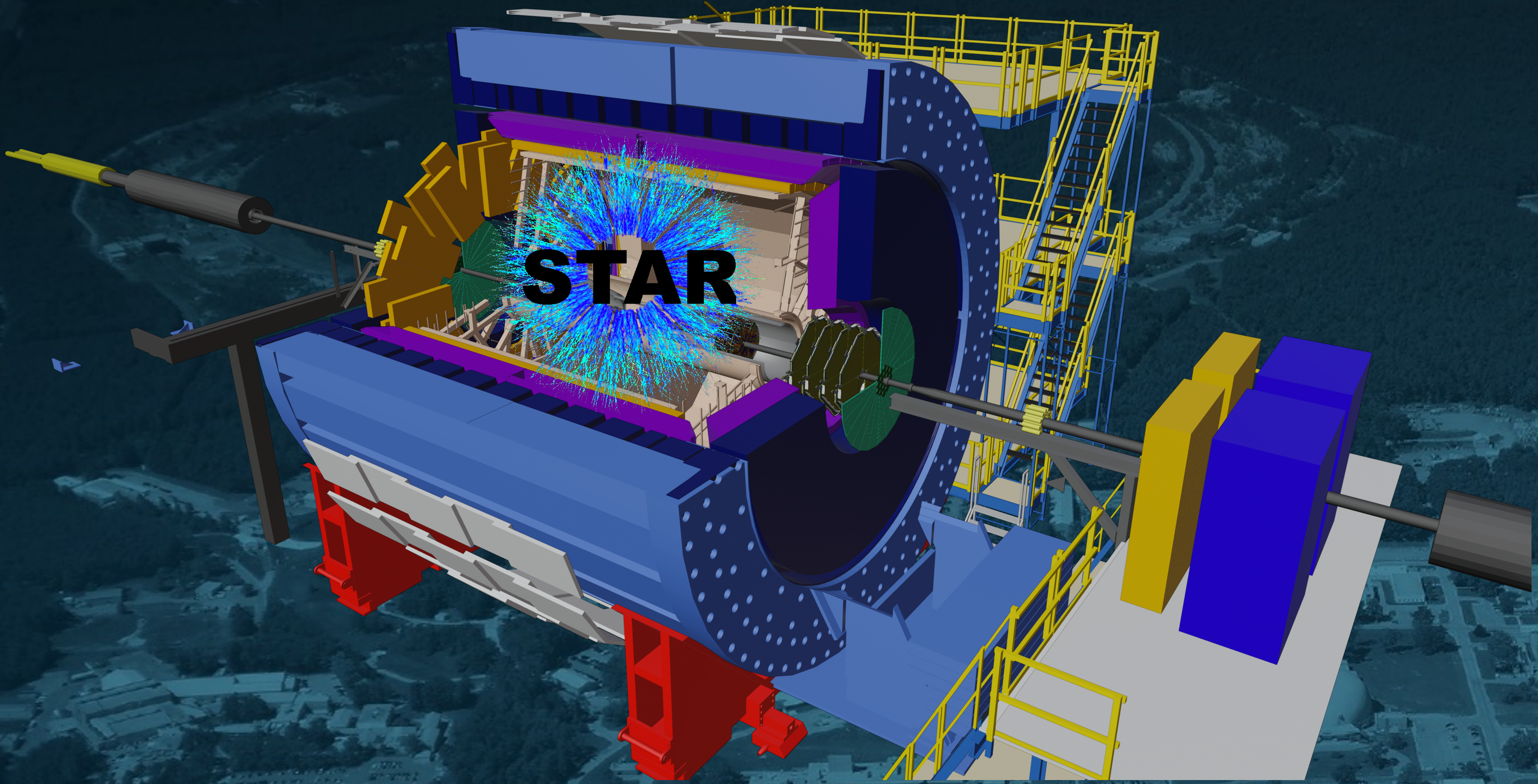


Brookhaven National Laboratory

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

Recent Highlights of Ultra Peripheral Collisions at STAR

Ashik Ikbal Sheikh

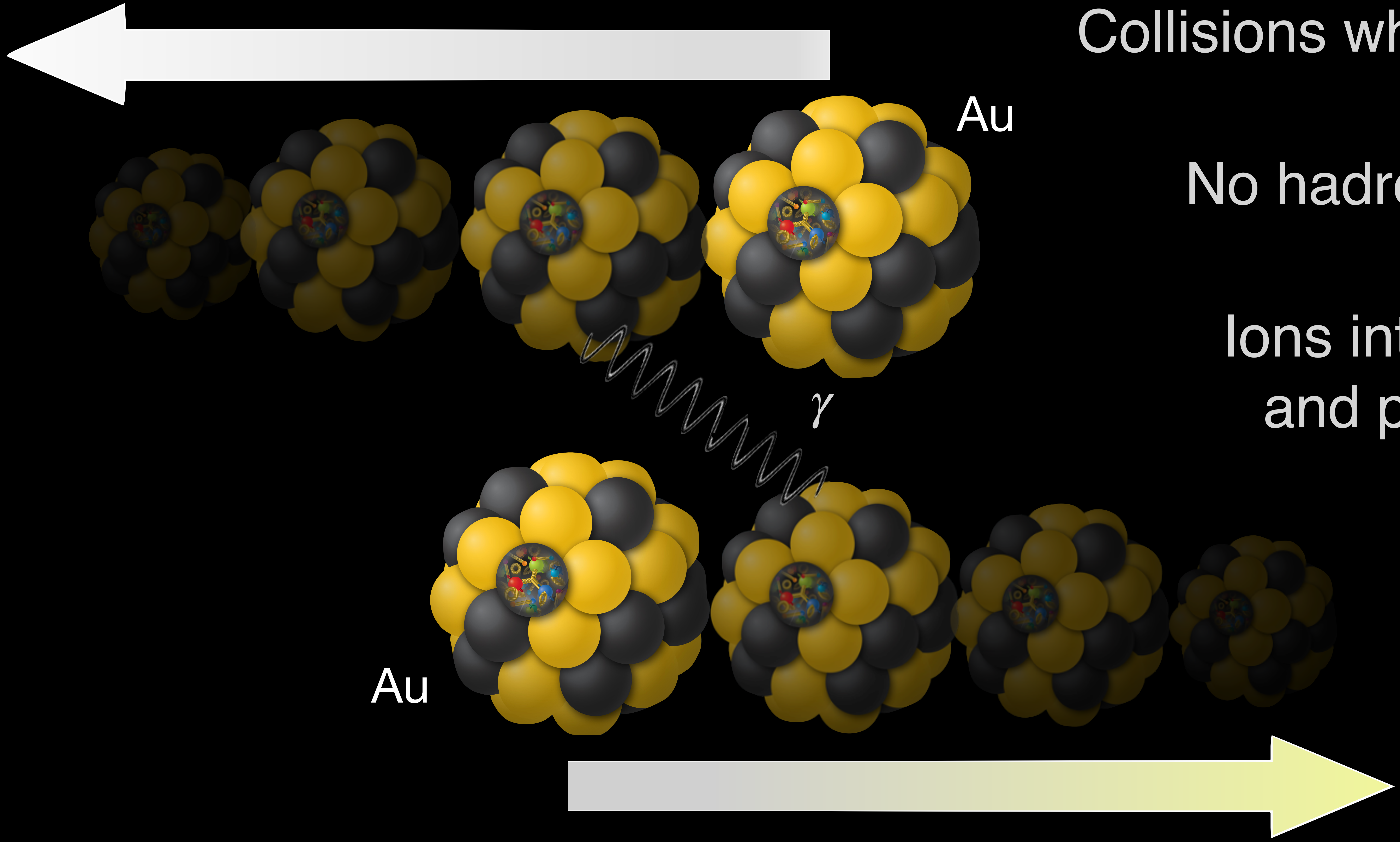
KENT STATE UNIVERSITY

2025 RHIC/AGS ANNUAL USERS' MEETING

RHIC 25:
A quarter century of discovery

May 20–23, 2025

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



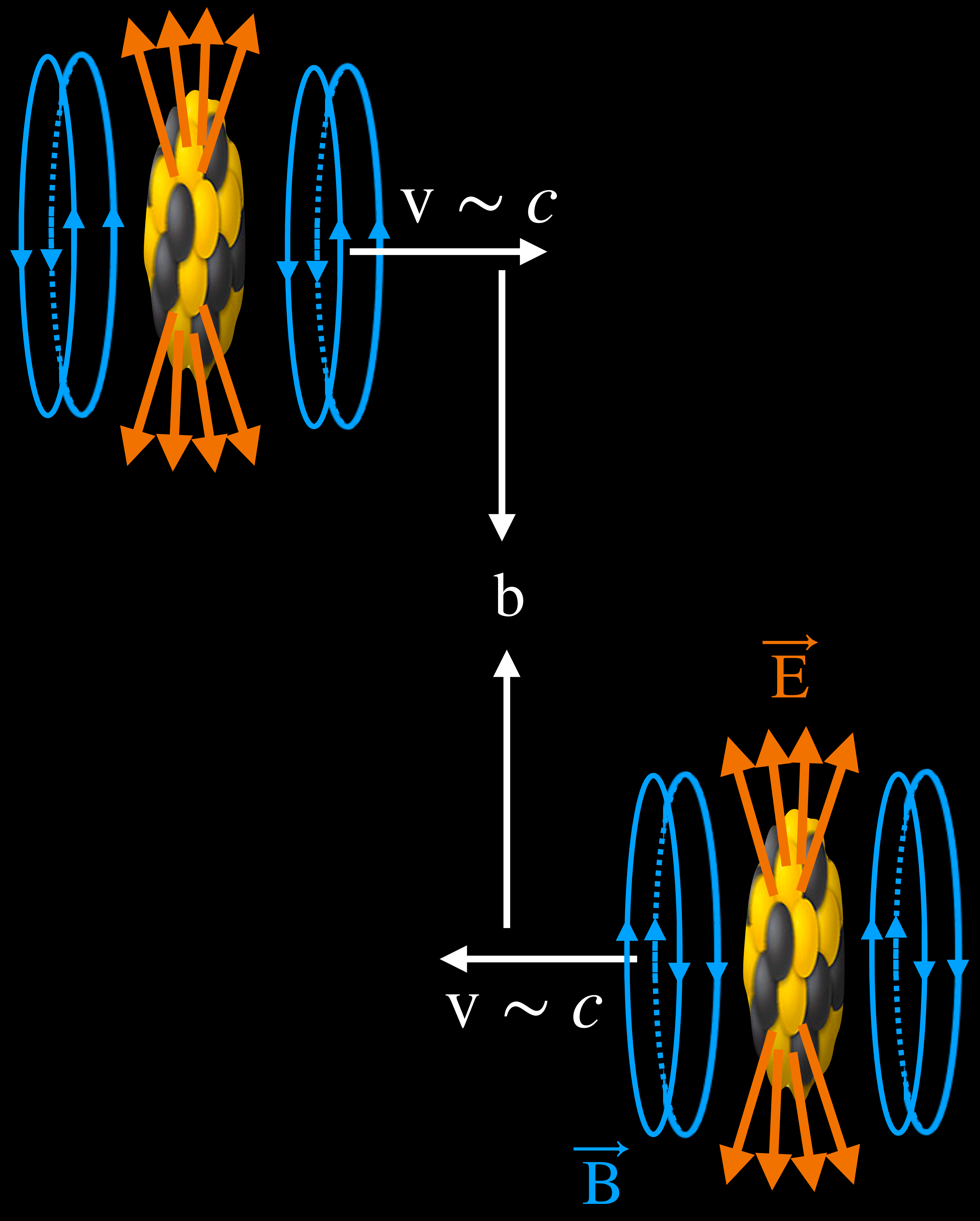
Collisions where nuclei do NOT collide

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

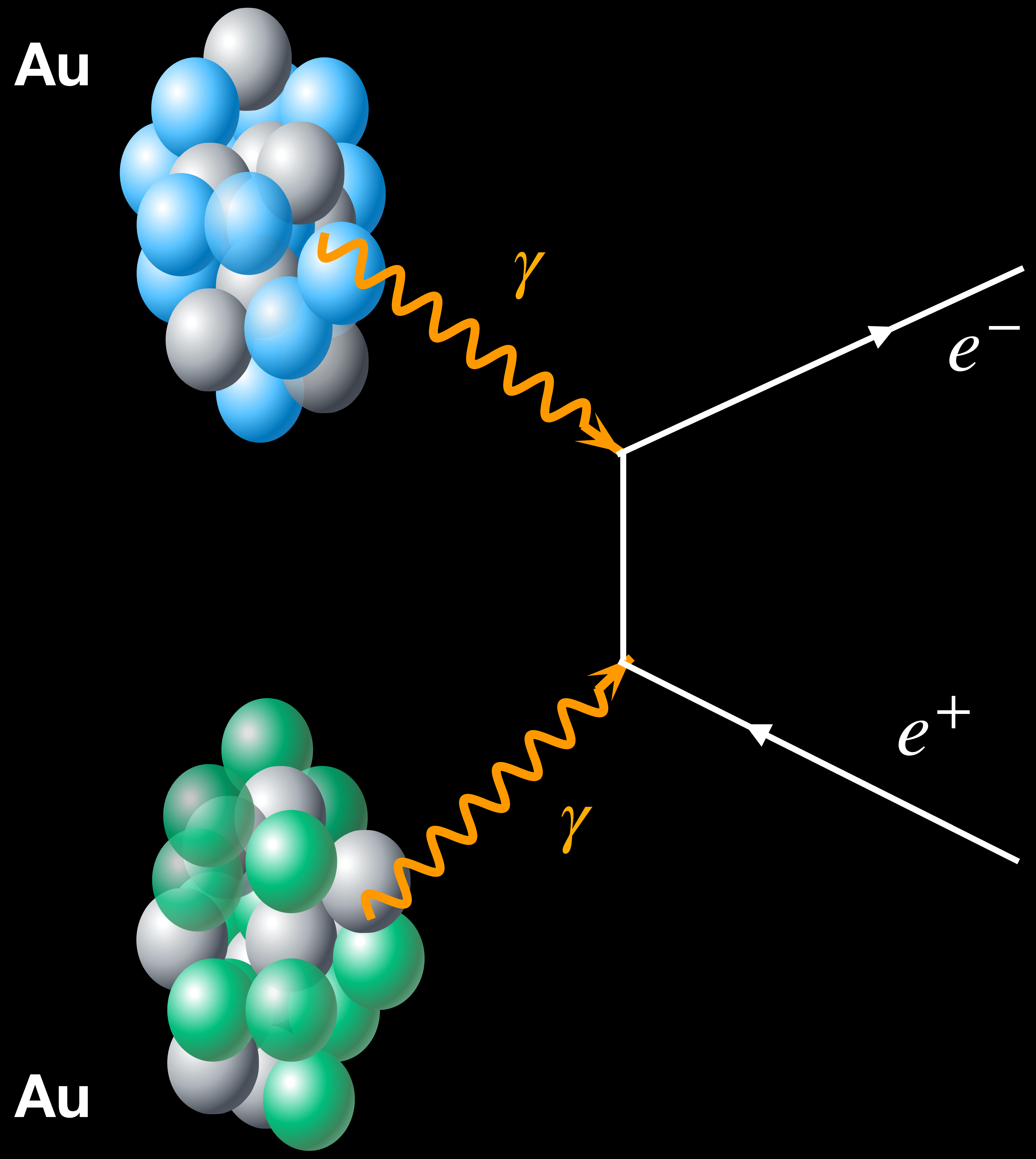
$$E_{\gamma,max} \sim \gamma \hbar c / R \; ;$$

$E_{\gamma,max} \sim 30$ GeV (RHIC@Au+Au 200 GeV)

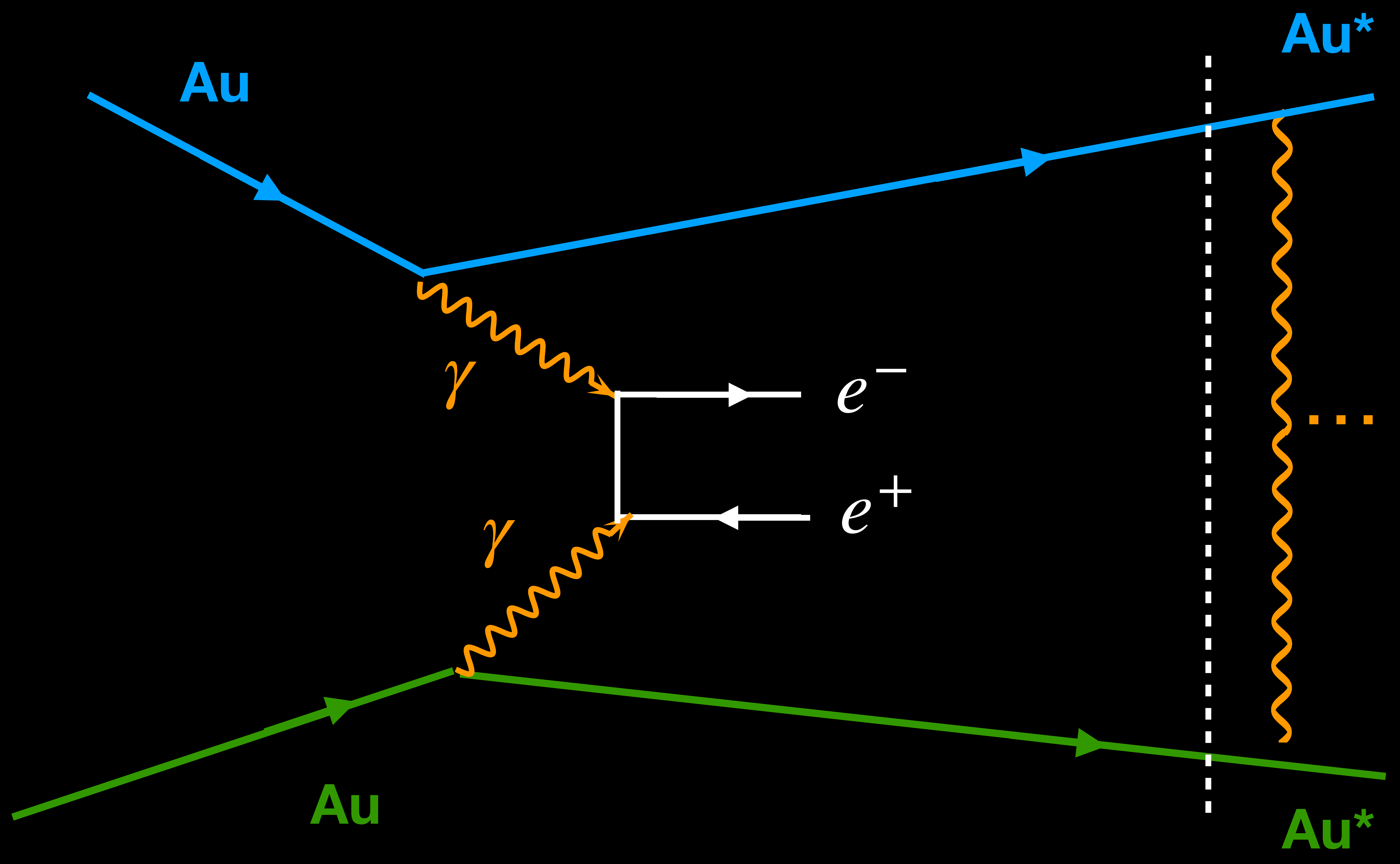
$E_{\gamma,max} \sim 80$ GeV (LHC@Pb+Pb 2.76 TeV)

