Probing gluon dynamic with high energy photons

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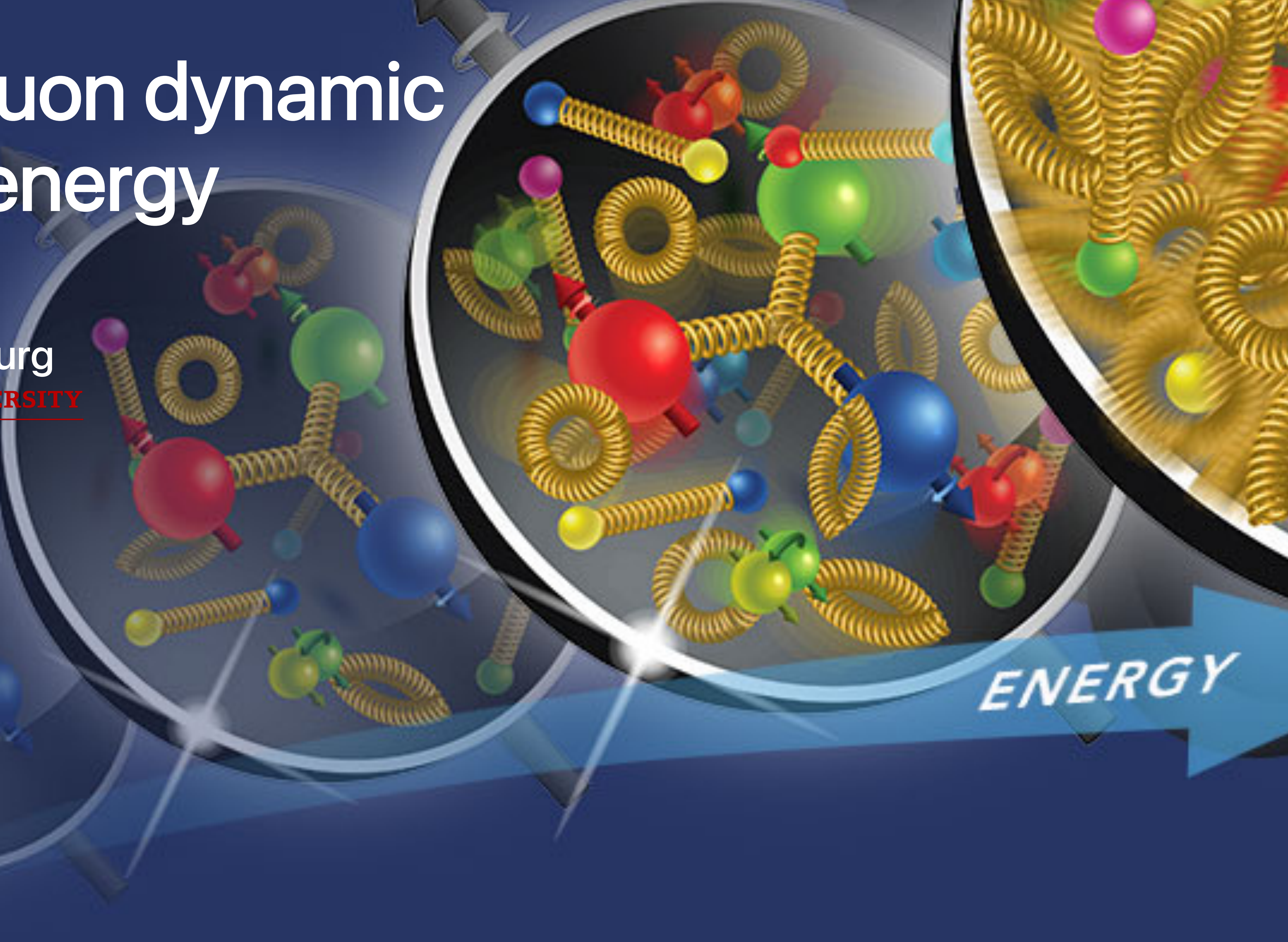
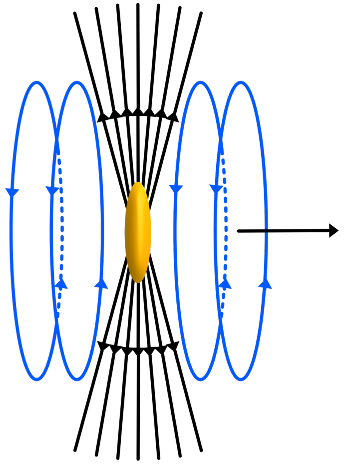
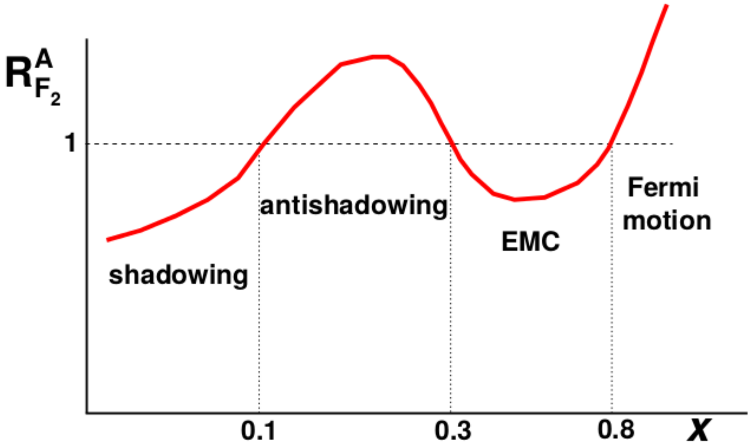


MESON2023
Krakow, Poland
23 June, 2023

Outline

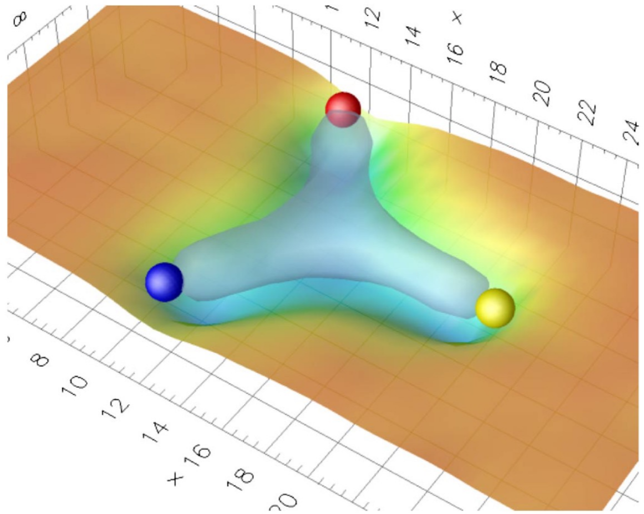
1. Introduction



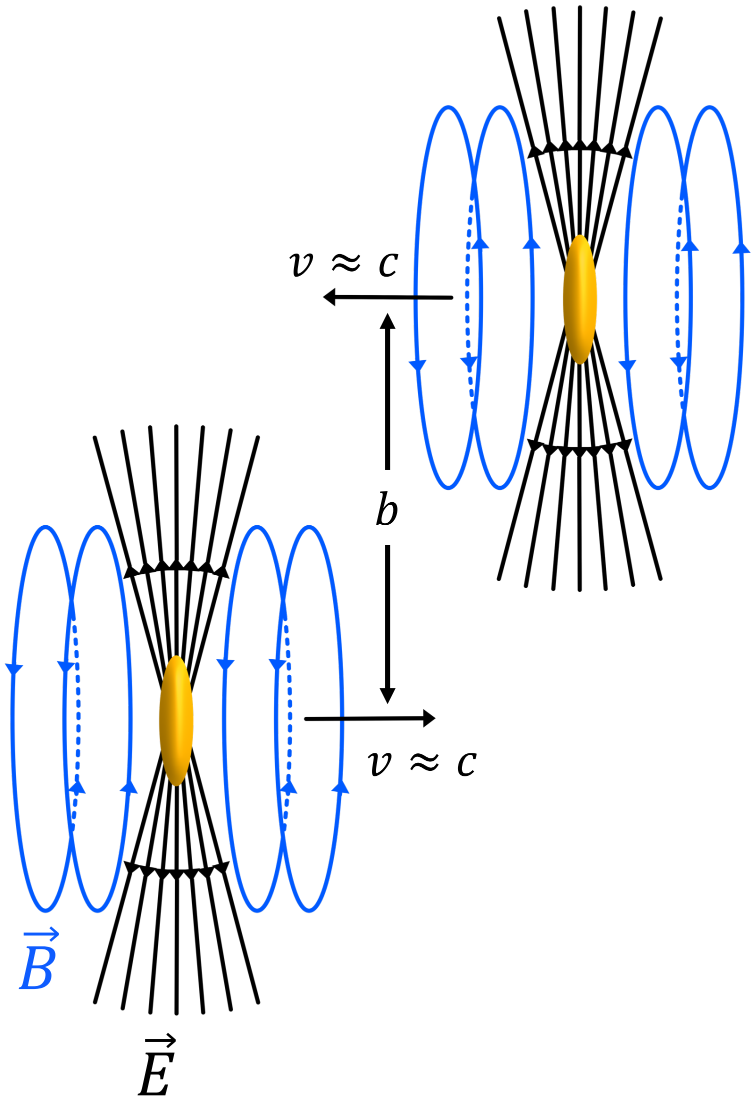


2. New approaches for answering open questions in gluon dynamics
    1. Imaging nuclear gluon distributions
    2. The Tensor Pomeron and the Elliptic Gluon Distribution in large nuclei
    3. The Baryon Junction: The true carrier of the Baryon quantum number?

3. Summary & Outlook



Ultra-Peripheral Heavy Ion Collisions



Ultra-relativistic charged nuclei produce highly Lorentz contracted electromagnetic field

Weizäcker-Williams *Equivalent Photon Approximation* (EPA):
→ In a specific phase space, <u>transverse</u> EM fields can be quantized as a flux of **quasi-real photons**
Weizsäcker, C. F. v. *Zeitschrift für Physik* 88 (1934): 612

$$n \propto \vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B} \approx \left|\vec{E}\right|^2 \approx \left|\vec{B}\right|^2$$

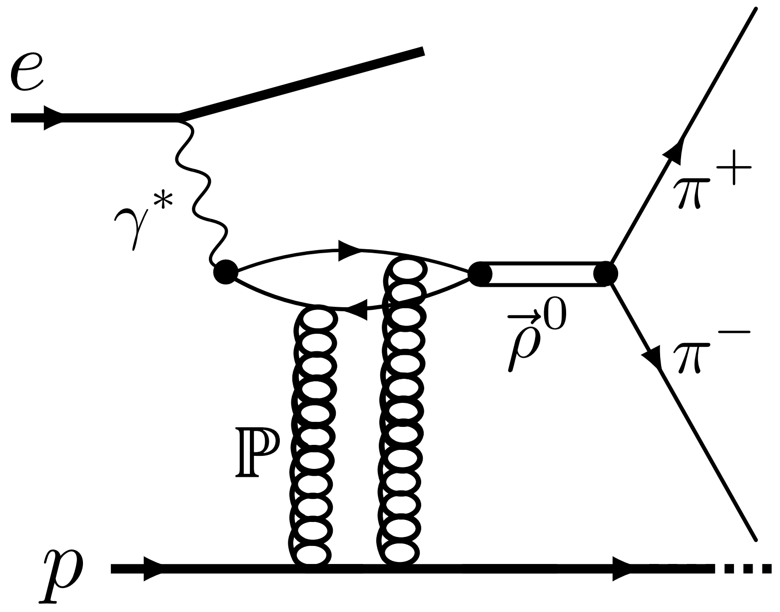
$Z\alpha \approx 1$ → High photon density
Ultra-strong electric and magnetic fields:
→ Expected magnetic field strength $\vec{\mathbf{B}} \approx \mathbf{10^{14} - 10^{16}}$ **T**
Skokov, V., et. al. *Int. J. Mod. Phys. A* 24 (2009): 5925–32

Test QED under extreme conditions[1]

K. Hattori and K. Itakura, *Photon and Dilepton Spectra from Nonlinear QED Effects in Supercritical Magnetic Fields Induced by Heavy-Ion Collisions*, Nuclear and Particle Physics Proceedings **276–278**, 313 (2016).
Light–by–Light scattering: ATLAS, Phys. Rev. Lett. 123, 052001 (2019)

Shining light on Gluons

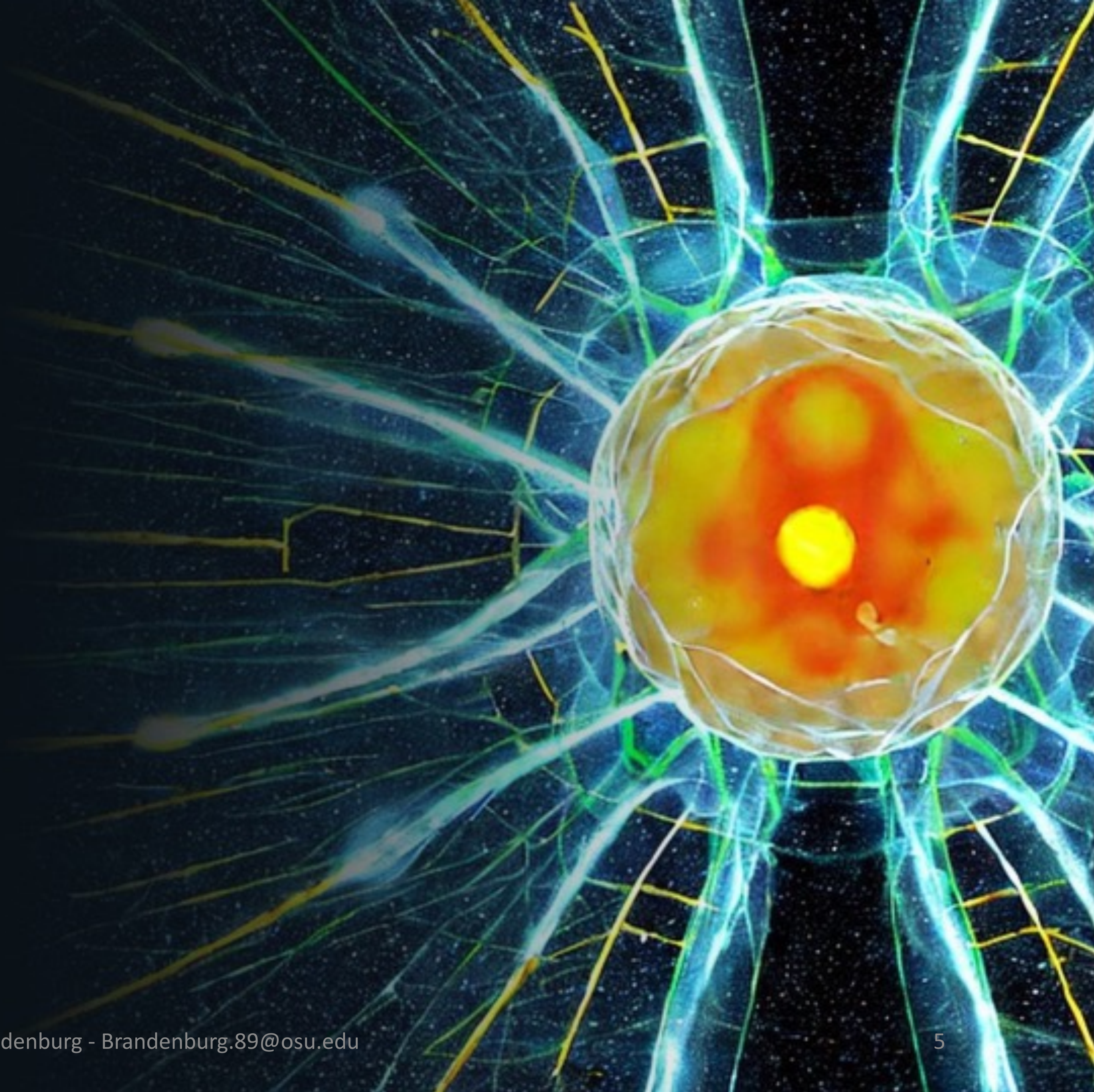
- Photo-nuclear measurements have been used to study QCD matter already for decades[1-3]



- Well known process for probing the **hadronic structure** of the photon
- Photon energies $\gtrsim 10$ GeV: probe gluon distribution - Interaction through $\mathbb{P}$omeron (two gluon state at lowest order)
- Lower energy scattering: probe gluons + quarks: Reggeon interactions are important
- Photon quantum numbers $J^{PC} = 1^{--}$
  - Can transform into a 'heavy photon'
  - i.e. a vector meson ($\rho^0, \phi, J/\psi$) with $J^P = 1^-$

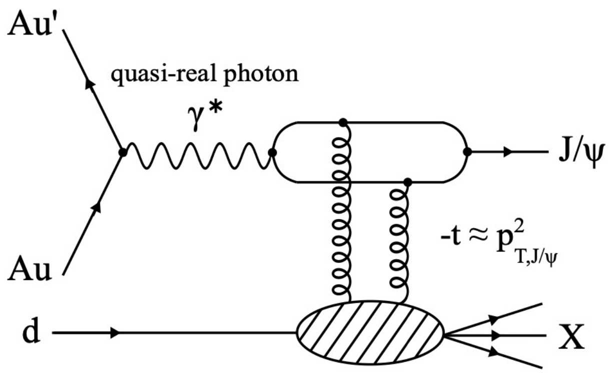
[1] H1 Collaboration. *J. High Energ. Phys.* **2010**, 32 (2010).
[2] ZEUS Collaboration. *Eur. Phys. J. C* **2**, 247–267 (1998).
[3] See refs 1-25 in [2]

Imaging Gluons within Nuclei



Probing the Gluonic Structure of the Deuteron

STAR Collaboration, Phys. Rev. Lett. **128**, 122303 (2022)

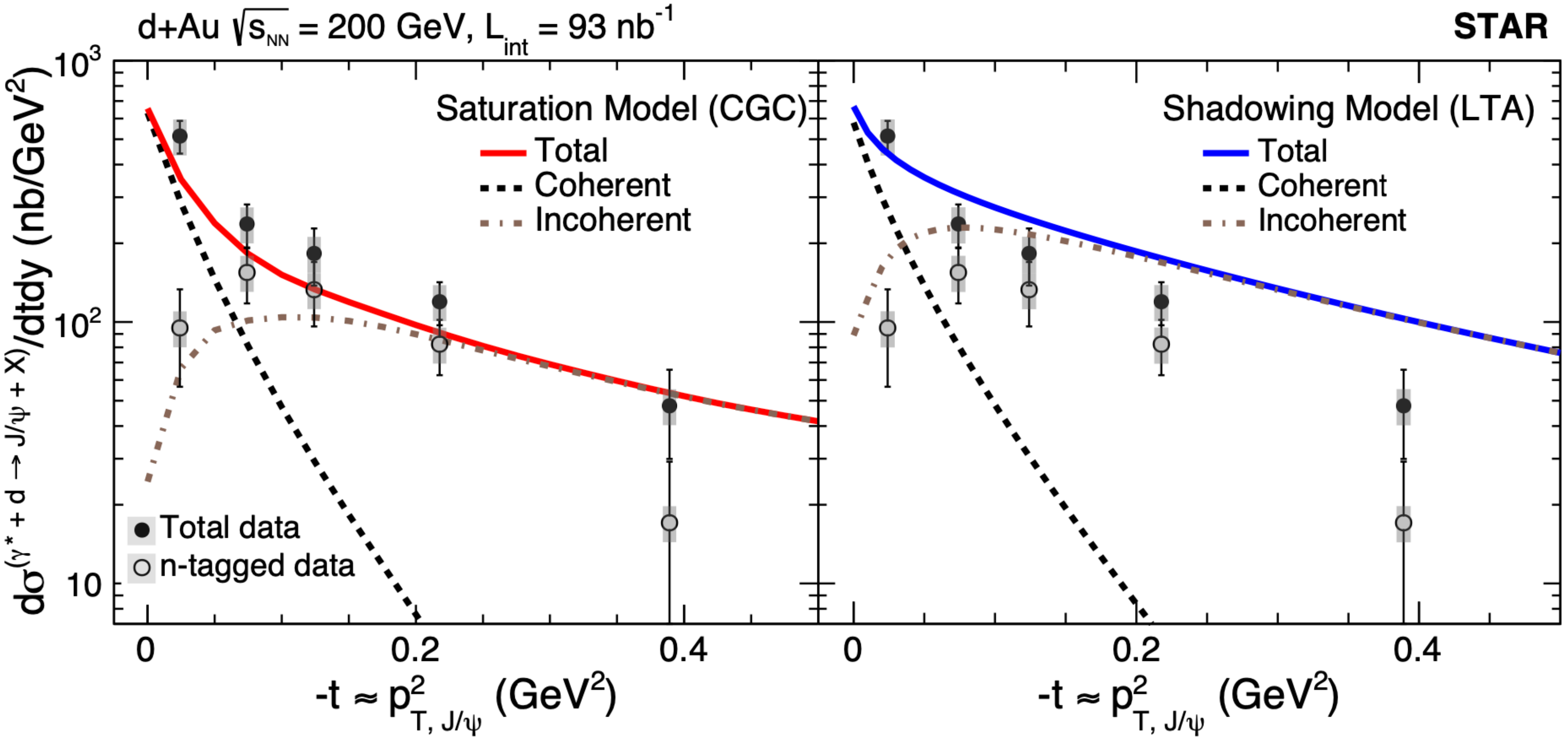


Deuteron is the smallest / simplest nucleus

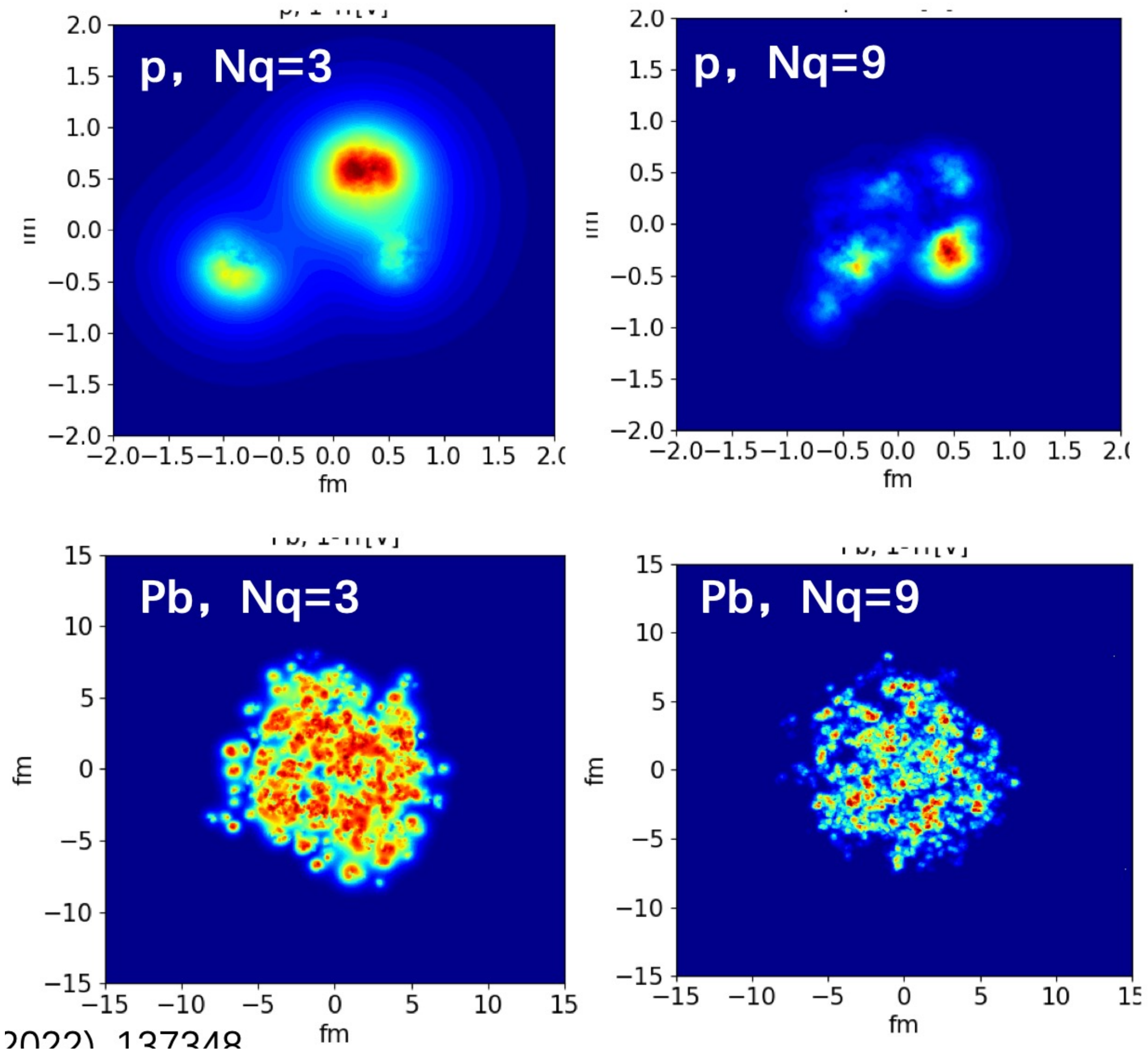
What is the origin of modified partonic structure of nucleons bounded in nuclei?

