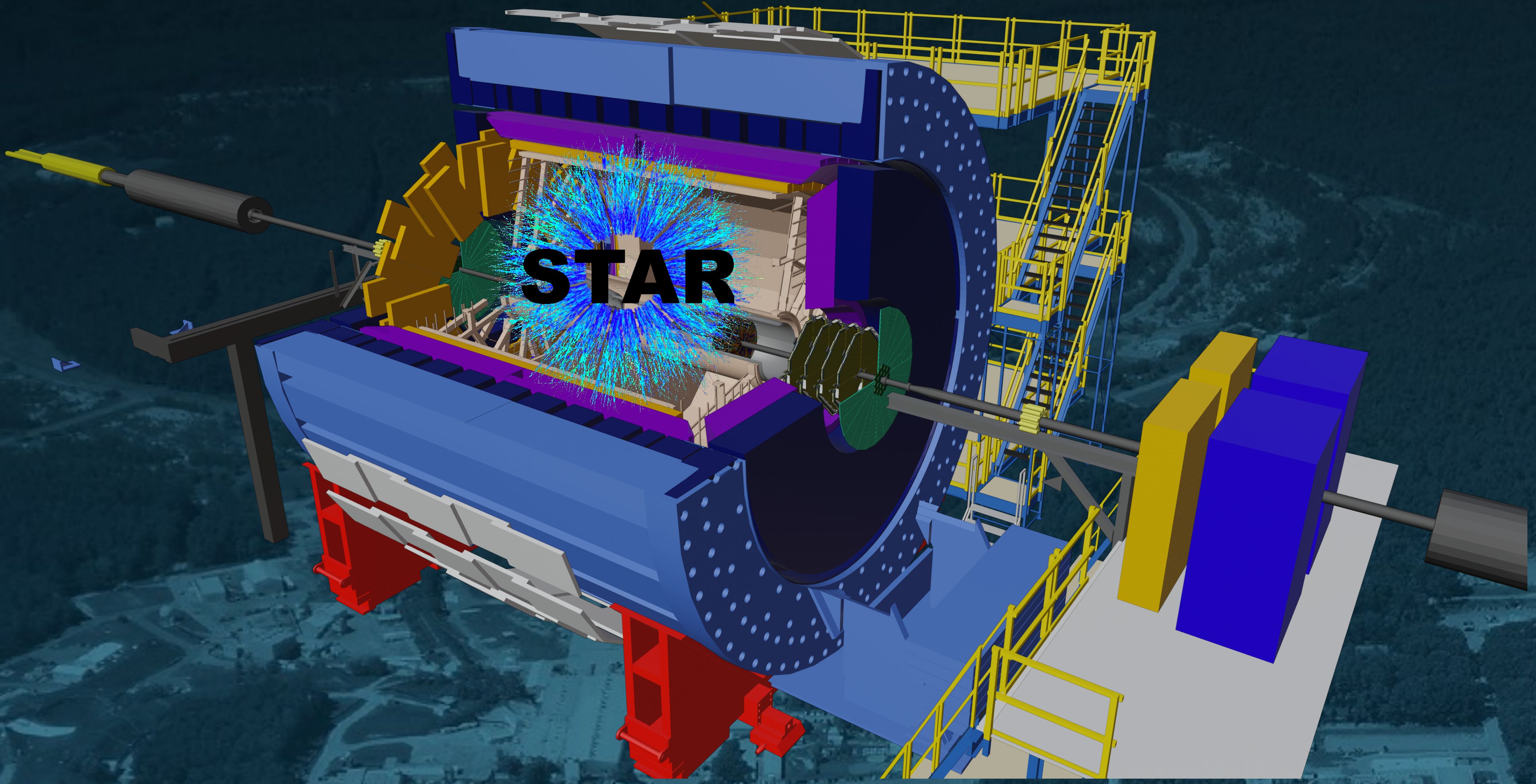

Photoproduction in UPCs at RHIC

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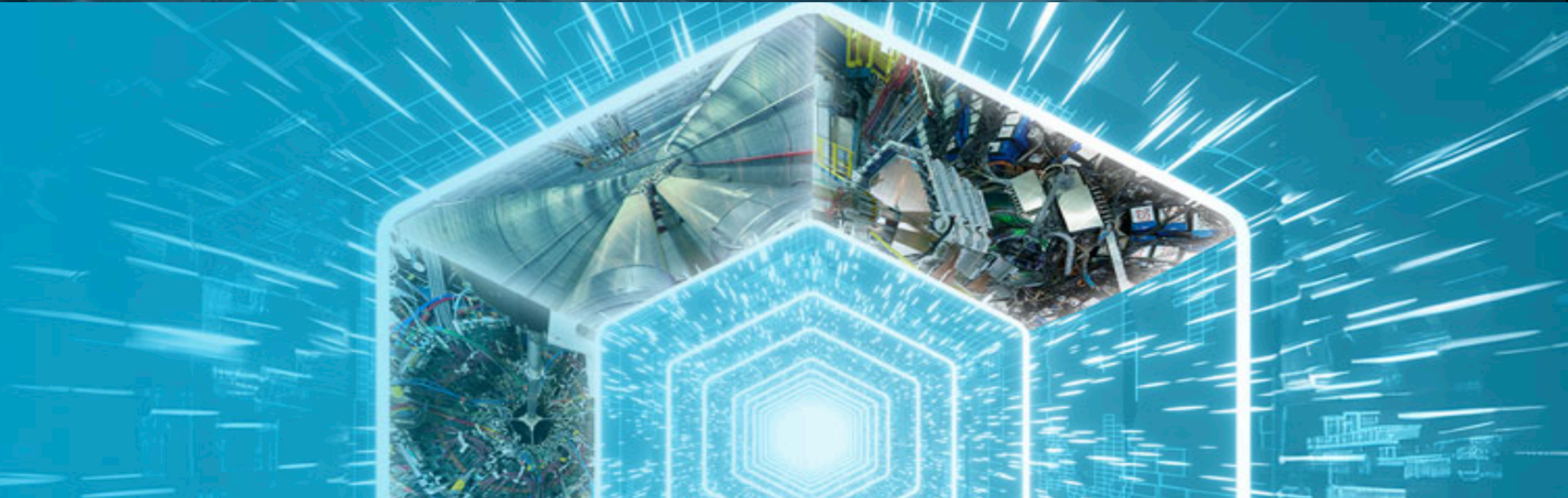
Brookhaven National Laboratory

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

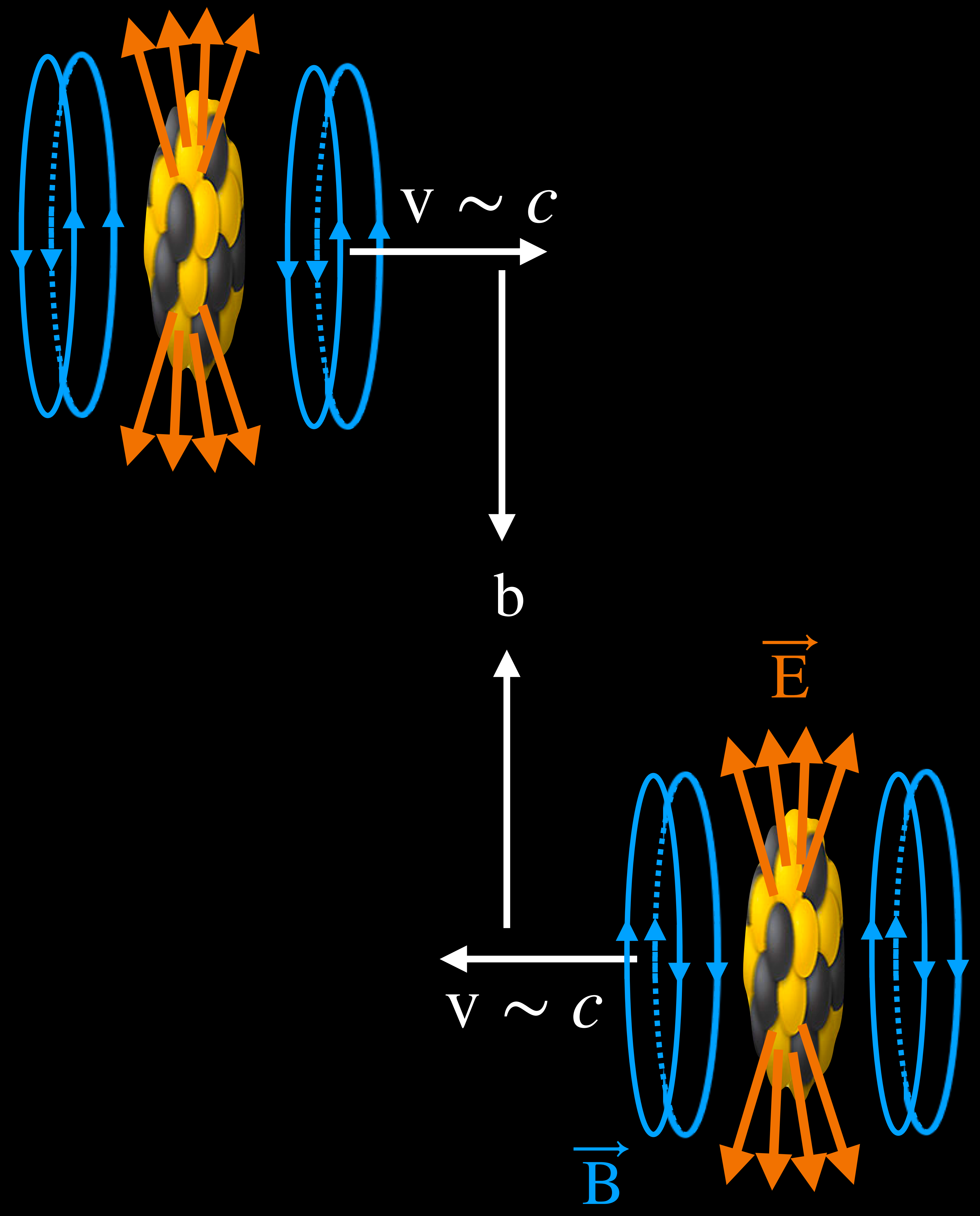
2024 RHIC/AGS ANNUAL USERS' MEETING

A New Era of Discovery
Guided by the New Long Range Plan for Nuclear Science

June 11–14, 2024
Brookhaven National Laboratory, USA



The strongest EM-fields in heavy ion collisions



- In heavy ion collisions,

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

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

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

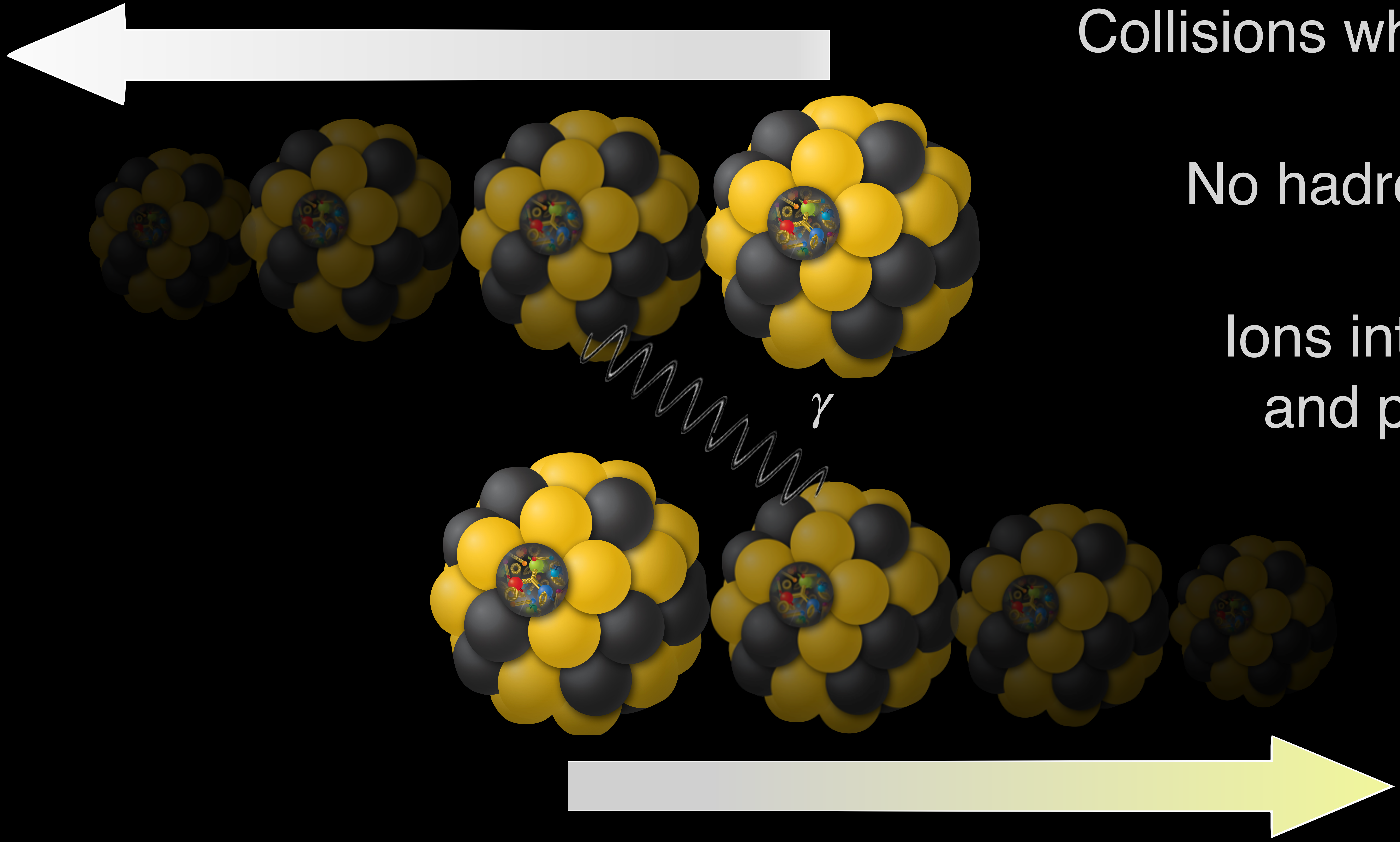
  $$W_{\gamma,max} \sim \gamma\hbar c/R\ ;$$

  $W_{\gamma,max} \sim 3$ GeV (RHIC)

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

=> EM-fields are quantized as photons

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



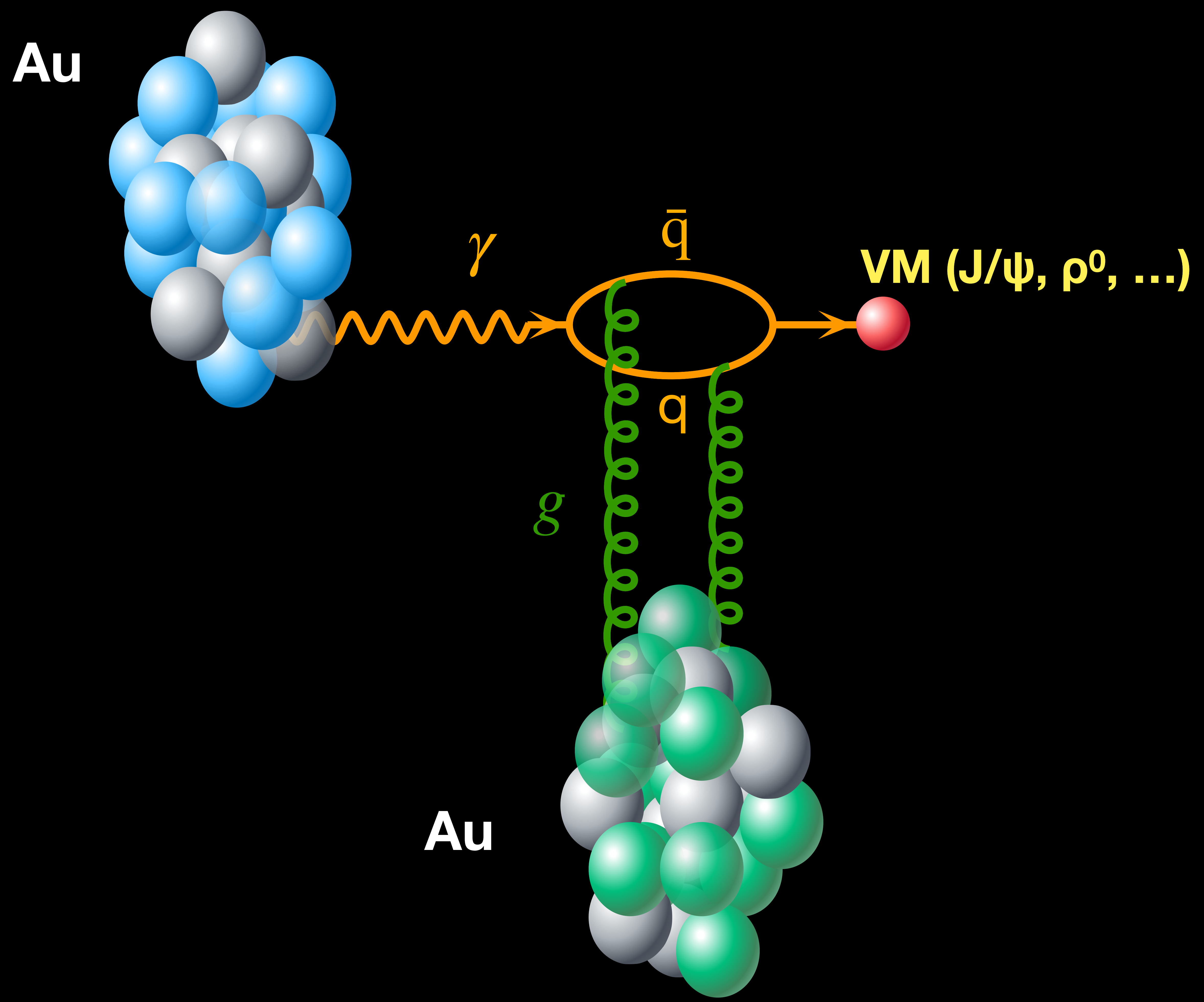
Collisions where nuclei do NOT collide

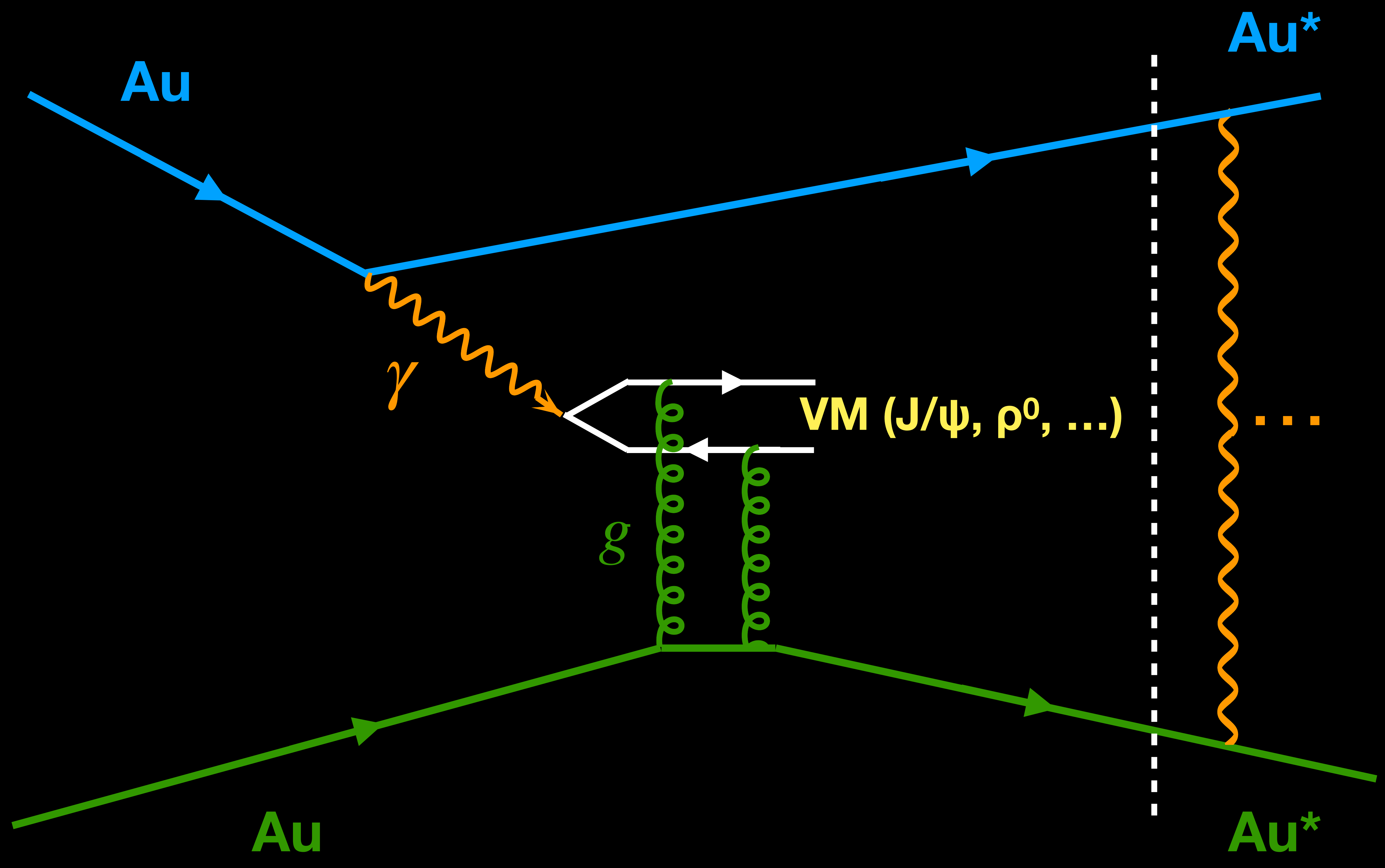
No hadronic collisions happen

Ions interact through photon-ion and photon-photon collisions

=> Called Ultra-peripheral collisions (UPCs)

