A PHOTON RUNS THROUGH IT

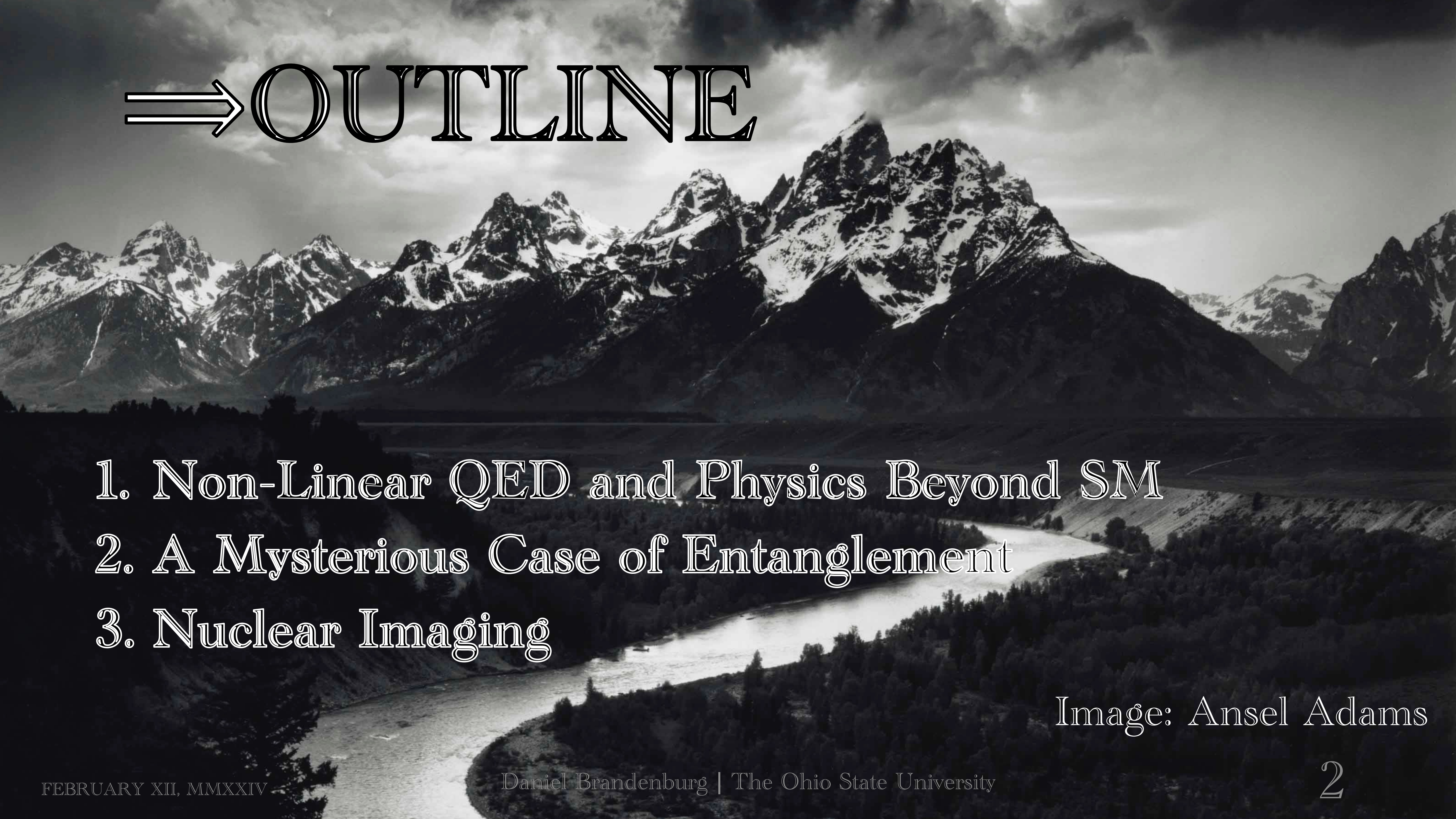
By James Daniel Brandenburg

A TALK AT THE XXXIX
WINTER WORKSHOP ON NUCLEAR DYNAMICS
FEBRUARY XII, MMXXIV

U.S. DEPARTMENT OF ENERGY
Office of Science

THE OHIO STATE UNIVERSITY

Image: Ansel Adams

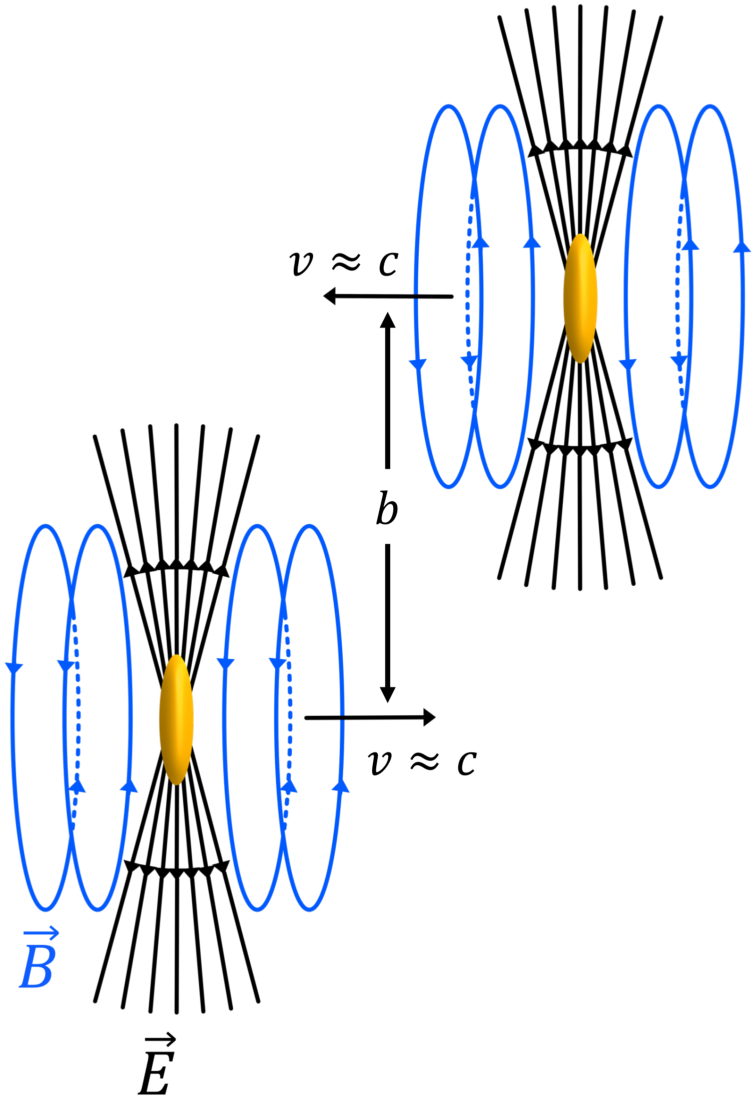


⇒OUTLINE

1. Non-Linear QED and Physics Beyond SM
2. A Mysterious Case of Entanglement
3. Nuclear Imaging

Image: Ansel Adams

UPC : 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

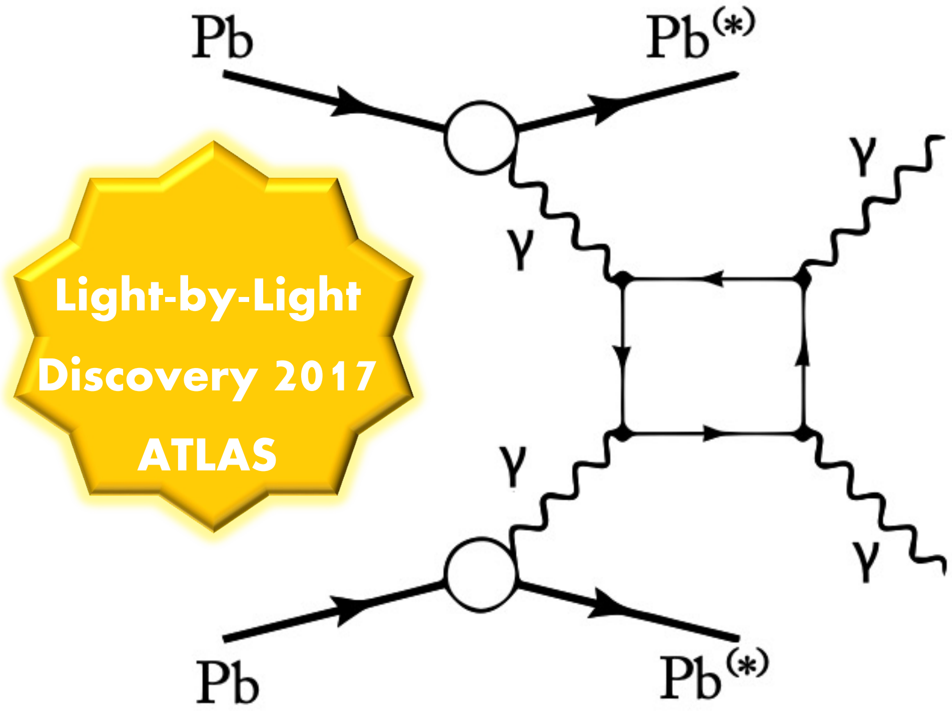
Must be treated in terms of photon quanta

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

80 GeV @ LHC
3 GeV @ RHIC

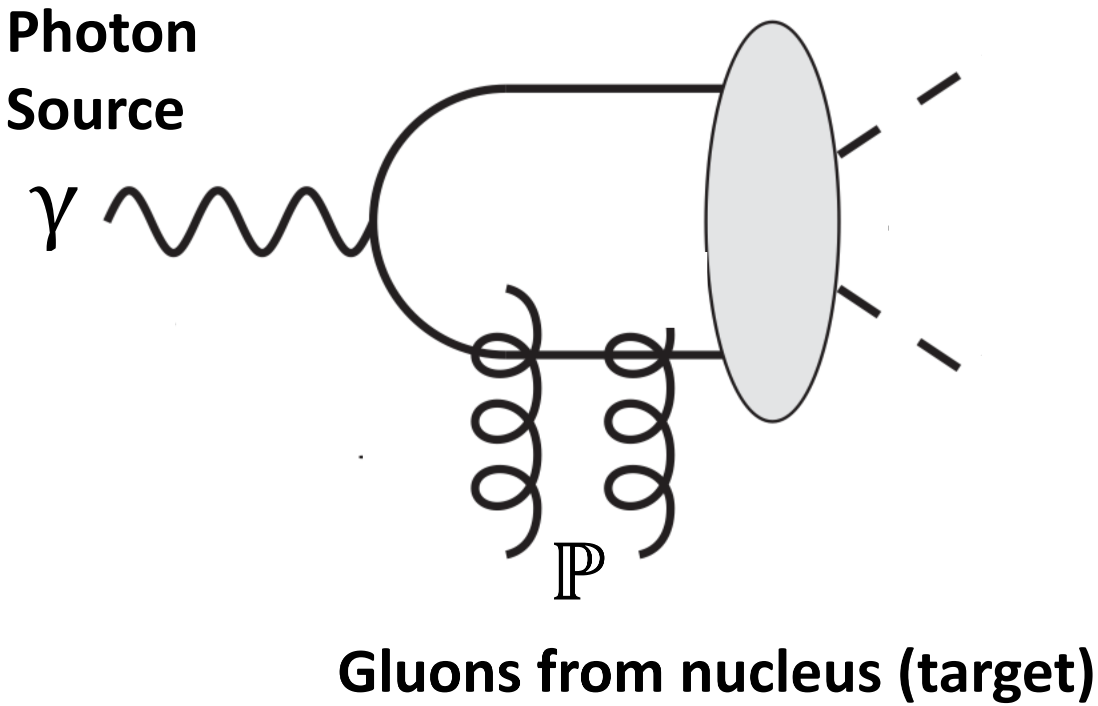
Types of Processes in UPC

Photon + photon



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

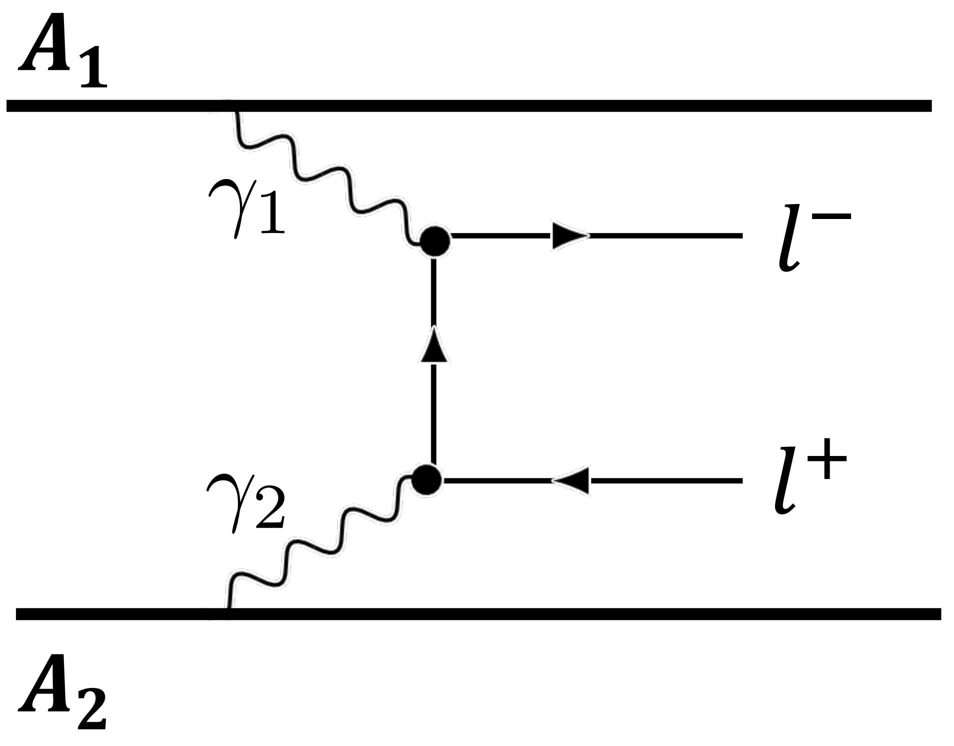
Photon + target



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

Types of Processes in UPC

Photon + photon



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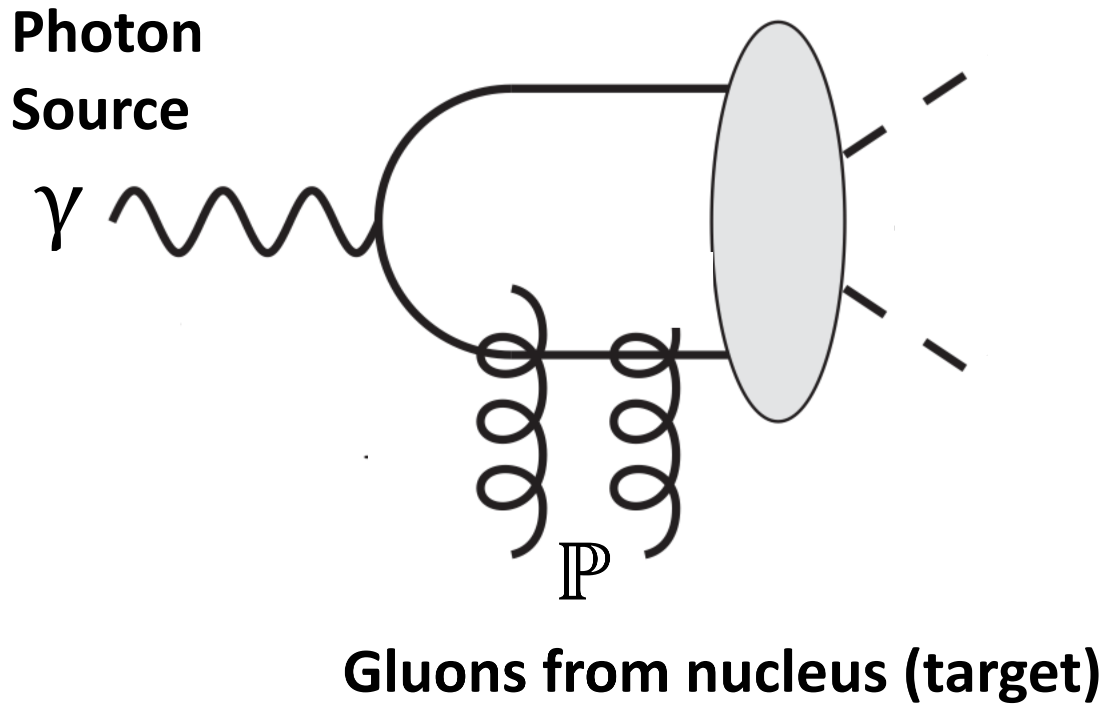
Photon + target



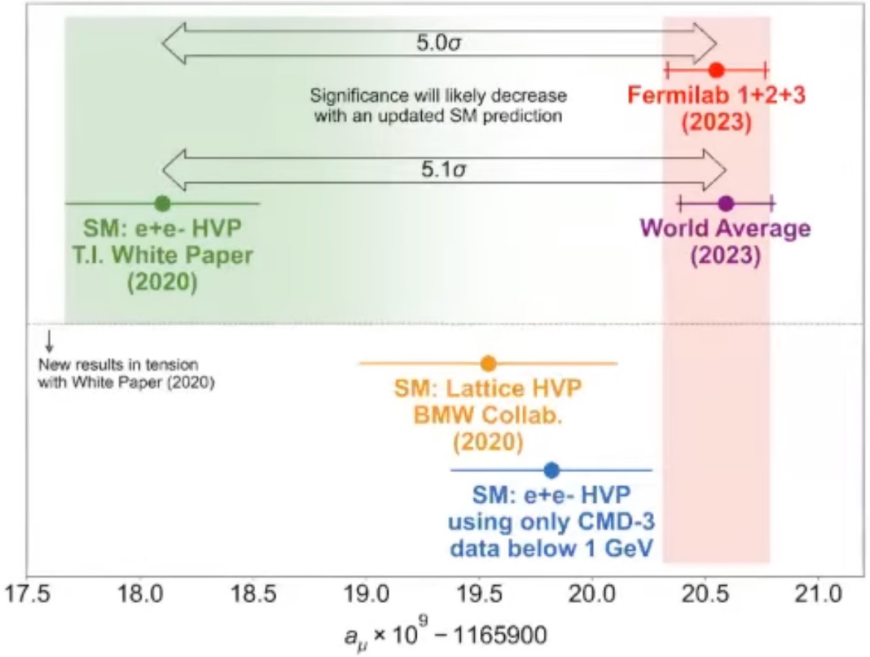
1. 'Image' nuclear gluon distributions
2. Test gluon saturation predictions
3. Investigate sub-nucleonic fluctuations
4. …

$\gamma\gamma \rightarrow \tau^+\tau^-$ Process

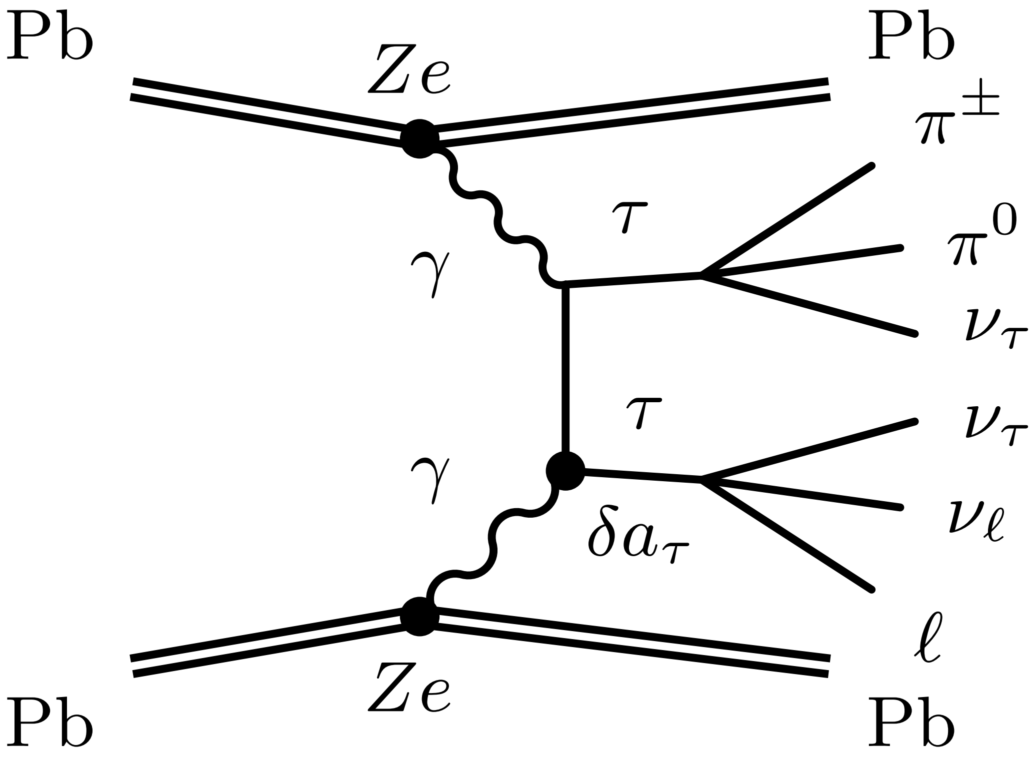
- Sensitivity to the tau anomalous magnetic moment!
- BSM sensitivity $\delta\alpha_l \propto m_l^2 \sim 280$x more sensitive than μ

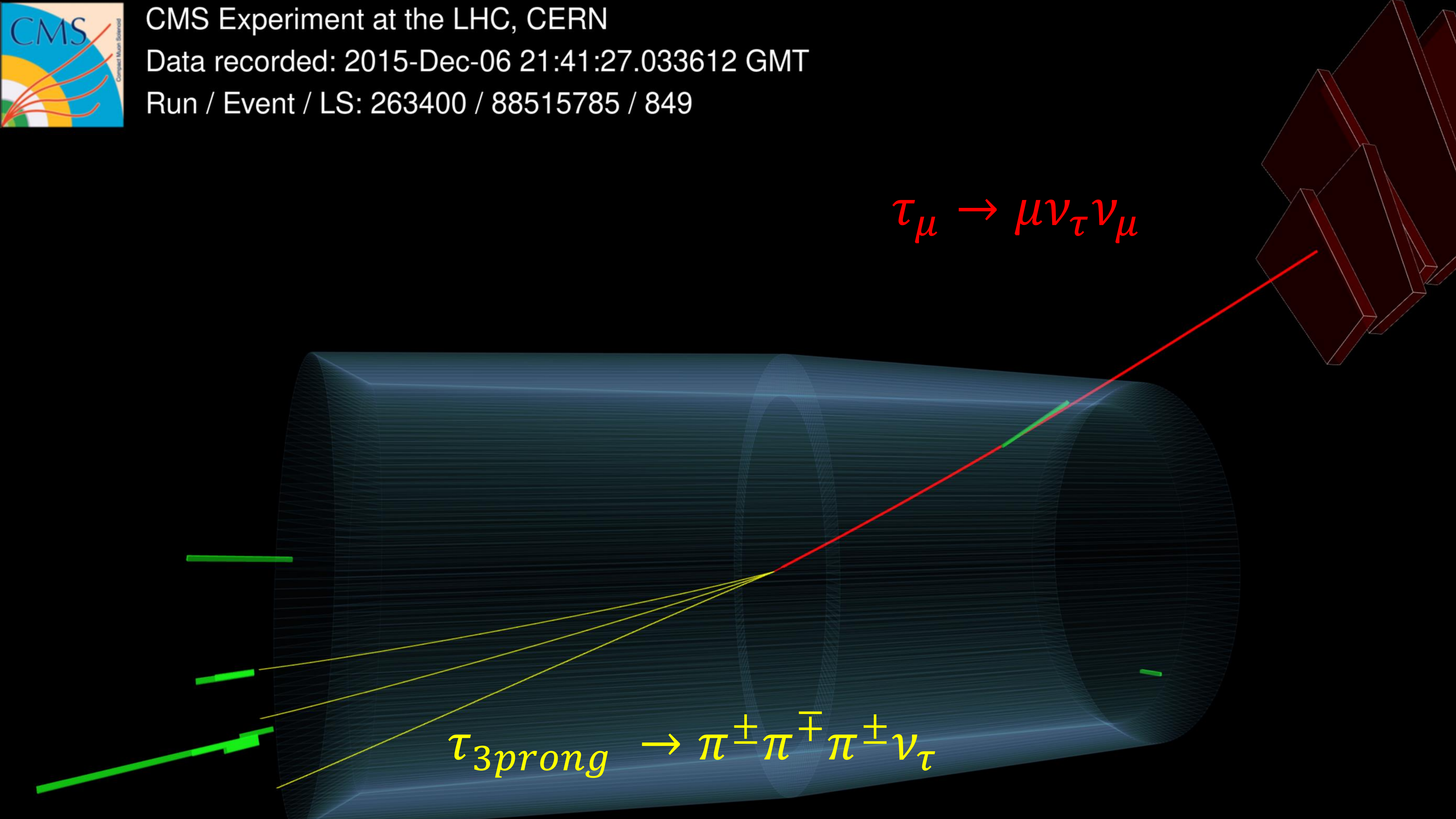
$$a_\tau = \frac{g_\tau - 2}{2}$$

Three channels available: eμ, μ+track, μ+3 tracks
Use $\gamma\gamma \rightarrow \mu^+\mu^-$ to help reduce systematic uncertainty from photon flux



[(Muon g-2 Collaboration) arXiv:2308.06230]

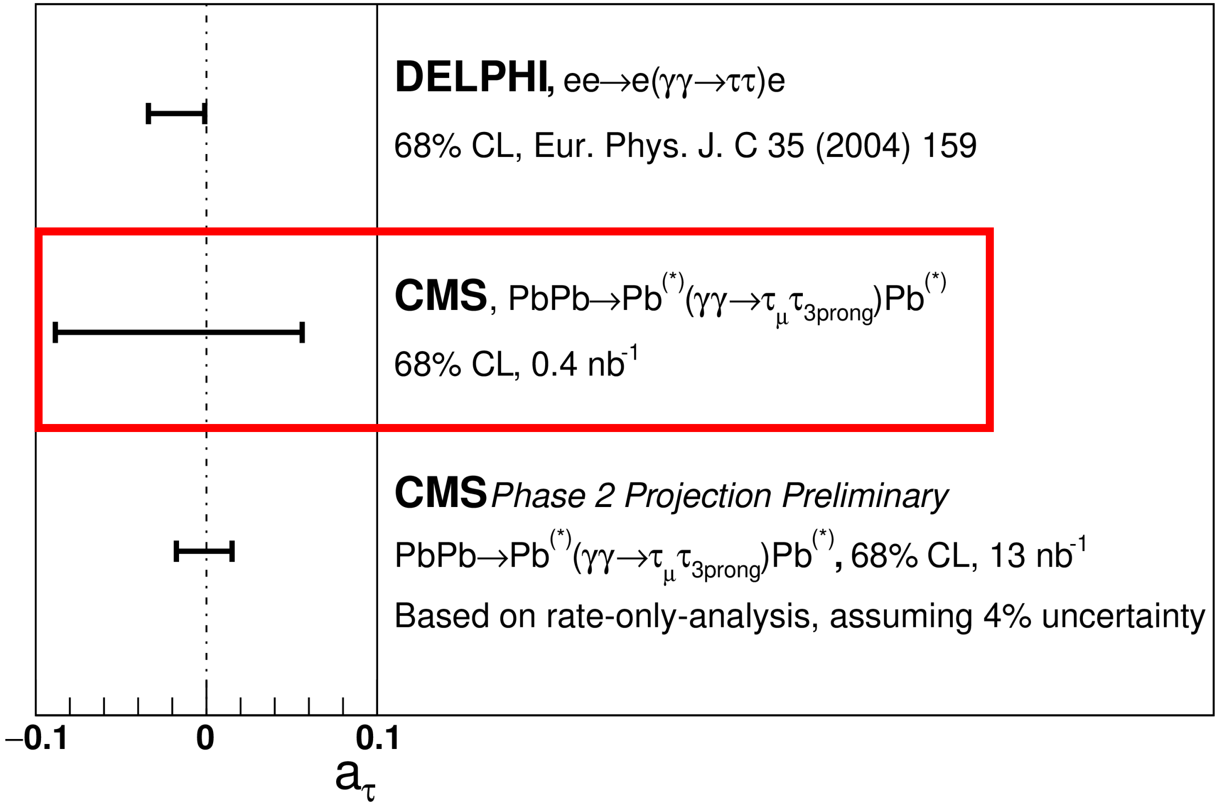




CMS
CMS Experiment at the LHC, CERN
Data recorded: 2015-Dec-06 21:41:27.033612 GMT
Run / Event / LS: 263400 / 88515785 / 849
$\tau_\mu \rightarrow \mu\nu_\tau\nu_\mu$
$\tau_{3prong} \rightarrow \pi^\pm\pi^\mp\pi^\pm\nu_\tau$

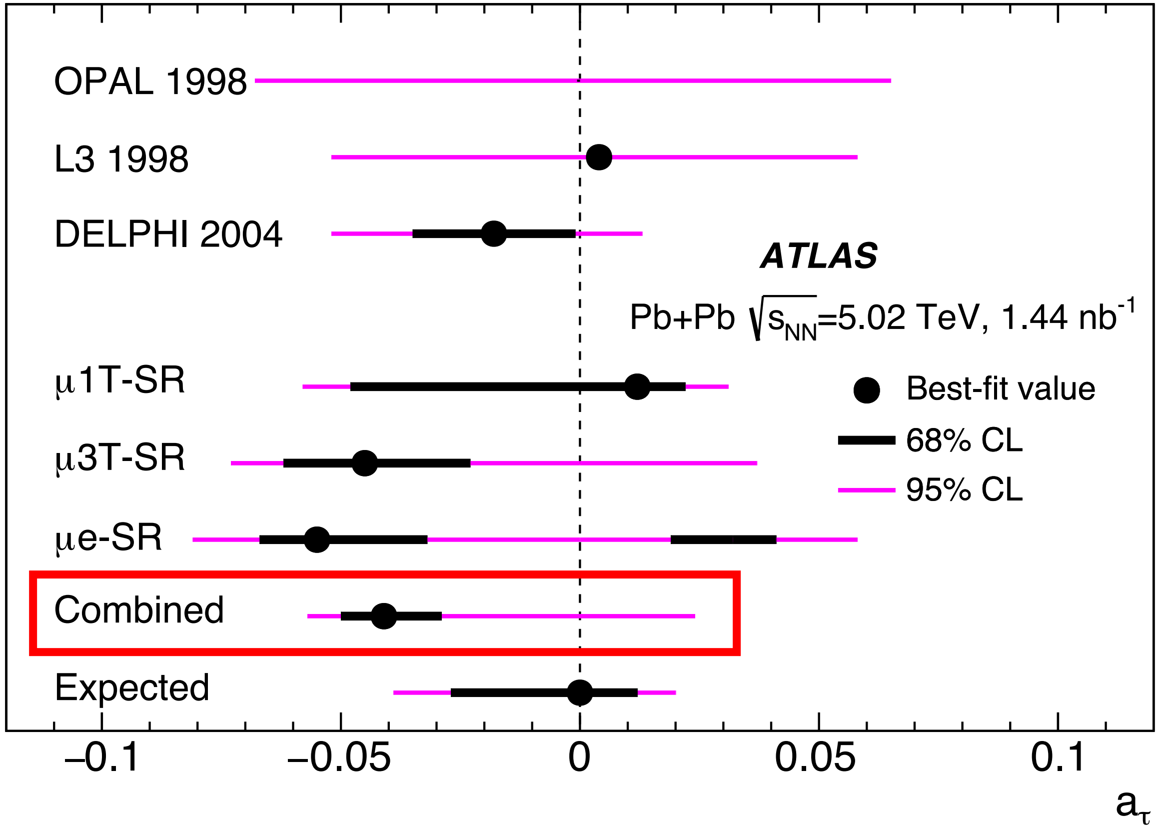
Anomalous Magnetic Moment of tau

Matthew Nickel (CMS)



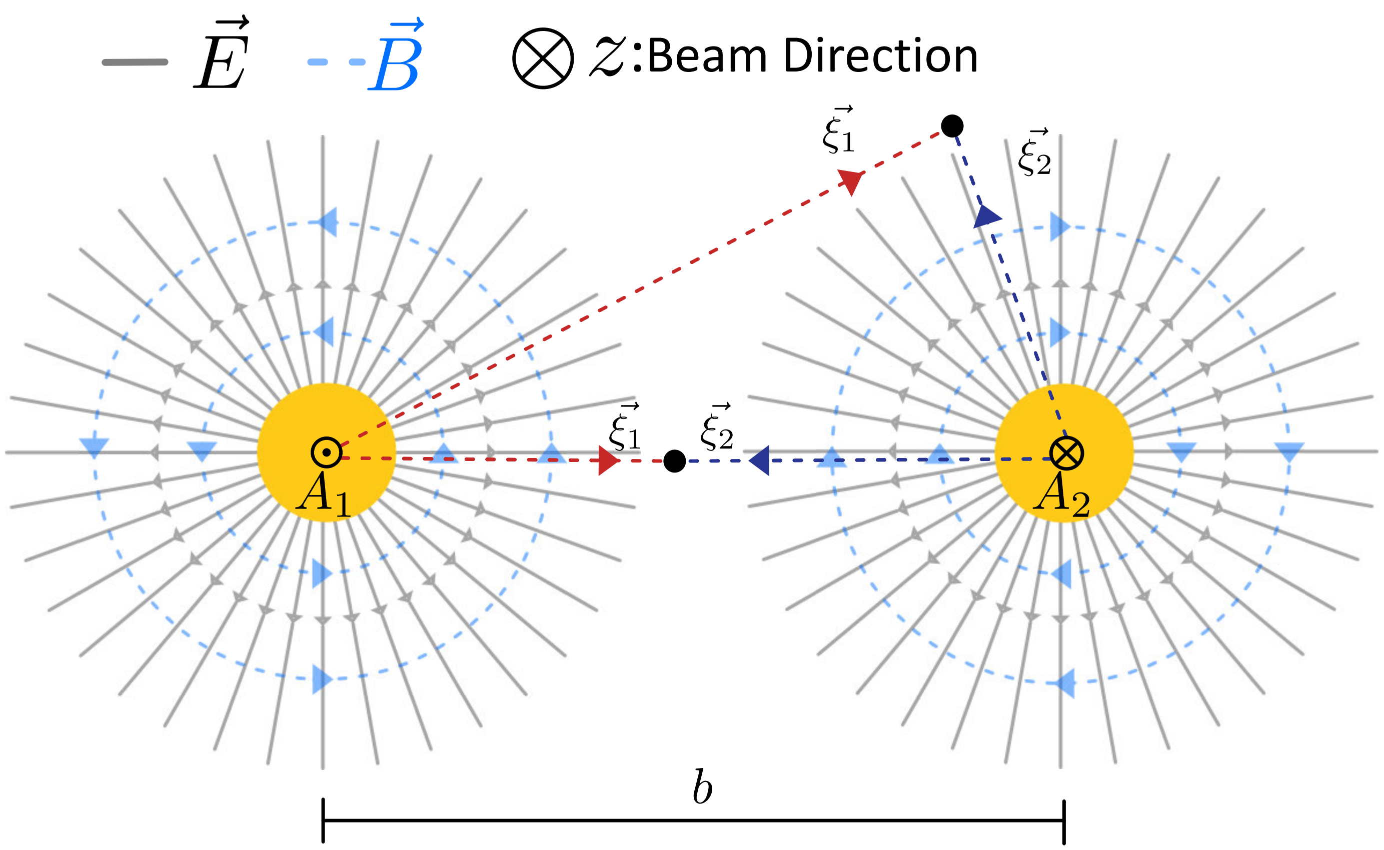
arXiv:2206.05192
Accepted to PRL as Editor's suggestion

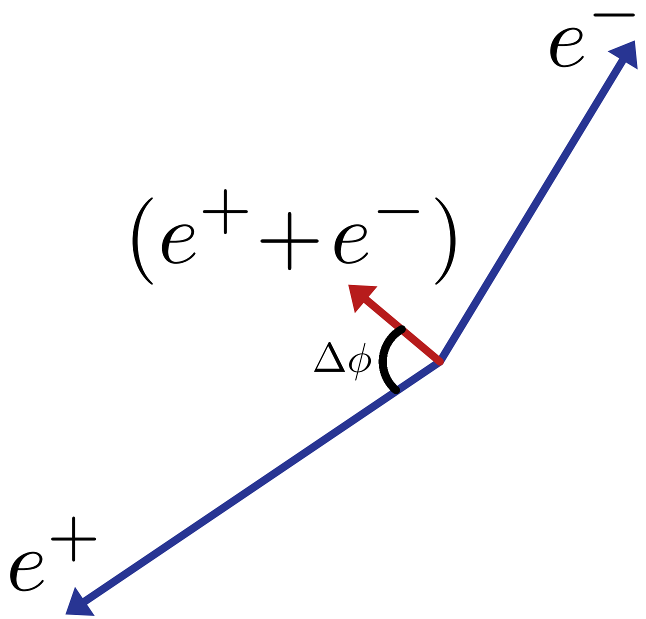
Peter Steinberg (ATLAS)



arXiv:2204.13478 acc. by PRL

Photon *Polarization* In UPC





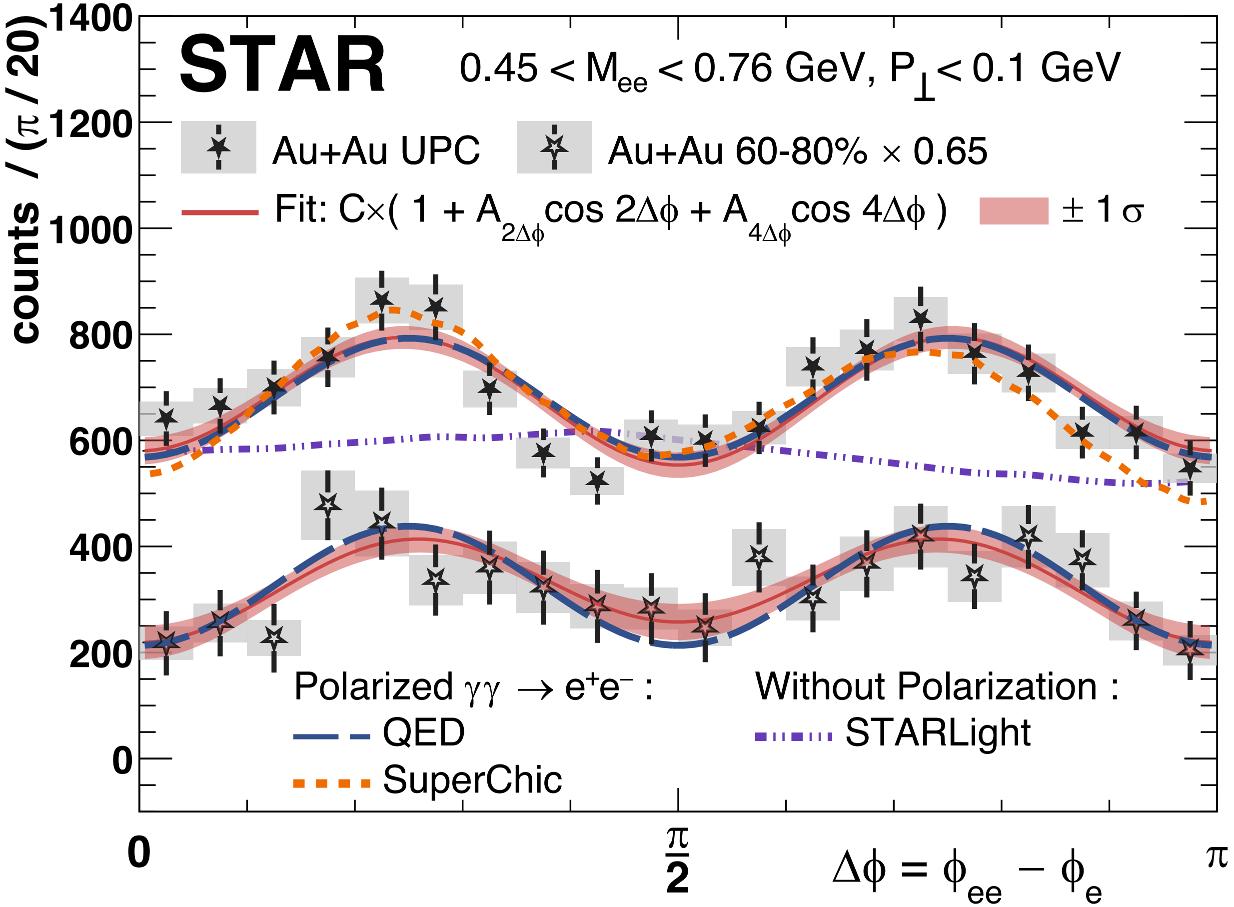
- Polarization vector ξ: aligned radially with the "emitting" source
- Intrinsic photon spin converted into **orbital angular momentum**
- Observable as anisotropy in $e^\pm$ momentum

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).