=> EM-fields are quantized as photons in UPCs

QED process in UPCs



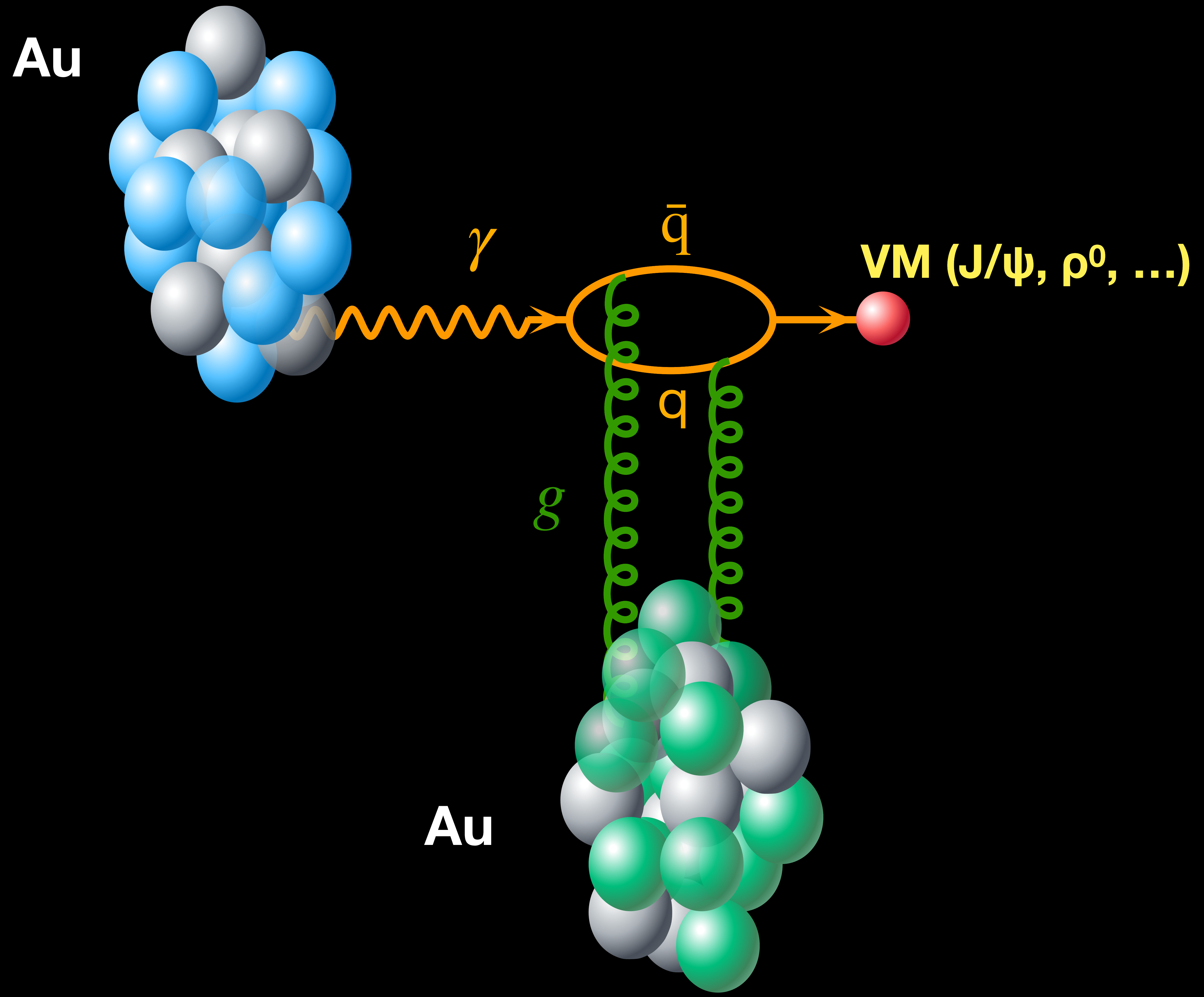
$$\gamma + \gamma \to e^+ + e^-$$



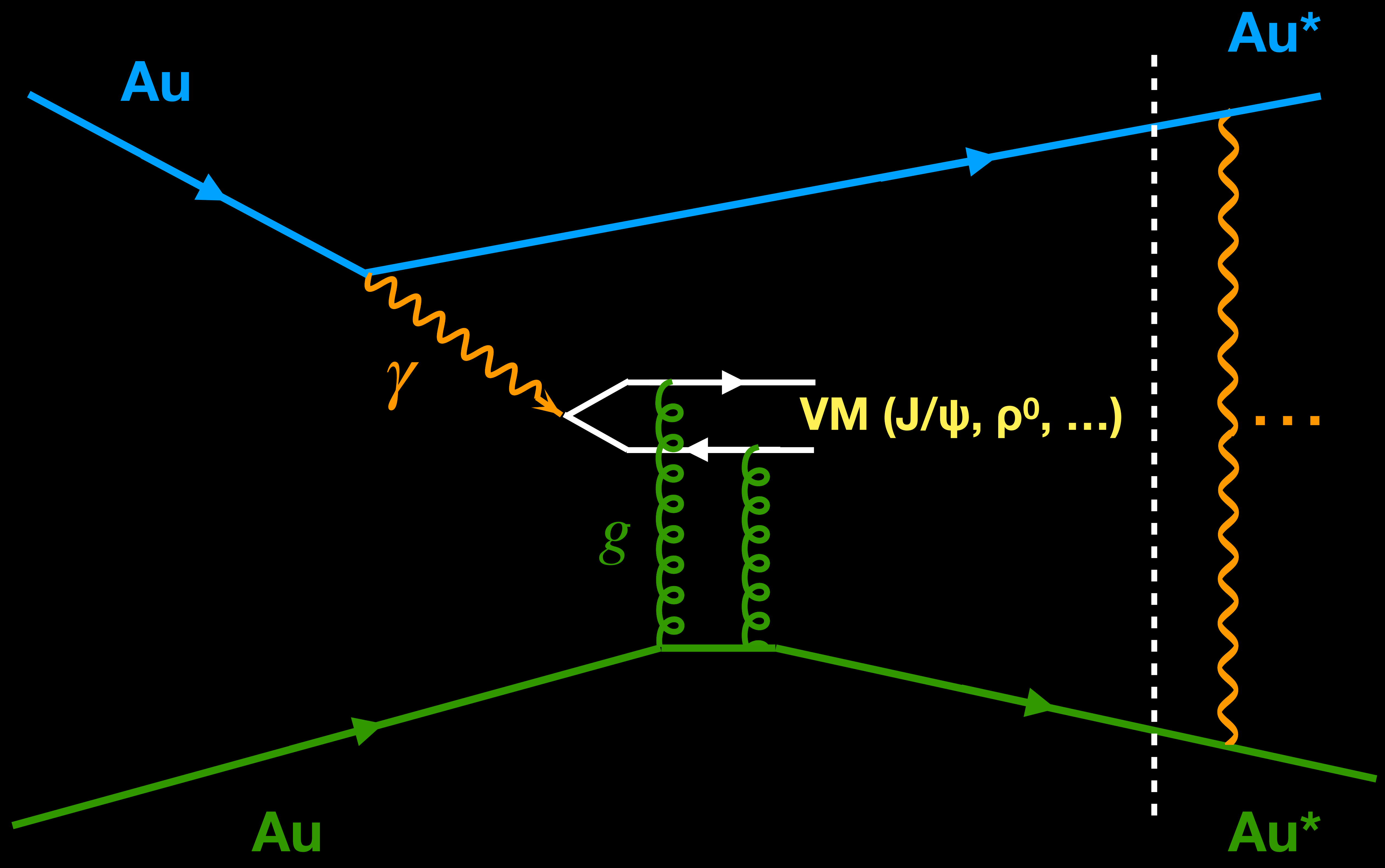
—> Explore QED processes

—> Test for Physics Beyond Standard Model

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

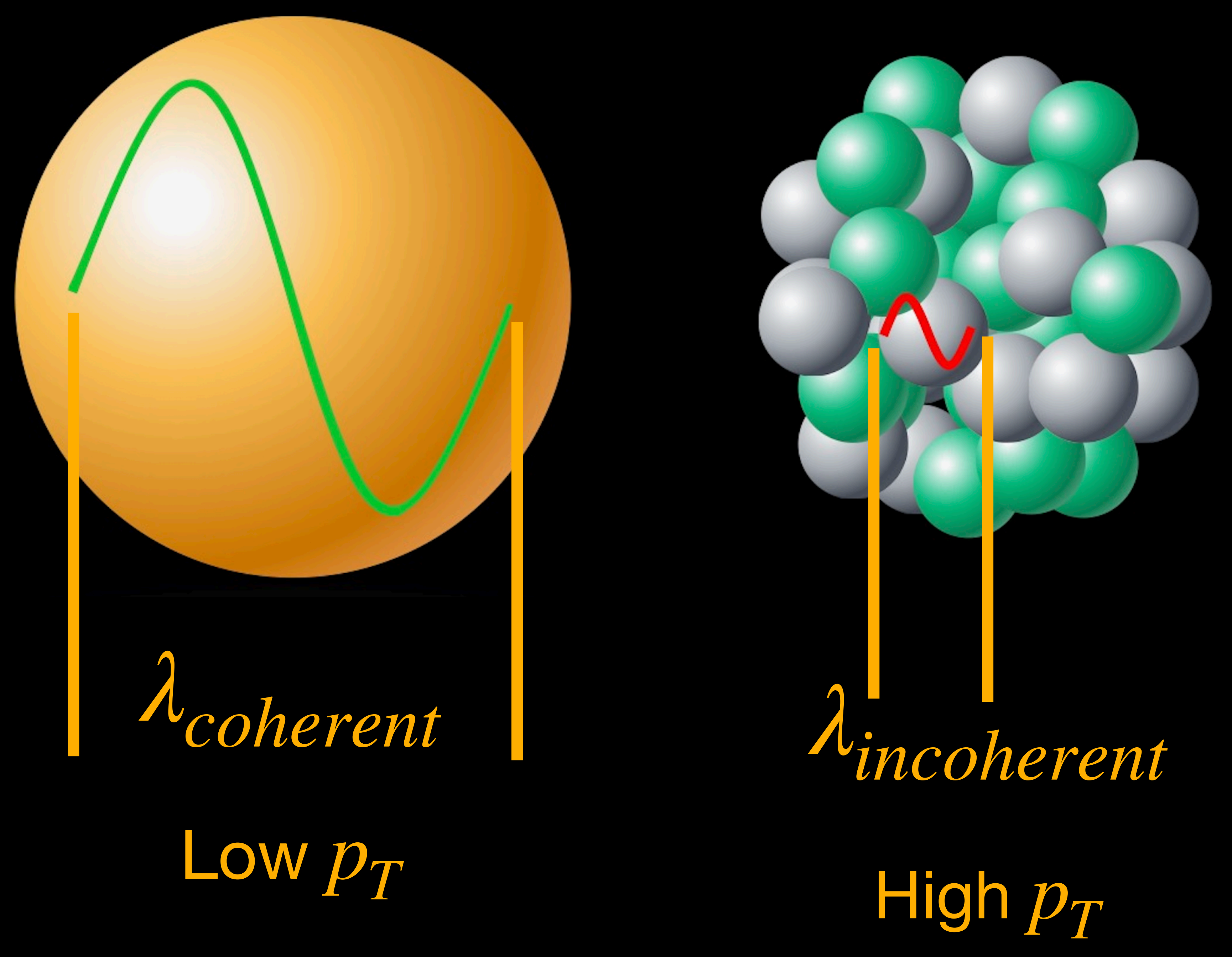


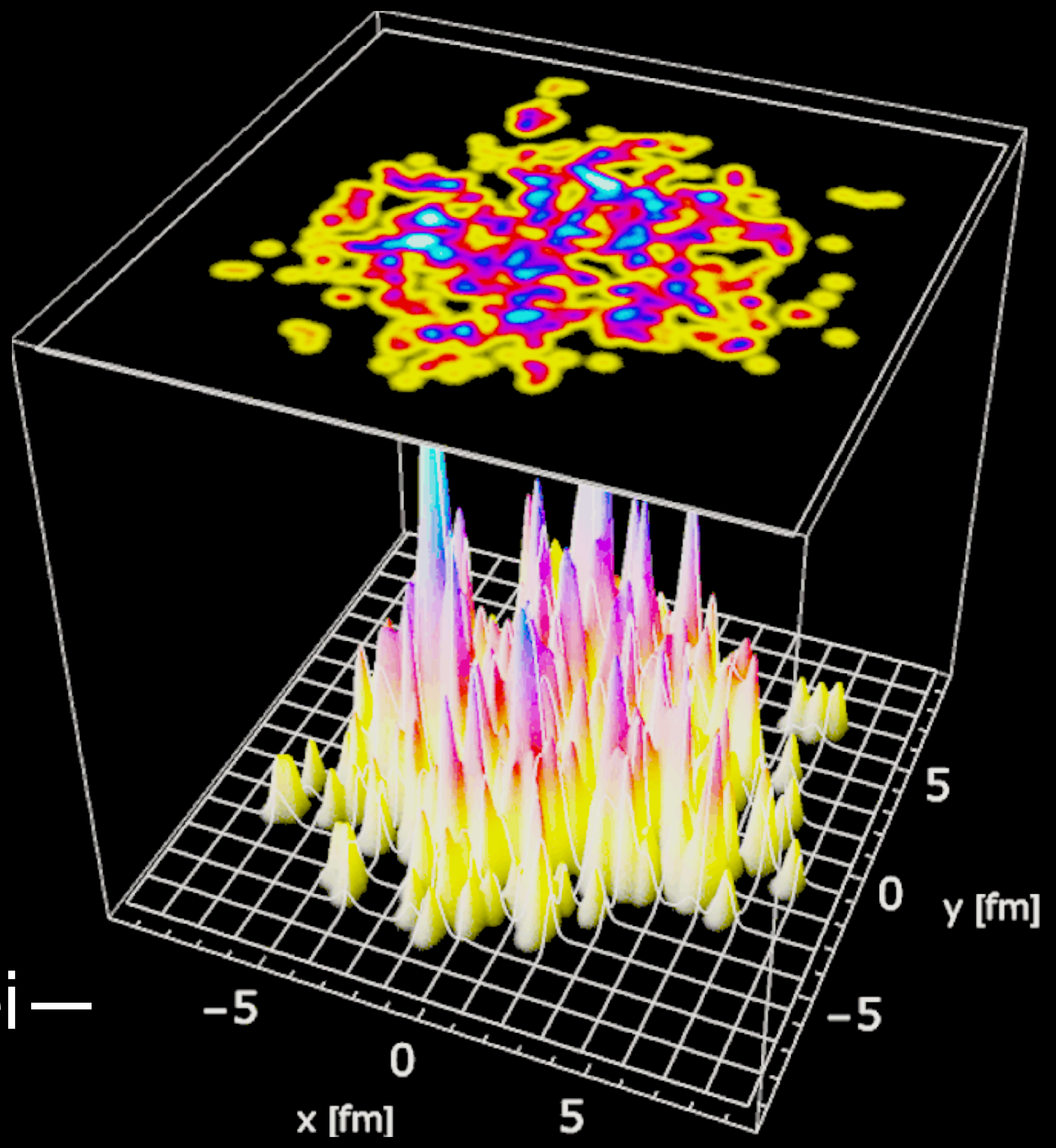
Photoproduction of Vector Mesons (VM) in UPC



UPC VM: Powerful probe of parton densities inside nuclei

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



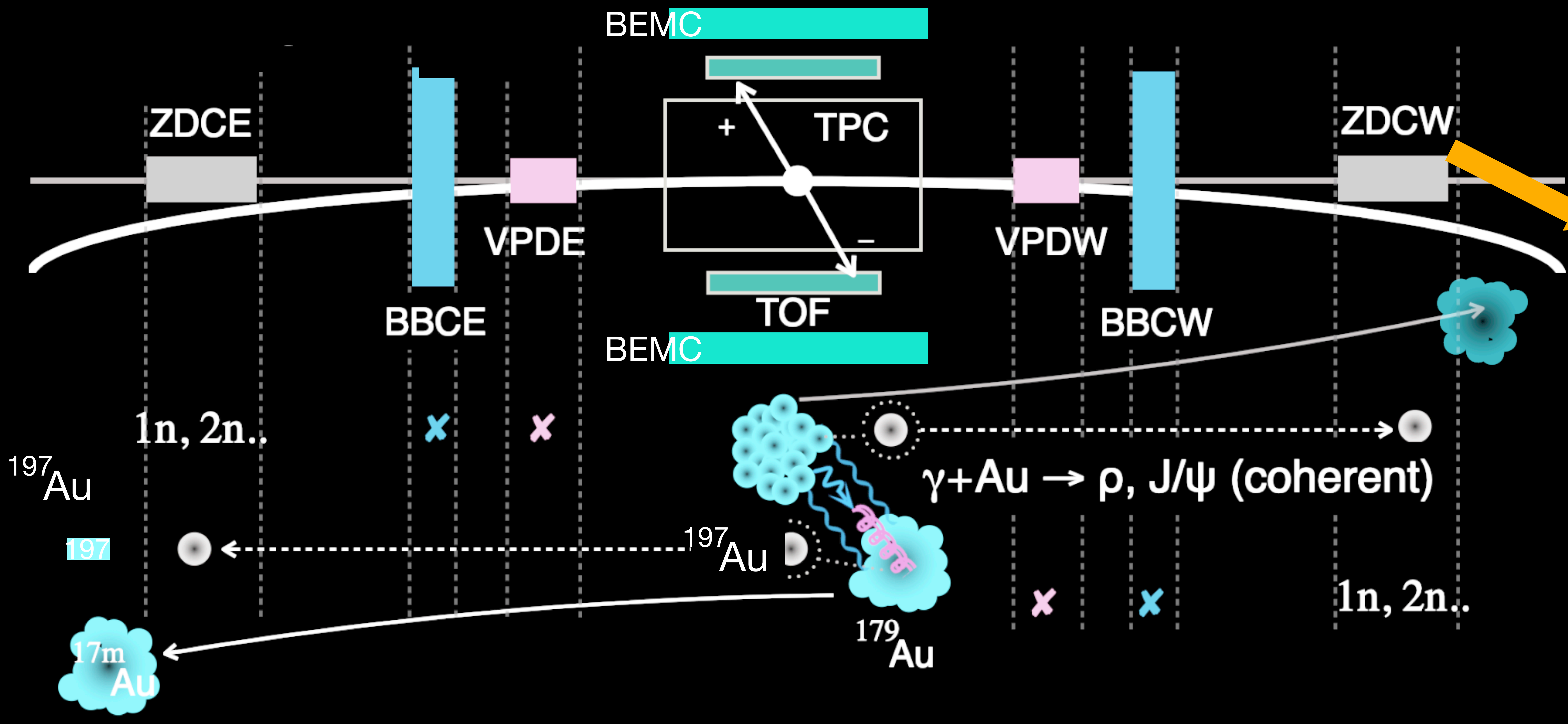


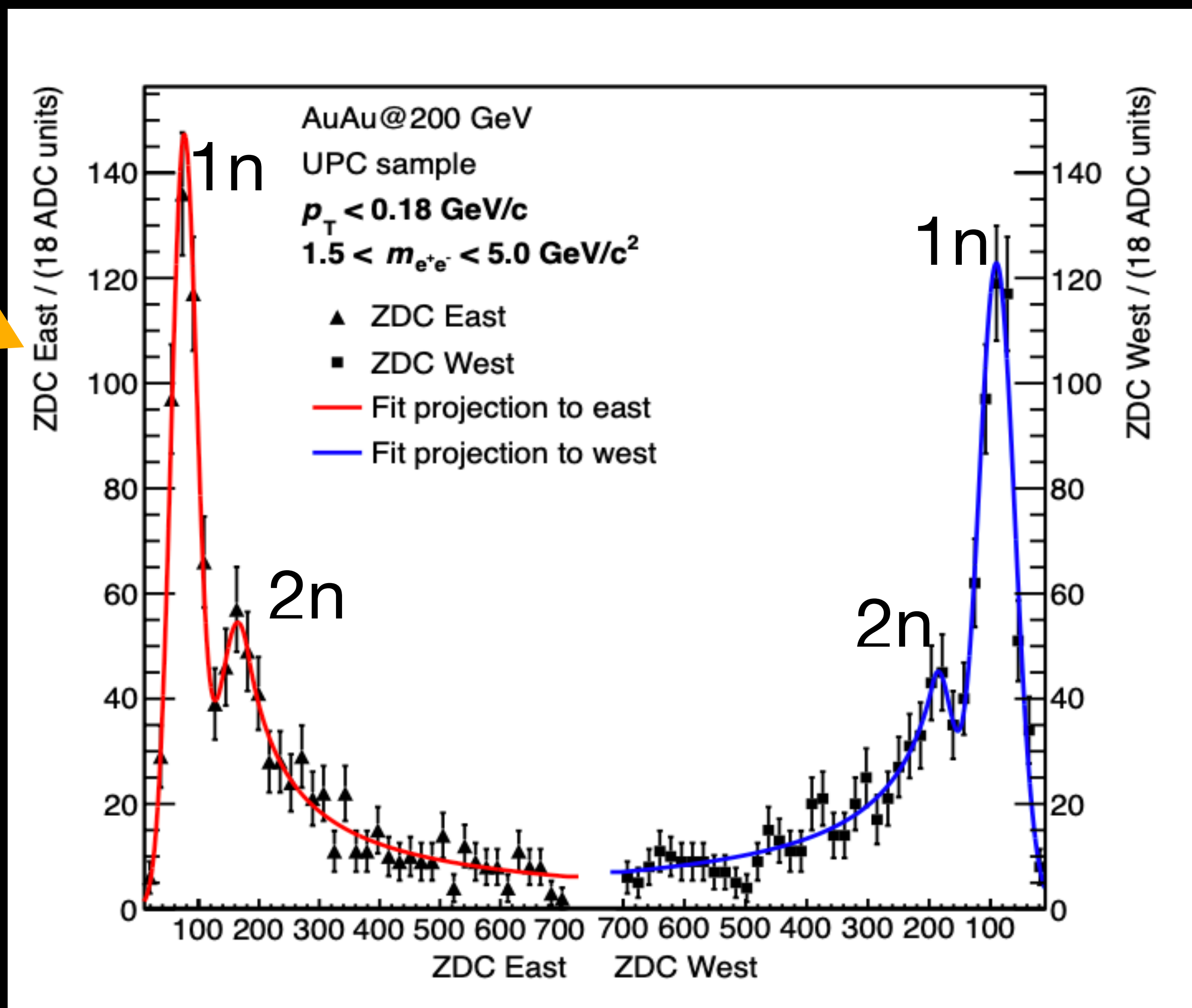
- Probes parton density & fluctuations inside nuclei— constraints for A+A collisions initial state

