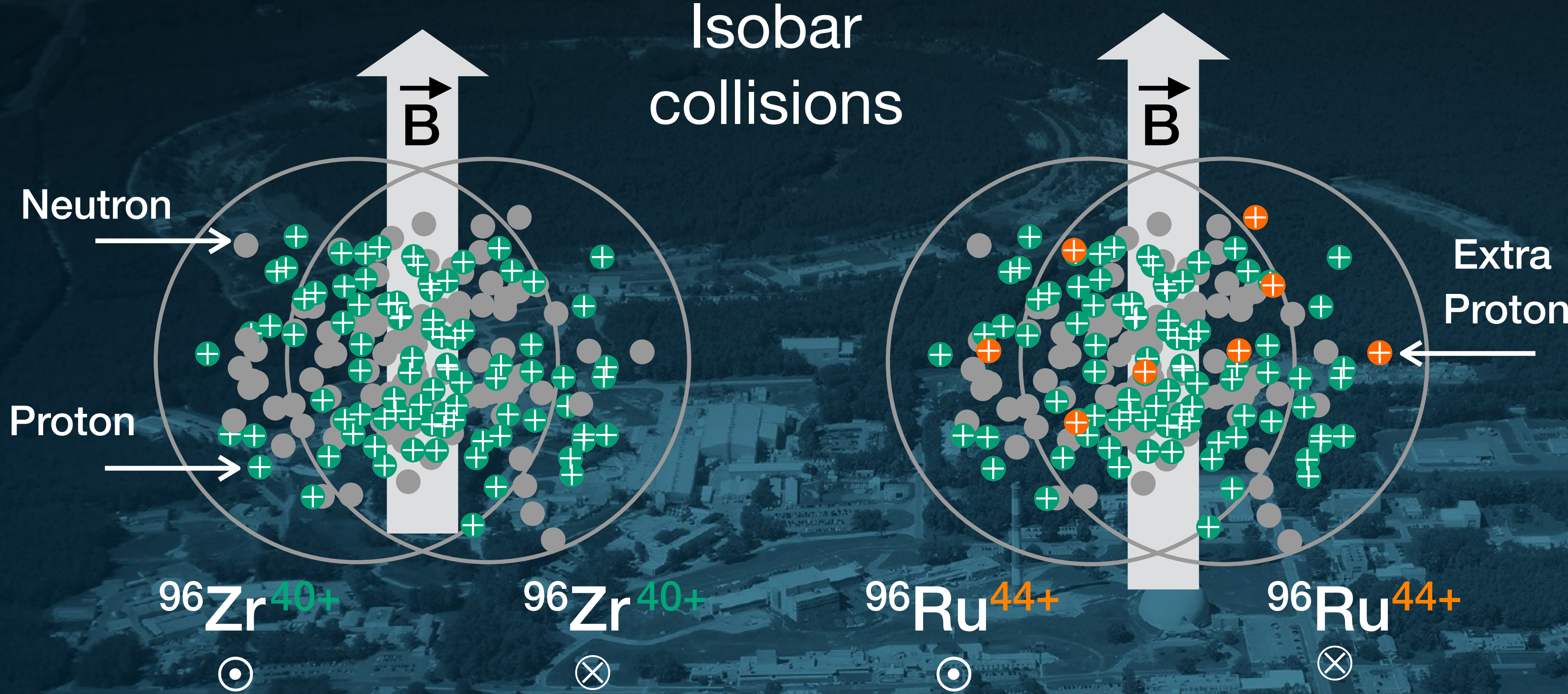


Blind analysis of isobar data for the CME search by the STAR collaboration

Prithwish Tribedy
(Brookhaven National Laboratory)

Free meson seminar, TIFR, Oct 7th, 2021

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

Isobar program: long journey since early 2018

arXiv.org > nucl-ex > arXiv:2109.00131

Nuclear Experiment

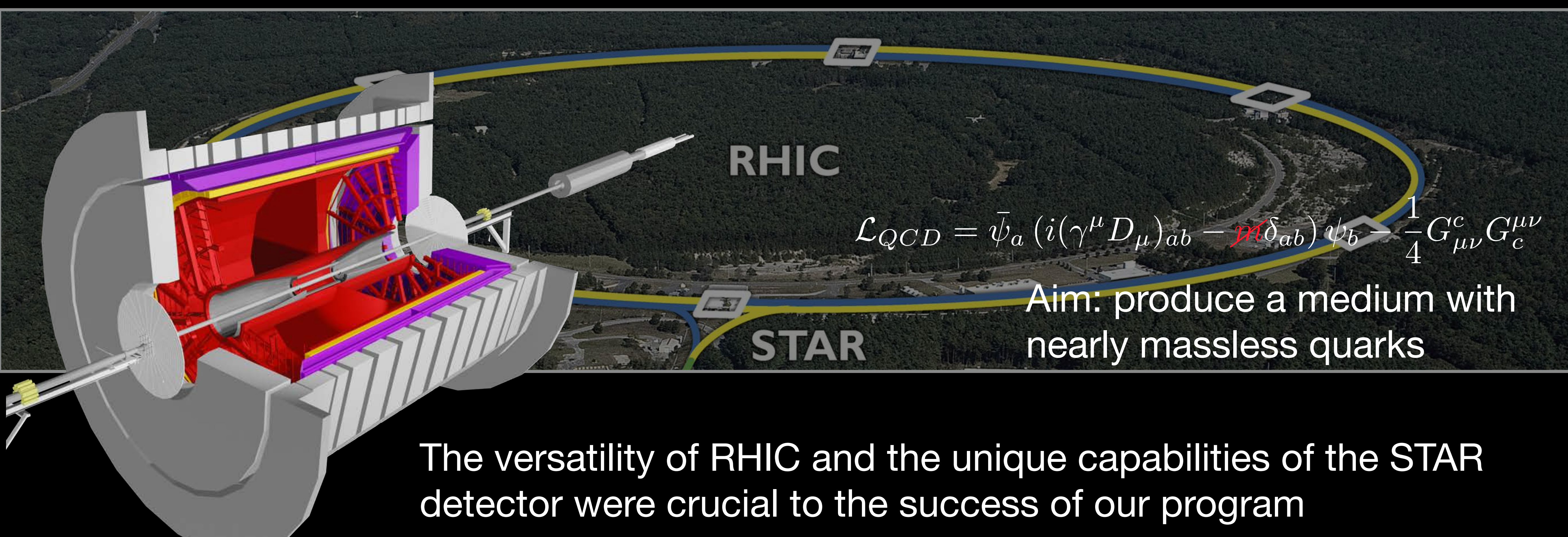
[Submitted on 1 Sep 2021]

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. 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.

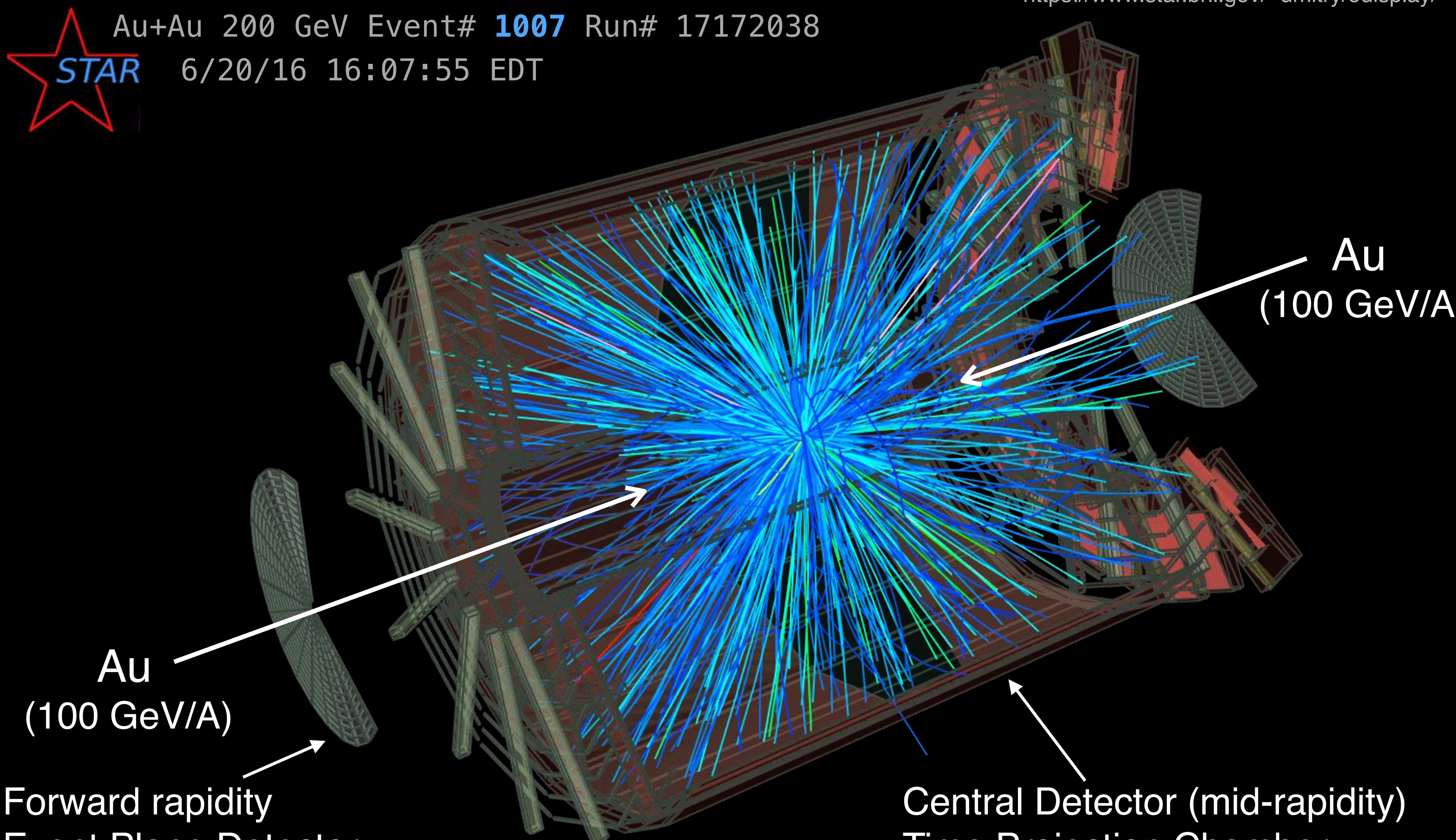
Comments: 43 pages, 27 figures
Subjects: **Nuclear Experiment (nucl-ex)**; High Energy Physics - Experiment (hep-ex); High Energy Physics - Phenomenology (hep-ph); Nuclear Theory (nucl-th)



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

A gold-gold collision @ STAR detector

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



Forward rapidity
Event Plane Detector
(Triggering events,
plane of collisions)

Central Detector (mid-rapidity)
Time Projection Chamber
(Momentum, charge state,
particle identification)

The Chiral Magnetic Effect

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PHYSICS LETTERS B
Physics Letters B 633 (2006) 260–264
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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

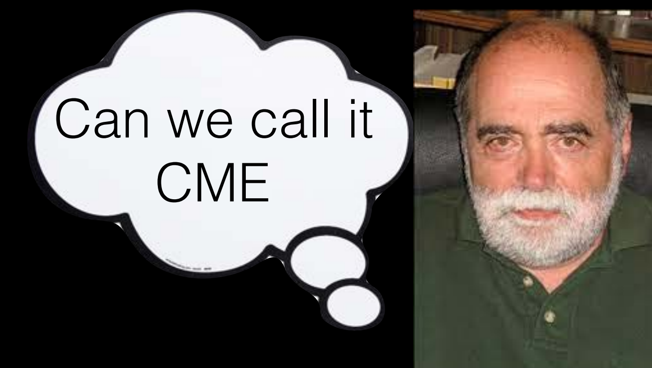
Received 23 December 2004; received in revised form 27 October 2005; accepted 23 November 2005

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 ☆

PRL **103,** 251601 (2009)
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS
week ending 18 DECEMBER 2009

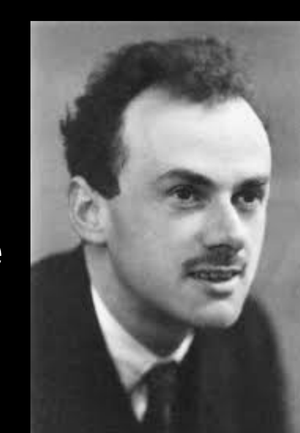
Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

(STAR Collaboration)

First experimental paper

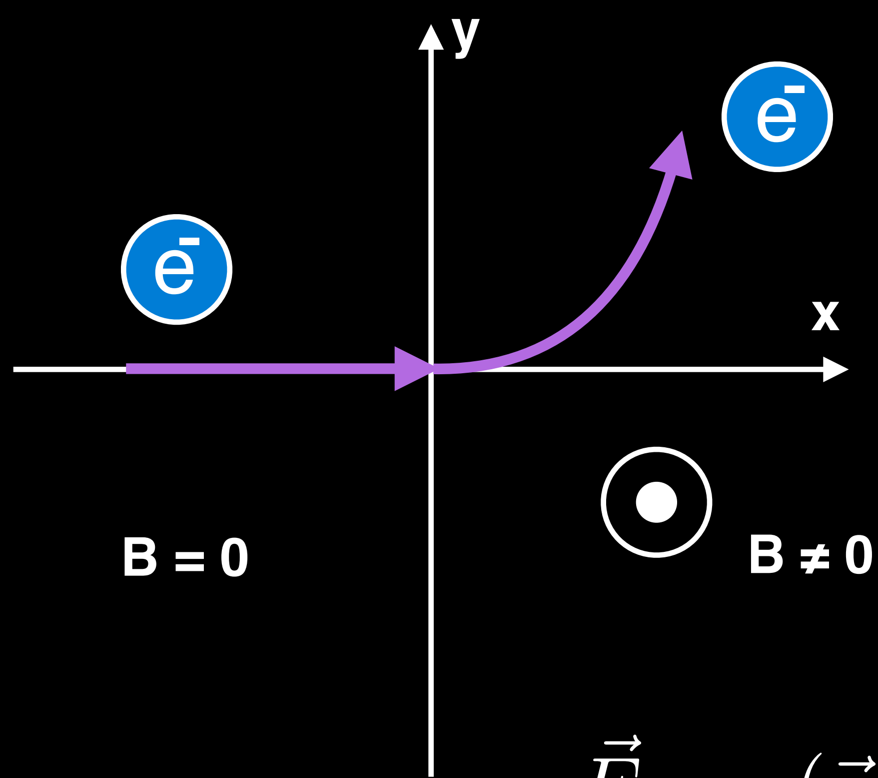
STAR collaboration, arXiv:0909.1739

The person who originates a new idea is really not in a best position to follow it up. Because the person is so scared that something will turn up which will knock the whole idea on the head — Paul A.M. Dirac



Chiral Magnetic Effect : why unique?

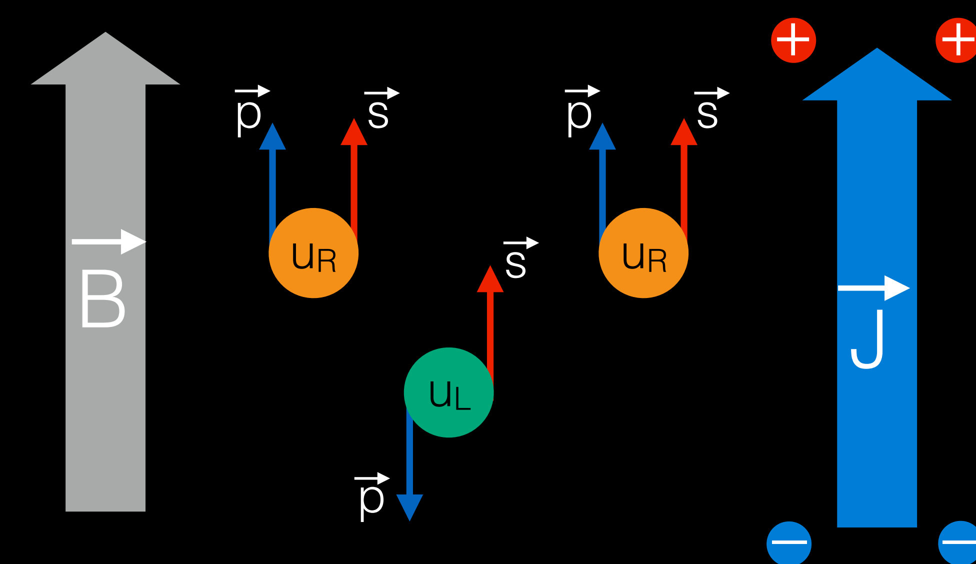
A phenomenon different from everyday motions of charge in EM-field



Motion of charge in EM-field

$$\vec{F} = q(\vec{v} \times \vec{B})$$

Chiral Magnetic Effect



$$\vec{J} = \sigma_{\rm CME} \vec{B}$$

CME: Generation of current along B-field due to chirality imbalance

Earliest Reference :
"Equilibrium Parity Violating Current In A Magnetic Field", A. Vilenkin, Phys.Rev.D 22 (1980) 3080-3084

Chiral Magnetic Effect & Parity

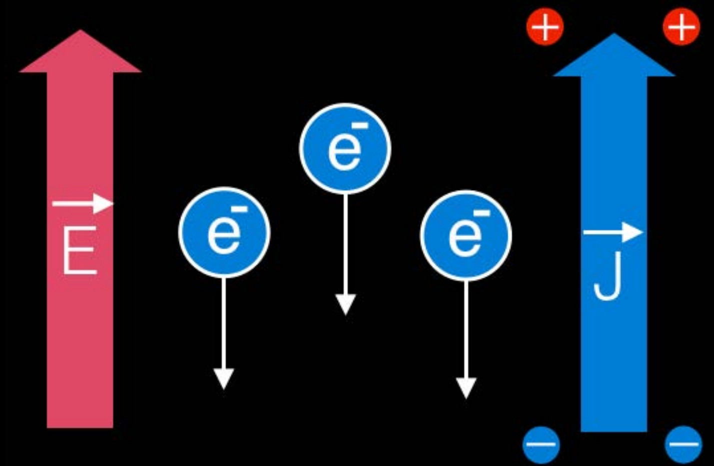
Ohm's law

$$\vec{J} = \sigma \vec{E}$$

Parity-odd

Parity even

Parity-odd



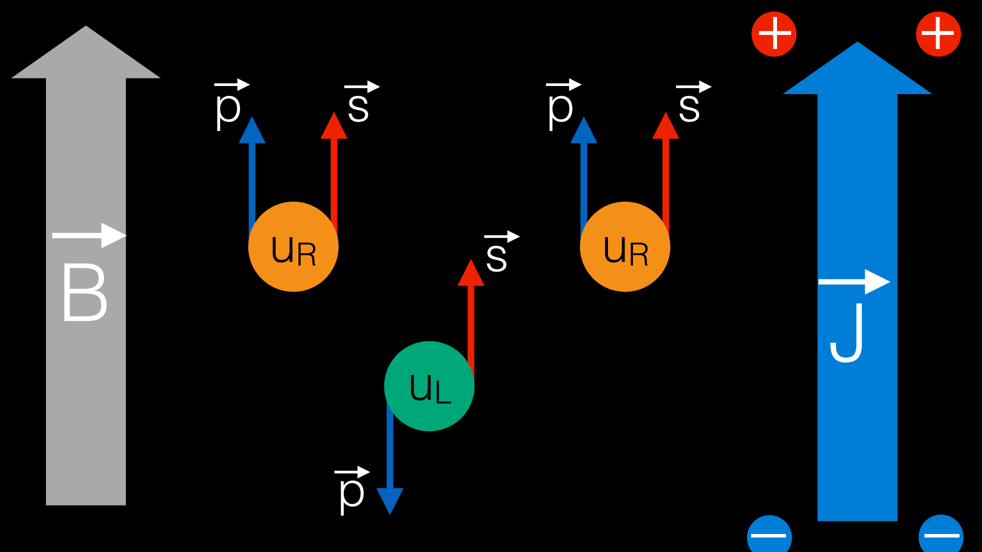
Chiral Magnetic Effect

$$\vec{J} = \sigma_{\mathrm{CME}} \vec{B}$$

Parity-odd

Parity-odd

Parity-even



Chiral Magnetic Effect : why unique?

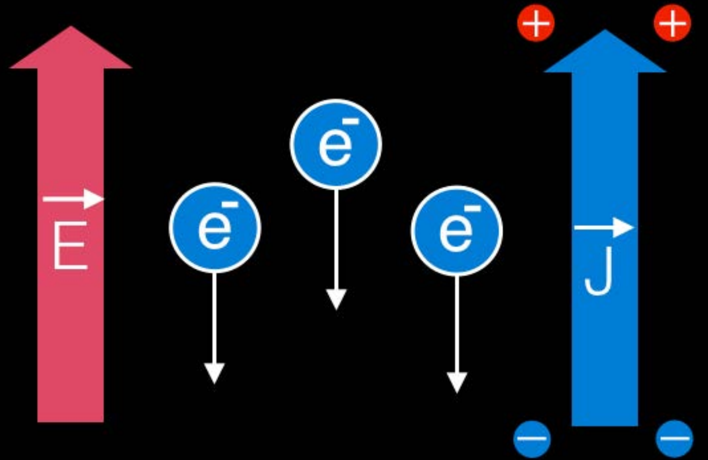
Ohm's law

$$\vec{J} = \sigma \vec{E}$$

T-odd

Dissipative

T-even



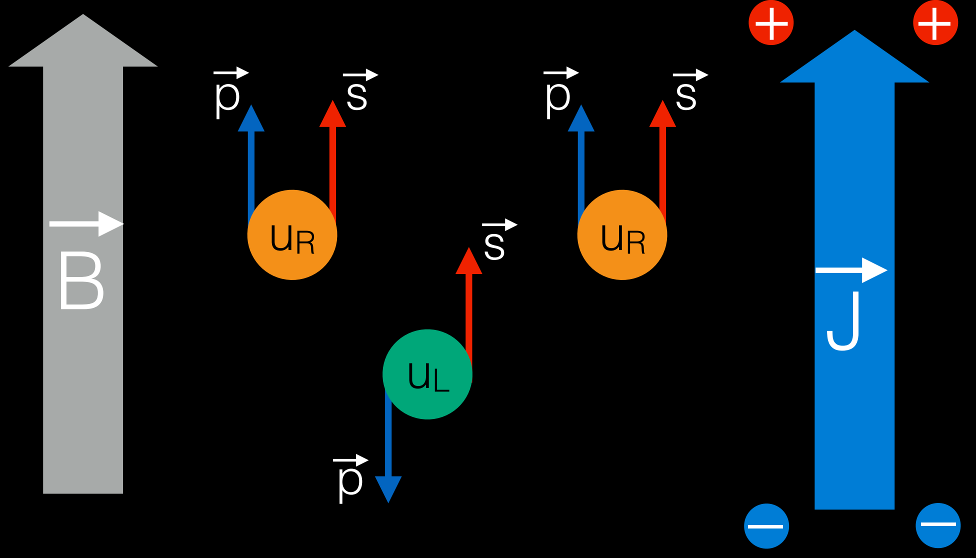
Chiral Magnetic Effect

$$\vec{J} = \sigma_{\mathrm{CME}} \vec{B}$$

T-odd

Non-dissipative

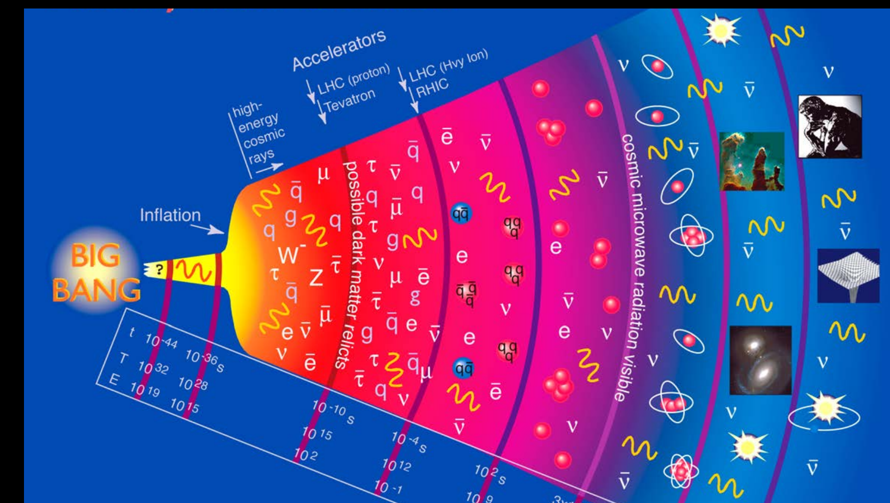
T-odd



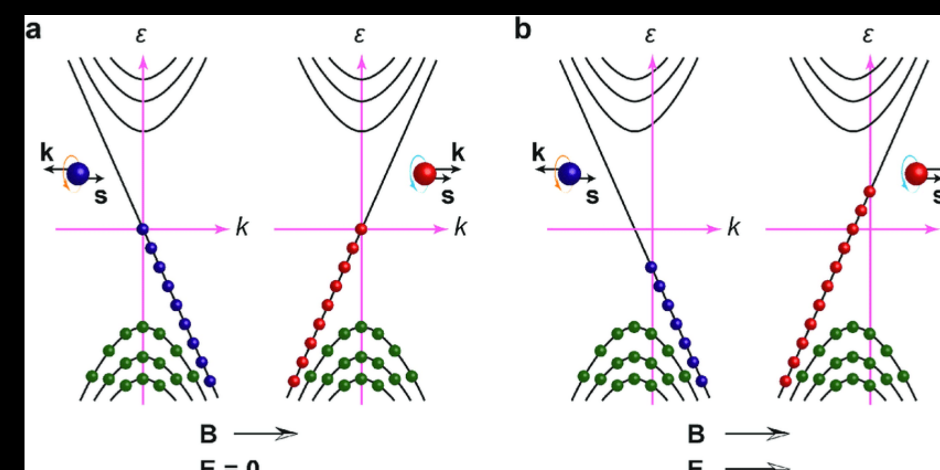
Chiral Magnetic Effect: scope & connections

