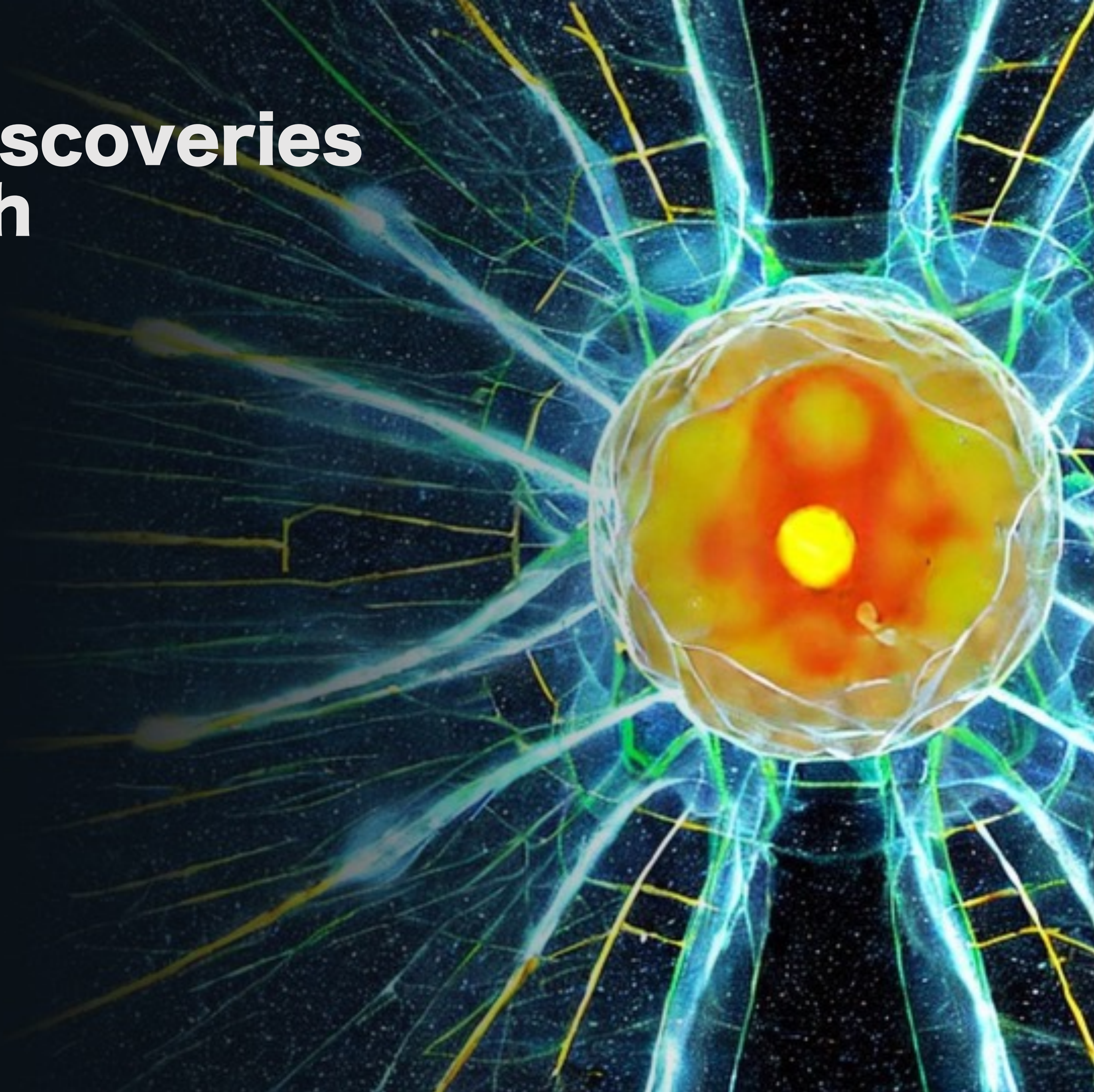
# From QED to QCD: Discoveries and Applications with Polarized Photons

(James) **Daniel Brandenburg**

THE OHIO STATE UNIVERSITY



Seminar,
@RHIC-BES online series
Tuesday, April 18th, 2023

# Outline : Nuclear tomography via diffractive vector meson photoproduction

## 1. Introduction: Light & QED

## 2. The Breit-Wheeler Process

- Polarized Photons in HICs
- Observation of the Breit Wheeler process & Vacuum Birefringence
- Applications

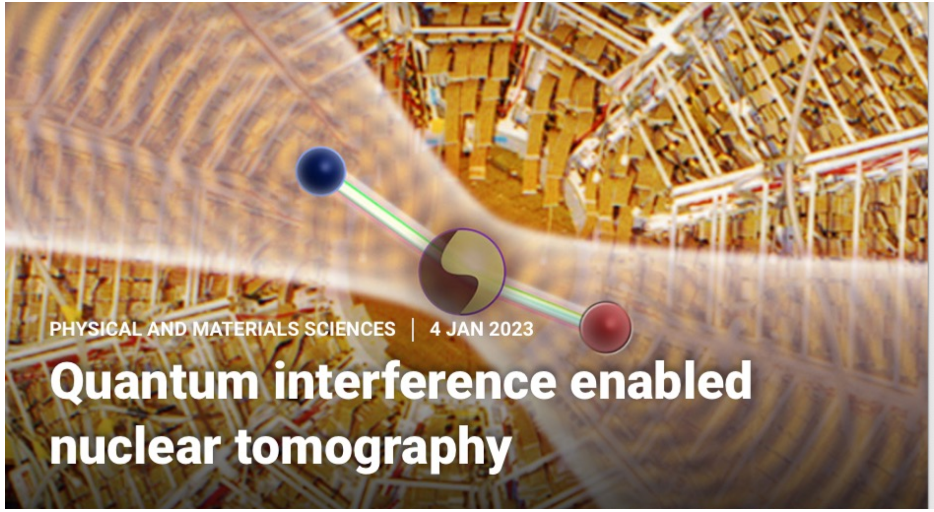
## 3. Entanglement Enabled Nuclear Tomography

- Interference of non-identical particles
- Entanglement and its origin
- ‘Imaging’ the nucleus

## 4. 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



PHYSICAL AND MATERIALS SCIENCES | 4 JAN 2023

Quantum interference enabled nuclear tomography

Featured article, Volume 9, issue 1, 2023

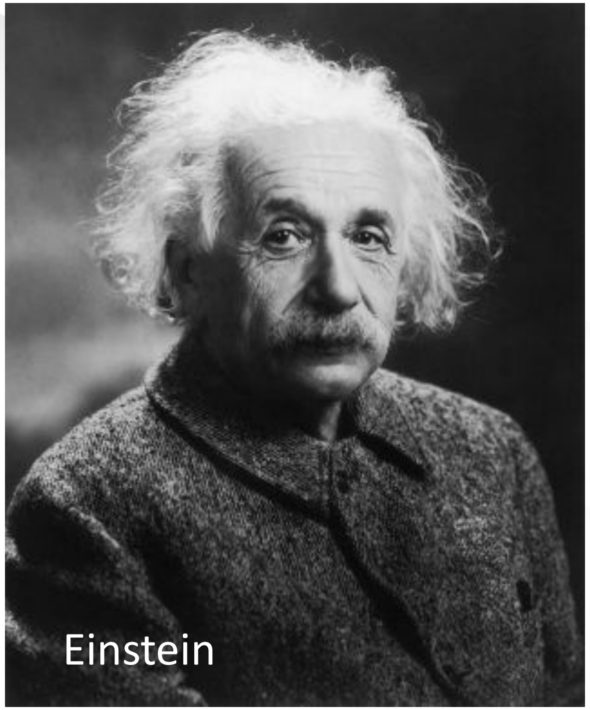
STAR Collaboration, Sci. Adv. **9**, eabq3903 (2023).

# From Classical to Quantum Electrodynamics (QED)

# Quantum Electrodynamics

Three important discoveries that alter the classical picture:

1. Einstein's energy-mass equivalence: $\boldsymbol{E = mc^2}$
2. Heisenberg's Uncertainty principle: $\Delta E \Delta t \geq \hbar/2$
3. Existence of positron : Dirac predicts negative electron energy states (1928), Anderson discovered positron in 1932



# Quantum Electrodynamics

Three important discoveries that <u>alter the classical picture</u>:

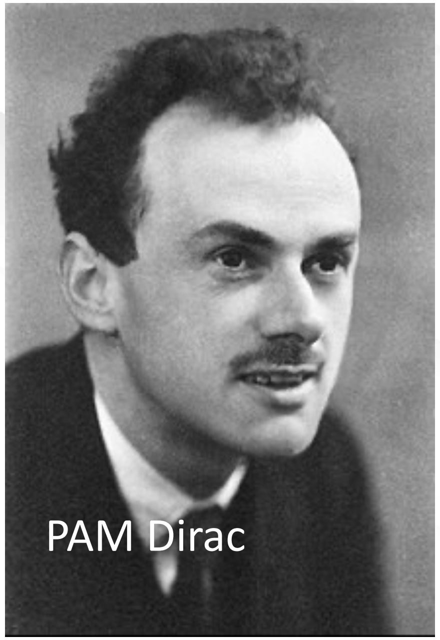
1. Einstein's energy-mass equivalence: $E = mc^2$
2. Heisenberg's Uncertainty principle: $\boldsymbol{\Delta E \Delta t \geq \hbar/2}$
3. Existence of positron : Dirac predicts negative electron energy states (1928), Anderson discovered positron in 1932

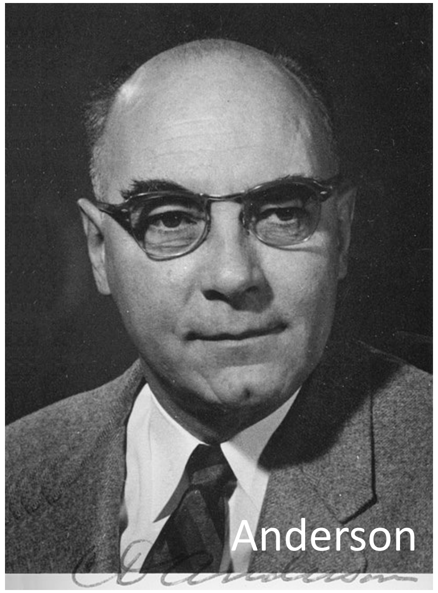

Werner
Heisenberg

# Quantum Electrodynamics

Three important discoveries that alter the classical picture:

1. Einstein's energy-mass equivalence: $E = mc^2$
2. Heisenberg's Uncertainty principle: $\Delta E \Delta t \geq \hbar/2$
3. **Existence of positron** : Dirac predicts negative electron energy states (1928), Anderson discovered positron in 1932


PAM Dirac

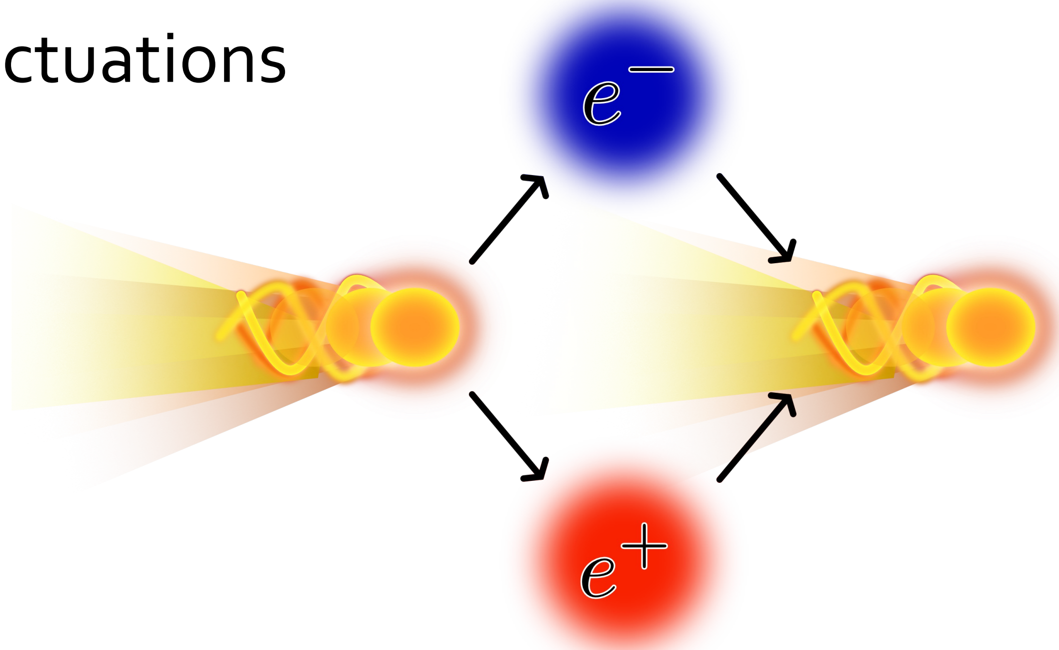

Anderson

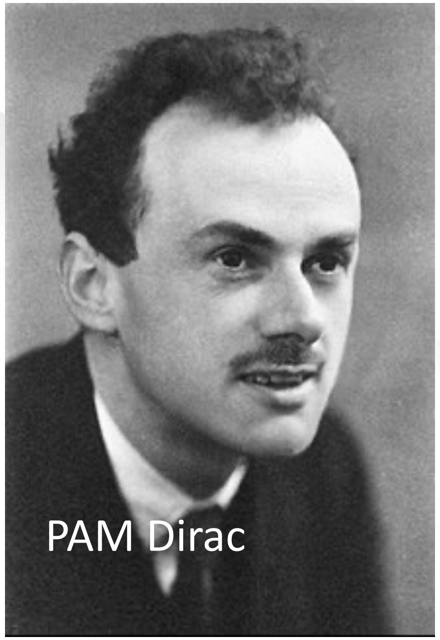
# Quantum Electrodynamics

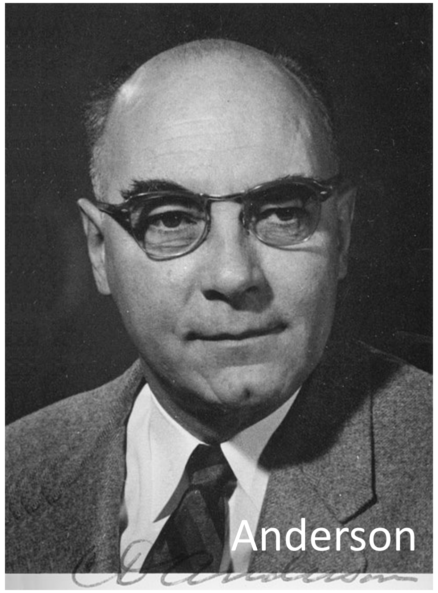
Three important discoveries that alter the classical picture:

1. Einstein's energy-mass equivalence: $E = mc^2$
2. Heisenberg's Uncertainty principle: $\Delta E \Delta t \geq \hbar/2$
3. Existence of positron : Dirac predicts negative electron energy states (1928), Anderson discovered positron in 1932

→ Vacuum fluctuations




PAM Dirac


Anderson

# Fundamental Interactions : light & matter

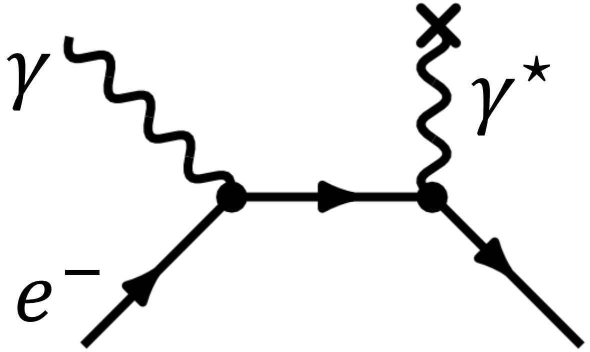
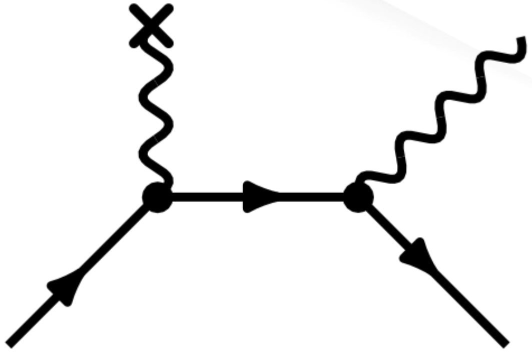
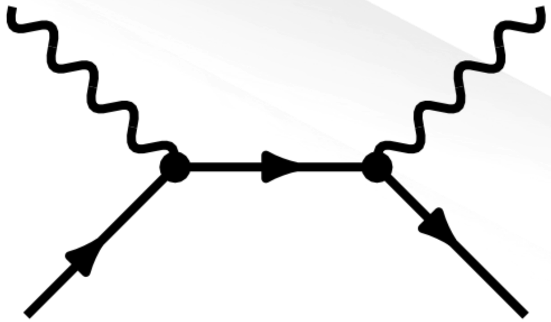


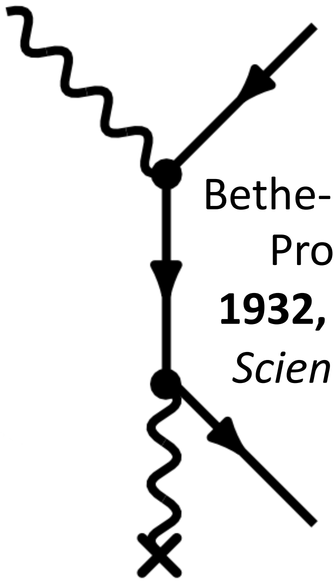
Photo Electric Effect
**1887** *Hertz, Ann Phys (Leipzig) 31, 983*



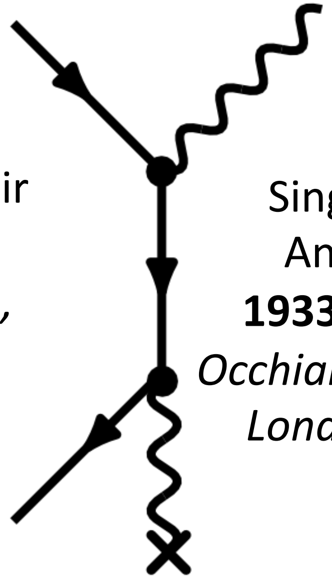
Bremsstrahlung
**1895** *Röntgen, Ann Phys (Leipzig) 300, 1*



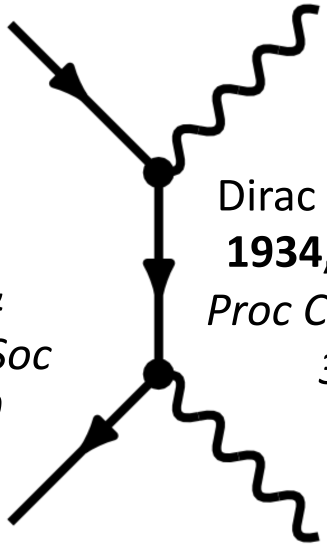
Compton Scattering
**1906** *Thomson, Conduction of Electricity through Gases*



Bethe-Heitler Pair Production
**1932,** *Anderson, Science 76,238*



Single Photon Annihilation
**1933,** *Blackett & Occhialini, Proc R Soc Lond A 139, 699*



Dirac Annihilation
**1934,** *Klemperer, Proc Camb Phil Soc 30, 347*

# Fundamental Interactions : light & matter

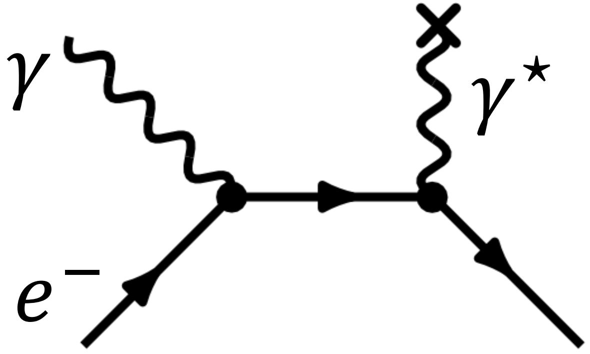
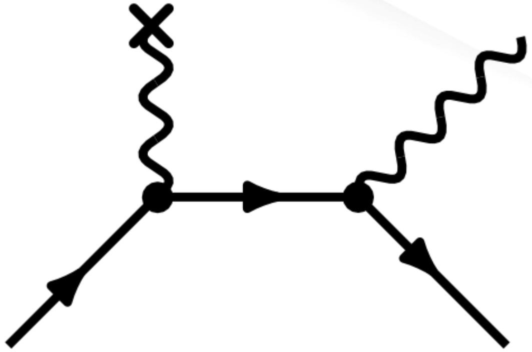
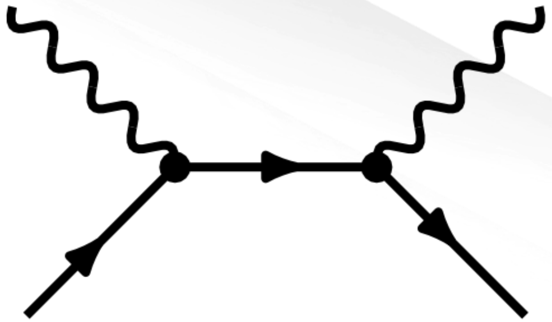


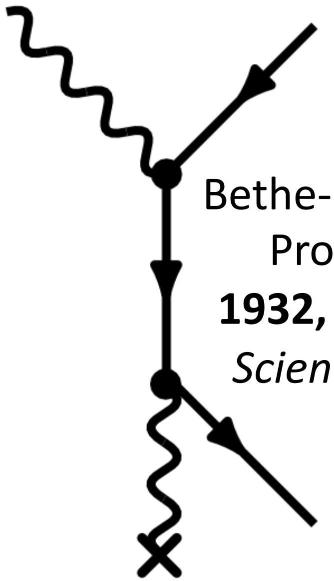
Photo Electric Effect
**1887** *Hertz, Ann Phys (Leipzig) 31, 983*



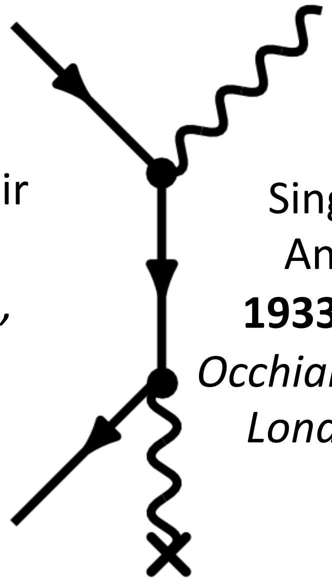
Bremsstrahlung
**1895** *Röntgen, Ann Phys (Leipzig) 300, 1*



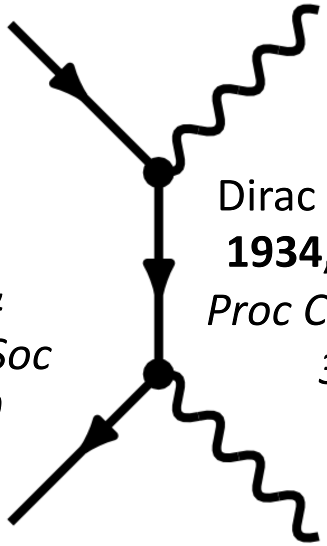
Compton Scattering
**1906** *Thomson, Conduction of Electricity through Gases*



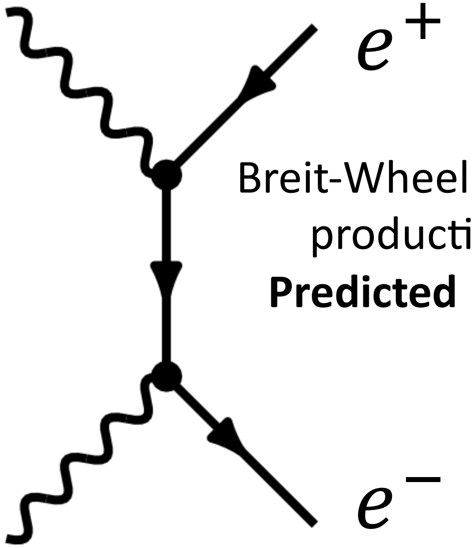
Bethe-Heitler Pair Production
**1932,** *Anderson, Science 76,238*



Single Photon Annihilation
**1933,** *Blackett & Occhialini, Proc R Soc Lond A 139, 699*



Dirac Annihilation
**1934,** *Klemperer, Proc Camb Phil Soc 30, 347*



Breit-Wheeler pair production
**Predicted 1934**

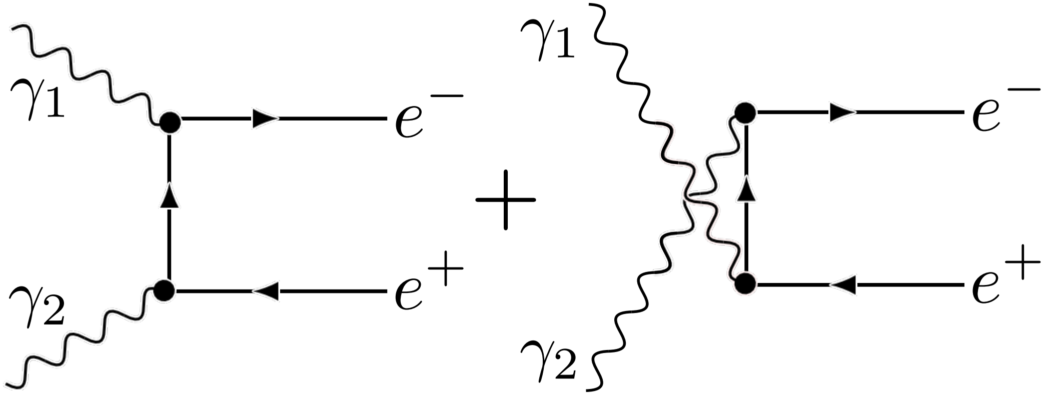
# The Breit-Wheeler Process

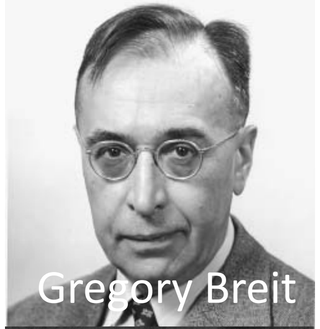
DECEMBER 15, 1934 PHYSICAL REVIEW VOLUME 46

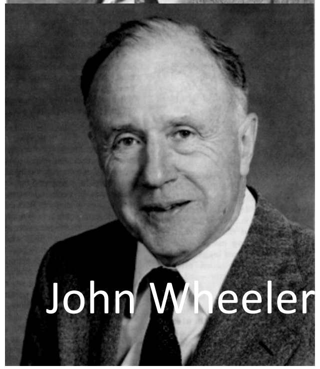
## Collision of Two Light Quanta

G. BREIT* AND JOHN A. WHEELER,** *Department of Physics, New York University*

(Received October 23, 1934)



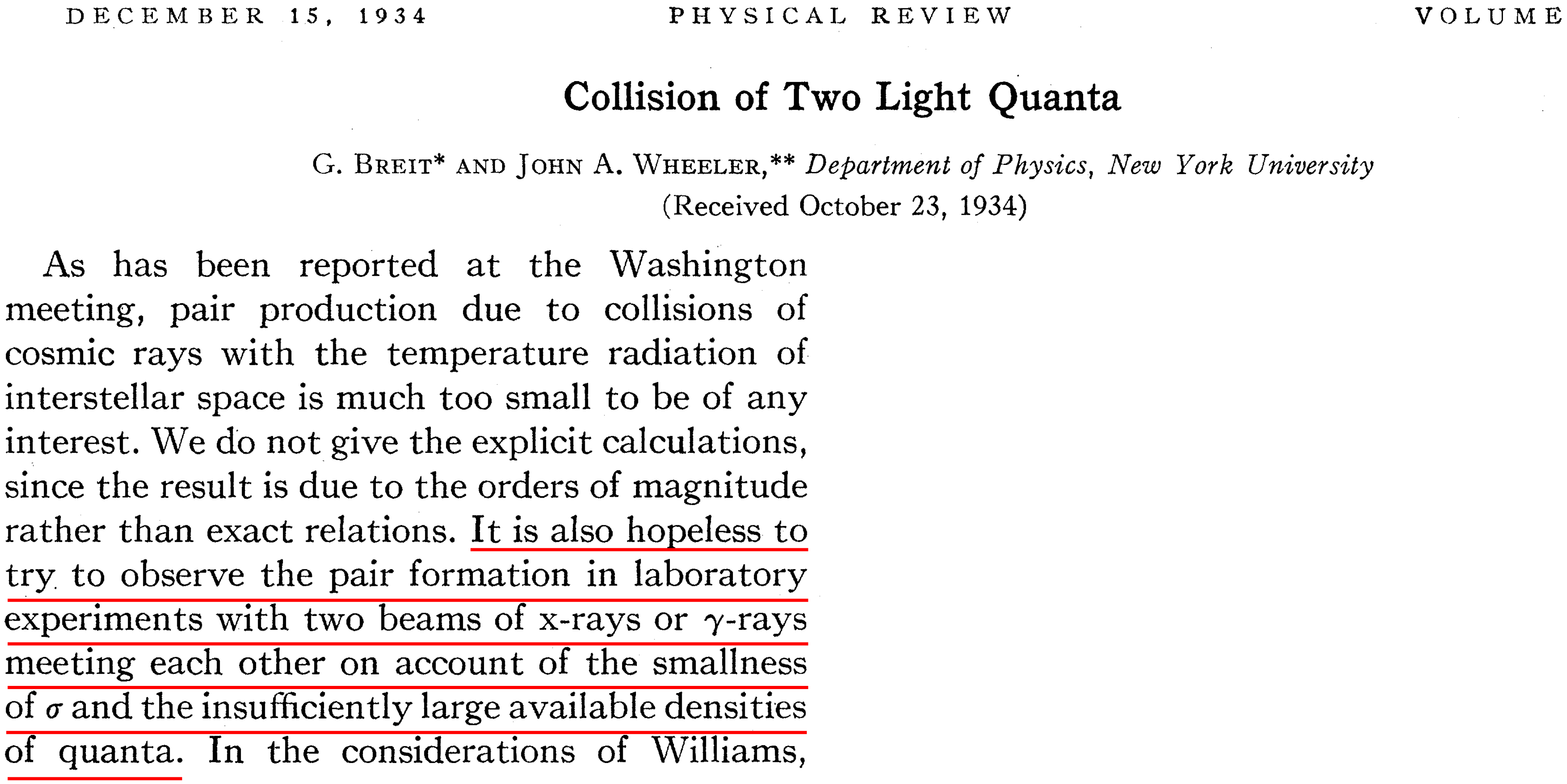




- Non-linear effect forbidden in classical electromagnetism
- At lowest order, two Feynman diagrams contribute and interfere
- Breit-Wheeler process: real photon collisions → important distinction
- Only tree level process still not observed observed after 80+ years!

