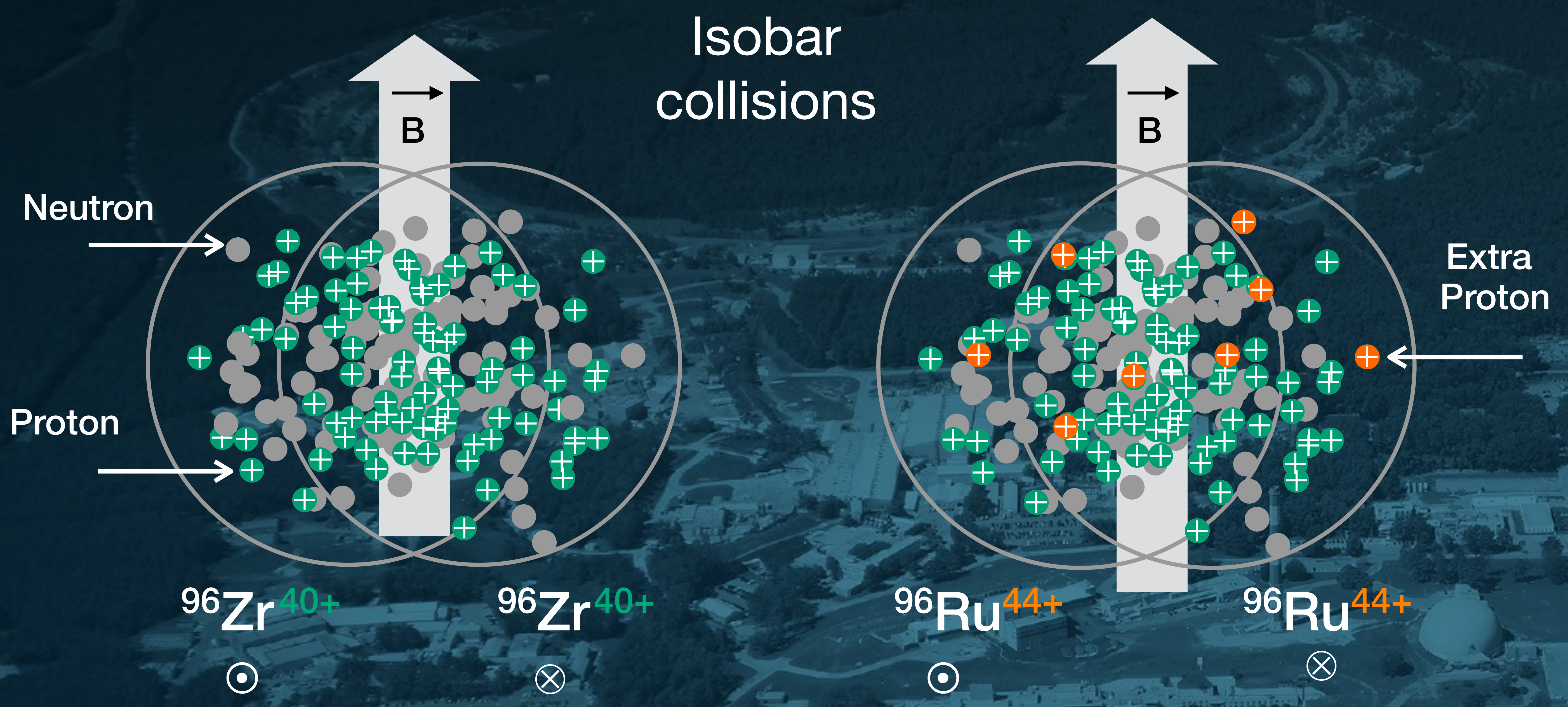
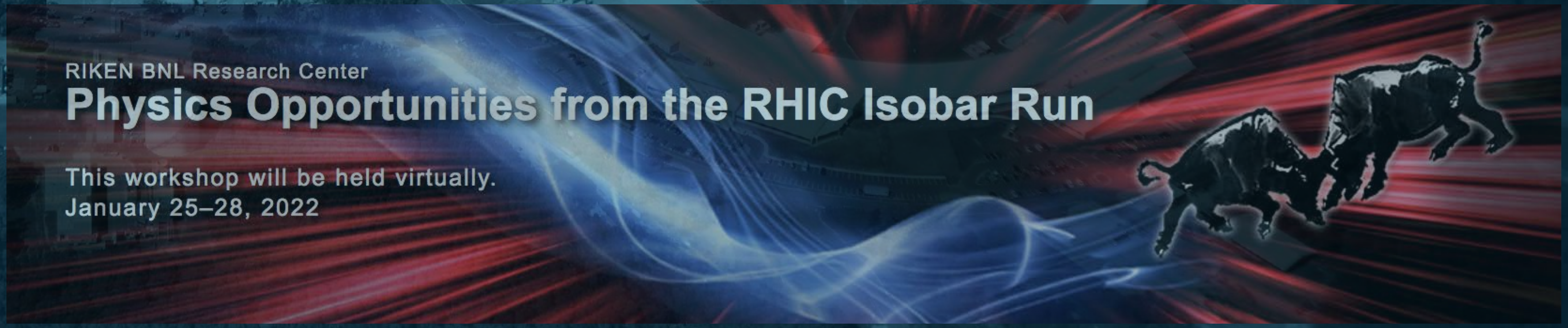


Blind analysis of isobar data for the CME search by the STAR collaboration

Based on: https://arxiv.org/abs/2109.00131 Phys. Rev. C 105, 014901 (2022)

Prithwish Tribedy

(Brookhaven National Laboratory)



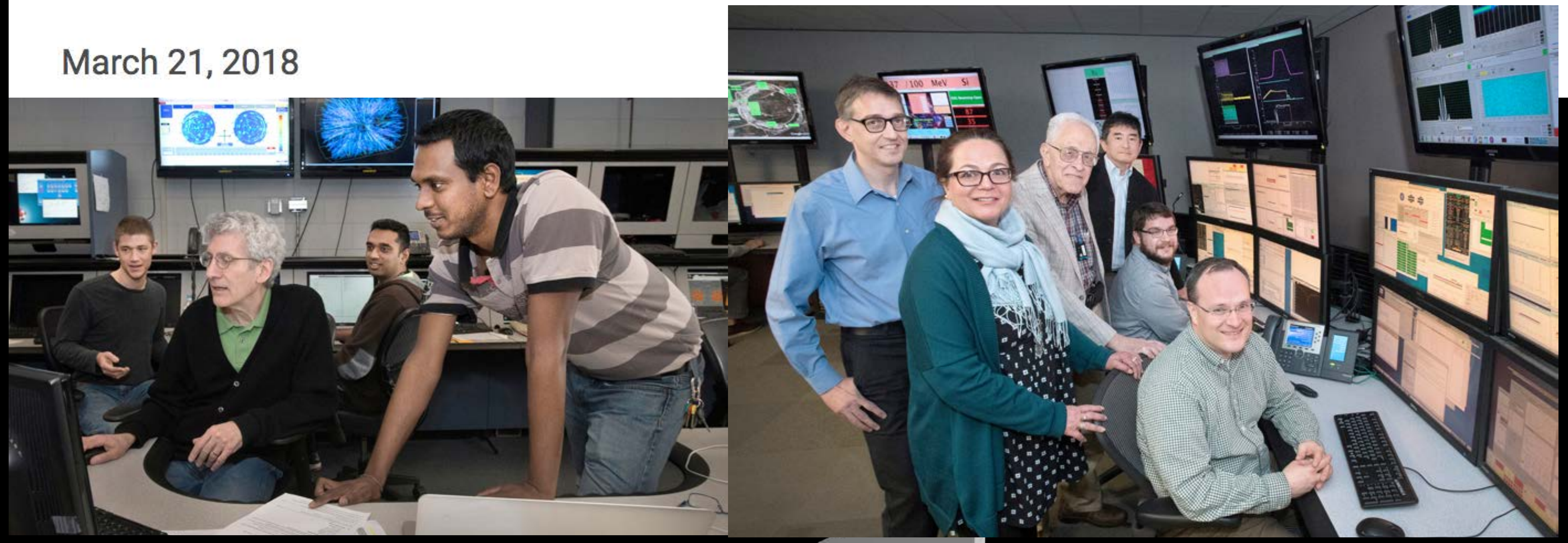
Isobar program at RHIC: journey since 2018

Brookhaven National Laboratory

Relativistic Heavy Ion Collider Begins 18th Year of Experiments

First smashups with 'isobar' ions and low-energy gold-gold collisions will test earlier hints of exciting discoveries as accelerator physicists tune up technologies to enable future science

March 21, 2018



2018

2019

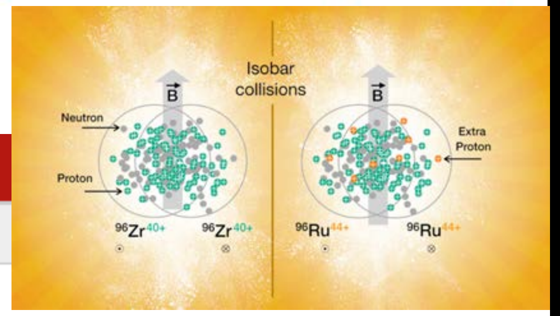
2020

2021

Results from Search for 'Chiral Magnetic Effect' at RHIC

Collisions of 'isobars' test effect of magnetic field, searching for signs of a broken symmetry

August 31, 2021



arXiv.org > nucl-ex > arXiv:2109.00131

Nuclear Experiment

[Submitted on 1 Sep 2021]

Search for the Chiral Magnetic Effect with Isobar Collisions at $\sqrt{s_{NN}}$ = 200 GeV by the STAR Collaboration at RHIC

STAR Collaboration: M. S. Abdallah, B. E. Aboona, J. Adam, L. Adamczyk, J. R. Adams, J. K. Adkins, G. Agakishiev, I. Aggarwal, M. M. Aggarwal, Z. Ahammed, I. Alekseev, D. M. An Ashraf, F. G. Atetalla, A. Attri, G. S. Averichev, V. Bairathi, W. Baker, J. G. Ball Cap, K. Barish, A. Behera, R. Bellwied, P. Bhagat, A. Bhasin, J. Bielcik, J. Bielcikova, I. G. Bordyuzhin, J. X. Z. Cai, H. Caines, M. Calderón de la Barca Sánchez, D. Cebra, I. Chakaberia, P. Chaloupka, B. K. Chan, F-H. Chang, Z. Chang, N. Chankova-Bunzarova, A. Chatterjee, S. Chattop Chen, Z. Chen, J. Cheng, M. Chevalier, S. Choudhury, W. Christie, X. Chu, H. J. Crawford, M. Csanád, M. Daugherity, T. G. Dedovich, I. M. Deppner, A. A. Derevschikov, A. Dhamija J. L. Drachenberg, E. Duckworth, J. C. Dunlop, N. Elsey, J. Engelage, G. Eppley, S. Esumi, O. Evdokimov, A. Ewigleben, O. Eyser, R. Fatemi, F. M. Fawzi, S. Fazio, P. Federic, J. Fedori Fisyak, A. Francisco, C. Fu, L. Fulek, C. A. Gagliardi, T. Galatyuk, F. Geurts, N. Ghimire, A. Gibson, K. Gopal, X. Gou, D. Grosnick, A. Gupta, W. Guryn, A. I. Hamad et al. (298 addit

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

M. S. Abdallah *et al.* (STAR Collaboration)
Phys. Rev. C **105**, 014901 – Published 3 January 2022

STAR detector (currently running)

RHIC: known for species (U, Au, Ru, Zr, Cu, Al..) and energy (γ~100-3.85) maneuver capability

STAR: known for precision measurement capability of hadrons over wide acceptance

The versatility of RHIC and the unique capabilities of the STAR detector were crucial to the success of our program

Parity Violation in Hot QCD: Chiral Magnetic Effect

Brookhaven National Laboratory

Available online at www.sciencedirect.com

SCIENCE DIRECT

ELSEVIER

PHYSICS LETTERS B

Physics Letters B 633 (2006) 260–264

www.elsevier.com/locate/physletb

Parity violation in hot QCD: Why it can happen, and how to look for it

Dmitri Kharzeev

Physics Department, Brookhaven National Laboratory, Upton, NY 11973-5000, USA

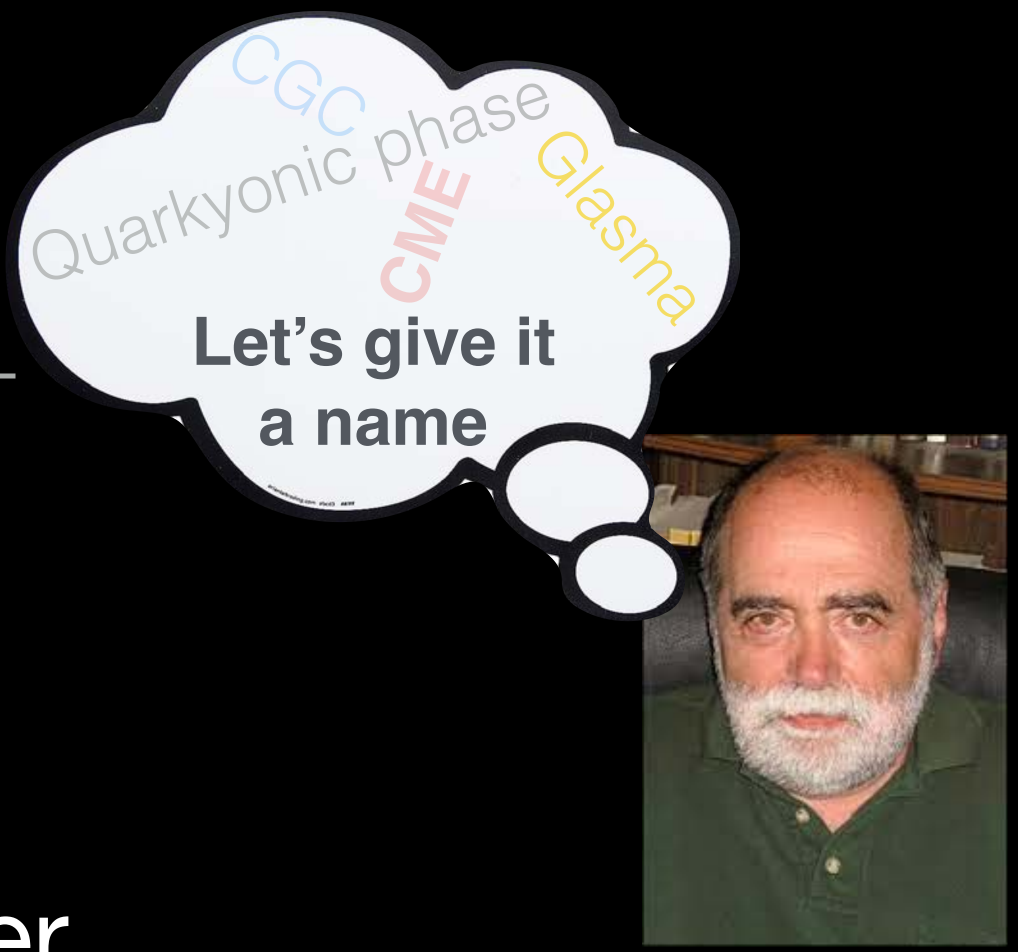
Received 23 December 2004; received in revised form 27 October 2005; accepted 23 November 2005

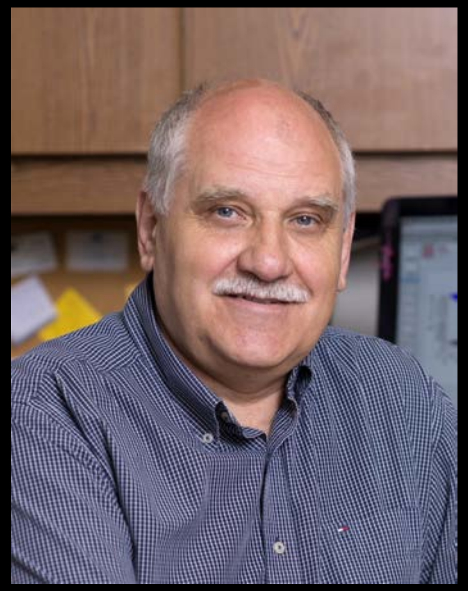
Available online 7 December 2005

Early theory paper

Kharzeev, hep-ph/0406125

Also see : Kharzeev et al, hep-ph/9906401, Kharzeev et al, hep-ph/9804221





PHYSICAL REVIEW C **70**, 057901 (2004)

Parity violation in hot QCD: How to detect it

Sergei A. Voloshin

Department of Physics and Astronomy, Wayne State University, Detroit, Michigan 48201, USA

(Received 5 August 2004; published 11 November 2004)

First method paper

Voloshin, hep-ph/0406311

Also: Finch et al Phys.Rev.C 65 (2002) 014908

STAR

Selected for a Viewpoint in *Physics*

PRL **103,** 251601 (2009) PHYSICAL REVIEW LETTERS week ending 18 DECEMBER 2009

Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

(STAR Collaboration)

First experimental paper

STAR collaboration, arXiv:0909.1739

STAR

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

M. S. Abdallah *et al.* (STAR Collaboration)

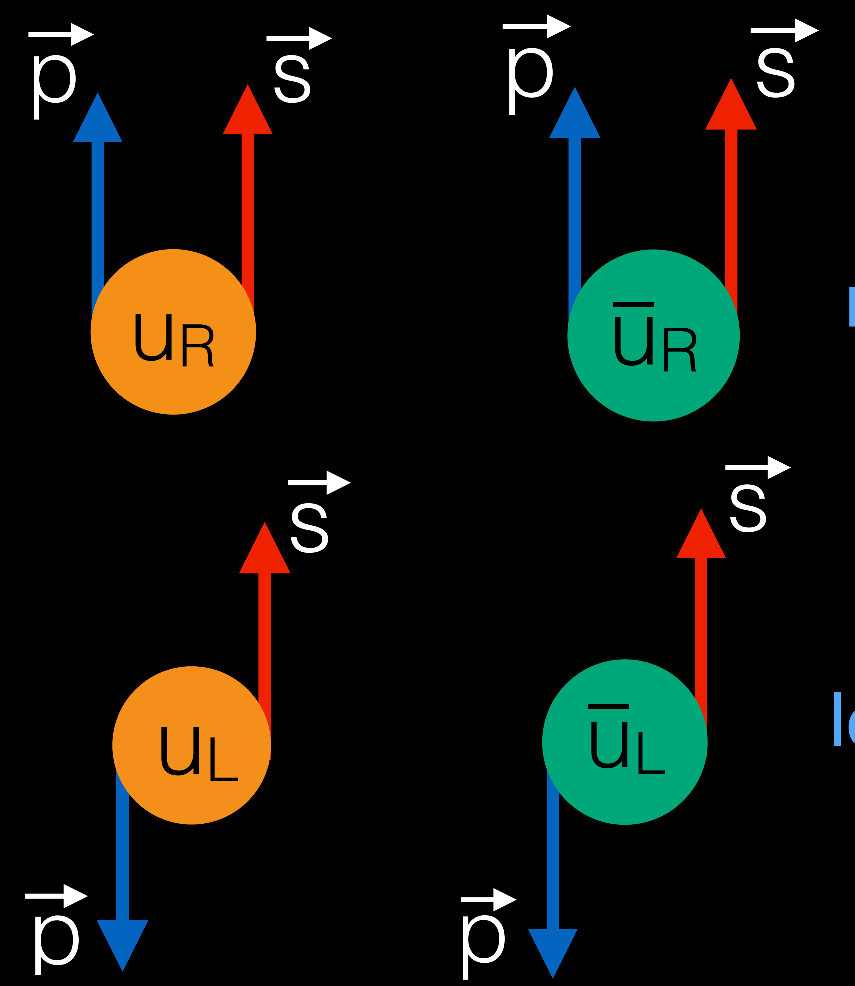
Phys. Rev. C **105**, 014901 – Published 3 January 2022

Blind analysis of the Isobar data

STAR collaboration, arXiv:2109.00131

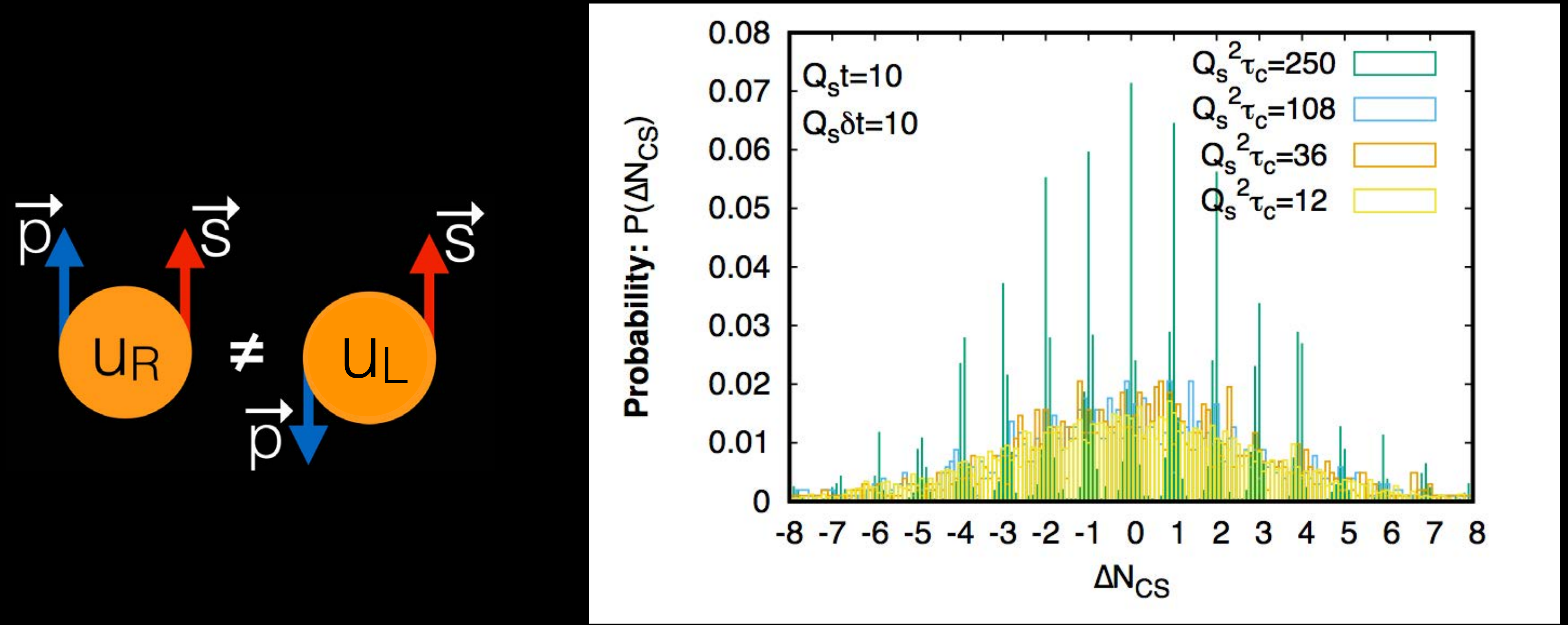
The chiral magnetic effect (CME) in four steps

1 Deconfined medium of massless quark (chiral symmetry restored)



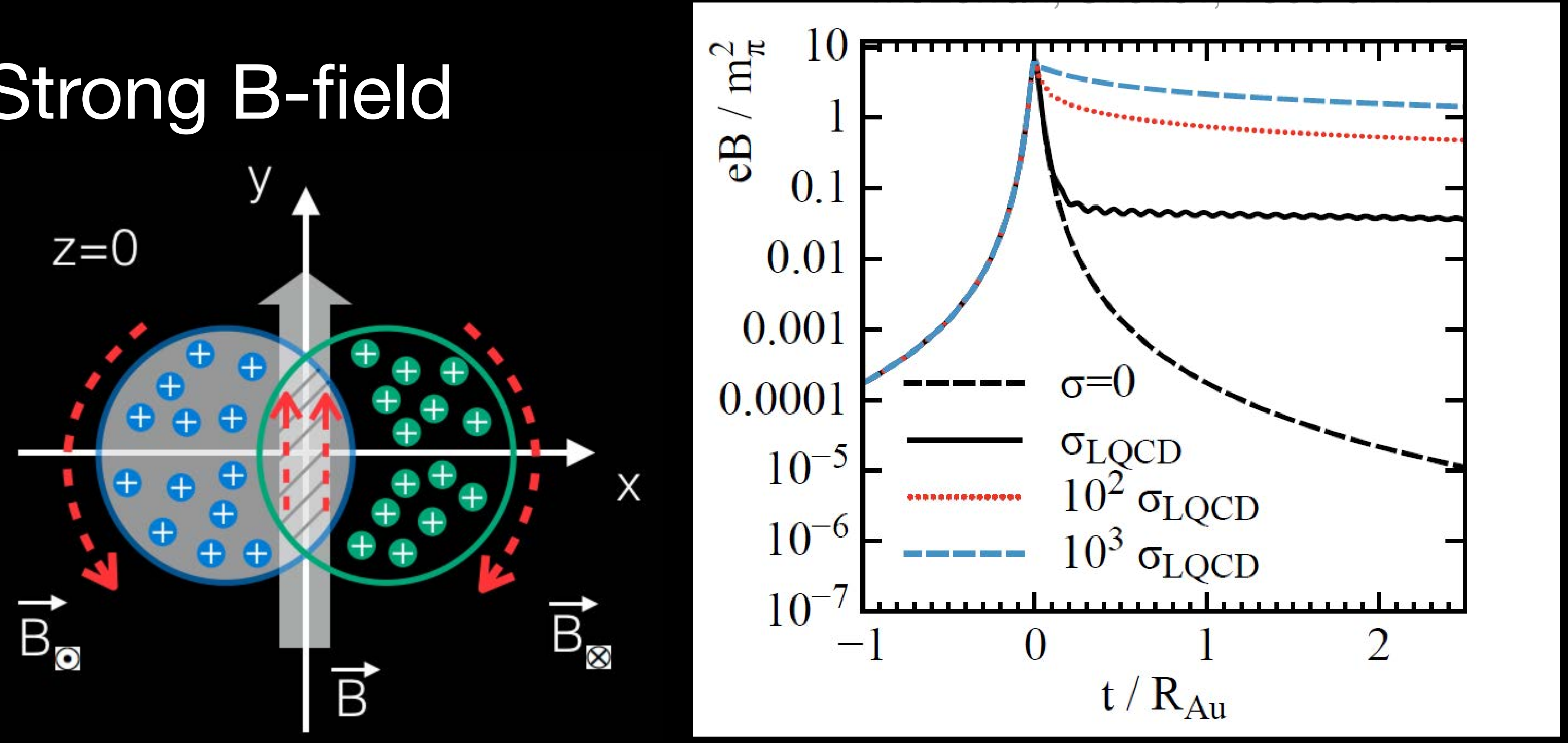
Kharzeev, McLerran,Warringa 0711.0950

2 Mechanism to create imbalance of left & right handed quarks

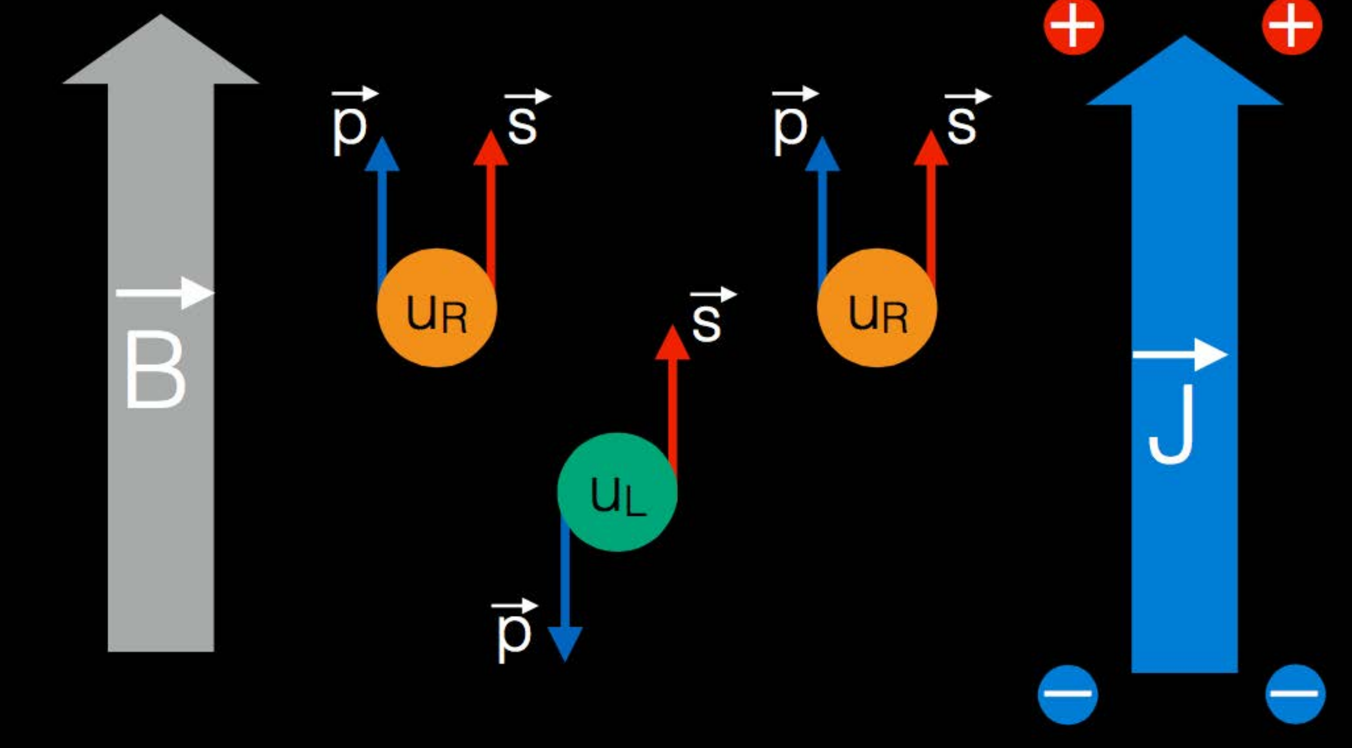


Kharzeev et al, hep-ph/0109253, Mace et al, 1601.07342, Muller et. al.1606.00342, Lappi et al,1708.08625

3 Strong B-field



4 The Chiral Magnetic Effect (J || B)



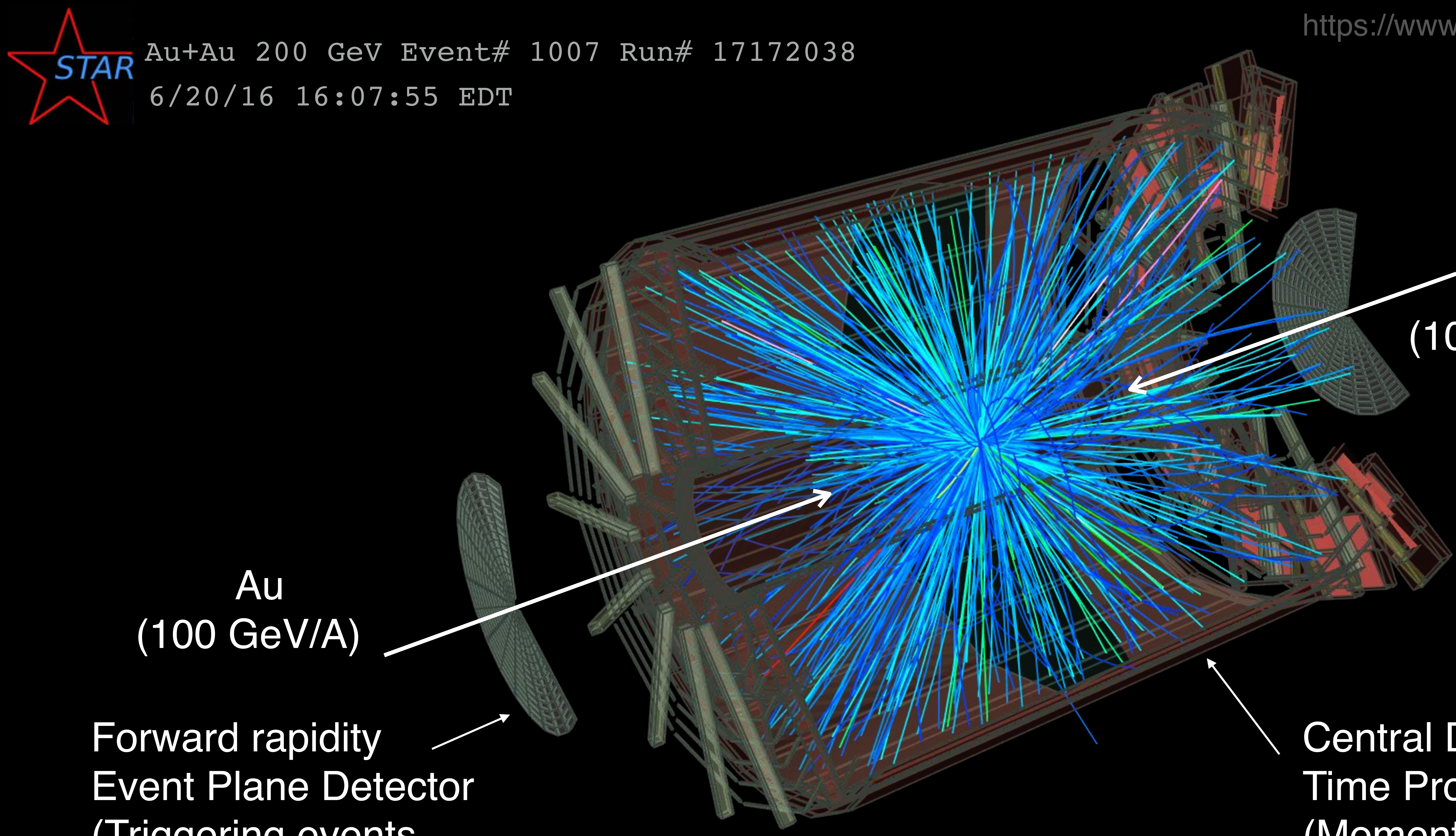
Kharzeev, arXiv:hep-ph/0406125

Kharzeev et al 0711.0950, Skokov et al 0907.1396, McLerran et al

Experimental Observables for CME search

A gold-gold collision @ STAR detector

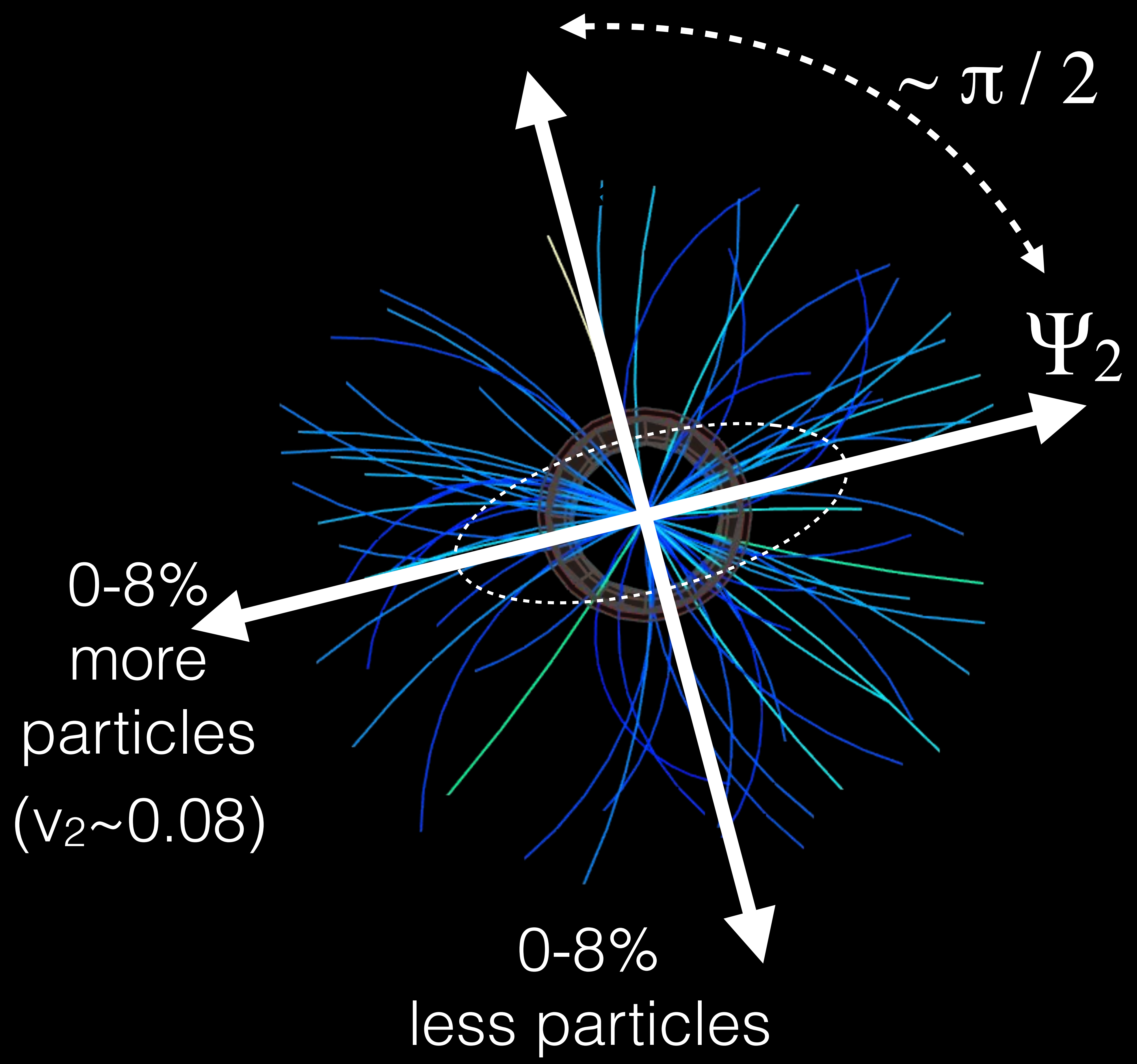
https://www.star.bnl.gov/~dmitry/edisplay/



Elliptic anisotropy in particle production

Elliptic anisotropy is measured by correlation between two particles

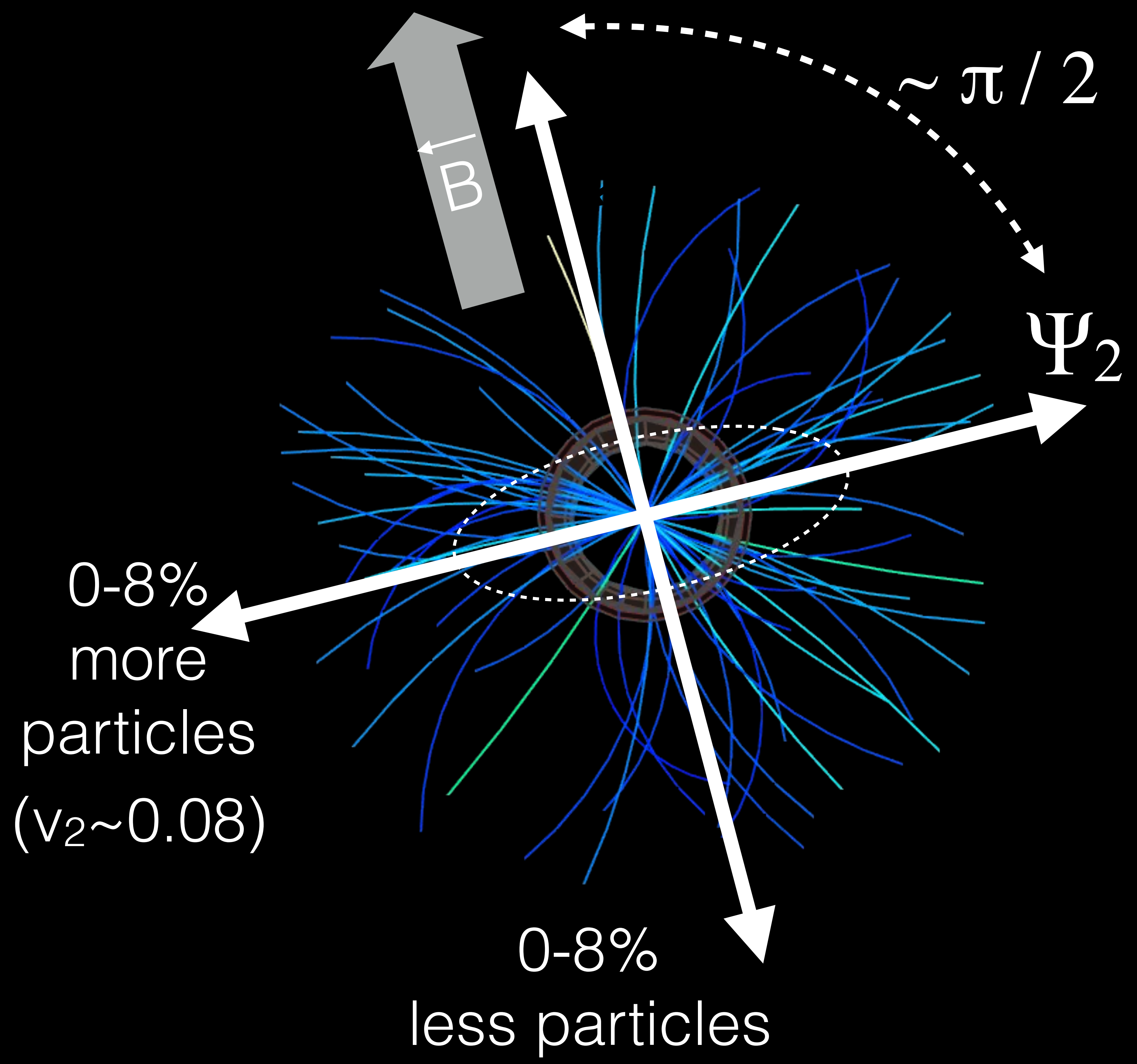
$$v_2\{EP\} = \langle \cos(2\phi_1 - 2\Psi_2) \rangle \qquad v_2\{2\}^2 = \langle \cos(2\phi_1 - 2\phi_2) \rangle$$