Relativistic Heavy ion collisions
(hep-ph/0406125)

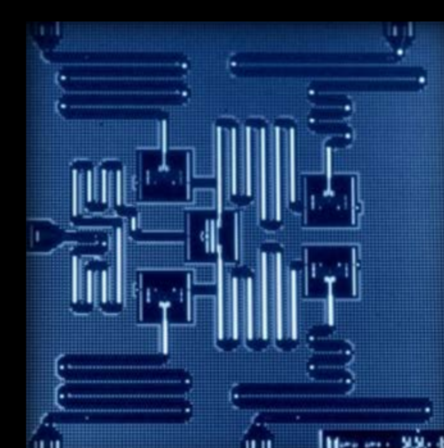
Early universe (1707.03385)

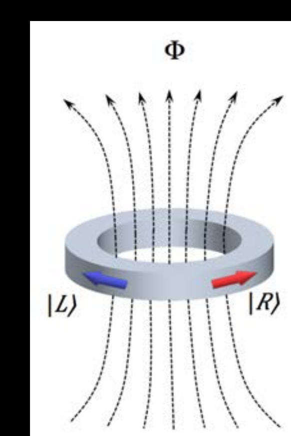


Condensed matter & Semimetals (1412.6543)

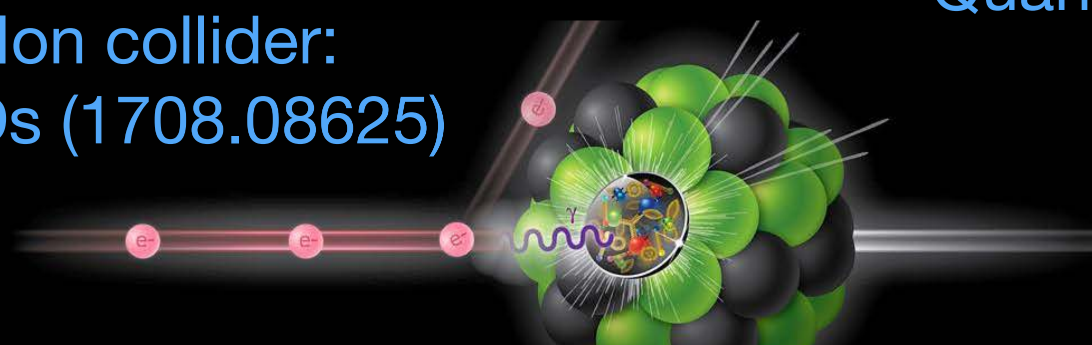


Quantum computer & Chiral Qbits (1903.07133)





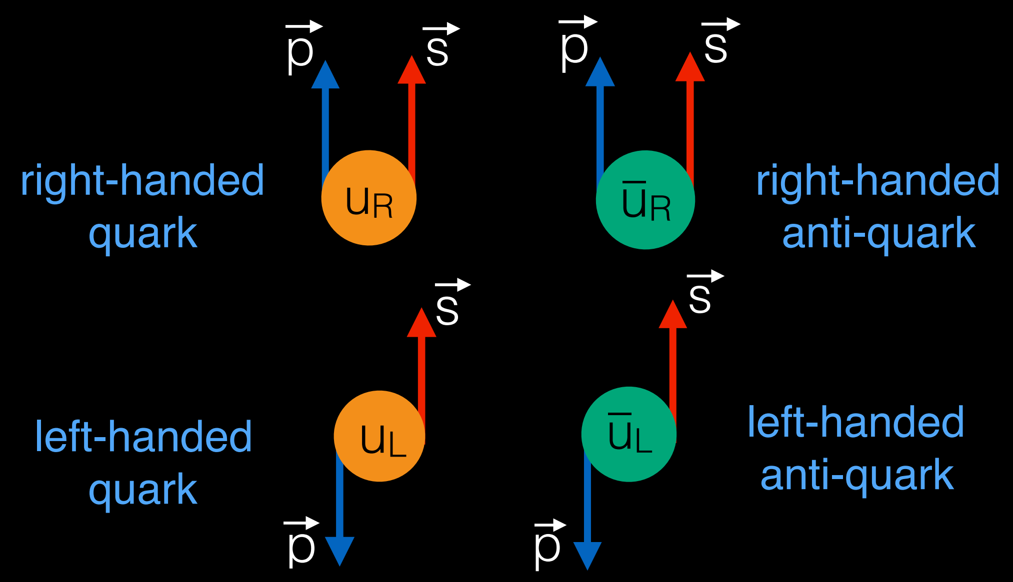
Electron-Ion collider:
WW TMDs (1708.08625)



$$\langle \dot{\nu}(x)\dot{\nu}(y)\rangle$$
$$\propto \left[(G^{(1)}_{A1}(x,y))^2(G^{(1)}_{A2}(x,y))^2 - (h^{(1)}_{\perp A1}(x,y))^2(h^{(1)}_{\perp A2}(x,y))^2\right]$$

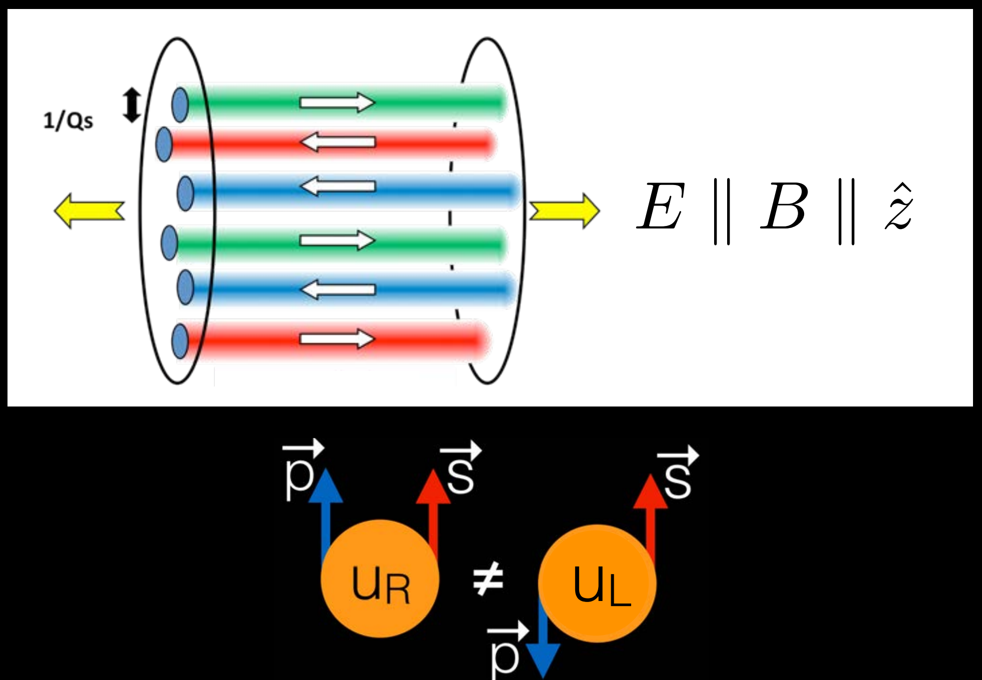
CME in hot QCD: key players in the game

1. Deconfined medium of massless quark (chiral symmetry restored)



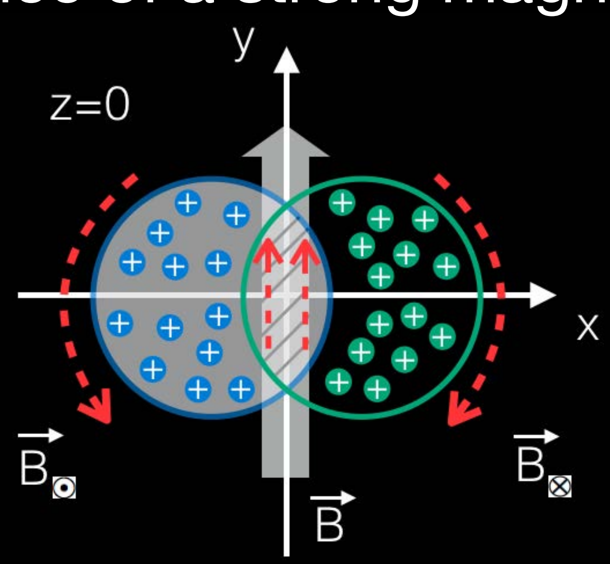
Kharzeev, McLerran,Warringa 0711.0950

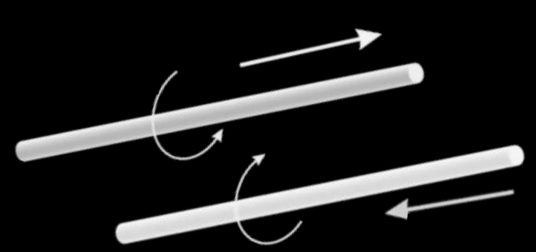
2. Mechanism to create imbalance of left & right handed quarks



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

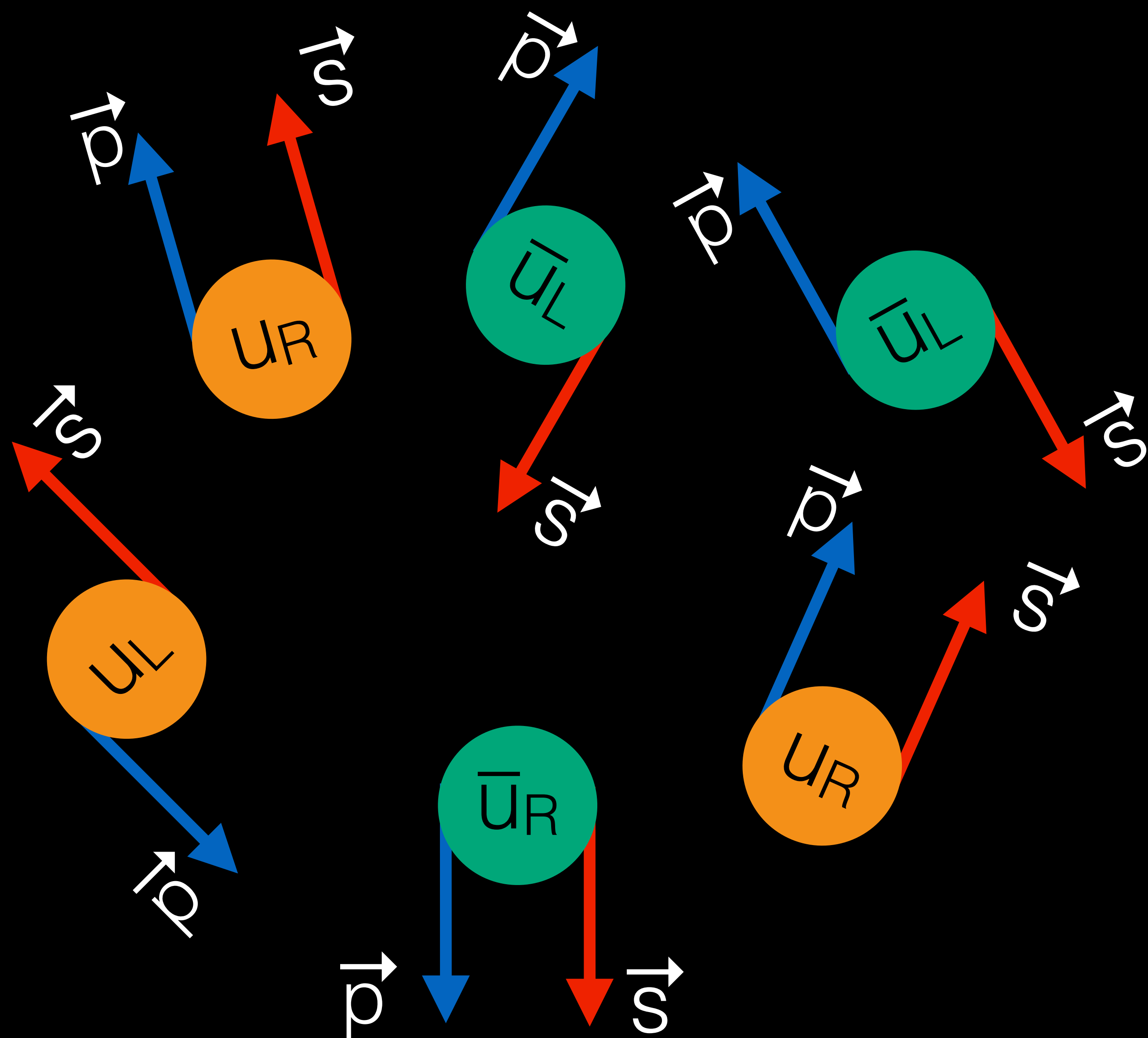
3. Presence of a strong magnetic-field





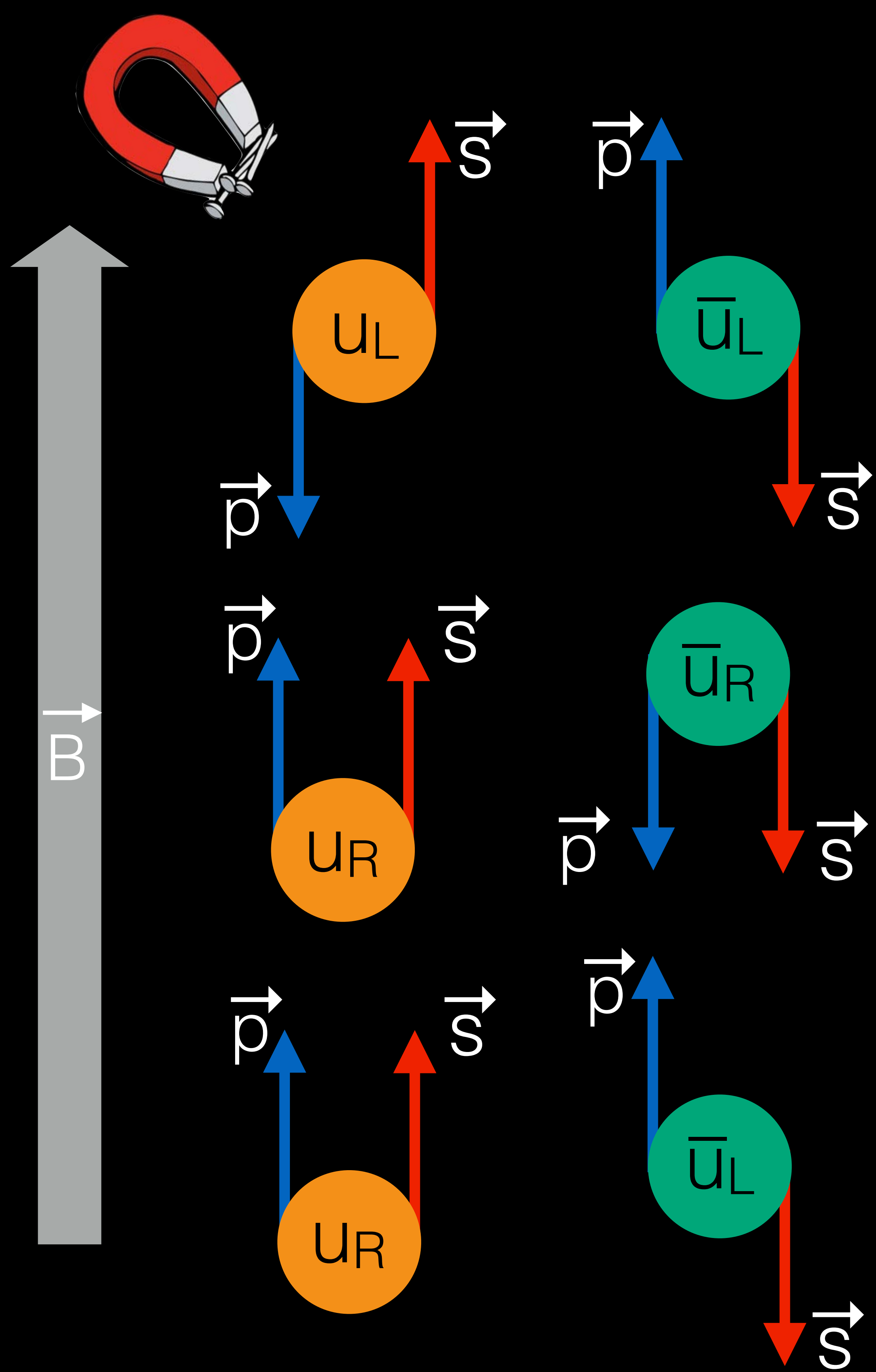
Kharzeev et al 0711.0950, Skokov et al 0907.1396, McLerran et al 1305.0774

Chiral Magnetic Effect



Massless Quarks produced in the system will have random spin orientations

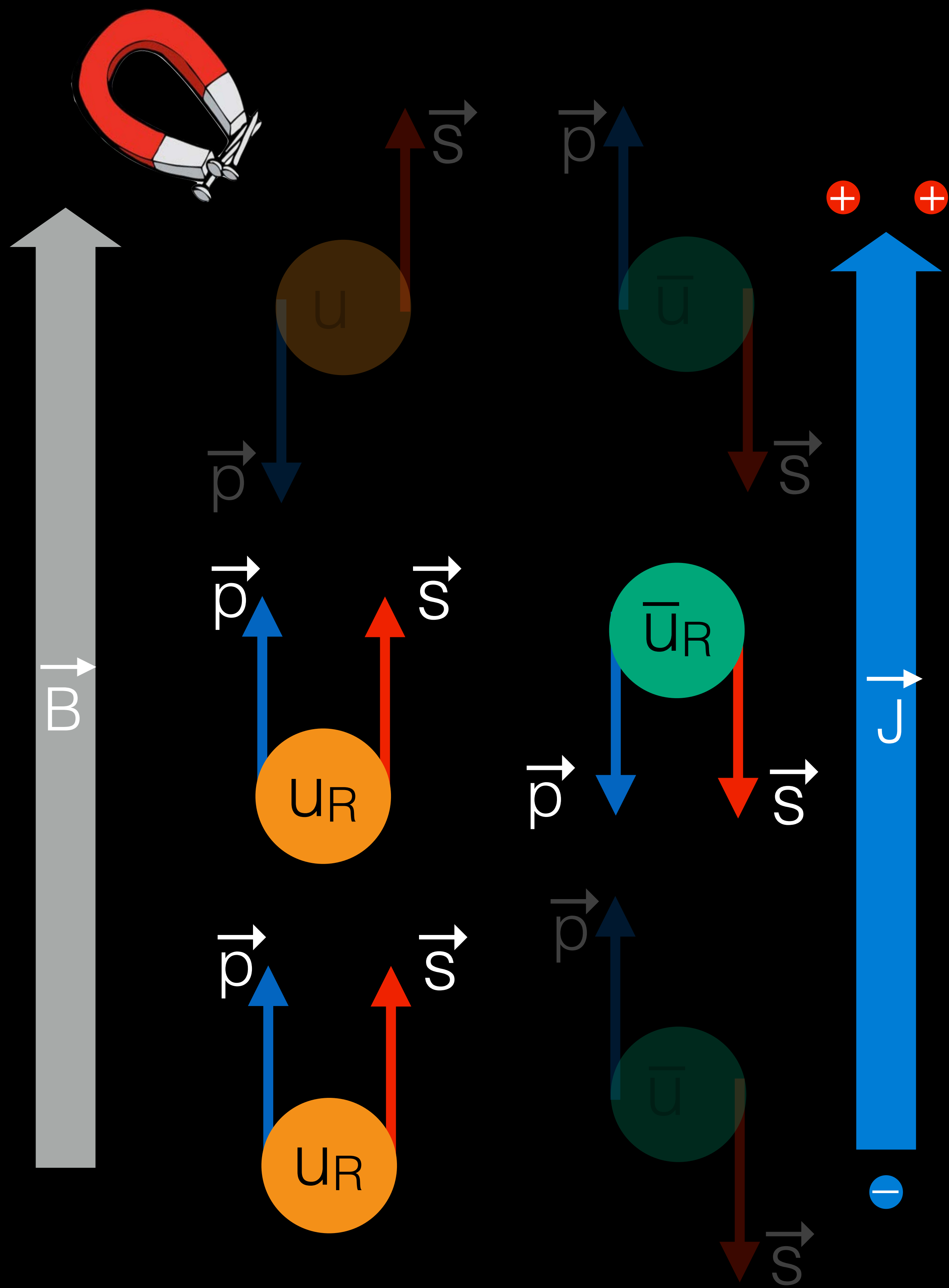
Chiral Magnetic Effect



Strong B-field will align the spin of the quarks due to magnetic polarization

Kharzeev, McLerran,Warringa 0711.0950

Chiral Magnetic Effect



Imbalance of chirality:

$$\mu_5 \sim (n_R - n_L)$$

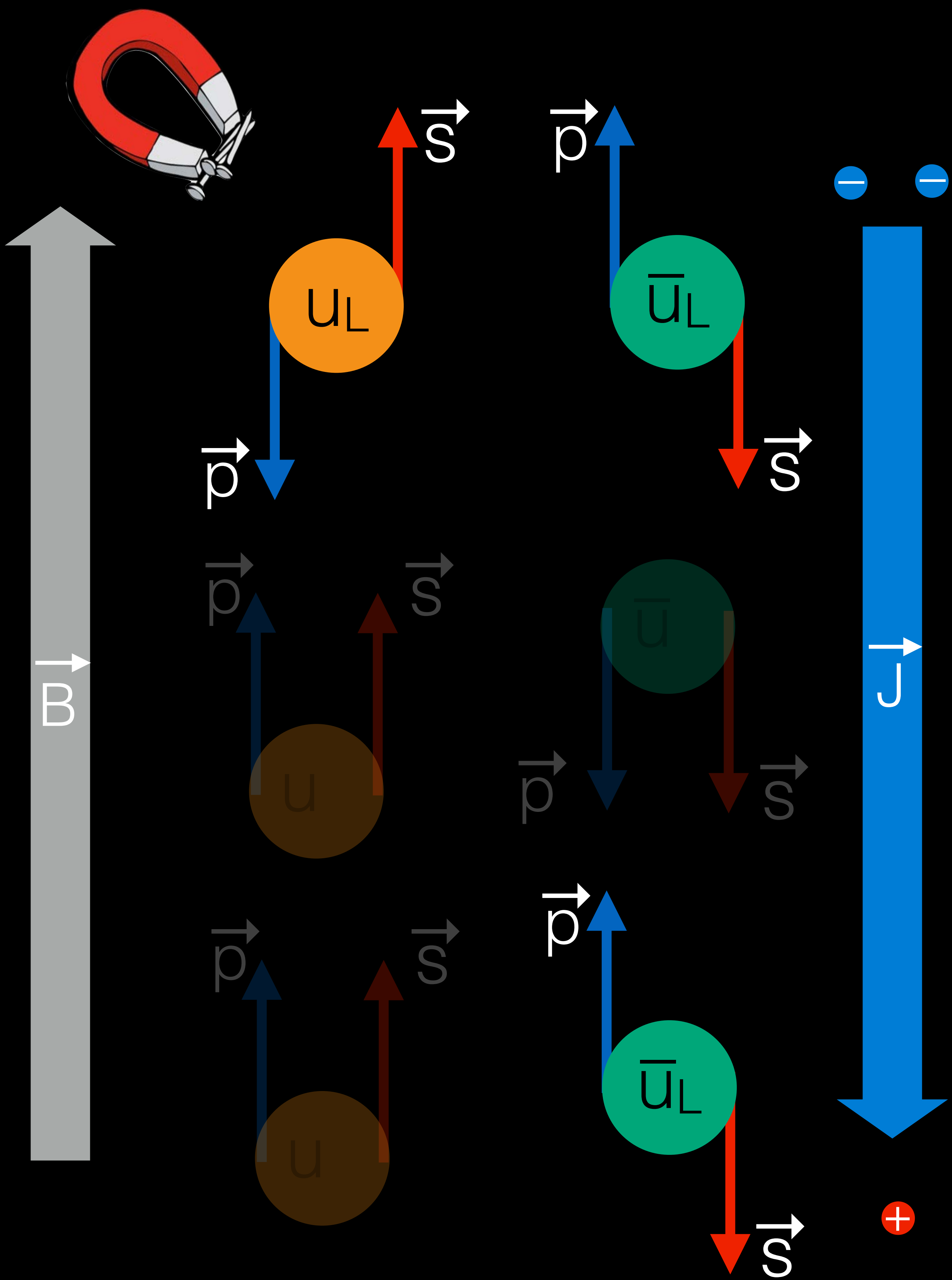
$$n_R > n_L$$

$$\vec{J} \propto \langle \vec{p} \rangle \propto (Qe)\mu_5 \vec{B}$$

Excess right-handed quarks
$\Rightarrow$ electric current along $\vec{B}$

Kharzeev, McLerran,Warringa 0711.0950

Chiral Magnetic Effect



Imbalance of chirality:

$$\mu_5 \sim (n_R - n_L)$$

$$n_R < n_L$$

$$\vec{J} \propto \langle \vec{p} \rangle \propto -(Qe)\mu_5 \vec{B}$$

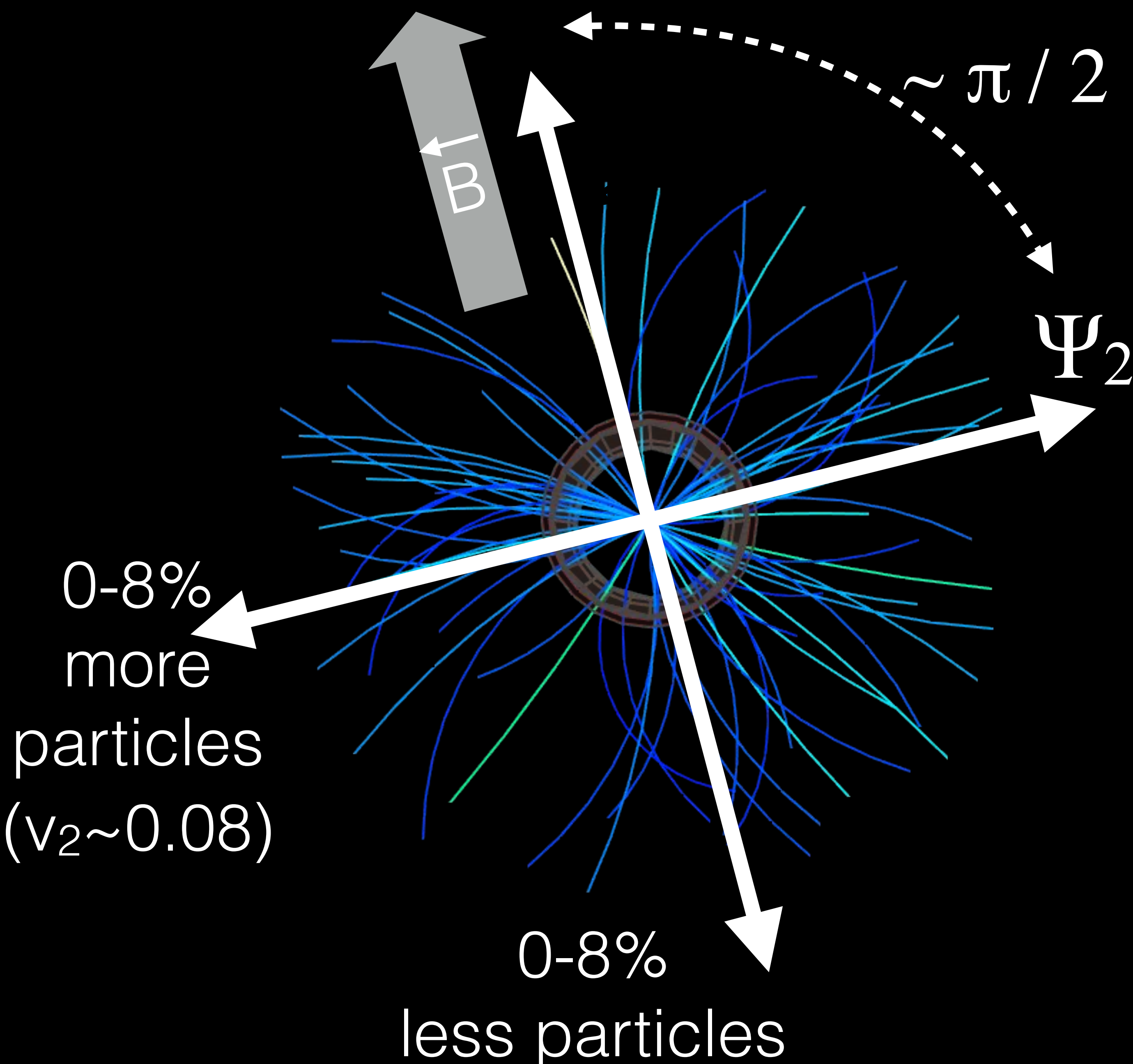
Excess left-handed quarks
$\Rightarrow$ electric current opposite to $\vec{B}$

Kharzeev, McLerran,Warringa 0711.0950

Experimental Observables for CME search

How to find B-field direction ?

Elliptic anisotropy is measured by correlation between two particles

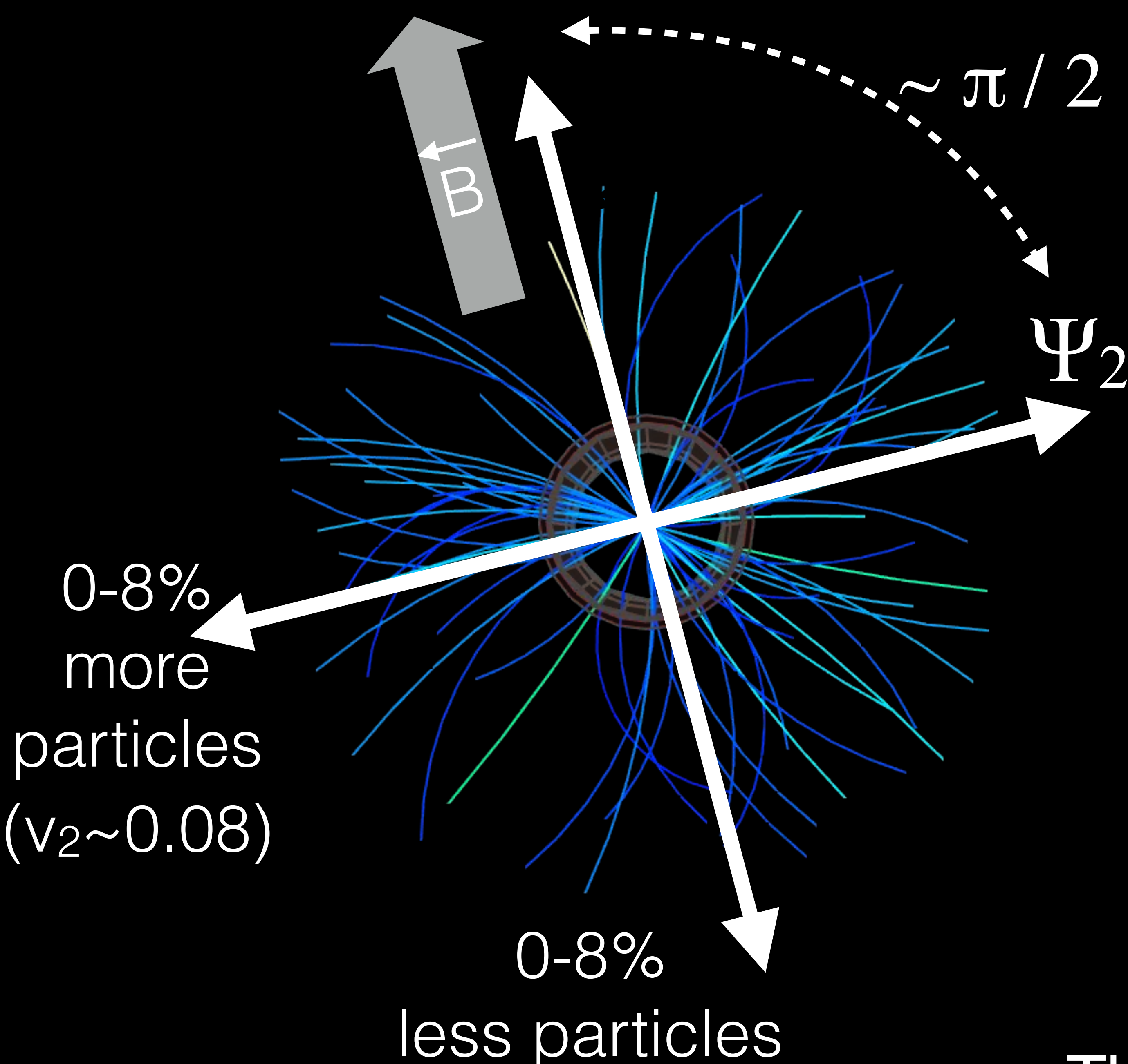


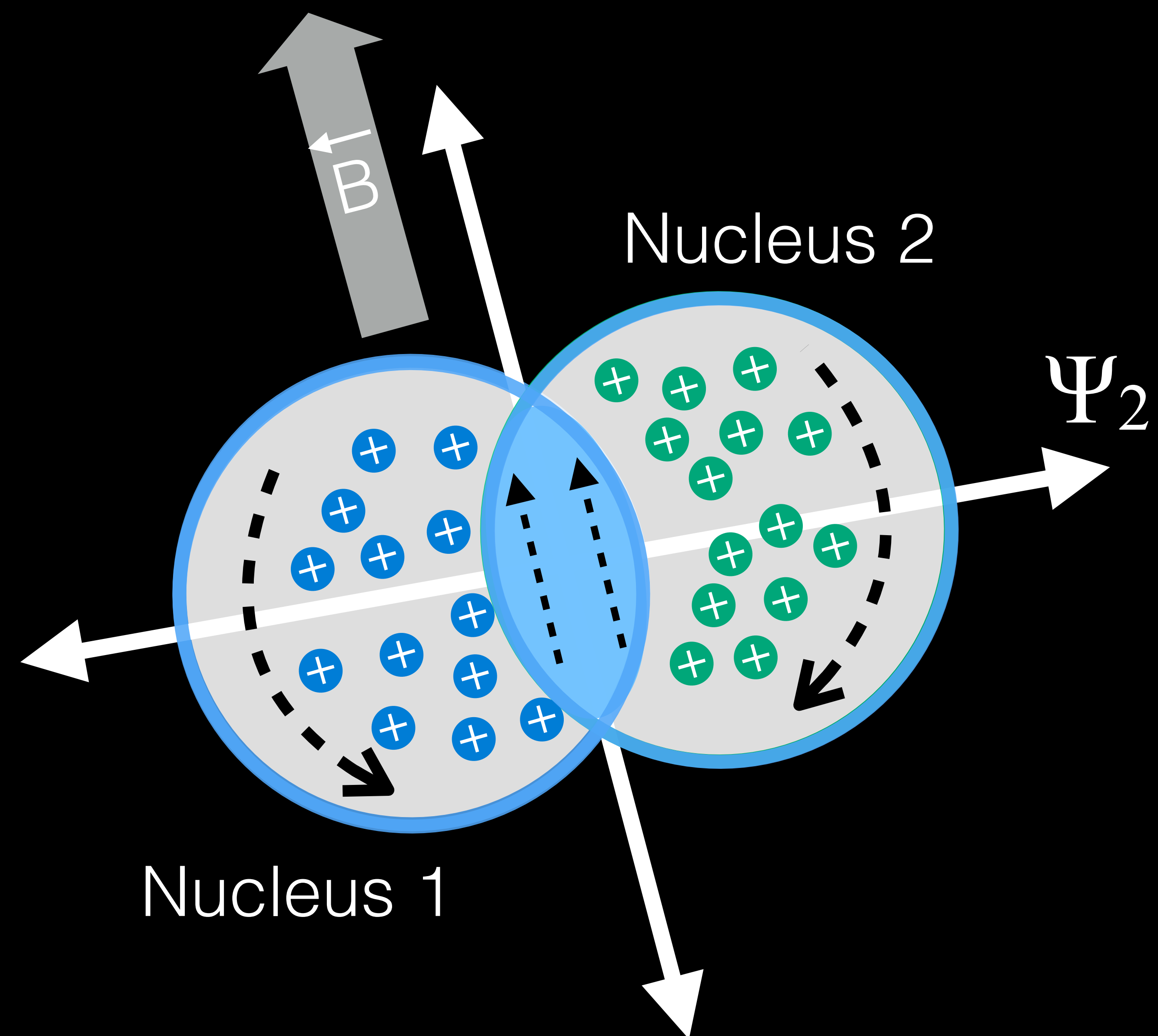
$$v_2\{EP\} = \langle \cos(2\phi_1 - 2\Psi_2) \rangle$$

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

How to find B-field direction ?

Elliptic anisotropy is measured by correlation between two particles

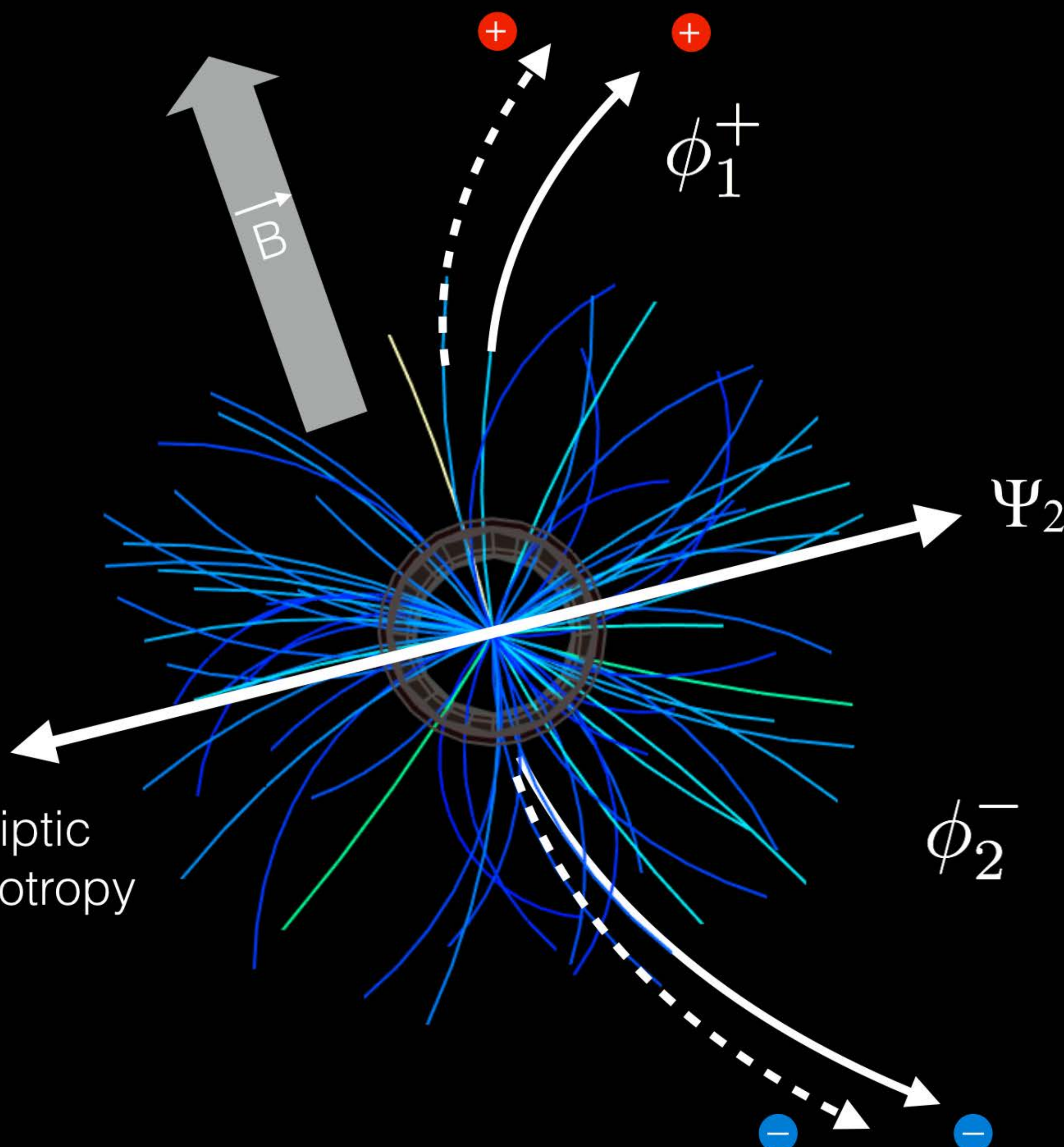




The plane of elliptic anisotropy Ψ_2 is correlated to B-field direction

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

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

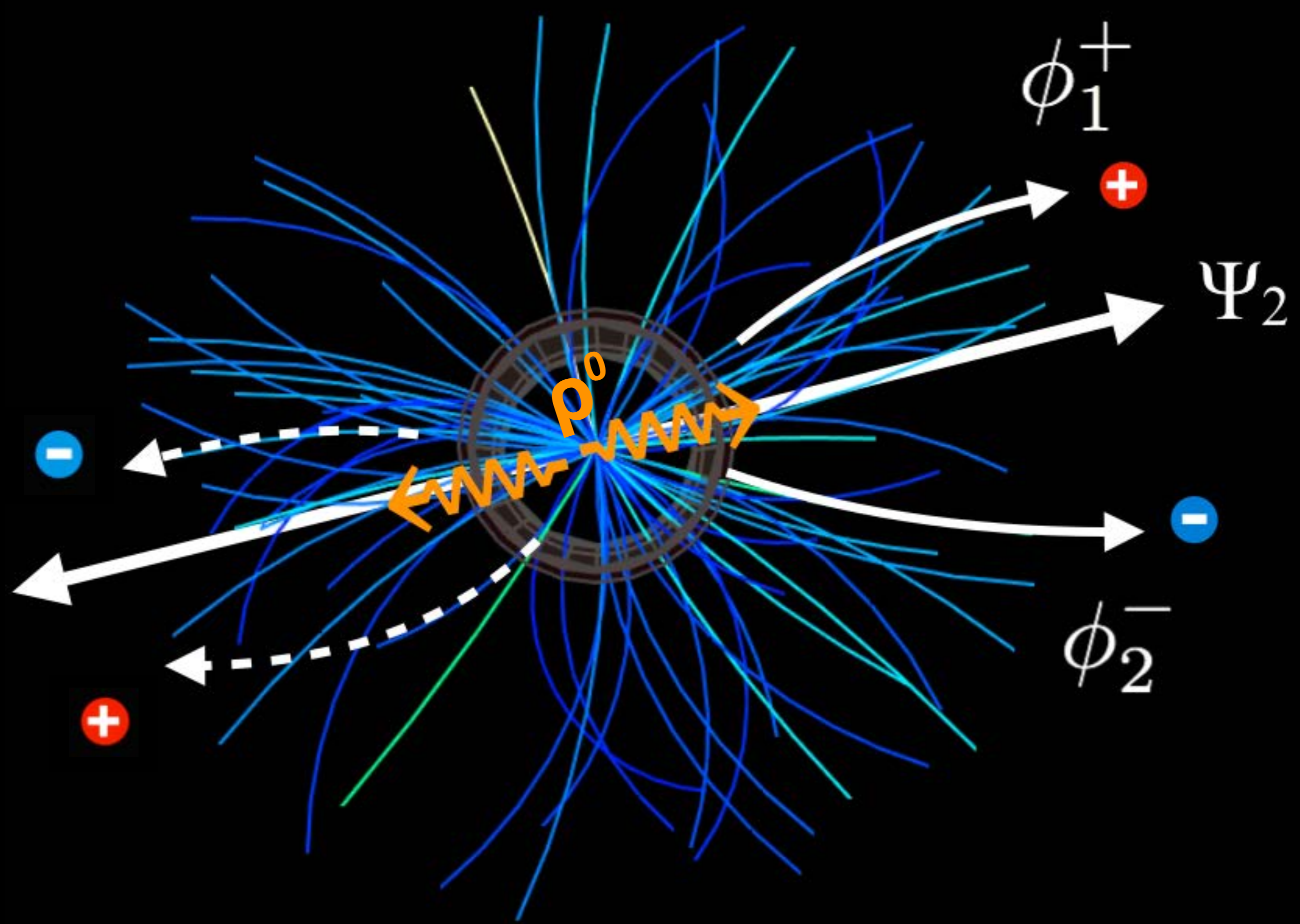
Quantity of interest:

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

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

How do we detect it : measure charge separation

Measure charge separation across Ψ_2 using the correlator:



Voloshin, hep-ph/0406311

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

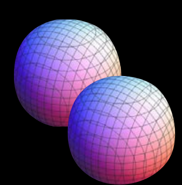
Flowing resonance decay: $\gamma^{SS} \neq \gamma^{OS}$

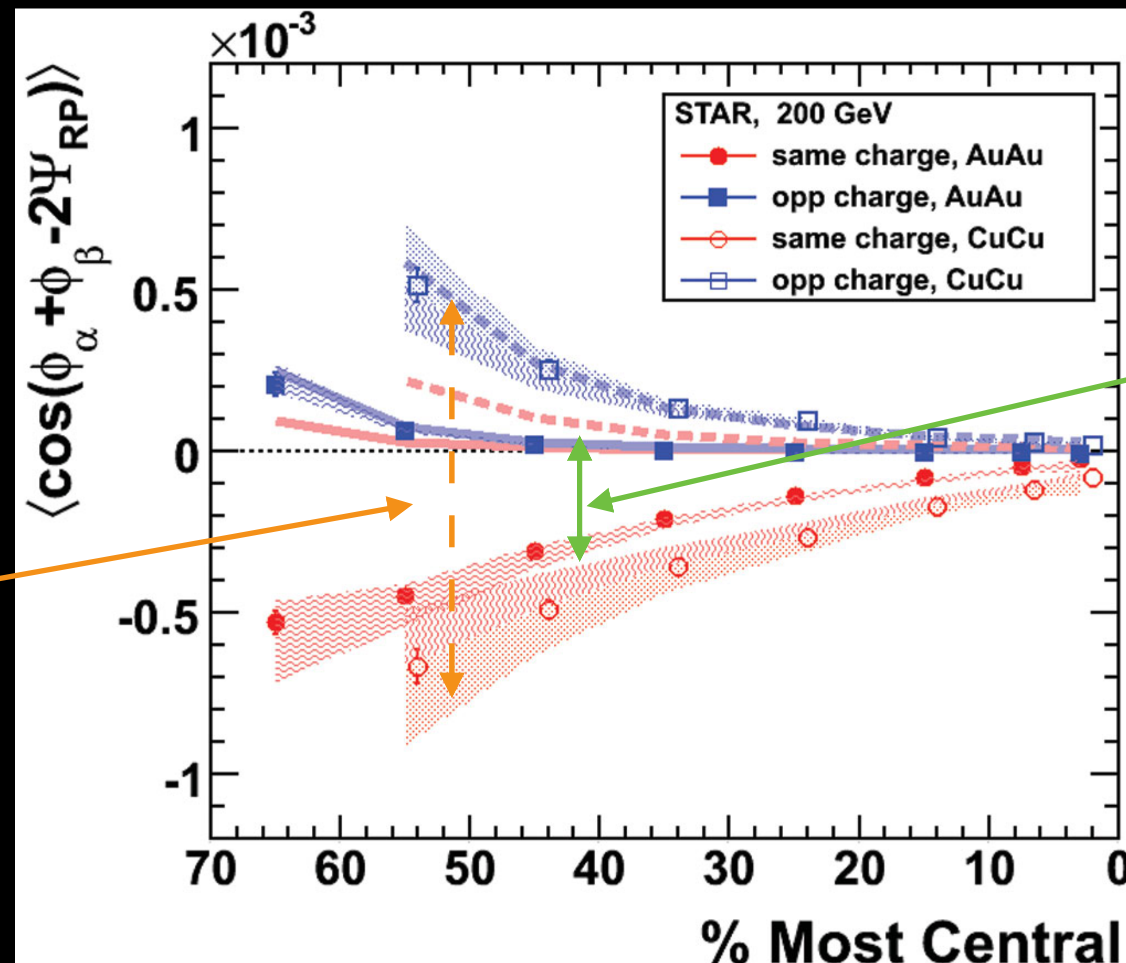
$$\gamma^{+-} = \cos(0+0+0) = 1$$
$$\gamma^{++,--} = \cos(0+\pi+0) = -1$$