# Breit-Wheeler Process, why so *elusive?*

- Already in 1934 Breit and Wheeler knew it was hard, maybe impossible?



DECEMBER 15, 1934 PHYSICAL REVIEW VOLUME

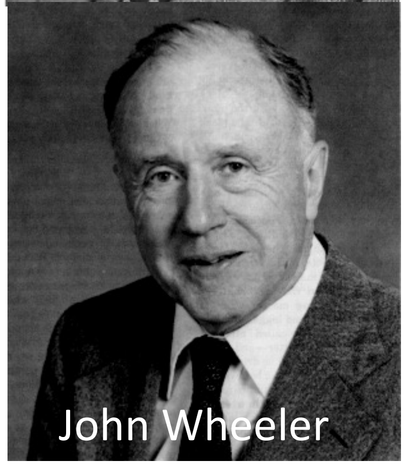
### Collision of Two Light Quanta

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

(Received October 23, 1934)

As has been reported at the Washington meeting, pair production due to collisions of cosmic rays with the temperature radiation of interstellar space is much too small to be of any interest. We do not give the explicit calculations, since the result is due to the orders of magnitude rather than exact relations. It is also hopeless to try to observe the pair formation in laboratory experiments with two beams of x-rays or $\gamma$-rays meeting each other on account of the smallness of $\sigma$ and the insufficiently large available densities of quanta. In the considerations of Williams,

Gregory Breit

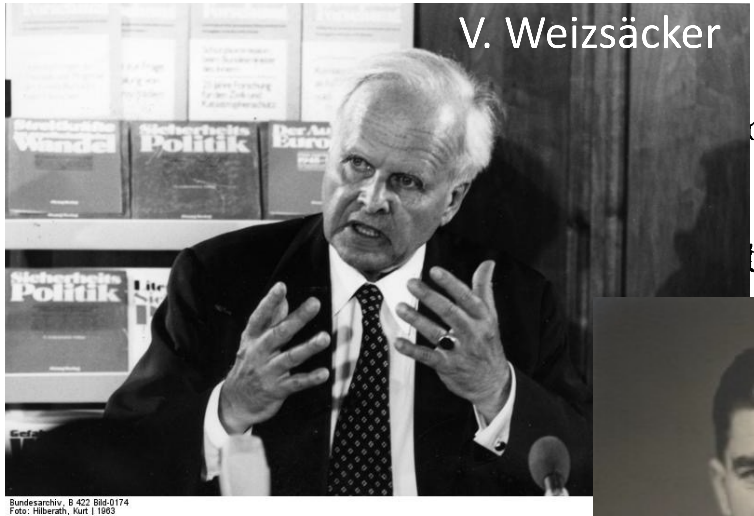


John Wheeler

# Breit-Wheeler Process, why so *elusive?*

- ○ Already in 1934 Breit and Wheeler knew it was hard, maybe impossible?

DECEMBER 15, 1934 PHYSICAL REVIEW VOLUME

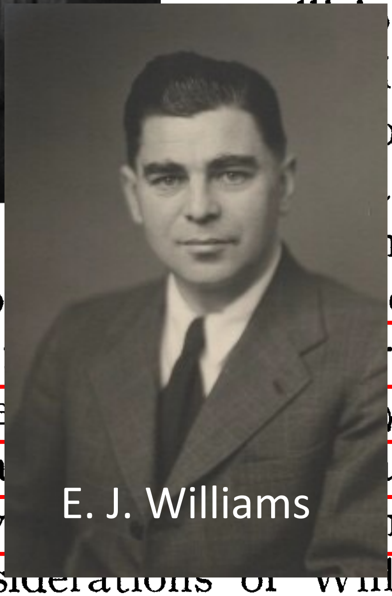

V. Weizsäcker

Bundesarchiv, B 422 Bild-0174
Foto: Hilberath, Kurt | 1963

## Collision of Two Light Quanta

OHN A. WHEELER,** *Department of Physics, New York University*

(Received October 23, 1934)


E. J. Williams

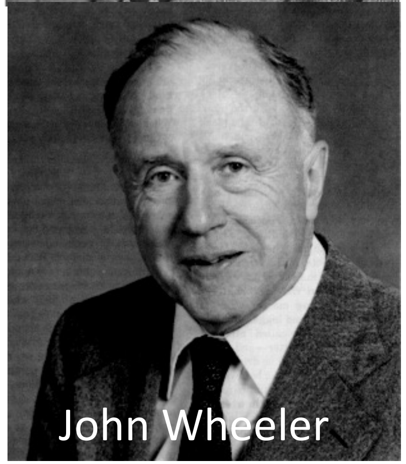
the Washington
ns of
on of
f any
tions,
since the result is due to … itude
rather than exact relatio… ess to
try to observe the pair … atory
experiments with two be… -rays
meeting each other on a… llness
of σ and the insufficiently… sities
of quanta. In the consi… Williams,

- ○ Or maybe not impossible!

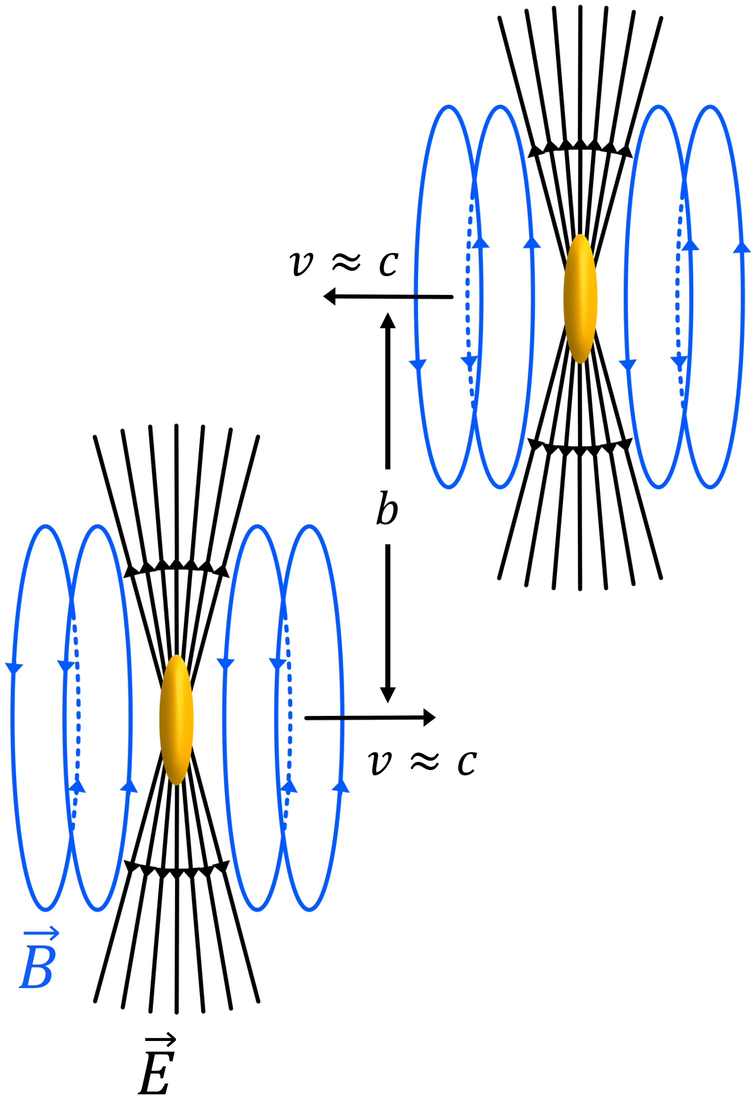
of quanta. In the considerations of Williams, however, the large nuclear electric fields lead to large densities of quanta in moving frames of reference. This, together with the large number of nucleii available in unit volume of ordinary materials, increases the effect to observable amounts. Analyzing the field of the nucleus into quanta by a procedure similar to that of v. Weizsäcker,[4] he finds that if one quantum $h\nu$

E. J. Williams Phys. Rev. **45**, 729 (1934)
K. F. Weizsacker, Z. Physik , 612 (1934)


Gregory Breit


John Wheeler

# 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

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

$Z\alpha \approx 1$ → High photon density

Ultra-strong electric and magnetic fields:

→ Expected magnetic field strength $\vec{\mathbf{B}} \approx \mathbf{10^{14} - 10^{16}}$ **T**

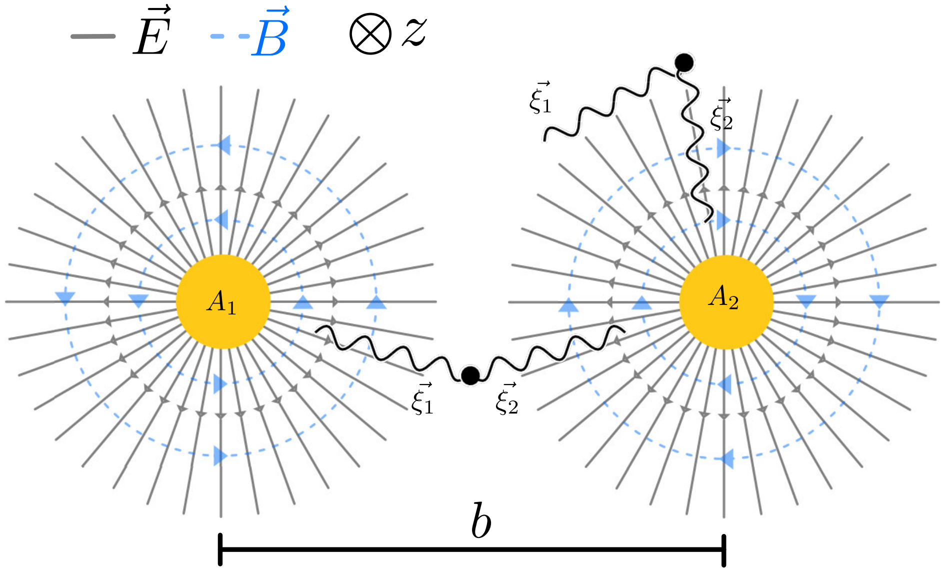
Skokov, V., et. al. *Int. J. Mod. Phys. A* 24 (2009): 5925–32

## 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).

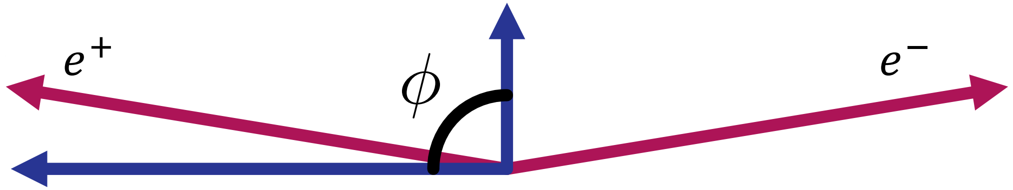
Light–by–Light scattering: ATLAS, Phys. Rev. Lett. 123, 052001 (2019)

# Polarization in 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:

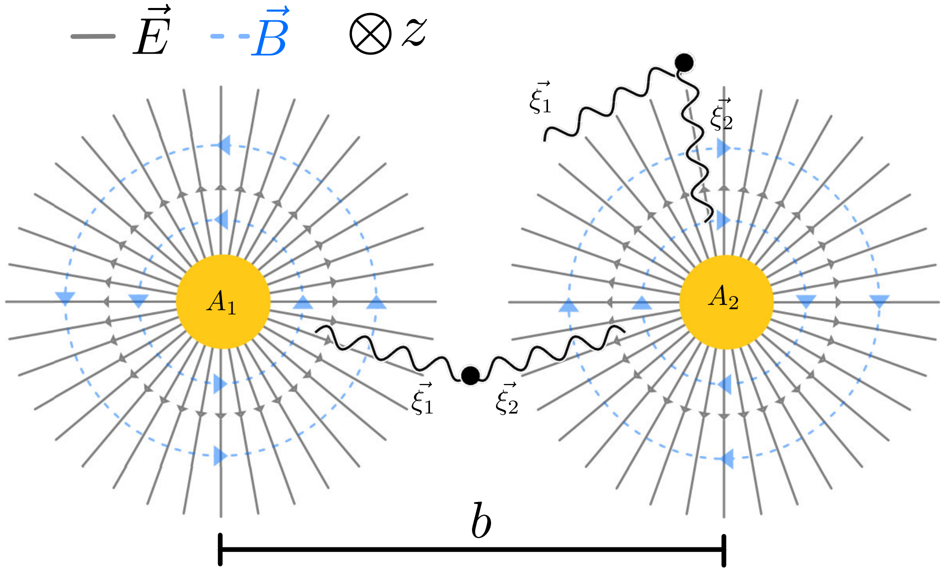
$$\rho^{a,a'} = \begin{pmatrix} \rho^{++} & \rho^{+0} & \rho^{+-} \\ \rho^{+0} & \rho^{00} & \rho^{+0} \\ \rho^{+-} & \rho^{+0} & \rho^{++} \end{pmatrix}$$

Spin 1 Photon helicity $a$ = $(-, 0, +)$

Helicity 0 : Forbidden for real photon

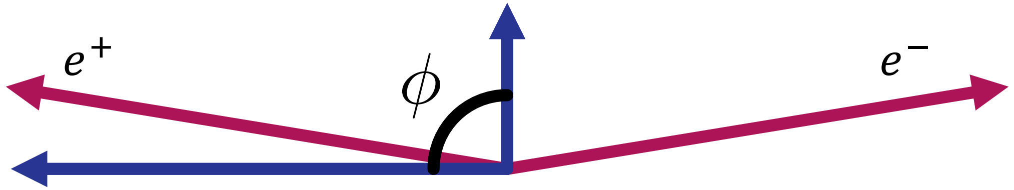
**Real photon: Allowed $J^P$ states: $2^{\pm}, 0^{\pm}$**

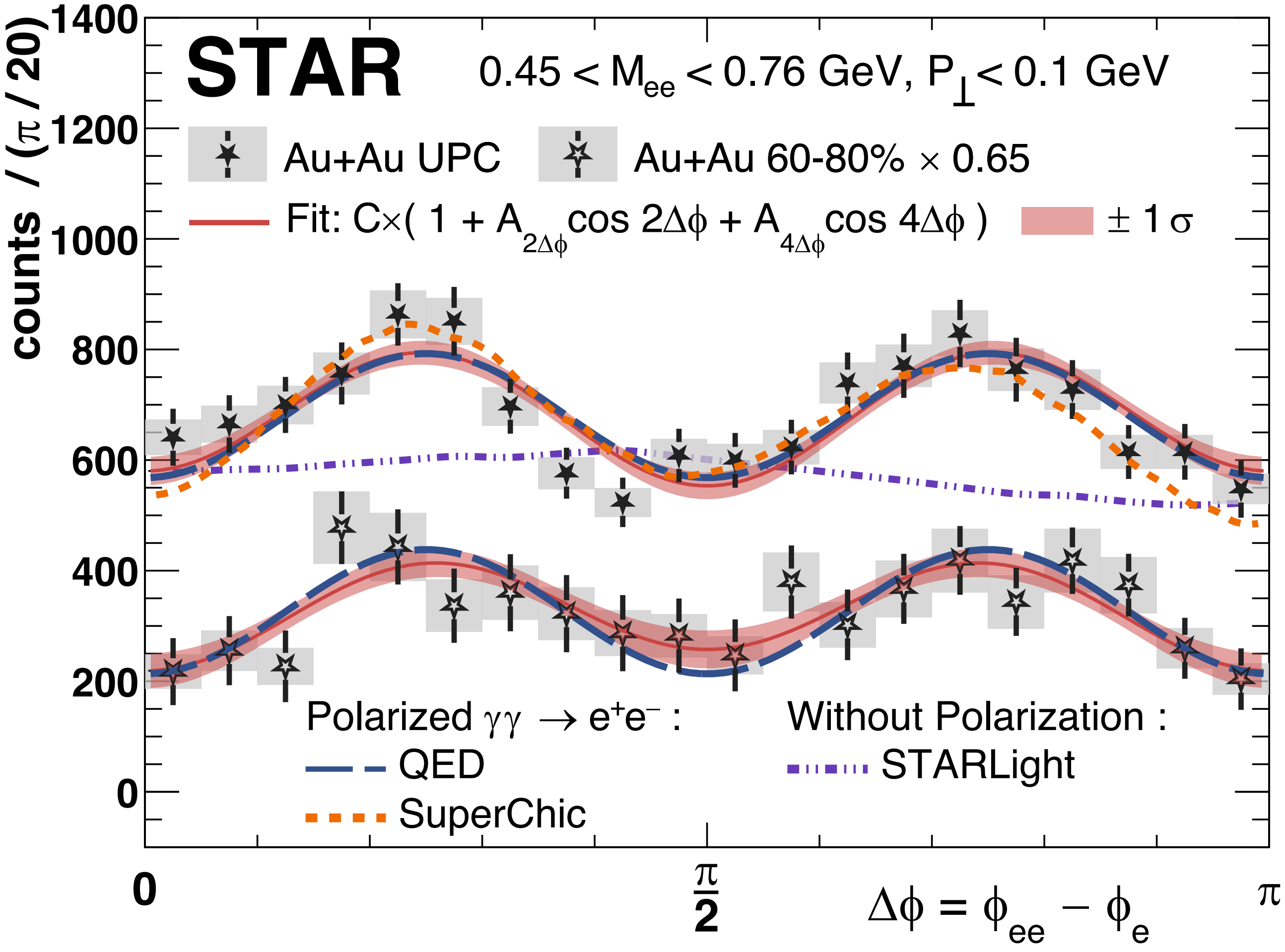
# Access to Photon Polarization Proven!



- 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**





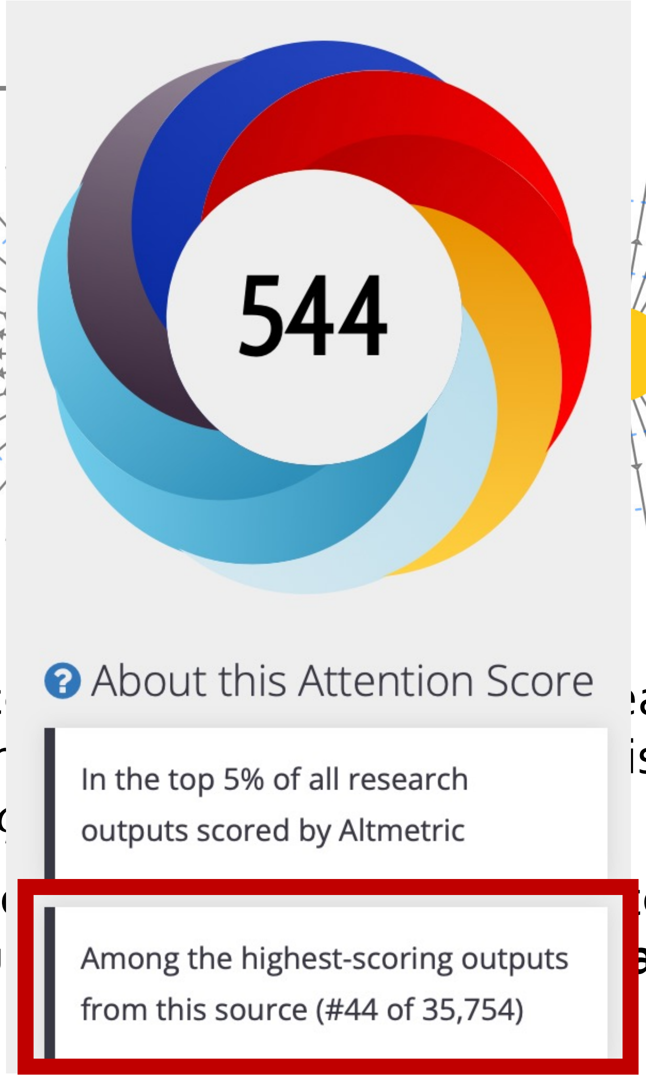
STAR Collaboration, Phys. Rev. Lett. **127**, 052302 (2021).

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

# Access to Photon Polarization Proven!

- The inc ads to
  vacuum isible as
  a cos 4

⇒ Precisi on
wavefu arization



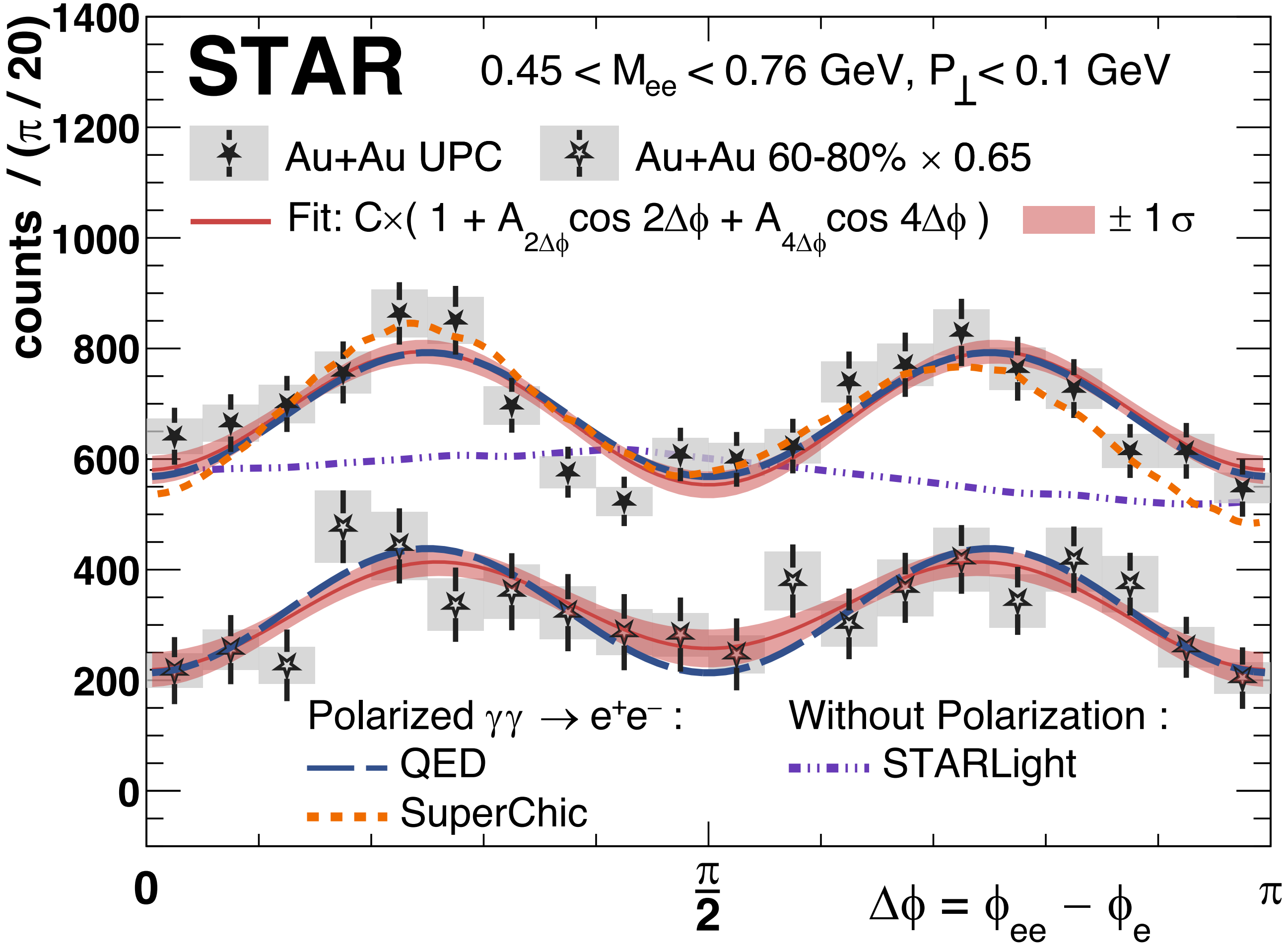
544

About this Attention Score

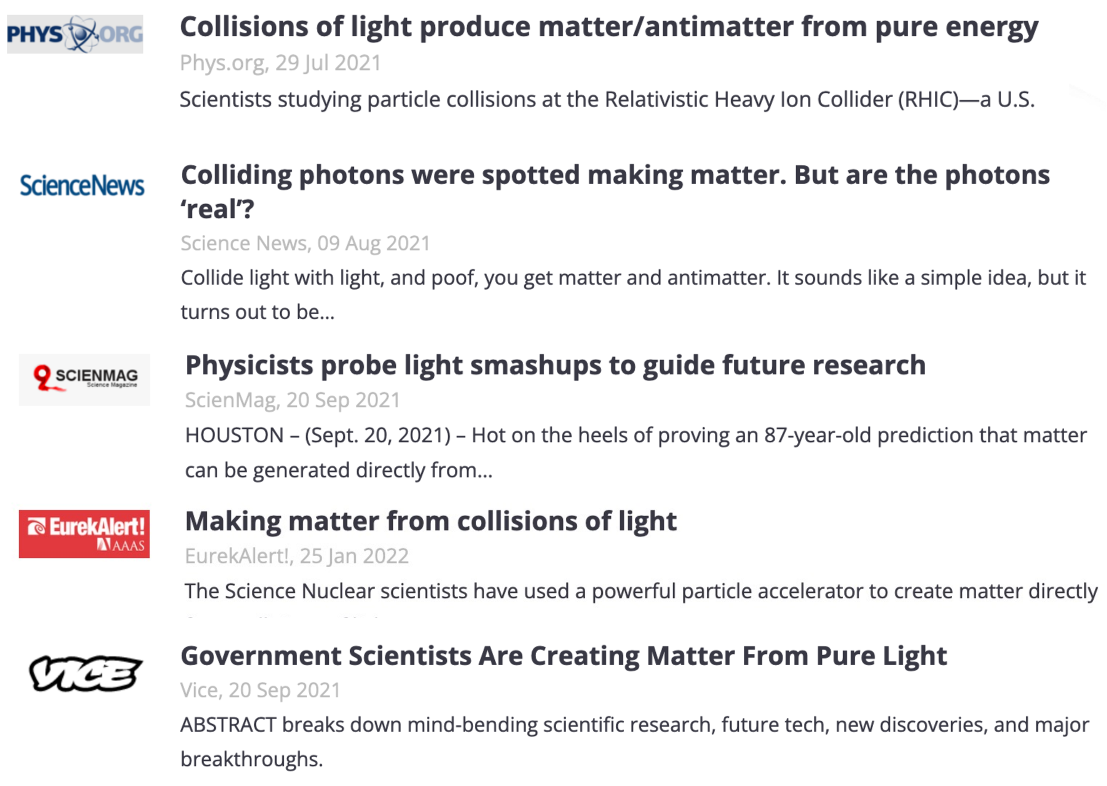
In the top 5% of all research outputs scored by Altmetric

Among the highest-scoring outputs from this source (#44 of 35,754)

Highest press coverage of any paper in high energy nuclear physics



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



**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

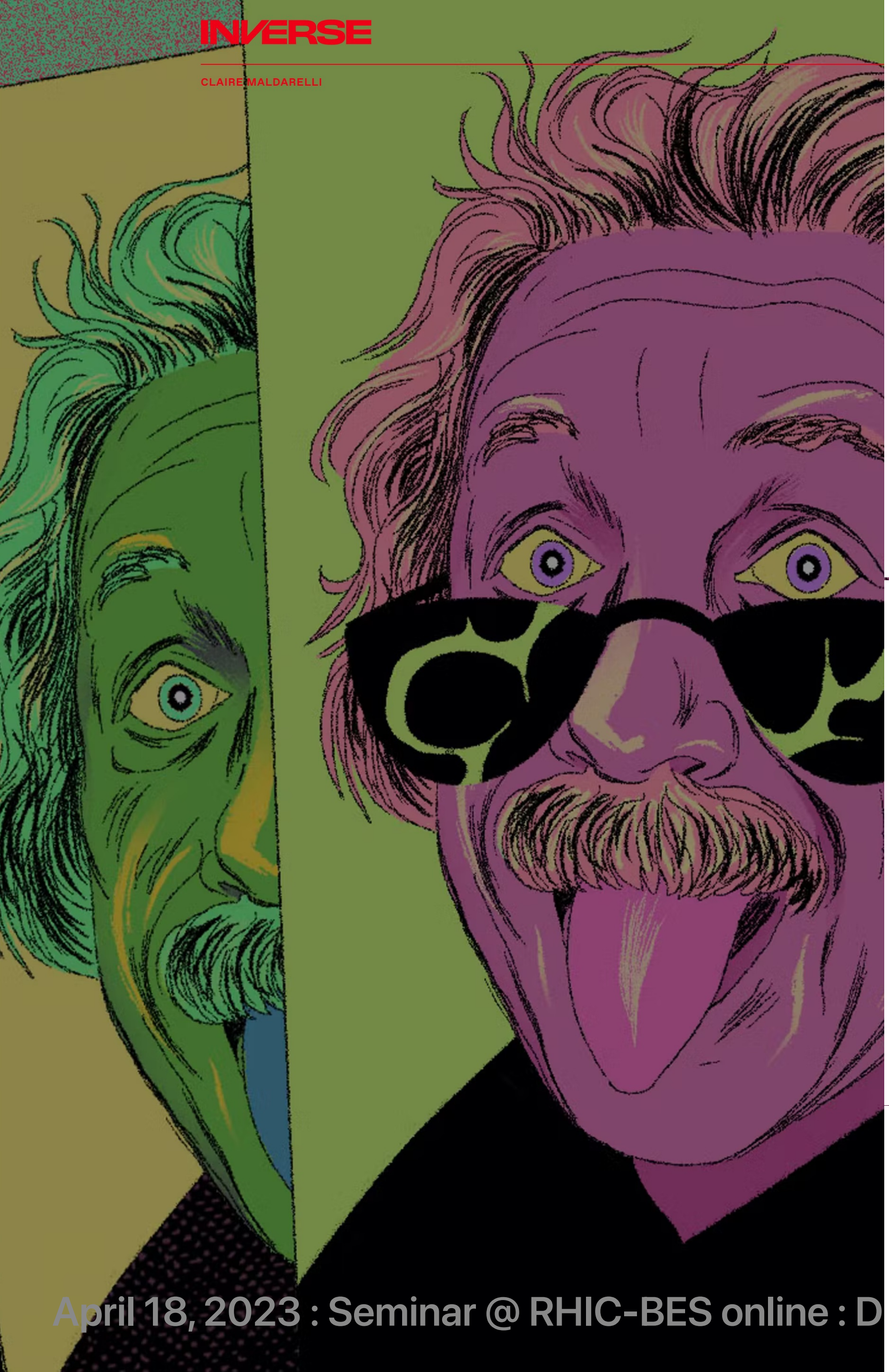
**Government Scientists Are Creating Matter From Pure Light**
Vice, 20 Sep 2021
ABSTRACT breaks down mind-bending scientific research, future tech, new discoveries, and major breakthroughs.

