Interplay between nuclear structure and chiral magnetic effect in isobar collisions

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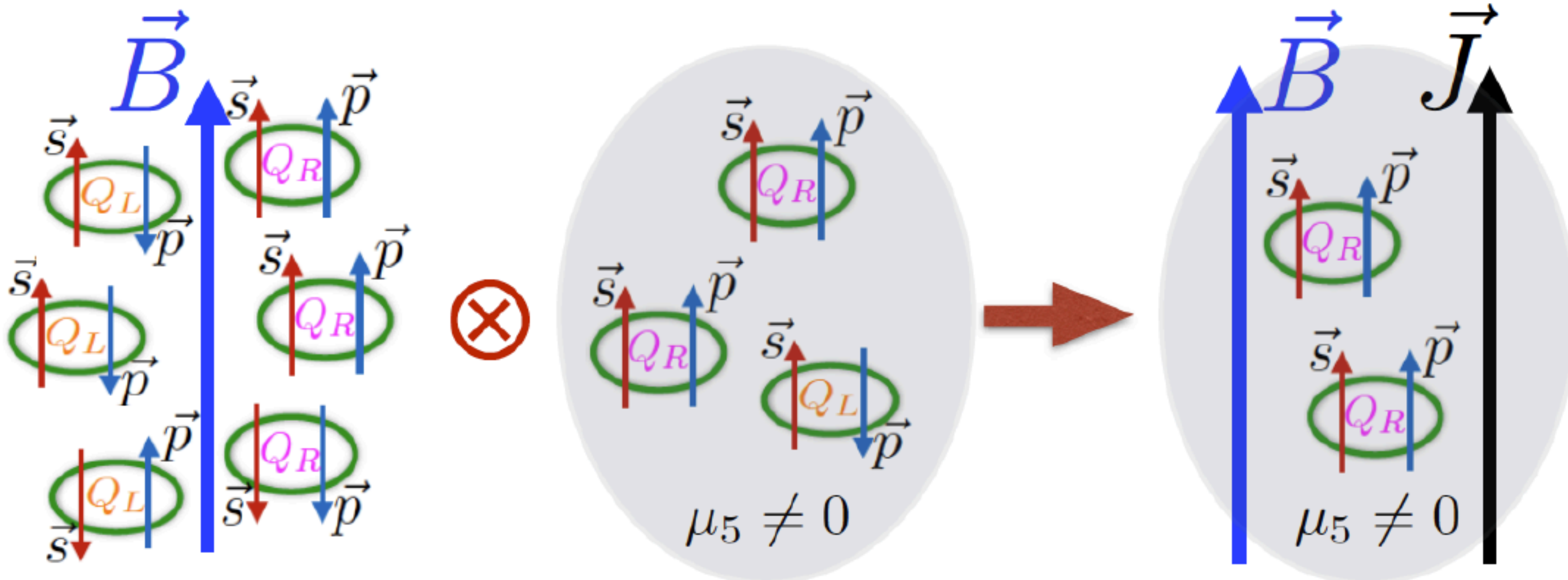
Outline

- Introduction
- CME in Au+Au collisions
- CME in isobar collisions
- Summary

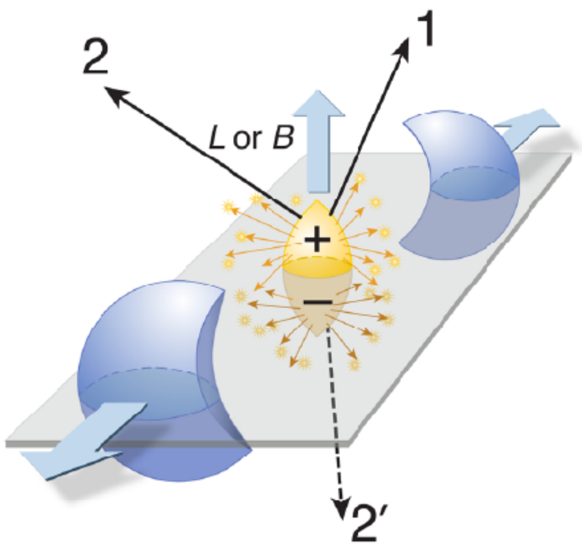
Chiral Magnetic Effect (CME)



●Initial fluctuations of topological charge in QCD vacuum → P and CP odd metastable domains → Charge separation in the direction of magnetic field

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

CME observable: charge azimuthal correlation γ



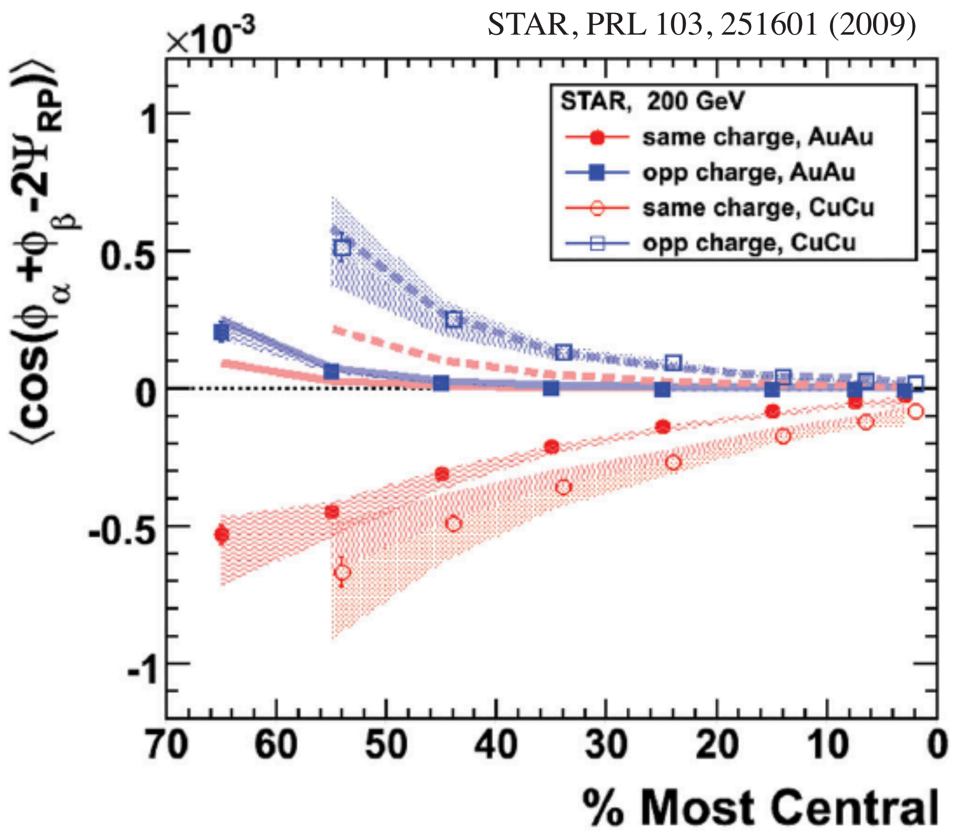
$$\gamma = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$$
$$= [\langle v_{1,\alpha} v_{1,\beta} \rangle + B_{in}] - [\langle a_\alpha a_\beta \rangle + B_{out}]$$

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

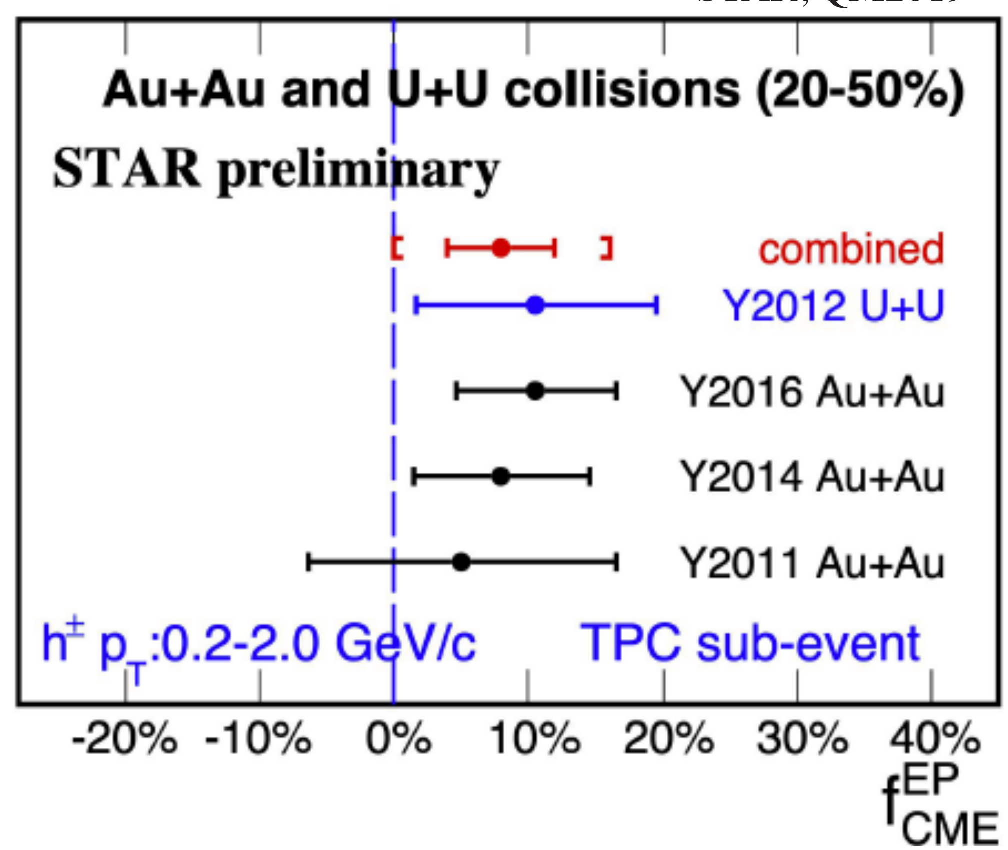
Directed flow: vanishes
if measured in a symmetric rapidity range

P-even quantity:
still sensitive to charge
separation

STAR, PRL 103, 251601 (2009)

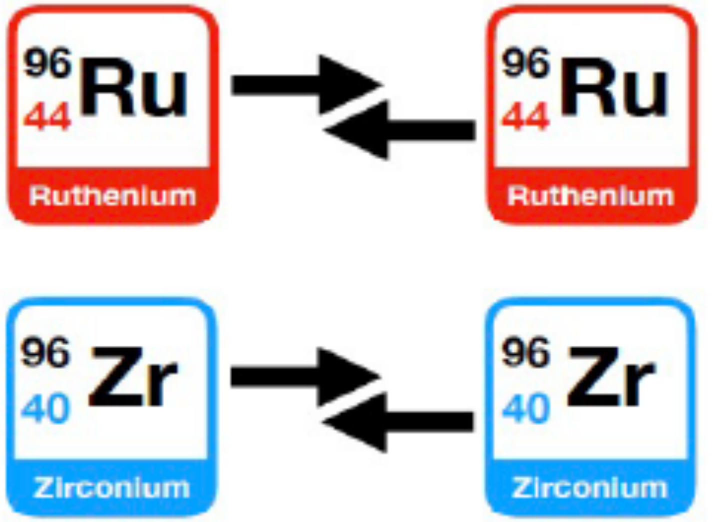


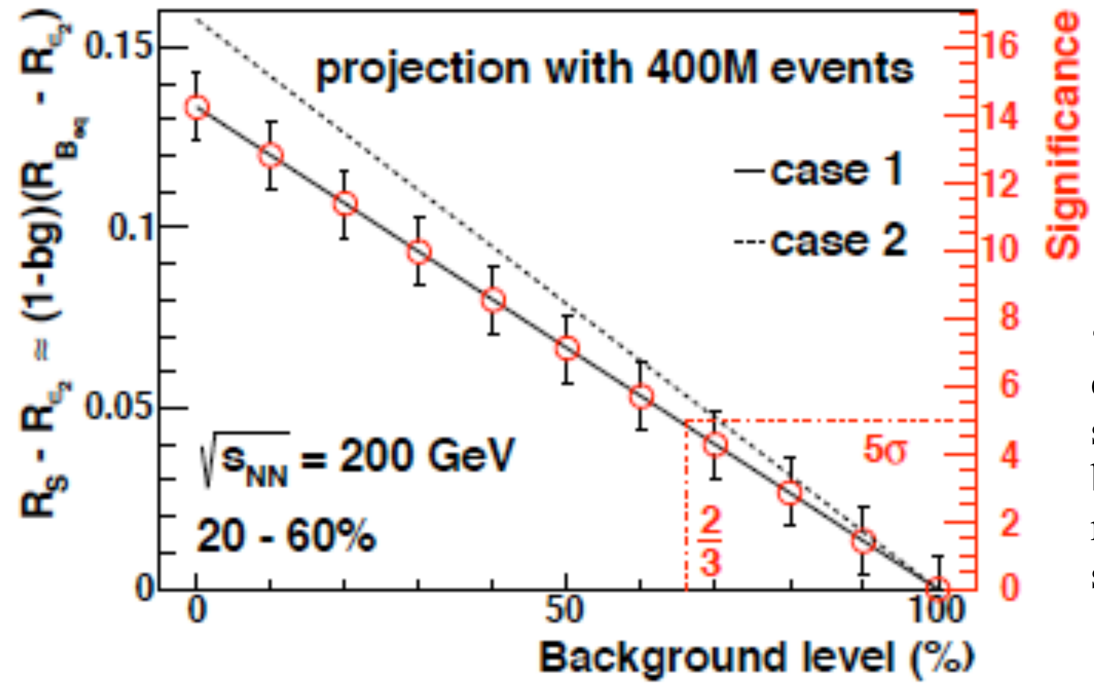
STAR, QM2019



- First STAR result was consistent with the CME expectation, dipole charge separation.
- Recent STAR result indicated the CME fraction in $\Delta\gamma$ is small, background is dominant.

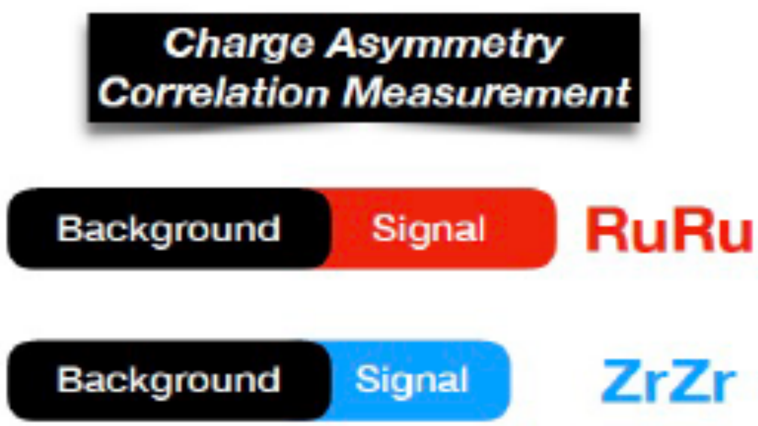
Isobar collision experiment



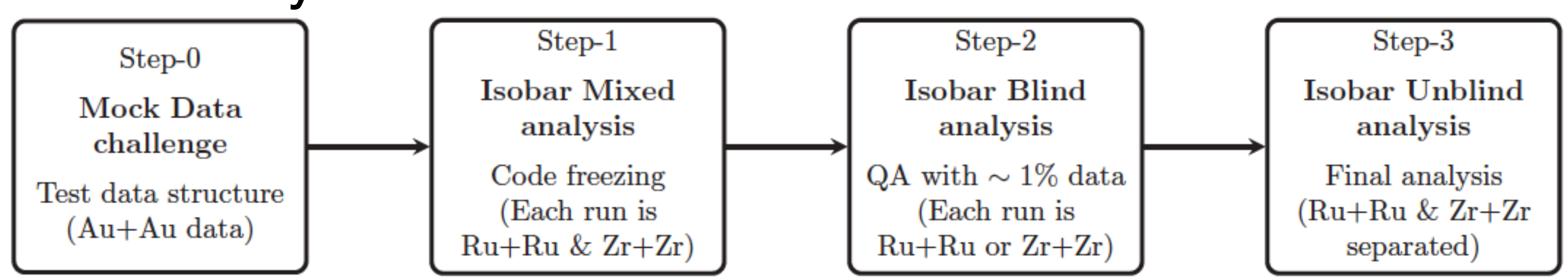


Wei-Tian Deng, Xu-Guang Huang, Guo-Liang Ma, Gang Wang, Phys. Rev. C 94 (R), 041901 (2016)

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



Blind analysis:



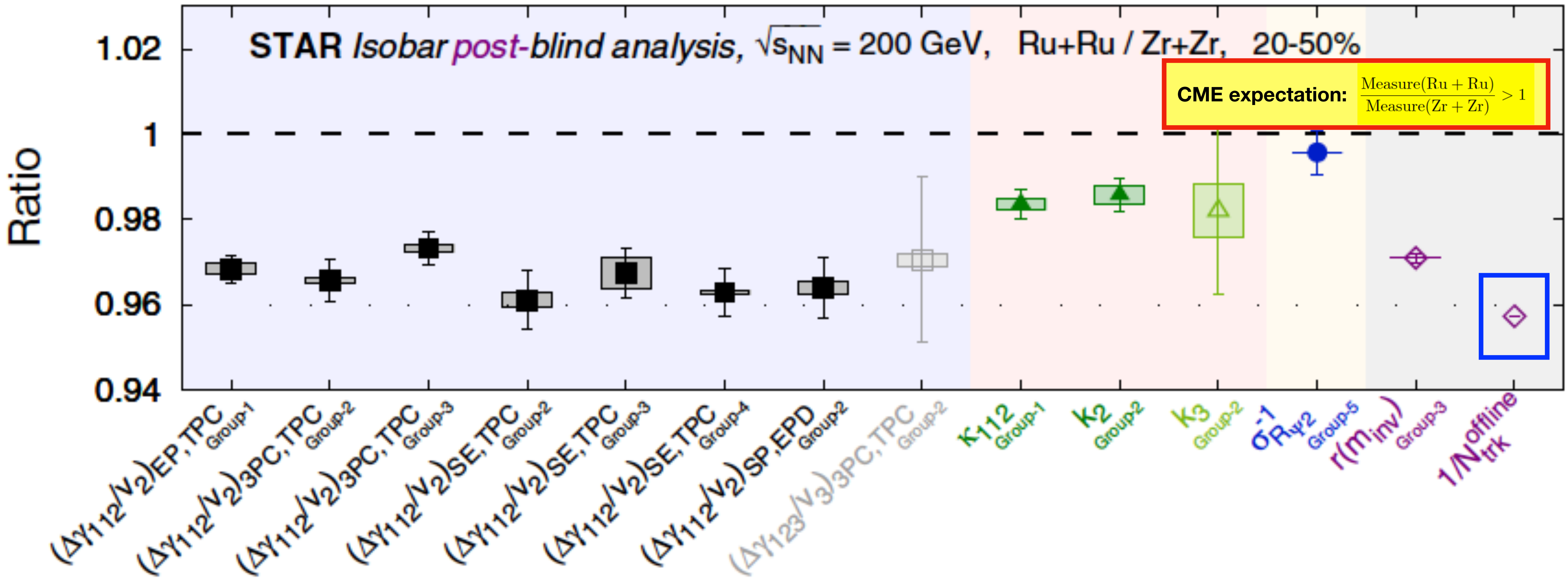
- In 2018, STAR collected isobar data (1.8B Ru+Ru && 2.0B Zr+Zr), looking for the CME expectation.
- Five teams conducted blind analysis.

CME expectation:

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

First isobar results from STAR experiment

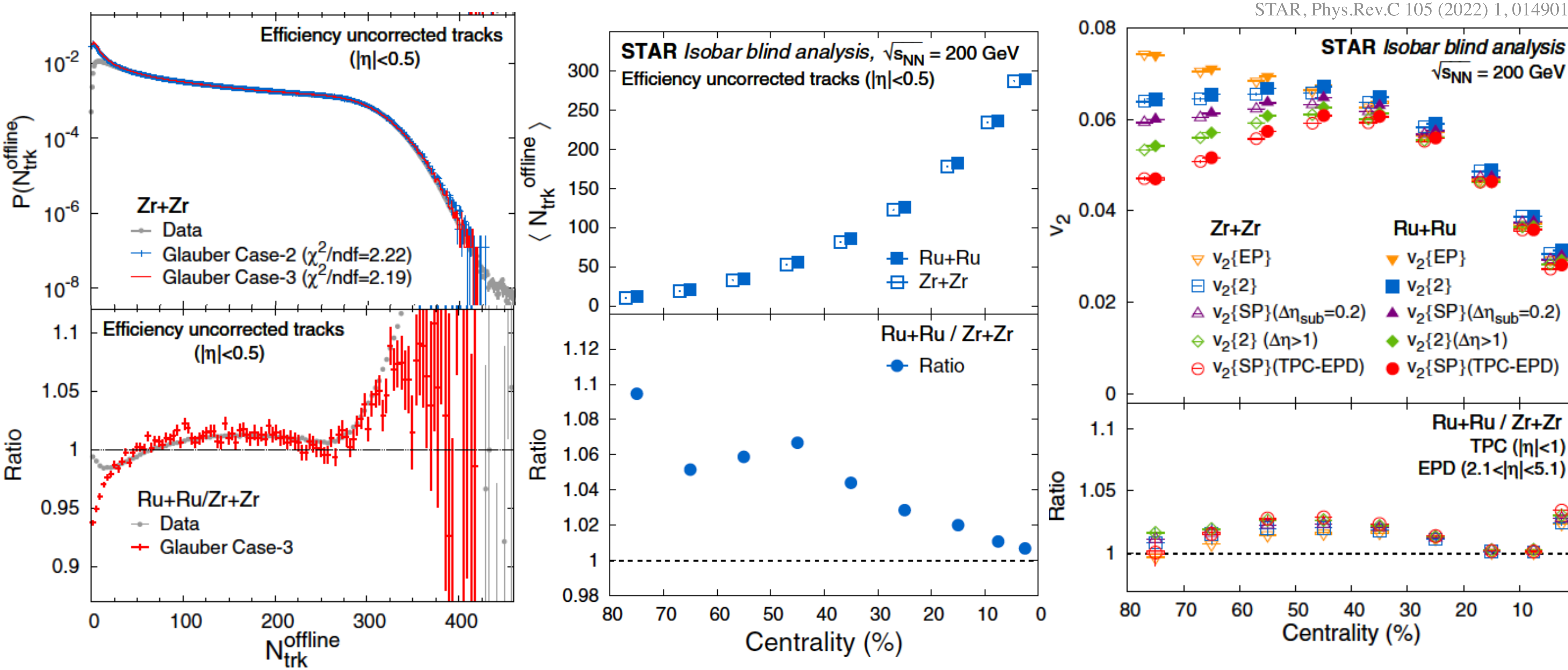
Search for the chiral magnetic effect with isobar collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR Collaboration at the BNL Relativistic Heavy Ion Collider



- Five analysis teams show a good agreement: "The ratios are generally less than 1, and no obvious CME signal is found"
- Need to better understand the baseline? set a new baseline?

Understand background difference in isobar collisions

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

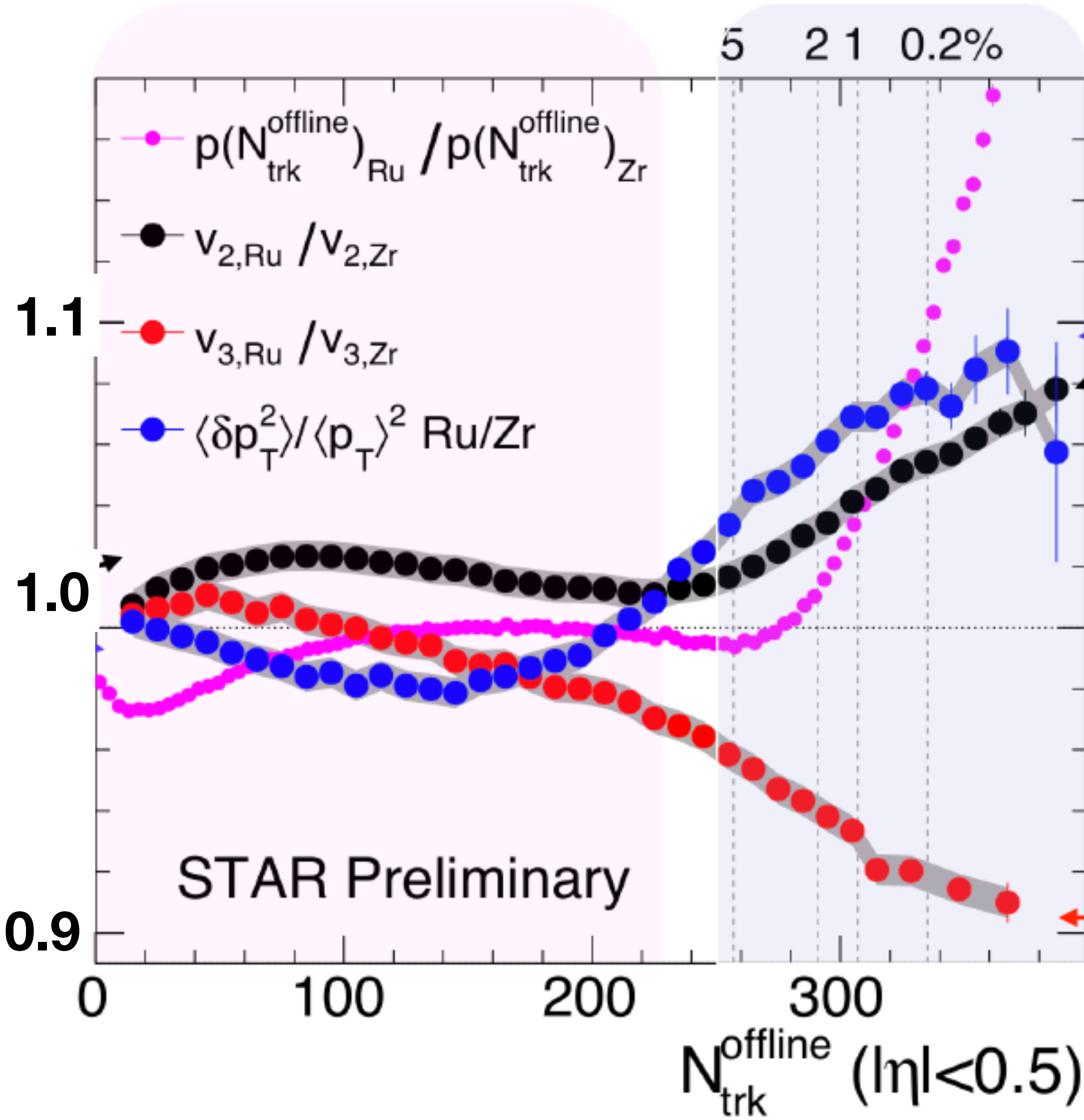


- Difference in multiplicity distribution, <Nch> and v2 between two isobar systems.
- Related to the nuclear deformation/structure?

