Angular modulation of photon-induced J/ψ and lepton pairs in heavy ion collisions at STAR

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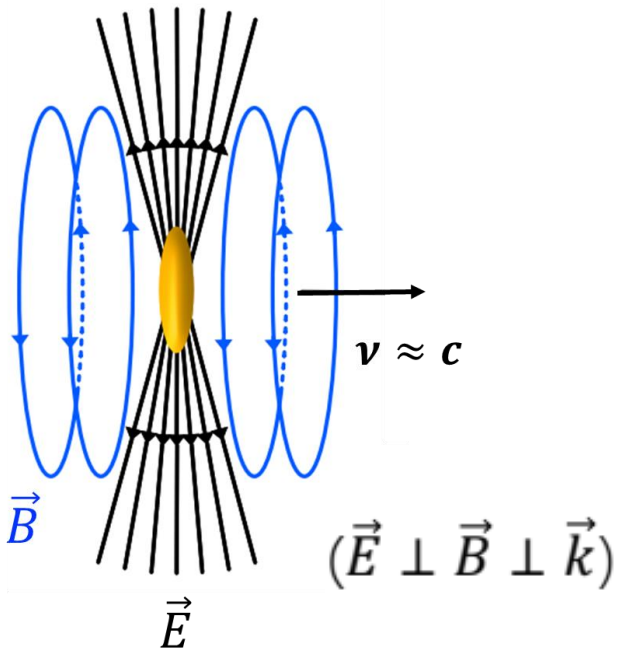
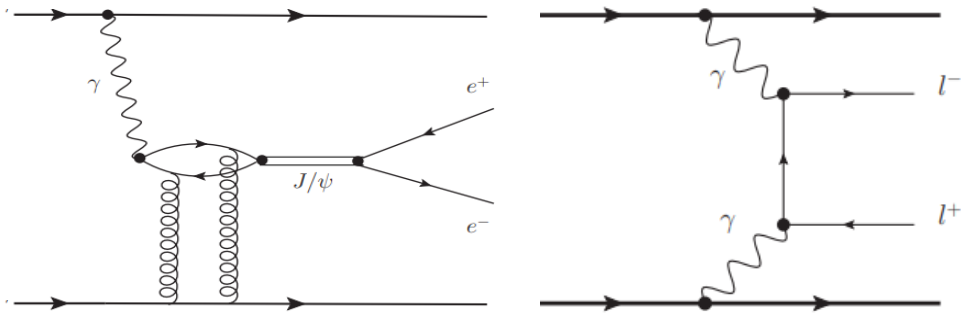
Outline

- Introduction
- Angular modulation of photon-induced J/ψ in isobaric collisions
- Angular modulation of photon-induced lepton pairs
- Summary

