Probing gluon structure with J/ψ photoproduction in isobaric ultra-peripheral collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV with STAR

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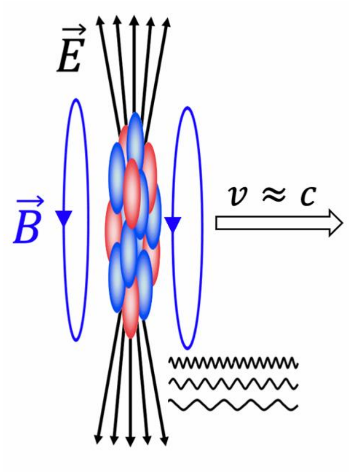
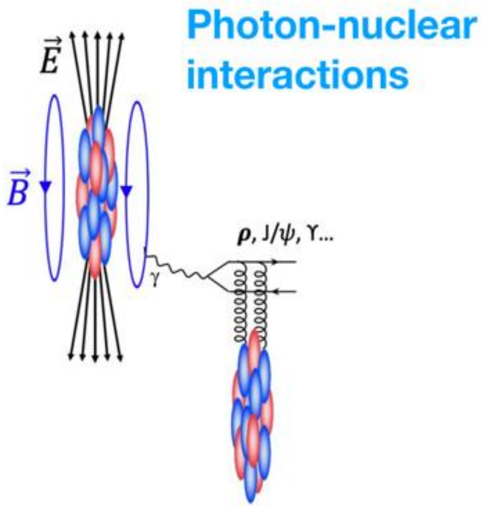
Outline

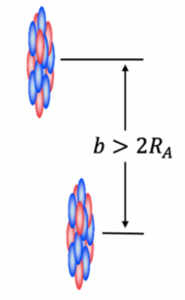
- Motivation
- Analysis details
  - Event and track selection
  - Signal extraction
  - Efficiency correction
- Physics results
  - Cross section and model comparison
  - Forward neutron dependence
- Summary

Equivalent photon in UPCs





- Ultra-peripheral collisions (UPCs)
  - Impact parameter (b) > 2 R_A → no hadronic interactions

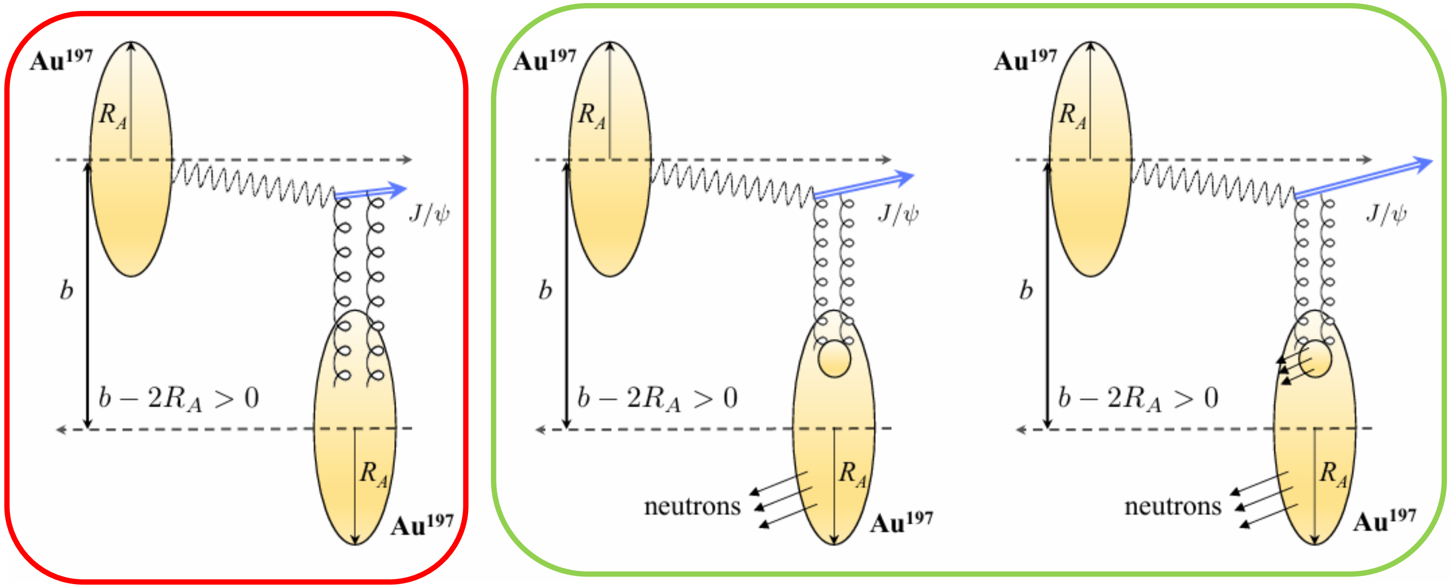


- Equivalent Photon Approximation
  - Photon flux ∝ Z^2
  - EM fields → quasi real photon ($Q^2 \sim 0$)
- Photon kinematics

maximum energy $E_{\gamma,max} \sim \gamma(\hbar c/R)$	**80 GeV in Pb+Pb@LHC** **3 GeV in Au+Au@RHIC**
typical p_T (& virtuality) $p_{Tmax} \sim \hbar c/R$	**O(30) MeV @ RHIC & LHC**

- Photon-photon or photon-nuclear collision

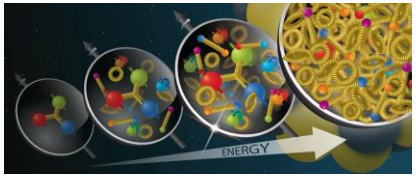
Photon-induced J/ψ meson production



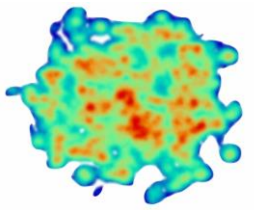
Coherent

Incoherent

Focus of this talk

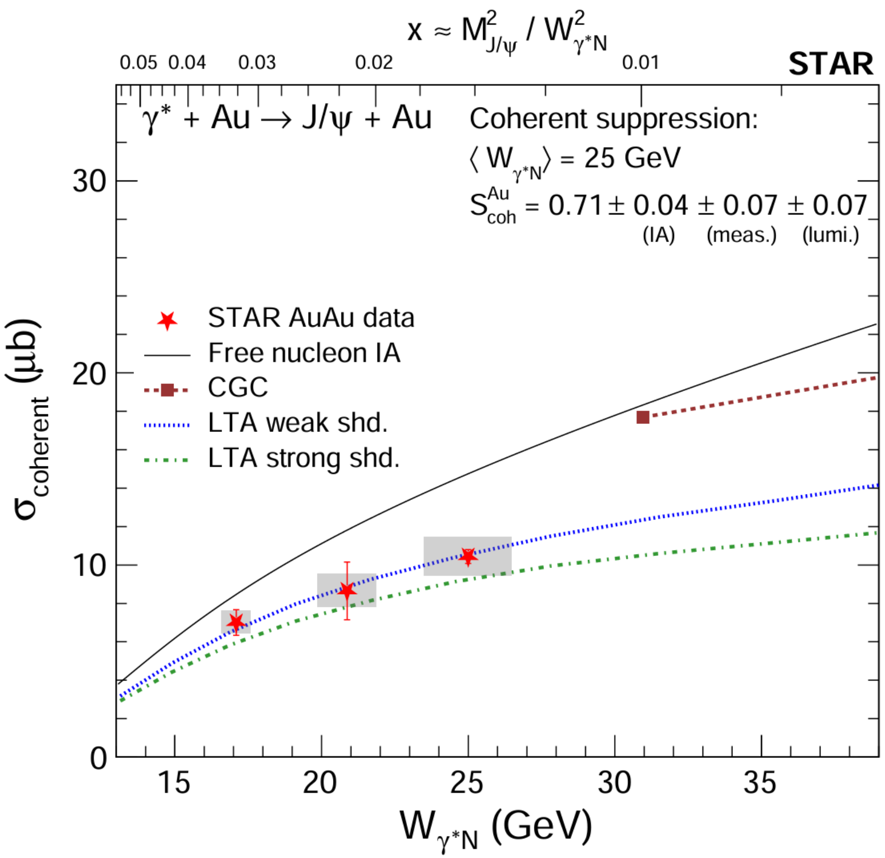


- Coherent: probe average gluon distribution in entire nucleus
- Incoherent: probe individual nucleon