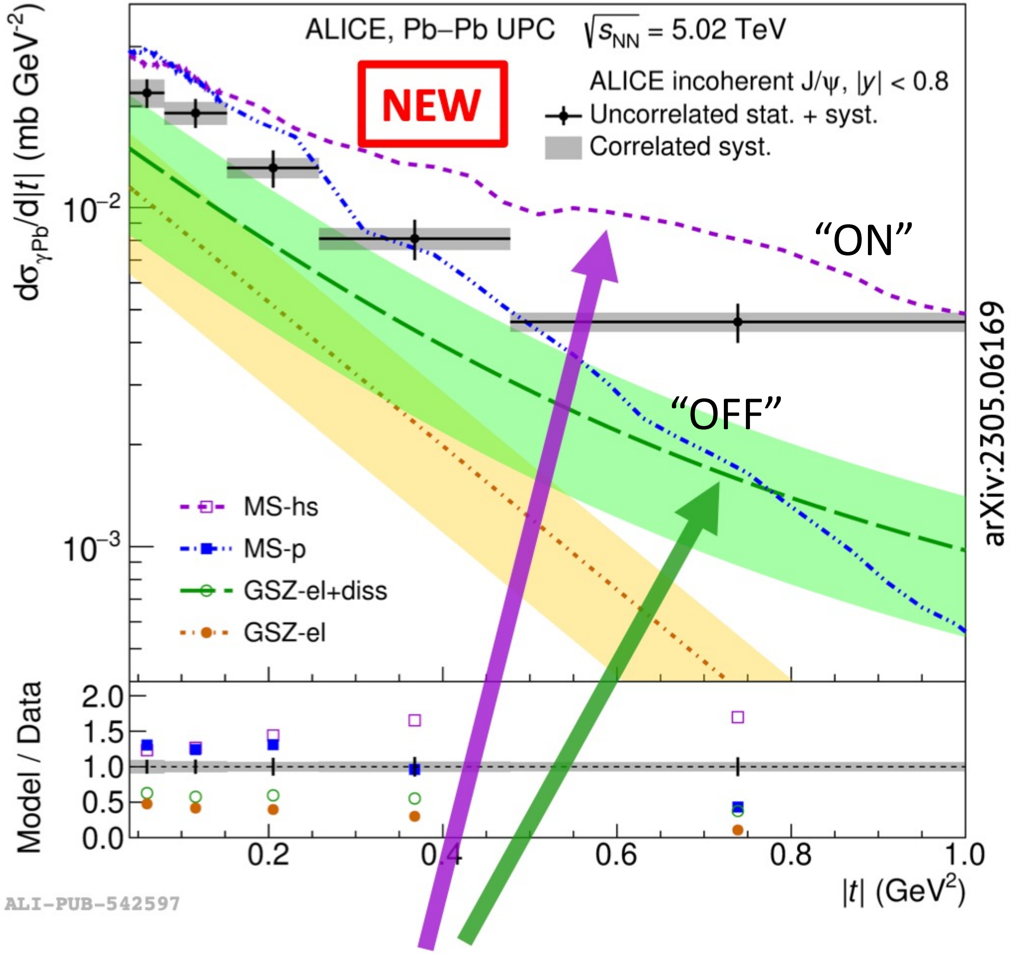
Bjorken-x ~ 0.01
Only small saturation / shadowing effects expected

Both models are consistent



Incoherent probes gluonic hotspots and saturation

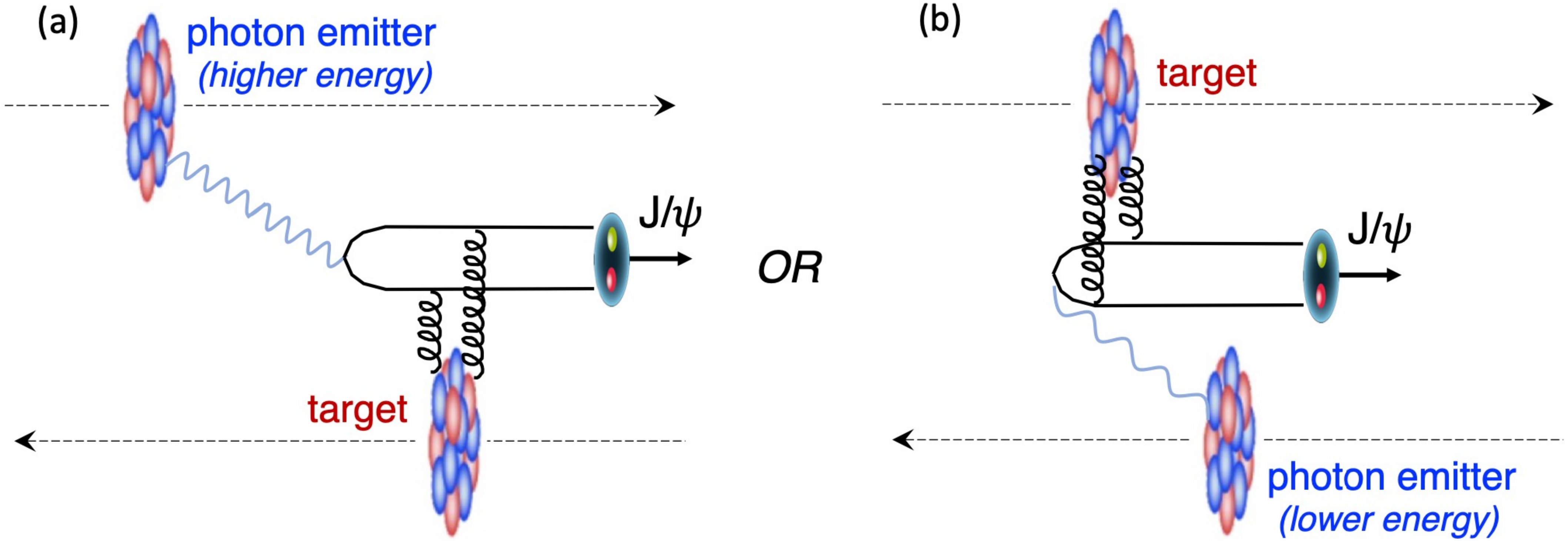




Consistent with gluonic hotspots fluctuation

H. Mantysaari, B.Schenke, C. Shen and W. Zhao, Phys. Lett. B 833 (2022), 137348
H. Mantysaari, B.Schenke, C. Shen and W. Zhao, [arXiv:2208.00396 [hep-ph]].

Photon Emitter Ambiguity



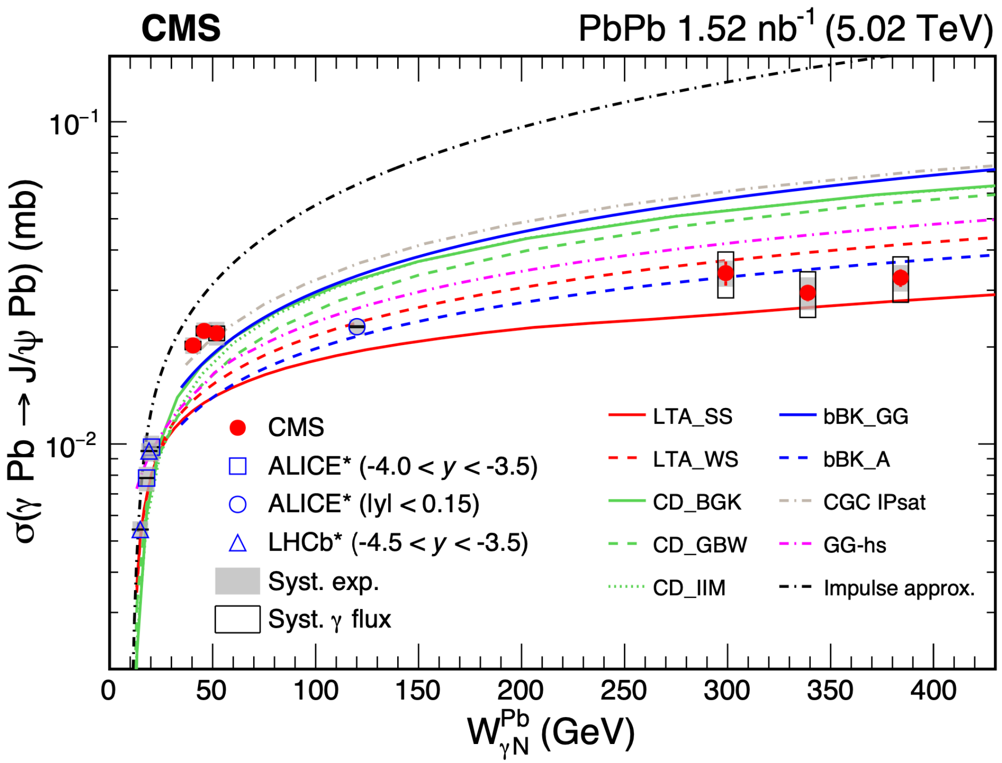
Recent experimental techniques for resolving the photon emitter ambiguity

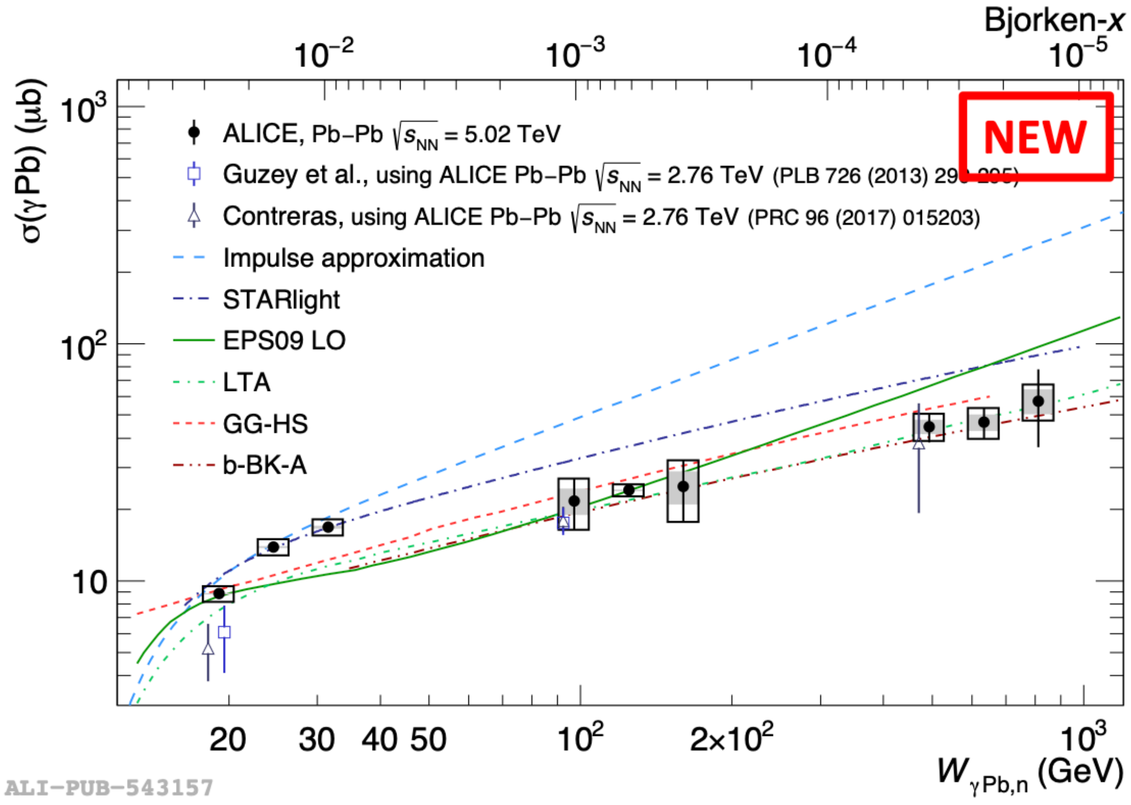
Able to explore process in terms of $W_{\gamma n}$ (photon-nucleus center-of-mass energy per nucleon)

New insights into the gluon distribution and dynamics

Gluon dynamics & Energy Dependence

The impulse approximation (IA) assumes that the nuclear scattering is given by the superposition of the scattering on the individual nucleons





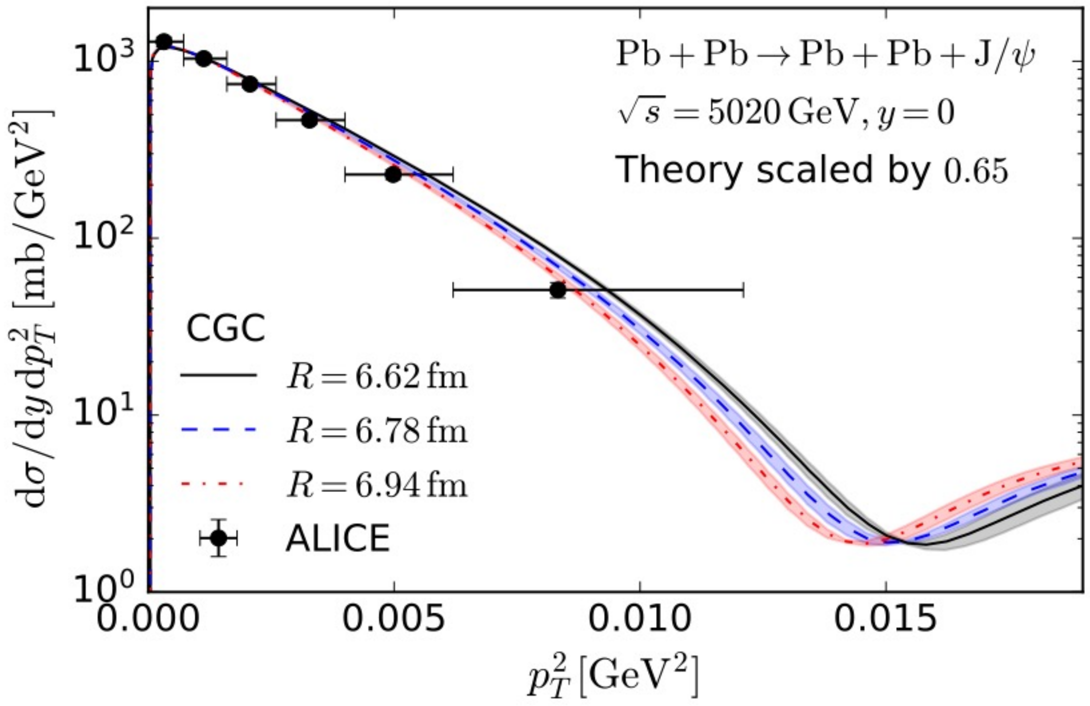
Both CMS and ALICE (new last week) have made measurements
Consistent results – rapid rise consistent with impulse approximation, then level off
Comparison to multiple models of Nucler Shadowing at leading Twist, multiple gluon saturation models
No individual model can describe trends in data – still more to learn

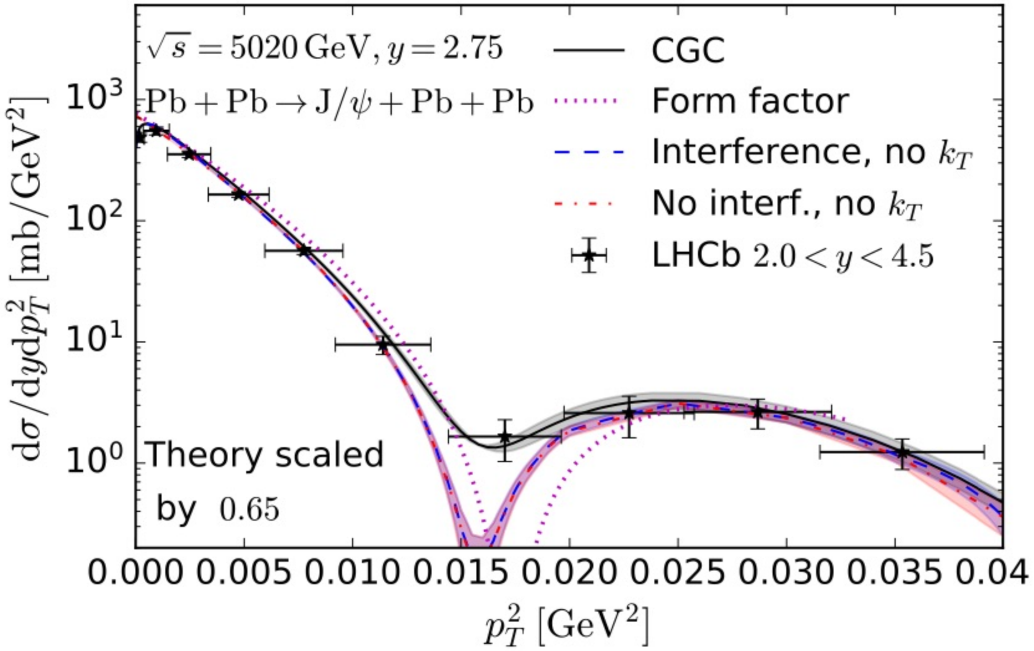
Nuclear Geometry and Saturation at Highest Energies

- Work by Bjorn Shenke (BNL) et. al.
  - Include full CGC treatment
  - Interference between amplitudes
  - Shape fluctuations

When saturation effects are included one obtains a good description of the exclusive J/ψ production spectra in ultra peripheral lead-lead collisions as recently measured by the ALICE

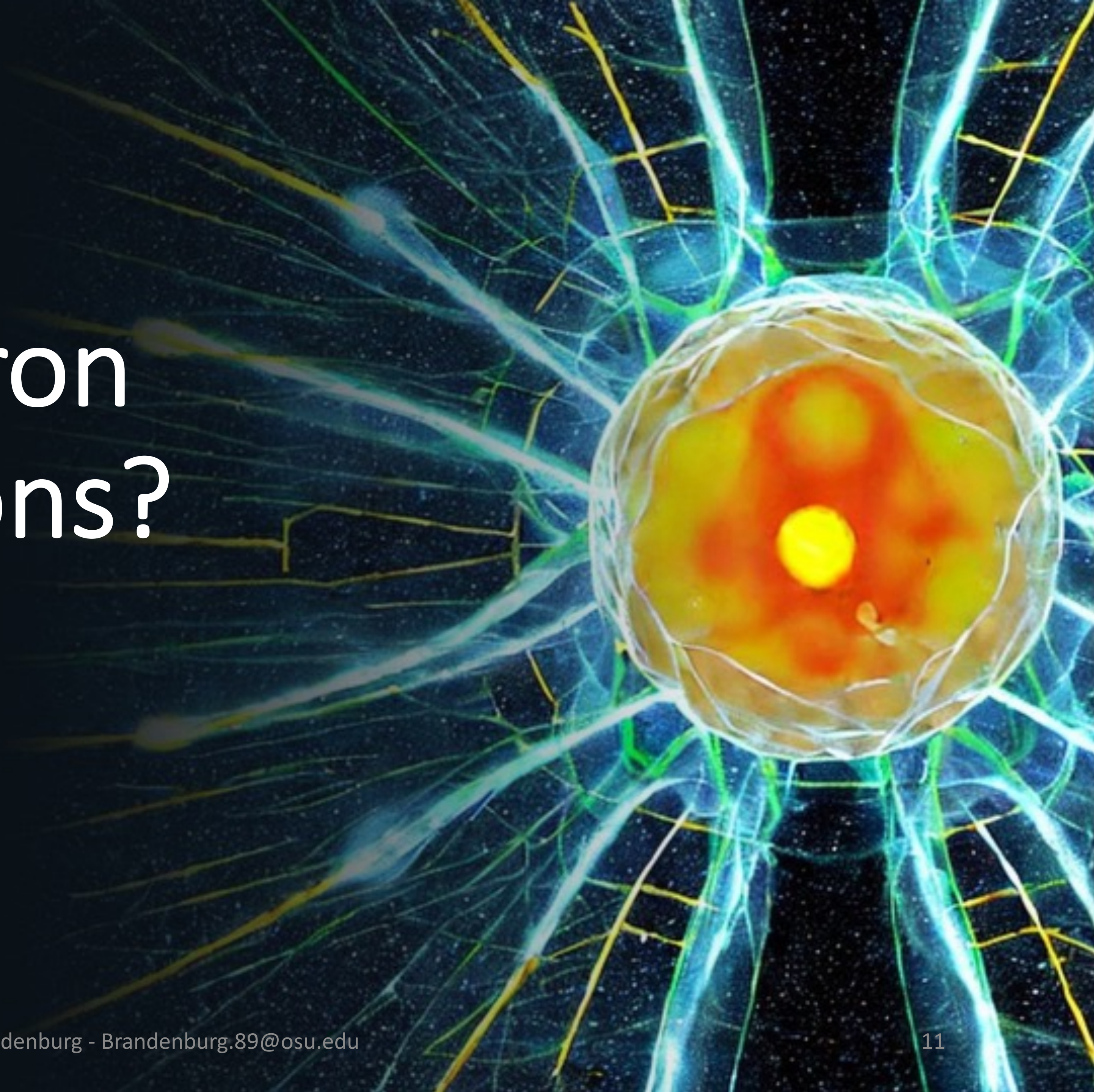
https://arxiv.org/abs/2207.03712



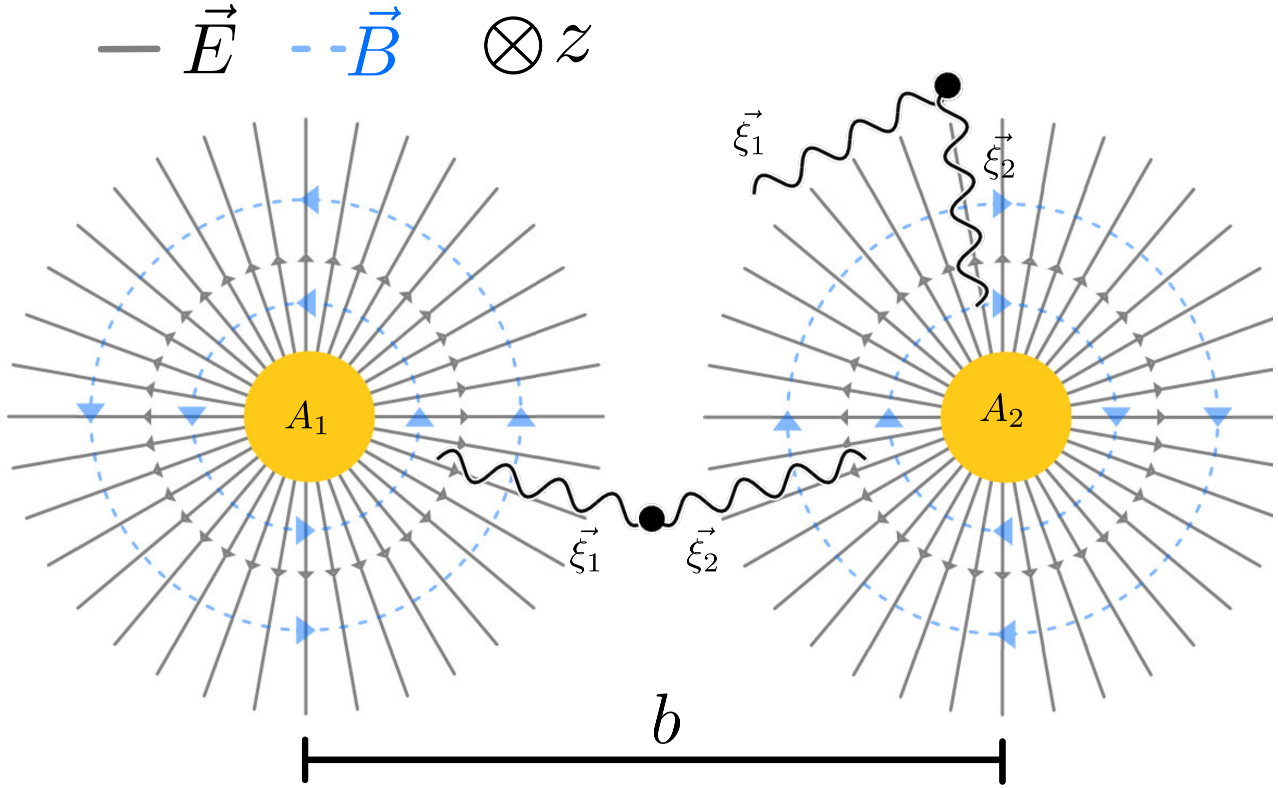


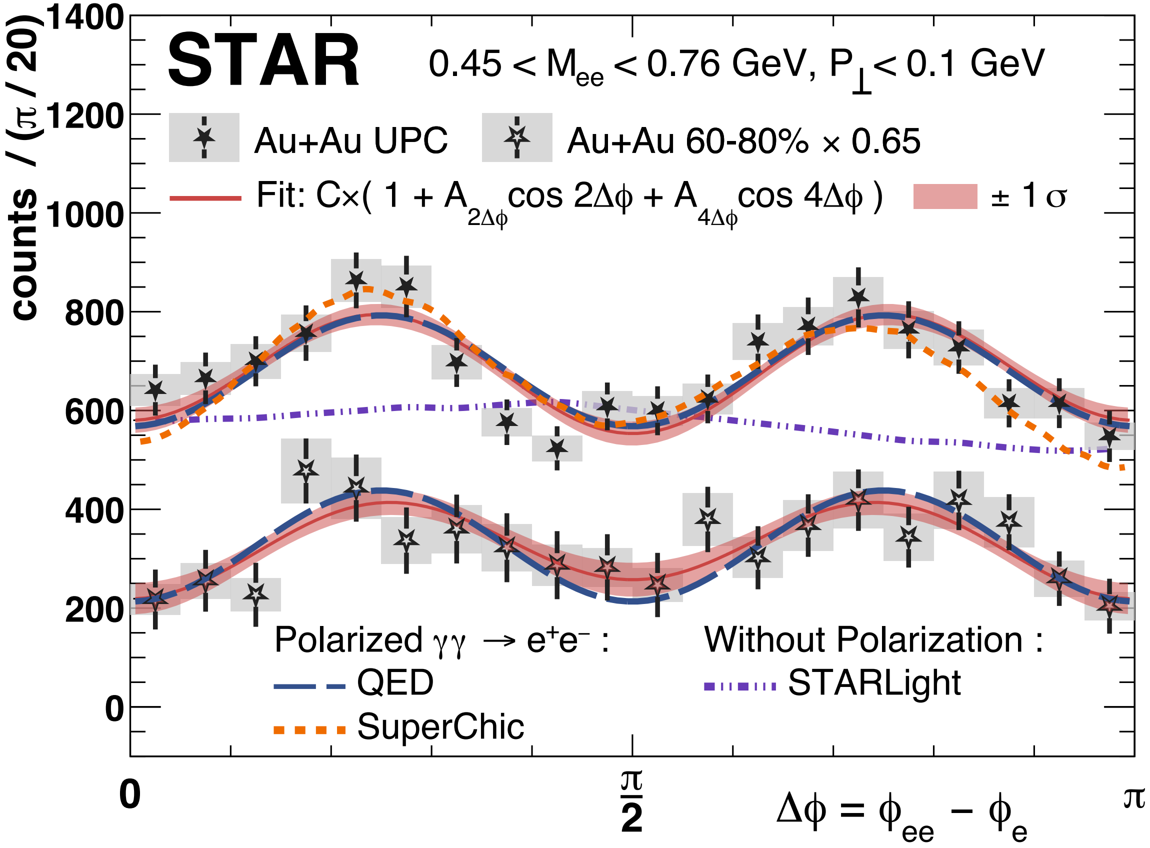
(a) Full p_T range

Nontrivial Pomeron Spin configurations?