Photon-induced process

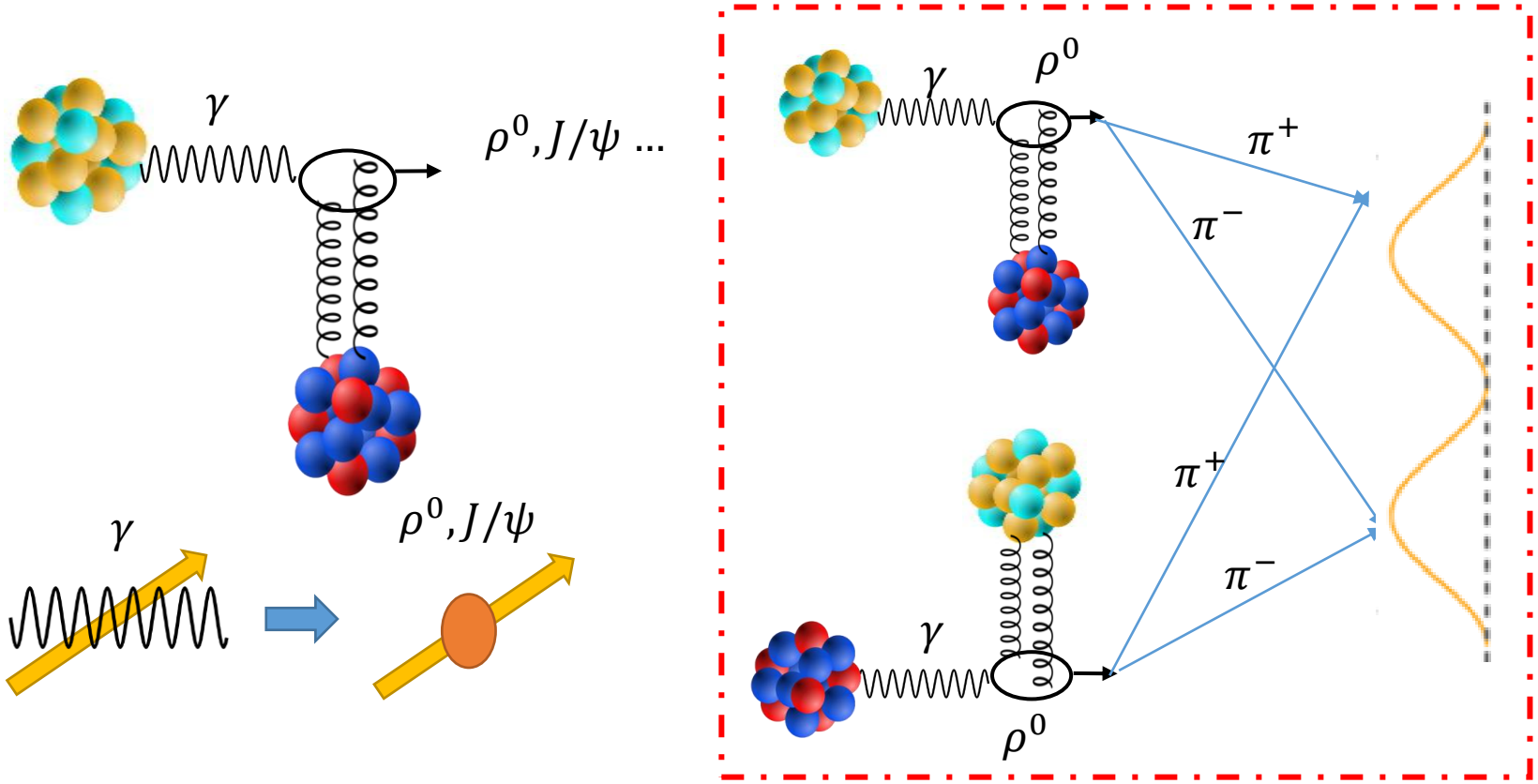




- Equivalent Photon Approximation
- Transverse EM fields can be quantized as a flux of quasi-real photons
- Flux of quasi-real photons $\propto Z^2$

- Photon induced process
  - ✓ $\gamma + A \rightarrow J/\psi + A$
  - ✓ $\gamma + \gamma \rightarrow l^+ + l^-$
- Quantized photons are linearly polarized
- Linearly polarized photons → final state polarization