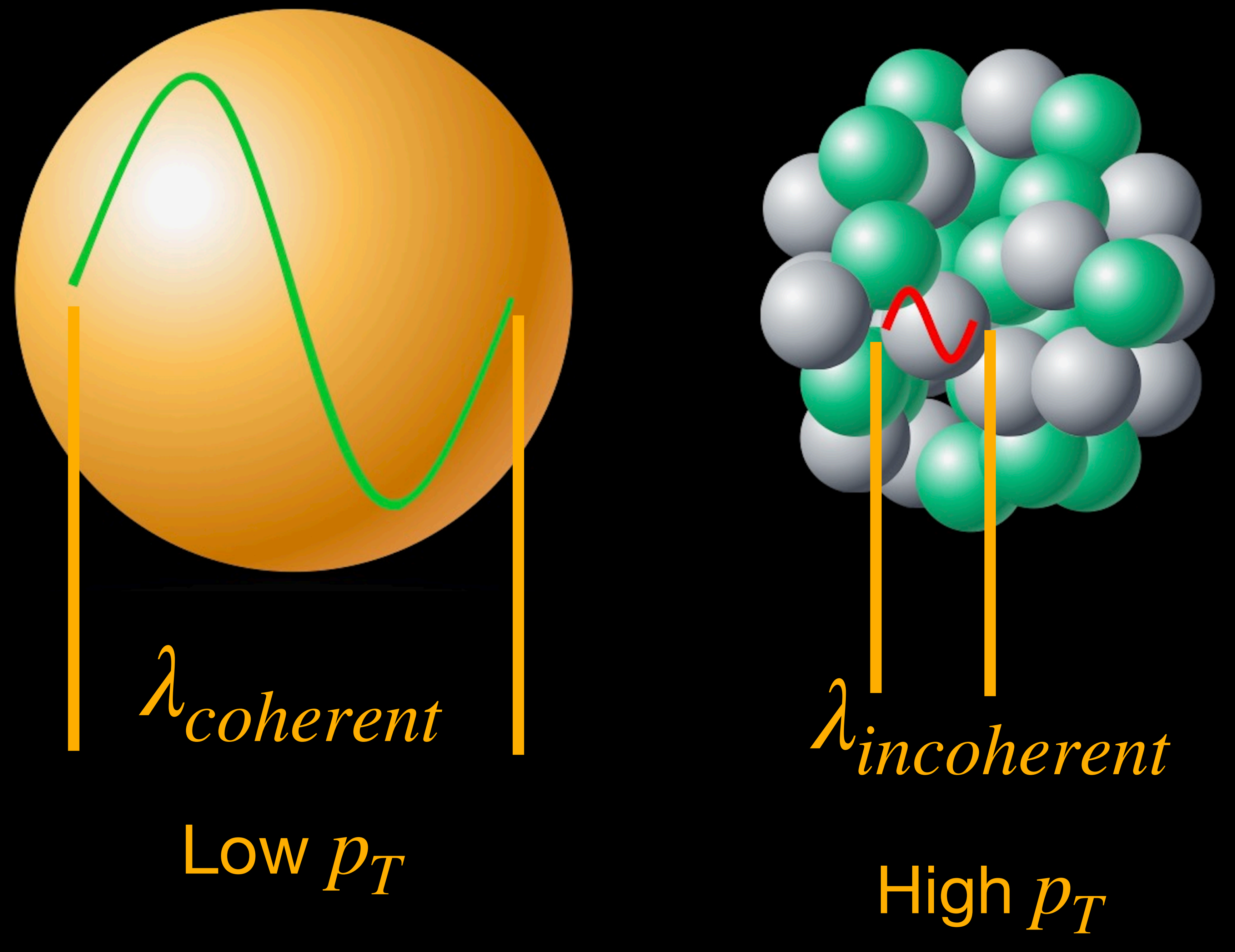
Photon-gluon scattering



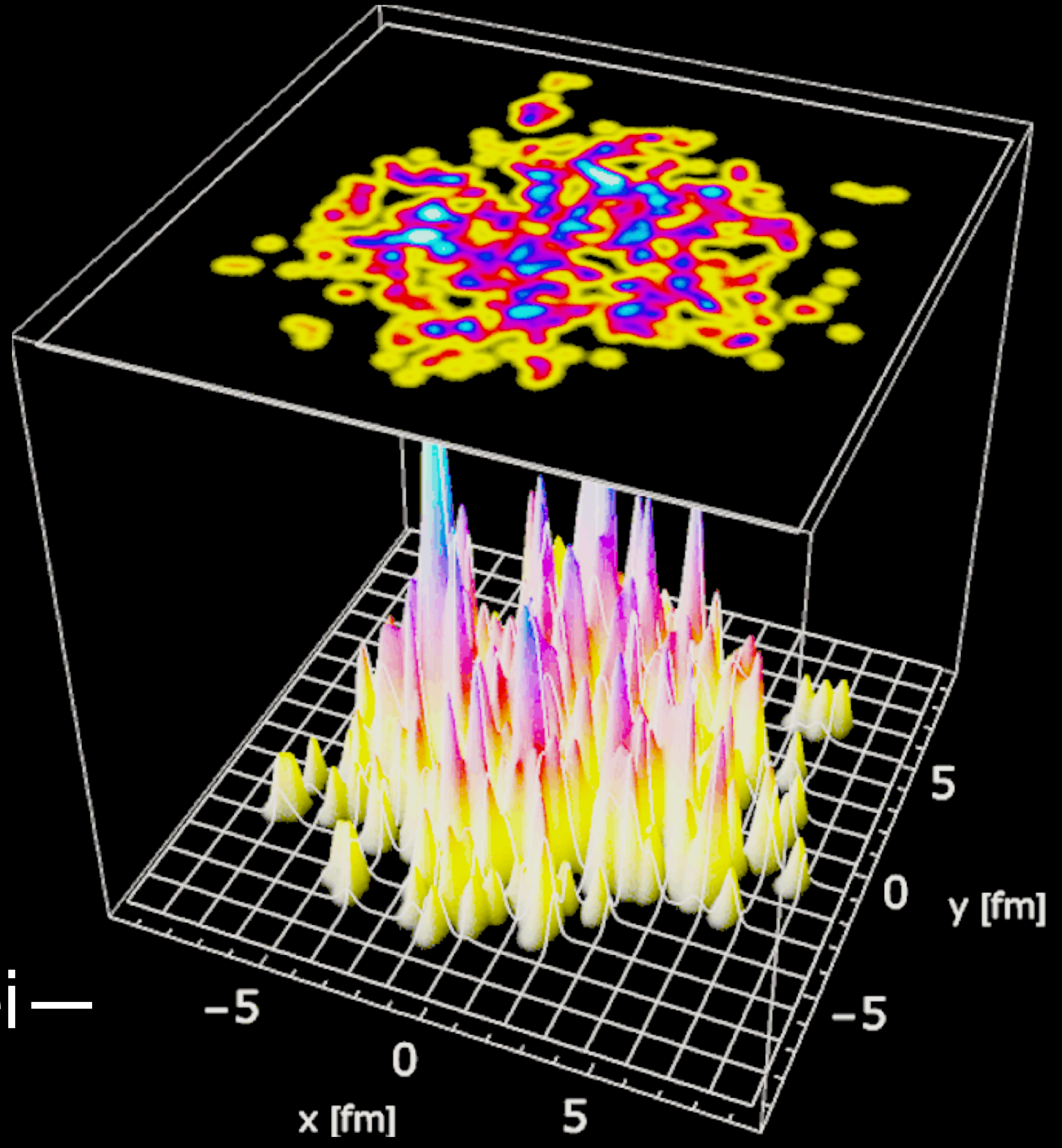


Photoproduction of Vector Mesons (VM) in UPC

UPC VM: Powerful probe of parton densities inside nuclei



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

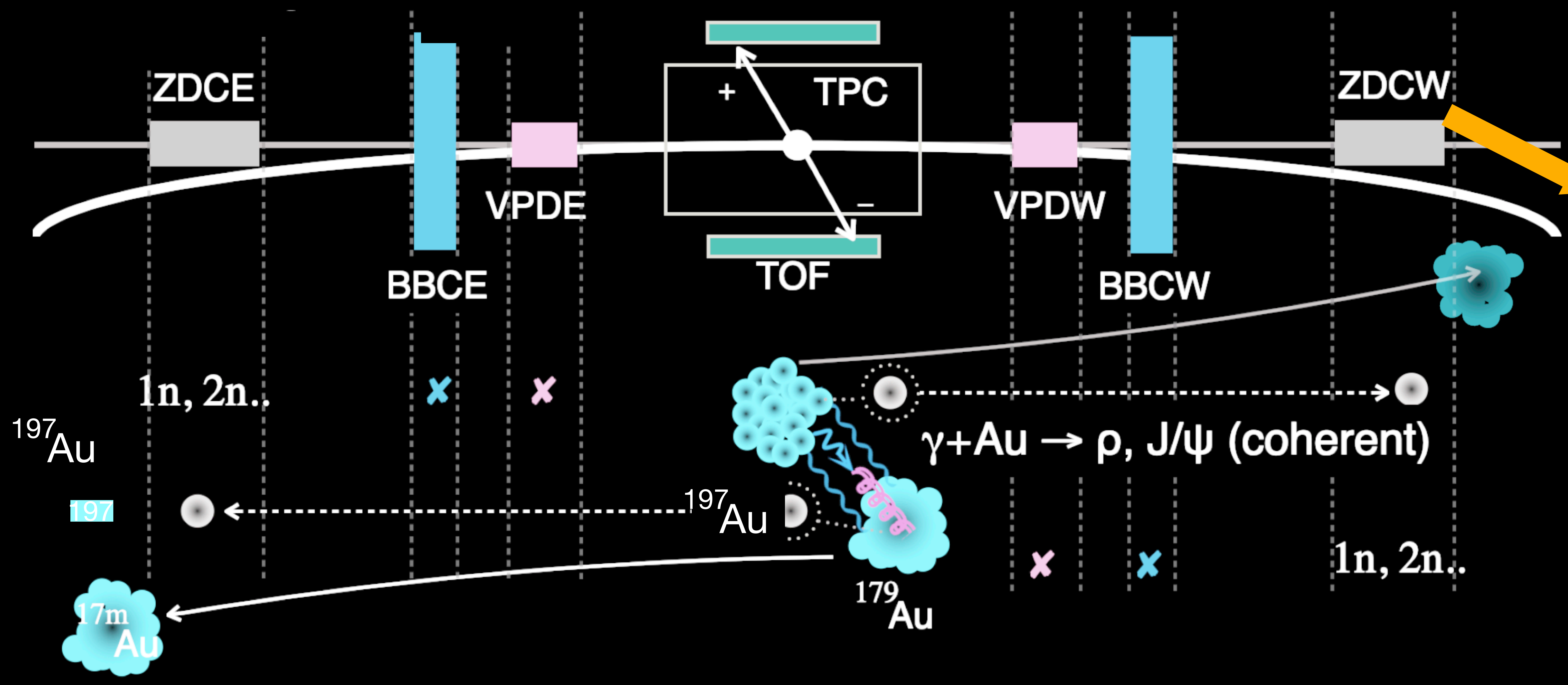


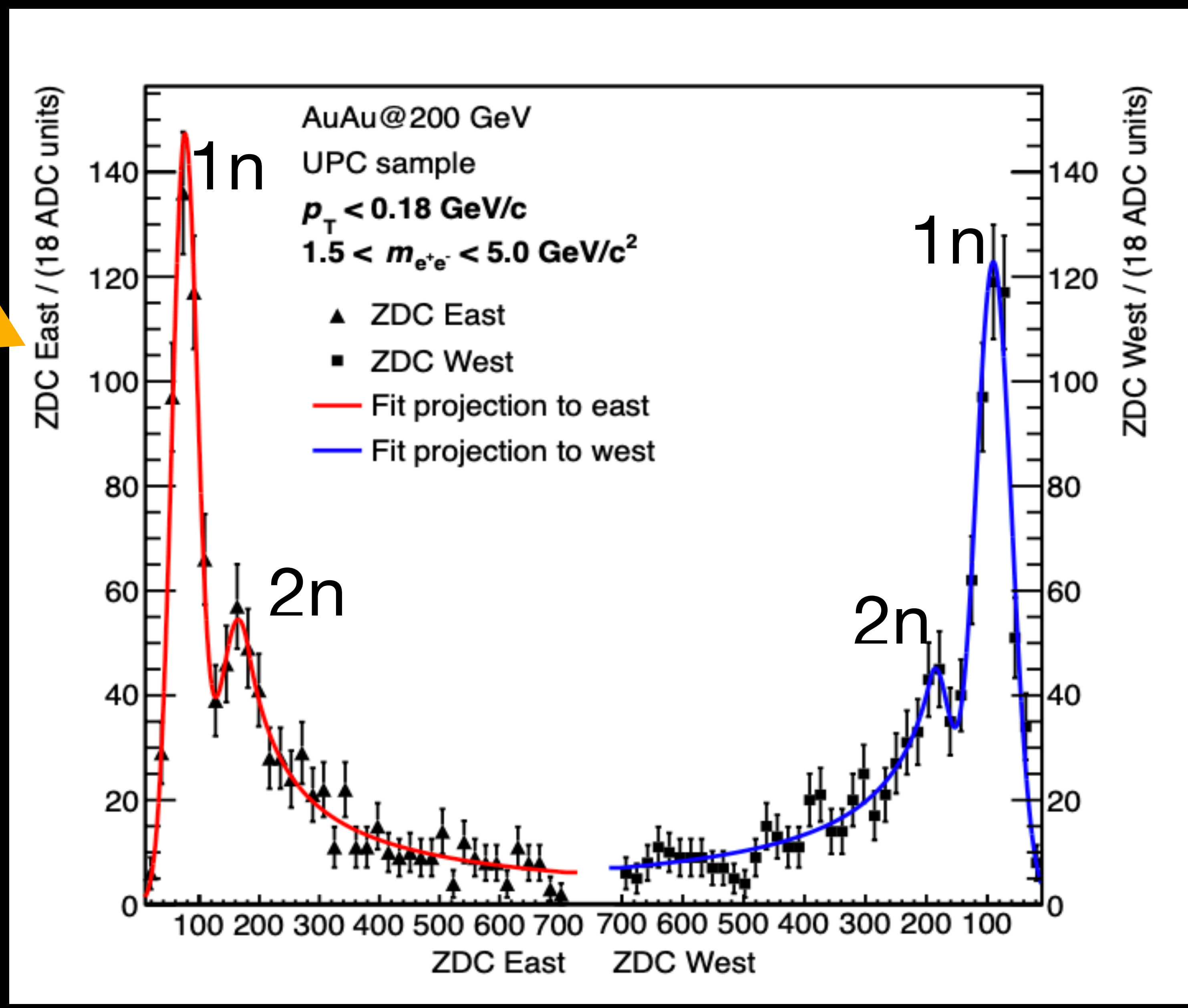
- Probes parton density & fluctuations inside nuclei — constraints for A+A initial state

