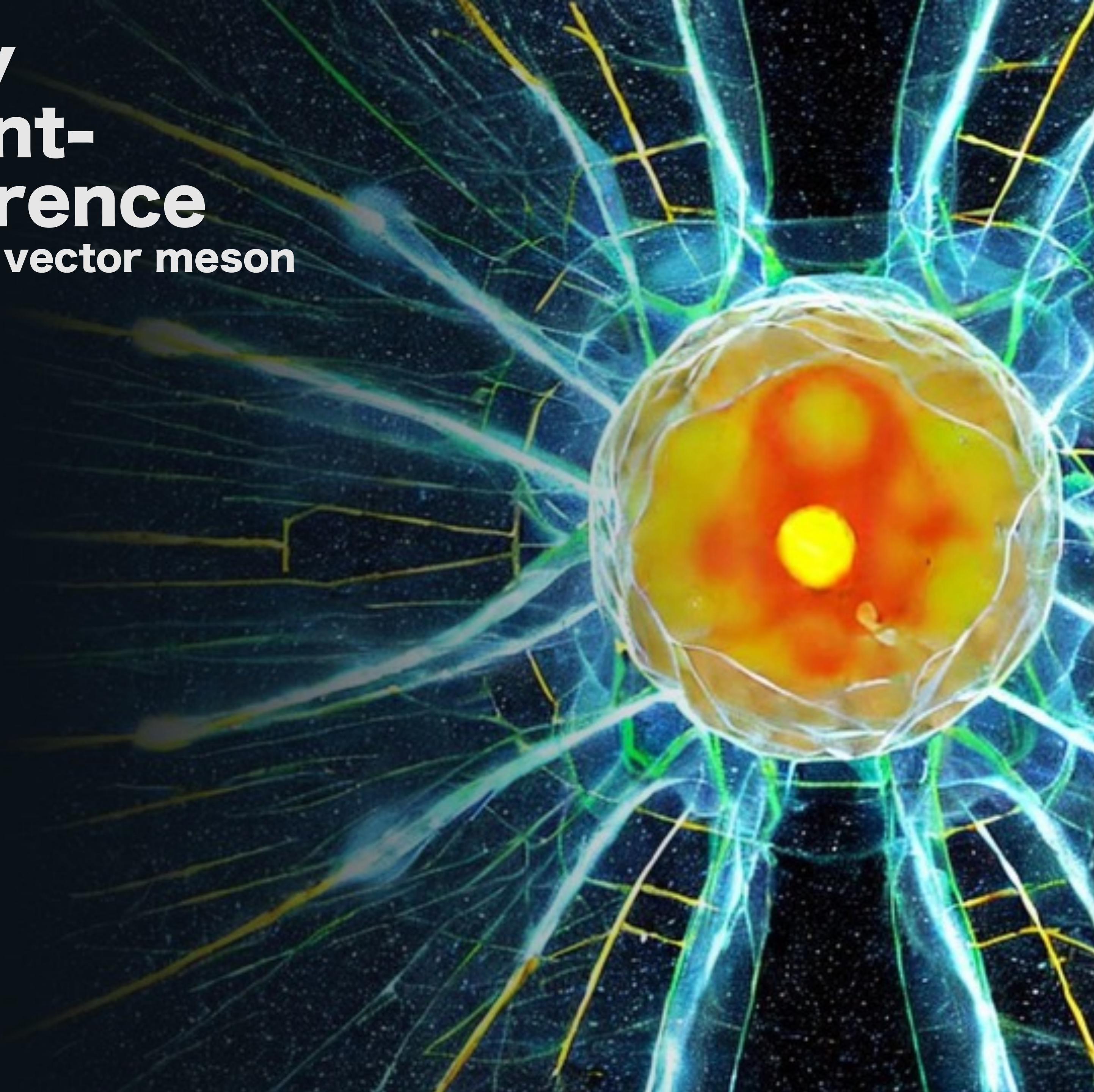
Nuclear Tomography through Entanglement-Enabled Spin Interference

“Nuclear tomography via diffractive vector meson photoproduction”

(James) **Daniel Brandenburg**

THE OHIO STATE UNIVERSITY



Intersection of nuclear structure and high-energy nuclear collisions
@Institute for Nuclear Theory,
University of Washington
Seattle, WA
February 22, 2023

Outline : Nuclear tomography via diffractive vector meson photoproduction

1. Intro: Light & “The Puzzle”

- Light and Polarization
- The puzzle in photonuclear interactions

2. Entanglement-Enabled Quantum Interference

- Experimental Signatures of Interference
- Entanglement Scenarios

3. Nuclear Tomography

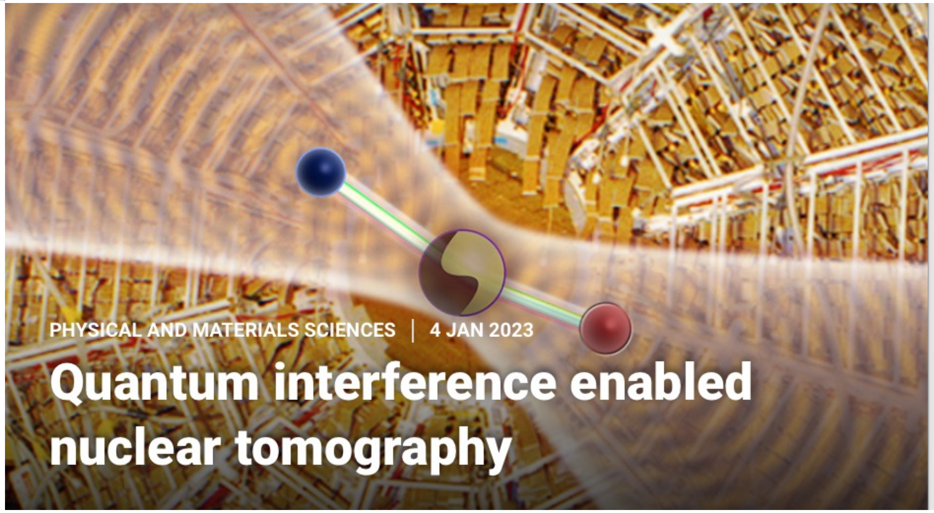
- ‘Imaging’ the nucleus
- Extracting the Neutrons Skin of Gold and Uranium

4. Future Directions & Applications

- Search for the elliptic gluon distribution
- Testing Quantum Mechanics
- Summary

[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] W. Zha, JDB, Z. Tang, and Z. Xu, Phys. Lett. B **800**, 135089 (2020).
[7] STAR Collaboration, Phys. Rev. Lett. **127**, 052302 (2021).
[8] STAR Collaboration, Phys. Rev. Lett. **121**, 132301 (2018).
[9] JDB, W. Li, et al., arXiv:2006.07365 [hep-ph, physics:nucl-th] (2020).
[10] JDB, STAR Collaboration, https://arxiv.org/abs/2204.01625

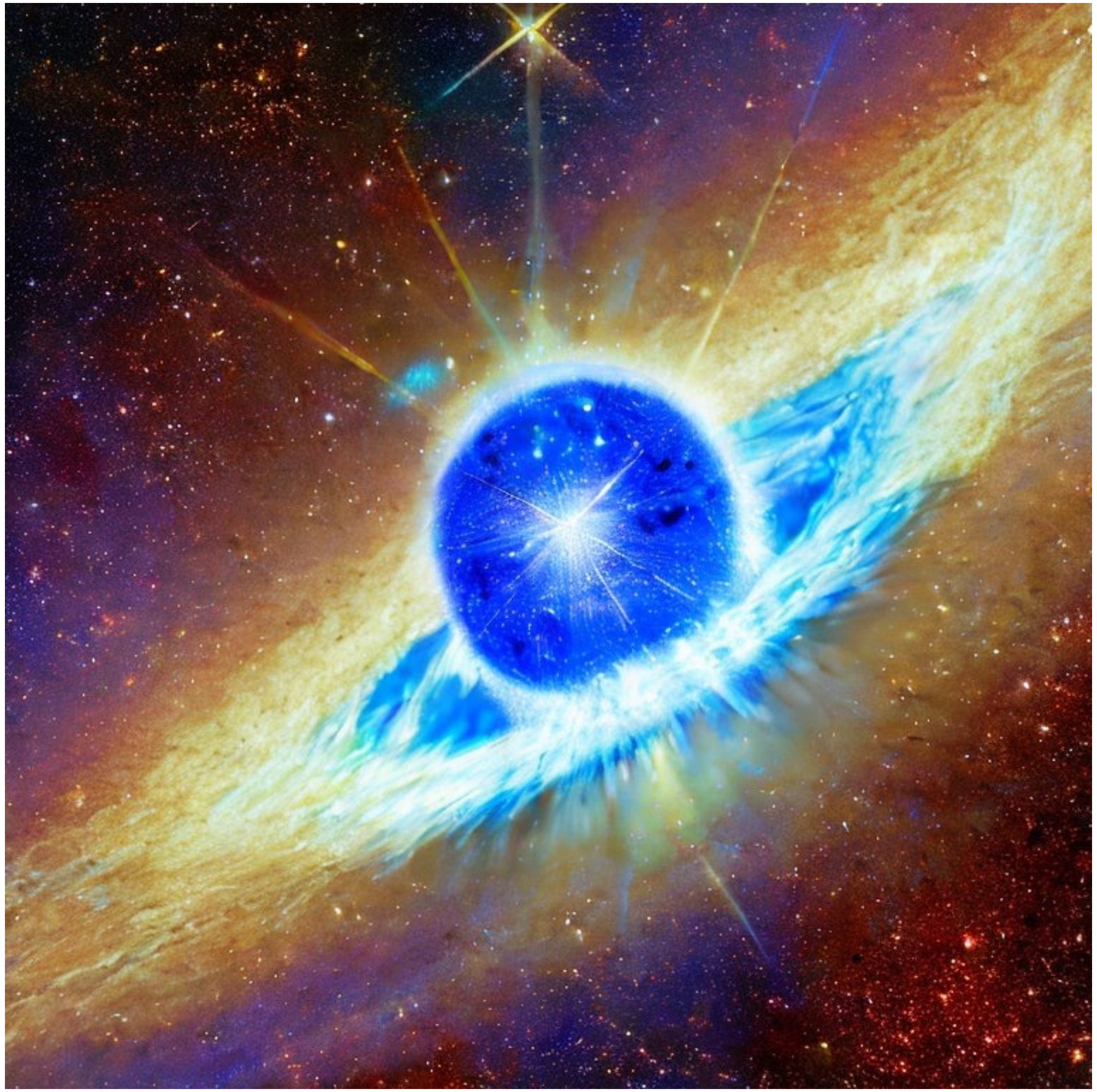
ScienceAdvances



Featured article, Volume 9, issue 1, 2023

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

Nuclear Tomography at high energy : Motivation



Nuclear matter is all around us from the tiniest atoms to huge interstellar objects

The Equation of State (EOS) of nuclear matter dictates the forms of matter over 10^{18} orders of magnitude in scale

The EOS determines the structure and stability of atomic nuclei, the formation of the elements, whether stars collapse into neutron stars or black holes, and the structure of neutron stars themselves

D. Adhikari *et al.* (PREX Collaboration) Phys. Rev. Lett. **126**, 172502 (2021)

Brendan T. Reed, F. J. Fattoyev, C. J. Horowitz, and J. Piekarewicz Phys. Rev. Lett. **126**, 172503 (2021)

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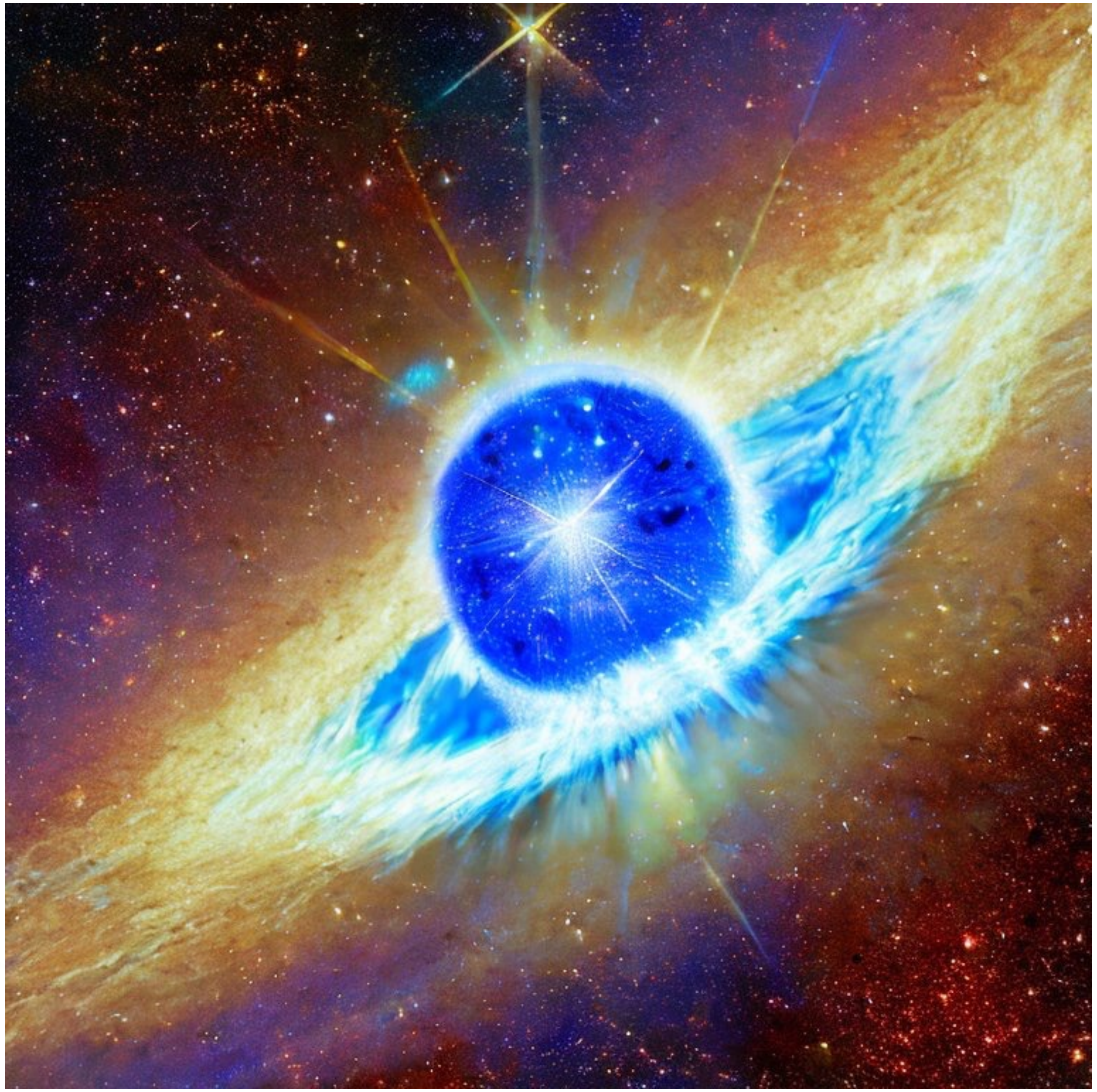

EOS constraints from astrophysics:

- NICER x-ray telescope has determined a pulsar radius to better than 10%
- Gravitational wave data from LIGO from a neutron star merger event has constrained neutron star tidal deformability

Still open questions:

- Significant nonzero strangeness component in neutron star interior?
- Phase transition within neutron star cores?

D. Adhikari *et al.* (PREX Collaboration) Phys. Rev. Lett. **126**, 172502 (2021)

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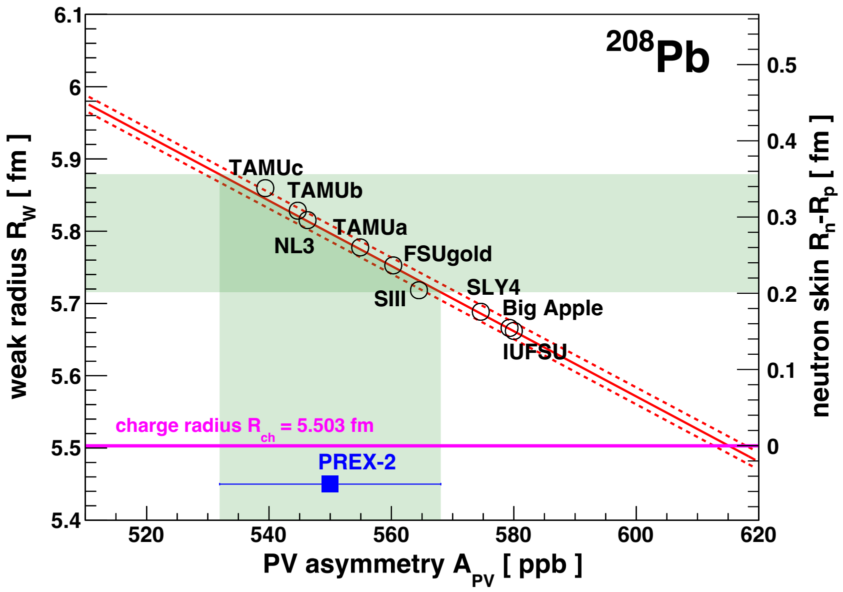

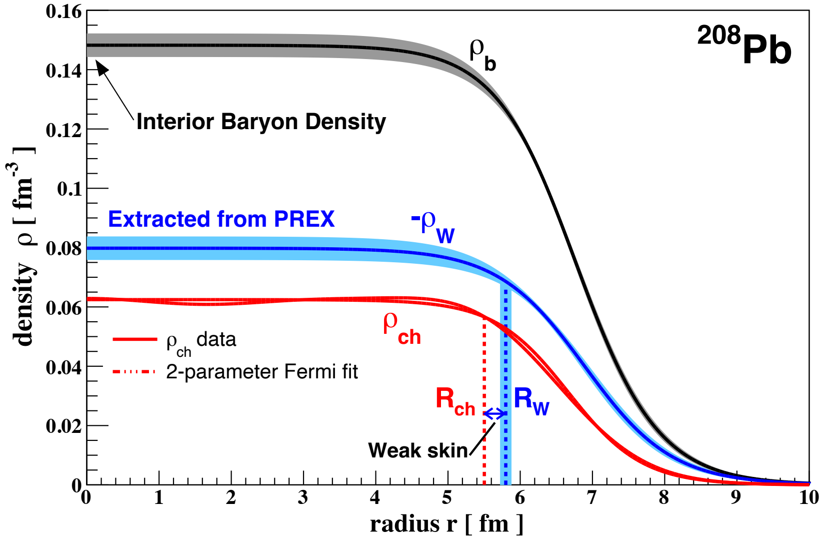

PREX-II: Precise measurement of the neutron skin of lead:

$$R_{\text{skin}} = R_n - R_p = (0.283 \pm 0.071)\ \text{fm}$$

Note: $\mathrm{R_n}$ and $\mathrm{R_p}$ are the root-mean-square radii of the neutron and proton distributions, respectively.

Measured through purely electroweak measurement, longitudinally polarized elastic electron scattering to determine the parity-violating asymmetry APV

$$A_{\text{PV}} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

σ_R, σ_L are the cross sections for scattering right/left handed electrons

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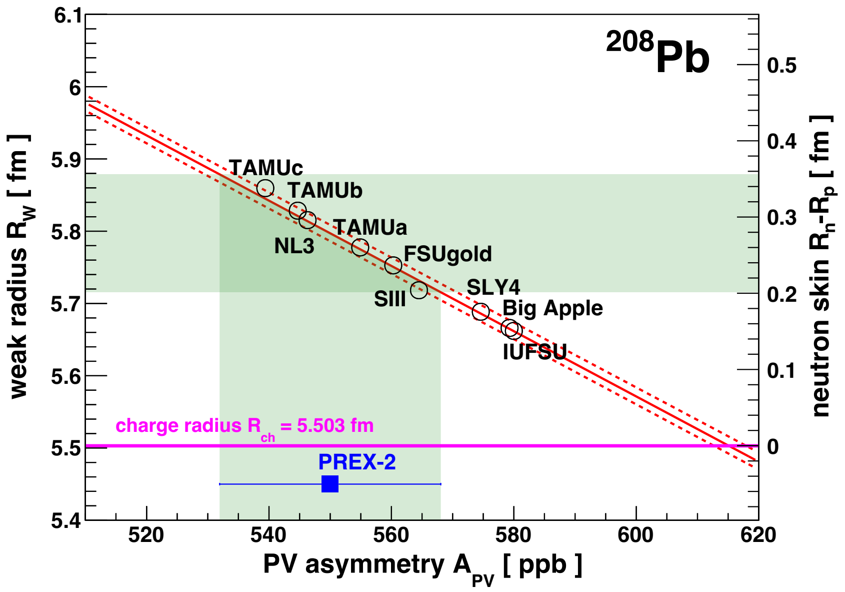

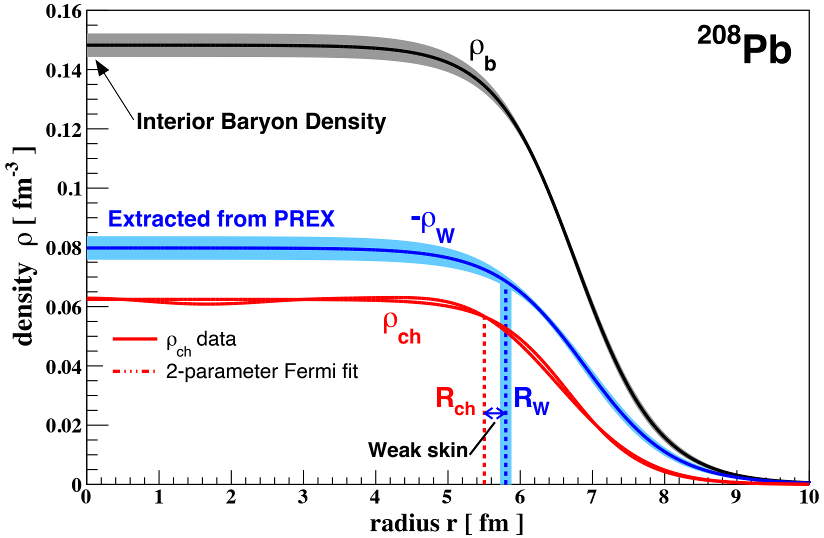

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OK GREAT, we are done right!?

D. Adhikari *et al.* (PREX Collaboration) Phys. Rev. Lett. **126**, 172502 (2021)

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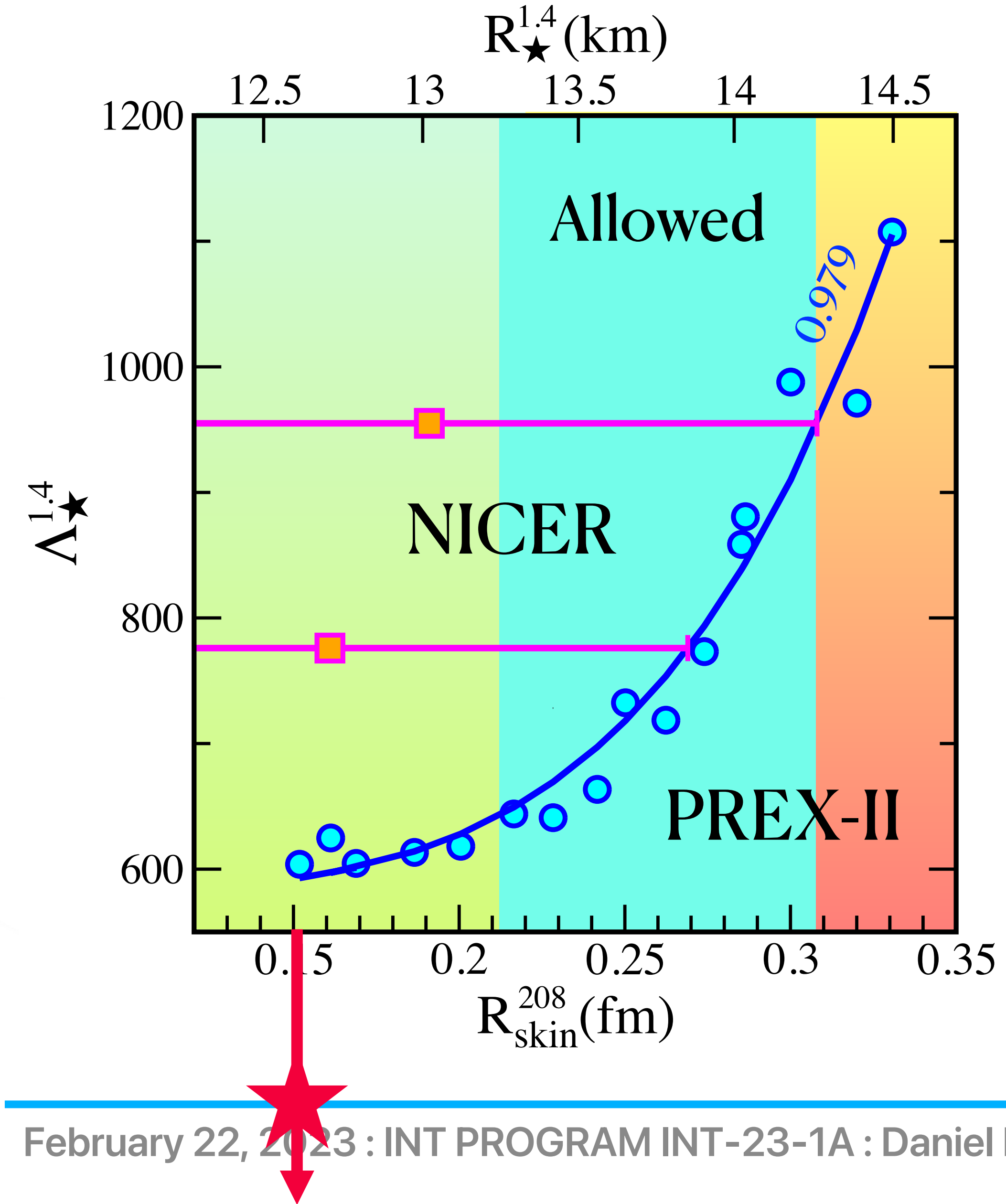
Gravitational Wave Discovery & Tension



NICER x-ray measurement of neutron star radius and PREX-II

$$0.21 \lesssim R_{\rm skin}({\rm fm}) \lesssim 0.31$$
$$13.25 \lesssim R_\star^{1.4}({\rm km}) \lesssim 14.26$$
$$642 \lesssim \Lambda_\star^{1.4} \lesssim 955.$$

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

$$\Lambda_{1.4} = 190^{+390}_{-120}$$

Strong tension with "allowed" region from NICER+PREX-II

B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) Phys. Rev. Lett. **119**, 161101 (2017)

