Entanglement-Enabled Spin Interference

By James Daniel Brandenburg

1. Mystery: Nuclear Radius Measurements
2. Solved?: Imaging with Polarized Light
3. The (Inverse) Cotler-Wilczek Process

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

2023 Workshop on Particle Correlations and Femtoscopy

Catania, Italy

NOVEMBER IX, MMXXIII

The Ohio State University

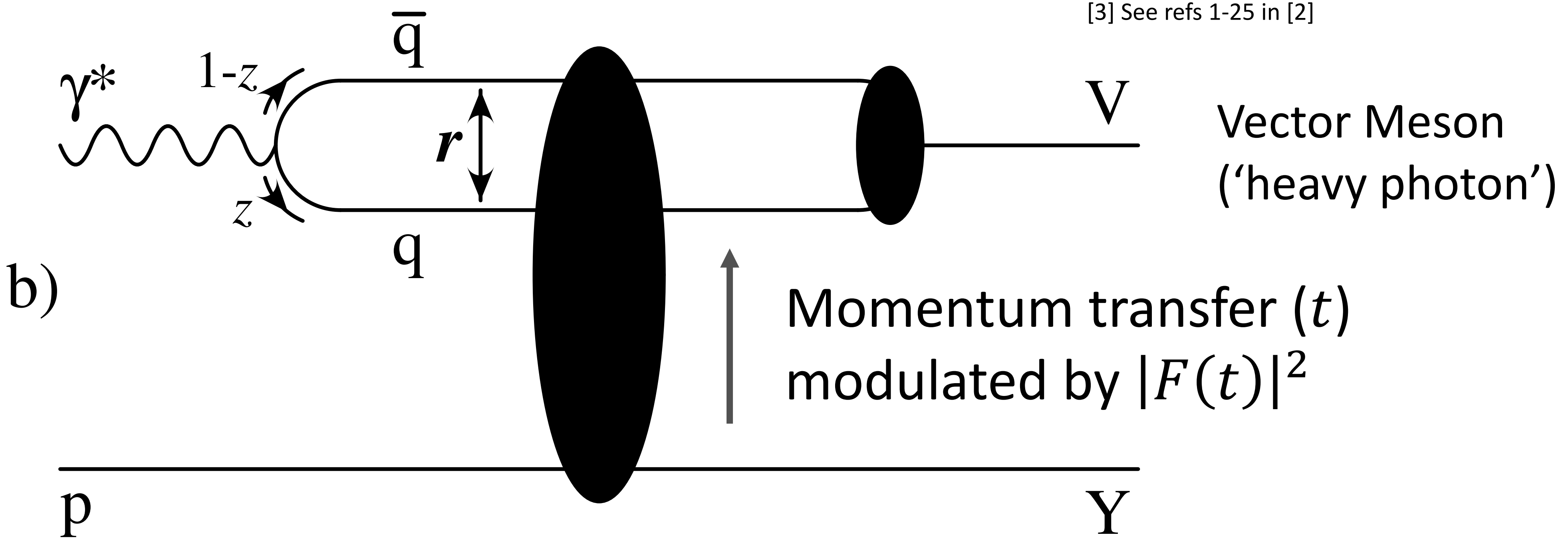
U.S. DEPARTMENT OF ENERGY
Office of Science

1. The Nuclear Radius Mystery in A+A

Shining light on Gluons

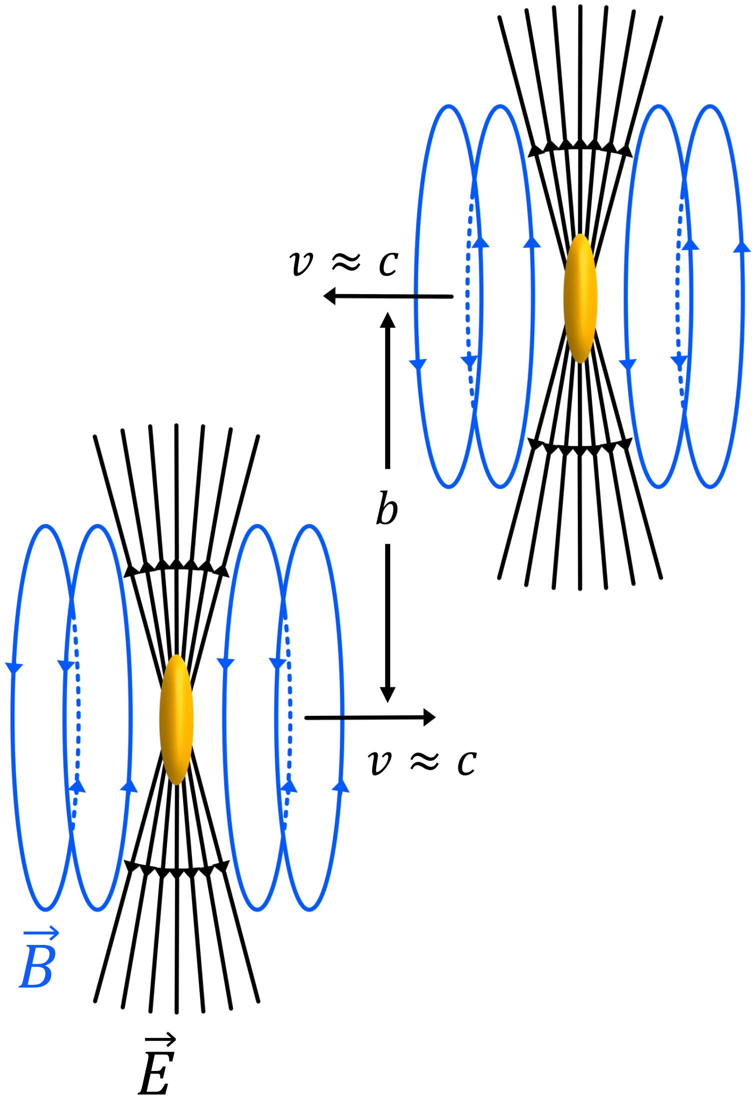
- Photo-nuclear measurements have been used to study QCD matter already for decades[1-3]

[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]



Well known process for probing the **hadronic structure** of the photon and nucleon (nuclear) target

UPCs: The Strongest Electromagnetic Fields



- In heavy-ion collisions:

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

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

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

Must be treated in terms of photon quanta

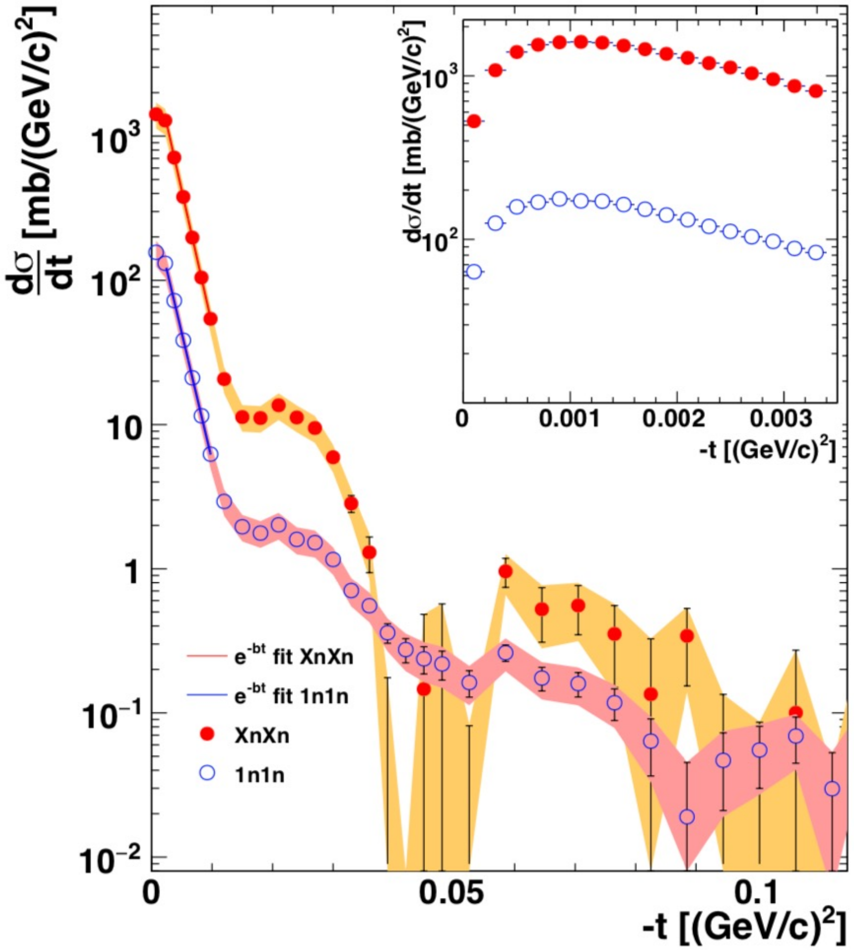
$$E_{\gamma,\max} \approx \gamma\hbar c/R$$

80 GeV @ LHC
3 GeV @ RHIC

High energy (small wavelength) photons can be used to ‘image’ the nucleus

Past Photo-Nuclear Measurements

- Many studies of $\gamma\mathbb{P} \rightarrow \rho^0 \rightarrow \pi^+\pi^-$ in the past



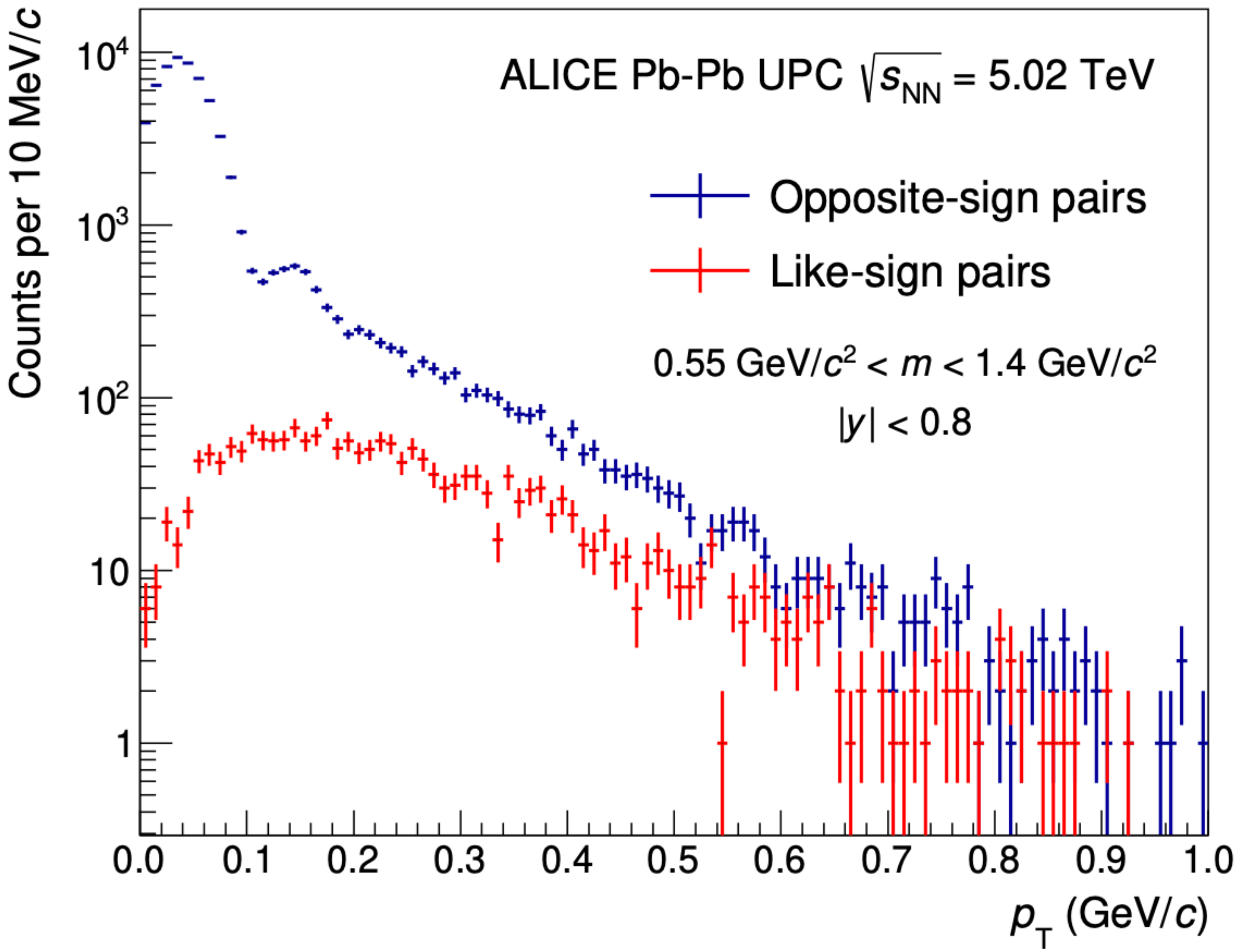
Coherent Diffractive Interactions:

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

$$\sigma(\gamma p \rightarrow Vp) = \left.\frac{d\sigma}{dt}\right|_{t=0} \int_{t_{\min}}^{\infty} |F(t)|^2 dt,$$

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



Other measurements at RHIC & LHC include:

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

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

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

So what's the problem?

Nuclear Radius, too big?

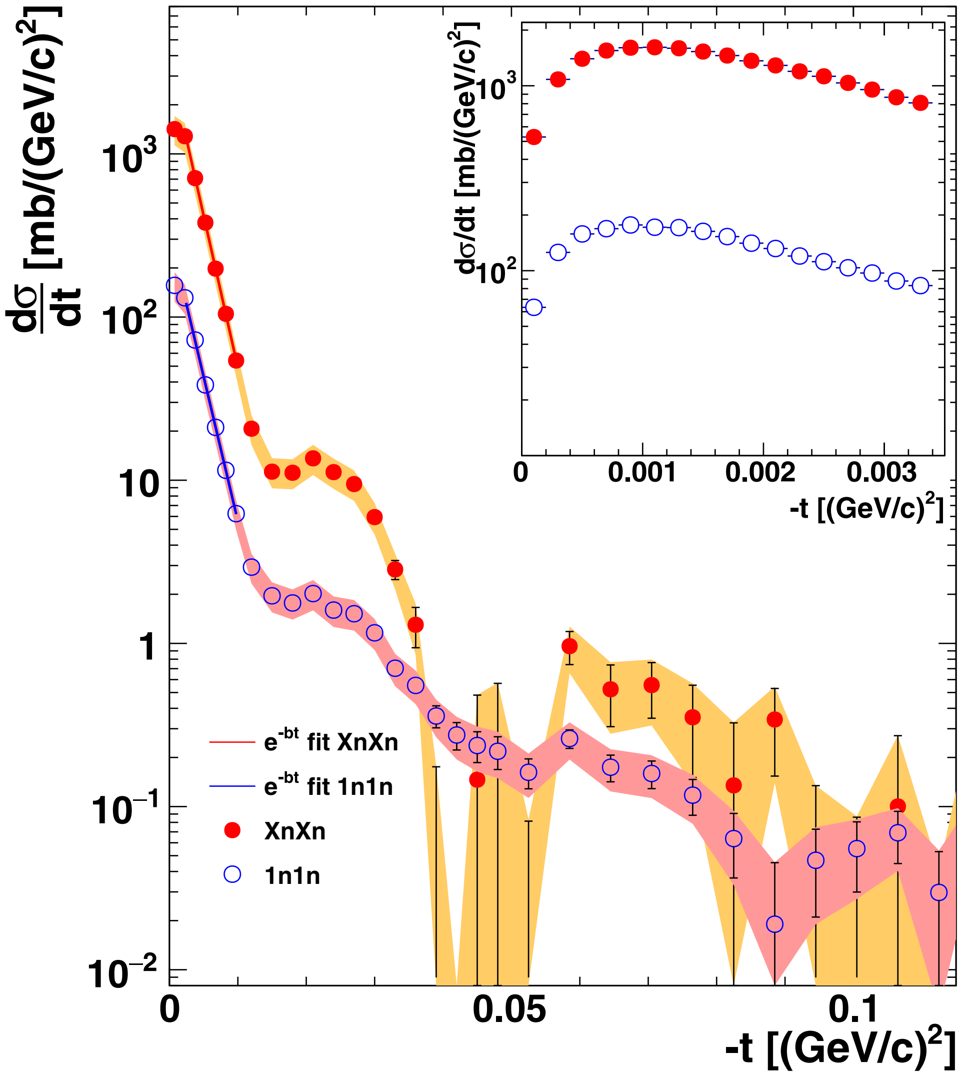


Photo-nuclear measurements have historically produced a |t| slope that corresponds to a **mysteriously large source!**

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

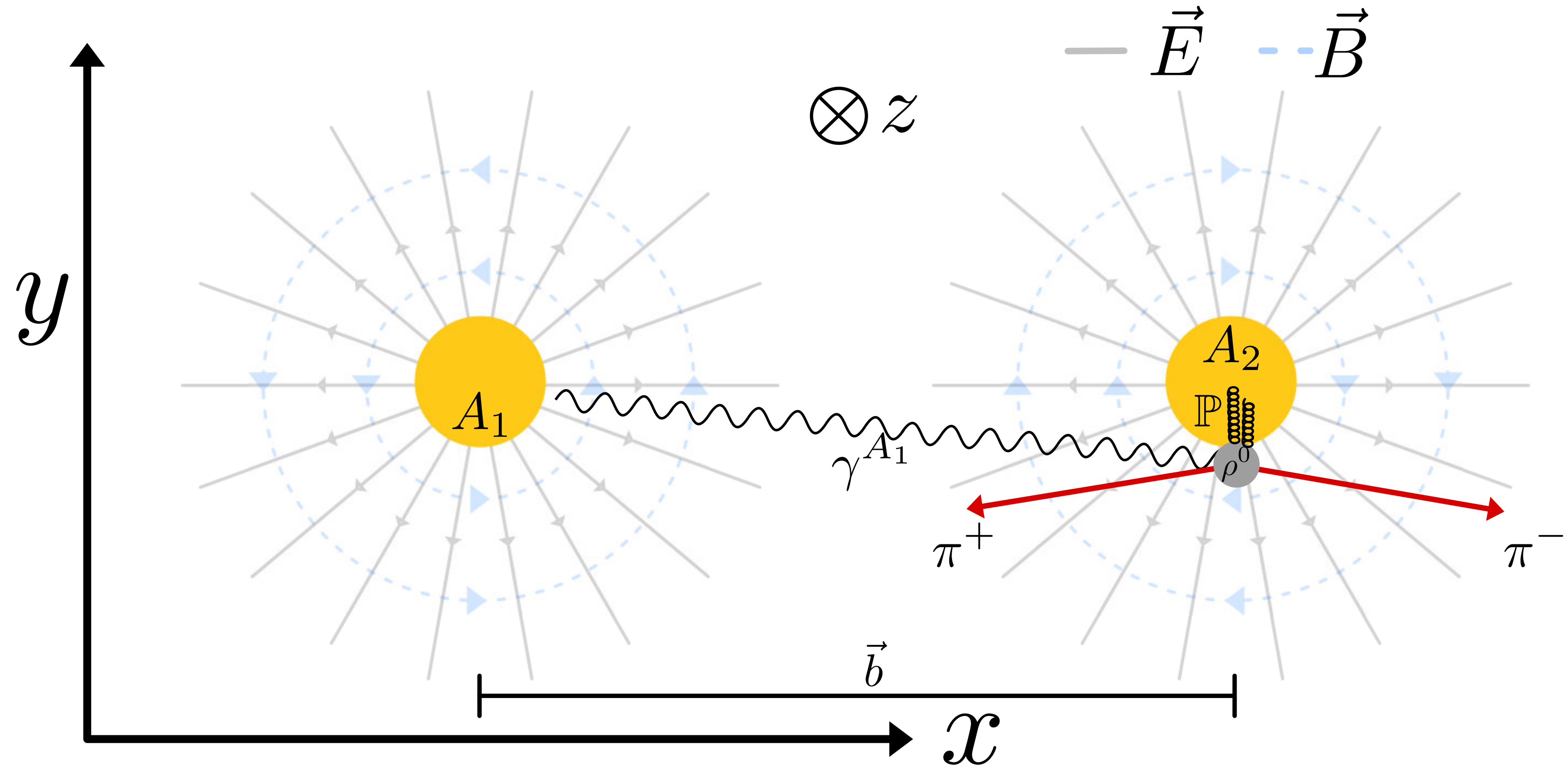
($R_{Pb}^{charged} \approx 6.62$ fm)

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.

2. Solving the Mystery in A+A

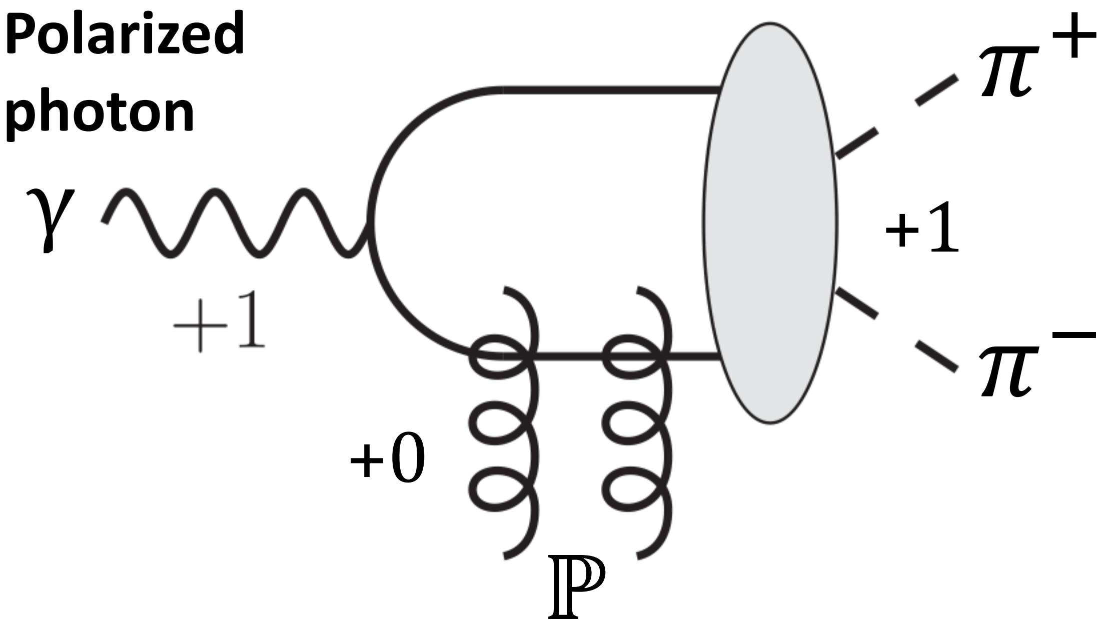
What is NEW with transversely polarized photons?

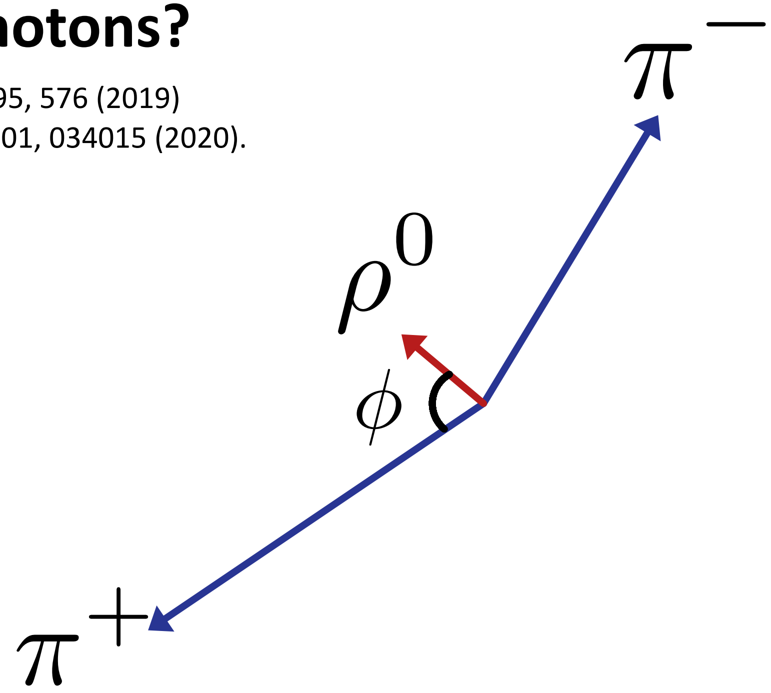


Imaging the Nucleus with Polarized Photons

What is NEW with transversely polarized photons?

