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

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Brookhaven National Laboratory

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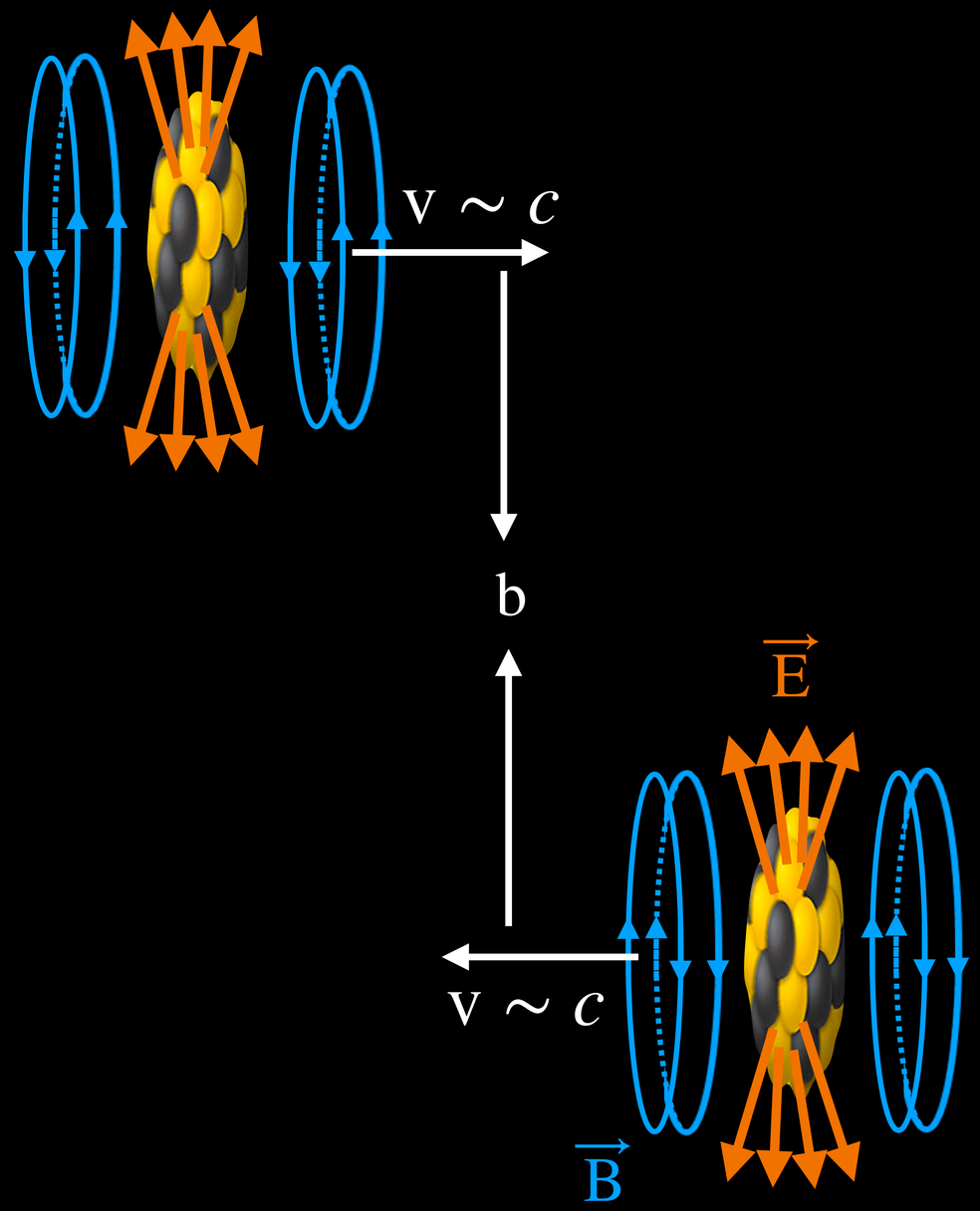
The strongest EM-fields in UPCs



- 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

- In UPCs, relativistic nuclei pass with large distance, and EM-field treated in terms of quasi-real photons

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

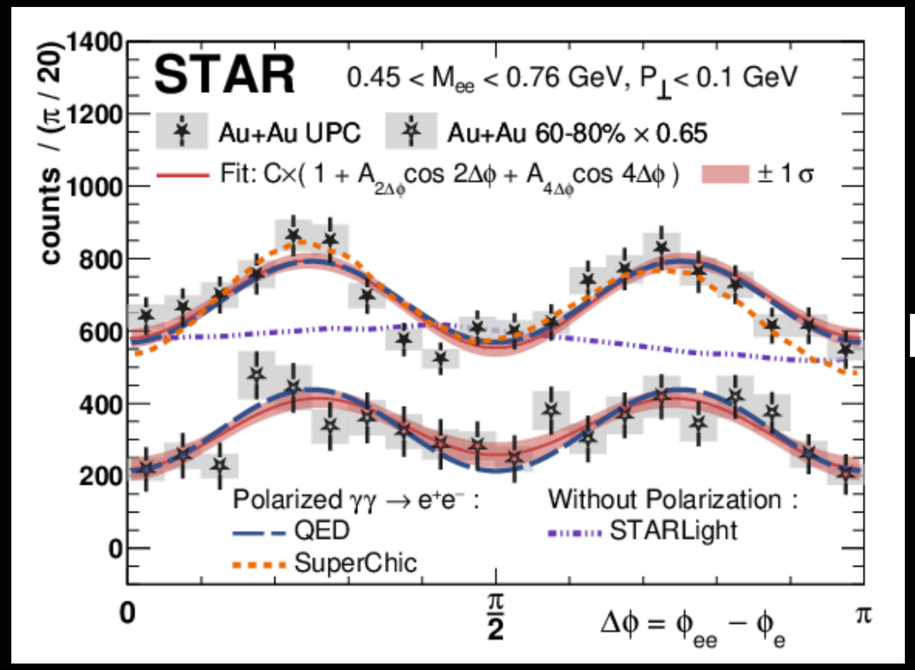
$E_{\gamma,max} \sim 3$ GeV (RHIC)

