Entanglement Enabled Spin Interference

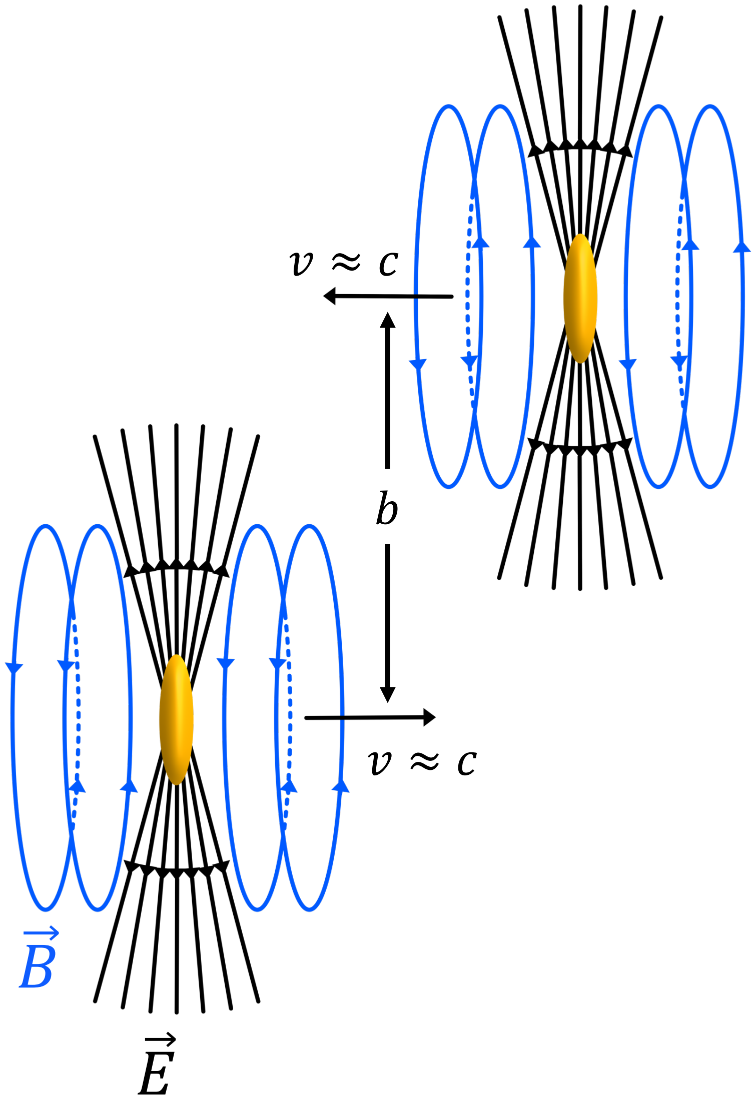
(STAR Collaboration) Phys. Rev. Lett. 127, 052302 (2021)
STAR Collaboration, Sci. Adv. 9, eabq3903 (2023).

James Daniel Brandenburg
The Ohio State University

Top Quark Physics at the Precision Frontier 2023
Purdue University, West Lafayette, IN 47906

U.S. Department of Energy
Office of Science

UPCs : The Strongest Electromagnetic Fields



- In heavy-ion collisions:

$$E_{max} = \frac{Ze\gamma}{b^2} \approx 5\times10^{16} - 10^{18}\ \text{V/cm}$$

$$B_{max} \sim 10^{14} - 10^{16}\ \text{T}$$

  - Strongest EM fields in the **Universe**
  - But very short lifetime – not constant

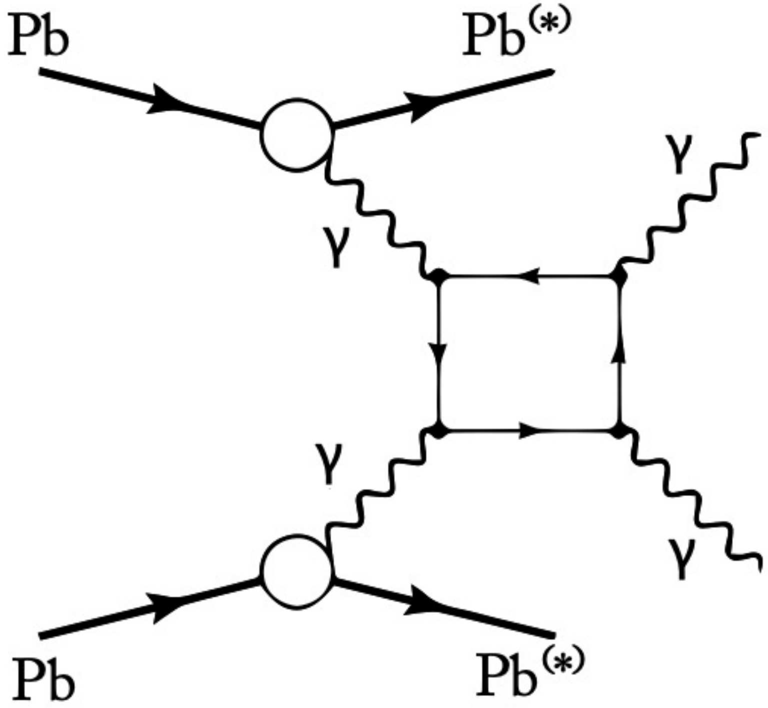
Must be treated in terms of photon quanta

$$E_{\gamma,\text{max}} \approx \gamma\hbar c/R$$

80 GeV @ LHC
3 GeV @ RHIC

Types of Processes in UPCs

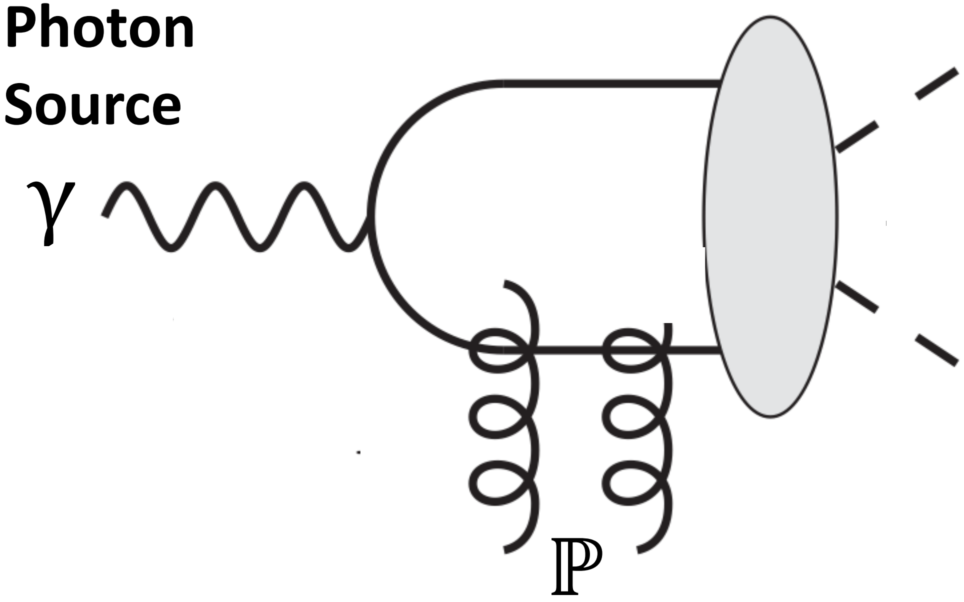
Photon + photon



1. Explore non-linear QED
2. Discoveries -> now tools
3. Test for Physics Beyond Standard Model
4. …

Photon + target

Photon Source

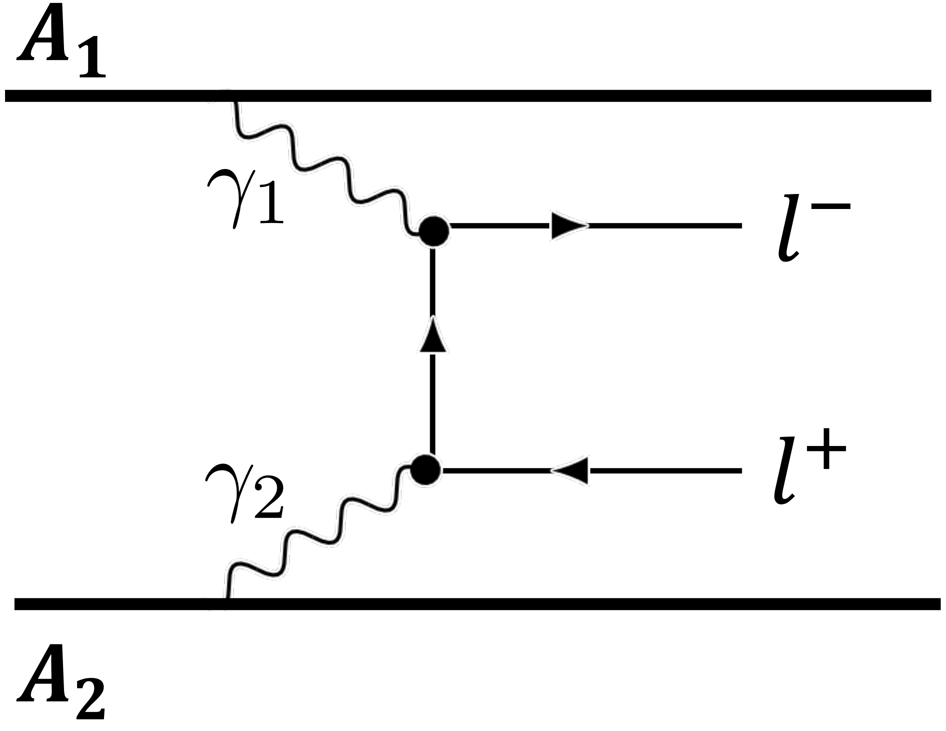


Gluons from nucleus (target)

1. ‘Image’ nuclear gluon distributions
2. Test gluon saturation predictions
3. Investigate sub-nucleonic fluctuations
4. …

Types of Processes in UPCs

Photon + photon



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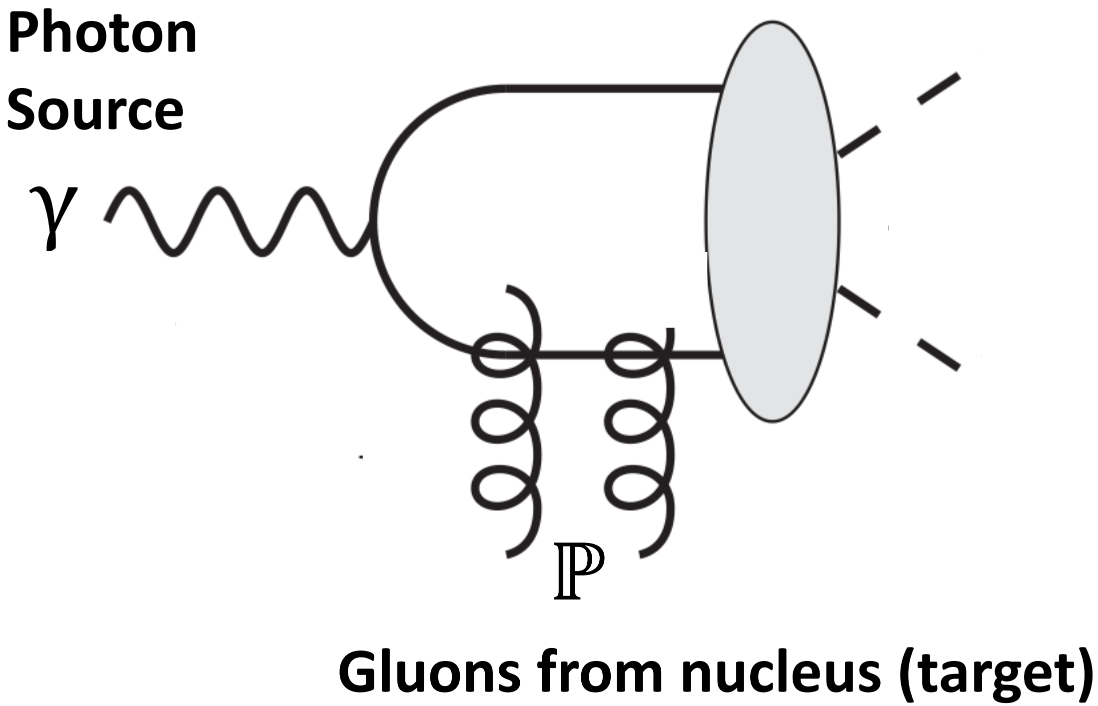
Photon + target



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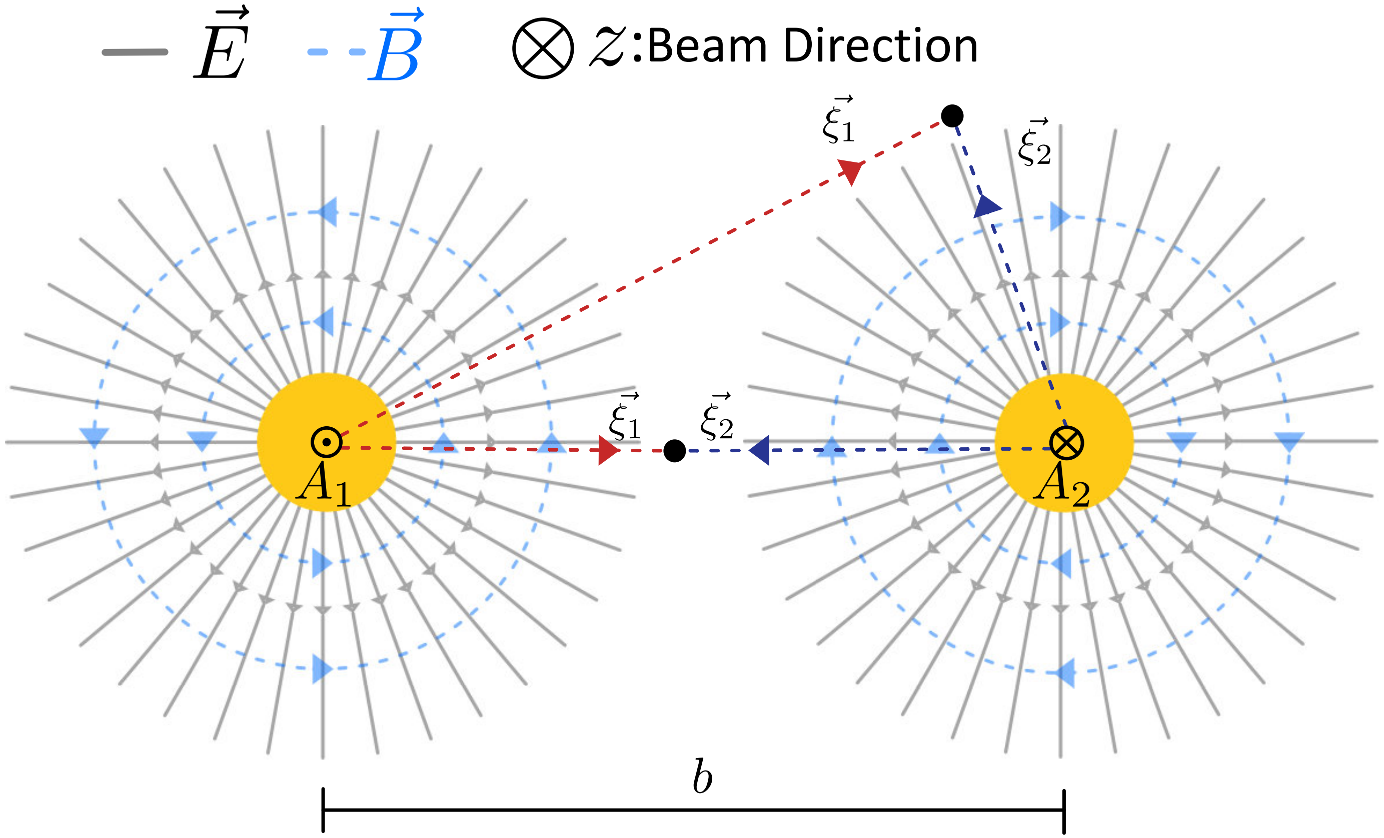
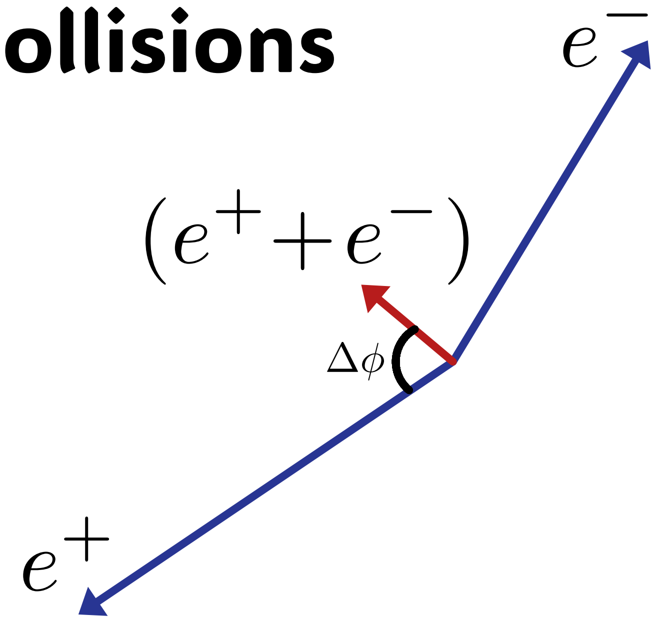
Photon *Polarization* In Ultra-Peripheral Collisions





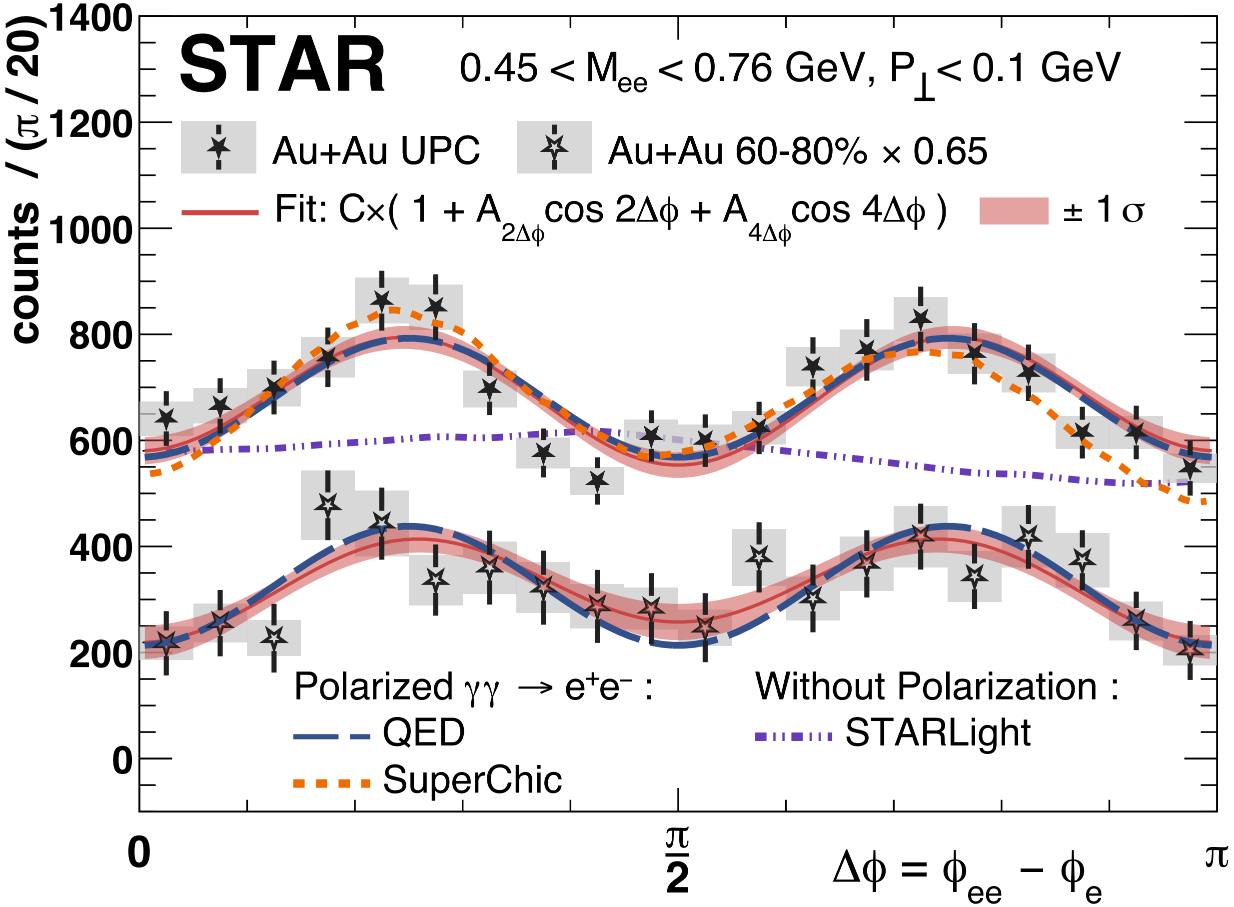
- Polarization vector ξ: aligned radially with the "emitting" source
- Intrinsic photon spin converted into **orbital angular momentum**
- Observable as anisotropy in $e^\pm$ momentum

For decades it was believed the polarization info was lost due to random event-by-event orientation!

