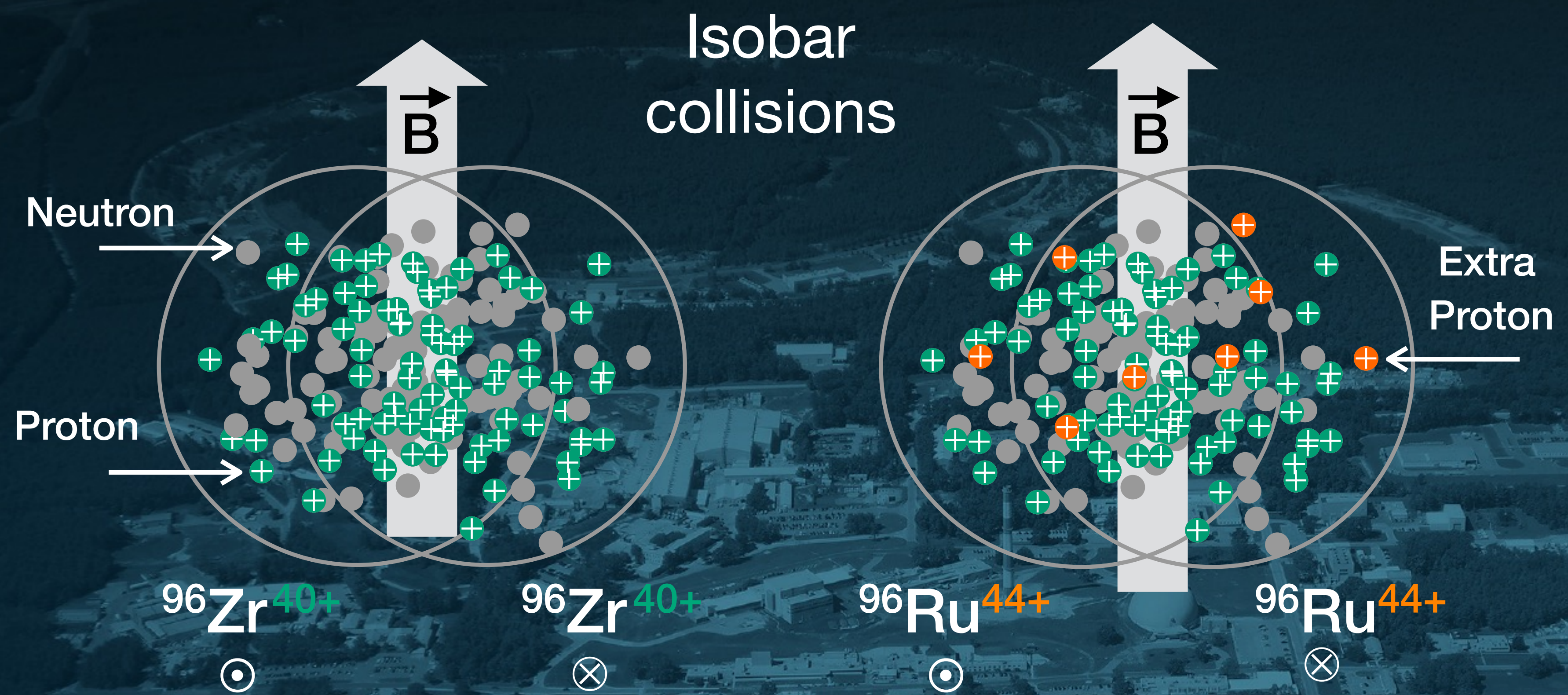


Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

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

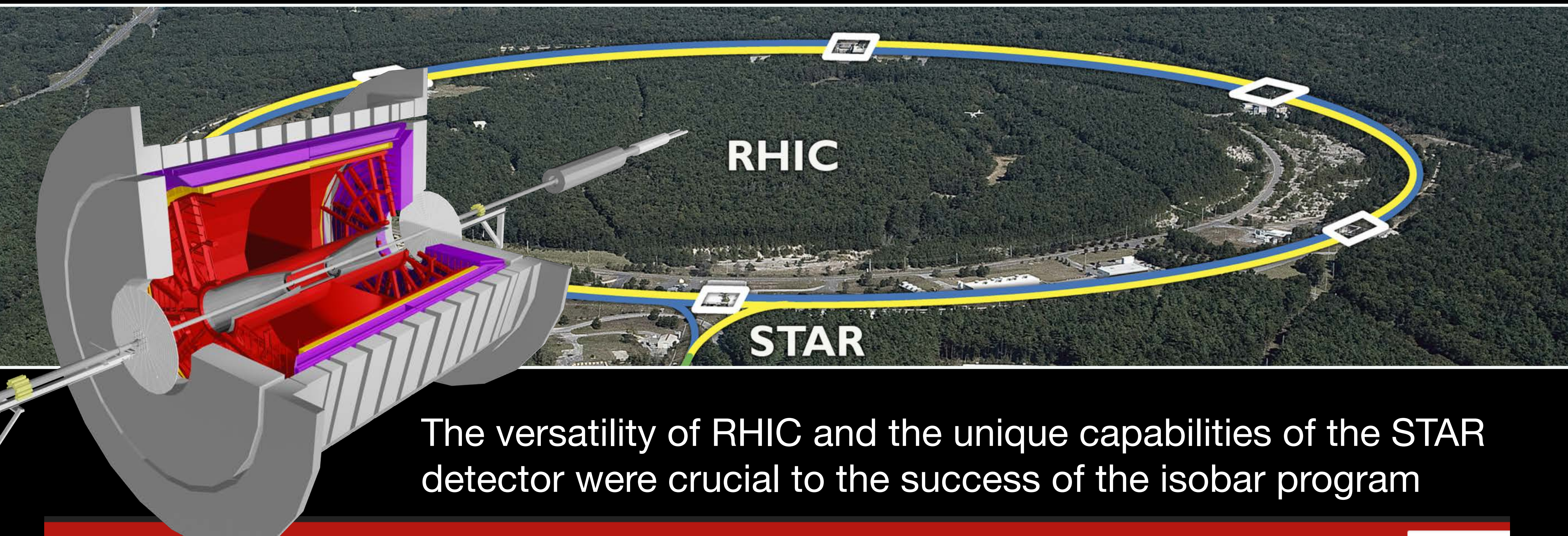
Prithwish Tribedy
(Brookhaven National Laboratory)

RBRC RIKEN BNL Research Center

RBRC seminar, Sept 2, 2021

Based on: https://arxiv.org/abs/2109.00131

Isobar program: long journey since early 2018



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

arXiv.org > nucl-ex > arXiv:2109.00131

Search...
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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

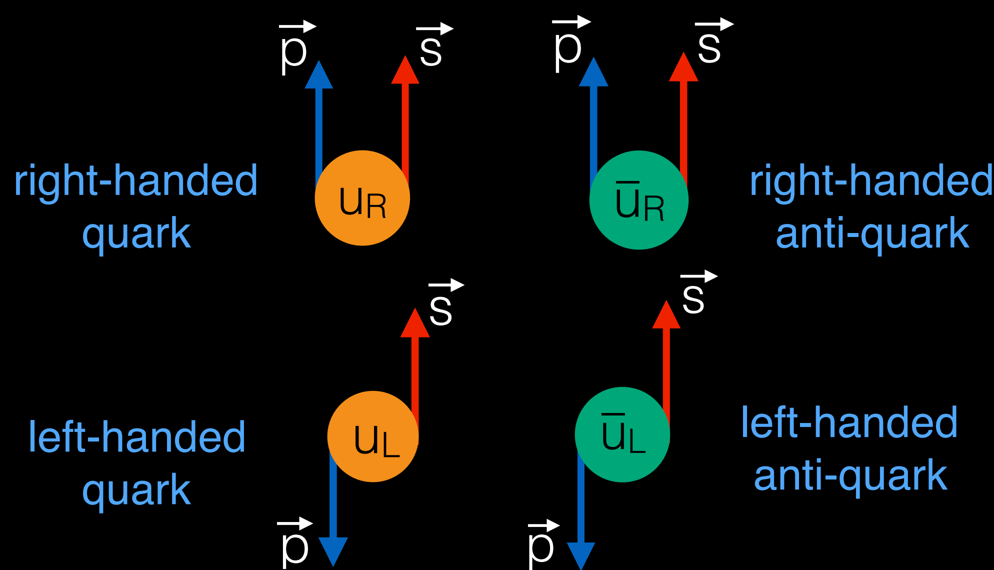
STAR Collaboration: M. S. Abdallah, B. E. Aboona, J. Adam, L. Adamczyk, J. R. Adams, J. K. Adkins, G. Agakishiev, I. Aggarwal, M. M. Aggarwal, Z. Ahammed, I. Alekseev, D. M. Anderson, A. Aparin, E. C. Aschenauer, M. U. Ashraf, F. G. Atetalla, A. Attri, G. S. Averichev, V. Bairathi, W. Baker, J. G. Ball Cap, K. Barish, A. Behera, R. Bellwied, P. Bhagat, A. Bhasin, J. Bielcik, J. Bielcikova, I. G. Bordyuzhin, J. D. Brandenburg, A. V. Brandin, I. Bunzarov, 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. Chattopadhyay, D. Chen, J. Chen, J. H. Chen, X. 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, L. Di Carlo, L. Didenko, P. Dixit, X. Dong, 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. Fedorisin, C. J. Feng, Y. Feng, P. Filip, E. Finch, Y. 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 additional authors not shown)

The chiral magnetic effect (CME) is predicted to occur as a consequence of a local violation of $\mathcal{P}$ and $\mathcal{CP}$ symmetries of the strong interaction amidst a strong electro-magnetic field generated in relativistic heavy-ion collisions. Experimental manifestation of the CME involves a separation of positively and negatively charged hadrons along the direction of the magnetic field. Previous measurements of the CME-sensitive charge-separation observables remain inconclusive because of large background contributions. In order to better control the influence of signal and backgrounds, the STAR Collaboration performed a blind analysis of a large data sample of approximately 3.8 billion isobar collisions of ${}^{96}_{44}$Ru+${}^{96}_{44}$Ru and ${}^{96}_{40}$Zr+${}^{96}_{40}$Zr at $\sqrt{s_{NN}} = 200$ GeV. Prior to the blind analysis, the CME signatures are predefined as a significant excess of the CME-sensitive observables in Ru+Ru collisions over those in Zr+Zr collisions, owing to a larger magnetic field in the former. A precision down to 0.4% is achieved, as anticipated, in the relative magnitudes of the pertinent observables between the two isobar systems. Observed differences in the multiplicity and flow harmonics at the matching centrality indicate that the magnitude of the CME background is different between the two species. No CME signature that satisfies the predefined criteria has been observed in isobar collisions in this blind analysis.

Comments: 43 pages, 27 figures
Subjects: **Nuclear Experiment (nucl-ex)**; High Energy Physics - Experiment (hep-ex); High Energy Physics - Phenomenology (hep-ph); Nuclear Theory (nucl-th)

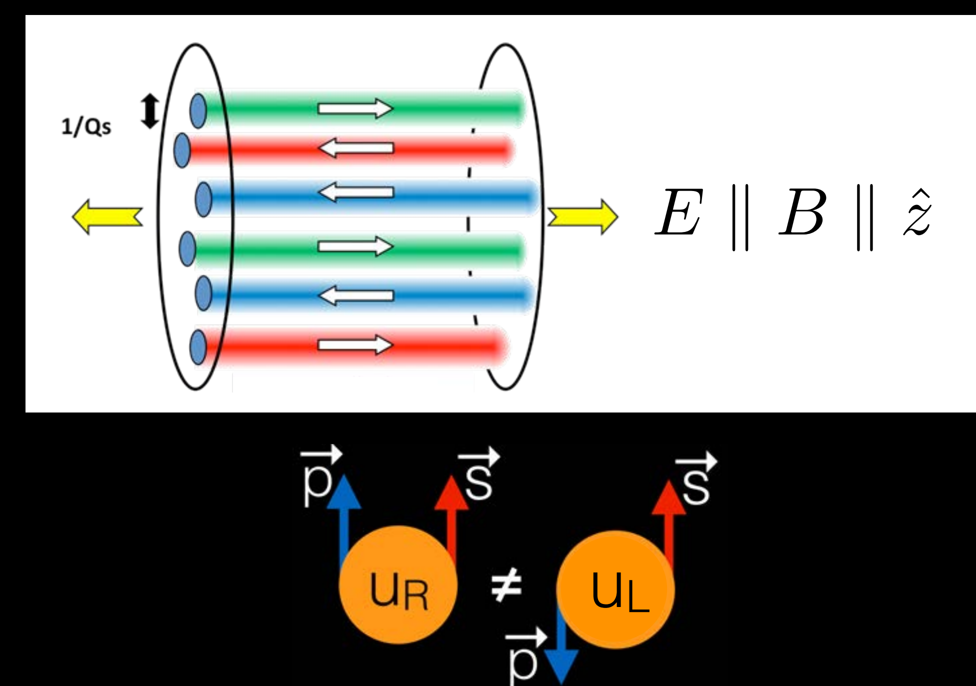
Key players in the game

1 Deconfined medium of massless quark (chiral symmetry restored)



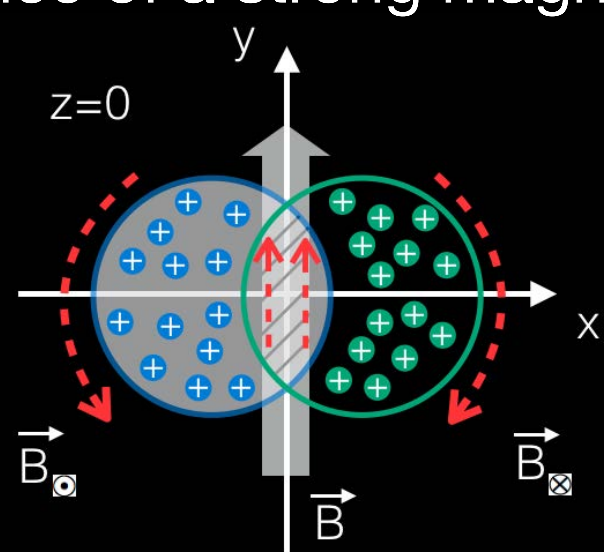
Kharzeev, McLerran,Warringa 0711.0950

2 Mechanism to create imbalance of left & right handed quarks



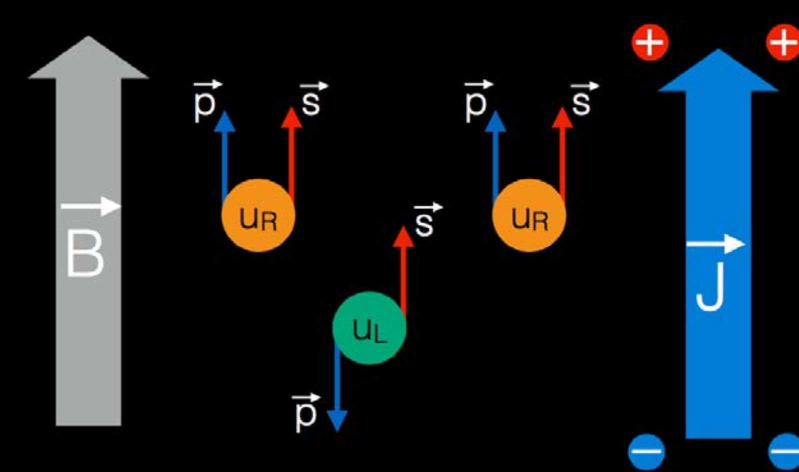
Kharzeev et al, hep-ph/0109253, Mace et al, 1601.07342, Muller et. al.1606.00342, Lappi et al,1708.08625

3 Presence of a strong magnetic-field



Kharzeev et al 0711.0950, Skokov et al 0907.1396, McLerran et al 1305.0774

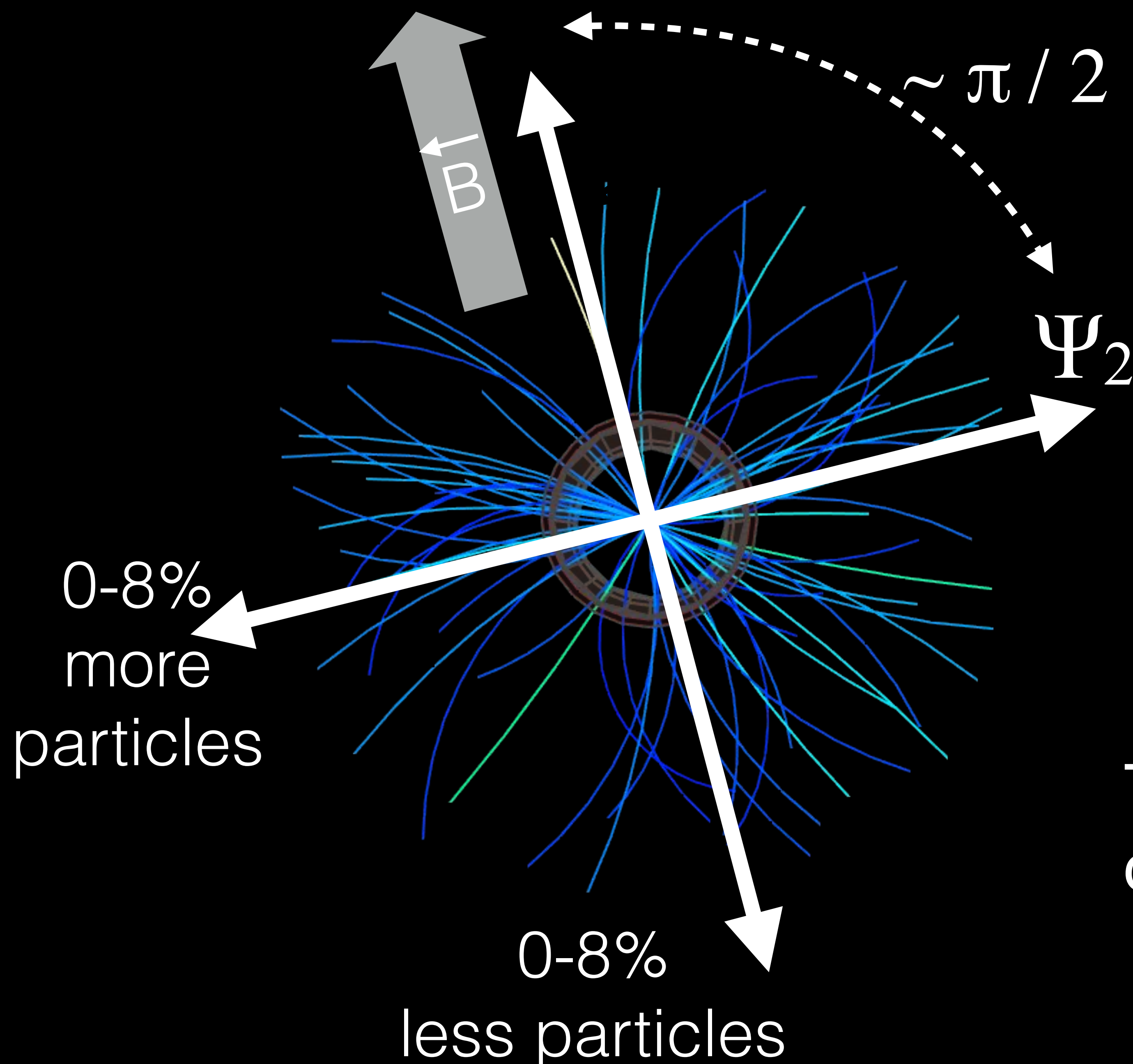
4 Chiral Magnetic Effect (J || B)



Kharzeev, arXiv:hep-ph/0406125

How do we detect it : find B-field direction

Elliptic anisotropy is measured by correlation between two particles



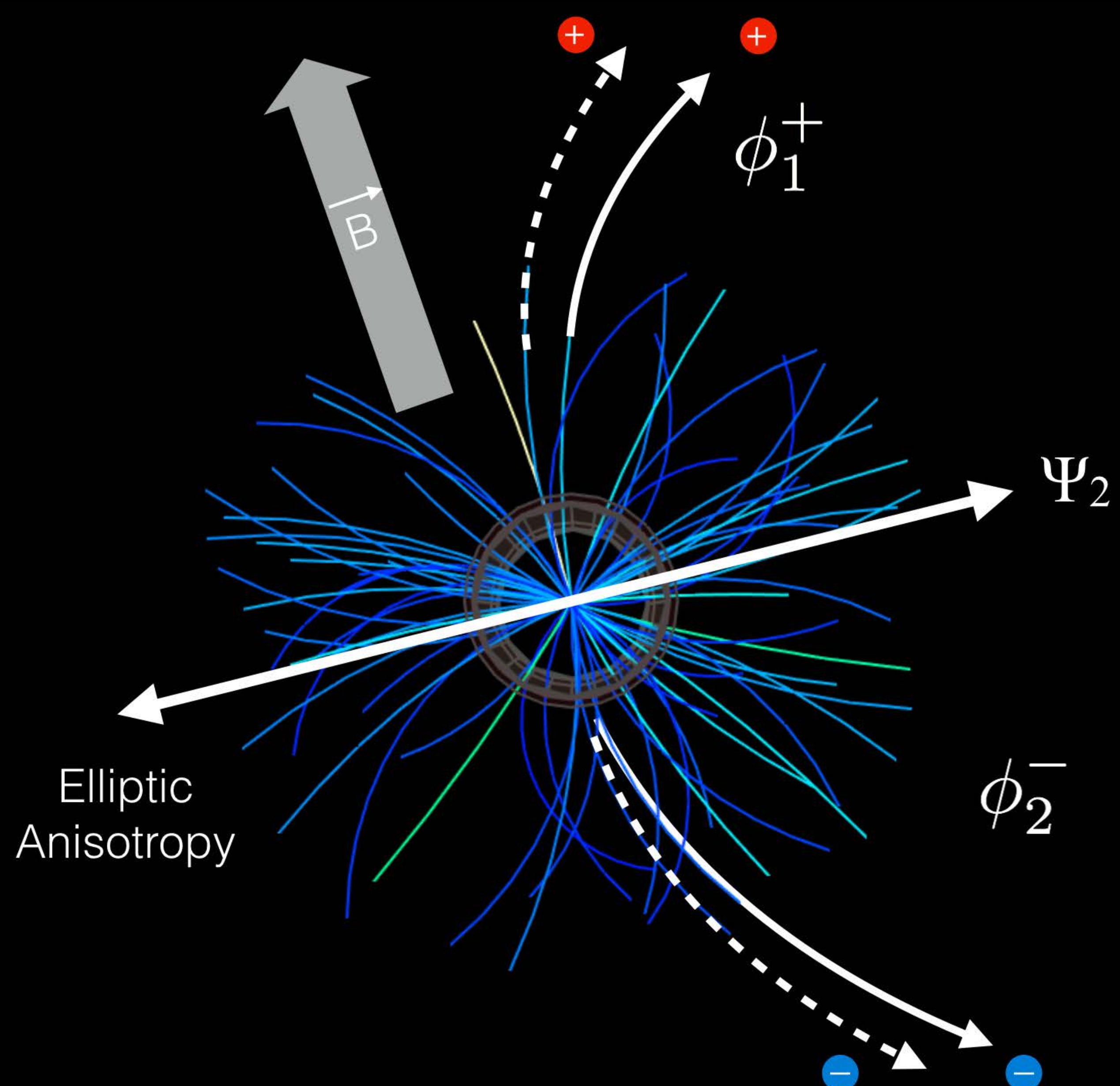
$$v_2\{EP\} = \langle \cos(2\phi_1 - 2\Psi_2) \rangle$$

