Supported in part by

KENT STATE UNIVERSITY

STAR

U.S. DEPARTMENT OF ENERGY | Office of Science

Exclusive J/ψ Photoproduction and Entanglement-Enabled Spin Interference in Ultra-Peripheral Collisions at STAR

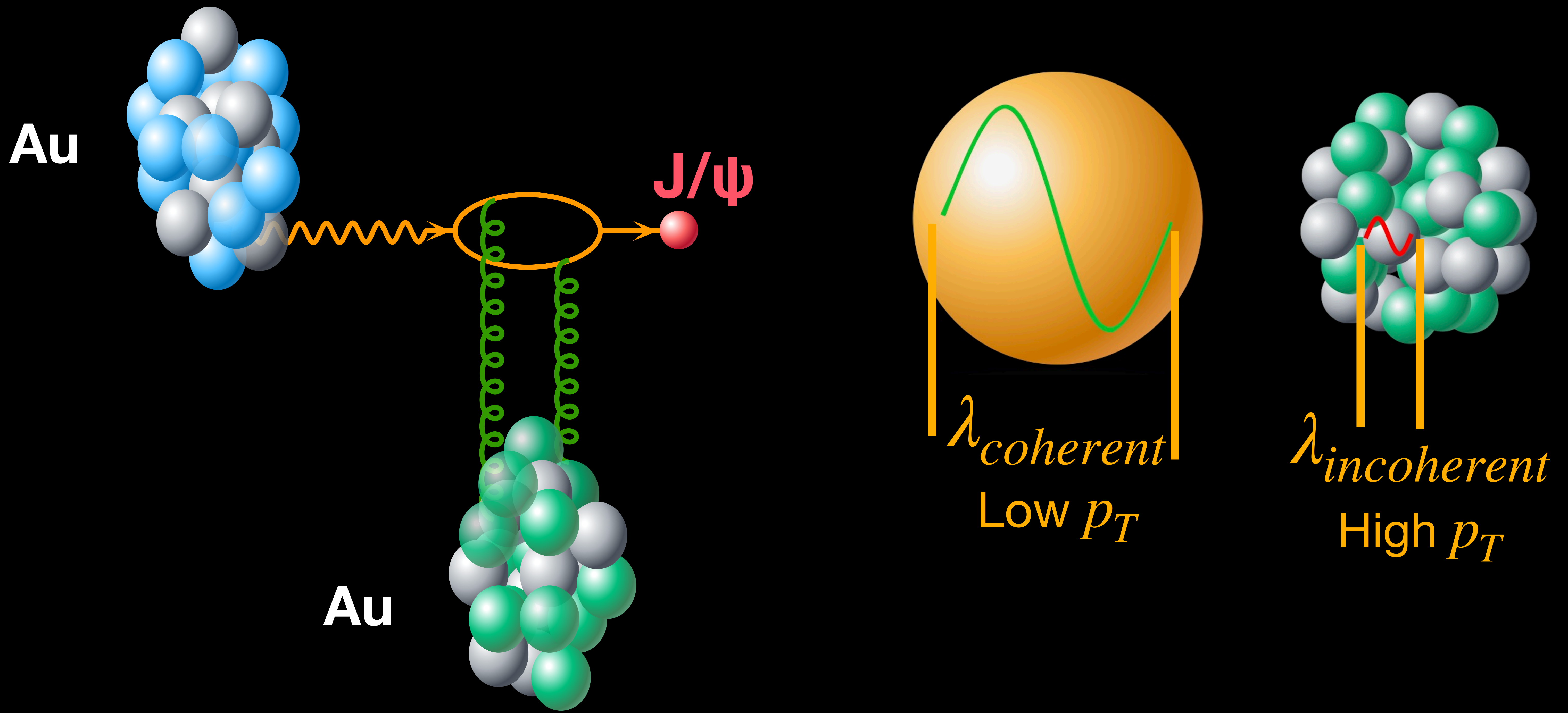
Ashik Ikbal Sheikh (for the STAR Collaboration)
Kent State University

QM 2023

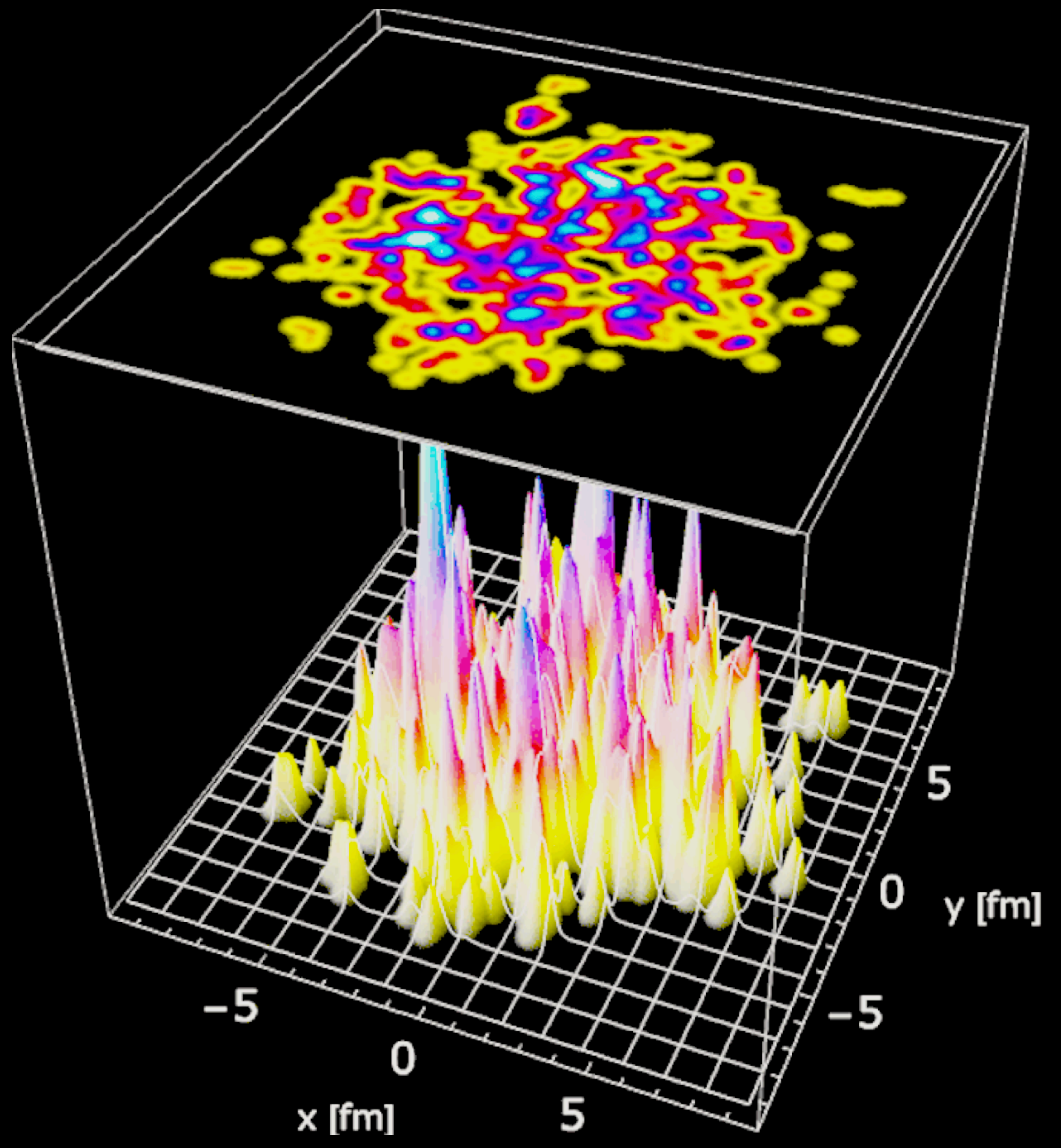
Brookhaven National Laboratory

SEPTEMBER 3-9, 2023 | HOUSTON, TEXAS |
Quark Matter 2023
The 30th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions

UPC J/ψ: powerful probe of parton densities inside nuclei



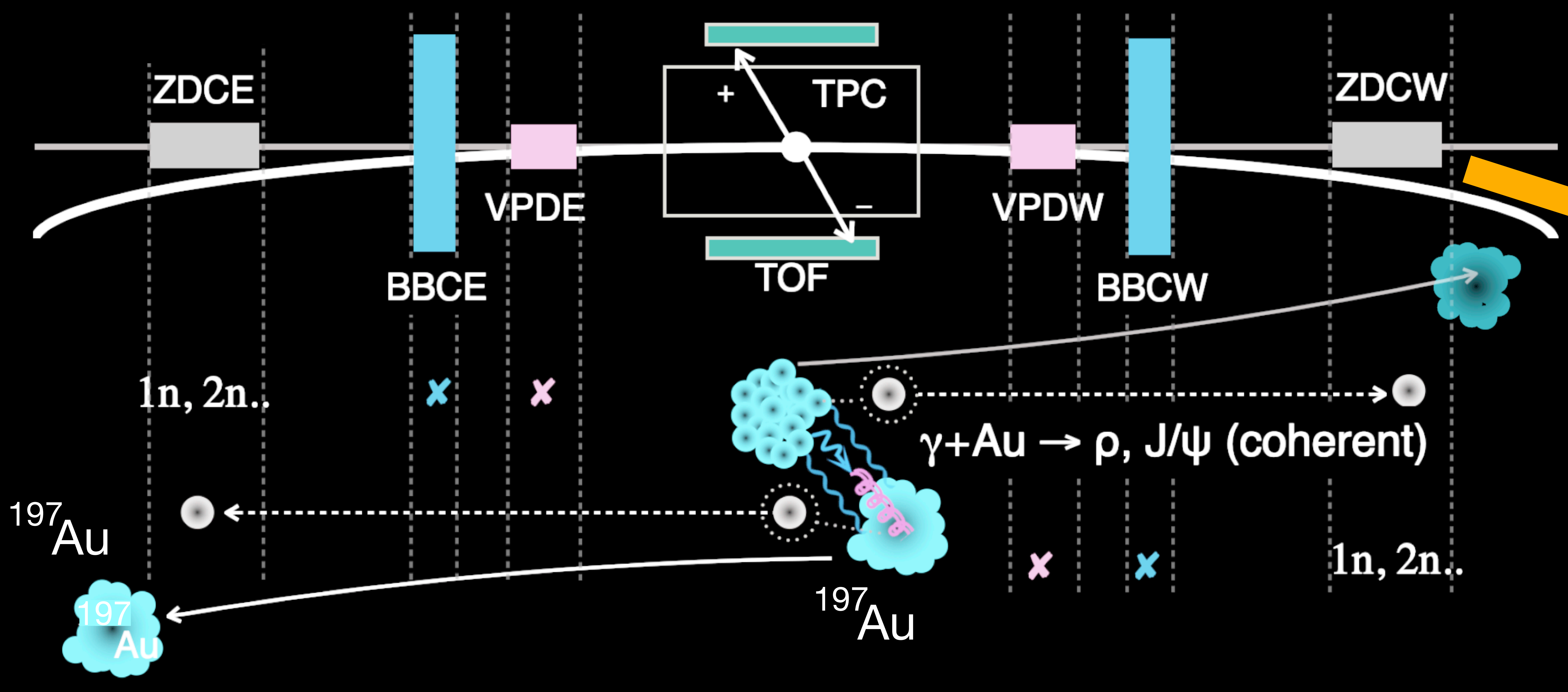
Satre simulation, Fig: A. Kumar

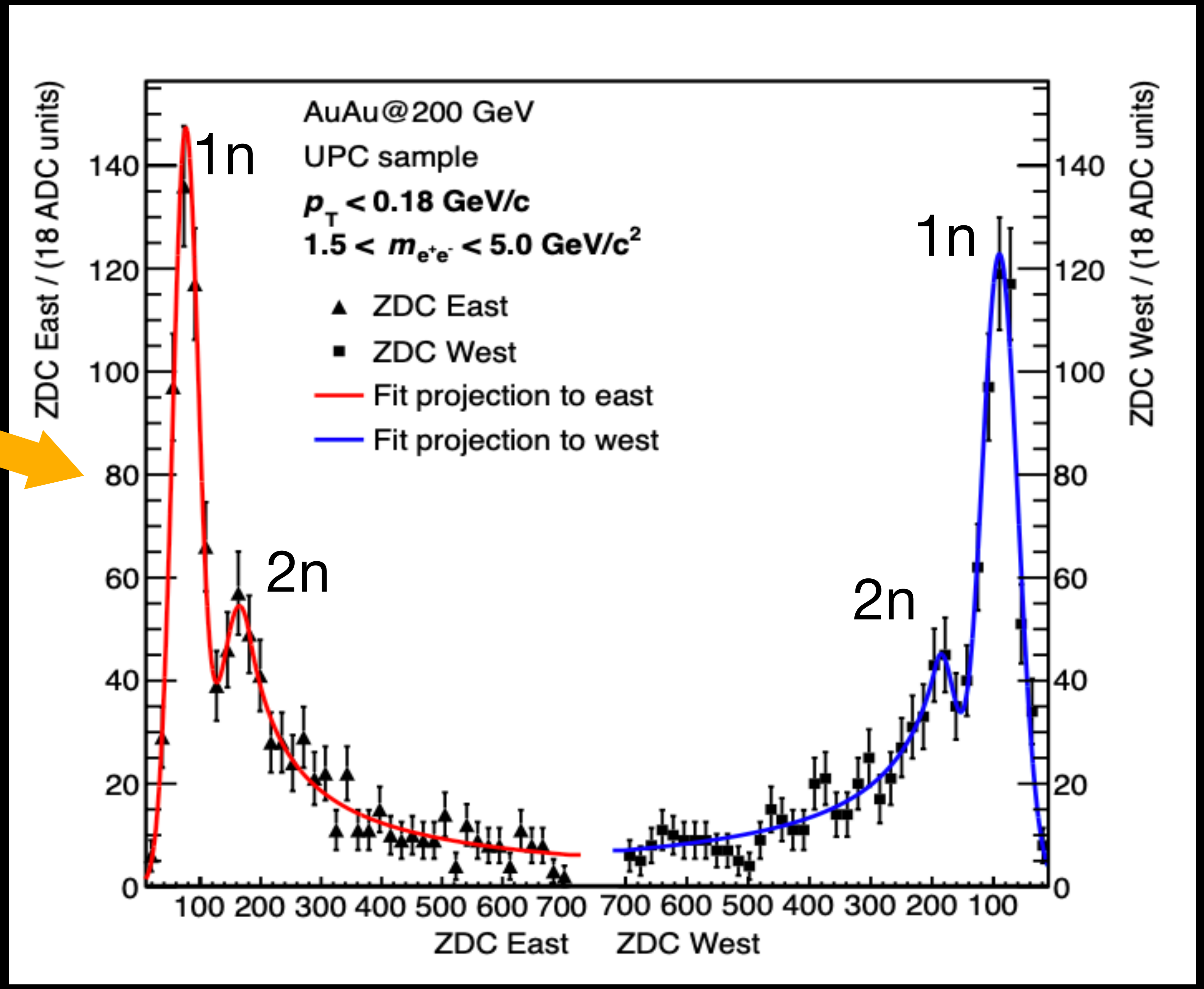


- UPC J/ψ probes parton density & fluctuations inside nuclei— constraints for A+A initial state
- Modification of parton densities in heavy nuclei - informative toward day-1 EIC science

=> J/ψ in UPCs helps to probe parton density inside nuclei before EIC era

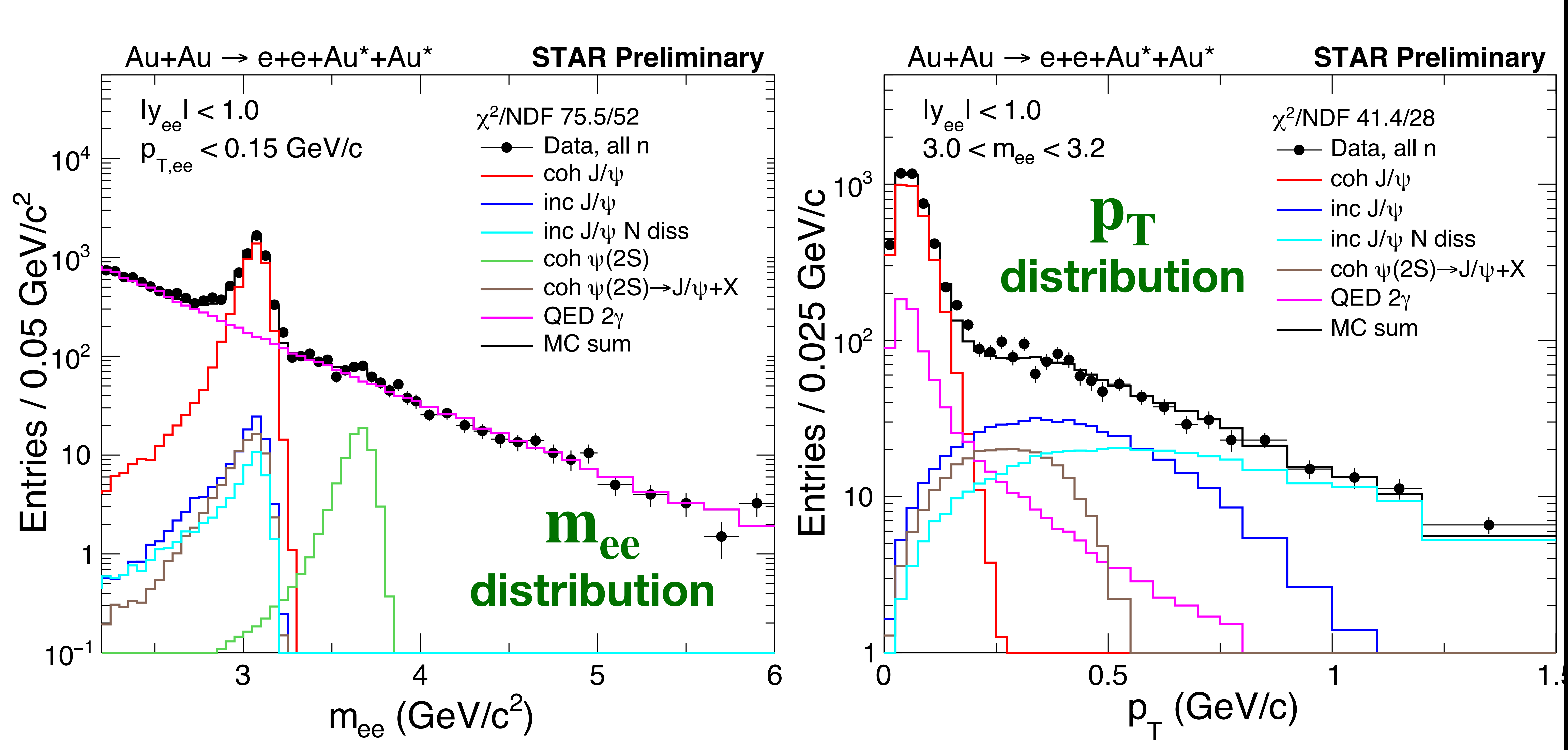
UPC events with STAR detector





- ◉ Both nuclei get excited and emit neutrons in beam direction
- ◉ Neutron(s) detected in ZDCs
- ◉ ZDC signals show peak structure for neutrons =>Way to trigger UPC events
- ◉ Two tracks of opposite charges in TPC
- ◉ No activity in both BBCs => Diffractive events (η-gap)