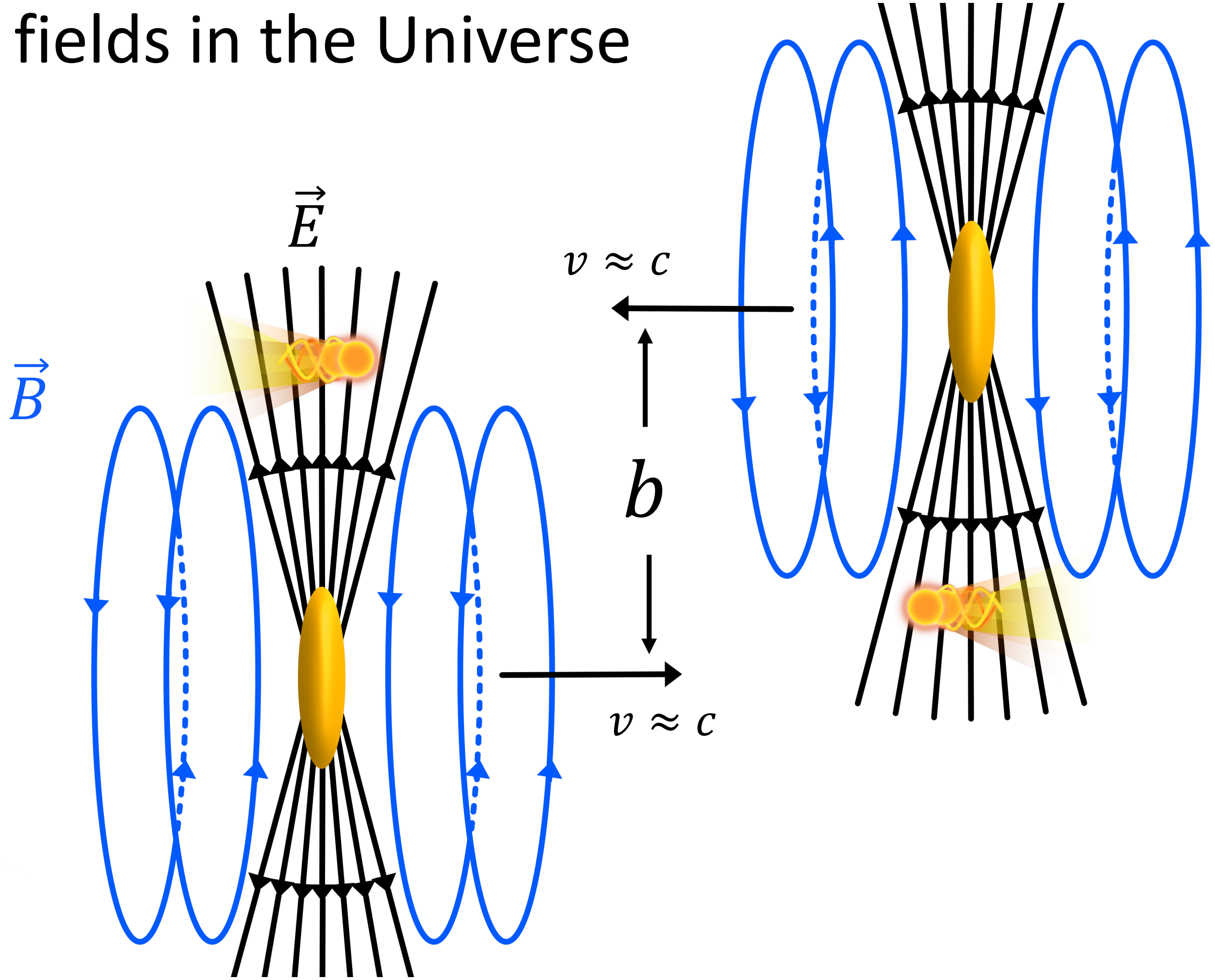
D. Adhikari *et al.* (PREX Collaboration) Phys. Rev. Lett. **126**, 172502 (2021)

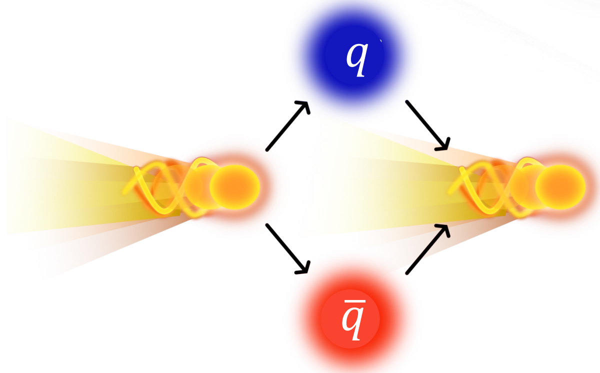
Brendan T. Reed, F. J. Fattoyev, C. J. Horowitz, and J. Piekarewicz Phys. Rev. Lett. **126**, 172503 (2021)

The Nuclear Mass Radius **Puzzle** in A+A

Ultra-Peripheral Heavy-Ion Collisions

Ultra-relativistic charged nuclei produce the strongest electromagnetic fields in the Universe





Photon Nucleus interactions:

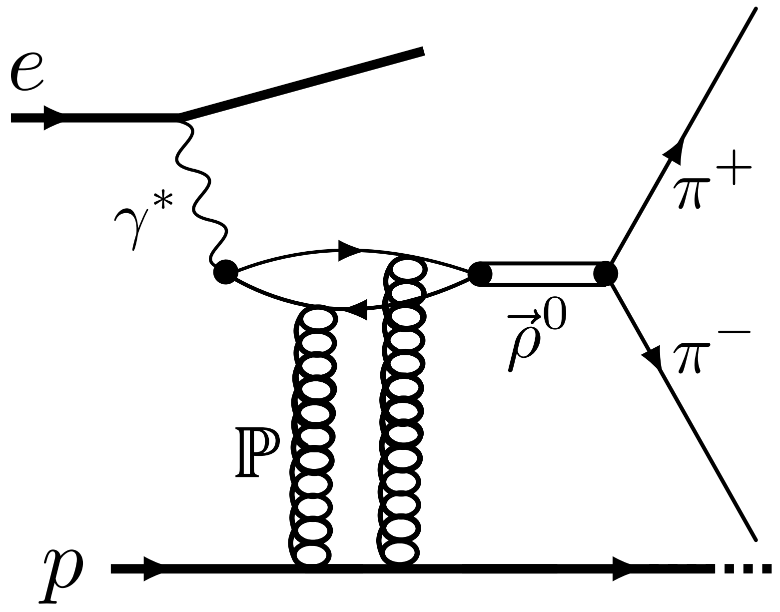
$\gamma\mathbb{P} \rightarrow \rho^0, J/\psi, etc.$: Photo-nuclear production of vector mesons ($J^P = 1^-$)

- Photon from the EM field of one nucleus fluctuates to a $q\bar{q}$ pair, interacts with pomeron (or Reggeon @ RHIC)
- Photon quantum numbers $J^{PC} = 1^{--}$

Klein, S. R. & Nystrand, J. *Phys. Rev. C* **60**, 014903 (1999).
Klein, S. R. & Nystrand, J. *Phys. Rev. Lett.* **84**, 2330–2333 (2000).

Shining light on Gluons

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

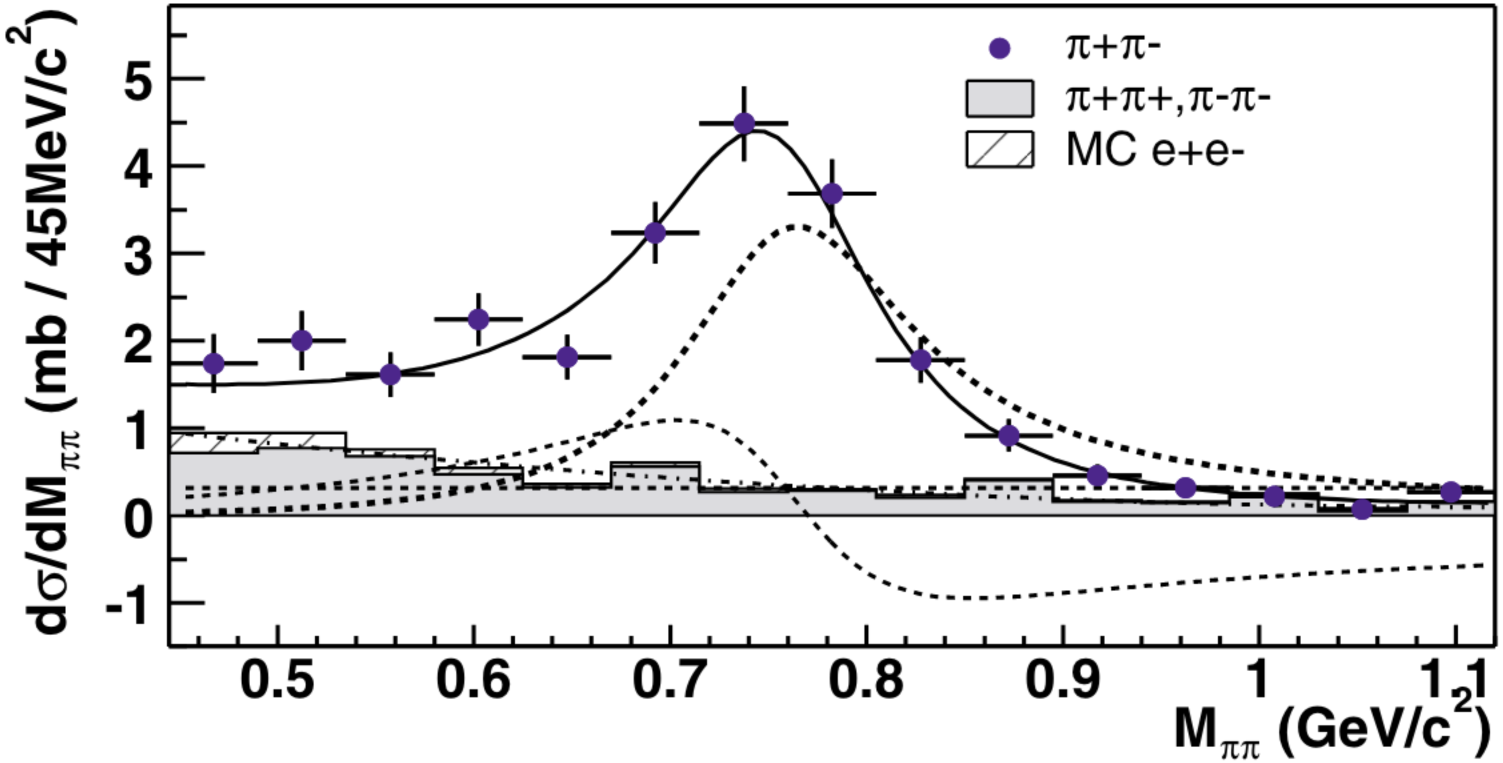


- Well known process for probing the **hadronic structure** of the photon
- Photon energies $\gtrsim 10$ GeV: probe gluon distribution - Interaction through $\mathbb{P}$omeron (two gluon state at lowest order)
- Lower energy scattering: probe gluons + quarks: Reggeon interactions are important
- Photon 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]

Past Photo-Nuclear Measurements

- STAR has studied $\gamma\mathbb{P} \rightarrow \rho^0 \rightarrow \pi^+\pi^-$ (and direct $\pi^+\pi^-$ production) in the past



Line shape results from amplitude level contributions: $\rho^0 \rightarrow \pi^+\pi^-$ + Drell Söding (direct $\pi^+\pi^-$) + $\omega \rightarrow \pi^+\pi^-$

STAR Collaboration *et al. Phys. Rev. Lett.* **89**, 272302 (2002).
STAR Collaboration *et al. Phys. Rev. Lett.* **102**, 112301 (2009).
STAR Collaboration *et al. Phys. Rev. C* **96**, 054904 (2017).

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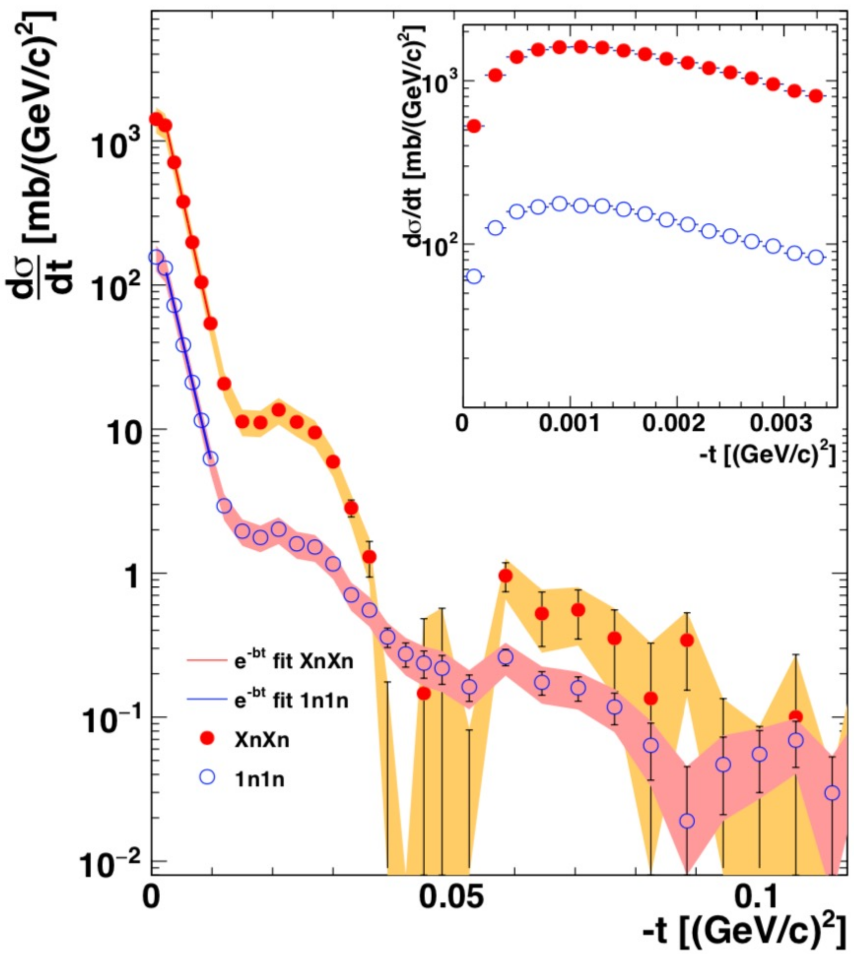

Coherent Interactions:

- Photon interacts with the entire nucleus
- Diffractive structure in $p_T^2 \approx -t$
- Transverse momentum related to Fourier transform of nuclear size

STAR Collaboration *et al. Phys. Rev. Lett.* **89**, 272302 (2002).
STAR Collaboration *et al. Phys. Rev. Lett.* **102**, 112301 (2009).
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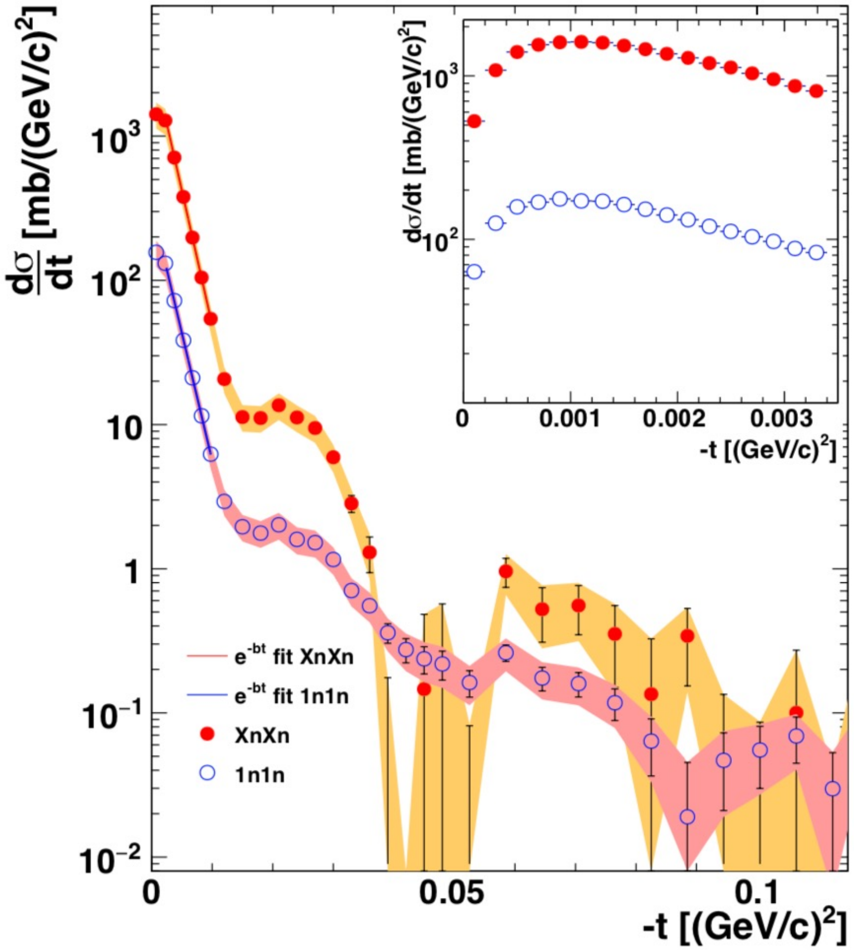

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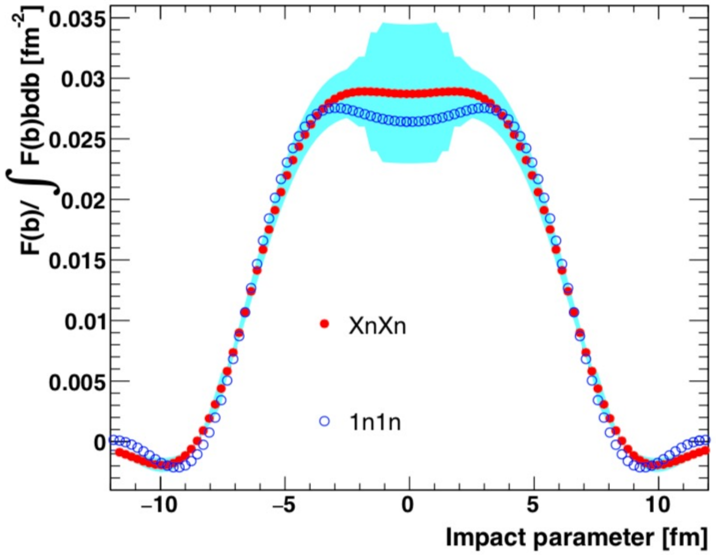
Extract gluon distribution



STAR Collaboration *et al. Phys. Rev. Lett.* **89**, 272302 (2002).
STAR Collaboration *et al. Phys. Rev. Lett.* **102**, 112301 (2009).
STAR Collaboration *et al. Phys. Rev. C* **96**, 054904 (2017).

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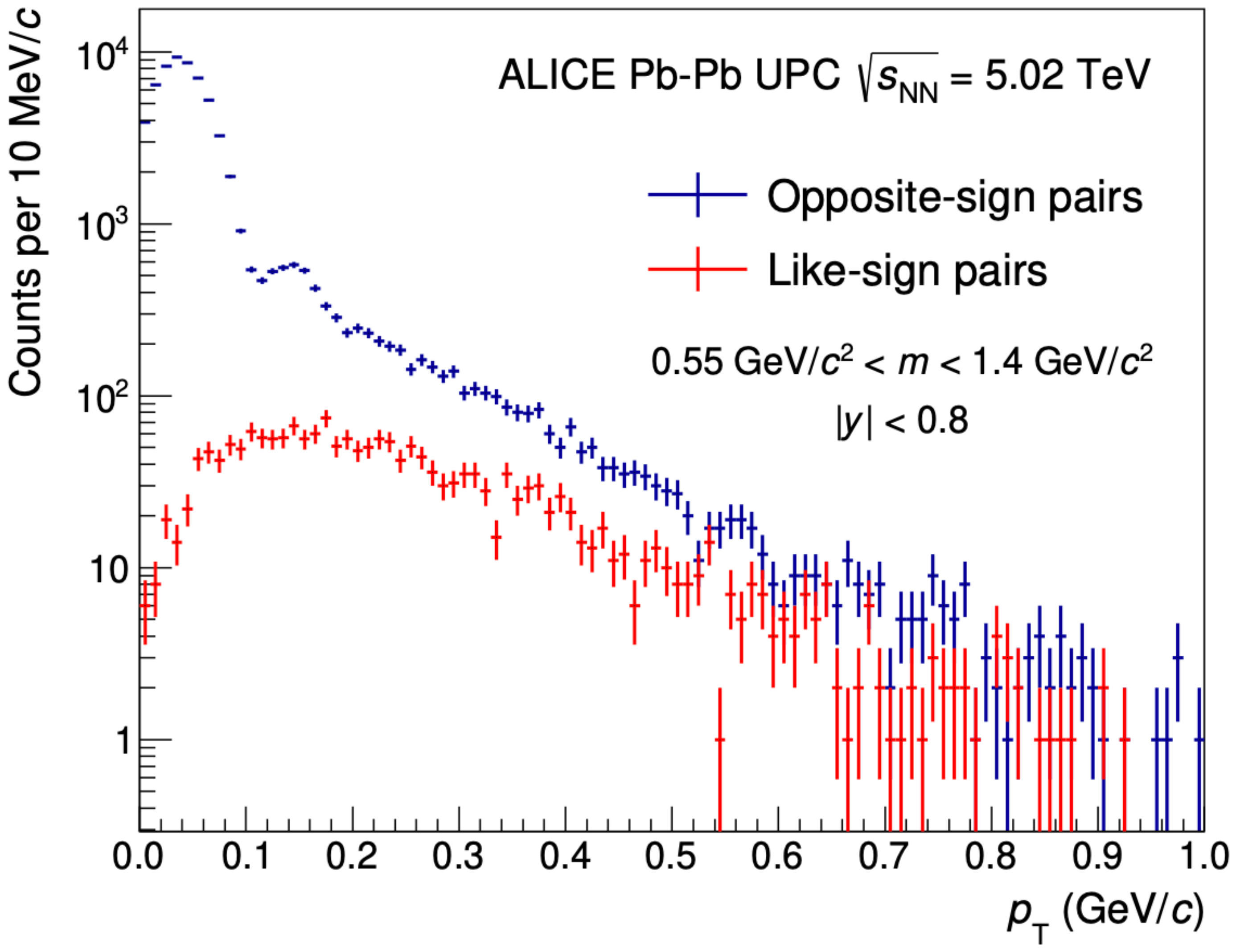


Other measurements at RHIC & LHC include:

Photoproduction of J/ψ in Au+Au UPC at $\sqrt{s_{NN}}$ = 200 GeV
PHENIX Phys.Lett.B679:321-329,2009

ρ^0 vector mesons in Pb-Pb UPC at $\sqrt{s_{NN}}$ = 5.02 TeV
ALICE, JHEP06 (2020) 35

J/ψ in Pb+Pb UPC at $\sqrt{s_{NN}}$ = 2.76 TeV
CMS, Phys. Lett. B 772 (2017) 489
… and many more

So what's the problem?

Nuclear Mass radius, too big?

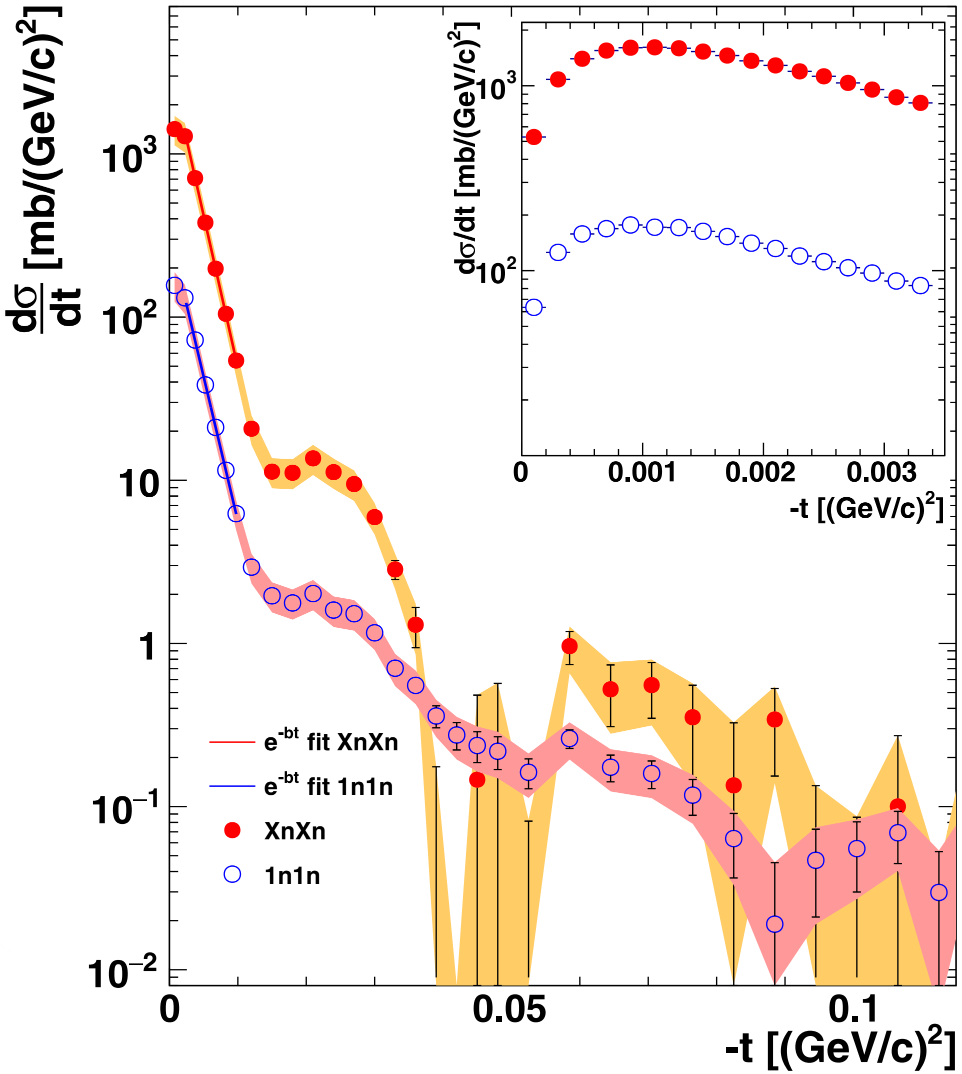


Photo-nuclear measurements have historically produced a |t| slope that corresponds to a **mysteriously large source!**

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 to be explainable

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.

So what’s new after 20+ years?

So what's new after 20+ years?