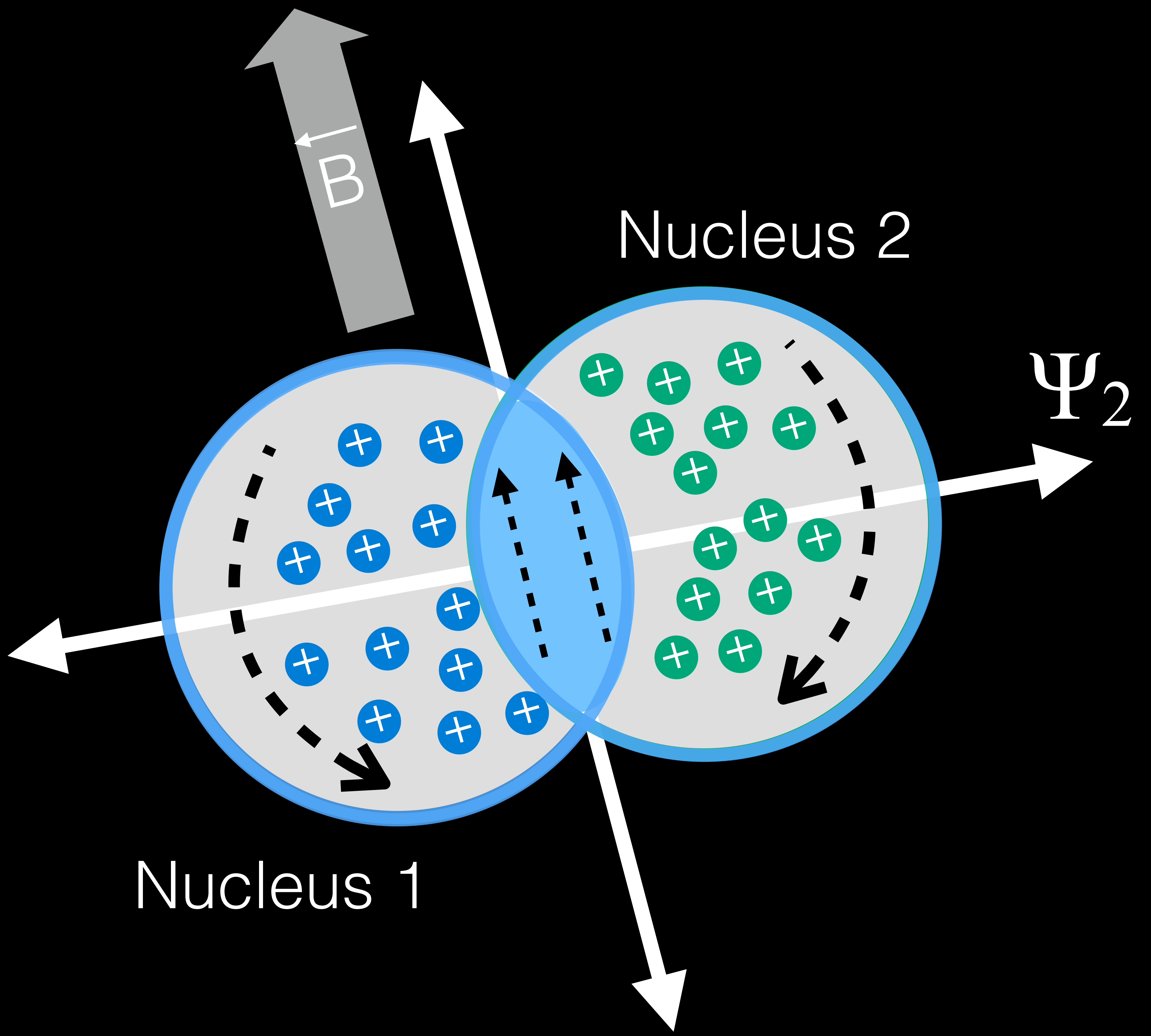


Elliptic anisotropy and B-field direction

Elliptic anisotropy is measured by correlation between two particles

$$v_2\{EP\} = \langle \cos(2\phi_1 - 2\Psi_2) \rangle \qquad v_2\{2\}^2 = \langle \cos(2\phi_1 - 2\phi_2) \rangle$$

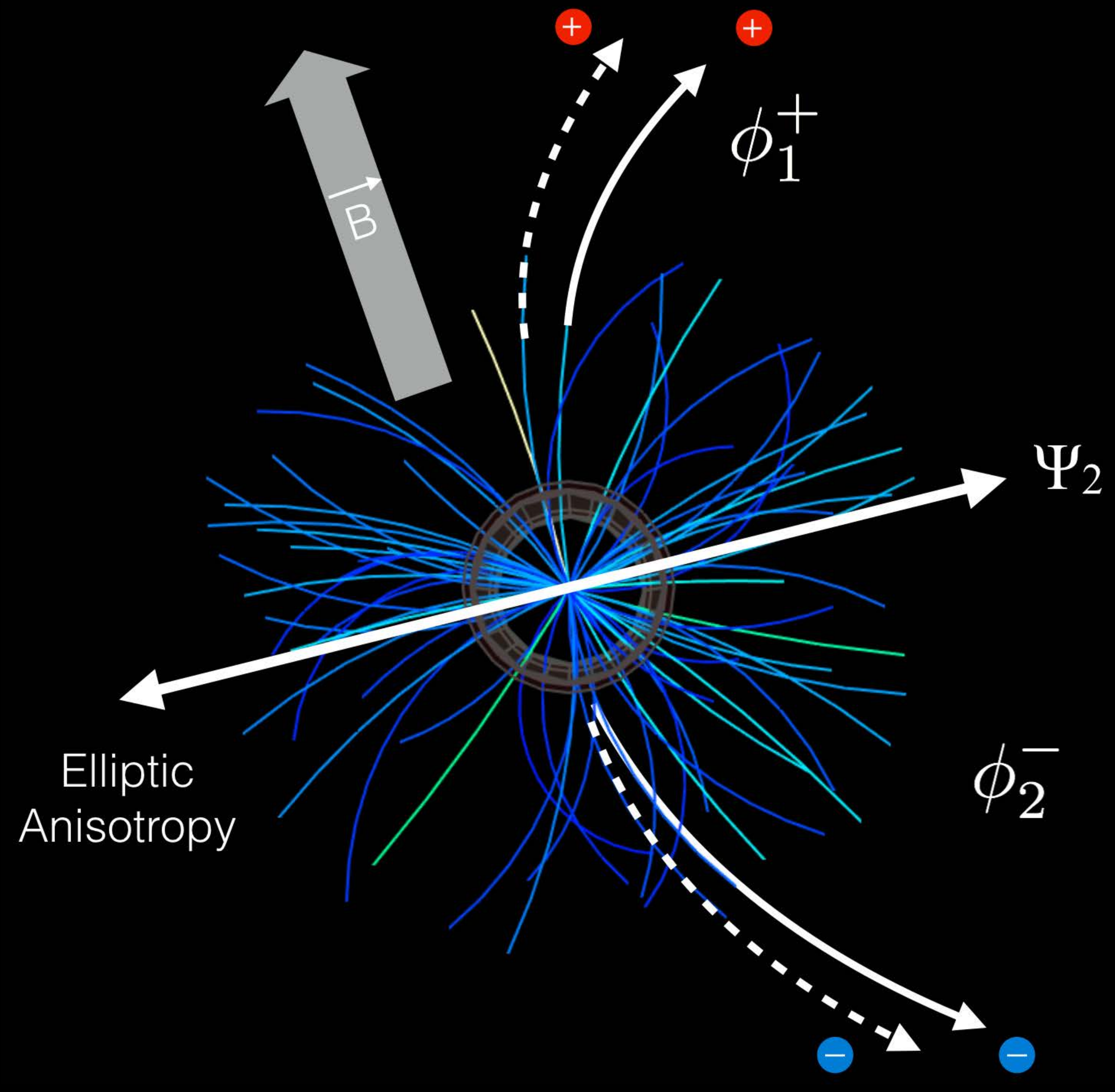




The plane of elliptic anisotropy Ψ_2 is correlated to B-field direction

How to measure charge separation due to CME ?

Measure charge separation across Ψ_2 using the correlator:



Voloshin, hep-ph/0406311

$$\gamma^{\alpha,\beta} = \langle \cos(\phi_1^\alpha + \phi_2^\beta - 2\Psi_2) \rangle$$

CME case : $\gamma^{SS} \neq \gamma^{OS}$

$$\gamma^{+-} = \cos(\pi/2 - \pi/2 + 0) = 1$$
$$\gamma^{++,--} = \cos(\pi/2 + \pi/2 + 0) = -1$$

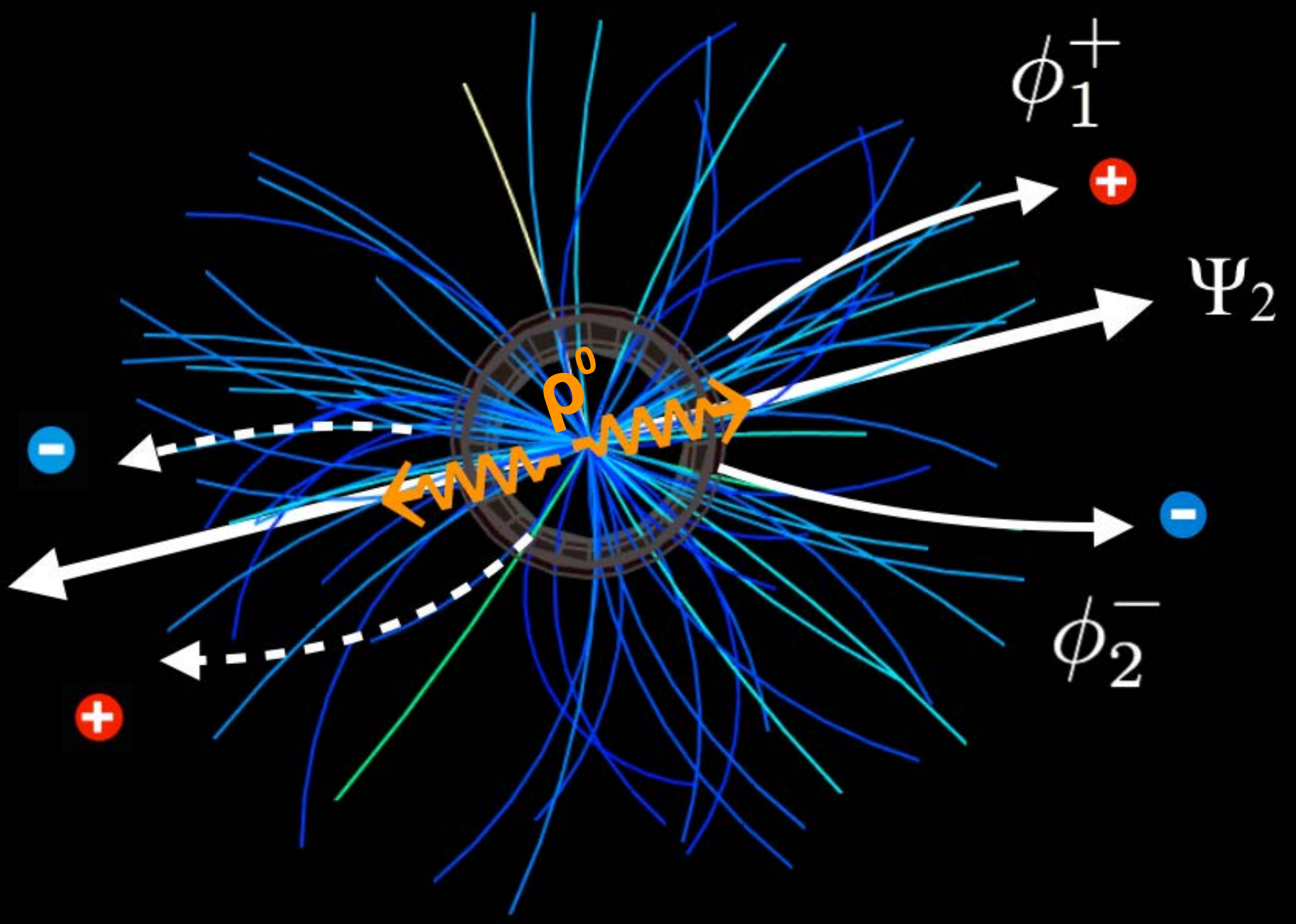
Quantity of interest:

$$\Rightarrow \Delta\gamma^{CME} = \gamma^{OS} - \gamma^{SS} > 0$$

CME causes difference in opposite-sign & same-sign correlation

Major source of background: decay of neutral clusters

Measure charge separation across Ψ_2 using the correlator:



Voloshin, hep-ph/0406311

$$\gamma^{\alpha,\beta} = \langle \cos(\phi_1^\alpha + \phi_2^\beta - 2\Psi_2) \rangle$$

Flowing resonance decay: $\gamma^{ss} \neq \gamma^{os}$

$$\gamma^{+-} = \cos(0+0+0) = 1$$
$$\gamma^{++,--} = \cos(0+\pi+0) = -1$$

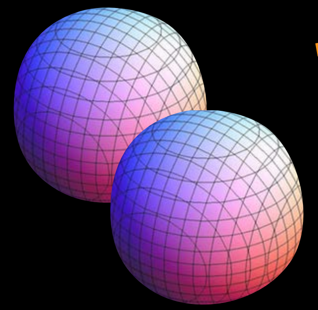
Non-CME effect such as flowing resonance decay can lead to difference

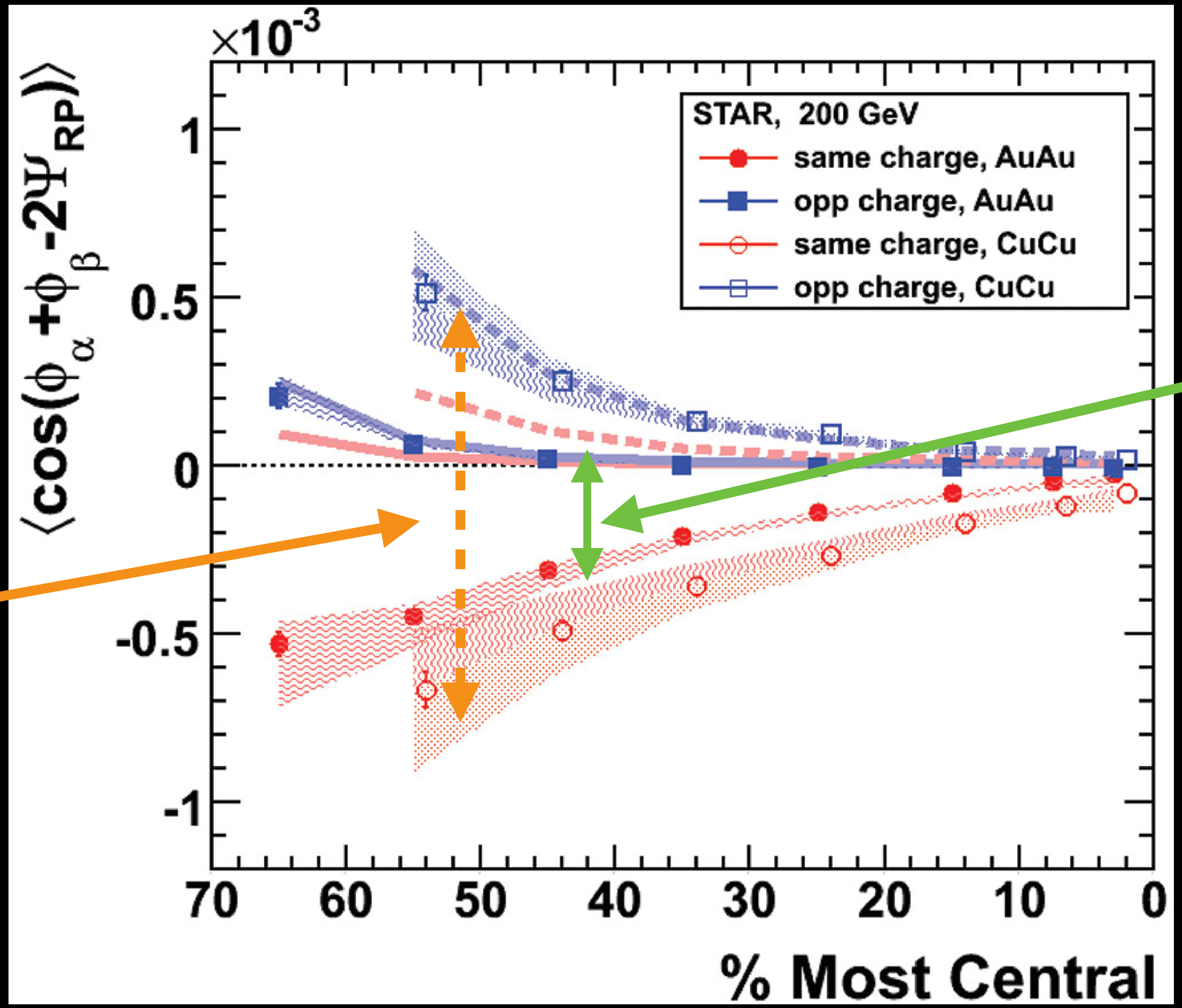
$$\Rightarrow \Delta\gamma^{reso} = \gamma^{os} - \gamma^{ss} \propto \frac{v_2^{reso}}{N}$$

Why we need isobars to search for CME ?

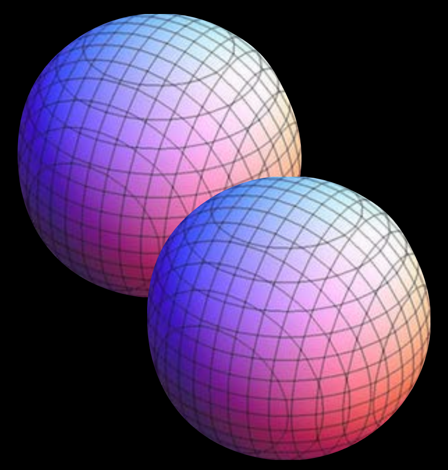
The first measurements at RHIC

Cu+Cu



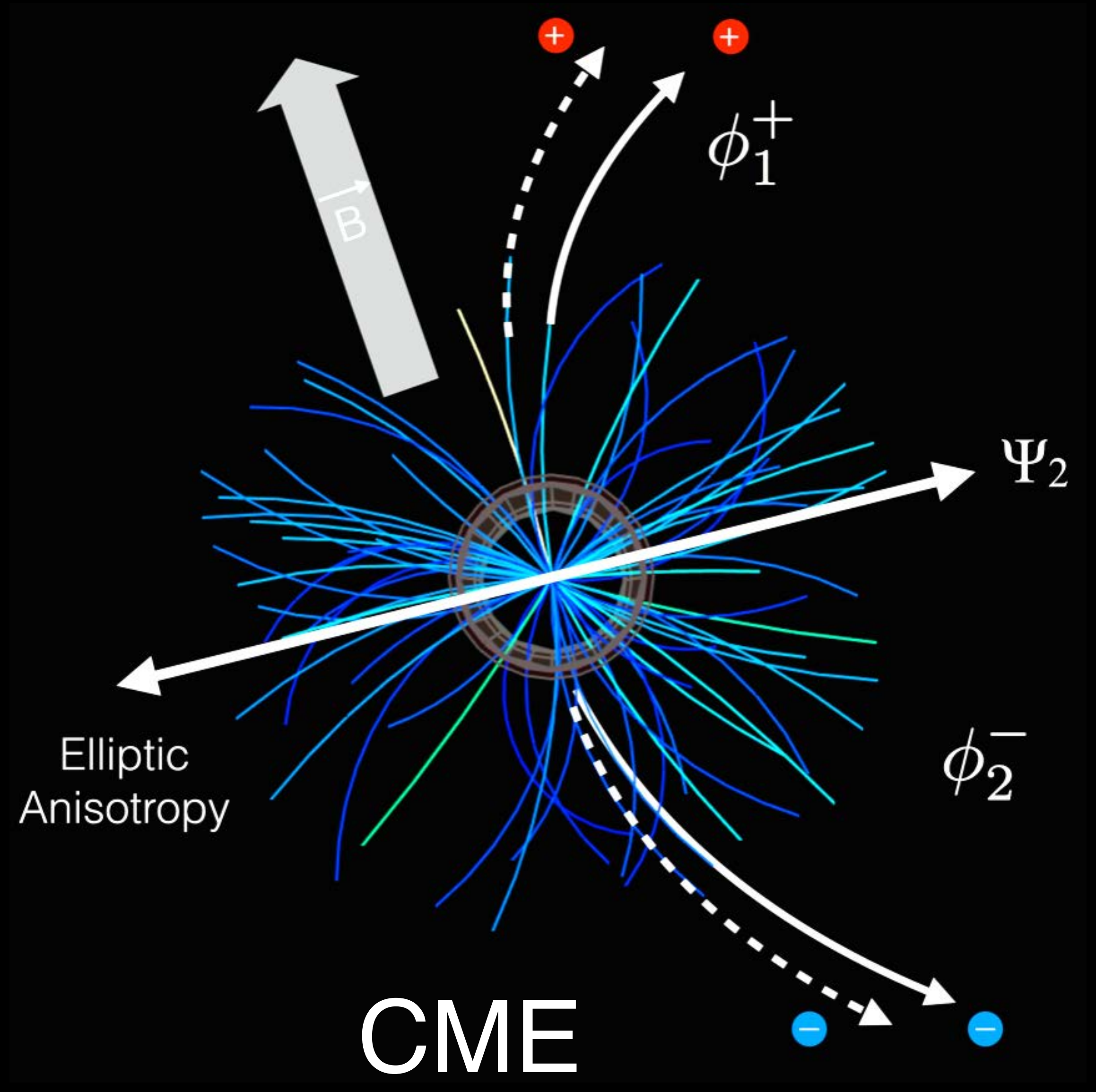


Au+Au



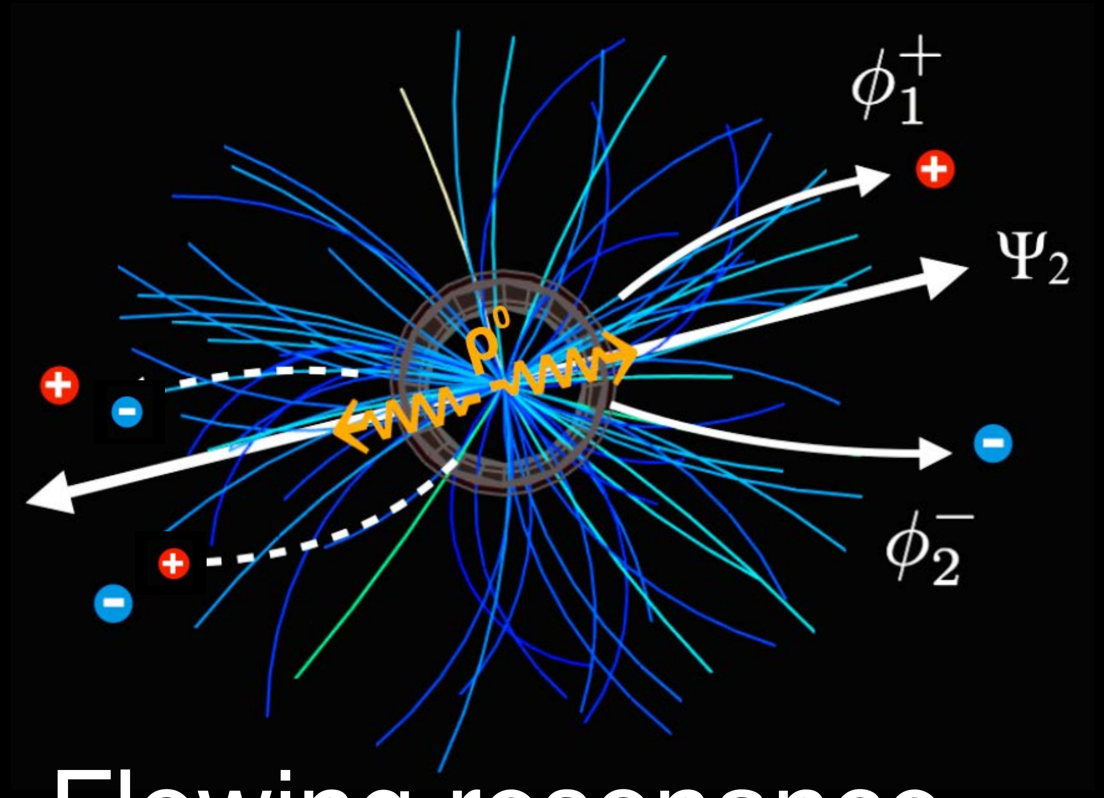
STAR collaboration, PRL 103, 251601 (2009

Three possible sources of charge separation



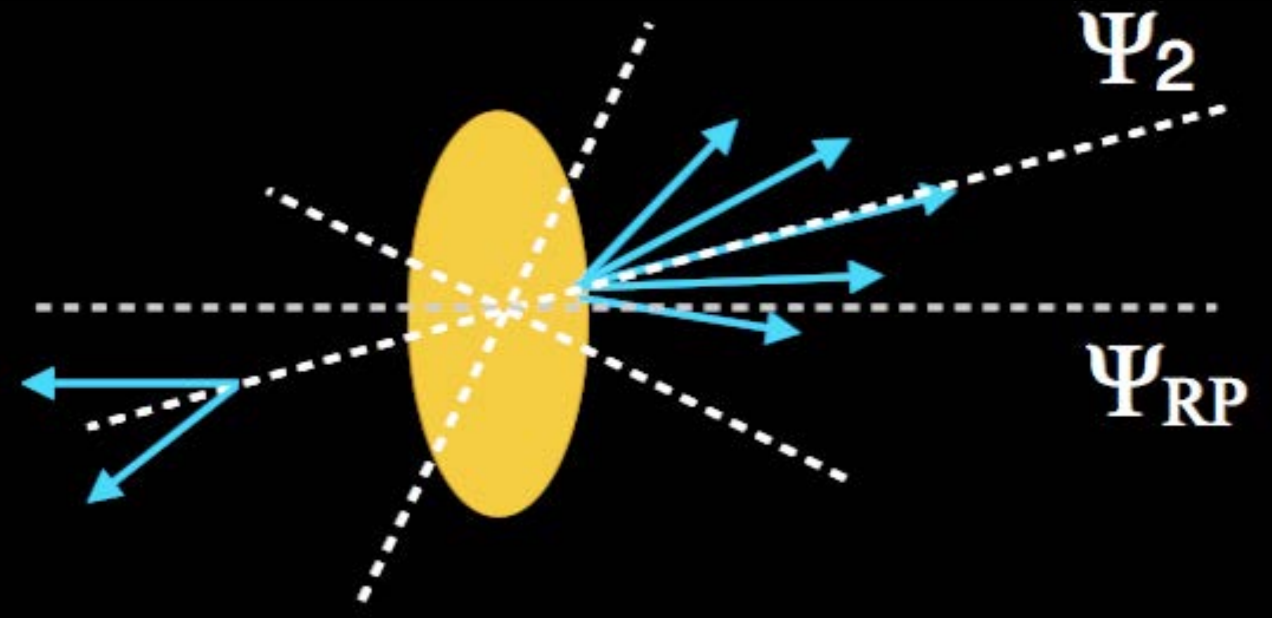
CME

\+



Flowing resonance

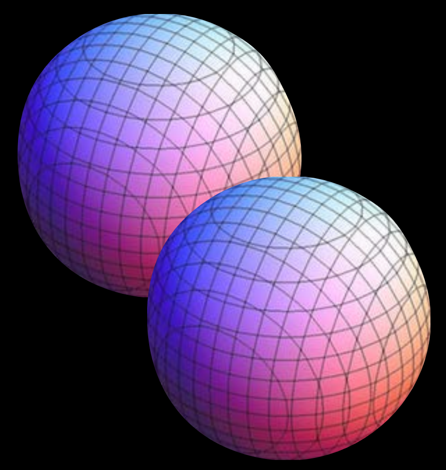
\+



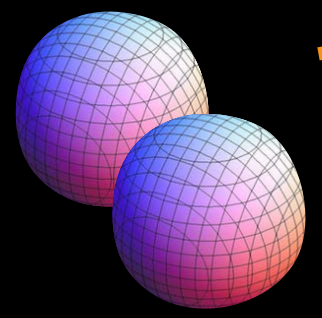
Di-jets (non-flow)

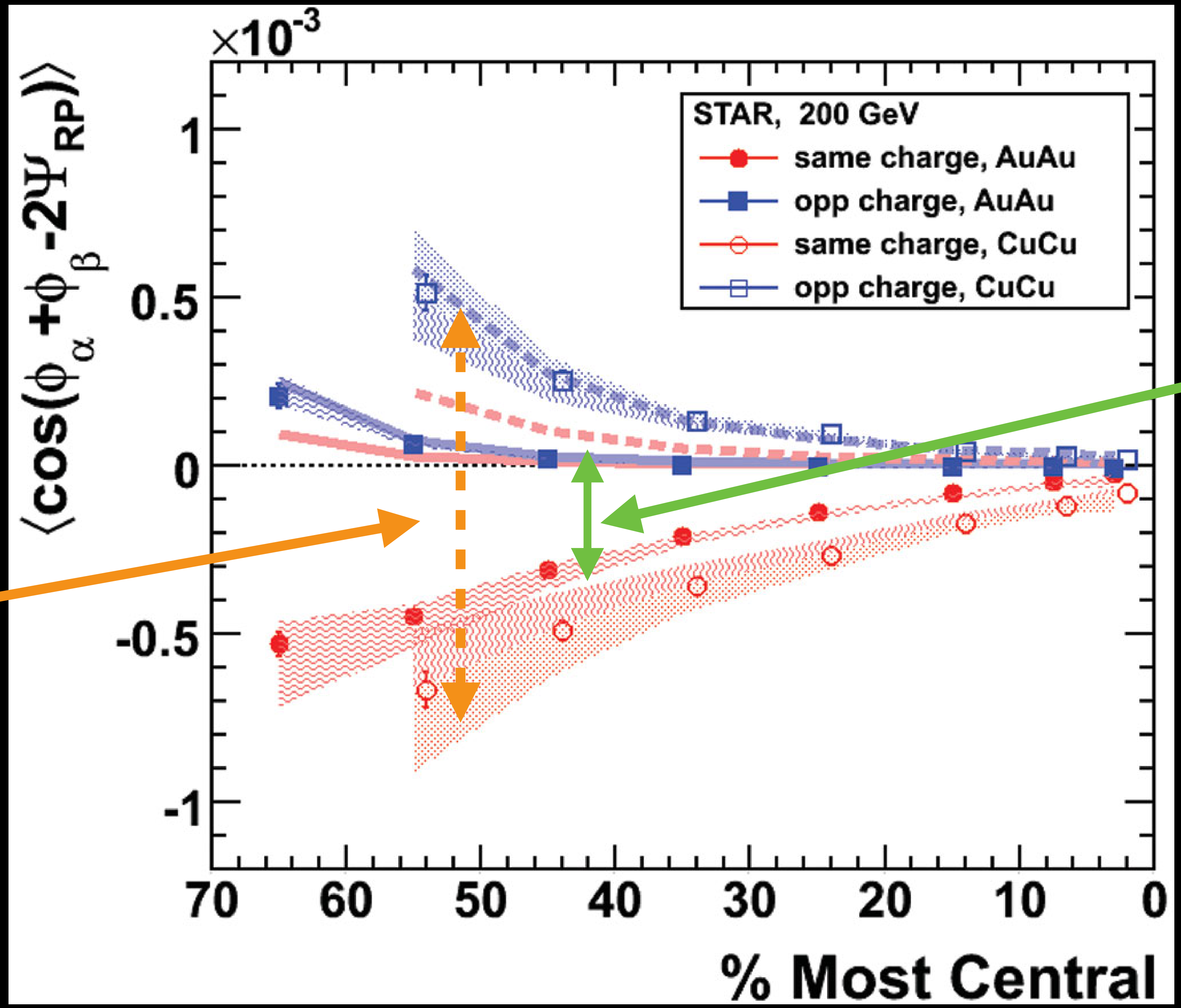
The first measurements at RHIC

Au+Au



Cu+Cu





STAR collaboration, PRL 103, 251601 (2009

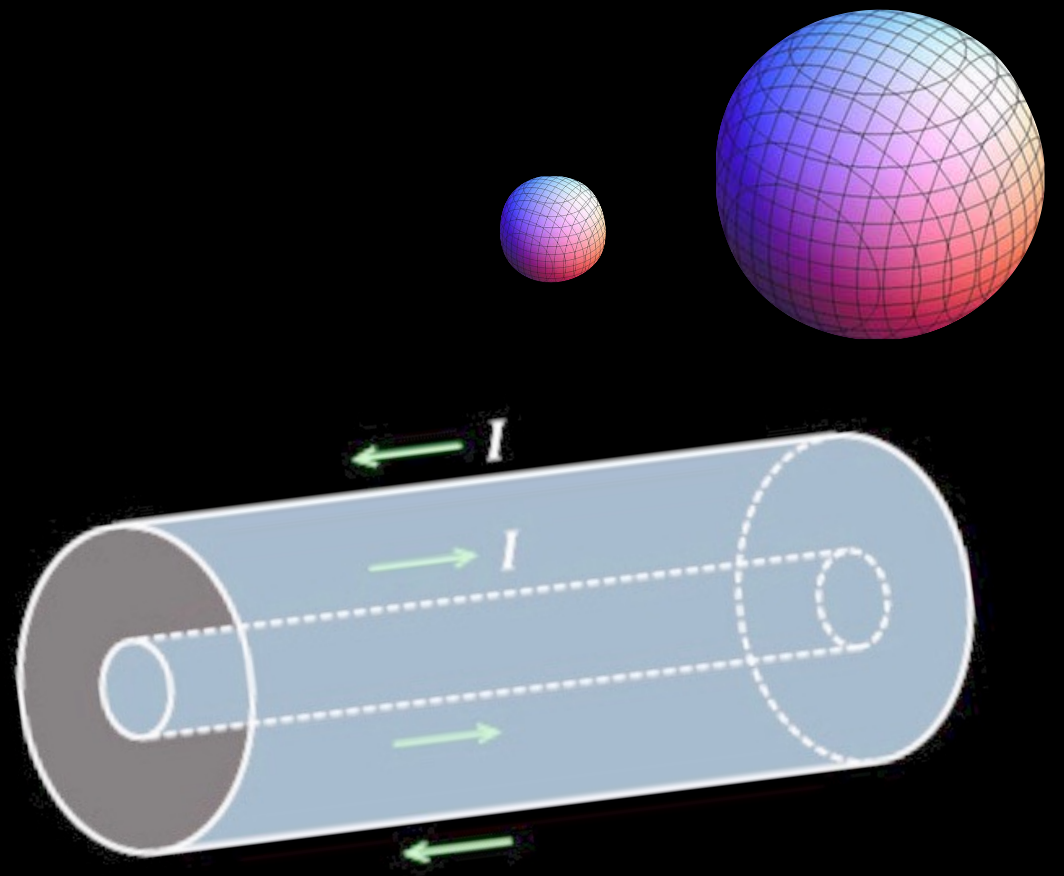
Significant charge separation observed, consistent with CME+ Background

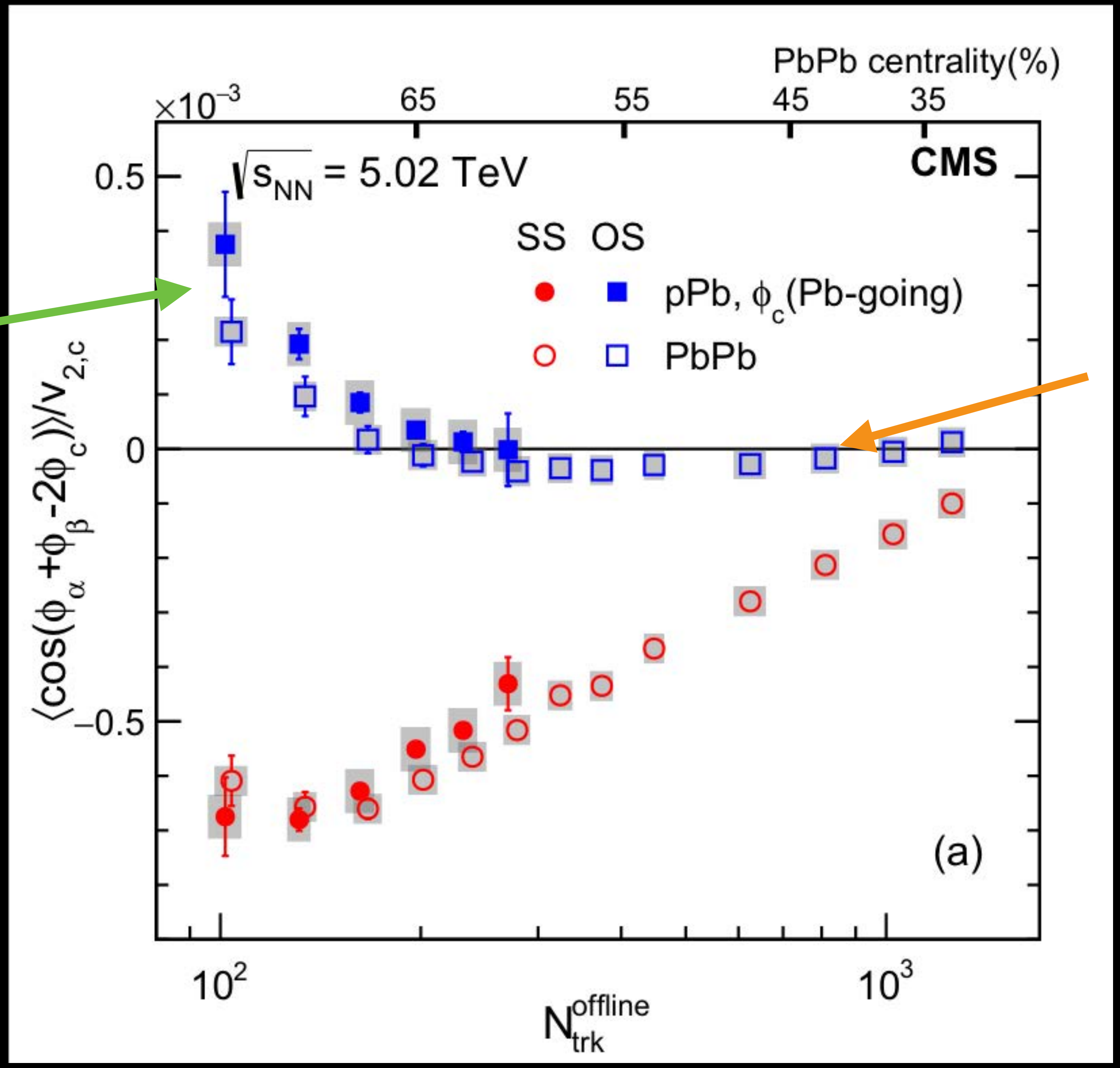
$$\Delta\gamma = \Delta\gamma^{CME} + k \times \frac{v_2}{N} + \Delta\gamma^{non-flow}$$