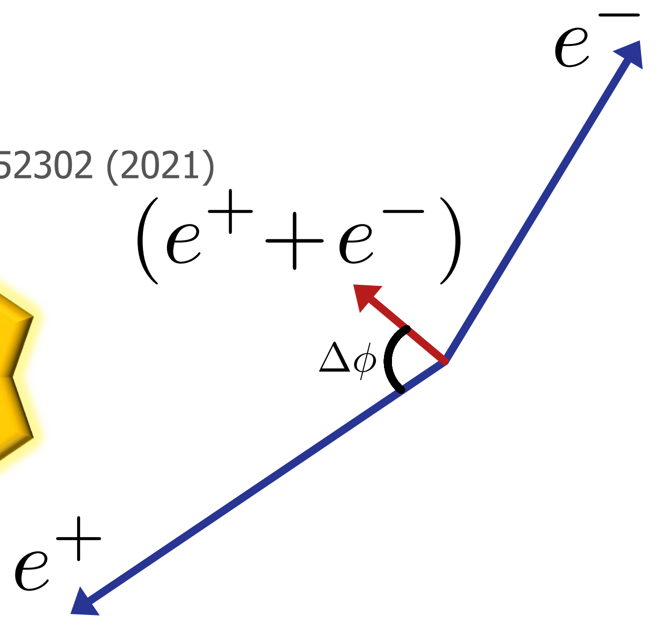
S. Bragin, et. al., *Phys. Rev. Lett.* 119 (2017), 250403
R. P. Mignani, *et al.*, *Mon. Not. Roy. Astron. Soc.* 465 (2017), 492

Photon *Polarization* In UPC



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

Breit-Wheeler Discovery 2021 STAR



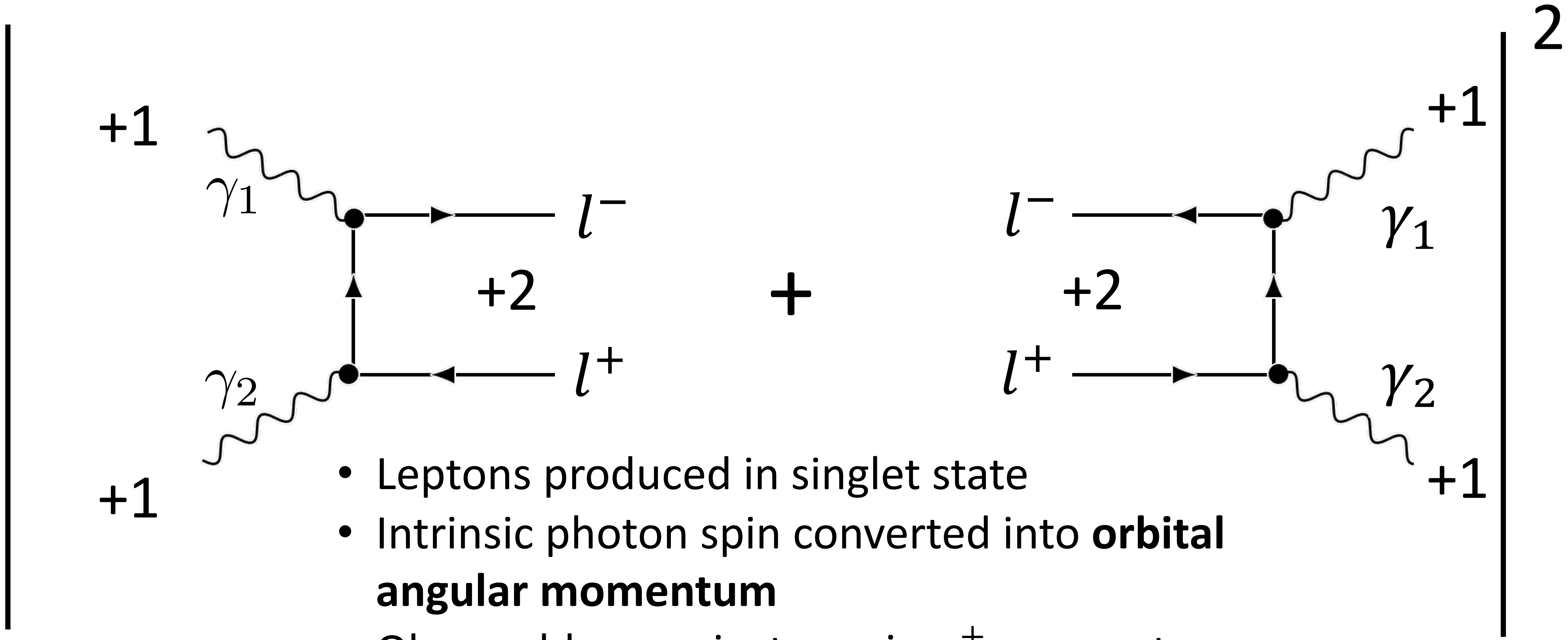
Experimental access to photon polarization demonstrated

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

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

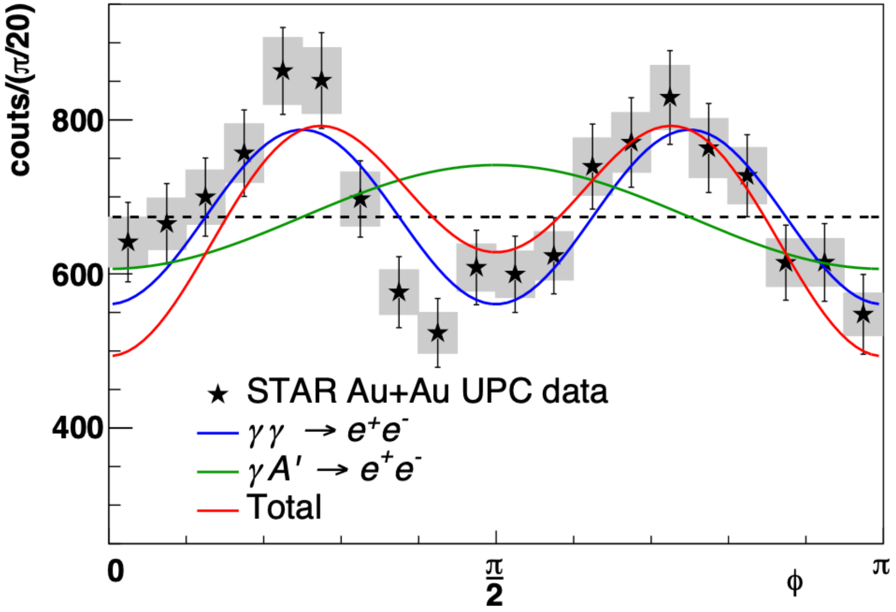
Signature of Polarization

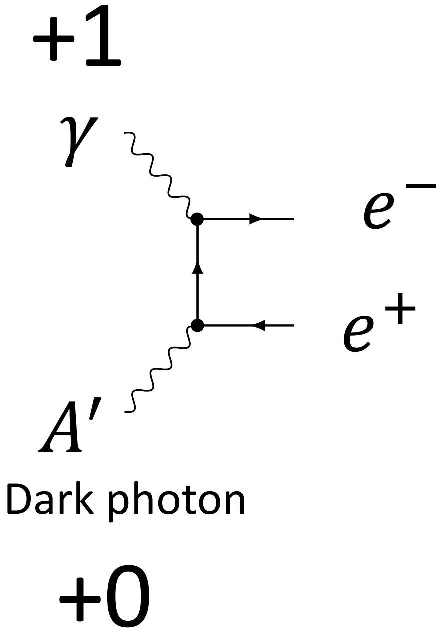


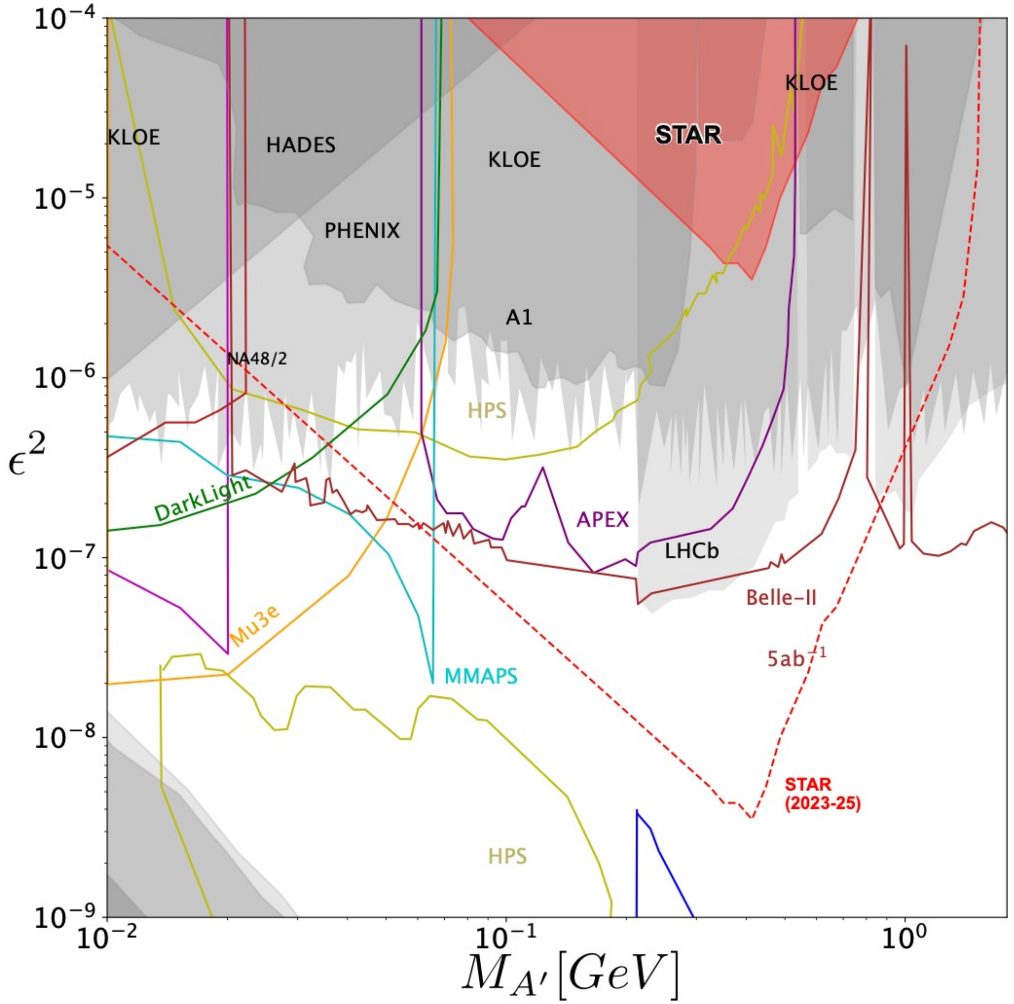
- Leptons produced in singlet state
- Intrinsic photon spin converted into **orbital angular momentum**
- Observable as anisotropy in $e^{\pm}$ momentum

Applications of $\gamma\gamma \to l^+l^-$

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

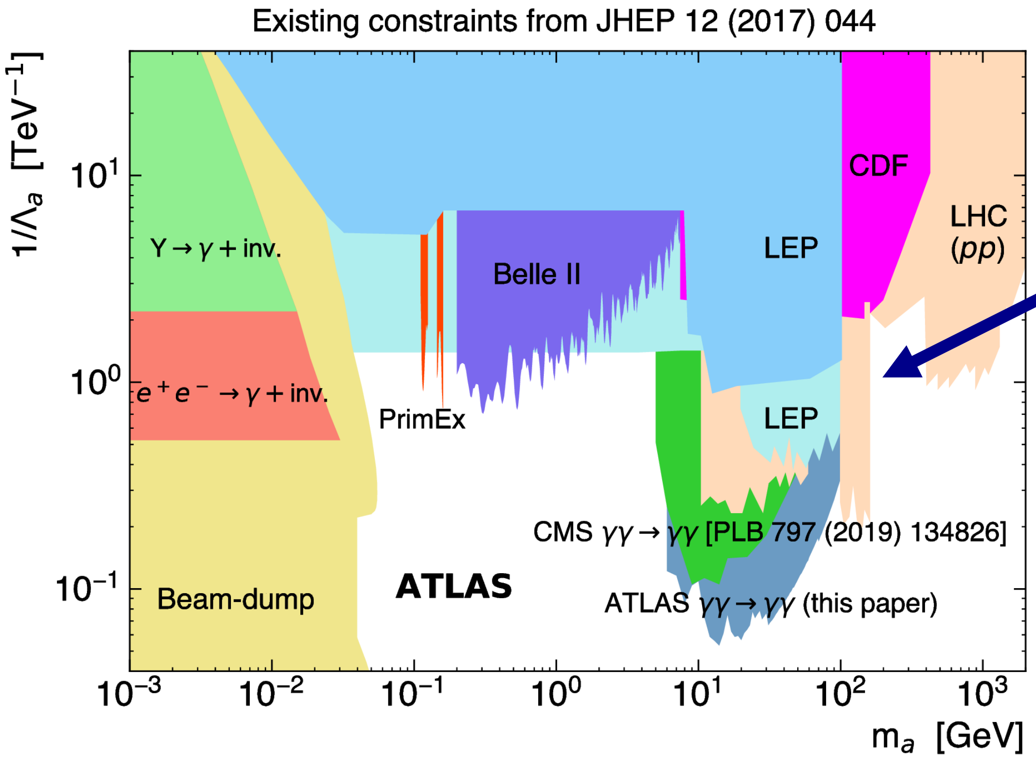
Relevant for LHC Axion search in Light-by-Light scattering

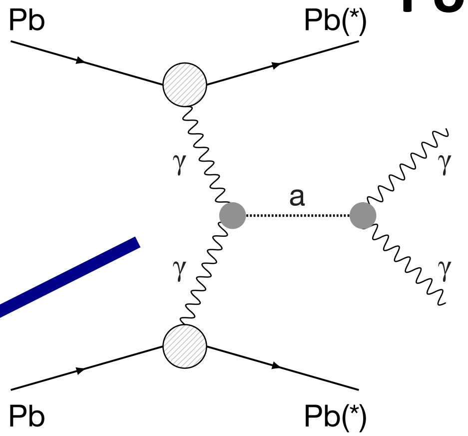
JDB, W. Zha, and Z. Xu, Eur. Phys. J. A 57, 299 (2021)

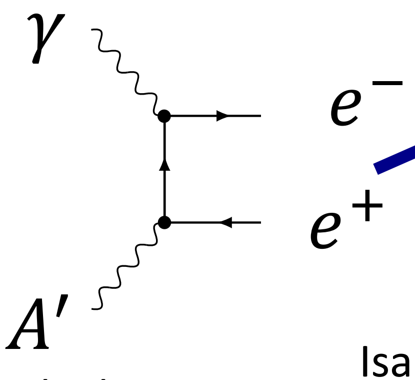
PAST Discoveries→Novel Tests of BSM Physics

▷Discoveries become tools to study new physics

Axion search in Light-by-Light Scattering

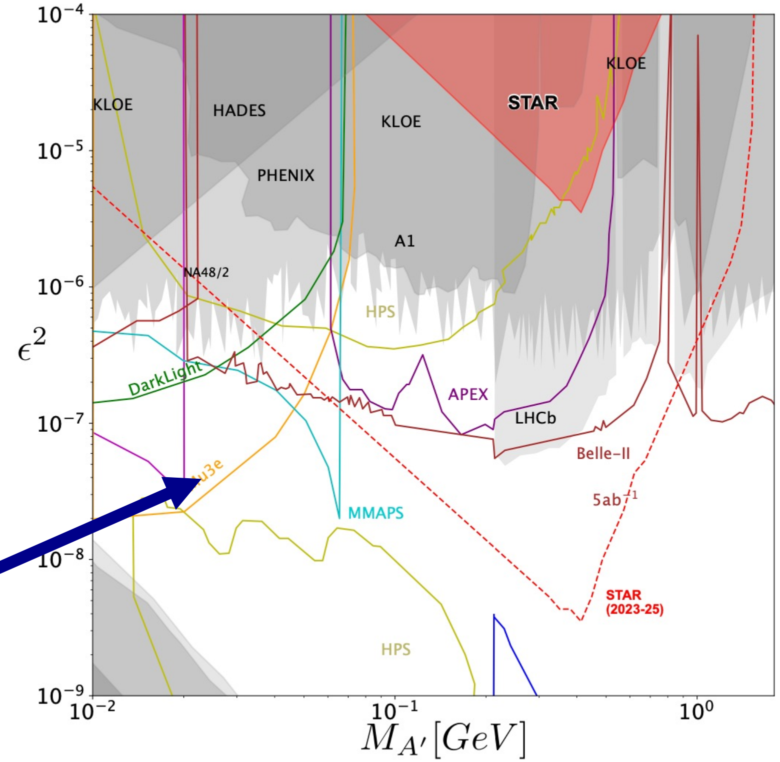






Dark photon

Dark Photon search with Polarized Breit-Wheeler Process



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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

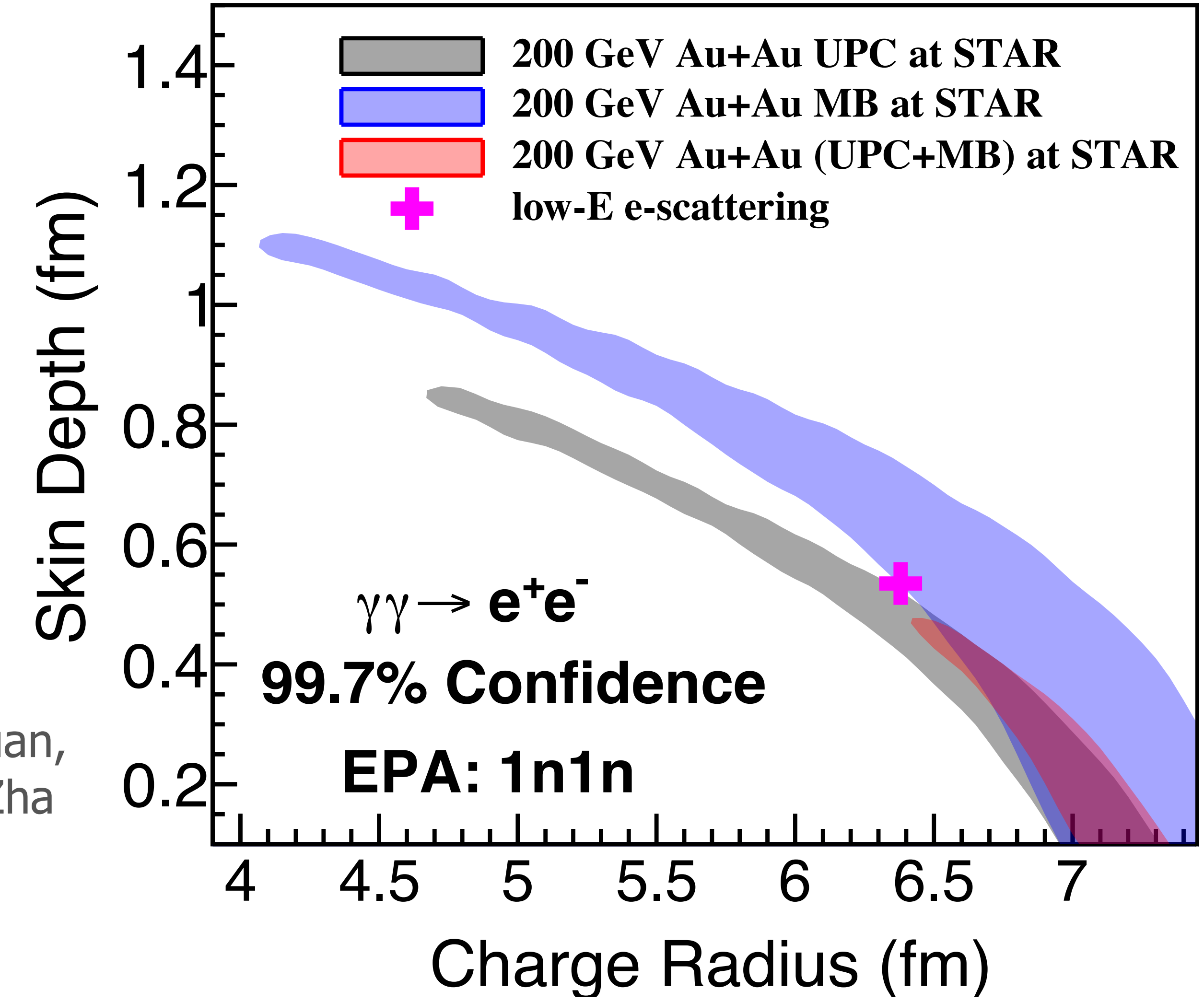
Low energy scattering: R=6.38 fm, d=0.535 fm
R. C. Barrett and D. F. Jackson, Nuclear Sizes and Structure (Oxford University Press, 1977)

- 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)

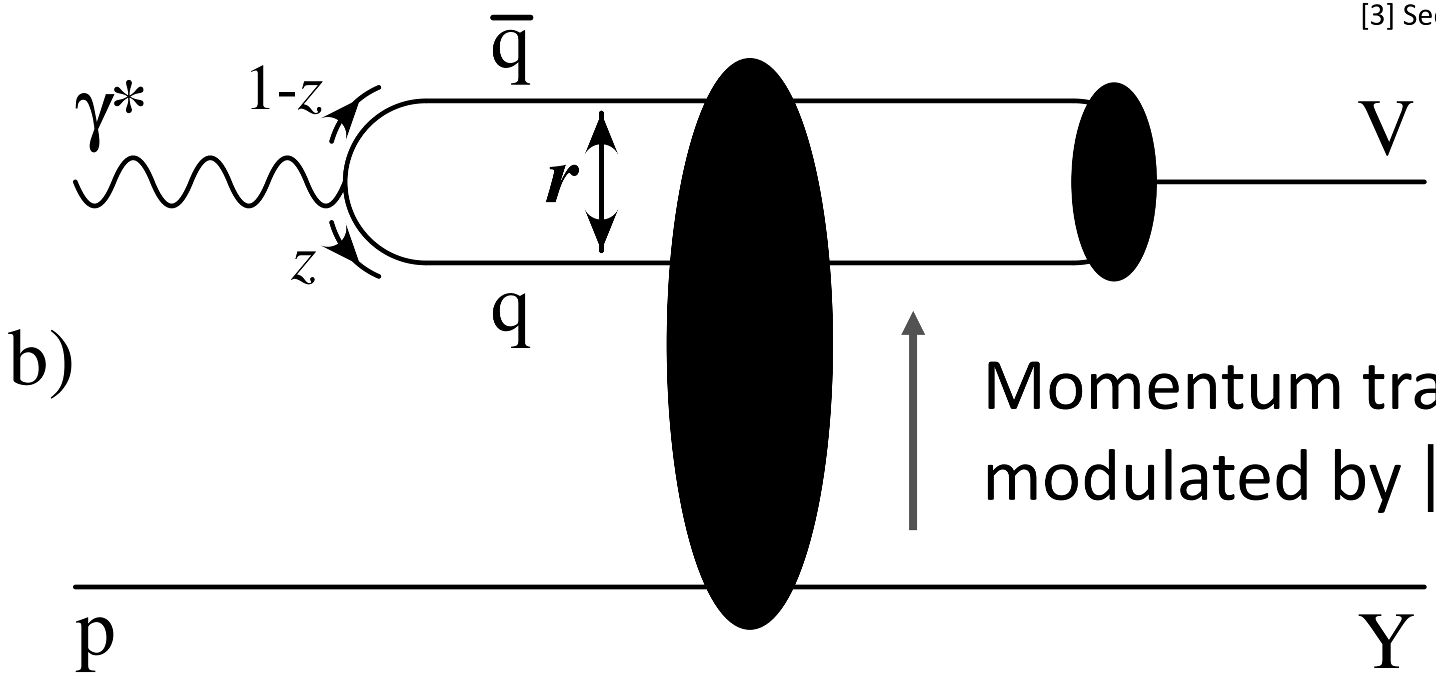
- NEW work looking at U+U, O+O, and Pb+Pb coming soon



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]



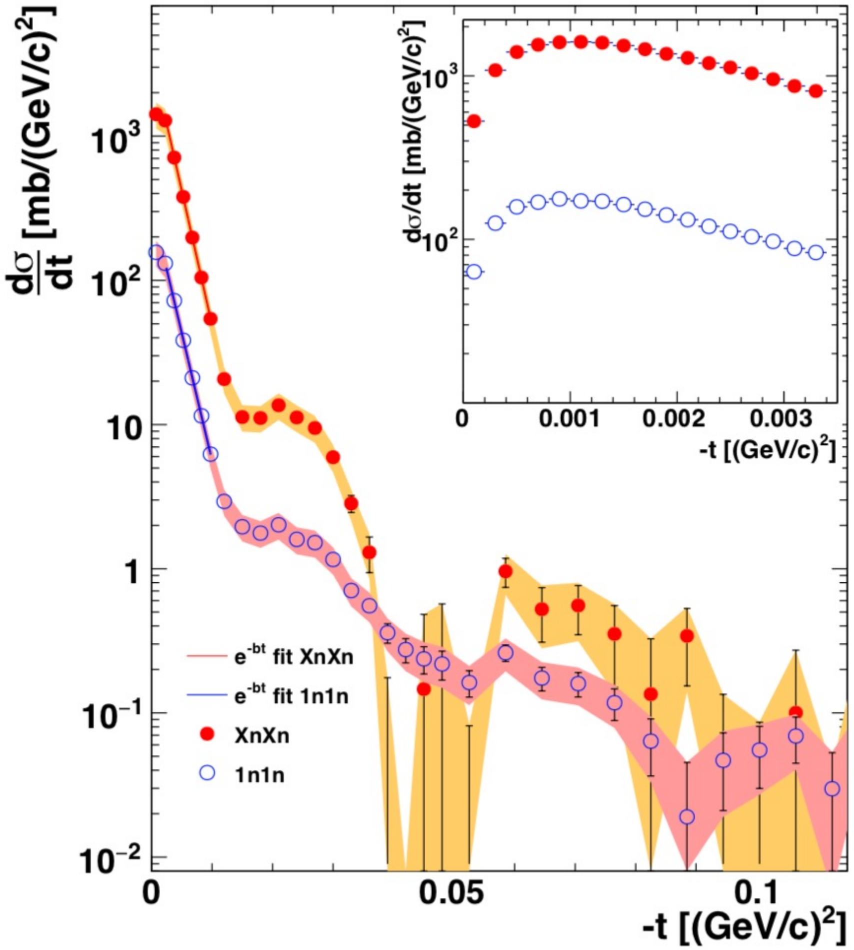
Vector Meson ('heavy photon')

Momentum transfer (t) modulated by $|F(t)|^2$

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

Past Photo-Nuclear Measurements

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



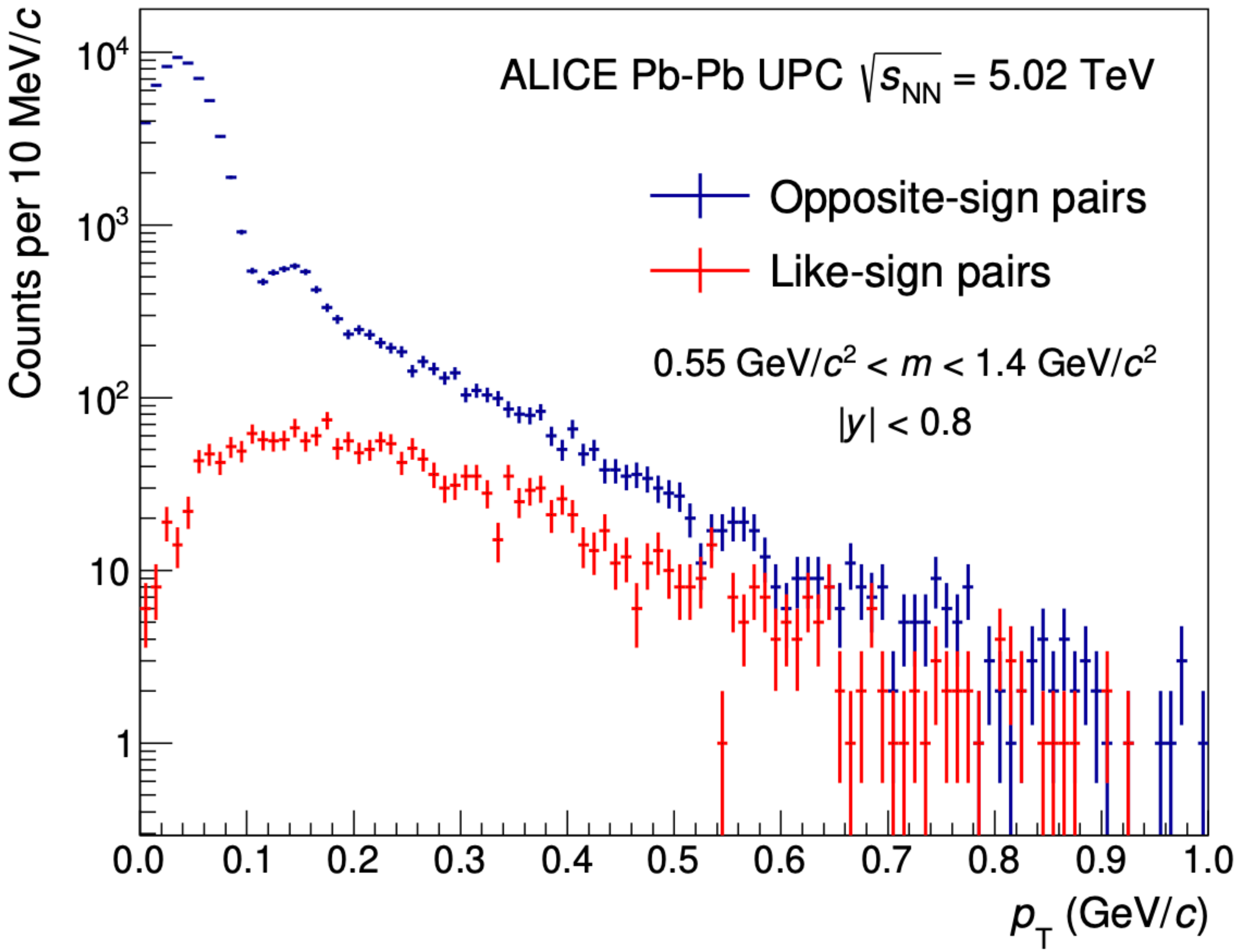
Coherent Diffractive Interactions:

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

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

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?

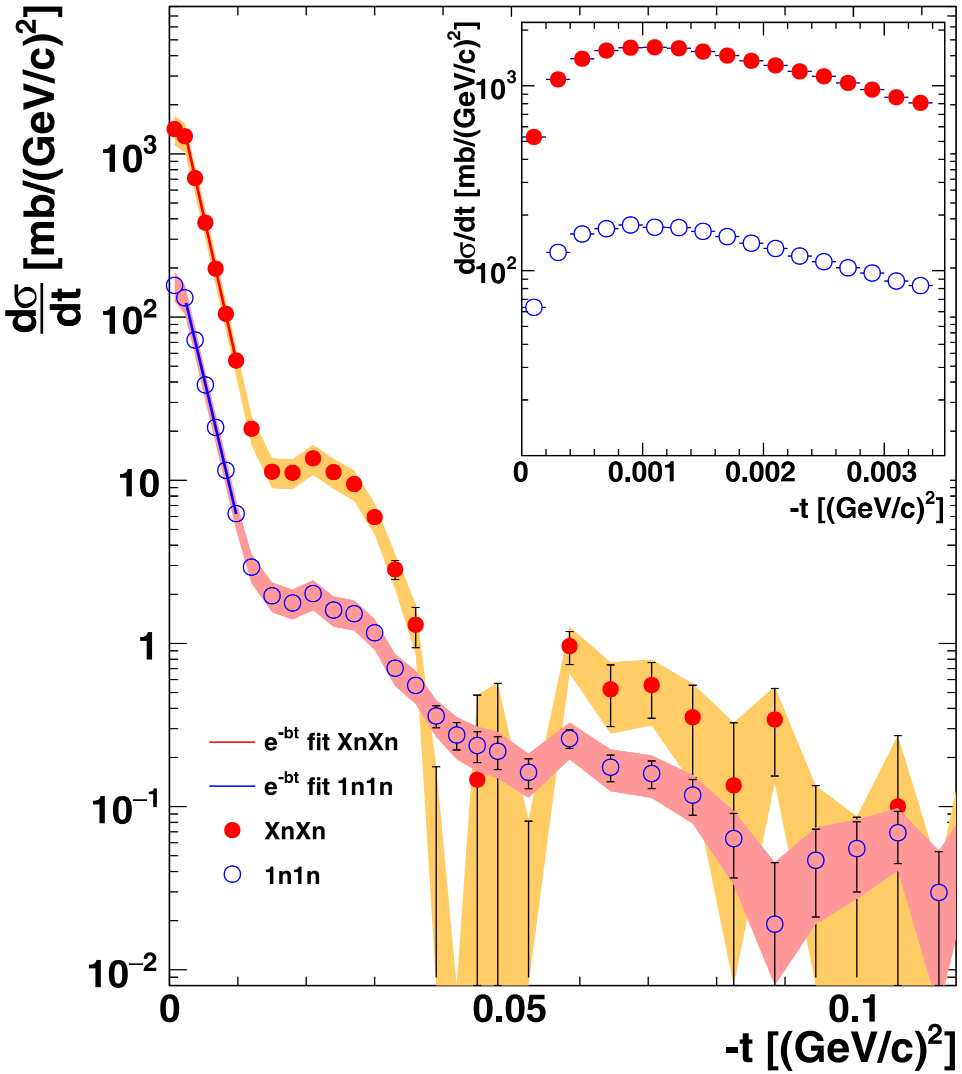


Photo-nuclear measurements have historically produced a |t| slope that corresponds to a **mysteriously large source!**

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 = $426 \pm 6 \pm 15\ (GeV/c)^{-2}$

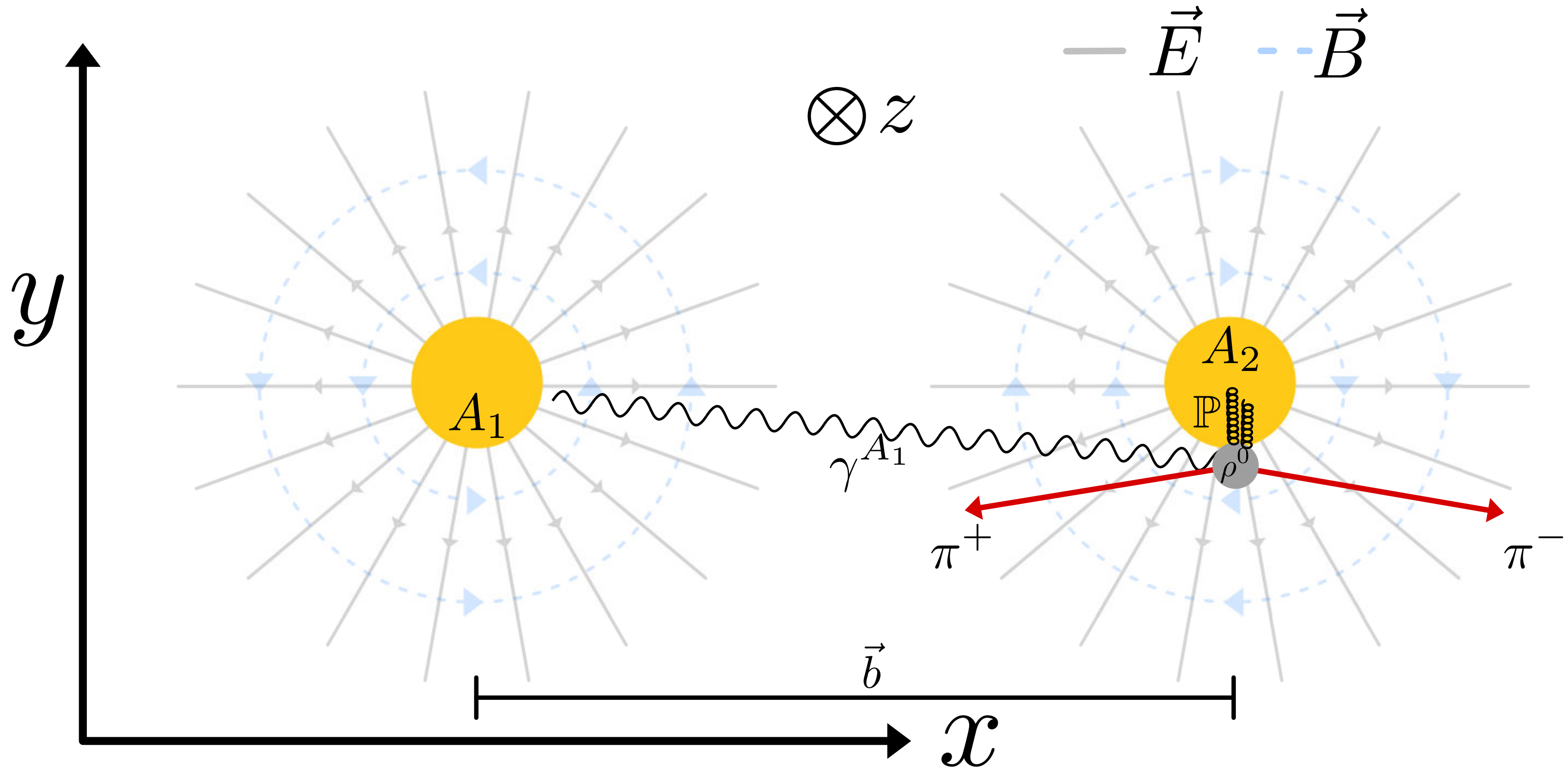
→ Effective radius of 8.1 fm

($R_{Pb}^{charged} \approx$ 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.