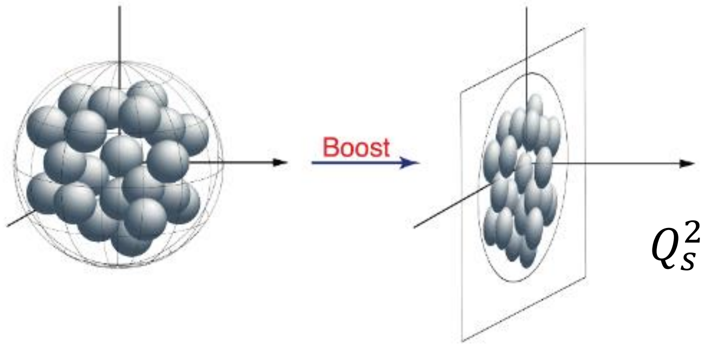


Cross section vs. energy at RHIC in AuAu UPCs

STAR, PRL 133 (2024) 052301
STAR, PRC 110 (2024) 014911



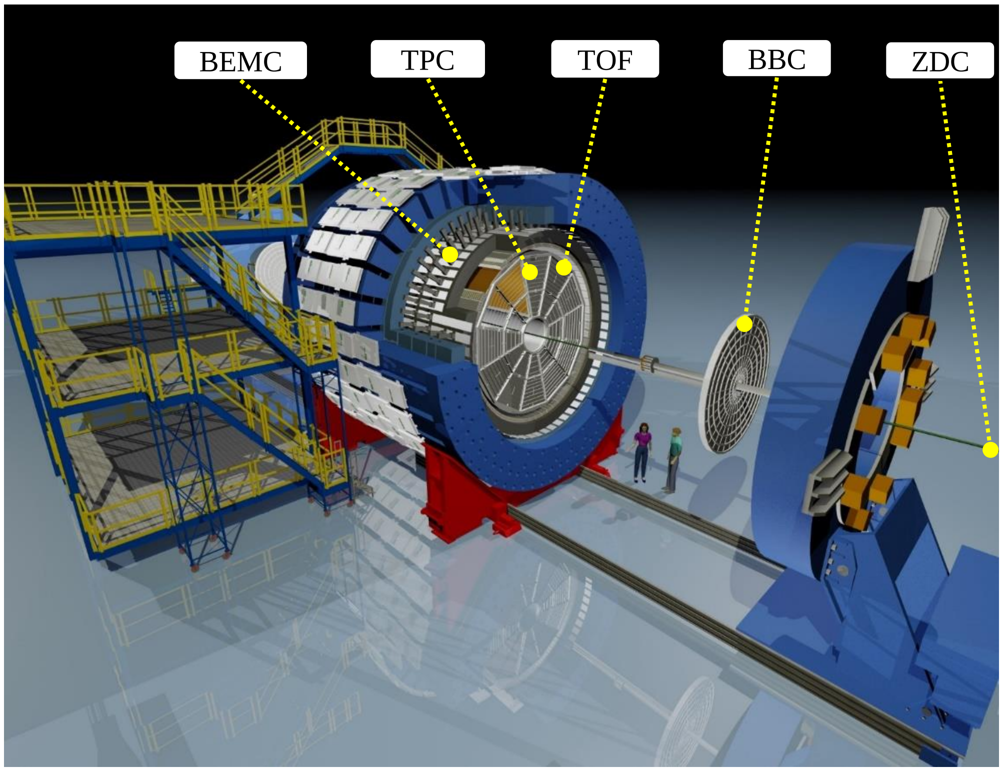
- Coherent J/ψ production in $^{197}_{79}Au + ^{197}_{79}Au$ collisions at $\sqrt{s_{NN}}$ = 200 GeV
  - Lower than Impulse Approximation (with free nucleon) → clear nuclear suppression
  - Consistent with the shadowing model
- Why isobar collisions ($^{96}_{44}Ru, ^{96}_{40}Zr$)?
  - System size dependence of gluon structure



$$Q_s^2 \sim A^{\frac{1}{3}}\left(\frac{1}{x}\right)^{\lambda}$$

L. D. McLerran and Raju Venugopalan, PRD 49 (1994) 2233-2241
L. D. McLerran and Raju Venugopalan, PRD 49 (1994) 3352-3355

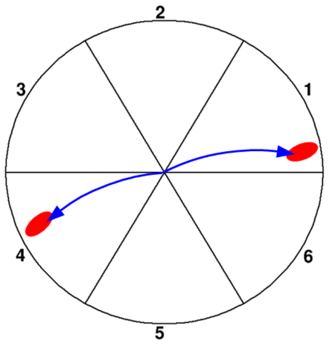
STAR experiment



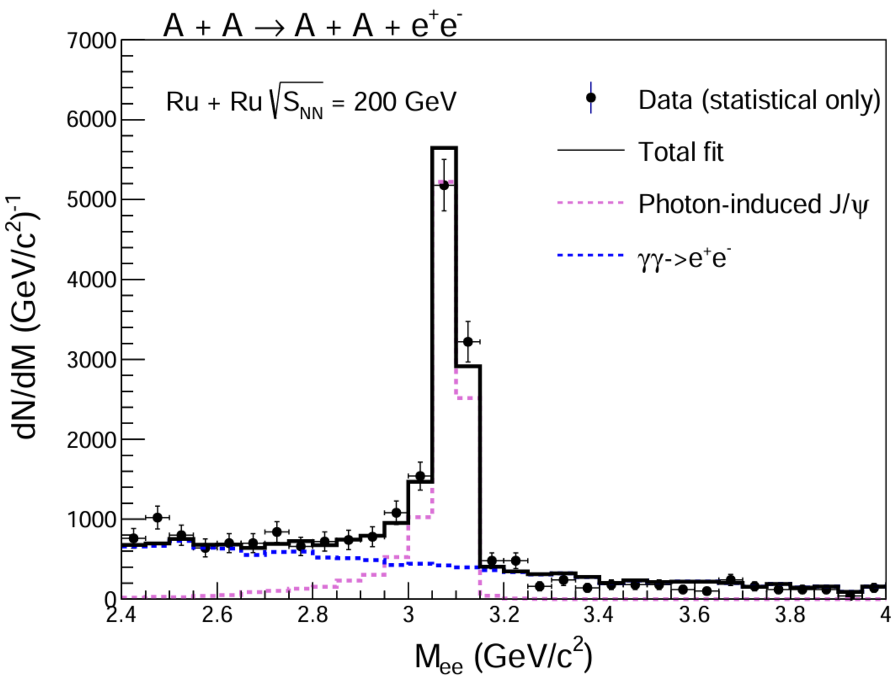
- Time Projection Chamber
  - Tracking
  - Particle identification (dE/dx)
- Barrel ElectroMagnetic Calorimeter
  - Trigger and identify electron/positron
- Time Of Flight Detector
  - Time of flight
  - Particle identification
- Beam-Beam Counters
  - Trigger UPC events
- Zero Degree Calorimeter
  - Neutron tagging