- Modification of parton densities in heavy nuclei

=> VMs help to probe parton density inside nuclei before EIC era

UPC events with STAR detector



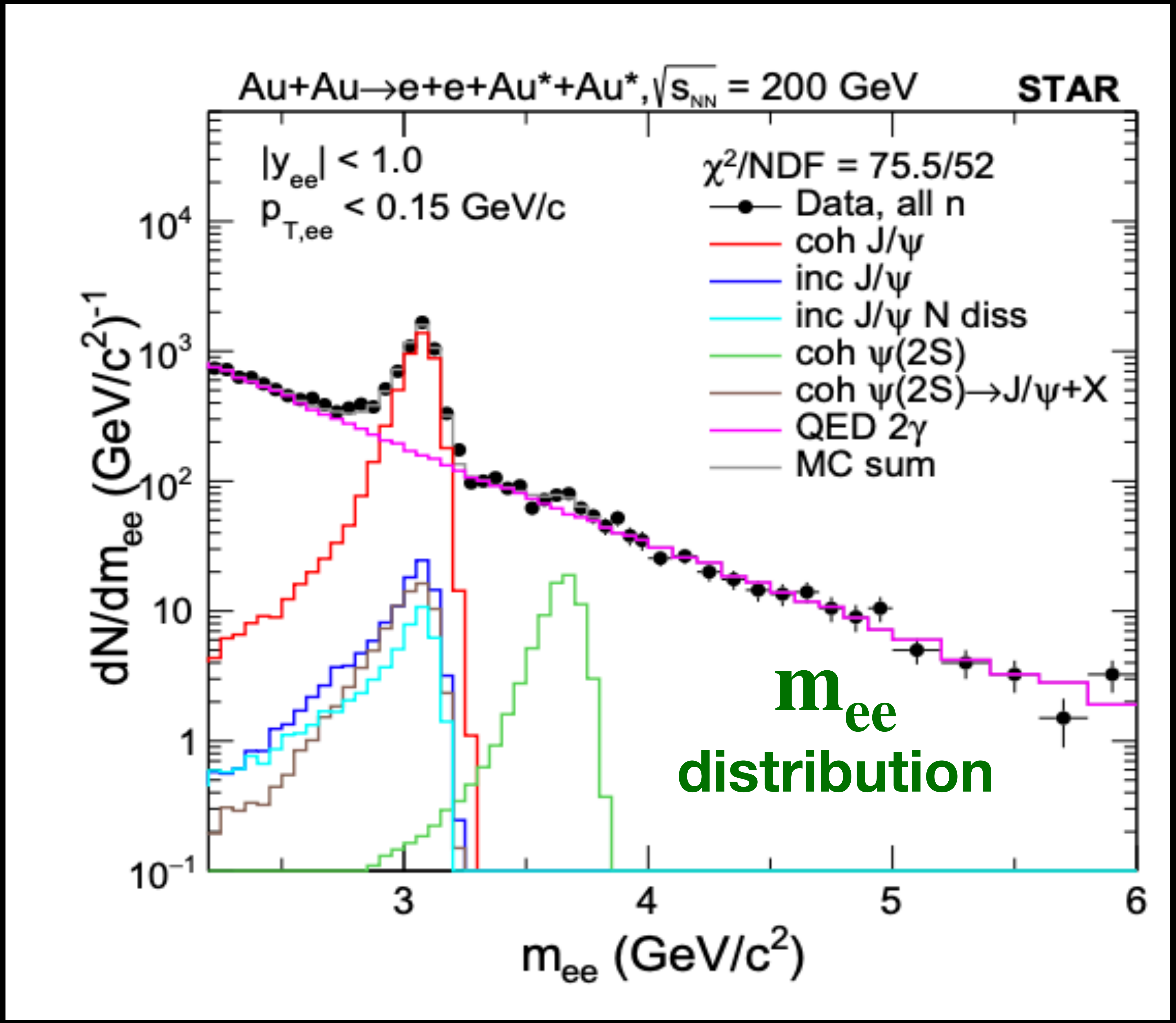


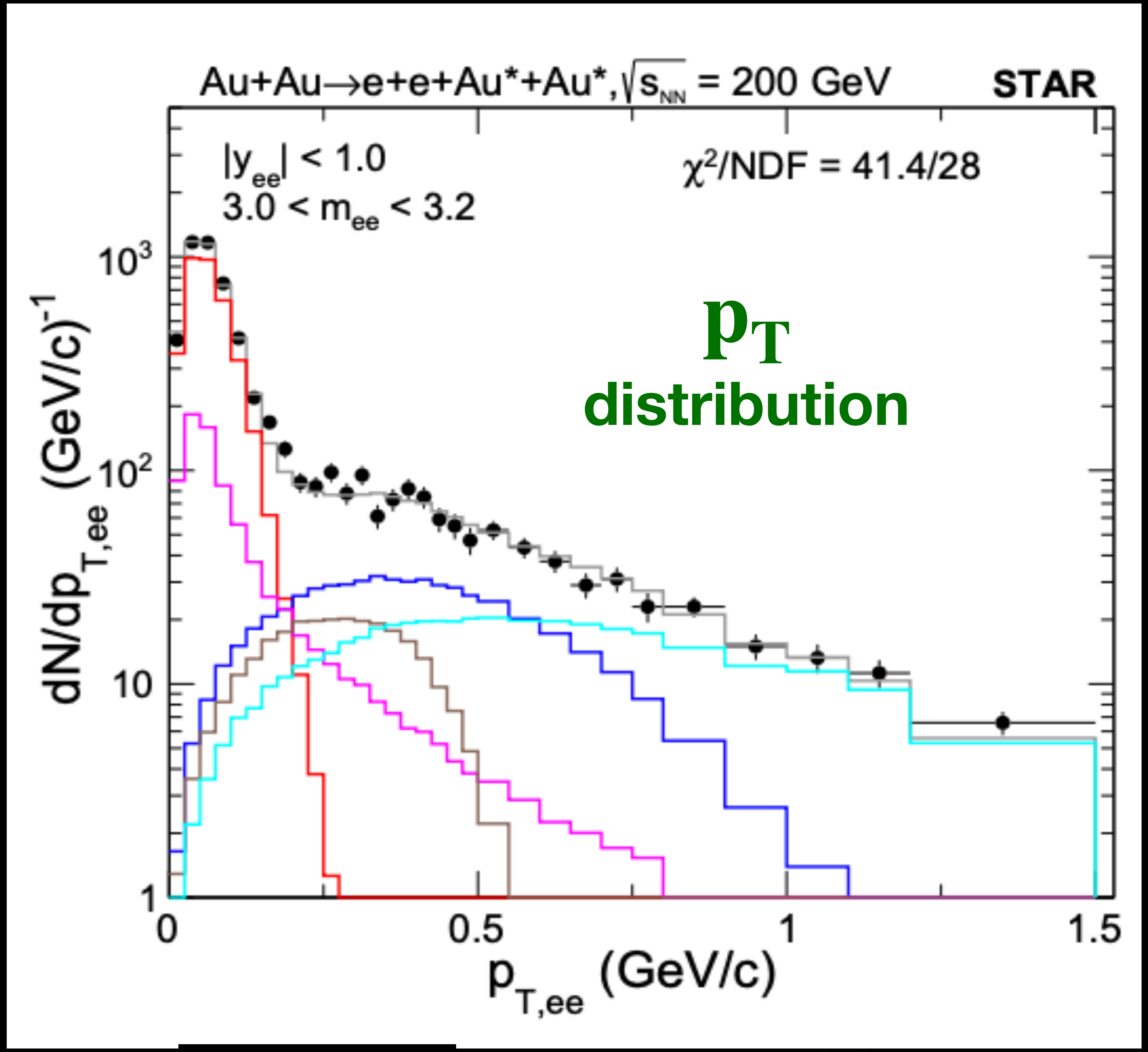
- ◉ Neutron(s) detected in ZDCs
- ◉ ZDC signals show peak structure for neutrons
- ◉ No activity in both BBCs => Diffractive events (η-gap)

=> Method to trigger UPC events

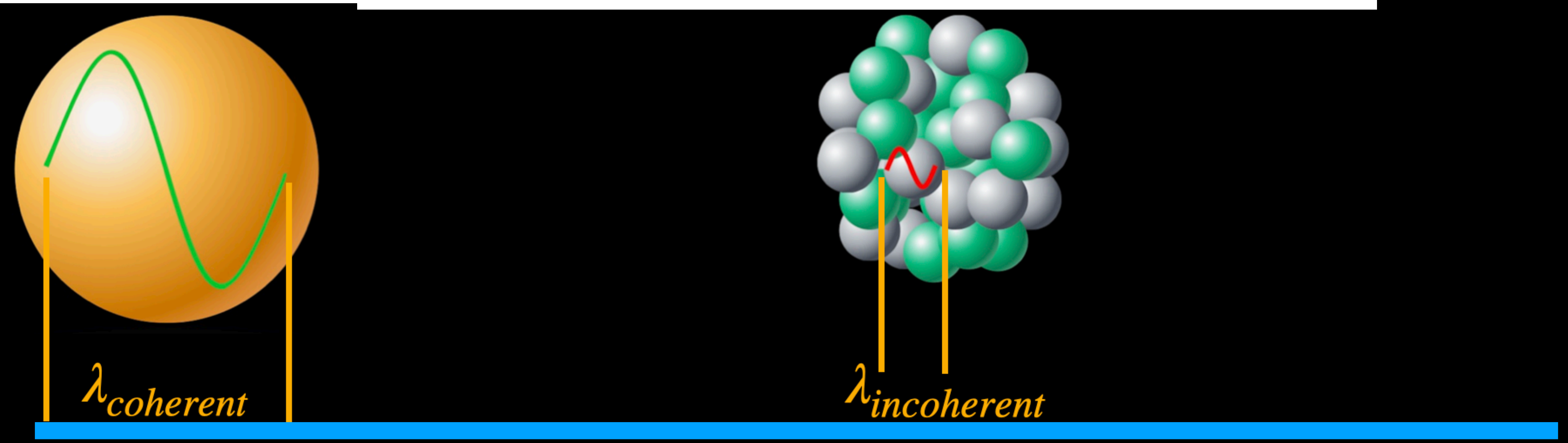
J/ψ measurements in 200 GeV Au+Au UPCs

STAR, arXiv:2311.13632





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

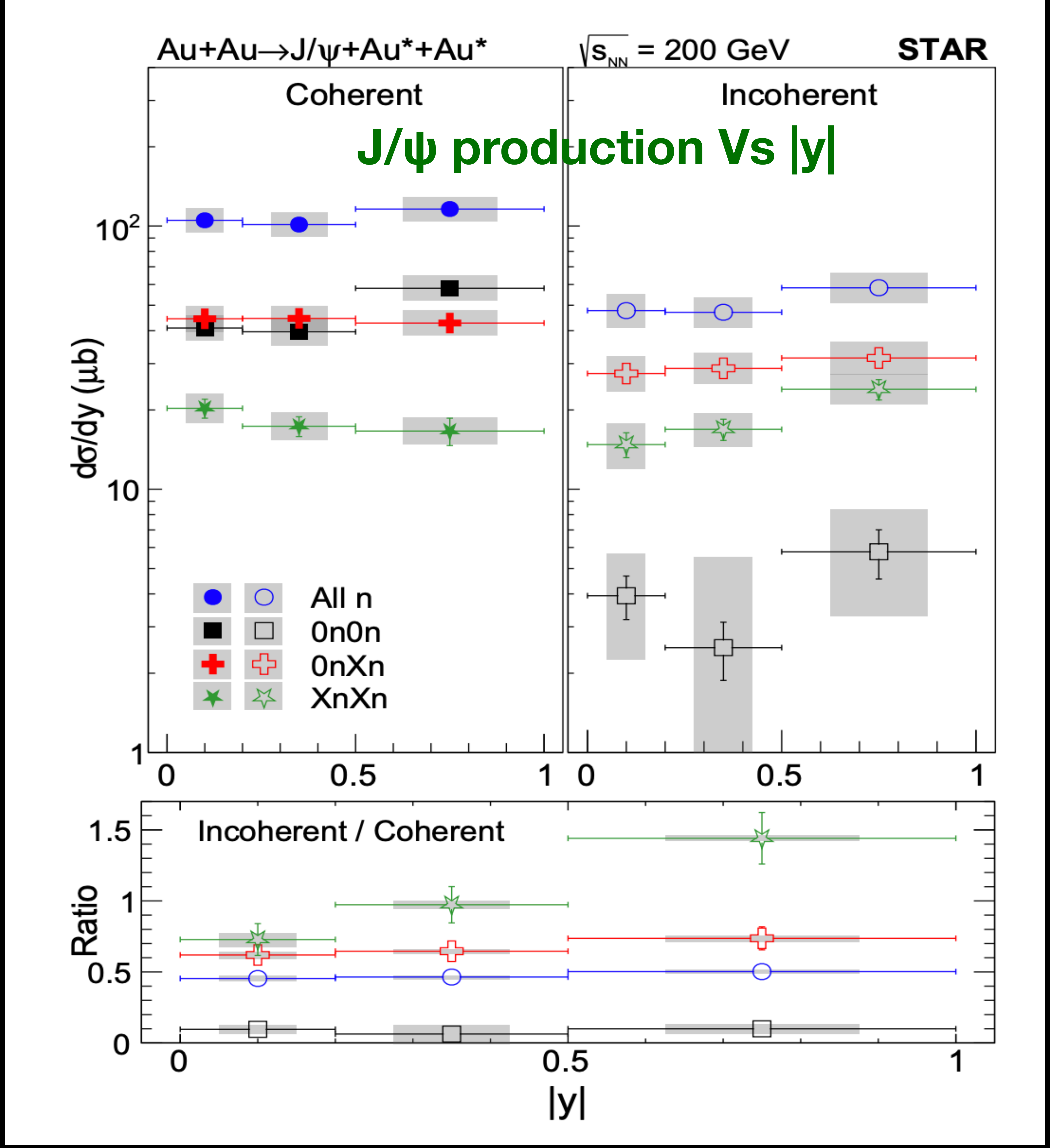


Rapidity dependence J/ψ production cross-section

STAR, arXiv:2311.13637

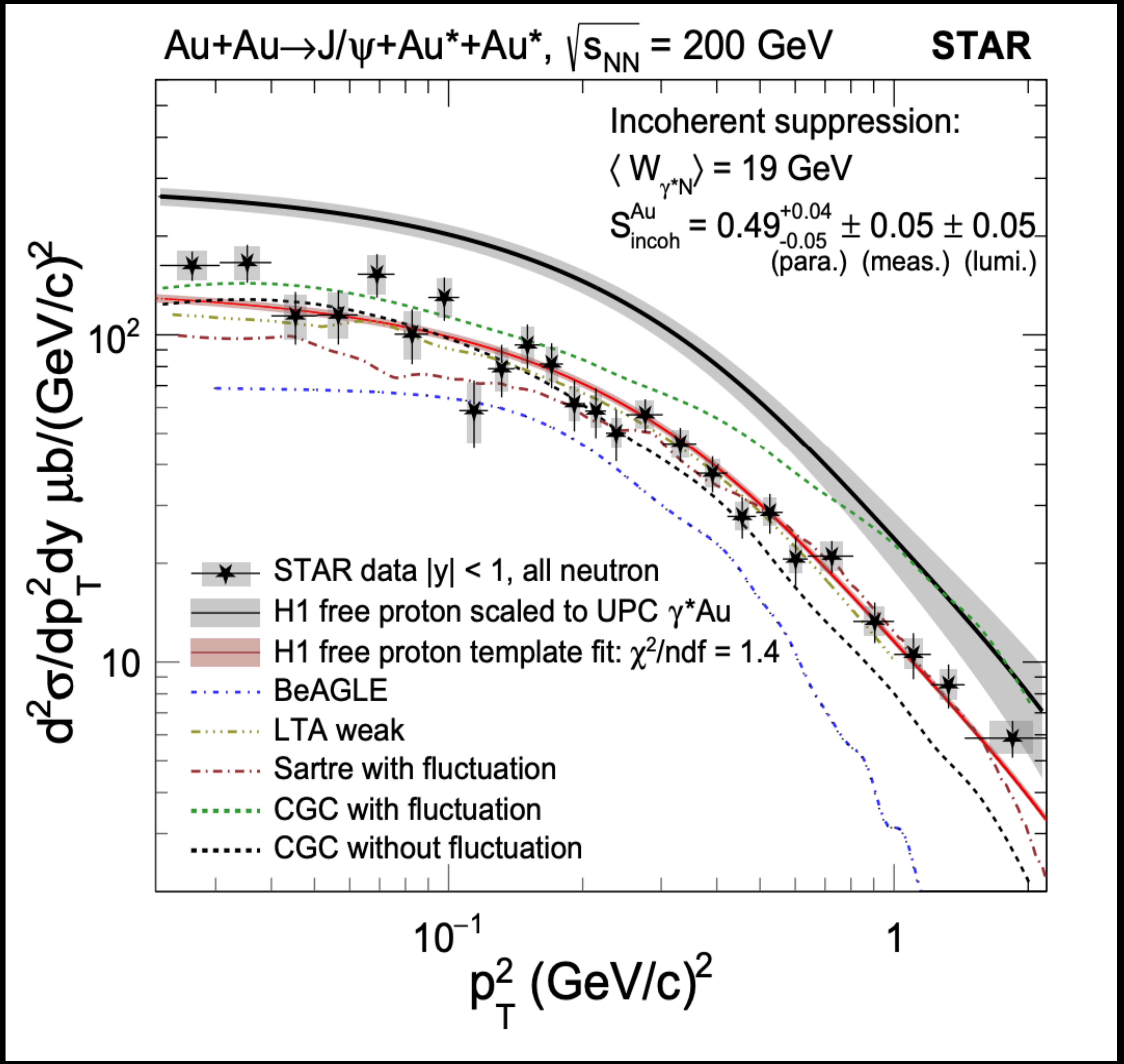
- Measured for coherent and incoherent contributions for different neutron emission in ZDCs
- Systematic unc. in incoherent to coherent cross-section ratio are largely cancelled
- Sensitive to the nuclear structure and deformation

=> Important to constrain theoretical models related to nuclear geometry



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

STAR, arXiv:2311.13632



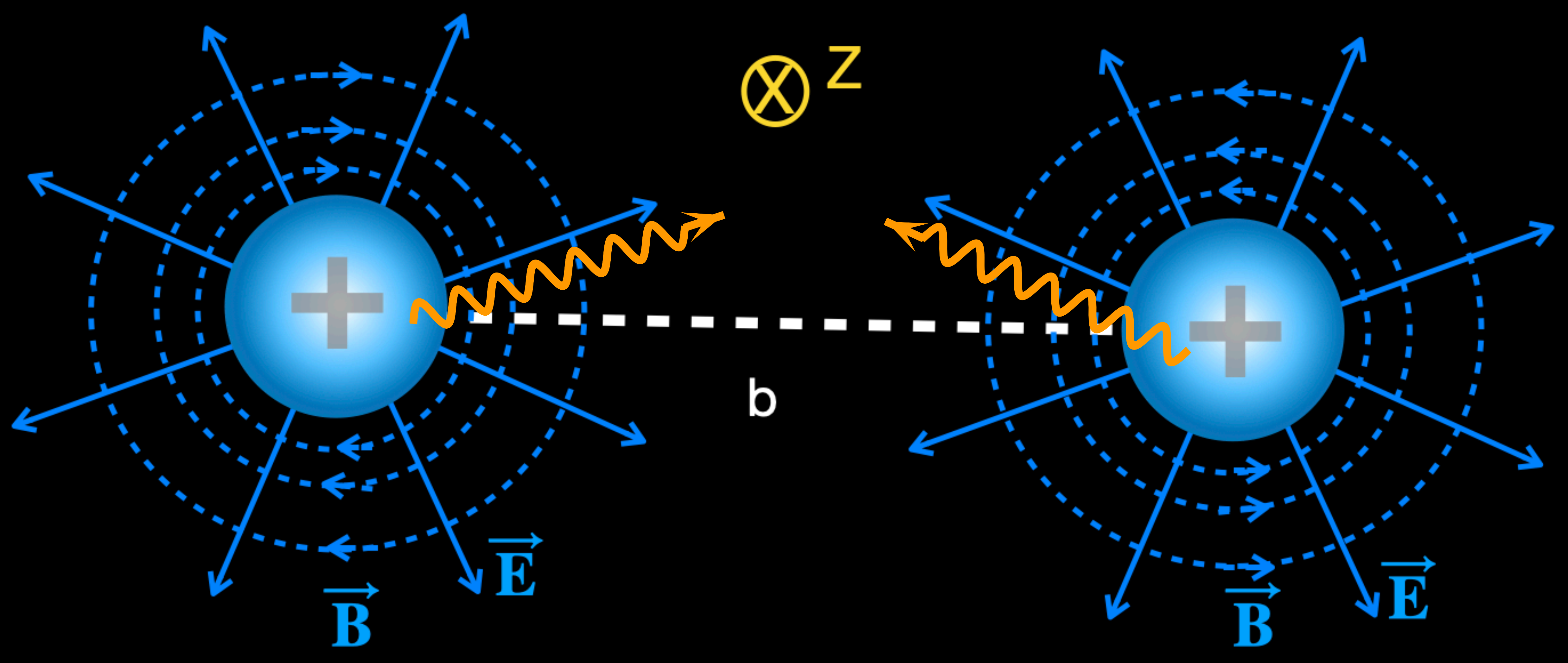
- ◉ Incoherent production compared with H1 data with free proton
- ◉ Strong nuclear suppression (~49%) seen
  (Mäntysaari et. al, Phys. Rev. Lett. **117** (2016) 5, 052301)
- ◉ Models found H1 data supports sub-nucleonic fluctuations
  (Mäntysaari et. al, Phys. Rev. D **106** (2022) 7, 074019)
- ◉ STAR 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

