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

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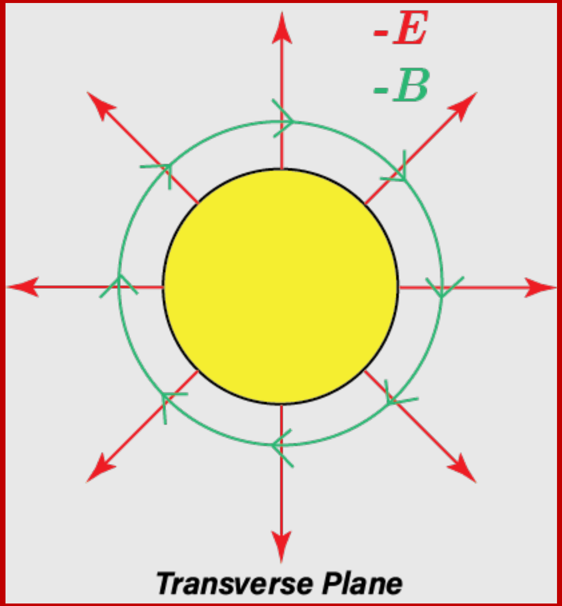
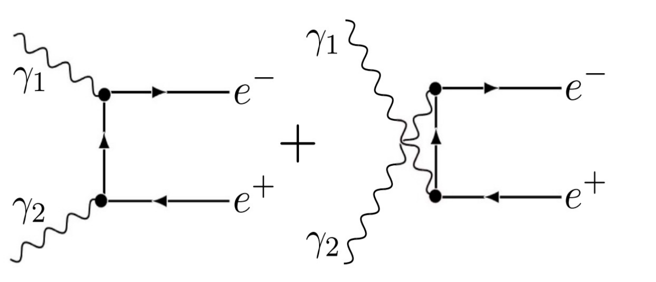
Breit-Wheeler Pair Production in Strong Electromagnetic Fields

- 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.

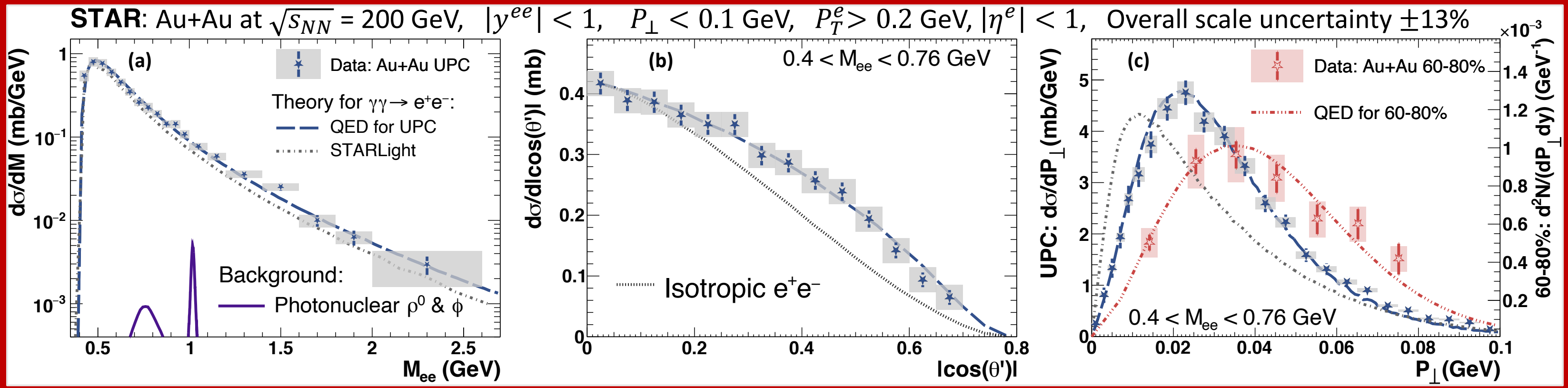




t and u channel of BW Process
(Brandenburg et al., 2023)

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.



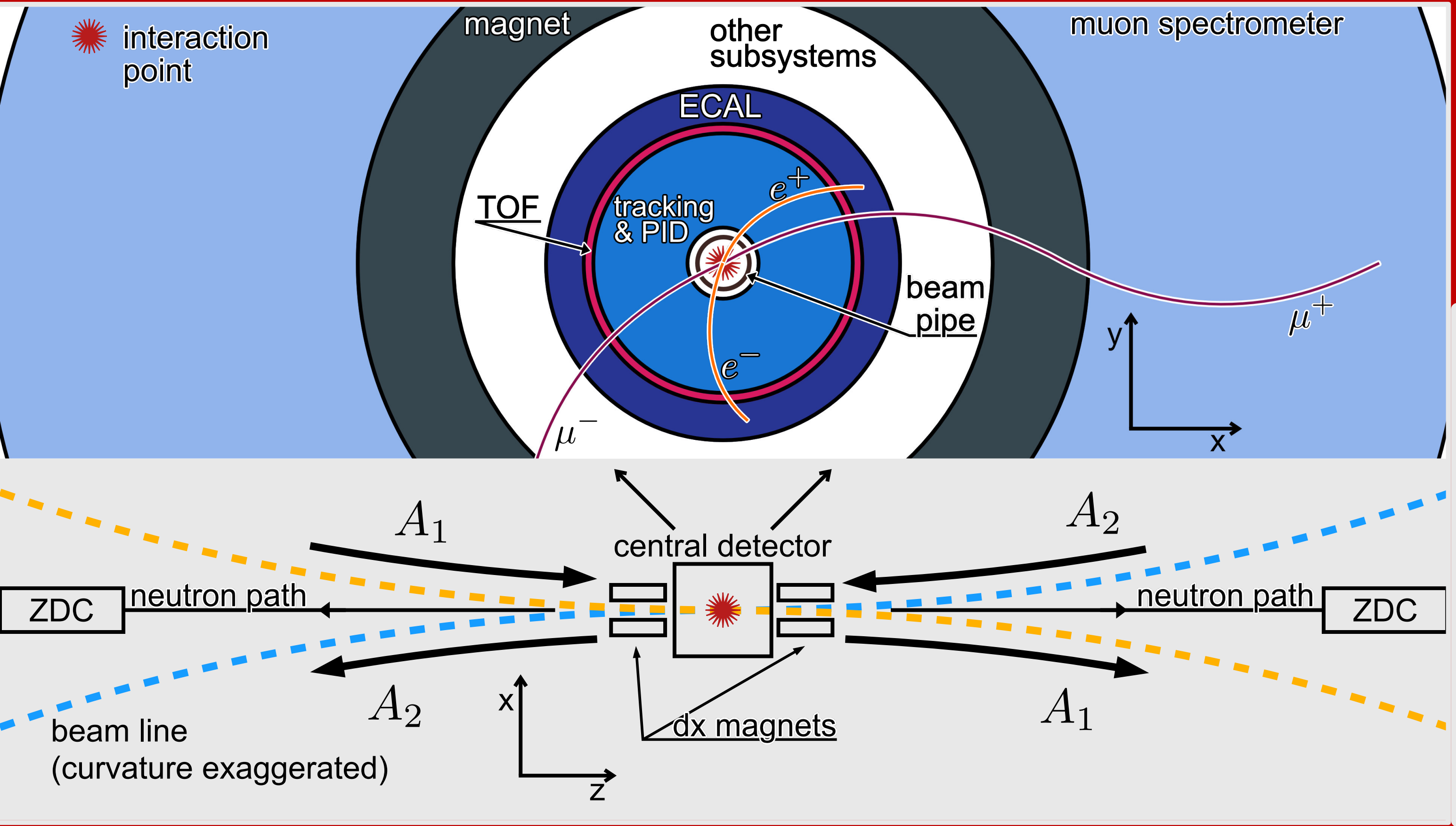
Adam et al. (2021)
Best fit:
$R = 6.7 \pm 0.2$ fm, $a = 0.2 \pm 0.2$ fm

