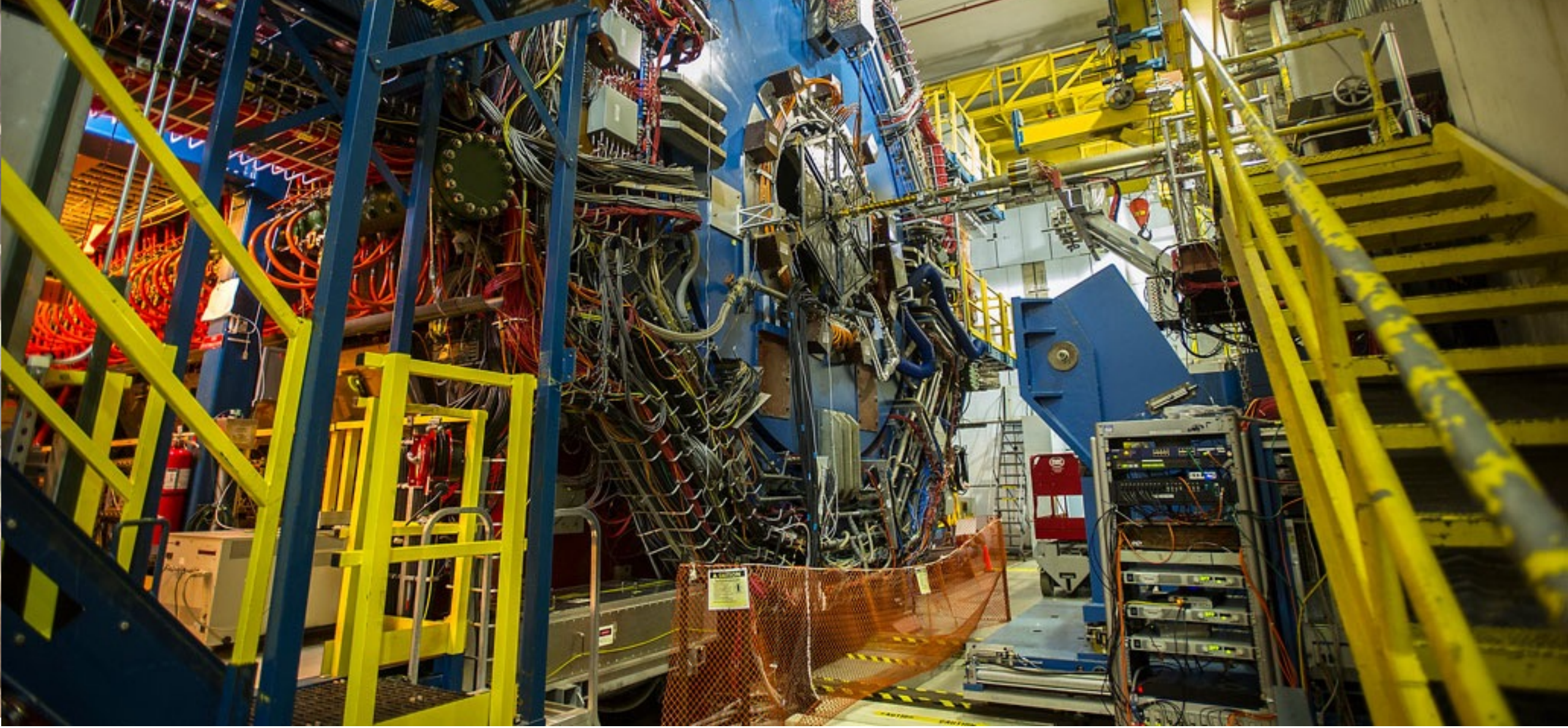

Ultraperipheral Collisions at STAR: 25 Years of Discovery

Daniel Brandenburg (OSU)

Dec 17 – 18, 2025

Brookhaven National Laboratory

From First Light to Quantum Imaging

A rough timeline of STAR's UPC journey

Year	Title/Publication	Key Result	Reference
2002	Coherent ρ^0 Production in UPC	First UPC vector meson	PRL 89 272302
2004	e+e- Pairs with Dissociation	Dileptons in UPC	PRC 70 031902
2008	ρ^0 Photoproduction in UPC	Incoherent, polarization	PRC 77 034910
2009	Two-Source Interference in ρ^0	Destructive interference	PRL 102 112301
2010	π+π-π+π- Photoproduction	Broad resonance	PRC 81 044901
2012	Energy Dependence of ρ^0	Cross-section vs. energy	PRC 85 014910
2016	Υ in U+U UPC	Bottomonium	PRC 94 064904
2017	Detailed ρ^0 Study	Transverse structure	PRC 96 054904
2018	Dileptons in Hadronic	p_T broadening	PRL 121 132301
2019	J/ψ in Hadronic	Excess, interference	PRL 123 132302
2021	Polarization in Dileptons	cos4ϕ, field mapping	PRL 127 052302
2022	J/ψ in d+Au UPC	Deuteron gluons	PRL 128 122303
2023	Spin Interference in ρ^0	Quantum entanglement	Sci. Adv. 9 eabq3903
2024	Exclusive J/ψ, ψ(2S), e+e-	Recent UPC results	PRC 110 014911
2024	Strong Suppression in J/ψ	UPC suppression	PRL 133 052301
2025			

* Not exhaustive

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2024	Strong Suppression in J/ψ	UPC suppression	**PRL 133 052301**

**** UPC accounts for ~10% of STAR's high impact jouranls (PRL + Science/Nature)**

* Not exhaustive

From First Light to Quantum Imaging

1. Early Years
2. Photonuclear Era
3. Paradigm Shifts
4. Looking Forward

Year	Title/Publication
2002	Coherent ρ^0 Production in UPC
2004	e+e- Pairs with Dissociation
2008	ρ^0 Photoproduction in UPC
2009	Two-Source Interference in ρ^0
2010	π+π-π+π- Photoproduction
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2016	Υ in U+U UPC
2017	Detailed ρ^0 Study
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2021	Polarization in Dileptons
2022	J/ψ in d+Au UPC
2023	Spin Interference in ρ^0
2024	Exclusive J/ψ, ψ(2S), e+e-
2024	Strong Suppression in J/ψ

* Not exhaustive

Foundations of UPC Physics at RHIC

"heavy ion collisions without actual collisions, are you kidding me?"

- Heavy-ion collisions: not just for nuclear physics!
- The viability of using heavy-ion collisions for testing purely electromagnetic processes was already a hot topic before RHIC started

<u>They outlined 3 main topics:</u>

➢ Purely electromagnetic (photon+photon)

➢ Photonuclear interactions (via the hadronic structure of the photon)

➢ Coulomb excitation

RELATIVISTIC COULOMB COLLISIONS AND THE VIRTUAL RADIATION SPECTRUM

C.A. BERTULANI* and G. BAUR

Institut für Kernphysik, Kernforschungsanlage Jülich, D-5170 Jülich, West Germany

Received 15 March 1985

HOT TOPICS IN ULTRA-PERIPHERAL ION COLLISIONS

G. BAUR[a], C. A. BERTULANI[b], M. CHIU[c], I. F. GINZBURG[d], K. HENCKEN[e], S. R. KLEIN[f], J. NYSTRAND[g],K. PIOTRZKOWSKI[h] C. G. ROLDAO[i] D. SILVERMYR[g], J. H. THOMAS[f], S. N. WHITE[j] and P. YEPES[k]

[a] *Forschungzentrum Jülich, Jülich, Germany*
[b] *Natl. Superconducting Cyclotron Lab., Michigan State University, East Lansing, MI, 48824 USA*
[c] *Columbia University, New York, NY, 10027 USA*
[d] *Sobolev Institute of Mathematics, SB RAN, 630090, Novosibirsk, Russia*
[e] *Universität Basel, 4056 Basel, Switzerland*
[f] *Lawrence Berkeley National Laboratory, Berkeley, CA, 94720, USA*
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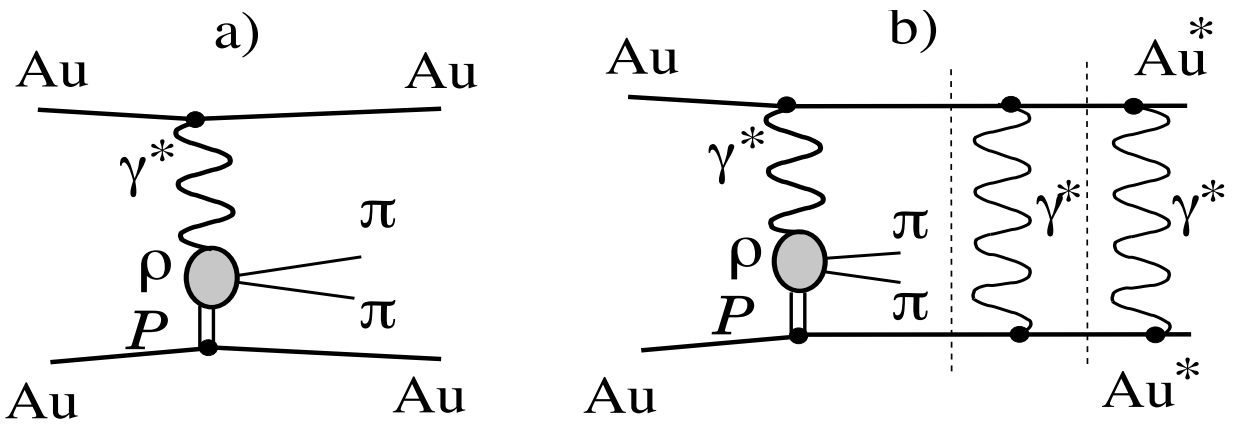
[h] *Departement de Physique, Universite Catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium*
[i] *Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paolo, Brazil*
[j] *Brookhaven National Laboratory, Upton, NY, 11973, USA*
[k] *Physics and Astronomy Dept., Rice University, Houston, TX, 77005, USA*

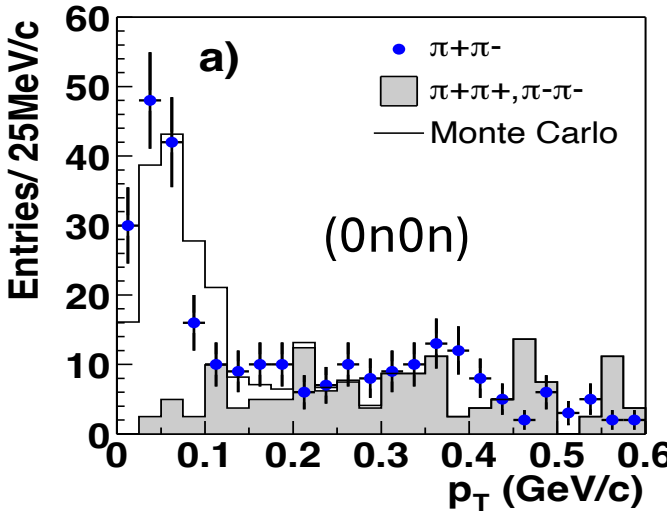
Ultra-peripheral collisions of relativistic heavy ions involve long-ranged electromagnetic interactions at impact parameters too large for hadronic interactions to occur. The nuclear charges are large; with the coherent enhancement, the cross sections are also large. Many types of photonuclear and purely electromagnetic interactions are possible. We present here an introduction to ultra-peripheral collisions, and present four of the most compelling physics topics. This note developed from a discussion at a workshop on "Electromagnetic Probes of Fundamental Physics," in Erice, Italy, Oct. 16-21, 2001.