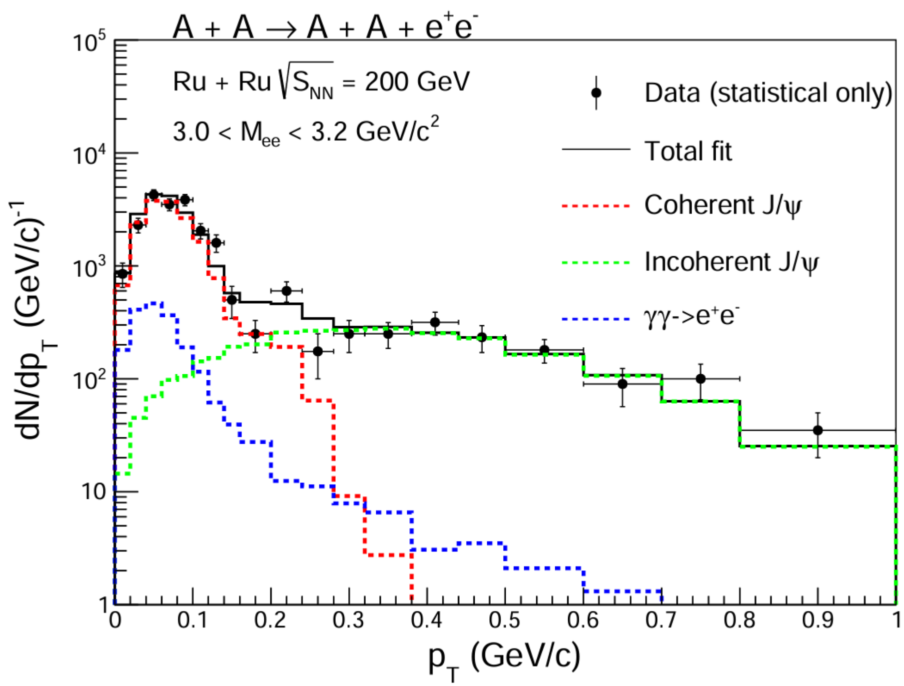
Dataset and analysis detail

Dataset	${}^{96}_{44}Ru + {}^{96}_{44}Ru, {}^{96}_{40}Zr + {}^{96}_{40}Zr$ $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV
Trigger requirements for UPC events	• No signal in BBCs from both sides • $2 \leq$ TOF multiplicity ≤ 6 • BEMC have back-to-back high tower hits
Event selections	• $\lvert V_Z \rvert$<100 cm • BEMC clusters $\leq$ 6
Track selections	• TPC hits used to reconstruct tracks ≥ 15 • TPC hits used to calculate dE/dx ≥ 11 • $p_T > 0.2$ GeV/c, $\lvert\eta\rvert < 1$
Electron identification	• $n\sigma_e = \frac{1}{R_{dE/dx}} log \frac{\langle dE/dx \rangle^{Mea.}}{\langle dE/dx \rangle_e^{Th.}}$ • $\chi^2_{ee} = n\sigma^2_{e1} + n\sigma^2_{e2} < 10$ && $\chi^2_{ee} < \chi^2_{\pi\pi}$



Coherent J/ψ raw yield extraction





Simulation input:
P. Wang et al., CPC 46 (2022) 074103
W. Zha et al., PLB 800 (2020) 135089

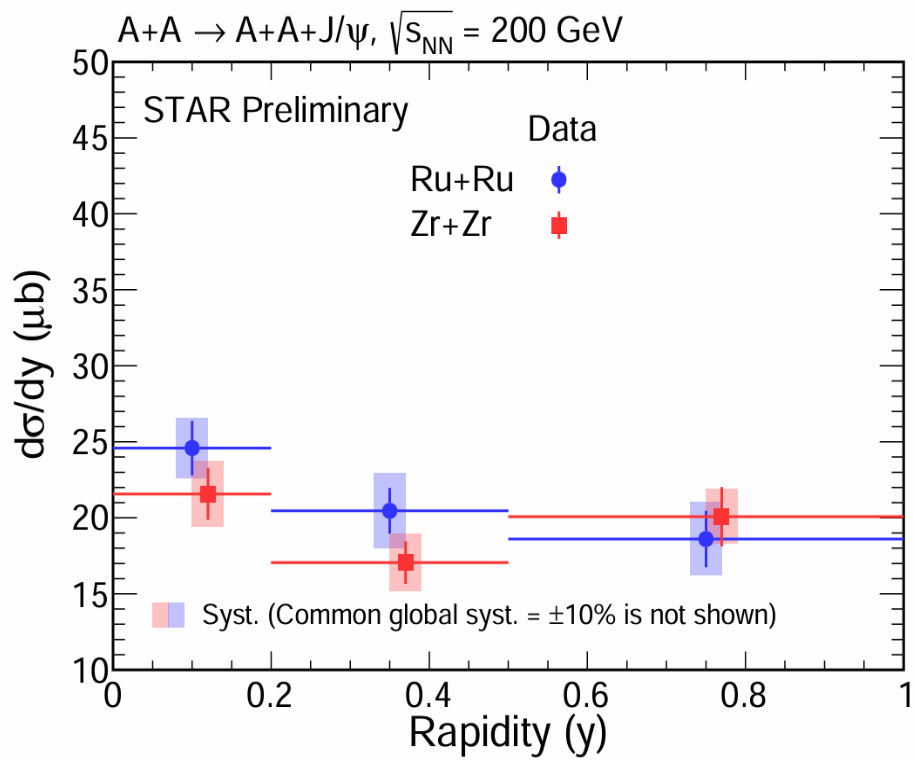
- A combined fit was applied to extract the coherent J/ψ yield:
  - Mass and p_T templates from MC (EPA-VMD and QED calculation) + Geant3

Efficiency correction

$$\frac{d\sigma_{J/\psi}}{dy} = \frac{N_{J/\psi}}{L * acc * eff * BR * \Delta y}$$

- $\sigma_{J/\psi}$: J/ψ cross section
- $N_{J/\psi}$: raw J/ψ yields
- acc: acceptance
- eff: efficiency
- L: total luminosity
- BR: branching ratio for $J/\psi \rightarrow e^{+}e^{-}$
- Δy: rapidity interval

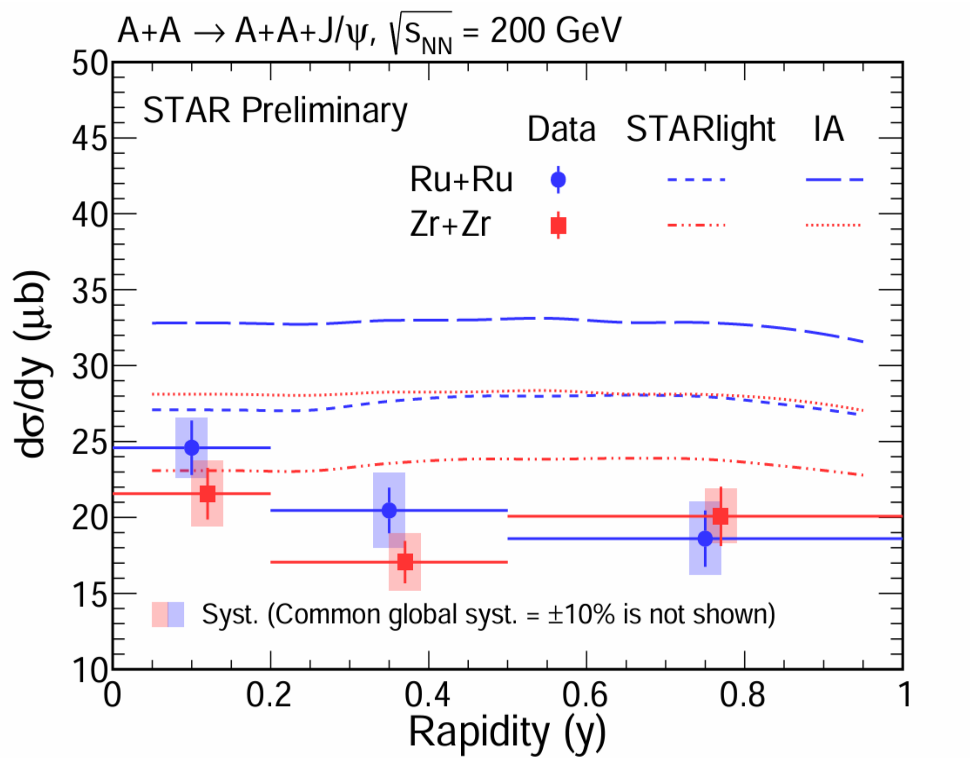
Differential cross section in isobar collision