Photon Polarization



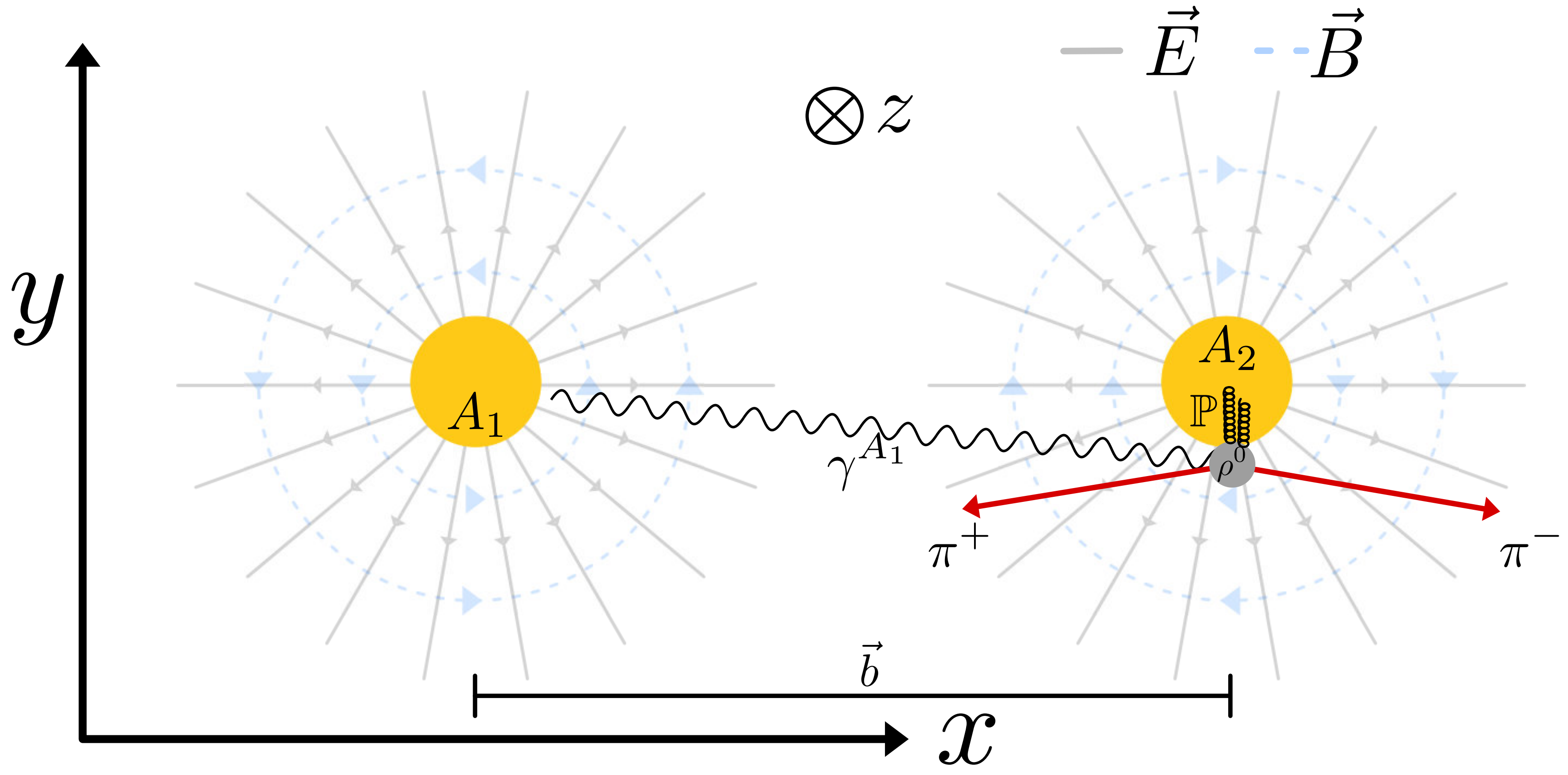


STAR Collaboration, Phys. Rev. Lett. **127**, 052302 (2021).

- Interacting photons are quasi-real, transverse linearly polarized
- Recently discovered by STAR in photon-photon (Breit-Wheeler) interactions through characteristic $\cos 4\phi$ modulation
- Initial (photon) spin is encoded into orbital angular momentum of final state particles

Imaging the Nucleus with Polarized Photons

Photon emitter ambiguity (but with polarized photons)



Imaging the Nucleus with Polarized Photons

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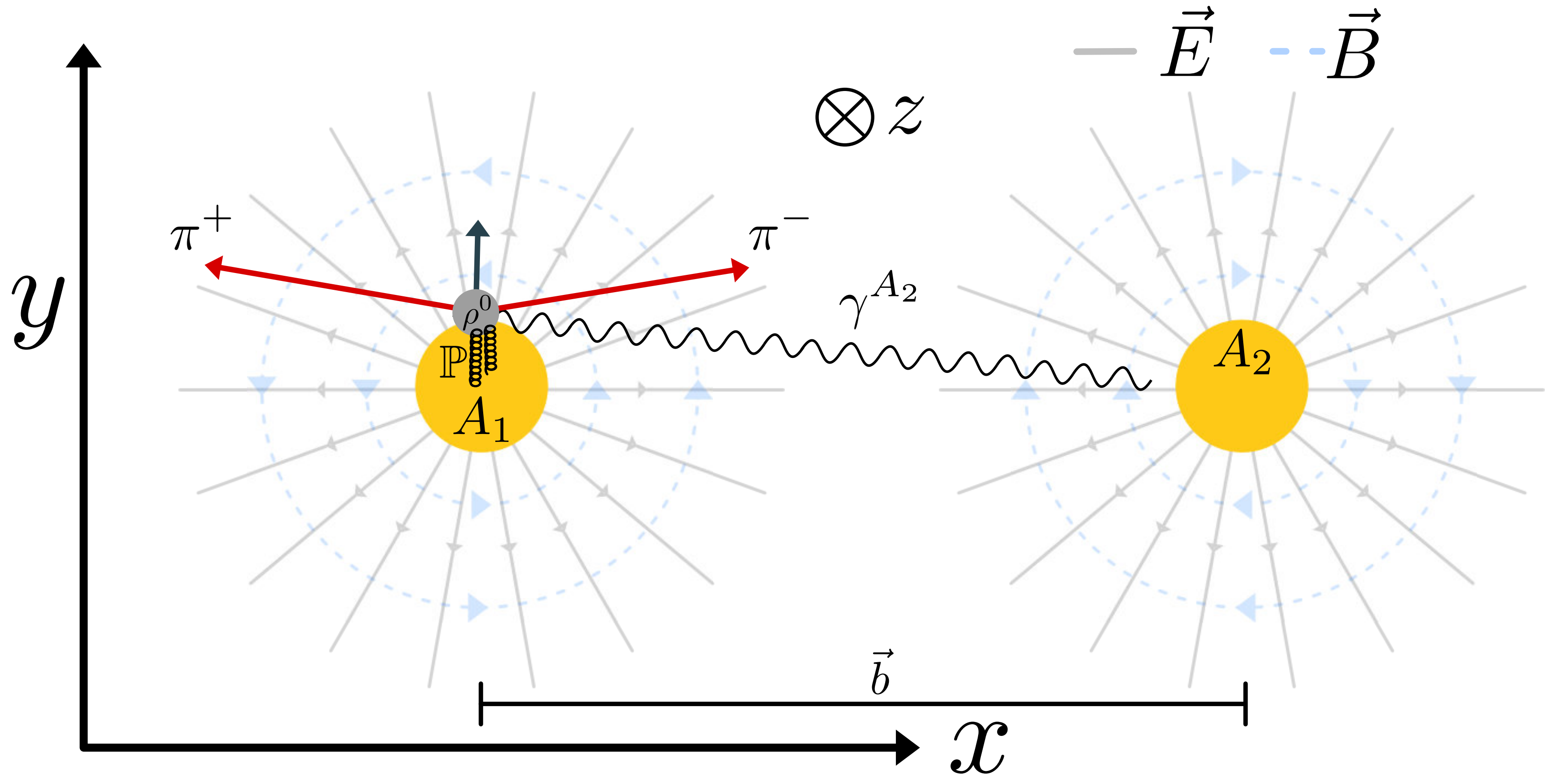

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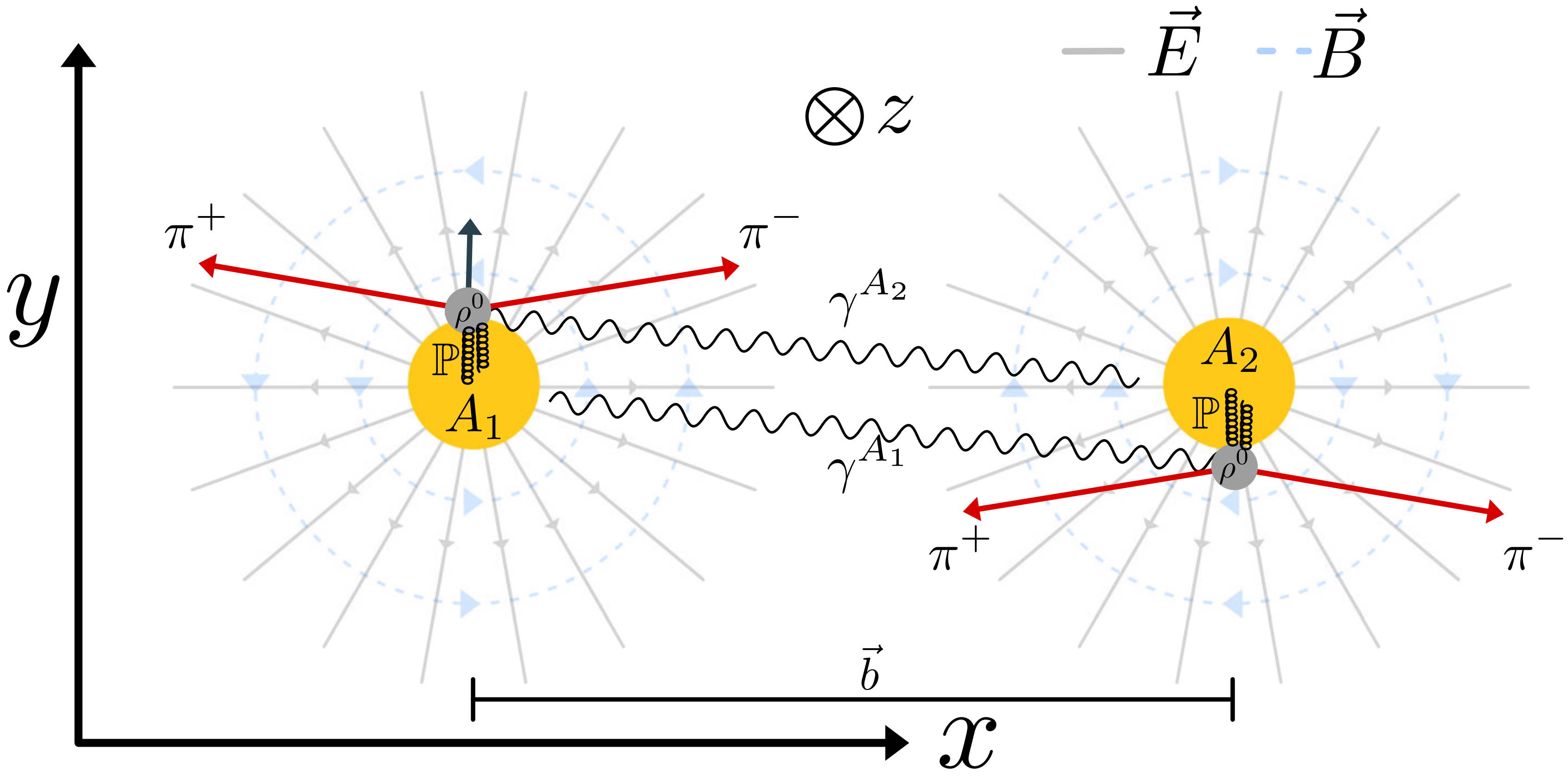
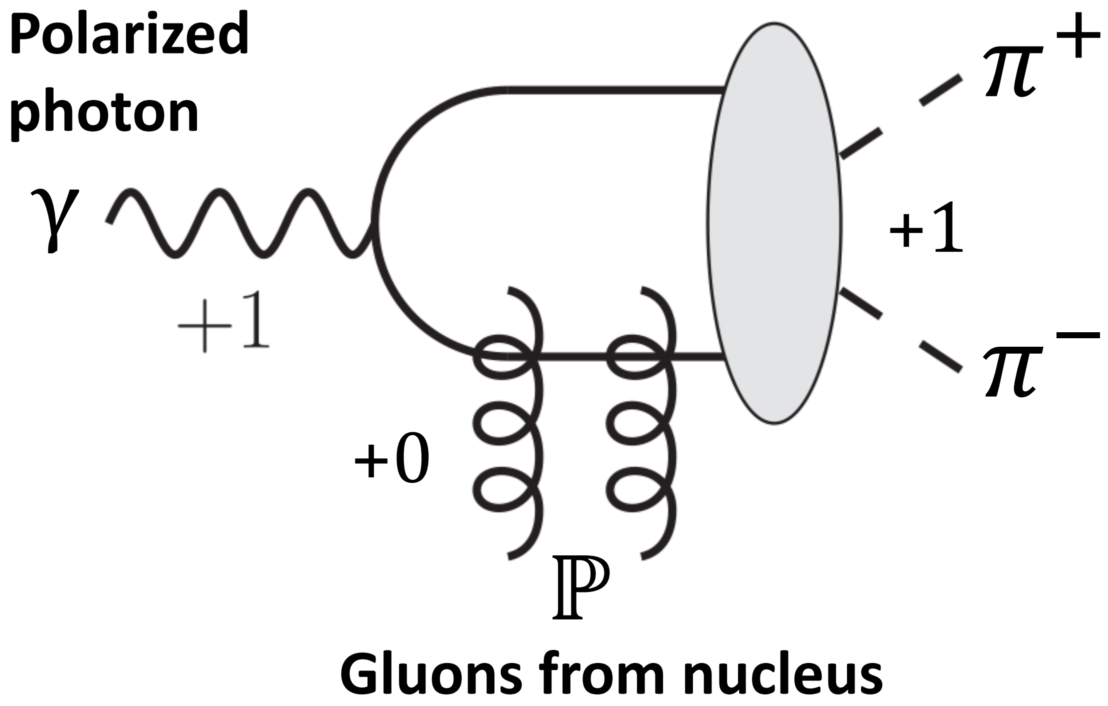
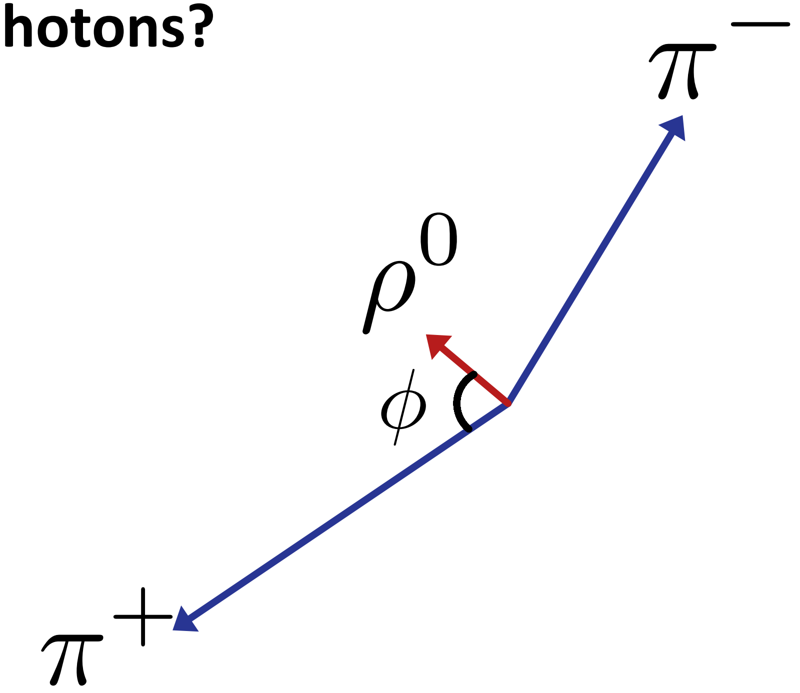


Both possibilities occur simultaneously

Imaging the Nucleus with Polarized Photons

What is NEW with transversely polarized photons?

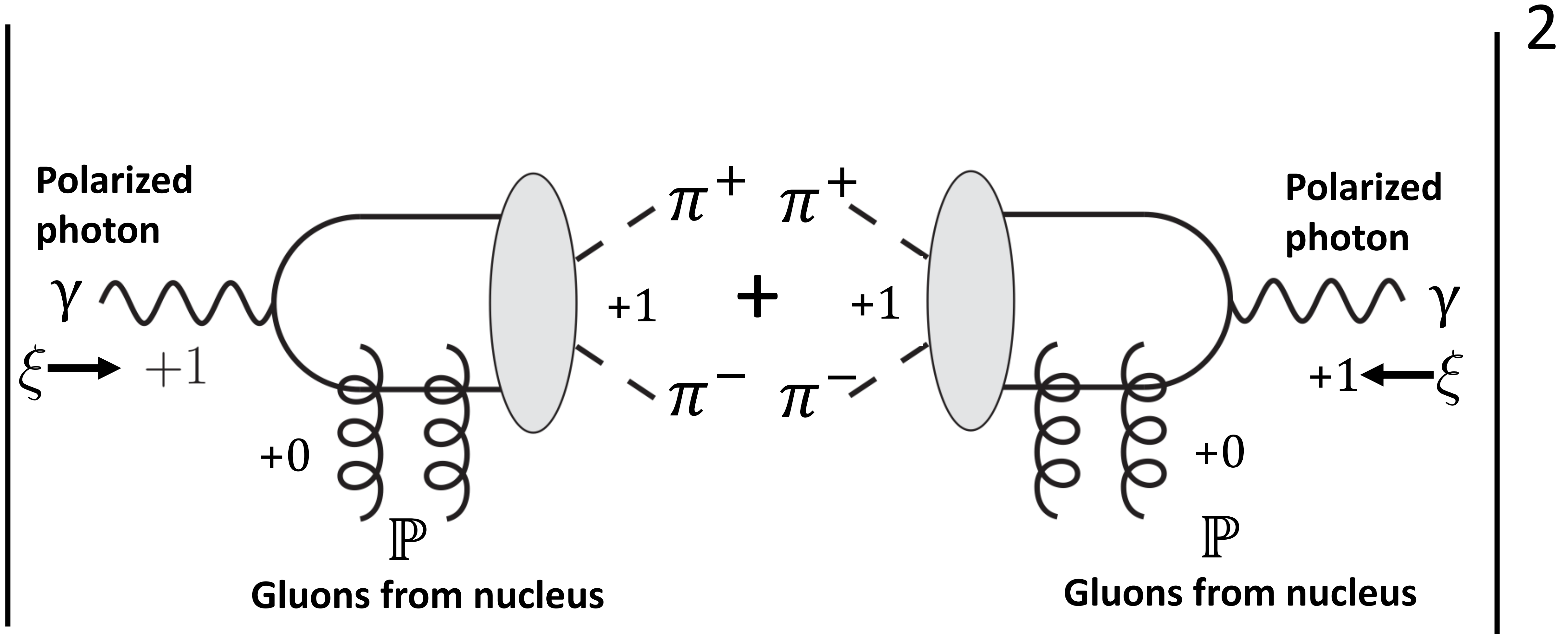




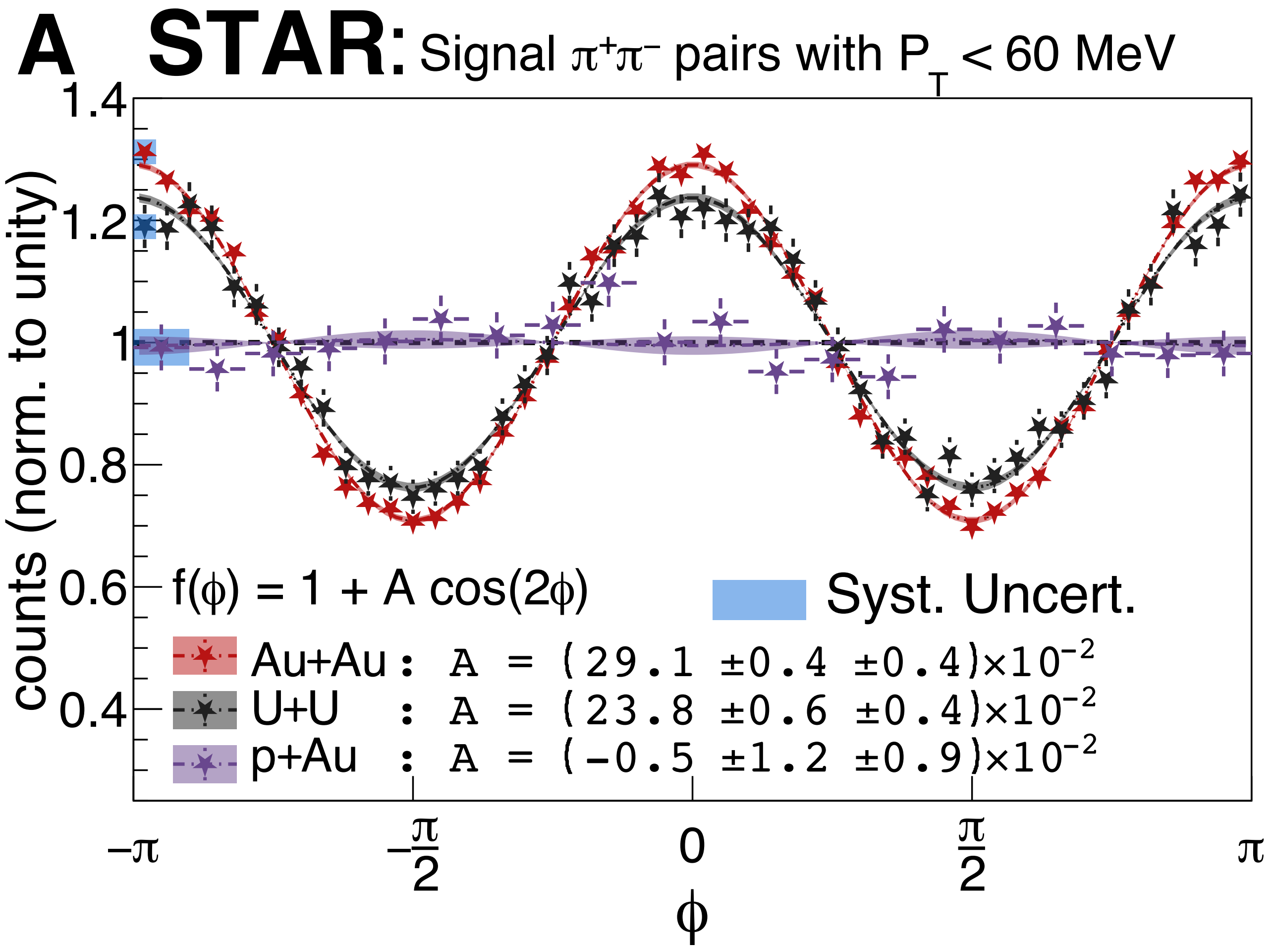
We can use the same experimental observable as the Breit-Wheeler process to access photon polarization

Access to initial photon polarization

Interference of two amplitudes



Observation of Spin Interference in γA



- Strong spin interference effect observed in A+A
- No effect in p+A
- $\cos 2\phi$ expected for total spin=2 (spin-1 photons and spin-0 Pomeron)
- Strong dependence on transverse momentum

H. Xing, C. Zhang, J. Zhou, Y.-J. Zhou, The cos 2ϕ azimuthal asymmetry in ρ^0 meson production in ultraperipheral heavy ion collisions. *J. High Energ. Phys.* **2020**, 064 (2020).

