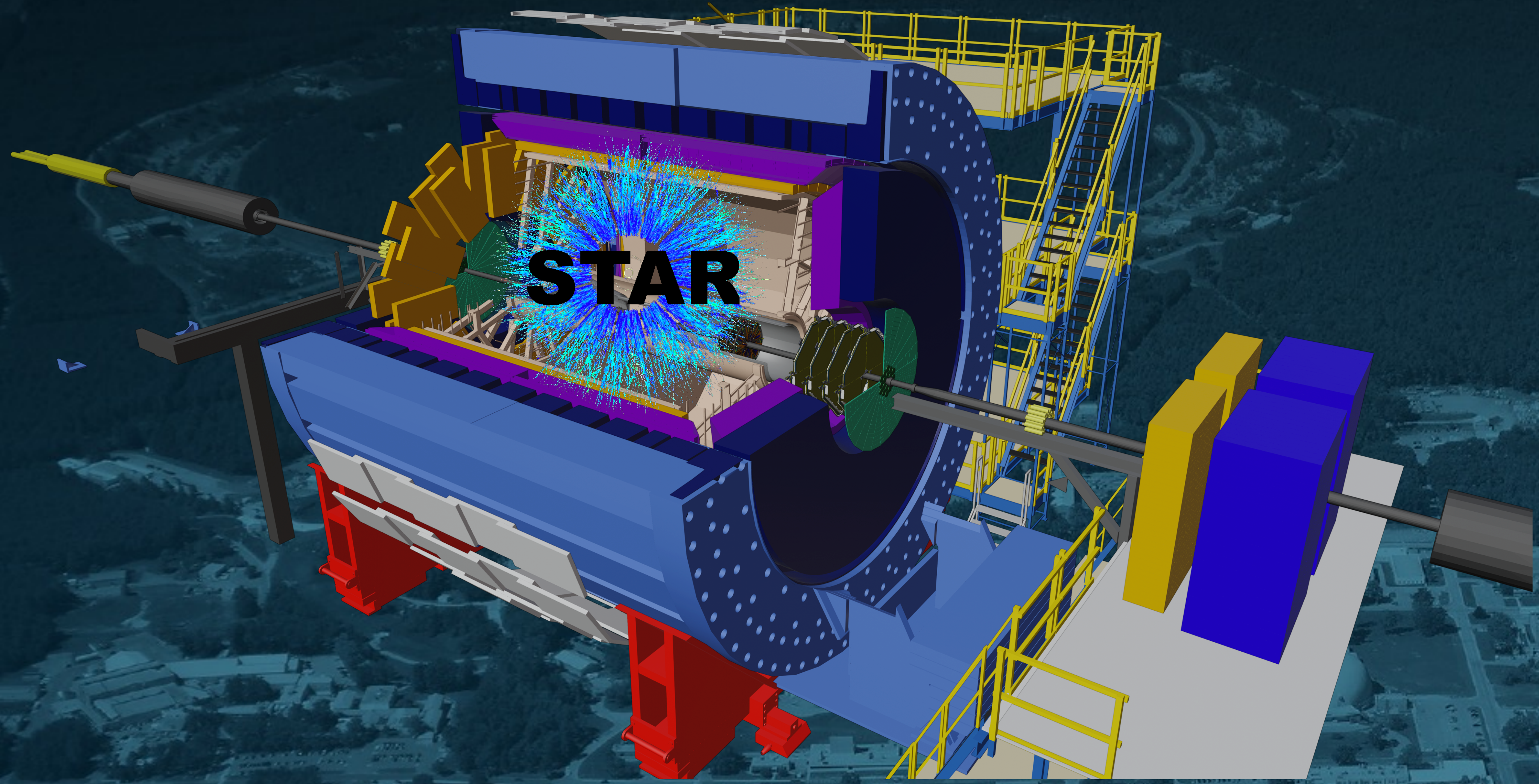


Brookhaven National Laboratory

APS April Meeting

April 3 - 6, 2024
Sacramento & Virtual

Exclusive Vector Meson Photoproduction and Interference Effects in Ultra Peripheral Collisions at STAR

Ashik Ikbal Sheikh
(For the STAR Collaboration)

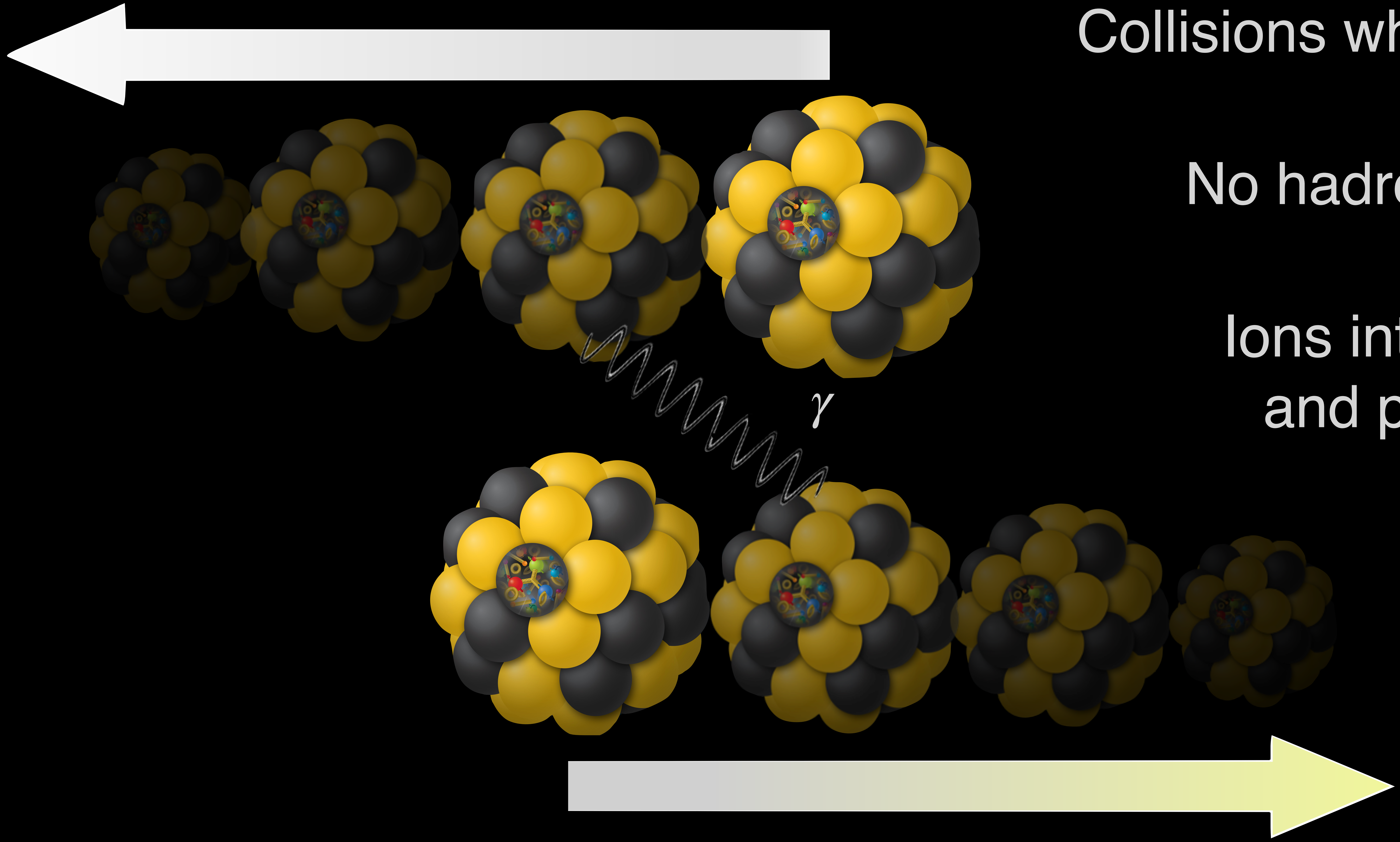
Kent State University

KENT STATE UNIVERSITY

Supported in part by
U.S. DEPARTMENT OF ENERGY | Office of Science

April 3 - 6, 2024, Sacramento, USA

Heavy Ions miss each other: Ultra-peripheral Collisions (UPCs)



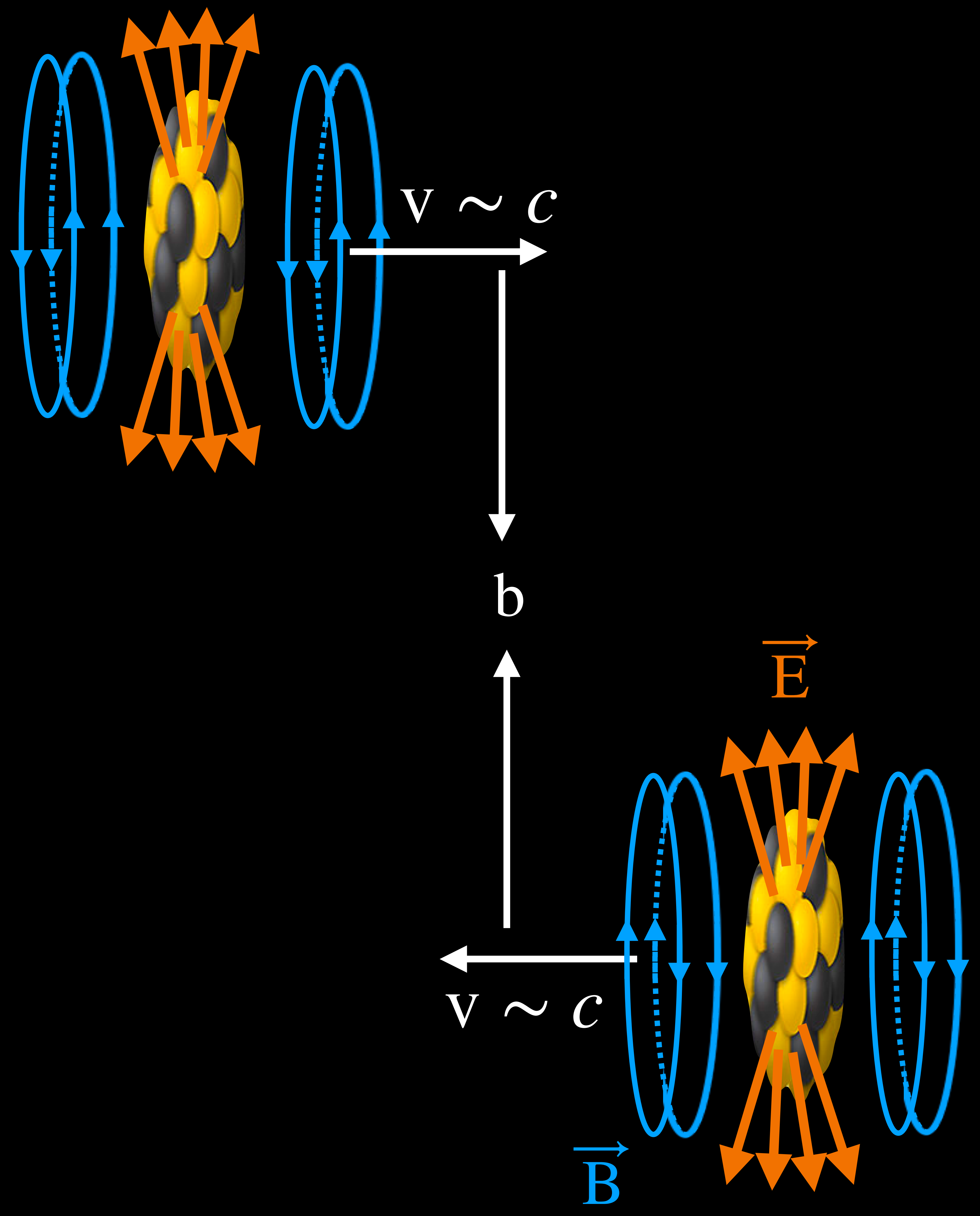
Collisions where nuclei do NOT collide

No hadronic collisions happen

Ions interact through photon-ion and photon-photon collisions

=> Called Ultra-peripheral collisions (UPCs)

The strongest EM-fields in UPCs



- In UPCs,

$$E_{max} = 10^{18}\ \text{V/m}\ ,\ B_{max} \sim 10^{14} - 10^{18}\ \text{T}$$

=> Strongest EM-field in the universe, but transient

- EM-field treated in terms of quasi-real photons

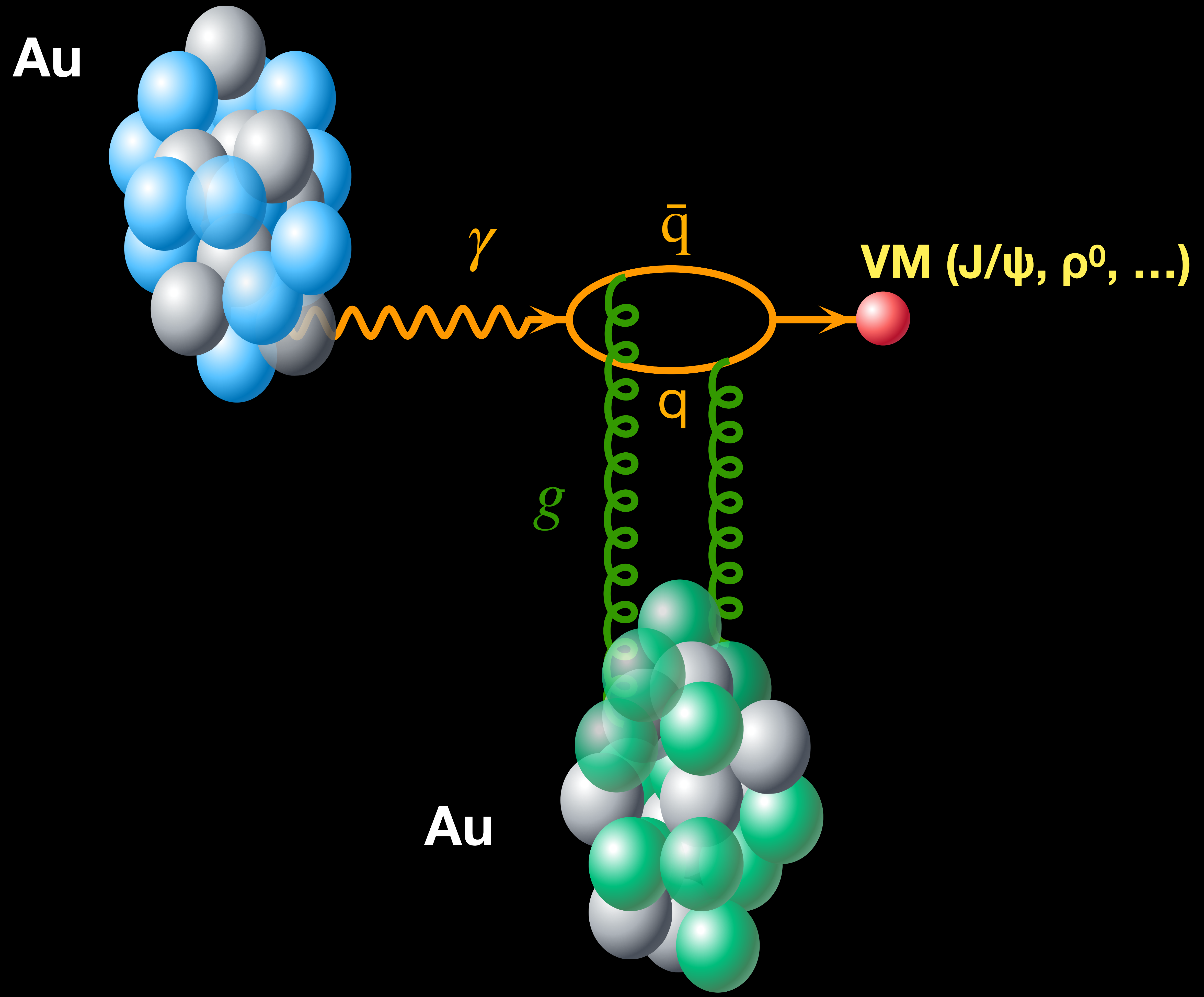
$$E_{\gamma,max} \sim \gamma\hbar c/R\ ;$$

$$E_{\gamma,max} \sim 30\ \text{GeV (RHIC)}$$

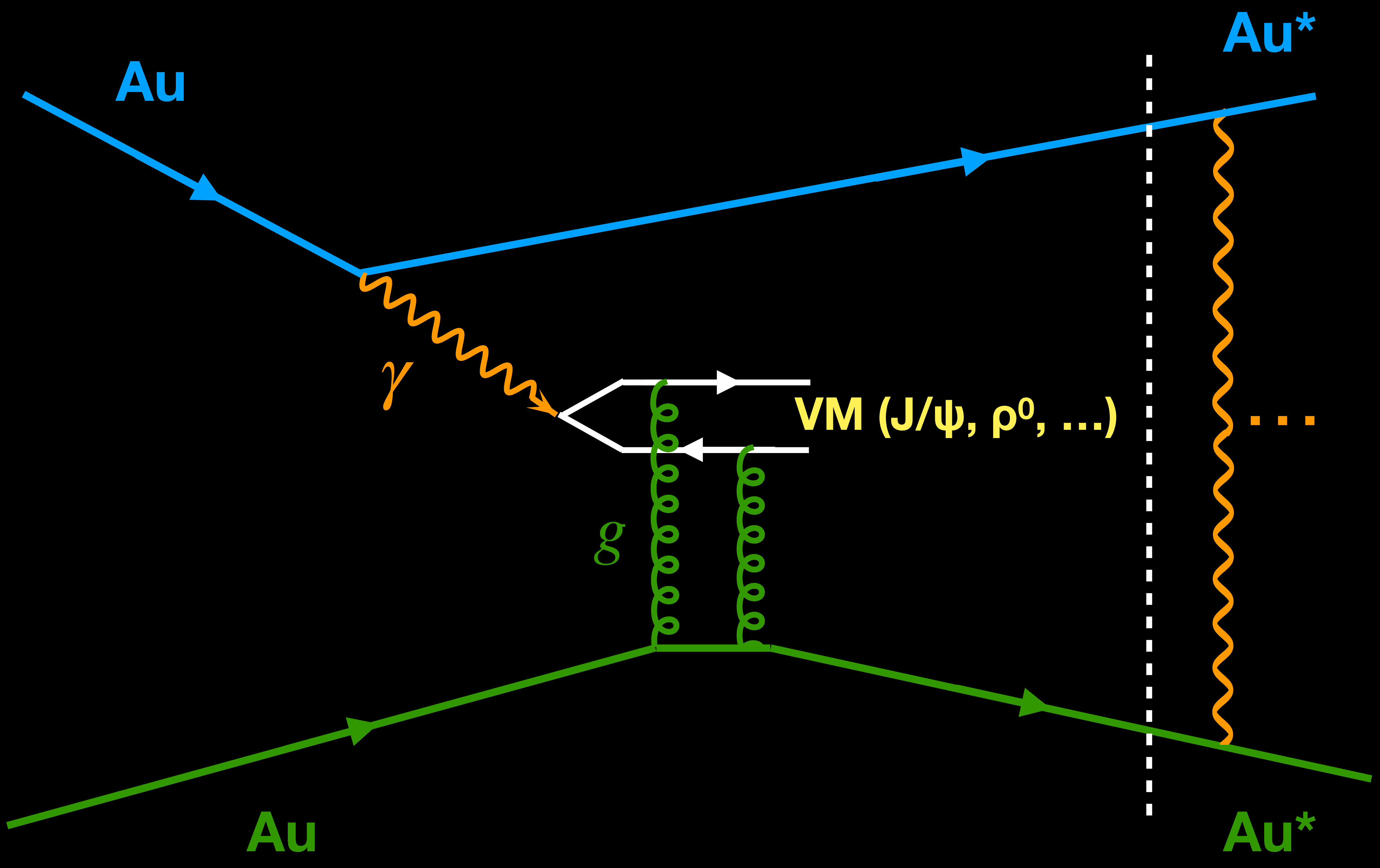
$$E_{\gamma,max} \sim 80\ \text{GeV (LHC)}$$

