Discoveries with Polarized Photons at STAR

(and other topics)

[1] JDB, J. Seger, Z. Xu, W. Zha, arXiv:2208.14943 **[hep-ph]**
[2] JDB, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685 **[hep-ph]**
[3] X. Wang, JDB, L. Ruan, F. Shao, Z. Xu, C. Yang, W. Zha, arXiv:2207.05595 **[nucl-th]**
[4] JDB, Z. Xu, W. Zha, C. Zhang, J. Zhou, Y. Zhou arXiv:2207.02478 **[hep-ph]**
[5] JDB, W. Zha, and Z. Xu, Eur. Phys. J. A **57**, 299 (2021).
[6] STAR Collaboration, Phys. Rev. Lett. 128, 122303 (2021)
[7] W. Zha, JDB, Z. Tang, and Z. Xu, Phys. Lett. B **800**, 135089 (2020).
[8] STAR Collaboration, Phys. Rev. Lett. **127**, 052302 (2021).
[9] STAR Collaboration, Phys. Rev. Lett. **121**, 132301 (2018).
[10] JDB, W. Li, et al., arXiv:2006.07365 [hep-ph, physics:nucl-th] (2020).
[11] JDB, STAR Collaboration, https://arxiv.org/abs/2204.01625

Daniel Brandenburg, Goldhaber Fellow
@ Brookhaven National Laboratory

New Vistas in Photon Physics,
September 19-22, 2022
@
AGH University of Science and Technology
Krakow, Poland

Brookhaven National Laboratory
STAR
Supported in part by:
U.S. DEPARTMENT OF ENERGY | Office of Science

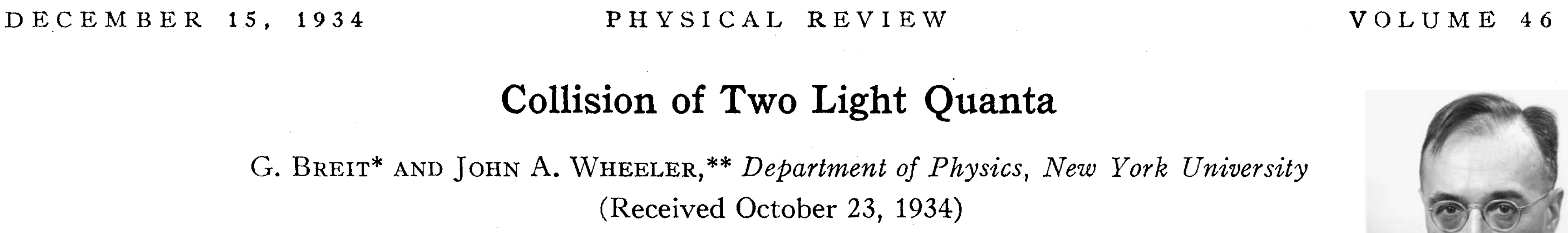
Outline of Topics

1. The Breit-Wheeler process
2. Quantum Entanglement Enabled Nuclear Tomography
3. The Baryon Junction

The Breit-Wheeler Process

$$\gamma\gamma \rightarrow e^{+}e^{-}$$

Observation of the Breit-Wheeler Process

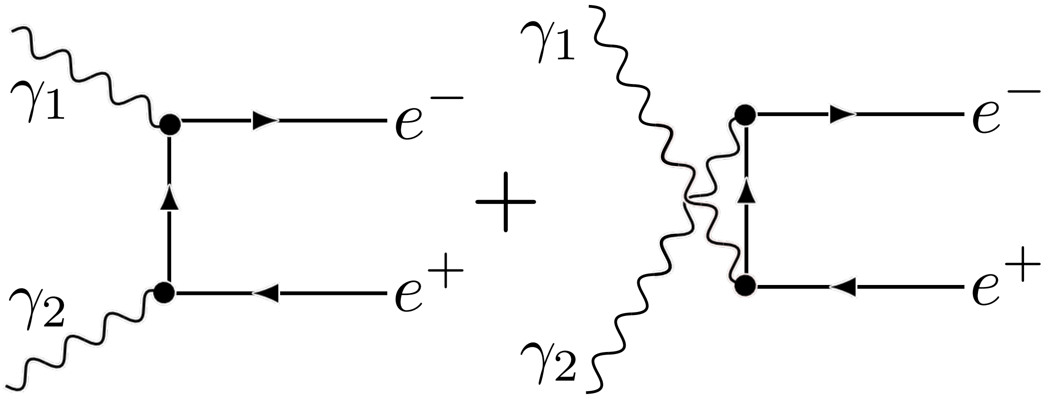


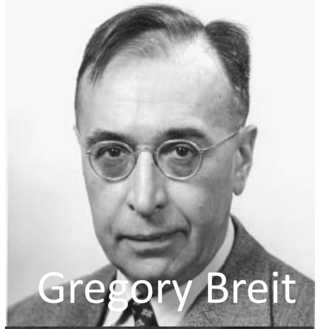
DECEMBER 15, 1934 PHYSICAL REVIEW VOLUME 46

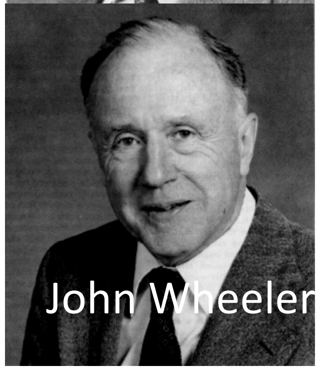
Collision of Two Light Quanta

G. Breit* and John A. Wheeler,** *Department of Physics, New York University*

(Received October 23, 1934)

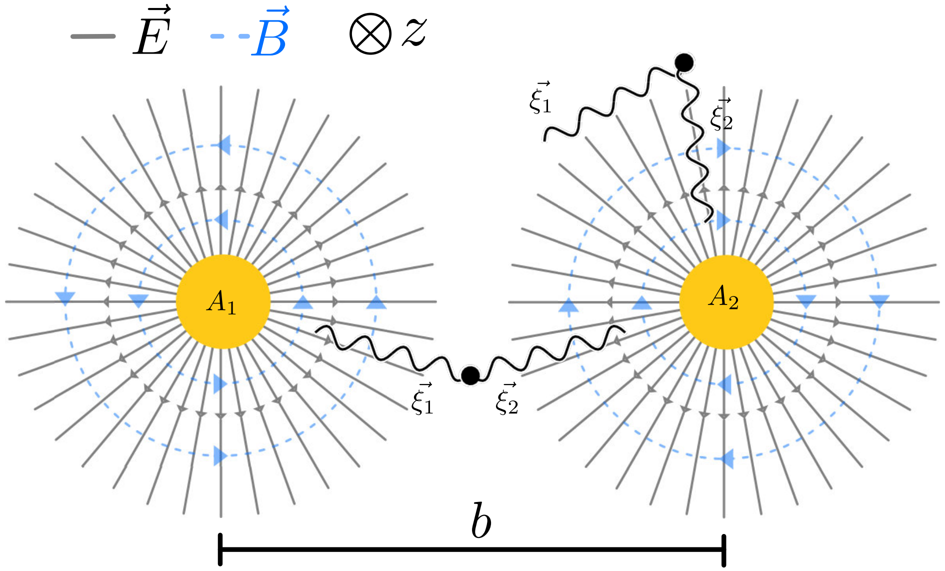



Gregory Breit


John Wheeler

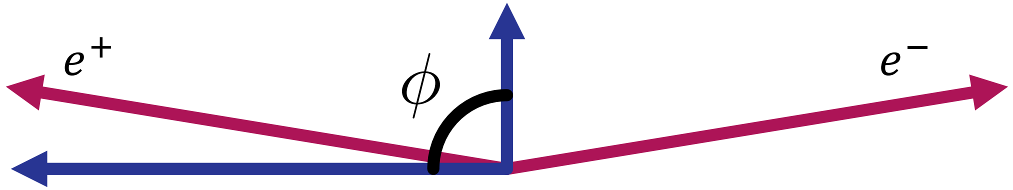
- Non-linear effect forbidden in classical electromagnetism
- At lowest order, two Feynman diagrams contribute and interfere
- Breit-Wheeler process: real photon collisions → important distinction
- Finally observed after 85+ years $\Longrightarrow$ **Applications in nuclear physics**

Observation of the Breit-Wheeler Process



- The incoming photon polarization leads to vacuum birefringence [Toll, 1952], visible as a $\cos 4\phi$ modulation [1,2]

⇒ Precision understanding of the photon wavefunction and **sensitivity to polarization**



General density matrix for the two-photon system:

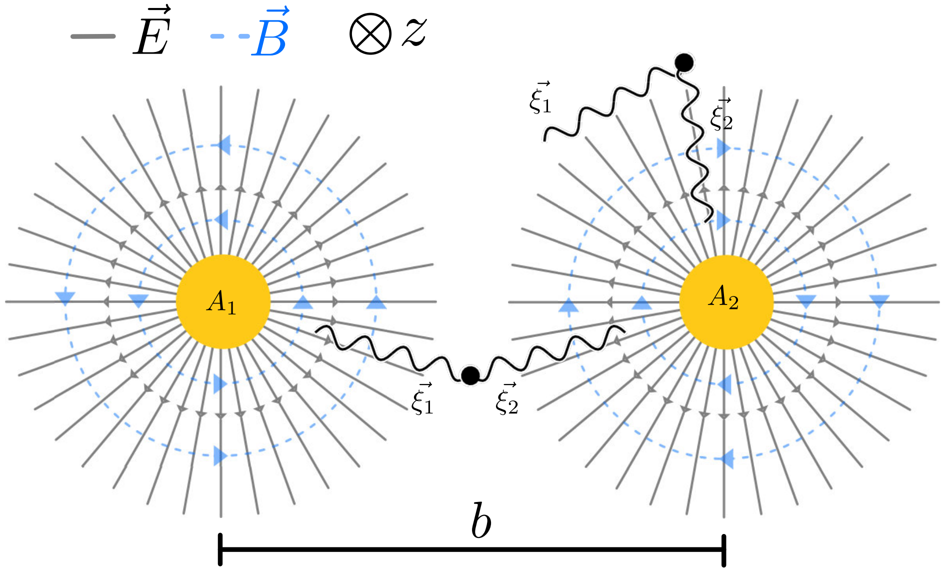
$$\rho^{a,a'} = \begin{pmatrix} \rho^{++} & \rho^{+0} & \rho^{+-} \\ \rho^{+0} & \rho^{00} & \rho^{+0} \\ \rho^{+-} & \rho^{+0} & \rho^{++} \end{pmatrix}$$

Spin 1 Photon helicity a = $(-,\boxed{0},+)$

Helicity 0 : Forbidden for real photon

Real photon: Allowed J^P states: $2^{\pm}, 0^{\pm}$

Discovery of the Breit-Wheeler Process



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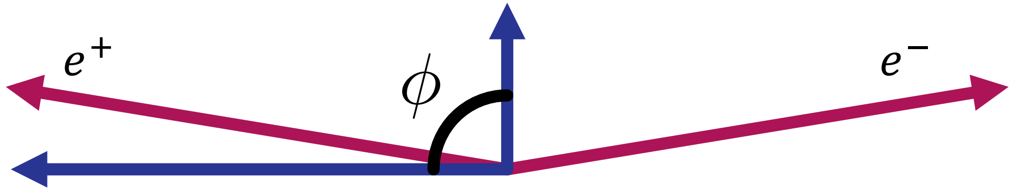

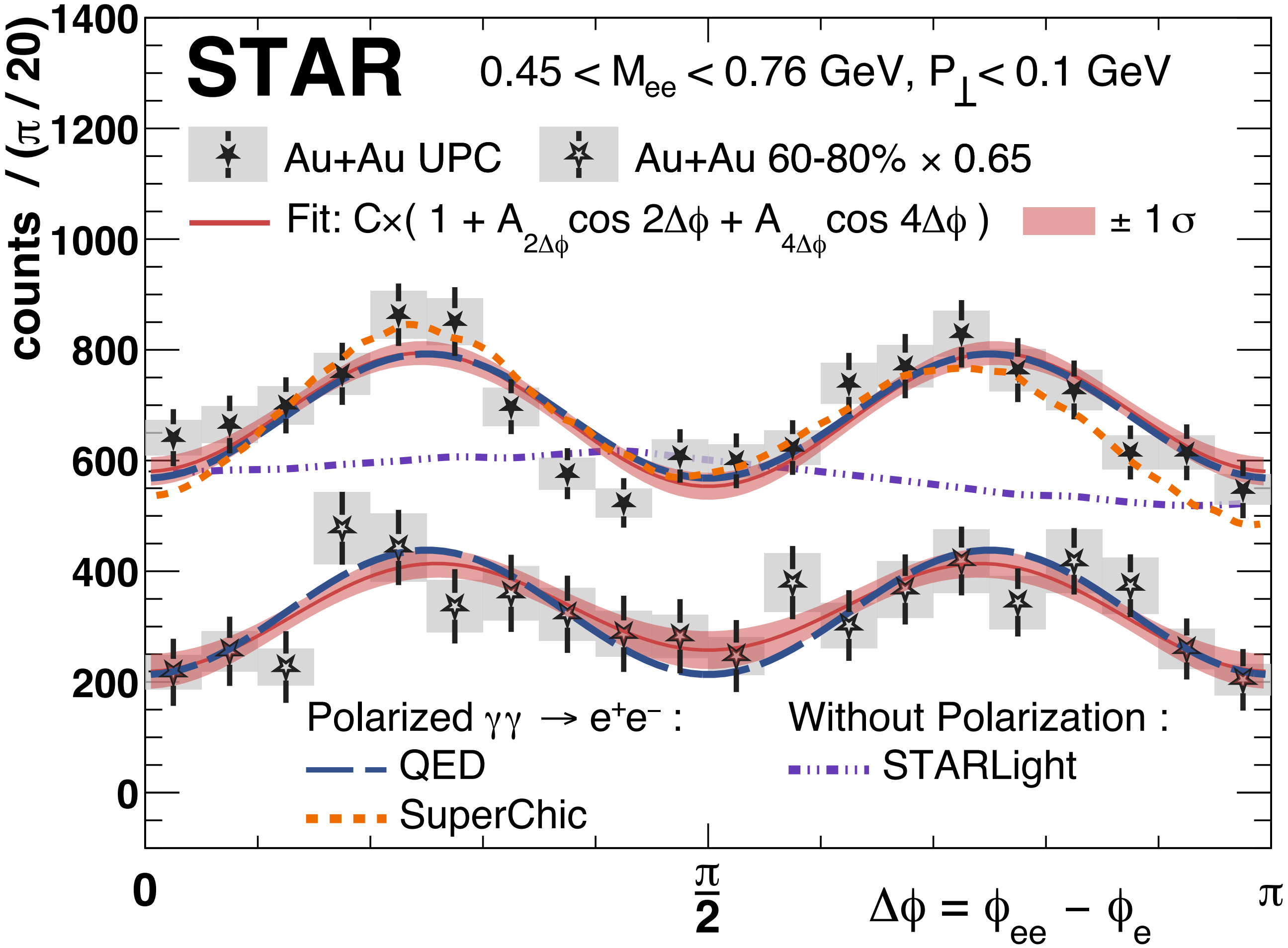

STAR Collaboration, Phys. Rev. Lett. 128, 122303 (2021)

The $J = 2$ states lead to $\pm\cos 4\phi$ azimuthal modulations

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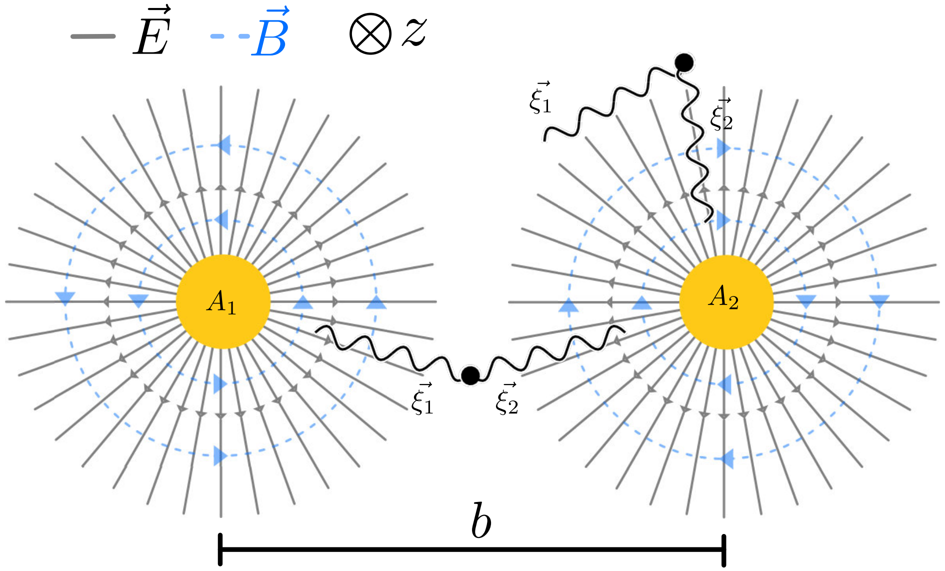

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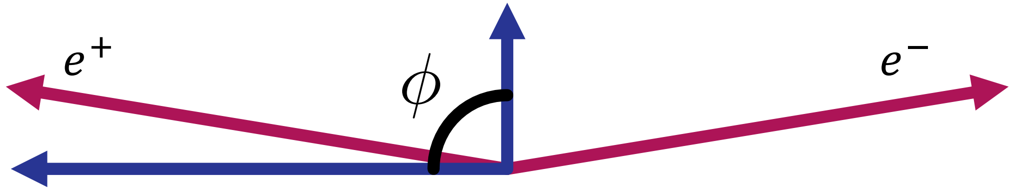

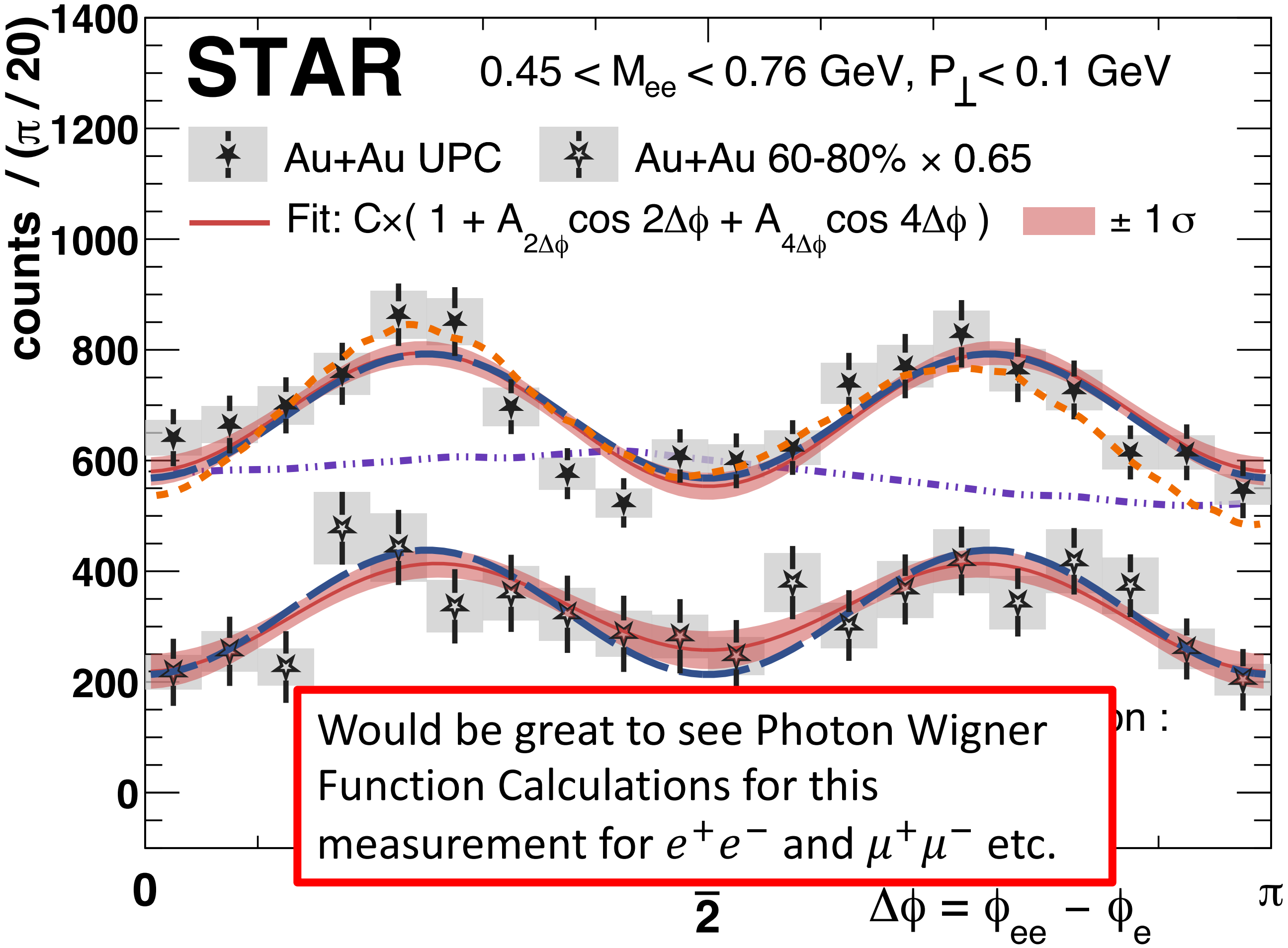

Would be great to see Photon Wigner Function Calculations for this measurement for e^+e^- and $\mu^+\mu^-$ etc.