Breit–Wheeler Measurement in Uranium Collisions

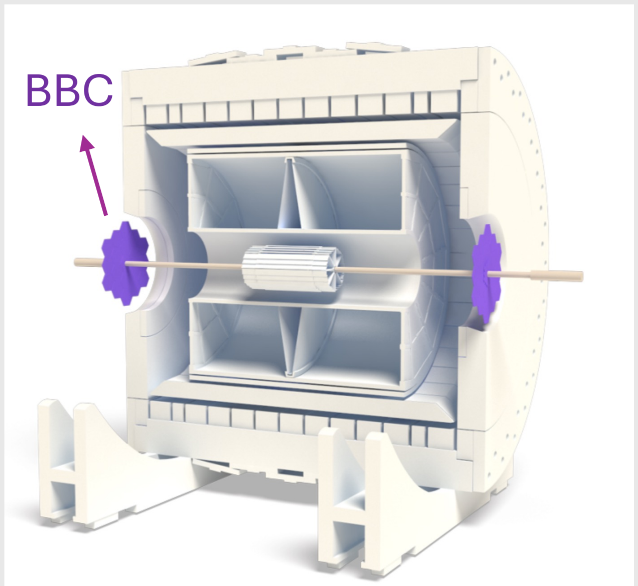
- Breit-Wheller UPC analysis has been published in Au+Au data, but as **not** been published in U+U.
- Au is an approximately spherical nucleus, so we have a spherically symmetric field. This is not the case for uranium.
- QED calculations do **not** use a 3D form factor that accounts for the nucleus 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



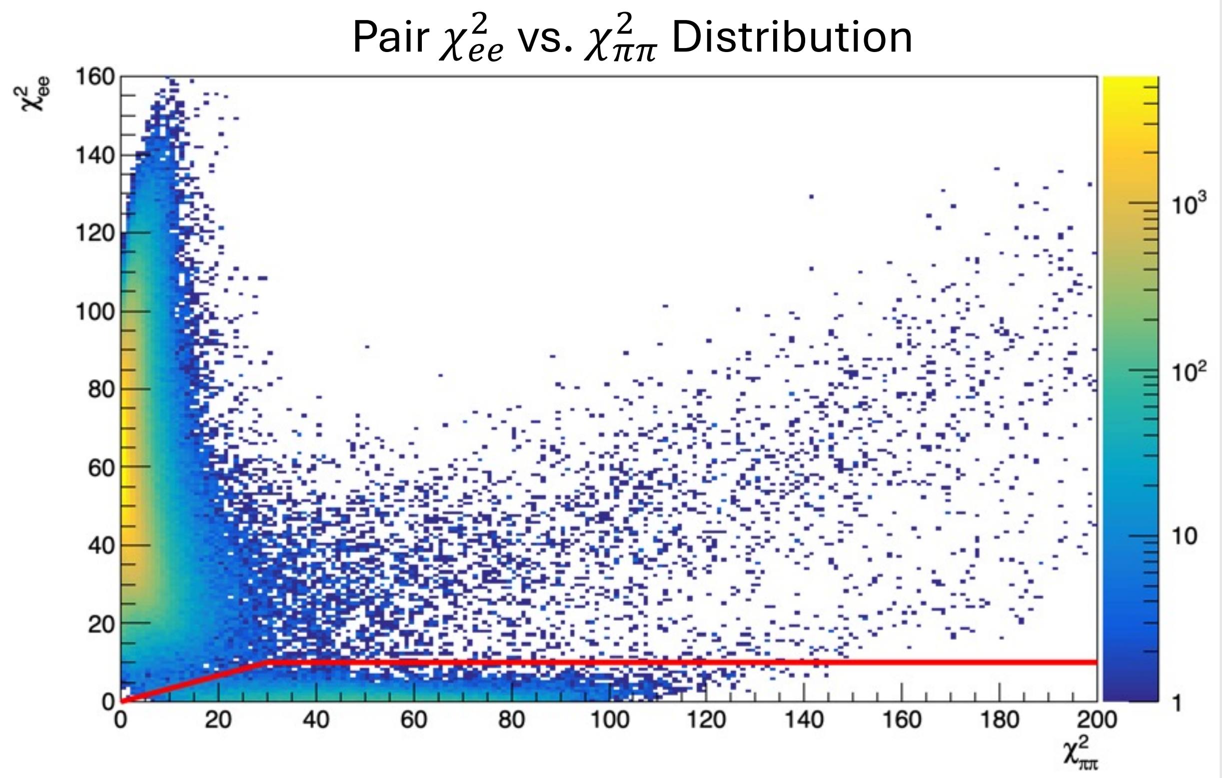
ZDC (Zero Degree Calorimeter): Detects forward neutrons from **Coulomb dissociation**, allowing classification of nuclear breakup (e.g., 0n0n, 1n1n) and triggering on UPC events.

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

Electron Pair Selection

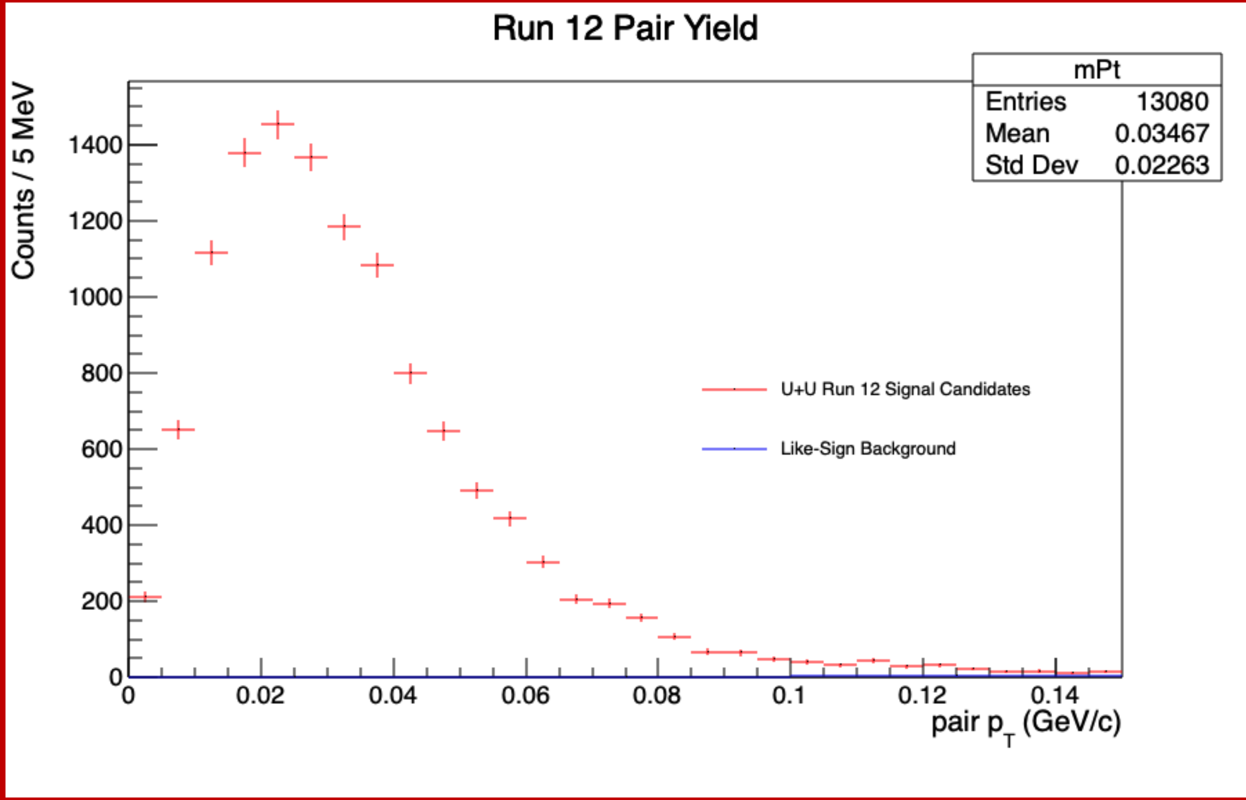
- Triggers and UPC Event Selections
  - Run 12 U+U at $\sqrt{s_{NN}}$ = 193 GeV
  - UPC Main, ZDC coincidence
  - $|V_z|$ < 100 cm
  - gRefMult <=4
- Track Quality Cuts
  - Track p_T > 0.2 GeV
  - NHitsDedx > 15 & NHitsFit > 10
  - DCA < 1

