Breit-Wheeler Process in U+U Ultra Peripheral Collisions
&
Coherent Photonuclear Production of ϕ Meson in Au+Au Ultra Peripheral Collisions at STAR

STAR

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U.S. DEPARTMENT OF ENERGY | Office of Science

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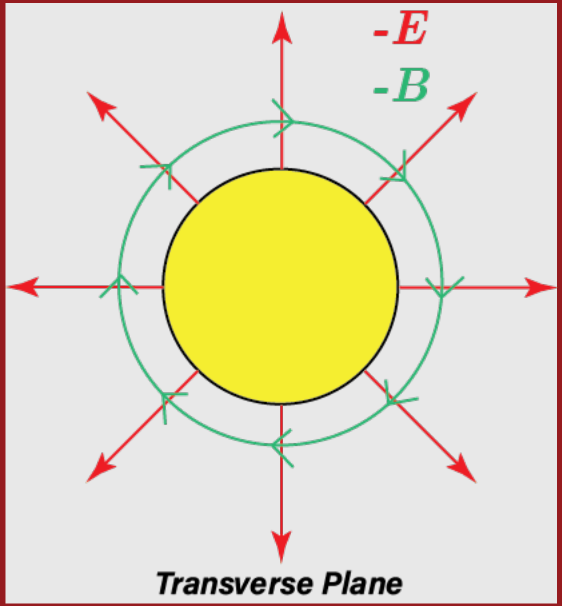
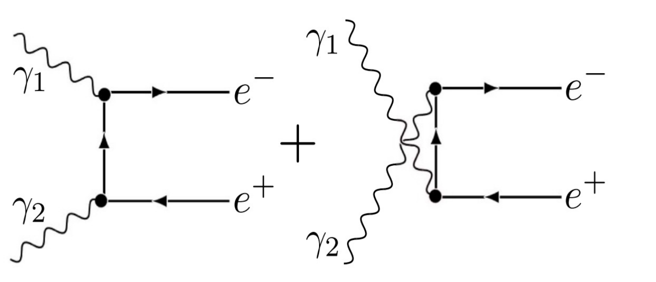
Breit-Wheeler Pair Production in Strong Electromagnetic Fields

- Ultra Peripheral Collision
  - **Ultra-Peripheral Collisions (UPC)**: nuclei pass each other at impact parameters > 2R.
  - **Lorentz-contracted EM fields** create intense transverse photon flux
  - **Photons treated as quasi-real** (Weizsäcker–Williams approximation)

- Breit-Wheeler Process $\gamma\gamma \rightarrow e^{+}e^{-}$ in vacuum via real photon fusion
  - Enabled by **intense EM fields** (Z^2 scaling) in heavy ion UPC
  - Occurs when field strength **exceeds Schwinger limit:** $E_c \equiv \frac{m_e c^2}{e\,\lambda_c} \approx 1.3 \cdot 10^{16}\ \mathrm{V\ cm^{-1}}$
  - Very low pair transverse momentum of the e^+e^- pair.

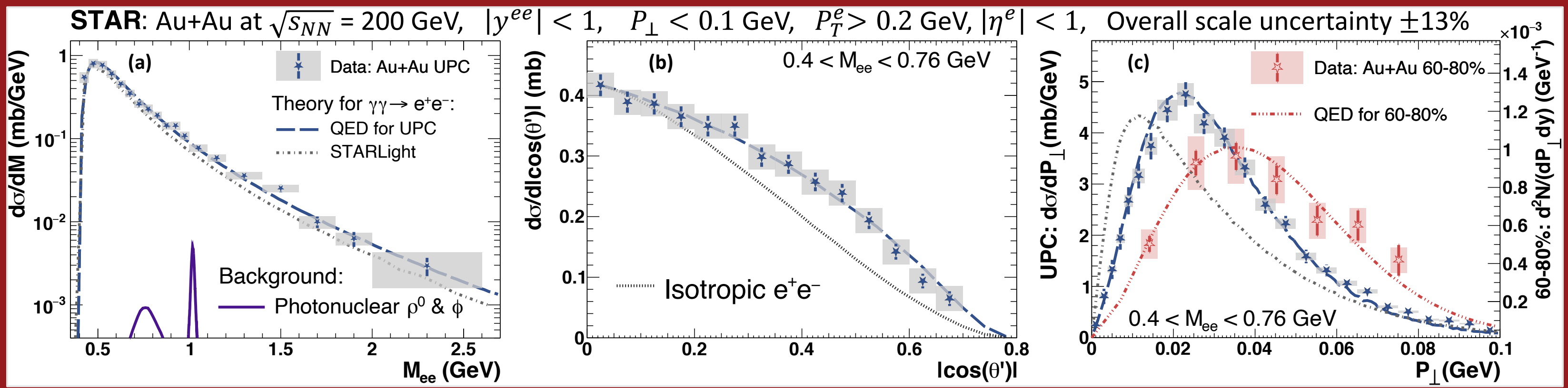




t and u channel of BW Process
(Brandenburg et al., *REP. Prog. Phys*, 2023)

Mapping Nuclear Geometry via the Breit–Wheeler Process

- EM Fields Reflect Nuclear Geometry
  - UPC ions generate **coherent EM fields** shaped by the nuclear charge distribution.
  - As a first approximation, one can use a Woods-Saxon distribution to estimate the nuclear charge distribution: $\rho(r) = \frac{\rho_0}{1+\exp(\frac{r-R_{WS}}{d})}$
- BW process is Sensitive to EM Field Profile
  - The photon k_T spectrum depends on the nuclear form factor $F(k) \equiv \int d^3r\, e^{i\,k\cdot r}\, \rho(r)$.
    - The lepton pair inherits the summed k_T of the photons: $p_T = k_{T1} + k_{T2}$.
  - Vary R_{WS} , d in $\rho(r)$ → predict p_T spectrum → compared to data.
  - Provides a clean **QED-based mapping** of EM field geometry in heavy nuclei.
- STAR has extracted R_{WS} and skin depth d for gold nuclei using BW p_T spectra.



STAR, *PRL* (2021)
Best fit:
$R = 6.7 \pm 0.2$ fm, $a = 0.2 \pm 0.2$ fm

Breit–Wheeler Measurement in Uranium Collisions

- Breit-Wheeler UPC analysis has been measured in Au+Au data, but as **not** been measured in U+U.