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

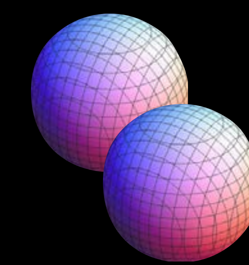
The first measurements at RHIC

Cu+Cu



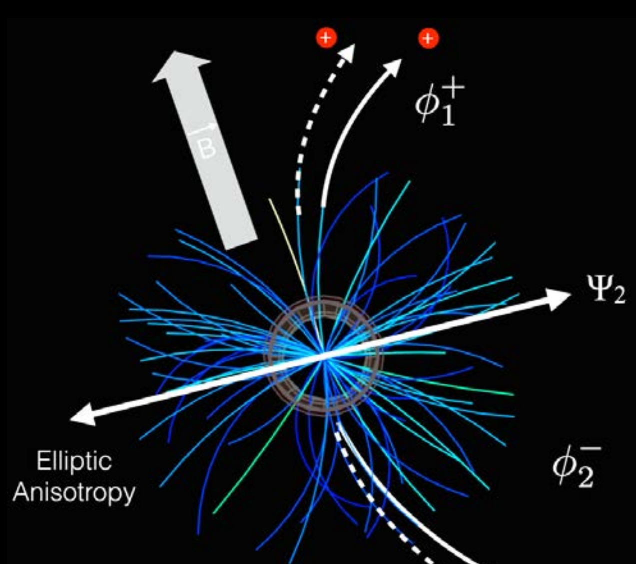


Au+Au



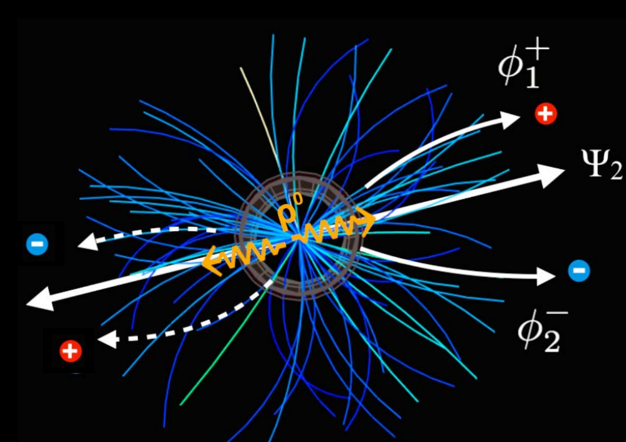
STAR collaboration, PRL 103, 251601 (2009

Three possible sources of charge separation



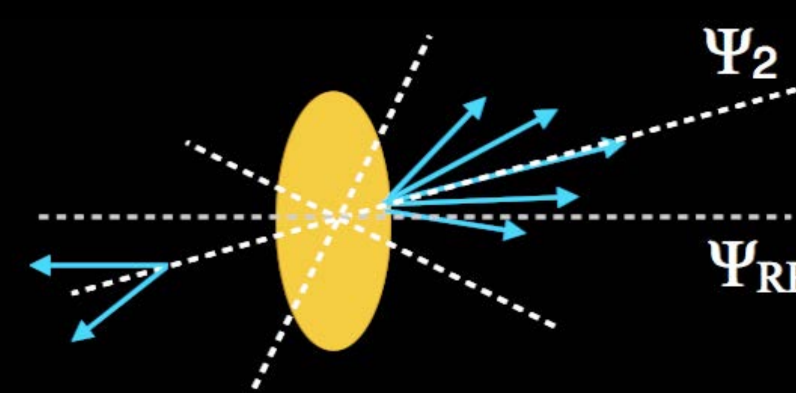
CME

+



Flowing resonance

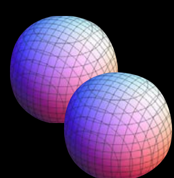
+

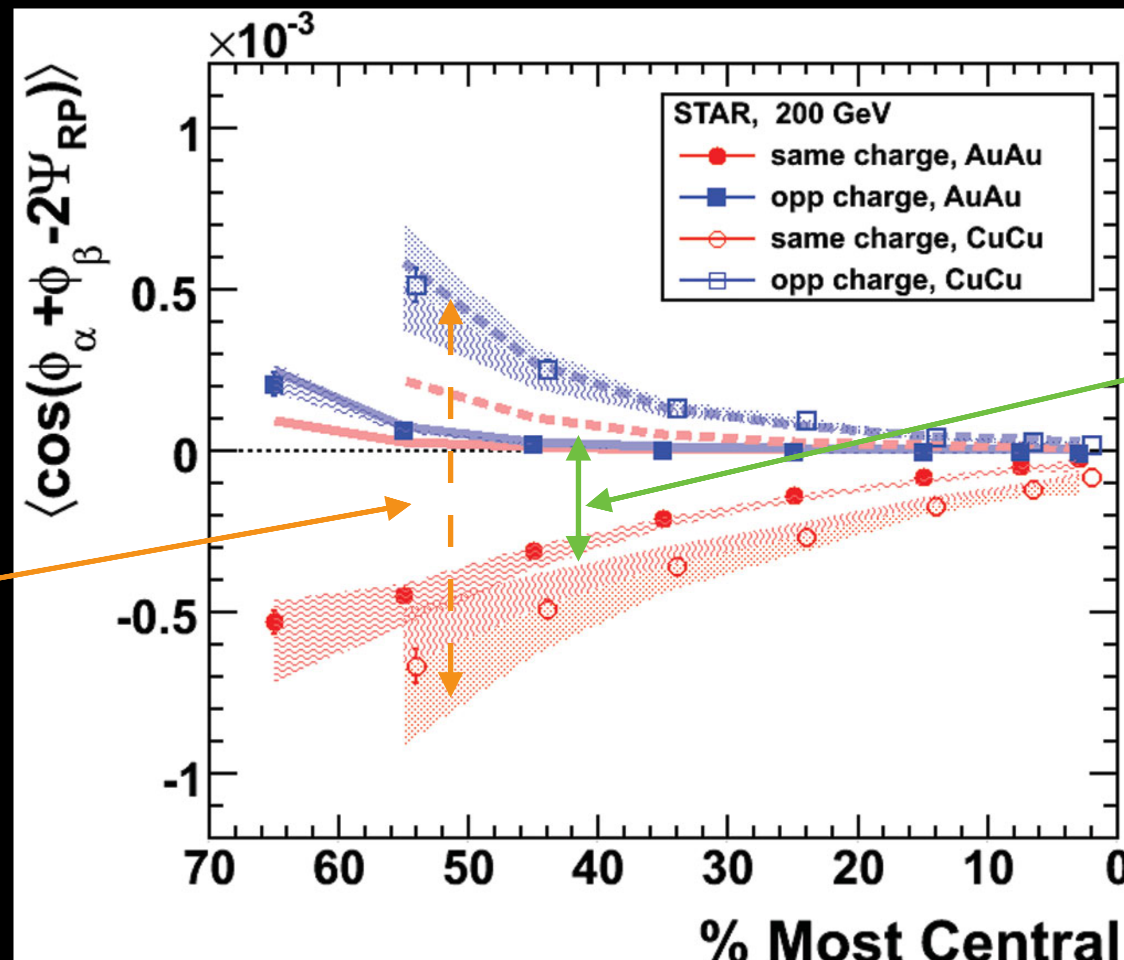


di-jets (non-flow)

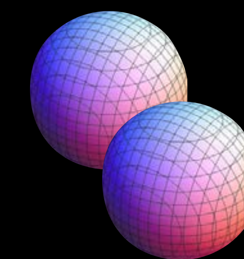
The first measurements at RHIC

Cu+Cu





Au+Au



STAR collaboration, PRL 103, 251601 (2009

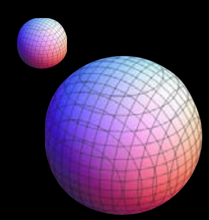
Significant charge separation observed, consistent with CME+ Background

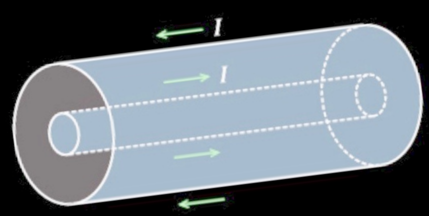
$$\Delta\gamma = \Delta\gamma^{CME} + k \times \frac{v_2}{N} + \Delta\gamma^{non-flow}$$

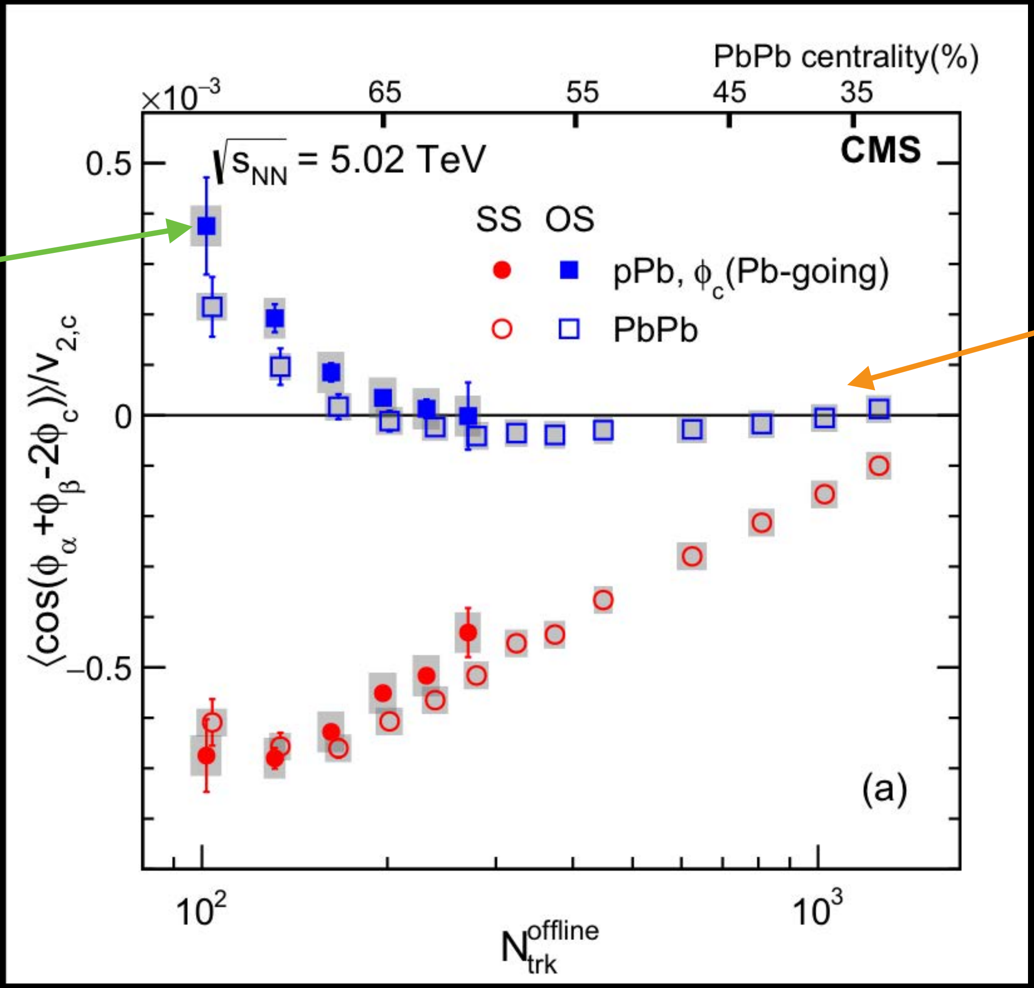
Measurement Signal Background-1 Background-2

Small system collisions to test CME

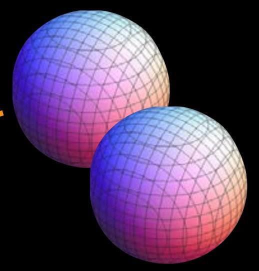
p+A

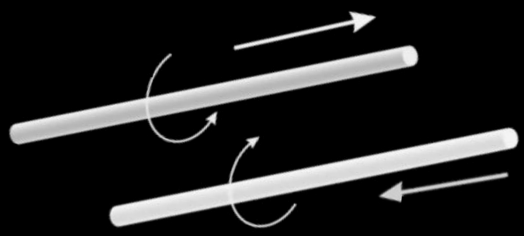






A+A





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

$$\begin{cases} \Delta\gamma^{A+A} = \Delta\gamma^{CME} + k \times \dfrac{v_2}{N} + \Delta\gamma^{non-flow} \\ \quad \| \qquad\quad \neq \qquad\quad \neq \qquad\qquad \neq \\ \Delta\gamma^{p+A} = \cancel{\Delta\gamma^{CME}} + k \times \dfrac{v_2}{N} + \Delta\gamma^{non-flow} \end{cases}$$

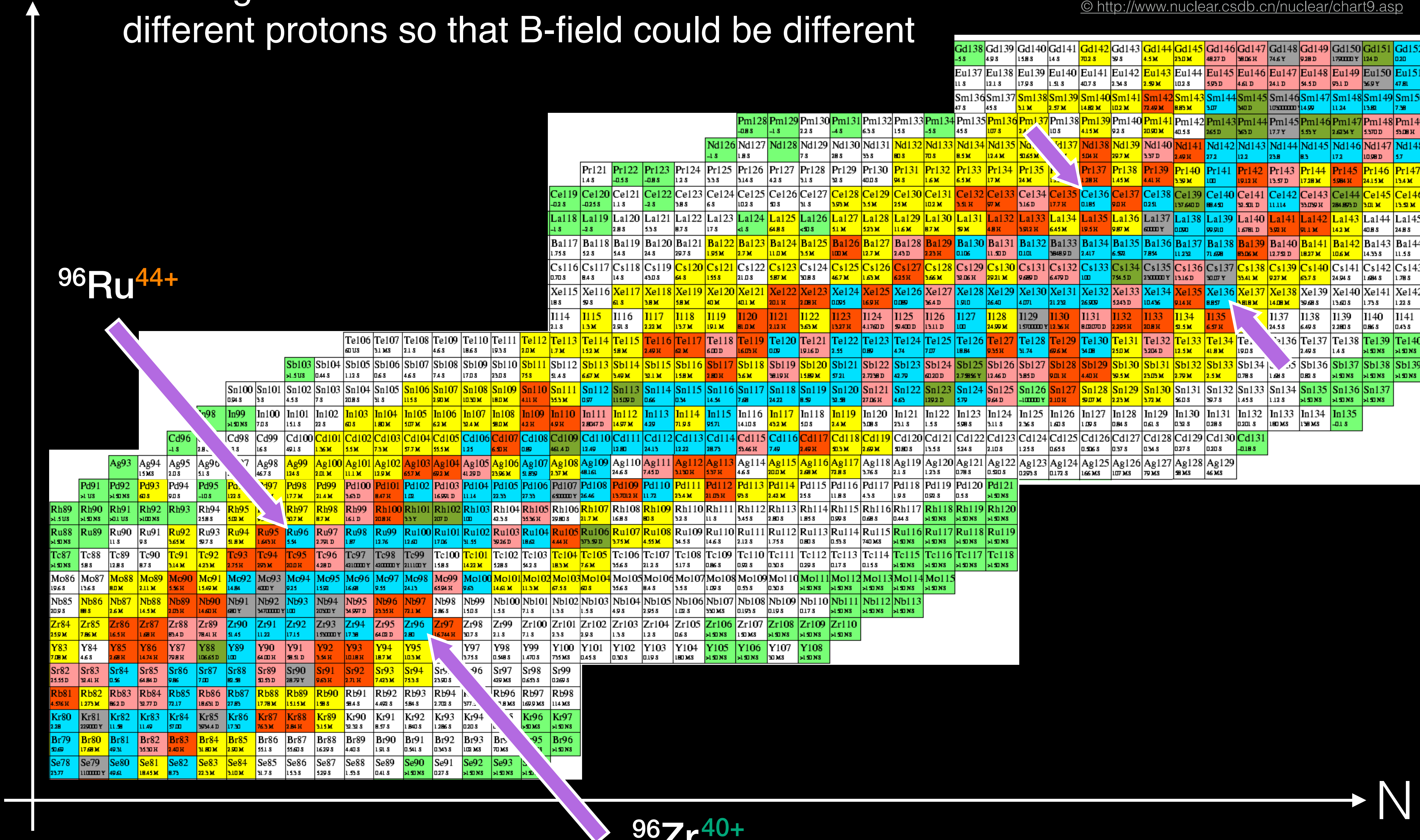
Only two equations & more unknowns difficult to prove if $\Delta\gamma^{CME} = 0$

Two systems of very different sizes → limited control over background

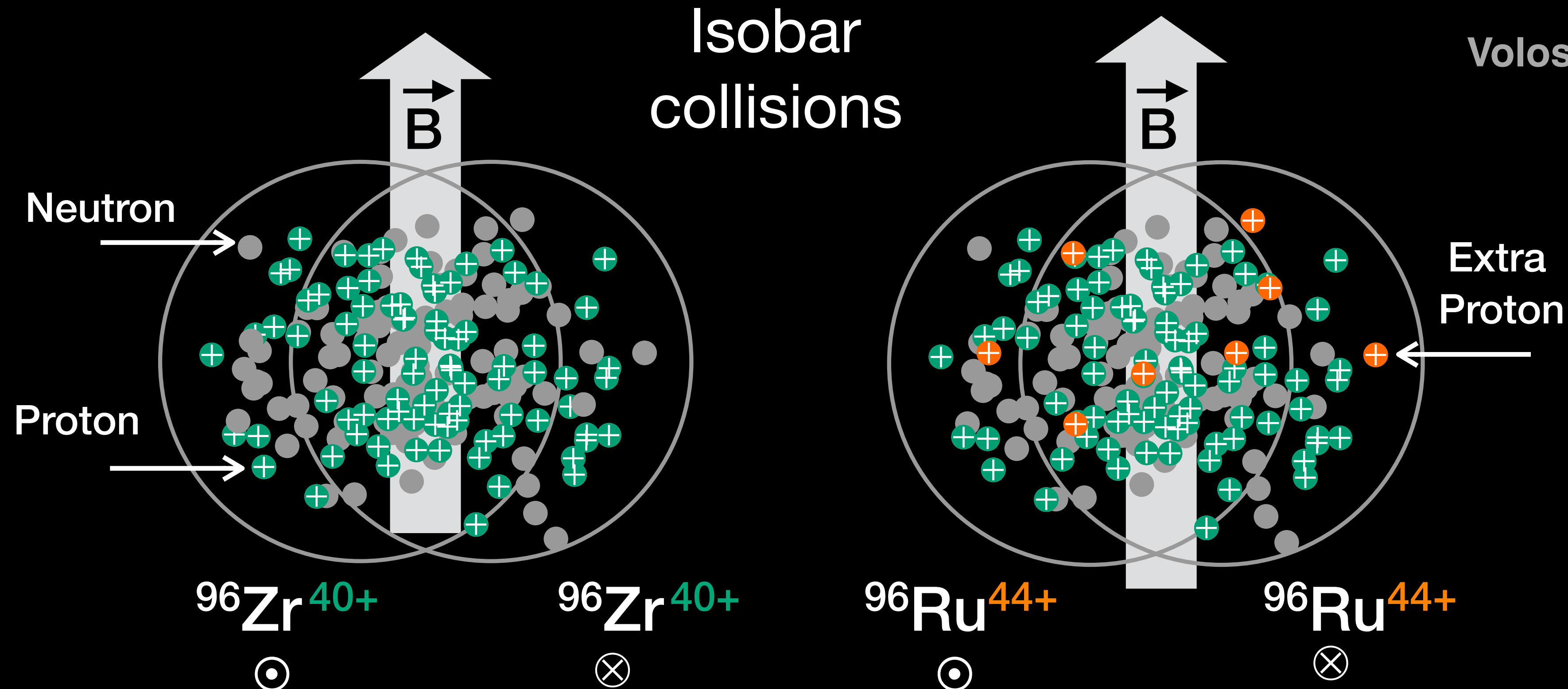
This naturally leads to the idea of using two systems of similar sizes

Isobar in the chart of nuclides

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

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

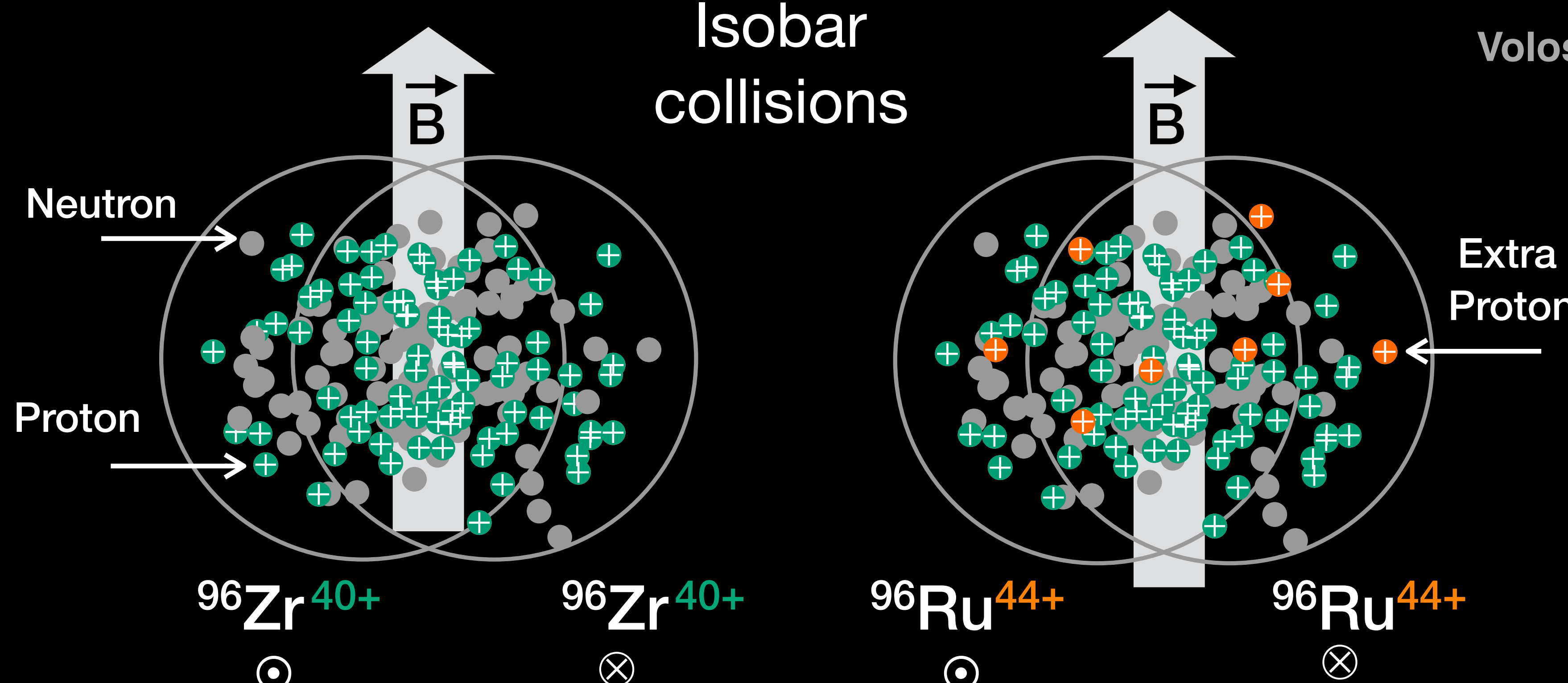
$$\begin{array}{cccc} ?? & \neq & \approx & \parallel \end{array}$$