Recent discovery of the Breit-Wheeler process in Heavy-ion Collisions

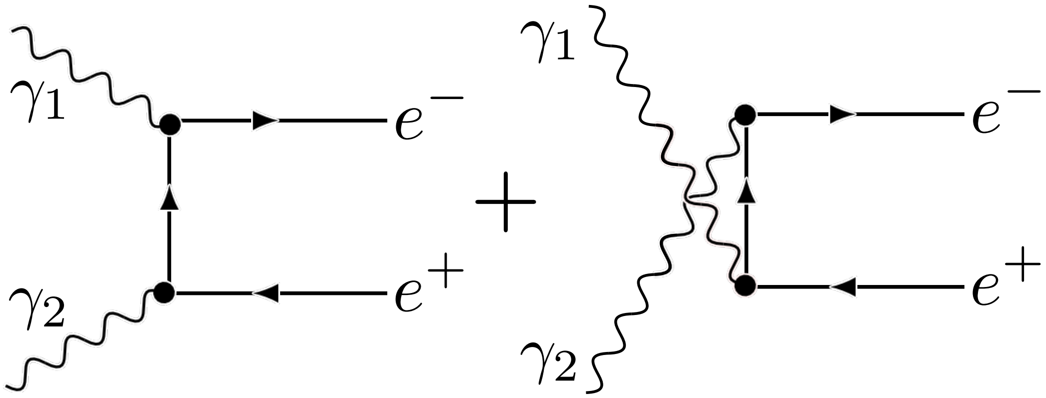
$$\gamma\gamma \rightarrow e^{+}e^{-}$$

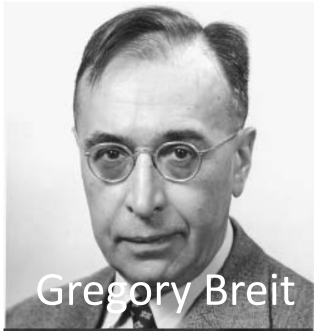
The Breit-Wheeler Process

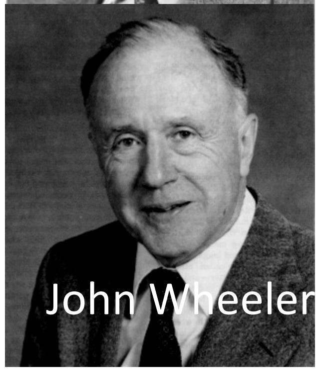
DECEMBER 15, 1934 PHYSICAL REVIEW VOLUME 46

Collision of Two Light Quanta

G. BREIT* AND JOHN A. WHEELER,** *Department of Physics, New York University*
(Received October 23, 1934)





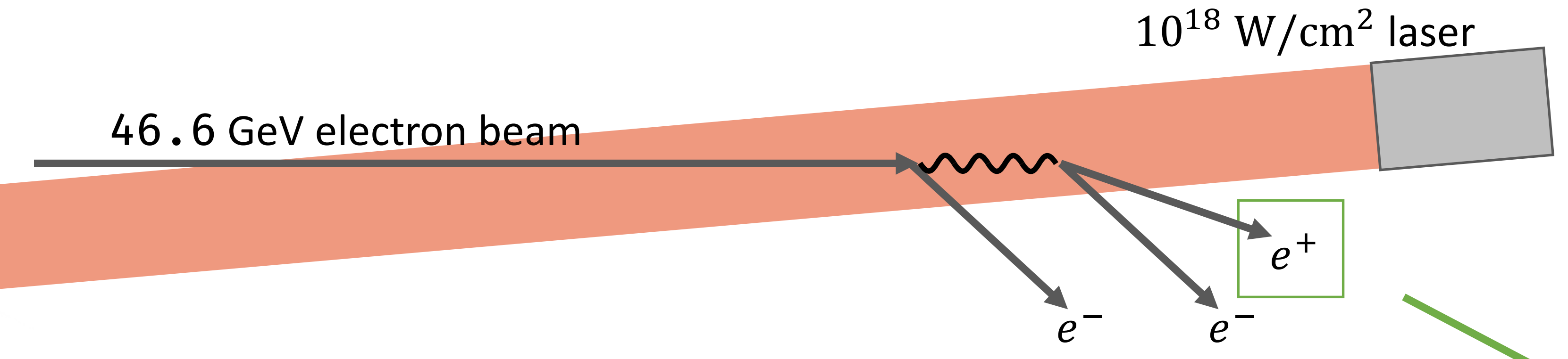


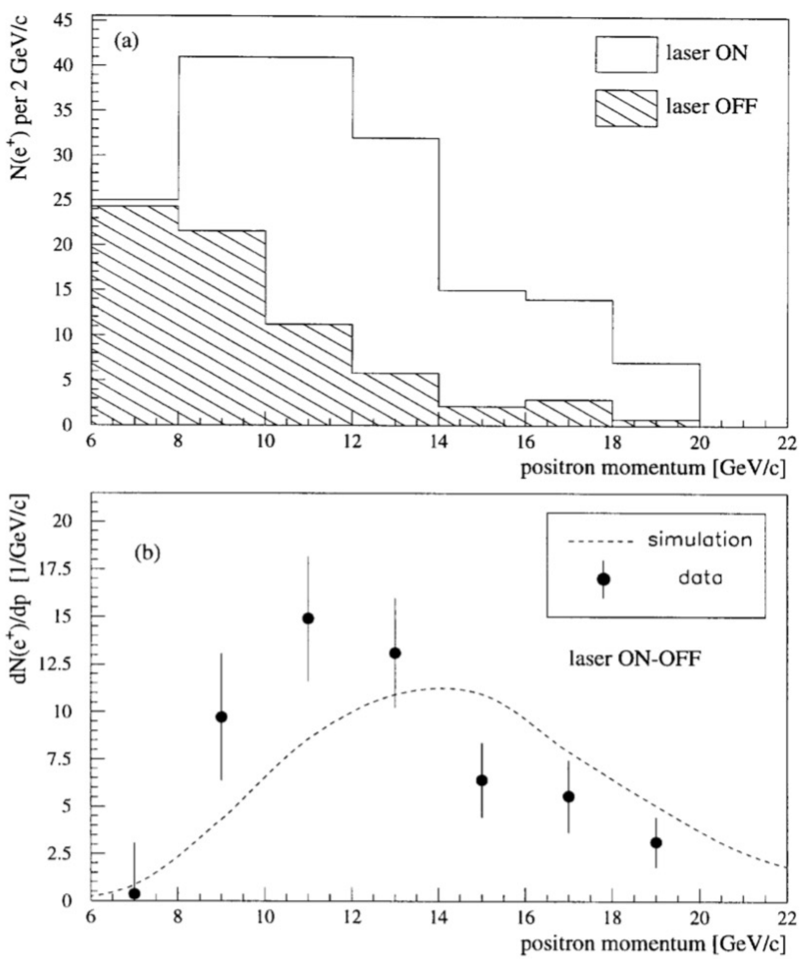
- Non-linear effect forbidden in classical electromagnetism
- At lowest order, two Feynman diagrams contribute and interfere
- Breit-Wheeler process: real photon collisions → important distinction
- Finally observed after 85+ years $\Longrightarrow$ **Applications in nuclear physics**

Progress Towards the Breit-Wheeler Process

SLAC E−144 Experiment

- Non-linear Breit-Wheeler Process: $\gamma + n\gamma_0 \rightarrow e^+e^-$
  - Two step process: Compton backscattering
  - Energy threshold requires $n > 4$ with $\langle n \rangle = 6.44$



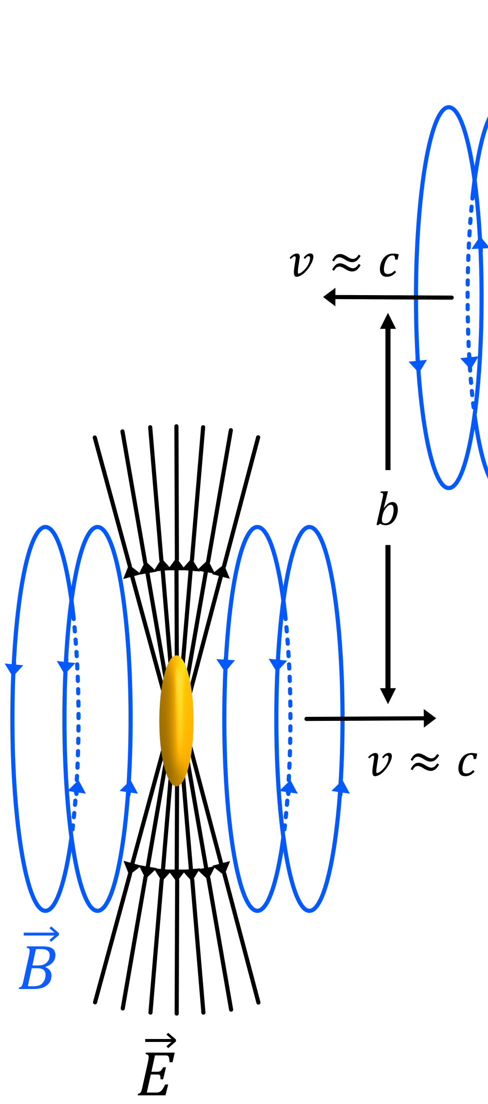


→No pair measurements
→No angular measurements

Excess of ~100 positrons detected in 20,000 shots

Burke et al., PRL79, 1626 (1997)
Hu & Müller, PRL107, 090402 (2010)

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, transverse EM fields can be quantized as a flux of **quasi-real photons**

Weizsäcker, C. F. v. *Zeitschrift für Physik* 88 (1934): 612

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

$Z\alpha \approx 1$ → 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

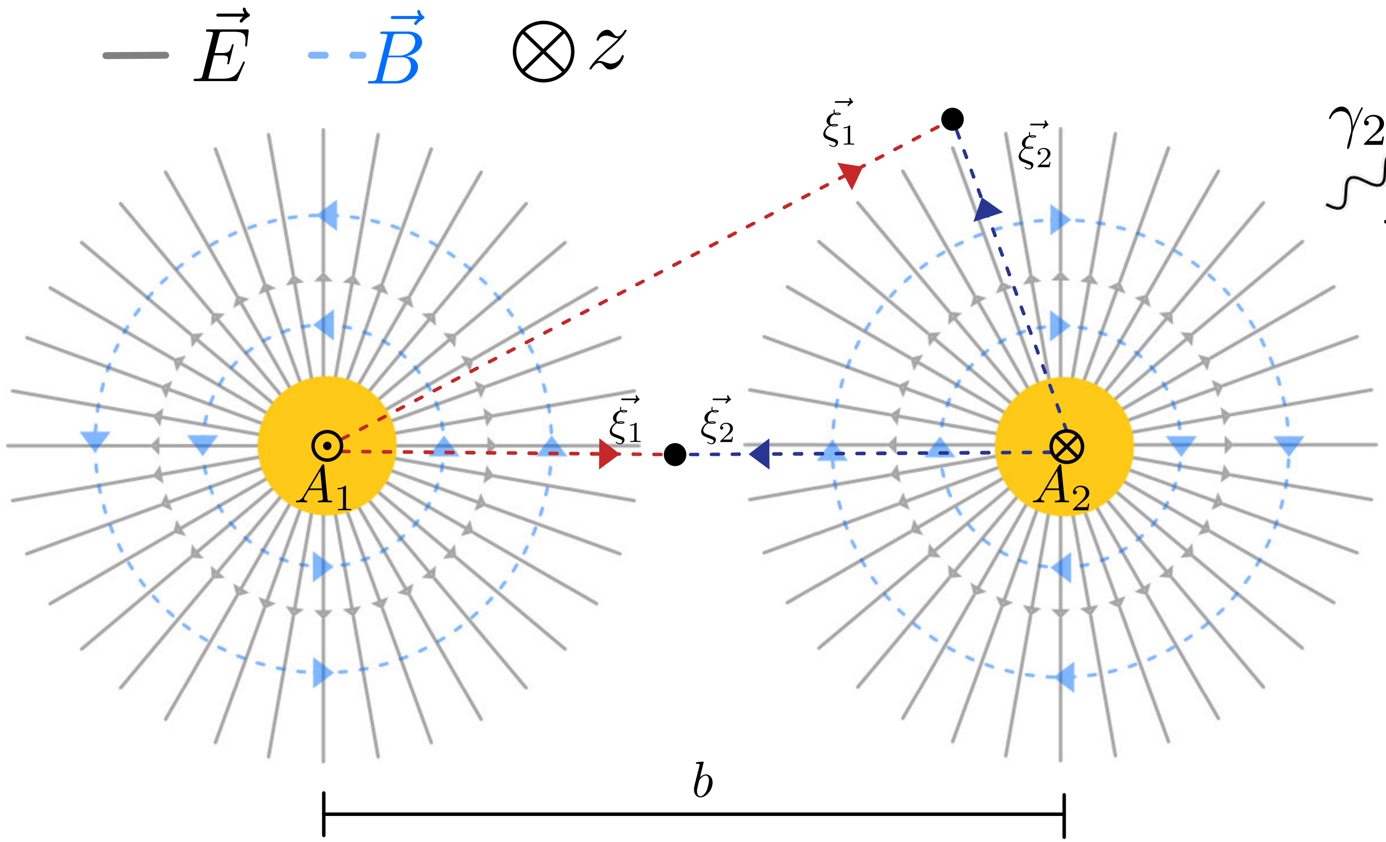
Test QED under extreme conditions[1]

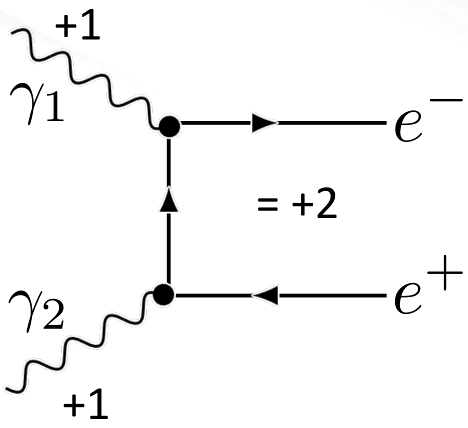
K. Hattori and K. Itakura, *Photon and Dilepton Spectra from Nonlinear QED Effects in Supercritical Magnetic Fields Induced by Heavy-Ion Collisions*, Nuclear and Particle Physics Proceedings **276–278**, 313 (2016).

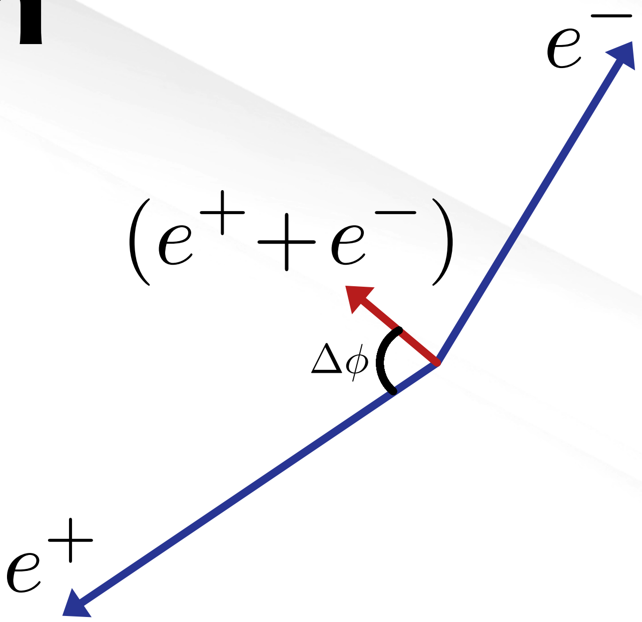
Light–by–Light scattering: ATLAS, Phys. Rev. Lett. 123, 052001 (2019)

Access to Photon Polarization

- Breit-Wheeler Process: $\gamma\gamma \rightarrow e^+e^-$





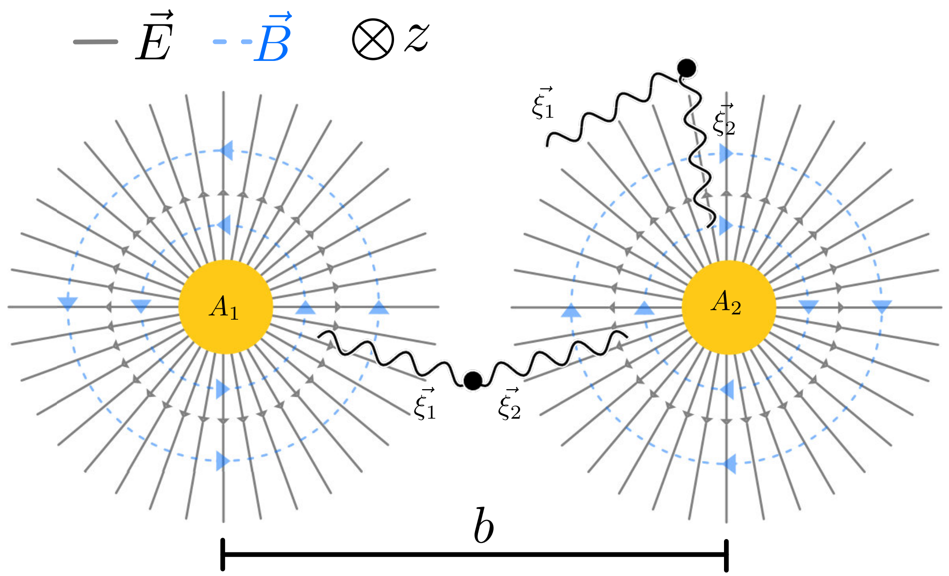


- Polarization vector ξ: aligned radially with the "emitting" source
- Intrinsic photon spin converted into **orbital angular momentum**
- Observable as anisotropy in $e^{\pm}$ momentum – a $\cos 4\phi$ modulation

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

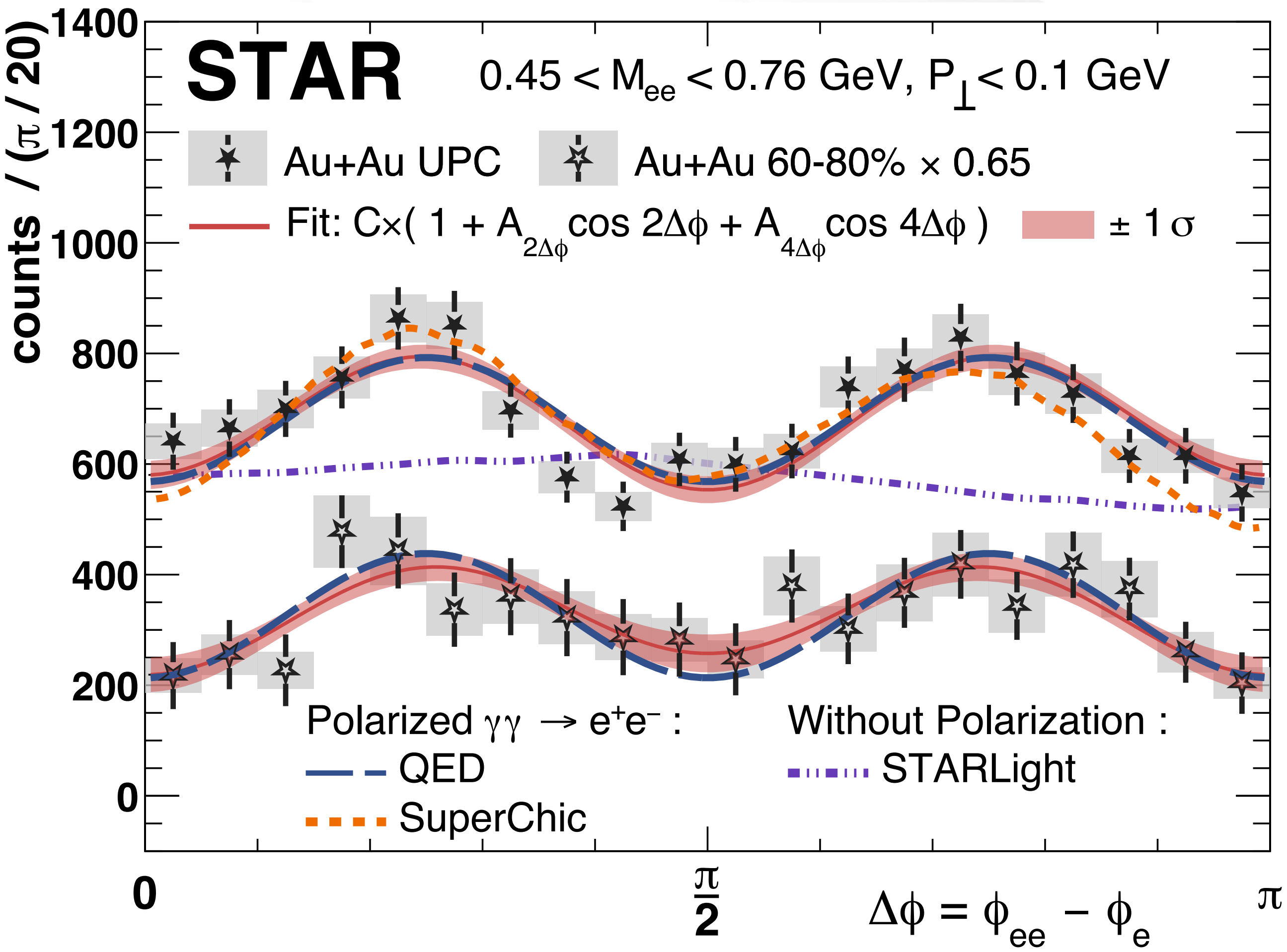
S. Bragin, et. al., *Phys. Rev. Lett.* 119 (2017), 250403
R. P. Mignani, *et al.*, *Mon. Not. Roy. Astron. Soc.* 465 (2017), 492

Access to Photon Polarization Proven!



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

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



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

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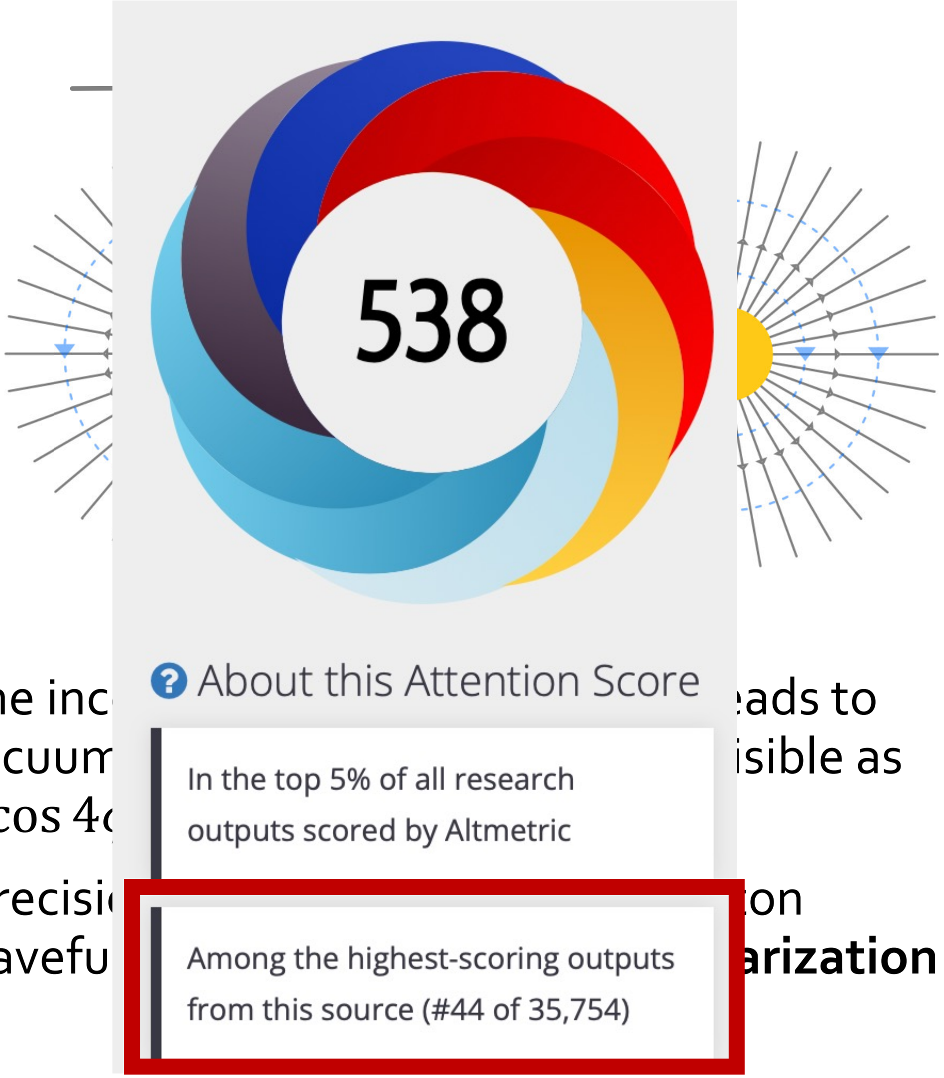
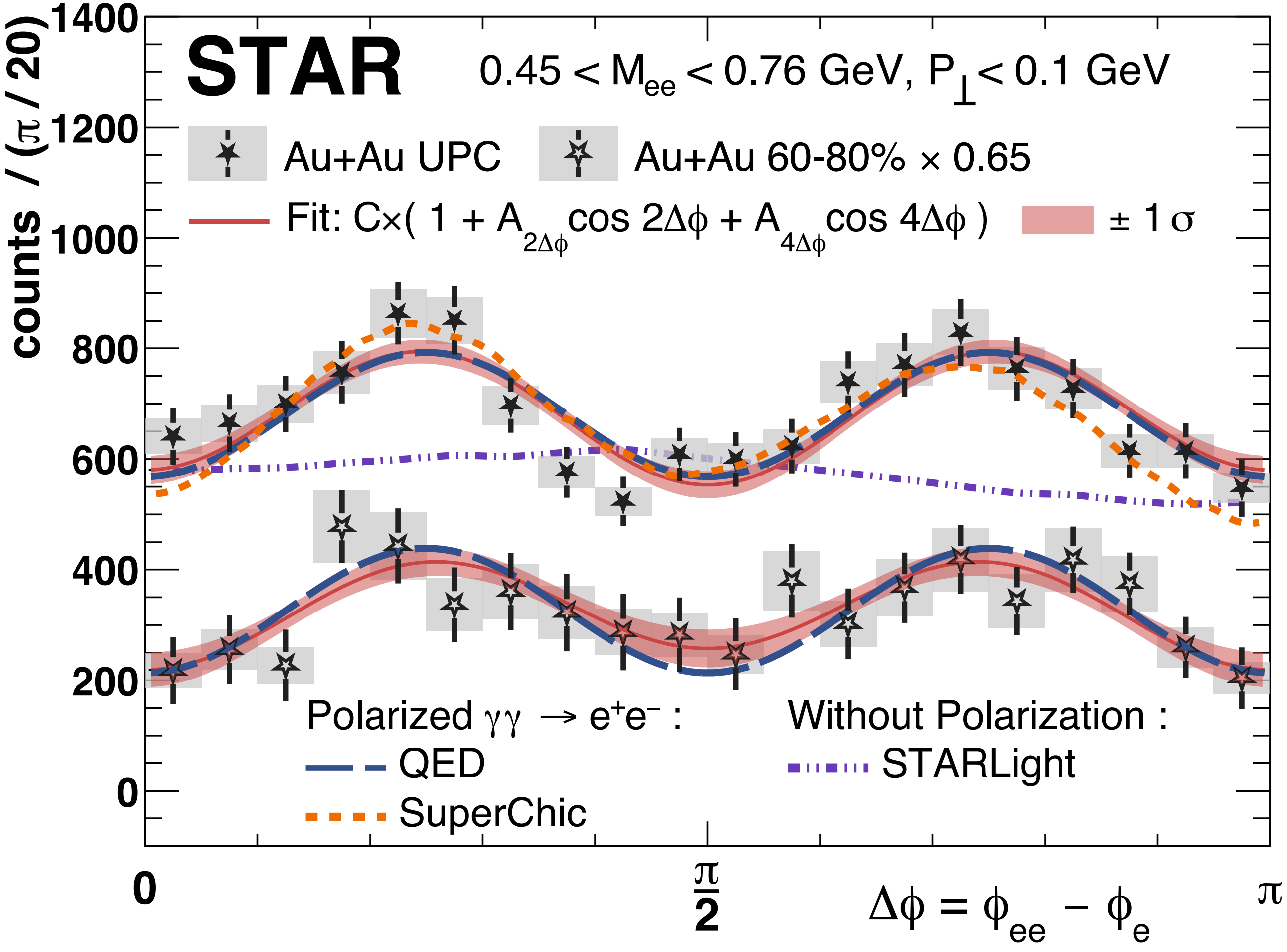


- The inc… eads to vacuum… isible as a cos 4(…

⇒ Precisi… on wavefu… **arization**

Highest press coverage of any paper in high energy nuclear physics



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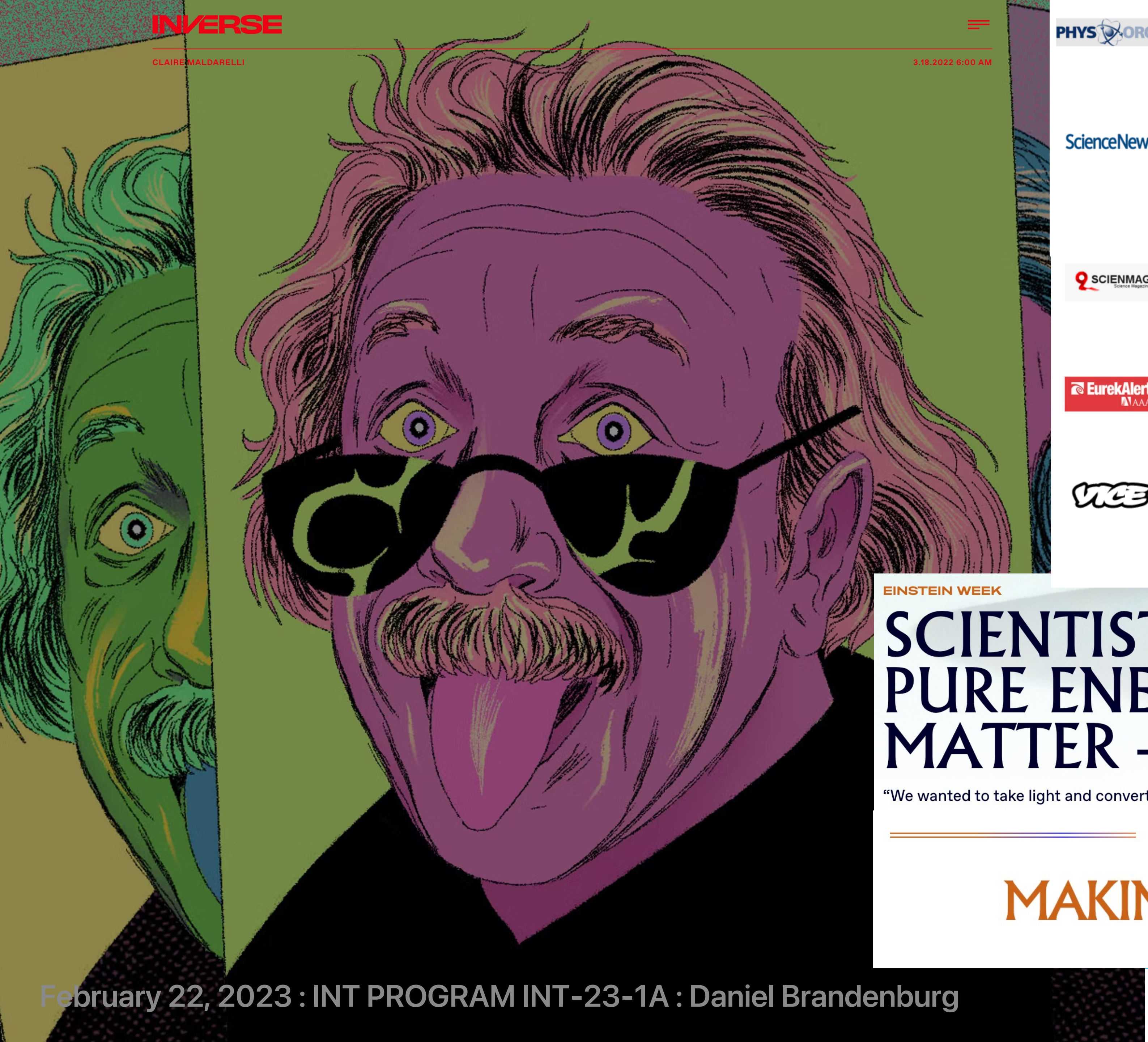


Collisions of light produce matter/antimatter from pure energy
Phys.org, 29 Jul 2021
Scientists studying particle collisions at the Relativistic Heavy Ion Collider (RHIC)—a U.S.