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

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

How do we detect it : measure charge separation

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 : $\gamma^{ss} \neq \gamma^{os}$

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

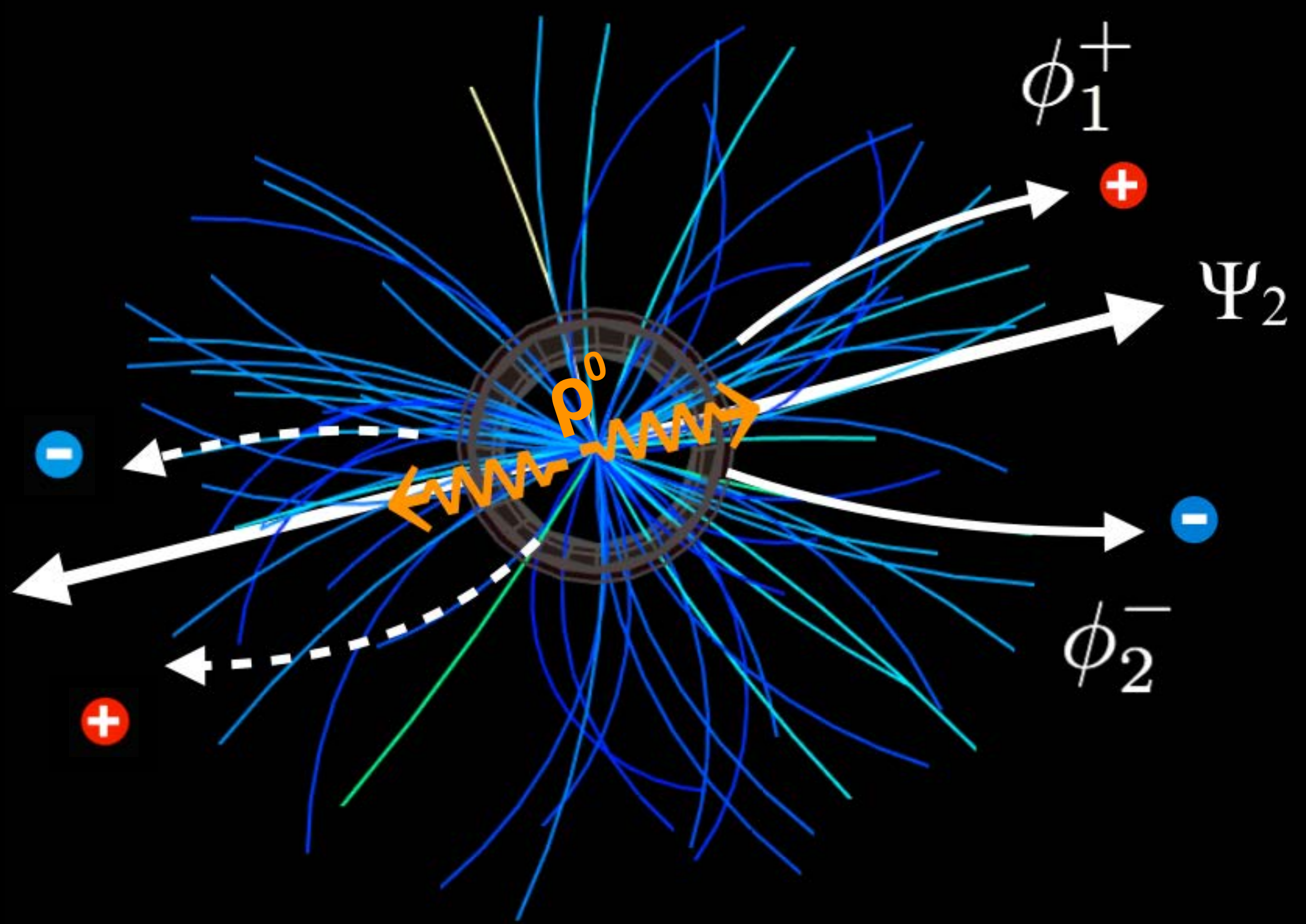
Quantity of interest:

$$\Rightarrow \Delta\gamma^{CME} = \gamma^{os} - \gamma^{ss} > 0$$

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

How do we detect it : measure charge separation

Measure charge separation across Ψ_2 using the correlator:



Voloshin, hep-ph/0406311

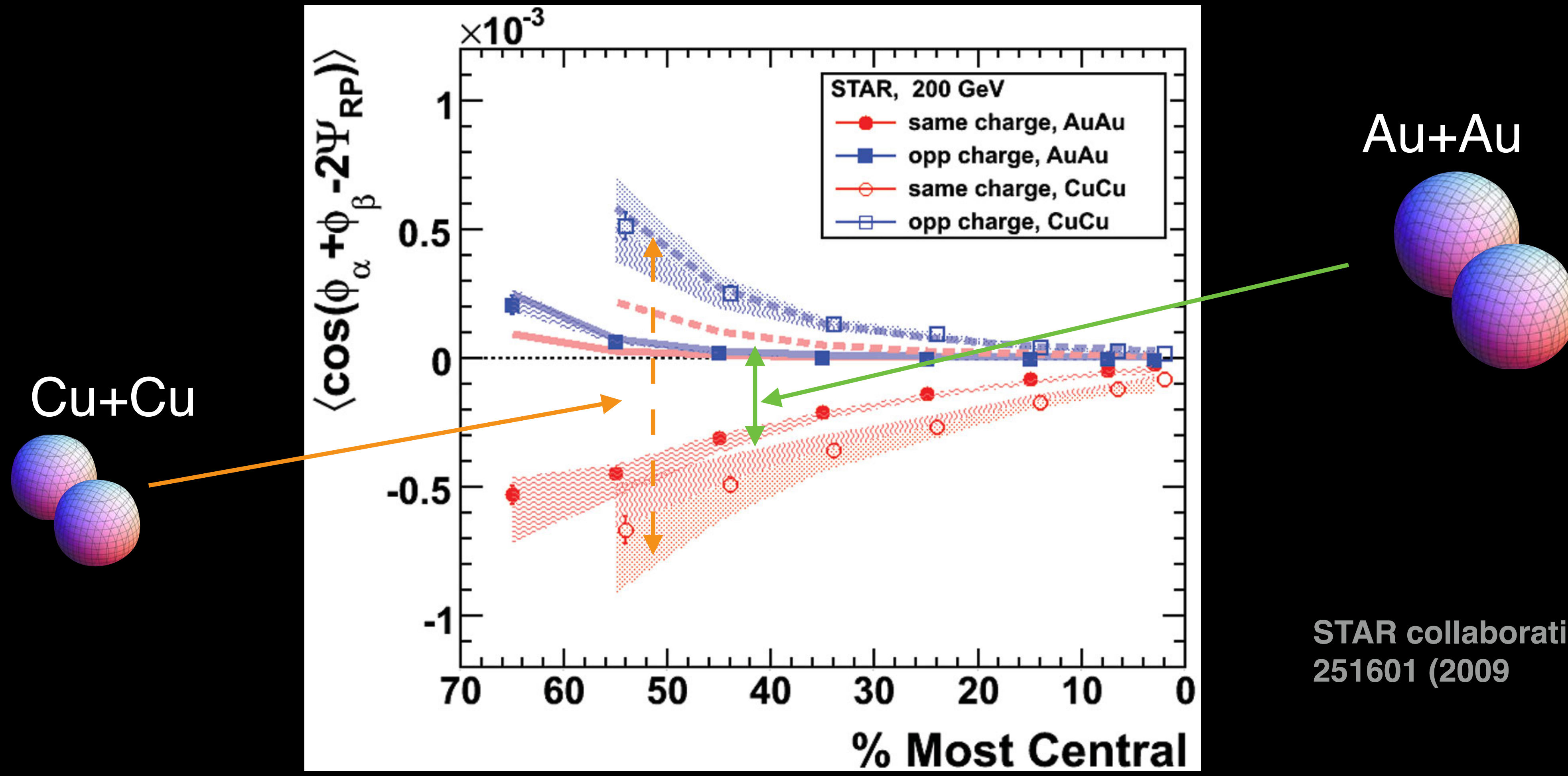
$$\gamma^{\alpha,\beta} = \langle \cos(\phi_1^\alpha + \phi_2^\beta - 2\Psi_2) \rangle$$

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

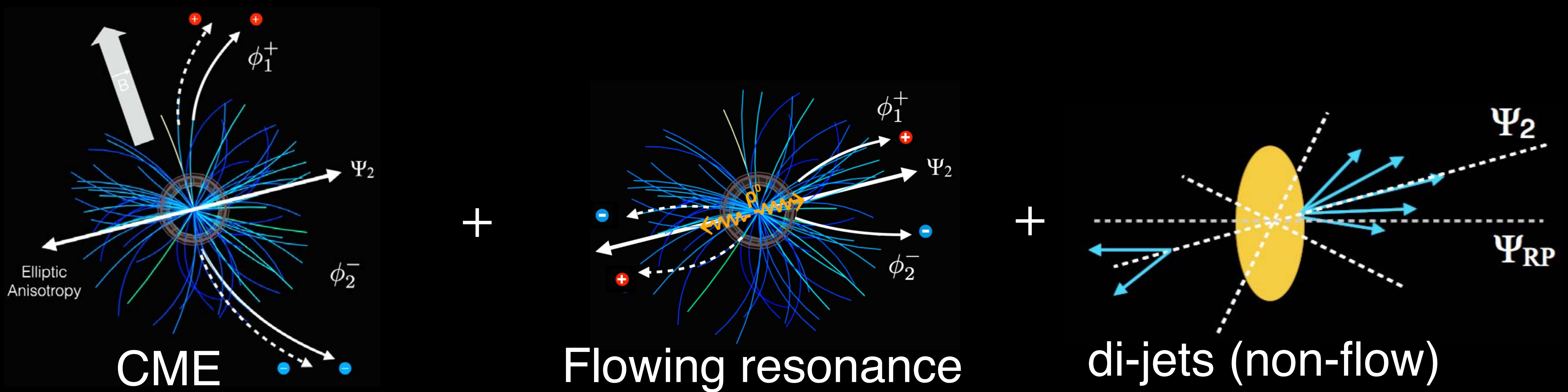
$$\gamma^{+-} = \cos(0+0+0) = 1$$
$$\gamma^{++,--} = \cos(0+\pi+0) = -1$$

Non-CME effect such as flowing resonance decay can lead to difference $\Rightarrow \Delta\gamma^{reso} = \gamma^{os} - \gamma^{ss} \propto \frac{v_2^{reso}}{N}$

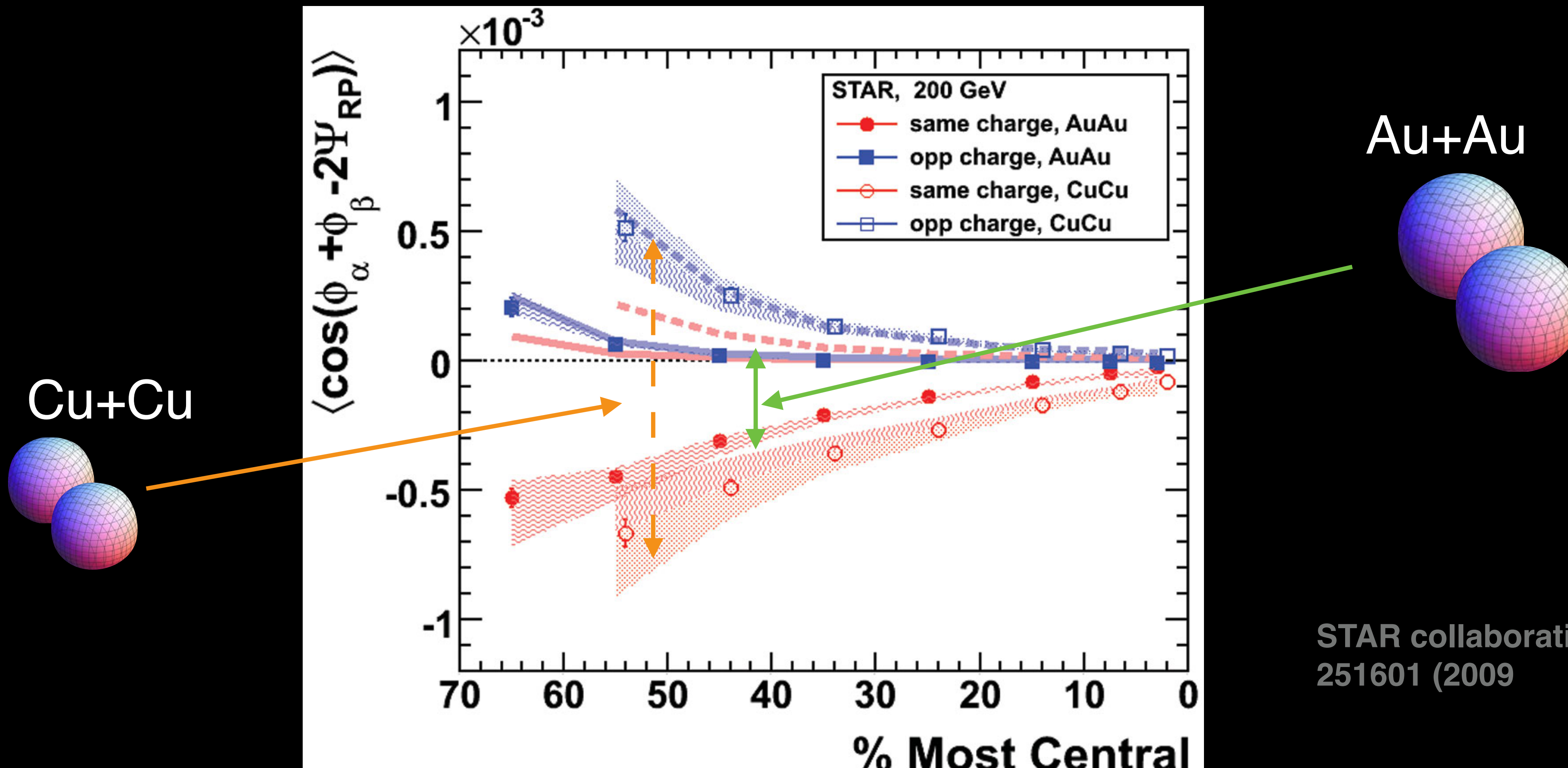
The first measurements at RHIC



STAR collaboration, PRL 103, 251601 (2009



The first measurements at RHIC



STAR collaboration, PRL 103, 251601 (2009

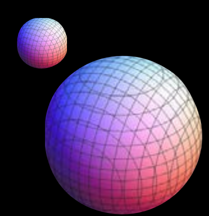
Significant charge separation observed, consistent with CME+ Background

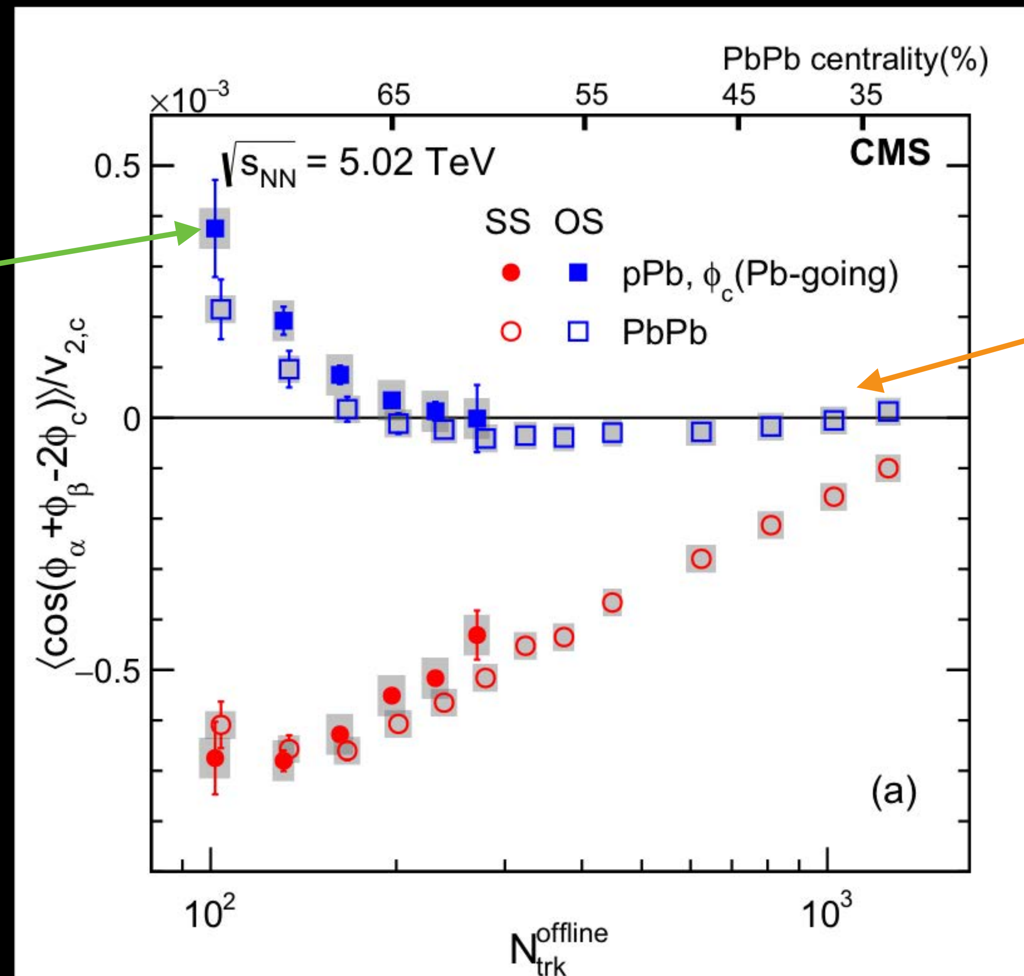
$$\Delta\gamma = \Delta\gamma^{CME} + k \times \frac{v_2}{N} + \Delta\gamma^{non-flow}$$

Measurement Signal Background-1 Background-2

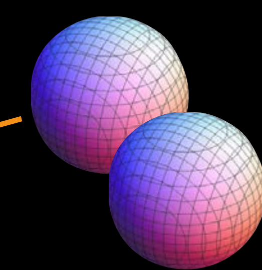
Small system collisions to test CME

p+A





A+A



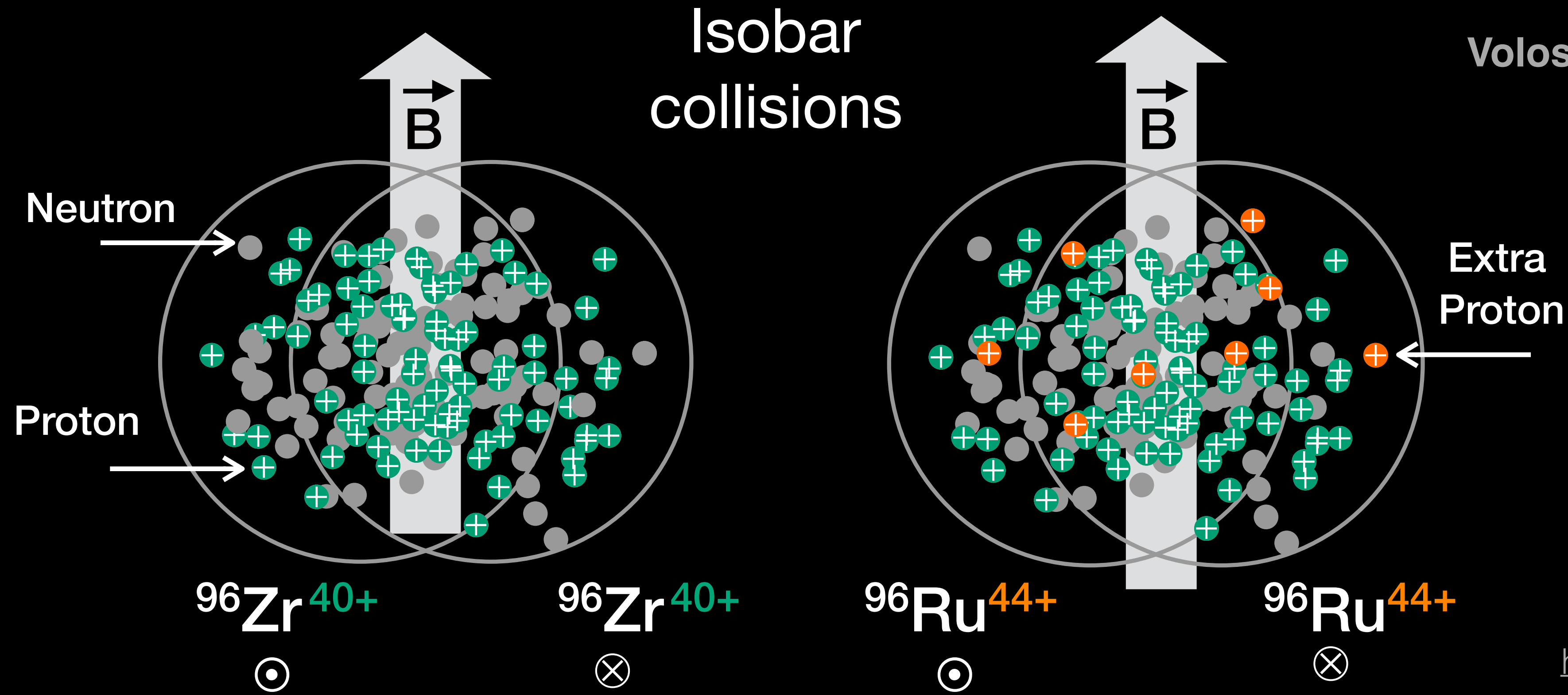
CMS collaboration, Phys. Rev Lett, 118 (2017) 122301

$$\left\{\begin{array}{l} \Delta\gamma^{A+A} = \Delta\gamma^{CME} + k \times \frac{v_2}{N} + \Delta\gamma^{non-flow} \\ \quad \| \qquad\quad \nparallel \qquad\quad \nparallel \qquad\qquad \nparallel \\ \Delta\gamma^{p+A} = \cancel{\Delta\gamma^{CME}} + k \times \frac{v_2}{N} + \Delta\gamma^{non-flow} \end{array}\right.$$