W. Zha, J. D. Brandenburg, L. Ruan, Z. Tang, Exploring the double-slit interference with linearly polarized photons. *Phys. Rev. D* **103**, 033007 (2021).

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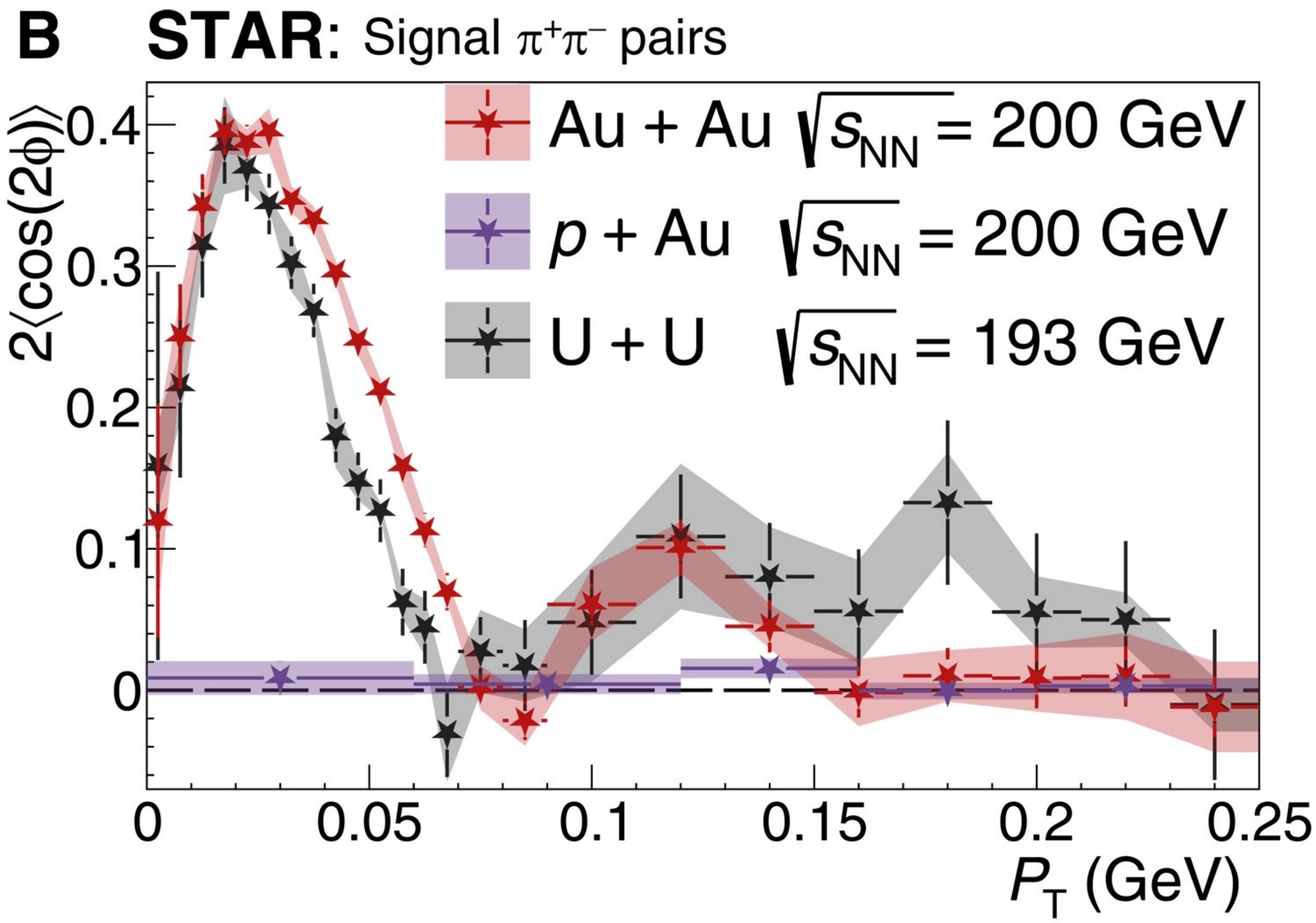

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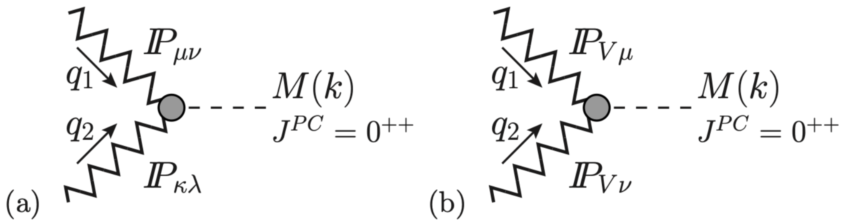
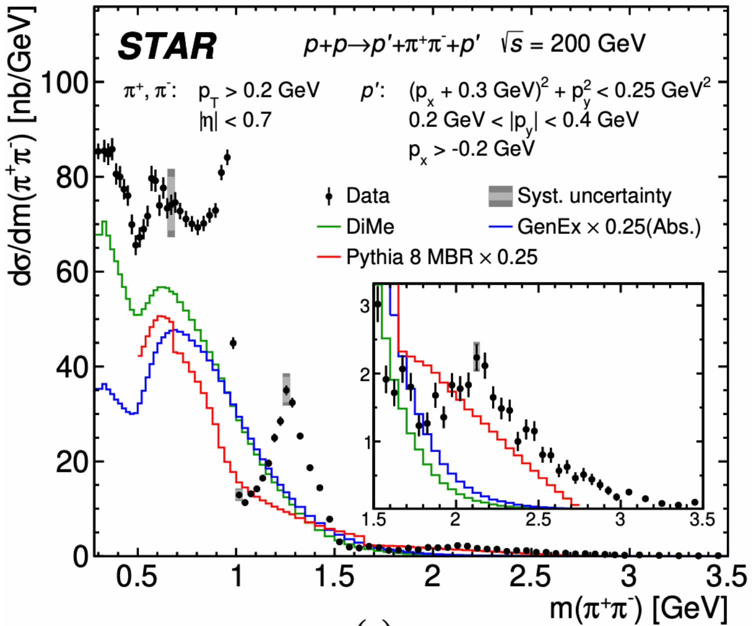
Elliptic Gluons and the Tensor Pomeron



- Intense theoretical interest
  - Signatures of Tensor pomeron
    P. Lebiedowicz, O. Nachtmann b, A. Szczurek Annals of Physics 344, 301-339 (2014)
    Y. Hagiwara, C. Zhang, J. Zhou, and Y-J Zhou Phys. Rev. D 104, no.9, 094021 (2021)
  - Glueballs arXiv:2305.04869 [hep-lat], arXiv:2212.11107 [hep-ph]
  - CEP and Meson production
    P. Lebiedowicz and A. Szczurek, *Exclusive pp → ppπ+π− reaction: From the threshold to LHC*, Phys. Rev. D **81**, 036003 (2010), doi:10.1103/PhysRevD.81.036003, 0912.0190.
- Rich history of experimental progress over decades
  - Log rising cross sections Nucl. Phys. B 141, 1 (1978)
  - Studies in single, double and central diffraction
    arXiv:2108.00686, 2212.00664 [hep-ex], 2210.13884 [hep-ex], 2209.04250 [nucl-ex] 2303.02579 [hep-ph],
  - Odderon discovery (TOTEM + D0) Phys. Rev. Lett. 127, 062003 (2021)
- Elliptic Gluon distribution in saturated nuclei
  J. Zhou Phys. Rev. D 94, 114017 (2016)

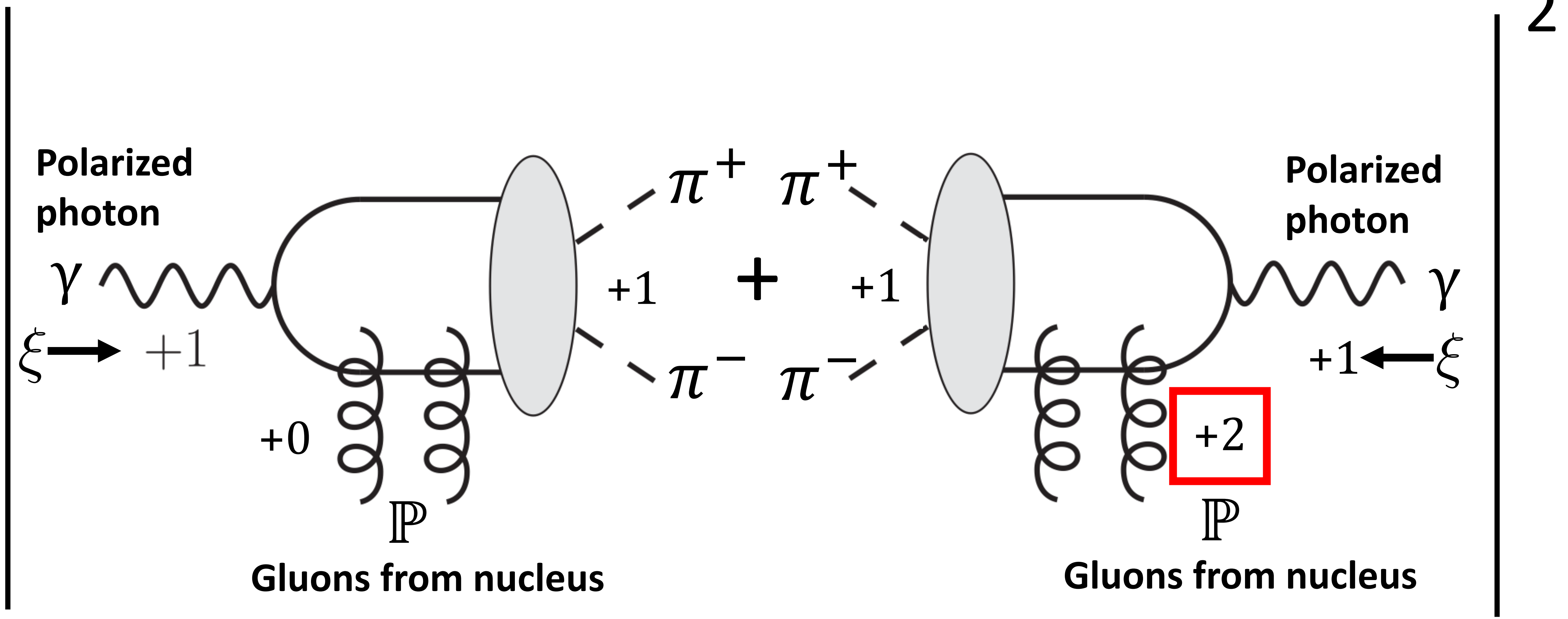
arXiv:2108.00686



(a)

Interference of two amplitudes

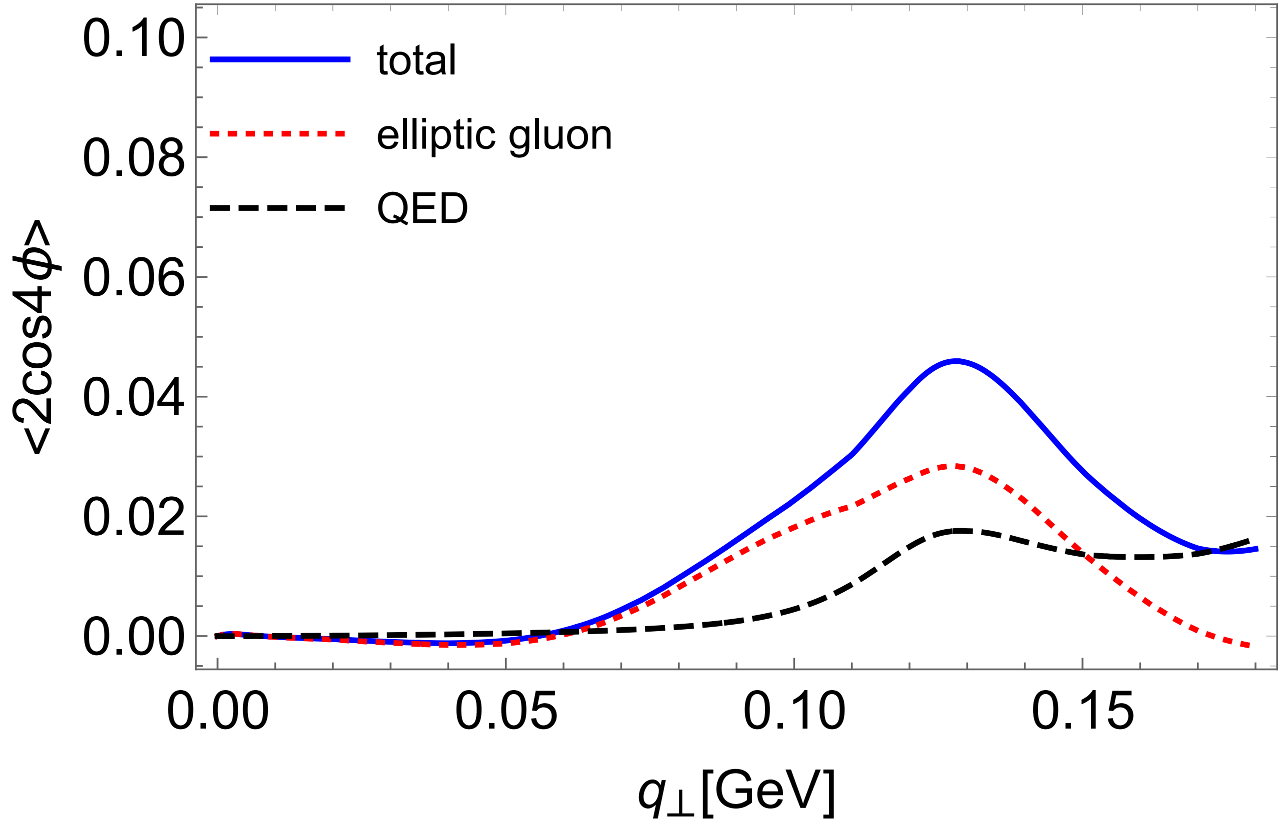
Now consider interference with a Tensor Pomeron



Tensor Pomeron

- Non-trivial pomeron spin structures have been proposed for some time
- Circumstantial evidence, but still no smoking gun
- This new measurement technique provides unprecedented access to spin of initial configuration
- What are the signatures of a tensor Pomeron in this case?

Y. Hagiwara, C. Zhang, J. Zhou, and Y-J Zhou Phys. Rev. D 104, no.9, 094021 (2021)



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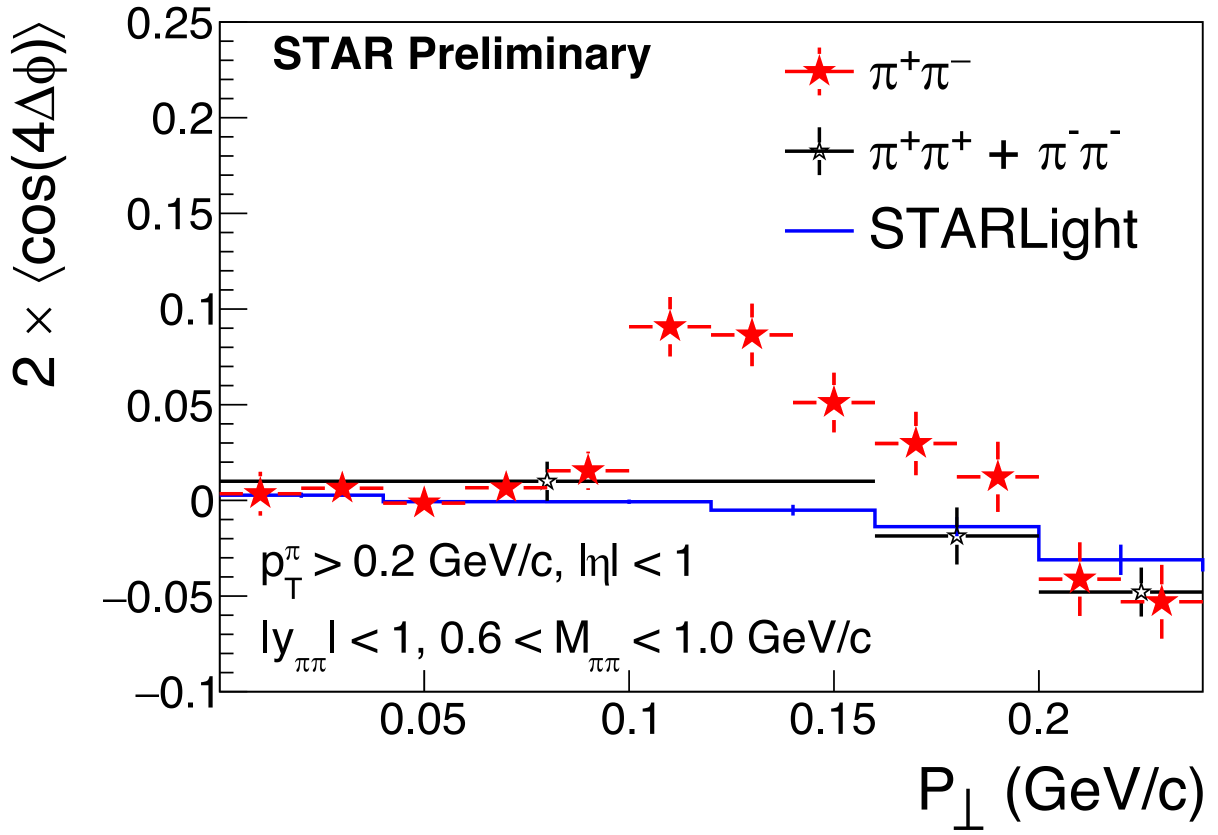
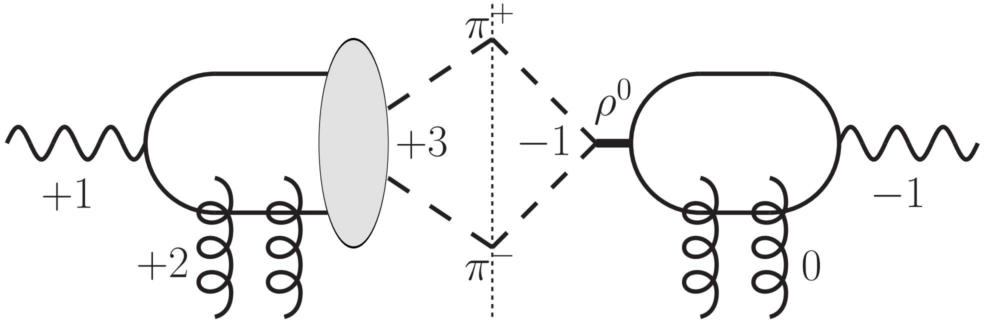
- Circumstantial evidence, but still no smoking gun

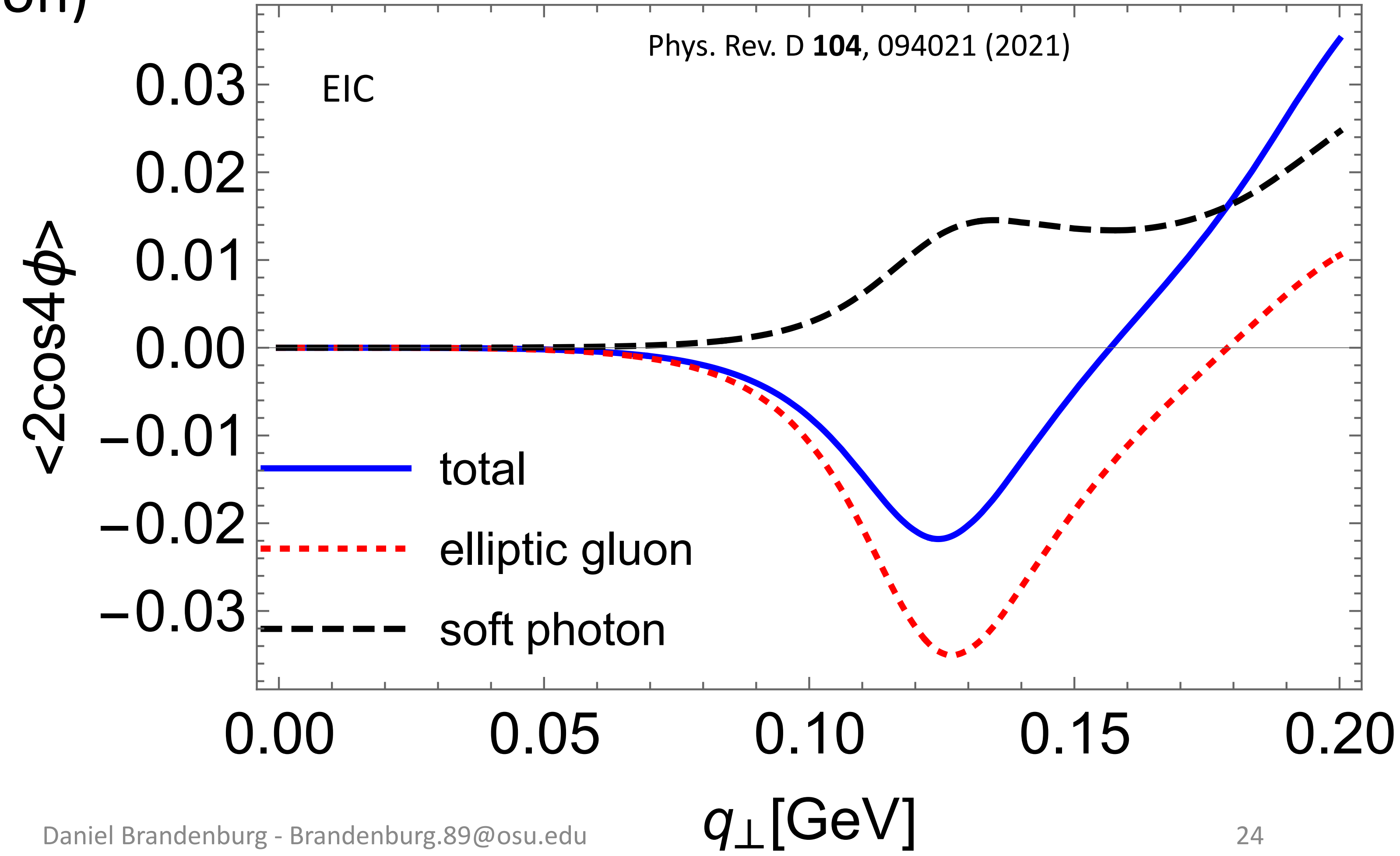
- This new measurement technique provides unprecedented access to spin of initial configuration
- What are the signatures of a tensor Pomeron in this case?
- Hint of a signal consistent with tensor pomeron prediction
- New STAR data!



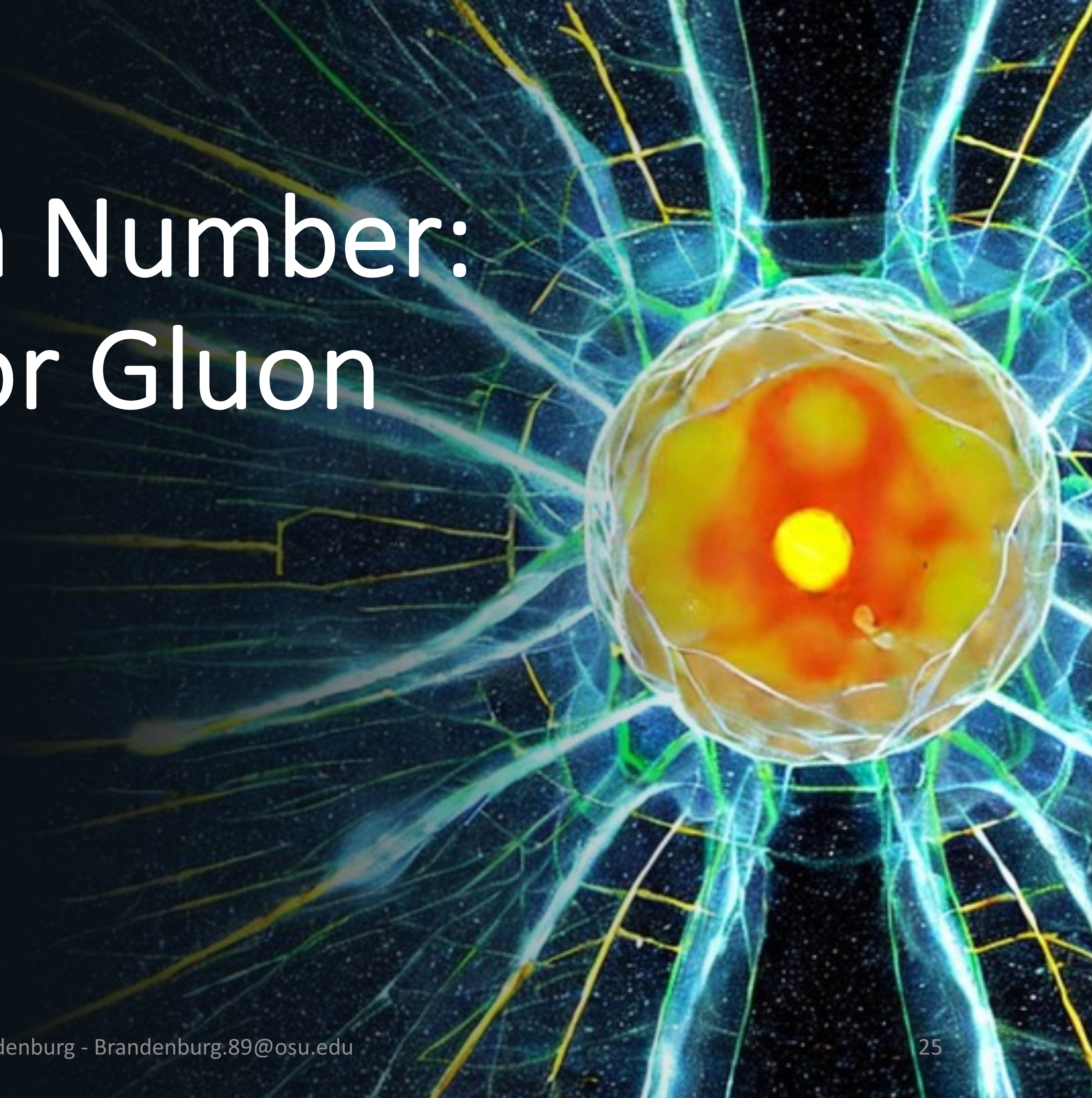
Tensor Pomeron @ EIC

At the EIC separation of QED and elliptic gluon (Tensor Pomeron) is easier due to expected difference in sign



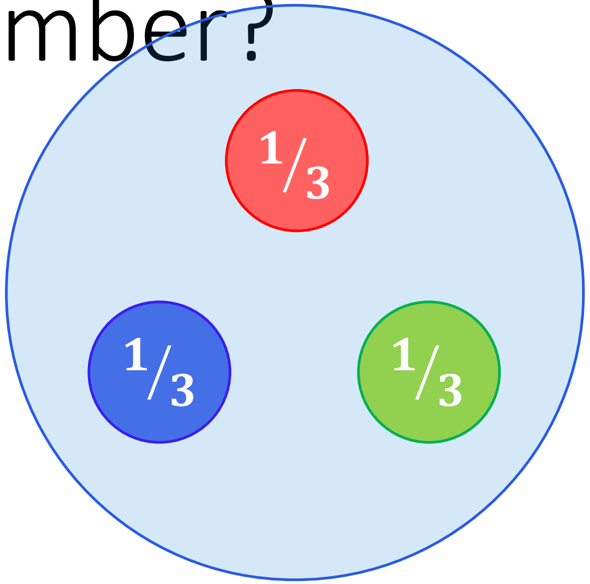


Baryon Quantum Number: Valence Quarks or Gluon Junction?