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.

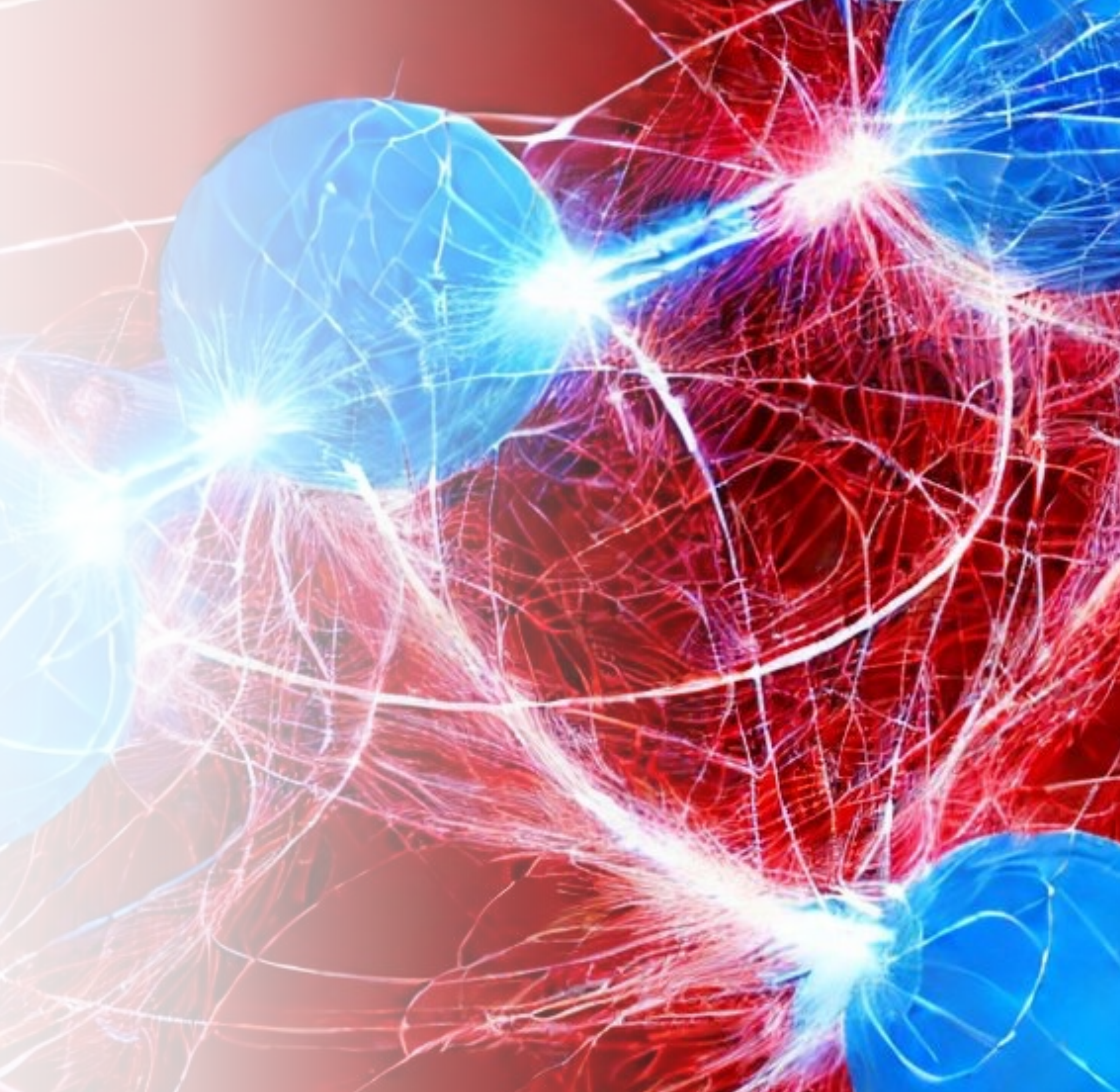
EINSTEIN WEEK

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

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

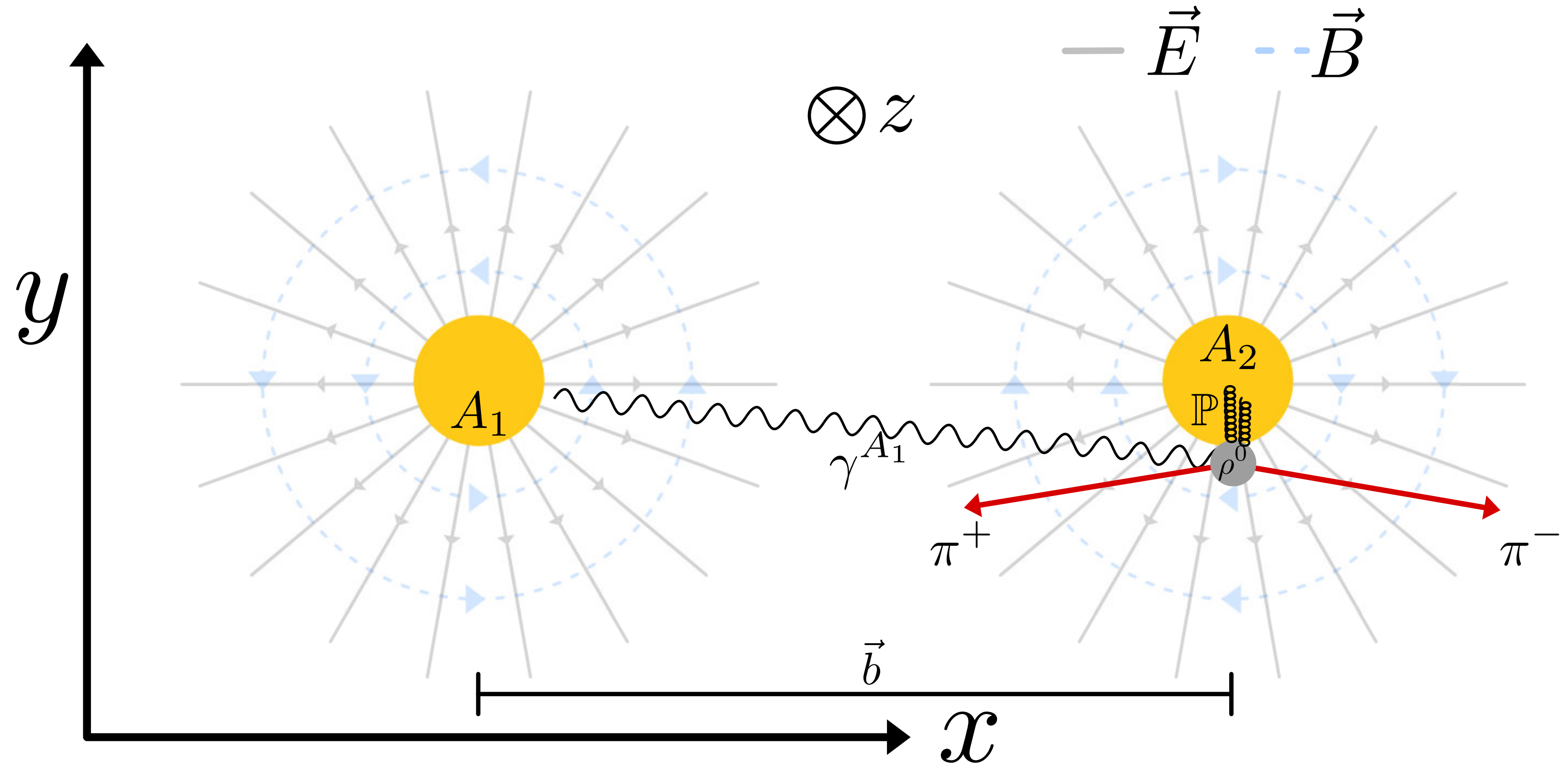
MAKING NEW PHYSICS POSSIBLE

Entanglement Enabled Quantum Interference



Imaging the Nucleus with Polarized Photons

What is NEW with transversely polarized photons?



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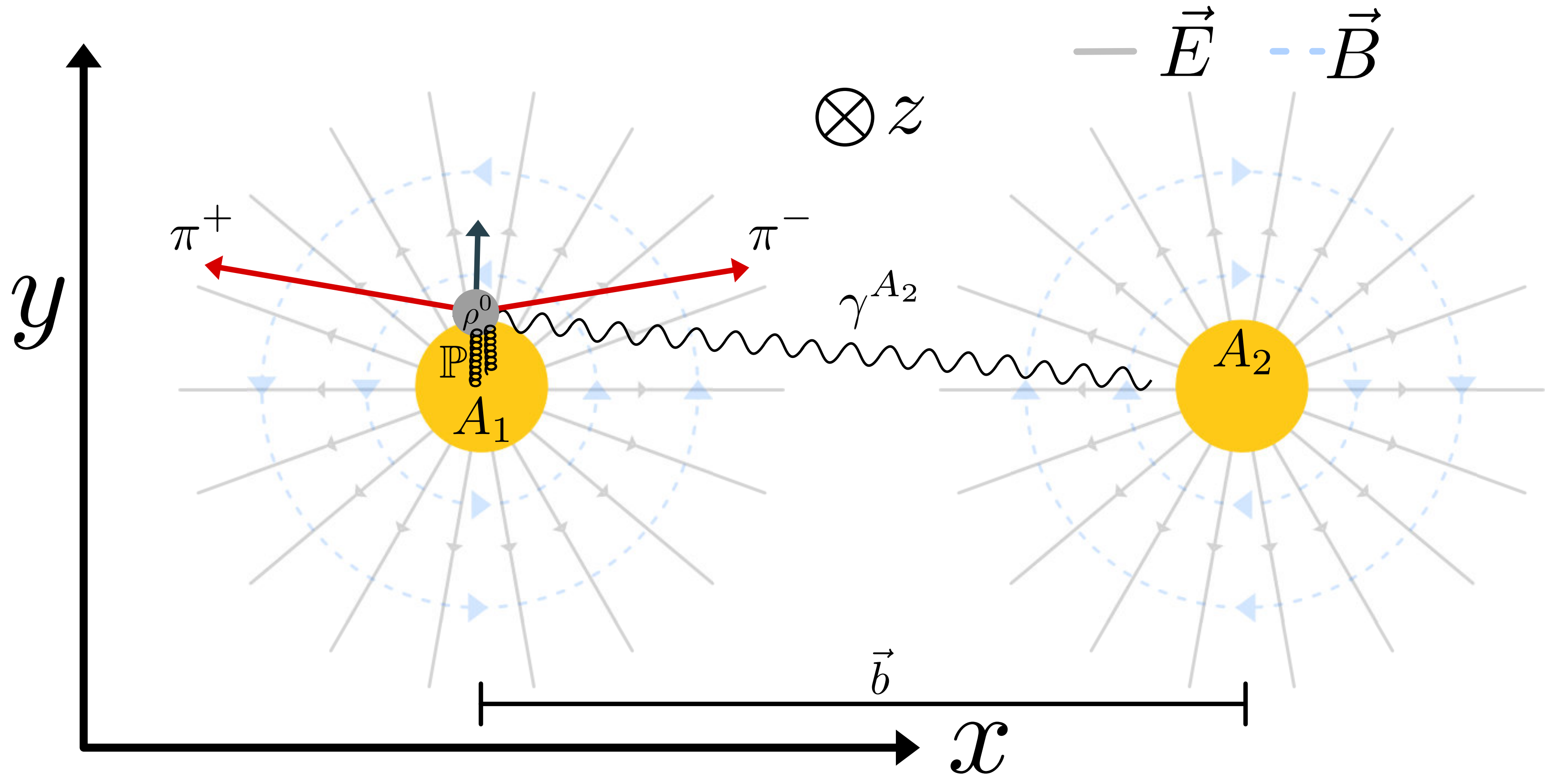

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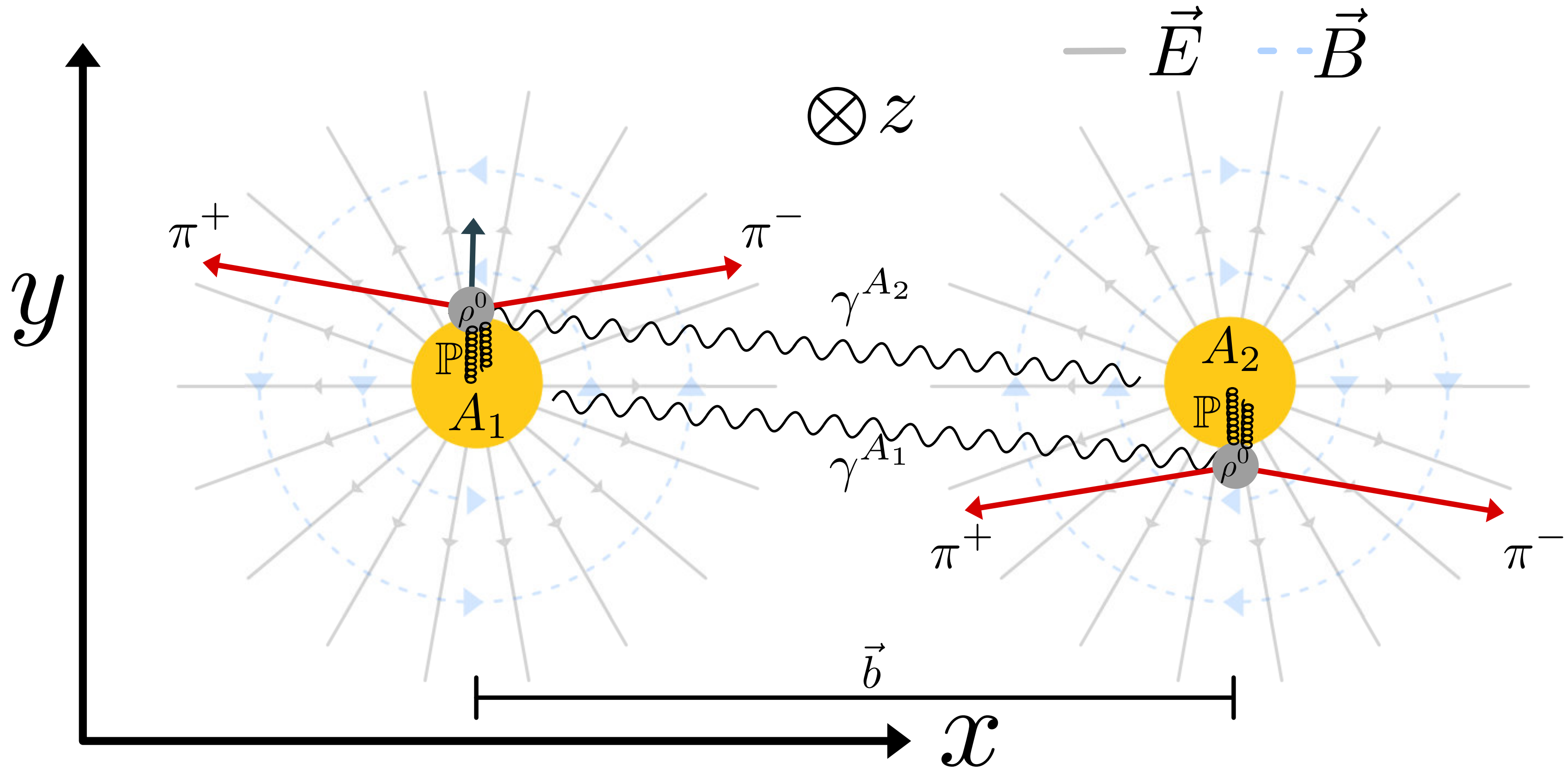
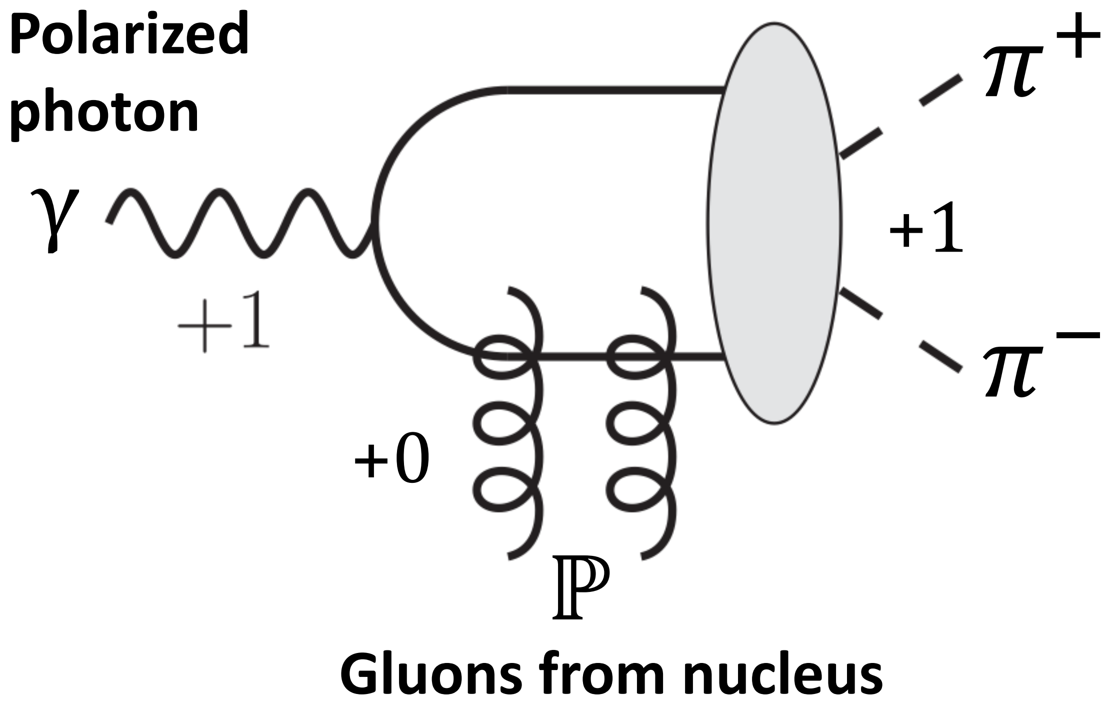
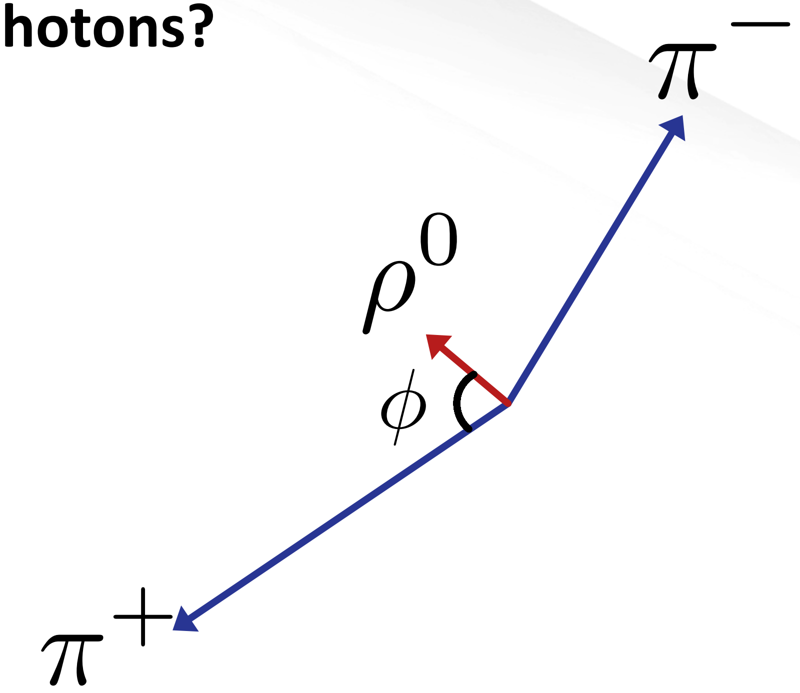


Both possibilities occur simultaneously

Imaging the Nucleus with Polarized Photons

What is NEW with transversely polarized photons?

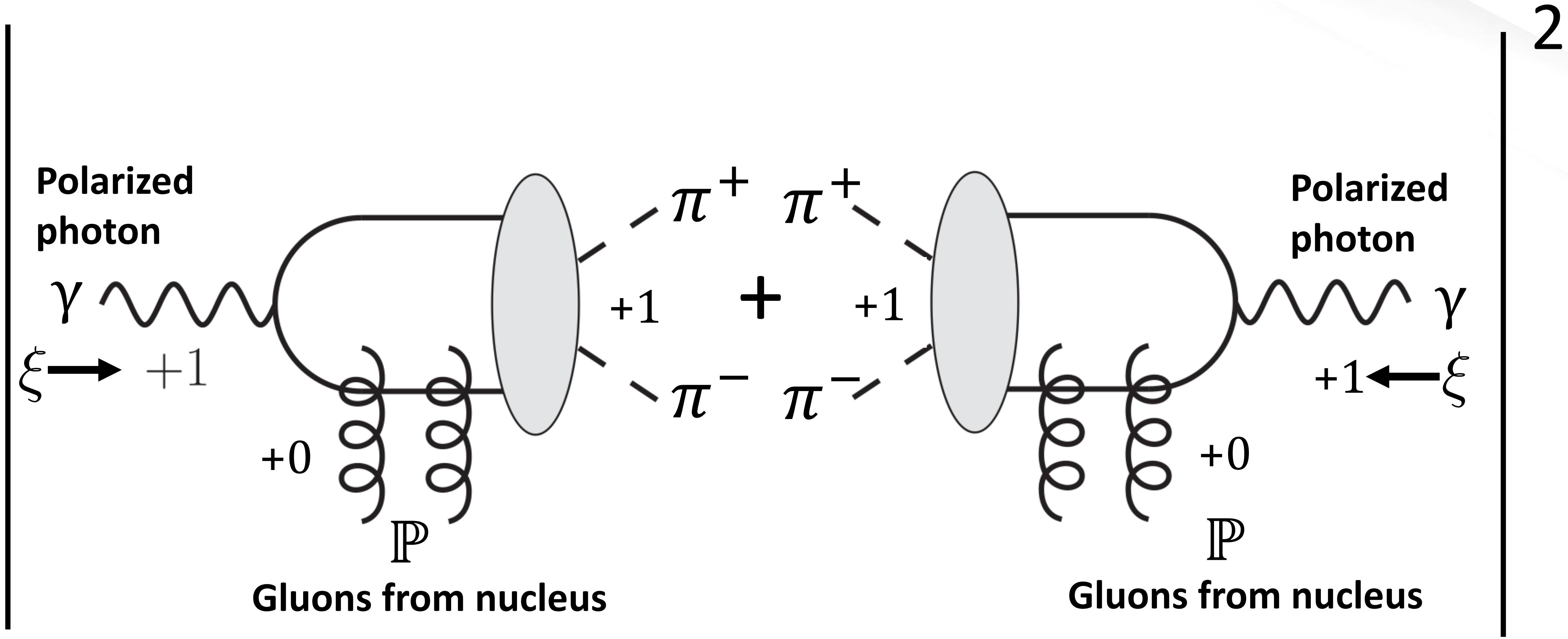




We can use the same experimental observable as the Breit-Wheeler process to access photon polarization

Access to initial photon polarization

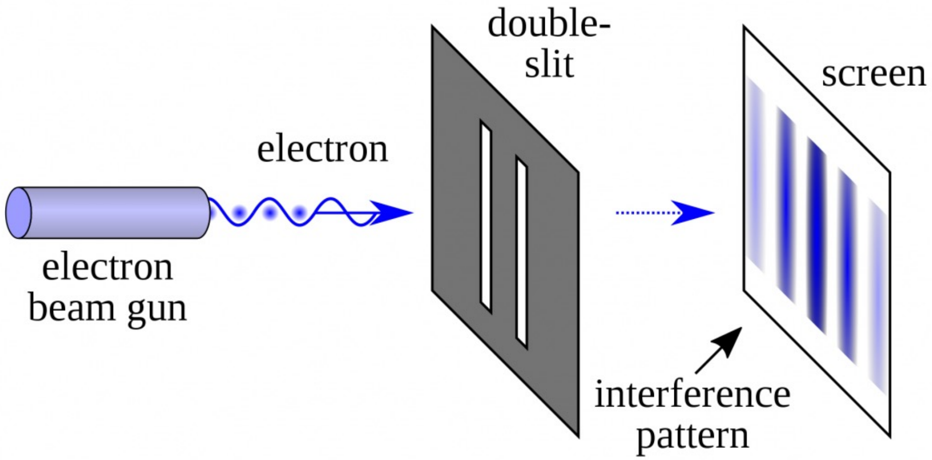
Interference of two amplitudes



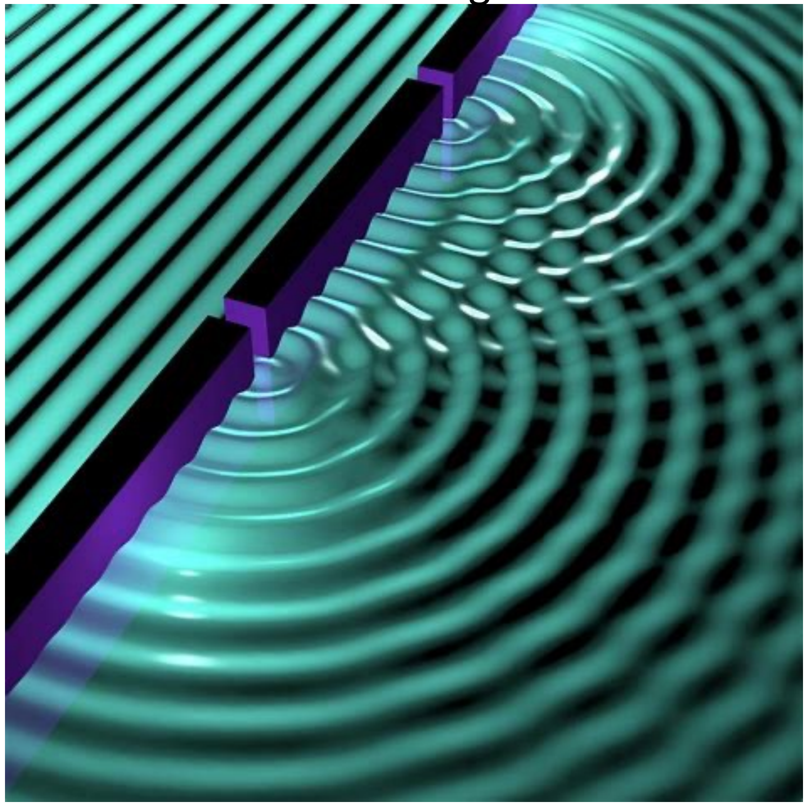
{Quantum} Double-Slit Experiment

- The double slit experiment is foundational in quantum mechanics

Quantum Double slit Experiment



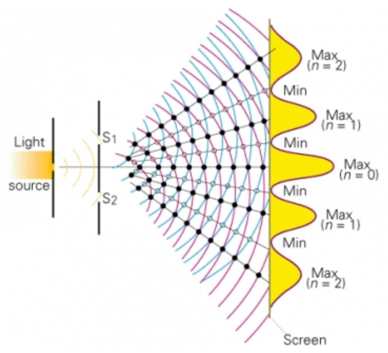
Water waves interfering in a double slit