J/ψ measurements in 200 GeV Au+Au UPCs



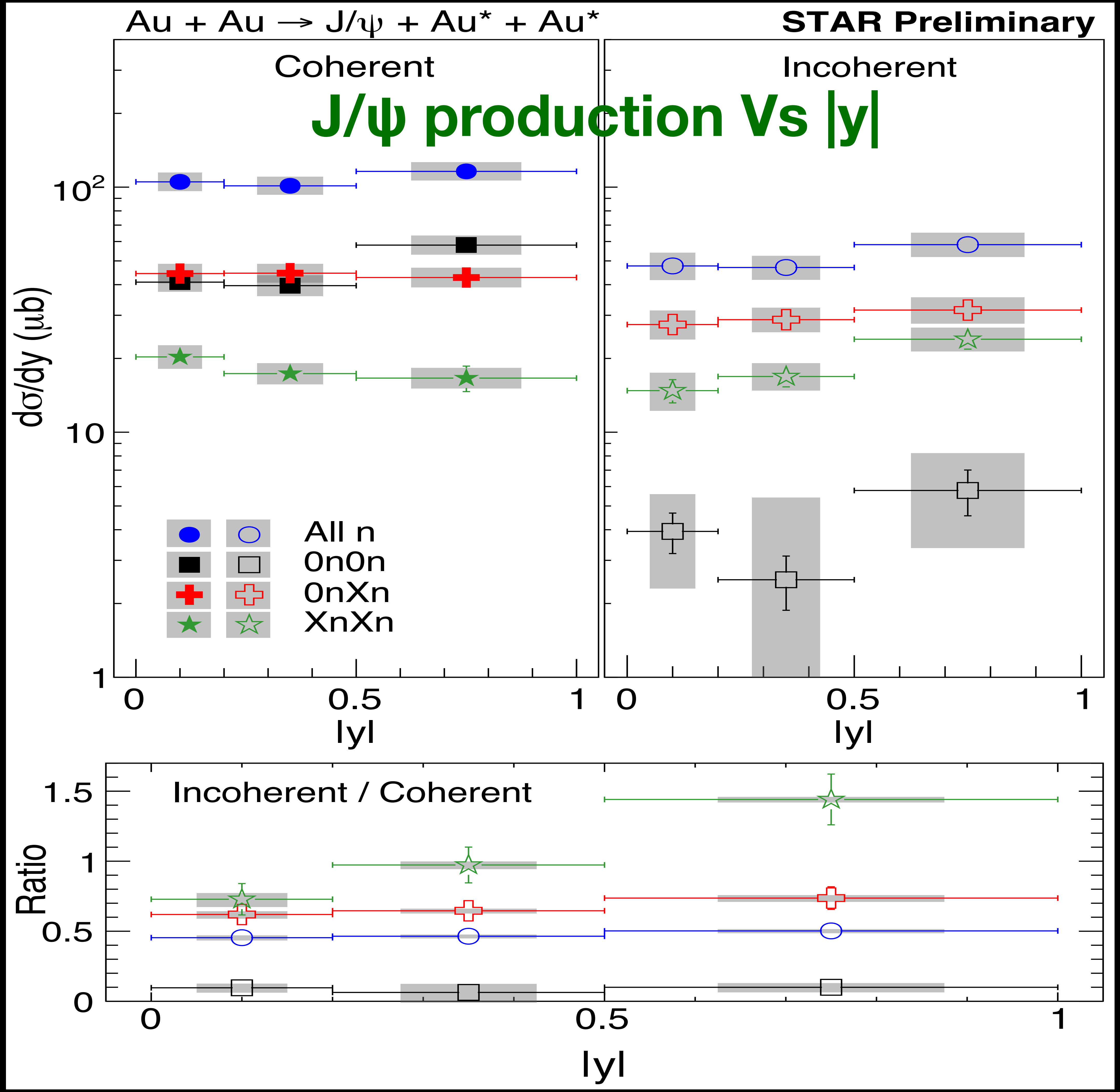
- Measured $J/\psi \to e^+e^-$ within $|y| < 1$
- MC templates from STARLight describe the signal and backgrounds
- Low p_T => coherent dominated
- High p_T => incoherent dominated

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

Rapidity dependence J/ψ production cross-section

- Rapidity dependent cross-section is 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

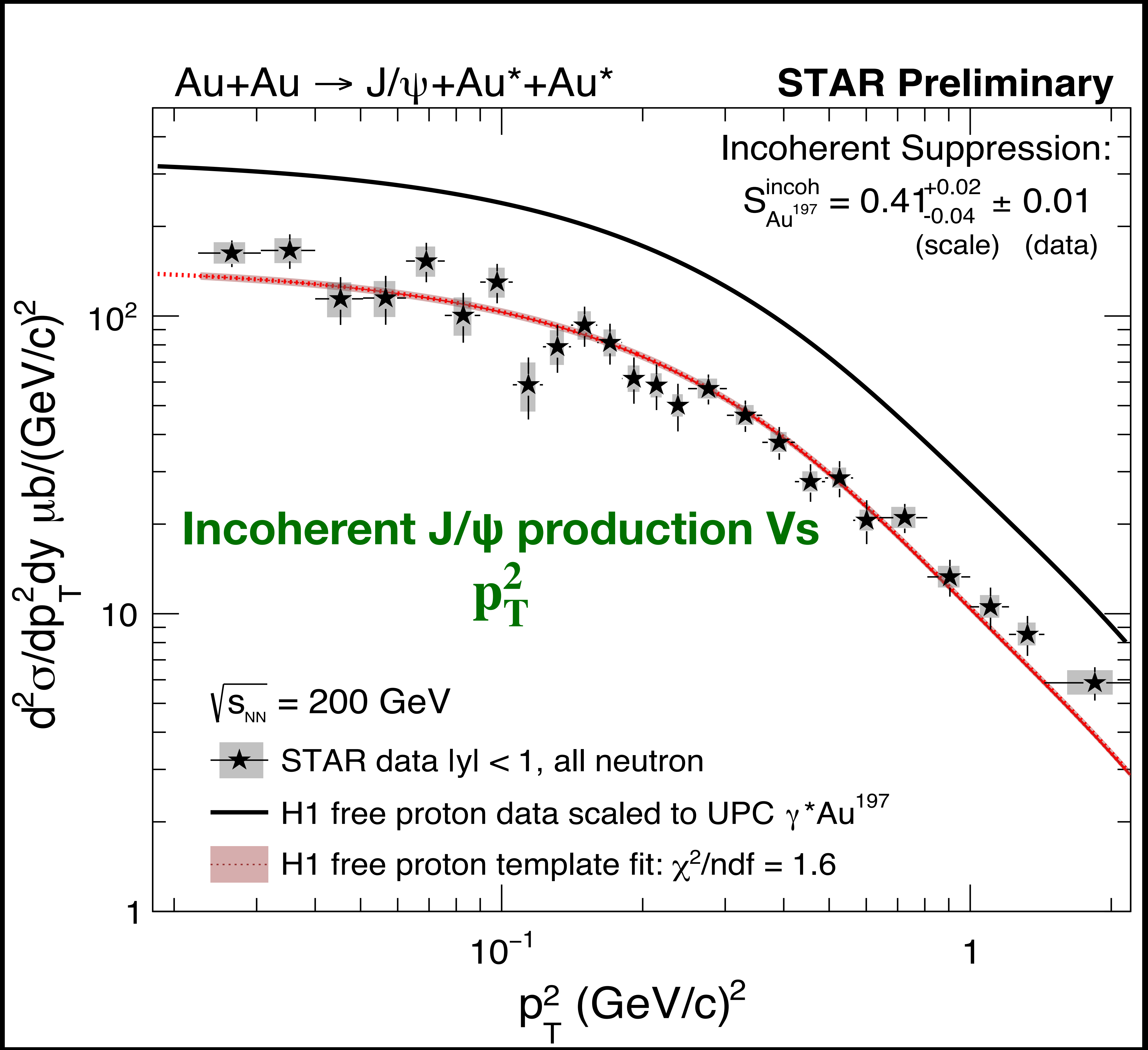
=> Important to constrain theoretical models related to nuclear geometry



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

- Incoherent production compared with H1 data with free proton
- Strong nuclear suppression seen for both coherent (~40%) and incoherent (~60%) production (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

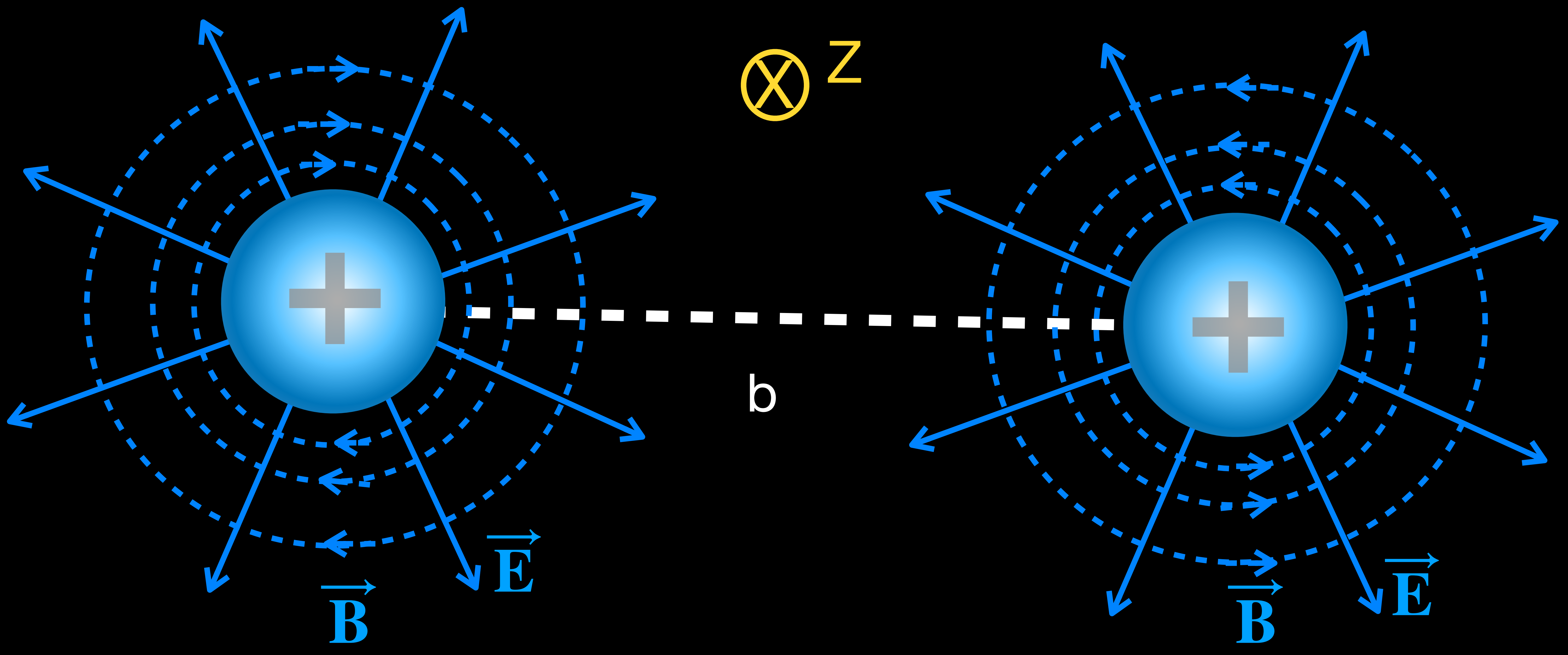
=> Strong nuclear suppression and sub-nucleonic fluctuations in Au nucleus