- 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
  - $\Delta\ \Delta$TOF < 0.5ns

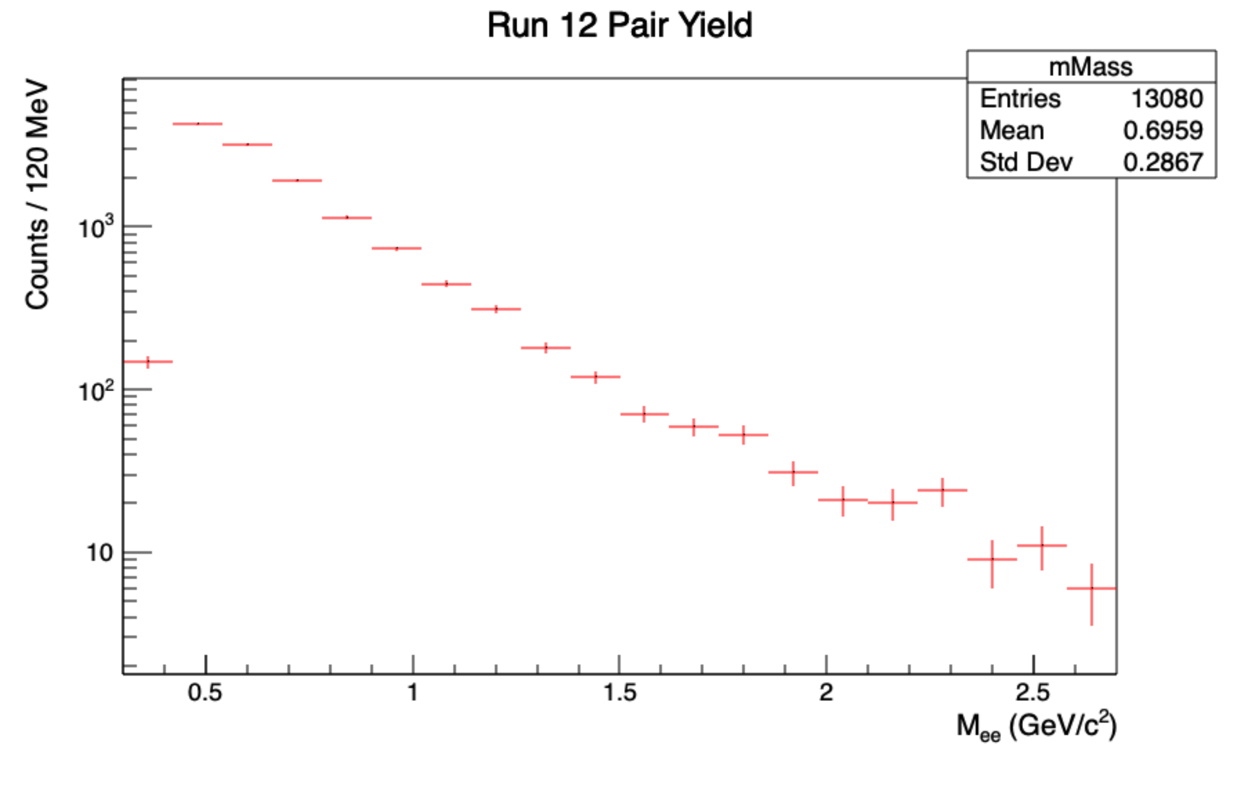


Electron Pair Signal Extraction

Excess production at low pair p_T



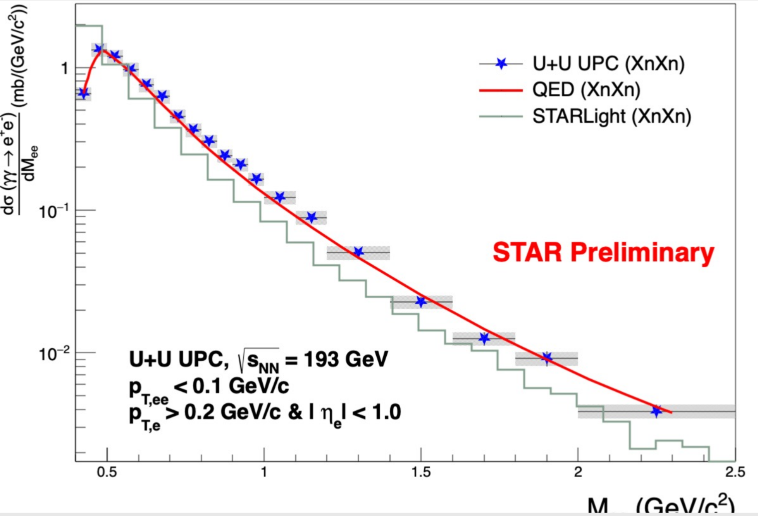
Broad continuum in pair invariant mass

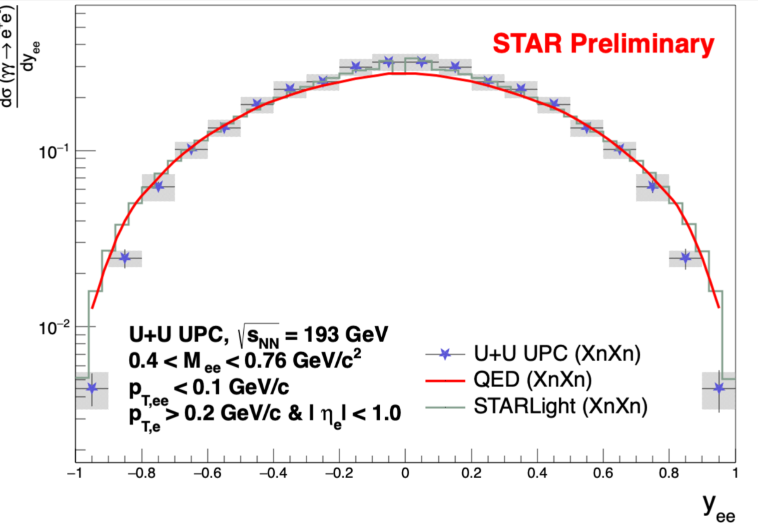


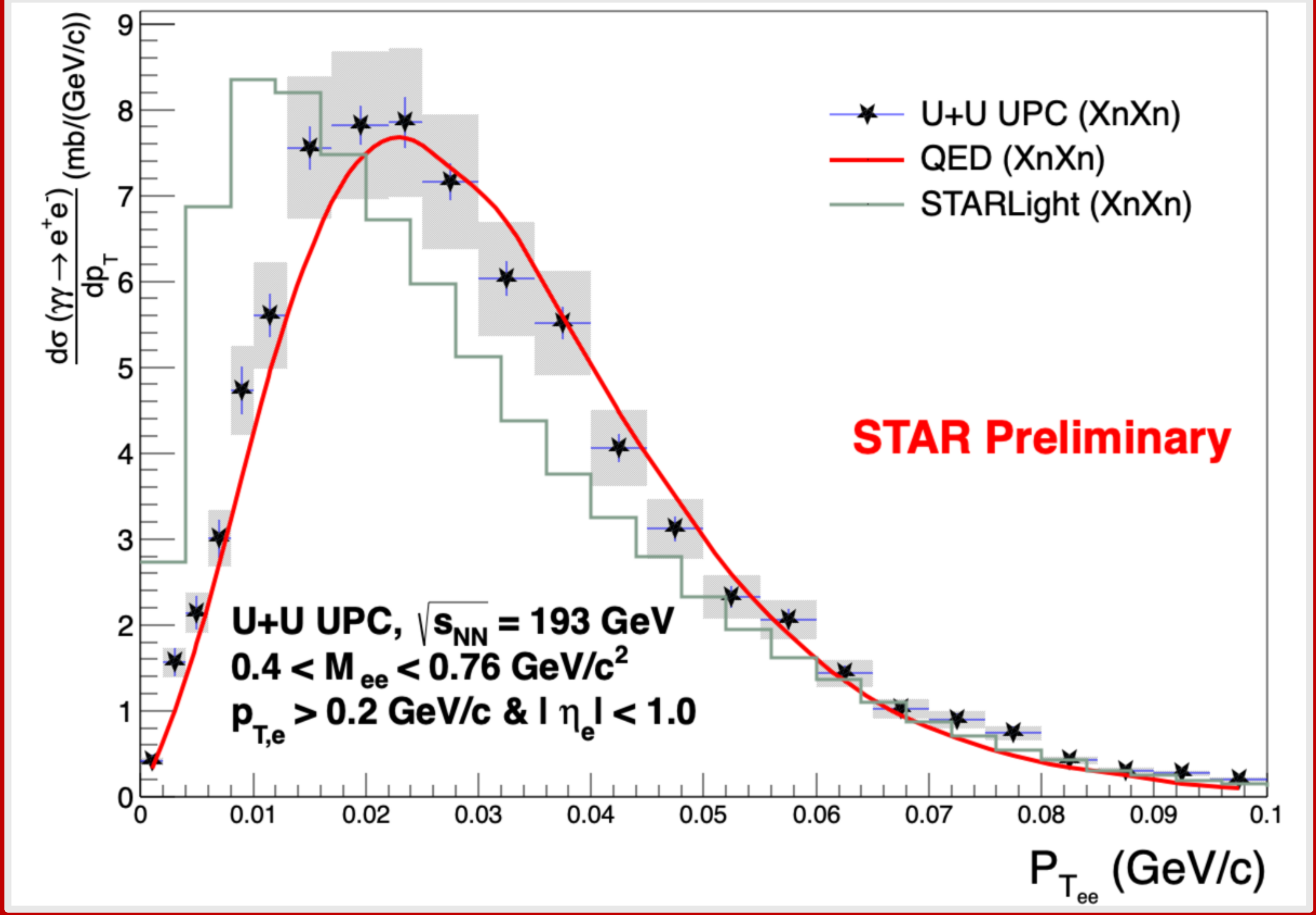
Differential Cross Sections of Breit–Wheeler Process in U+U UPC

- QED accurately describes both the mass and rapidity differential cross section and the photon energy spectrum, as evidenced by the observed mass/rapidity distribution shape.

- STARLight: hard sphere geometry.