- 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

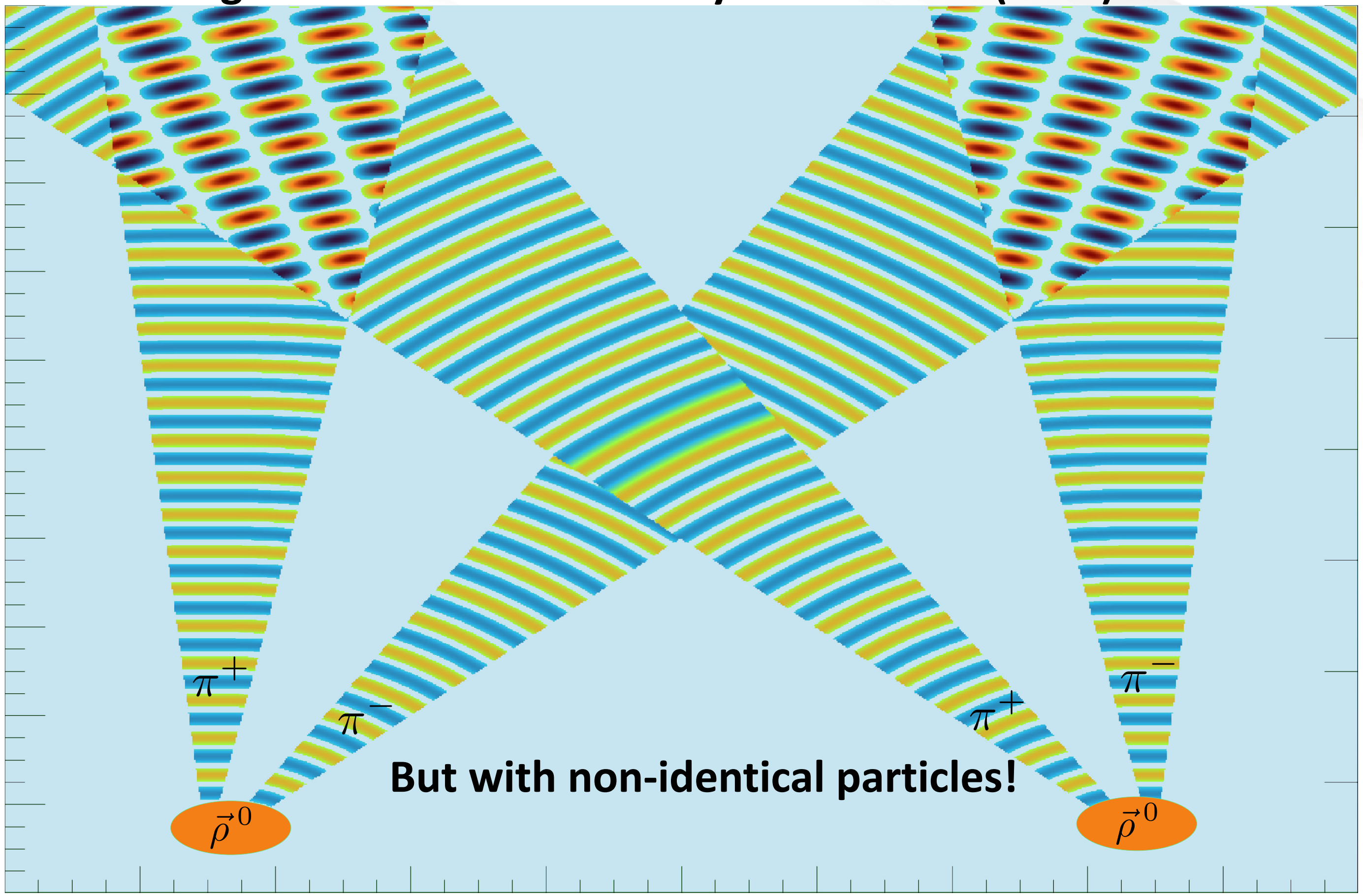


BUT WAIT…

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

Interference occurs between **distinguishable** particles

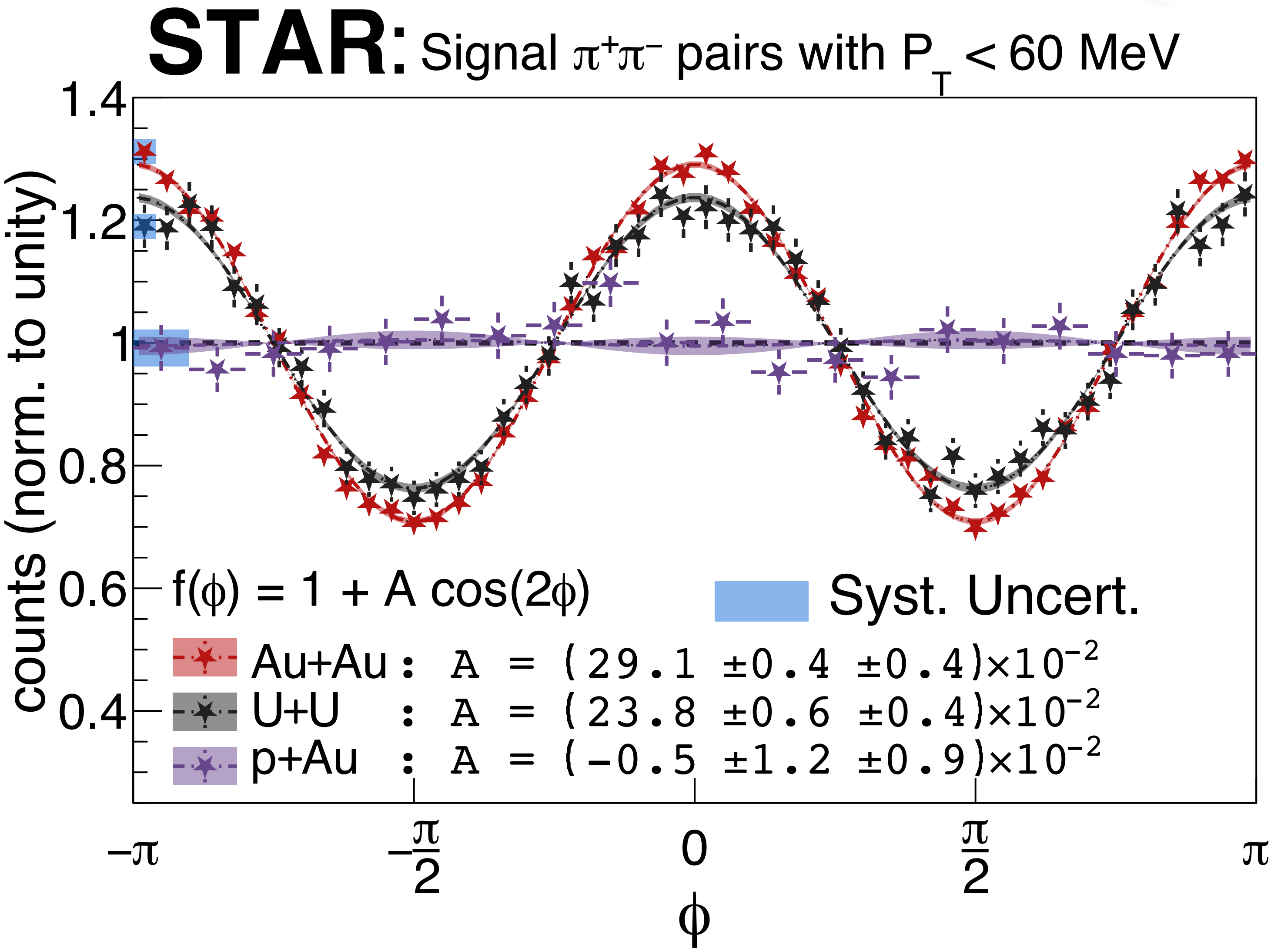
Entanglement Enabled Intensity Interference ($\mathbf{E^2I^2}$)

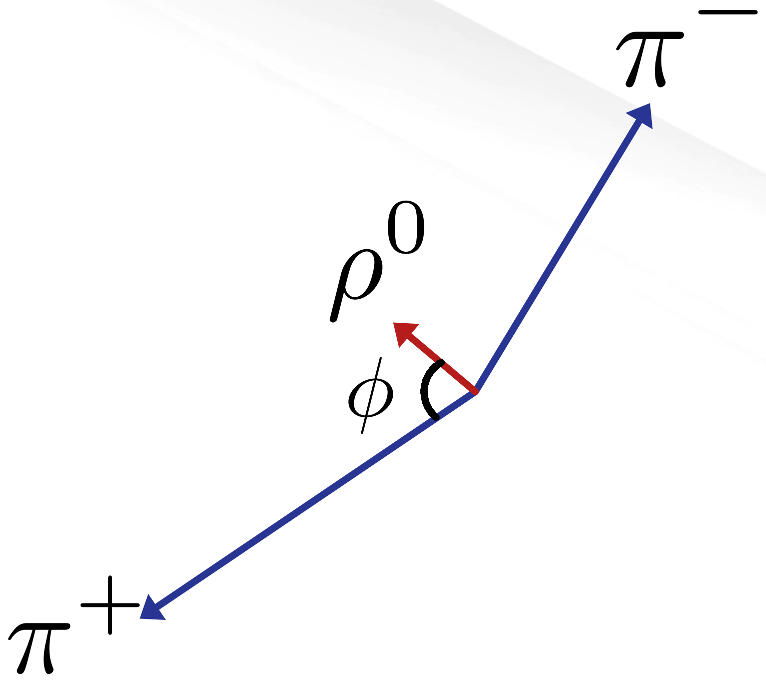


Possible theoretical explanation from Frank Wilczeck's group at MIT – Entanglement enabled interference of amplitudes from non-identical particles

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

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





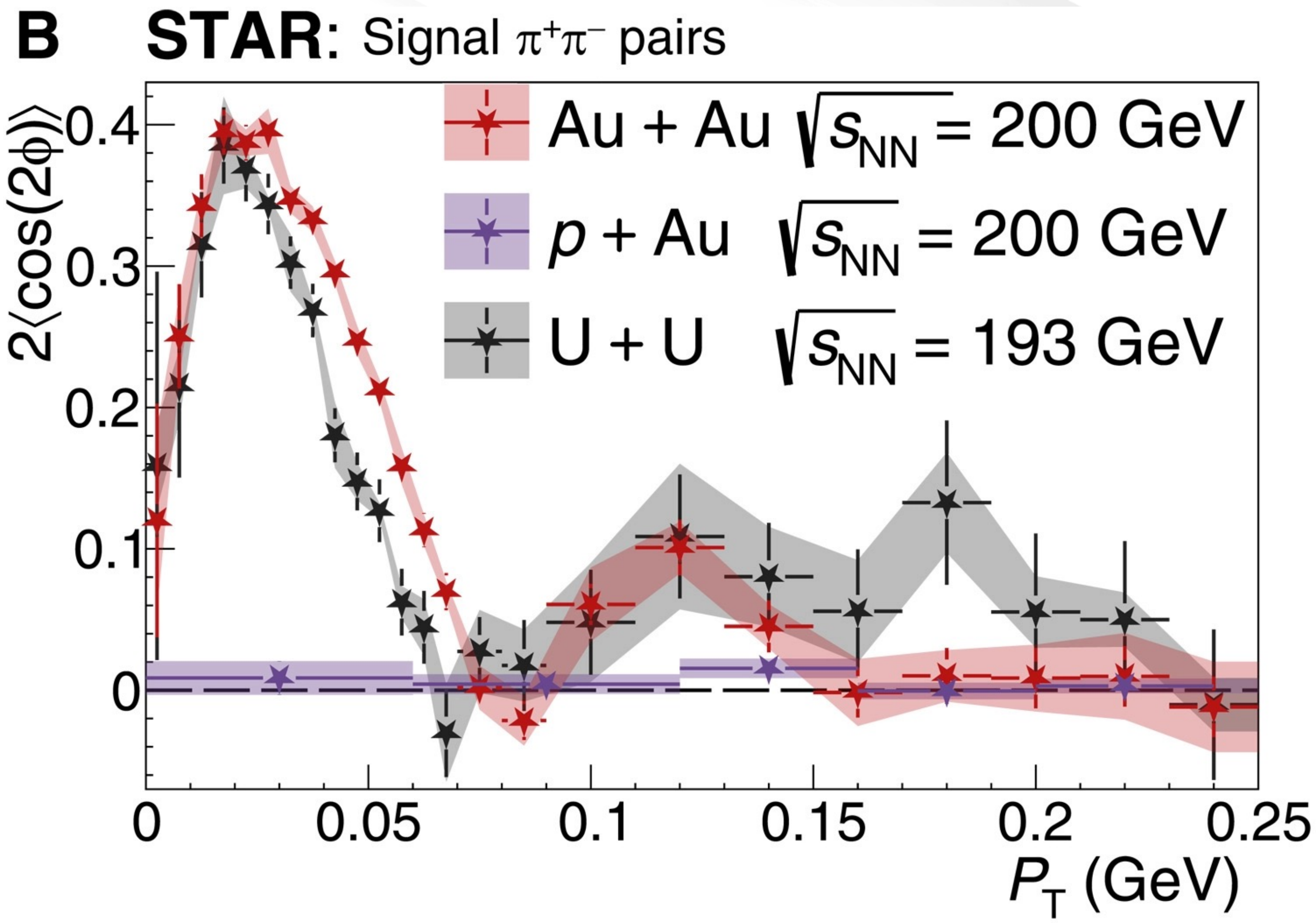
- Intrinsic photon spin transferred to ρ^0
- ρ^0 spin converted into **orbital angular momentum** between pions
- Observable as anisotropy in $\pi^\pm$ momentum

Momentum Dependence

Clear structure reminiscent of the diffractive cross section

Clear difference between Au+Au, U+U -> sensitivity to nuclear geometry

Null case: p+Au



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).

Origin of the Entanglement?

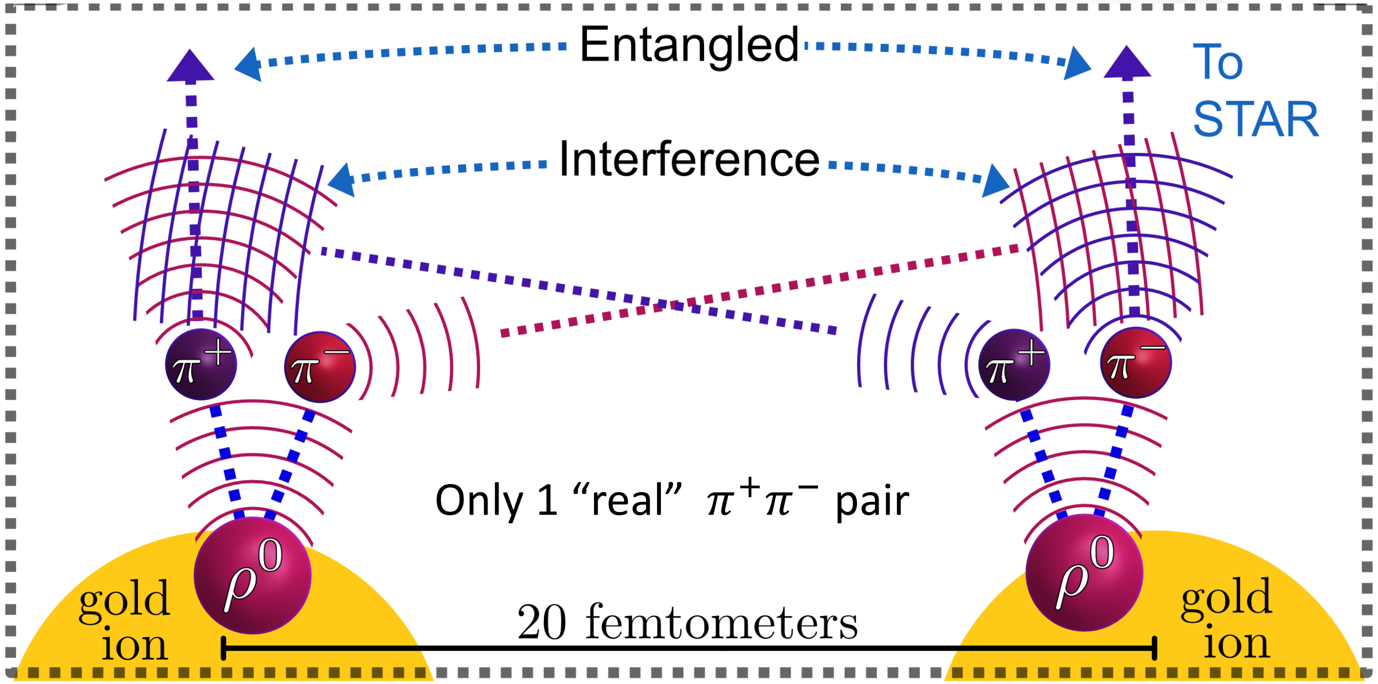
Case 1 : {Entangled} Double-Slit Experiment

- 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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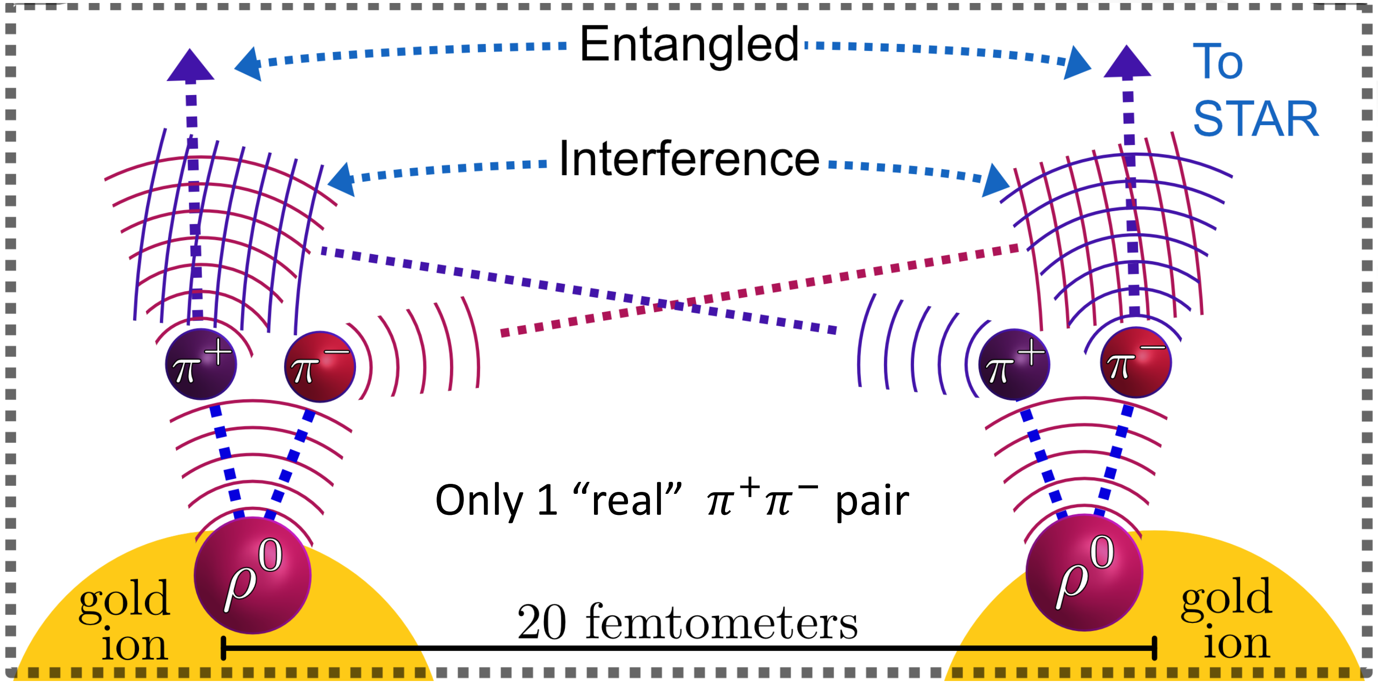


"What's so wonderful," Cotler says, "is that these contemporary experiments are still pushing the boundaries of our understanding of both quantum mechanics and measurement and opening up new horizons for both theory and experiment." – Jordan Cotler

Case 2: Entanglement: Nobel Prize 2022

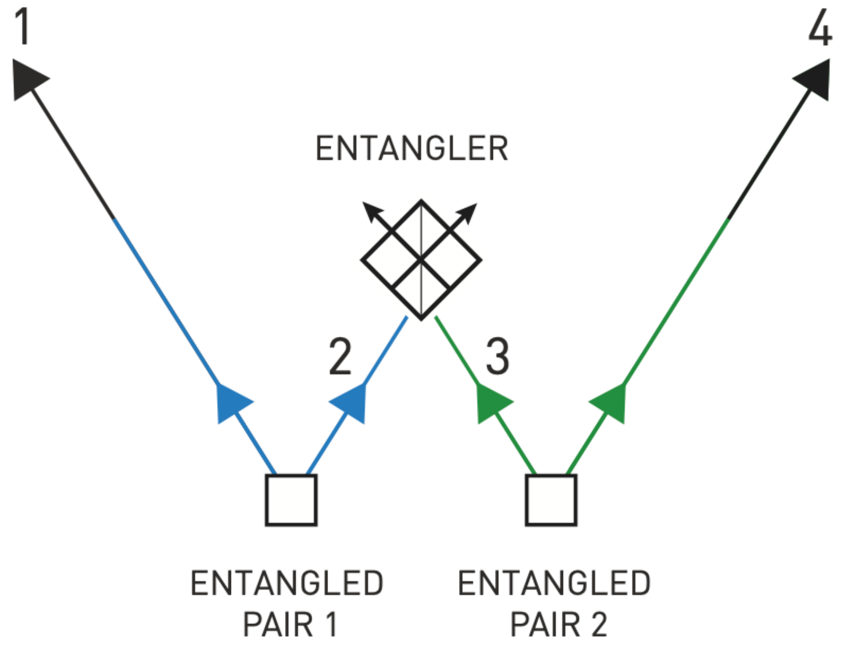
Alain Aspect, John Clauser and **Anton Zeilinger**

Quantum teleportation:

Transferring quantum information through entanglement

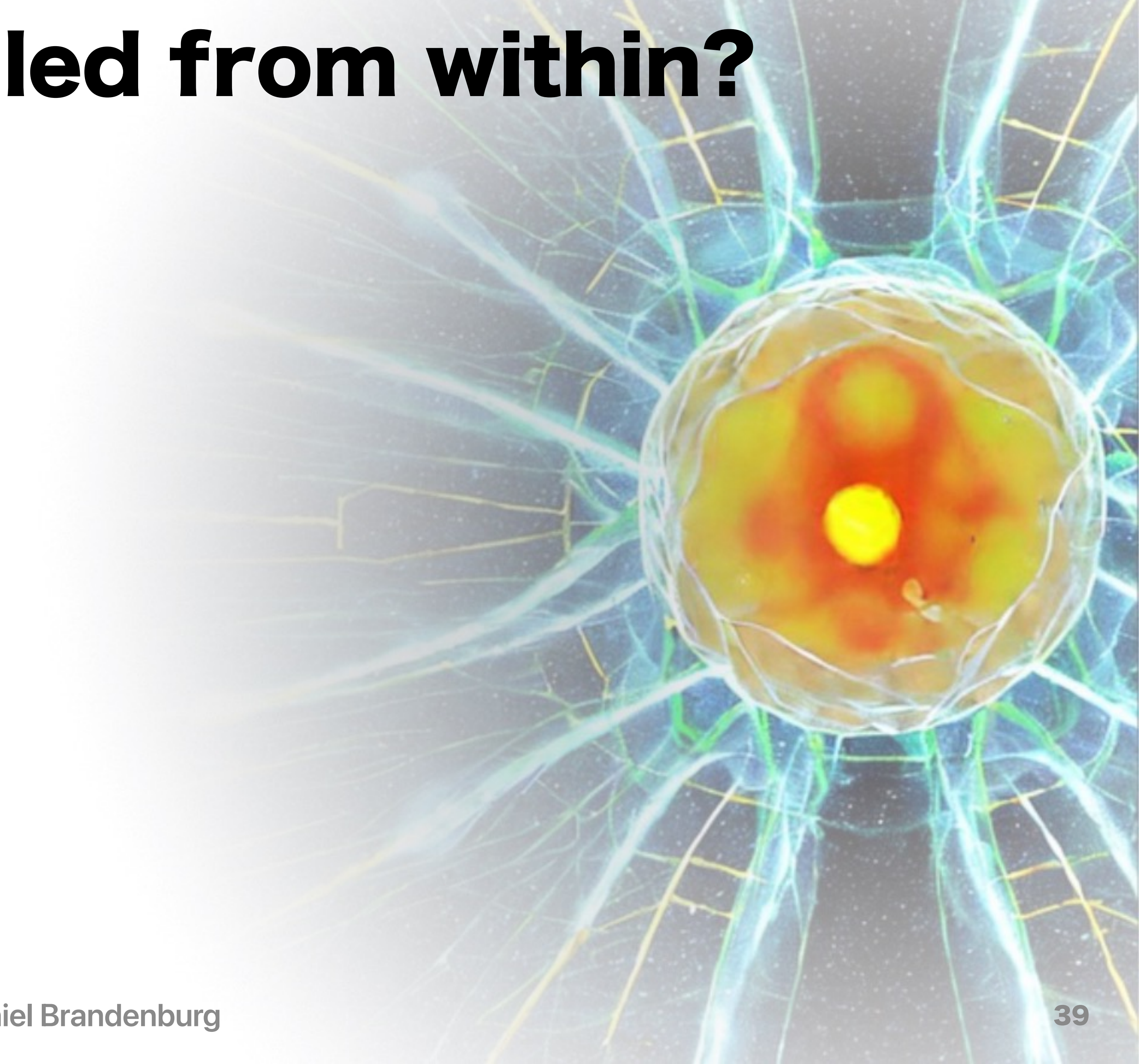
Entangled particles that never met

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.



Can something similar happen at the wavefunction level?

Case 3 : Entangled from within?



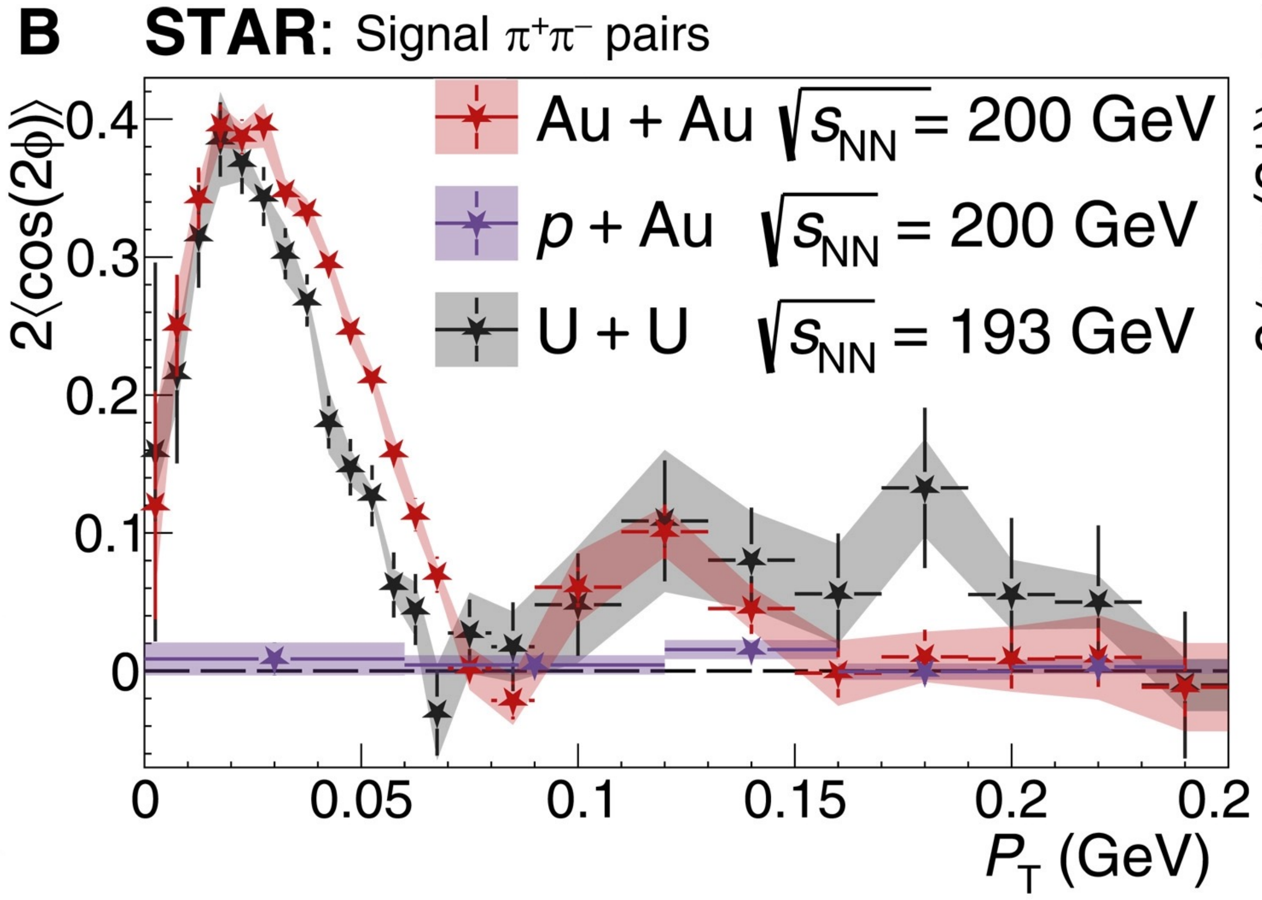
Maybe the entanglement originates even earlier in the interaction?