STAR Collaboration, Phys. Rev. Lett. 128, 122303 (2021)

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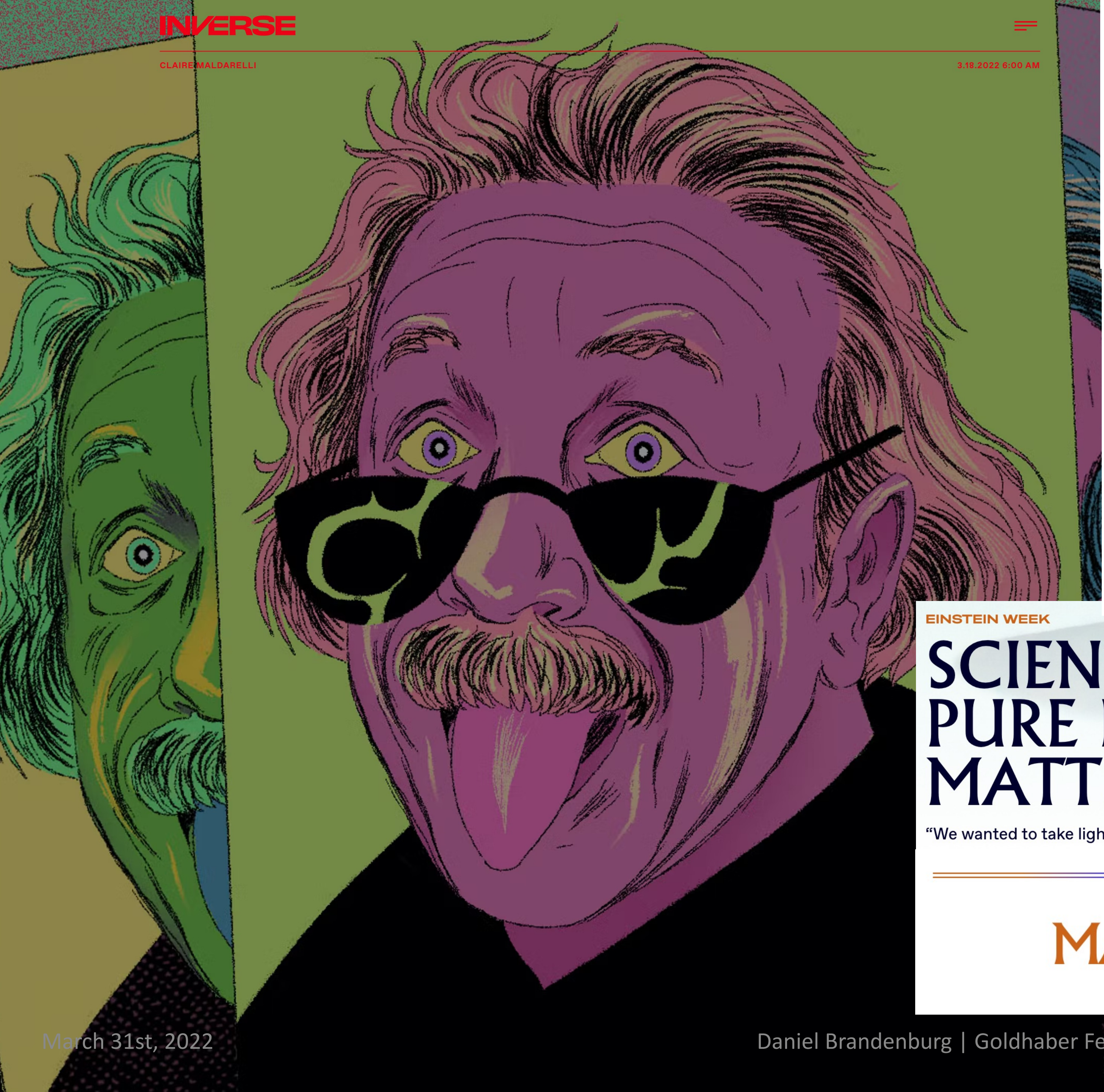
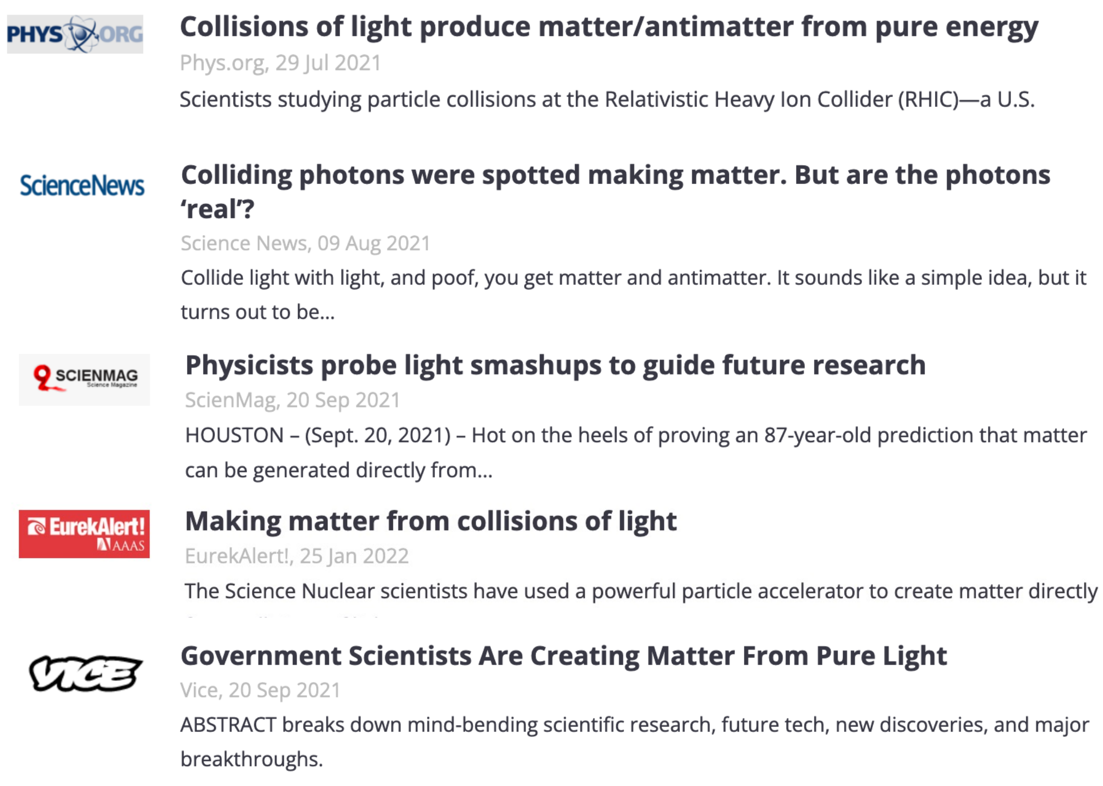




Collisions of light produce matter/antimatter from pure energy

Phys.org, 29 Jul 2021

Scientists studying particle collisions at the Relativistic Heavy Ion Collider (RHIC)—a U.S.

Colliding photons were spotted making matter. But are the photons 'real'?

Science News, 09 Aug 2021

Collide light with light, and poof, you get matter and antimatter. It sounds like a simple idea, but it turns out to be...

Physicists probe light smashups to guide future research

ScienMag, 20 Sep 2021

HOUSTON – (Sept. 20, 2021) – Hot on the heels of proving an 87-year-old prediction that matter can be generated directly from...

Making matter from collisions of light

EurekAlert!, 25 Jan 2022

The Science Nuclear scientists have used a powerful particle accelerator to create matter directly

Government Scientists Are Creating Matter From Pure Light

Vice, 20 Sep 2021

ABSTRACT breaks down mind-bending scientific research, future tech, new discoveries, and major breakthroughs.

EINSTEIN WEEK

SCIENTISTS MANAGED TO TAKE PURE ENERGY AND CREATE MATTER — AND NEW PHYSICS

"We wanted to take light and convert it into matter." Wish fulfilled.

MAKING NEW PHYSICS POSSIBLE

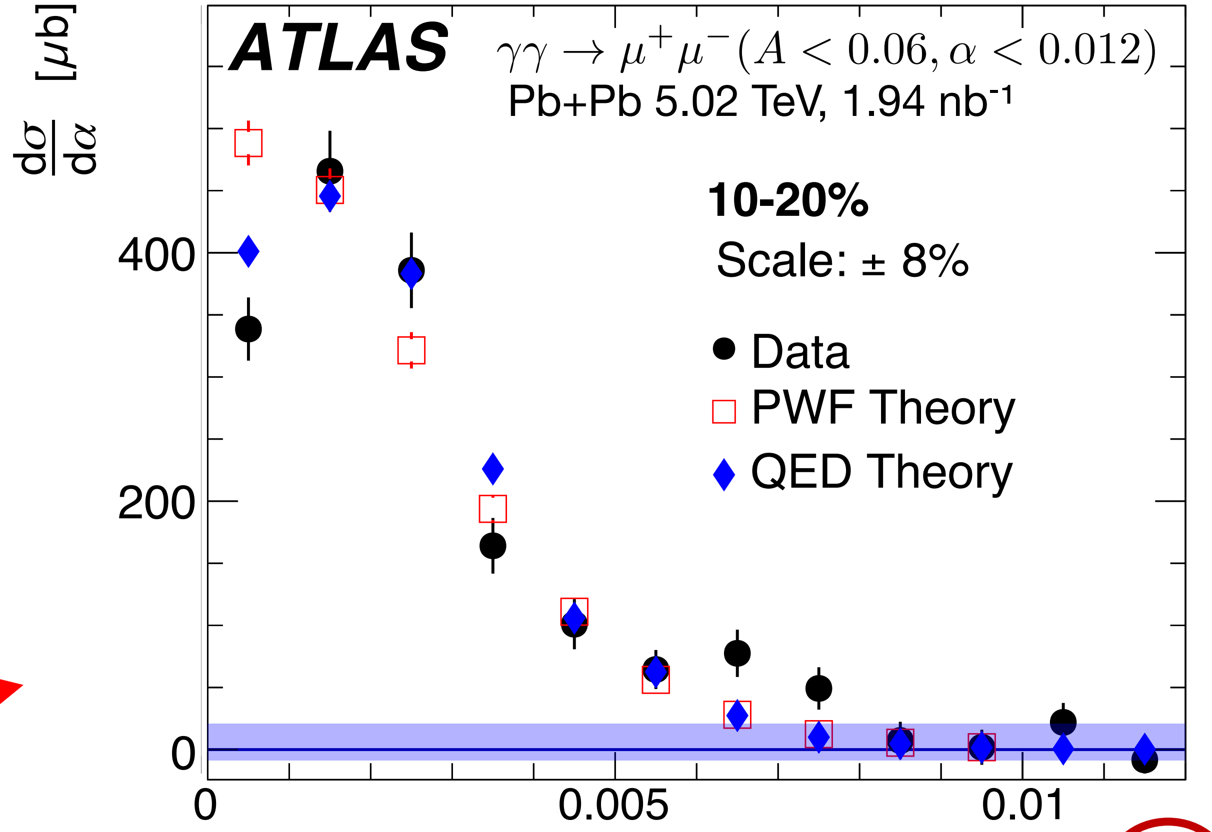
Breit-Wheeler Process in HICs

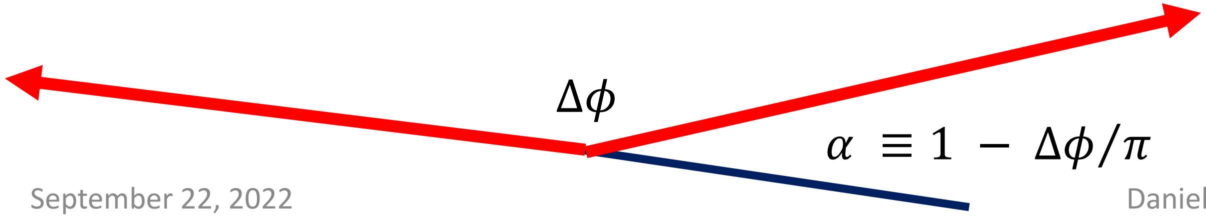
- Under what condition do these photons interact as real photons?
  - Photon Wigner Function (PWF) formalism & LO-QED formalism agree very well
  - How to understand the minor differences between them?

- Consider the S-Matrix behavior to identify the region where photons are real at leading order:

$$\omega/\gamma \lesssim k_\perp \lesssim 1/R \ll \omega,$$

$$\frac{\sqrt{2}}{\gamma} \lesssim \frac{\pi}{2}\alpha \lesssim \frac{\sqrt{2}}{\omega R} \ll 1$$

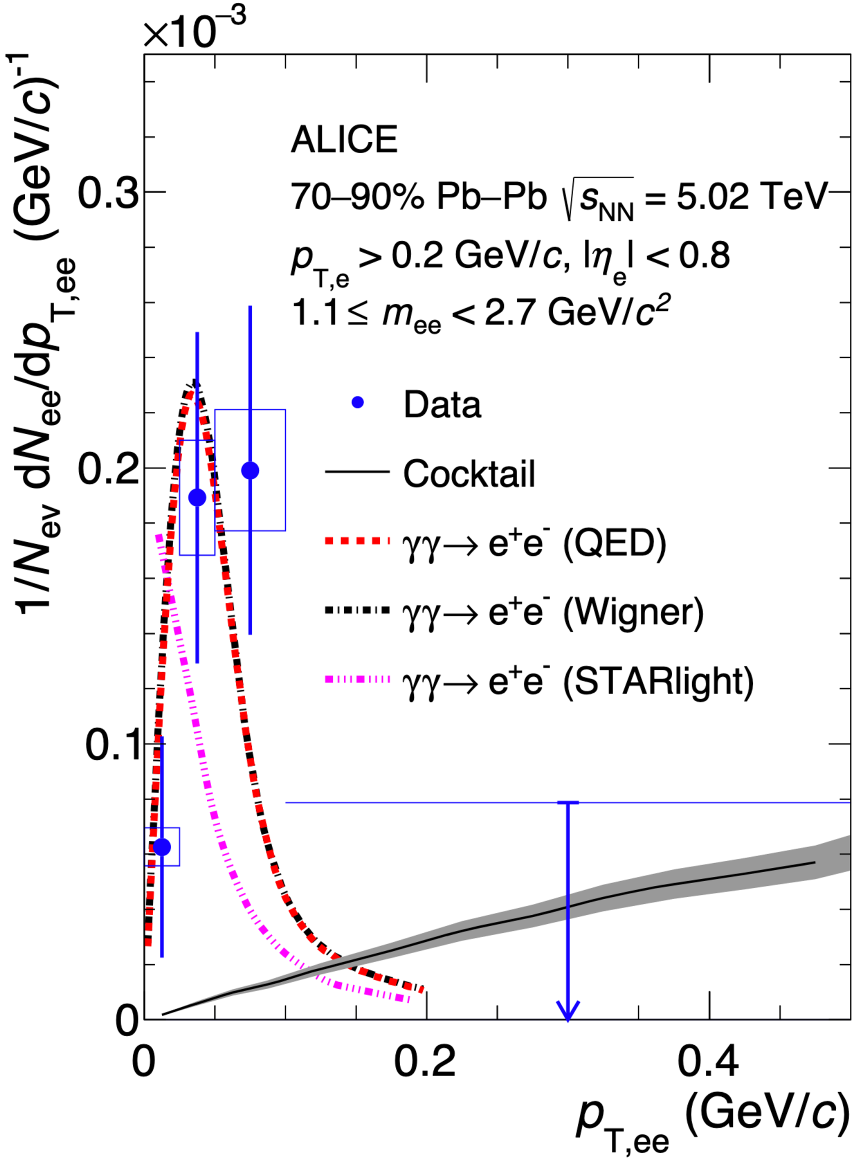




$\alpha \equiv 1 - \Delta\phi/\pi$

Breit-Wheeler Process in HICs

- Under what condition are these quasi-real
  - Photon Wigner Function (PWF) formalism & L
  - How to understand the minor differences betv



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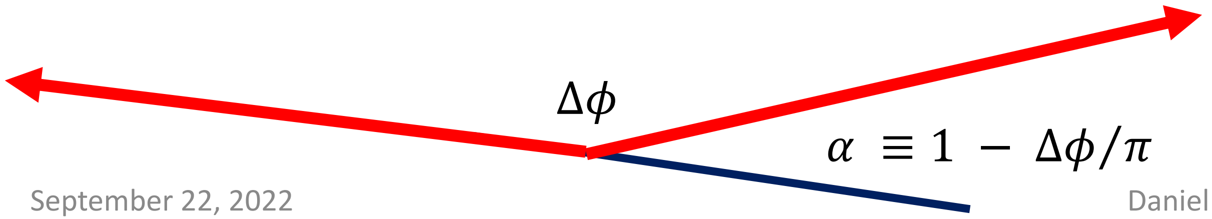
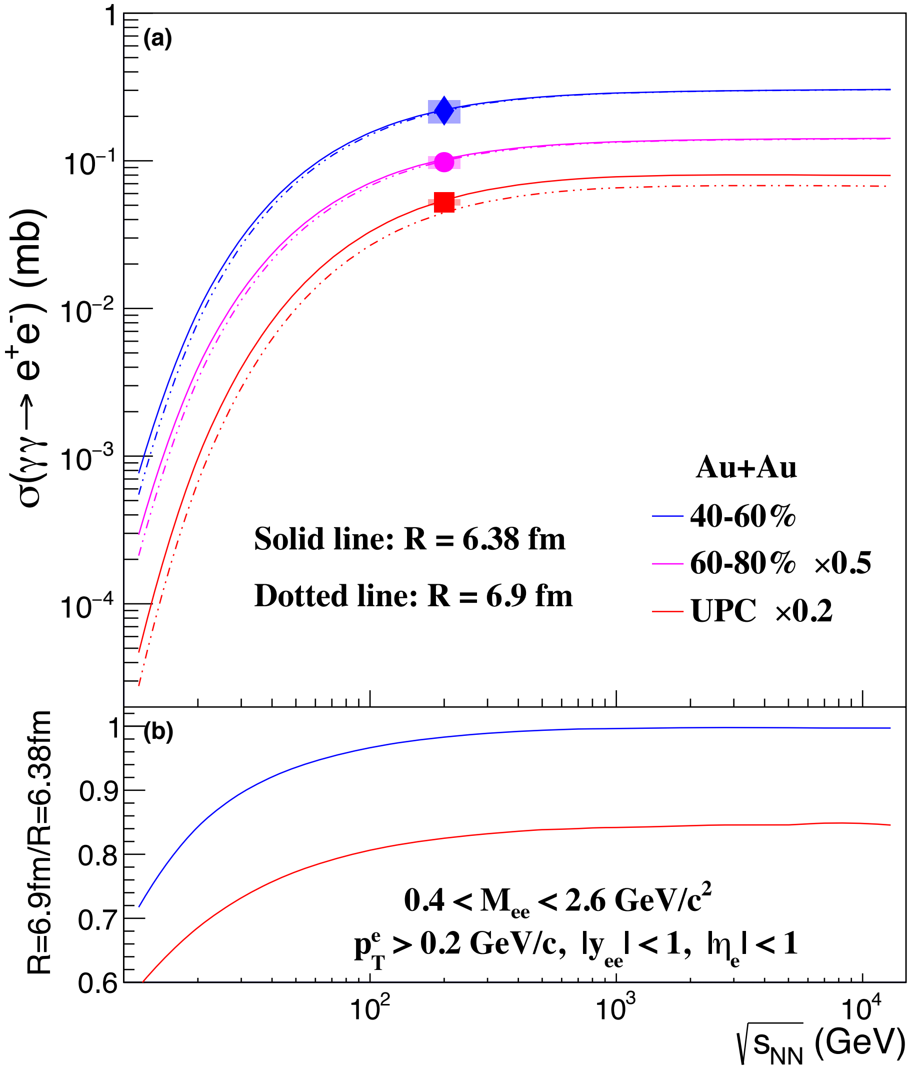


Energy Dependence & Infrared Divergence

- RHIC beam energy scan → unique capability to study low energy behavior



$$n(\omega) = \frac{(Ze)^2}{\pi\omega}\int_0^\infty \frac{d^2k_\perp}{(2\pi)^2}\left[\frac{F\left(\left(\frac{\omega}{\gamma}\right)^2 + \vec{k}_\perp^{\,2}\right)}{\left(\frac{\omega}{\gamma}\right)^2 + \vec{k}_\perp^{\,2}}\right]^2 \vec{k}_\perp^{\,2},$$

- As $k_\perp \rightarrow 0$ flux increases
- Only cutoff by the ${}^{\omega}/_{\gamma}$ term
- Allowed phase space for Breit-Wheeler processes plumets as $\sqrt{s_{NN}} \rightarrow 0$
- Sensitivity to details of the charge distribution

NB. RHIC BES: Au+Au collisions from $\sqrt{s_{NN}} = 7.7 - 64$ GeV

X. Wang, JDB, L. Ruan, F. Shao, Z. Xu, C. Yang, W. Zha, arXiv:2207.05595 **[nucl-th]**

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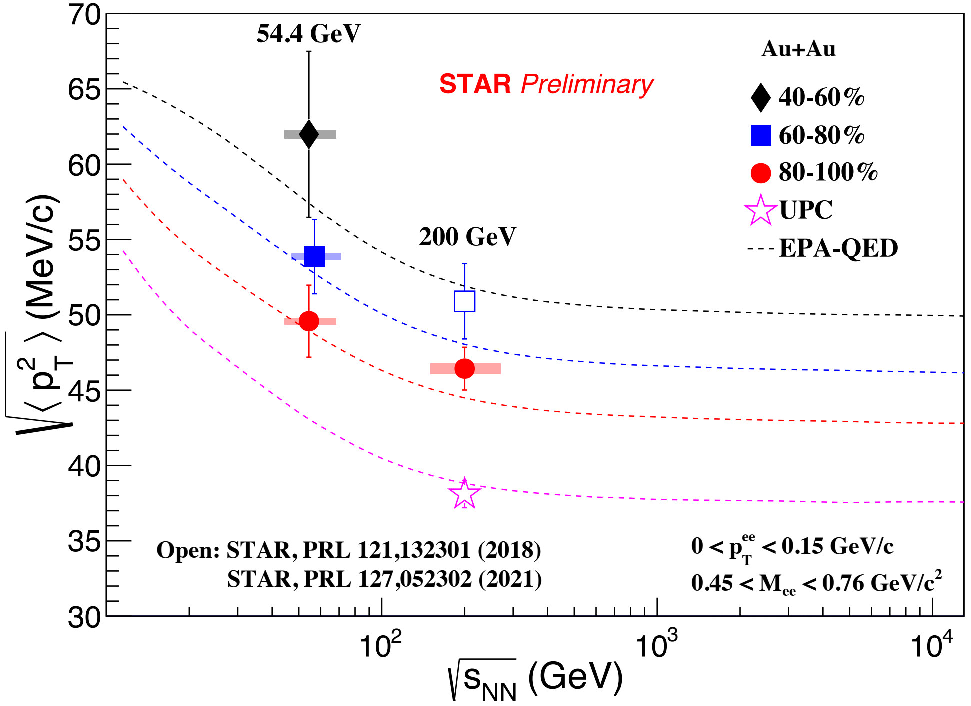

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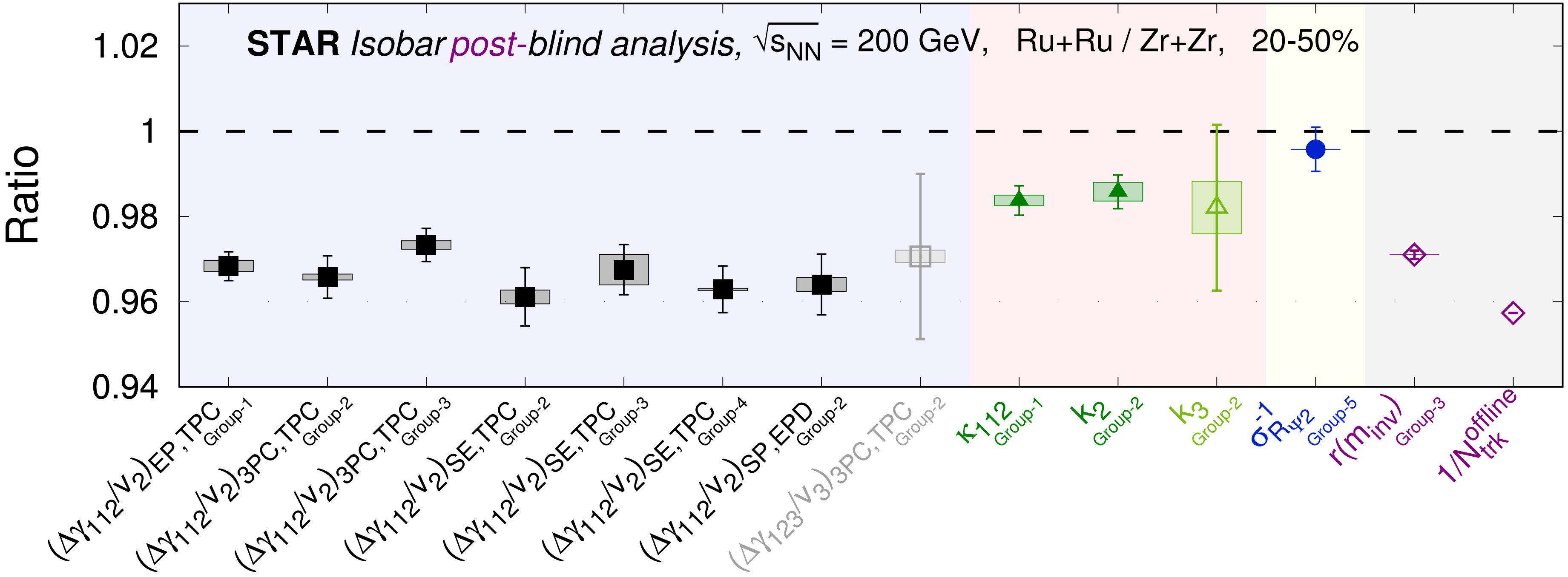
- Only cutoff by the $^{\omega}/_{\gamma}$ term
- Allowed phase space for Breit-Wheeler processes plumets as $\sqrt{s_{NN}} \to 0$
- Sensitivity to details of the charge distribution
- **Pair transverse momentum (at fixed b) increases with decreasing energy**

NON-UPC: hint of systematic increase above QED baseline → effect of long lived B-field in QGP?