- Rapidity differential cross section of coherent J/ψ:
  - No clear rapidity (y) dependence

Cross section and model comparisons

Model input:
S.R. Klein et al., CPC 212 (2017) 258

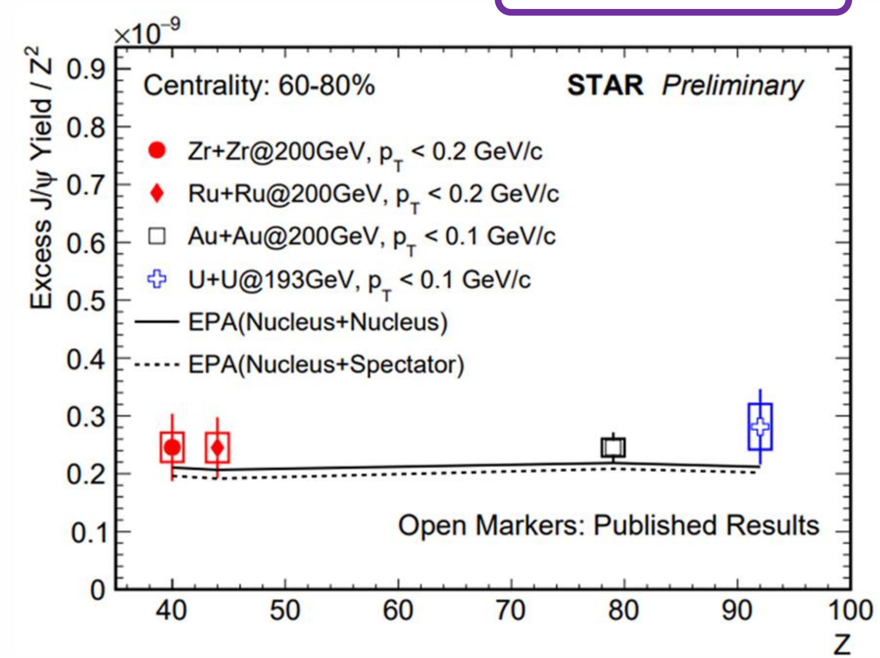


- Rapidity differential cross section of coherent J/ψ:
  - No clear rapidity (y) dependence
- Model comparisons:
  - Data ~ 30% lower than IA → Strong suppression in Ru/Zr collisions
  - Data ~ 20% lower than STARlight (with nuclear shadowing)