	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

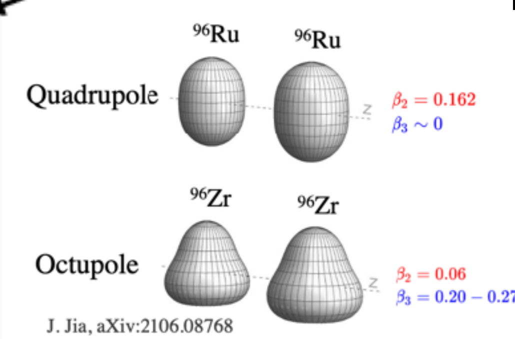
Other cases?

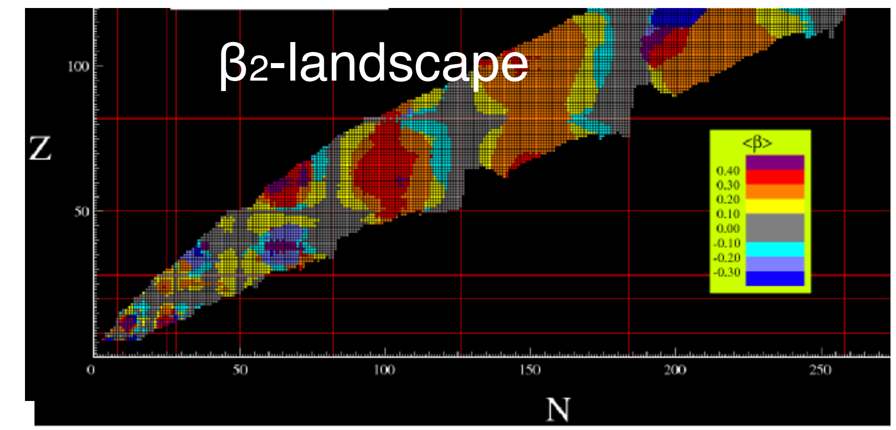
Nuclear structure in relativistic heavy-ion collisions

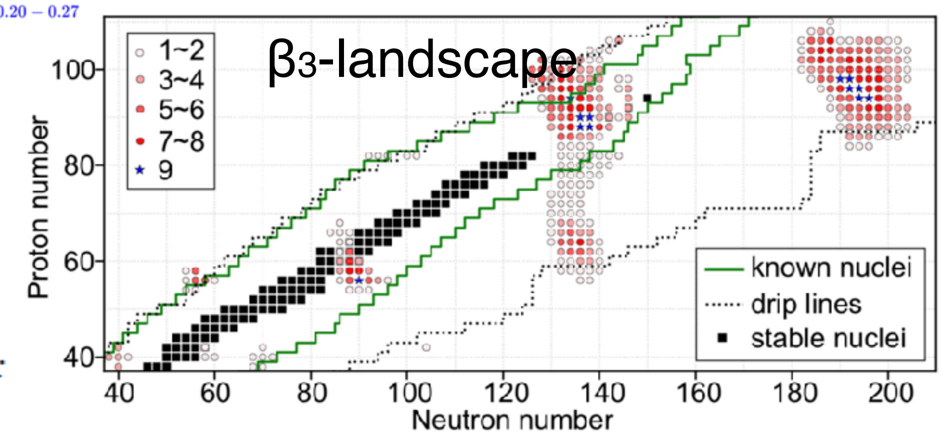


Large $\beta_{2,Ru}$

Large $\beta_{3,Zr}$



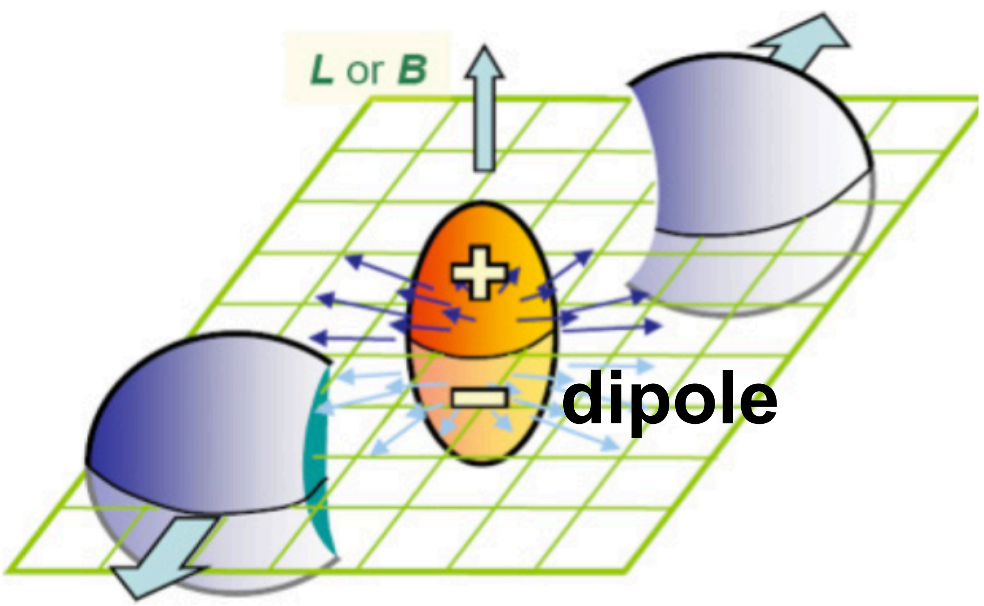


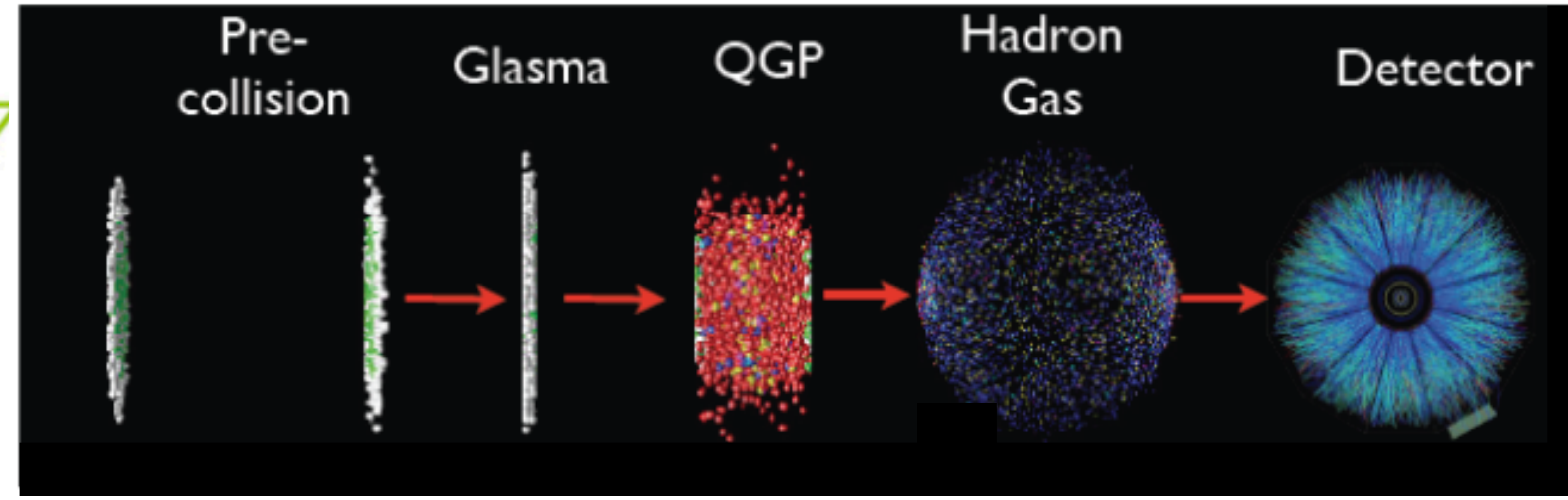


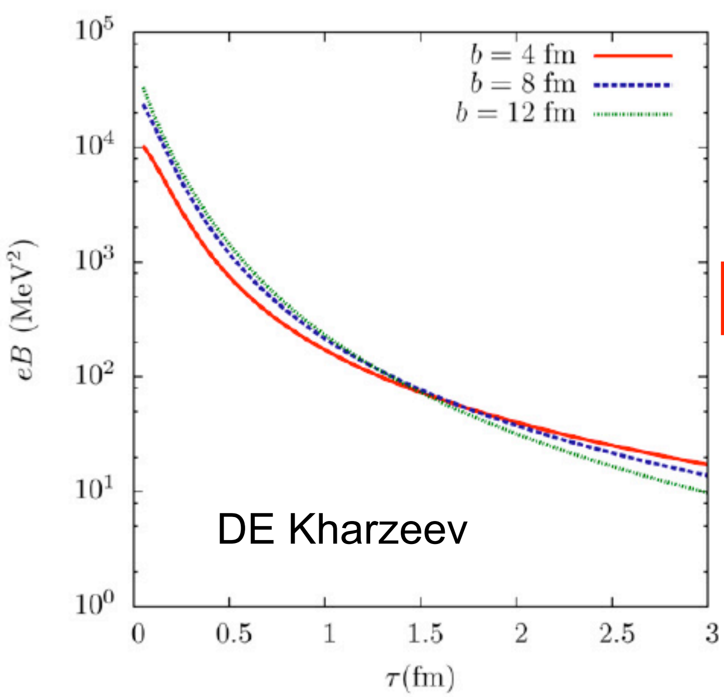
- The ratios between isobar systems is sensitive to nuclear deformation/structure!
- Open a window to see nuclear structure

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

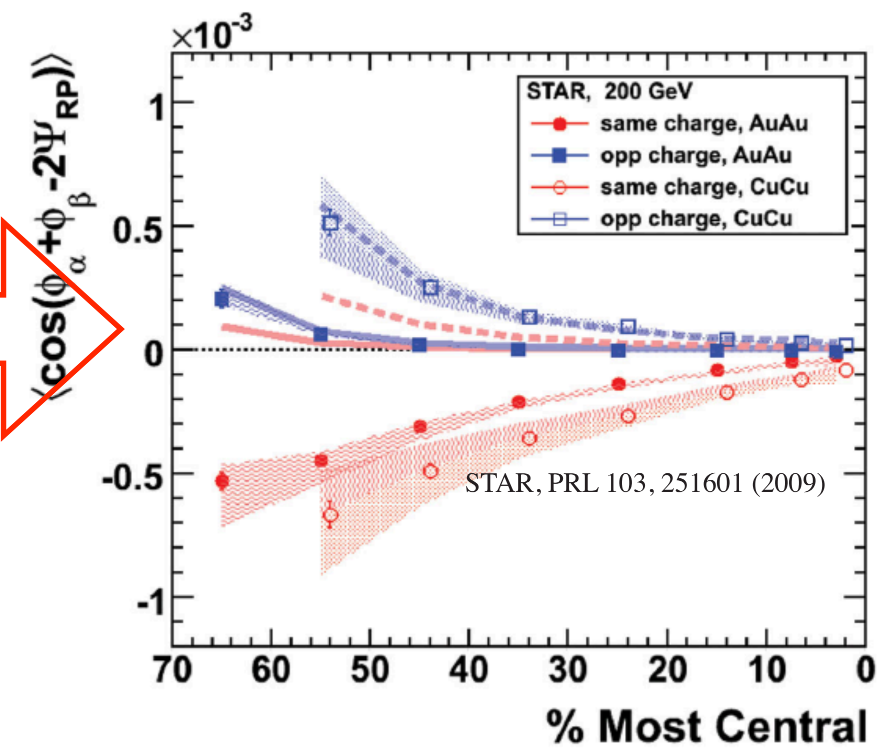
Survival of CME in relativistic heavy-ion collisions







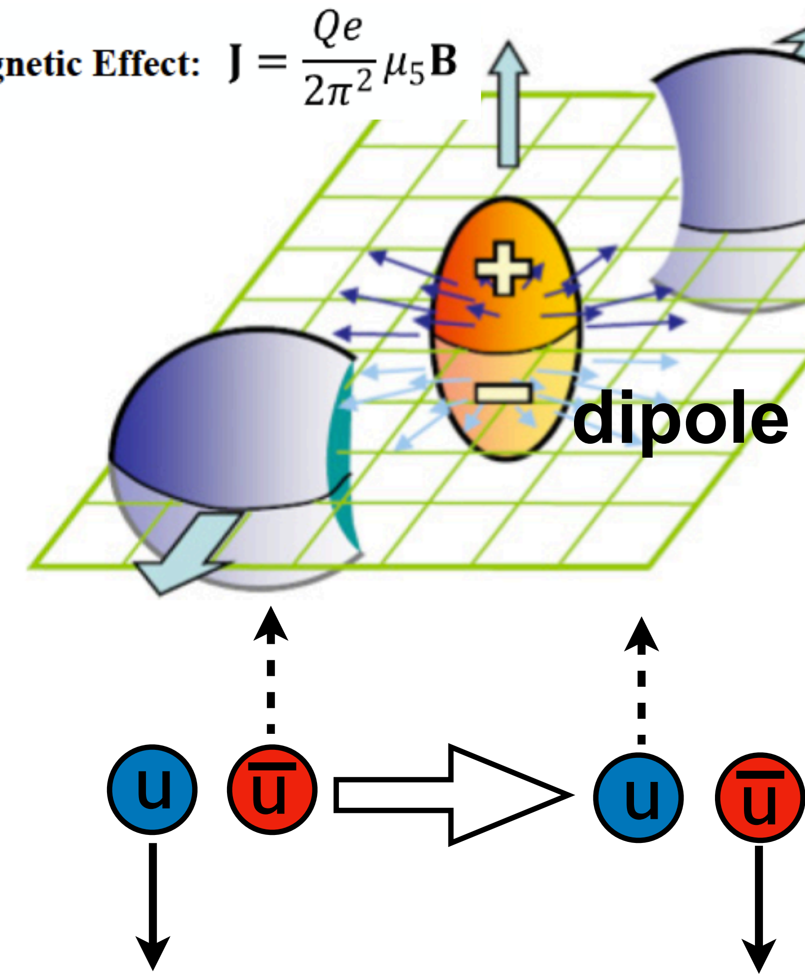
final state interaction effects



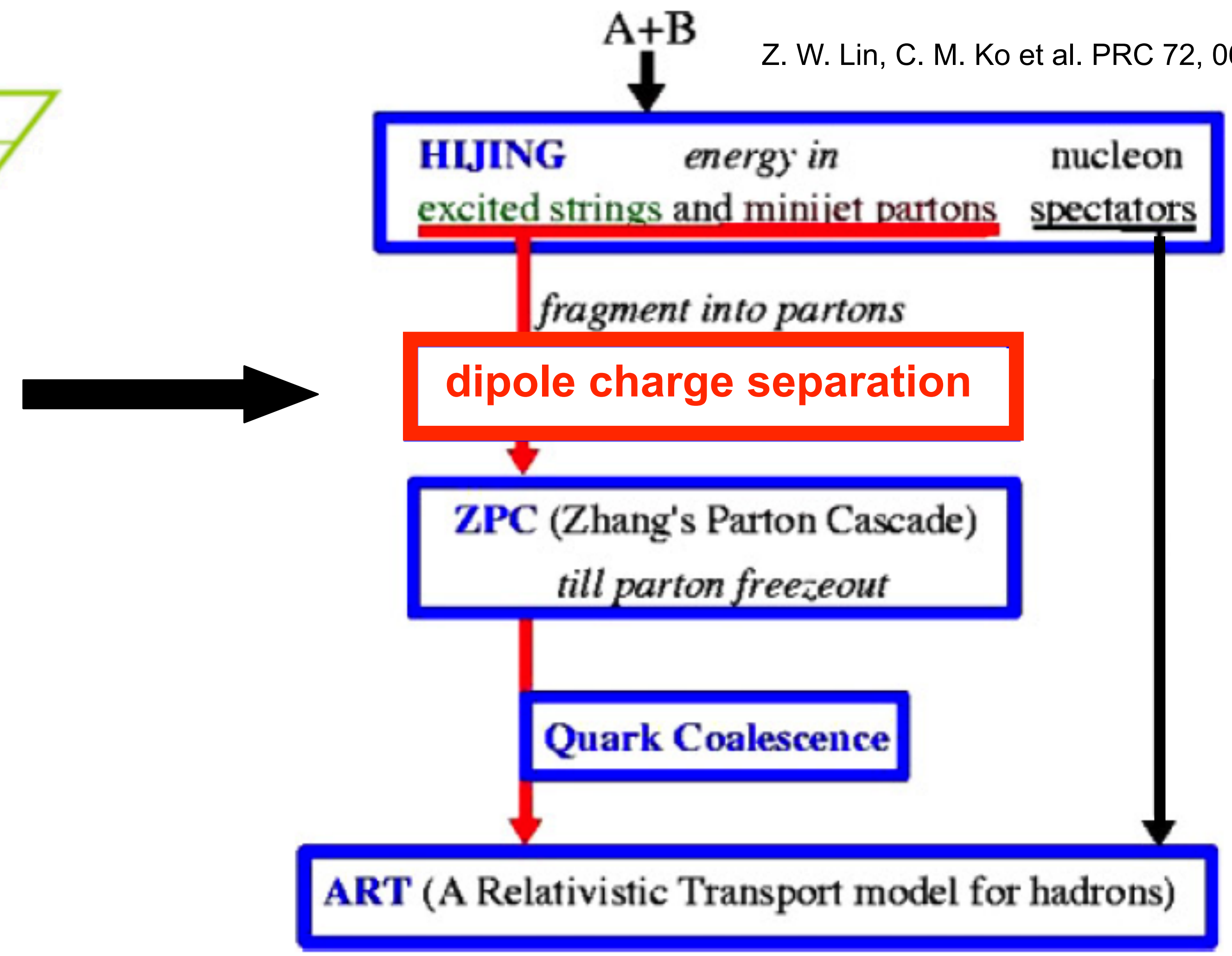
- It is important to study FSI effects on initial CME to see if CME can survive from FSI in heavy-ion collisions.

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 strength:

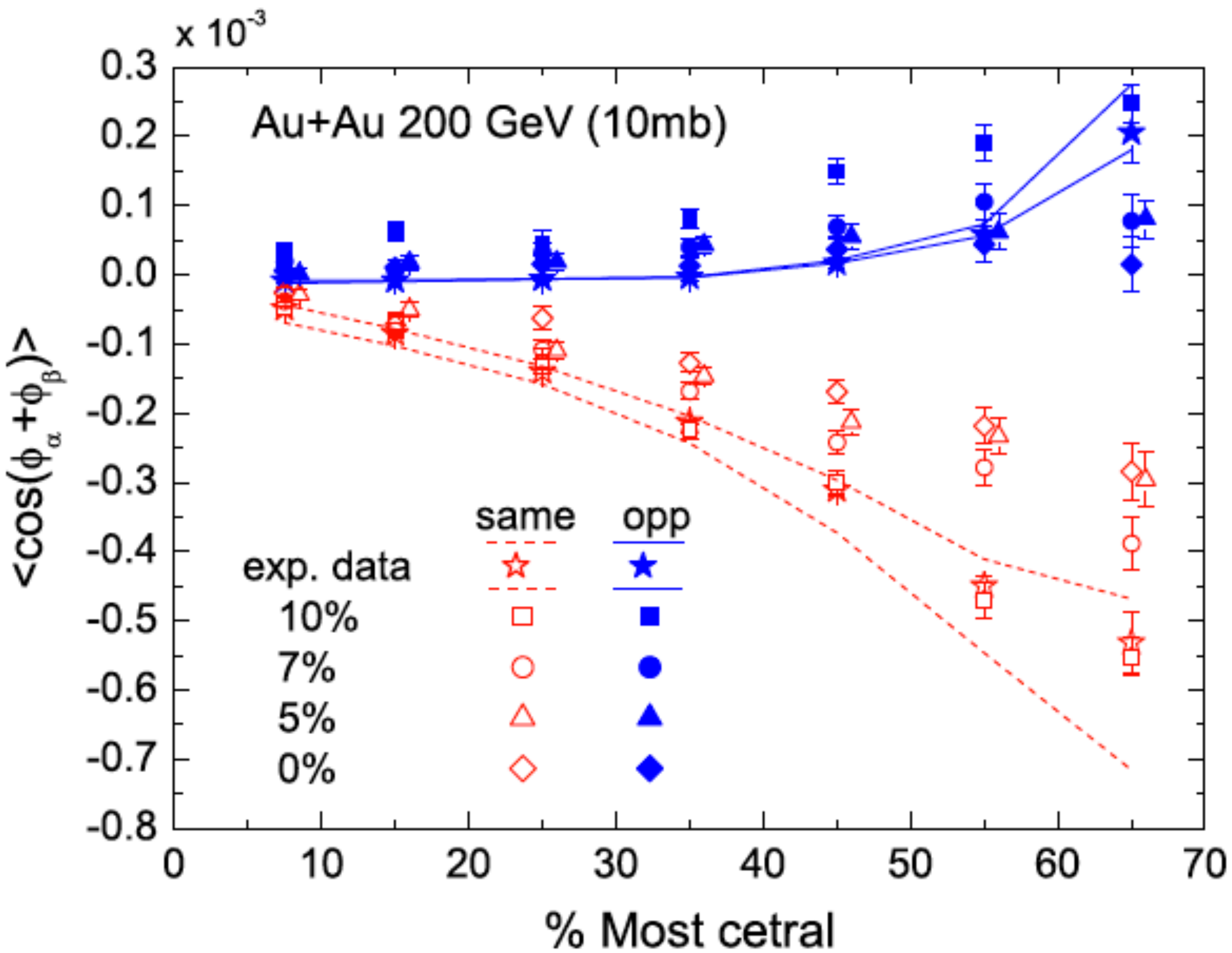
$f\% = (N^+_{upward} - N^+_{downward})/(N^+_{upward} + N^+_{downward})$

- **To include initial dipole charge separation (CME) into AMPT model,**

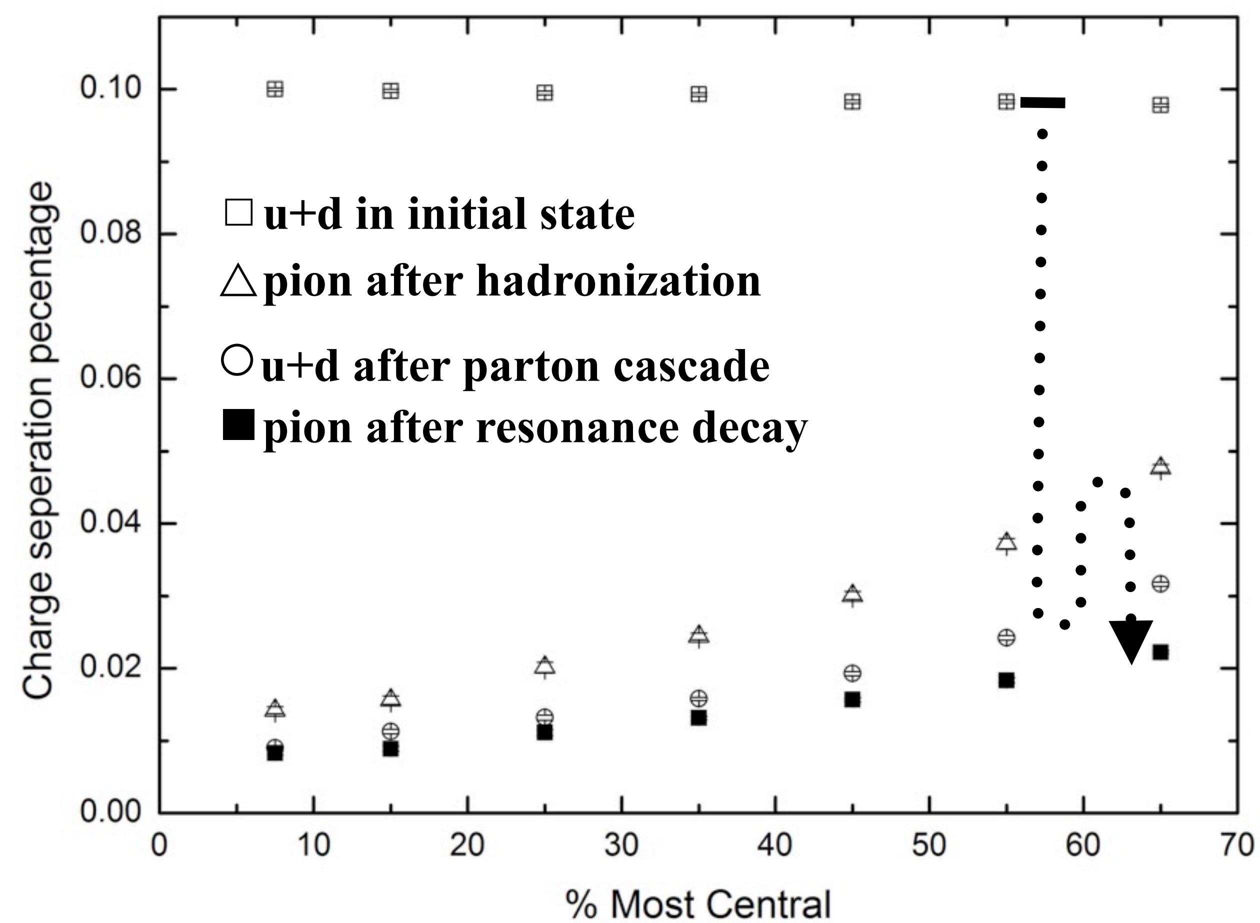
We switch p_y of f% of the downward moving u quarks with those of the upward moving u-bar quarks, and likewise for d-bar and d quarks.

