Nuclear structure input and CME

Guo-Liang Ma
(Fudan University)

"Intersection of nuclear structure and high - energy nuclear collisions"
—INT PROGRAM INT-23-1A

Based on arXiv: Xin-Li Zhao, Bang-Xiang Chen, GLM, 2203.15214, 2301.12076

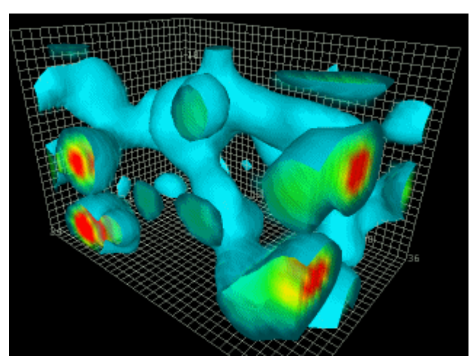
Outline

- Introduction
- Model setup
- Nuclear structure and CME in isobar collisions
- Reexamine two-plane method
- Summary and outlook

Detect QCD vacuum and symmetry with CME

Looking for QCD vacuum fluctuation

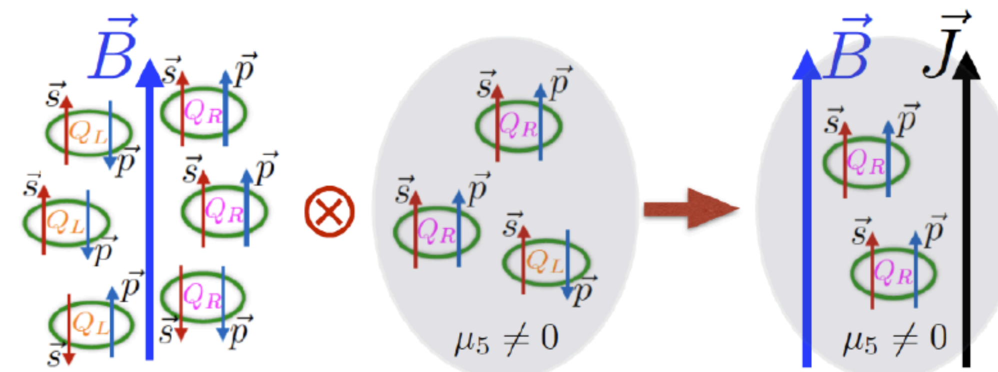
$$Q_W = \frac{\alpha_s}{8\pi}\int G^{\alpha}_{\mu\nu}\tilde{G}^{\mu\nu}_{\alpha}\, d\mathbf{r}dt$$



Topological charge: $Q_w \neq 0$

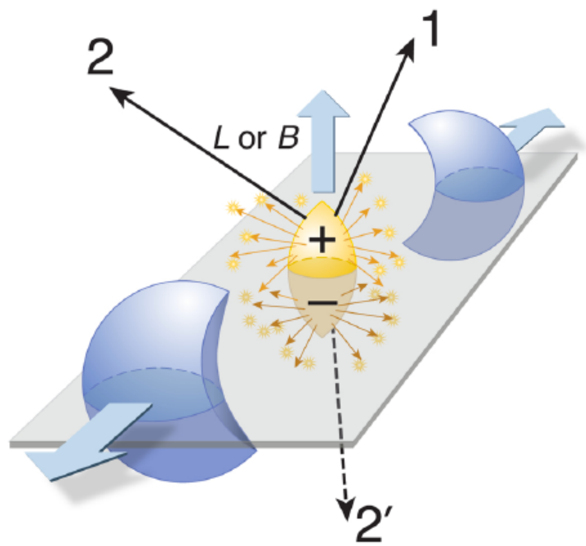
- Chiral imbalance: $Q_w = N_L - N_R \neq 0$
- Local $\mathcal{P}$ or $\mathcal{CP}$ violation in strong interactions

CME induces
electric dipole charge separation



Chiral Magnetic Effect: $\mathbf{J} = \frac{Qe}{2\pi^2}\mu_5 \mathbf{B}$

CME experimental observable: charge azimuthal correlation γ



Voloshin 2004

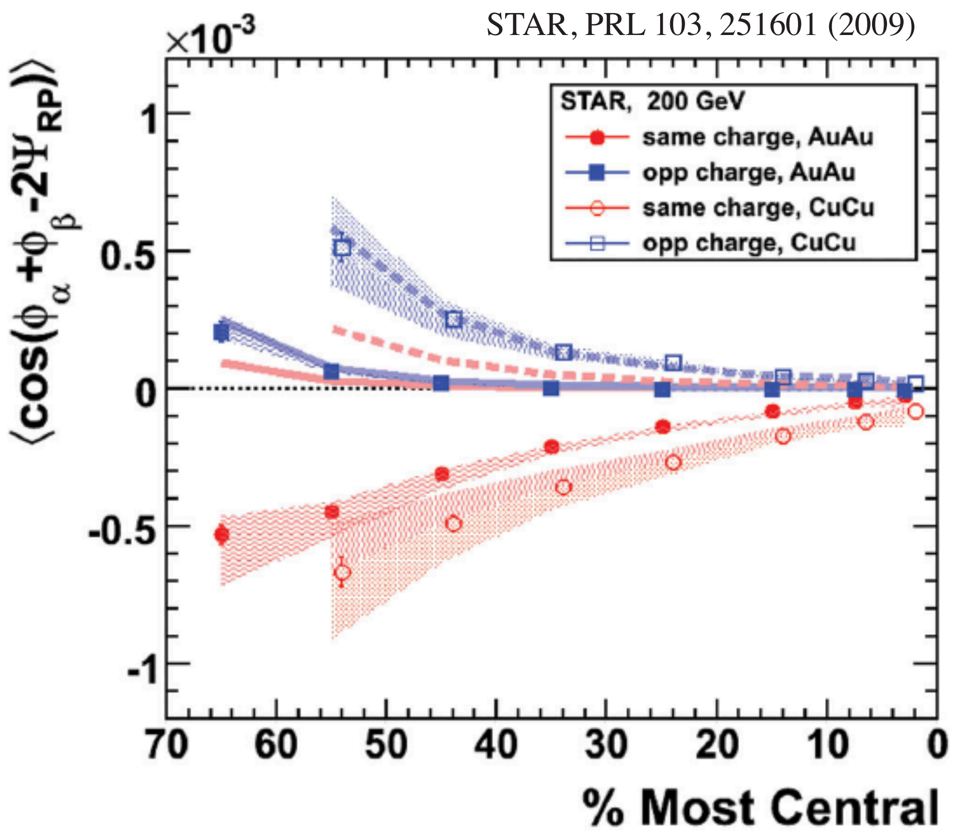
$$\gamma = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle = [\langle v_{1,\alpha} v_{1,\beta} \rangle + B_{in}] - [\langle a_\alpha a_\beta \rangle + B_{out}]$$

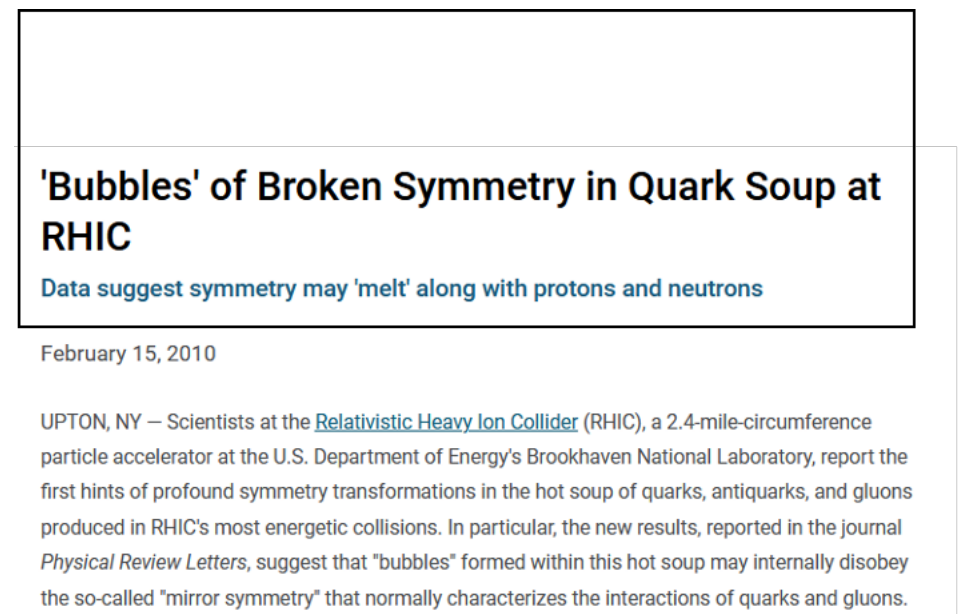
Non-flow/non-parity effects: largely cancel out

Directed flow: vanishes if measured in a symmetric rapidity range

P-even quantity: still sensitive to charge separation

STAR, PRL 103, 251601 (2009)



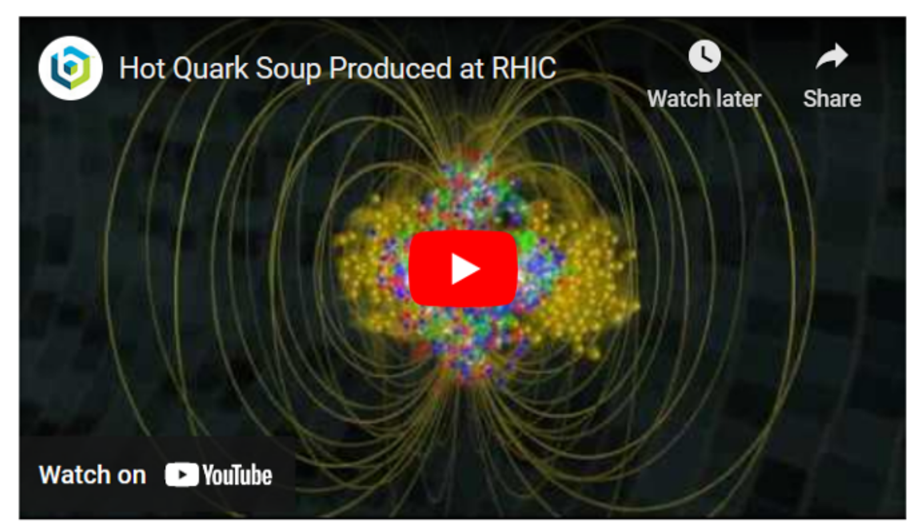


'Bubbles' of Broken Symmetry in Quark Soup at RHIC

Data suggest symmetry may 'melt' along with protons and neutrons

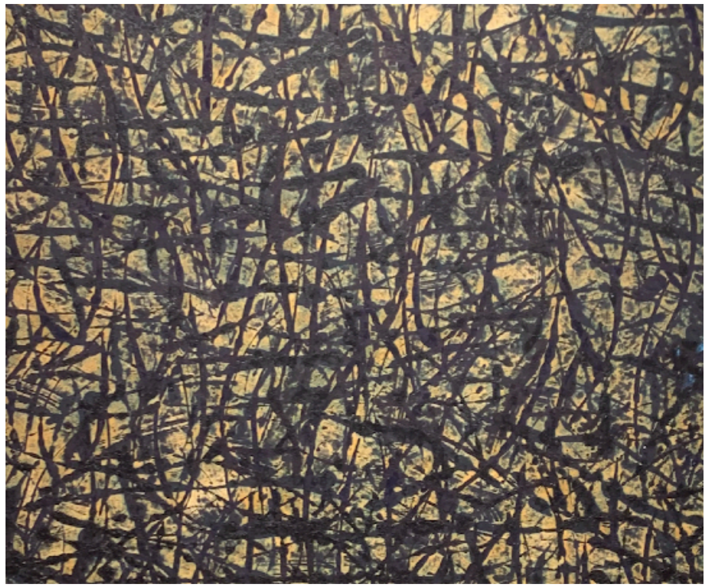
February 15, 2010

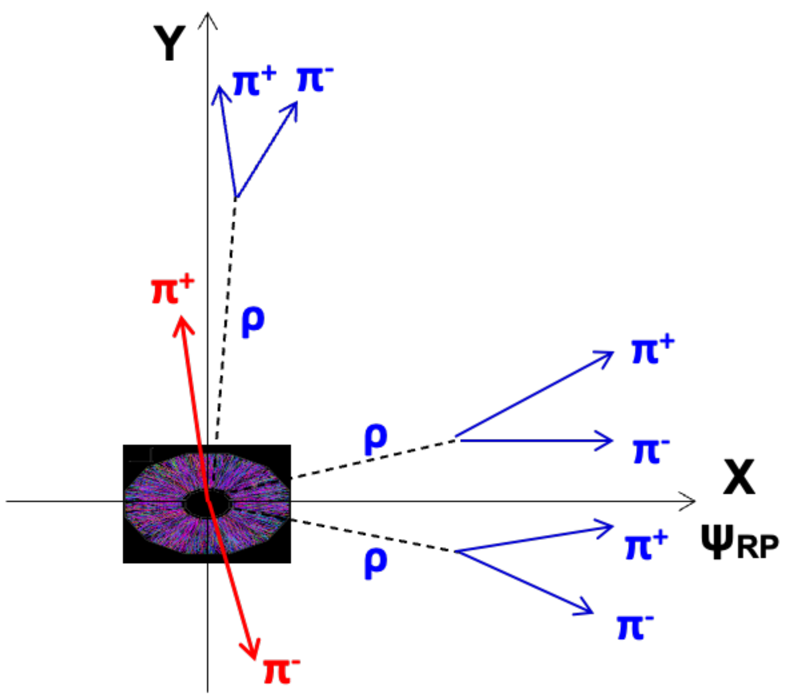
UPTON, NY — Scientists at the Relativistic Heavy Ion Collider (RHIC), a 2.4-mile-circumference particle accelerator at the U.S. Department of Energy's Brookhaven National Laboratory, report the first hints of profound symmetry transformations in the hot soup of quarks, antiquarks, and gluons produced in RHIC's most energetic collisions. In particular, the new results, reported in the journal *Physical Review Letters*, suggest that "bubbles" formed within this hot soup may internally disobey the so-called "mirror symmetry" that normally characterizes the interactions of quarks and gluons.



• The first STAR experiment result is consistent with 'Dipole Charge Separation' as expected by CME.

Background vs signal

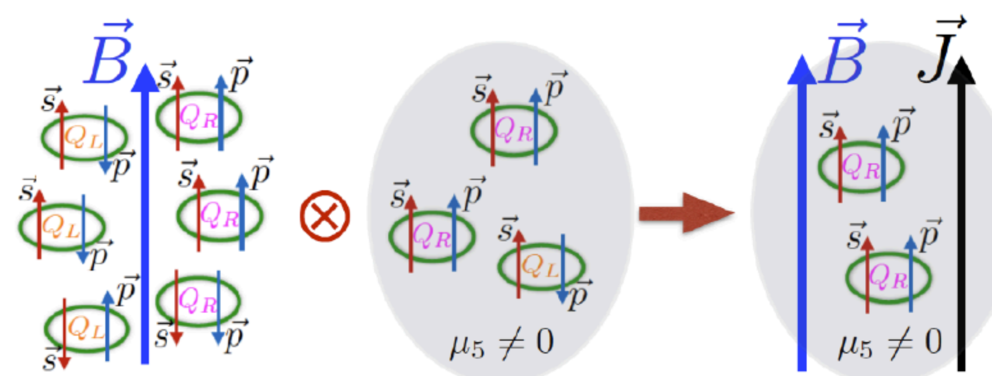




Fuqiang 2009; Bzdak, Koch, Liao 2010;
Pratt, Schlichting 2010; ⋯

•Backgrounds: elliptic flow, resonance, LCC etc.

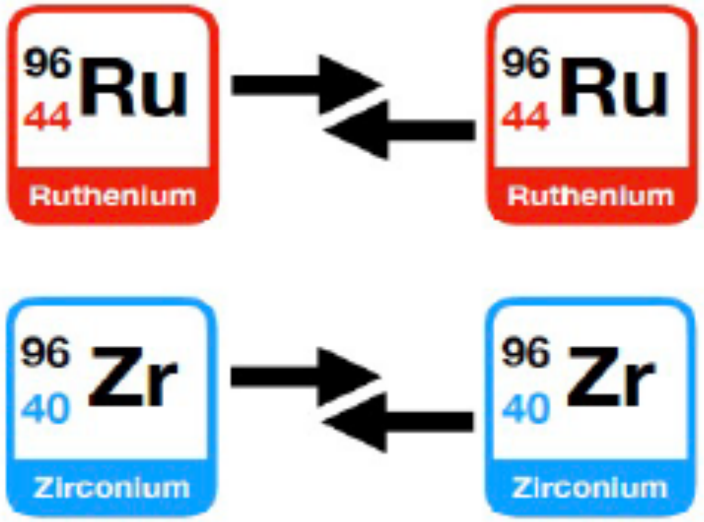
•Recent STAR results indicate that the CME fraction inside $\Delta\gamma$ is small, and the background is dominant!

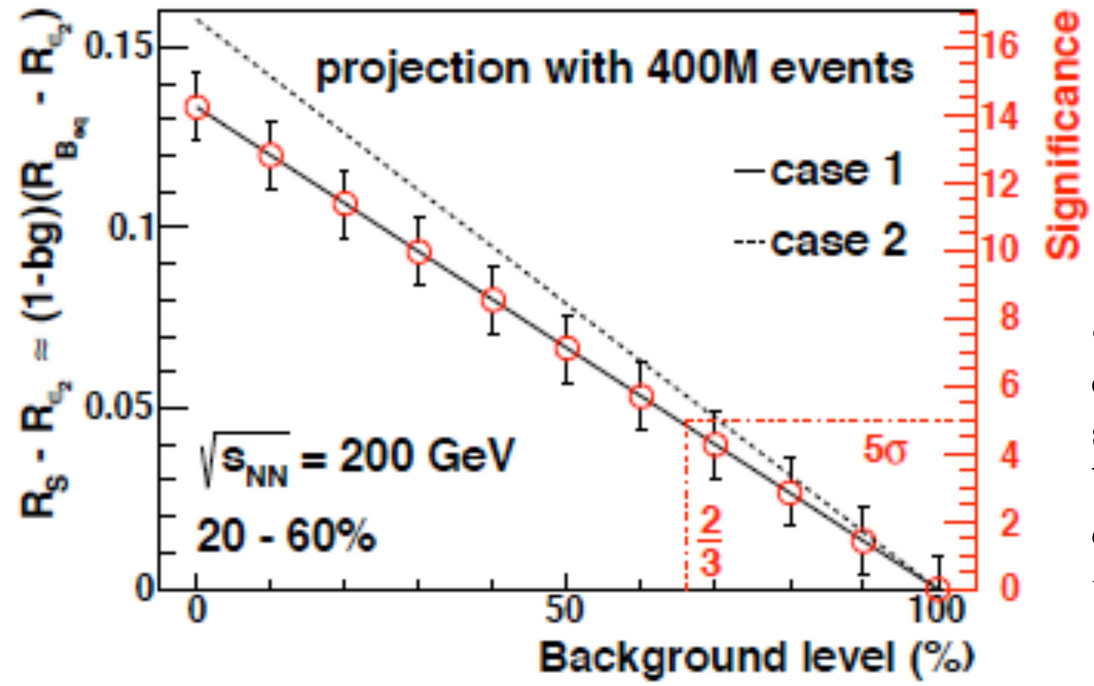


Chiral Magnetic Effect: $\mathbf{J} = \dfrac{Qe}{2\pi^2}\mu_5\mathbf{B}$

•What is a good way to reduce the influence of the background to find the signal?

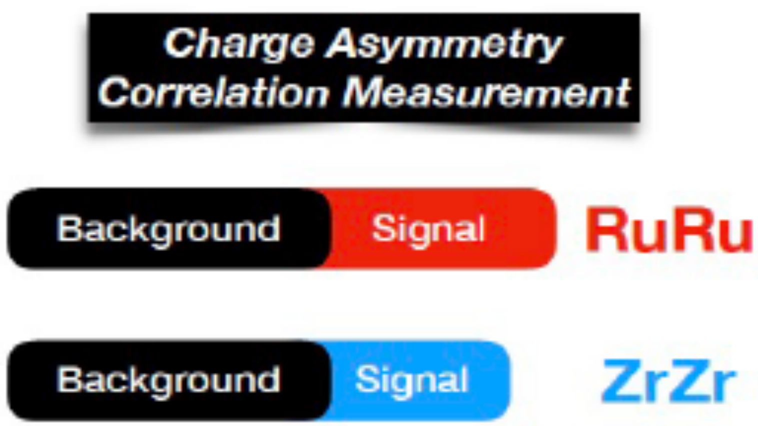
Isobar collisions



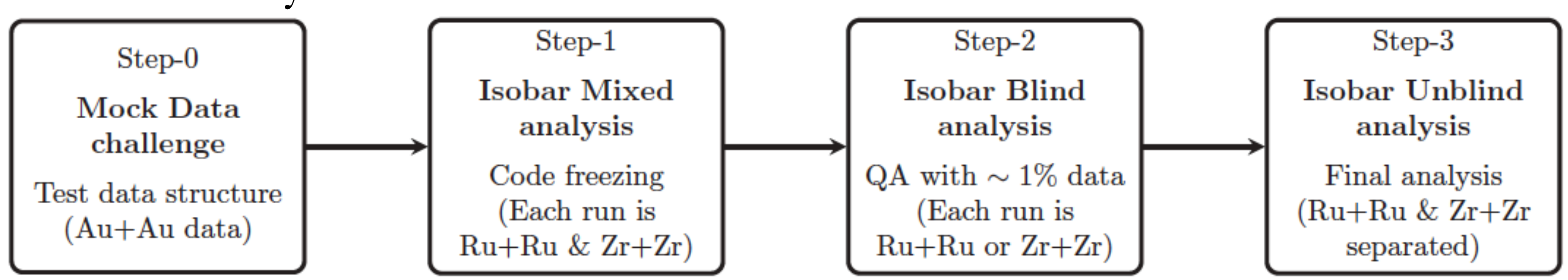


WTD, XGH, GLM, GW, Phys. Rev. C 94 (R), 041901 (2016)

- 400 million simulation events at 2/3 background scale, relative difference between two isobar collisions reaches 5%, and the significance is 5σ.