Only two equations & more unknowns 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 collisions



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

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

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

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

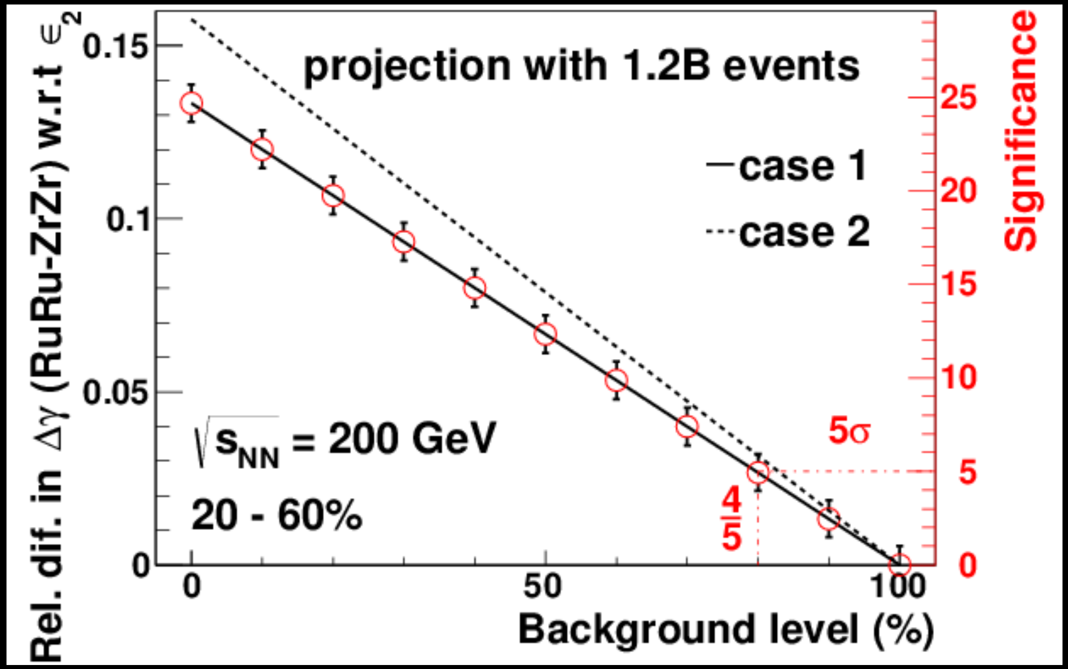
?? $\quad \nparallel \quad \approx \quad \parallel$

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

B-field 10-18% larger in Ru

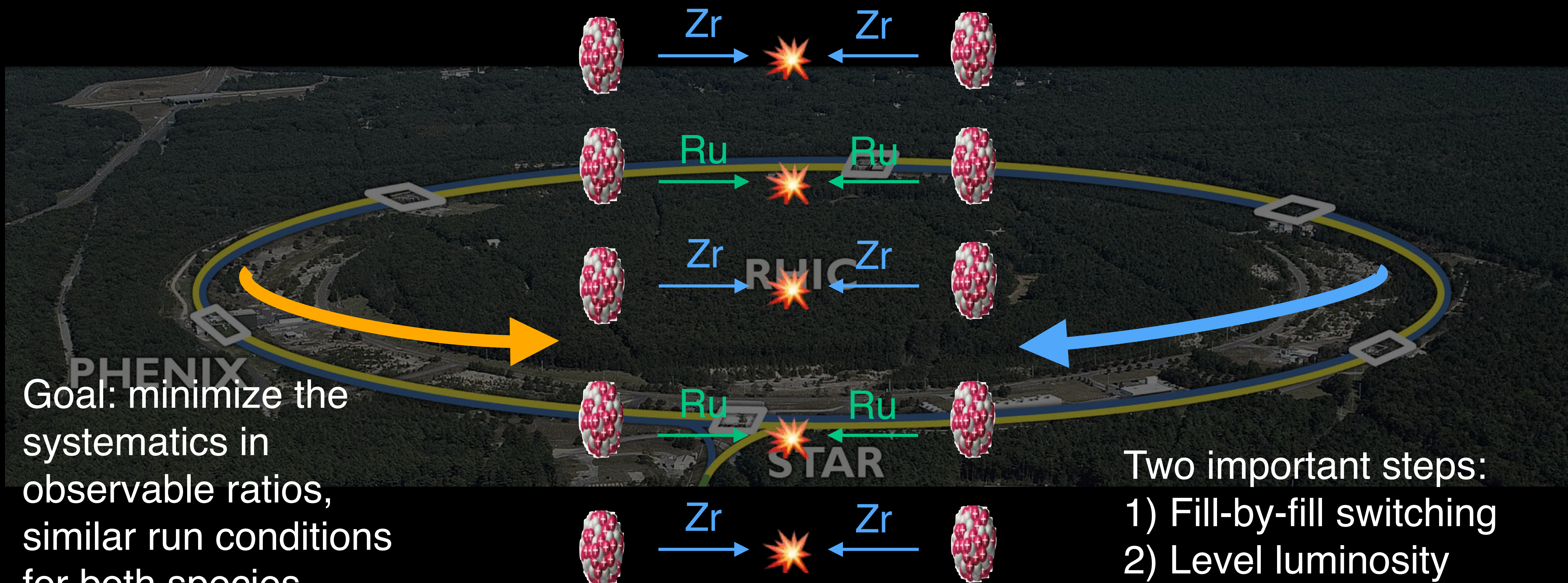
Within 0-4%

Same



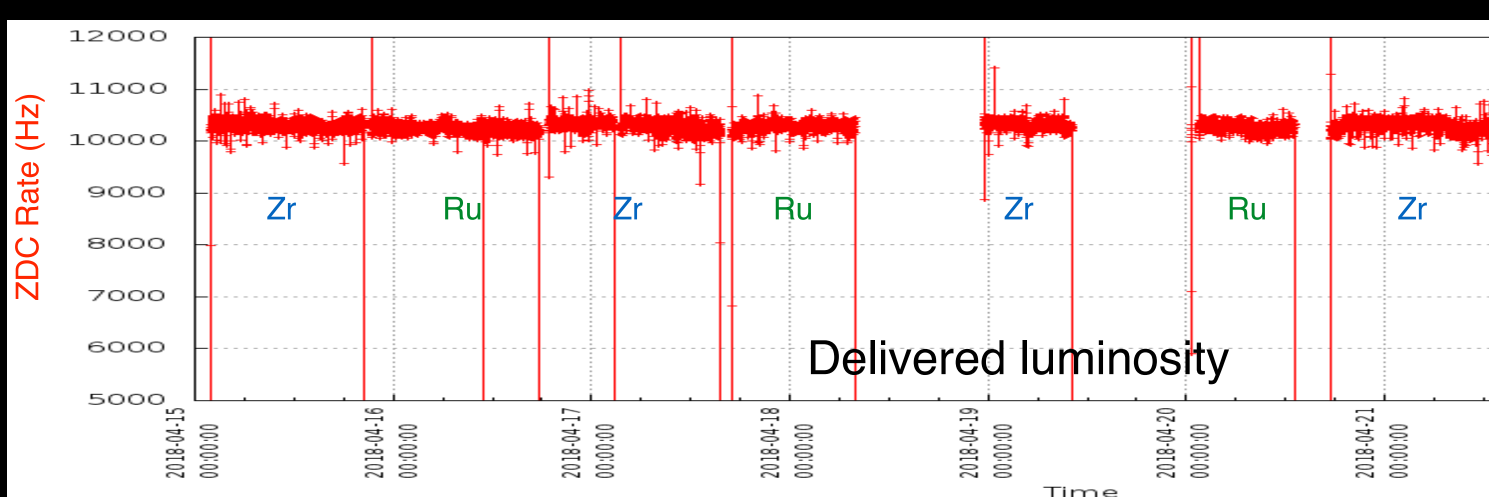
Larger signal in Ru: 1.2 B events can give 5σ significance for 20% signal level

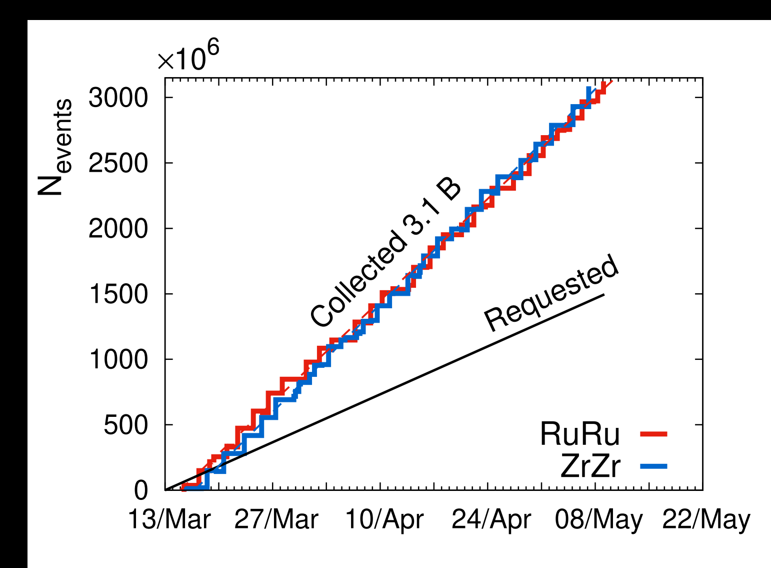
Details Of The Data Taking Of The Isobar Run



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

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





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

Blind analysis of the isobar data

Steps of Isobar blind analysis

Step-0
Mock Data challenge
Test data structure (Au+Au data)

→

Step-1
Isobar Mixed analysis
Code freezing (Each run is Ru+Ru & Zr+Zr)

→

Step-2
Isobar Blind analysis
QA with ~ 1% data (Each run is Ru+Ru or Zr+Zr)

→

Step-3
Isobar Unblind analysis
Final analysis (Ru+Ru & Zr+Zr separated)

Paper Review Committee ↔ Blinding Committee
Five Analysis Groups

NPP PAC recommended a blind analysis of isobar data

Blinding committee decides the procedure

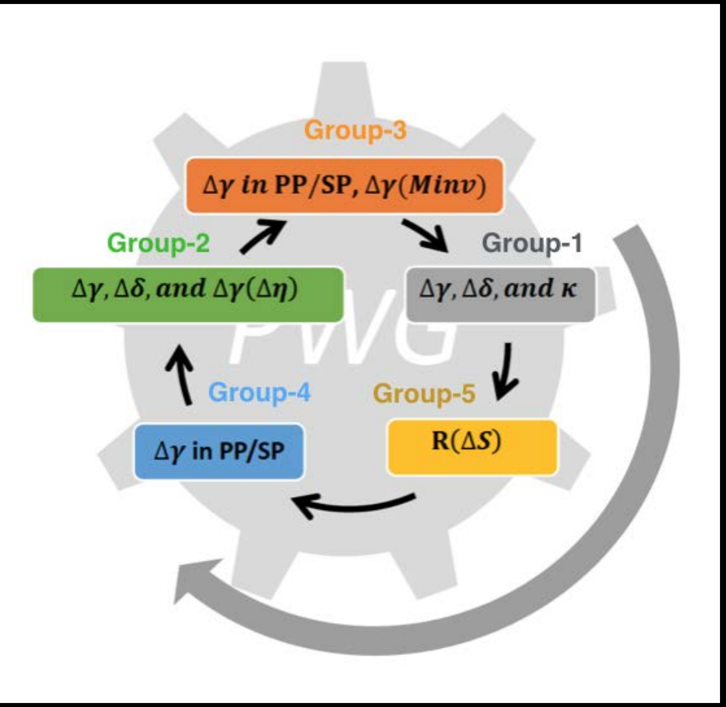
Five independent groups will perform analysis

No access to species-specific information before last step

Everything documented (not written → not allowed)

Case for CME & interpretation must be pre-defined

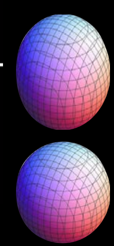
All codes must be frozen and run by another person



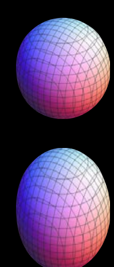
Centrality determination

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

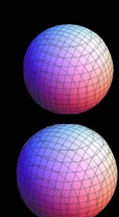
Nucleus	Case-1 [83] R (fm)	a (fm)	β_2
$^{96}_{44}$Ru	5.085	0.46	0.158
$^{96}_{40}$Zr	5.02	0.46	0.08

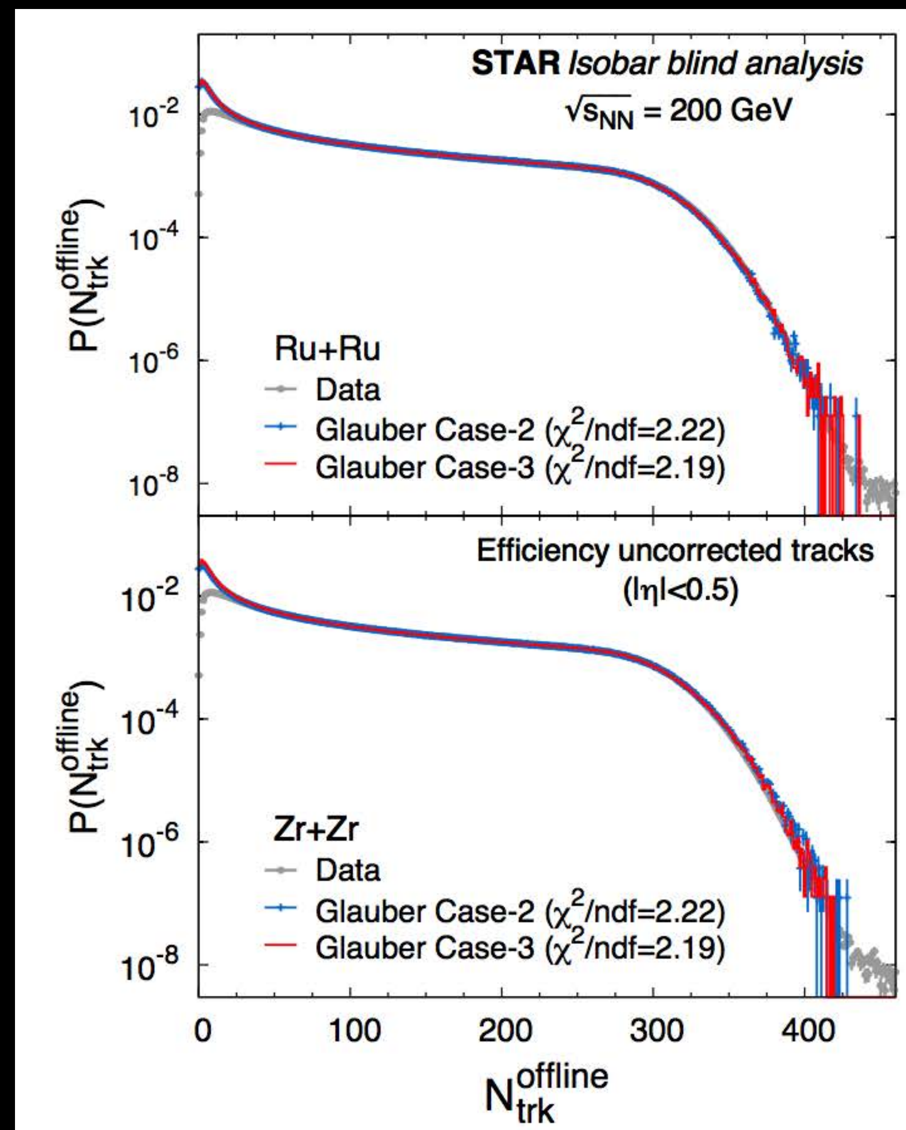


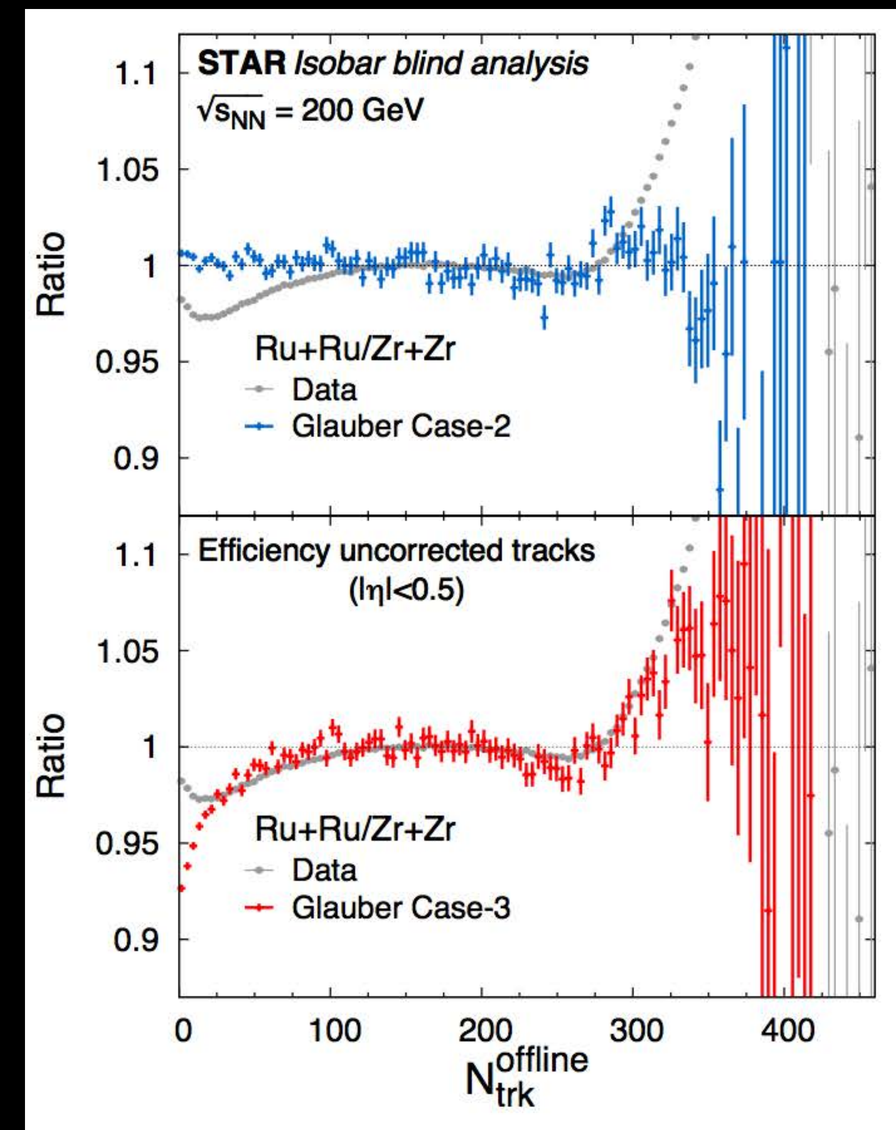
Nucleus	Case-2 [83] R (fm)	a (fm)	β_2
$^{96}_{44}$Ru	5.085	0.46	0.053
$^{96}_{40}$Zr	5.02	0.46	0.217



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



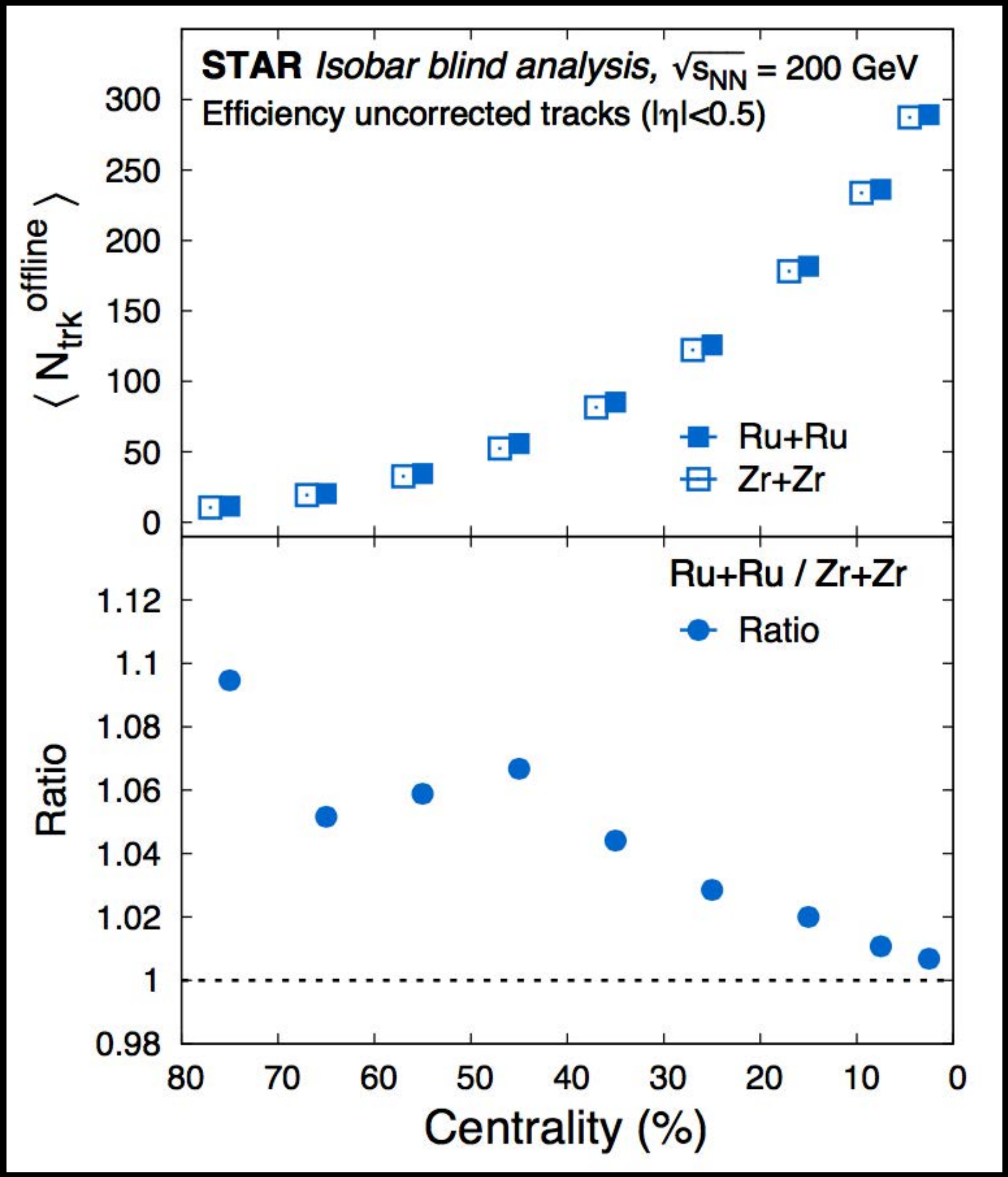




See references in:
[83] Deng et. al., Phys. Rev. C 94, 041901 (2016), arXiv:1607.04697 [nucl-th].
[113] Xu et. al., Phys. Rev. Lett. 121, 022301 (2018), arXiv:1710.03086 [nucl-th].