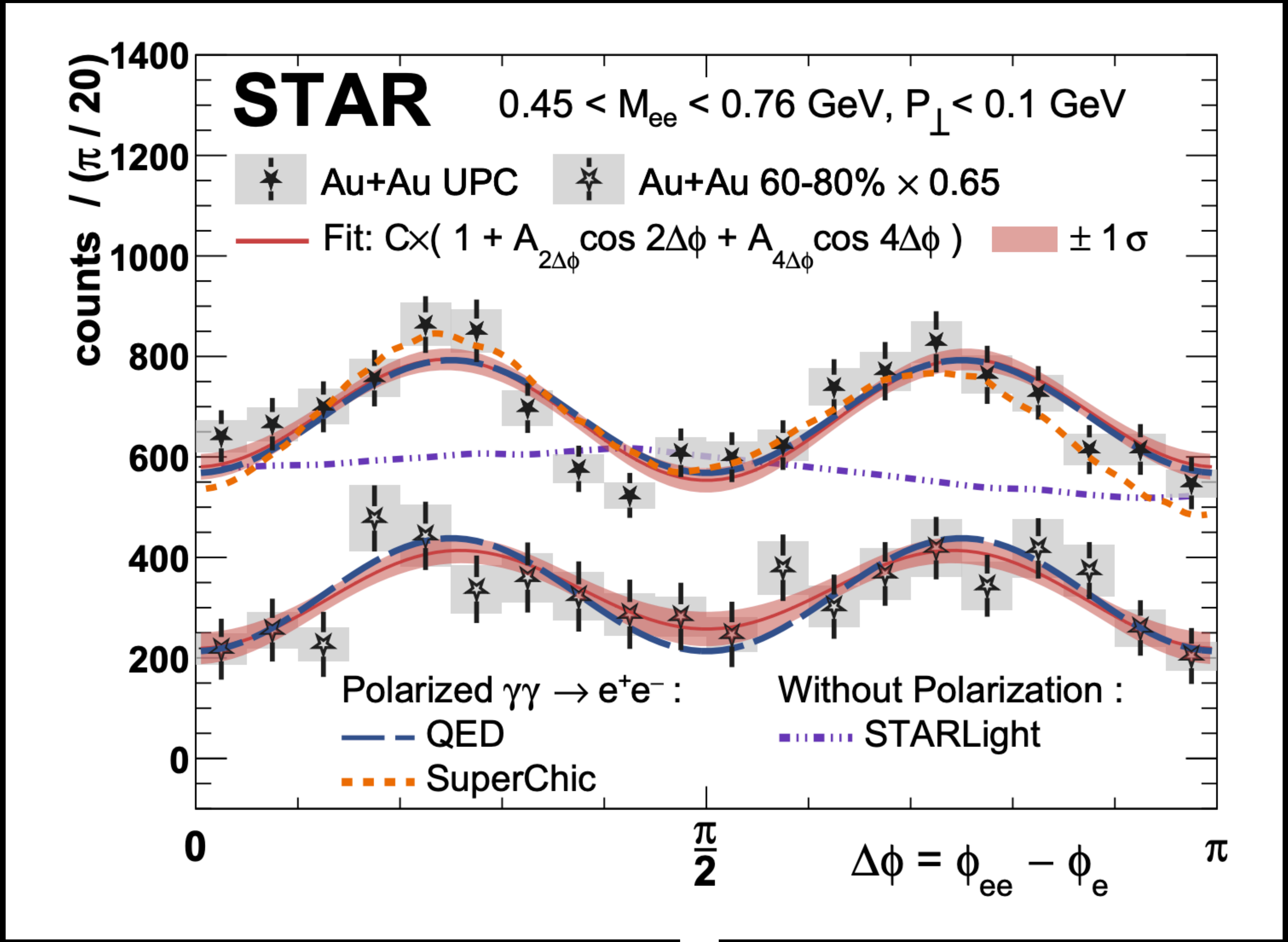
VM spin interference: A novel quantum phenomenon for high resolution gluon imaging

Polarized Photons from colliding nuclei

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



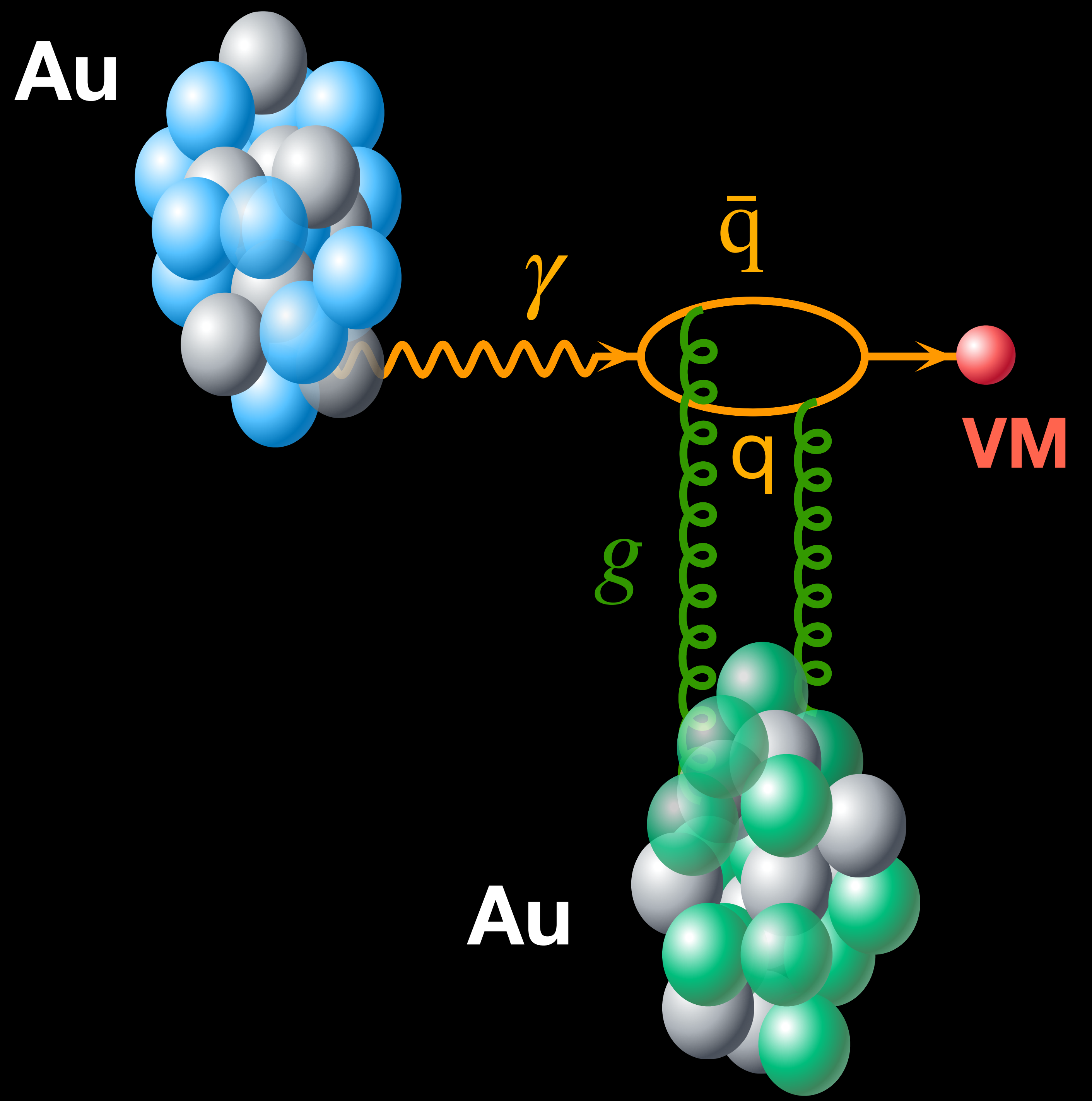
Transverse view of Lorentz contracted nuclei

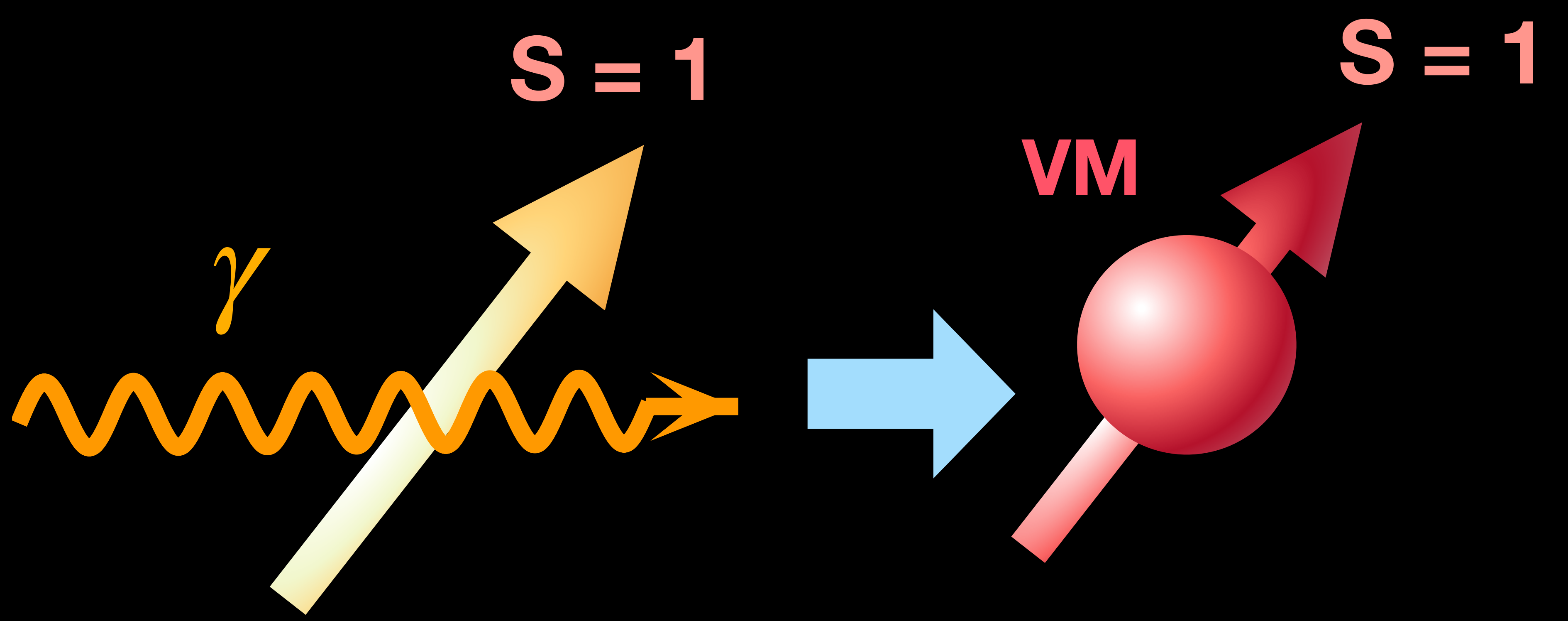


=> Photons in UPC are linearly polarized

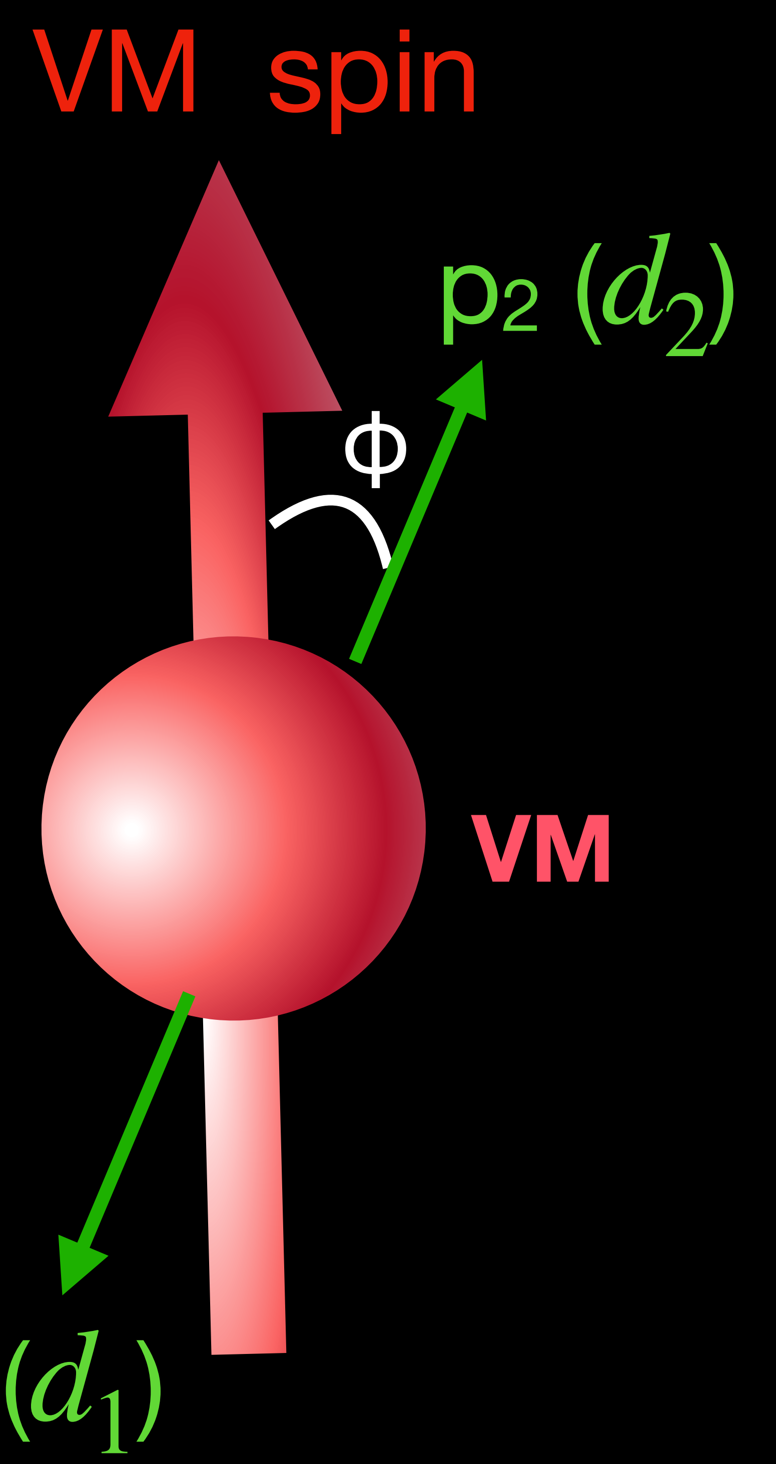
Experimental access to photon polarization demonstrated by STAR, measuring the Breit-Wheeler process, $\gamma\gamma \rightarrow e^{+}e^{-}$

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)

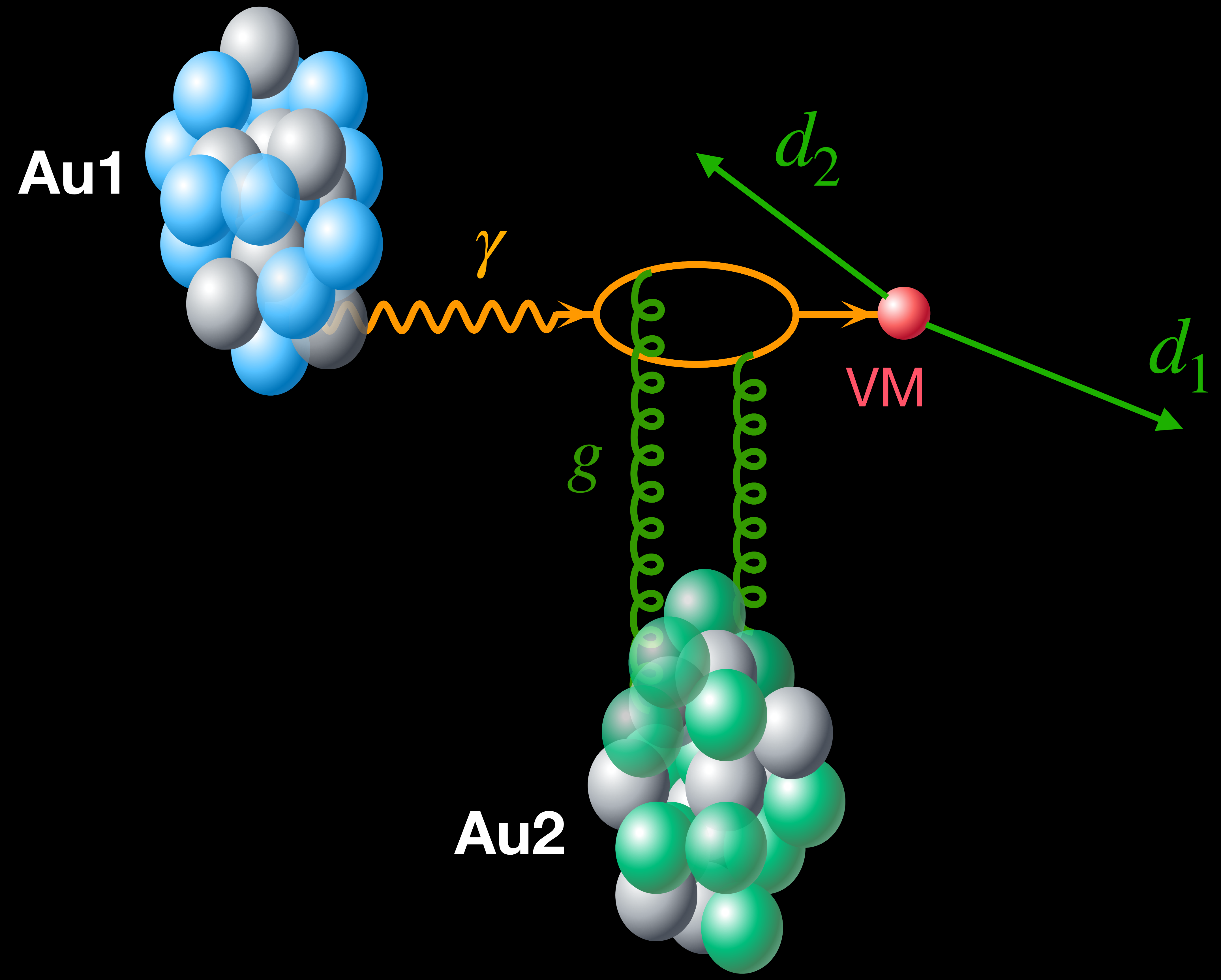
=> The cos(2ϕ) modulation in VM momentum distribution w.r.t photon polarization direction