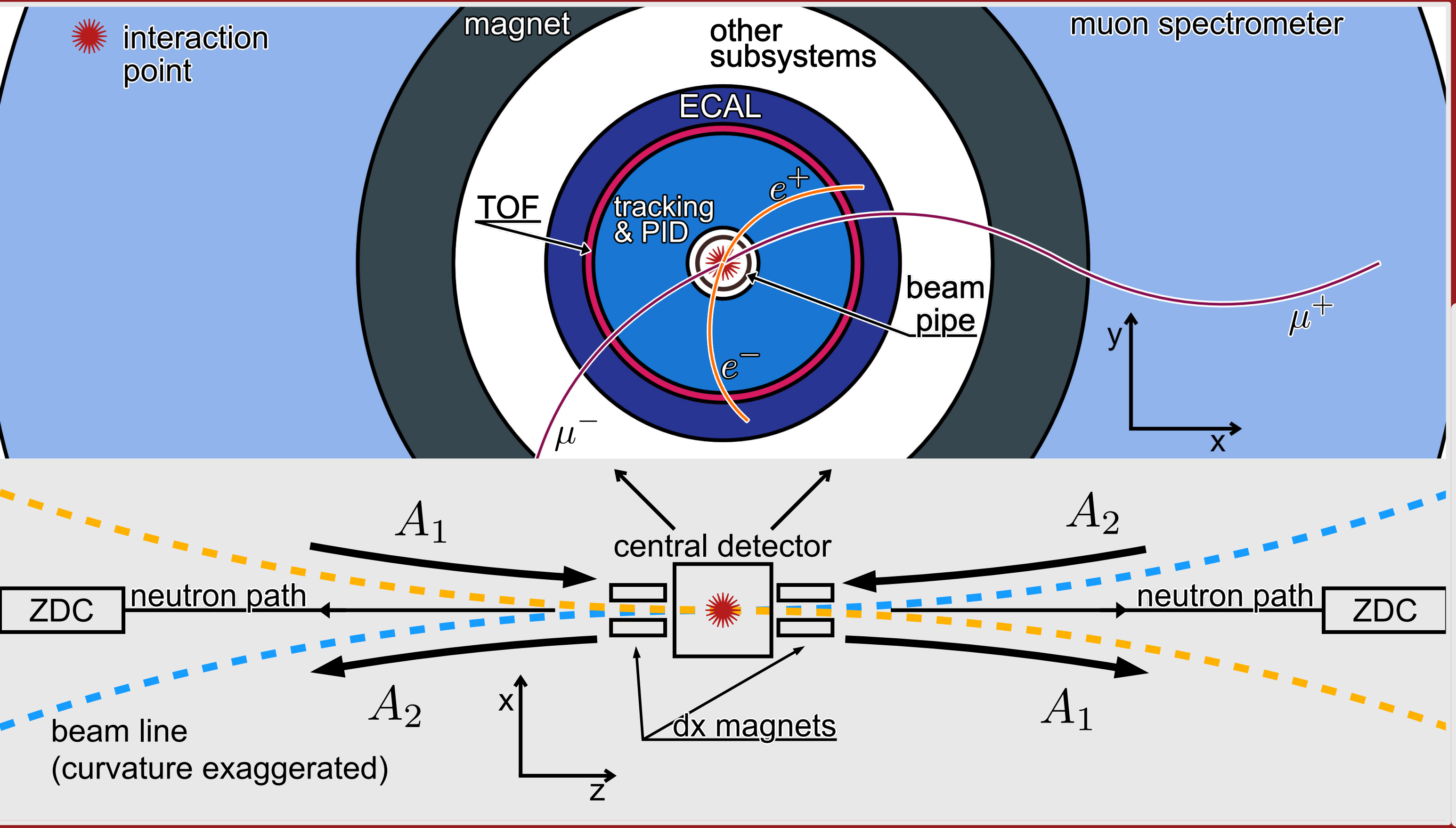
- Au is an **approximately spherical nucleus**, so we have a spherically symmetric field. This is **not** the case for uranium.

- QED calculations do **not** use a 3D form factor that accounts for the nucleus deformation.

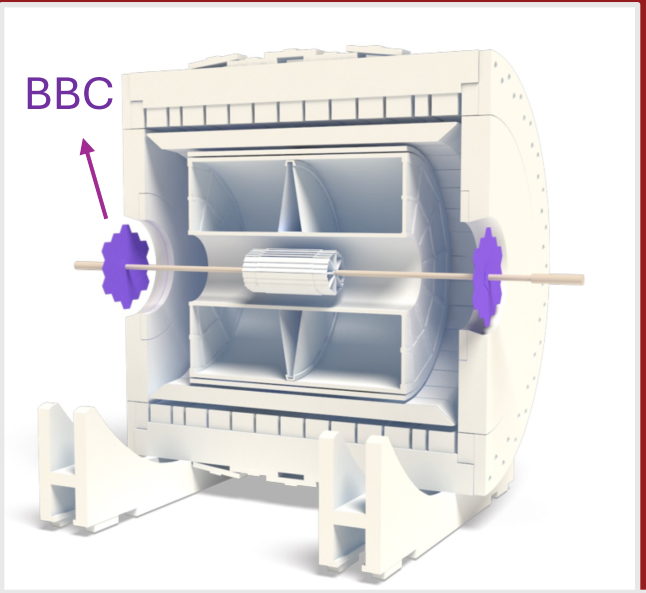
- Uranium has a prolate nucleus, and we want to test sensitivity to potential modifications in the BW cross section shape.

The STAR Detector and UPC

UPC exclusive production signatures:
Minimal hadronic break-up
Forward rapidity gap



Cross sectional and longitudinal view of the STAR detector



ZDC (Zero Degree Calorimeter): Detects forward neutrons from **Coulomb dissociation**, allowing classification of nuclear breakup (e.g., 0n0n, 1n1n) and triggering on UPC events.

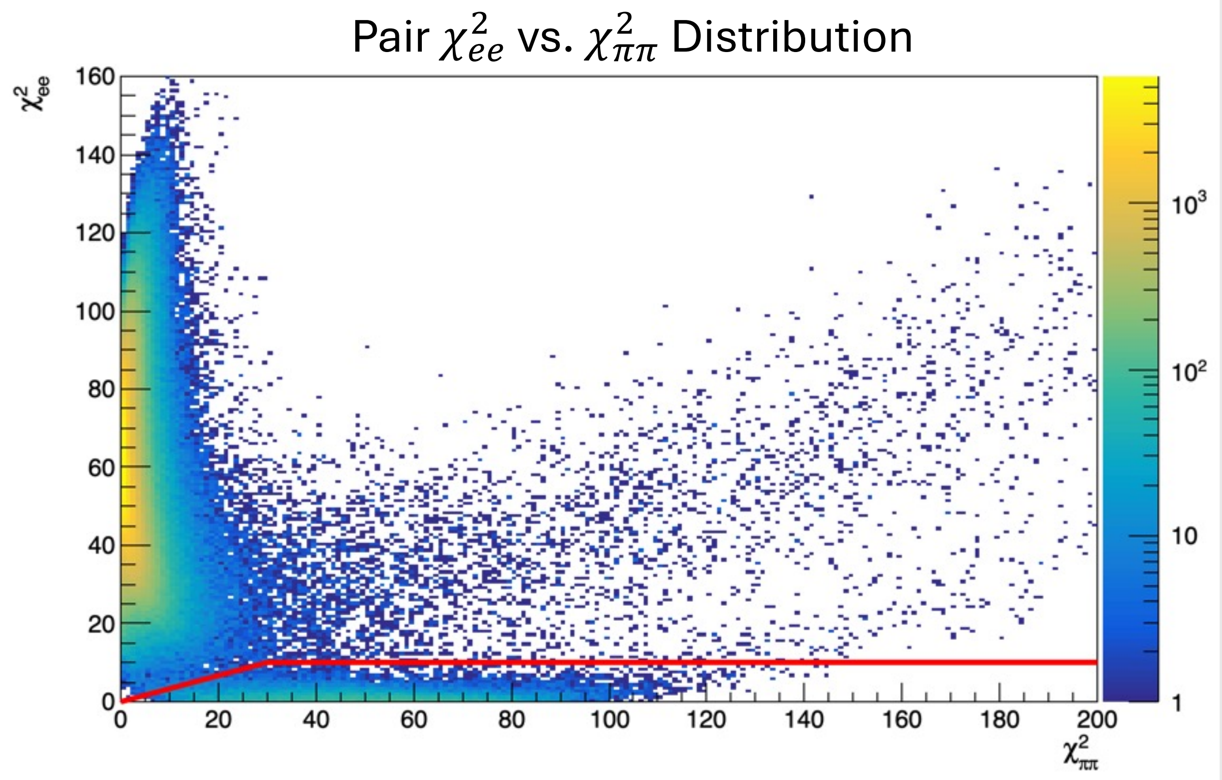
BBC (Beam-Beam Counter): Vetoes hadronic interactions by requiring **no forward activity**, ensuring the exclusivity of UPC events.