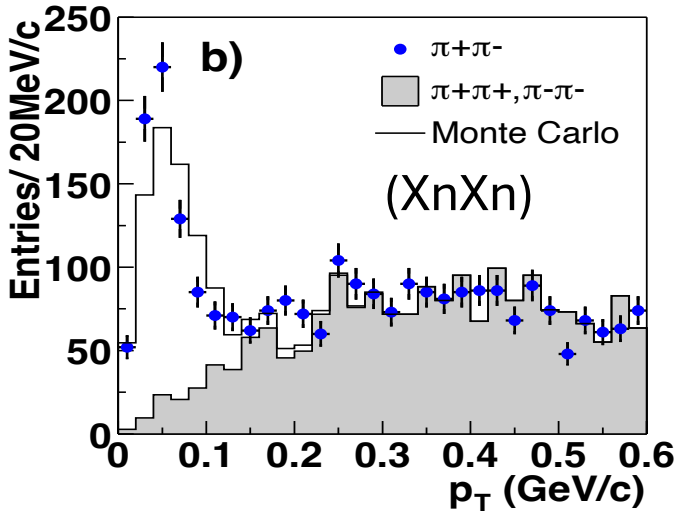
2002 : First Photonuclear Measurements

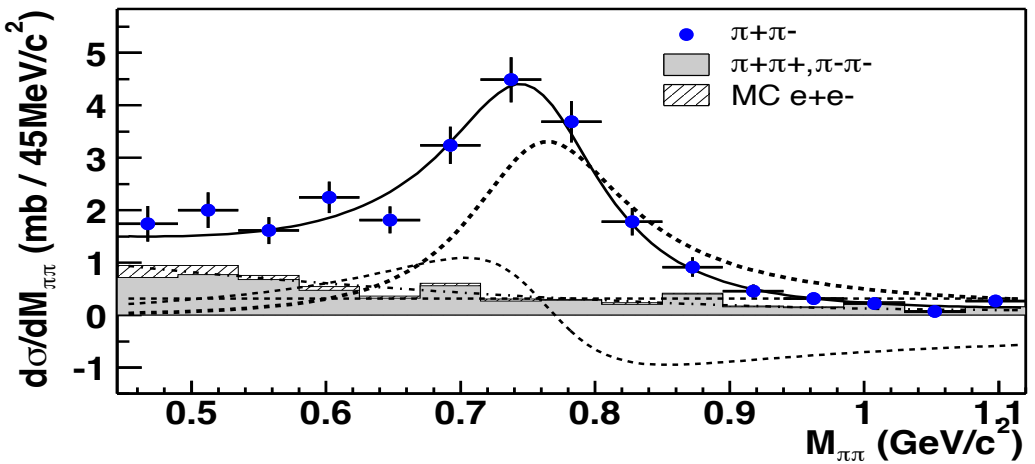


- 787 events (after selection) from Au+Au collisions at $\sqrt{s_{NN}} =$ 130 GeV
- Half field (0.25 T)
- ZDC-based 'minimum-bias' trigger and topological (for 0n0n)

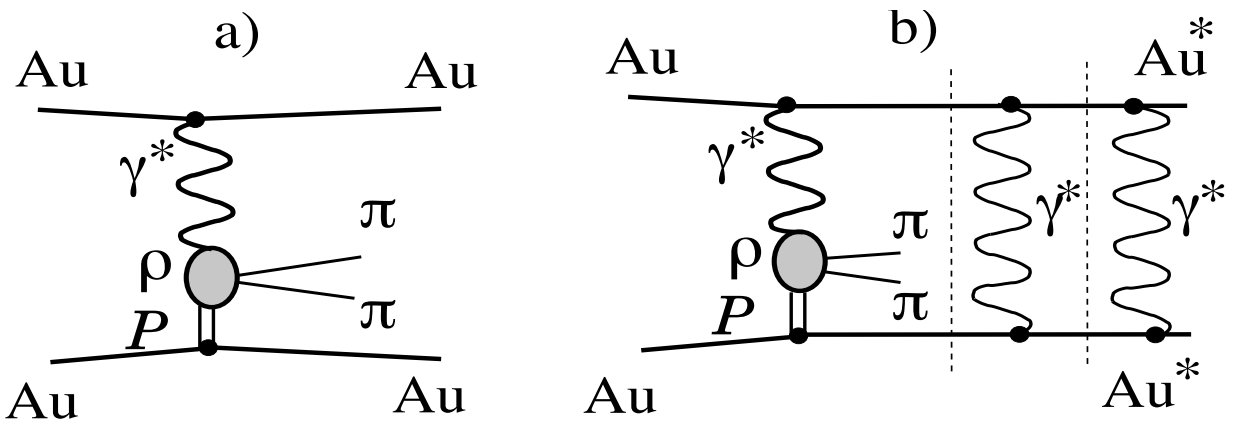
Phys.Rev.Lett.89:272302,2002





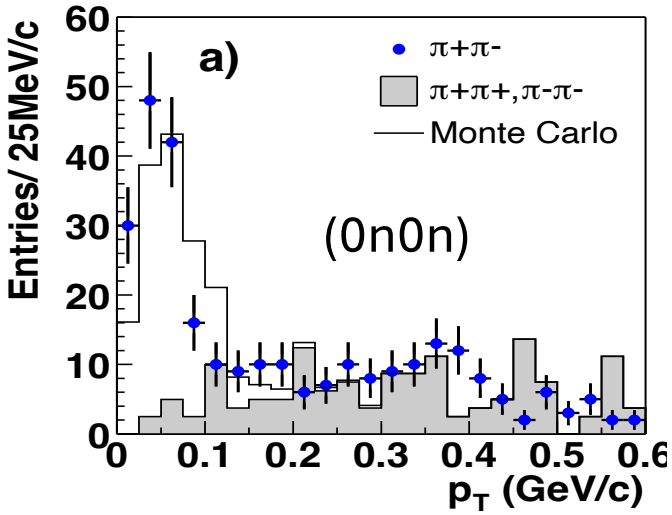


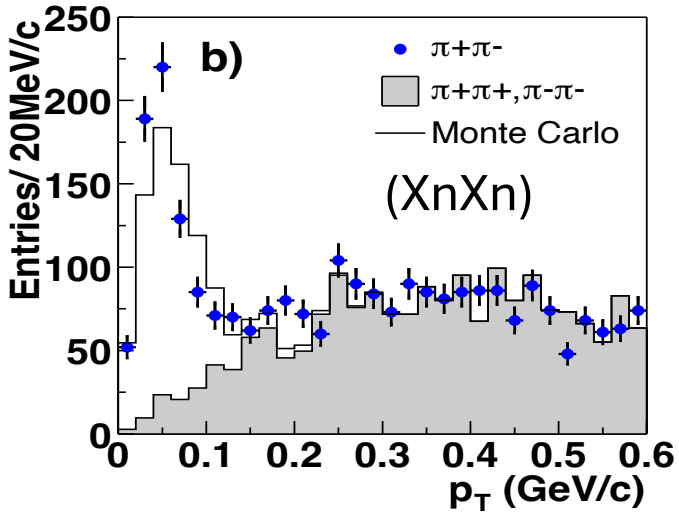
2002 : First Photonuclear Measurements

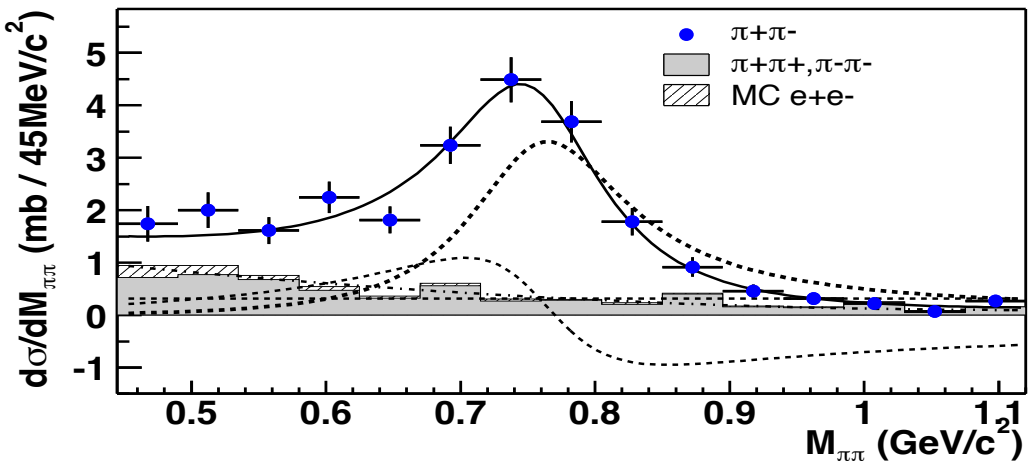


- 787 events from Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV
- Half field (0.25 T)
- ZDC-based 'minimum-bias' trigger and topological (for 0n0n)
- **Low-Pt = coherent production**
- **Cross section shows that central process and mutual Coulomb Excitation are separable**

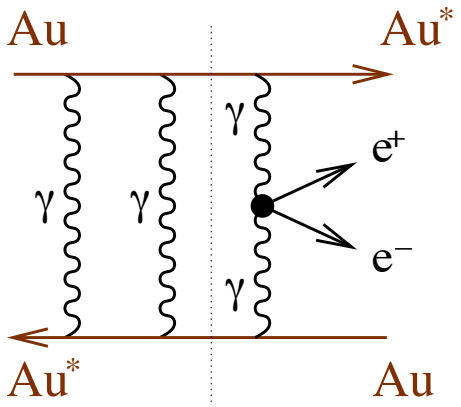
Phys.Rev.Lett.89:272302,2002

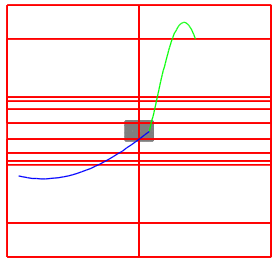


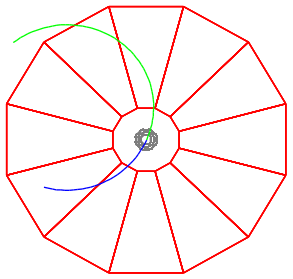




2004: First Photon-Photon Measurements







Electron-Positron Production in Ultra-Peripheral Heavy-Ion Collisions with the STAR Experiment

by

Vladimir Borisovitch Morozov

B. S. (Moscow Institute of Physics and Technology) 1997
M. A. (University of California at Berkeley) 1999

A dissertation submitted in partial satisfaction of the
requirements for the degree of
Doctor of Philosophy

in

Physics

in the

GRADUATE DIVISION
of the
UNIVERSITY OF CALIFORNIA, BERKELEY

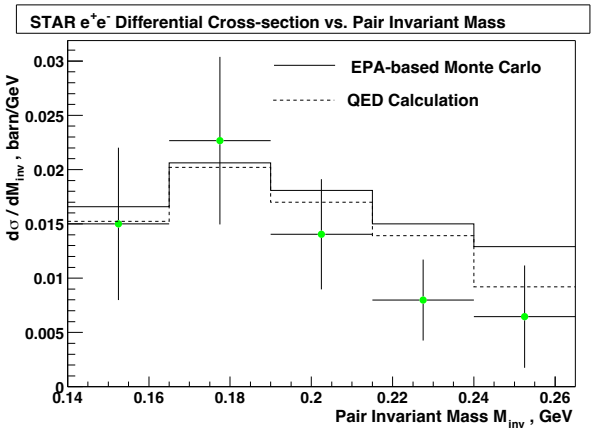
Committee in charge:
Professor Marjorie D. Shapiro, Chair
Doctor Spencer R. Klein
Professor Richard Marrus
Professor Steven N. Evans

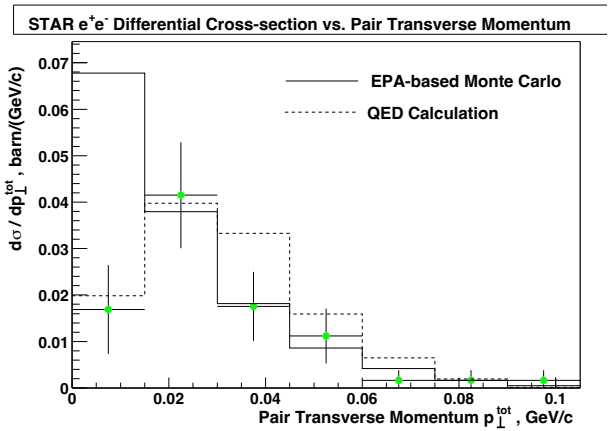
Fall 2003

STAR's 7th thesis
(according to Drupal)

- 800000 min-bias events from Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV
- After applying signal selection (2 tracks only) – 52 signal events remained
- First comparisons with leading order QED

