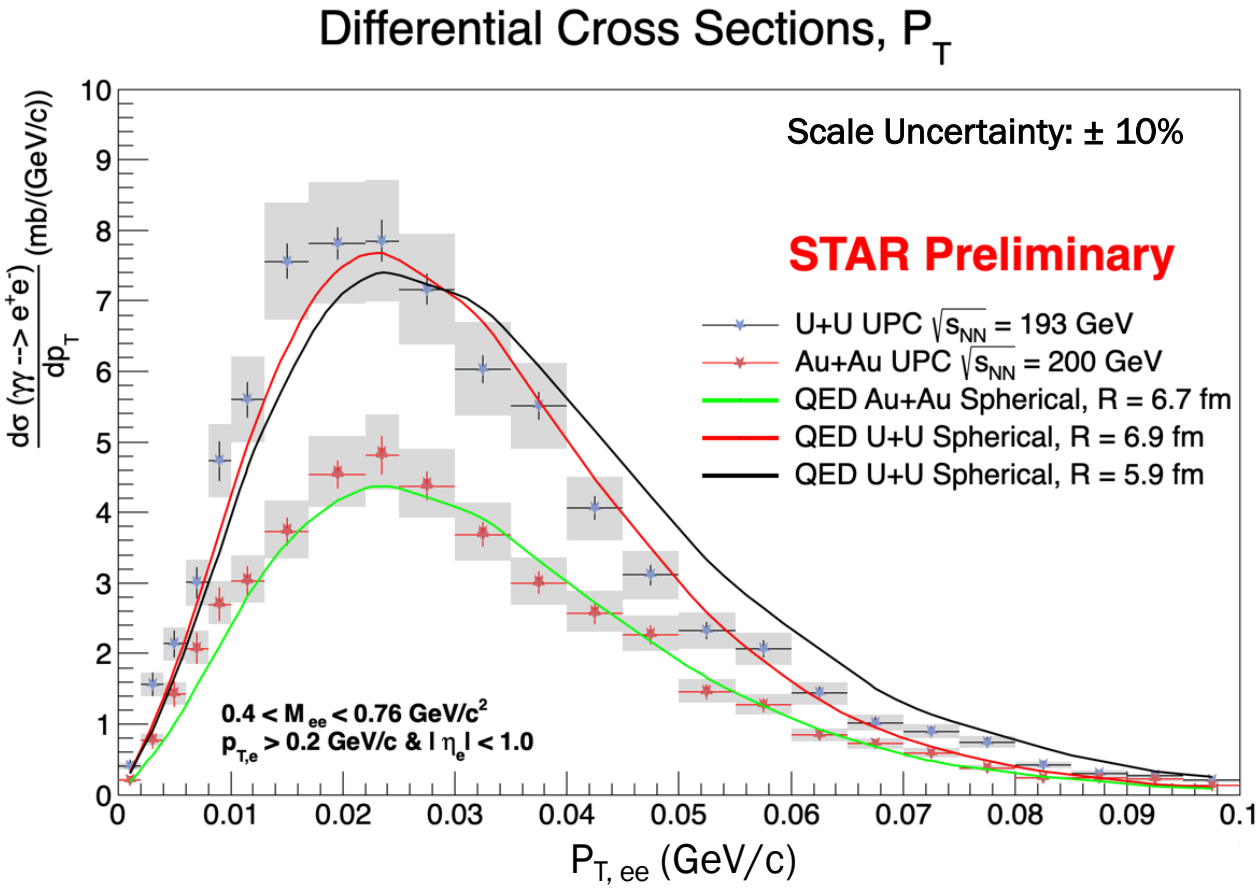
- A smaller radius shifts the peak to higher p_T