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

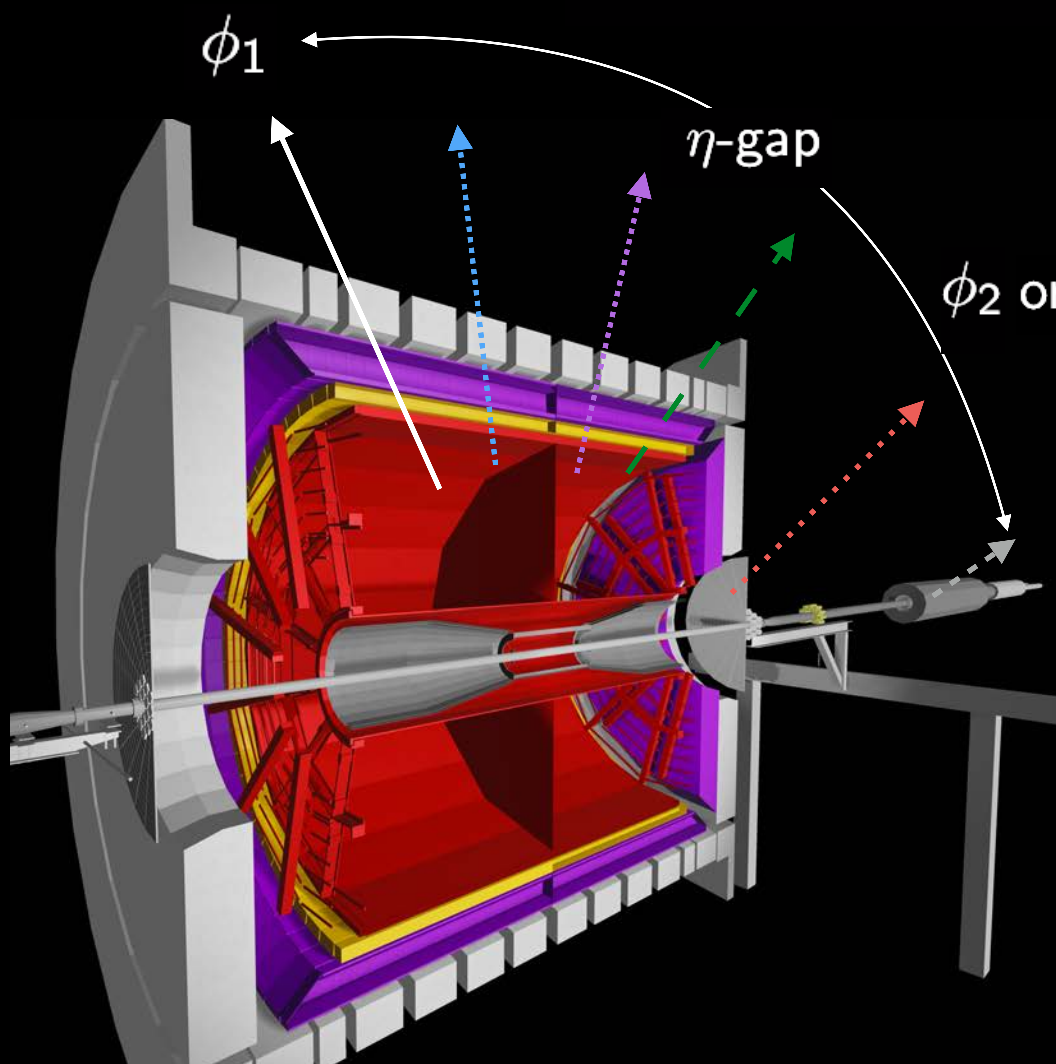
Multiplicity difference between the isobars

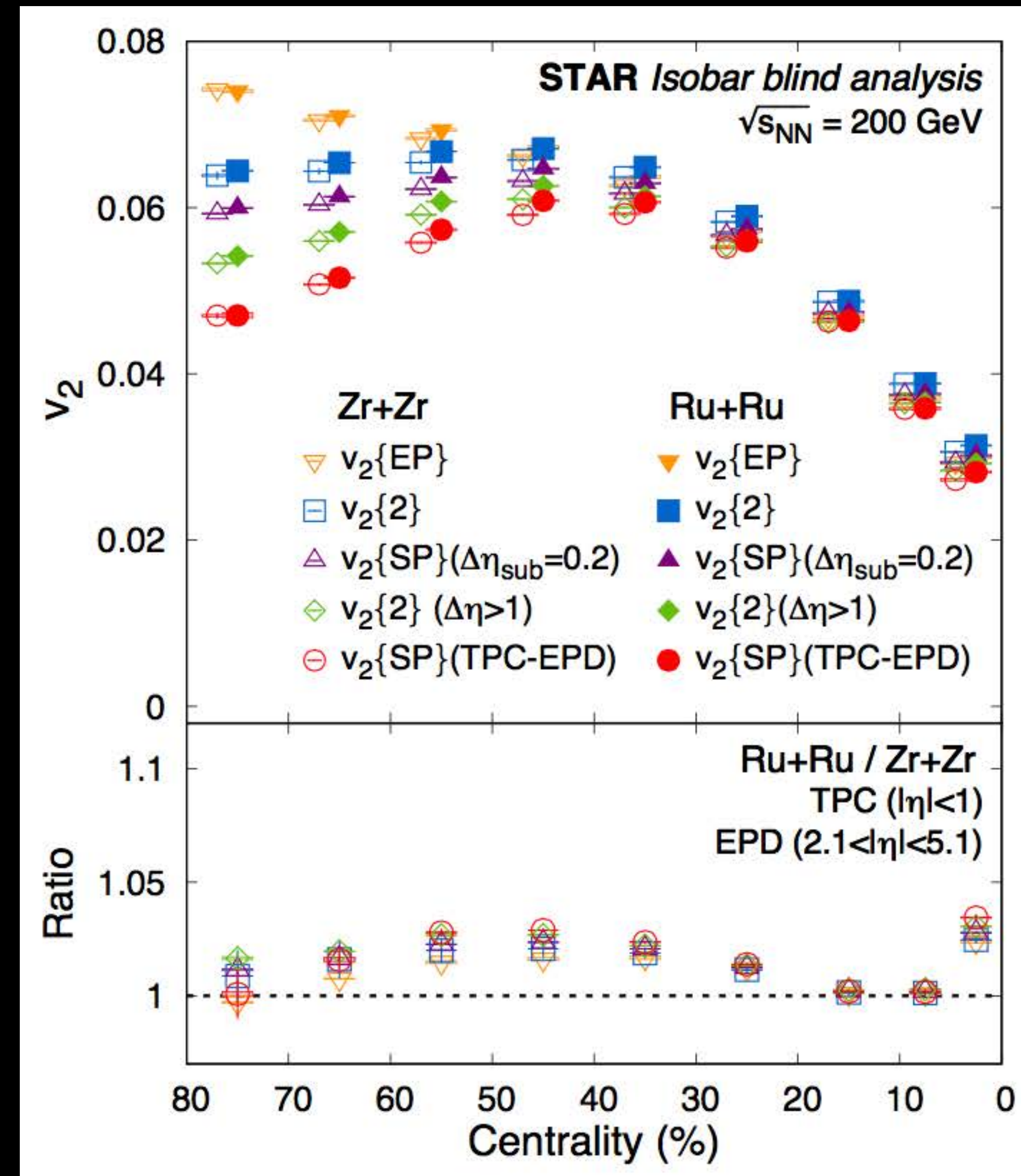


Mean efficiency uncorrected multiplicity density is larger in Ru than in Zr in a matching centrality, this can affects signal and background difference between isobars

Elliptic flow difference between the isobars

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

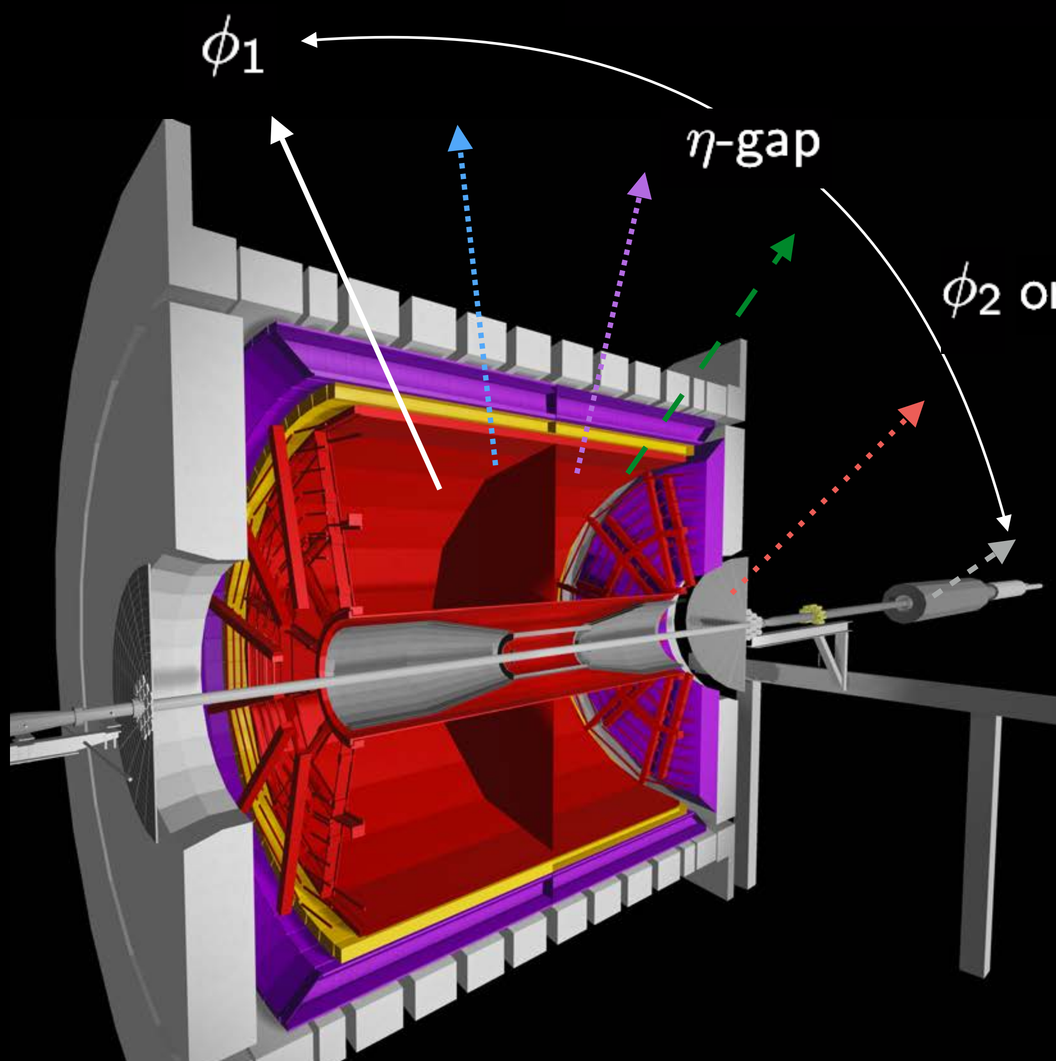


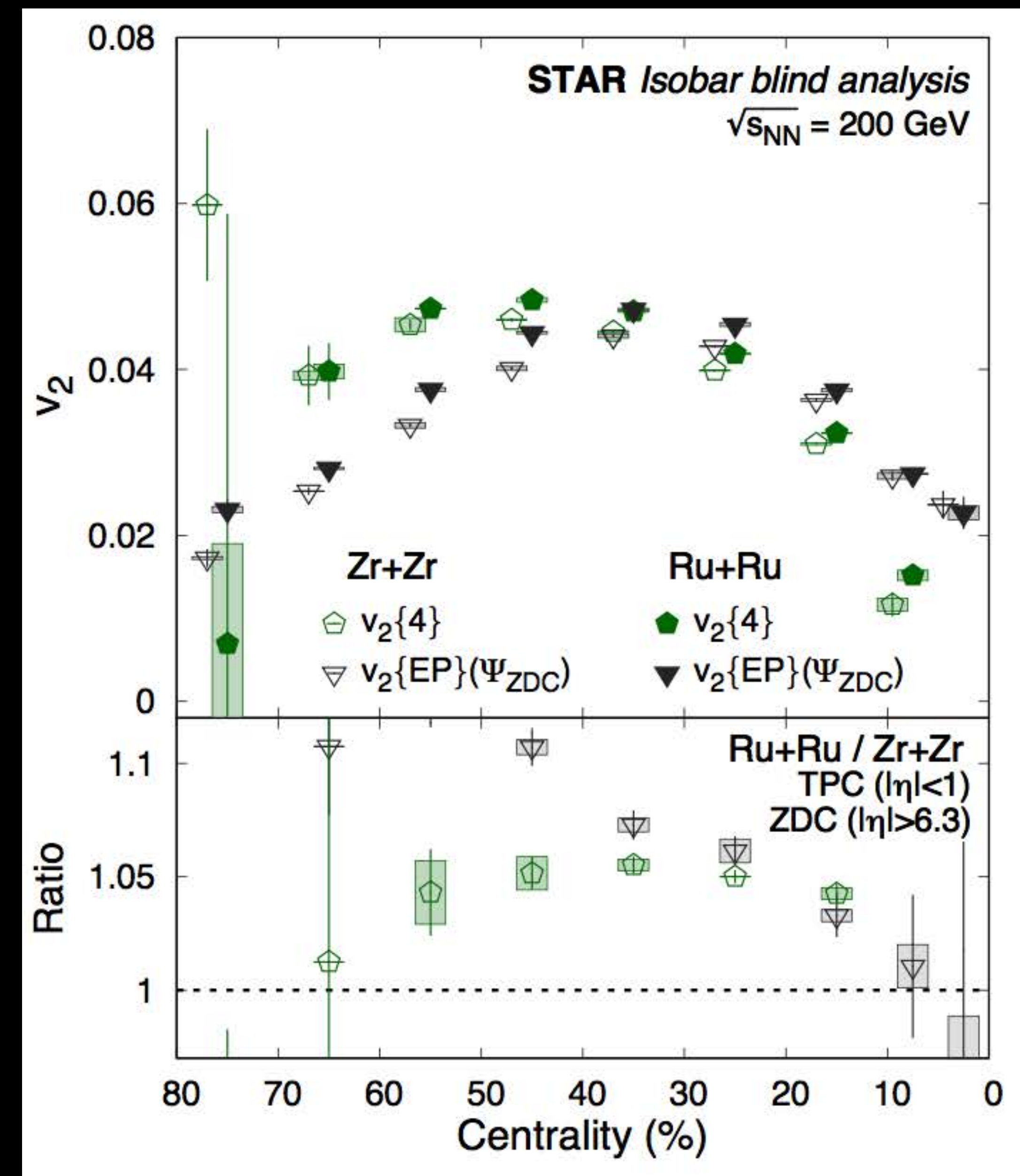


v_2 studied η-gap (including EPDs), ratio deviates from unity indicating difference in the shape, nuclear structure between two isobars (larger quadruple deformation in Ru+Ru)