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

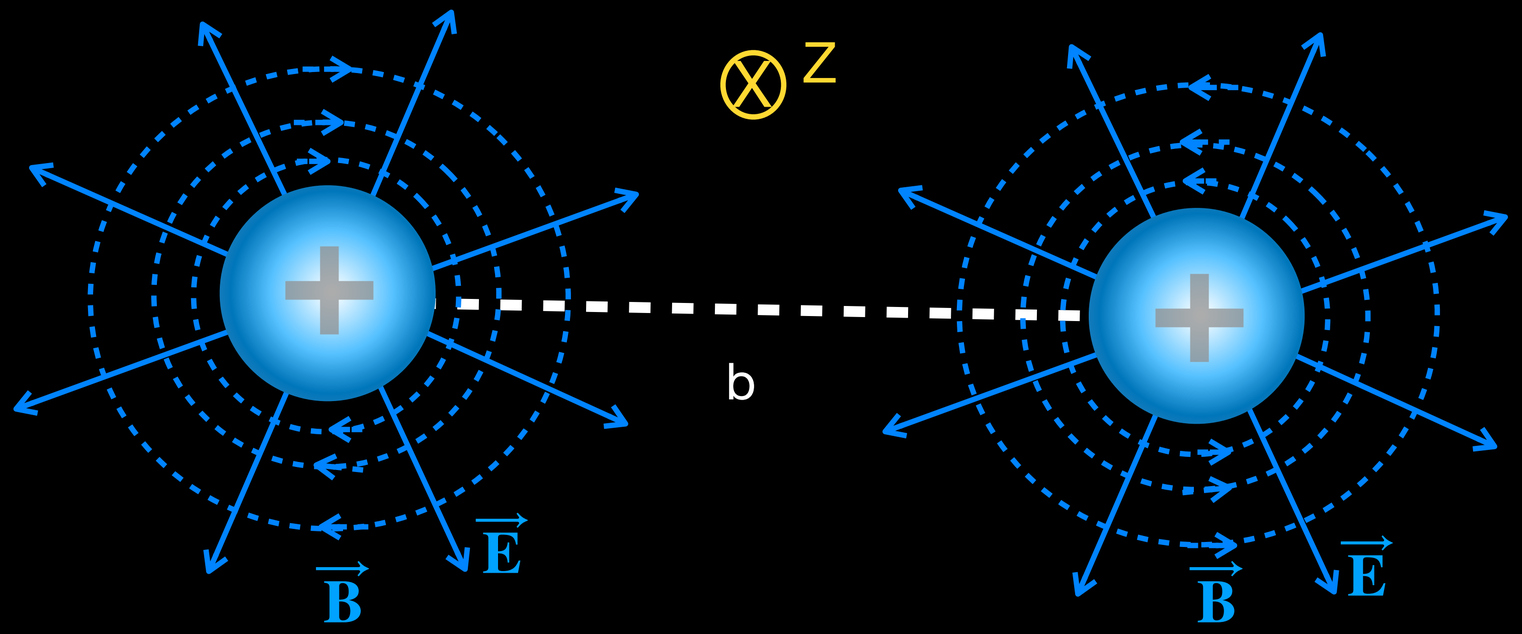
=> EM-fields are quantized as photons in UPCs

UPC photons are polarized

- The EM-fields are highly Lorentz contracted
- E-field points radially outward and B-field circulating
- Quantized photons are polarized and polarization vector is radially outward along the emitting source



Transverse view of Lorentz contracted nuclei

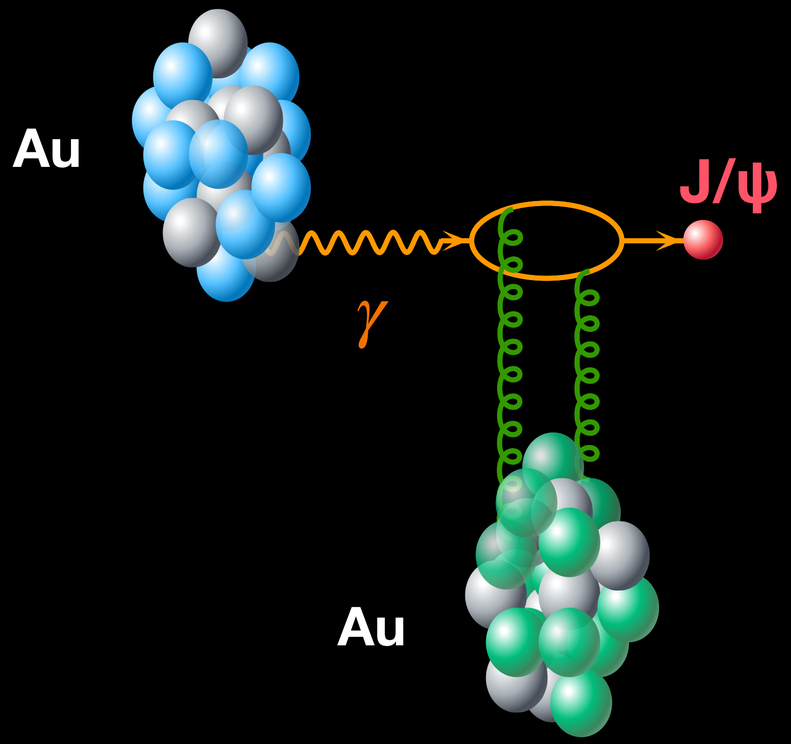


Experimental access to photon polarization demonstrated by STAR, measuring the Breit-Wheeler process, $\gamma\gamma \rightarrow e^+e^-$

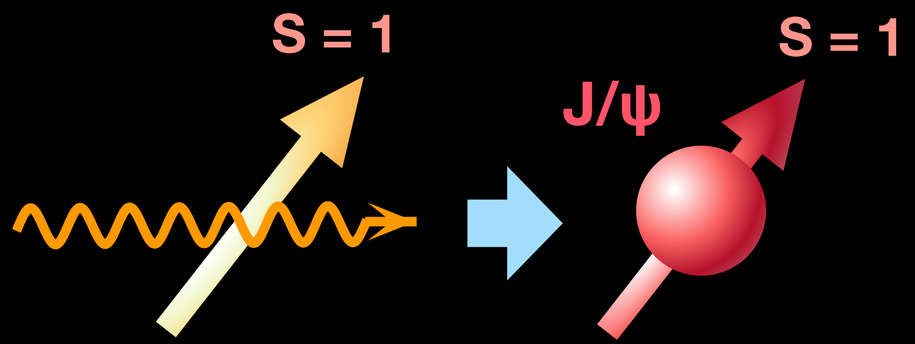
=> Photons are polarized and experimentally confirmed by STAR

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

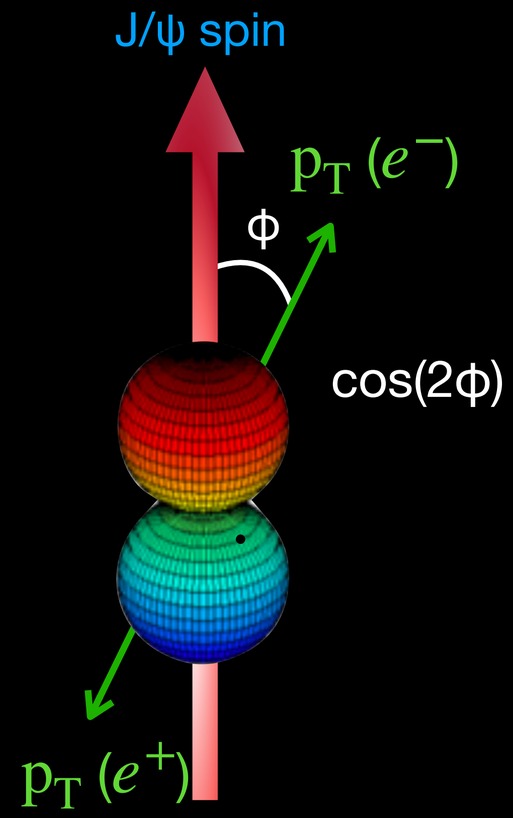
J/ψ photo-production with polarized photons in UPCs