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

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

Isobar collisions

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



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

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

?? $\qquad \nparallel \qquad \wr$

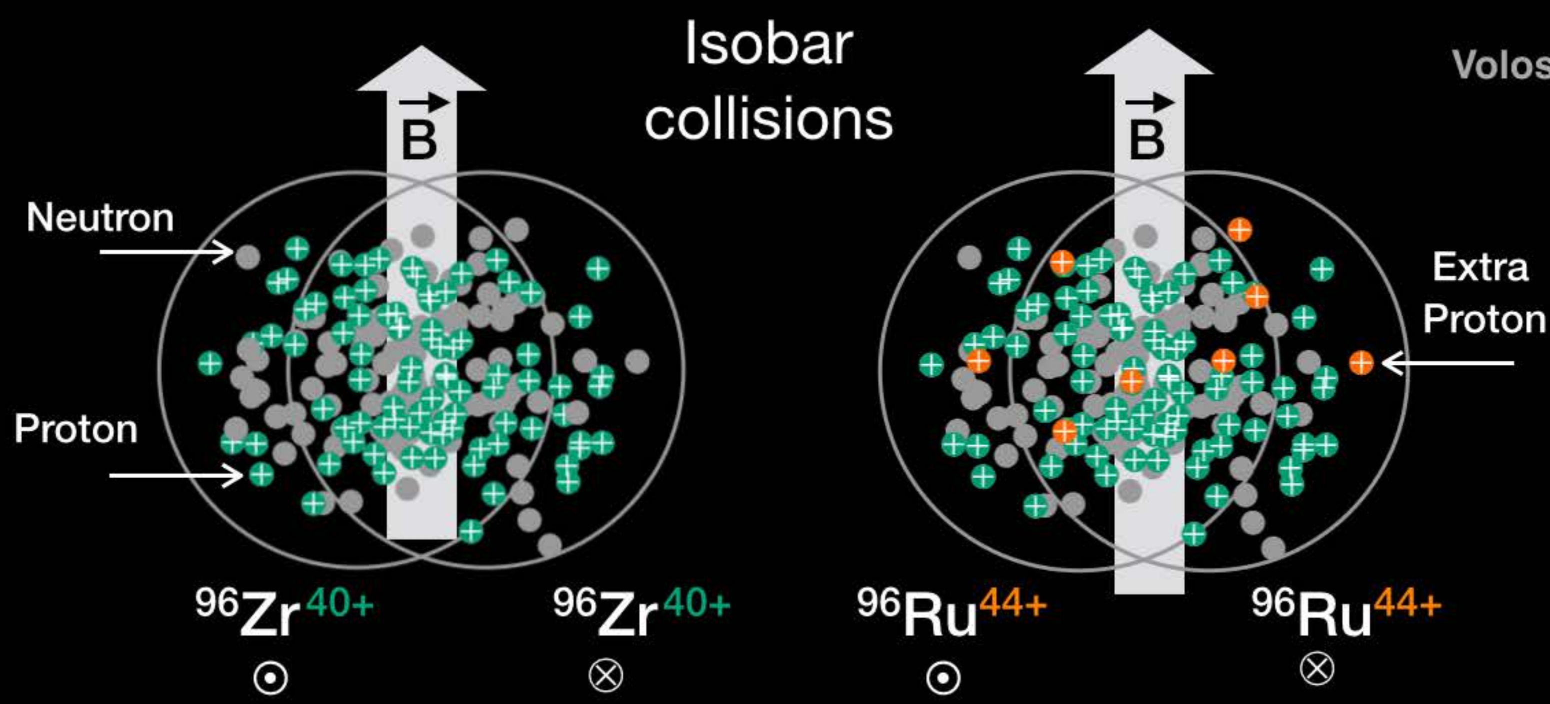
$$\Delta\gamma^{\text{Zr+Zr}} = \Delta\gamma^{CME} + k \times \frac{v_2}{N}$$

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

If multiplicity (N) is same in two isobars:

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

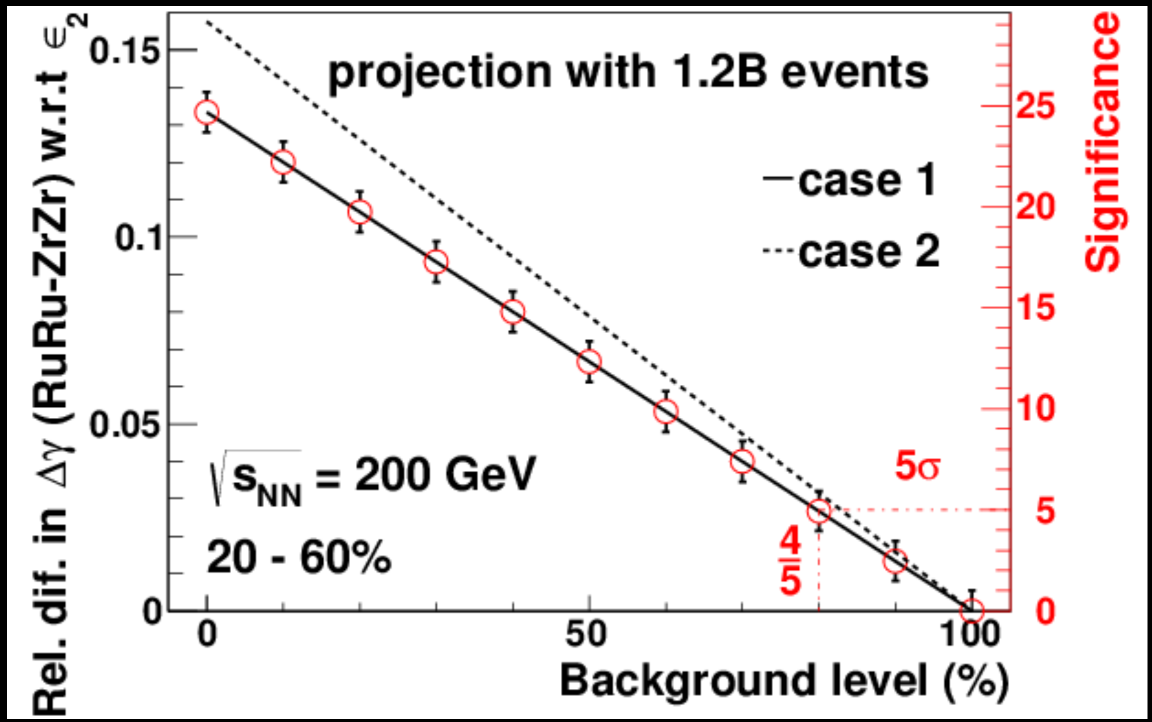
Isobar collisions



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

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

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



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

> 1 (for CME)

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

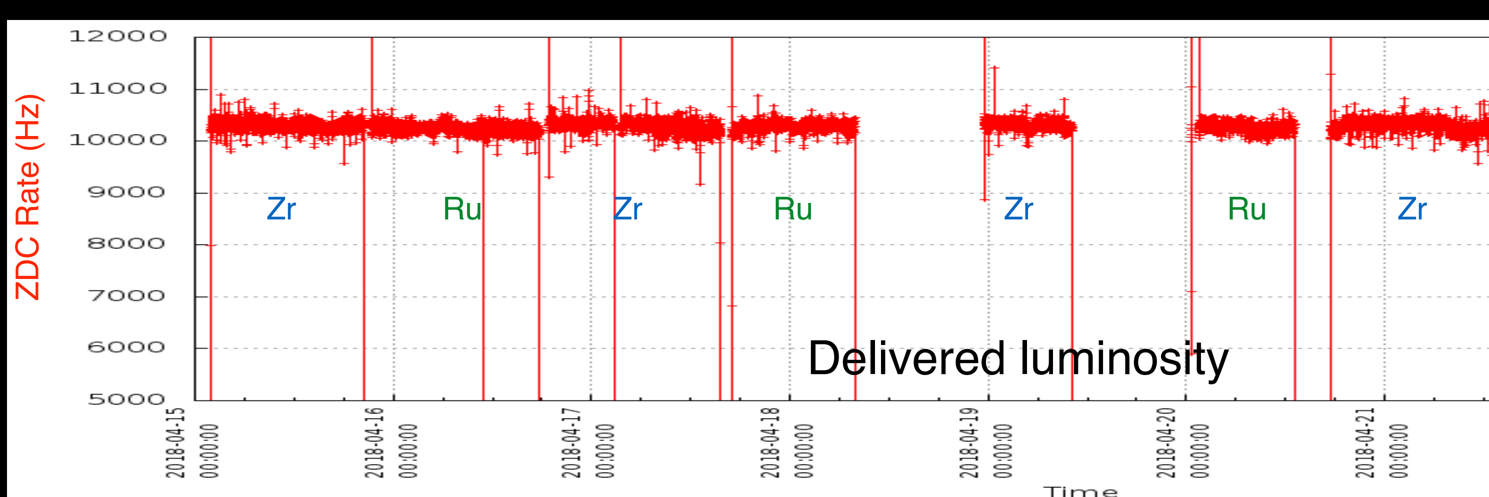
1.2 B collision events for each species can give 5σ significance for 20% signal level (f_{CME} ~ 0.2)

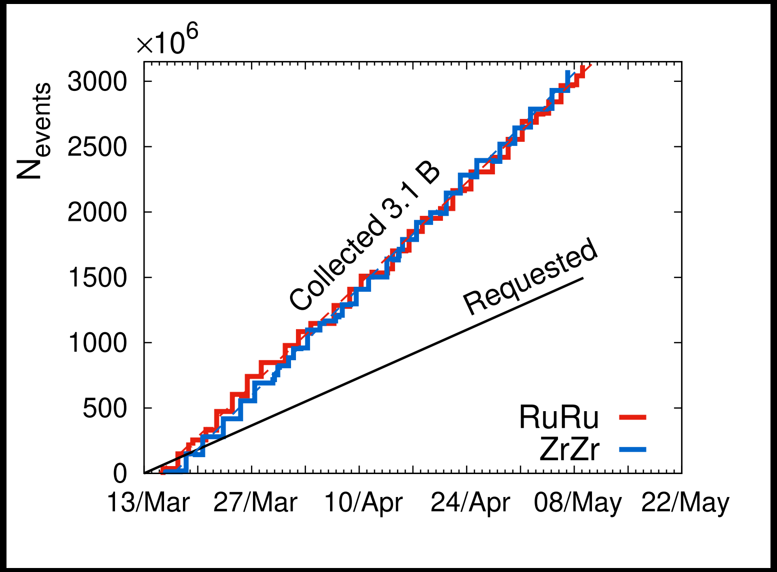
(A precision of 0.5% is needed !!)

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



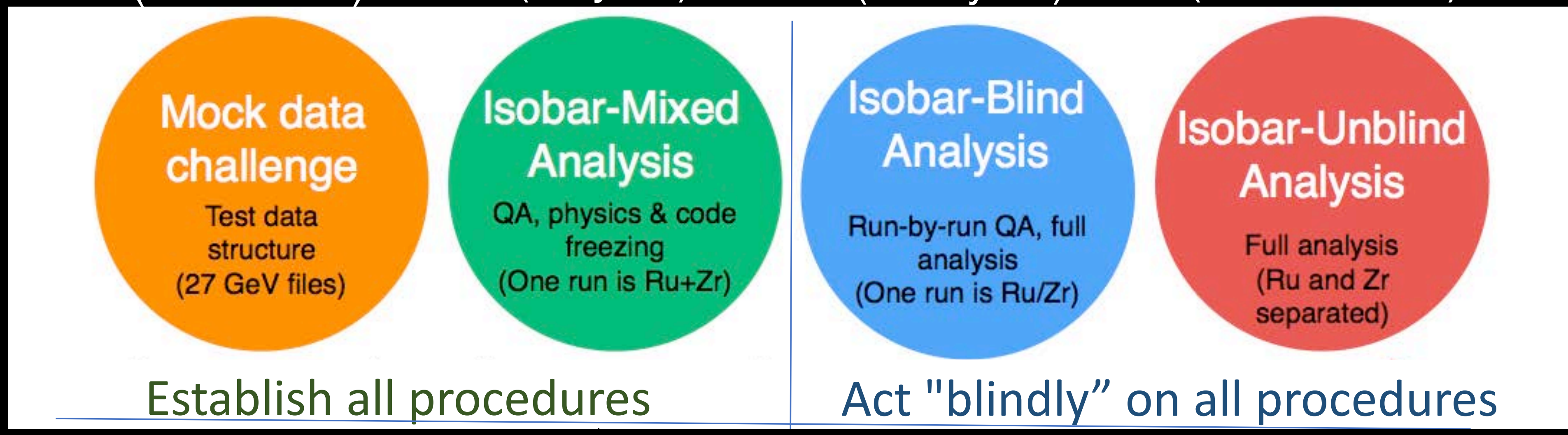


G. Marr et al., in 10th International Particle Accelerator Conference (2019) pp. 28–32.

Blind analysis of the isobar data

Steps of Isobar blind analysis

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



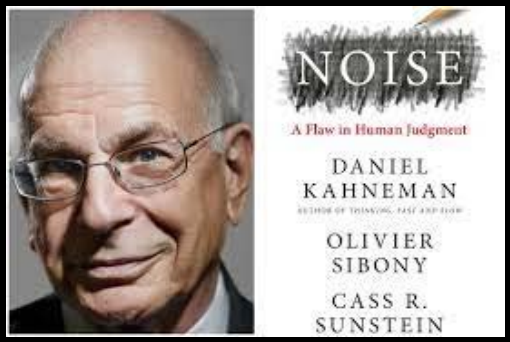
NPP PAC recommended a blind analysis of isobar data
Blinding committee decides the procedure
No access to species-specific information before last step
Everything documented (not written → not allowed)

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

Case for CME & interpretation must be pre-defined

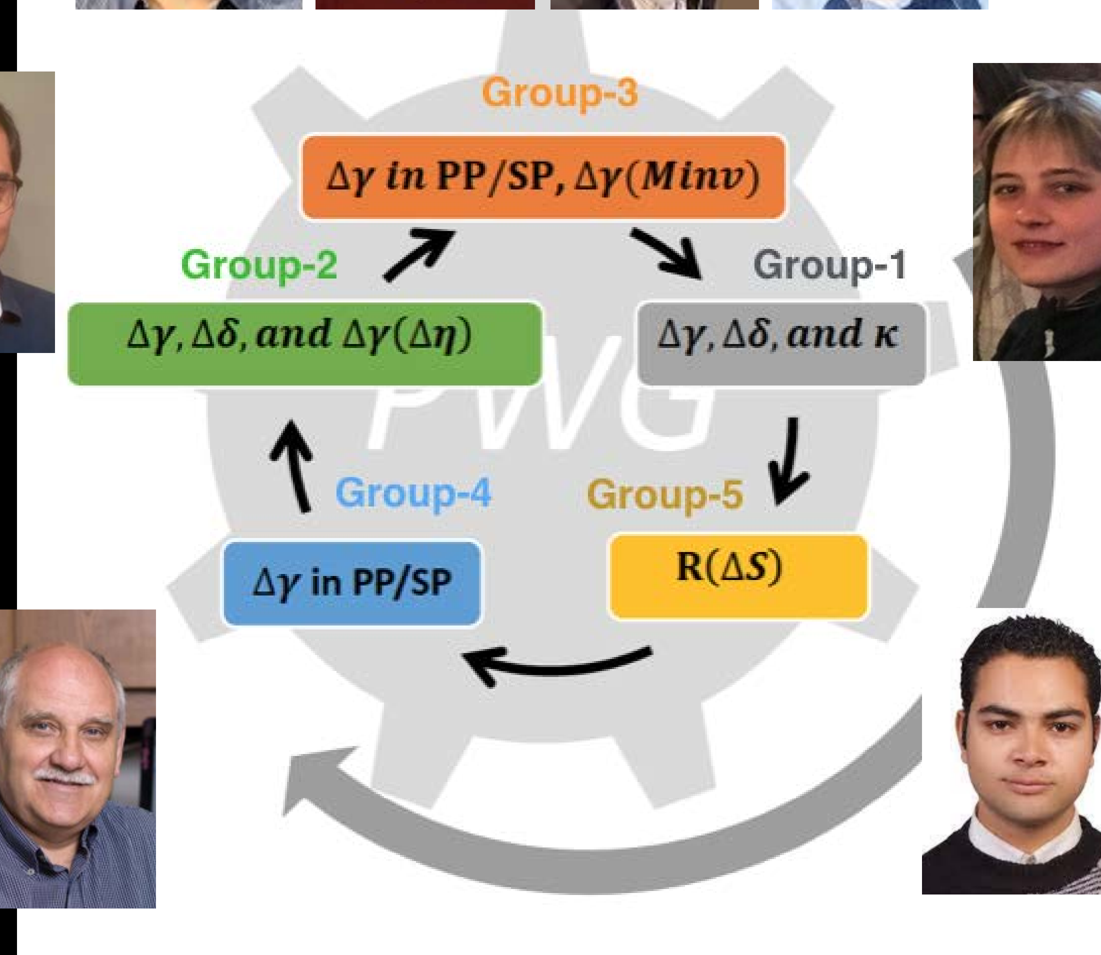
Quality assurance is done by pattern recognition algorithms to remove bias & noise

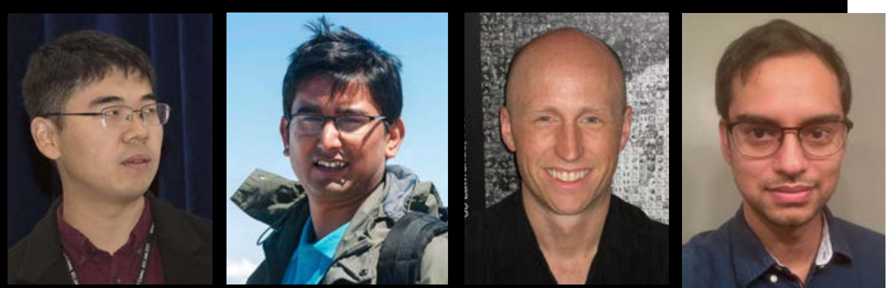
~~Huristics~~ → Algorithms



Five independent groups did isobar blind analysis

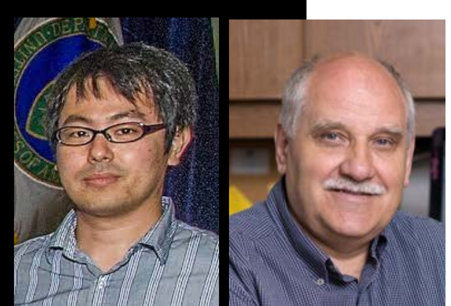
Purdue-Huzhou (group-3)
Yicheng Feng, Haojie Xu, Jie Zhao, Fuqiang Wang





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

UCLA (group-1)
Maria Sergeeva, Gang Wang

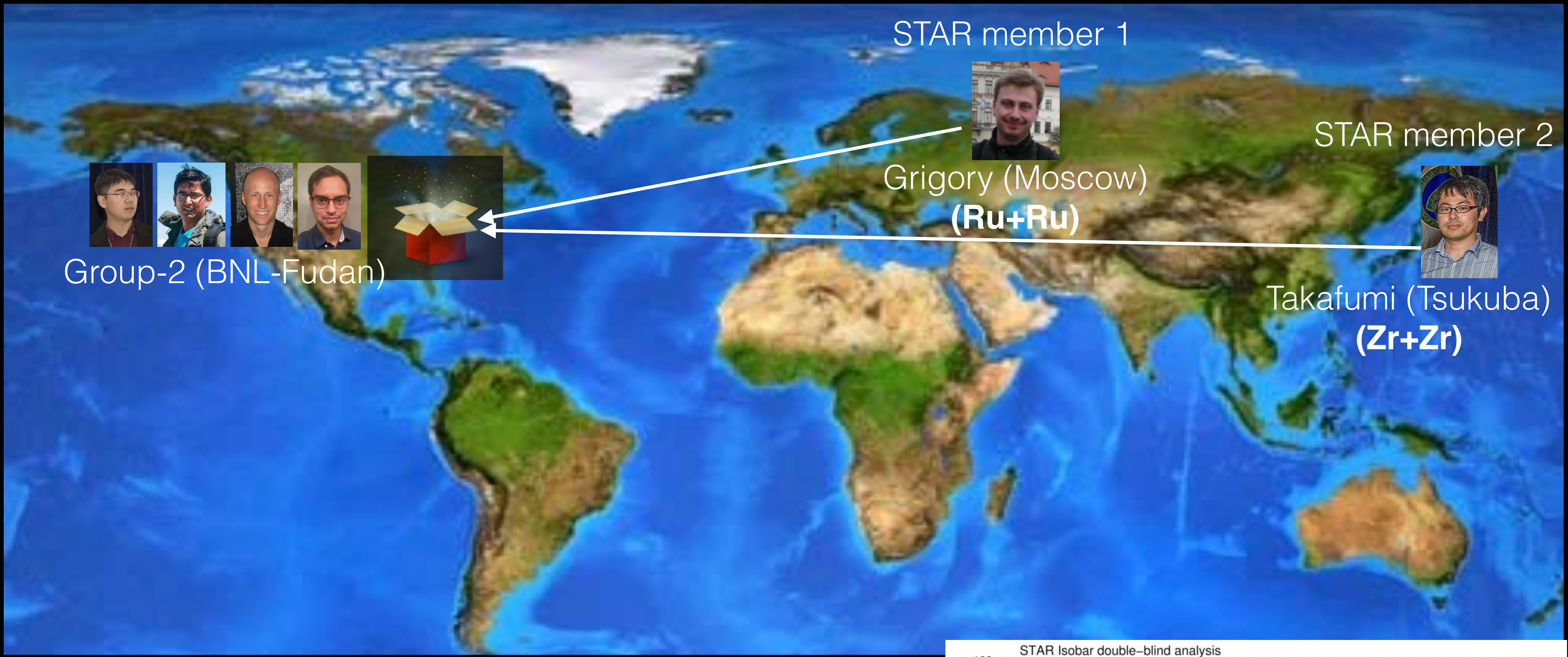


WSU-Tsukuba (group-4)
Takafumi Niida, Sergei Voloshin

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

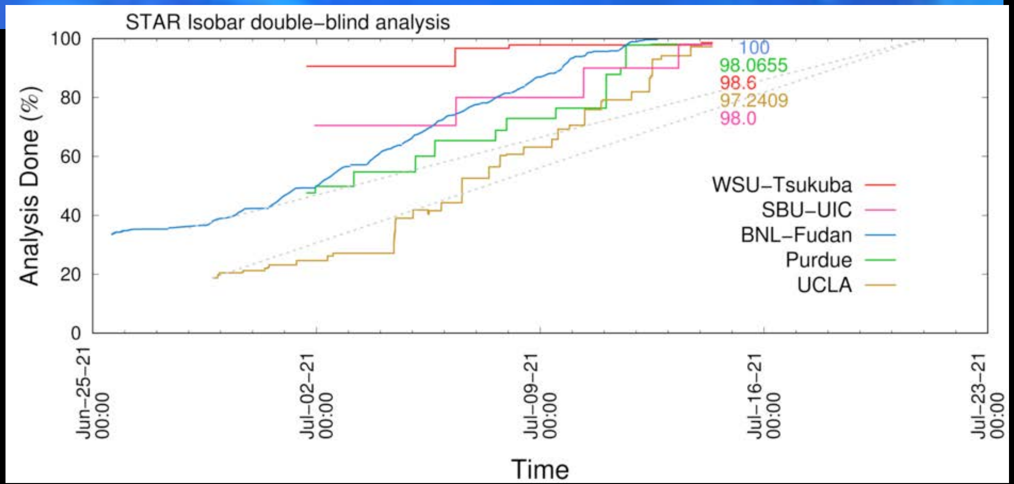
Five independent groups will perform analysis, all codes must be frozen and run by another person, results have to directly sent for publication