Measurement Signal Background-1 Background-2

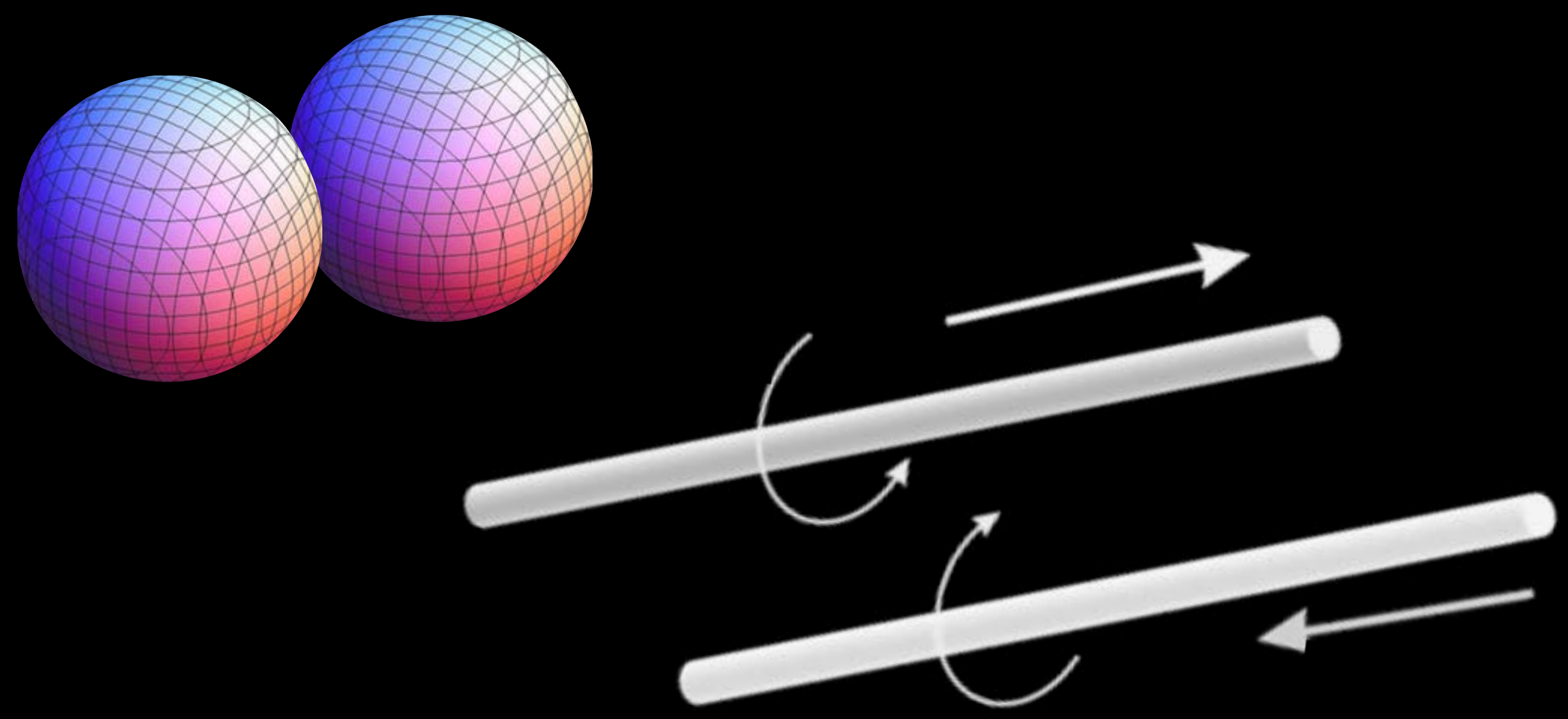
CME search in small systems

p+Pb





Pb+Pb



CMS collaboration, Phys. Rev Lett, 118 (2017) 122301

$$\Delta\gamma^{A+A} = \Delta\gamma^{CME} + k \times \frac{v_2}{N} + \Delta\gamma^{non-flow}$$

$$\Vert \qquad \nparallel \qquad \nparallel \qquad \nparallel$$

$$\Delta\gamma^{p+A} = \cancel{\Delta\gamma^{CME}} + k \times \frac{v_2}{N} + \Delta\gamma^{non-flow}$$

Flow and non-flow contributions are too different, less control and difficult to prove if

$$\Delta\gamma^{CME} = 0$$

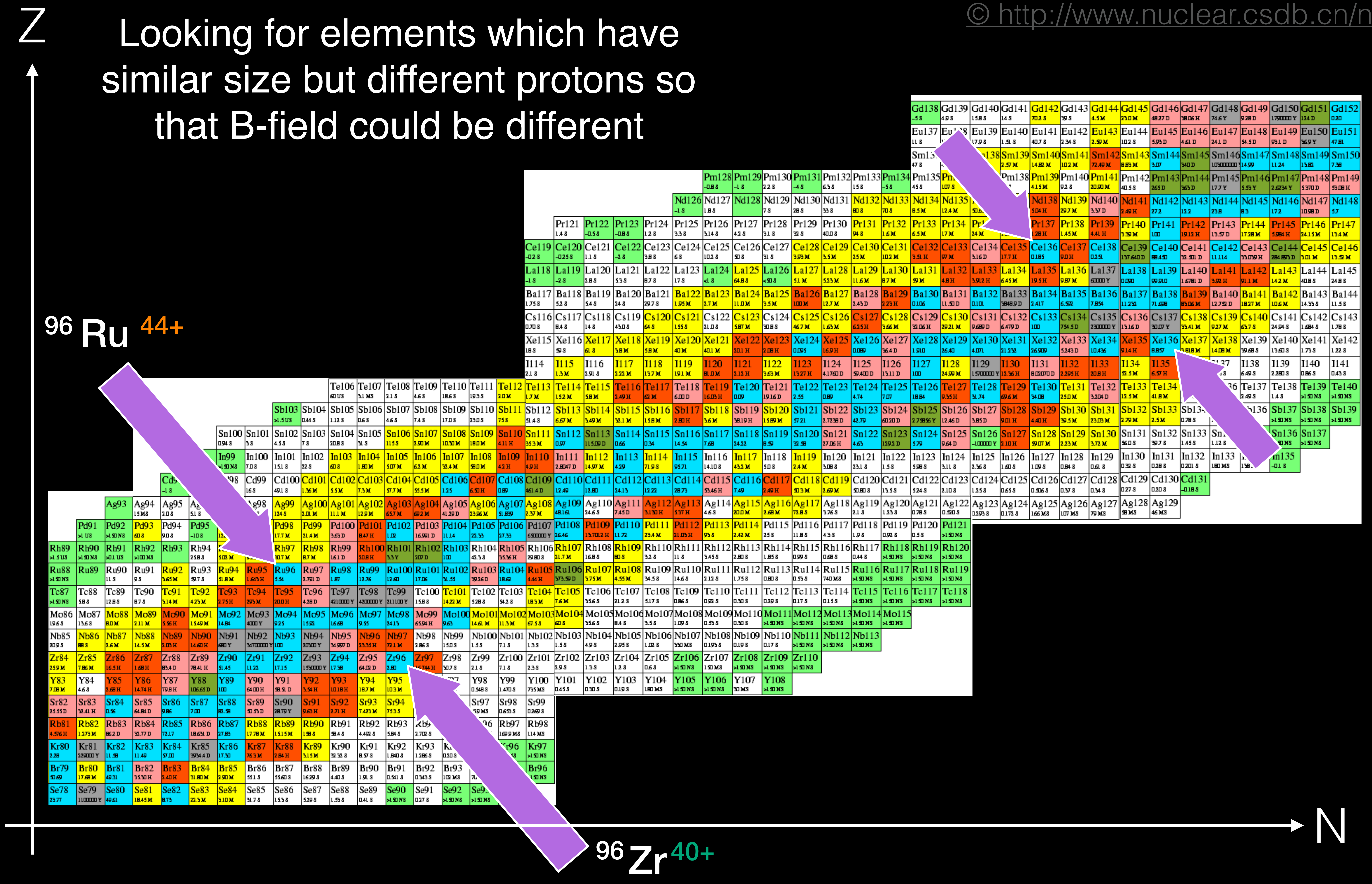
Two systems of very different sizes → limited control over background
This naturally leads to the idea of using two systems of similar sizes

Isobar in the chart of nuclides

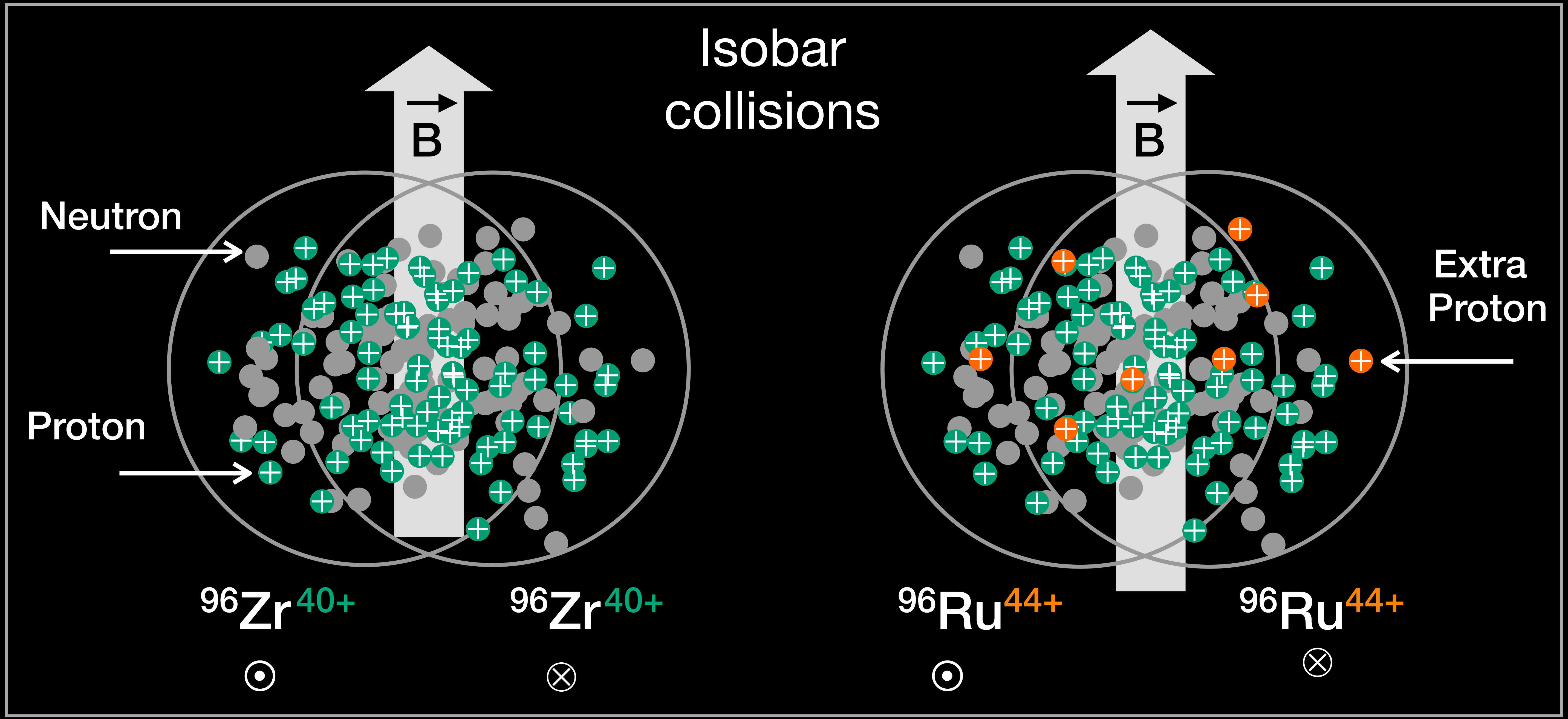
Brookhaven National Laboratory

© http://www.nuclear.csdb.cn/nuclear/chart9.asp

Looking for elements which have similar size but different protons so that B-field could be different



Isobar collisions



Voloshin, Phys.Rev.Lett. 105 (2010) 172301

B-field square is 10-18% larger in Ru+Ru

$$\Delta\gamma^{\text{Ru+Ru}} = \Delta\gamma^{CME} + k \times \frac{v_2}{N} + \Delta\gamma^{non-flow}$$

?? $\quad\quad \neq \quad\quad \approx \quad\quad \parallel$

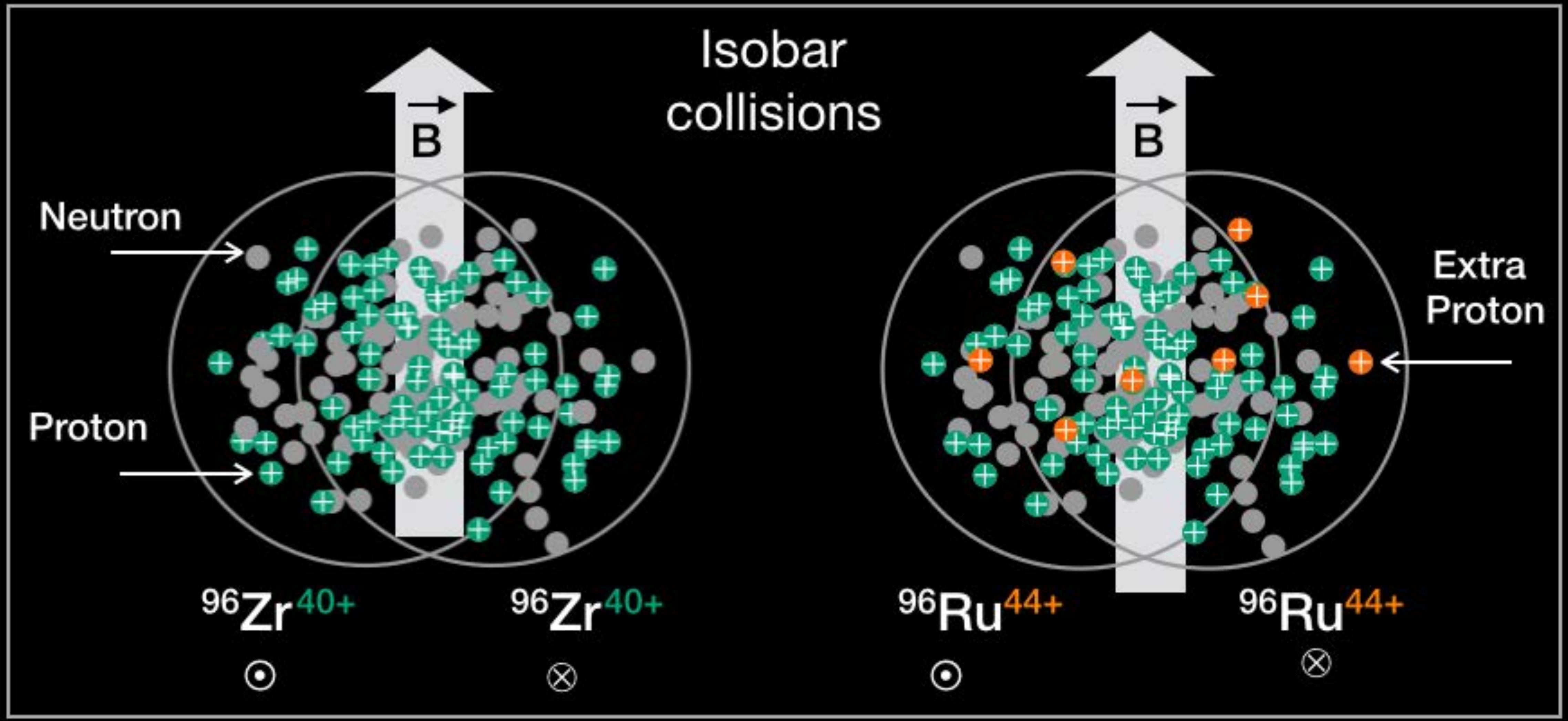
$$\Delta\gamma^{\text{Zr+Zr}} = \Delta\gamma^{CME} + k \times \frac{v_2}{N} + \Delta\gamma^{non-flow}$$

Isobar collisions provide the best possible control of signal and background compared to all previous experiments

$$\boxed{\frac{(\Delta\gamma/v_2)_{\mathrm{Ru+Ru}}}{(\Delta\gamma/v_2)_{\mathrm{Zr+Zr}}} \approx 1 + \underset{\uparrow\ \text{Unknown}}{f_{\mathrm{CME}}^{\mathrm{Zr+Zr}}}\,[\underbrace{(B_{\mathrm{Ru+Ru}}/B_{\mathrm{Zr+Zr}})^2 - 1}_{0.18}]}$$

Modality of the Isobar Run

Isobar collisions



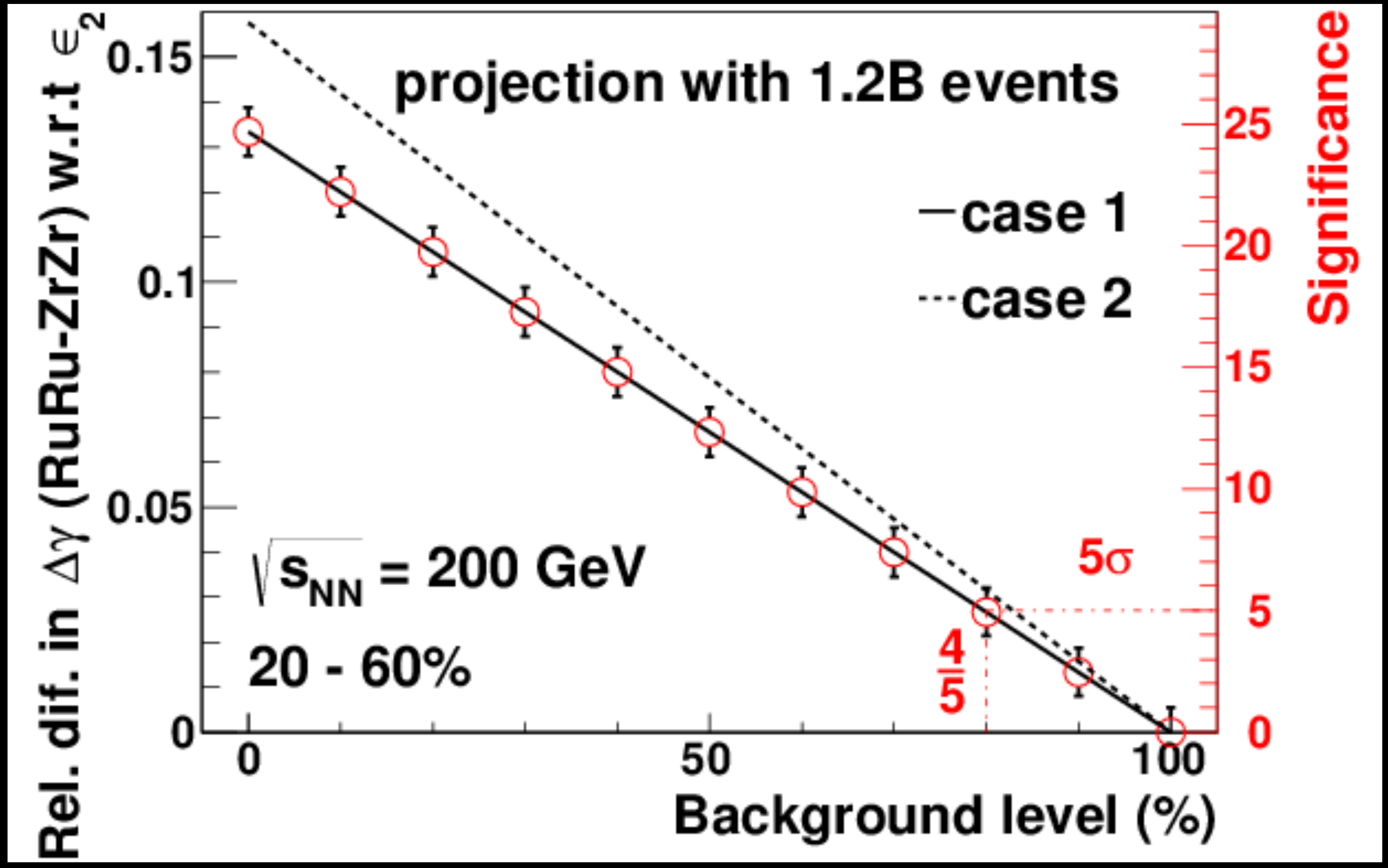
Voloshin, Phys.Rev.Lett. 105 (2010) 172301

B-field square is 10-18% larger in Ru+Ru

$$\frac{(\Delta\gamma/v_2)_{\mathrm{Ru+Ru}}}{(\Delta\gamma/v_2)_{\mathrm{Zr+Zr}}} \approx 1 + \underset{\text{Unknown}}{f_{\mathrm{CME}}^{\mathrm{Zr+Zr}}}\underbrace{[(B_{\mathrm{Ru+Ru}}/B_{\mathrm{Zr+Zr}})^2 - 1]}_{0.18}$$

$$\boxed{> 1 \ (\text{for CME})}$$

https://drupal.star.bnl.gov/STAR/system/files/STAR_BUR_Run1718_v22_0.pdf



$$(1 - f_{\mathrm{CME}}) \times 100\%$$

1.2 B collision events for each species can give 5σ significance for 20% signal level ($f_{CME} \sim 0.2$)

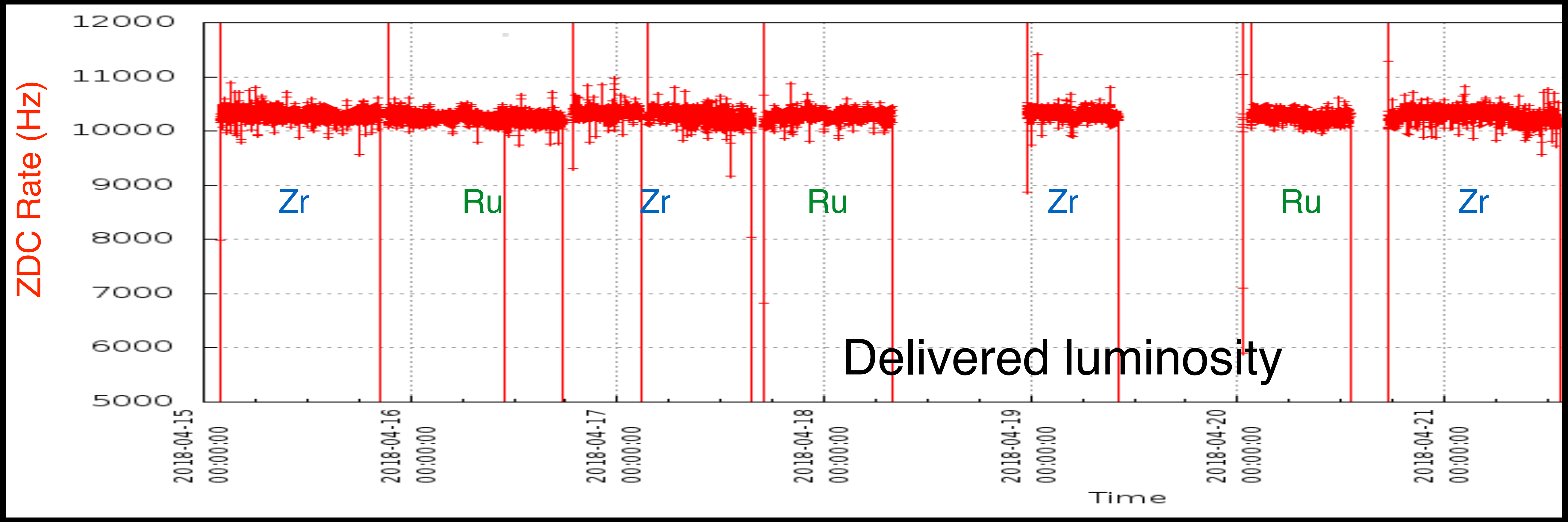
(A precision of 0.5% is needed !!)

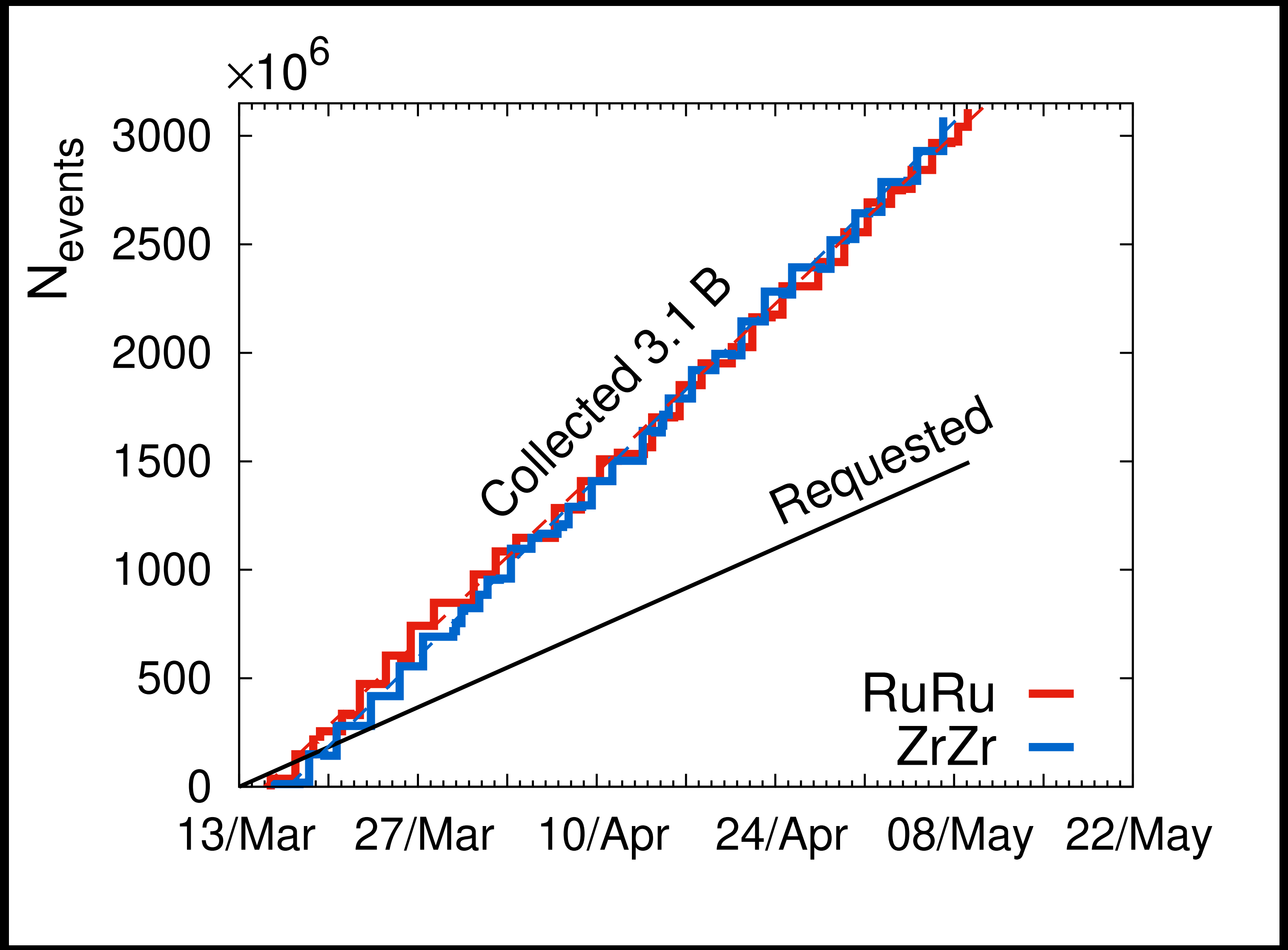
Details Of The Data Taking Of The Isobar Run

G. Marr et al., in 10th International Particle Accelerator Conference (2019) pp. 28–32.

Goal: minimize the systematics in observable ratios, similar run conditions for both species

Two important steps:
1) Fill-by-fill switching
2) Level luminosity



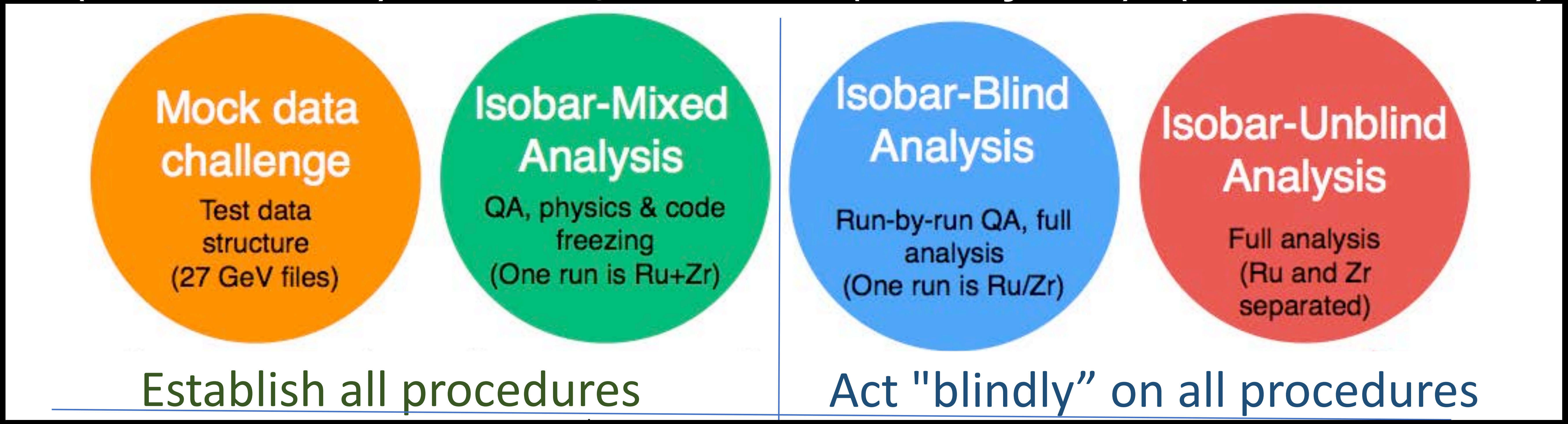


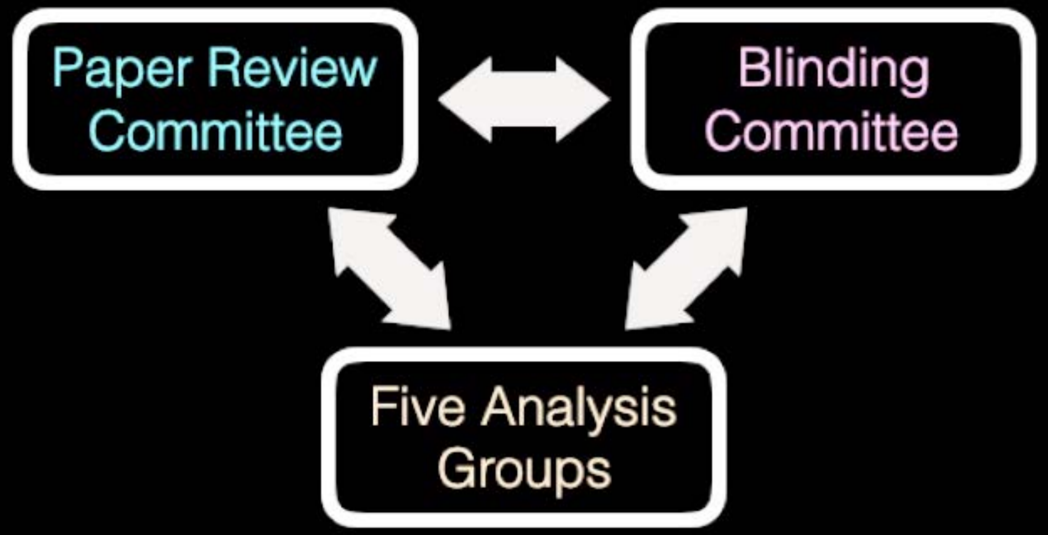
Blind analysis of the isobar data

Steps of Isobar blind analysis

Step-I (~2 months) | Step-II (~1 year) | Step-III (~1/2 year) | Step-IV (~2-3 months)

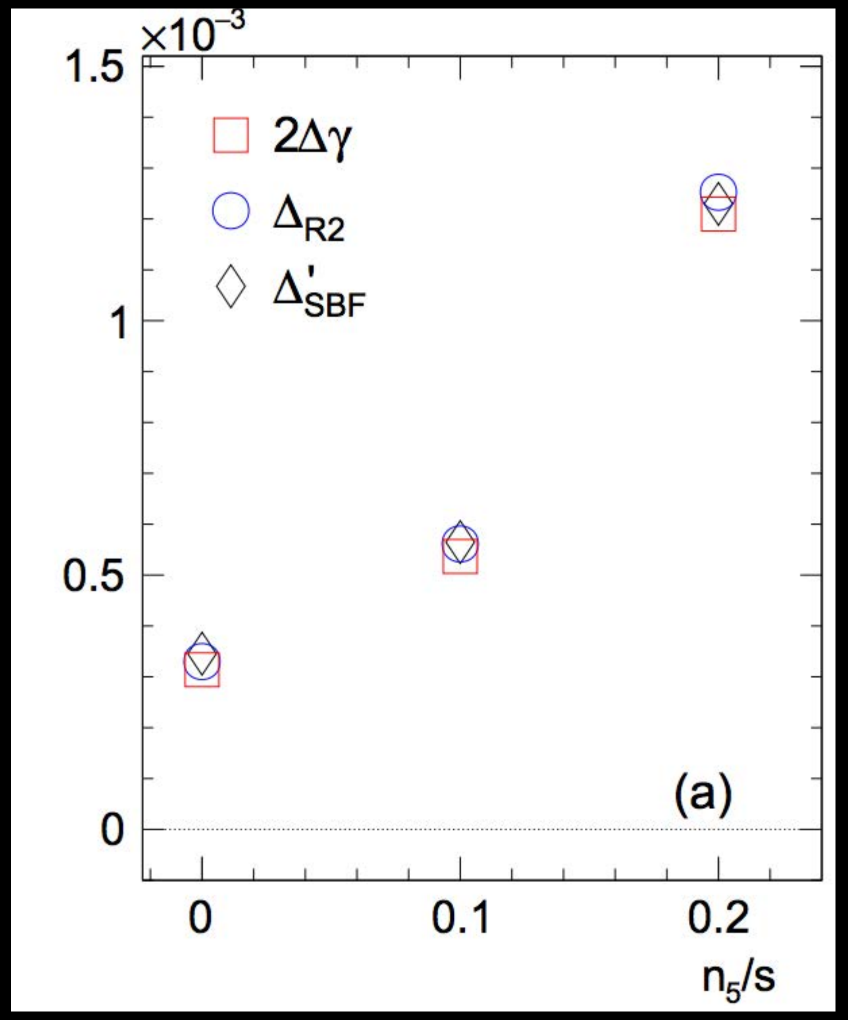
Blind analysis method:
STAR Collaboration
Nucl.Sci.Tech. 32 (2021) 5, 48
arXiv:1911.00596 [nucl-ex]



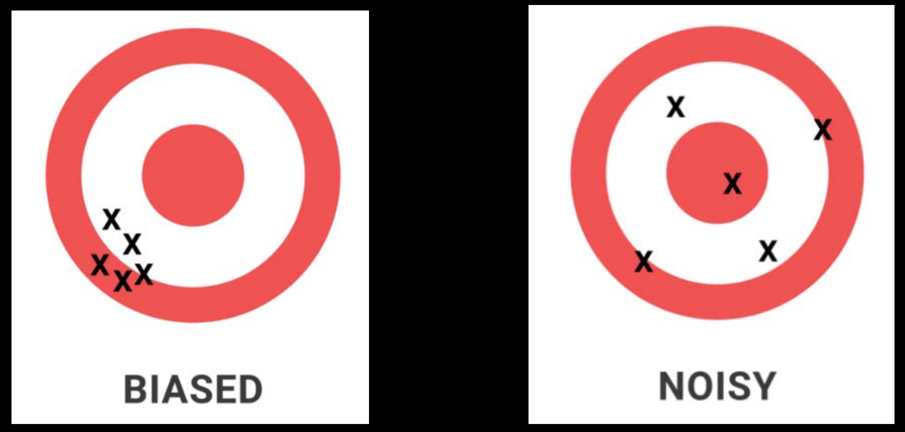


- NPP PAC recommended a blind analysis of isobar data Blinding
- No access to species-specific information before last step
- Everything documented (not written → not allowed)
- Case for CME & interpretation must be pre-defined

Sensitivity of CME observables verified using framework of BEST collaboration
Choudhury et. al. arXiv:2105.06044



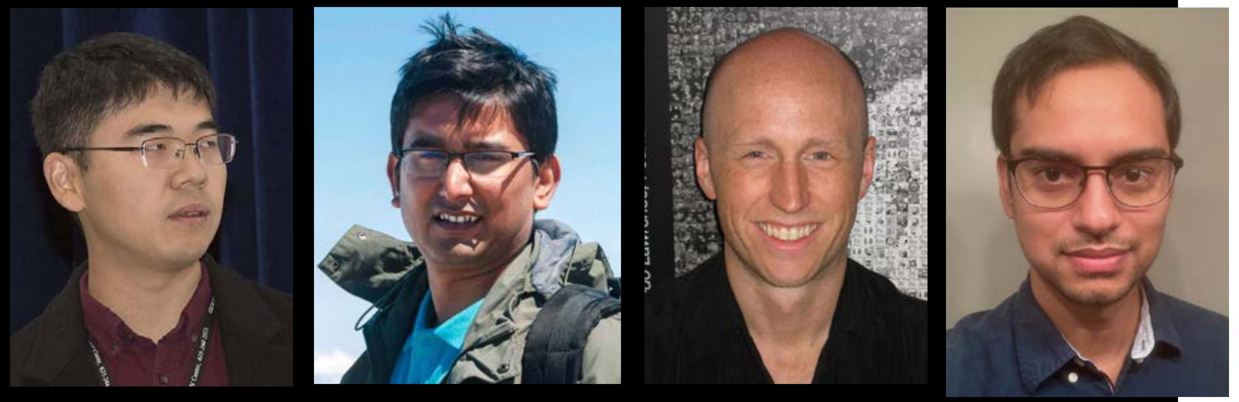
Quality assurance is done by pattern recognition algorithms to remove bias & noise

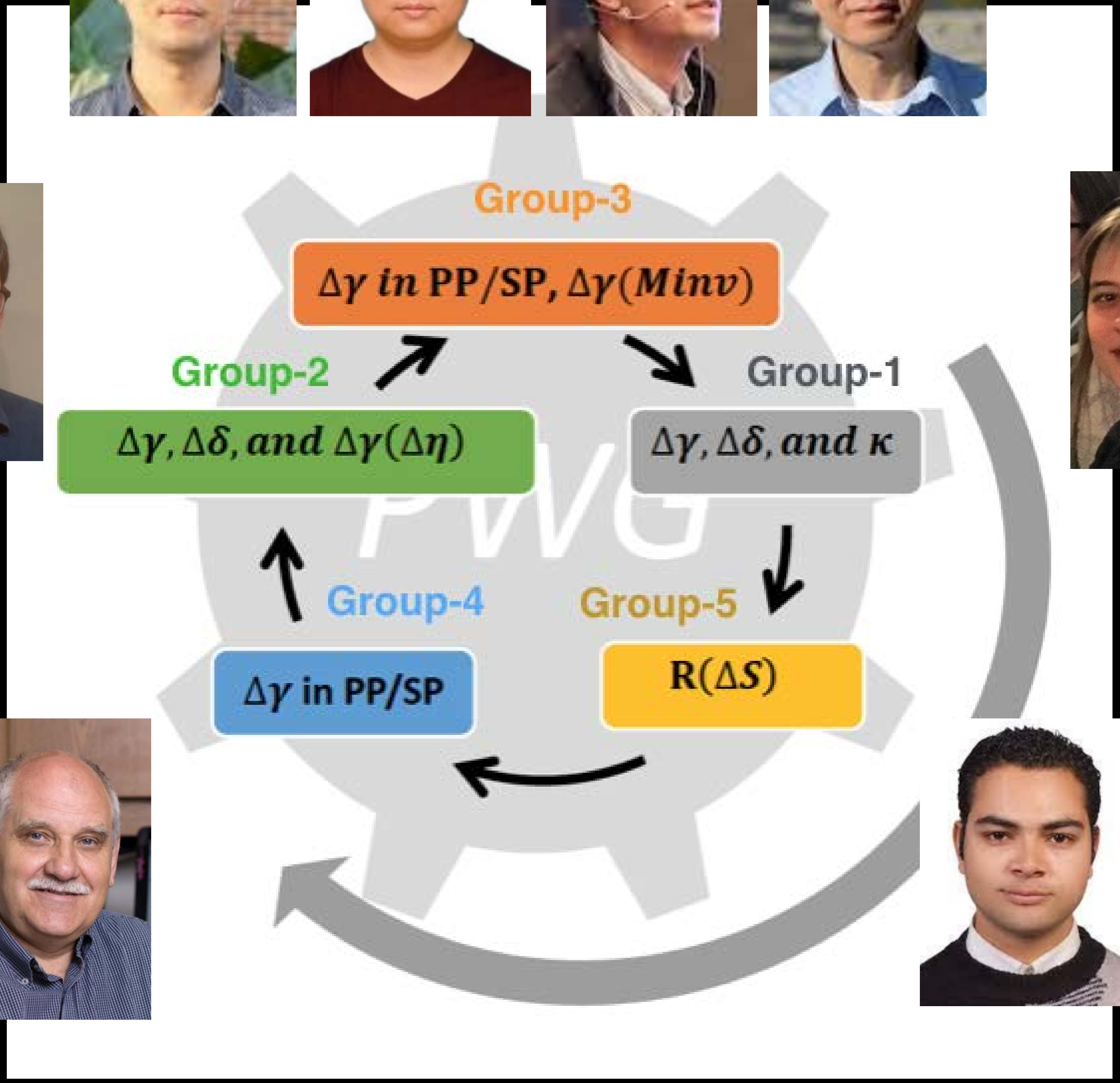


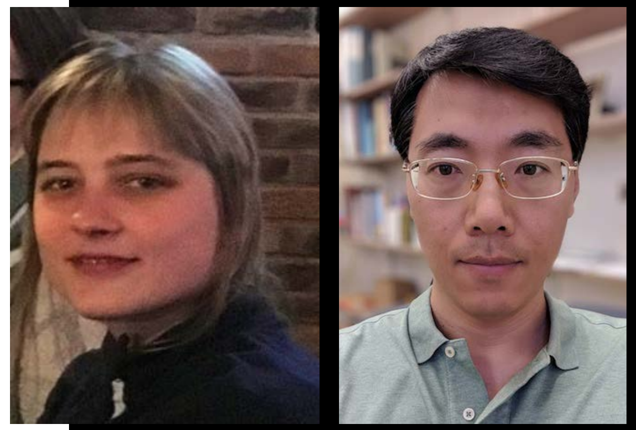
~~Huristics~~ → Algorithms

Five independent groups did isobar blind analysis

Purdue-Huzhou (group-3)
Yicheng Feng, Haojie Xu, Jie Zhao, Fuqiang Wang

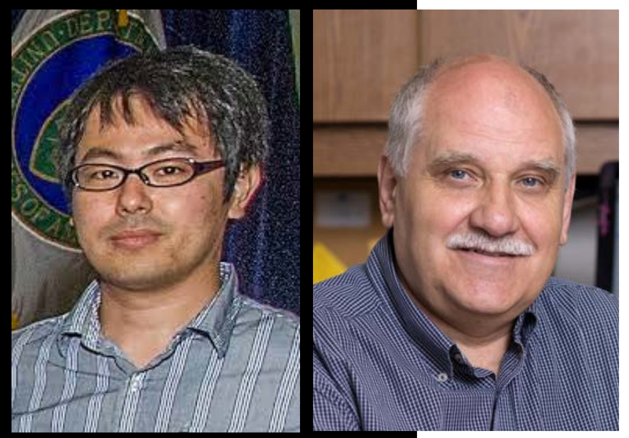






BNL-Fudan (group-2)
Yu Hu, Subikash Choudhury, Paul Sorensen, Prithwish Tribedy

UCLA (group-1)
Maria Sergeeva, Gang Wang



WSU-Tsukuba (group-4)
Takafumi Niida, Sergei Voloshin

SBU-UIC (group-5)
Niseem Magdy, Roy Lacey

Five independent groups will perform analysis, all codes must be frozen and run by another person, results have to directly sent for publication