Electron Pair Selection

- Triggers and UPC Event Selections
  - Run 12 U+U at $\sqrt{s_{NN}}$ = 193 GeV
  - UPC Main, ZDC coincidence
  - $|V_z|$ < 100 cm
  - gRefMult <=4

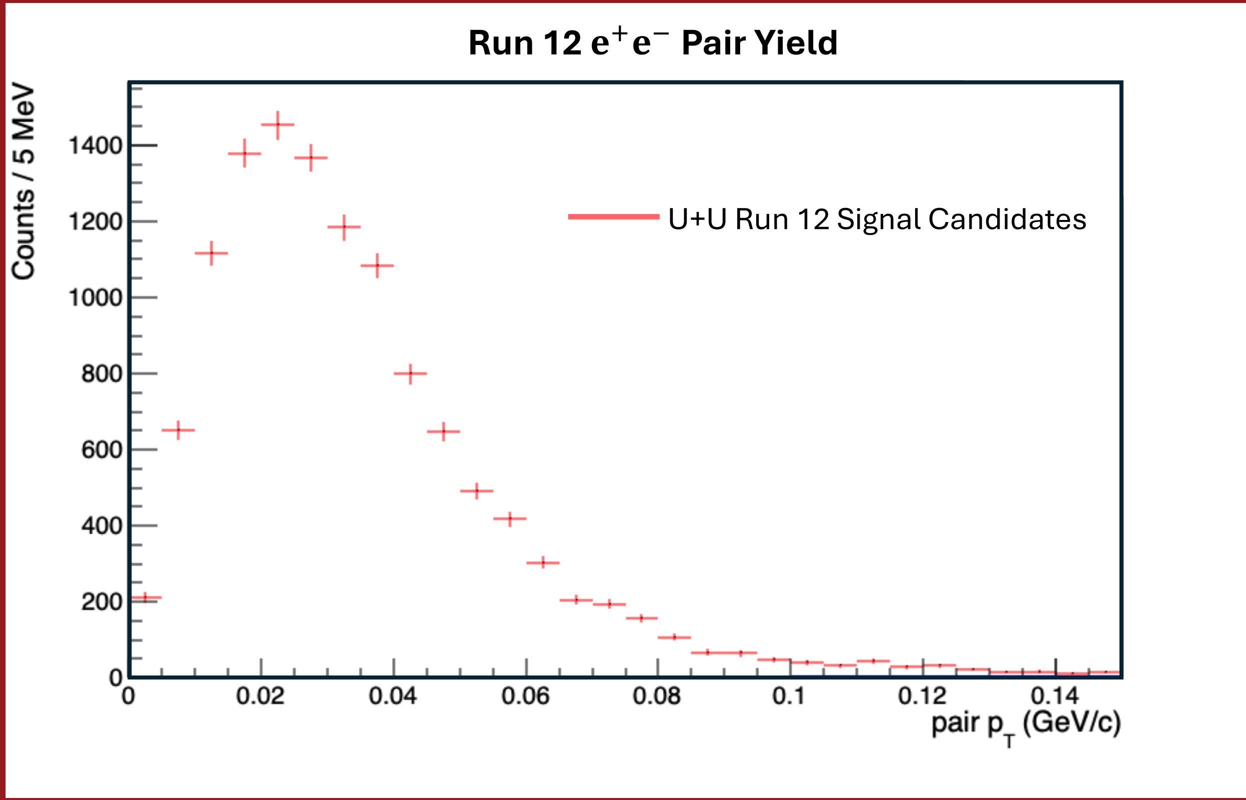
- Track Quality Cuts
  - Track p_T > 0.2 GeV
  - NHitsDedx > 15
  - DCA < 1cm

- PID and Signal Candidate
  - $\chi^2_{ee} = n\sigma^2_{e1} + n\sigma^2_{e2} < 10$
  - $\chi^2_{\pi\pi} > 3\ \chi^2_{ee}$- pions are primary source of background
  - $\Delta\ \Delta\mathrm{TOF}$ < 0.5ns