What carries the Baryon Quantum Number?

- **Baryon number –** a strictly conserved quantum number
- **Conventional model:** Baryon number is assumed to be carried by the valence quarks:

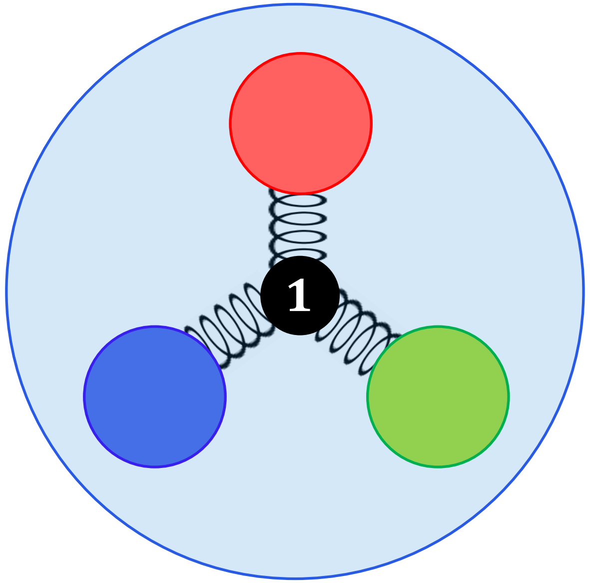


- **Alternative model:** the baryon junction
  - Nonperturbative configuration of low momentum gluons linked to all three valence quarks

    X. Artru, Nucl. Phys. B **85,** 442 (1975)
  - Carries the baryon number

    D. Kharzeev, Physics Letters B **378**, 238 (1996)
- Neither scenarios have been experimentally verified
- Strong motivation from QCD + Lattice

VS



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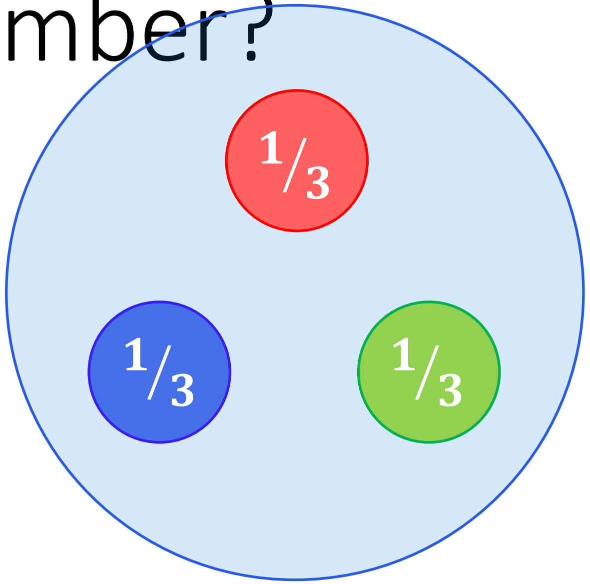

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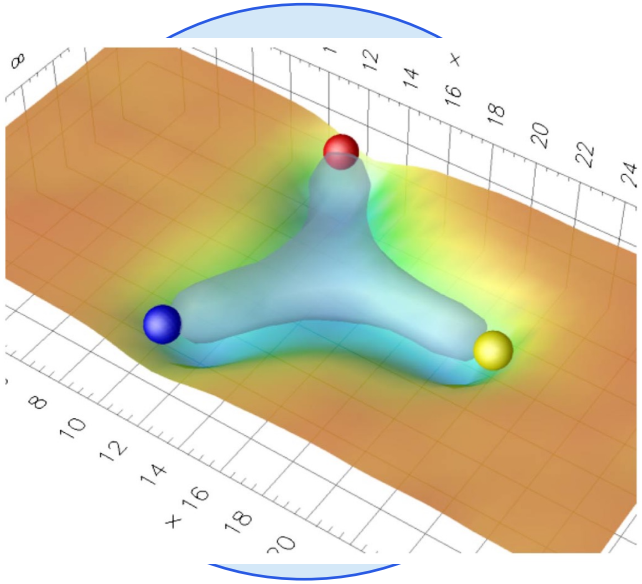

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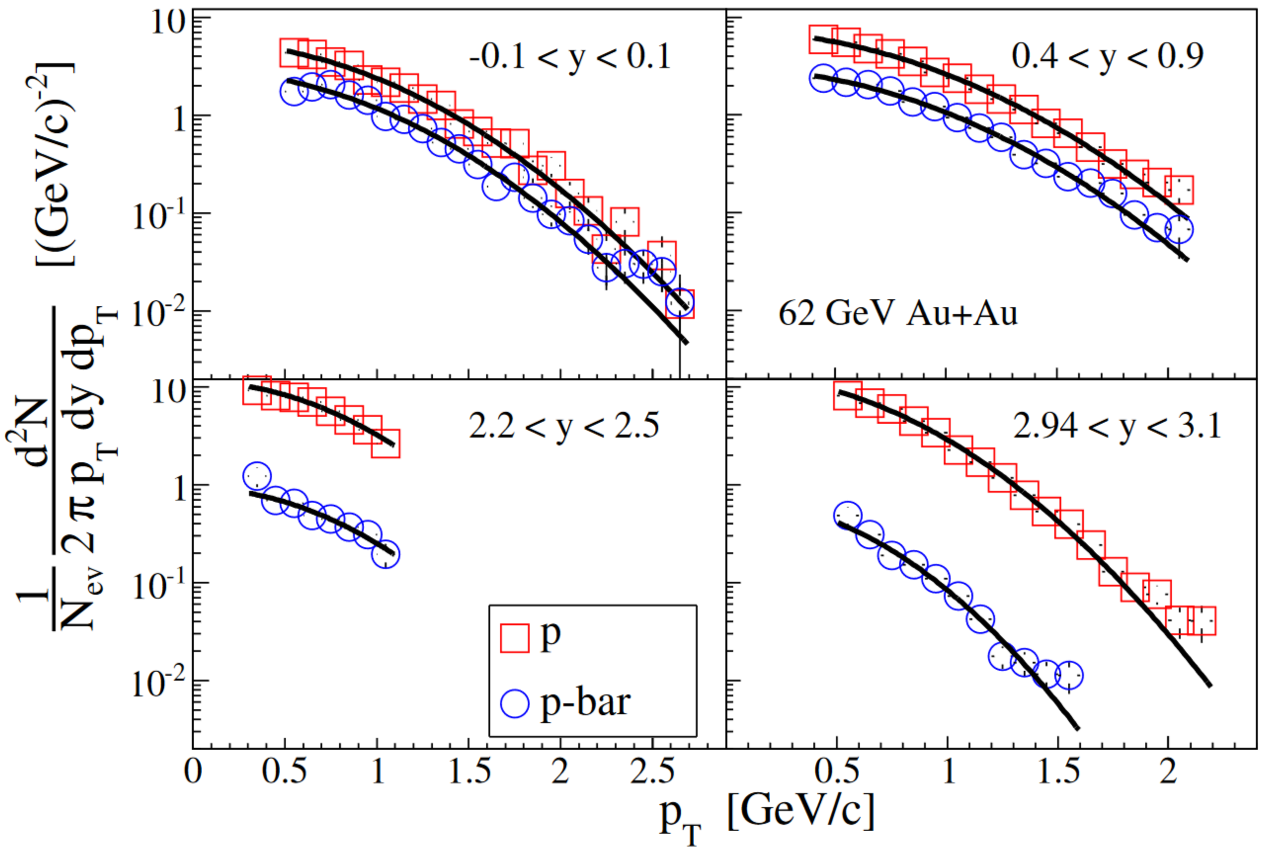
T. T. Takahashi, *et al* Phys. Rev. Lett. **86**, 18 (2001)

T. Takahashi, *et al*, Phys. Rev. D **65**, 114509 (2002)

Experimental Observations of Baryon Stopping

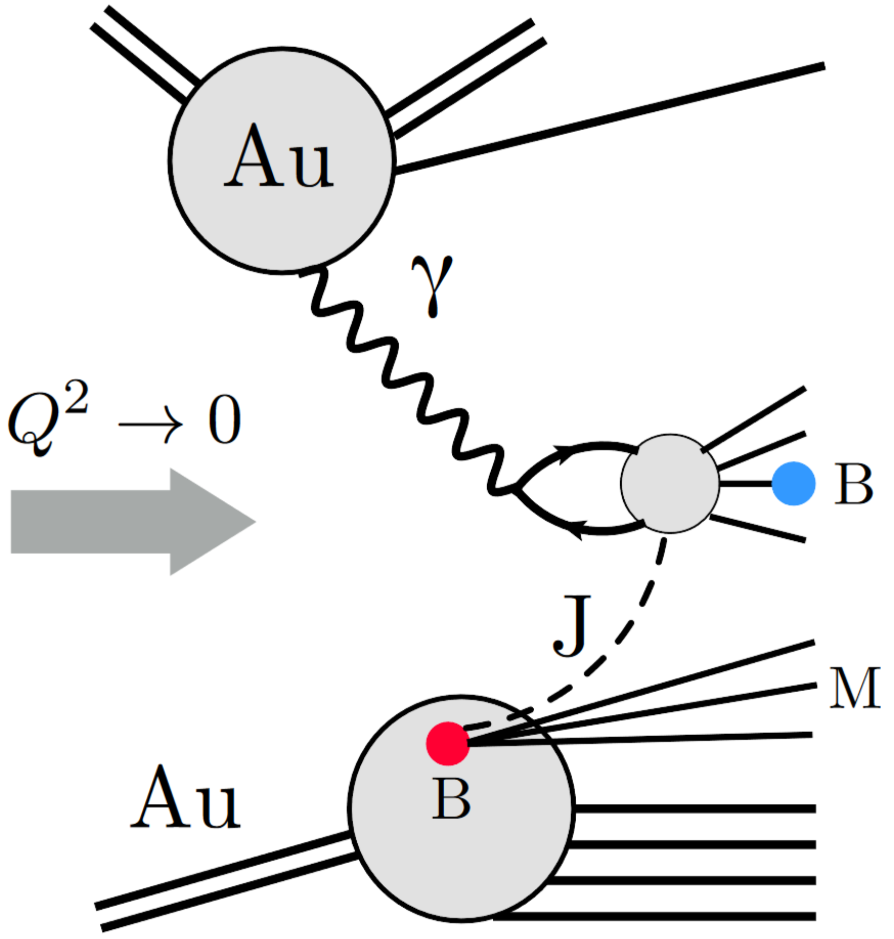


BRAHMS Collaboration, Phys. Lett. B **677,** 267-271 (2009)

- More baryons than antibaryons, even at midrapidity
  - Baryons from the colliding nuclei are veered away from the beam line
- The energy required for particle production in heavy-ion collisions comes from the kinetic energy lost by the baryons in the colliding nuclei
  - Larger effect in collisions with higher multiplicity (small impact parameter)
- Net-baryon yield can be estimated from the net-proton yield: difference in number of protons and anti-protons

Baryon Junction and Photonuclear Interactions

- Inclusive particle production in photonuclear collisions
  - Large flux of quasi-real photons produced by ultra-relativistic large-Z nuclei
  - Similar to eA collisions except that the photon has much smaller virtuality
- Can be used to study baryon stopping with the simplest possible heavy ion collisions
  - Probes the nucleus at low-x
  - Asymmetric collision: target can only be traveling in one direction

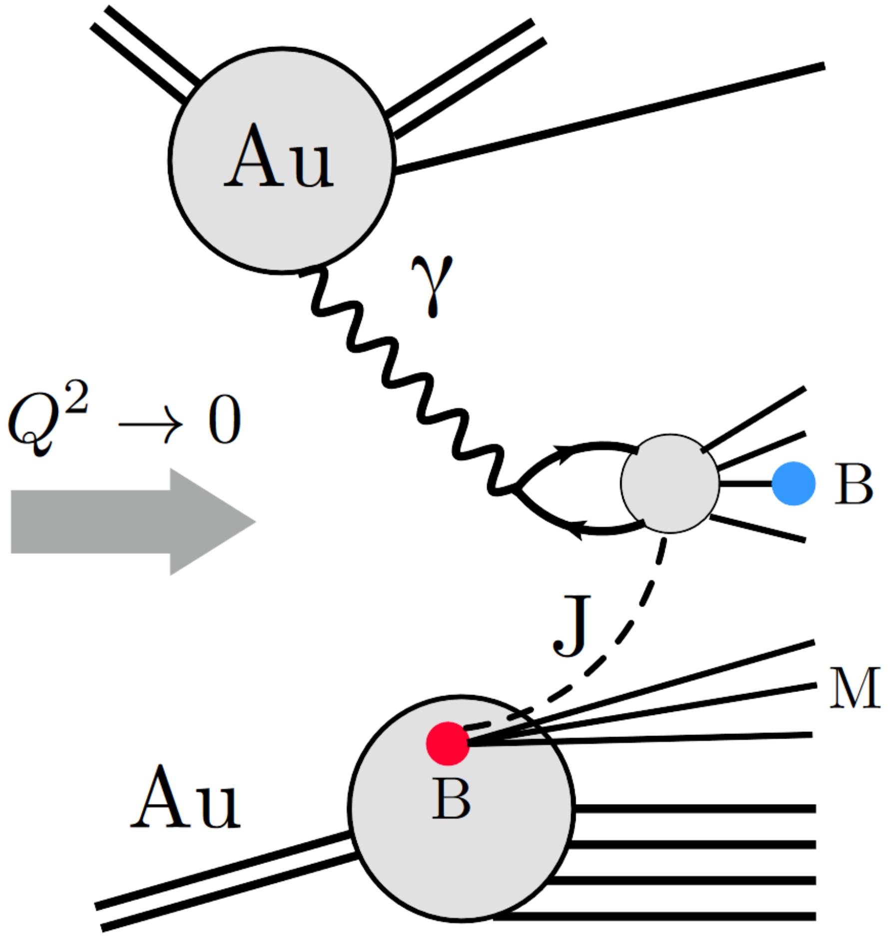


J. D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685 (2022)

Baryon Junction and Photonuclear Interactions

- $q\bar{q}$ + baryon junction producing a midrapidity proton
  - Asymmetric collision: target can only be traveling in one direction
  - Predicted rapidity distribution of $dN/dy \propto \exp(-y/2)$

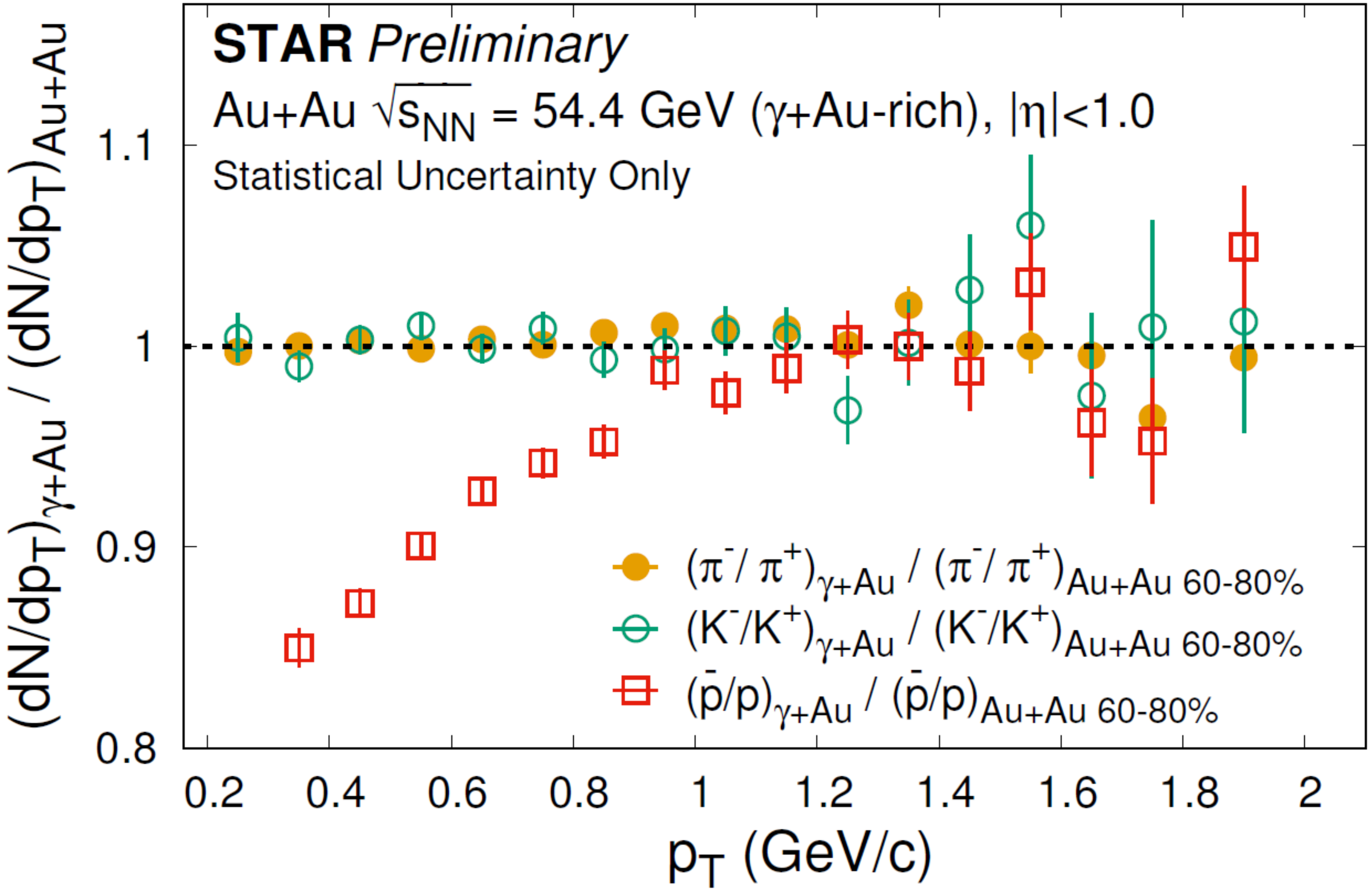
    D. Kharzeev, Physics Letters B **378**, 238 (1996)
- γA is a good tool to study the gluon junction because
  - **At high x:** photon is a very small color dipole, very small cross section to interact with 3 quarks at the same time
  - **At low x:** A is dominated by the gluons



J. D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685 (2022)

Low p_T Baryon Enhancement in γA

- Double ratio: antiparticle/particle in $(\gamma A)/(AA)$
- $\bar{p}/p < 1$ for $p_T \lesssim 1\ \mathrm{GeV}/c$
  → Indication of soft baryon stopping in γA collisions
- Not corrected for efficiency, but largely cancels in the double ratio

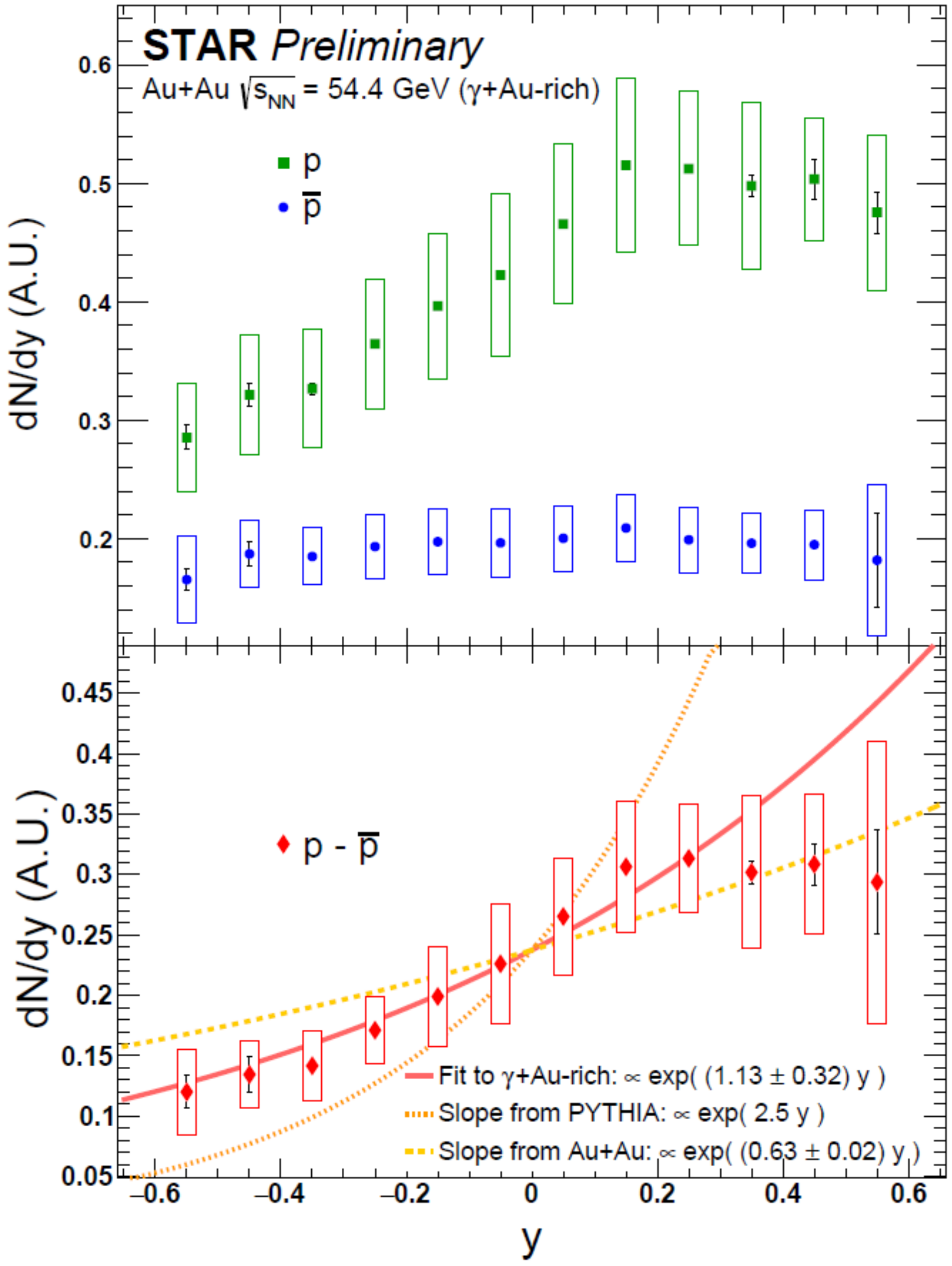


Rapidity Asymmetry in $\gamma + \mathrm{Au}$

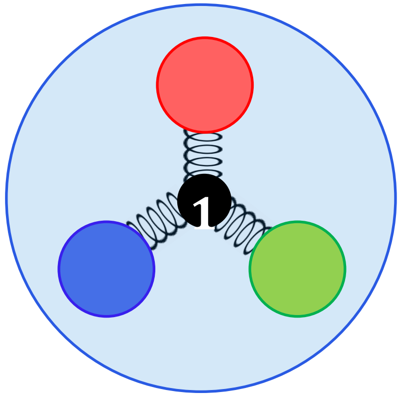
- $\bar{p}\ dN/dy$ slope is flat with y
  - Positive slope: asymmetric particle production in γA
  - Negative slope: Regge theory predicts that $p\bar{p}$ pair production should have an opposite rapidity dependence to the junction mechanism