How the isobar blind analysis was done

Brookhaven National Laboratory

Independent STAR collaborator 1

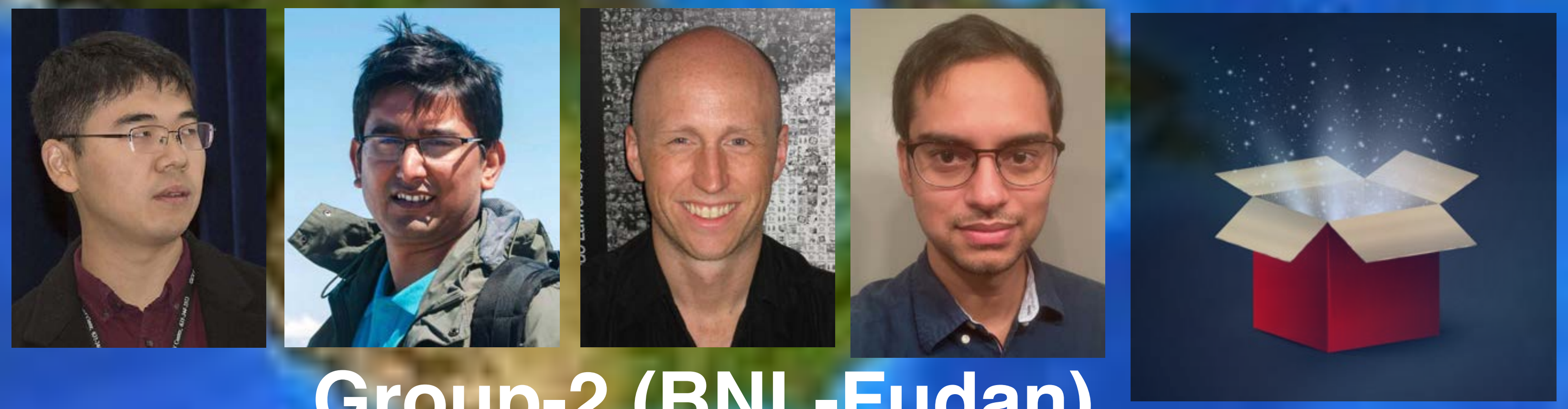
(Moscow)

Independent STAR collaborator 2

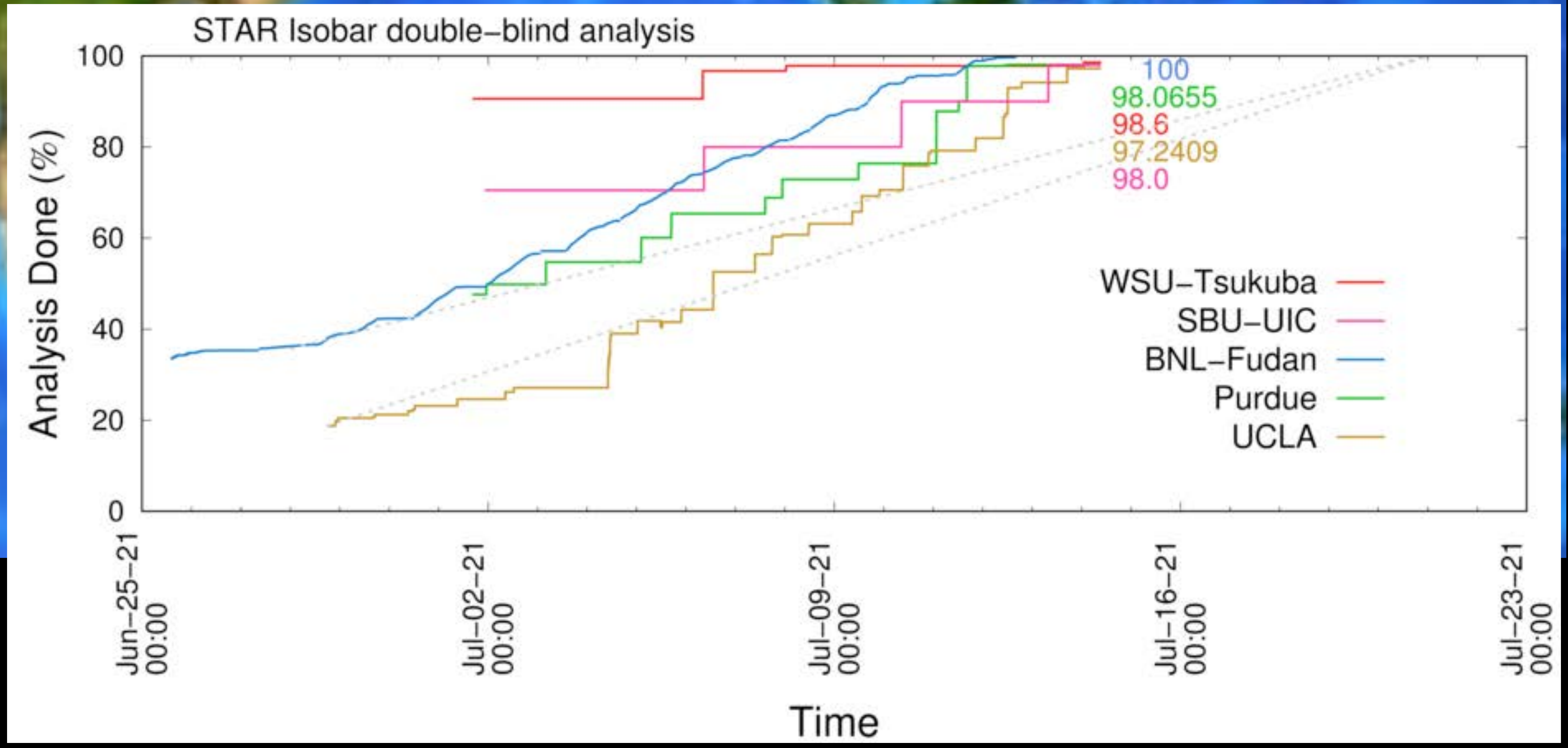
(Tsukuba)

(Ru+Ru)

(Zr+Zr)



Group-2 (BNL-Fudan)



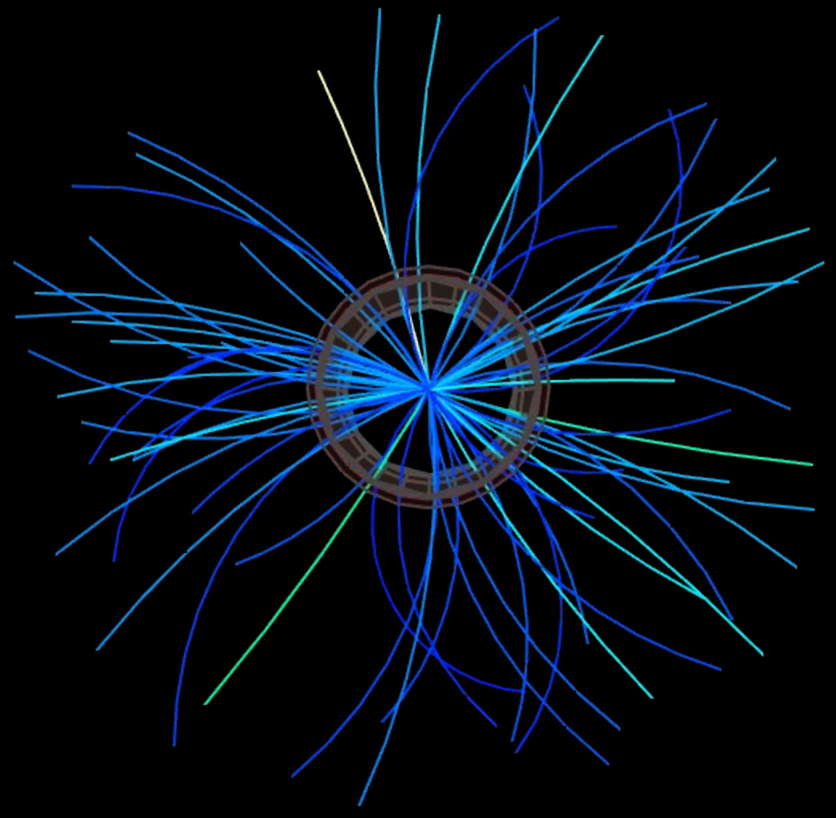
Different people run frozen codes

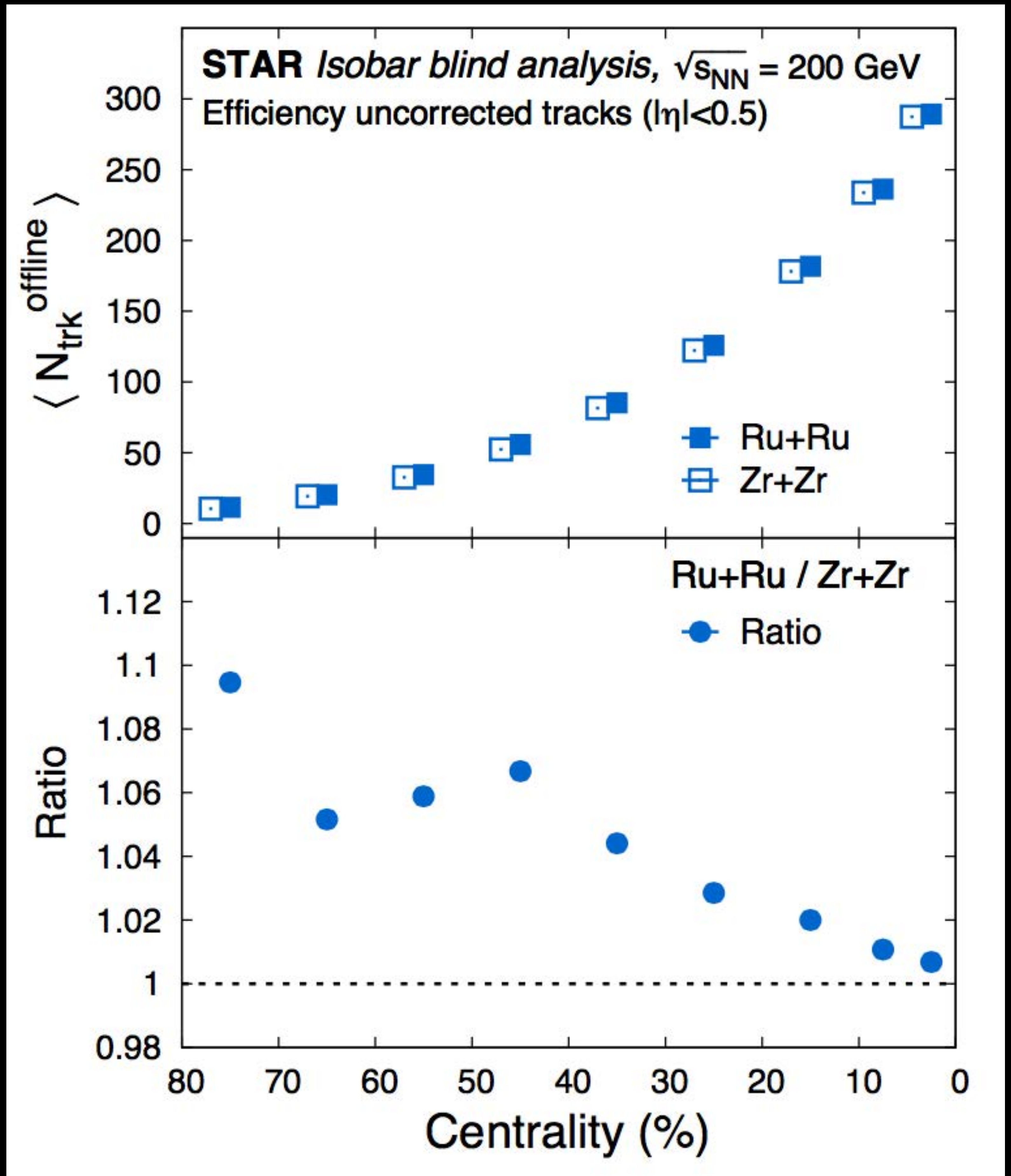
→ Analyzers open box → Directly publish the result

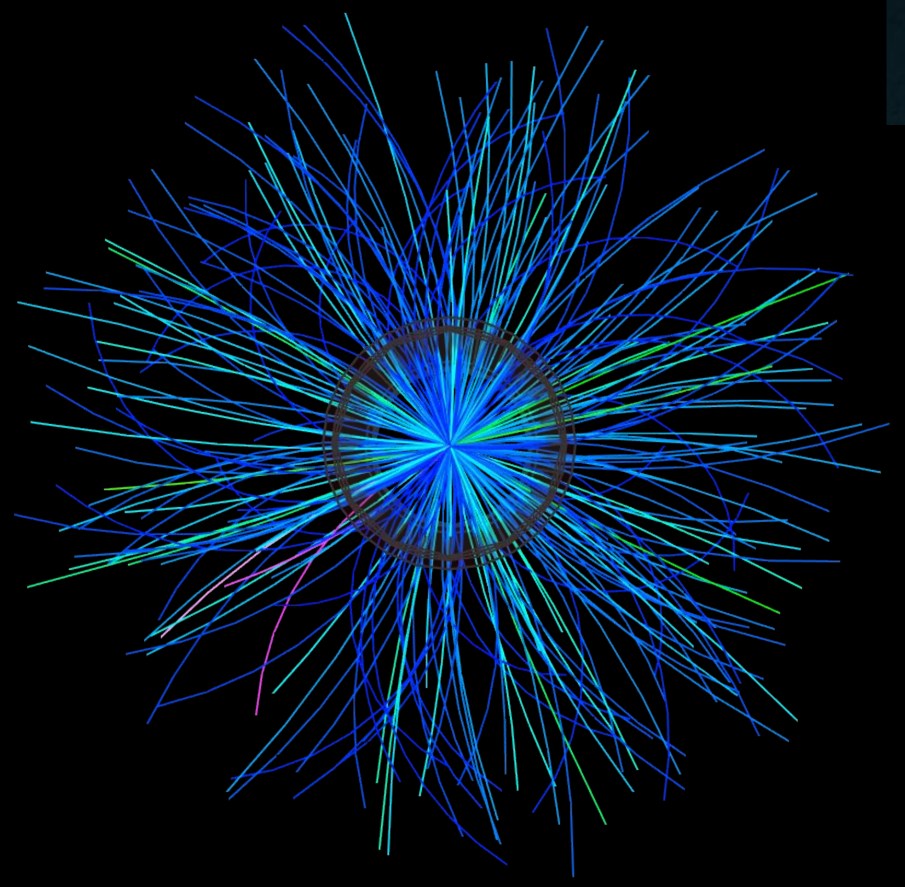
(Took all nodes of RHIC comp. facility for a month)

Results from Isobar blind analysis

Multiplicity difference between the isobars







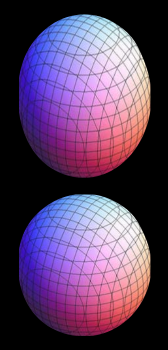
Mean efficiency uncorrected multiplicity density is larger in Ru than in Zr in a matching centrality, this can affects signal and background difference between isobars

Quite unexpected result!!

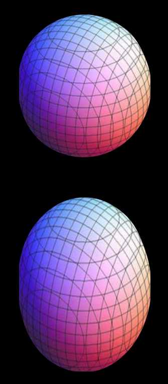
What is the shape of the isobar nuclei?

Blind analysis: we decided to compare observables at same centralities between isobars

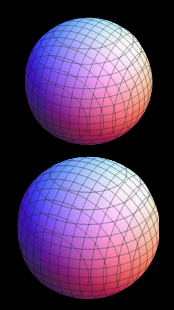
Case-1 [83]			
Nucleus	R (fm)	a (fm)	β_2
$^{96}_{44}$Ru	5.085	0.46	0.158
$^{96}_{40}$Zr	5.02	0.46	0.08

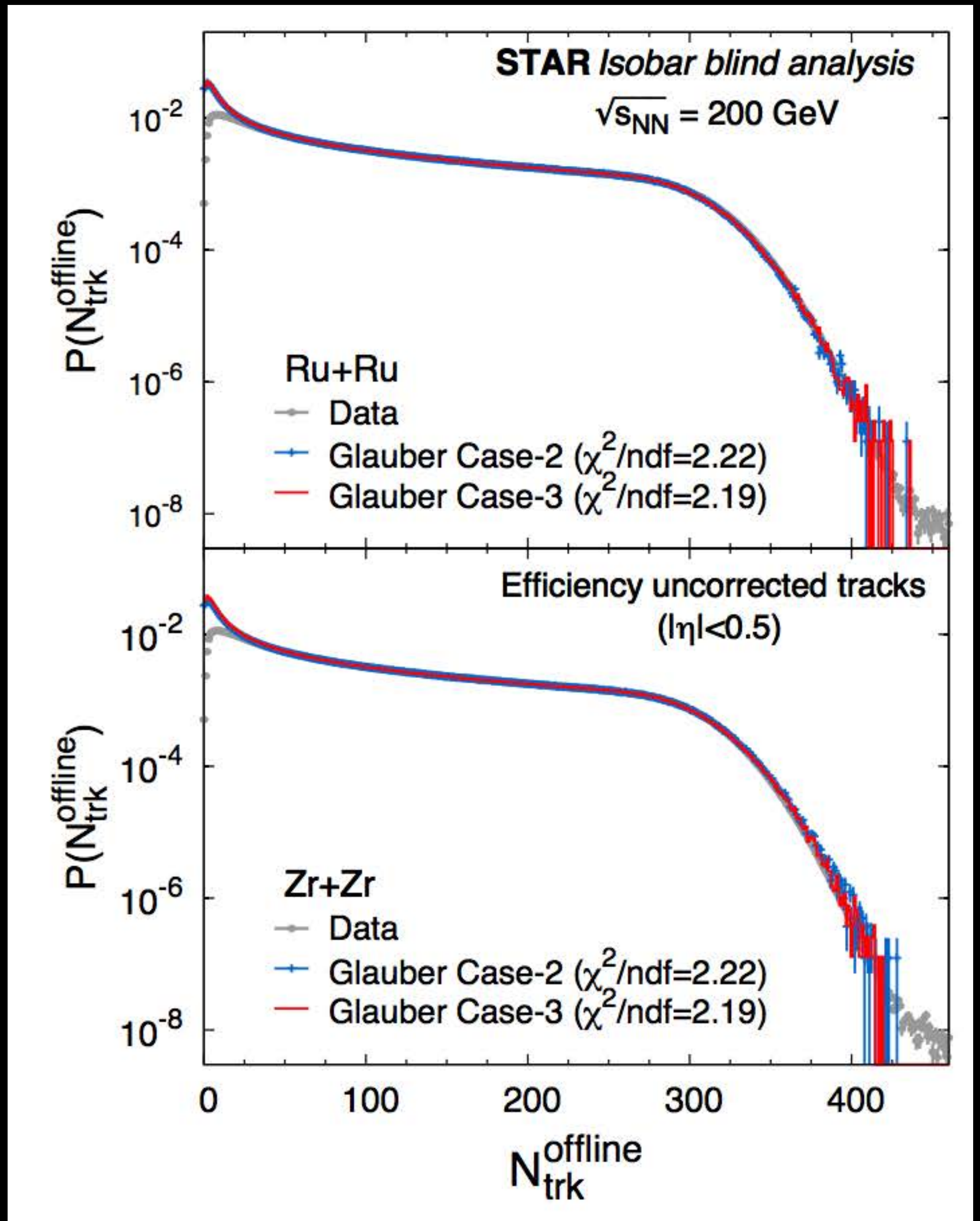


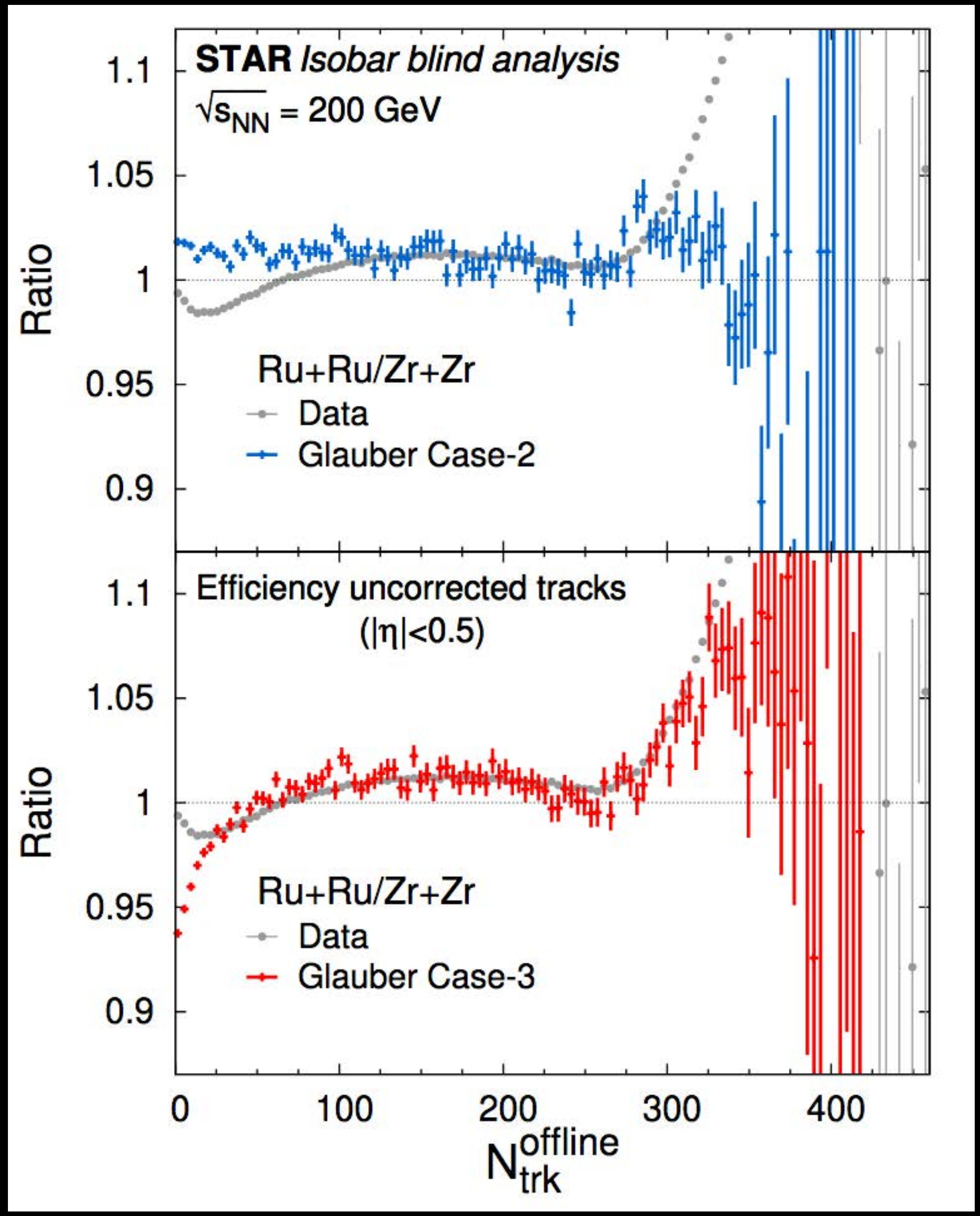
Case-2 [83]			
Nucleus	R (fm)	a (fm)	β_2
$^{96}_{44}$Ru	5.085	0.46	0.053
$^{96}_{40}$Zr	5.02	0.46	0.217



Case-3 [113]			
Nucleus	R (fm)	a (fm)	β_2
$^{96}_{44}$Ru	5.067	0.500	0
$^{96}_{40}$Zr	4.965	0.556	0





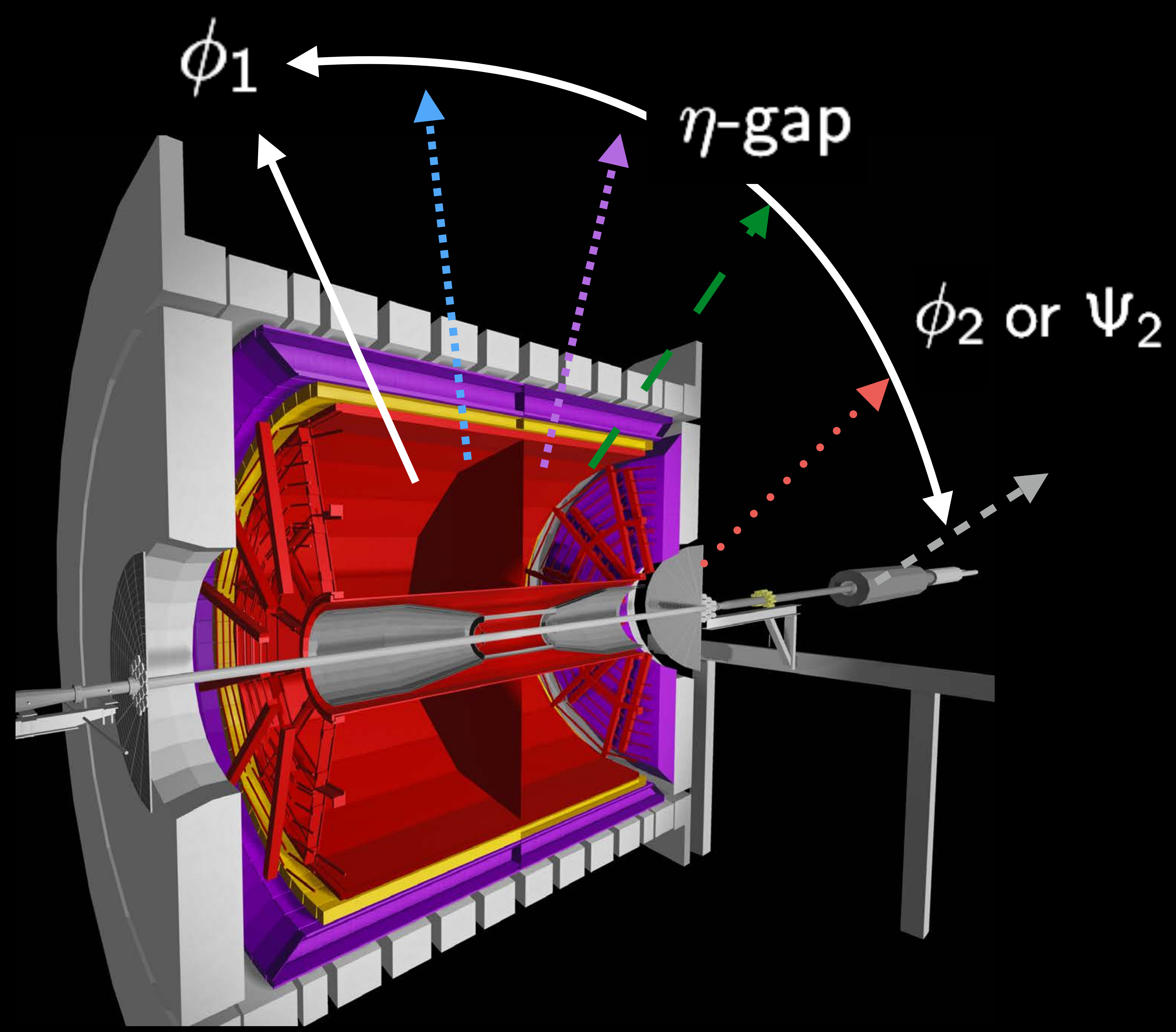


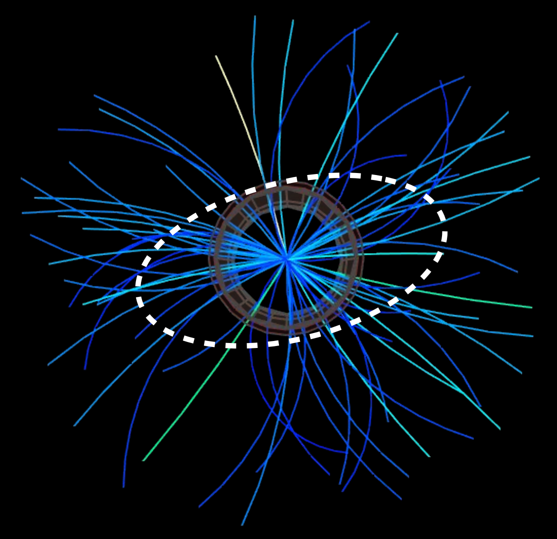
See references in:
Deng et. al., Phys. Rev. C 94, 041901 (2016), arXiv:1607.04697 [nucl-th].
Xu et. al., Phys. Rev. Lett. 121, 022301 (2018), arXiv:1710.03086 [nucl-th].

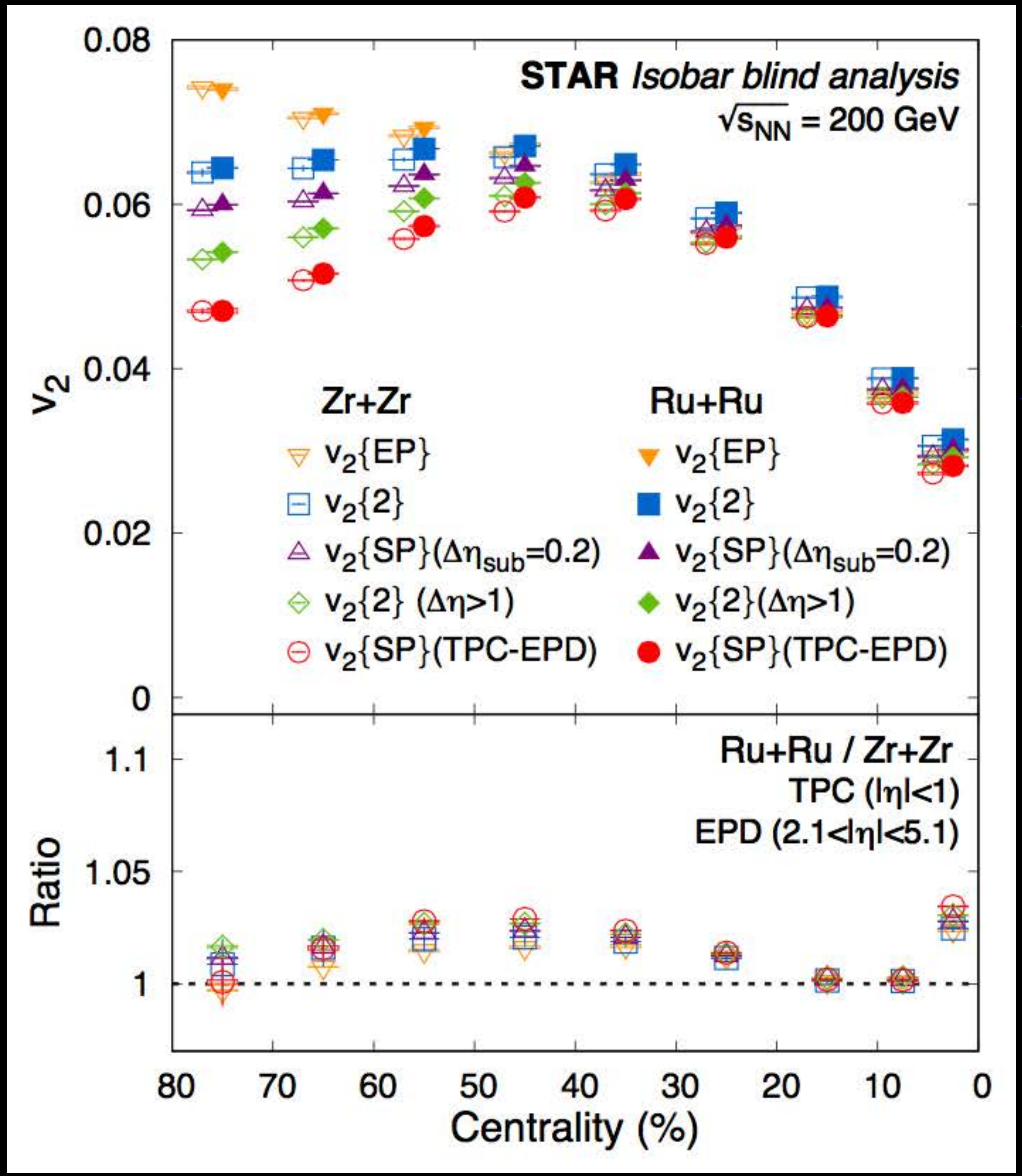
MC-Glauber with two-component model used to describe uncorrected multiplicity distribution. WS parameters with no deformation (thinker neutron skin in Zr) provides the best description of the multiplicity distributions

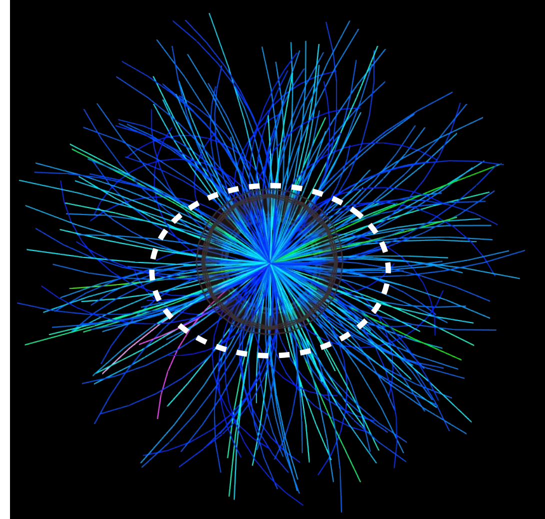
Elliptic anisotropy

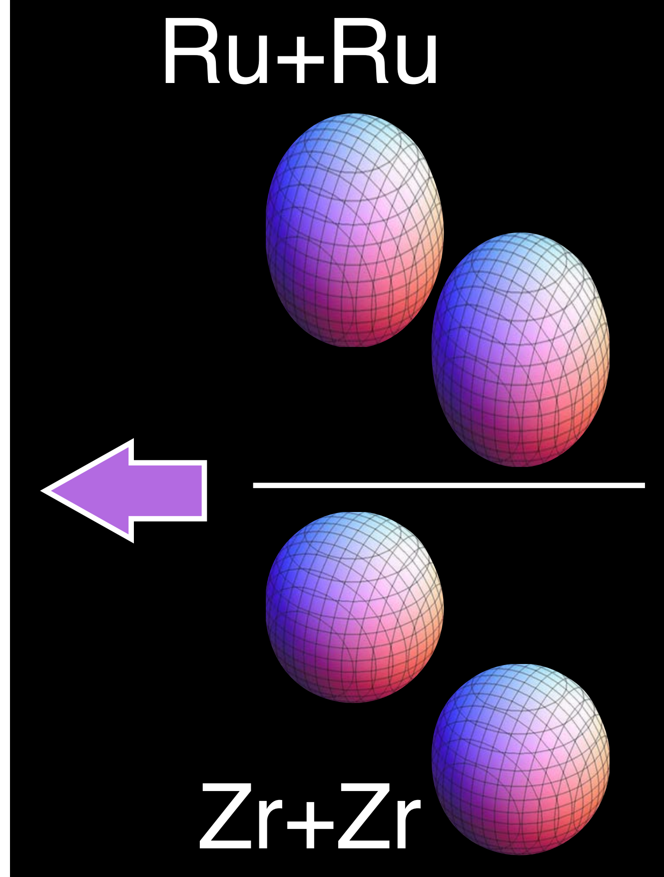
$$v_2\{EP\} = \langle \cos(2\phi_1 - 2\Psi_2) \rangle$$







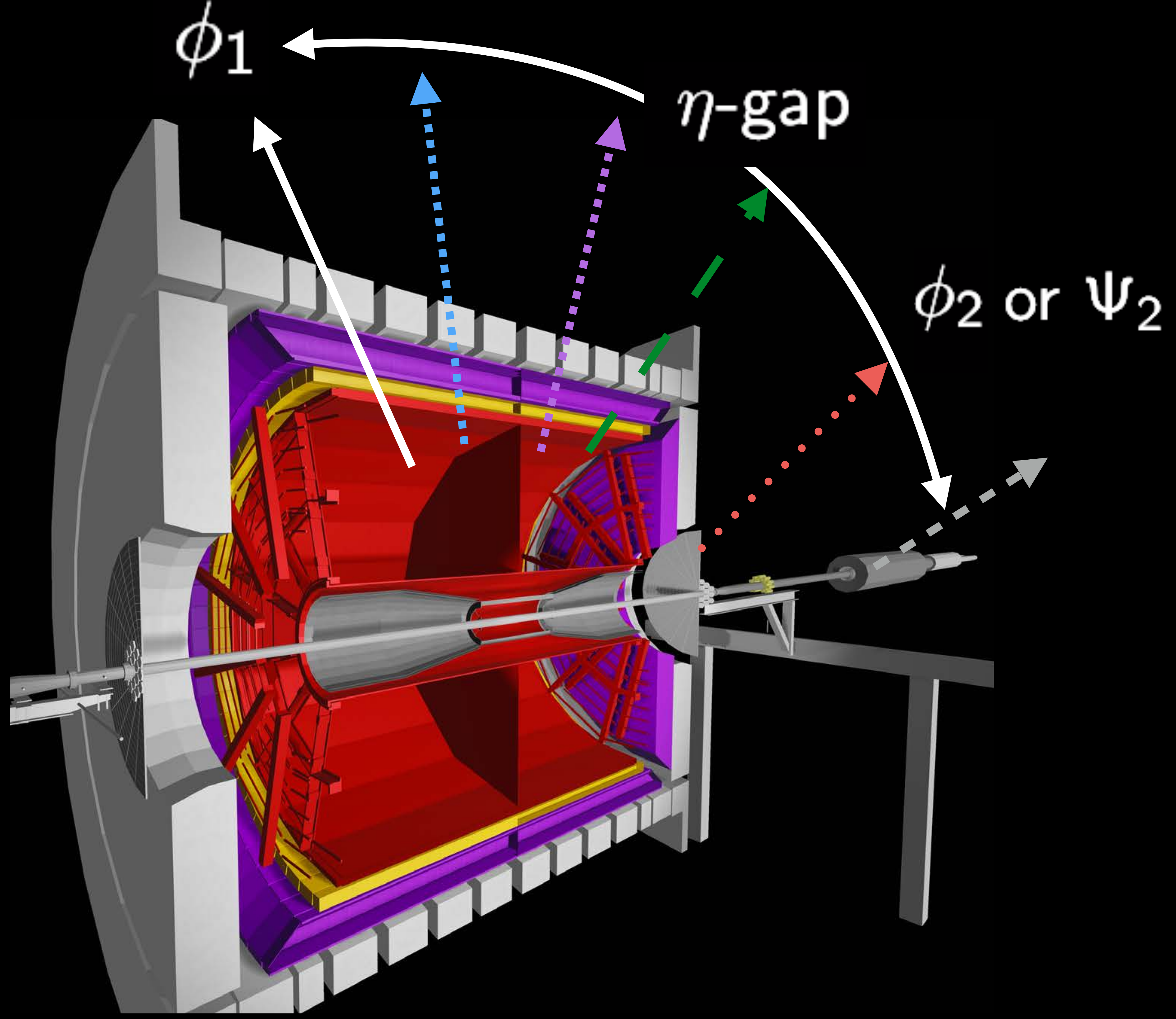


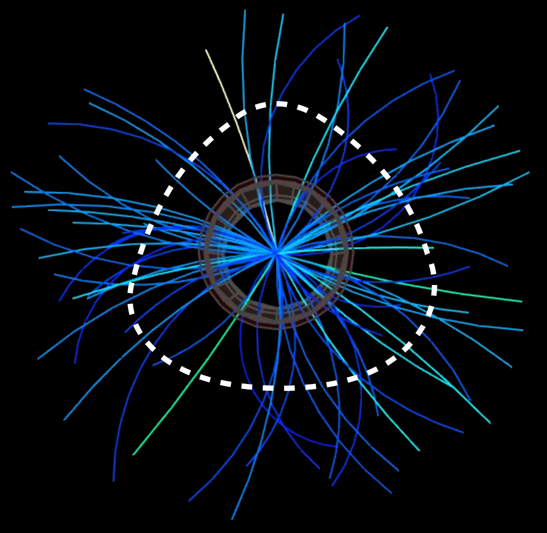


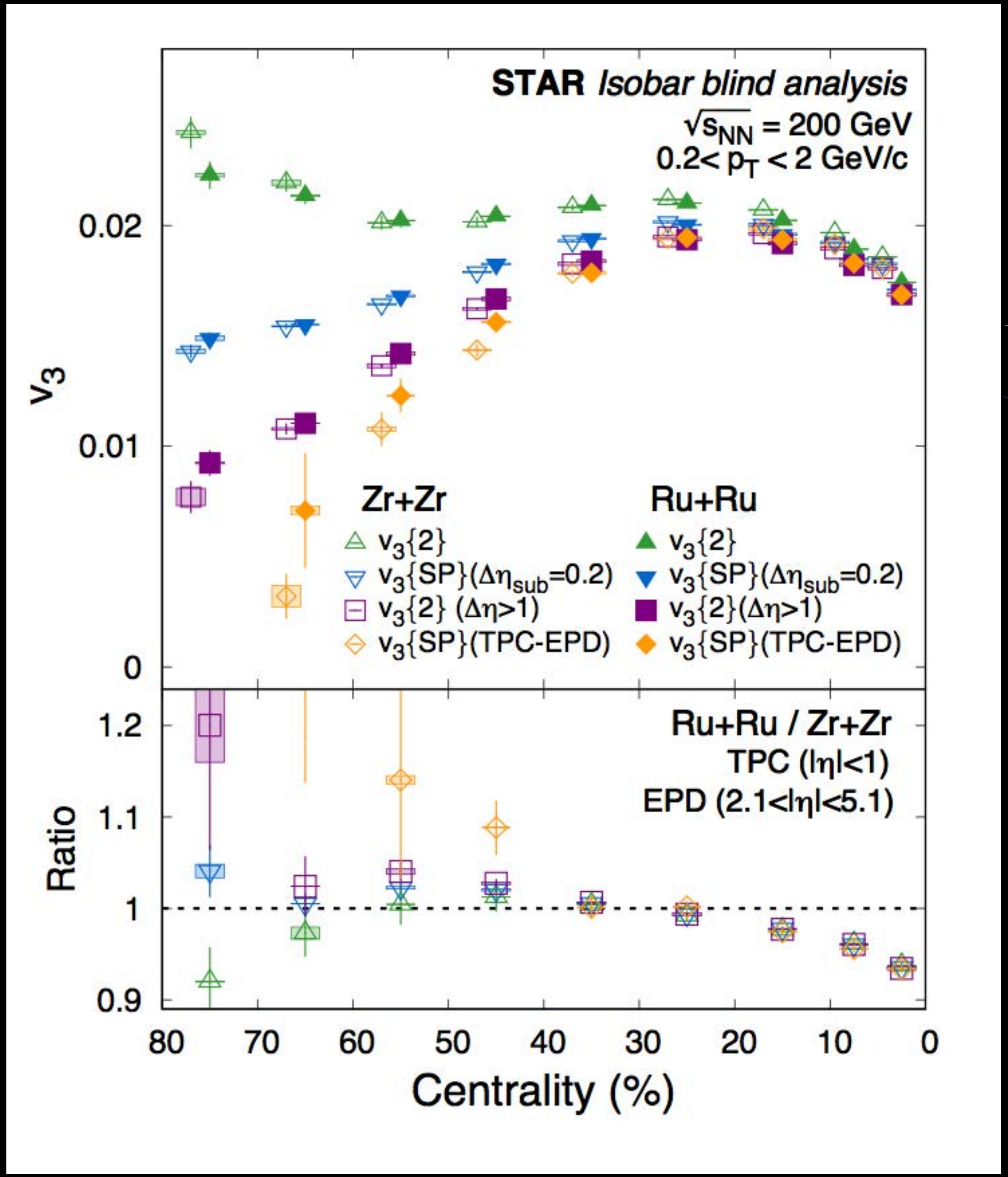
v_2 studied η-gap, ratio deviates from unity indicating difference in the shape, nuclear structure between two isobars (larger quadruple deformation in Ru+Ru)