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





Recently realized that asymmetries in angle ϕ related to polarization

Access to initial photon polarization

Imaging the Nucleus with Polarized Photons

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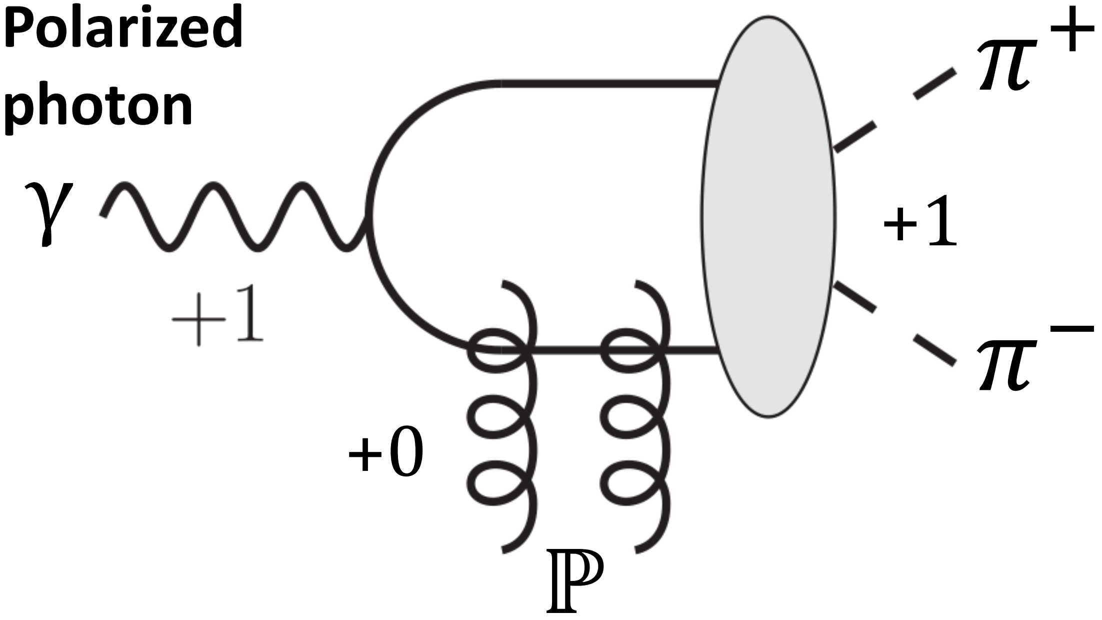
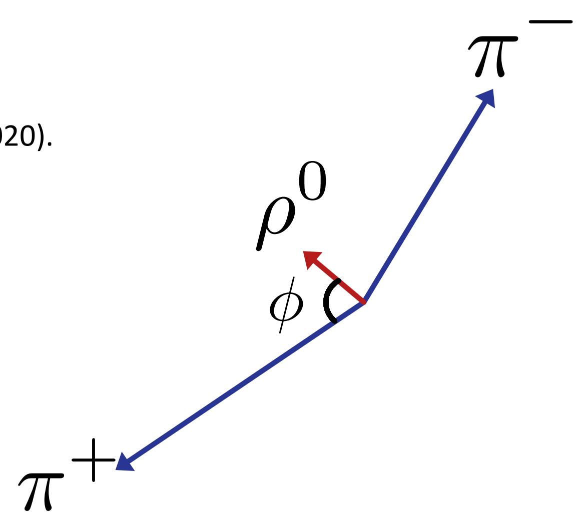
C. Li, J. Zhou, Y. Zhou, Phys. Lett. B 795, 576 (2019)
C. Li, J. Zhou & Y. Zhou Phys. Rev. D 101, 034015 (2020).

Polarized photon



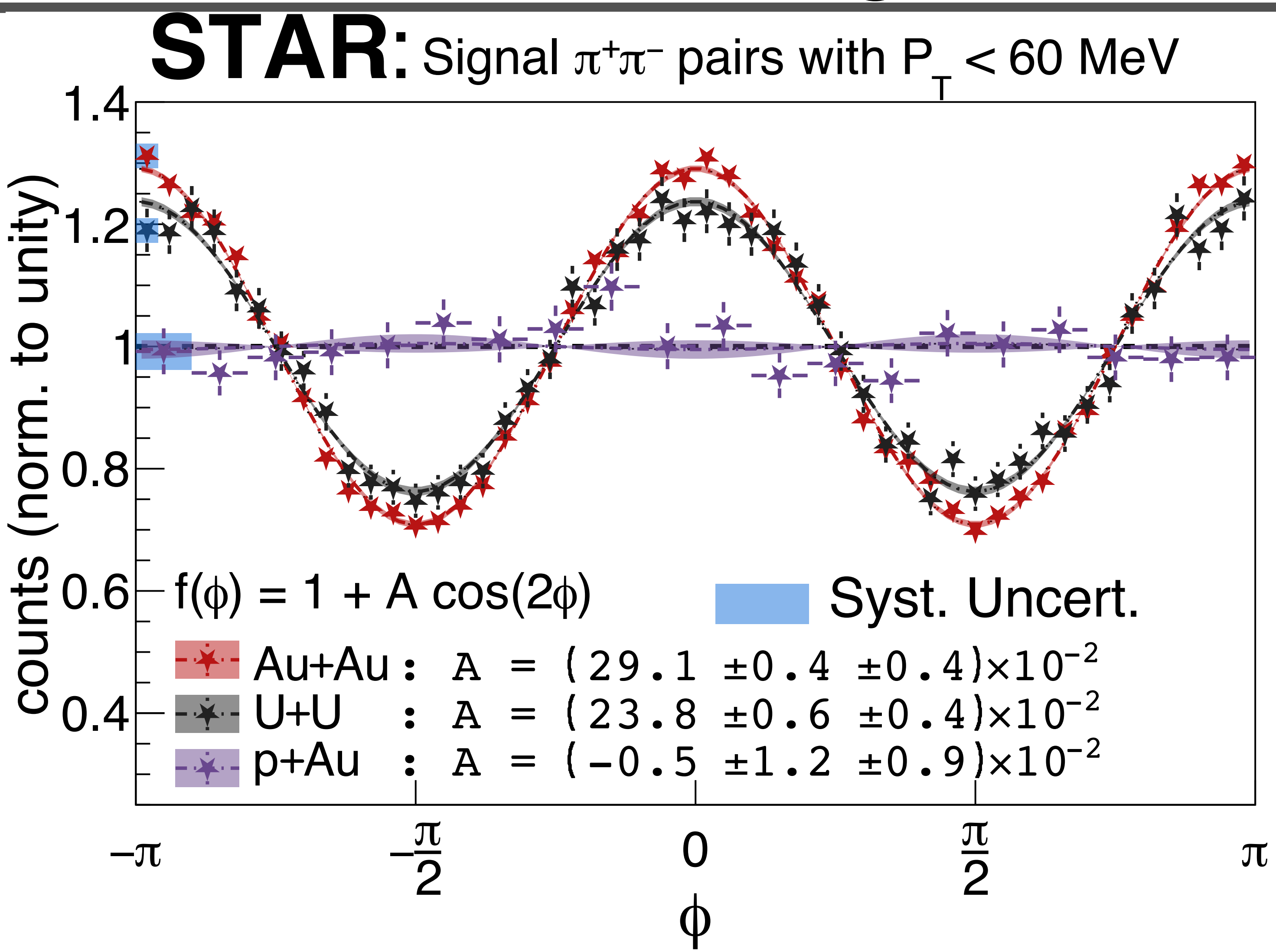
Gluons from nucleus

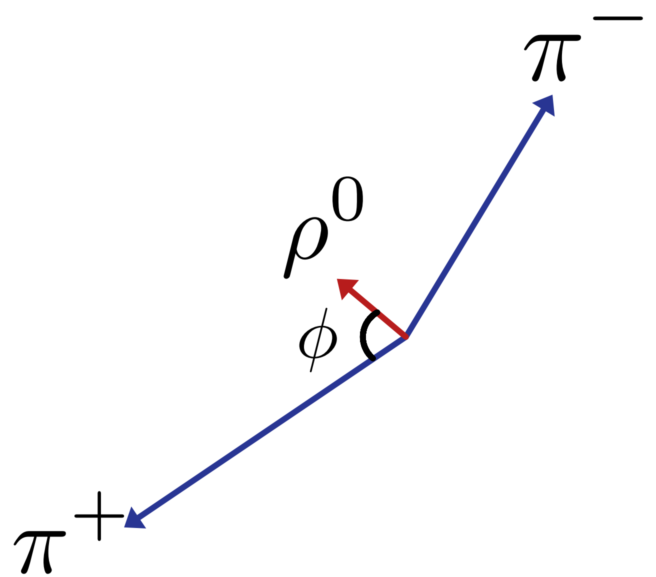


- Intrinsic photon spin transferred to ρ^0
- ρ^0 spin converted into **orbital angular momentum** between pions
- Observable as anisotropy in $\pi^\pm$ momentum

Access to initial photon polarization

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





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

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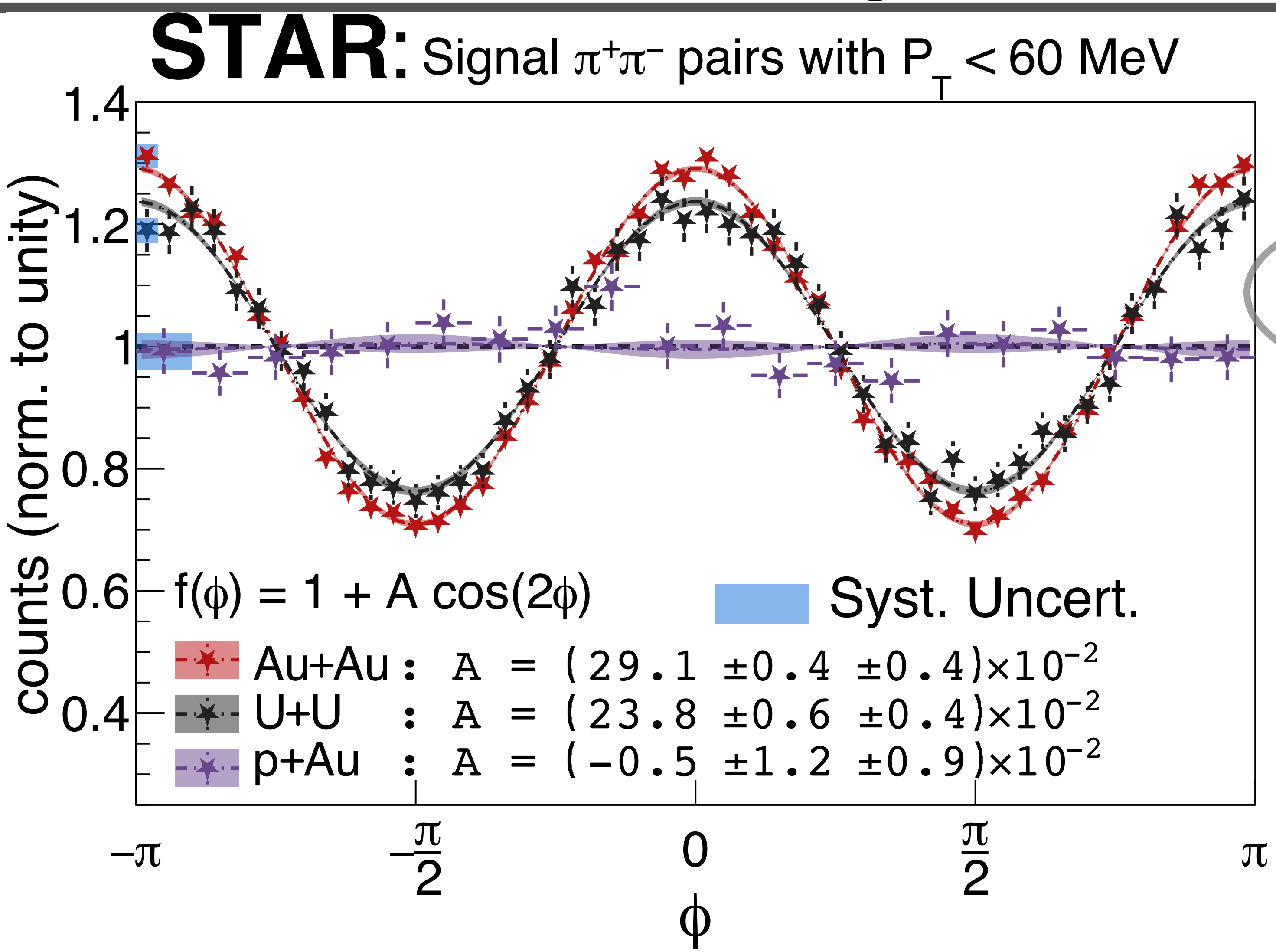

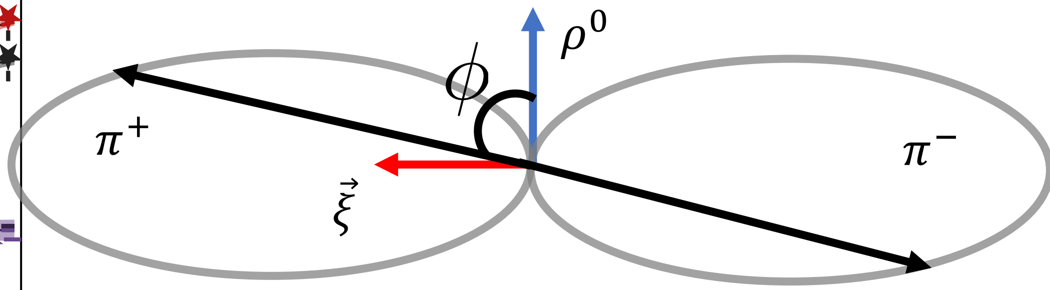

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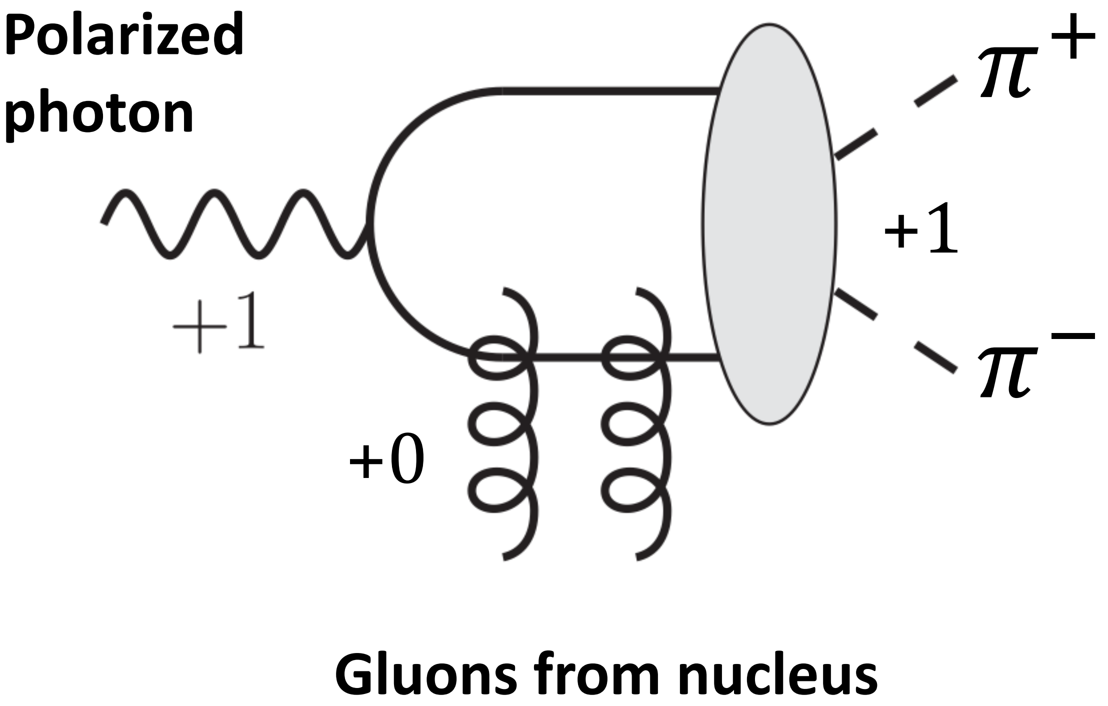
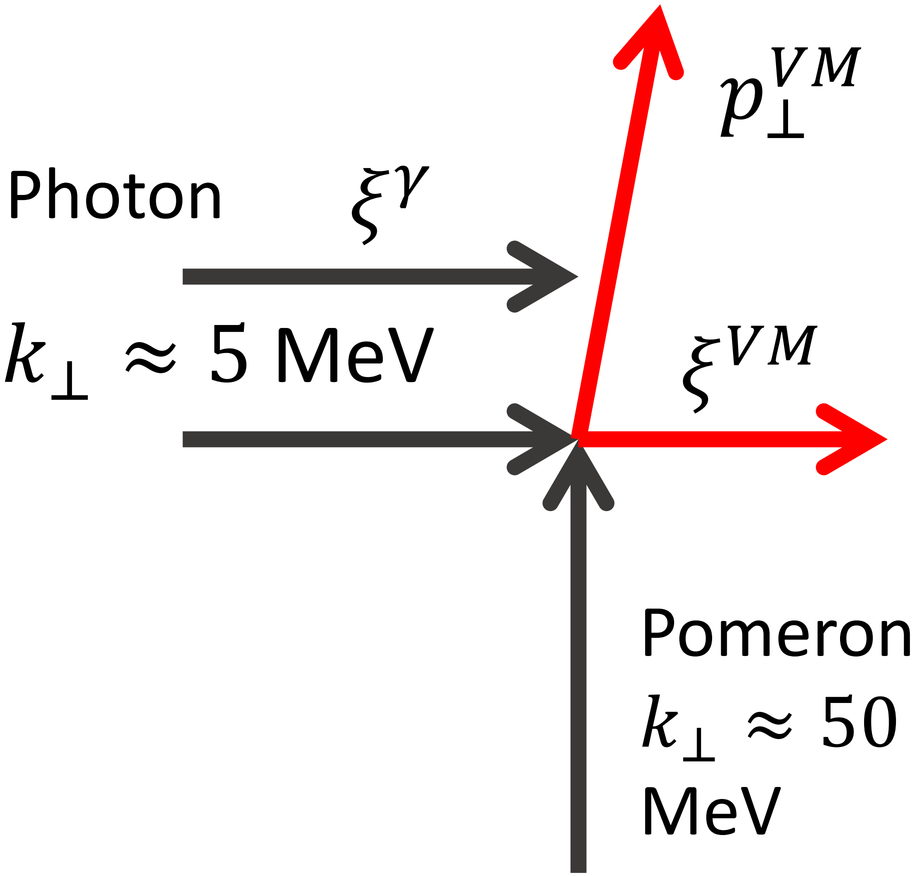
Trivial Spin-Momentum Alignment?

For a single diagram (pA)



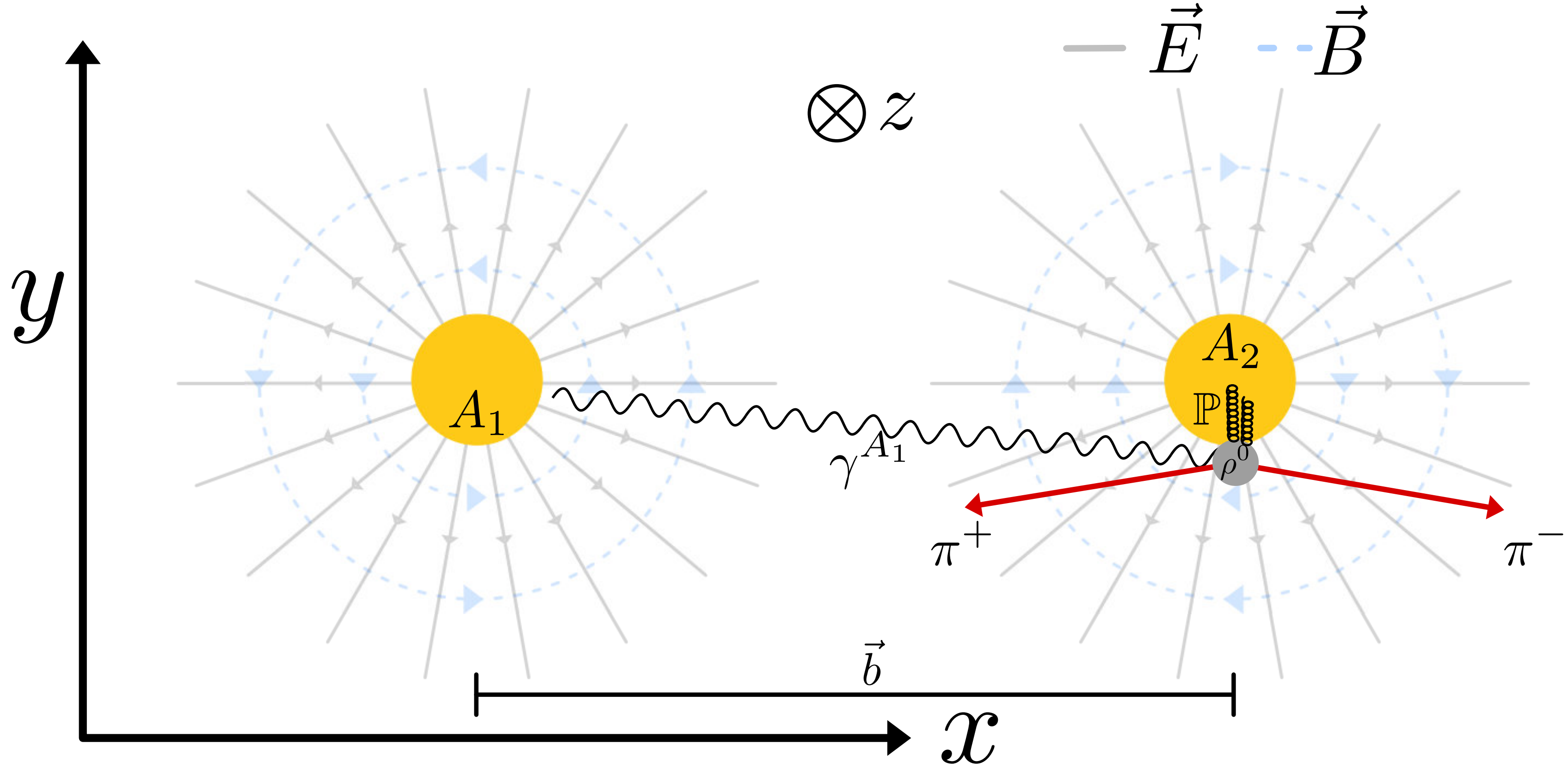


VM inherits the spin from photon (no helicity flip)

Diffractive -> VM momentum dominantly from the Pomeron

→ VM has no alignment between spin and momentum

What is NEW with transversely polarized photons?