=> EM-fields are quantized as photons in UPCs

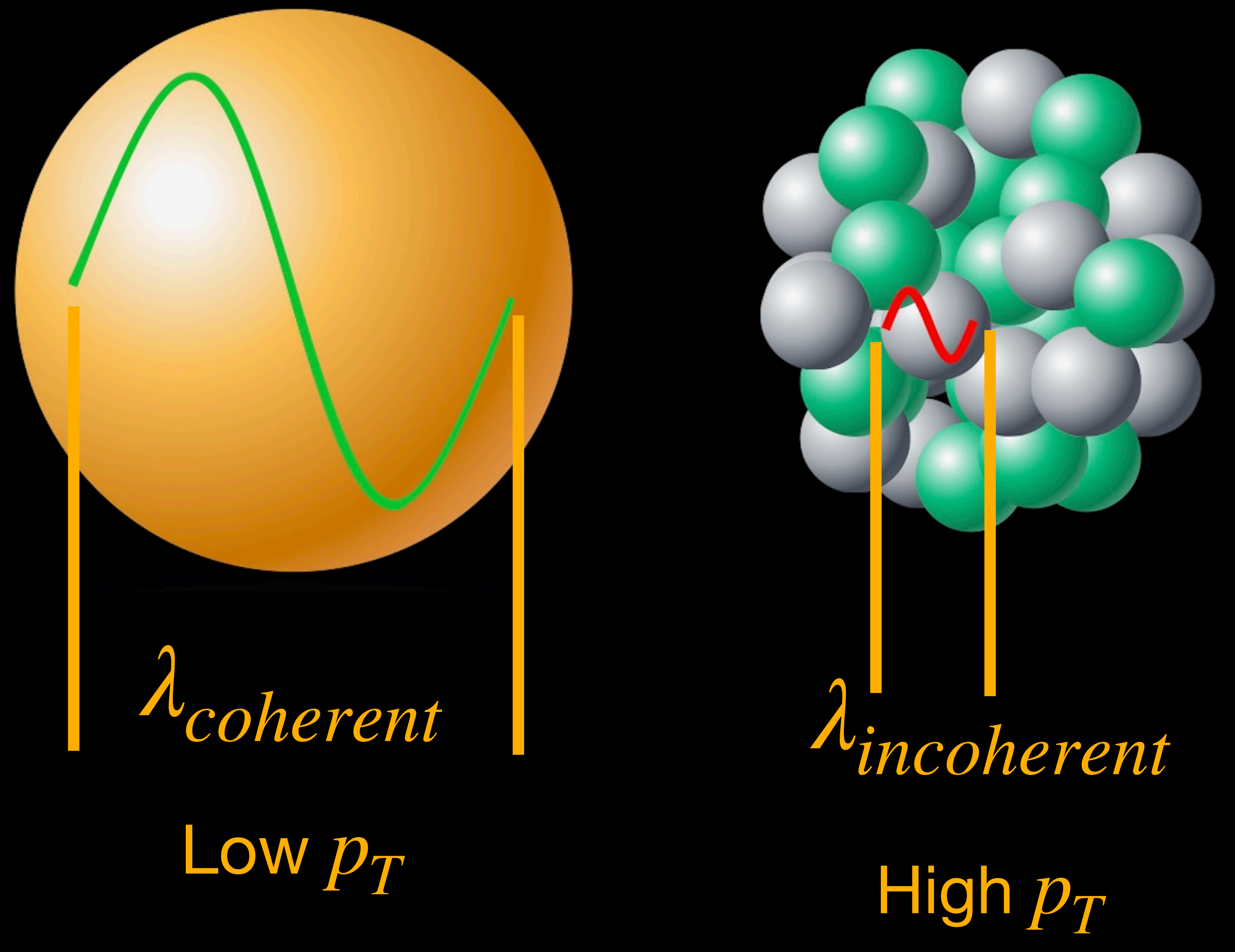
Photon-gluon scattering: Vector meson (VM) production via photon-nuclear interactions



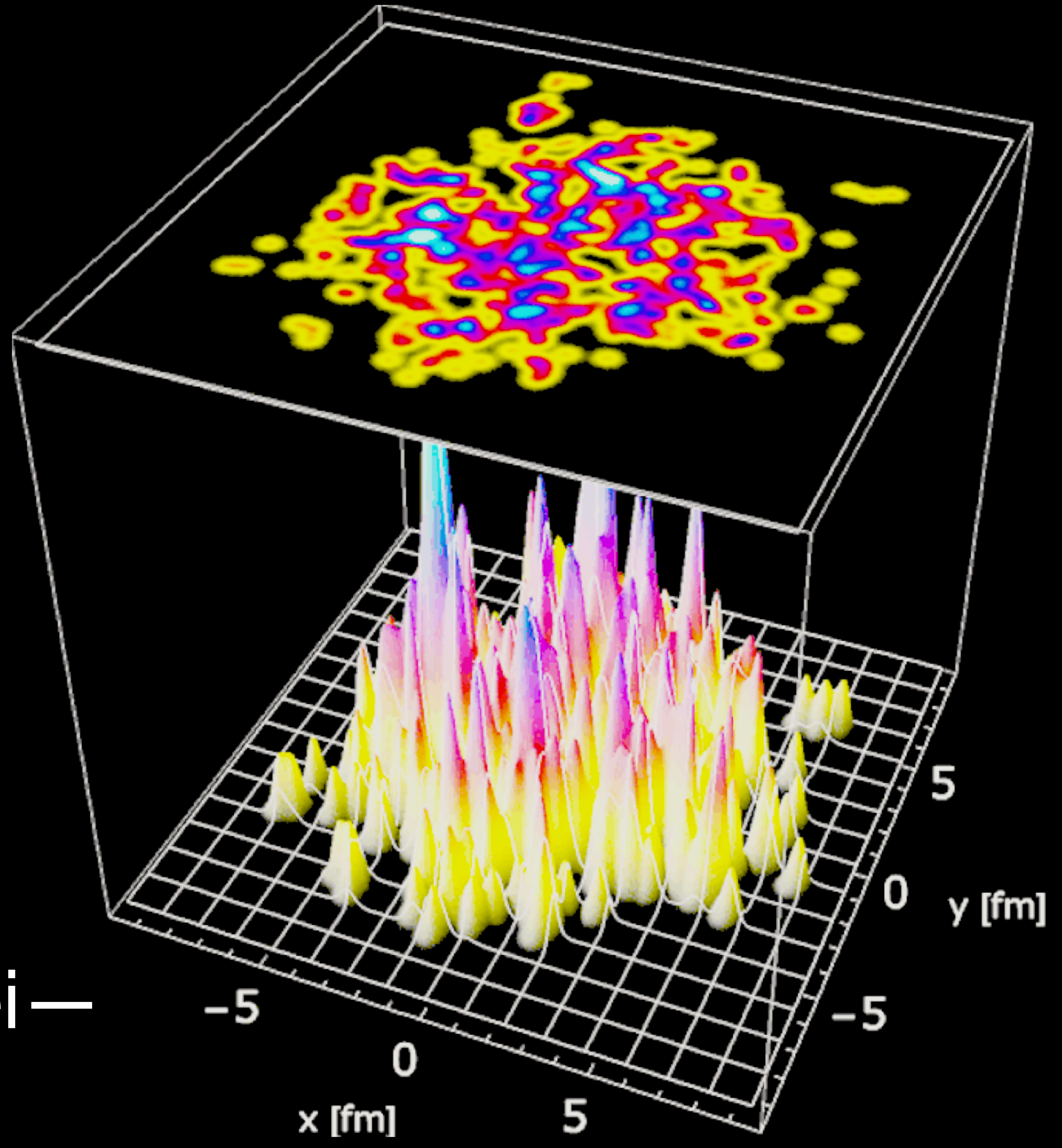
Photoproduction of Vector Mesons (VM) in UPC



UPC VM: Powerful probe of parton densities inside nuclei



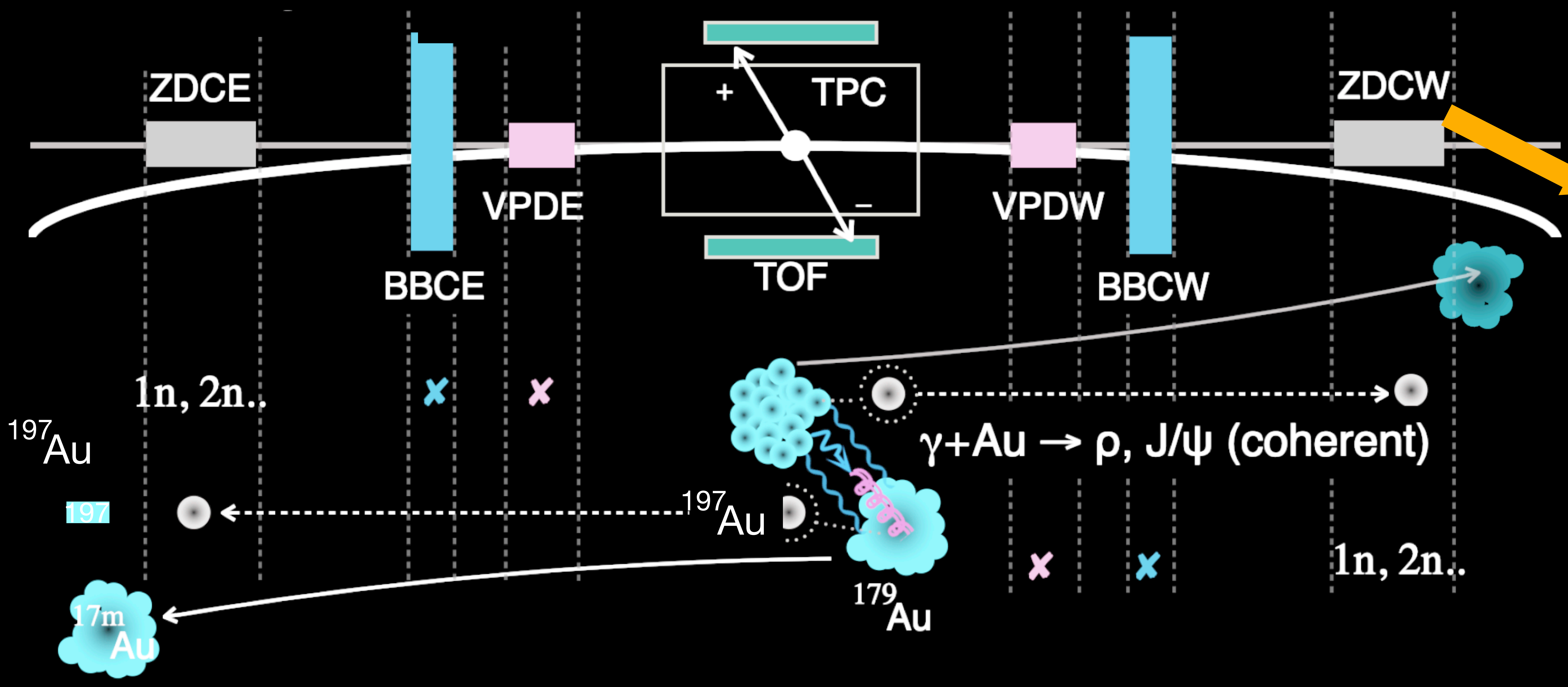
Satre simulation of parton density fluctuations, Fig: A. Kumar

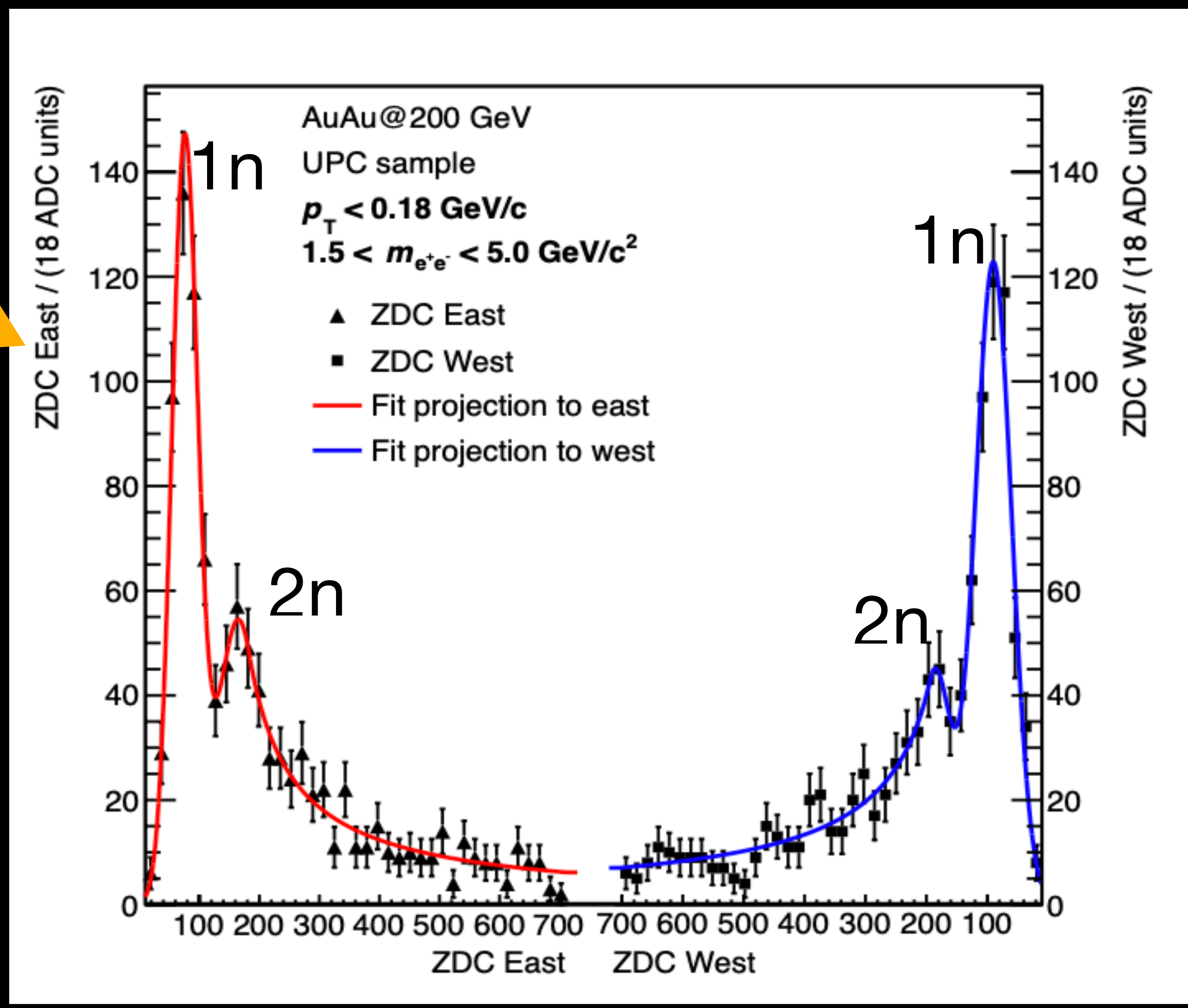


- Probes parton density & fluctuations inside nuclei— constraints for A+A initial state
- Modification of parton densities in heavy nuclei