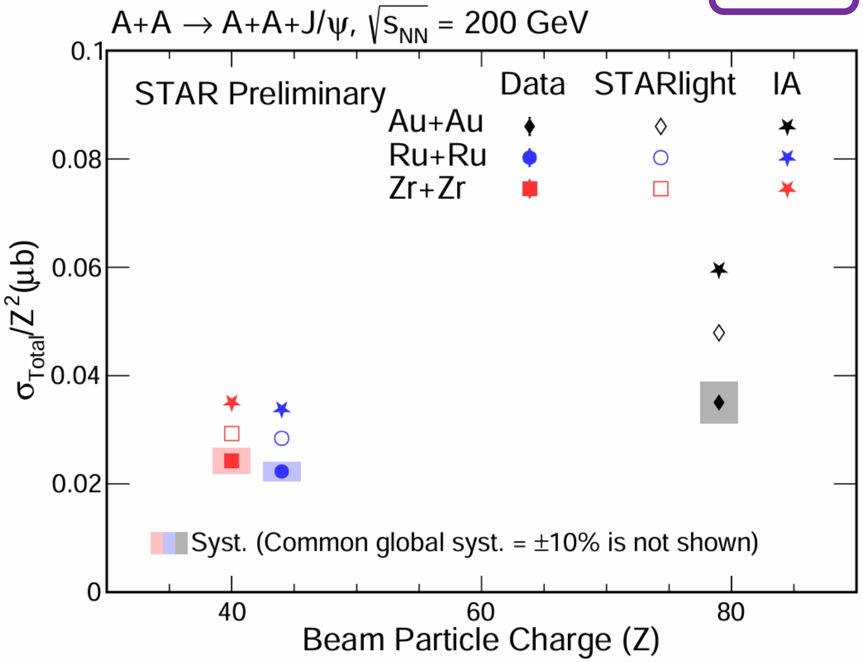
Z dependence of coherent J/ψ production

STAR, PRL 123 (2019) 132302
W. Zha et al., PRC 97 (2018) 044910

Peripheral collision

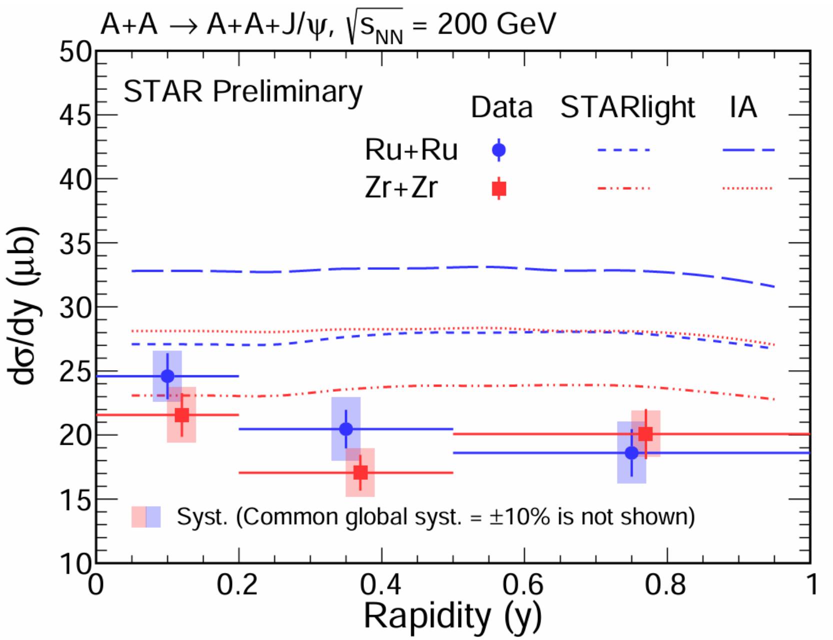


UPCs

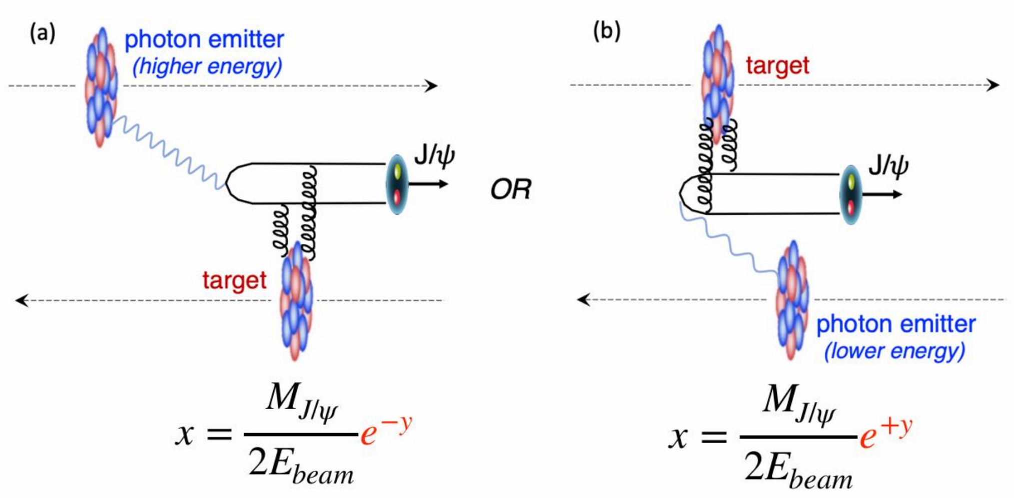


- Roughly cancel out photon flux dependence by dividing by Z^2
  - Data in peripheral collision are found to be flat vs. Z
  - Data in isobaric UPCs are consistent within uncertainties
  - A hint of enhancement (less than 3σ) in Au + Au w.r.t. isobar

"Two-way ambiguity" in AA collision



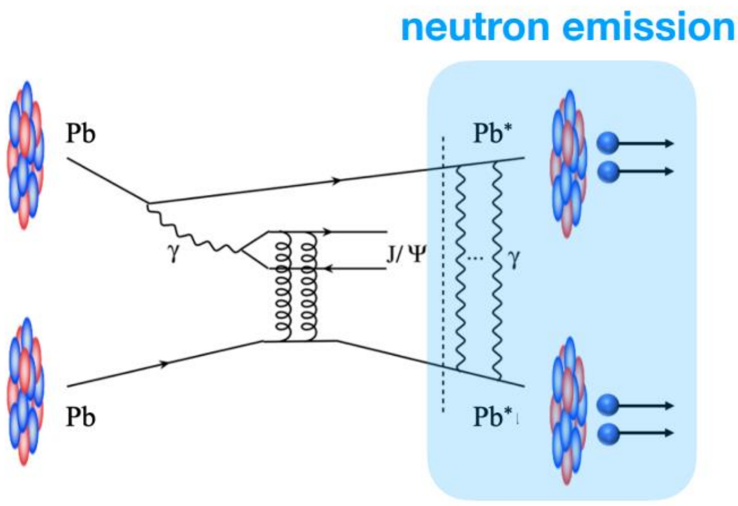
Two-way ambiguity in A+A UPC



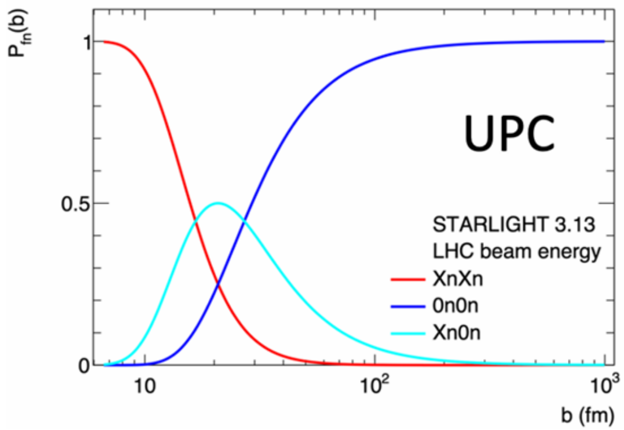
$$\frac{d\sigma_{AA\to AA'J/\psi}}{dy} = N_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N_{\gamma/A}(\omega_2)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_2)}$$

- Obtain fraction of the J/ψ cross section produced by high energy photons - low *x* gluons (or vice versa)

How to disentangle smaller and larger x



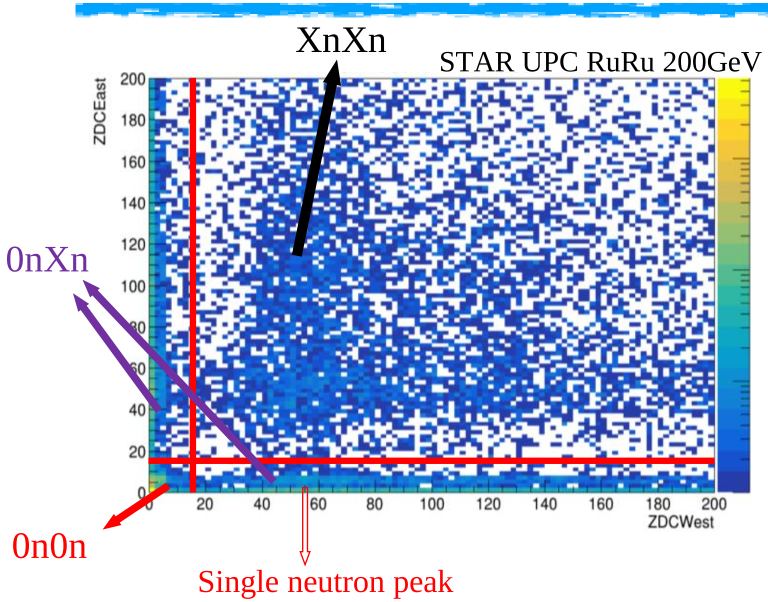
Klein and Steinberg, ARNPS 70 (2020) 323

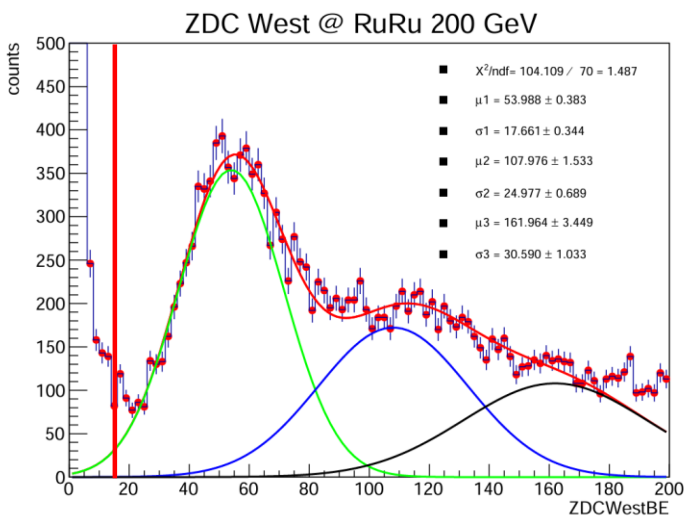


$$N(k) = \int d^2N(k,,b)P_{0had}(b)P_1(b)P_2(b)\,, P_i(b) \propto 1/b^2$$

- Nuclei may exchange soft photon(s) leading to nuclear dissociation and neutron emission. The nuclear dissociation probability is related to impact parameter (b)
- Neutron multiplicity (0n0n, 0nXn, XnXn) can help to control b
  - $b_{XnXn} < b_{0nXn} < b_{0n0n}$

A solution to the "Photon energy ambiguity"





Experimental measurements

Photon flux from theory

$$\frac{d\sigma^{0n0n}_{AA\to AA'J/\psi}}{dy} = N^{0n0n}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{0n0n}_{\gamma/A}(\omega_2)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_2)}$$