Entanglement-enabled spin interference of UPC J/ψ

Polarized Photons from colliding nuclei

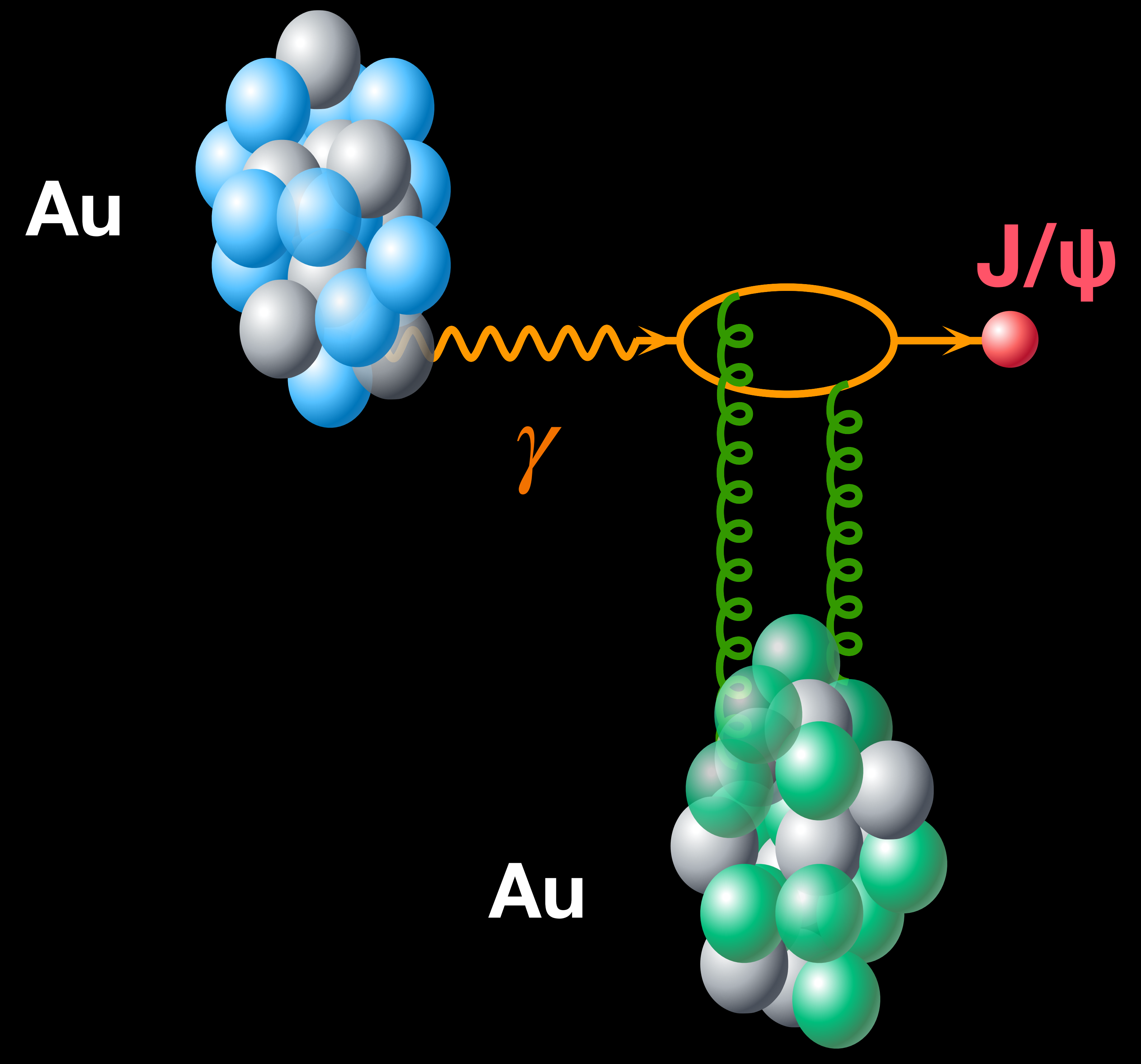
- Lorentz boosted nuclei produce strong EM fields
- E-field points radially outward and B-field circulating in the azimuthal direction
- Quantized as a flux of quasi-real photons — Linearly polarized



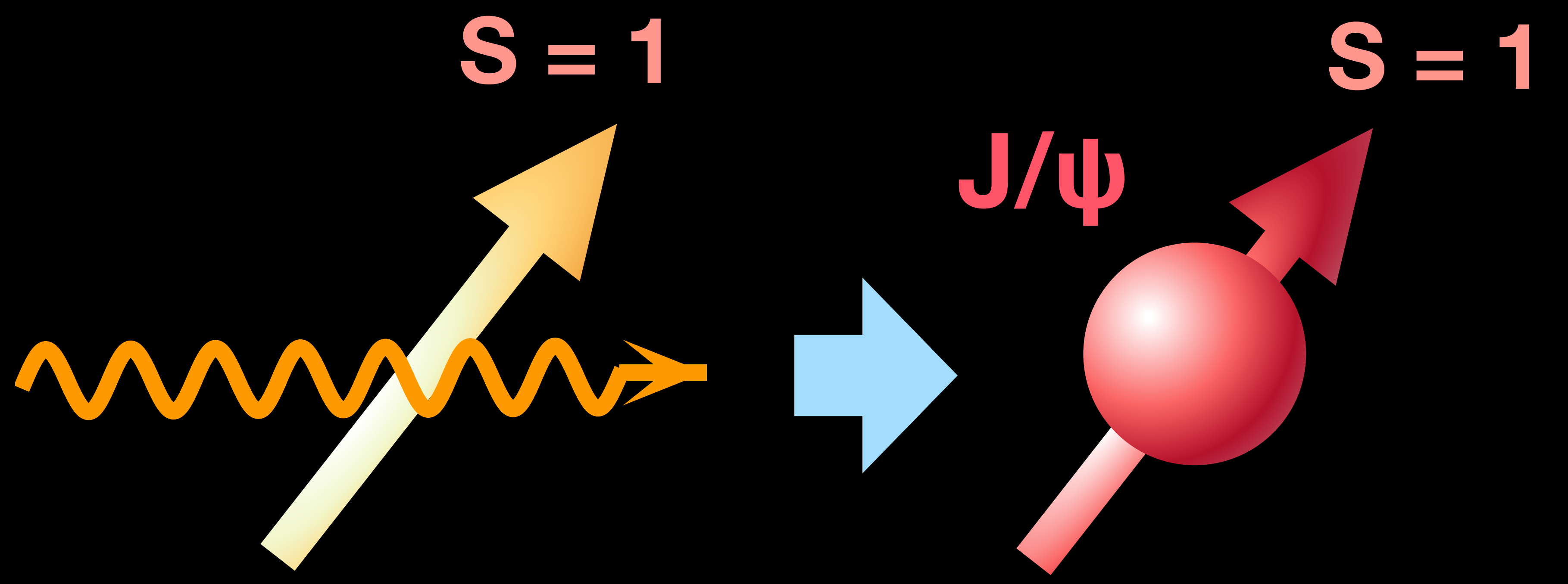
Transverse view of Lorentz contracted nuclei

=> Photons in UPC are linearly polarized

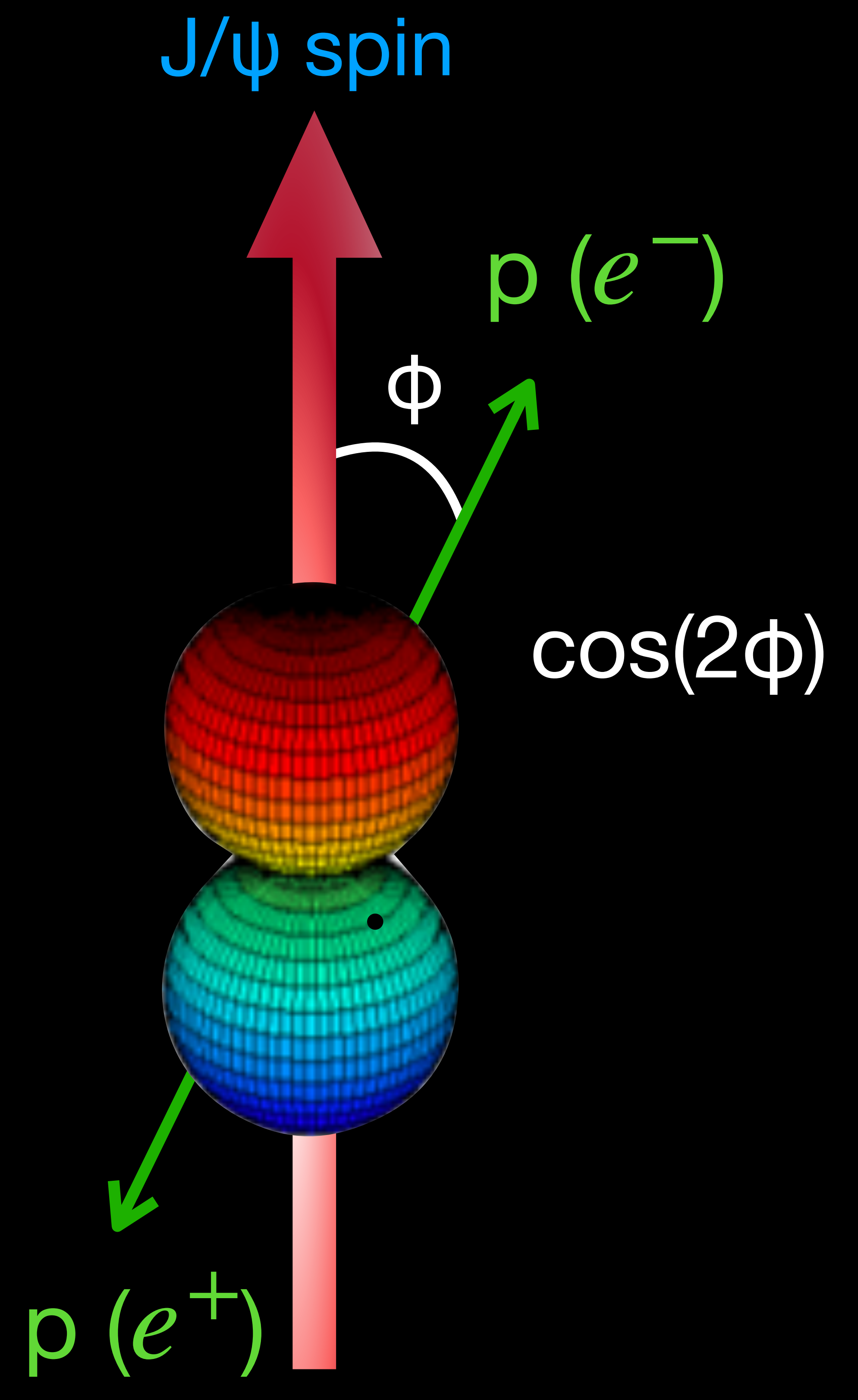
J/ψ spin and decay daughter correlations in UPCs