- **We focus on FSI effects on the charge separation, including parton cascade, hadronization, resonance decays after $\vec{B}$ and $\vec{E}$ vanish quickly.**

AMPT results on the observable γ



G.-L. Ma and B. Zhang, Phys. Lett. B 700 (2011) 39



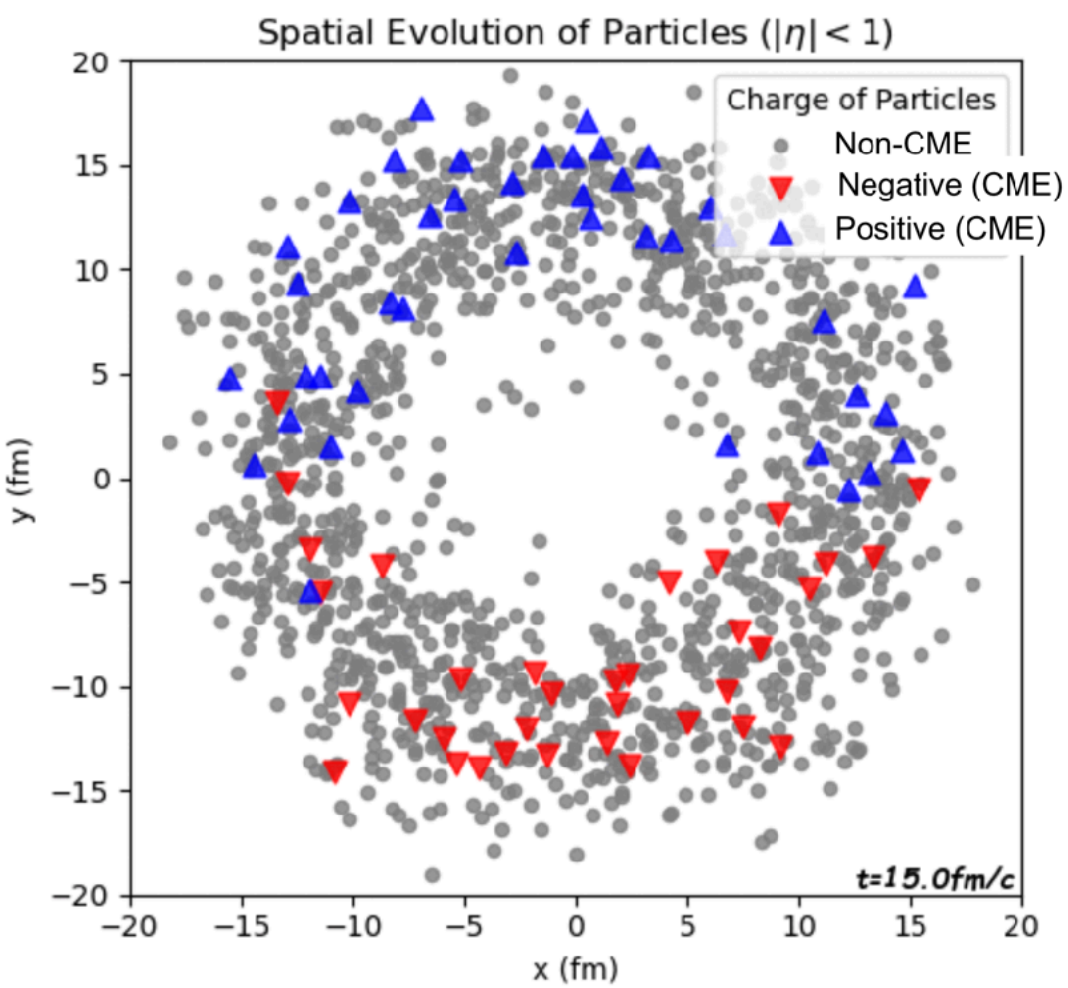
- γ **= BG + CME**
  - An initial charge separation ~10% is needed to describe Au+Au data
- **Non-linear sensitivity**: γ can not response to a CME strength of f<=5%
- **Final state interaction effect**: Only a small faction of CME can survive

Parton cascade effect on the CME signal

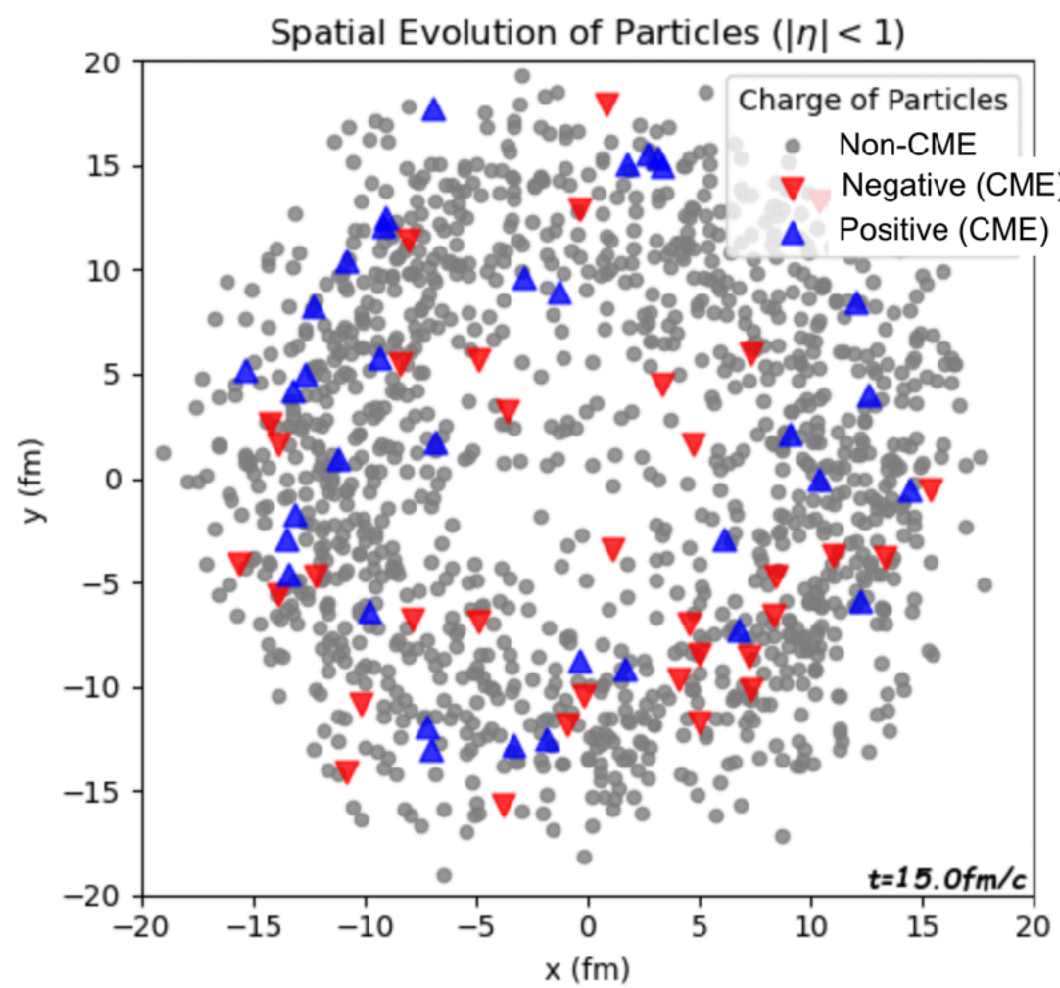
Au+Au 200 GeV (b=8fm), AMPT+CME(10%)

J

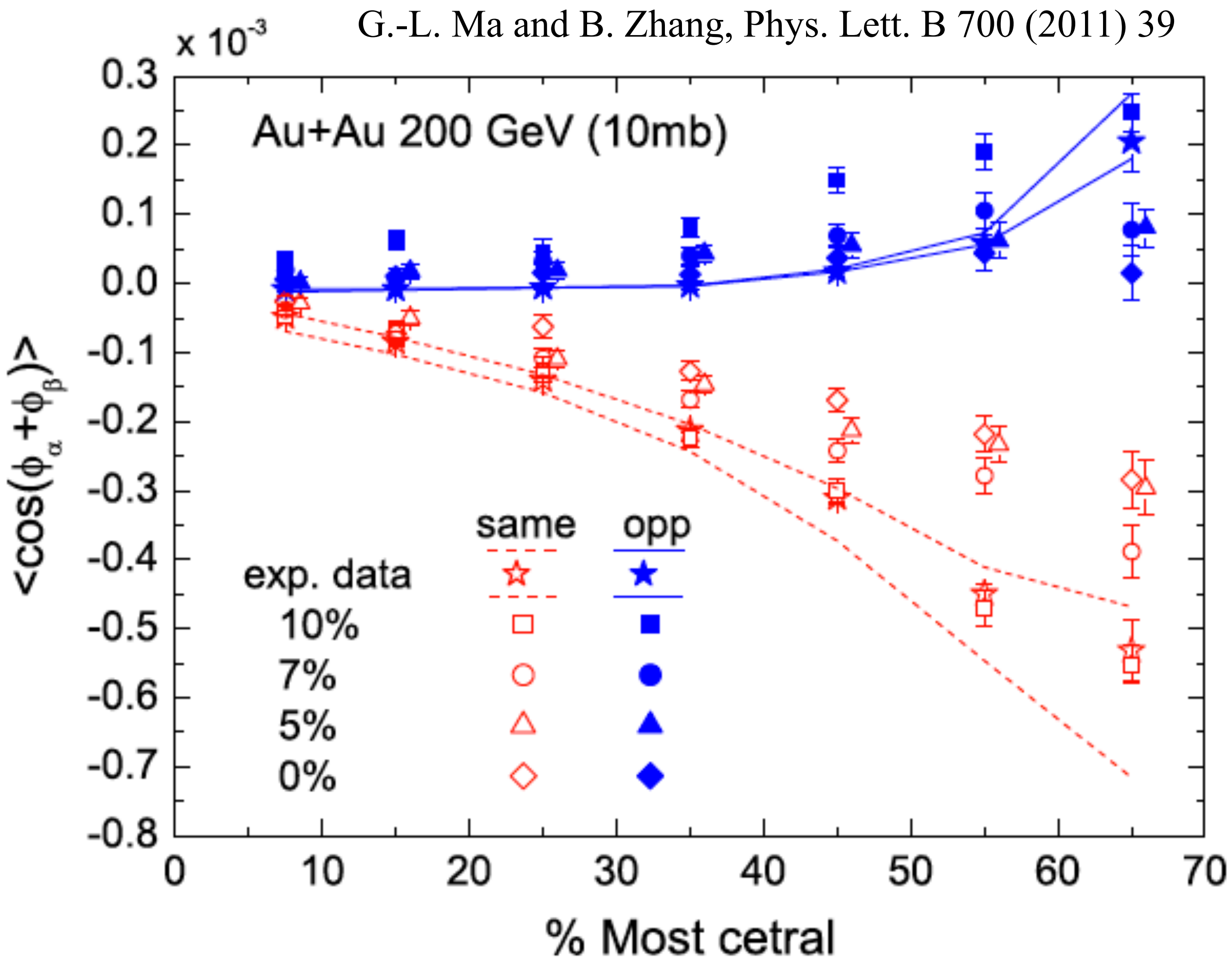
0 mb

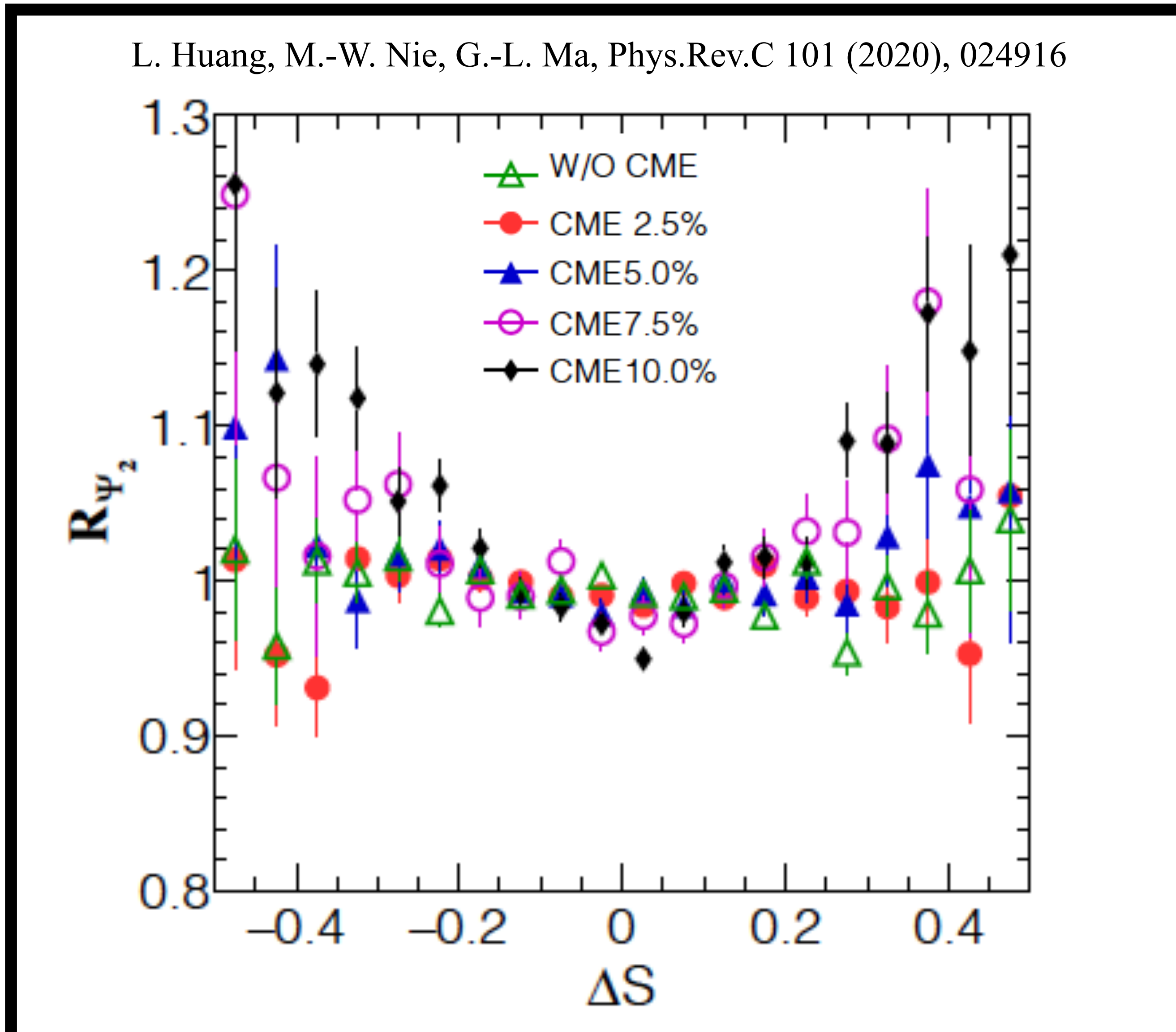


3 mb



AMPT results on the observables γ and R_{Ψ_2}



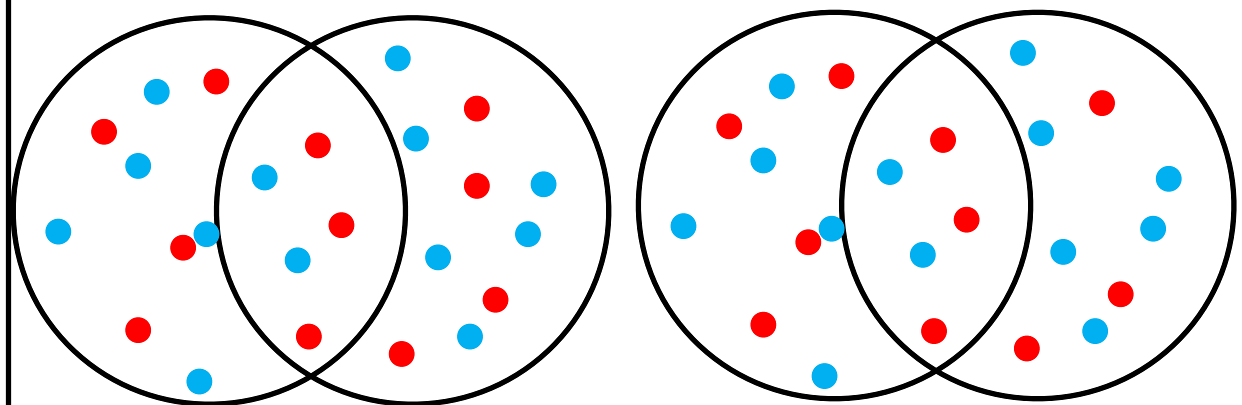


- R_{Ψ_2} can not response to CME strength of $f \le 5\%$
- With increase of CME strength ($f \ge 5\%$), the width of R_{Ψ_2} decreases.

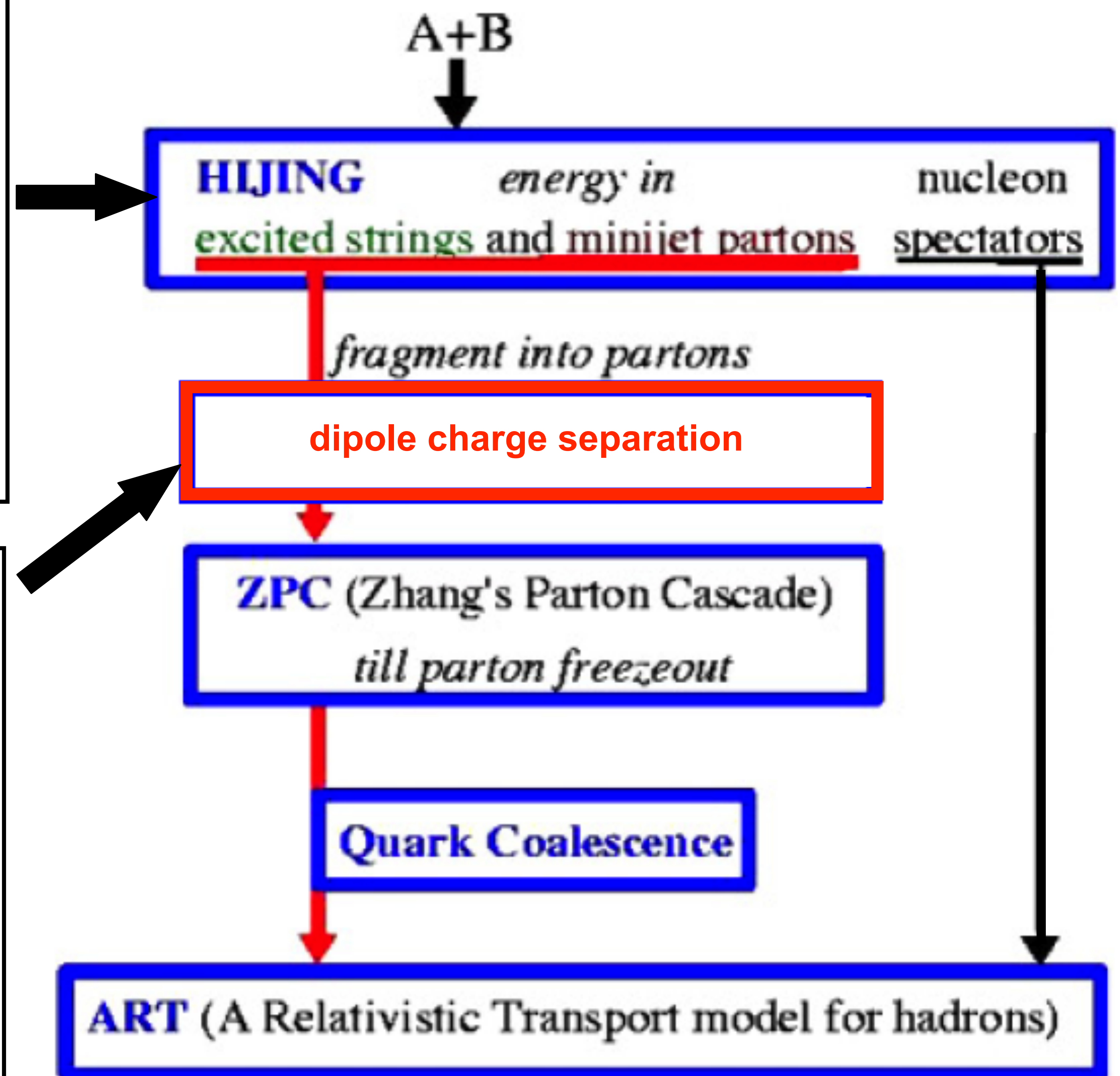
★$\Delta\gamma$ and R_{Ψ_2} non-linearly responses to the CME strength due to FSI.

Simulating CME in isobar collisions using AMPT

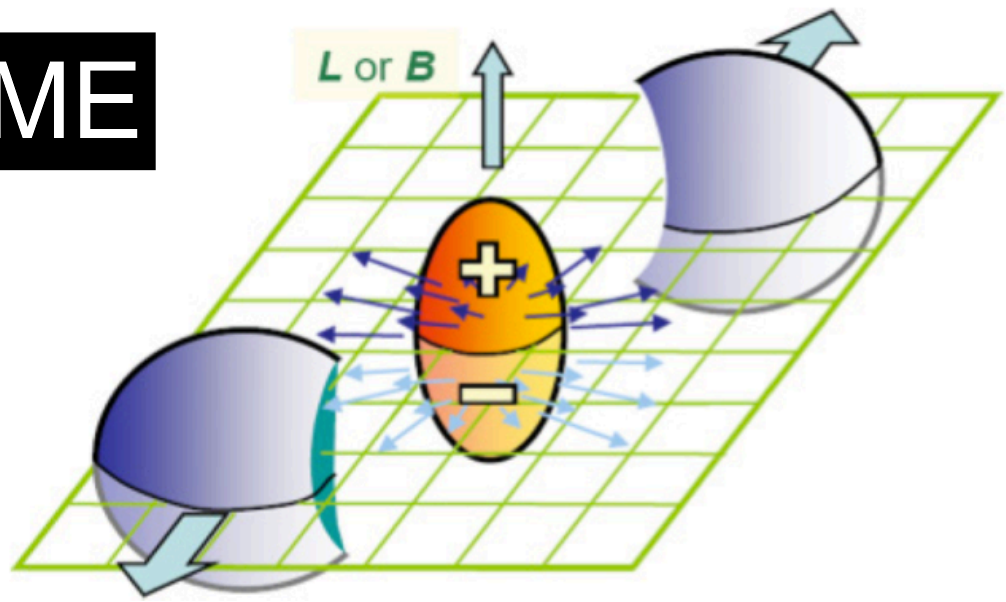
Initialization of isobar



$^{96}_{44}Ru + ^{96}_{44}Ru$ $\quad$ $^{96}_{40}Zr + ^{96}_{40}Zr$



CME



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

Geometry initialization of isobar nuclei

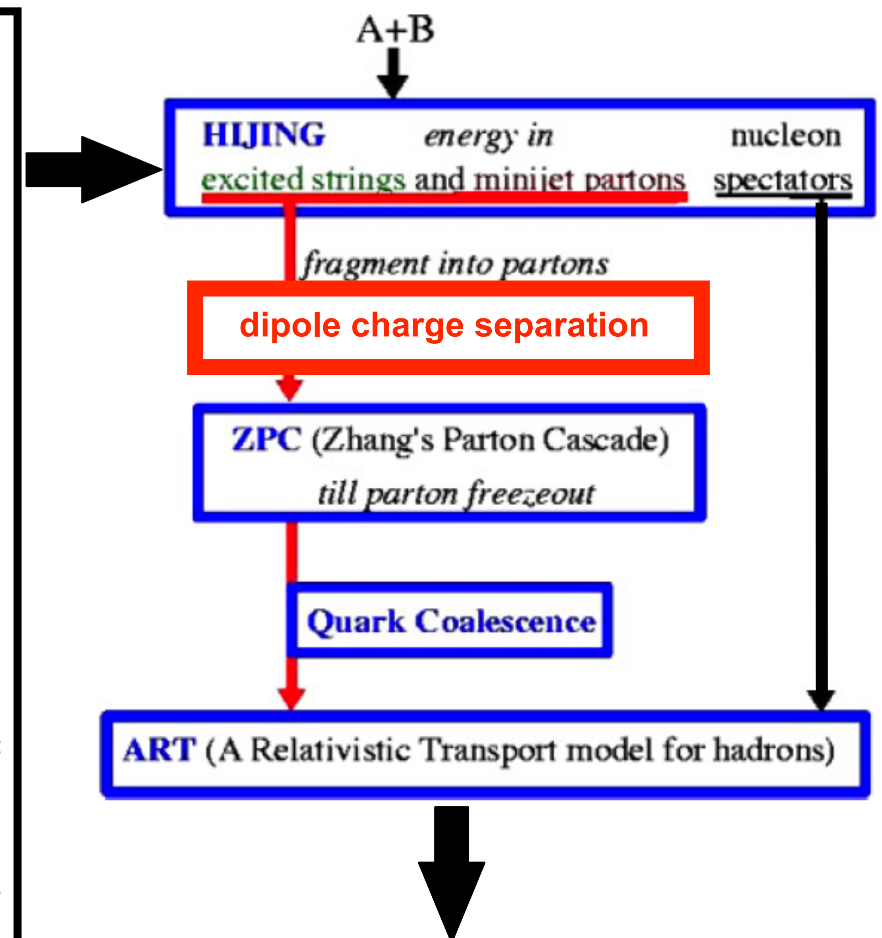
Woods-Saxon form of spatial distribution of nucleons:

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

	old Case1			old Case2			Case1			Case2			Case3		
	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	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 one is good among 15 cases?**
- **Our criterion is the ratios in final state:**