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

Photon *Polarization* In Ultra-Peripheral Collisions



(STAR Collaboration)
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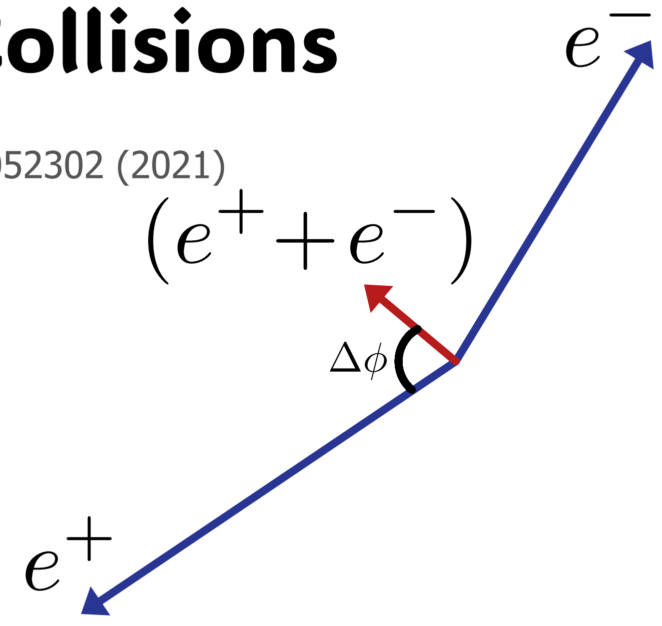

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Experimental access to photon polarization demonstrated

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C. Li, J. Zhou & Y. Zhou Phys. Rev. D 101, 034015 (2020).

S. Bragin, et. al., *Phys. Rev. Lett.* 119 (2017), 250403
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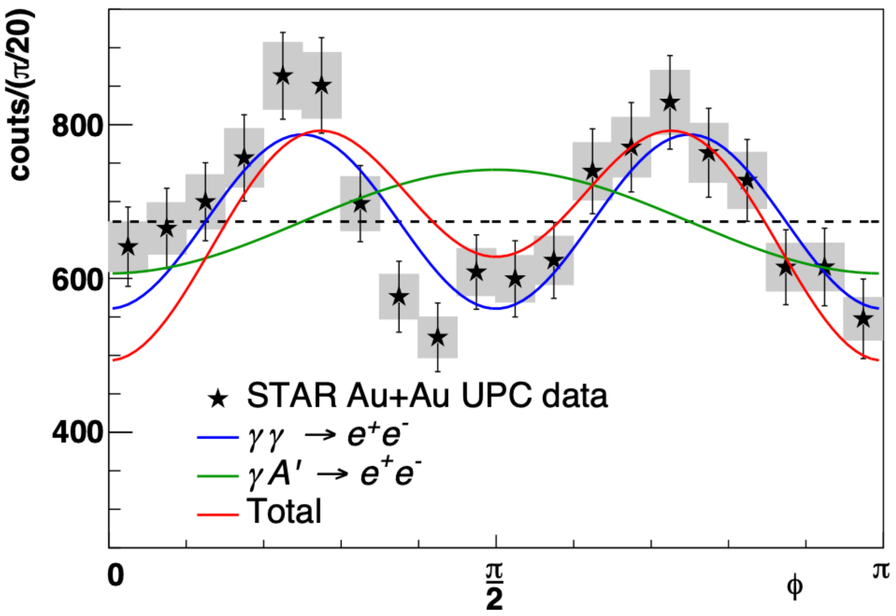
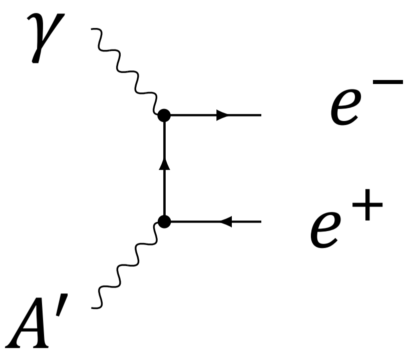
Applications of $\gamma\gamma \rightarrow l^+l^-$

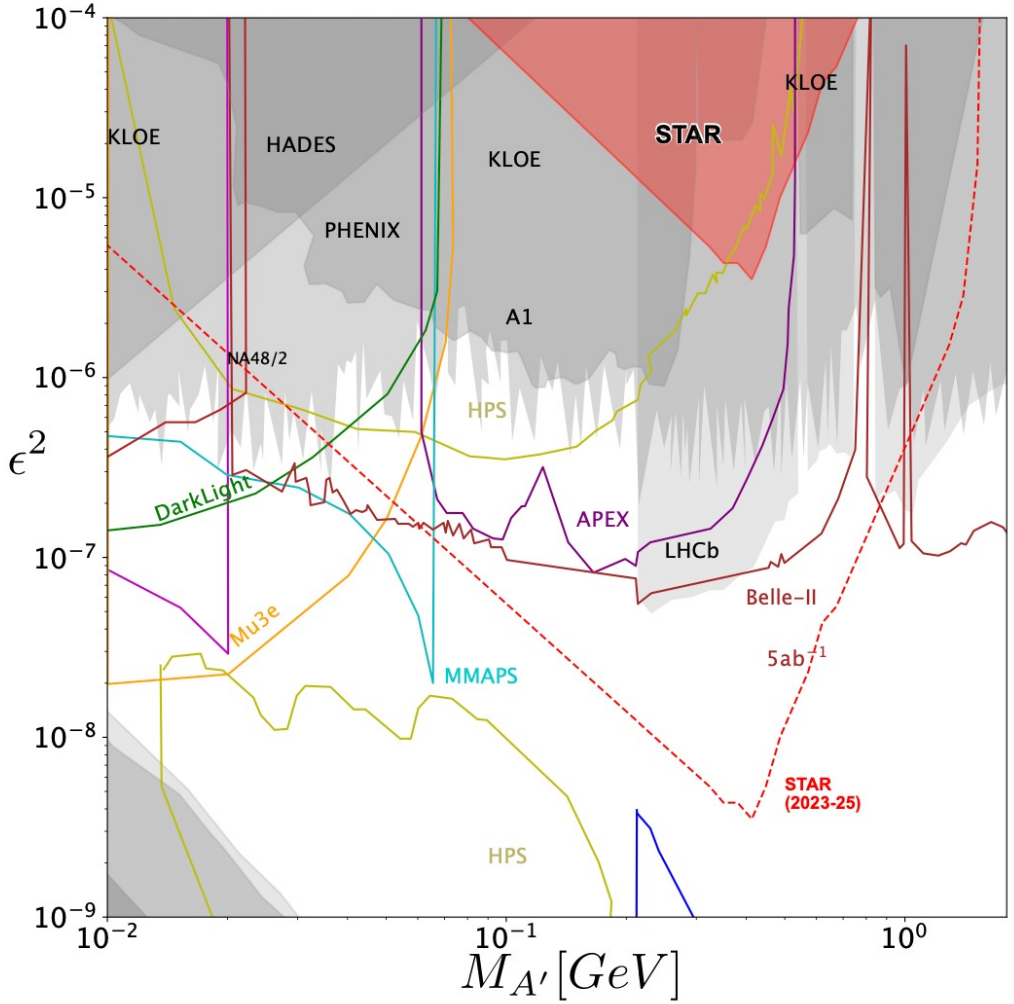
Sensitivity to spin states → novel approach for constraining massive dark photons



Isabel Xu, Nicole Lewis, Xiaofeng Wang, James Daniel Brandenburg, Lijuan Ruan
arxiv:2211.02132



Dark photon



Relevant for LHC Axion search in Light-by-Light scattering

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

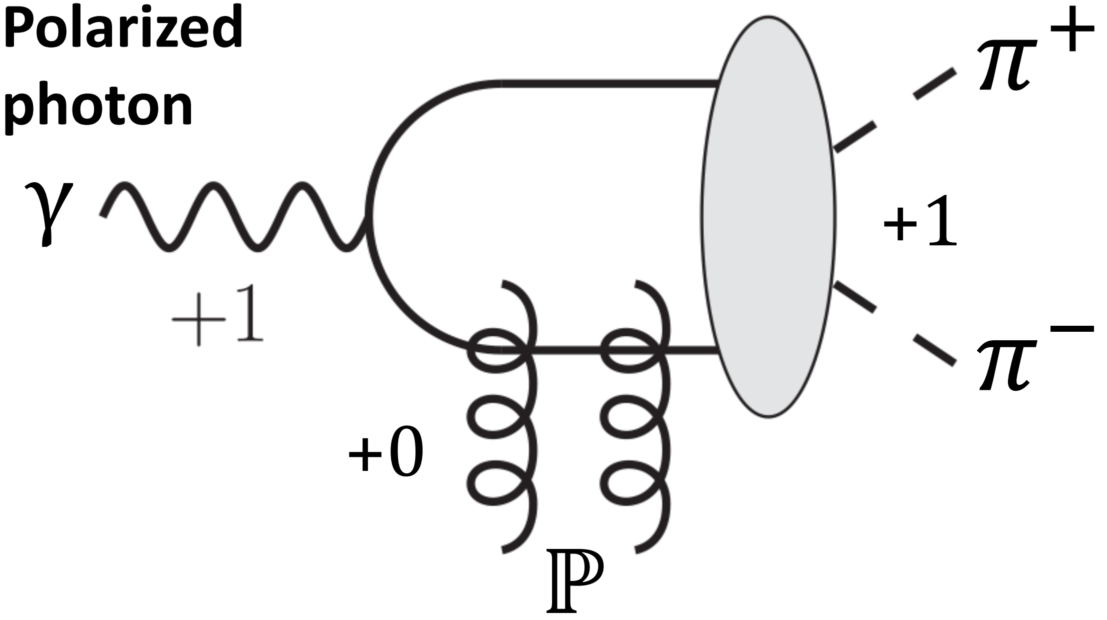
Entanglement Enabled Spin Interference

A novel Quantum phenomenon

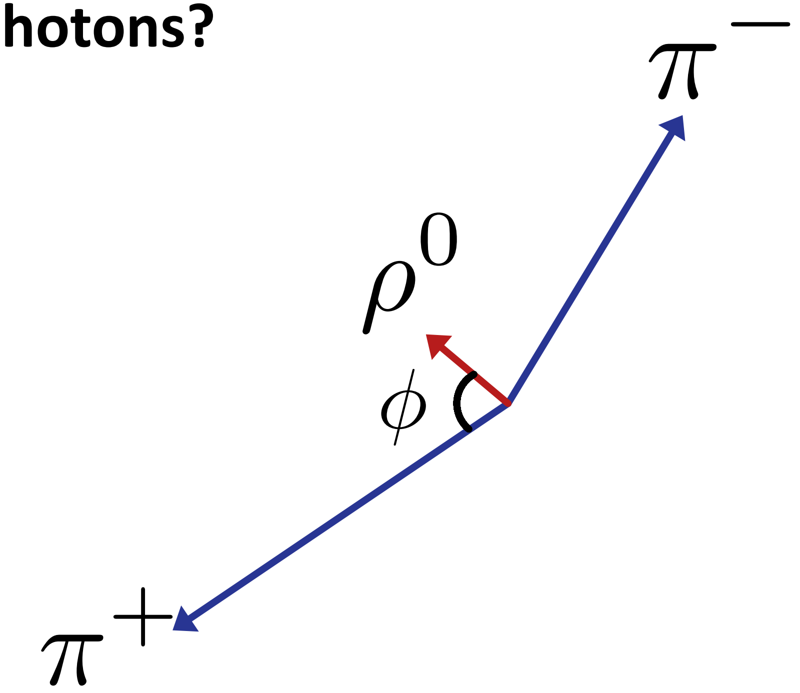
Imaging the Nucleus with Polarized Photons

What is NEW with transversely polarized photons?

Polarized photon



Gluons from nucleus

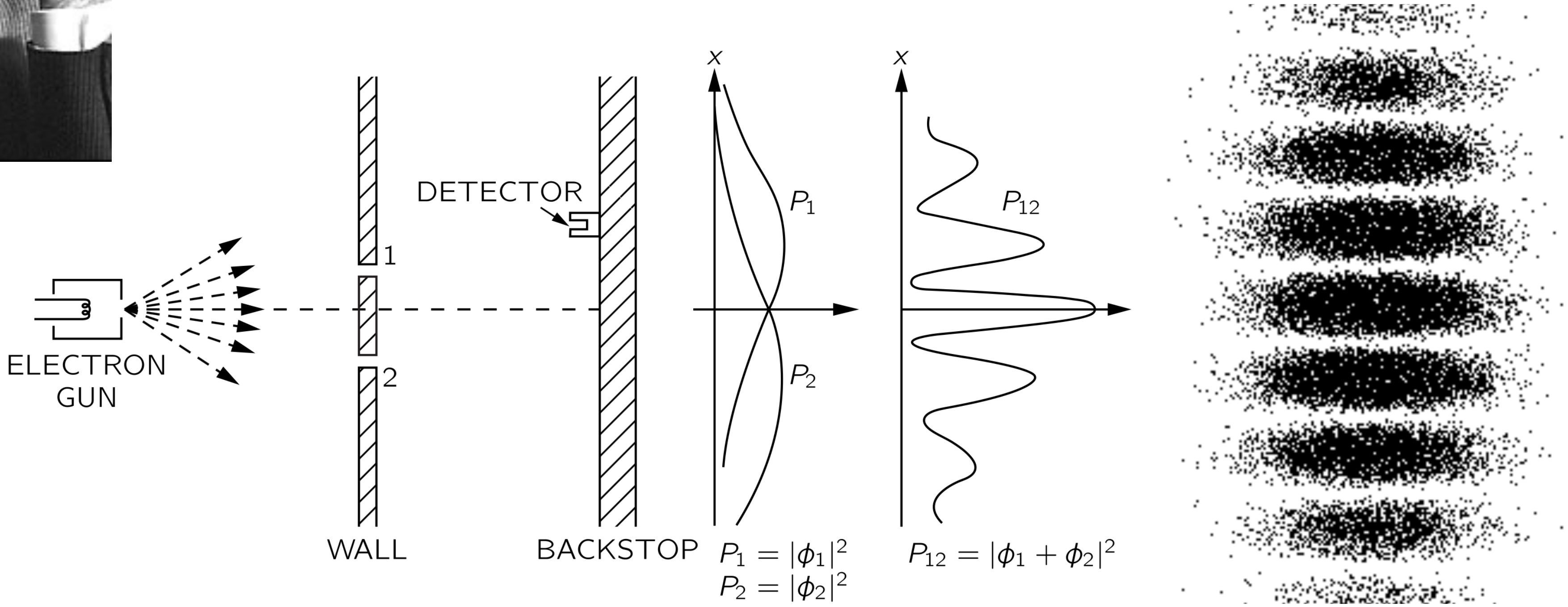


We can use the same experimental observable as the Breit-Wheeler process to access photon polarization

Access to initial photon polarization

I will take just this one experiment, which has been designed to contain all of the *mystery* of quantum mechanics, to put you up against the *paradoxes* and *mysteries* and *peculiarities* of nature one hundred per cent. Any other situation in quantum mechanics, it turns out, can always be explained by saying, '*You remember the case of the experiment with the two holes? It's the same thing*'.