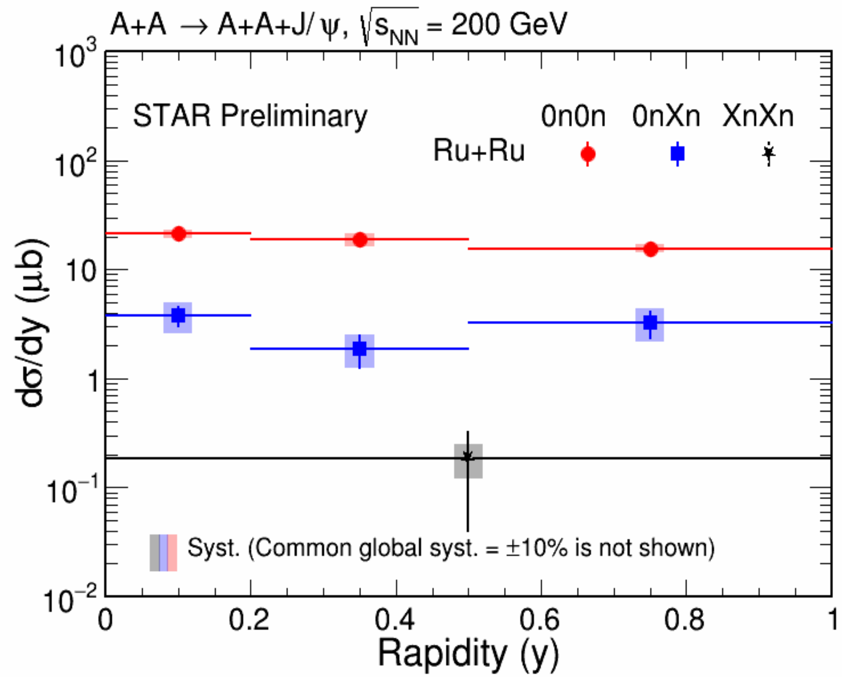
$$\frac{d\sigma^{0nXn}_{AA\to AA'J/\psi}}{dy} = N^{0nXn}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{0nXn}_{\gamma/A}(\omega_2)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_2)}$$

$$\frac{d\sigma^{XnXn}_{AA\to AA'J/\psi}}{dy} = N^{XnXn}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{XnXn}_{\gamma/A}(\omega_2)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_2)}$$

What we want!

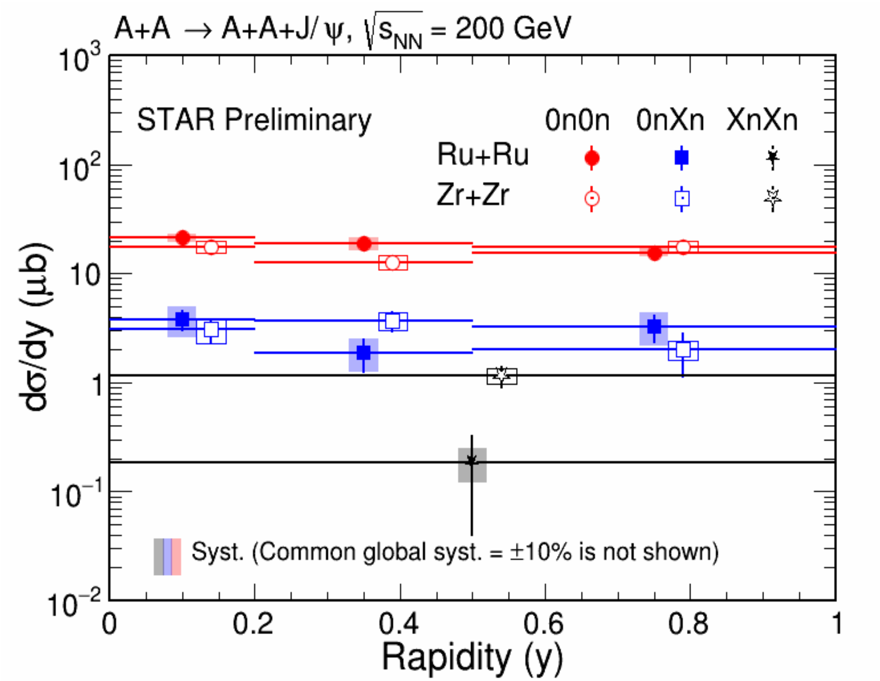
- Clear neutron signals in ZDC detector
- Gaussian function is used to fit the neutron peak
- Measuring cross sections in different neutron multiplicities (0n0n, 0nXn, XnXn) can solve the two-way ambiguity

dσ/dy with different neutron multiplicity



- Fully corrected data (eff, acc and neutron multiplicity migration…)
  - dσ/dy distributions with different neutron multiplicity are flat vs. y

dσ/dy with different neutron multiplicity



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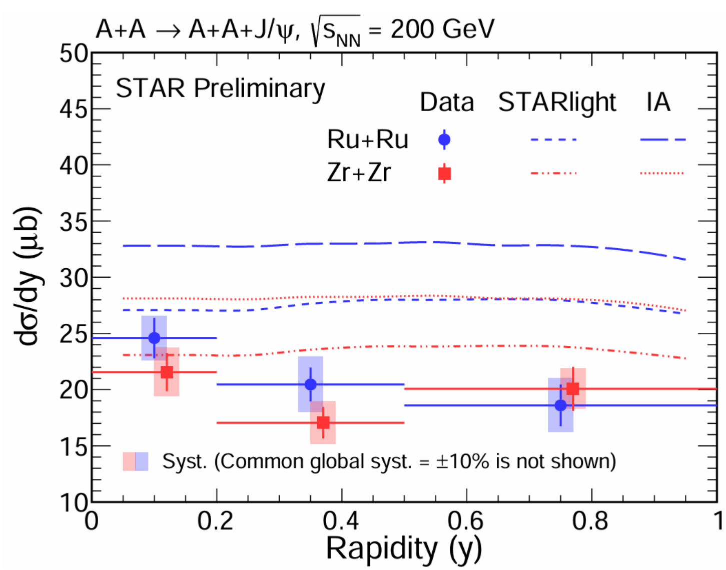
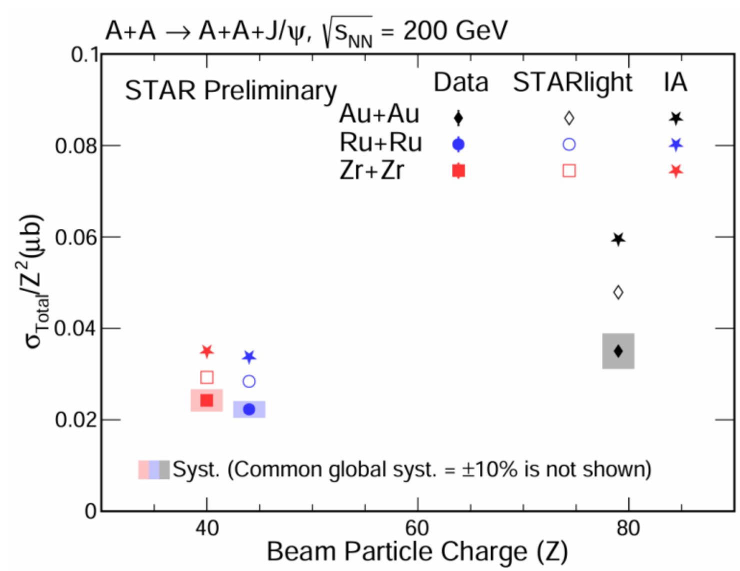
Summary