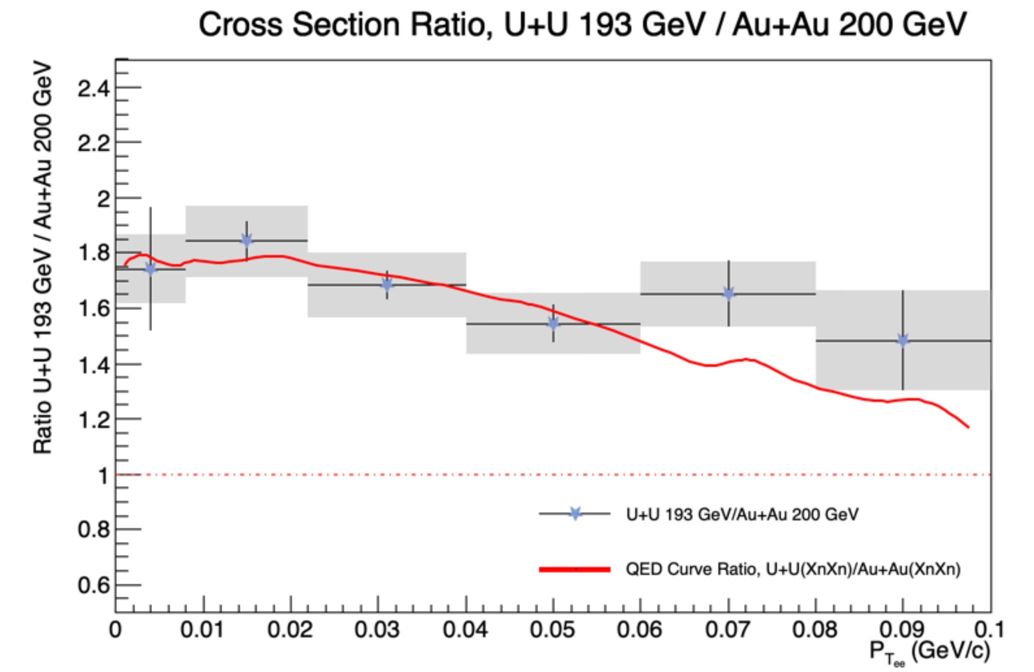


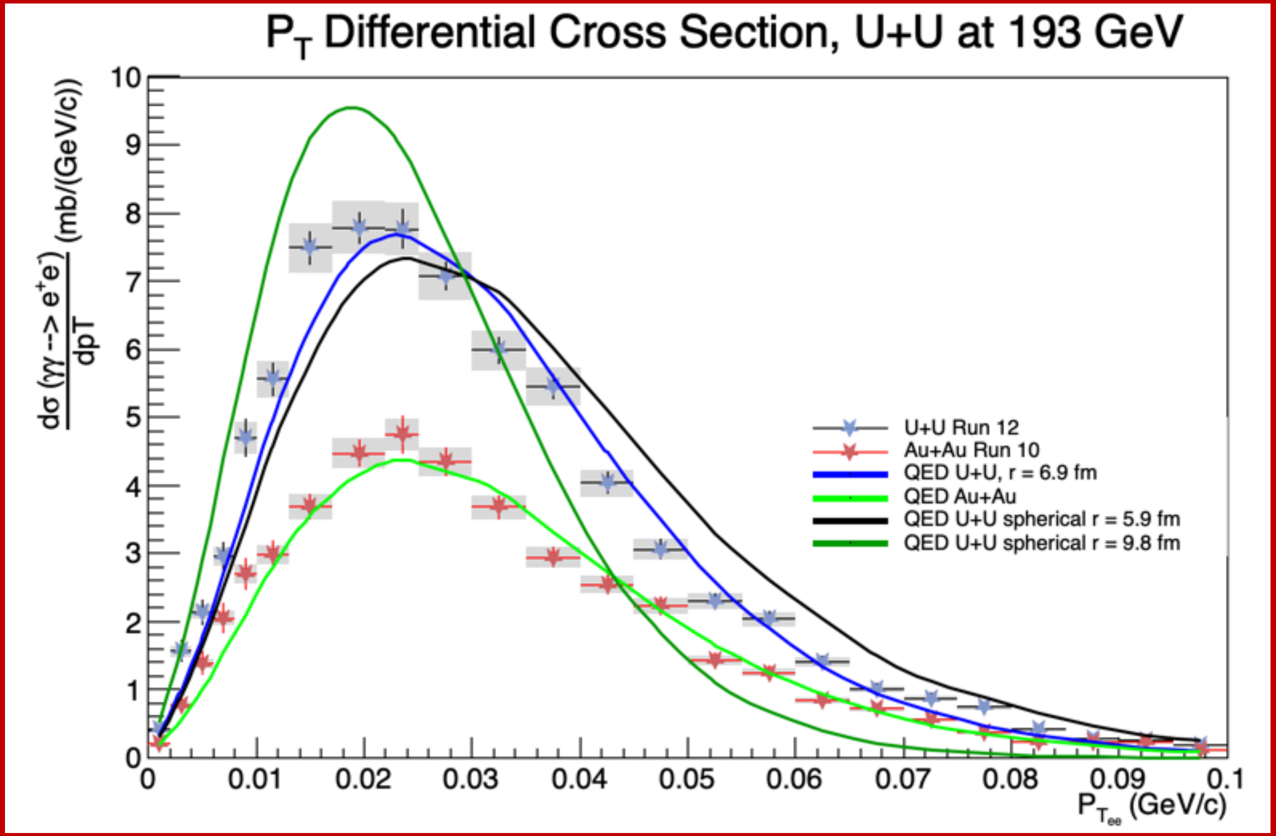
Takeaways: Nuclear Shape Effects in Photon-Photon Collisions

- Spherical uranium (semi-major or semi-minor radius) fails to describe the measured p_T distribution.
  - p_T spectrum is sensitive to nuclear deformation.

- **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.