-Richard Feynman



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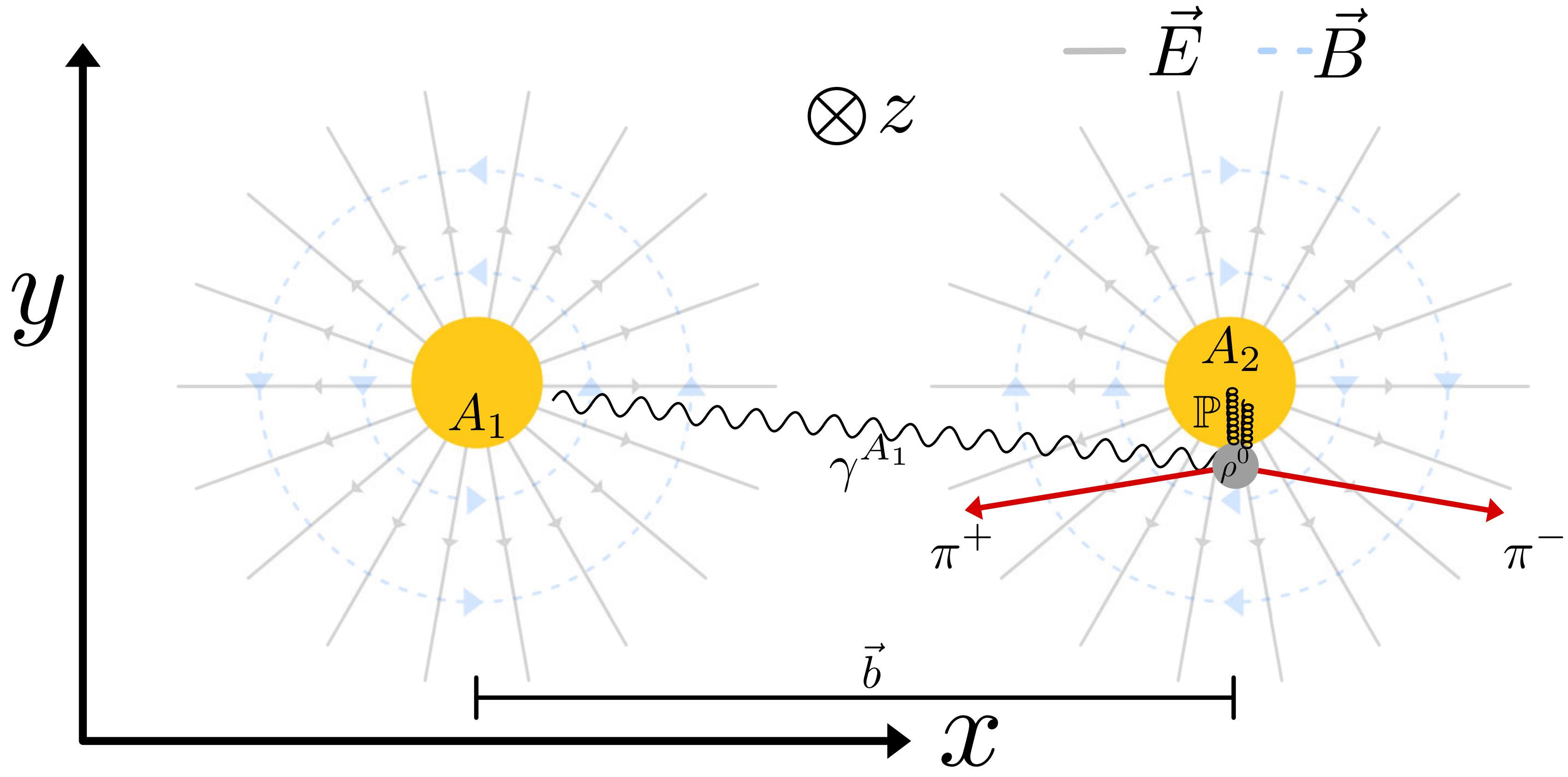
What is NEW with transversely polarized photons?



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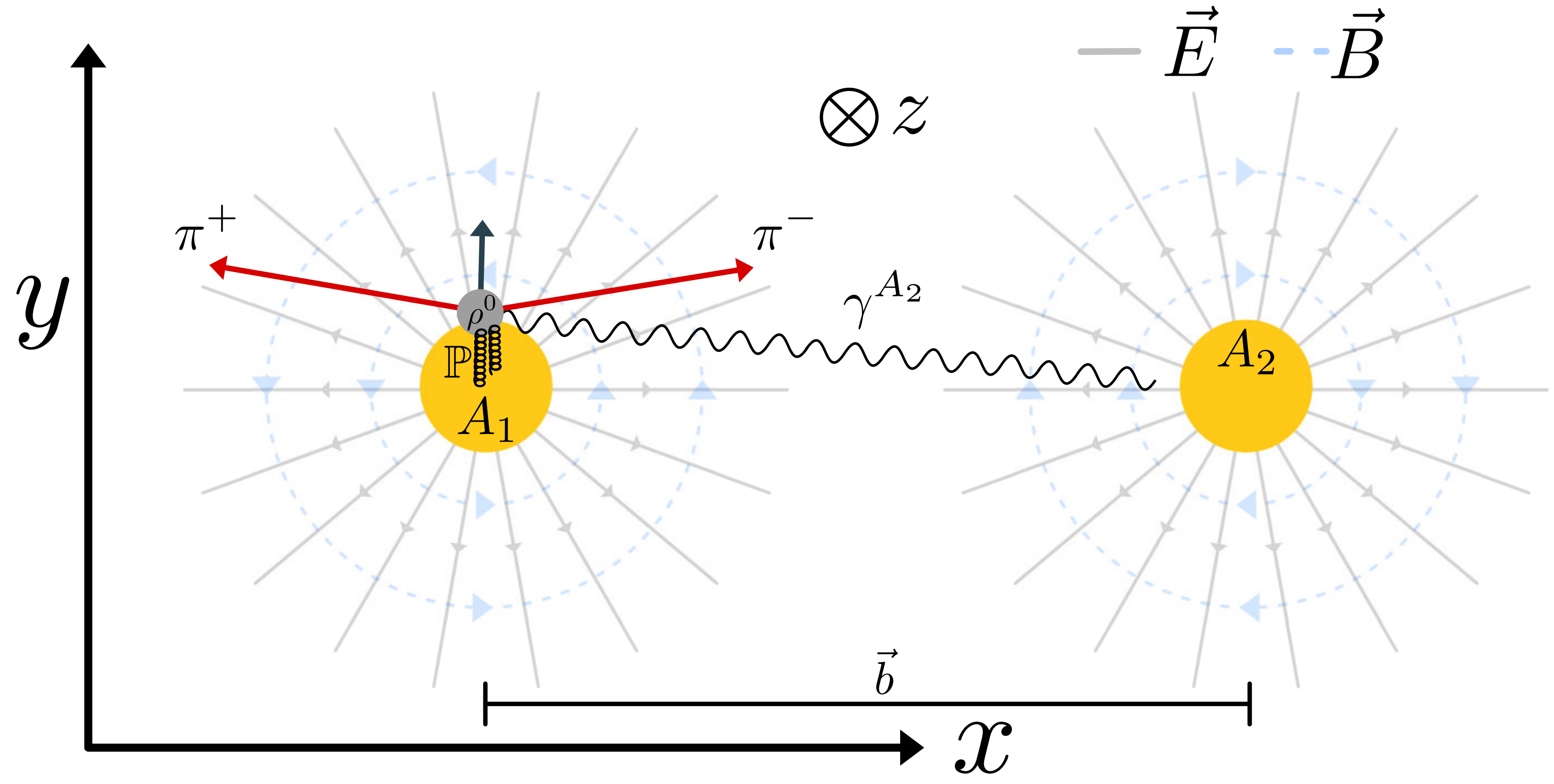

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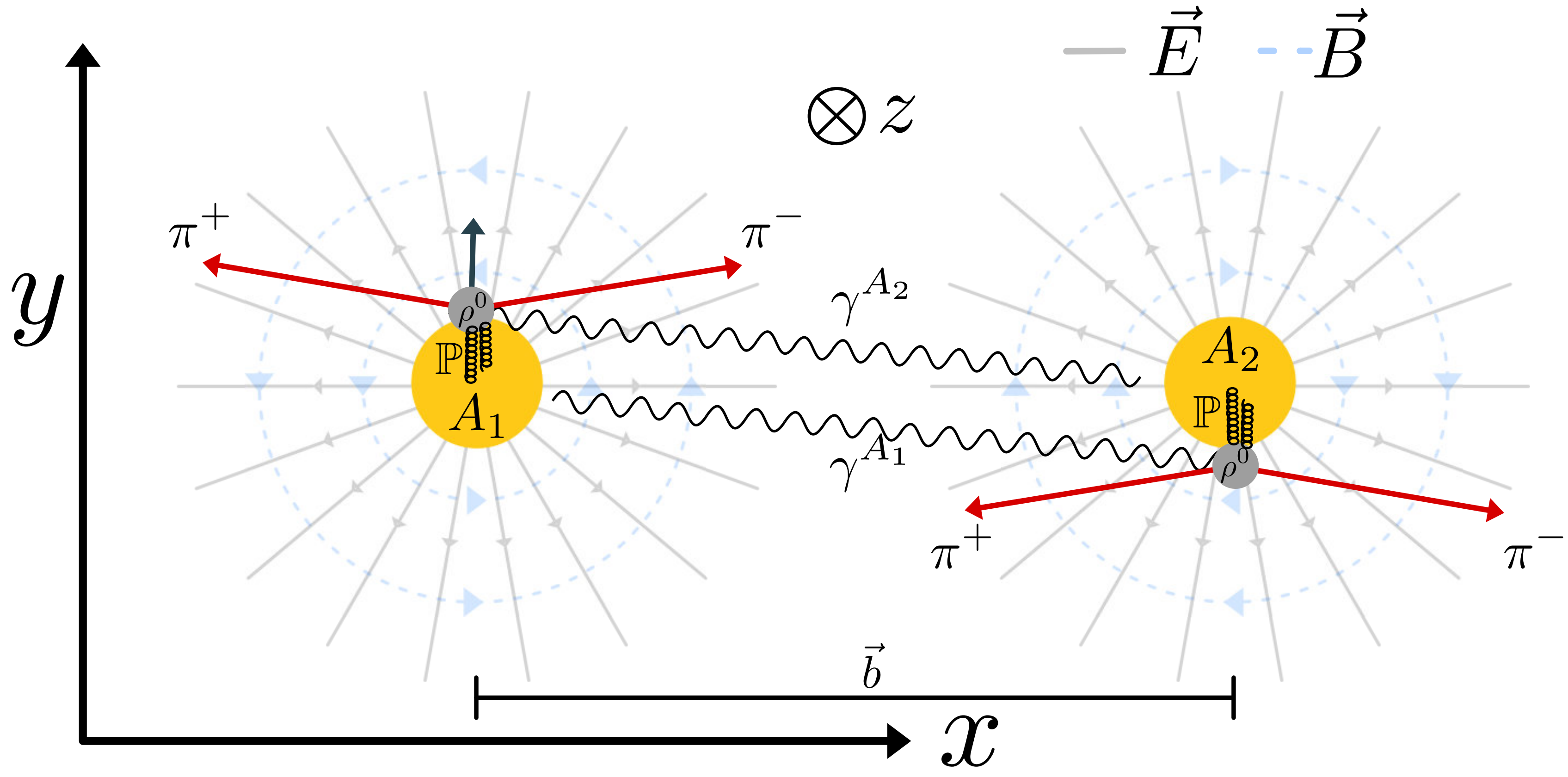
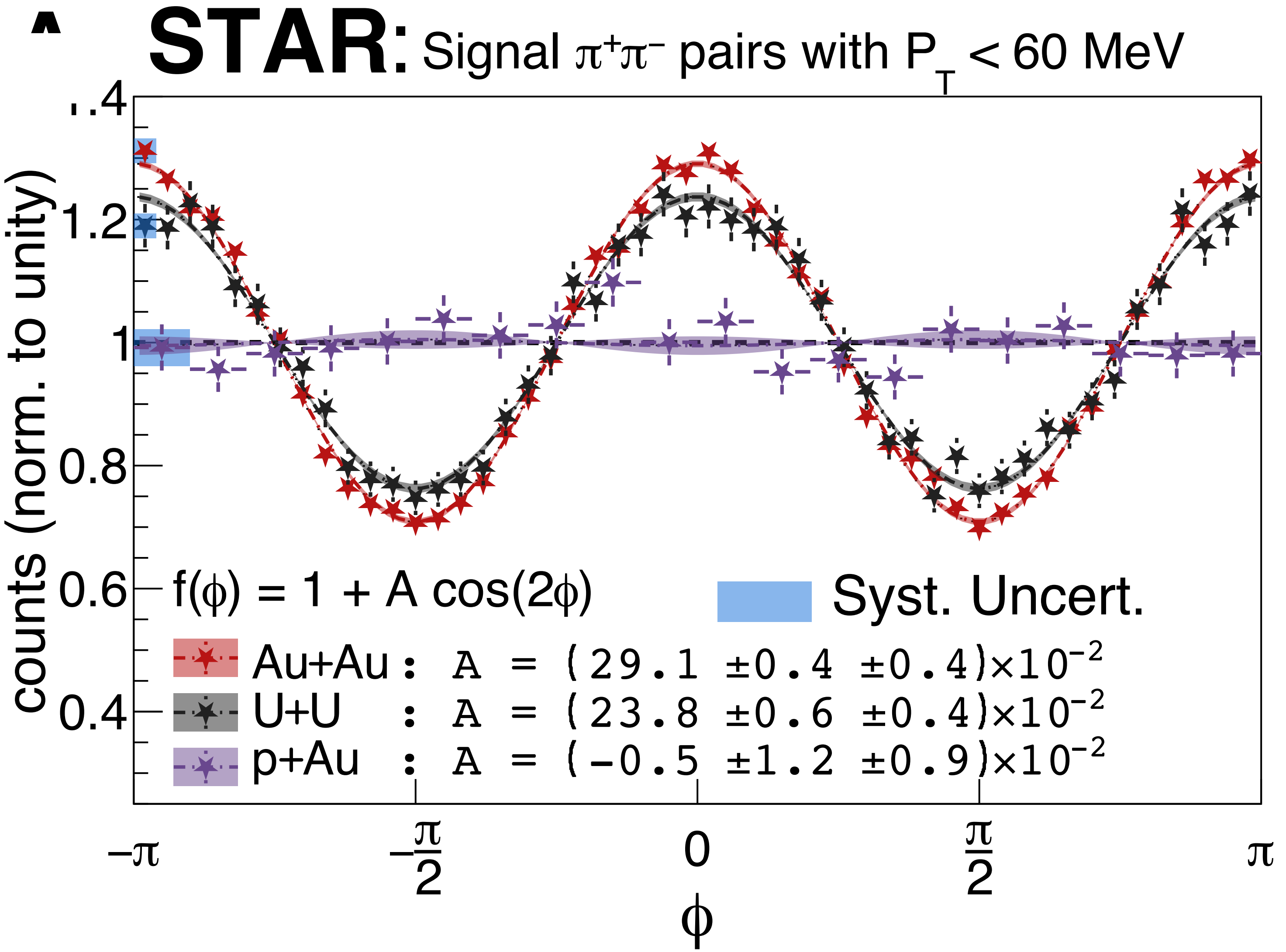
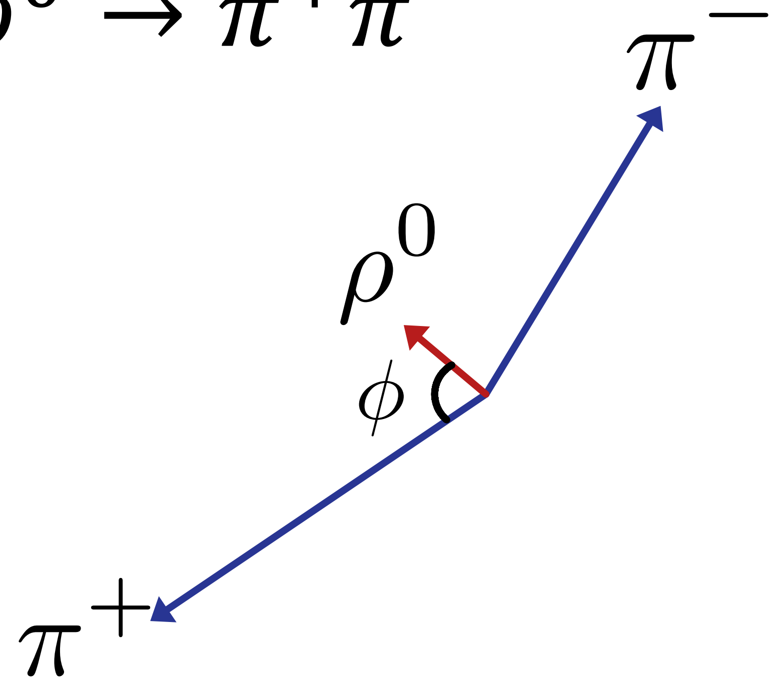


Both possibilities occur simultaneously

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





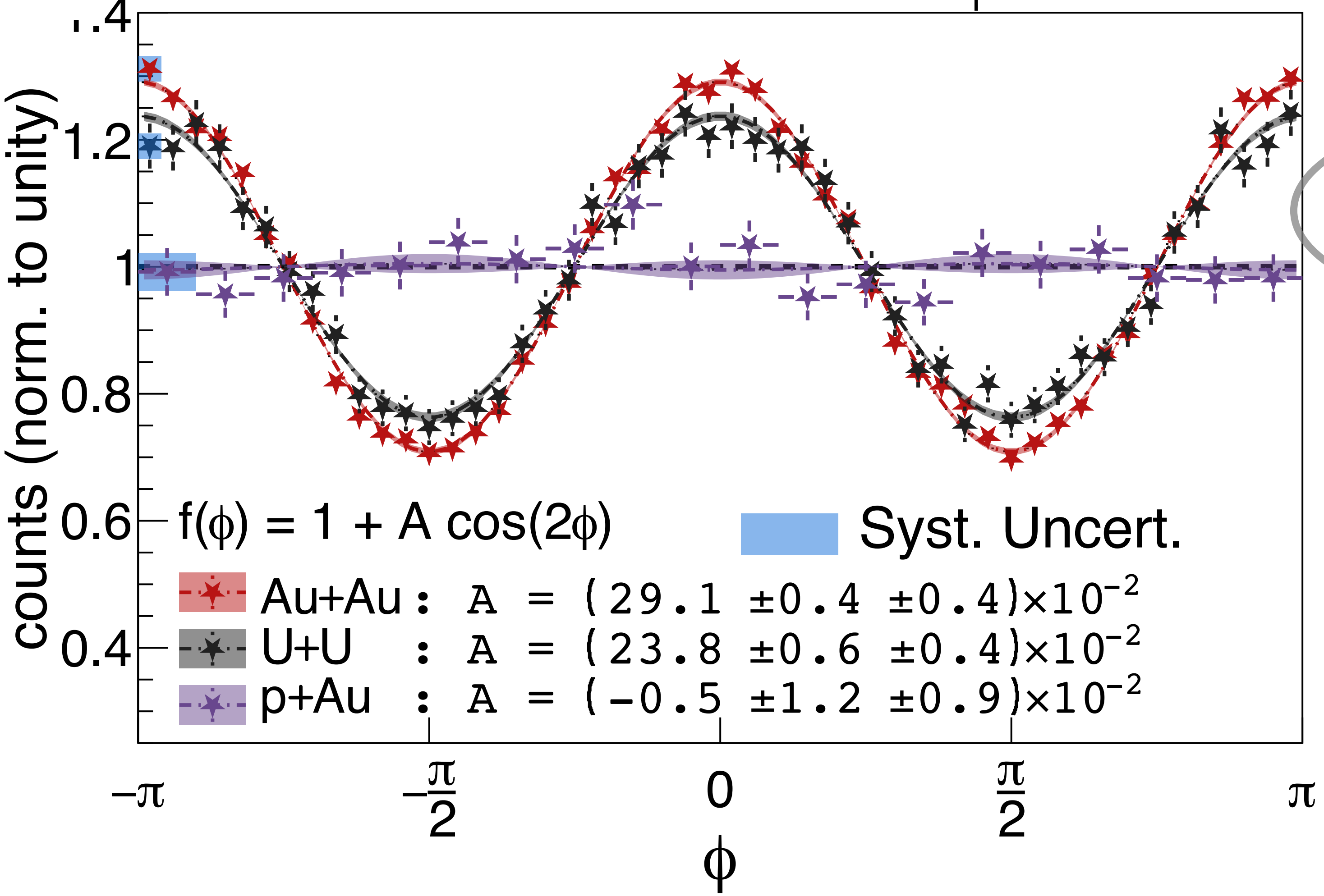
- Intrinsic photon spin transferred to ρ^0
- ρ^0 spin converted into **orbital angular momentum** between pions
- Observable as anisotropy in $\pi^\pm$ momentum

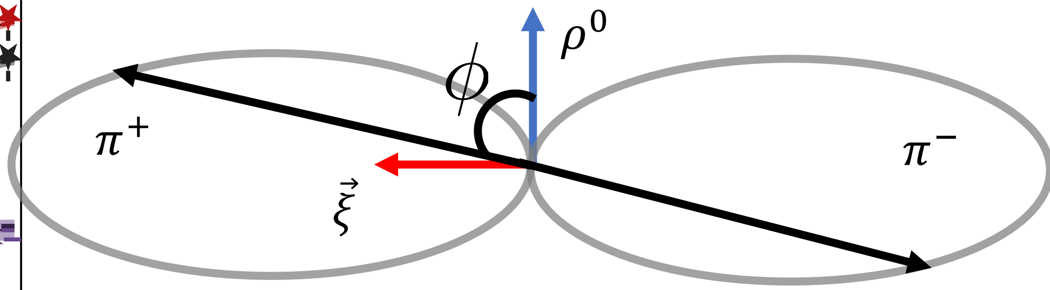
STAR Collaboration, Sci. Adv. **9**, eabq3903 (2023).