Photoproduction of J/ψ
occurs in UPCs



Polarization of photon
→ Polarization of J/ψ

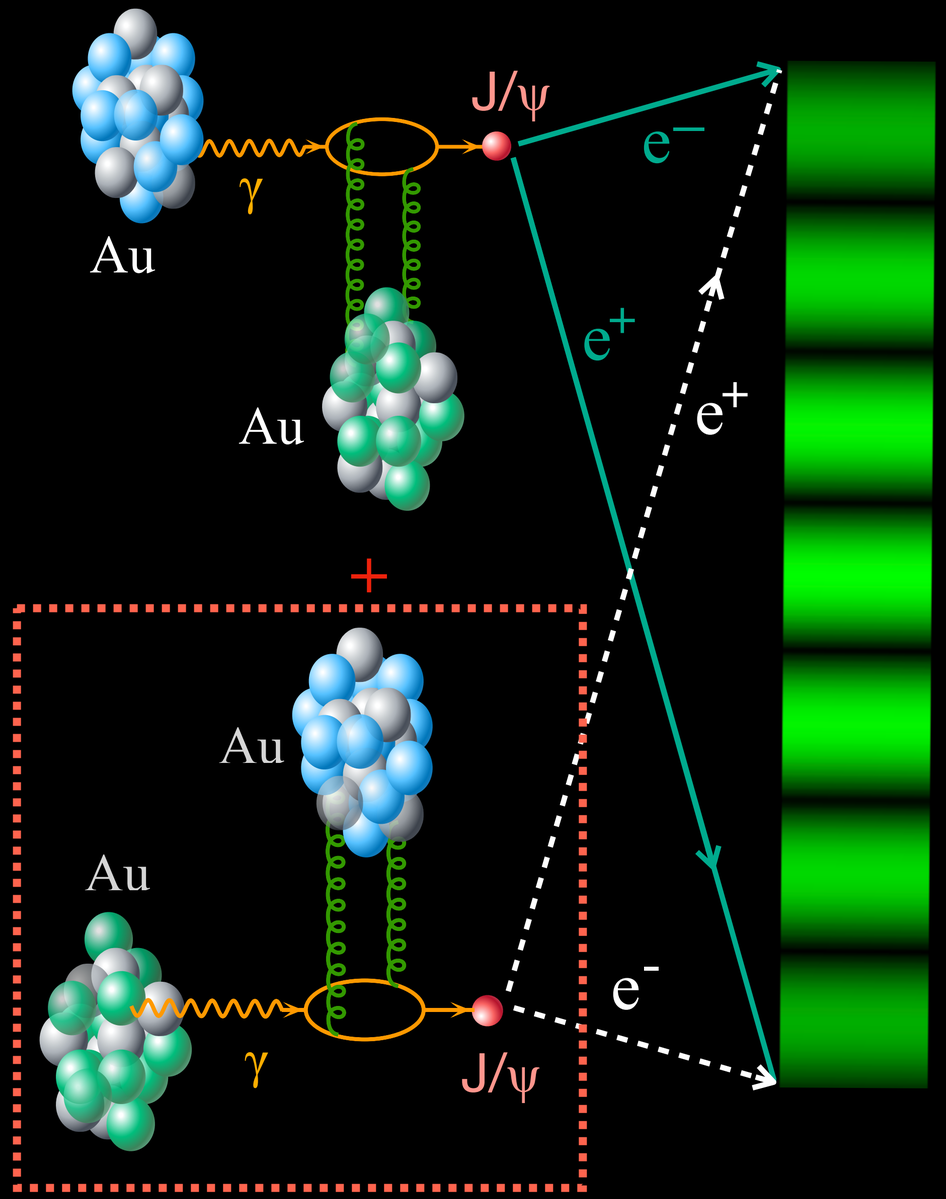


Decay $J/\psi \rightarrow e^- e^+$
Leads to cos(2ϕ) pattern
(L+S conservation)

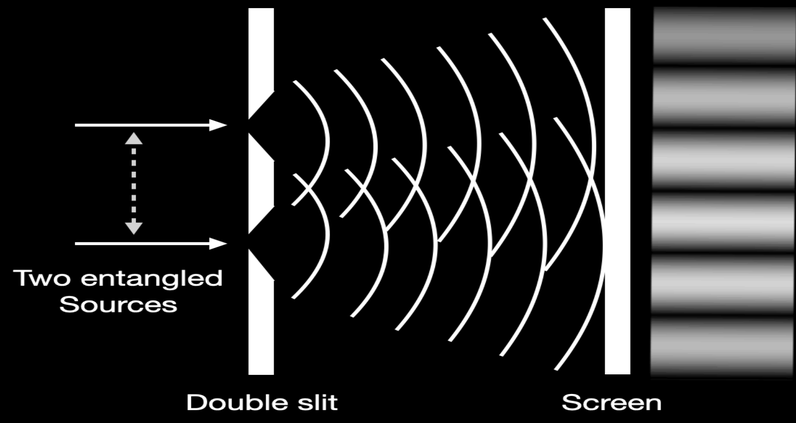
=> Decay electrons of the photo produced are correlated

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 allows to observe the interference => (cos(2ϕ)) pattern survives
- Analogy: Double slit experiment with two entangled sources



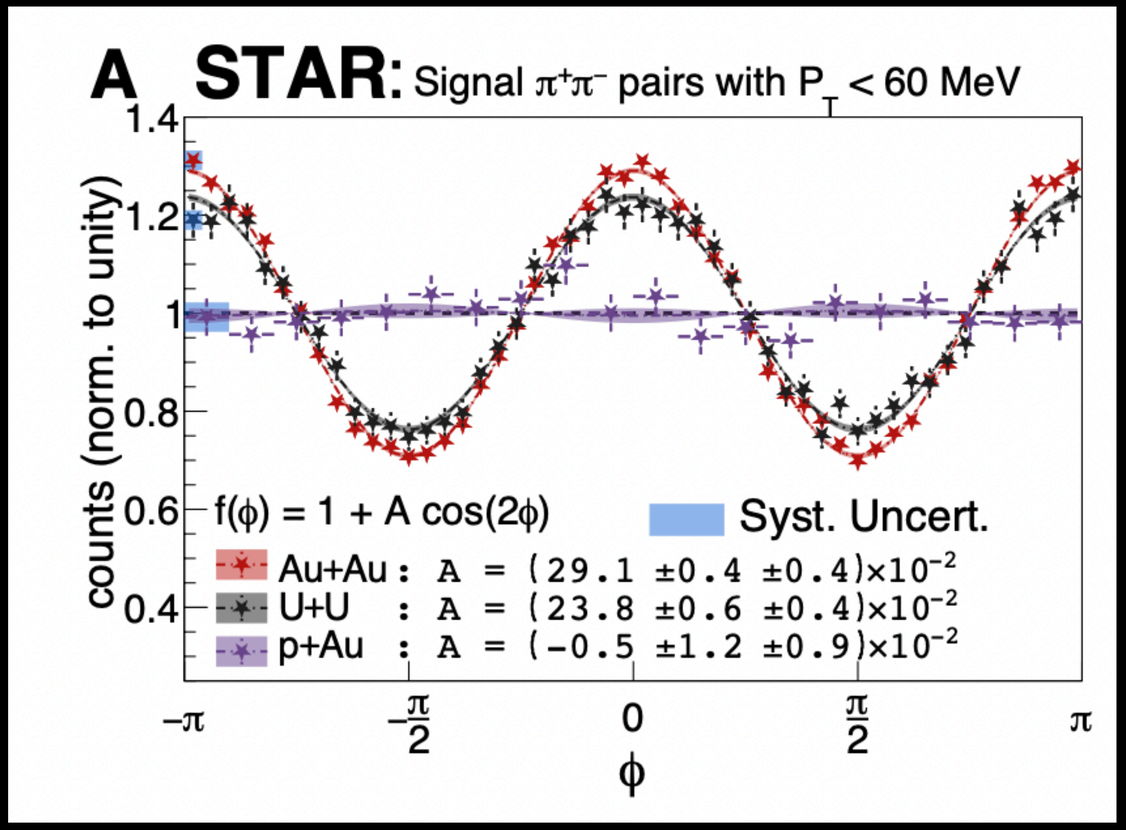
=> Entanglement ensures the spin interference in J/ψ photoproduction