    D. Kharzeev, Physics Letters B **378**, 238 (1996)
- p and net-proton dN/dy increases with y
  - Possibly due to the baryon junction mechanism
- Net-proton exponential slope: 1.13 ± 0.32
  - Closer to the slope of the beam energy dependence in $\mathrm{Au + Au}$
  - PYTHIA, which does not include a baryon junction mechanism, predicts a slope of ~ -2.5

    J. D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685 (2022)

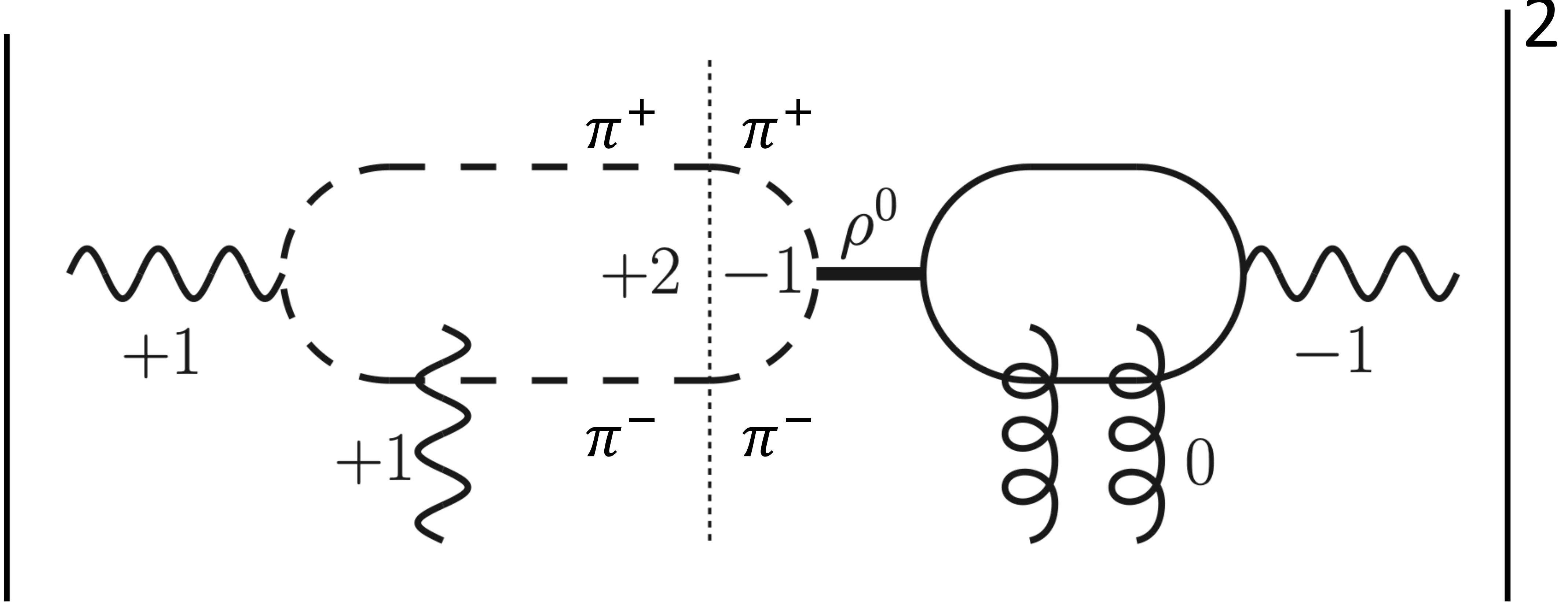


Summary & Outlook



- Gluons play a central yet elusive role in nuclear systems
- Big open questions
  - What are the properties of guon dynamics in extreme regimes, e.g. at low-x?
  - Does the pomeron have a non-trivial spin structure?
  - What carries the Baryon quantum number? Complex gluon configurations or quarks?
- STAR data 2023-2025
  - Investigate Tensor pomeron and baryon junction
  - High statistics data campaign currently underway
- LHC physics program is beginning to quantitatively address gluon saturation / shadowing models – more data coming soon
- The future Electron Ion Collider - eA collisions will provide ultimate precision, but still ~10 years away
- **Near-future potential to answer some big questions!**

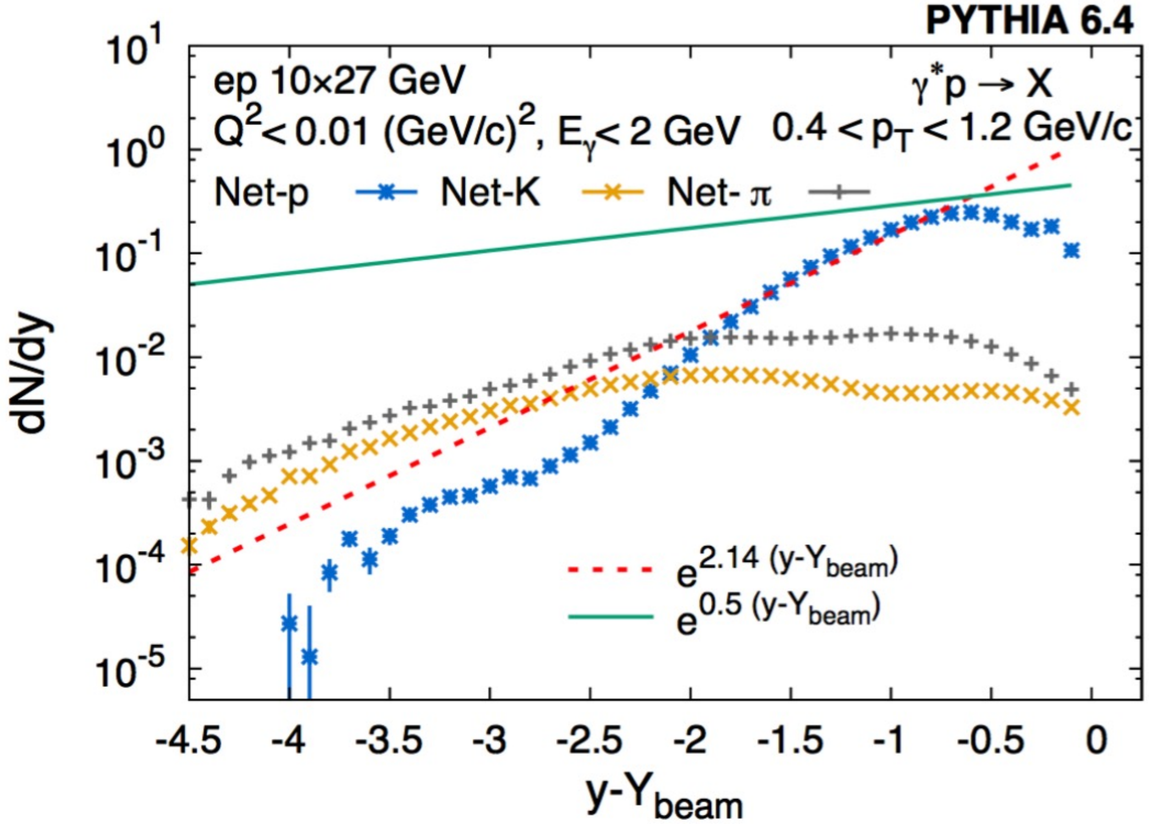
Access to Hadronic Light-by-Light



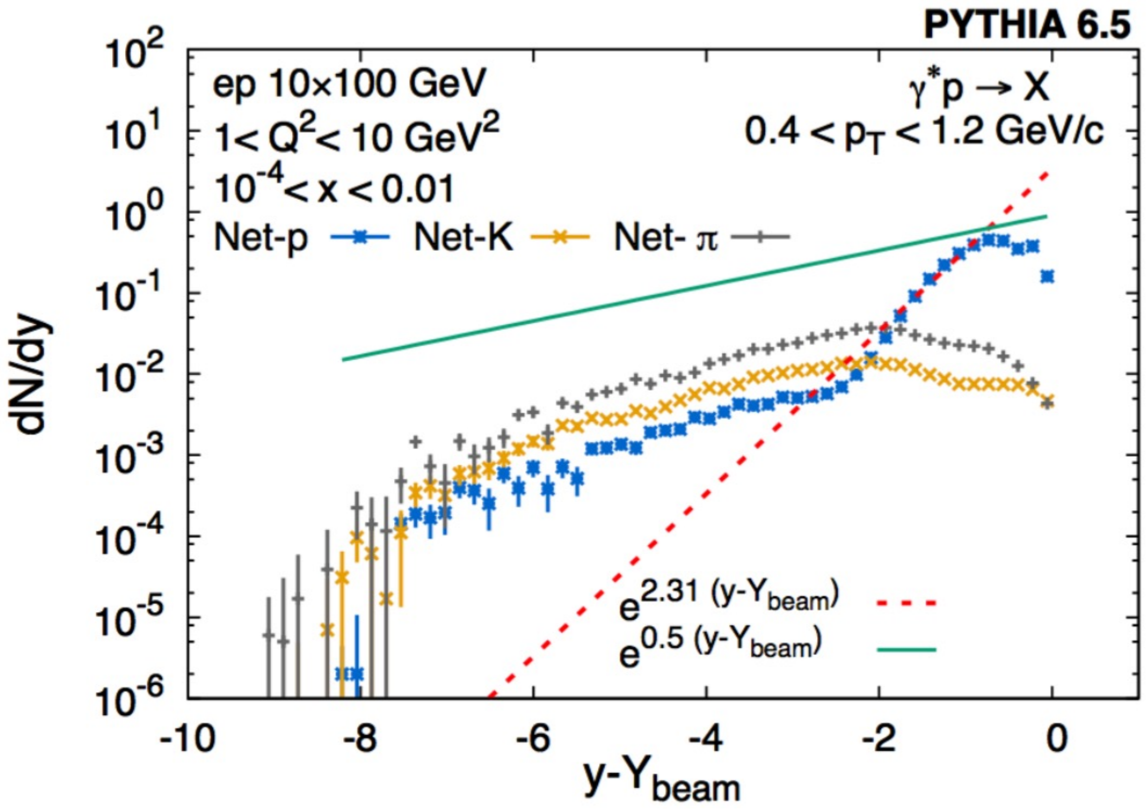
Interference with the hadronic light-by-light diagram
Leads to a unique signature -> odd spin configurations in specific phase space

Photonuclear vs Electron-Ion Collisions

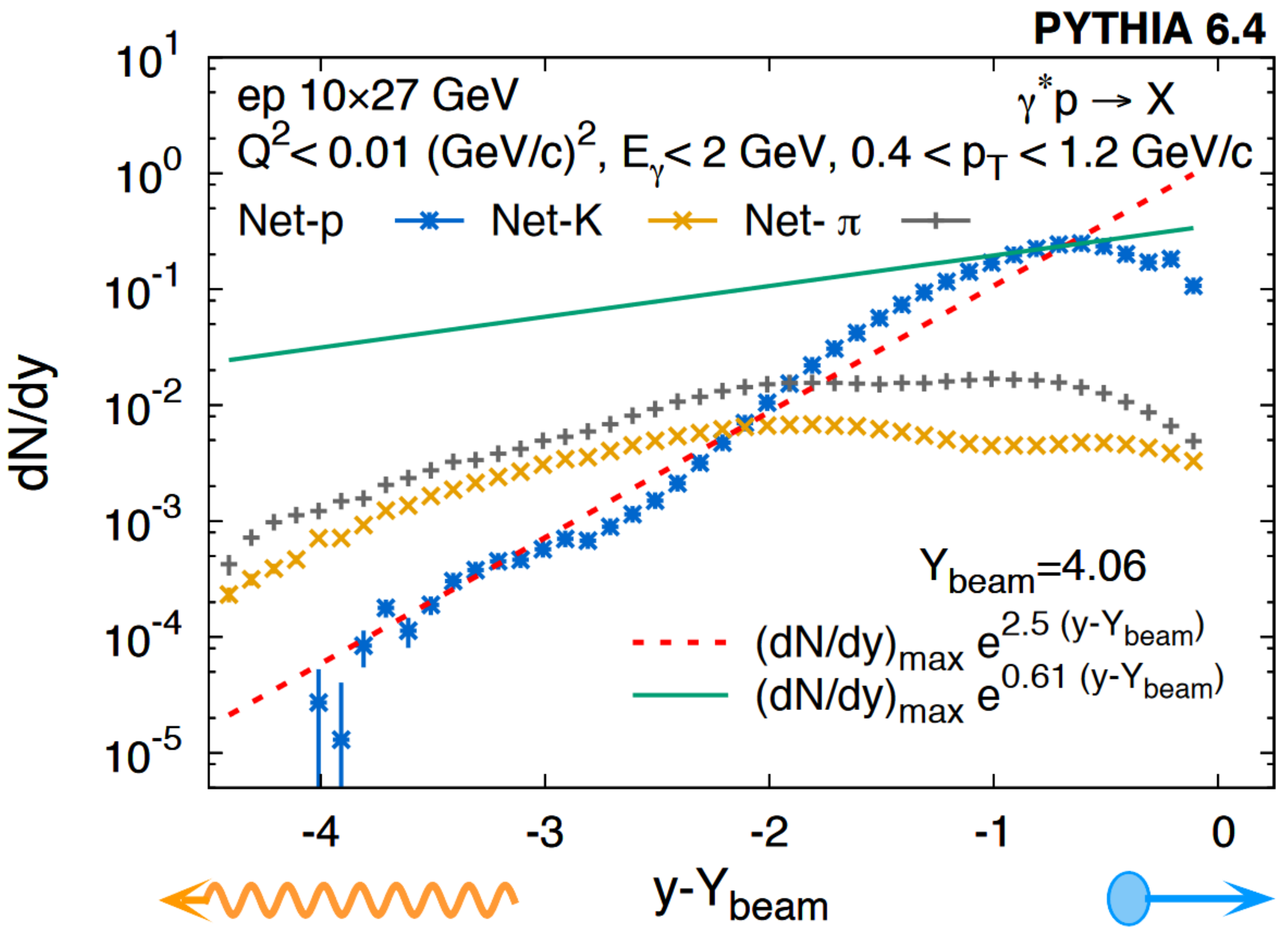
RHIC Photonuclear Kinematics

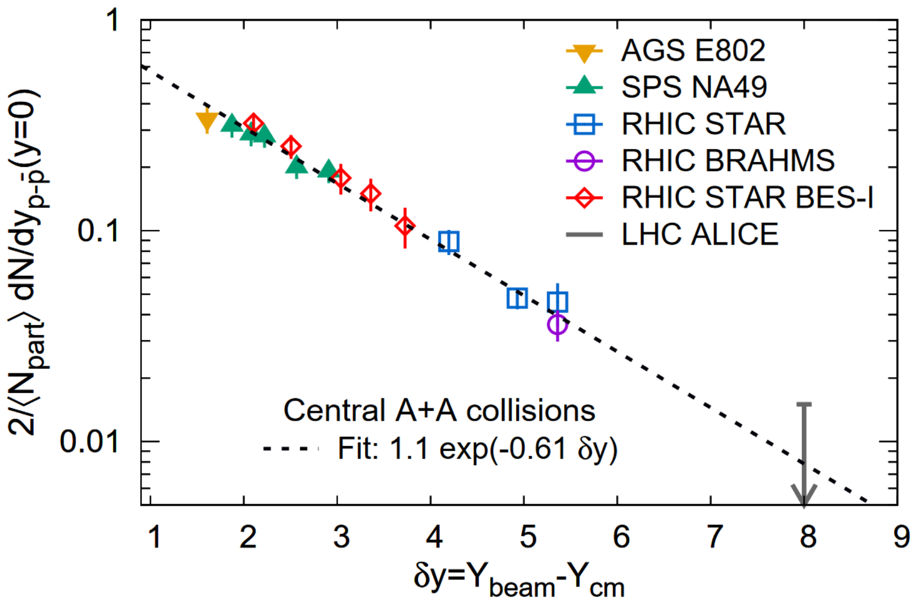


Possible EIC DIS Kinematics



Comparison to PYTHIA





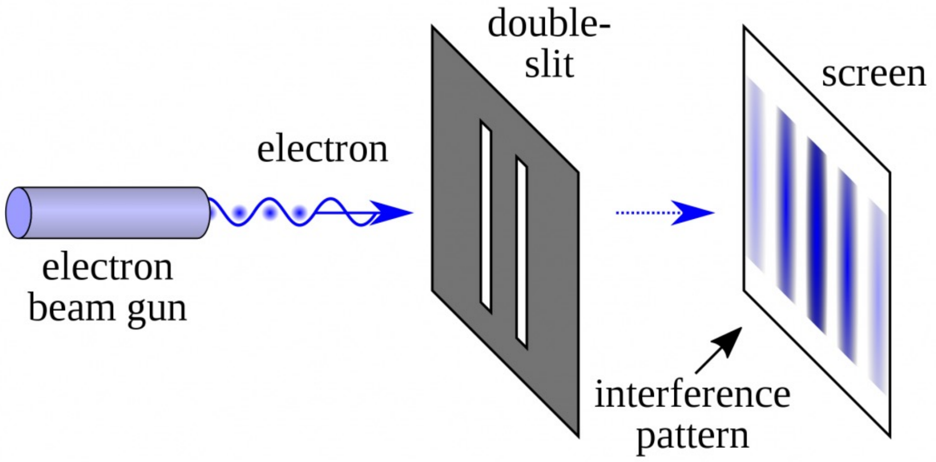
- PYTHIA6 does not implement a baryon junction
- Prediction for baryon stopping caused by the baryon junction
$$dN/dy \propto \exp(-y/2)$$

J. D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685 (2022)

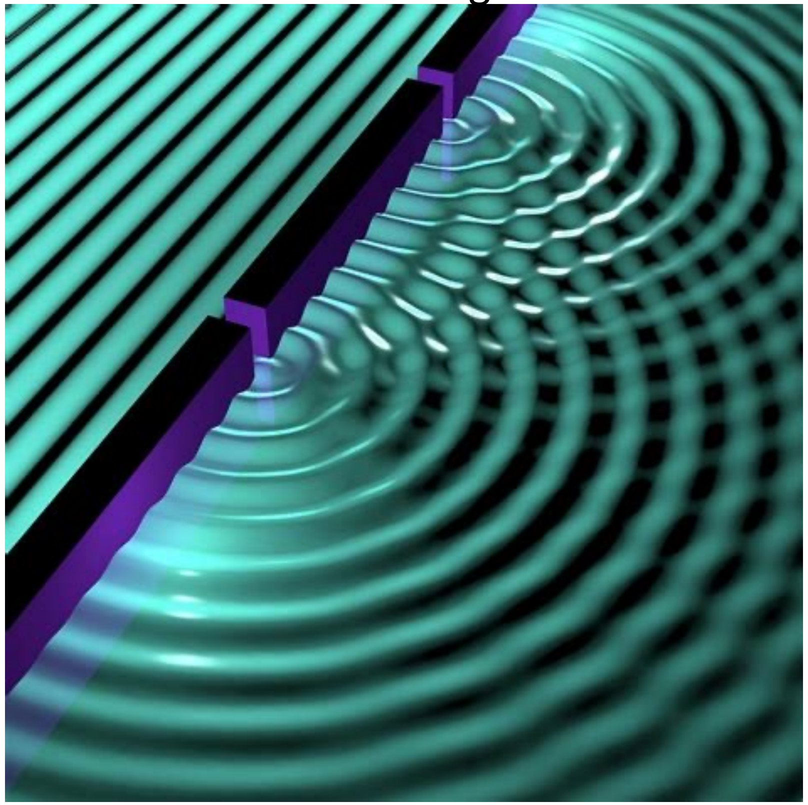
{Quantum} Double-Slit Experiment

- The double slit experiment is foundational in quantum mechanics

Quantum Double slit Experiment



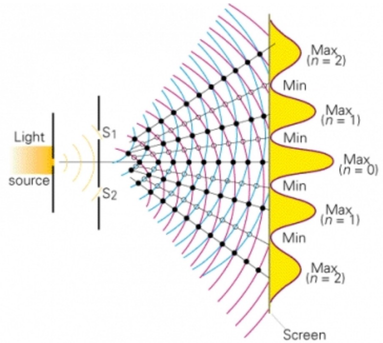
Water waves interfering in a double slit



- Shoot single electron (photon) through a double slit
- Wave interference observed!
- Quantum mechanics generally requires the interfering states to be **indistinguishable**

Novel Form of Quantum Interference

Similar to double-slit experiment

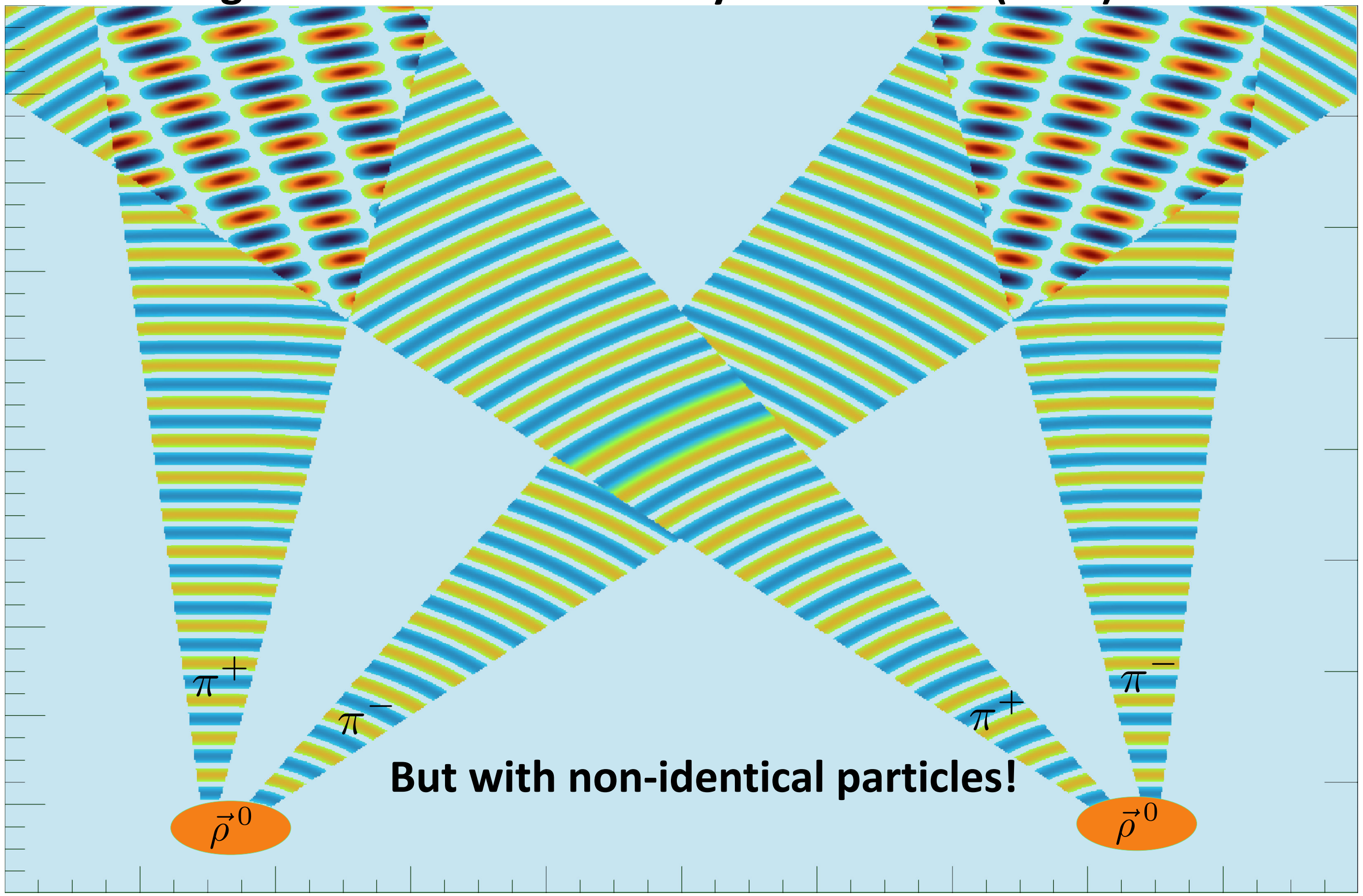


BUT WAIT…

The ρ^0 lifetime is only ($c\tau \sim 1$ fm)
$\rightarrow$ Decays to $\pi^+\pi^-$