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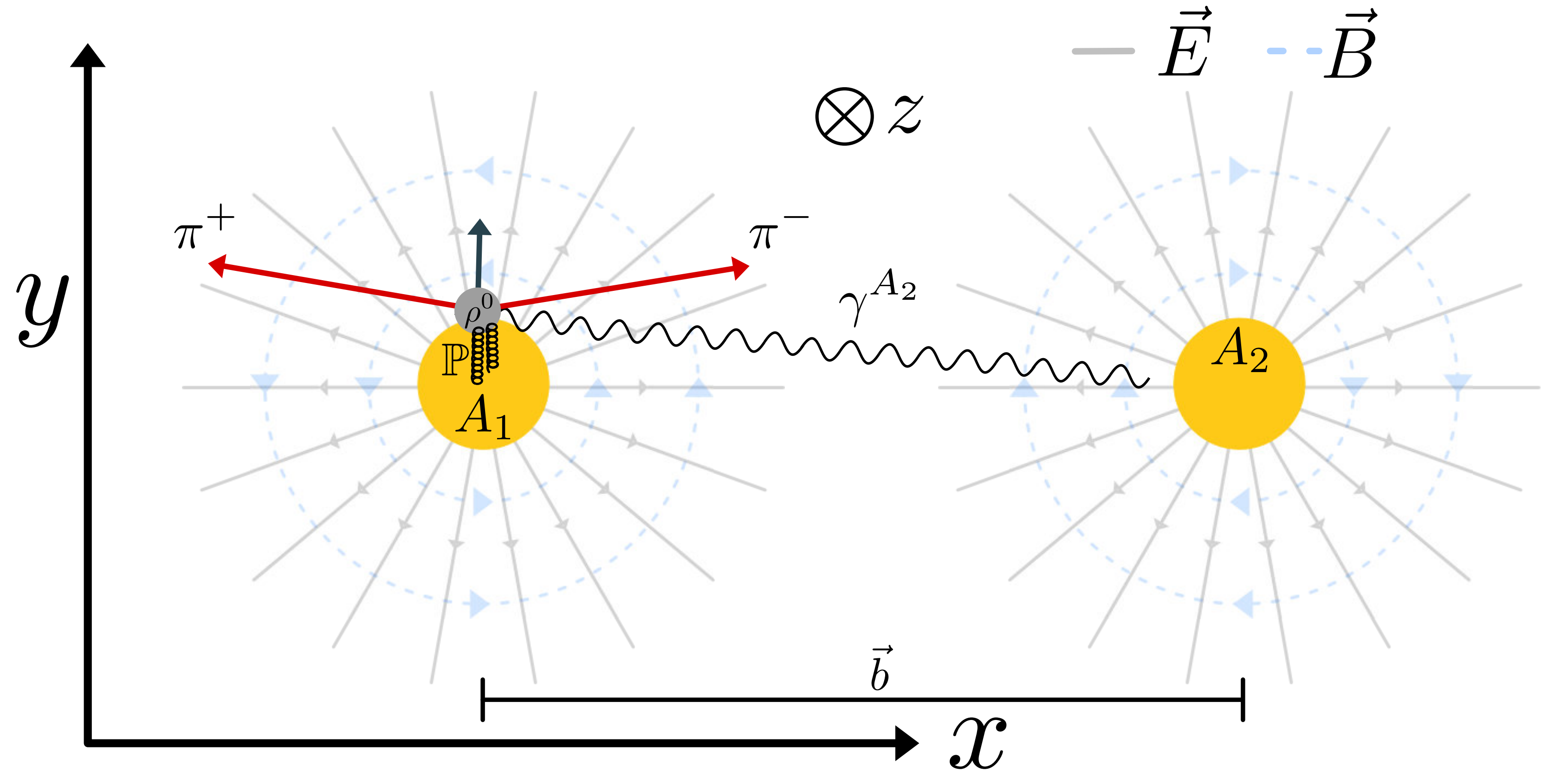

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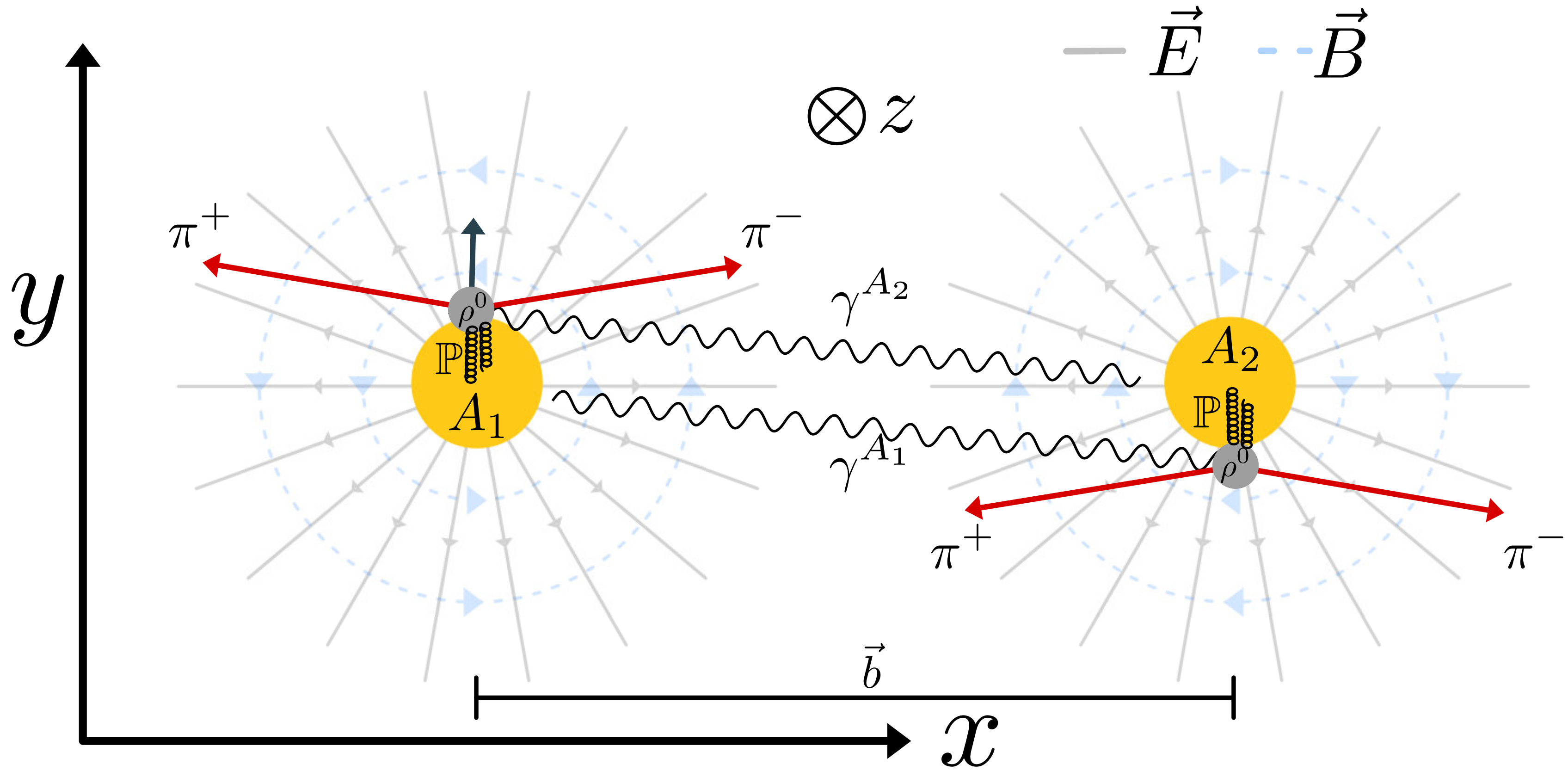
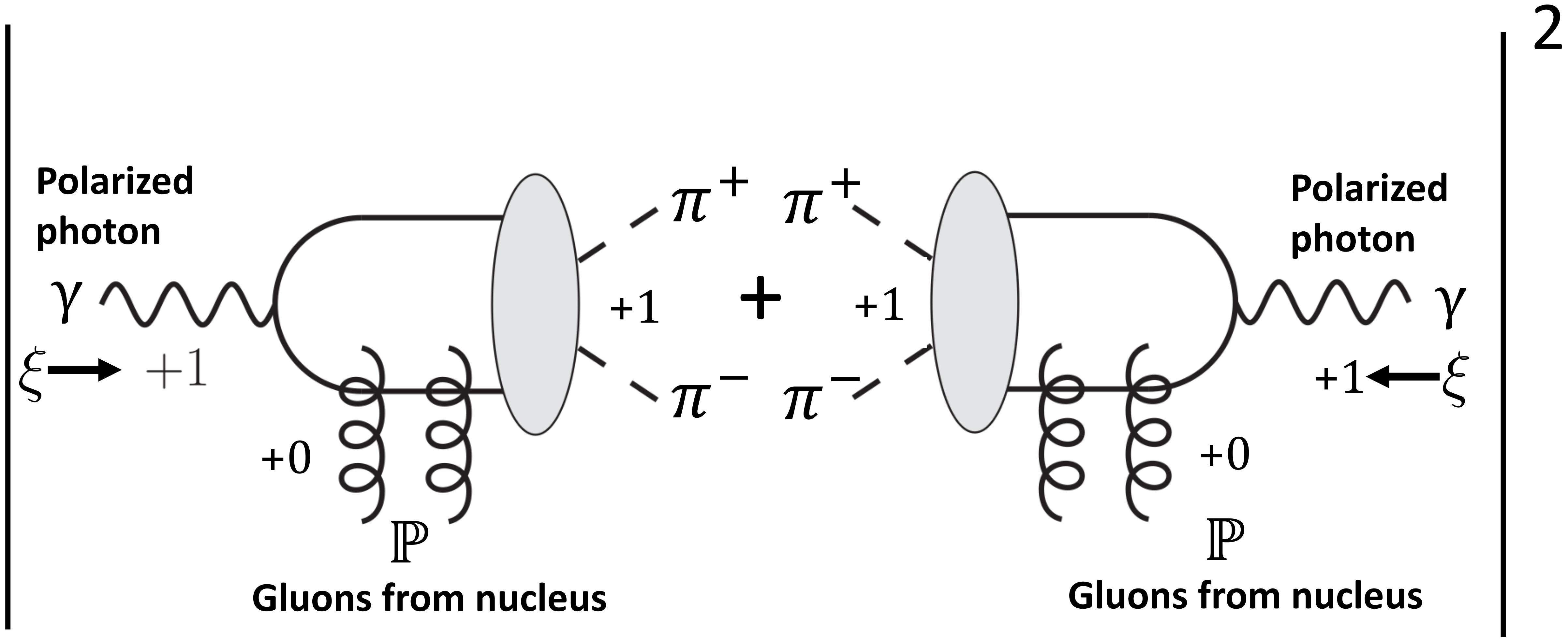


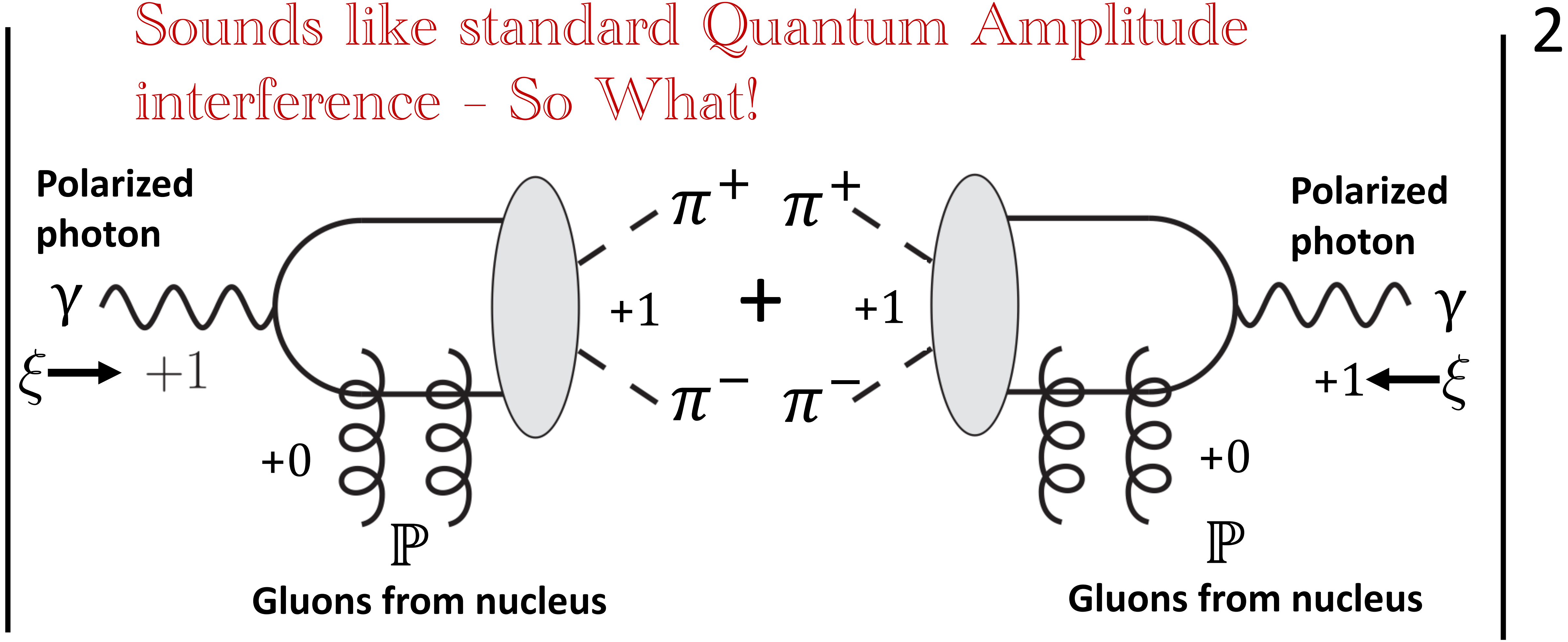
Both possibilities occur simultaneously

Interference of two amplitudes

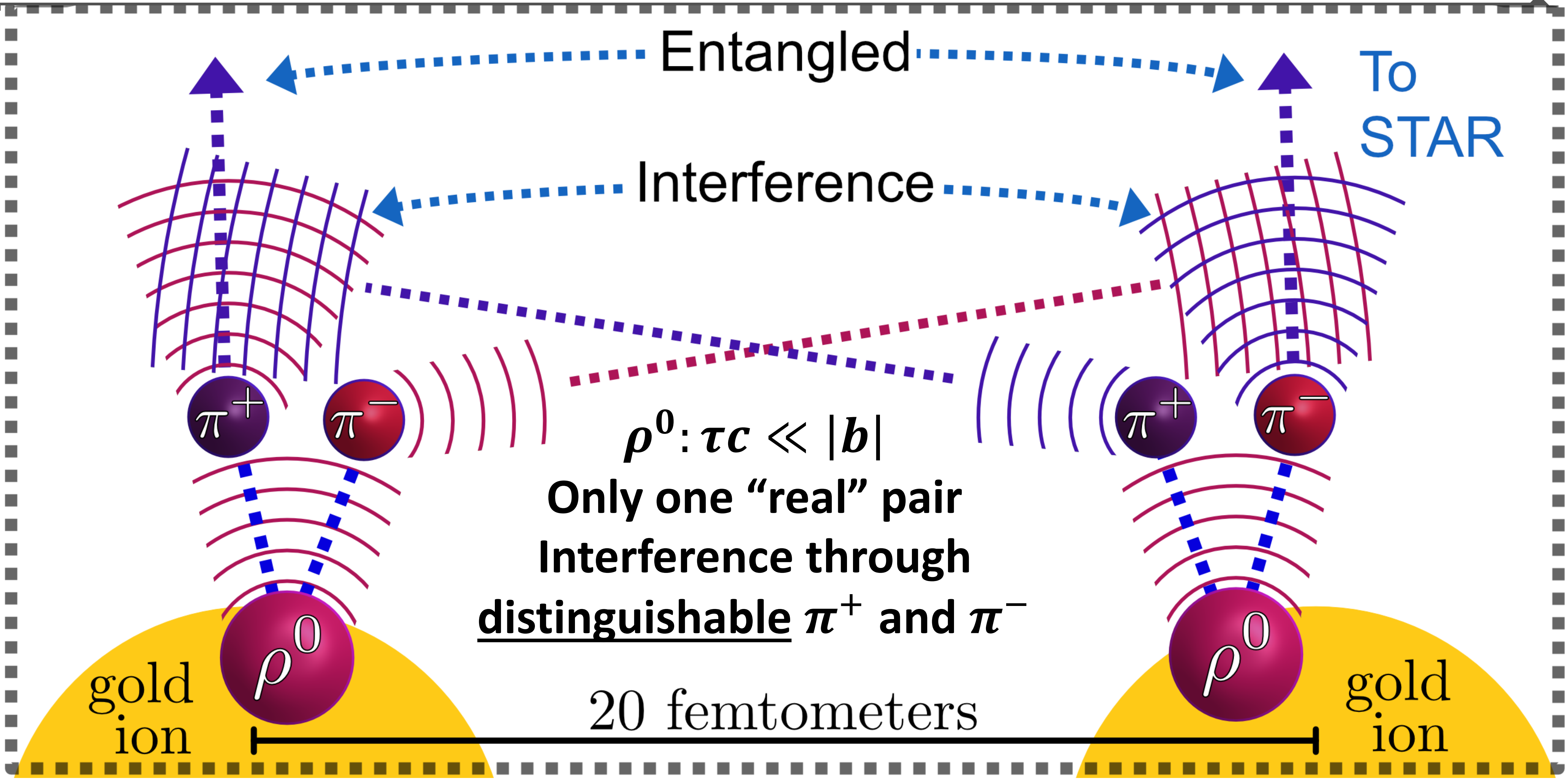


Interference of two amplitudes

Sounds like standard Quantum Amplitude interference – So What!



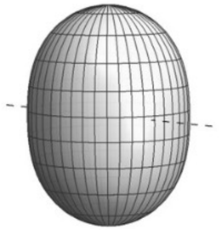
Interference of Amplitudes, so what!?

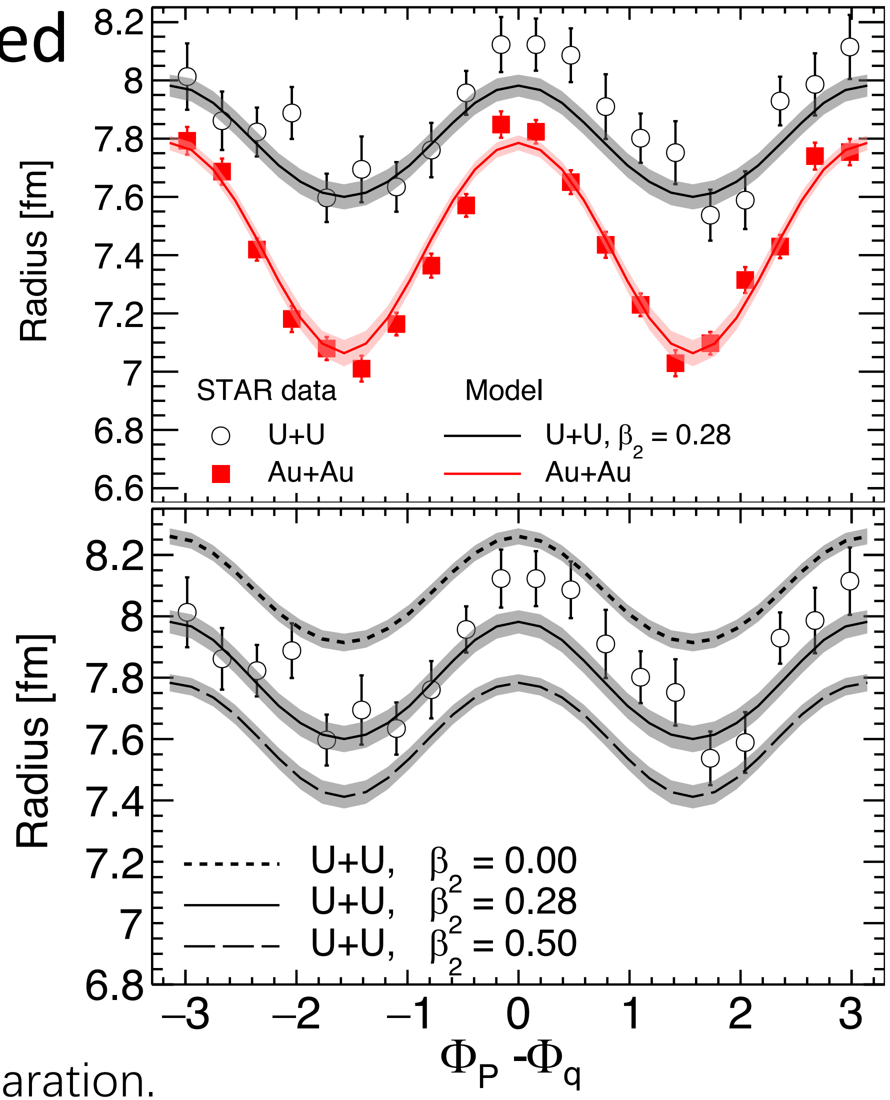


Robust Theoretical Description

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

$\boldsymbol{\beta_2}$





- 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.

3. The Cotler-Wilczek Process

Intensity Interferometry

Credit: Albert Stebbins
Fermilab

Intensity interference:

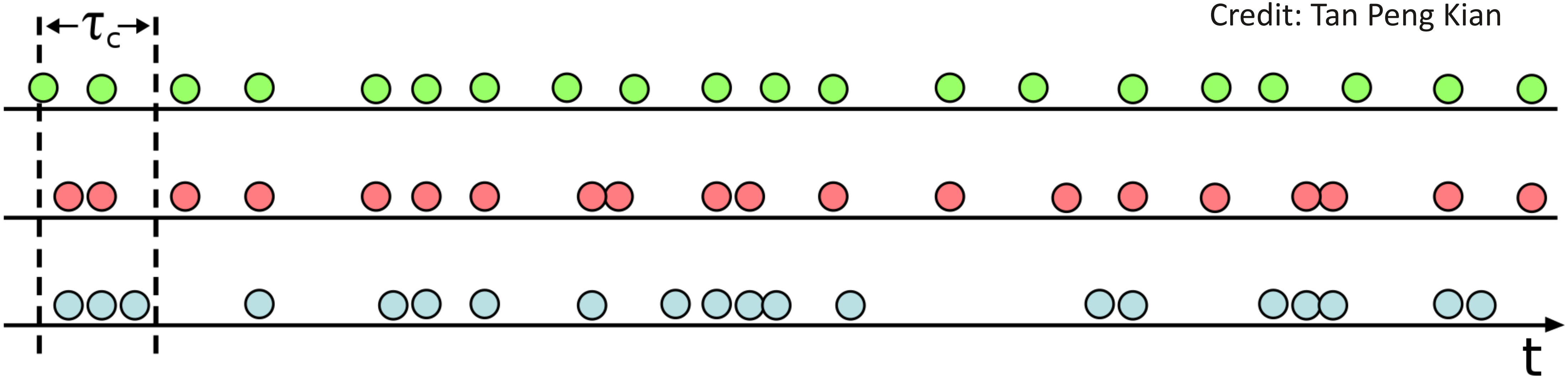
- **Two** photon measurement from **incoherent source**
- "image" encoded in transverse correlations
- Requires photons be **indistinguishable**

Intensity Interferometry

- Incoherent Source
- Interference results from second-order coherence
- Quantum statistics determines bunching vs. anti-bunching

$g^{(2)}(t)$ second-order correlation

Credit: Tan Peng Kian



Photon detections as function of time for a) antibunched, b) random, and c) bunched light