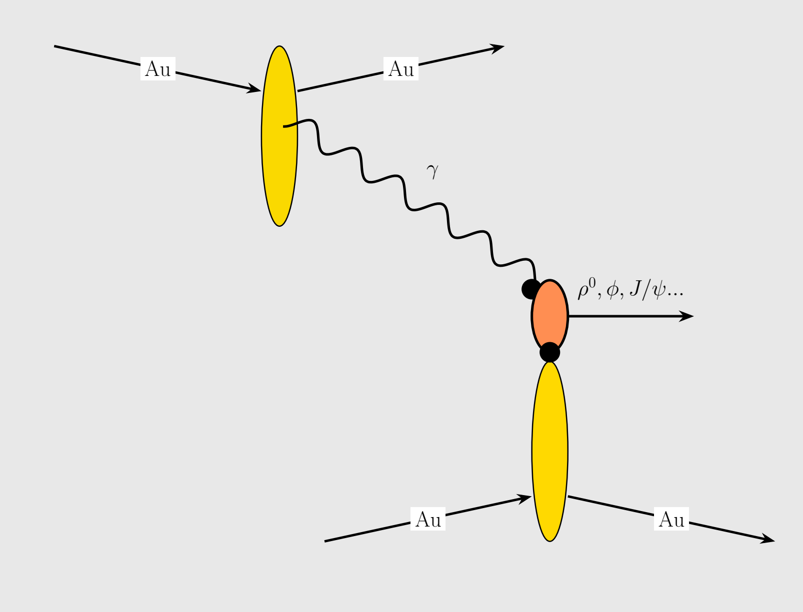




Exclusive Vector Meson Production in UPC

- $\gamma A \rightarrow VA$ 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

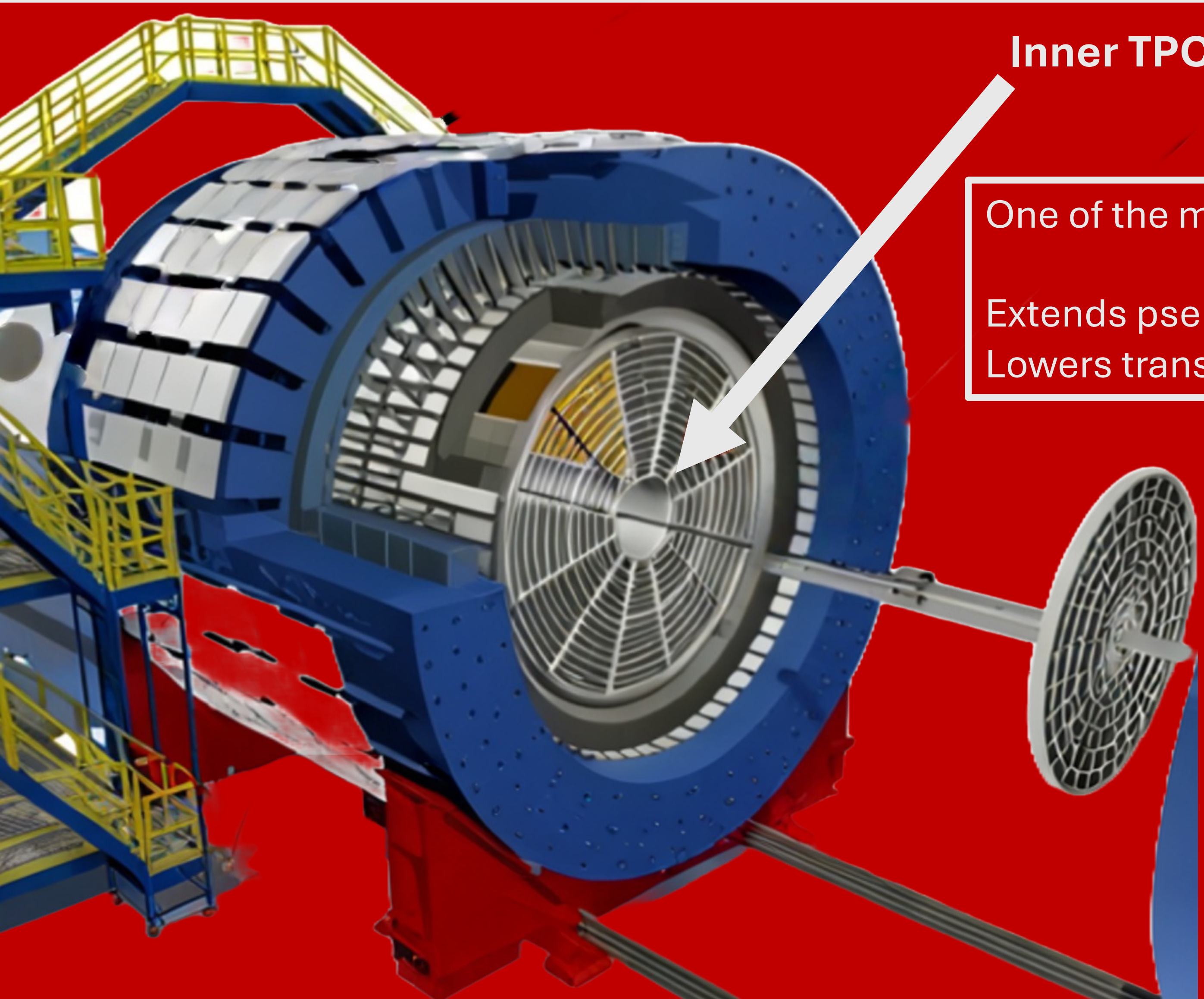


UPC Coherent/Incoherent Photoproduction of $\rho, J/\psi$ has bee measured at STAR.
We present the first measurement of UPC ϕ photoproduction at STAR.