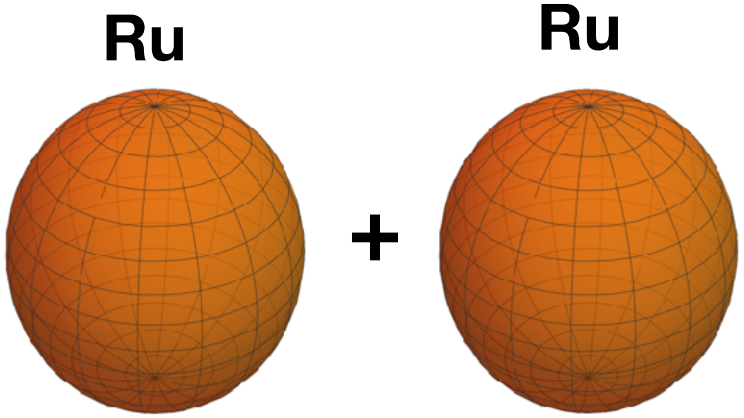
I) Mult. dist. ratio

II) <N_{ch}> ratio vs centrality

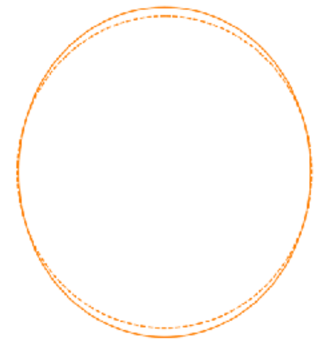
III) v_2 ratio vs centrality

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

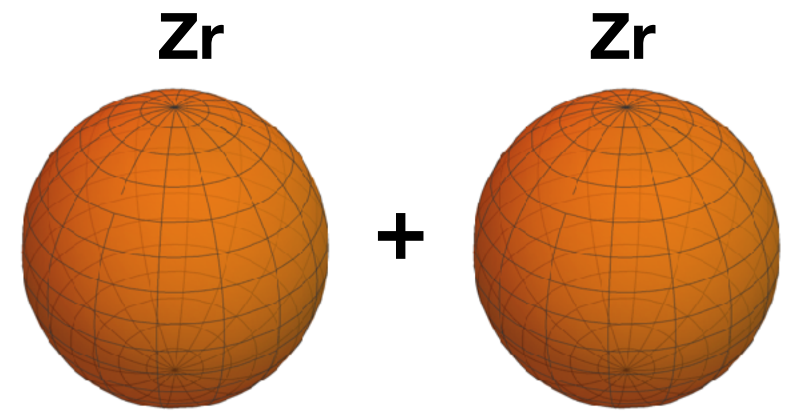
Old Case1

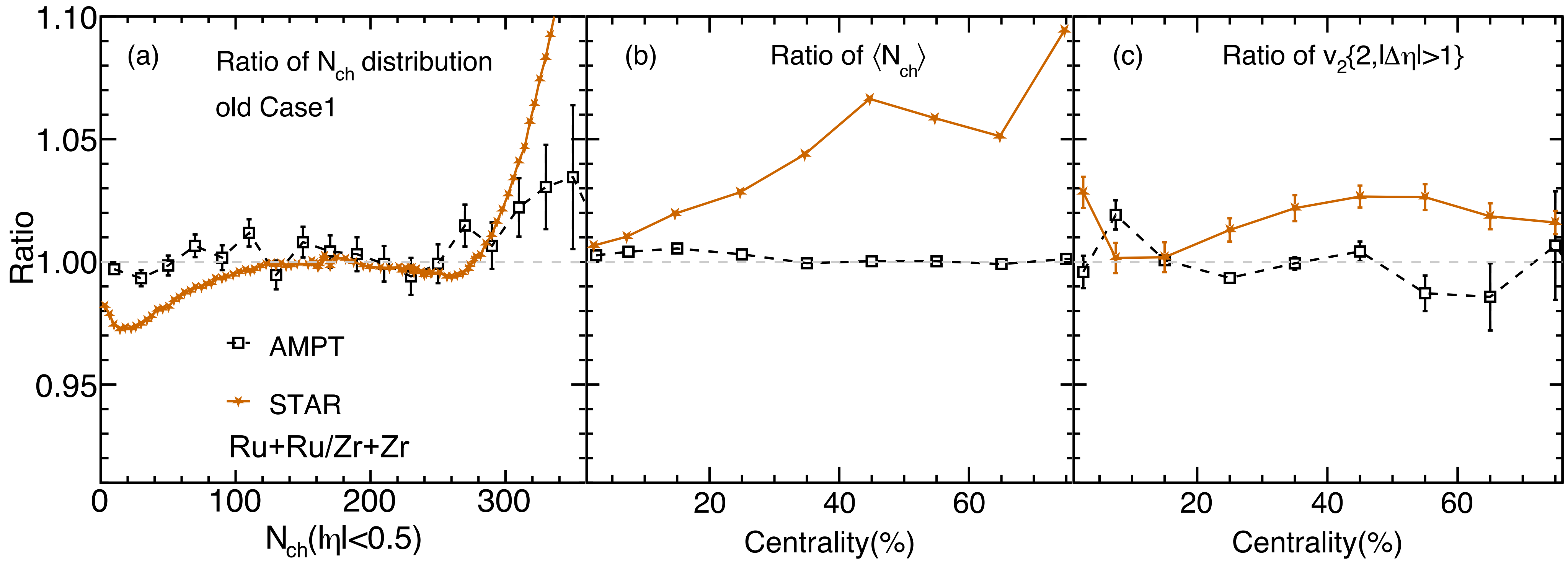


	old Case1		
	R_0	a	β_2
$^{96}_{44}$Ru	5.13	0.46	0.13
$^{96}_{40}$Zr	5.06	0.46	0.06



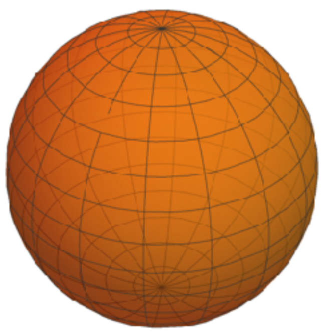
X. L. Zhao, G. L. Ma and Y. G. Ma, Phys. Rev. C 99, no.3, 034903 (2019).





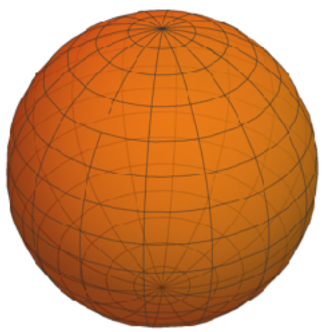
Old Case2

Ru



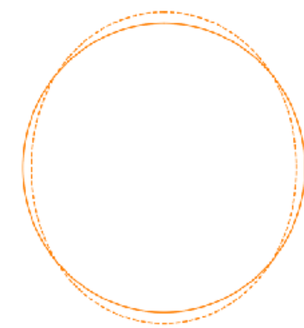
+

Ru



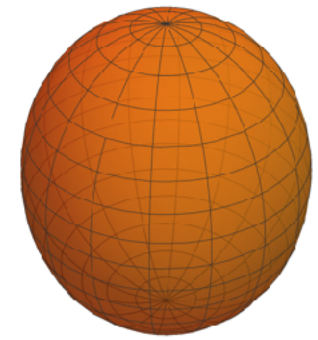
	old Case2		
	R_0	a	β_2
$^{96}_{44}$Ru	5.13	0.46	0.03
$^{96}_{40}$Zr	5.06	0.46	0.18

Solid: Ru+Ru, Dash: Zr+Zr



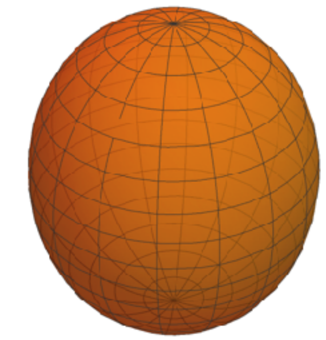
X. L. Zhao, G. L. Ma and Y. G. Ma, Phys. Rev. C 99, no.3, 034903 (2019).

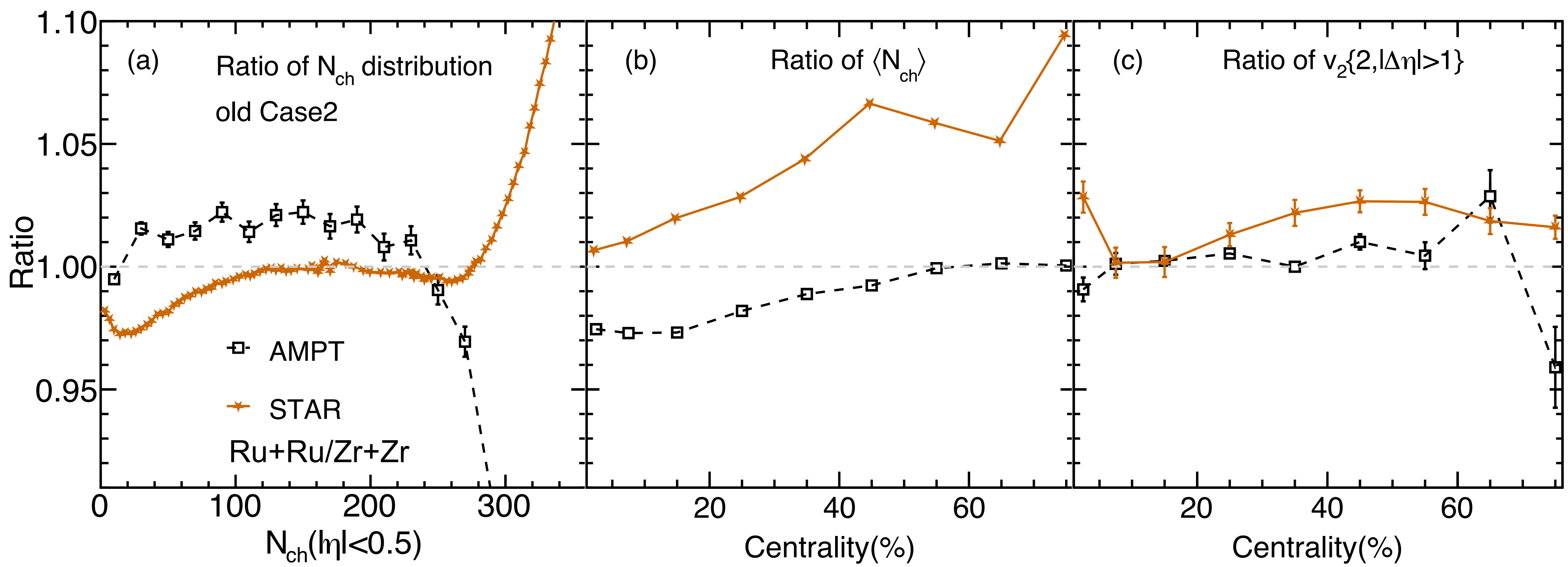
Zr



+

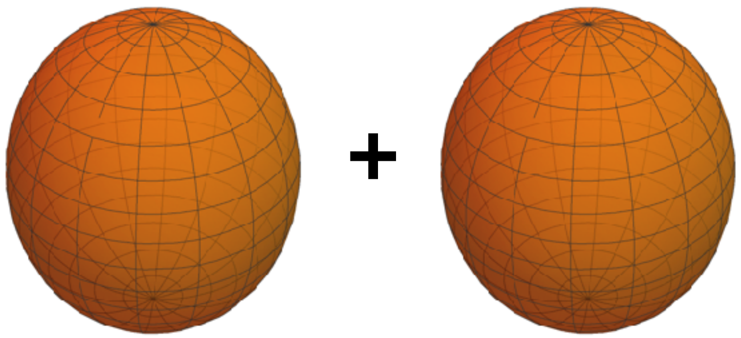
Zr





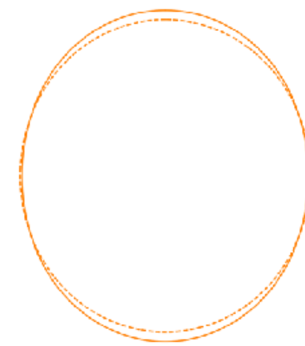
Case1

Ru Ru



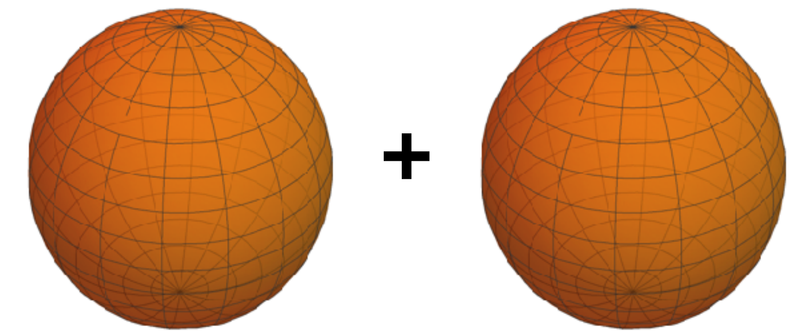
	Case1		
	R_0	a	β_2
$^{96}_{44}$Ru	5.085	0.46	0.158
$^{96}_{40}$Zr	5.02	0.46	0.080

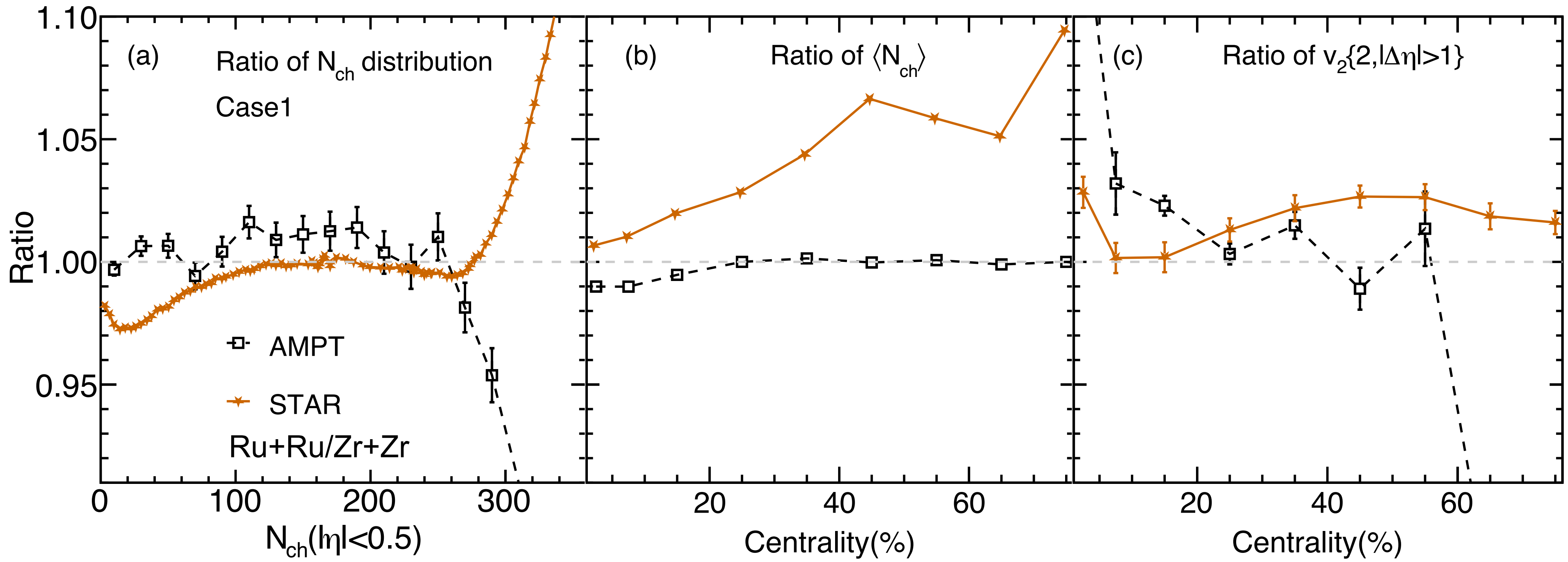
Solid: Ru+Ru, Dash: Zr+Zr



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).
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

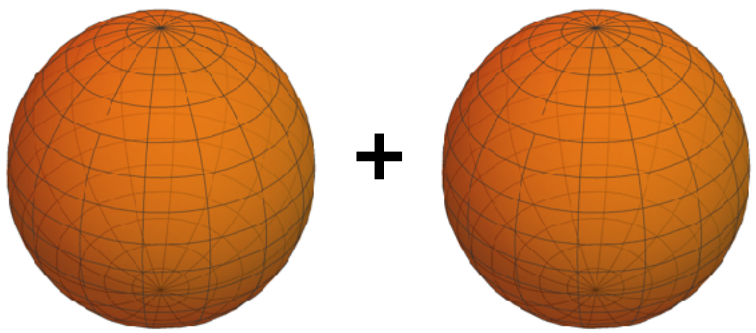
Zr Zr



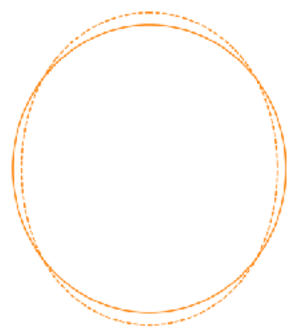


Case2

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



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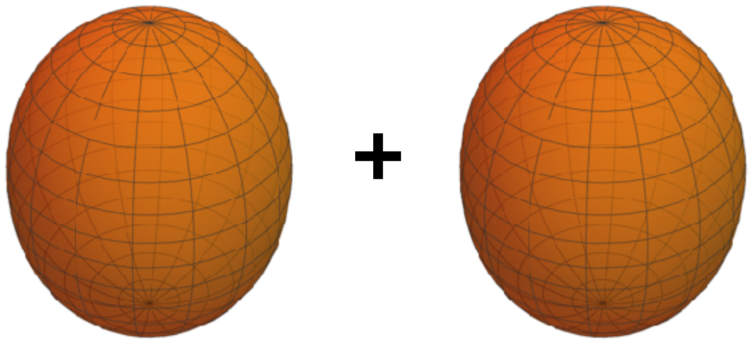
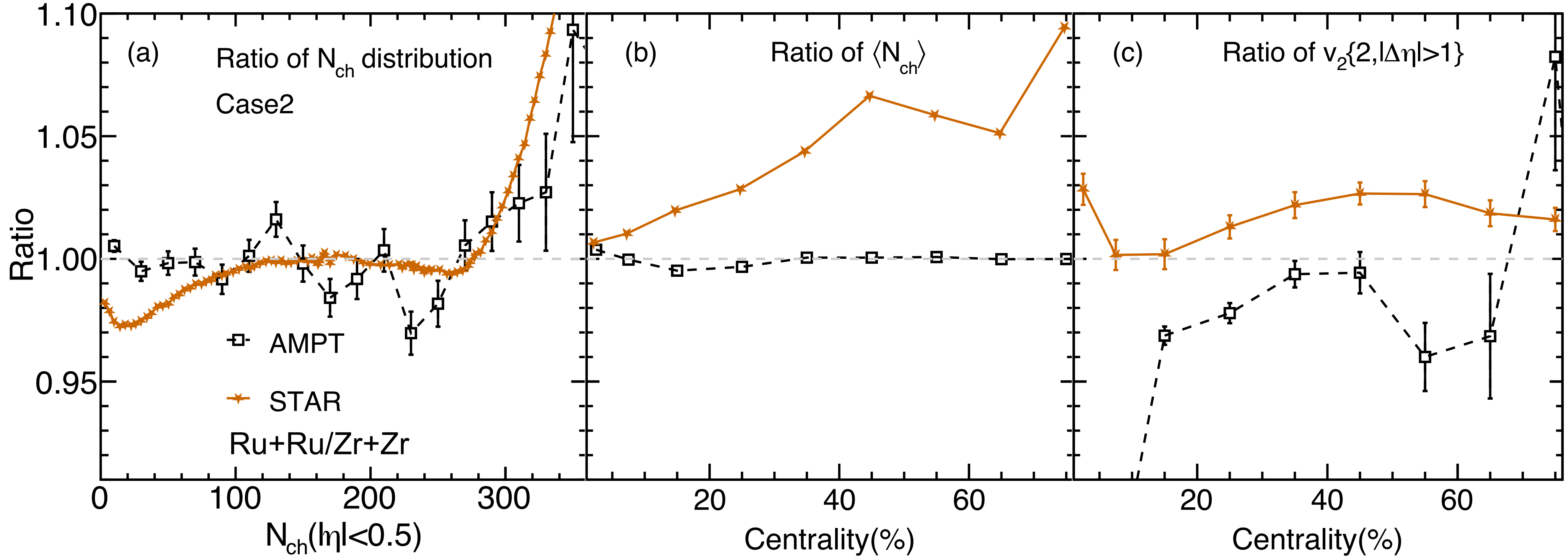
G. Fricke, C. Bernhardt, K. Heilig, L. A. Schaller, L. Schellenberg, E. B. Shera and C. W. de Jager, Atom. Data Nucl. Data Tabl. 60, 177-285 (1995).
P. Moller, J. R. Nix, W. D. Myers and W. J. Swiatecki, Atom. Data Nucl. Data Tabl. 59, 185-381 (1995).
M. Abdallah et al. [STAR], Phys.Rev.C 105 (2022)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

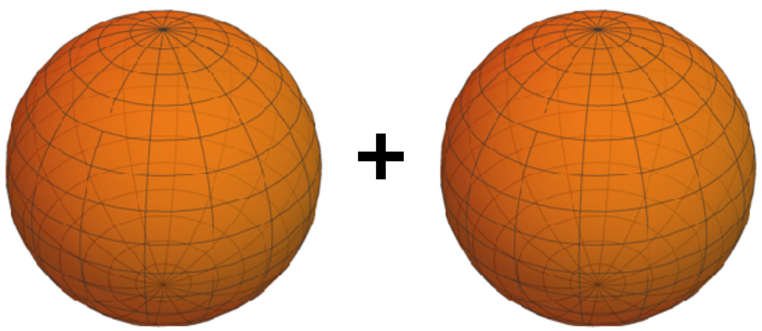
Zr + Zr





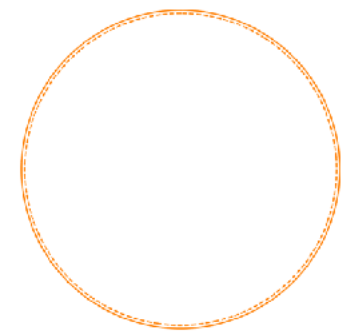
Case3

Ru Ru



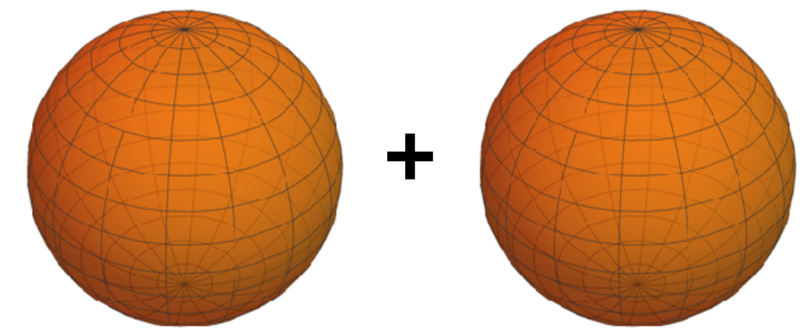
	Case3		
	R_0	a	β_2
$^{96}_{44}$Ru	5.067	0.500	0
$^{96}_{40}$Zr	4.965	0.556	0

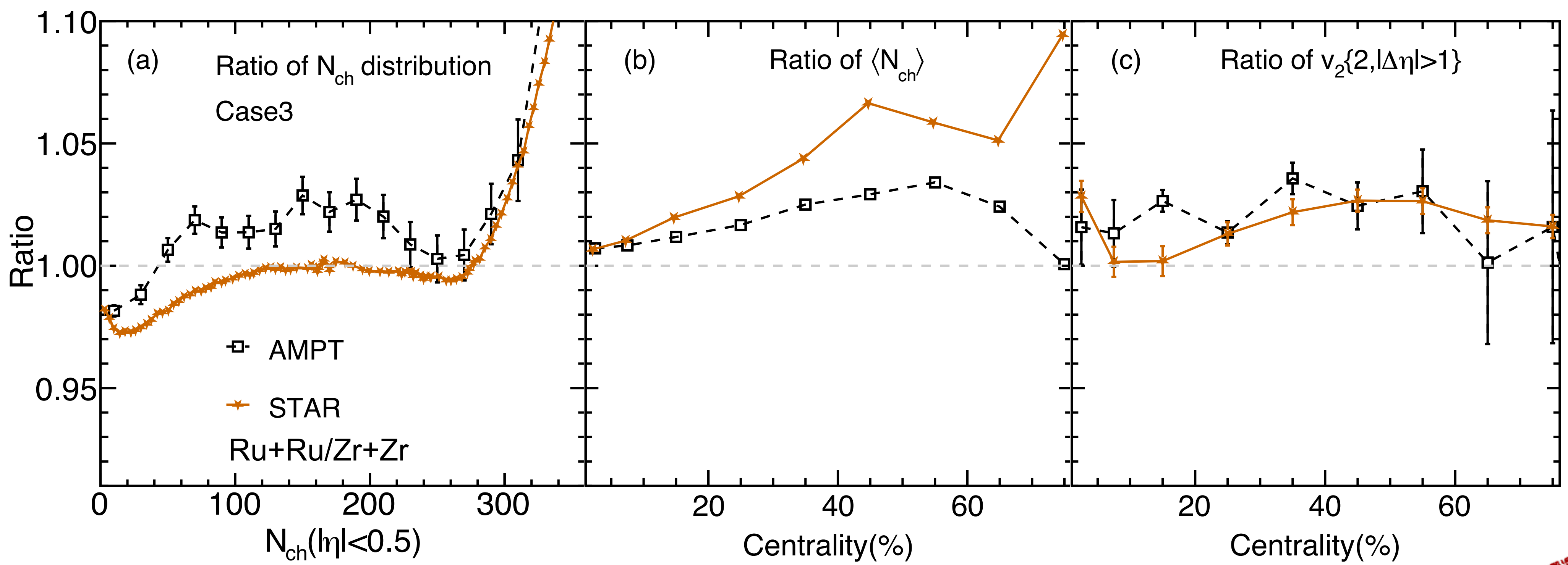
Solid: Ru+Ru, Dash: Zr+Zr



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).