- Modification of parton densities in heavy nuclei

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

UPC events with STAR detector



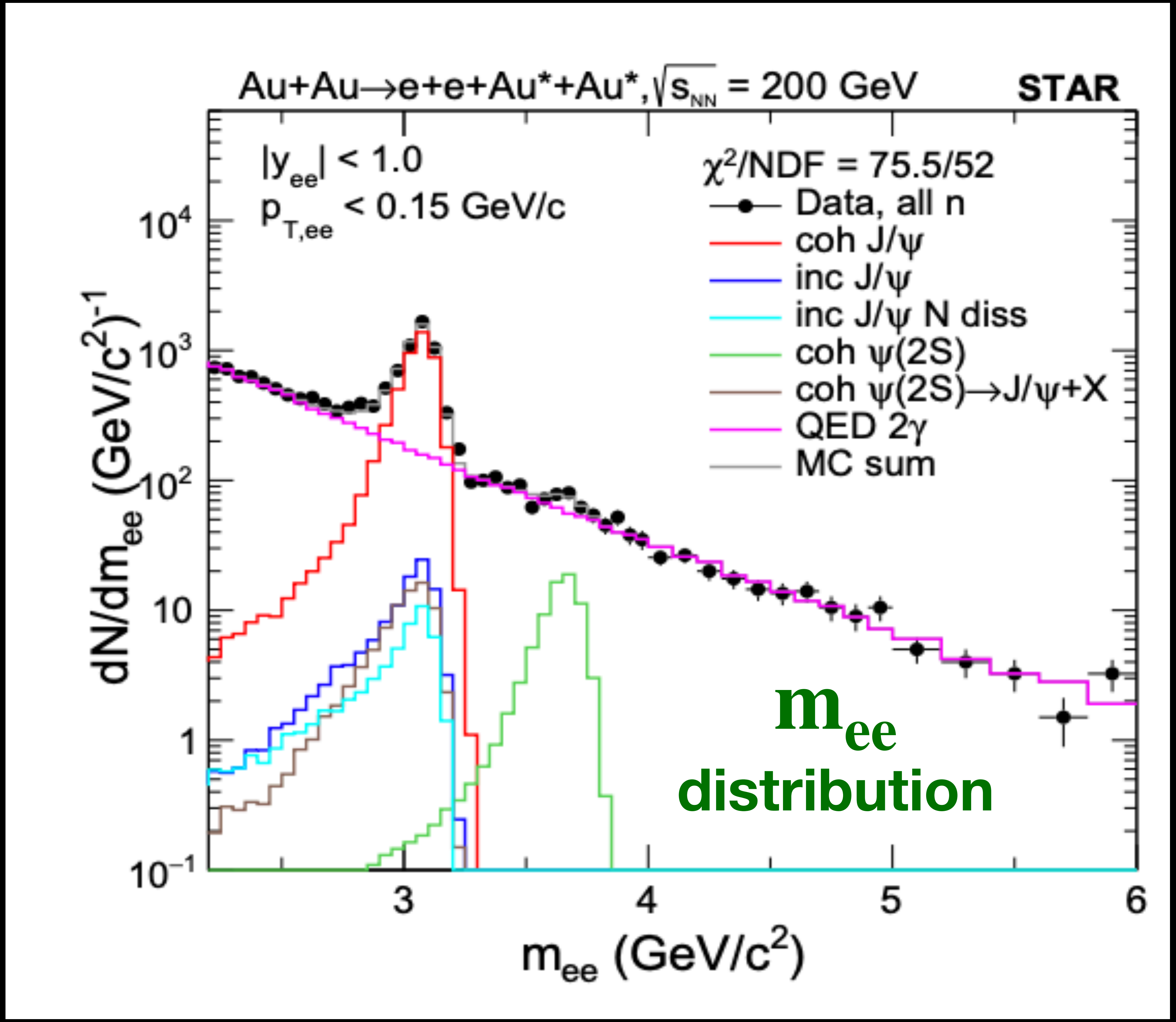


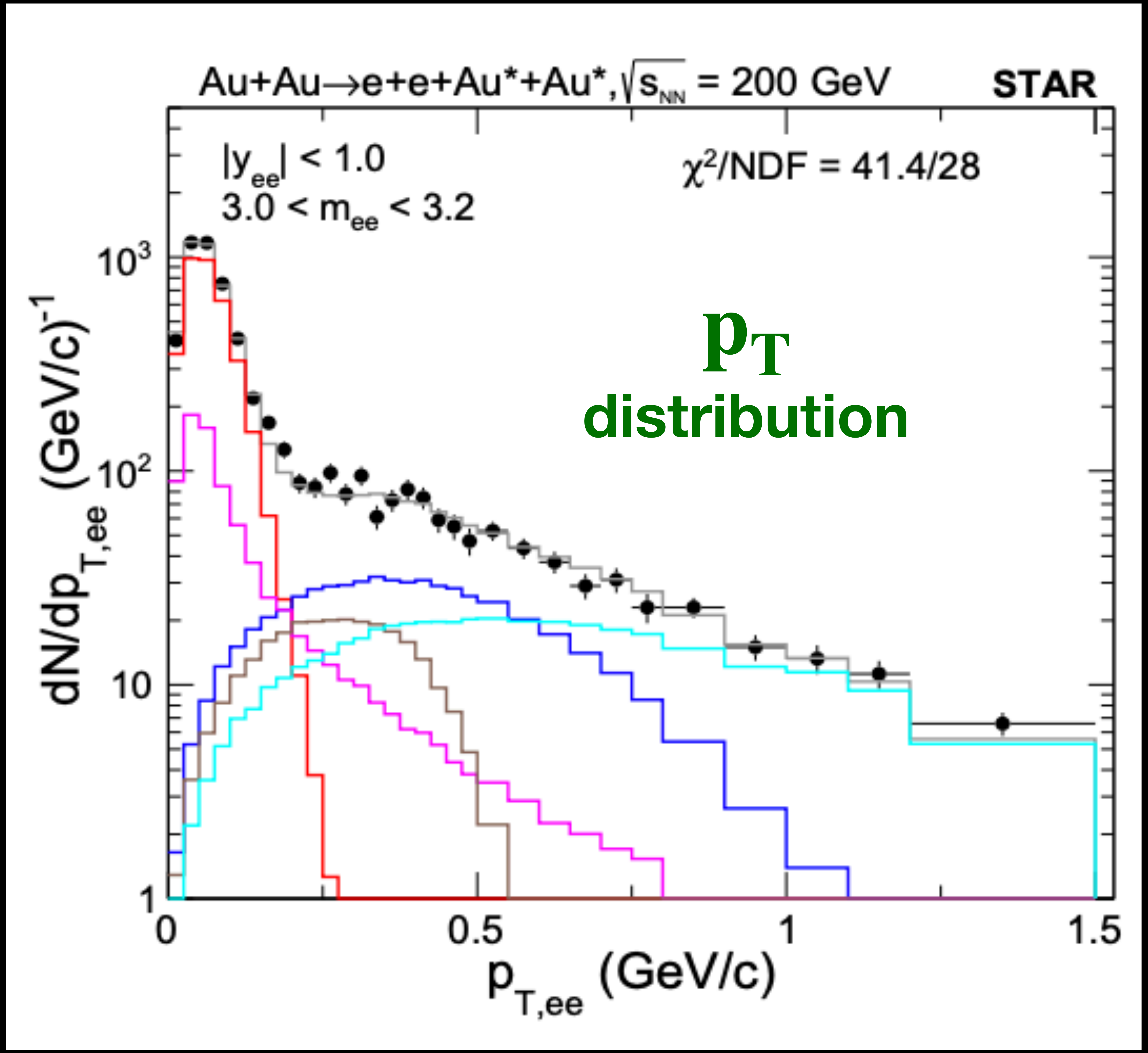
- ◉ Neutron(s) detected in ZDCs
- ◉ ZDC signals show peak structure for neutrons
- ◉ No activity in both BBCs => Diffractive events (η-gap)

=> Method to trigger UPC events

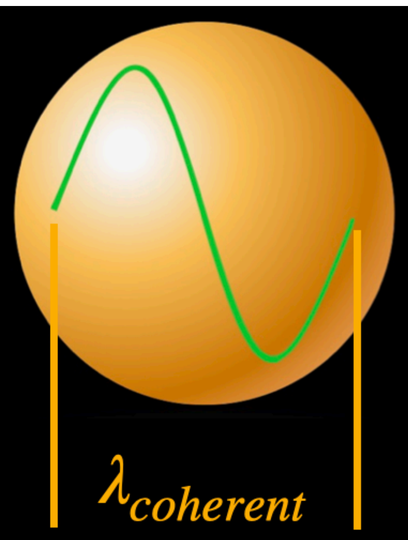
J/ψ measurements in 200 GeV Au+Au UPCs

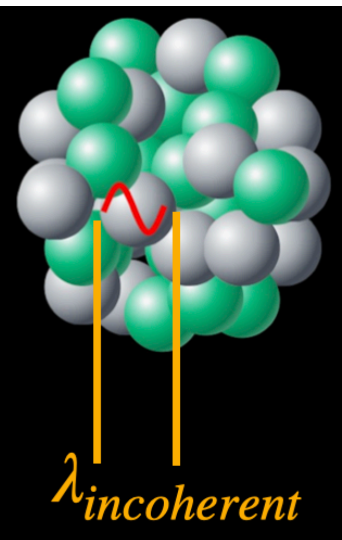
STAR, *Phys.Rev.C* 110 (2024) 1, 014911





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



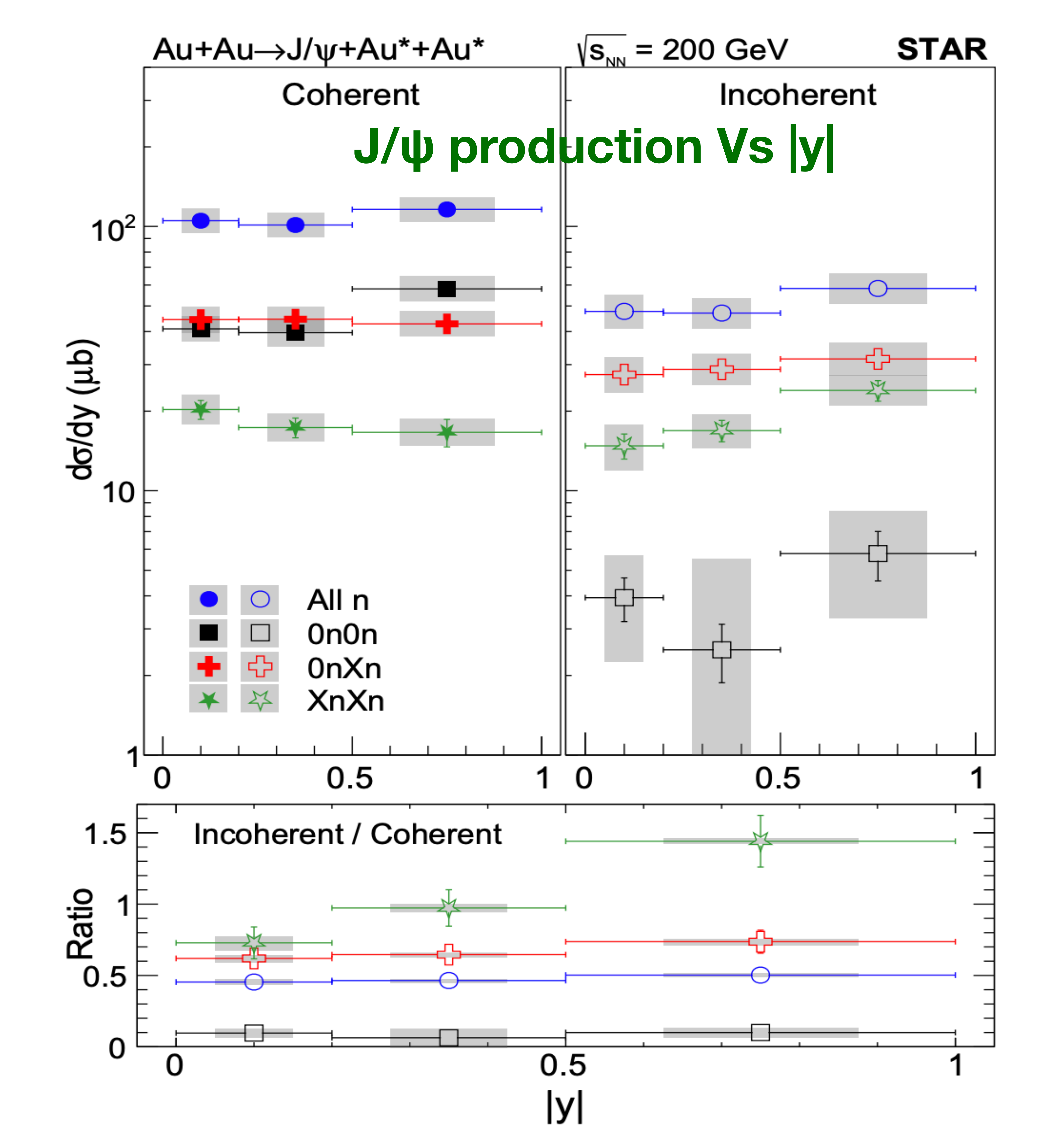


Rapidity dependence J/ψ production cross-section

STAR, *Phys Rev Lett* 133 (2024) 5, 052301

- ◉ Measured for coherent and incoherent contributions for different neutron emission in ZDCs
- ◉ Systematic uncertainties 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

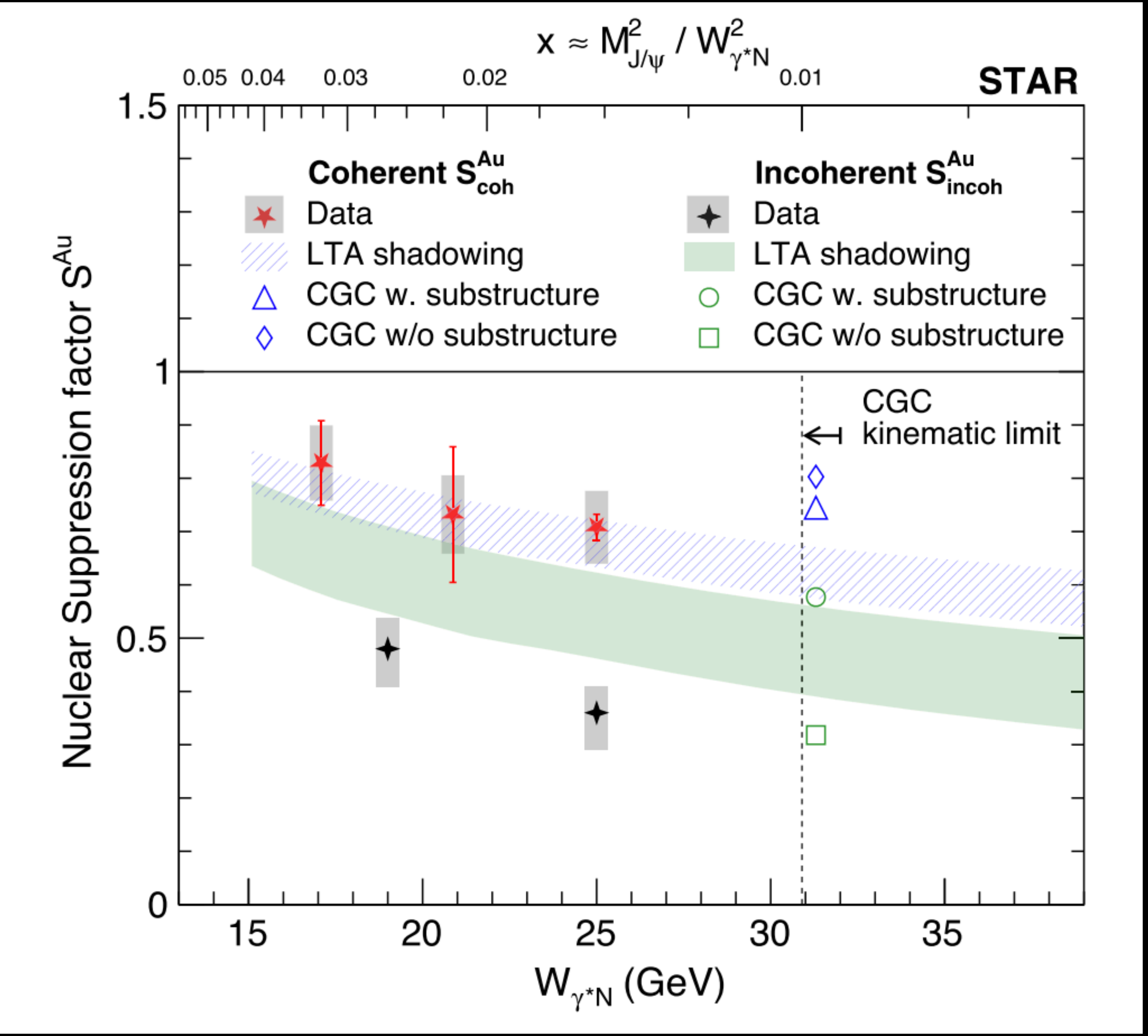


J/ψ Nuclear suppression factors

STAR, *Phys Rev Lett* 133 (2024) 5, 052301

- Coherent cross-section suppressed by ~30% w.r.t free nucleon
- The incoherent supp. is ratio b/w incoh x-sec with HERA (H1) free proton data
- Incoherent photoproduction has been suppressed by ~65% (at $W_{\gamma^* N} = 25$ GeV) w.r.t free proton H1 data
- Stronger incoherent suppressions than model predictions — Even does not directly support the CGC with subnucleonic fluctuations

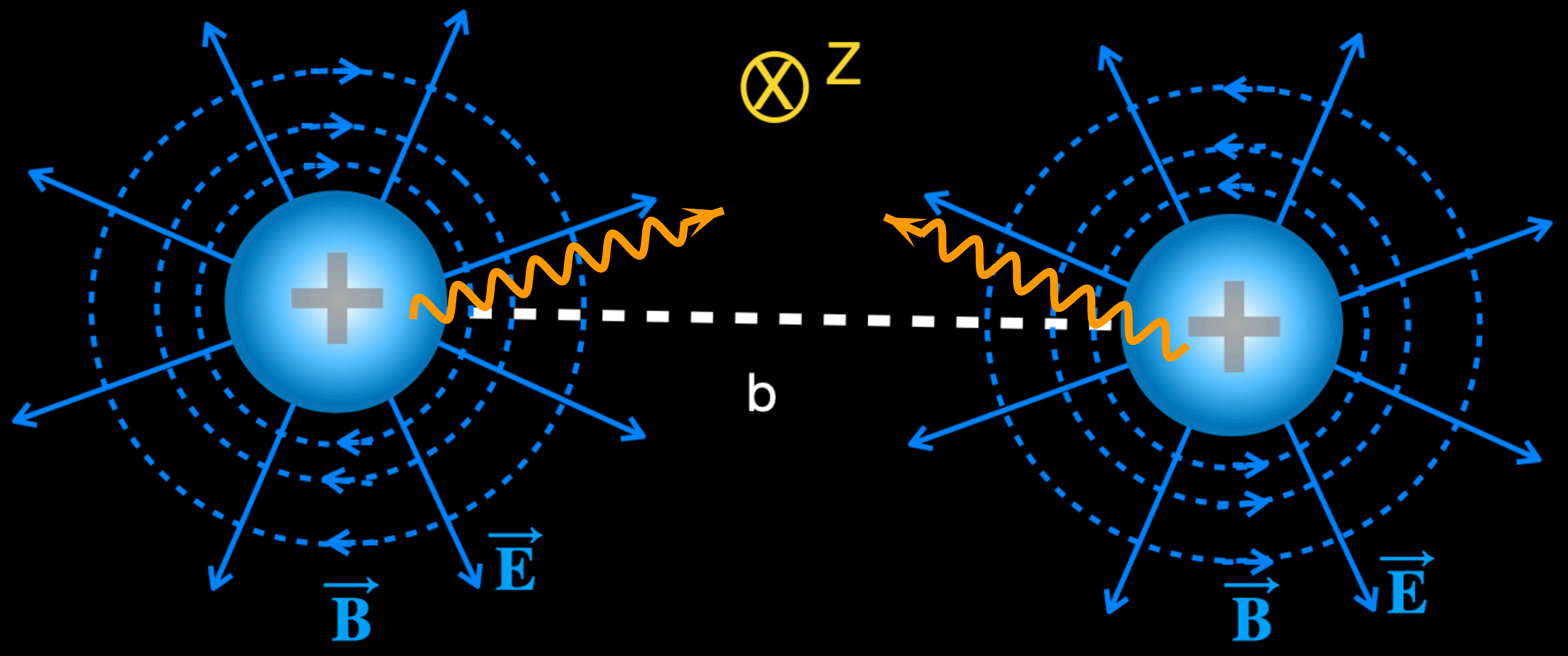
=> Provides constraints to the parton density and baseline for future measurements in EIC