We measure ϕ to the channel $\phi \rightarrow K^+K^-$.

This measurement pushes STAR's tracking limit as the transverse momentum of the daughter kaon is ~ 100MeV.

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.

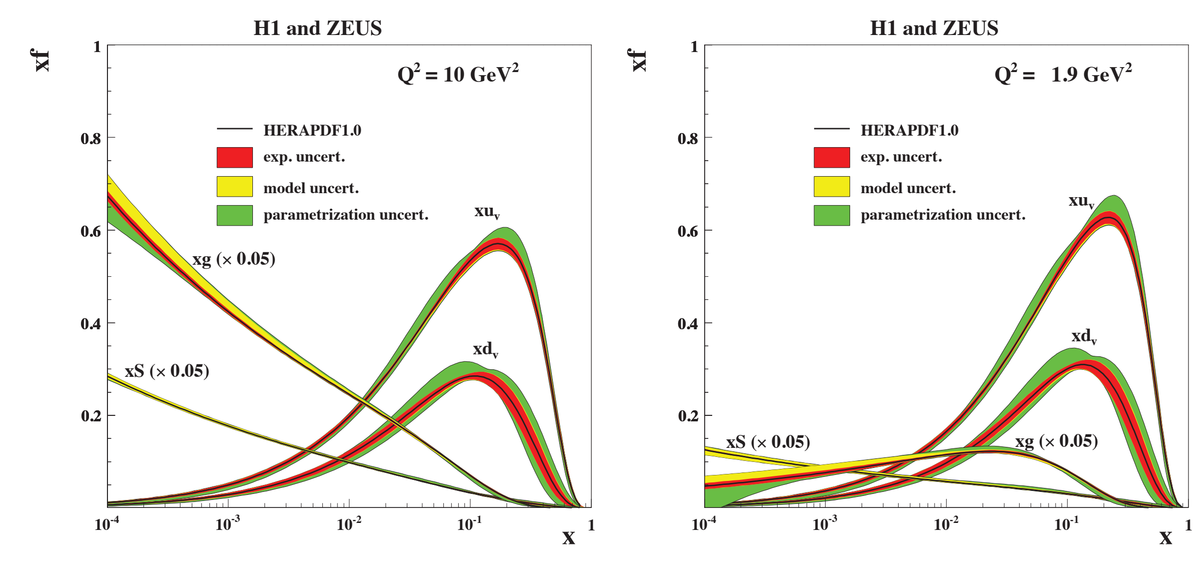
The **iTPC upgrade** greatly enhances tracking of **low-p_T kaons** (~100 MeV), which is essential for reconstructing **coherent $\phi \rightarrow K^+K^-$**.

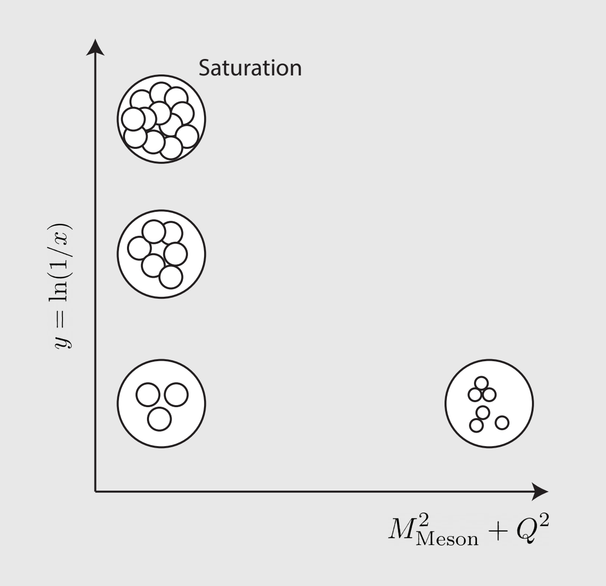
This analysis uses the first fully operational dataset from the upgraded iTPC.

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 (gluon recombination) set in — VM production can probe this regime.
  - **Suppression or modification** of cross sections (vs. linear QCD expectations) 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.





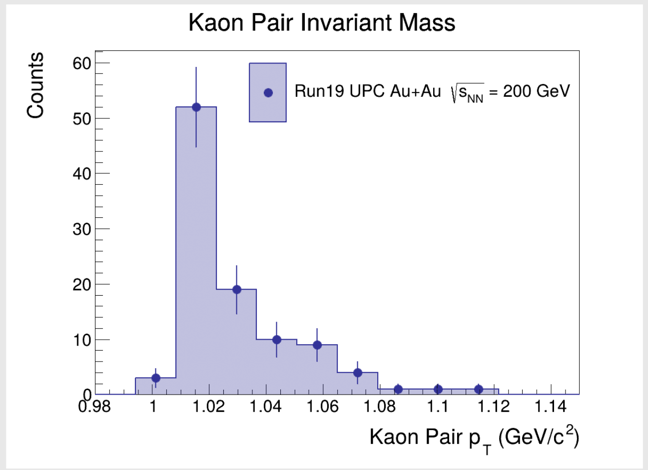
(Aaron et al., 2010)
electron-proton DIS nucleon structure PDF at HERA