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/c), localized wave function << b — interference occurs in the daughter pions (spin 0) level

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



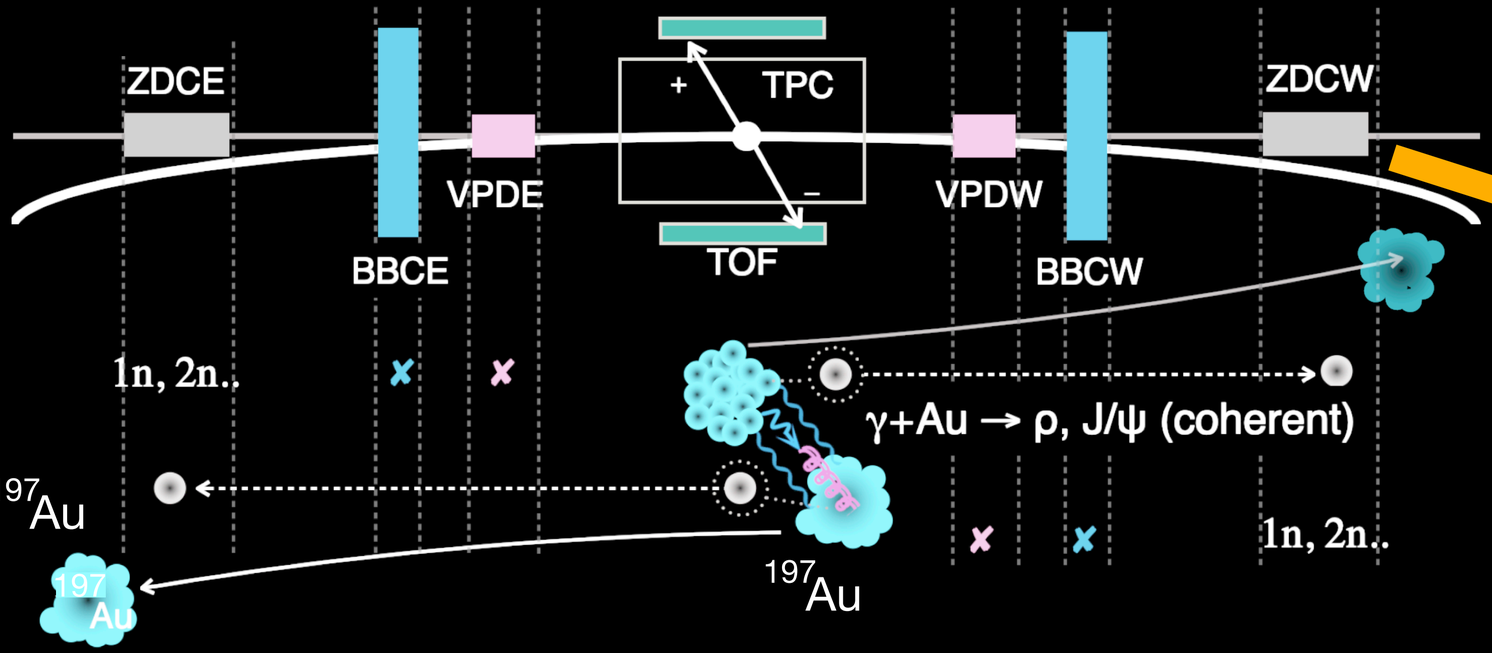
◉ J/ψ has longer lifetime, extended wave function

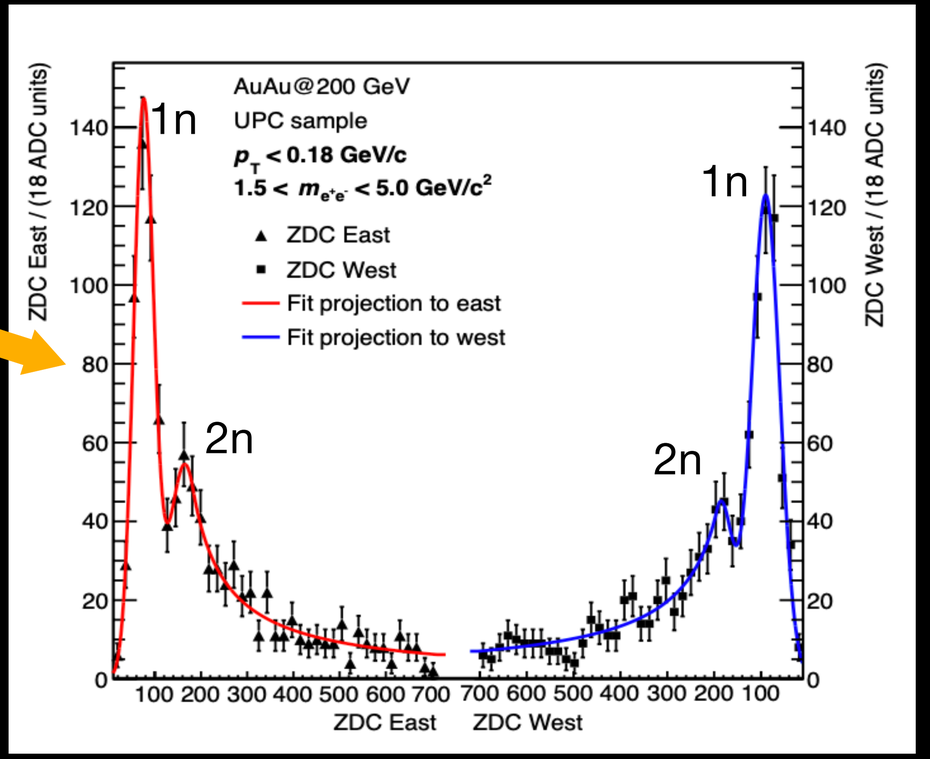
◉ J/ψ decay daughters, electrons (spin 1/2) are fermions, J/ψ → e^+e^-