Photon induced polarization in VM production

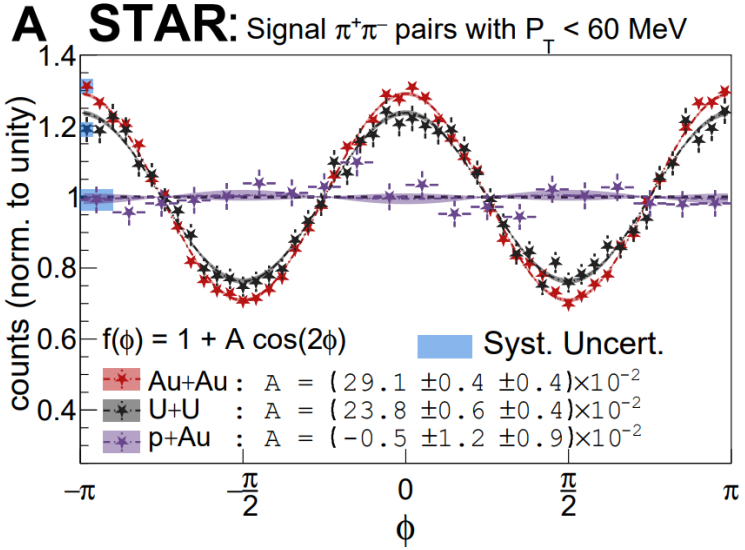


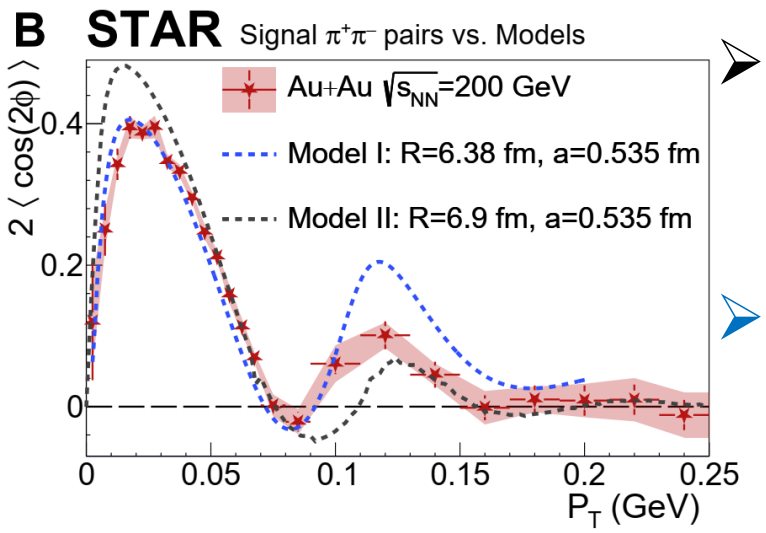
Double slit experiment @ fm scale

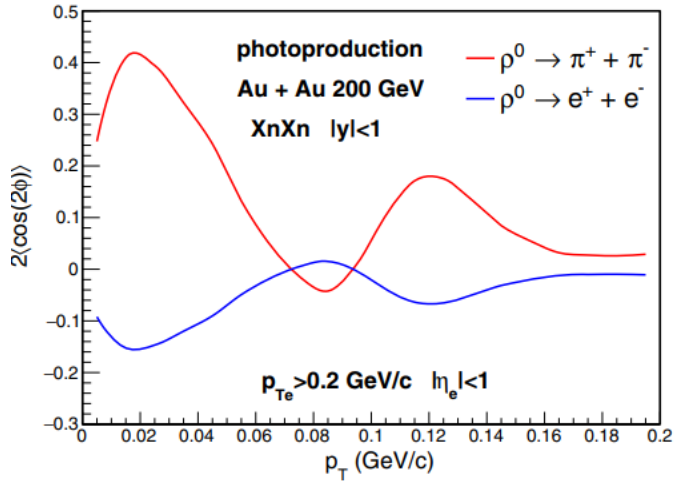
- The polarization of photons could be transferred to Vector Mesons ($\rho^0, J/\psi \ldots$)
- Two sources for ρ^0 photo-production lead to final state interference effect

Spin interference effect

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







W. Zha et.al PHYSICAL REVIEW D 103, 033007 (2021)

- Spin interference effect has been observed with ρ^0
- Sensitive to nuclear structure

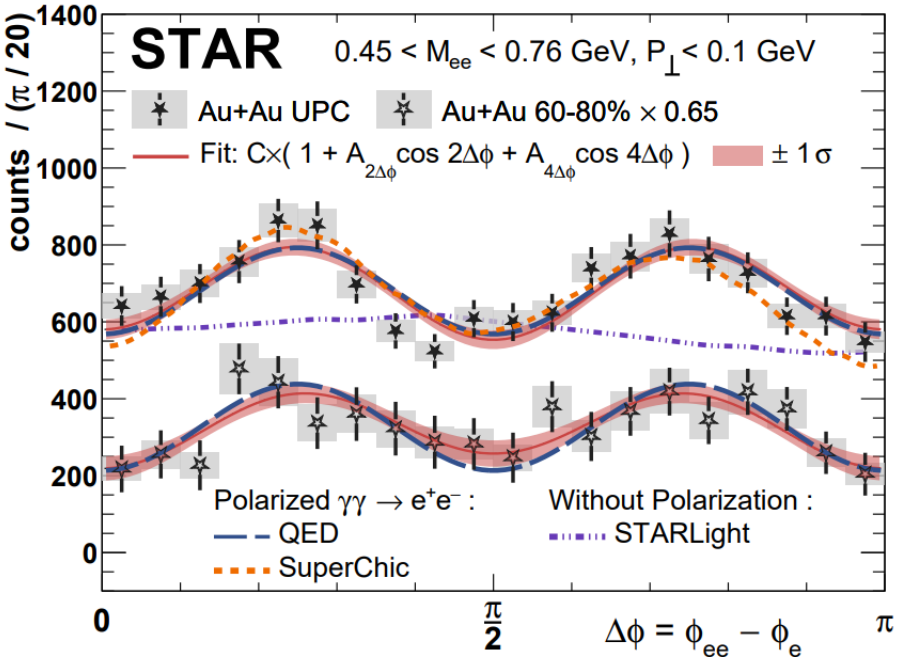
How about J/ψ ?