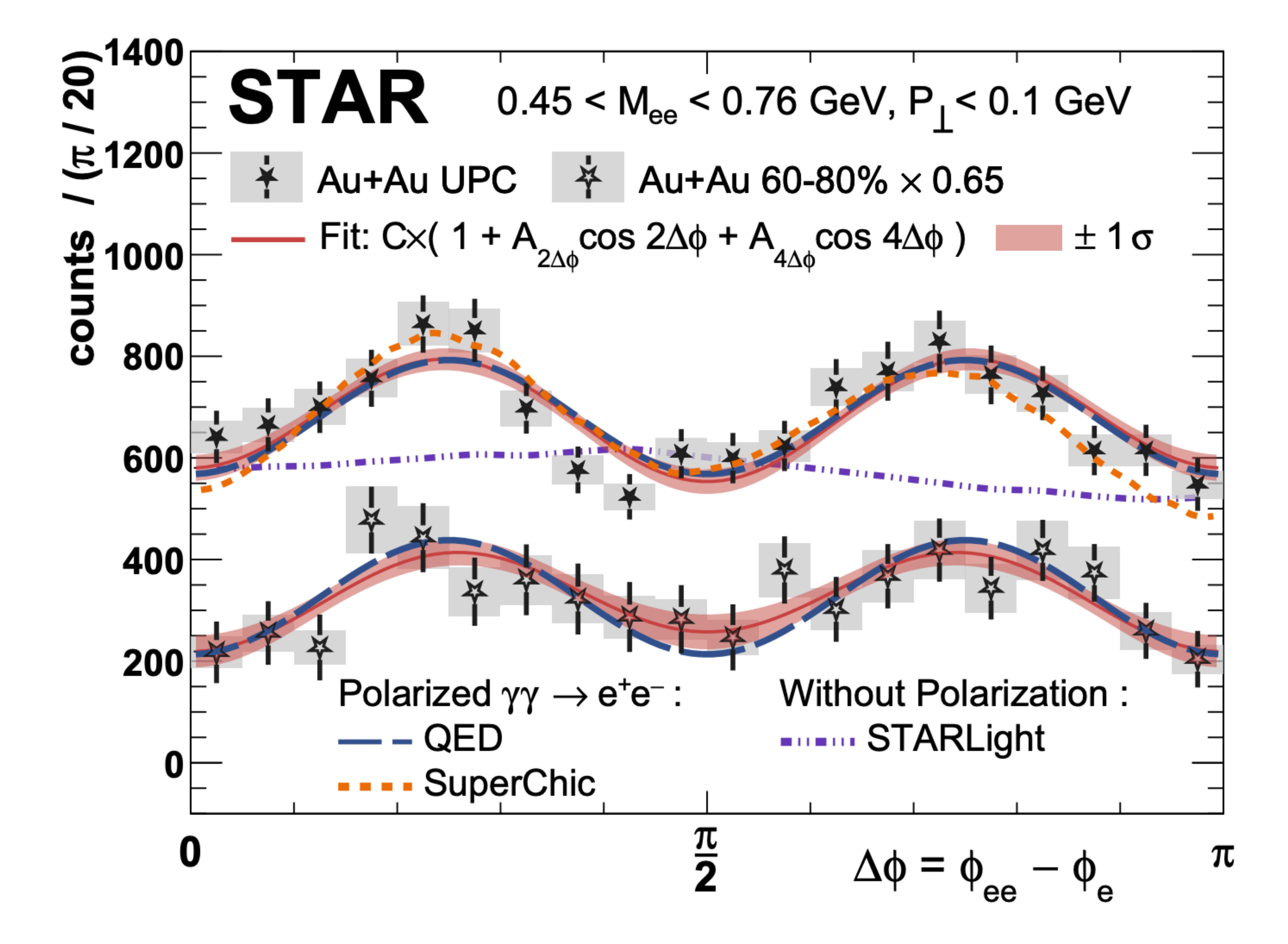
VM spin interference: A novel quantum phenomenon for high resolution gluon imaging

Polarized Photons from colliding nuclei

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



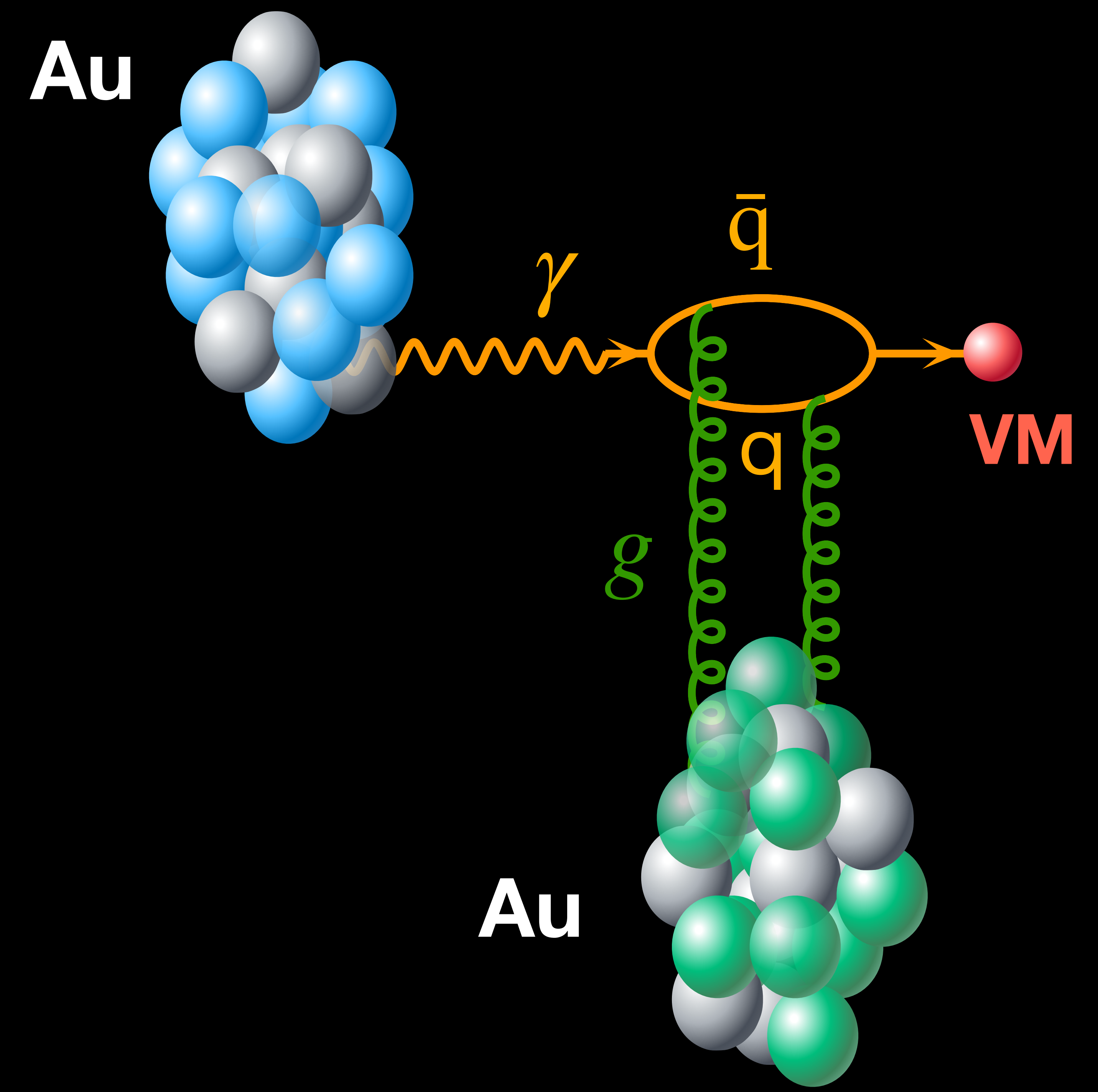
Transverse view of Lorentz contracted nuclei

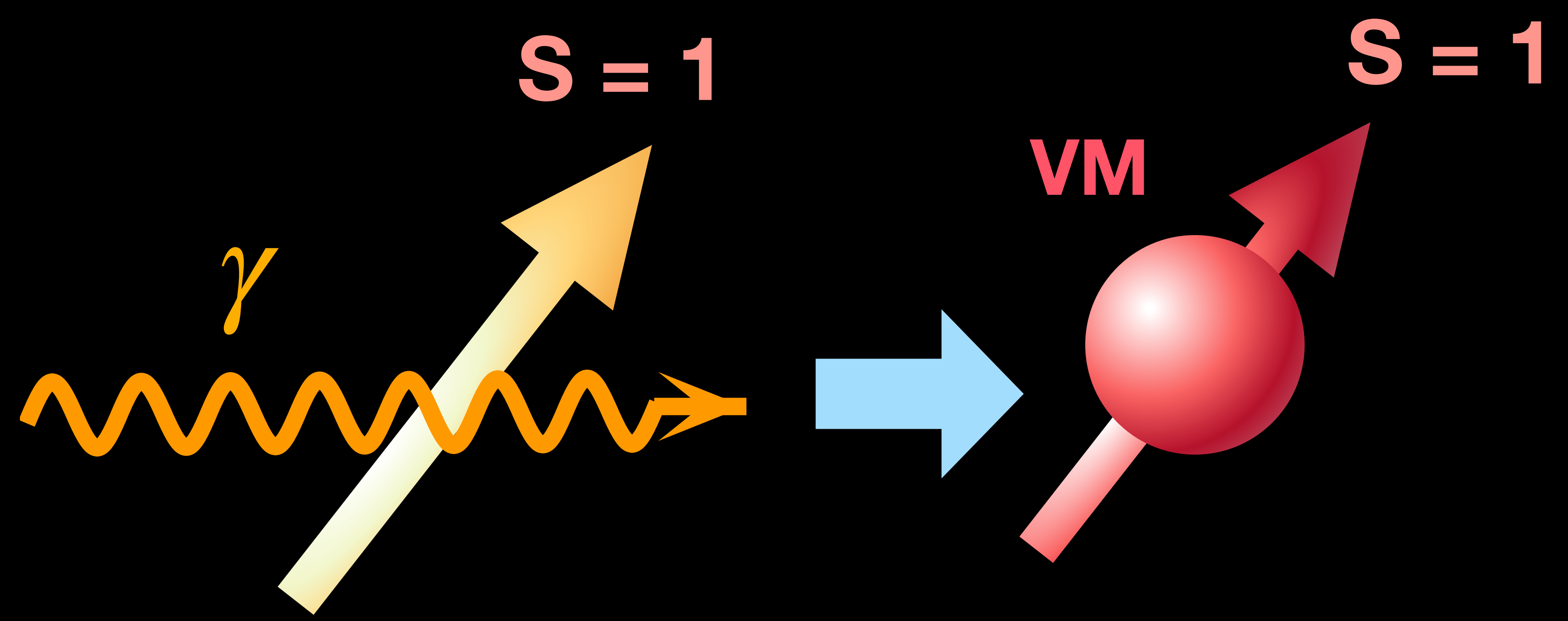


=> Photons in UPC are linearly polarized — polarization is roughly along impact parameter

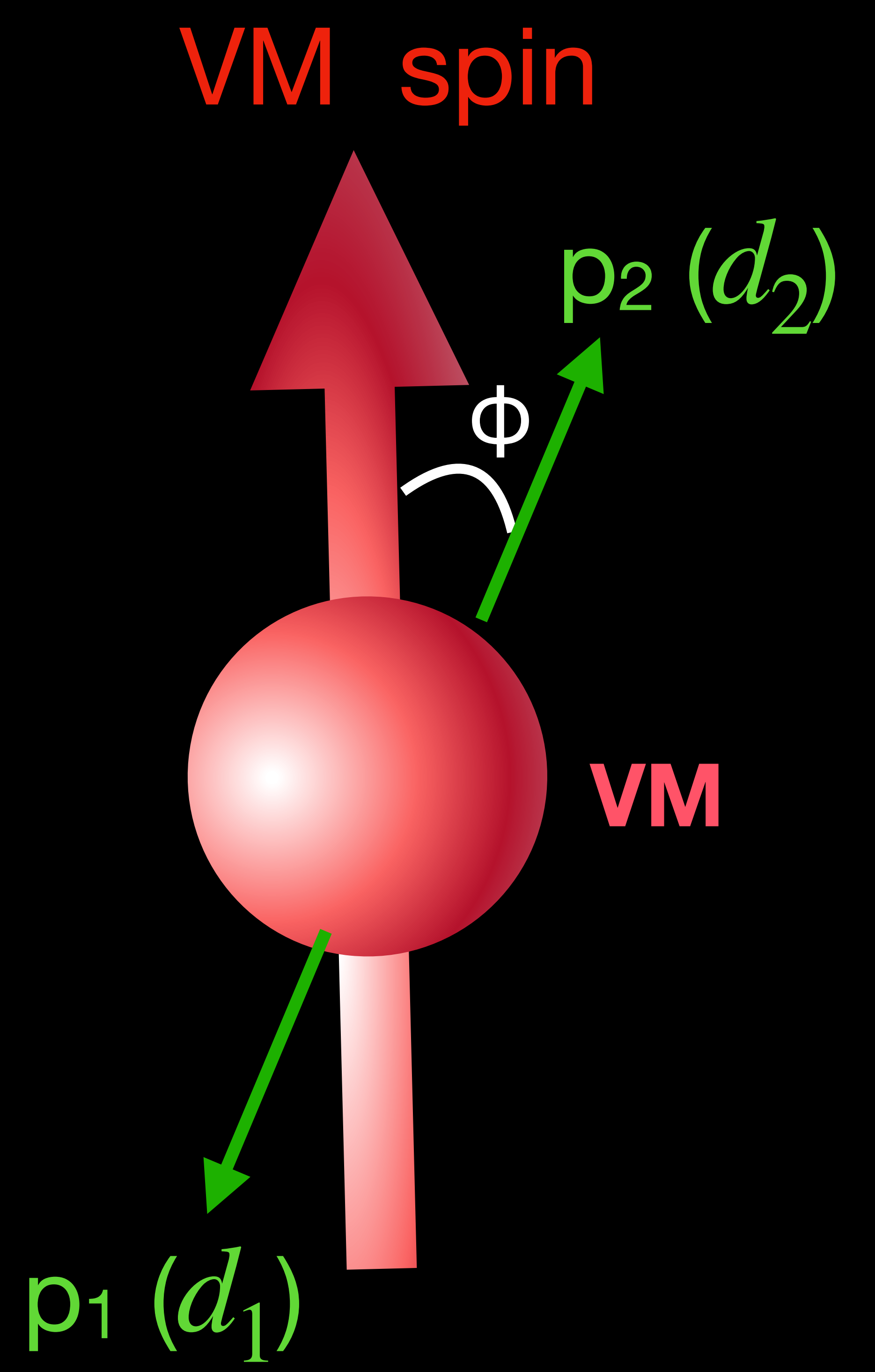
Experimental access to photon polarization demonstrated by STAR, measuring the Breit-Wheeler process, $\gamma\gamma \rightarrow e^+e^-$

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)

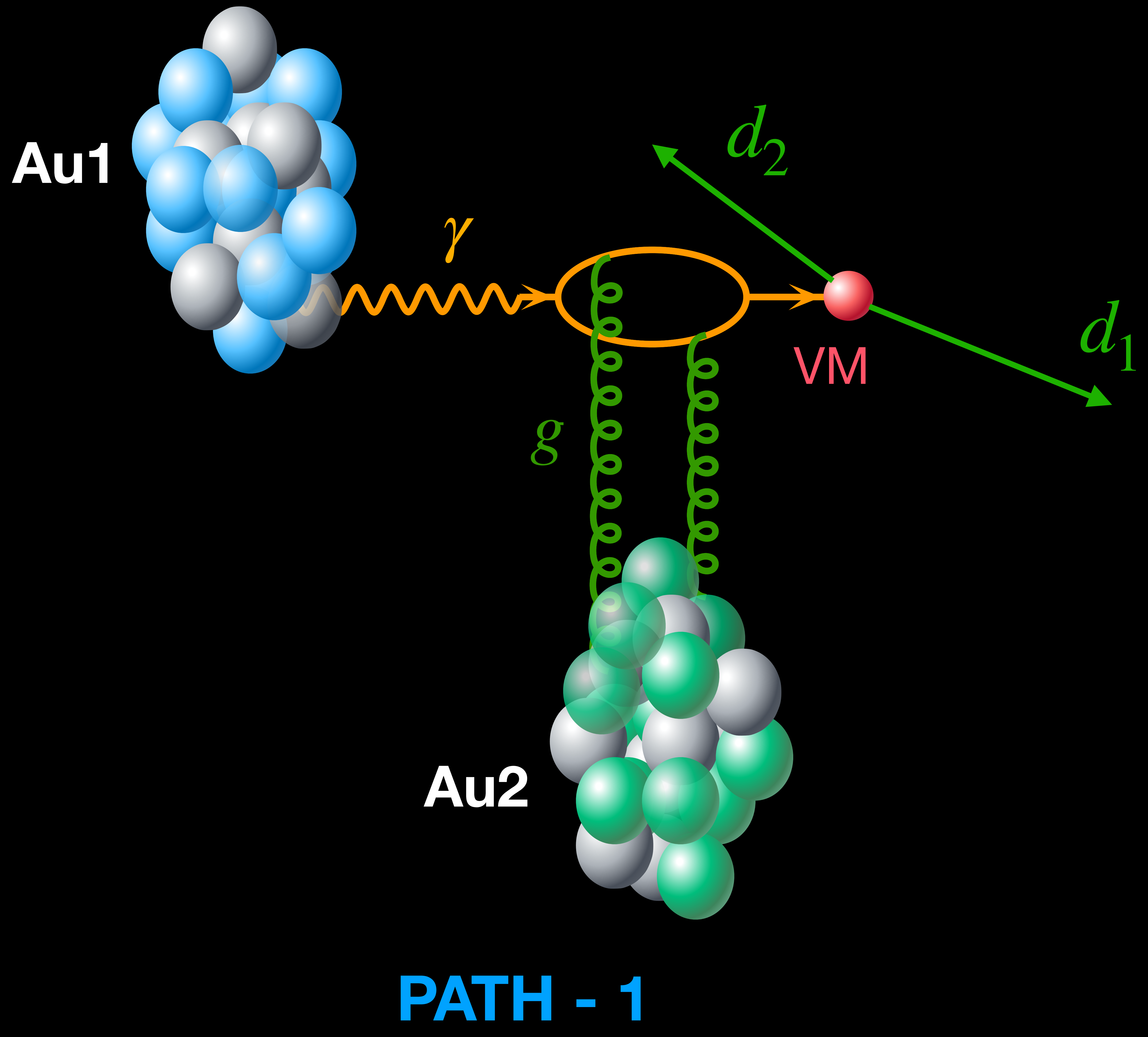
=> The cos(2ϕ) modulation in VM momentum distribution w.r.t photon polarization direction

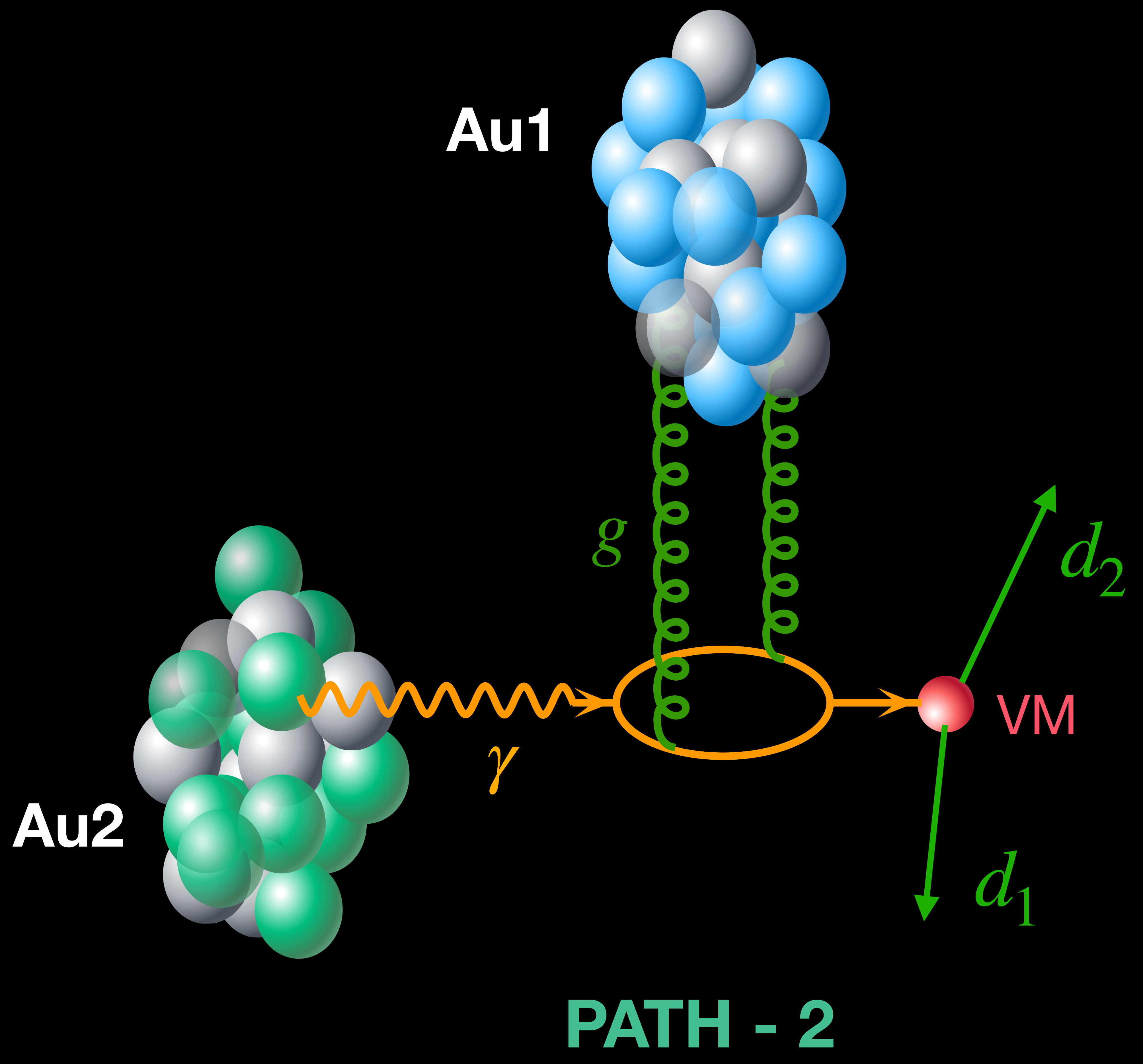
Measuring the modulation over a large no. of events