◉ 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

UPC events with STAR detector



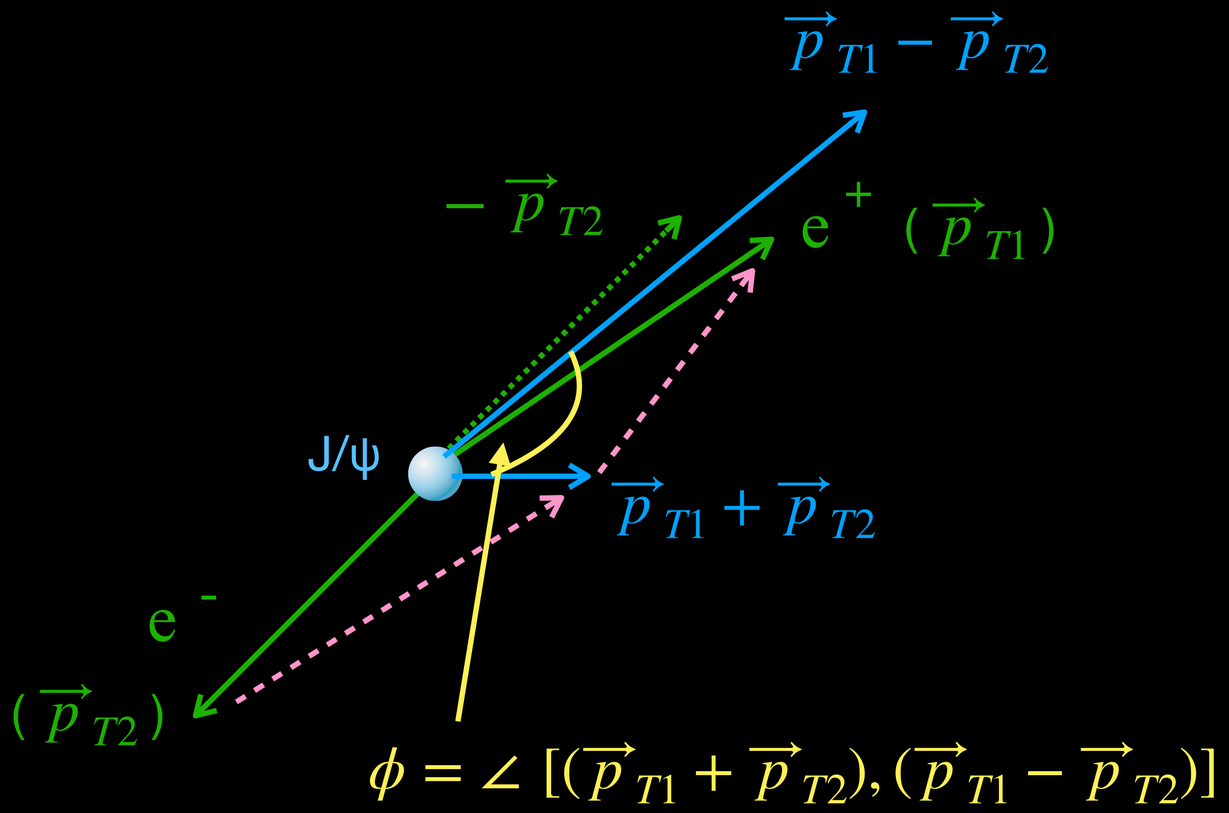


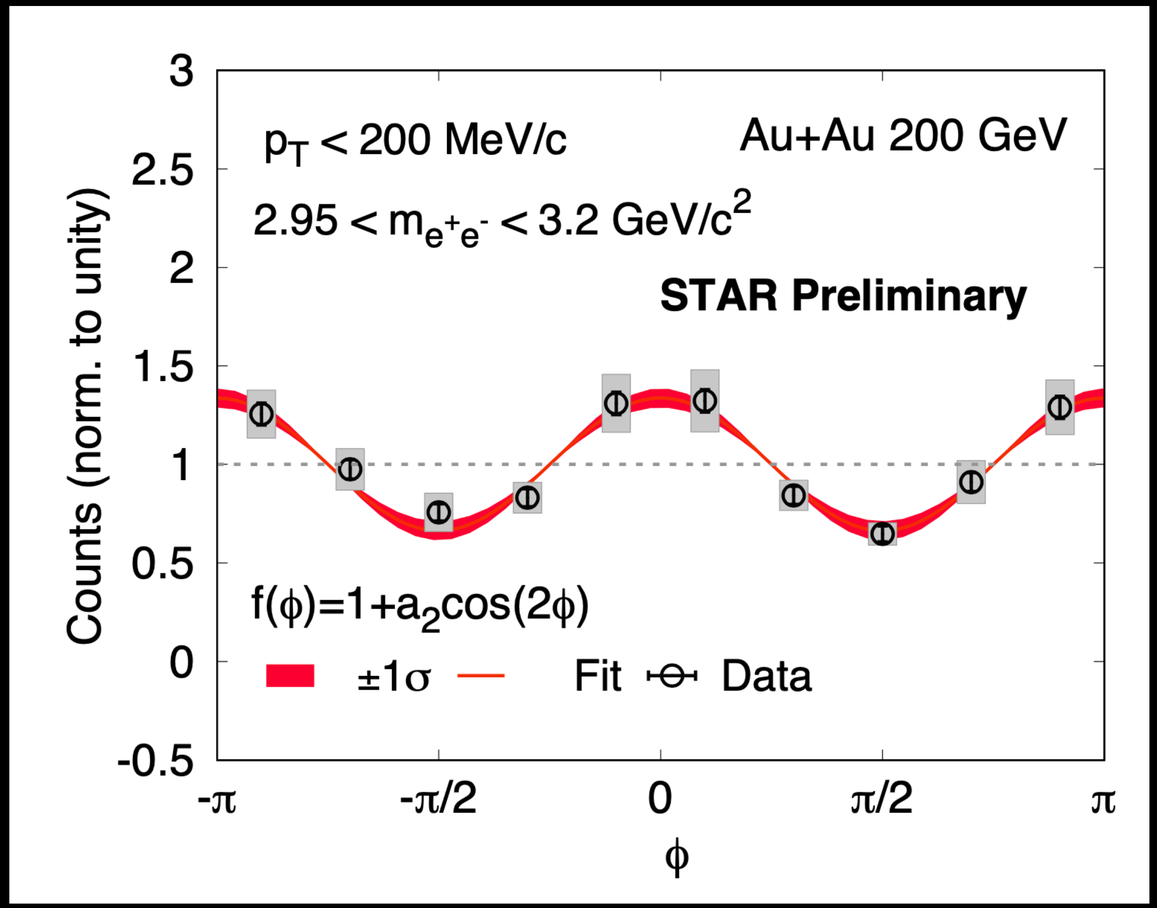
- Both nuclei get excited and emit neutrons in beam direction
- Neutron(s) detected in ZDCs
- ZDC signals show peak structure for neutrons

  => Way to trigger UPC events

- Two tracks of opposite charges in TPC
- No activity in both BBCs => Diffractive events (η-gap)