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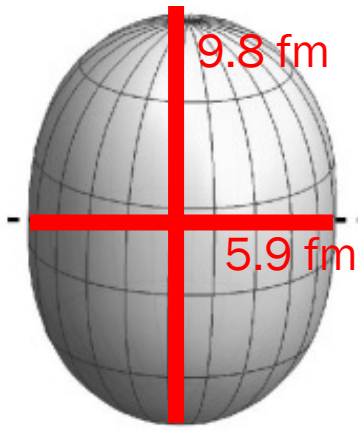
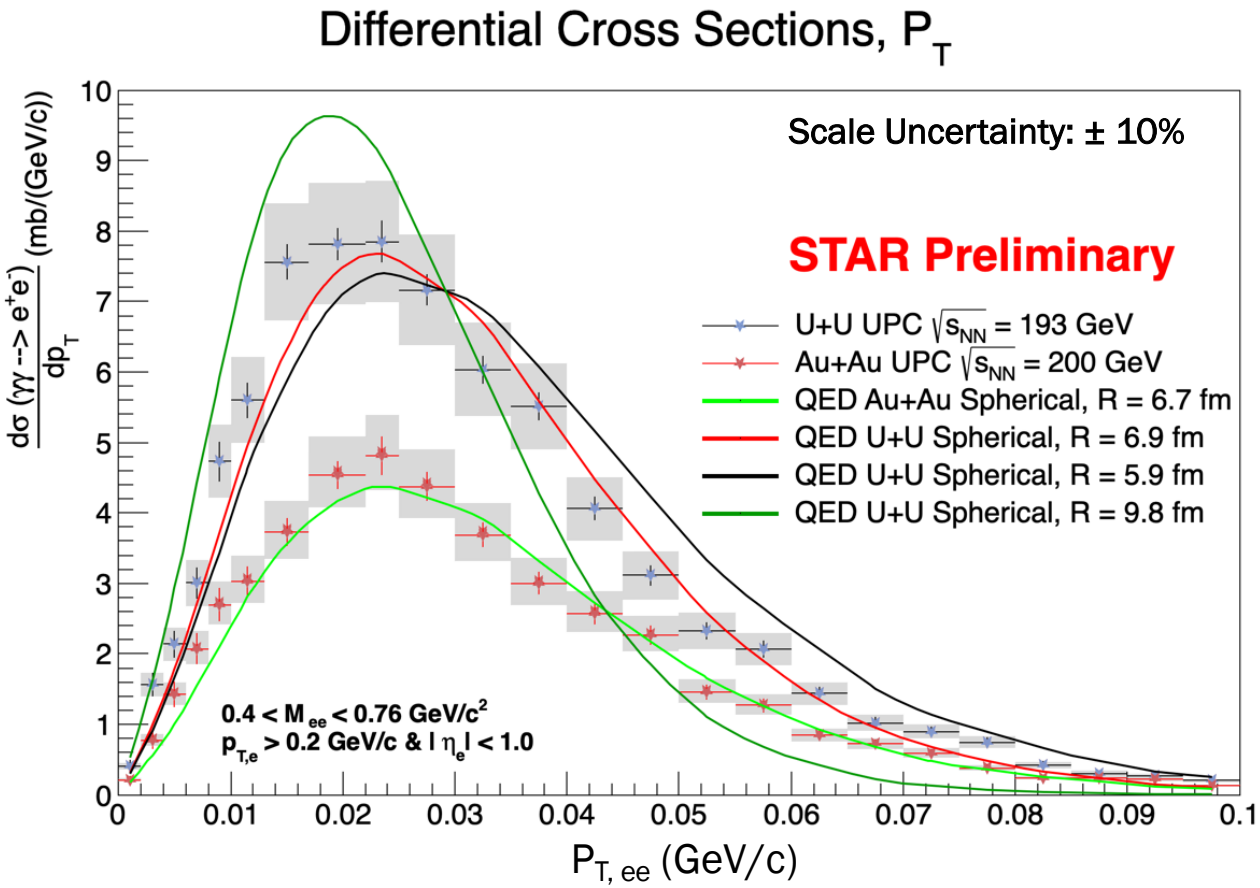
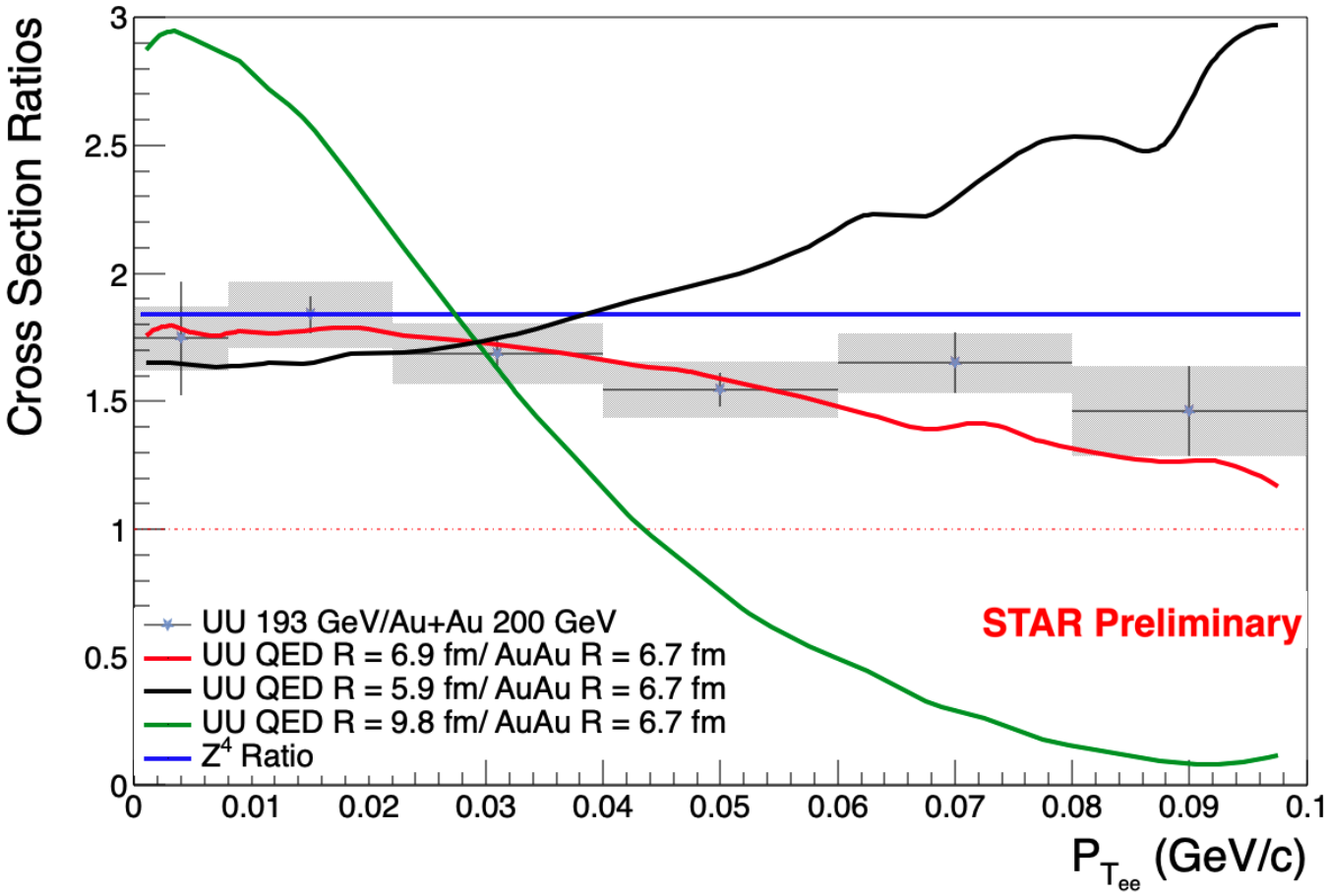
- A smaller radius shifts the peak to higher p_T
- A larger radius does the opposite