Photoproduction of J/ψ
occurs in UPCs



Polarization of photon
→ Polarization of J/ψ

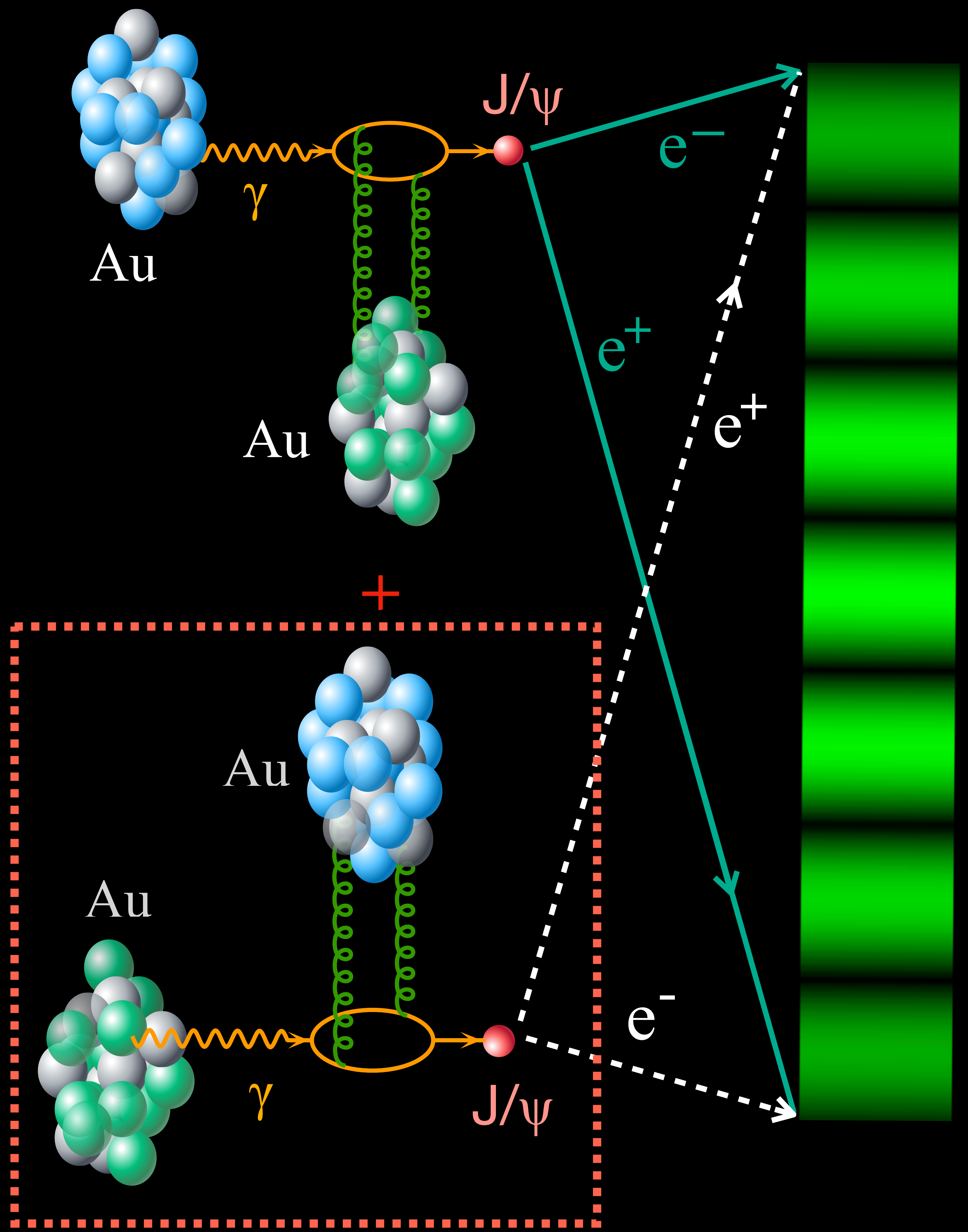


Decay $J/\psi \to e^- e^+$
Leads to cos(2ϕ) pattern
(L+S conservation)

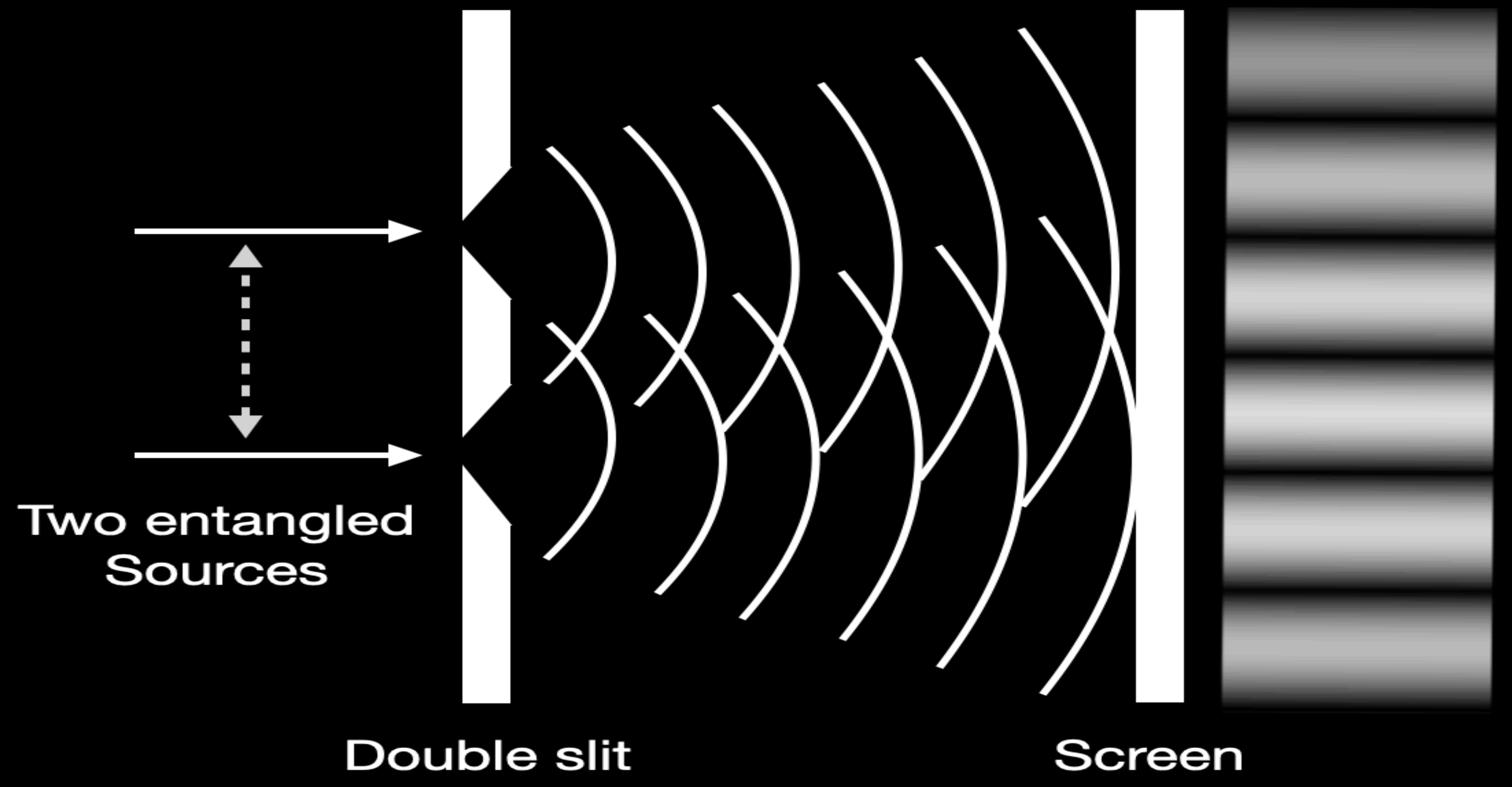
=> J/ψ are photoproduced in UPCs and decay electrons are correlated

Spin interference effect with J/ψ

Klein et. al, Phys. Rev. Lett. **84**, 2330 (2000)
Brandenburg et. al, Phys. Rev. D 106, 074008 (2022)



- Polarization direction changes event-by-event => <cos(2ϕ)> vanishes over many events
- Two ways for J/ψ photoproduction— the two wave functions are created independently
- Wave functions locked in phase through phase entanglement of initial γ and Pomeron
- Entanglement makes sure to observe the interference => (cos(2ϕ)) pattern survives
- Analogy: Double slit experiment with two entangled sources