How the isobar blind analysis was done



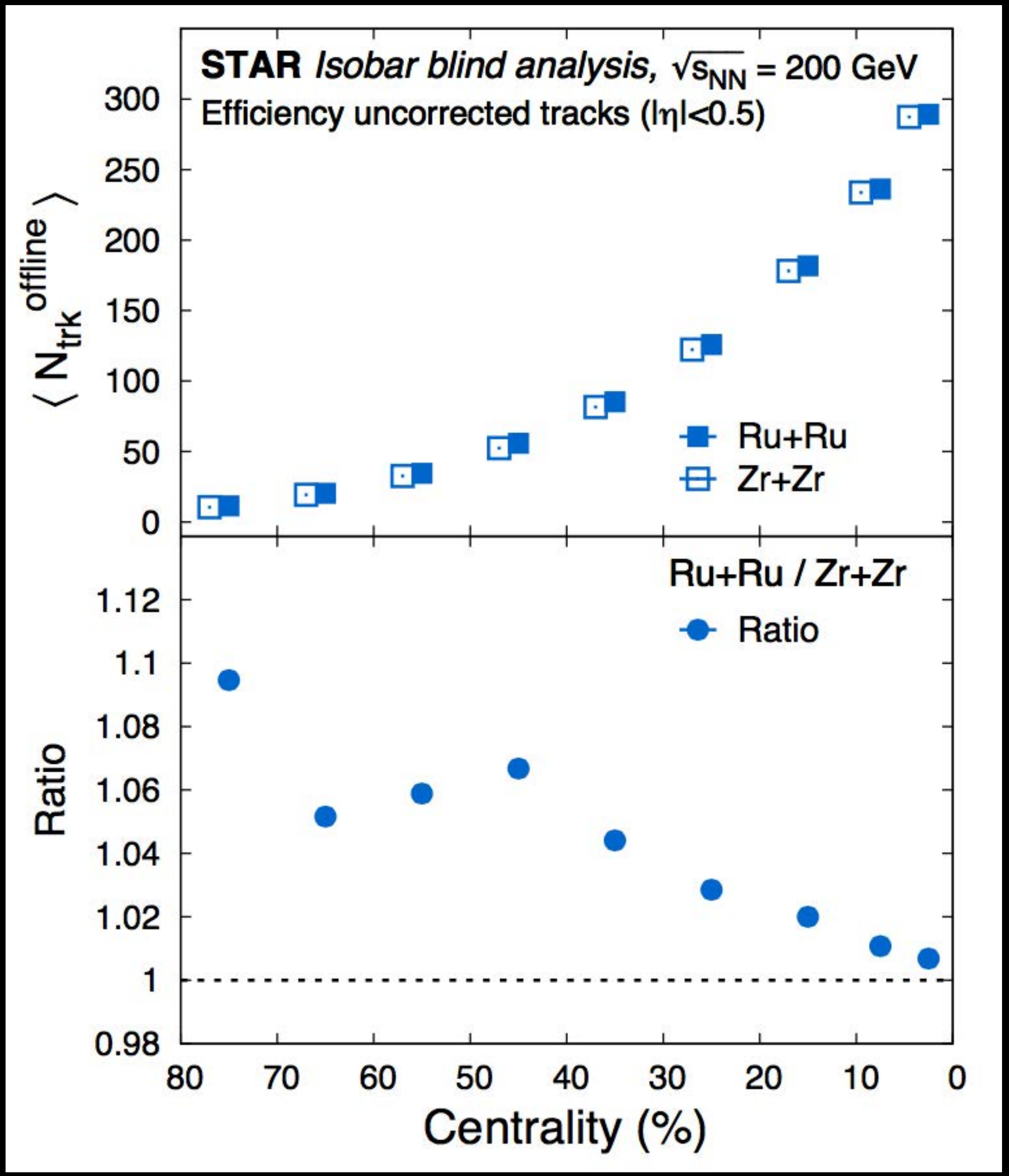
Different people run frozen codes → Analyzers open the box → Directly publish the result

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



Results from Isobar blind analysis

Multiplicity difference between the isobars

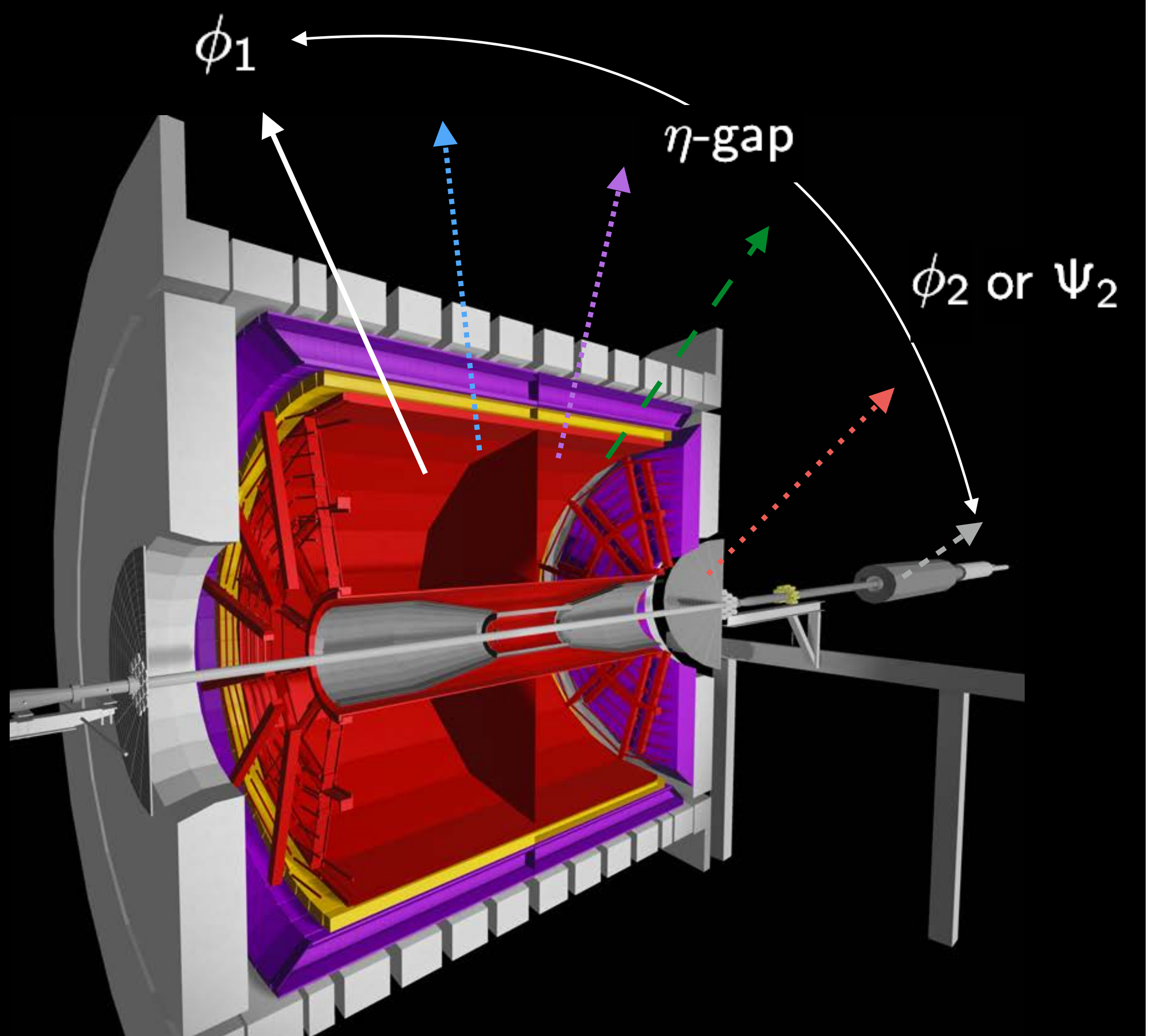


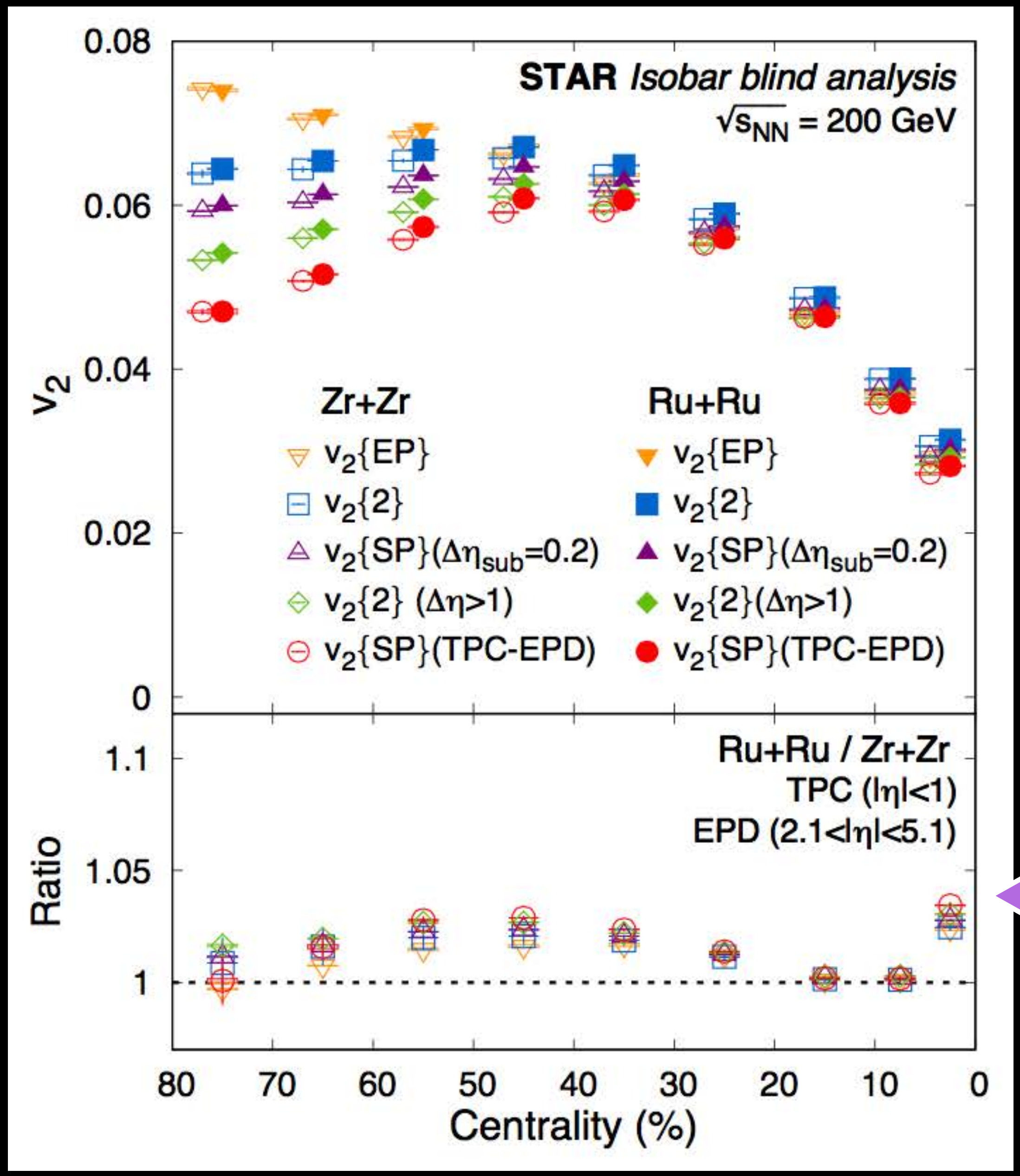
Mean efficiency uncorrected multiplicity density is larger in Ru than in Zr in a matching centrality, this can affects signal and background difference between isobars

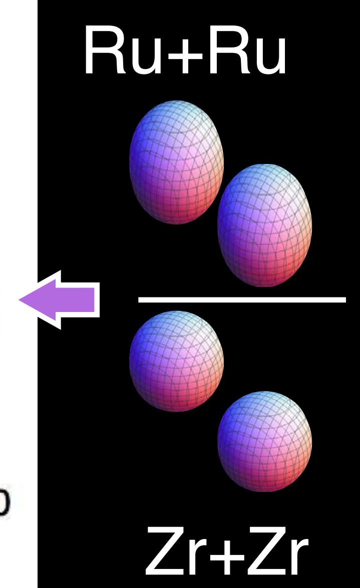
Quite unexpected result!!

Elliptic flow difference between the isobars

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



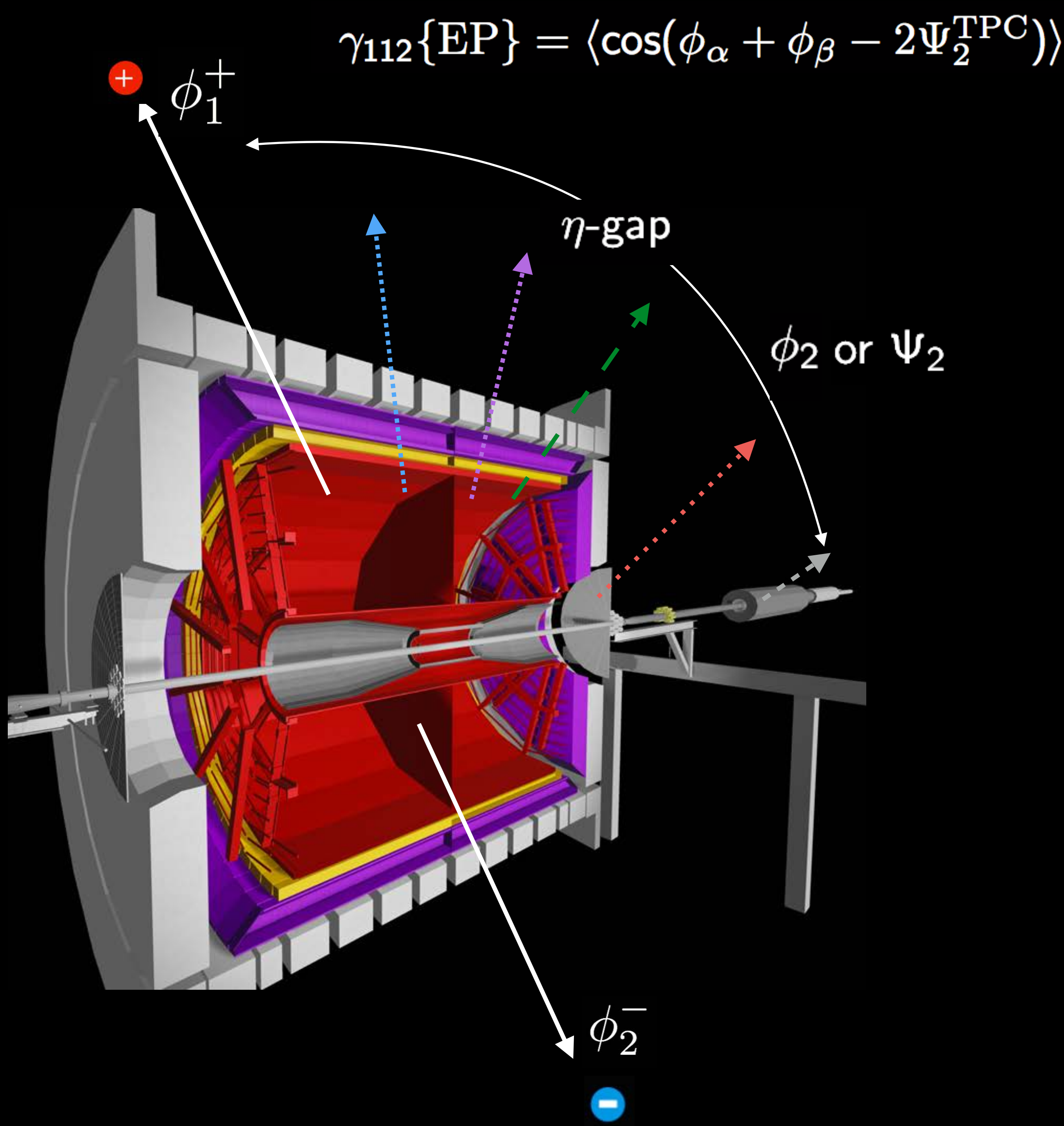


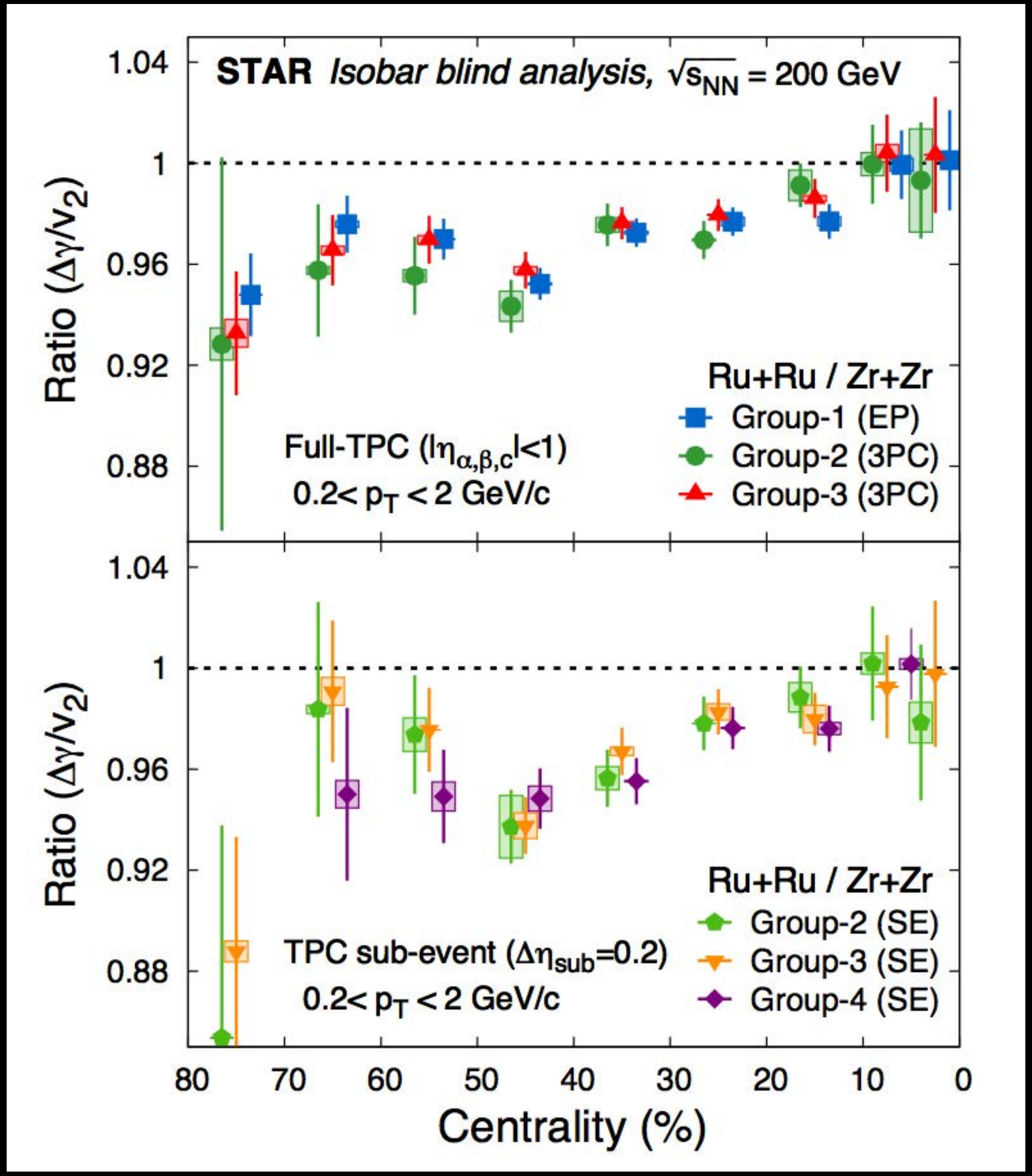


v_2 studied η-gap, ratio deviates from unity indicating difference in the shape, nuclear structure between two isobars (larger quadruple deformation in Ru+Ru)

Results on CME sensitive variables

Charge separation scaled by elliptic flow





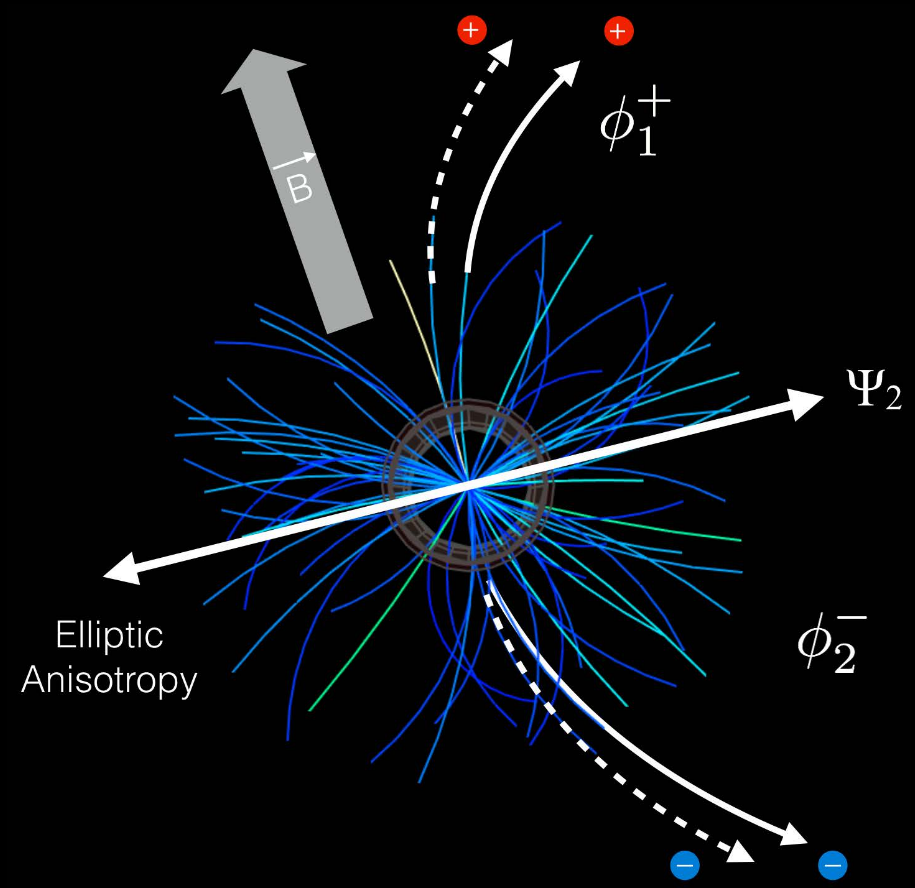
$$\frac{(\Delta\gamma/v_2)_{\mathrm{Ru+Ru}}}{(\Delta\gamma/v_2)_{\mathrm{Zr+Zr}}} \approx 1 + \underset{\text{Unknown}}{f_{\mathrm{CME}}^{\mathrm{Zr+Zr}}}\underbrace{[(B_{\mathrm{Ru+Ru}}/B_{\mathrm{Zr+Zr}})^2 - 1]}_{0.18}$$

Pre-defined criteria for CME

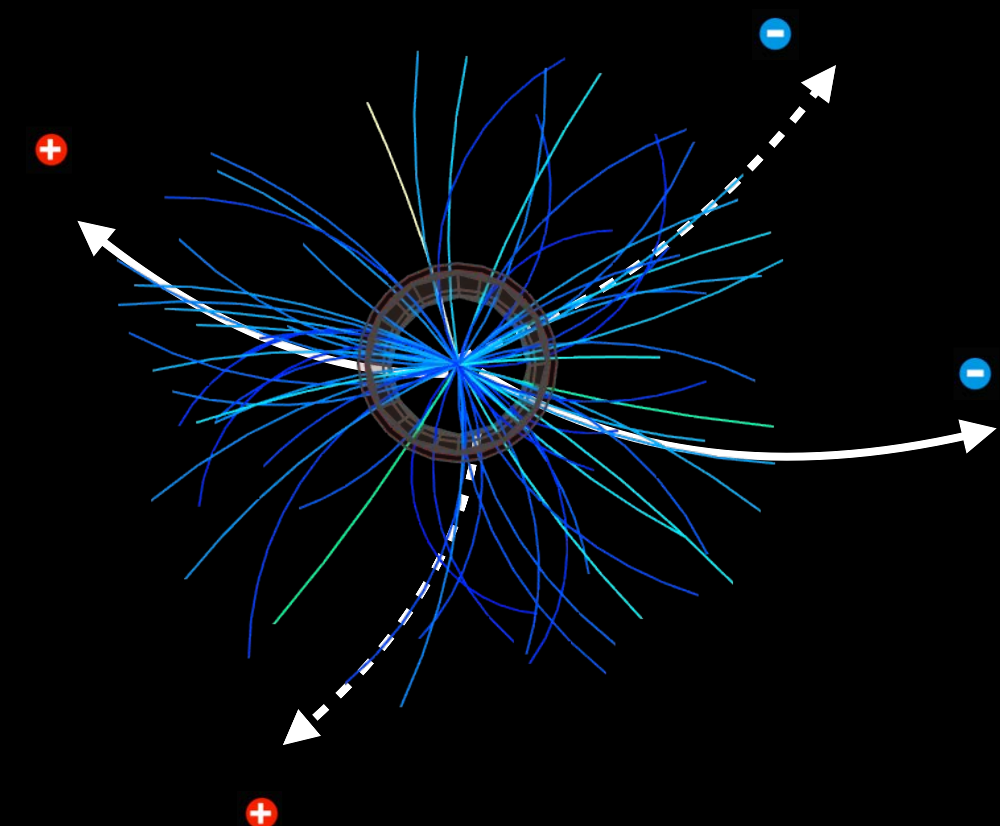
$$\frac{(\Delta\gamma/v_2)_{\mathrm{RuRu}}}{(\Delta\gamma/v_2)_{\mathrm{ZrZr}}} > 1$$ NOT seen!!