=> VM helps to probe parton density inside nuclei before EIC era

UPC events with STAR detector



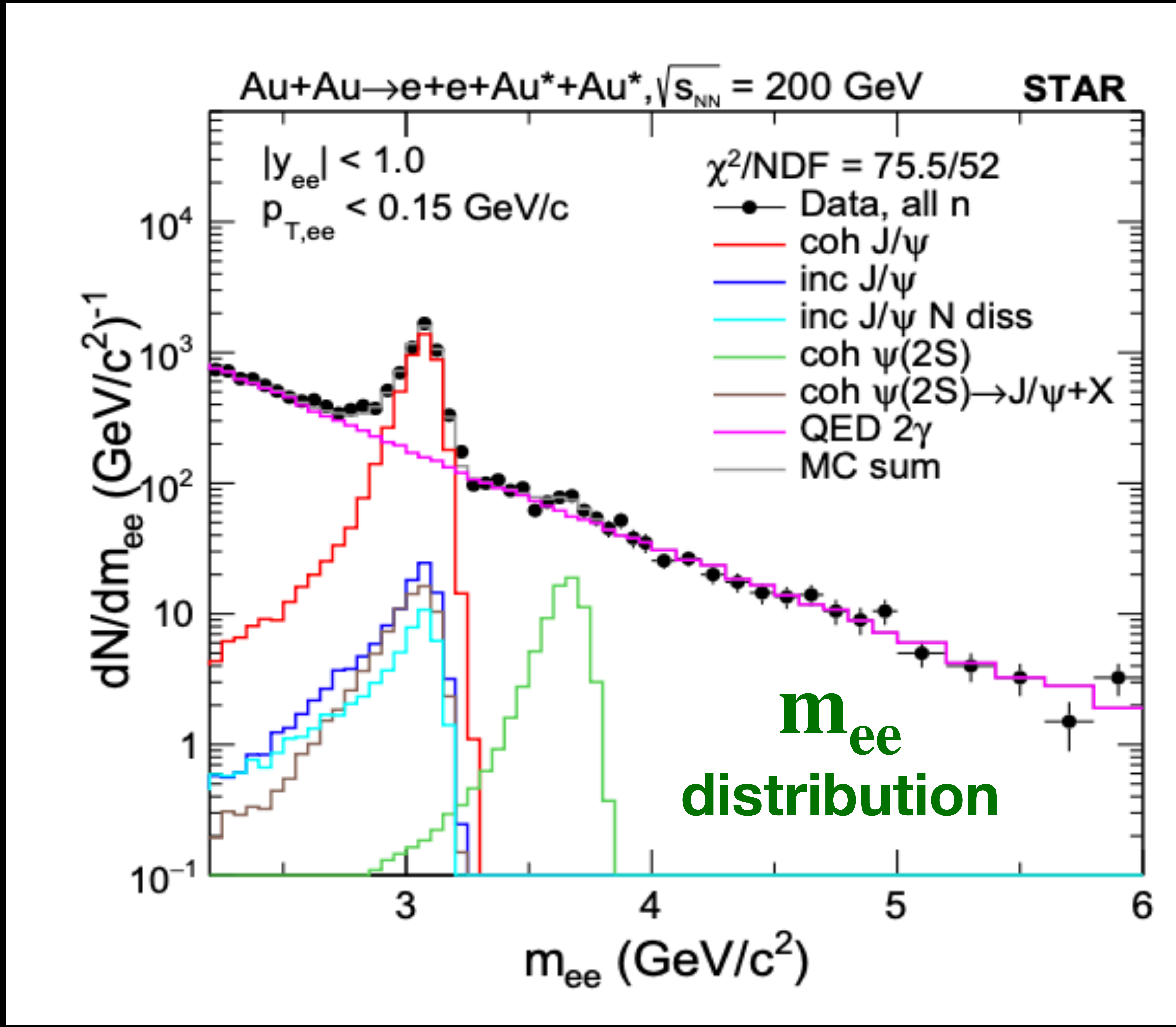


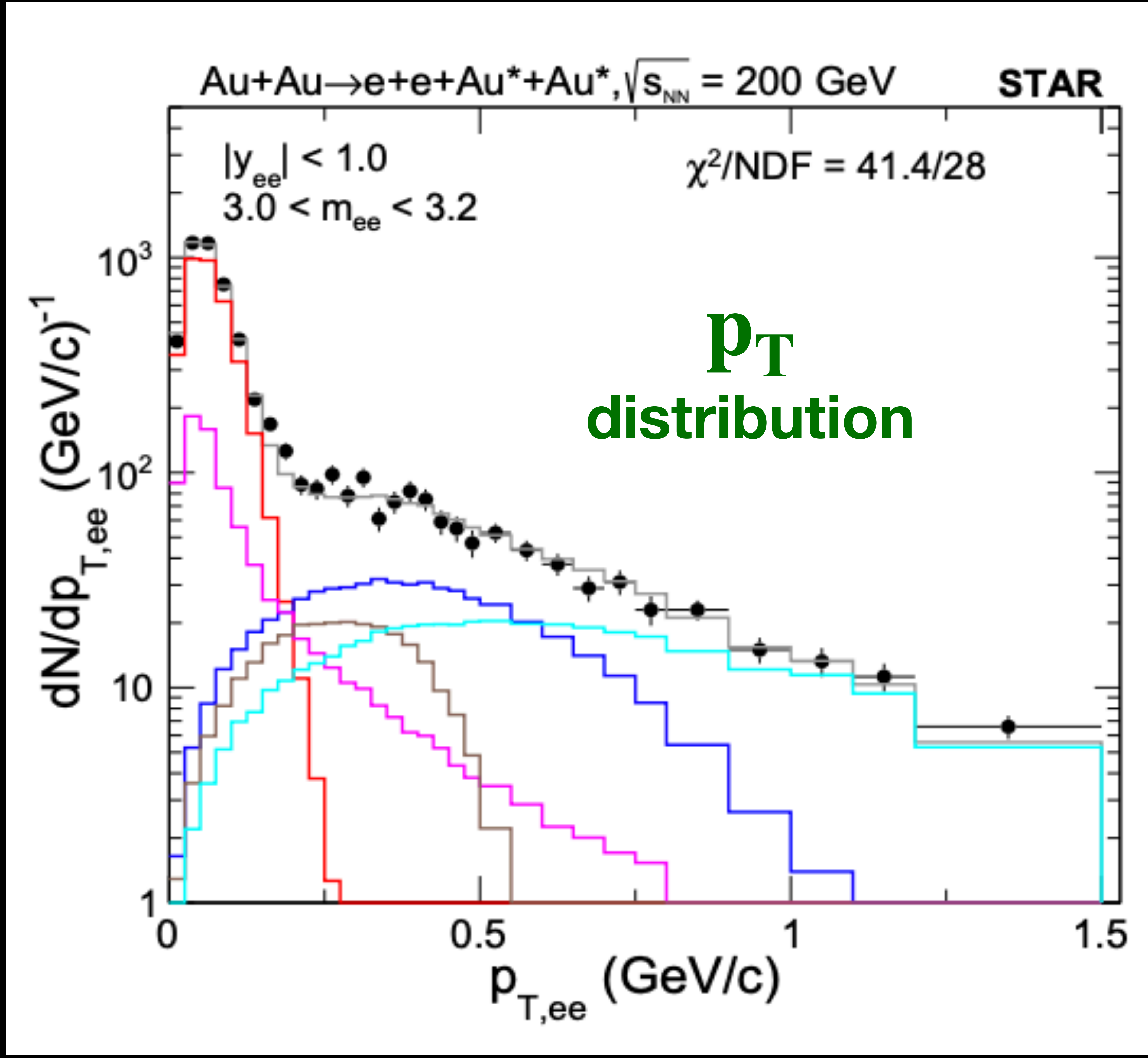
- ◉ Neutron(s) detected in ZDCs
- ◉ ZDC signals show peak structure for neutrons
- ◉ No activity in both BBCs => Diffractive events (η-gap)

=> Method to trigger UPC events

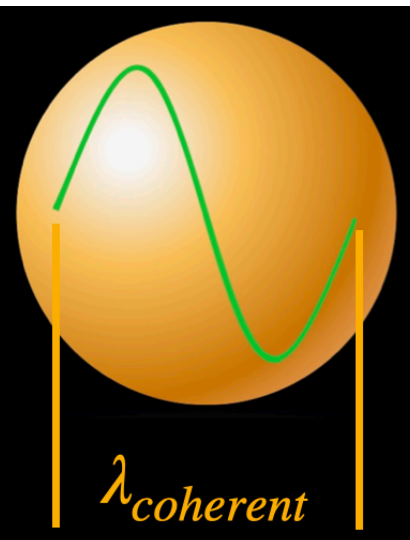
J/ψ measurements in 200 GeV Au+Au UPCs

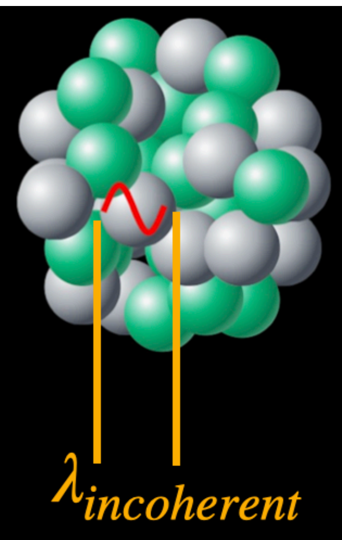
STAR, arXiv:2311.13632





=> Coherent and incoherent contributions can be disentangled via the combined fit of mass and p_T



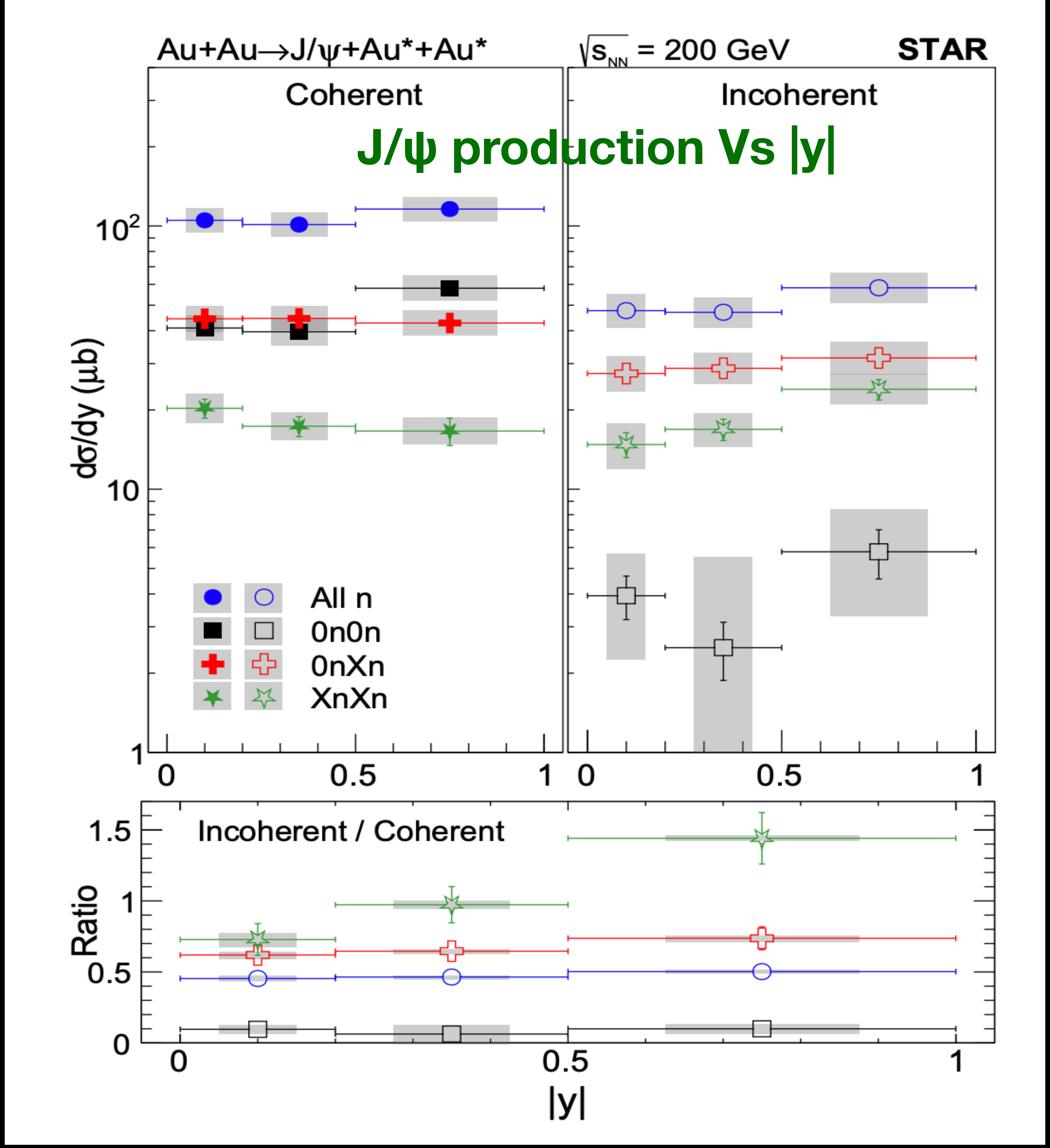


Rapidity dependence J/ψ production cross-section

STAR, arXiv:2311.13637

- Measured for coherent and incoherent contributions for different neutron emission in ZDCs
- Systematic unc. in incoherent to coherent cross-section ratio are largely cancelled
- Sensitive to the nuclear structure and deformation

=> Important to constrain theoretical models related to nuclear geometry

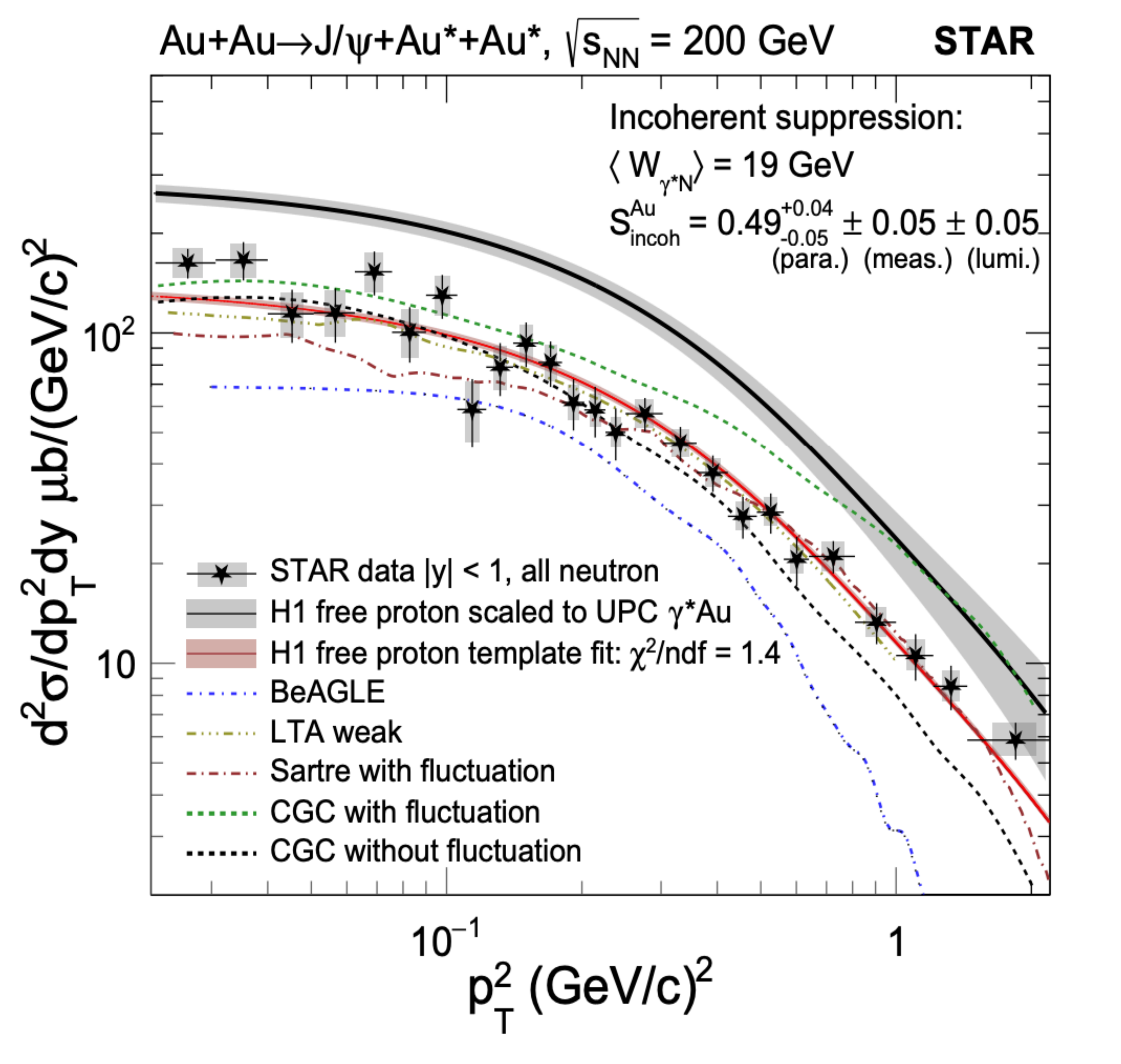


Incoherent J/ψ production cross-section vs p_T^2

STAR, arXiv:2311.13632

- ◉ Incoherent production compared with H1 data with free proton
- ◉ Strong nuclear suppression (~49%) seen
  (Mäntysaari et. al, Phys. Rev. Lett. **117** (2016) 5, 052301)
- ◉ Models found H1 data supports sub-nucleonic fluctuations
  (Mäntysaari et. al, Phys. Rev. D **106** (2022) 7, 074019)
- ◉ STAR data shows the bound nucleon has similar shape as the free proton — similar sub-nucleonic fluctuations in heavy nuclei

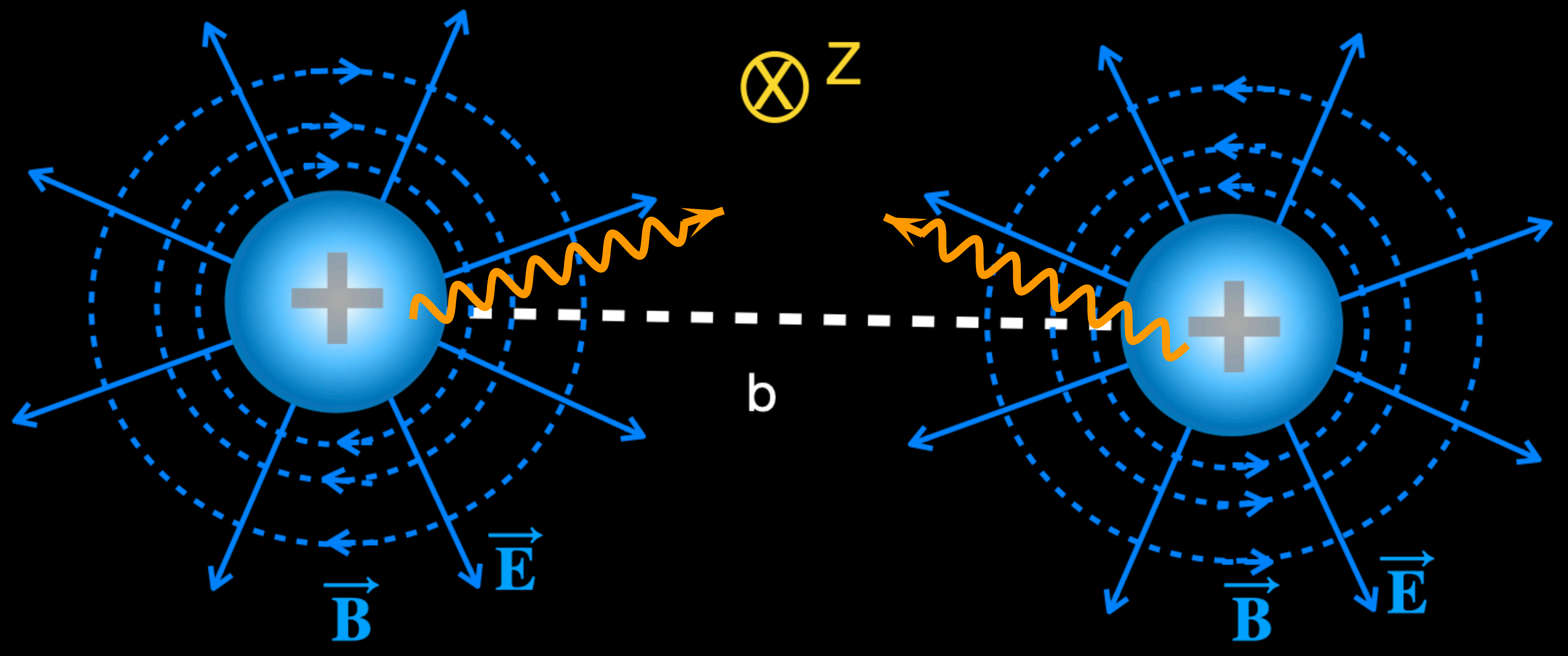
=> Strong nuclear suppression and sub-nucleonic fluctuations in Au nucleus