Elliptic flow difference between isobars

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

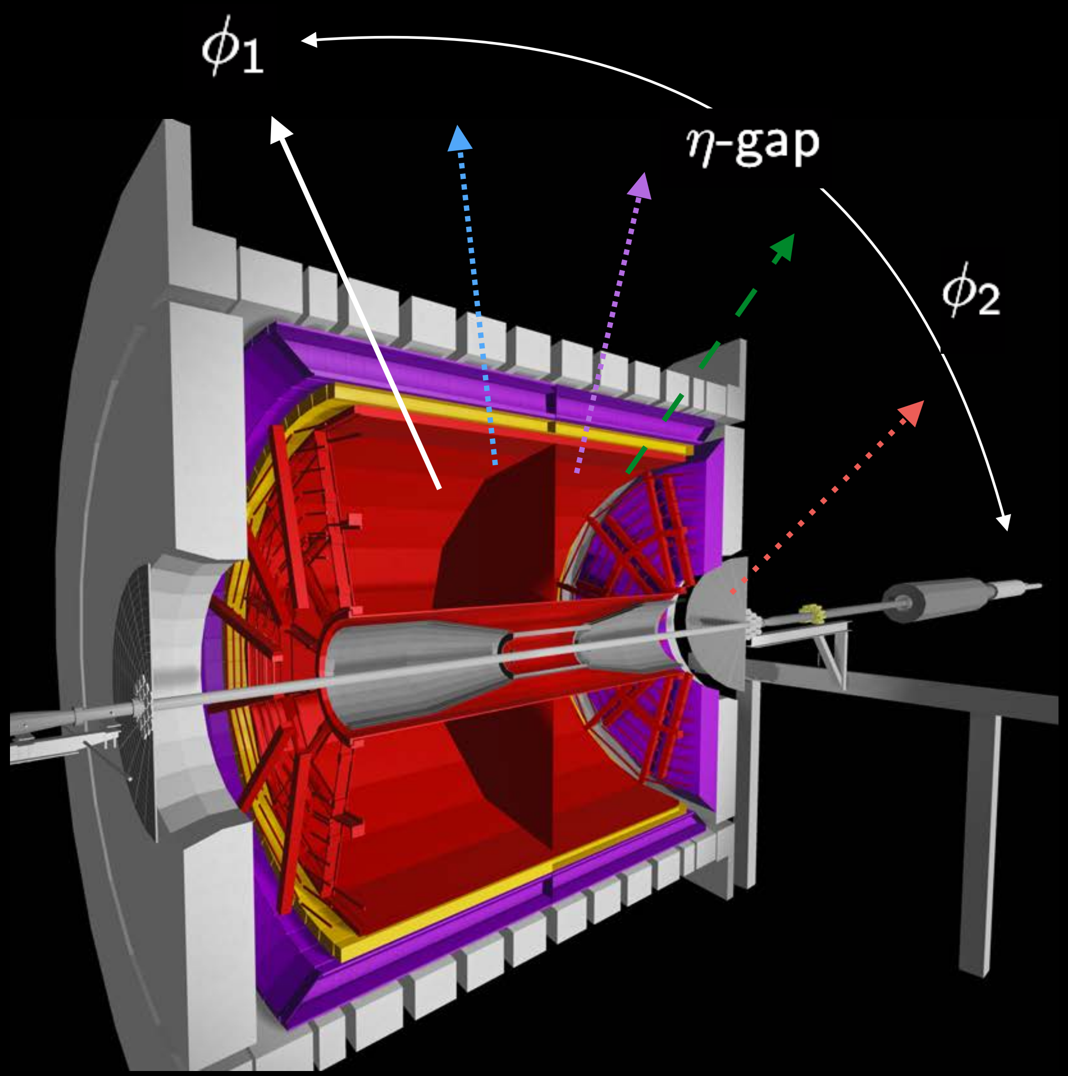


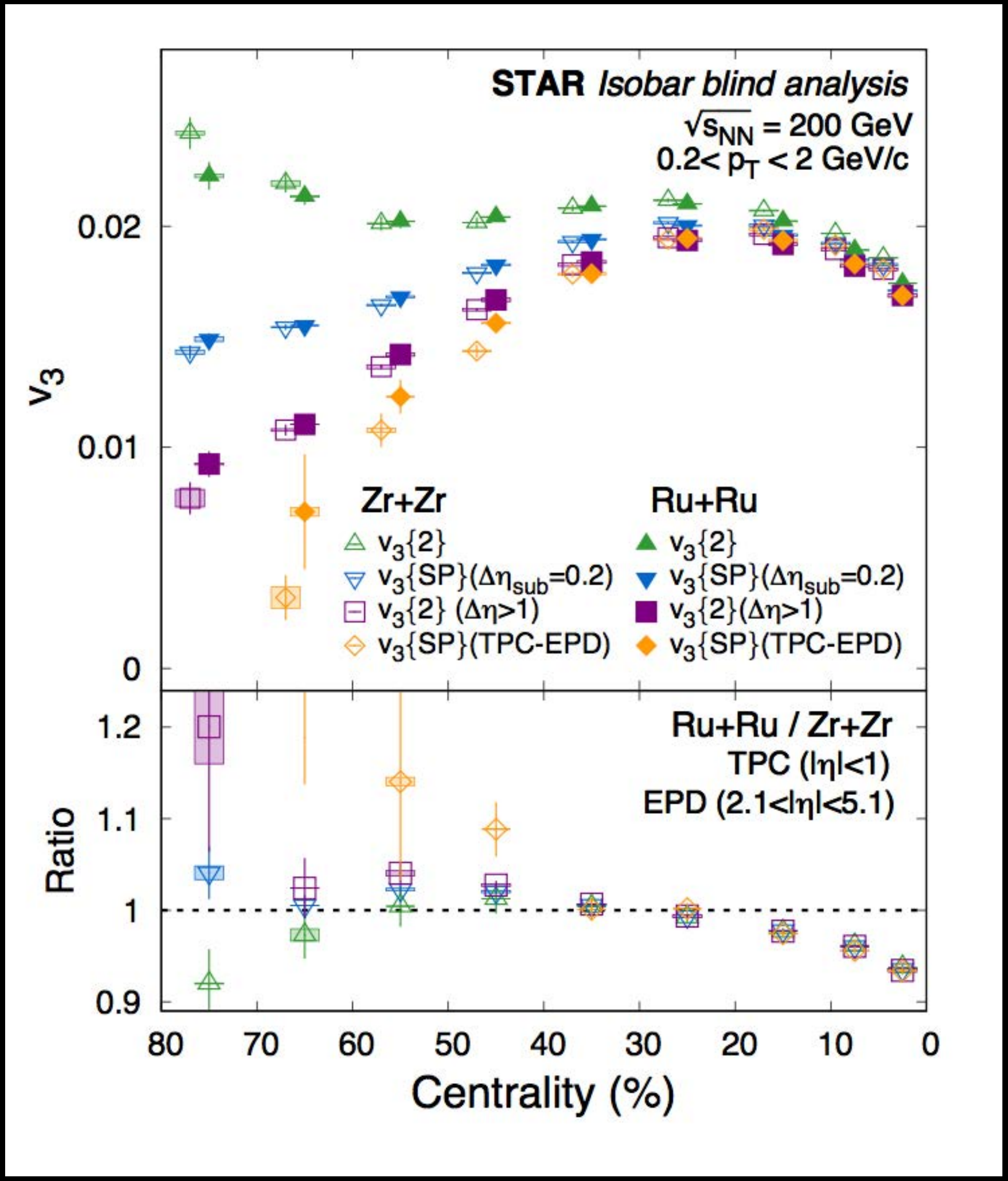


v_2 studied η-gap (including EPDs), ratio deviates from unity indicating difference in the shape, nuclear structure between two isobars (larger quadruple deformation in Ru+Ru)

Triangular flow difference between isobars

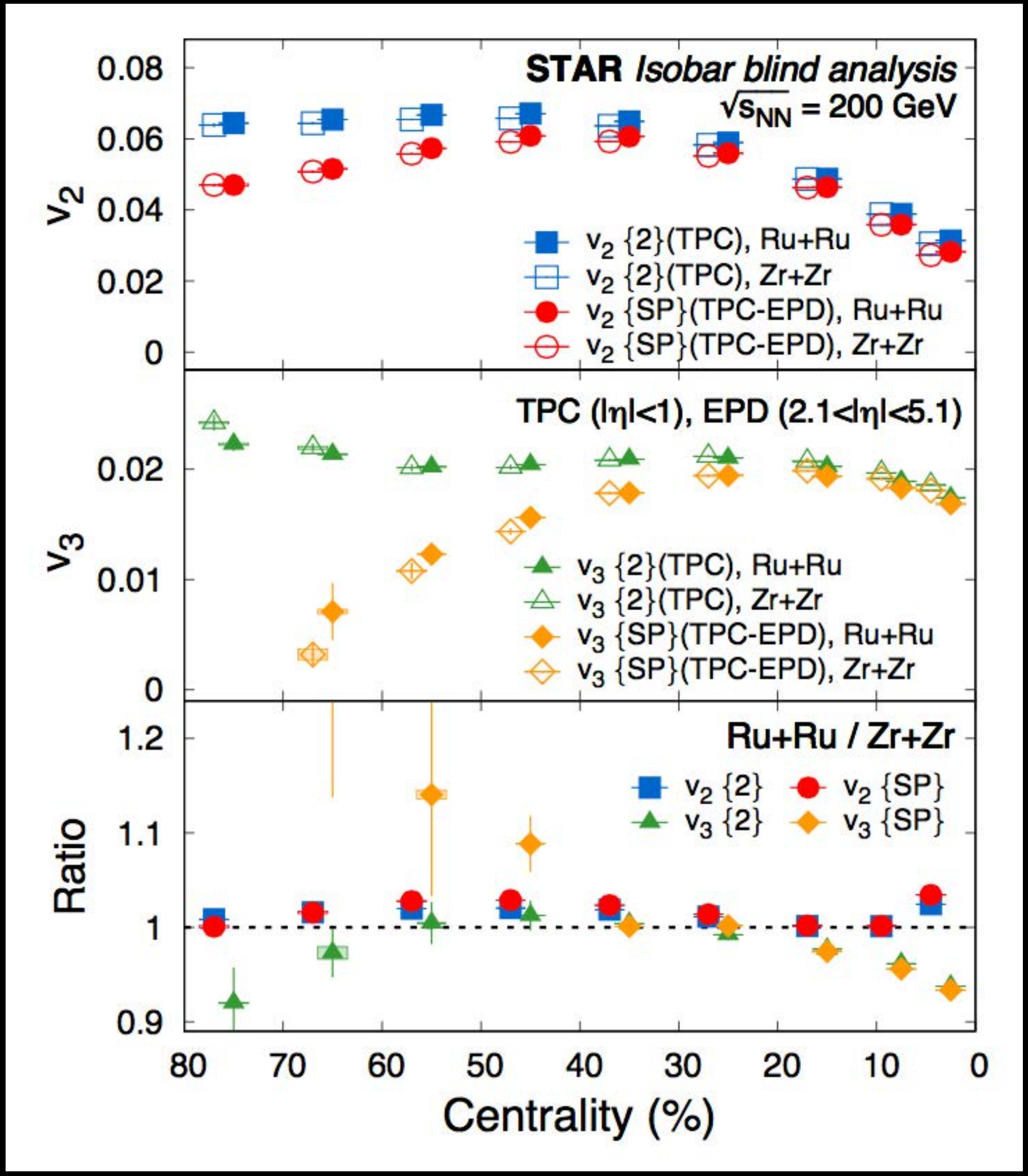
$$v_3\{2\}^2 = \langle\cos(3\phi_1 - 3\phi_2)\rangle$$





Strong rapidity dependence, ratio below unity in central collisions, not fully understood

v2 and v3 comparison for the isobars

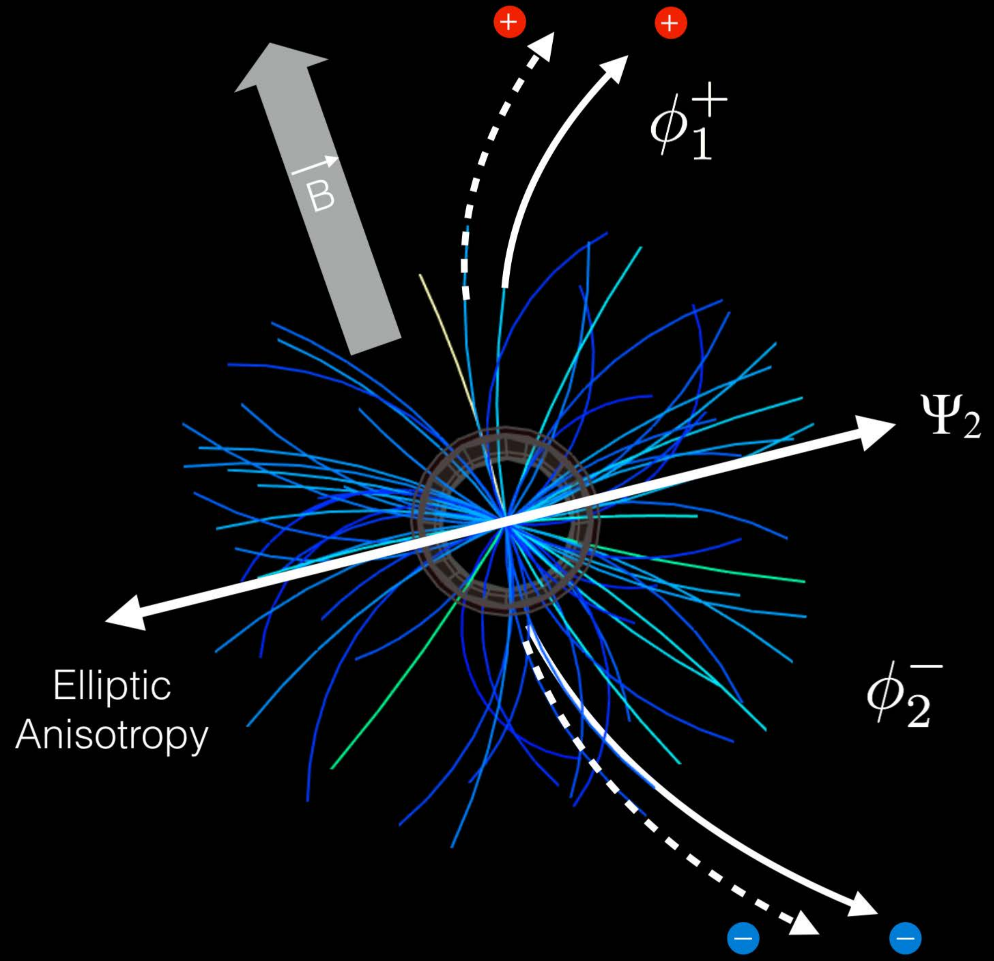


v_n ratio deviates from unity indicating difference in the shape, nuclear structure between two isobars. v_n drives flow-driven background:

$$\Delta\gamma^{bkg} = \gamma^{OS} - \gamma^{SS} \propto \frac{v_2^{reso}}{N}$$

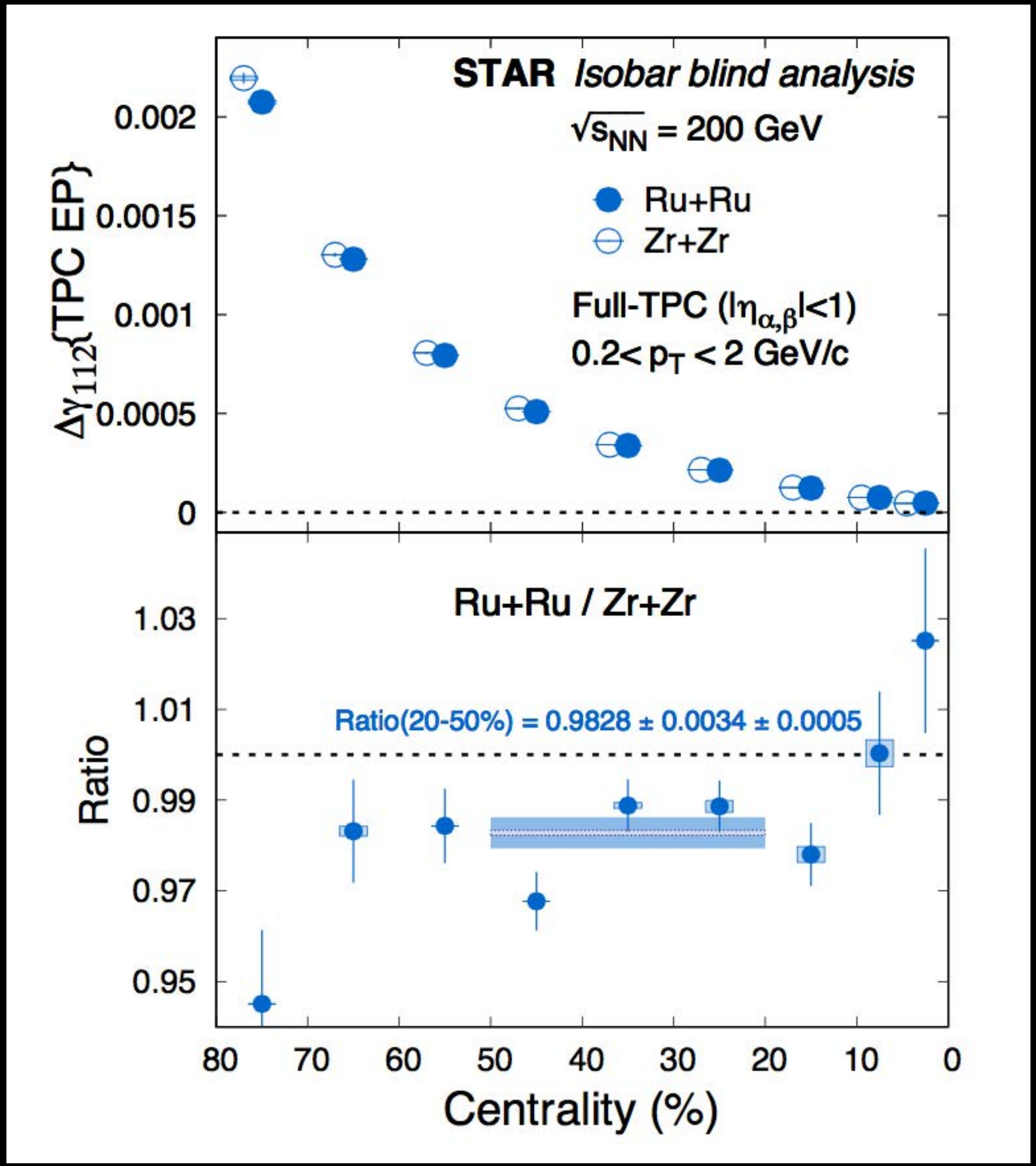
Results on CME sensitive variables

Charge separation across elliptic flow plane



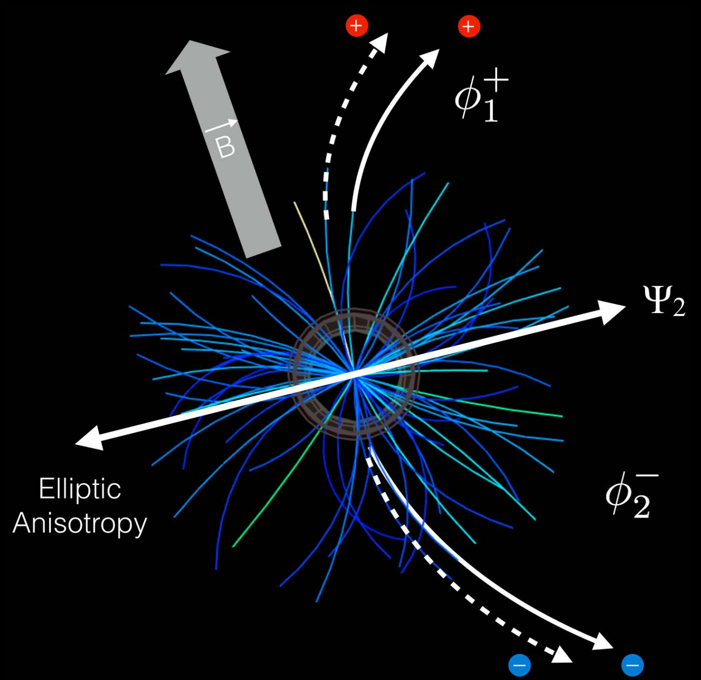
$$\gamma_{112}\{\mathrm{EP}\} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2^{\mathrm{TPC}}) \rangle$$

$$\Delta\gamma = \gamma_{112}(OS) - \gamma_{112}(SS)$$



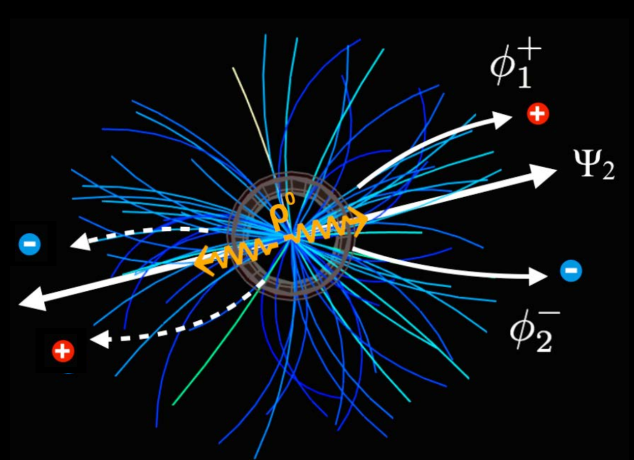
Ratio of charge separation correlated to elliptic flow plane is below unity, however only this quantity is not decisive

Charge separation scaled by elliptic flow



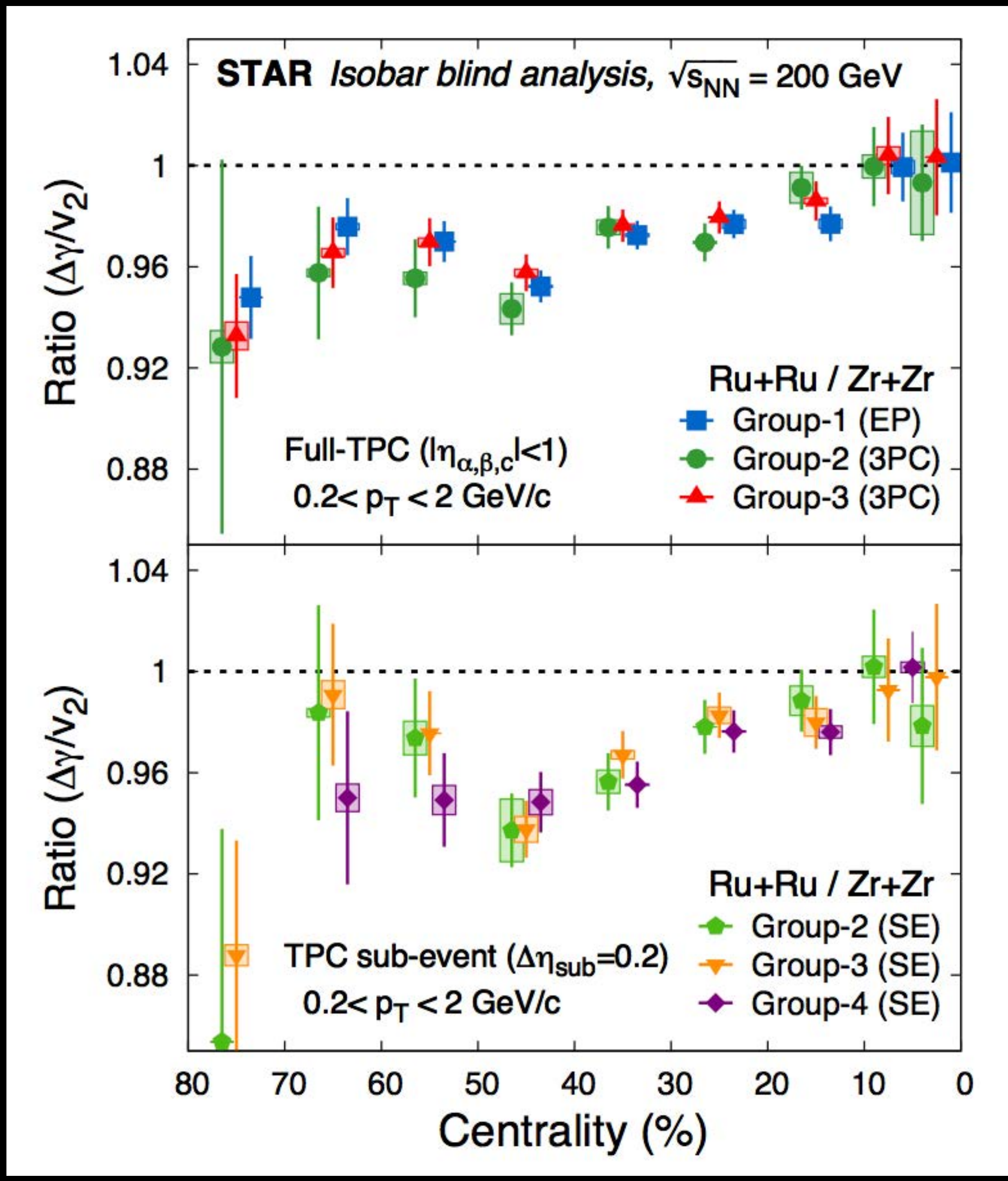
$$\gamma_{112}\{\mathrm{EP}\} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2^{\mathrm{TPC}}) \rangle$$

$$\Delta\gamma = \gamma_{112}(OS) - \gamma_{112}(SS)$$



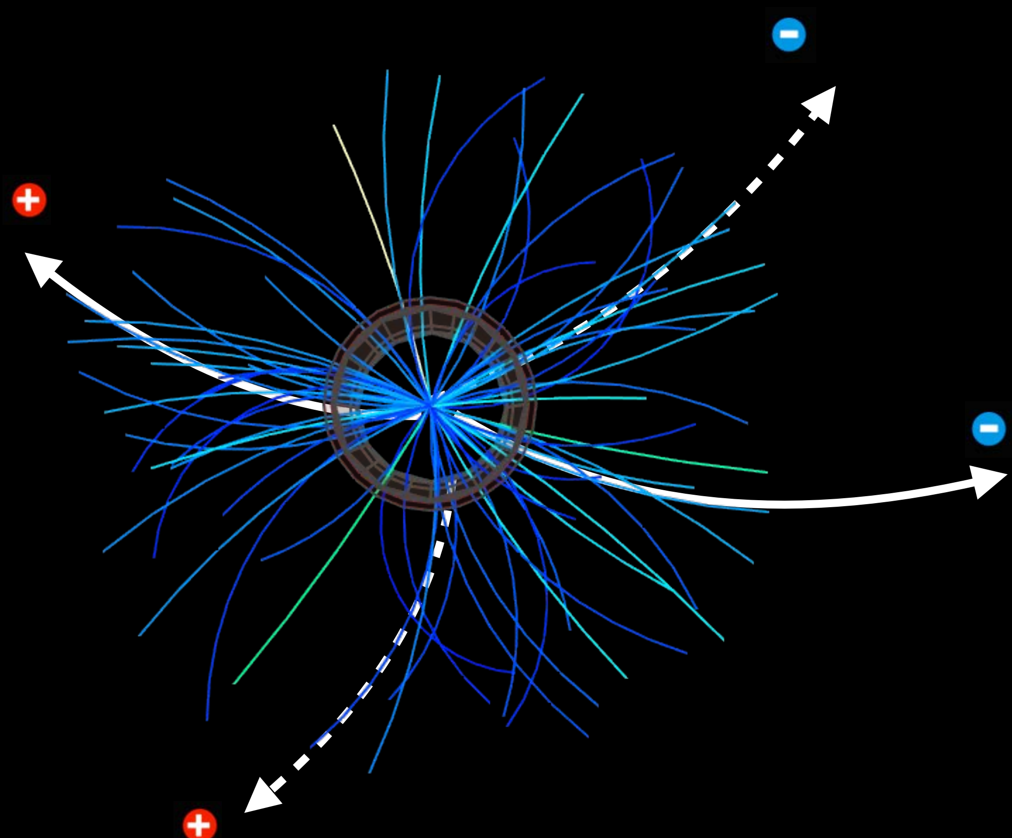
$$\Delta\gamma^{bkg} = \gamma^{OS} - \gamma^{SS} \propto \frac{v_2^{reso}}{N}$$