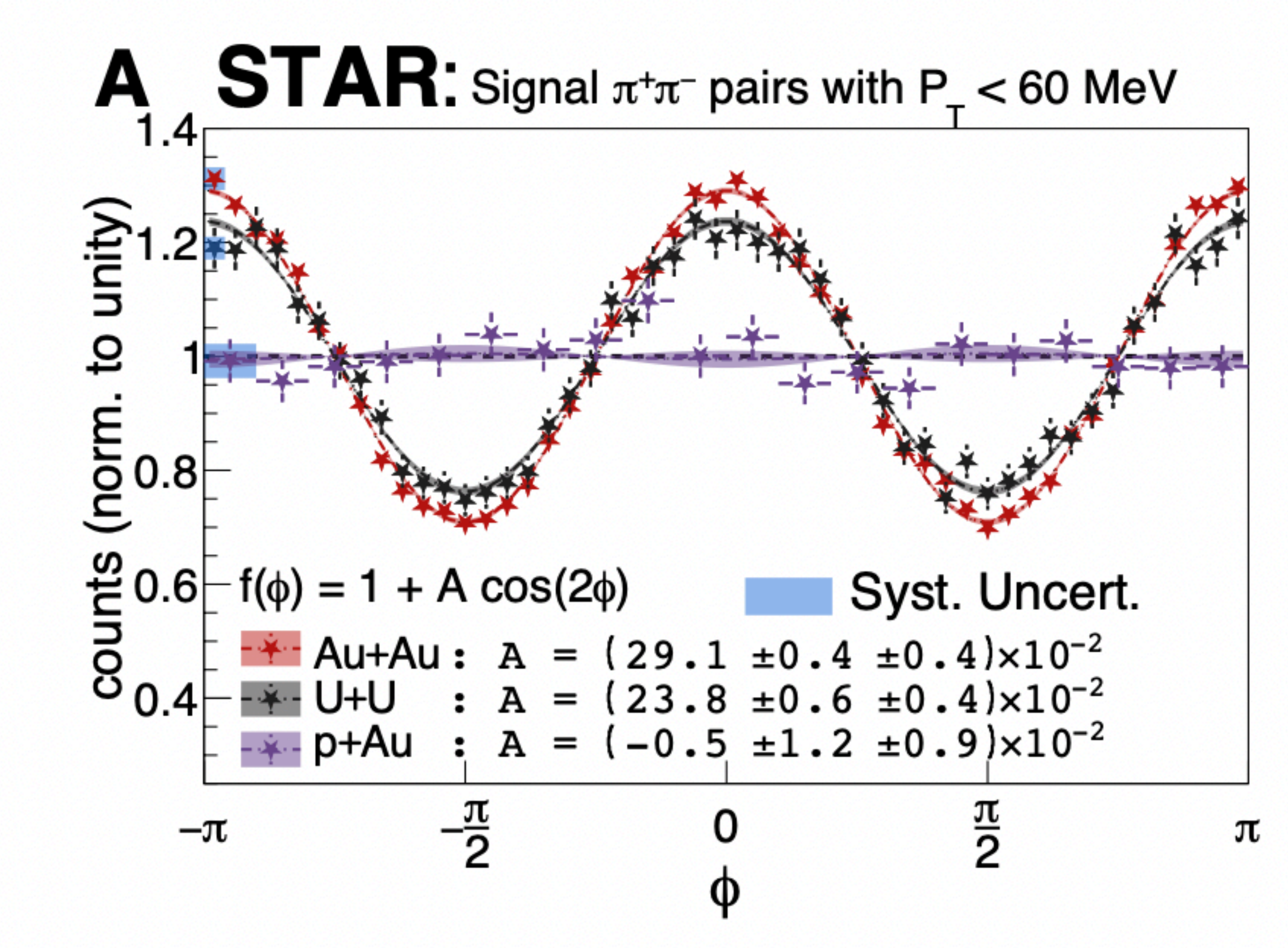
=> Entanglement ensures the spin interference in J/ψ photoproduction

New insight on spin interference effect with J/ψ

- STAR observed the entanglement-enabled spin interference effect with UPC ρ^0

- $\rho^0 \rightarrow \pi^+\pi^-$: short lifetime (1 fm), localized wave function << b — interference occurs in the daughter pions (spin 0) level

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



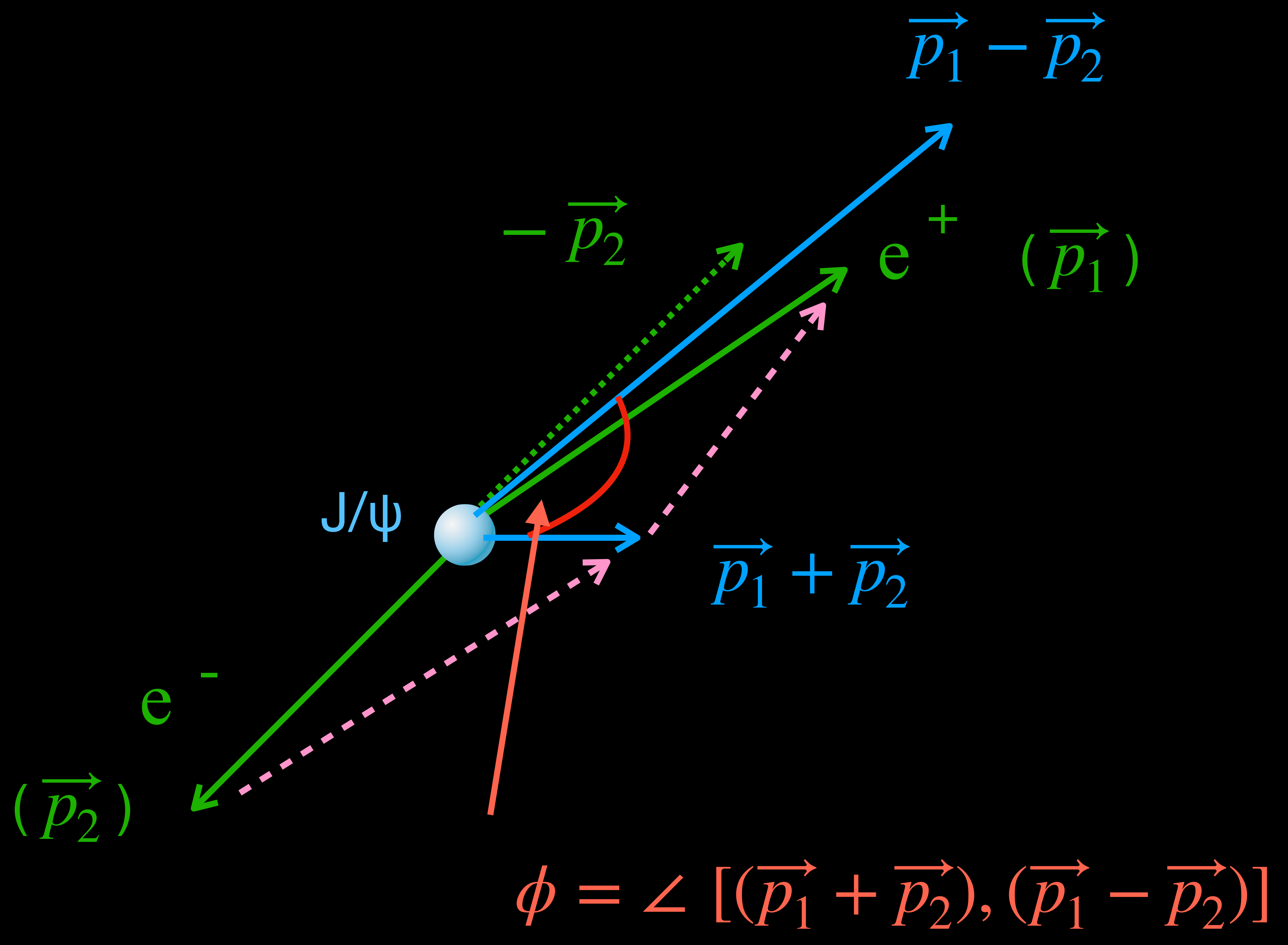
- J/ψ has longer lifetime, extended wave function

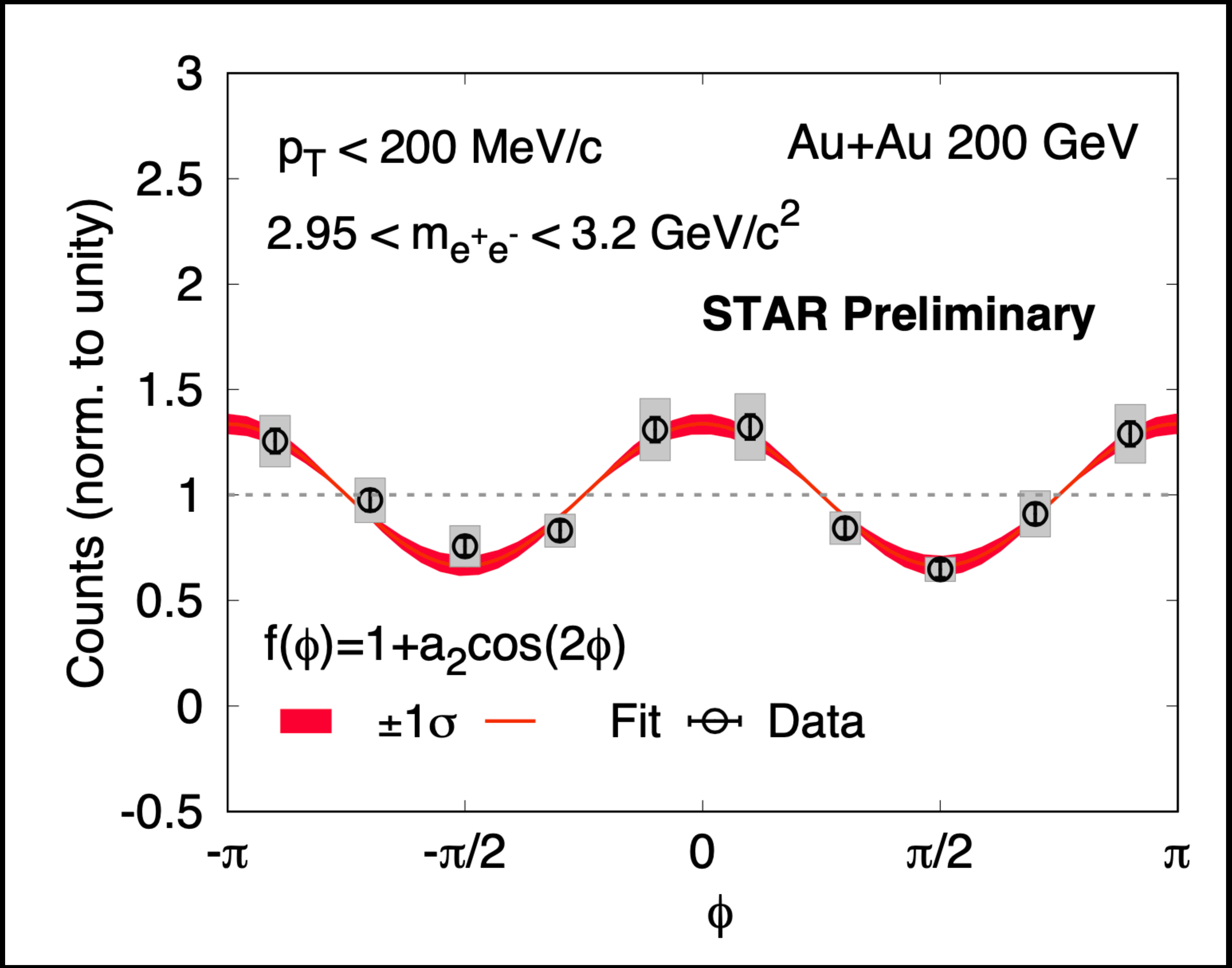
- J/ψ decay daughters, electrons (spin 1/2) are fermions, $J/\psi \rightarrow e^+e^-$