Blind analysis:



- In 2018, STAR collected isobar data (1.8B Ru+Ru && 2.0B Zr+Zr), looking for the CME expectation.
- Five teams conducted blind analysis.

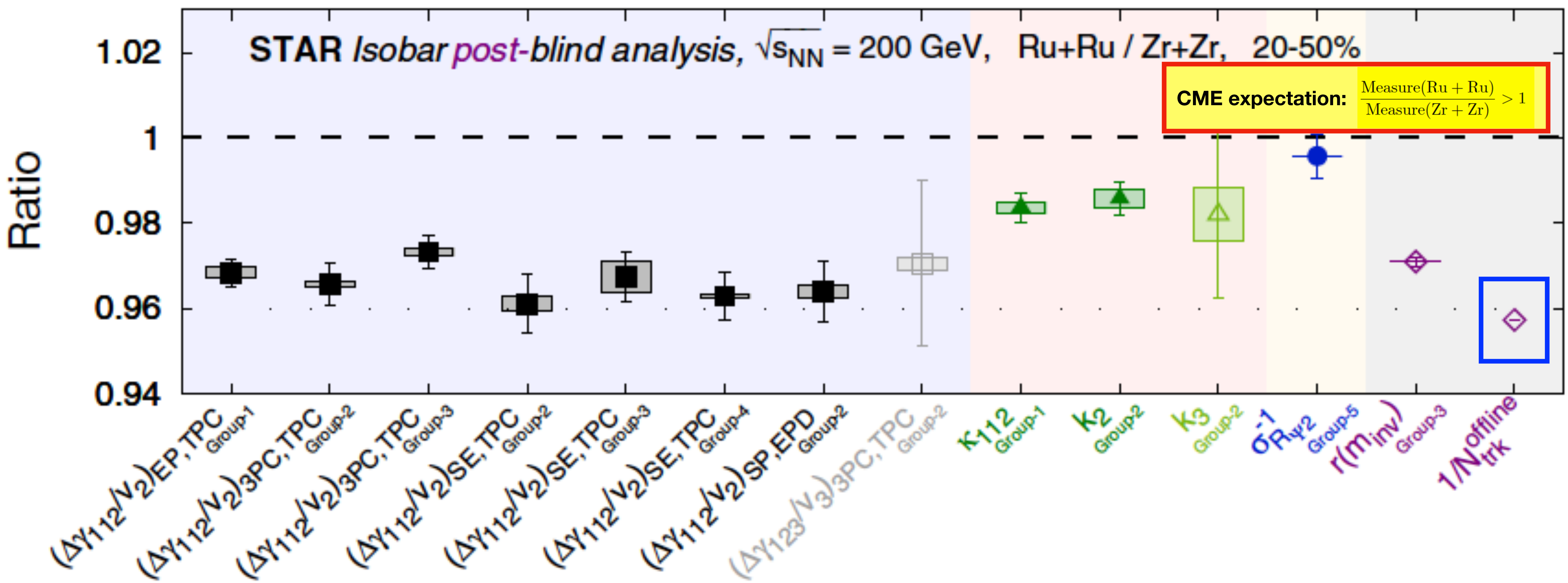
CME expectation:

$$\frac{\text{Measure}(\text{Ru}+\text{Ru})}{\text{Measure}(\text{Zr}+\text{Zr})} > 1$$

PHYSICAL REVIEW C **105**, 014901 (2022)

First isobar results from STAR experiment

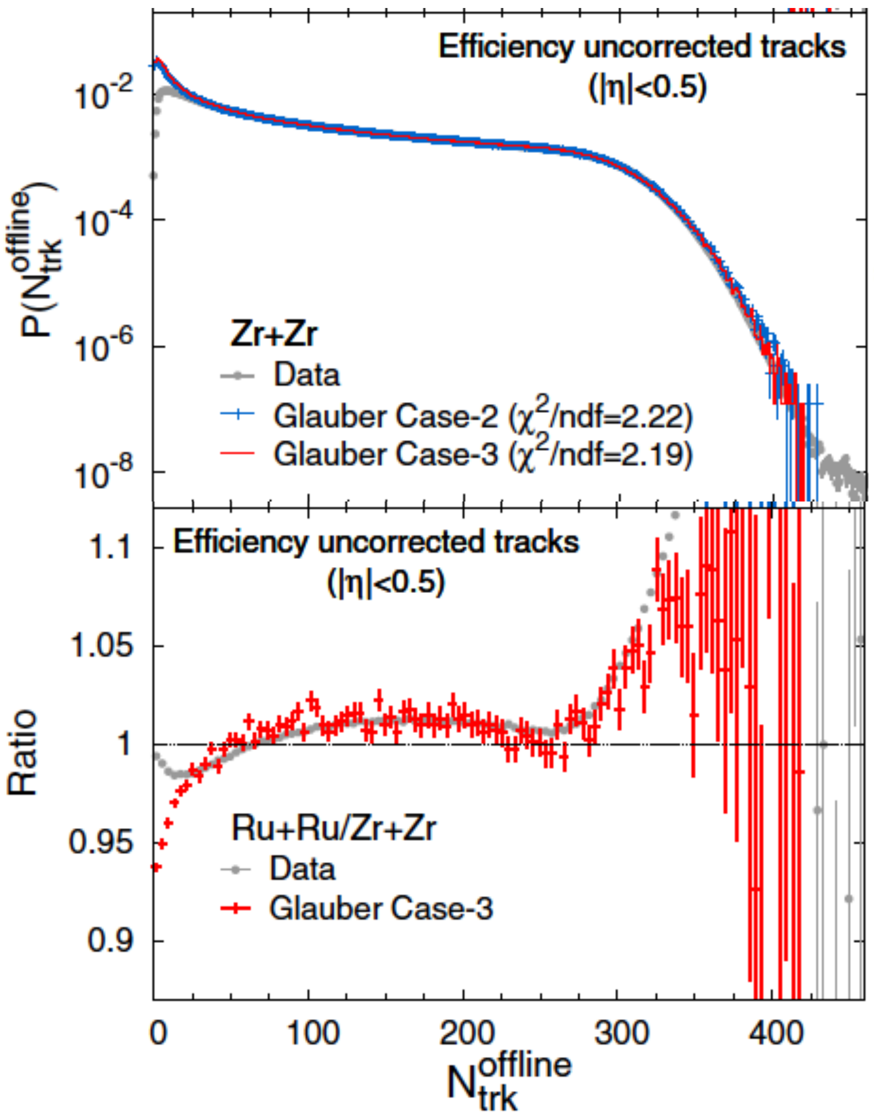
Search for the chiral magnetic effect with isobar collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR Collaboration at the BNL Relativistic Heavy Ion Collider

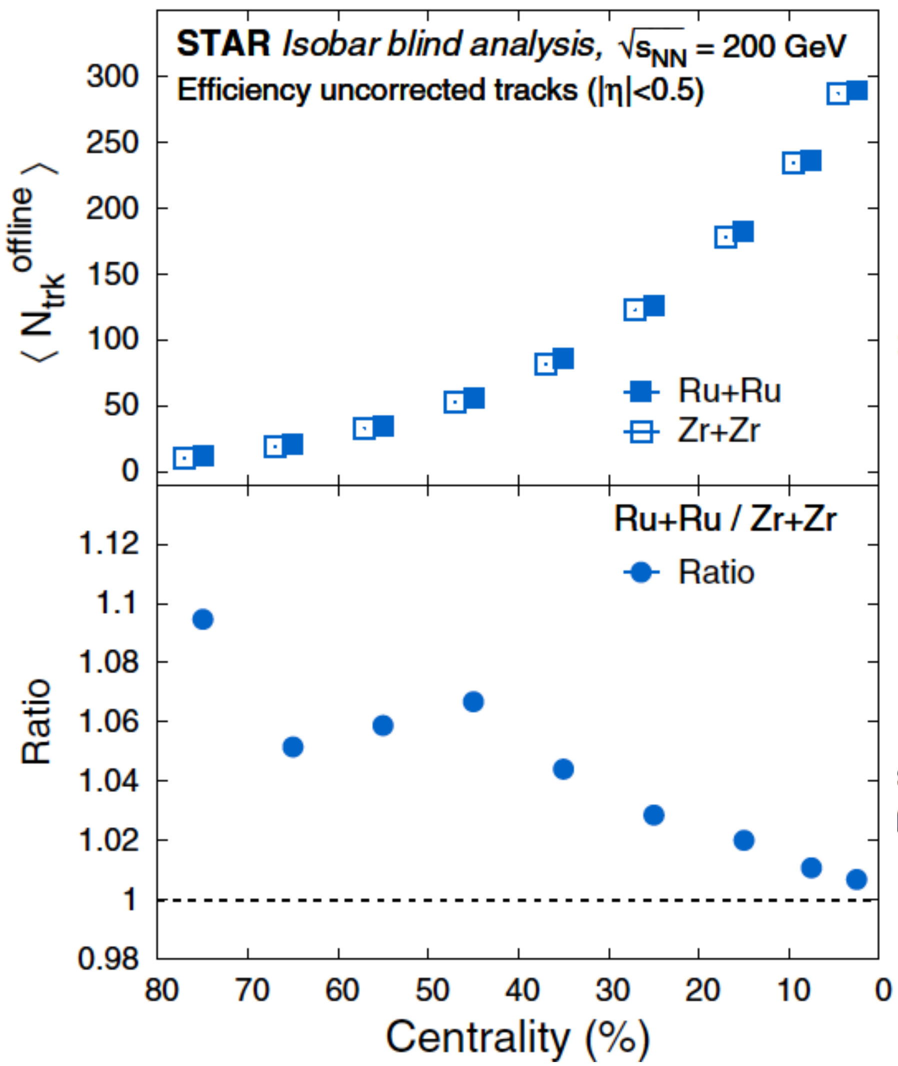


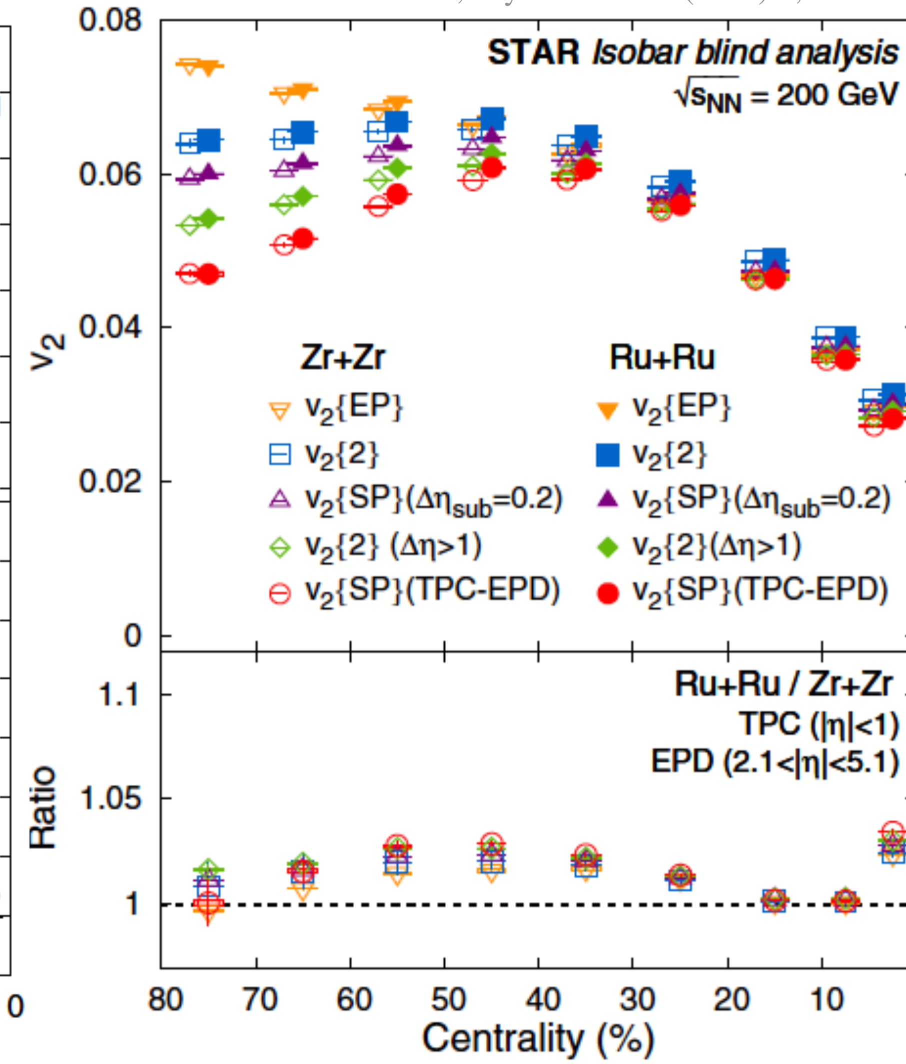
- The five experimental analysis groups agreed that "The ratios are generally less than 1, and no obvious CME signal is found.”
- How to understand these results?

Why different backgrounds between isobar collisions

STAR, Phys.Rev.C 105 (2022) 1, 014901







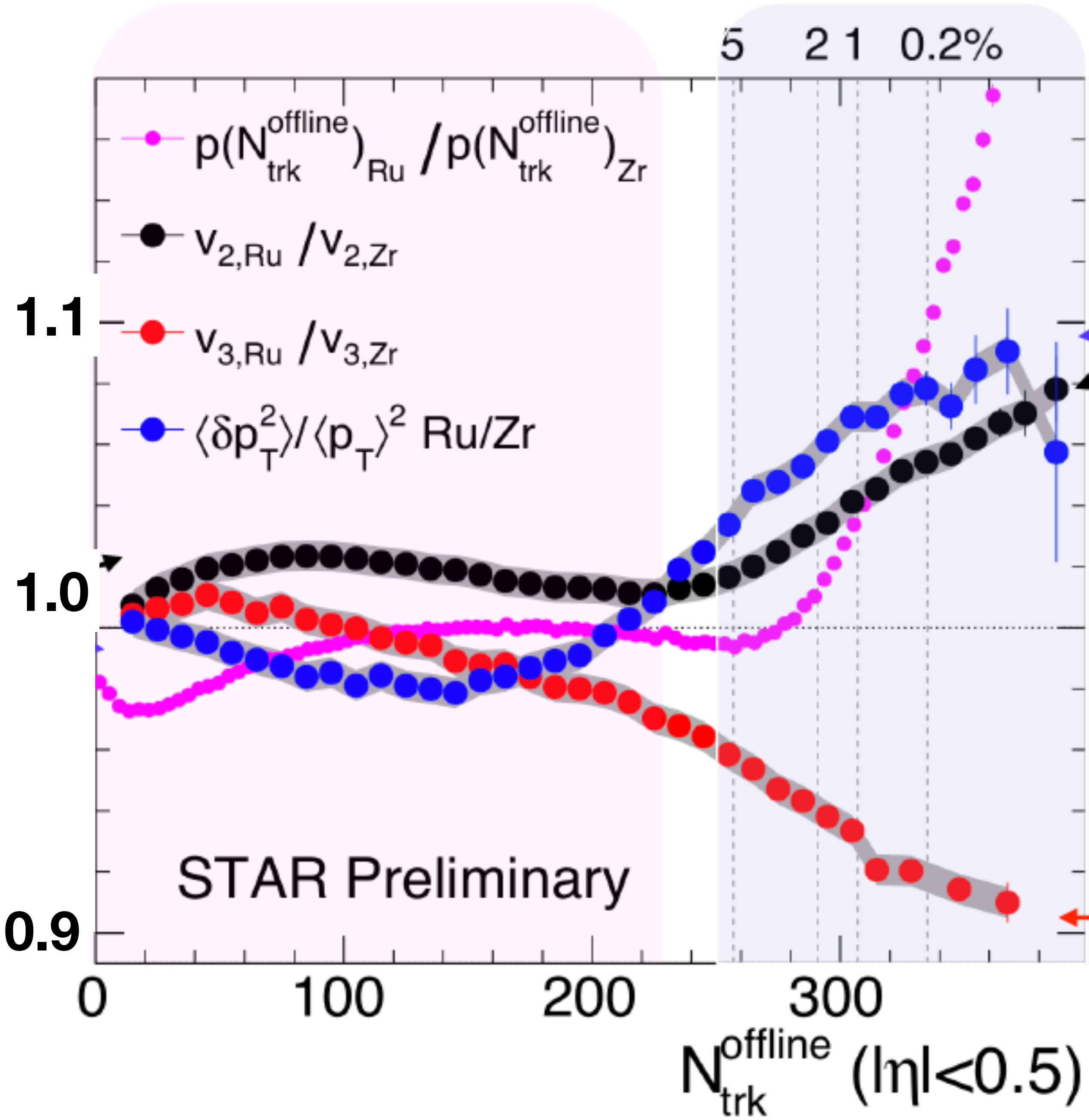
- Differences in multiplicity distribution, <Nch> and v2 between two isobar systems.

	Case-1 [83]			Case-2 [83]			Case-3 [113]		
Nucleus	*R* (fm)	*a* (fm)	β_2	*R* (fm)	*a* (fm)	β_2	*R* (fm)	*a* (fm)	β_2
$^{96}_{44}$Ru	5.085	0.46	0.158	5.085	0.46	0.053	5.067	0.500	0
$^{96}_{40}$Zr	5.02	0.46	0.08	5.02	0.46	0.217	4.965	0.556	0

Other cases?

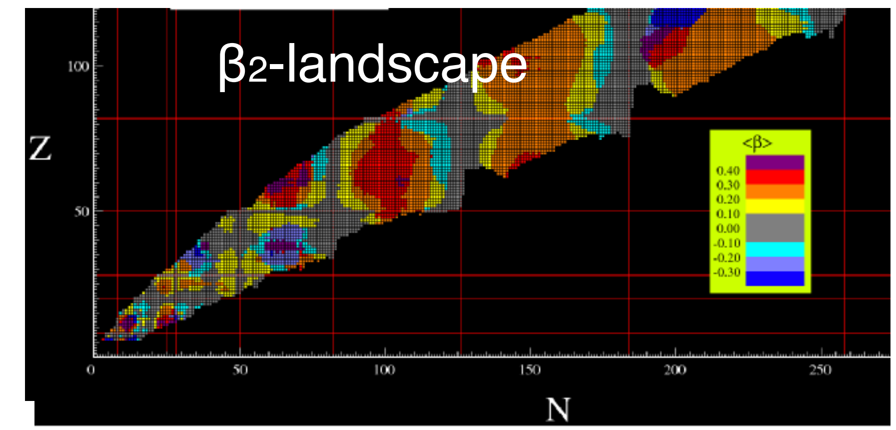
- Related to nuclear deformation/structure.