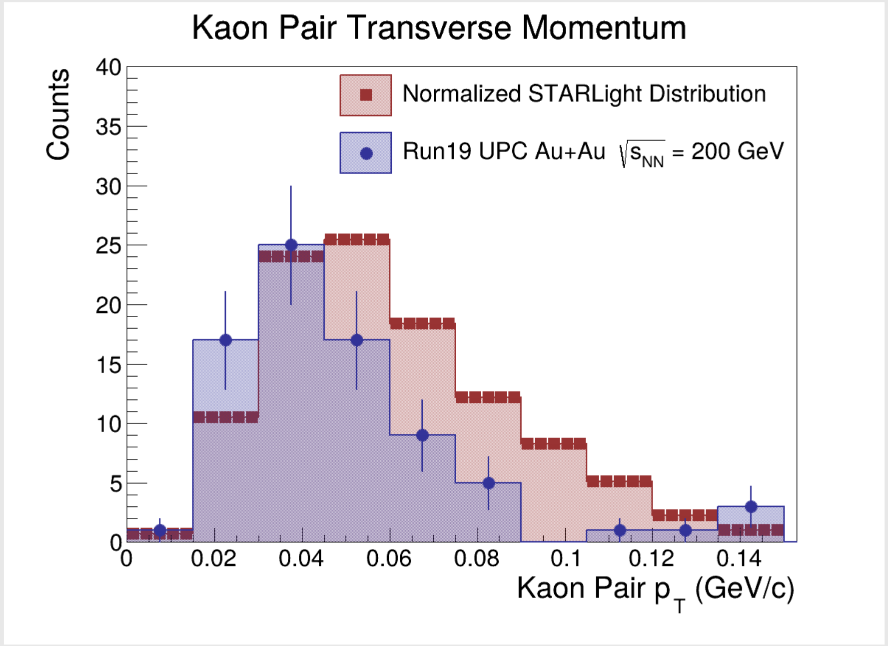
Event Selection and Signal Extraction

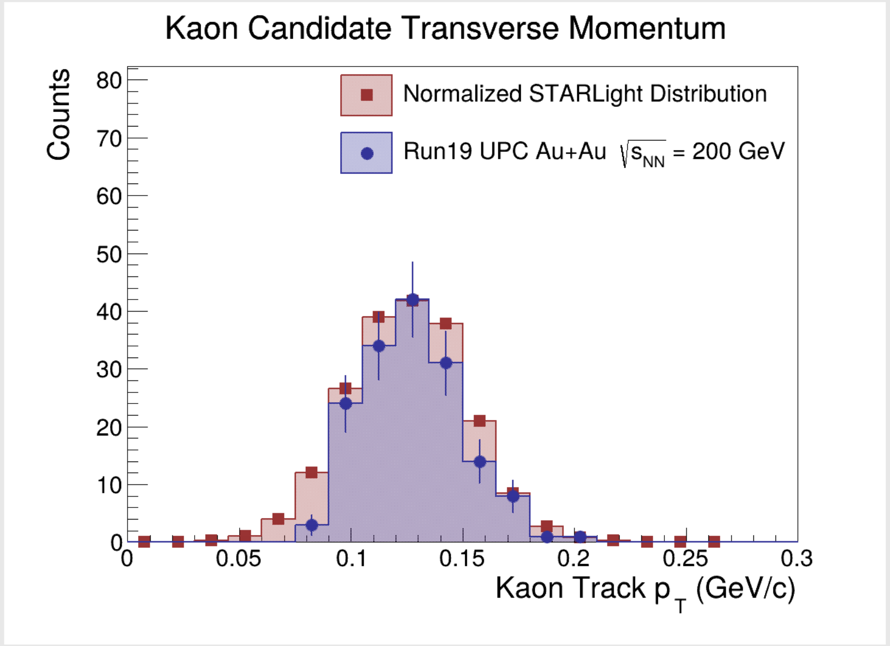
- Event Selection
  - Quality Cuts:
    - |Vz| < 50
  - UPC Selection
    - BBC Veto

- 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





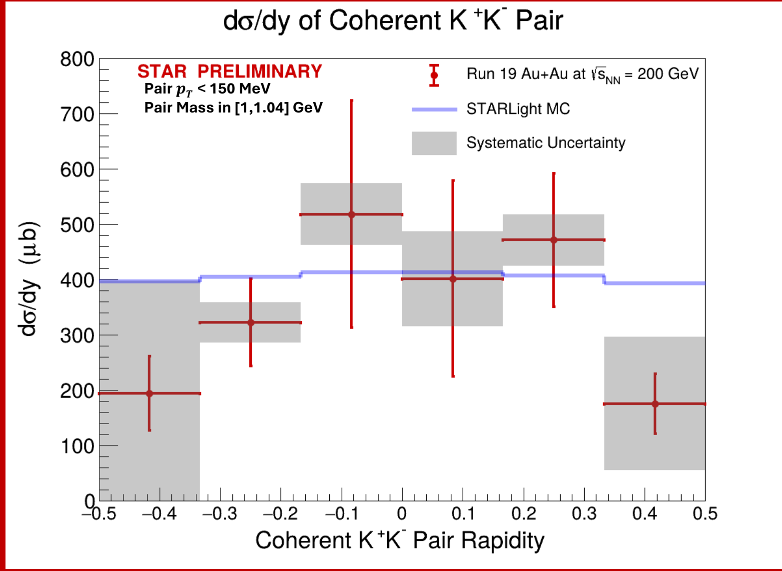


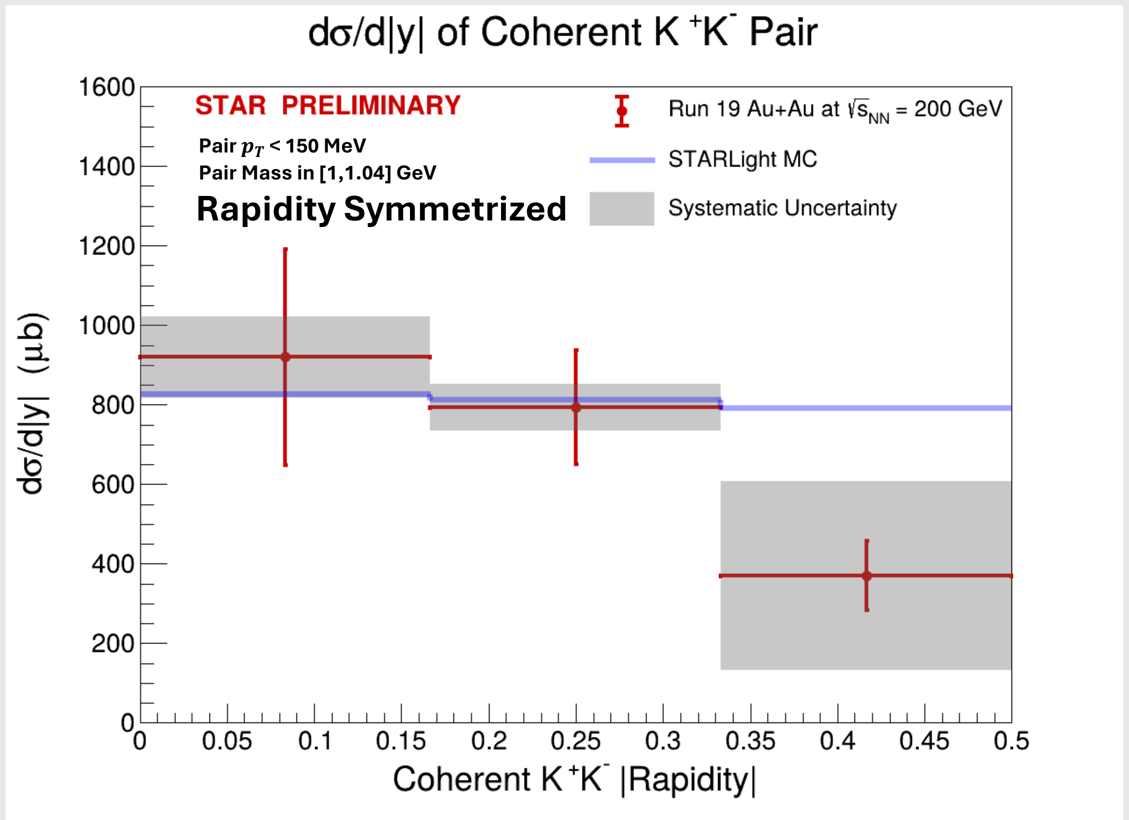
Differential Cross Section Preliminary Result