Experimental baseline-1 : δ-correlator

Charge separation correlated to event plane



Charge separation NOT correlated to event plane



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

$\Longleftrightarrow$

$$\delta \equiv \langle \cos(\phi_\alpha - \phi_\beta) \rangle$$
$$\Delta\delta = \delta(OS) - \delta(SS)$$

Old criterion for CME:

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

New criterion for CME:

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

Experimental baseline-1 : δ-correlator

New criterion for CME:

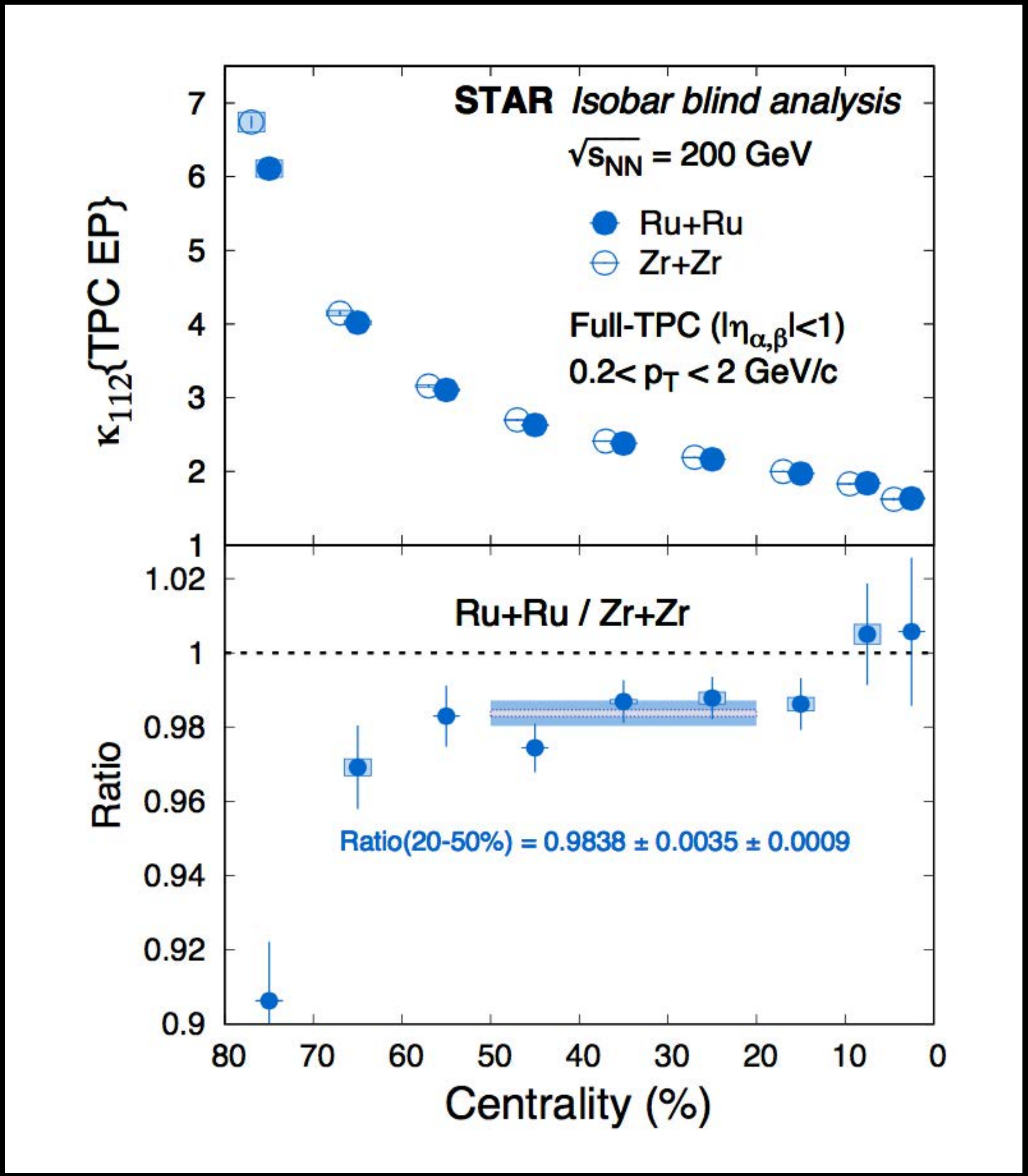
$$\frac{(\Delta\gamma/v_2)_{\mathrm{RuRu}}}{(\Delta\gamma/v_2)_{\mathrm{ZrZr}}} > \frac{(\Delta\delta)_{\mathrm{RuRu}}}{(\Delta\delta)_{\mathrm{ZrZr}}}$$

Slight re-definition:

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

Pre-defined CME criteria:

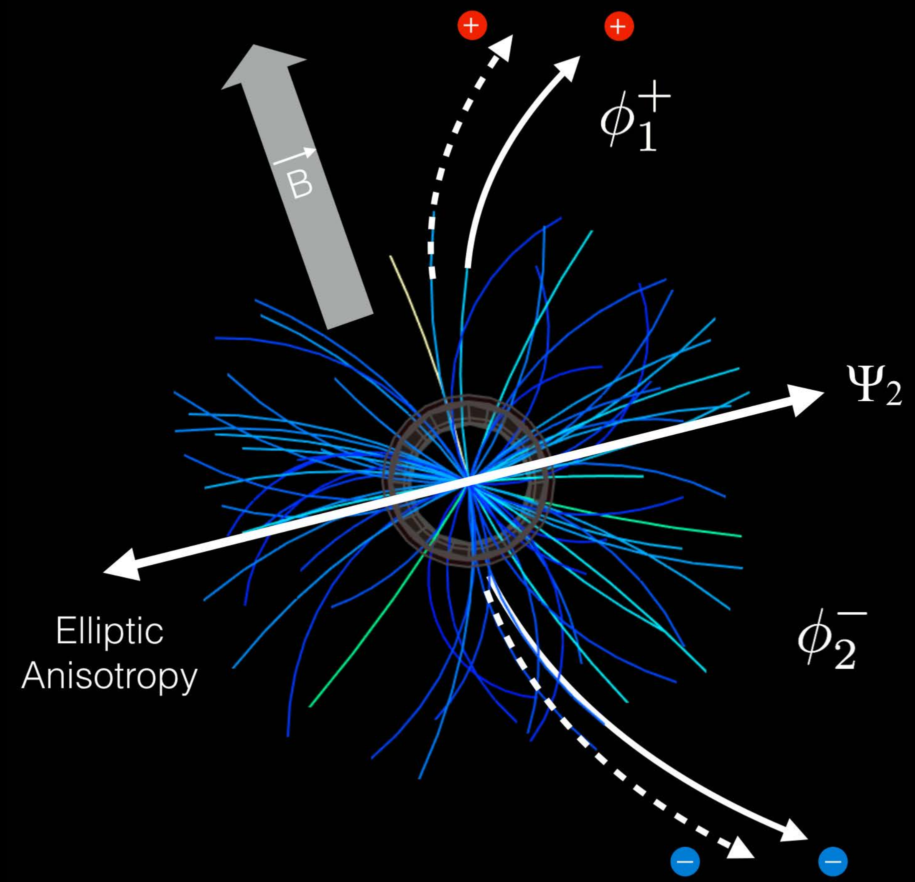
$$\frac{\kappa_{112}^{\mathrm{Ru+Ru}}}{\kappa_{112}^{\mathrm{Zr+Zr}}} > 1$$



This pre-defined CME signature is NOT seen !!

Experimental baseline-2 : Third harmonic plane

B-field is corrected to Ψ_2 plane



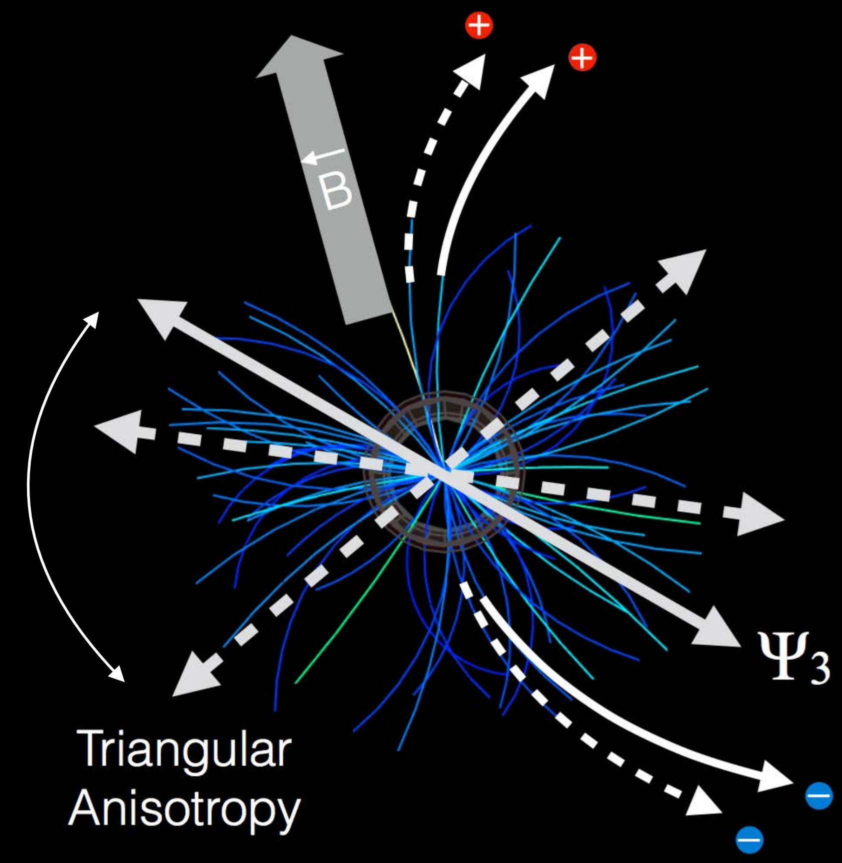
$$\gamma_{112} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2) \rangle$$

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

Old criterion for CME:

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

B-field is not-corrected to Ψ_3 plane



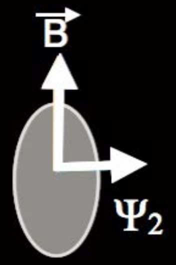
$$\gamma_{123} = \langle \cos(\phi_\alpha + 2\phi_\beta - 3\Psi_3) \rangle$$

Background only ($\propto v_3$)

New criterion for CME:

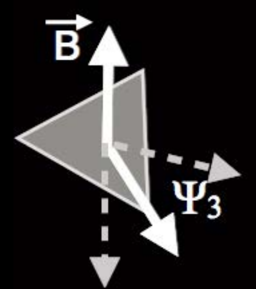
$$\frac{(\Delta\gamma_{112}/v_2)^{RuRu}}{(\Delta\gamma_{112}/v_2)^{ZrZr}} > \frac{(\Delta\gamma_{123}/v_3)^{RuRu}}{(\Delta\gamma_{123}/v_3)^{ZrZr}}$$

Charge separation across Ψ_2 and Ψ_3 planes



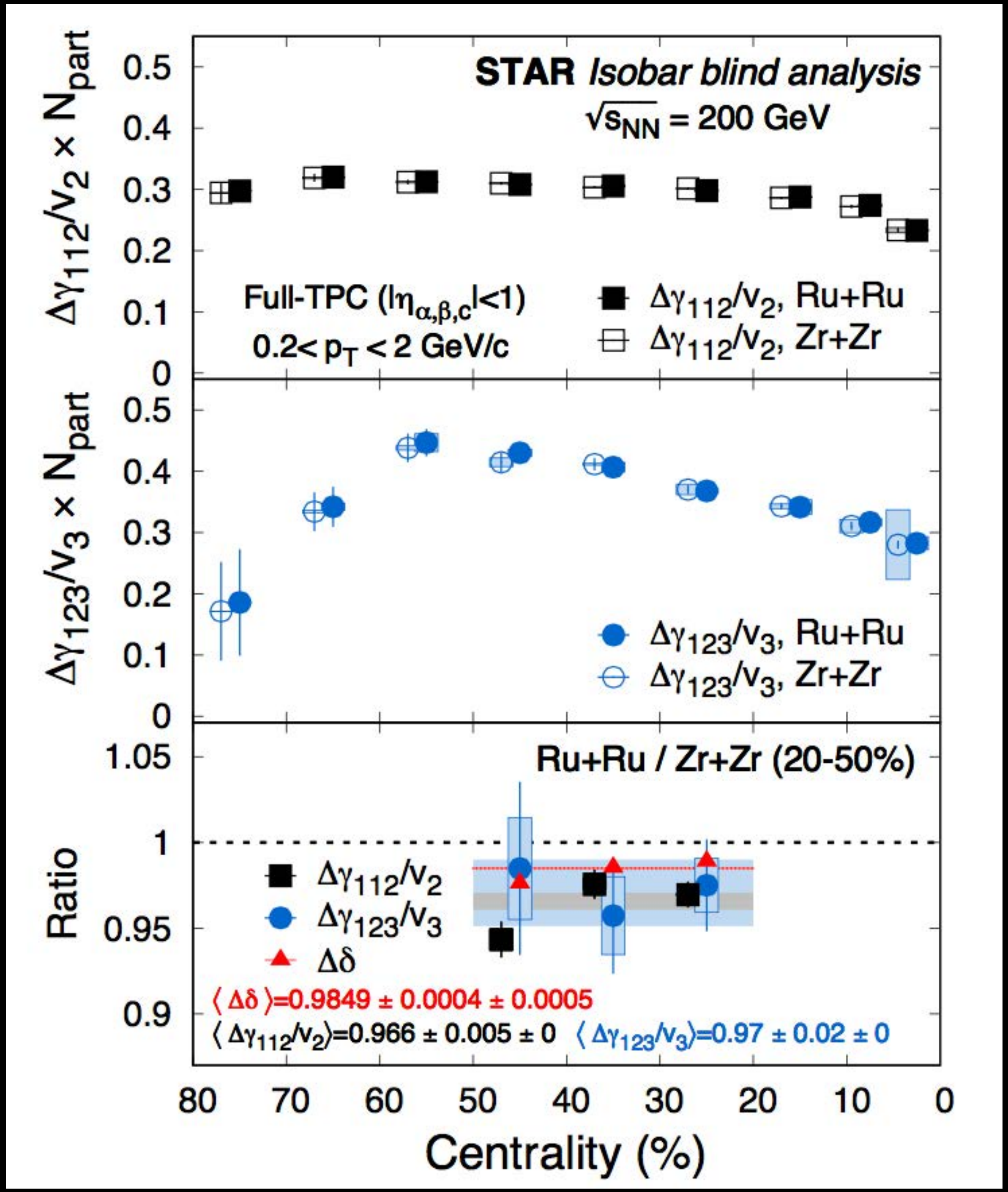
$$\gamma_{112} = \left\langle \cos(\phi_1^\alpha + \phi_2^\beta + 2\Psi_2) \right\rangle$$

signal + background



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

100% background



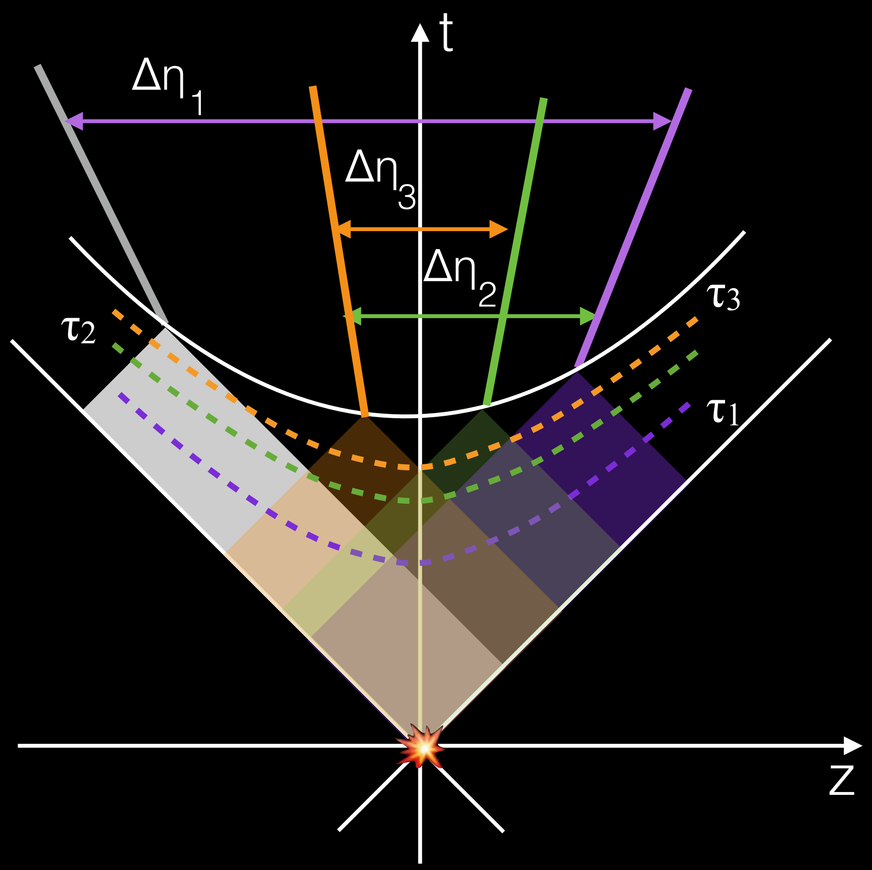
Pre-defined CME criteria:

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

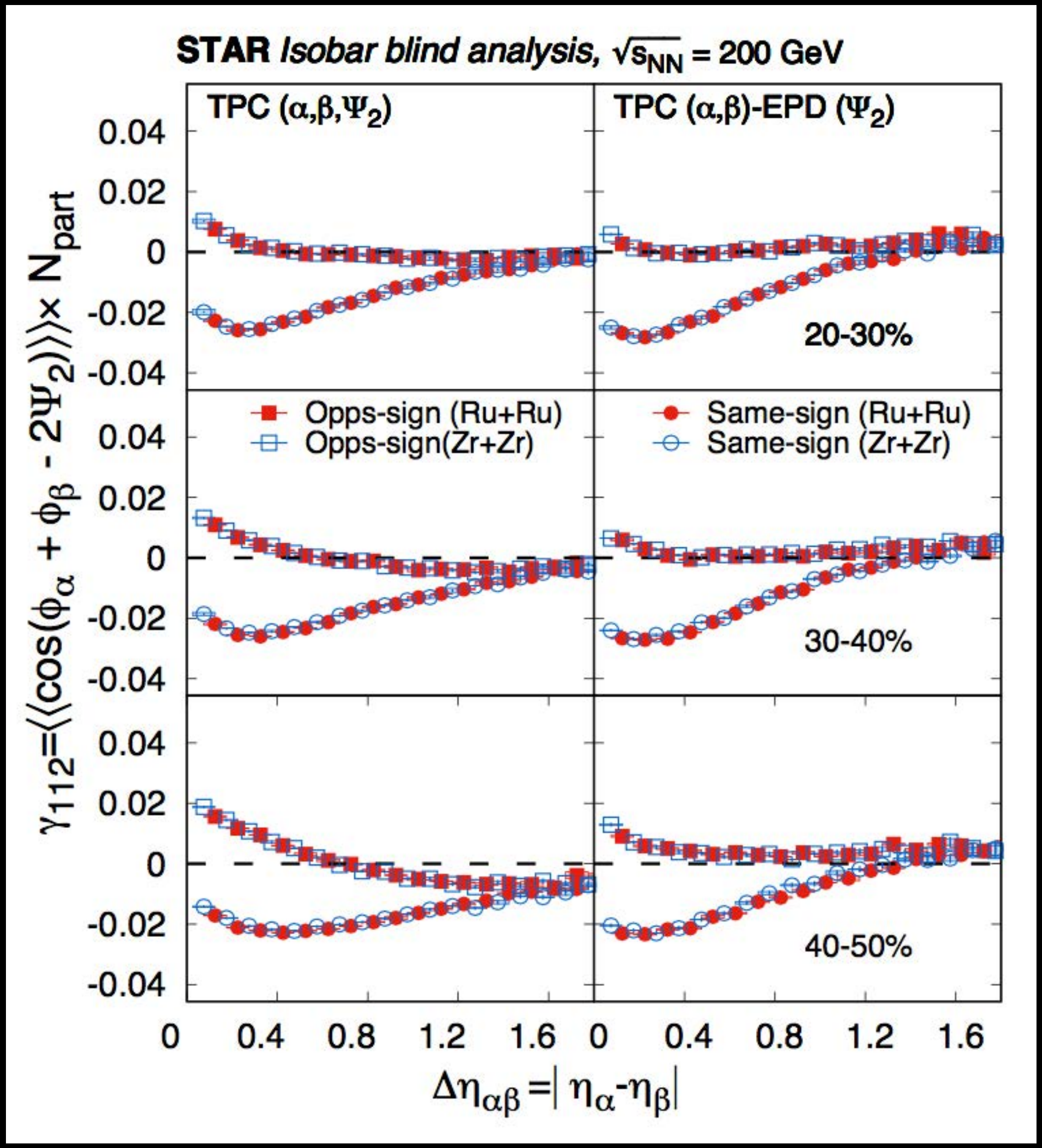
This pre-defined CME signature is NOT seen

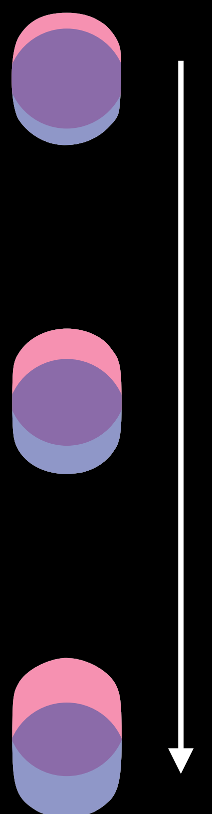
Relative pseudorapidity dependence

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



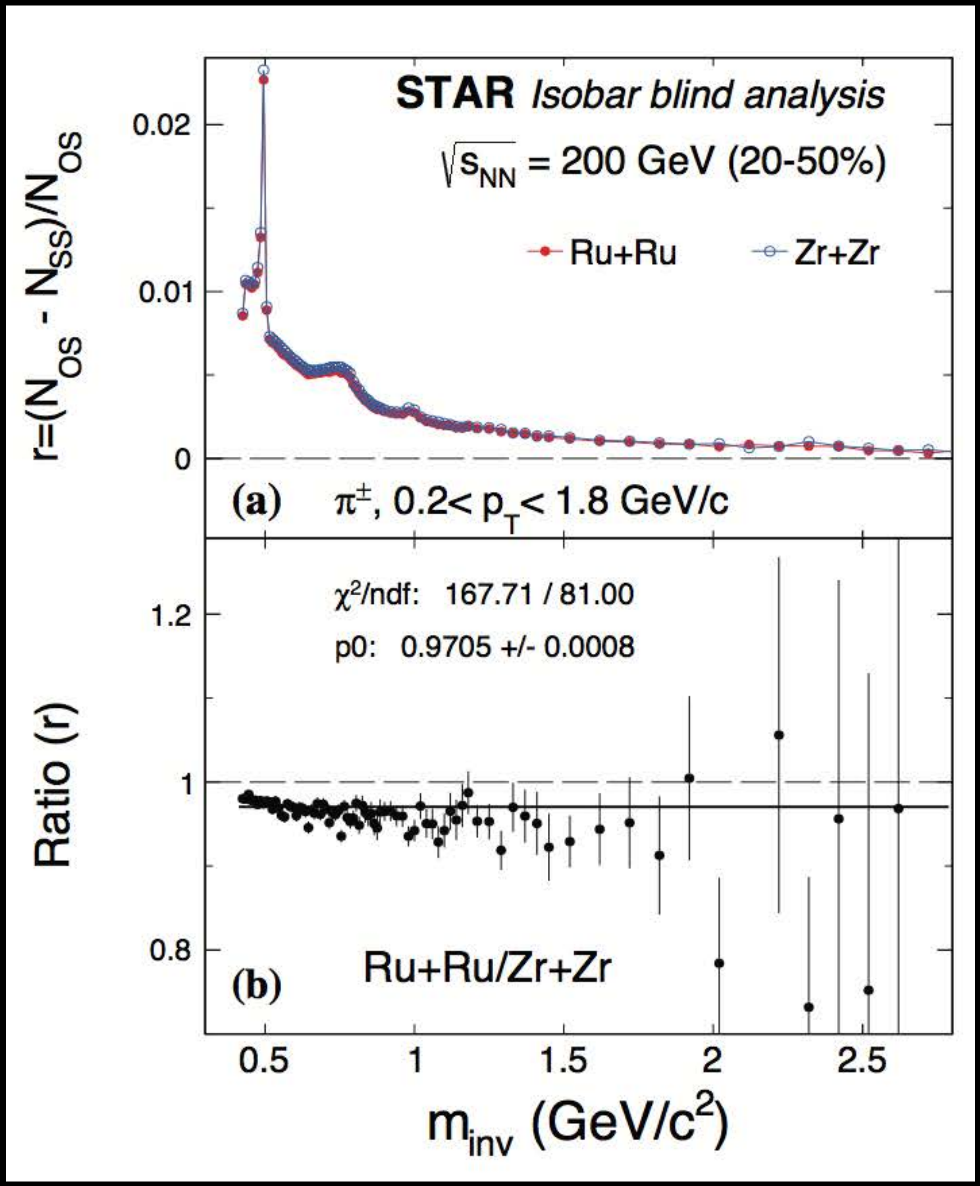
B-field driven charge separation: large Δη>1
Resonance decay: smaller Δη<1