X. Wang, JDB, L. Ruan, F. Shao, Z. Xu, C. Yang, W. Zha, arXiv:2207.05595 **[nucl-th]**

QCD in Strong Magnetic Fields



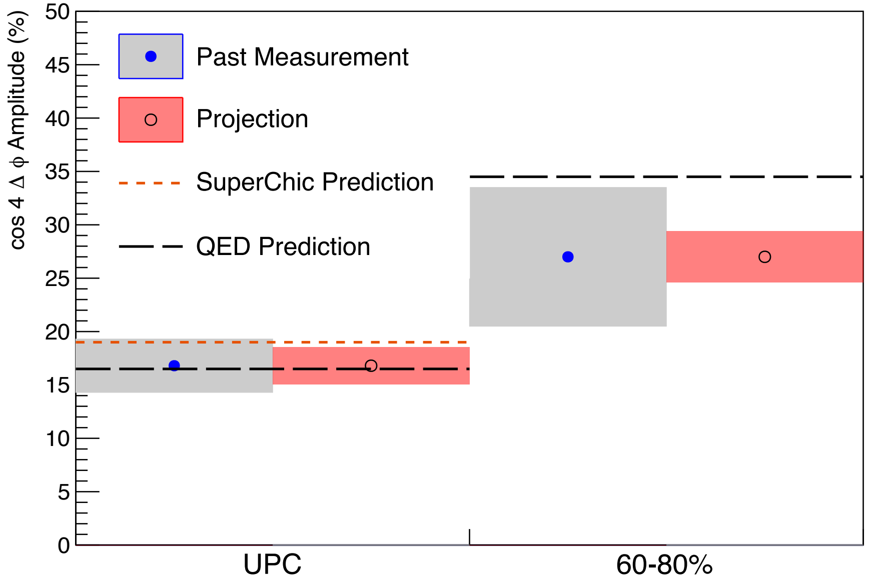
Can we provide **experimental** constraints on the magnetic field in heavy-ion collisions?

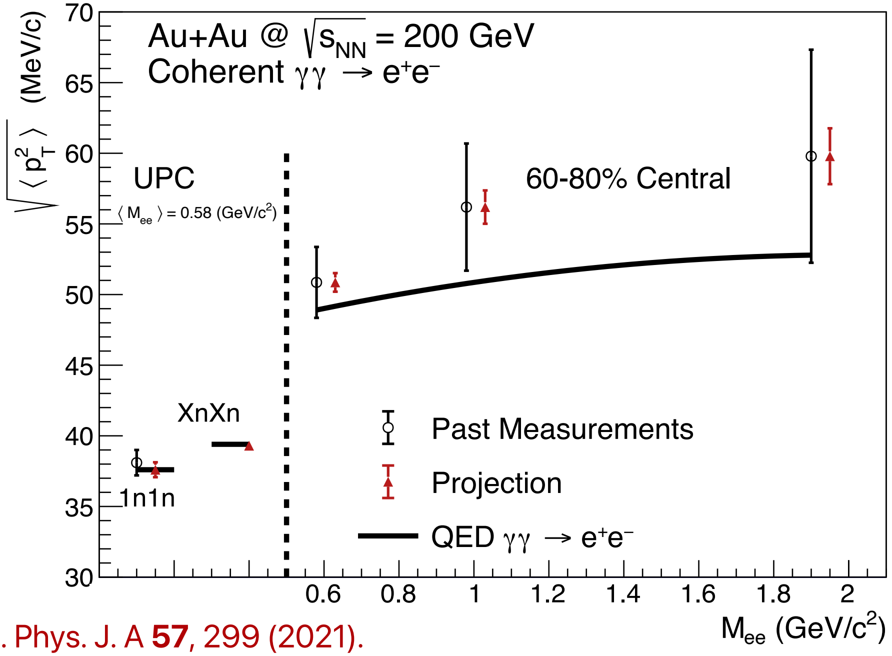
- Low-x behavior of the fields?
- Lifetime of electro(magnetic) fields?
- Effect of event-by-event fluctuations? …

STAR Collaboration, et al., *Phys.Rev.C* 105 (2022) arXiv:2109.00131

Opportunities @ STAR 2023-2025

- RHIC Run 23 + 25 = **20B / 40 nb−1 Au+Au events**
  - Plan: trigger events with Zero Degree Calorimeters
  - Nearly perfect for selecting UPC interactions
- Test QED processes for deviation from baseline
  - → Indication of some final state effect (trapped $\vec{B}$-field)?





STAR BUR Runs 23-25

JDB, W. Zha, and Z. Xu, Eur. Phys. J. A **57**, 299 (2021).

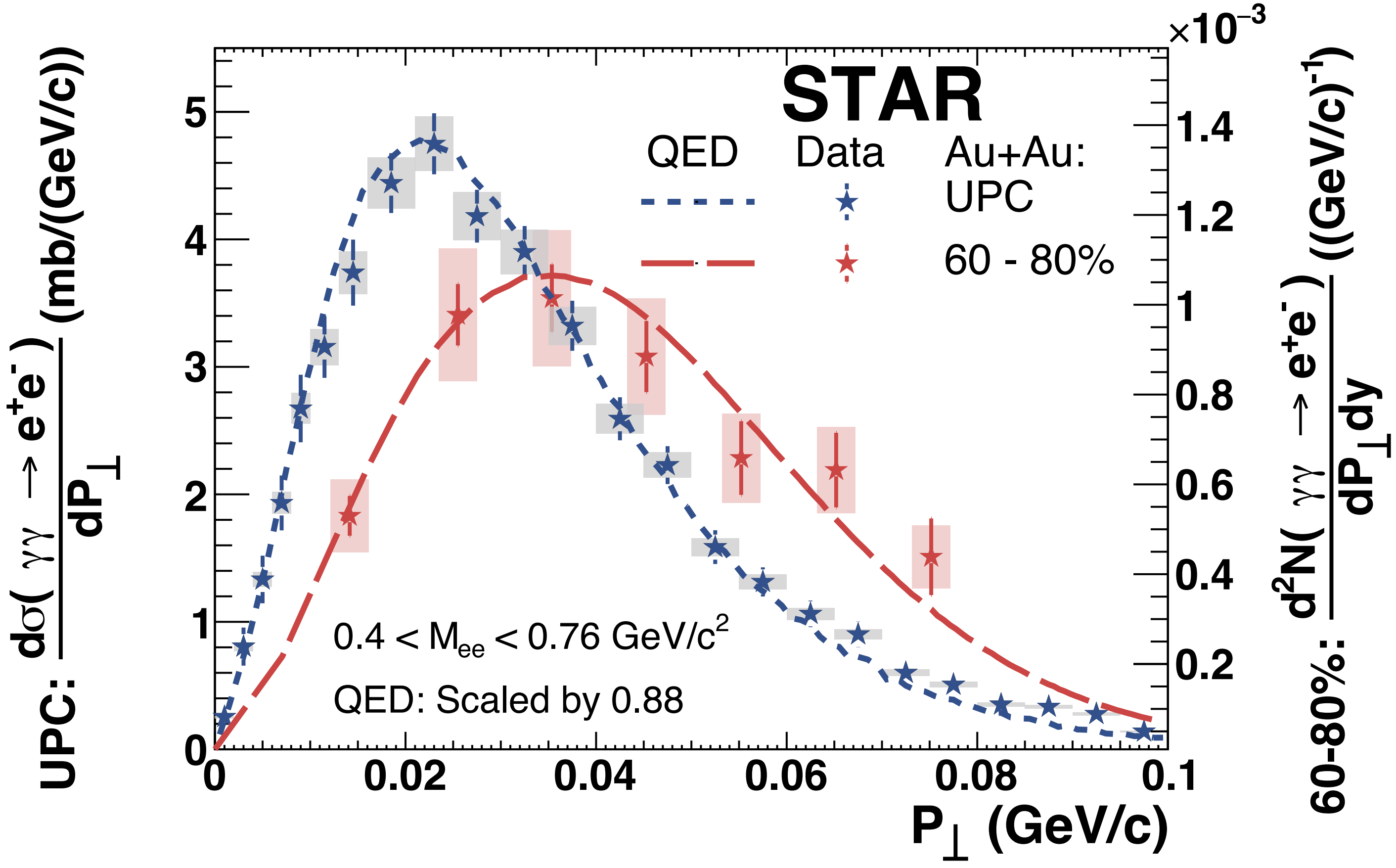
These pairs have very low p_T, so they are susceptible to Lorentz-force bending from trapped B-field AND/OR electromagnetic scattering off QGP

Expected effect:

Decorrelation (weakening) of $\cos 4\phi$ AND broadening of p_T

Imaging the Nuclear Charge Distribution

- $\gamma\gamma \rightarrow l^+l^-$ can be used to image the nuclear charge distribution at high-energy



X. Wang, JDB, L. Ruan, F. Shao, Z. Xu, C. Yang, W. Zha, arXiv:2207.05595 **[nucl-th]**
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Low energy scattering: R=6.38 fm, d=0.535 fm

R. C. Barrett and D. F. Jackson, Nuclear Sizes and Structure (Oxford University Press, 1977)

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- Combined data favors a charge distribution slightly larger than low-energy scattering result at 3σ
- Energy dependence measurements may prove important

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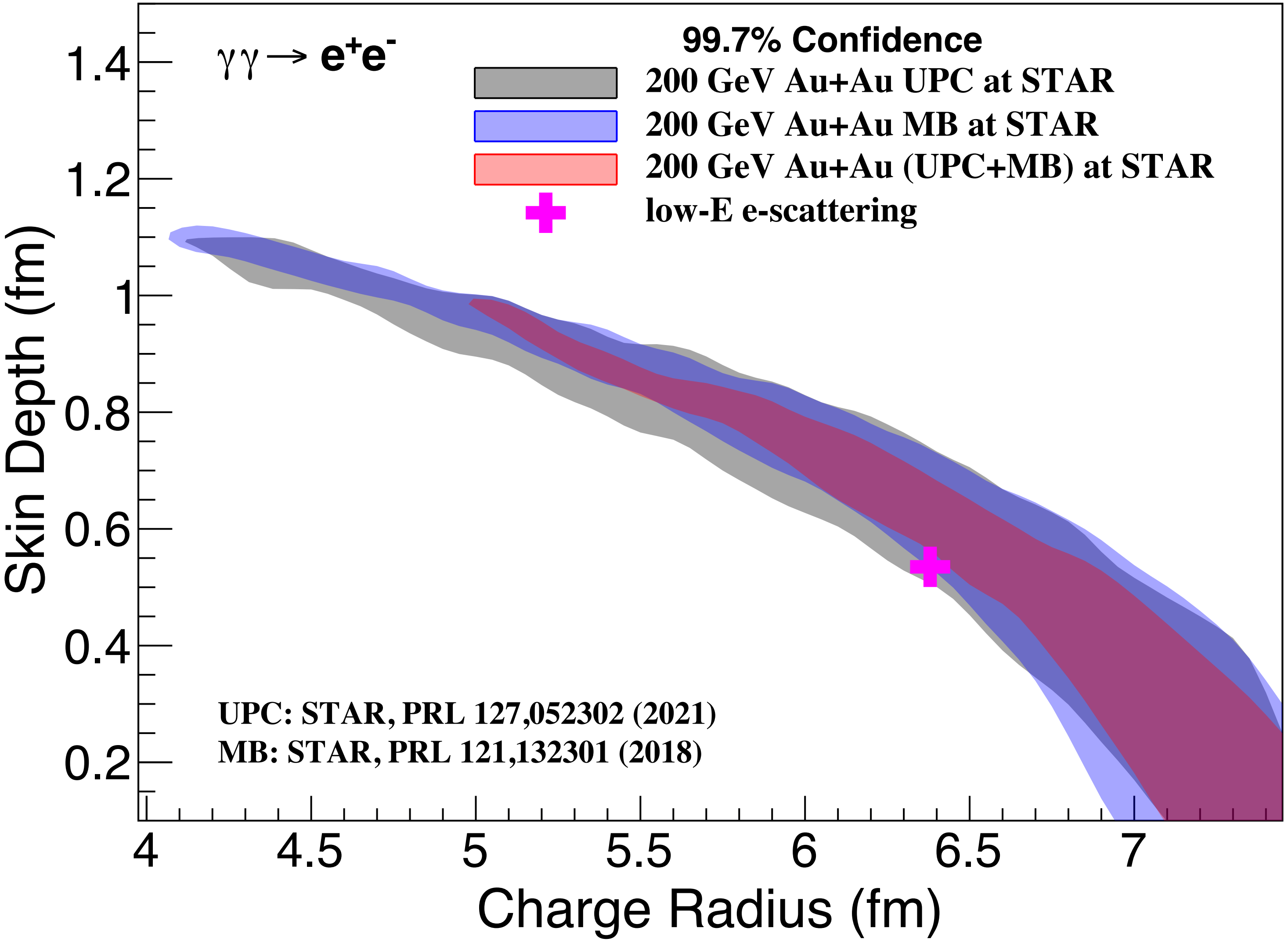

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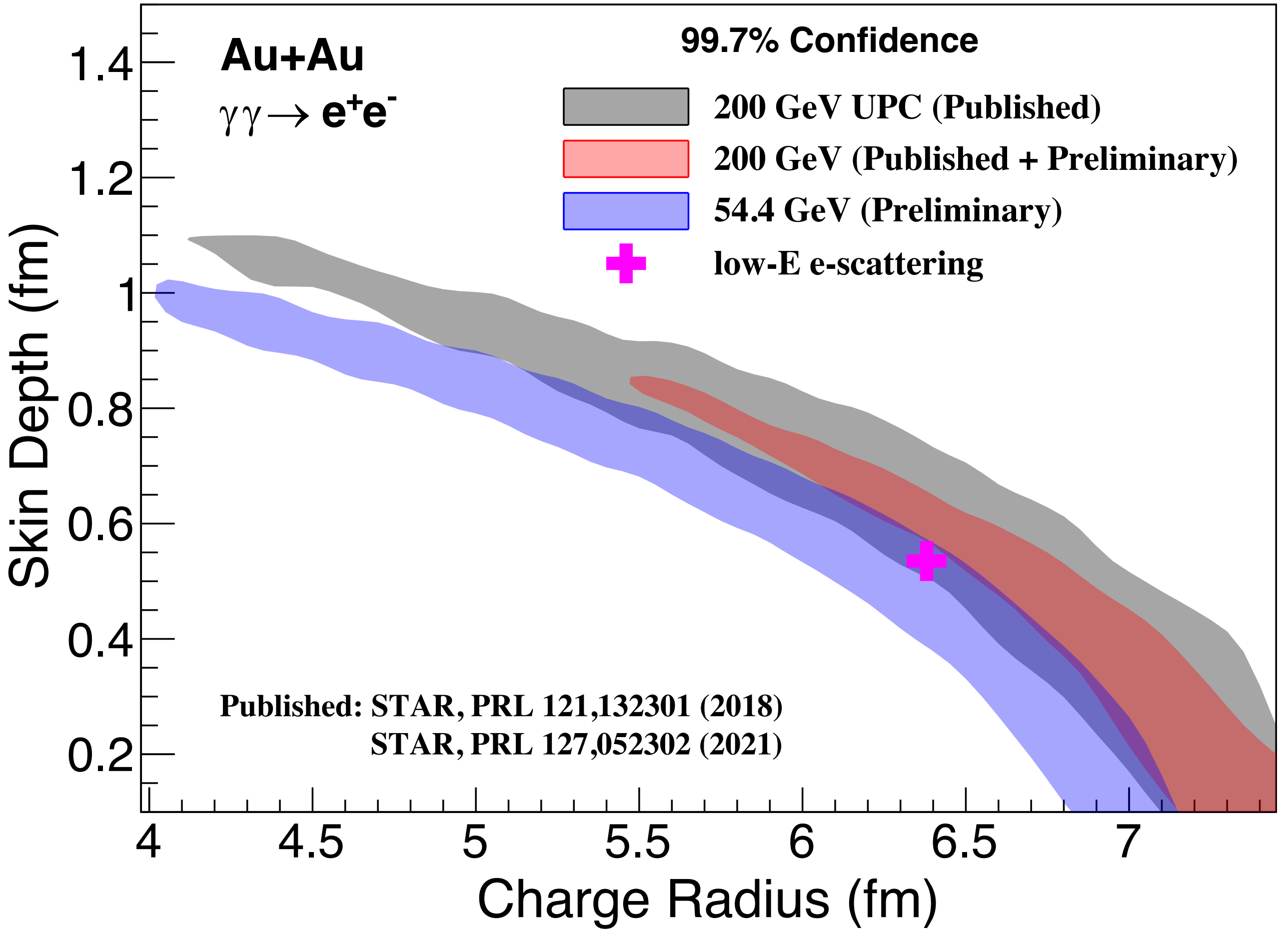