PRC 70 031902



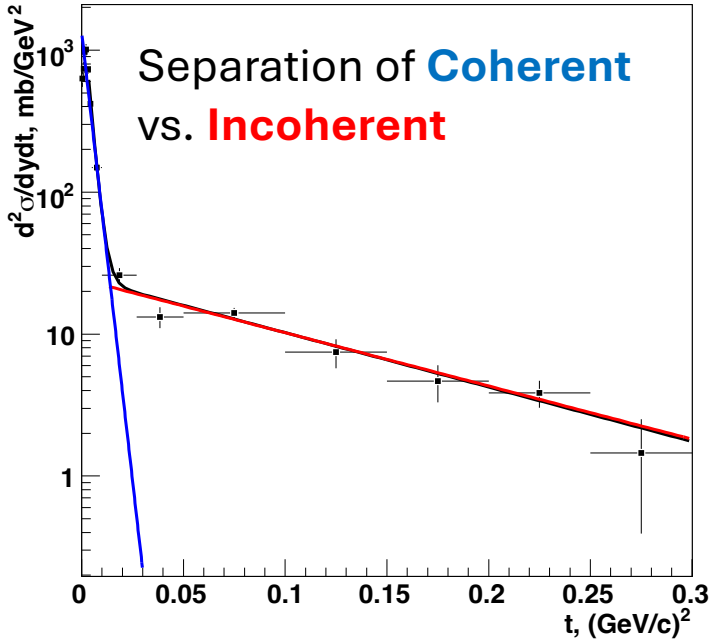


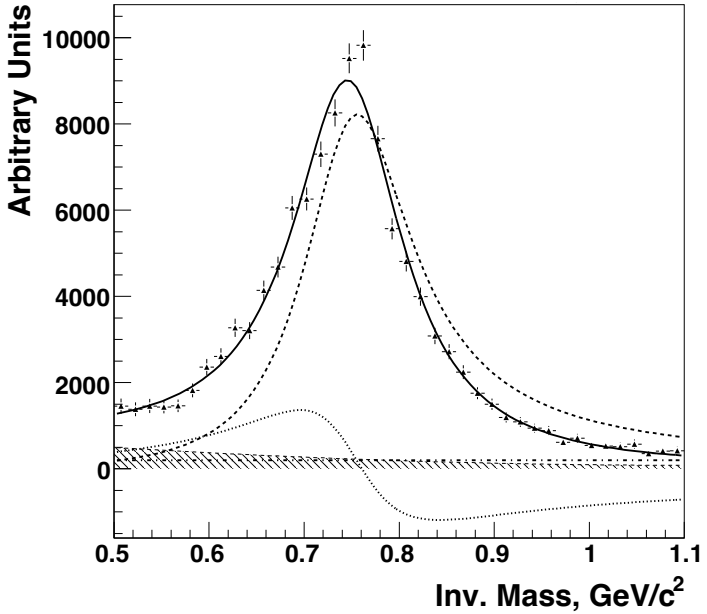
The Photonuclear Era 2005-10: Light Vector Mesons

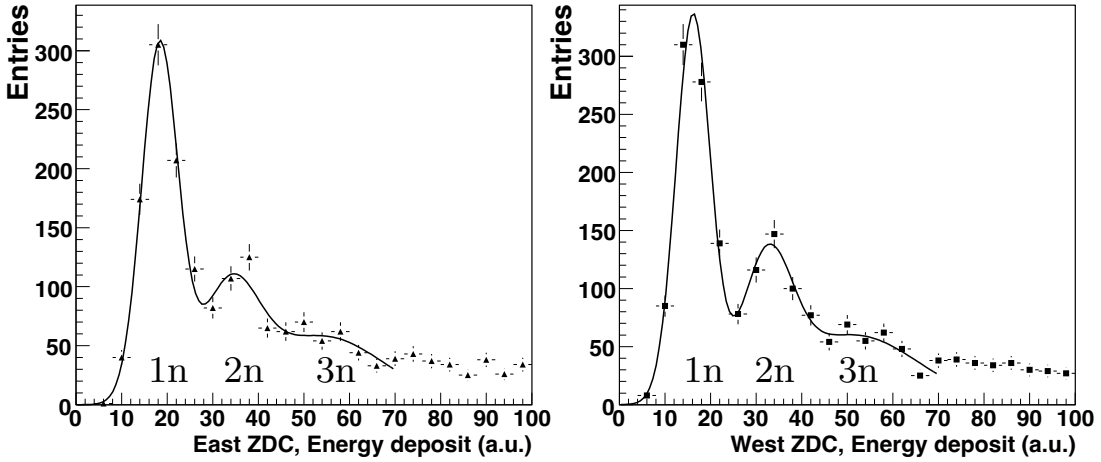
Larger datasets opens new physics oportunities

- Improving RHIC luminosity and trigger tuning led to huge increase in available statistics
- ~100K signal-like events (compared to ~1k from 2004)

Phys.Rev.C77:034910,2008

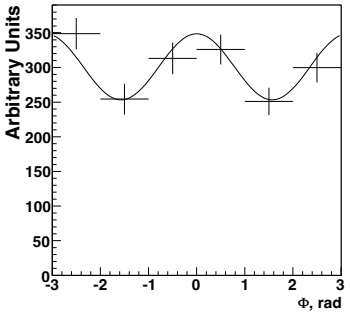






First extraction of spin-density matrix elements. Consistent with spin-1 meson

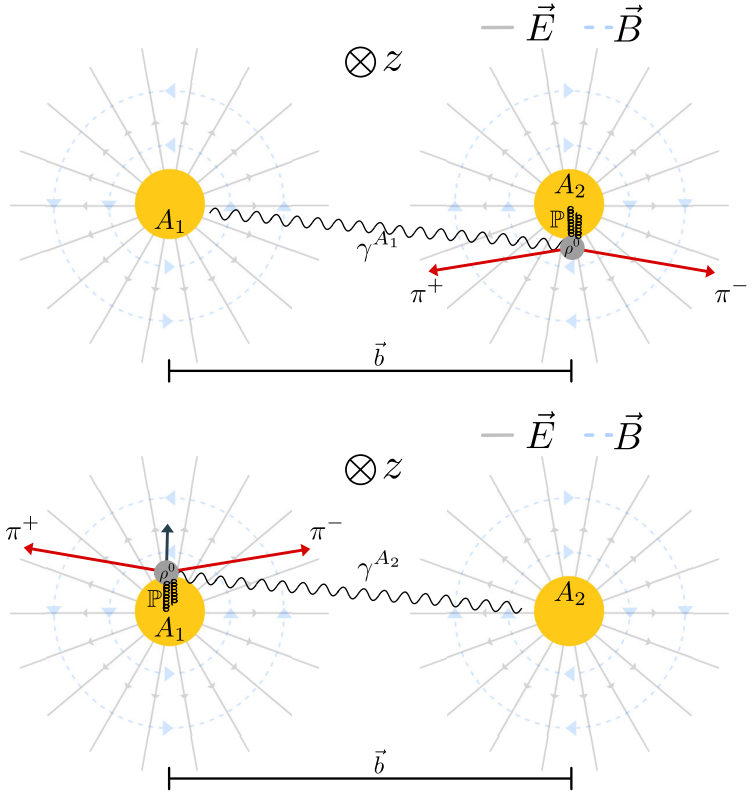
$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos(\Theta_h)d\Phi_h} = \frac{3}{4\pi}\cdot[\frac{1}{2}(1-r^{04}_{00}) + \frac{1}{2}(3r^{04}_{00}-1)\cos^2(\Theta_h) - \sqrt{2}\Re e[r^{04}_{10}]\sin(2\Theta_h)\cos(\Phi_h) - r^{04}_{1-1}\sin^2(\Theta_h)\cos(2\Phi_h)].$$



The Photonuclear Era 2005-10: Light Vector Mesons

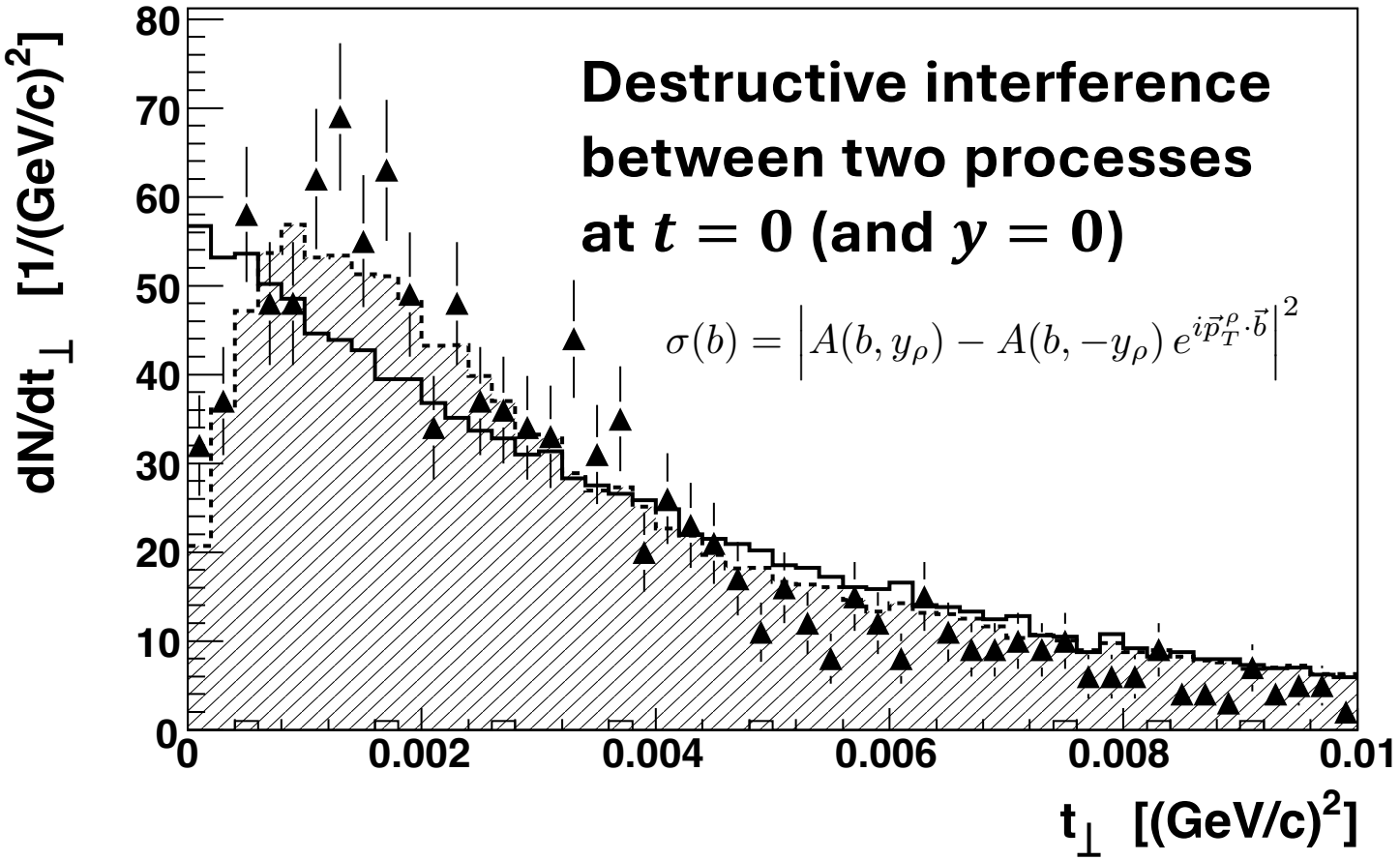
Increased precision -> First test of the “double-slit” interference