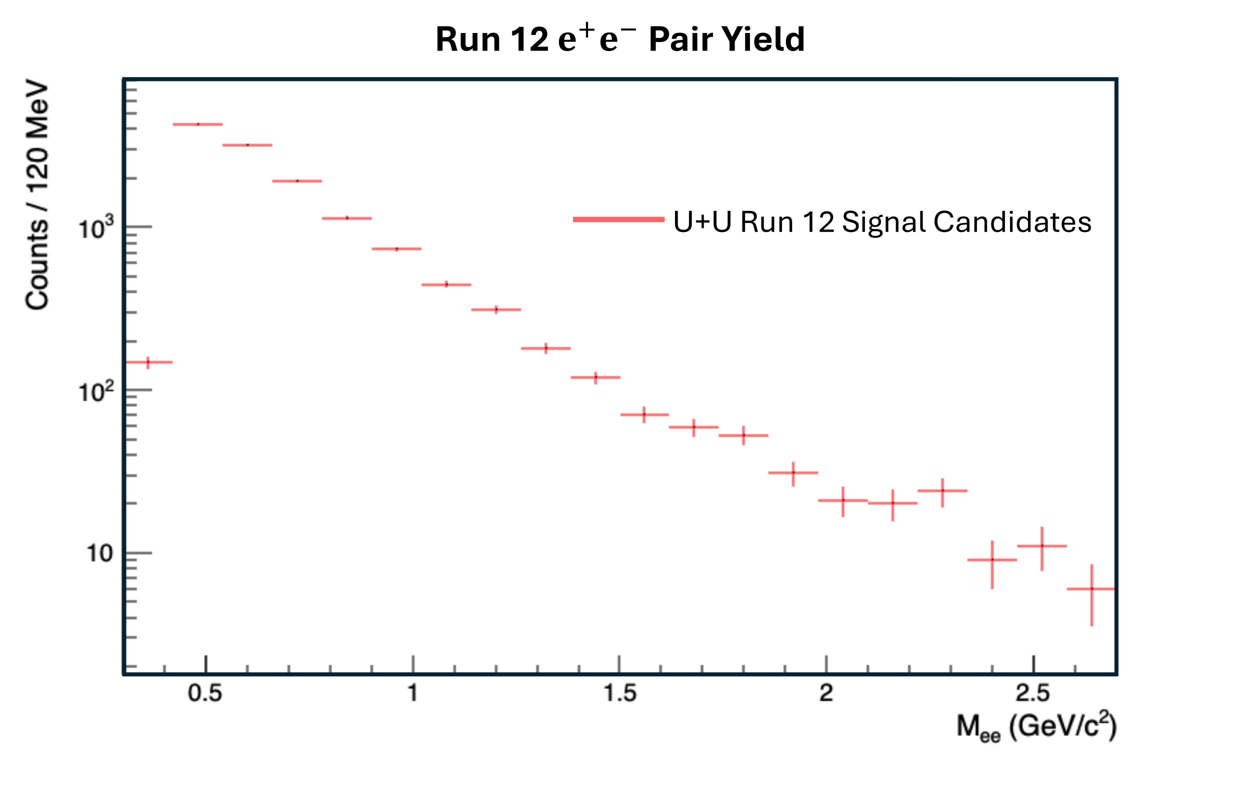


Electron Pair Signal Extraction

Excess production at low pair p_T



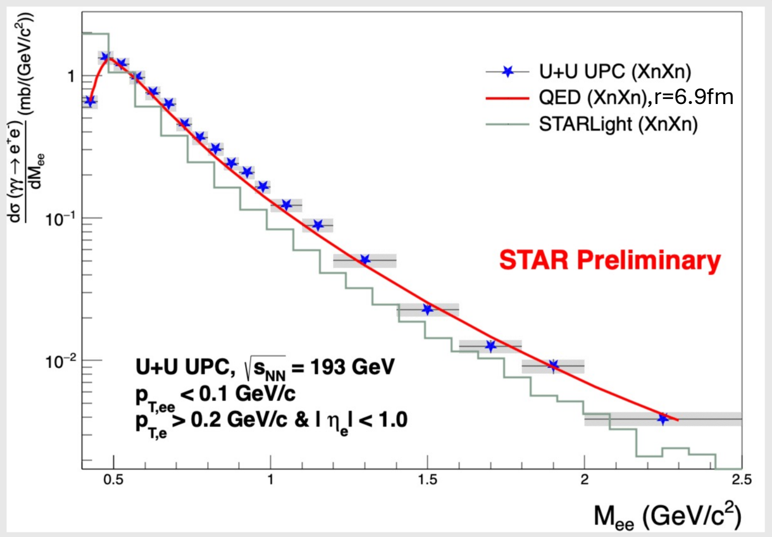
Broad continuum in pair invariant mass

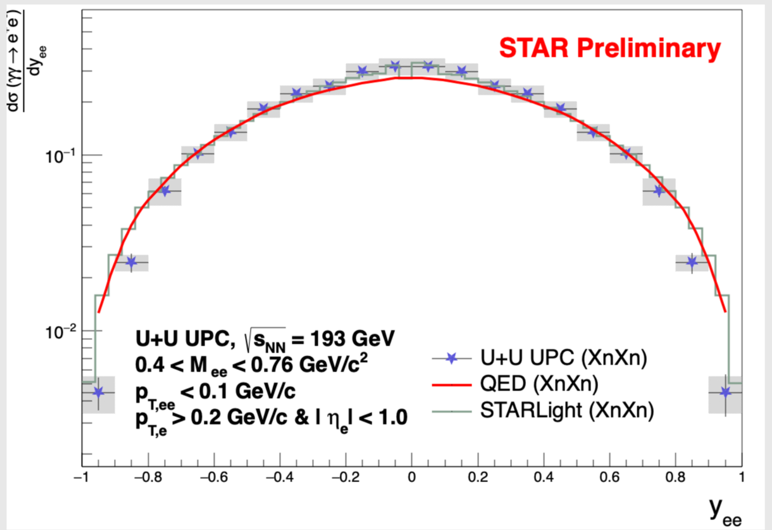


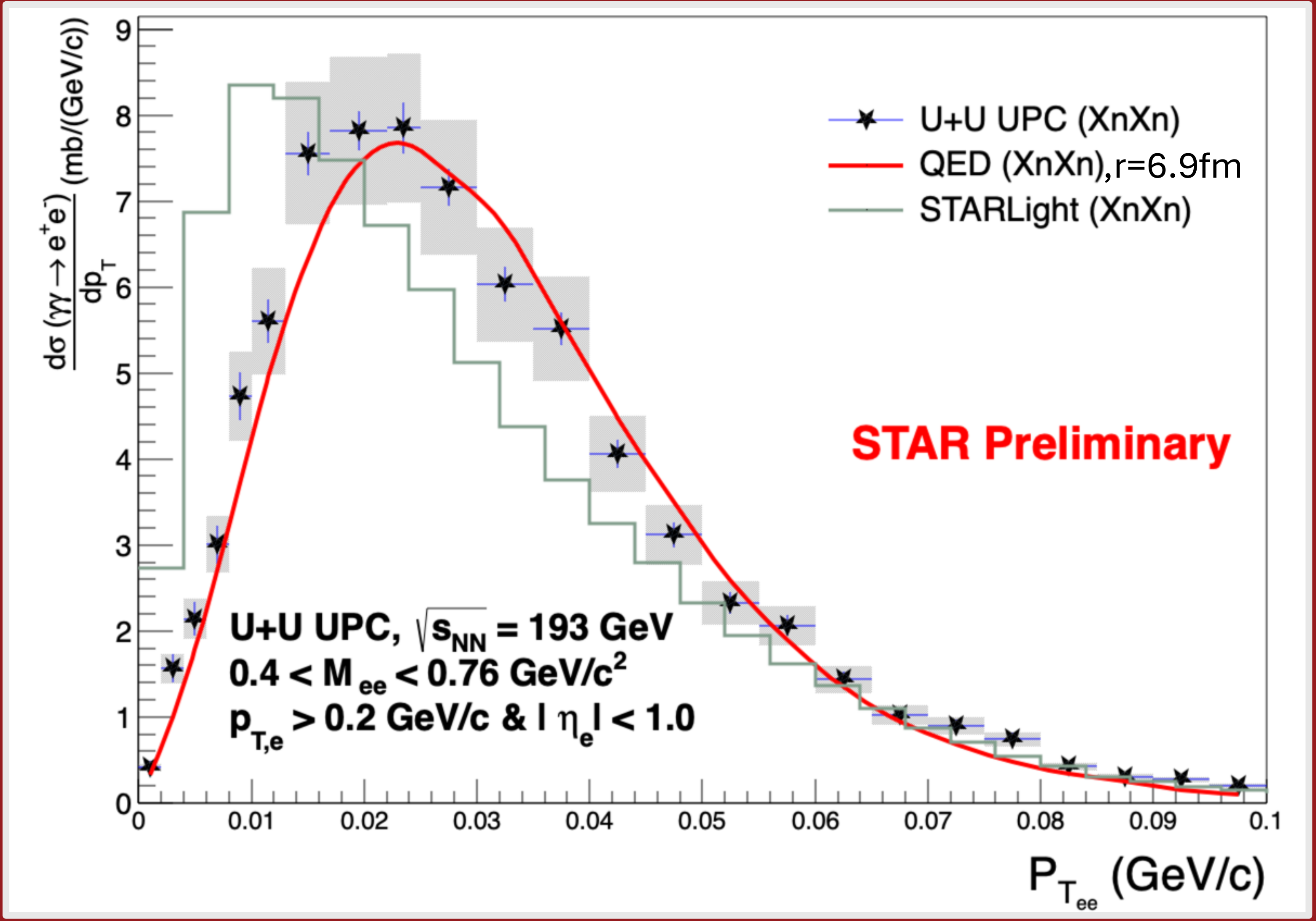
Differential Cross Sections of Breit–Wheeler Process in U+U UPC

- QED accurately describes both the mass and rapidity differential cross section and the photon energy spectrum from data.

- STARLight: hard sphere geometry.
- **QED: Spherical Woods-Saxon, radius=6.9fm.**