Cross Section Ratio

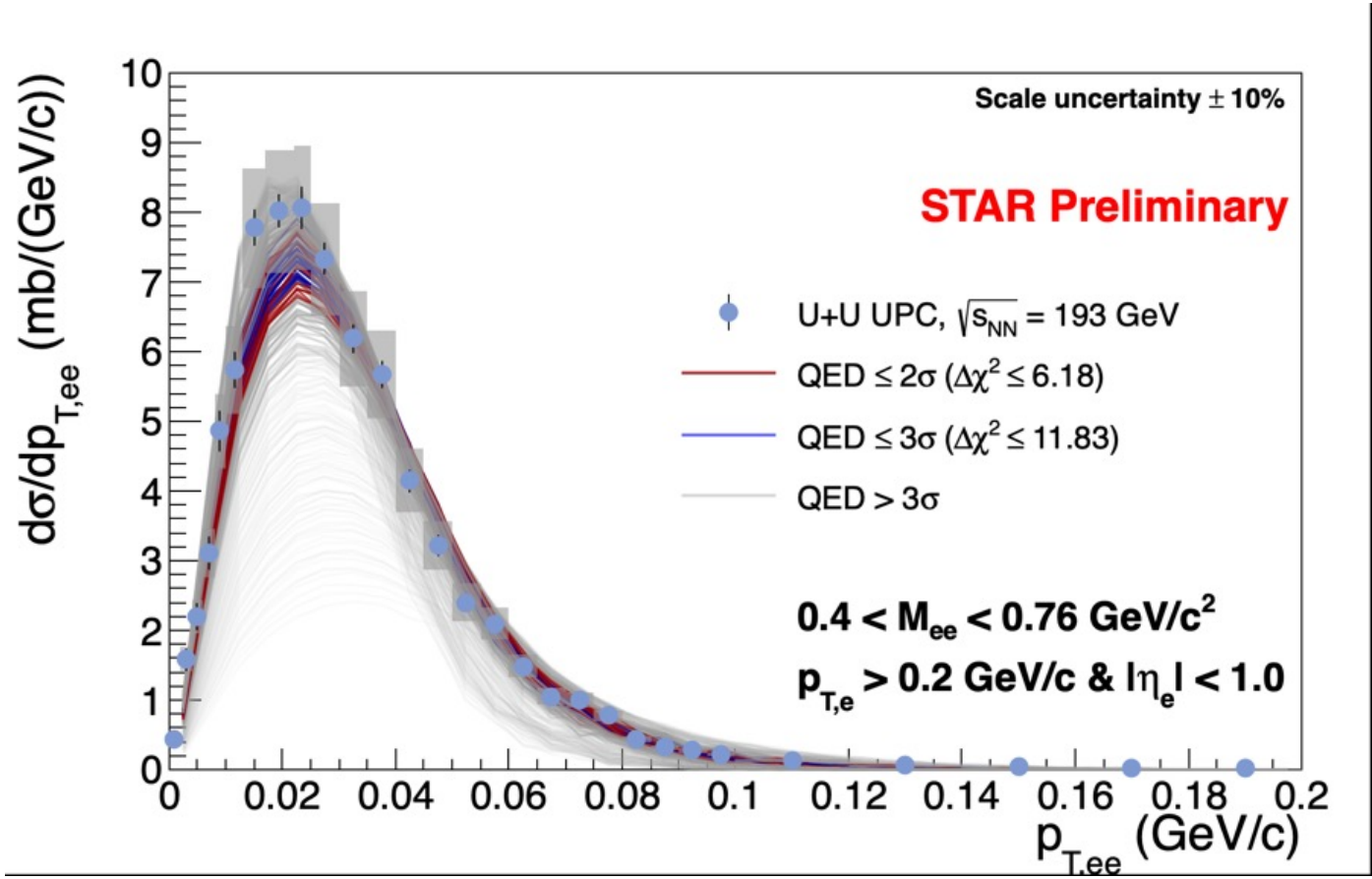
Comparison with Data Ratio	X^2 / (ndf = 6)
UU QED R = 6.9 fm/ AuAu QED R = 6.7 fm	2.9 / 6 = 0.5
UU QED R = 5.9 fm/ AuAu QED R = 6.7 fm	66.7 / 6 = 11.1
UU QED R = 9.8 fm/ AuAu QED R = 6.7 fm	197.0 / 6 = 32.8
Z^4 Ratio	10.5 / 6 = 1.8