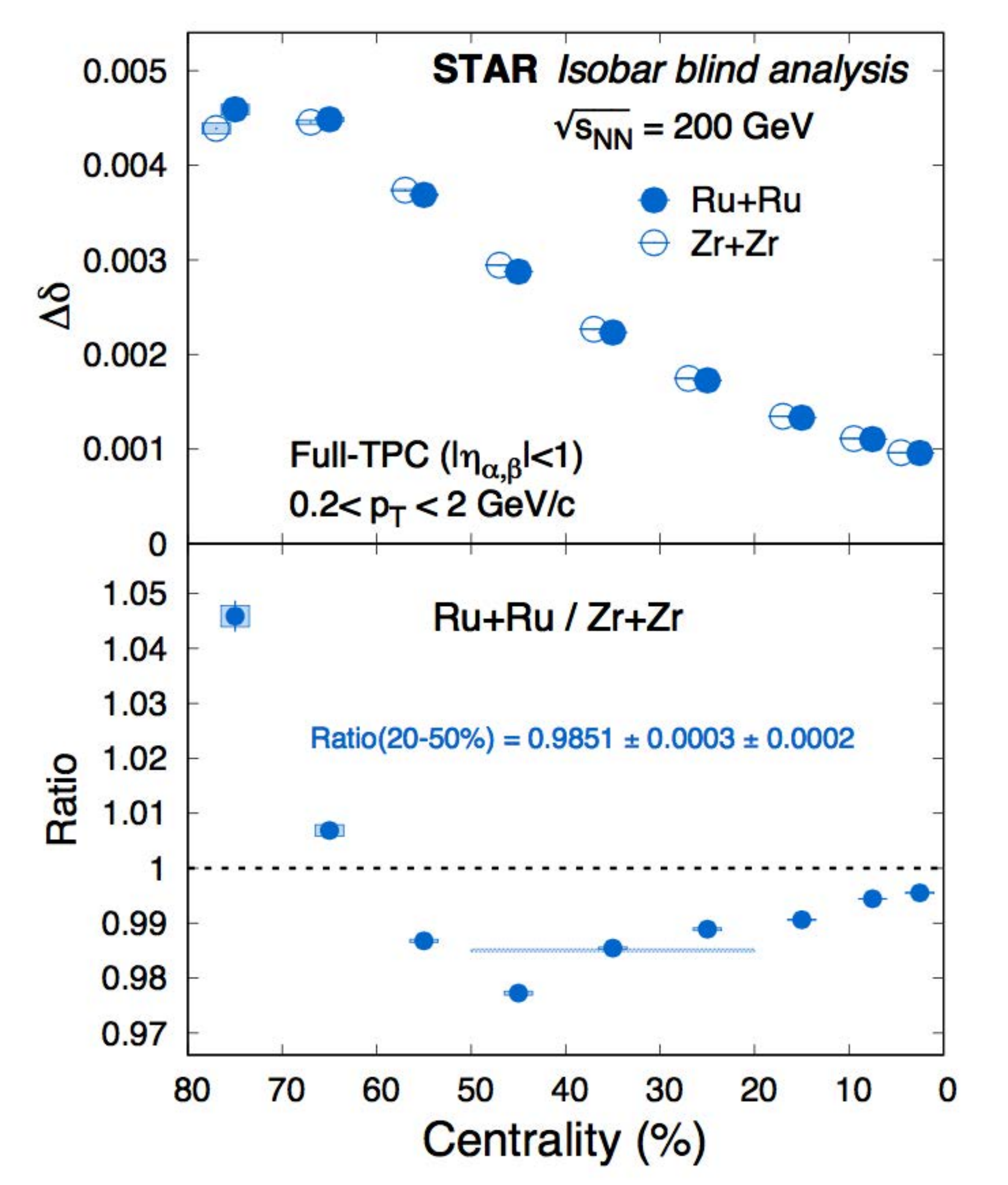
$$\Rightarrow \frac{\Delta\gamma}{v_2}$$



Pre-defined criteria for CME $\frac{(\Delta\gamma/v_2)_{\mathrm{RuRu}}}{(\Delta\gamma/v_2)_{\mathrm{ZrZr}}} > 1$ NOT seen

Two-particle correlator of charge separation





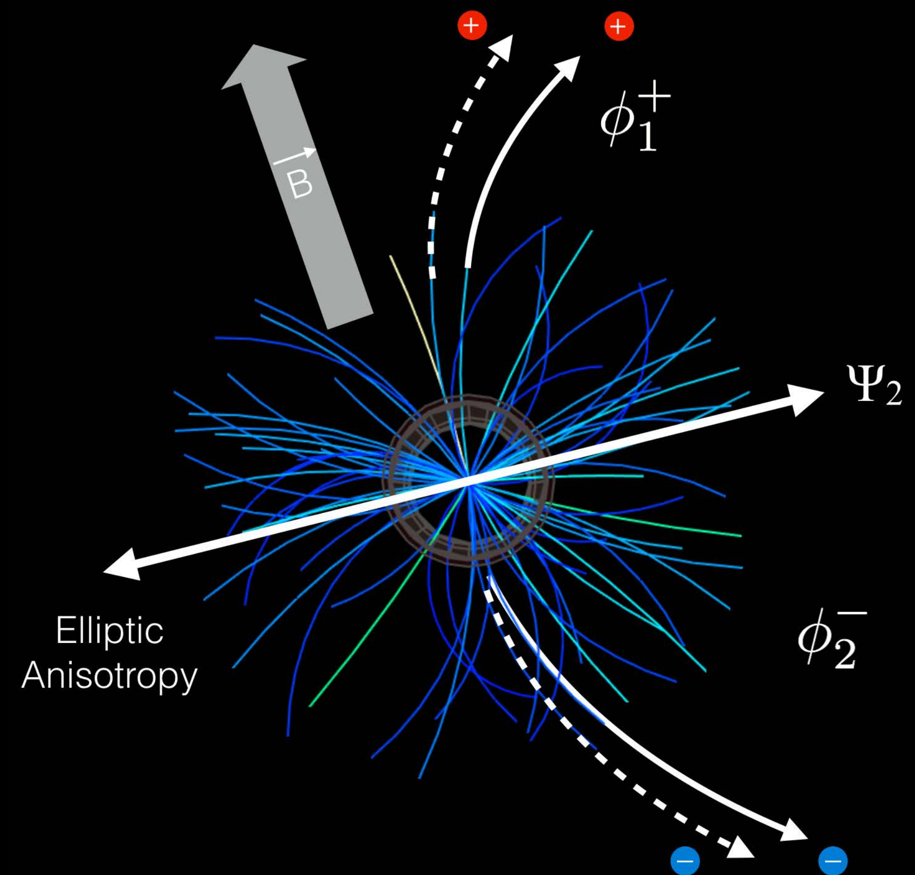
$$\delta \equiv \langle \cos(\phi_\alpha - \phi_\beta) \rangle$$

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

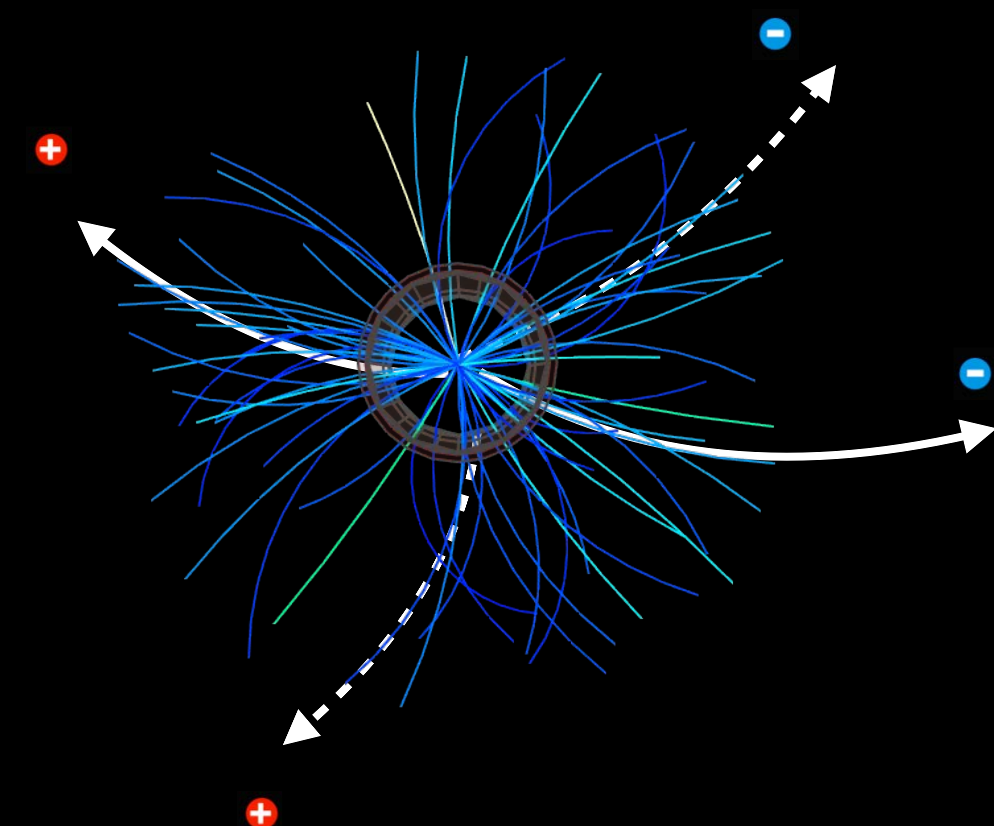
Two particle-charge separation observable δ-correlator — measures charge separation that may or may not be correlated to event plane.

Charge separation across elliptic flow plane

Charge separation correlated to event plane



Charge dependent two-particle correlation



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

$$\Longleftrightarrow$$

$$\delta = \langle \cos(\phi_\alpha - \phi_\beta)\rangle$$
$$\times$$
$$v_2 = \langle \cos(2\phi - \Psi_2)\rangle$$

$$\gamma_{112} \equiv \kappa_{112}\,\delta\, v_2$$

This factorization breaking coefficient should be >1 and can help test CME

Ratio of factorization breaking

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

$$\Delta\gamma = \gamma_{112}(OS) - \gamma_{112}(SS)$$

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

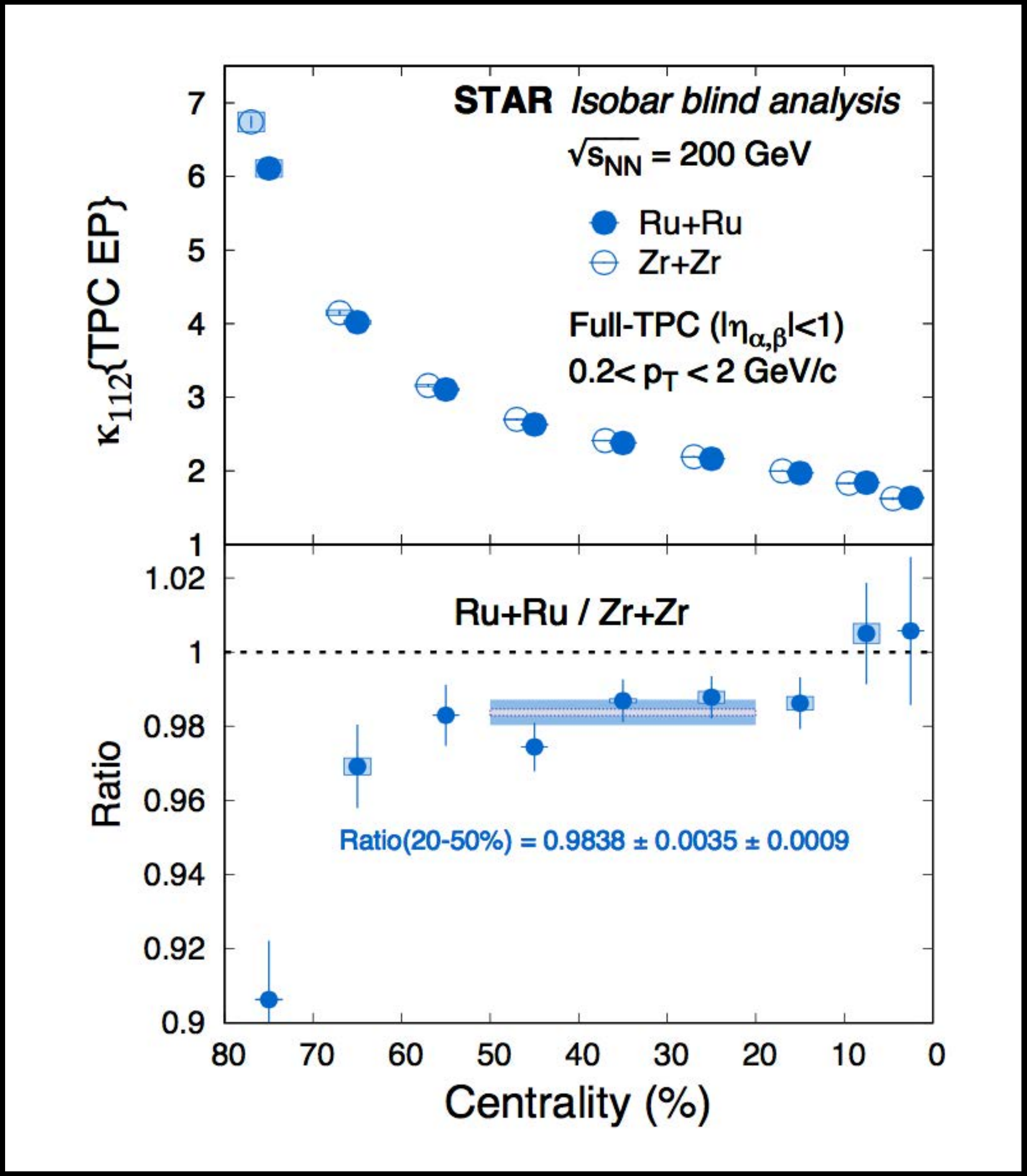
$$\Delta\delta = \delta(OS) - \delta(SS)$$

Factorization breaking:

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

Pre-defined CME criteria:

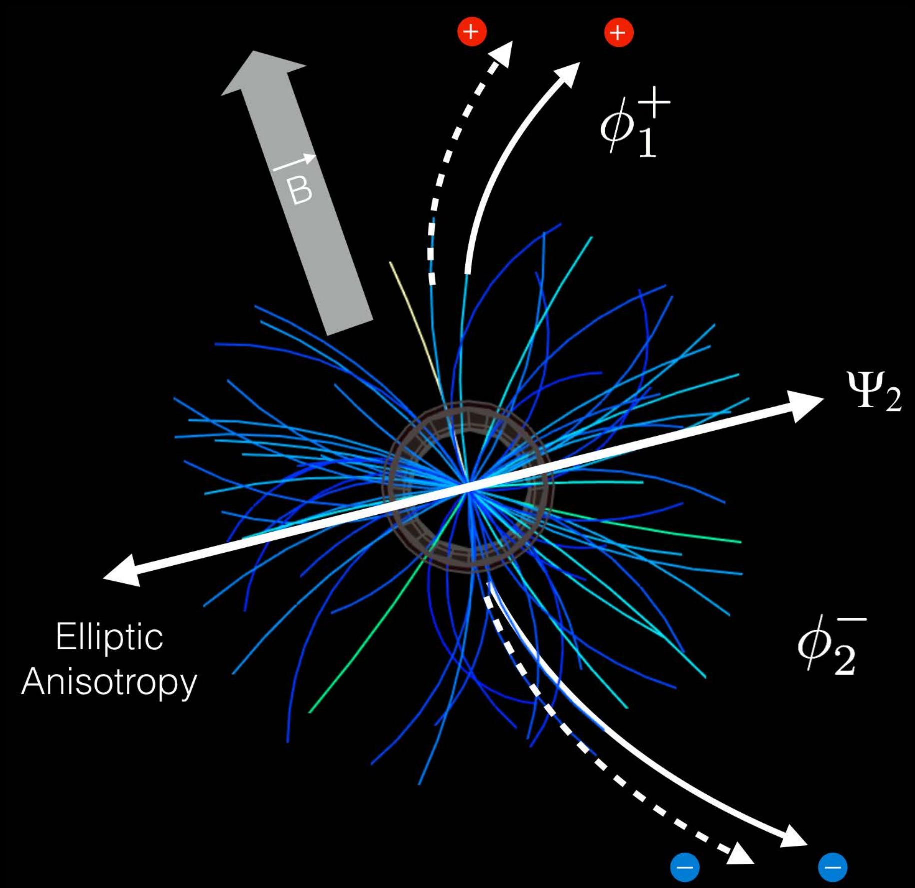
$$\frac{\kappa_{112}^{\mathrm{Ru+Ru}}}{\kappa_{112}^{\mathrm{Zr+Zr}}} > 1$$



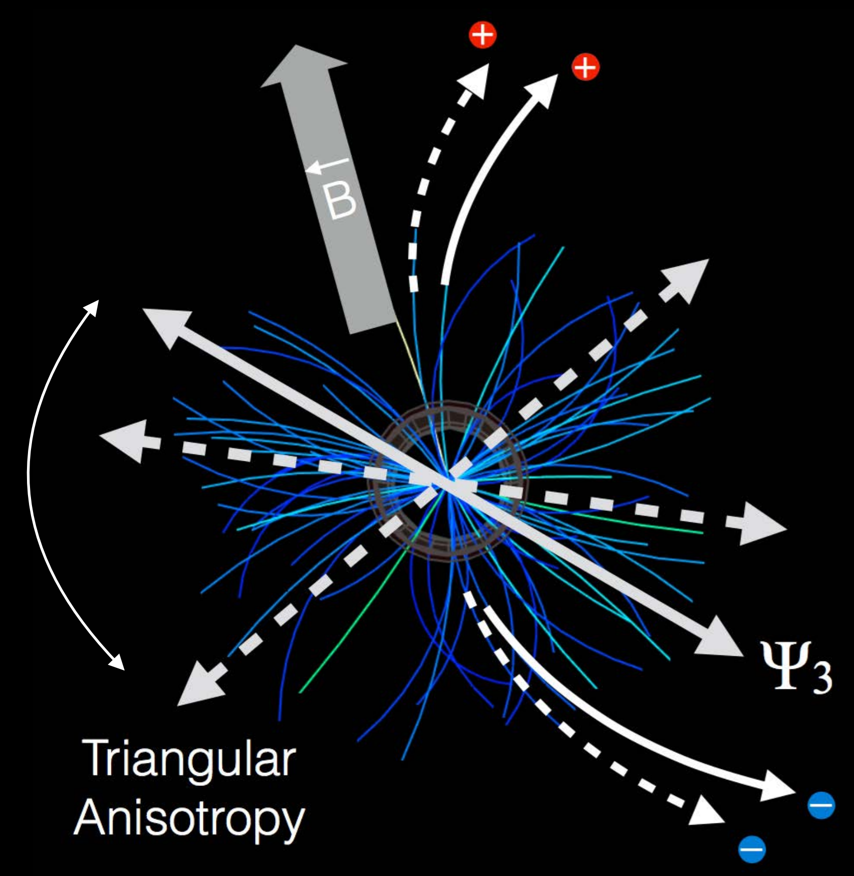
This pre-defined CME signature is NOT seen

Charge separation across triangular flow plane

B-field is corrected to Ψ_2 plane



B-field is not-corrected to Ψ_3 plane



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

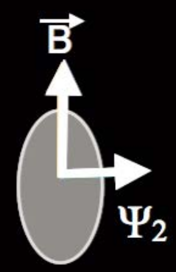
Signal (B-field) + Background ($\propto v_2$)

$$\gamma_{123} = \langle \cos(\phi_\alpha + 2\phi_\beta - 3\Psi_2) \rangle$$

Background only ($\propto v_3$)