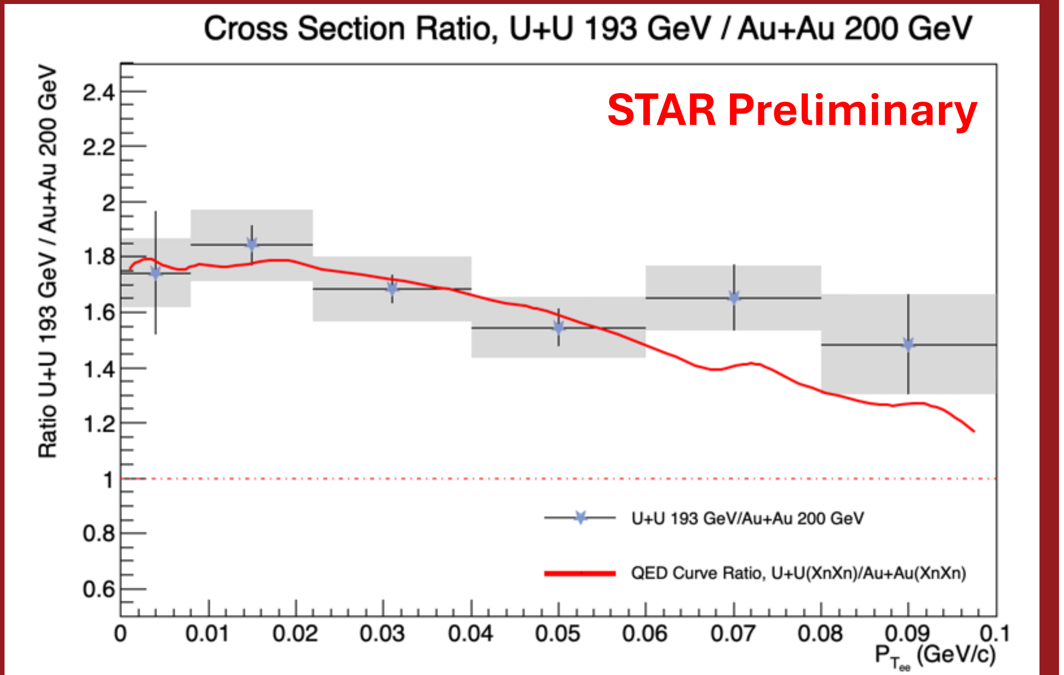


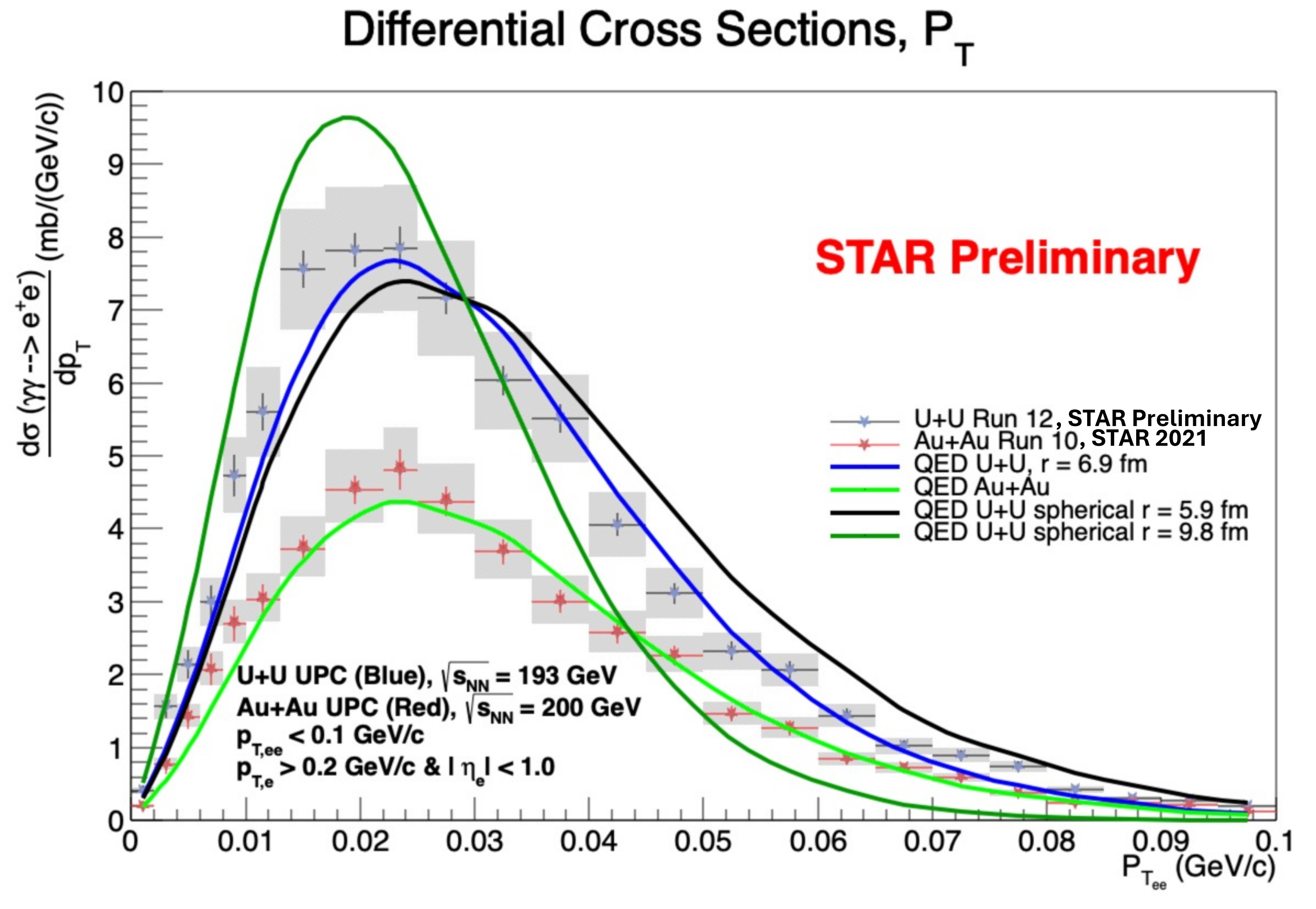


Takeaways: Nuclear Shape Effects in Photon-Photon Collisions

- **QED calculations assume a spherical, Woods-Saxon charge distribution.**
- Spherical uranium (semi-major or semi-minor radius) fails to describe the measured p_T distribution.
- **Accurate nuclear shape modeling is essential for photon-photon processes.**

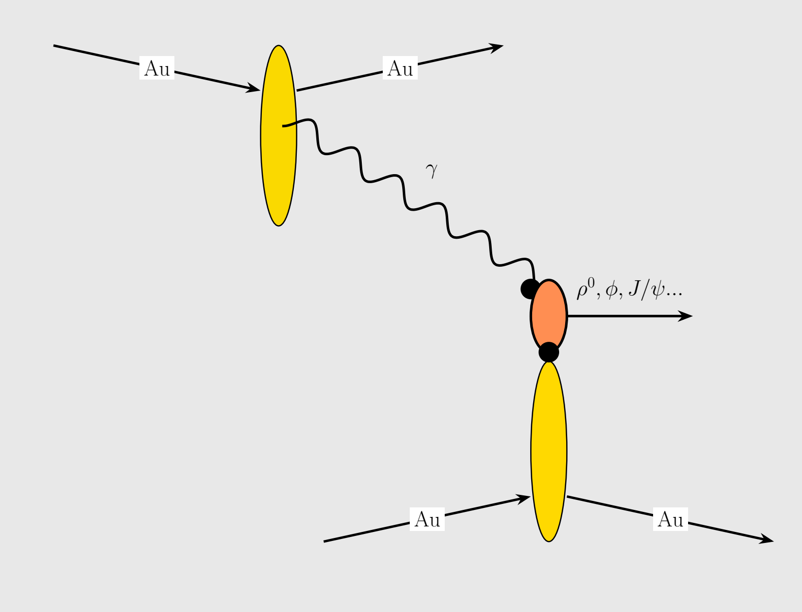
Higher-order azimuthal correlations like $\cos(n\Delta\phi)$ in U+U collisions may exhibit enhanced sensitivity to nuclear deformation compared to the p_T spectrum alone.





Exclusive Vector Meson Production in UPC

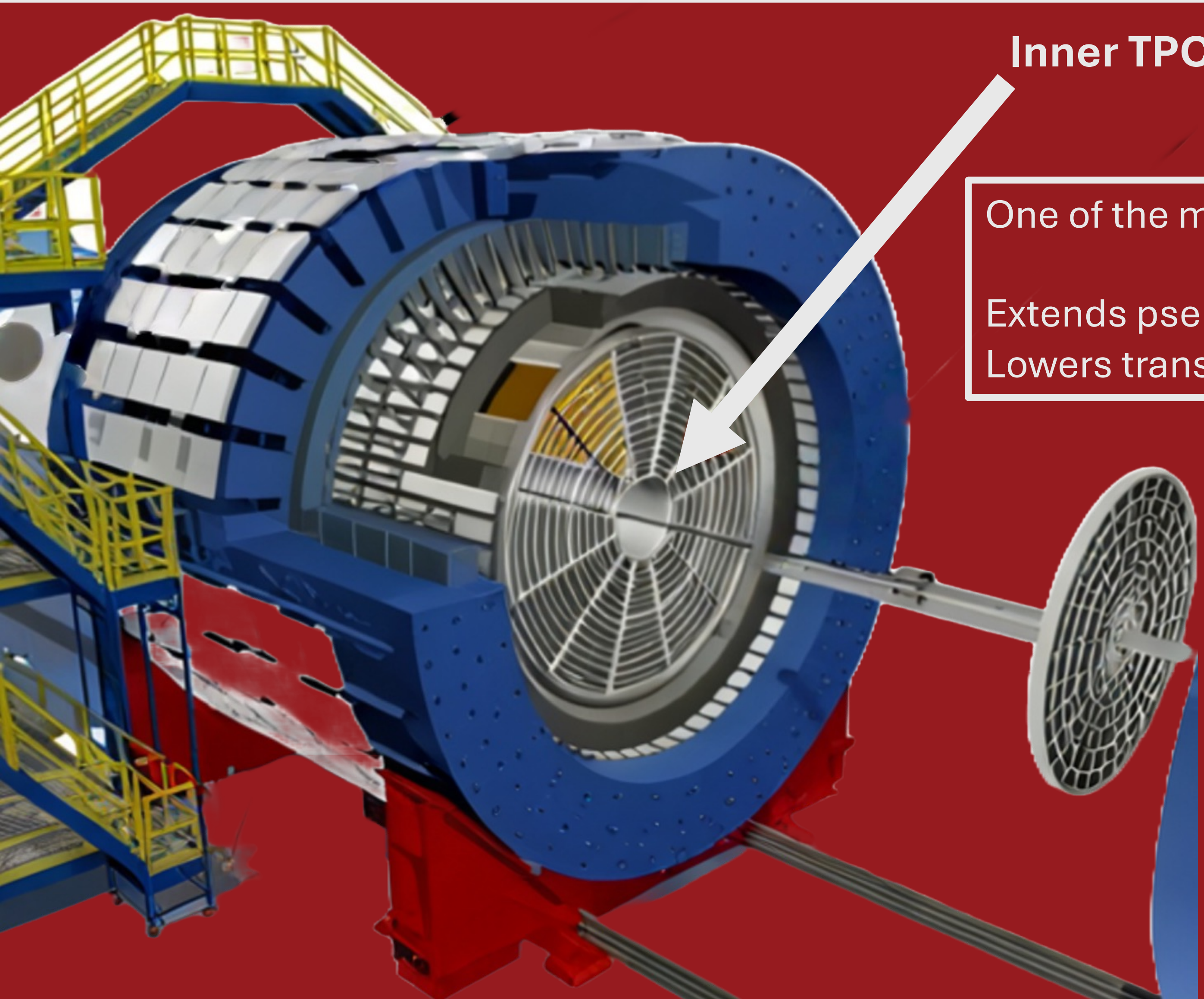
- $\gamma A \to VA$ process
  - A quasi-real photon from the Lorentz-contracted EM field fluctuates into a quark–antiquark pair.
  - This color dipole interacts with the nucleus via a colorless 2-gluon exchange (Pomeron).
  - The exclusive interaction produces a vector meson: $\rho, \boldsymbol{\phi}, \mathrm{J}/\psi, \Upsilon, \ldots$