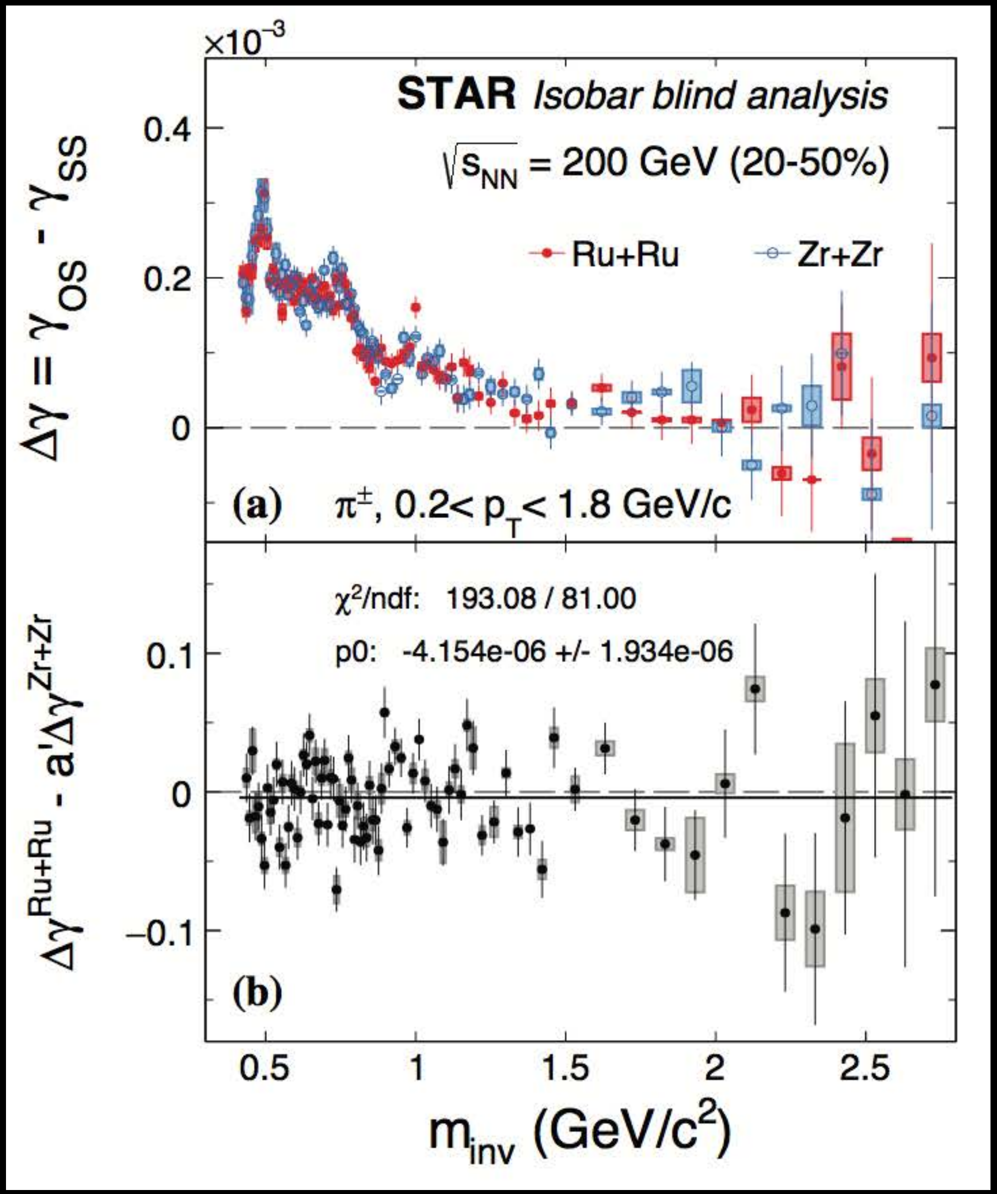


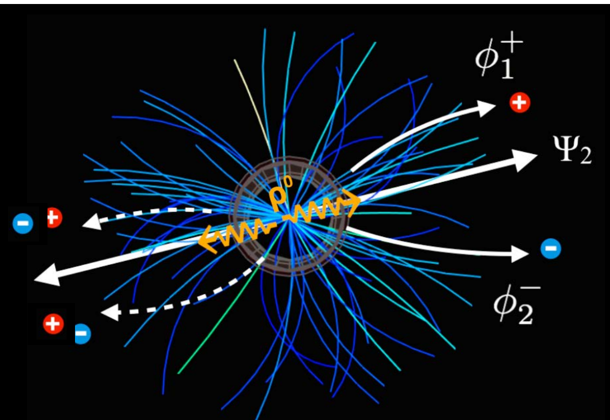


The relative pseudorapidity dependence is similar between the two species

Invariant mass dependence







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

Post-blinding analysis (limited)

Postblinding

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

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

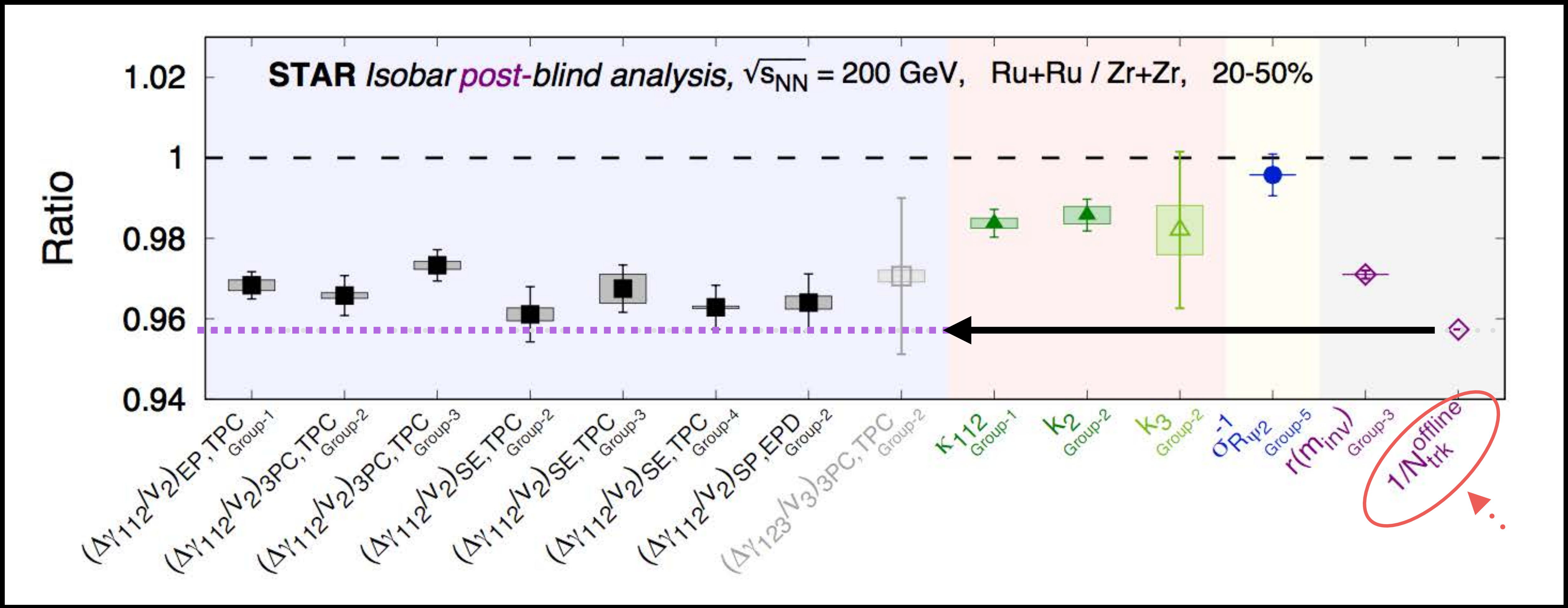
$$?? \qquad \neq \qquad \approx$$

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

Inverse multiplicity scaling: different for two isobar, was not know before blind analysis

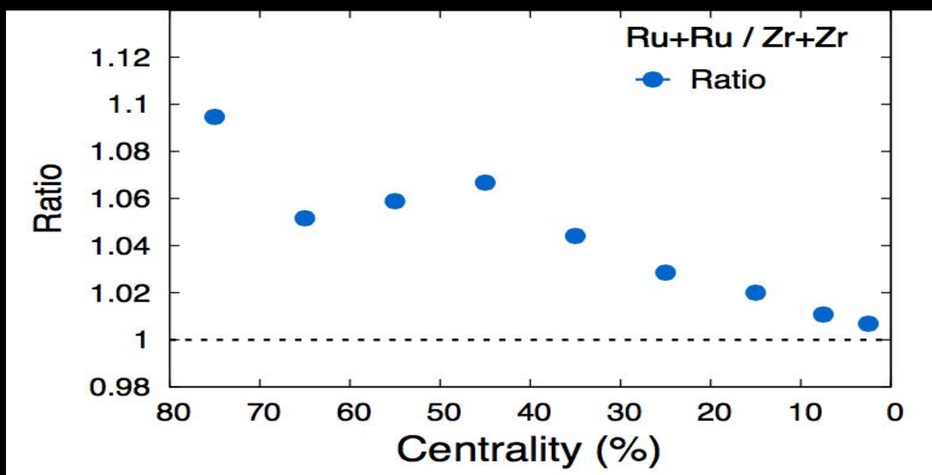
Post-blinding criterion for CME:

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



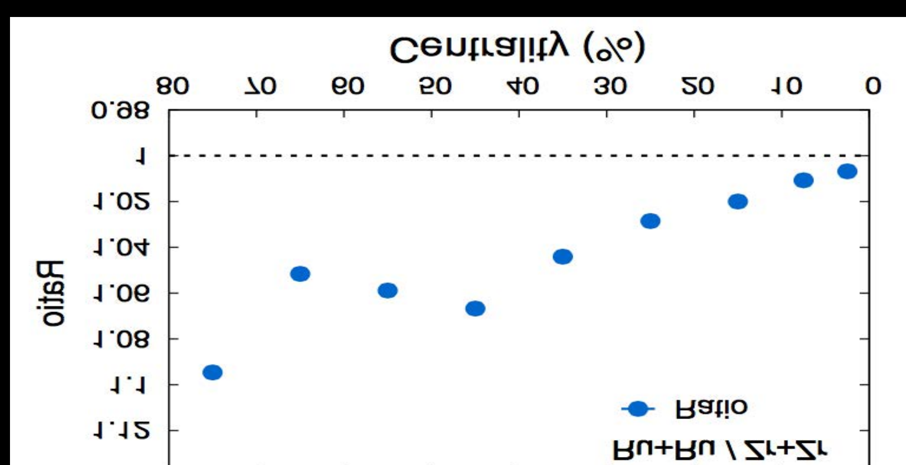
Multiplicity scaling & towards CME limit

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

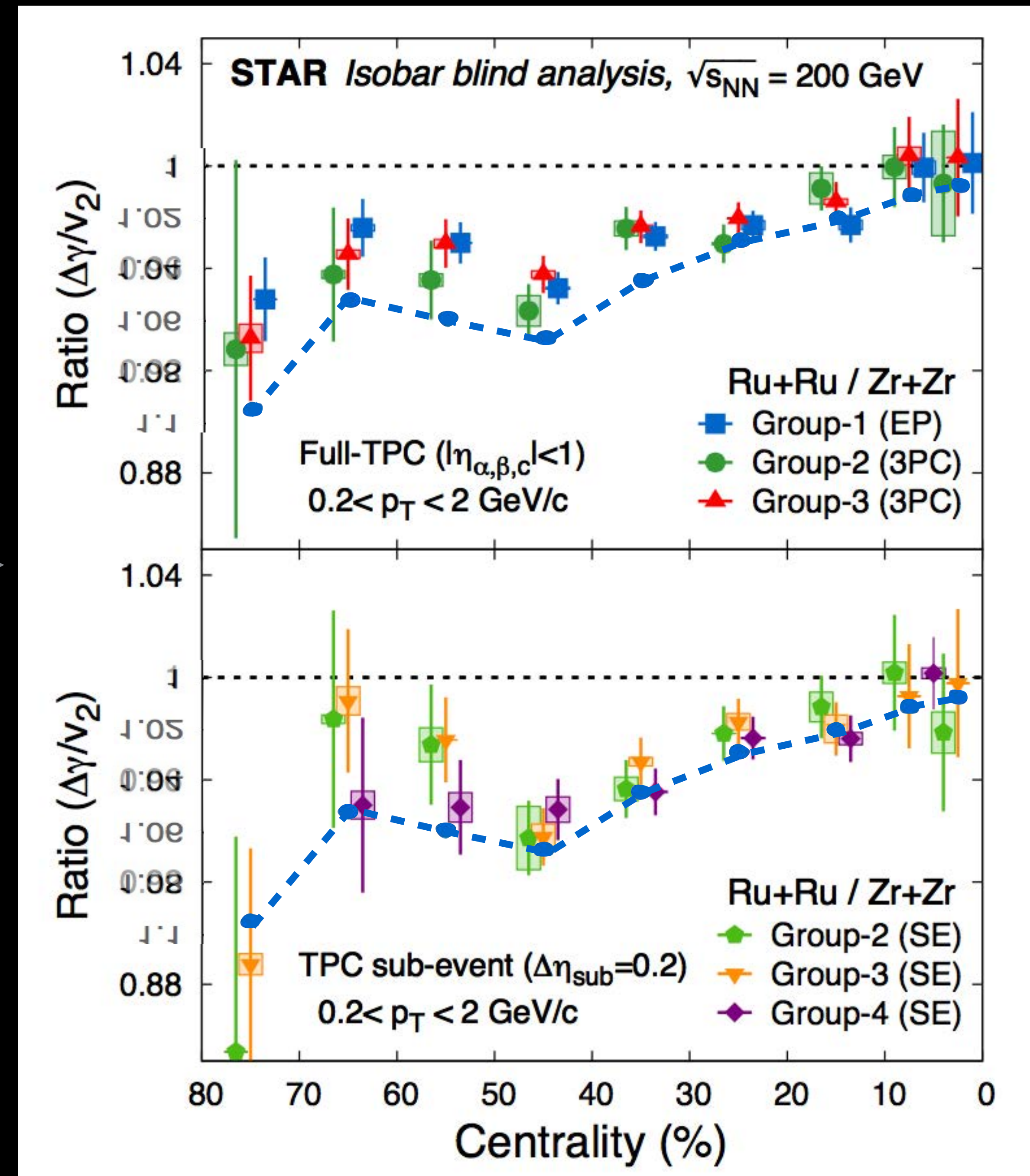


overlay

Flip



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



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

Ref: talk by Voloshin

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

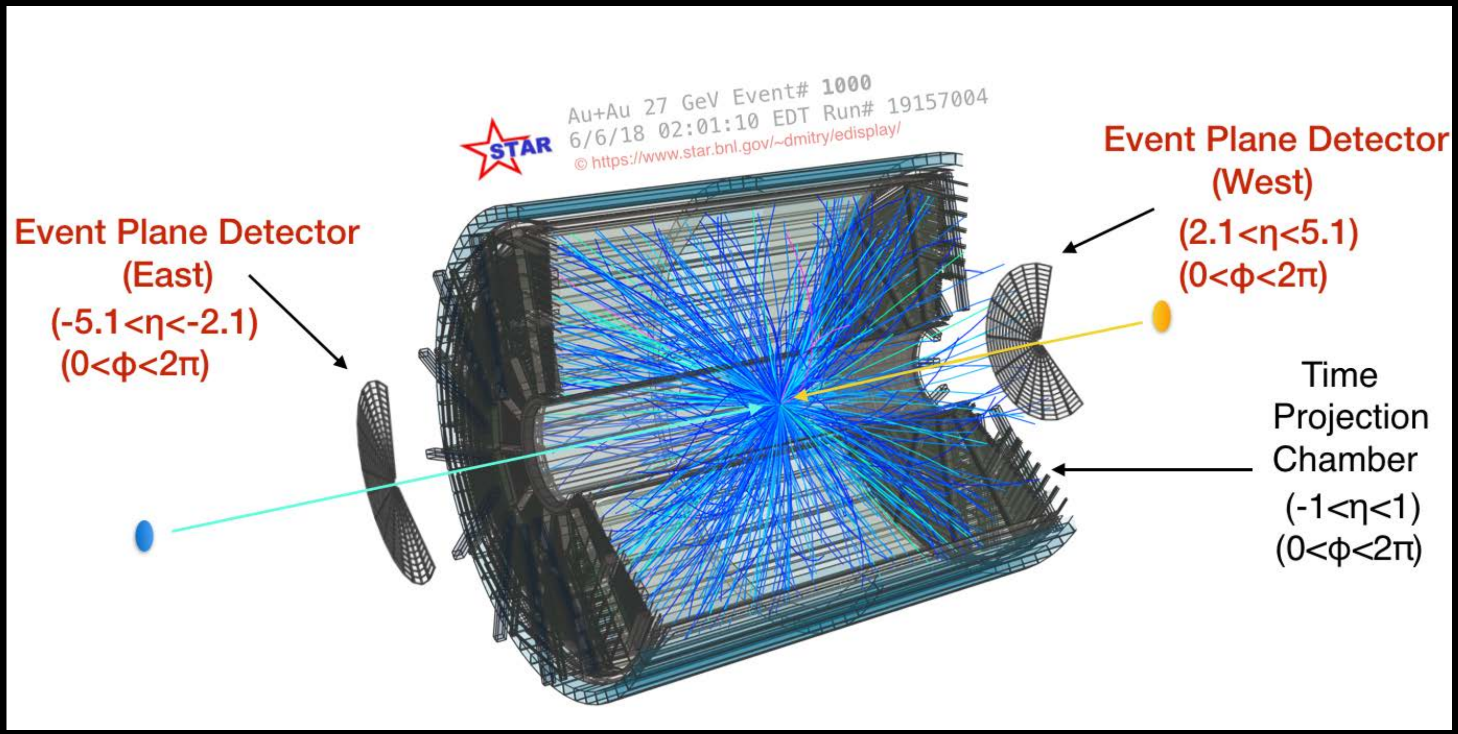
The observed multiplicity difference between the isobars requires future CME analyses to better understand the baselines in order to best utilize the precision demonstrated in this analysis. Better understanding of the non-flow may be another goal.

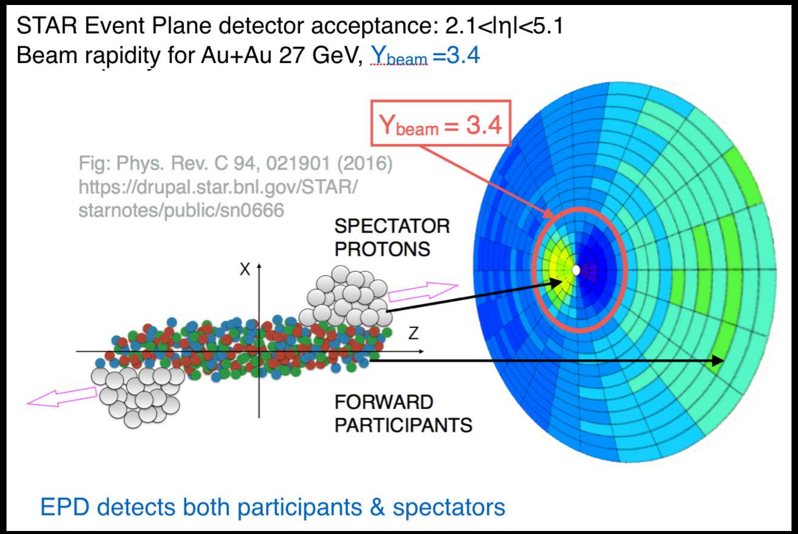
CME search has been narrowed down, future program will look for upper limit (1% level)

Future program

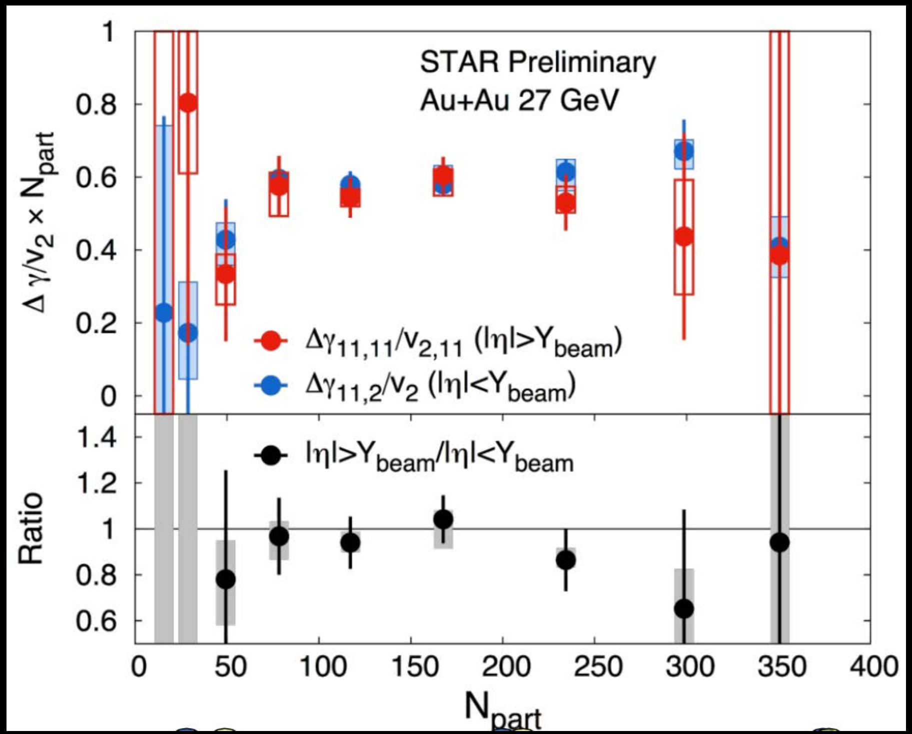
Coming up soon

The new Event plane detector brings exciting opportunity for CME search at BES-II

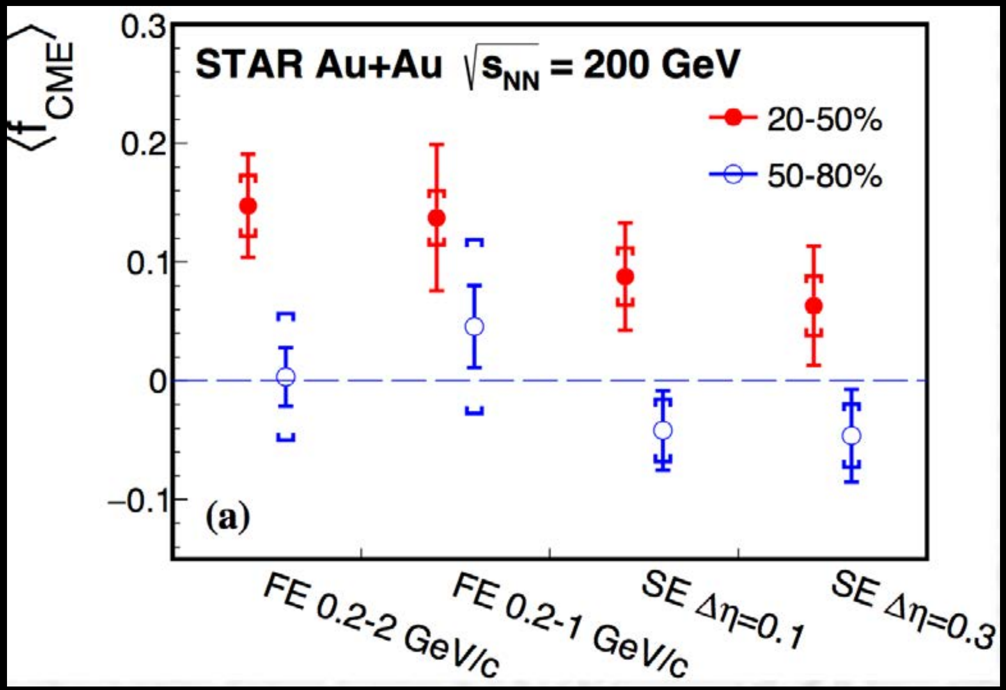




High statistics BES-II Au+Au data



High statistics Run 2023 Au+Au run



Thanks