- Decay daughters, e^+e^- are fermions
- Longer lifetime than impact parameter

ρ^0 ~ 1.3 fm/c J/ψ ~ 2160 fm/c b ~ 20 fm

Birefringence of the QED vacuum

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

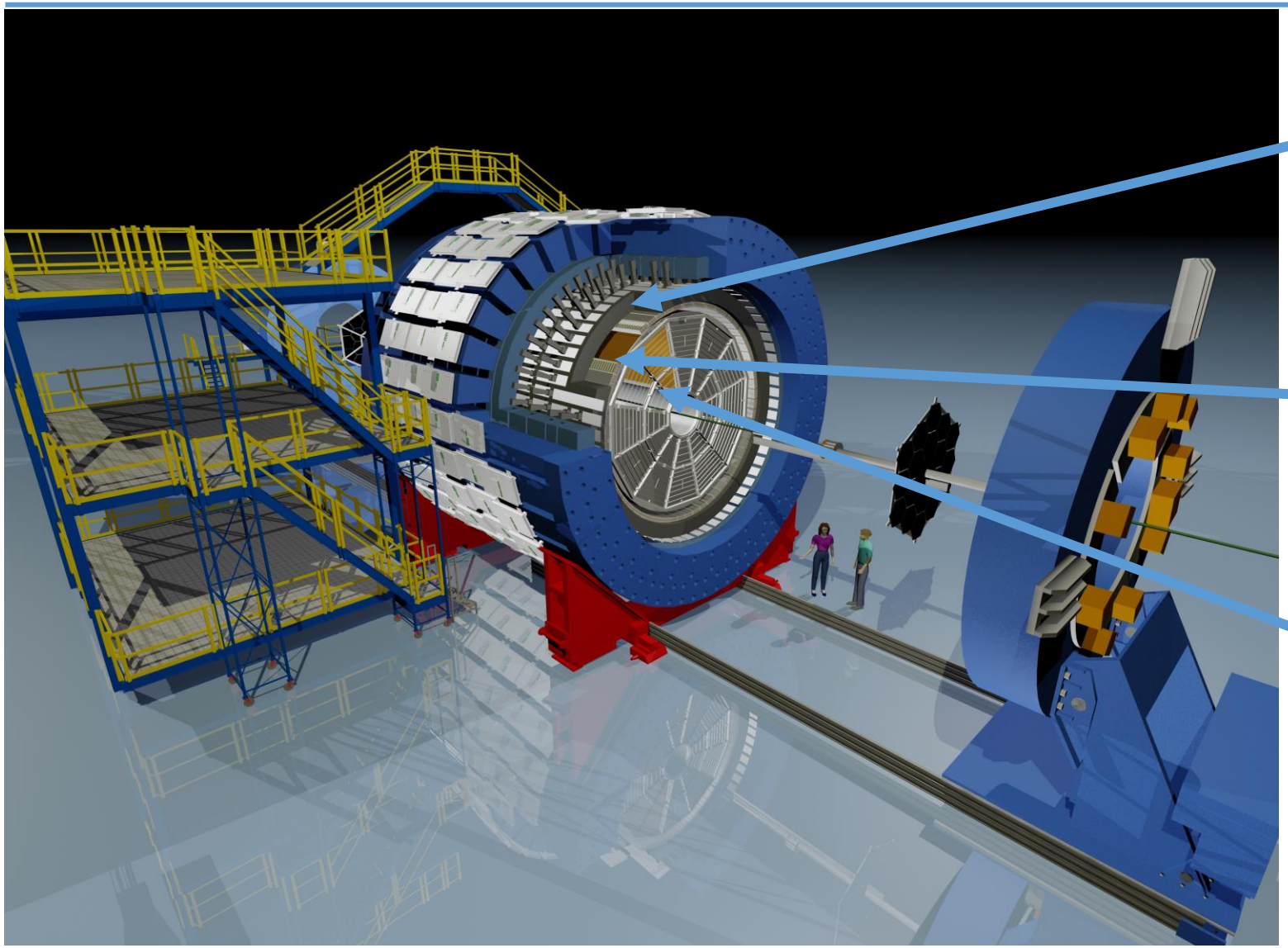


✓ Related to vacuum birefringence.

✓ Evidence of photon-photon interactions

- Sensitive to initial geometry
  - Comparison between Ru+Ru&Zr+Zr vs. Au+Au
- cos2Δϕ azimuthal asymmetry sensitive to daughter mass ∝ $m^2/p_\perp^2$
  - Expected to be sizable for $\mu^+\mu^-$ pair production

The Solenoidal Tracker At RHIC (STAR)



- ✓ BEMC: Particle identification, trigger
- ✓ TOF: Time of flight, particle identification
- ✓ TPC: Tracking, momentum and dE/dx

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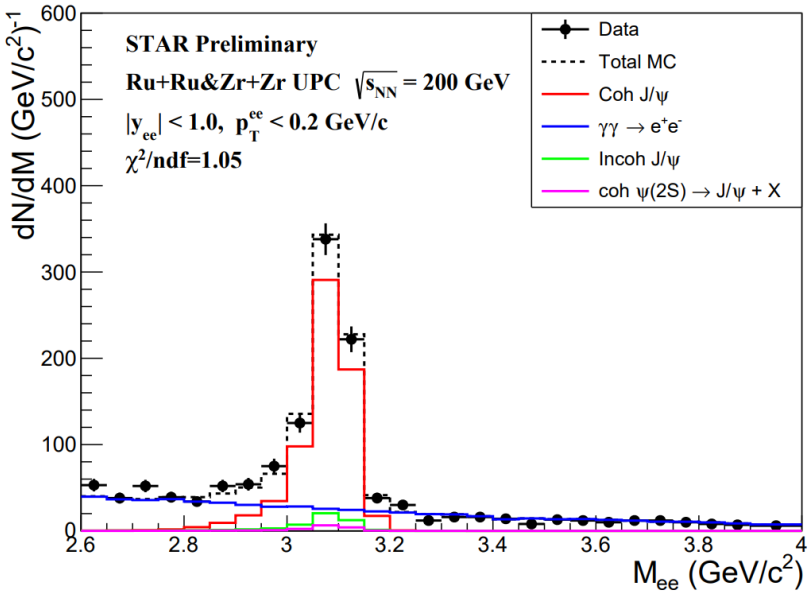
J/ψ measurements in 200 GeV isobaric UPCs