H. Xing, C. Zhang, J. Zhou and Y. J. Zhou, JHEP 10(2020), 064.

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

STAR: Signal $\pi^+\pi^-$ pairs with $P_T < 60$ MeV





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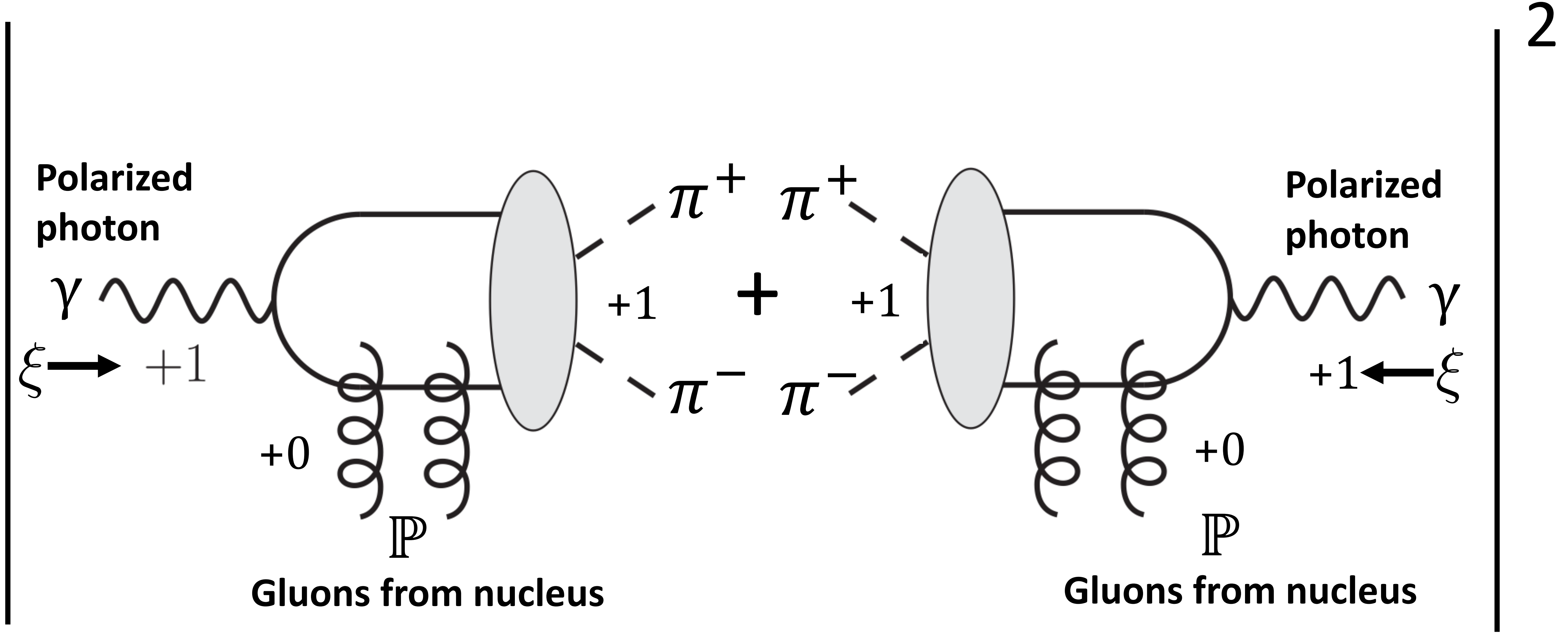
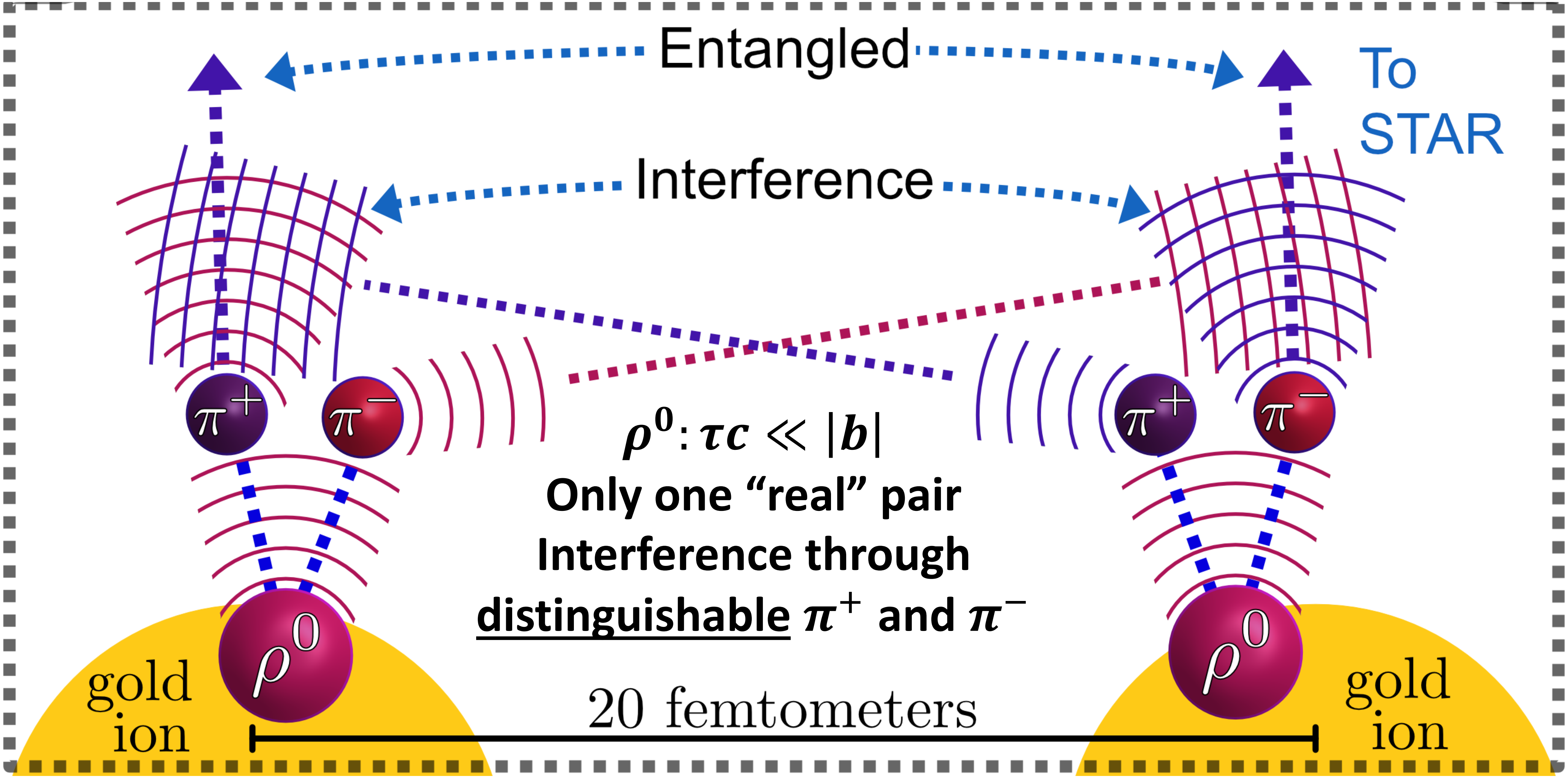
Interference of two amplitudes



Interference of Amplitudes, so what!?



$\boldsymbol{\rho^0}$**:** $\boldsymbol{\tau c \ll |b|}$

Only one "real" pair

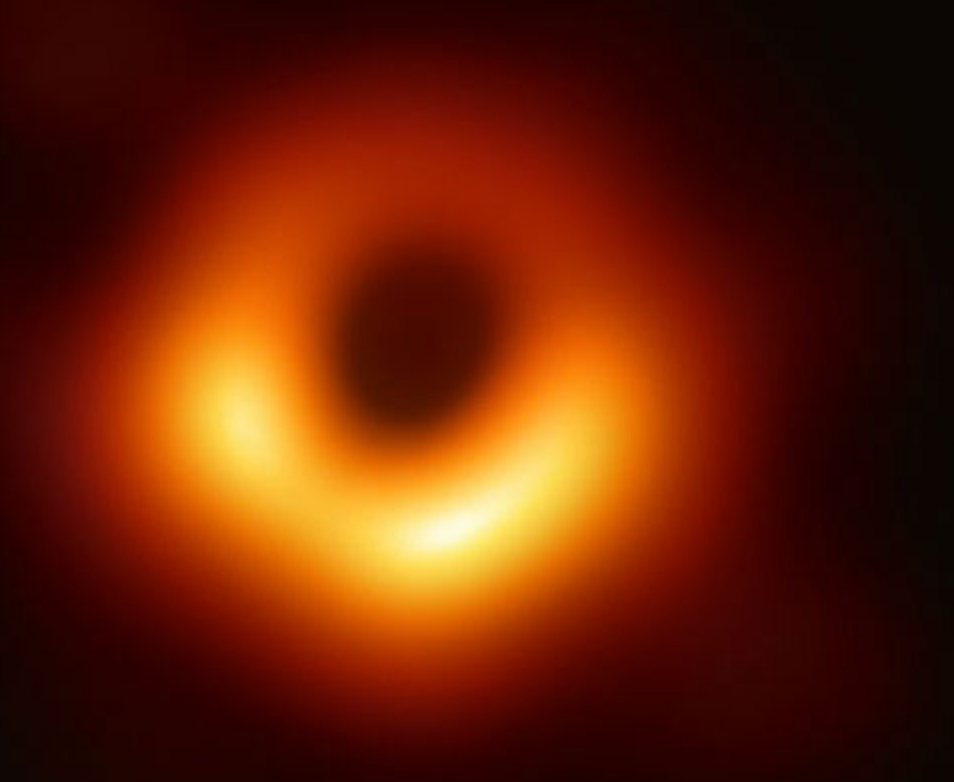
Interference through

<u>distinguishable</u> $\boldsymbol{\pi^+}$ **and** $\boldsymbol{\pi^-}$

Event Horizon Telescope

Analogy to Interferometry in Astro-Physics

Quantum Interference provides sub-diffraction limited imaging



M87 Supermassive Black hole

Event Horizon Telescope

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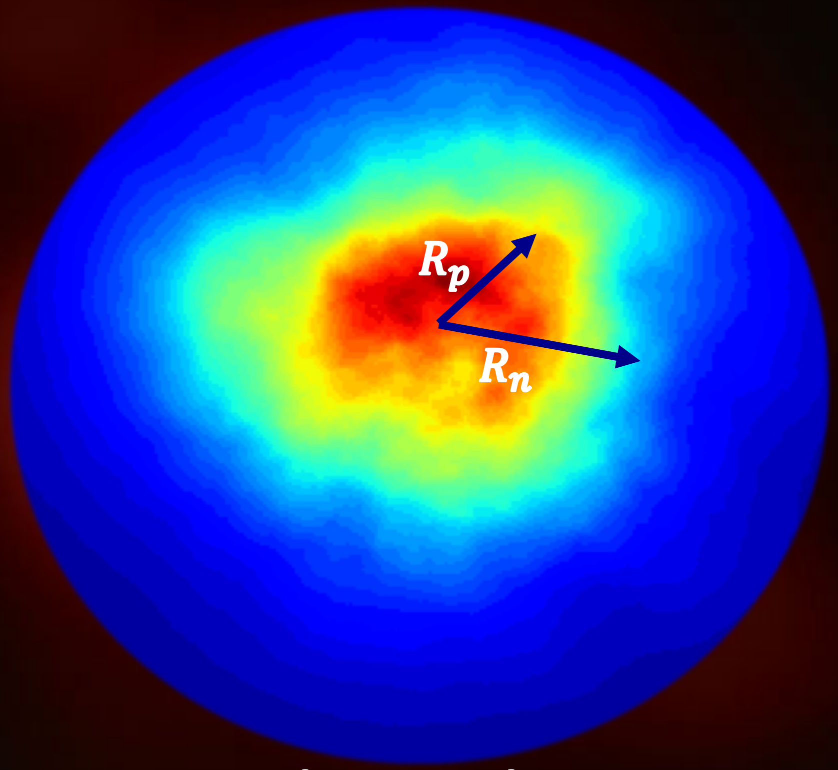
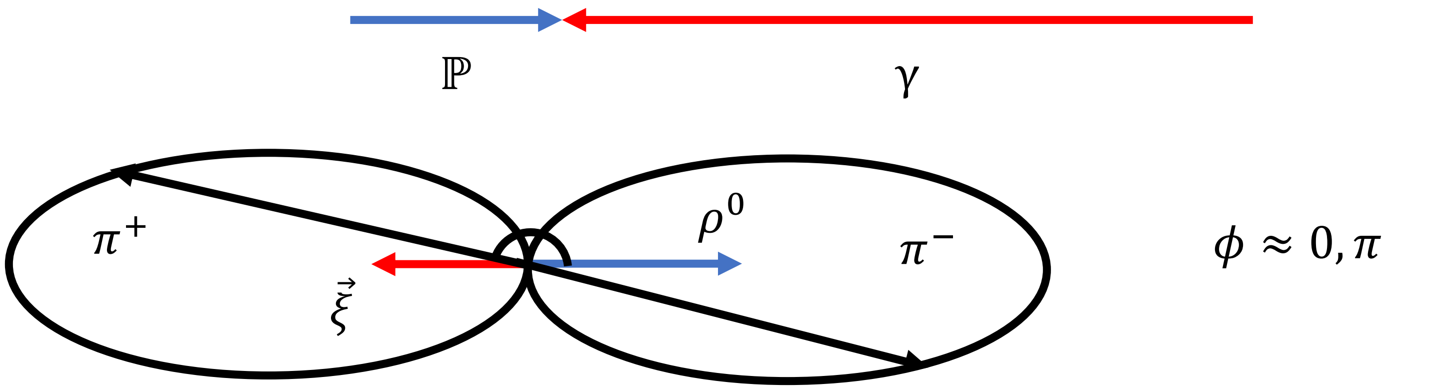


Nuclear Gluon distribution

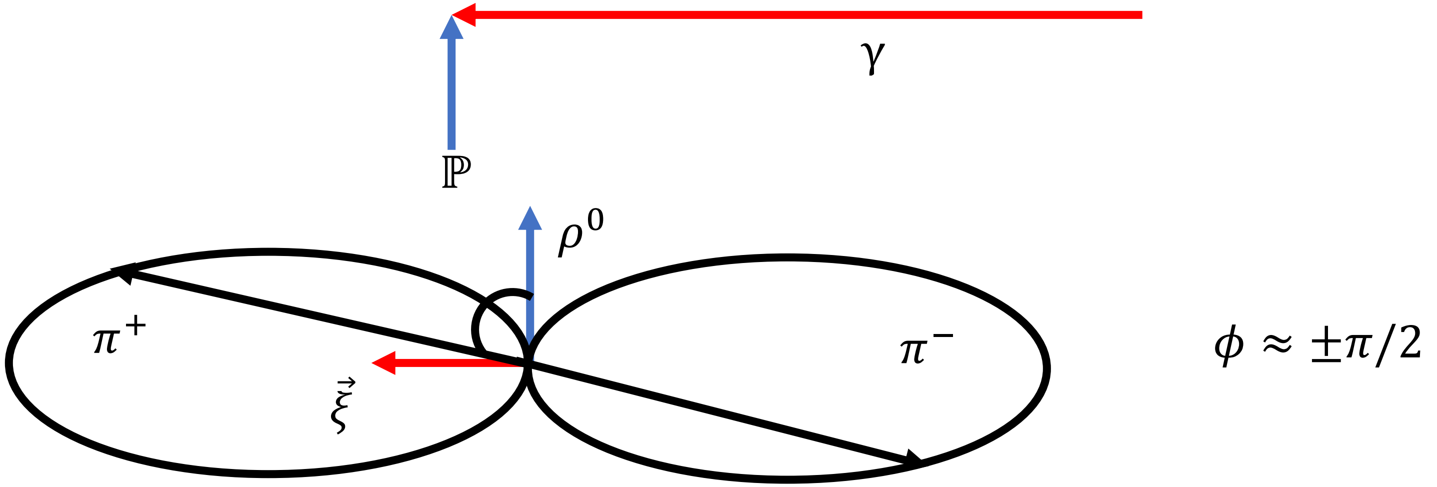
Access to details of gluon distribution and neutron skin at high energy