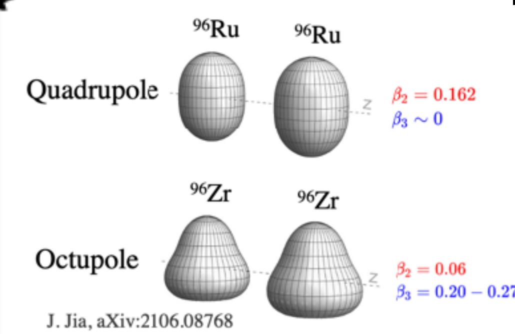
Nuclear structure in relativistic heavy-ion collisions

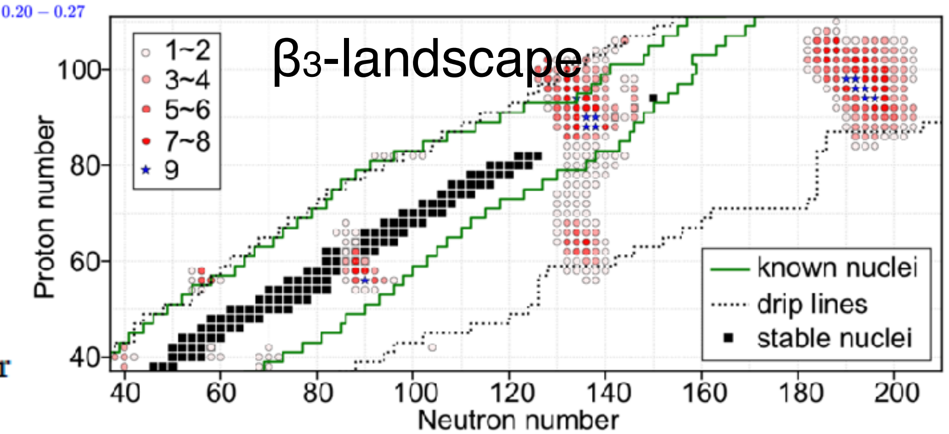


Large $\beta_{2,Ru}$

Large $\beta_{3,Zr}$





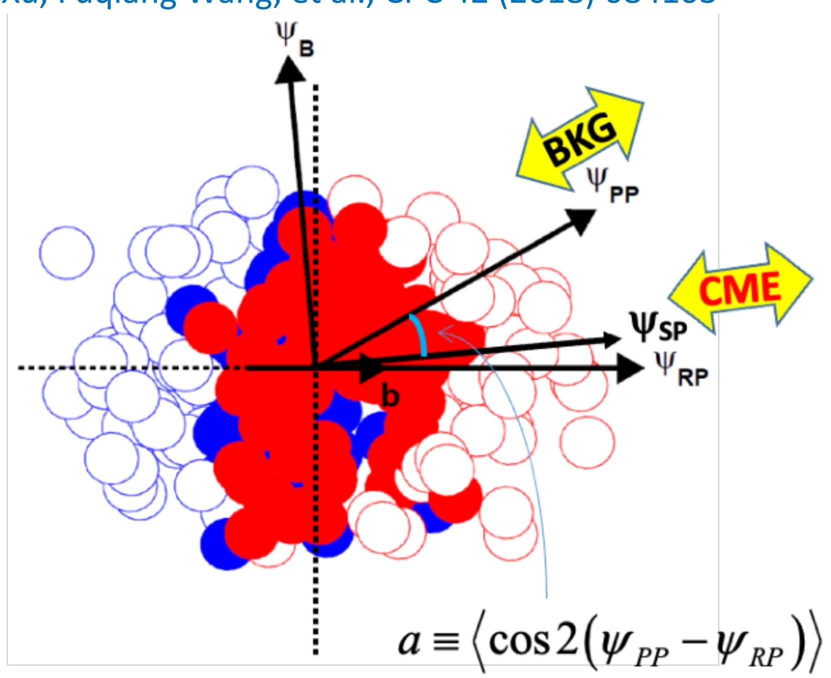


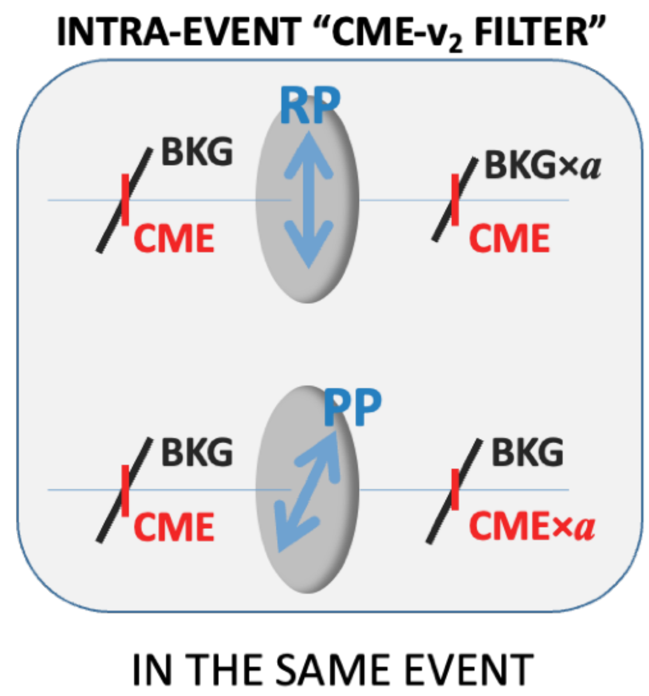
- The ratios of observables between systems are sensitive to nuclear deformation/structure.
- When God closes a door, he opens a window. Is the door closed tight?

STAR, Phys.Rev.C 105 (2022) 1, 014901
H. Li et al., Phys.Rev.C 98 (2018) 5, 054907
H. J. Xu, Phys.Lett.B 819 (2021) 136453
J. Jia, arXiv:2109.00604
J. Jia, Phys.Rev.C 105, 014905 (2022)
C. Zhang and J. Jia, Phys.Rev.Lett. 128 (2022), 022301
G. Giacalone et al., Phys.Rev.Lett. 127 (2021), 242301
J. Jia and C. Zhang, arXiv:2111.15559

Filtering CME and BG by the two-plane method

Haojie Xu, Fuqiang Wang, et al., CPC 42 (2018) 084103





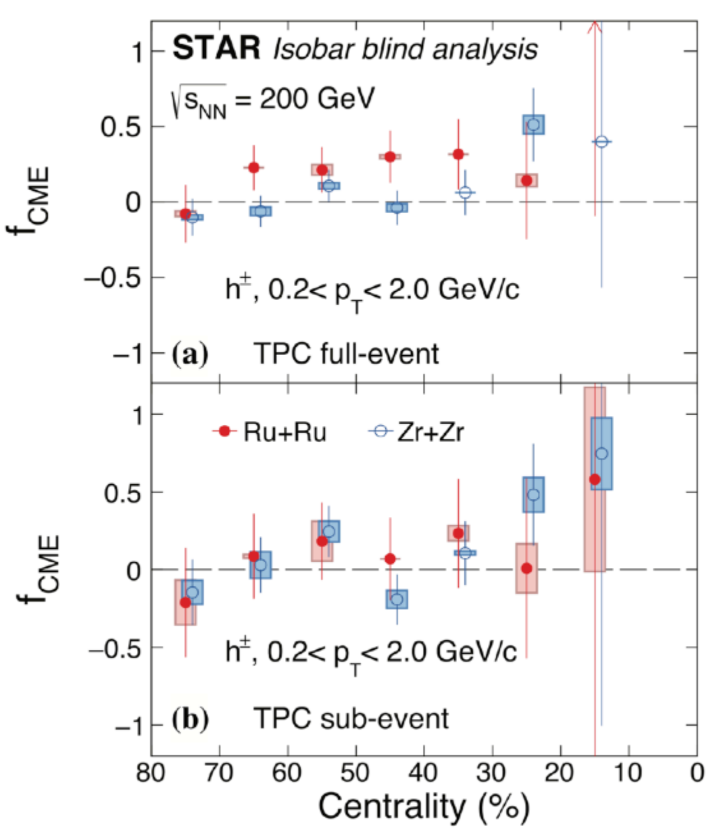
$$\Delta\gamma\{\psi\} = \Delta\gamma_{\rm Bkg}\{\psi\} + \Delta\gamma_{\rm CME}\{\psi\}$$

$$\Delta\gamma\{\rm SP\} = \frac{\Delta\gamma_{\rm CME}\{\rm PP\}}{a} + a\Delta\gamma_{\rm Bkg}\{\rm PP\}$$

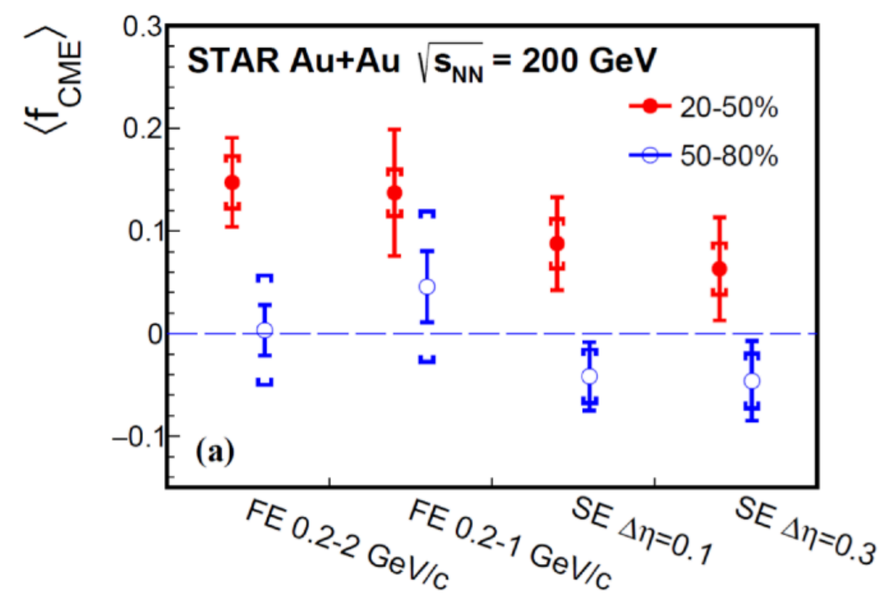
$$\Delta\gamma\{\rm PP\} = \Delta\gamma_{\rm CME}\{\rm PP\} + \Delta\gamma_{\rm Bkg}\{\rm PP\}$$

$$f_{\rm CME} = \frac{\Delta\gamma_{\rm CME}\{\rm PP\}}{\Delta\gamma\{\rm PP\}} = \frac{A/a - 1}{1/a^2 - 1}$$

$$A = \Delta\gamma\{\rm SP\}/\Delta\gamma\{\rm PP\},\ \ a = v_2\{\rm SP\}/v_2\{\rm PP\}$$



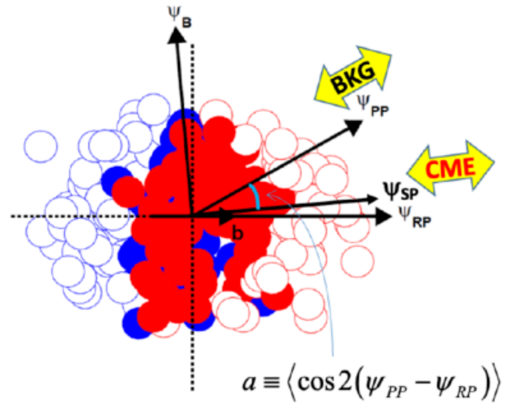
➢Isobar data: CME signal is consistent with zero in isobar collisions.

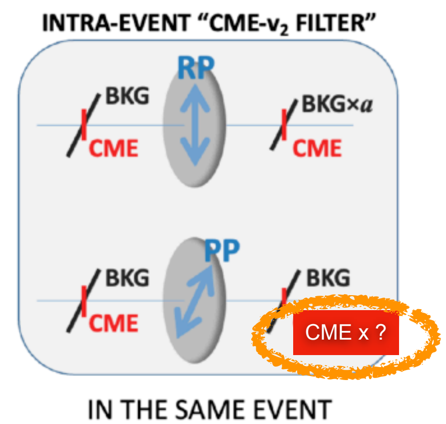


➢Au+Au data:a limited CME signal but with less significance

Are the transmittances for CME and BG same?

b=a,CME x *a*





b ≠ a,CME x *b*

$$\Delta\gamma\{\text{PP}\} = \Delta\gamma_{\text{Bkg}}\{\text{PP}\} + \Delta\gamma_{\text{CME}}\{\text{PP}\}$$

$$\Delta\gamma\{\text{SP}\} = a\Delta\gamma_{\text{Bkg}}\{\text{PP}\} + \Delta\gamma_{\text{CME}}\{\text{PP}\}/a$$

$$\Delta\gamma_{\text{Bkg}}\{\text{SP}\} = a\Delta\gamma_{\text{Bkg}}\{\text{PP}\}$$

$$\Delta\gamma_{\text{CME}}\{\text{PP}\} = a\Delta\gamma_{\text{CME}}\{\text{SP}\}$$

$$a = v_2\{\text{SP}\}/v_2\{\text{PP}\}$$

$$A = \Delta\gamma\{\text{SP}\}/\Delta\gamma\{\text{PP}\}$$

$$f_{\text{CME}} = \frac{\Delta\gamma_{\text{CME}}\{\text{PP}\}}{\Delta\gamma\{\text{PP}\}} = \frac{A/a - 1}{1/a^2 - 1}$$

$$\Delta\gamma\{\text{PP}\} = \Delta\gamma_{\text{Bkg}}\{\text{PP}\} + \Delta\gamma_{\text{CME}}\{\text{PP}\}$$

$$\Delta\gamma\{\text{SP}\} = a\Delta\gamma_{\text{Bkg}}\{\text{PP}\} + \Delta\gamma_{\text{CME}}\{\text{PP}\}/b$$

$$\Delta\gamma_{\text{Bkg}}\{\text{SP}\} = a\Delta\gamma_{\text{Bkg}}\{\text{PP}\}$$

$$\Delta\gamma_{\text{CME}}\{\text{PP}\} = b\Delta\gamma_{\text{CME}}\{\text{SP}\}$$

$$a = v_2\{\text{SP}\}/v_2\{\text{PP}\}$$

$$A = \Delta\gamma\{\text{SP}\}/\Delta\gamma\{\text{PP}\}$$

$$b = \frac{\Delta\gamma_{\text{CME}}\{\text{PP}\}}{\Delta\gamma_{\text{CME}}\{\text{SP}\}}$$

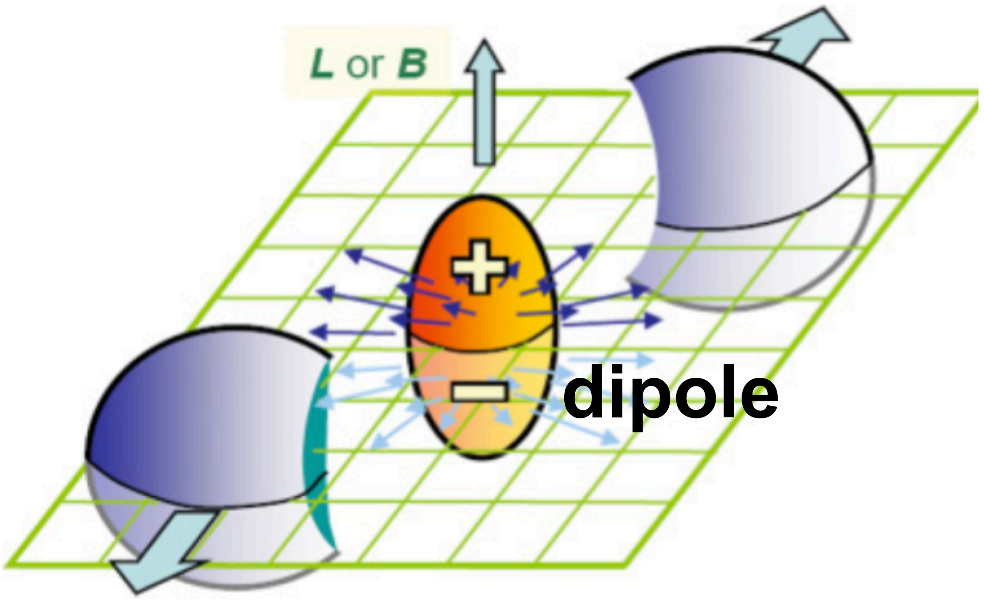
$$f_{\text{CME}}\{b\} = \frac{\Delta\gamma_{\text{CME}}\{\text{PP}\}}{\Delta\gamma\{\text{PP}\}} = \frac{A/a - 1}{1/ab - 1}$$

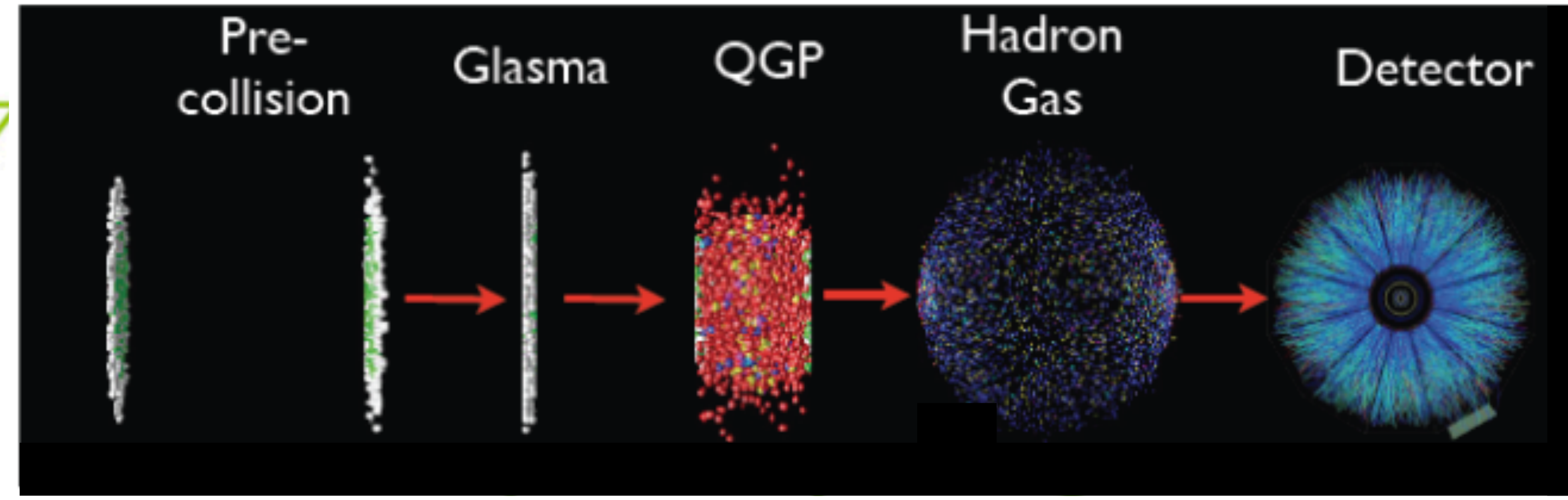
- The transmittance for CME b is not experimentally measurable, but can be calculated using a theoretical model.
- In fact, since the CME signal depends on both initial and final states, b could be time-dependent, and b $\neq$ a.