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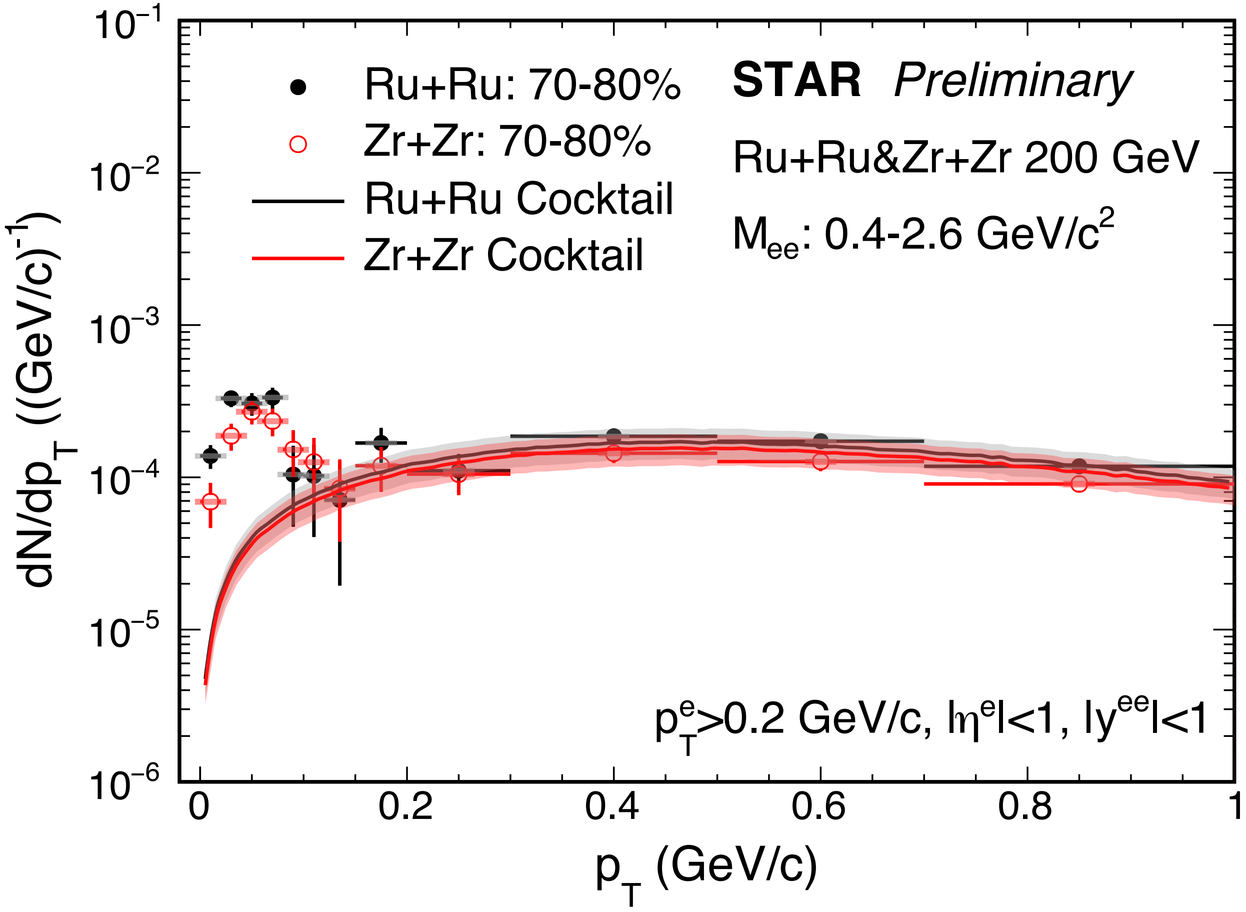
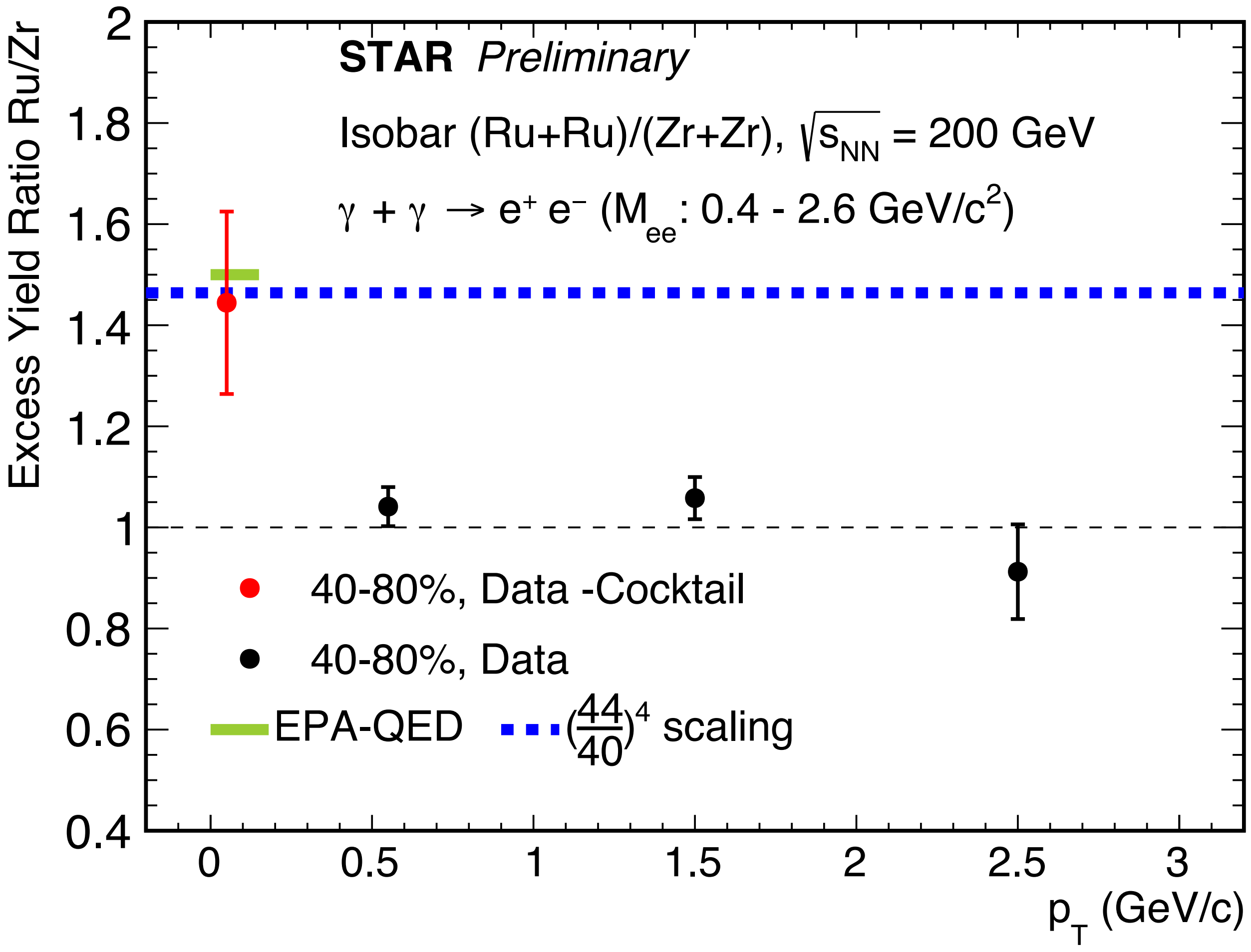
EPA-QED: J. D. Brandenburg et al, Eur. Phys. J. A 57 (2021) 299.

Experimental Constraints on Initial EM Fields



- Possible null CME result has opened questions:
  - How well are the initial EM fields really known?
  - Do event by-event fluctuations wash out differences?

Experimental Constraints on Initial EM Fields



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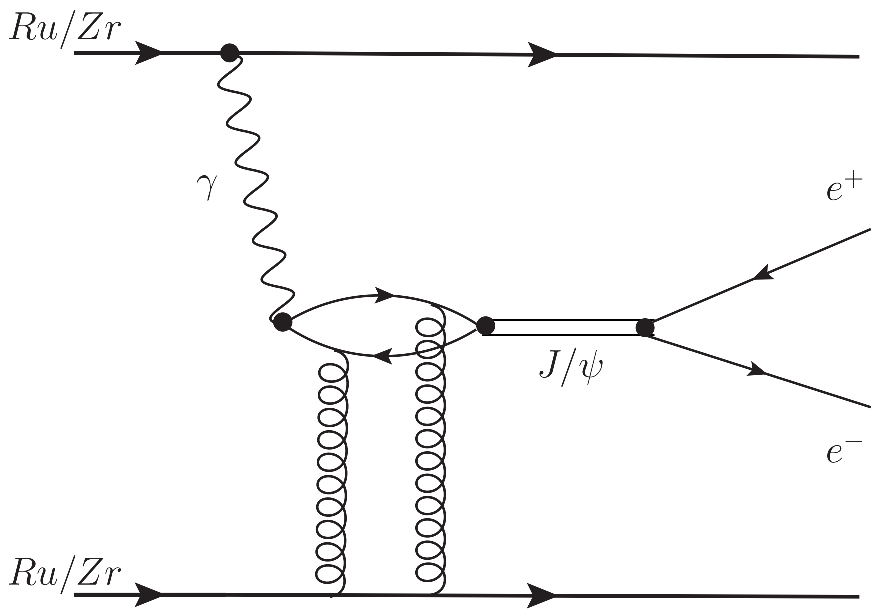
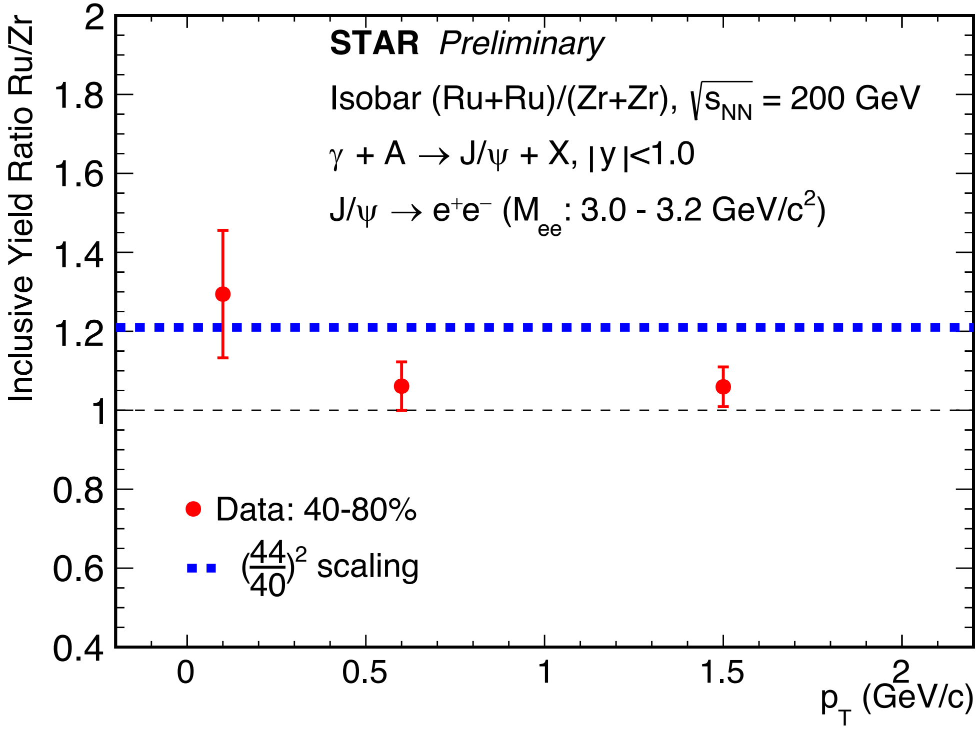
Ratio is consistent with $\left(\frac{44}{40}\right)^4$ at very low p_T

Initial EM field is different in $\mathbf{Ru+Ru}$ and $\mathbf{Zr+Zr}$ (~3σ)

Addition of dimuon data pending

Constraints from Photo-Nuclear Processes

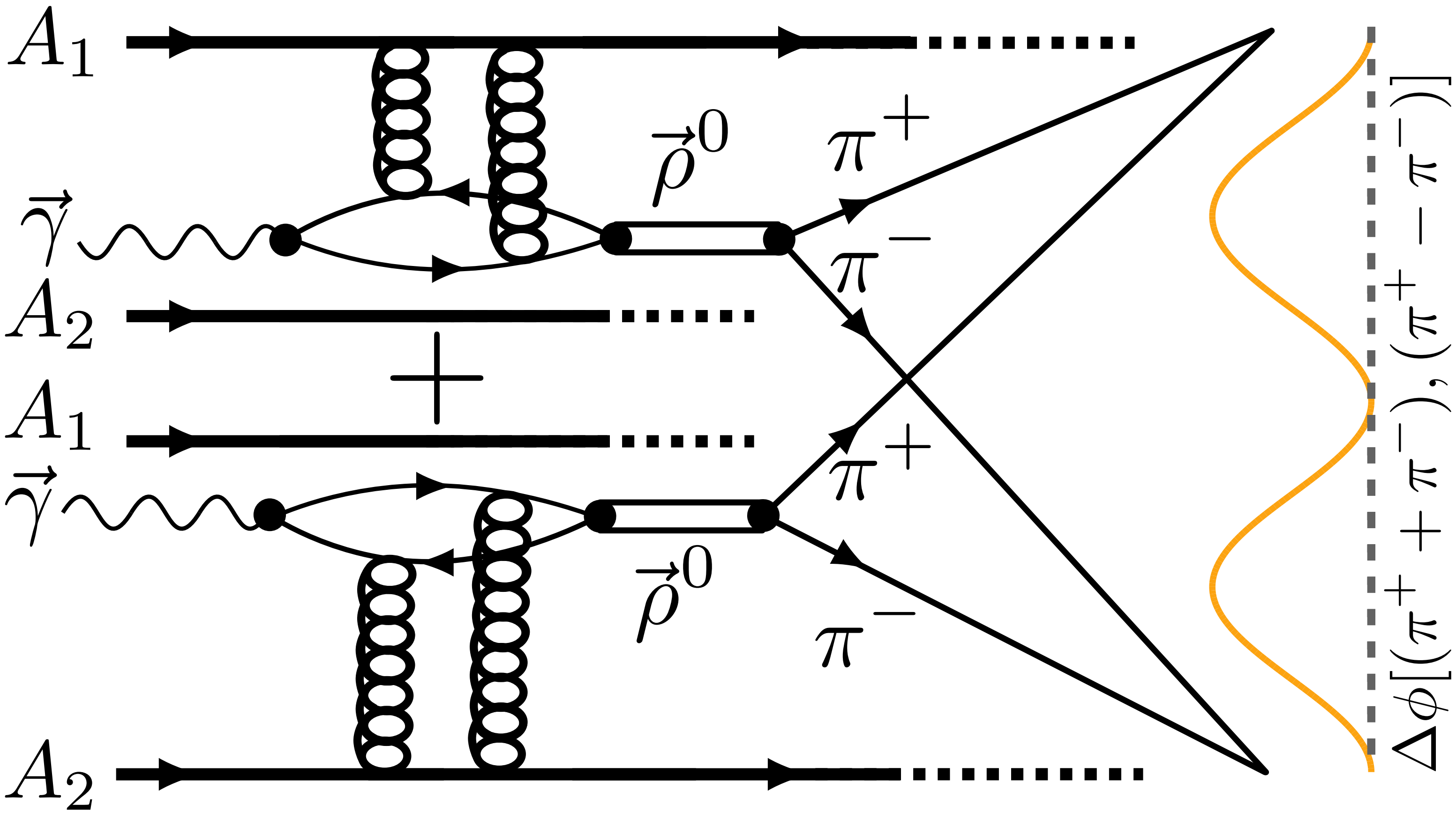




- At very low p_T, J/ψ dominated by $\gamma A \rightarrow J/\psi$
- Ratio is consistent with $\left(\frac{44}{40}\right)^2$ at very low p_T
- Initial EM field is different in $\mathrm{Ru+Ru}$ and $\mathrm{Zr+Zr}$ ($\sim 1.7\sigma$)
- At p_T > 0.2 GeV/c, hadronic production contributions to J/ψ are similar in $\mathrm{Ru+Ru}$ and $\mathrm{Zr+Zr}$

Evidence that initial fields are similar to expectations

Quantum Entanglement Enabled Nuclear Tomography



Nuclear Radius is Too Large???

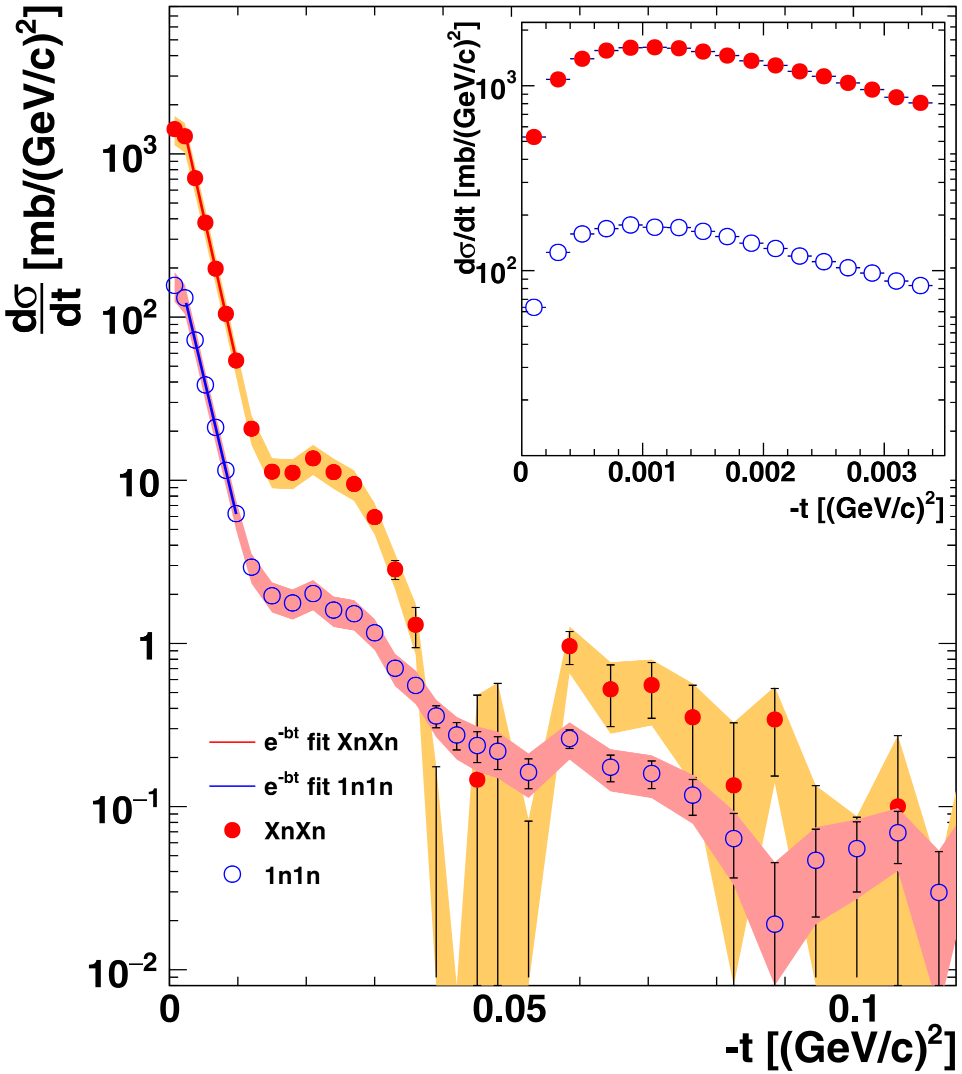


Photo-nuclear measurements have historically produced a |t| slope that corresponds to a **mysteriously large source!**

STAR (2017): |t| slope = $407.8 \pm 3 (GeV/c)^{-2}$

→ Effective radius of 8 fm

$(R_{Au}^{charged} \approx 6.38$ fm)

ALICE (Pb) : |t| slope = $426 \pm 6 \pm 15\ (GeV/c)^{-2}$

→ Effective radius of 8.1 fm

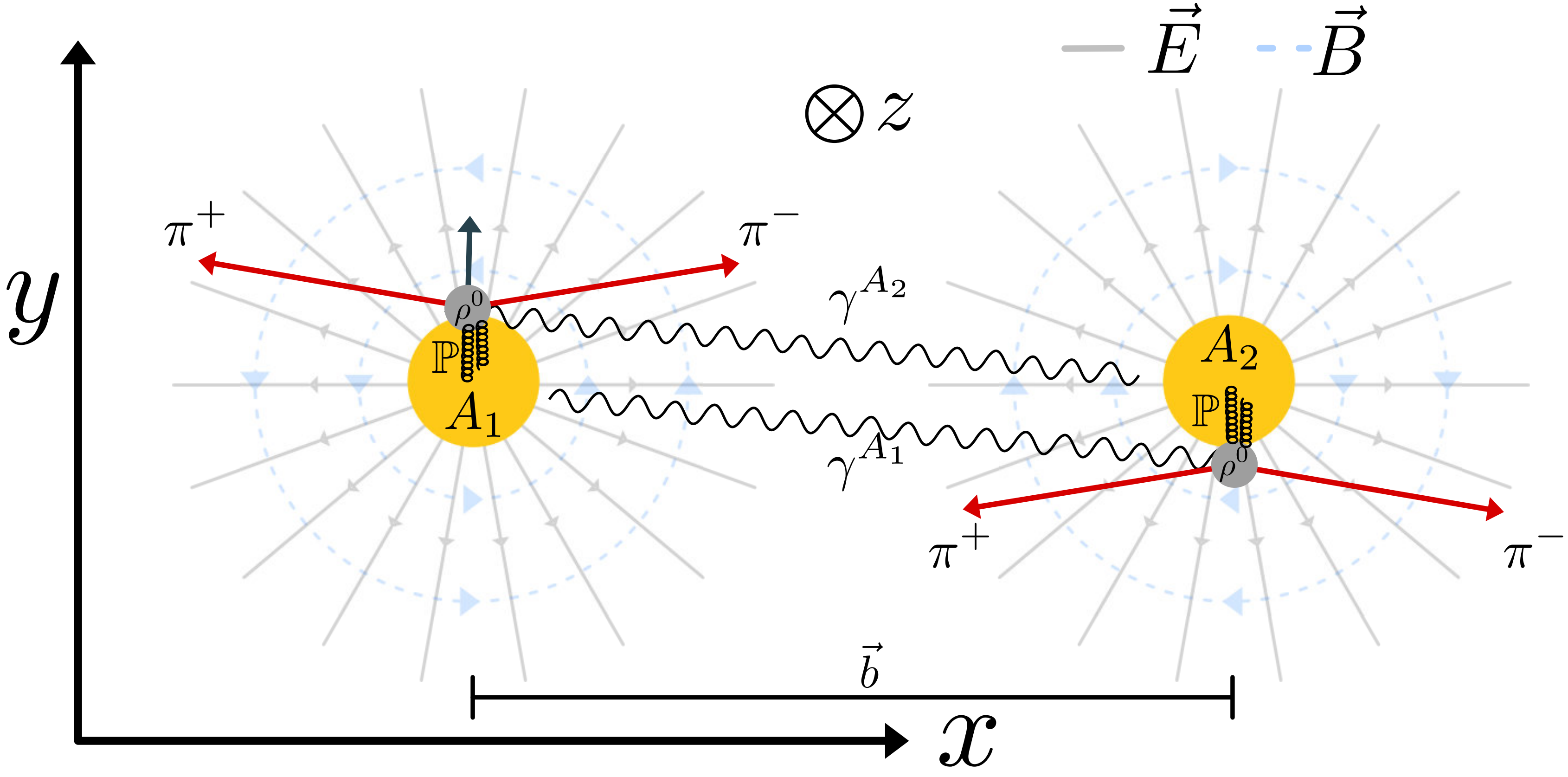
$(R_{Pb}^{charged} \approx 6.62$ fm)

Extracted nuclear radii are way too large

STAR Collaboration, L. Adamczyk, *et al.*, *Phys. Rev. C* 96, 054904 (2017).
J. Adam *et al.* (ALICE Collaboration), J. High Energy Phys. 1509 (2015) 095.