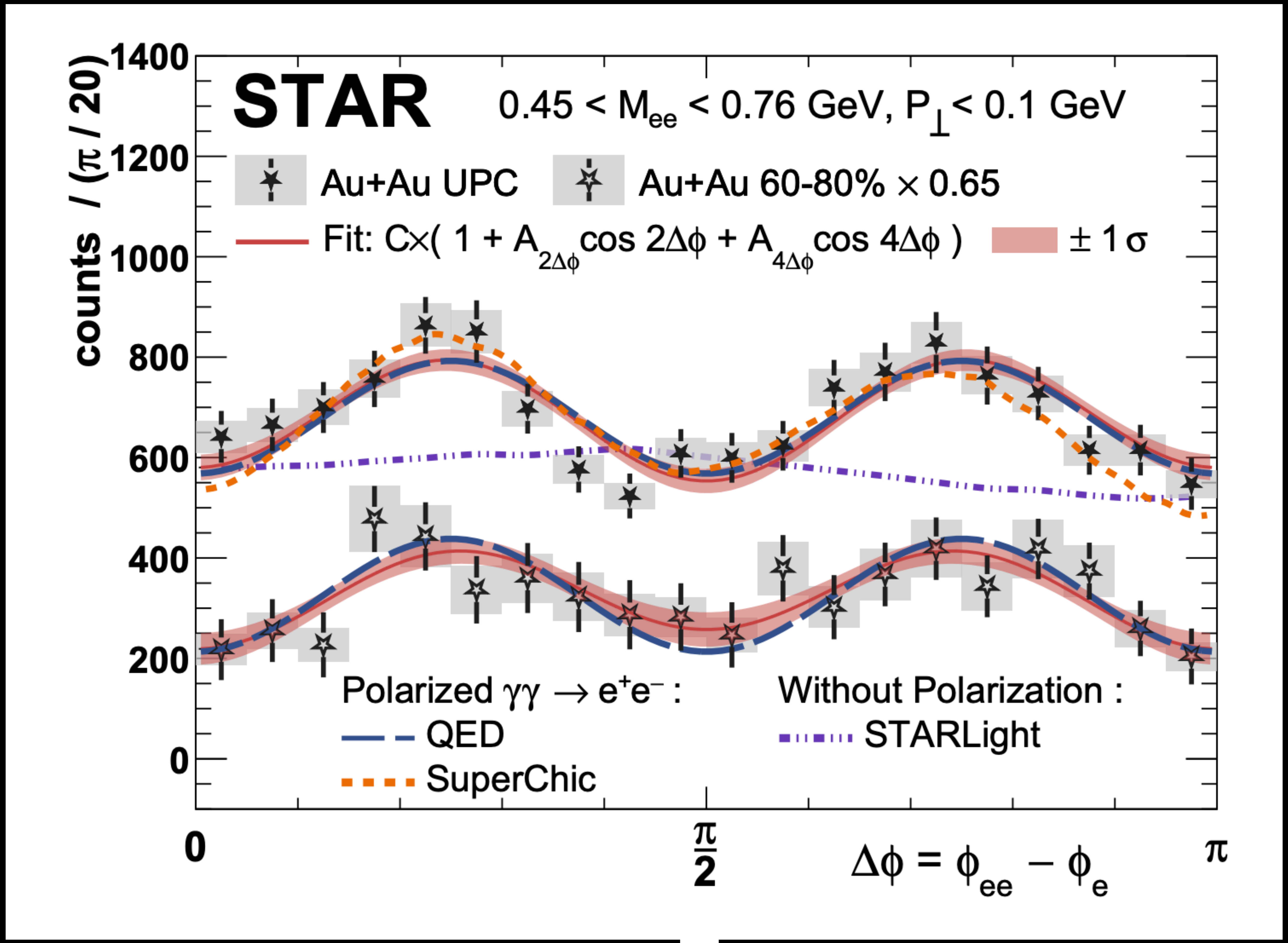
VM spin interference: A novel quantum phenomenon for high resolution gluon imaging

Polarized Photons from colliding nuclei

STAR, Phys. Rev. Lett. 127 (2021) 52302



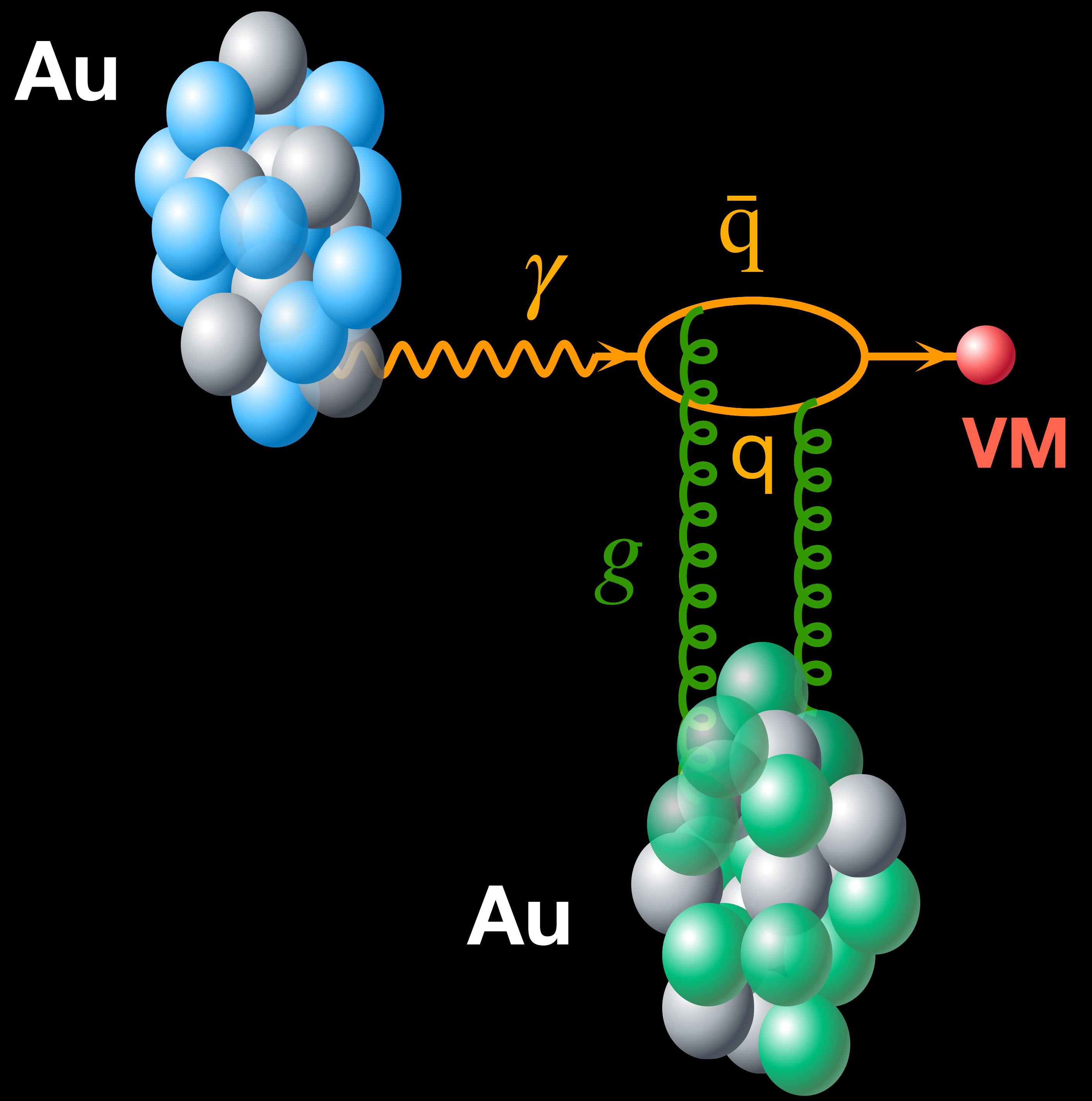
Transverse view of Lorentz contracted nuclei

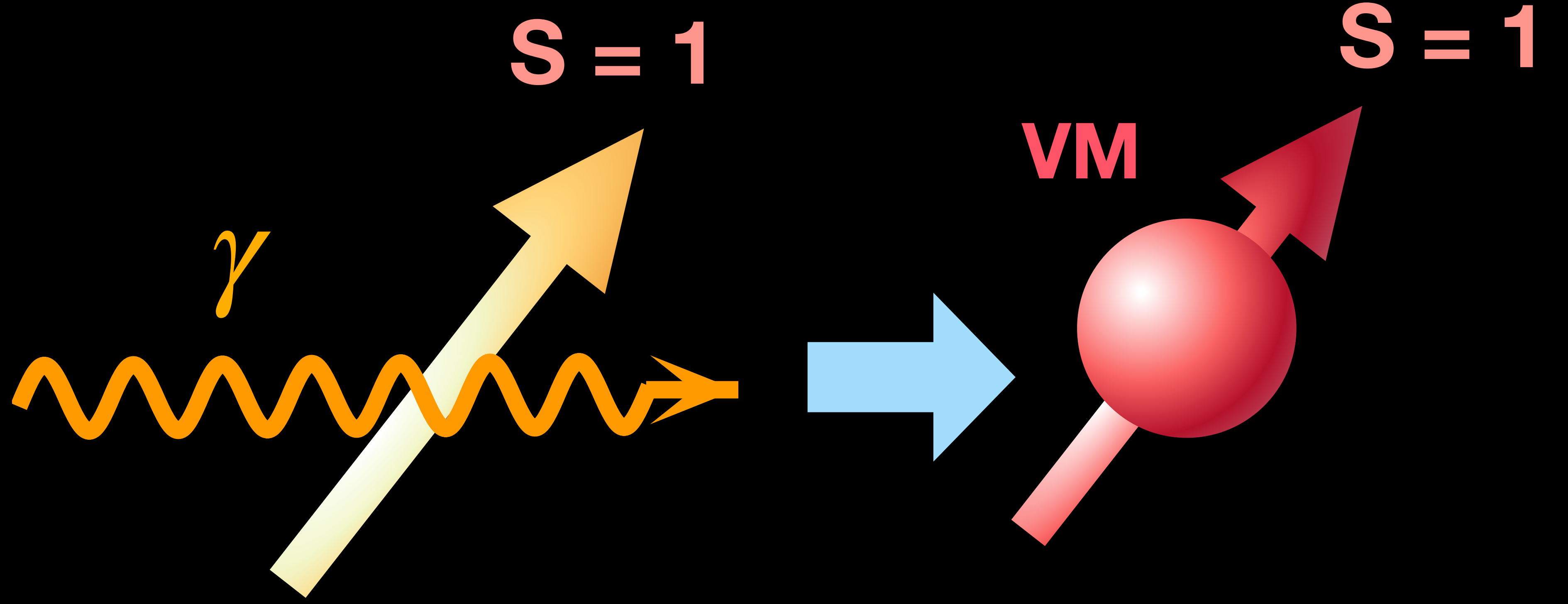


=> Photons in UPC are linearly polarized

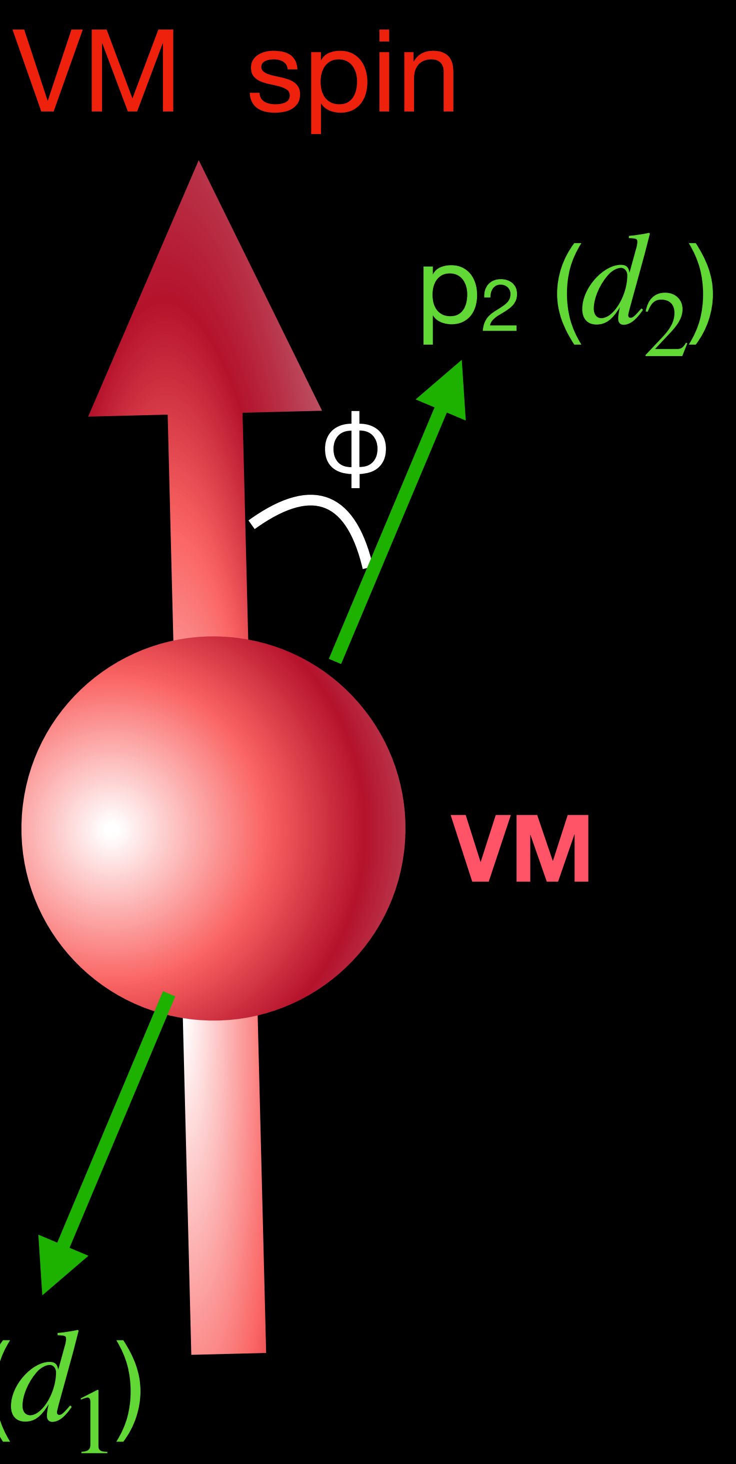
Experimental access to photon polarization demonstrated by STAR, measuring the Breit-Wheeler process, $\gamma\gamma \rightarrow e^+e^-$

UPC vector meson spin and decay daughters are correlated





Polarization of photon
→ Inherited by VM



Decay VM → $d_1 d_2$ daughters
preferentially emitted
(L+S conservation)

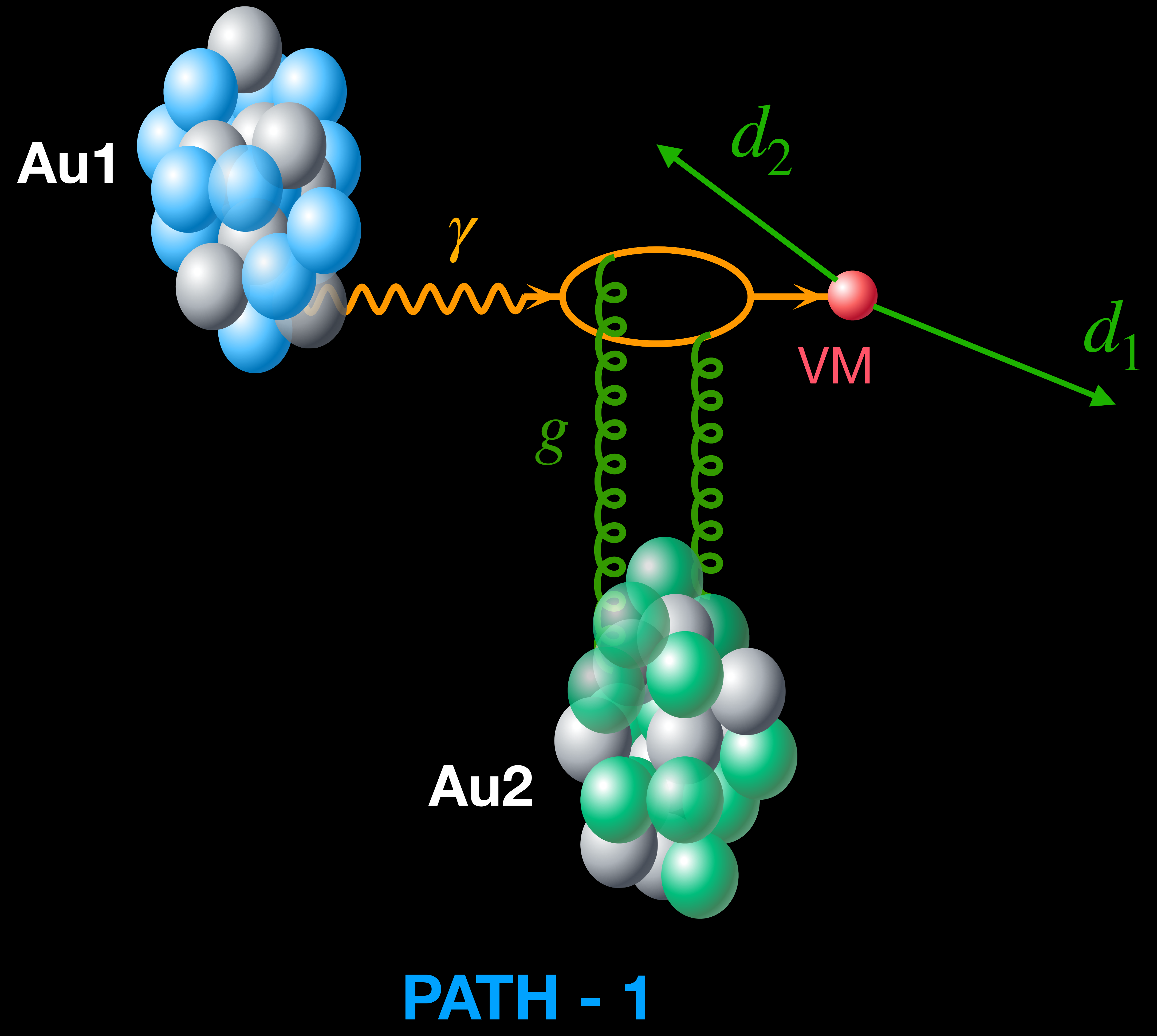
=> The cos(2ϕ) modulation in VM momentum distribution w.r.t photon polarization direction

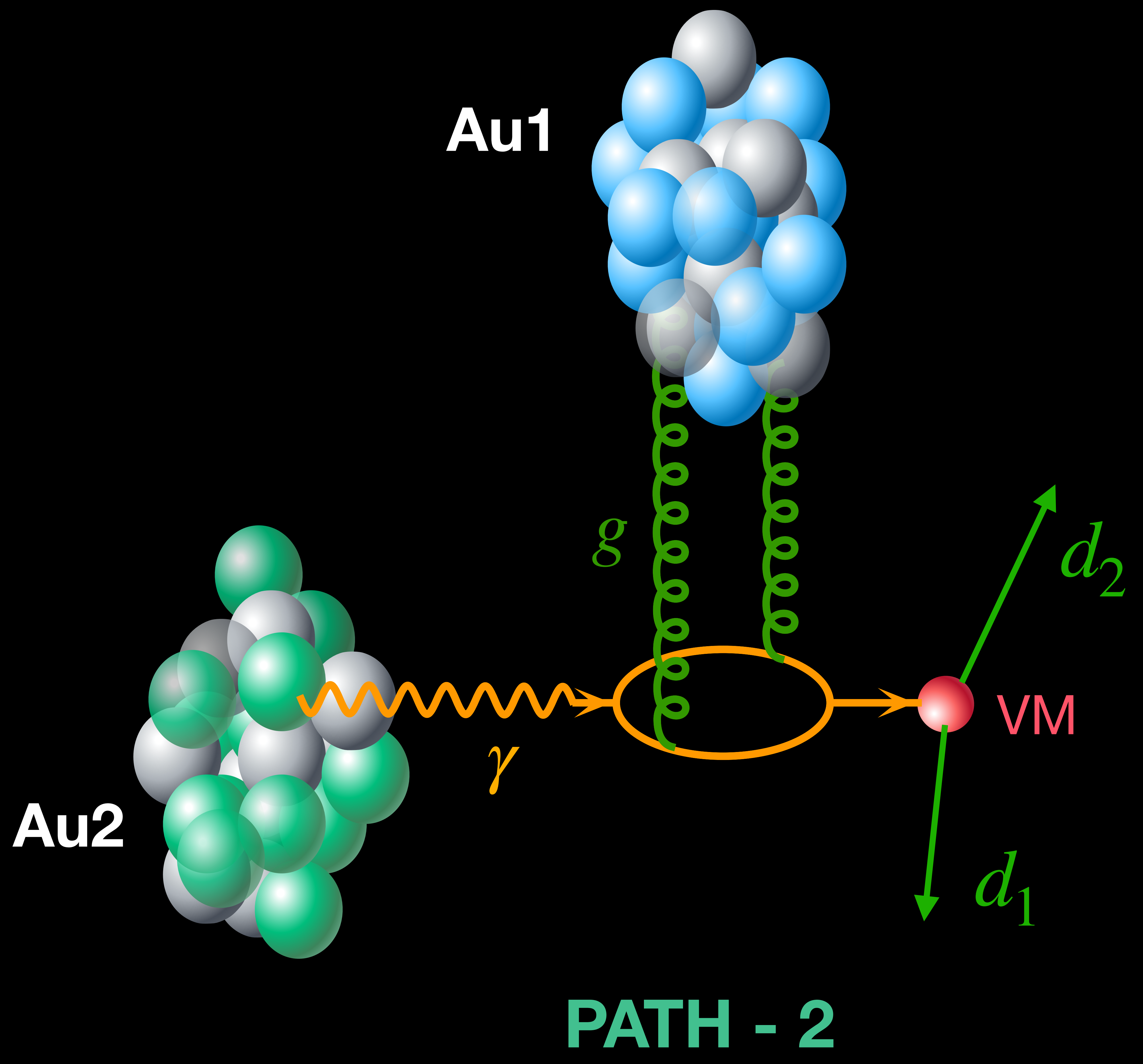
Measuring the modulation over a large no. of events