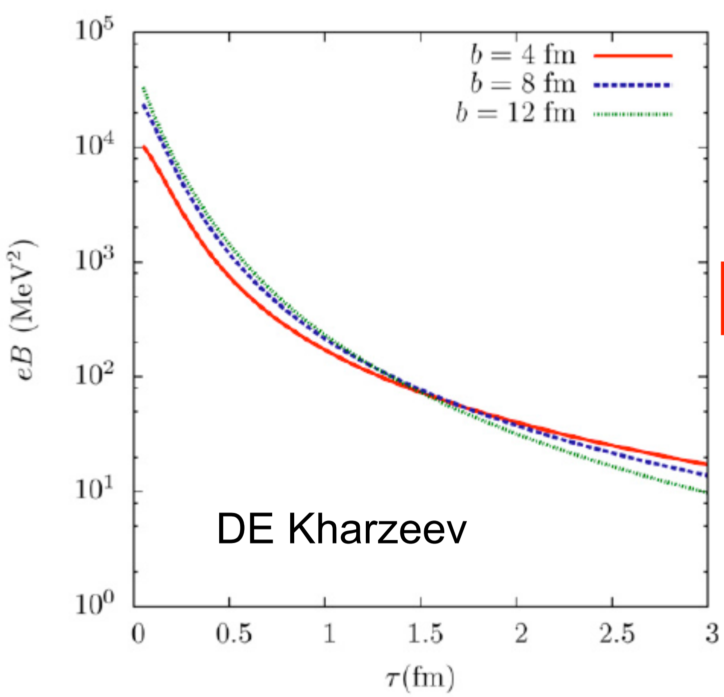
In AMPT model :

$$b = \frac{\Delta\gamma_{\text{CME}}\{\text{PP}\}}{\Delta\gamma_{\text{CME}}\{\text{SP}\}} = \frac{\Delta\gamma\{\text{PP}\}(p \neq 0) - \Delta\gamma\{\text{PP}\}(p = 0)}{\Delta\gamma\{\text{SP}\}(p \neq 0) - \Delta\gamma\{\text{SP}\}(p = 0)}$$

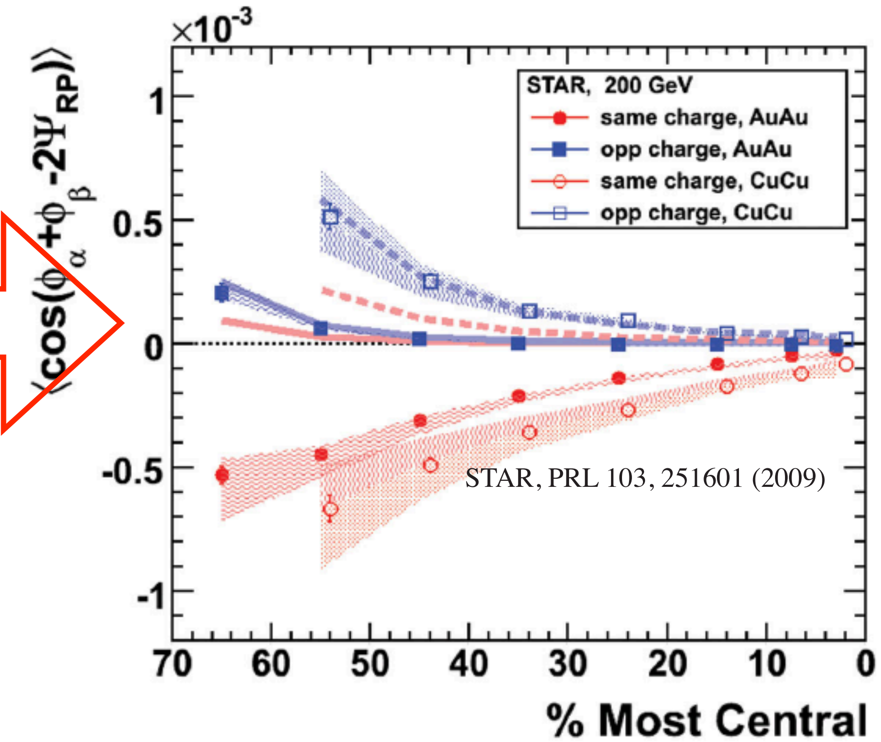
Survival of CME in relativistic heavy-ion collisions







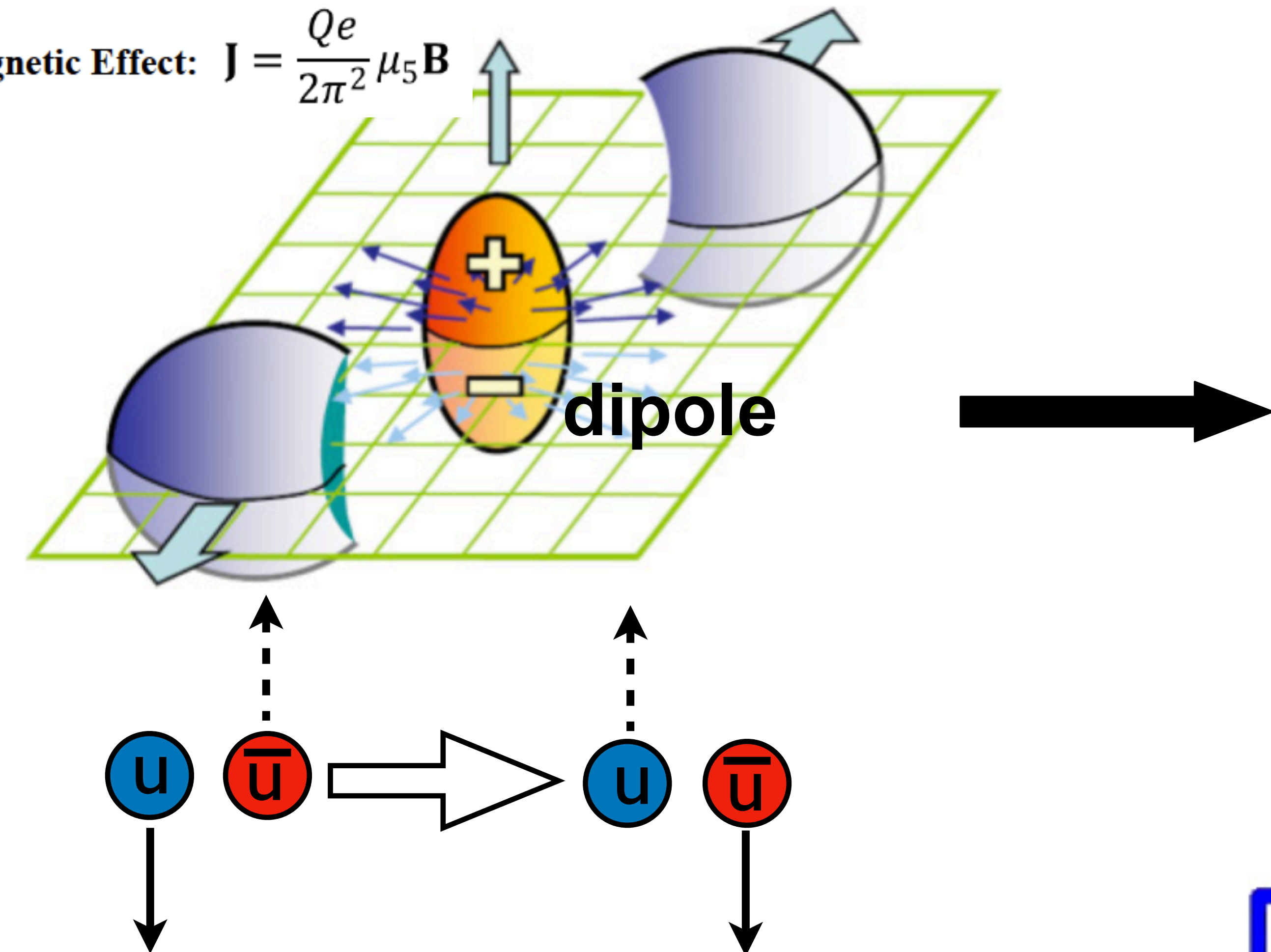
final state
interaction
effects



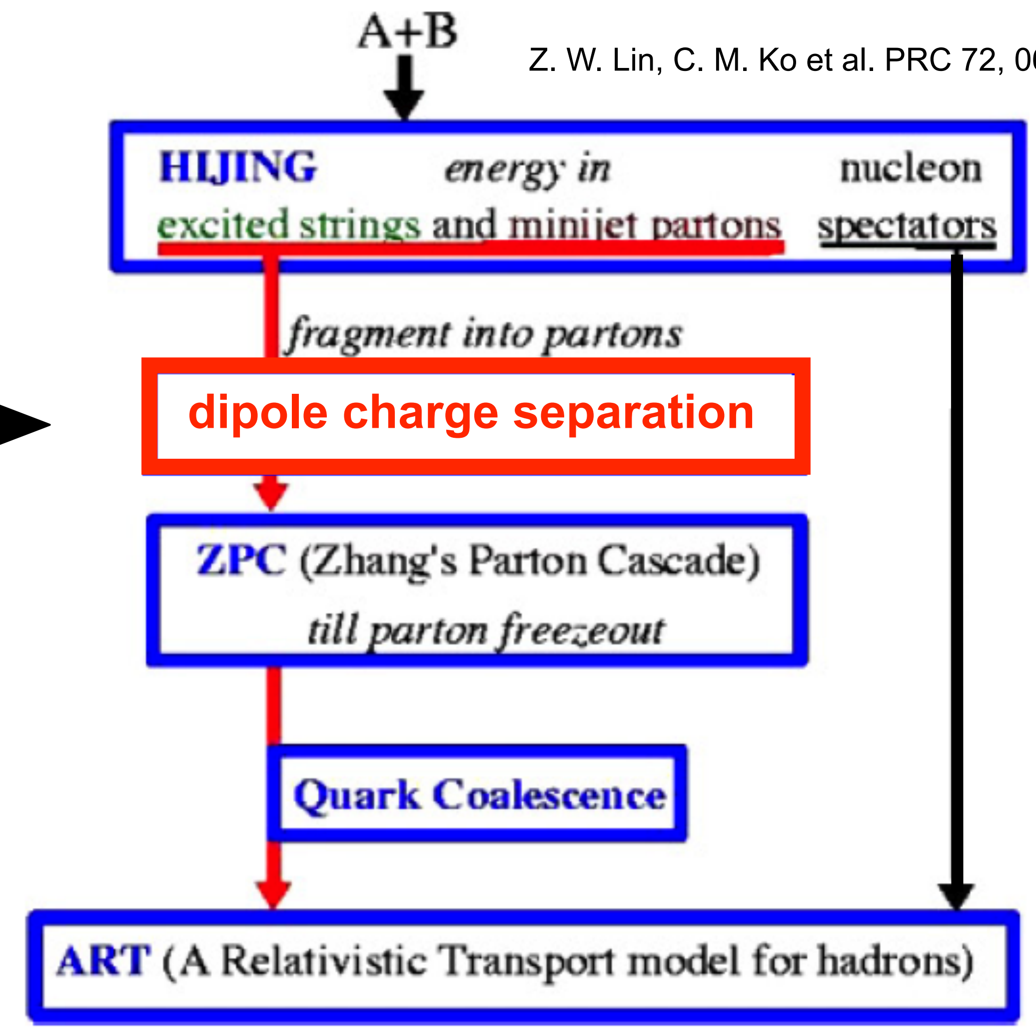
- Can the initial CME survive final-state interactions (FSI) in relativistic heavy-ion collisions?

AMPT model with CME-type charge separation

Chiral Magnetic Effect: $\mathbf{J} = \frac{Qe}{2\pi^2}\mu_5 \mathbf{B}$



Z. W. Lin, C. M. Ko et al. PRC 72, 064901 (2005)



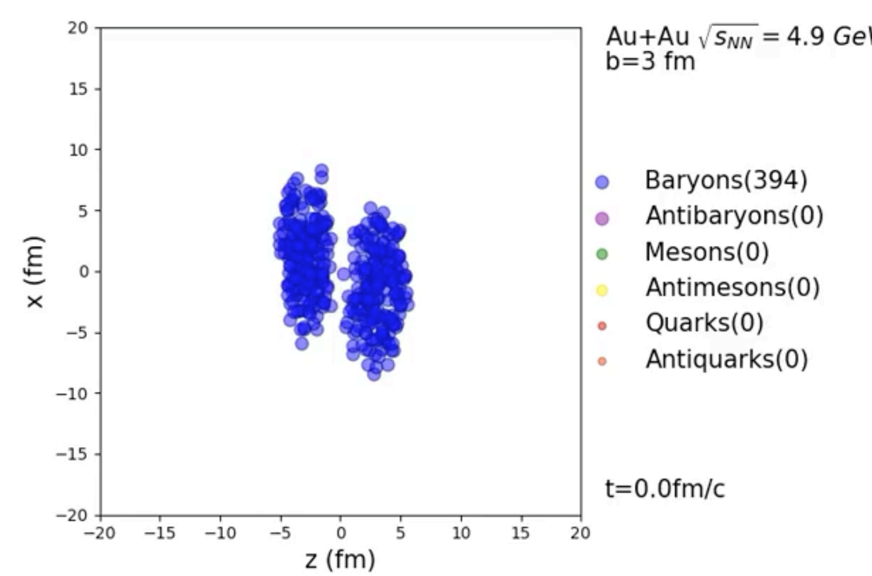
CME percentage:

$f\% = (N^{+}_{upward} - N^{+}_{downward}) / (N^{+}_{upward} + N^{+}_{downward})$

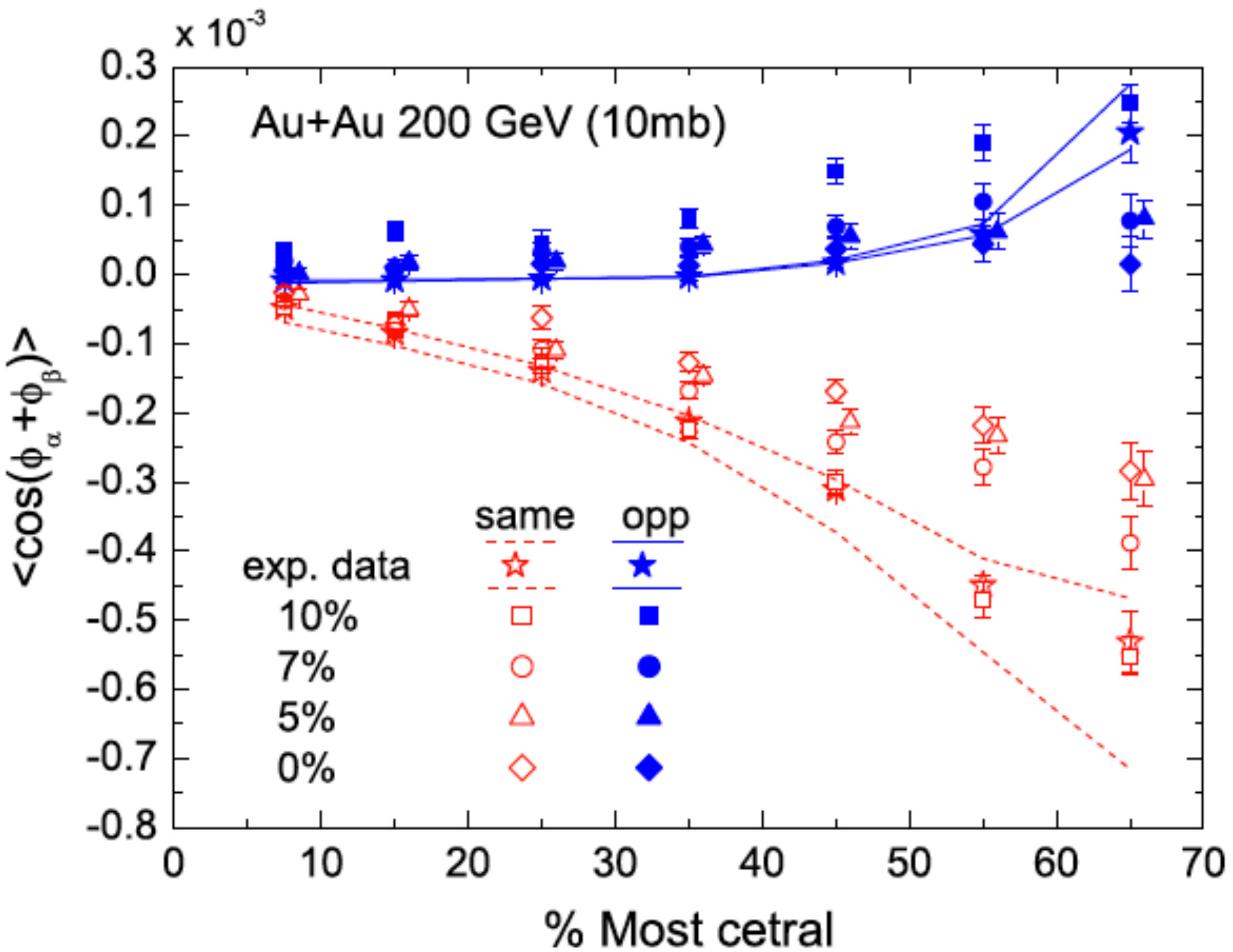
- Introducing initial dipole charge separation (CME):

We switch the momentum of f% of the downward moving u quarks with those of the upward moving u-bar quarks, and likewise for d-bar and d quarks.

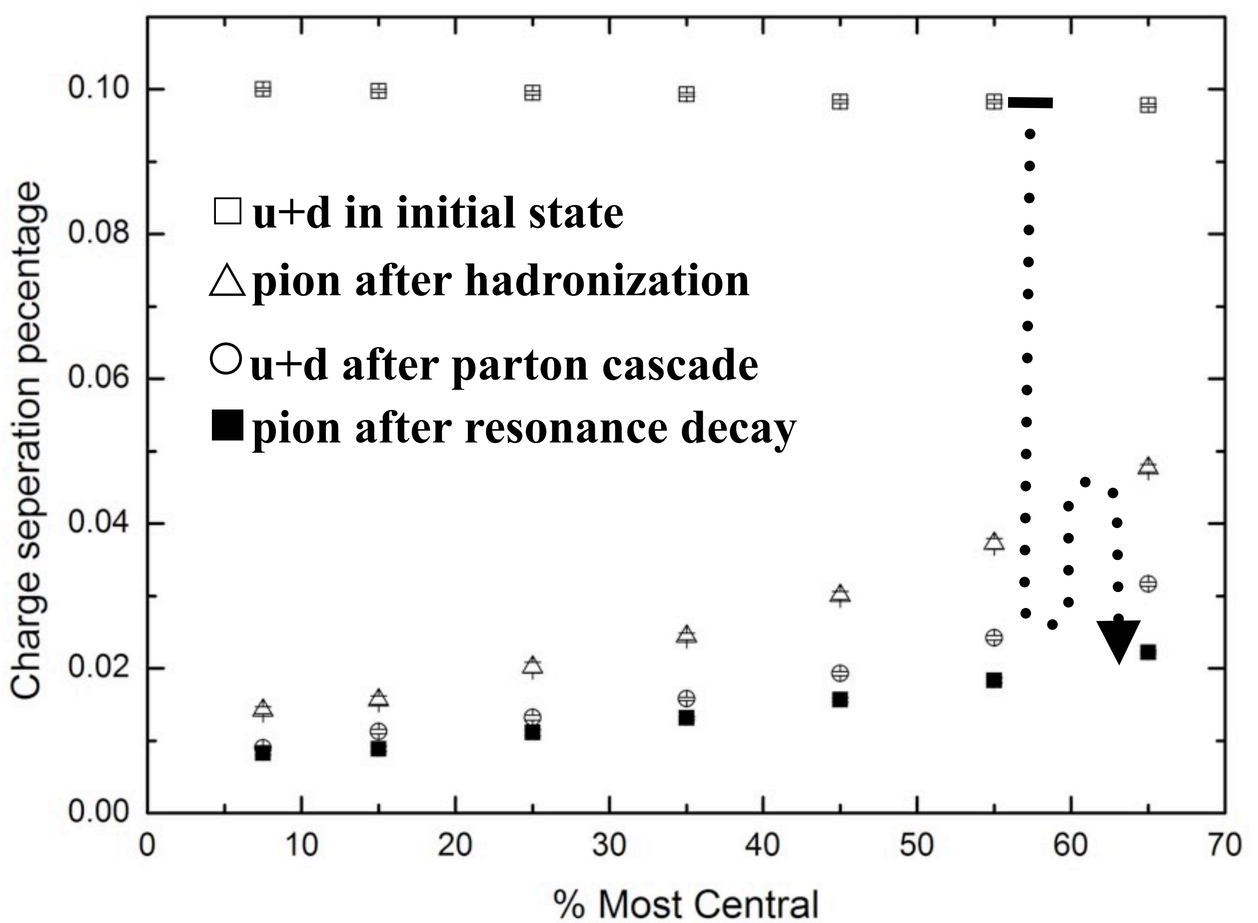
- Study the FSI effect on charge separation, including parton cascades, hadronization, and resonance decays, assuming that the electromagnetic field vanishes rapidly.