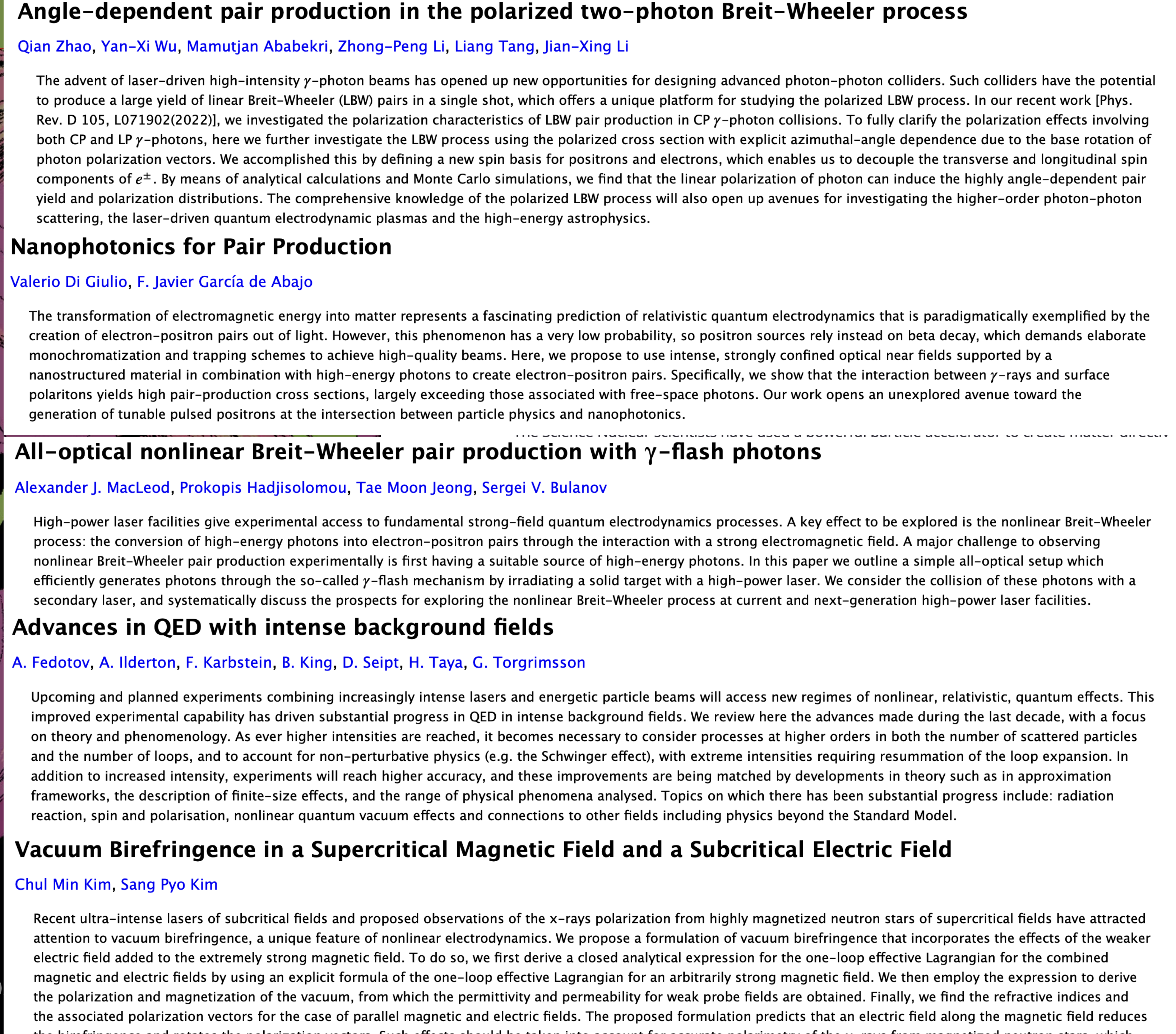
EINSTEIN WEEK

# 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





## Angle-dependent pair production in the polarized two-photon Breit-Wheeler process

Qian Zhao, Yan-Xi Wu, Mamutjan Ababekri, Zhong-Peng Li, Liang Tang, Jian-Xing Li

The advent of laser-driven high-intensity $\gamma$-photon beams has opened up new opportunities for designing advanced photon-photon colliders. Such colliders have the potential to produce a large yield of linear Breit-Wheeler (LBW) pairs in a single shot, which offers a unique platform for studying the polarized LBW process. In our recent work [Phys. Rev. D 105, L071902(2022)], we investigated the polarization characteristics of LBW pair production in CP $\gamma$-photon collisions. To fully clarify the polarization effects involving both CP and LP $\gamma$-photons, here we further investigate the LBW process using the polarized cross section with explicit azimuthal-angle dependence due to the base rotation of photon polarization vectors. We accomplished this by defining a new spin basis for positrons and electrons, which enables us to decouple the transverse and longitudinal spin components of $e^{\pm}$. By means of analytical calculations and Monte Carlo simulations, we find that the linear polarization of photon can induce the highly angle-dependent pair yield and polarization distributions. The comprehensive knowledge of the polarized LBW process will also open up avenues for investigating the higher-order photon-photon scattering, the laser-driven quantum electrodynamic plasmas and the high-energy astrophysics.

## Nanophotonics for Pair Production

Valerio Di Giulio, F. Javier García de Abajo

The transformation of electromagnetic energy into matter represents a fascinating prediction of relativistic quantum electrodynamics that is paradigmatically exemplified by the creation of electron-positron pairs out of light. However, this phenomenon has a very low probability, so positron sources rely instead on beta decay, which demands elaborate monochromatization and trapping schemes to achieve high-quality beams. Here, we propose to use intense, strongly confined optical near fields supported by a nanostructured material in combination with high-energy photons to create electron-positron pairs. Specifically, we show that the interaction between $\gamma$-rays and surface polaritons yields high pair-production cross sections, largely exceeding those associated with free-space photons. Our work opens an unexplored avenue toward the generation of tunable pulsed positrons at the intersection between particle physics and nanophotonics.

## All-optical nonlinear Breit-Wheeler pair production with $\gamma$-flash photons

Alexander J. MacLeod, Prokopis Hadjisolomou, Tae Moon Jeong, Sergei V. Bulanov

High-power laser facilities give experimental access to fundamental strong-field quantum electrodynamics processes. A key effect to be explored is the nonlinear Breit-Wheeler process: the conversion of high-energy photons into electron-positron pairs through the interaction with a strong electromagnetic field. A major challenge to observing nonlinear Breit-Wheeler pair production experimentally is first having a suitable source of high-energy photons. In this paper we outline a simple all-optical setup which efficiently generates photons through the so-called $\gamma$-flash mechanism by irradiating a solid target with a high-power laser. We consider the collision of these photons with a secondary laser, and systematically discuss the prospects for exploring the nonlinear Breit-Wheeler process at current and next-generation high-power laser facilities.

## Advances in QED with intense background fields

A. Fedotov, A. Ilderton, F. Karbstein, B. King, D. Seipt, H. Taya, G. Torgrimsson

Upcoming and planned experiments combining increasingly intense lasers and energetic particle beams will access new regimes of nonlinear, relativistic, quantum effects. This improved experimental capability has driven substantial progress in QED in intense background fields. We review here the advances made during the last decade, with a focus on theory and phenomenology. As ever higher intensities are reached, it becomes necessary to consider processes at higher orders in both the number of scattered particles and the number of loops, and to account for non-perturbative physics (e.g. the Schwinger effect), with extreme intensities requiring resummation of the loop expansion. In addition to increased intensity, experiments will reach higher accuracy, and these improvements are being matched by developments in theory such as in approximation frameworks, the description of finite-size effects, and the range of physical phenomena analysed. Topics on which there has been substantial progress include: radiation reaction, spin and polarisation, nonlinear quantum vacuum effects and connections to other fields including physics beyond the Standard Model.

## Vacuum Birefringence in a Supercritical Magnetic Field and a Subcritical Electric Field

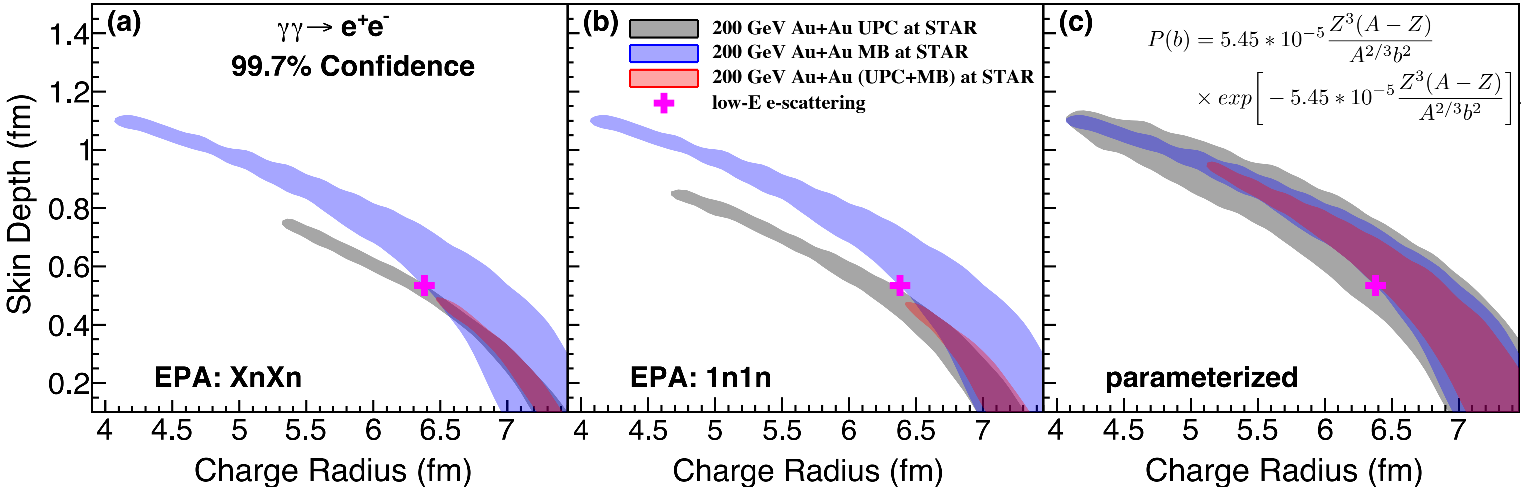
Chul Min Kim, Sang Pyo Kim

Recent ultra-intense lasers of subcritical fields and proposed observations of the x-rays polarization from highly magnetized neutron stars of supercritical fields have attracted attention to vacuum birefringence, a unique feature of nonlinear electrodynamics. We propose a formulation of vacuum birefringence that incorporates the effects of the weaker electric field added to the extremely strong magnetic field. To do so, we first derive a closed analytical expression for the one-loop effective Lagrangian for the combined magnetic and electric fields by using an explicit formula of the one-loop effective Lagrangian for an arbitrarily strong magnetic field. We then employ the expression to derive the polarization and magnetization of the vacuum, from which the permittivity and permeability for weak probe fields are obtained. Finally, we find the refractive indices and the associated polarization vectors for the case of parallel magnetic and electric fields. The proposed formulation predicts that an electric field along the magnetic field reduces

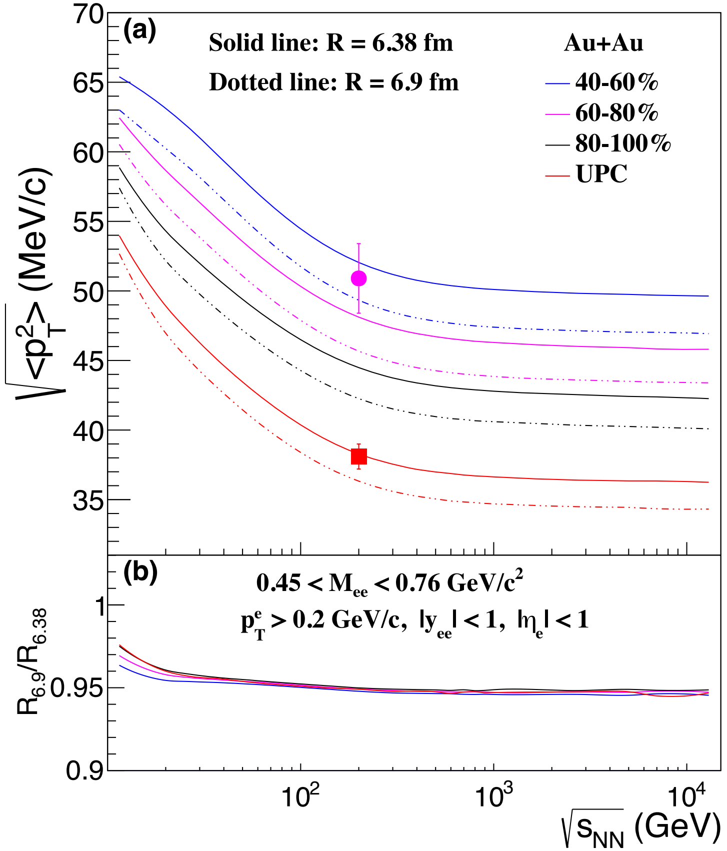
# Energy Dependence & Application

Xiaofeng Wang

- Breit-Wheeler process in HICs –sensitive to EM field configuration
- Extract the in-situ charge distribution of colliding heavy-nuclei



- Probe the low-x electromagnetic field

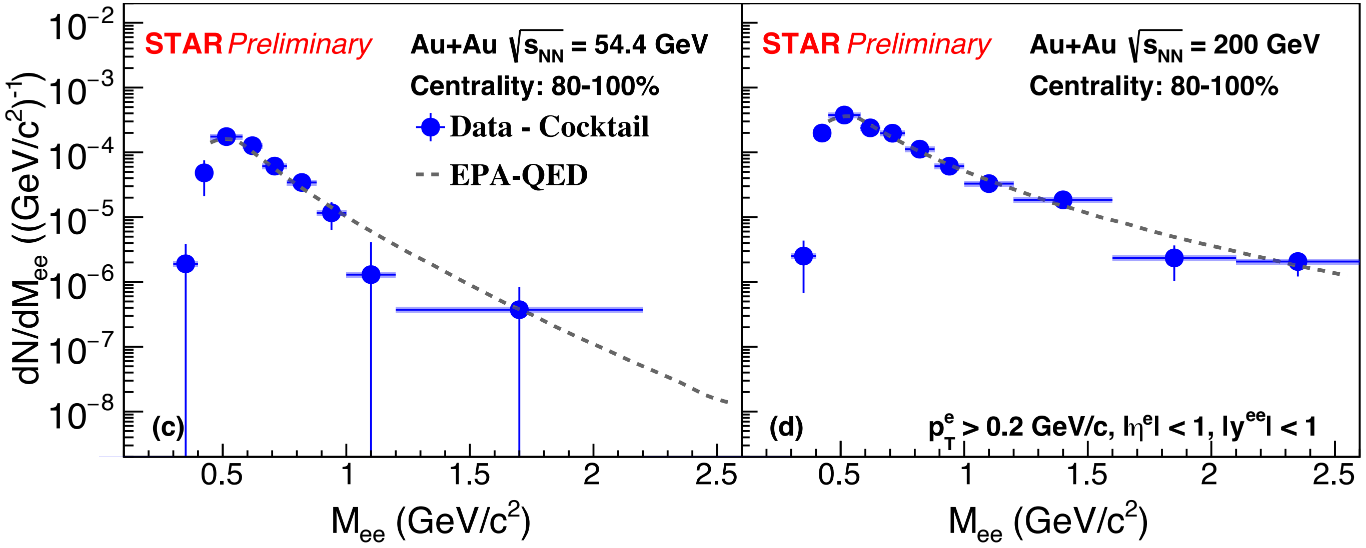


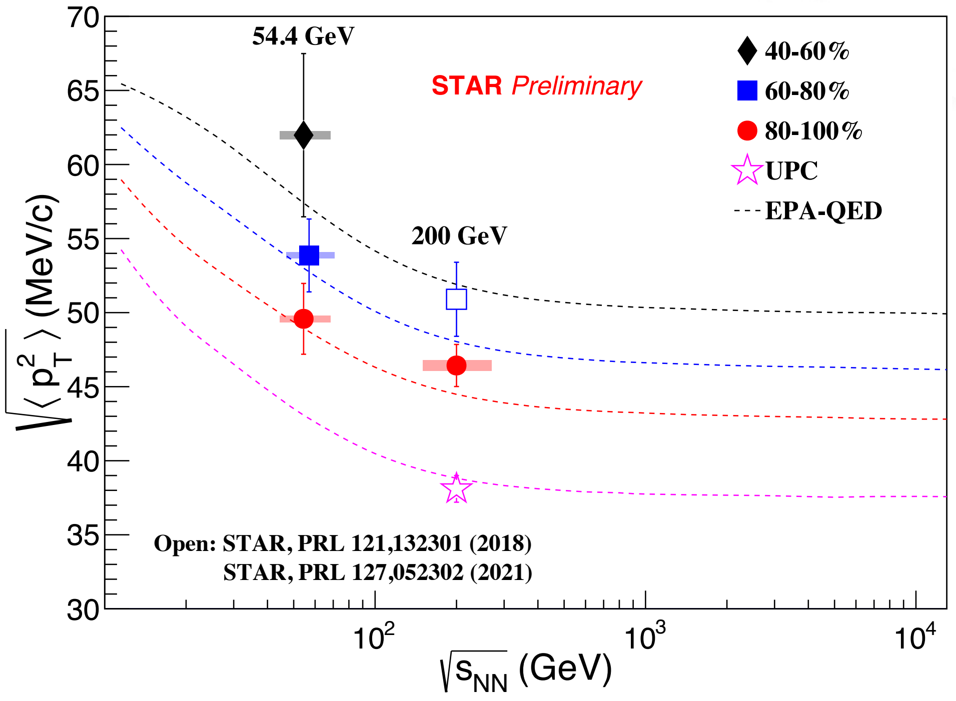
arXiv:2207.05595, Accepted by PRC

# Energy Dependence & Application

Xiaofeng Wang

- Breit-Wheeler process in HICs –sensitive to EM field configuration
- Extract the in-situ charge distribution of colliding heavy-nuclei



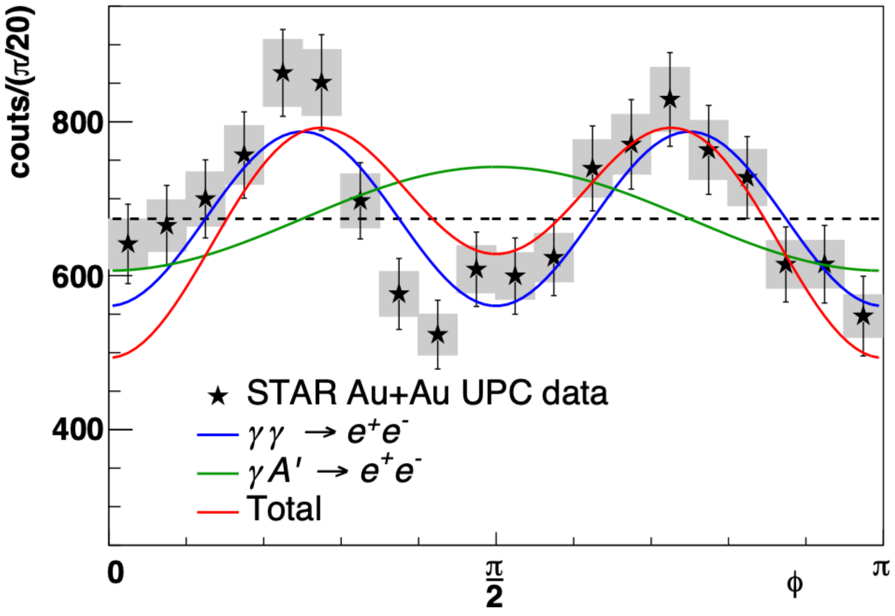


- Probe the low-x electromagnetic field
- Access energy dependence of BW process
- Hint of medium effects – increased $\langle p_T^2 \rangle$ over QED baseline

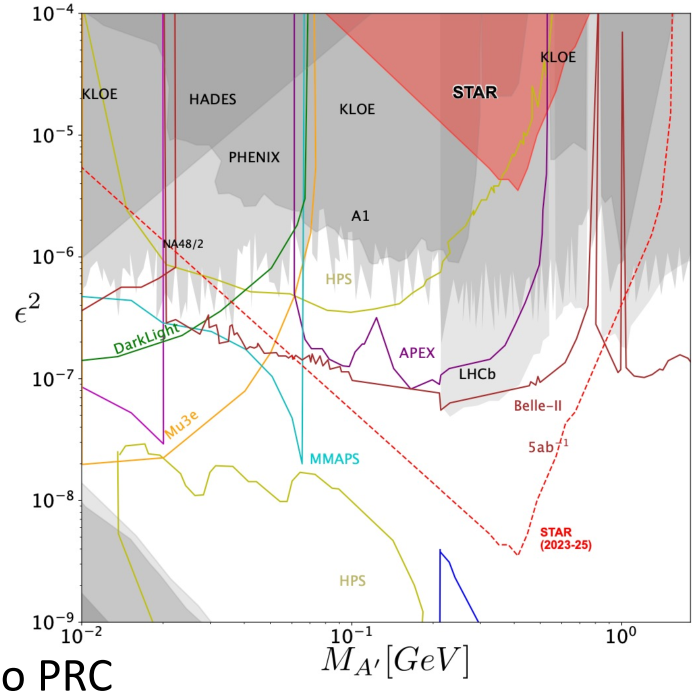
# Applications Beyond the Standard Model

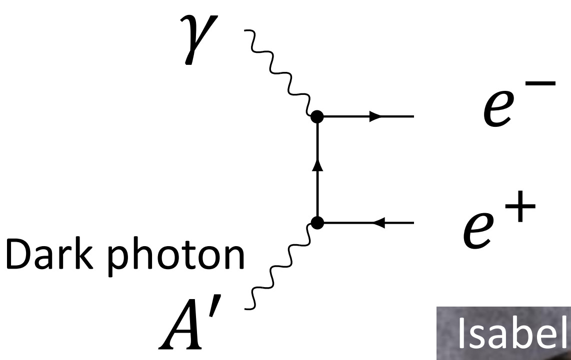
- Dark Photon search : (High School student, BNL summer research program)
- Relevant for LHC Axion search in Light-by-Light scattering
  - JDB, W. Zha, and Z. Xu, Eur. Phys. J. A 57, 299 (2021)
  - I. Xu, N. Lewis, X. Wang, JDB, I. Ruan, arXiv:2211.02132 (2023).

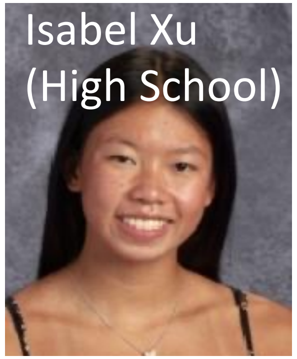
$$\rho^{a,a'} = \overset{\gamma}{\begin{pmatrix} \rho^{++} & \rho^{+0} & \rho^{+-} \\ \rho^{+0} & \rho^{00} & \rho^{+0} \\ \rho^{+-} & \rho^{+0} & \rho^{++} \end{pmatrix}}_{A'}$$



https://arxiv.org/abs/2211.02132 submitted to PRC

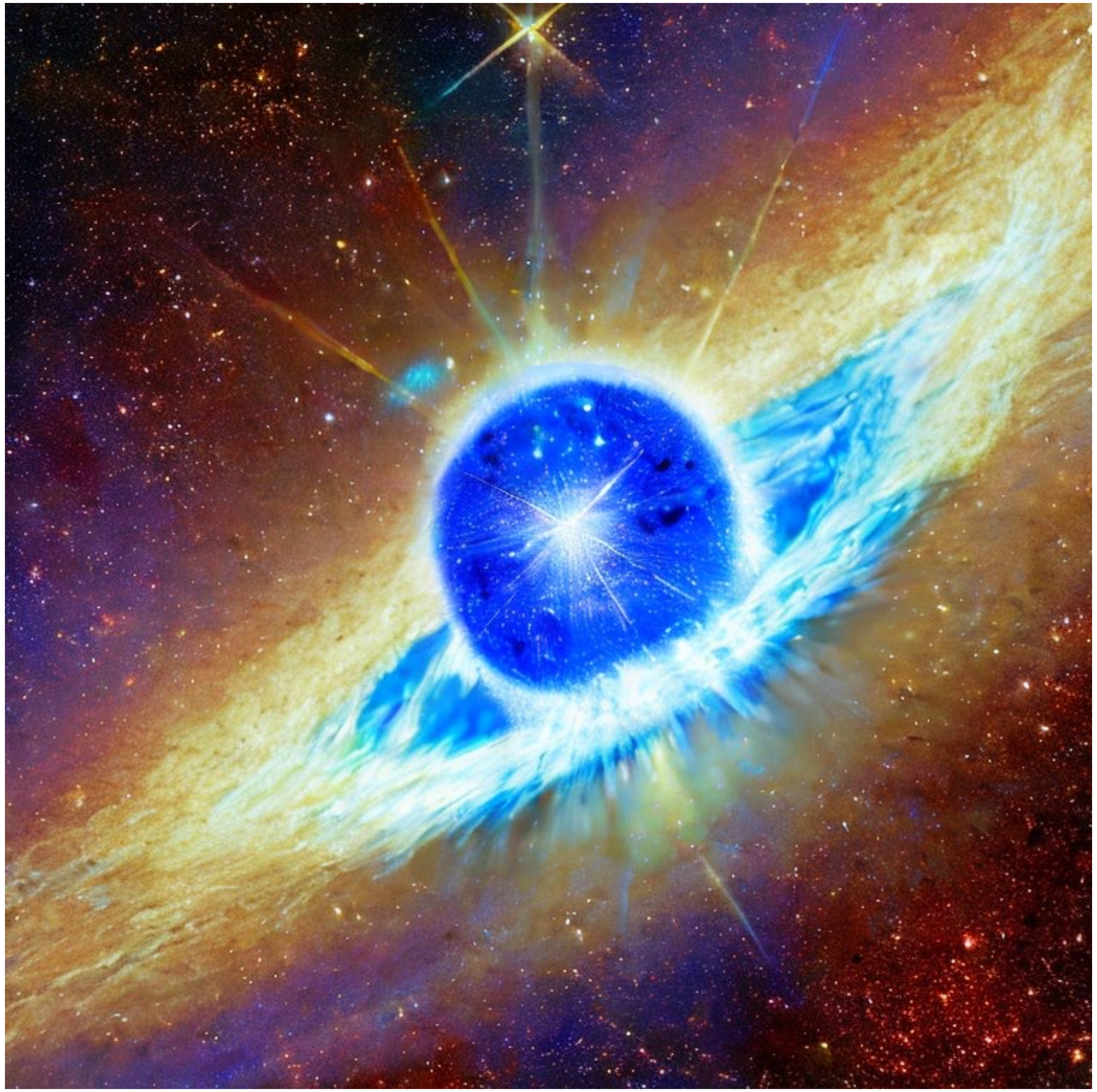





Isabel Xu
(High School)

# Quantum Chromodynamics (QCD)

# Nuclear Tomography at high energy : Motivation



## Equation of State 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

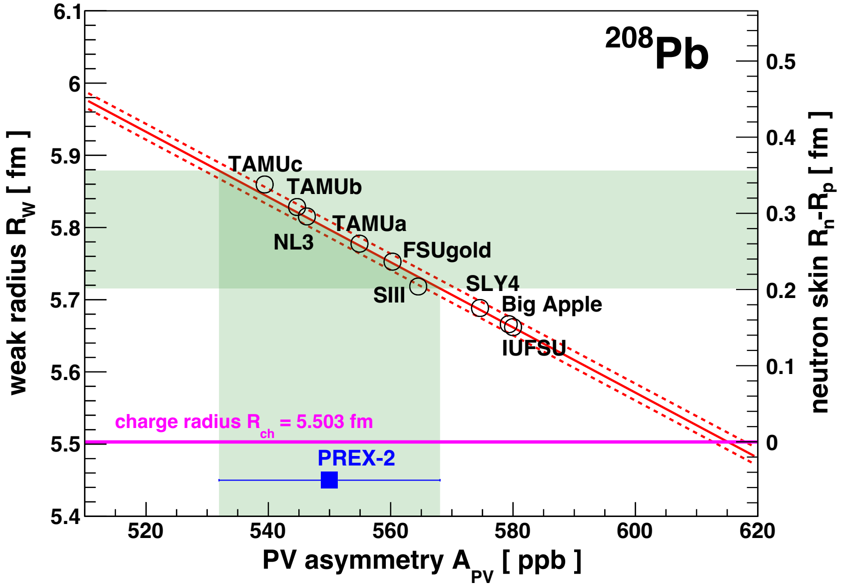
## Still open questions:

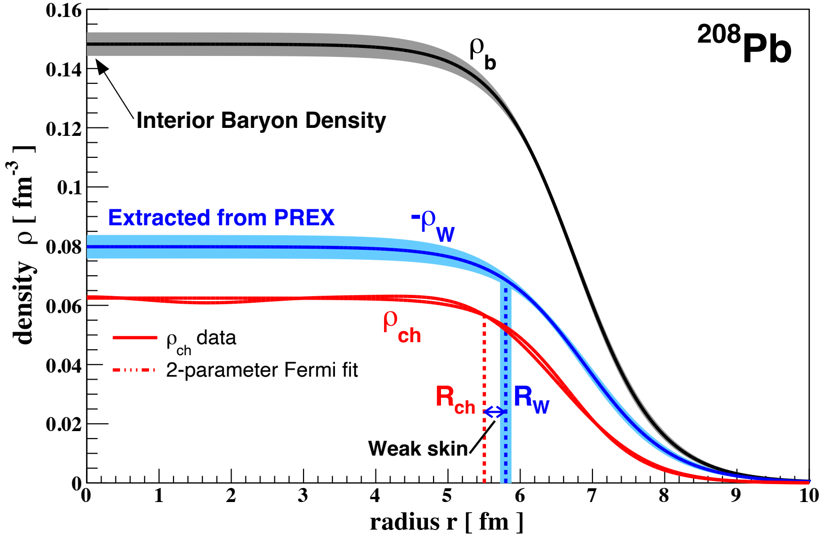
- Significant nonzero strangeness component in neutron star interior?
- Phase transition within neutron star cores?