- Measurements of the spin interference with J/ψ will bring more info

=> J/ψ spin interference is an opportunity to study new physics in this domain

Spin interference of J/ψ





◉ Measured the raw cos(2ϕ) modulations for J/Ψ ($2.95 < m_{ee} < 3.2$ GeV) with p_T < 200 MeV/c

◉ The cos(2ϕ) modulation strength obtained from fit: $1 + a_2 \cos(2\phi)$ => a_2 is the measure of the modulation

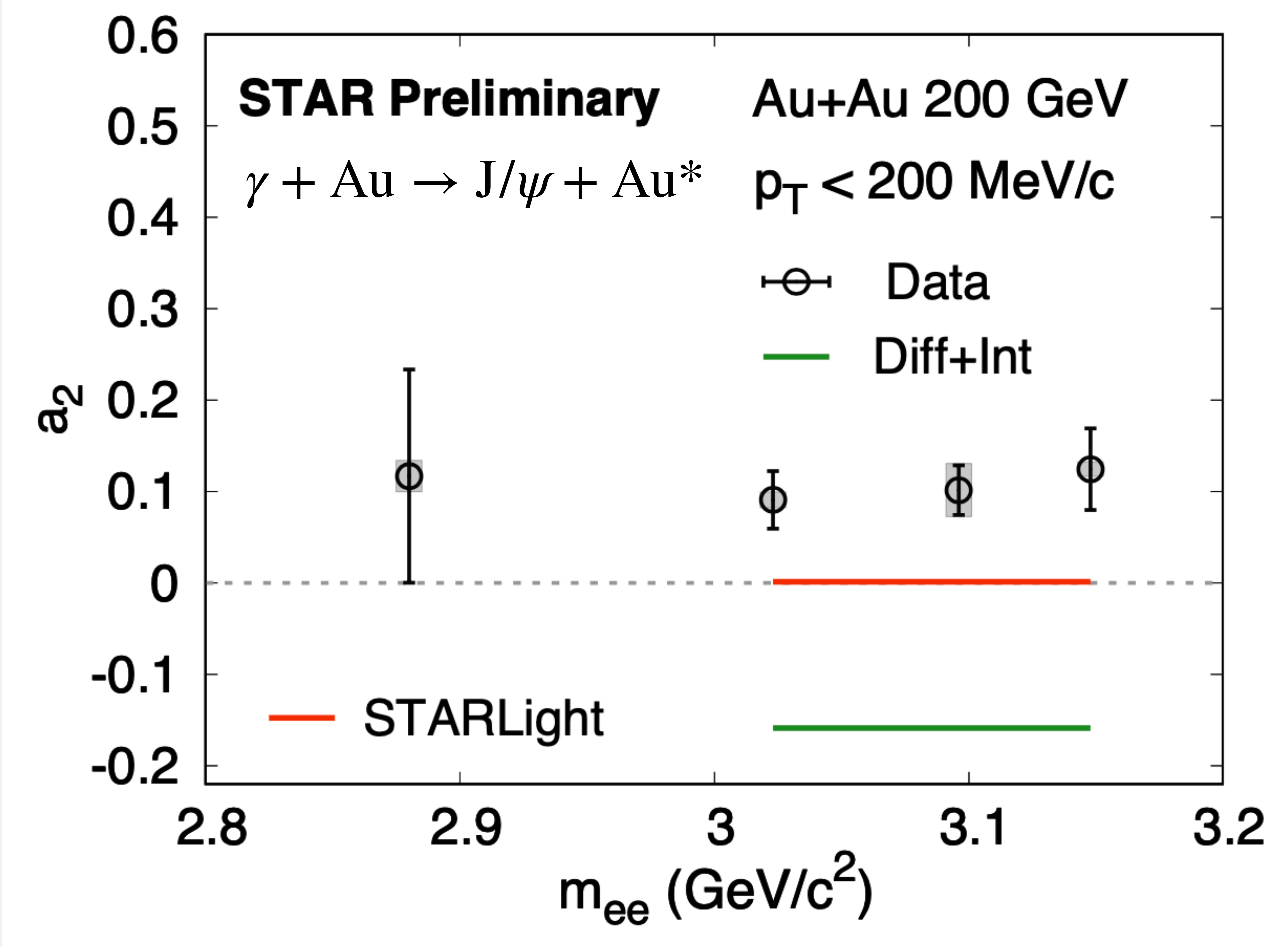
=> Cos(2ϕ) modulation is present in the raw data — Need to extract the modulation strength

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 for true modulation signal

Signal for J/ψ Spin interference



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

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

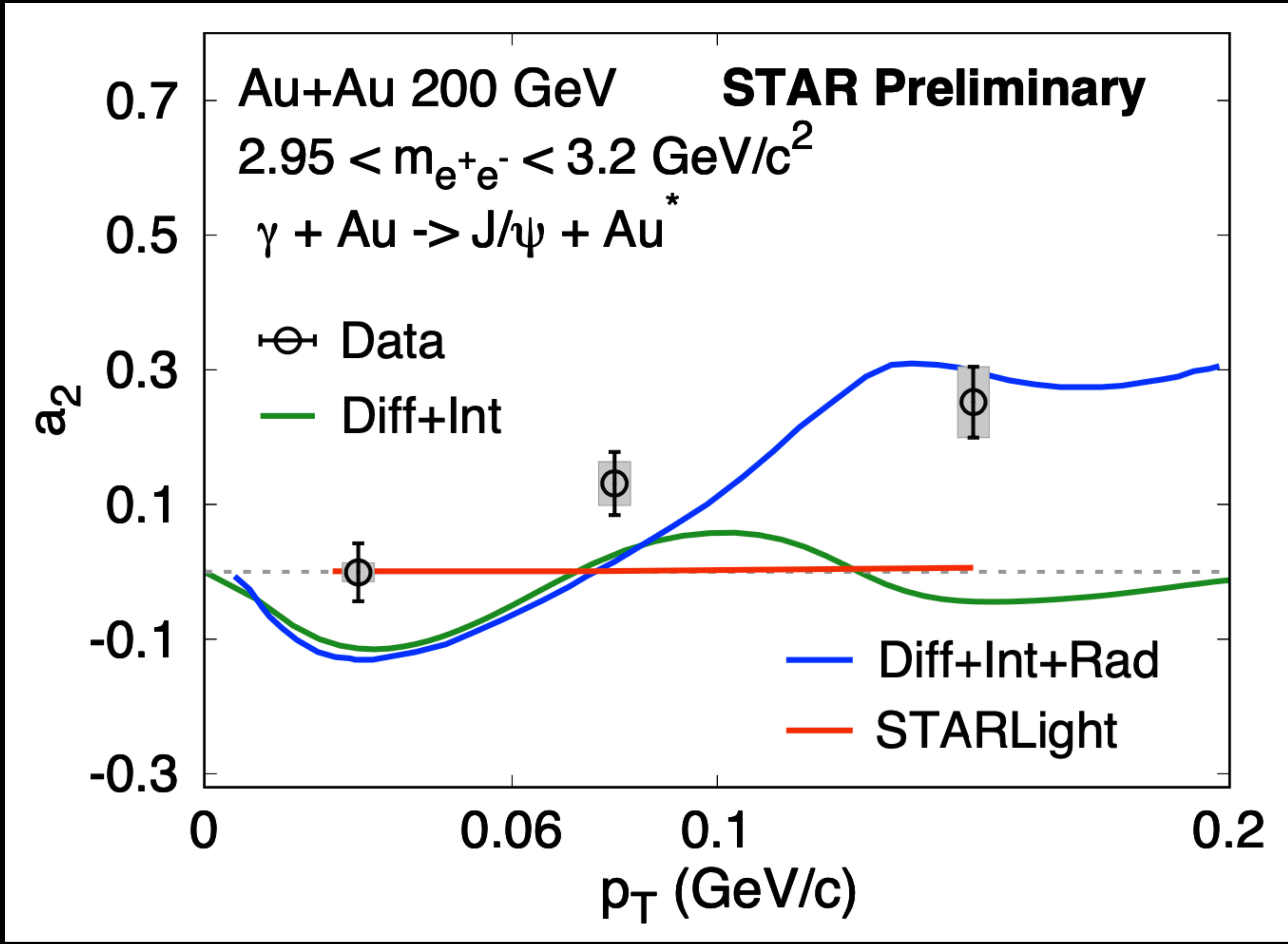
- Measurement has ~3σ significance above zero
- Compared with STARLight and theory calculations
- STARLight has no spin interference physics — consistent with zero
- Theory (Diffractive+Interference) predicts negative modulation

Theory predictions : W.B. Zhao et al. (private communication) & arXiv:2207.03712

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

The p_T-dependent interference of J/ψ

- Measured interference signal shows strong p_T dependence and rises toward positive
- STARLight prediction is consistent with zero
- Diffractive+interference calculations have the negative value and increase with p_T
- Diffractive+interference with additional γ radiation predicts negative at low p_T and rises towards positive value at higher p_T