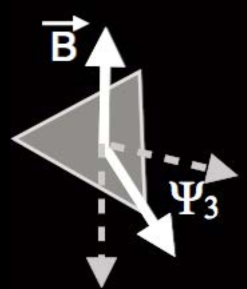
Charge separation across third harmonic plane can serve as data-driven baseline

Charge separation across Ψ_2 and Ψ_3 planes



$$\gamma_{112} = \left\langle \cos(\phi_1^\alpha + \phi_2^\beta + 2\Psi_2) \right\rangle$$

signal + background

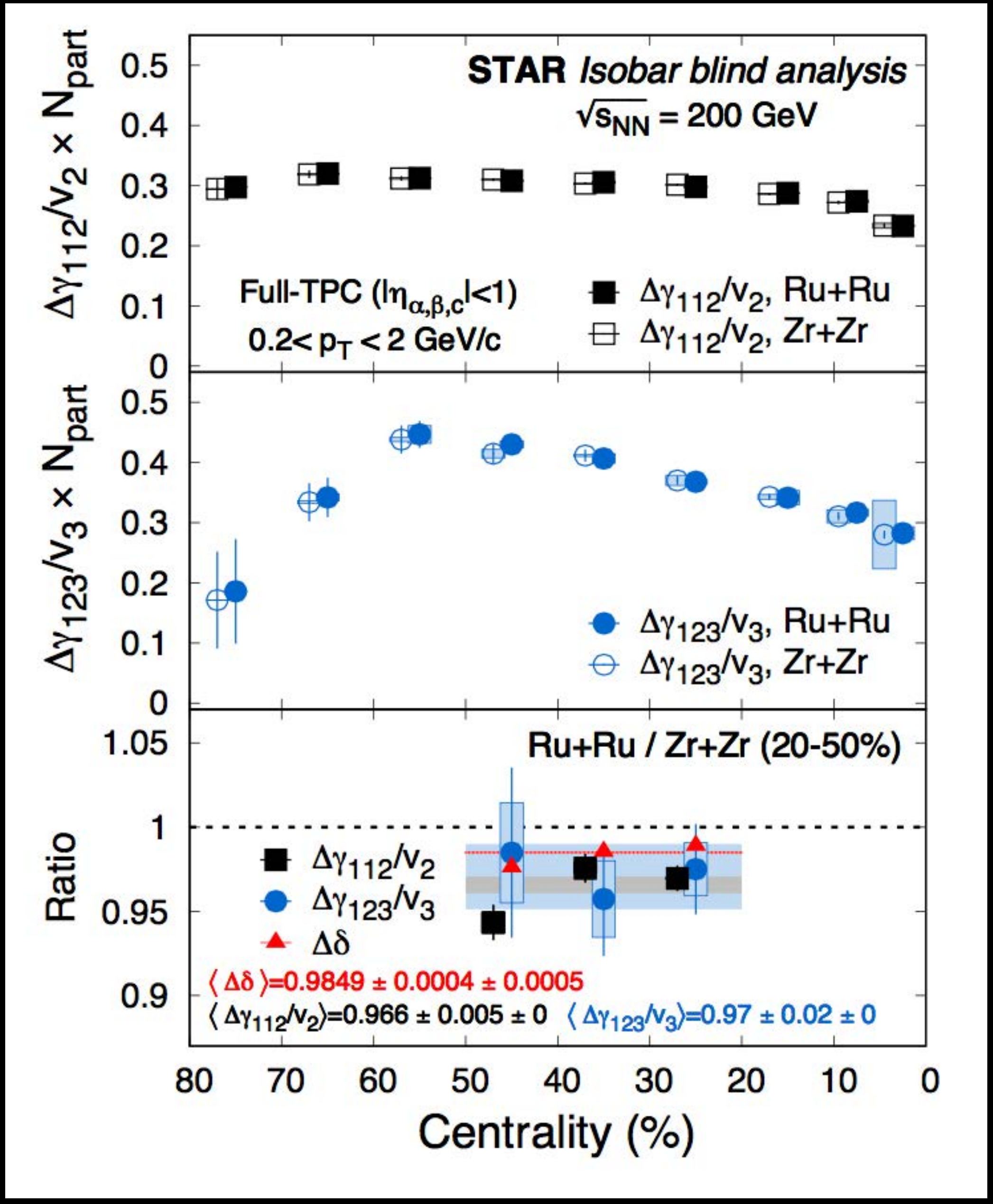


$$\gamma_{123} = \left\langle \cos(\phi_1^\alpha + 2\phi_2^\beta - 3\Psi_3) \right\rangle$$

100% background

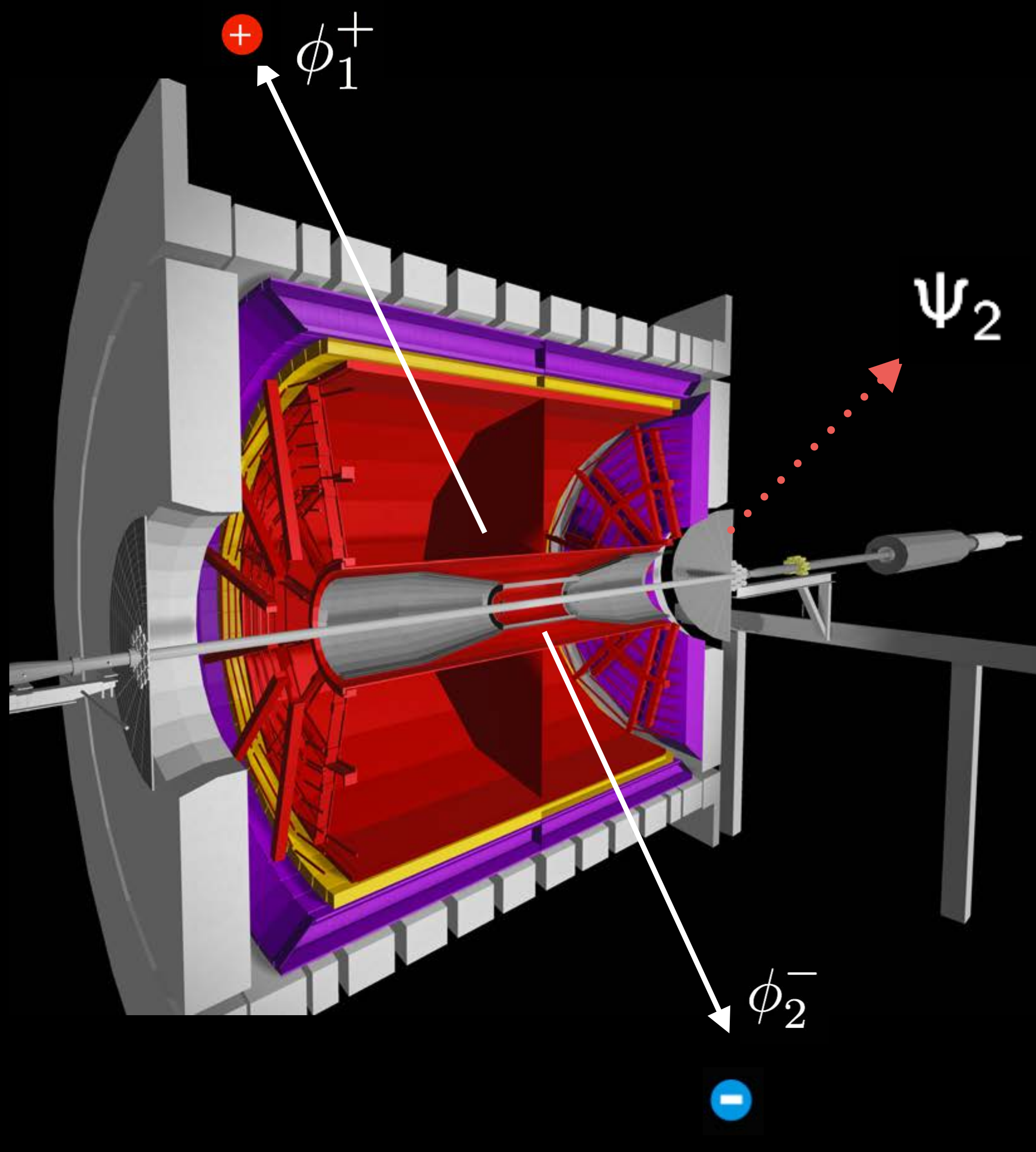
Pre-defined CME criteria:

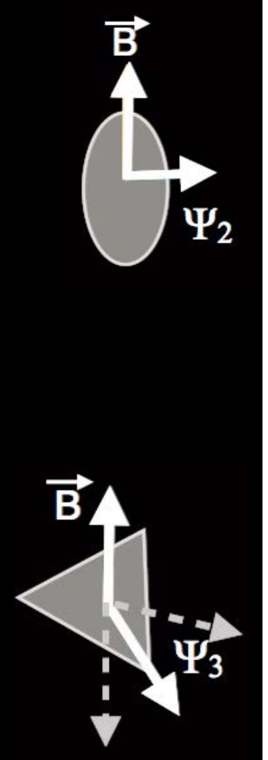
$$\frac{(\Delta\gamma_{112}/v_2)^{RuRu}}{(\Delta\gamma_{112}/v_2)^{ZrZr}} > \frac{(\Delta\gamma_{123}/v_3)^{RuRu}}{(\Delta\gamma_{123}/v_3)^{ZrZr}}$$

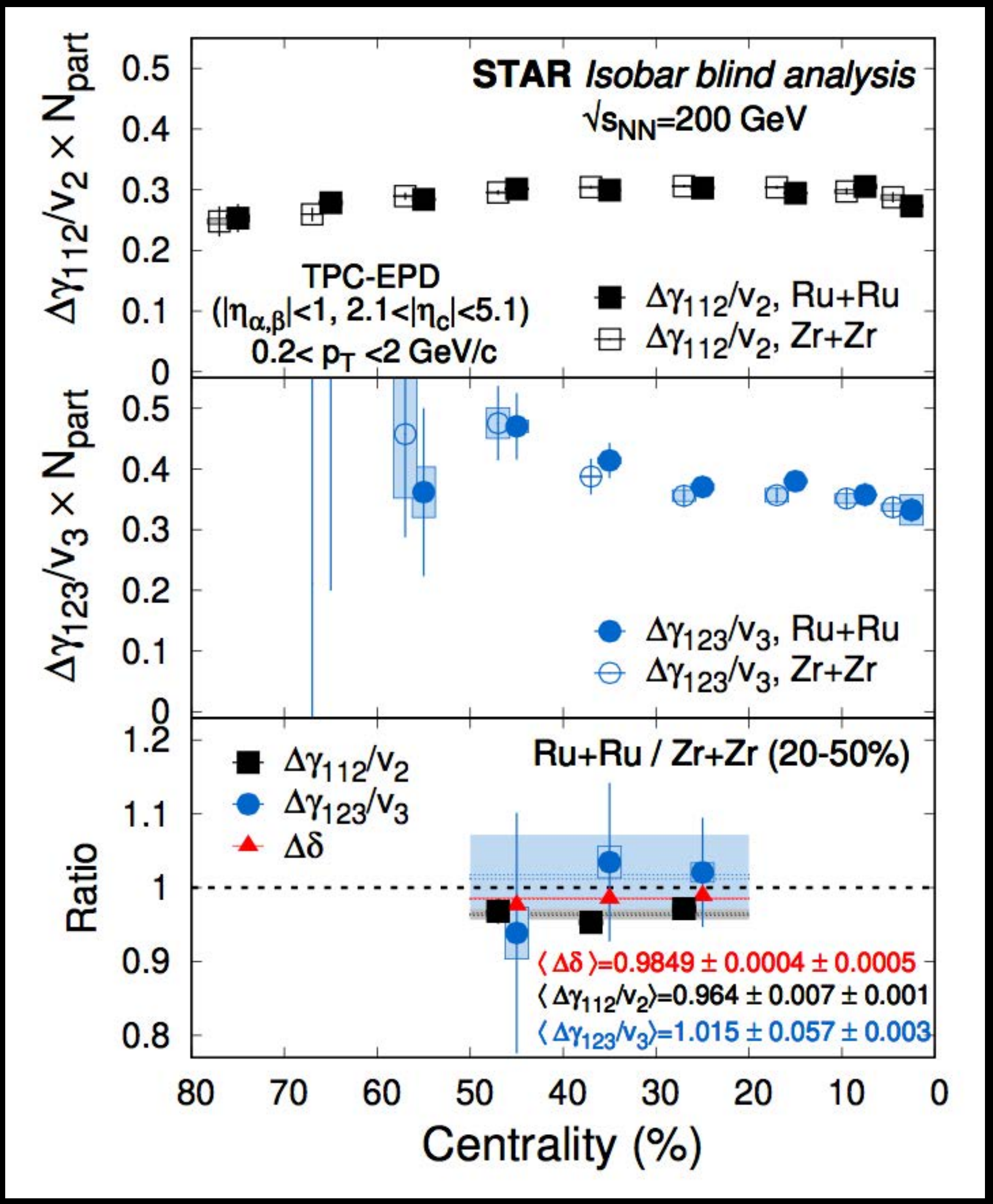


This pre-defined CME signature is NOT seen

Measurement using STAR EPD (for the first time)







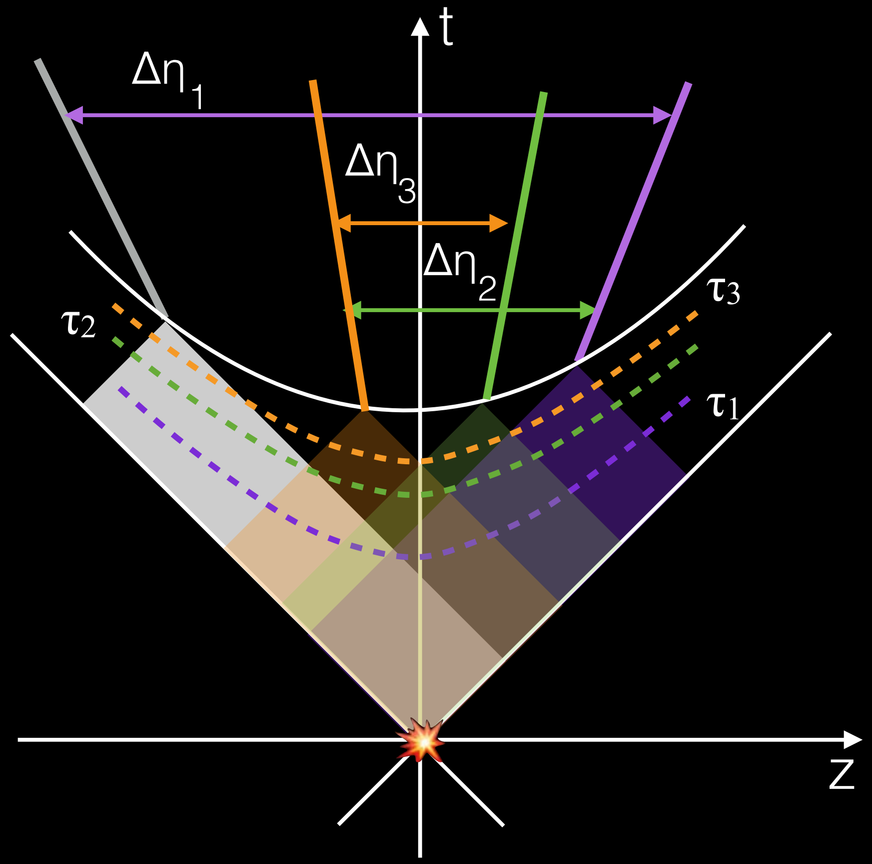
Pre-defined CME criteria:

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

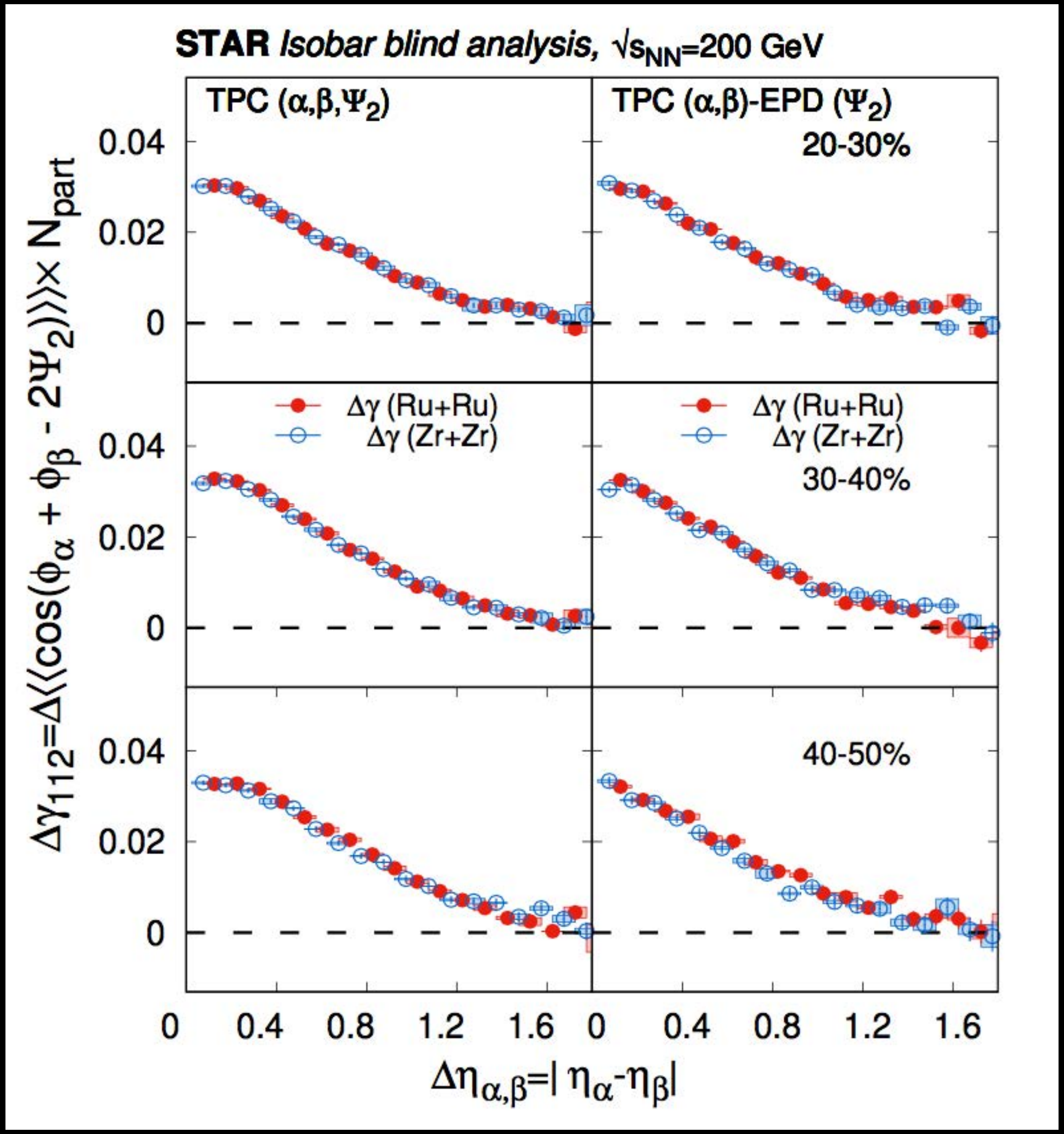
This pre-defined CME signature is NOT seen

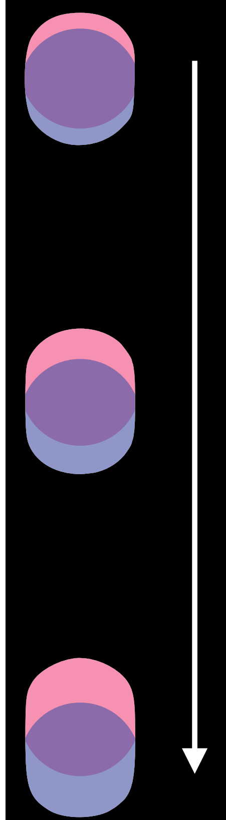
Relative pseudorapidity dependence of γ_{112}

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



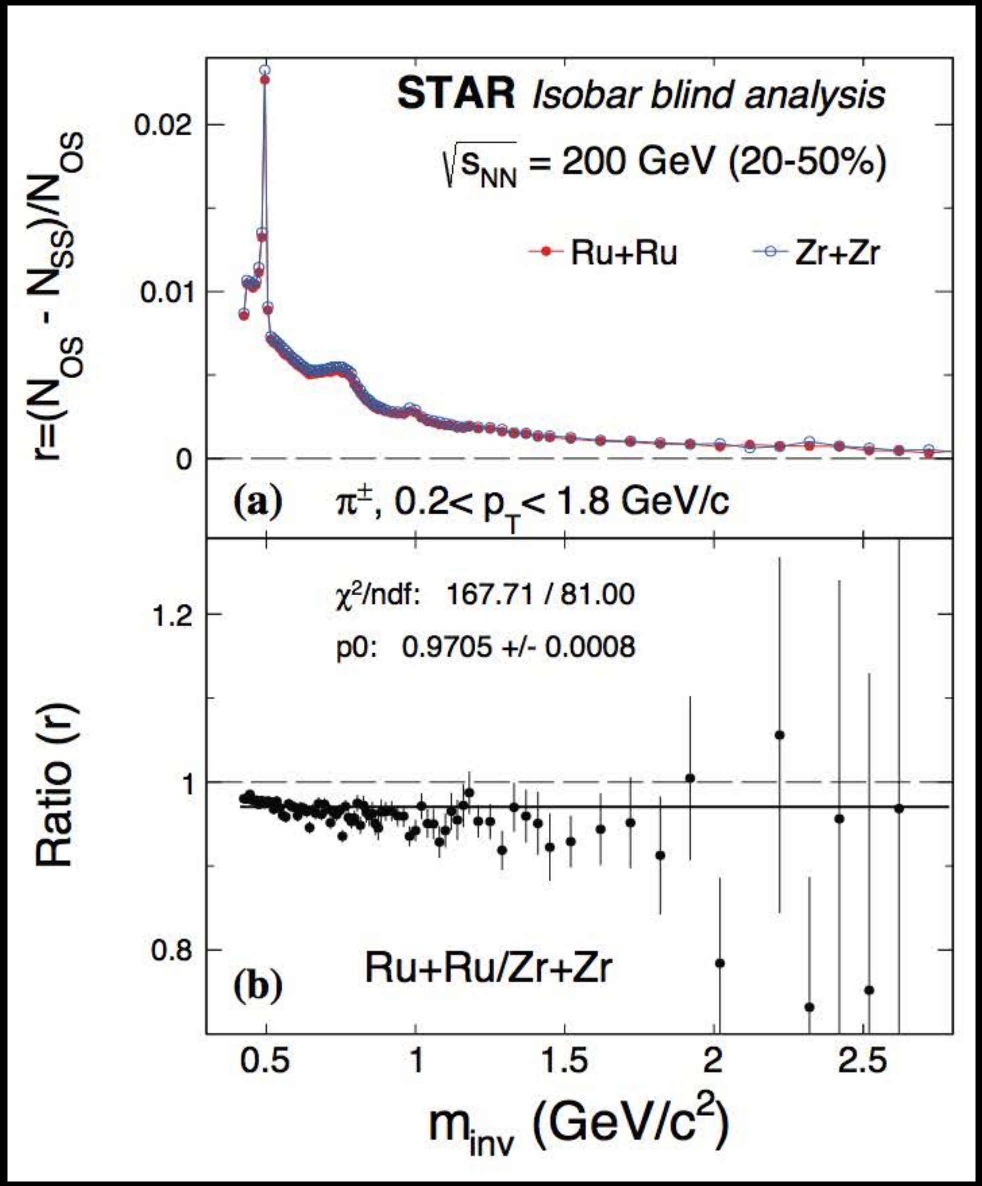
B-field driven charge separation: large Δη>1
Resonance decay: smaller Δη<1