➢EPR-like effect since ρ^0 decays before interacting



Photon-emitter vs. target ambiguity

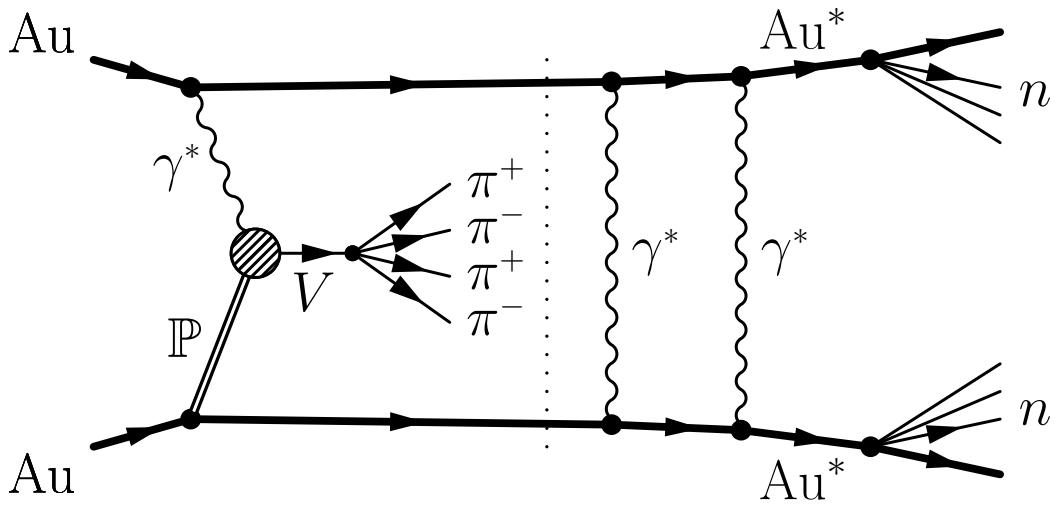
PRL 102 112301, 2009



The Photonuclear Era 2008-10: Light Vector Mesons

2010: First measurement of 4 pion final states

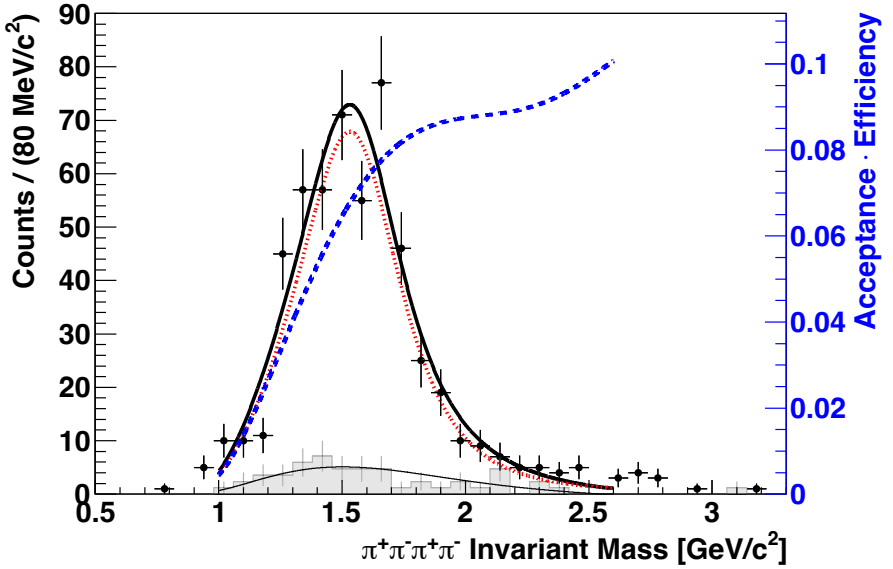
- Low-pT consistent with coherent production
- Initial tests of decay models (ρ' branching to $\pi^+\pi^-$ vs. $\pi^+\pi^-\pi^+\pi^-$)

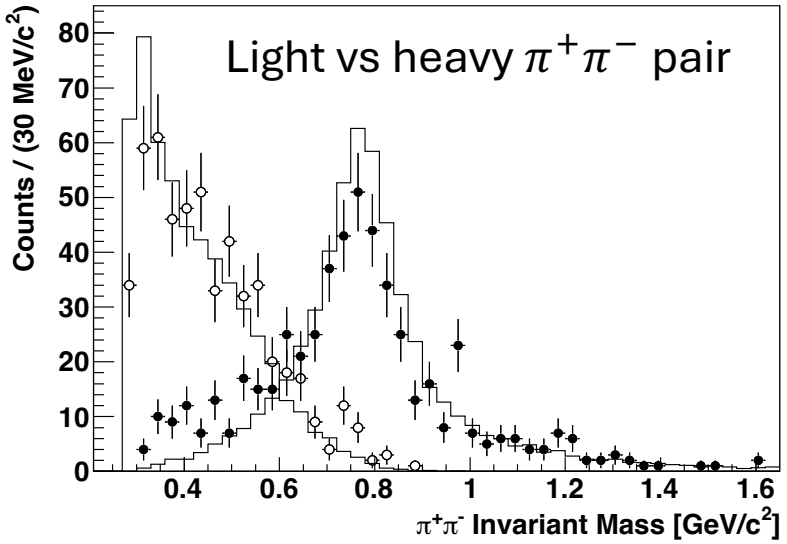


- Roughly consistent with

$$\rho' \to \rho^0(770)\ f_0(600) \to [\pi^+\pi^-]_{P\text{-wave}}\ [\pi^+\pi^-]_{S\text{-wave}}$$

PRC 81 044901, 2010





Paradigm Shifts : Challenging Conventional Picture

1. Photon virtuality, polarization, and interference

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

2. Electromagnetic interactions in hadronic heavy-ion collisions

   Phys. Rev. Lett. 121, 132301 (2018)
   Phys. Rev. Lett. 121, 132302 (2018)

3. Nuclear Tomography and interference of distinct (entangled) particles

   Sci. Adv. 9 eabq3903, 2023

   PRL 128 122303 (2022)

   PRL 133 052301 (2024)

   arXiv:2512.02865, Submitted to PRL

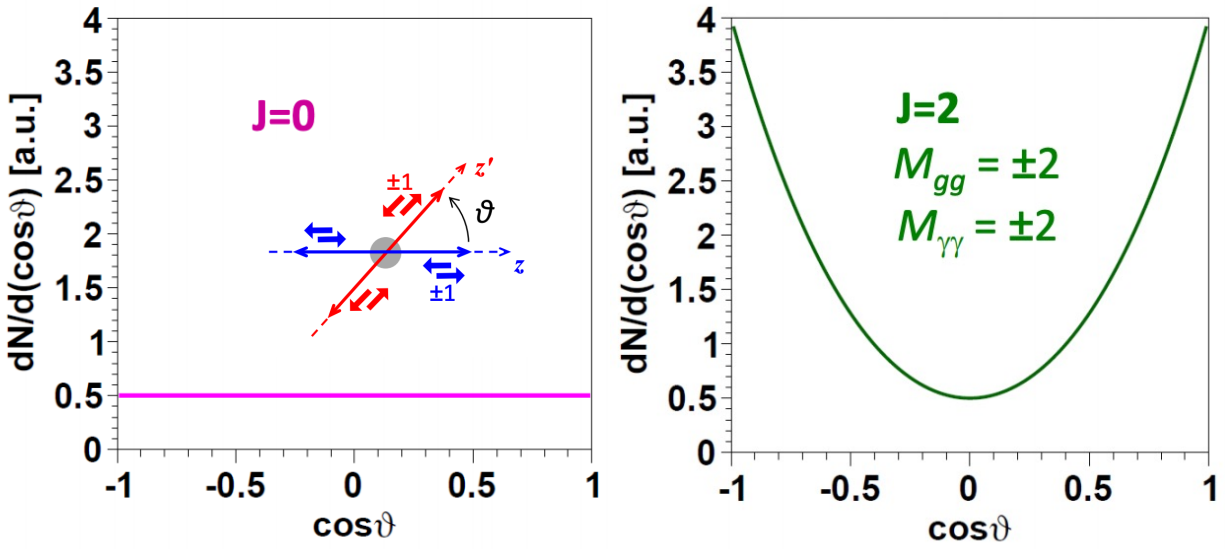
*slightly out of chronological order

Another look at $\gamma\gamma \rightarrow e^+e^-$ (aka Breit-Wheeler process)

→ **Perform a precision measurement of the differential cross sections**

Angular distribution allows identification of quantum numbers - e.g. Higgs Boson

SM Higgs boson



Are photon-photon interactions dominated by high photon virtuality?

General density matrix for the two-photon system:

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

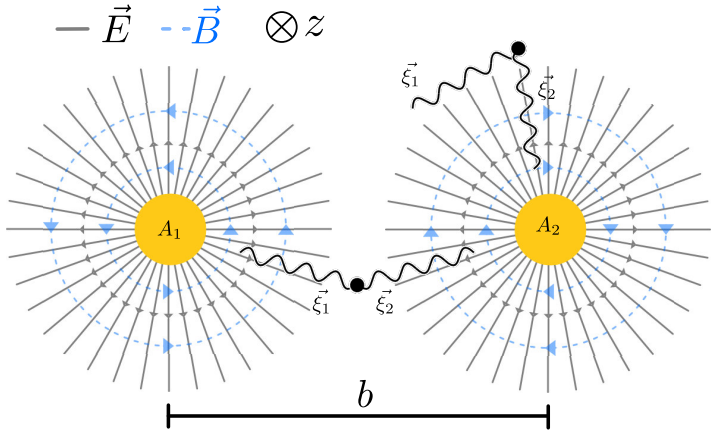
Spin 1 Photon helicity $a = (-, 0, +)$

Helicity 0 : Forbidden for real photon

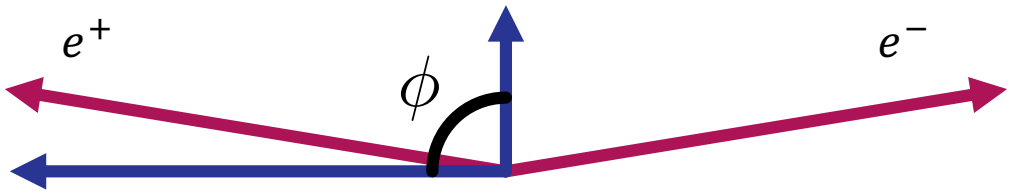
Real photon: Allowed J^P states: $2^{\pm}, 0^{\pm}$

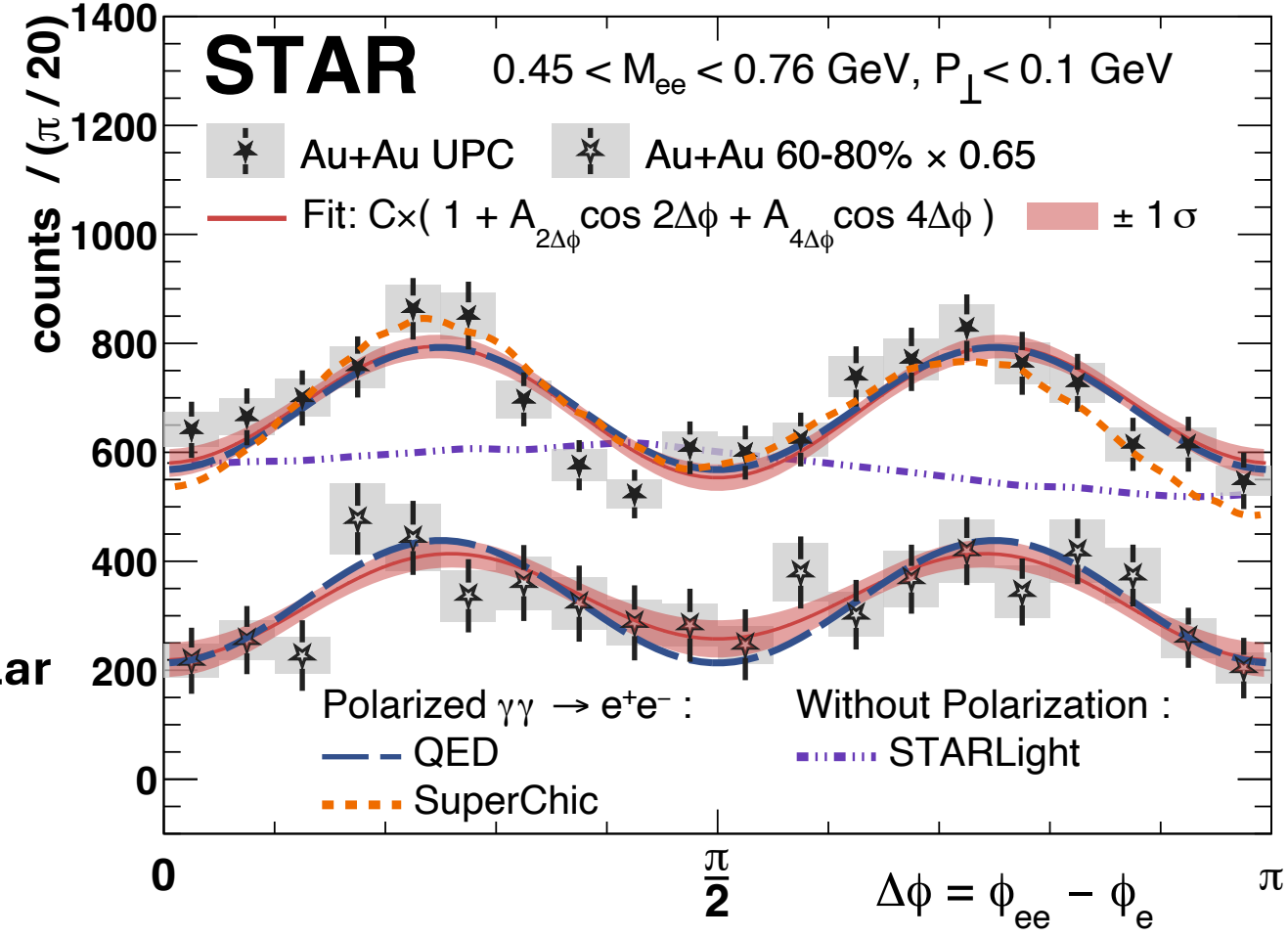
<u>TEST by measuring angular distributions</u>