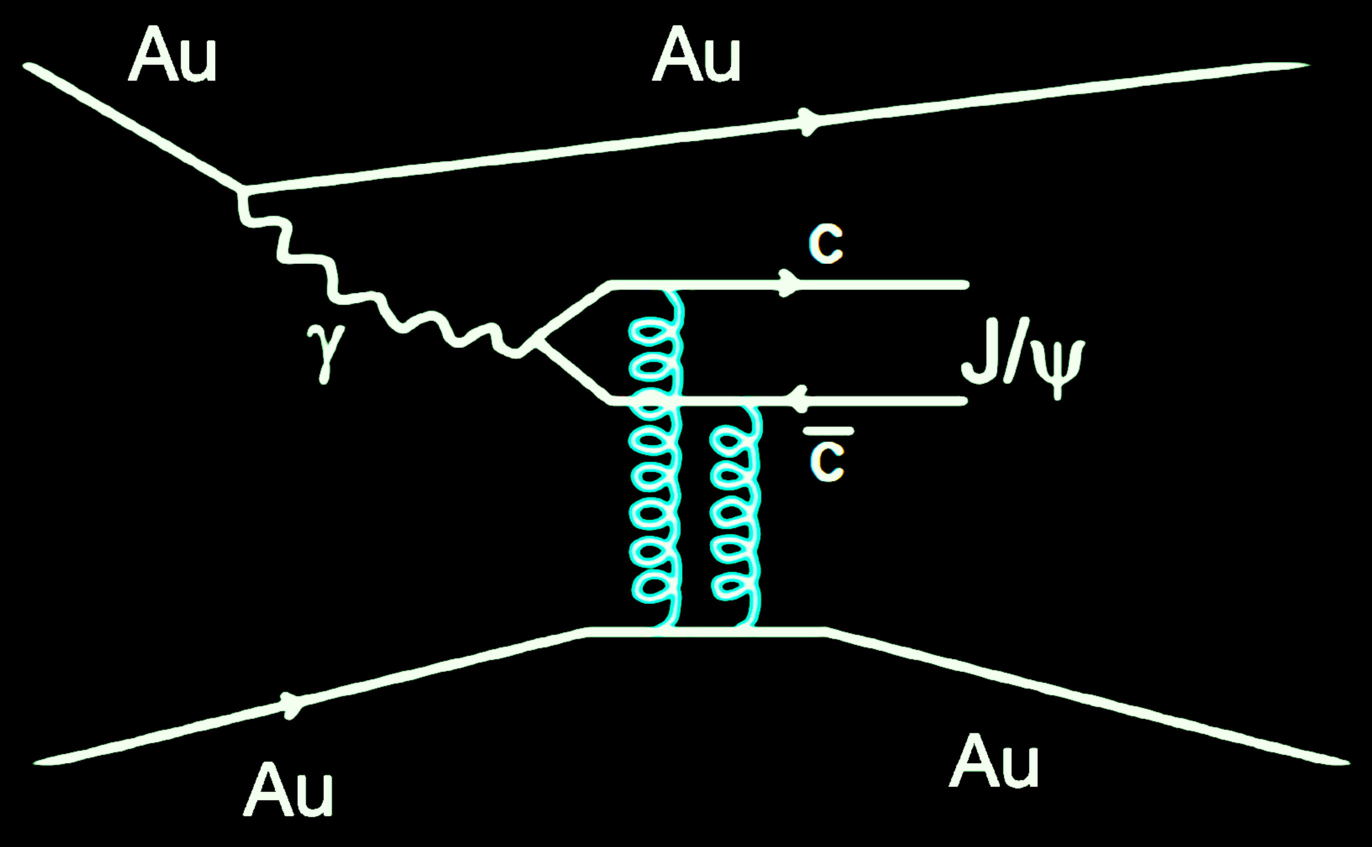


Diff+Int predictions : W.B. Zhao et al. (private communication) & arXiv:2207.03712
Diff+Int+Rad predictions : Brandenburg et. al, Phys. Rev. D 106, 074008 (2022)

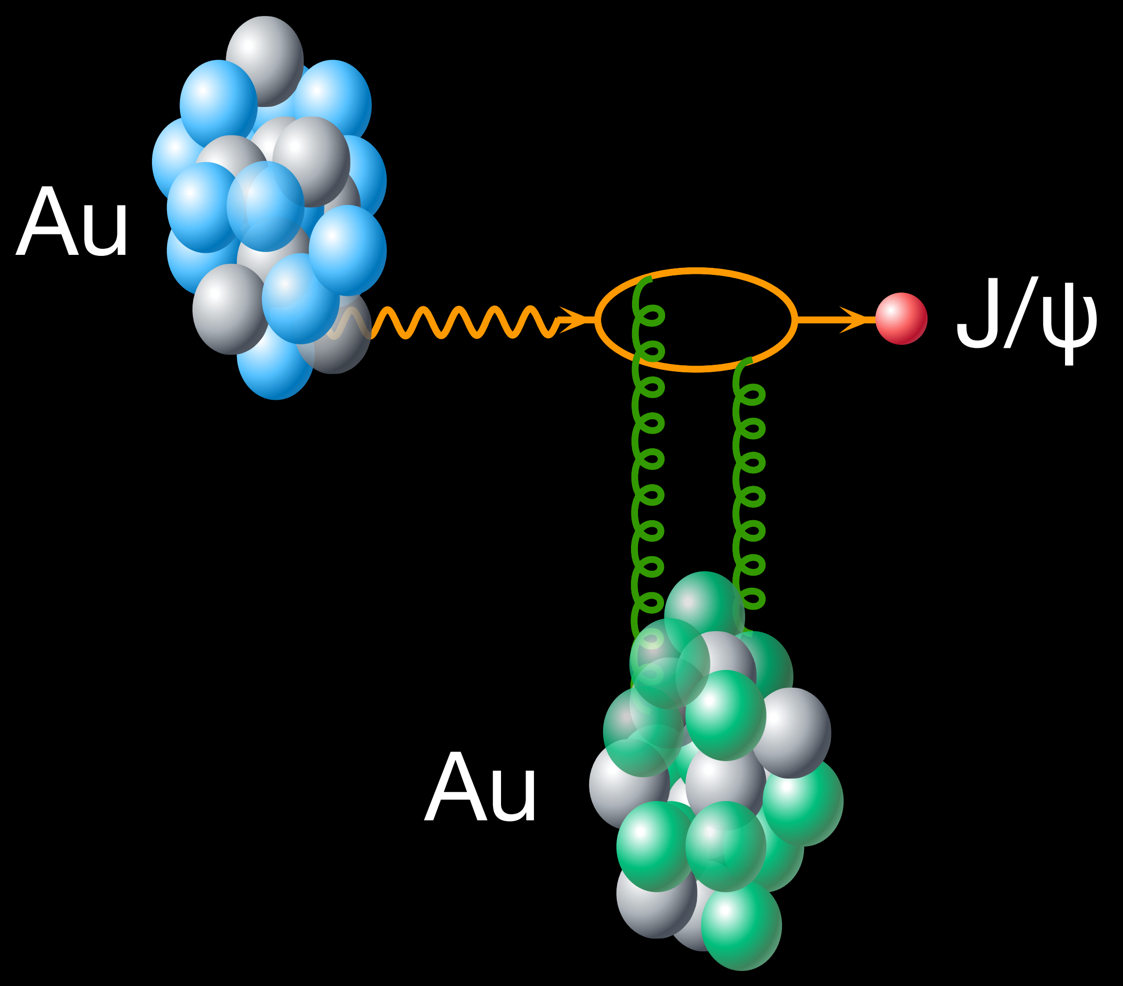
=> Modulation strength positively increases with p_T

Summary and take home

- Measured separately the coherent and incoherent J/ψ p_T distributions in Au+Au UPCs
- STAR observed the spin interference of the photoproduced 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

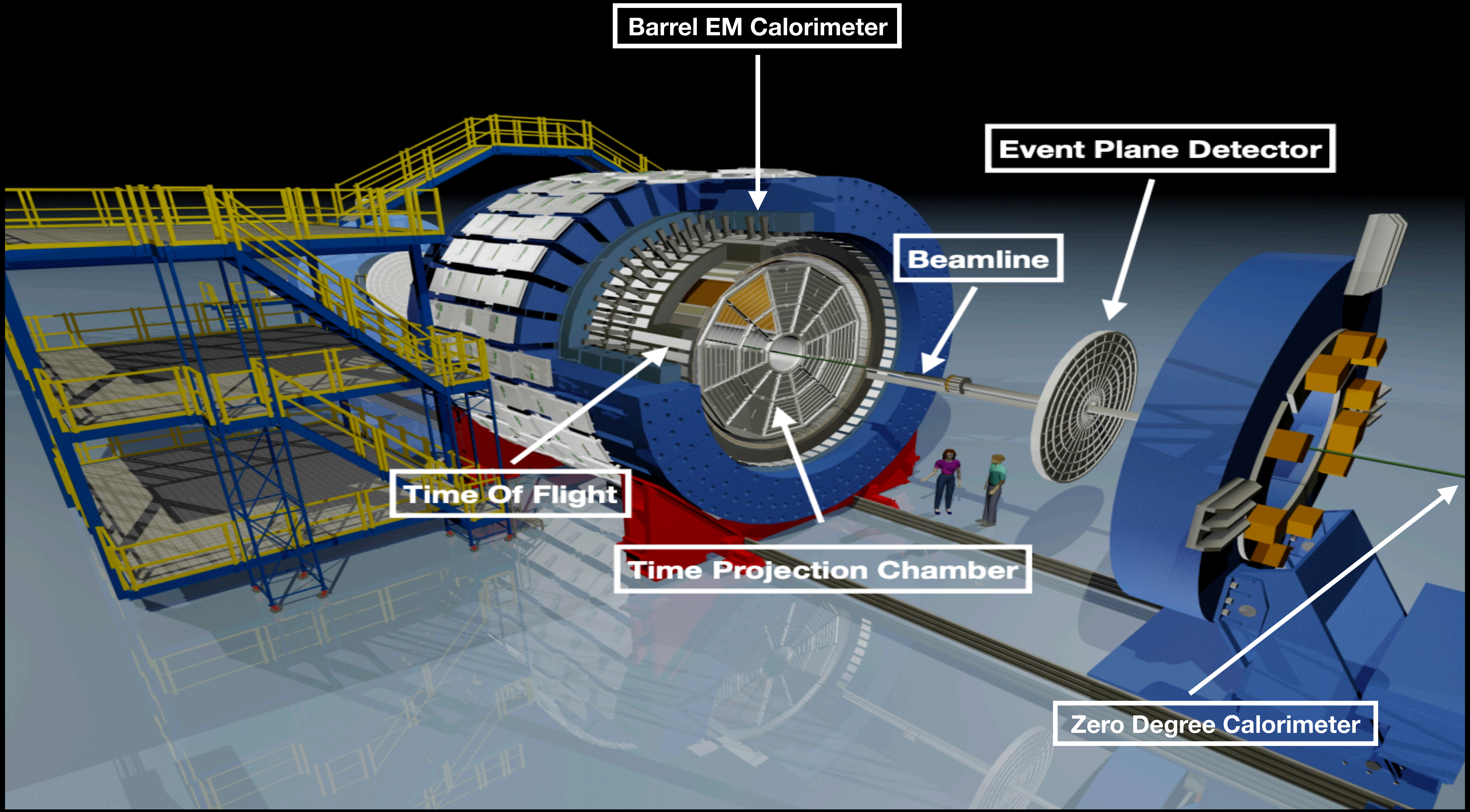


Thank You



Backup

STAR detector



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