Interference Reveals Event Configurations

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

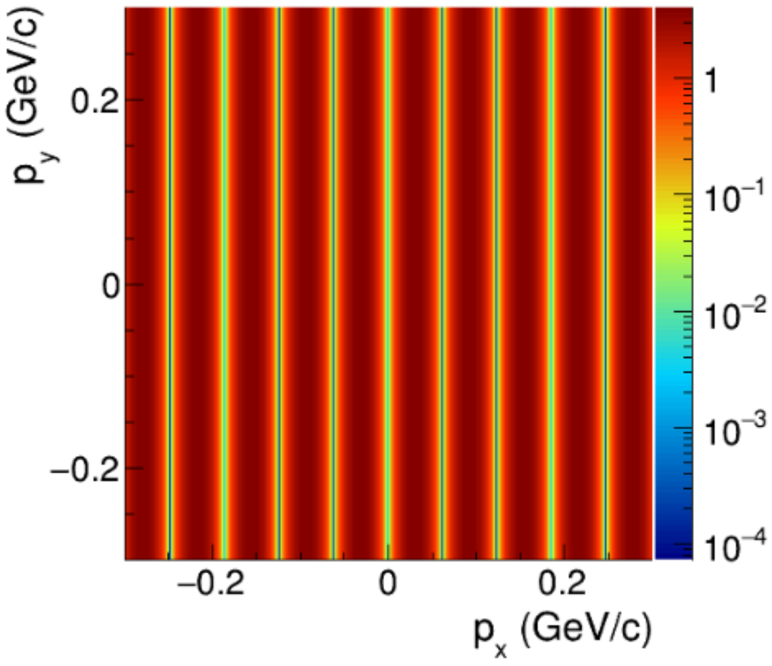


- Case II : Photon & Pomeron are perpendicular



Motivation for 2D Analysis :P_x vs P_y

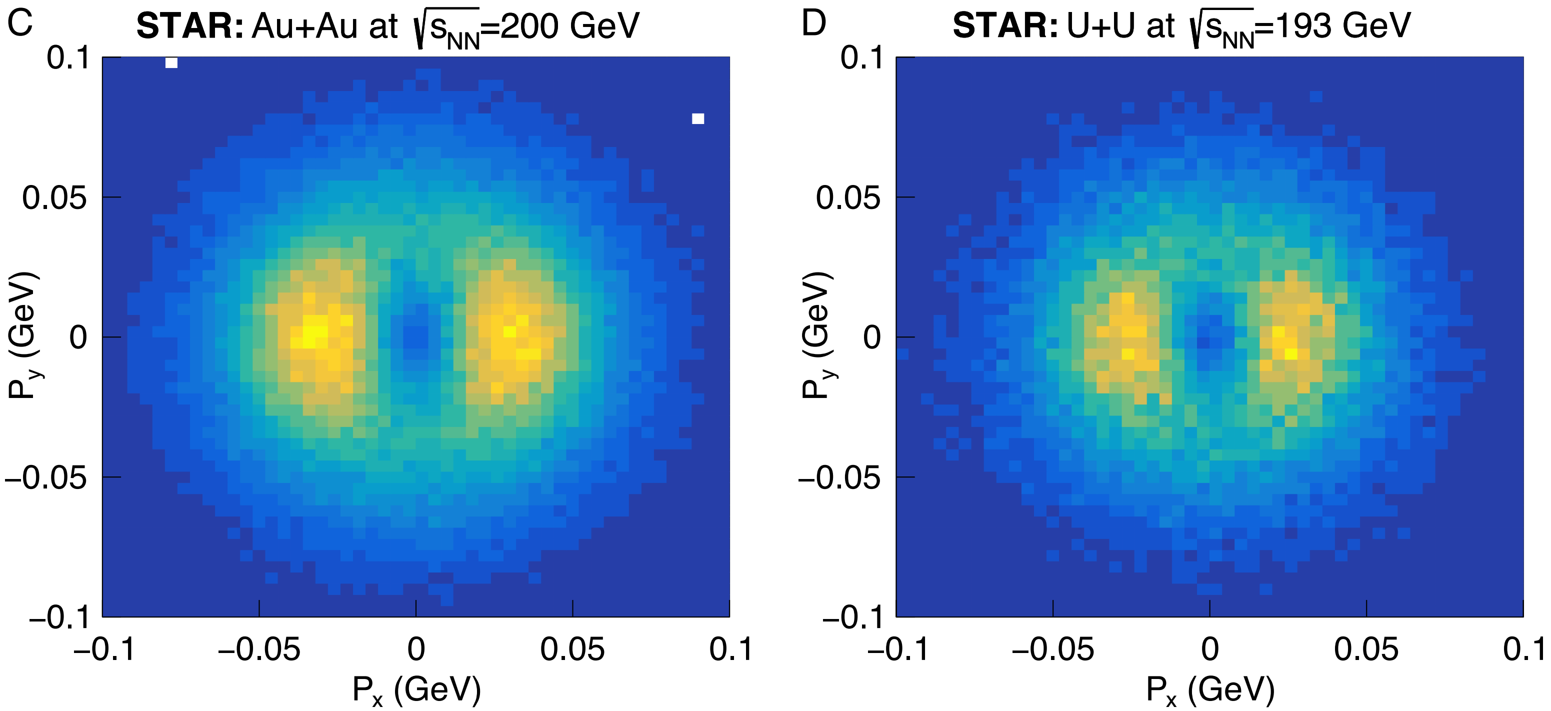
- Photon polarization is aligned with $\vec{b}$ (exactly for point source)
- Two source interference takes place in x-axis (impact parameter direction)



- 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



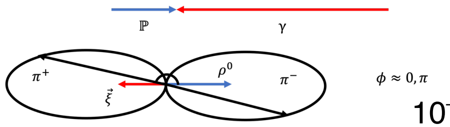
- Express ρ^0 transverse momentum in two-dimensions:
  - $P_x = p_T \times \cos\phi$
  - $P_y = p_T \times \sin\phi$

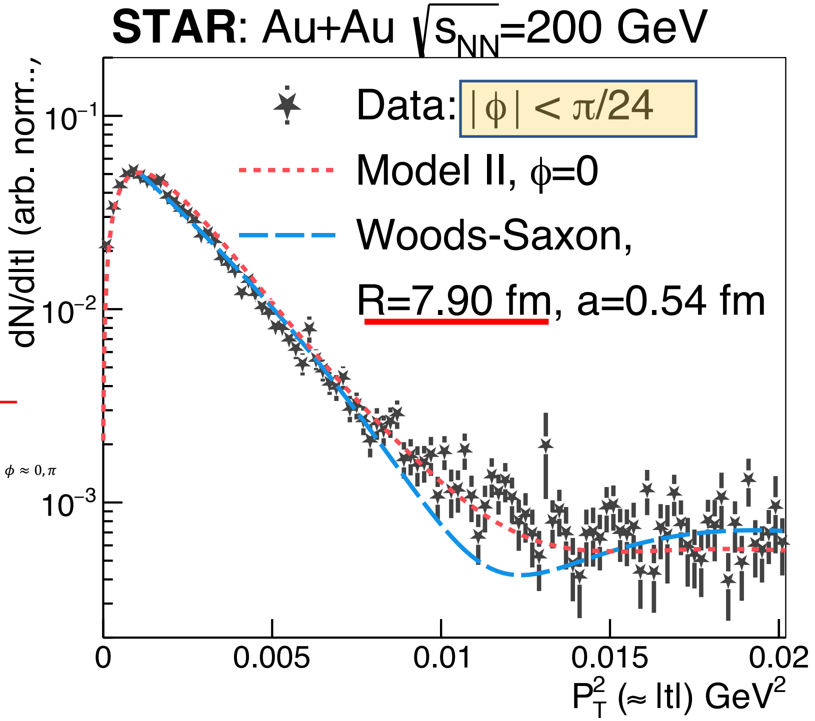
- Clear asymmetry in P_x vs. P_y due to interference effect in both Au+Au and U+U
- Illustrated "2D" tomography

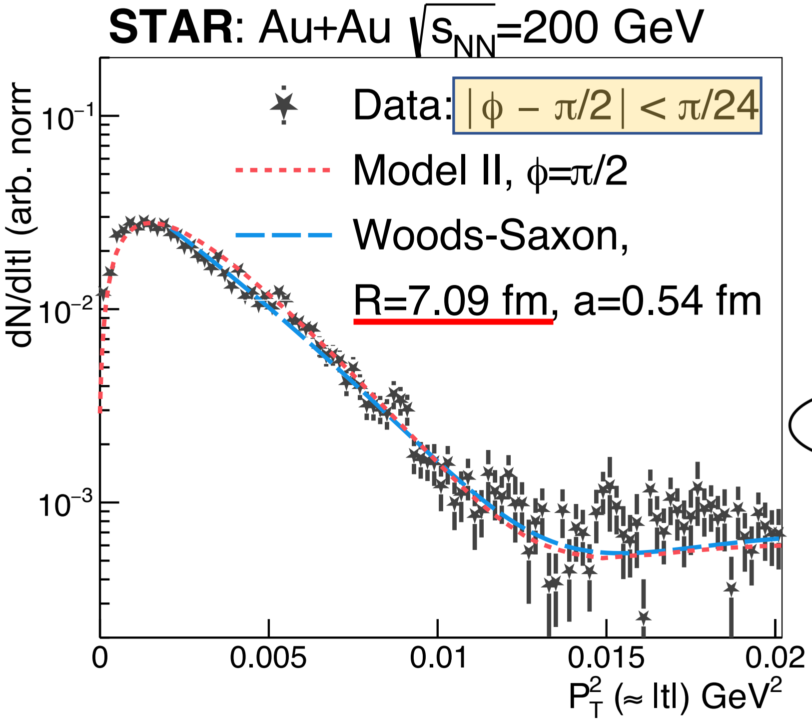
STAR Collaboration, Sci. Adv. **9**, eabq3903 (2023).

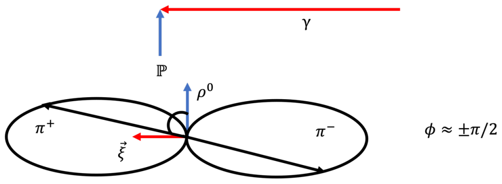
|t| vs. ϕ, which radius is 'correct'?

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)

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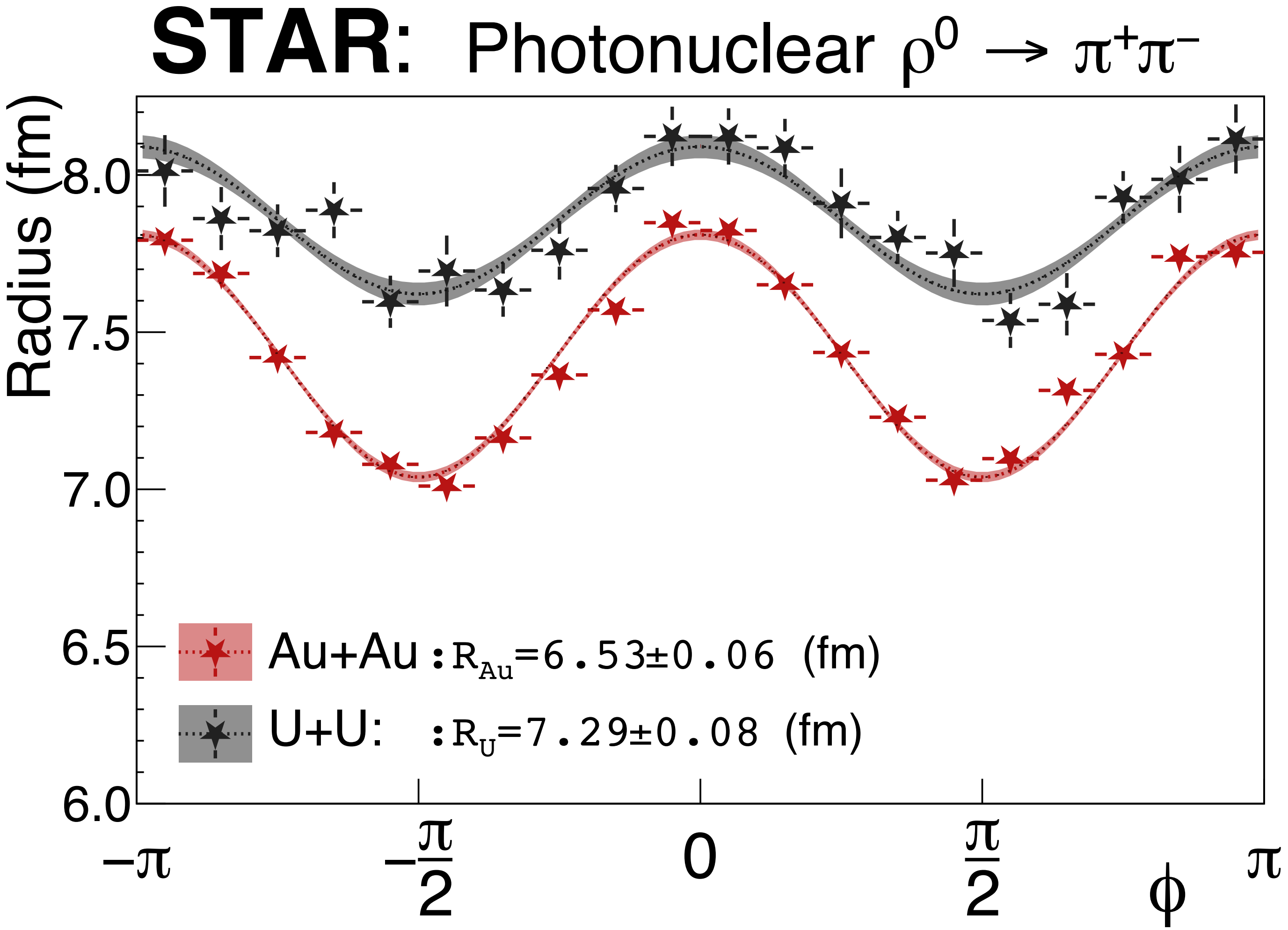
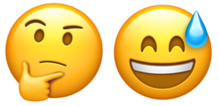


Interference pattern used for diffraction tomography of gluon distribution → analog to x-ray diffraction tomography

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 ≈ 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).

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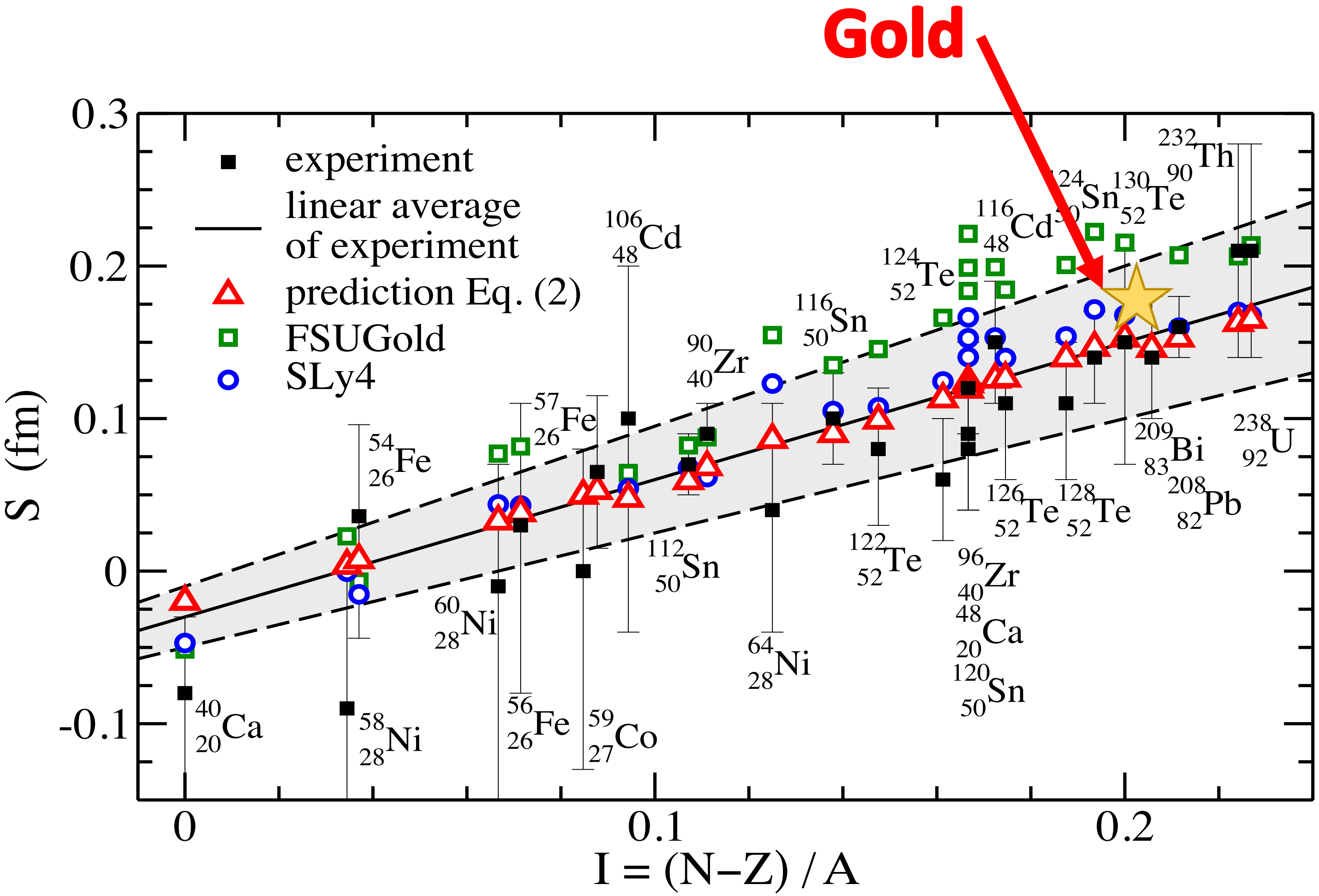
Neutron Skins at High-Energy



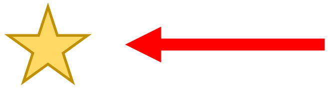
$S_{Au} = 0.17 \pm 0.03\text{(stat.)}$
$\pm 0.08\text{(syst.) fm}$

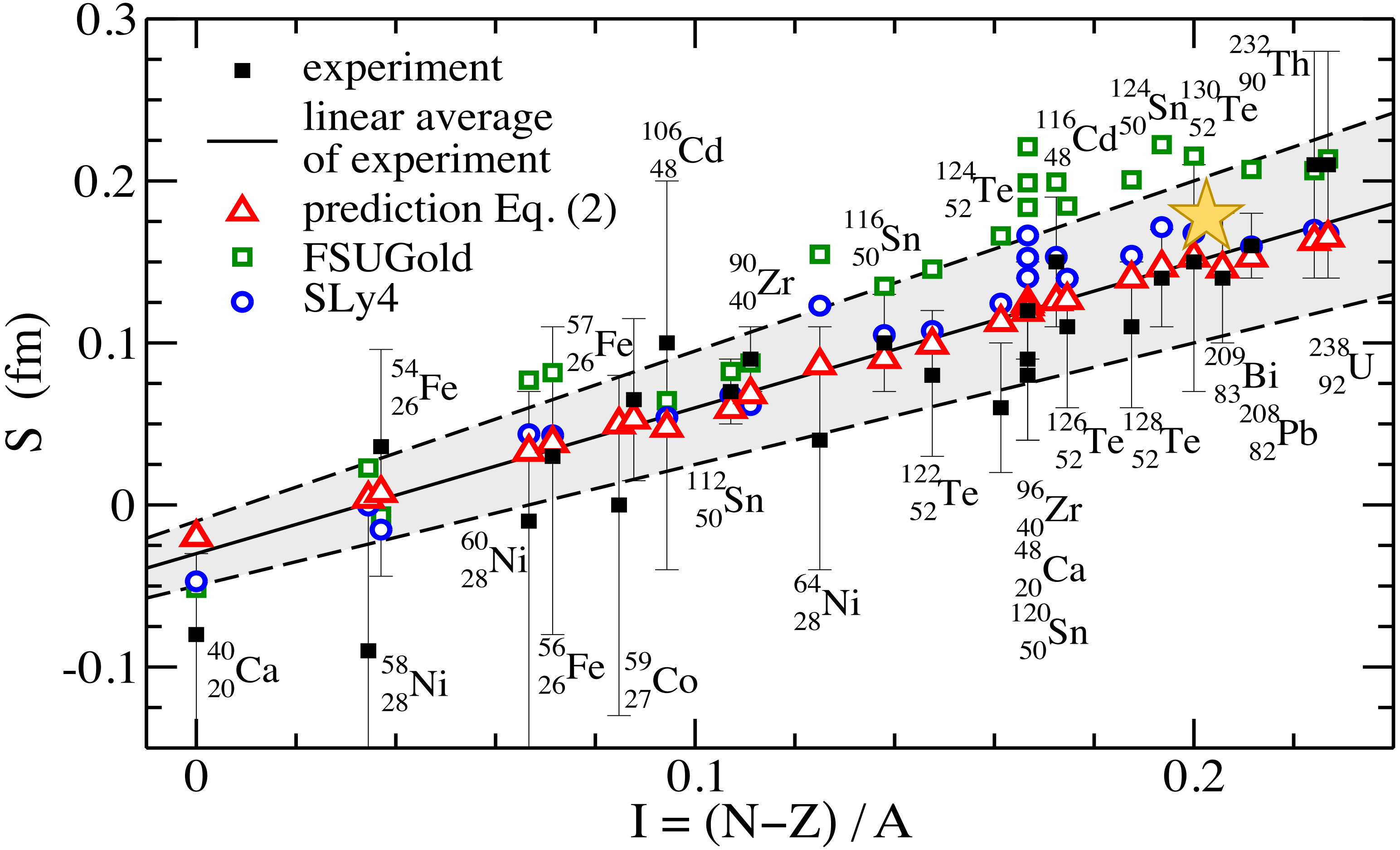
$S_{Au}^{MR-EDF} = 0.17$ fm

Bally, B., Giacalone, G. & Bender, M. *Eur. Phys. J. A* **59**, 58 (2023).