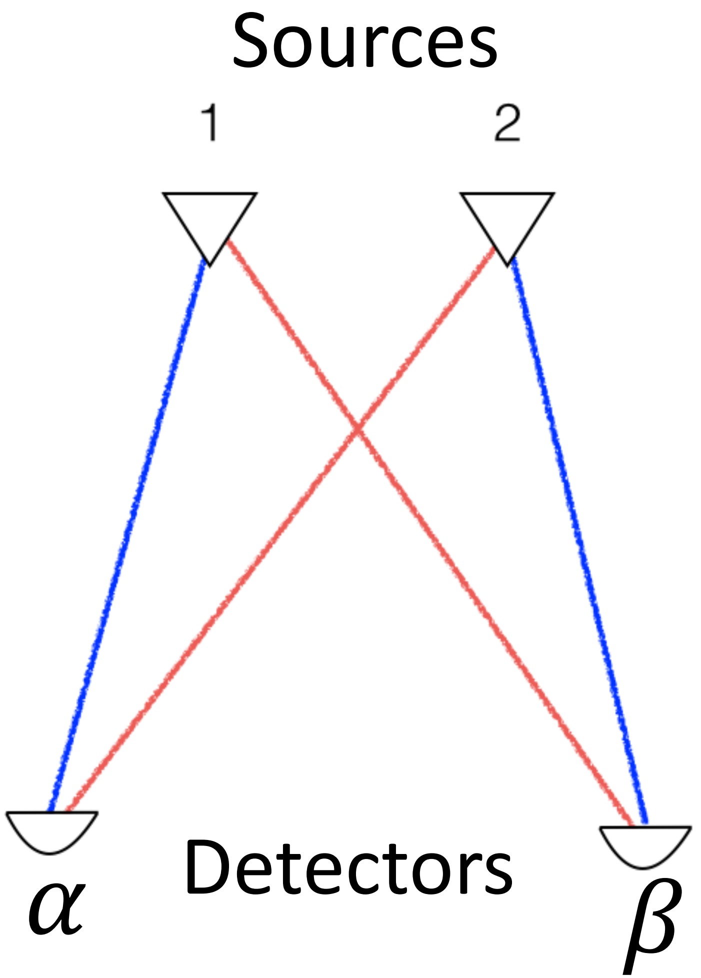
Intensity Interferometry

- Results from higher order coherence

$$|\phi\rangle = \Big(A_{1\alpha}A_{2\beta} + A_{2\alpha}A_{1\beta}\Big)|\omega,\omega\rangle$$

$$\langle\phi|\phi\rangle = |A_{1\alpha}|^2|A_{2\beta}|^2 + |A_{2\alpha}|^2|A_{1\beta}|^2$$
$$+ A_{1\alpha}A_{2\beta}A^*_{2\alpha}A^*_{1\beta} + A^*_{1\alpha}A^*_{2\beta}A_{2\alpha}A_{1\beta}$$

$$\langle A_{1\alpha}A^*_{1\beta}\rangle_E \neq 0$$



Intensity Interferometry

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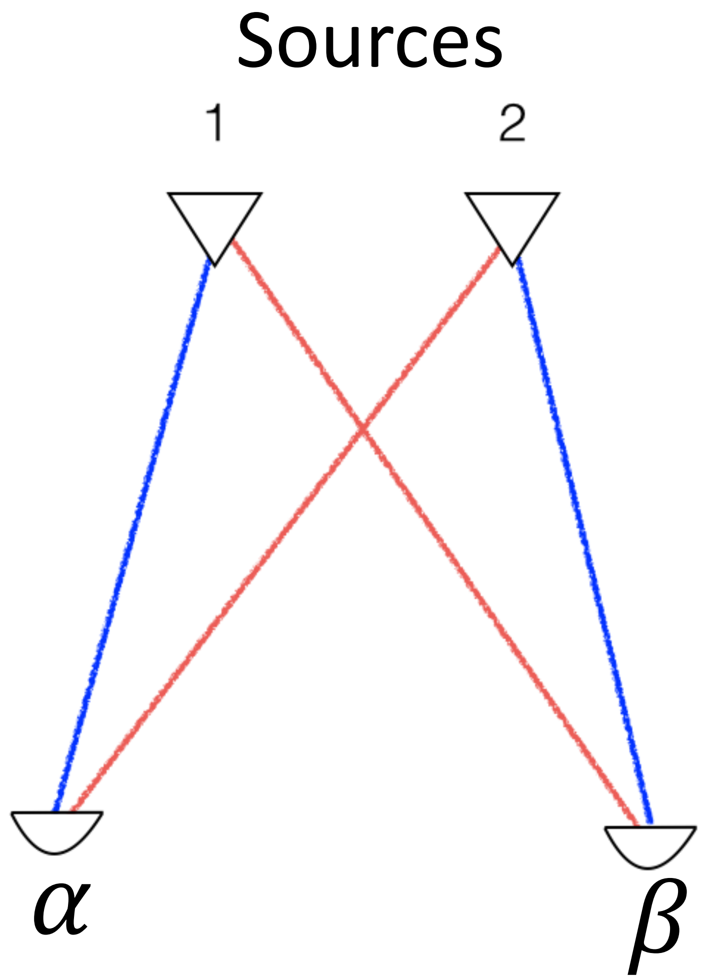
$$\langle\phi|\phi\rangle = |A_{1\alpha}|^2|A_{2\beta}|^2 + |A_{2\alpha}|^2|A_{1\beta}|^2$$

$$+ A_{1\alpha}A_{2\beta}A^*_{2\alpha}A^*_{1\beta} + A^*_{1\alpha}A^*_{2\beta}A_{2\alpha}$$

$$\langle A_{1\alpha}A^*_{1\beta}\rangle_E \neq 0$$

Requires indistinguishable states!

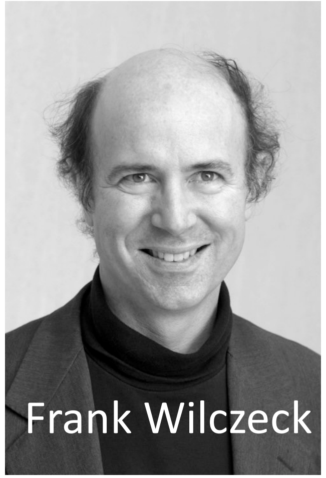


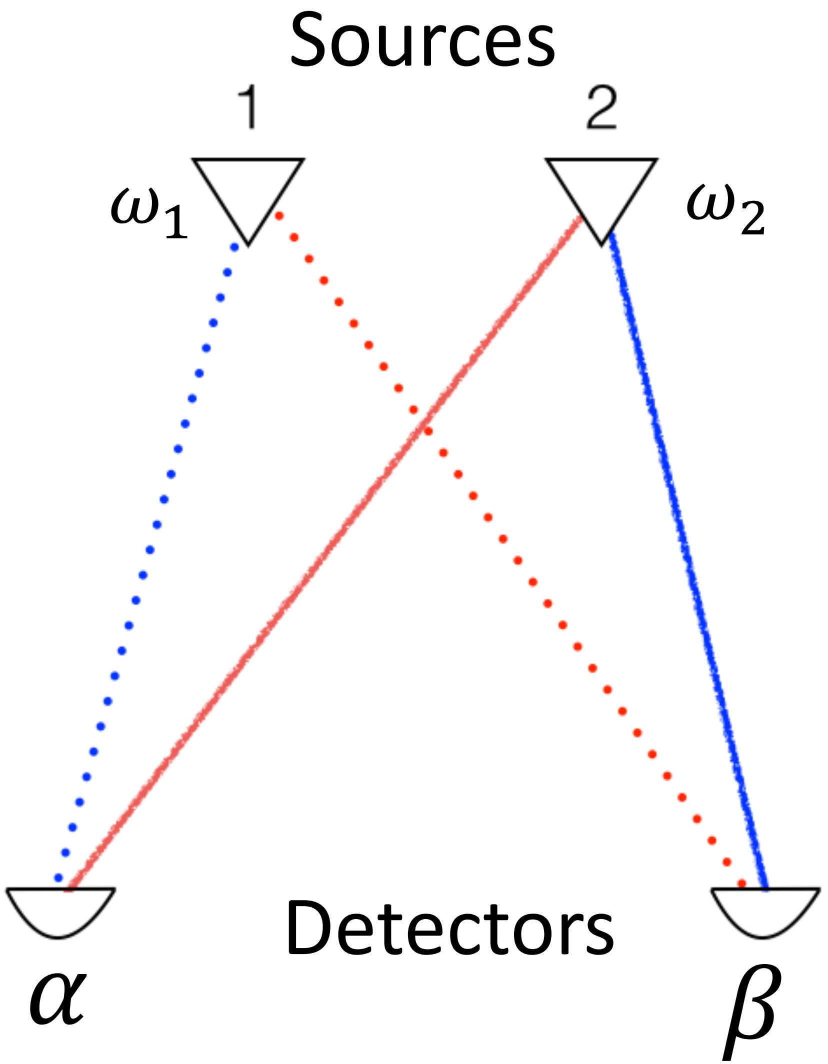
The Cotler-Wilczek Process

$$|\psi\rangle = A_{1\alpha}A_{2\beta}|\omega_1, \omega_2\rangle + A_{2\alpha}A_{1\beta}|\omega_2, \omega_1\rangle$$

$$\langle\psi|\psi\rangle = |A_{1\alpha}A_{2\beta}|^2 + |A_{2\alpha}A_{1\beta}|^2$$

Distinguishable states = NO Interference!





arXiv:1502.02477

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

The Cotler-Wilczek Process

$$|\psi\rangle = A_{1\alpha}A_{2\beta}|\omega_1, \omega_2\rangle + A_{2\alpha}A_{1\beta}|\omega_2, \omega_1\rangle$$

1. **Entangler** performs unitary transformation:

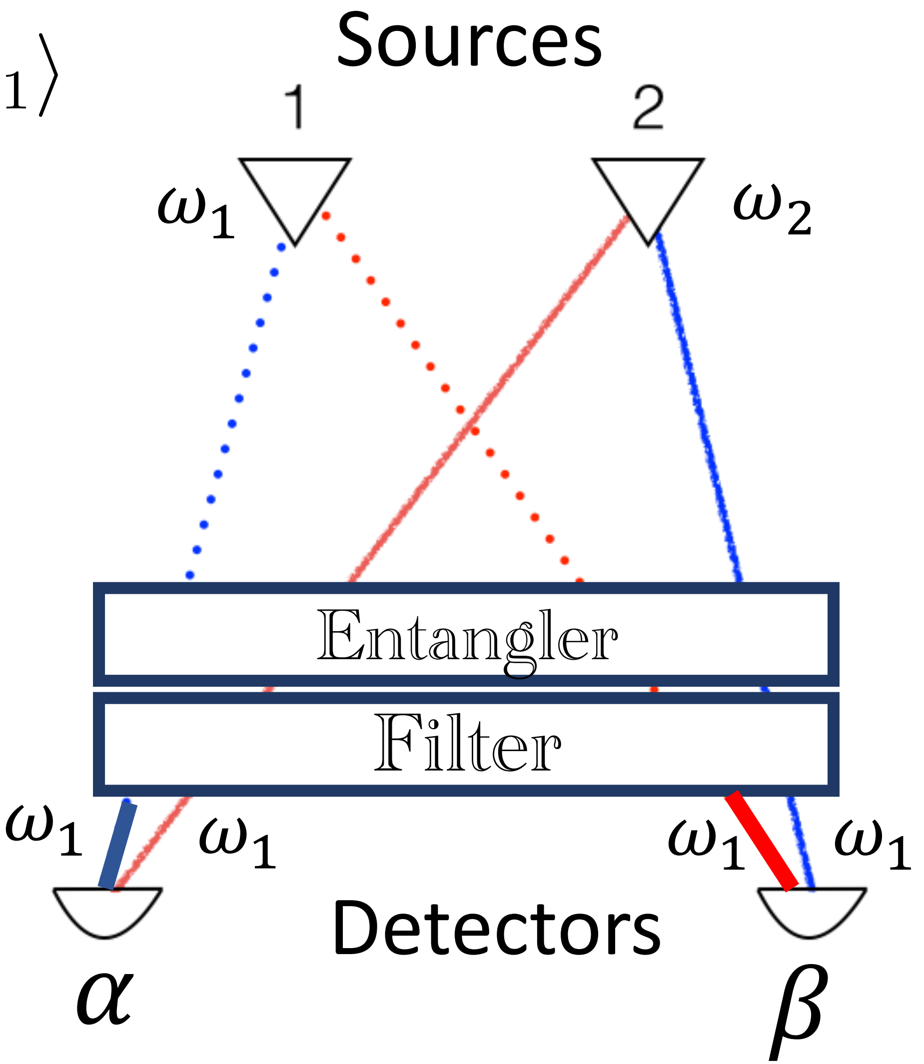
$$U|\omega_1\rangle = \cos(\theta)|\omega_1\rangle + \sin(\theta)e^{i\omega_0}|\omega_2\rangle$$

$$U|\omega_2\rangle = \sin(\theta)e^{-i\omega_0}|\omega_1\rangle + \cos(\theta)|\omega_2\rangle$$

2. **Filter** projects common state:

$$|\omega_1\omega_2\rangle \rightarrow \cos(\theta)\sin(\theta)e^{-i\omega_0}|\omega_1, \omega_1\rangle$$

$$|\omega_2\omega_1\rangle \rightarrow \cos(\theta)\sin(\theta)e^{-i\omega_0}|\omega_1, \omega_1\rangle$$



Interference Recovered! $\langle A_{1\alpha}A^*_{1\beta}\rangle_E \neq 0$

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

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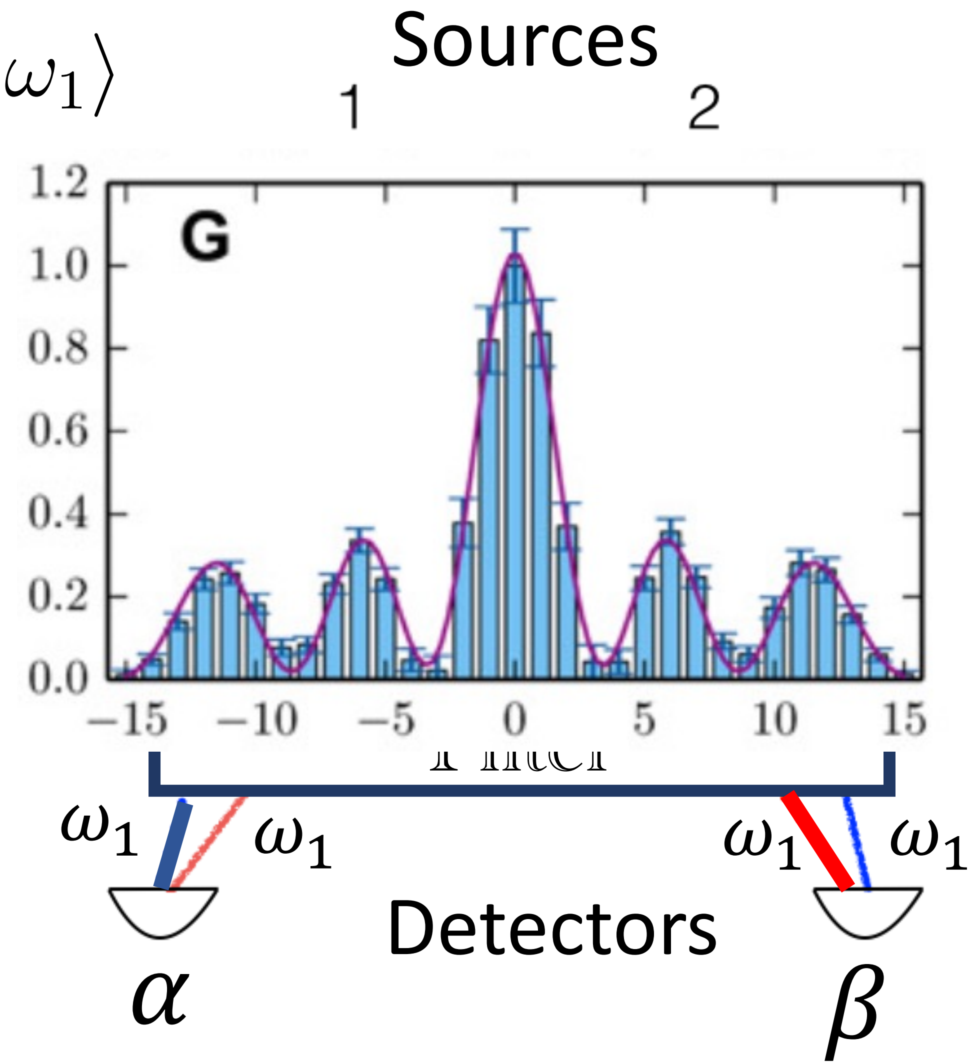

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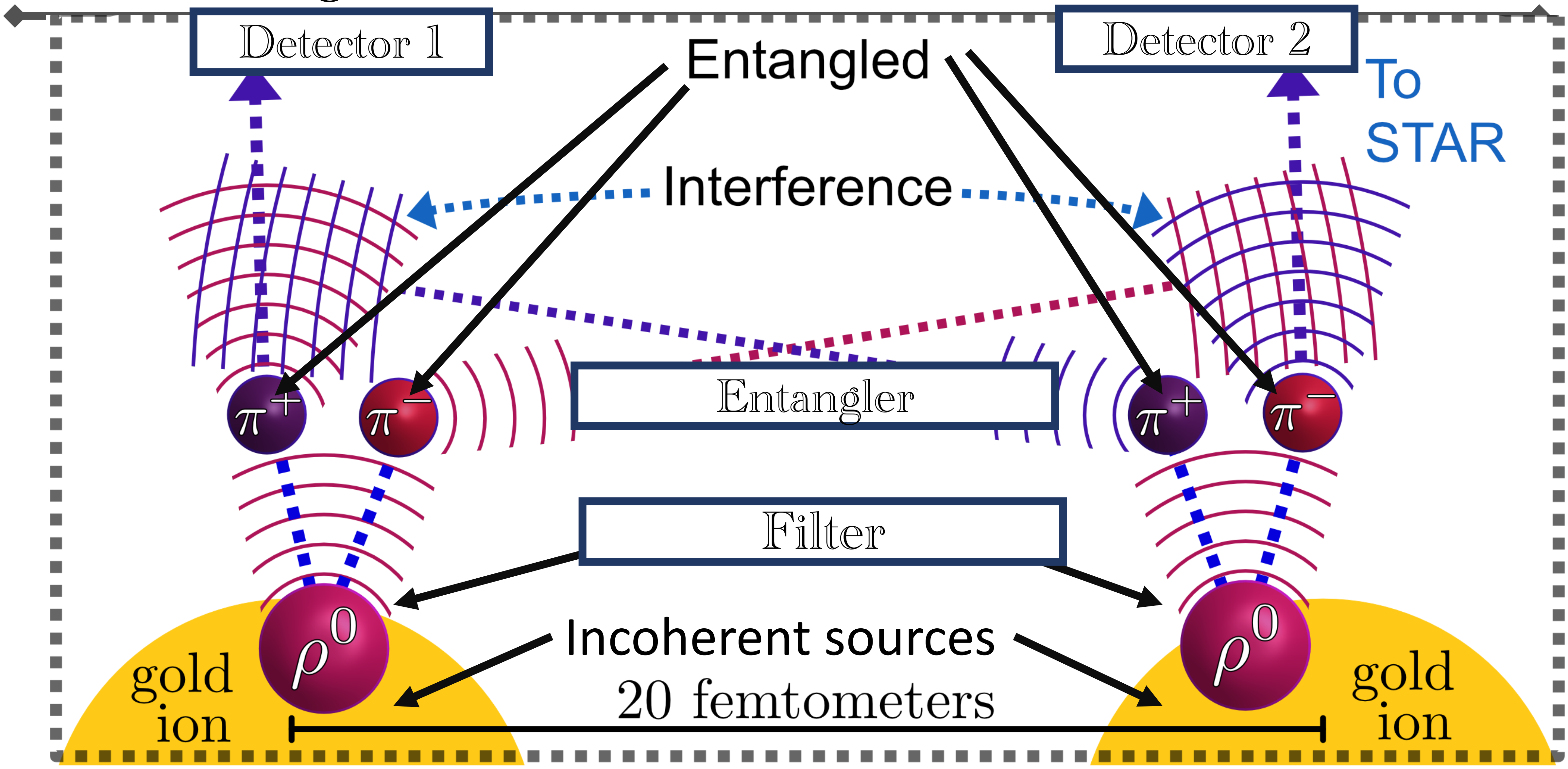
Entanglement Enabled Intensity Interference



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

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

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

Entanglement Enabled Intensity Interferometry

"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

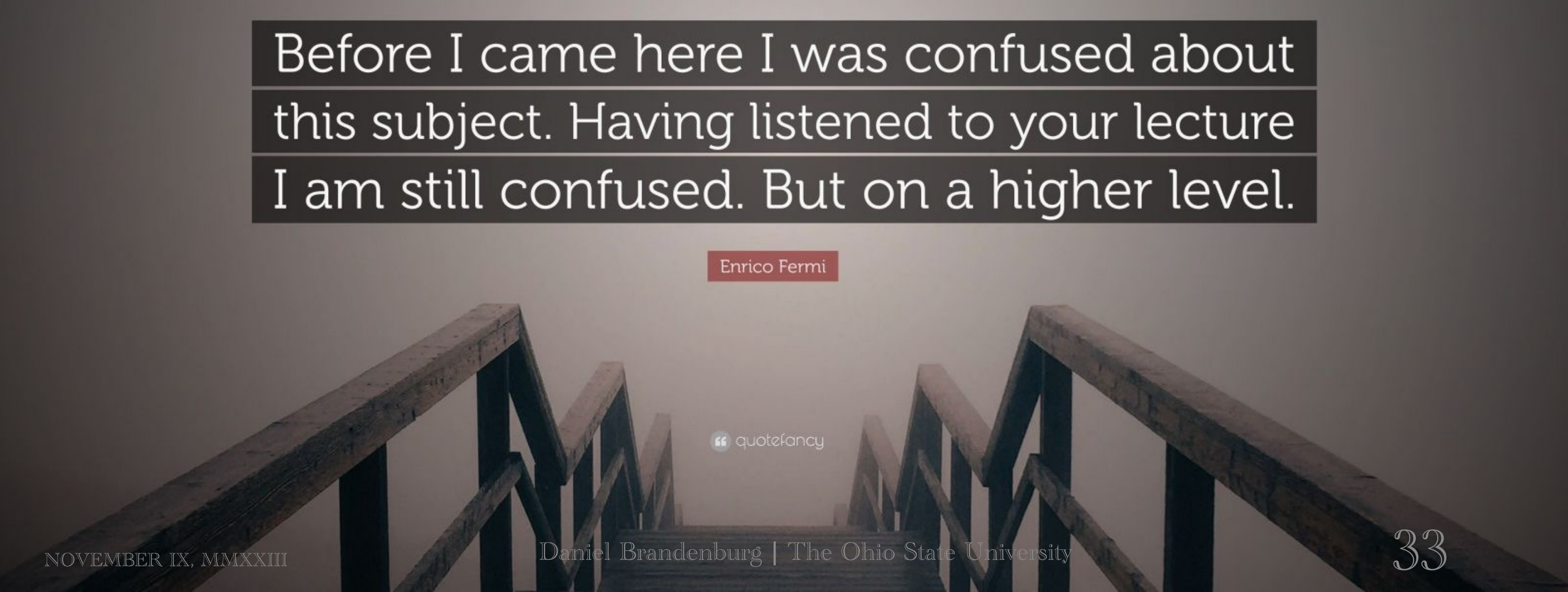
SCIENTIFIC AMERICAN

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

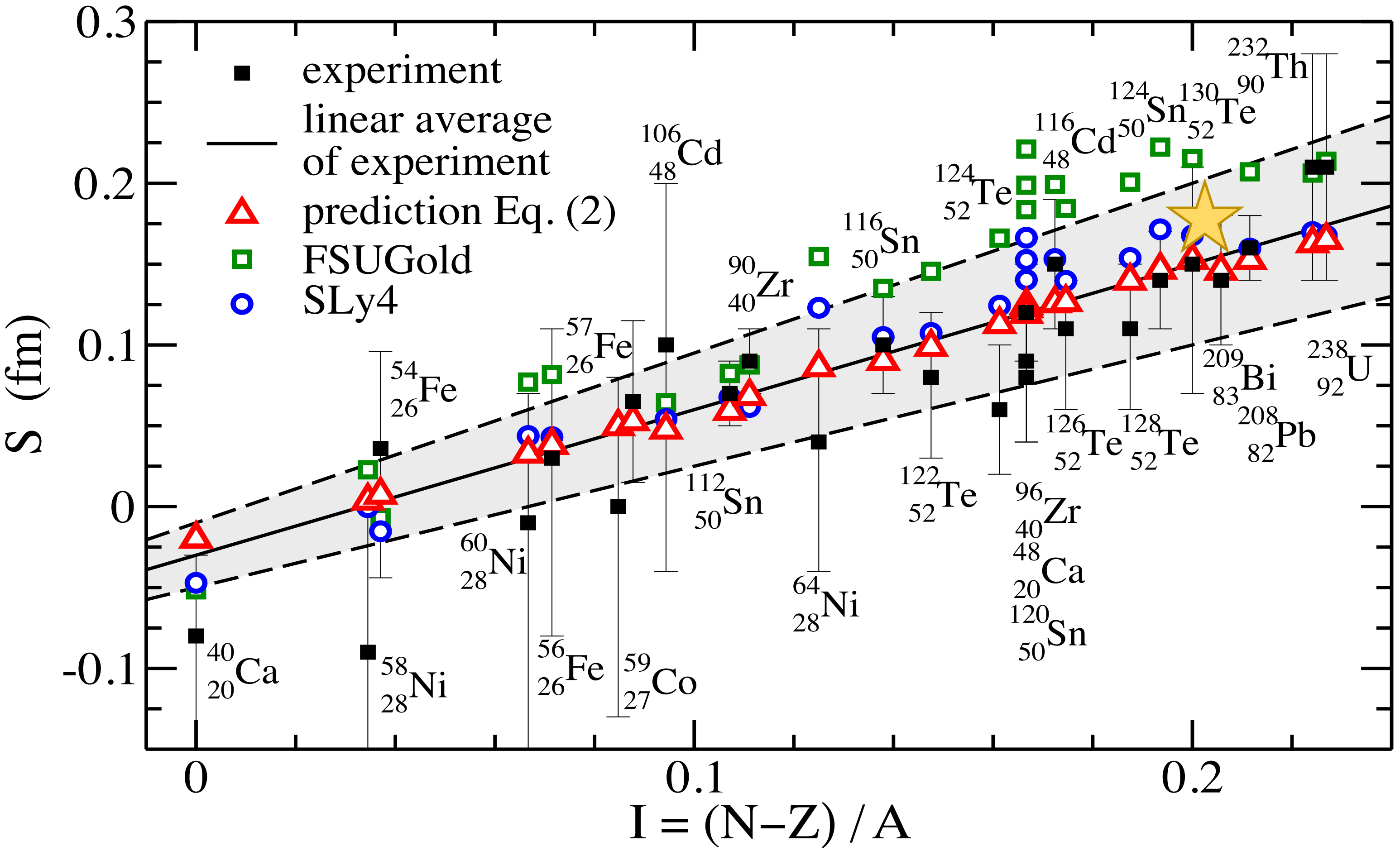
J. Cotler, F. Wilczek, and V. Borish, Annals of Physics **424**, 168346 (2021).