- Photon-induced coherent J/ψ cross section in isobar UPCs at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV
  - Strong nuclear suppression is observed
  - A Hint of enhancement (less than 3σ) from Isobar to Au at the top RHIC energy
- Cross sections in different neutron multiplicity are measured
  - Next: disentangle the smaller and larger x contributions





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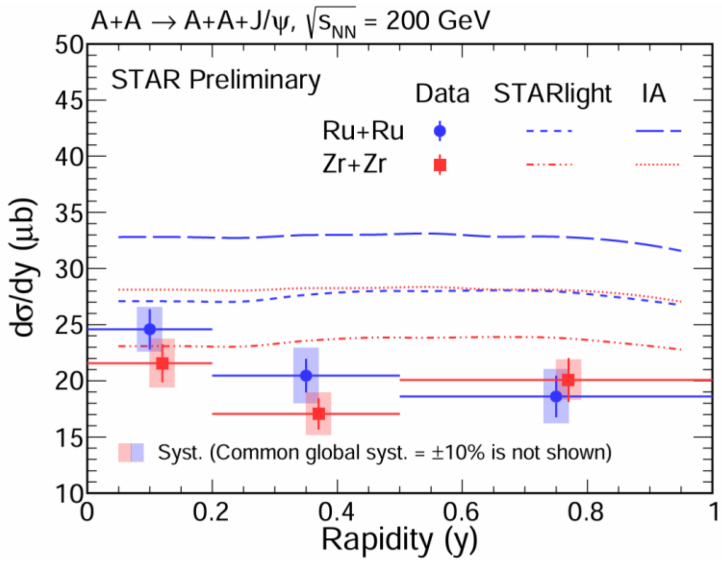
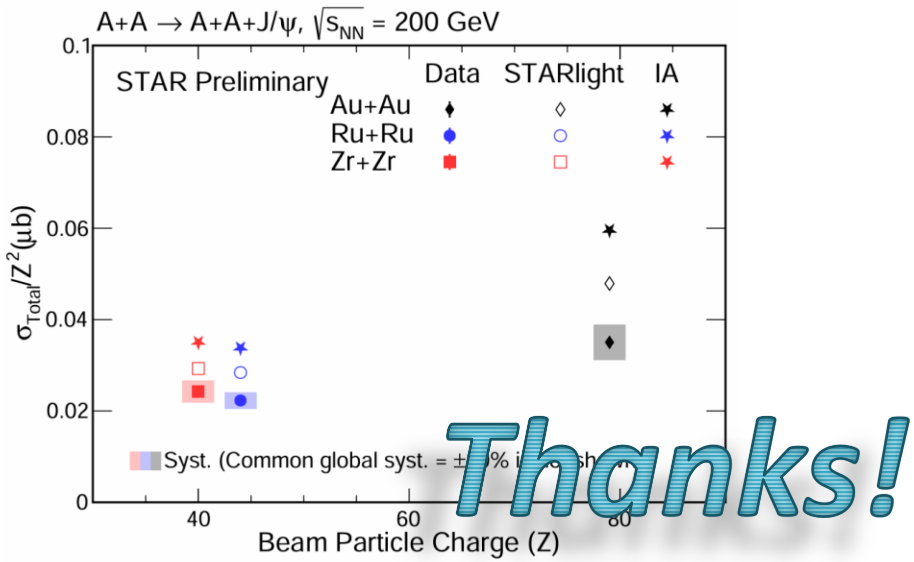
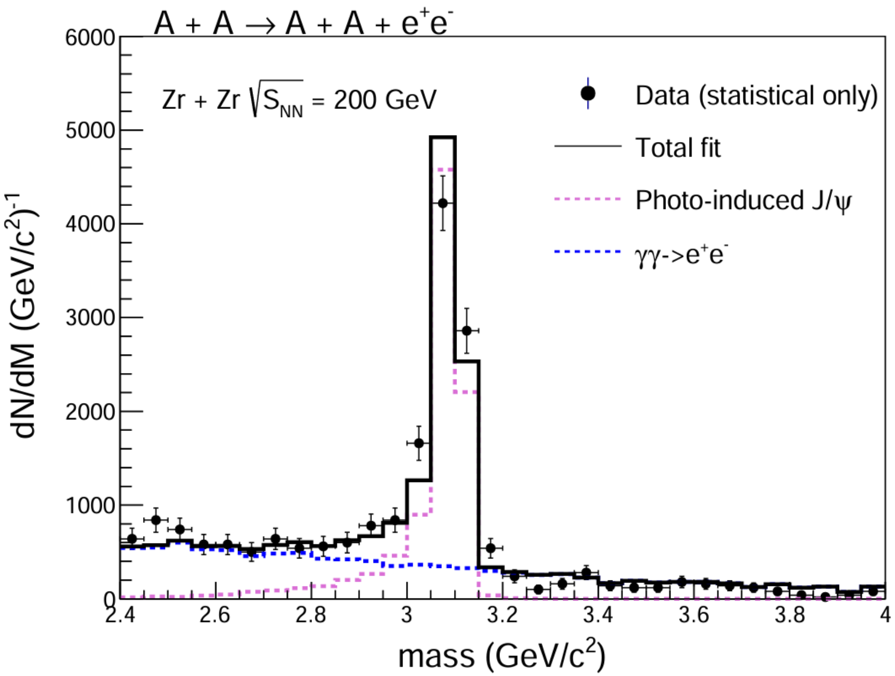
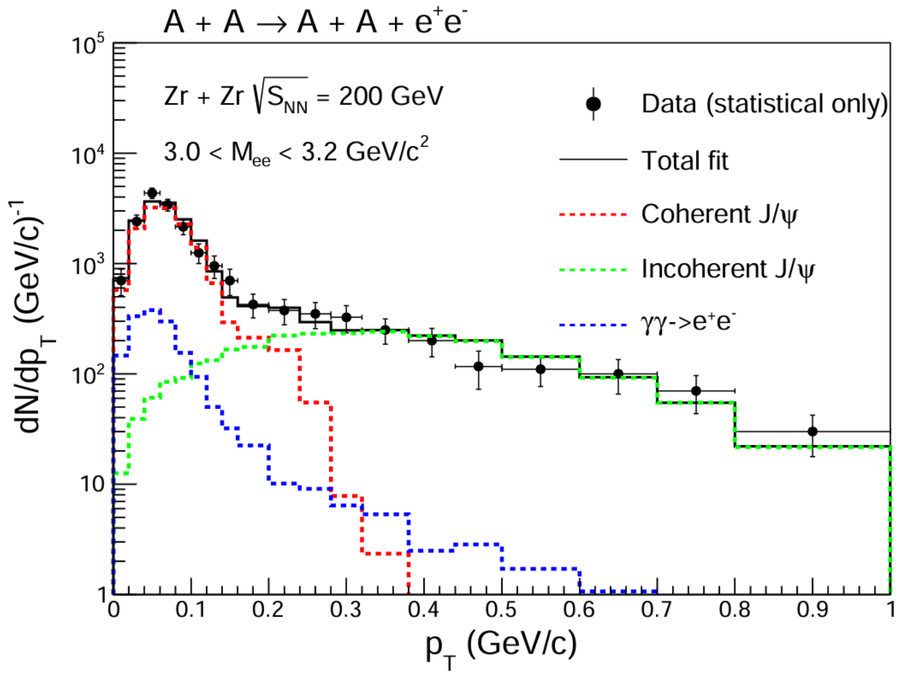




Back up

J/ψ raw yields extraction



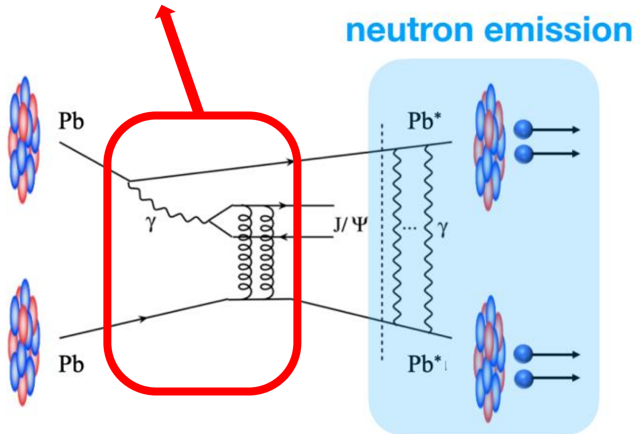


- The same method is used to get the contribution of the coherent J/ψ in the Zr + Zr collision, and the fit results in mass and p_T spectrum are shown

Migration

- Most of the efficiencies have no neutron multiplicity dependence.