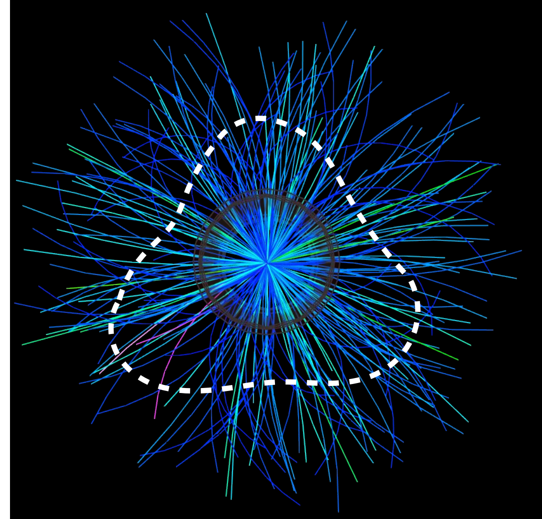
Elliptic anisotropy

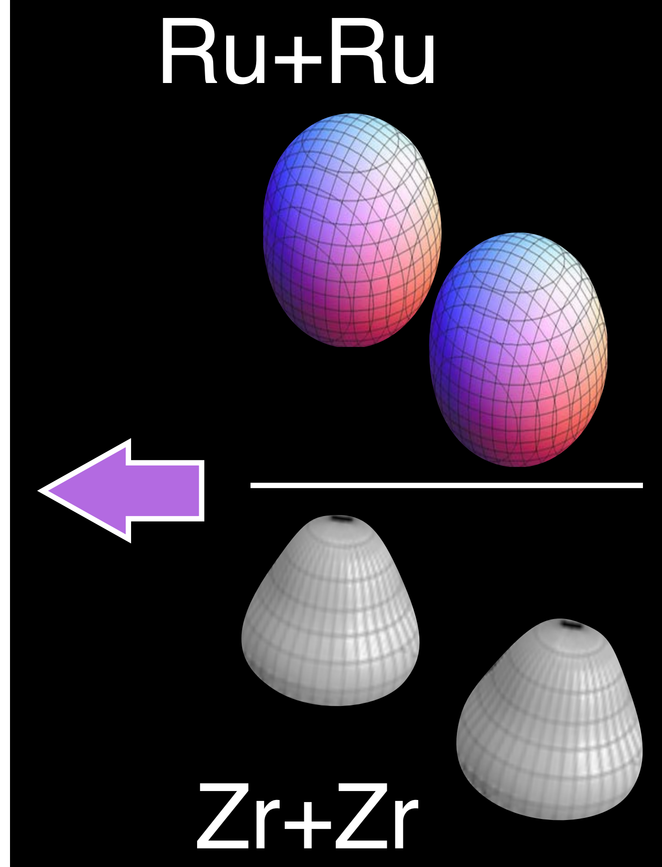
$$v_3\{2\}^2 = \langle \cos(3\phi_1 - 3\phi_2) \rangle$$









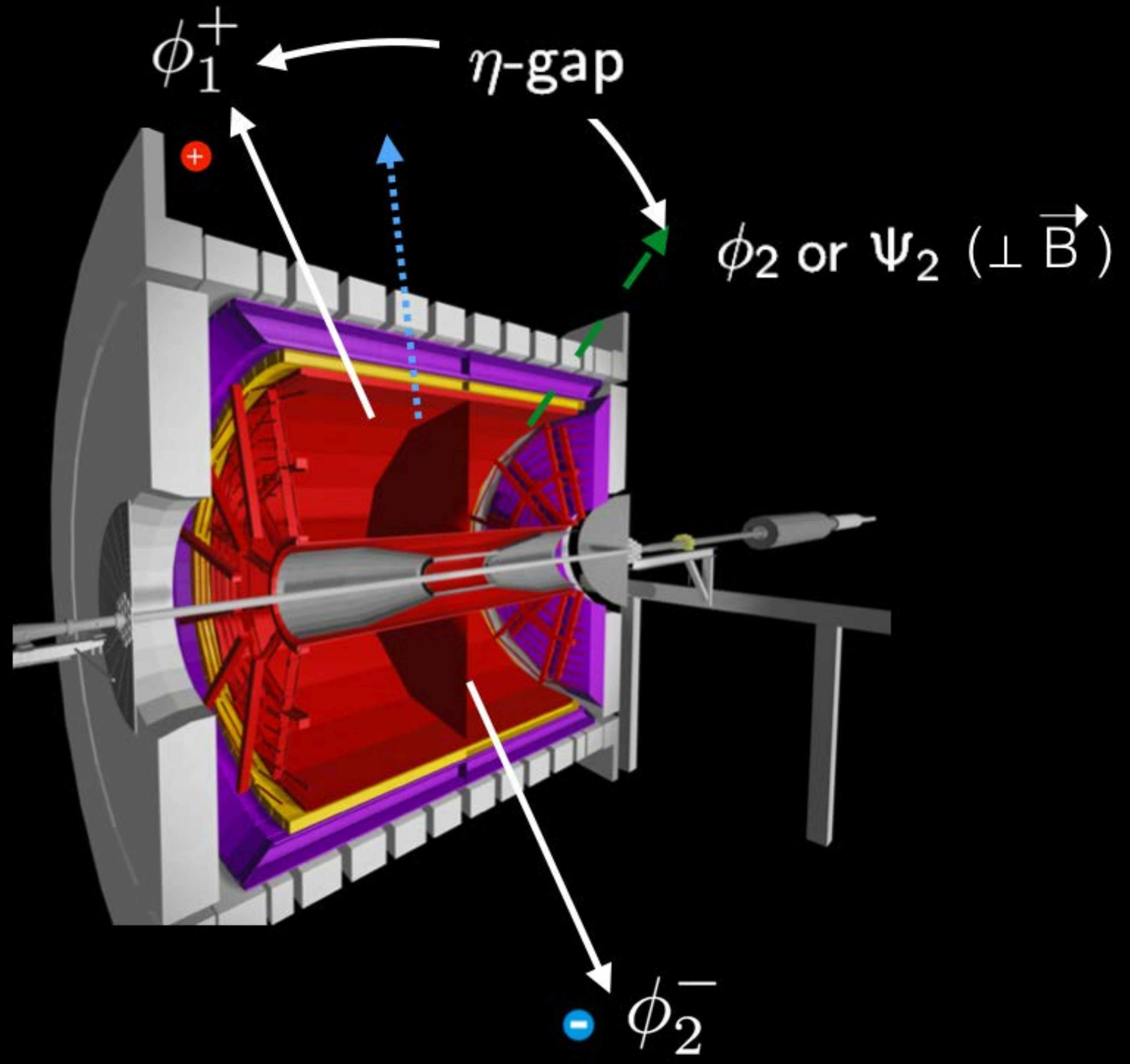


v_2 studied η-gap, ratio deviates from unity indicating difference in the shape, nuclear structure between two isobars (larger octupole deformation in Zr+Zr)

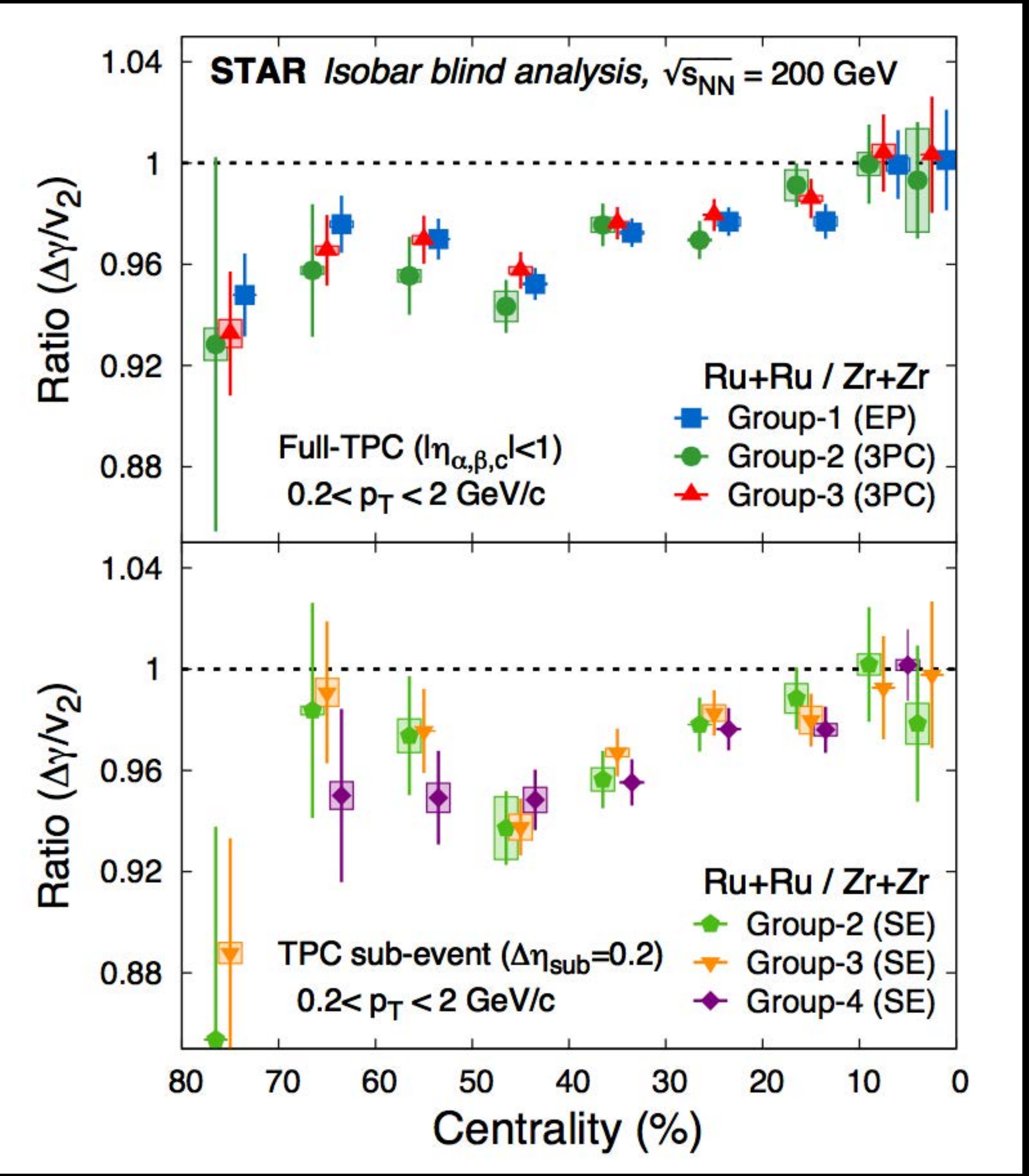
CME sensitive observables

Charge separation scaled by elliptic flow

$$\gamma_{112}\{\mathrm{EP}\} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2^{\mathrm{TPC}}) \rangle$$



$$\frac{(\Delta\gamma/v_2)_{\mathrm{Ru+Ru}}}{(\Delta\gamma/v_2)_{\mathrm{Zr+Zr}}} \approx 1 + \underset{\substack{\uparrow \\ \text{Unknown}}}{f_{\mathrm{CME}}^{\mathrm{Zr+Zr}}} \underbrace{[(B_{\mathrm{Ru+Ru}}/B_{\mathrm{Zr+Zr}})^2 - 1]}_{0.18}$$

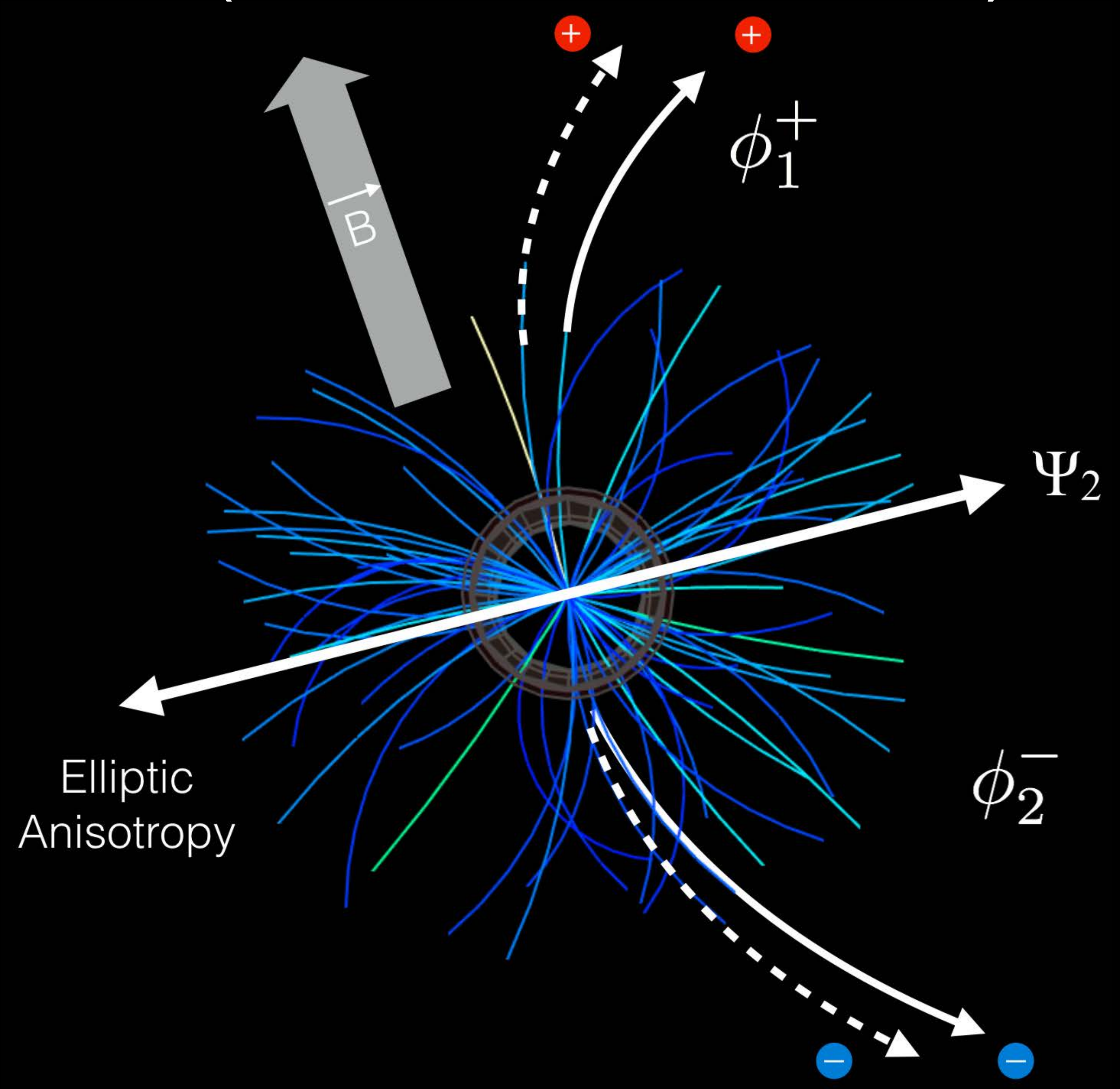


Pre-defined criteria for CME

$$\frac{(\Delta\gamma/v_2)_{\mathrm{RuRu}}}{(\Delta\gamma/v_2)_{\mathrm{ZrZr}}} > 1$$ NOT seen!!

Experimental baseline-1: Randomize correlation with B-field

Charge separation across Ψ_2 plane (correlated to B-field)



$$\gamma_{112} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2) \rangle$$

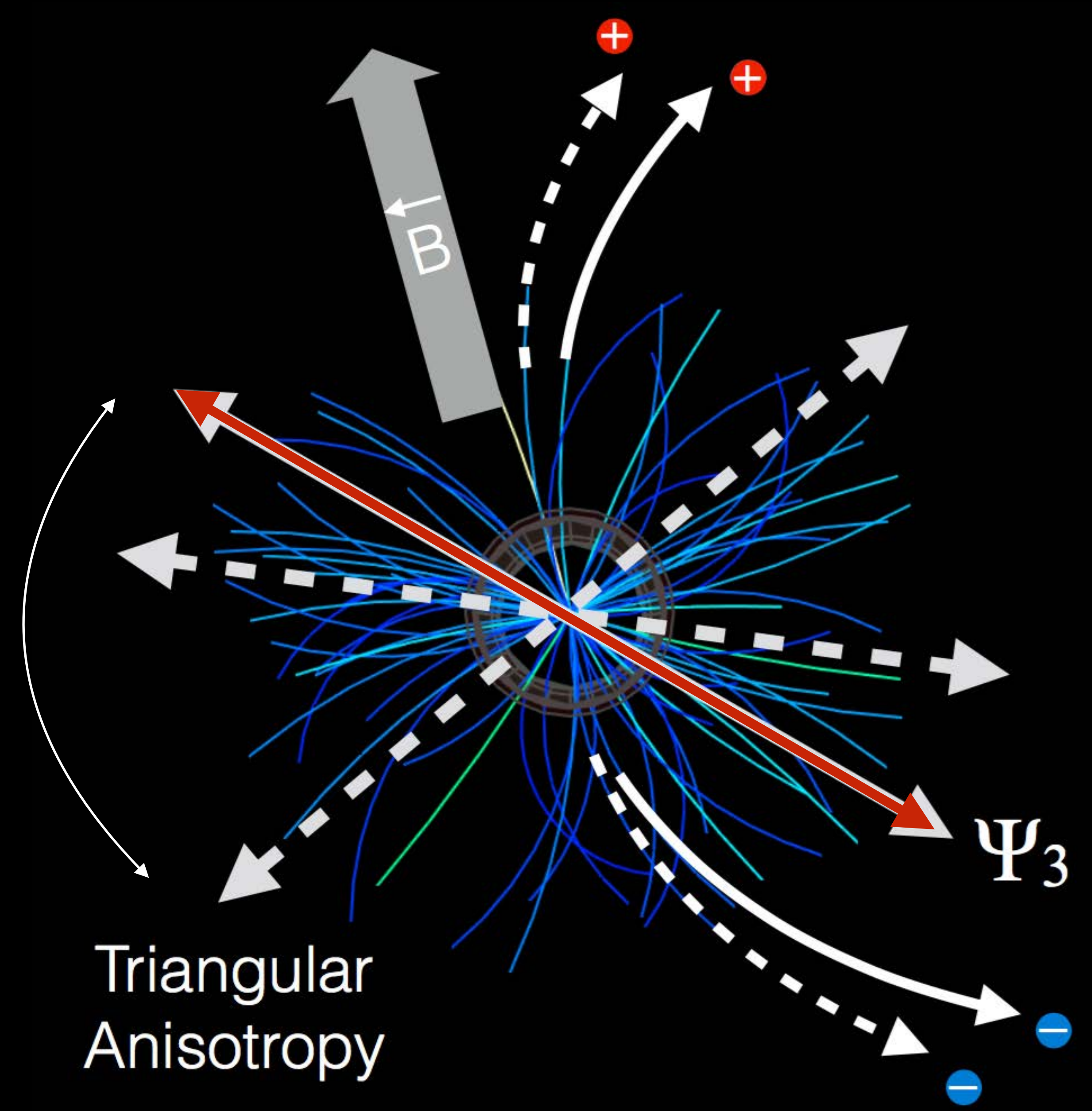
Signal (B-field) + Background ($\propto v_2$)

Old criterion for CME:

$$\frac{(\Delta\gamma/v_2)_{\mathrm{RuRu}}}{(\Delta\gamma/v_2)_{\mathrm{ZrZr}}} > 1$$

$\Longleftrightarrow$

Charge separation across Ψ_3 plane (NOT correlated to B-field)



$$\gamma_{123} = \langle \cos(\phi_\alpha + 2\phi_\beta - 3\Psi_3) \rangle$$

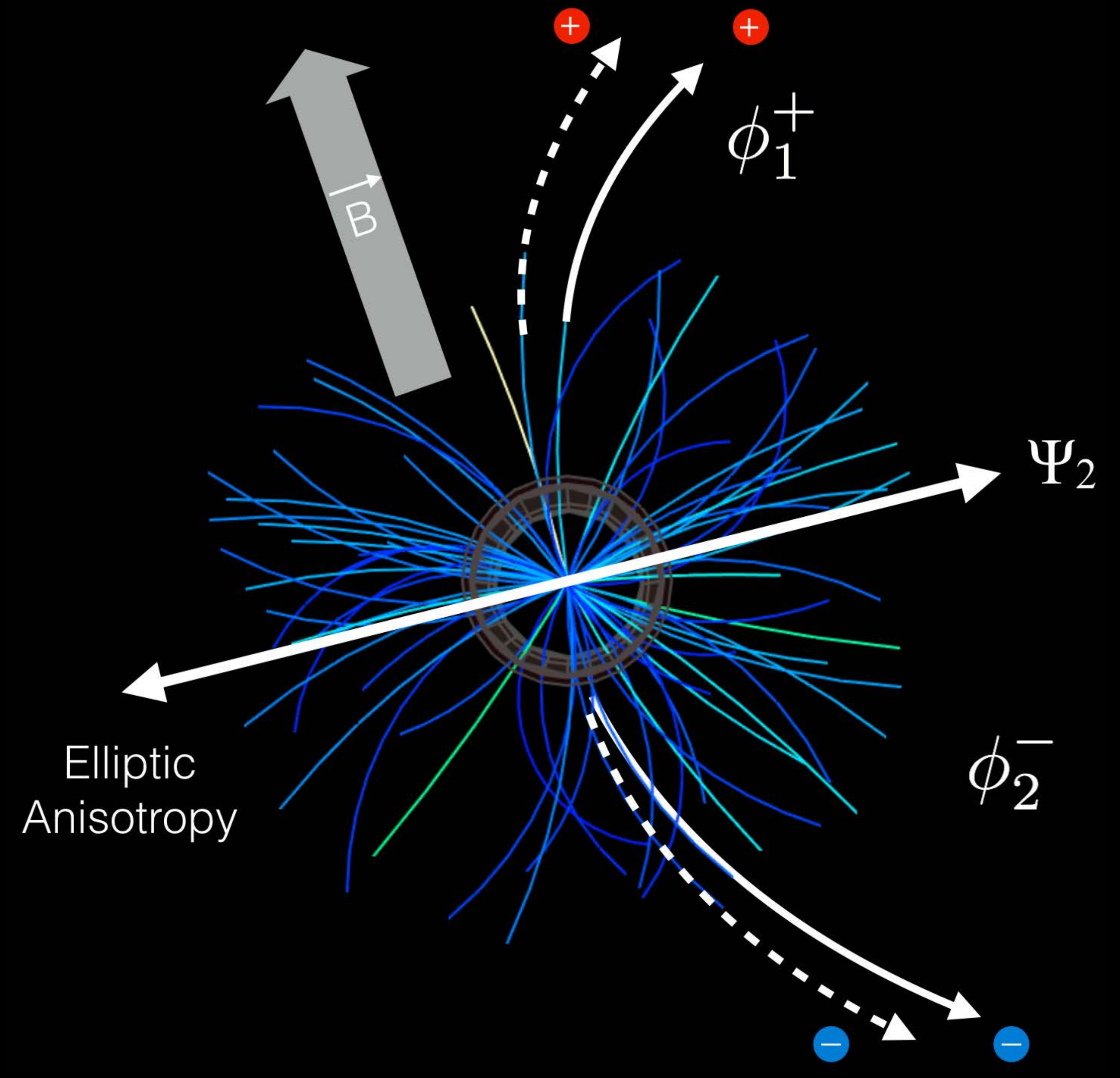
Background only ($\propto v_3$)

New criterion for CME:

$$\frac{(\Delta\gamma_{112}/v_2)^{RuRu}}{(\Delta\gamma_{112}/v_2)^{ZrZr}} > \frac{(\Delta\gamma_{123}/v_3)^{RuRu}}{(\Delta\gamma_{123}/v_3)^{ZrZr}}$$

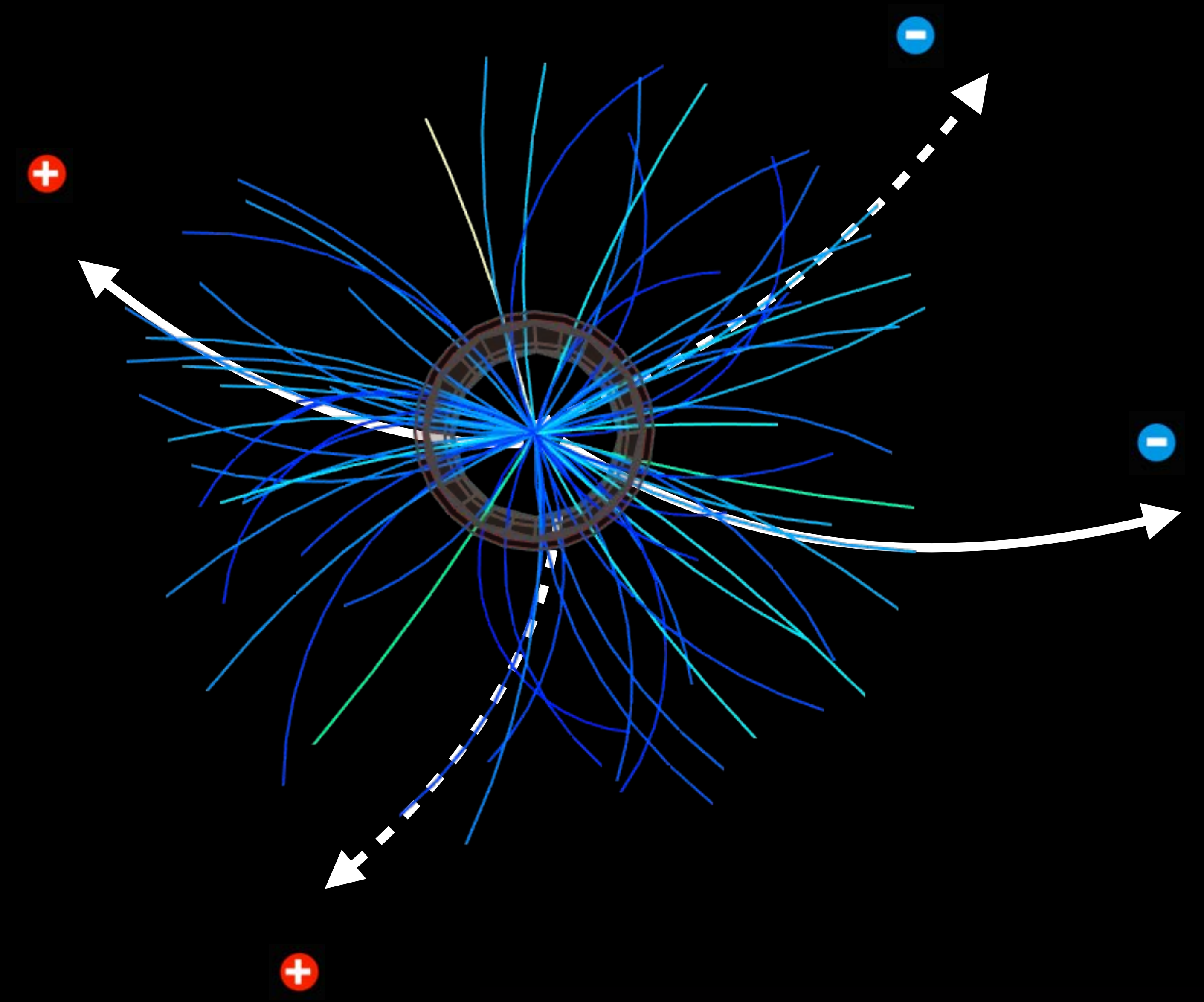
Experimental baseline-2: Ignore B-field direction

Charge separation correlated to event plane



$\Longleftrightarrow$

Charge separation NOT requiring correlation to event plane



$$\delta \equiv \langle \cos(\phi_\alpha - \phi_\beta) \rangle$$

$$\Delta\delta = \delta(OS) - \delta(SS)$$

$$\gamma_{112} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2) \rangle$$

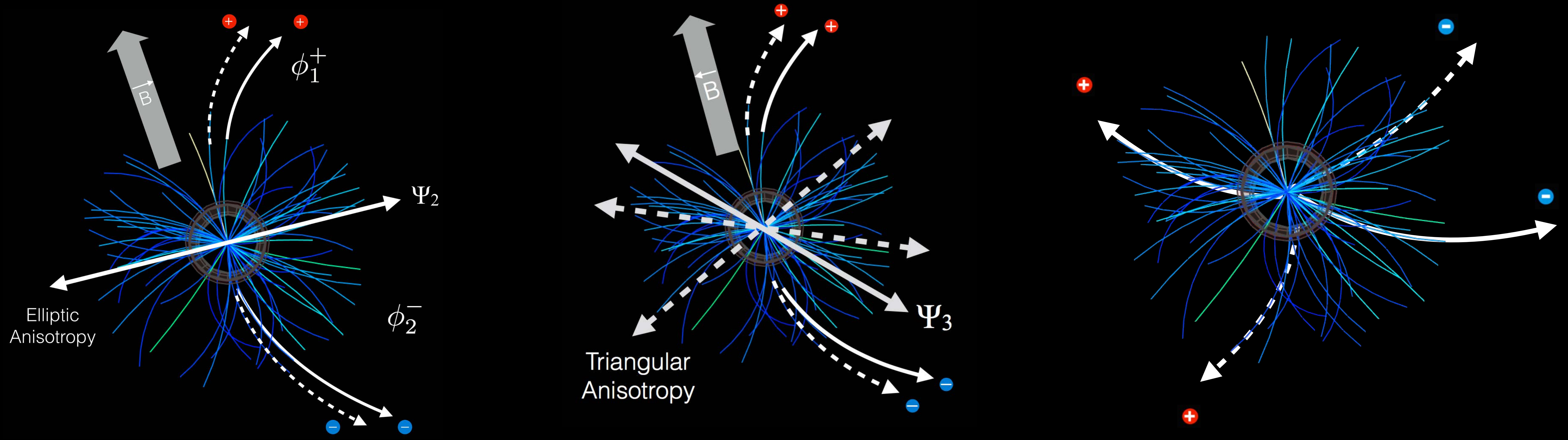
Old criterion for CME:

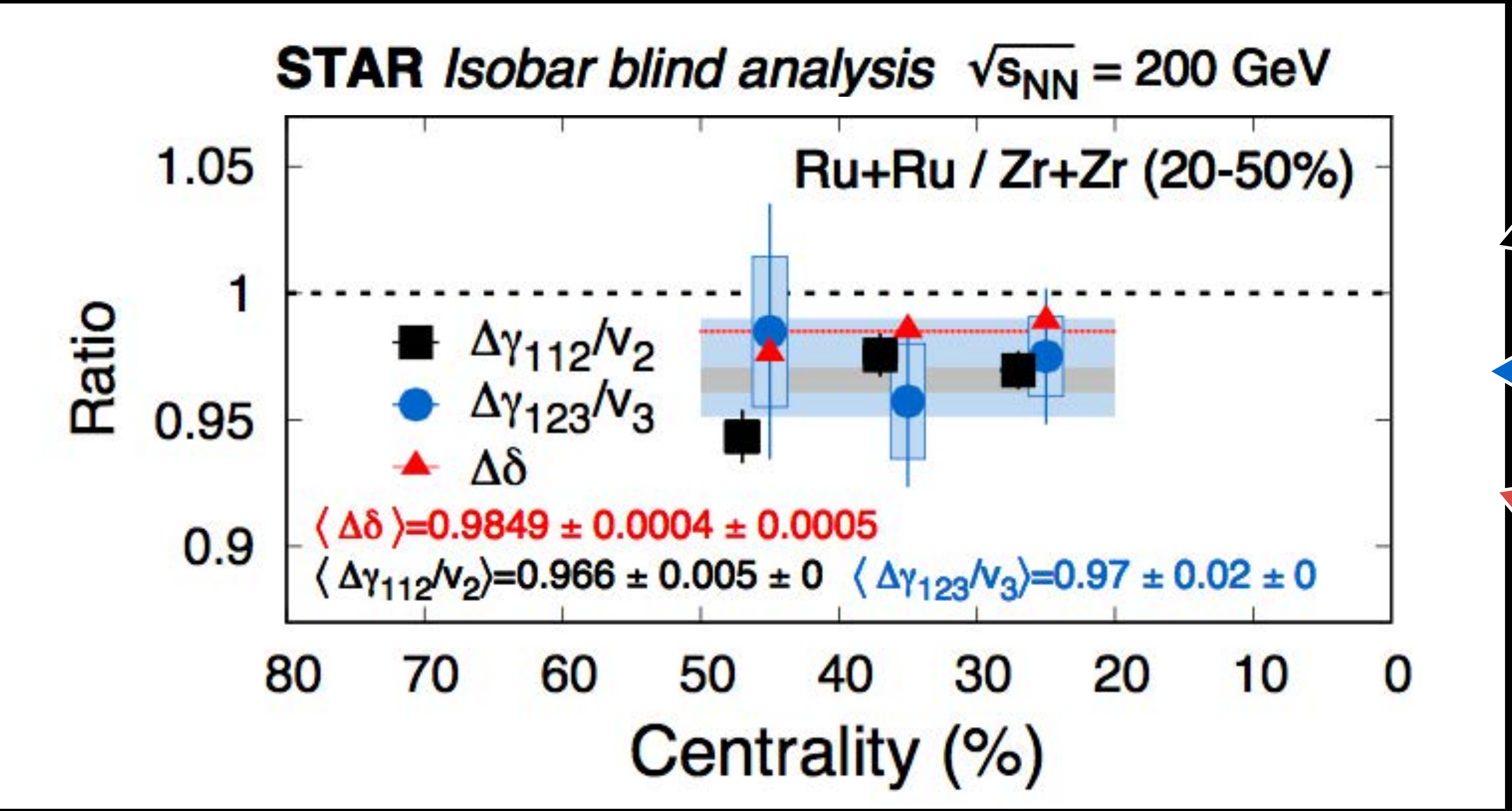
$$\frac{(\Delta\gamma/v_2)_{\mathrm{RuRu}}}{(\Delta\gamma/v_2)_{\mathrm{ZrZr}}} > 1$$

New criterion for CME:

$$\frac{(\Delta\gamma/v_2)_{\mathrm{RuRu}}}{(\Delta\gamma/v_2)_{\mathrm{ZrZr}}} > \frac{(\Delta\delta)_{\mathrm{RuRu}}}{(\Delta\delta)_{\mathrm{ZrZr}}}$$

Baseline measurement to put further constraints





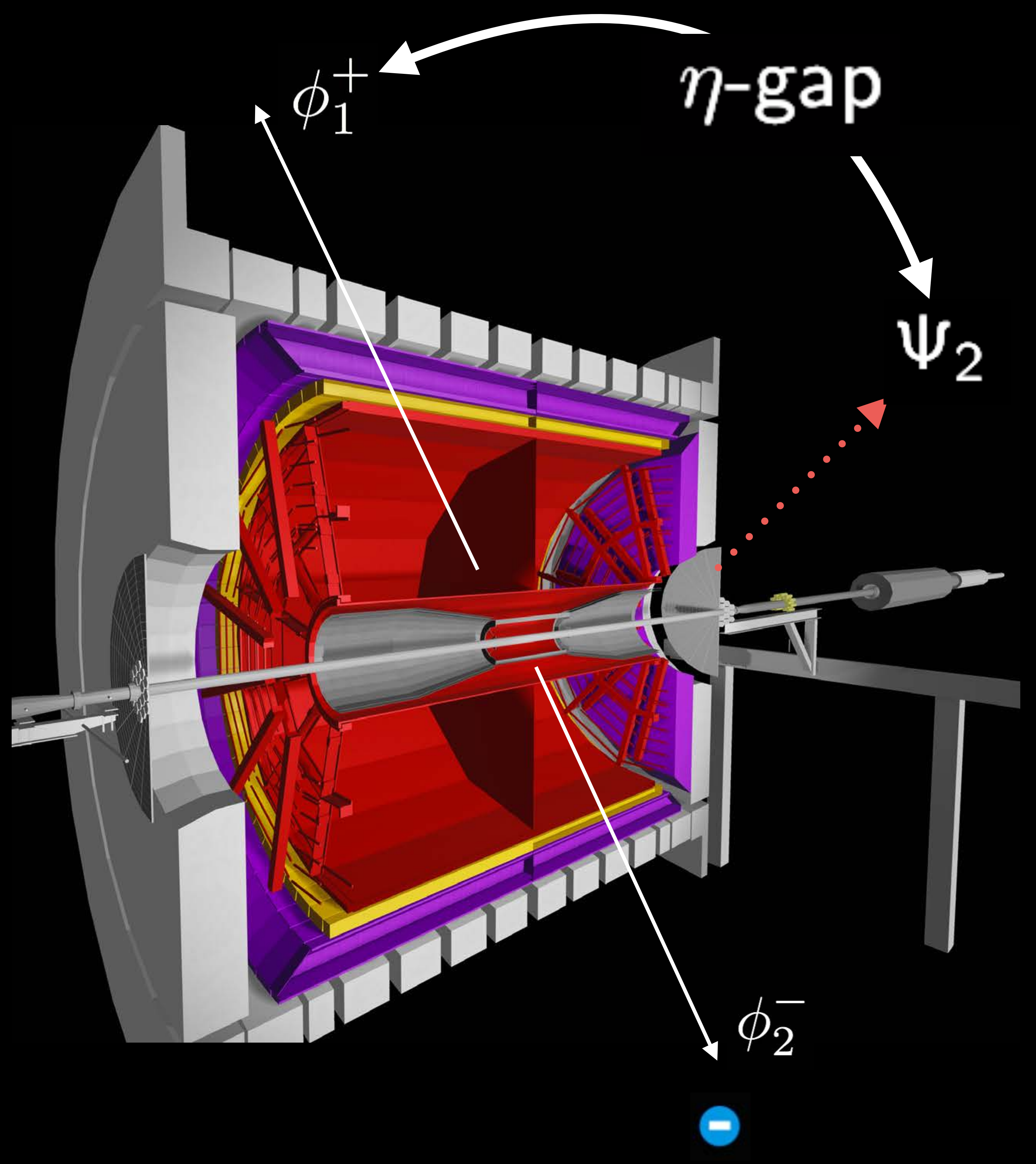
$$\frac{(\Delta\gamma/v_2)_{\mathrm{RuRu}}}{(\Delta\gamma/v_2)_{\mathrm{ZrZr}}} > 1$$ Black above unity

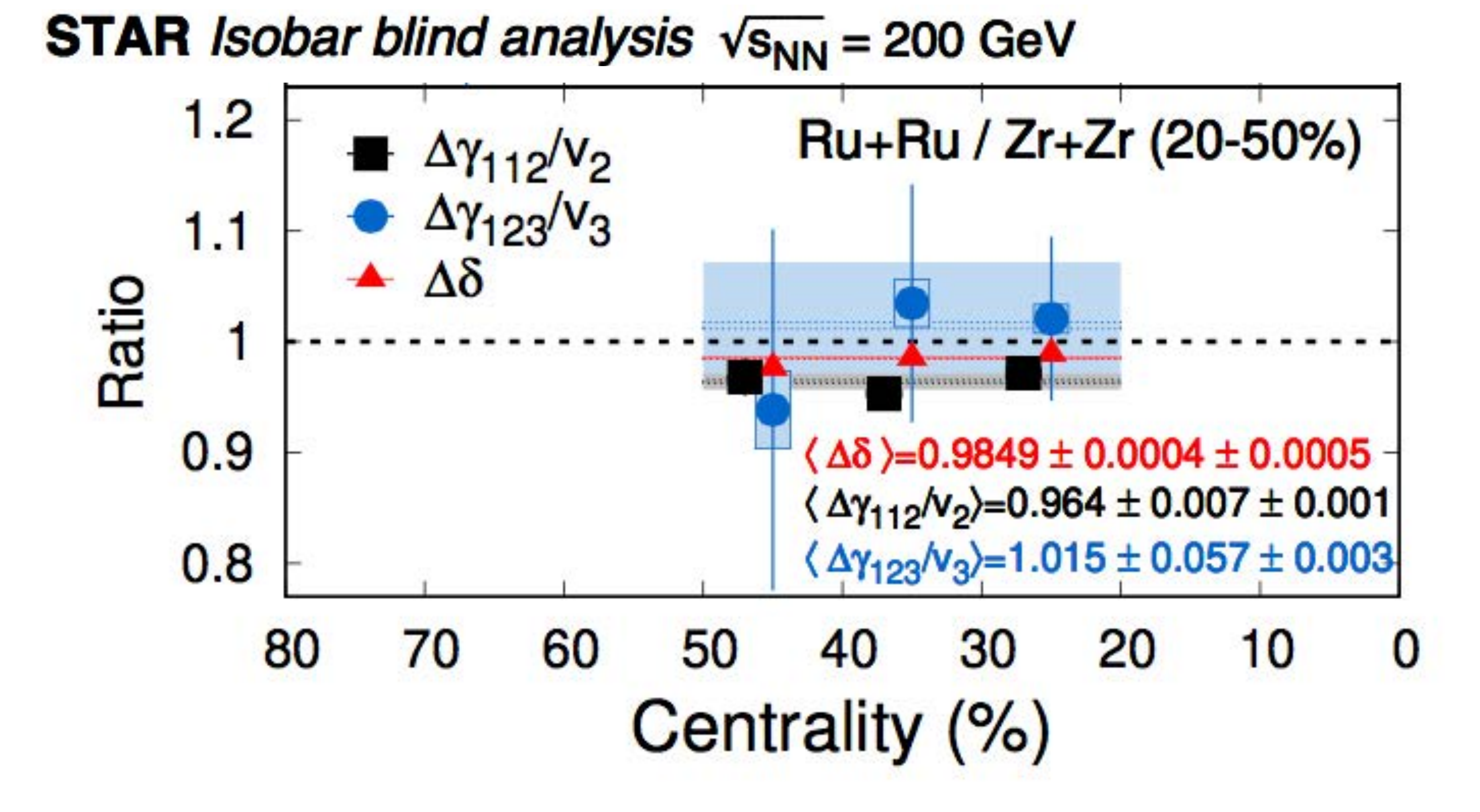
$$\frac{(\Delta\gamma_{112}/v_2)^{RuRu}}{(\Delta\gamma_{112}/v_2)^{ZrZr}} > \frac{(\Delta\gamma_{123}/v_3)^{RuRu}}{(\Delta\gamma_{123}/v_3)^{ZrZr}}$$ Black above blue

$$\frac{(\Delta\gamma/v_2)_{\mathrm{RuRu}}}{(\Delta\gamma/v_2)_{\mathrm{ZrZr}}} > \frac{(\Delta\delta)_{\mathrm{RuRu}}}{(\Delta\delta)_{\mathrm{ZrZr}}}$$ Black above red

Data not compatible with any of the pre-defined CME signatures!!