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

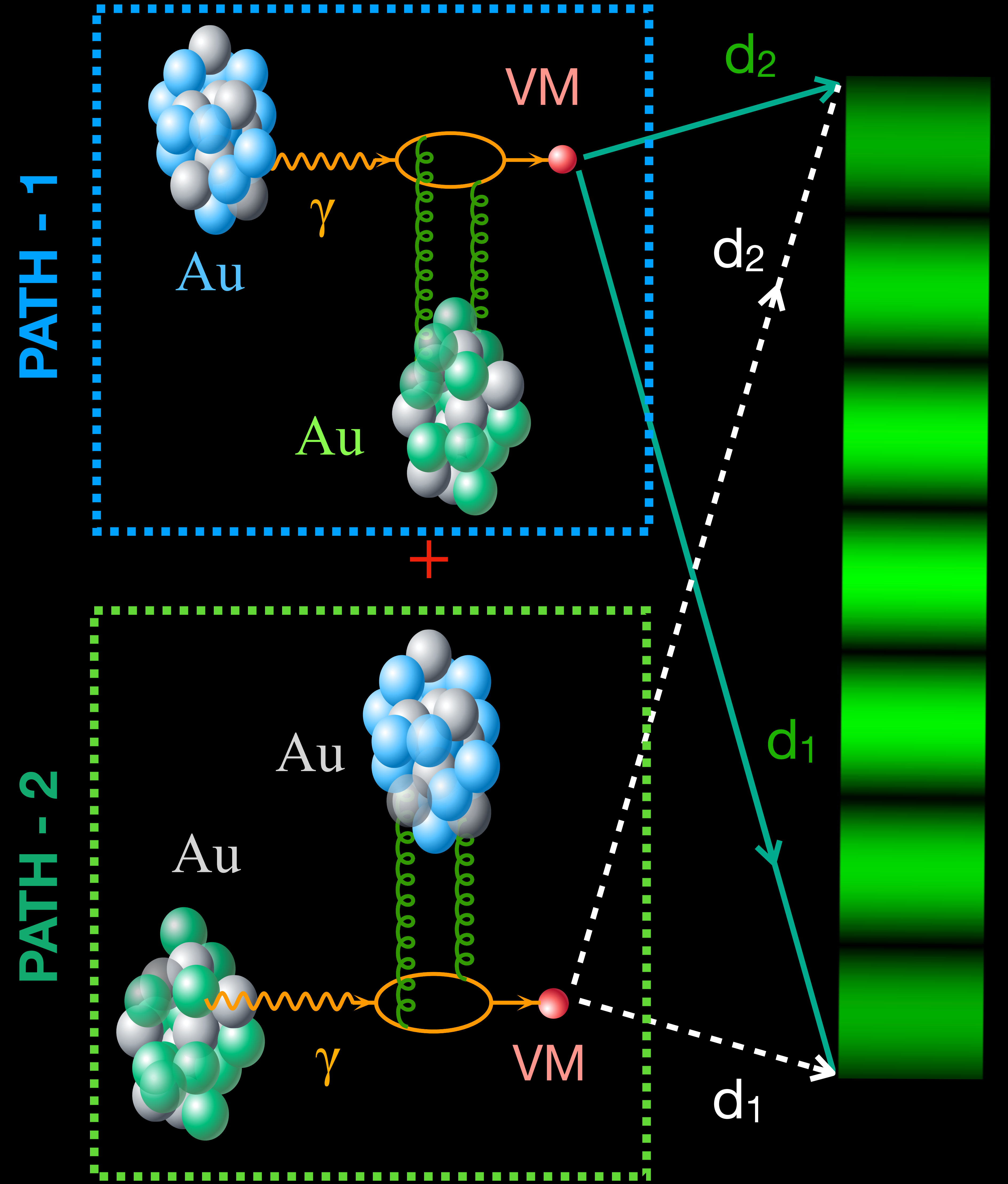




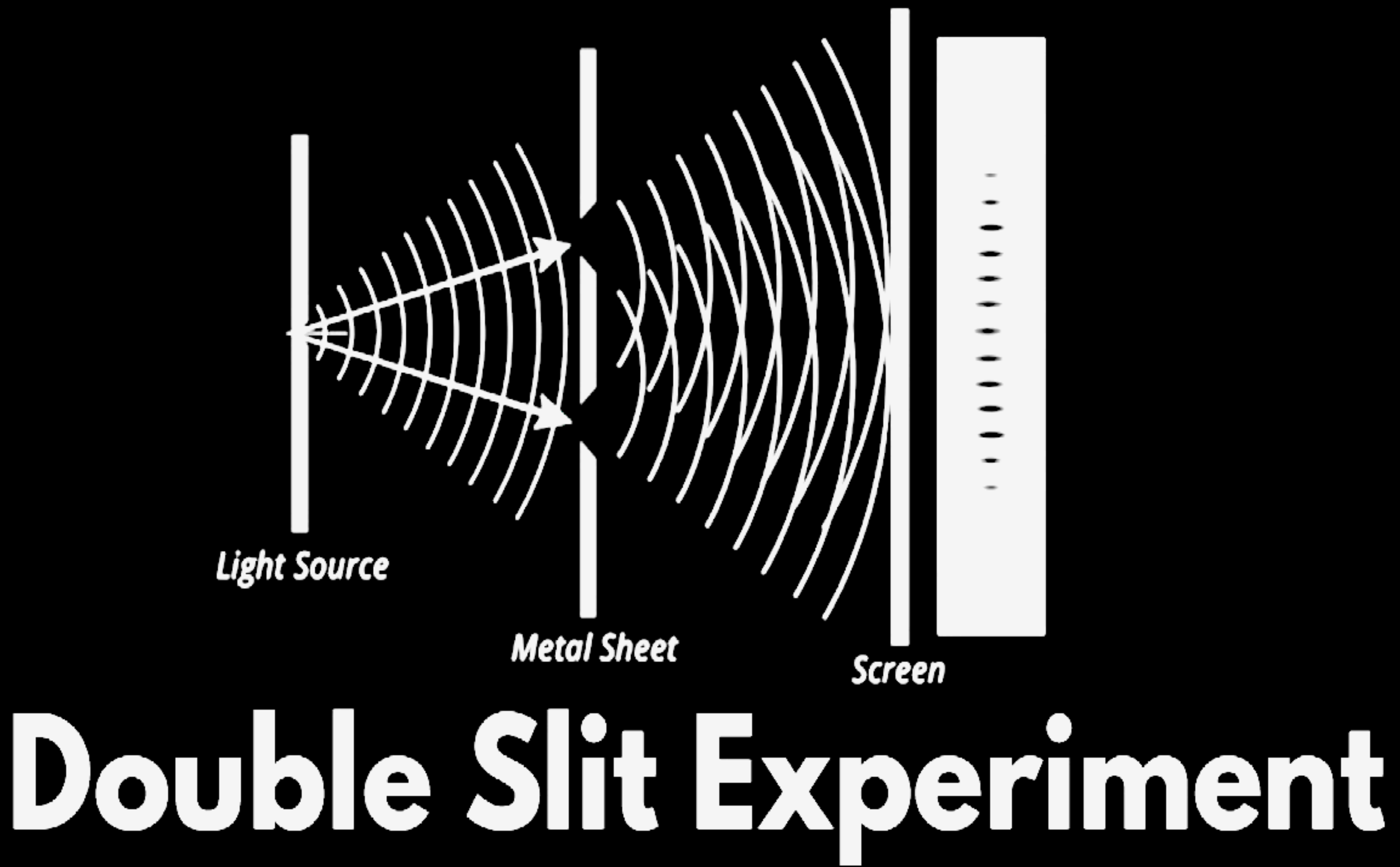
=> Two independent paths of VM production

—> The paths are indistinguishable

Interference makes the modulation observable in experiment



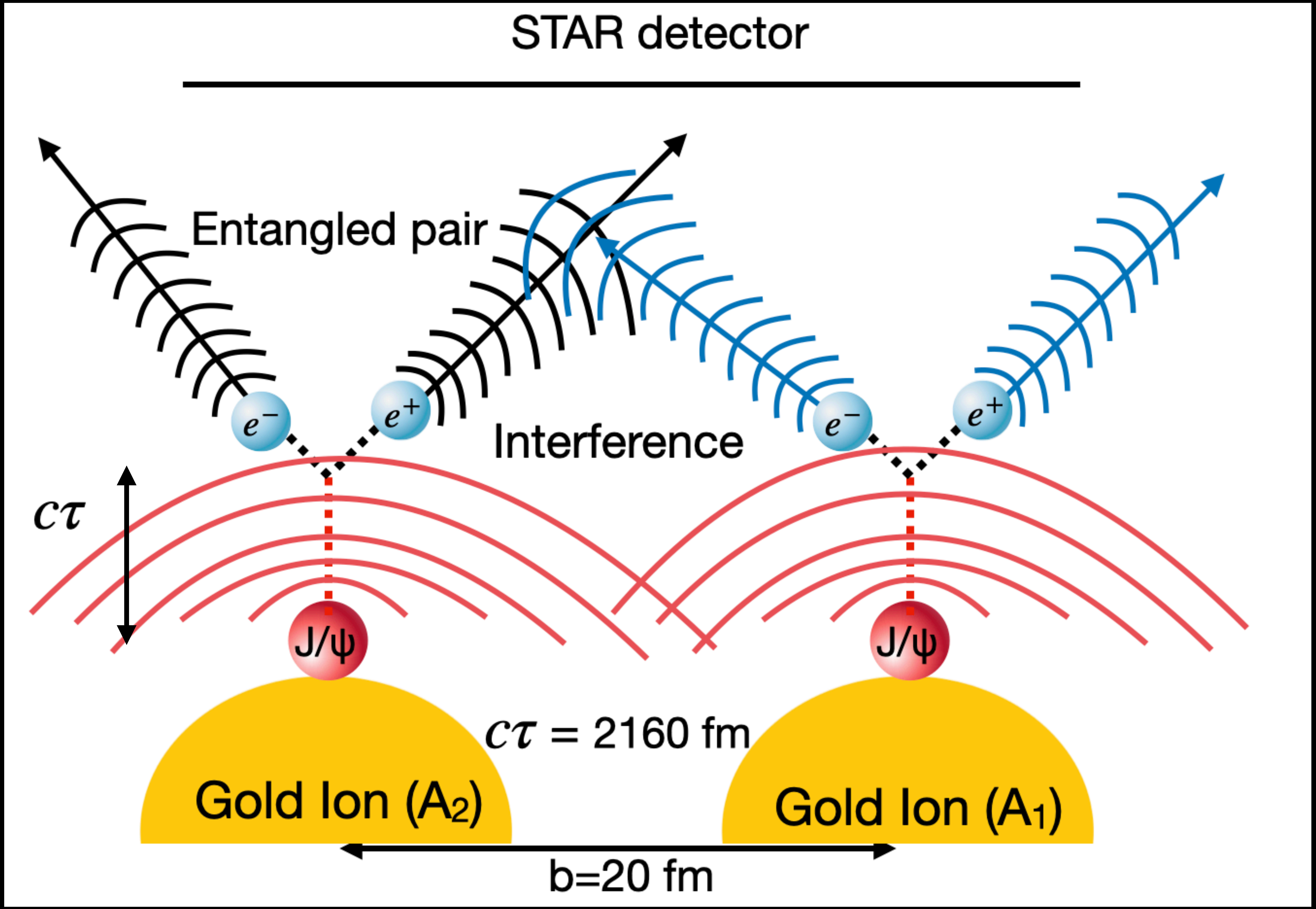
Photon source ambiguity: Interference among amplitudes of two possible paths



Best analogy: Double slit experiment in Optics

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

Entanglement as an origin of interference



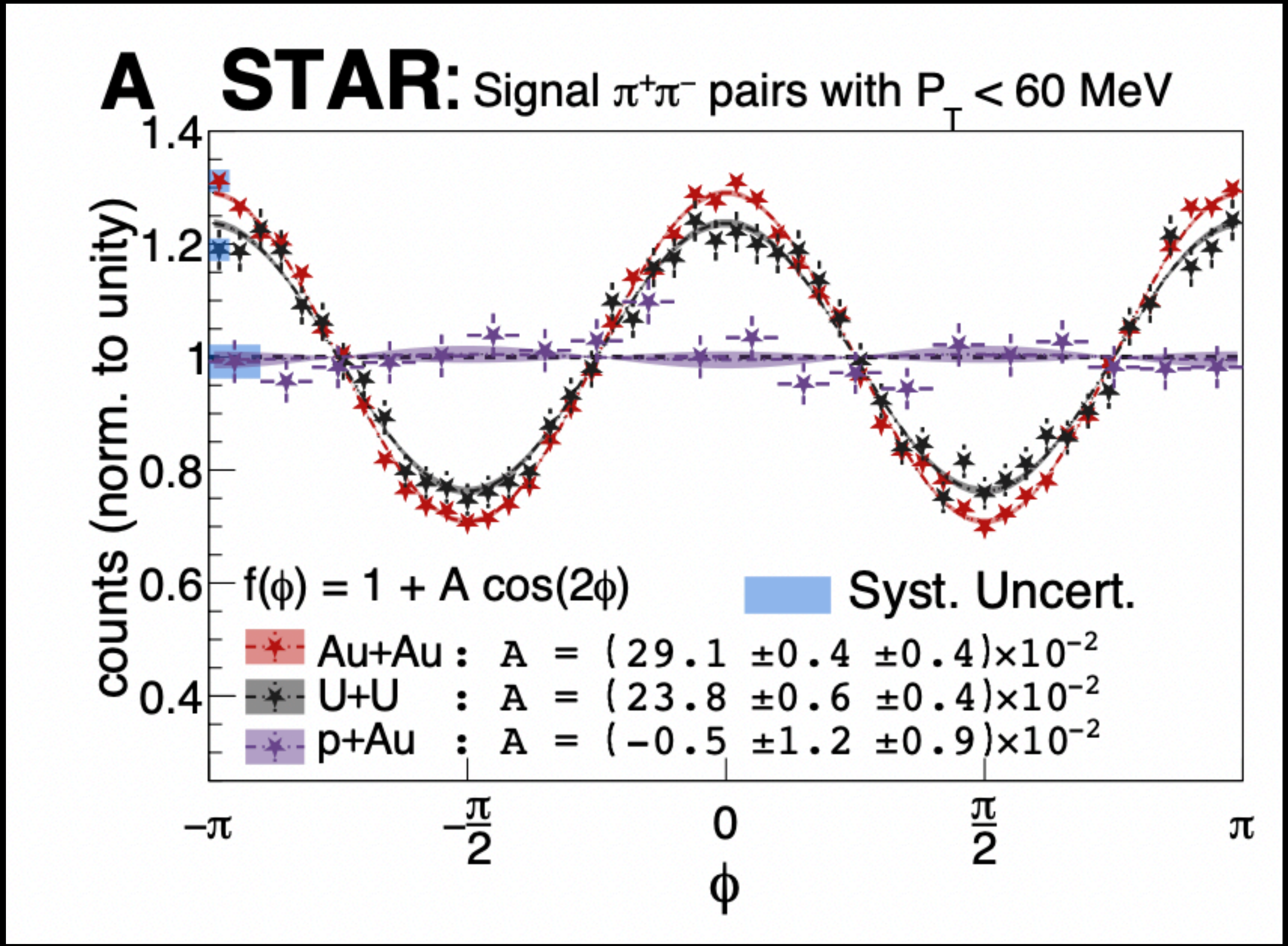
—> Vector meson decay acts as a entanglement filter

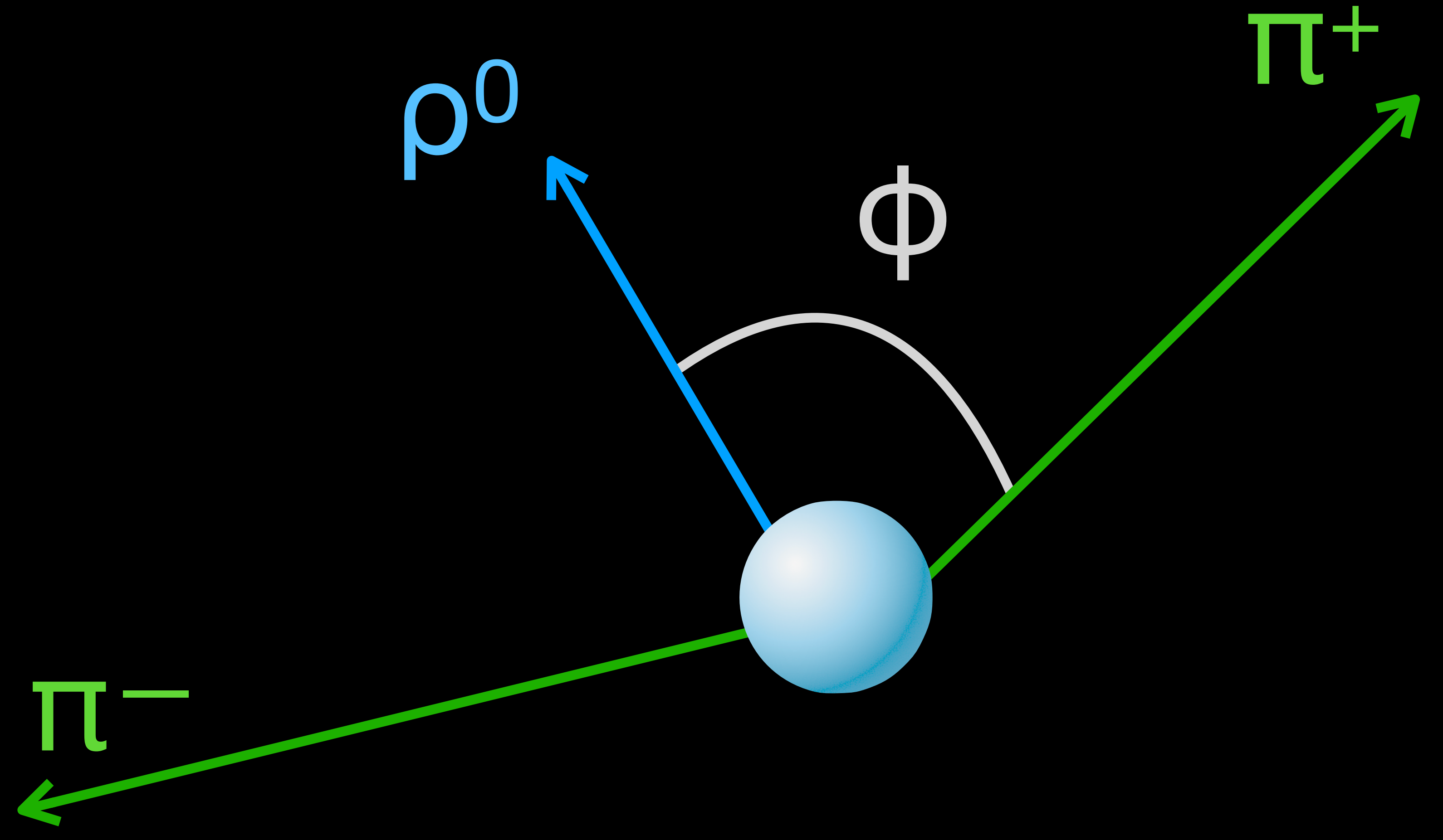
—> Decay electrons entangled — Wave function gets locked