Coherent Production:	Incoherent Production:
Color dipole couples to entire nucleus	Color dipole couples to individual nucleon
Low vector meson transverse momentum ~50MeV	Vector Meson transverse momentum ~ 400MeV
Probe the averaged gluon density	Probe local gluon density fluctuation

We present the first measurement of UPC ϕ photoproduction at STAR via $\boldsymbol{\phi \to K^+K^-}$.

The iTPC Upgrade: Enabling Low-p_T Kaon Tracking at STAR



One of the major upgrades in STAR BES-II: the Inner TPC (iTPC).

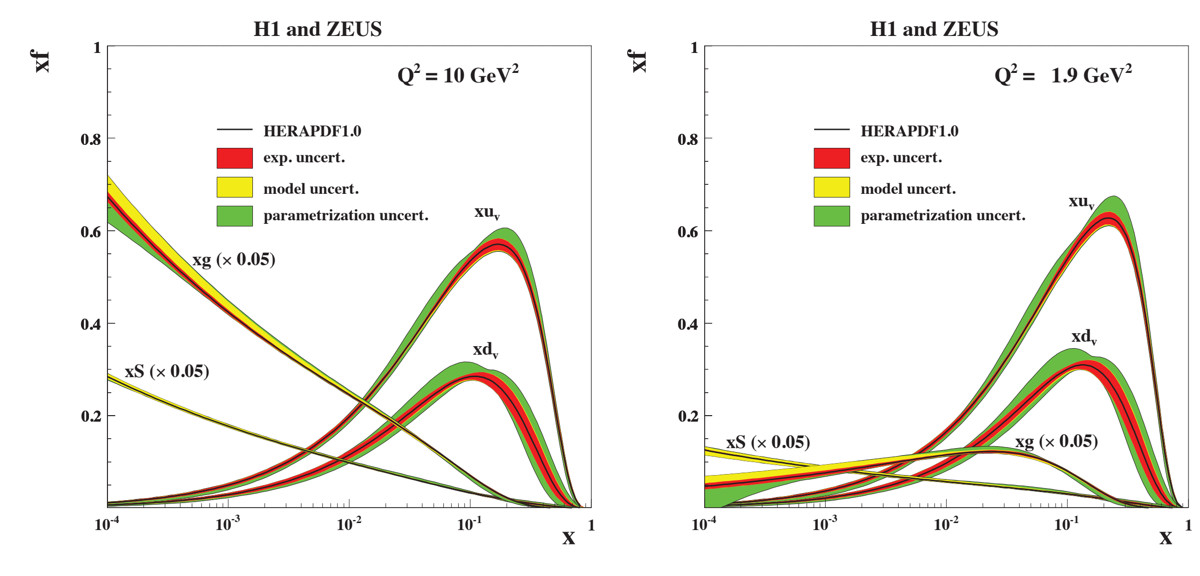
Extends pseudorapidity coverage: $|\eta| < 1.0 \rightarrow |\eta| < 1.5$.
Lowers transverse momentum threshold: p_T $125 \ \rightarrow 60$ MeV/c.

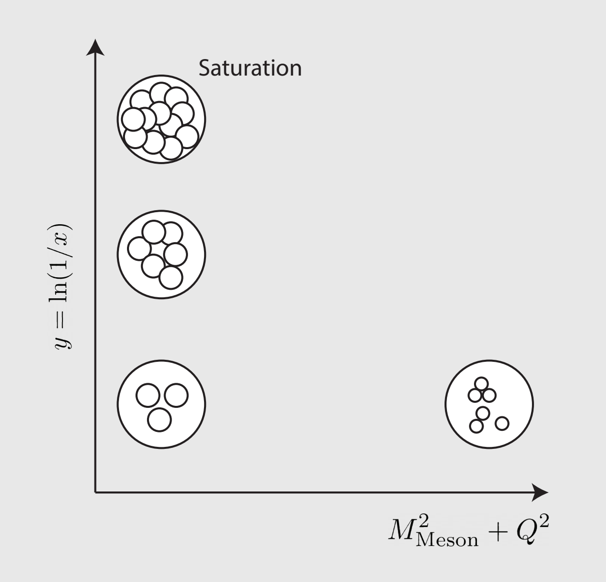
The **iTPC upgrade** greatly enhances tracking of **low-p_T kaons** (~100 MeV).
This analysis uses the first fully operational dataset from the upgraded iTPC.

Vector Meson as a Probe for Gluon Saturation

- Gluon Saturation:
  - **VM production is mediated by photon-gluon fusion,** making it directly sensitive to the gluon distribution in the target nucleus.
  - At small Bjorken-x, the gluon density grows rapidly, and non-linear effects set in — VM production can probe this regime.
  - **Suppression or modification** of cross sections may signal the onset of gluon saturation.

- ϕ vs. other vector mesons:
  - Larger dipole size than the J/ψ which enhances ϕ's sensitivity to saturation effects.
  - Larger invariant mass (1019 MeV) compared to the ρ^0 meson (770 MeV), enables more reliable perturbative QCD calculations.





H1 and ZEUS, *JHEP* (2010)
electron-proton DIS nucleon structure PDF at HERA

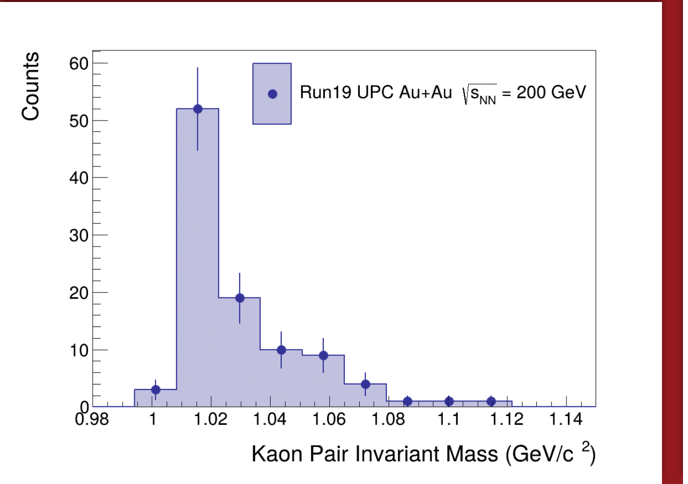
Event Selection and Signal Extraction

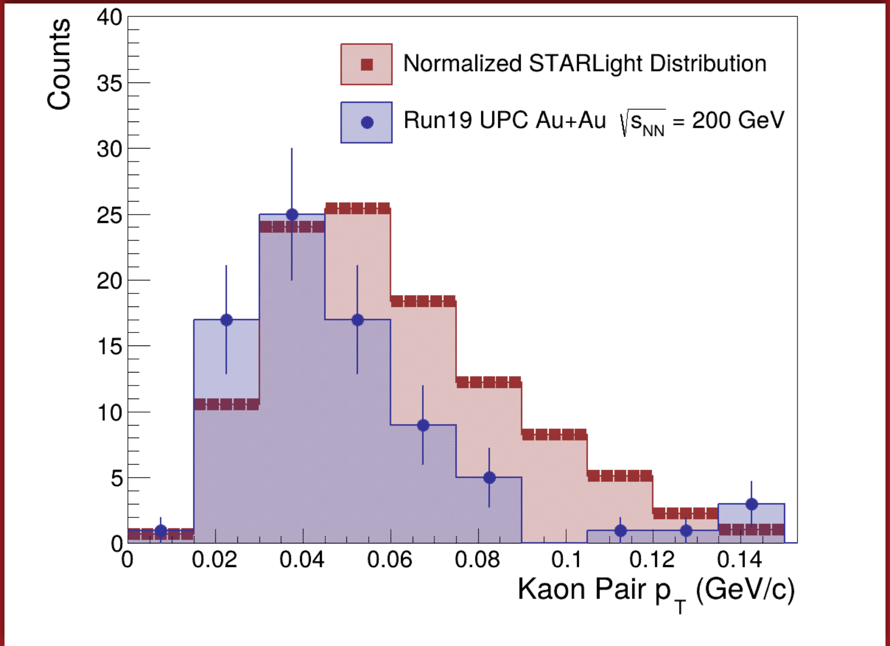
- Event Selection
  - Quality Cuts:
    - |Vz| < 50
  - UPC Selection
    - BBC Veto