Measurement using STAR EPD (for the first time)





Pre-defined CME criteria:

$$\frac{(\Delta\gamma/v_2)_{\mathrm{RuRu}}}{(\Delta\gamma/v_2)_{\mathrm{ZrZr}}} > 1$$

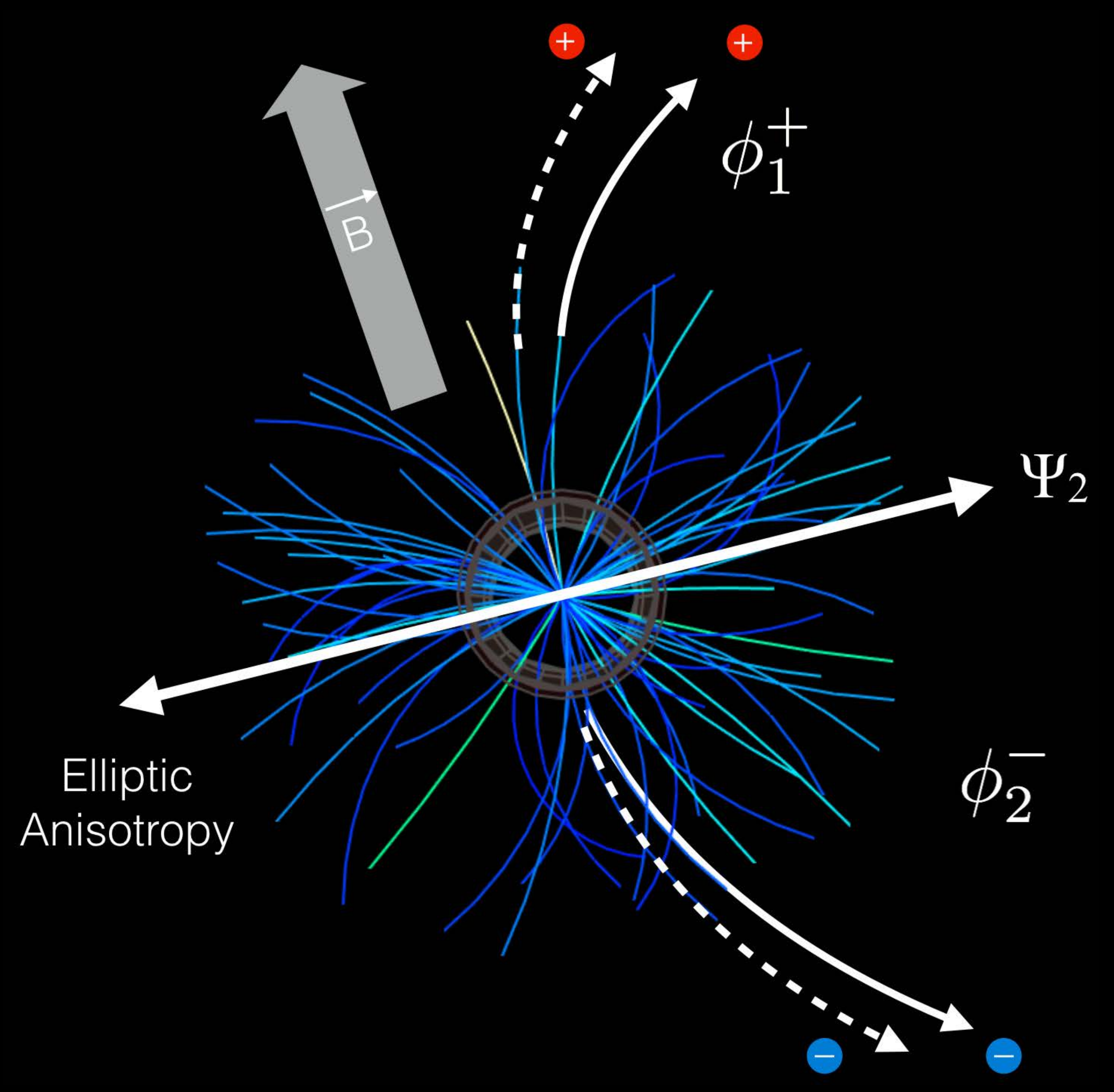
$$\frac{(\Delta\gamma_{112}/v_2)^{RuRu}}{(\Delta\gamma_{112}/v_2)^{ZrZr}} > \frac{(\Delta\gamma_{123}/v_3)^{RuRu}}{(\Delta\gamma_{123}/v_3)^{ZrZr}}$$

$$\frac{(\Delta\gamma/v_2)_{\mathrm{RuRu}}}{(\Delta\gamma/v_2)_{\mathrm{ZrZr}}} > \frac{(\Delta\delta)_{\mathrm{RuRu}}}{(\Delta\delta)_{\mathrm{ZrZr}}}$$

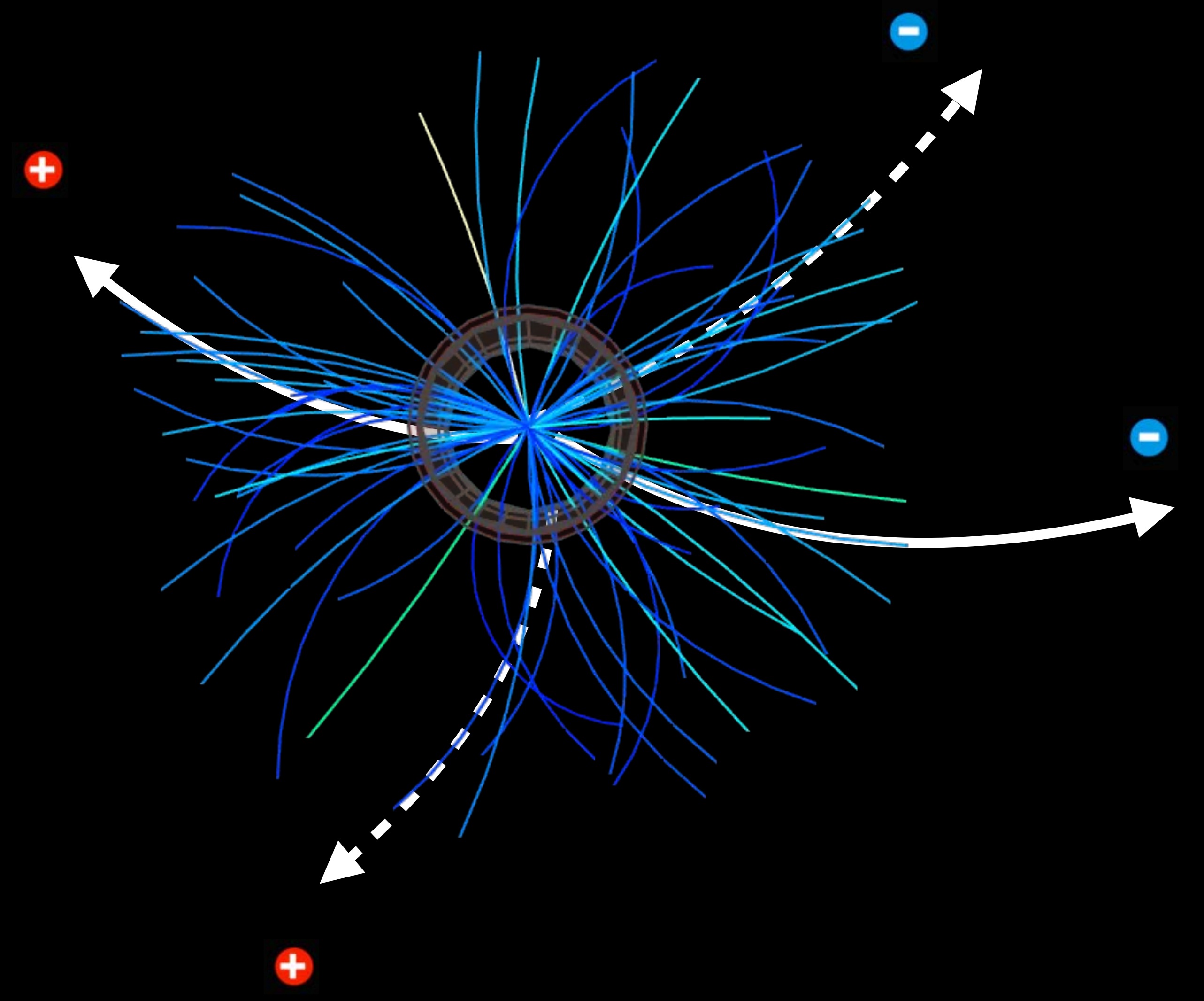
This pre-defined CME signatures are NOT seen

Factorization breaking

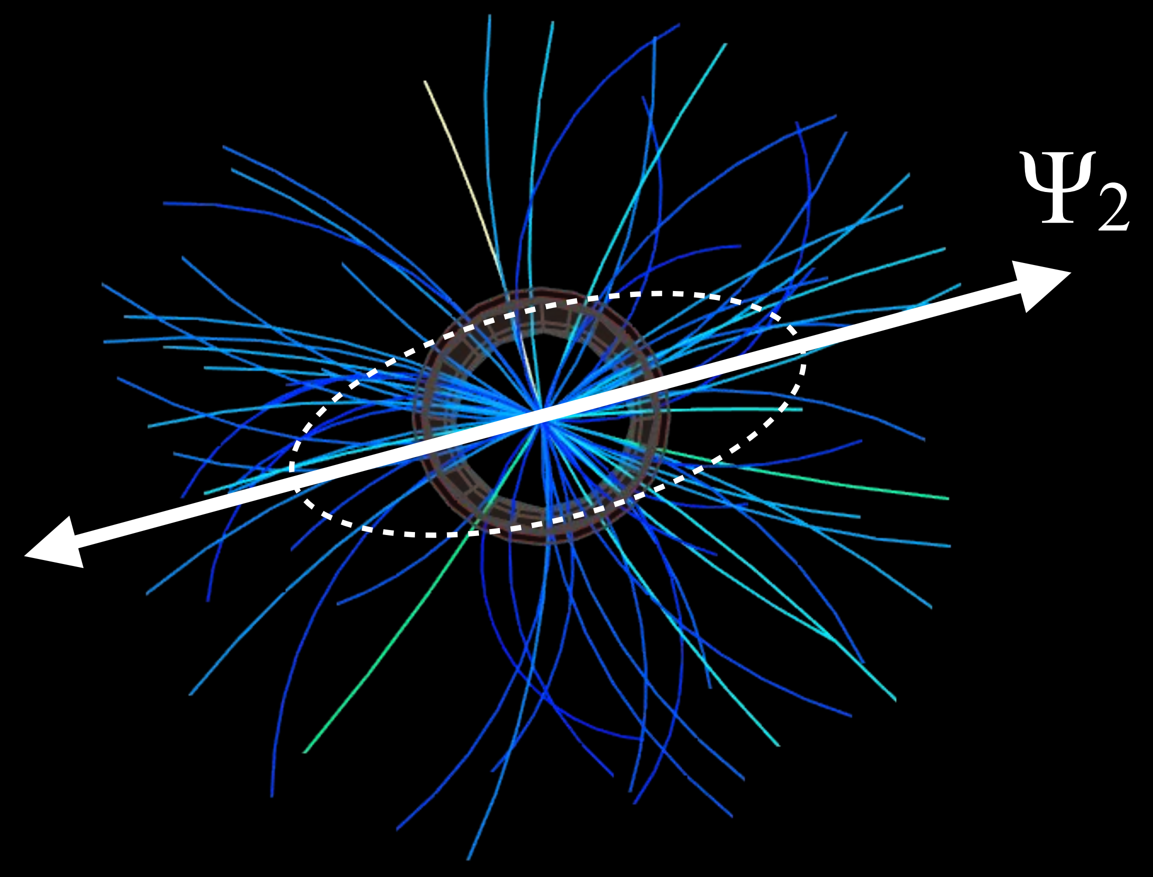
Primary observable



$\Longleftrightarrow$



$\times$



$$\gamma_{112}\{\mathrm{EP}\} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2^{\mathrm{TPC}}) \rangle \quad \Longleftrightarrow \quad \delta = \langle \cos(\phi_\alpha - \phi_\beta) \rangle \quad \times \quad v_2 = \langle \cos(2\phi - \Psi_2) \rangle$$

$$\gamma_{112} = \langle \cos(\phi_\alpha - \phi_\beta + 2\phi_\beta - 2\Psi_2) \rangle \approx \langle \cos(\phi_\alpha - \phi_\beta) \cos(2\phi_\beta - 2\Psi_2) \rangle = \kappa_{112} \langle \cos(\phi_\alpha - \phi_\beta) \rangle \langle \cos(2\phi_\beta - 2\Psi_2) \rangle$$

$$\gamma_{112} = \kappa_{112}\, \Delta\delta \times v_2$$

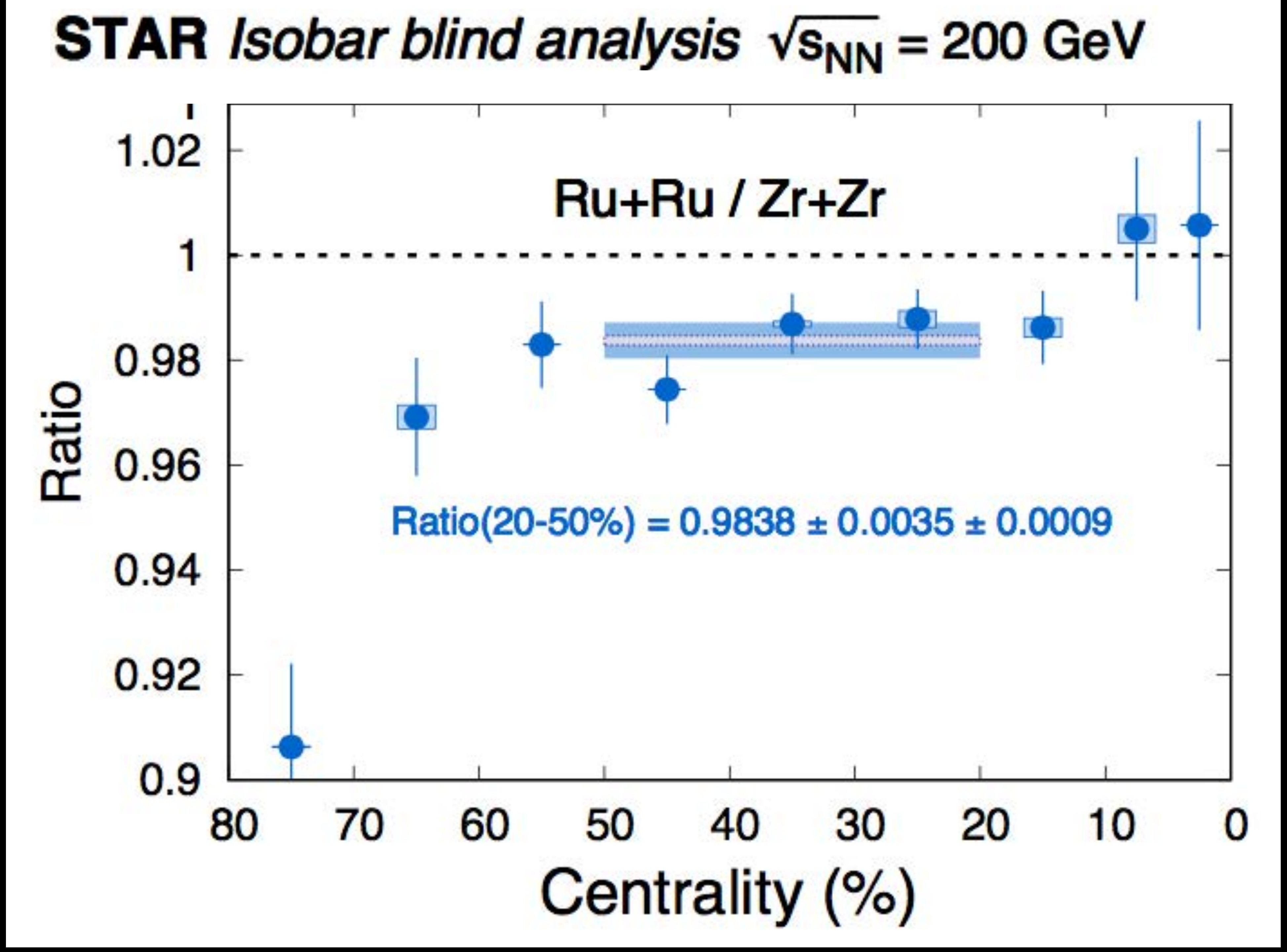
Measurement of factorization breaking observables

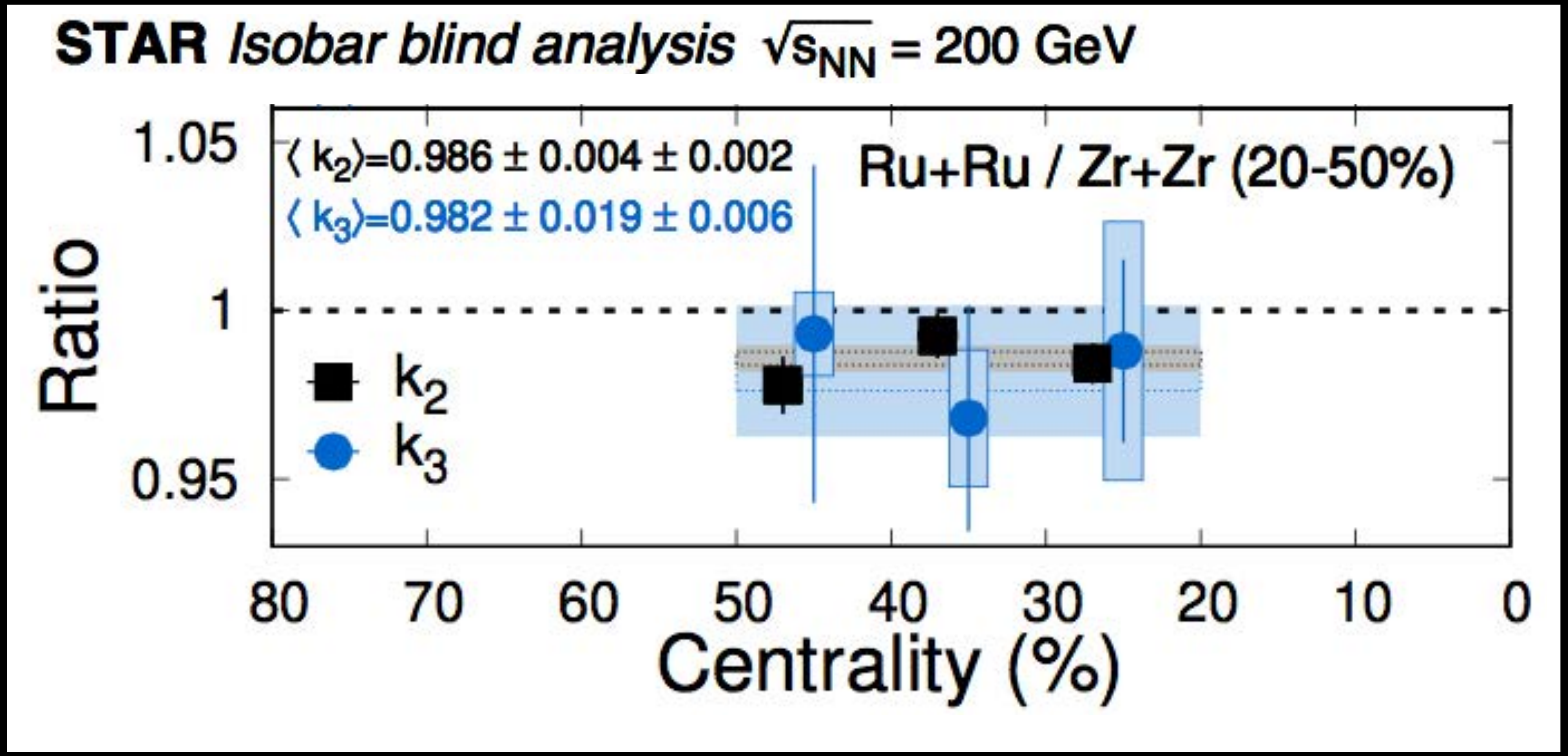
$$\frac{(\Delta\gamma/v_2)_{\mathrm{RuRu}}}{(\Delta\gamma/v_2)_{\mathrm{ZrZr}}} > \frac{(\Delta\delta)_{\mathrm{RuRu}}}{(\Delta\delta)_{\mathrm{ZrZr}}} \Rightarrow \frac{(\Delta\gamma/v_2\,\Delta\delta)_{\mathrm{Ru+Ru}}}{(\Delta\gamma/v_2\,\Delta\delta)_{\mathrm{Zr+Zr}}} > 1$$

$$\frac{(\kappa_{112})_{\mathrm{Ru+Ru}}}{(\kappa_{112})_{\mathrm{Zr+Zr}}} > 1$$

$$k_n = \frac{\Delta\langle\langle\cos(\Delta\phi_{\alpha\beta})\cos(n\Delta\phi_{\beta c})\rangle\rangle}{\Delta\delta_{\alpha,\beta}\times v_n^2\{2\}}$$

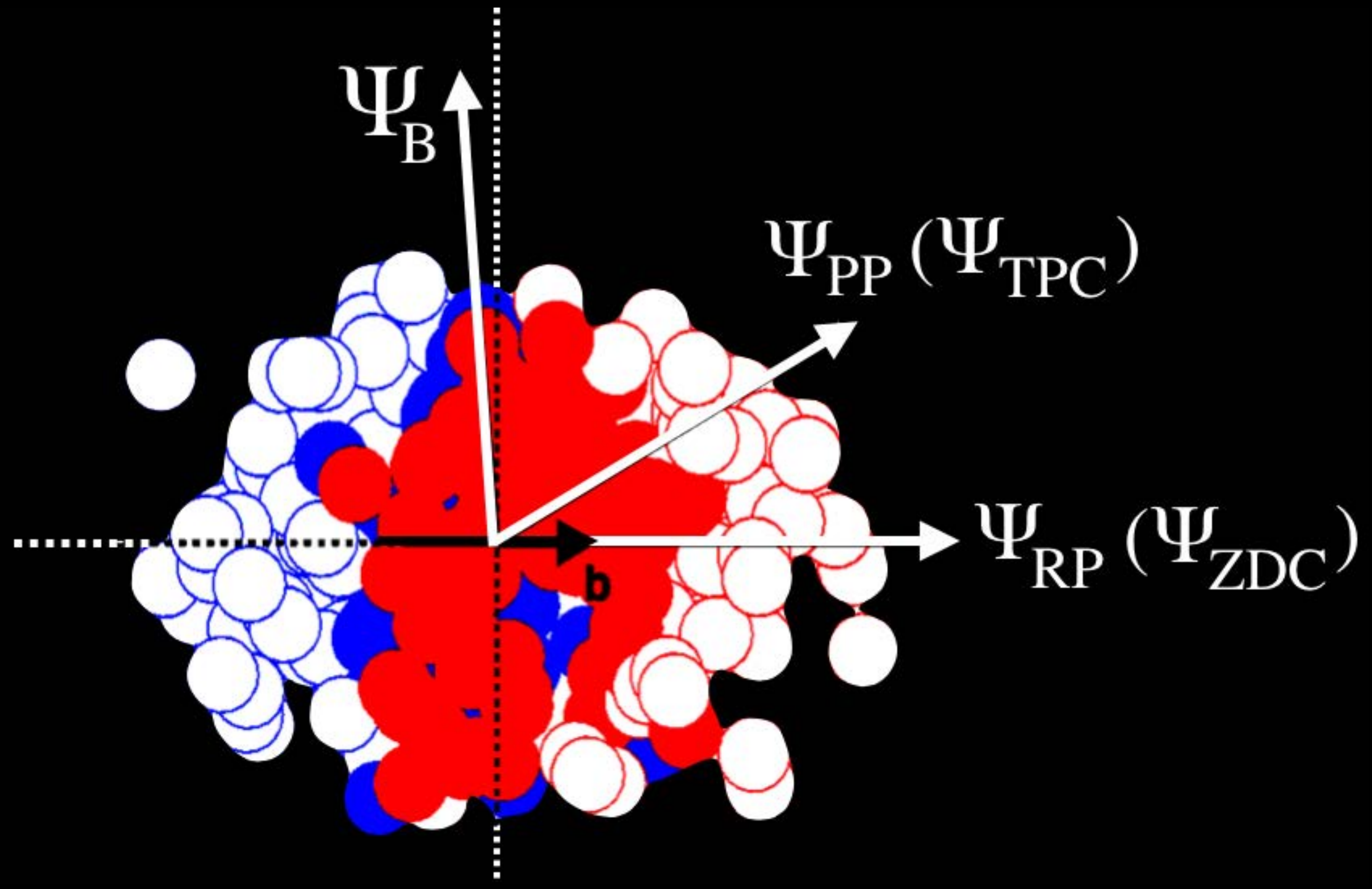
$$\frac{k_2^{Ru+Ru}}{k_2^{Zr+Zr}} > \frac{k_3^{Ru+Ru}}{k_3^{Zr+Zr}}$$





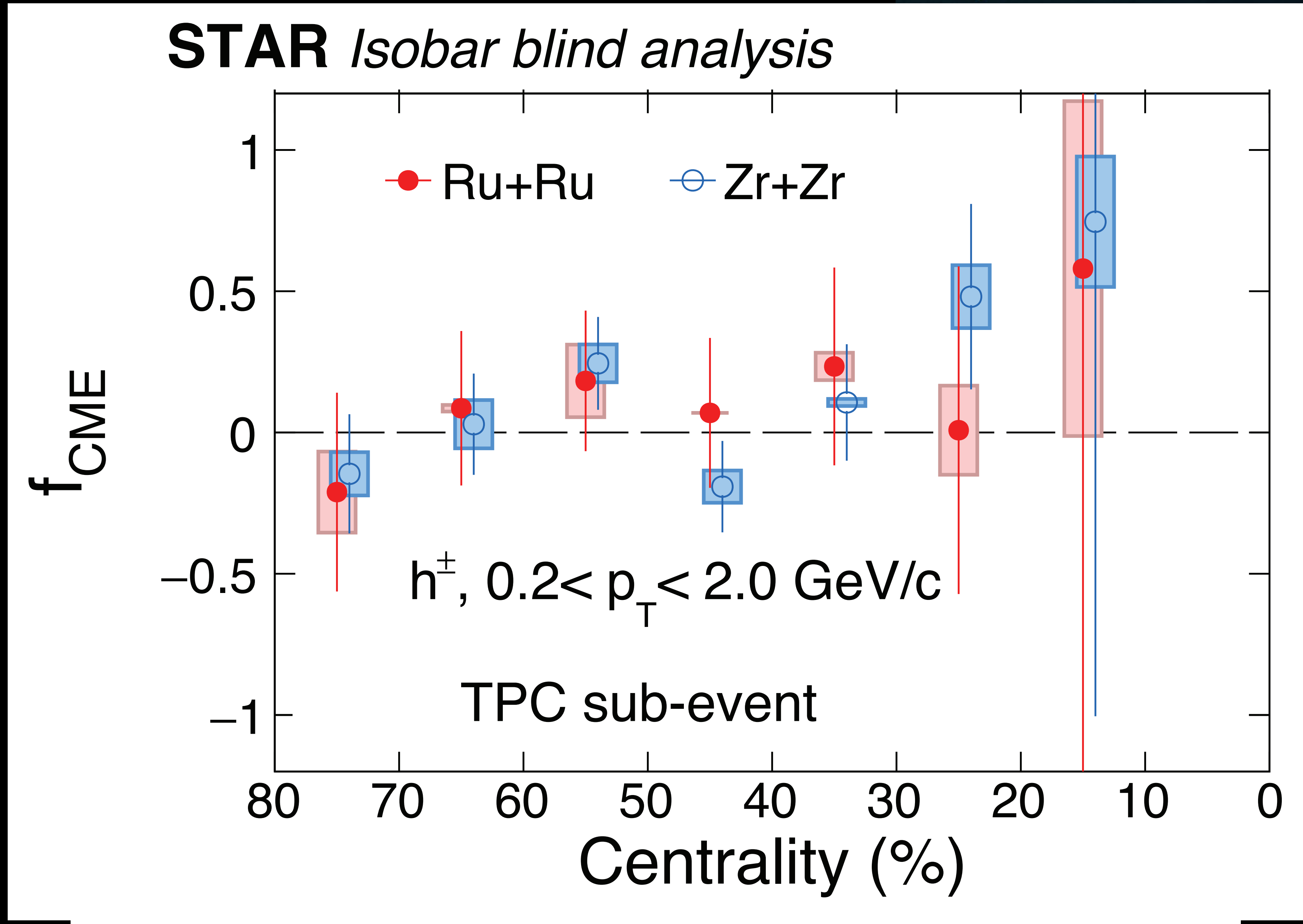
Measurements of CME fraction

CME fraction using spectator/participant planes



$$\Delta\gamma = \Delta\gamma^{\rm sig} + \Delta\gamma^{\rm bkg}$$

$$f_{\rm CME} = \frac{\Delta\gamma^{\rm sig}}{\Delta\gamma}$$



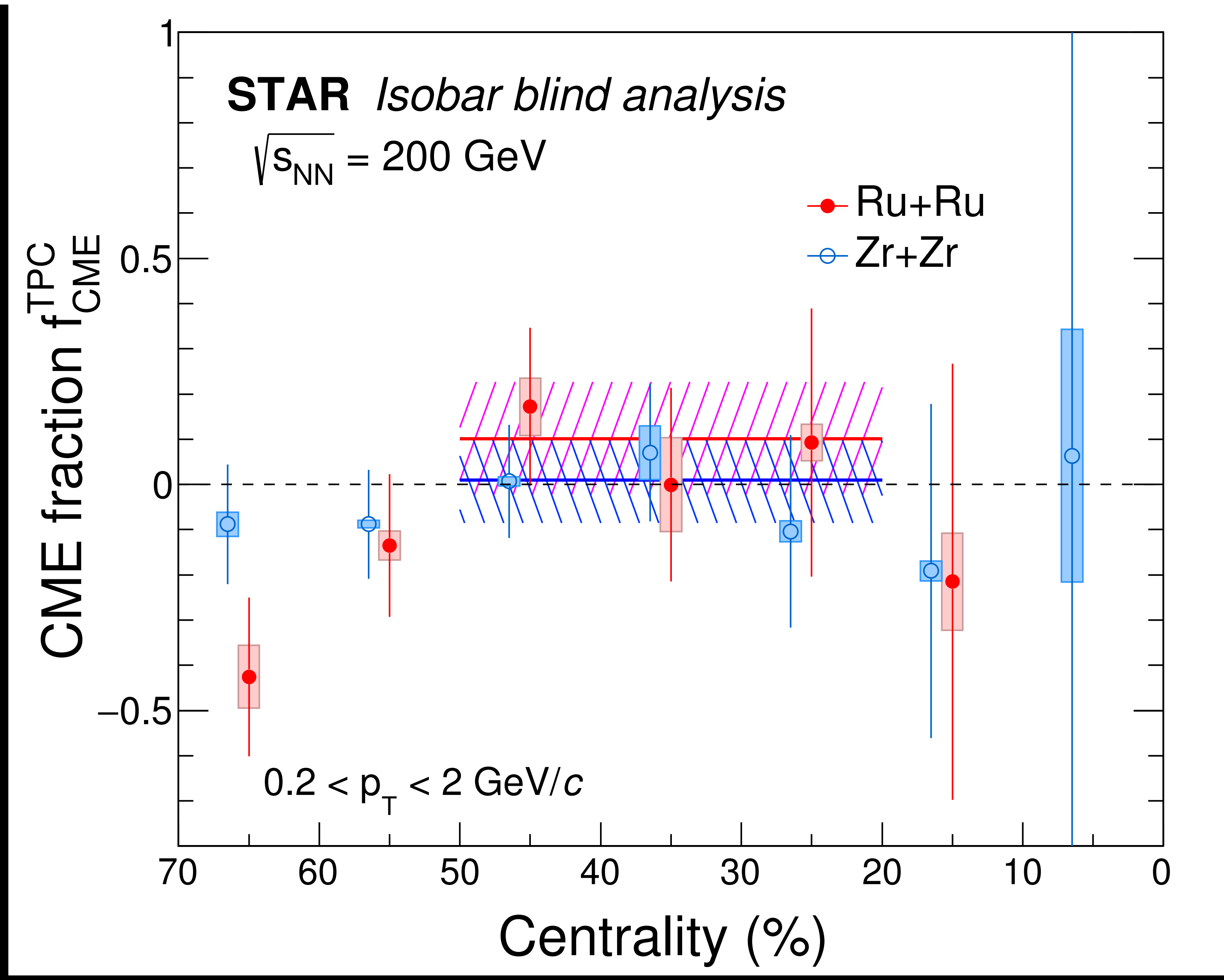
Four equations, four unknowns:

$$\Delta\gamma^{\rm sig}(\Psi_{\rm ZDC}) + \Delta\gamma^{\rm bkg}(\Psi_{\rm ZDC}) = \Delta\gamma(\Psi_{\rm ZDC})$$

$$\Delta\gamma^{\rm sig}(\Psi_{\rm TPC}) + \Delta\gamma^{\rm bkg}(\Psi_{\rm TPC}) = \Delta\gamma(\Psi_{\rm TPC})$$

$$\Delta\gamma^{\rm bkg}(\Psi_{\rm ZDC})/\Delta\gamma^{\rm bkg}(\Psi_{\rm TPC}) = v_2(\Psi_{\rm ZDC})/v_2(\Psi_{\rm TPC})$$

$$\Delta\gamma^{\rm sig}(\Psi_{\rm ZDC})/\Delta\gamma^{\rm sig}(\Psi_{\rm TPC}) = v_2(\Psi_{\rm TPC})/v_2(\Psi_{\rm ZDC})$$



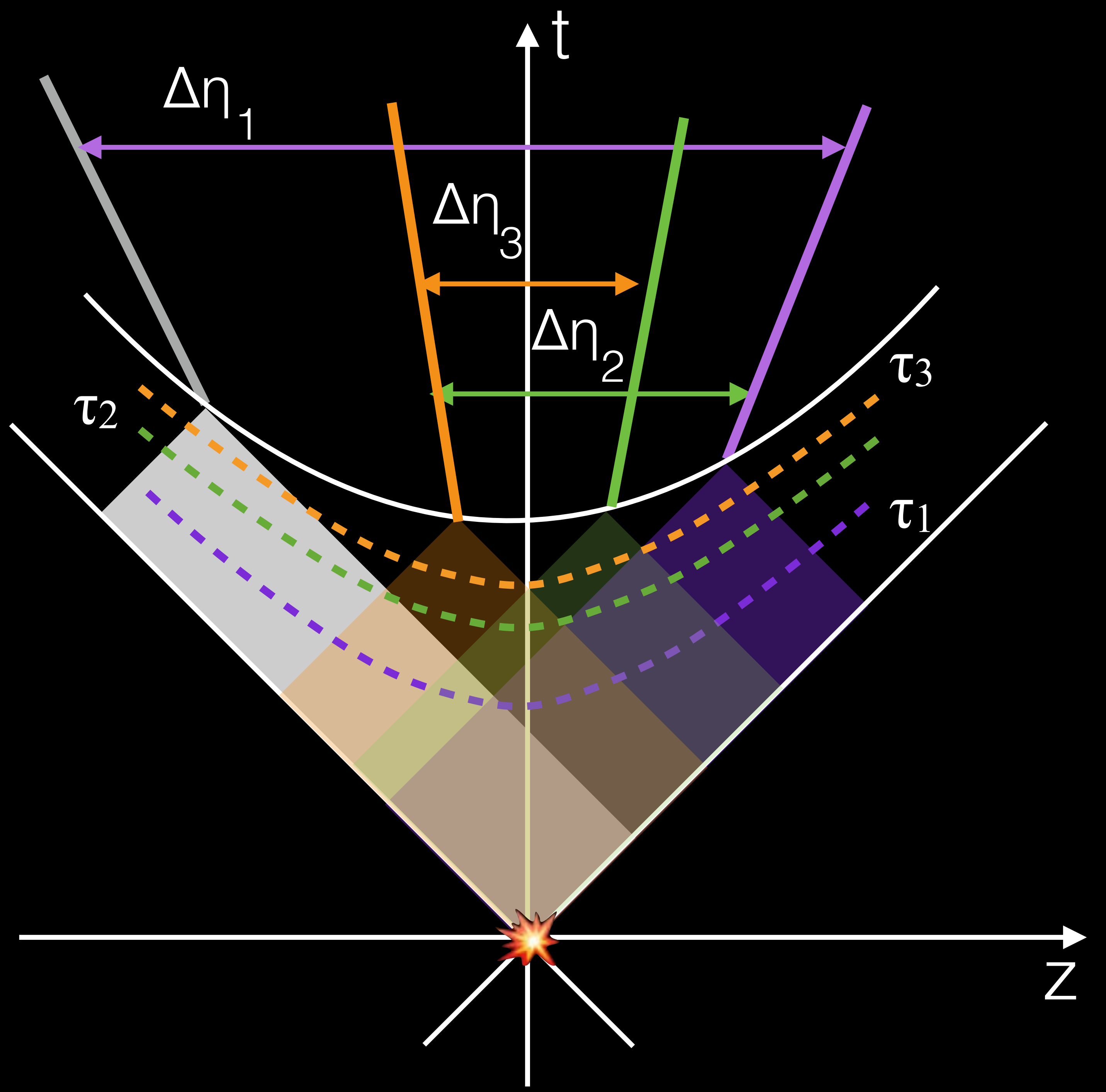
Case of CME from this analysis is $f_{\rm CME}$ (Ru) > $f_{\rm CME}$ (Zr)