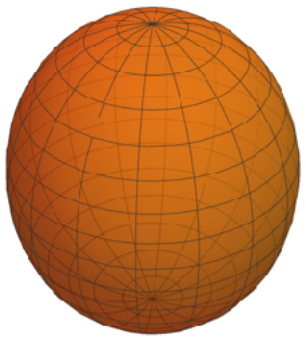
Zr Zr





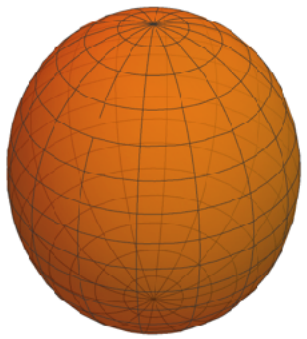
Case4

Ru



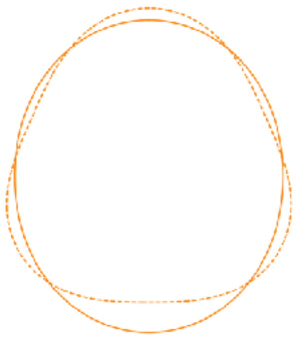
+

Ru



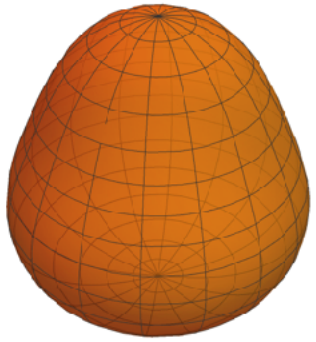
Solid: Ru+Ru, Dash: Zr+Zr

Case4	R_0	a	β_2	β_3
$^{96}_{44}$Ru	5.09	0.46	0.162	0
$^{96}_{40}$Zr	5.09	0.52	0.060	0.2



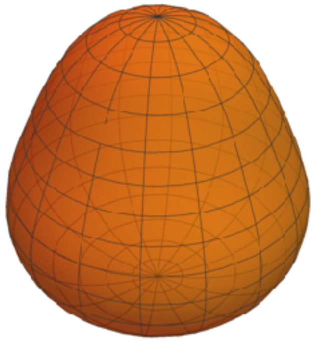
J. Jia and C. J. Zhang, arXiv:2111.15559.

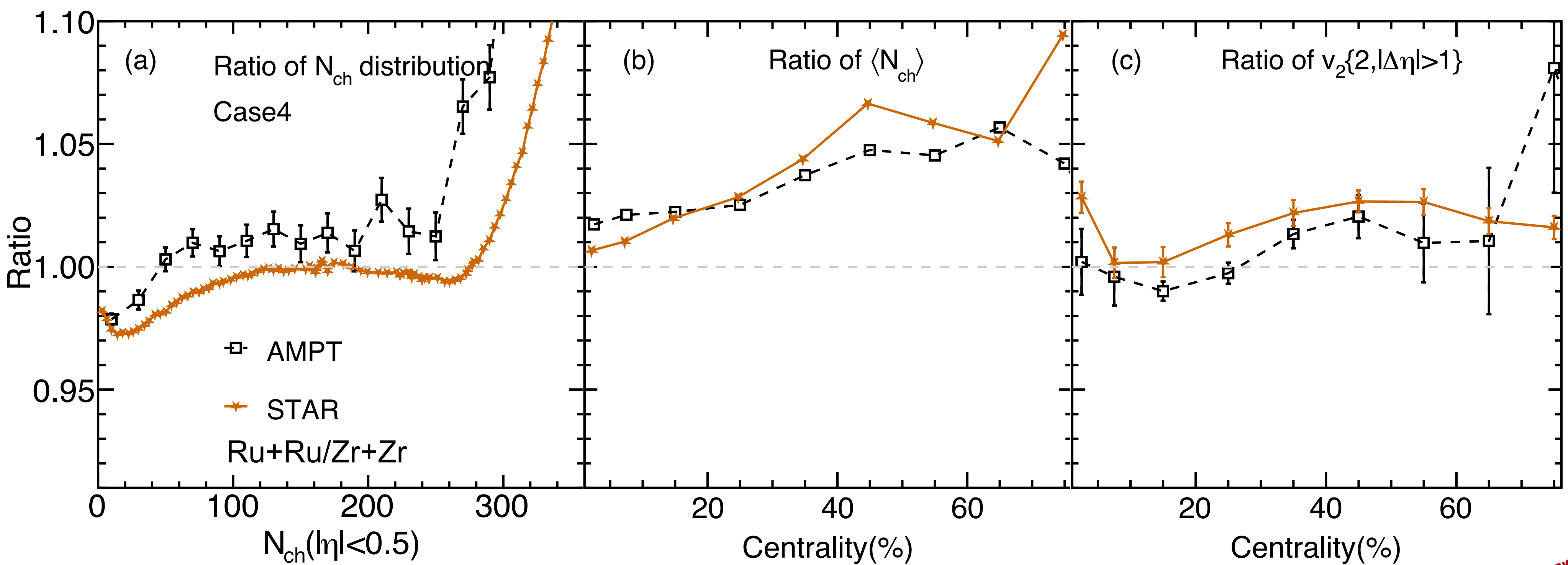
Zr



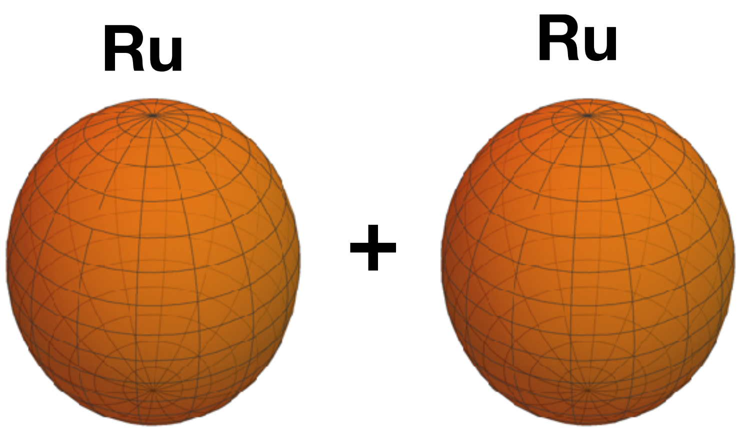
+

Zr

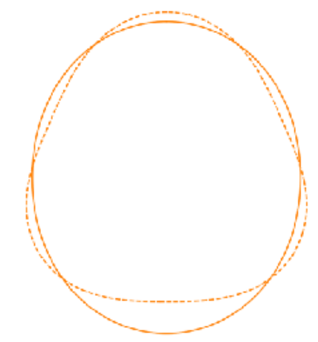




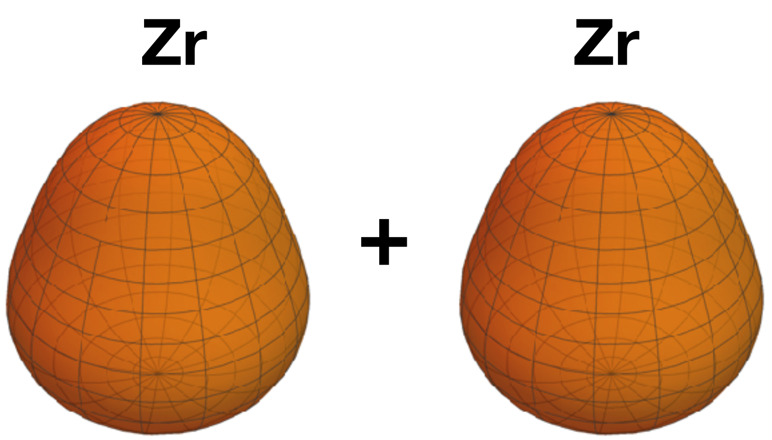
Case5

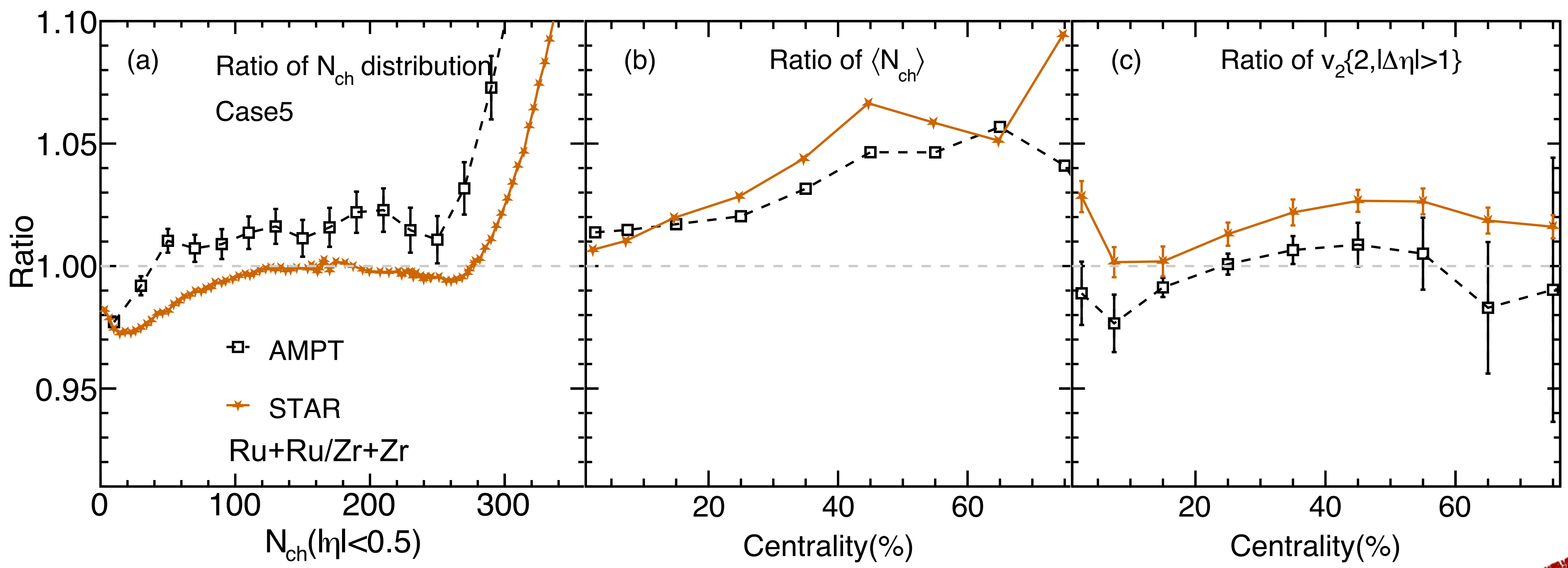


	Case5			
	R_0	a	β_2	β_3
$^{96}_{44}$Ru	5.09	0.46	0.162	0
$^{96}_{40}$Zr	5.02	0.46	0.060	0.2



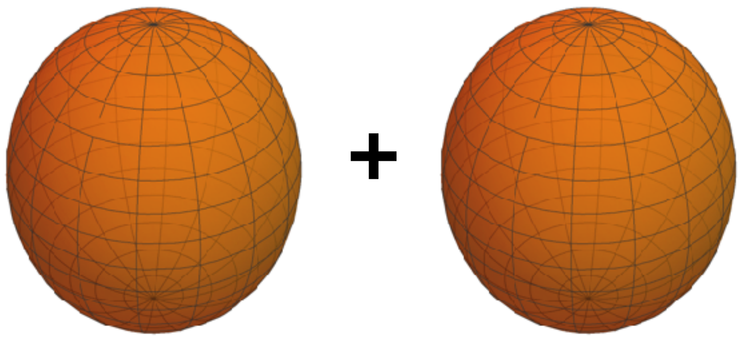
J. Jia and C. J. Zhang, arXiv:2111.15559.





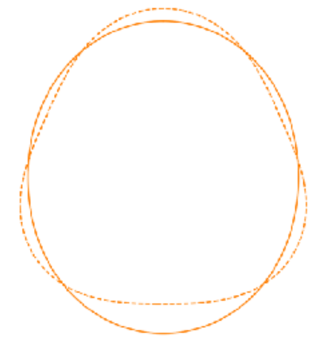
Case6

Ru Ru



	Case6			
	R_0	a	β_2	β_3
$^{96}_{44}$Ru	5.09	0.52	0.154	0
$^{96}_{40}$Zr	5.09	0.52	0.060	0.2

Solid: Ru+Ru, Dash: Zr+Zr



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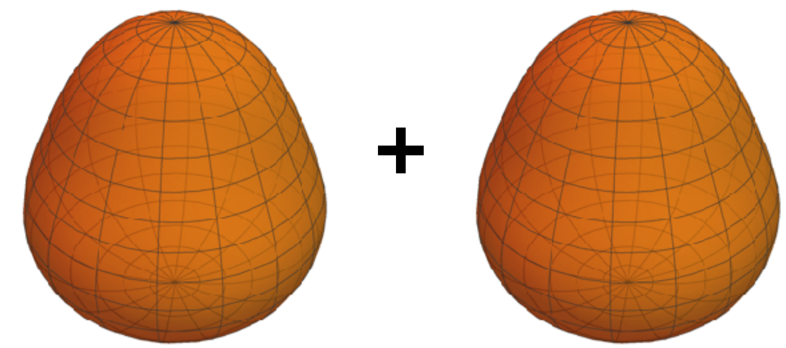
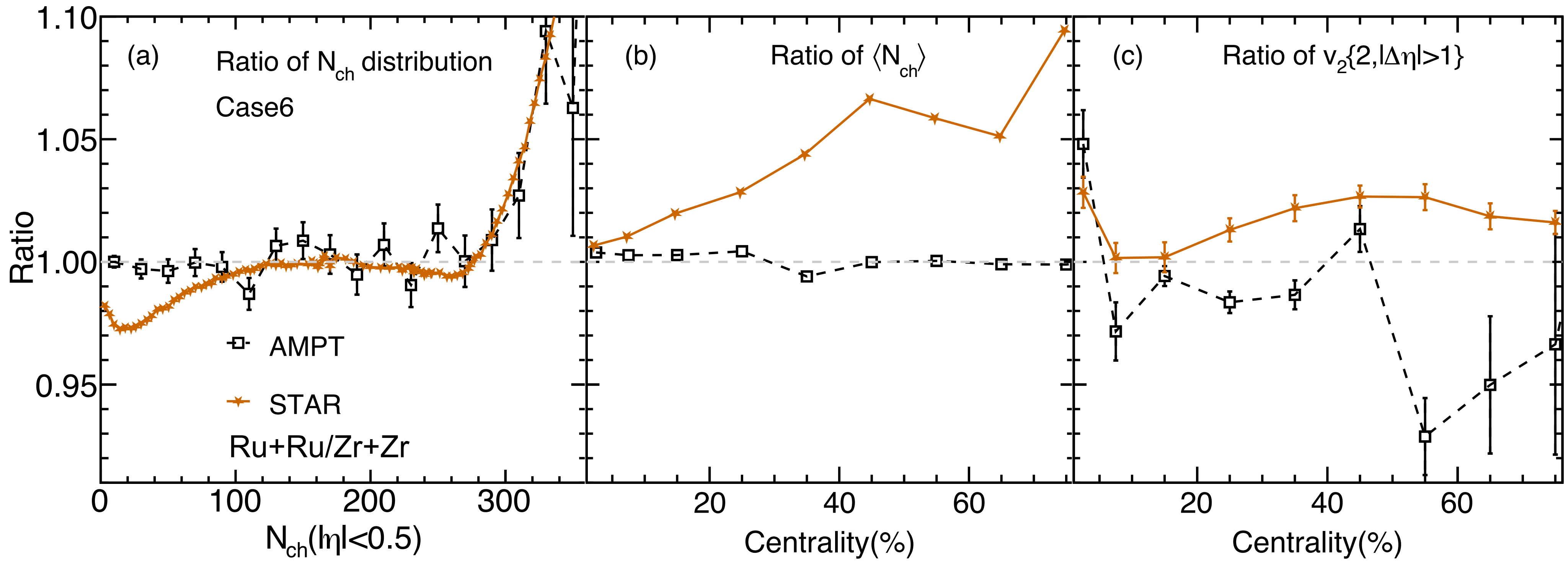
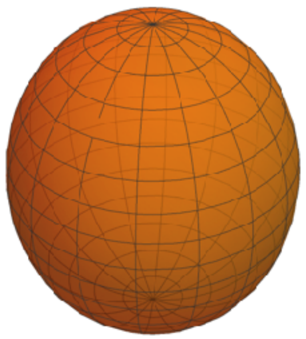
Zr Zr





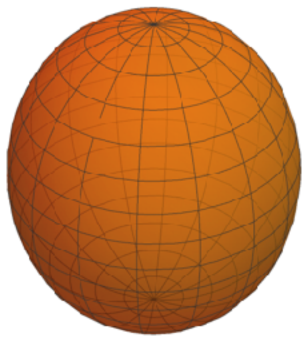
Case7

Ru



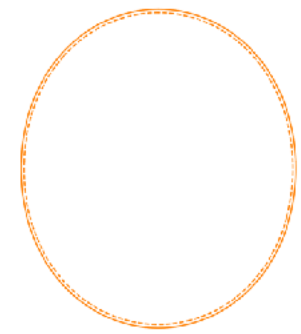
+

Ru



Solid: Ru+Ru, Dash: Zr+Zr

	Case7		
	R_0	a	β_2
$^{96}_{44}$Ru	5.065	0.485	0.16
$^{96}_{40}$Zr	4.961	0.544	0.16



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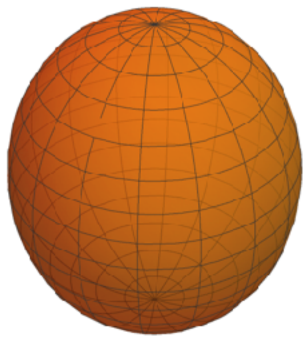
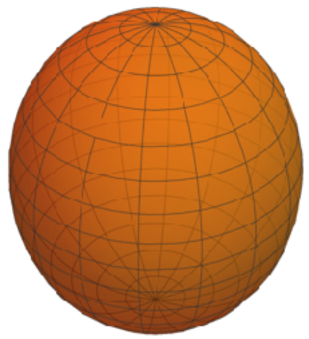
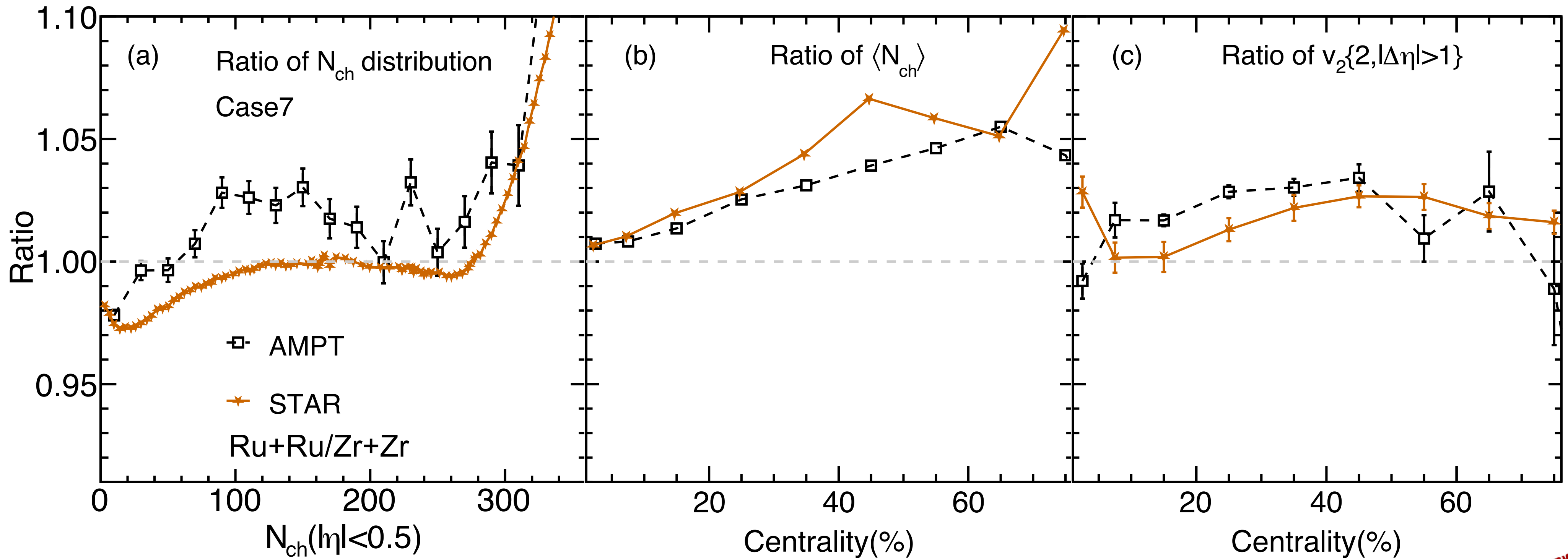
Zr



+

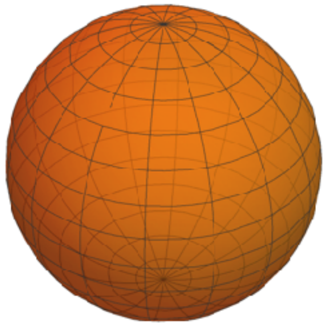
Zr



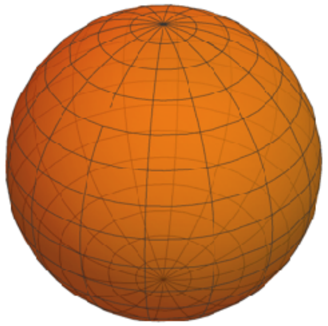


Case8

Ru Ru

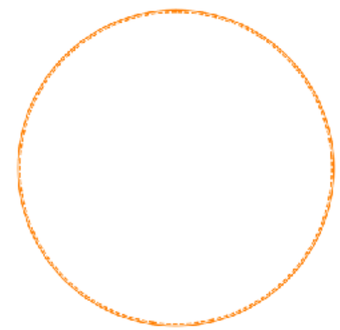


+



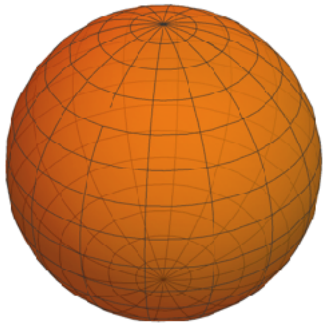
	Case8		
	R_0	a	β_2
$^{96}_{44}$Ru	5.085	0.523	0
$^{96}_{40}$Zr	5.021	0.523	0

Solid: Ru+Ru, Dash: Zr+Zr



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

Zr Zr



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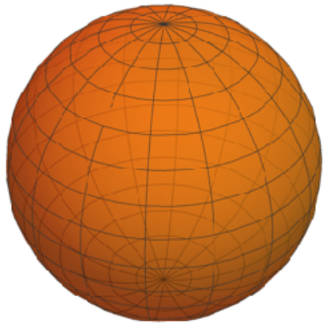
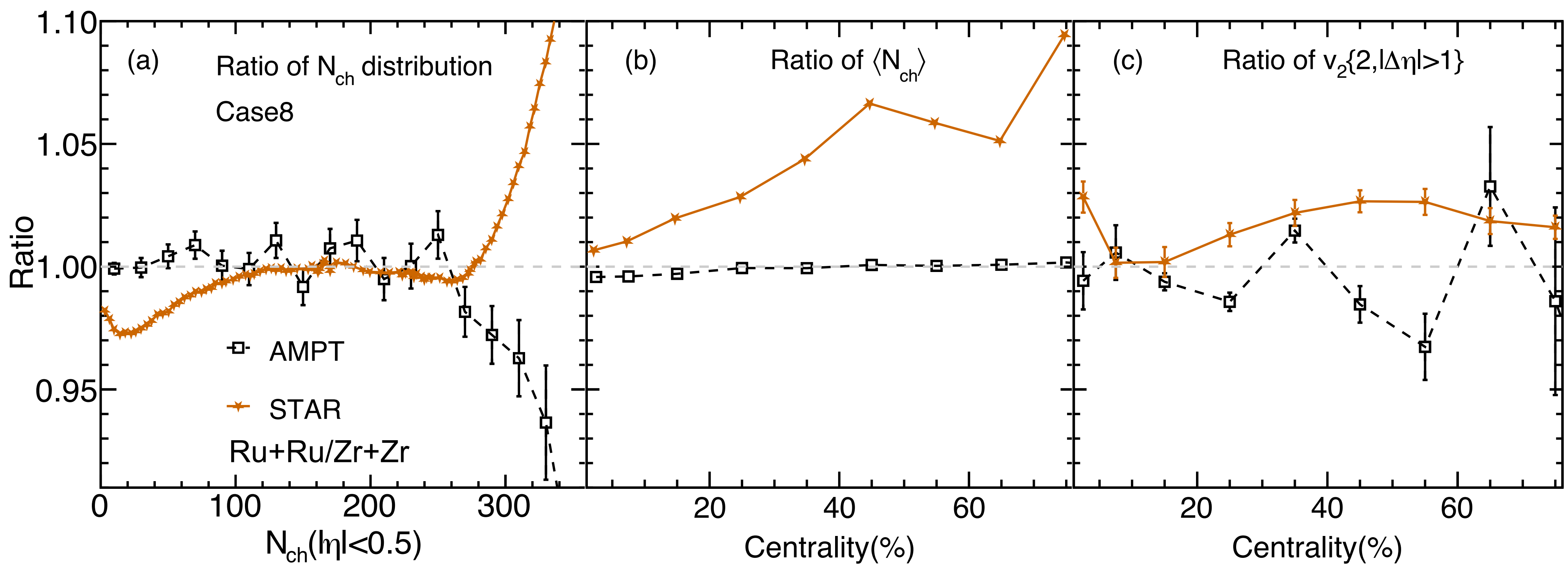
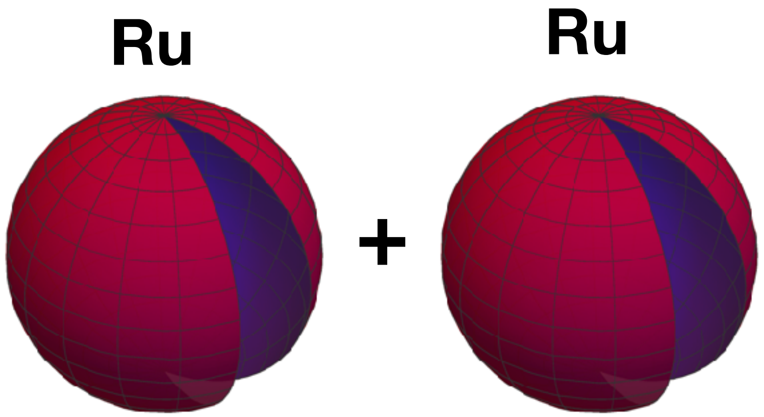
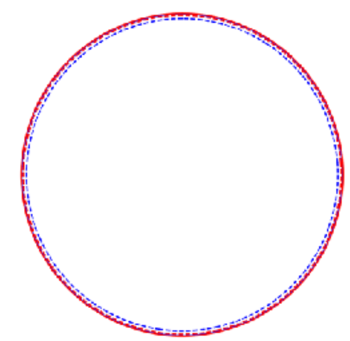