Interference in γA process

Nuclei 'take turns' emitting photon vs. Pomeron

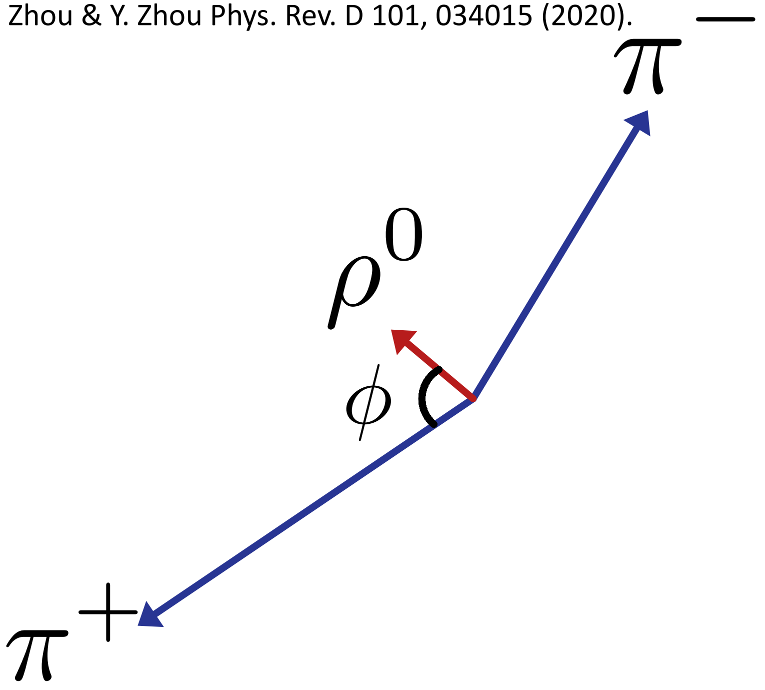


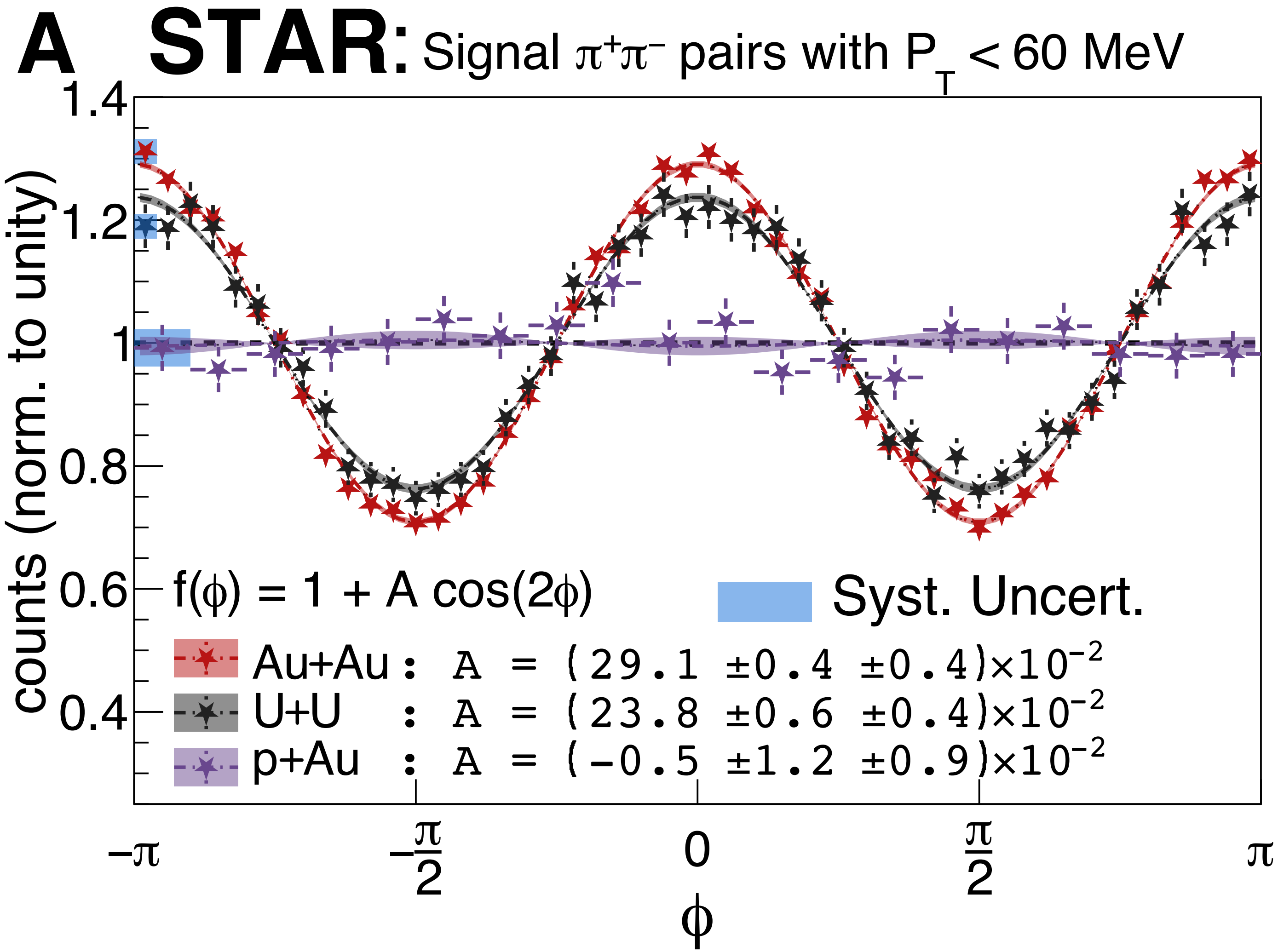
Interference between two **indistinguishable** cases

arXiv:2204.01625

ϕ Measurement in Au+Au and U+U Collisions

C. Li, J. Zhou, Y. Zhou, Phys. Lett. B 795, 576 (2019)
C. Li, J. Zhou & Y. Zhou Phys. Rev. D 101, 034015 (2020).





Quantify the difference in strength for Au+Au vs. U+U via a fit:

$$f(\Delta\phi) = 1 + a\ \cos 2\Delta\phi$$

Au+Au : $a = 0.292 \pm 0.004$ (stat) ± 0.004 (syst.)
U+U : $a = 0.237 \pm 0.006$ (stat) ± 0.004 (syst.)
Difference of 4.3σ (stat. & syst.):

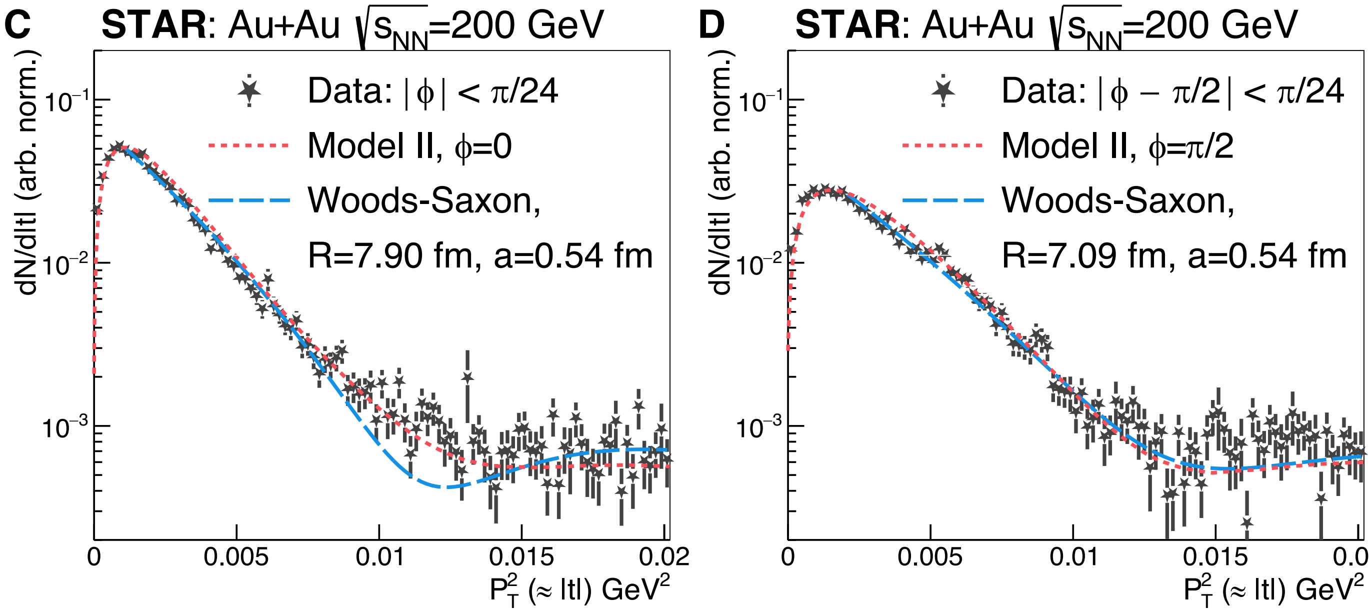
arXiv:2204.01625

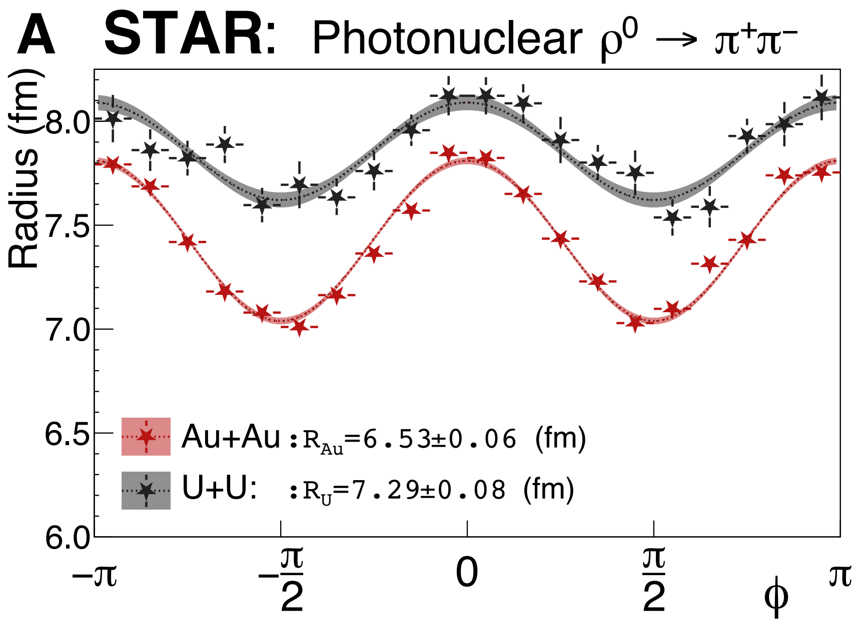
- Interference effect is sensitive to the nuclear geometry (gluon distribution) – difference between Au and U

Precision Pb Neutron Skin Measurement at RHIC

Spin Interference effect causes apparent increase of nuclear size. For 20 years, extracted radius appeared ~1 fm too large

Precision measurement of ^{197}Au and ^{238}U mass radii via interference effect in diffractive photonuclear production





- Direct measurement of the radius (R) and skin depth (a) with small uncertainty
- **First technique for measuring neutron skin at high-energy!**

Extracted neutron skin (S_A):

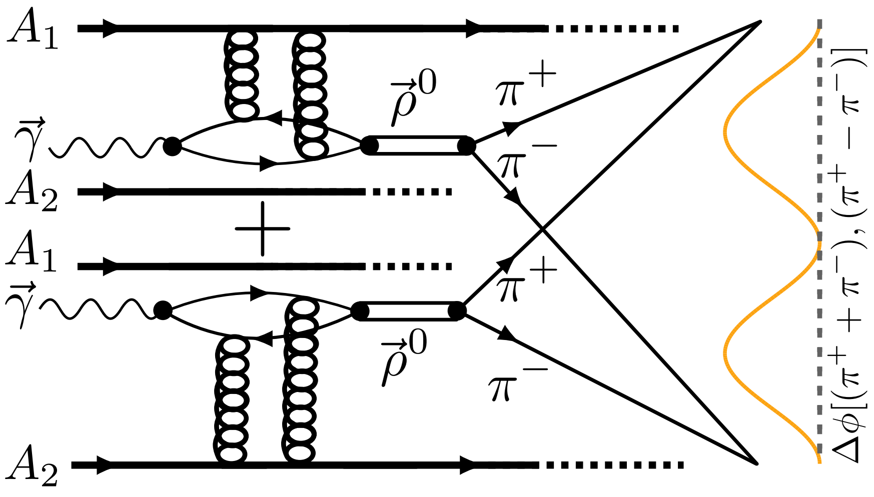
$S_{Au} = 0.17 \pm 0.03(\text{stat.}) \pm 0.08(\text{syst.})$ fm

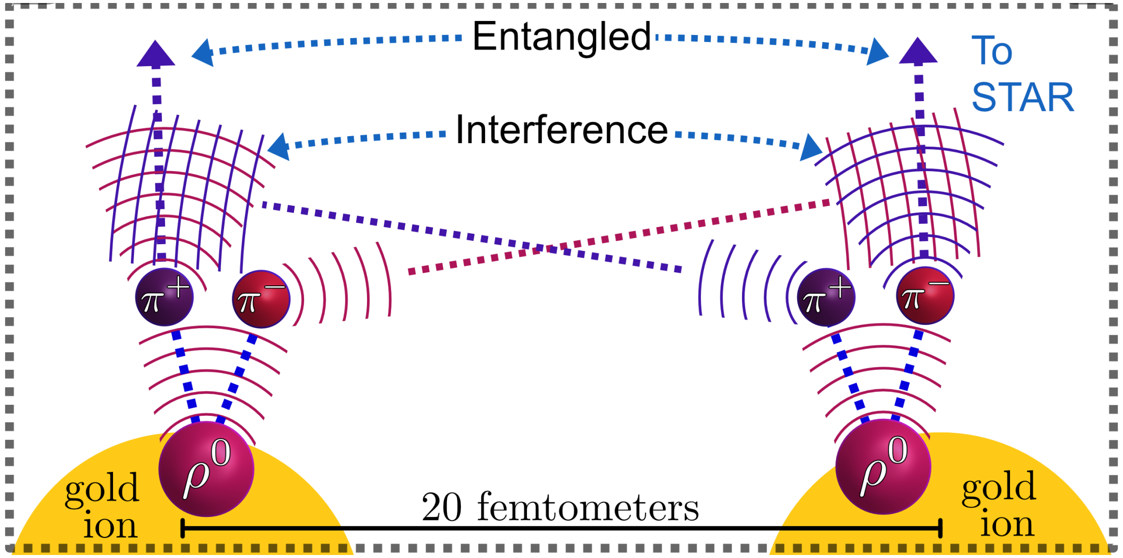
$S_U = 0.44 \pm 0.05(\text{stat.}) \pm 0.08(\text{syst.})$ fm

JDB, STAR Collaboration, https://arxiv.org/abs/2204.01625

Discovery of Novel Quantum Entanglement Enabled Spin Interference

- Final-state Interference between **distinguishable** particles
- Resolves a ~20-year puzzle in diffractive photonuclear measurements
- Calibrated source of linearly polarized photons provides a **precision probe of gluon distribution within heavy nuclei**





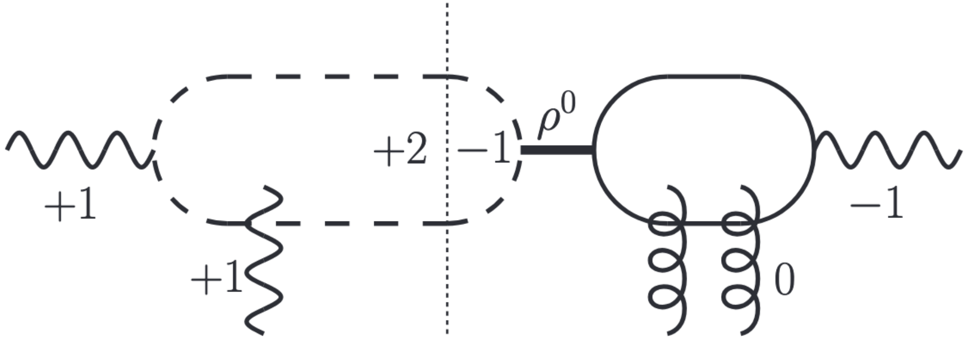
J. Cotler, F. Wilczek, and V. Borish, Annals of Physics **424**, 168346 (2021).

- For the first time: we can measure neutron skin at **high-energy**!

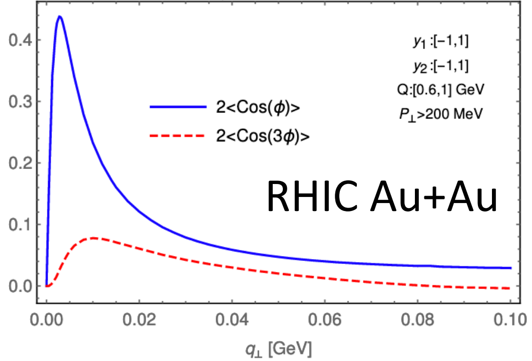
Quantum Entanglement and Gluon Tomography

JDB, et. al., arXiv:2207.02478 [hep-ph]

New approach to Coulomb-Nuclear Interference

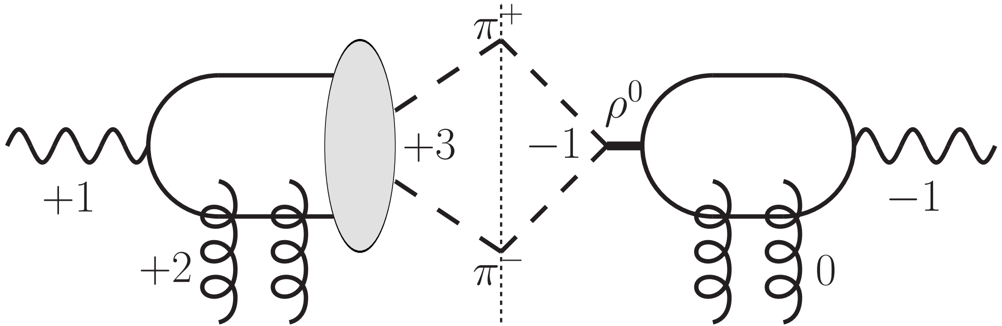


Phys. Rev. D 103, 074013 (2021)

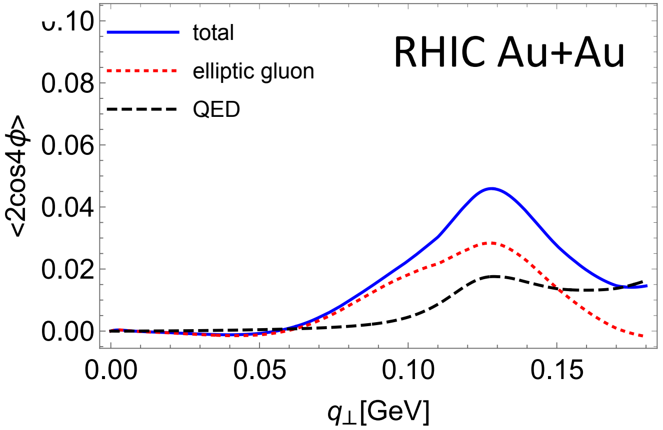


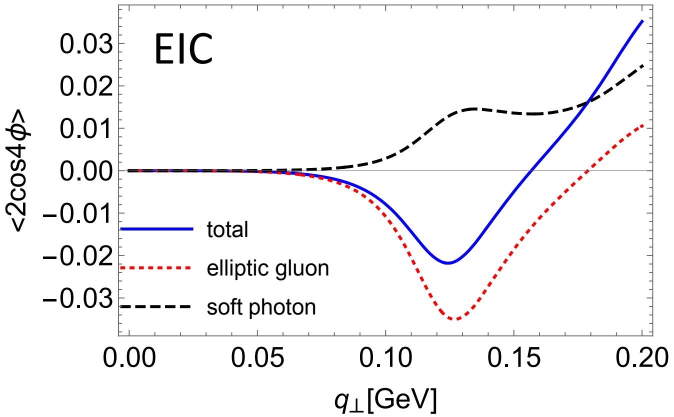
Final state asymmetries due to QED-QCD interference, reveals phase between photon and gluon fields

Gluon tomography at RHIC and EIC



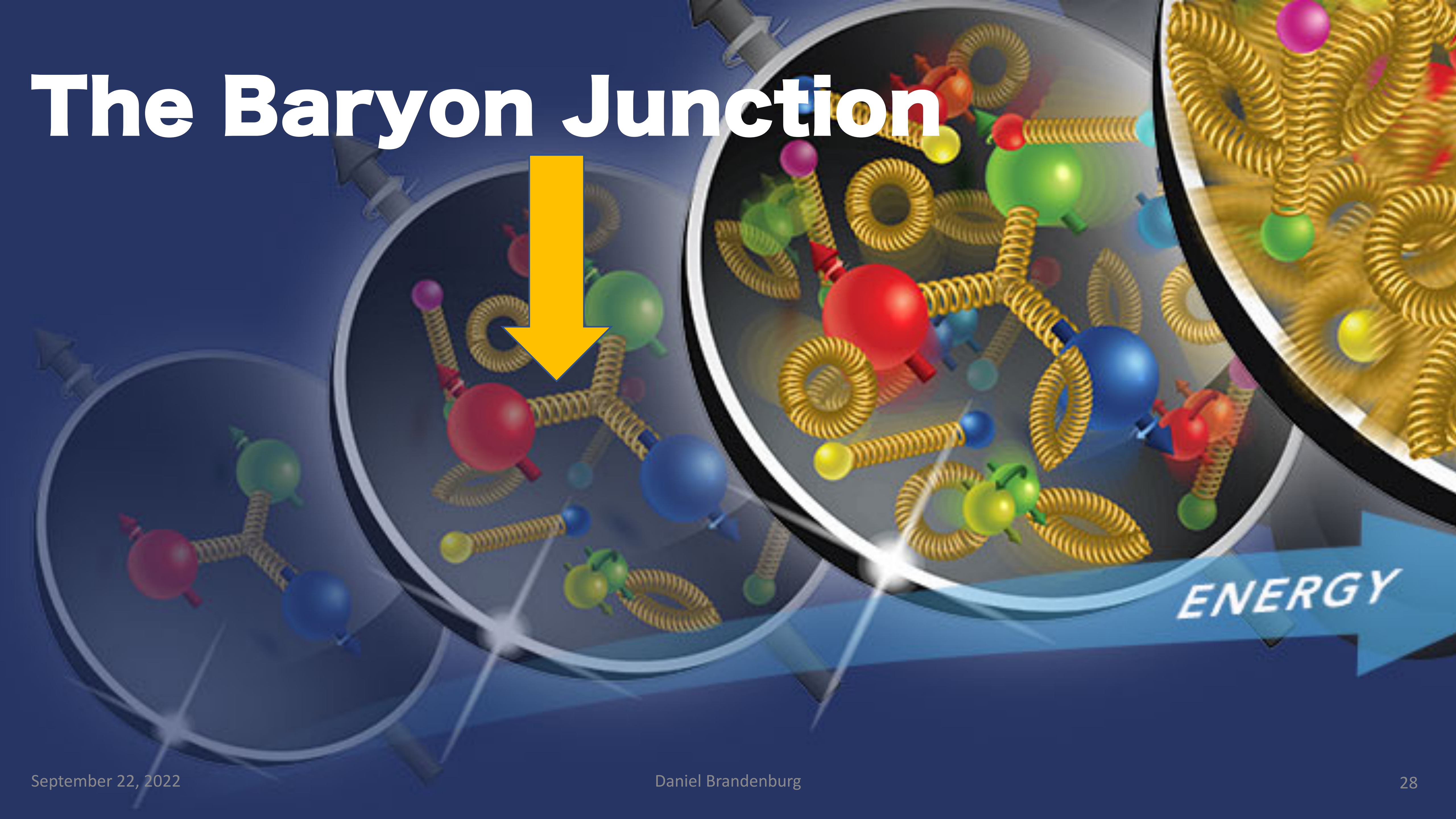
Phys. Rev. D **104**, 094021 (2021)