AMPT results on the observable γ



GLM && B. Zhang, Phys. Lett. B 700 (2011) 39

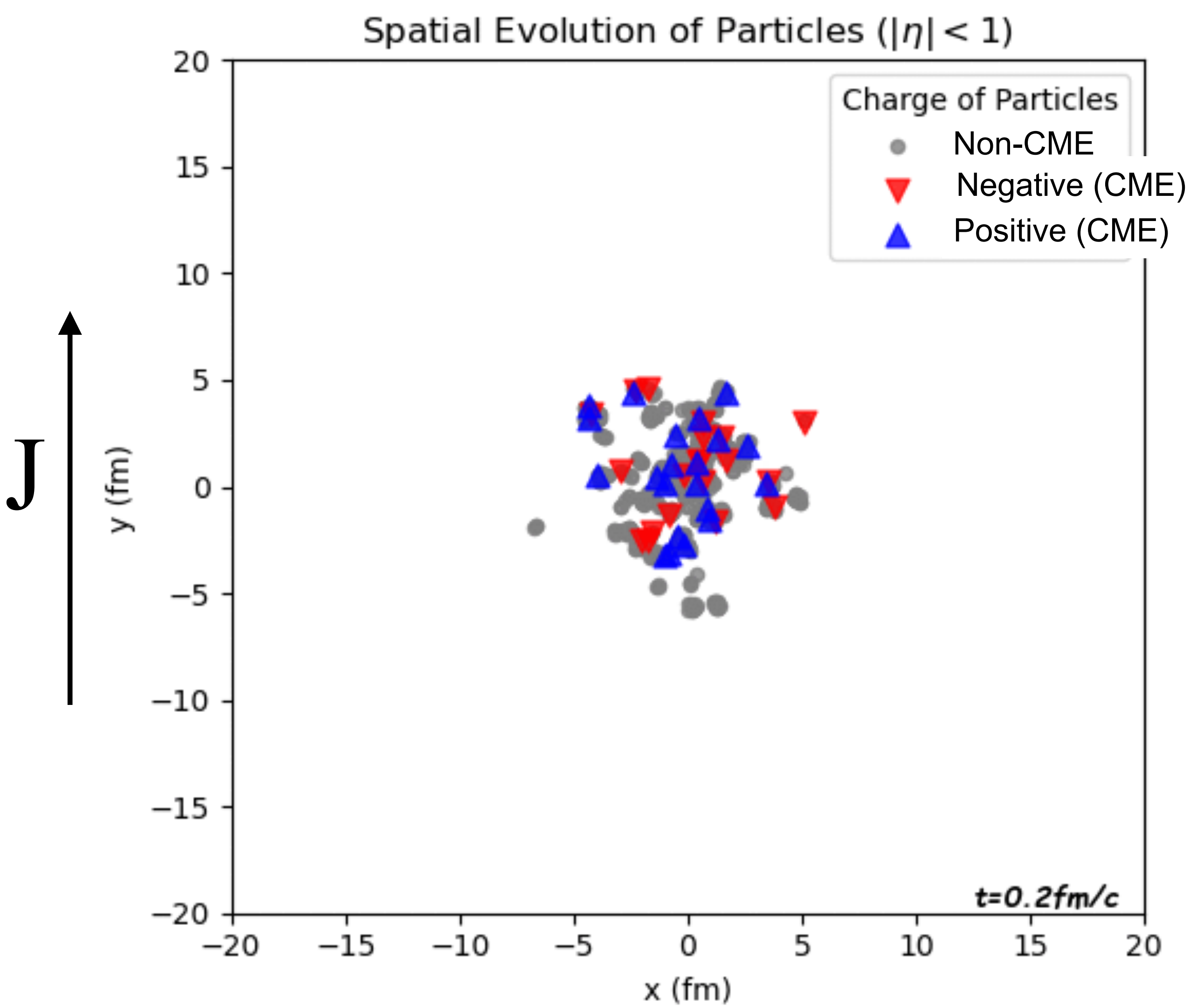


- γ = background + CME signal
  - An initial charge separation ~10% is needed to describe Au+Au data
- Nonlinear sensitivity: γ can not respond to a CME strength of f<=5%
- FSI effect : Only a small faction of CME can survive

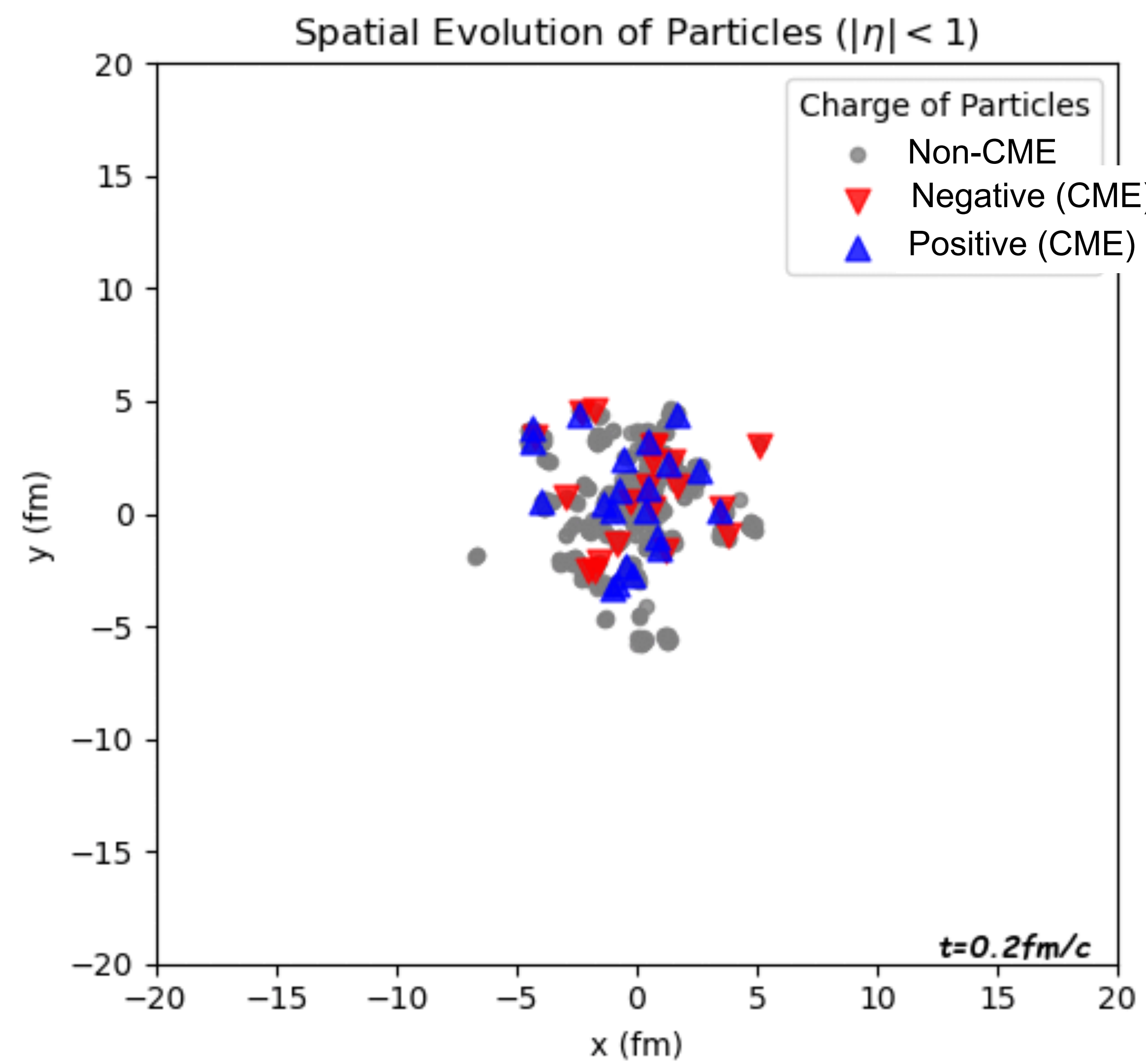
Parton cascade effect on the CME signal

Au+Au 200 GeV (b=8fm), AMPT+CME(10%)

0 mb



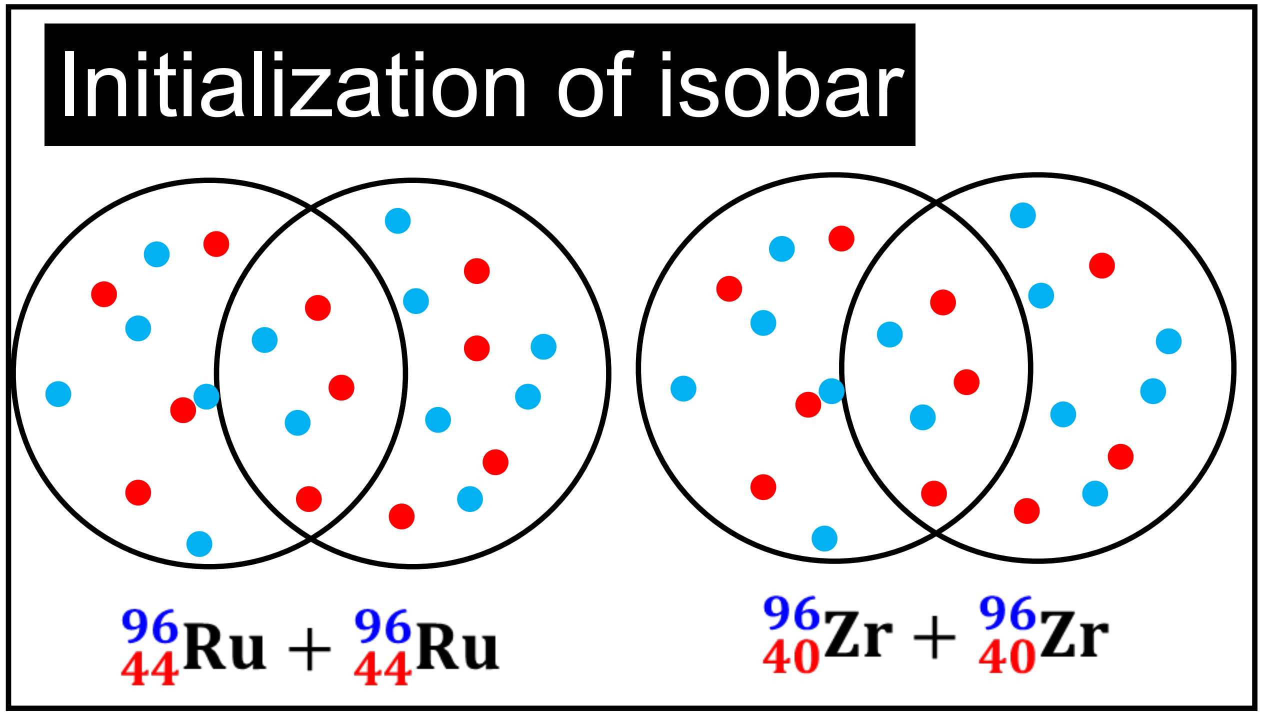
3 mb

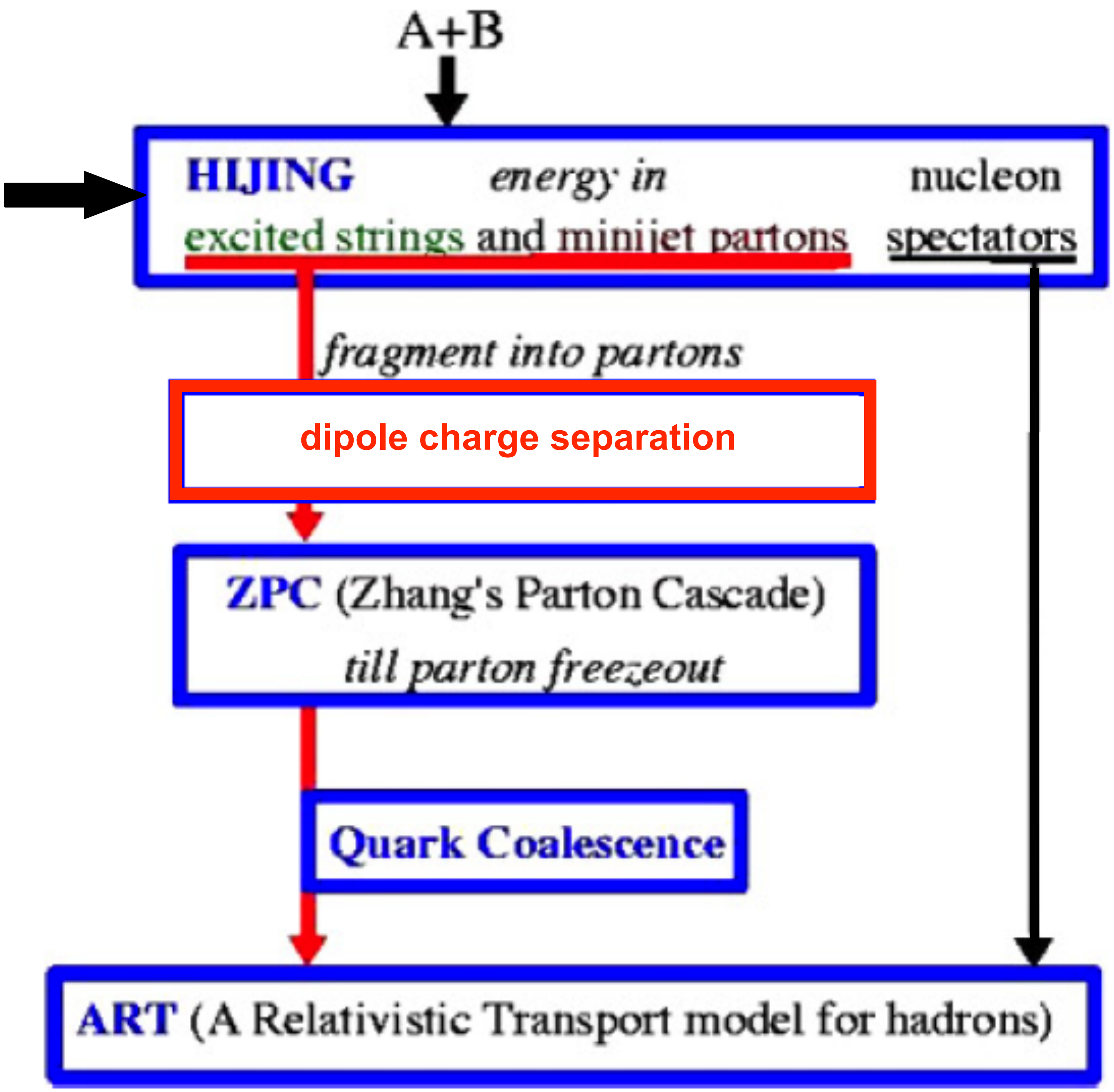


将军百战死，壮士十年归——《木兰诗》

The soldiers have been through hundreds of battles. Some died and only a few returned victorious after many years.

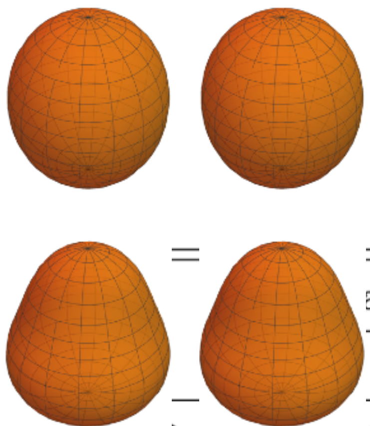
Simulating isobar collisions using AMPT





Initialization of isobar nuclei with geometry

Woods-Saxon form of spatial distribution of nucleons:

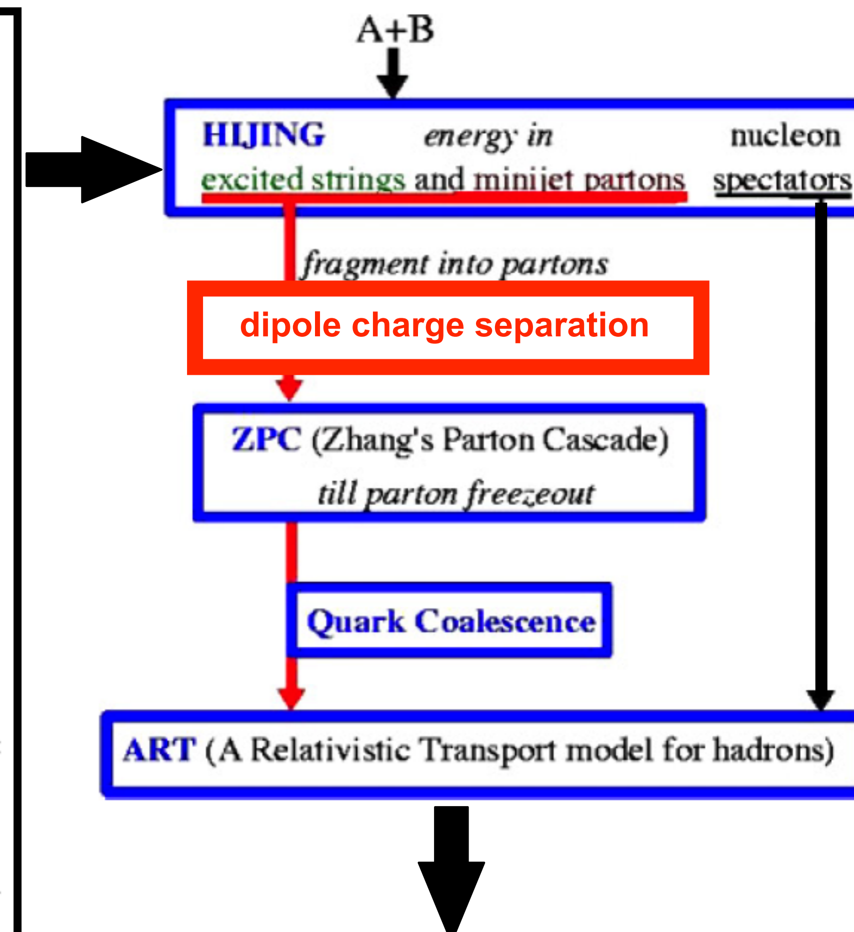


$$\rho(r,\theta,\phi) \propto \frac{1}{1+e^{[r-R_0(1+\beta_2 Y_2^0(\theta,\phi)+\beta_3 Y_3^0(\theta,\phi))]/a}}$$

	ase1			old Case2			Case1			Case2			Case3		
			β_2	R_0	a	β_2	R_0	a	β_2	R_0	a	β_2	R_0	a	β_2
$_{44}$Ru	5.13	0.46	0.13	5.13	0.46	0.03	5.085	0.46	0.158	5.085	0.46	0.053	5.067	0.500	0
$^{96}_{40}$Zr	5.06	0.46	0.06	5.06	0.46	0.18	5.02	0.46	0.080	5.02	0.46	0.217	4.965	0.556	0

	Case4				Case5				Case6				Case7			Case8		
	R_0	a	β_2	β_3	R_0	a	β_2	β_3	R_0	a	β_2	β_3	R_0	a	β_2	R_0	a	β_2
$^{96}_{44}$Ru	5.09	0.46	0.162	0	5.09	0.46	0.162	0	5.09	0.52	0.154	0	5.065	0.485	0.16	5.085	0.523	0
$^{96}_{40}$Zr	5.09	0.52	0.060	0.2	5.02	0.46	0.060	0.2	5.09	0.52	0.060	0.2	4.961	0.544	0.16	5.021	0.523	0

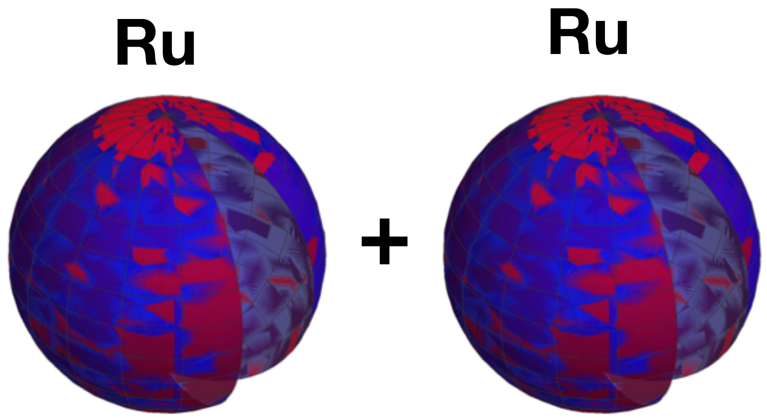
		Case9			Case10			Case11			skin-type			halo-type		
		R_0	a	β_2	R_0	a	β_2	R_0	a	β_2	R_0	a	β_2	R_0	a	β_2
$^{96}_{44}$Ru	n	5.075	0.505	0	5.073	0.490	0.16	5.085	0.46	0.158	5.085	0.523	0	5.085	0.523	0
$^{96}_{44}$Ru	p	5.060	0.493	0	5.053	0.480	0.16	5.085	0.46	0.158	5.085	0.523	0	5.085	0.523	0
$^{96}_{40}$Zr	n	5.015	0.574	0	5.007	0.564	0.16	5.080	0.46	0	5.194	0.523	0	5.021	0.592	0
$^{96}_{40}$Zr	p	4.915	0.521	0	4.912	0.508	0.16	5.080	0.34	0	5.021	0.523	0	5.021	0.523	0



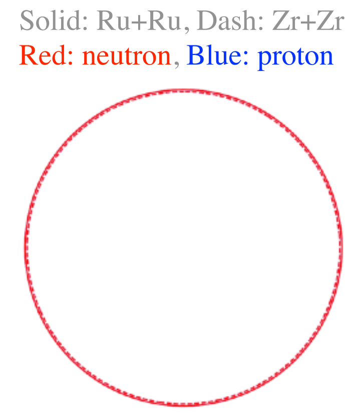
- Which is better or worse?
- Three ratios are our judging criteria:
  1) Mult. dist. ratio
  2) <N_{ch}> ratio vs centrality
  3) v_2 ratio vs centrality

✳ **1 M events for each case are used to test if it can pass the criterion test.**