Photon polarization correlated with Impact parameter —> random from one event to the next

=> Event average washes out the cos(2ϕ) modulation w.r.t photon polarization direction

Photon source ambiguity

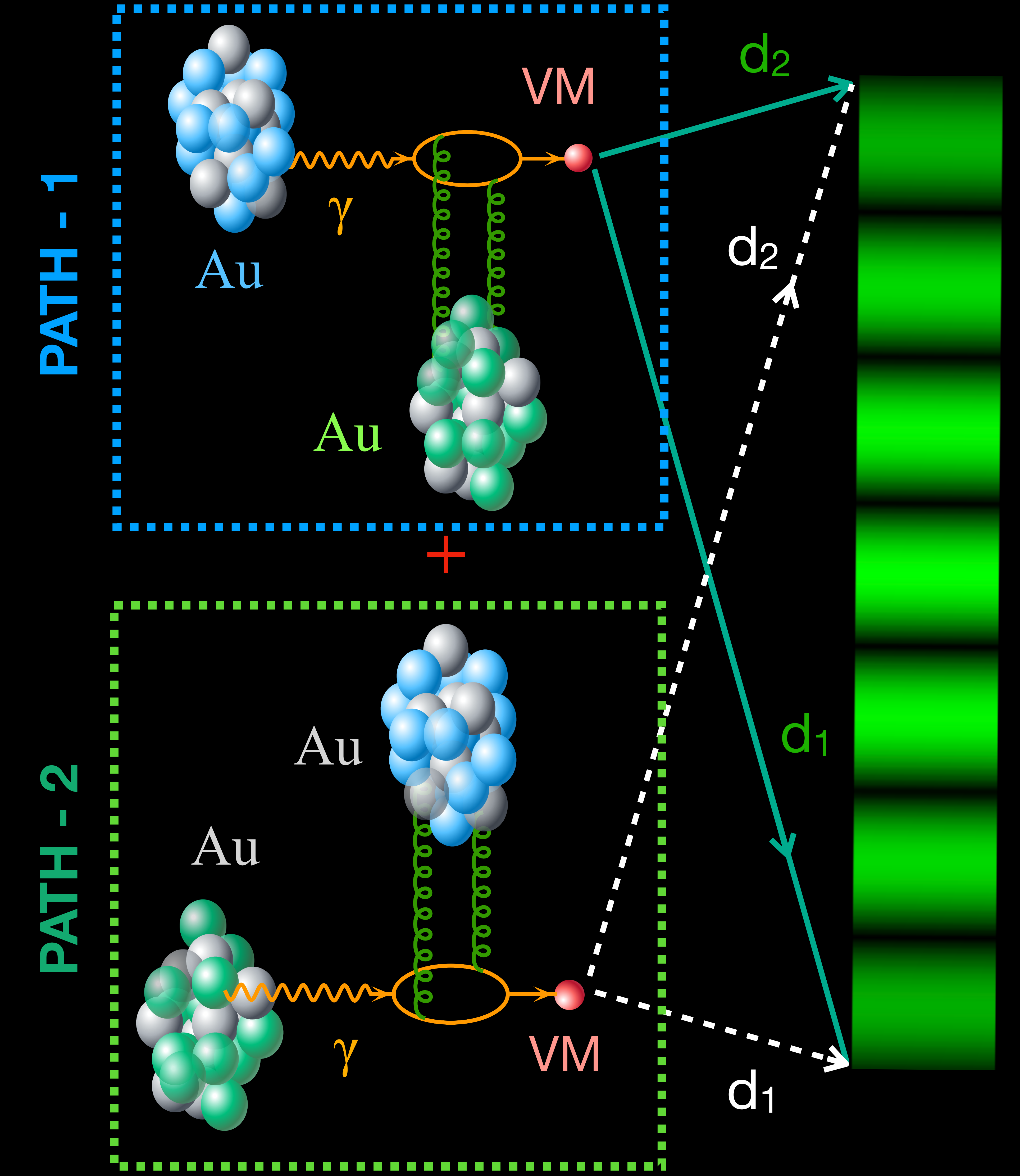




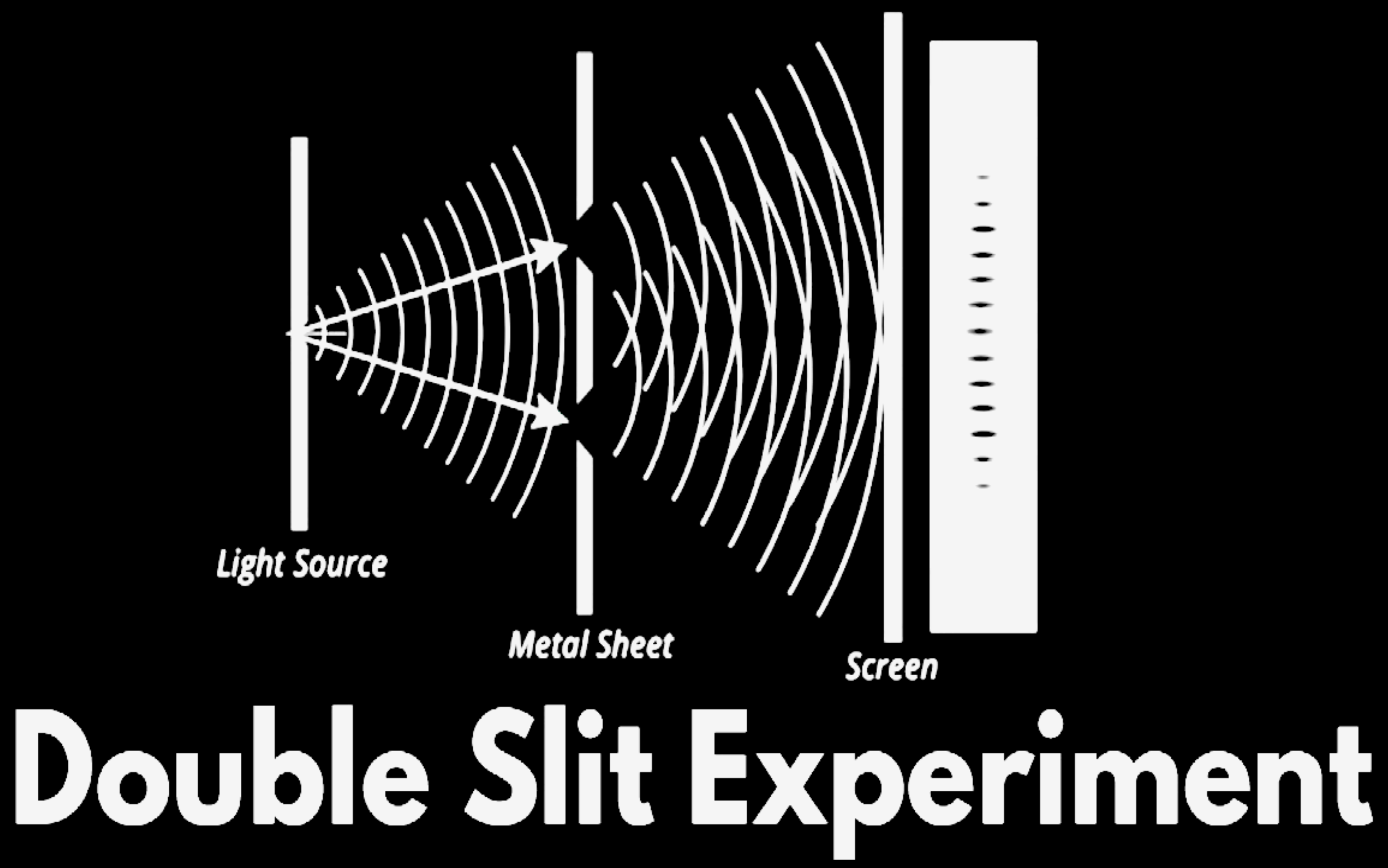
=> Two independent paths of VM production

—> The paths are indistinguishable

Interference makes the modulation observable in experiment



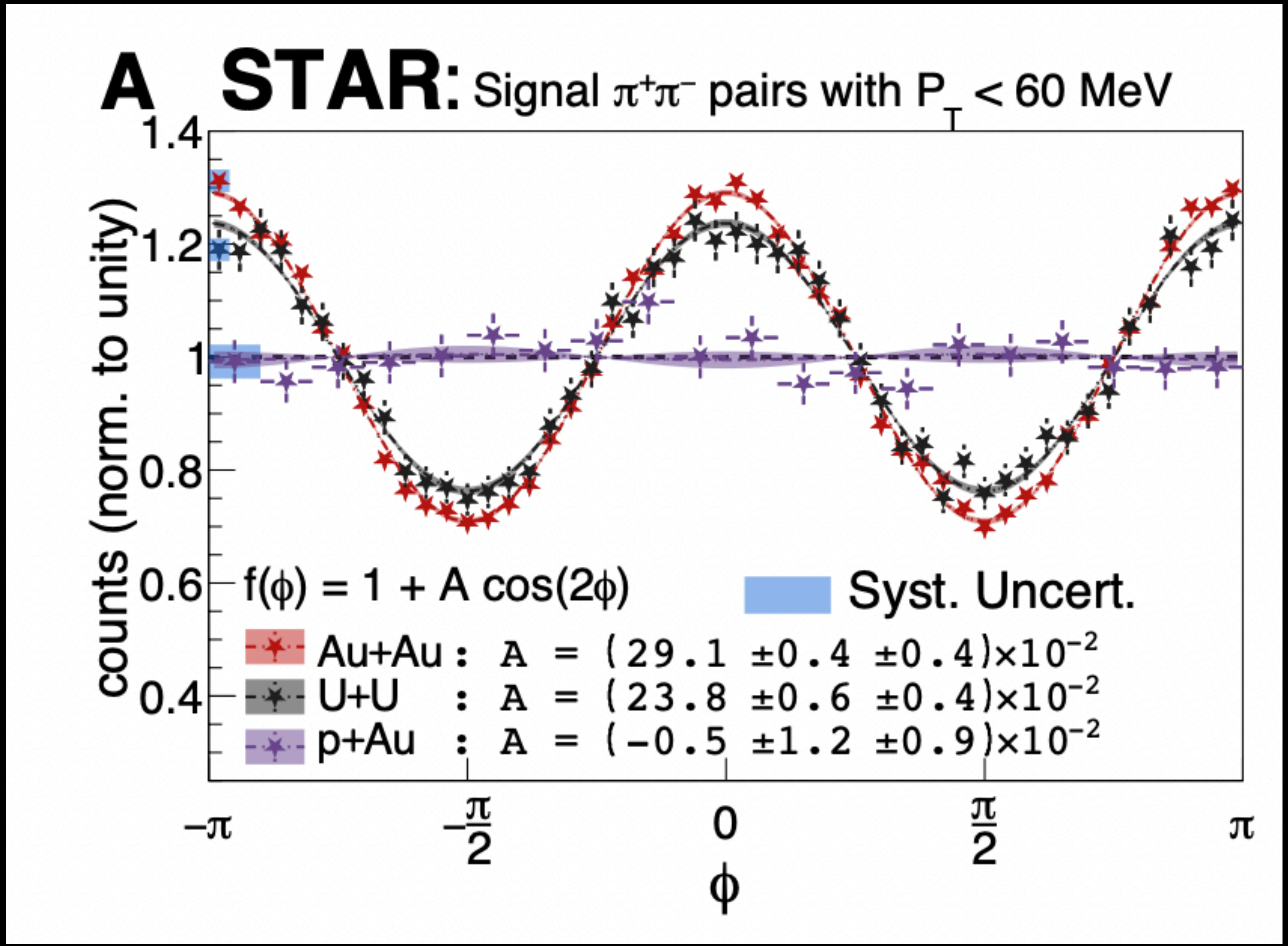
Photon source ambiguity: Interference among amplitudes of two possible paths

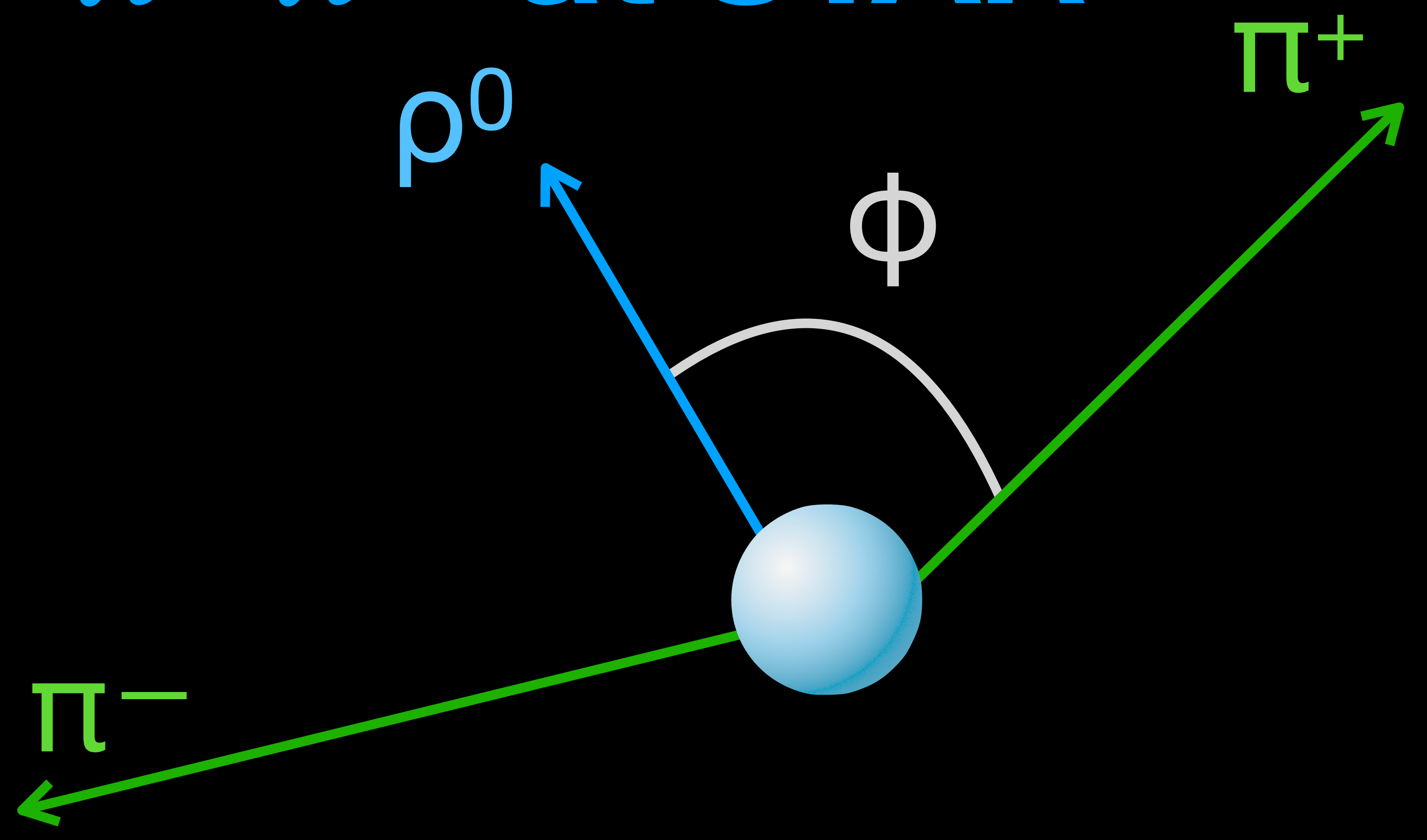


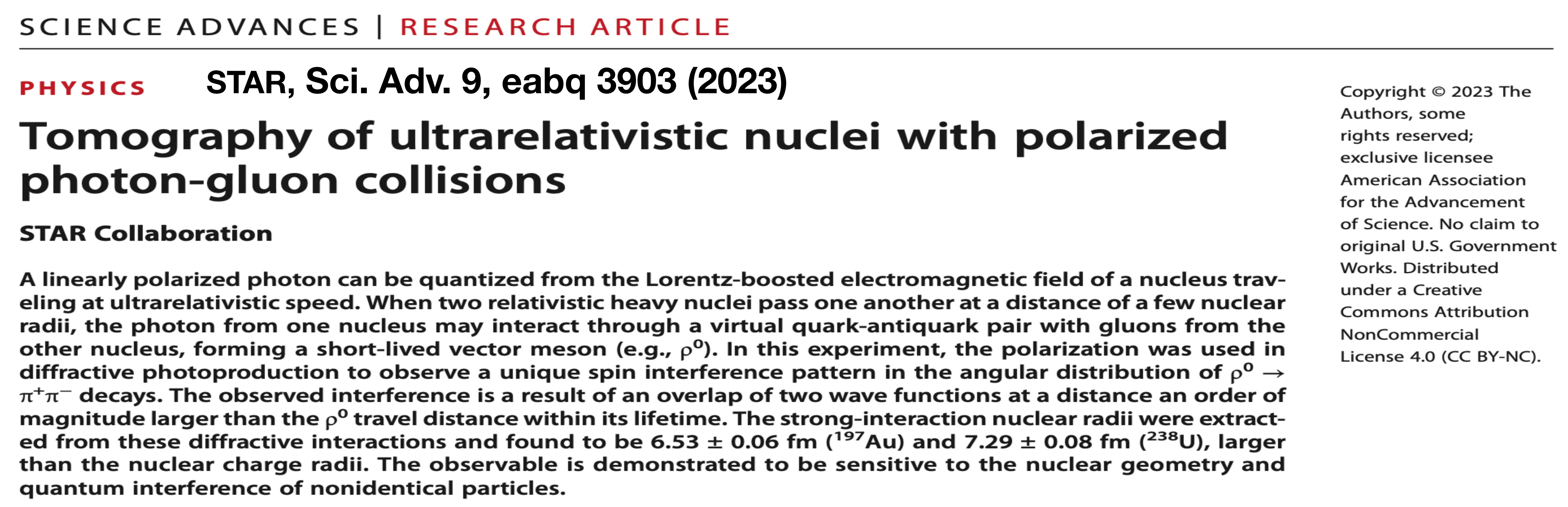
Best analogy: Double slit experiment in Optics