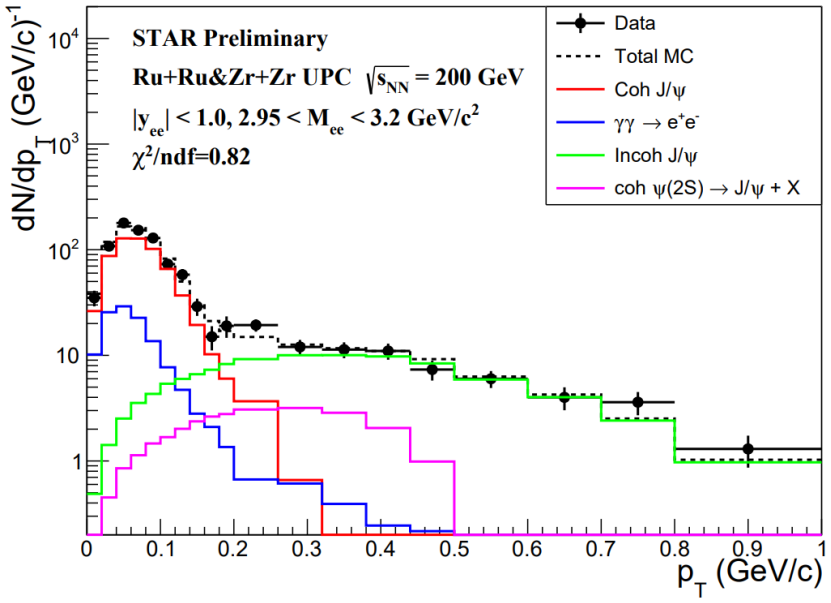
Collision species (taken in 2018)

- $^{96}_{44}Ru+^{96}_{44}Ru$, $\sqrt{s_{\mathrm{NN}}}$=200 GeV
- $^{96}_{40}Zr+^{96}_{40}Zr$, $\sqrt{s_{\mathrm{NN}}}$=200 GeV

✓ Similar nuclear size

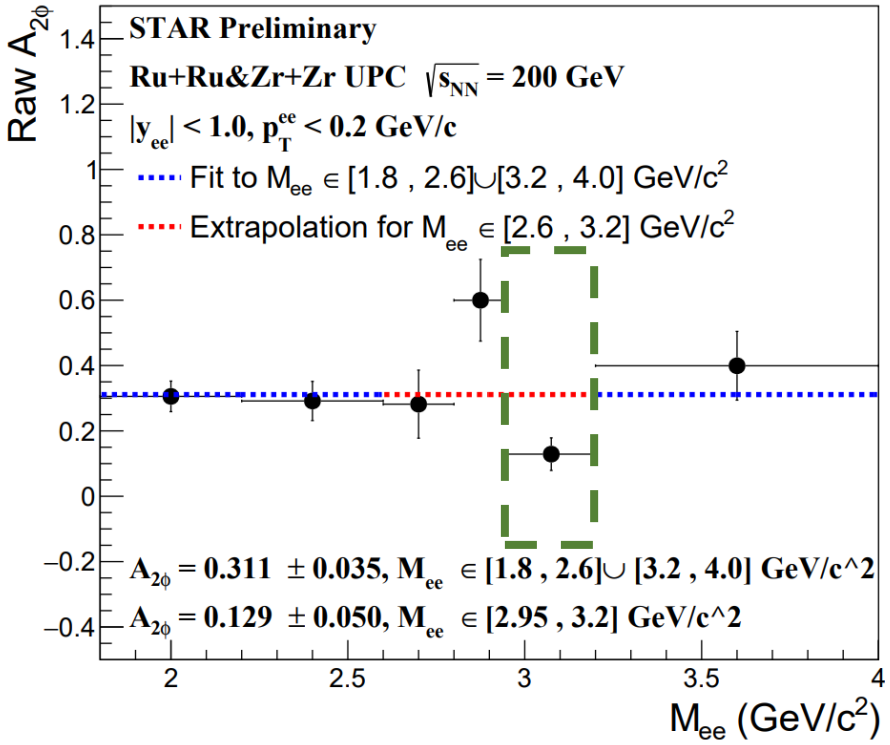
- Measured $\gamma A \to J/\psi \to e^+e^-$ & $\gamma\gamma \to e^+e^-$ (in the mass continuum) within |y| < 1
- Signal extractions are performed via fitting to the M_{ee} & p_T distributions

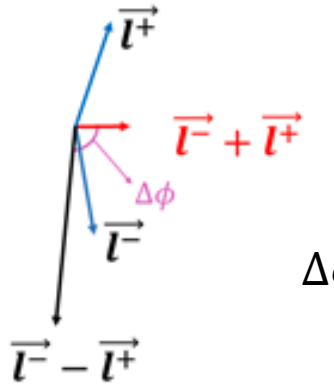




MC input
P. Wang et al 2022 Chinese Phys. C 46 074103
W. Zha et al Phys. Lett. B 800,135089 (2020)