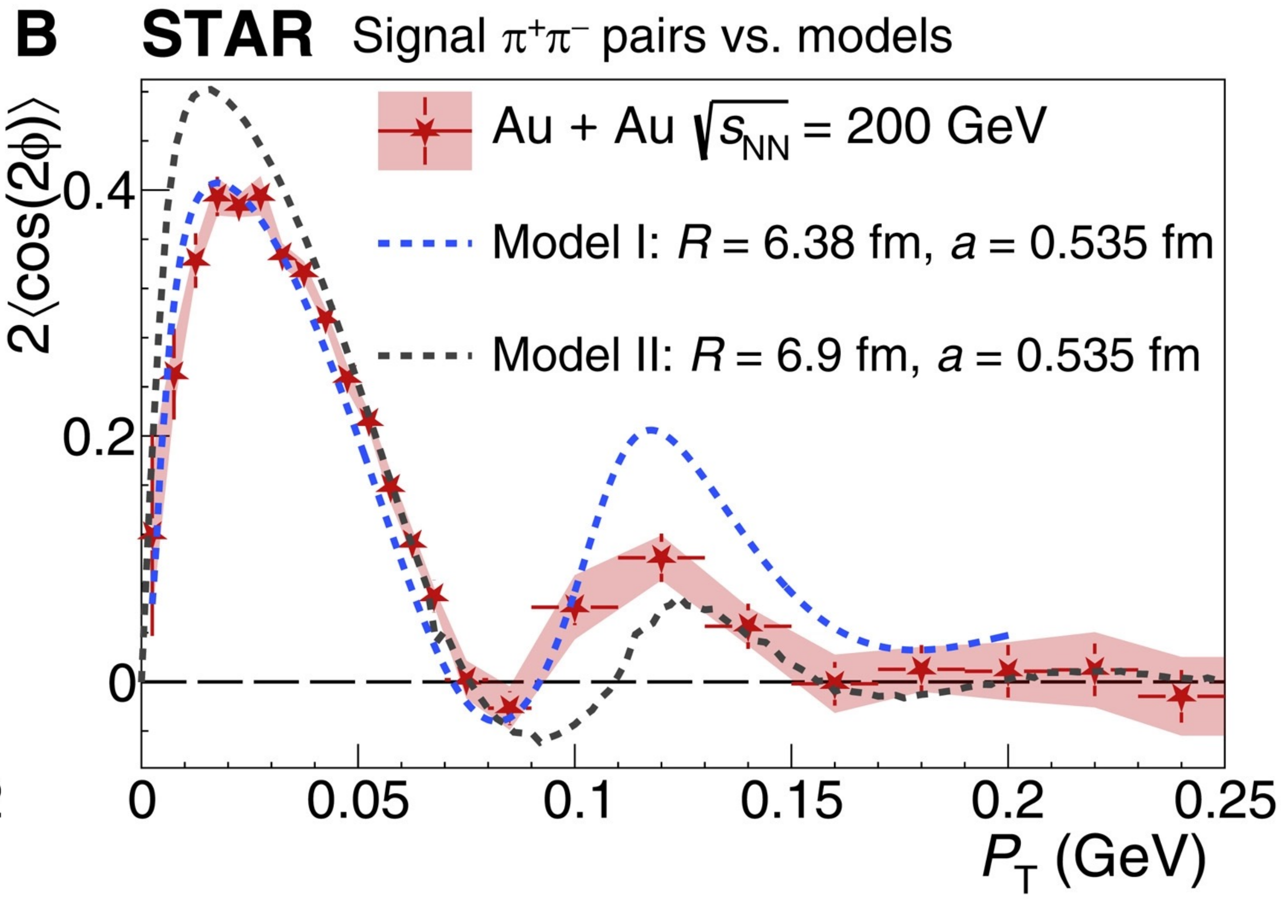
We expect that the nucleus (and the nucleons) are highly entangled states

BUT…

We have no experimental proof of this entanglement at rest

Comparison with theory





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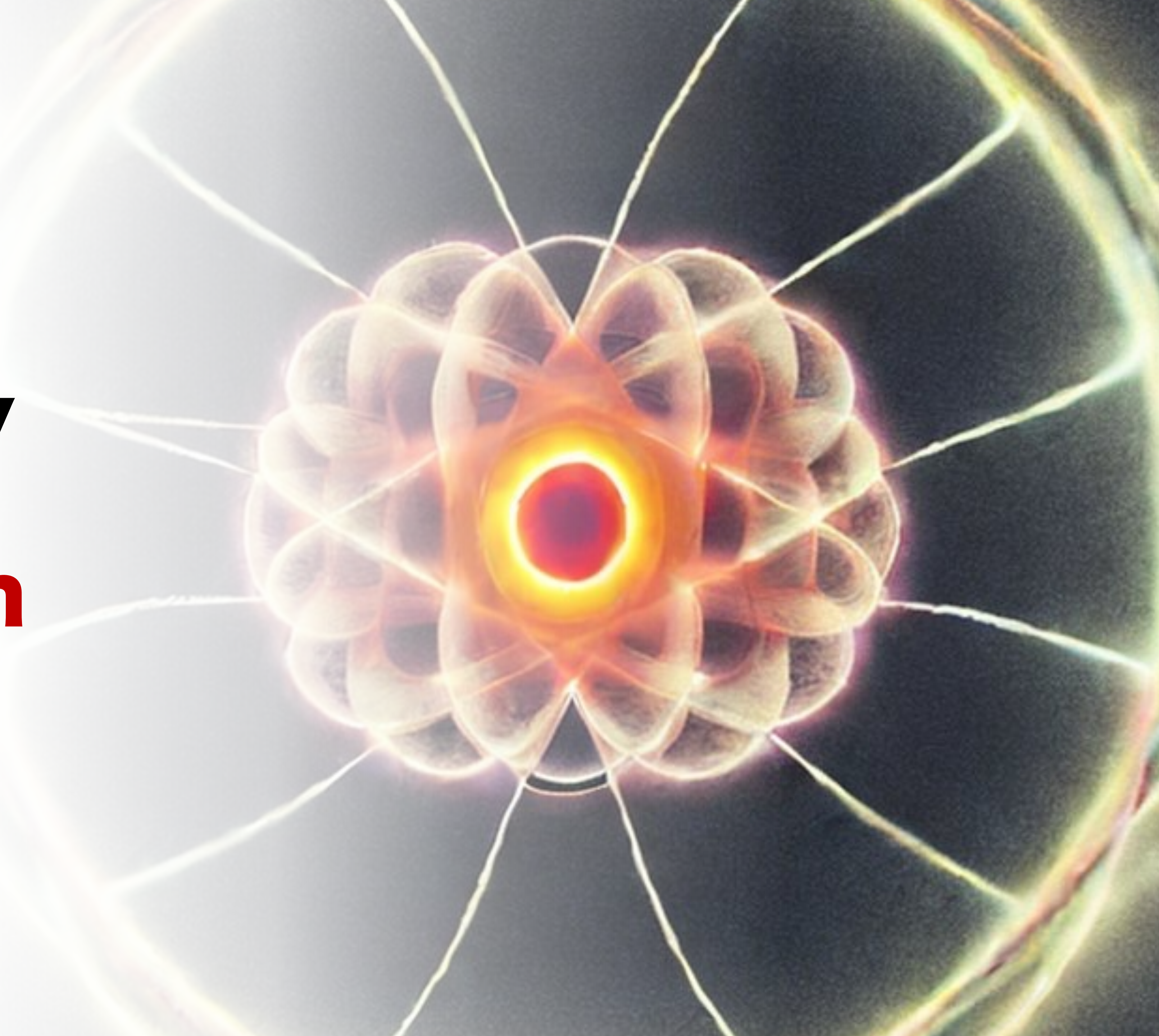
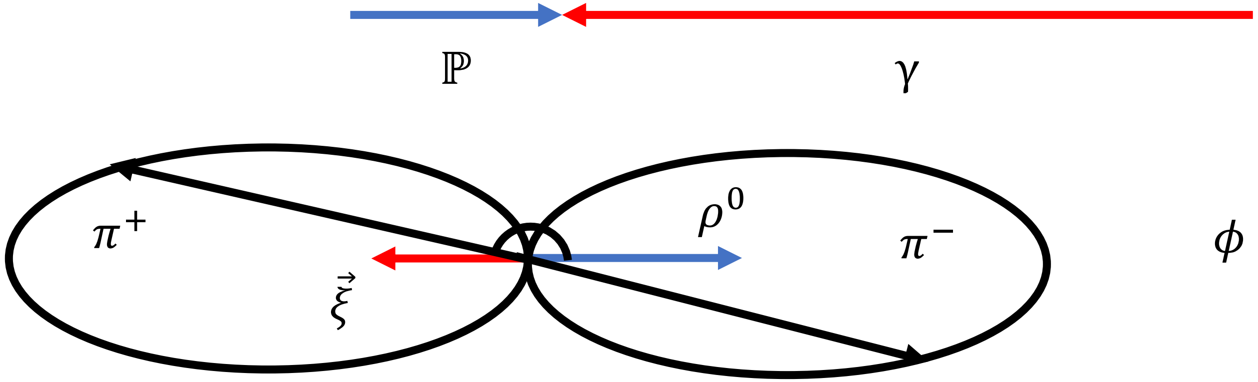
Nuclear Tomography and the Neutron skin



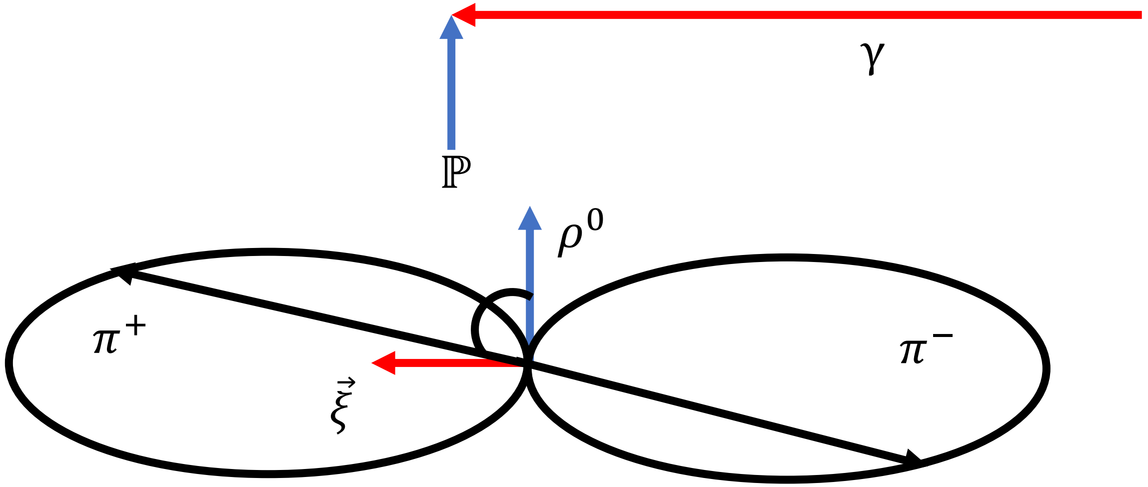
Interference Reveals Event Configurations

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



$\phi \approx 0, \pi$

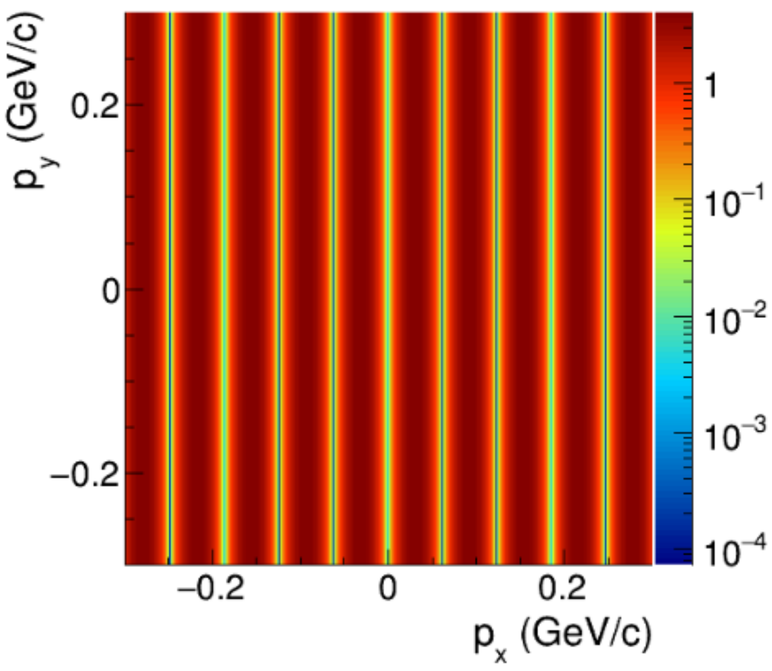
- Case II : Photon & Pomeron are perpendicular



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

Motivation for 2D Analysis : P_x vs P_y

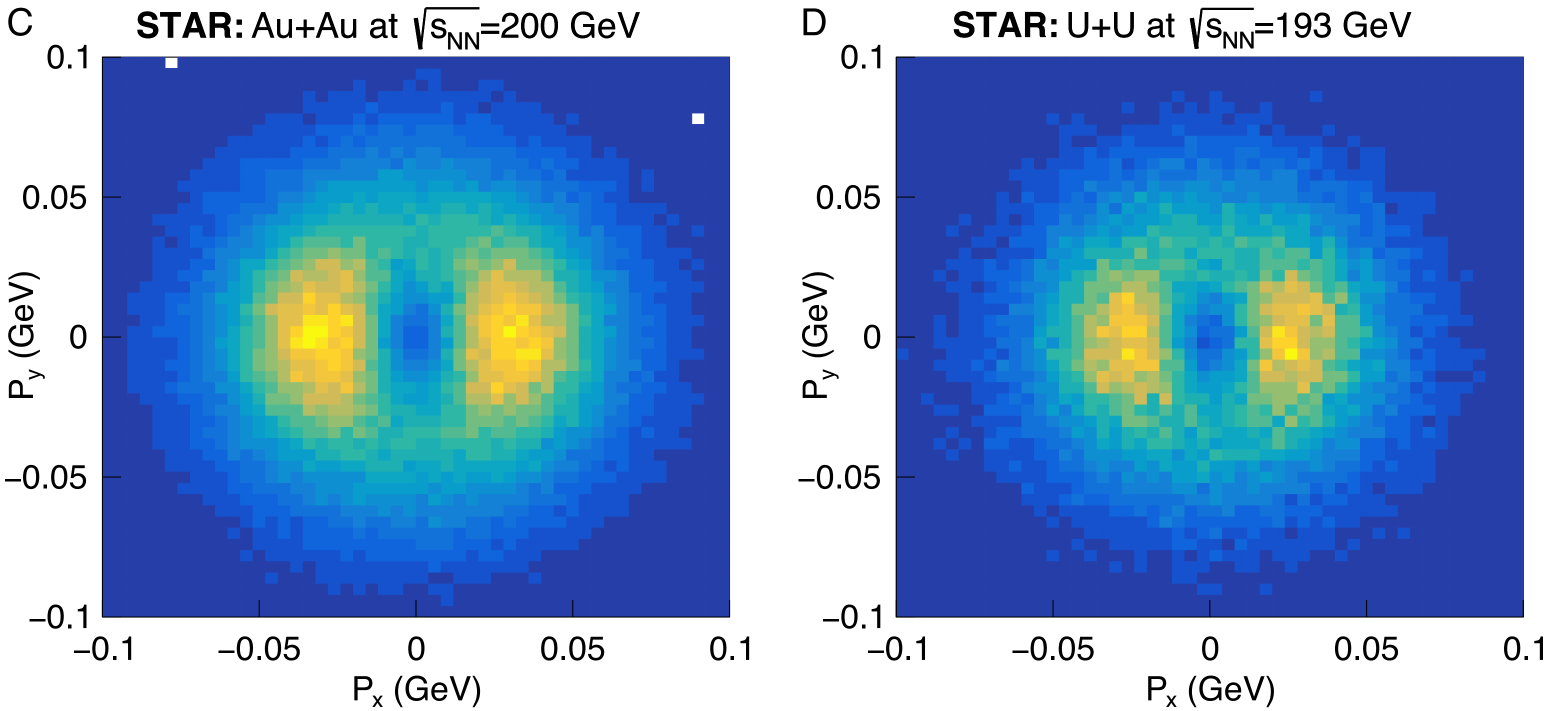
- Photon polarization is aligned with $\vec{b}$ (exactly for point source)
- Two source interference takes place in x-axis (impact parameter direction)



- 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



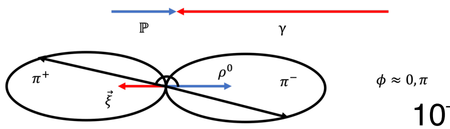
- Express ρ^0 transverse momentum in two-dimensions:
  - $P_x = p_T \times \cos\phi$
  - $P_y = p_T \times \sin\phi$

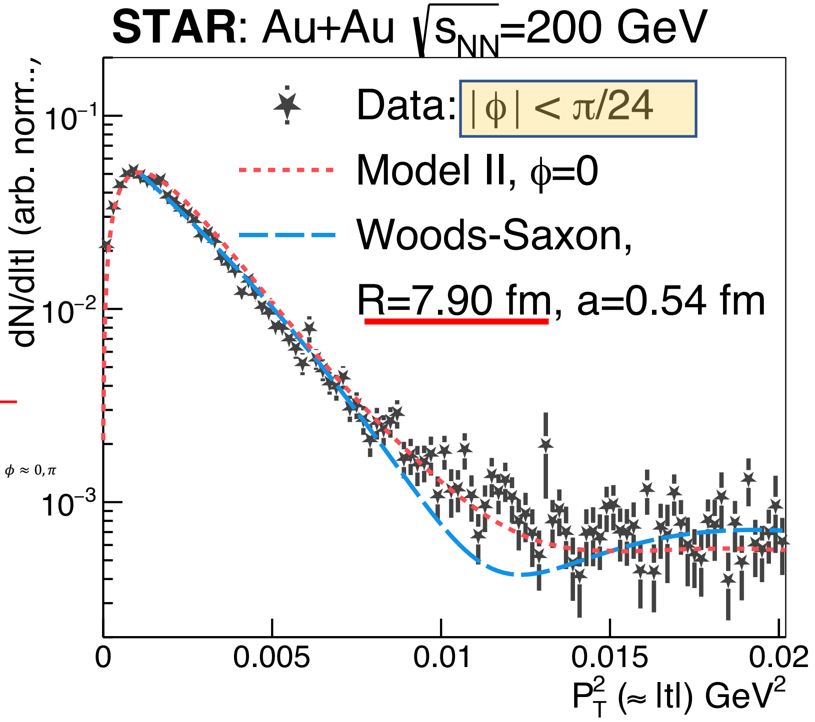
- Clear asymmetry in P_x vs. P_y due to interference effect in both Au+Au and U+U
- Illustrated "2D" tomography

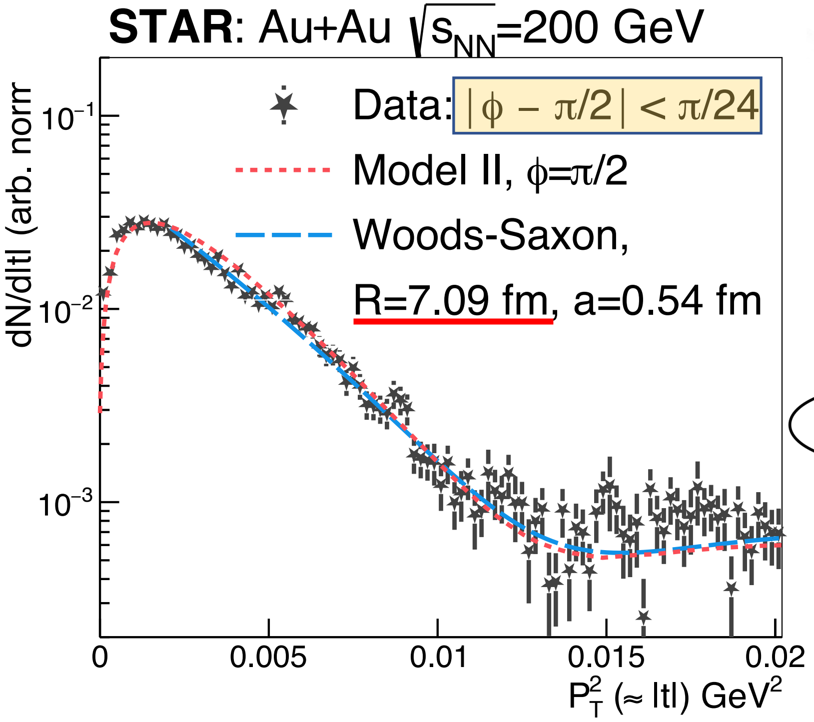
STAR Collaboration, Sci. Adv. **9**, eabq3903 (2023).

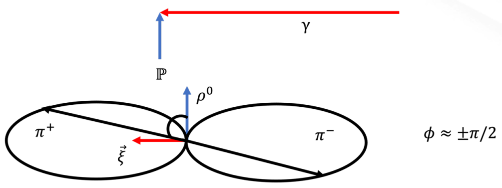
|t| vs. ϕ, which radius is 'correct'?

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







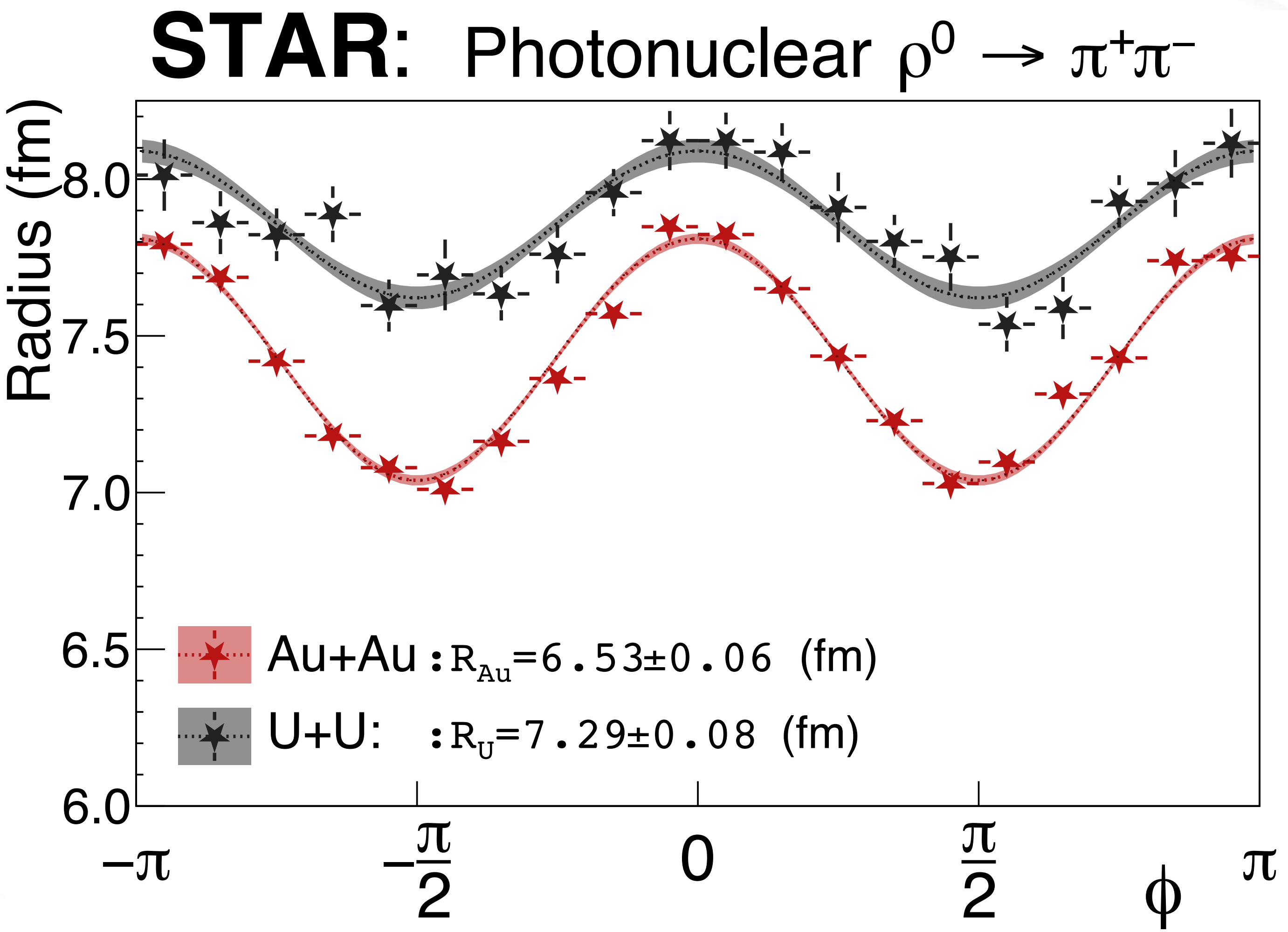


- Drastically different radius depending on ϕ, still way too big
- Notice how much better the Woods-Saxon dip is resolved for $\phi = \pi/2$ -> experimentally able to **remove photon momentum, which blurs diffraction pattern**
- **Can we extract the 'true' nuclear radius from |t| vs. ϕ information?**