What is NEW with transversely polarized photons?



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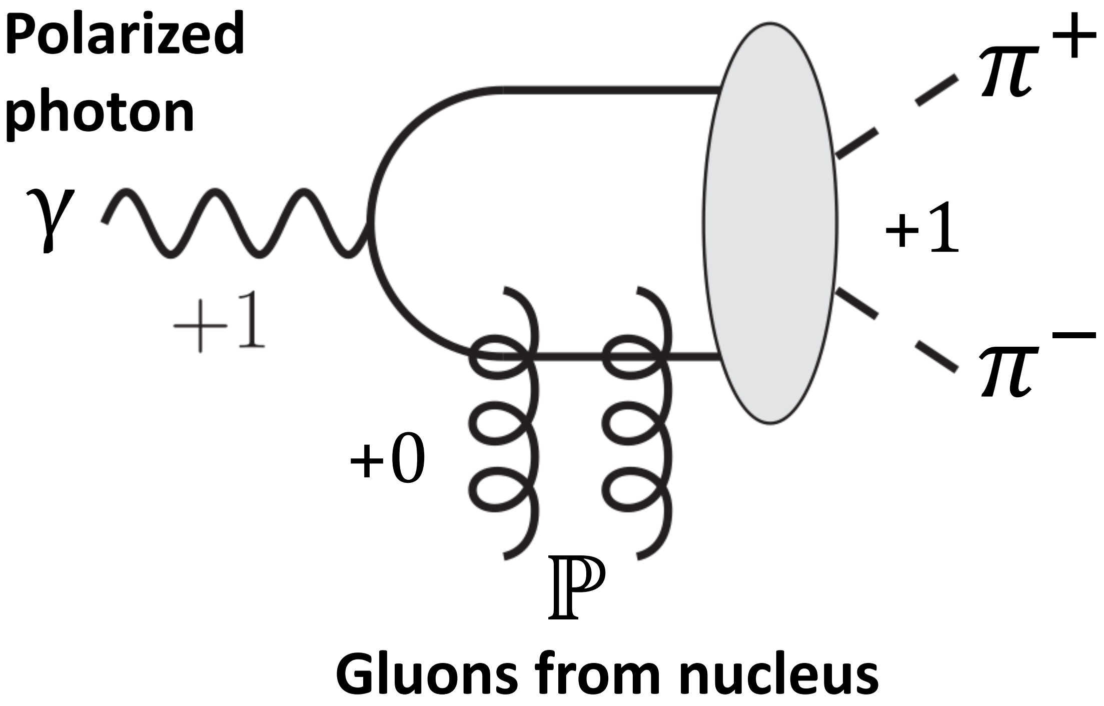
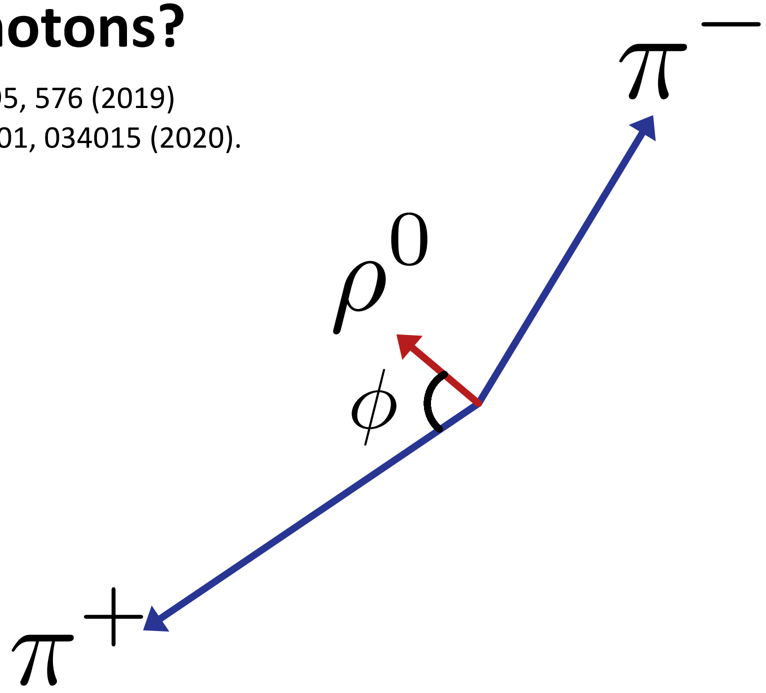
C. Li, J. Zhou & Y. Zhou Phys. Rev. D 101, 034015 (2020).





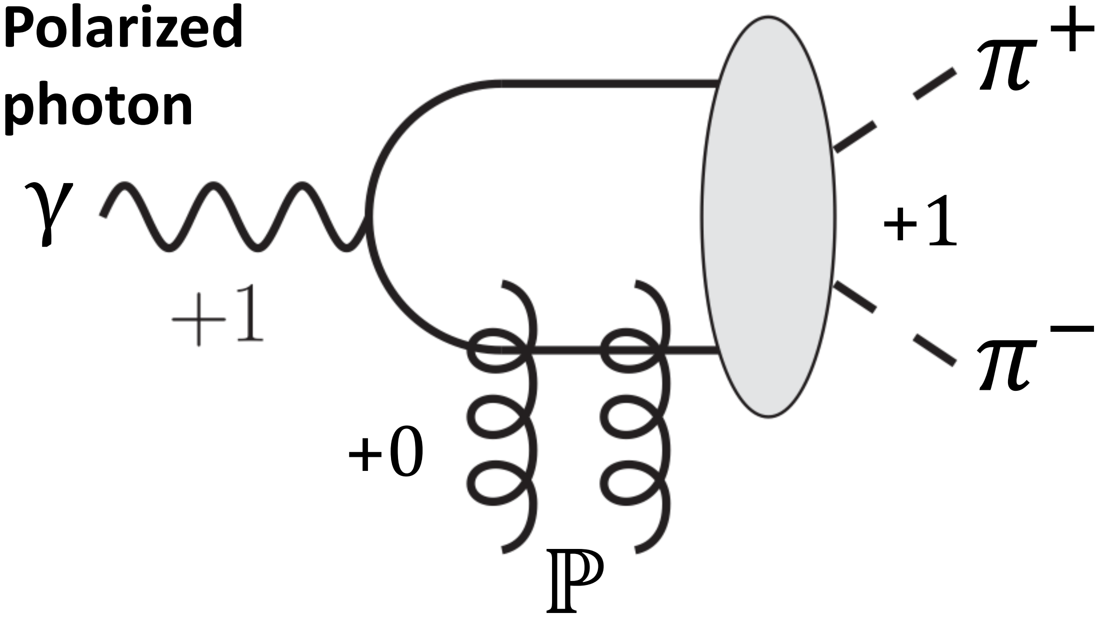
Recently realized that asymmetries in angle ϕ related to polarization

Access to initial photon polarization

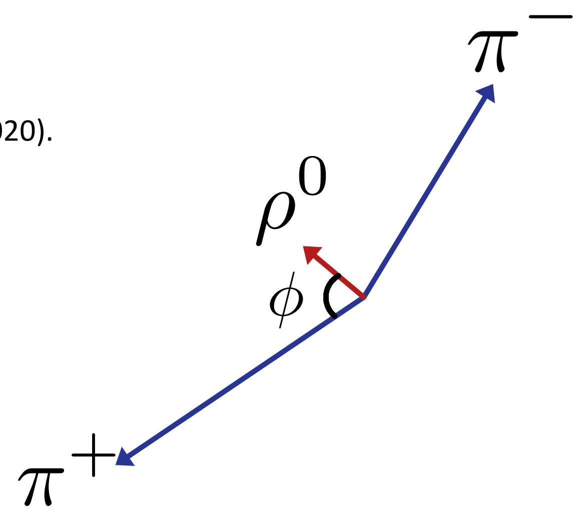
What is NEW with transversely polarized photons?

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

Polarized photon



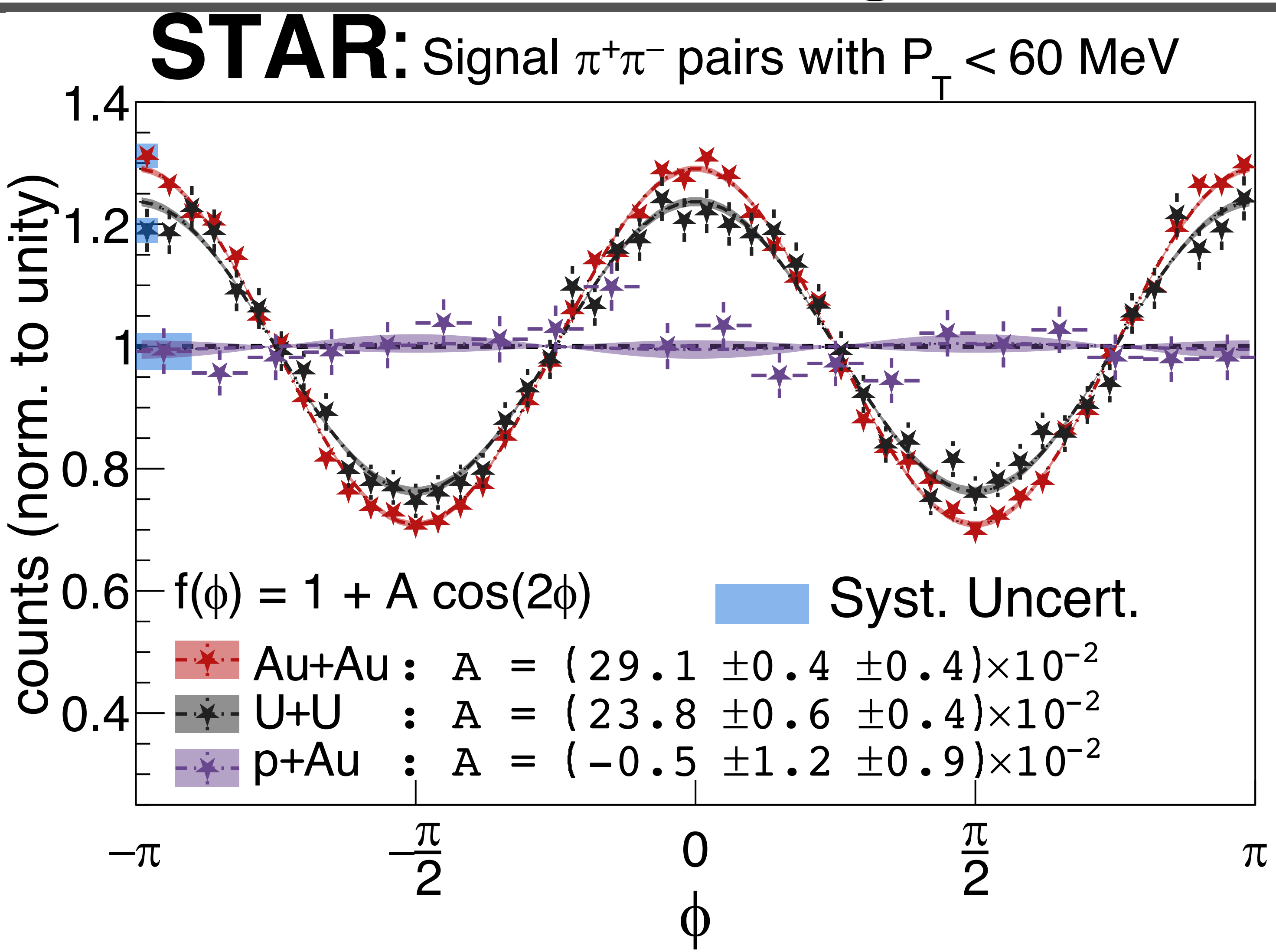
Gluons from nucleus

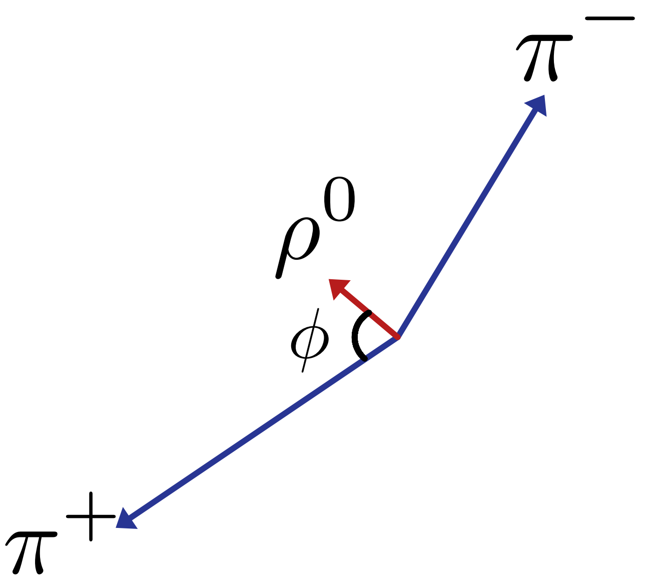


- Intrinsic photon spin transferred to ρ^0
- ρ^0 spin converted into **orbital angular momentum** between pions
- Observable as anisotropy in $\pi^\pm$ momentum

Access to initial photon polarization

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





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STAR Collaboration, Sci. Adv. **9**, eabq3903 (2023).
H. Xing, C. Zhang, J. Zhou and Y. J. Zhou, JHEP 10(2020), 064.

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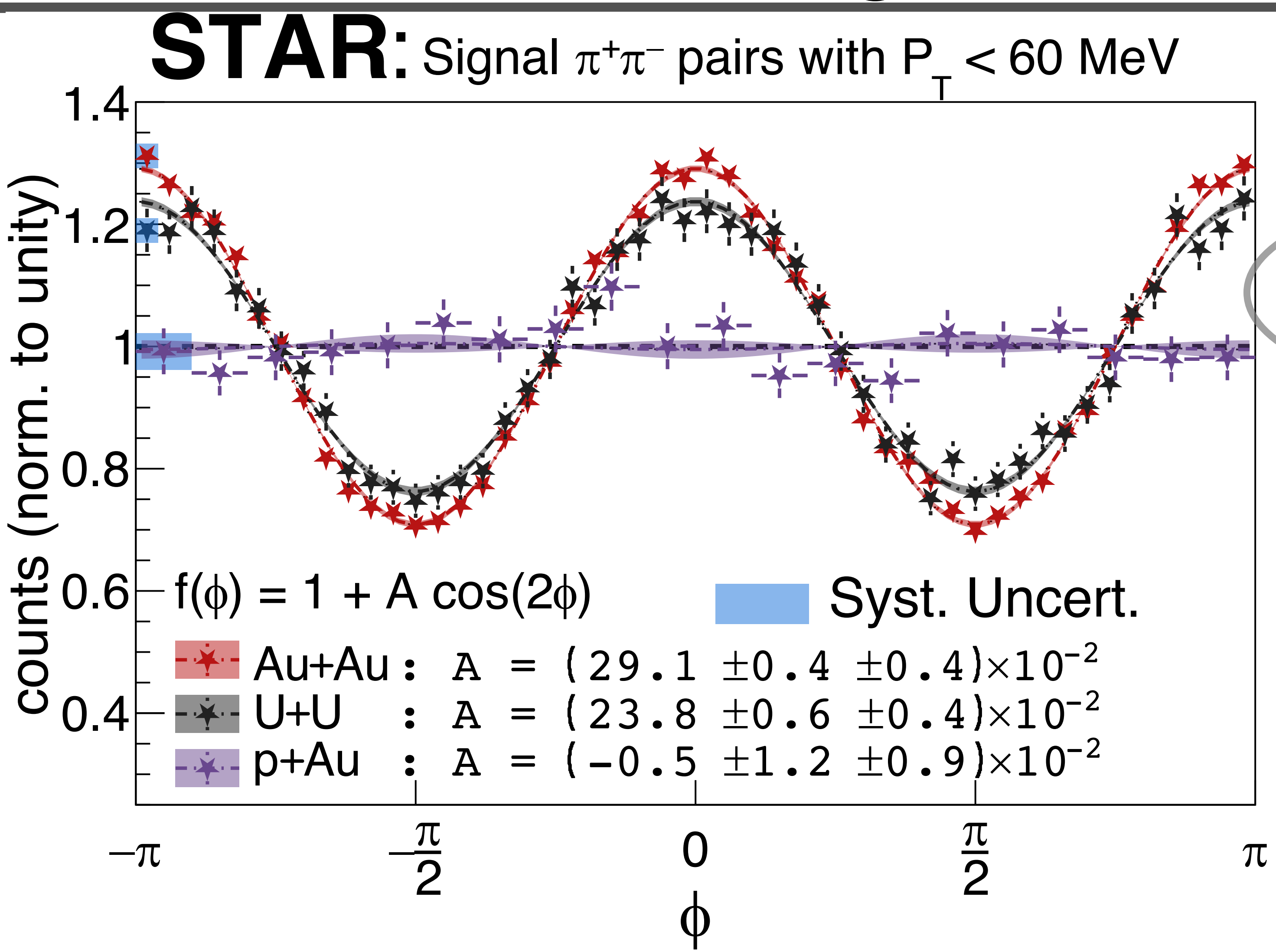

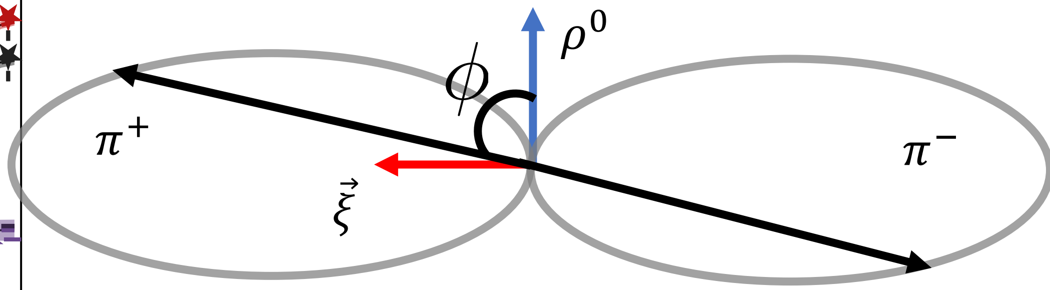

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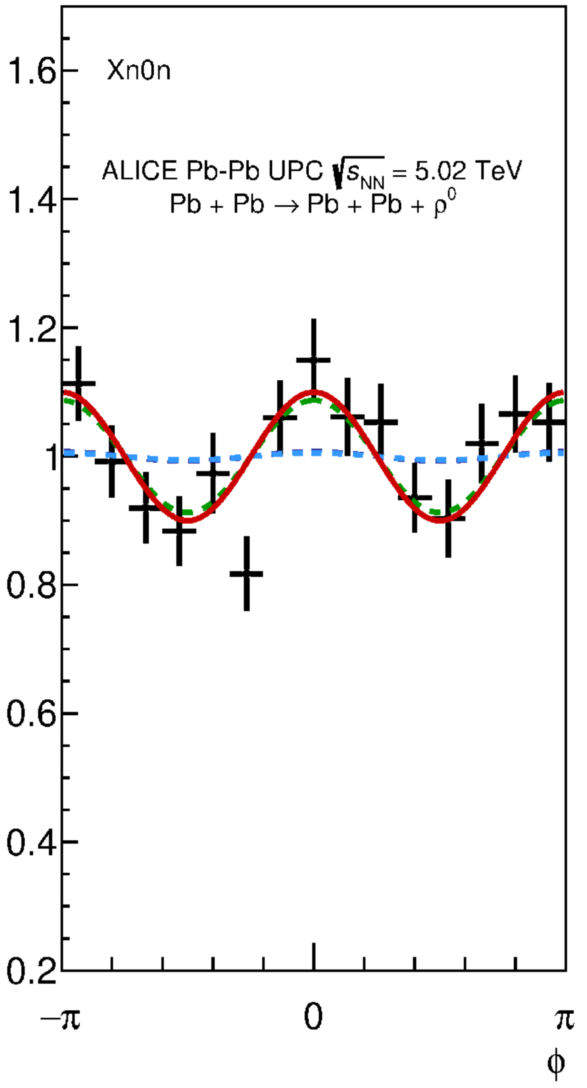
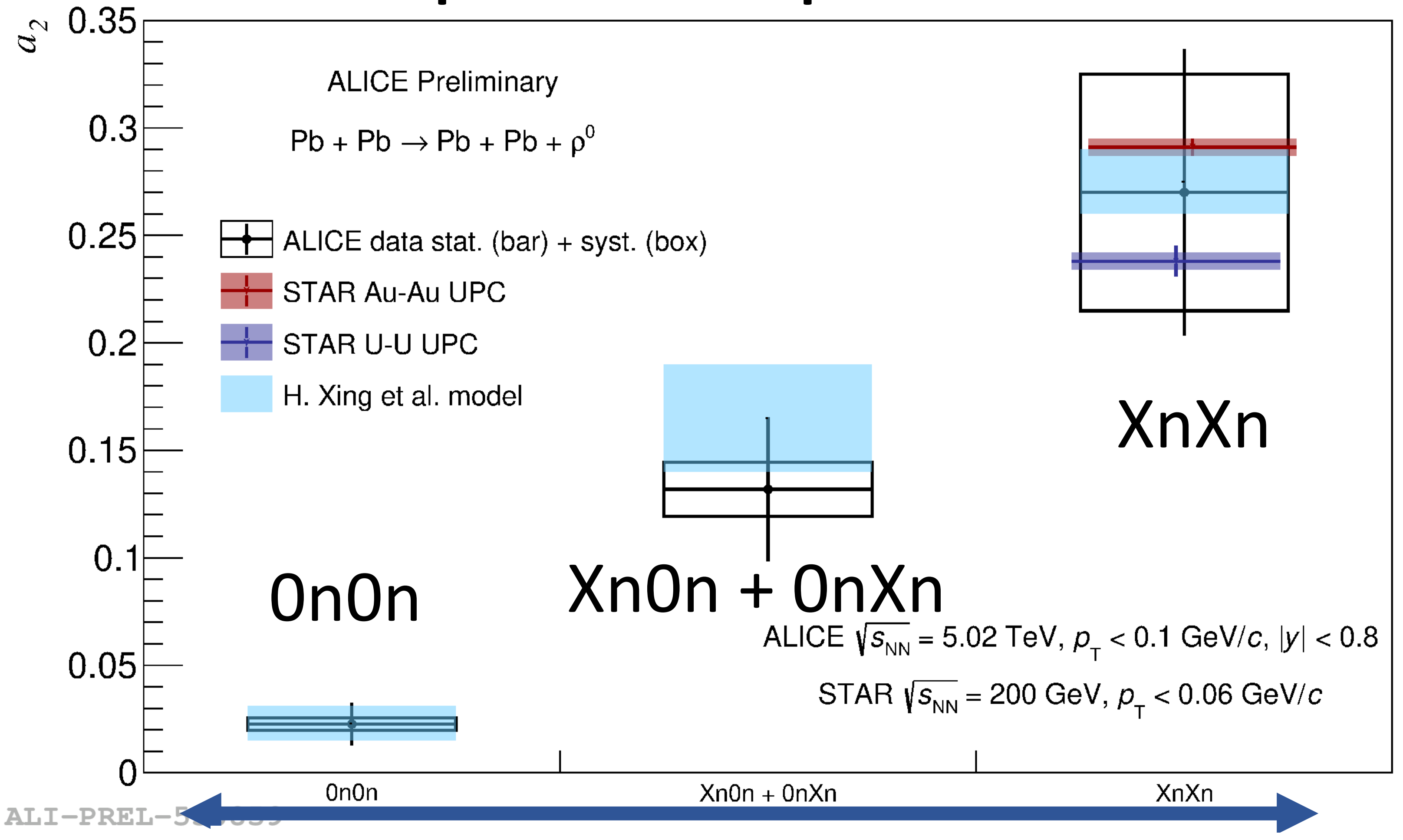
H. Xing, C. Zhang, J. Zhou and Y. J. Zhou, JHEP 10(2020), 064.

Confirmation from ALICE

Andrea Riffero (ALICE)



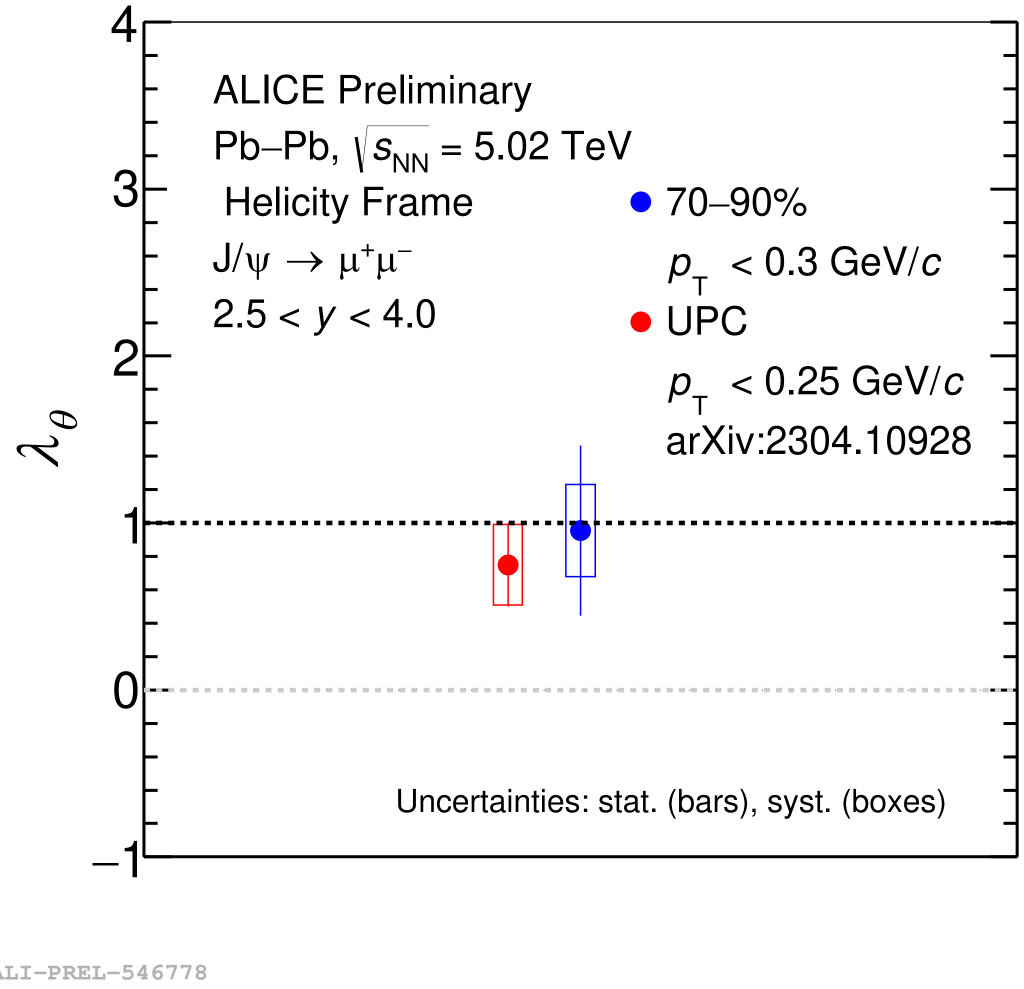
Neutron emission categories test the impact parameter dependence



Large b **Small b**

Polarization effects: coherent diffractive J/ψ

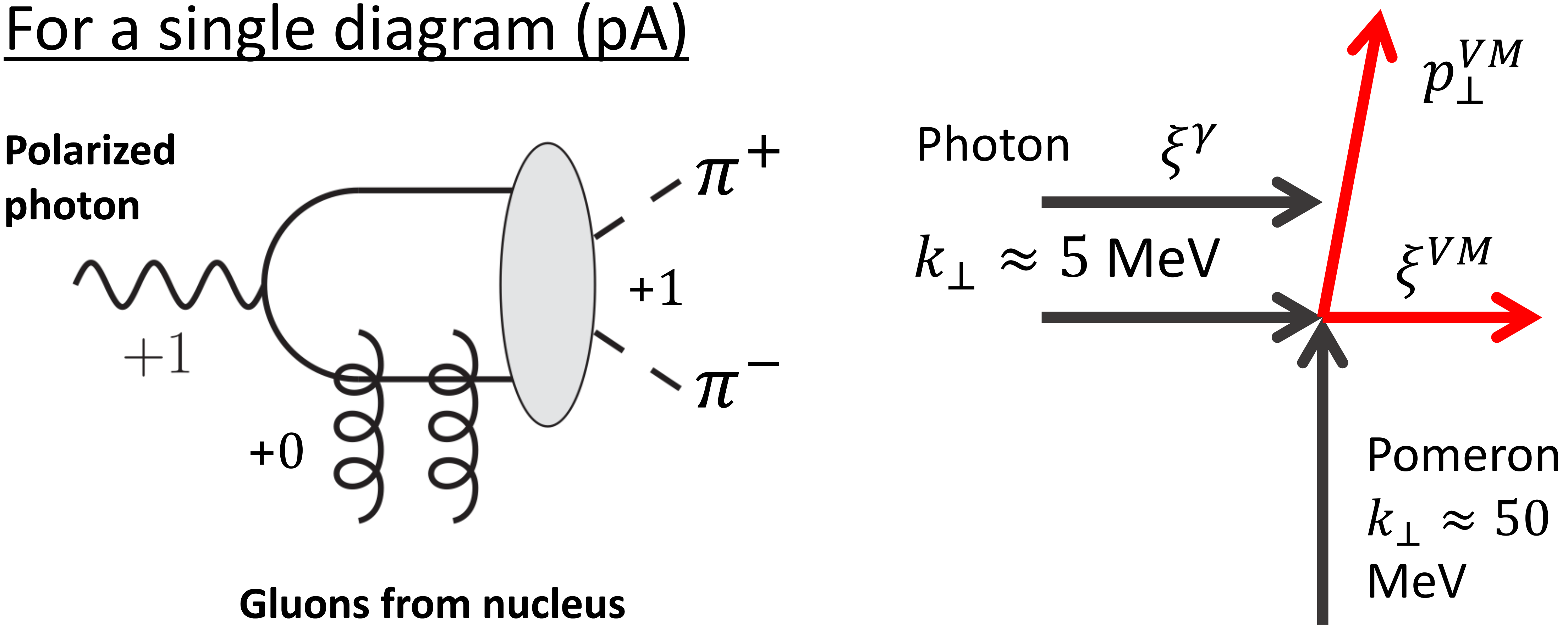
- ALICE measurement of spin density matrix elements of J/ψ
- Spin alignment found at forward rapidity
- Consistent with transverse polarized J/ψ



Afnan Shatat (ALICE)

Trivial Spin-Momentum Alignment?

For a single diagram (pA)

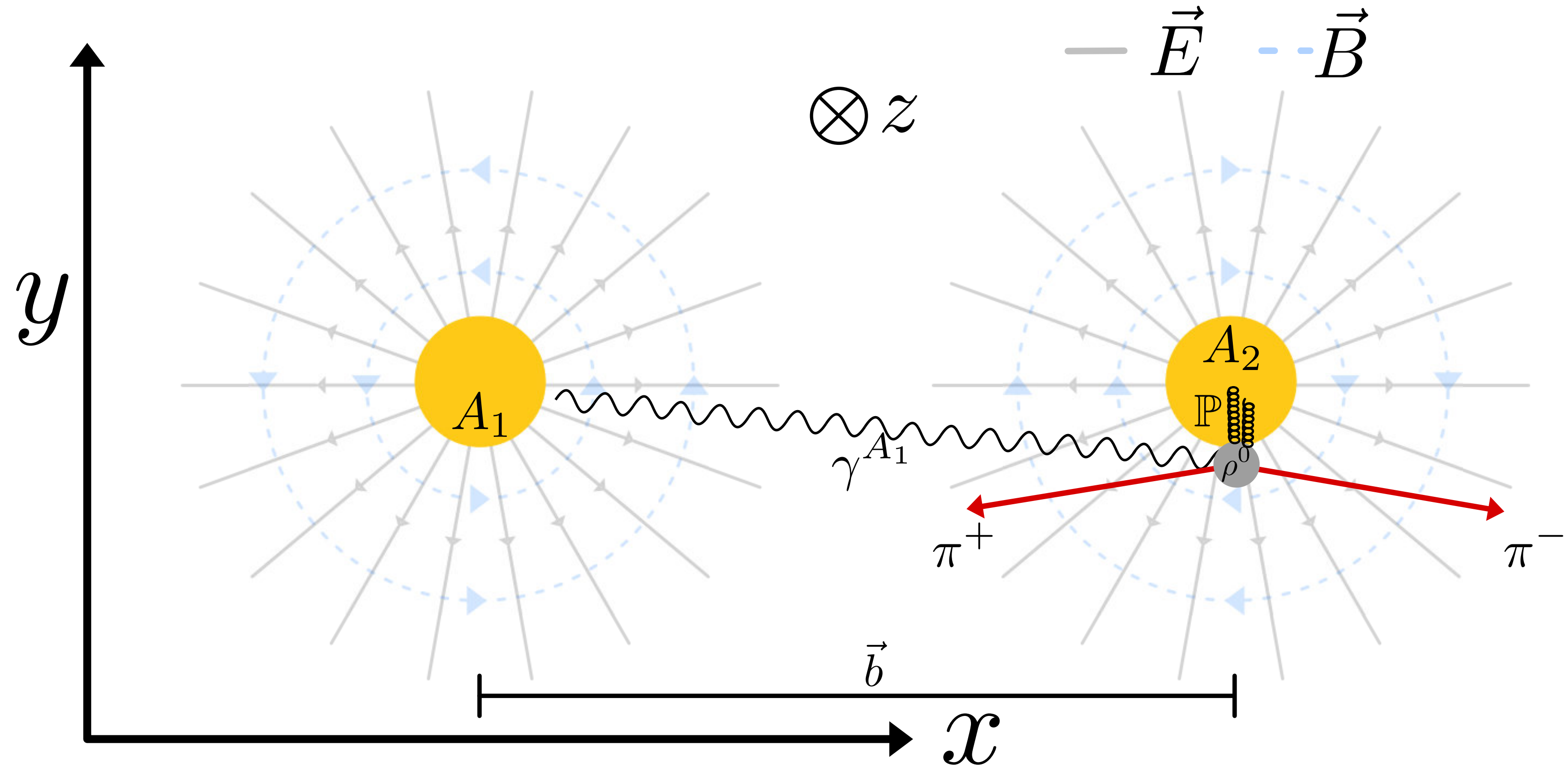


VM inherits the spin from photon (no helicity flip)

Diffractive -> VM momentum dominantly from the Pomeron

→ VM has no alignment between spin and momentum

What is NEW with transversely polarized photons?