2021: Discovery of the Breit-Wheeler Process



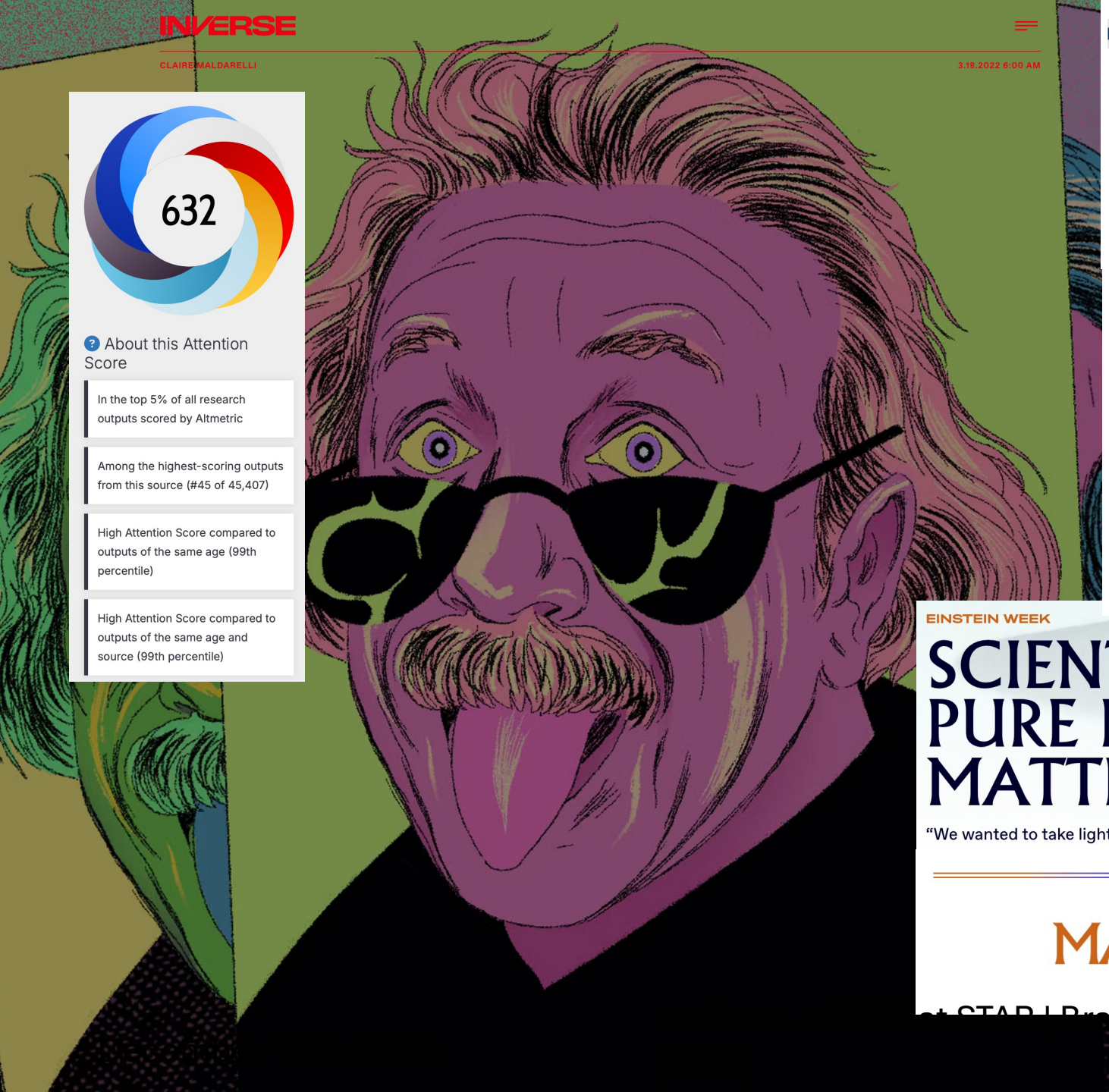
- Polarization vector ξ: aligned radially with the "emitting" source
- Intrinsic photon spin converted into **orbital angular momentum**
- Observable as anisotropy in $e^{\pm}$ momentum – a $\cos 4\phi$ modulation





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

Photons are polarized + polarization is experimentally observable



632

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

Among the highest-scoring outputs from this source (#45 of 45,407)

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

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

PHYS.ORG

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.

ScienceNews

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...

SCIENMAG

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...

EurekAlert! AAAS

Making matter from collisions of light

EurekAlert!, 25 Jan 2022

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

VICE

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

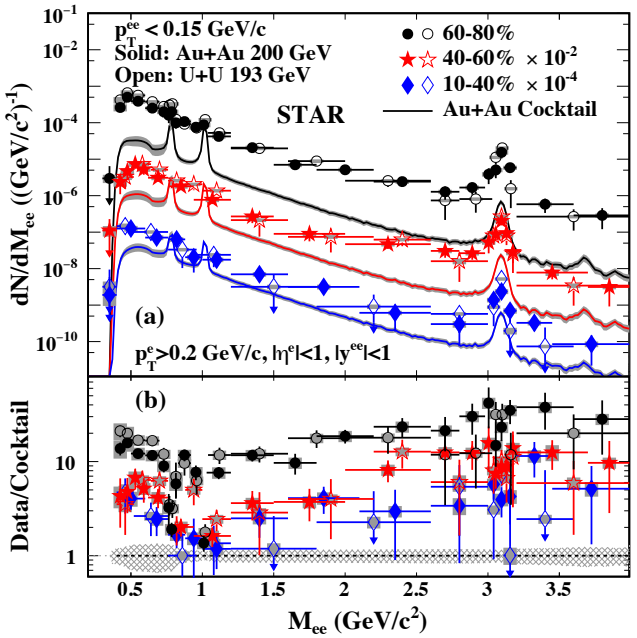
"We wanted to take light and convert it into matter." Wish fulfilled.

MAKING NEW PHYSICS POSSIBLE

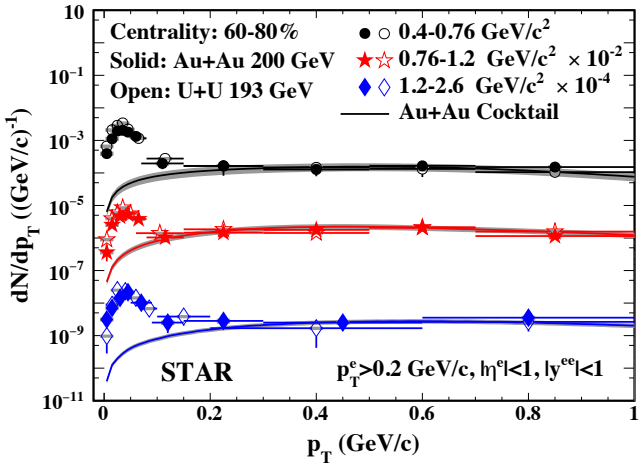
at STAR | Brandenburg

Electromagnetic interactions in Hadronic heavy-ion collisions

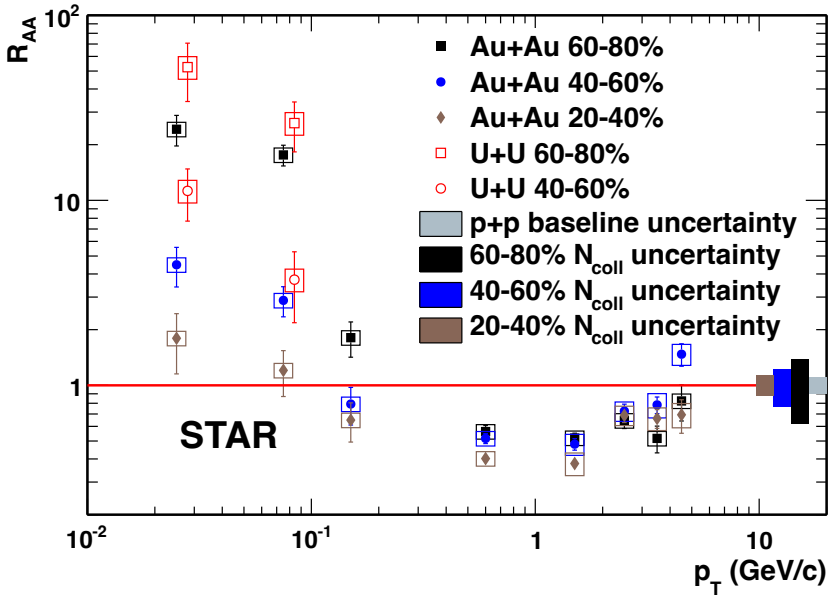
- Conventionally, electromagnetic interactions not expected in hadronic collisions
- Conventional picture of coherence is challenged – if the nucleus breaks up, what is the coherent photon emitter?



10x enhanced production compared to expected hadronic sources



Dominant production cross section at low-pt -> consistent with Coherent $\gamma\gamma \rightarrow e^+e^-$ production



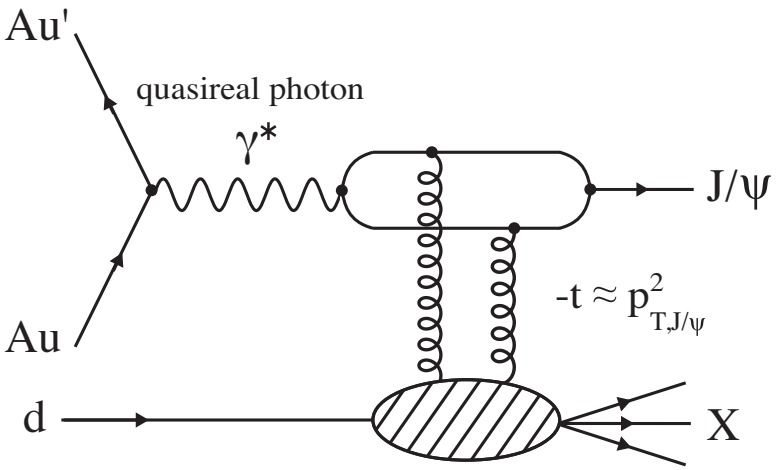
Similar enhancement observed in $\gamma A \rightarrow J/\psi$ production