—> Daughters carry memory of phase information b/w two paths

—> Interference survives

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





SCIENCE ADVANCES | RESEARCH ARTICLE

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

Tomography of ultrarelativistic nuclei with polarized photon-gluon collisions

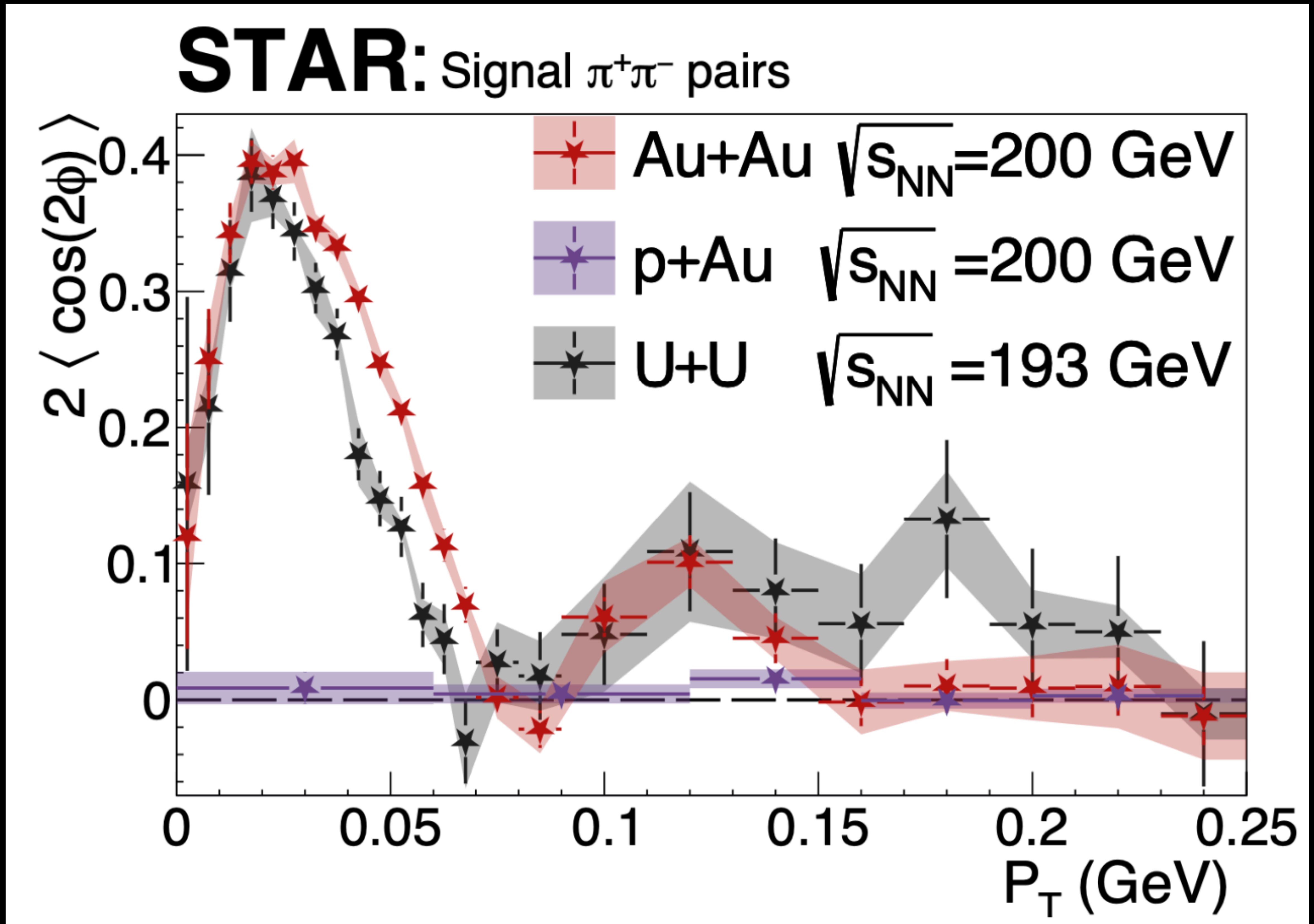
STAR Collaboration

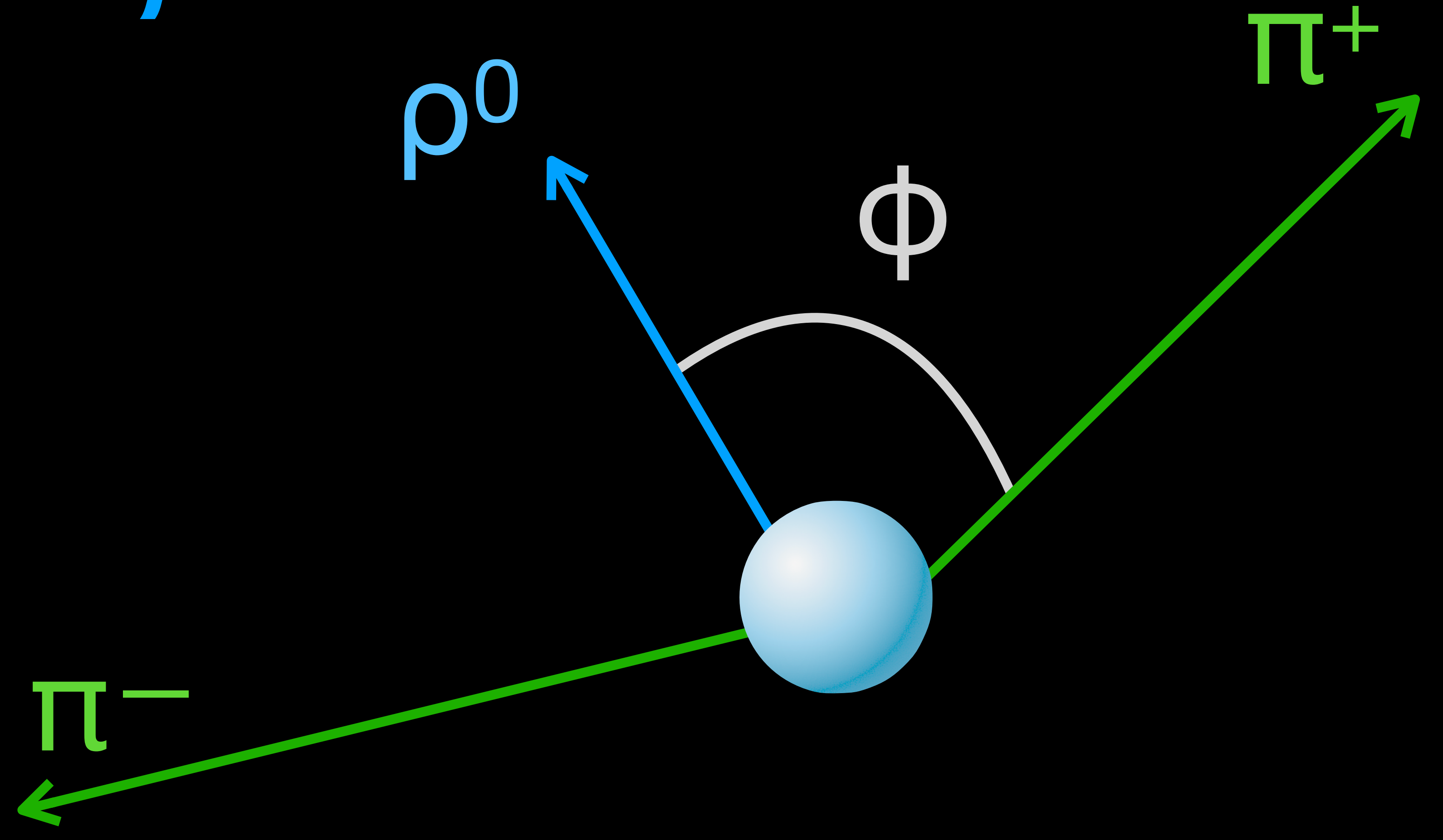
A linearly polarized photon can be quantized from the Lorentz-boosted electromagnetic field of a nucleus traveling at ultrarelativistic speed. When two relativistic heavy nuclei pass one another at a distance of a few nuclear radii, the photon from one nucleus may interact through a virtual quark-antiquark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

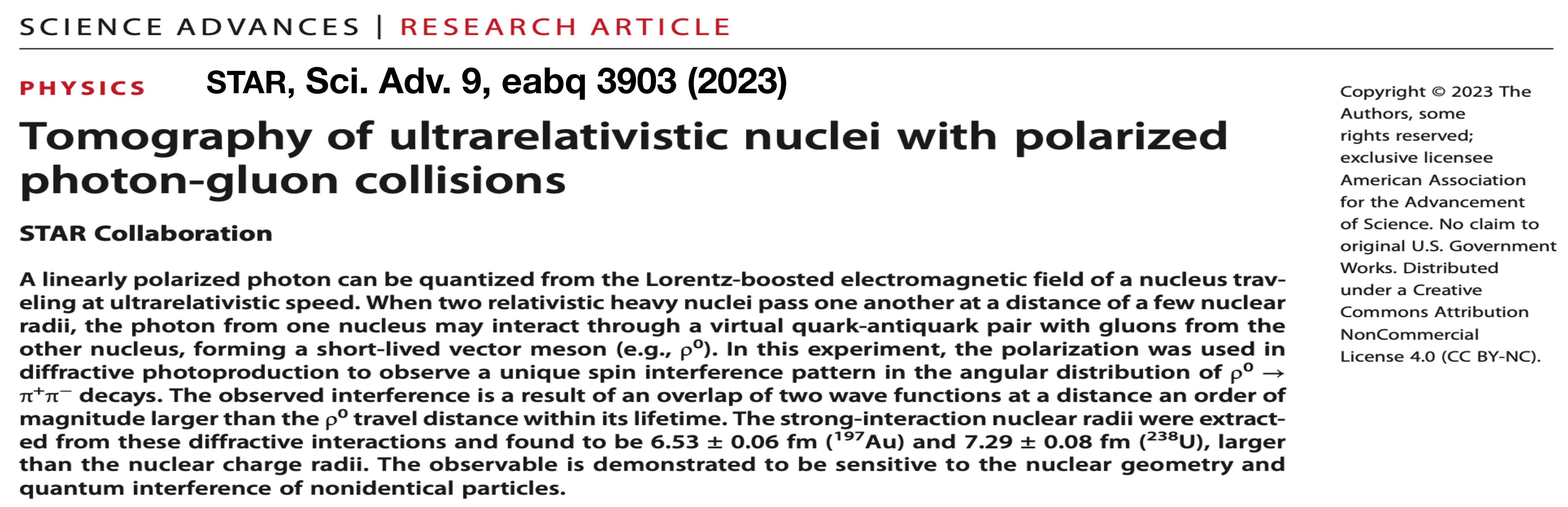
Observed the interference for coherent ρ^0 photoproduction in UPCs

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







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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

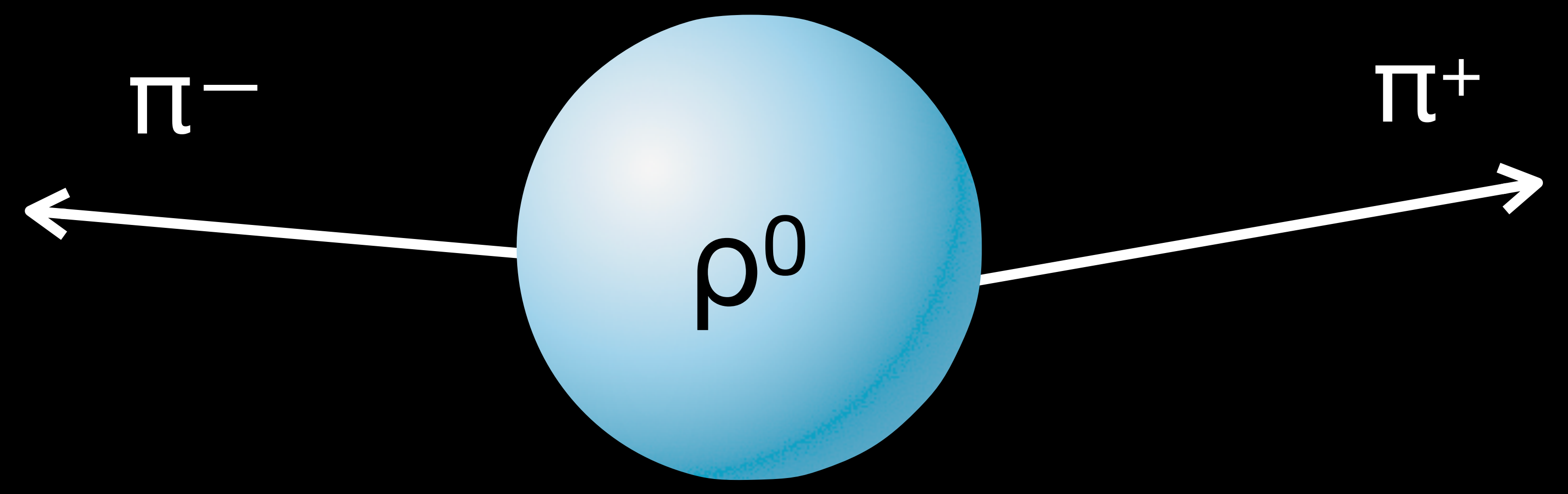
STAR, Sci. Adv. 9, eabq 3903 (2023)

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 ± 0.06 fm; R (U) = 7.29 ± 0.08 fm

Limitations of ρ^0 measurements



$$\rho^0 \rightarrow \pi^+ + \pi^-$$

Boson Boson

Open questions/concerns:

1. Ambiguity in interference origin: Parent vs Daughters ?

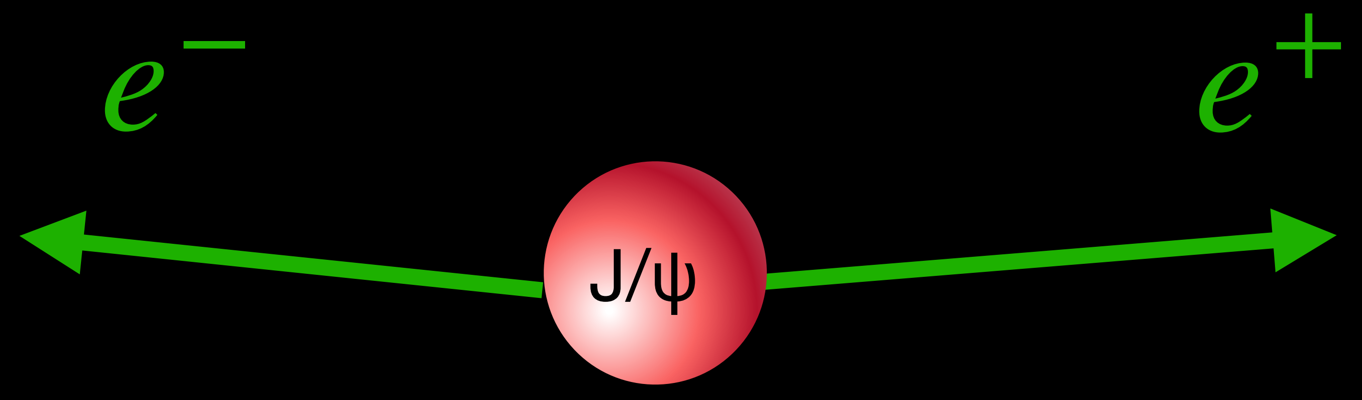
2. ρ^0 light vector meson and larger dipole size —> Limits spatial resolution, blurs small - x features

3. ρ^0 falls in non-perturbative QCD regime —> large theory uncertainties

4. Poor CGC testbed: ρ^0 not ideal for cleanly validating saturation predictions in CGC

=> Heavy vector meson like J/ψ sheds light on this

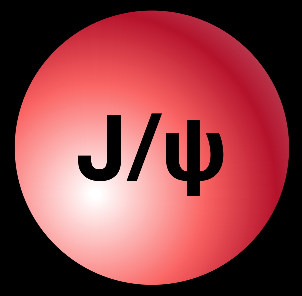
Why J/ψ is ideal probe?



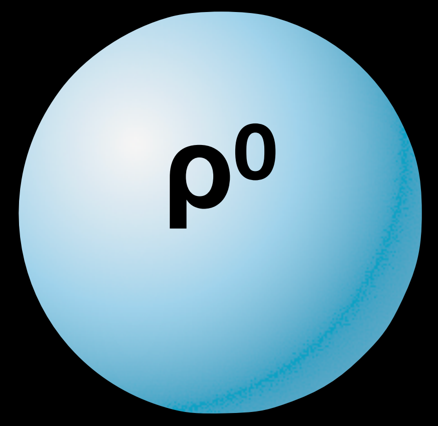
$J/\psi \rightarrow e^+e^-$

Boson Fermion

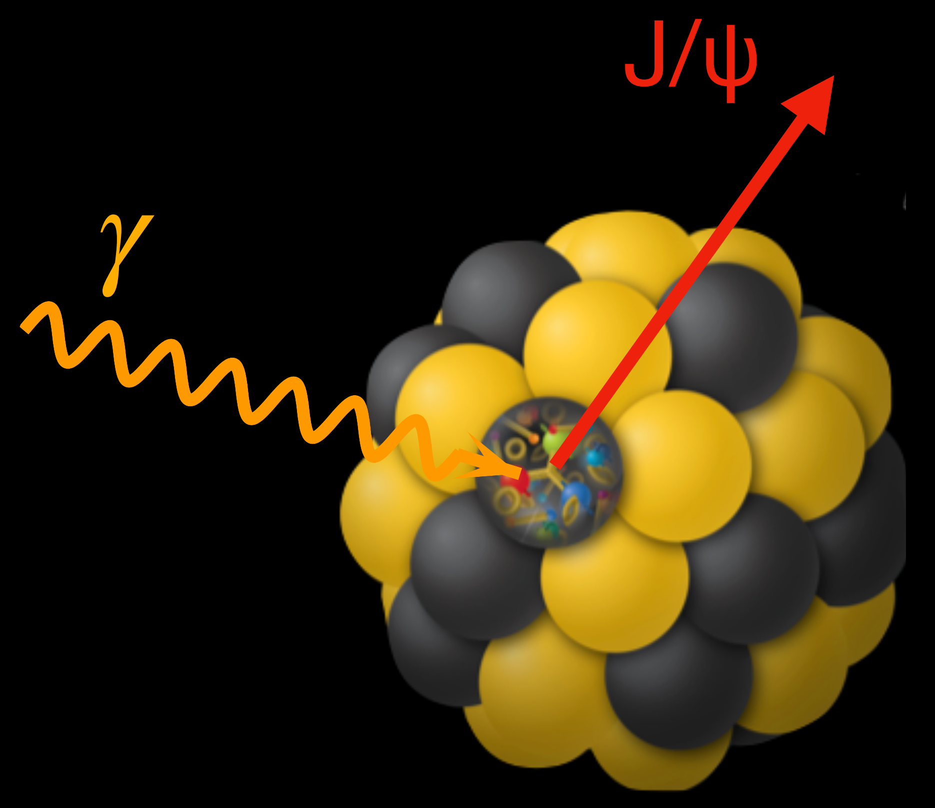
1. Clean interference interpretation: Fermionic decay products help unambiguous identification of interference origin