Thank you for your attention!
I hope you can at least say:



Neutron Skins at High-Energy

Uranium

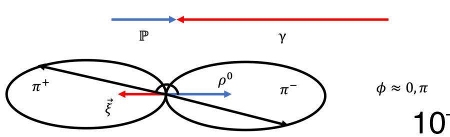


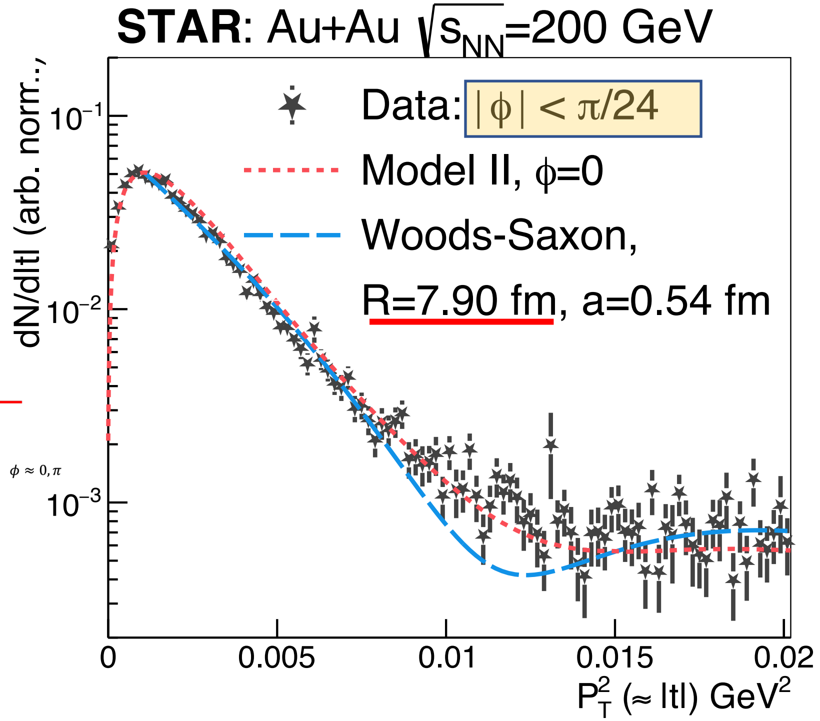
$$S_U = 0.44 \pm 0.05 \text{ (stat.)} \pm 0.08 \text{ (syst.) fm}$$

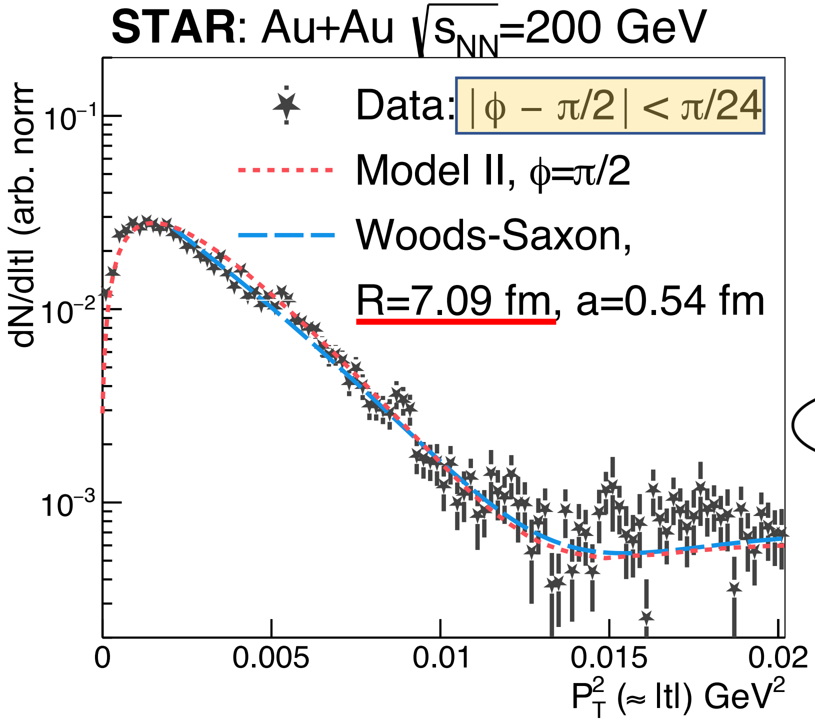
- Uranium neutron skin appears surprisingly large?
- Above trend and low-energy measurements?

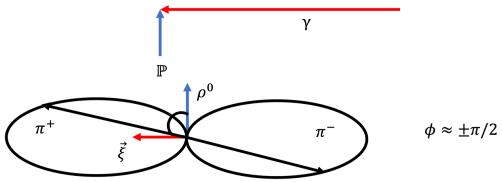
Which Radius is 'correct'?

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?**

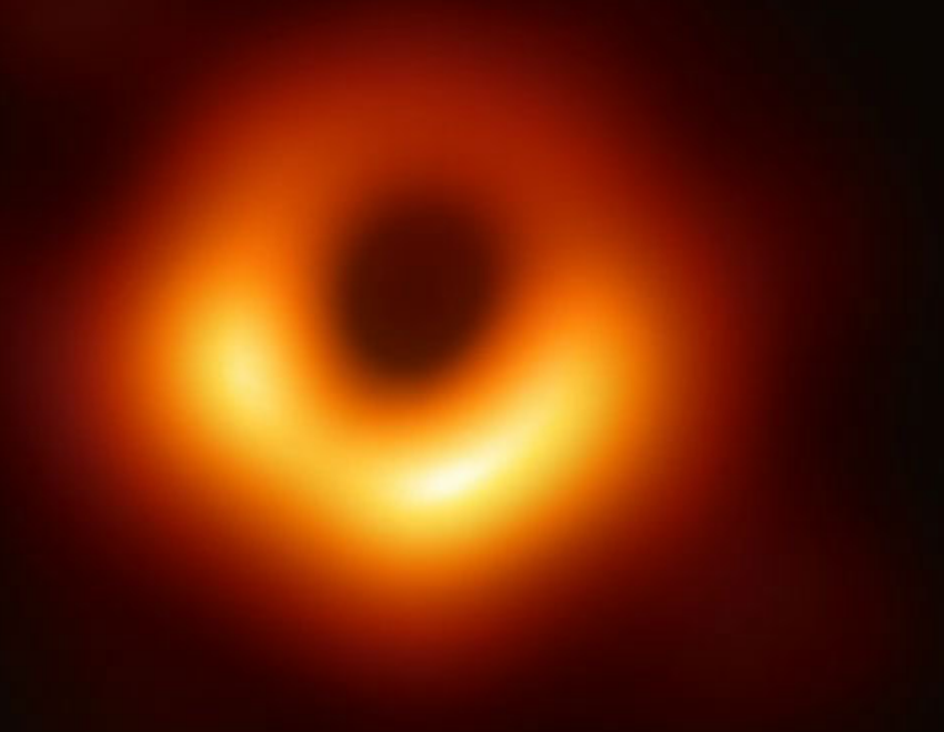
STAR Collaboration, Sci. Adv. **9**, eabq3903 (2023).

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

Event Horizon Telescope

Analogy to Interferometry in Astro-Physics

Quantum Interference provides sub-diffraction limited imaging

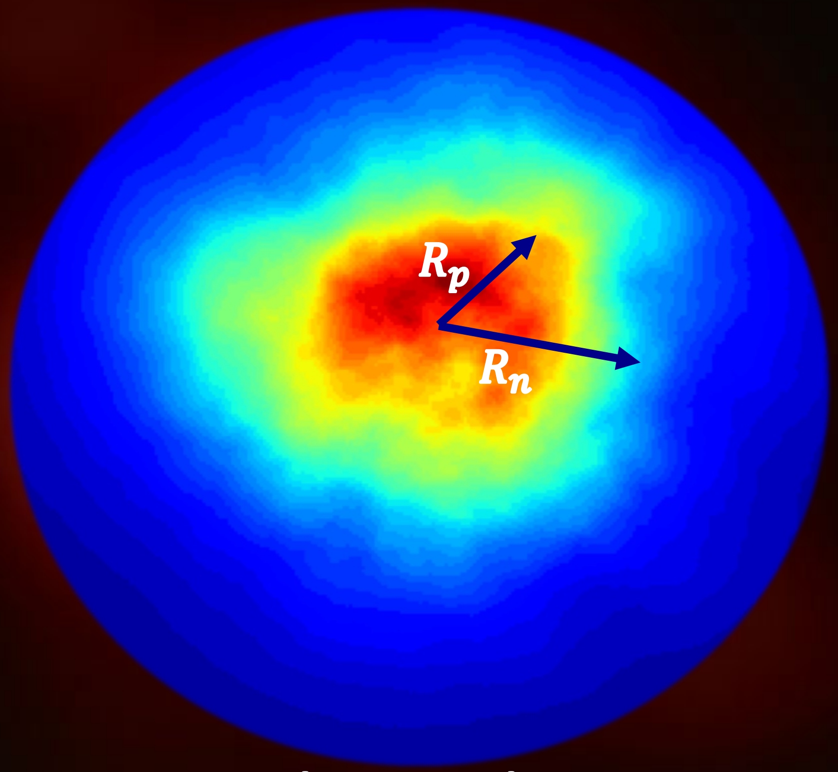


M87 Supermassive Black hole

Event Horizon Telescope

Analogy to Interferometry in Astro-Physics

Quantum Interference provides sub-diffraction limited imaging

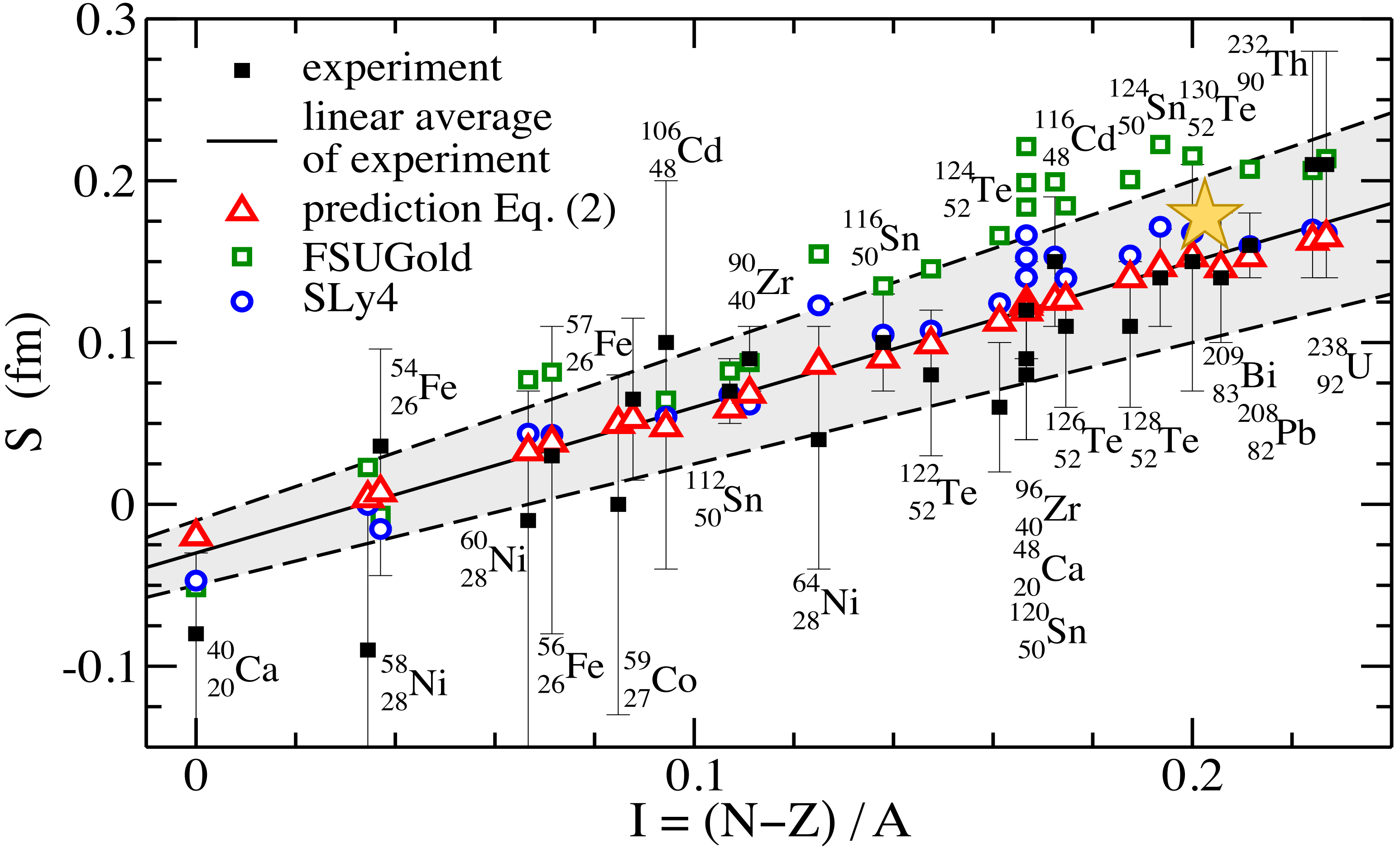


Nuclear Gluon distribution

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

Neutron Skins at High-Energy

★ ← **Uranium**



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

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- Above trend and low-energy measurements?
- Theoretical approach based on CGC finds similar result as phenomenological approach

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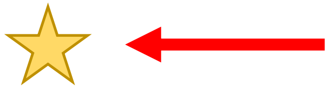

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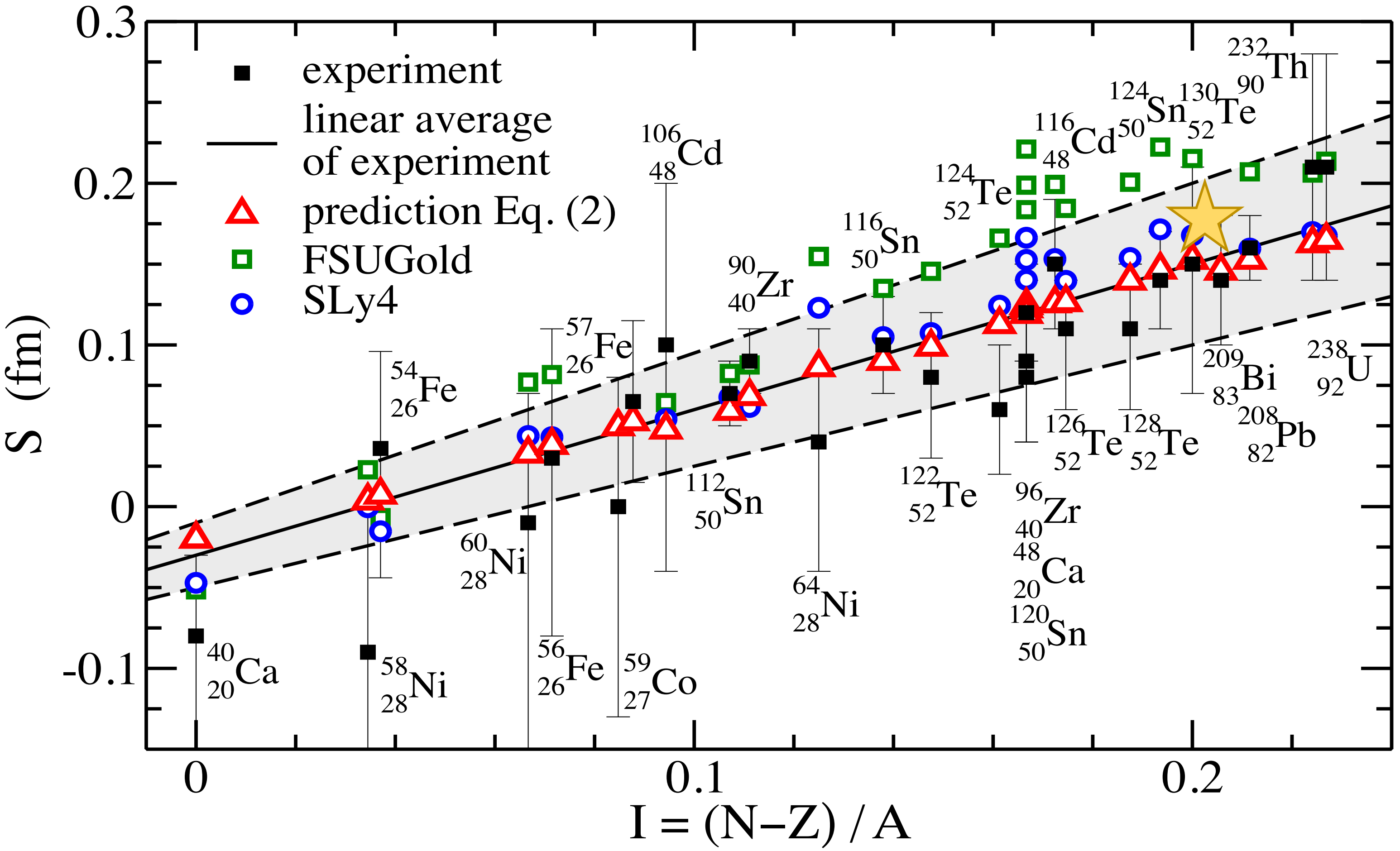

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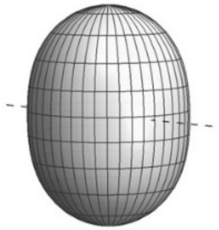
- Sensitivity to nuclear geometry!

β_2



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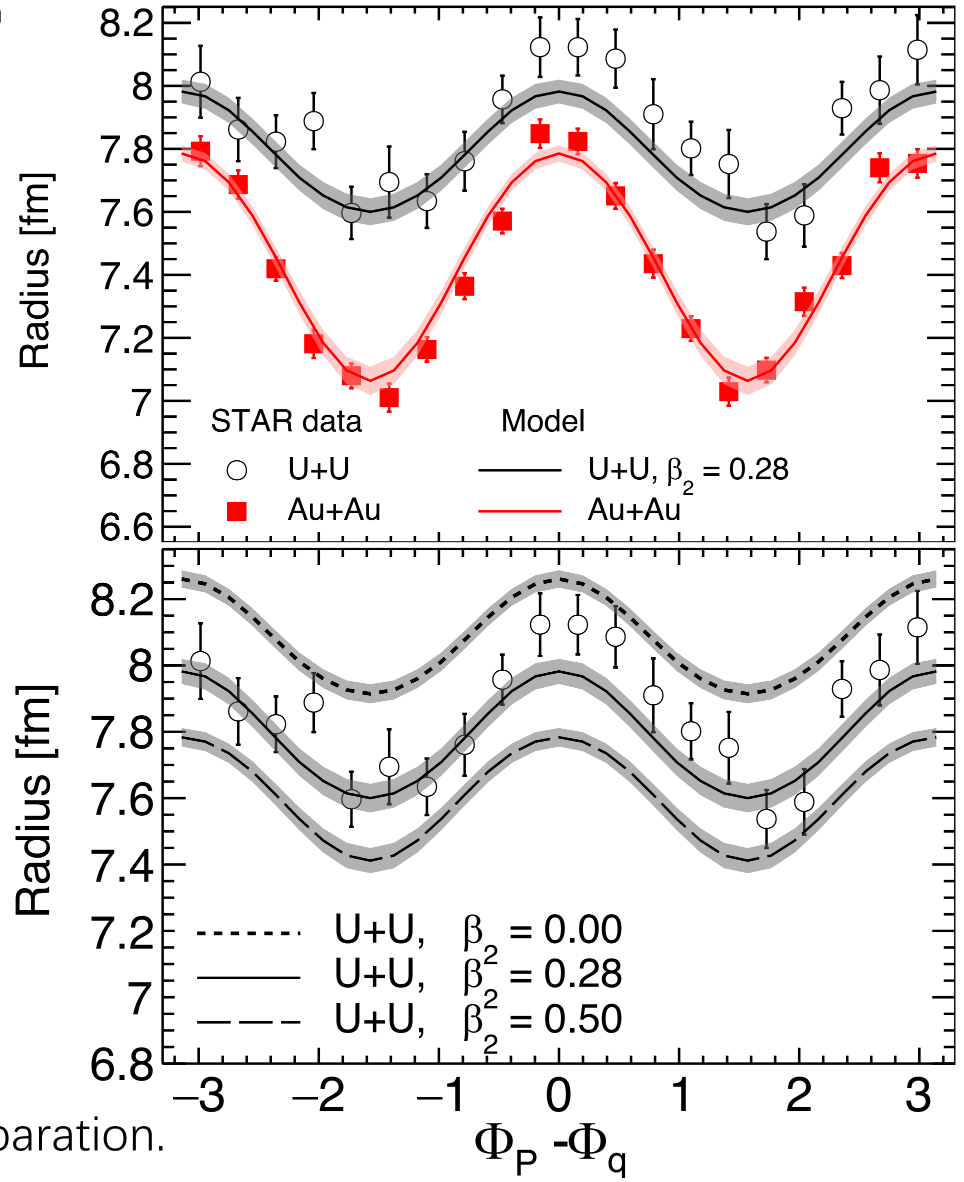
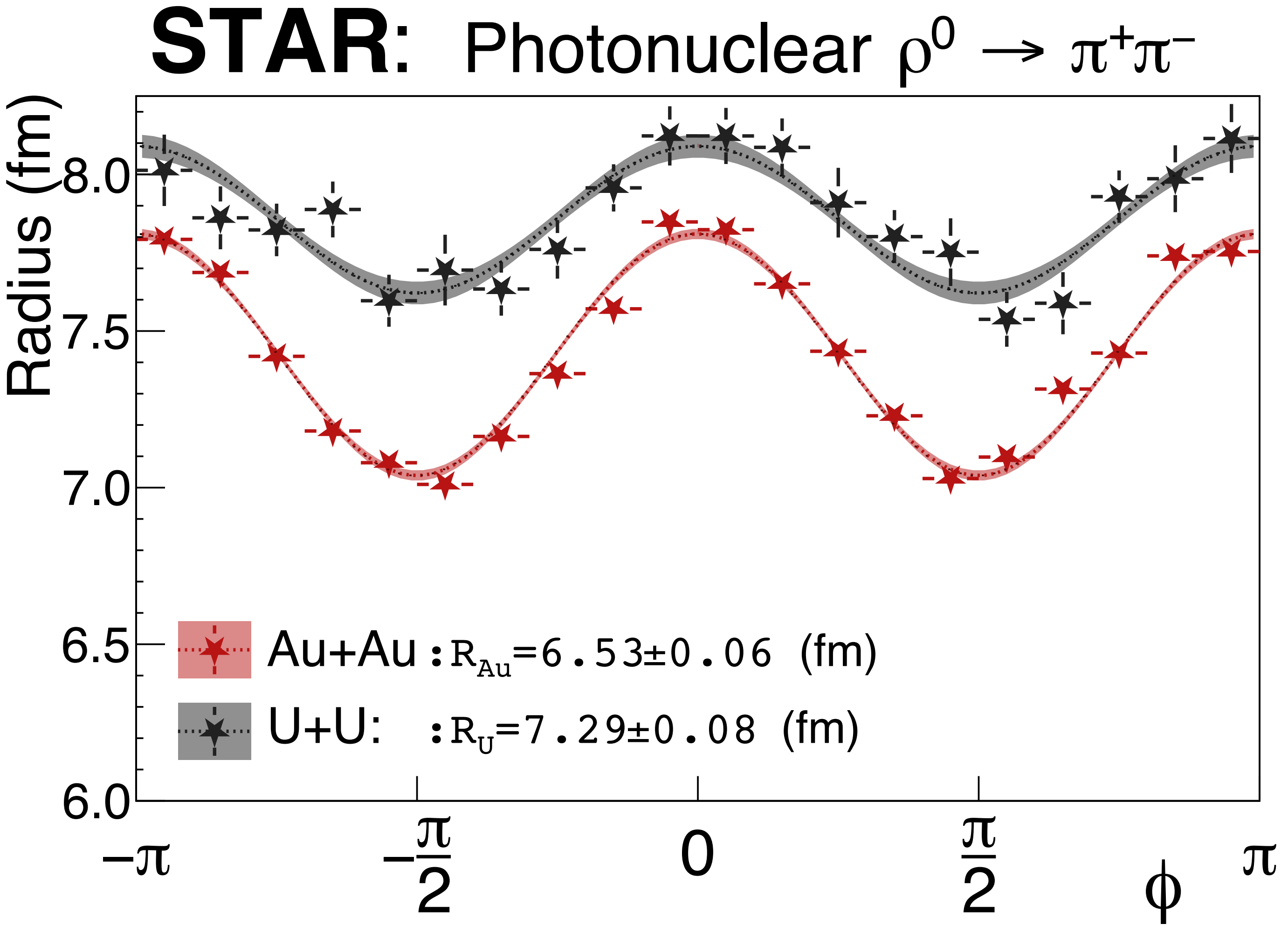
- Also require very large U radius
- Assumes amplitude interference for coherent process