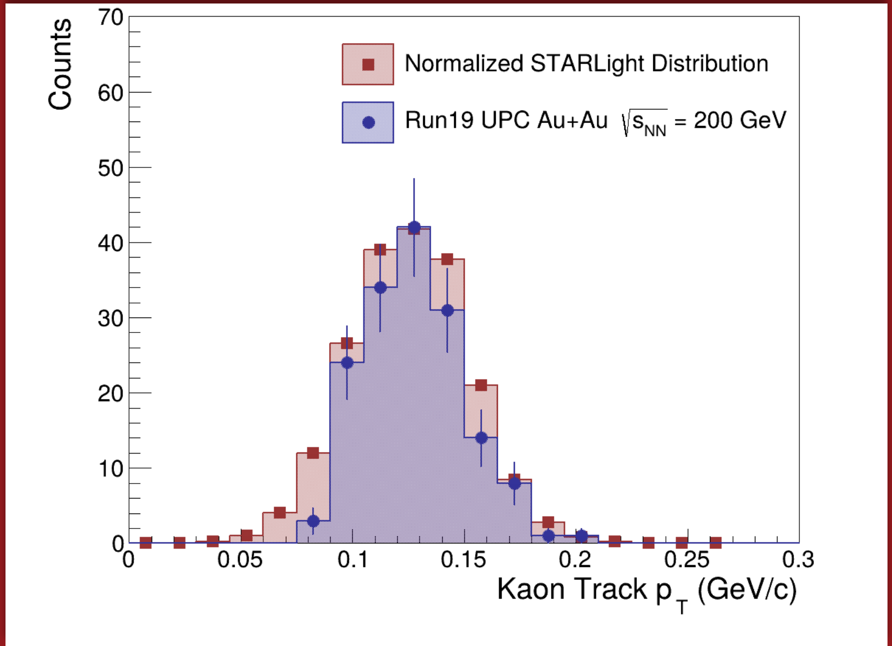
- Pair selection
  - Kaon Selection
    - TPC $\frac{dE}{dx}$, $\chi^2_{KK} \equiv N\sigma^2_{k1} + N\sigma^2_{k2} < 20$
  - Kinematics Selection
    - K^+K^- Pair p_T < 150 MeV- isolate coherent pair

Number of Total Coherent Pair: 79

STARLight distributions are normalized to have the same peak value as data.







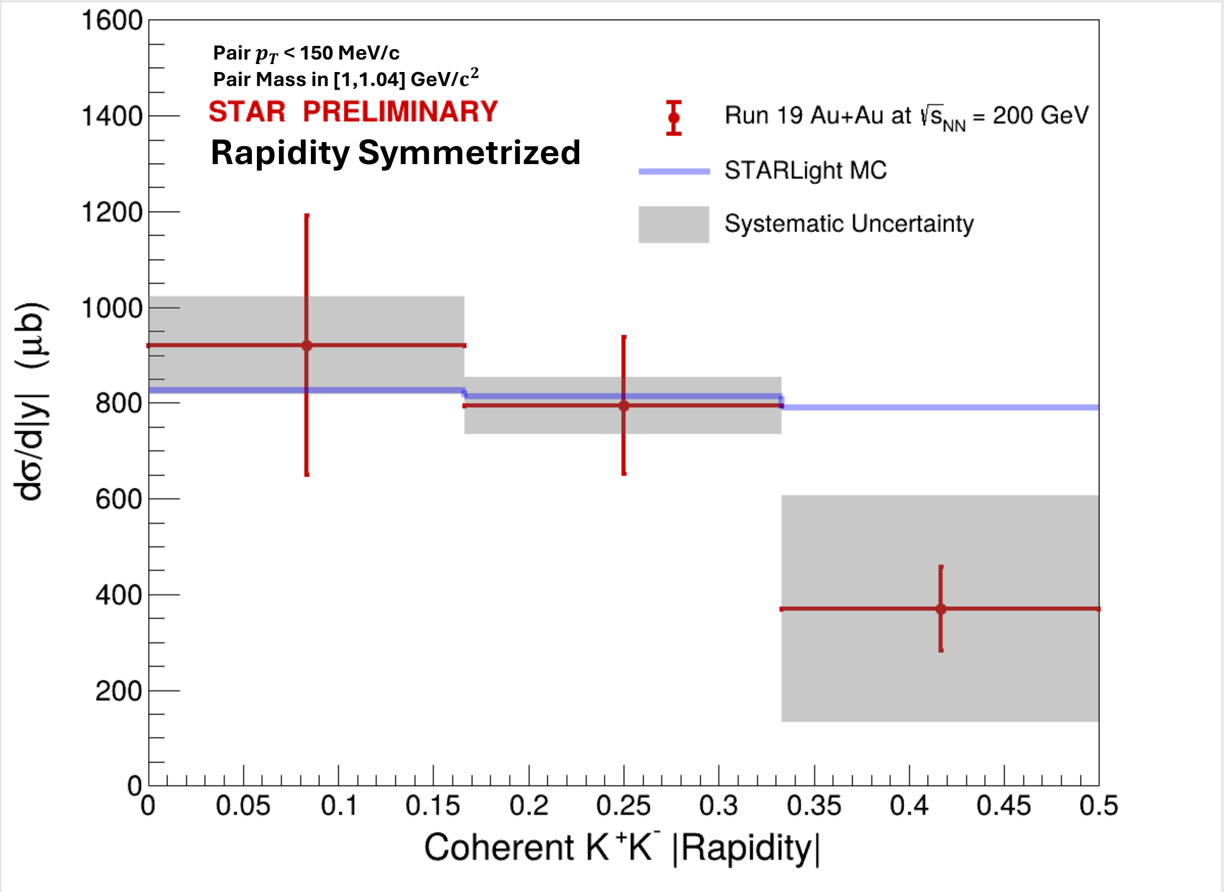
Differential Cross Section Preliminary Result