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

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

# Nuclear Tomography at high energy : Motivation





## 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

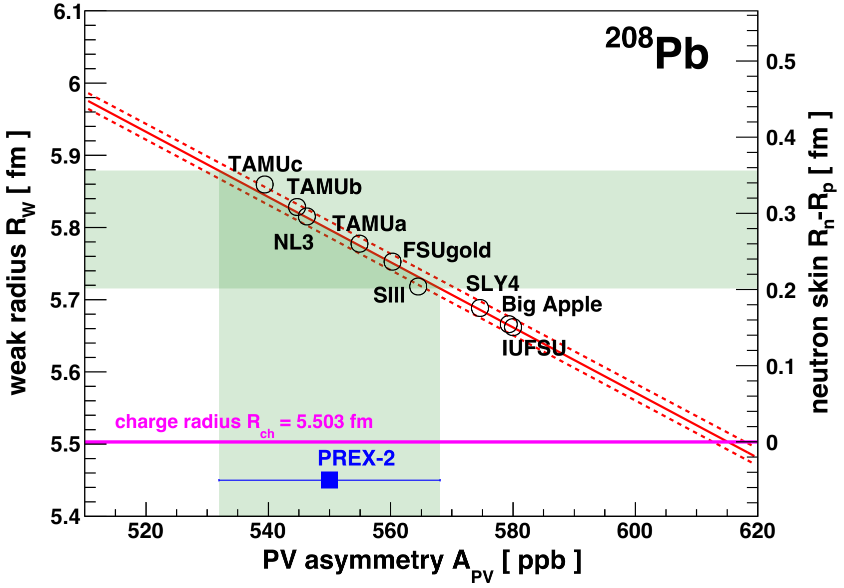
$$A_{\text{PV}} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

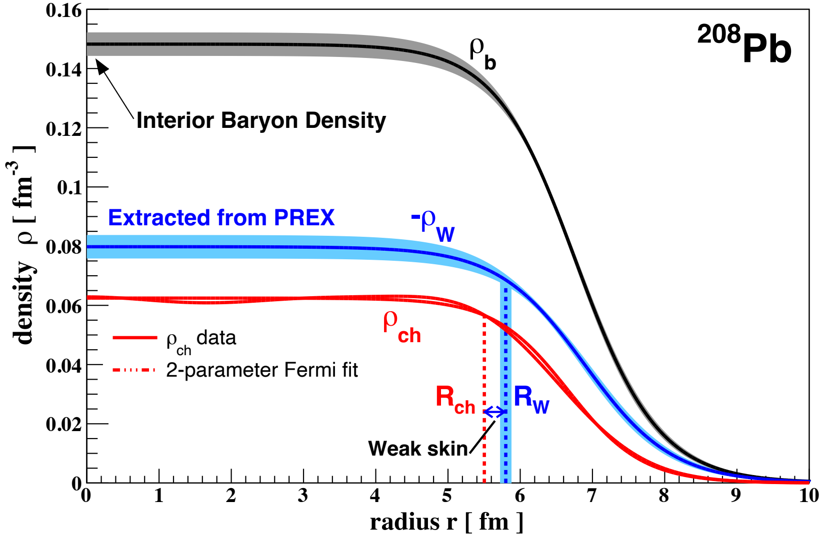
$\sigma_{\mathrm{R}}, \sigma_{\mathrm{L}}$ are the cross sections for scattering right/left handed electrons

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)

# Nuclear Tomography at high energy : Motivation





## 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

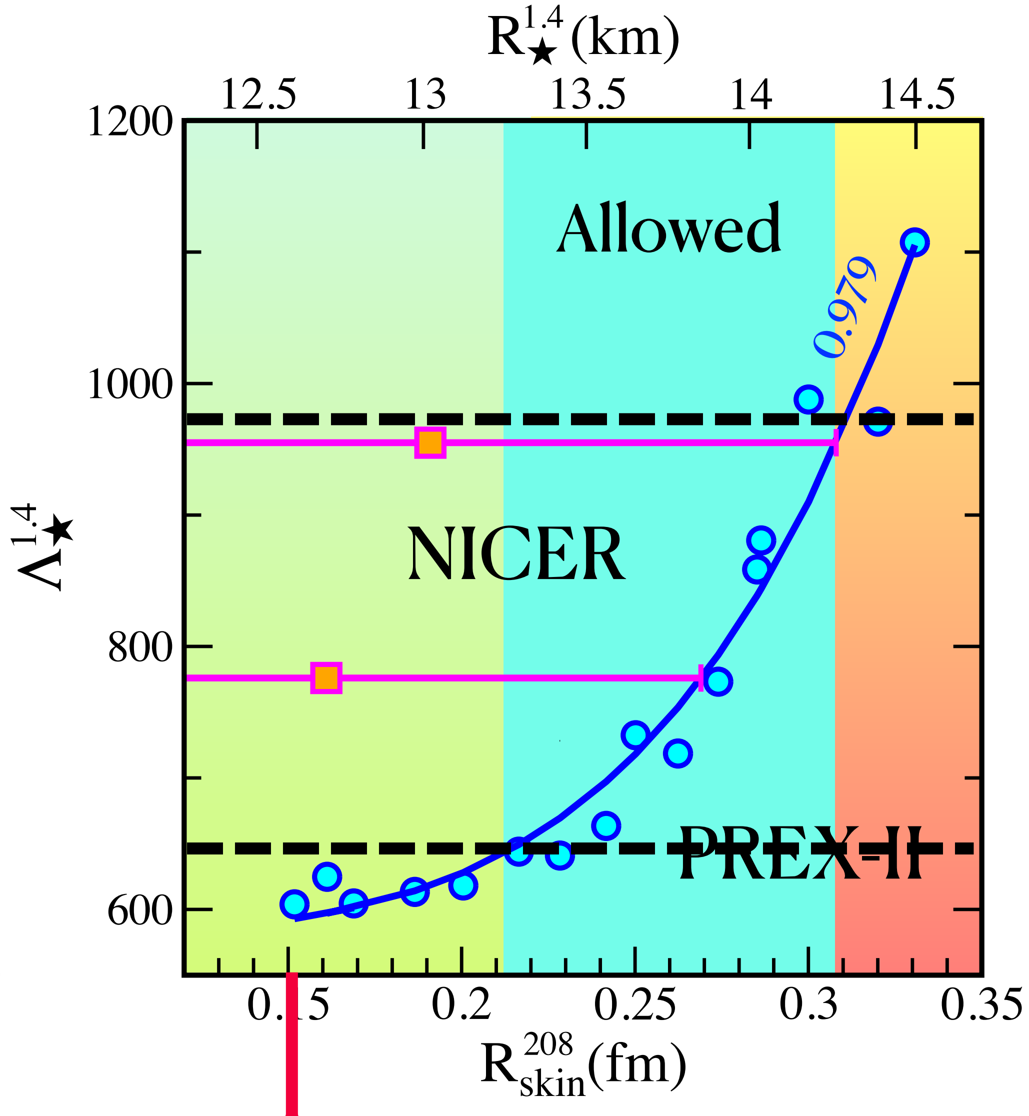
$$A_{\text{PV}} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

$\sigma_R$, $\sigma_L$ are the cross sections for scattering right/left handed electrons

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)

# Gravitational Wave Discovery & Tension



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

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

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

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

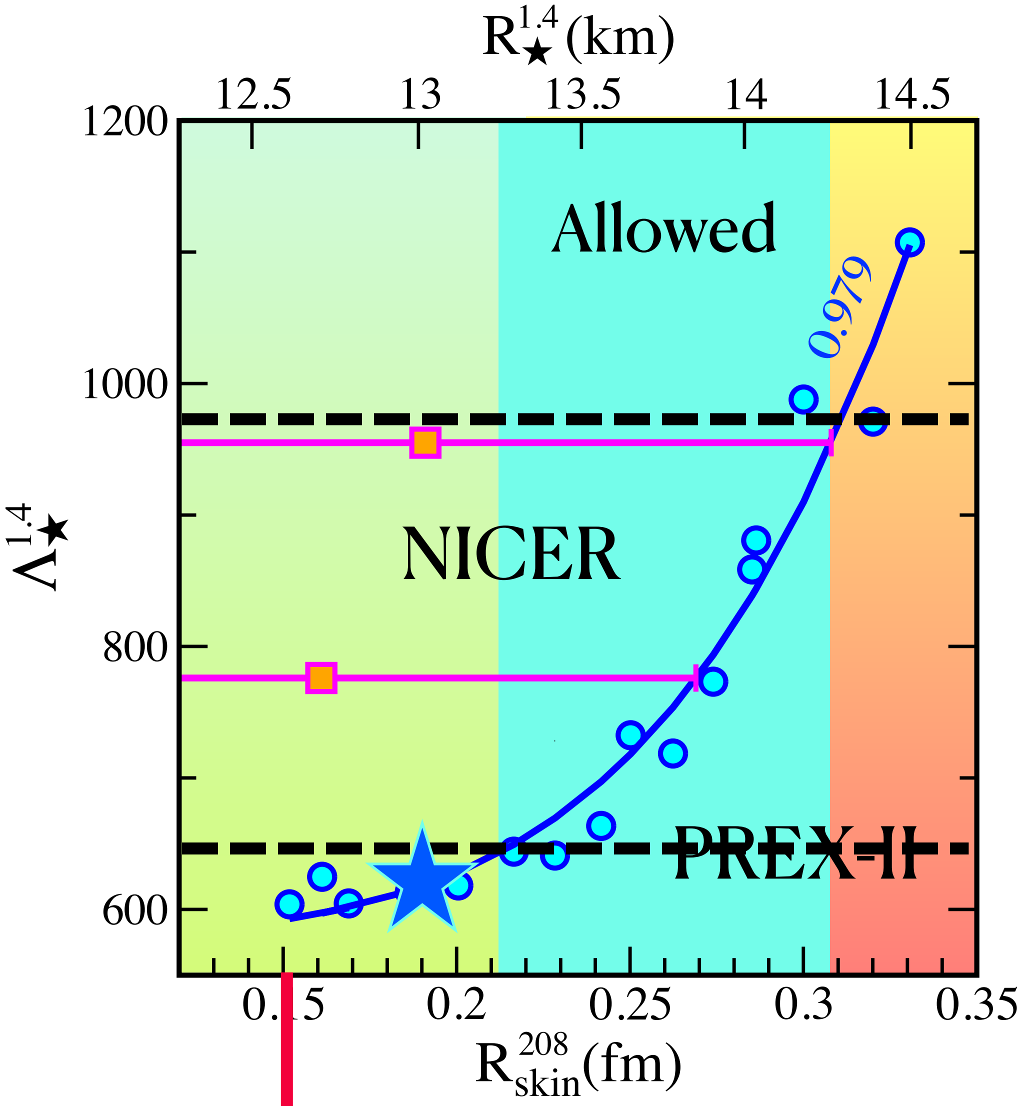
**Strong tension with "allowed" region from NICER+PREX-II**

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)

# Gravitational Wave Discovery & Tension



**BUT wait…**

**Some uncertainty in the PREX-II translation of $A_{PV}$ to $R_{skin}$?**

PHYSICAL REVIEW LETTERS

Information Content of the Parity-Violating Asymmetry in $^{208}$Pb

Paul-Gerhard Reinhard, Xavier Roca-Maza, and Witold Nazarewicz
Phys. Rev. Lett. **127**, 232501 – Published 29 November 2021

$R_{skin} = 0.19 \pm 0.02$ for $^{208}Pb$ from PREX-II data

**We need more precision measurements of $R_{skin}$**

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

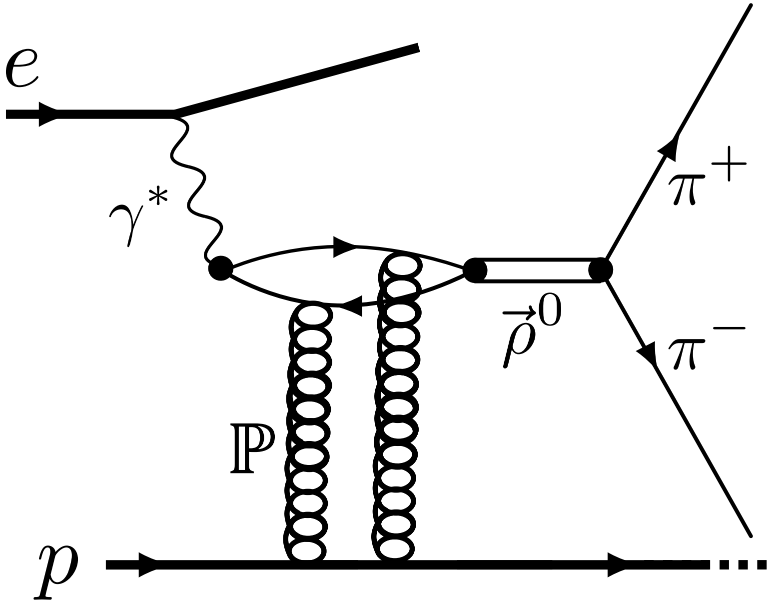
D. Adhikari *et al.* (PREX Collaboration) Phys. Rev. Lett. **126**, 172502 (2021)

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

# Shining light on Gluons

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

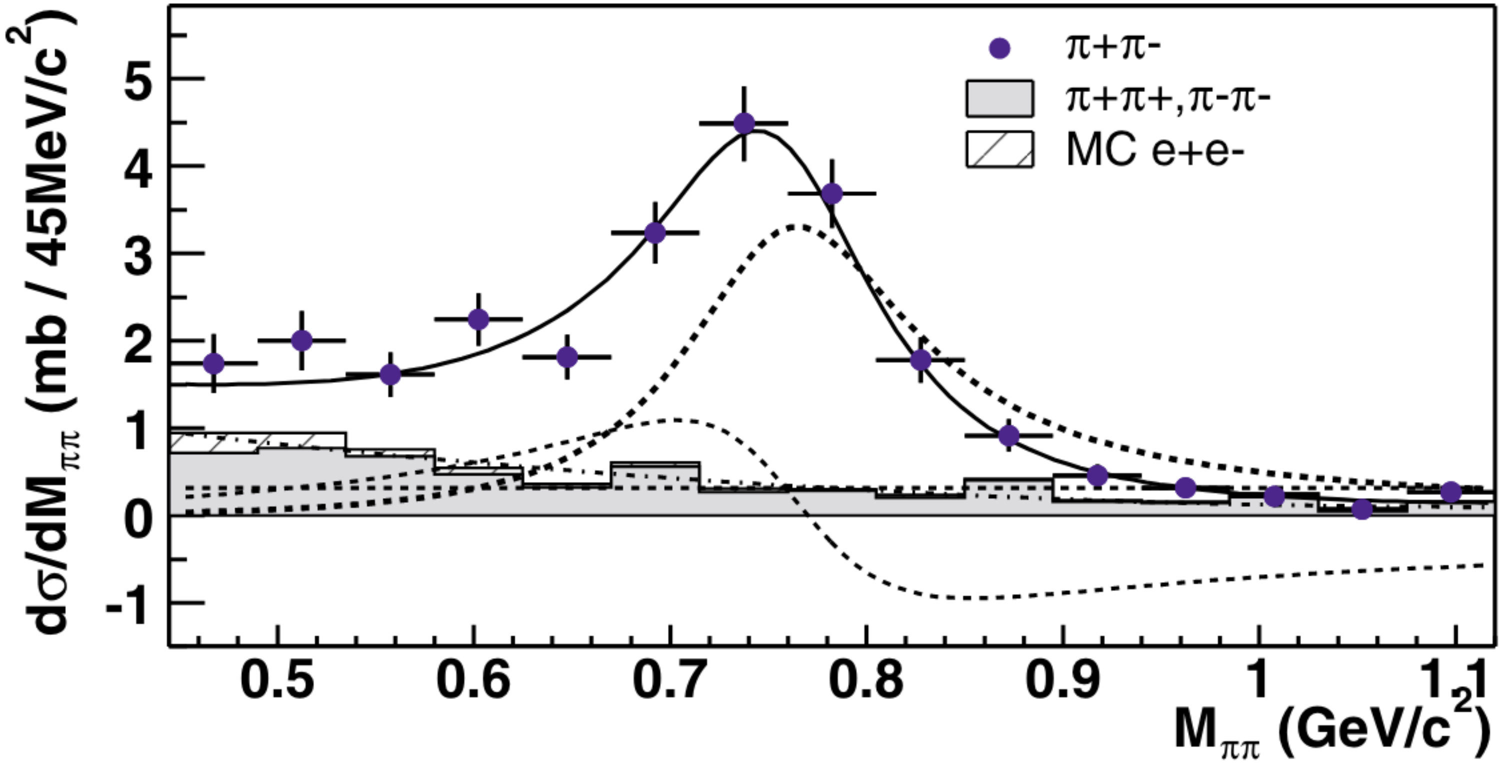


- Well known process for probing the **hadronic structure** of the photon
- Photon energies $\gtrsim 10$ GeV: probe gluon distribution - Interaction through $\mathbb{P}$omeron (two gluon state at lowest order)
- Lower energy scattering: probe gluons + quarks: Reggeon interactions are important
- Photon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

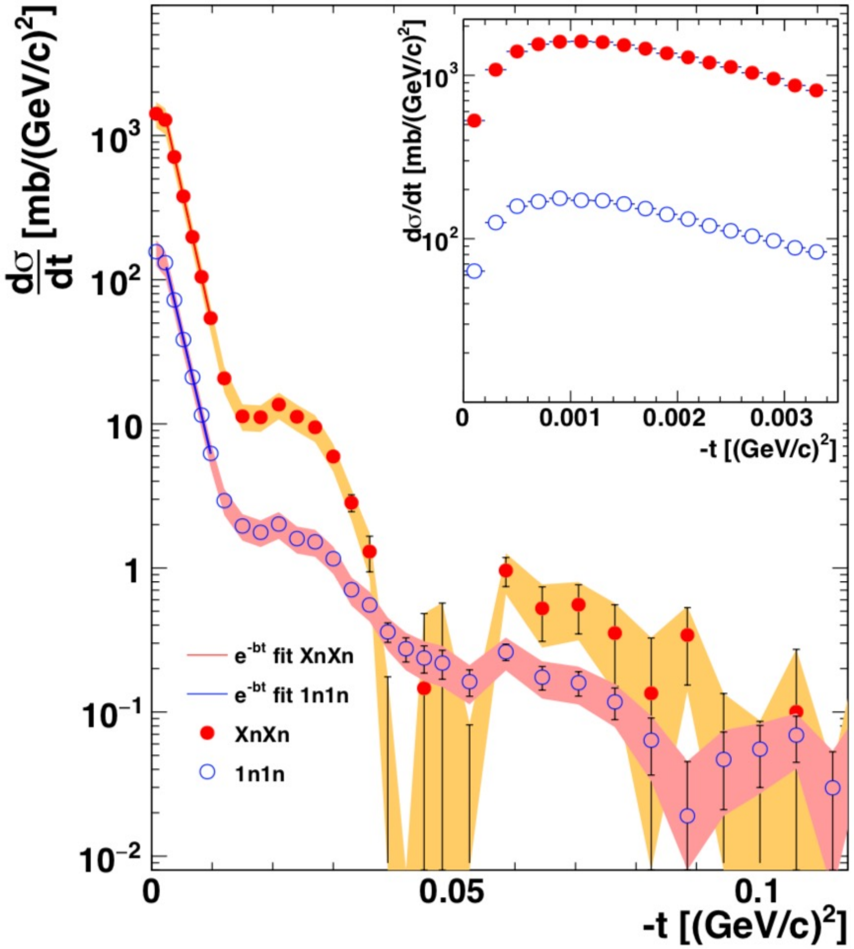


Line shape results from amplitude level contributions: $\rho^0 \rightarrow \pi^+\pi^-$ + Drell Söding (direct $\pi^+\pi^-$) + $\omega \rightarrow \pi^+\pi^-$

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).

# Past Photo-Nuclear Measurements

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



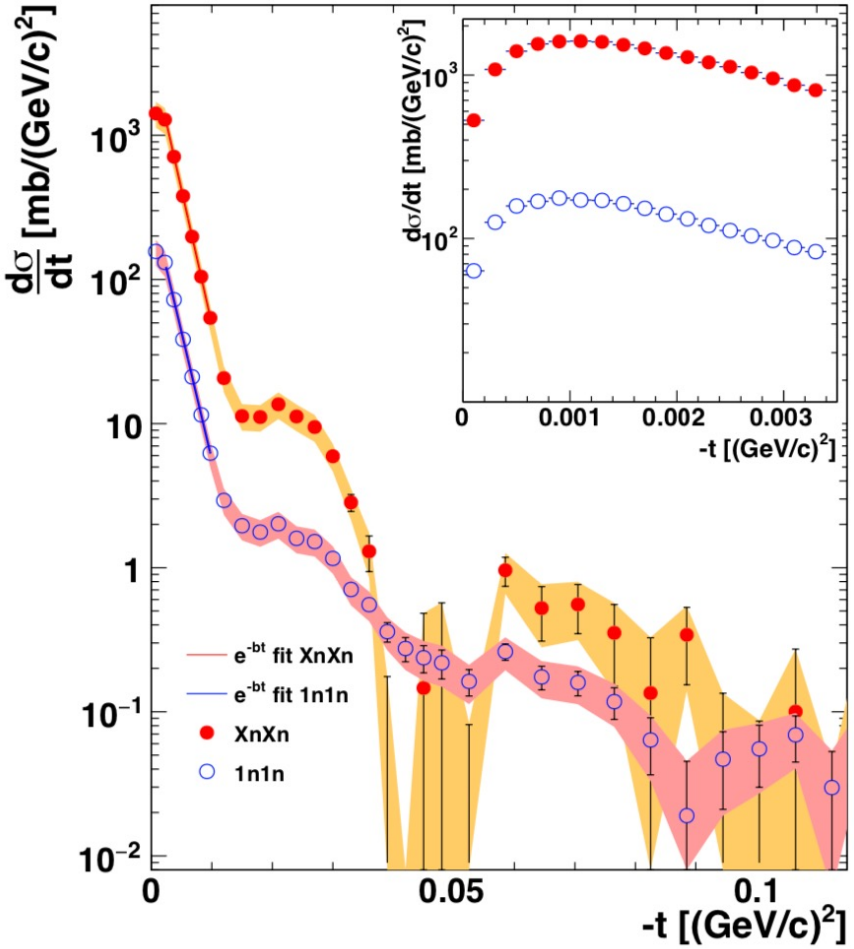
**Coherent Interactions:**

- 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).
STAR Collaboration *et al. Phys. Rev. C* **96**, 054904 (2017).

# Past Photo-Nuclear Measurements

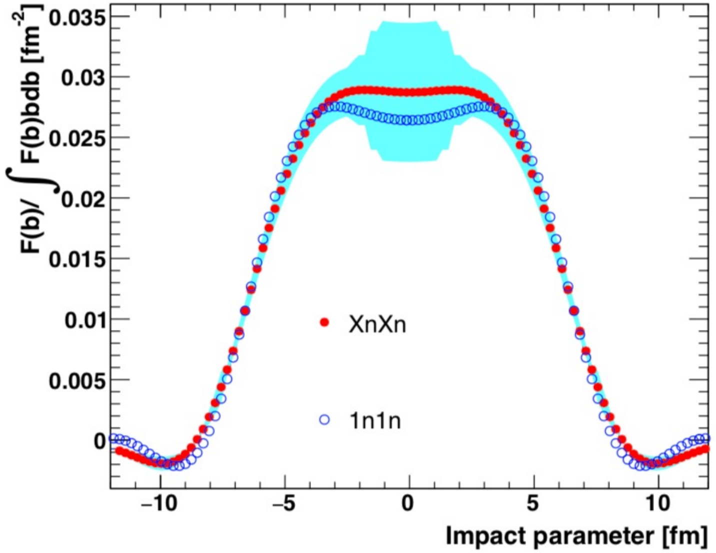
- STAR has studied $\gamma\mathbb{P} \rightarrow \rho^0 \rightarrow \pi^+\pi^-$ (and direct $\pi^+\pi^-$ production) in the past



**Coherent Interactions:**

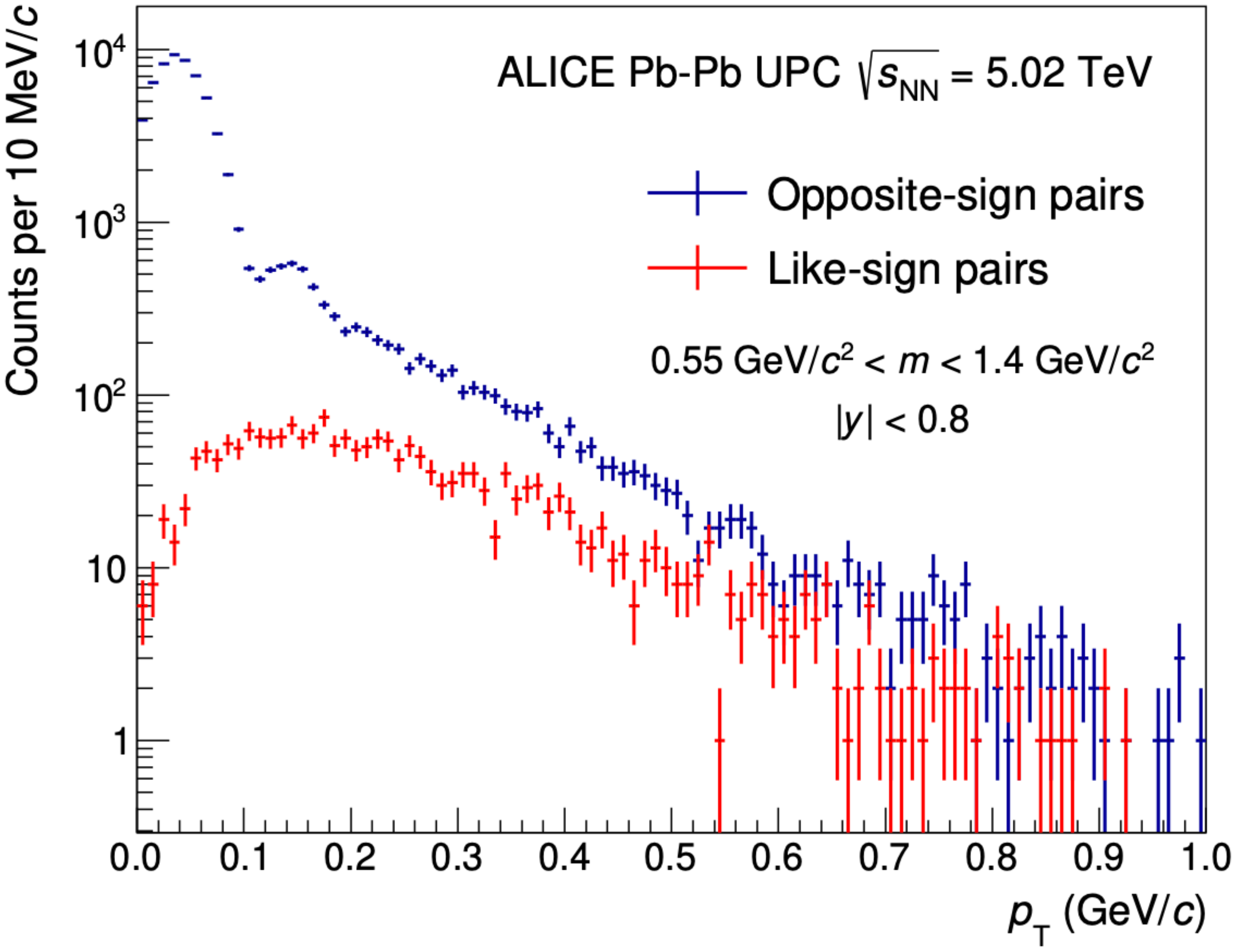
- Photon interacts with the entire nucleus
- Diffractive structure in $p_T^2 \approx -t$
- Transverse momentum related to Fourier transform of nuclear size

Extract gluon distribution



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

# Past Photo-Nuclear Measurements



Other measurements at RHIC & LHC include:

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

$\rho^0$ 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?