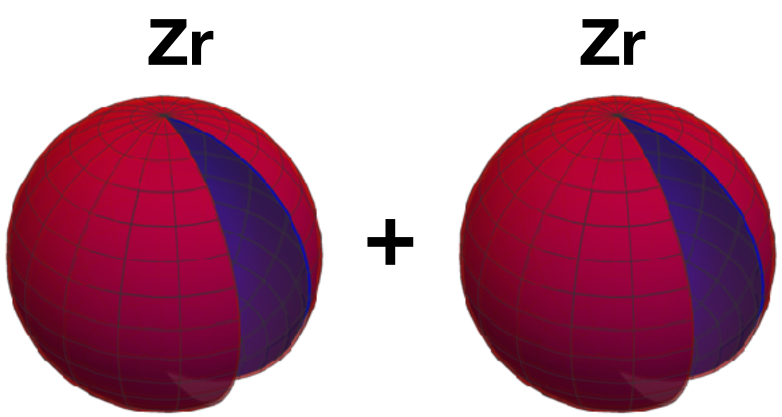
Case9

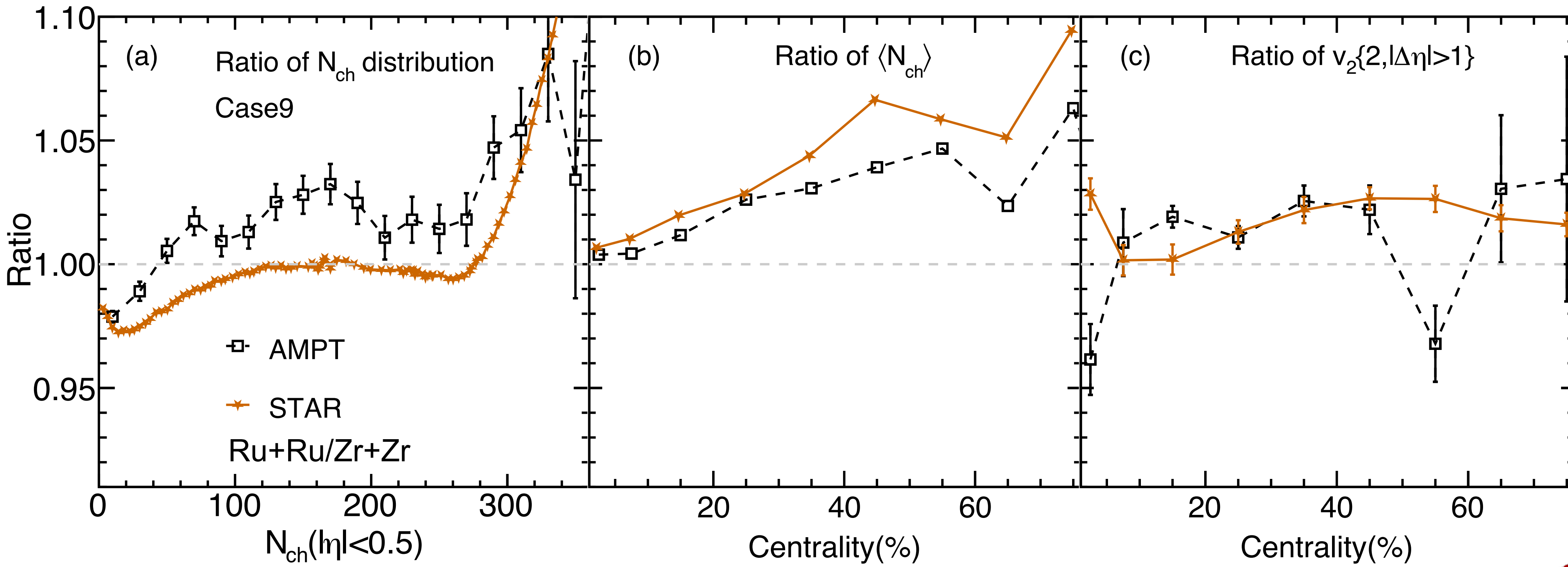


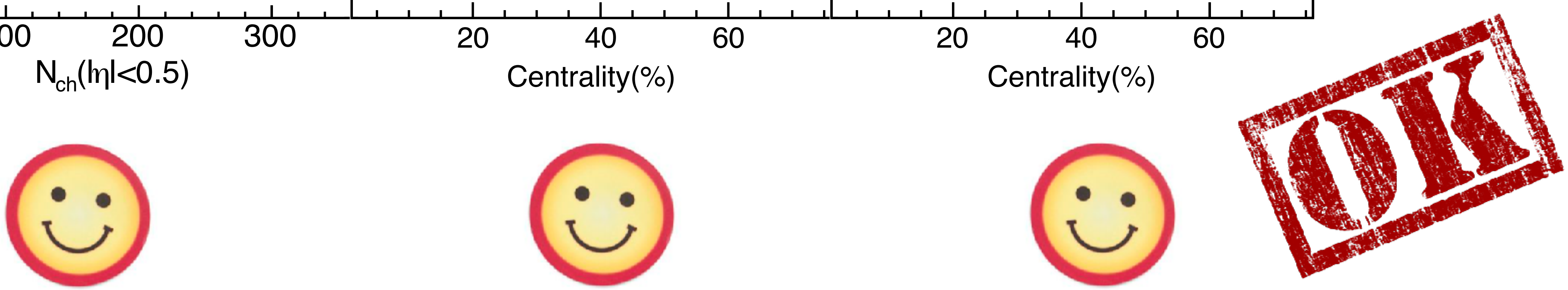
Case9		R_0	a	β_2
$^{96}_{44}$Ru	n	5.075	0.505	0
$^{96}_{44}$Ru	p	5.060	0.493	0
$^{96}_{40}$Zr	n	5.015	0.574	0
$^{96}_{40}$Zr	p	4.915	0.521	0



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

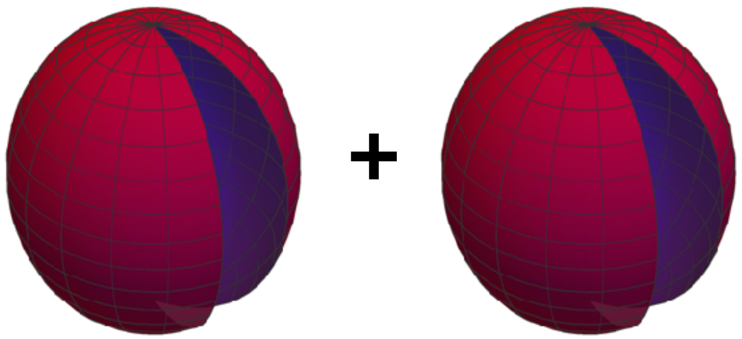




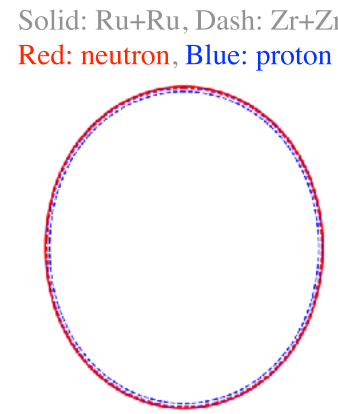


Case10

Ru Ru

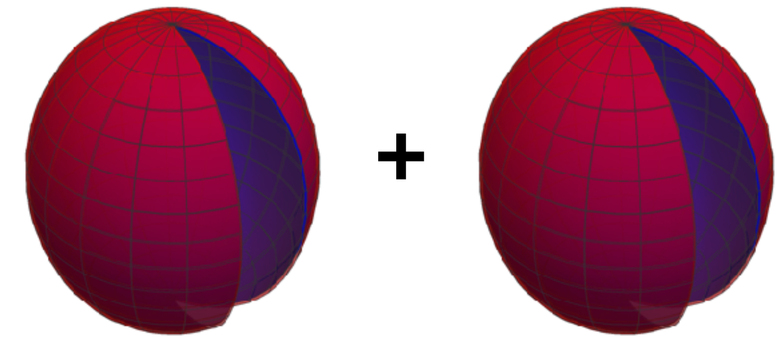


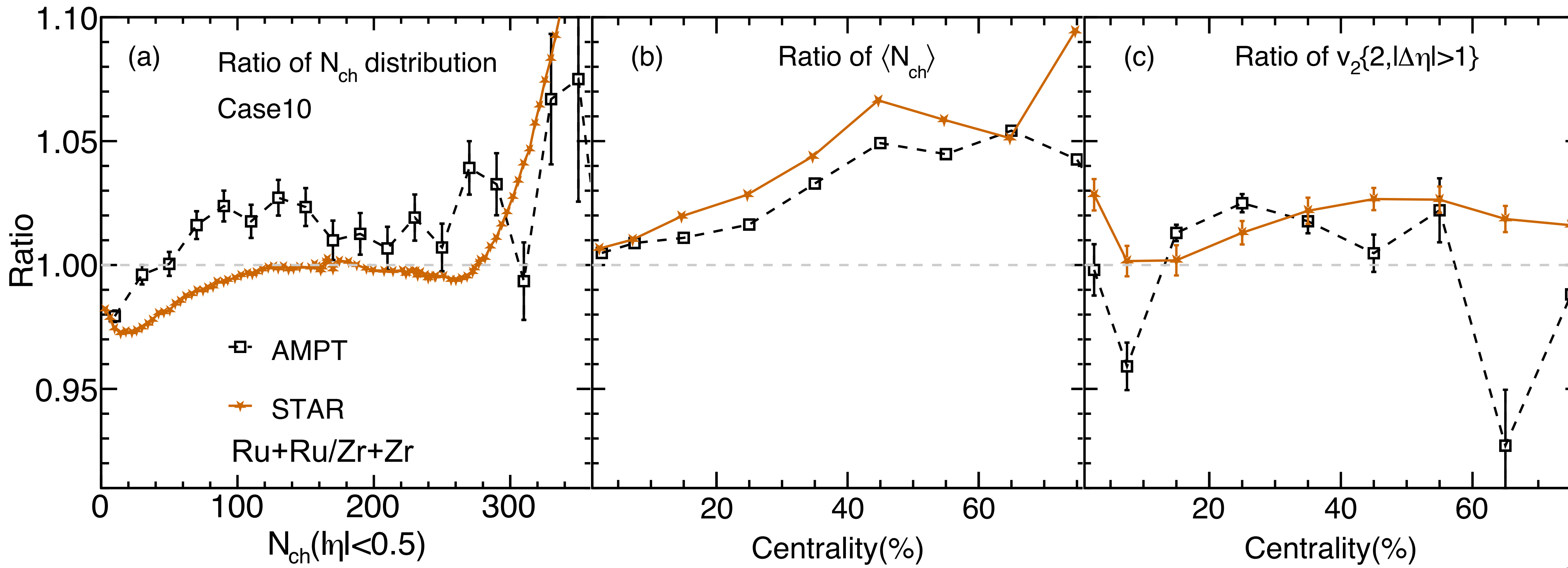
Case10		R_0	a	β_2
$^{96}_{44}$Ru	n	5.073	0.490	0.16
$^{96}_{44}$Ru	p	5.053	0.480	0.16
$^{96}_{40}$Zr	n	5.007	0.564	0.16
$^{96}_{40}$Zr	p	4.912	0.508	0.16



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

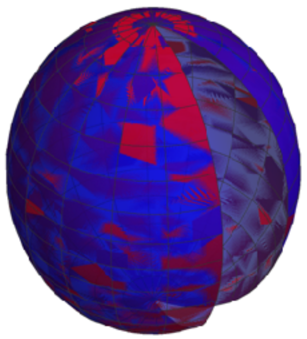
Zr Zr





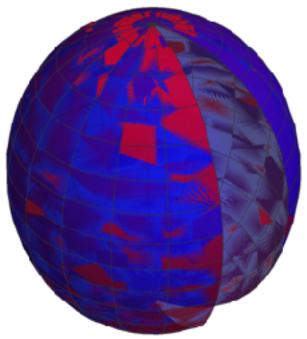
Case11

Ru



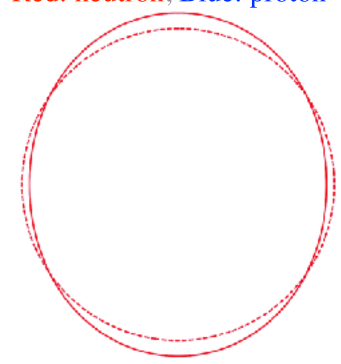
+

Ru



		Case11		
		R_0	a	β_2
$^{96}_{44}$Ru	n	5.085	0.46	0.158
$^{96}_{44}$Ru	p	5.085	0.46	0.158
$^{96}_{40}$Zr	n	5.080	0.46	0
$^{96}_{40}$Zr	p	5.080	0.34	0

Solid: Ru+Ru, Dash: Zr+Zr
Red: neutron, Blue: proton



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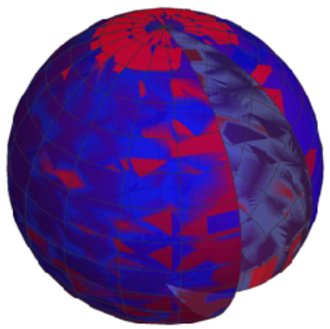
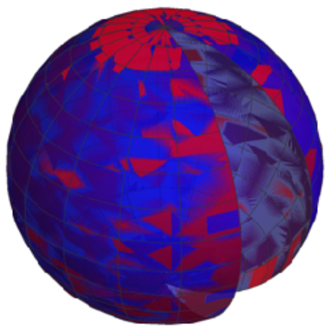
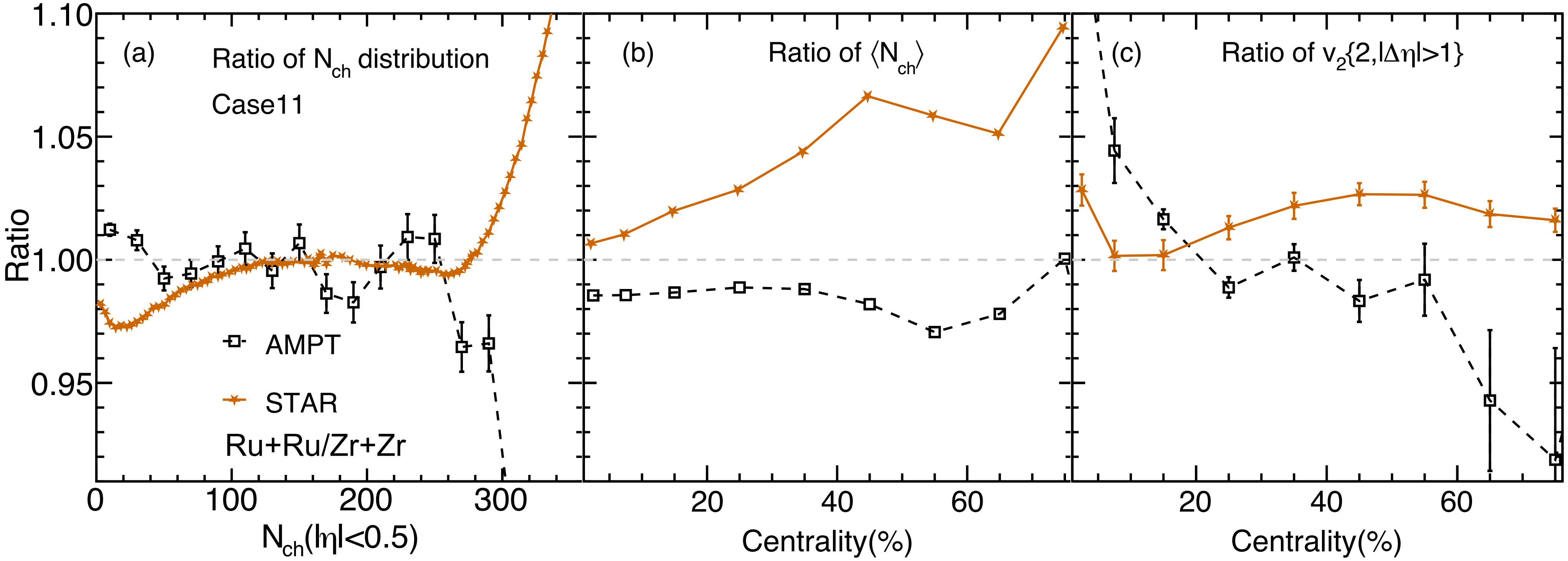
Zr



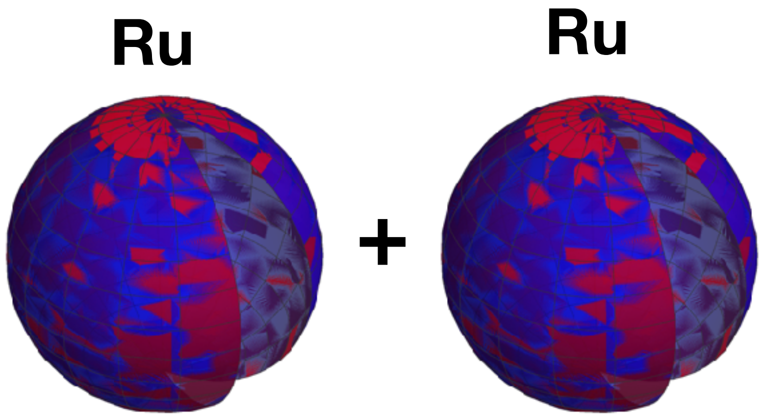
+

Zr

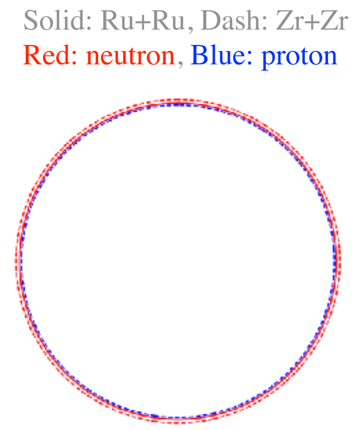




Skin-type



		skin-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	5.194	0.523	0
$^{96}_{40}$Zr	p	5.021	0.523	0



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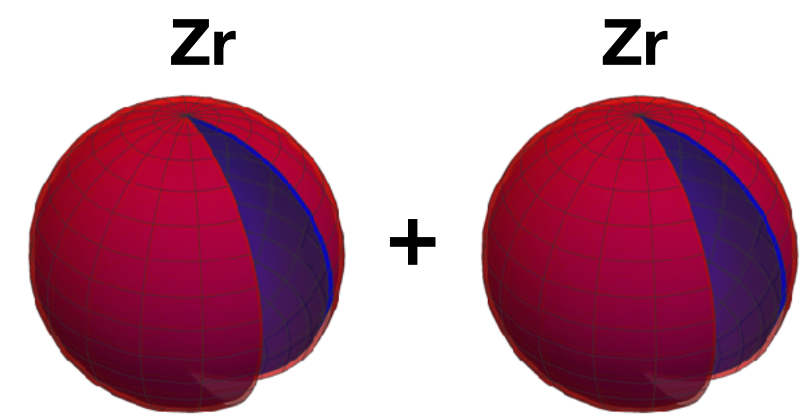
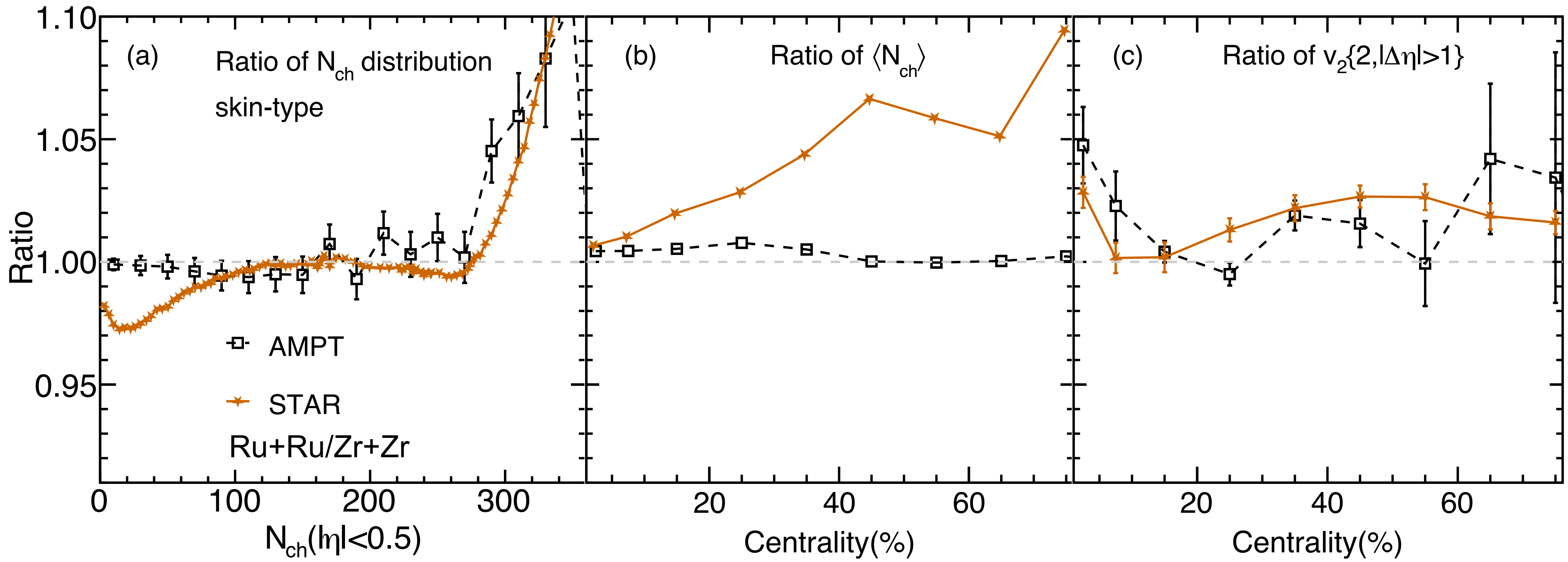
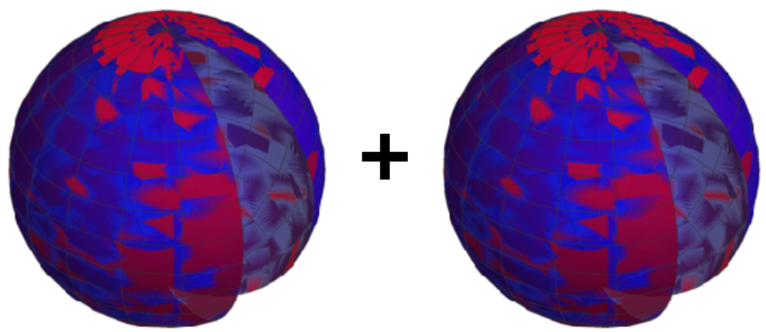




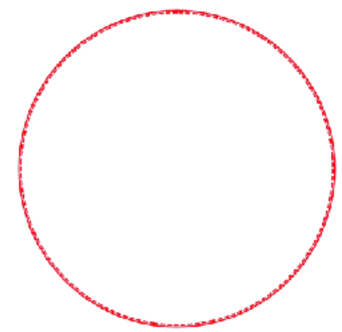
Halo-type

Ru Ru



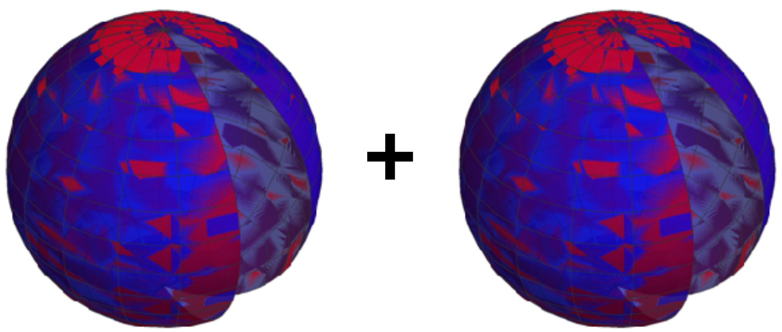
		halo-type		
		R_0	a	β_2
$^{96}_{44}$Ru	n	5.085	0.523	0
$^{96}_{44}$Ru	p	5.085	0.523	0
$^{96}_{40}$Zr	n	5.021	0.592	0
$^{96}_{40}$Zr	p	5.021	0.523	0