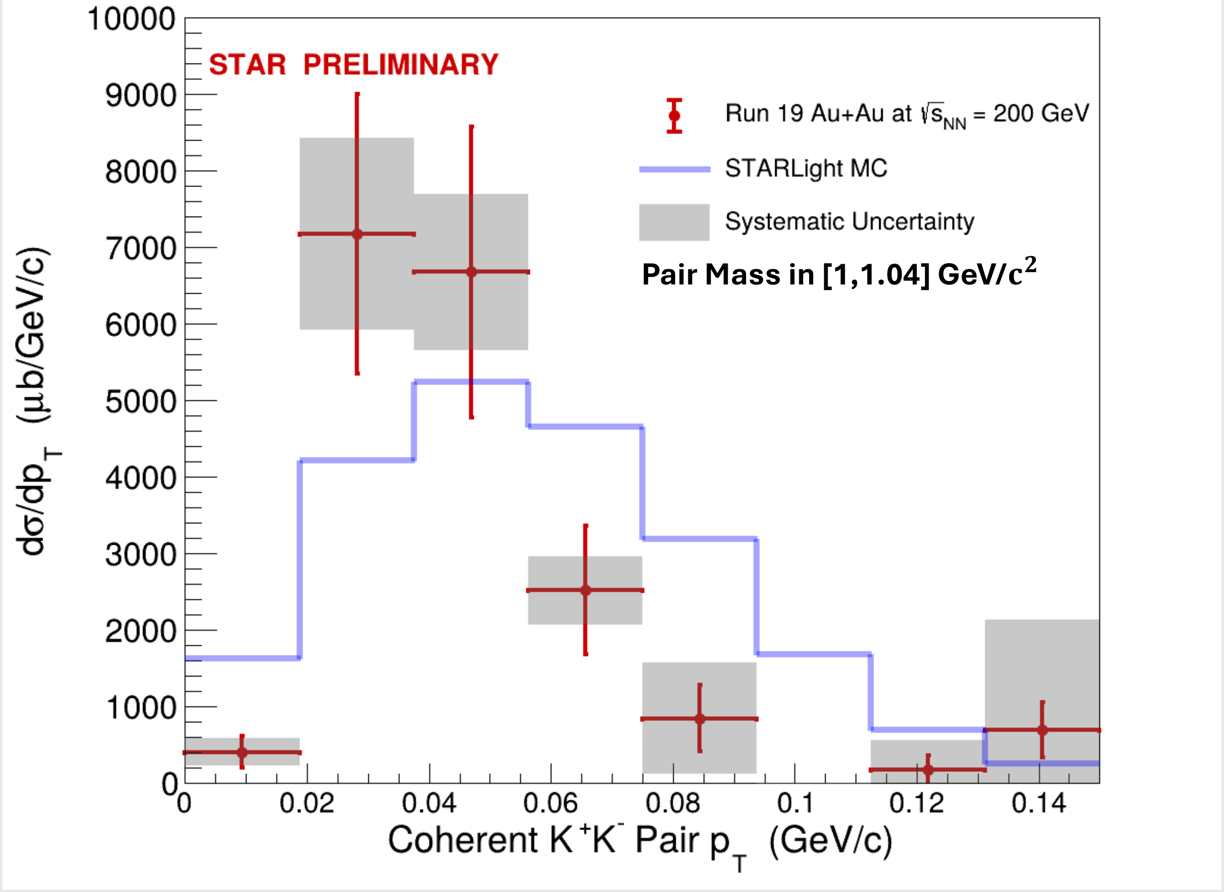
$$\sigma = \frac{N}{L_{\text{total}} \cdot \epsilon_{\text{tracking}} \cdot \epsilon_{\text{PID}} \cdot \epsilon_{\text{kinematic cut}} \cdot \epsilon_{\text{BBC Veto}} \cdot \epsilon_{\text{Vz cut}} \cdot \epsilon_{\text{Trigger}}}$$

$$N = 79, \qquad L_{total} = 13.6\ \mu b^{-1}$$

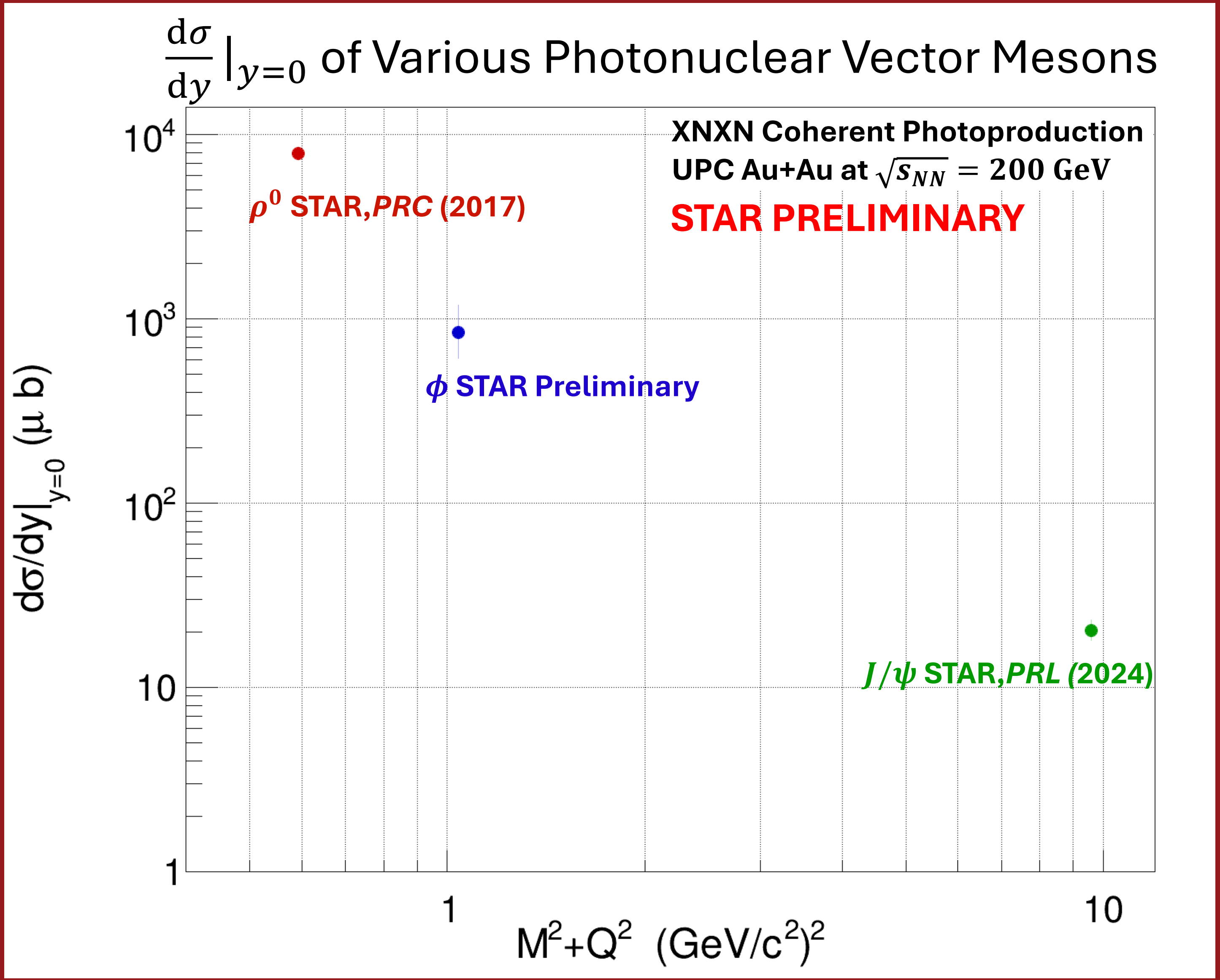
$$W_{\gamma N}|_{y=0} \approx 14.3\ \text{GeV},\ x \equiv \frac{M_V^2}{W_{\gamma N}^2} \approx 0.005$$

STARLight distributions are shown directly from Monte Carlo output.





Cross Section Vector Meson Mass Dependence



- Future comparisons with shadowing and saturation models will test the mass dependence of coherent cross sections and probe nuclear gluon distributions at different scales.

Summary and Outlook

- **First differential cross section measurement of UPC photonuclear ϕ meson at STAR.**
  - Future work will compare the measured ϕ meson cross section with theoretical predictions for vector mesons of varying masses to explore mass-dependent nuclear effects.

- Run23 production at STAR may yield **~1000× more coherent** ϕ events:
  - More differential measurements:
    - ZDC class dependence, resolving photon energy ambiguity
    - Precise transverse momentum spectrum

- Incoherent ϕmeasurements:
  - Sensitive to **gluon fluctuations and hotspots**
  - **Ratio** of coherent/incoherent yields: key observable for **gluon saturation dynamics**

Citations

- J.D. Brandenburg *et al.*, *Rep. Prog. Phys.* **86** (2023) 083901, https://doi.org/10.1088/1361-6633/acdae4
- **STAR Collaboration**, J. Adam *et al.*, *Phys. Rev. Lett.* **127** (2021) 052302, https://doi.org/10.1103/PhysRevLett.127.052302
- **H1 Collaboration**, F.D. Aaron *et al.*, *JHEP* **01** (2010) 109, https://doi.org/10.1007/JHEP01(2010)109
- **STAR Collaboration**, M.I. Abdulhamid *et al.*, *Phys. Rev. Lett.* **133** (2024) 052301, https://doi.org/10.1103/PhysRevLett.133.052301

Back-up

- Full rapidity results