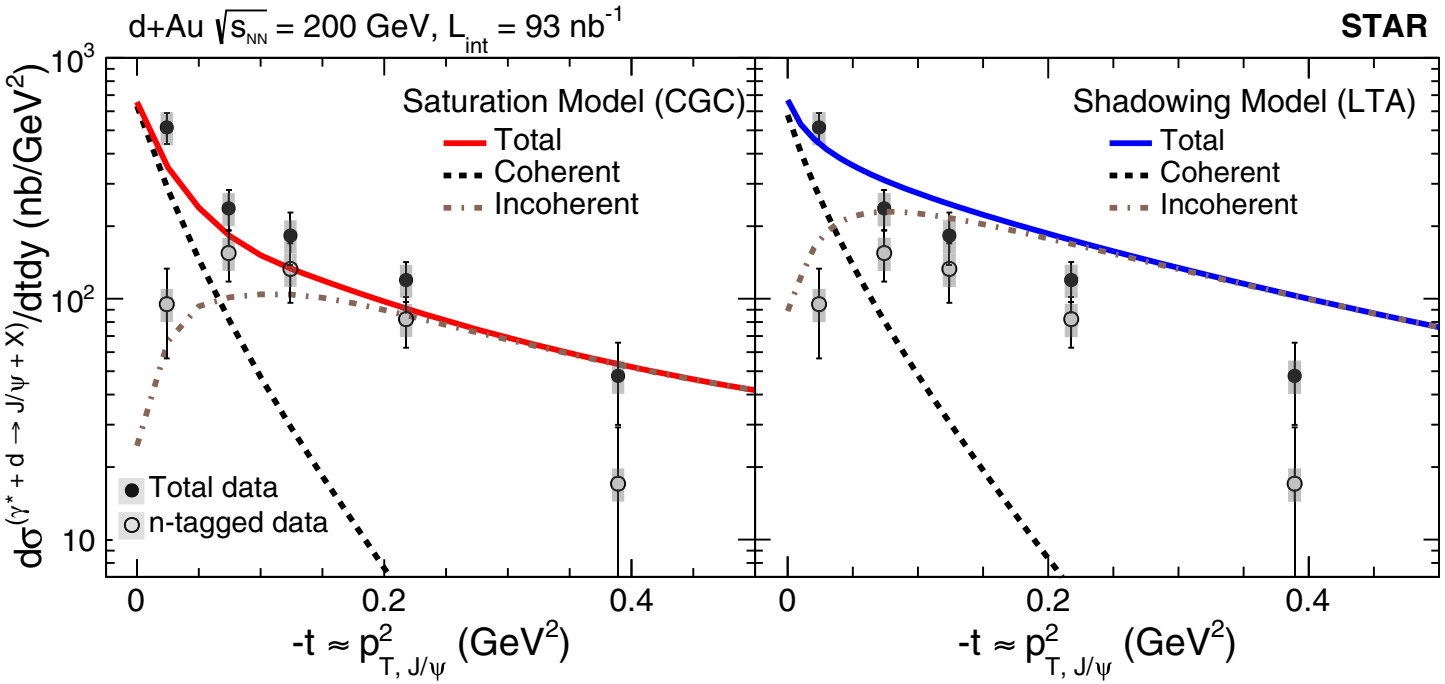
Photo-processes can and do take place in HADRONIC heavy ion collisions

2022: Advances in Nuclear Tomography

Imaging the smallest bound nucleus

Phys. Rev. Lett. 128, 122303 (2022)





CGC Model Ref: H. Mäntysaari and B. Schenke, Phys. Rev. C 101, 015203 (2020), arXiv:1910.03297 [hep-ph].

LTA Model: V. Gauzy, M. Strickman, E. Kryshen, and M. Zhalov (2021)

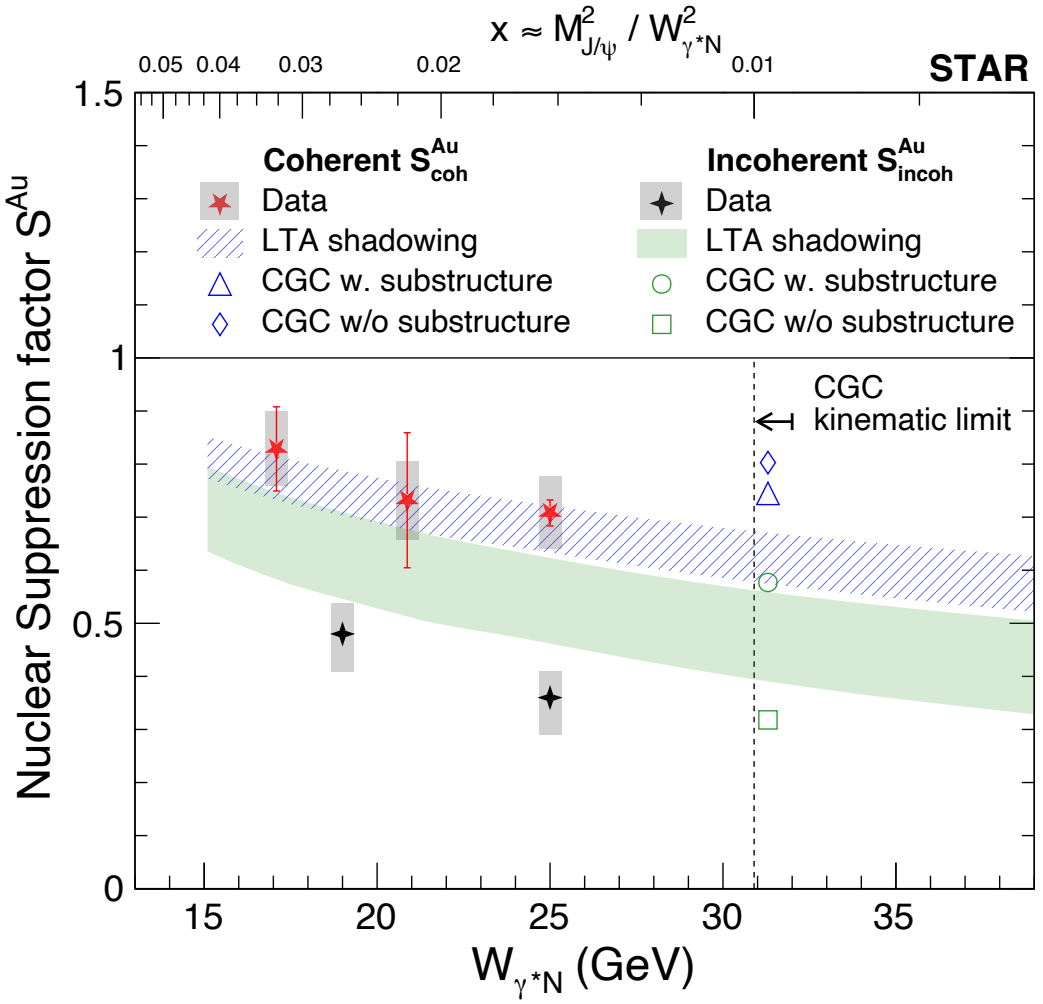
- integrated luminosity of 93 nb^{-1} of d+Au data collected in 2016
- $J/\psi \rightarrow e^+e^-$ decay channel

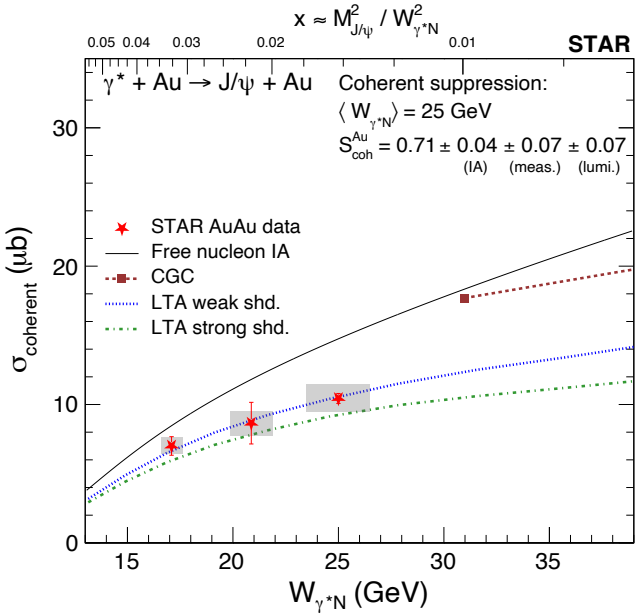
- first J/ψ produced off a light ion
  - deuteron loosely bound => ideal for testing baseline nuclear effects

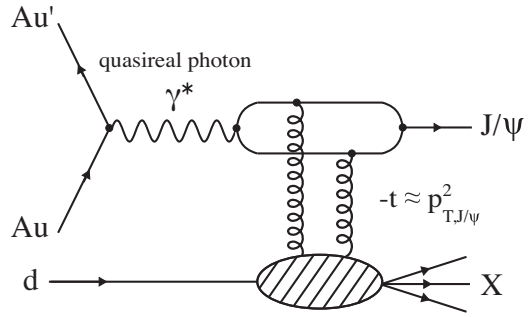
- n-tagged data provide the first direct measurement of incoherent diffractive J/ψ production at low $-t$
- essential experimental baseline for a high precision measurement at EIC

2024: Probing Gluons inside Large Nuclei

PRL 133 052301, 2024







- Strong suppression compared to impulse approximation -> nuclear effects
- Test of leading twist, shadowing strength, saturation

In memory of W. Shmidke

Advances in Nuclear Tomography

$$\frac{d\sigma}{dt} \propto |F(t)|^2$$ **-> Image the nucleus**

.... BUT

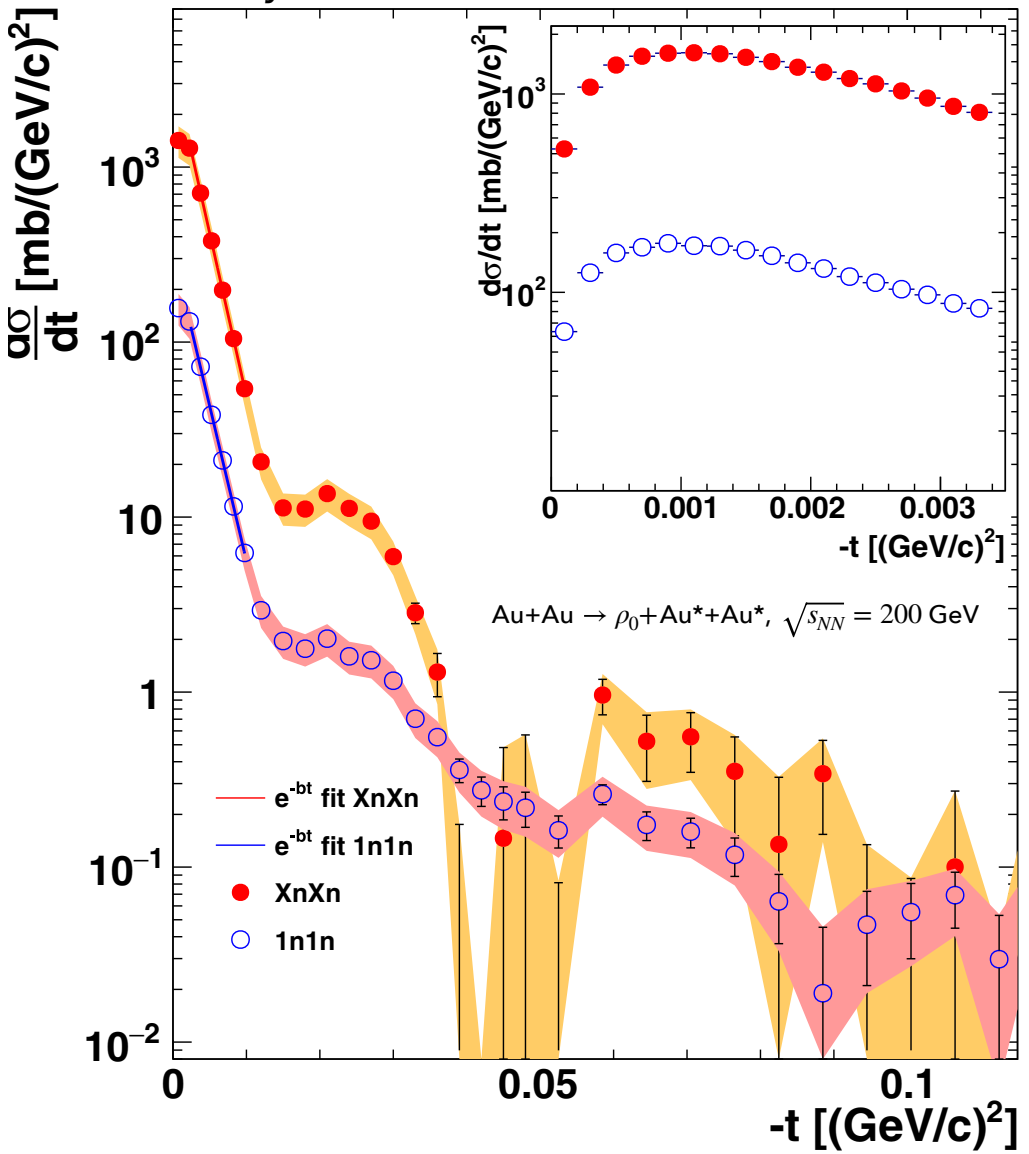
Photo-nuclear measurements (in A+A) have historically produced a |t| slope that corresponds to a **mysteriously large source!**

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)