EXTENDING THE FRAMEWORK

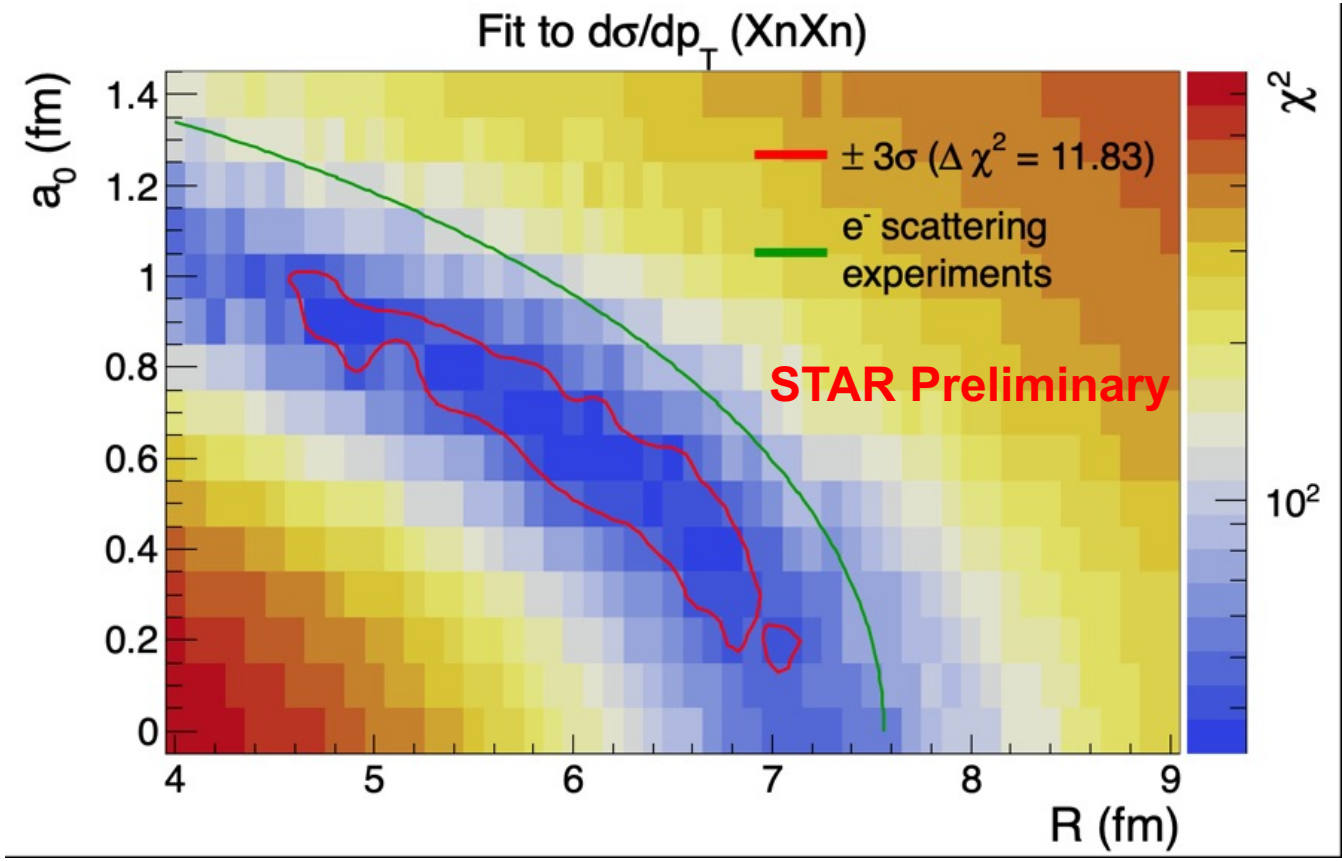
Procedure

- Modeling uranium with a spherically-symmetric Woods-Saxon, perform LOQED calculation for a grid of radius and skin depth values
- Vertically scale each curve to best fit the data and calculate the χ^2
- Weighting each curve's transparency by the χ^2, we see a large group of curves that fit well qualitatively