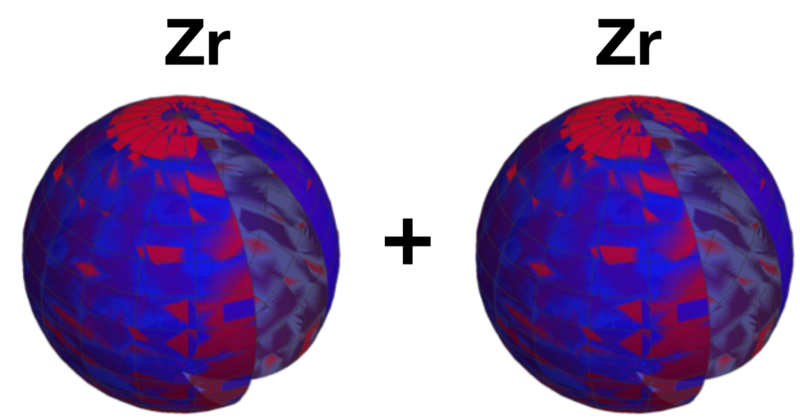
Champion player： Halo-type

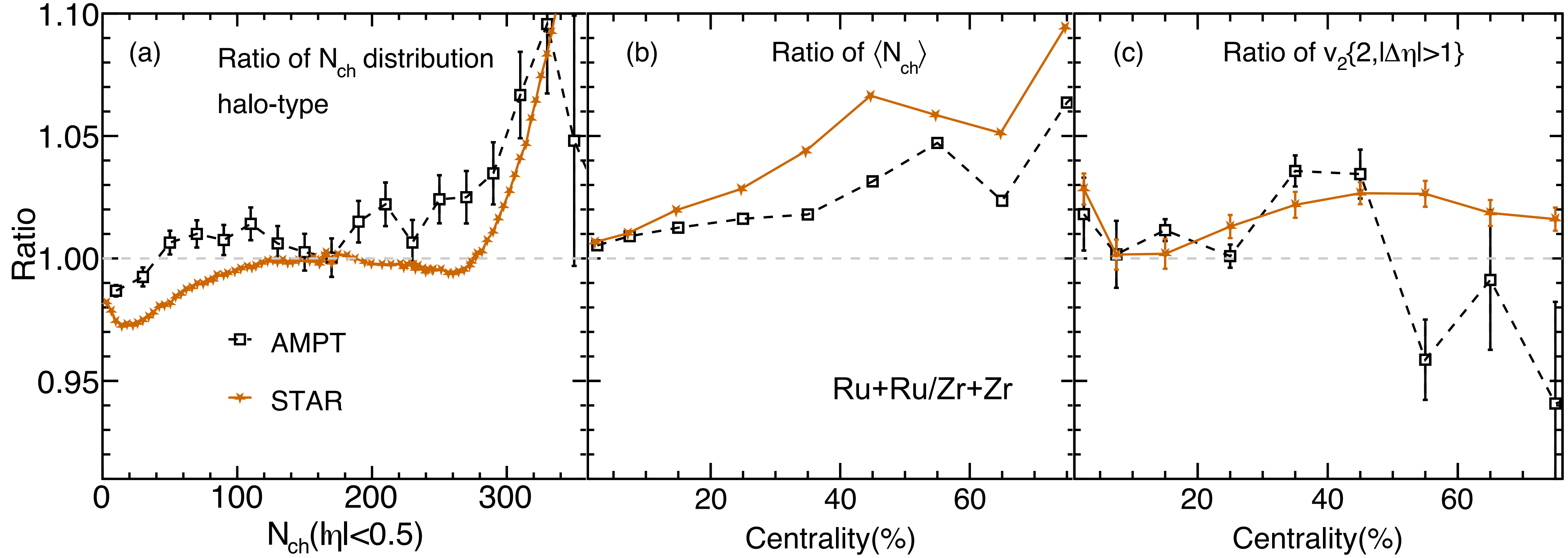


		halo-type		
		R_0	a	β_2
$^{96}_{44}$Ru	n	5.085	0.523	0
$^{96}_{44}$Ru	p	5.085	0.523	0
$^{96}_{40}$Zr	n	5.021	0.592	0
$^{96}_{40}$Zr	p	5.021	0.523	0



H. j. Xu, H. Li, X. Wang, C. Shen and F. Wang, Phys. Lett. B 819, 136453 (2021)



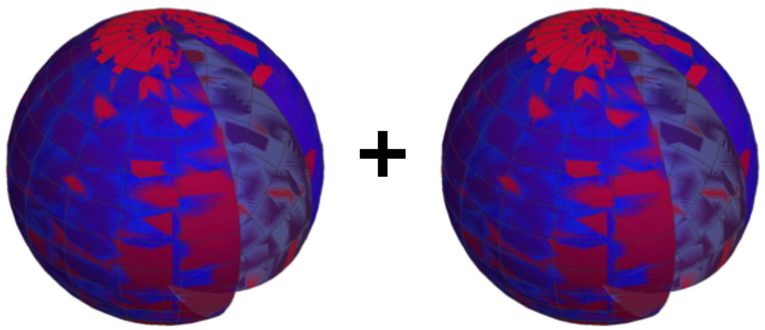


χ^2 index：

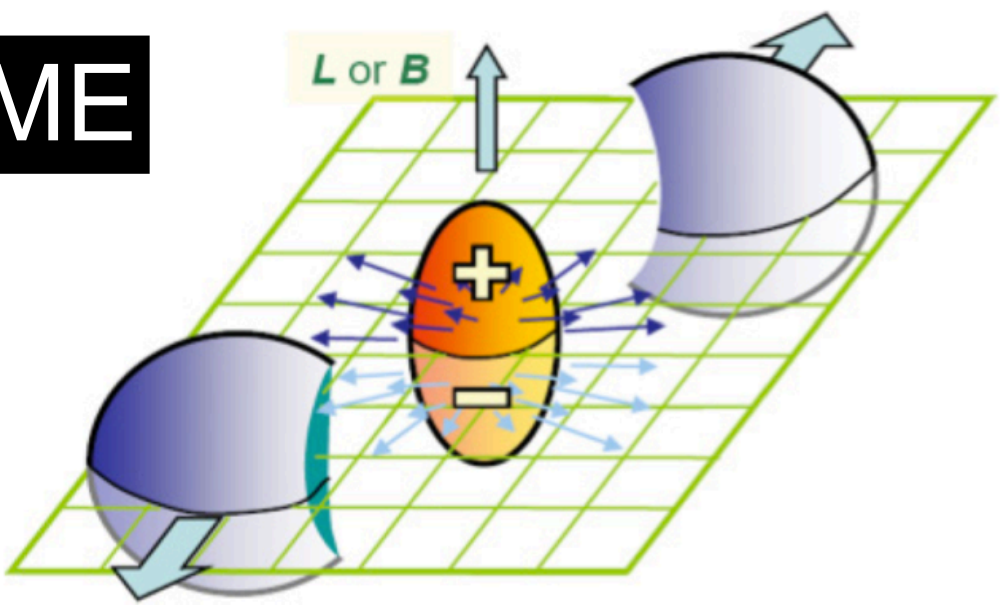
	old Case 1	old Case 2	Case 1	Case 2	Case 3	Case 4
$\langle\chi^2\rangle$	0.204	0.682	0.255	0.400	0.097	0.053
	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10
$\langle\chi^2\rangle$	0.049	0.224	0.051	0.227	0.057	0.048
	Case 11	skin-type	halo – type	Case 1 w/ β_3	Case 2 w/ β_3	Case 3 w/ β_3
$\langle\chi^2\rangle$	0.430	0.177	0.047	0.247	0.506	0.166

Simulating CME in isobar collisions using AMPT

Initialization of halo-type isobar

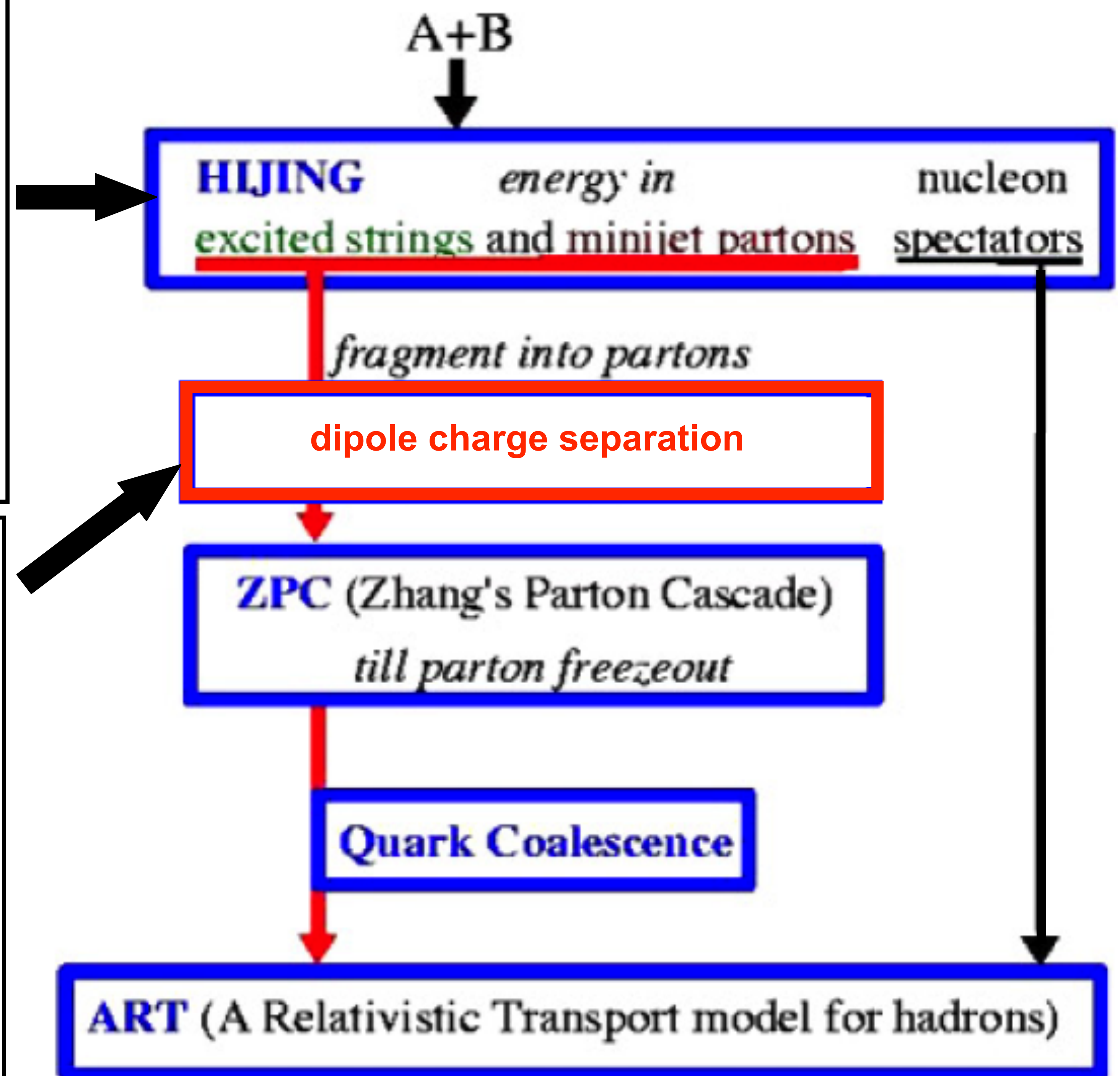


CME



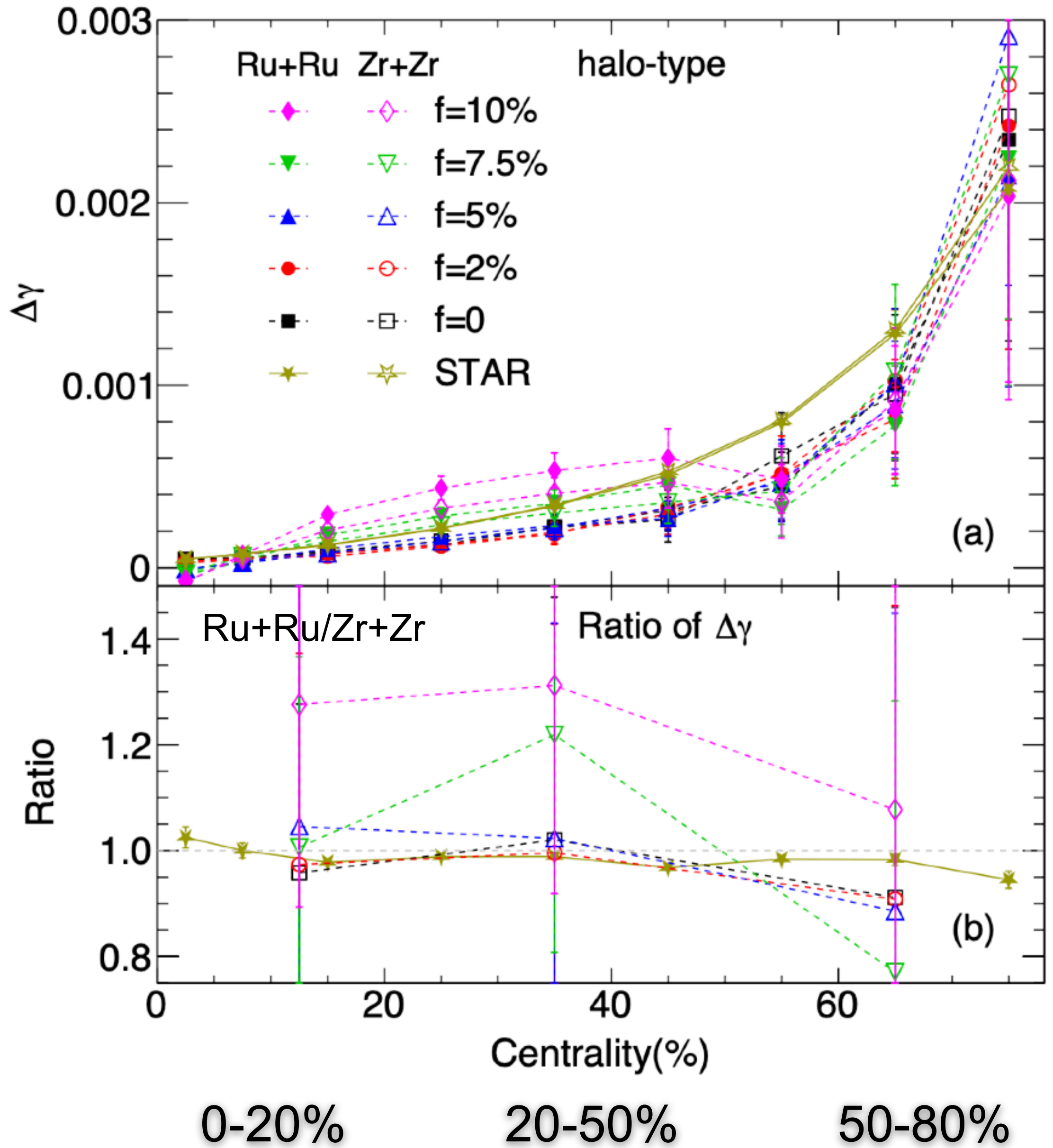
$f=(N^{+}_{upward}-N^{+}_{downward})/(N^{+}_{upward}+N^{+}_{downward})$

- f(Ru+Ru)/f(Zr+Zr)~$(44/40)^2$
- CME current || **B** field

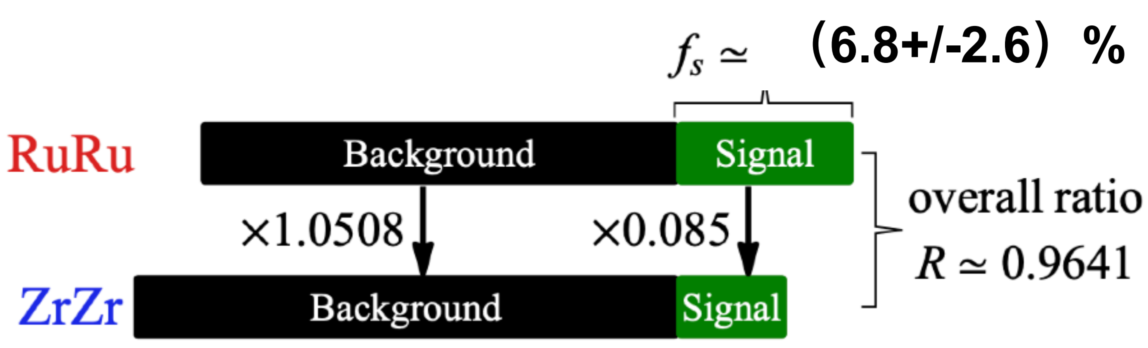


CME observable: $\Delta\gamma/v2$ ratio

Xin-Li Zhao and GLM, Phys. Rev. C 106, 034909 (2022)



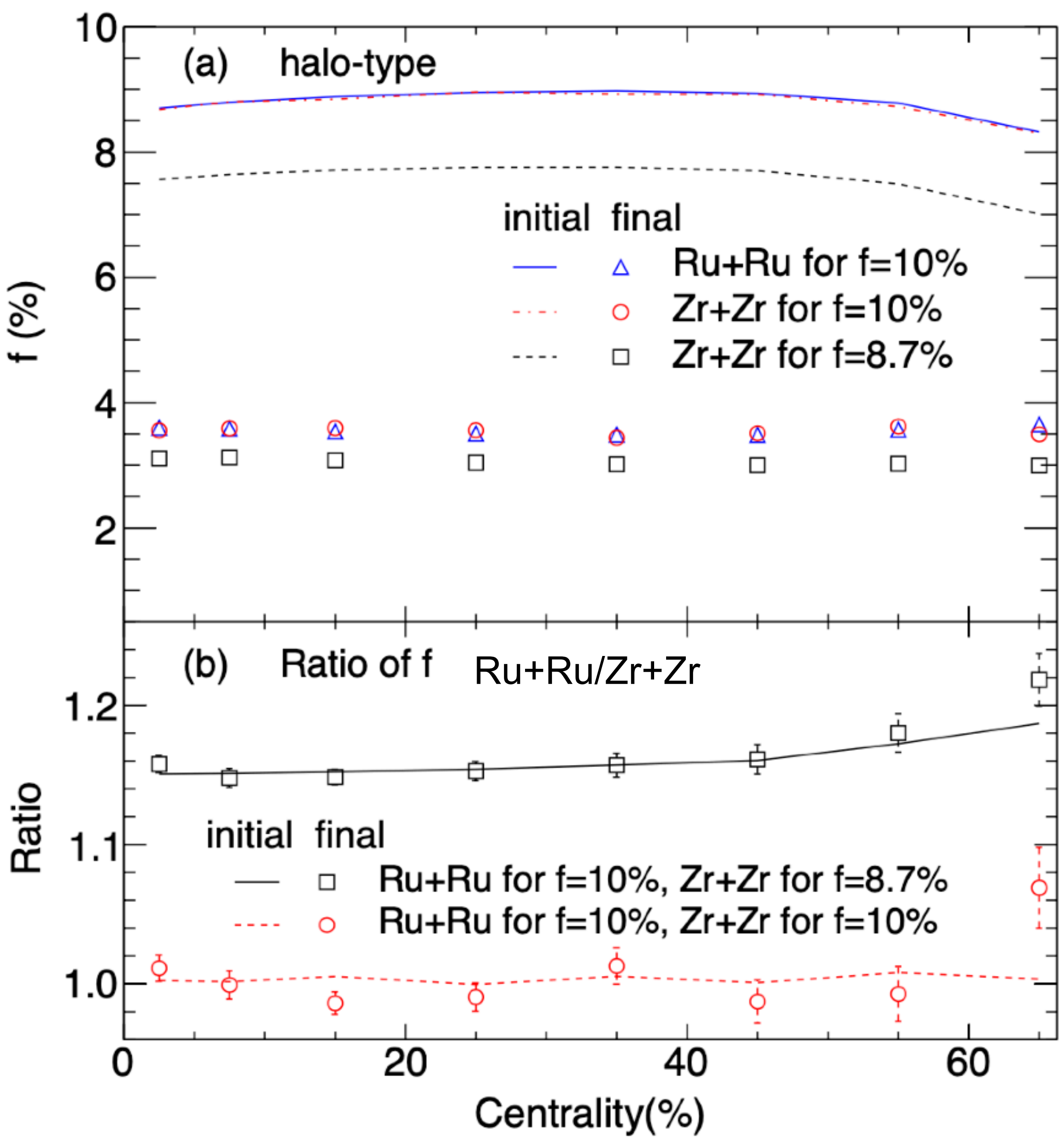
- $f \leq 5\%$is close to the experimental result.
- $f = 2\%$ and $f = 5\%$ look consistent with $f = 0$.
- Consistent with the latest results from AVFD.