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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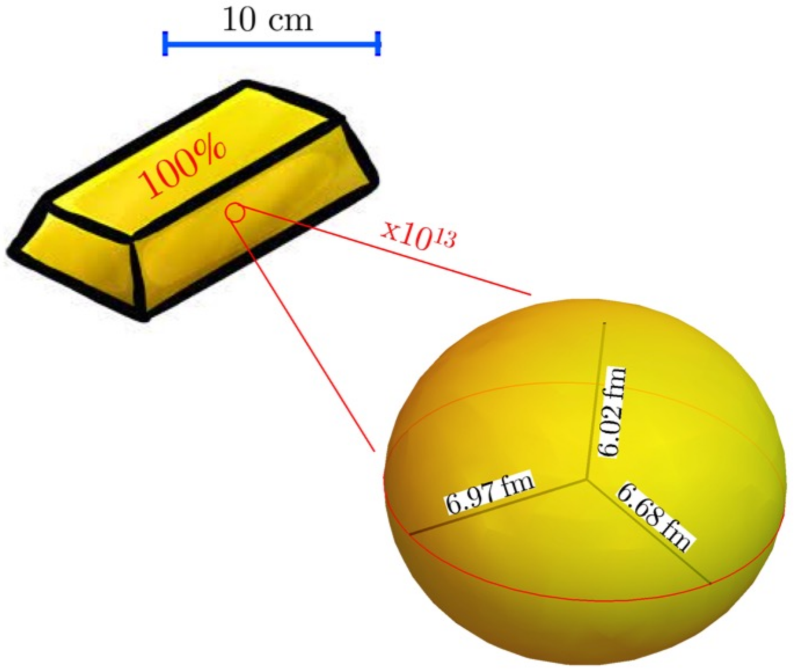
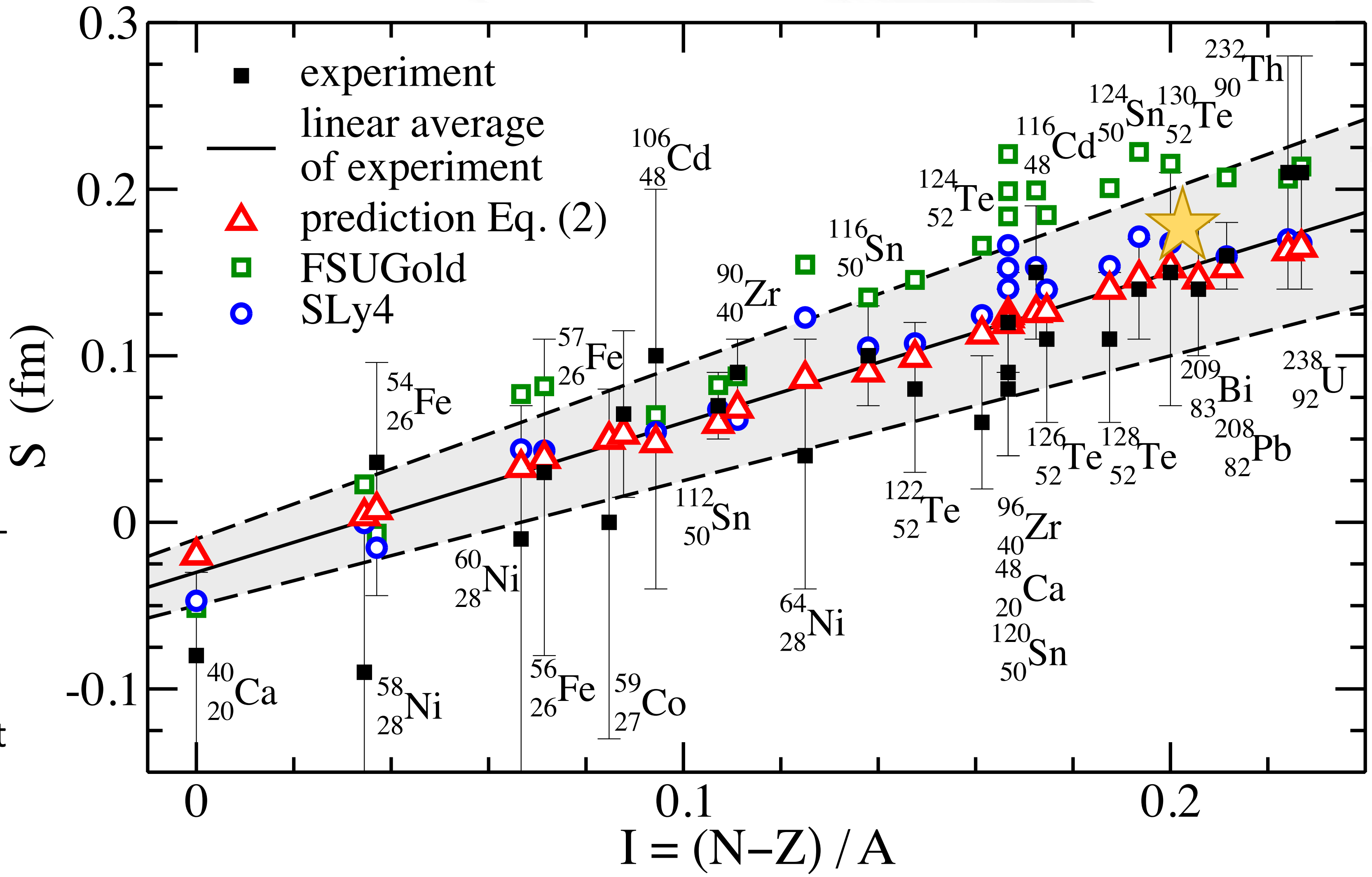
Neutron Skins across Nuclei



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

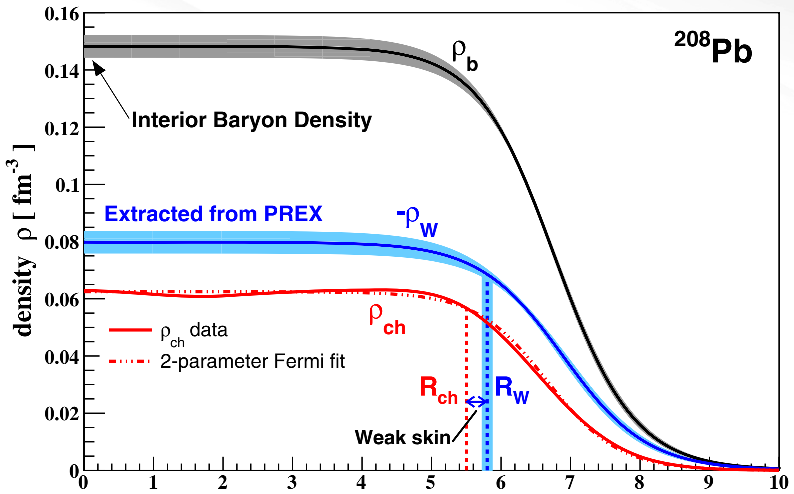
$$S_{Au} = 0.17\ \text{fm}$$

In good agreement with our measurement



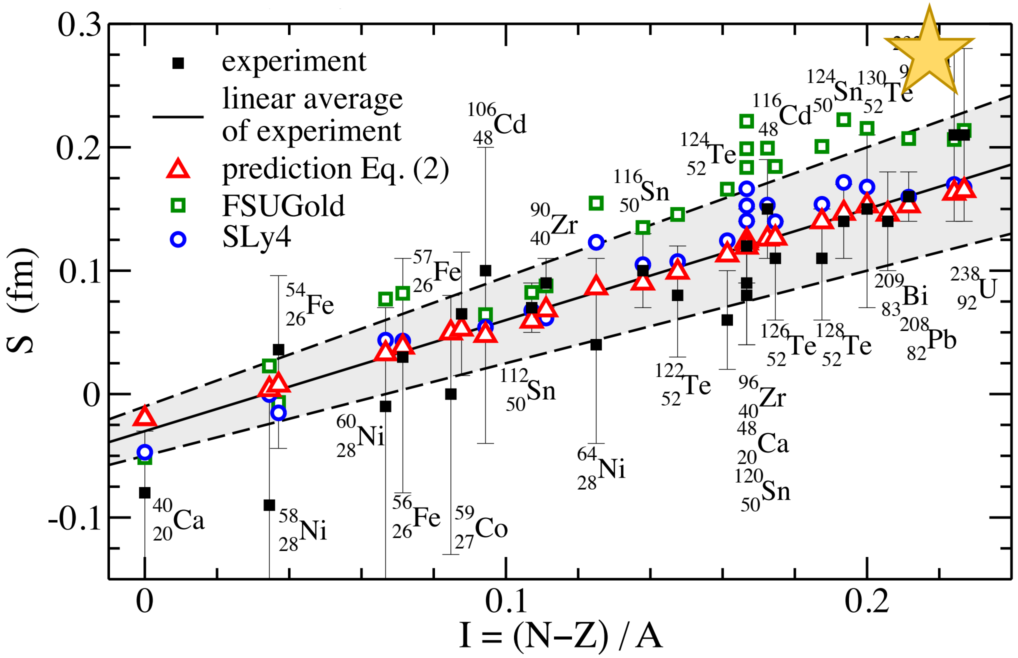
B. Bally, G. Giacalone, M. Bender https://arxiv.org/abs/2301.02420

The neutron skin of ^{208}Pb



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

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



ScienceAdvances
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Tomography of ultrarelativistic nuclei with polarized photon-gluon collisions

Overview of attention for article published in Science Advances, January 2023

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NATIONAL GEOGRAPHIC

Esta es la imagen más precisa de un átomo

National Geographic, 12 Jan 2023

Ciencia Un misterioso fenómeno cuántico desvela una imagen de un átomo como nunca se había hecho.

Популярная Механика

Таинственный квантовый феномен позволил ученым заглянуть в сердце атома

Popmech, 12 Jan 2023

, 09:24 Теперь у исследователей есть новый инструмент, который уже позволил расширить научное представление о протонах и нейтрона...

THE SCIENCE TIMES

What Does Atom's Heart Look Like? Quantum Interference Enables Researchers To Delve Into Atoms Like Never Before

SCIENTIFIC AMERICAN.

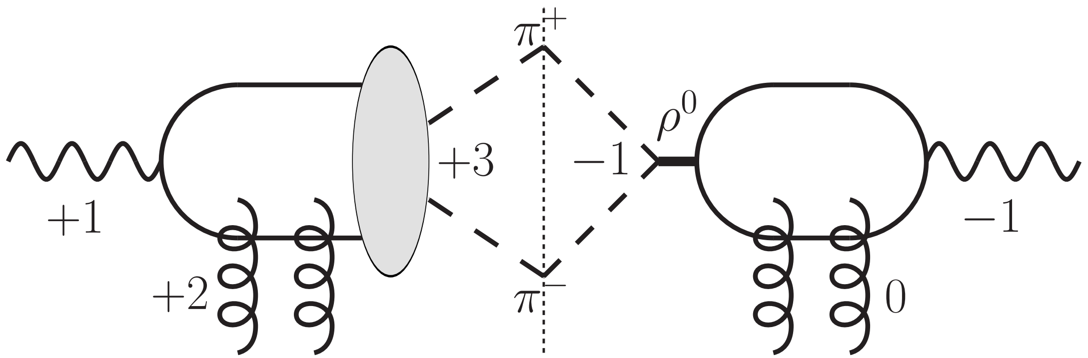
Scientists See Quantum Interference between Different Kinds of Particles for First Time

A newly discovered interaction related to quantum entanglement between dissimilar particles opens a new window into the nuclei of atoms

- **~ 15k Downloads (from SA)**
- **Already more than 10 citations**

Future Directions and Applications

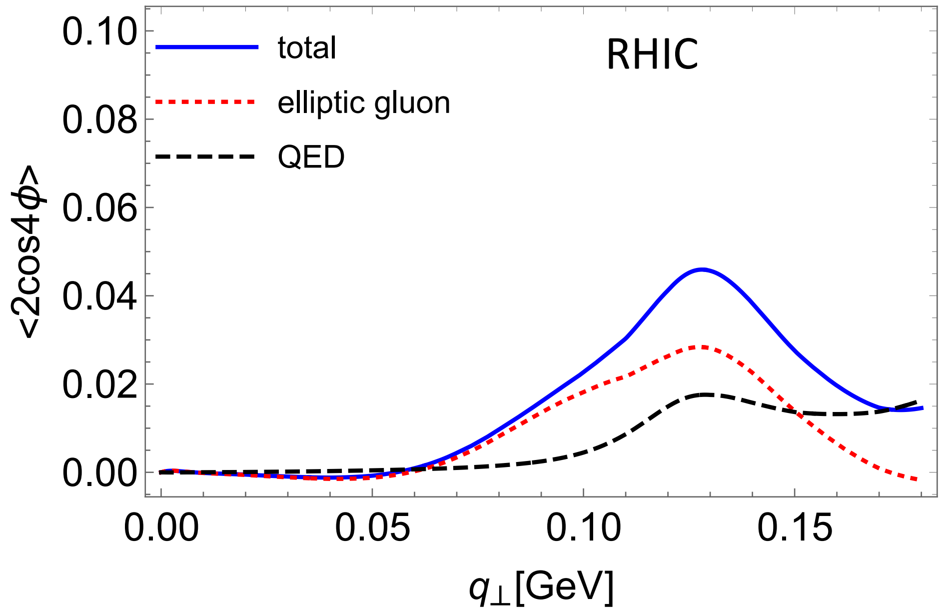
Elliptic Gluon Tomography (Tensor Pomeron)

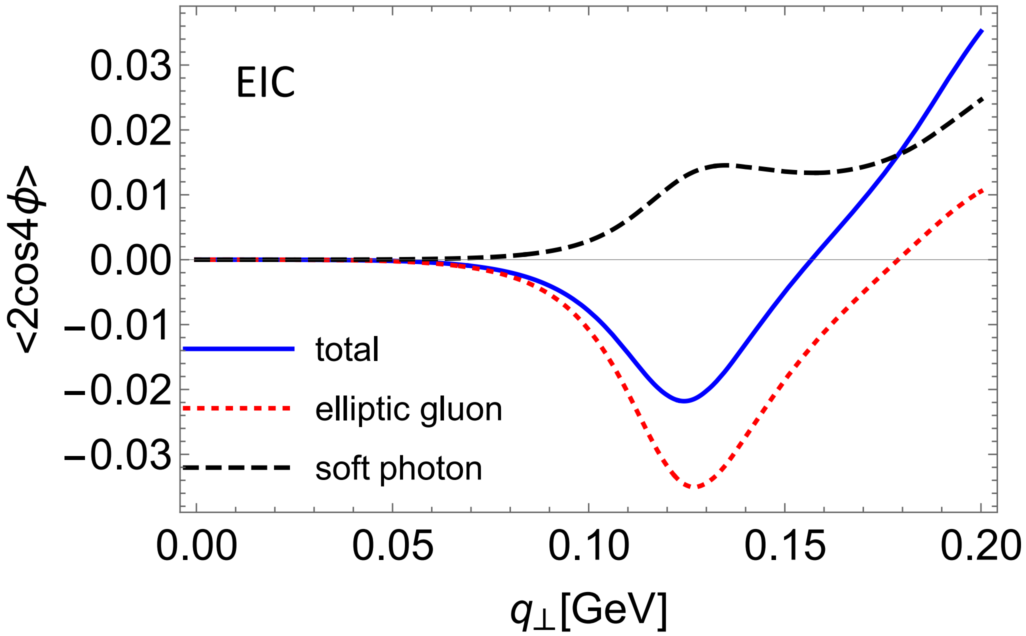


Phys. Rev. D **104**, 094021 (2021)

Elliptic gluon distribution: correlation between impact parameter and momentum

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





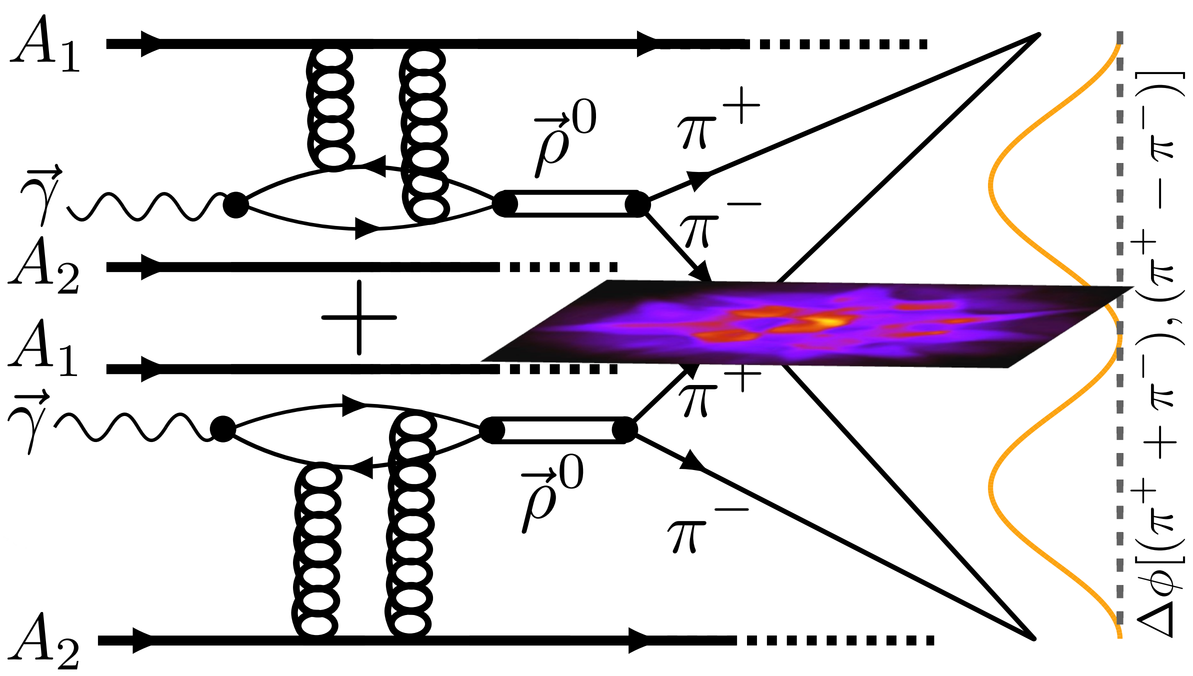
Testing Quantum Mechanics

Decoherence and collapse are fundamental open questions of Quantum Mechanics

→ Test wavefunction collapse in femto-scale environment

1. Measurement of photonuclear process in peripheral to central collisions
2. Comparison of $\rho^0 \to \pi^+\pi^-$ vs. $J/\psi \to l^+l^-$ (better from theoretical side)

- Will interaction with medium induce decoherence?



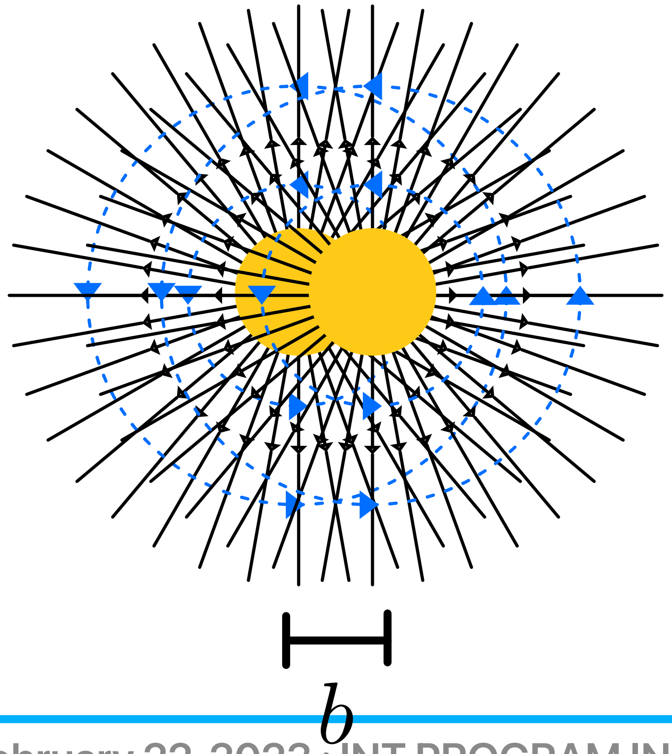
- Unlike leptons, π interact via strong force
- Presence of strongly interacting medium → **wavefunction collapse?**
  - I.e. no interference?
  - Difference between pion vs. lepton final states?

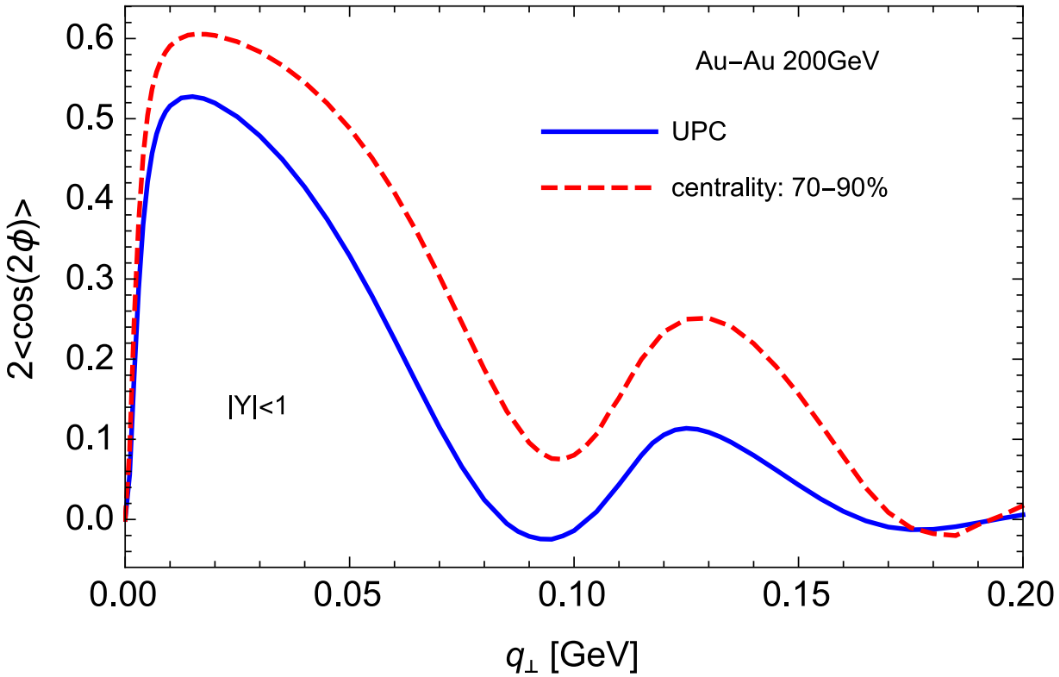
Diffractive Production in non-UPC

- STAR and ALICE have demonstrated that diffractive photo-nuclear interactions can occur even in peripheral collisions

STAR Collaboration, PRL.121(13), 132301 (2018).
J. Adam *et al.* (ALICE Collaboration) Phys. Rev. Lett. 116, 222301

- At smaller impact parameters → greater overlap of photon polarization vectors, larger interference effect expected





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

Source of Entanglement?

$\rho^0 \to \pi^+\pi^-$ vs. $J/\psi \to e^+e^-$

- For $\rho^0 \to \pi^+\pi^-$ (spin 0 daughters)

$$\frac{d^2N}{d\cos\theta d\phi} = \frac{3}{8\pi}\sin^2\theta[1+\cos 2(\phi-\Phi)], \qquad (1)$$

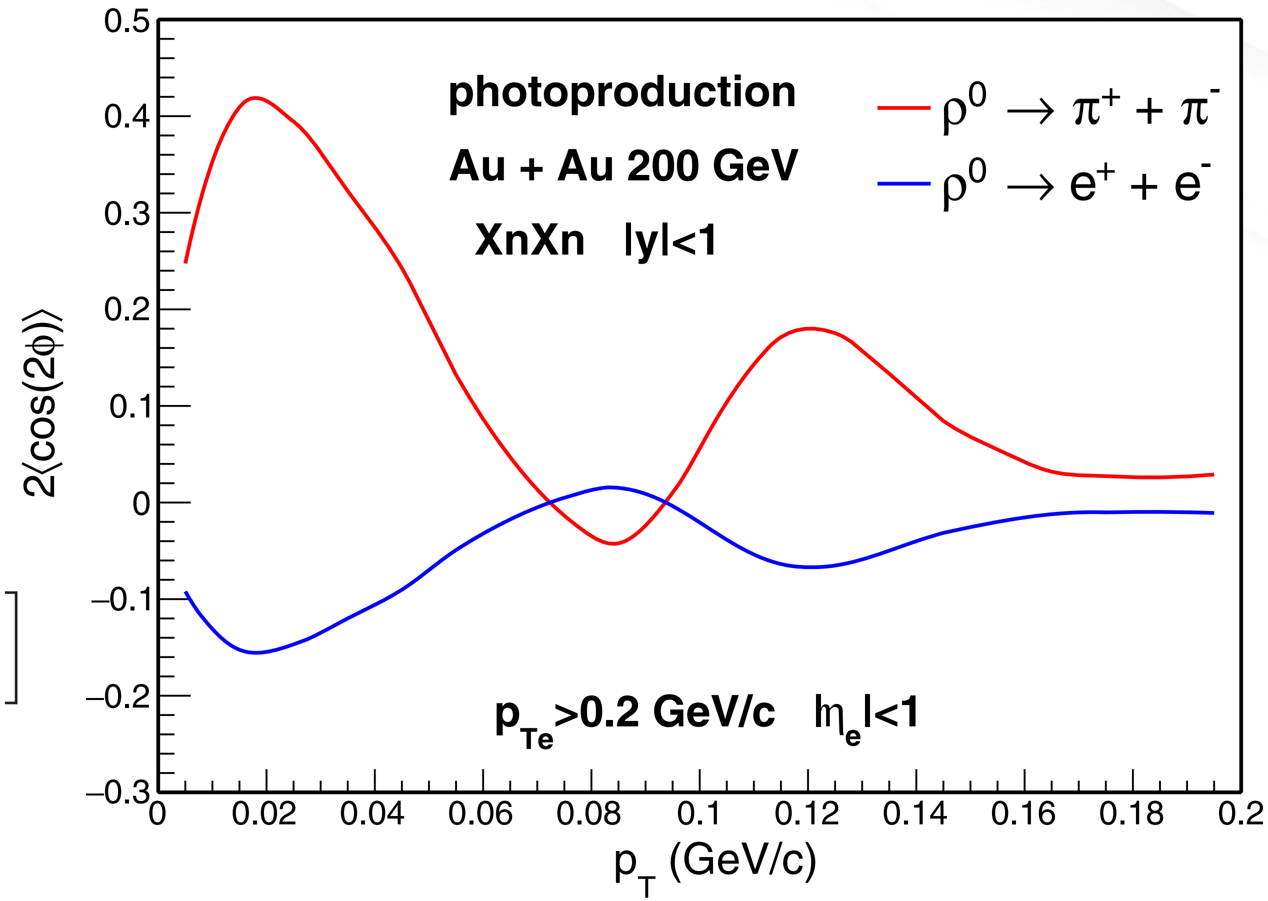
$$2\langle\cos(2\phi)\rangle = \cos(2\Phi)$$

- For $\rho^0 \to e^+e^-$ (spin 1/2 daughters)

$$\frac{d^2N}{d\cos\theta d\phi} = \frac{3}{16\pi}(1+\cos^2\theta)\left[1-\frac{\sin^2\theta}{1+\cos^2\theta}\cos 2(\phi-\Phi)\right]$$

$$2\langle\cos(2\phi)\rangle = -\frac{\sin^2\theta}{1+\cos^2\theta}\cos(2\Phi)$$

Zha, W., Brandenburg, J. D., Ruan, L. & Tang, Z. *Phys. Rev. D* **103**, 033007 (2021).

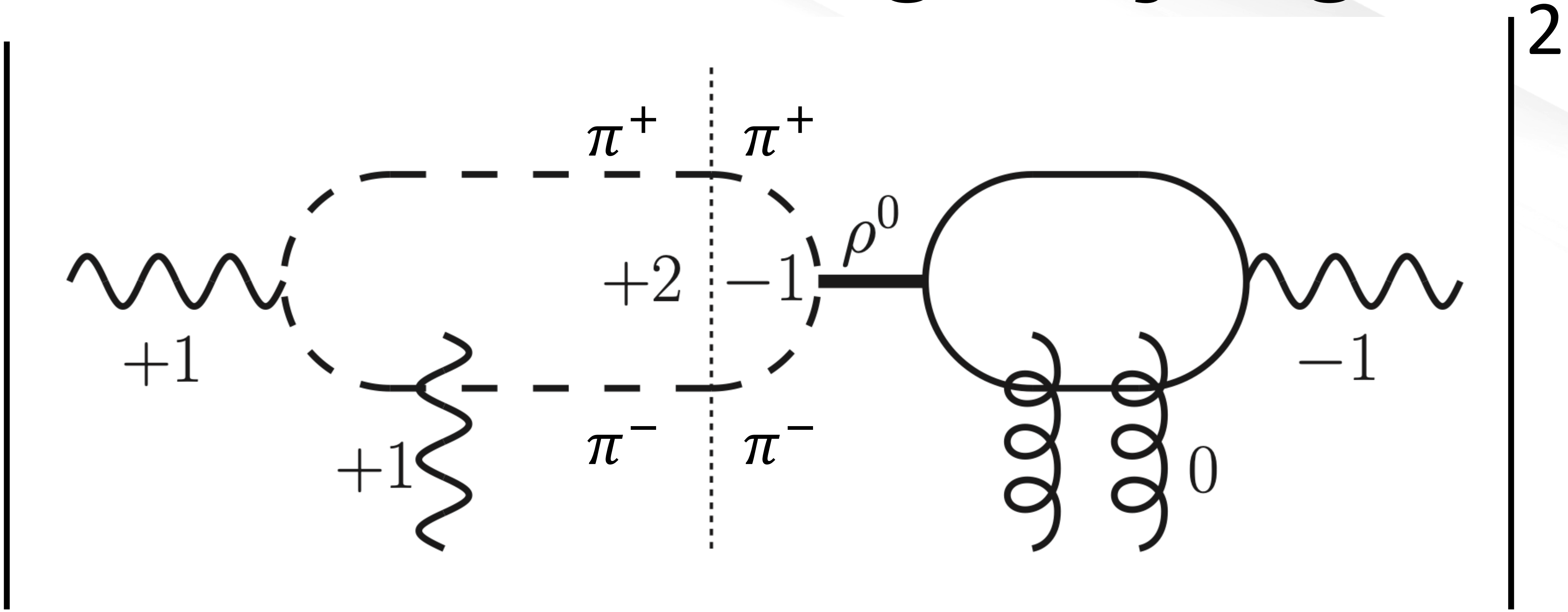


Where the angle Φ denotes the angle between the photon polarization plane and vector meson production plane.