Valuable measurement but not decisive due to large uncertainties

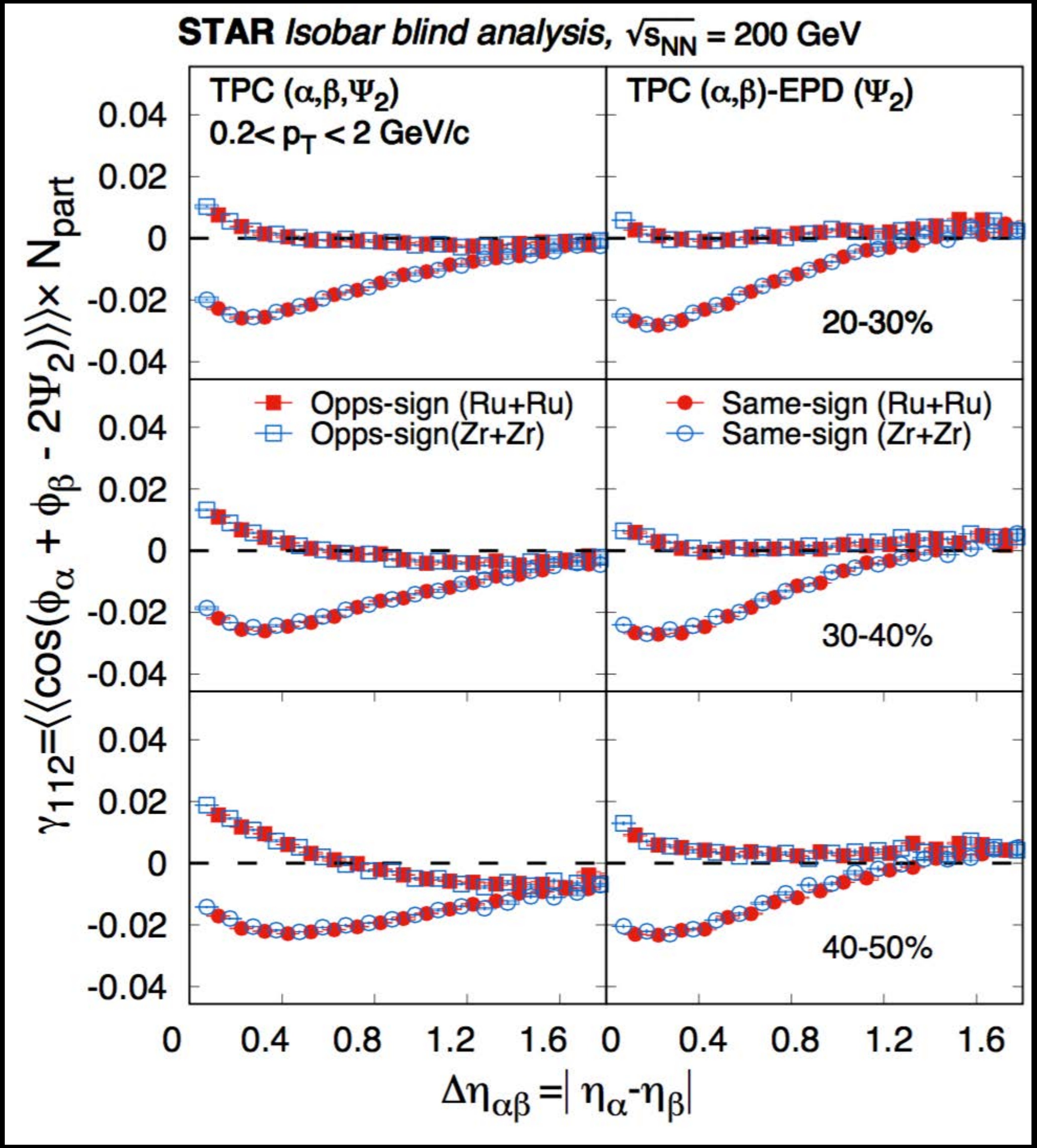
Differential measurements of charge separation

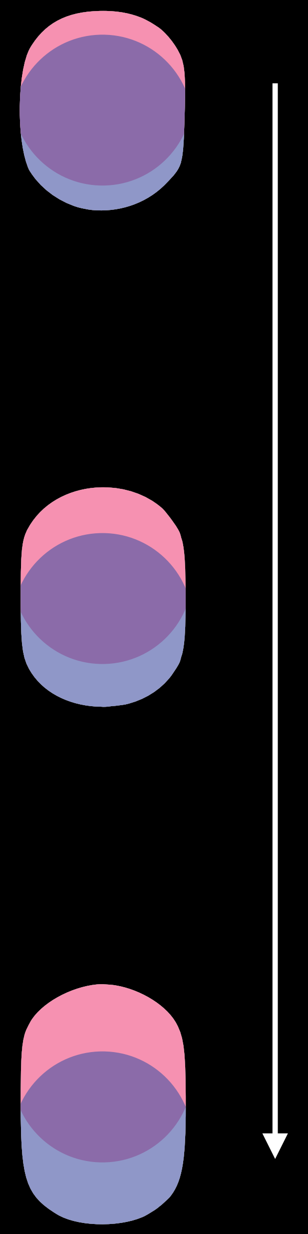
Pseudorapidity distribution of charge separation

Causality precludes late-time correlations to spread over large η (wide acceptance → strength)



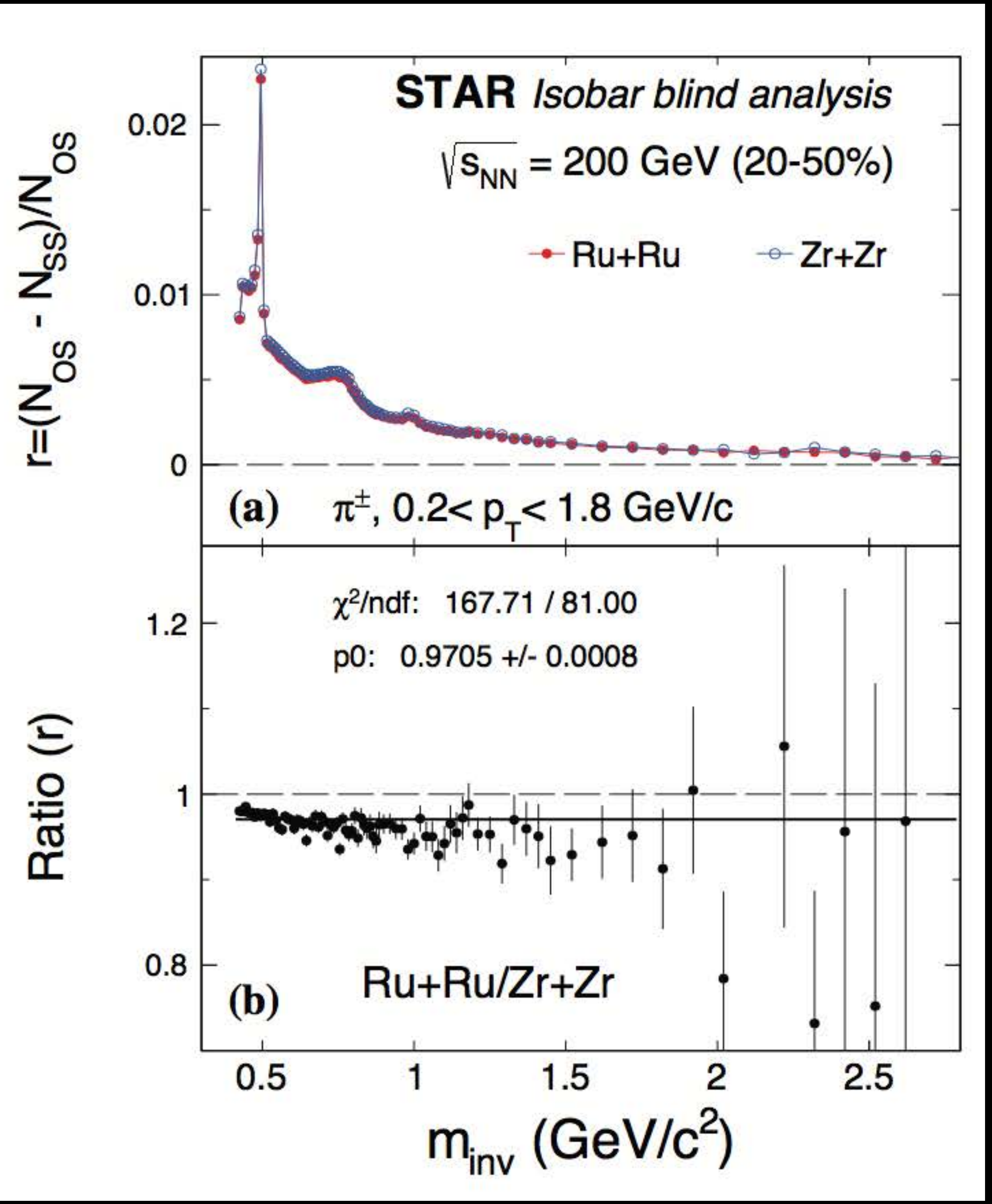
B-field driven charge separation: large Δη>1
Resonance decay: smaller Δη<1



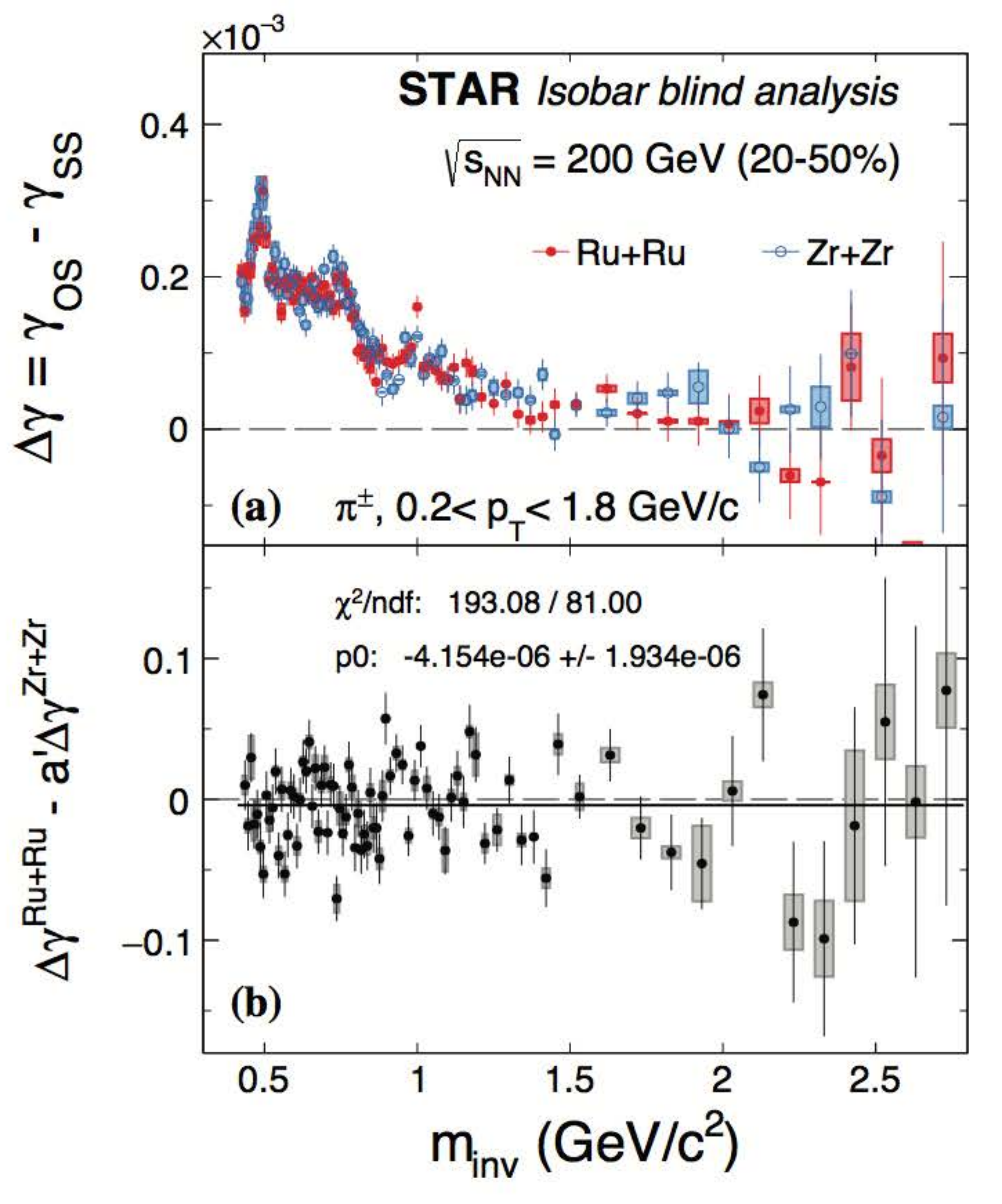


The relative pseudorapidity dependence is similar between the two species

Invariant mass dependence of charge separation



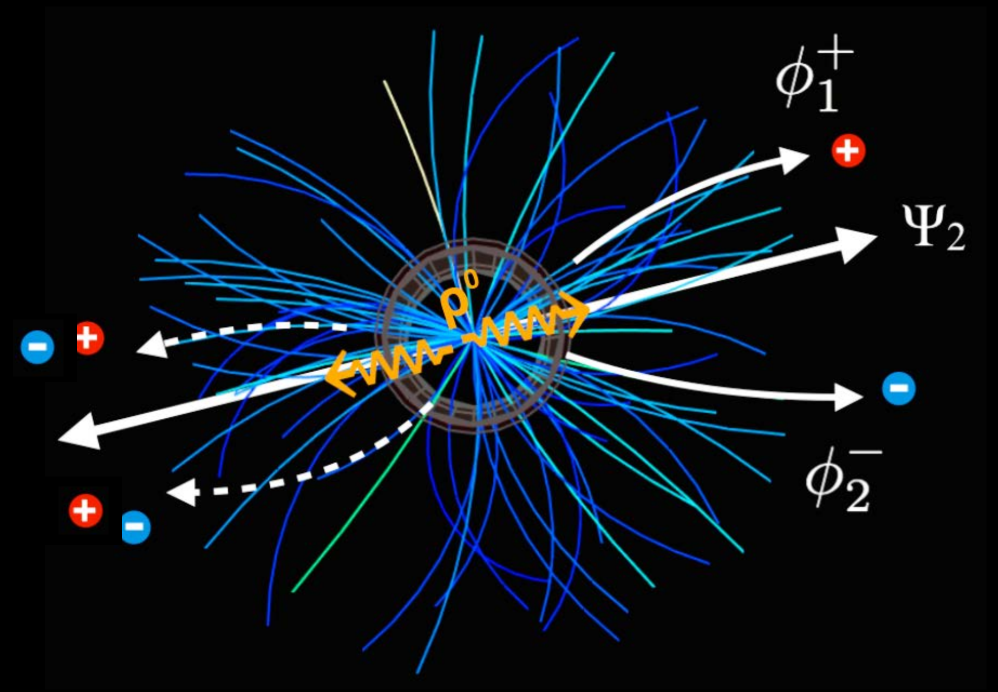
Resonances are identifiable as peaks in invariant mass distribution



Pre-defined CME criteria:

$$\Delta\gamma^{\mathrm{Ru+Ru}} - a'\Delta\gamma^{\mathrm{Zr+Zr}} > 0$$

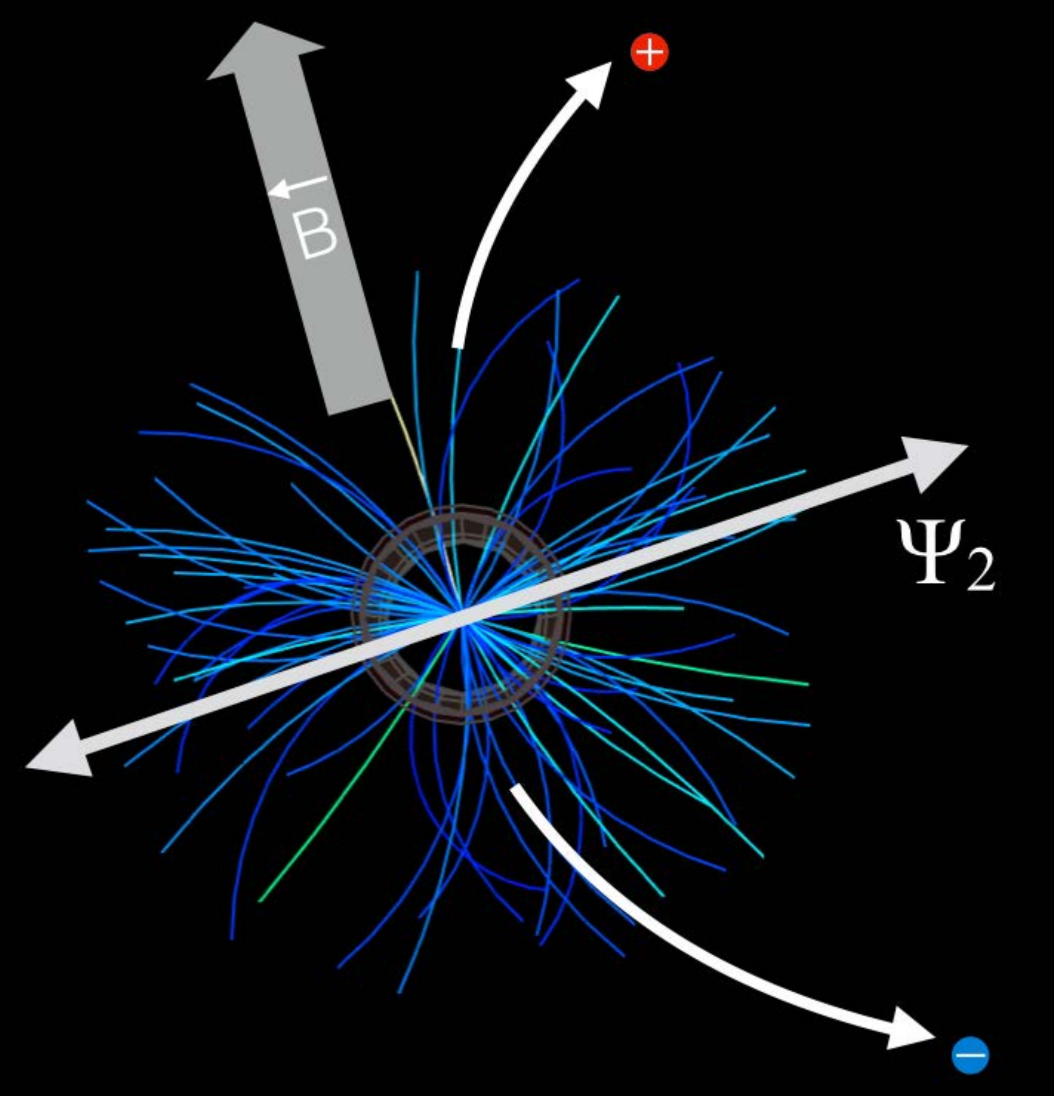
$$\boxed{a' = v_2^{\mathrm{Ru+Ru}} / v_2^{\mathrm{Zr+Zr}}}$$



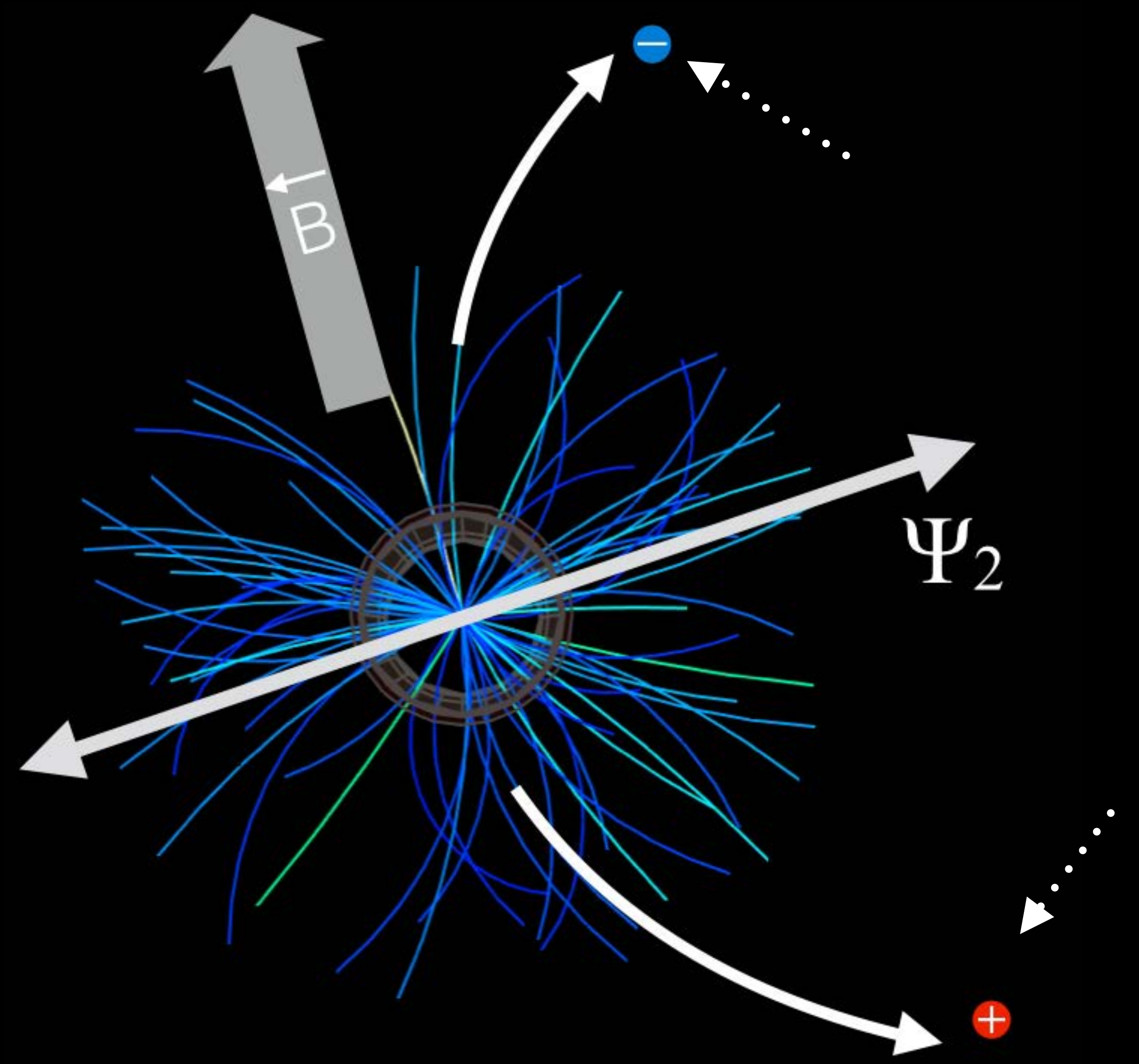
This pre-defined signature is NOT seen

Alternative approach: The R variable

R variable: an alternate measure of charge separation



Real-Event



Shuffled-Event

R-variable is a ratio of distribution
(of event-by-event charged-dependent dipole anisotropy)

$$R_{\Psi_2}(\Delta S) = C_{\Psi_2}(\Delta S)/C^{\perp}_{\Psi_2}(\Delta S),$$

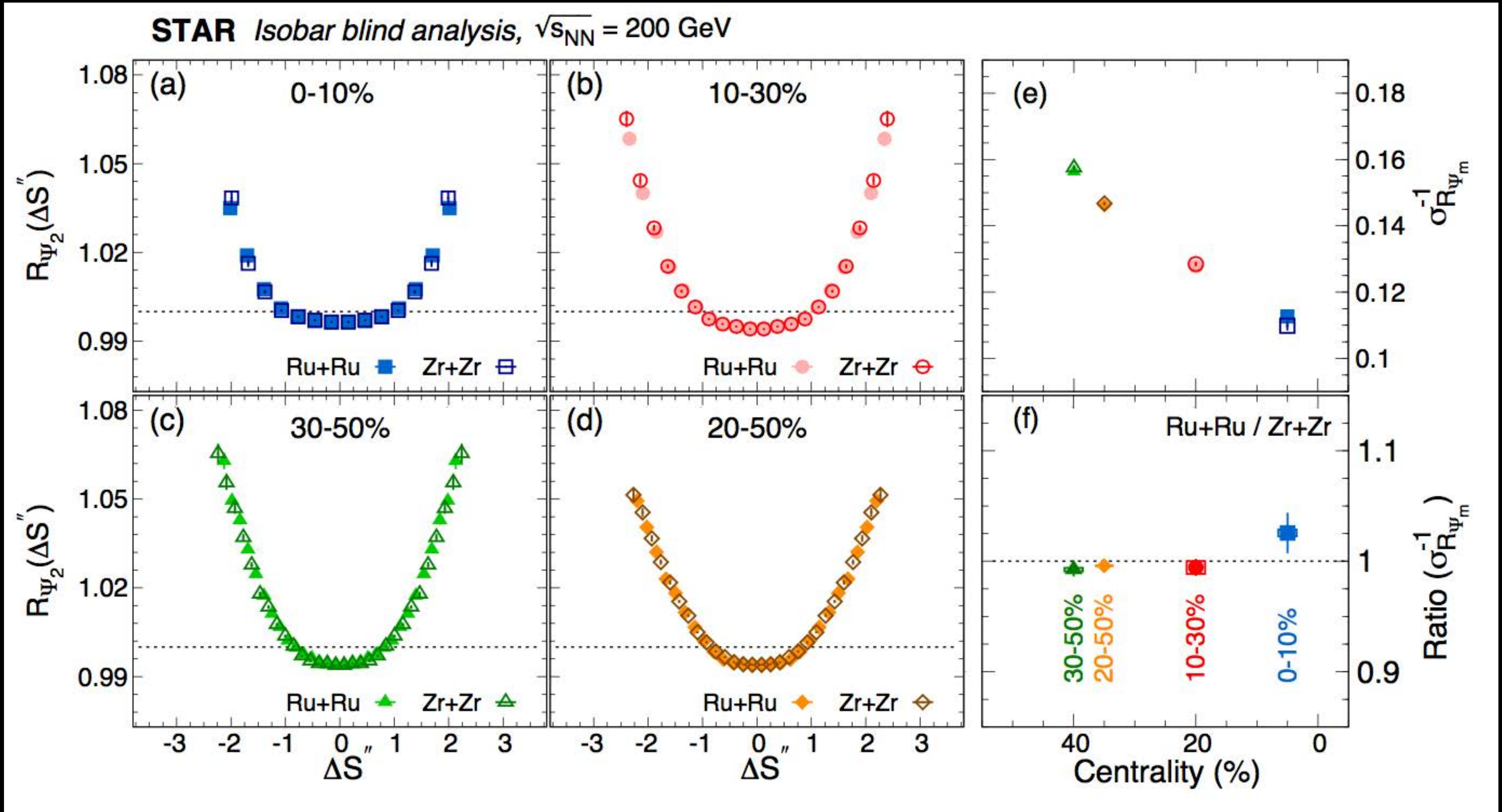
$$C_{\Psi_2}(\Delta S) = \frac{N_{\rm real}(\Delta S)}{N_{\rm shuffled}(\Delta S)},$$

$$\Delta S = \frac{\sum_1^{n^+} w_i^+ \sin(\Delta\varphi_2)}{\sum_1^{n^+} w_i^+} - \frac{\sum_1^{n^-} w_i^- \sin(\Delta\varphi_2)}{\sum_1^{n^-} w_i^-},$$

The width of R-variable is sensitive to signal + Background

The case for CME is: $1/\sigma_{R_{\Psi_2}}(\mathrm{Ru+Ru}) > 1/\sigma_{R_{\Psi_2}}(\mathrm{Zr+Zr})$

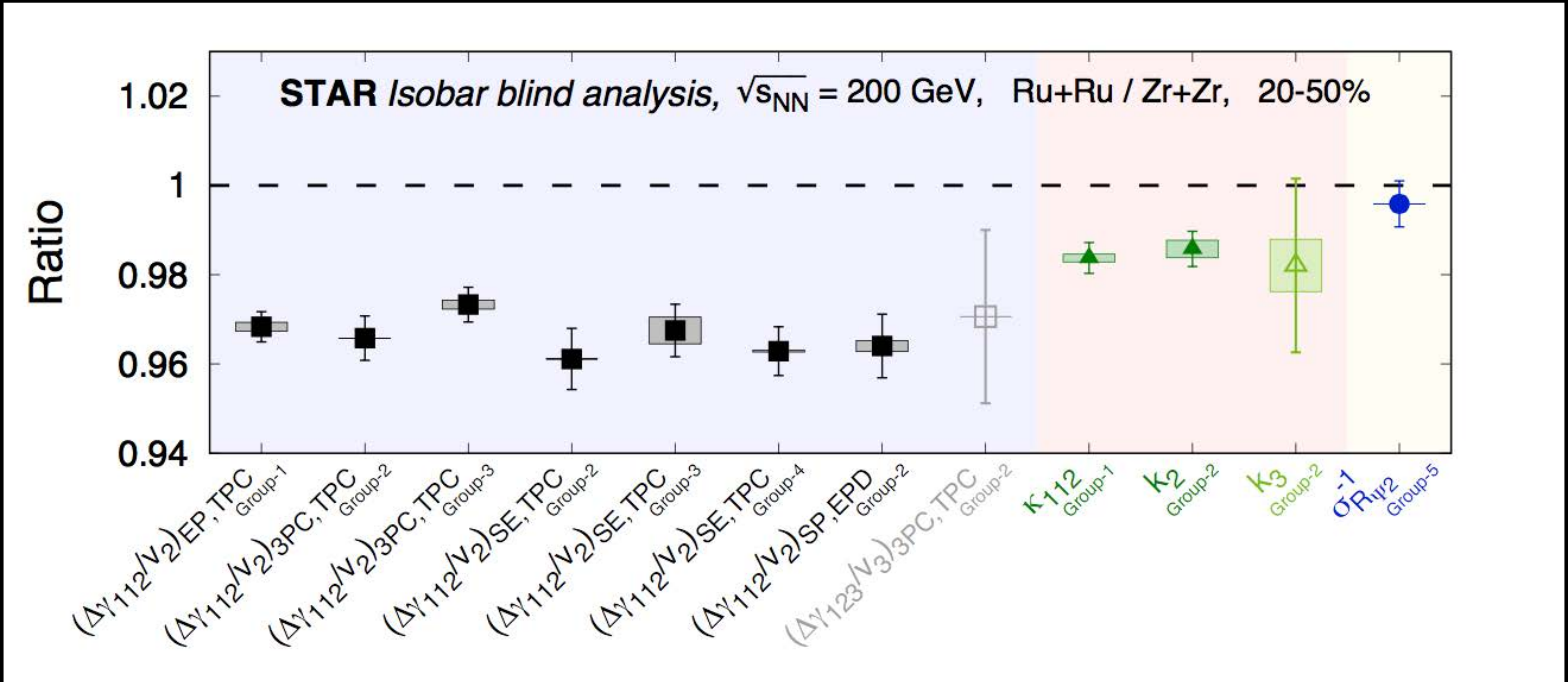
R variable: an alternate measure of charge separation



Pre-defined CME criteria: $1/\sigma_{R_{\Psi_2}}(\mathrm{Ru+Ru}) > 1/\sigma_{R_{\Psi_2}}(\mathrm{Zr+Zr})$

This pre-defined signature is NOT seen

Compilation of results



Good consistency between results from different groups.

Predefined CME signatures: Ratios involving Ψ_2 > those involving Ψ_3, and > 1

None of the predefined signatures have been observed in the blind analysis

Modifications to pre-defined CME baseline and upper limit

Limited Post-blind analysis: modified CME baseline

Challenge: Multiplicity turned out to be different for the two isobar, was not know before blind analysis, dilution of signal & background ~ 1/multiplicity, this effect is different for two species

Blind analysis criterion for CME: $\frac{(\Delta\gamma/v_2)_{\rm RuRu}}{(\Delta\gamma/v_2)_{\rm ZrZr}} > 1$

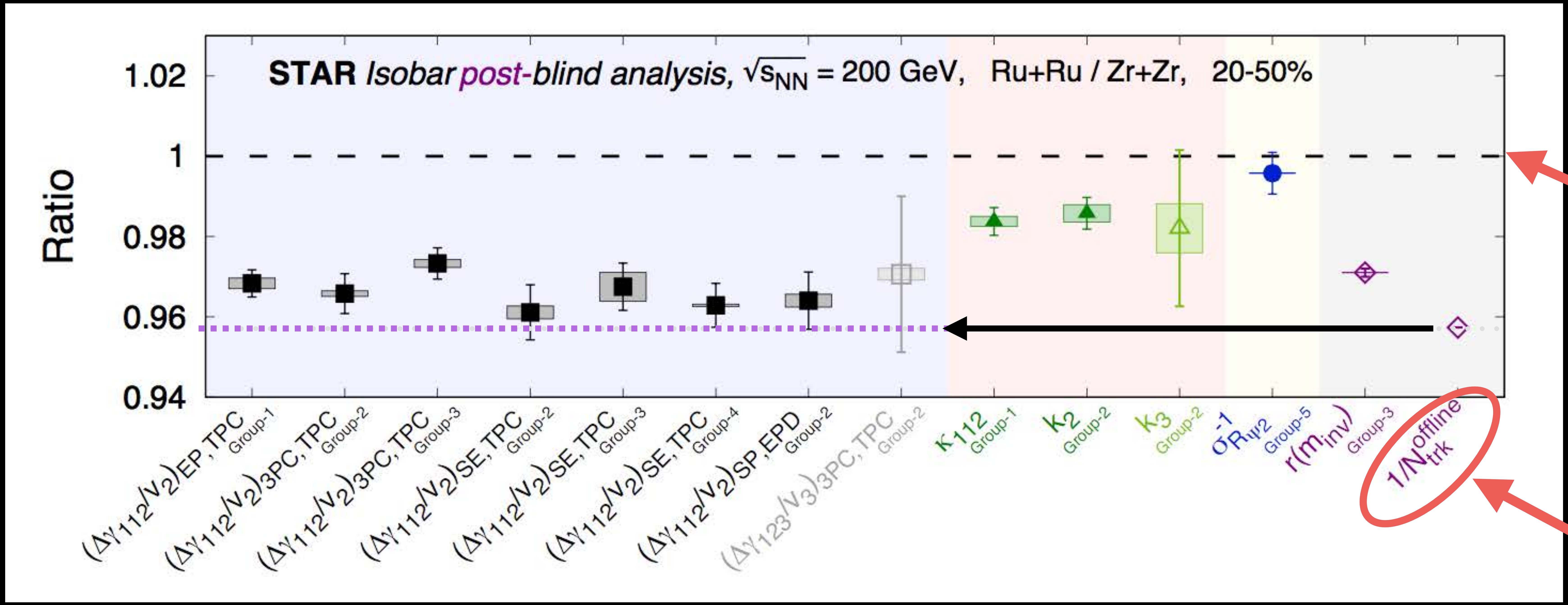
$$\Delta\gamma^{\text{Ru+Ru}} = \Delta\gamma^{CME} + k \times \frac{v_2}{N}$$

$$?? \qquad \not\parallel \qquad \approx$$

$$\Delta\gamma^{\text{Zr+Zr}} = \Delta\gamma^{CME} + k \times \frac{v_2}{N}$$

Post-blinding criterion for CME:

$$\frac{(\Delta\gamma/v_2)_{\rm RuRu}}{(\Delta\gamma/v_2)_{\rm ZrZr}} > \frac{(1/N_{\rm ch})_{\rm RuRu}}{(1/N_{\rm ch})_{\rm ZrZr}}$$



Blind analysis baseline

Post-blinding modified baseline

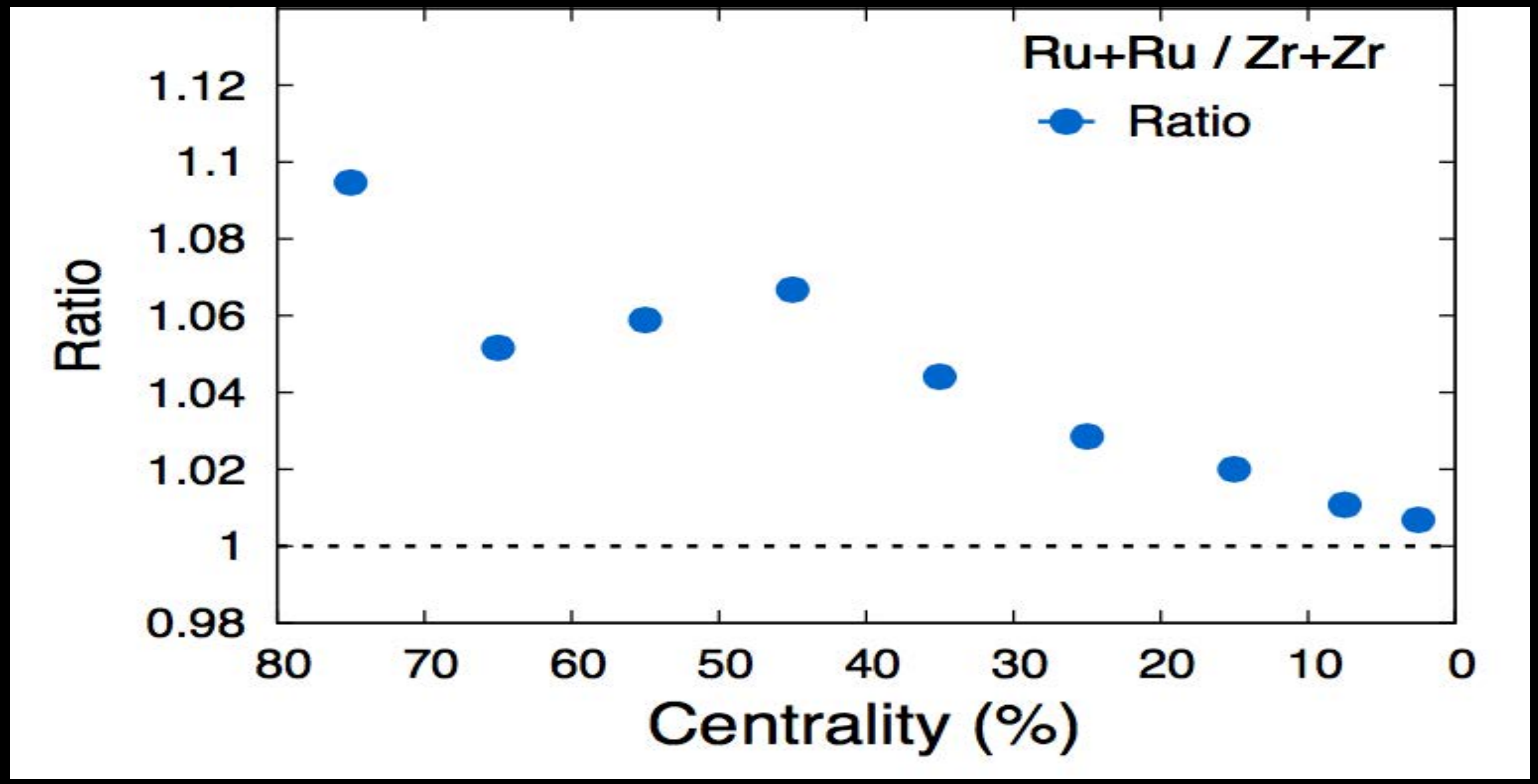
Some recent exploration, developments and ideas