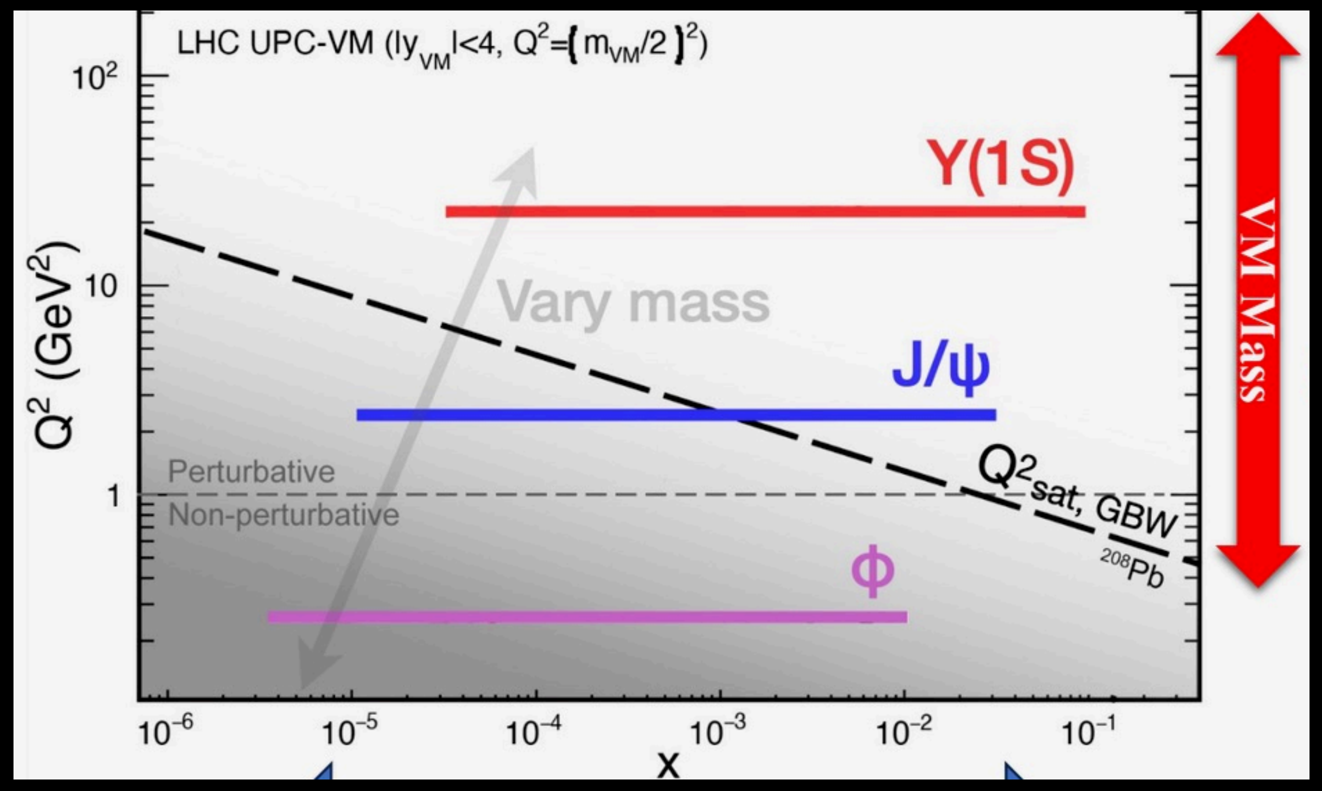


Mass: 3.1 GeV/c²
Lifetime: 2160 fm/c



Mass: 0.7 GeV/c²
Lifetime: 1.3 fm/c





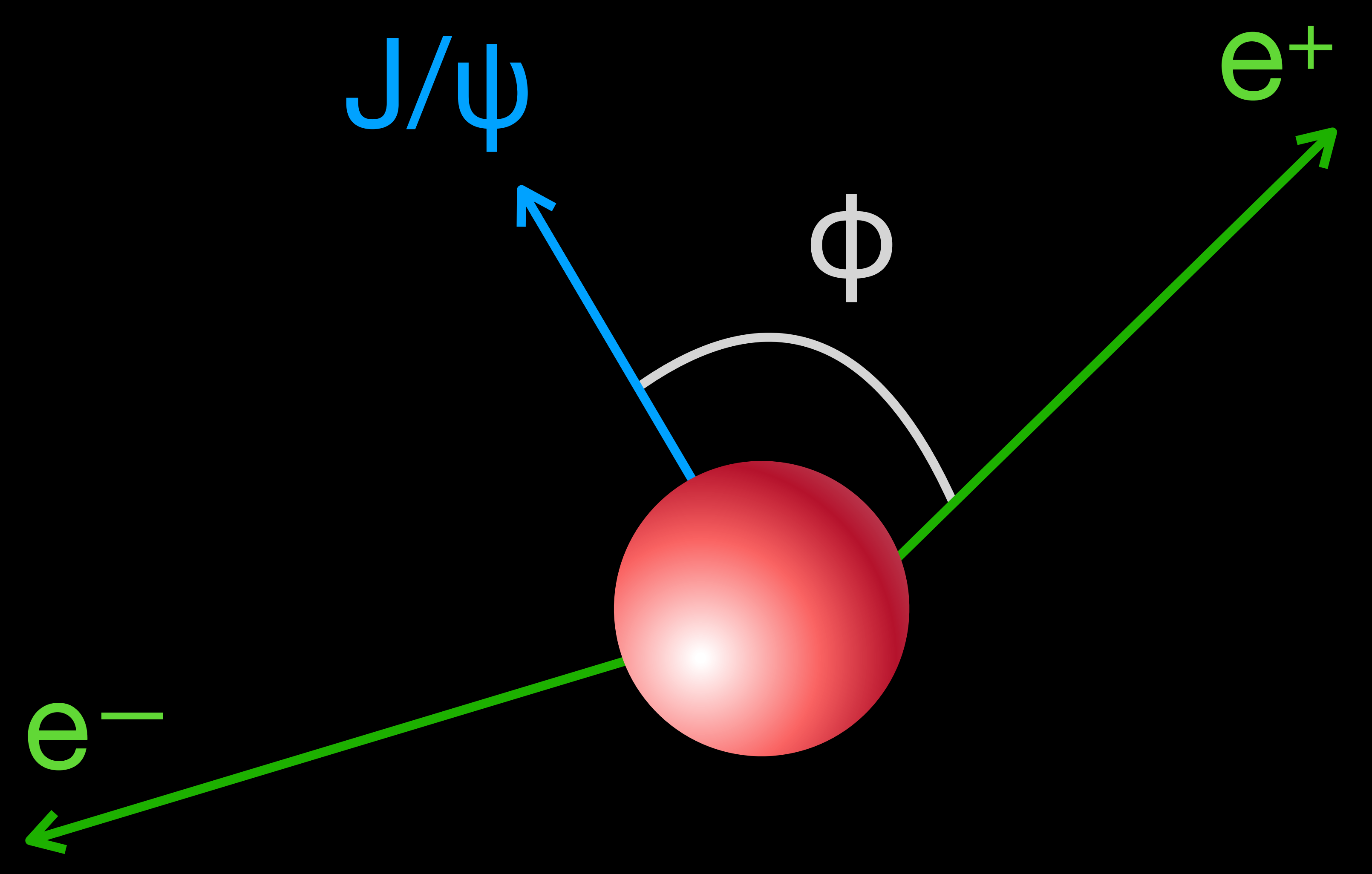
2. J/ψ heavier and more compact dipole size => probes finer resolutions

3. J/ψ has longer life time => extended wave functions and better overlap—> good for interference study

4. J/ψ is applicable for perturbative QCD & CGC based theory calculations

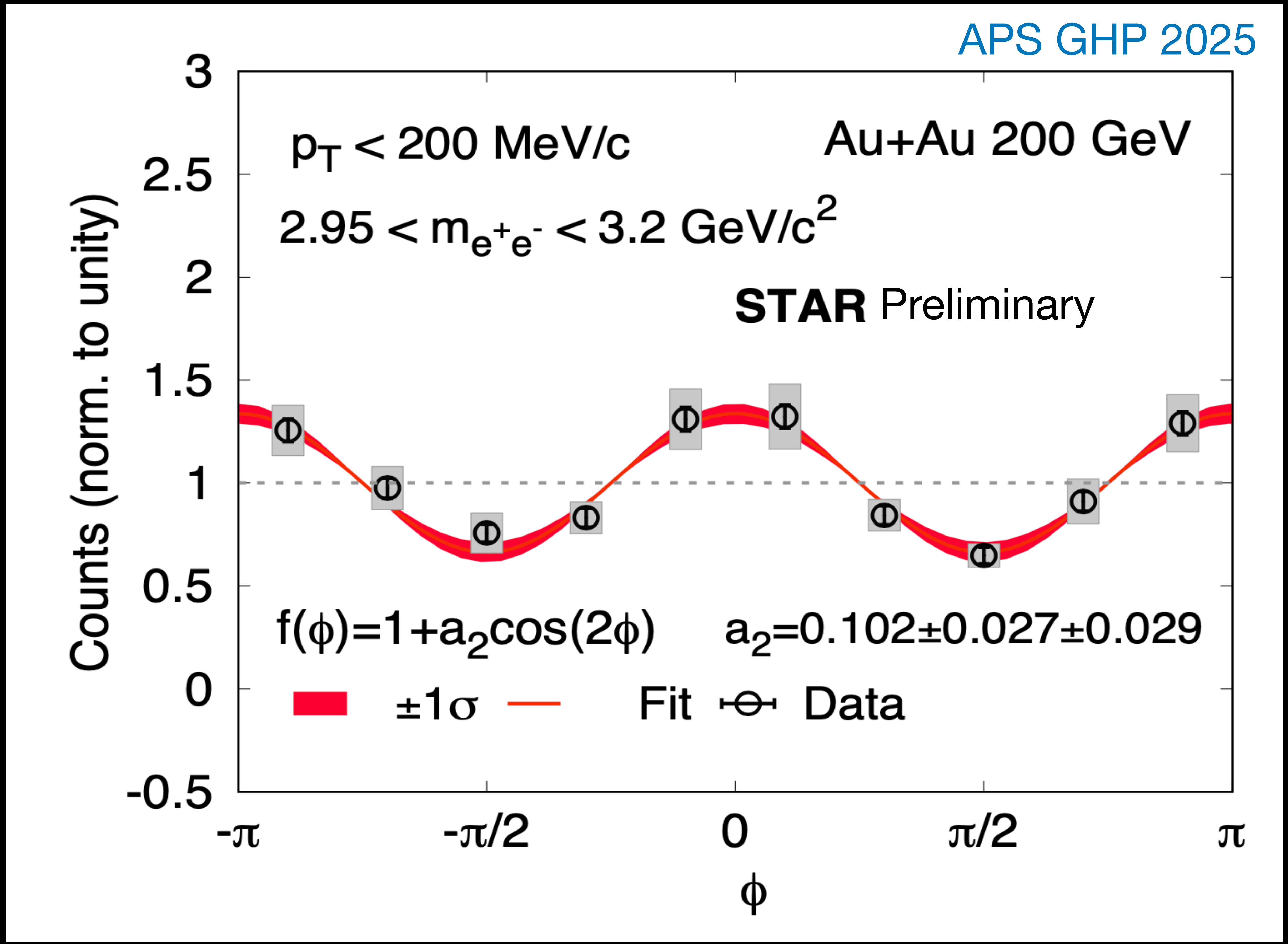
=> J/ψ is precision probe for spin interference and gluon structure

Measured spin interference with J/ψ → e^+e^-



Observable for J/ψ spin interference

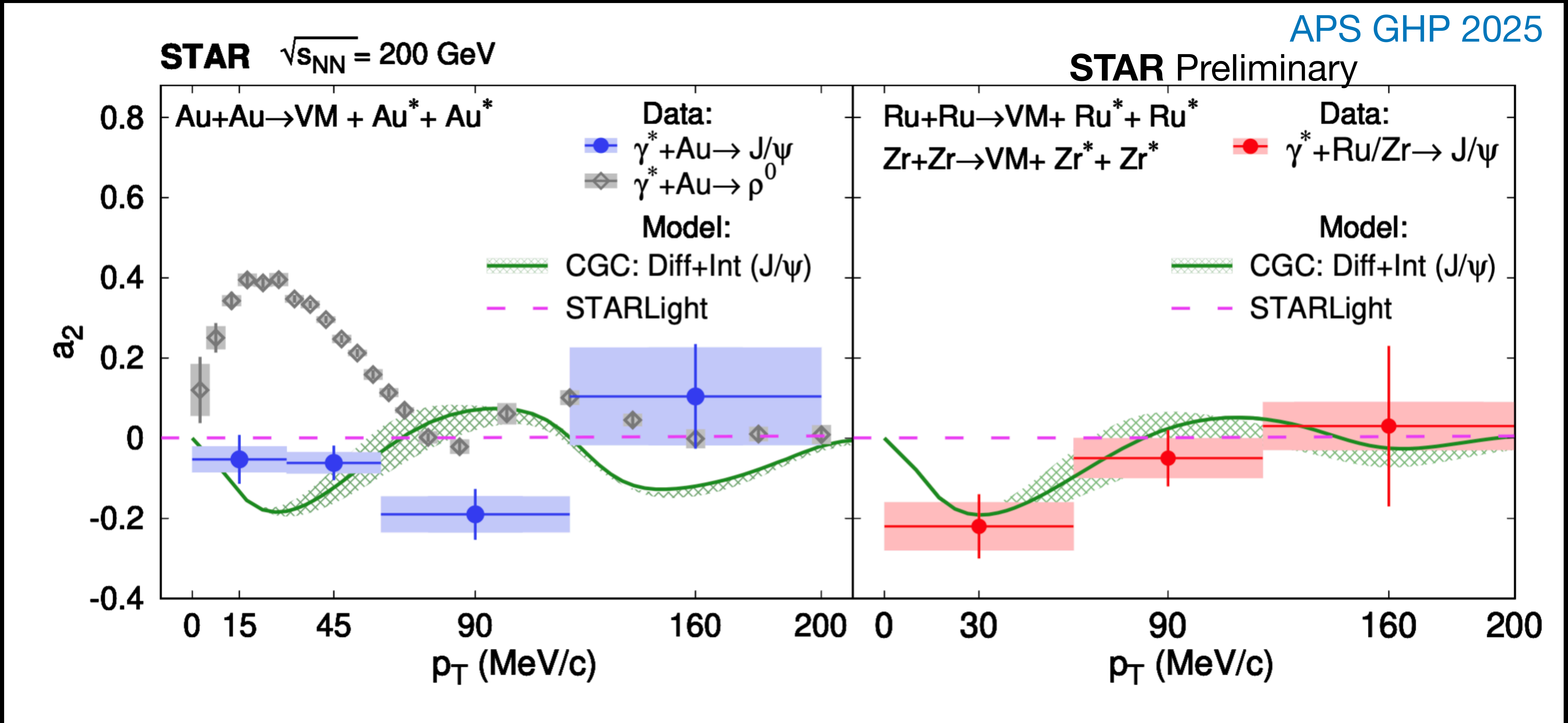
Interference signal fitted with: 1+ a_2 cos(2ϕ) => a_2 is the measure of the modulation

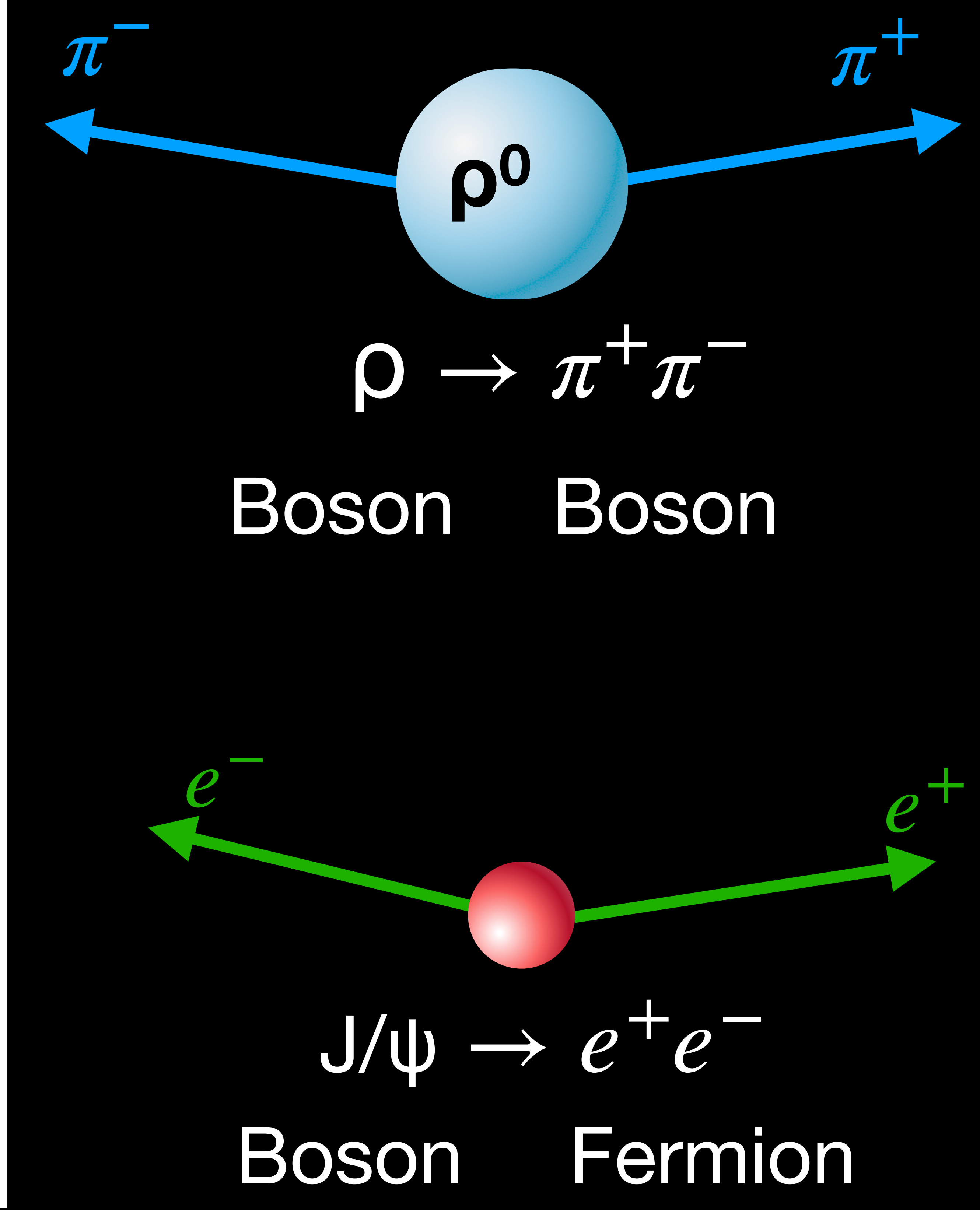


Measured cos(2ϕ) for spin interference of J/ψs

Observed spin interference for J/ψ → e^+e^-

The p_T-dependent interference of J/ψ



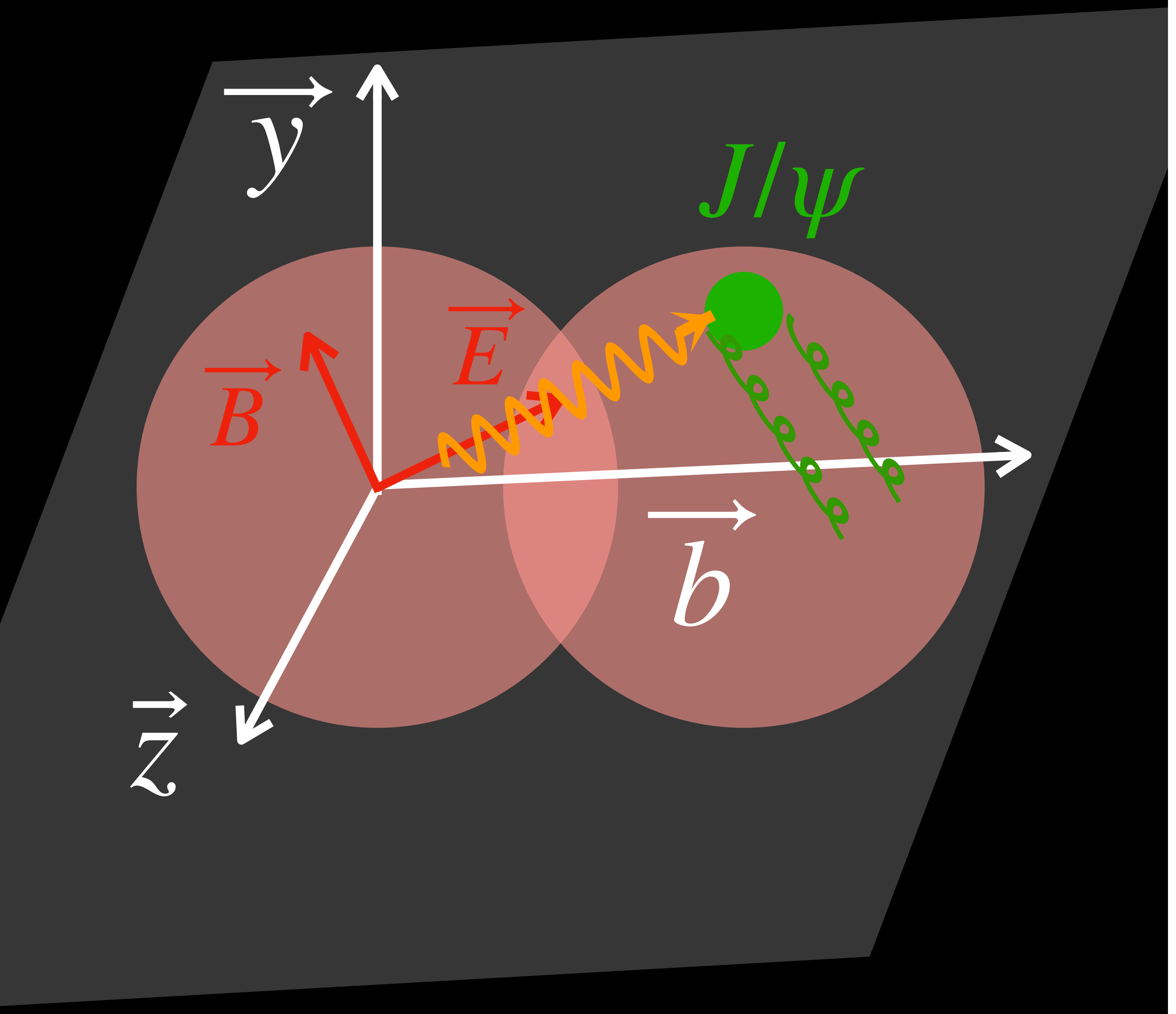


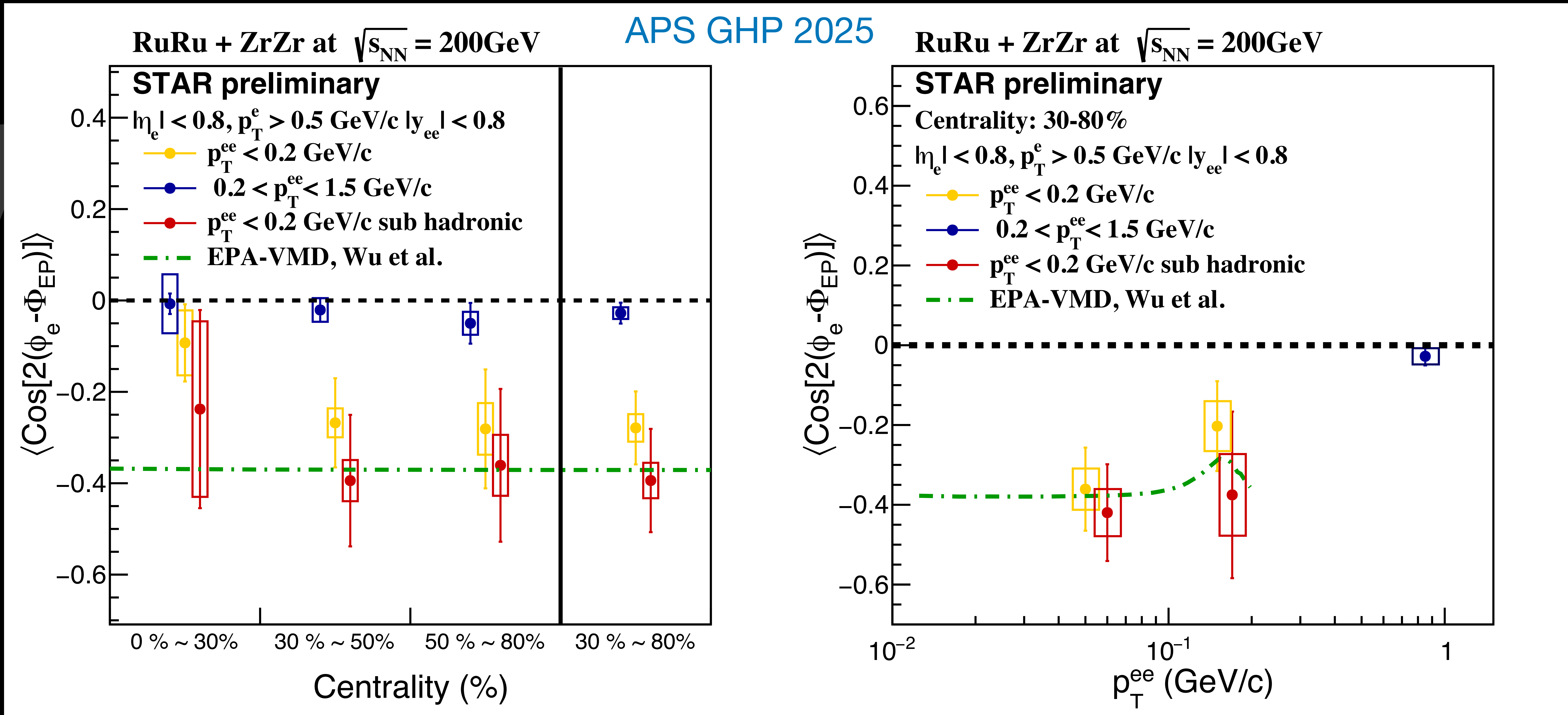
Diff+Int predictions : Mäntysaari et al. Phys.Rev.C 109 (2024) 2, 024908