Main process   Another process



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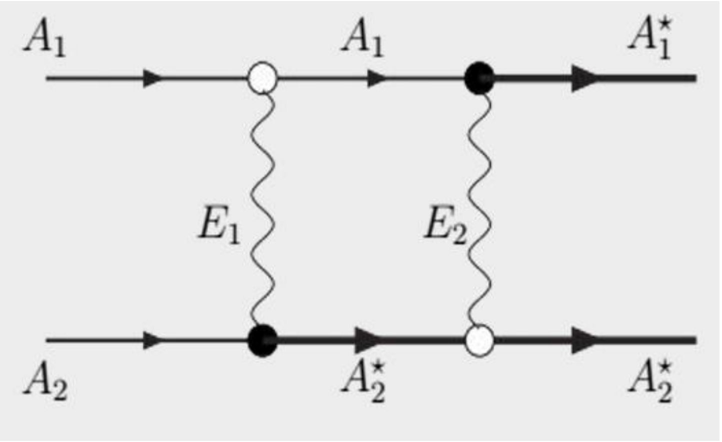


signal event

noise event

- One is the interested photo-nclear event which may be in conjunction with the dissociation of the same ion pair, the other is pure lead dissociation event without photo-pomeron interaction. It’s dissociative pileup -> “Migration”.

Migration correction

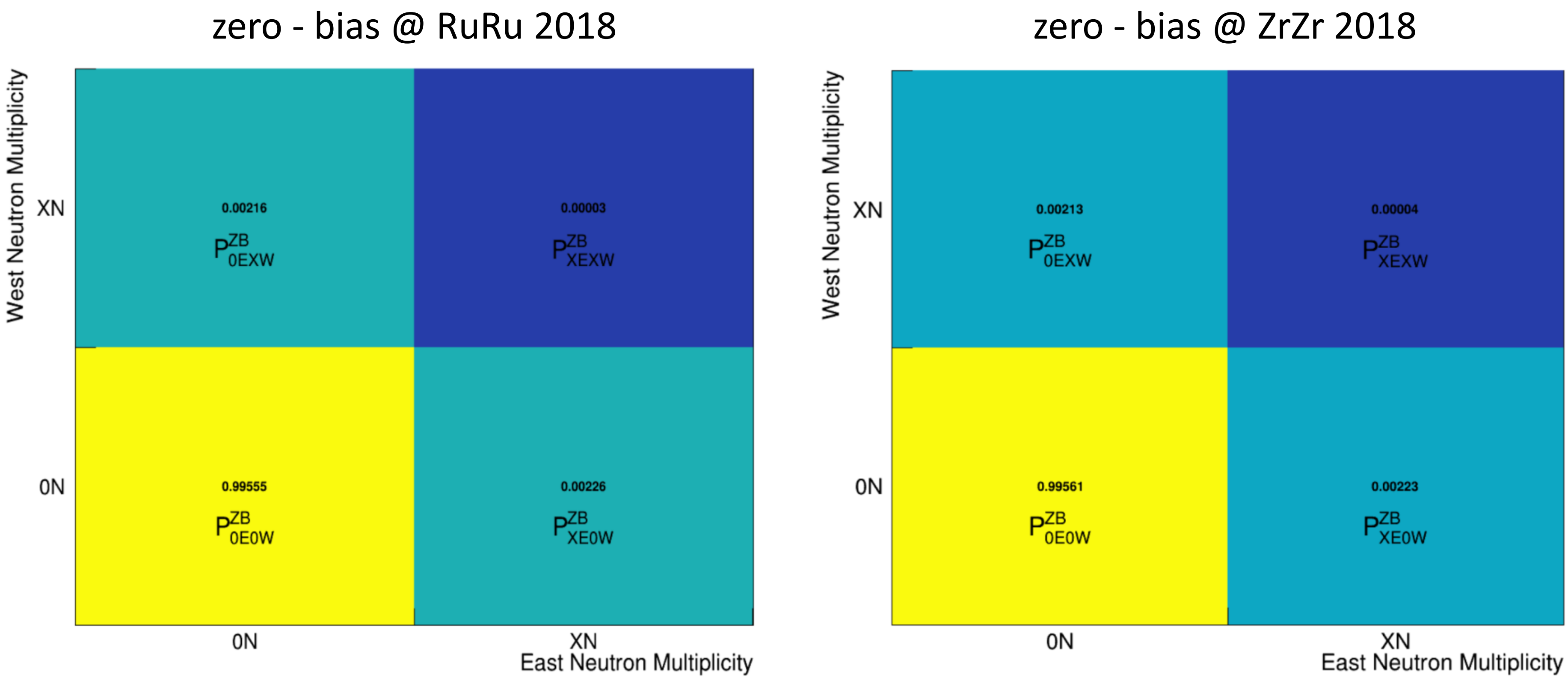
- The relation between measured yields and true yields for various neutron multiplicity bins can be found in this matrix:

$$\begin{bmatrix} 0E0W \\ 0EXW \\ XE0W \\ XEXW \end{bmatrix}^{measure} = \begin{bmatrix} P_{0E0W}^{0E0W} & 0 & 0 & 0 \\ P_{0E0W}^{0EXW} & P_{0EXW}^{0EXW} & 0 & 0 \\ P_{0E0W}^{XE0W} & 0 & P_{XE0W}^{XE0W} & 0 \\ P_{0E0W}^{XEXW} & P_{0EXW}^{XEXW} & P_{XE0W}^{XEXW} & P_{XEXW}^{XEXW} \end{bmatrix} \begin{bmatrix} 0E0W \\ 0EXW \\ XE0W \\ XEXW \end{bmatrix}^{\mathrm{ture}}$$

- $[True] = [P]^{-1}[Measure]$
- The matrix elements is the migration probability, and can be get by using the zero-bias data

$$\begin{aligned}
&P_{0E0W}^{0E0W} = P_{0E0W}^{ZB} \\
&P_{0E0W}^{0EXW} = P_{0EXW}^{ZB},\ P_{0EXW}^{0EXW} = P_{0E0W}^{ZB} + P_{0EXW}^{ZB} \\
&P_{0E0W}^{XE0W} = P_{XE0W}^{ZB},\ P_{XE0W}^{XE0W} = P_{0E0W}^{ZB} + P_{XE0W}^{ZB} \\
&P_{0E0W}^{XEXW} = P_{XEXW}^{ZB},\ P_{0EXW}^{XEXW} = P_{XE0W}^{ZB} + P_{XEXW}^{ZB},\ P_{XE0W}^{XEXW} = P_{0EXW}^{ZB} + P_{XEXW}^{ZB},\ P_{XEXW}^{XEXW} = 1
\end{aligned}$$

Migration correction



Selections:

- BBC have no hits in both sides, nTOFMult ≤ 6, nPrimaryTracks $= 0$ are used to reject the hadronic contribution.