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

Imaging the Nucleus with Polarized Photons



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

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

🤔 😅

Technique provides quantitative access to gluon saturation effects

BUT measurements via other vector mesons are needed for to validate QCD theoretical predictions/interpretations

Future measurements with ϕ meson and J/ψ are important

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

Nuclear Radius Comparison

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

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

Measured radius of Uranium shows evidence of significant neutron skin

[1] STAR Collaboration, L. Adamczyk, *et al.*, *Phys. Rev. C* 96, 054904 (2017).
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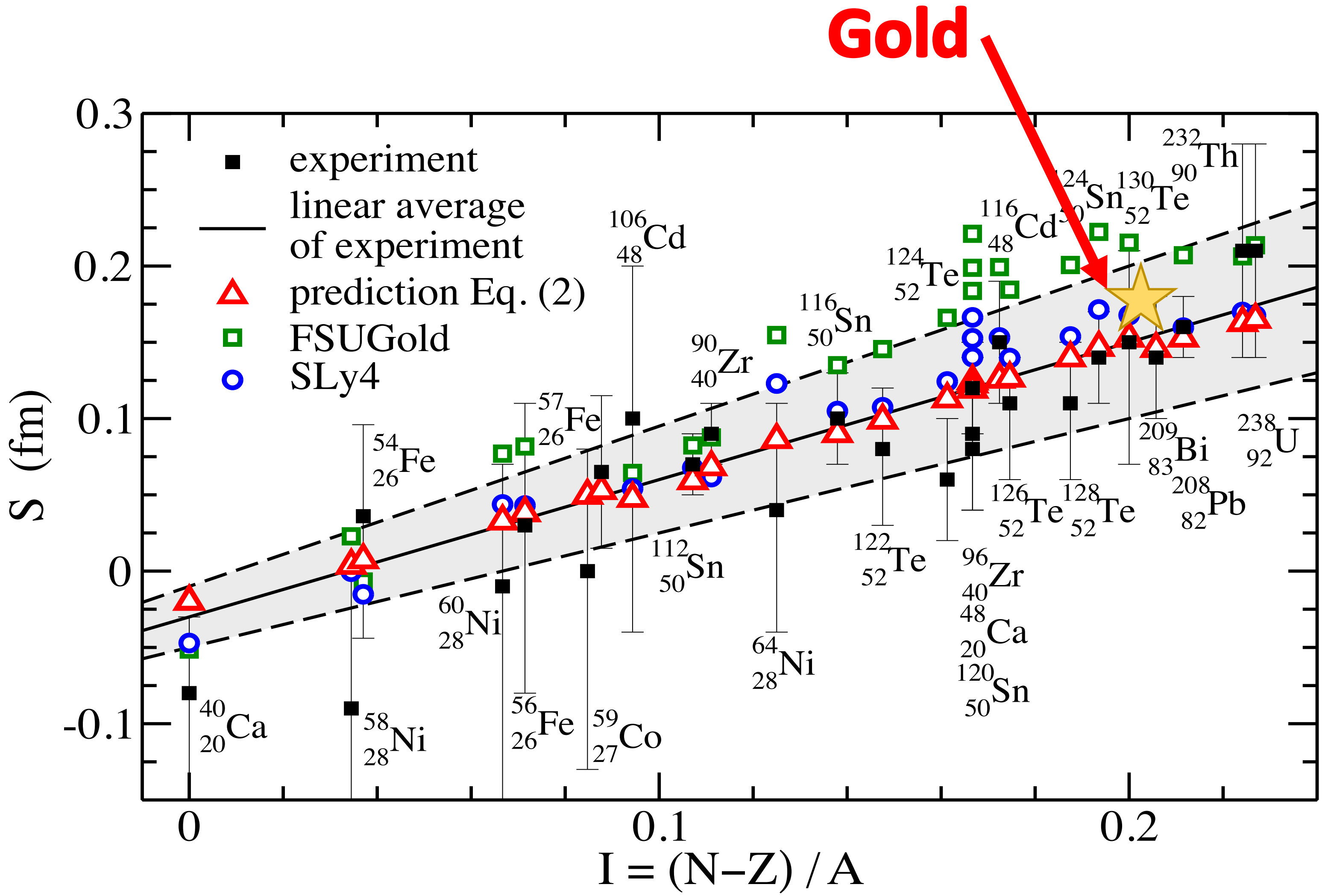


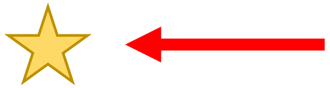
$$S_{Au} = 0.17 \pm 0.03(\text{stat.}) \pm 0.08(\text{syst.})\ \text{fm}$$

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

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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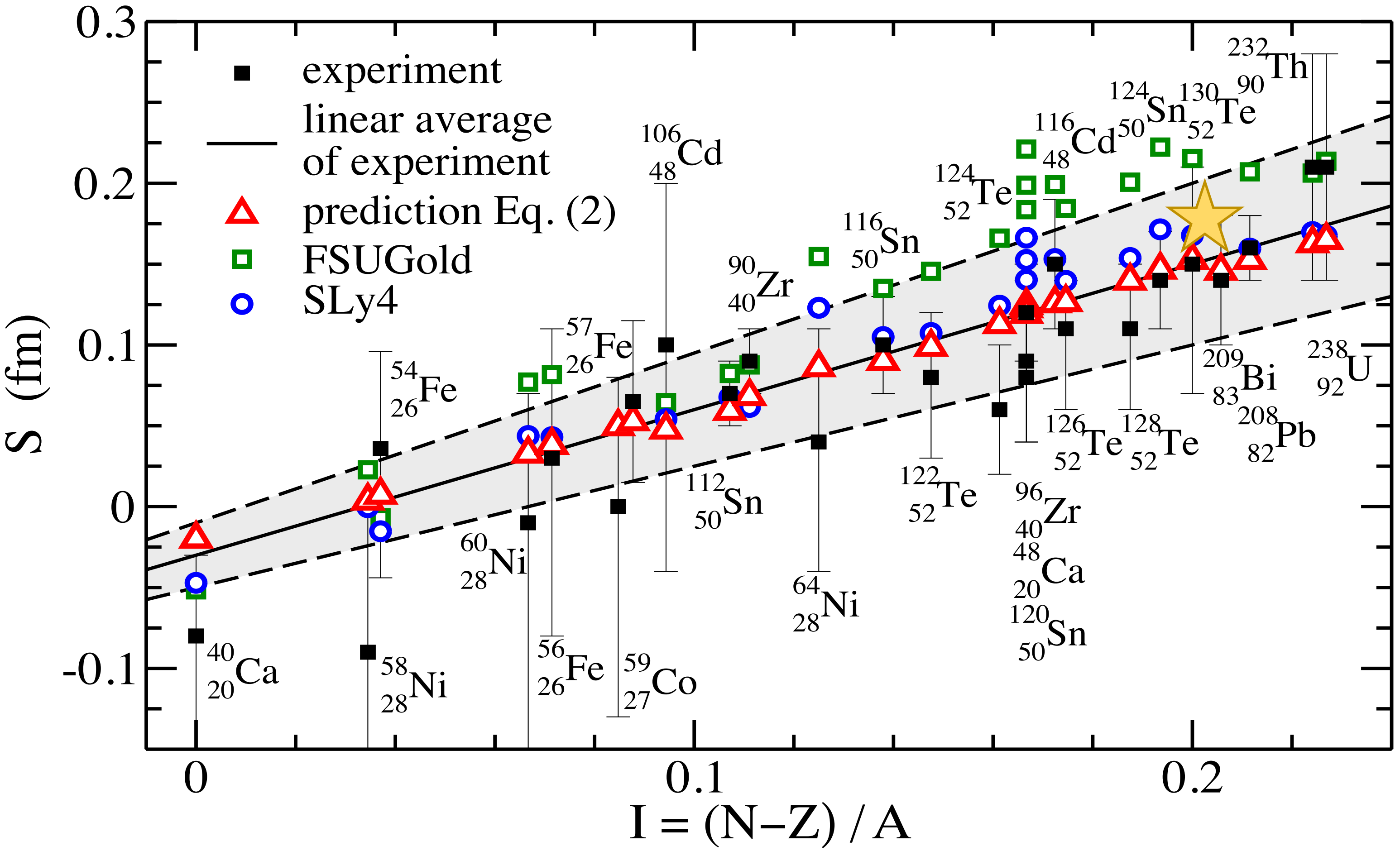

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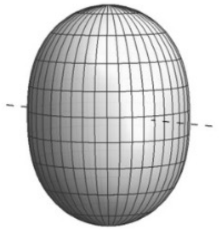

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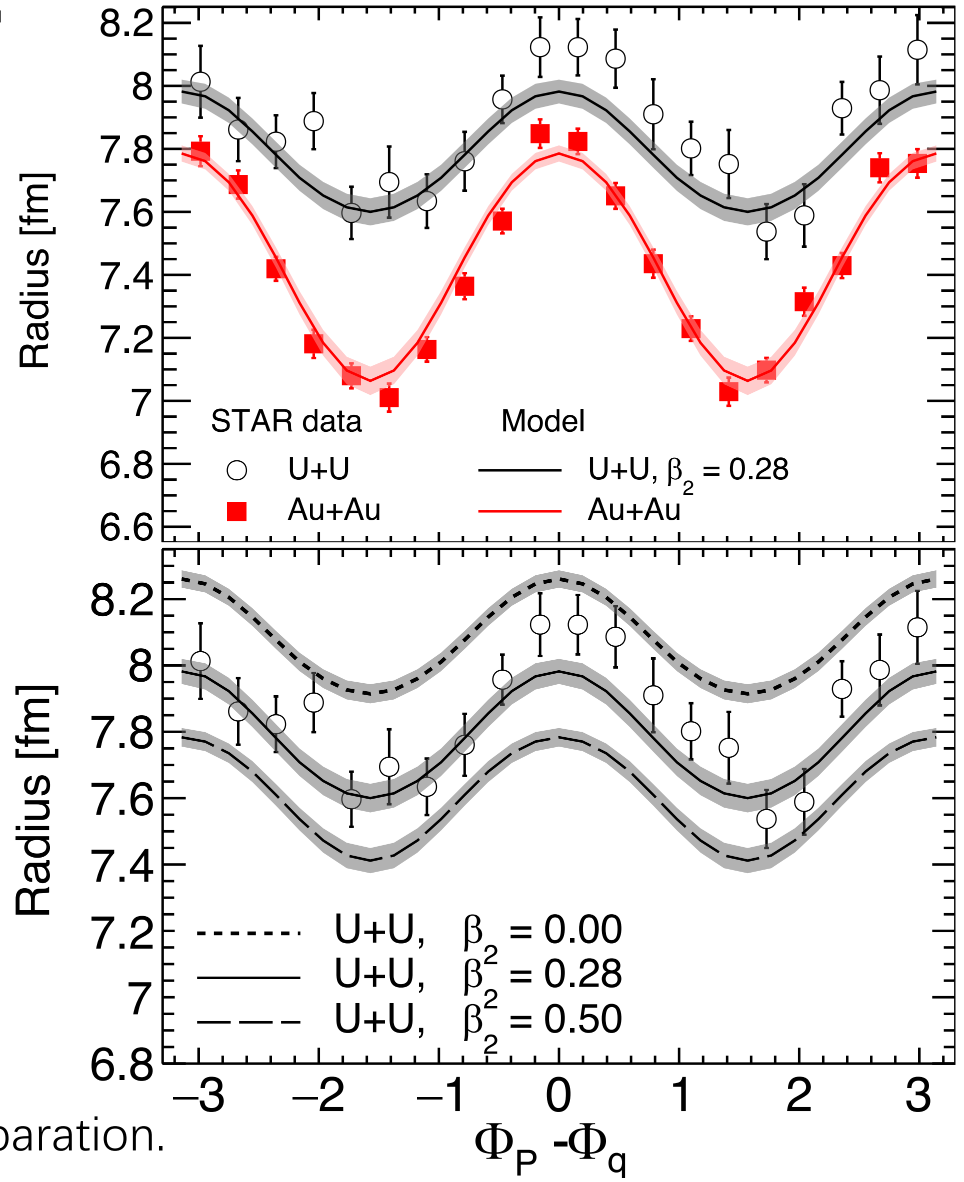
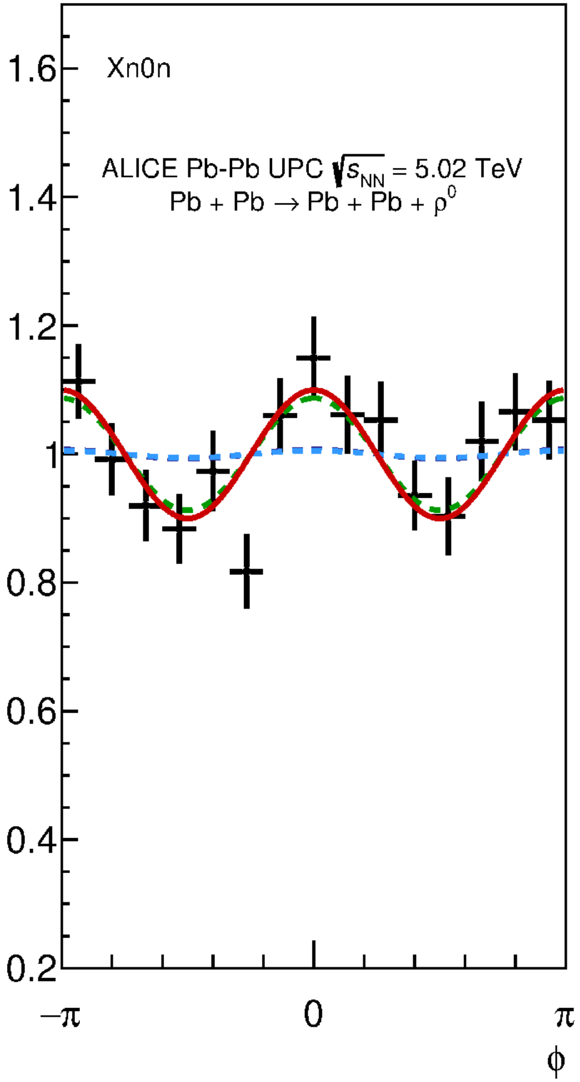
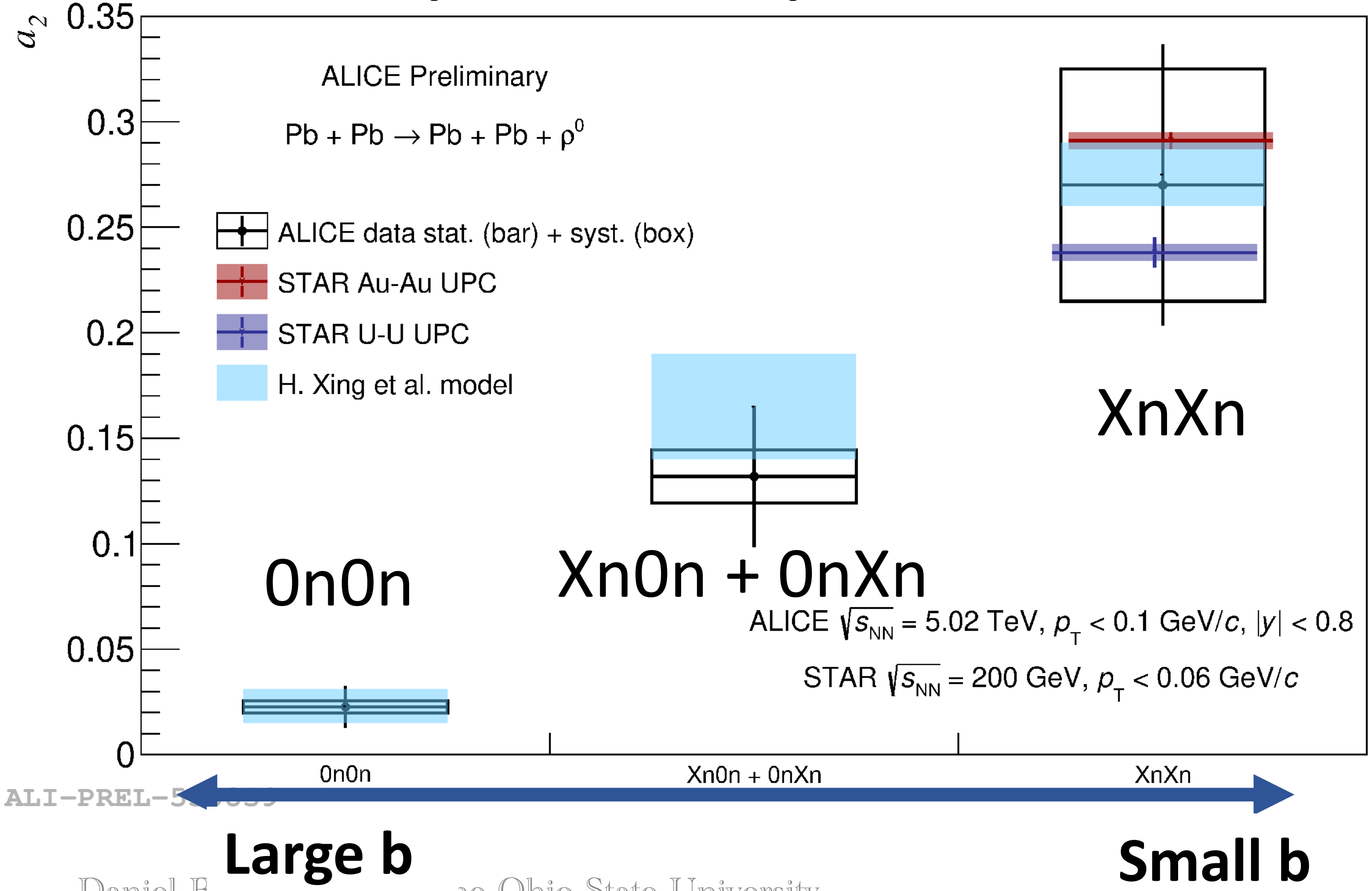


H.Mantysaari, F. Salazar, B.Schenke, C. Shen and W. Zhao, in preparation.