Measuring the modulation over a large no. of events

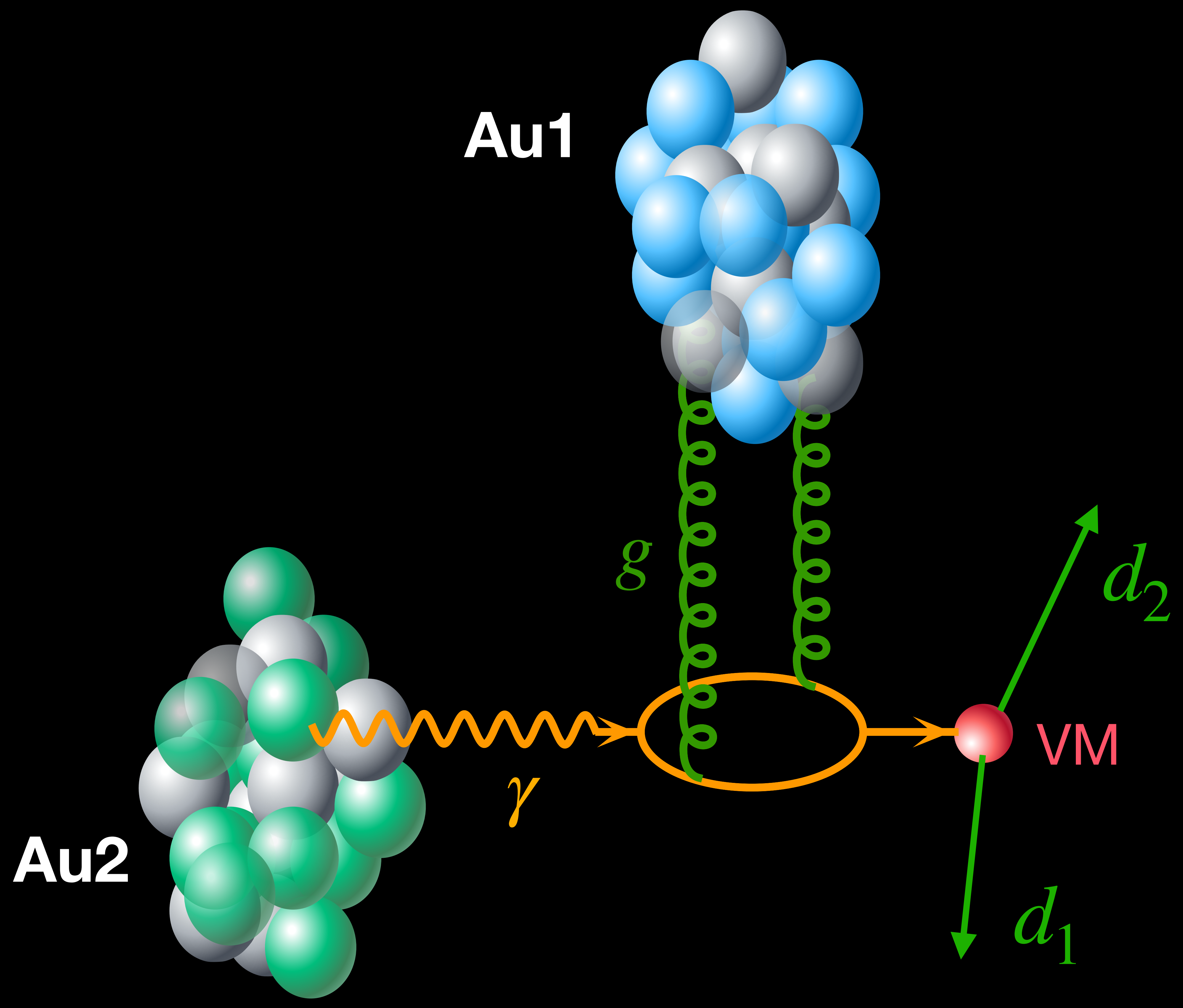
Photon polarization correlated with Impact parameter —> random from one event to the next

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

Photon source ambiguity



PATH - 1

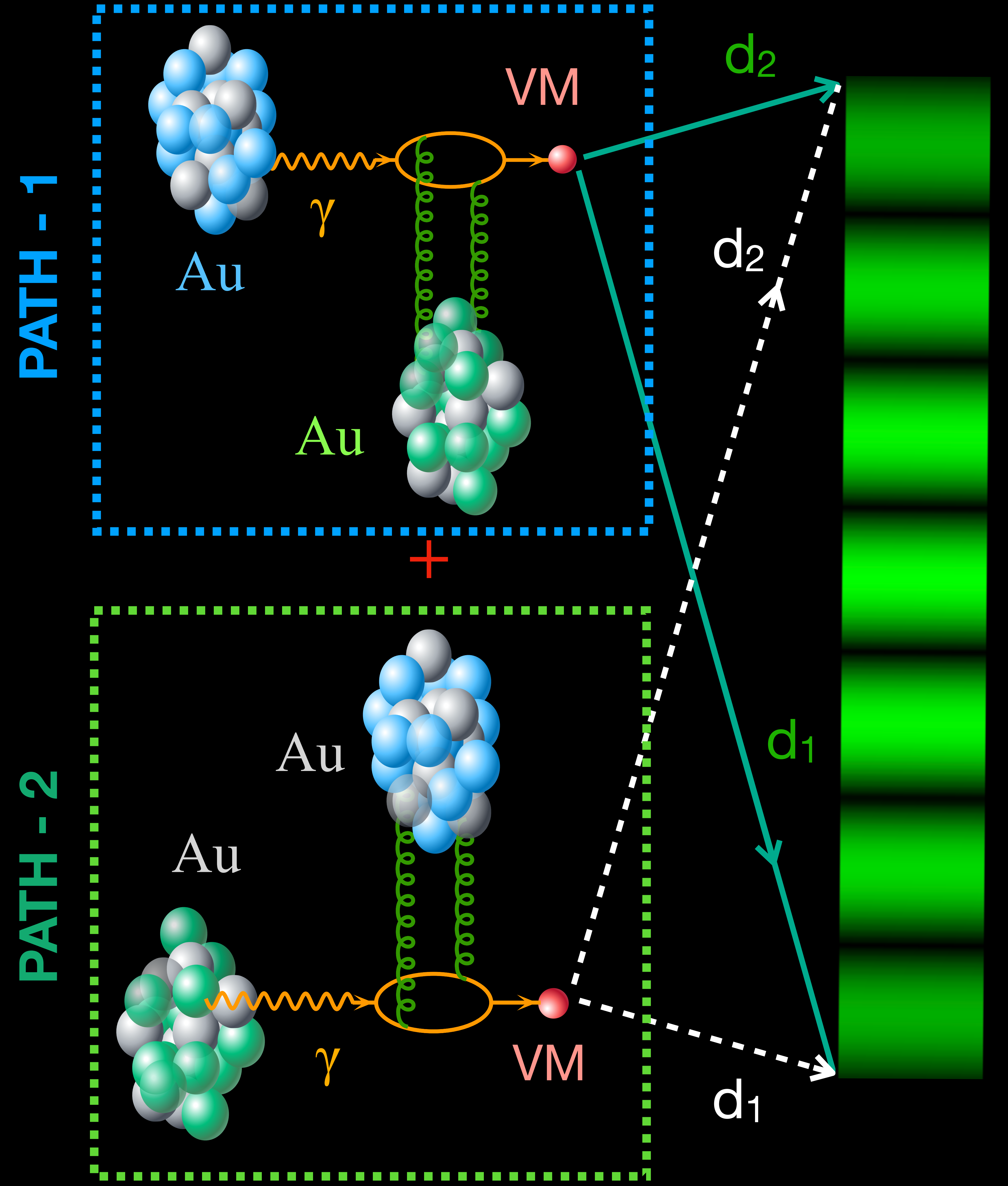


PATH - 2

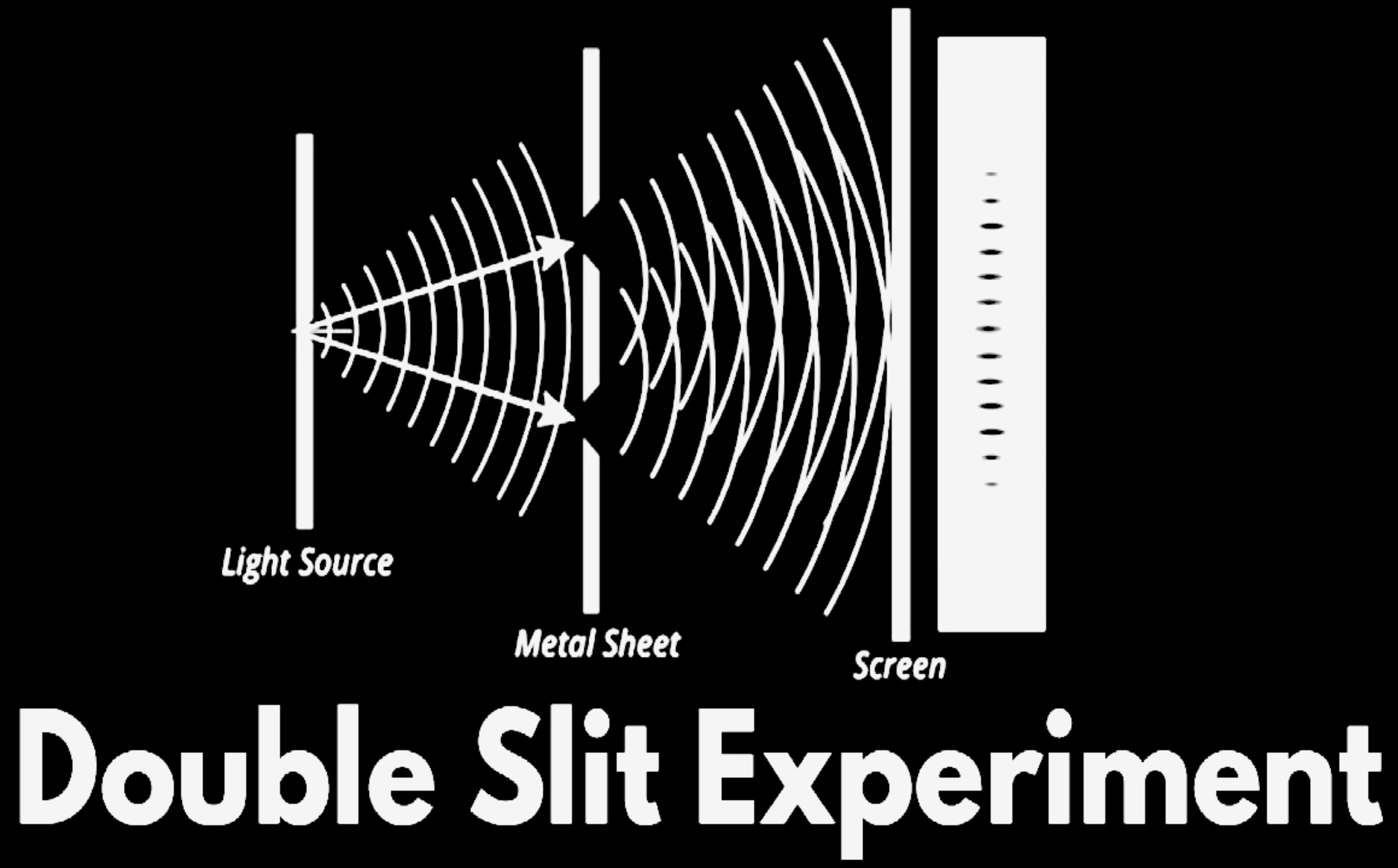
=> Two independent paths of VM production

—> The paths are indistinguishable

Interference makes the modulation observable in experiment



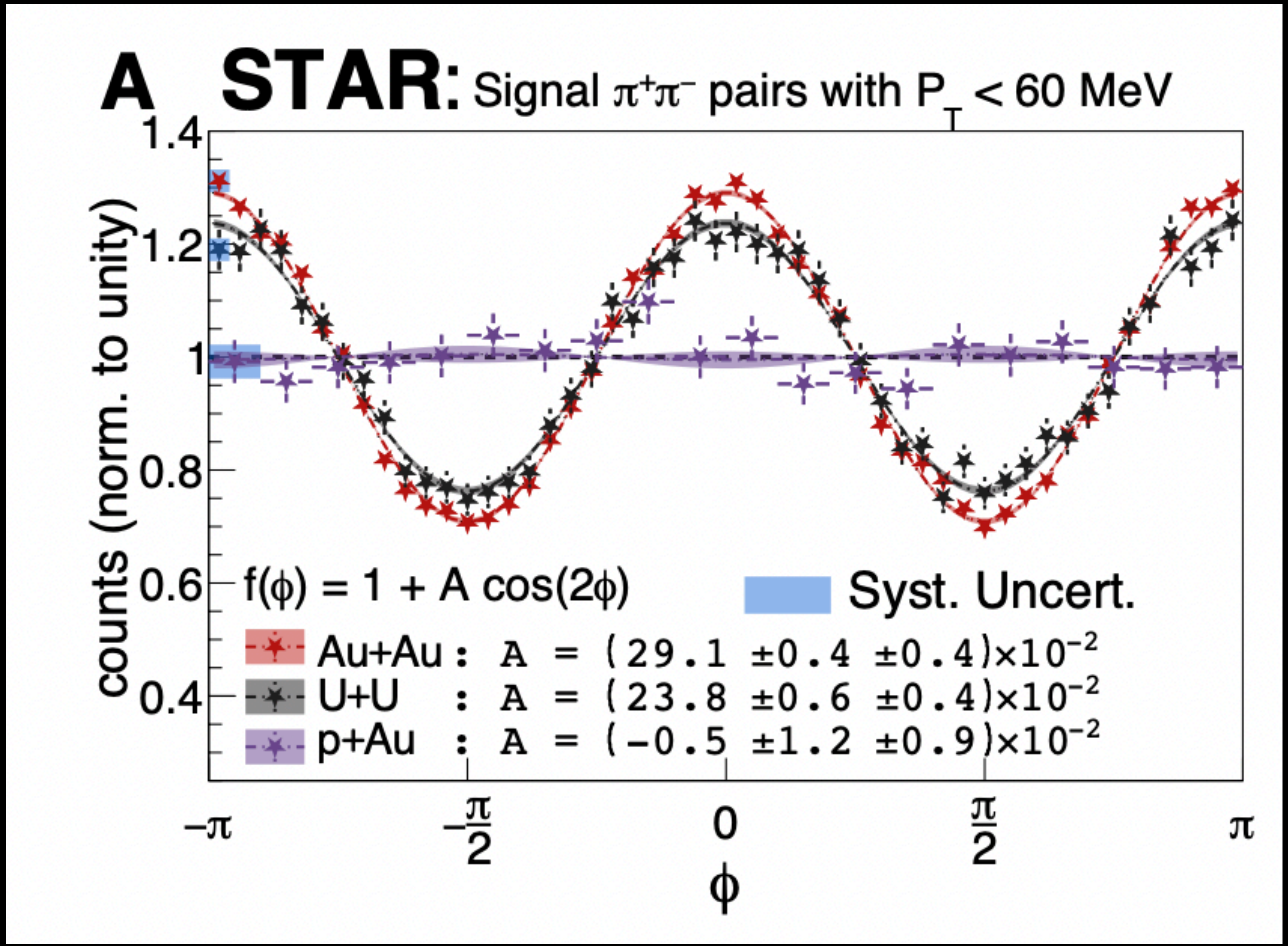
Photon source ambiguity: Interference among amplitudes of two possible paths



Best analogy: Double slit experiment in Optics

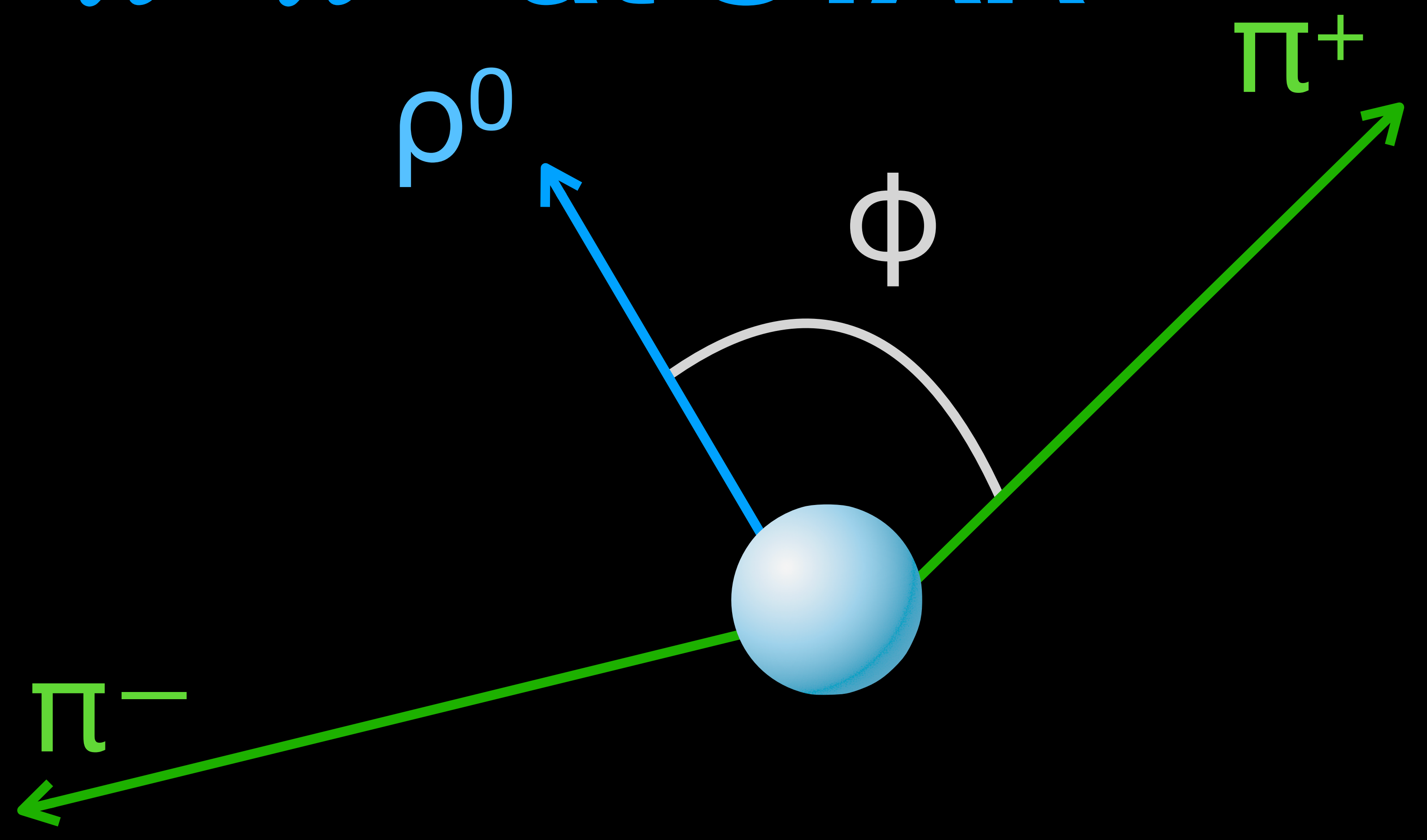
=> Two indistinguishable paths may interfere and make the cos(2ϕ) modulation observable