Imaging the Nucleus with Polarized Photons

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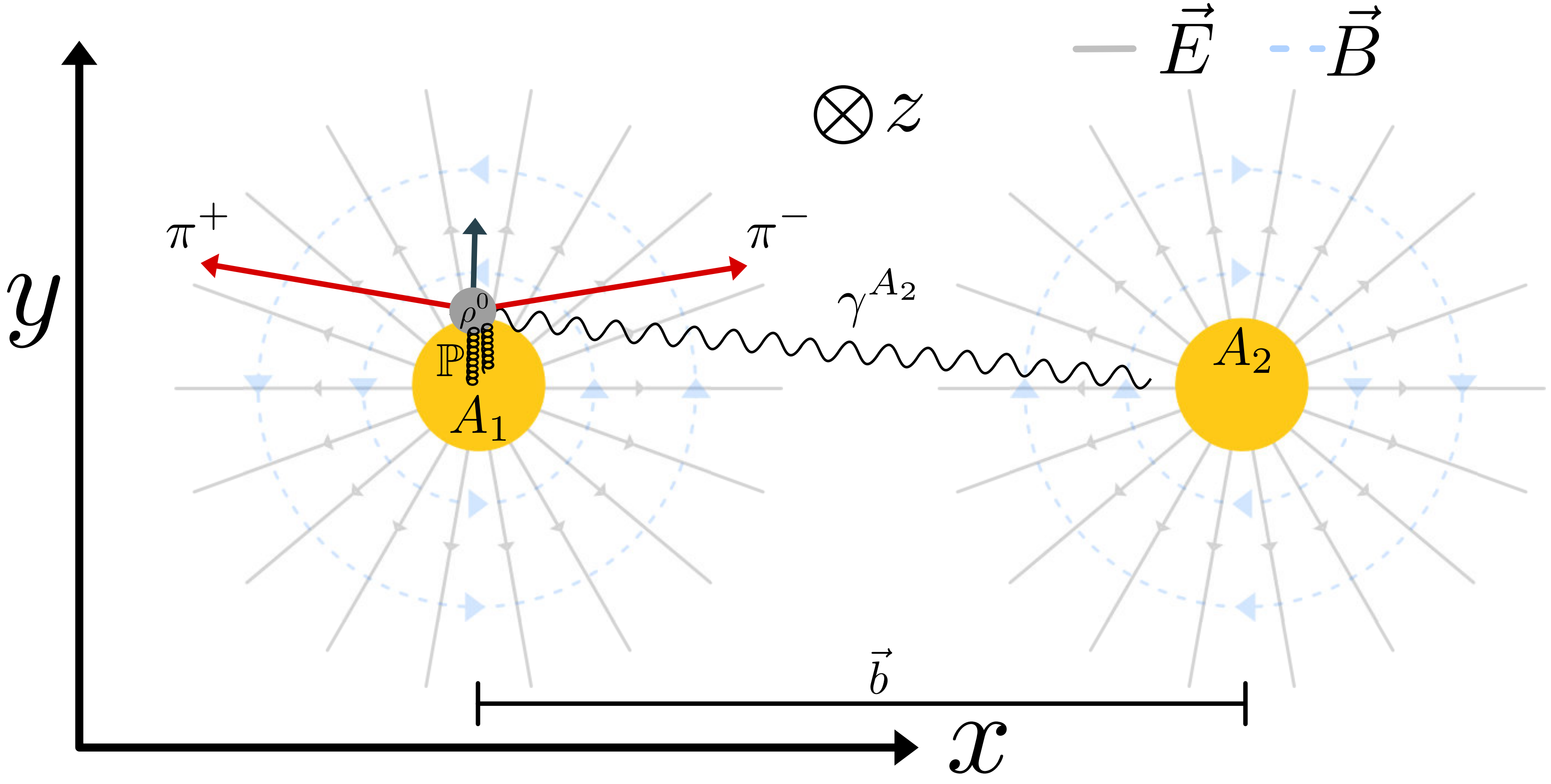

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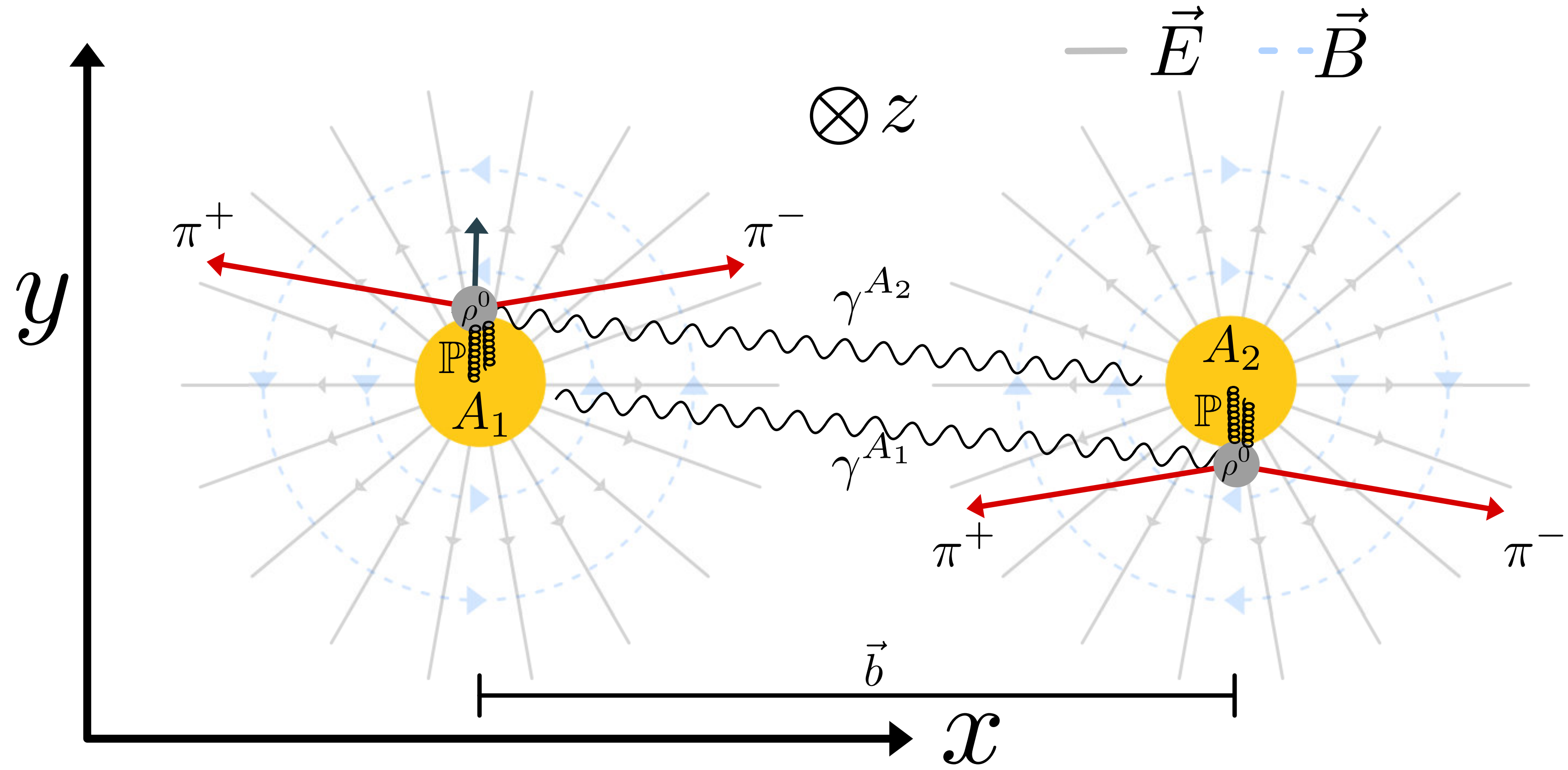
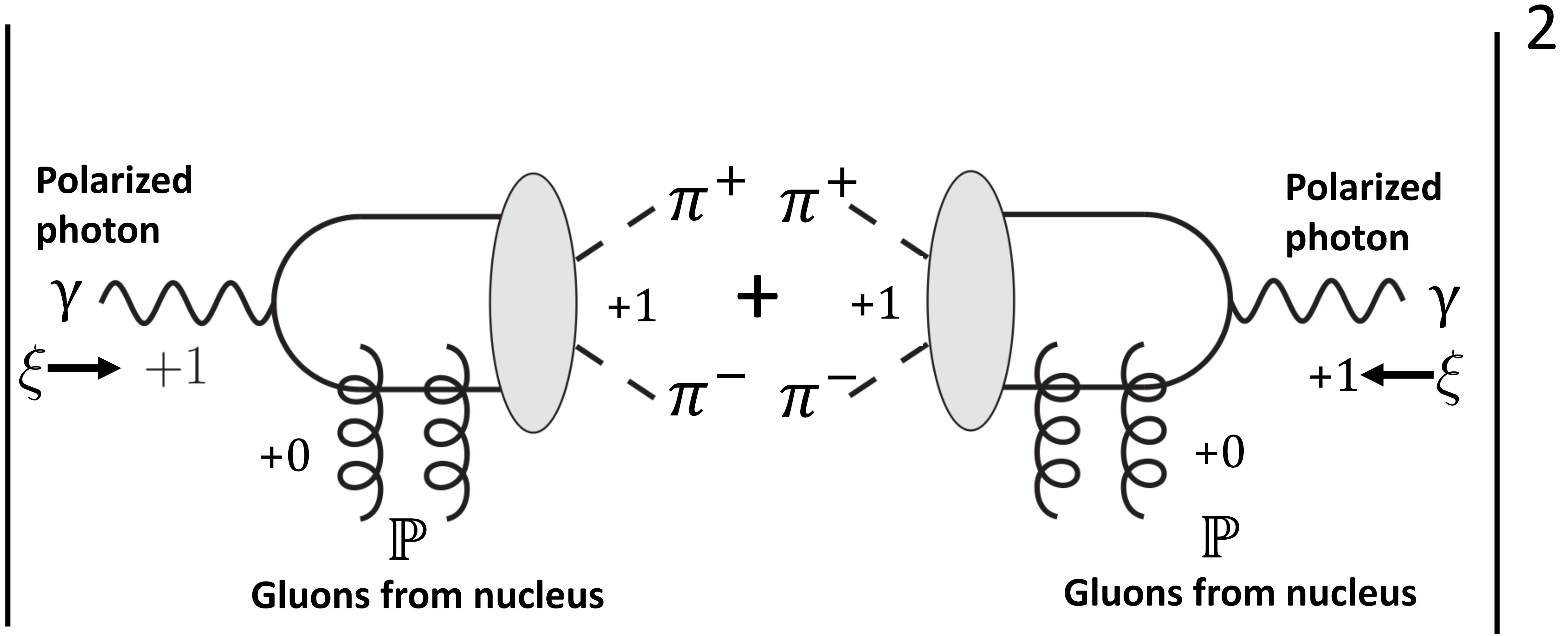


At Mid-rapidity: Both possibilities occur simultaneously

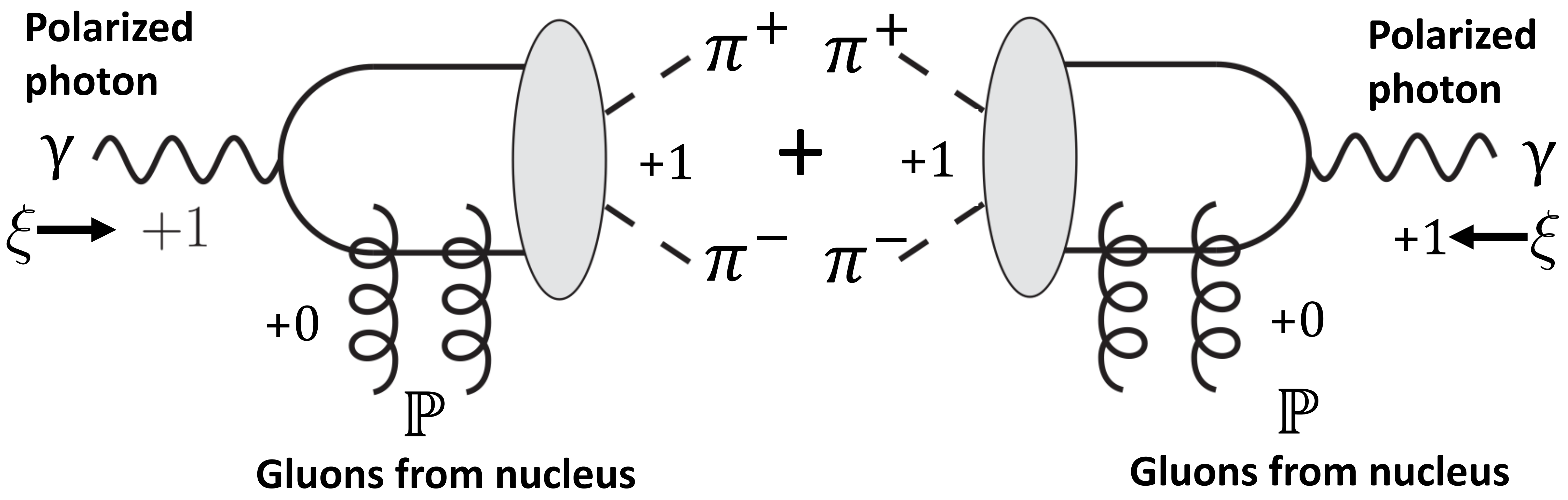
Interference of two amplitudes



Interference of two amplitudes

Cool trick, but sounds like standard Quantum Amplitude interference – So What!

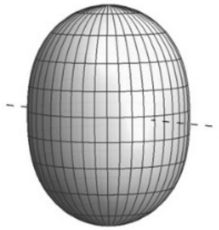
2



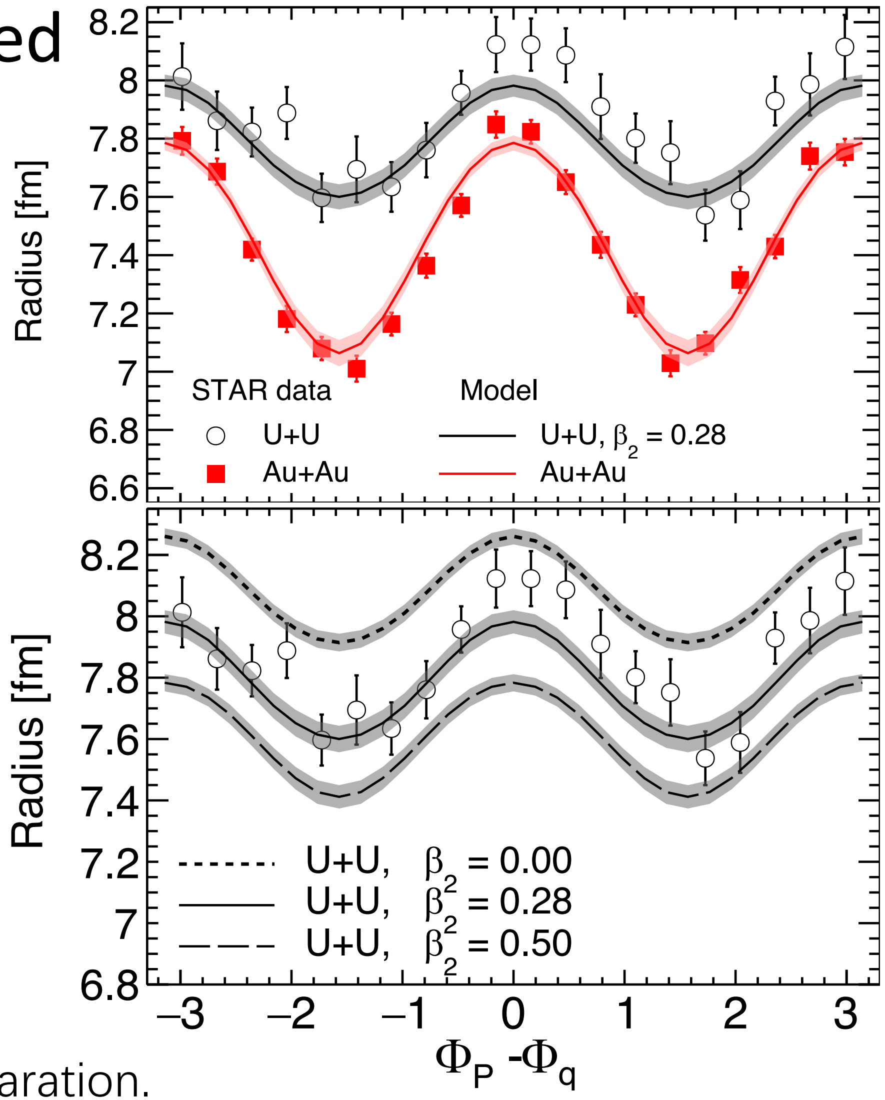
Robust Theoretical Description?

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

β_2

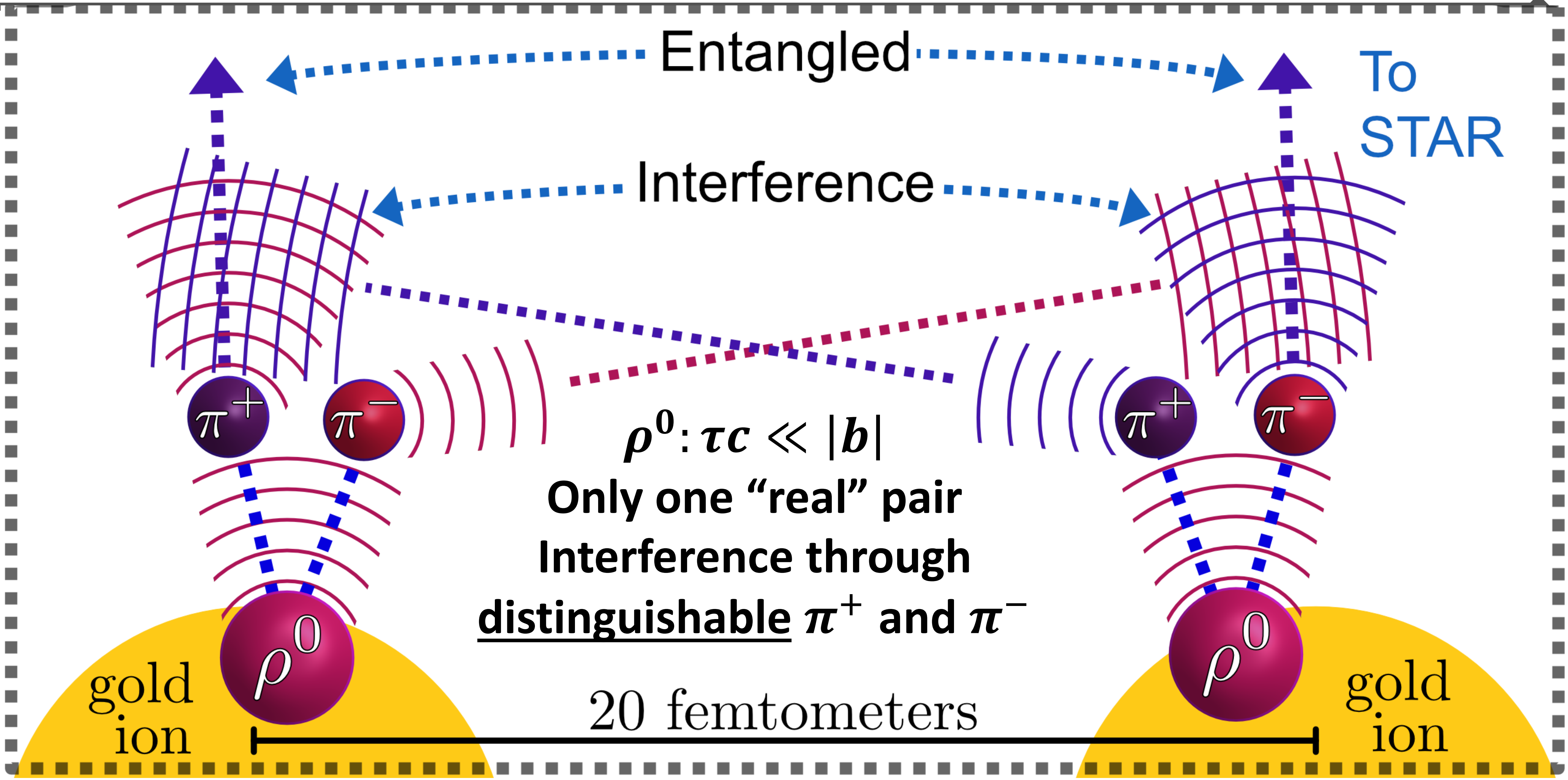


- 2D Tomography possible through Interference effect
- Also require very large U radius
- Assumes amplitude interference for coherent process



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

Interference of Amplitudes, so what!?



Intensity Interferometry

Credit: Albert Stebbins
Fermilab

Intensity interference:

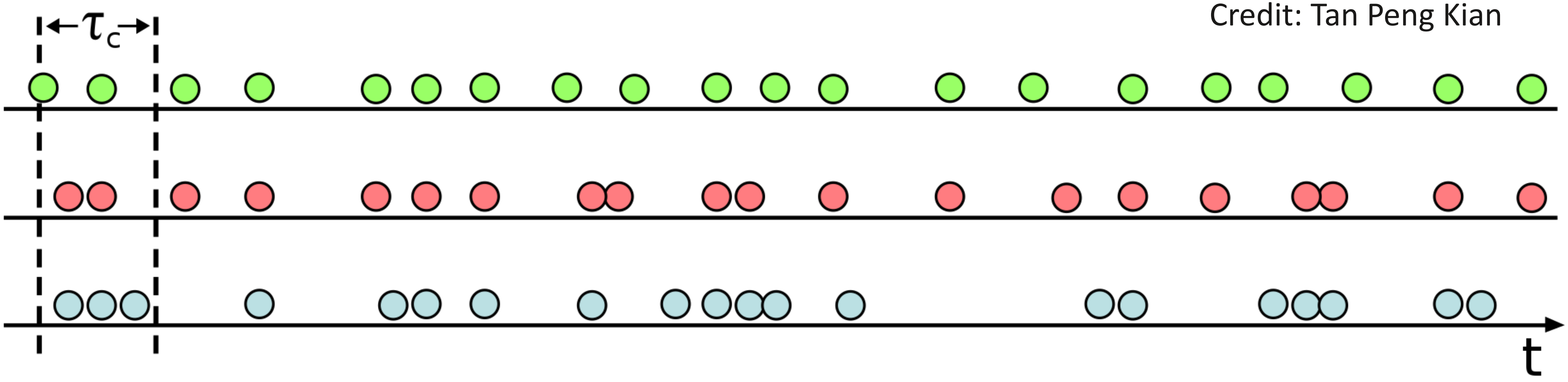
- **Two** photon measurement from **incoherent source**
- "image" encoded in transverse correlations
- Requires photons be **indistinguishable**

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

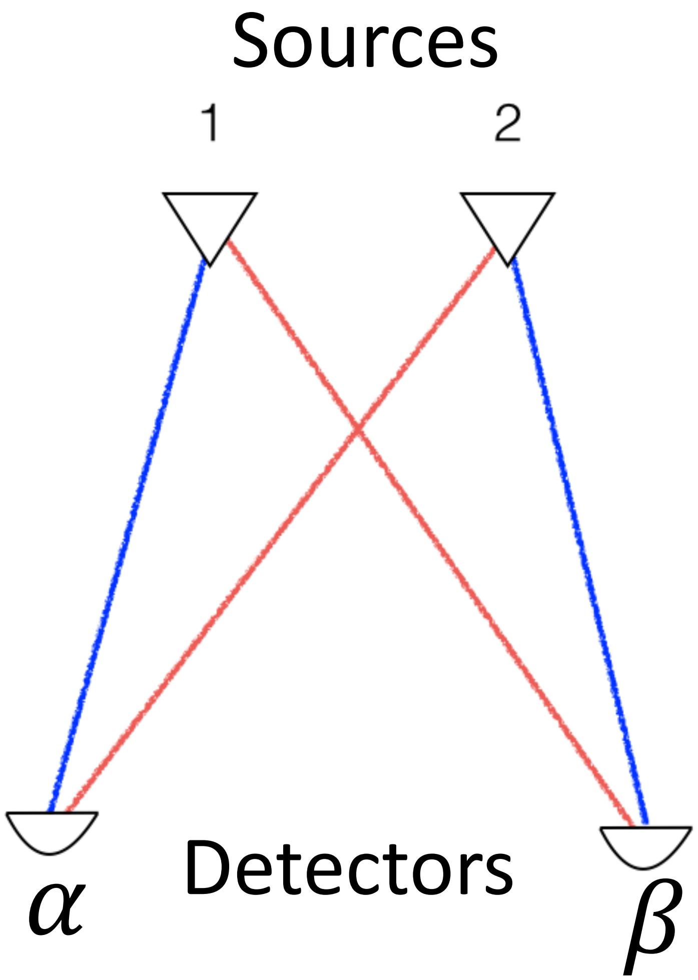
- Results from higher order coherence

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

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

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

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



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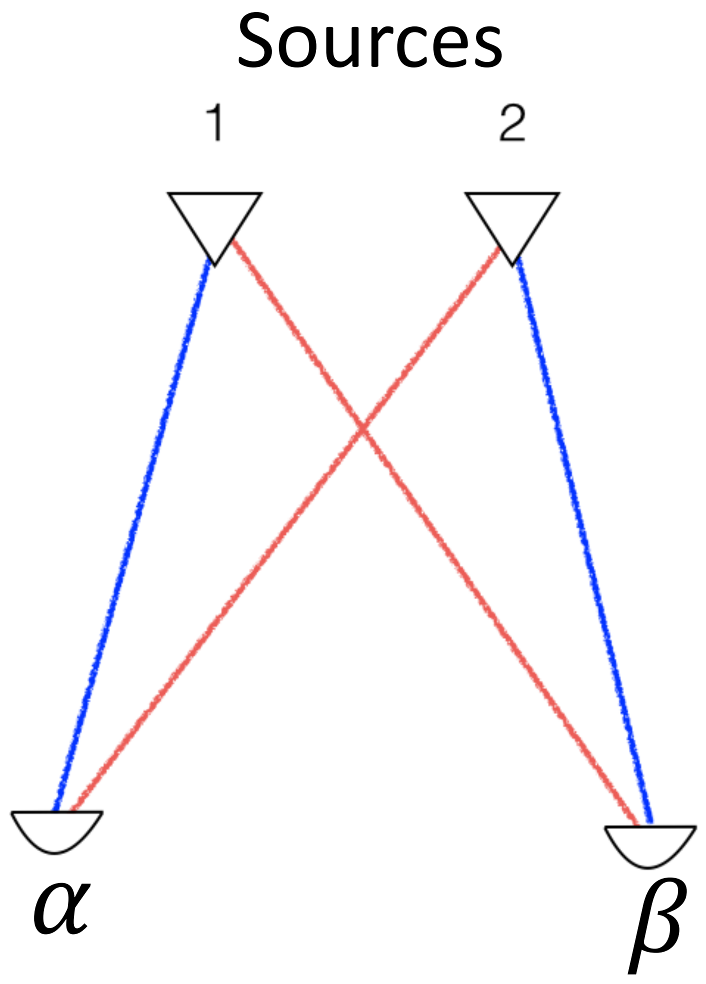
$$\langle A_{1\alpha}A^*_{1\beta}\rangle_E \neq 0$$

Requires indistinguishable states!

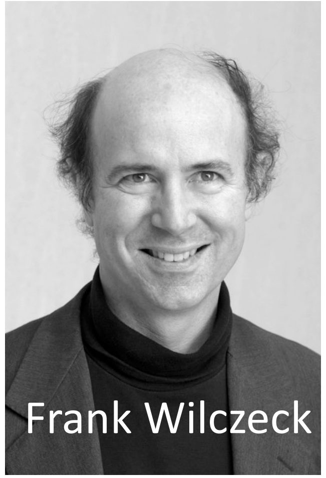


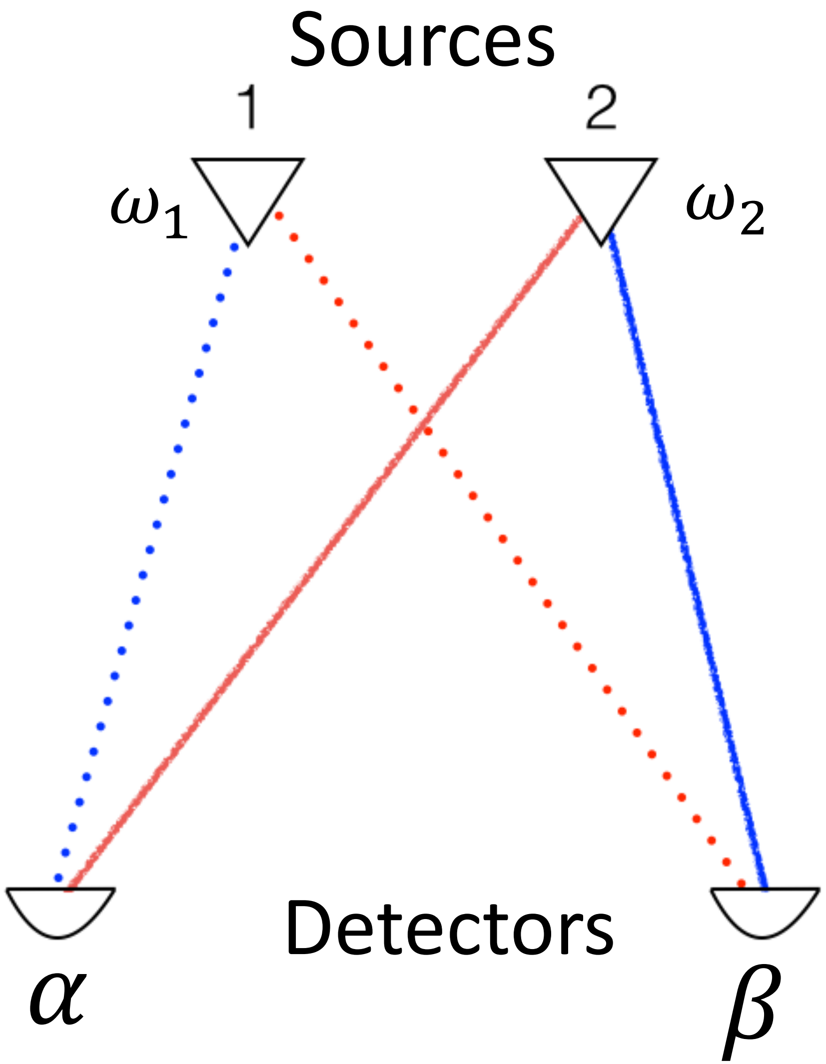
The Cotler-Wilczek Process

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

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

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:

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

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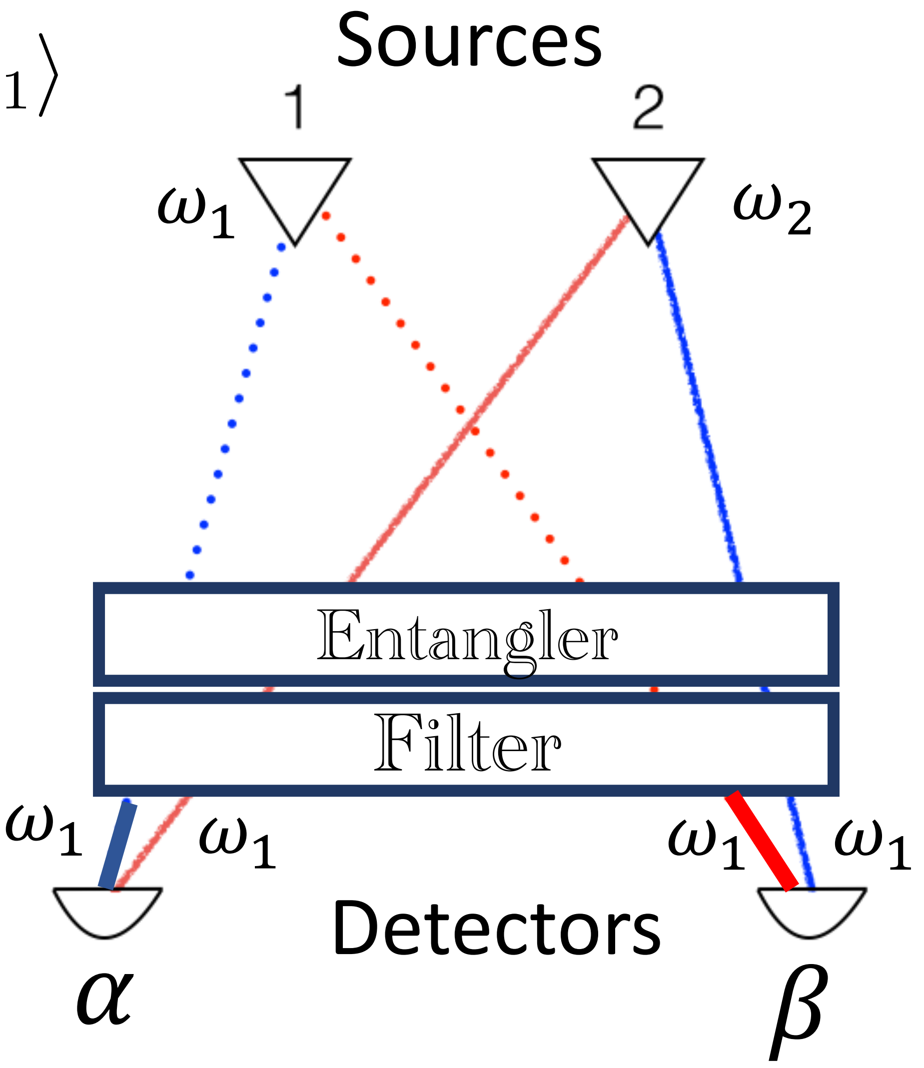

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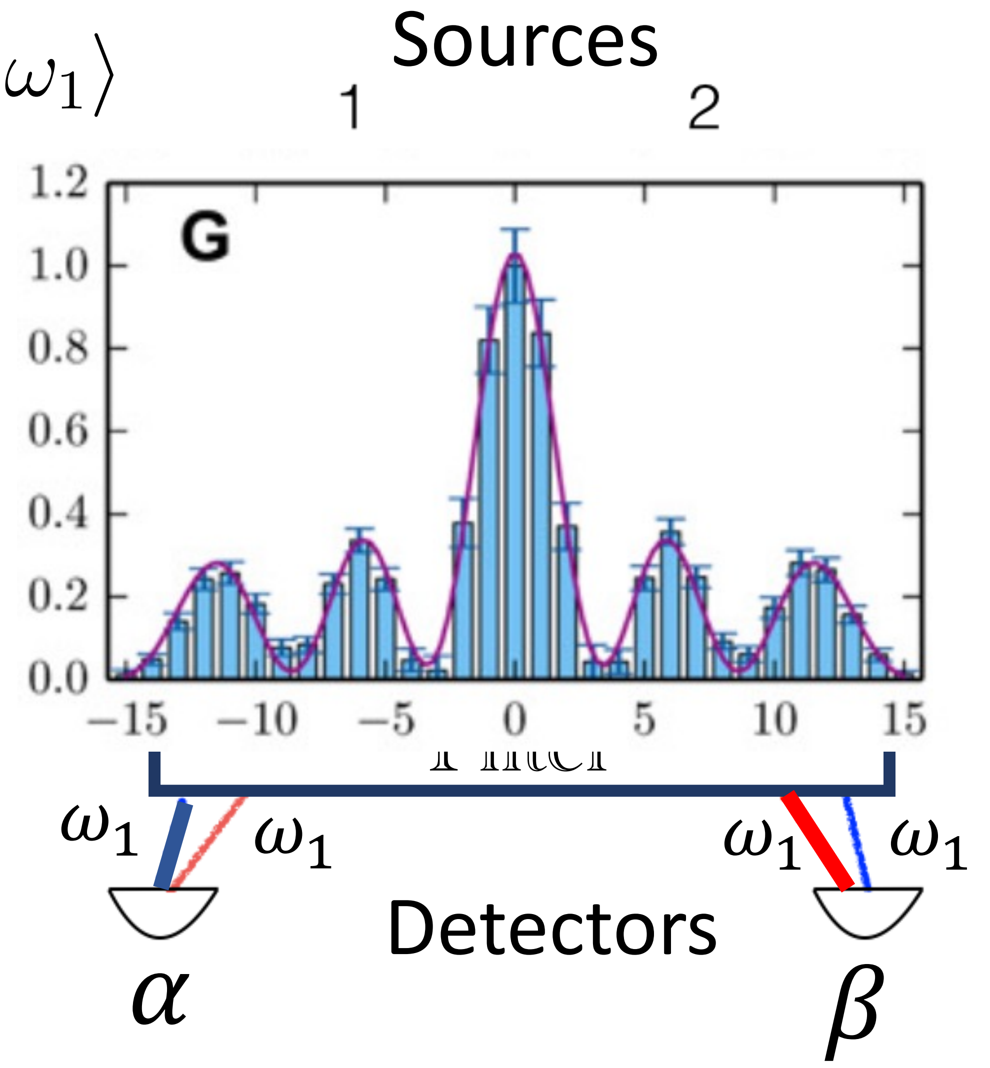