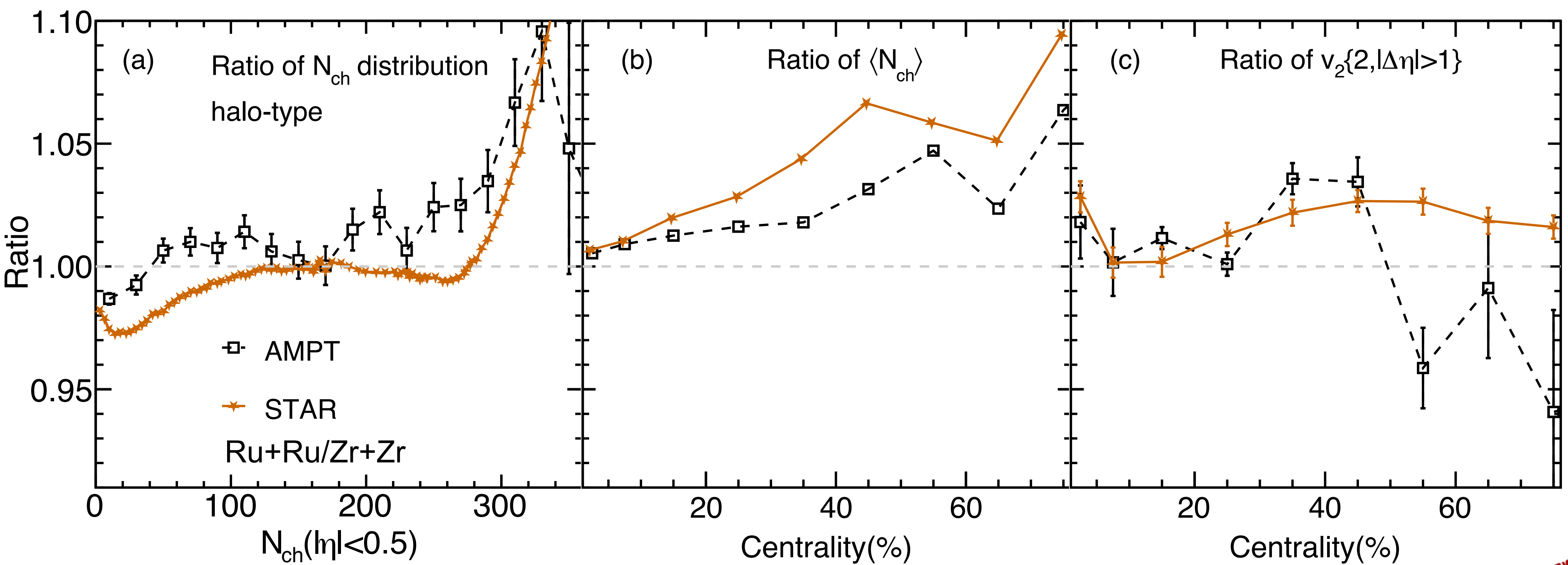
Solid: Ru+Ru, Dash: Zr+Zr
Red: neutron, Blue: proton



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

Zr Zr





Good geometry configurations of isobar nuclei

Woods-Saxon form of spatial distribution of nucleons:

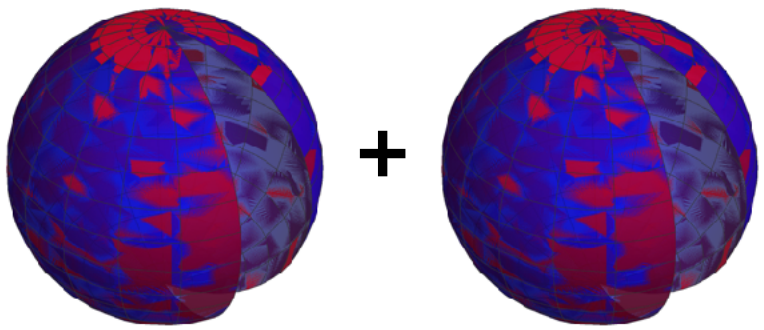
	old Case1			old Case2			Case1			Case2			Case3		
	R_0	a	β_2	R_0	a	β_2	R_0	a	β_2	R_0	a	β_2	R_0	a	β_2
${}^{96}_{44}$Ru	5.13	0.46	0.13	5.13	0.46	0.03	5.085	0.46	0.158	5.085	0.46	0.053	5.067	0.500	0
${}^{96}_{40}$Zr	5.06	0.46	0.06	5.06	0.46	0.18	5.02	0.46	0.080	5.02	0.46	0.217	4.965	0.556	0

	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

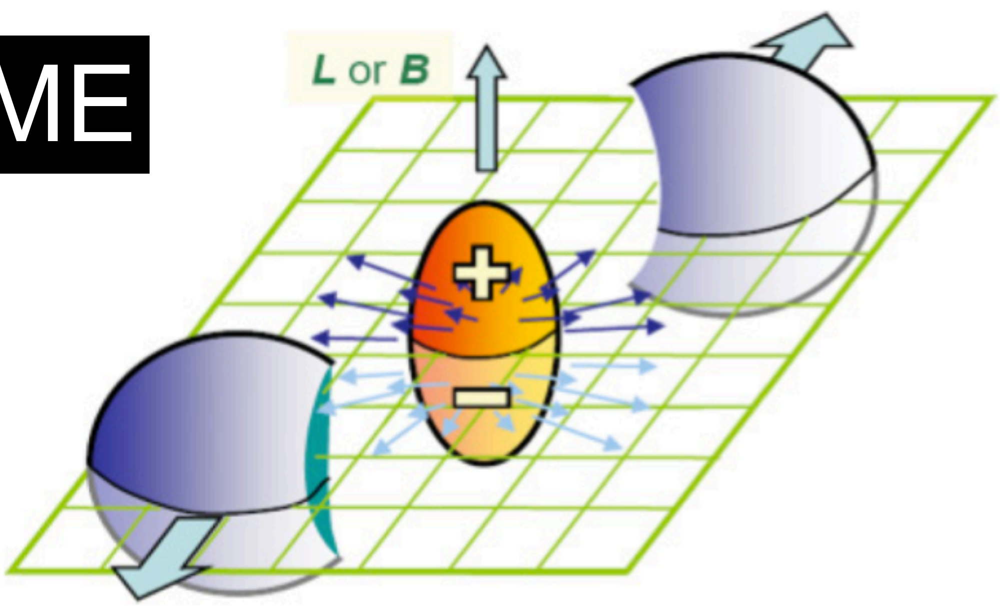
	Case9			Case10			Case11			skin-type			halo-type		
	R_0	a	β_2	R_0	a	β_2	R_0	a	β_2	R_0	a	β_2	R_0	a	β_2
${}^{96}_{44}$Ru n	5.075	0.505	0	5.073	0.490	0.16	5.085	0.46	0.158	5.085	0.523	0	5.085	0.523	0
${}^{96}_{44}$Ru p	5.060	0.493	0	5.053	0.480	0.16	5.085	0.46	0.158	5.085	0.523	0	5.085	0.523	0
${}^{96}_{40}$Zr 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

Simulating CME in isobar collisions using AMPT

Initialization of halo-type isobar

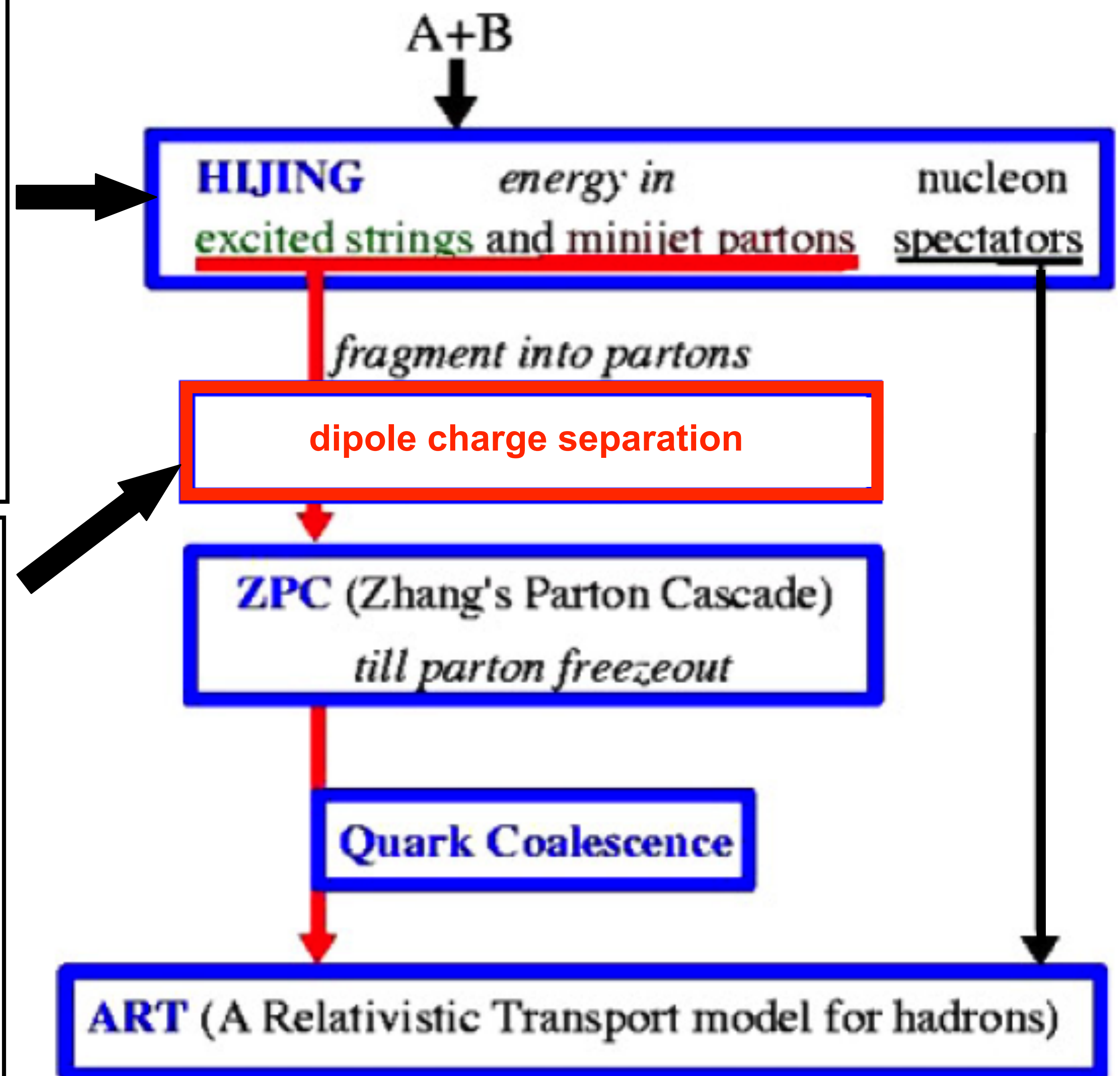


CME



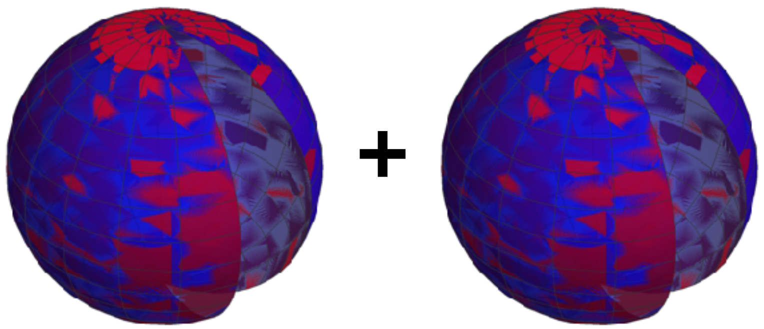
$f = (N^{+}_{upward} - N^{+}_{downward}) / (N^{+}_{upward} + N^{+}_{downward})$

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



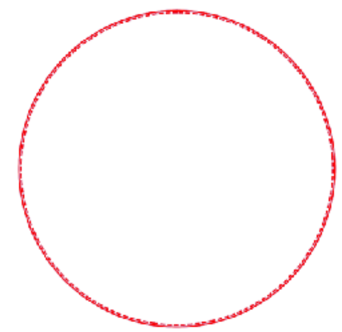
Can CME affect the ratios?

Ru Ru



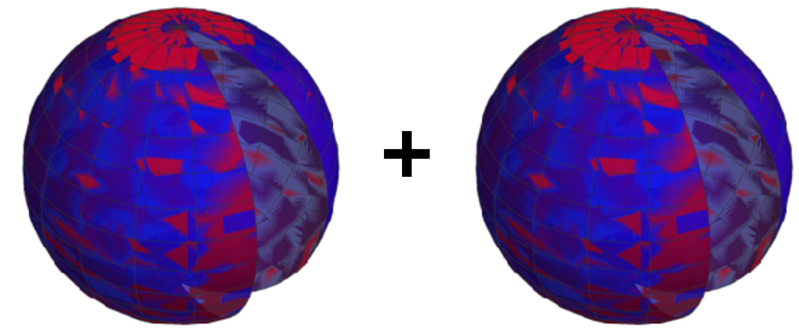
		halo-type		
		R_0	a	β_2
$^{96}_{44}$Ru	n	5.085	0.523	0
$^{96}_{44}$Ru	p	5.085	0.523	0
$^{96}_{40}$Zr	n	5.021	0.592	0
$^{96}_{40}$Zr	p	5.021	0.523	0

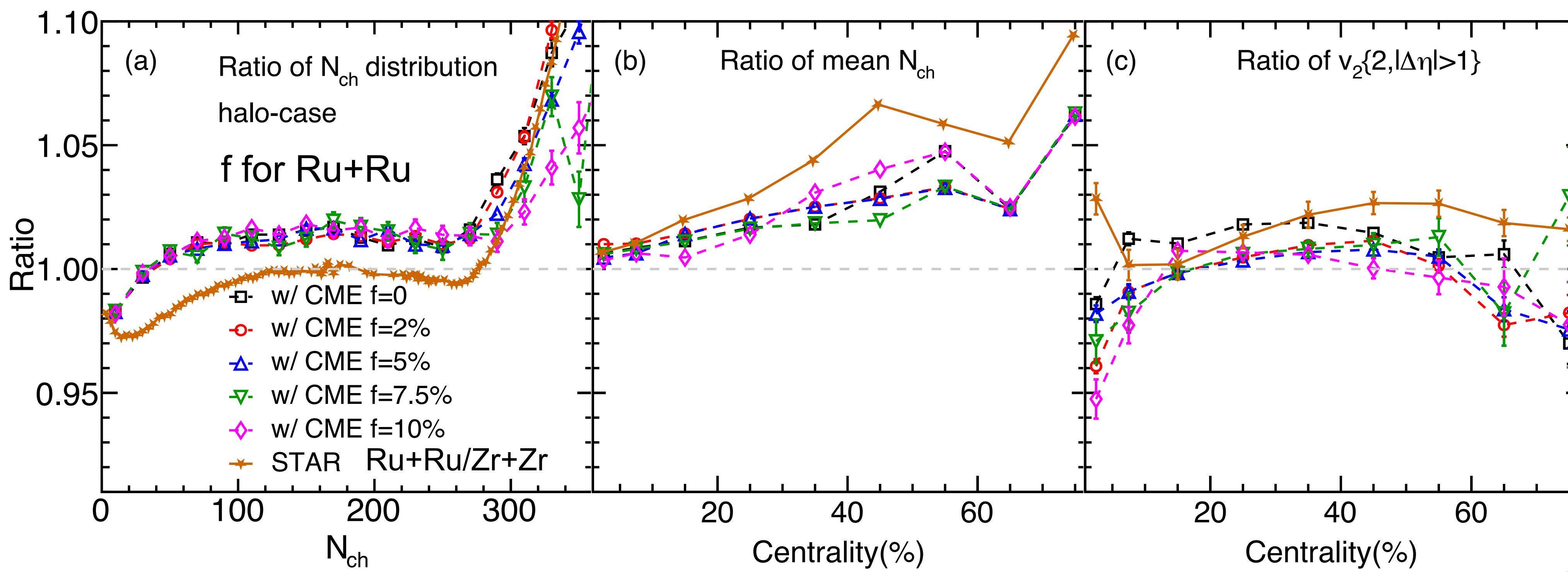
Solid: Ru+Ru, Dash: Zr+Zr
Red: neutron, Blue: proton



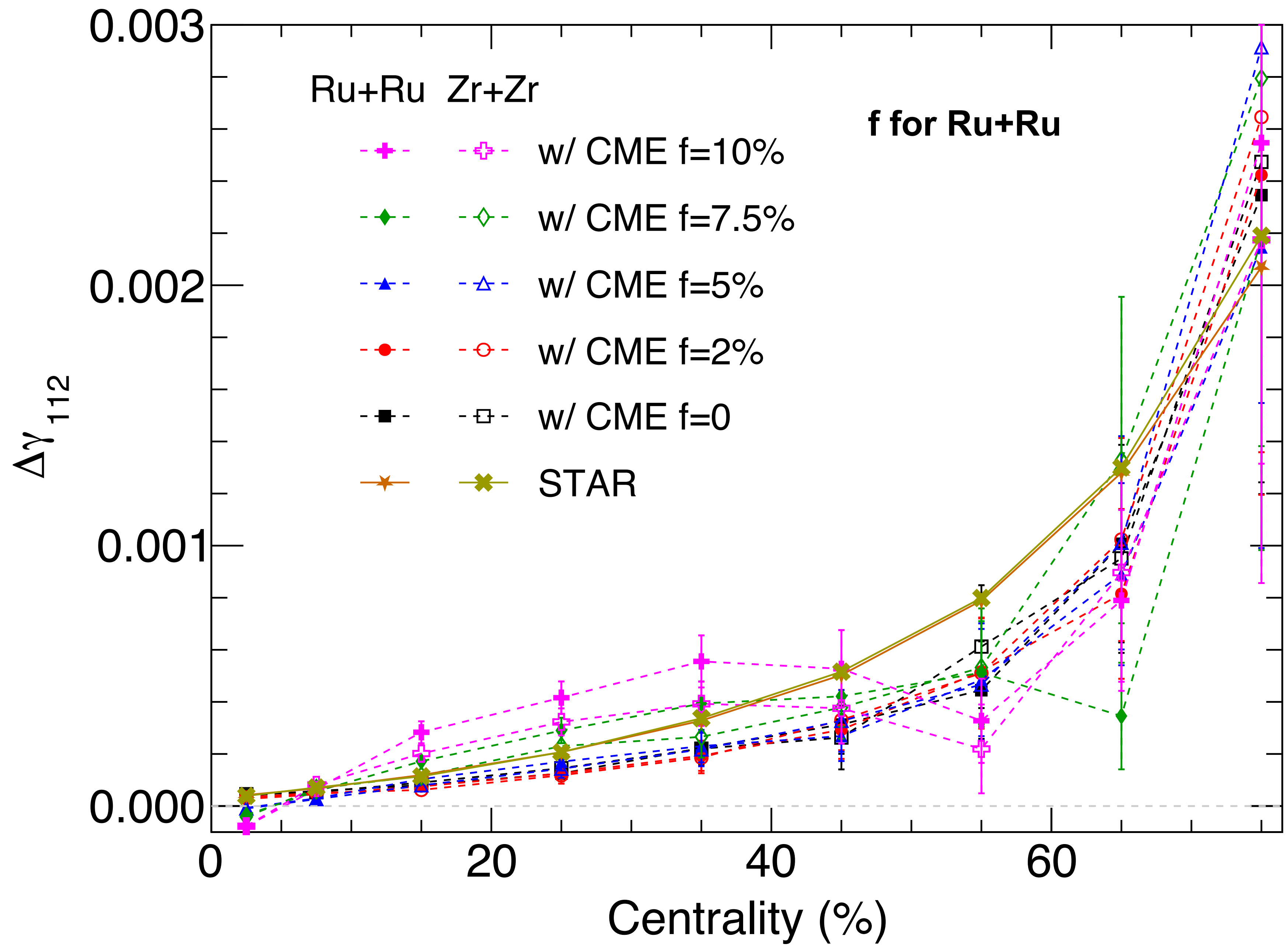
H. j. Xu, H. Li, X. Wang, C. Shen and F. Wang, Phys. Lett. B 819, 136453 (2021)

Zr Zr





The CME observable Δγ in isobar collisions

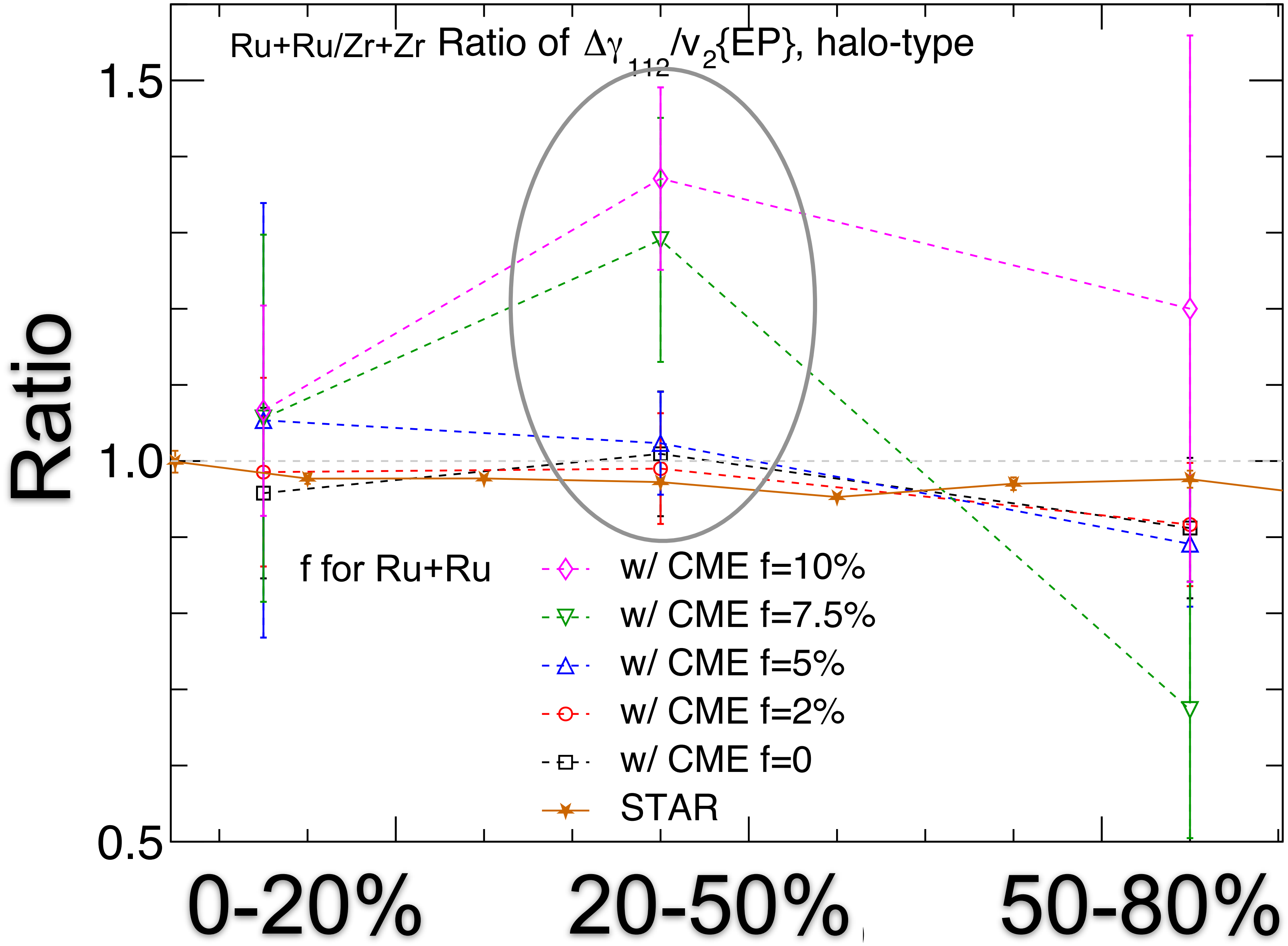


- $\Delta\gamma$ (f=0%) ≈ $\Delta\gamma$ (f=2%) ≈ $\Delta\gamma$ (f=5%) < $\Delta\gamma$ (f=7.5%) < $\Delta\gamma$ (f=10%)

✳ 28 M events for f=0%; 38 M events for f=2%; 38 M events for f=5%; 6 M events for f=7.5%; 6 M events for f=10%

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

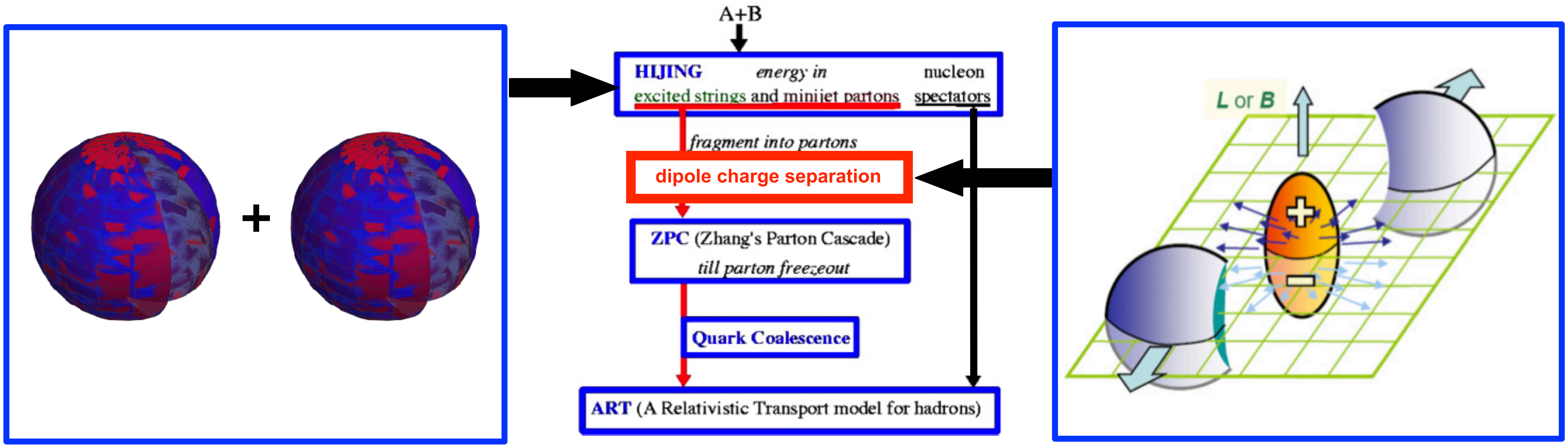
X. L. Zhao and G. L. Ma, in preparation



For 20-50%:

- $\Delta\gamma$/v2 ratios for f=0, 2% and 5% are consistent with exp. data, within stat. errors.
- $\Delta\gamma$/v2 ratios for f= 7.5% and 10% are significantly greater than one.
- Due to the non-linear sensitivity of the CME observable?