Spin interference of J/ψ



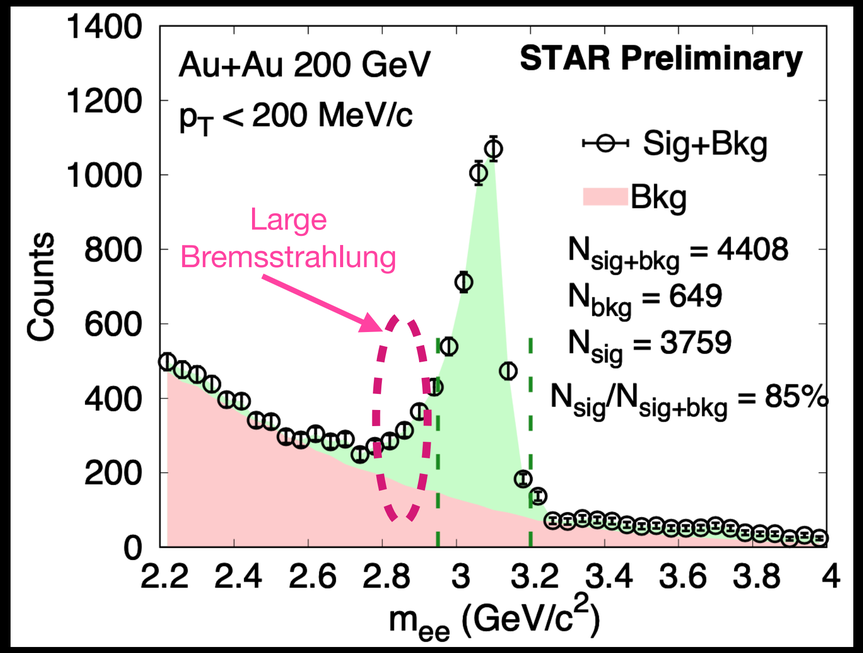


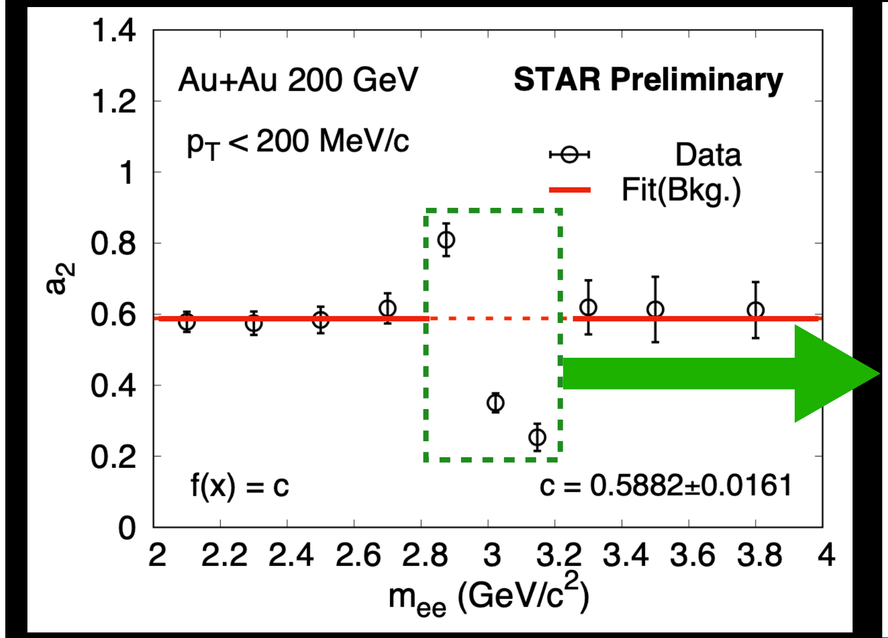
◉ Measured the raw cos(2ϕ) modulations of e^+e^- from J/ψ mass window ($2.95 < m_{ee} < 3.2$ GeV) with p_T < 200 MeV/c

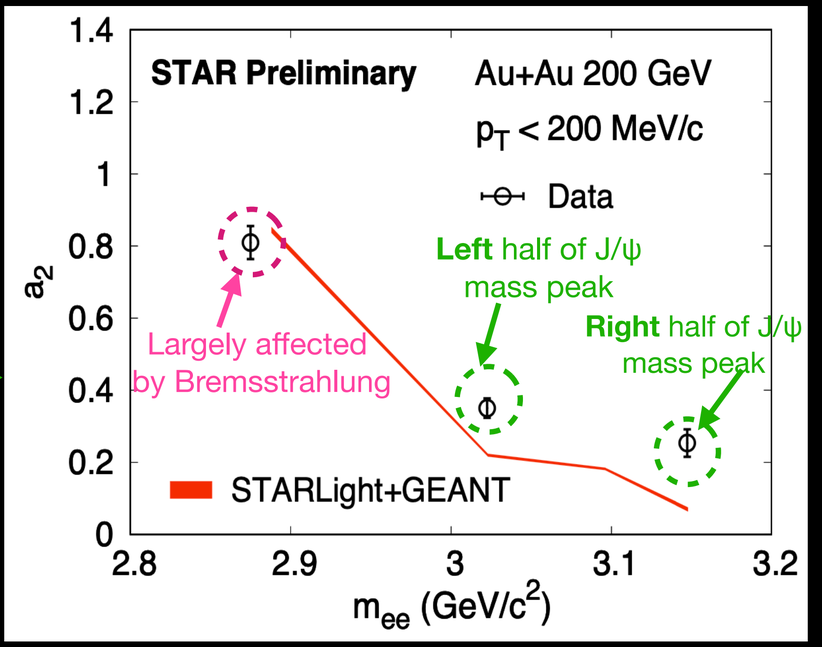
◉ The cos(2ϕ) modulation strength obtained from fit: 1+ a_2 cos(2ϕ) => a_2 is the measure of the modulation