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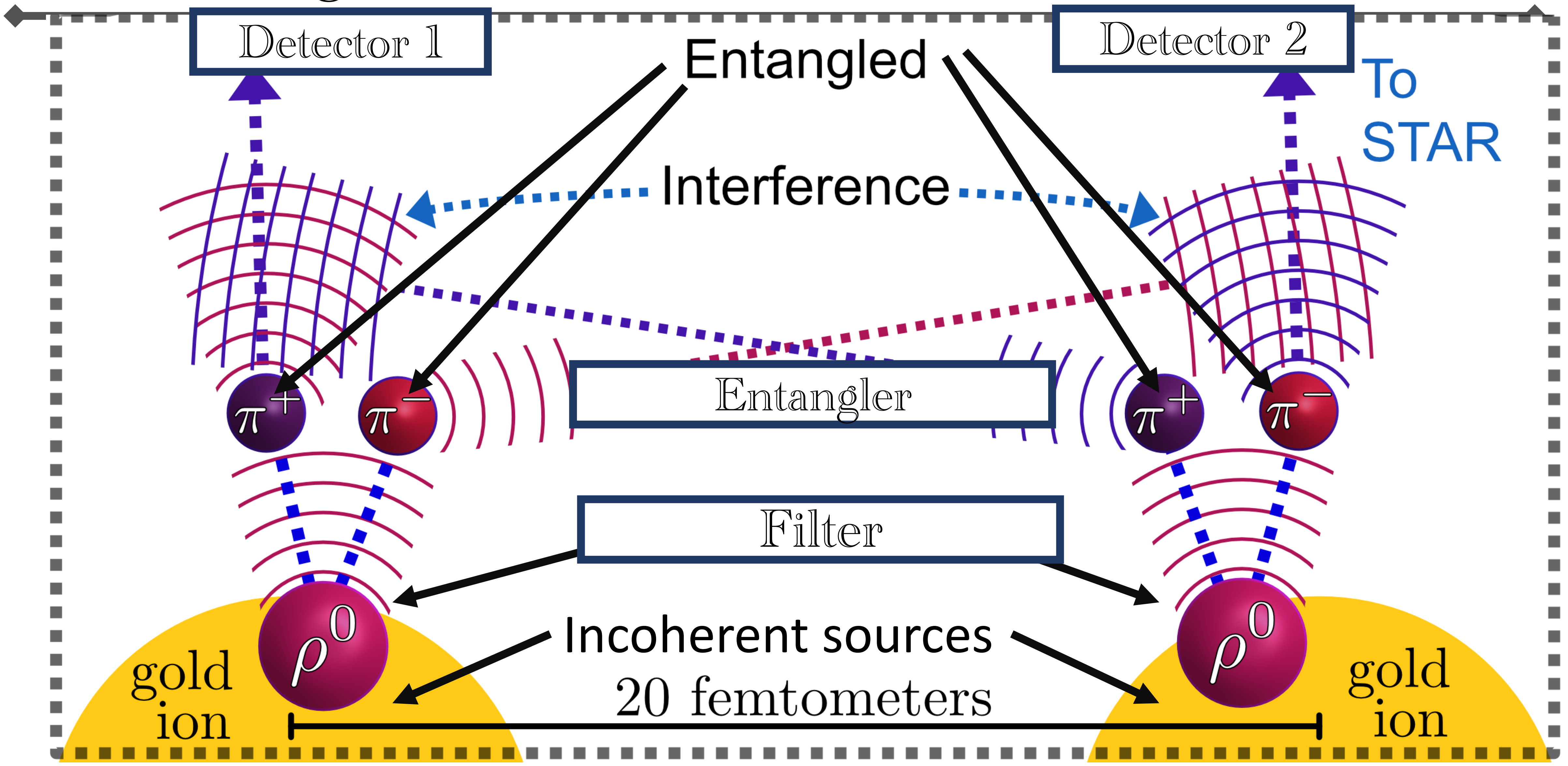
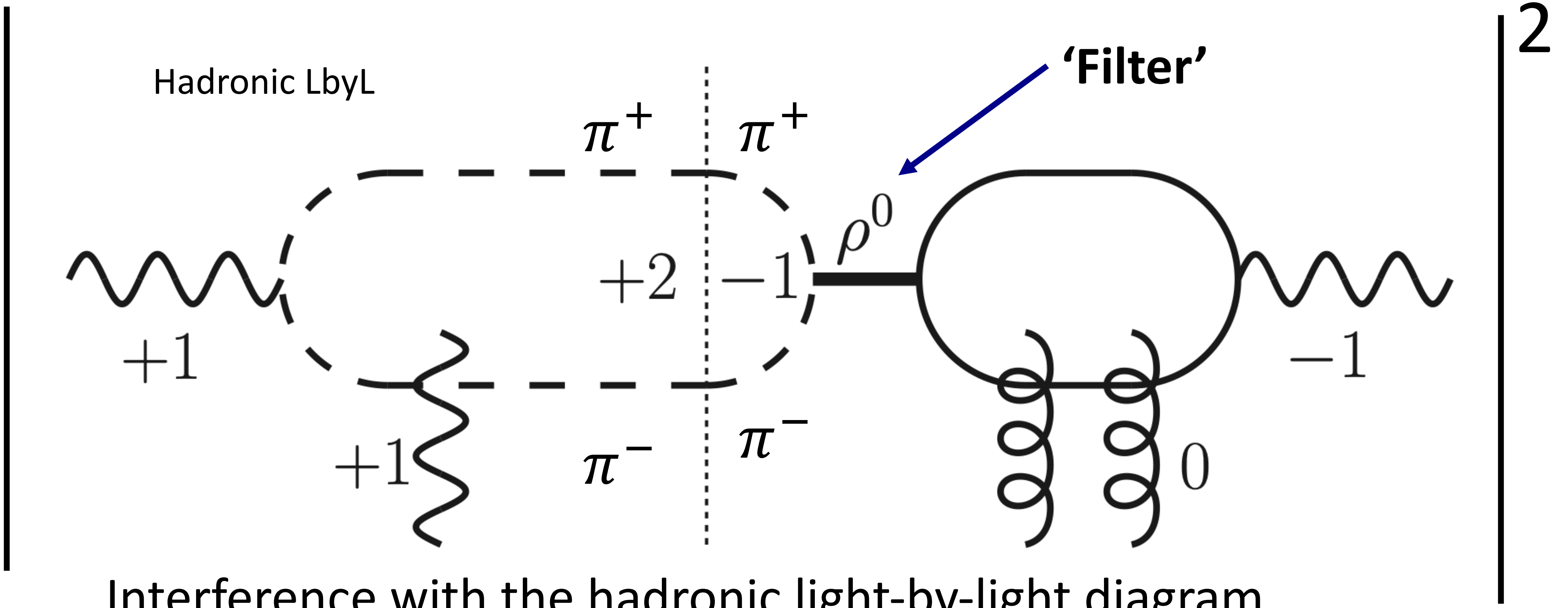
J. Cotler, F. Wilczek, and V. Borish, Annals of Physics **424**, 168346 (2021).

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

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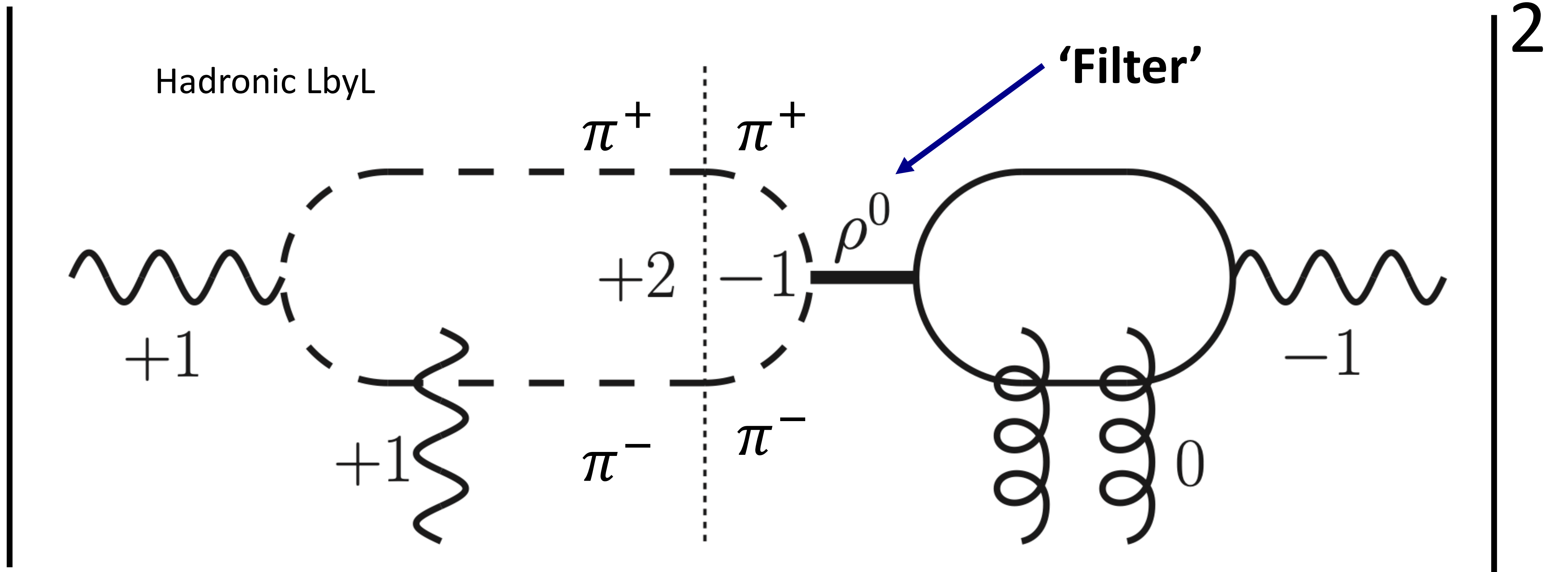

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Novel Experimental input for muon g-2

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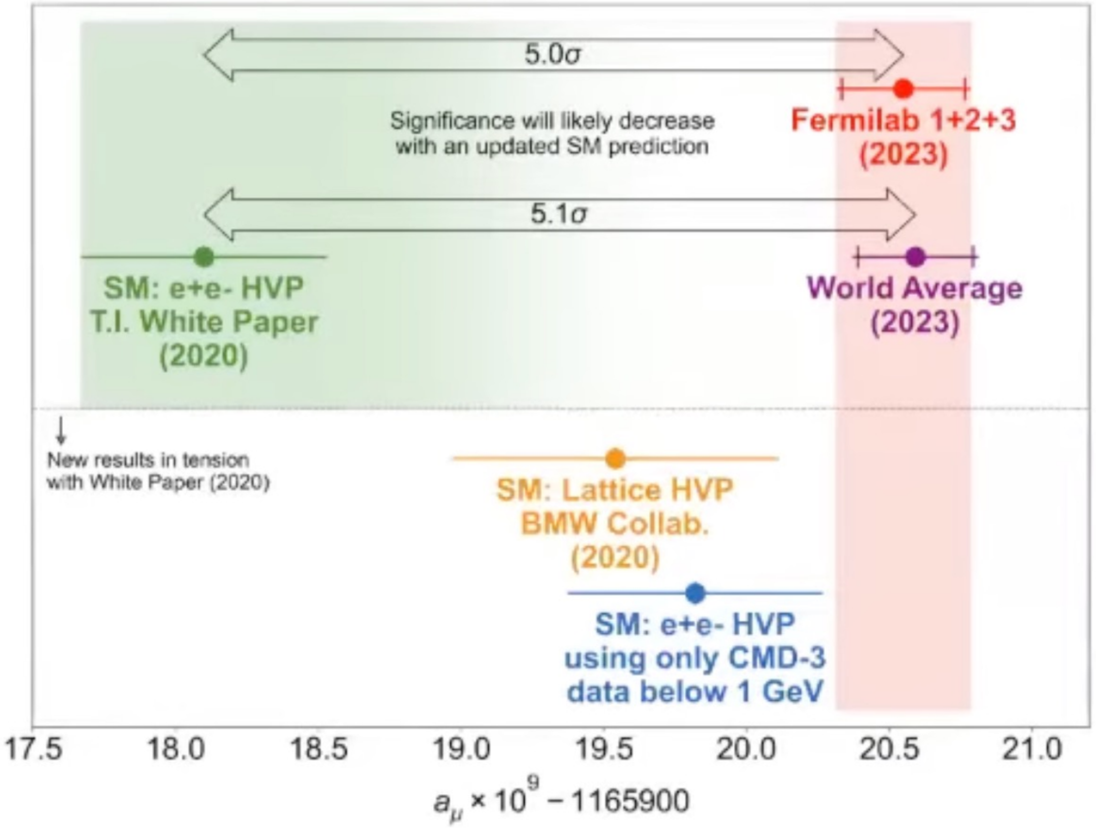
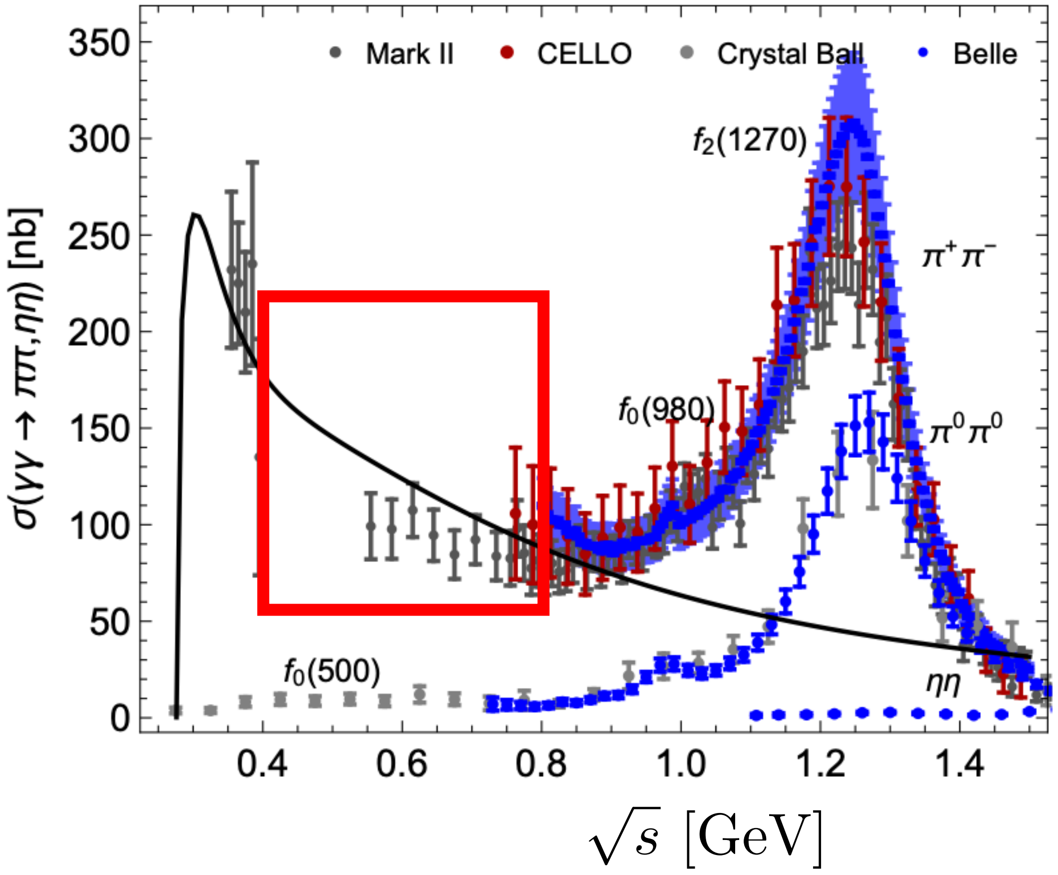
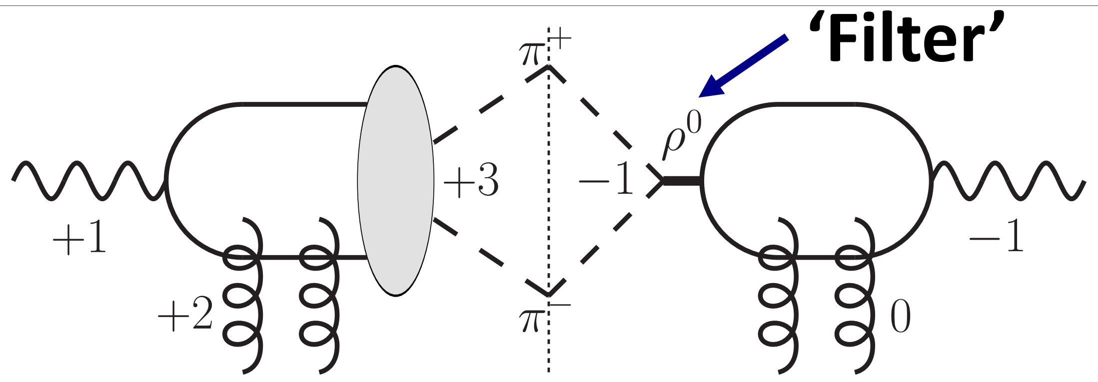




Elliptic Gluon Tomography (Tensor Pomeron)



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

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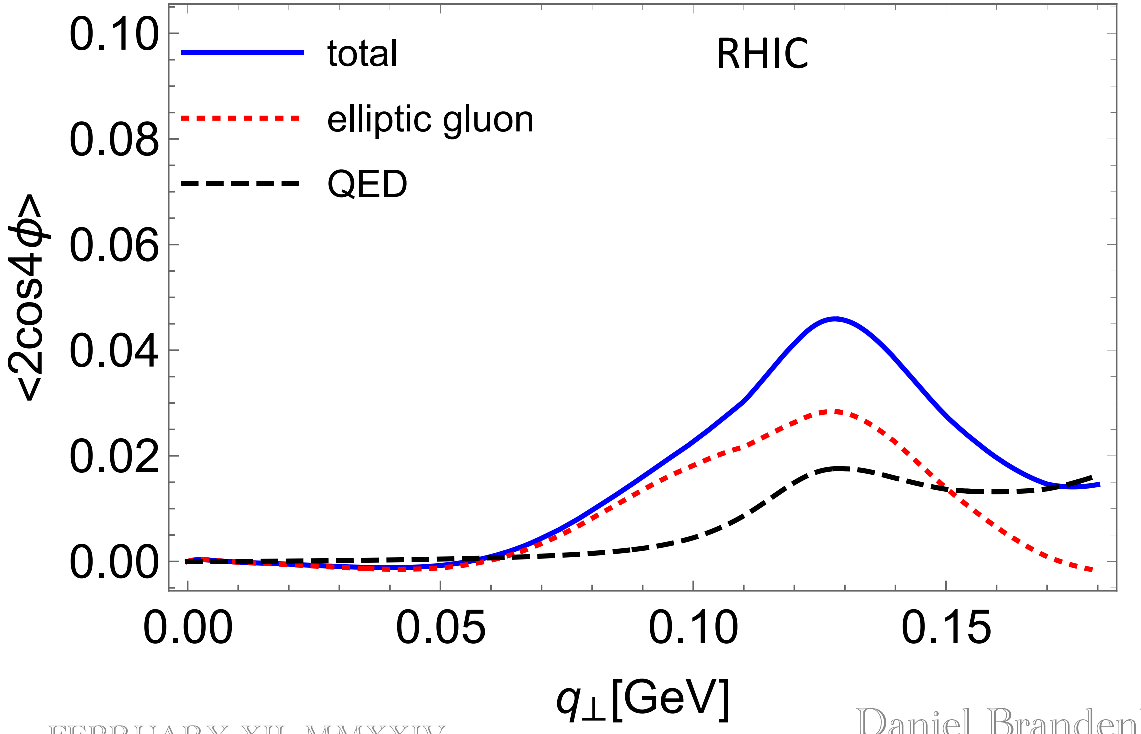
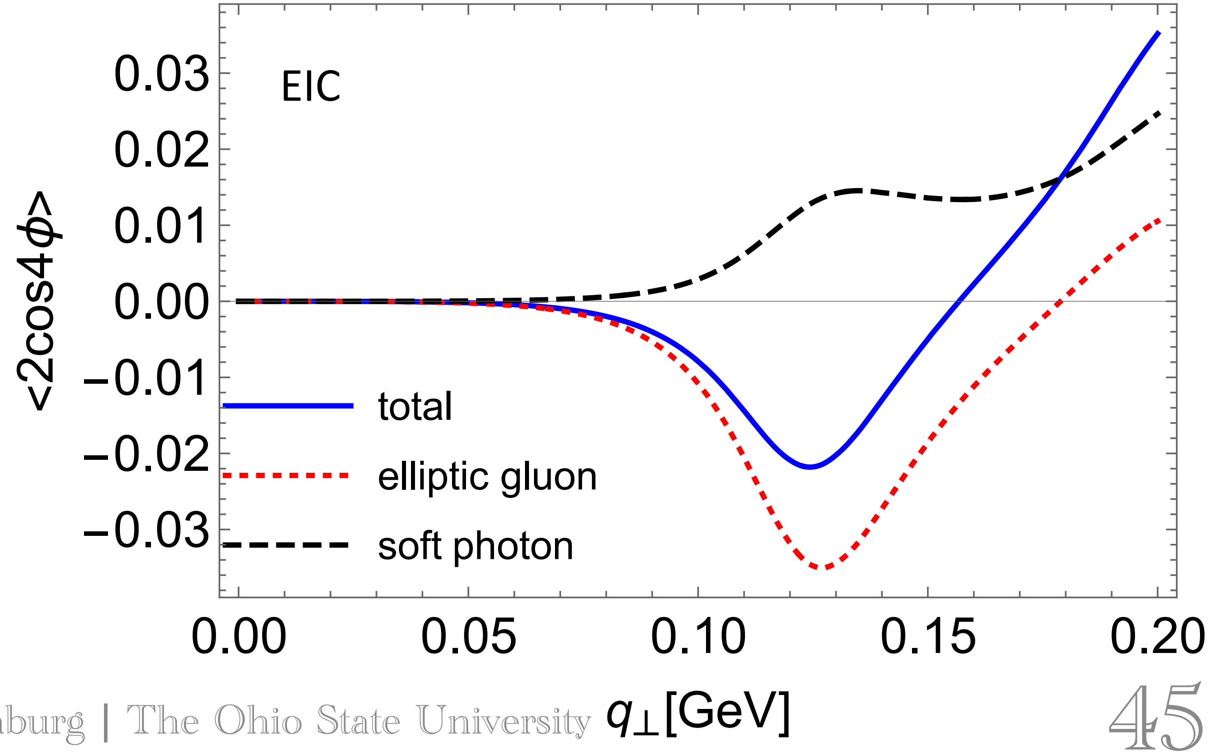
- Complimentary measurements at RHIC and EIC





Analogy to Interferometry in Astro-Physics

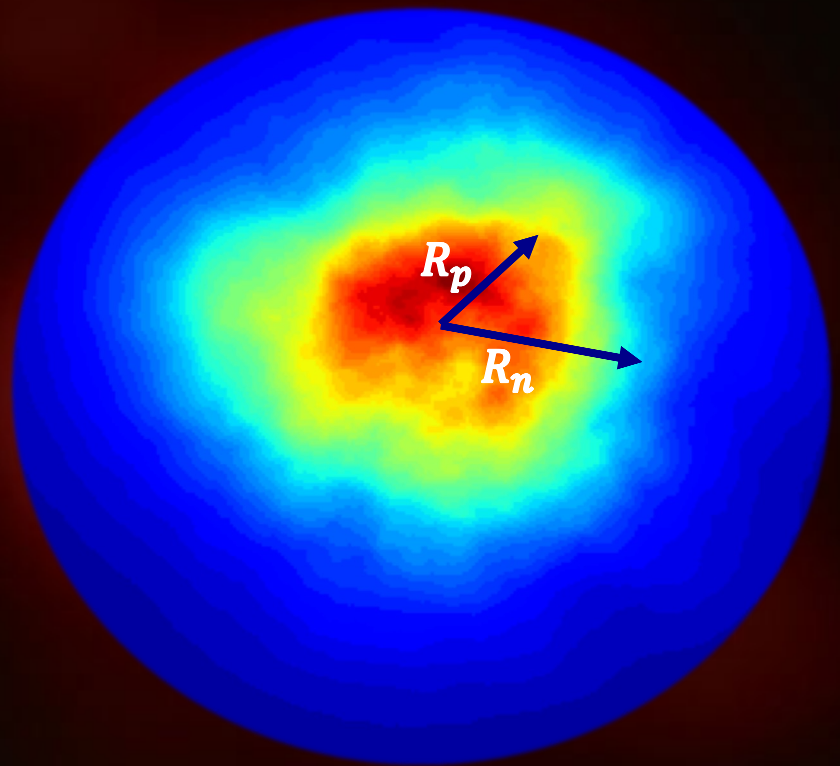
Event Horizon Telescope

M87 Supermassive Black hole

Quantum Interference provides sub-diffraction limited imaging

Analogy to Interferometry in Astro-Physics

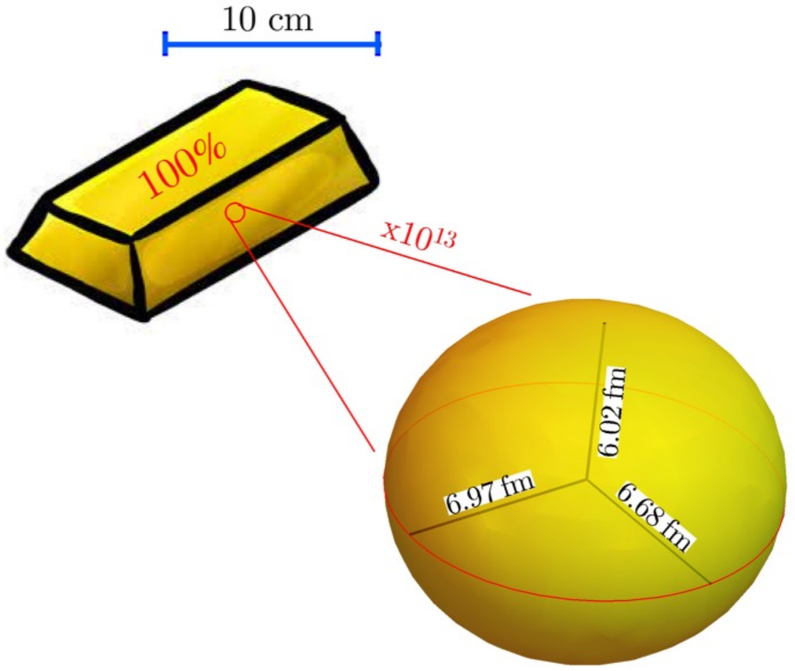
Quantum Interference provides sub-diffraction limited imaging

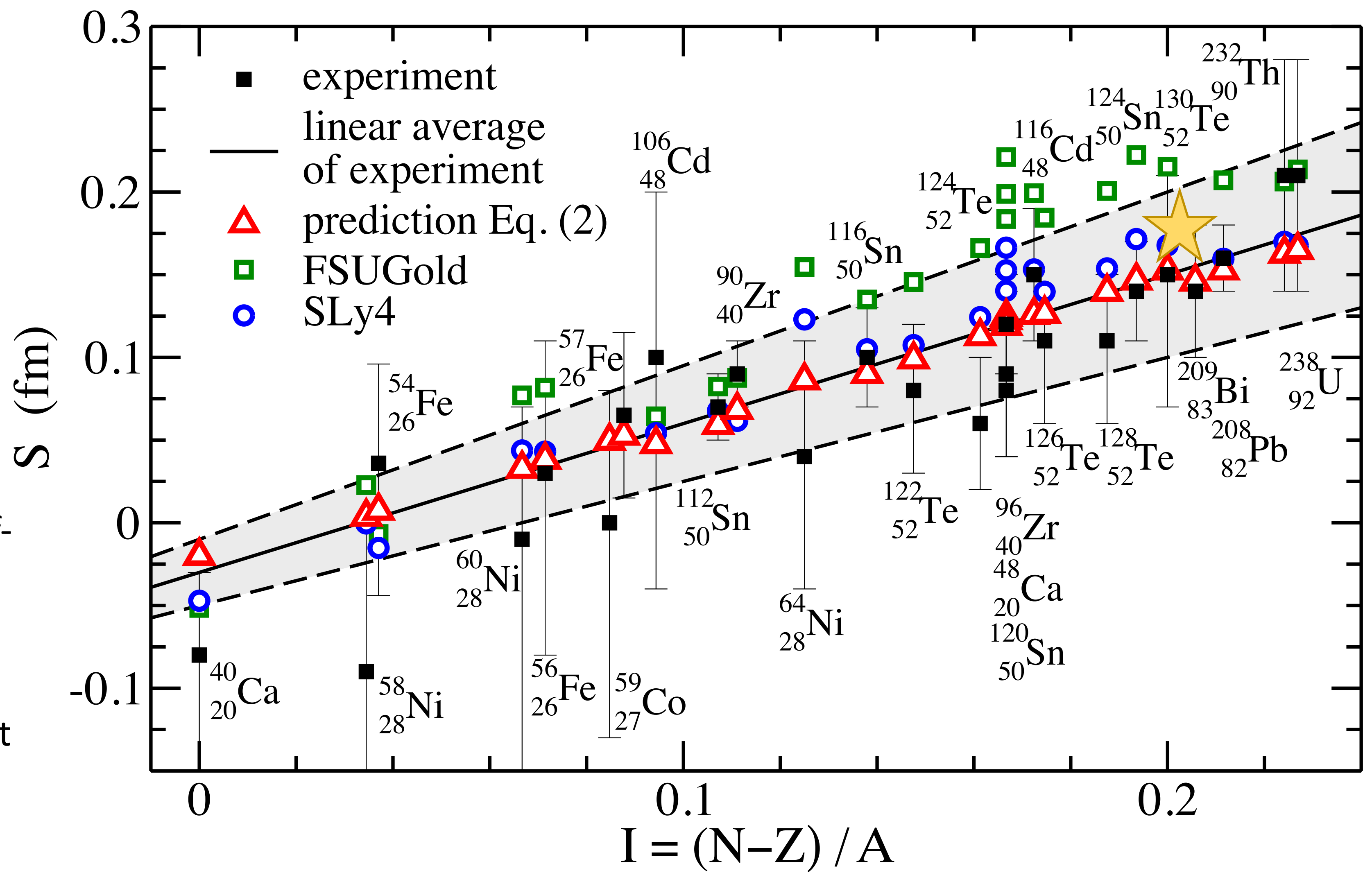


Nuclear Gluon distribution

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

Neutron Skins across Nuclei





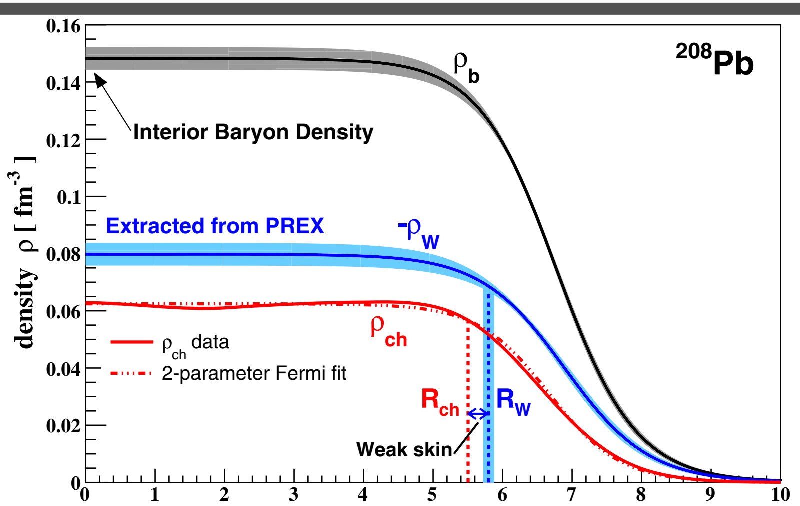
Recent theoretical approach from state-of-the-art multi-reference energy density functional (MR-EDF) calculations:

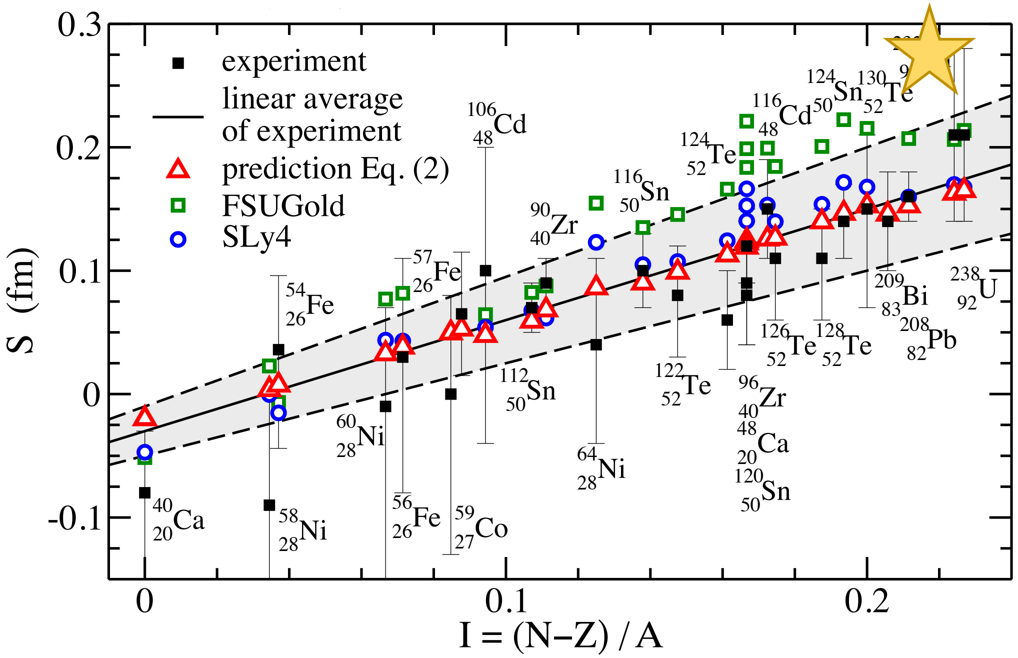
$$S_{Au} = 0.17 \text{ fm}$$

In good agreement with our measurement

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

The neutron skin of ^{208}Pb

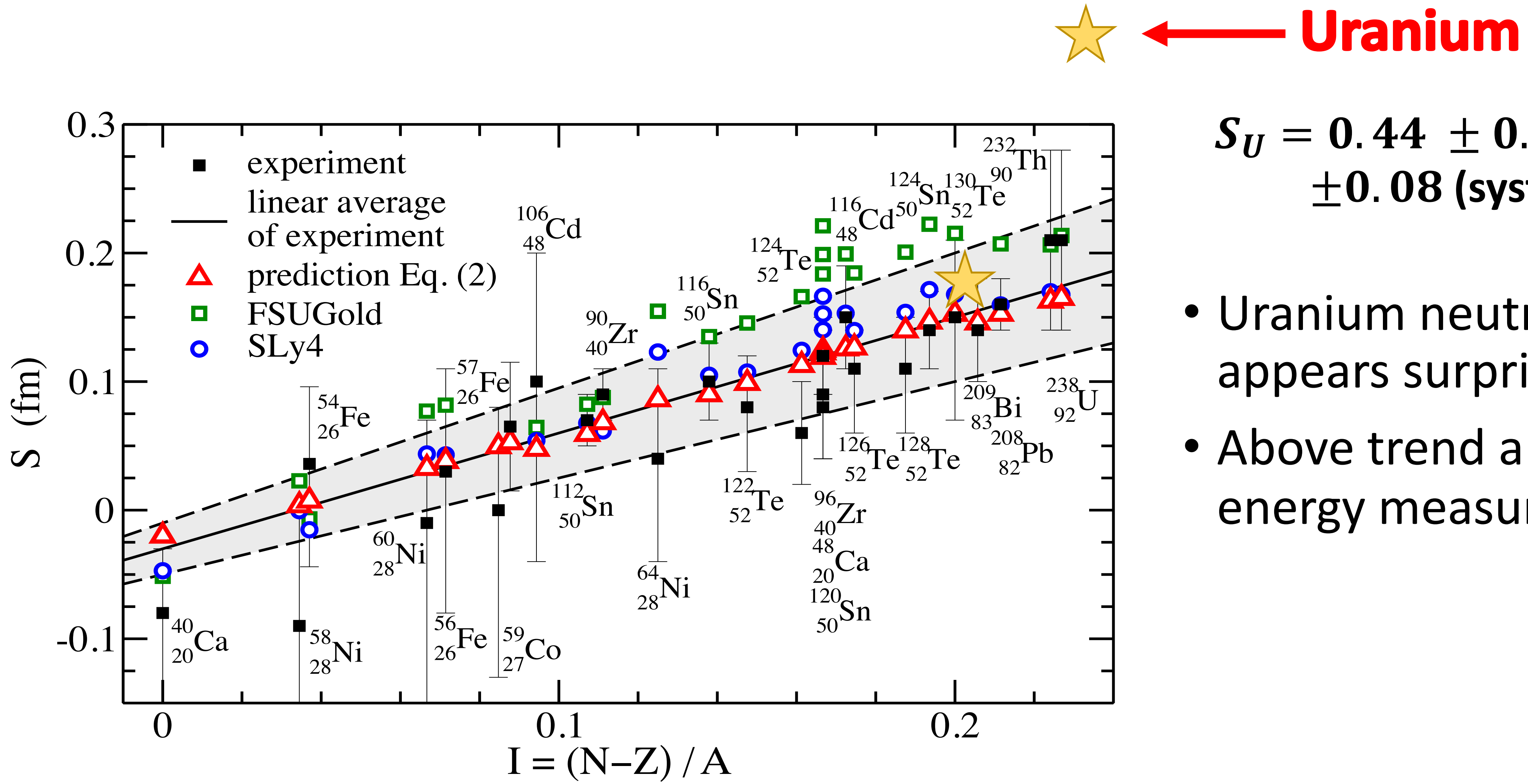




PREX-II neutron skin measurement for ^{208}Pb

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

Neutron Skins at High-Energy

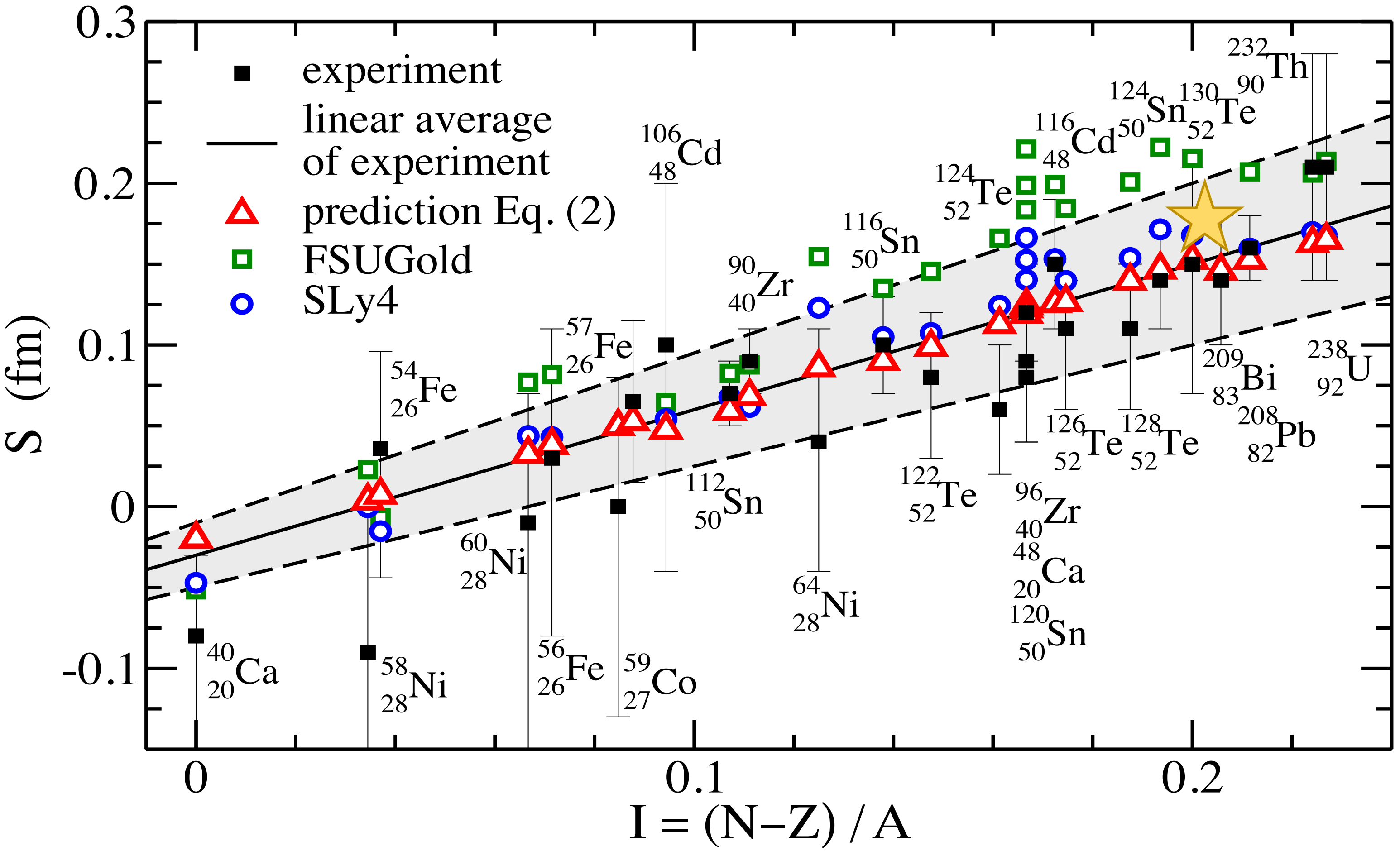


$S_U = 0.44 \pm 0.05$ (stat.) ± 0.08 (syst.) fm

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

Neutron Skins at High-Energy

Uranium



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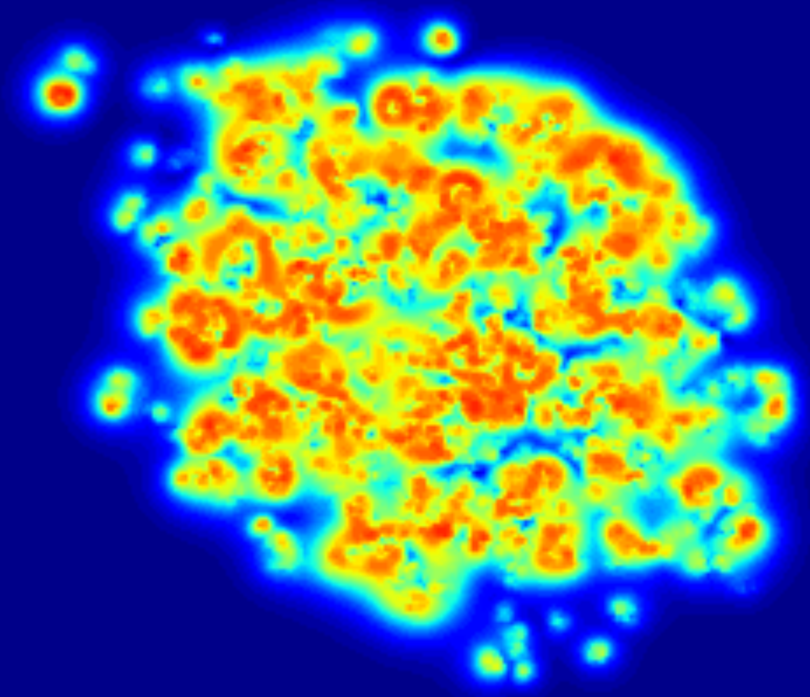
Thank you for your attention!
I hope you can at least say:

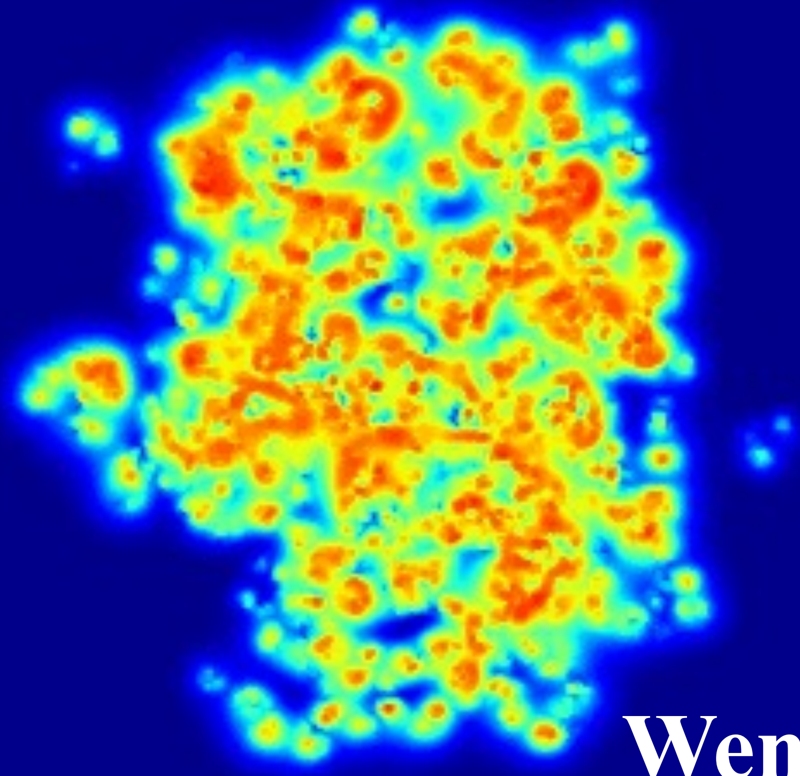
Sub-Nucleonic Imaging

$^{238}\mathrm{U}, \boldsymbol{\beta_2 = 0.5}$



event-1

$^{238}\mathrm{U}, \boldsymbol{\beta_2 = 0.5}$

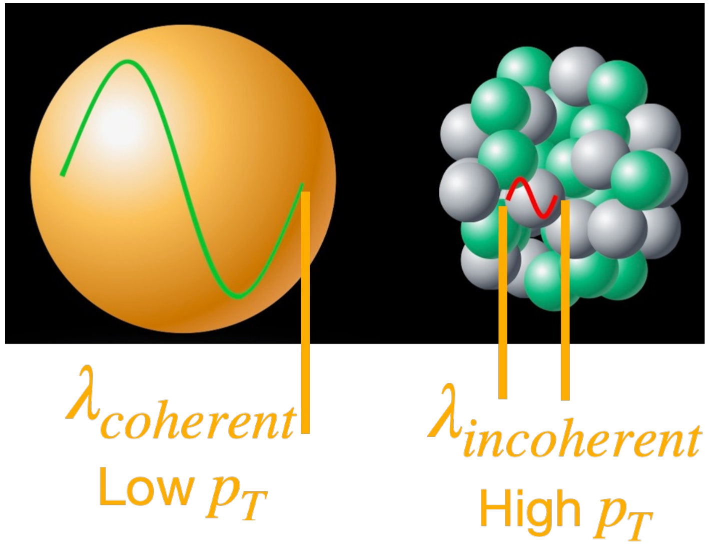


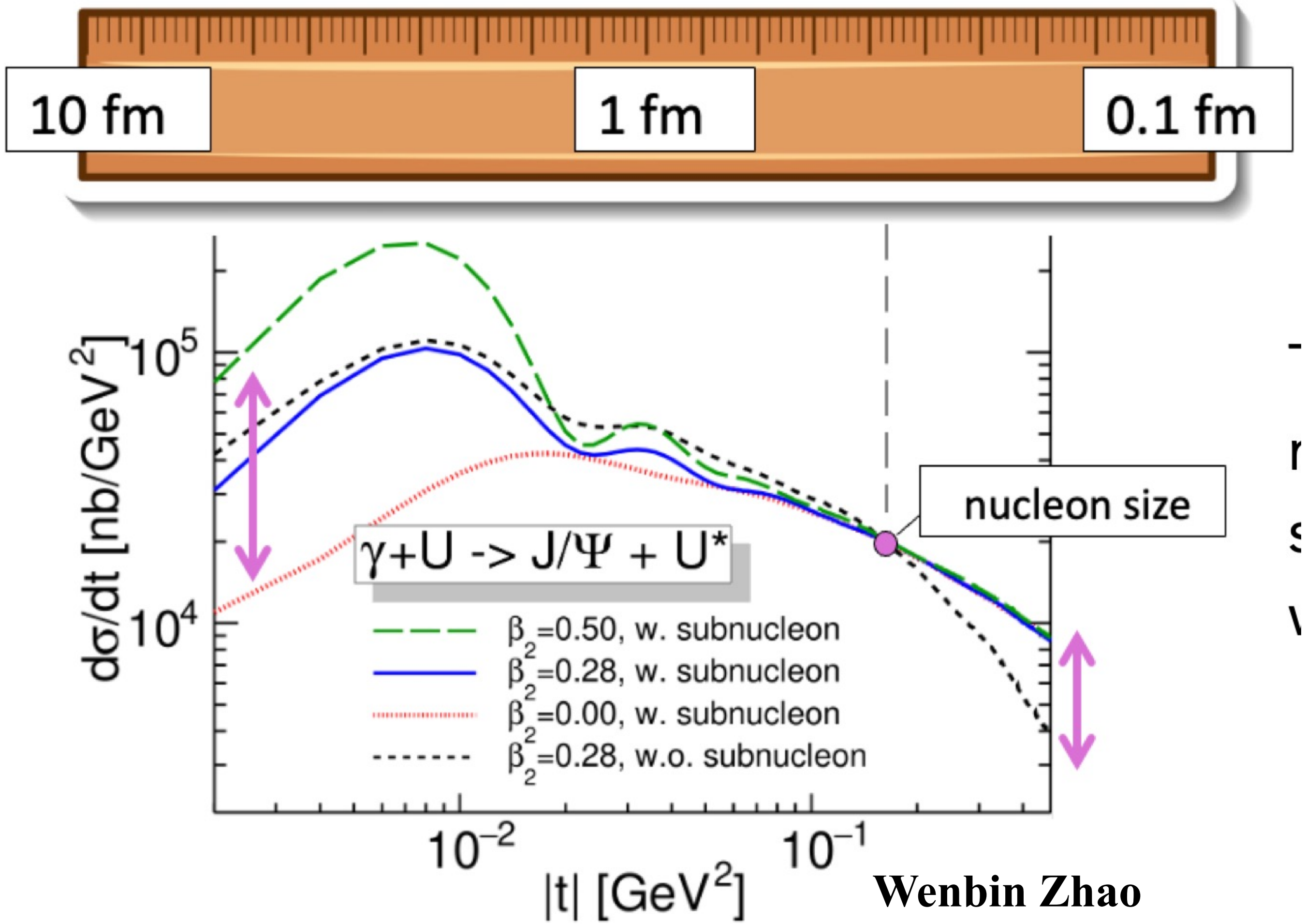
event-2

Wenbin Zhao

Incoherent Process, Not just a Background!

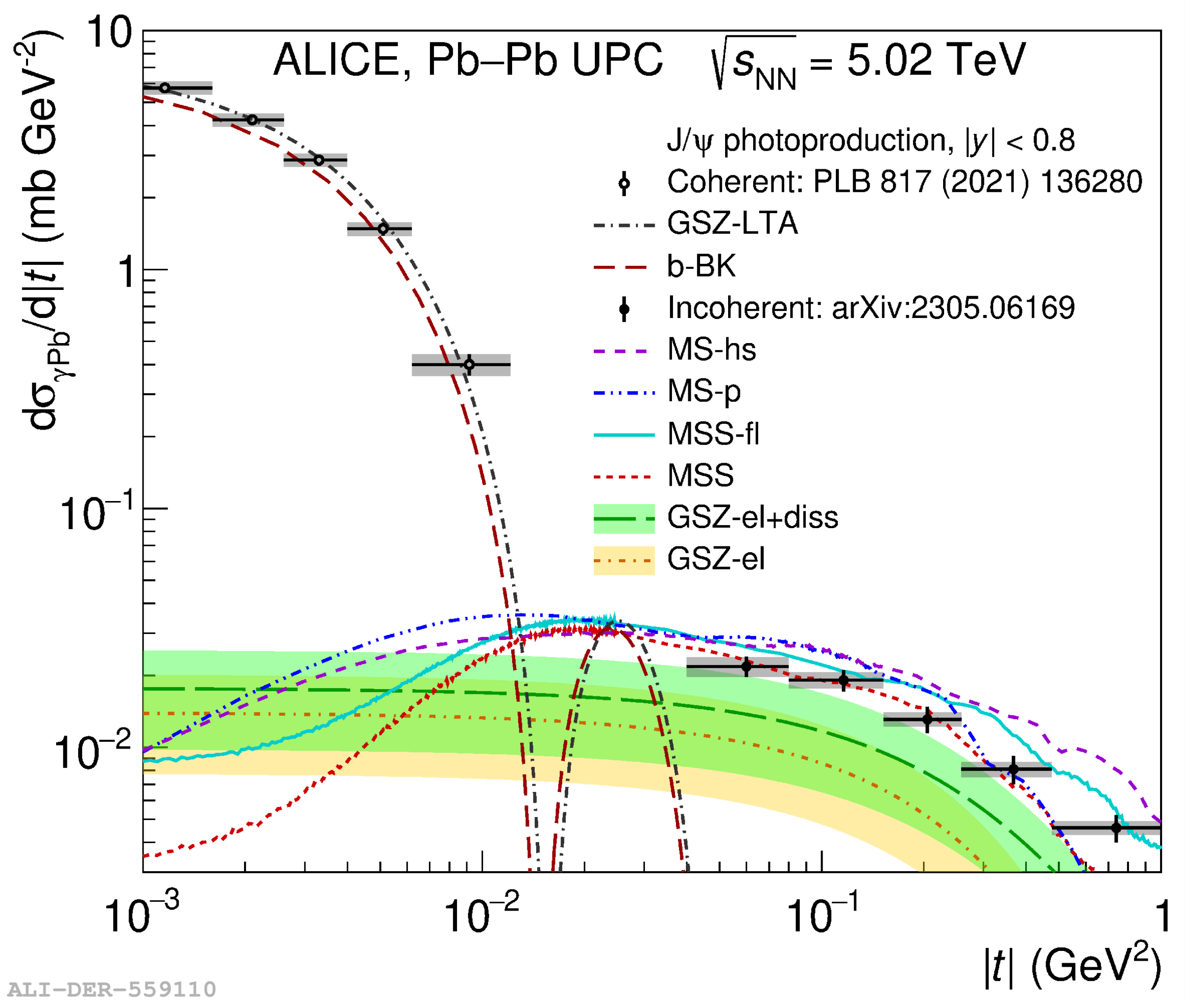
- Transverse momentum sets the length scale
- ‘See’ structures from whole nucleus, to nucleons, to quarks

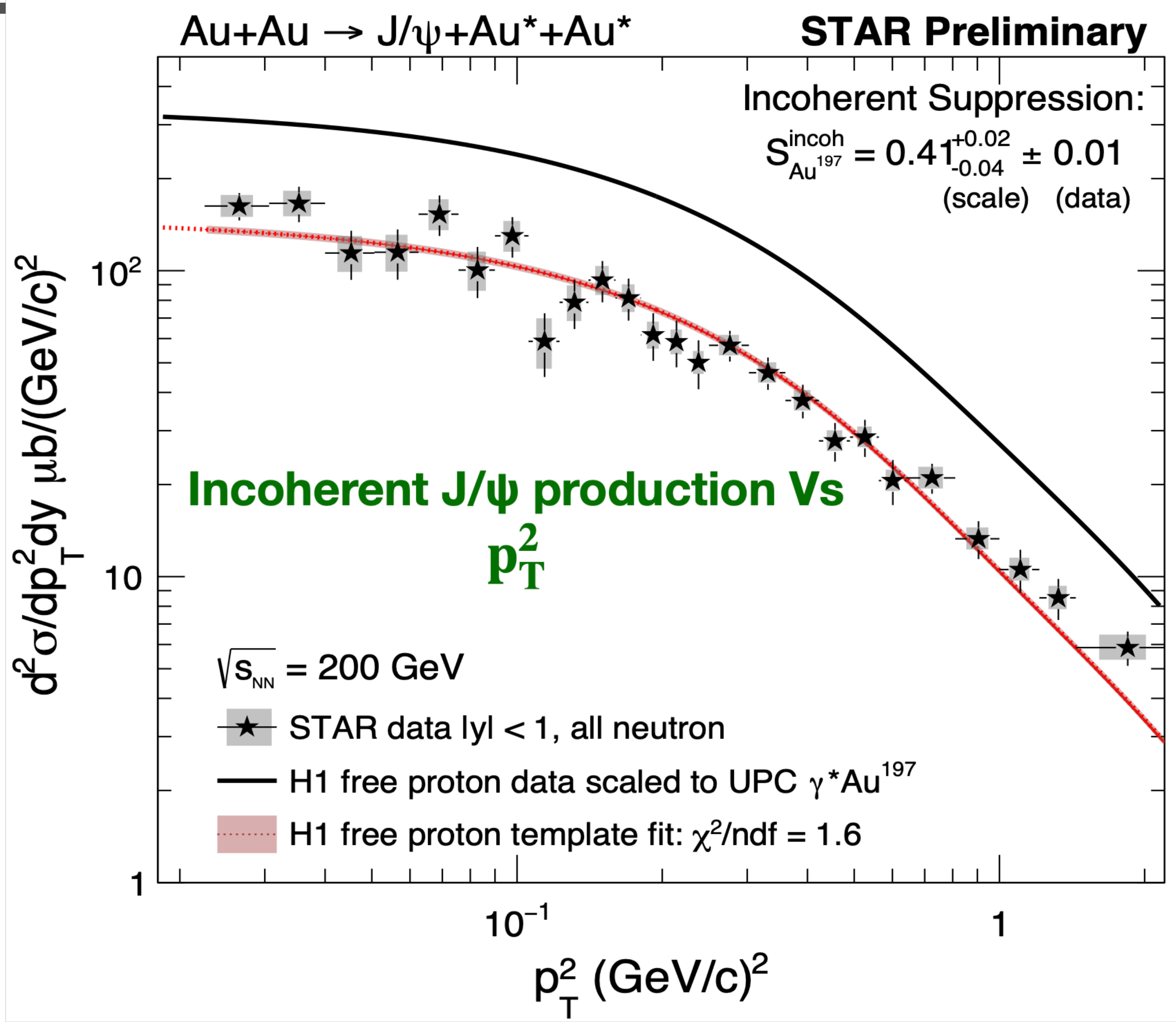




Wenbin Zhao

Incoherent J/ψ – Sub-Nucleonic Imaging





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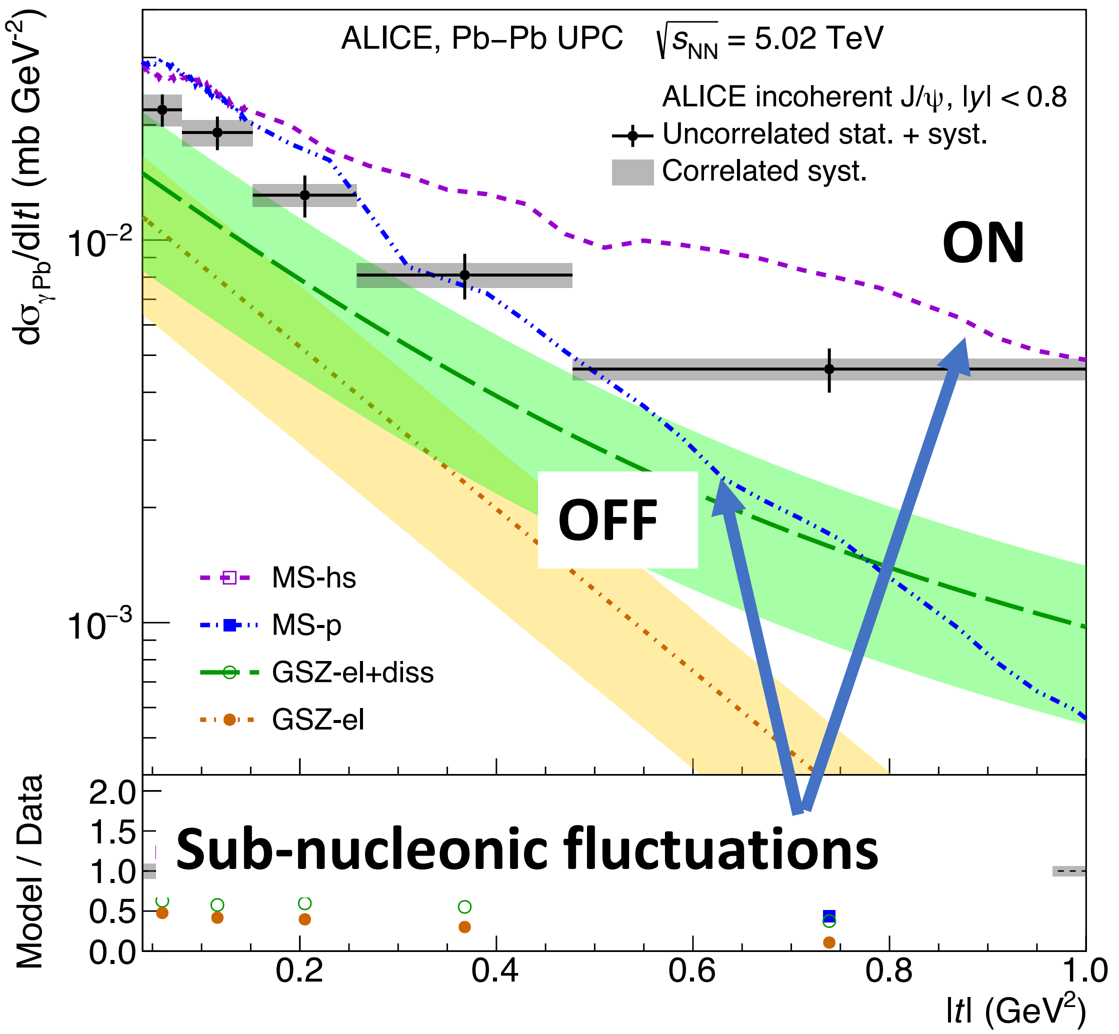
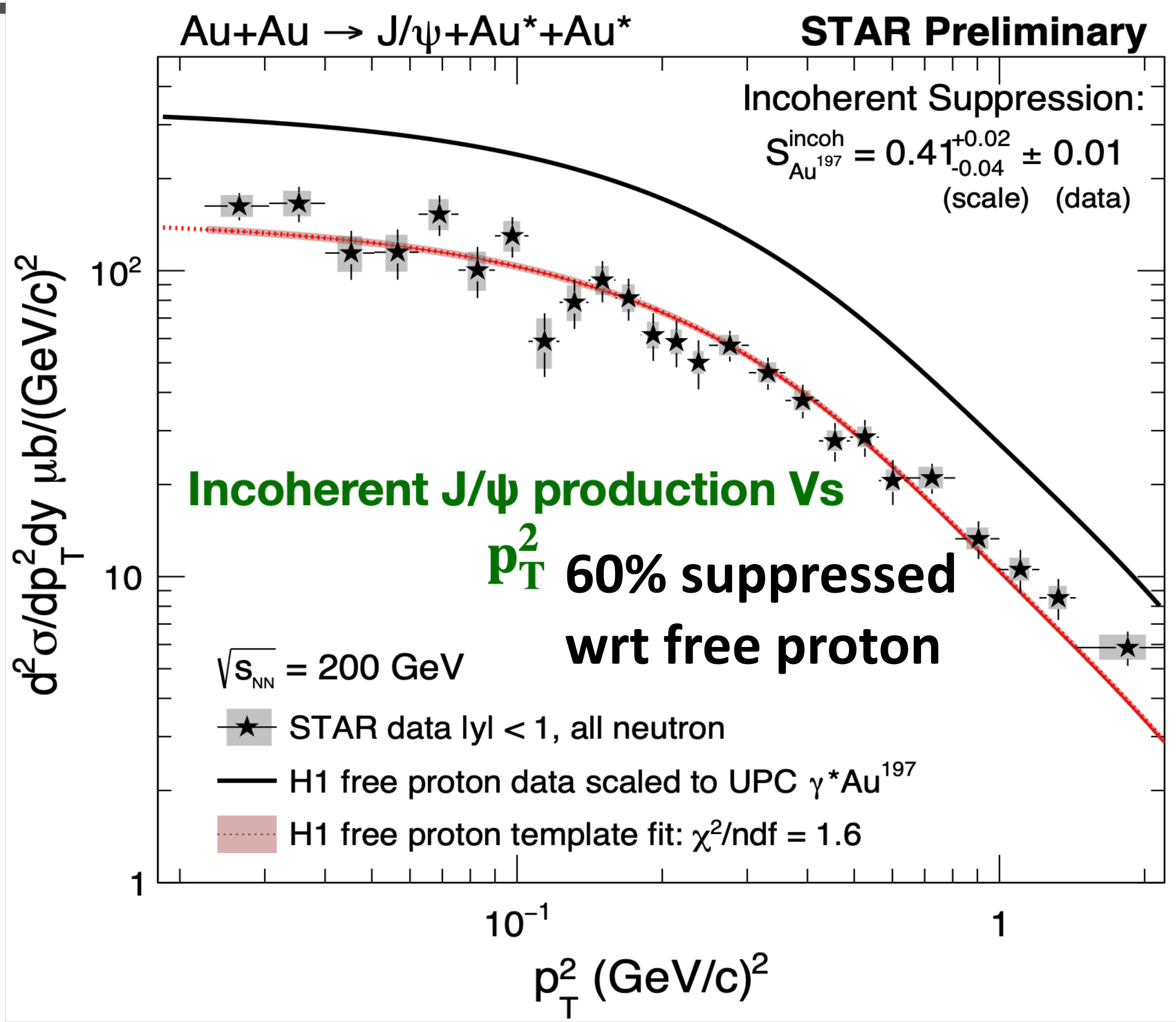
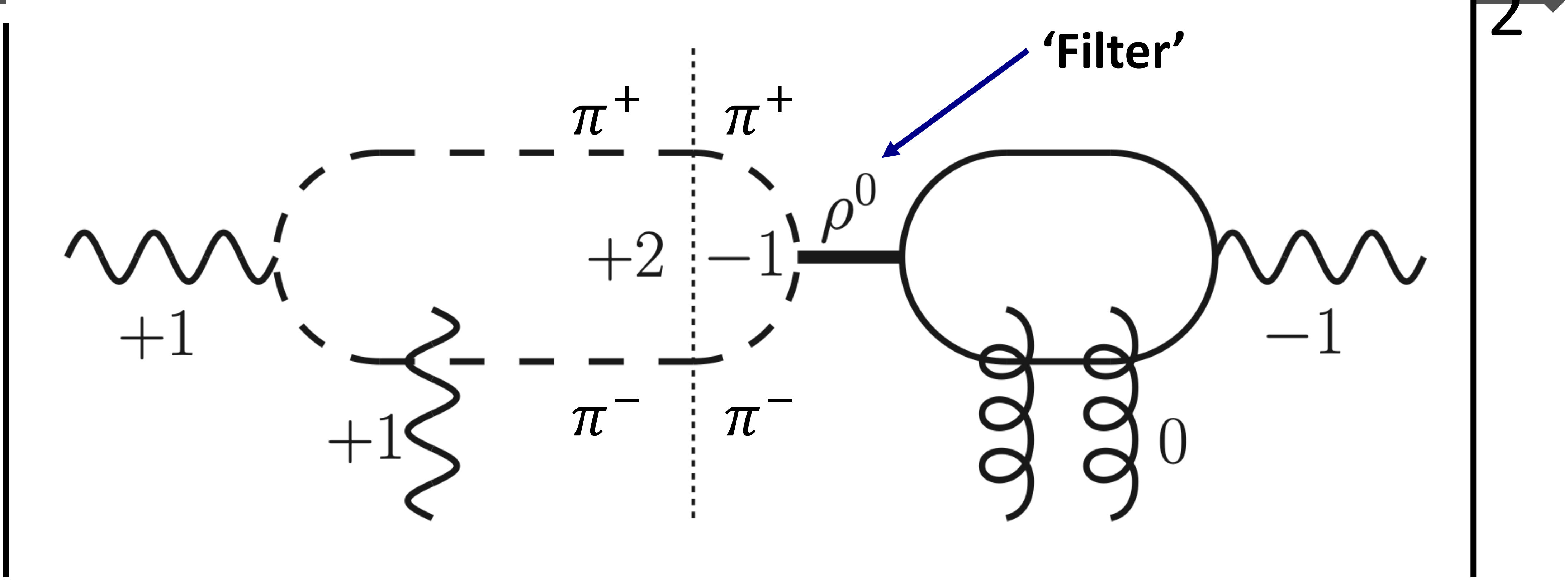




Mäntysaari et al, Phys. Rev. D **106** (2022) 7, 074019)

Access to Hadronic Light-by-Light



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Leads to a unique signature -> odd spin configurations

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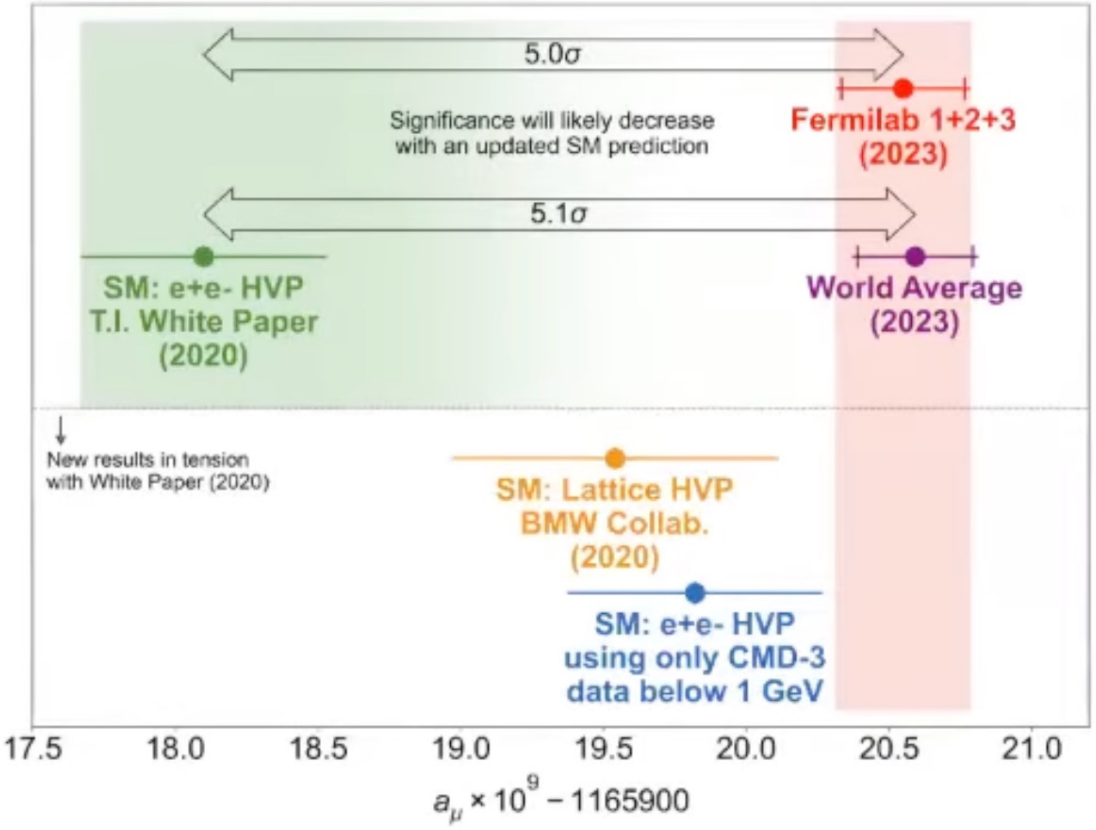

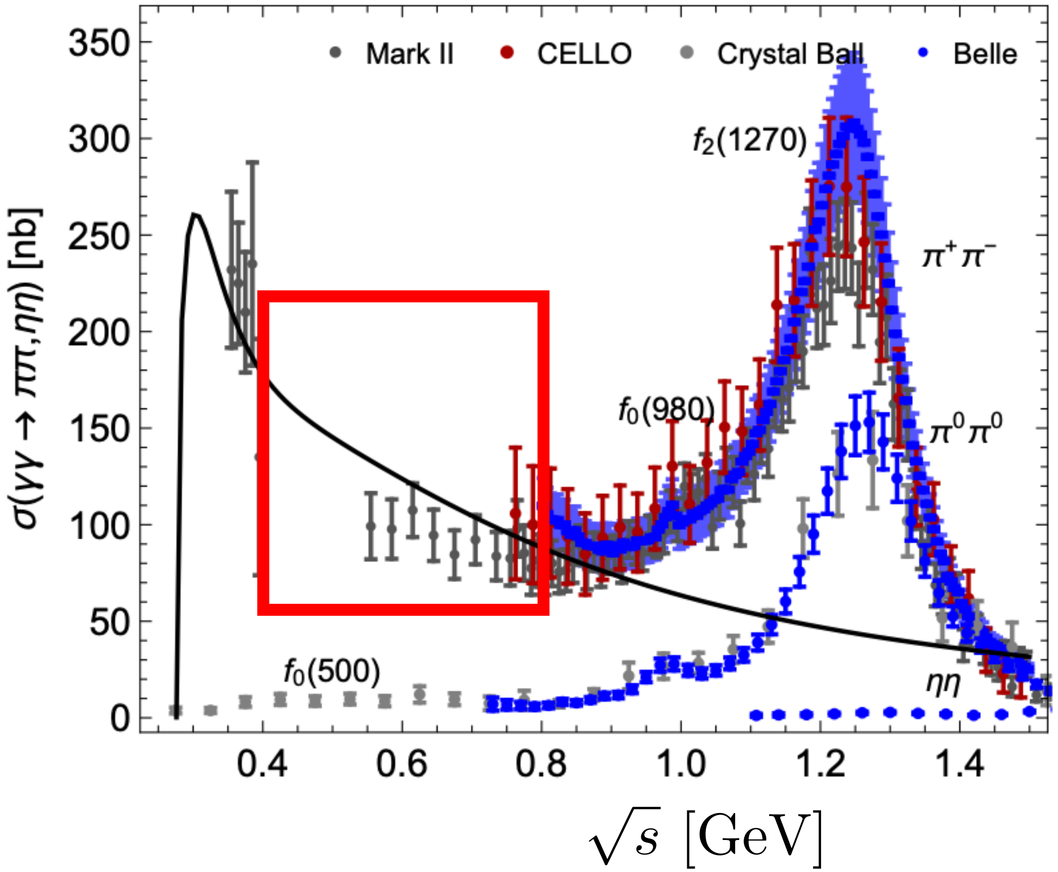

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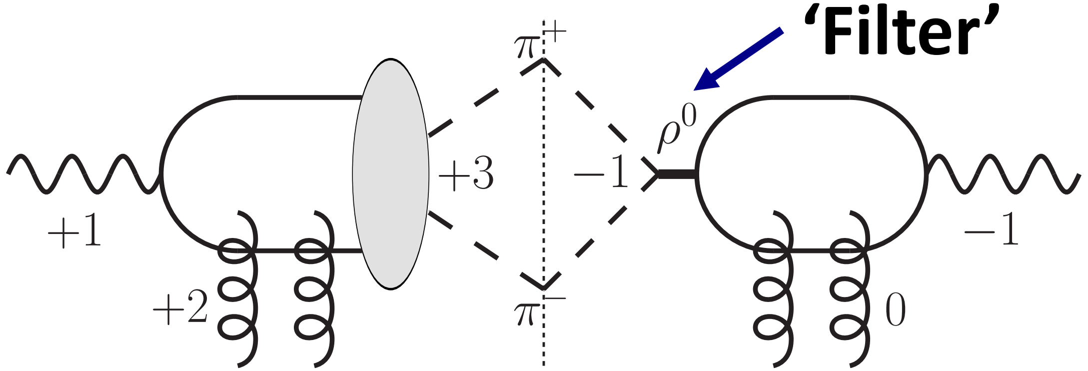