Dmitri E. Kharzeev, Jinfeng Liao, Shuzhe Shi, Phys.Rev.C 106 (2022) 5, L051903

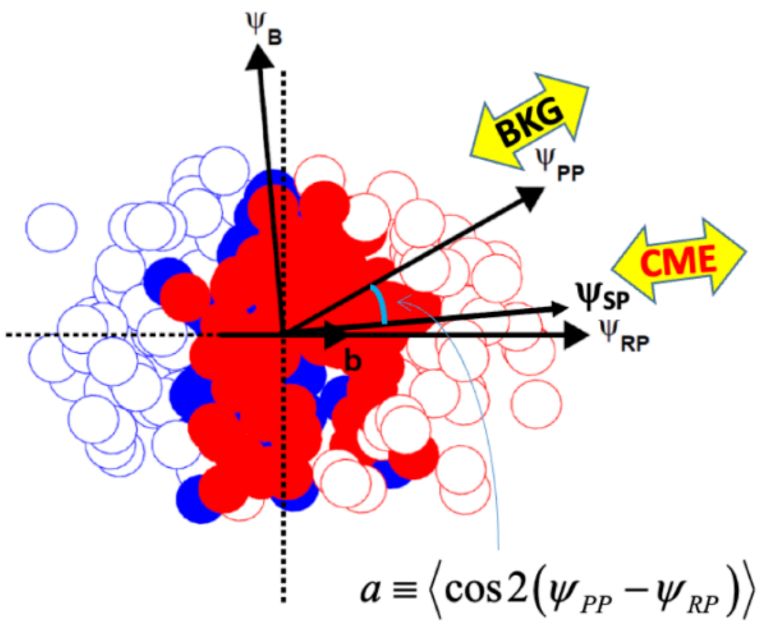
FSI effects in isobar collisions

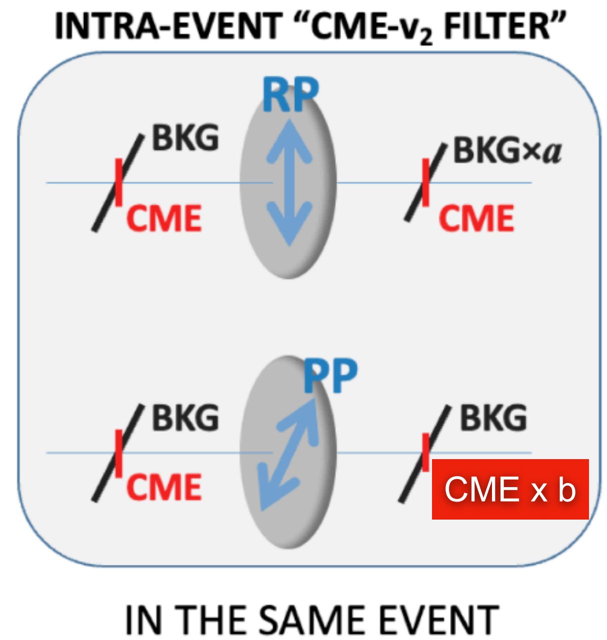
Xin-Li Zhao and GLM, Phys. Rev. C 106, 034909 (2022)



- FSI greatly reduce the CME signal.
- The f ratios between two isobar collisions are consistent in the initial and final states.
- Isobar difference in the CME signal is preserved up to the final state. However, the signal is too small to be observed due to nonlinear sensitivity.
- Is there a good way to extract the CME signal?

Two-plane method: Comparing a and b



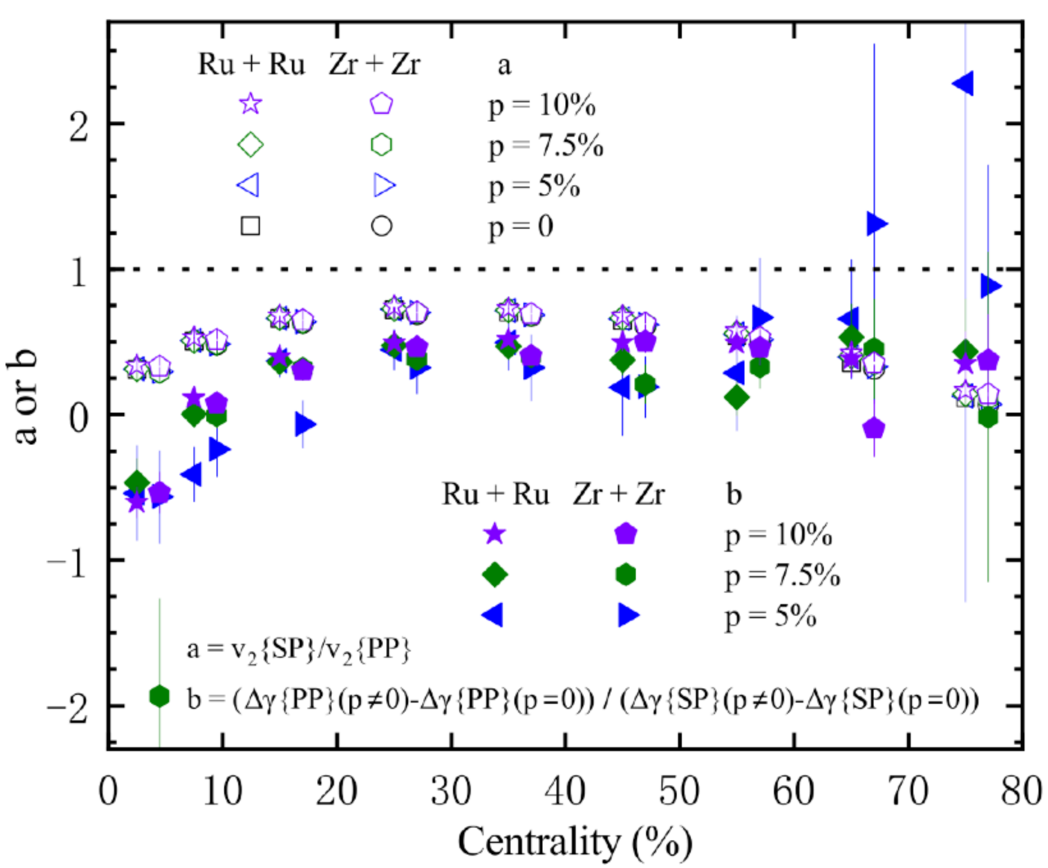


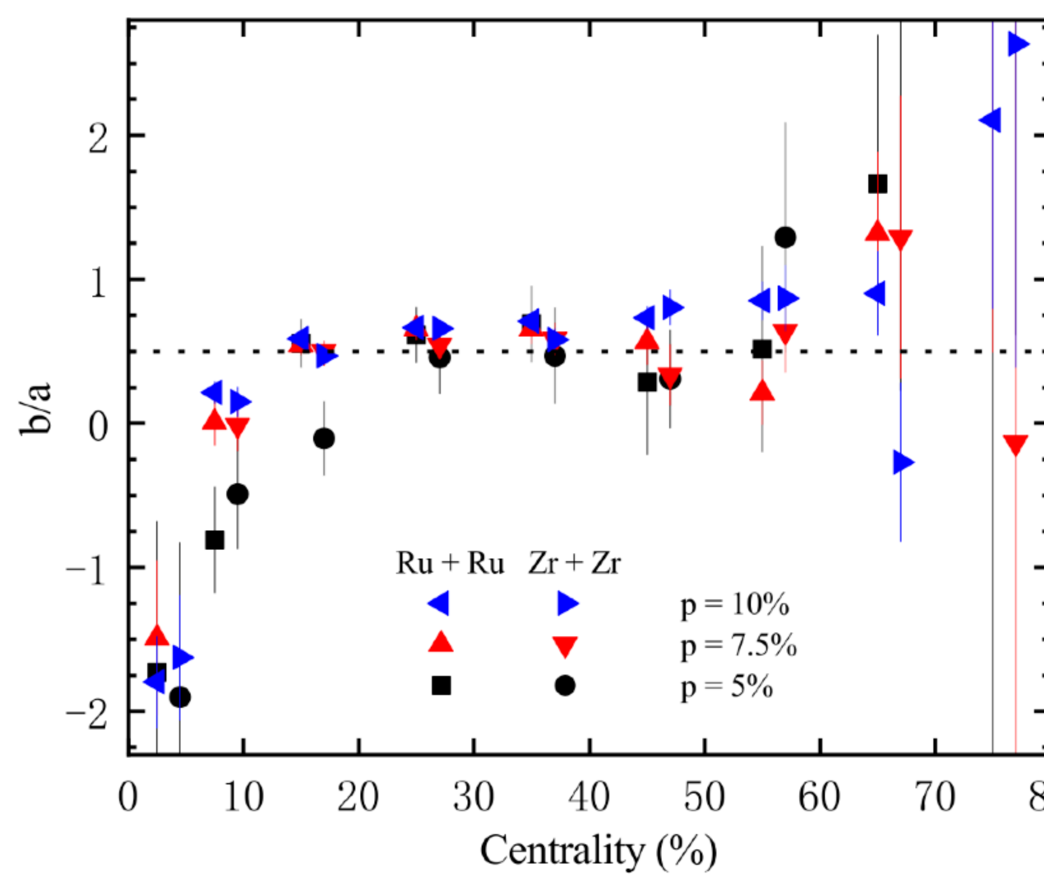
Bang-Xiang Chen, Xin-Li Zhao and GLM, arXiv:2301.12076

a: BKG transmittance

b: CME transmittance

$a \stackrel{?}{=} b$

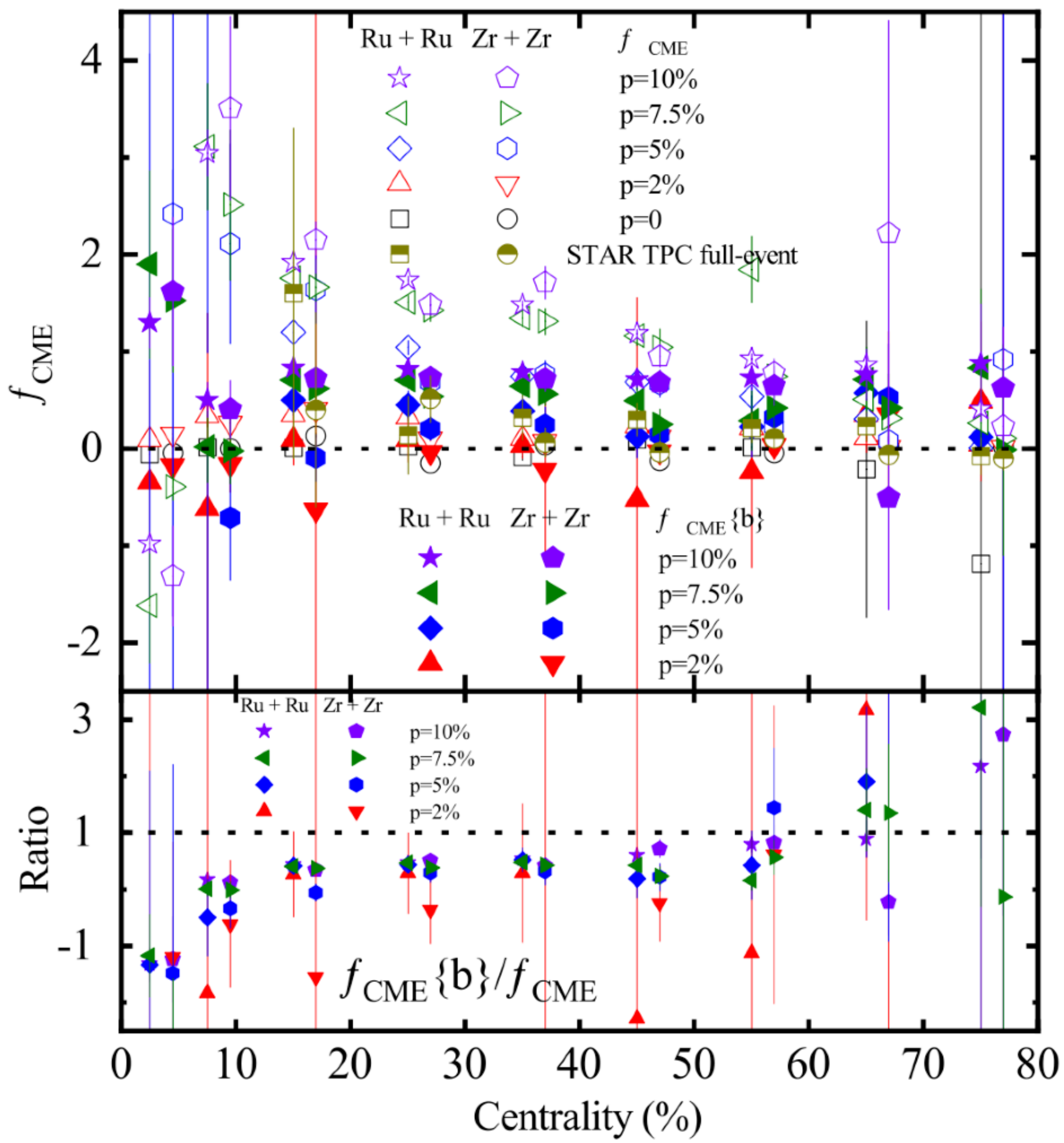




- b is smaller than a, about 1/2 of a in isobar collisions(20-50%).

What is the impact of b on f_{CME}

Bang-Xiang Chen, Xin-Li Zhao and GLM, arXiv:2301.12076



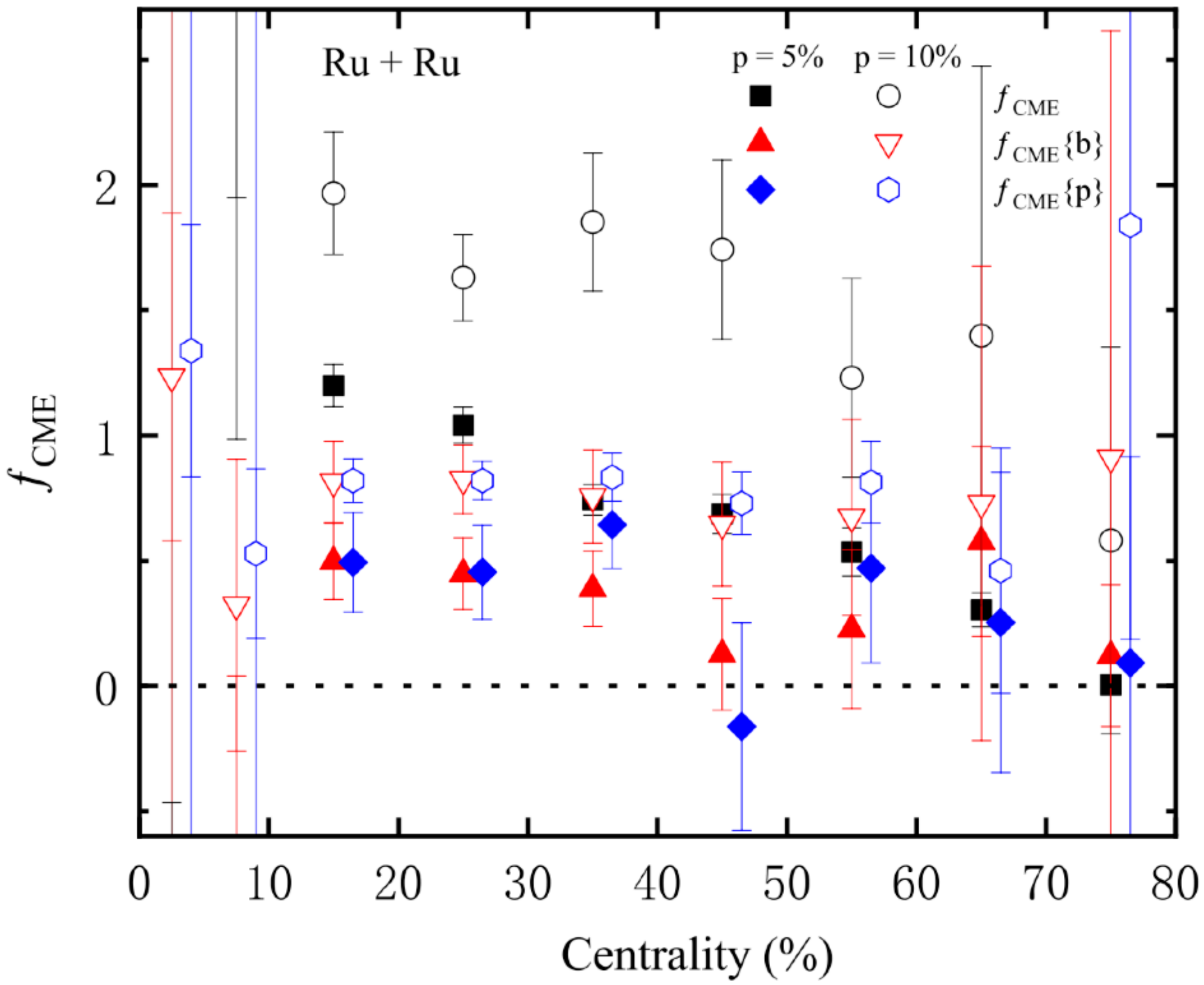
(1) $$f_{\mathrm{CME}} = \frac{\Delta\gamma_{\mathrm{CME}}\{\mathrm{PP}\}}{\Delta\gamma\{\mathrm{PP}\}} = \frac{A/a - 1}{1/a^2 - 1}$$ open symbols

(2) $$f_{\mathrm{CME}}\{b\} = \frac{\Delta\gamma_{\mathrm{CME}}\{\mathrm{PP}\}}{\Delta\gamma\{\mathrm{PP}\}} = \frac{A/a - 1}{1/ab - 1}$$ solid symbols

- After including b, f_{CME} will be decreased.
- Which one is closer to the real one?

Which f_{CME} is more real

Bang-Xiang Chen, Xin-Li Zhao and GLM, arXiv:2301.12076



(1) $f_{\mathrm{CME}} = \frac{\Delta\gamma_{\mathrm{CME}}\{PP\}}{\Delta\gamma\{PP\}} = \frac{A/a - 1}{1/a^2 - 1}$ black symbols

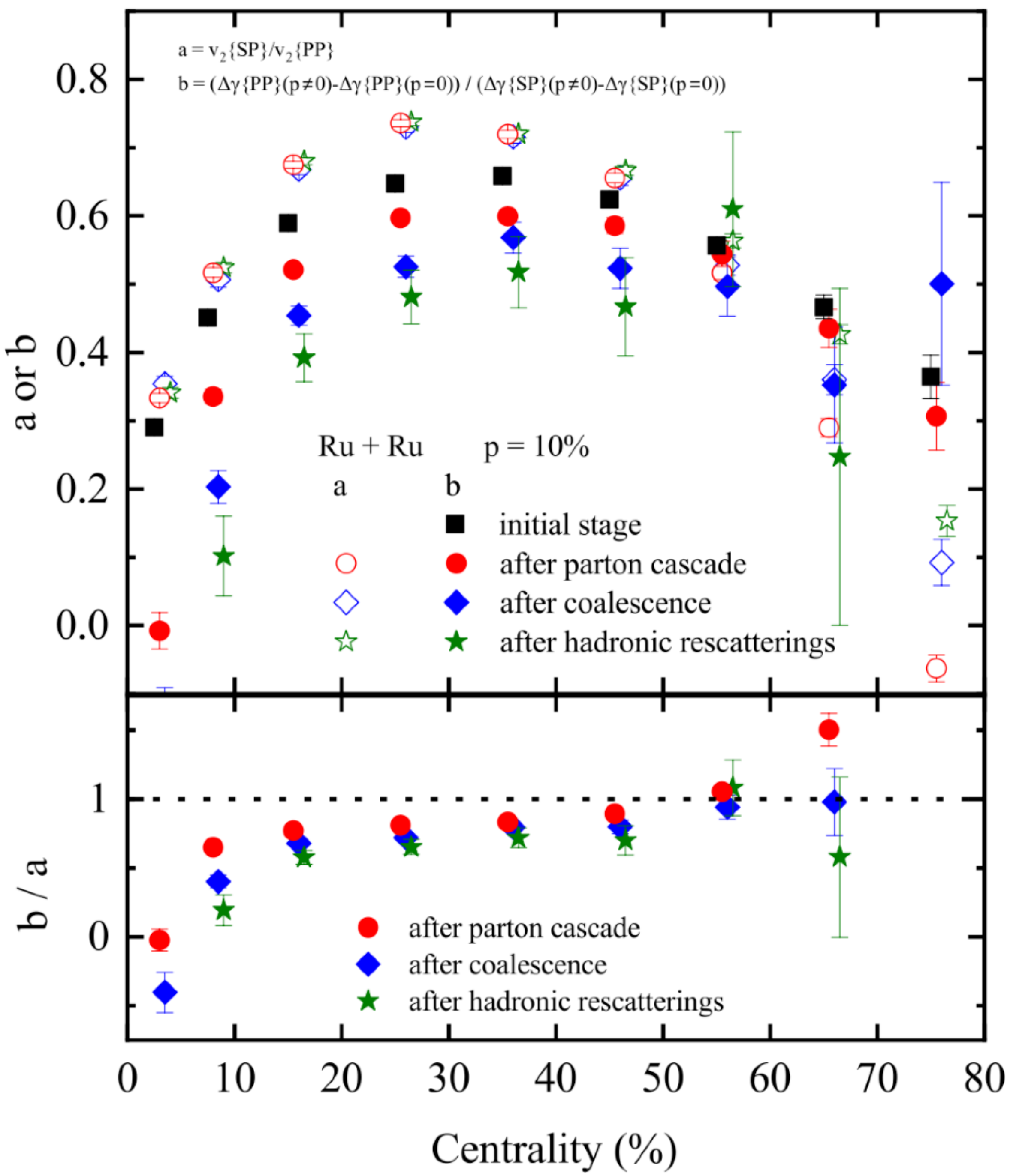
(2) $f_{\mathrm{CME}}\{b\} = \frac{\Delta\gamma_{\mathrm{CME}}\{PP\}}{\Delta\gamma\{PP\}} = \frac{A/a - 1}{1/ab - 1}$ red symbols

(3) $f_{\mathrm{CME}}\{p\} = \frac{\Delta\gamma\{PP\}(p \neq 0) - \Delta\gamma\{PP\}(p = 0)}{\Delta\gamma\{PP\}(p \neq 0)}$ blue symbols

- f_{CME} {b} with b will be closer to the real value f_{CME} {p} than f_{CME} without b.
- The current experimental way (without b) may overestimate f_{CME}.