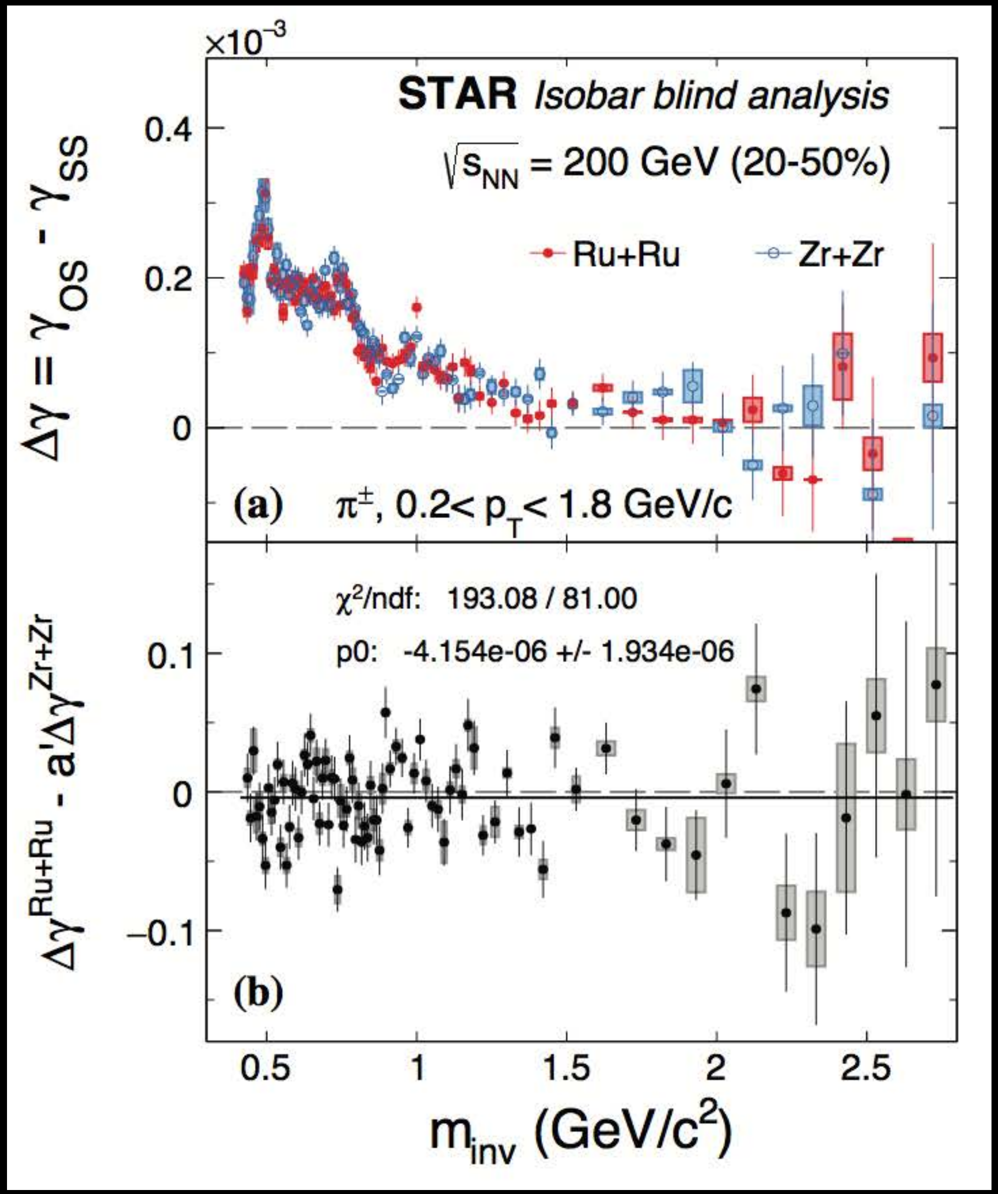


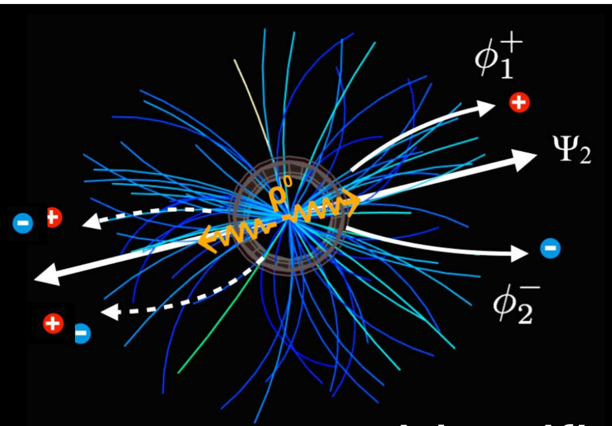


The relative pseudorapidity dependence is similar between the two species

Invariant mass dependence of γ_{112}







Resonances are identifiable as peaks in invariant mass distribution

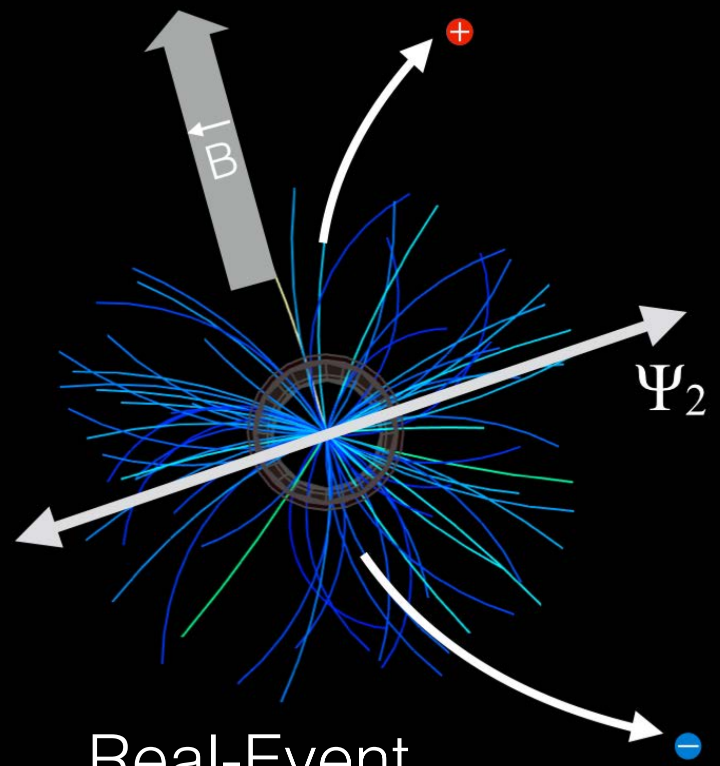
Pre-defined CME criteria:

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

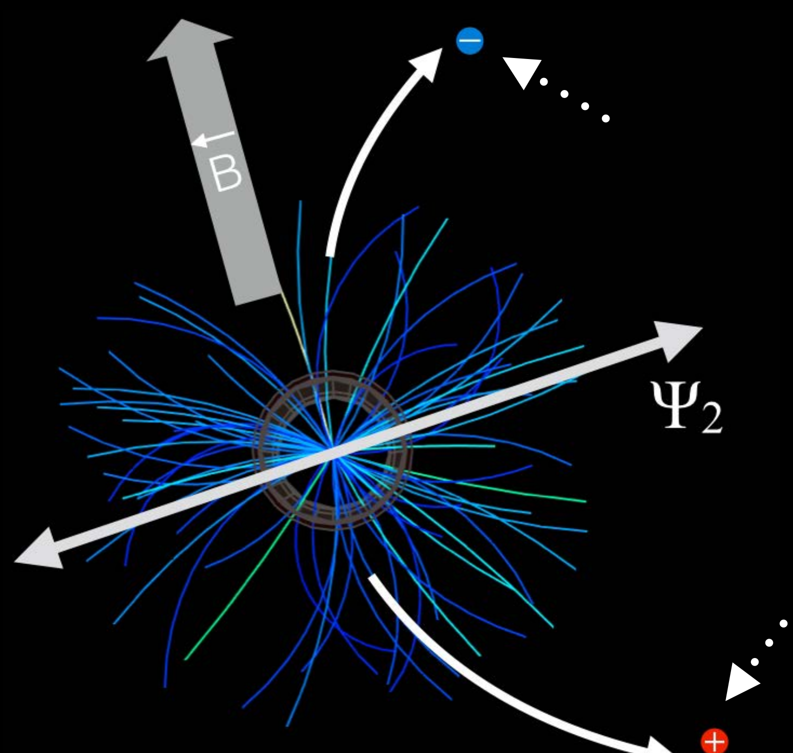
$$\boxed{a' = v_2^{\mathrm{Ru+Ru}} / v_2^{\mathrm{Zr+Zr}}}$$

This pre-defined signature is NOT seen

Alternate charge separation measure: R-variable



Real-Event



Shuffled-Event

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

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

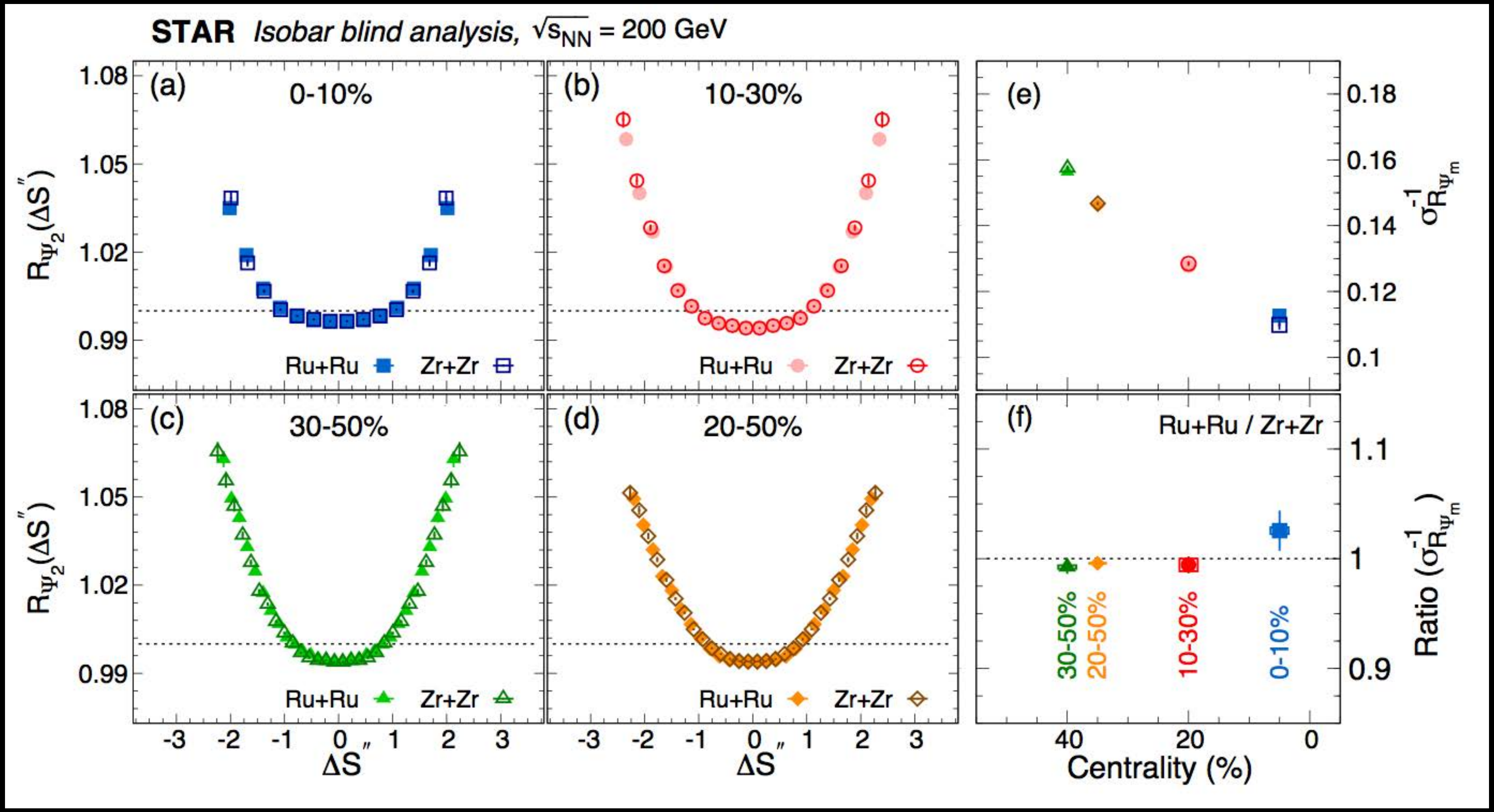
$$C_{\Psi_2}(\Delta S) = \frac{N_{\text{real}}(\Delta S)}{N_{\text{shuffled}}(\Delta S)},$$

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

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

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

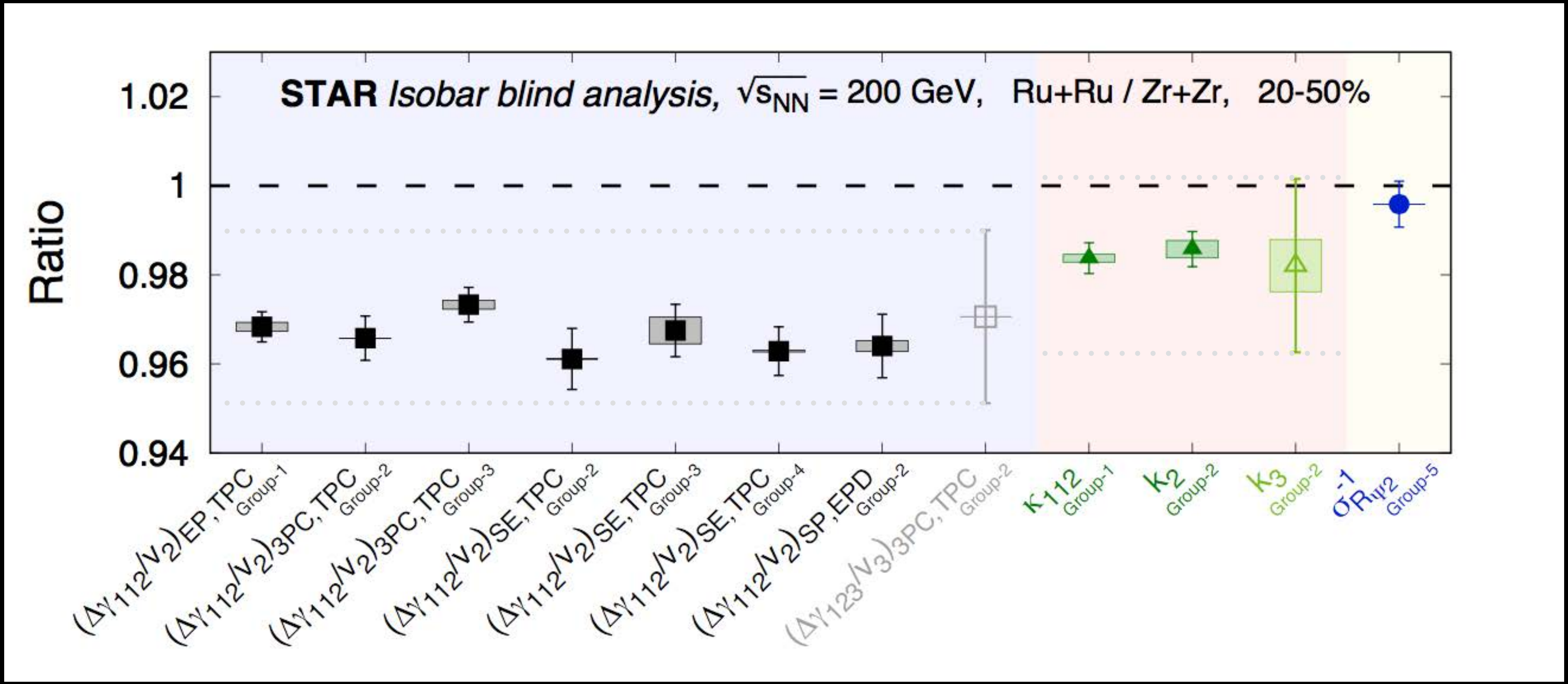
Alternate charge separation measure: R-variable



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

This pre-defined signature is NOT seen

Compilation of all the results

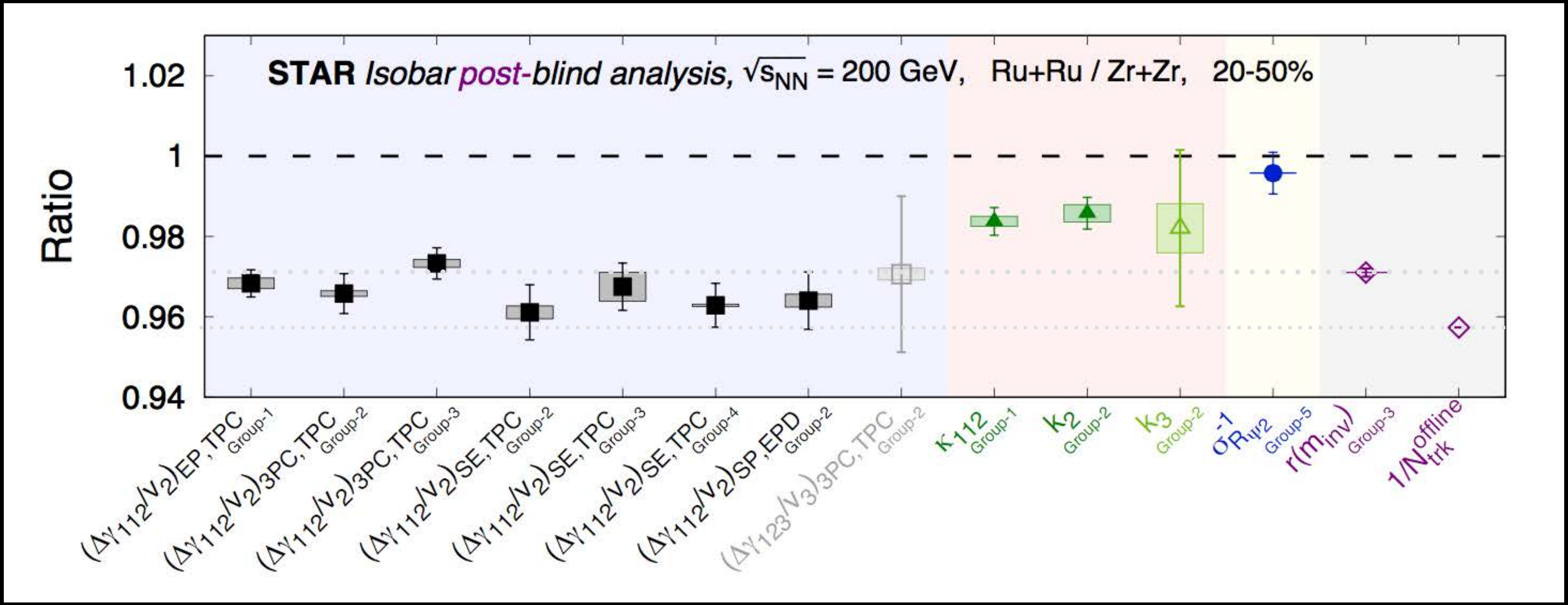


Good consistency between results from different groups.

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

Postblinding



Why ratios of Δγ/v2 are below unity?

Inverse of multiplicities, or as an alternative r maybe better baselines compared to unity used in the pre-defined blind analysis documentation

Alternate baselines also do not present a clear case for CME

Conclusion

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

Multiplicity distributions and mean multiplicity are different between isobars

v_2 (2.5%) & v_3 (7%) difference between the isobars seen in central events

A precision down to 0.4% achieved in the primary CME variable

All criteria to observe CME were pre-defined and none observed

CME observables $\Delta\gamma/v_2$ baseline are affected by the multiplicity difference (4% in 20-50%), post-blind analysis compared two possibilities, no clear case for CME

The observed multiplicity difference between the isobars requires future CME analyses to better understand the baselines in order to best utilize the precision demonstrated in this analysis. Better understanding of the non-flow may be another goal.