=> Two indistinguishable paths may interfere and make the cos(2ϕ) modulation observable

Observation of interference for $\rho^0 \rightarrow \pi^+\pi^-$ at STAR







SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS STAR, Sci. Adv. 9, eabq 3903 (2023)

Tomography of ultrarelativistic nuclei with polarized photon-gluon collisions

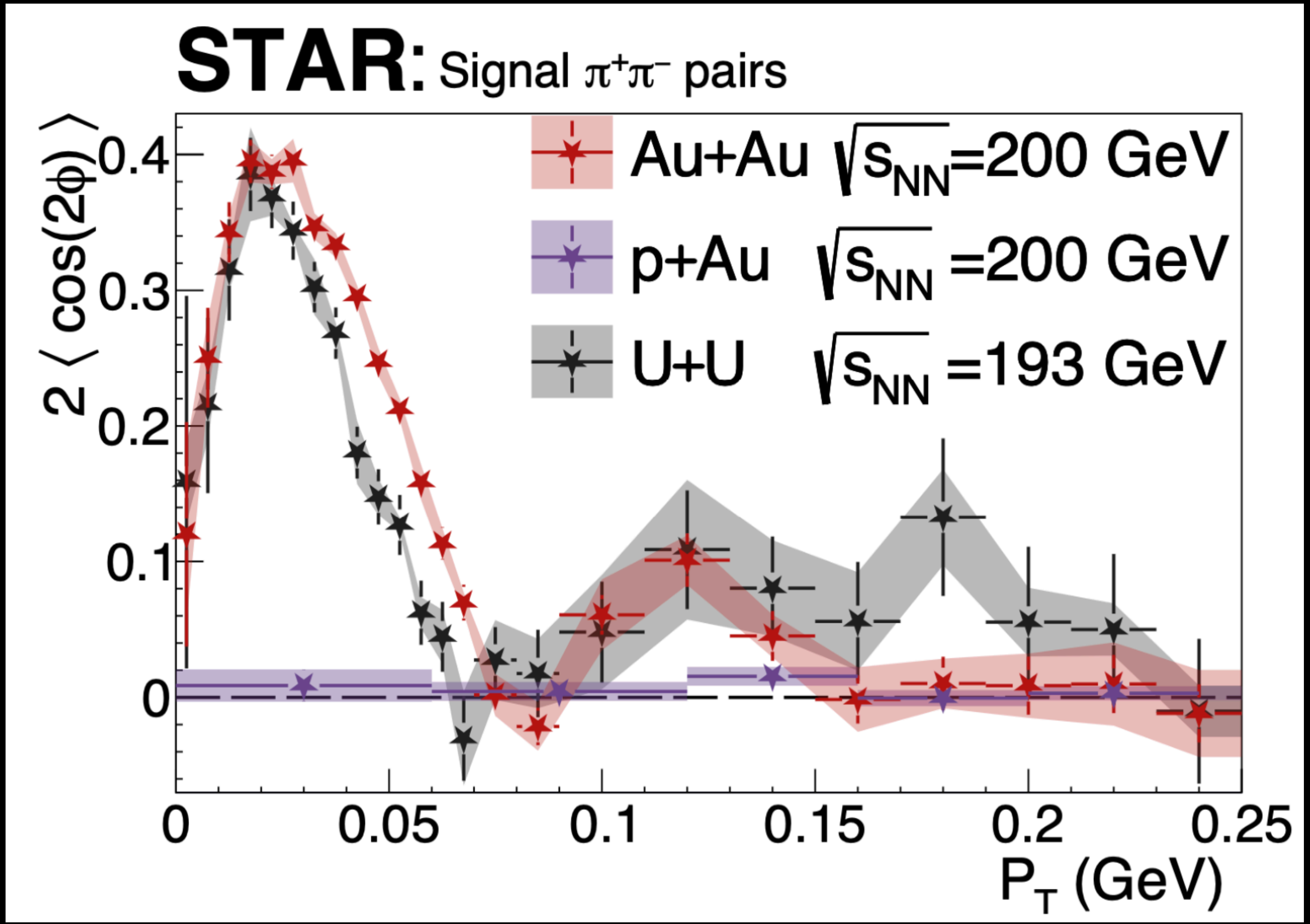
STAR Collaboration

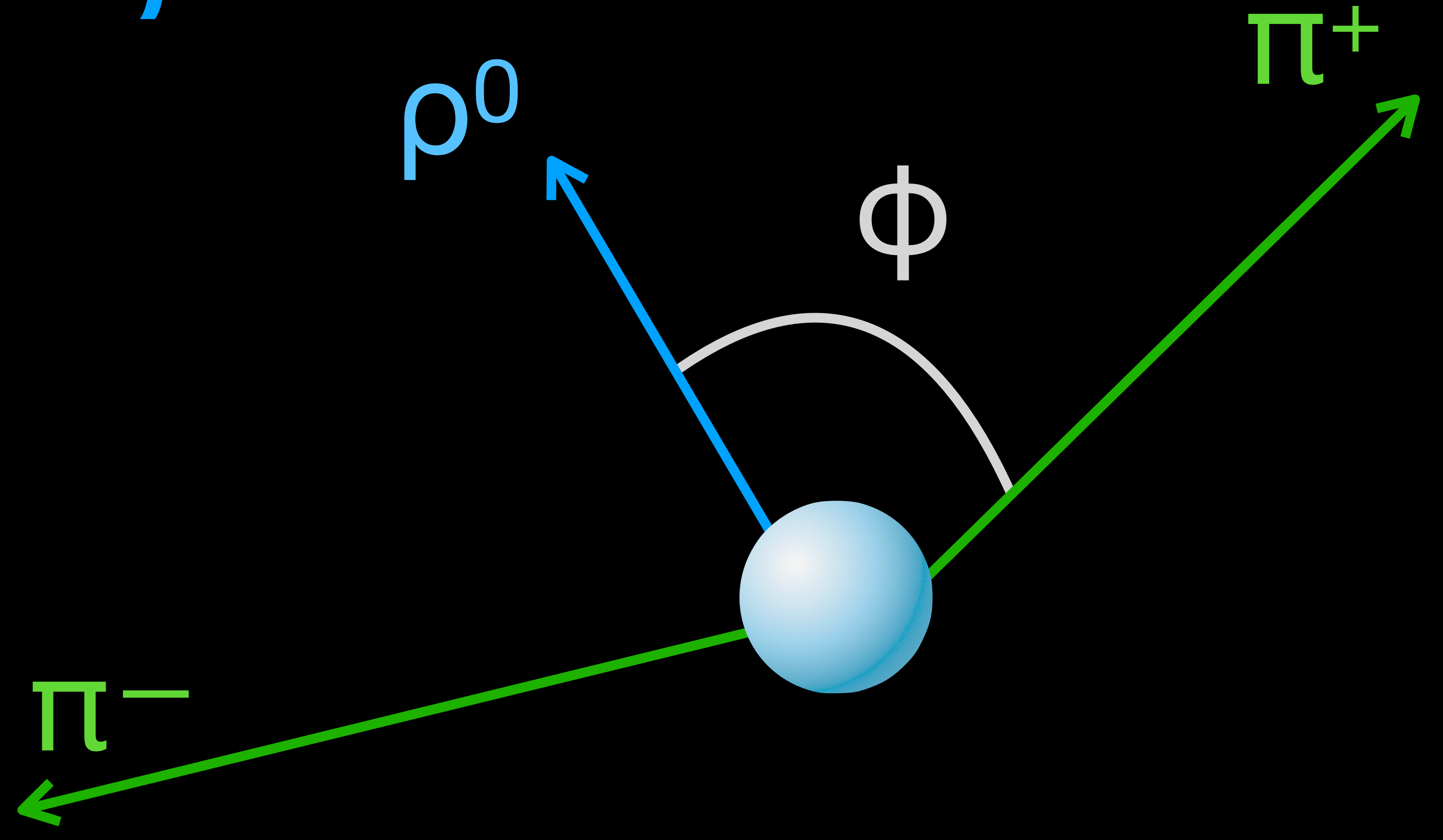
A linearly polarized photon can be quantized from the Lorentz-boosted electromagnetic field of a nucleus traveling at ultrarelativistic speed. When two relativistic heavy nuclei pass one another at a distance of a few nuclear radii, the photon from one nucleus may interact through a virtual quark-antiquark pair with gluons from the other nucleus, forming a short-lived vector meson (e.g., ρ^0). In this experiment, the polarization was used in diffractive photoproduction to observe a unique spin interference pattern in the angular distribution of $\rho^0 \rightarrow \pi^+\pi^-$ decays. The observed interference is a result of an overlap of two wave functions at a distance an order of magnitude larger than the ρ^0 travel distance within its lifetime. The strong-interaction nuclear radii were extracted from these diffractive interactions and found to be 6.53 ± 0.06 fm (^{197}Au) and 7.29 ± 0.08 fm (^{238}U), larger than the nuclear charge radii. The observable is demonstrated to be sensitive to the nuclear geometry and quantum interference of nonidentical particles.

Observed the interference for coherent ρ^0 photoproduction in UPCs

Measured in 3 different collision systems: Au+Au, U+U, p+Au —> Sensitive to nuclear shape/size

The p_T dependence of interference for $\rho^0 \rightarrow \pi^+\pi^-$ at STAR





SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS

Tomography of ultrarelativistic nuclei with polarized photon-gluon collisions

STAR Collaboration

A linearly polarized photon can be quantized from the Lorentz-boosted electromagnetic field of a nucleus traveling at ultrarelativistic speed. When two relativistic heavy nuclei pass one another at a distance of a few nuclear radii, the photon from one nucleus may interact through a virtual quark-antiquark pair with gluons from the other nucleus, forming a short-lived vector meson (e.g., ρ^0). In this experiment, the polarization was used in diffractive photoproduction to observe a unique spin interference pattern in the angular distribution of $\rho^0 \rightarrow \pi^+\pi^-$ decays. The observed interference is a result of an overlap of two wave functions at a distance an order of magnitude larger than the ρ^0 travel distance within its lifetime. The strong-interaction nuclear radii were extracted from these diffractive interactions and found to be 6.53 ± 0.06 fm (^{197}Au) and 7.29 ± 0.08 fm (^{238}U), larger than the nuclear charge radii. The observable is demonstrated to be sensitive to the nuclear geometry and quantum interference of nonidentical particles.

Clear p_T dependence of interference observed

Interference gets weak at higher p_T —
Incoherent processes take over

Radius measurement with interference for $\rho^0 \rightarrow \pi^+\pi^-$ at STAR

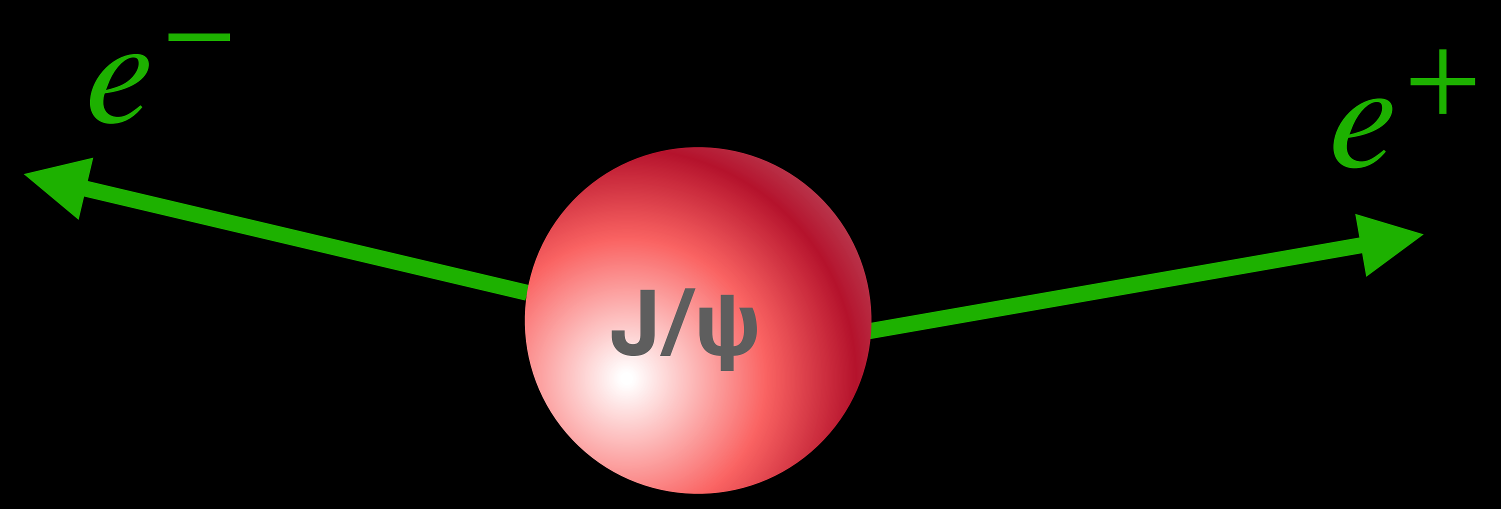
STAR, Sci. Adv. 9, eabq 3903 (2023)

Impact of spin interference on |t| distribution studied in different ϕ bins

Improved measurement of mass radii using spin interference effect

R (Au) = 6.53 ± 06 fm; R (U) = 7.29 ± 08 fm

Spin interference with J/ψ $\rightarrow e^+e^-$

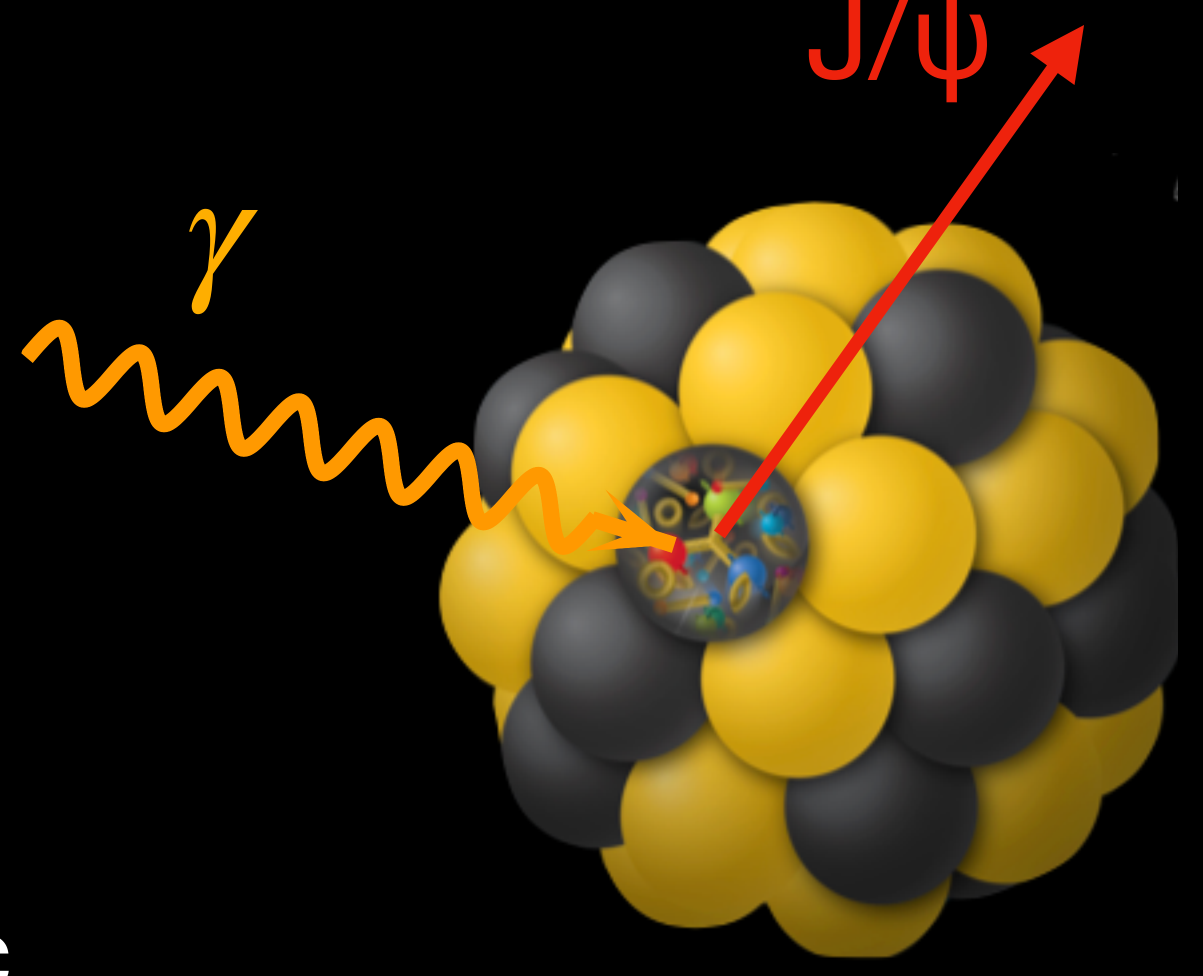


J/ψ $\rightarrow e^+e^-$

Boson Fermions

Mass: 0.7 GeV/c²
Lifetime: 1.3 fm/c

Mass: 3.1 GeV/c²
Lifetime: 2160 fm/c



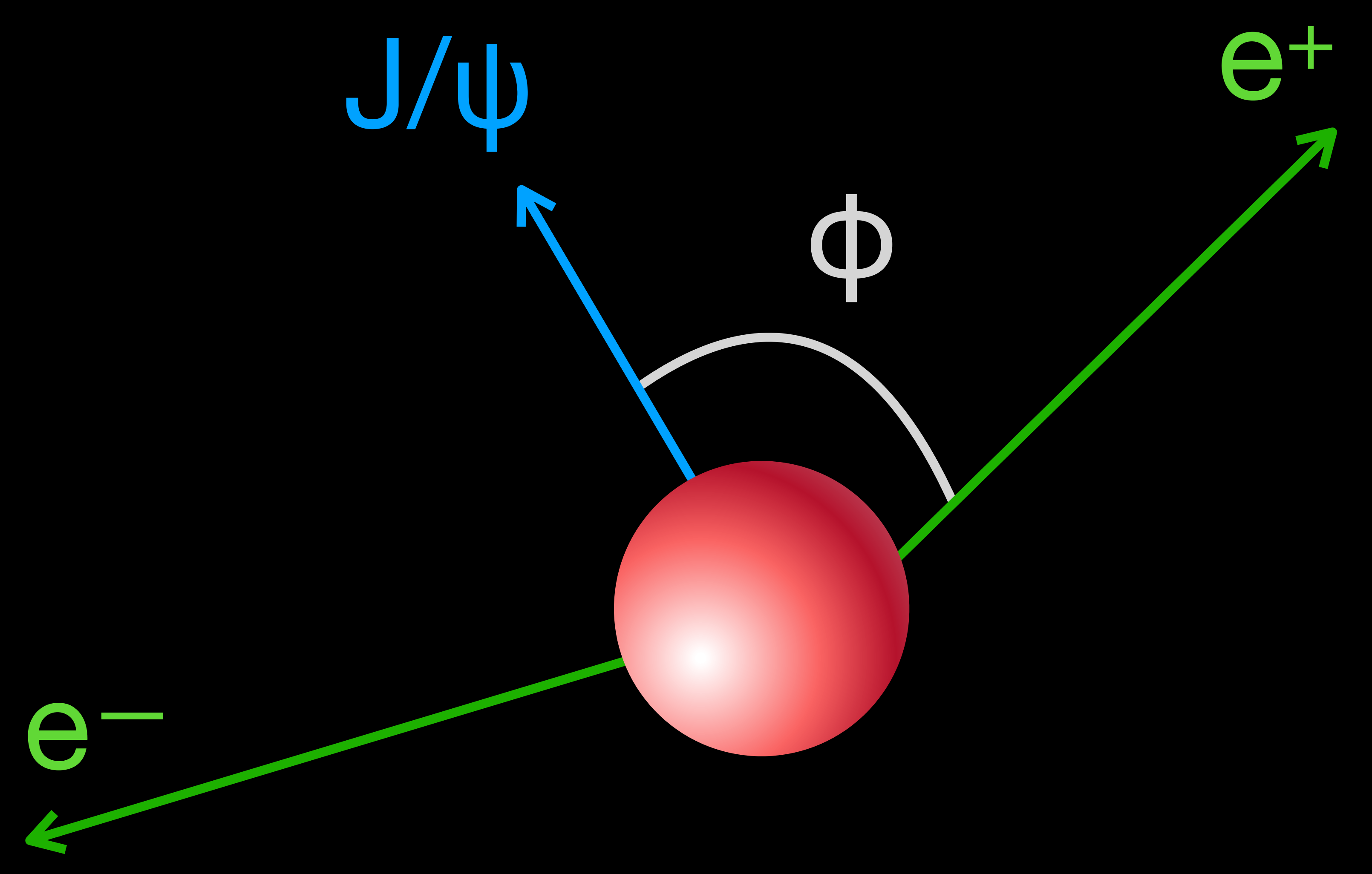
Measured sign of the interference tells us the level of interference