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



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

Observed the interference for coherent ρ^0 photoproduction in UPCs



SCIENCE ADVANCES | RESEARCH ARTICLE

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

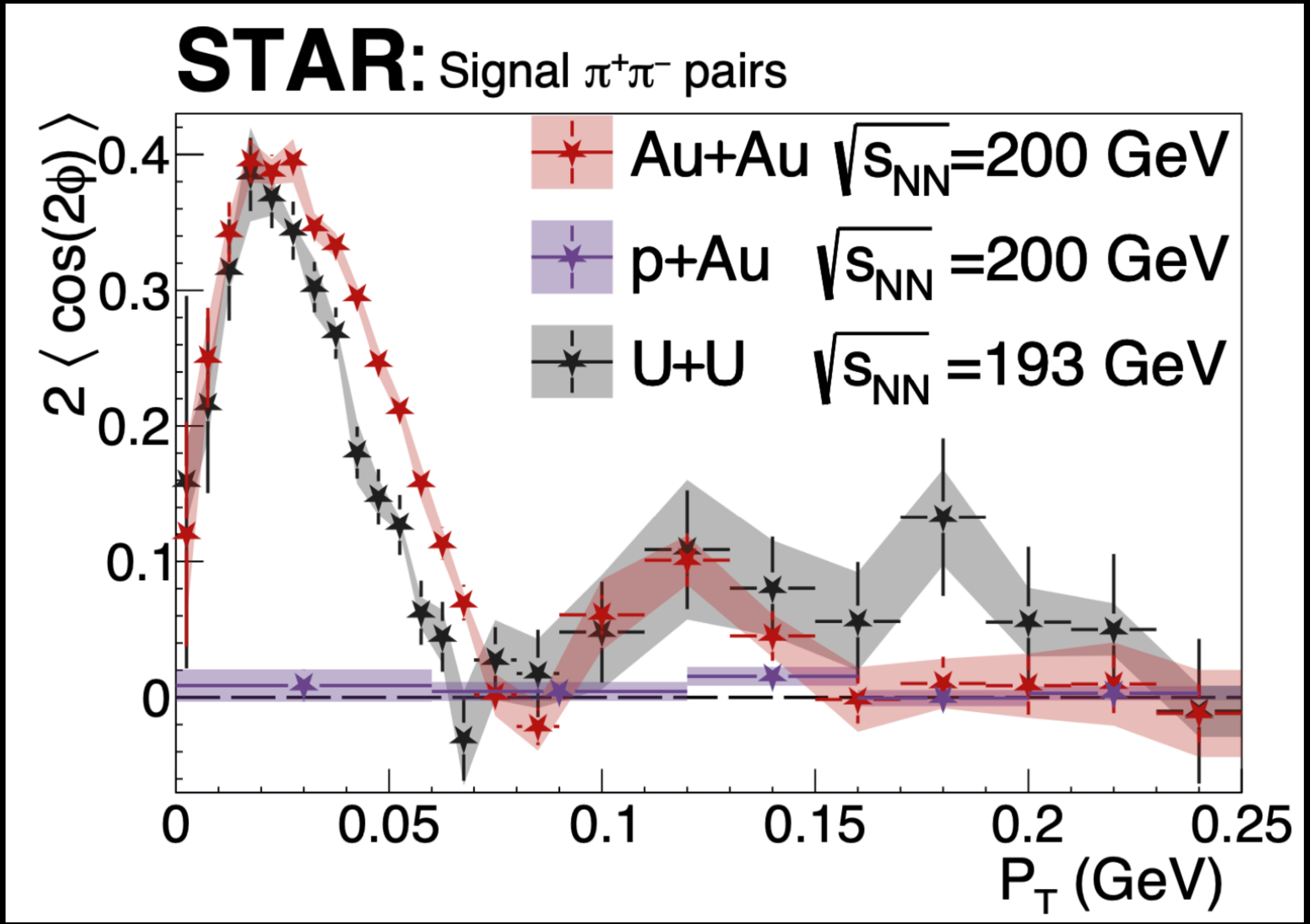
Tomography of ultrarelativistic nuclei with polarized photon-gluon collisions

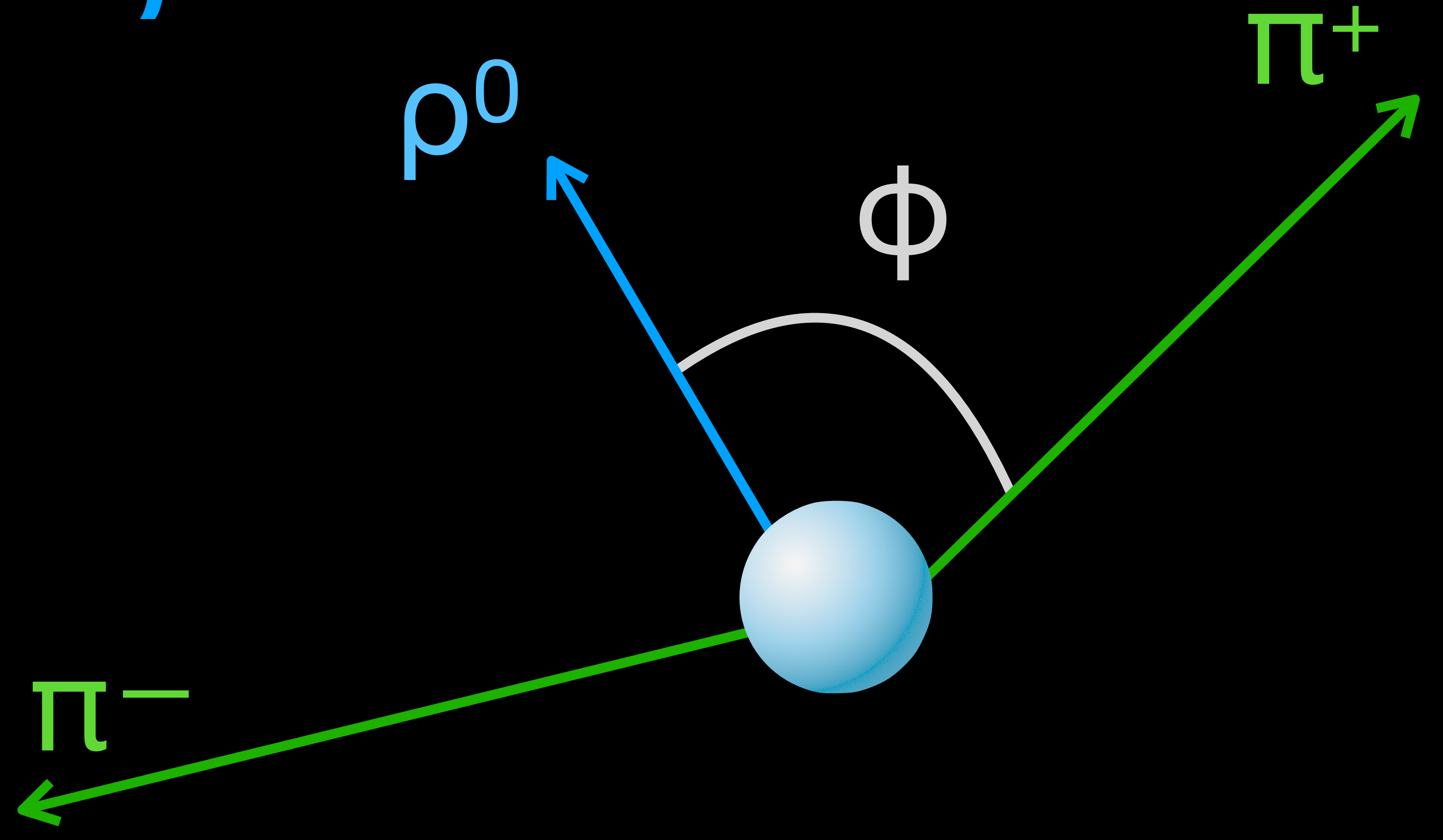
STAR Collaboration

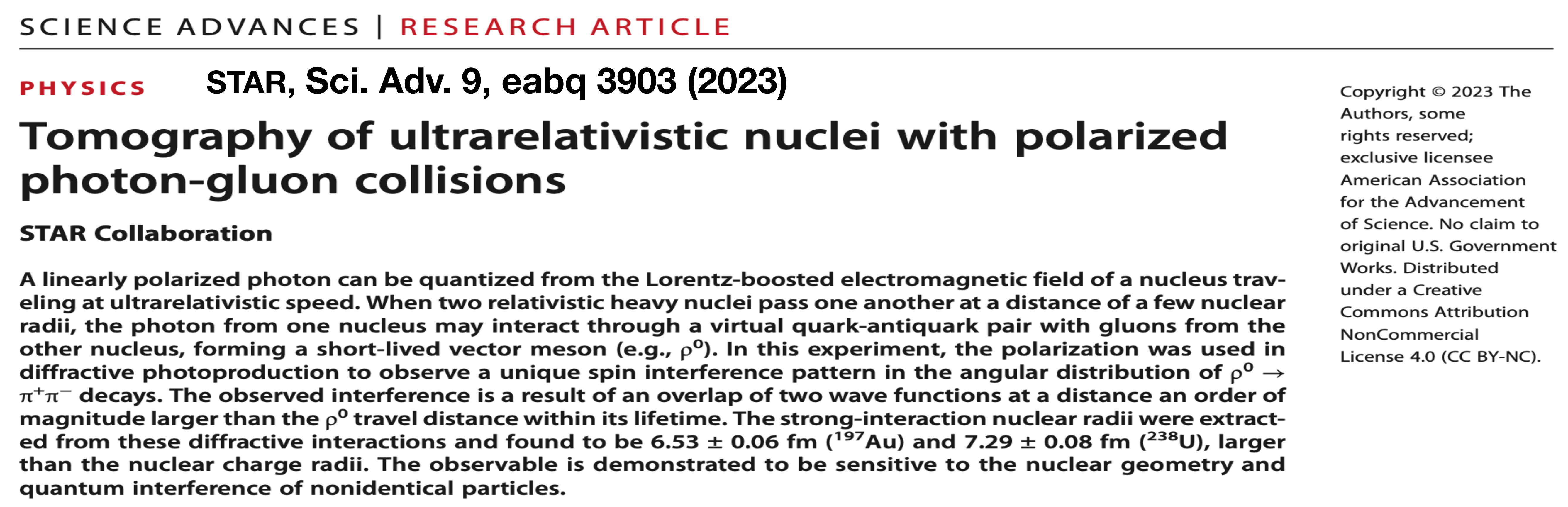
A linearly polarized photon can be quantized from the Lorentz-boosted electromagnetic field of a nucleus traveling at ultrarelativistic speed. When two relativistic heavy nuclei pass one another at a distance of a few nuclear radii, the photon from one nucleus may interact through a virtual quark-antiquark 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 $\rho^0 \to \pi^+\pi^-$ 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.

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







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

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

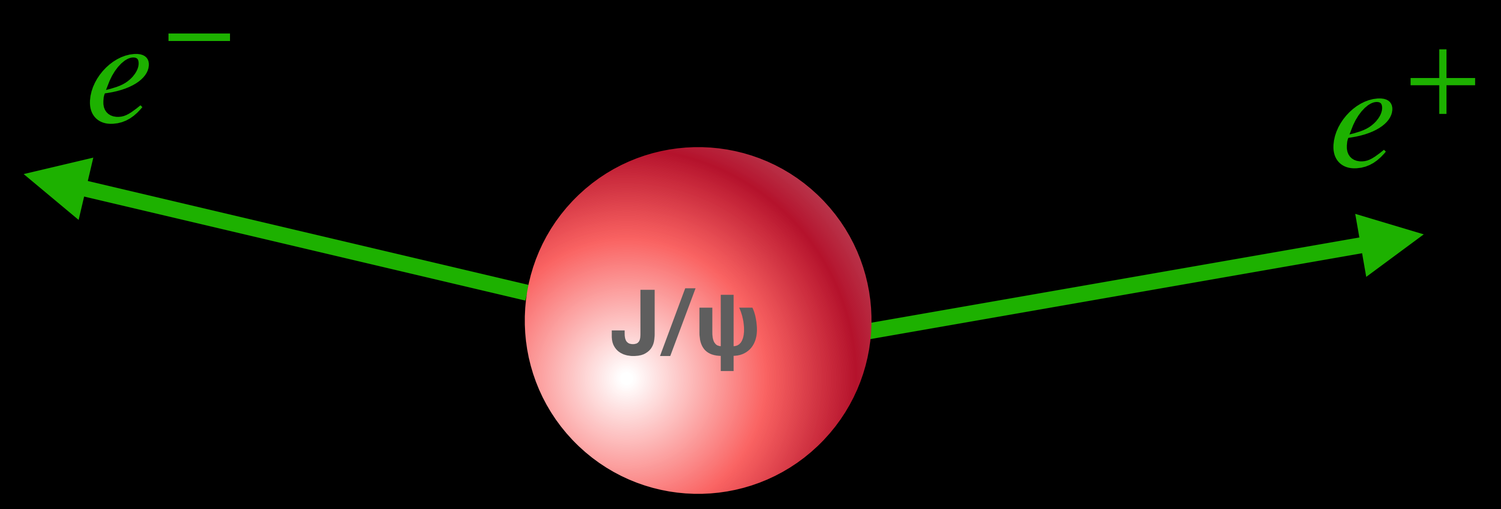
STAR, Sci. Adv. 9, eabq 3903 (2023)

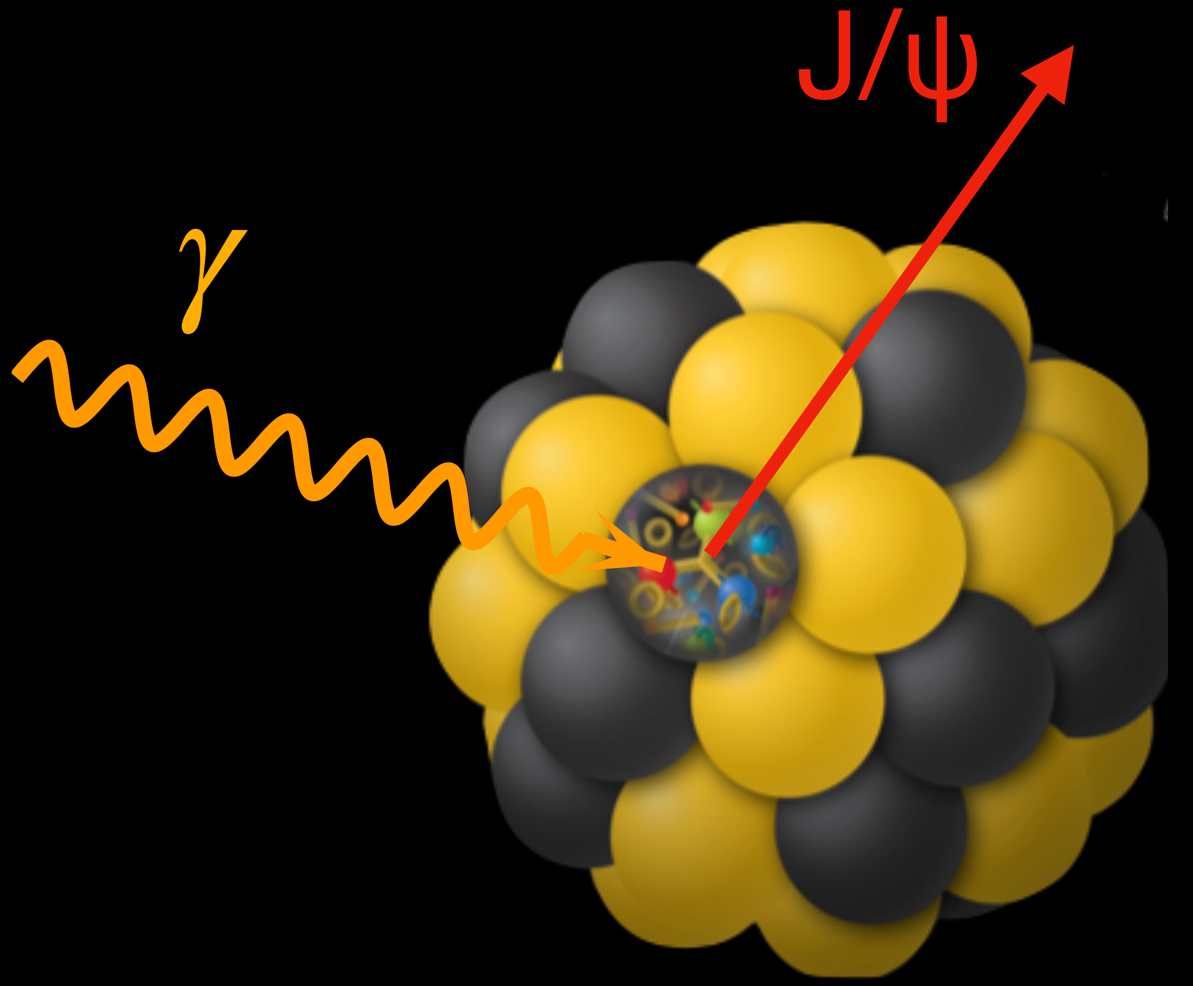
Impact of spin interference on |t| distribution studied in different ϕ bins

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/c^2
Lifetime: 1.3 fm/c

Mass: 3.1 GeV/c^2
Lifetime: 2160 fm/c

Measured sign of the interference tells us the level of interference

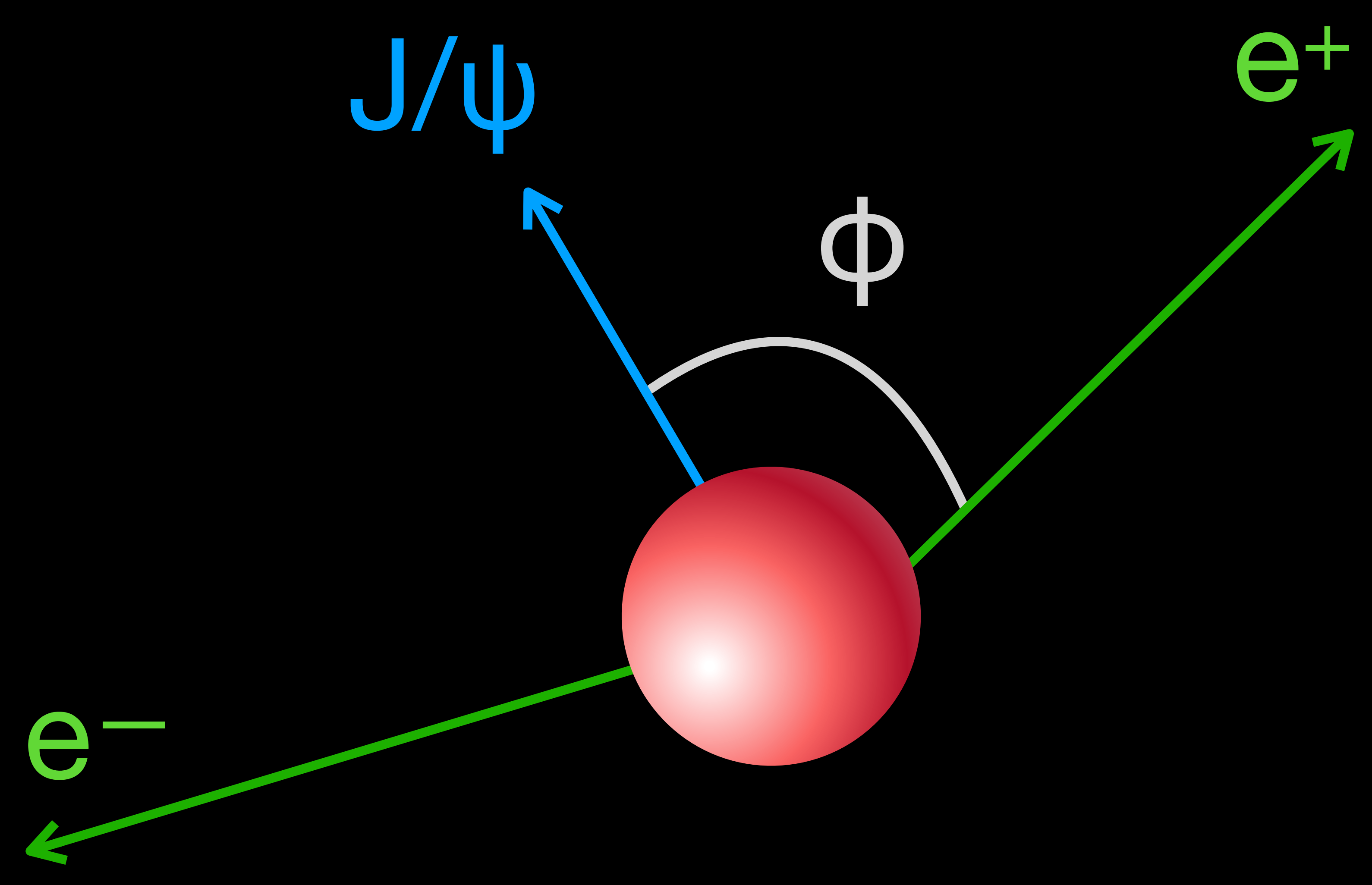
Interference of quantum particles —> Spin interference