Limited Post-blind analysis: modified CME baseline

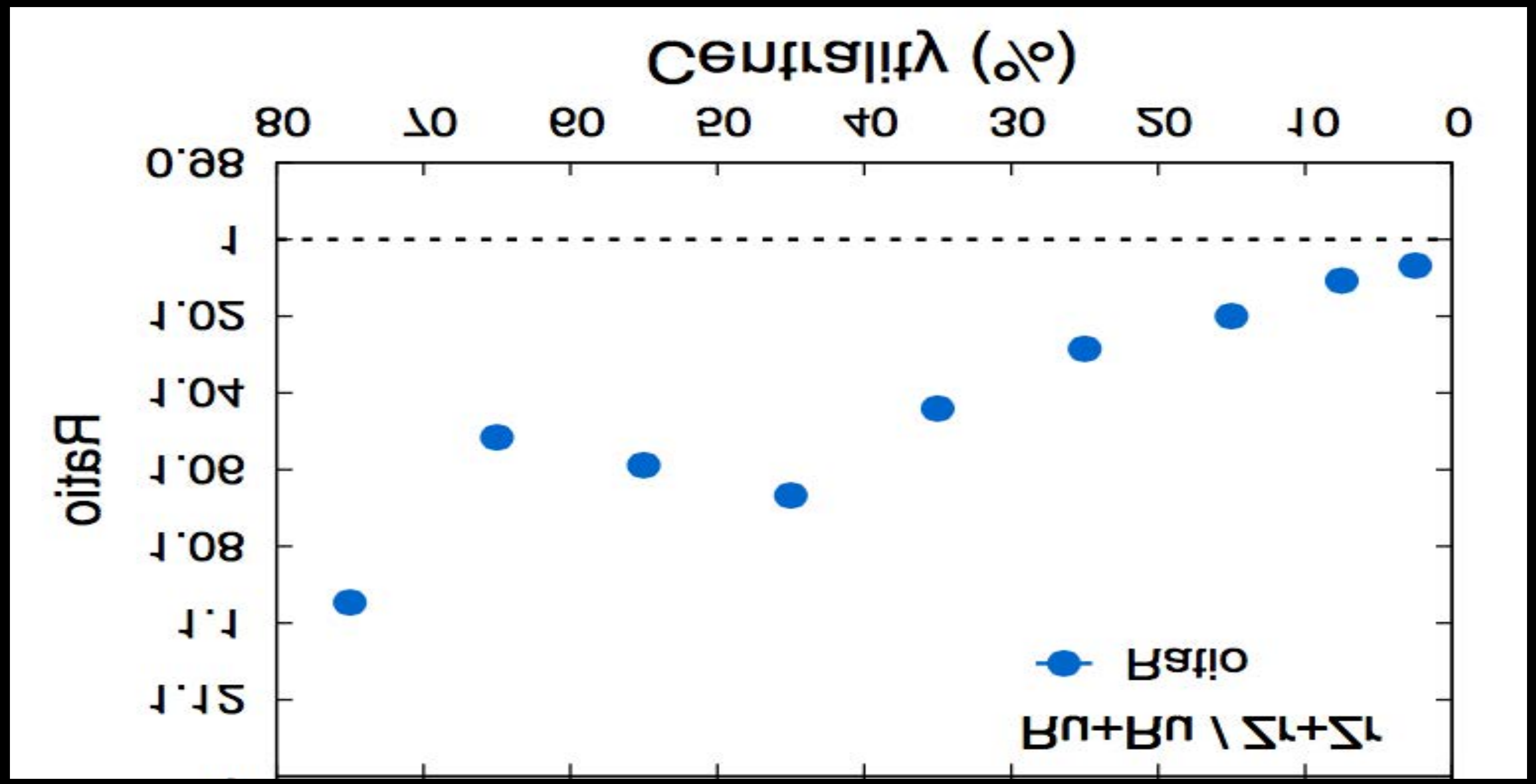
Sergei Voloshin, DNP 2021

$$\frac{(N_{\rm ch})_{\rm RuRu}}{(N_{\rm ch})_{\rm ZrZr}}$$

Multiplicity is larger in Ru+Ru



Flip



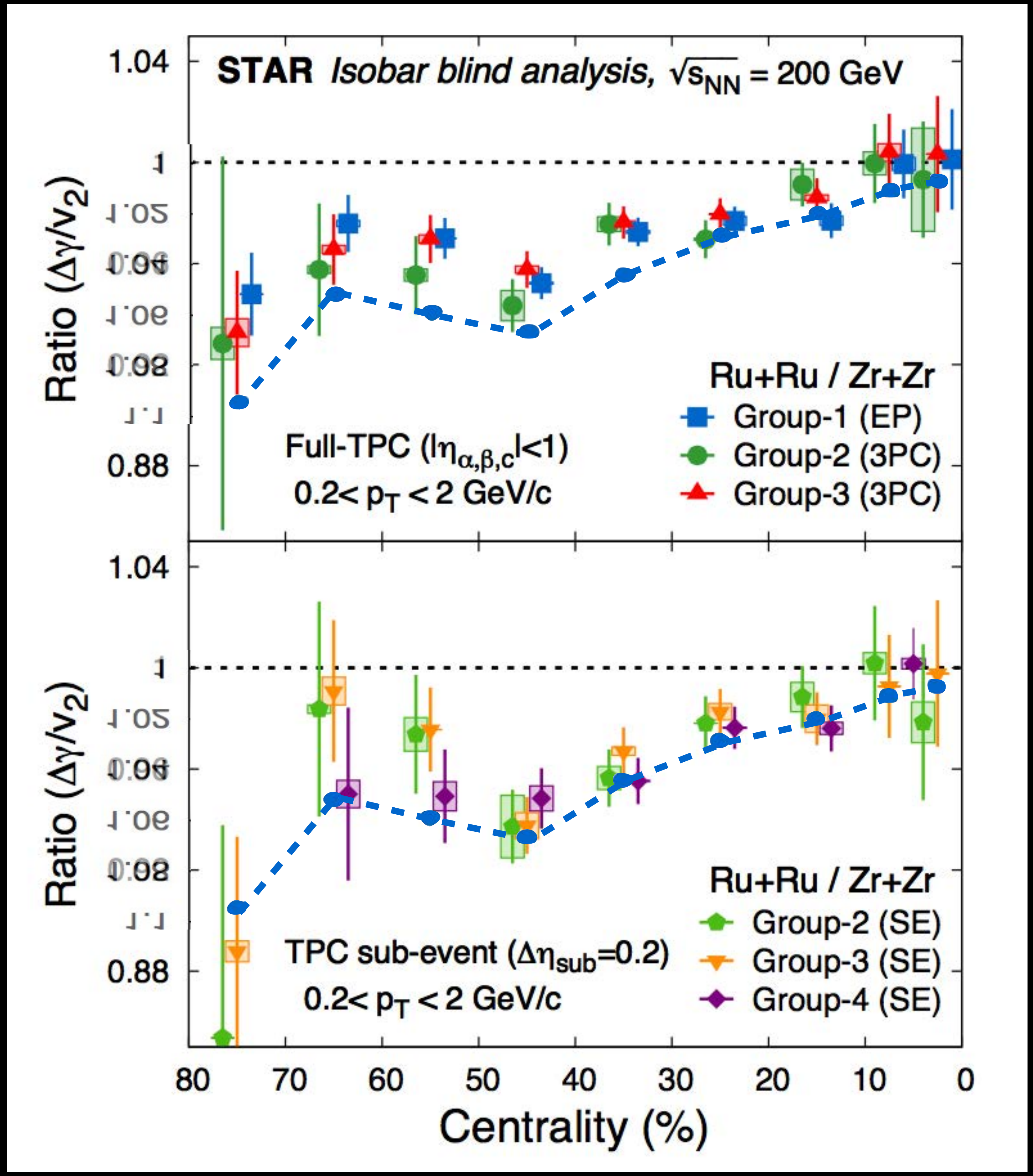
Dilution ~ 1/multiplicity is more in Ru+Ru

$$\frac{(1/N_{\rm ch})_{\rm RuRu}}{(1/N_{\rm ch})_{\rm ZrZr}}$$

overlay

Change of baseline from “1” to 1/multiplicity

$$\frac{(\Delta\gamma/v_2)_{\rm Ru+Ru}}{(\Delta\gamma/v_2)_{\rm Zr+Zr}} \leftrightarrow \frac{N_{\rm Zr+Zr}}{N_{\rm Ru+Ru}}$$

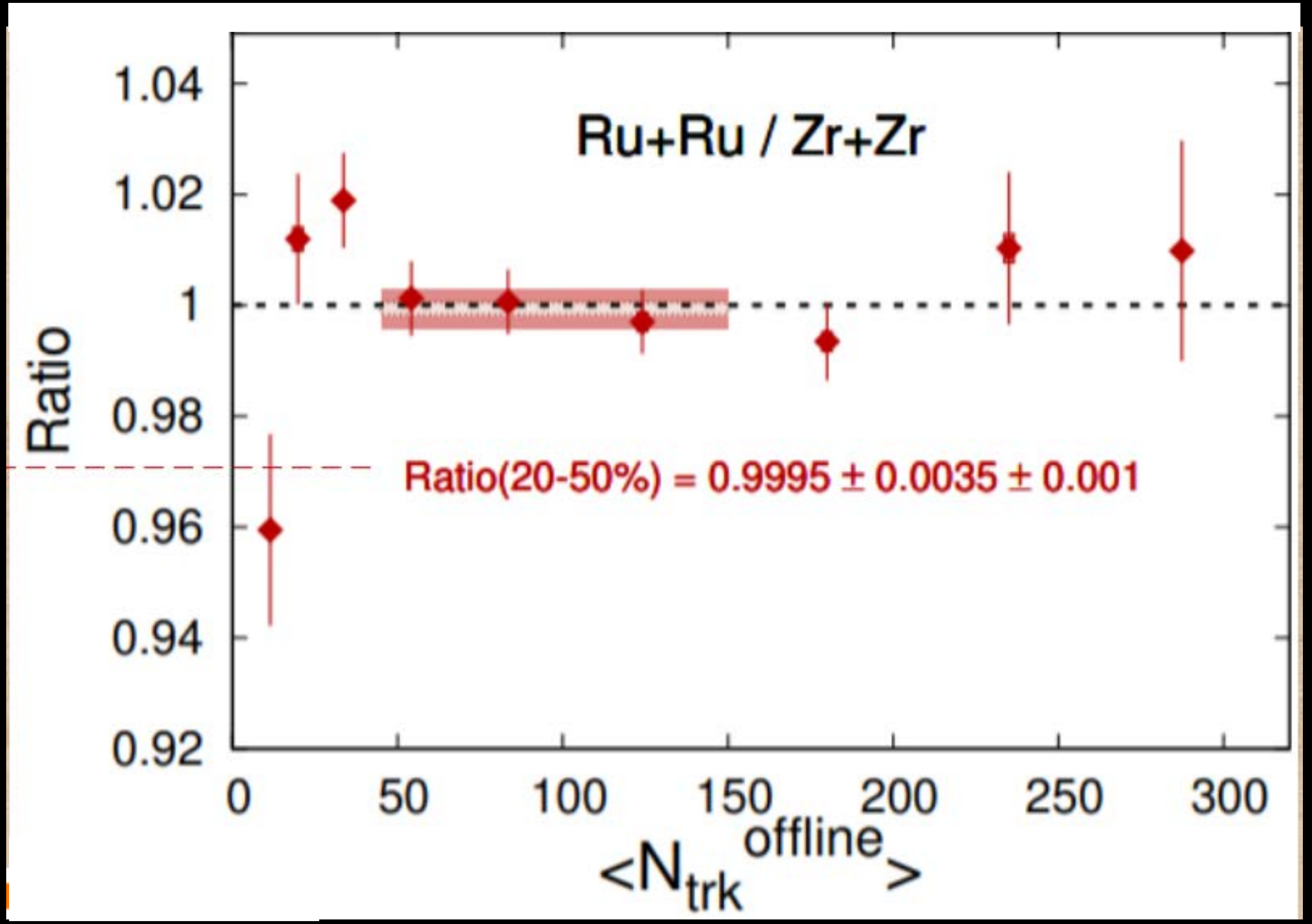


Investigation is on to extract a CME upper-limit

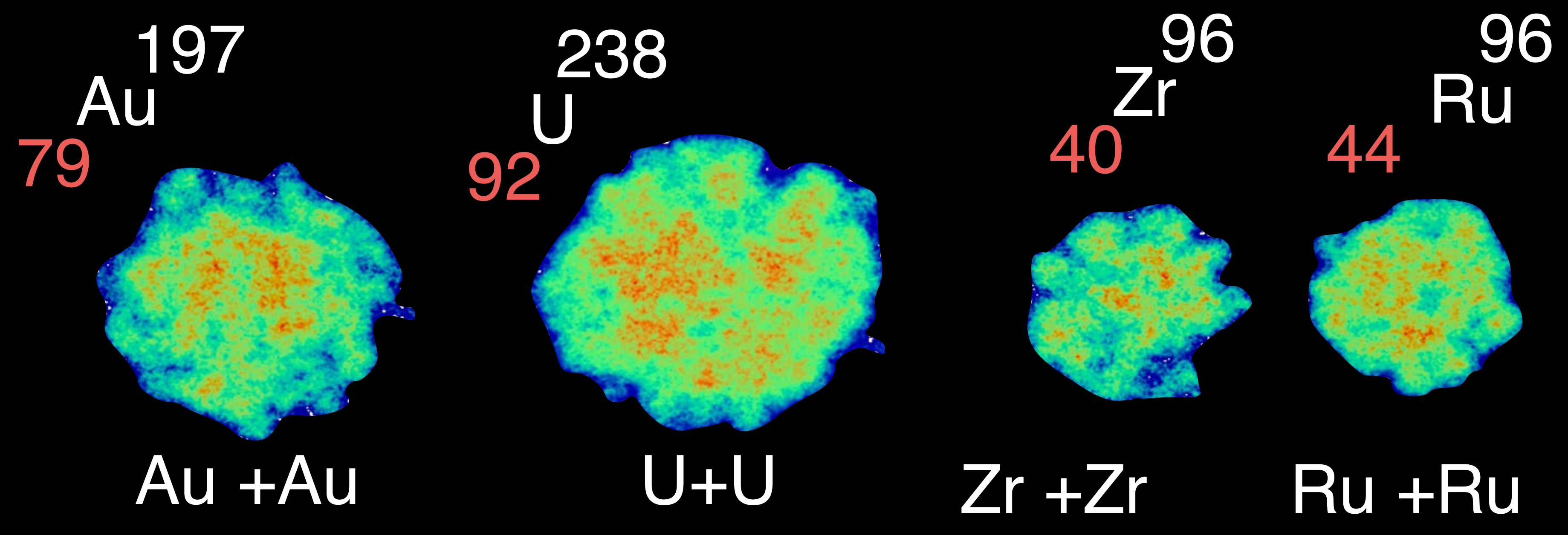
How to understand isobar results ?

Gang Wang, Chirality workshop, 2021

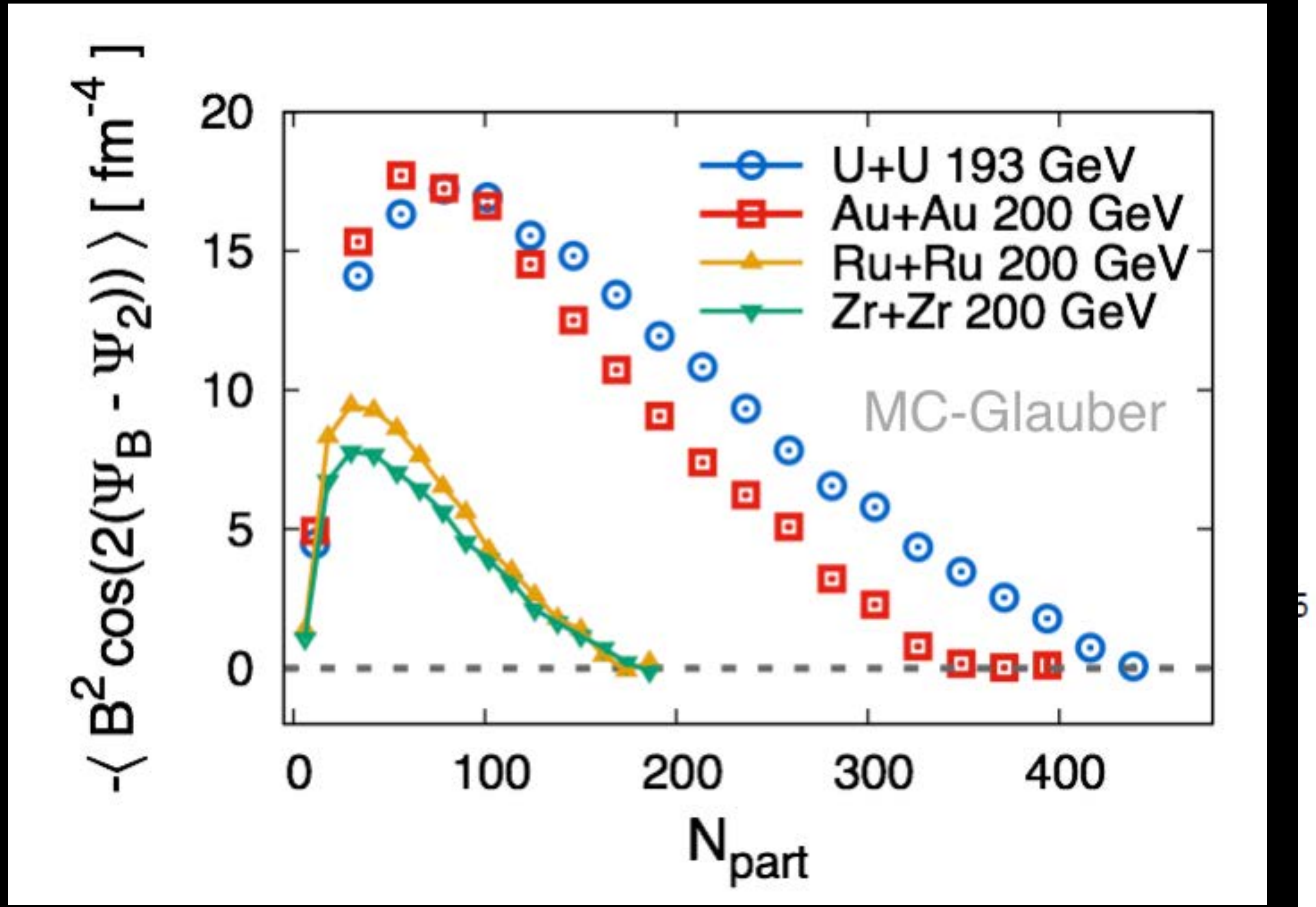
$$\kappa_{112} \equiv \frac{\Delta\gamma_{112}}{v_2 \cdot \Delta\delta}$$



Interpolation (not re-analysis) at same multiplicity

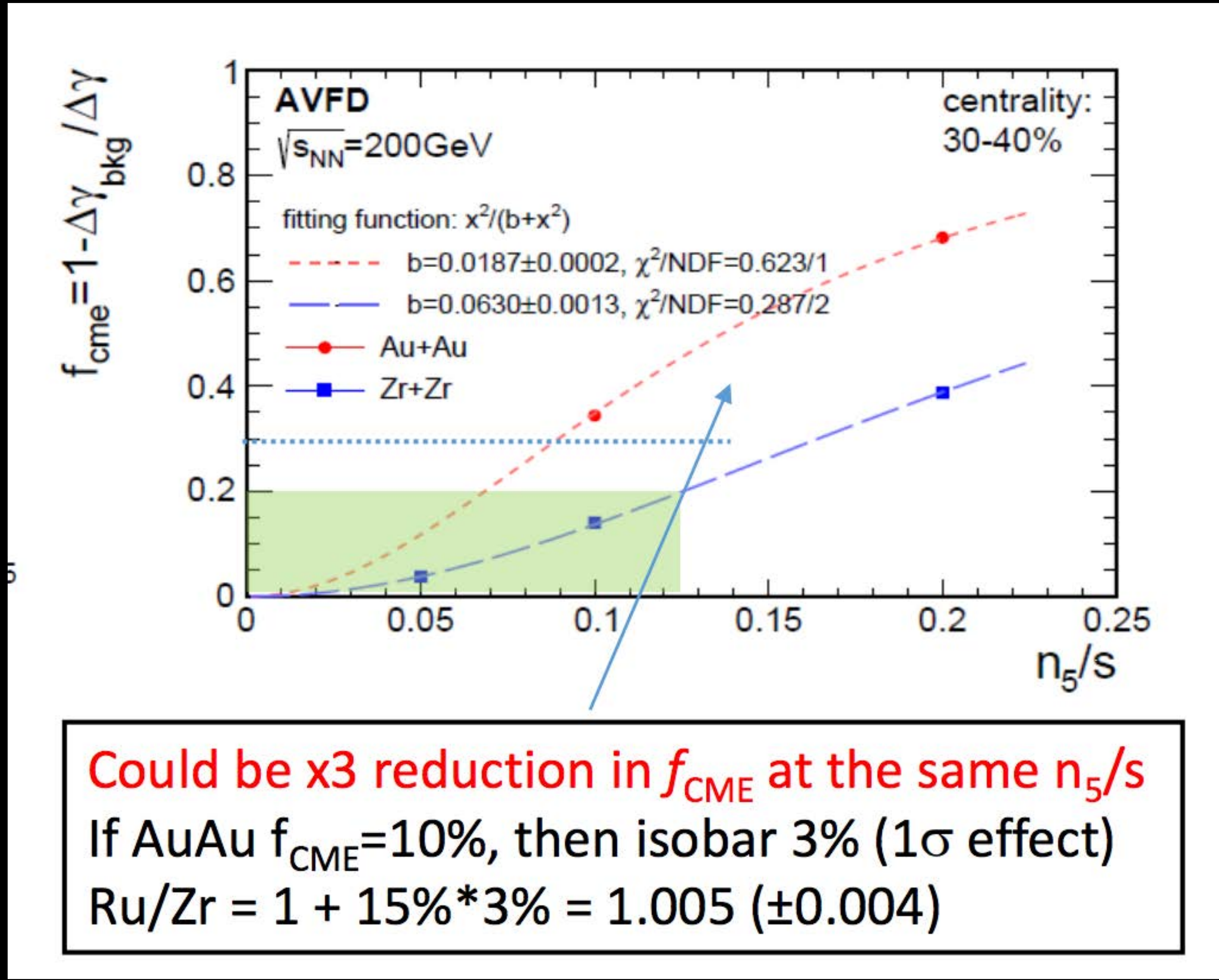


Single (b=0) collision in IP-Glasma model, Ru, Zr parameters : Deng et al PRC 94,041901 (2016)



B-filed in isobars compared to Au+Au/U+U

Fuqiang Wang, Chirality workshop, 2021

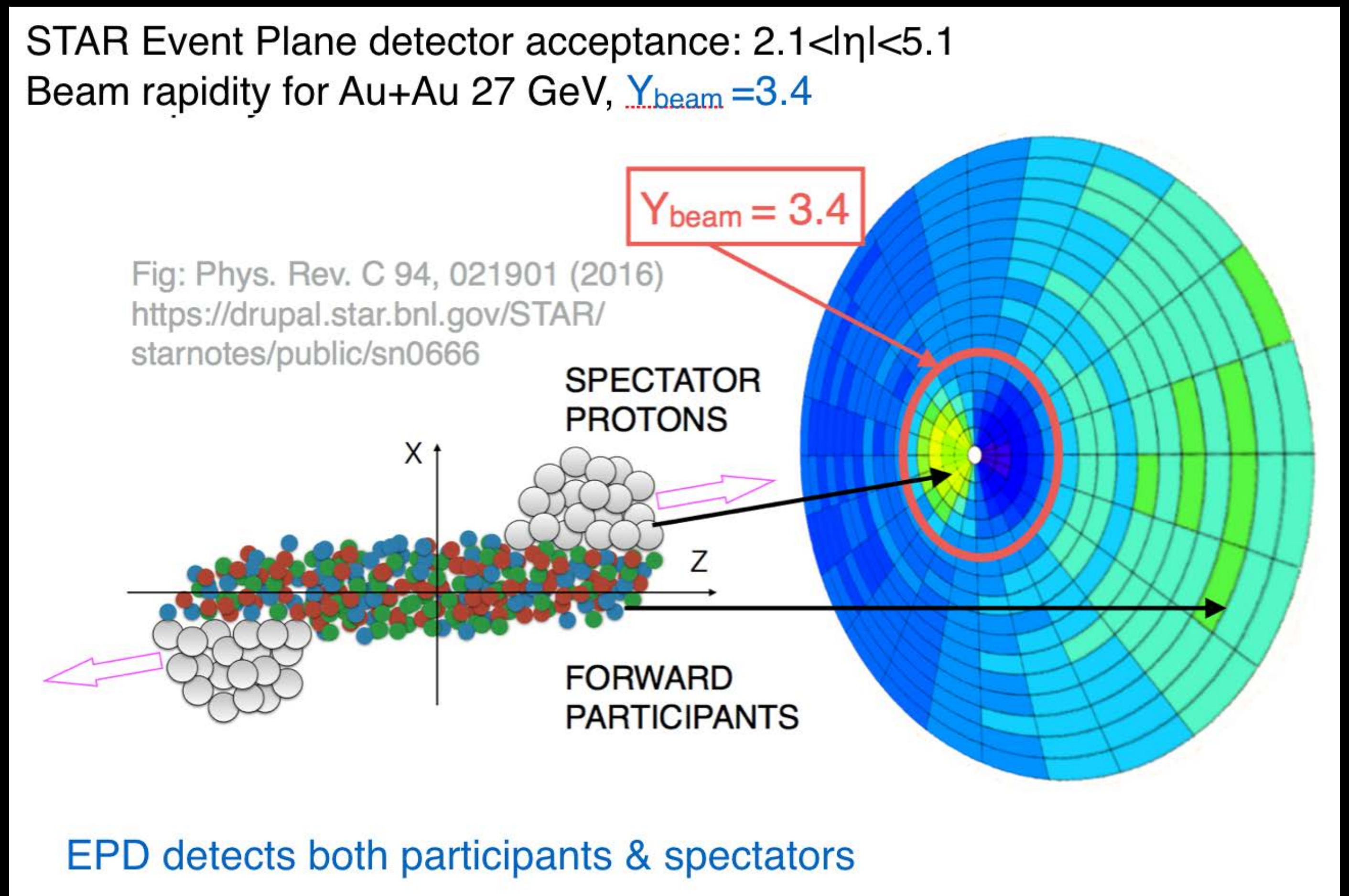


Reduction of signal in isobar system

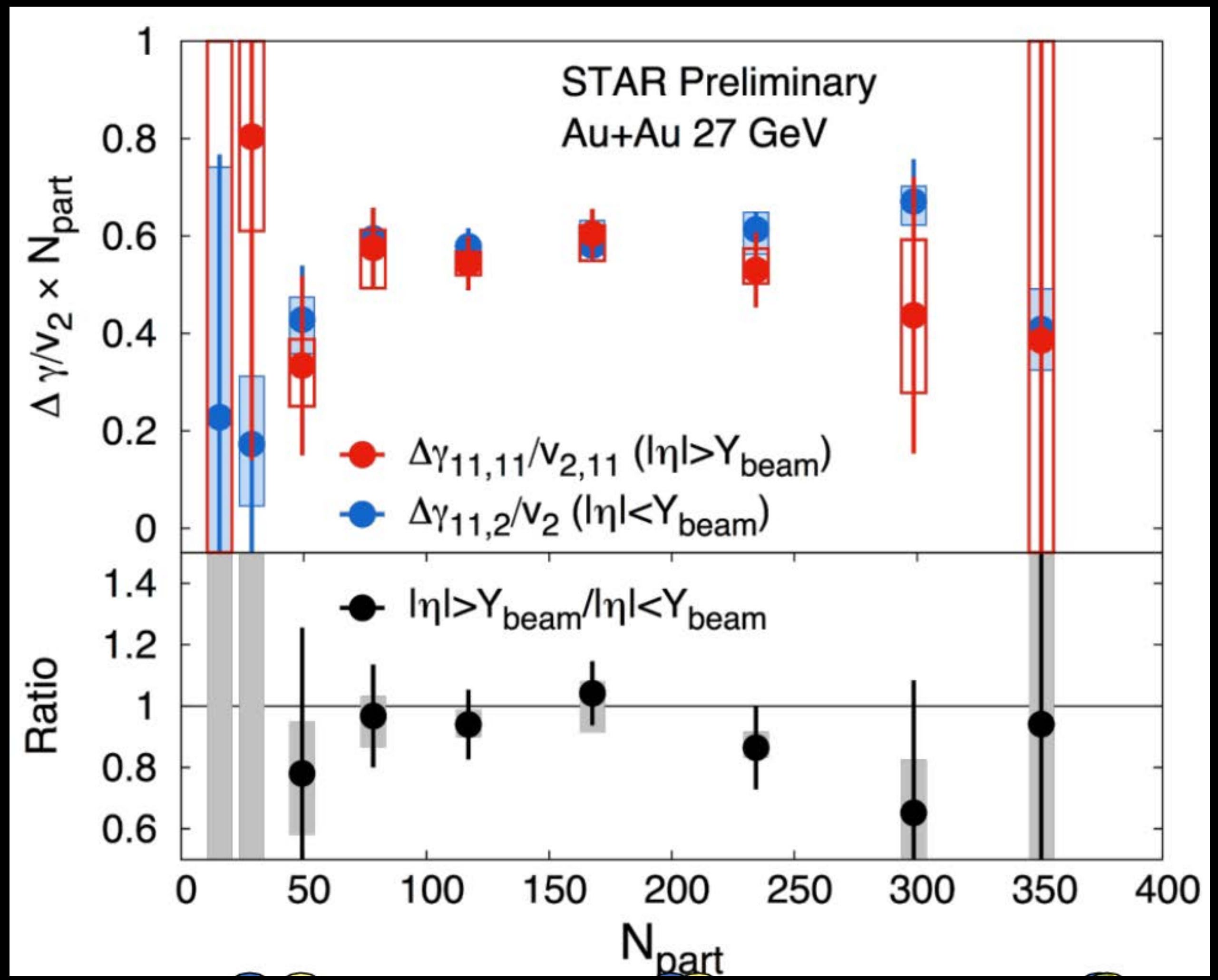
Y. Feng et. al., Phys. Lett. B 820, 136549 (2021), arXiv:2103.10378 [nucl-ex].

What is the future of CME search?

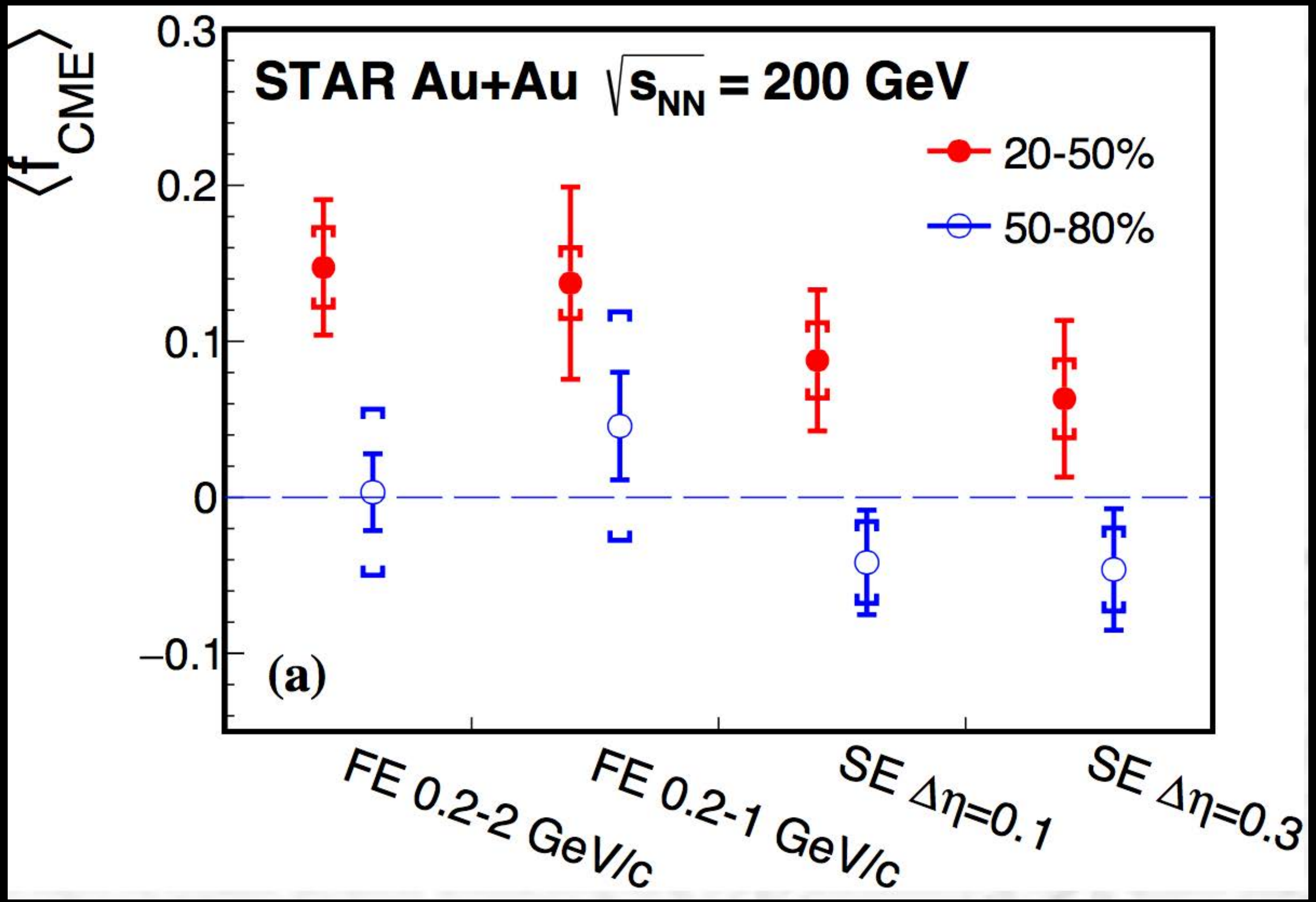
STAR EPD: better handle on B-field direction (1912.05243)



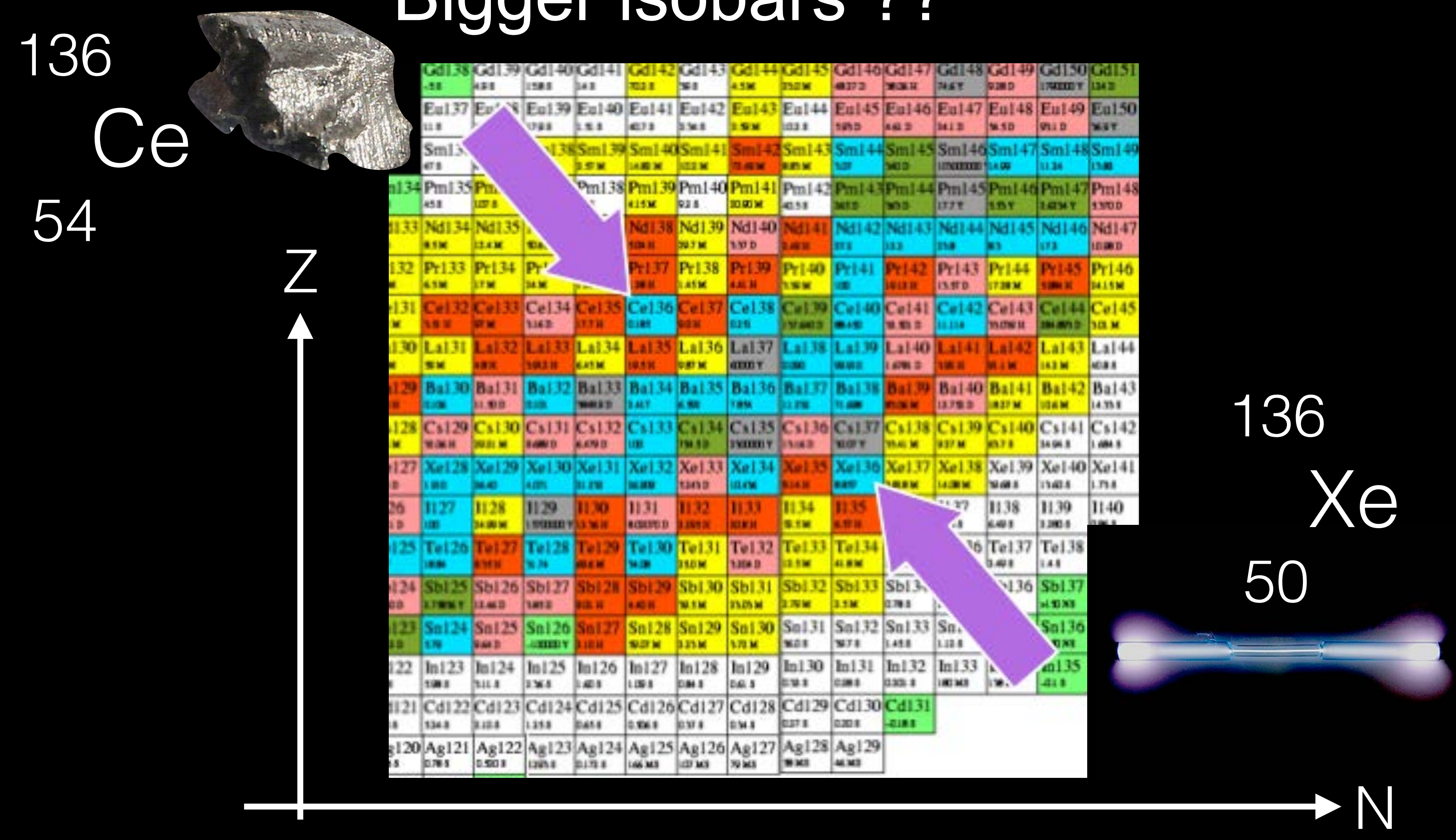
CME @ BES-II data arXiv:2110.15937
Criticality & CME 2012.02926



High statistics RHIC 2023 run
CME in Au+Au (2106.09243)



Bigger isobars ??



CME search with AIML
(2105.13761)

DeepDream

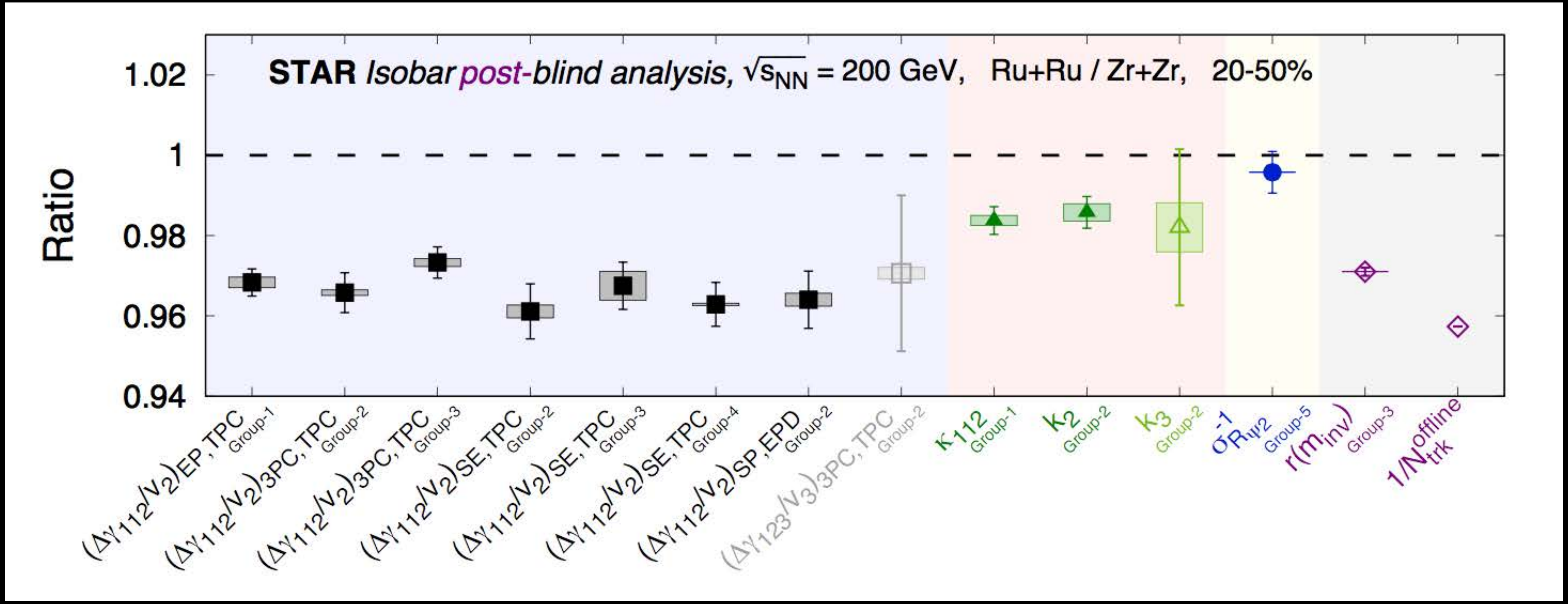
Summary

Experimental test of CME in isobar collisions performed using a blind analysis

A precision down to 0.4% achieved but no pre-defined signature of CME is observed

Primary CME observable $\Delta\gamma/v_2$ baseline is affected by the multiplicity difference (4% in 20-50%), post-blind analysis is needed to search for residual CME signal

CME search has been narrowed down, future program will look for upper limit (1% level)



Thank You