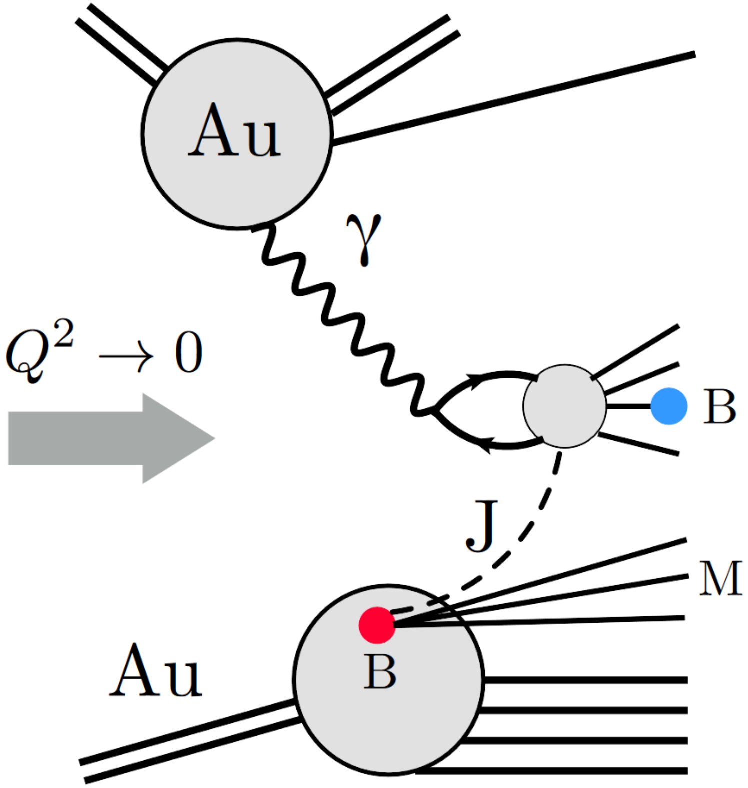
Clear signature of elliptic gluon distribution within nuclei. Complimentary measurements at RHIC and EIC

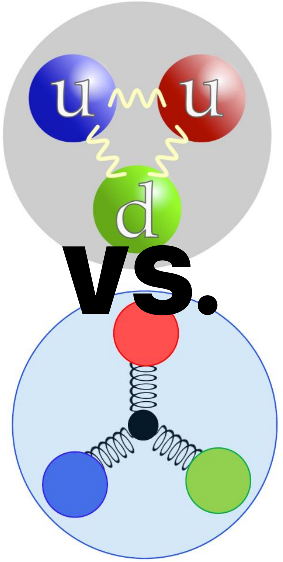
The Baryon Junction



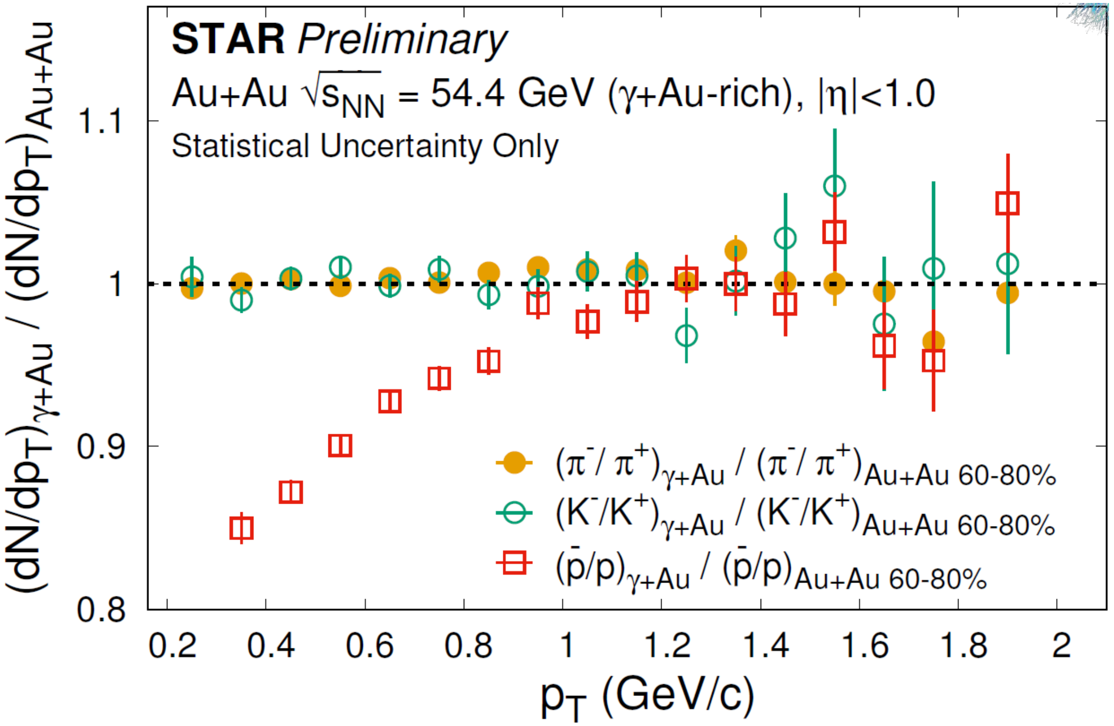
Searching for the Baryon Number

- Baryon Number is one of the most strictly conserved quantum numbers





J. D. Brandenburg *et al*, arXiv 2205.05685



- Double ratio: $\bar{p}/p < 1$ at lower p_T

- Soft baryon stopping that is **stronger** in γA compared to peripheral AA
  - Indication of a baryon junction existing inside nucleon

D. Kharzeev, Physics Letters B **378**, 238-246 (1996)

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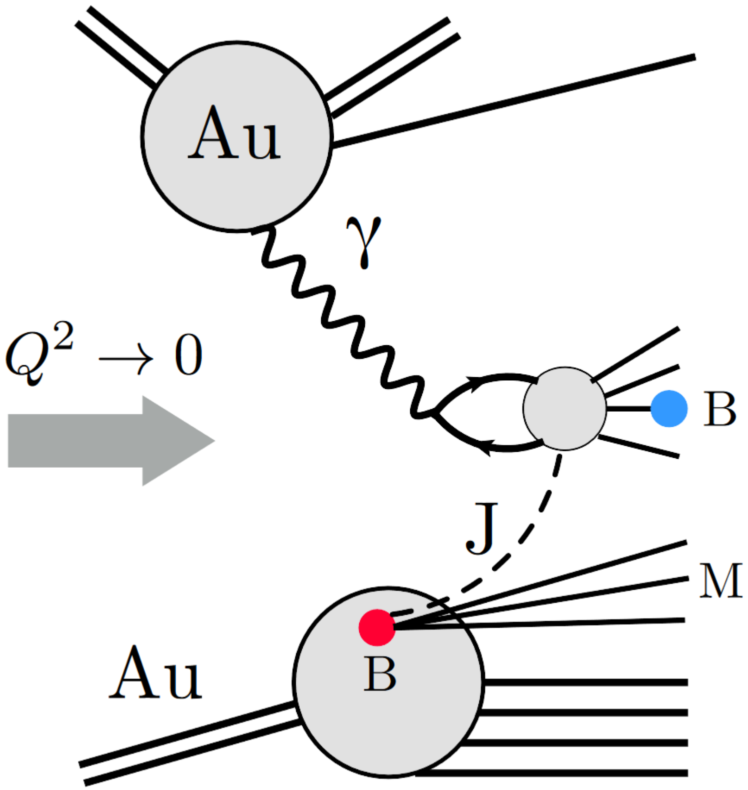
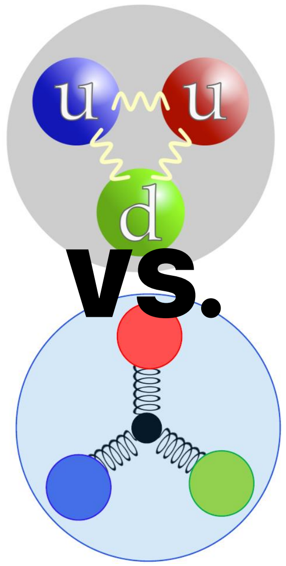
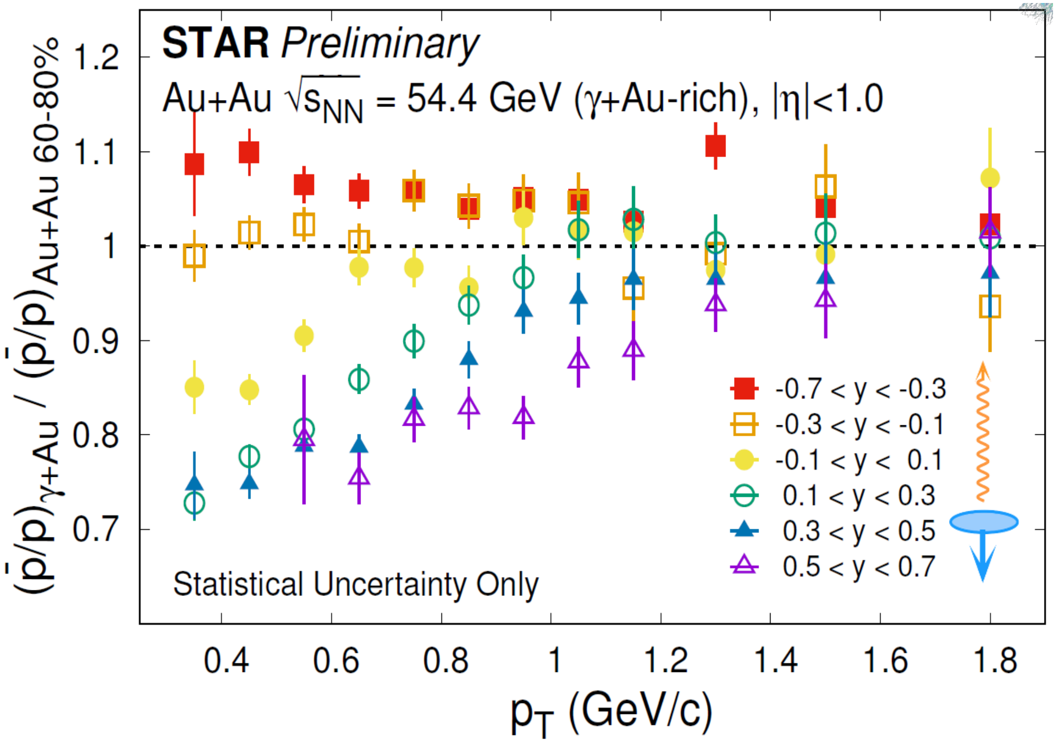


J. D. Brandenburg *et al*, arXiv 2205.05685





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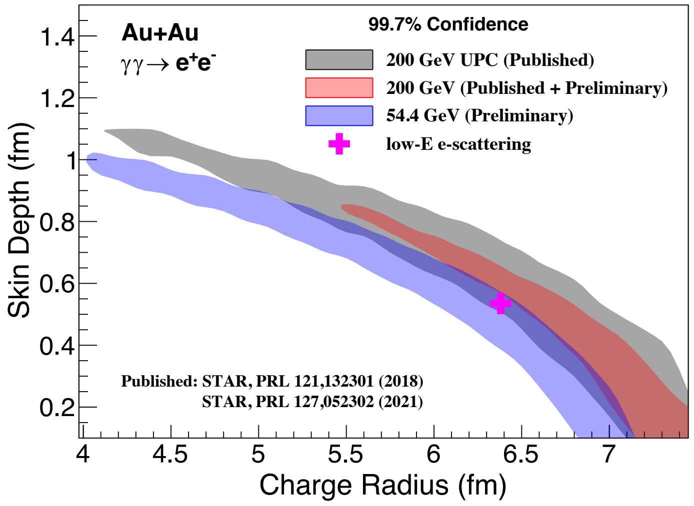
D. Kharzeev, Physics Letters B **378**, 238-246 (1996)

Discoveries at STAR with Polarized Photons



EPA-QED: J. D. Brandenburg et al, Eur. Phys. J. A 57 (2021) 299.

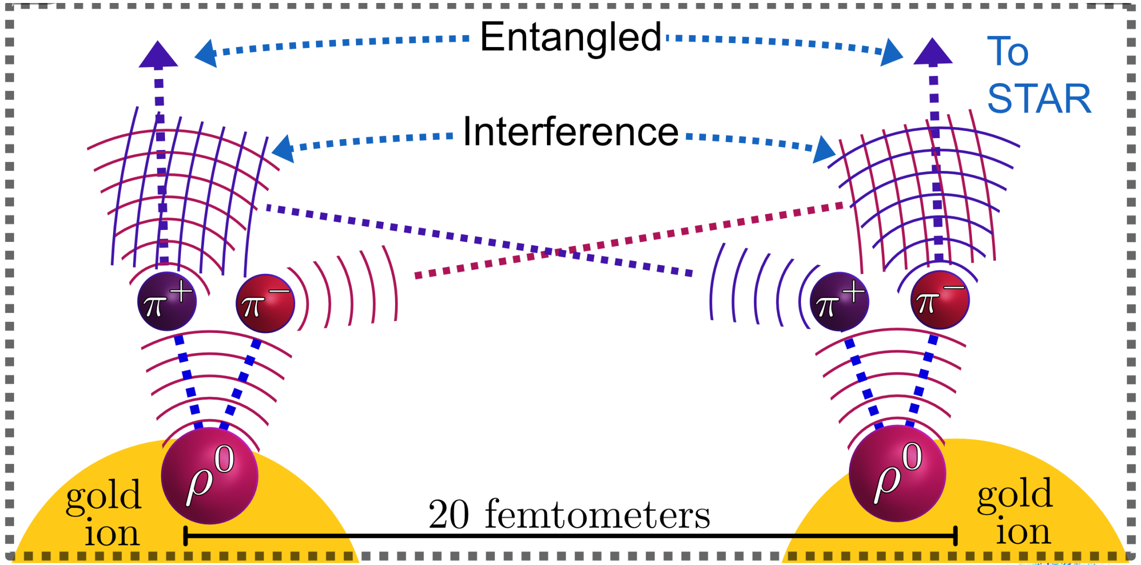
1. Observation of the Breit-Wheeler process

- Vacuum Birefringence effects provide precision calibration of photon wavefunction
- Image nuclear charge distribution & experimentally constrain initial EM fields of e.g. Isobar collisions

2. Discovery of Spin Interference Enabled Nuclear Tomography

- Precision neutron skin measurements:

$$S_{Au} = 0.17 \pm 0.03(\text{stat.}) \pm 0.08(\text{syst.})\ \text{fm}$$
$$S_{U} = 0.44 \pm 0.05(\text{stat.}) \pm 0.08(\text{syst.})\ \text{fm}$$

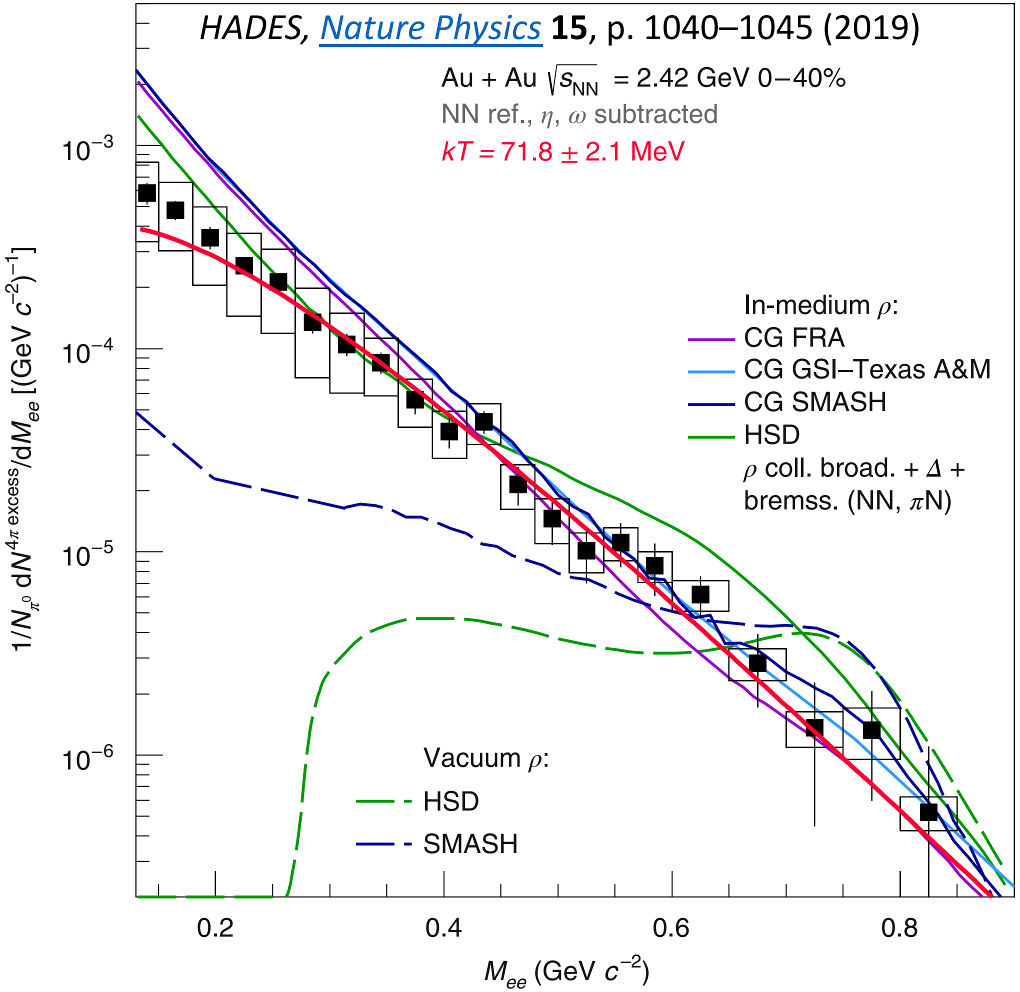


FUTURE: Baryon Number is a fundamental conserved quantum number

- How is it manifest / carried by nucleons?
- **Baryon Junction provides potential explanation of increased stopping observed in γA compared to AA**

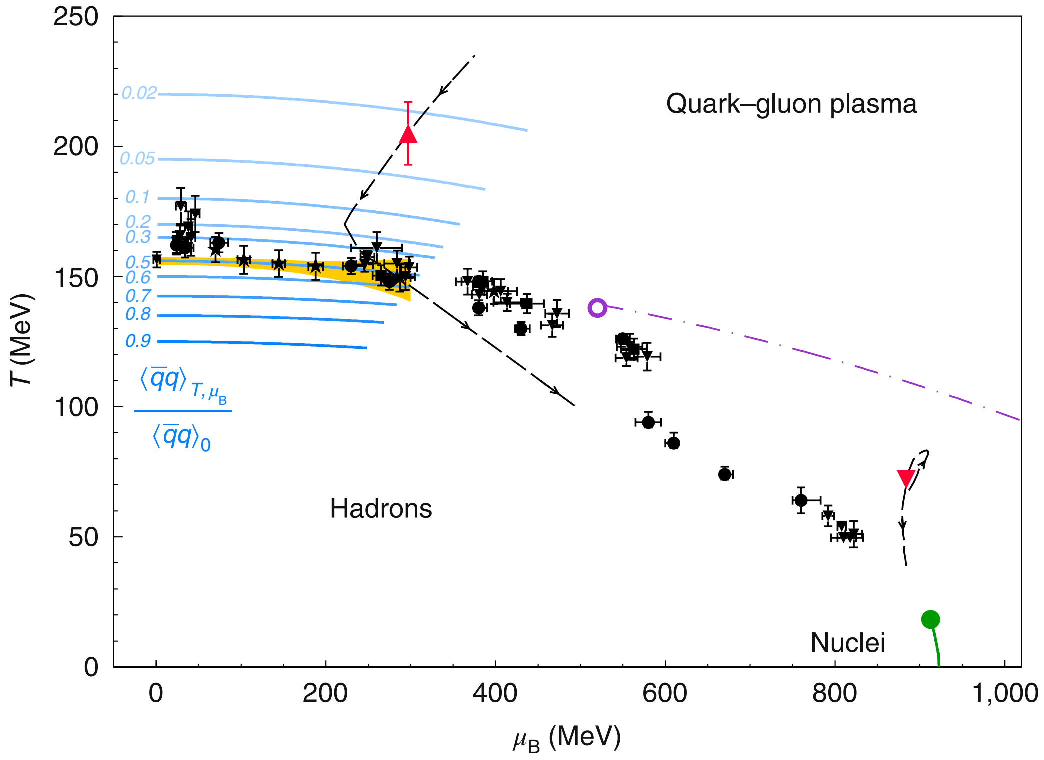
Thermal Dileptons

- Thermal dileptons: direct access to system properties



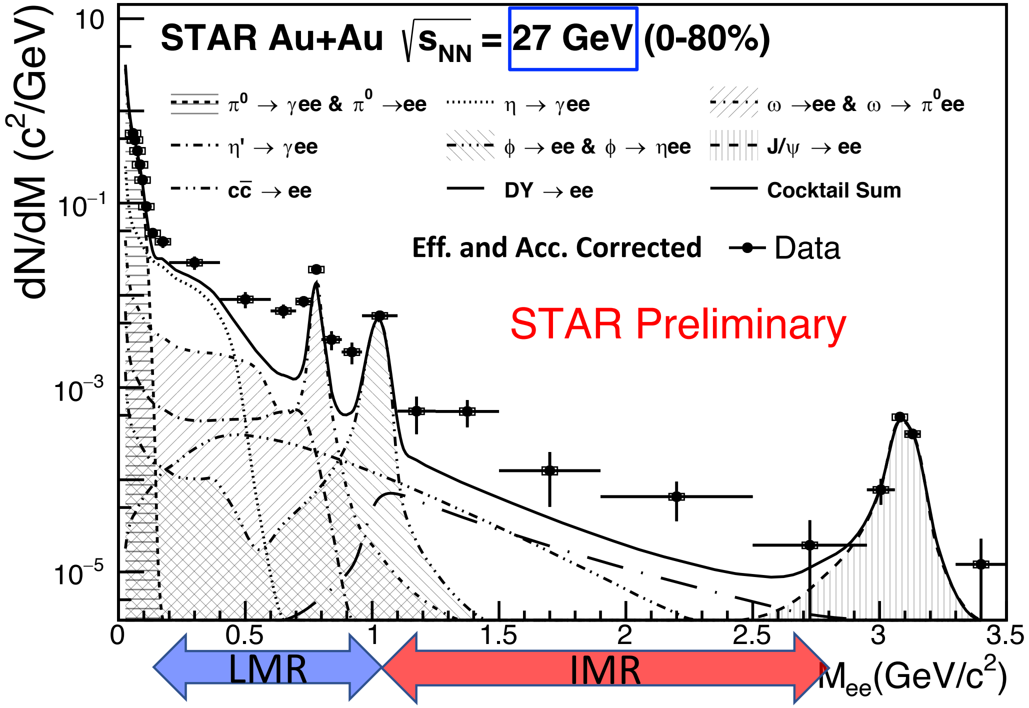
HADES, *Nature Physics* **15**, p. 1040–1045 (2019)