Interference of quantum particles —> Spin interference

J/ψ heavier than ρ^0 and J/ψ has longer lifetime

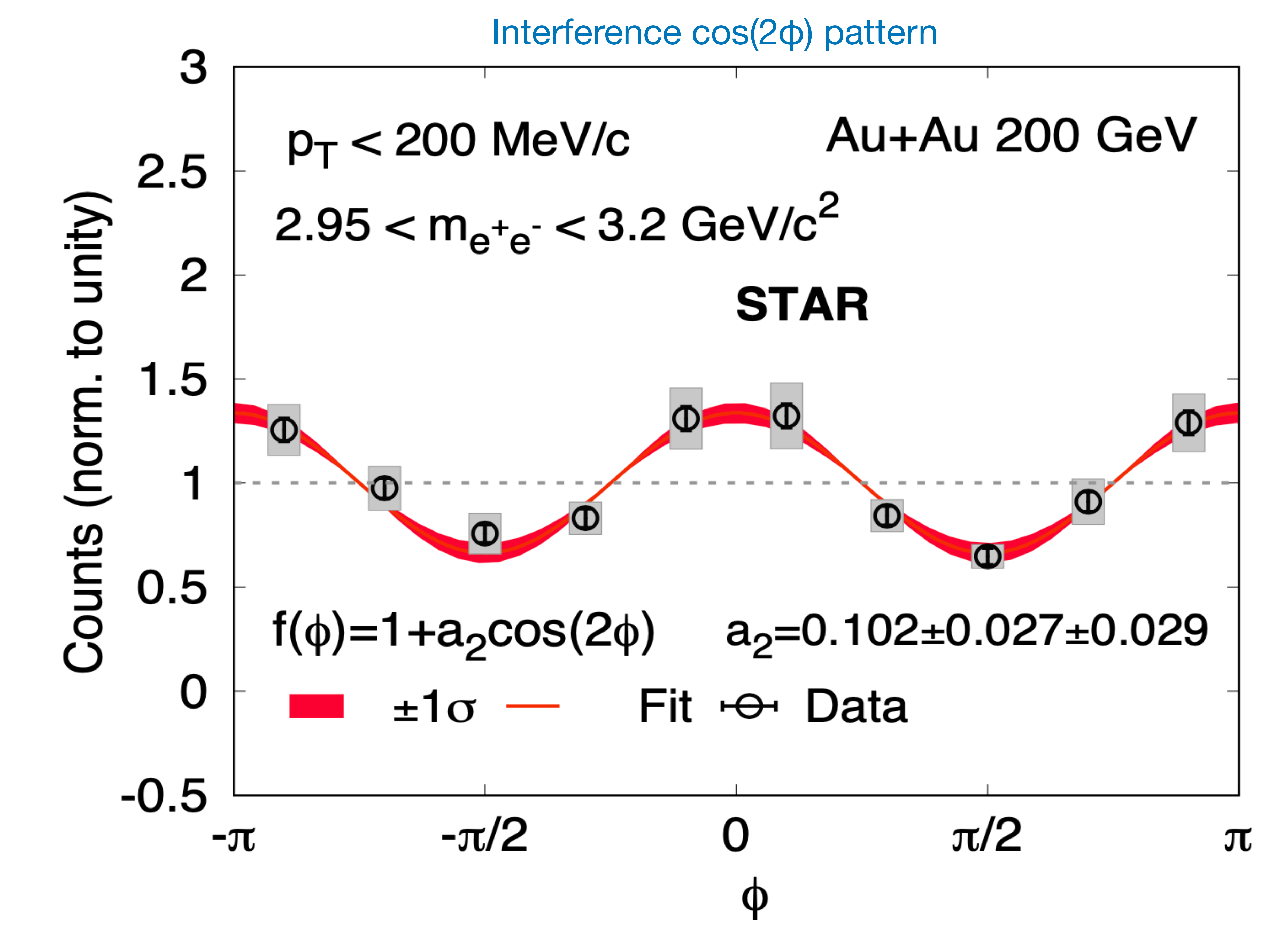
Probes finer structure and captures high quality images of the gluon distributions

Measured spin interference with J/ψ $\rightarrow e^+e^-$



Observable for J/ψ spin interference

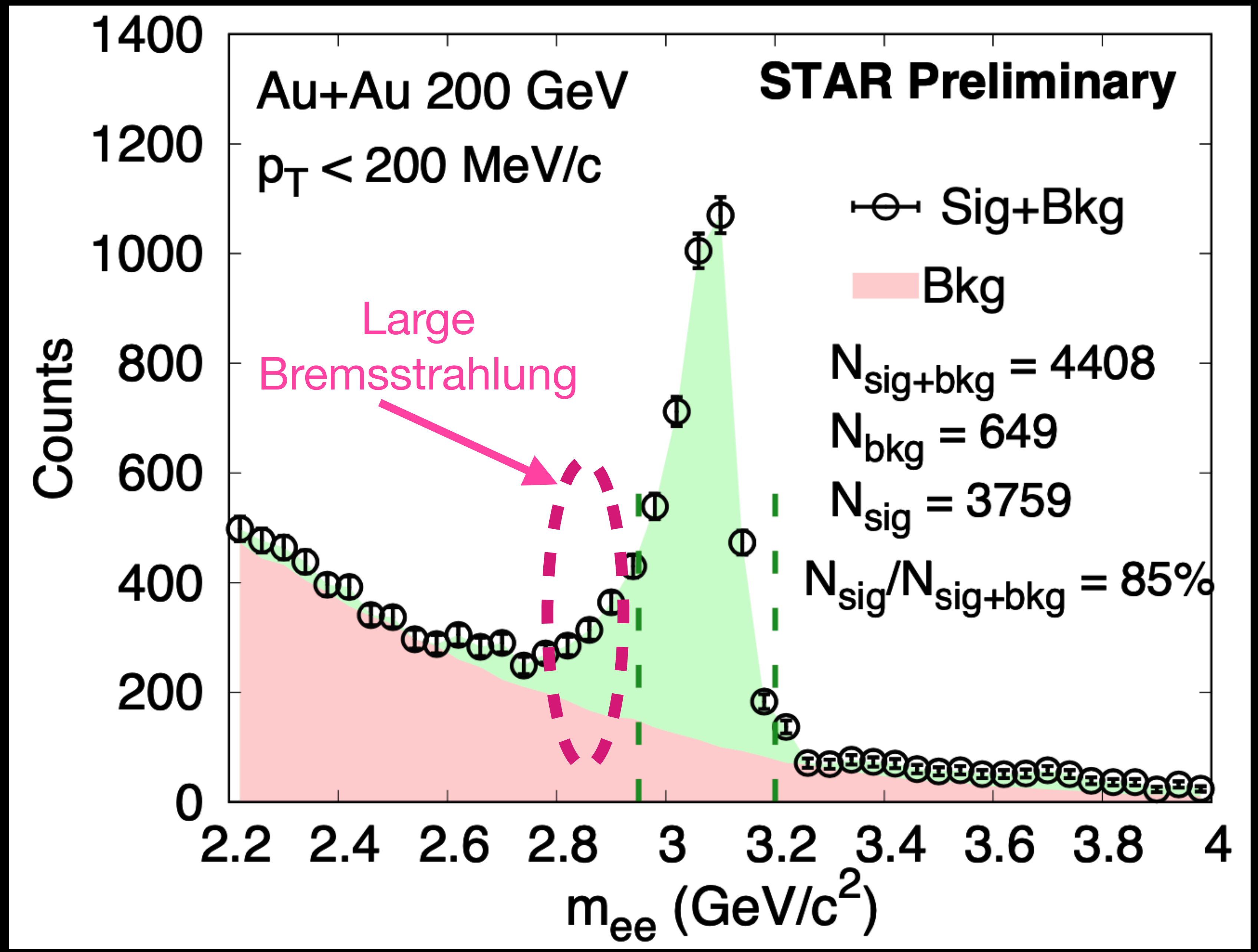
Interference signal fitted with: 1+ a_2 cos(2ϕ) => a_2 is the measure of the modulation

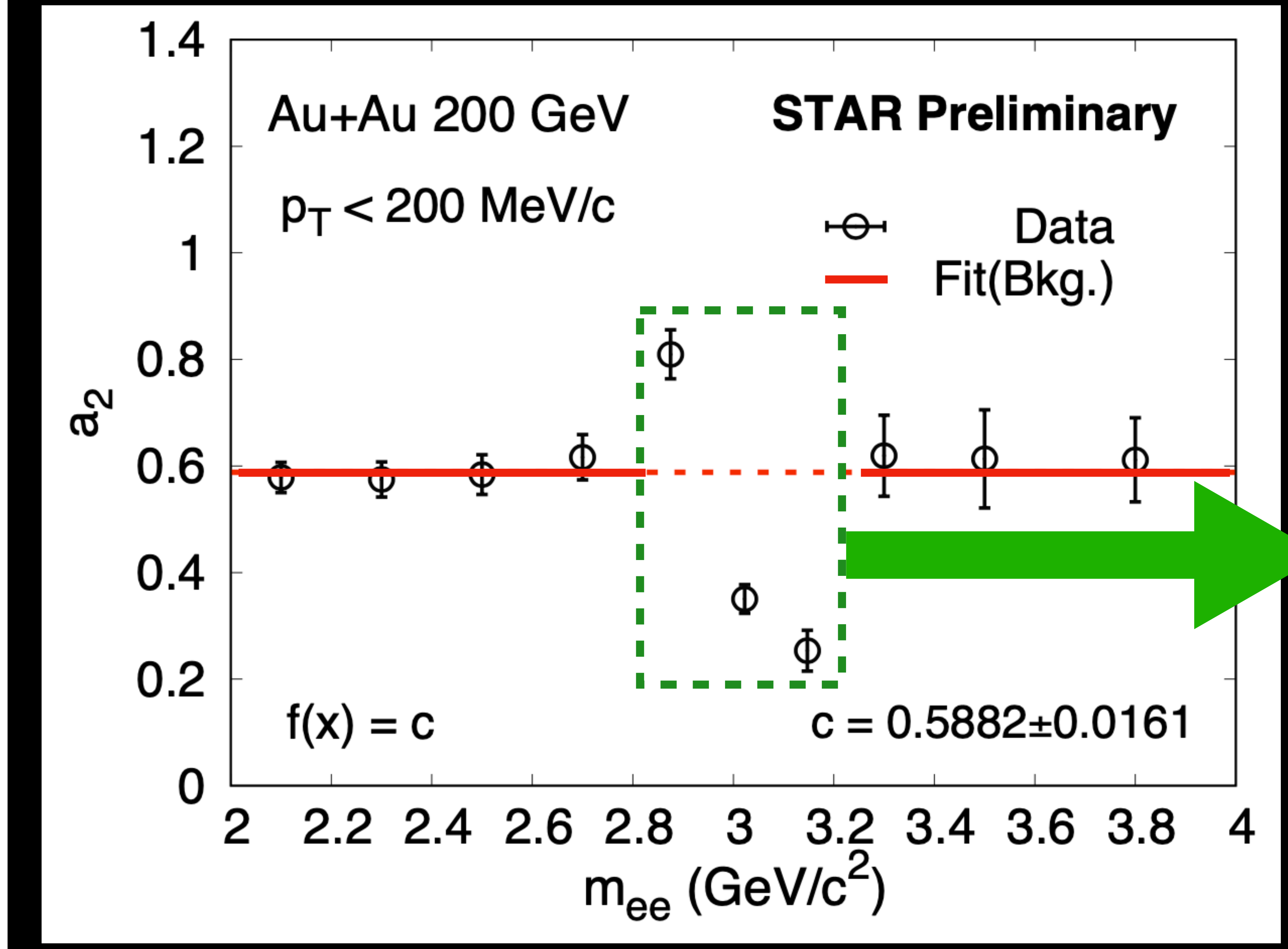


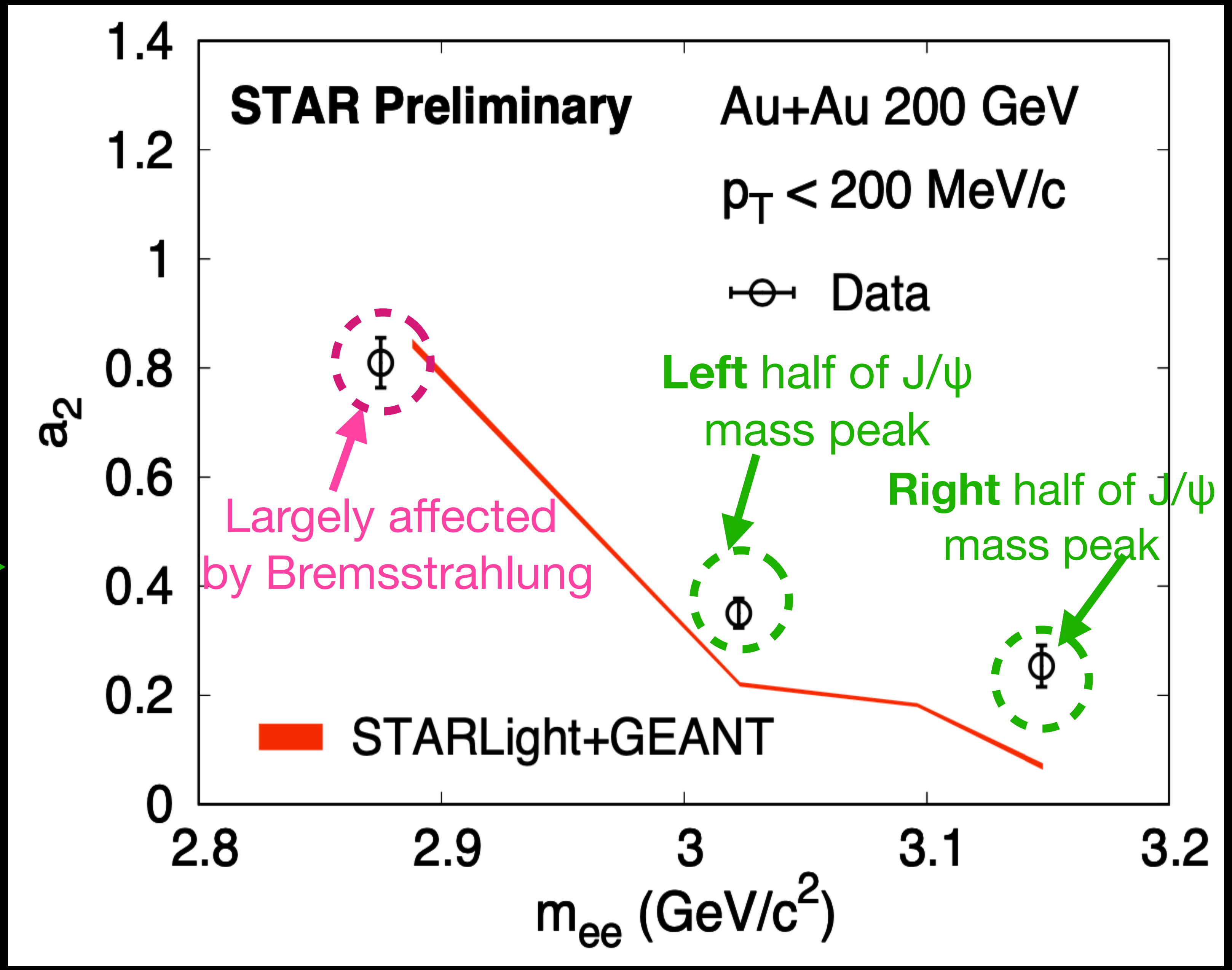
Observed spin interference for J/ψ $\rightarrow e^+e^-$