Interference occurs between **distinguishable** particles

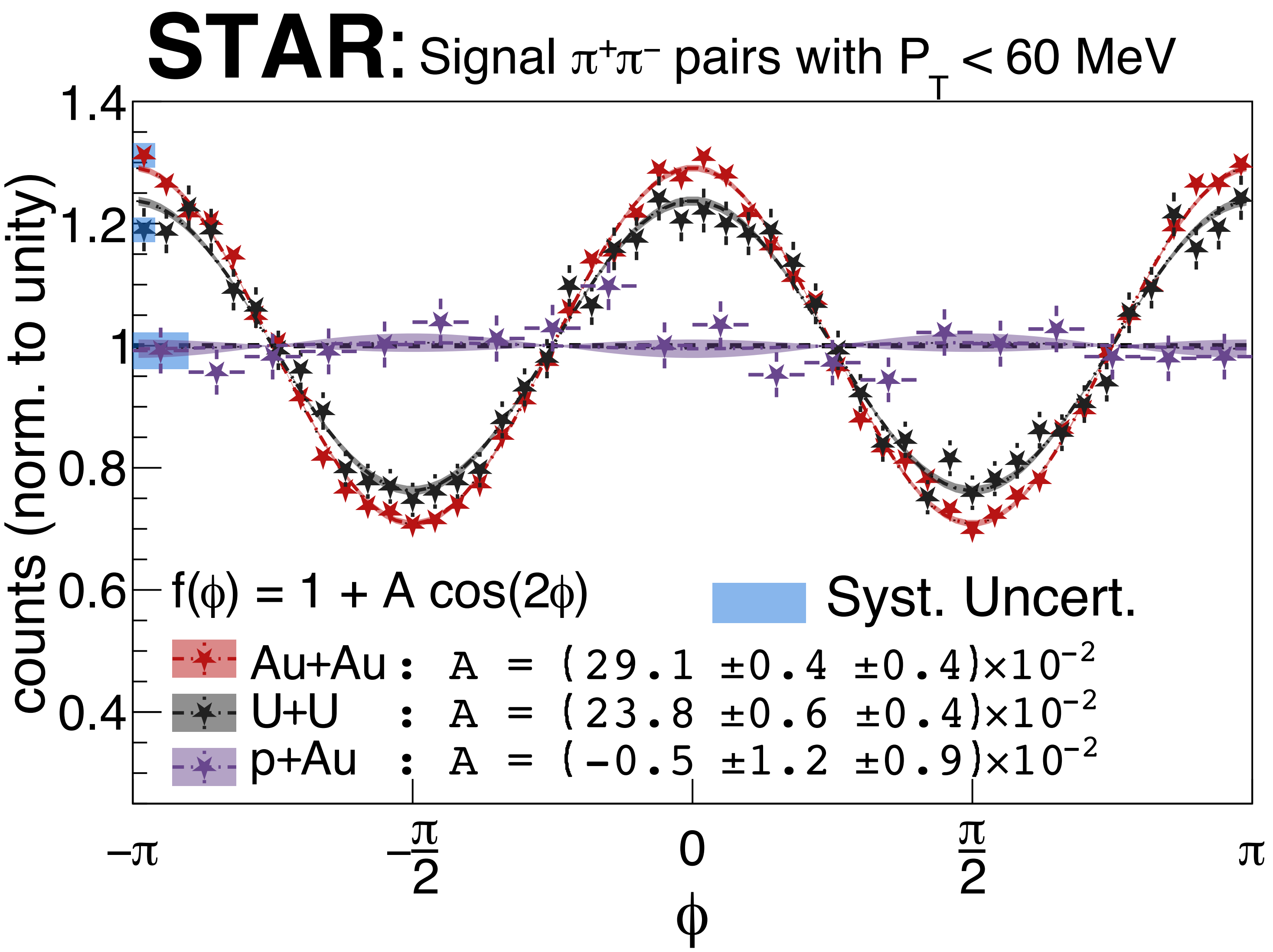
Entanglement Enabled Intensity Interference ($\mathbf{E^2I^2}$)

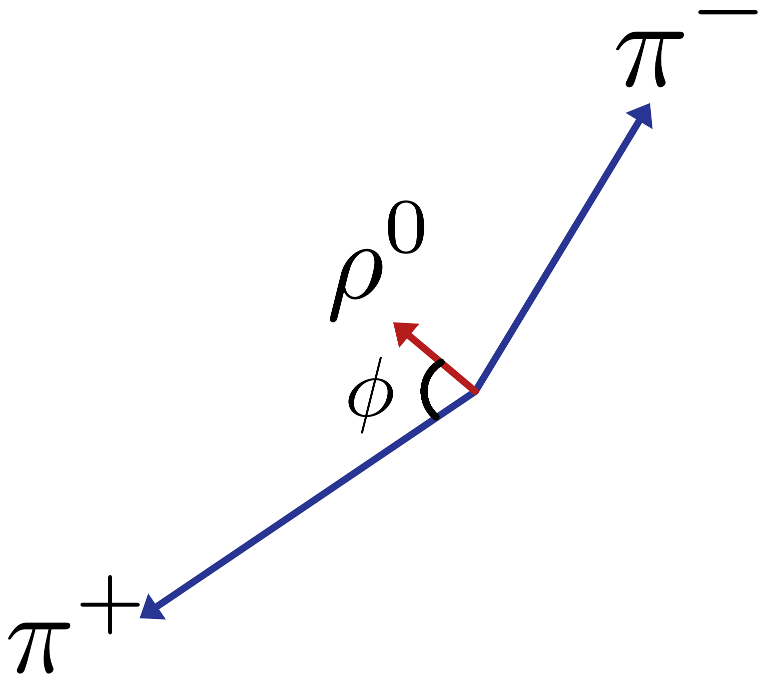


Possible theoretical explanation from Frank Wilczeck's group at MIT – Entanglement enabled interference of amplitudes from non-identical particles

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

Observation of Interference in $\rho^0 \rightarrow \pi^+\pi^-$





- Intrinsic photon spin transferred to ρ^0
- ρ^0 spin converted into **orbital angular momentum** between pions
- Observable as anisotropy in $\pi^\pm$ momentum

Origin of the Entanglement?

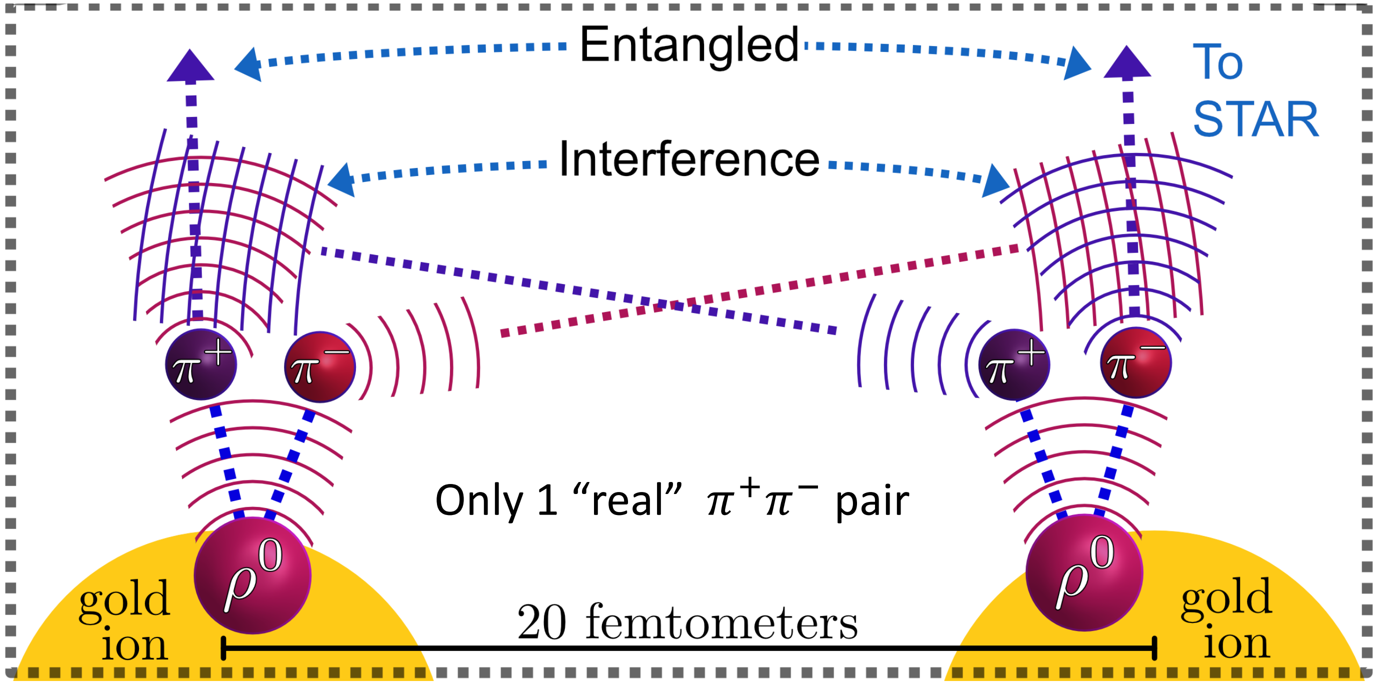
Case 1 : {Entangled} Double-Slit Experiment

- Well known that particle decay (or interaction in general) leads to entanglement

$$\langle \rho^0 | \pi^+ \pi^- \rangle \neq \langle \rho^0 | \pi^+ \rangle \langle \rho^0 | \pi^- \rangle$$

- Individually the π^+ wavefunctions interfere and separately the π^-
- Phase locking (through entanglement) causes π^+ and π^- to interfere at the real particle level

Similar to Entanglement Enabled Intensity Interference ($\mathbf{E^2I^2}$)



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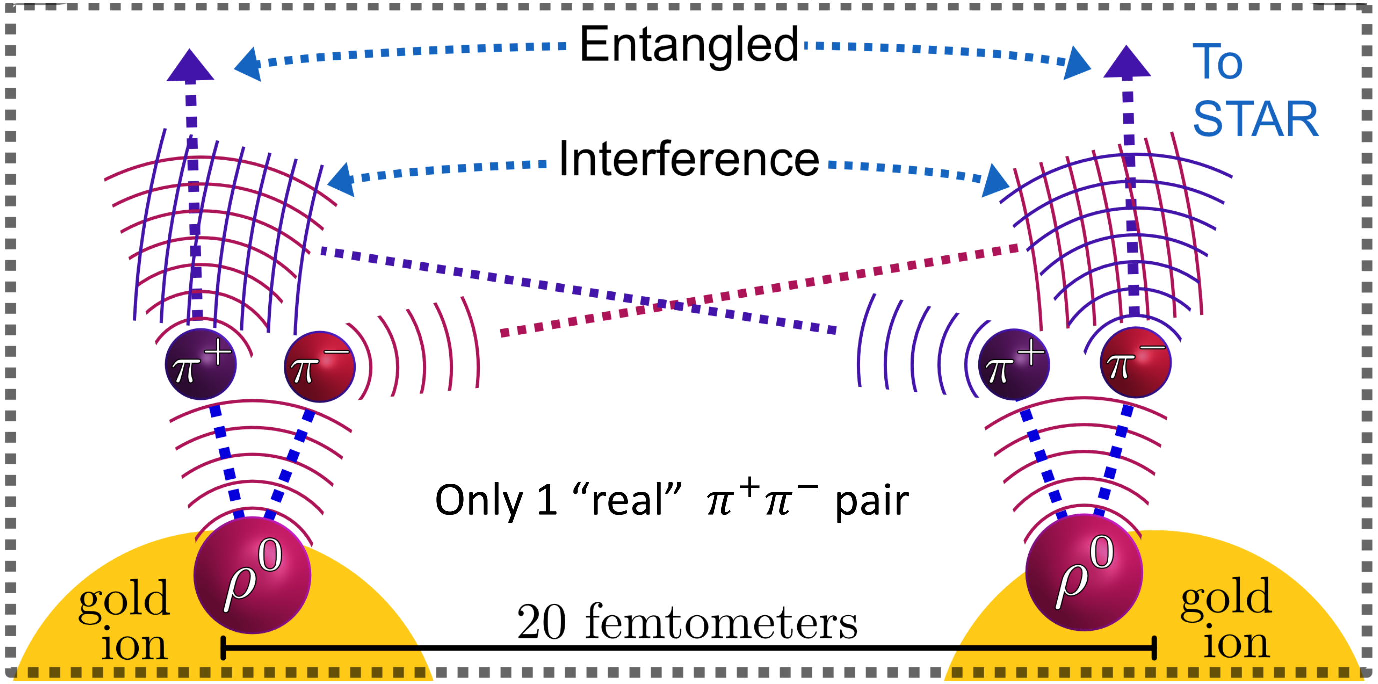


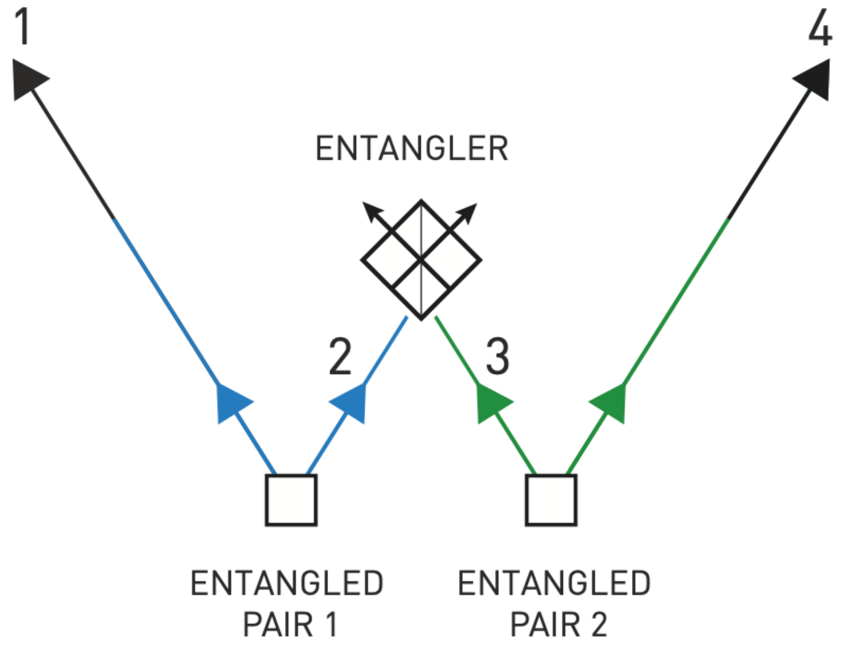
“What’s so wonderful,” Cotler says, “is that these contemporary experiments are still pushing the boundaries of our understanding of both quantum mechanics and measurement and opening up new horizons for both theory and experiment.” – Jordan Cotler

Case 2: Entanglement: Nobel Prize 2022

Alain Aspect, John Clauser and **Anton Zeilinger**

Entangled particles that never met

Two pairs of entangled particles are emitted from different sources. One particle from each pair is brought together in a special way that entangles them. The two other particles (1 and 4 in the diagram) are then also entangled. In this way, two particles that have never been in contact can become entangled.



Quantum teleportation:

Transferring quantum information through entanglement

Can something similar happen at the wavefunction level?

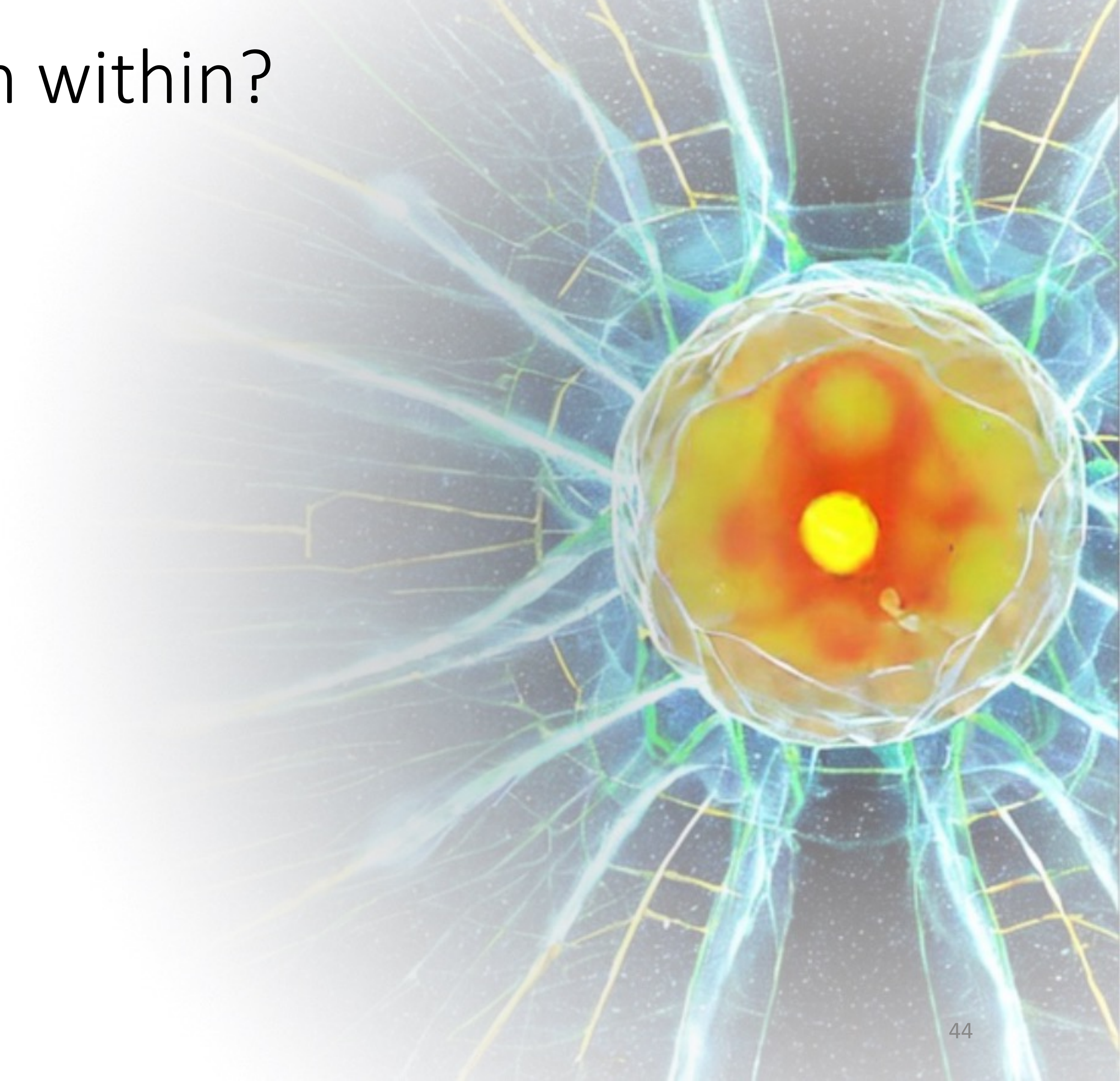
Case 3 : Entangled from within?

Maybe the entanglement originates even earlier in the interaction?

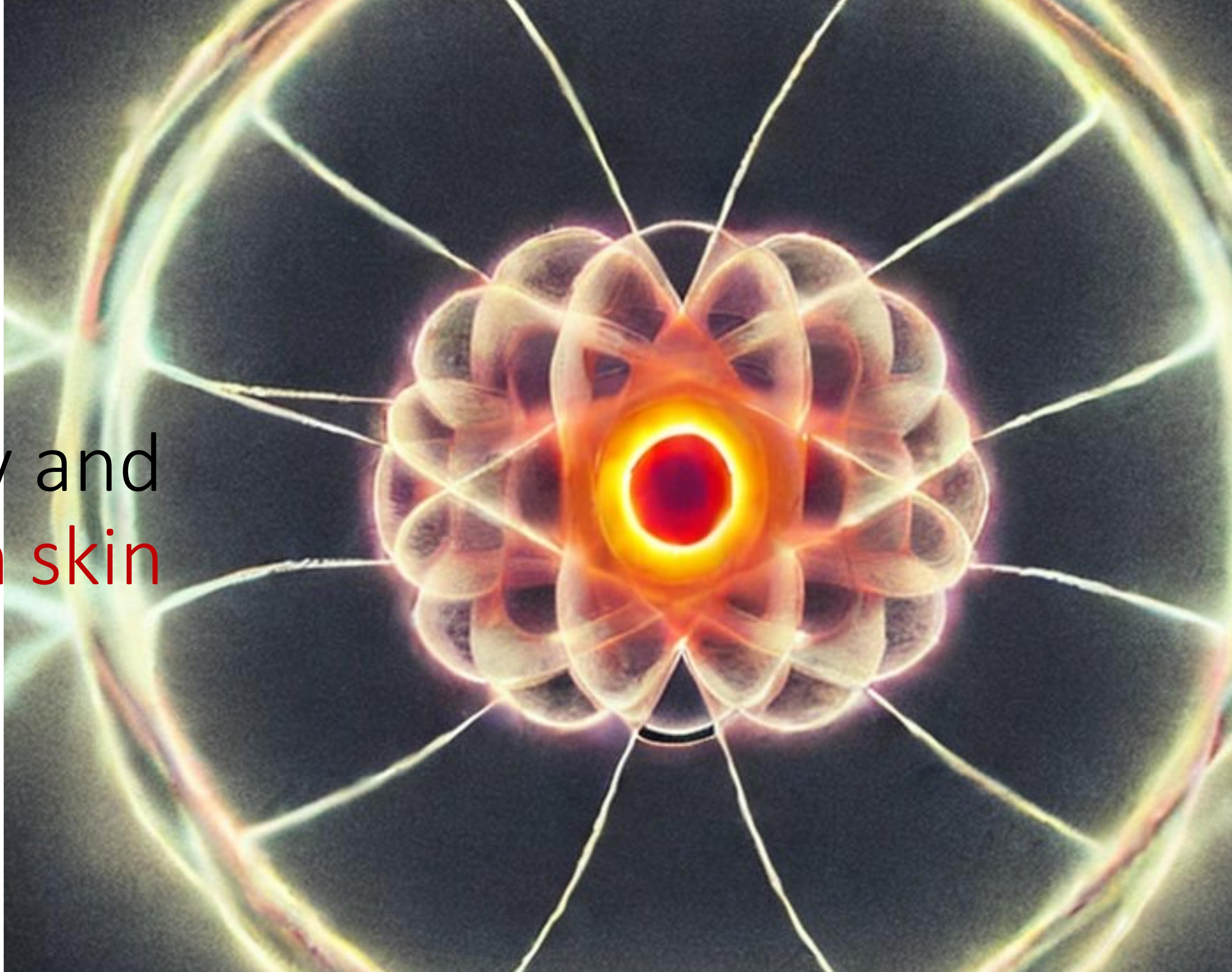
We expect that the nucleus (and the nucleons) are highly entangled states

BUT…

We have no experimental proof of this entanglement at rest

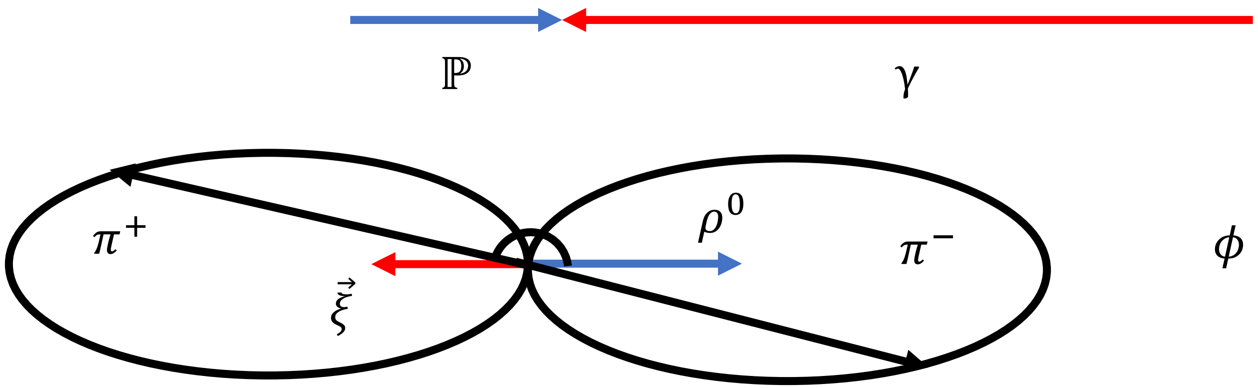


Nuclear Tomography and the Neutron skin



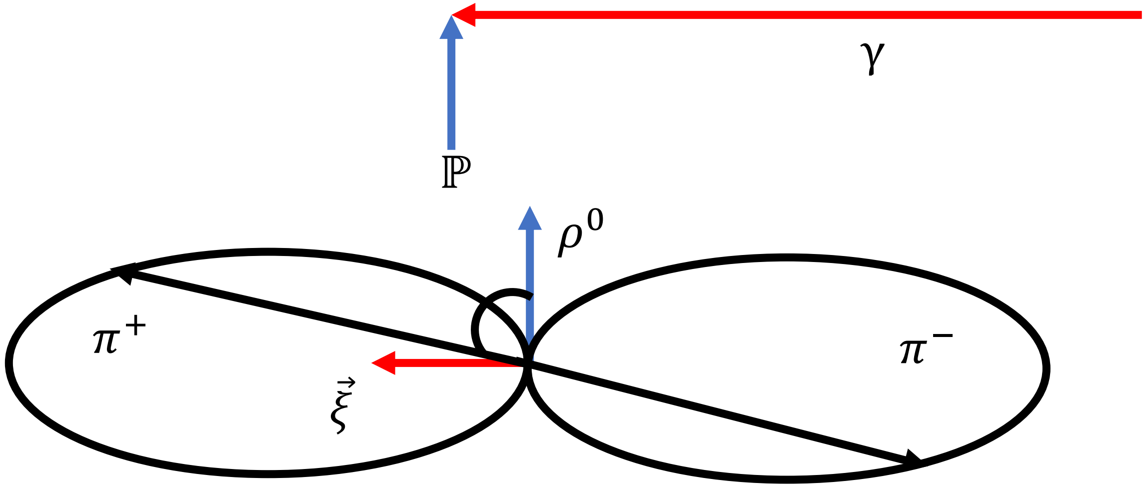
Interference Reveals Event Configurations