J/ψ interference signal extraction





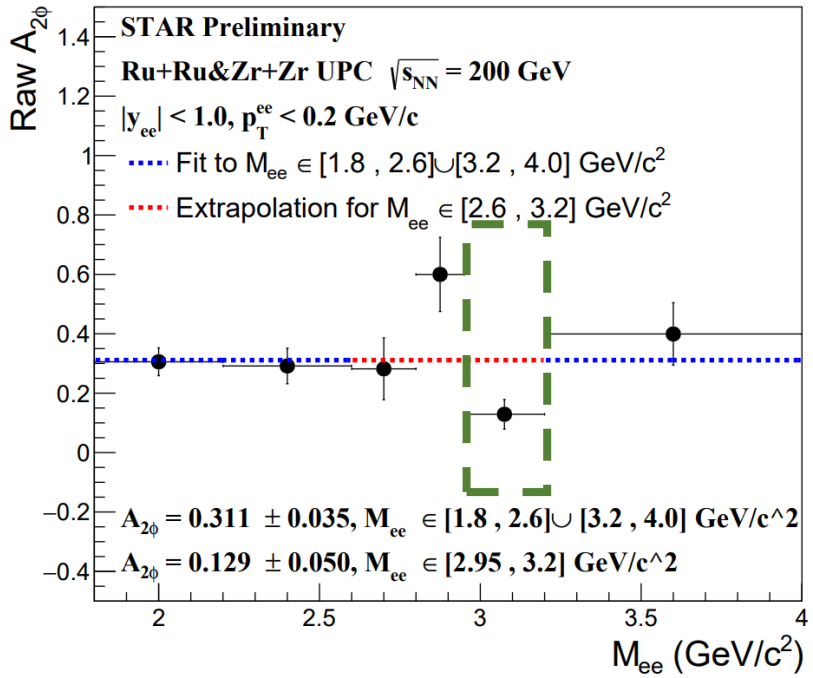
$$\Delta\boldsymbol{\phi} = \boldsymbol{\phi}_{\vec{l}^+ + \vec{l}^-} - \boldsymbol{\phi}_{\vec{l}^+ - \vec{l}^-}$$

- ✓ Sizeable contributions from $\gamma\gamma \rightarrow e^+e^-$ process
- ✓ Enhancement on left side of J/ψ peak → Bremsstrahlung & soft photon radiation

J/ψ interference signal extraction

What contributes to interference background?

- $\gamma\gamma \rightarrow e^+e^- \rightarrow$ Extrapolation from mass continuum



$$A_2^{raw} = \frac{N_{J/\psi} \times A_2^{J/\psi} + N_{\gamma\gamma} \times A_2^{\gamma\gamma}}{N_{J/\psi} + N_{\gamma\gamma}}$$

$$A_2^{J/\psi} = \left(1 + \frac{N_{\gamma\gamma}}{N_{J/\psi}}\right) \times A_2^{raw} - \left(\frac{N_{\gamma\gamma}}{N_{J/\psi}}\right) \times A_2^{\gamma\gamma}$$

$N_{\gamma\gamma}$&$N_{J/\psi}$: From fitting of M_{ee} spectrum

$A_2^{\gamma\gamma}$: Extrapolated from $M_{ee} \in [1.8, 2.6] \cup [3.2, 4.0]\ GeV/c^2$

J/ψ interference signal extraction

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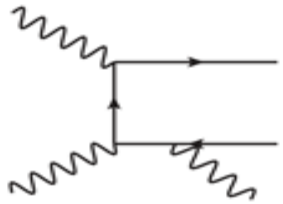
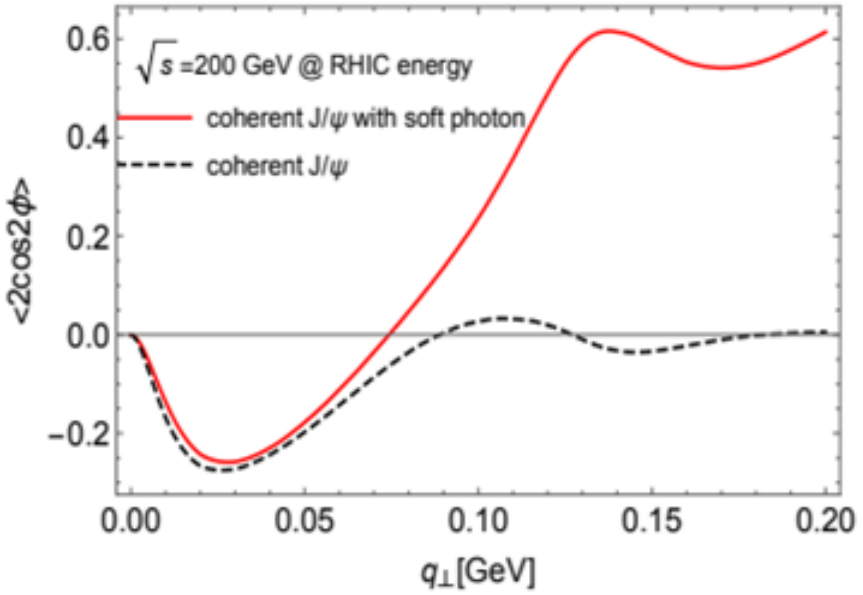