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

Corrections for interference signal



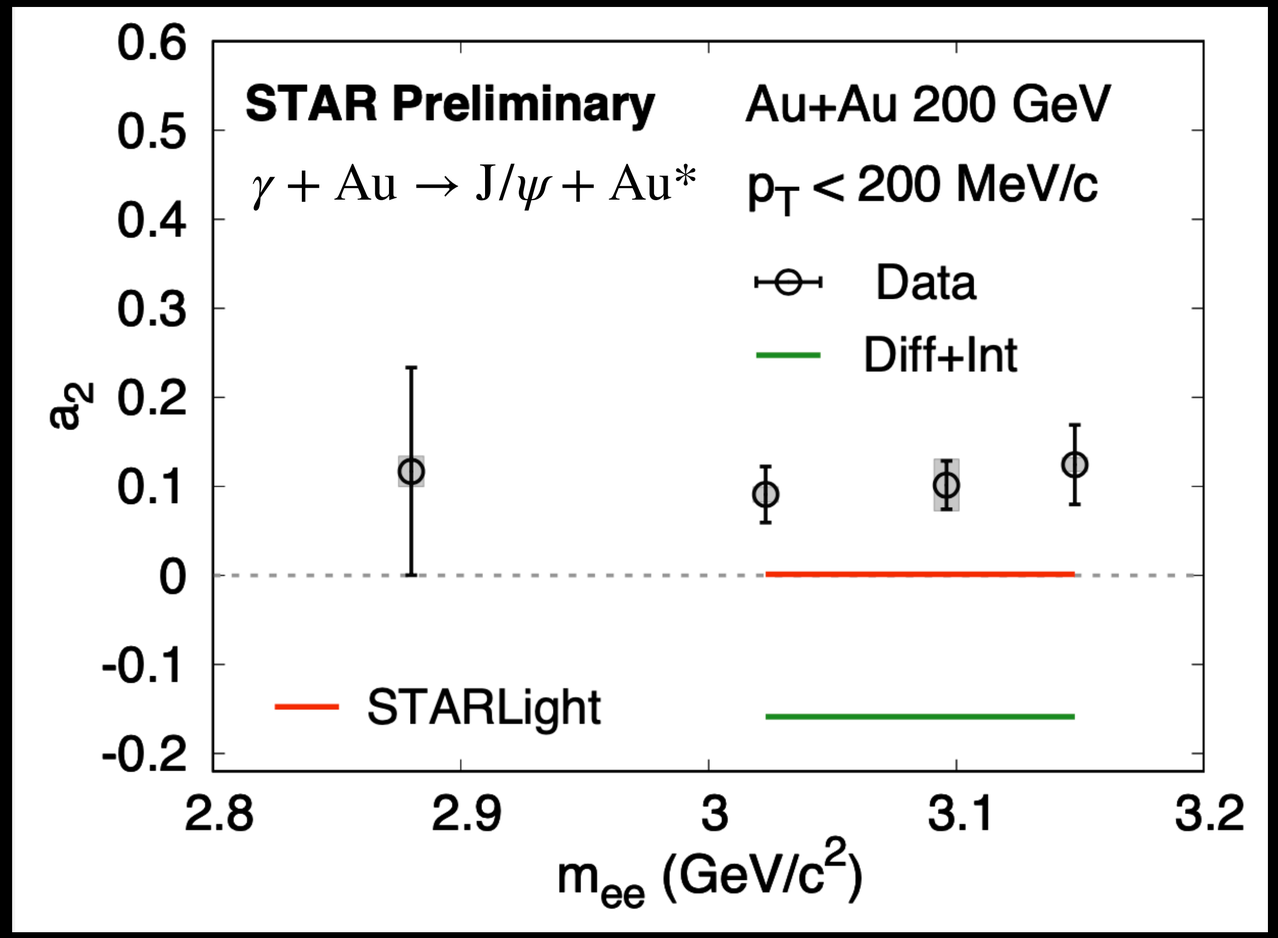




- The $\gamma + \gamma \rightarrow e^+ + e^-$ has also the J/ψ interference like pattern due to detector effect
- We correct for the 2γ process with : $a_2 = f \times a_2^{bkg} + (1-f) \times a_2^{sig}$, with $f = \frac{N_{bkg}}{N_{sig} + N_{bkg}}$
- We considered the Bremsstrahlung process and J/ψ $\rightarrow e^+ + e^- + \gamma$, 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 in $p_T < 200$ MeV/c:

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

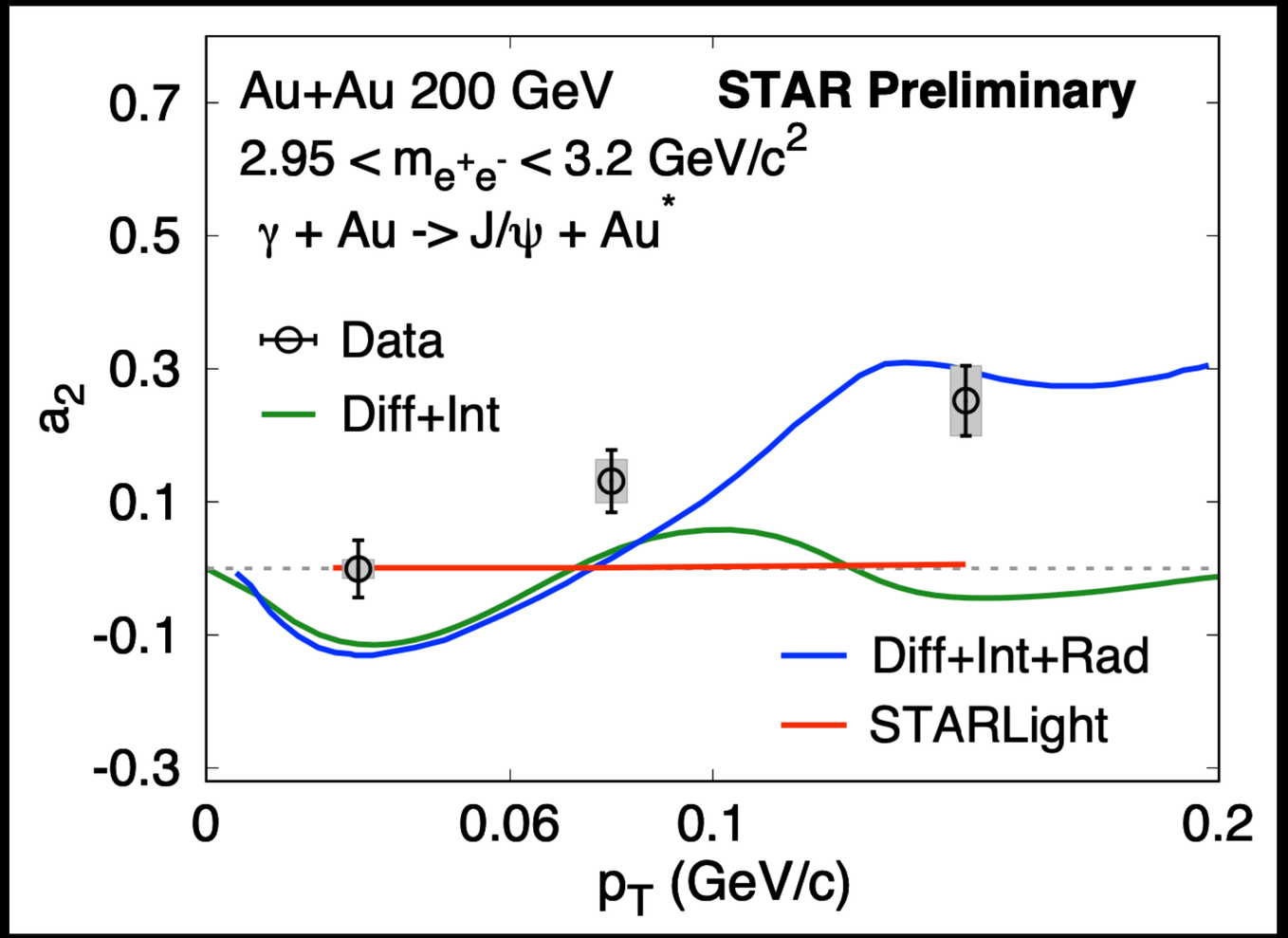
- Measurement has ~3σ significance above zero
- Compared with STARLight and theory calculations
- STARLight has no spin interference physics — consistent with zero
- Theory (Diffractive+Interference) predicts negative modulation

Theory predictions : W.B. Zhao et al. (private communication) & arXiv:2310.15300

=> 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 towards positive
- STARLight prediction is consistent with zero
- Diffractive+interference calculations are negative at low and high p_T
- Diffractive+interference with additional γ radiation predicts negative at low p_T and rises towards positive value at higher p_T