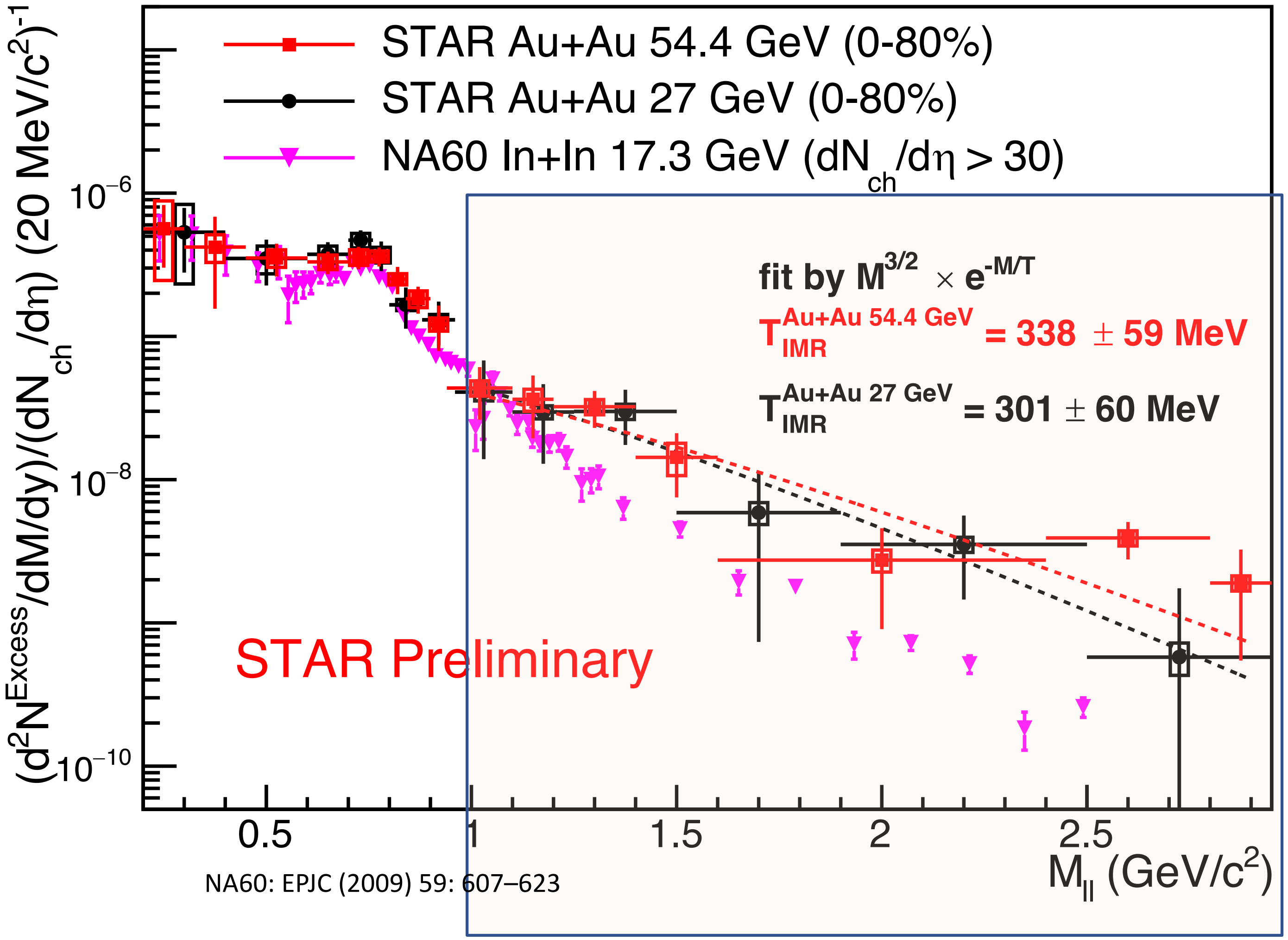
- True temperature measurement unmodified by flow dynamics



Thermal Dileptons at STAR – BES II

- BES II datasets allow drastically greater precision & energy reach





NA60: EPJC (2009) 59: 607–623

- STAR is able to extract the true QGP temperature from IMR dileptons for the first time

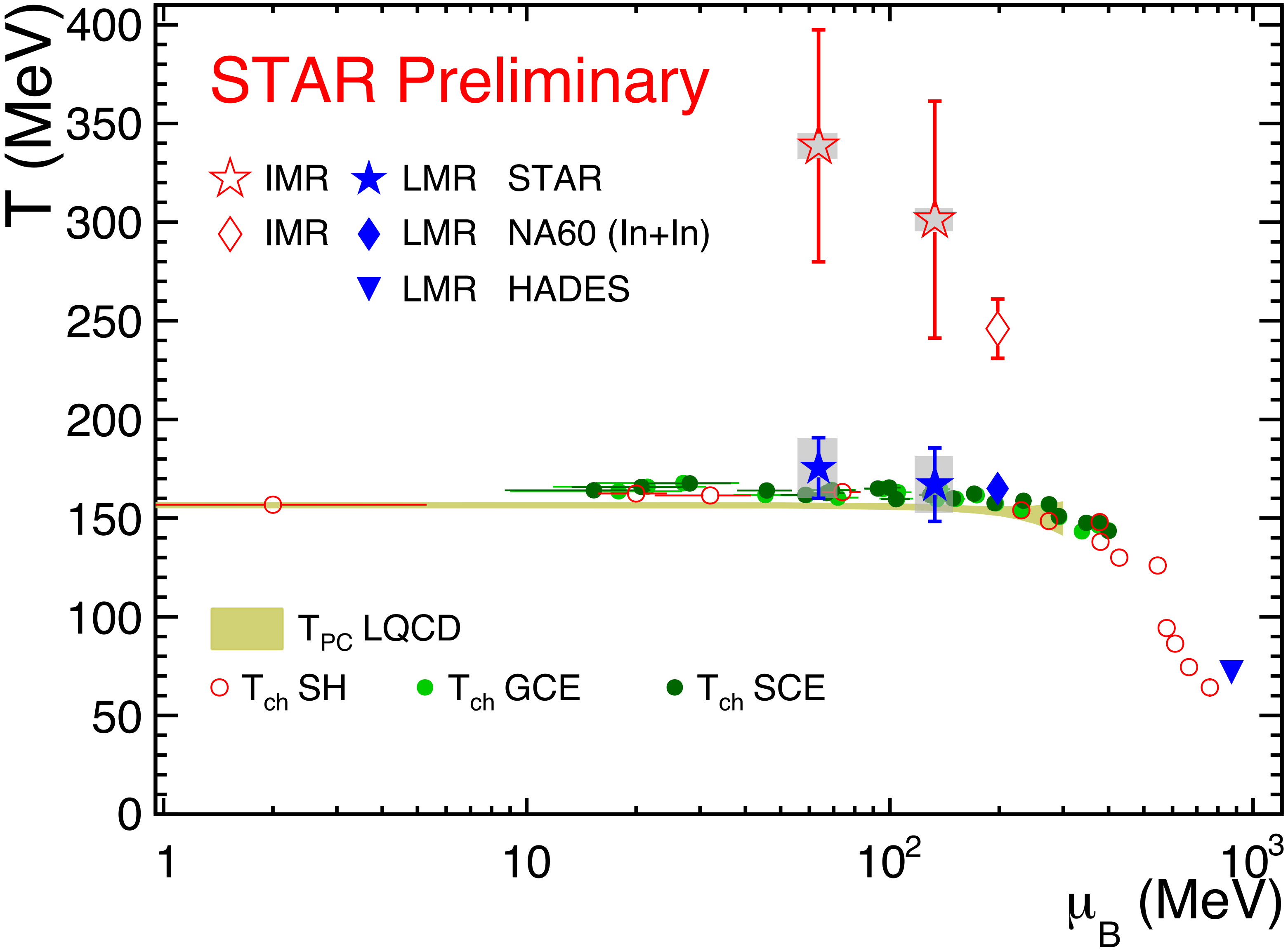
Thermal Dileptons at STAR – BES II

- Low Mass Range (LMR)
  - Extracted T is close to T_{PC} from LQCD and T_{ch} from spectra
  - Emitted from hadronic phase, near transition

- Intermediate Mass Range (IMR)
  - Extracted T found to be higher than T_{PC}
  - Dileptons emitted during the QGP phase

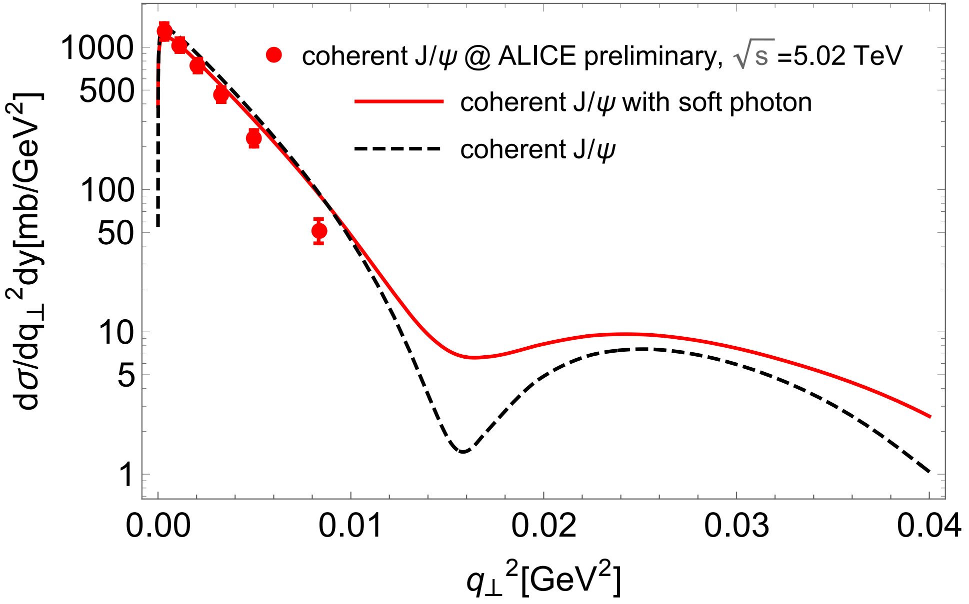
First TRUE temperature measurement of QGP phase (blue-shift-free)

- More measurements at lower BES II beam energies coming soon!

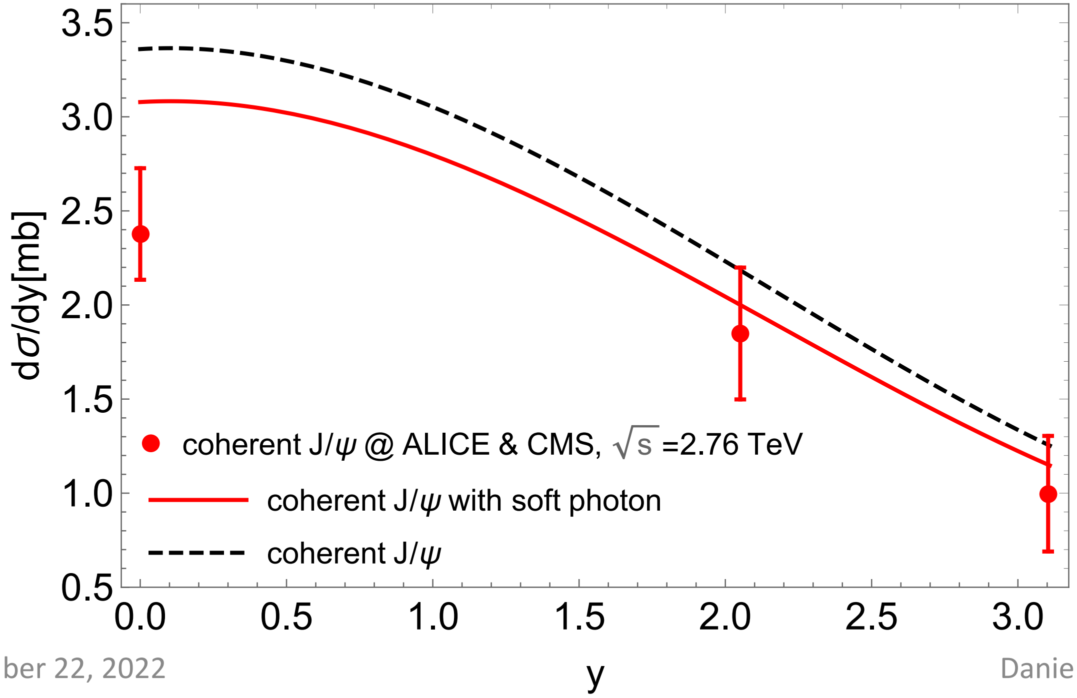


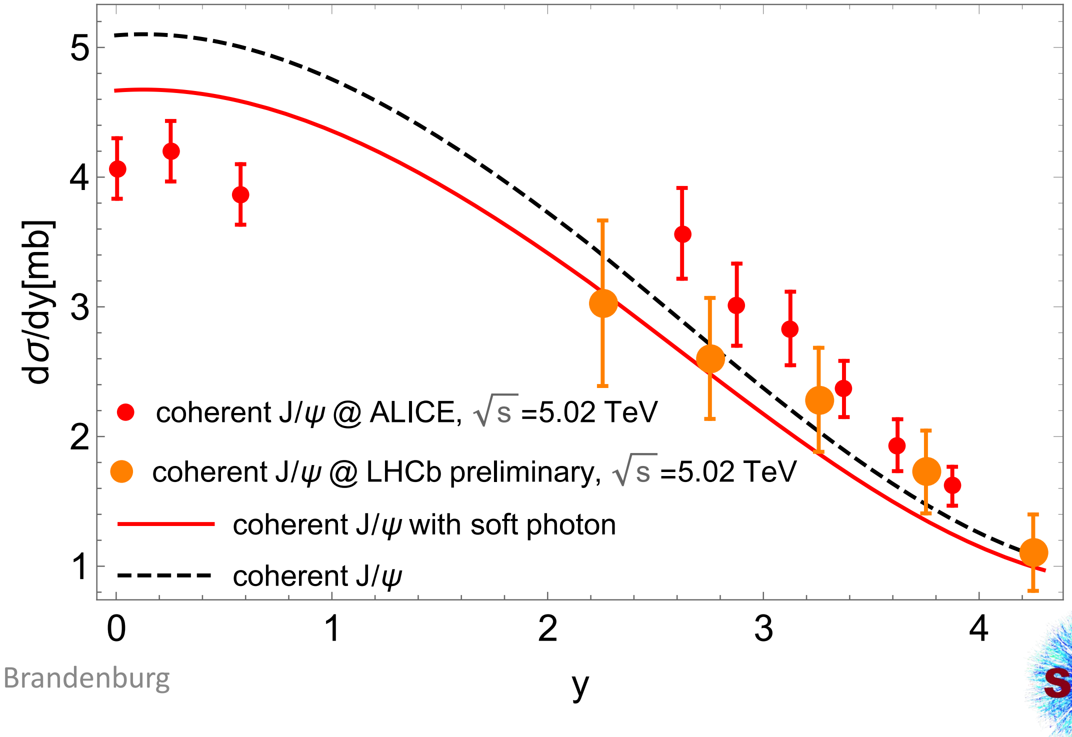
EXTRA

J/ψ ALICE data



JDB, et. al., arXiv:2207.02478 **[hep-ph]**





Azimuthal asymmetry in coherent J/ψ

JDB, et. al., arXiv:2207.02478 **[hep-ph]**

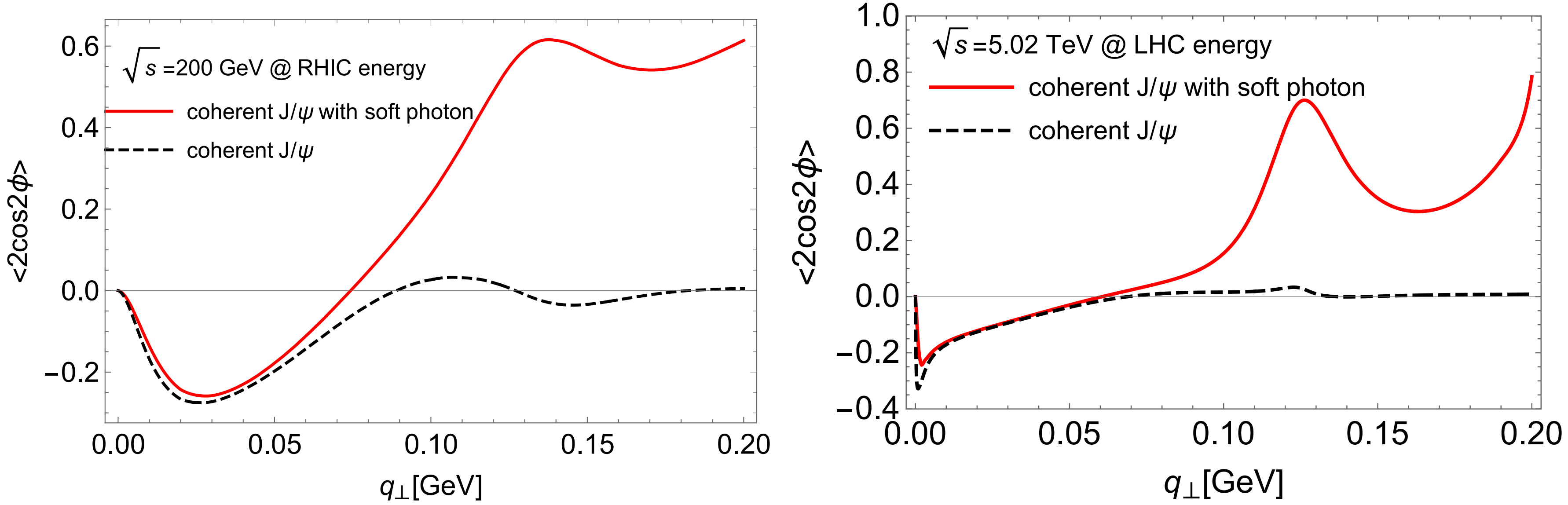
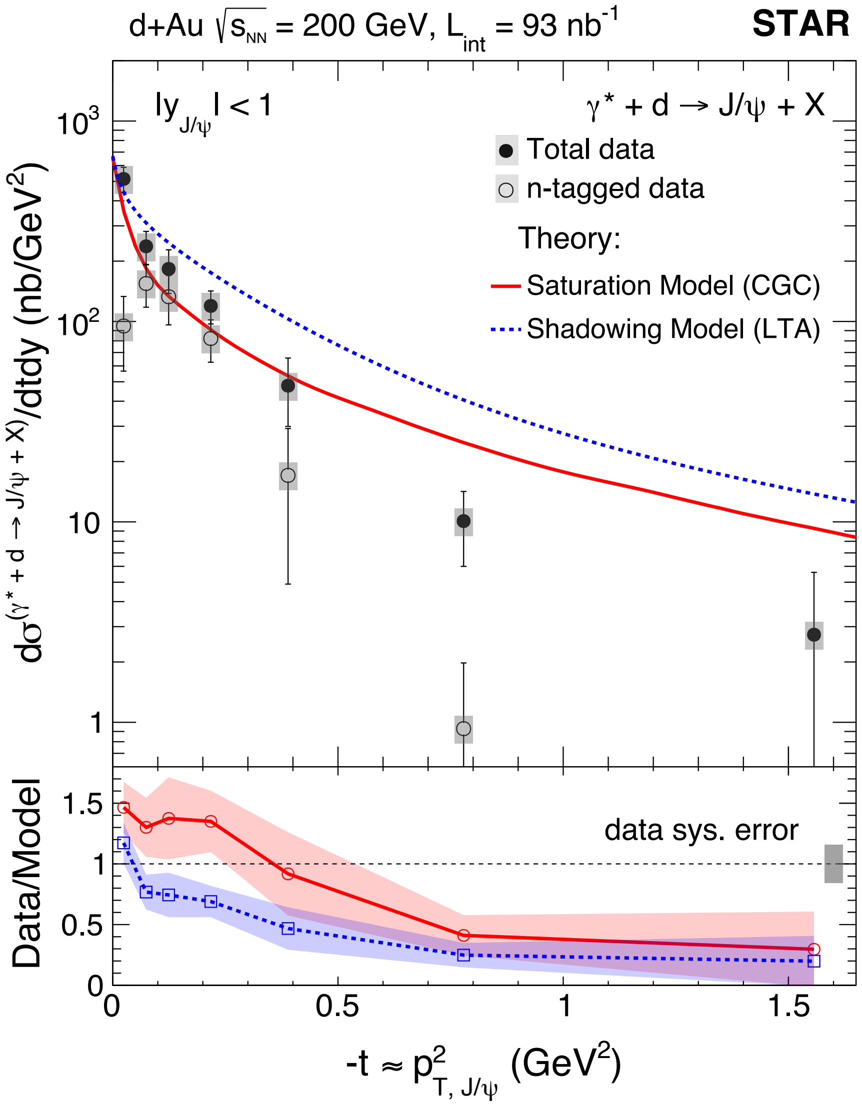


FIG. 3: $\cos 2\phi$ azimuthal asymmetry in coherent J/ψ production at RHIC energy and LHC energy. The rapidity of the di-lepton pair is integrated over the range [-1, 1] at RHIC kinematics and [-0.8,0.8] at LHC kinematics. J/ψ is reconstructed via the decay mode $J/\psi \to e^+e^-$ at RHIC and $J/\psi \to \mu^+\mu^-$ at LHC, respectively.