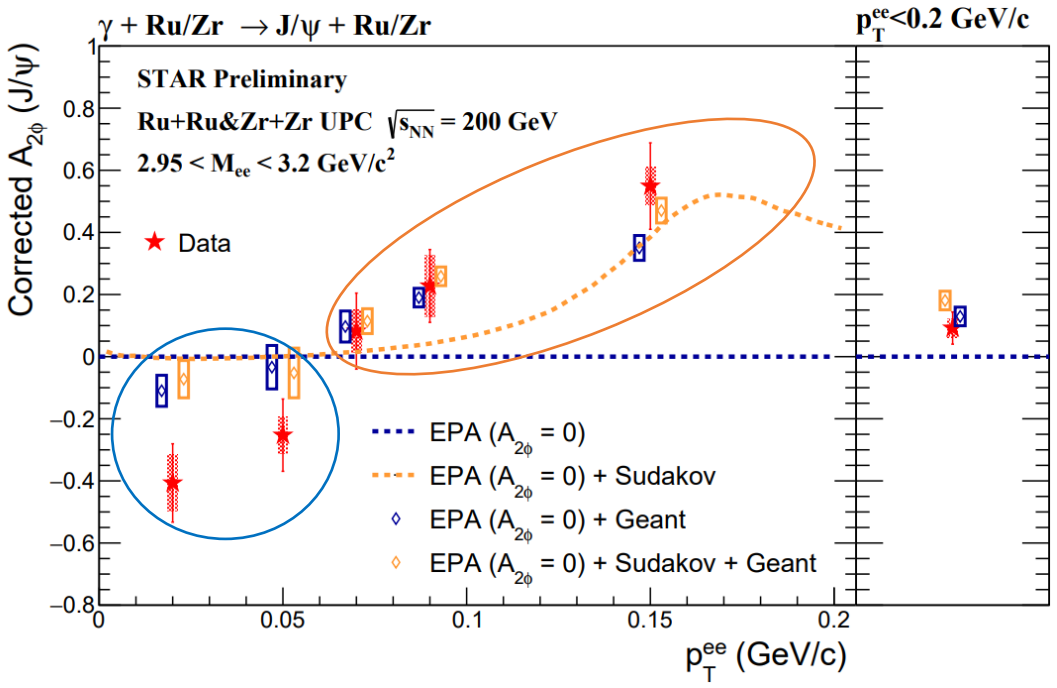
- Internal radiation effect
- Bremsstrahlungs
- Momentum smearing

Geant simulation with model input



J. D. Brandenburg et al.
Phys.Rev.D 106 7, 074008 (2022)

p_T-dependent modulation of J/ψ



- Data: J/ψ modulation extracted from raw signals
- EPA + Geant: zero amplitude of modulations input
  - Bremsstrahlung & detector effect
- EPA + Sudakov + Geant: internal photon radiation modulation input
  - Soft photon radiation
  - Bremsstrahlung & detector effect

✓ J/ψ signal shows an increasing trend from negative to positive

➢ MC with soft photon radiation well describes increase trend @ $p_T > 0.1\ GeV/c$

➢ 2.4 σ lower than MC with zero modulation input @ $p_T < 0.06\ GeV/c$

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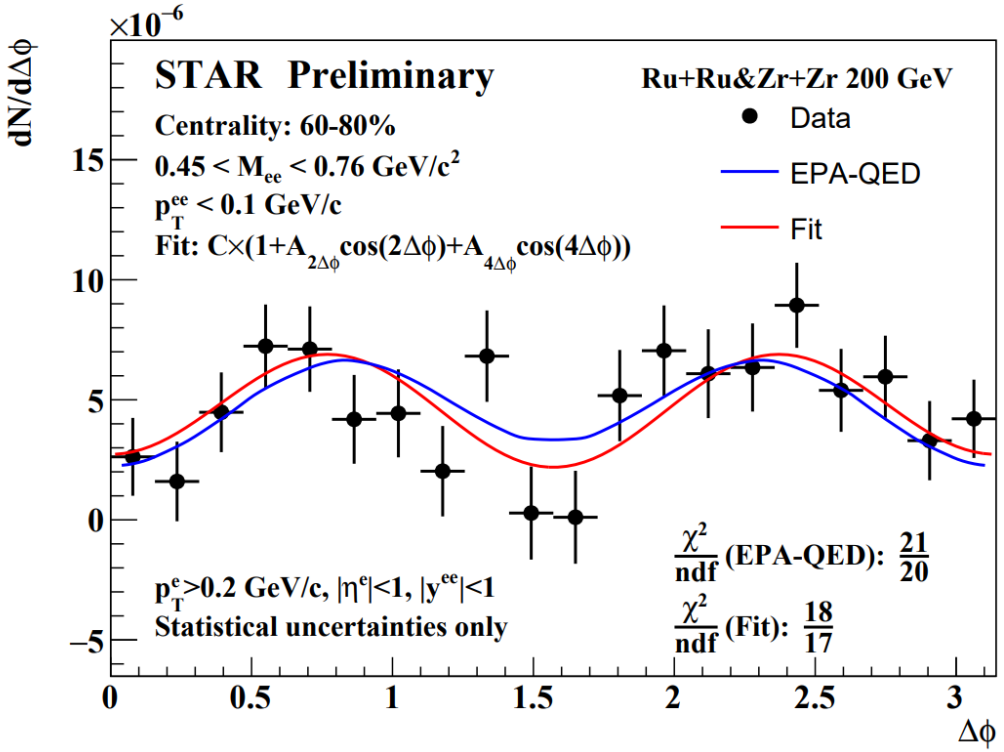
Modulation of di-electron in isobaric peripheral collisions