Phys. Rev. D **104**, 094021 (2021)

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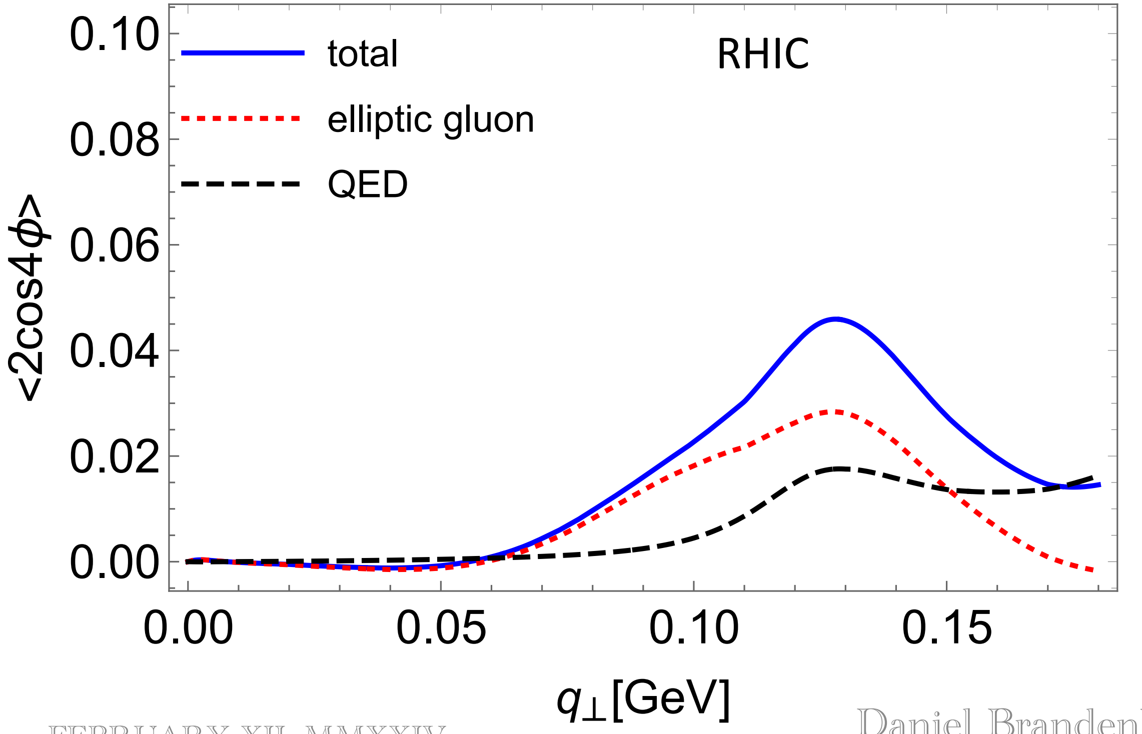
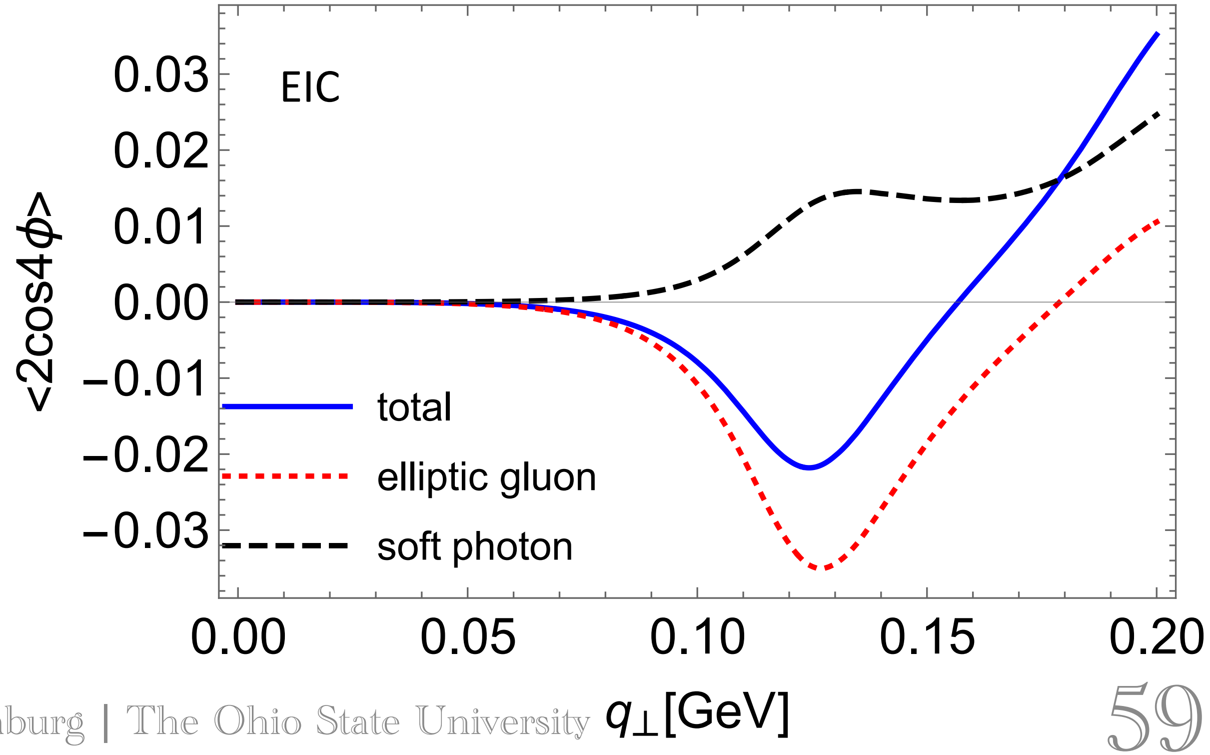
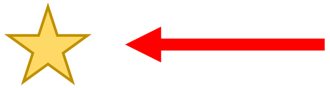
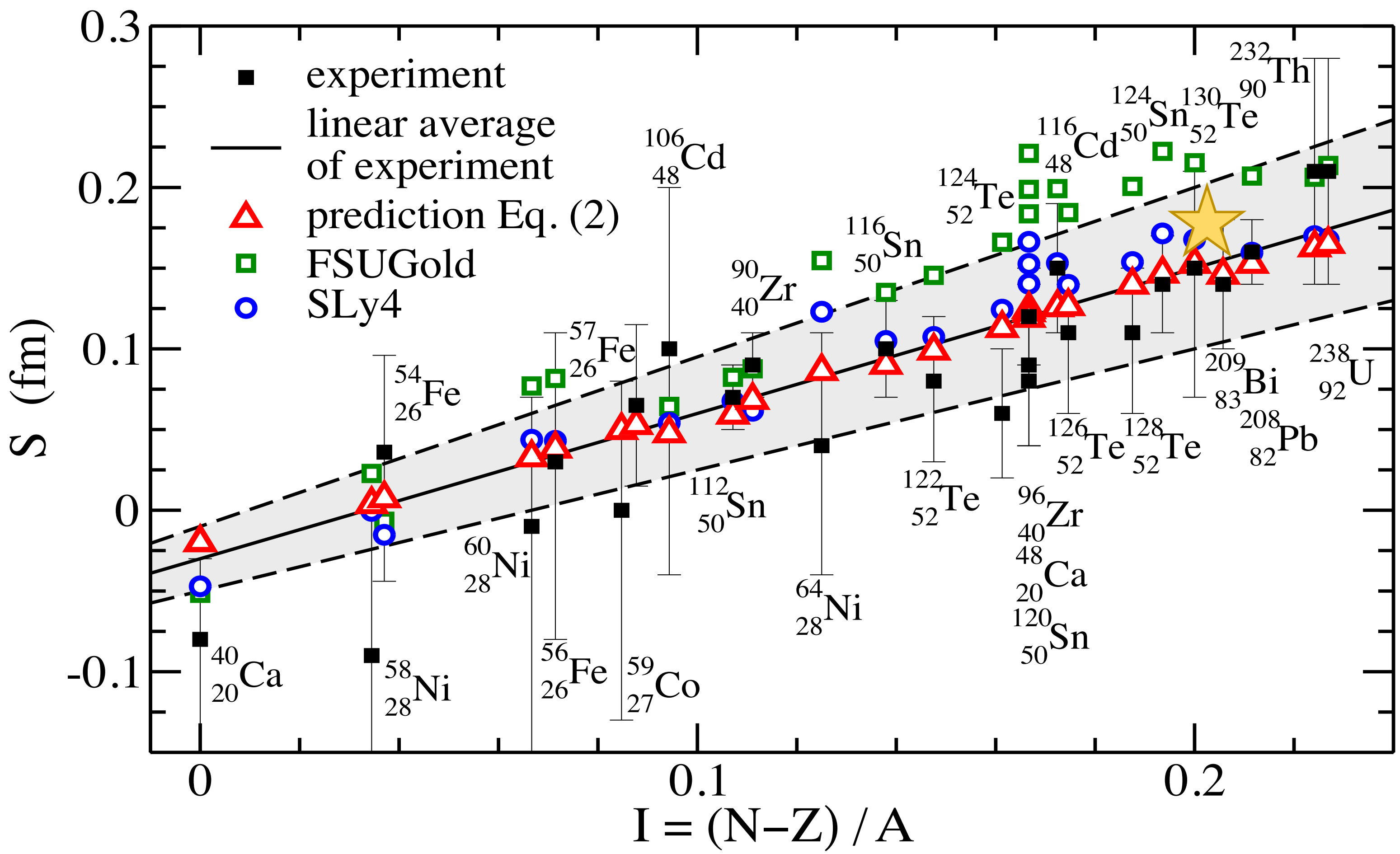




Neutron Skins at High-Energy



Uranium



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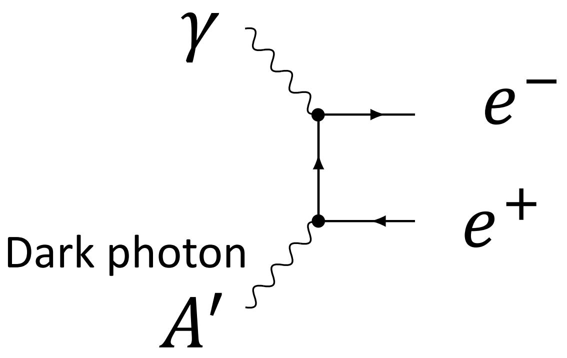
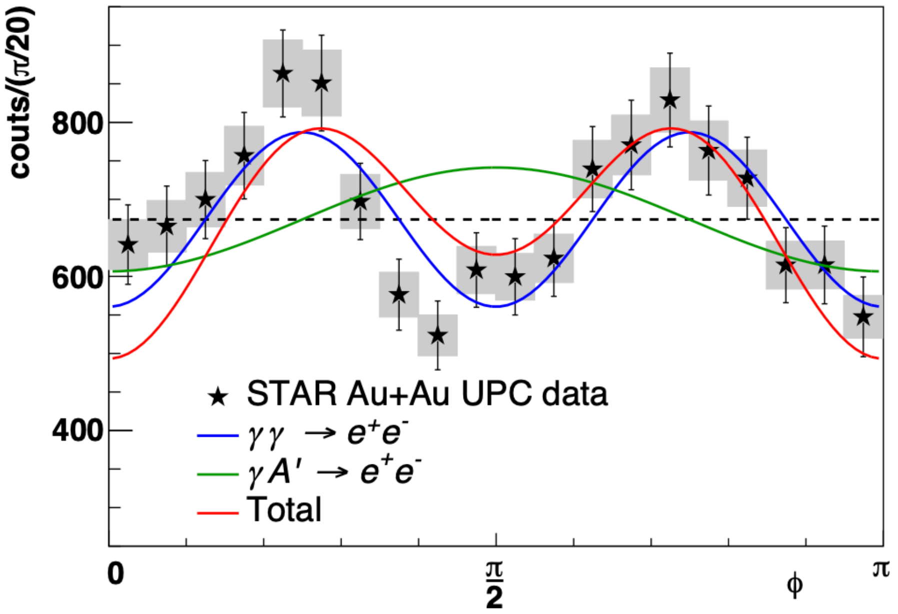
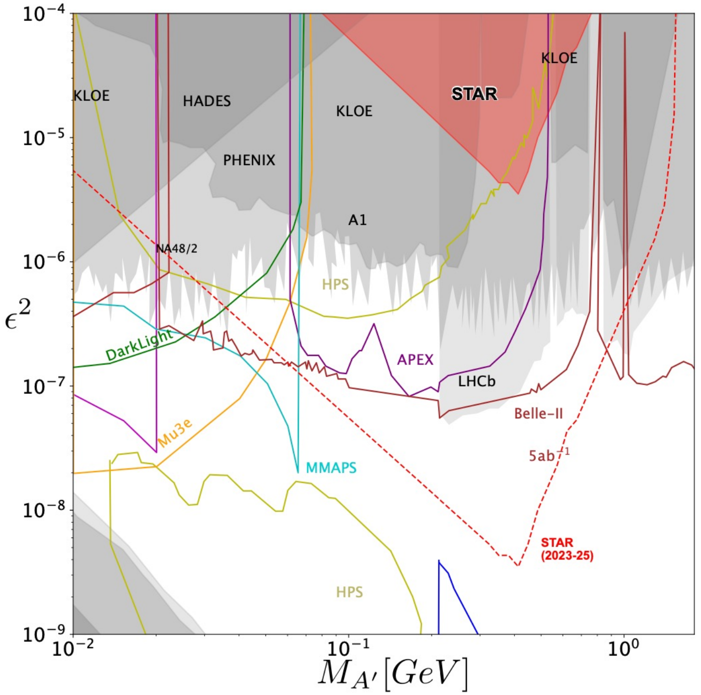
Applications & Broader Impact

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)
  - JDB, W. Li, et al., arXiv:2006.07365 (2020).





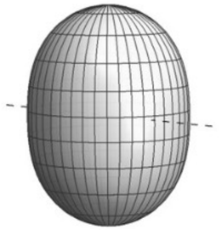


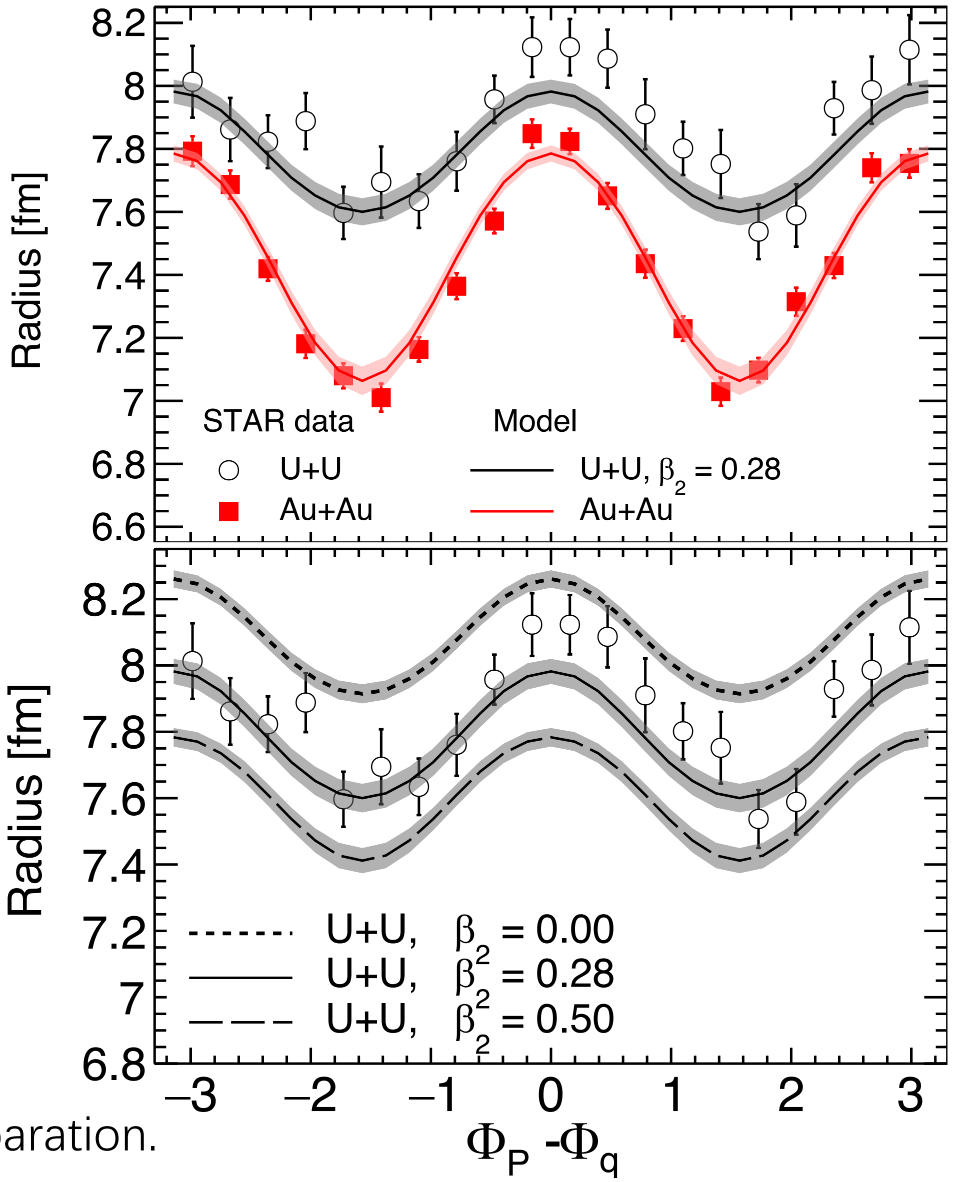
In preparation, https://arxiv.org/abs/2211.02132

Robust Theoretical Description

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

β_2

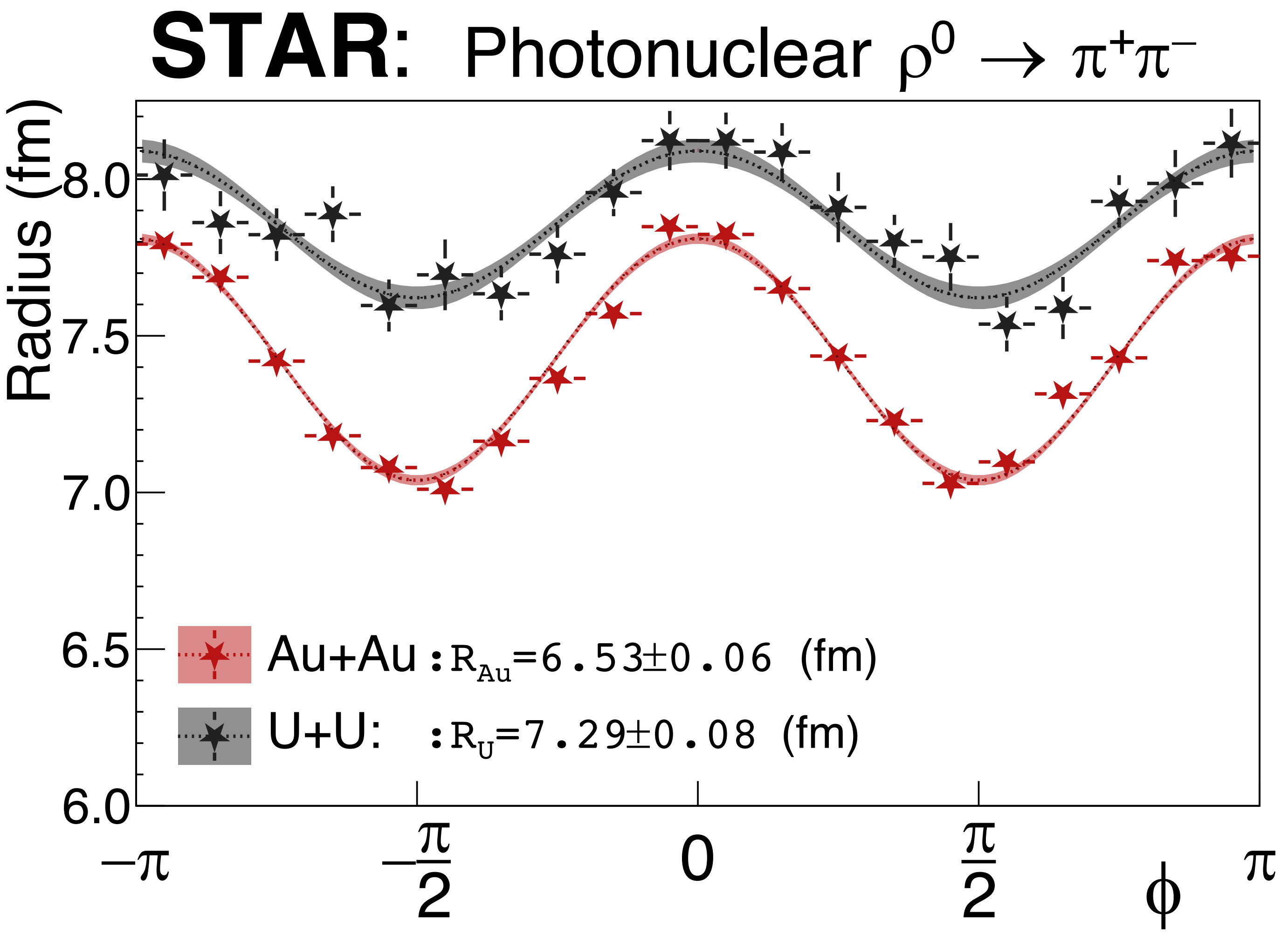




- 2D Tomography possible through Interference effect
- Also require very large U radius
- Assumes amplitude interference for coherent process

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

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

🤔 😅

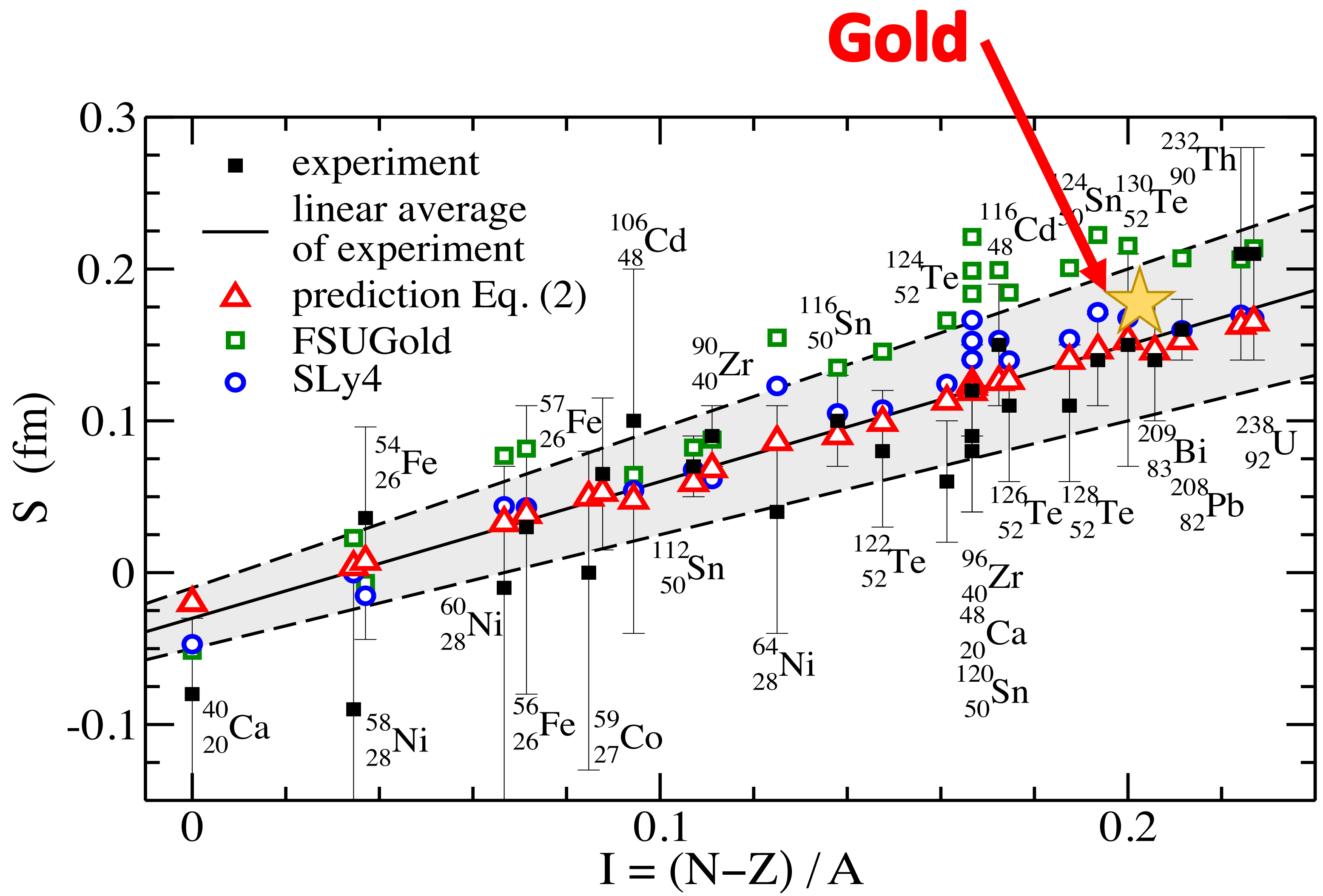
✅ Technique provides quantitative access to gluon saturation effects

❌ 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).

Neutron Skins at High-Energy



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$\pm 0.08(\text{syst.})$ fm

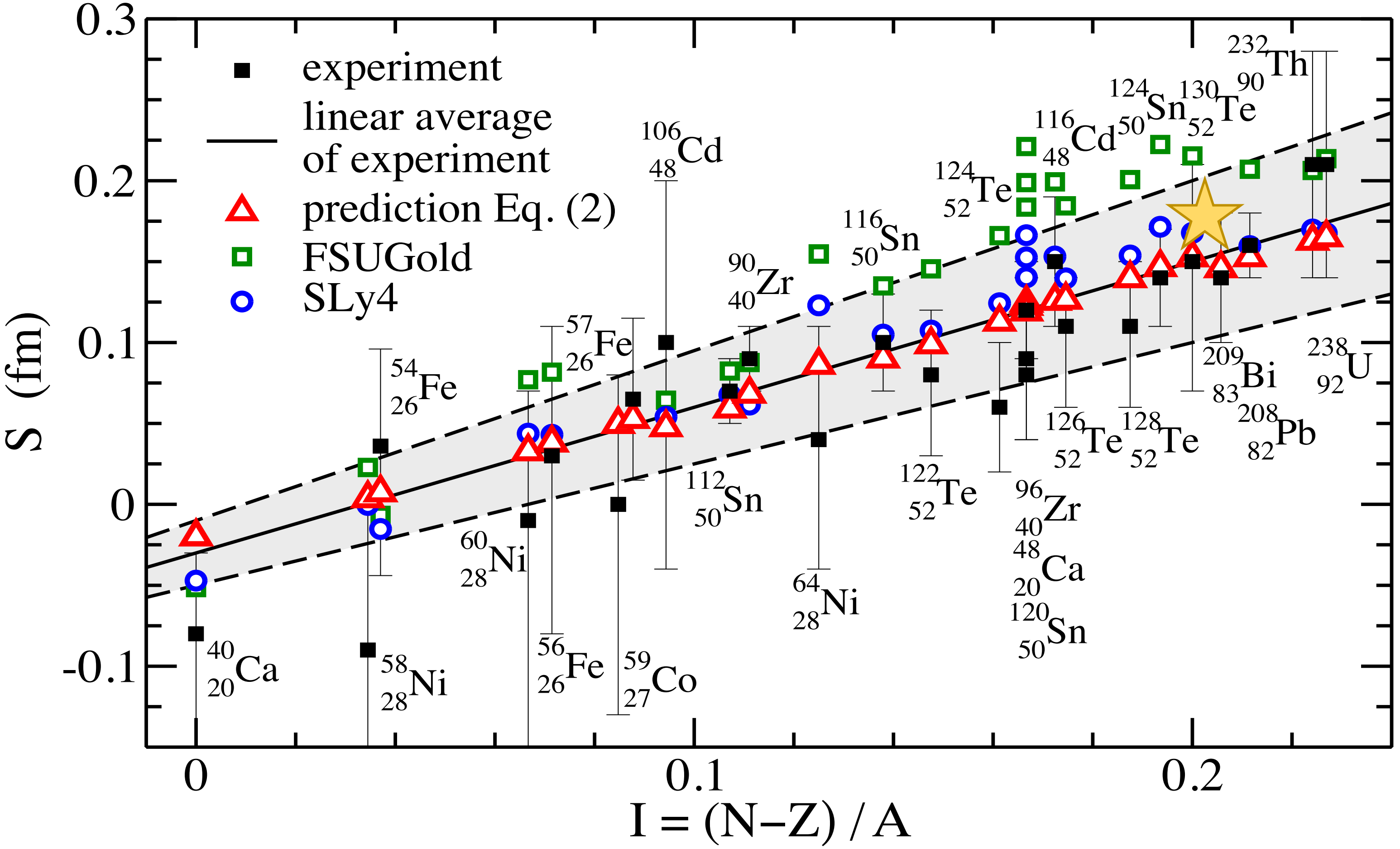
$S_{Au}^{MR-EDF} = 0.17$ fm

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

☆ ← **Uranium**



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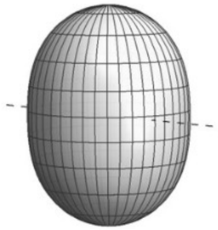
$\boldsymbol{\beta_2}$



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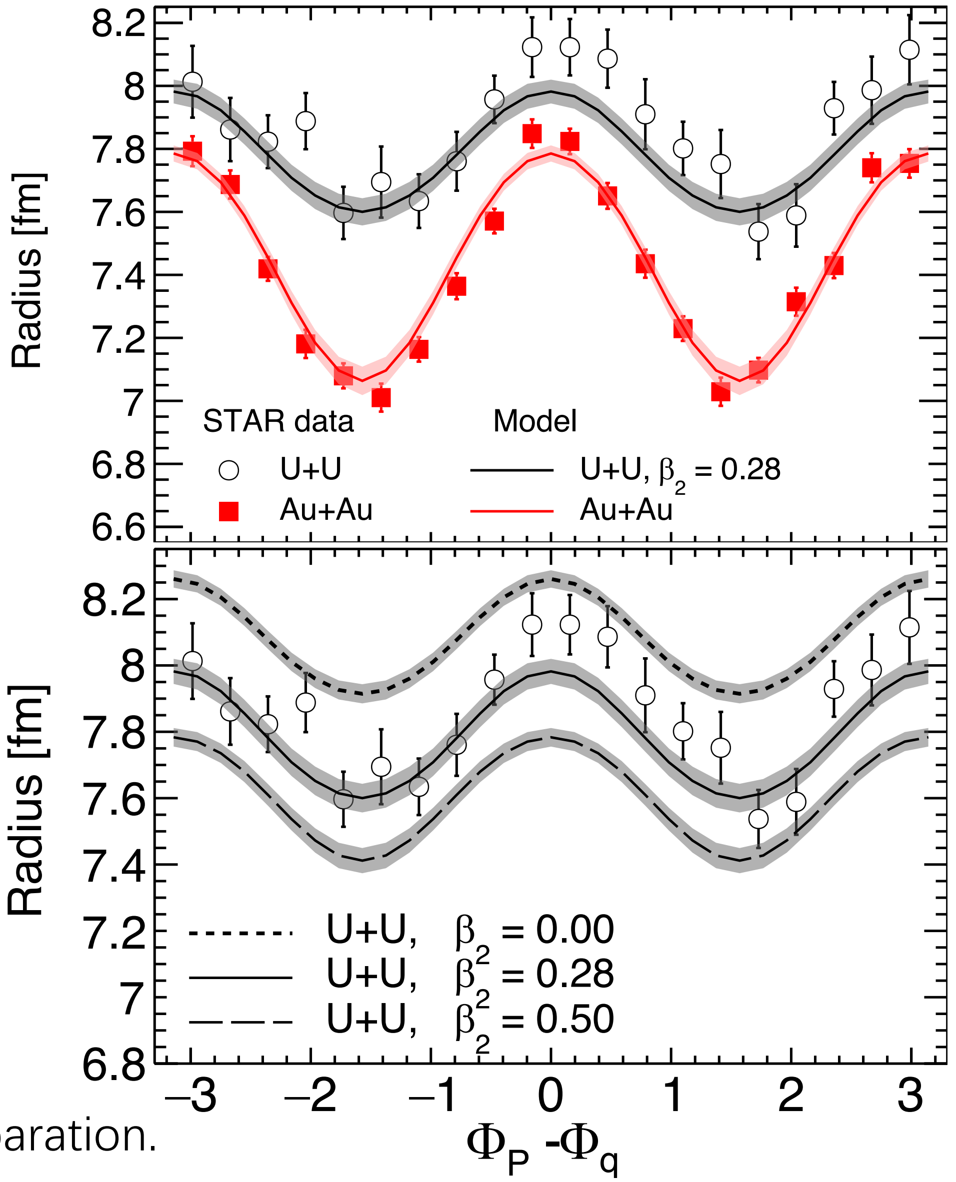
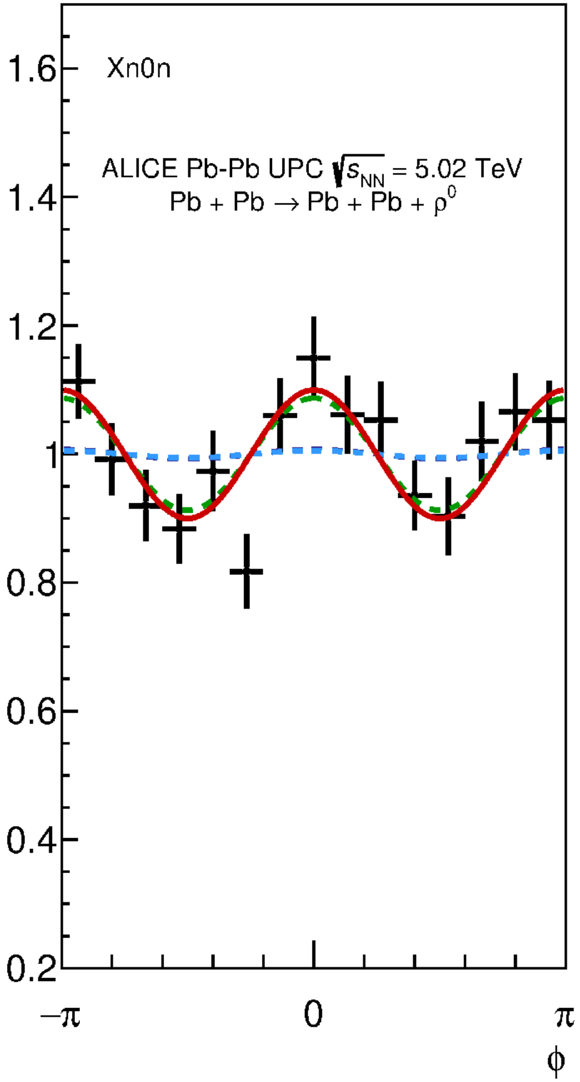
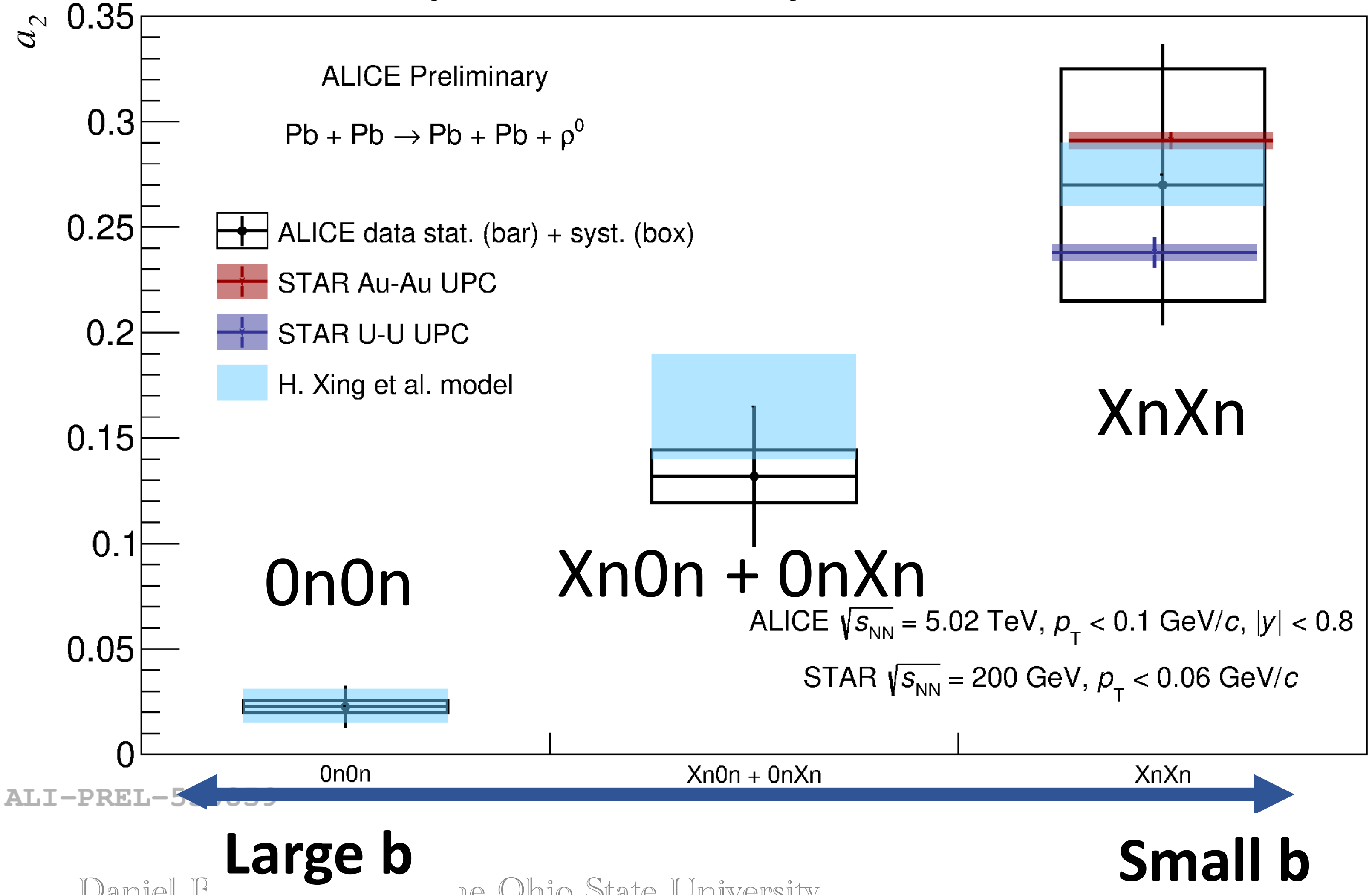


H.Mantysaari, F. Salazar, B.Schenke, C. Shen and W. Zhao, in preparation.