Results

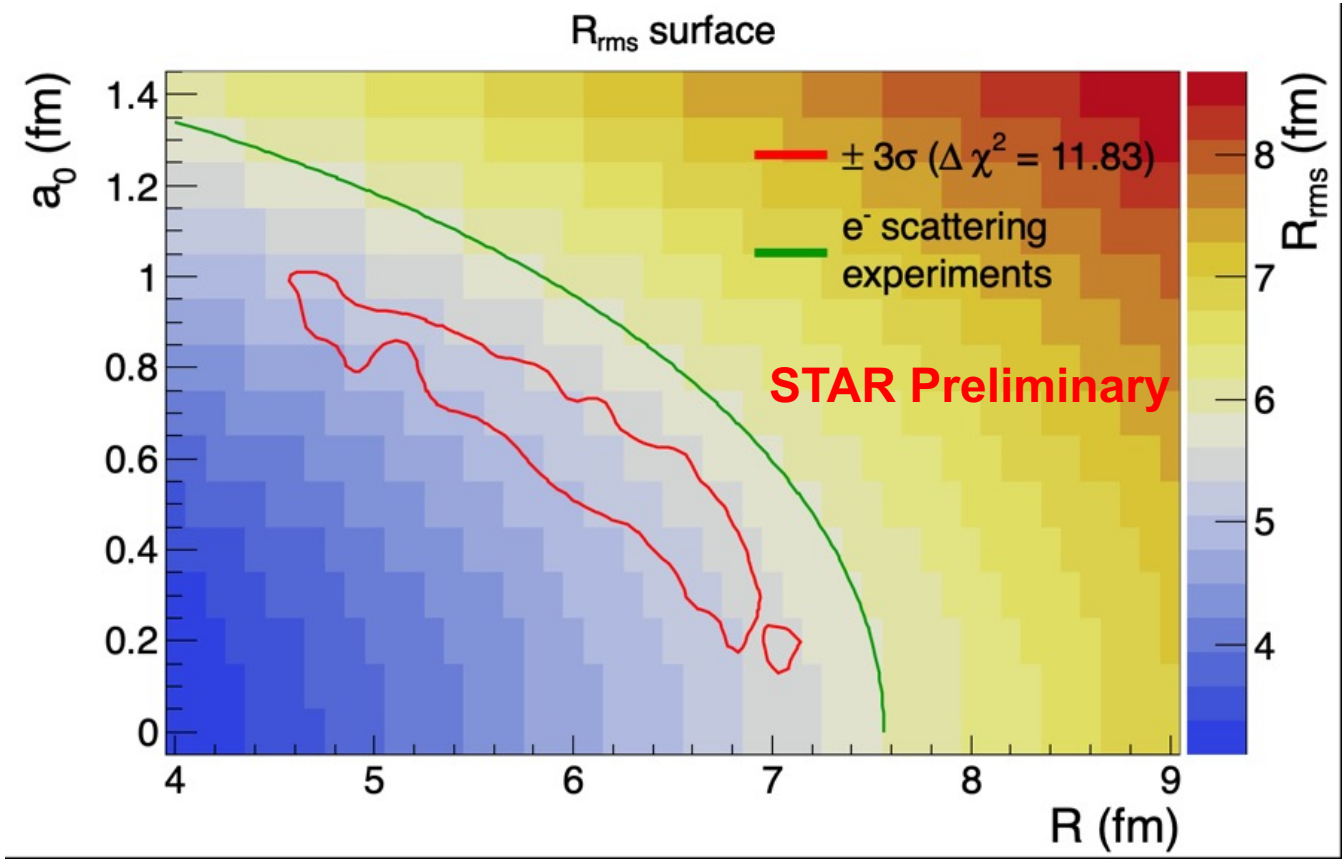
- To quantify the fit better, make a 2D map plotting each curve's χ^2 as a function of the input radius and skin depth
- Plot 3 standard deviation contour
- Low-energy e^- scattering experiments rely on EM interactions with the protons in the nucleus
  - *Sensitive to nuclear charge radius*
- Compare results across completely different energy regimes