- Case I : Photon & Pomeron are (anti-) parallel



$\phi \approx 0, \pi$

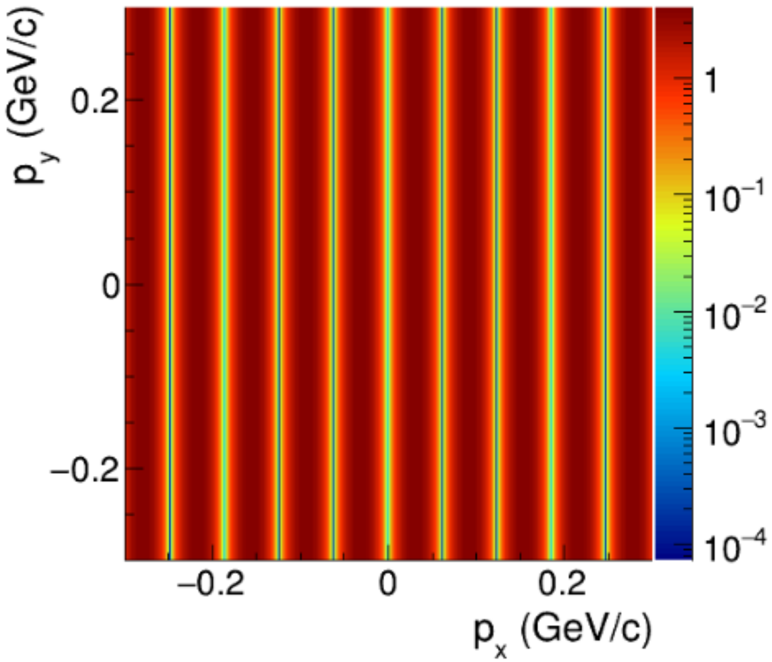
- Case II : Photon & Pomeron are perpendicular



$\phi \approx \pm\pi/2$

Motivation for 2D Analysis :P_x vs P_y

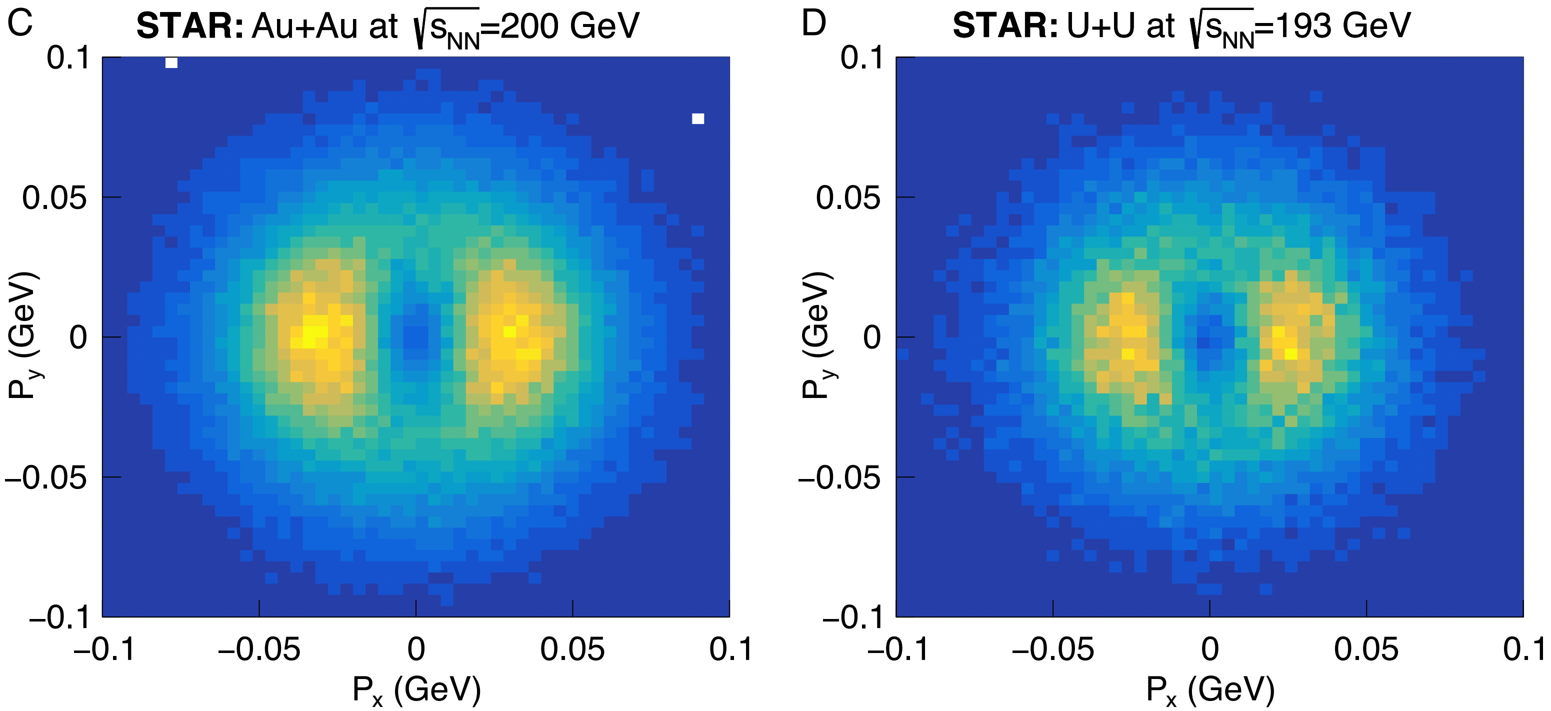
- Photon polarization is aligned with $\vec{b}$ (exactly for point source)
- Two source interference takes place in x-axis (impact parameter direction)



- Interference pattern disappears in P_y direction
- Due to polarization of the ρ^0, daughter pions aligned with photon polarization.
- Express ρ^0 transverse momentum in 2D:
  - $P_x = p_T \times \cos\phi$
  - $P_y = p_T \times \sin\phi$

Phys. Rev. D 103, 033007 (2021), https://arxiv.org/abs/2006.12099

2D "Imaging" : Clear difference in P_x vs. P_y



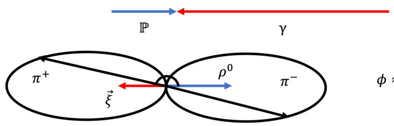
- Express ρ^0 transverse momentum in two-dimensions:
  - $P_x = p_T \times \cos\phi$
  - $P_y = p_T \times \sin\phi$

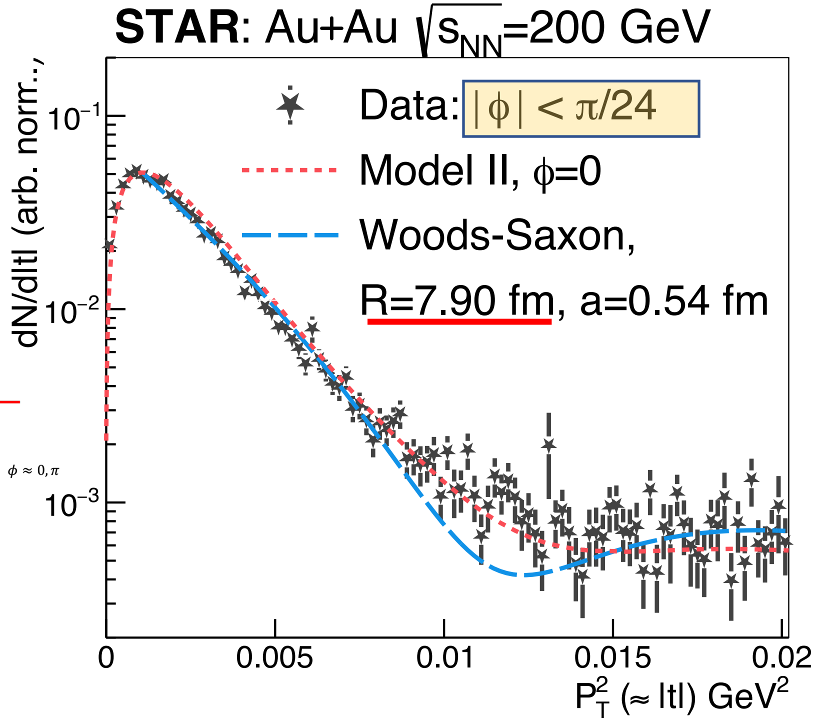
- Clear asymmetry in P_x vs. P_y due to interference effect in both Au+Au and U+U
- Illustrated "2D" tomography

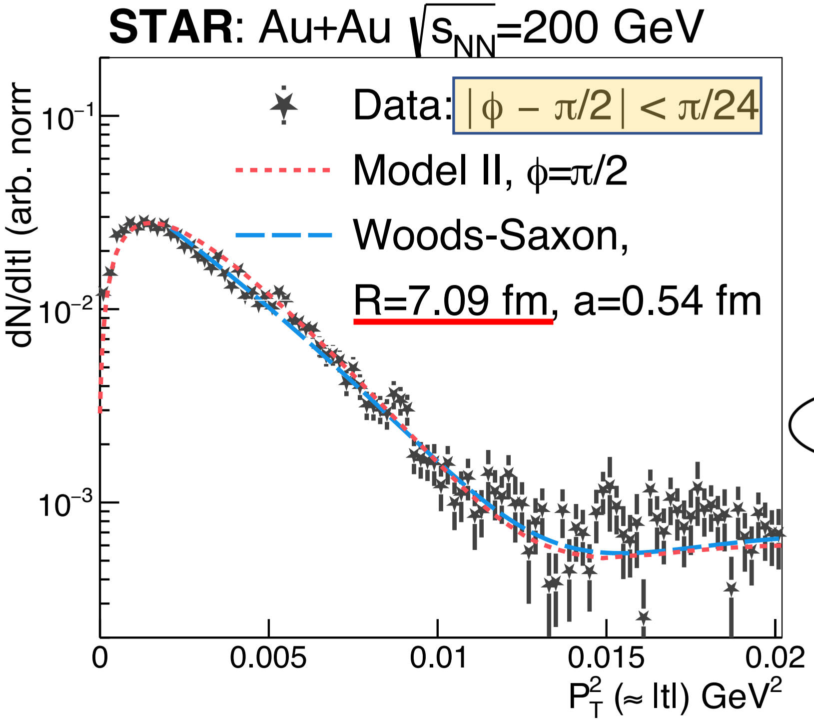
STAR Collaboration, Sci. Adv. **9**, eabq3903 (2023).

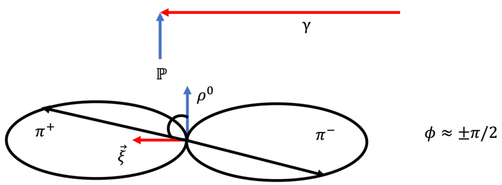
|t| vs. ϕ, which radius is 'correct'?

Now instead of p_x and p_y lets look at $|t|$ with a 2D approach







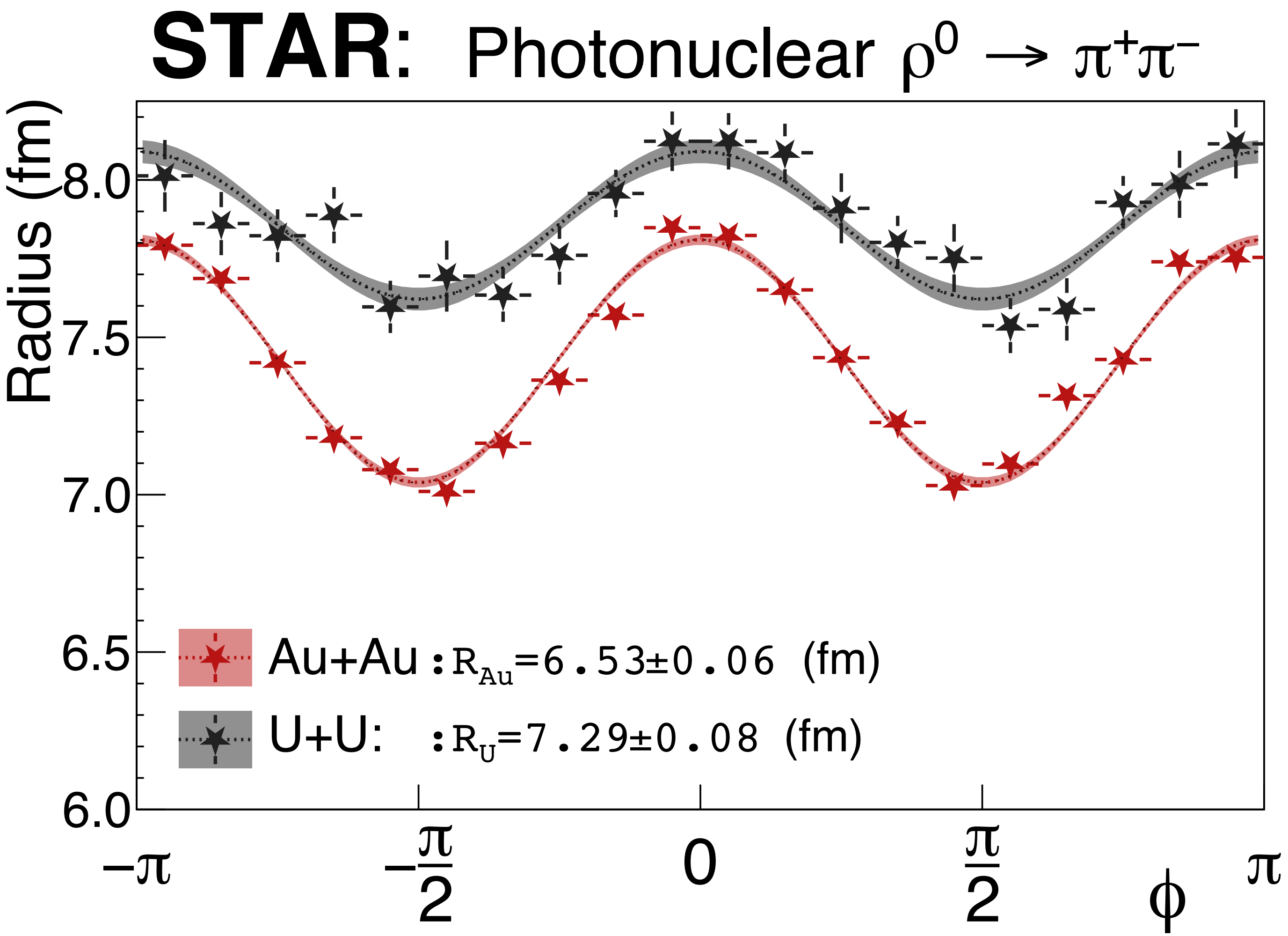


- Drastically different radius depending on ϕ, still way too big
- Notice how much better the Woods-Saxon dip is resolved for $\phi = \pi/2$ -> experimentally able to **remove photon momentum, which blurs diffraction pattern**
- **Can we extract the 'true' nuclear radius from |t| vs. ϕ information?**

STAR Collaboration, Sci. Adv. **9**, eabq3903 (2023).

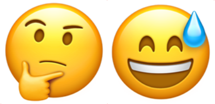
Xing, H et.al. *J. High Energ. Phys.* **2020**, 64 (2020)

Imaging the Nucleus with Polarized Photons



Interference pattern used for diffraction tomography of gluon distribution → analog to x-ray diffraction tomography

First high-energy measurements of gluon distribution with sub-femtometer resolution



Technique provides quantitative access to gluon saturation effects
BUT measurements via other vector mesons are needed for to validate QCD theoretical predictions/interpretations

Future measurements with ϕ meson and J/ψ are important

[STAR Collaboration, Sci. Adv. **9**, eabq3903 (2023).]

Nuclear Radius Comparison

	Au+Au (fm)	U+U (fm)
Charge Radius	6.38 (long: 6.58, short: 6.05)	6.81 (long: 8.01, short: 6.23)
Inclusive |t| slope (STAR 2017) [1]	7.95 ± 0.03	--
Inclusive |t| slope (WSFF fit)*	7.47 ± 0.03	7.98 ± 0.03
Tomographic technique*	6.53 ± 0.03 (stat.) ± 0.05 (syst.)	7.29 ± 0.06 (stat.) ± 0.05 (syst.)
DESY [2]	6.45 ± 0.27	6.90 ± 0.14
Cornell [3]	6.74 ± 0.06	--
Neutron Skin * (Tomographic Technique)	0.17 ± 0.03(stat.) ± 0.08(syst.) $\sim 2\sigma$	0.44 ± 0.05 (stat.) ± 0.08 (syst.) $\sim 4.7\sigma$ (Note: for Pb $\approx$ 0.3)
		*STAR Collaboration, Sci. Adv. **9**, eabq3903 (2023).

Precision measurement of <u>nuclear</u> interaction radius at <u>high-energy</u>

Measured radius of Uranium shows evidence of significant neutron skin

[1] STAR Collaboration, L. Adamczyk, *et al.*, *Phys. Rev. C* 96, 054904 (2017).
[2] H. Alvensleben, *et al.*, *Phys. Rev. Lett.* 24, 786 (1970).
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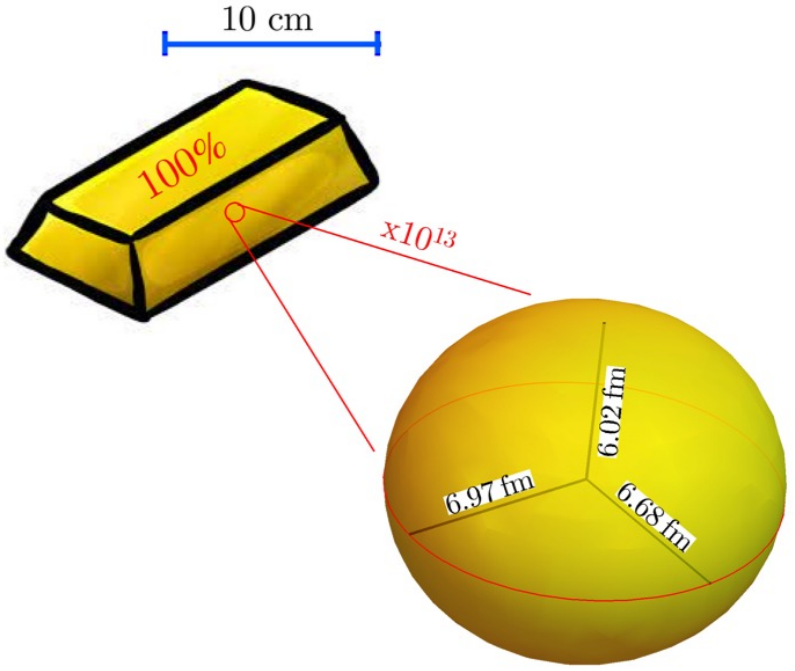
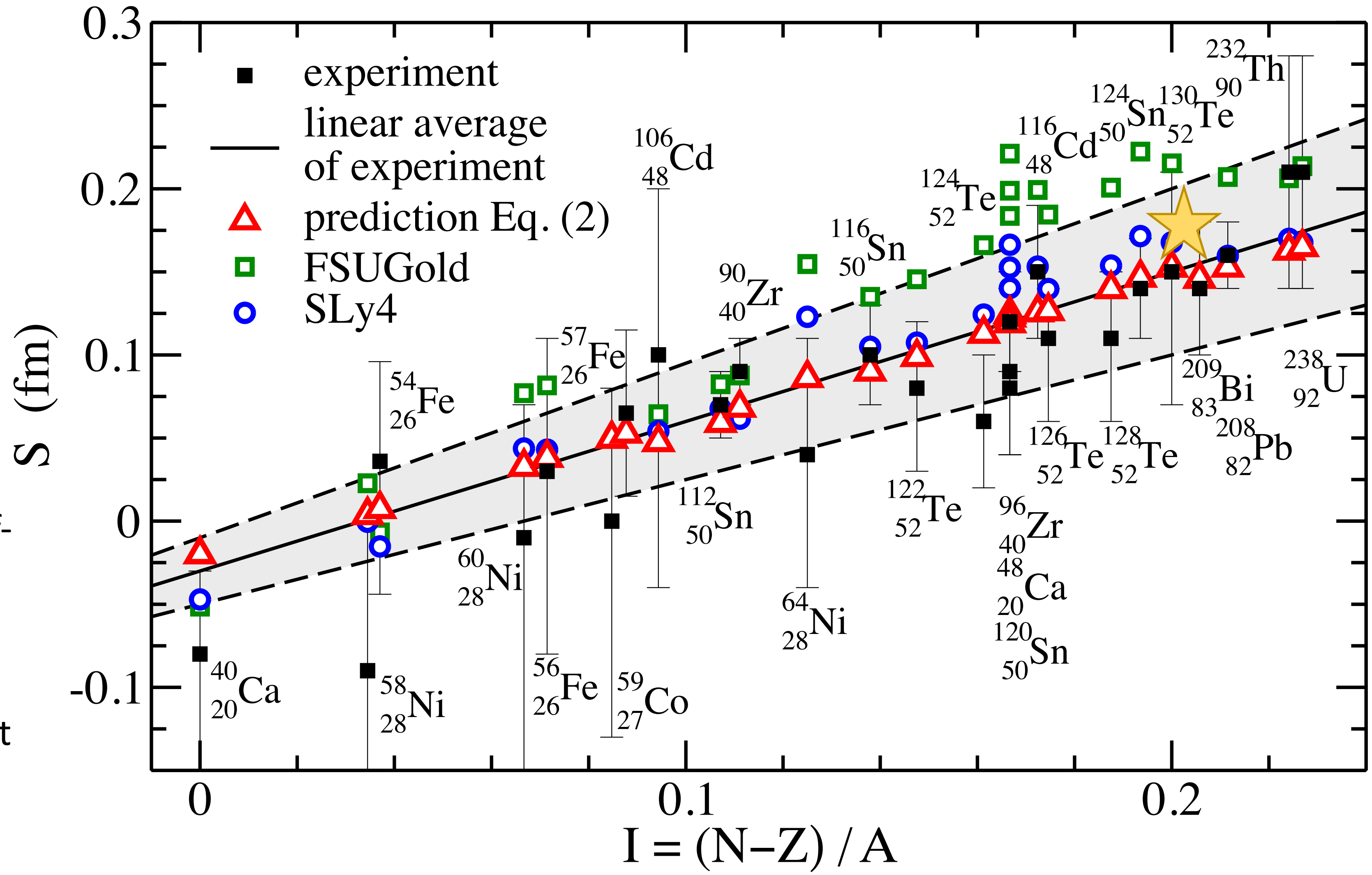
Neutron Skins across Nuclei



Recent theoretical approach from state-of-the-art multi-reference energy density functional (MR-EDF) calculations:

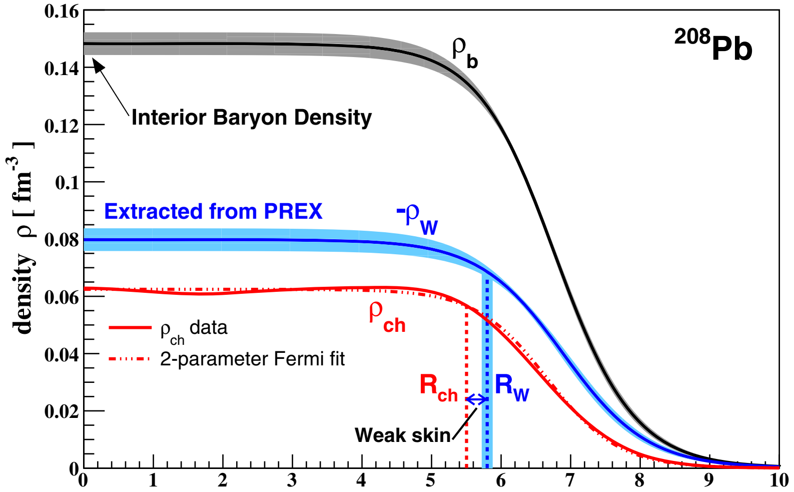
$$S_{Au} = 0.17 \text{ fm}$$

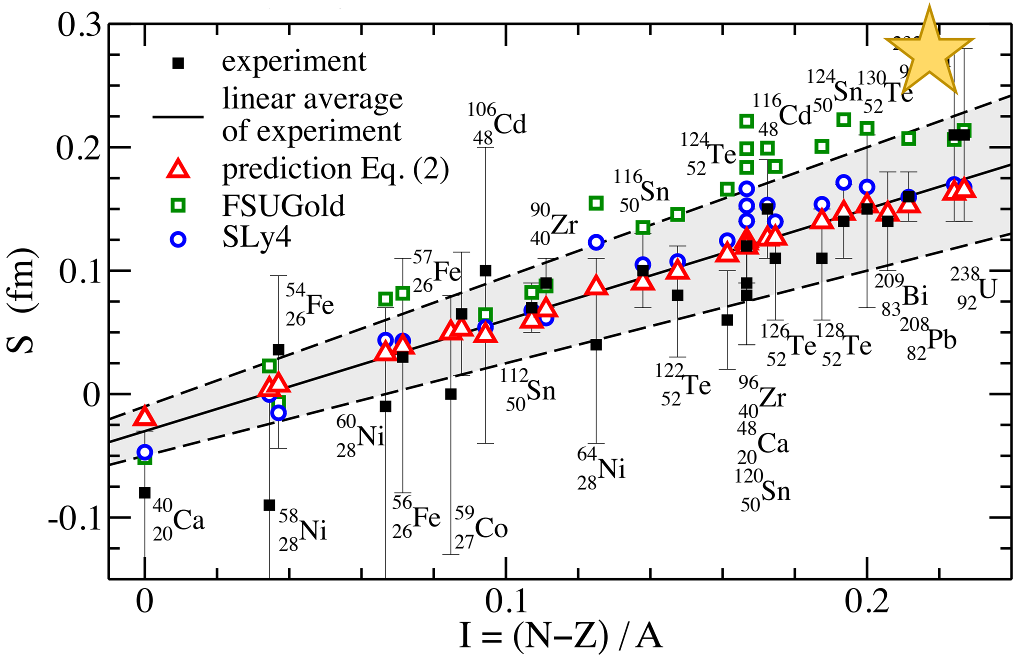
In good agreement with our measurement



B. Bally, G. Giacalone, M. Bender https://arxiv.org/abs/2301.02420

The neutron skin of ^{208}Pb





PREX-II neutron skin measurement for ^{208}Pb

$S_{Pb} = 0.283 \pm 0.071$ fm