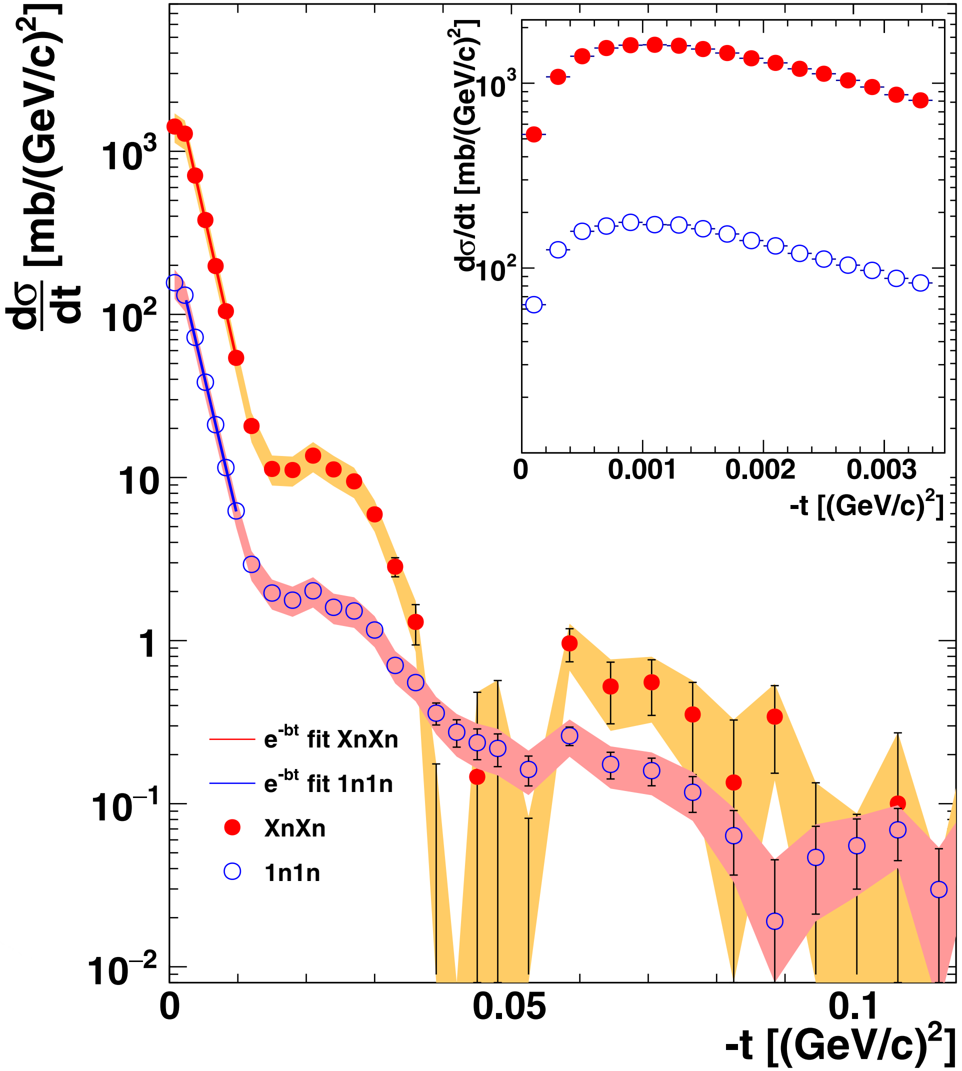


Photo-nuclear measurements have historically produced a |t| slope that corresponds to a **mysteriously large source!**

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)

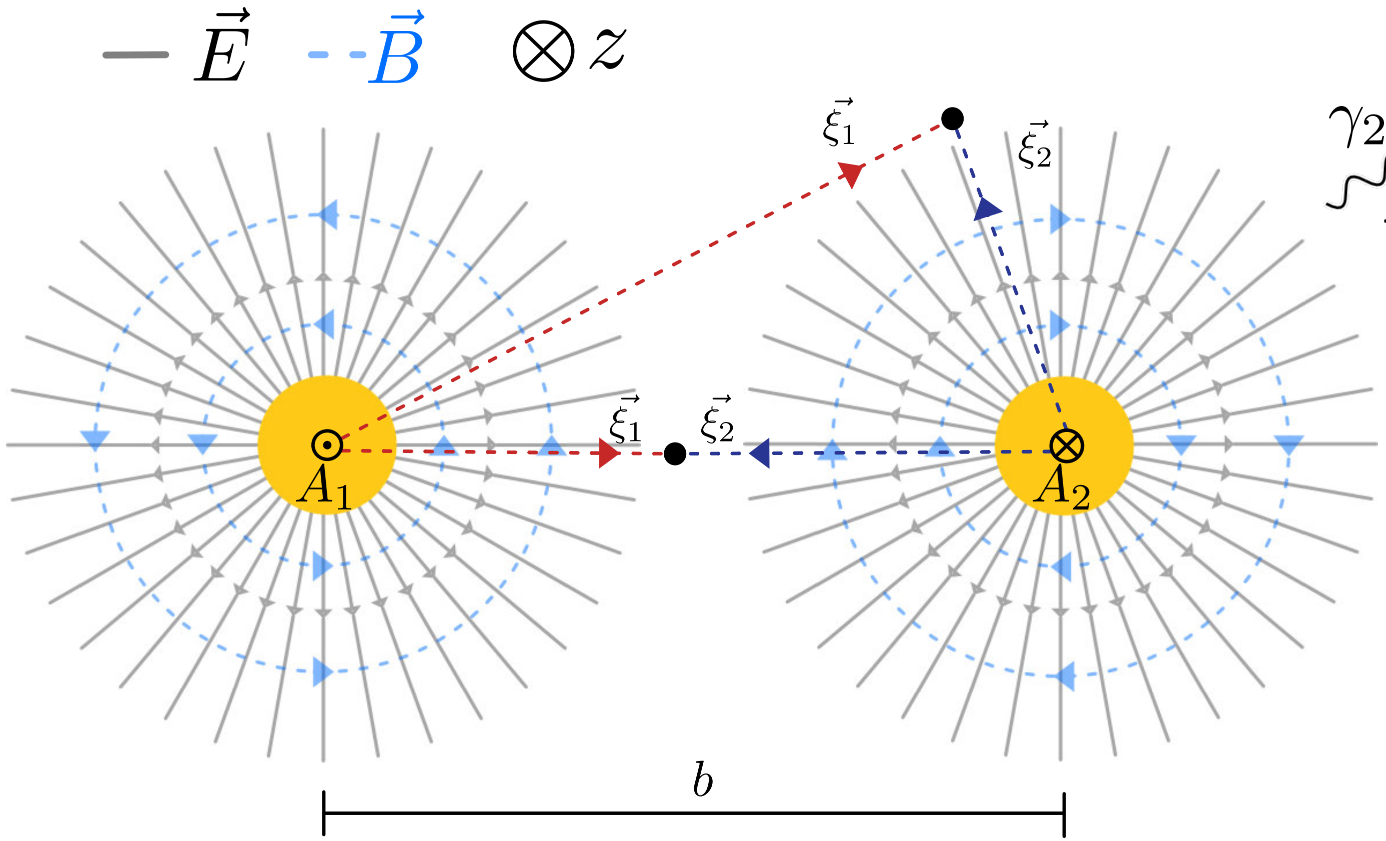
**Extracted nuclear radii are way too large to be explainable**

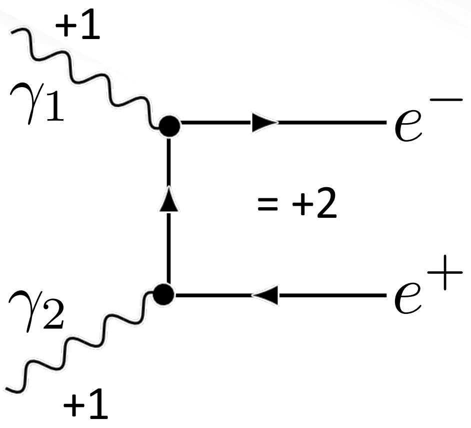
STAR Collaboration, L. Adamczyk, *et al.*, *Phys. Rev. C* 96, 054904 (2017).
J. Adam *et al.* (ALICE Collaboration), J. High Energy Phys. 1509 (2015) 095.

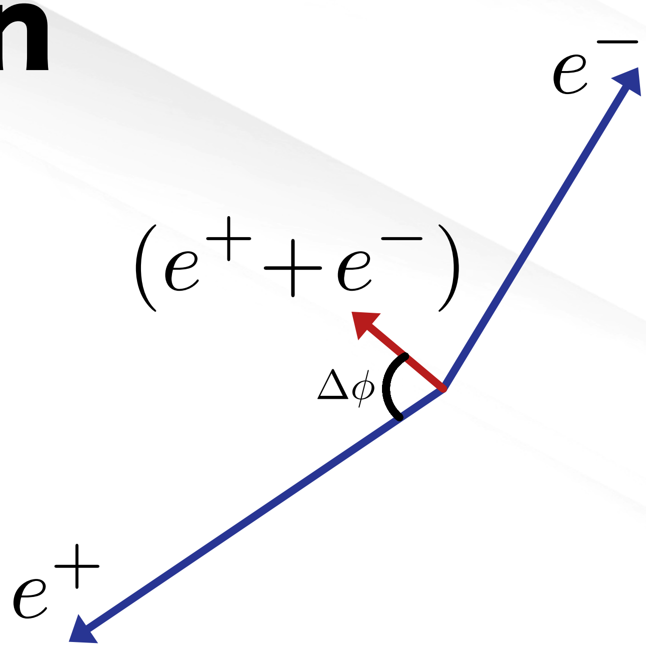
# So what’s new after 20+ years?

# Access to Photon Polarization

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





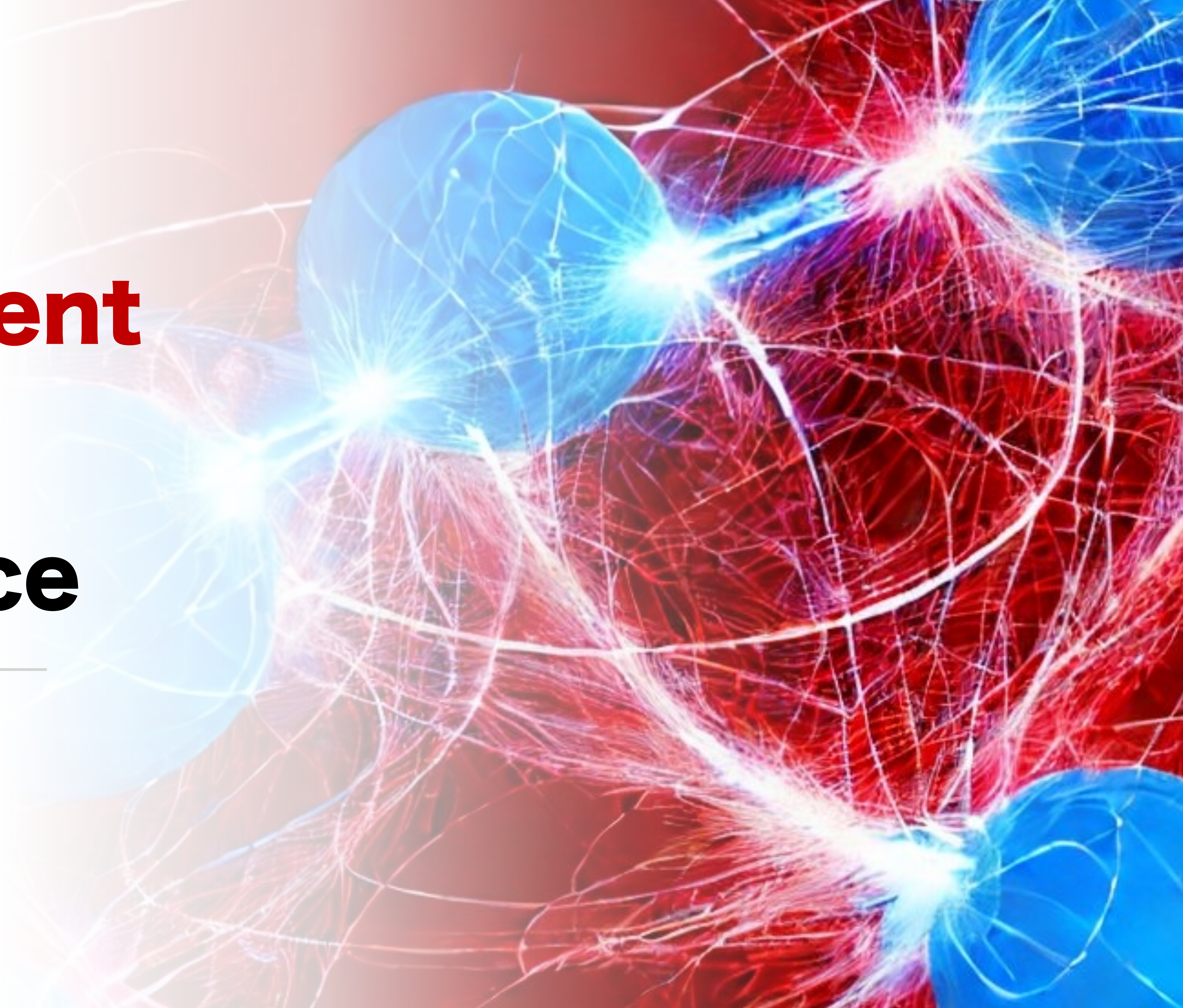


- Polarization vector $\xi$: aligned radially with the "emitting" source
- Intrinsic photon spin converted into **orbital angular momentum**
- Observable as anisotropy in $e^\pm$ momentum – a $\cos 4\phi$ modulation

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

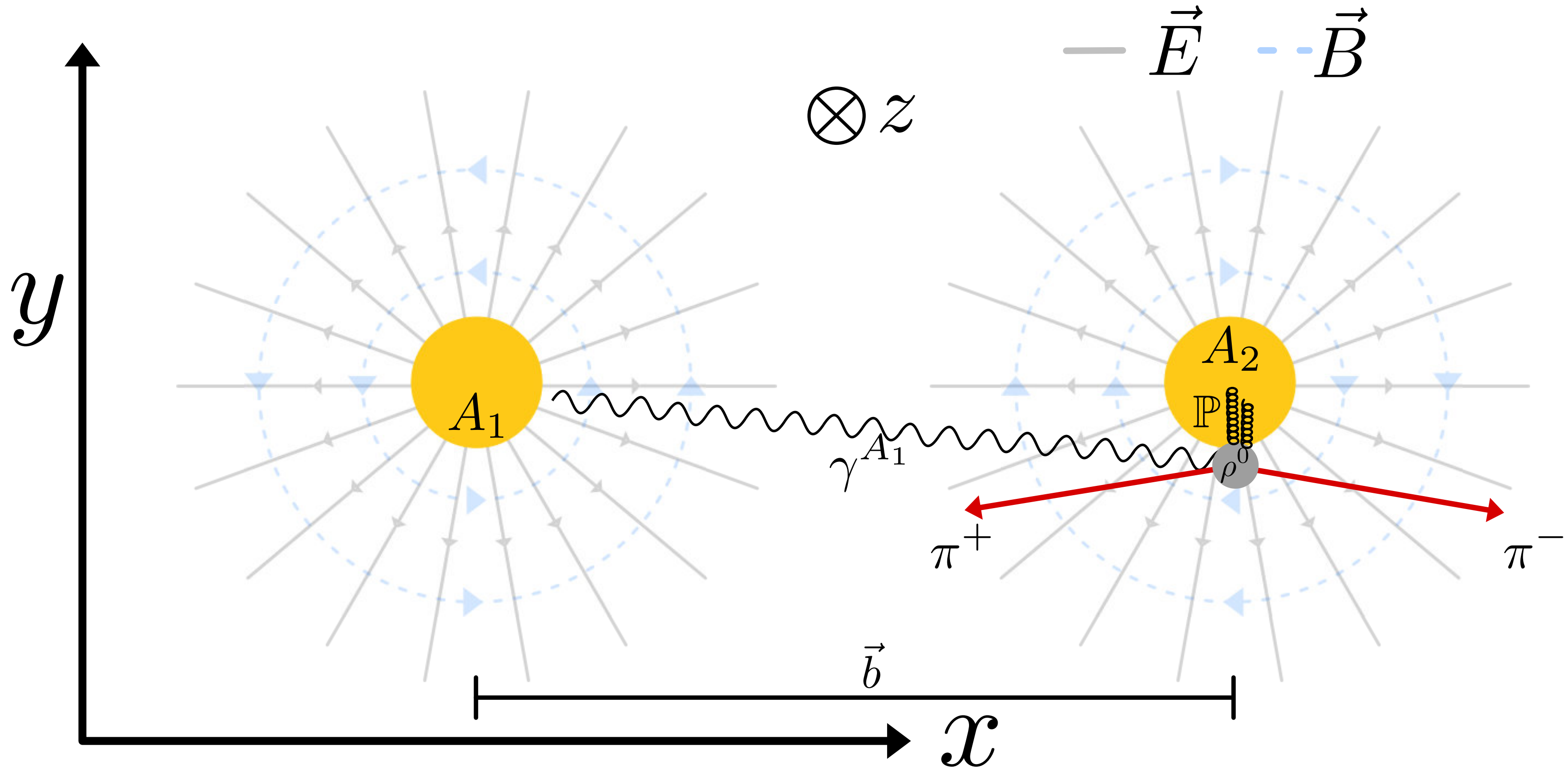
S. Bragin, et. al., *Phys. Rev. Lett.* 119 (2017), 250403
R. P. Mignani, *et al.*, *Mon. Not. Roy. Astron. Soc.* 465 (2017), 492

# Entanglement Enabled Quantum Interference



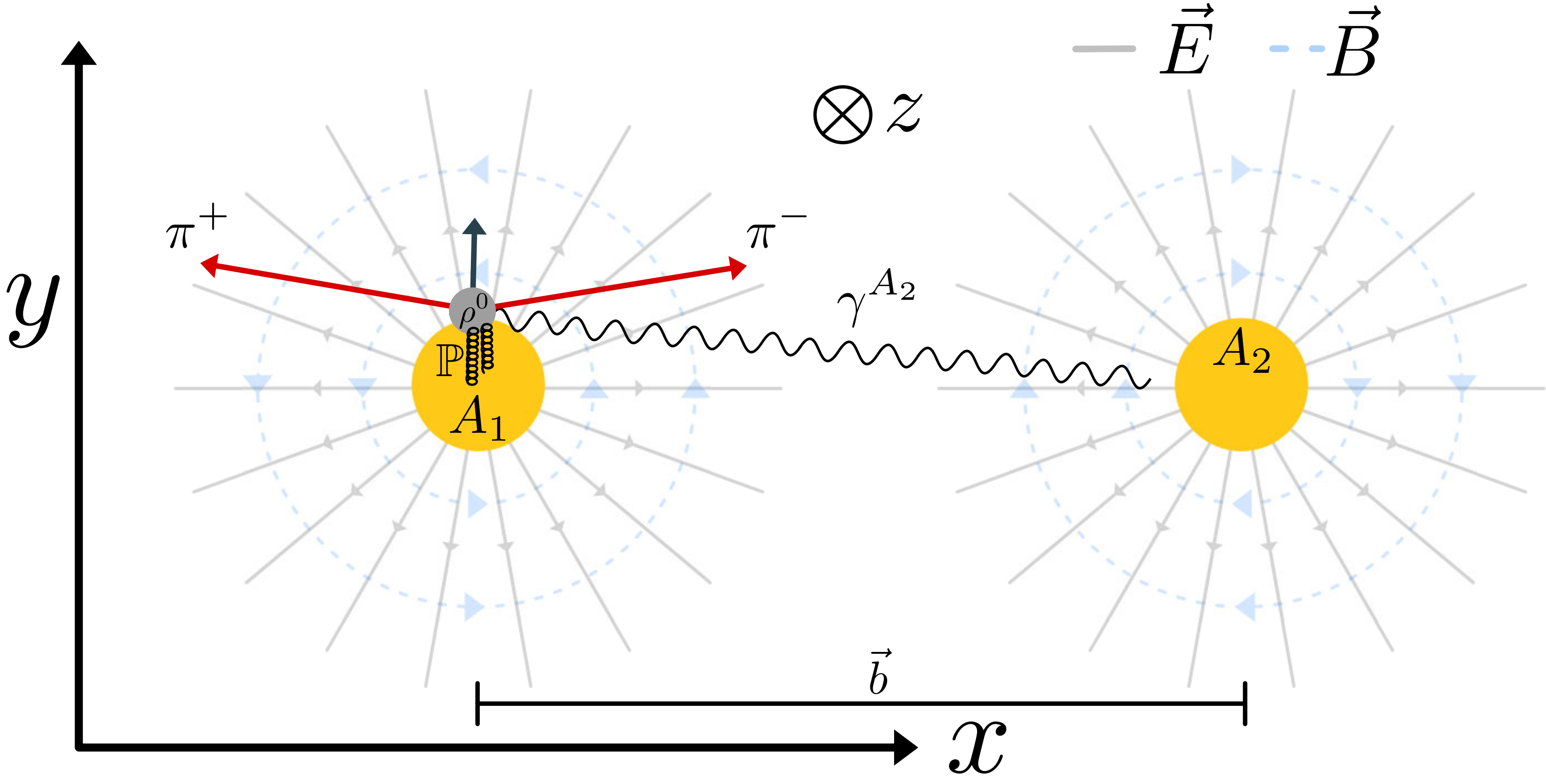
# Imaging the Nucleus with Polarized Photons

What is NEW with transversely polarized photons?



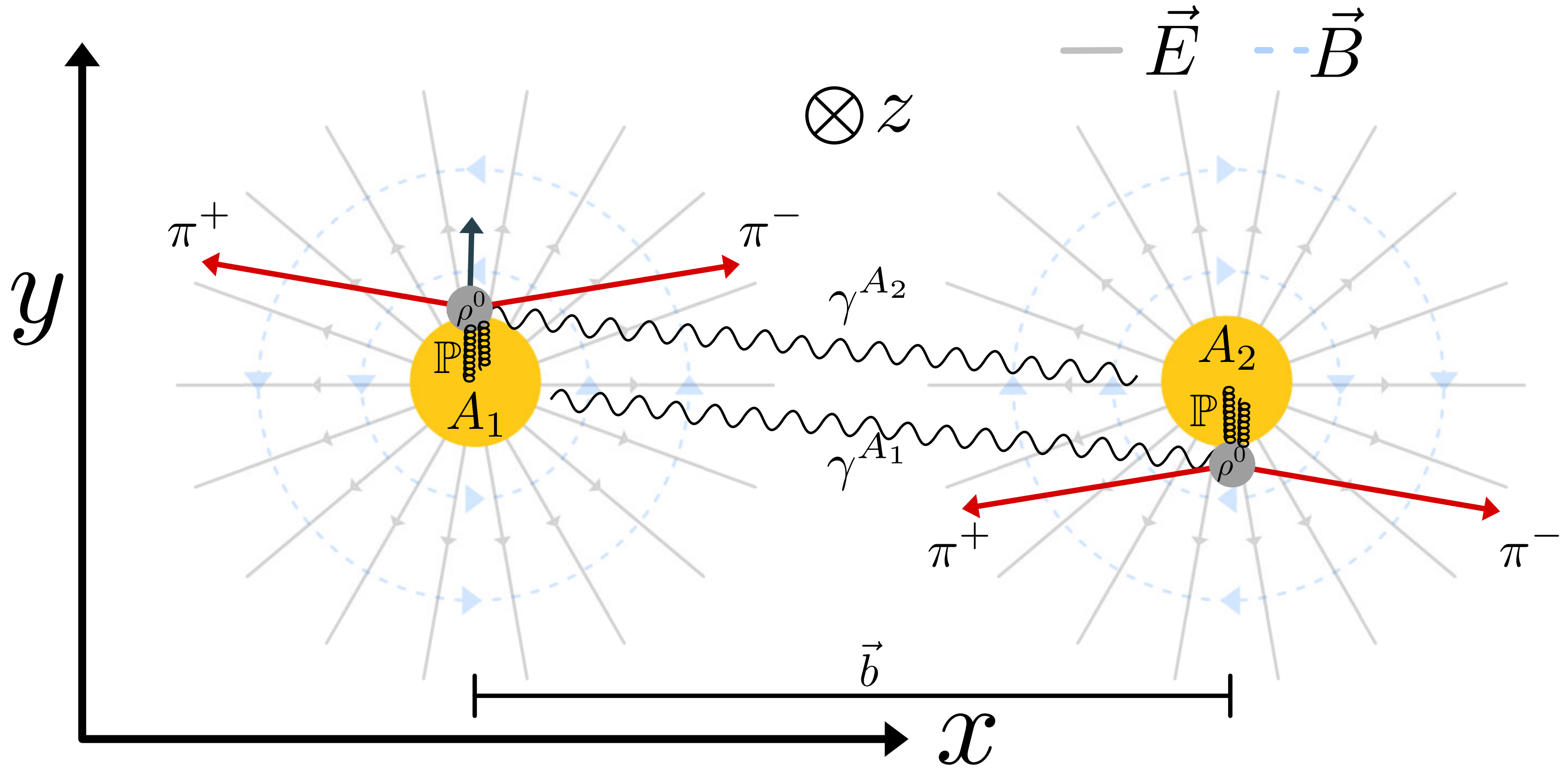
# Imaging the Nucleus with Polarized Photons

## What is NEW with transversely polarized photons?



# Imaging the Nucleus with Polarized Photons

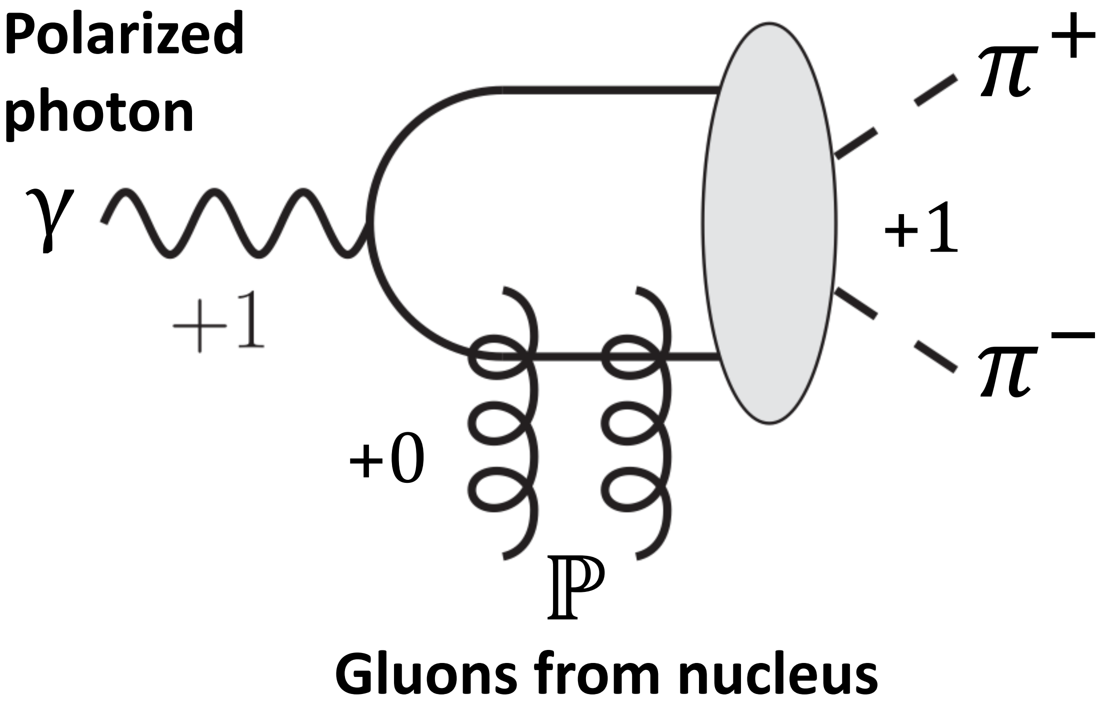
**What is NEW with transversely polarized photons?**