I. Angeli and K.P. Marinova, *At. Data Nucl. Data Tables* **99**, 69 (2013).

Results

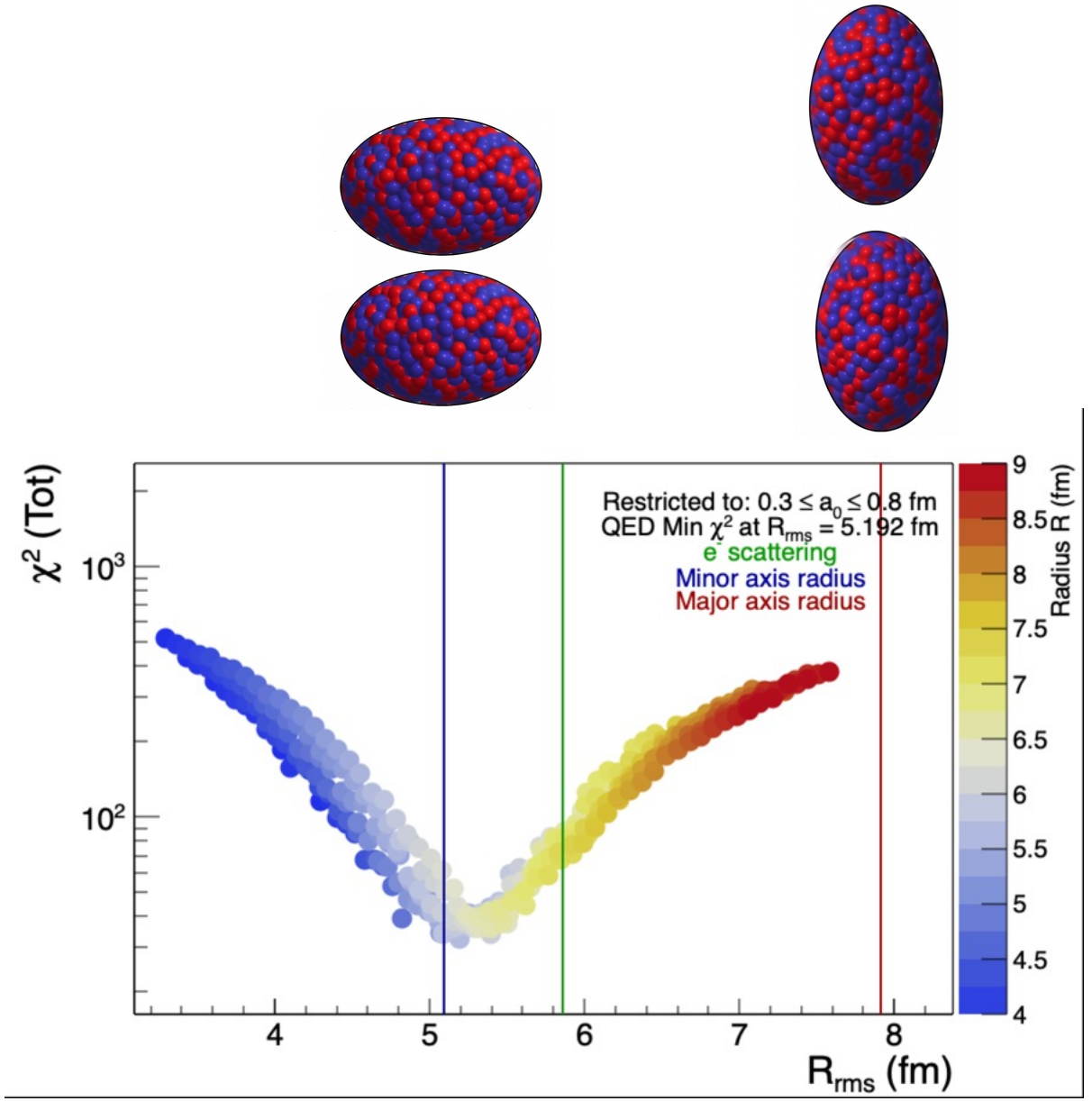
- Electron scattering experiments report an RMS radius
- $R_{RMS} = \sqrt{\langle r^2 \rangle} = \sqrt{\frac{\int_0^\infty r^4 \rho(r) dr}{\int_0^\infty r^2 \rho(r) dr}} \approx \sqrt{\frac{3}{5}R^2 + \frac{7}{5}\pi^2 a_0^2}$