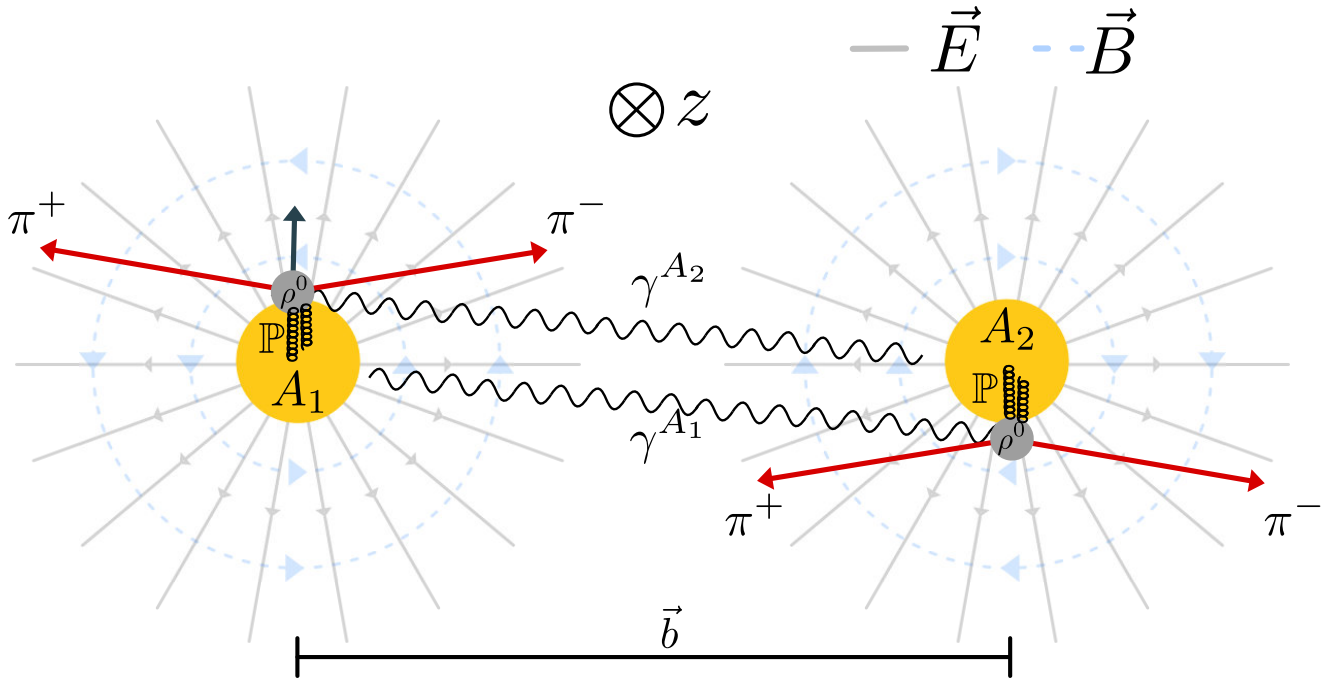
Extracted nuclear radii are way too large

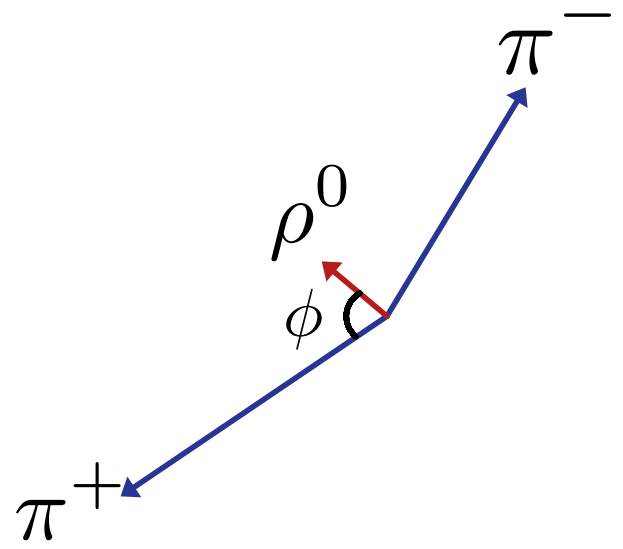
Phys. Rev. C 96, 054904, 2017



Interference in $\gamma A \rightarrow \rho^0 \rightarrow \pi^+\pi^-$

What is NEW with transversely polarized photons?



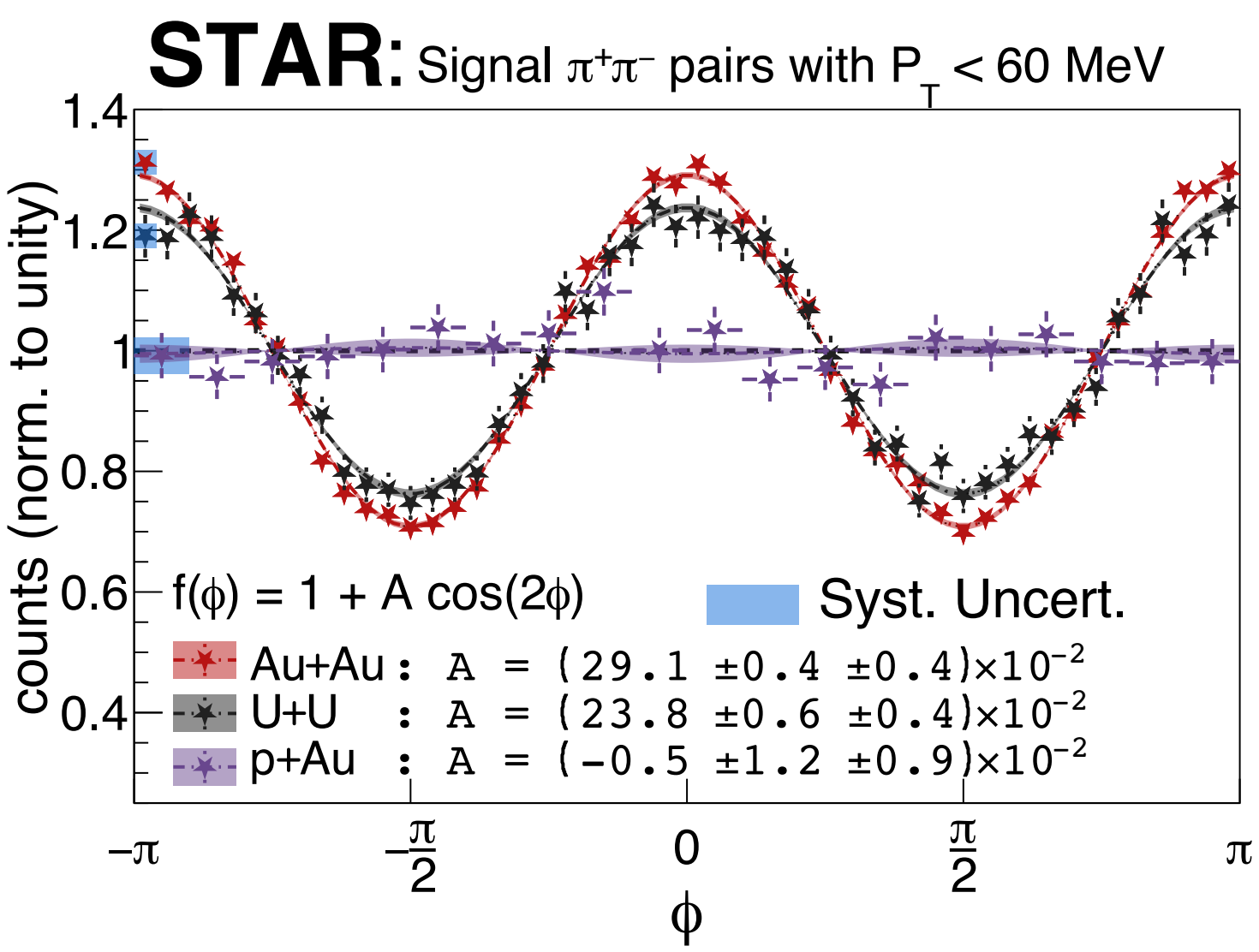


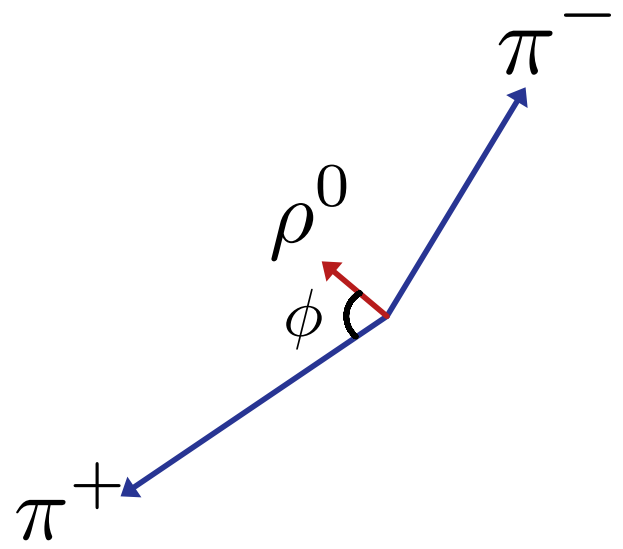
- Intrinsic photon spin transferred to ρ^0
- ρ^0 spin converted into **orbital angular momentum**
- Observable as anisotropy in $\pi^{\pm}$ momentum

Both possibilities occur simultaneously

NB: Recently confirmed by ALICE,
Phys. Lett. B 858 (2024) 139017

Interference in $\gamma A \rightarrow \rho^0 \rightarrow \pi^+\pi^-$





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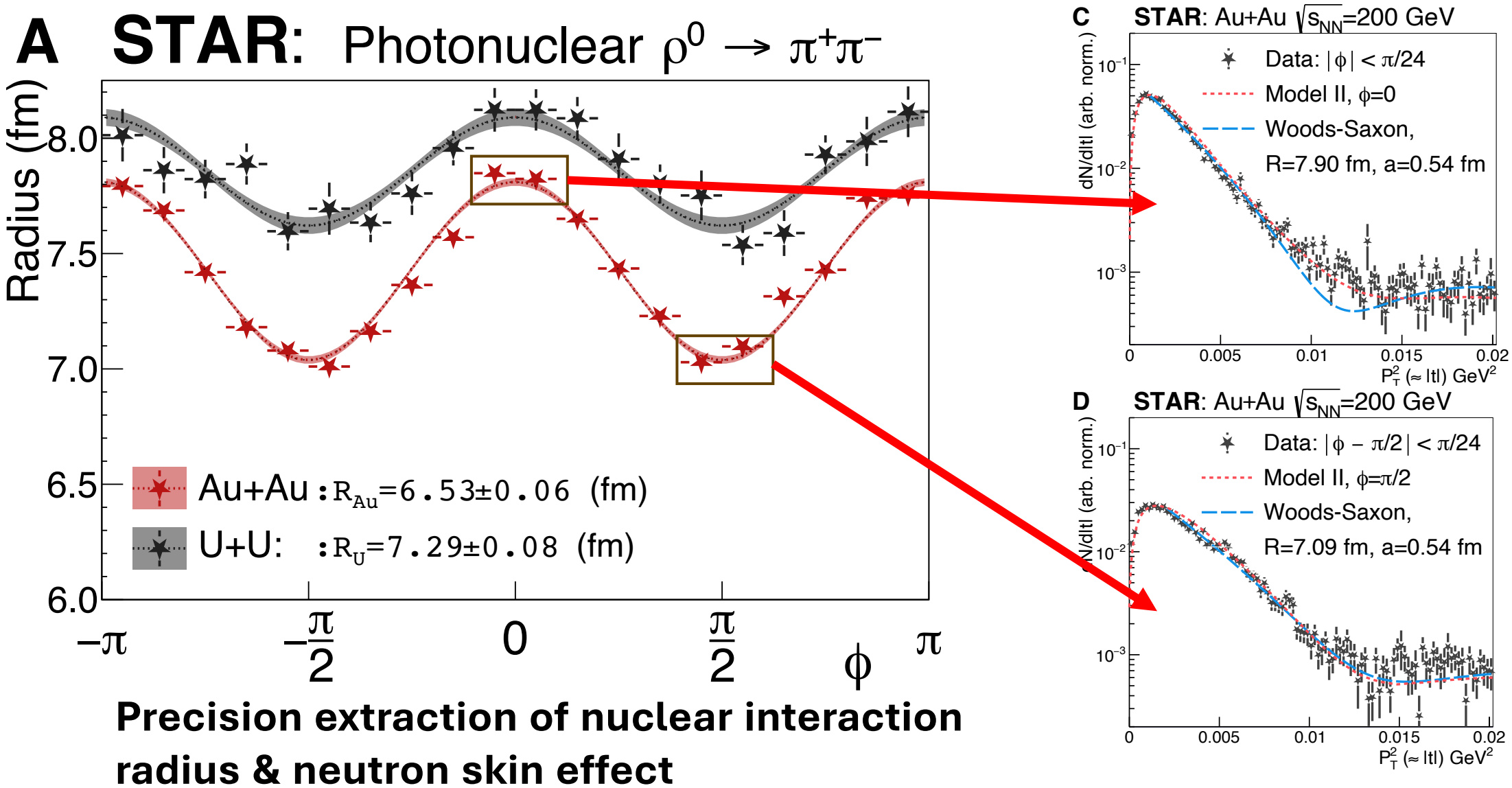
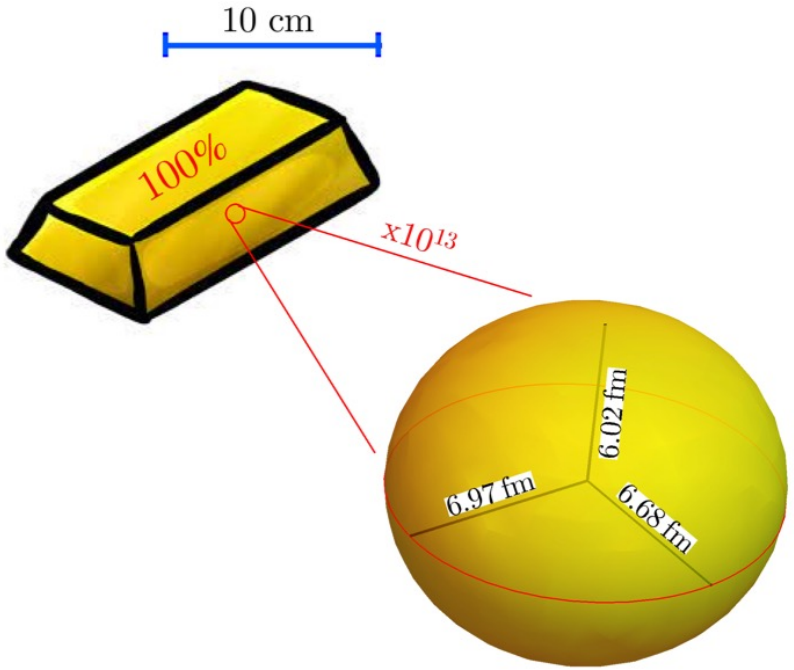
Observation of Interference in $\rho^0 \to \pi^+\pi^-$