Confirmation from ALICE (New at QM Sept 2023)

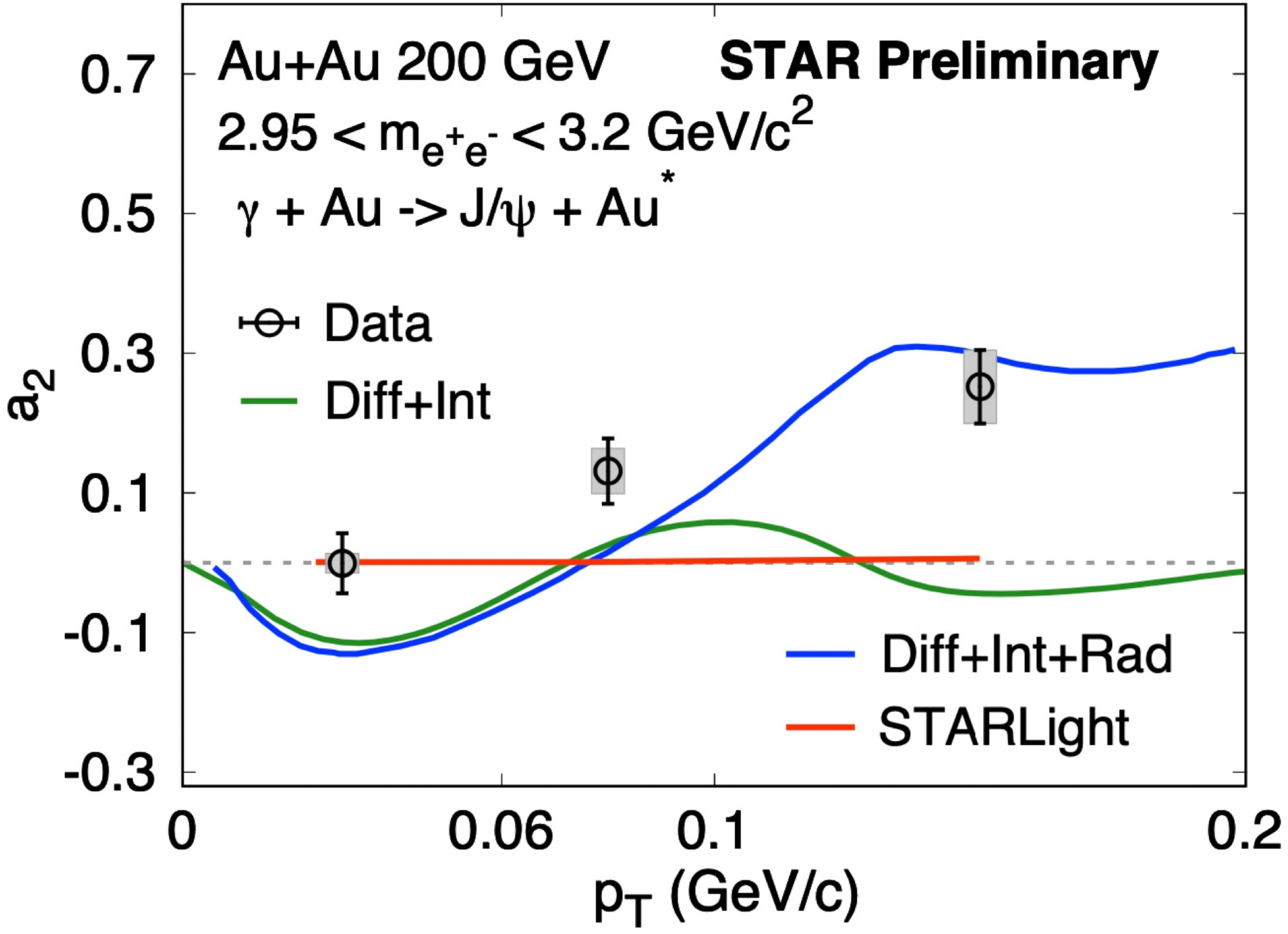


Neutron emission categories test the impact parameter dependence



Polarization effects: coherent diffractive J/ψ

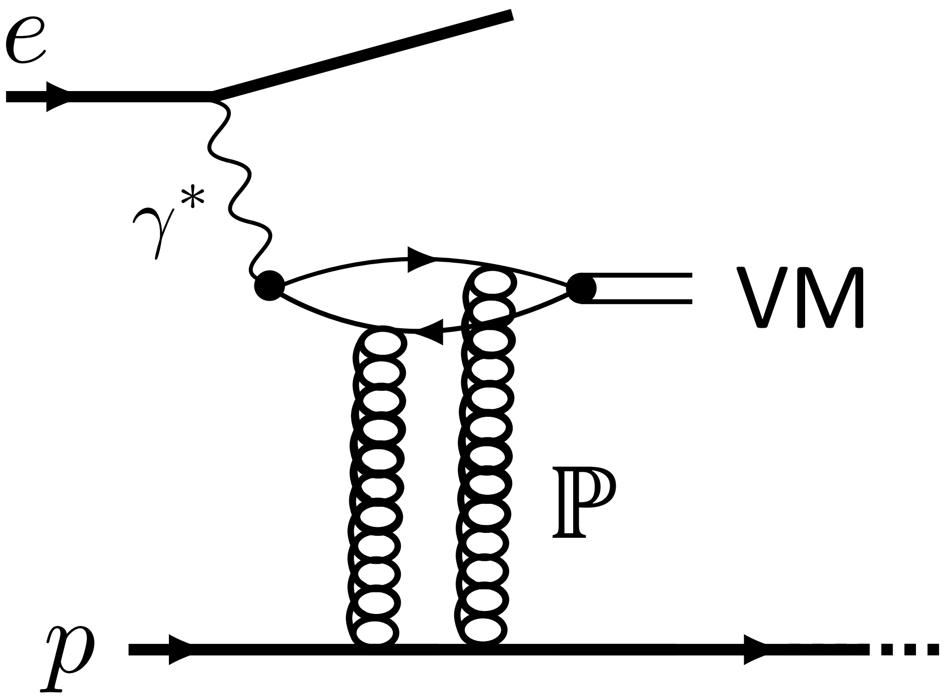
- New STAR measurement of J/ψ at QM in Sept 2023
- Consistent within error with Diffraction + Interference (Diff+Int) effect at low p_T
- Effect of Soft Photon radiation (Rad) visible at higher p_T



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]



Photon energies $\gtrsim$ 10 GeV: probe gluon distribution - Interaction through $\mathbb{P}$omeron (two gluon state at lowest order)

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[2] ZEUS Collaboration. *Eur. Phys. J. C* **2**, 247–267 (1998).
[3] See refs 1-25 in [2]

The amplitude has three components:

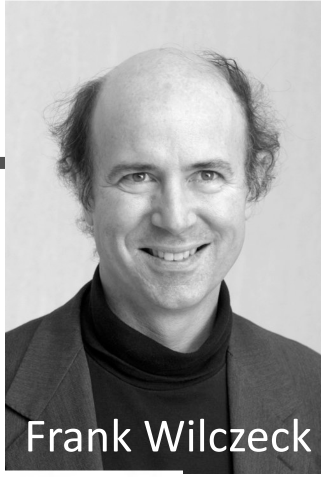
$$T^{\gamma^\star p \to Vp}(x;t) = \int_0^1 \mathrm{d}z \int \mathrm{d}^2\mathbf{r}\, \Psi^\gamma(z,\mathbf{r}) \cdot \sigma^{q\bar{q}-p}(x,\mathbf{r};t) \cdot \Psi^V(z,\mathbf{r})$$

Photon — Diffractive Dipole — Vector Meson

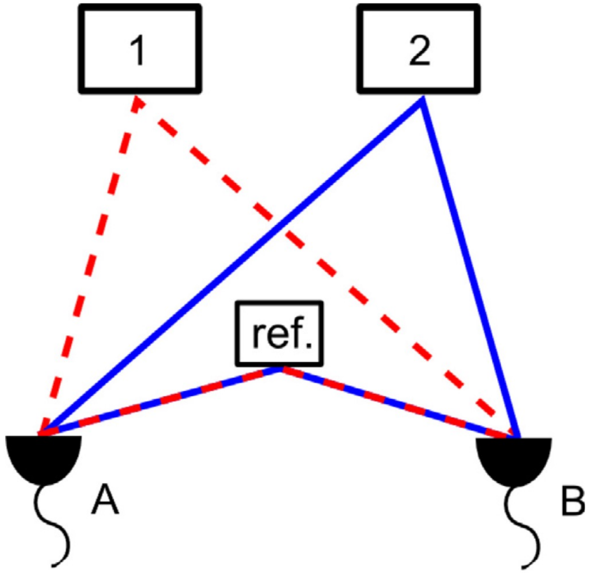
Photon quantum numbers $J^{PC} = 1^{--}$: Can transform into a 'heavy photon'

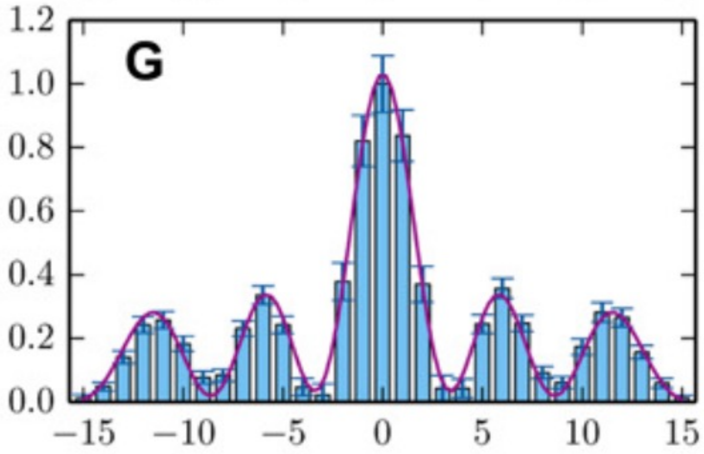
i.e. a vector meson ($\rho^0, \phi, J/\psi$) with $J^P = 1^-$

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).

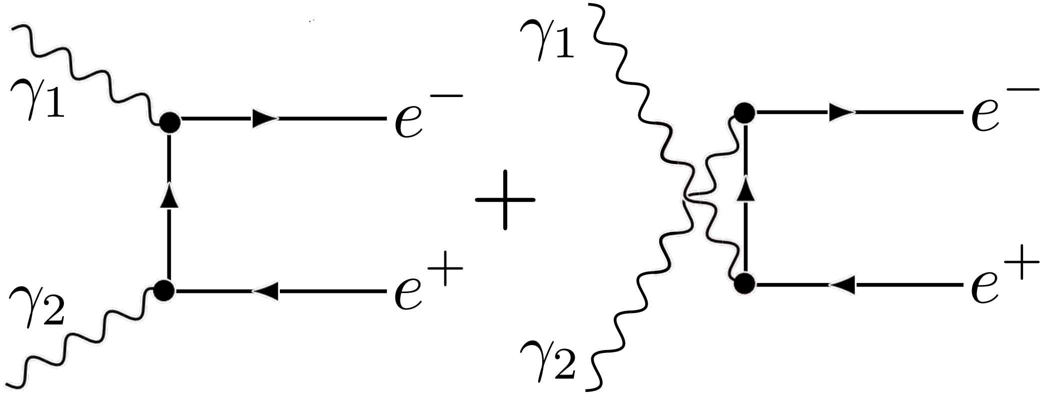
The Breit-Wheeler Process

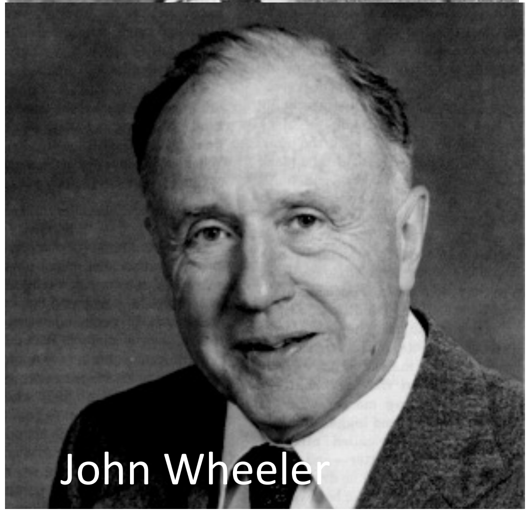
DECEMBER 15, 1934 PHYSICAL REVIEW VOLUME 46

Collision of Two Light Quanta

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

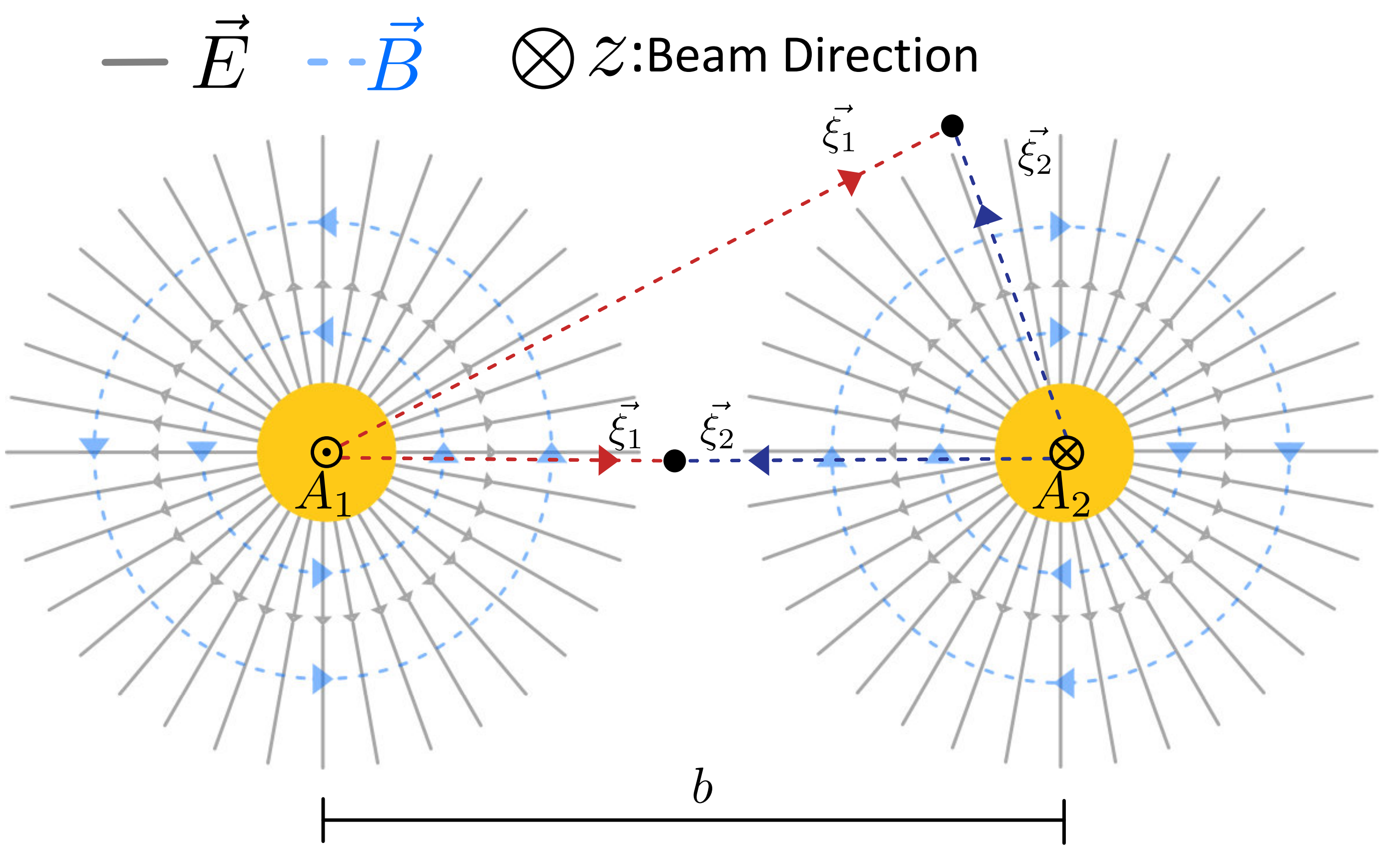
(Received October 23, 1934)

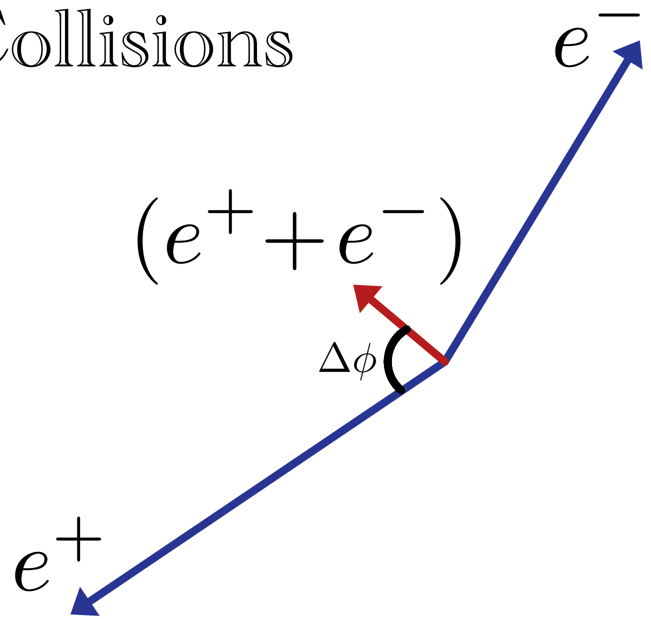




- Non-linear effect forbidden in classical electromagnetism
- At lowest order, two Feynman diagrams contribute and interfere
- Only tree level process still not observed observed after 80+ years!

Photon *Polarization* In Ultra-Peripheral Collisions





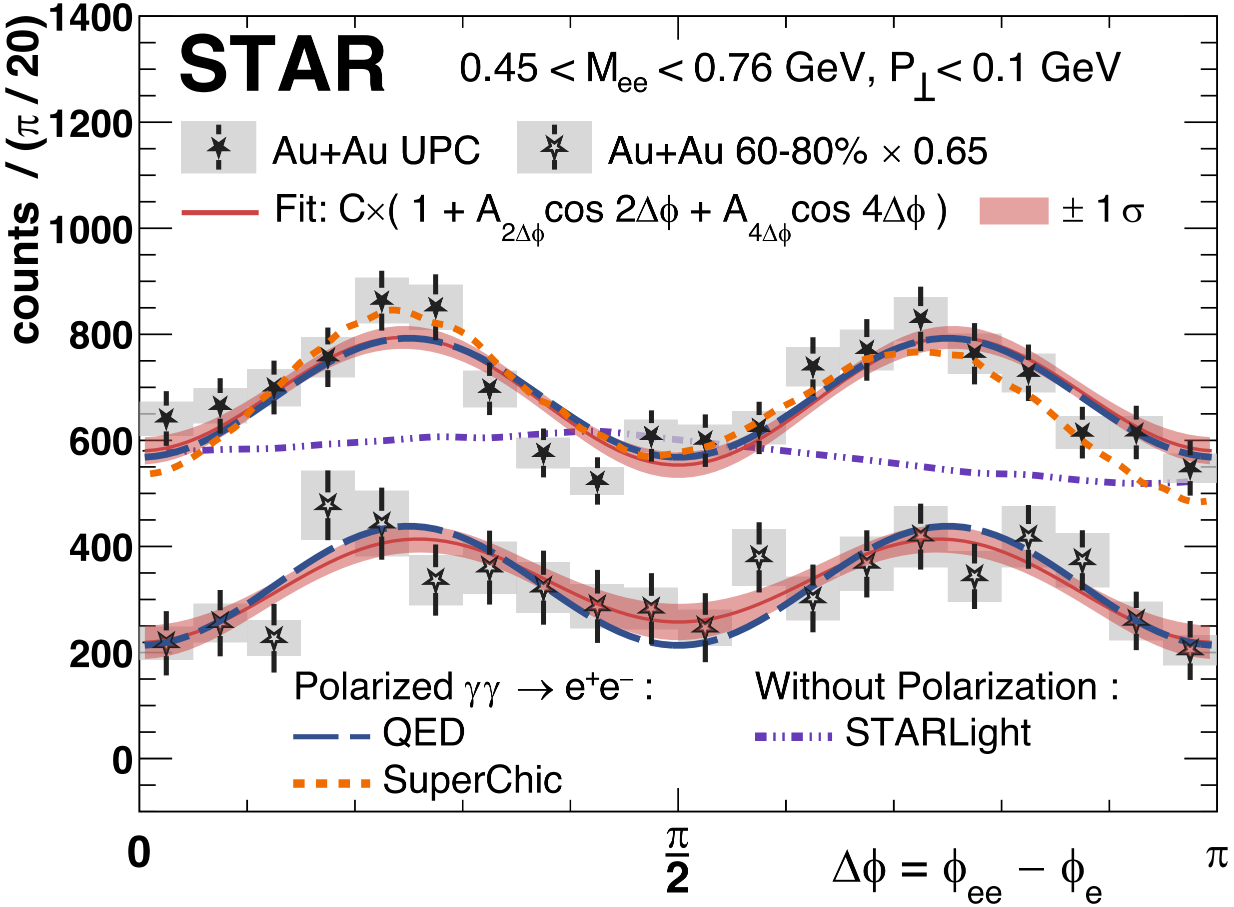
- Polarization vector ξ: aligned radially with the "emitting" source
- Intrinsic photon spin converted into **orbital angular momentum**
- Observable as anisotropy in $e^\pm$ momentum

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).

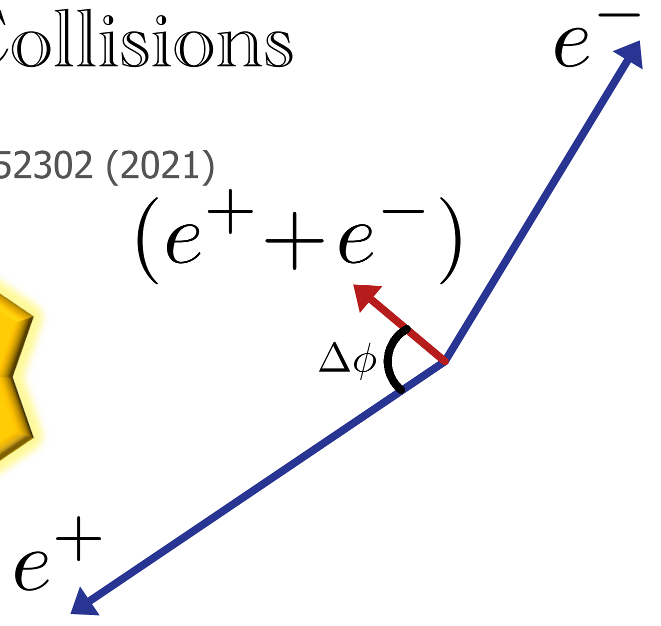
S. Bragin, et. al., *Phys. Rev. Lett.* 119 (2017), 250403
R. P. Mignani, *et al.*, *Mon. Not. Roy. Astron. Soc.* 465 (2017), 492

Photon *Polarization* In Ultra-Peripheral Collisions



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

Breit-Wheeler Discovery 2021 STAR



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Experimental access to photon polarization demonstrated

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
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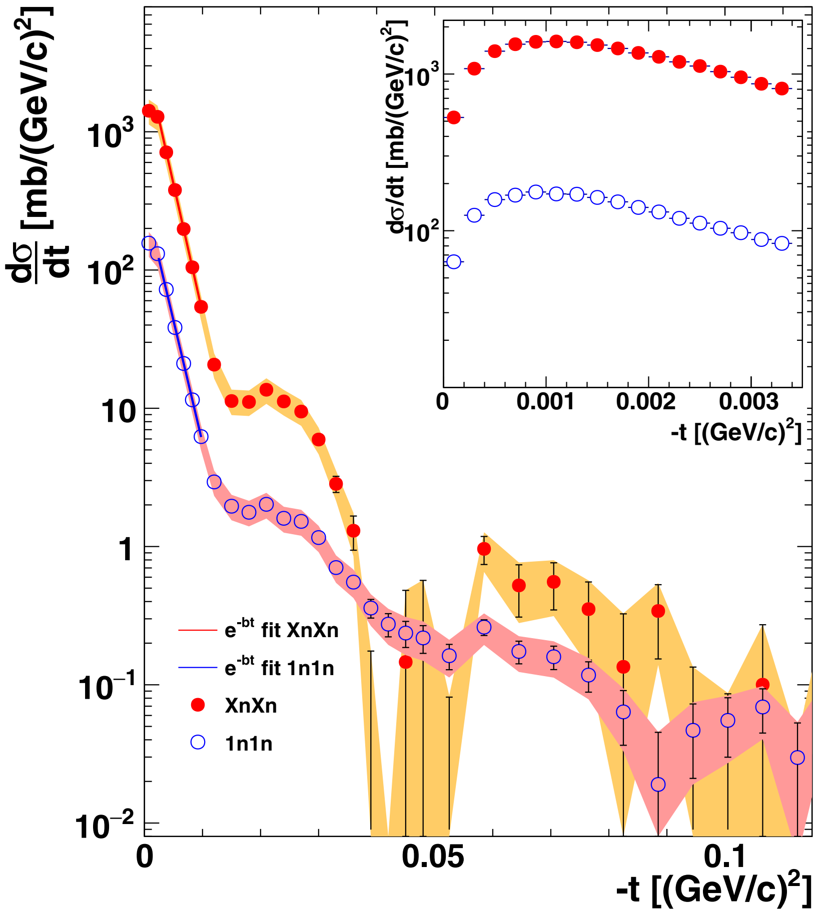
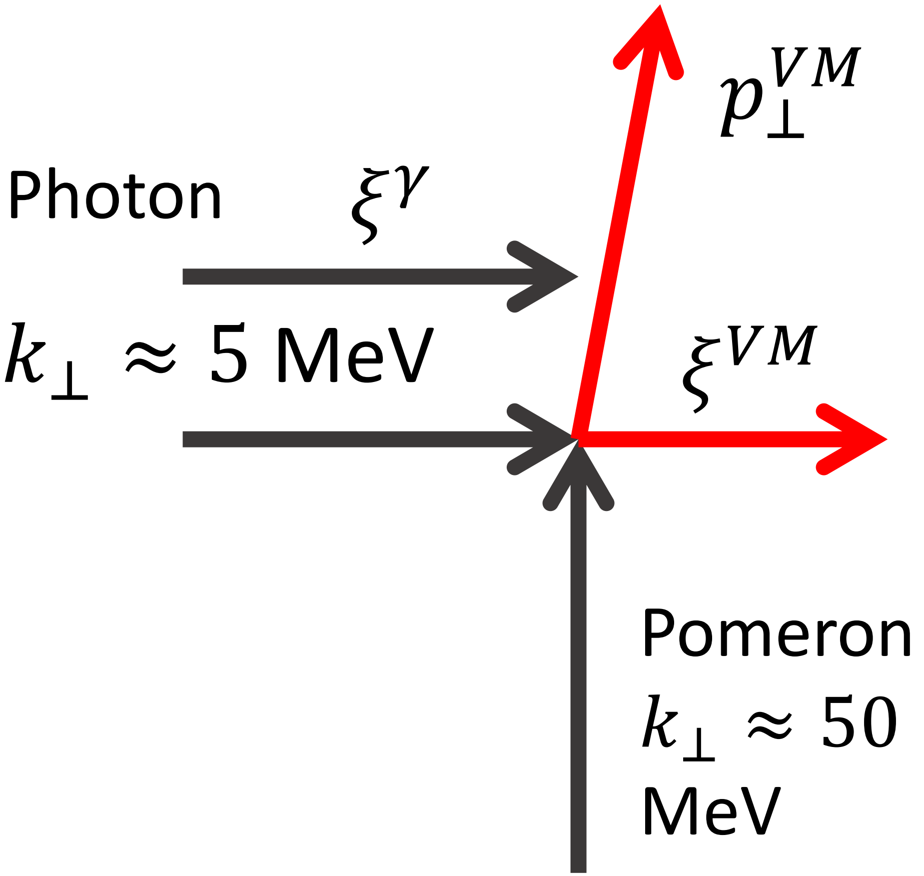
Trivial Spin-Momentum Alignment?





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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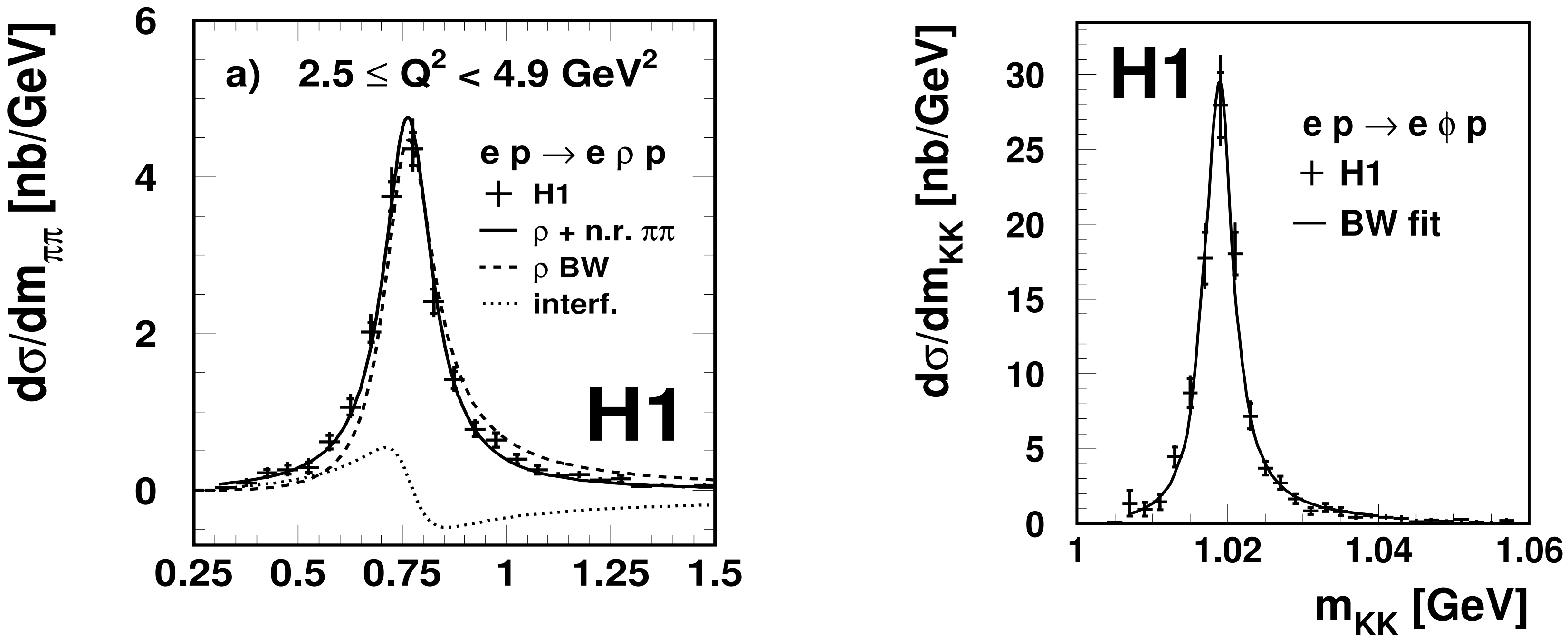
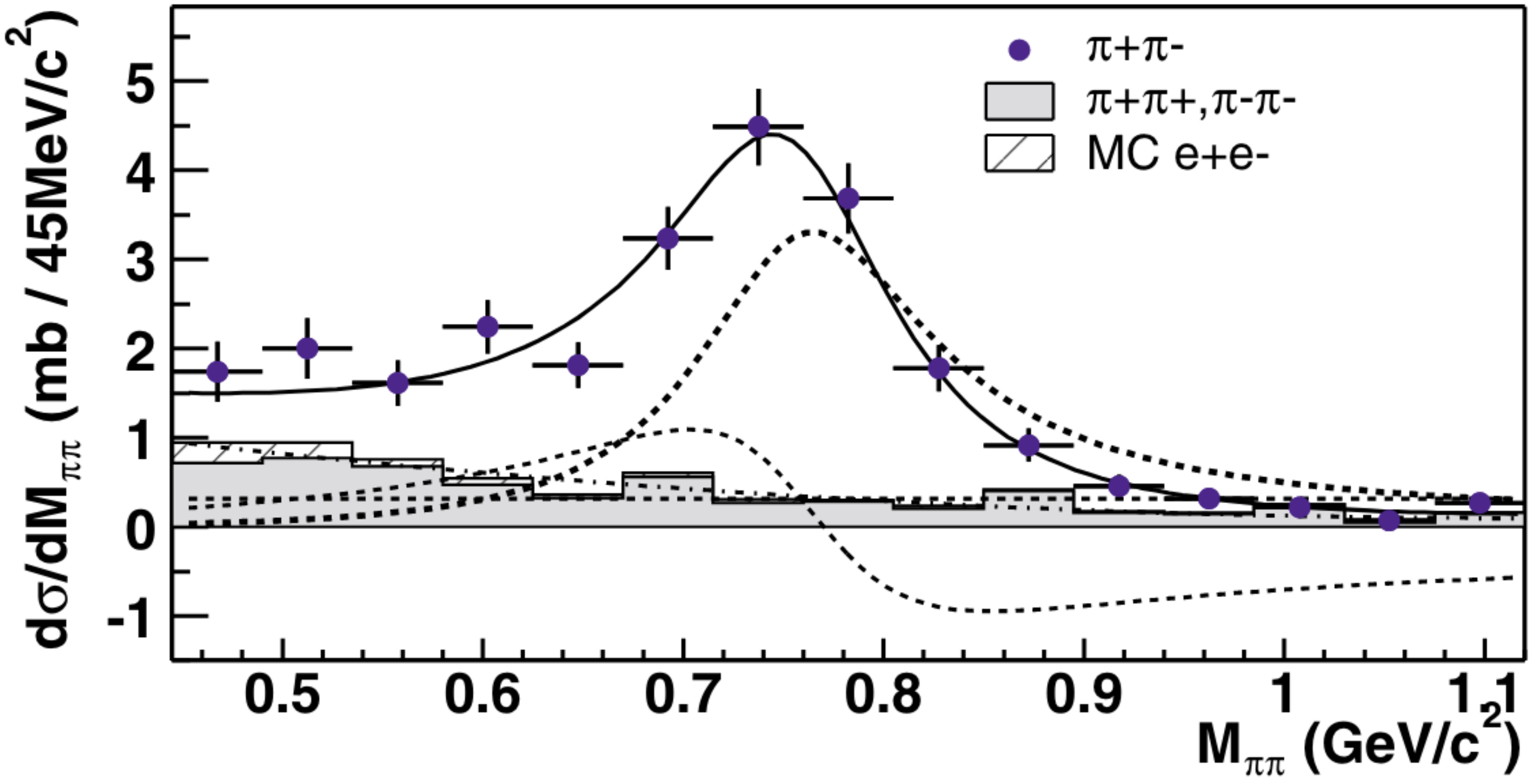


Measurements from H1, ZEUS etc. explored proton via diffractive ρ^0 and ϕ production

Past Photo-Nuclear Measurements

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



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

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

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**