Probing the Gluons within Deuteron

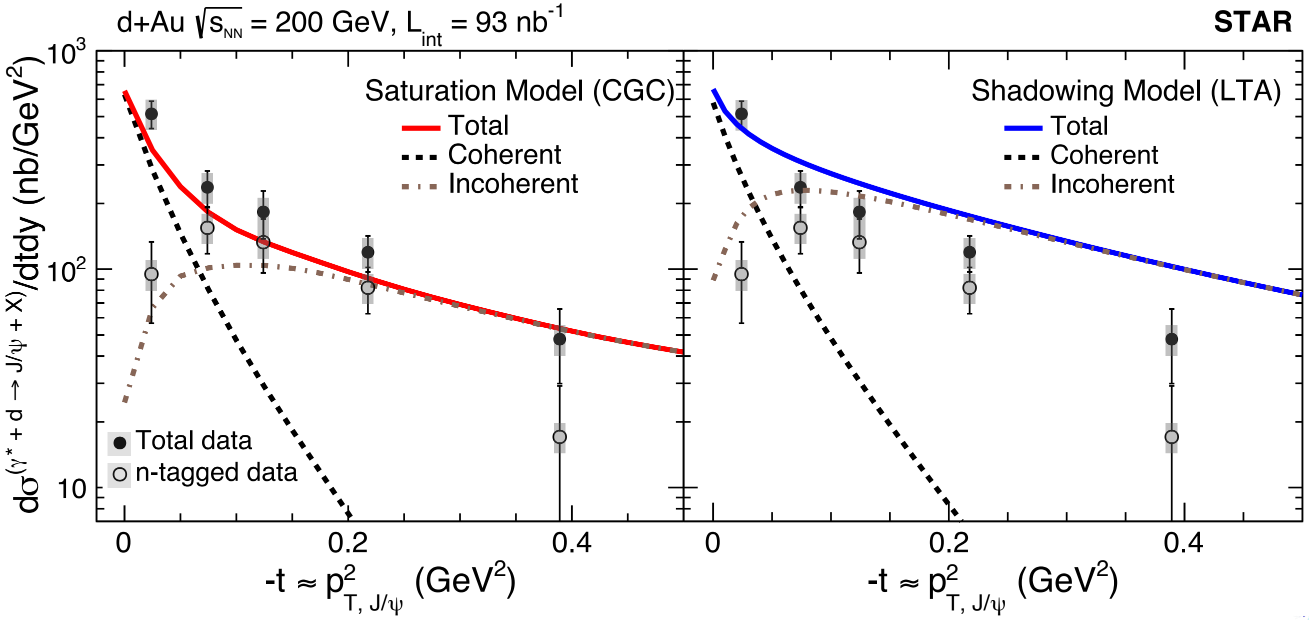
- Photoproduction of J/ψ in d+Au UPC events STAR Collaboration, [Phys. Rev. Lett. 128, 122303 (2021)](https://doi.org/10.1103/PhysRevLett.128.122303)



Why nucleus is nucleus instead of a few free nucleons sitting together?

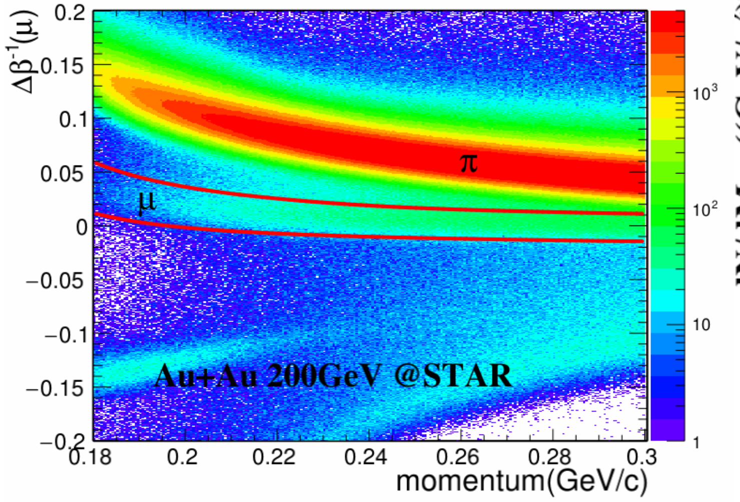
Study the simplest and lightest nuclei

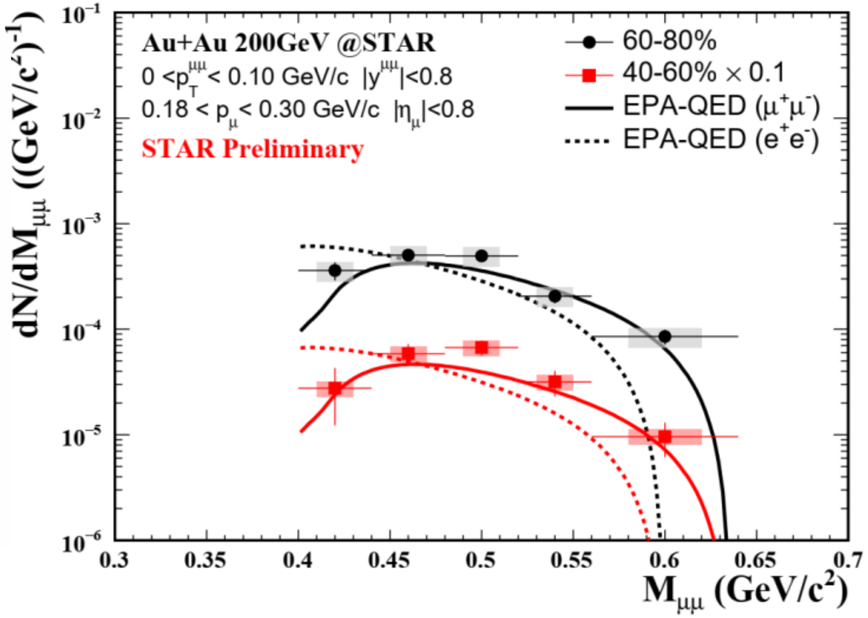
- More proton-like or nuclei-like?
- Possible to control its configurations at
- the initial state?
- UPC dAu collisions at RHIC can be a perfect testing ground

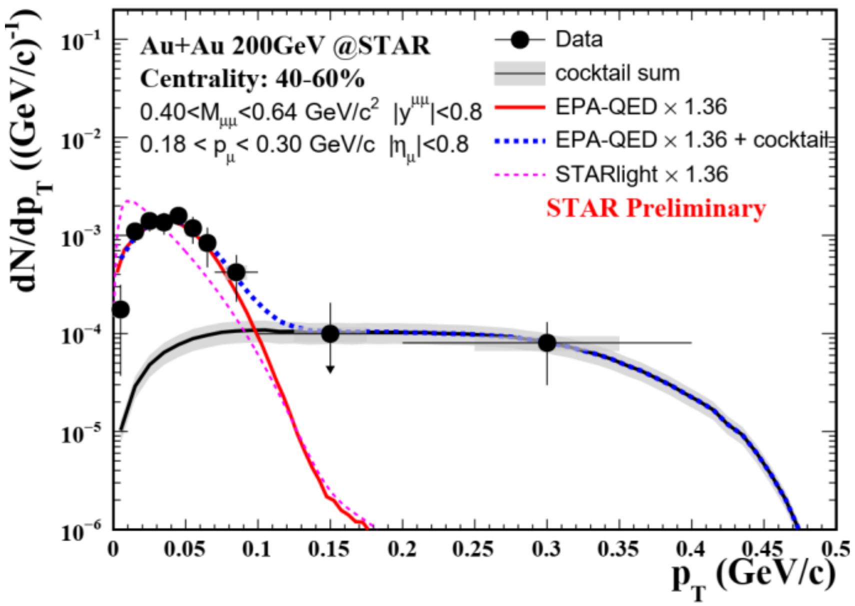


Measuring $\gamma\gamma \rightarrow \mu^+\mu^-$ at STAR

- Combining STAR's Time Projection Chamber + Time-Of-Flight PID allows identification of very low momentum muons





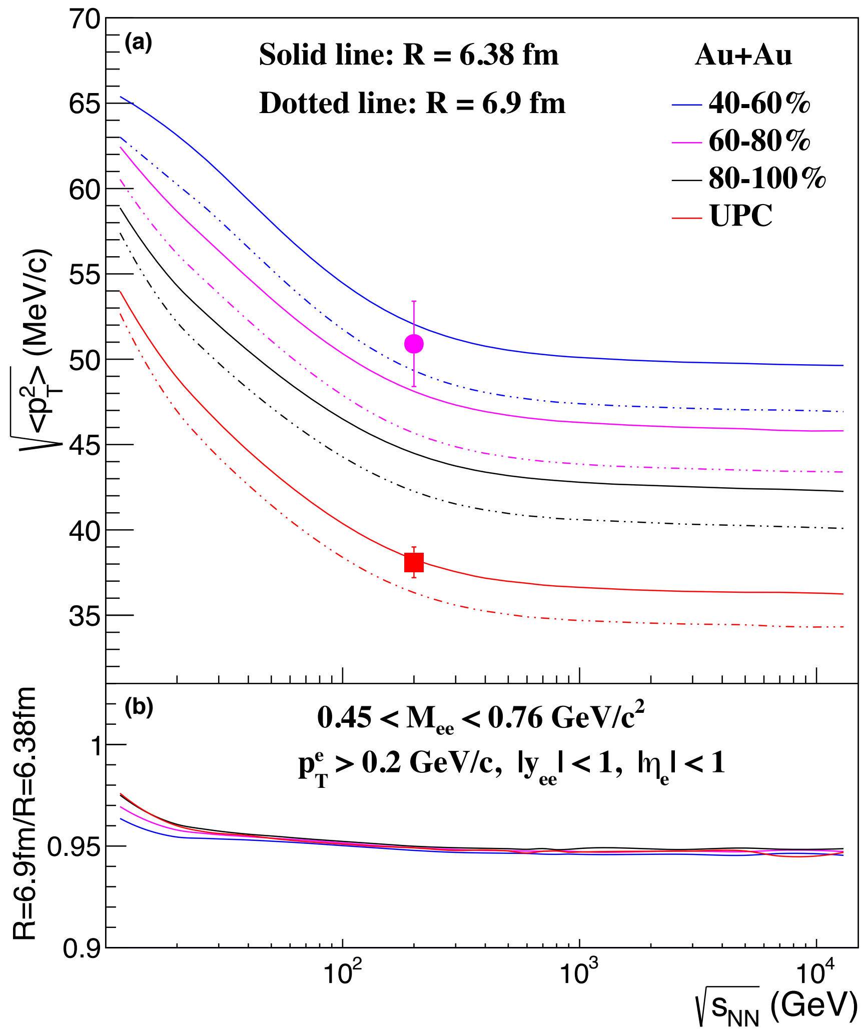


EPA-QED: W.M. Zha et al., 2020 Phys. Lett. B 800 135089

- Cross-check between e^+e^- and $\mu^+\mu^-$ demonstrate lack of photon virtuality

Energy Dependence & Infrared Divergence

- RHIC beam energy scan → unique capability to study low energy behavior



$$n(\omega) = \frac{(Ze)^2}{\pi\omega}\int_0^\infty \frac{d^2k_\perp}{(2\pi)^2}\left[\frac{F\left(\left(\frac{\omega}{\gamma}\right)^2 + \vec{k}_\perp^{\,2}\right)}{\left(\frac{\omega}{\gamma}\right)^2 + \vec{k}_\perp^{\,2}}\right]^2 \vec{k}_\perp^{\,2},$$

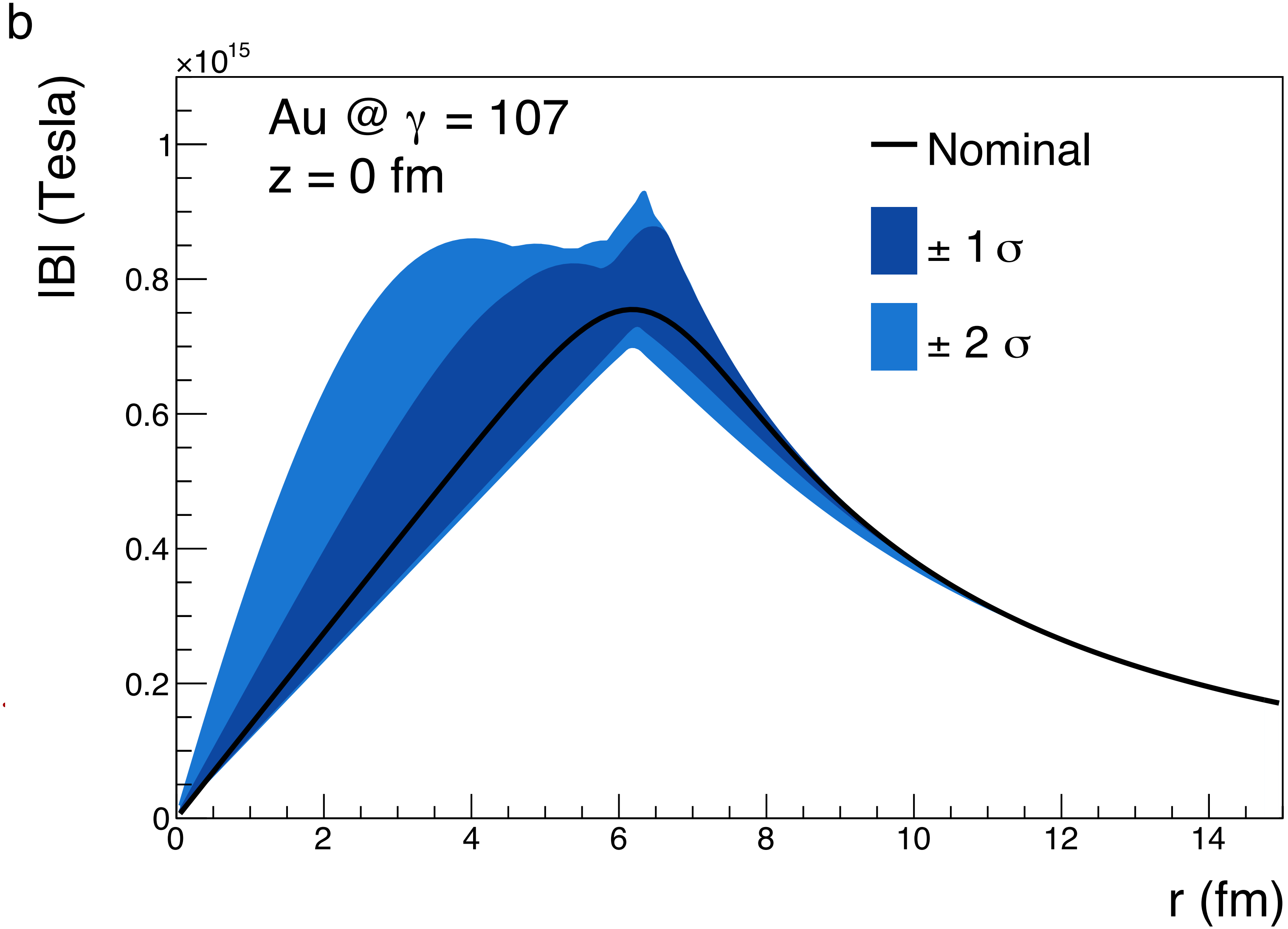
- As $k_\perp \rightarrow 0$ flux increases
- Only cutoff by the ${}^{\omega}/_{\gamma}$ term
- Allowed phase space for Breit-Wheeler processes plumets as $\sqrt{s_{NN}} \rightarrow 0$
- Sensitivity to details of the charge distribution
- Pair transverse momentum (at fixed b) increases with decreasing energy

Imaging the Nuclear Charge Distribution

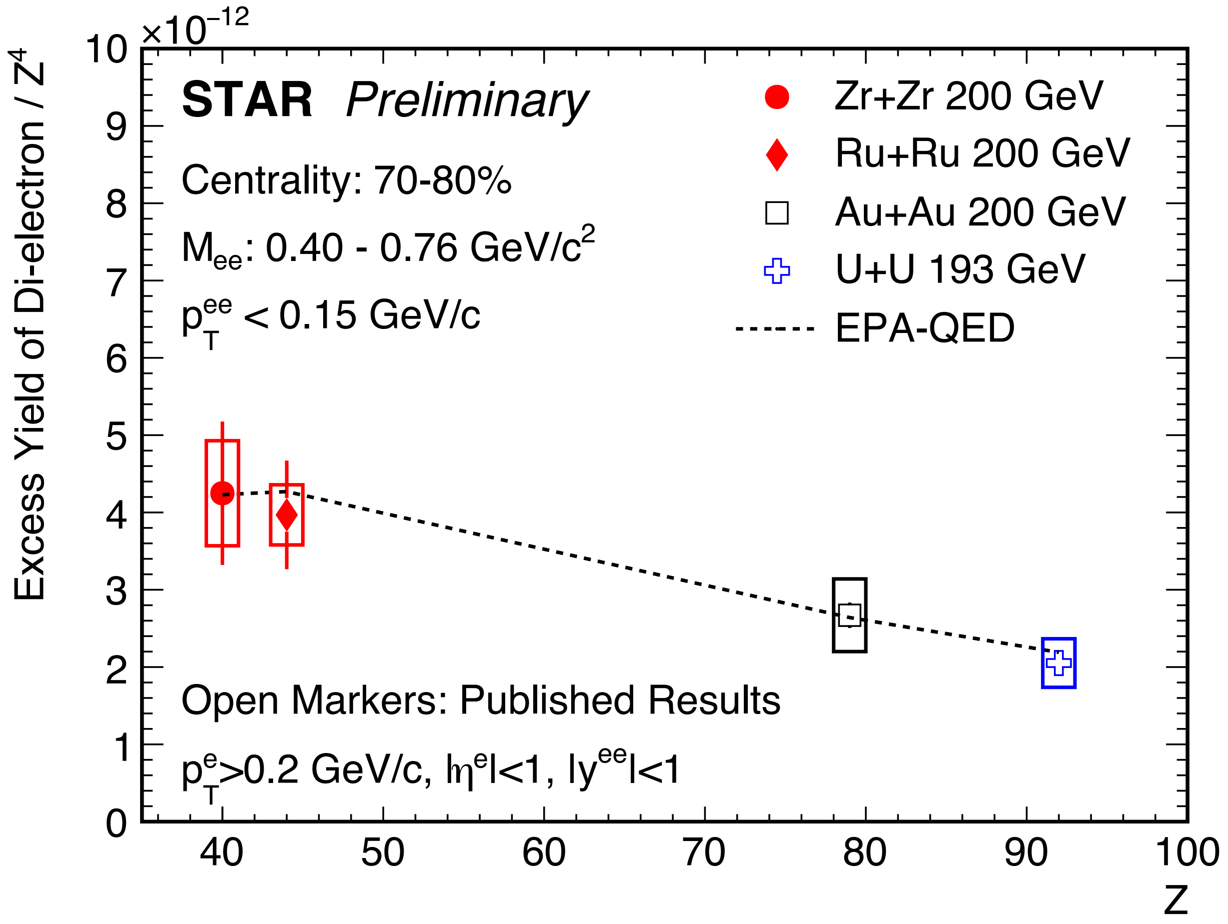
- $\gamma\gamma \rightarrow l^+l^-$ can be used to image the nuclear charge distribution at high-energy
- Combined data favors a charge distribution slightly larger than low-energy scattering result at 3σ
- Energy dependence measurements may prove important

X. Wang, JDB, L. Ruan, F. Shao, Z. Xu, C. Yang, W. Zha, arXiv:2207.05595 **[nucl-th]**
JDB, W. Zha, and Z. Xu, Eur. Phys. J. A **57**, 299 (2021)

Low energy scattering: R=6.38 fm, d=0.535 fm
R. C. Barrett and D. F. Jackson, Nuclear Sizes and Structure (Oxford University Press, 1977)



Experimental Constraints on Initial EM Fields



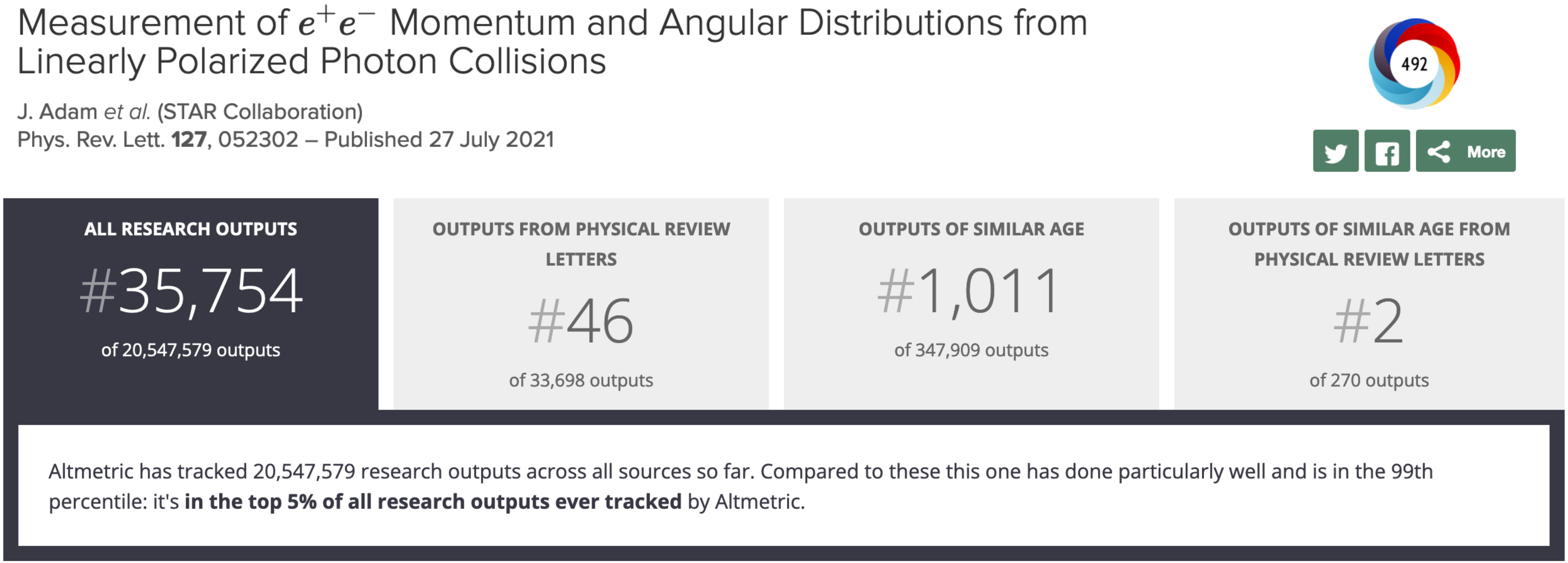
- Possible null CME result has opened questions:
  - How well are the initial EM fields really known?
  - Do event by-event fluctuations wash out differences?

Ratio is consistent with $\left(\frac{44}{40}\right)^4$ at very low p_T

Initial EM field is different in $\mathbf{Ru+Ru}$ and $\mathbf{Zr+Zr}$ (~3σ)

Addition of dimuon data pending

Reception



Measurement of e^+e^- Momentum and Angular Distributions from Linearly Polarized Photon Collisions

J. Adam *et al.* (STAR Collaboration)
Phys. Rev. Lett. **127**, 052302 – Published 27 July 2021

ALL RESEARCH OUTPUTS	OUTPUTS FROM PHYSICAL REVIEW LETTERS	OUTPUTS OF SIMILAR AGE	OUTPUTS OF SIMILAR AGE FROM PHYSICAL REVIEW LETTERS
#35,754	#46	#1,011	#2
of 20,547,579 outputs	of 33,698 outputs	of 347,909 outputs	of 270 outputs

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