- Gold agrees well with state-of-the-art energy density functional calculations
- Consistent with trend from low energy measurements

Neutron Skins at High-Energy





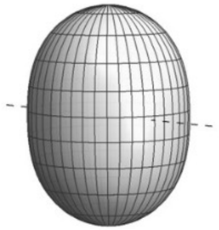
$S_U = 0.44 \pm 0.05$ (stat.) ± 0.08 (syst.) fm

- Uranium neutron skin appears surprisingly large?
- Above trend and low-energy measurements?

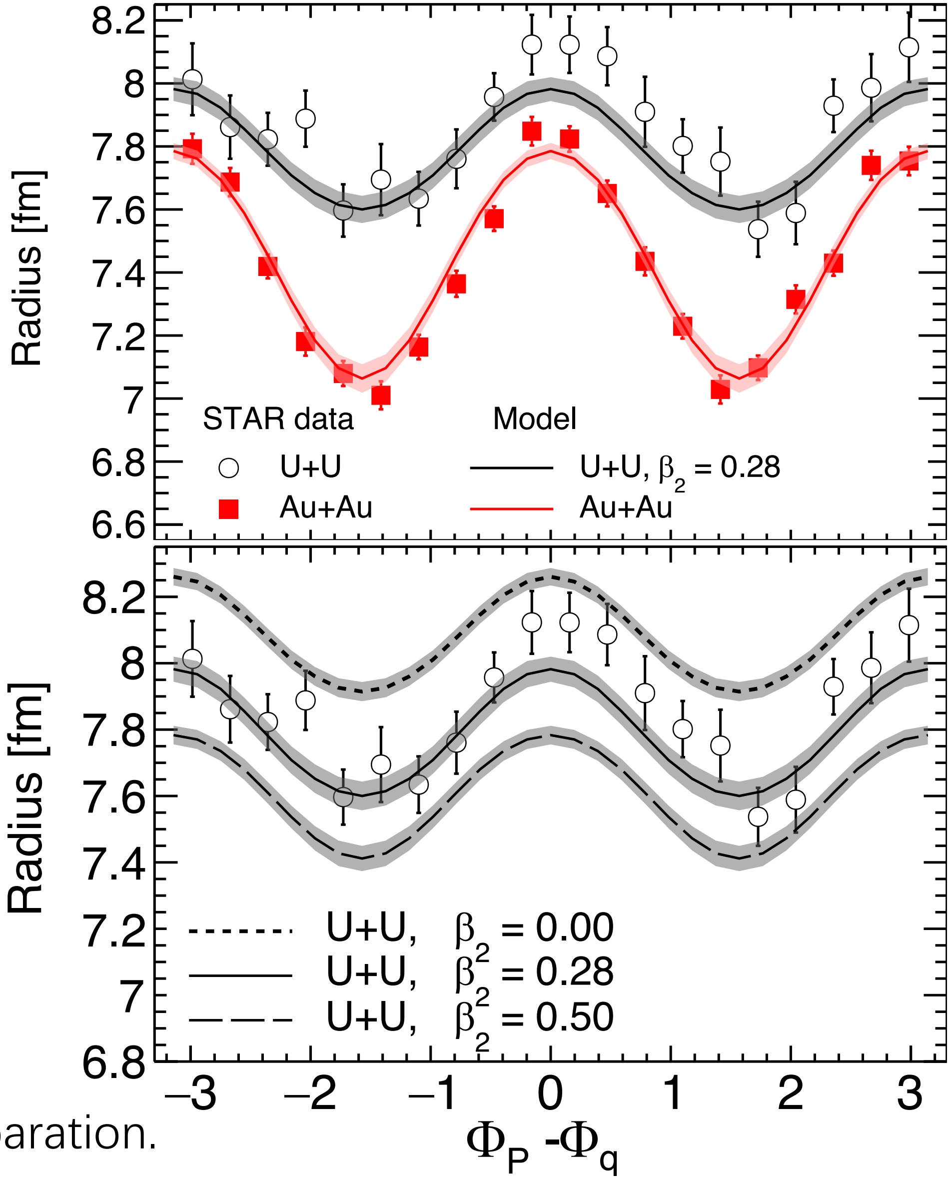
Robust Theoretical Description

- First theoretical prediction for deformed Uranium
- Sensitivity to nuclear geometry!

β_2



- 2D Tomography possible through Interference effect
- Also require very large U radius
- Assumes amplitude interference for coherent process



H.Mantysaari, F. Salazar, B.Schenke, C. Shen and W. Zhao, in preparation.

Aside: Intensity Interferometry

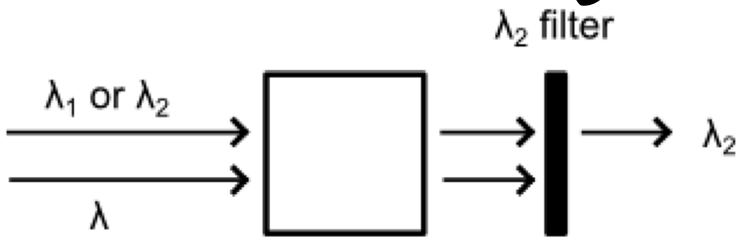
Credit: Albert Stebbins
Fermilab

Intensity interference:

- **Two** photon measurement from incoherent source
- "image" encoded in transverse correlations
- Requires photons be indistinguishable

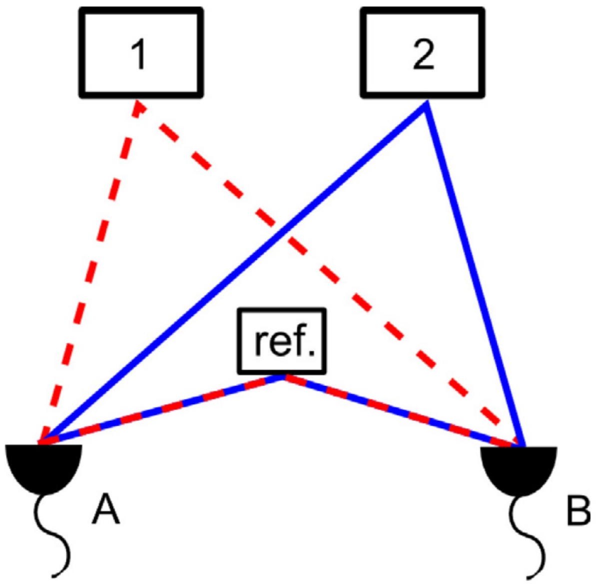
Entanglement Enabled Intensity Interferometry of different wavelengths of light

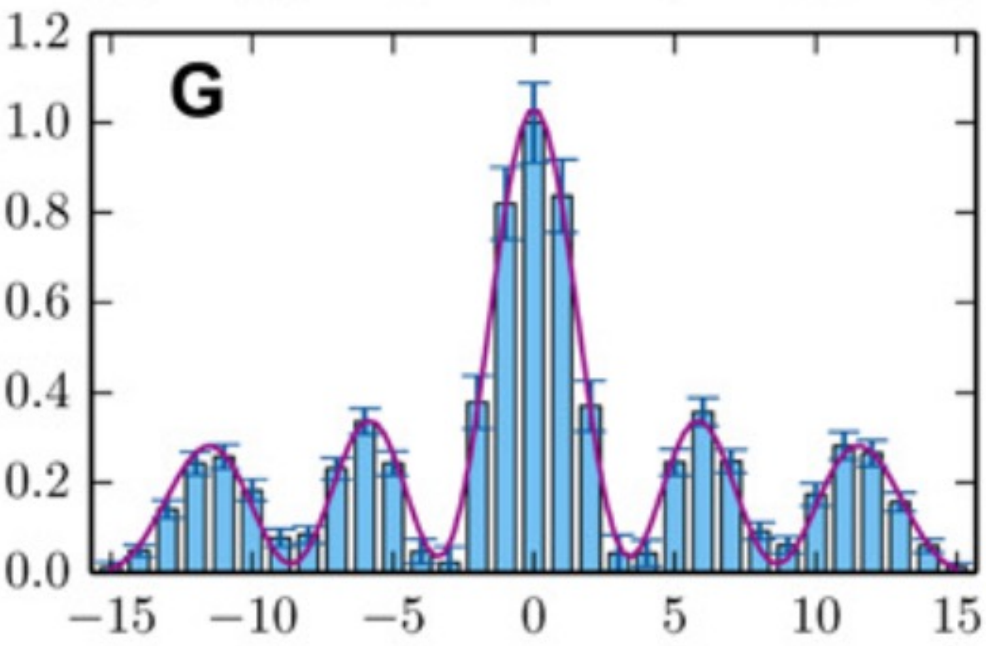
Jordan Cotler [a], Frank Wilczek [b c d e f], Victoria Borish [g]

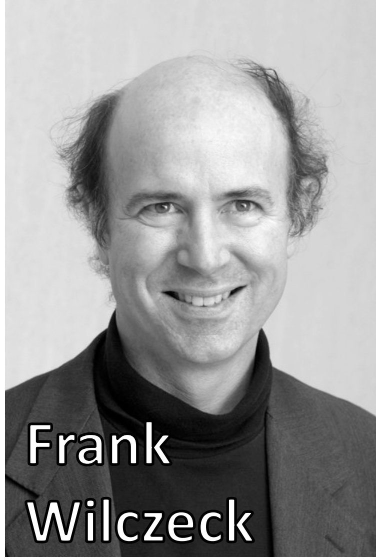


Cotler-Wilczek Process: use entanglement 'filter' to convert **different wavelengths** of light to a common state→ interference

Annals of Physics Volume 424, 168346 (2021)







Entanglement Enabled Intensity Interferometry

Entanglement enabled Intensity Interferometry from exclusive $\pi^+\pi^-$ measurements in UPC's as an inverse Cotler-Wilczek process

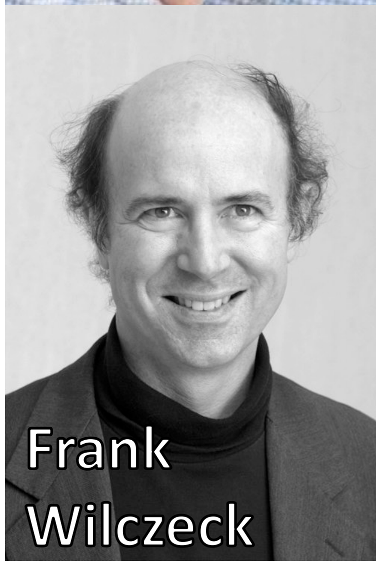
Haowu Duan, Raju Venugopalan, Zhoudunming Tu, Zhangbu Xu, James Daniel Brandenburg, In preparation

Inverse Cotler-Wilczek Process: 'Filter' ρ^0 state comes first.

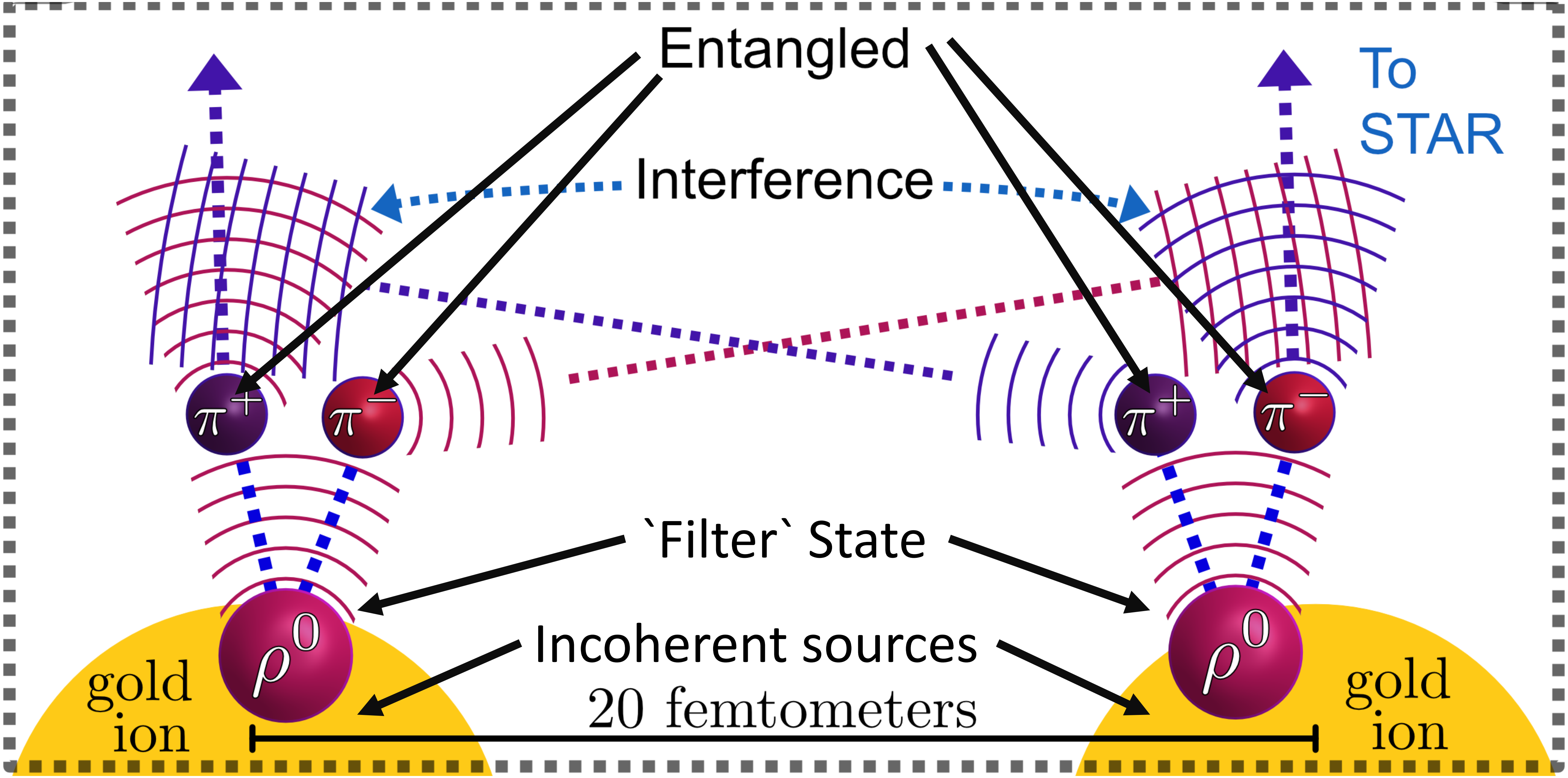
Entanglement of daughter pions enables interference

$$\begin{aligned} < N_A N_B|\pi^+\pi^- > &= < N_A N_B|\rho_A >< \rho_A|\pi^+\pi^-, A > \\ &\times < \pi^+\pi^-, A|\Big(|\pi^+, 1 > |\pi^-, 2 > +|\pi^+, 2 > |\pi^-, 1 > \Big) \\ &+ < N_A N_B|\rho_B >< \rho_B|\pi^+\pi^-, B > \\ &\times < \pi^+\pi^-, B|\Big(|\pi^+, 1 > |\pi^-, 2 > +|\pi^+, 2 > |\pi^-, 1 > \Big). \end{aligned} \tag{16}$$

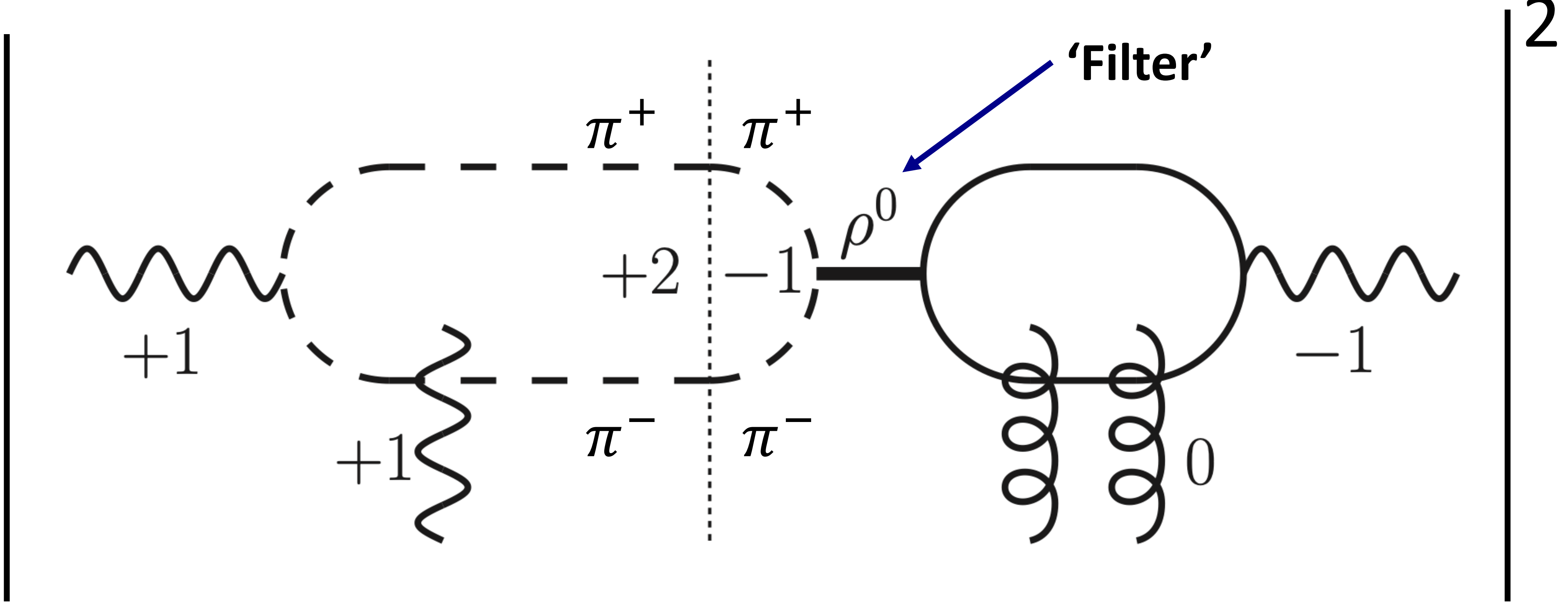
Interference only occurs if final state particles are <u>entangled</u>!