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

—> J/ψ decay length much longer than typical distance b/w two colliding nuclei in UPCs

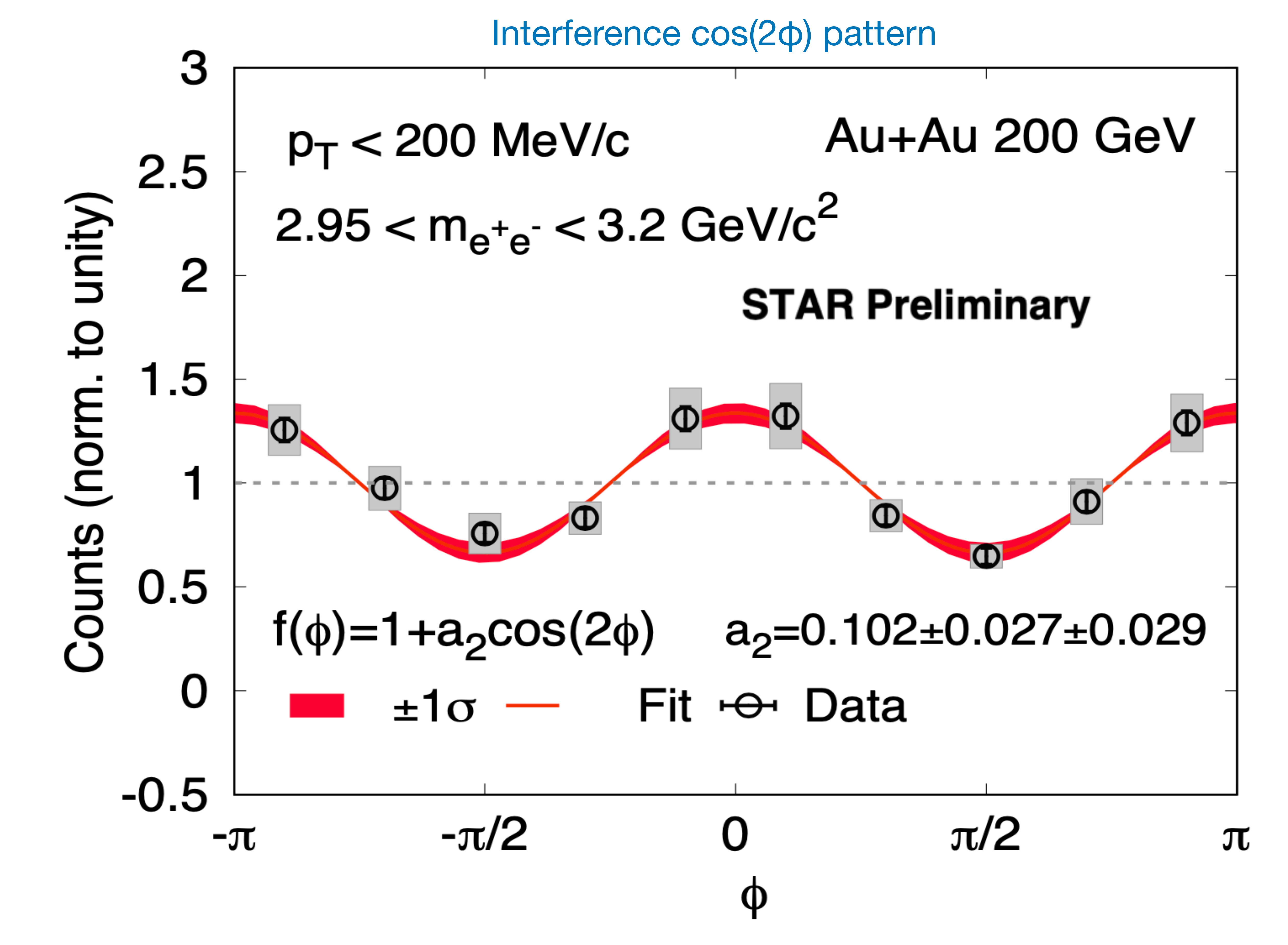
—> Probes finer structure and captures high quality images of the gluon distributions

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



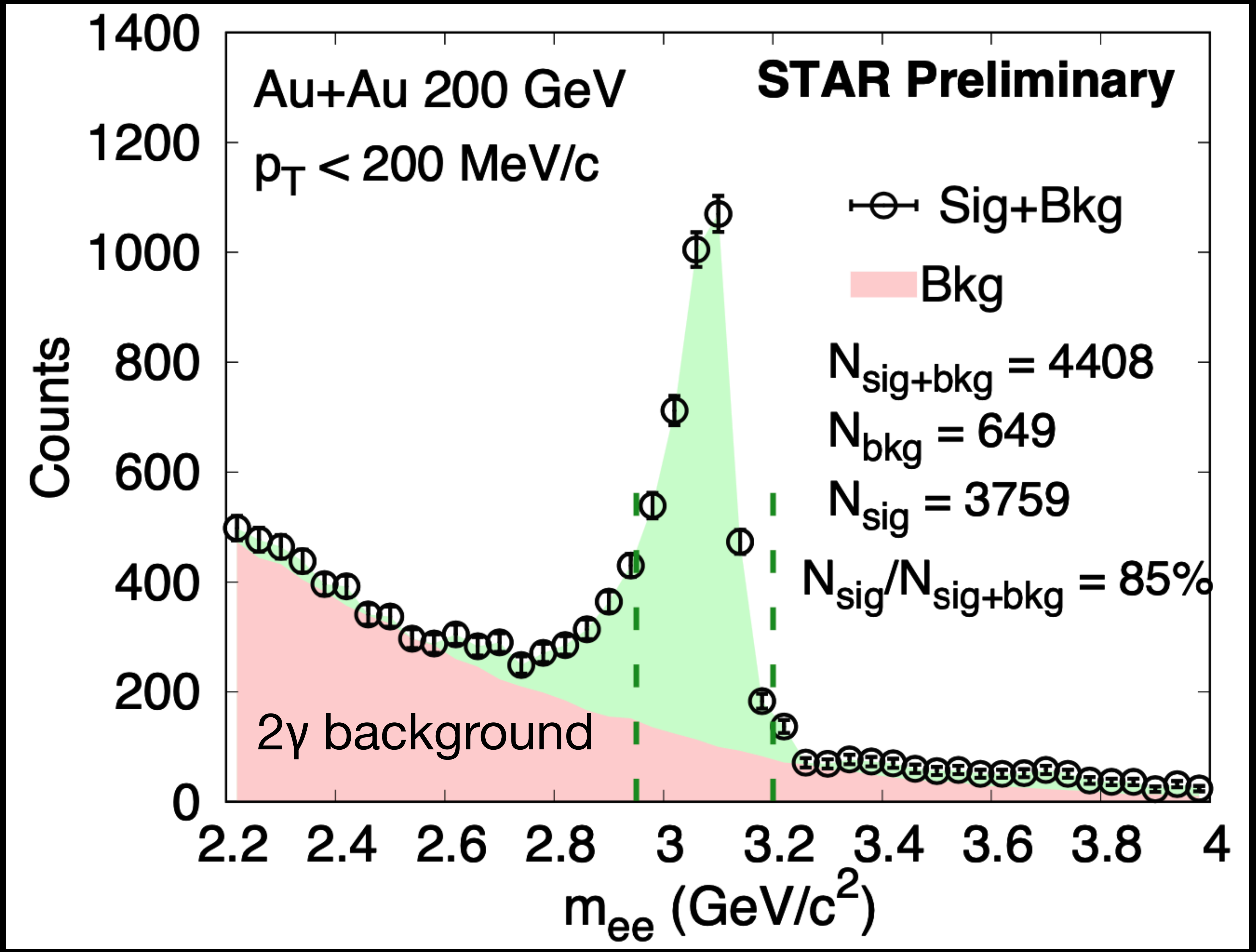
Observable for J/ψ spin interference

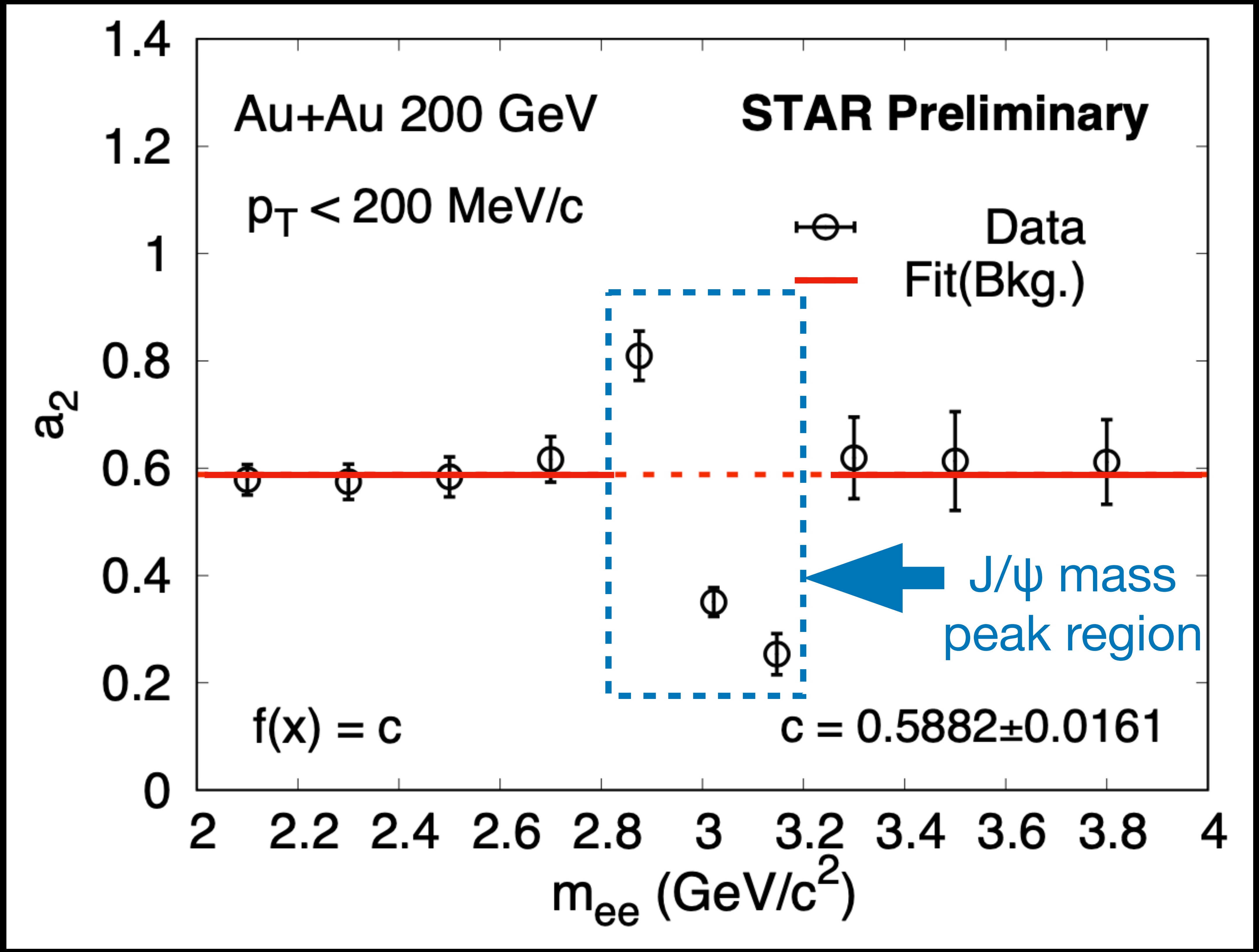
Interference signal fitted with: 1+ a_2 cos(2φ) => a_2 is the measure of the modulation



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

Corrections of interference signal due to 2γ background

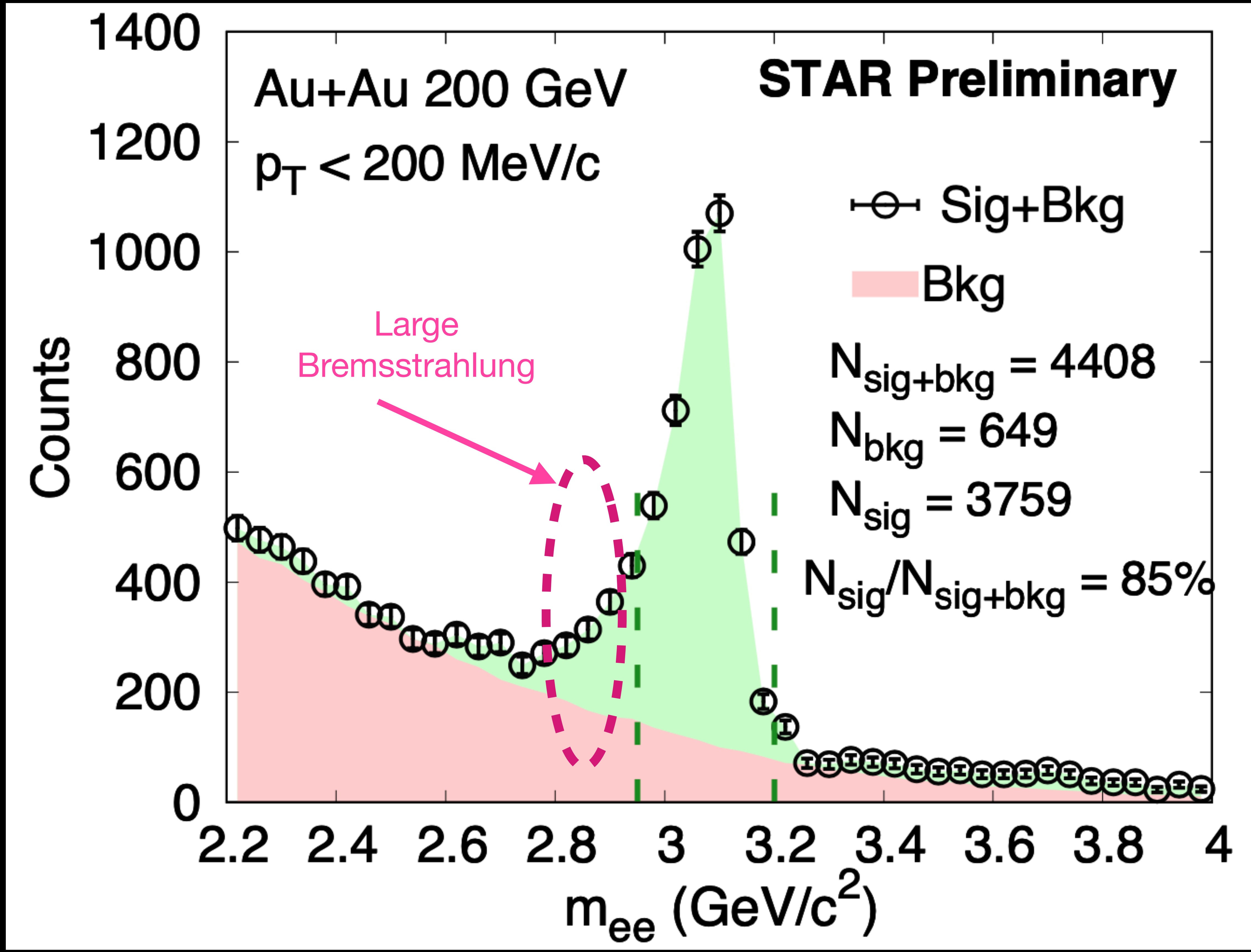


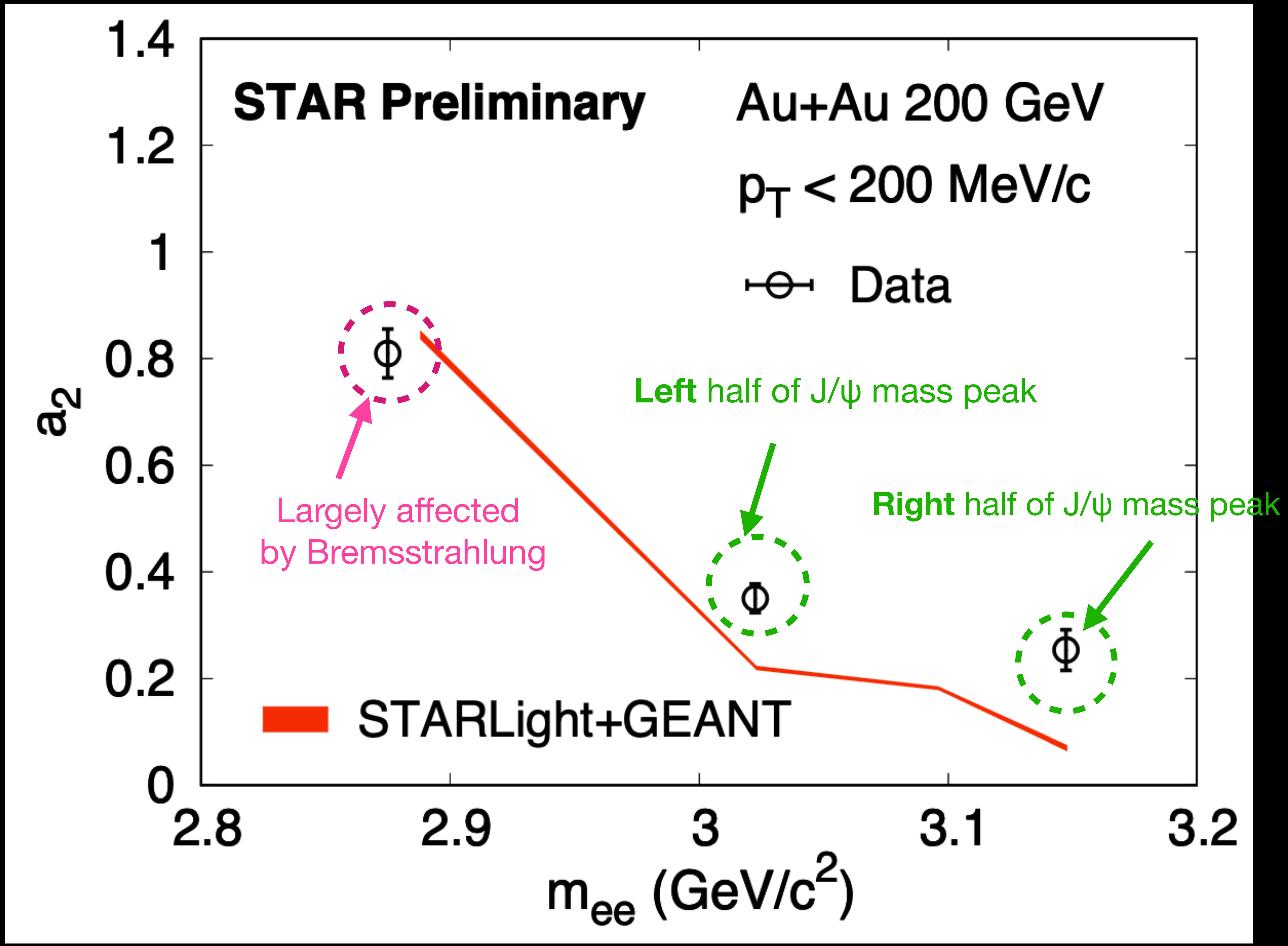


- The $\gamma + \gamma \rightarrow e^+ + e^-$ has also the J/Ψ interference like pattern due to detector effect
- We correct for the 2γ process with : $a_2 = f \times a_2^{bkg} + (1 - f) \times a_2^{sig}$, with $f = \frac{N_{bkg}}{N_{sig} + N_{bkg}}$