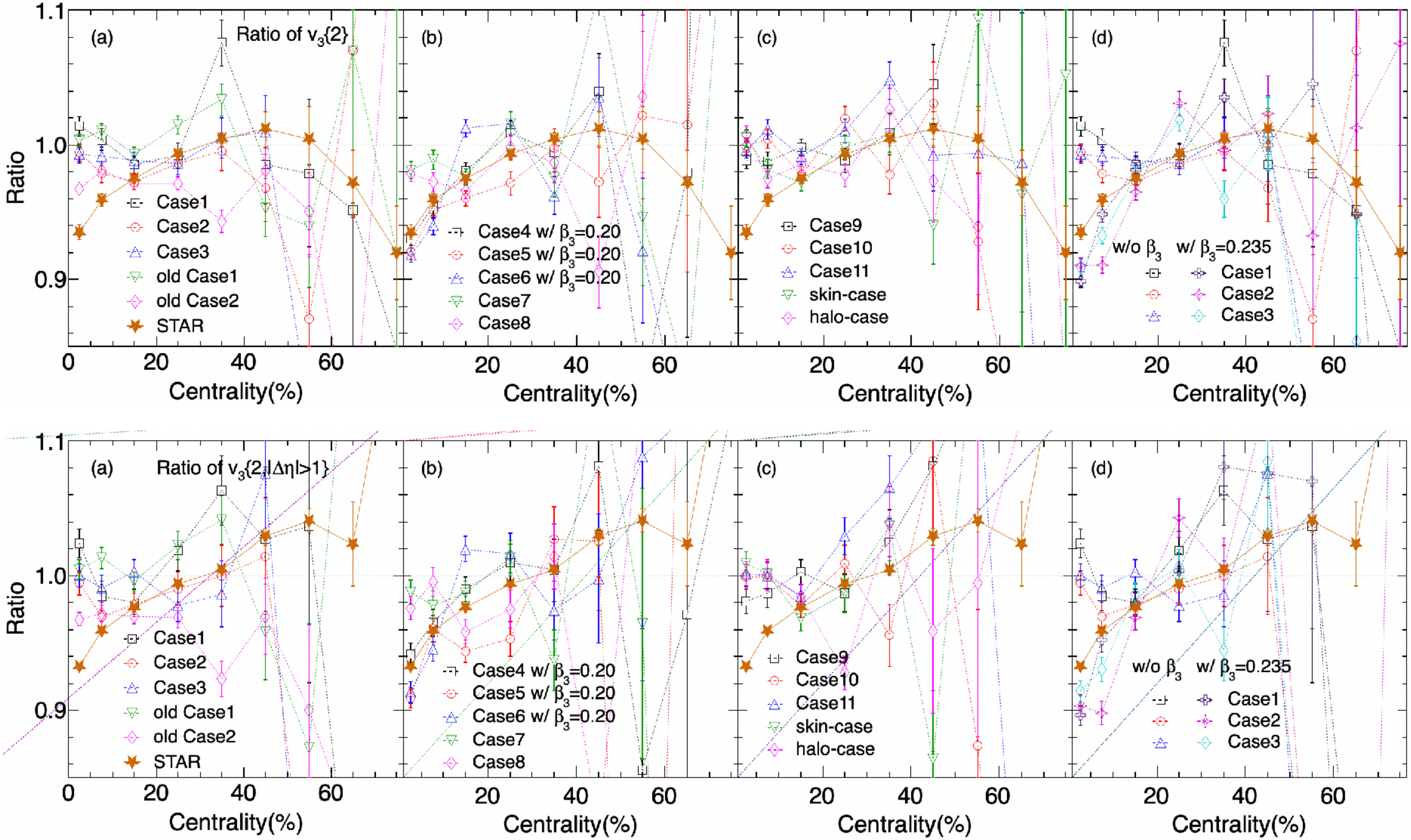
Summary



- **Using AMPT model including nuclear structure and CME**
  - Final state interactions significantly reduce the CME signal.
  - Non-linear sensitivity of the CME observables due to FSI.
  - The $\Delta\gamma/v2$ ratio between two isobar systems may not response to the CME if the CME strength f<5%.

Thanks for your attention!

v3 ratio in isobar collisions



- **Our v3 ratios are with large stat. errors due to our limited events. Stay tuned.**

A multiphase transport (AMPT) model

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

Melting AMPT Model

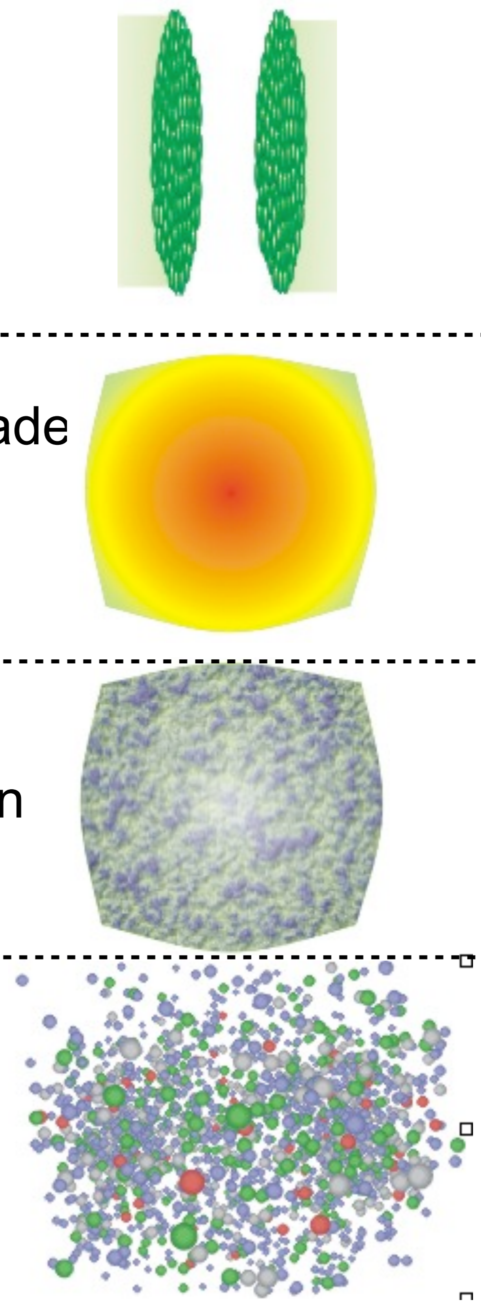
(1) initial condition

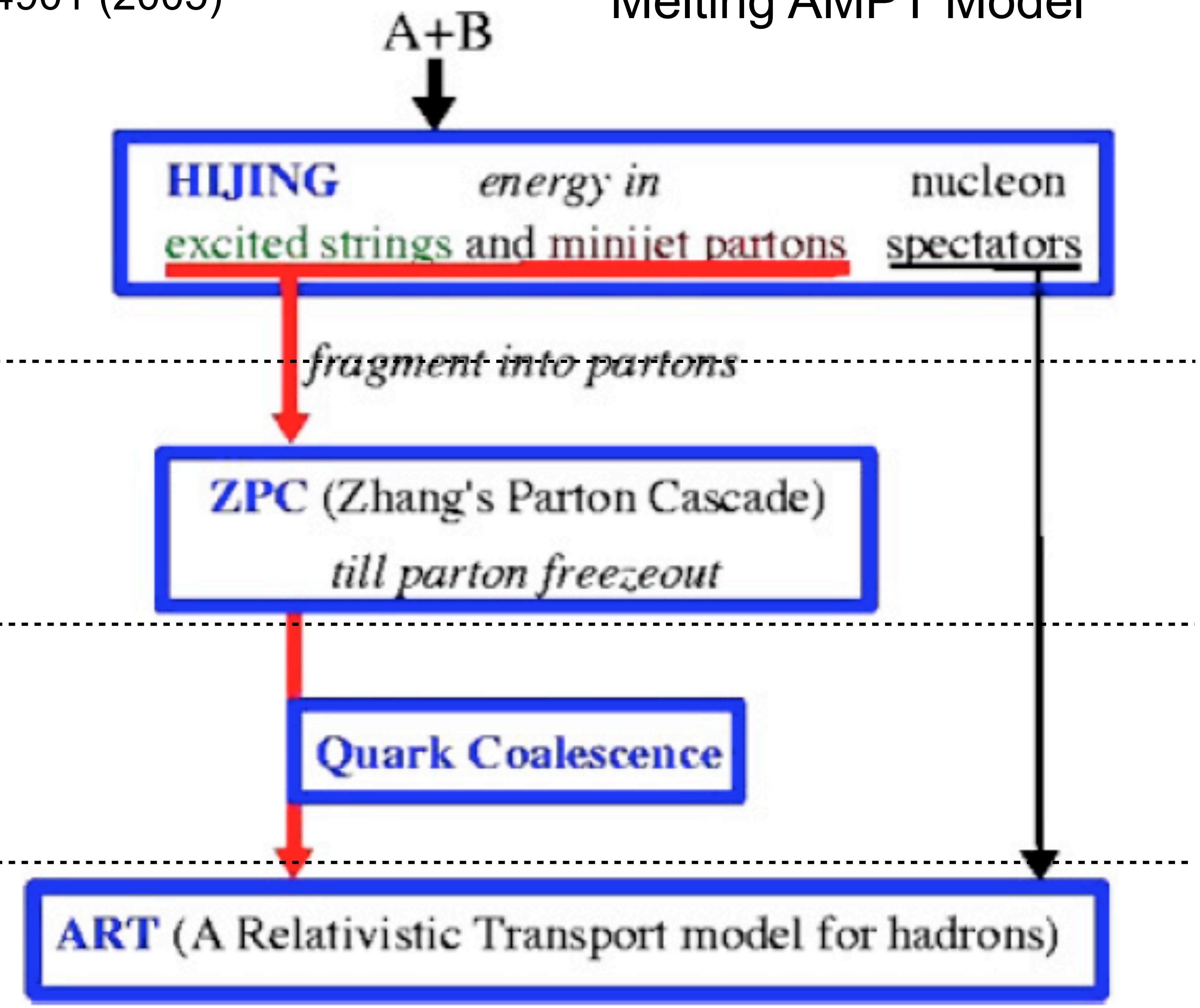
(2) parton cascade

[2<->2 elastic collisions]

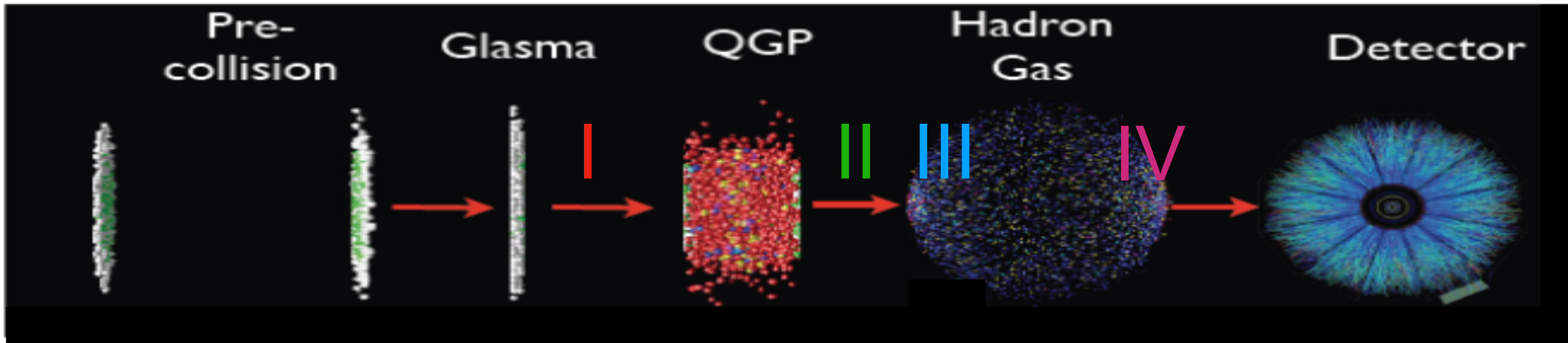
(3) hadronization

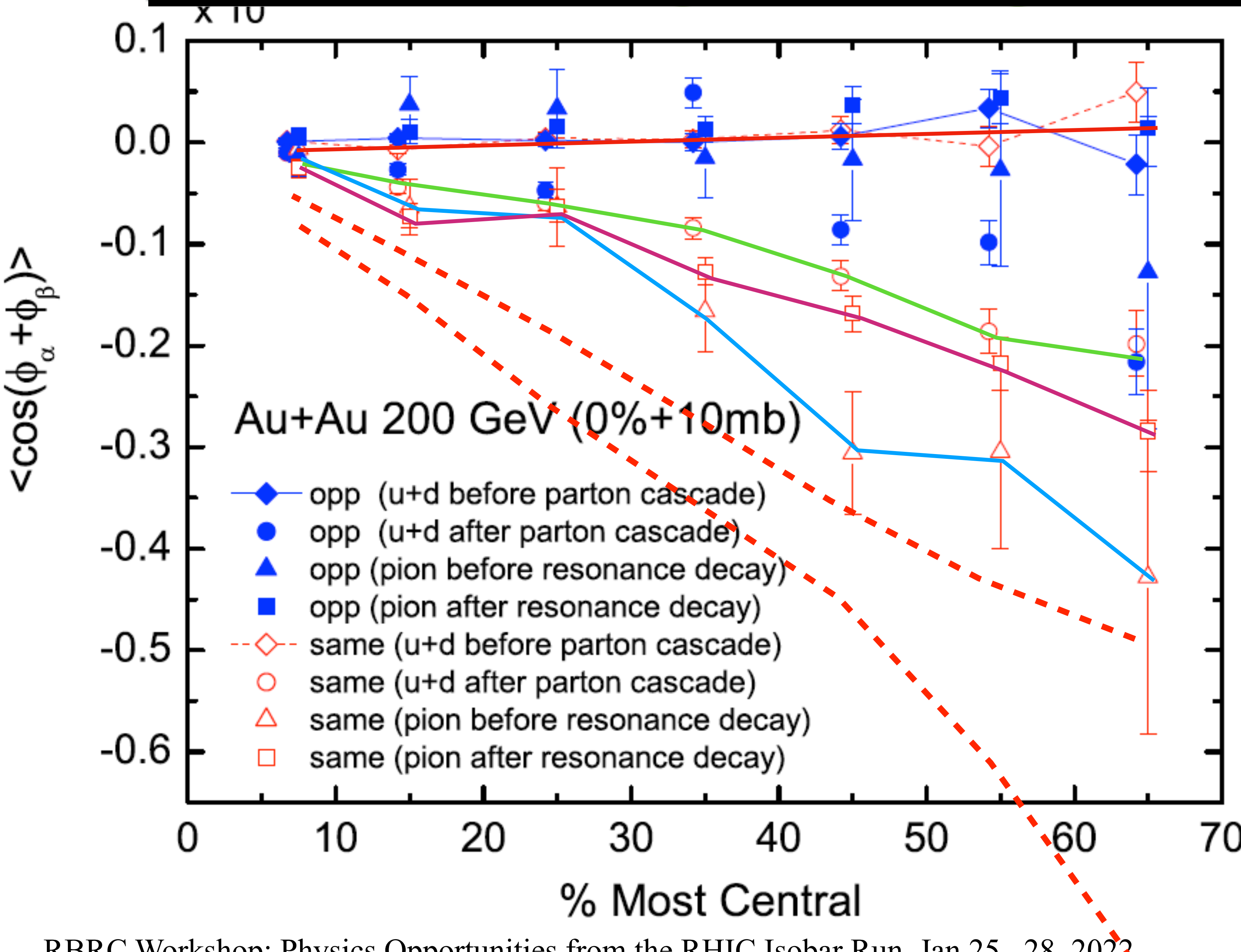
(4) hadronic rescatterings





Stage evolution of CME background in AMPT





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

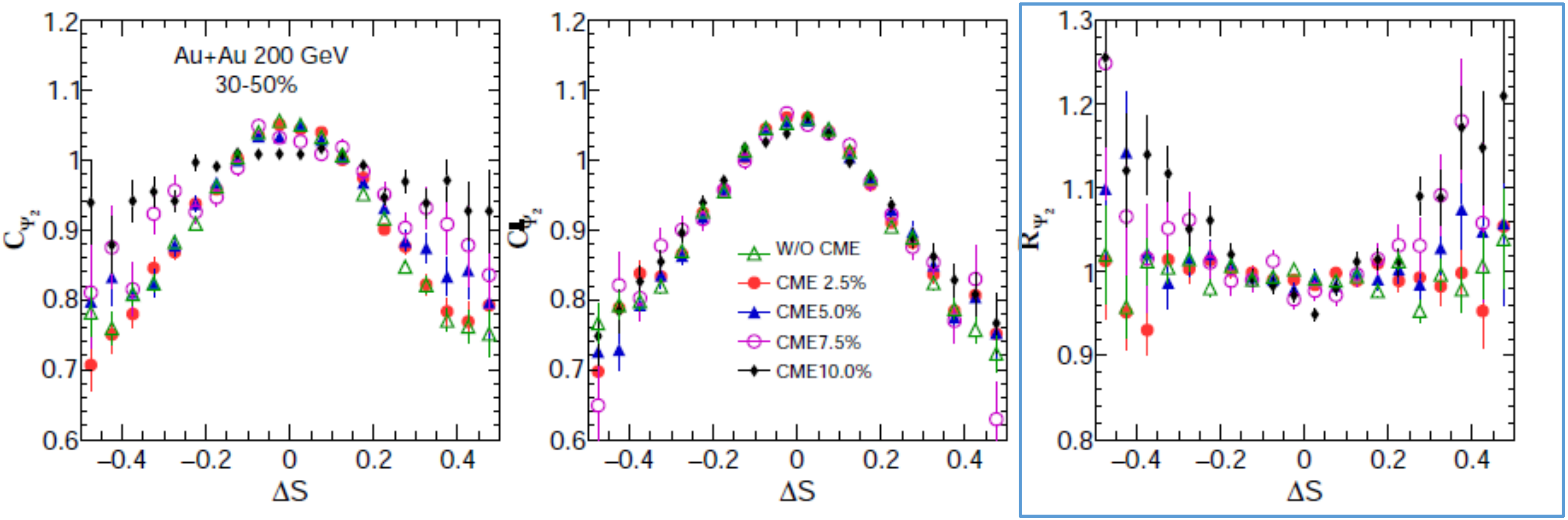
II. being negative through parton cascae due to Flow+TMC.(○)

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

IV. Resonance decays reduce signal. (□)

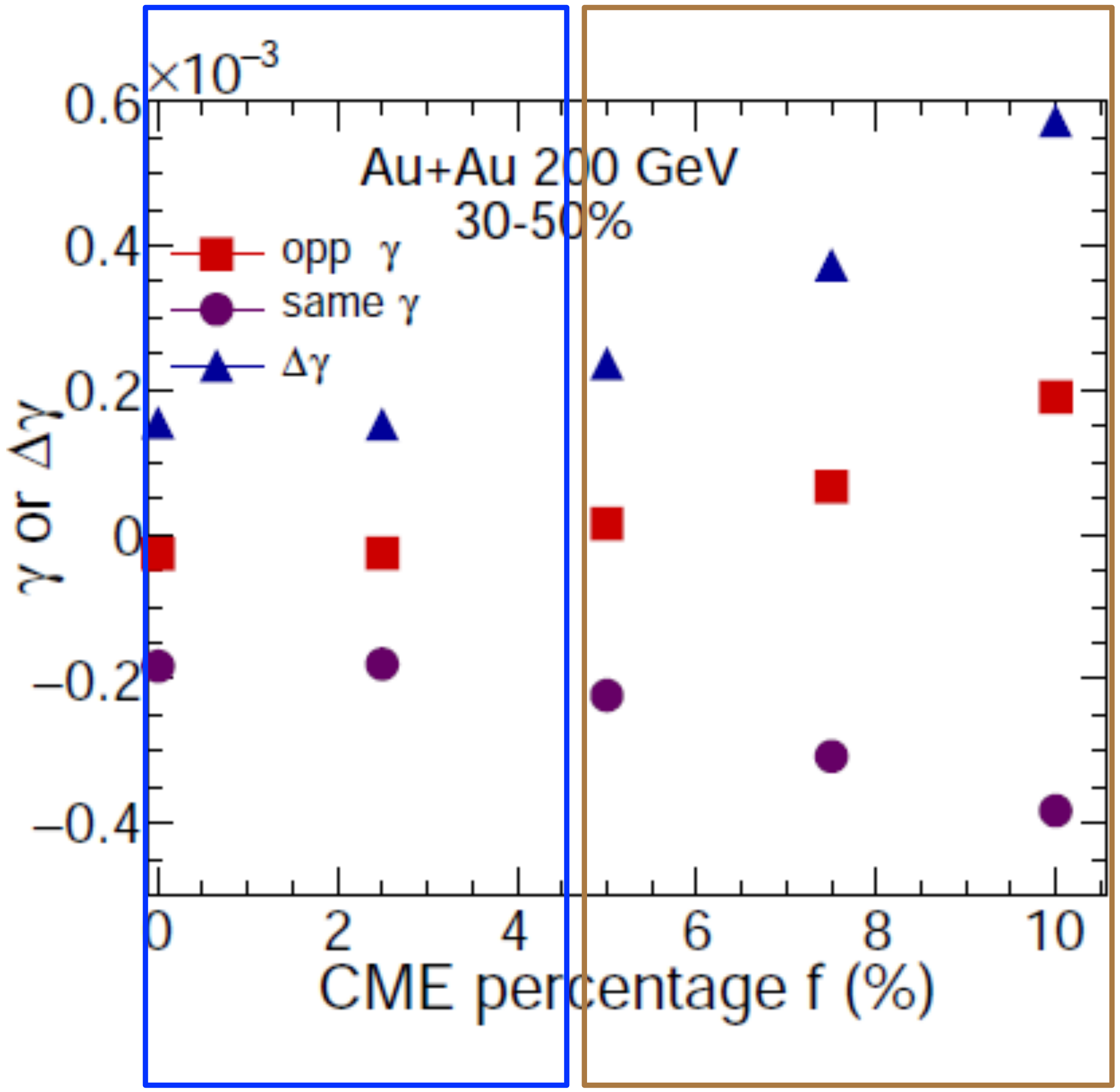
C_{Ψ_2} & R_{Ψ_2} for different CME percentages

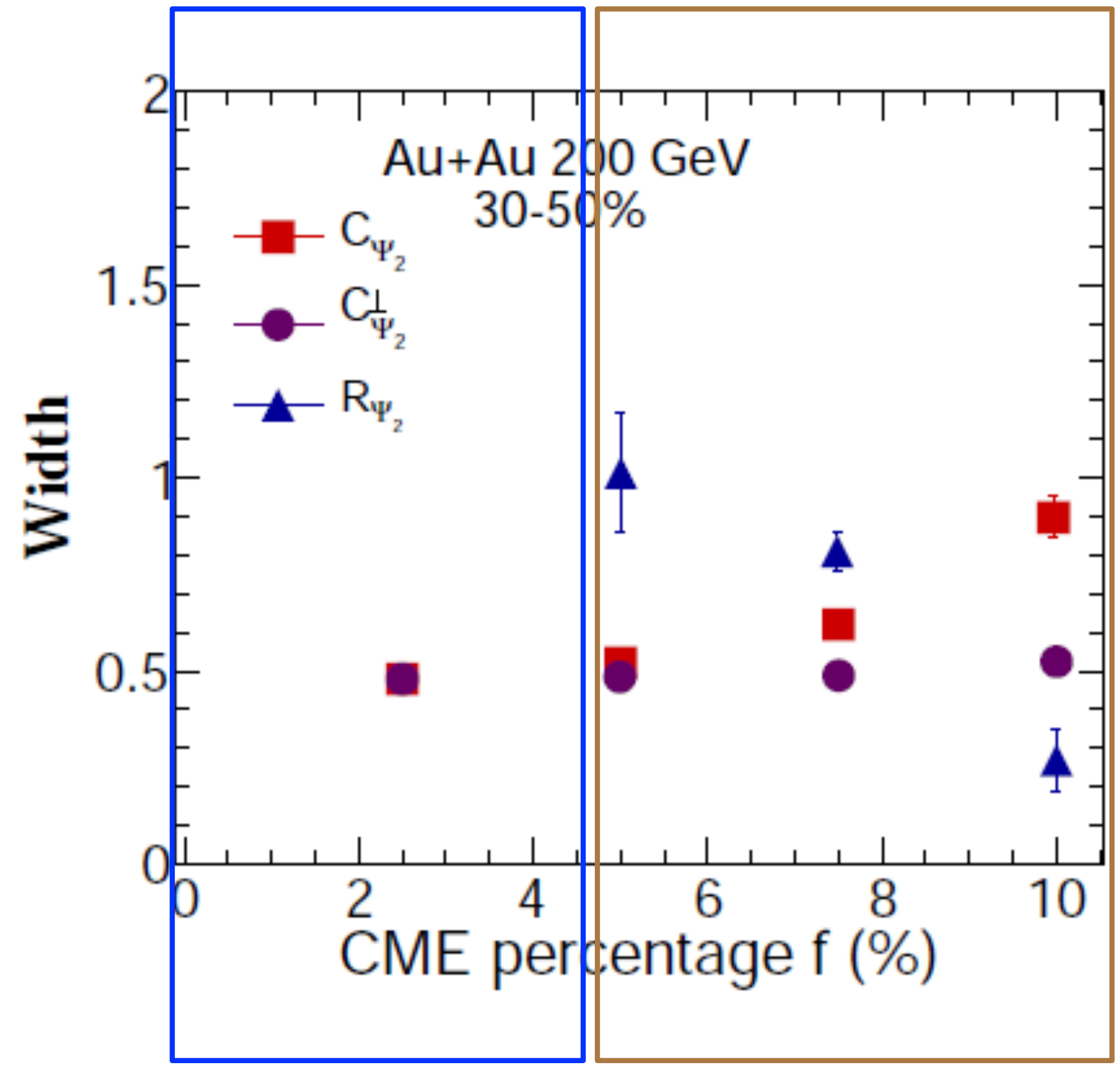
AMPT results on R_{Ψ_2} for different initial CME percentages :



- R_{Ψ_2} (f=2.5%) is similar to R_{Ψ_2}(W/O CME), they look flat within current statistics.
- The shape of R_{Ψ_2} (f>5%) is concave
- With increase of CME strength (f>5%), the shape becomes more concave

Sensitivity of $\Delta\gamma$ and R_{Ψ_2} to CME





- γ and R_{Ψ_2} (f<5%) look similar to those (W/O CME) .
- γ and R_{Ψ_2} response to CME strength of f>5%

★**$\Delta\gamma$ and R_{Ψ_2} are non-linearly response to the CME strength.**

L. Huang, M.-W. Nie, G.-L. Ma, Phys.Rev.C 101 (2020), 024916