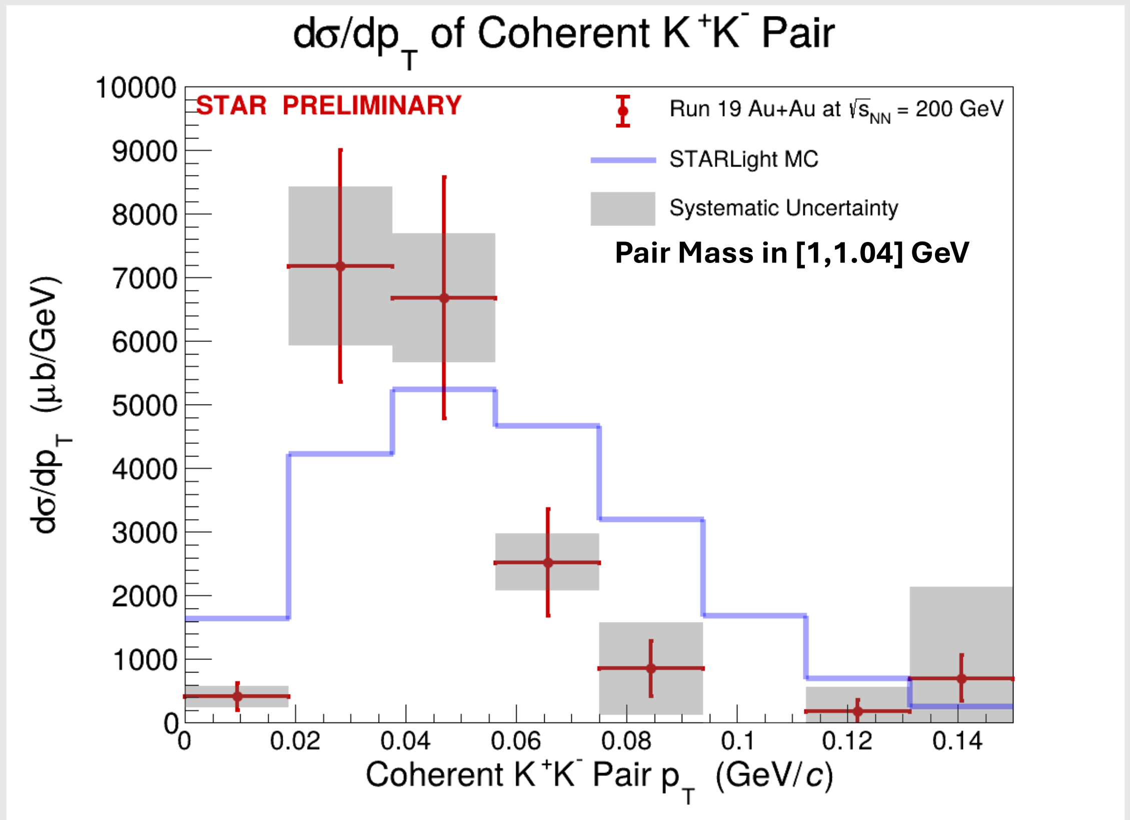
$$\sigma = \frac{N}{L_{\text{total}} \cdot \epsilon_{\text{tracking}} \cdot \epsilon_{\text{PID}} \cdot \epsilon_{\text{kinematic cut}} \cdot \epsilon_{\text{BBC Veto}} \cdot \epsilon_{\text{Vz cut}} \cdot \epsilon_{\text{Trigger}}}$$

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

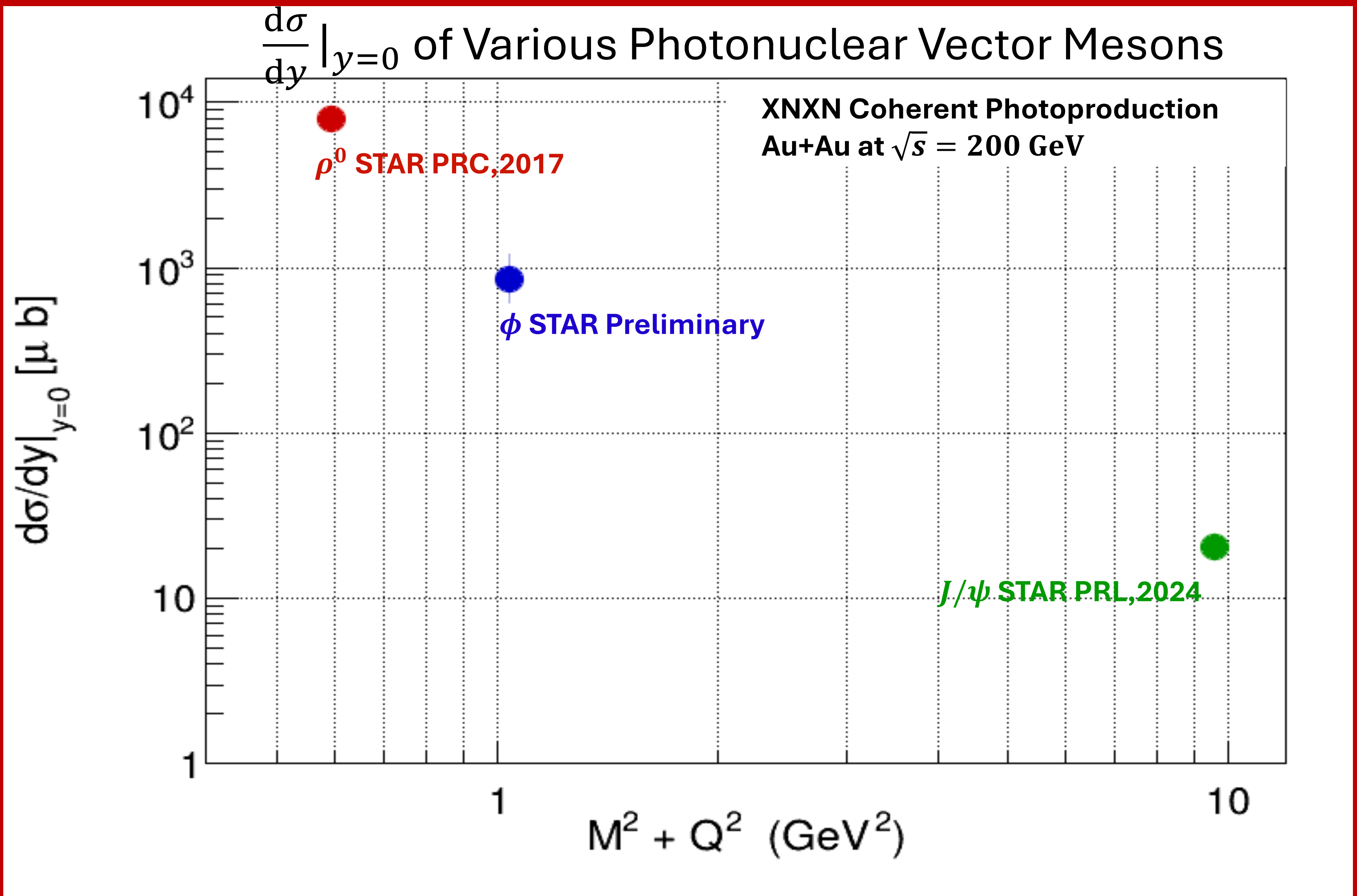
$$W_{\gamma N}|_{y=0} \approx 14.3\ \text{GeV},\ x \equiv \frac{M_V^2}{W_{\gamma N}^2} \approx 0.005$$







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.
- Such comparisons can help isolate nuclear effects—like shadowing or saturation—across various vector mesons, offering constraints on small-x dynamics and nuclear PDFs.

Summary and Outlook

✅ First differential cross section measurement of UPC photonuclear ϕ meson at STAR.

- New data 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 ϕ measurements:
  - Sensitive to **gluon fluctuations and hotspots**
  - **Ratio** of coherent/incoherent yields: key observable for **gluon saturation dynamics**

Citations

- Brandenburg, J. D., Seger, J., Xu, Z., & Zha, W. (2023). Report on progress in physics: Observation of the breit–wheeler process and vacuum birefringence in heavy-ion collisions. *Reports on Progress in Physics*, *86*(8), 083901. https://doi.org/10.1088/1361-6633/acdae4
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