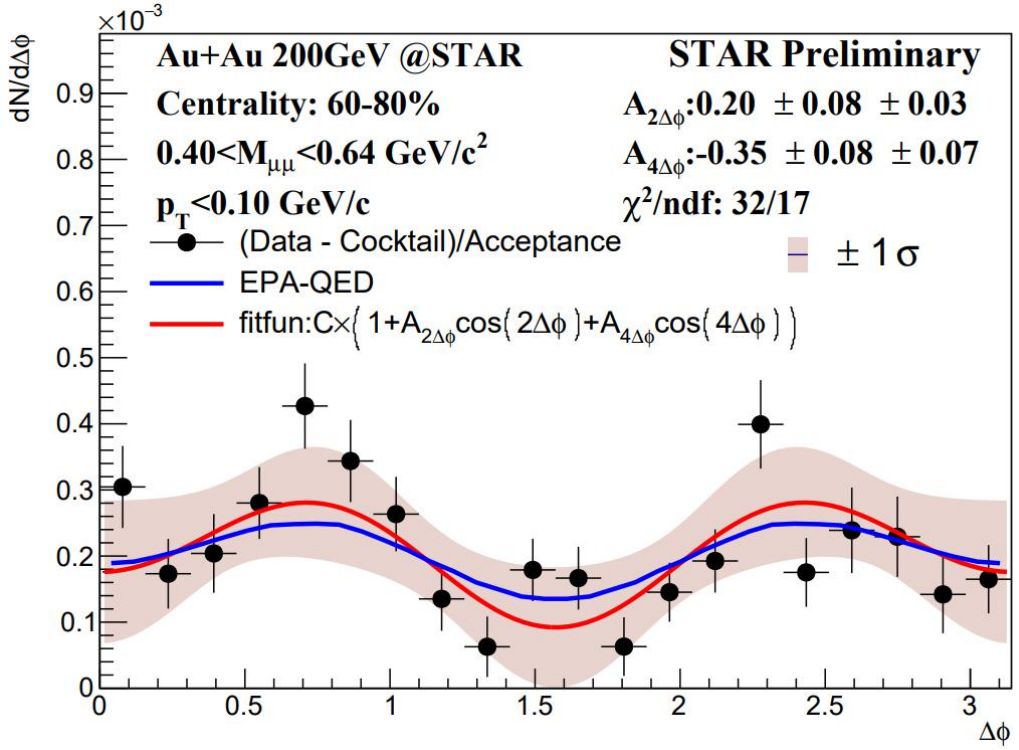


W.M. Zha et al., Phys. Lett. B 800 (2020) 135089

	$\lvert A_{4\Delta\phi}\rvert$ (%)	$\lvert A_{2\Delta\phi}\rvert$ (%)	χ^2/ndf
Isobar(60-80%)	47±13	6±13	18/17
Au+Au(60-80%)	27±6	6±6	10/17
QED-EPA for Isobar	40	0	

- Clear cos(4Δϕ) signal (~3.6σ) in isobaric collisions: $\lvert A_{4\Delta\phi}\rvert$ = 0.47±0.13(stat)±0.05(sys)
- Hint of larger modulation in isobaric collisions than Au+Au collisions (0.27±0.06) → b dependence

Modulation of di-muon in Au+Au peripheral collisions



	Measured	χ^2/ndf	QED-EPA
$\lvert A_{4\Delta\phi}\rvert$ (%)	35 ± 11	32/17	22
$\lvert A_{2\Delta\phi}\rvert$ (%)	20 ± 9		13

- Observation of non-zero 4th-order azimuthal angular modulation of $\mu^+\mu^-$ pairs (3.3σ).
- First indication of non-zero the 2nd-order azimuthal angular modulation (2.3σ)!

Summary

- J/ψ cos2$\Delta\phi$ modulation in isobaric UPC shows strong p_T dependence
  - 2.4 σ negative modulation @ $p_T < 0.06\ GeV/c$
- Angular modulation of photon-induced lepton pairs in peripheral collisions
  - Hint of impact parameter dependence in isobar & Au+Au collisions
  - Hint of non-zero cos2$\Delta\phi$ modulation in $\gamma\gamma \rightarrow \mu^+\mu^-$ in Au+Au peripheral collisions

Thank you