I. Angeli and K.P. Marinova, *At. Data Nucl. Data Tables* **99**, 69 (2013).

Results

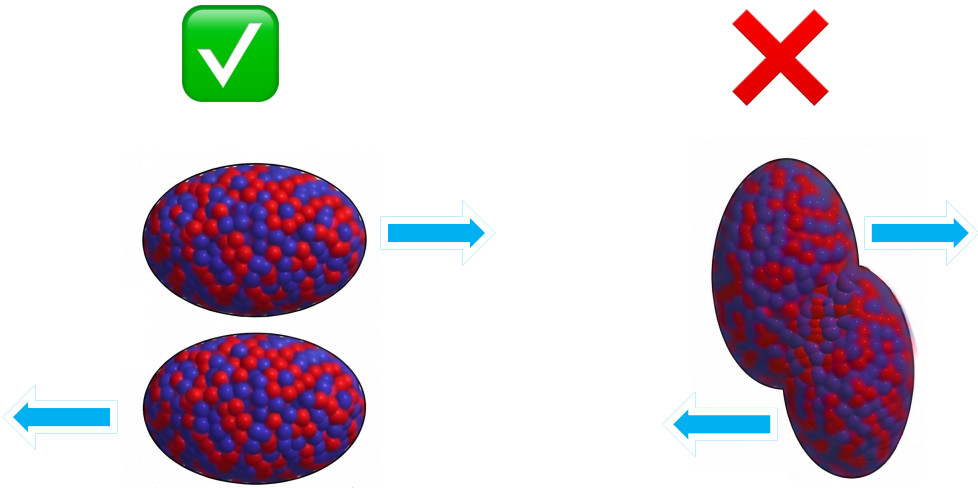
- Fit the minimum to a parabolic shape, **best fit RMS radius of 5.276 ± 0.033 fm**
- **This disagrees with electron scattering experiments, which report an RMS radius of 5.8571 ± 0.0033 fm**
- Published Au+Au data agrees well with low-energy electron scattering experiments
- A spherically-symmetric Woods-Saxon model fails to capture the nuances of the initial state geometry for uranium
- Bias towards the minor axis radius of uranium at lower impact parameter



I. Angeli and K.P. Marinova, *At. Data Nucl. Data Tables* **99**, 69 (2013).
Phys. Rev. C **111** (2025) 14909.

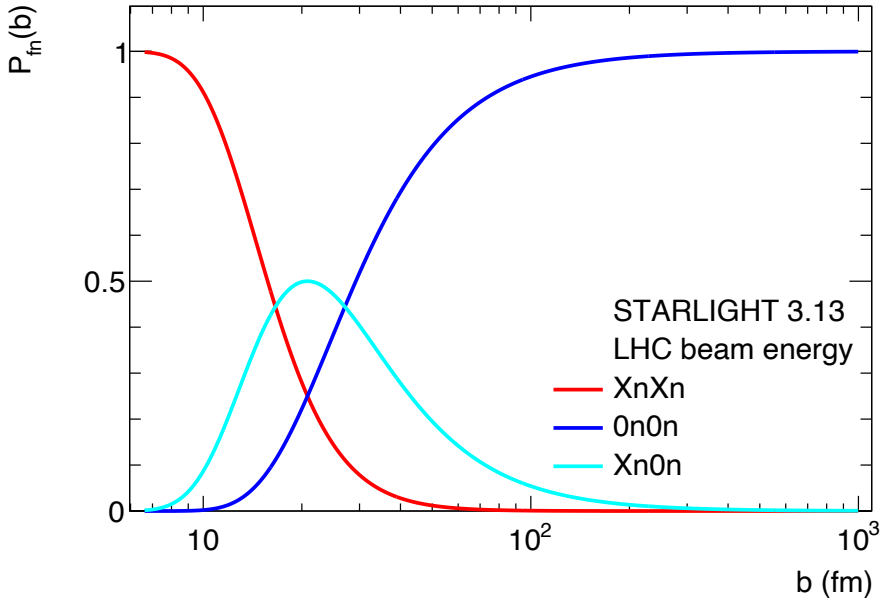
Results

- By selecting XnXn events and veto on hadronic events, we bias towards **smaller** impact parameter and side-on initial configuration
- $B_{min} \cong 2R_{minor}$



For a range of small impact parameters, we only get UPCs from configurations near the left picture, “seeing” a smaller effective radius