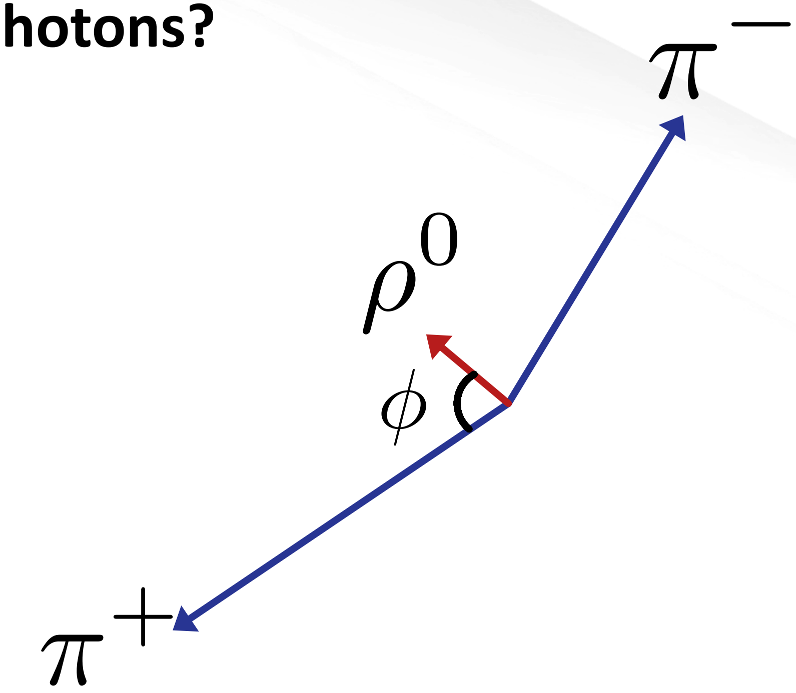


**Both possibilities occur simultaneously**

# Imaging the Nucleus with Polarized Photons

**What is NEW with transversely polarized photons?**

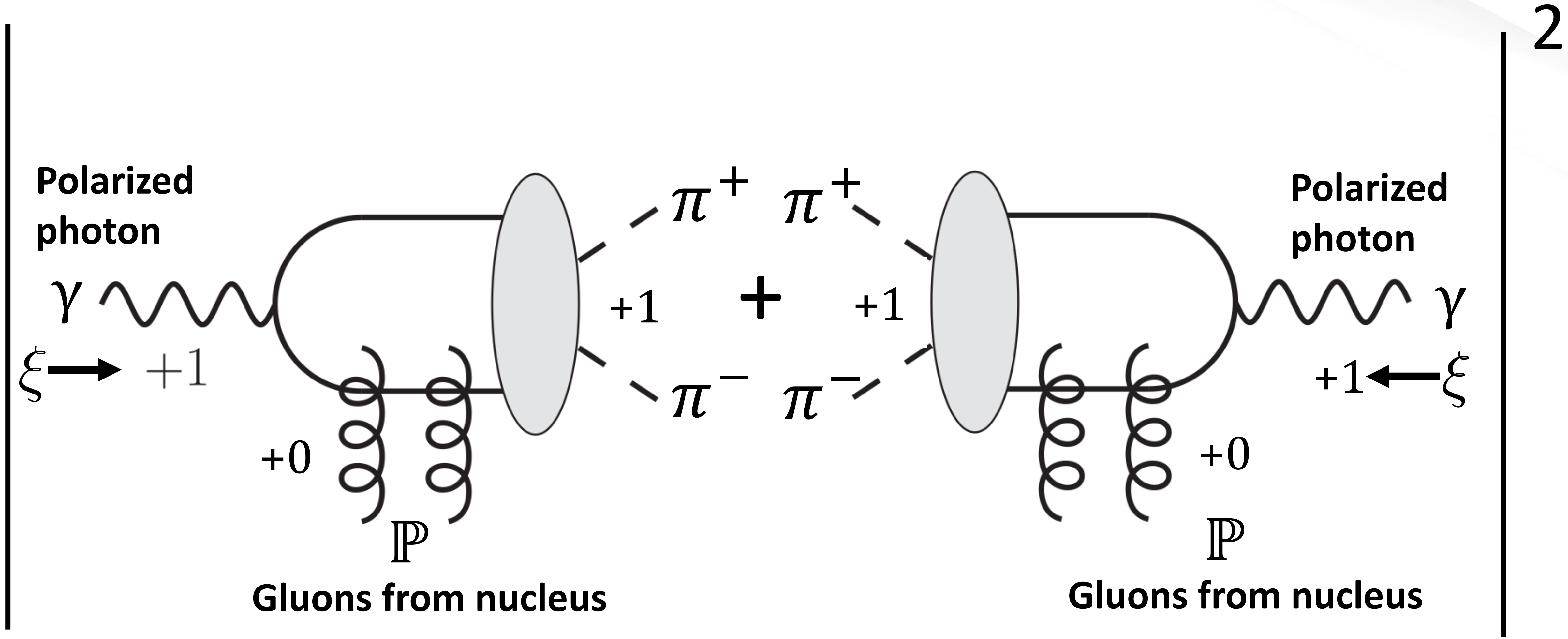




We can use the same experimental observable as the Breit-Wheeler process to access photon polarization

## Access to initial photon polarization

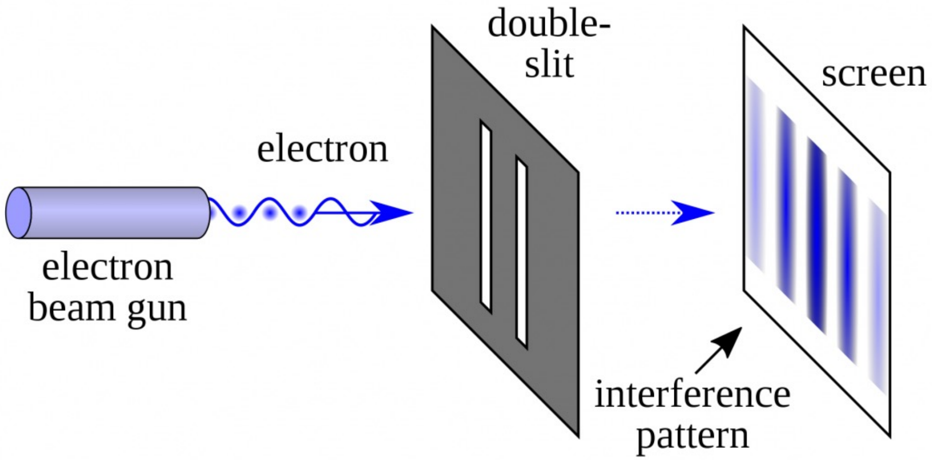
# Interference of two amplitudes



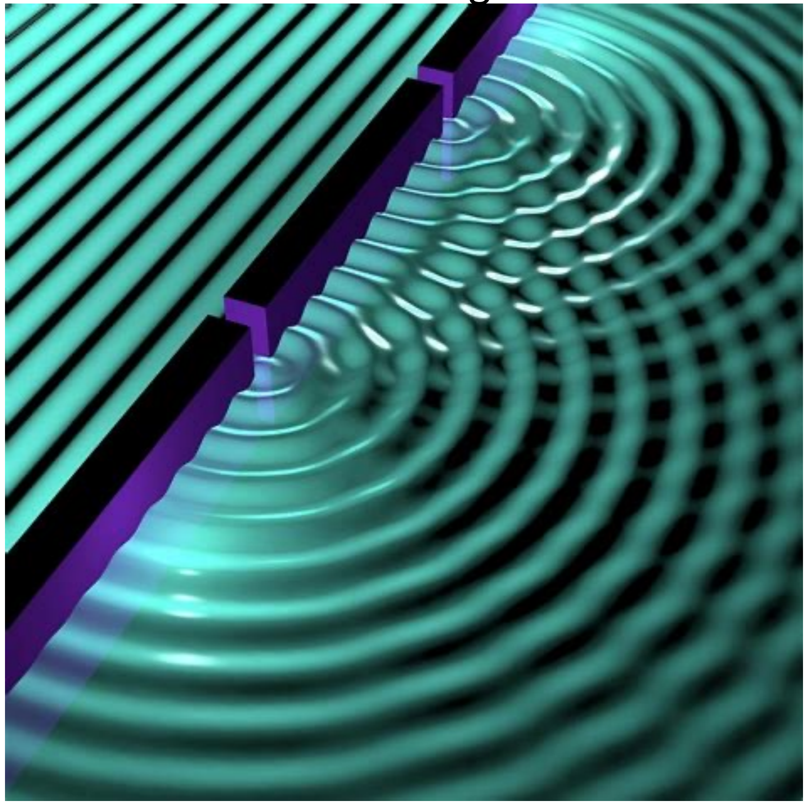
# {Quantum} Double-Slit Experiment

- The double slit experiment is foundational in quantum mechanics

Quantum Double slit Experiment



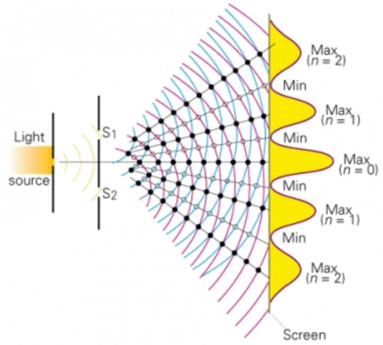
Water waves interfering in a double slit



- 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



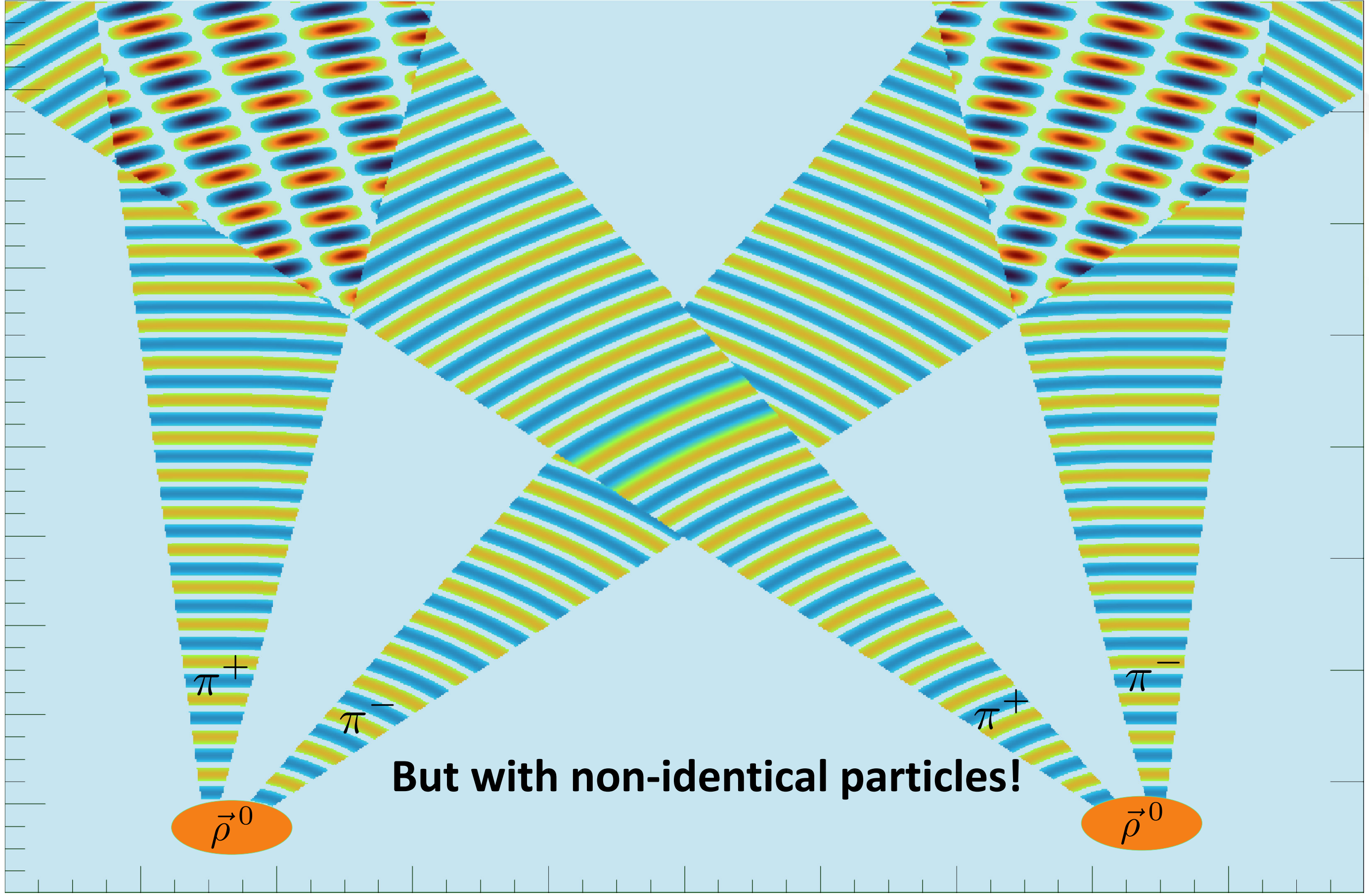
**BUT WAIT…**

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

Interference occurs between **distinguishable** particles

😮🤯

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

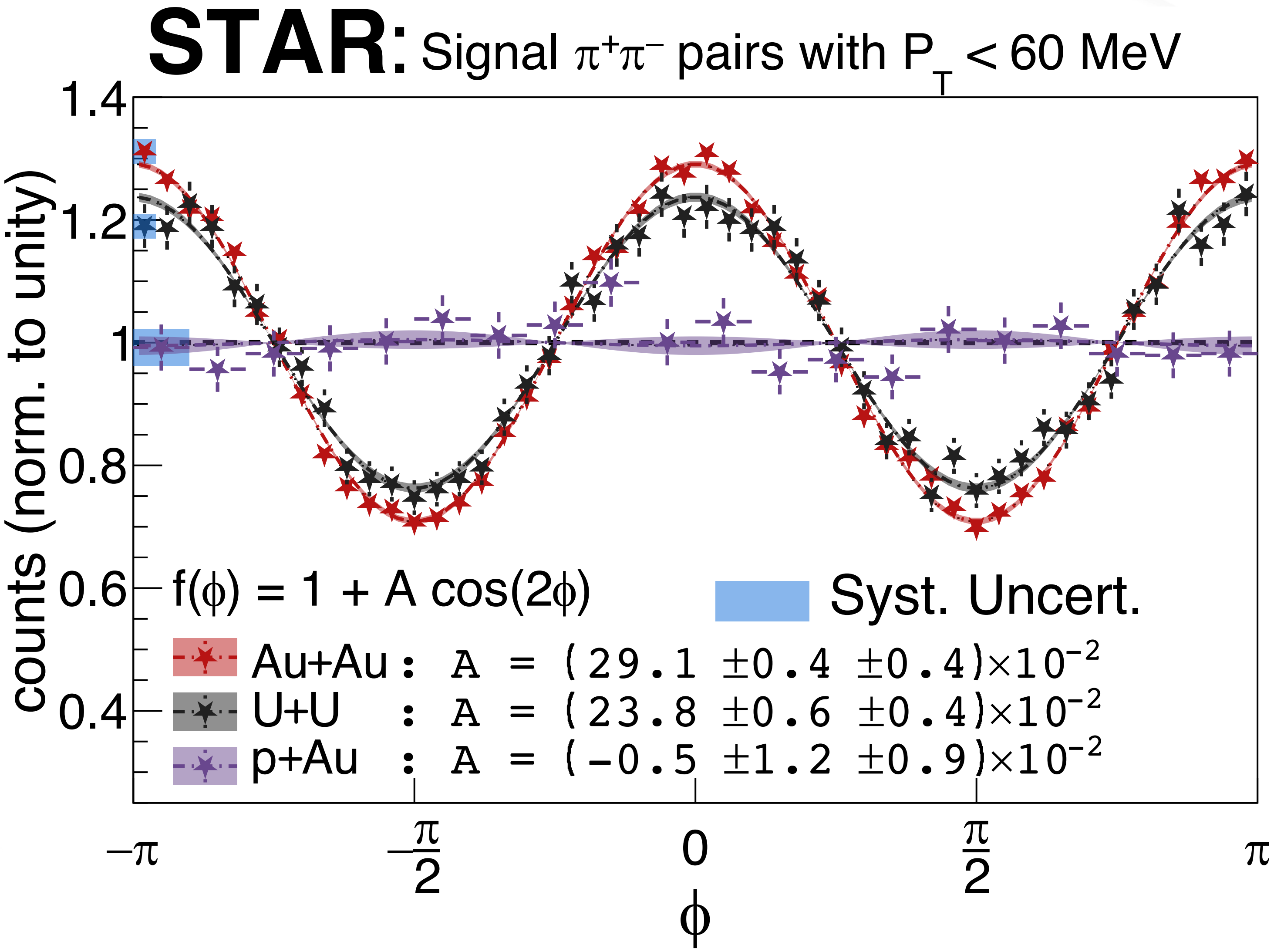


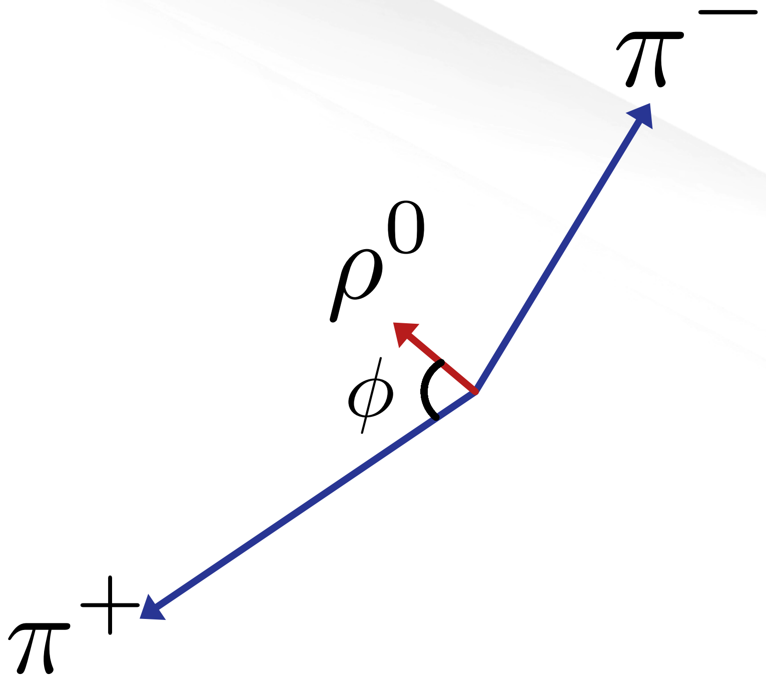
**But with non-identical particles!**

**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 $\rho^0$
- $\rho^0$ spin converted into **orbital angular momentum** between pions
- Observable as anisotropy in $\pi^\pm$ momentum

# Origin of the Entanglement?

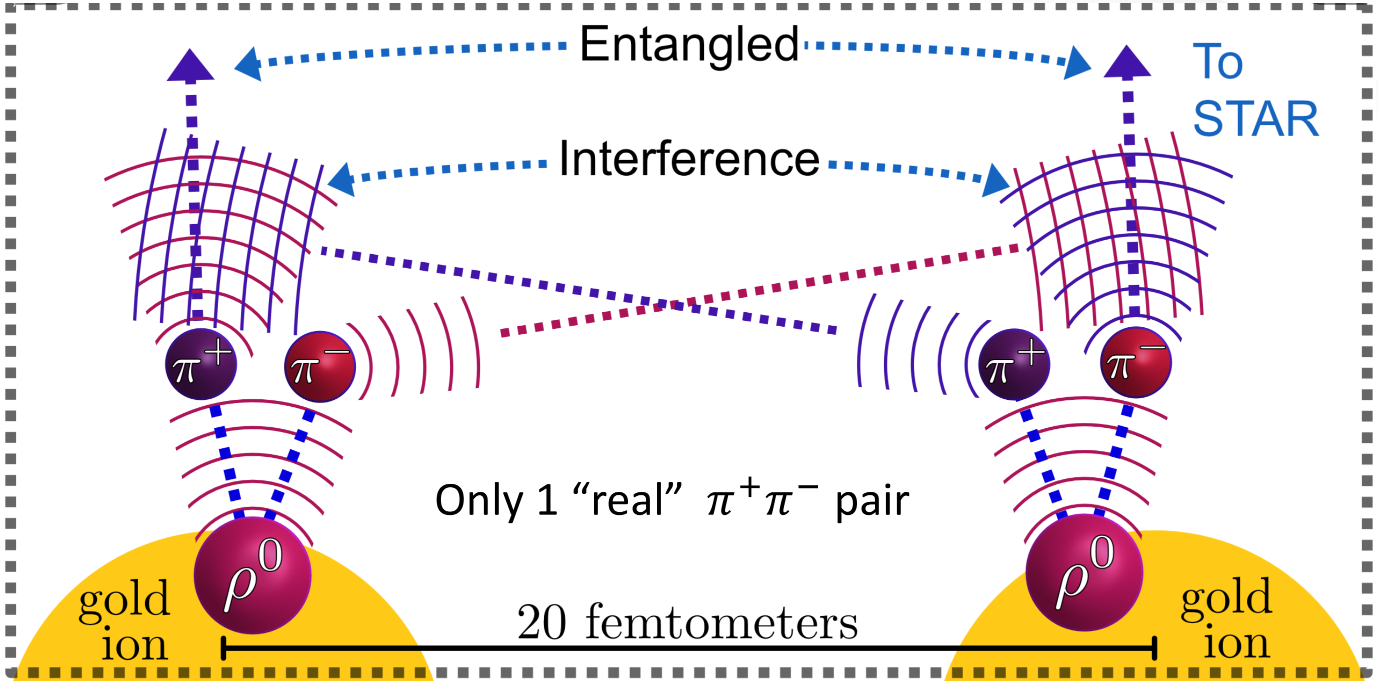
# Case 1 : {Entangled} Double-Slit Experiment

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

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



**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).

# Case 2: Entanglement: Nobel Prize 2022

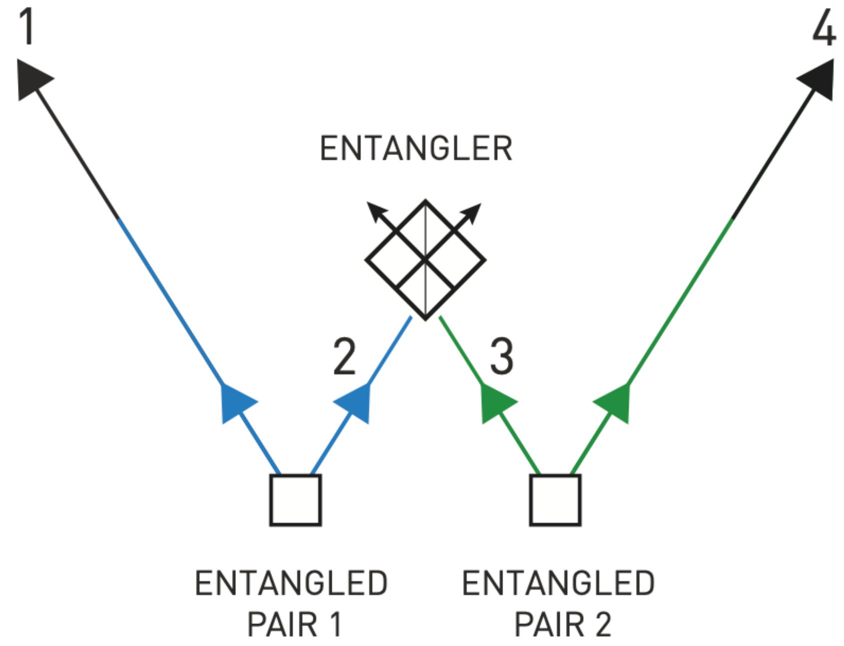
Alain Aspect, John Clauser and **Anton Zeilinger**

## 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.

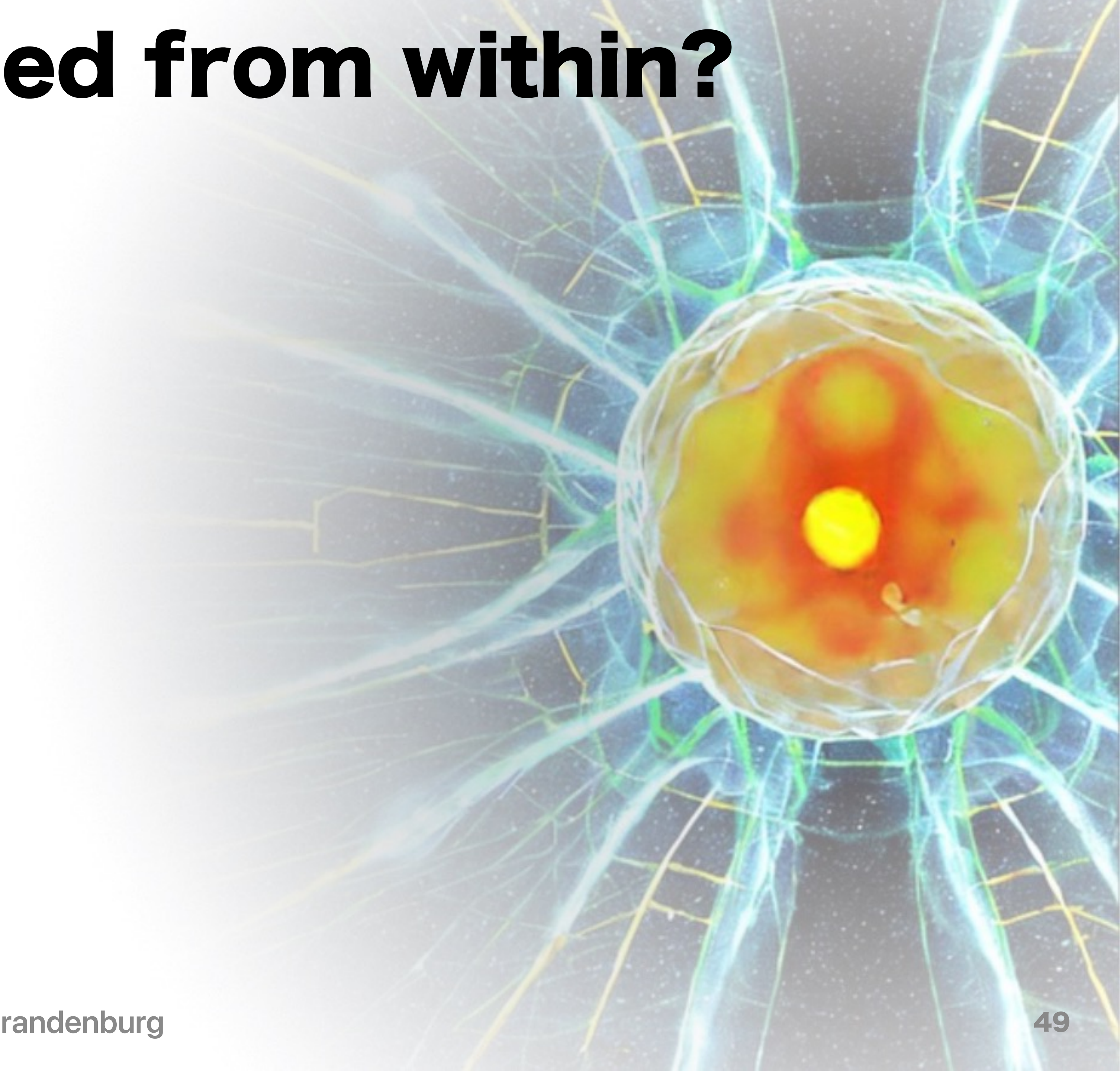
**Quantum teleportation:**

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?

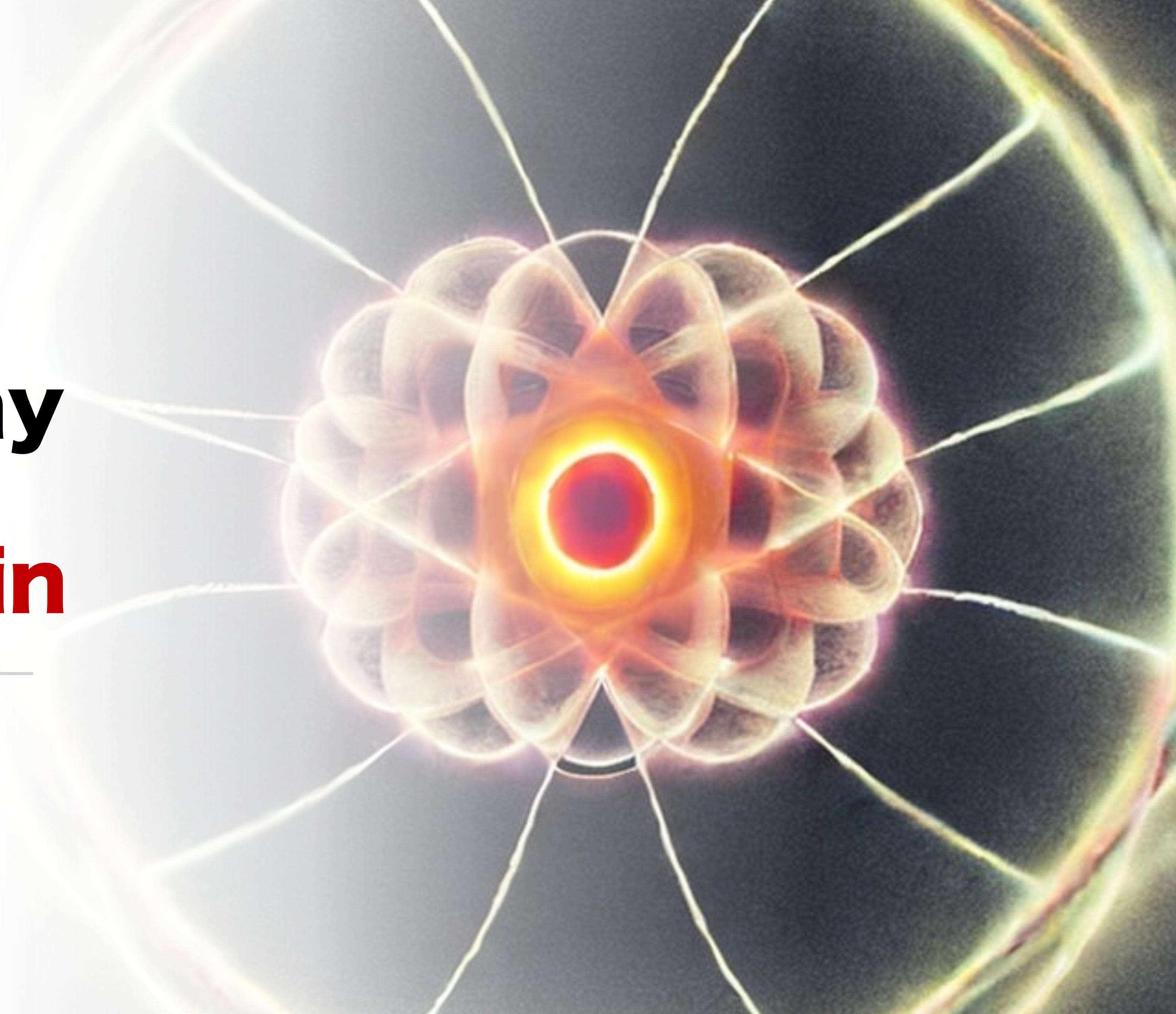
We expect that the nucleus (and the nucleons) are highly entangled states

BUT…

We have no experimental proof of this entanglement at rest

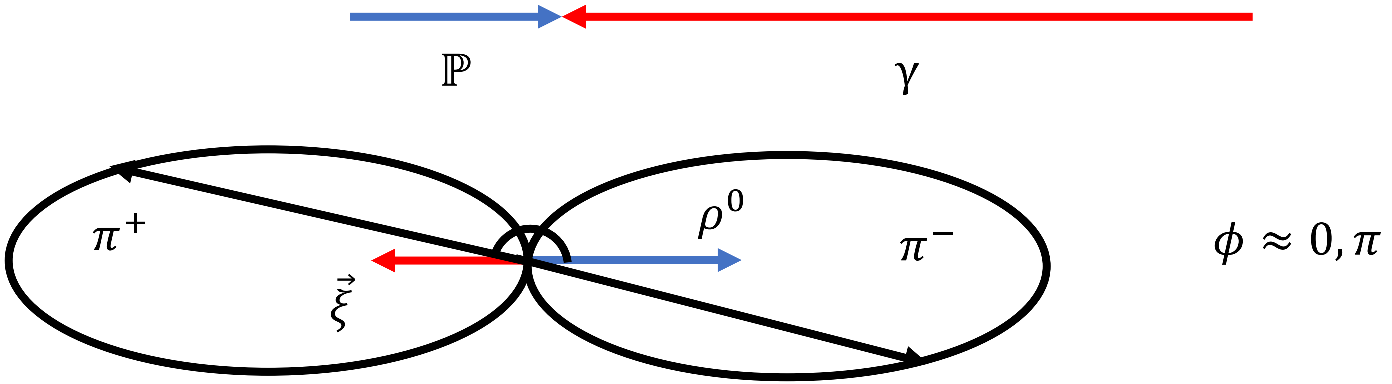
New STAR measurements for QM23!