Entanglement Enabled Intensity Interference



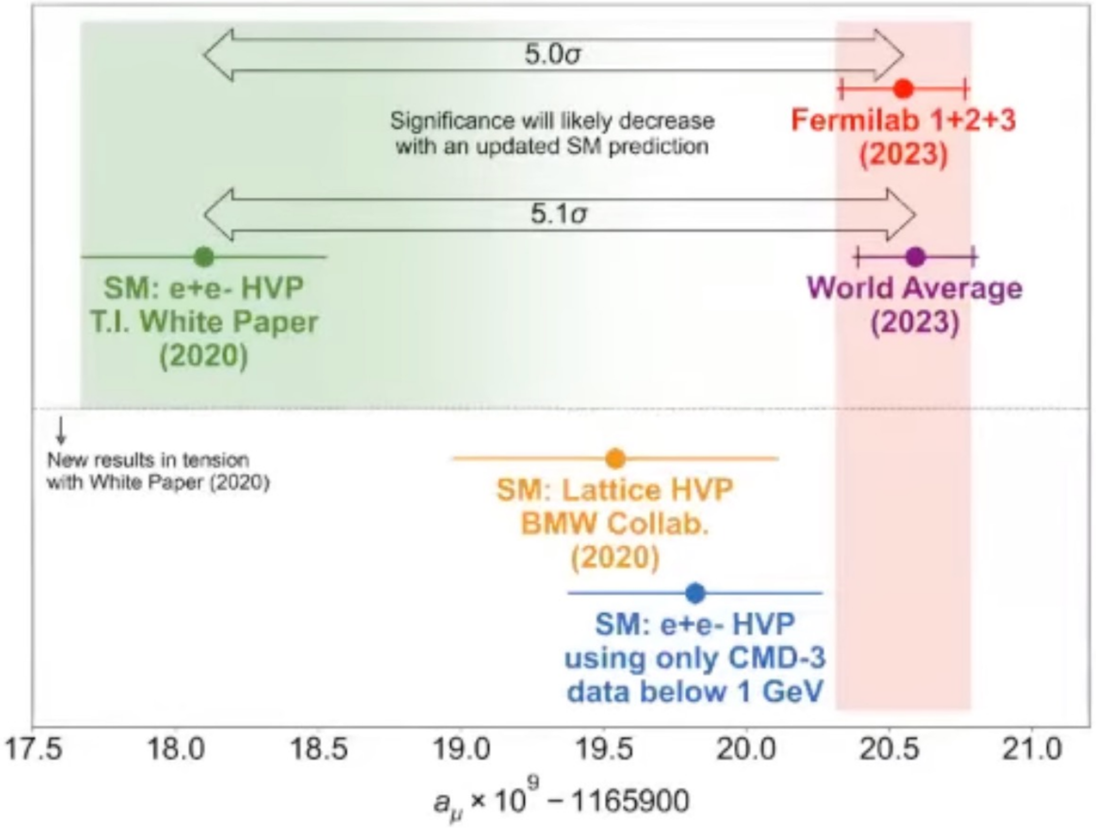
Access to Hadronic Light-by-Light

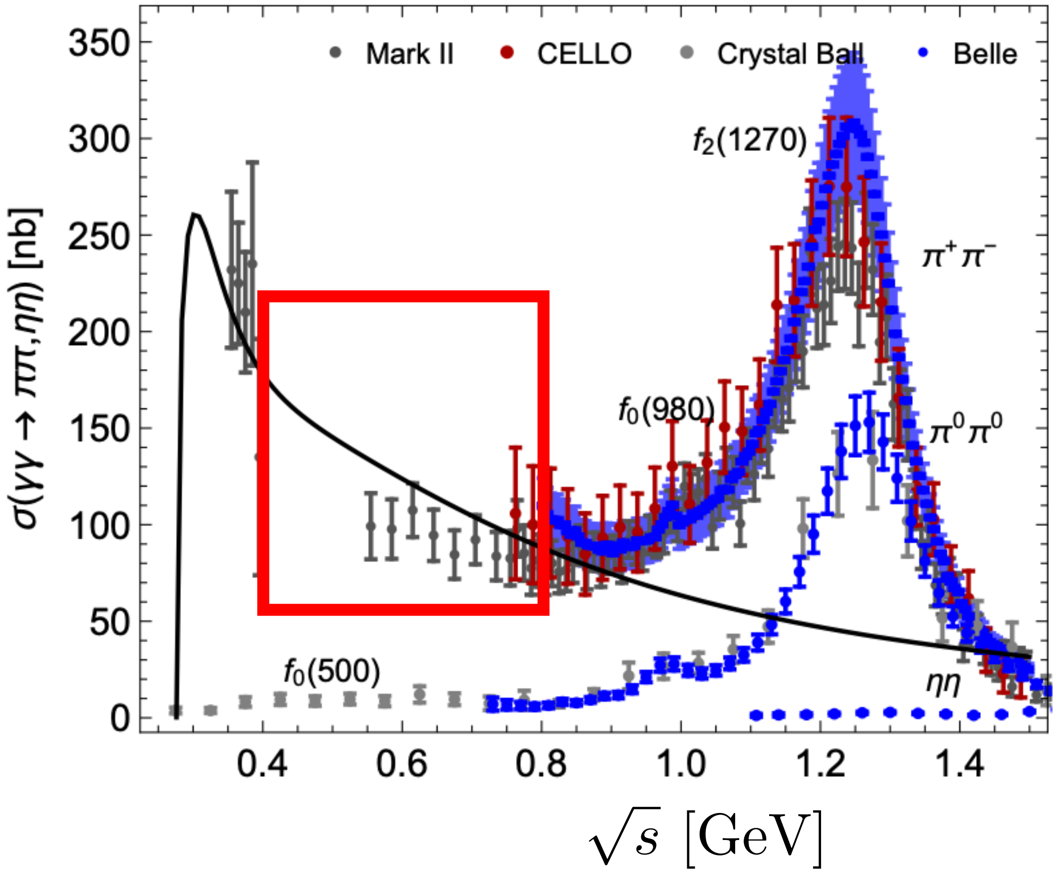


Interference with the hadronic light-by-light diagram
Leads to a unique signature -> odd spin configurations

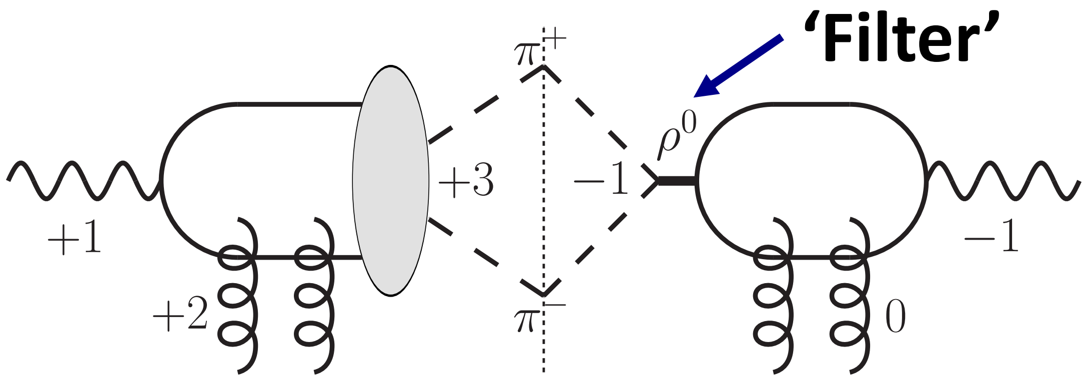
Novel Experimental input for muon g-2

Contribution from Hadronic Vacuum Polarization and Hadronic Light-by-Light are **the largest theoretical uncertainties** for Standard Model muon g-2





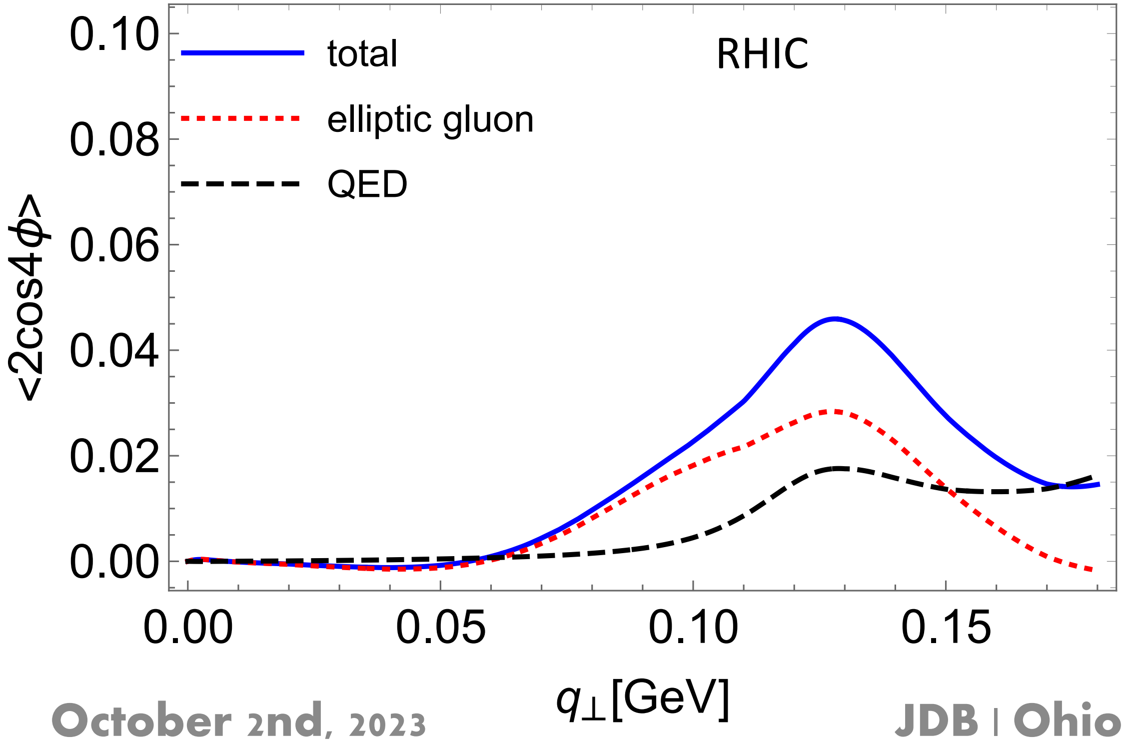
Elliptic Gluon Tomography (Tensor Pomeron)

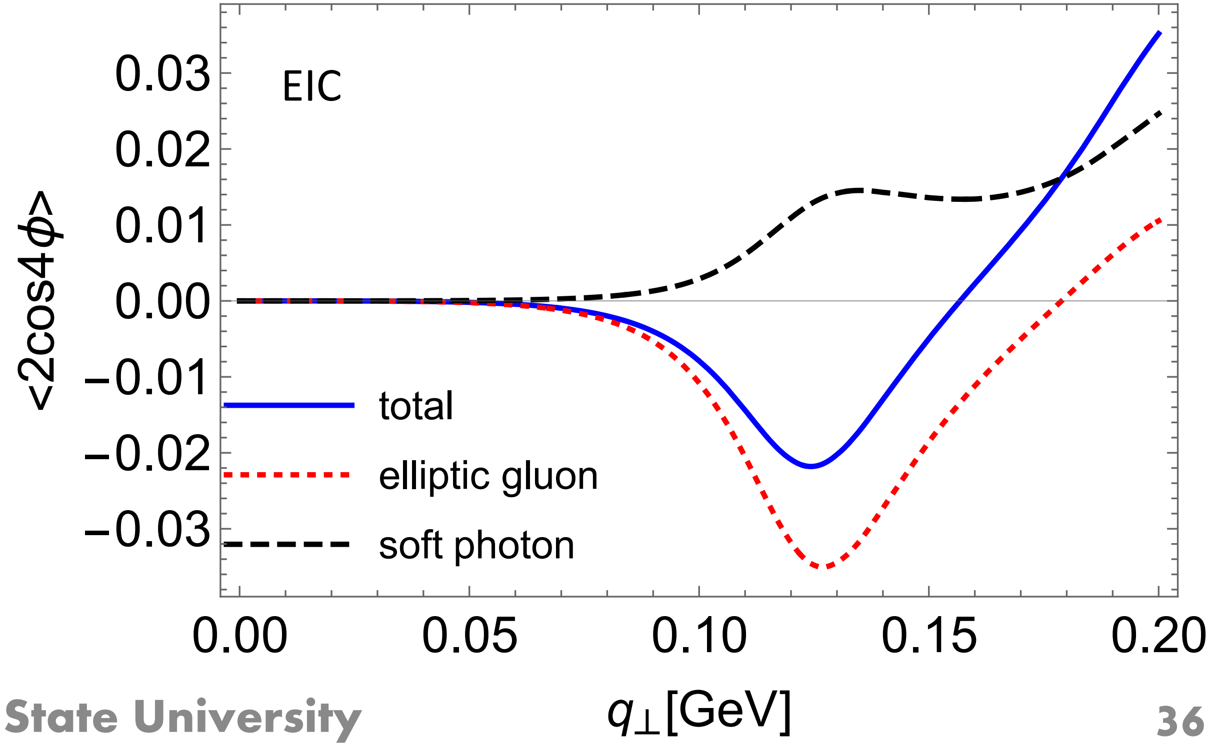


Phys. Rev. D **104**, 094021 (2021)

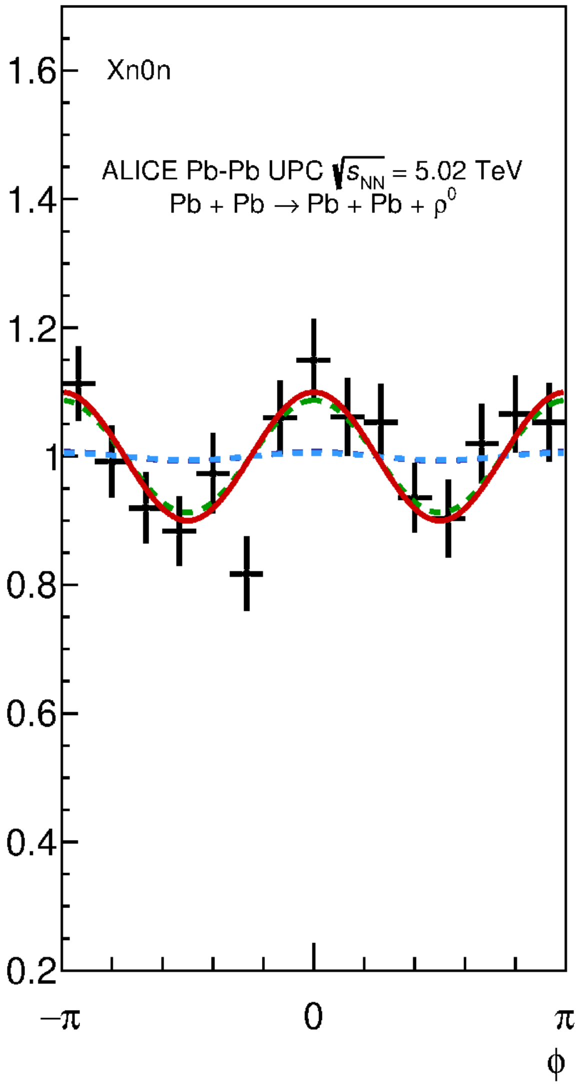
Elliptic gluon distribution: correlation between impact parameter and momentum

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

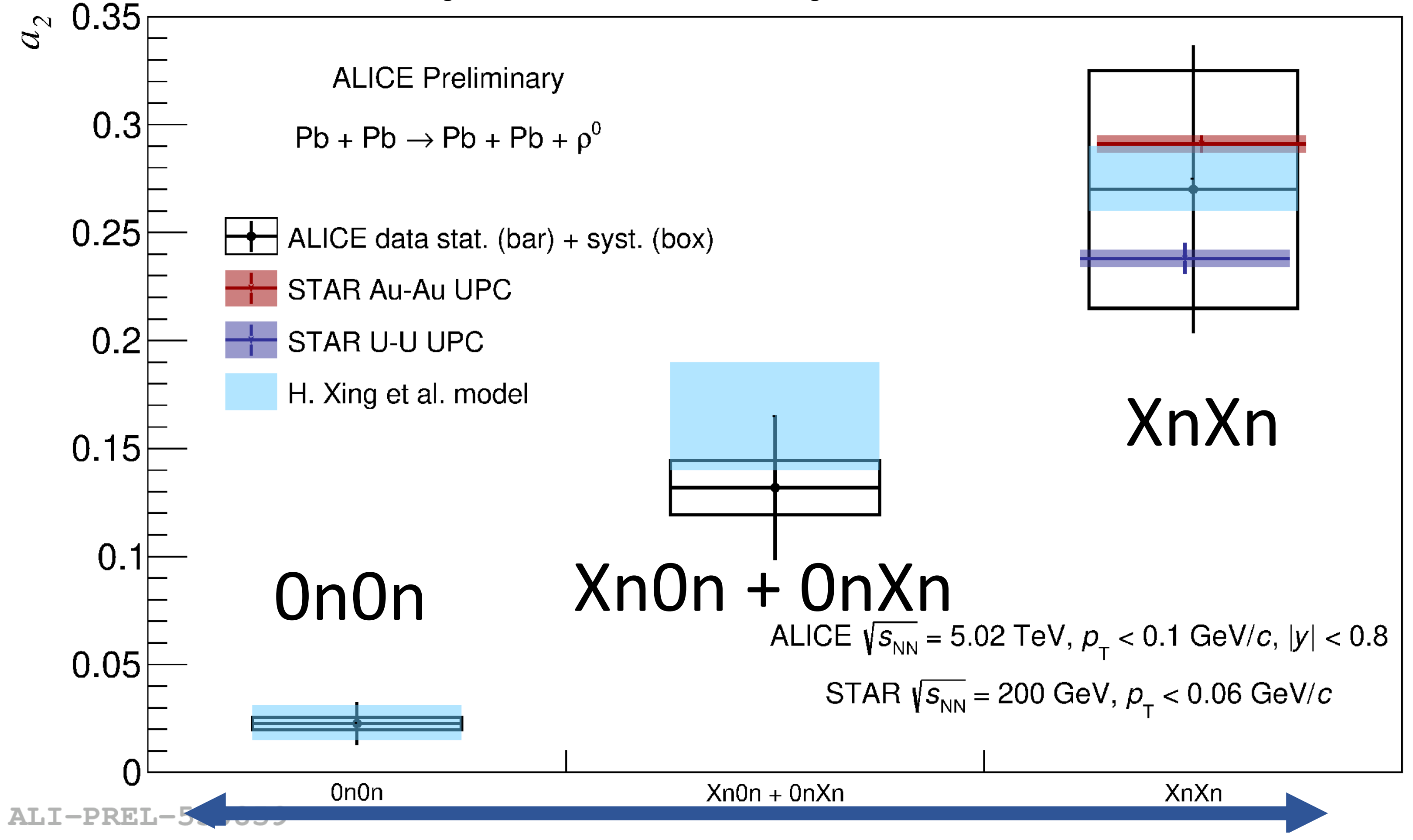




Confirmation from ALICE (New at QM Sept 2023)