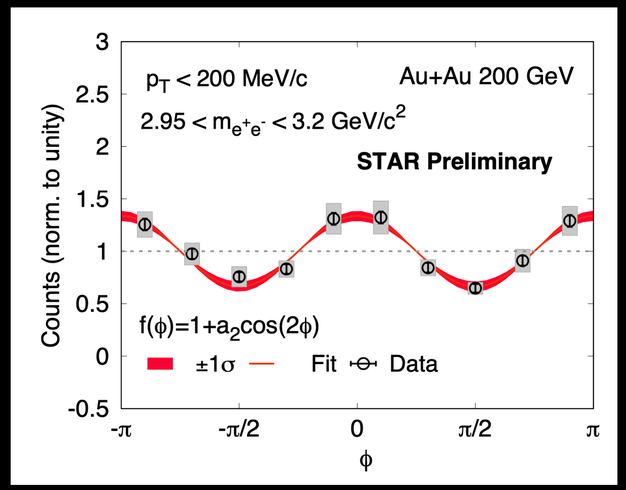


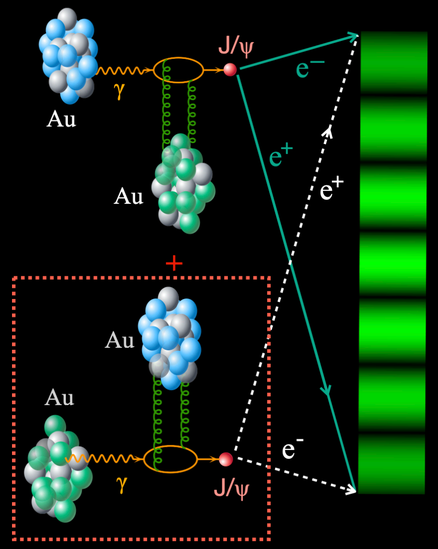
Diff+Int predictions : W.B. Zhao et al. (private communication) & arXiv:2310.15300
Diff+Int+Rad predictions : Brandenburg et. al, Phys. Rev. D 106, 074008 (2022)

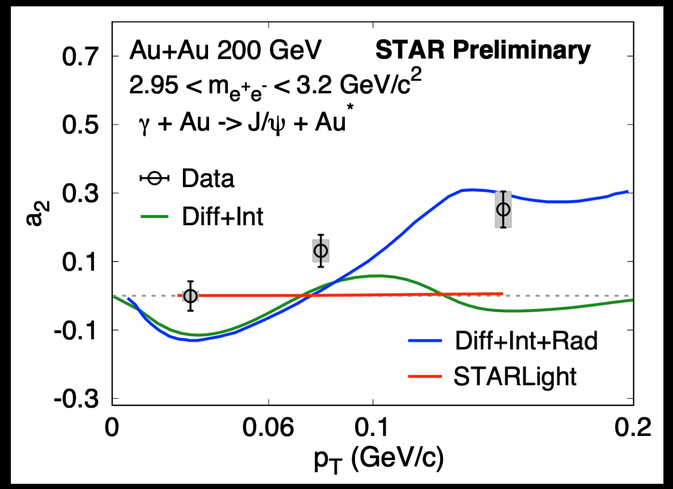
=> Modulation strength positively increases with p_T

Summary and take home message

- STAR observed the spin interference of the photoproduced J/ψ in $p_T < 200$ MeV/c with ~3σ significance
- Measured modulation strength increases with p_T , consistent with the expectation from soft photon radiation
- 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



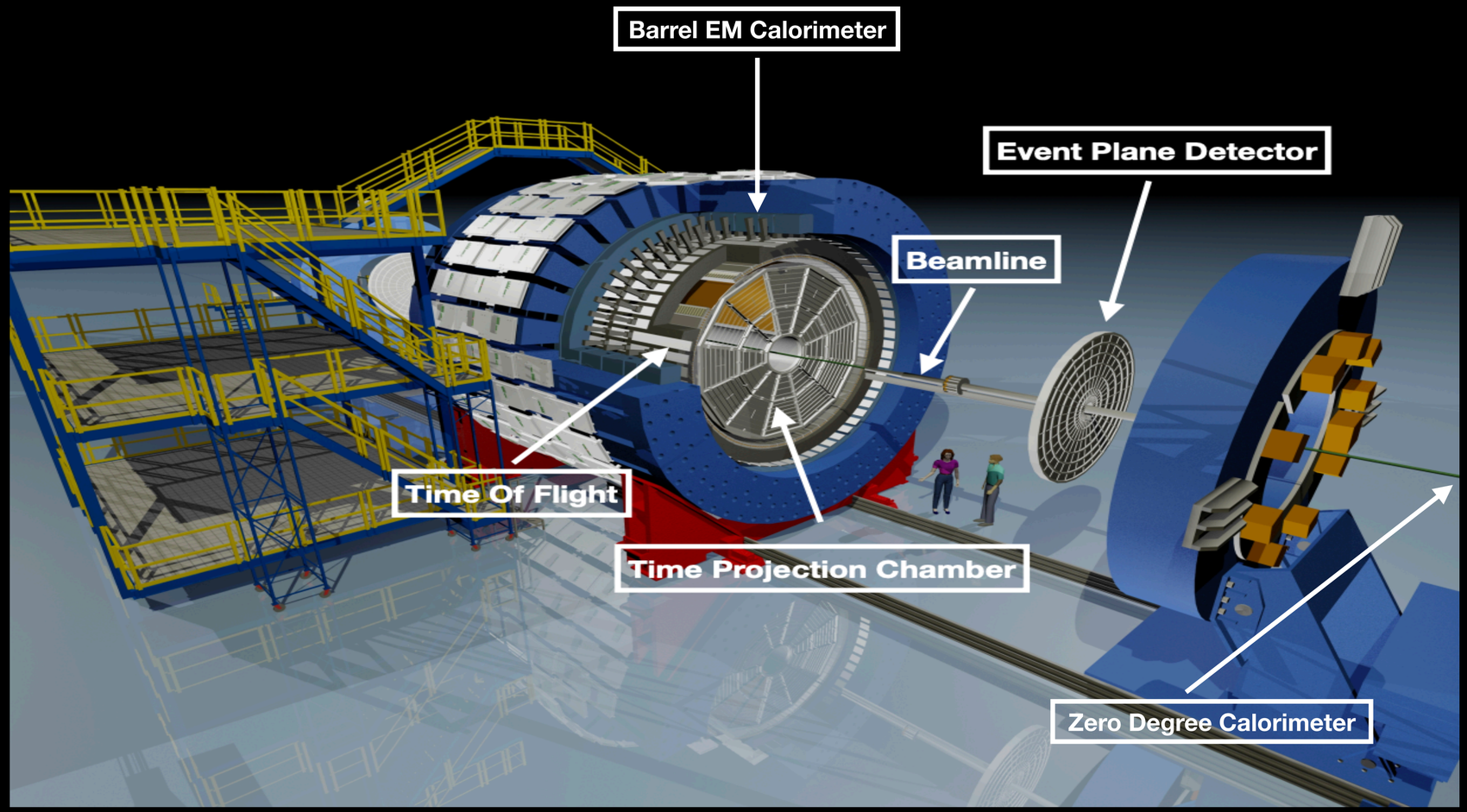





Gracias!

Backup

STAR detector



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