# Nuclear Tomography and the Neutron skin

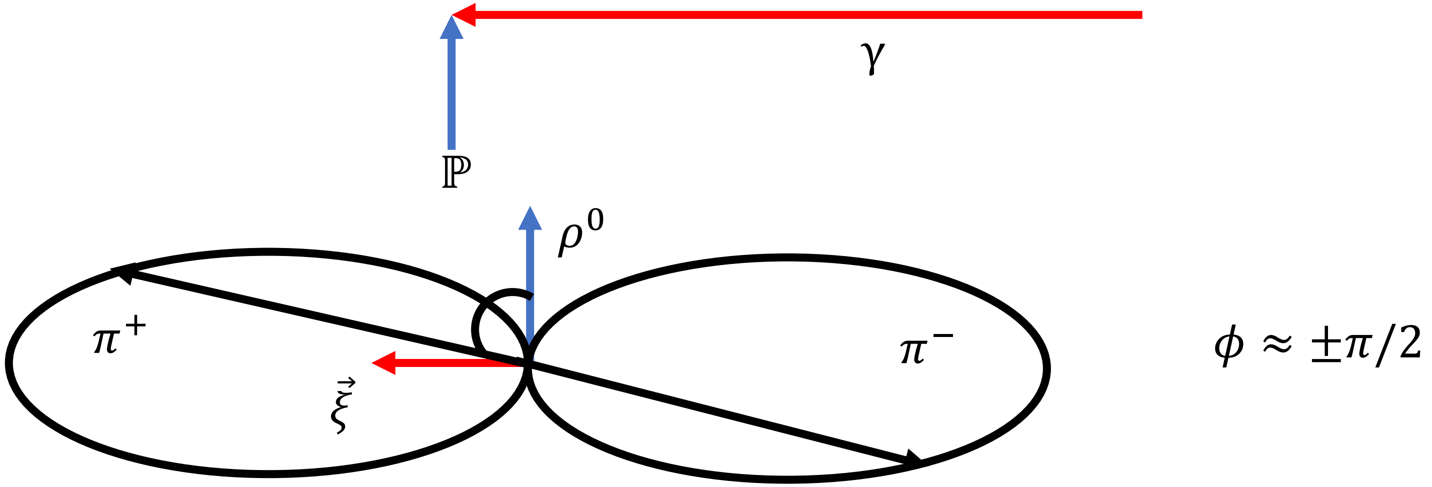


# Interference Reveals Event Configurations

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

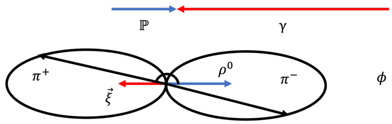


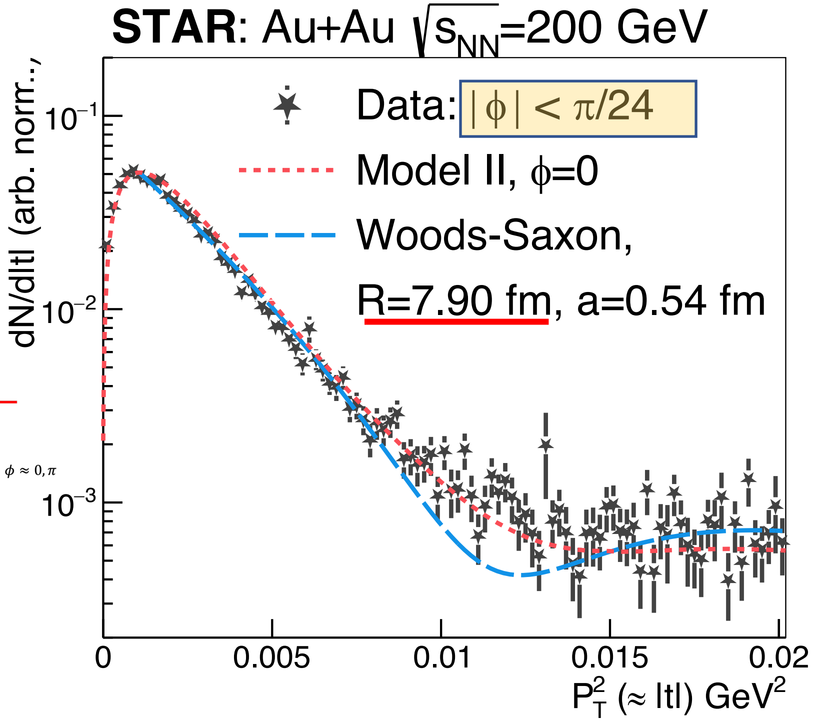
- Case II : Photon & Pomeron are perpendicular

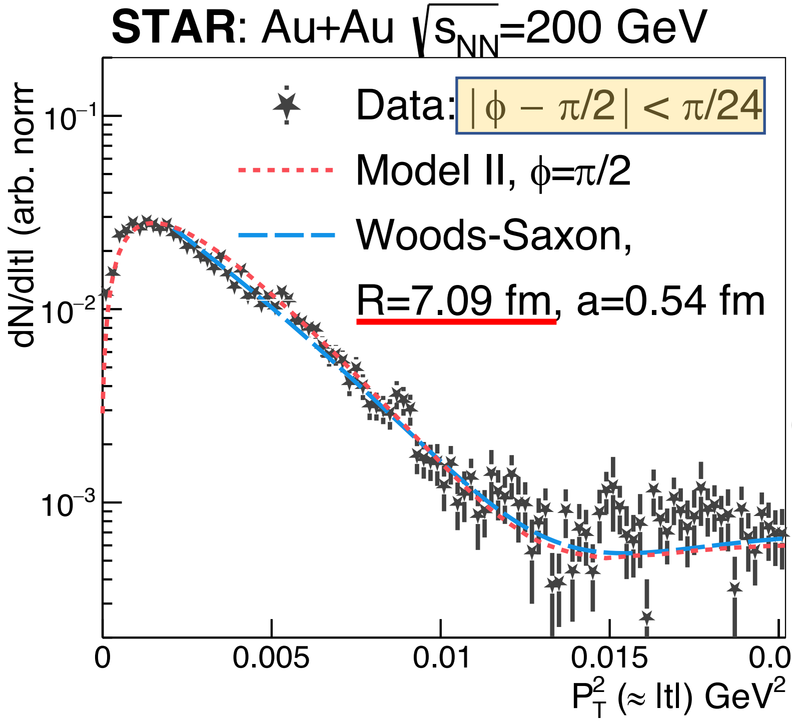


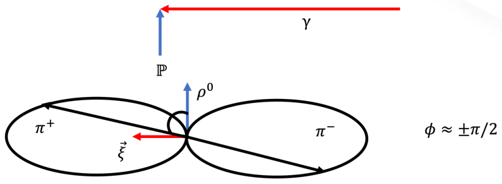
# |t| vs. $\phi$, which radius is 'correct'?

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









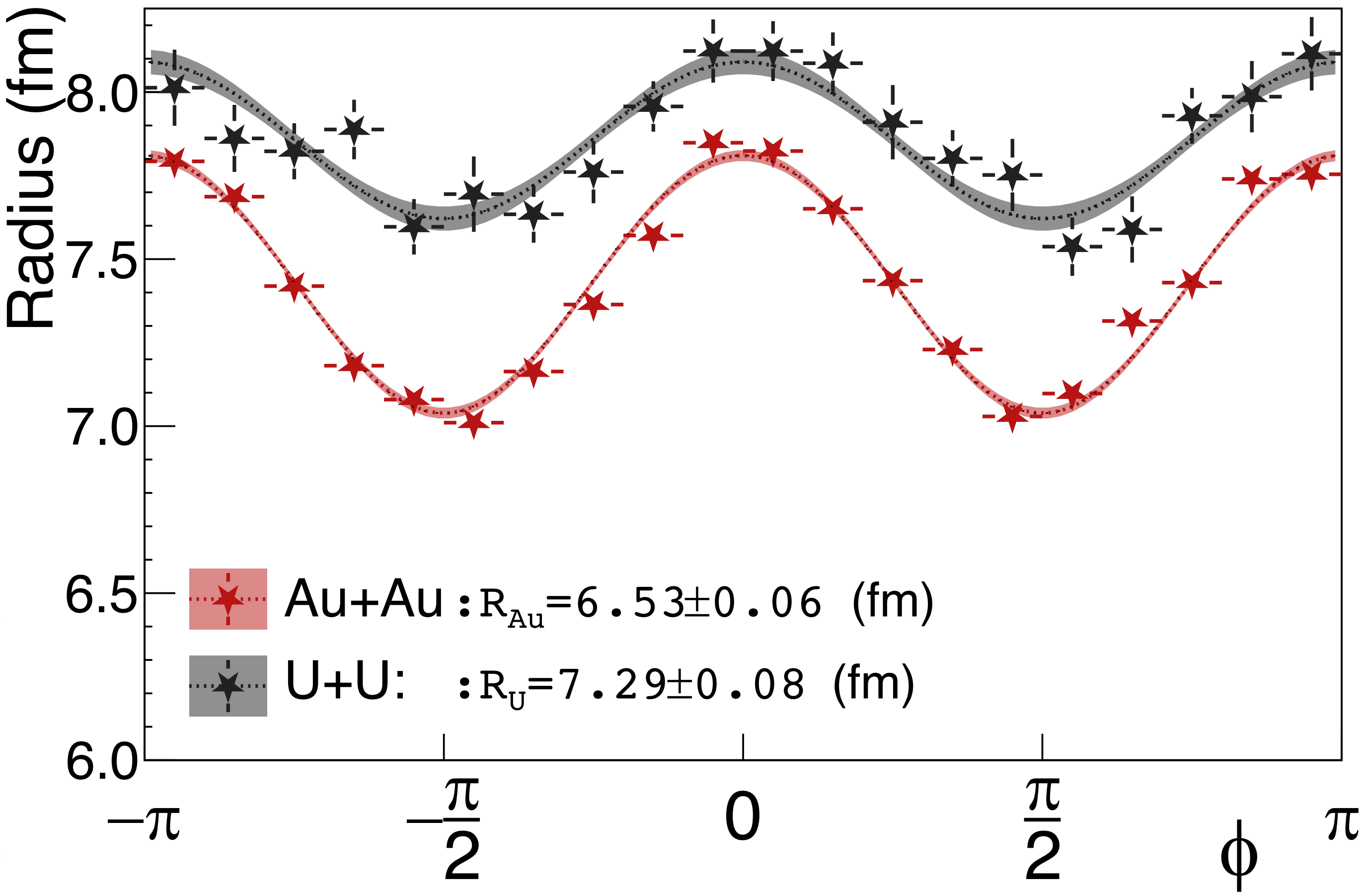
- Drastically different radius depending on $\phi$, still way too big
- Notice how much better the Woods-Saxon dip is resolved for $\phi = \pi/2$ -> experimentally able to **remove photon momentum, which blurs diffraction pattern**
- **Can we extract the 'true' nuclear radius from |t| vs. $\phi$ information?**

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

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

# Imaging the Nucleus with Polarized Photons

**STAR:** Photonuclear $\rho^0 \rightarrow \pi^+\pi^-$



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 $\phi$ meson and $J/\psi$ 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 *<br>(Tomographic Technique) | 0.17 ± 0.03(stat.) ±0.08(syst.)<br>$\sim 2\sigma$ | 0.44 ± 0.05 (stat.) ±0.08 (syst.)<br>$\sim 4.7\sigma$ (Note: for Pb ≈ 0.3 ) |
| | | *STAR Collaboration, Sci. Adv. **9**, eabq3903 (2023). |

**Precision measurement of nuclear interaction radius at high-energy**

**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).

[3] G. McClellan, *et al.*, *Phys. Rev. D* 4, 2683 (1971).

# Nuclear Radius Comparison

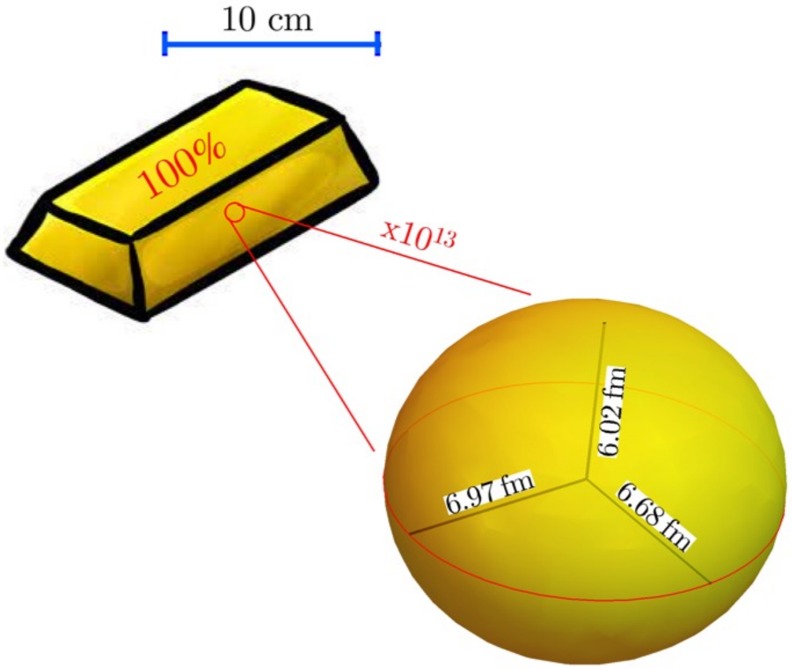
| | Au+Au (fm) | U+U (fm) |
|---|---|---|
| Charge Radius | 6.38 (long: 6.58, short: 6.05 ) | 6.81 (long: 8.01, short: 6.23) |
| Inclusive \|t\| slope (STAR 2017) [1] | $7.95 \pm 0.03$ | -- |
| Inclusive \|t\| slope (WSFF fit)* | $7.47 \pm 0.03$ | $7.98 \pm 0.03$ |
| Tomographic technique* | $6.53 \pm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

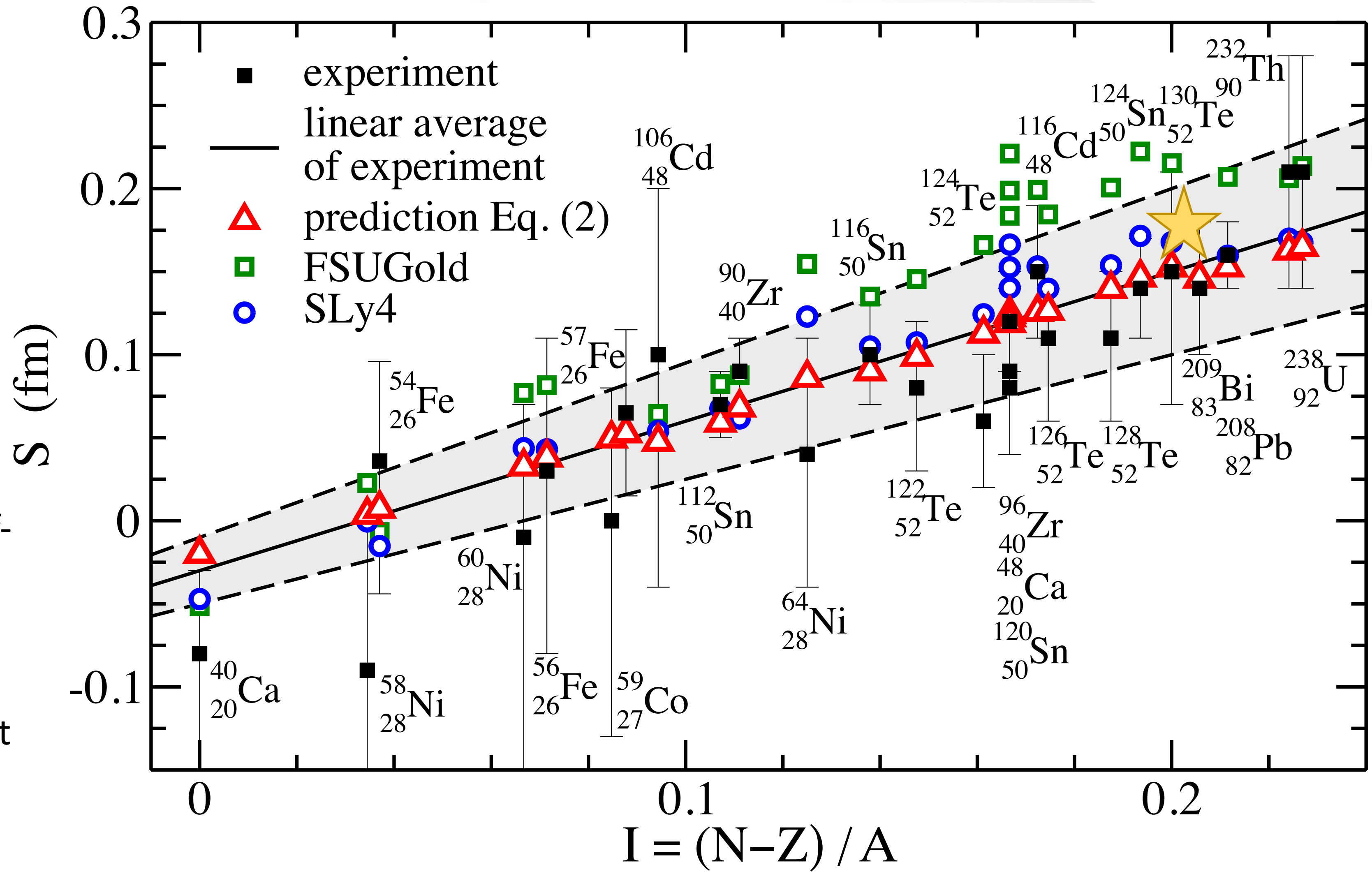
**Precision measurement of <u>nuclear</u> interaction radius at <u>high-energy</u>**

**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).
[3] G. McClellan, *et al.*, *Phys. Rev. D* 4, 2683 (1971).

# Neutron Skins across Nuclei





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

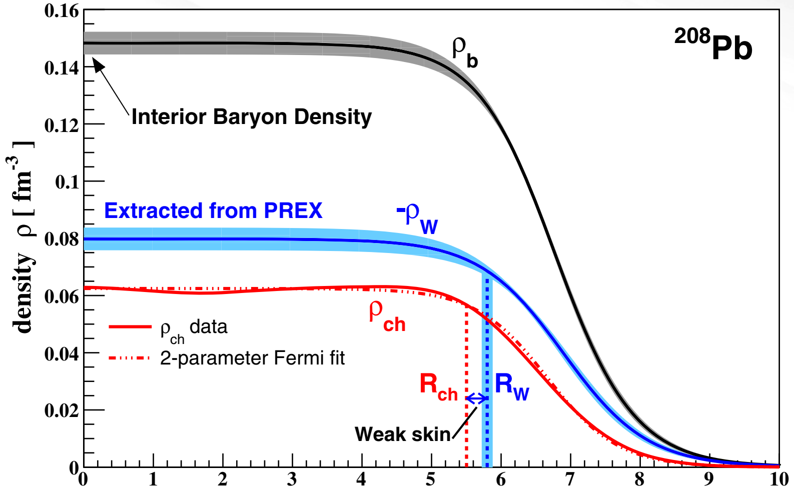
$$S_{Au} = \mathbf{0.17\ fm}$$

In good agreement with our measurement

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

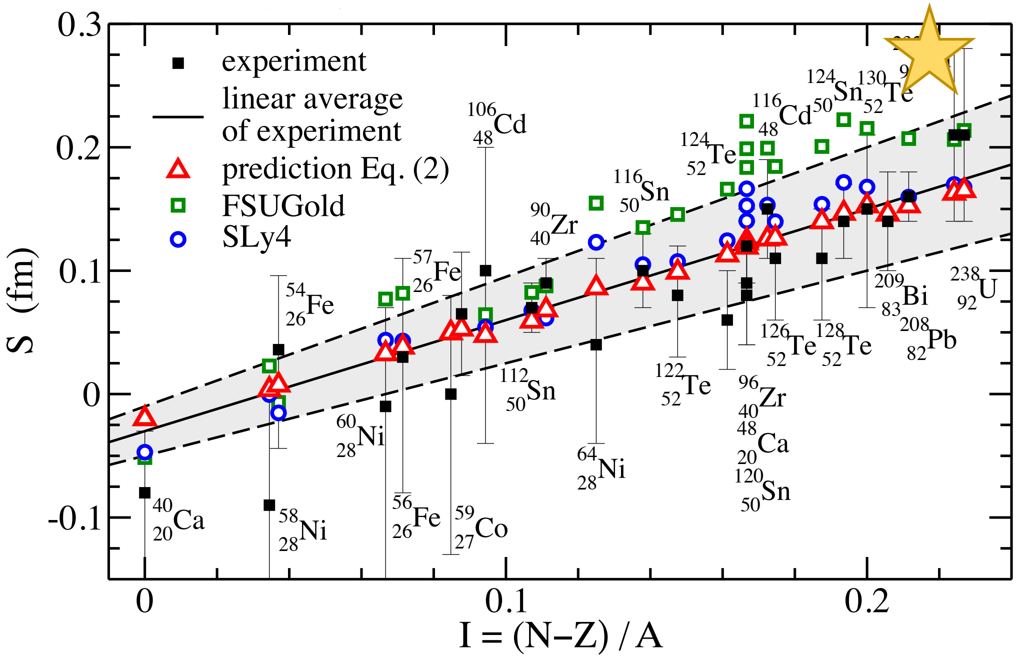
# The neutron skin of $^{208}$Pb

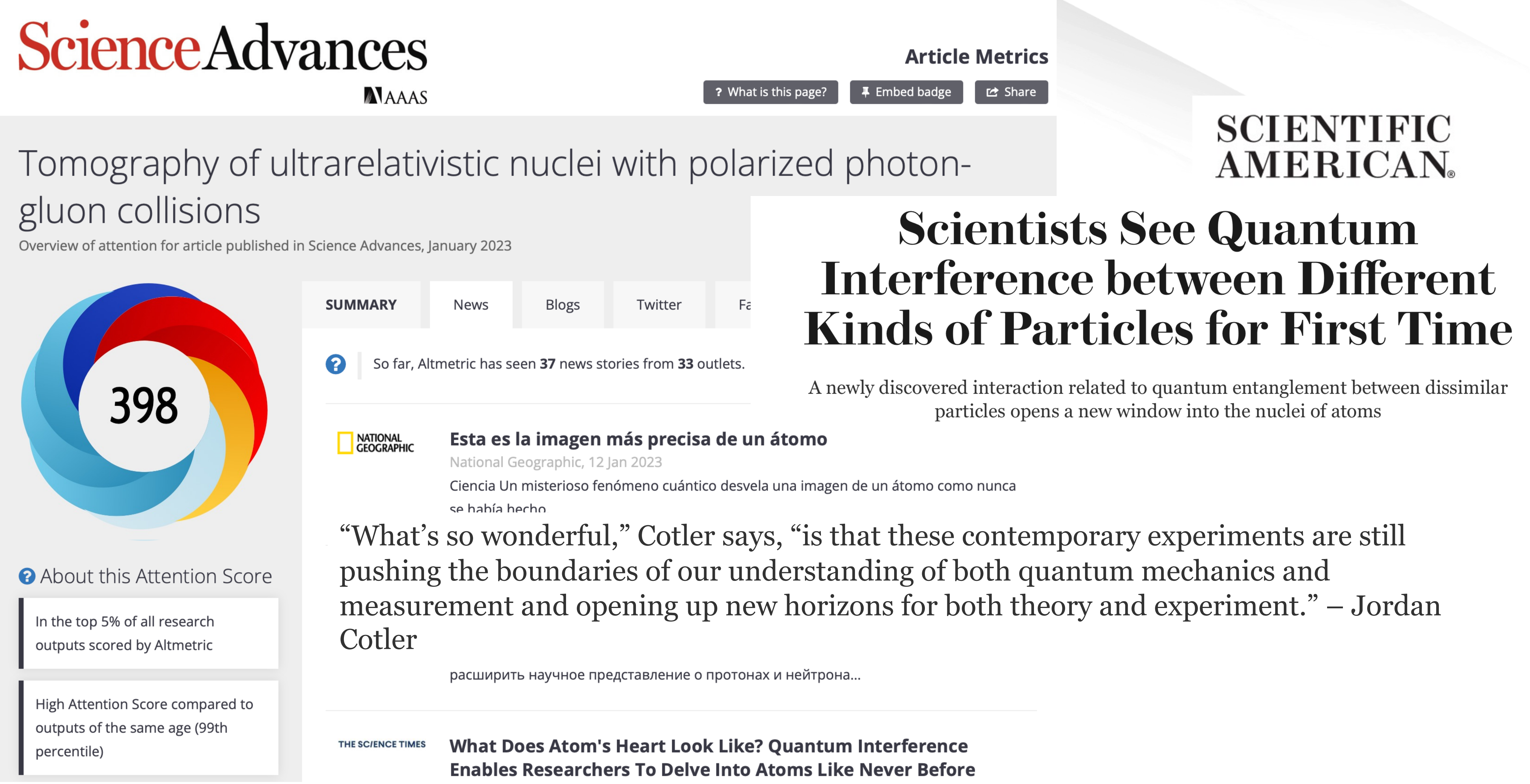
Currently some tension between PREX-II neutron skin measurement and existing neutron star EOS predictions



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

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





Science Advances
AAAS

**Article Metrics**

# Tomography of ultrarelativistic nuclei with polarized photon-gluon collisions

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

So far, Altmetric has seen **37** news stories from **33** outlets.

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

About this Attention Score

In the top 5% of all research outputs scored by Altmetric

High Attention Score compared to outputs of the same age (99th percentile)

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

“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

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**

# Summary

1. **Discovery of Breit-Wheeler process and Vacuum Birefringence in QED**
2. **Led to the discovery of interference between distinguishable particles!**
3. **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!