Precision extraction of nuclear interaction radius & neutron skin effect

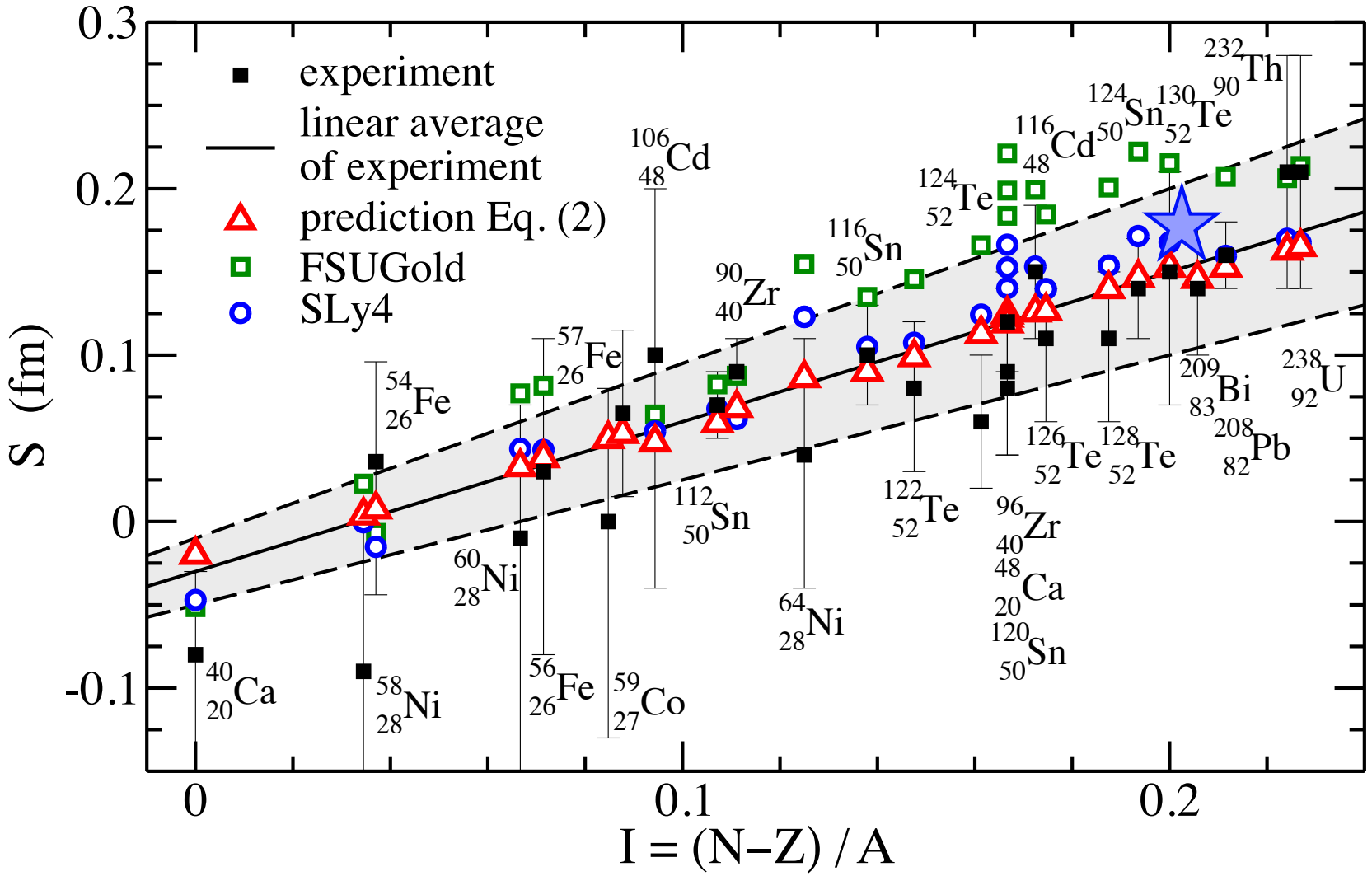
Neutron Skins across Nuclei



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

Looking Forward: Legacy and Future Directions

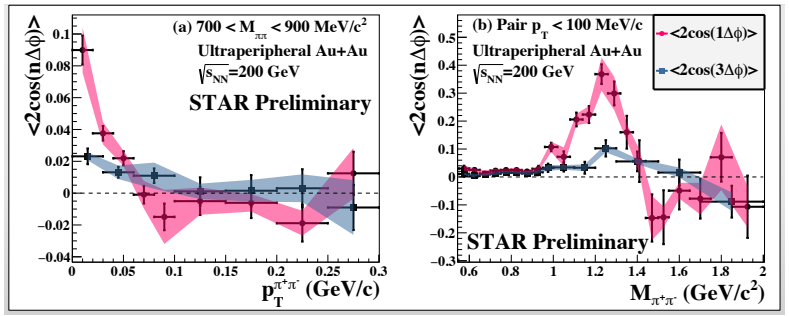
UPC had an outsized impact on the legacy of the STAR & RHIC physics programs

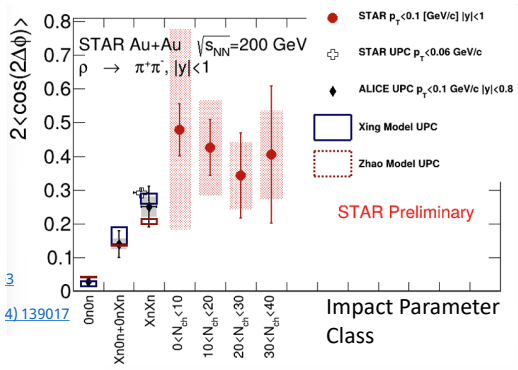
25 years of discovery:

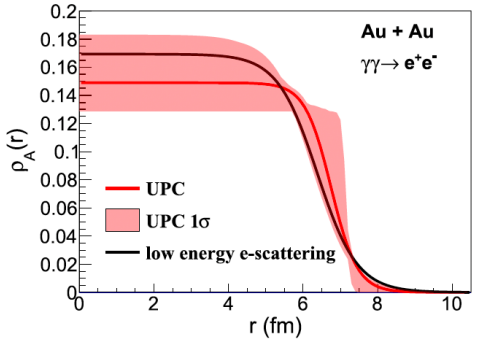
- From first observation to precision measurements
- From light to heavy vector mesons
- From cross sections to quantum interference
- Demonstrated quantum interference at the femtometer scale
- Observed fundamental QED processes (Breit-Wheeler, vacuum birefringence)

Future / ongoing Studies (we are halfway there):

- Access to Hadronic Light-by-Light
- Imaging of nuclear charge distributions in asymmetric nuclei
- Quantum interference in hadronic collisions
- Higher order QED (Sudakov soft photon radiation)
- Nuclear structure in Isobar and light ions
- Quantum interference with heavy vector mesons
- Precision spectroscopy ($\pi^+\pi^-\pi^+\pi^-$) and ϕ-meson
- Collectivity in the smallest systems + Baryon transport
- ....

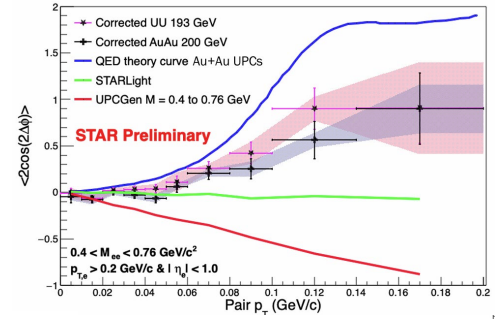


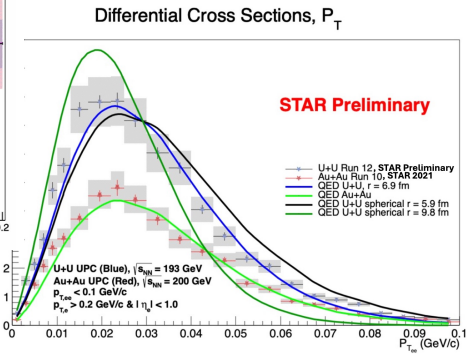




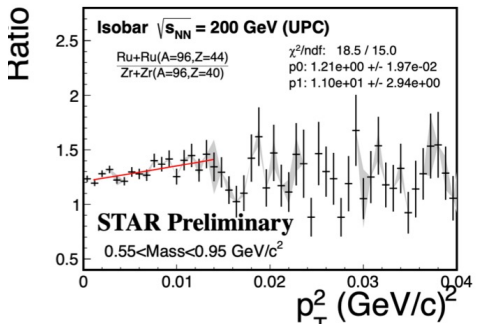
STAR, PRC 111, 014909 (2025)

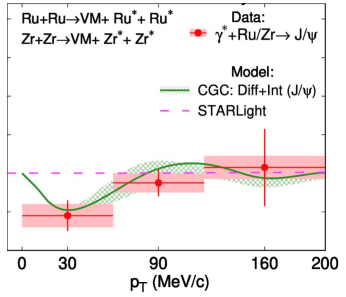
$< 2\cos(2\Delta\phi) >$

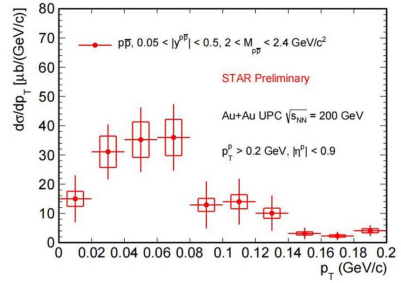




dN/dt slope difference in Isobar UPC







25 Years of Scientific Discovery

Thank you STAR, RHIC, and everyone involved over the many years