$\rho^0 \to e^+e^-$: Relevant for $J/\psi \to e^+e^-$ case

STAR J/ψ measurement in 2023-2025 : ±4% @ 50 MeV/c

Access to Hadronic Light-by-Light



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

Summary

1. **Discovery of interference between distinguishable particles!**
2. **Technique for precise neutron skin measurement at high energy**

- Exact source of entanglement still unclear – nuclei as entangled objects?
- Potential for testing fundamental aspects of quantum mechanics
- Many future opportunities: ^{208}Pb, elliptic gluons, hadronic light-by-light, etc.

Thank you!

- Xiaofeng Wang (PhD student)
- Zhen Wang (PhD Student)
- Isabel Xu (High School Student)
- Isaac Upsal (Post-doc)
- Chi Yang (SDU)
- Wangmei Zha (USTC)
- Janet Seger (Creighton University)
- Frank Geurts (Rice University)
- Zhangbu Xu (BNL)
- Lijuan Ruan (BNL)

Papers related to this talk:

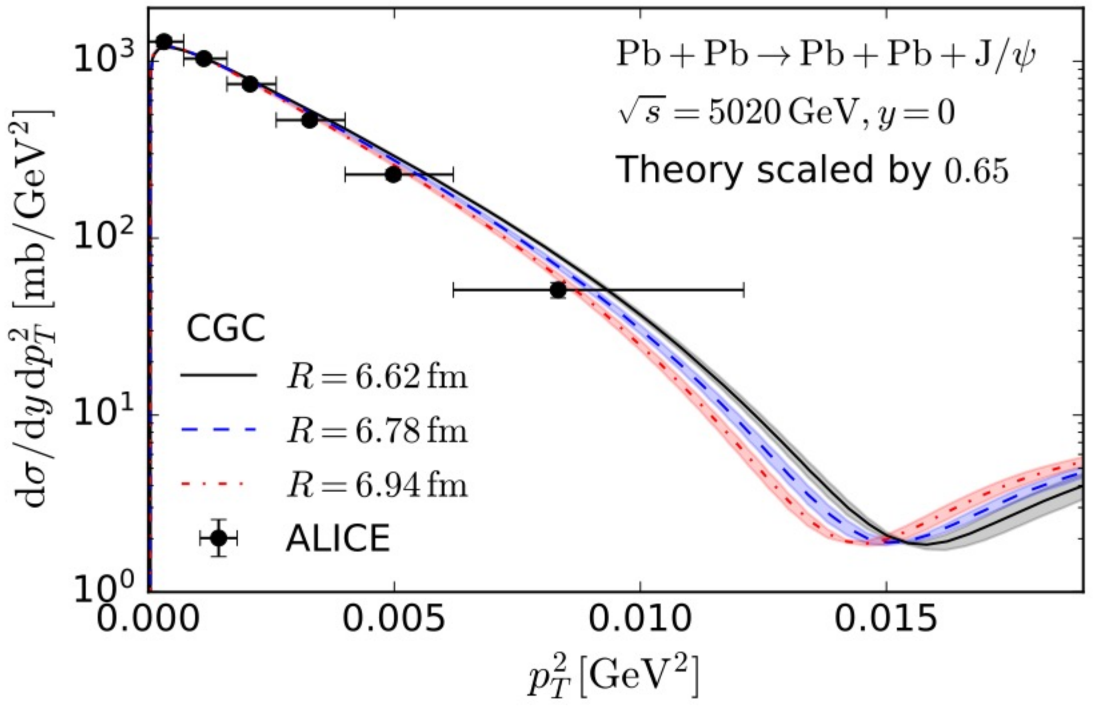
[1] JDB, W. Zha, and Z. Xu, Eur. Phys. J. A **57**, 299 (2021).
[2] JDB, W. Li, et al., arXiv:2006.07365 [hep-ph, physics:nucl-th] (2020).
[3] W. Zha, JDB, Z. Tang, and Z. Xu, Physics Letters B **800**, 135089 (2020).
[4] STAR Collaboration, Phys. Rev. Lett. **127**, 052302 (2021).
[5] STAR Collaboration, Phys. Rev. Lett. **121**, 132301 (2018).
[6] WZ, JDB, *Phys. Rev. D* **103**, 3 (2021).
[7] JDB, PoS, Vol. **387** (2021).
[8] STAR Collaboration, Science Advances, (2023).
[9] JDB, W. Zha, Z. Xu, Report on Progress in Physics (2022).

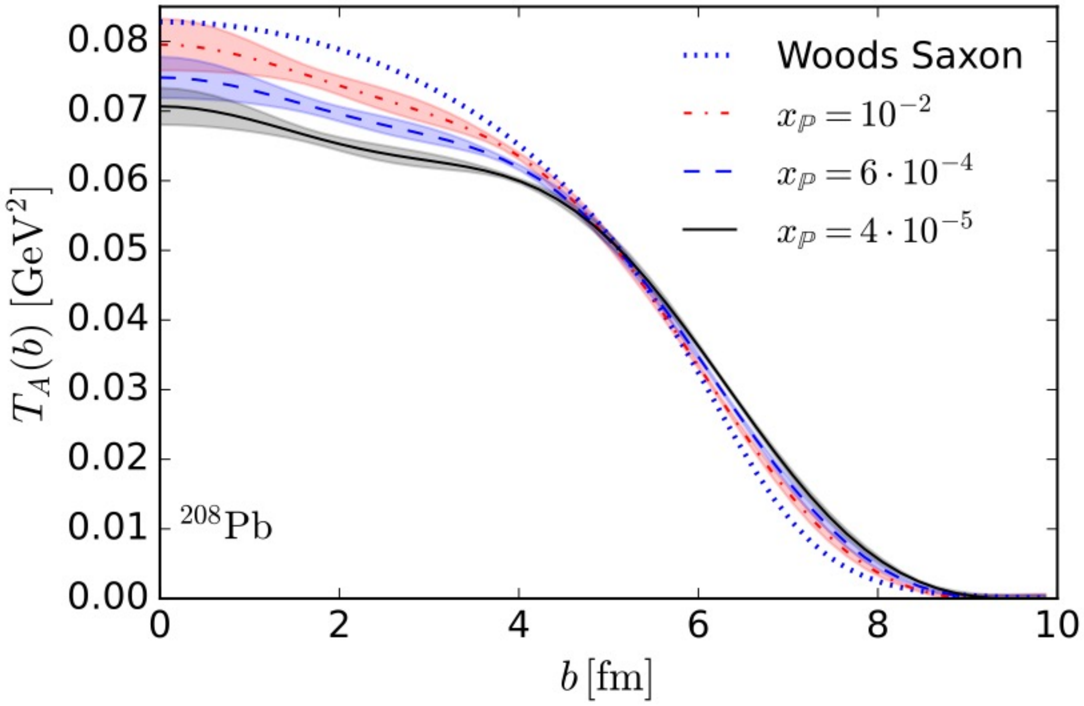
Nuclear Geometry at (even) Higher Energy

- 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





Mysteriously large?

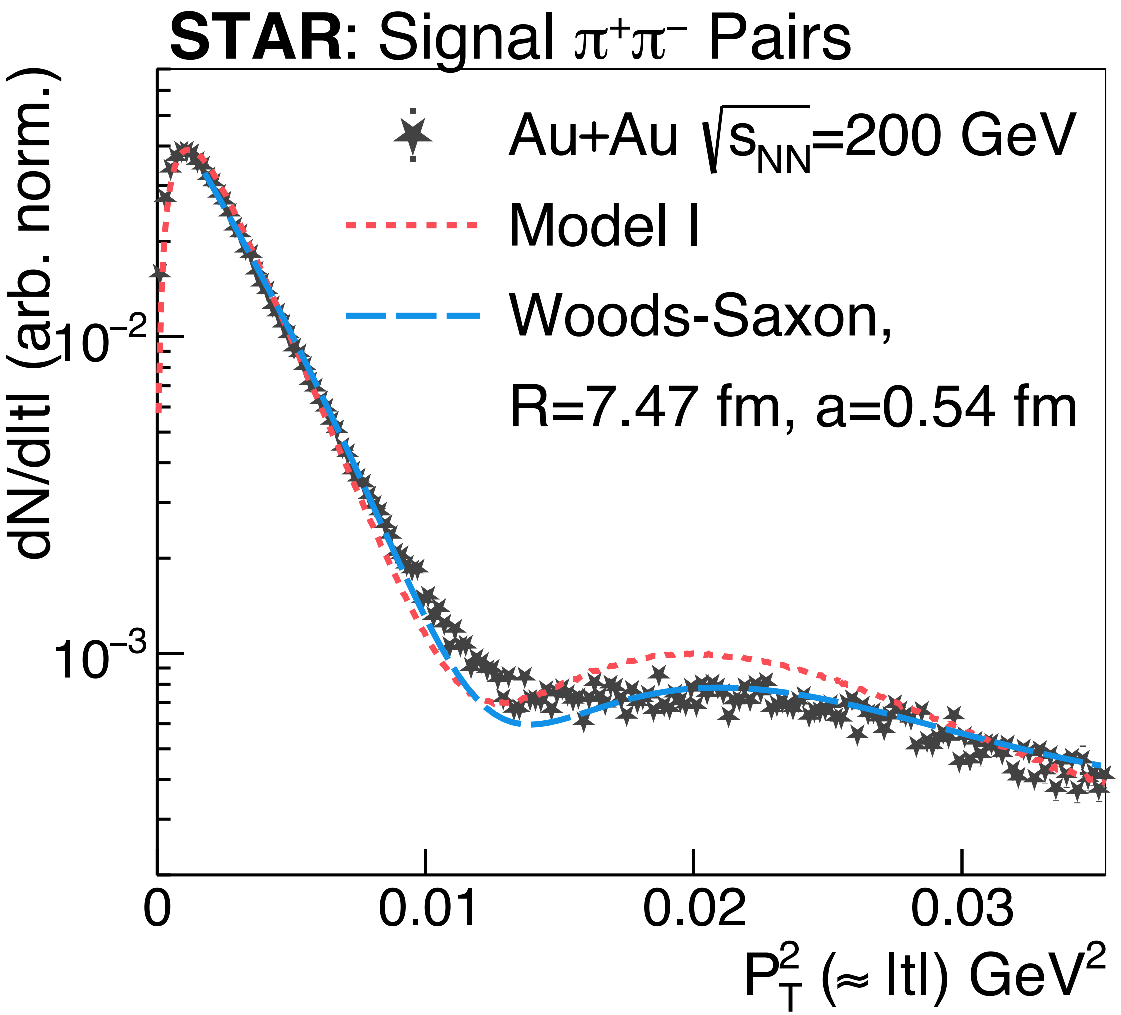


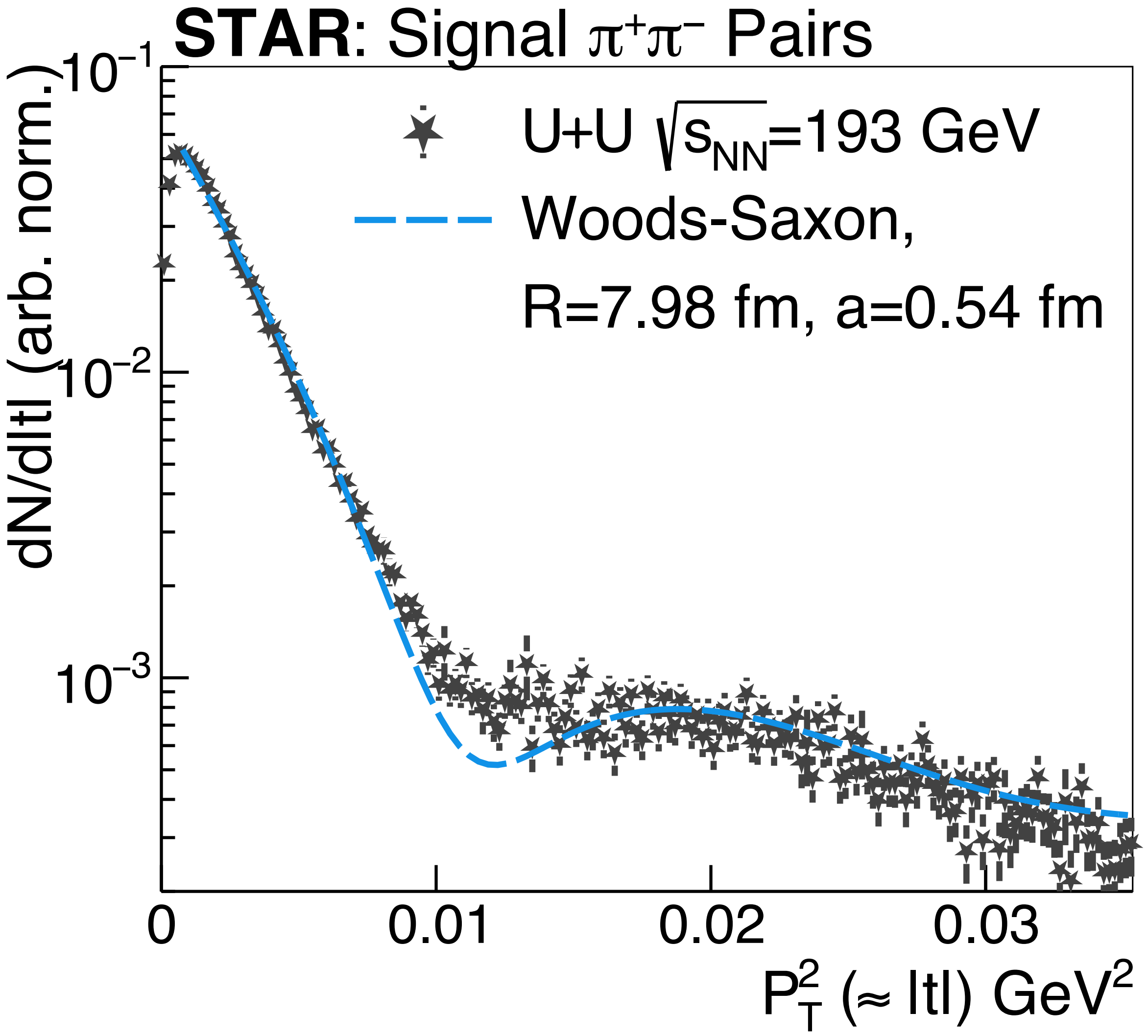
Photo-nuclear measurements have historically produced a |t| slope that corresponds to a **mysteriously large source!**

STAR (2017): |t| slope = $407.8 \pm 3 (GeV/c)^{-2}$
ALICE (Pb) : |t| slope = $426 \pm 6 \pm 15\ (GeV/c)^{-2}$
→ Effective radius of >8 fm?!?
($R_{Au}^{charged} \approx$ 6.38 fm, $R_{Pb}^{charged} \approx$ 6.62 fm)

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.

arXiv:2204.01625

Mysteriously large?



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→ Effective radius of >8 fm?!?
($R_{Au}^{charged}$ ≈ 6.38 fm, $R_{Pb}^{charged}$ ≈ 6.62 fm)

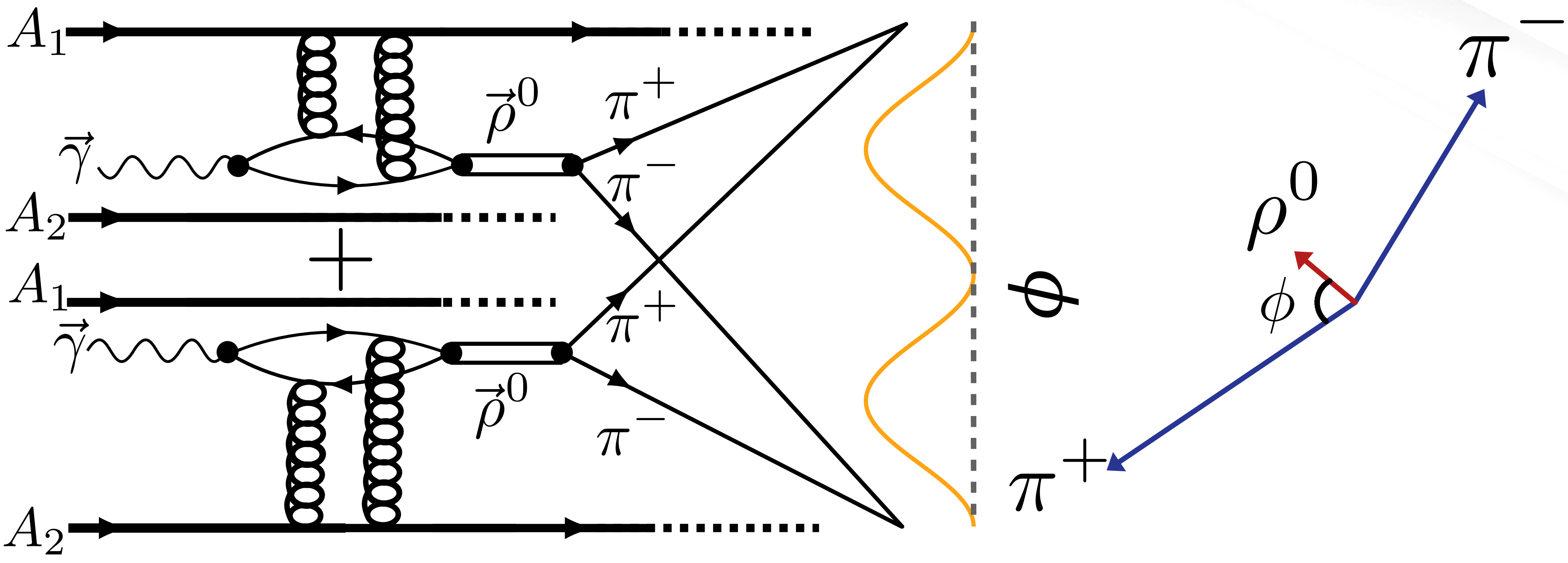
- Uranium has the same issue, >1 fm larger than charge radius ($R_{U}^{charged}$ ≈ 6.81 fm)

arXiv:2204.01625

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.

Imaging the Nucleus with Polarized Photons

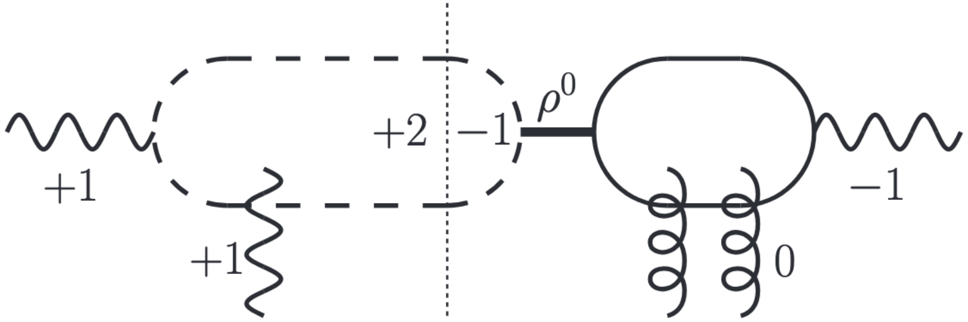
What is NEW with transversely polarized photons?



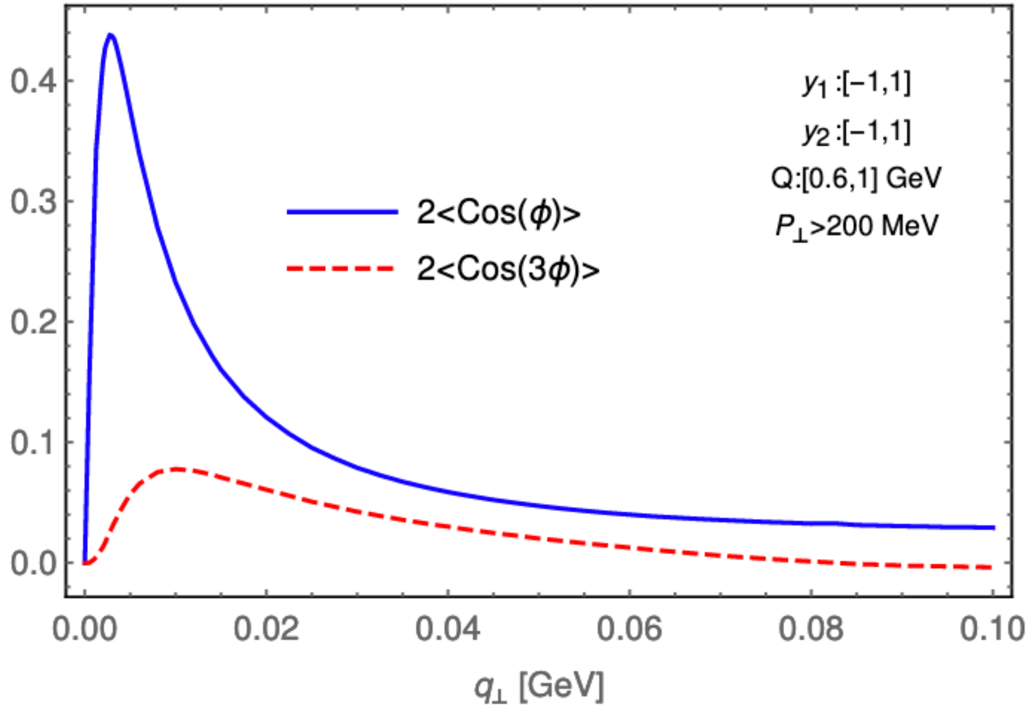
Interference between two **indistinguishable** cases

Connection to Hadronic Light-by-light

Hadronic Light-by-Light Interference
to probe entanglement

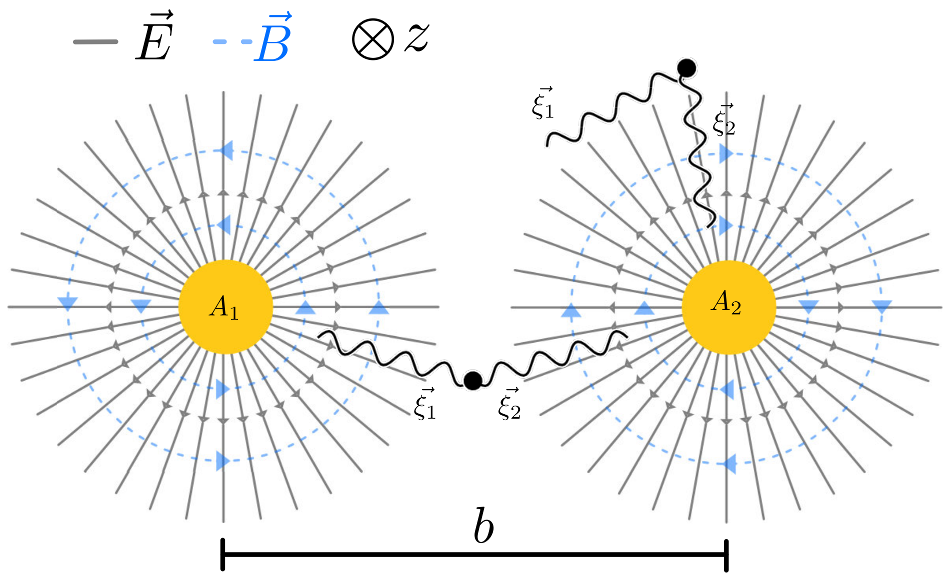


Final state asymmetries due to QED-QCD interference, reveals phase between photon and gluon fields



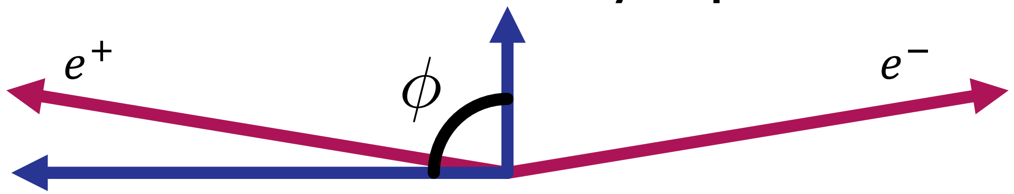
- [1] JDB, J. Seger, Z. Xu, W. Zha, arXiv:2208.14943 **[hep-ph]**
- X. Wang, JDB, L. Ruan, F. Shao, Z. Xu, C. Yang, W. Zha, arXiv:2207.05595 **[nucl-th]**
- JDB, Z. Xu, W. Zha, C. Zhang, J. Zhou, Y. Zhou arXiv:2207.02478 **[hep-ph]**
- JDB, W. Zha, and Z. Xu, Eur. Phys. J. A **57**, 299 (2021).
- W. Zha, JDB, Z. Tang, and Z. Xu, Phys. Lett. B **800**, 135089 (2020).
- STAR Collaboration, Phys. Rev. Lett. **127**, 052302 (2021).
- STAR Collaboration, Phys. Rev. Lett. **121**, 132301 (2018).
- JDB, W. Li, et al., arXiv:2006.07365 [hep-ph, physics:nucl-th] (2020).

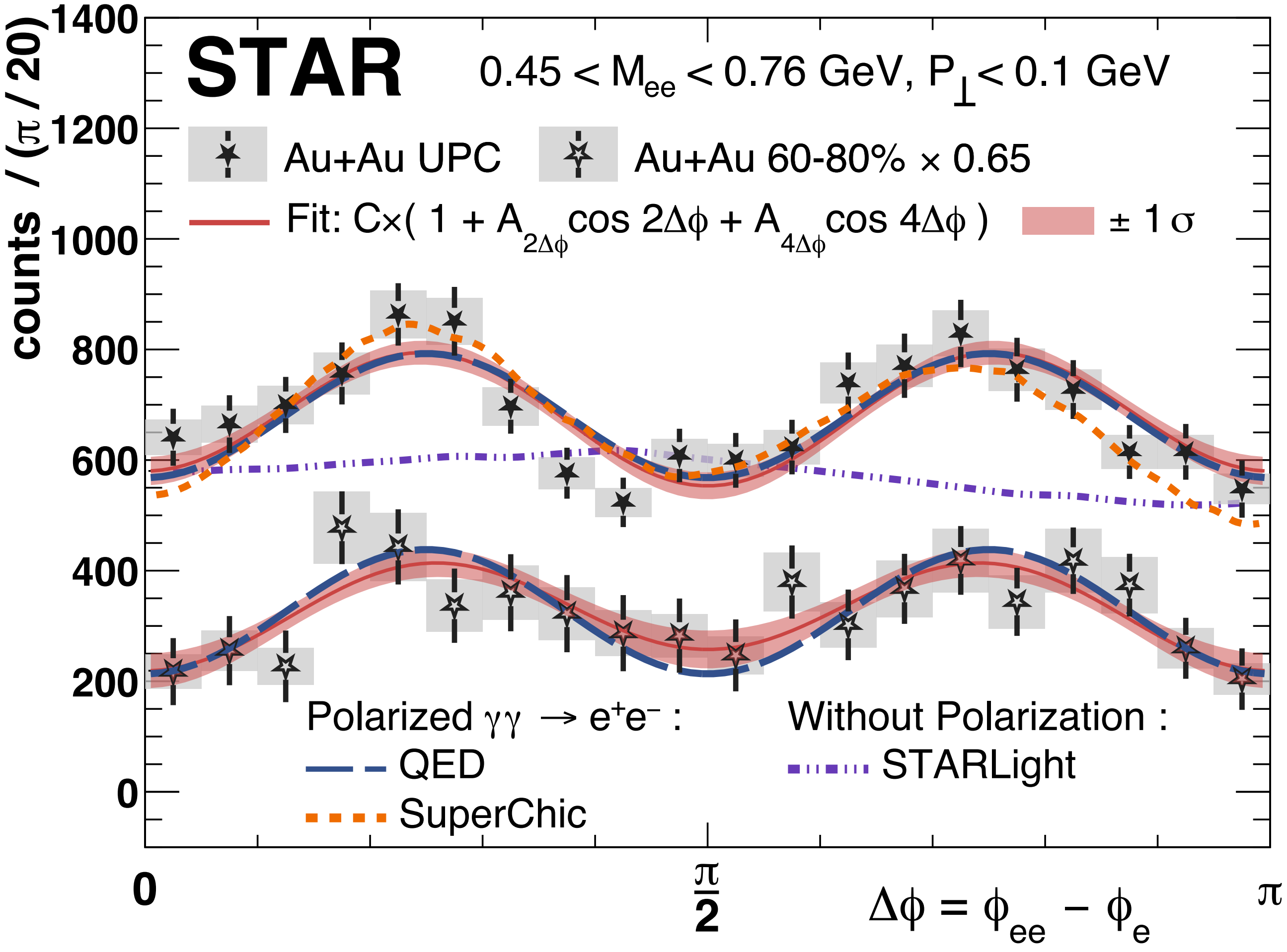
Discovery of the Breit-Wheeler Process



- 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**





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

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