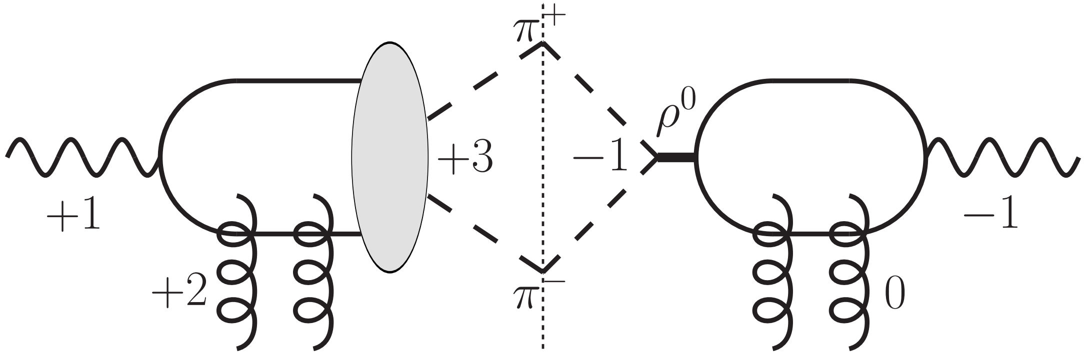
- Xiaofeng Wang (PhD student)
- Zhen Wang (PhD Student)
- Isabel Xu (High School Student)
- Isaac Upsal (Post-doc)
- Chi Yang (SDU)
- Wangmei Zha (USTC)
- Janet Seger (Creighton University)
- Frank Geurts (Rice University)
- Zhangbu Xu (BNL)
- Lijuan Ruan (BNL)

**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).

# Future Directions and Applications

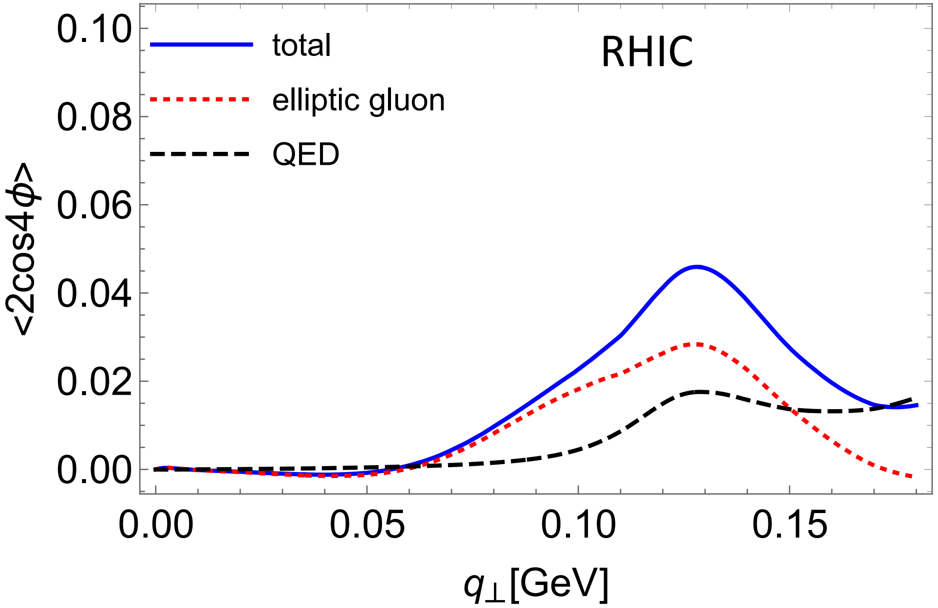
# Elliptic Gluon Tomography (Tensor Pomeron)

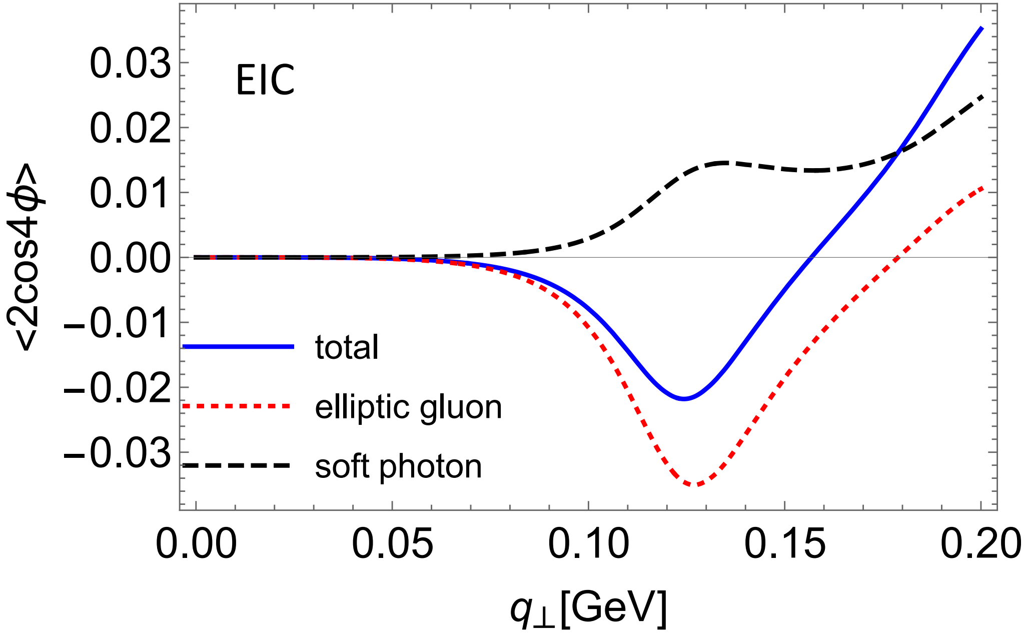


Phys. Rev. D **104**, 094021 (2021)

**Elliptic gluon distribution:** correlation between impact parameter and momentum

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





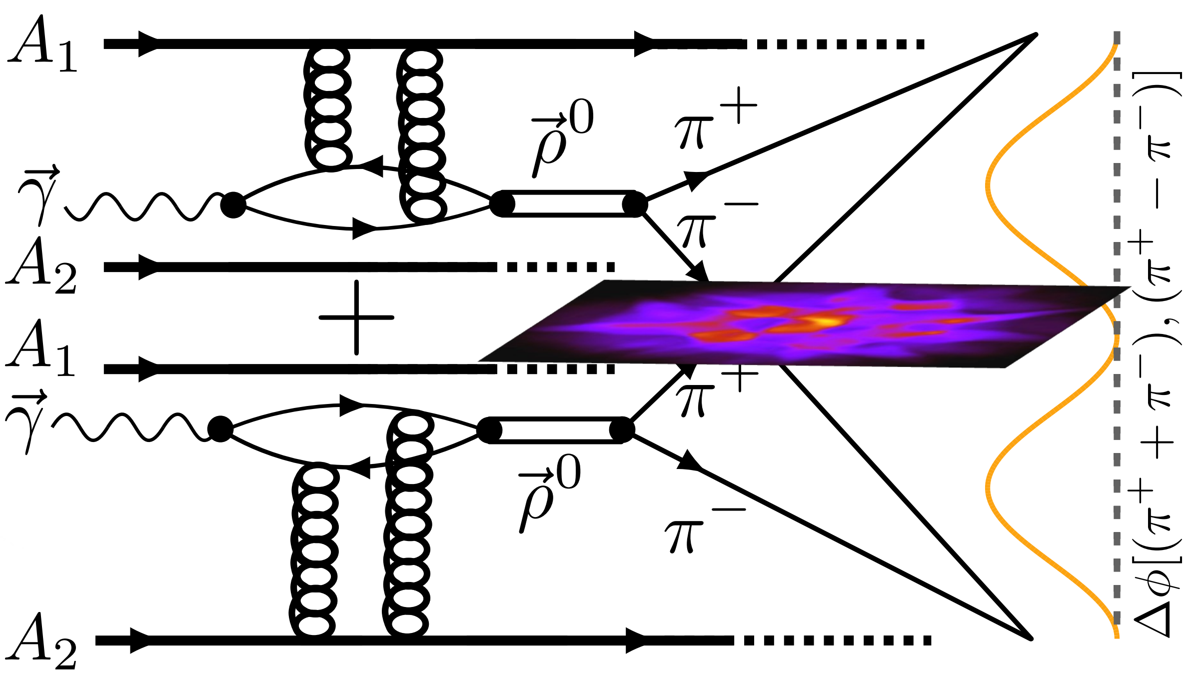
# Testing Quantum Mechanics

**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 $\rho^0 \rightarrow \pi^+\pi^-$ vs. $J/\psi \rightarrow l^+l^-$ (better from theoretical side)

- Will interaction with medium induce decoherence?



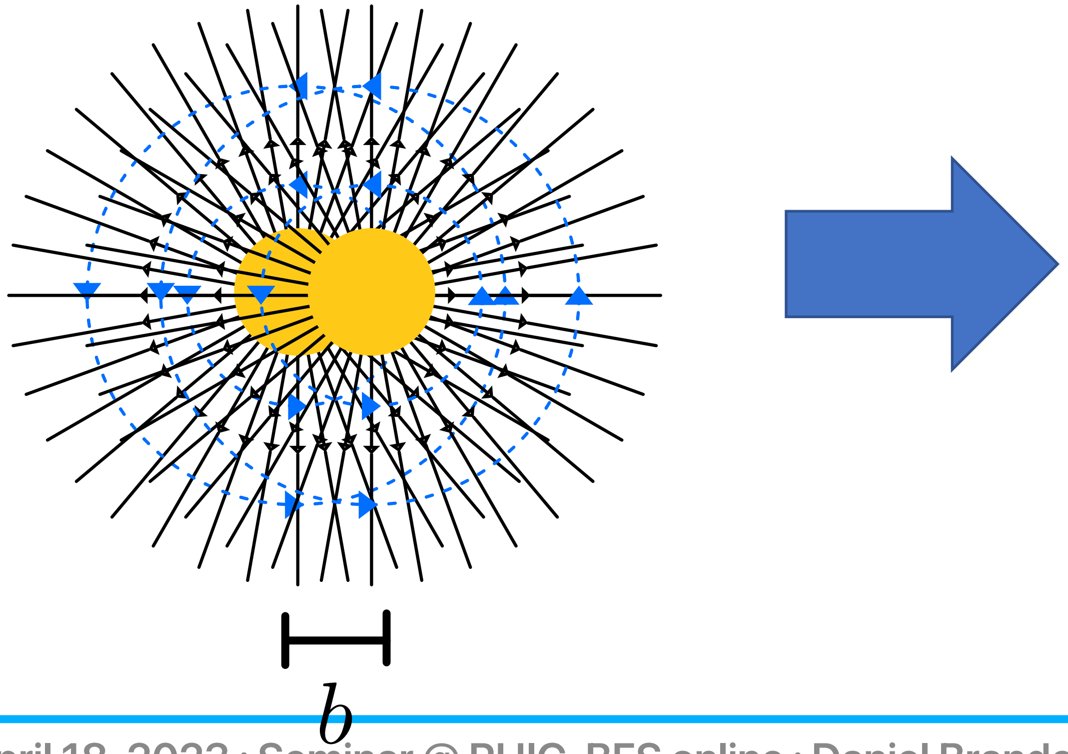
- Unlike leptons, $\pi$ interact via strong force
- Presence of strongly interacting medium → **wavefunction collapse?**
  - I.e. no interference?
  - Difference between pion vs. lepton final states?

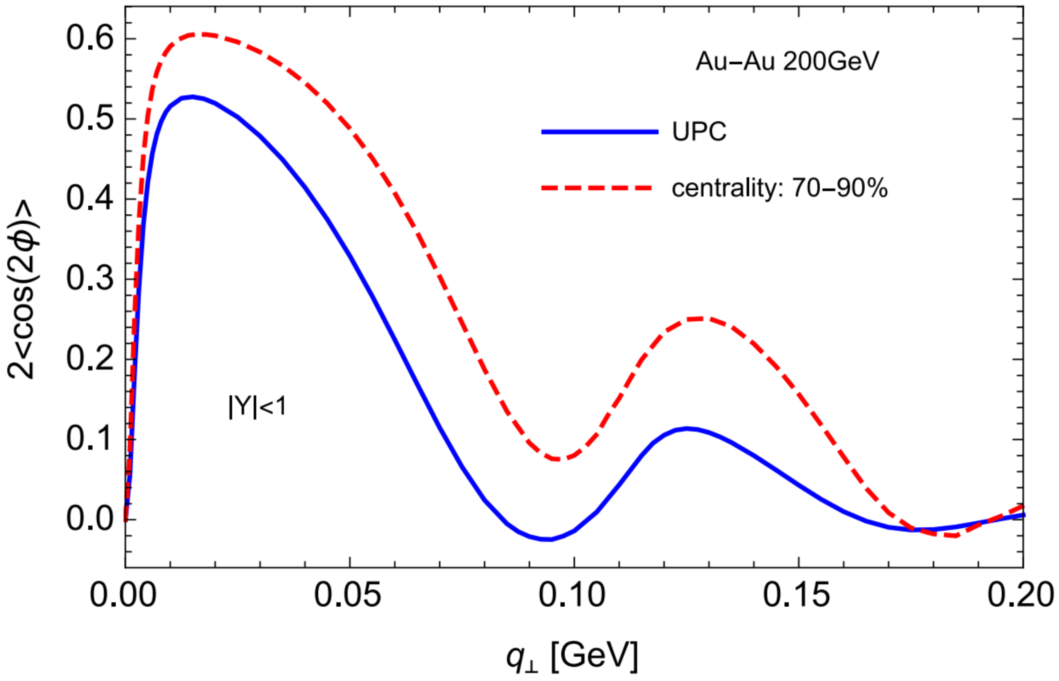
# Diffractive Production in non-UPC

- 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)

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

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

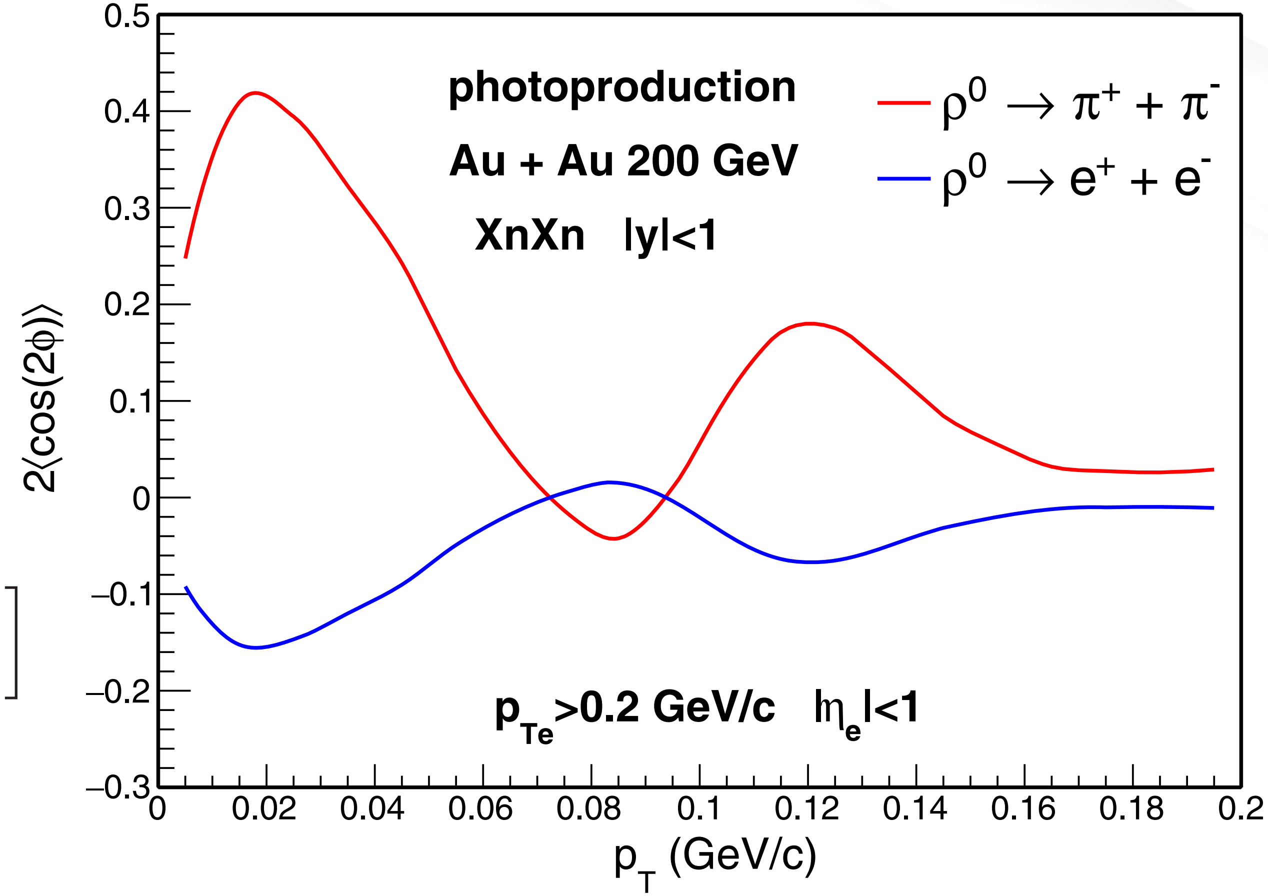
- For $\rho^0 \to e^+e^-$ (spin 1/2 daughters)

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

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

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

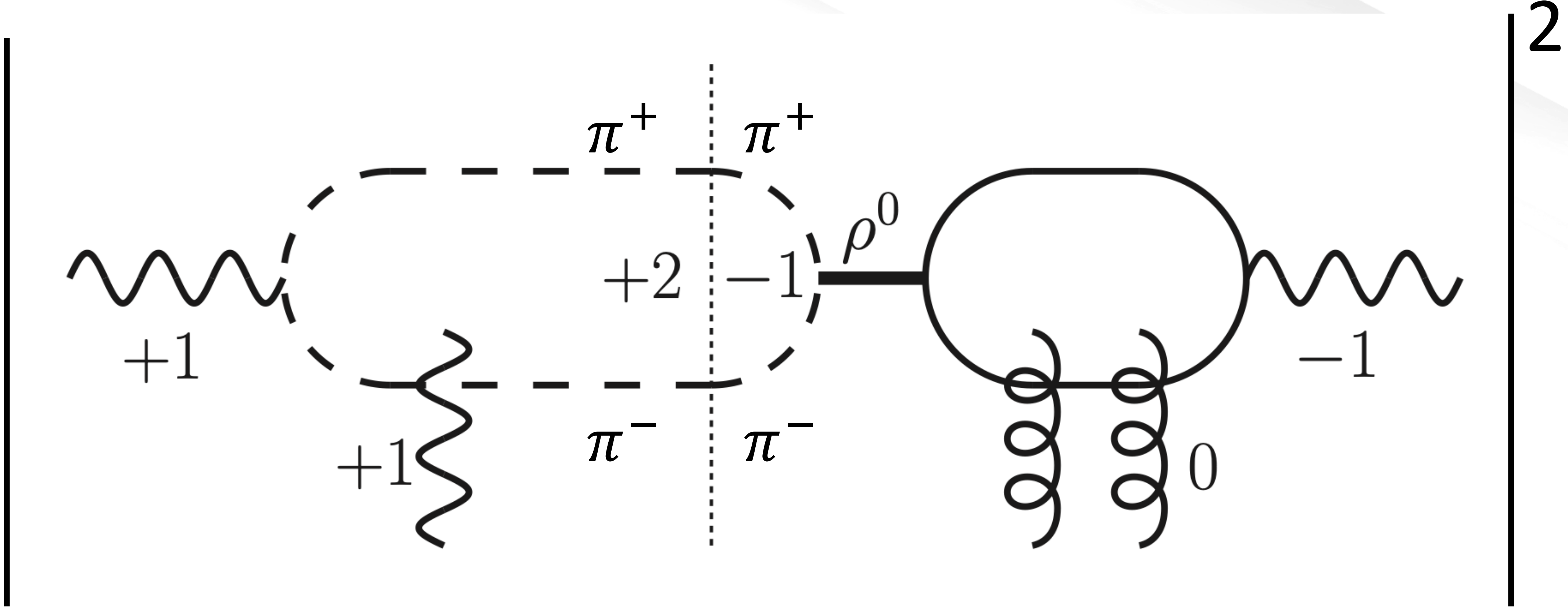
Zha, W., Brandenburg, J. D., Ruan, L. & Tang, Z. *Phys. Rev. D* **103**, 033007 (2021).



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

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

# Access to Hadronic Light-by-Light



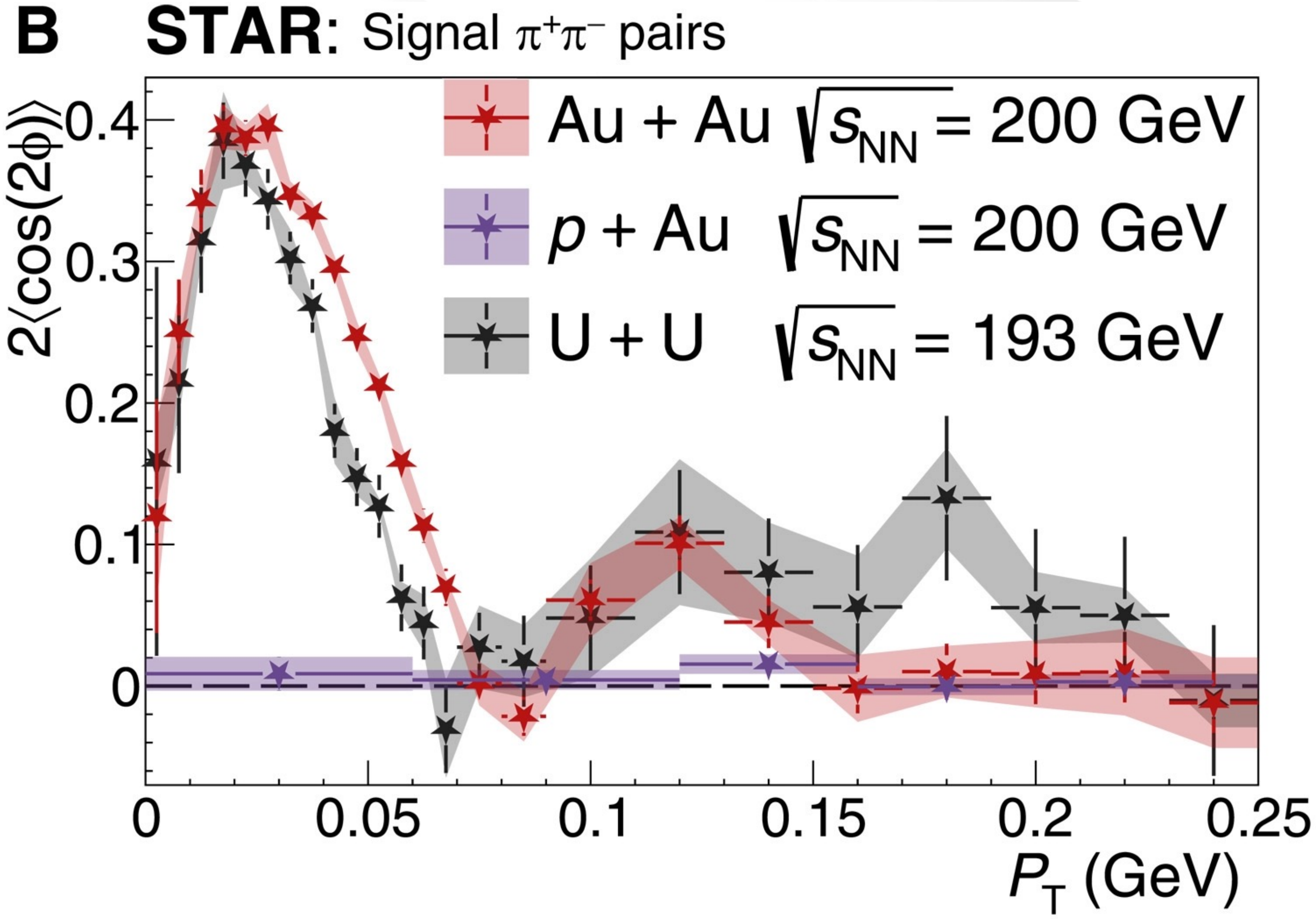
Interference with the hadronic light-by-light diagram
Leads to a unique signature -> odd spin configurations

# Momentum Dependence

Clear structure reminiscent of the diffractive cross section

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

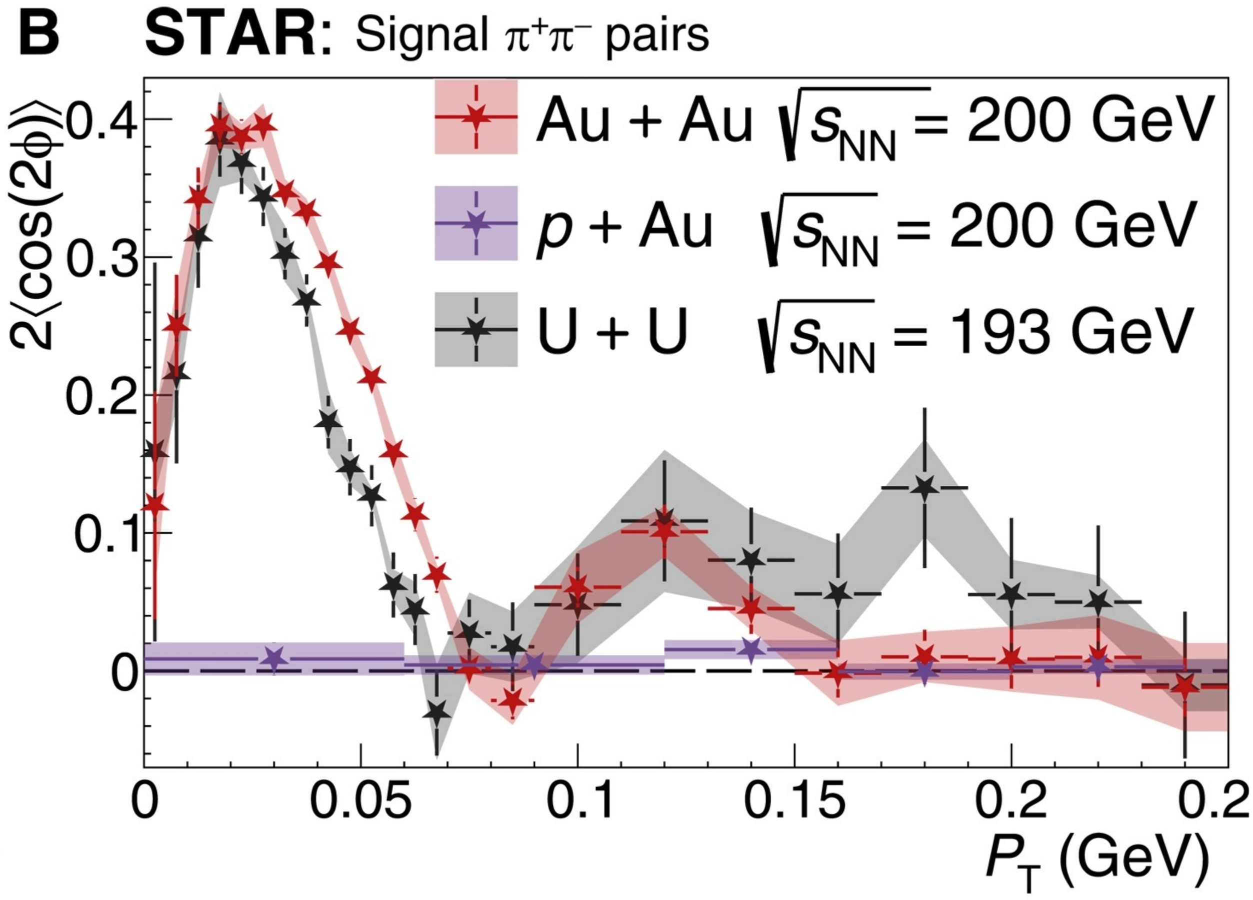
Null case: p+Au



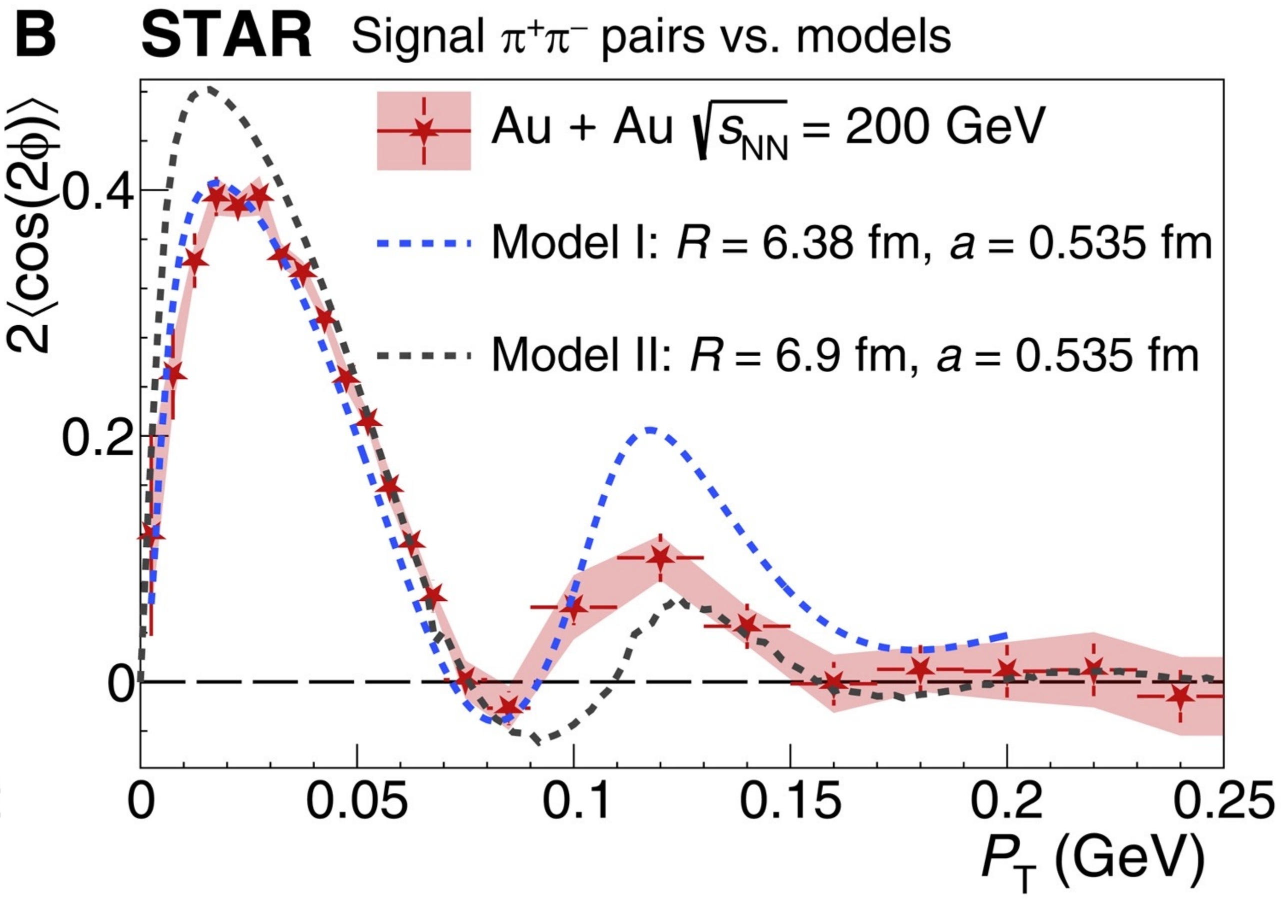
H. Xing, C. Zhang, J. Zhou, Y.-J. Zhou, The cos 2ϕ azimuthal asymmetry in $\rho^0$ meson production in ultraperipheral heavy ion collisions. *J. High Energ. Phys.* **2020**, 064 (2020).

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

# Comparison with theory



H. Xing, C. Zhang, J. Zhou, Y.-J. Zhou, The cos 2ϕ azimuthal asymmetry in $\rho^0$ 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).

# 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