a



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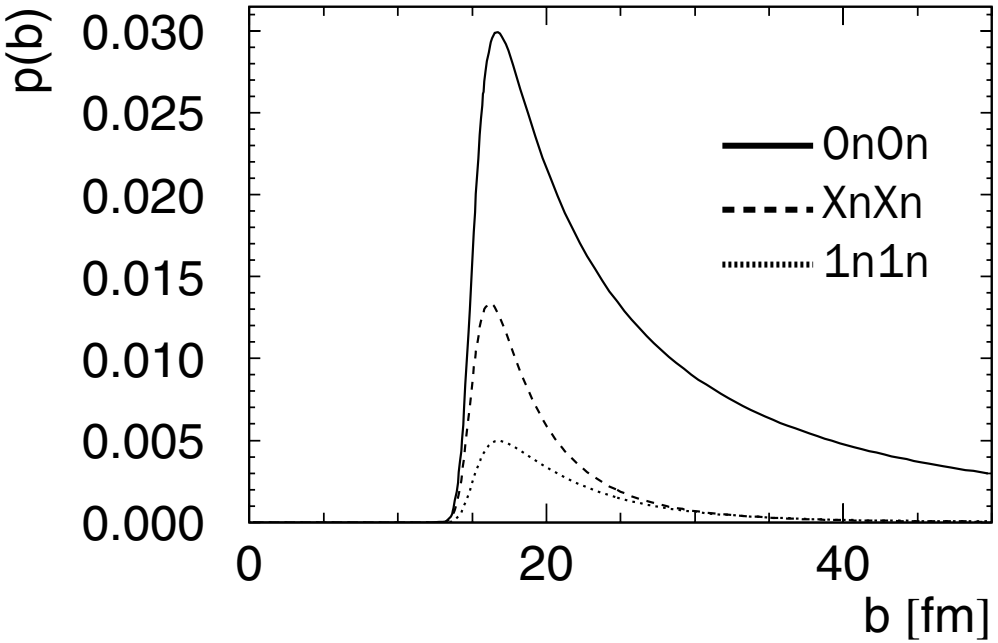
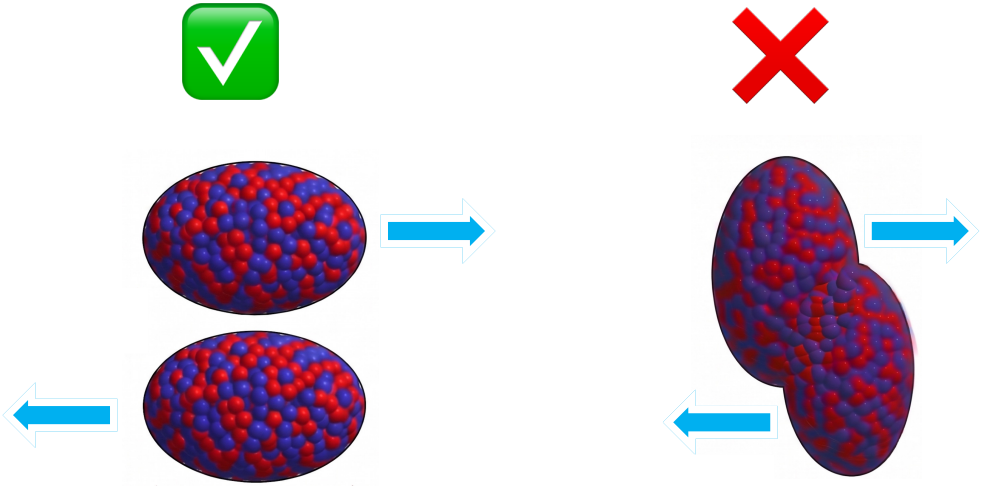


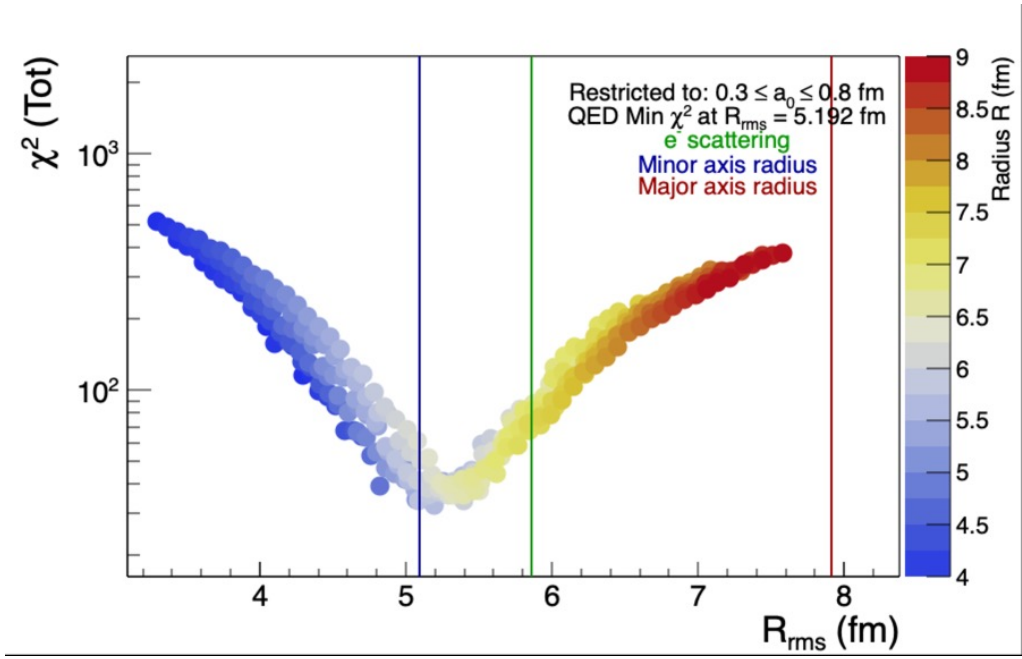
S. R. Klein and P. Steinberg, Annu. Rev. Nucl. Part. Sci. 70, 323 (2020)

SUMMARY AND OUTLOOK

Summary and Outlook

- UPC cross sections are unique, purely electromagnetic probes for investigating nuclear shape
- First Breit-Wheeler cross section measurements in a deformed nucleus
- Modeling uranium as a spherically-symmetric Woods-Saxon fails to capture certain initial-stage configurations that measurably affect the cross sections
- Opportunity to improve the model by employing a 2D deformed form factor in the model





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