- Interference signal for J/ψ shows p_T dependence
- Positive modulation for ρ and negative for J/ψ ($a_2 \sim -12\,\%$ with 3σ for pT<100 MeV)
- Diffractive+interference calculations cannot describe the data well

=> Useful for gluon tomography within the nucleus

Decay anisotropy of photo-produced J/ψ in heavy ion peripheral collisions





=> Significant modulation (~39%) w.r.t reaction plane

=> Probes photon polarization and the initial collision geometry

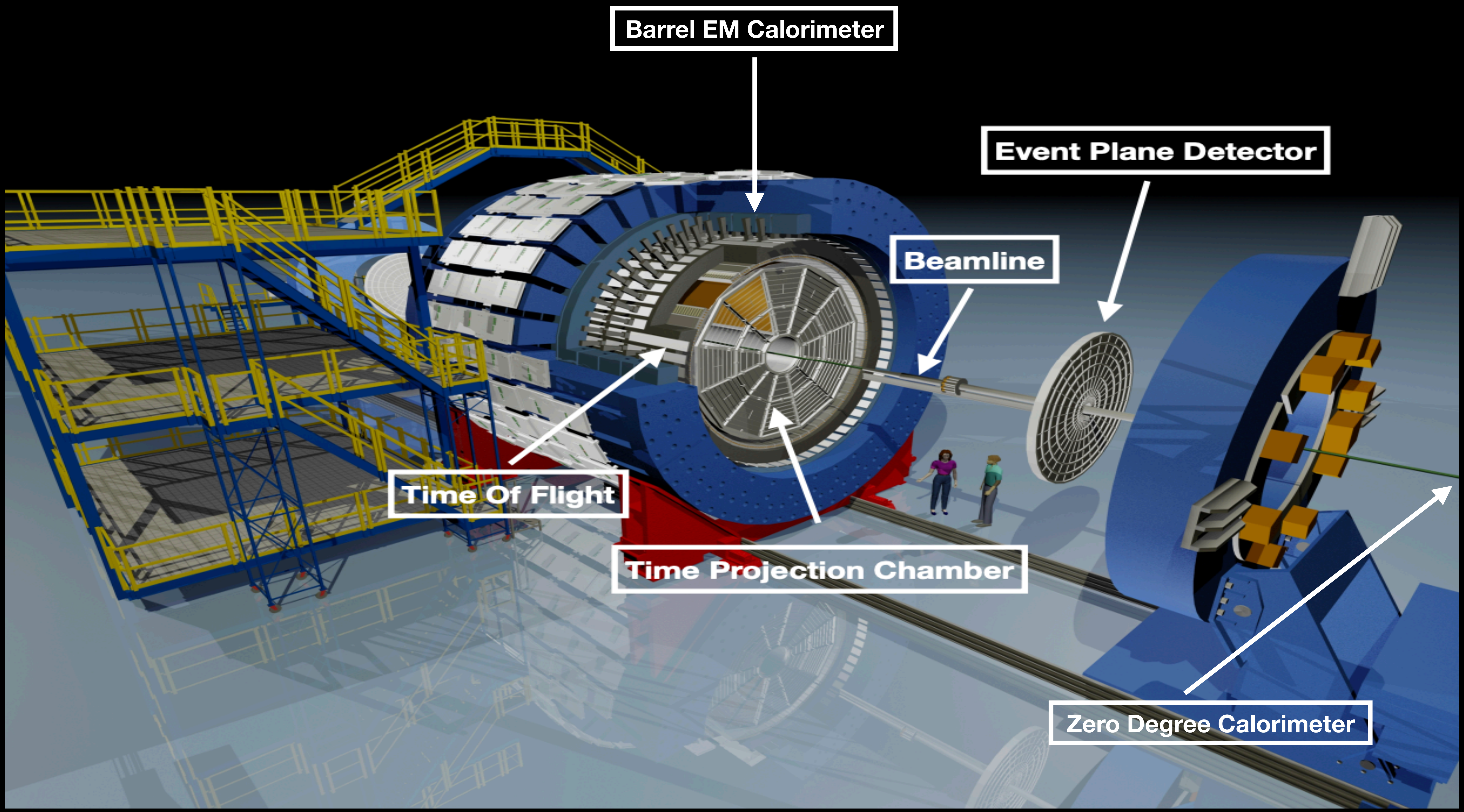
Summary and take home

- STAR 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 has p_T dependence
- Measured the photon induced J/ψ polarization w.r.t reaction plane in peripheral collisions
- 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



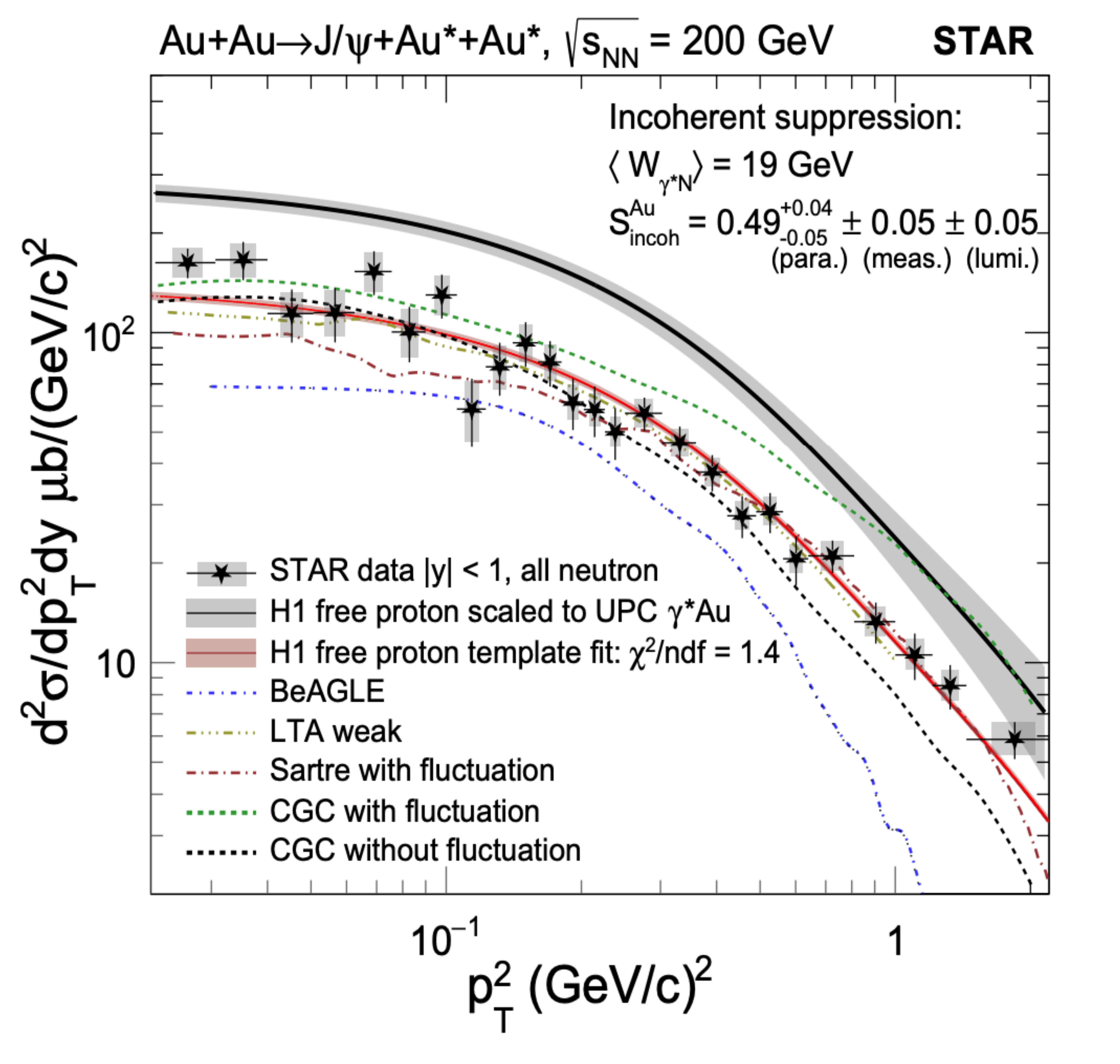
- Main central barrel detectors for UPC measurements: TPC, TOF, BEMC
- Forward detectors: BBC or EPD, ZDC

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

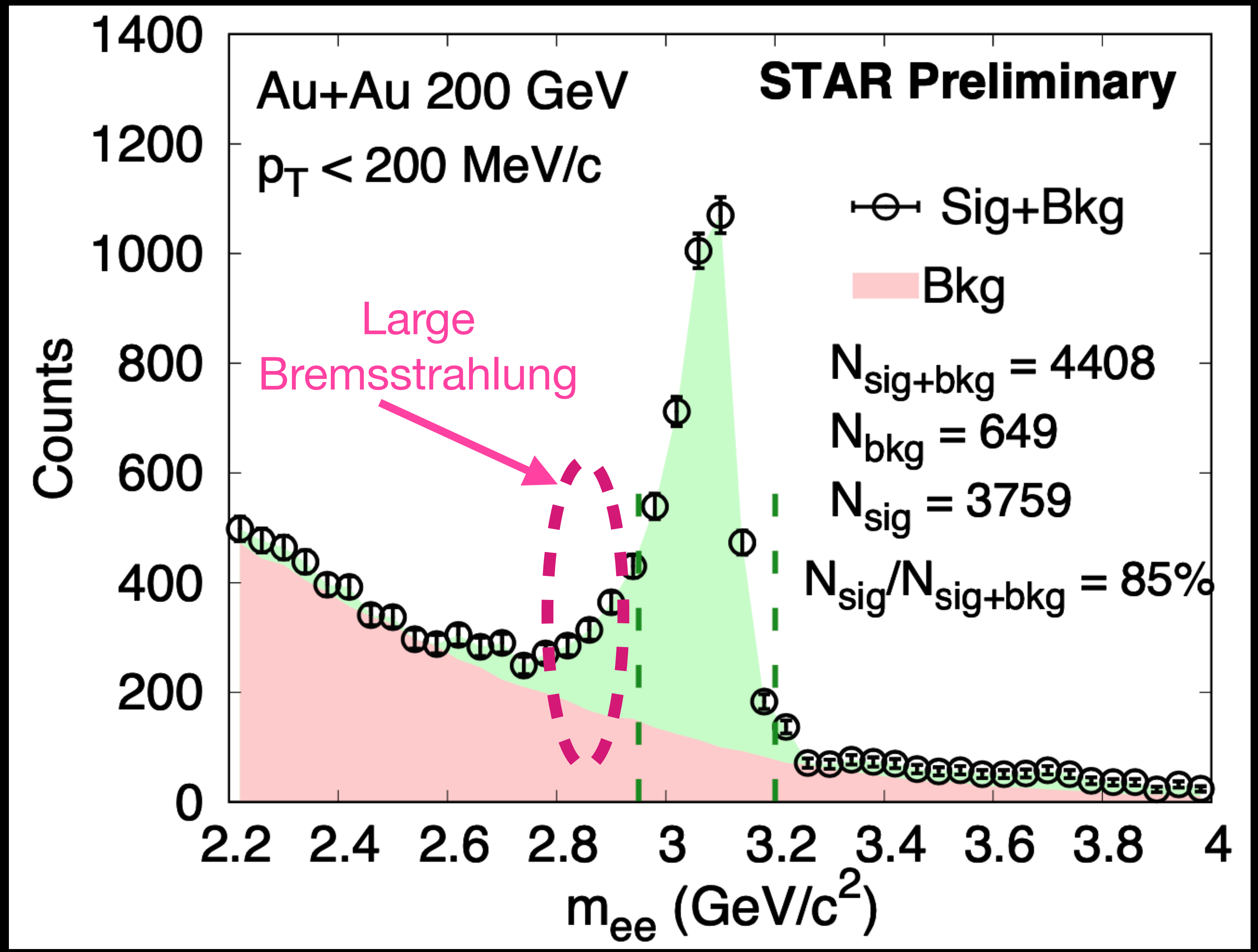
STAR, *Phys Rev Lett* 133 (2024) 5, 052301

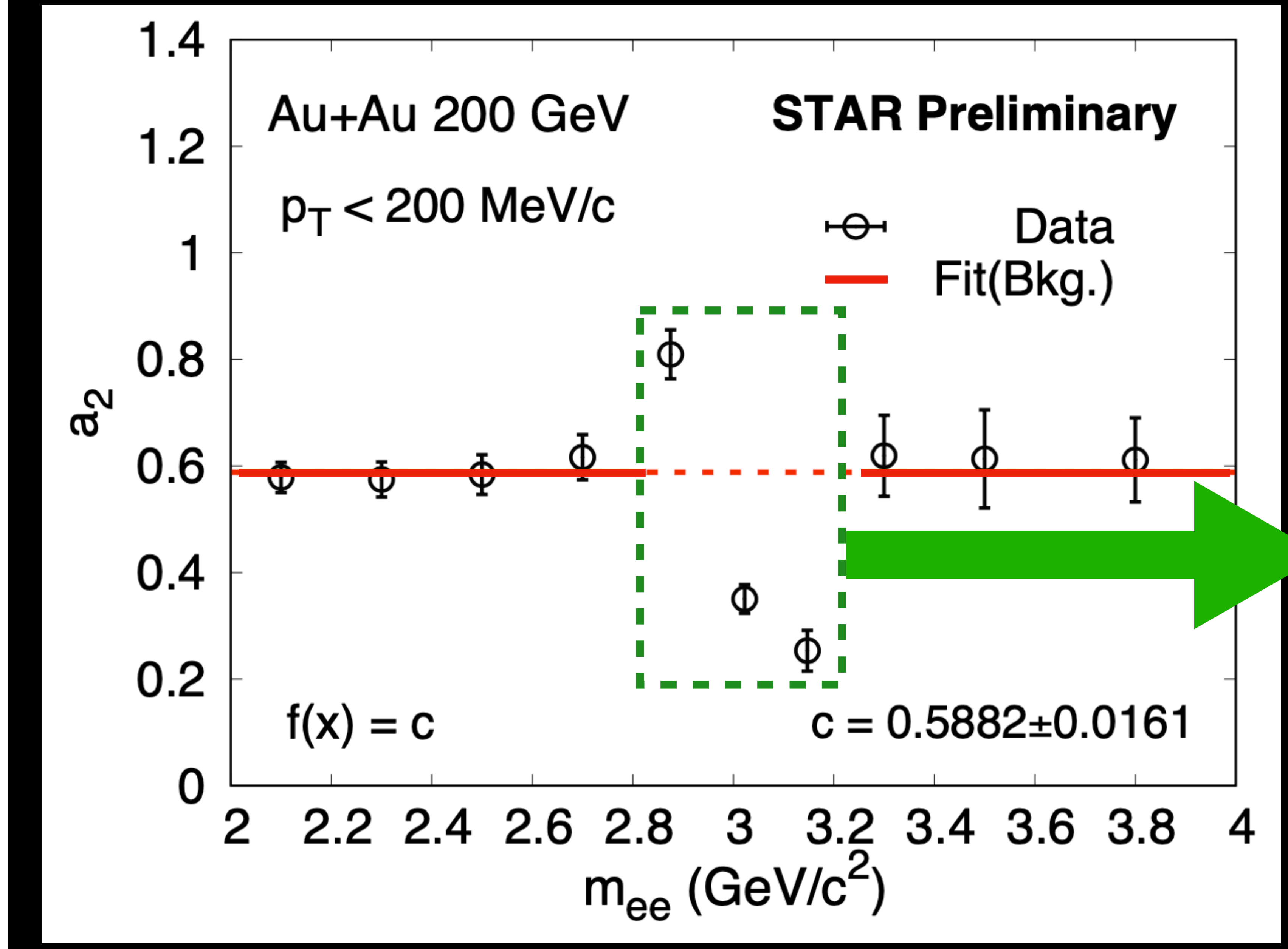
- Incoherent production compared with H1 data with free proton
- Strong nuclear suppression (~49%) seen
  (Mäntysaari et. al, Phys. Rev. Lett. **117** (2016) 5, 052301)
- Models found H1 data supports sub-nucleonic fluctuations
  (Mäntysaari et. al, Phys. Rev. D **106** (2022) 7, 074019)
- STAR data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

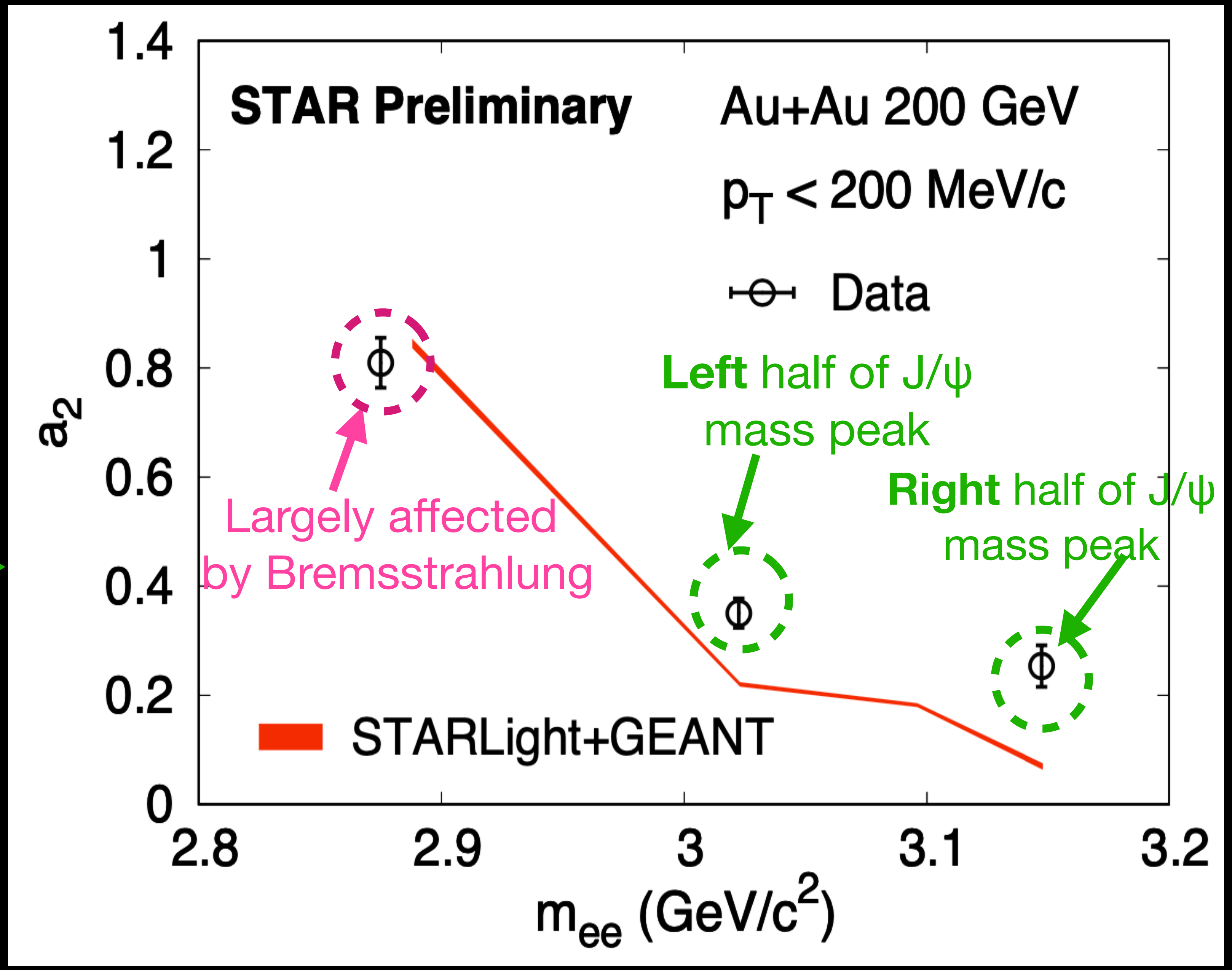
=> Strong nuclear suppression and sub-nucleonic fluctuations in Au nucleus



Corrections for interference signal







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