Confirmation from ALICE (New at QM Sept 2023)

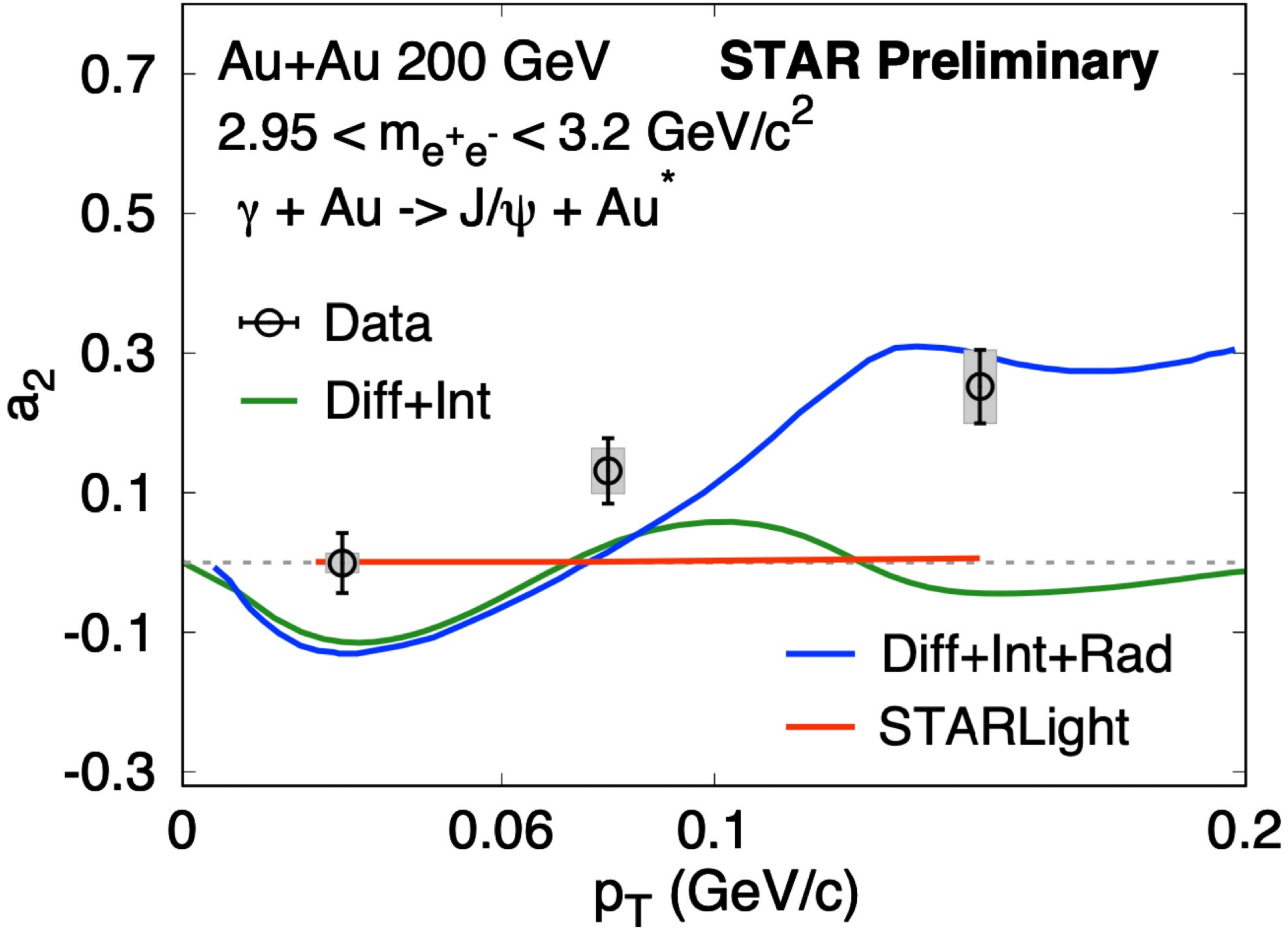


Neutron emission categories test the impact parameter dependence

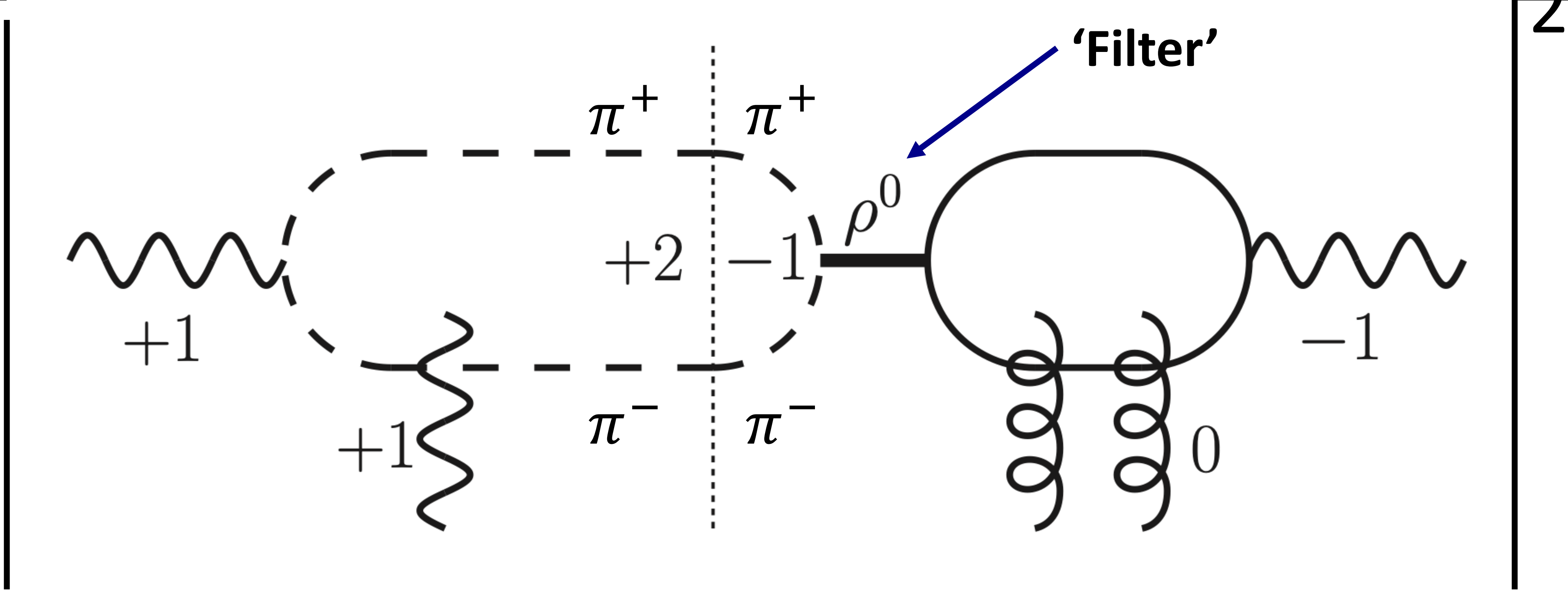


Polarization effects: coherent diffractive J/ψ

- 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



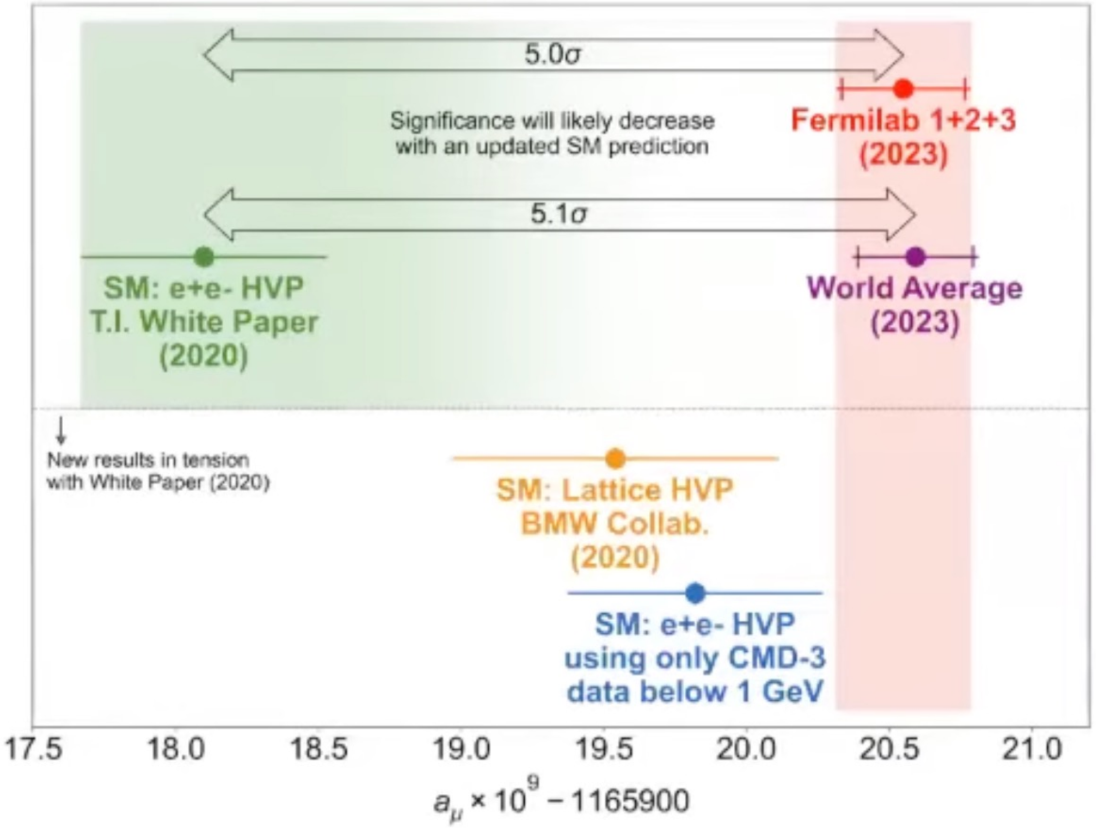
Access to Hadronic Light-by-Light

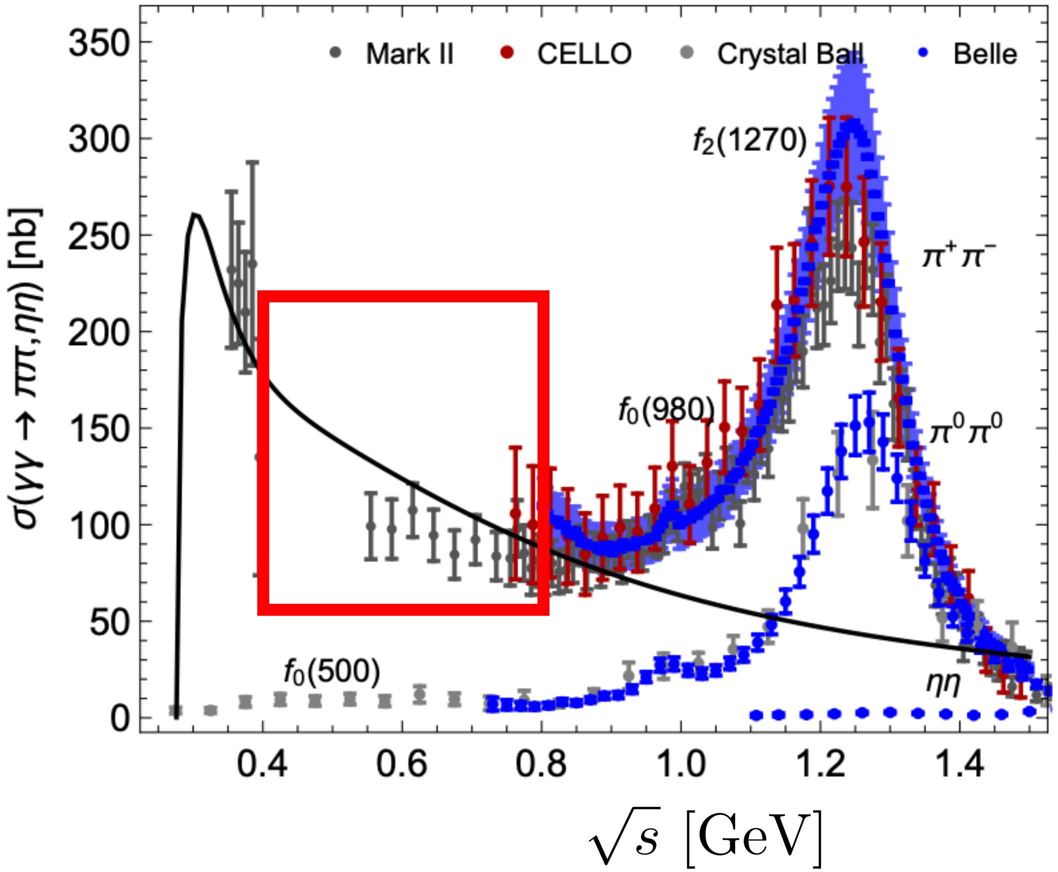


Interference with the hadronic light-by-light diagram
Leads to a unique signature -> odd spin configurations

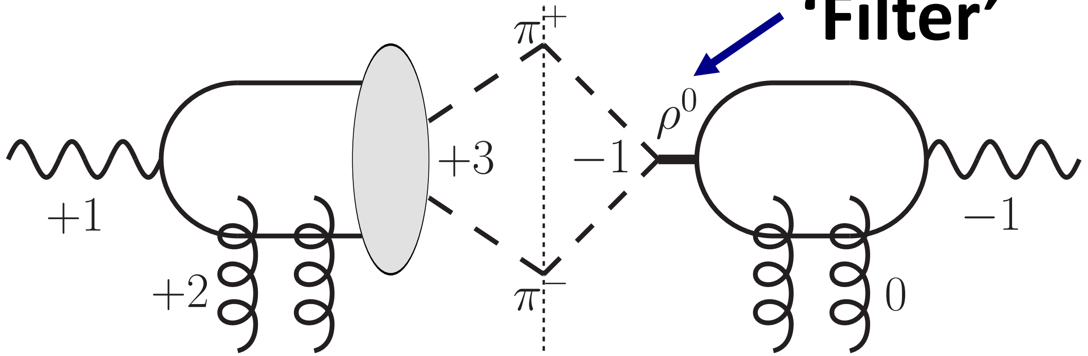
Novel Experimental input for muon g-2

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





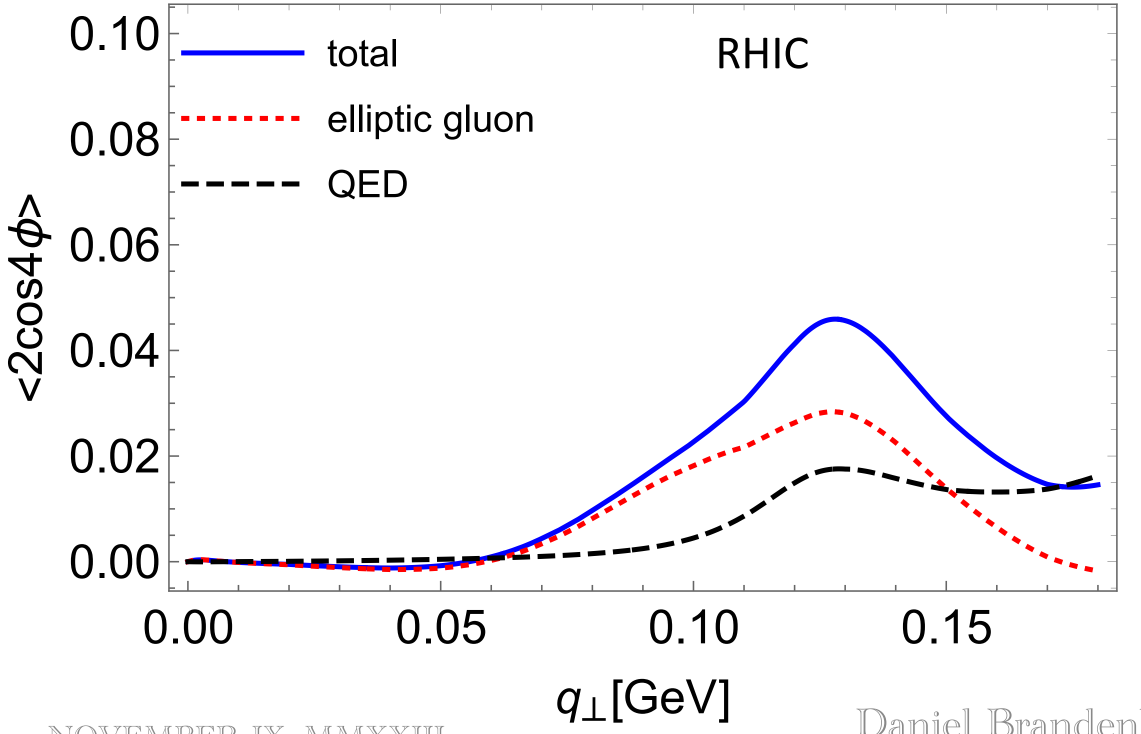
Elliptic Gluon Tomography (Tensor Pomeron)

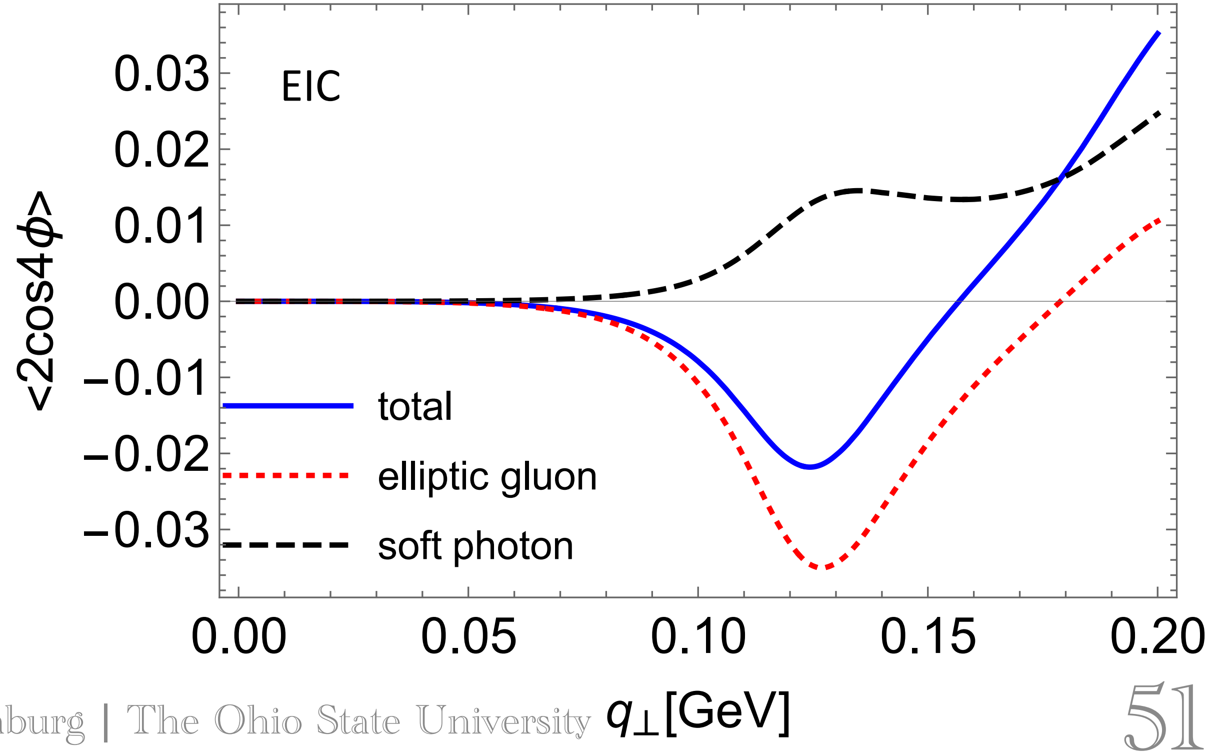


Phys. Rev. D **104**, 094021 (2021)

Elliptic gluon distribution: correlation between impact parameter and momentum

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





Shining light on Gluons

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

[1] H1 Collaboration. *J. High Energ. Phys.* **2010**, 32 (2010).
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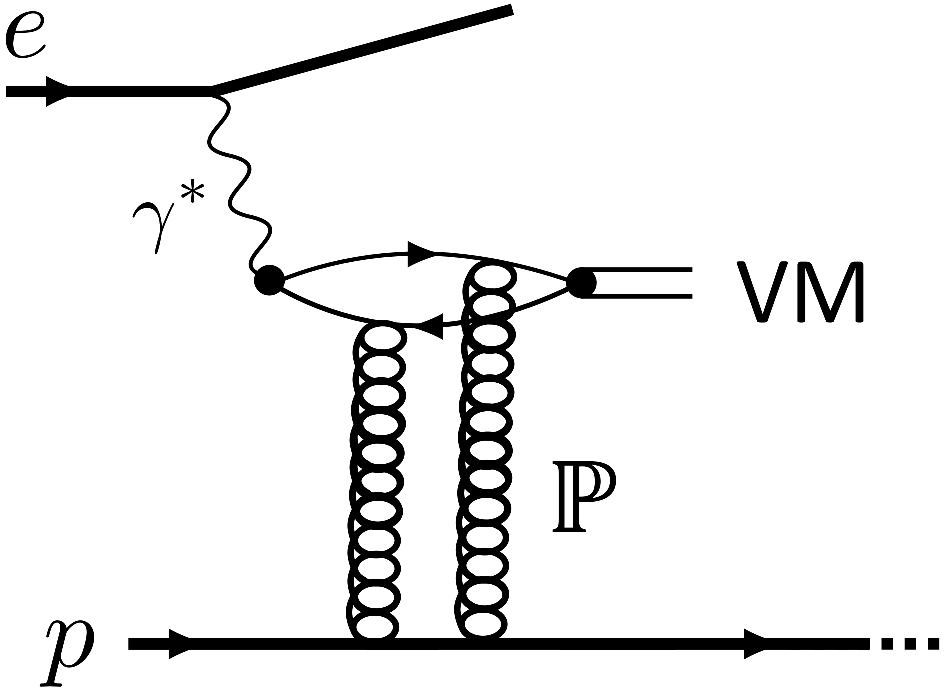

Photon energies $\gtrsim$ 10 GeV: probe gluon distribution - Interaction through ℙomeron (two gluon state at lowest order)

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The amplitude has three components:

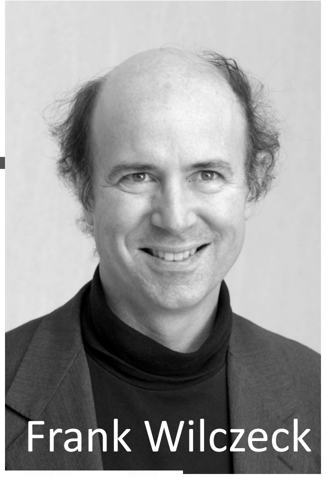
$$T^{\gamma^\star p\to Vp}(x;t) = \int_0^1 \mathrm{d}z \int \mathrm{d}^2\mathbf{r}\, \Psi^\gamma(z,\mathbf{r}) \cdot \sigma^{q\bar{q}-p}(x,\mathbf{r};t) \cdot \Psi^V(z,\mathbf{r})$$

Photon | Diffractive Dipole | Vector Meson

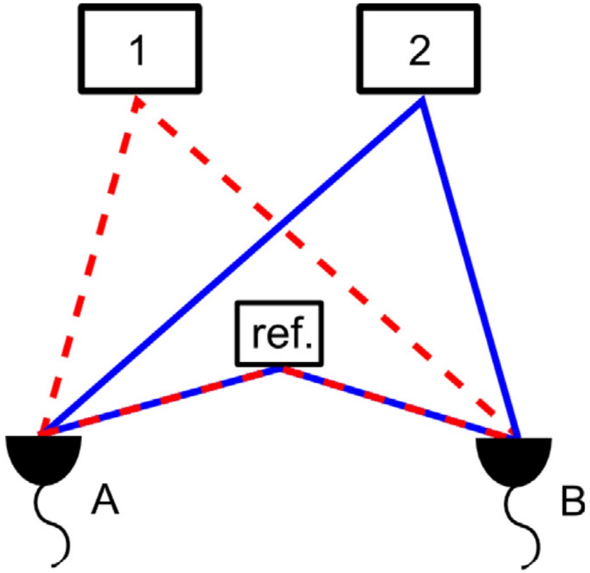
Photon quantum numbers $J^{PC} = 1^{--}$: Can transform into a 'heavy photon'

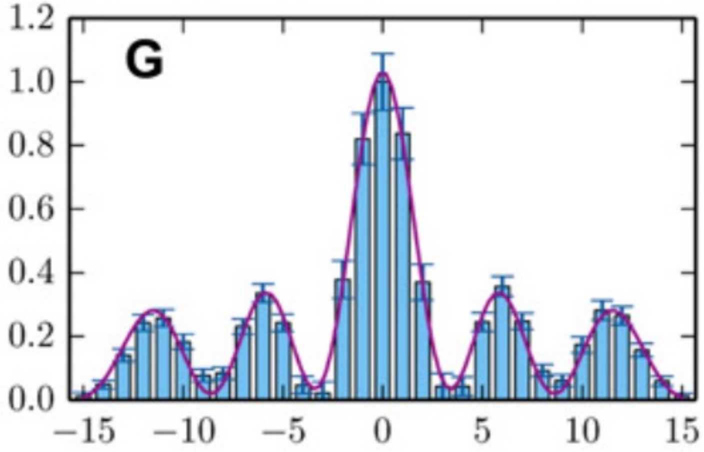
i.e. a vector meson ($\rho^0, \phi\ , J/\psi$) with $J^P = 1^-$

Entanglement Enabled Intensity Interferometry



Hanbury Brown and Twiss effect is a two (identical) particle interference due to quantum statistics





States must be identical to interfere, otherwise incoherent sum:

$$\left| D_{1A}D_{2B}\,|\mathrm{RB}\rangle + D_{2A}D_{1B}\,|\mathrm{BR}\rangle \right|^2 = |D_{1A}D_{2B}|^2 + |D_{2A}D_{1B}|^2$$

After entangling interference is restored:

$$|D_{1A}|^2\,|D_{2B}|^2 + |D_{2A}|^2\,|D_{1B}|^2 + 2\,\mathrm{Re}\,D_{1A}D_{2B}D^*_{2A}D^*_{1B}$$