Measured the spin interference of J/ψs

Corrections for interference signal



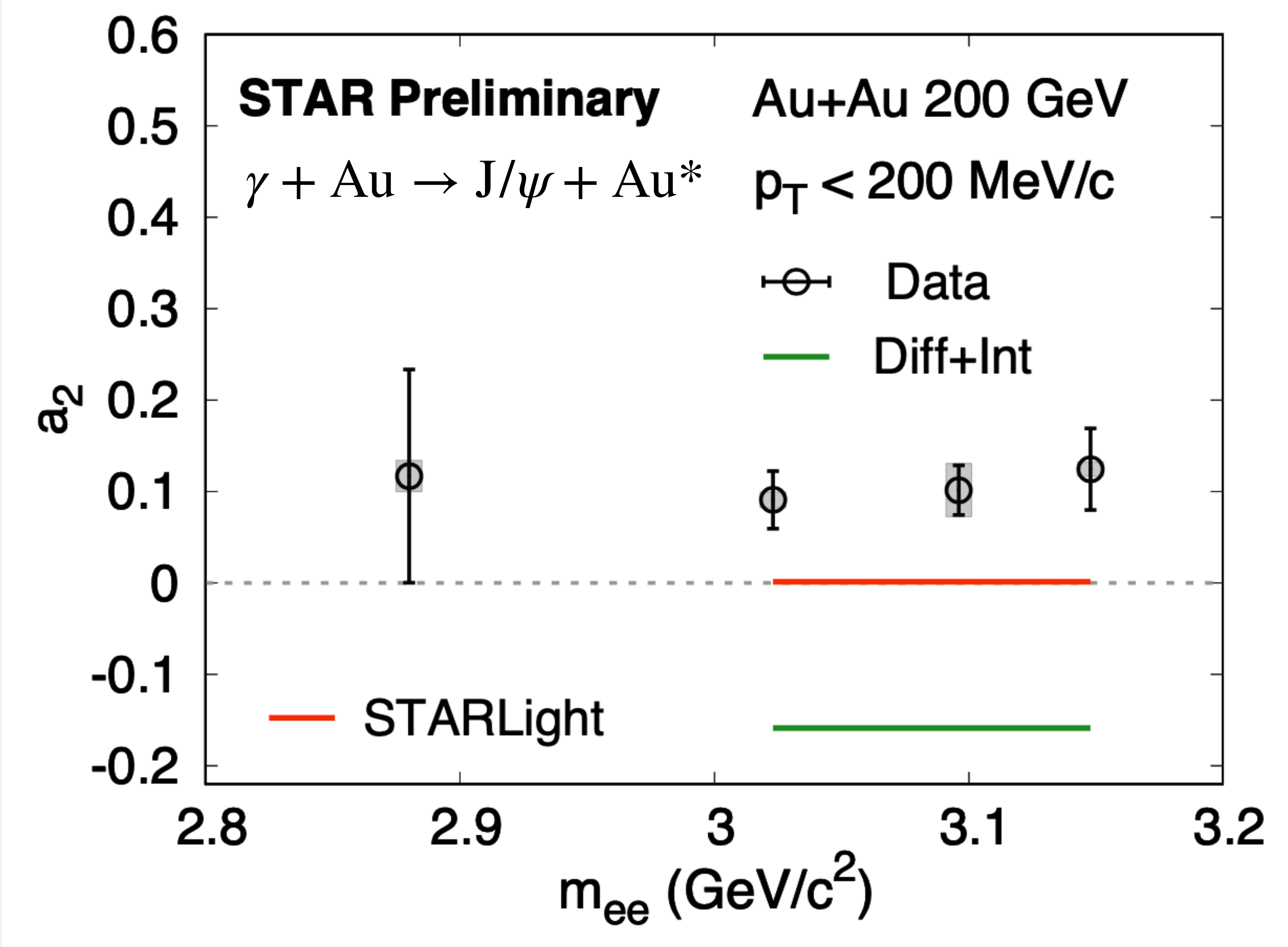




- The $\gamma + \gamma \rightarrow e^+ + e^-$ has also the J/Ψ interference like pattern due to detector effect
- We correct for the 2γ process with : $a_2 = f \times a_2^{bkg} + (1-f) \times a_2^{sig}$, with $f = \frac{N_{bkg}}{N_{sig} + N_{bkg}}$
- We considered the Bremsstrahlung process and $J/\Psi \rightarrow e^+ + e^- + \gamma$, using the STARLight+Geant simulations

=> Background correction is done to extract true modulation signal

Signal for J/ψ Spin interference



- Measured and corrected signal for J/Ψ spin interference:

$$a_2 = 0.102 \pm 0.027 \pm 0.029$$

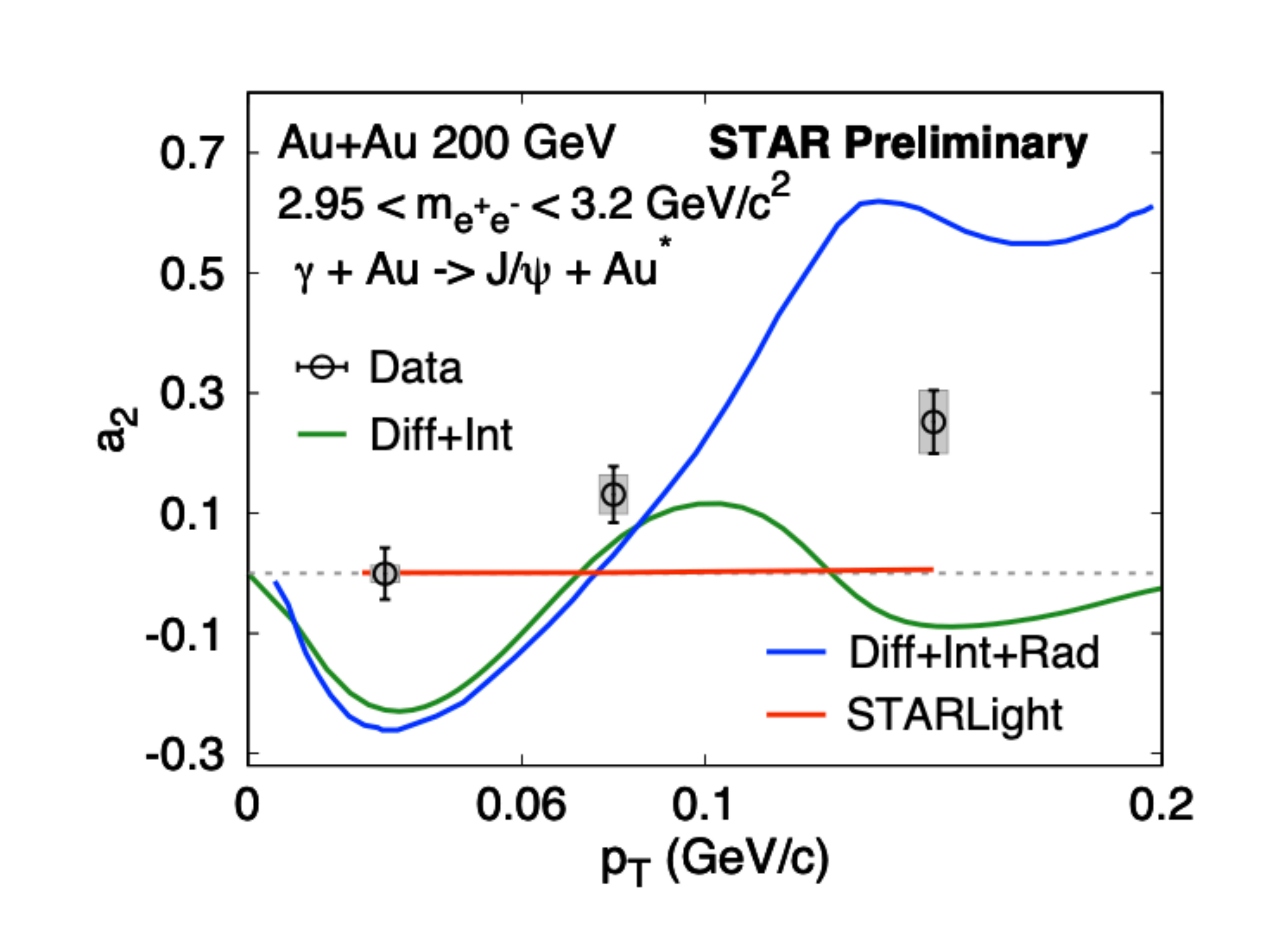
- Measurement has ~3σ significance above zero
- Compared with STARLight and theory calculations
- STARLight has no spin interference physics — consistent with zero
- Theory (Diffractive+Interference) predicts negative modulation

Diff+Int predictions : Mäntysaari et al. Phys.Rev.C 109 (2024) 2, 024908

=> Observed spin interference signal ~10% in the measured kinematic range

The p_T-dependent interference of J/ψ

- Interference signal shows strong p_T dependence and rises toward positive
- STARLight predicts zero
- Diffractive+interference calculations are negative at low and high p_T
- Diffractive+interference with additional soft γ radiation predicts negative at low p_T and rises towards positive value at higher p_T

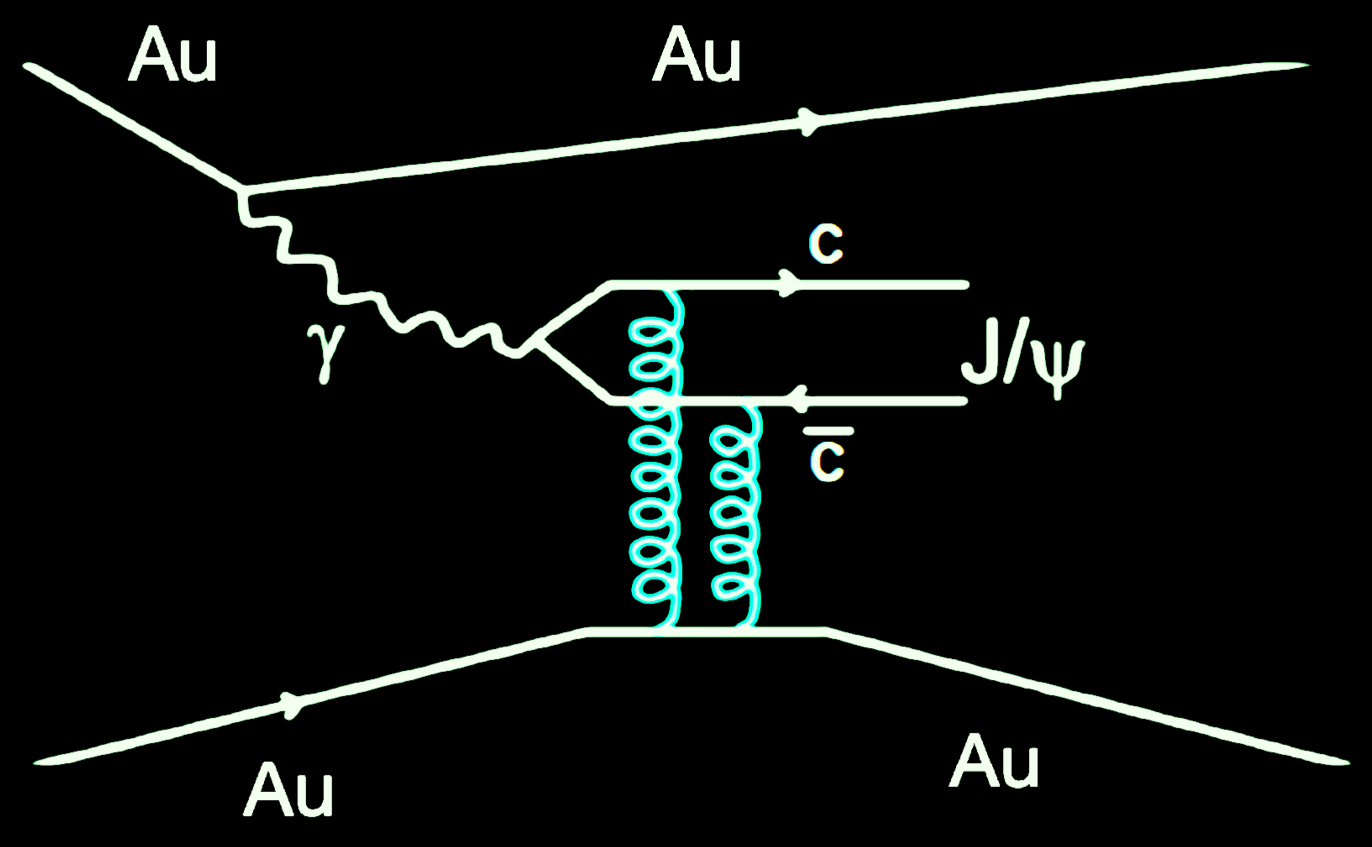


Diff+Int predictions : Mäntysaari et al. Phys.Rev.C 109 (2024) 2, 024908
Diff+Int+Rad predictions : Brandenburg et. al, Phys. Rev. D 106, 074008 (2022)

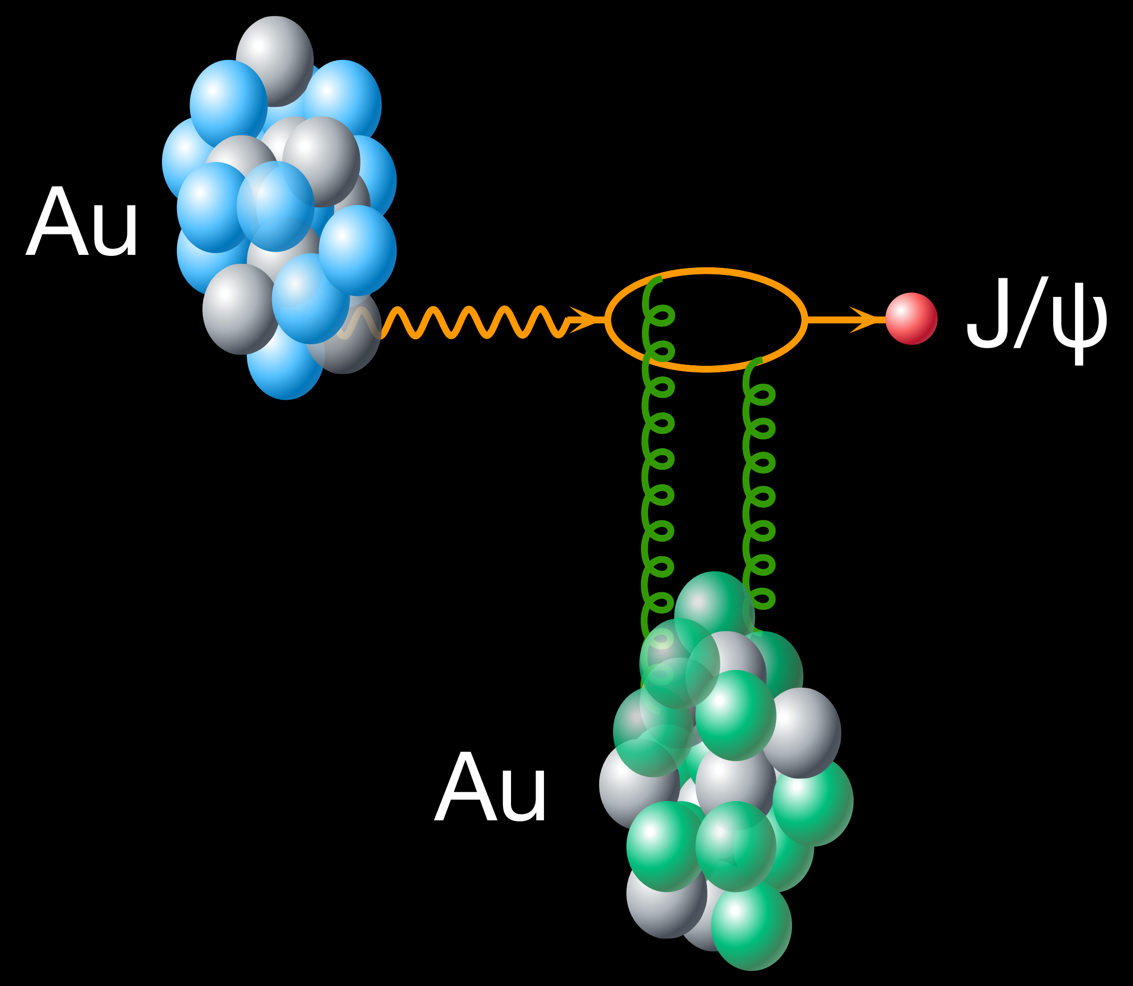
=> Modulation strength positively increases with p_T

Summary and take home

- Measured the coherent and incoherent J/ψ production in Au+Au UPCs
- STAR observed the spin interference of the photoproduced ρ^0 and J/ψ
- Measured interference signal increases with p_T
- Measurements are sensitive to nuclear geometry and useful to constrain the theoretical models
- RHIC, LHC and future EIC experiments can provide further insights into these

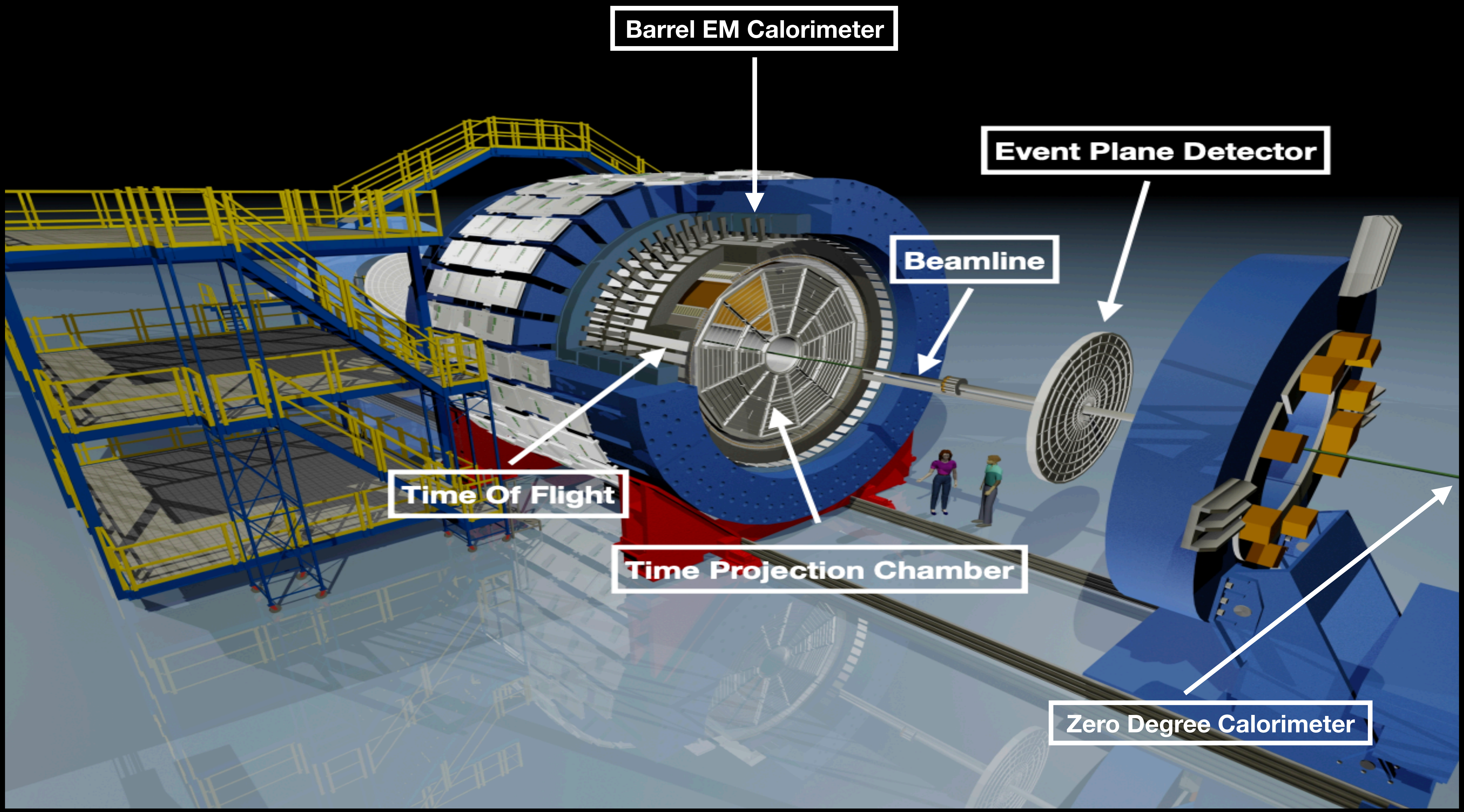


Thank You!



Backup

STAR detector



- Main central barrel detectors for UPC measurements: TPC, TOF, BEMC
- Forward detectors: BBC or EPD, ZDC