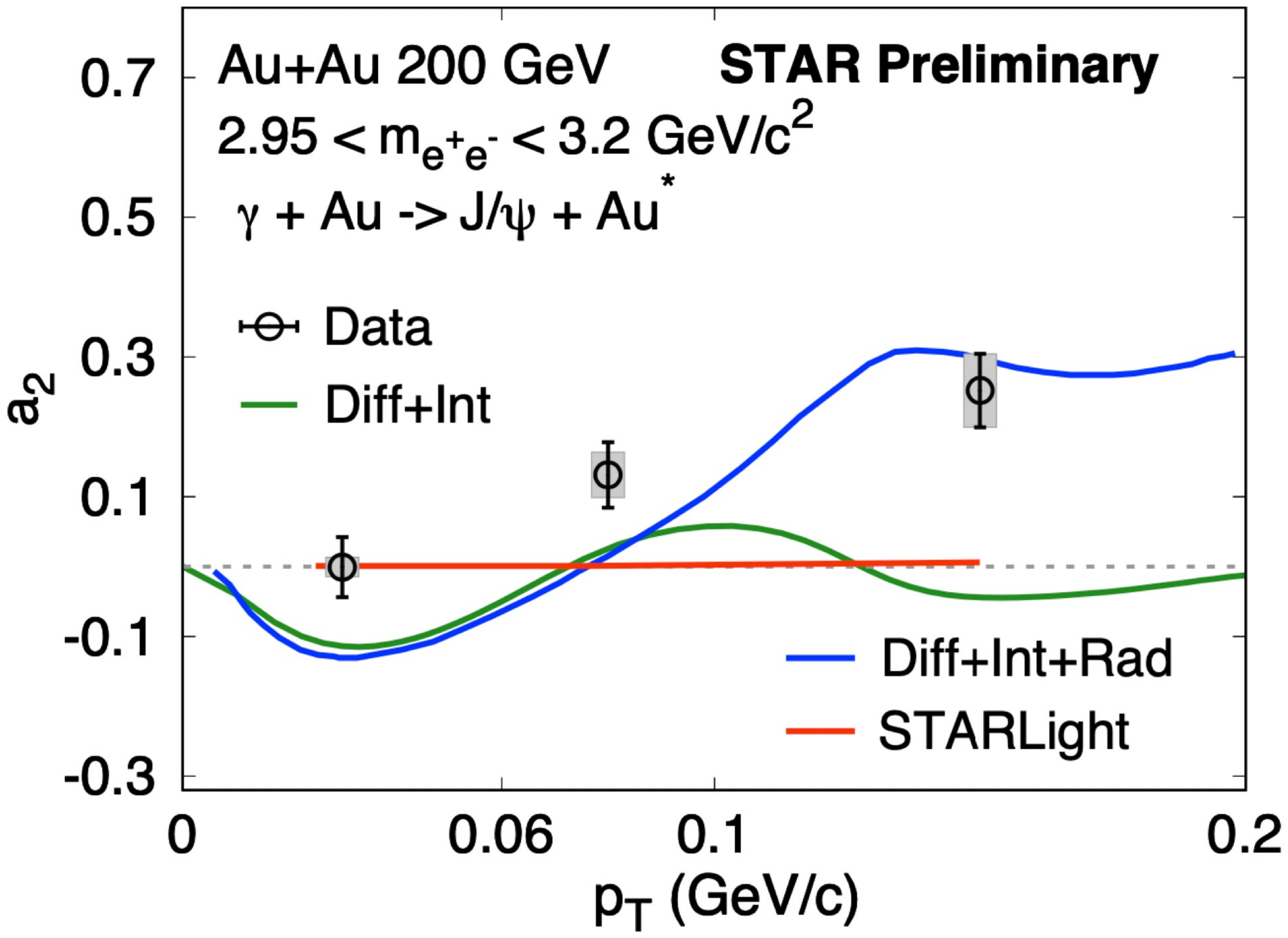


Neutron emission categories test the impact parameter dependence



Polarization effects: coherent diffractive J/ψ

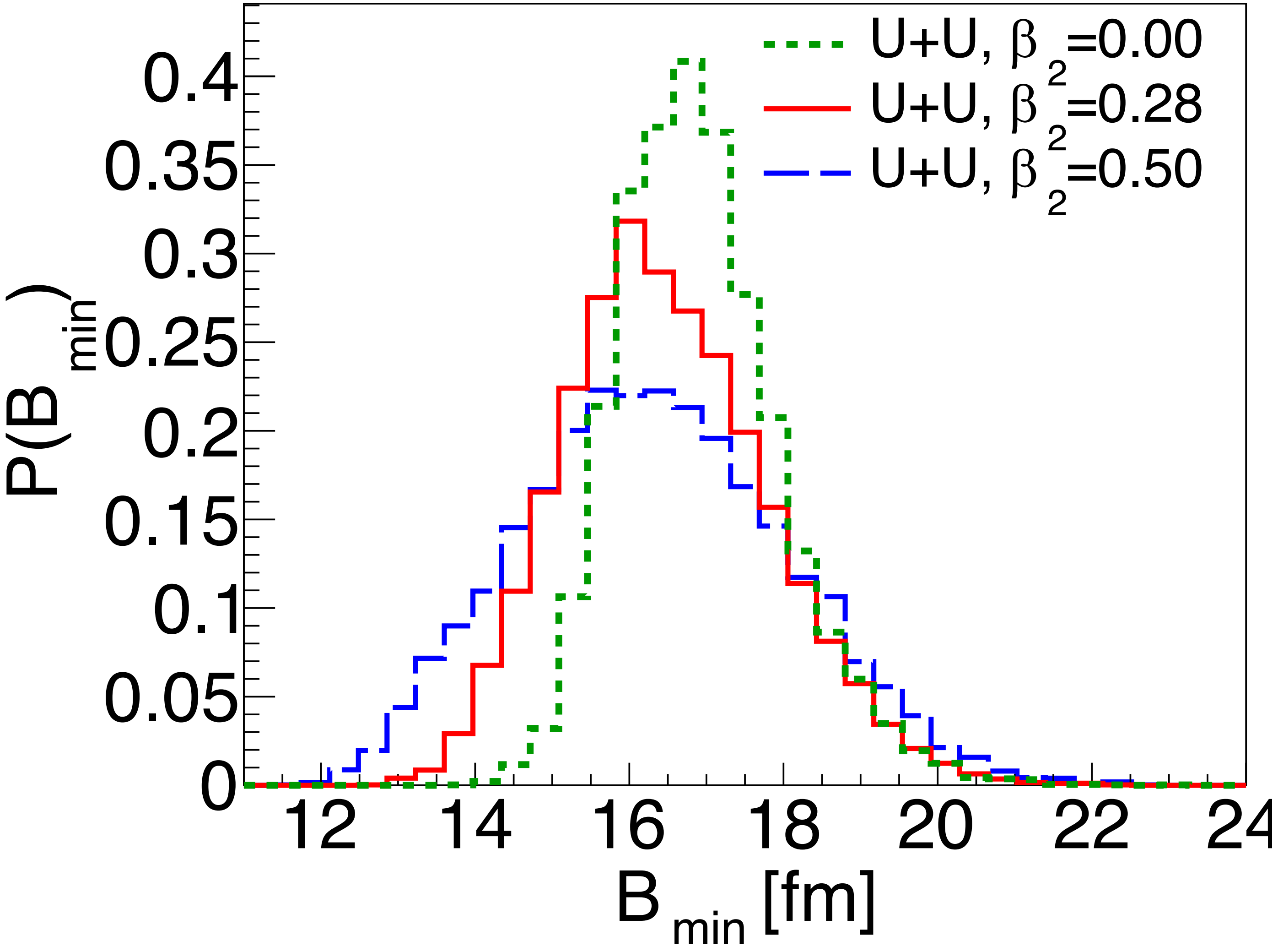
- New STAR measurement of J/ψ at QM in Sept 2023
- Consistent within error with Diffraction + Interference (Diff+Int) effect at low p_T
- Effect of Soft Photon radiation (Rad) visible at higher p_T



Summary – Entanglement Enabled Spin Interference

- Ultra-peripheral collisions provide a unique laboratory for exploring the frontiers of QED, QCD and BSM physics
- Polarized Breit-Wheeler process: access to photon polarization
- Photonuclear processes: novel incarnation of the 'double-slit' experiment
- Analogy to HBT intensity interferometry, but requires entanglement
- Immediate applications:
  - Tomography of gluon distributions within large nuclei at high energy -> neutron skin
  - Interference access to hadronic light-by-light in unconstrained region -> inform BSM searches through anomalous magnetic moments
  - Interference access to Pomeron with higher spin states -> gluon spin correlations within large nuclei, signatures of gluon saturation & nonlinear dynamics

Bmin distribution in UPCs



H.Mantysaari, B.Schenke, C. Shen and W. Zhao, Phys. Lett. B 833 (2022), 137348.

Imaging the Nuclear Charge Distribution

$\gamma\gamma \rightarrow l^+l^-$ can be used to constrain nucleus charge distribution at RHIC energy

STAR data compared to EPA-QED

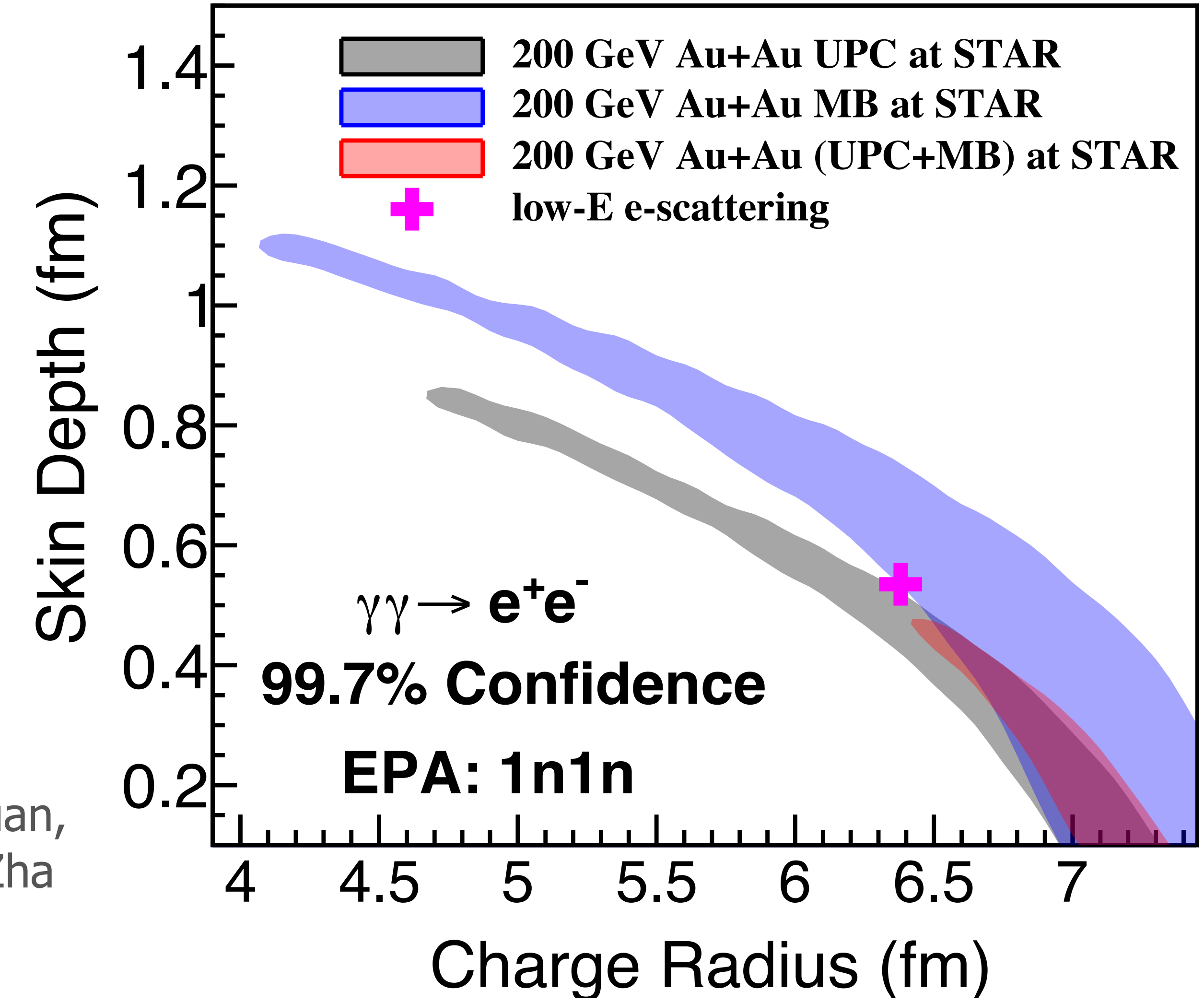
Low energy scattering: R=6.38 fm, d=0.535 fm

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

- Explore the effective charge distribution vs. energy and impact parameter

Xiaofeng Wang, James Daniel Brandenburg, Lijuan Ruan, Fenglan Shao, Zhangbu Xu, Chi Yang, and Wangmei Zha

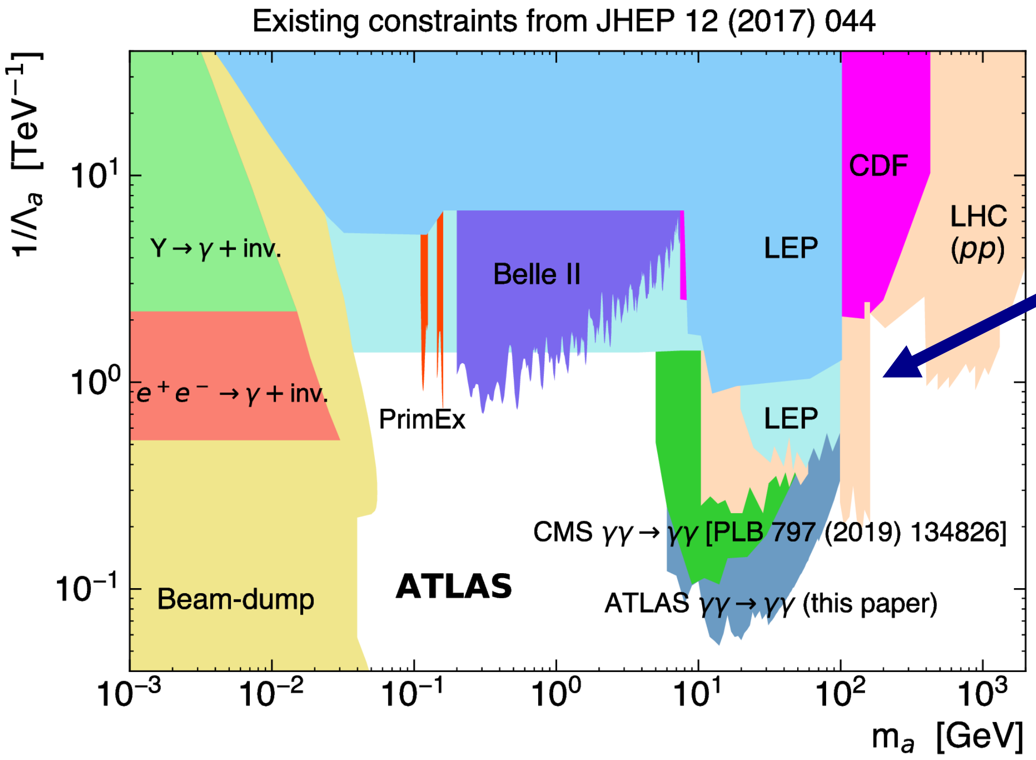
Phys. Rev. C 107, 044906 (2023)

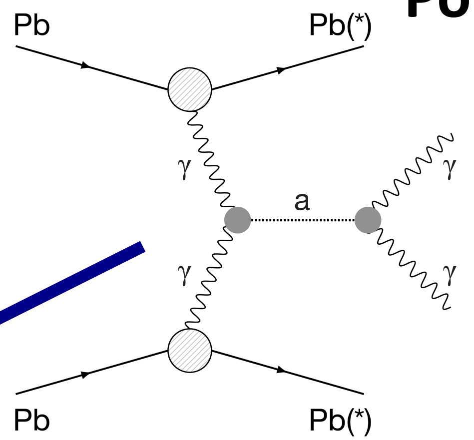


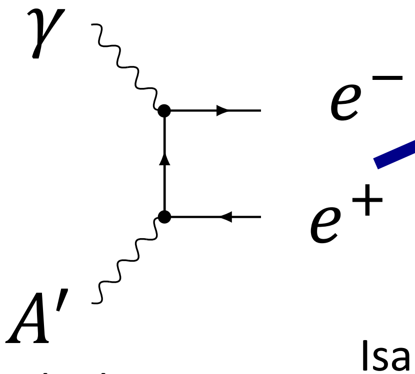
PAST Discoveries→Novel Tests of BSM Physics

▷Discoveries become tools to study new physics

Axion search in Light-by-Light Scattering

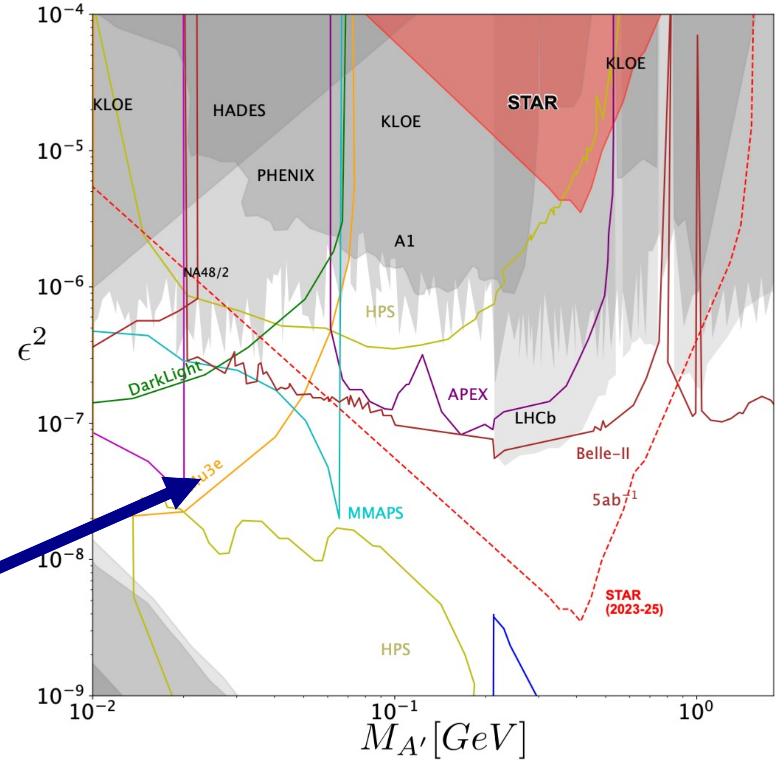






Dark photon

Dark Photon search with Polarized Breit-Wheeler Process



Isabel Xu, Nicole Lewis, Xiaofeng Wang, James Daniel Brandenburg, Lijuan Ruan
arxiv:2211.02132