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

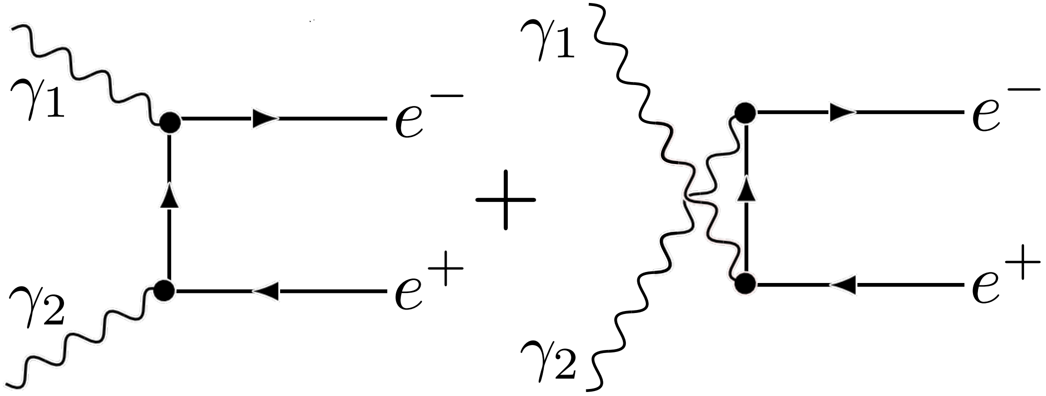
The Breit-Wheeler Process

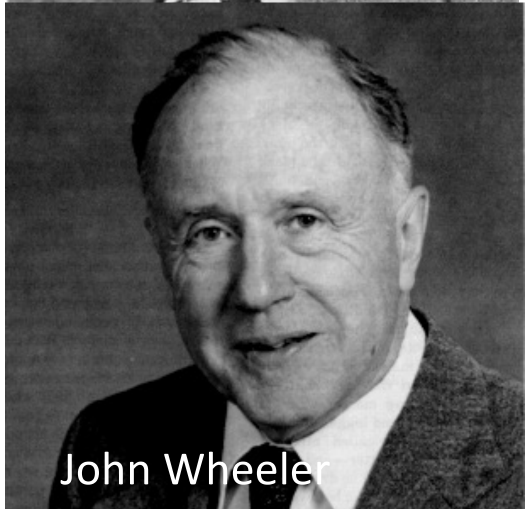
DECEMBER 15, 1934 PHYSICAL REVIEW VOLUME 46

Collision of Two Light Quanta

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

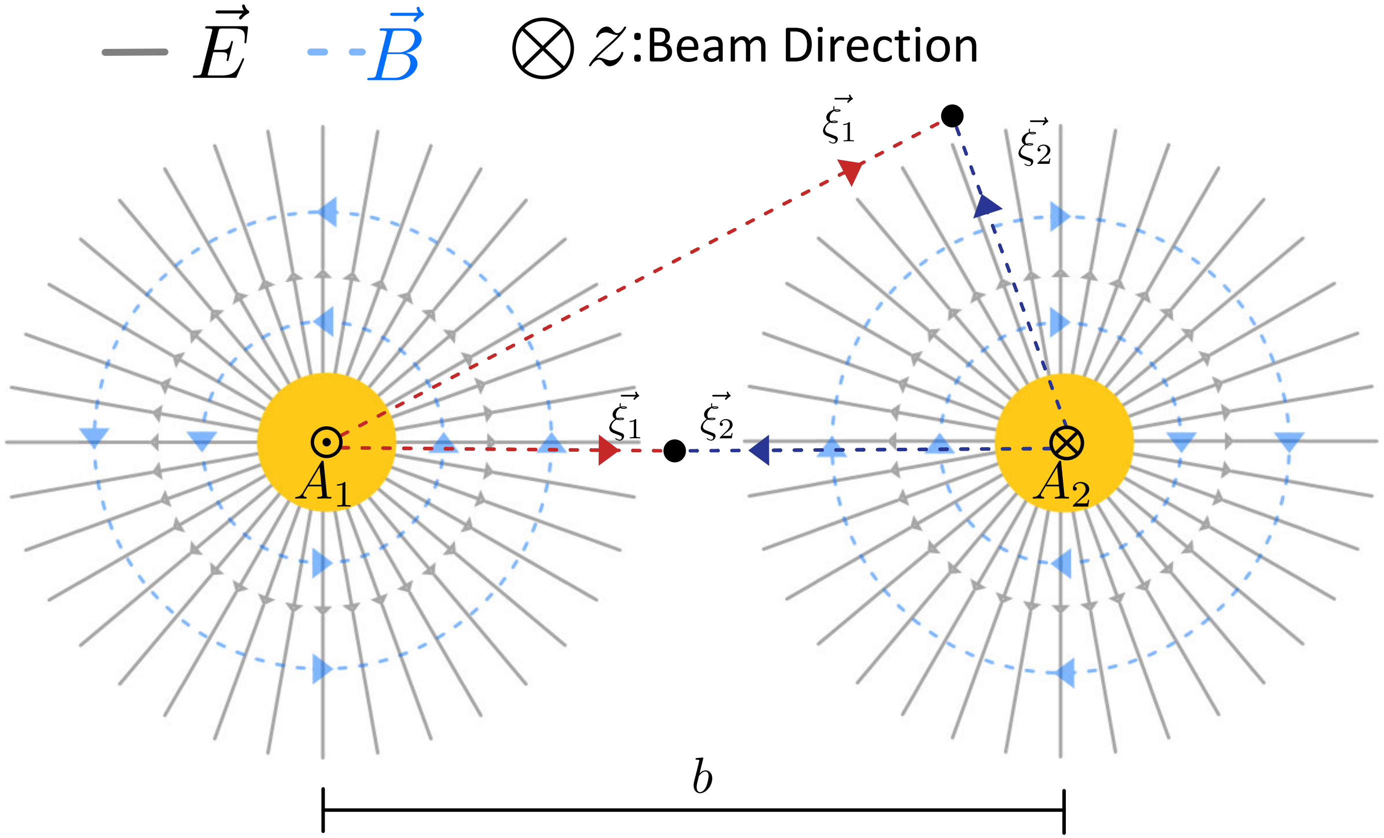
(Received October 23, 1934)

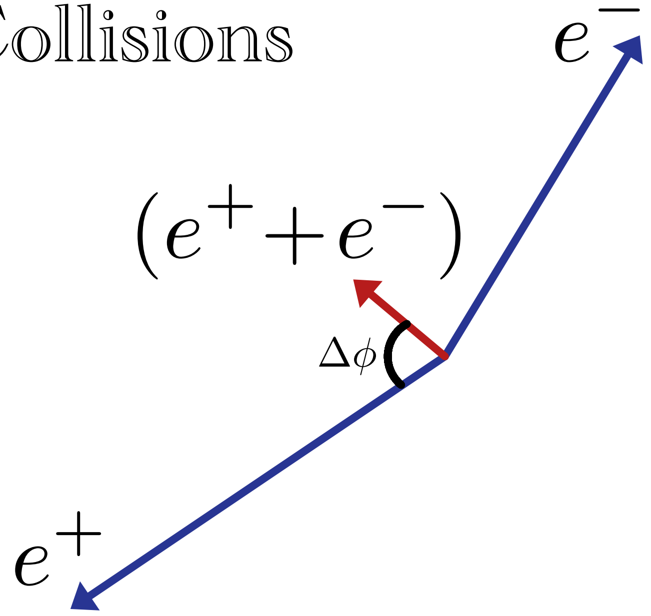




- Non-linear effect forbidden in classical electromagnetism
- At lowest order, two Feynman diagrams contribute and interfere
- Only tree level process still not observed observed after 80+ years!

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

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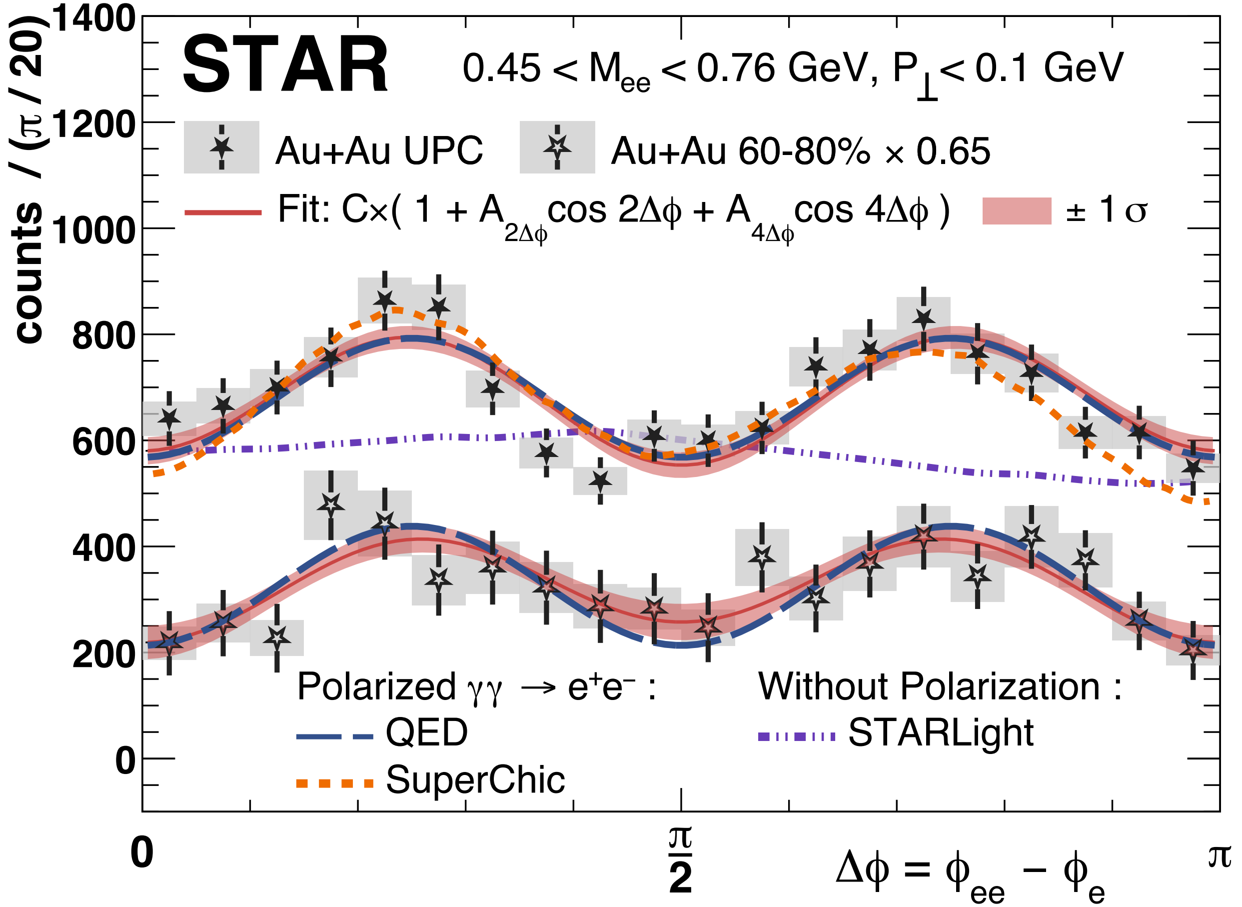
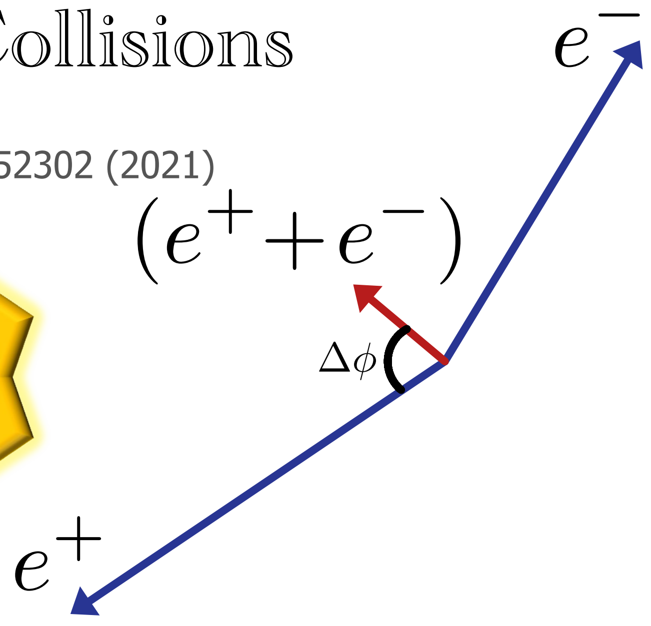


(STAR Collaboration)
Phys. Rev. Lett. **127**, 052302 (2021)

Breit-Wheeler Discovery 2021 STAR



Experimental access to photon polarization demonstrated

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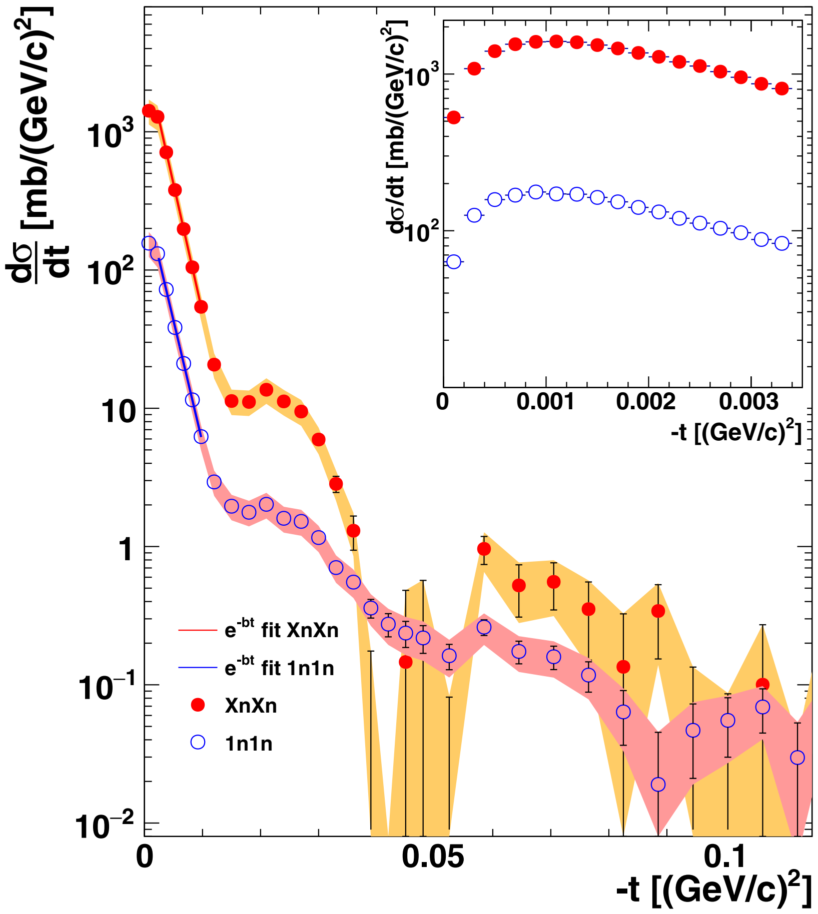
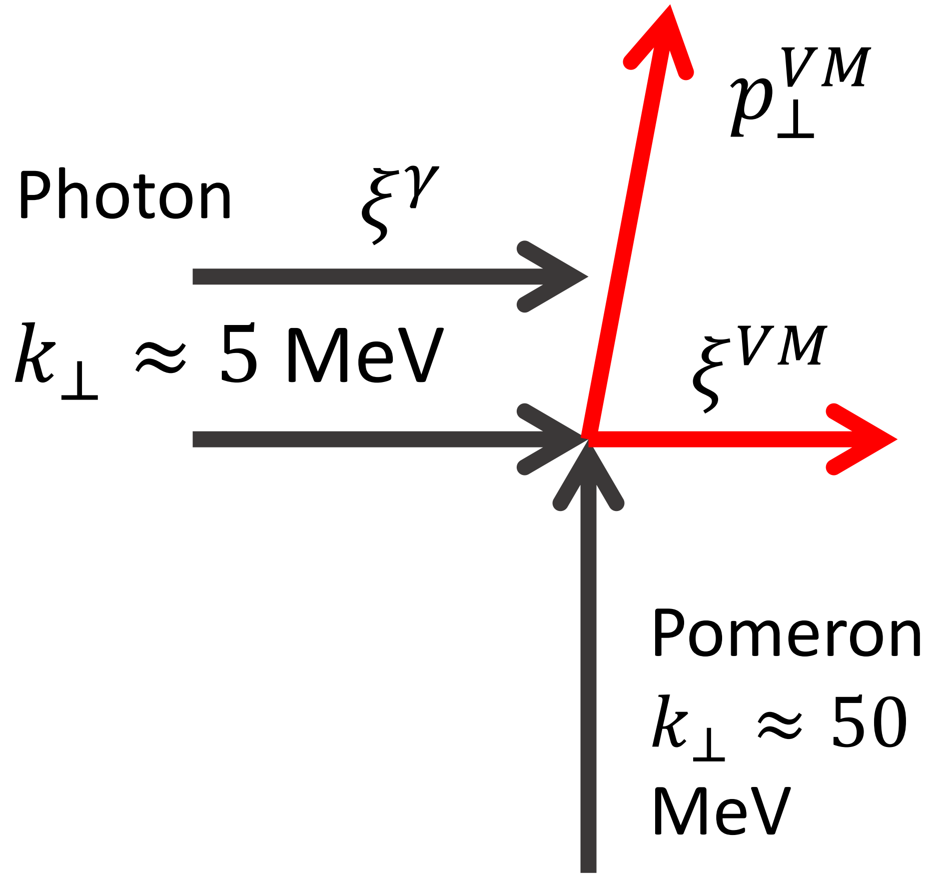
Trivial Spin-Momentum Alignment?





VM inherits the spin from photon (no helicity flip)

Diffractive -> VM momentum dominantly from the Pomeron

→ VM has no alignment between spin and momentum

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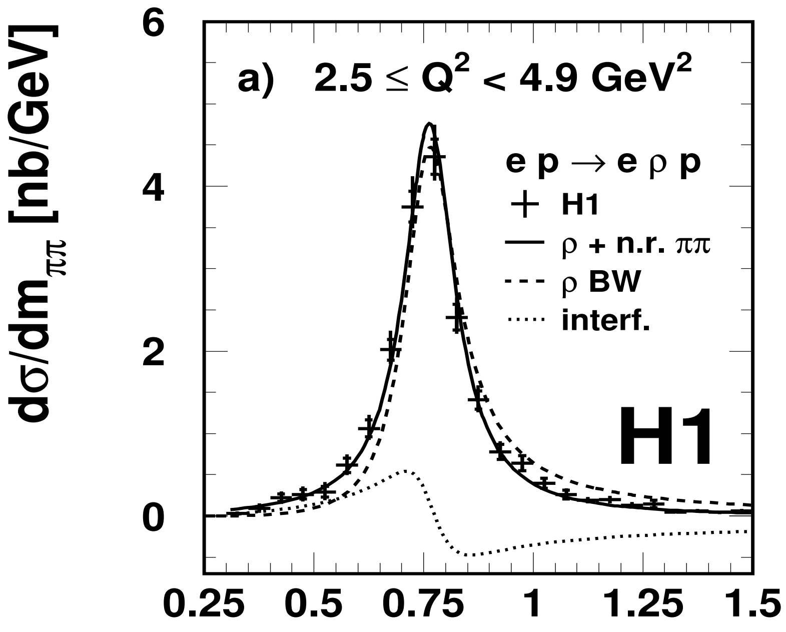
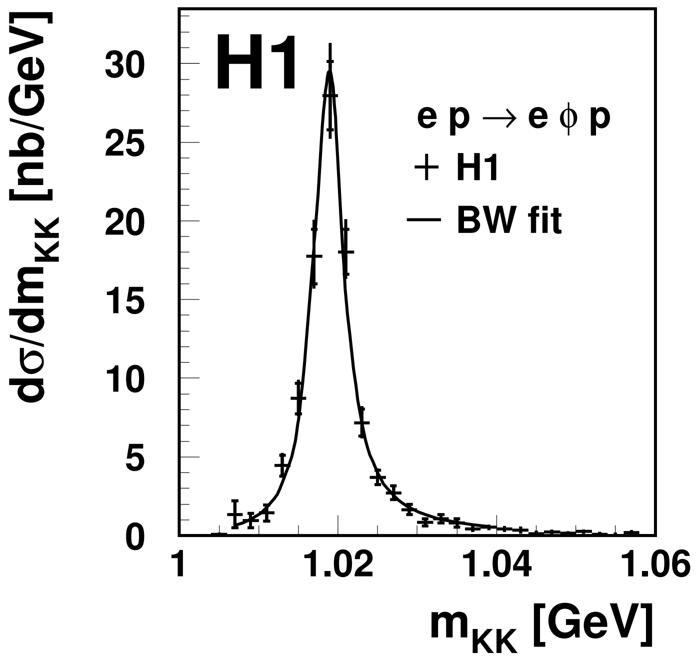
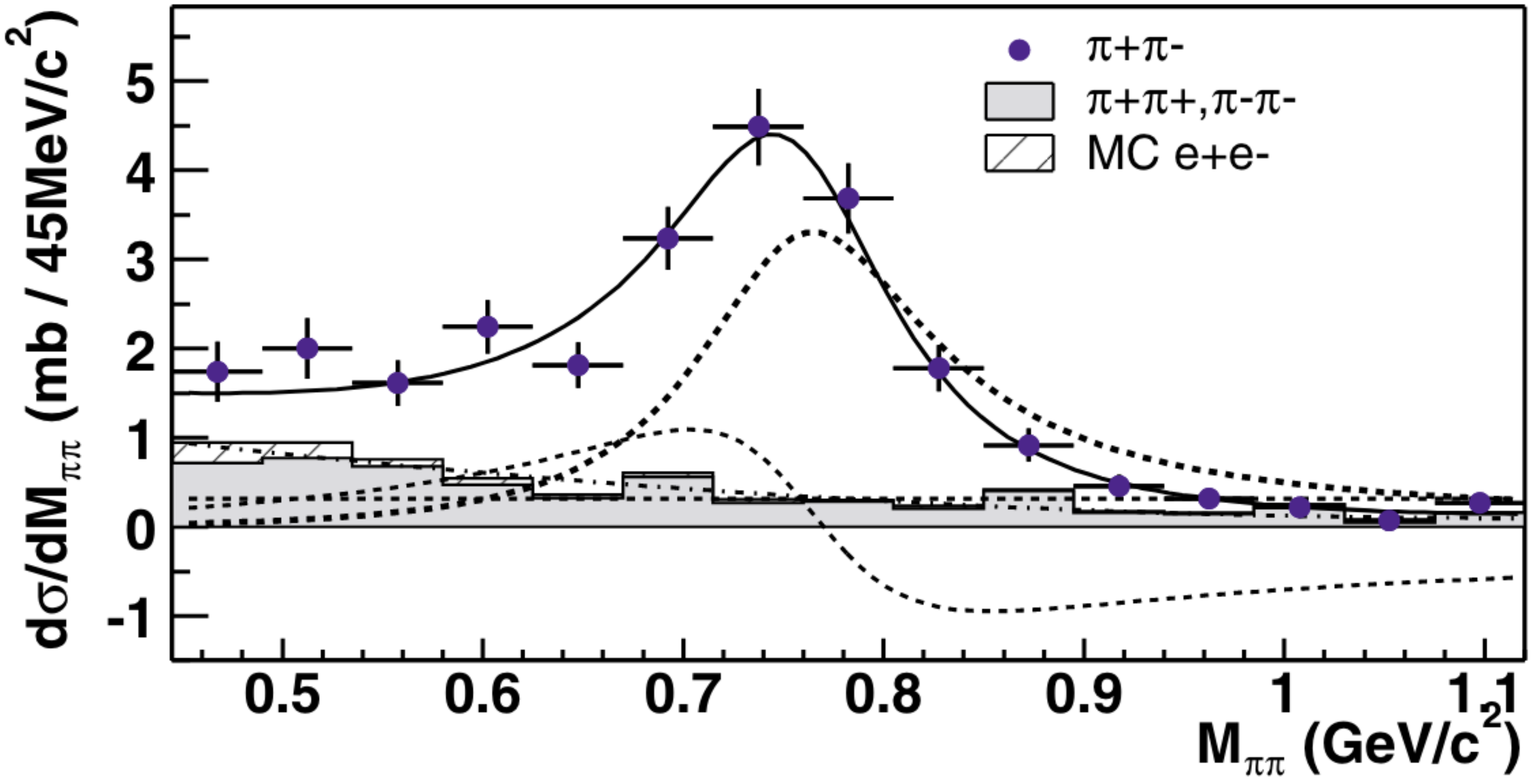




Measurements from H1, ZEUS etc. explored proton via diffractive ρ^0 and ϕ production

Past Photo-Nuclear Measurements

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



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

$$\propto \left| \frac{\sqrt{m_{\pi\pi}\ m_\rho\ \Gamma(m_{\pi\pi})}}{m_\rho^2 - m_{\pi\pi}^2 + i\ m_\rho \Gamma(m_{\pi\pi})} + \frac{f_I}{2} \right|^2 ,$$

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).

I will take just this one experiment, which has been designed to contain all of the *mystery* of quantum mechanics, ... 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**