Why a and b are different

Bang-Xiang Chen, Xin-Li Zhao and GLM, arXiv:2301.12076



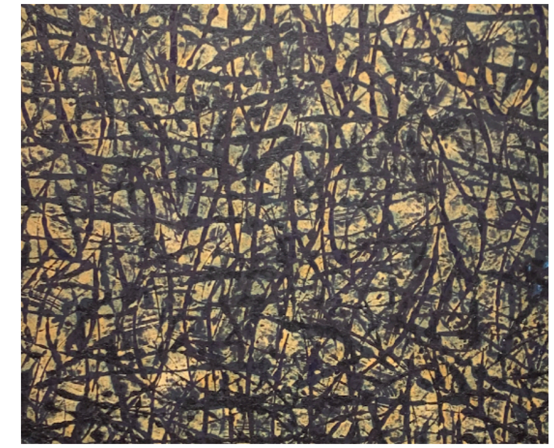
$$a = \frac{v_2\{SP\}}{v_2\{PP\}} \qquad b = \frac{\Delta\gamma_{CME}\{PP\}}{\Delta\gamma_{CME}\{SP\}}$$

- The a is independent of stage evolution.
- Initial b is smaller than a after parton cascade, as B field direction is not as exactly the same as reaction plane.
- The b decreases stage by stage. Due to the decorrelation of CME relative to SP and PP?
- a and b are more different in Au+Au? Can it decrease the currently observed finite f_{CME} in Au+Au?

Summary

AMPT model

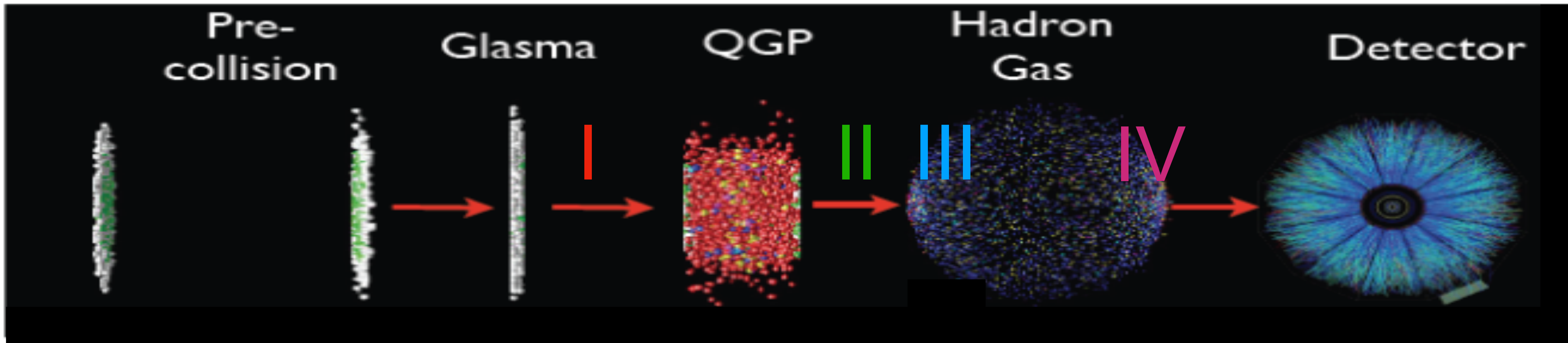
+ CME

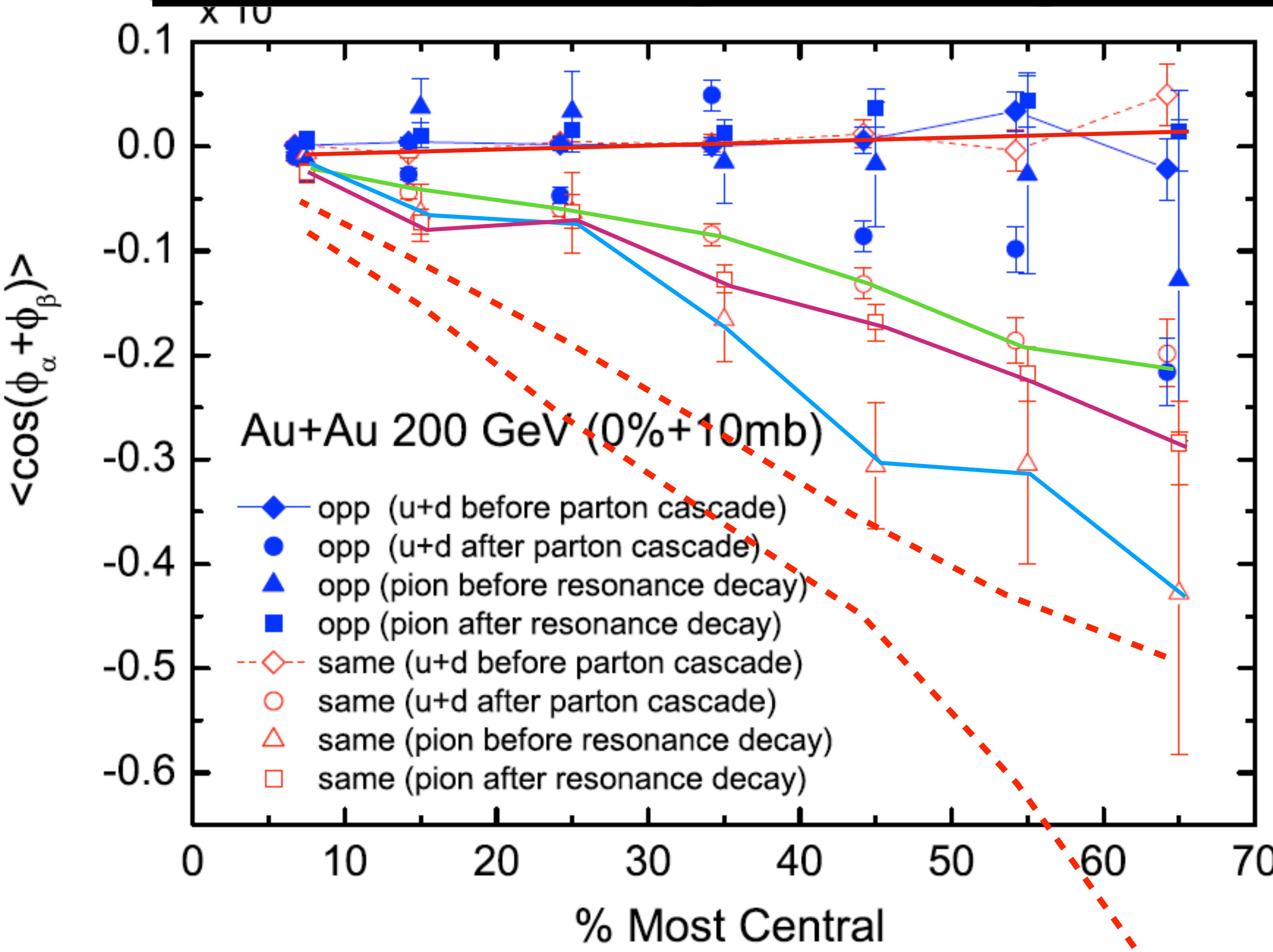


- Final-state interactions greatly reduce the CME signal
- Non-linear sensitivity of CME observations to the CME signal
- Very low strength of CME signals in isobar collisions.
- The b correction to the two-plane method will lead to a reduction in the CME fraction
- More accurate search for CME in higher statistical Au+Au data in the future

Thank you!

Stage evolution of CME background in AMPT





I. Opp-charge and same-charge are consistent with zero initially.(◇)

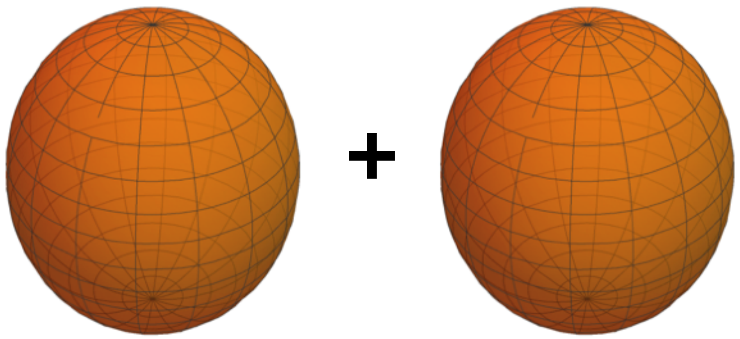
II. being negative through parton cascae due to Flow+TMC.(○)

III. Coalesce enhances same-charge and reduce opp-charge. (△)

IV. Resonance decays reduce signal. (□)

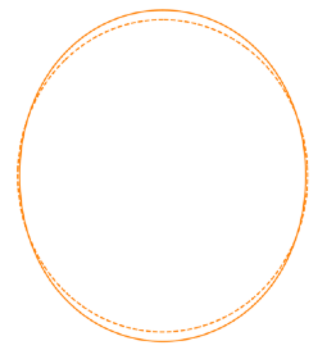
Case1

Ru Ru



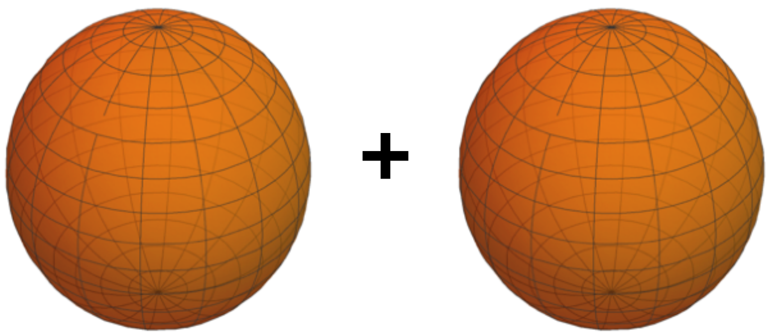
Solid: Ru+Ru, Dash: Zr+Zr

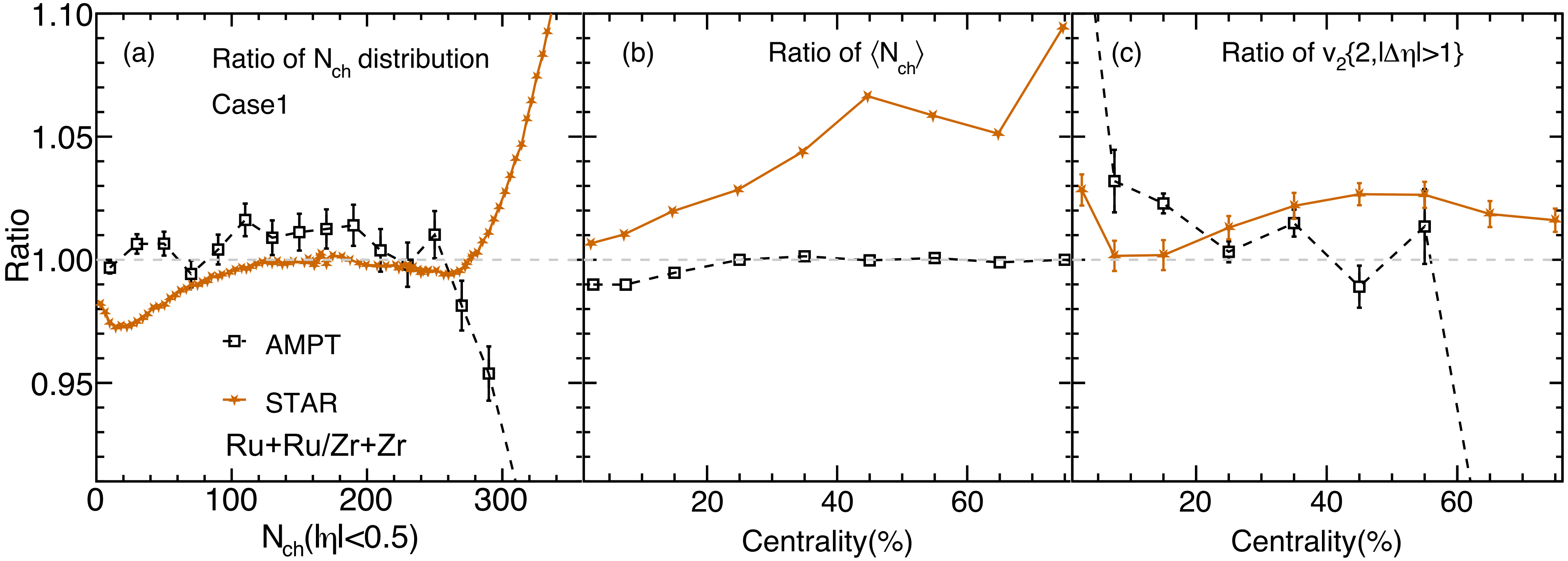
	Case1		
	R_0	a	β_2
$^{96}_{44}$Ru	5.085	0.46	0.158
$^{96}_{40}$Zr	5.02	0.46	0.080



W. T. Deng, X. G. Huang, G. L. Ma and G. Wang, Phys. Rev. C 94, 041901 (2016).
G. Fricke, C. Bernhardt, K. Heilig, L. A. Schaller, L. Schellenberg, E. B. Shera and C. W. de Jager, Atom. Data Nucl. Data Tabl. 60, 177-285 (1995).
S. Raman, C. W. G. Nestor, Jr and P. Tikkanen, Atom. Data Nucl. Data Tabl. 78, 1-128 (2001).
M. Abdallah et al. [STAR], Phys.Rev.C 105 (2022) 1, 014901

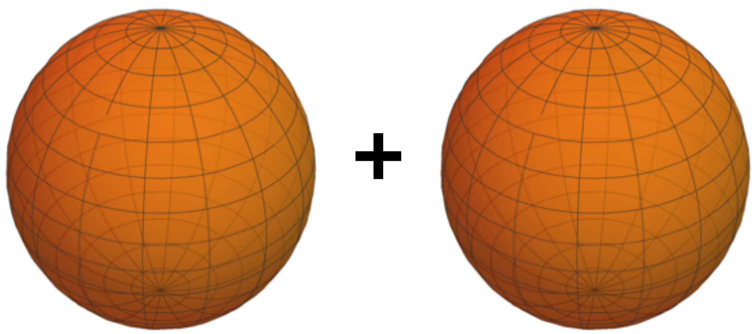
Zr Zr





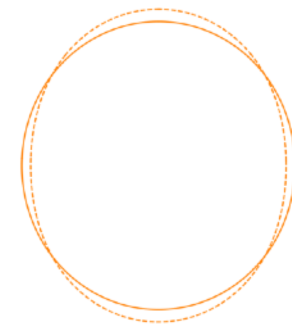
Case2

Ru Ru



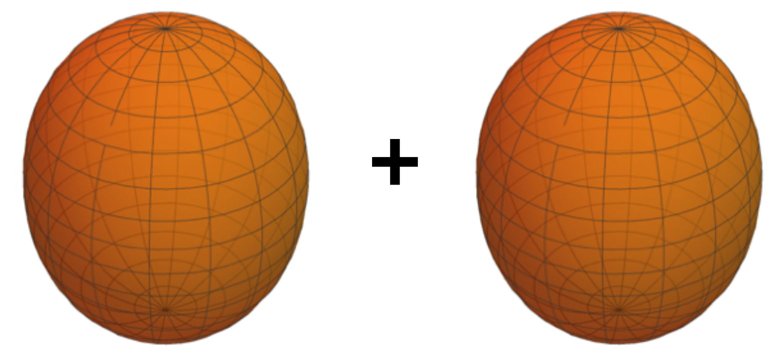
	Case2		
	R_0	a	β_2
$^{96}_{44}$Ru	5.085	0.46	0.053
$^{96}_{40}$Zr	5.02	0.46	0.217

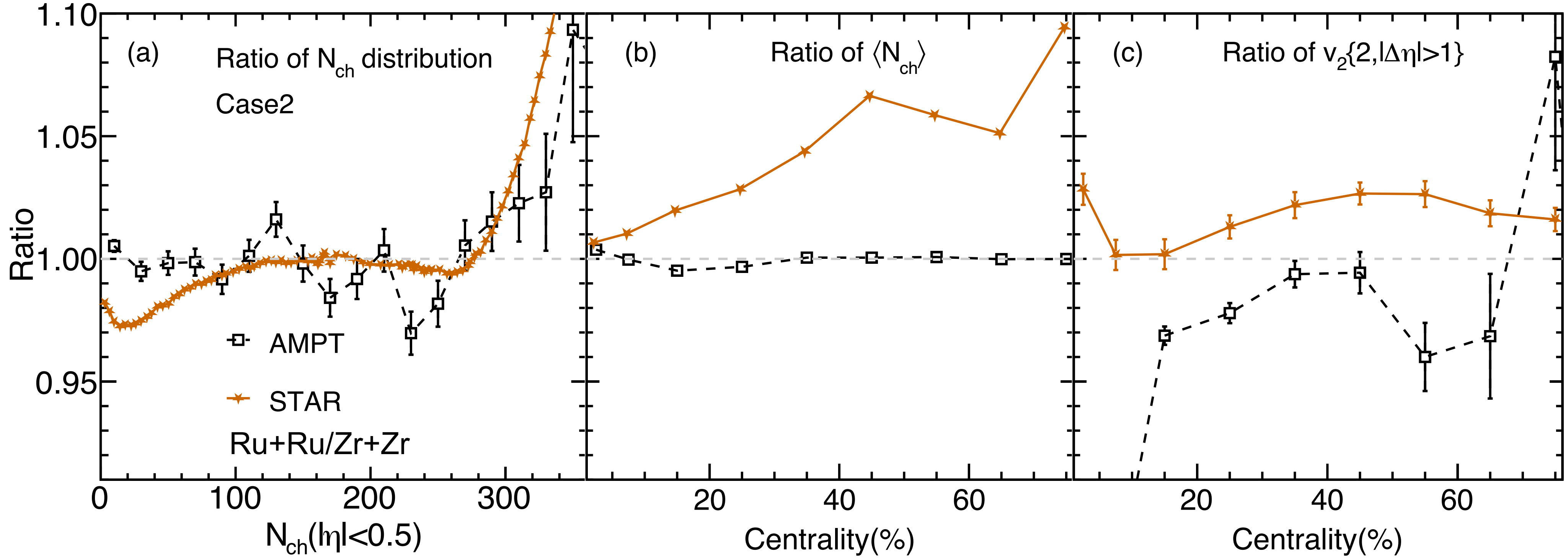
Solid: Ru+Ru. Dash: Zr+Zr



W. T. Deng, X. G. Huang, G. L. Ma and G. Wang, Phys. Rev. C 94, 041901 (2016).
G. Fricke, C. Bernhardt, K. Heilig, L. A. Schaller, L. Schellenberg, E. B. Shera and C. W. de Jager, Atom. Data Nucl. Data Tabl. 60, 177-285 (1995).
P. Moller, J. R. Nix, W. D. Myers and W. J. Swiatecki, Atom. Data Nucl. Data Tabl. 59, 185-381 (1995).
M. Abdallah et al. [STAR], Phys.Rev.C 105 (2022) 1, 014901

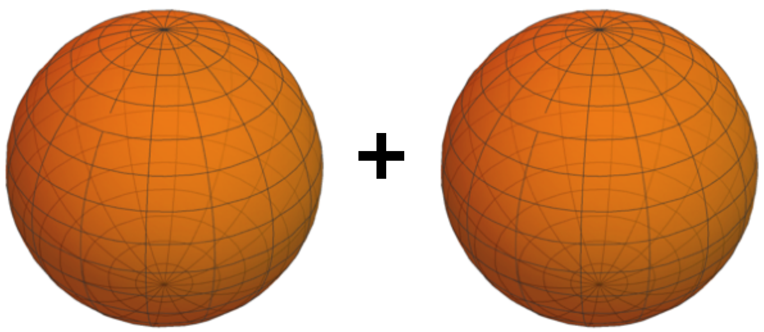
Zr Zr



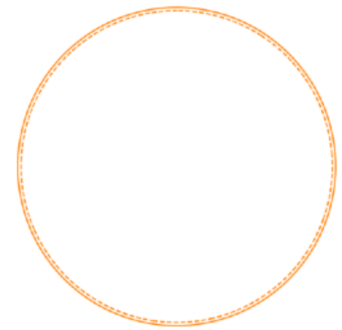


Case3

Ru Ru



Case3	R_0	a	β_2
$^{96}_{44}$Ru	5.067	0.500	0
$^{96}_{40}$Zr	4.965	0.556	0



M. Abdallah et al. [STAR], Phys.Rev.C 105 (2022) 1, 014901
H. j. Xu, H. Li, X. Wang, C. Shen and F. Wang, Phys. Lett. B 819, 136453 (2021).

Zr Zr