=> Background correction is done to extract true modulation signal

Corrections of interference signal due to bremsstrahlung process

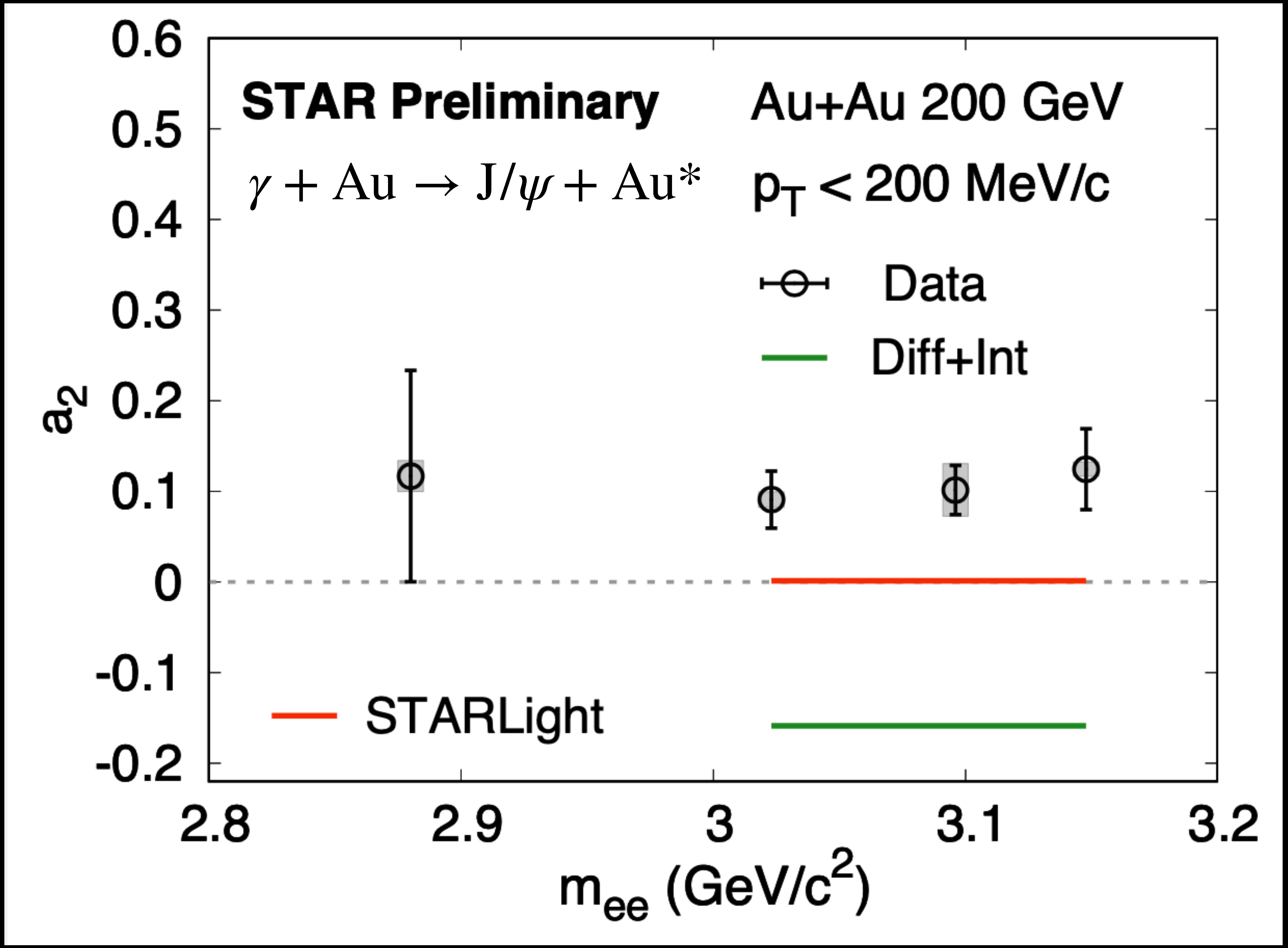




◉ We considered the Bremsstrahlung process and $J/\Psi \rightarrow e^{+} + e^{-} + \gamma$, using the STARLight+Geant simulations

=> Bremsstrahlung correction performed for true modulation signal

Signal for J/ψ Spin interference



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

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

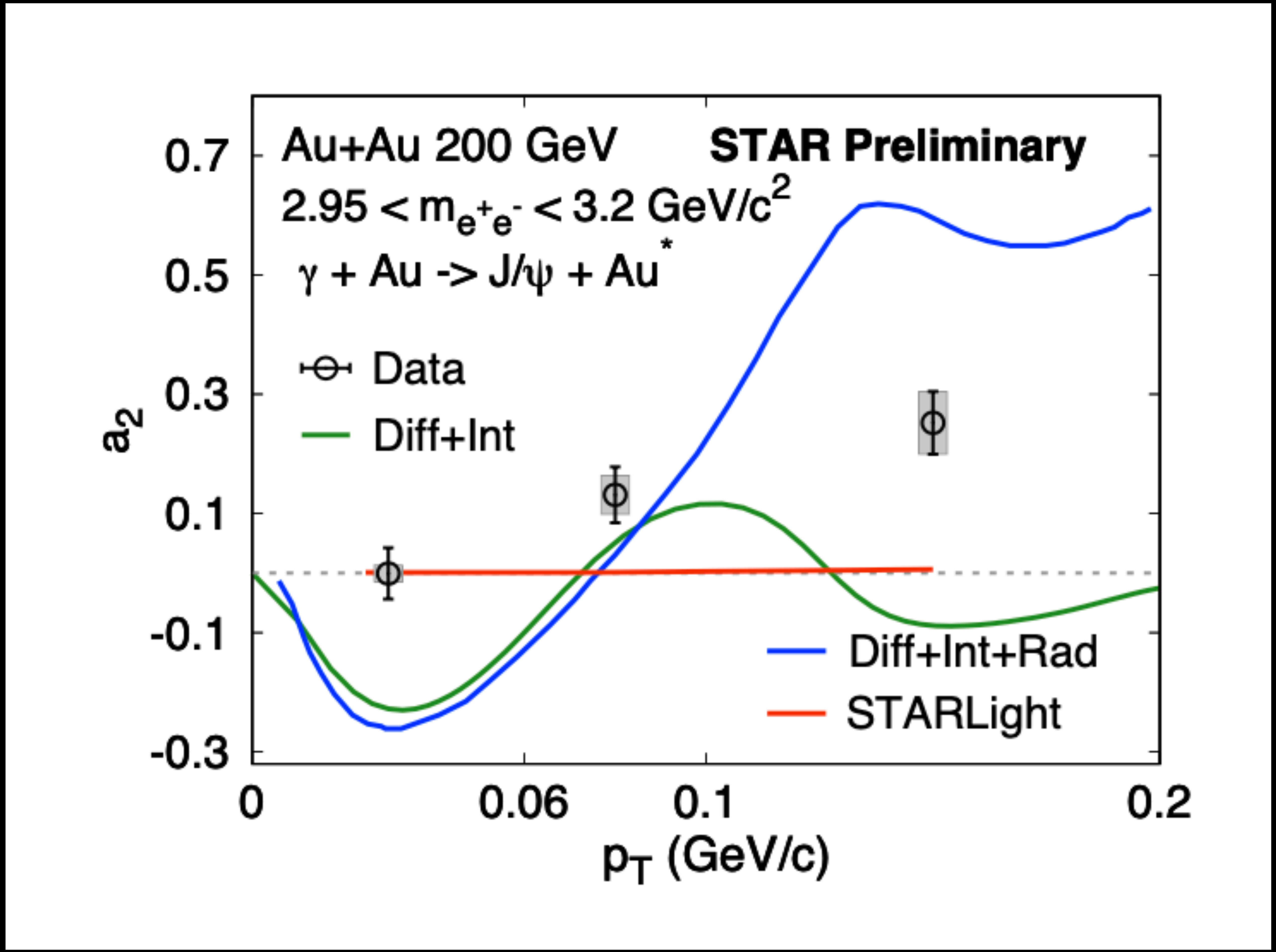
- Measurement has ~3σ significance above zero
- Compared with STARLight and theory calculations
- STARLight has no spin interference physics — consistent with zero
- Theory (Diffractive+Interference) predicts negative modulation

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

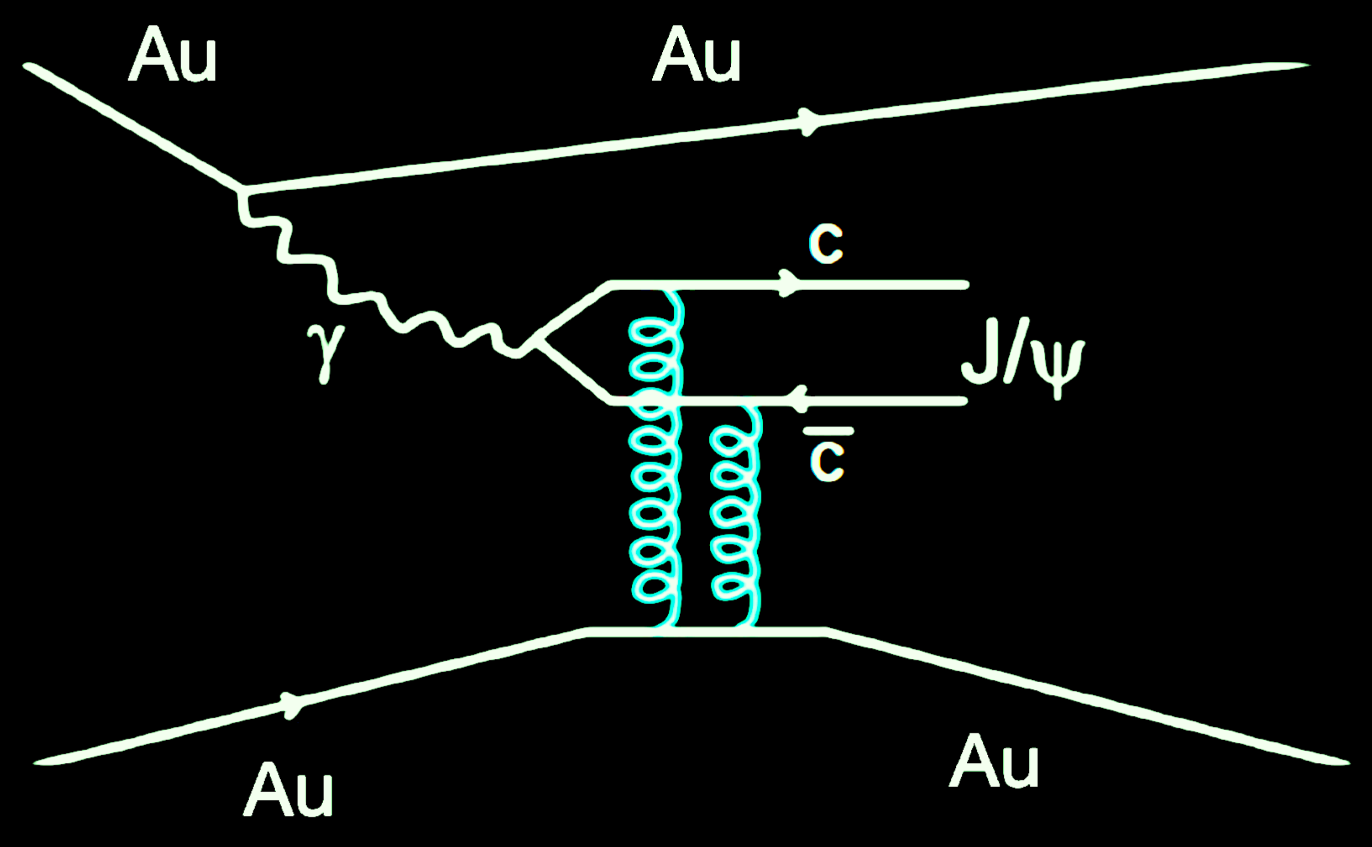


Diff+Int predictions : Mäntysaari et al. Phys.Rev.C 109 (2024) 2, 024908
Diff+Int+Rad predictions : Brandenburg et. al, Phys. Rev. D 106, 074008 (2022)

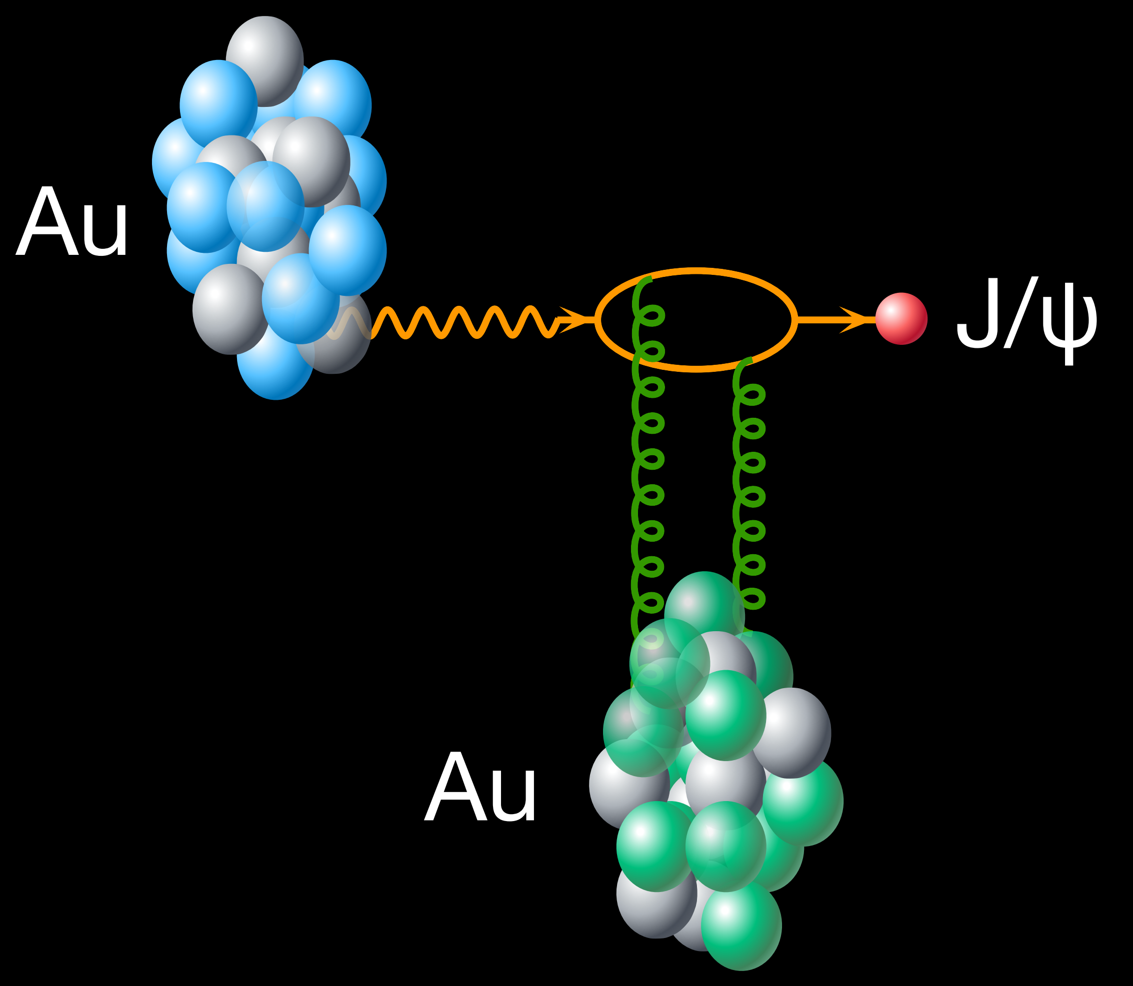
=> Modulation strength in data positively increases with p_T in the measured kinematics

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

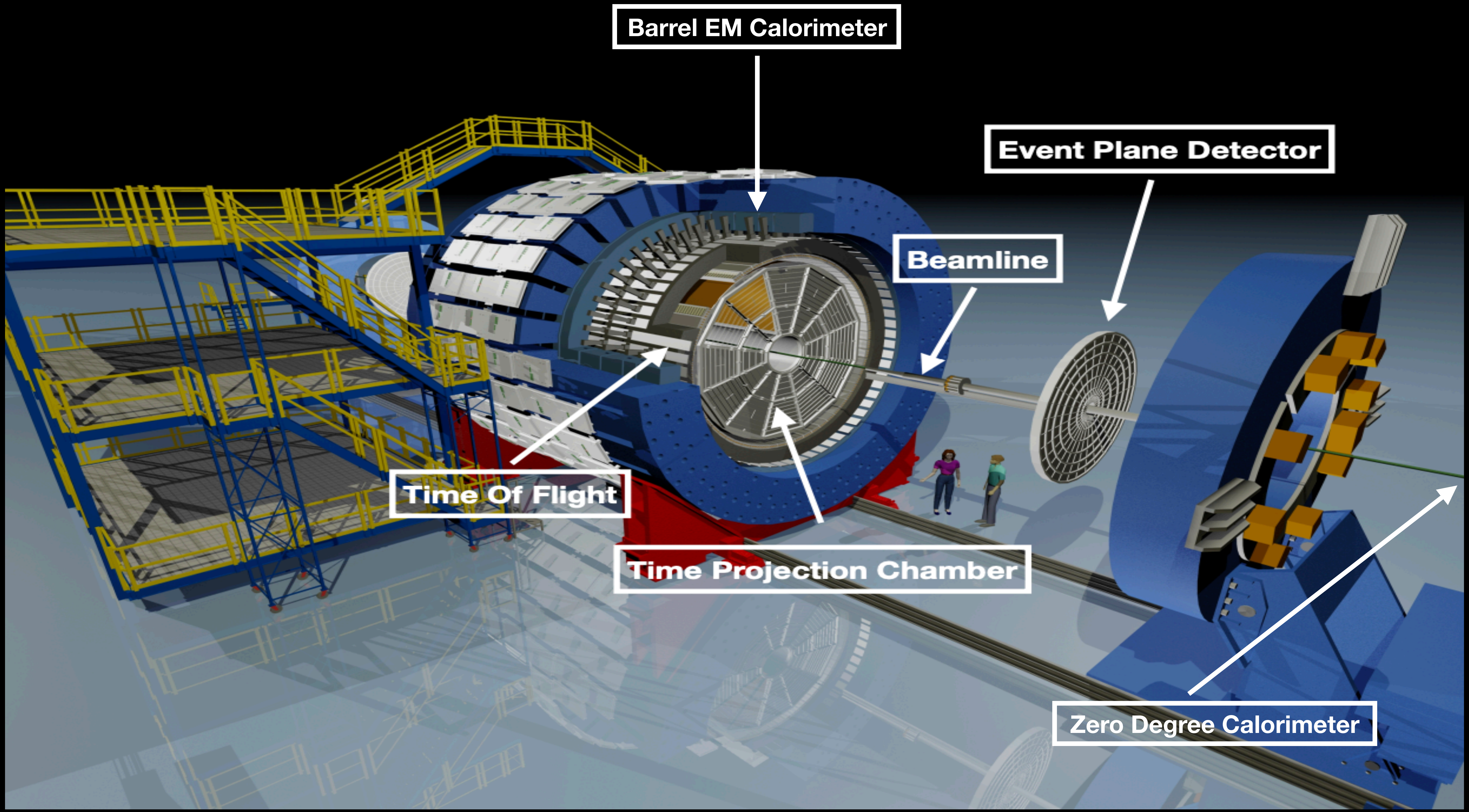


Thank You!



Backup

STAR detector



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