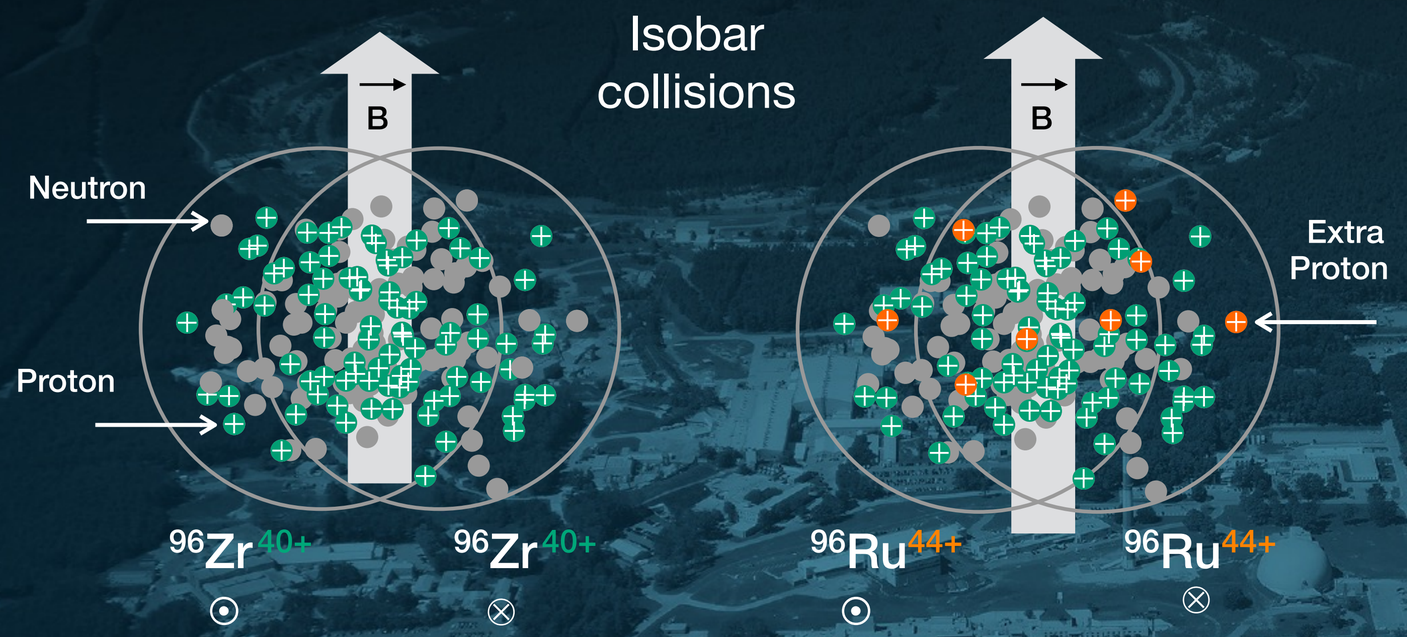


Experimental CME searches at RHIC

Prithwish Tribedy
(Brookhaven National Laboratory)

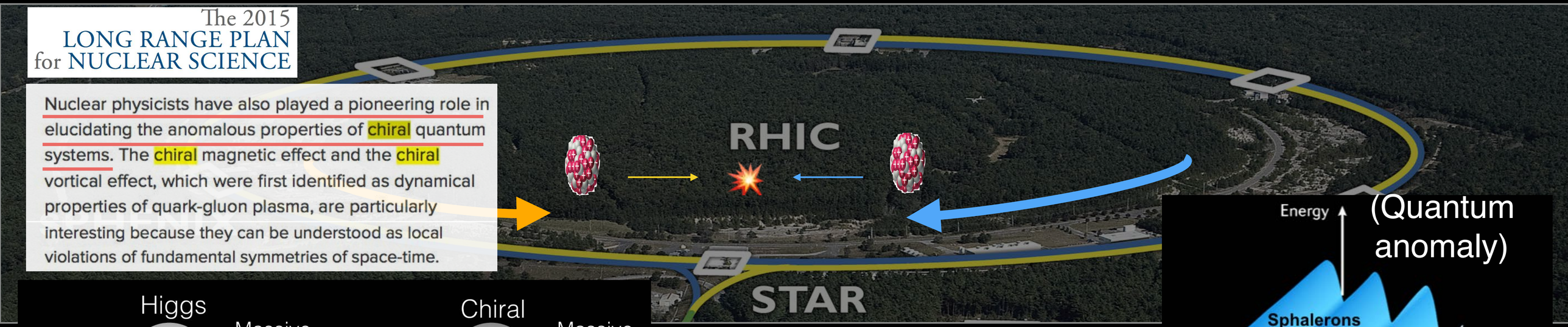
ptribedy@bnl.gov

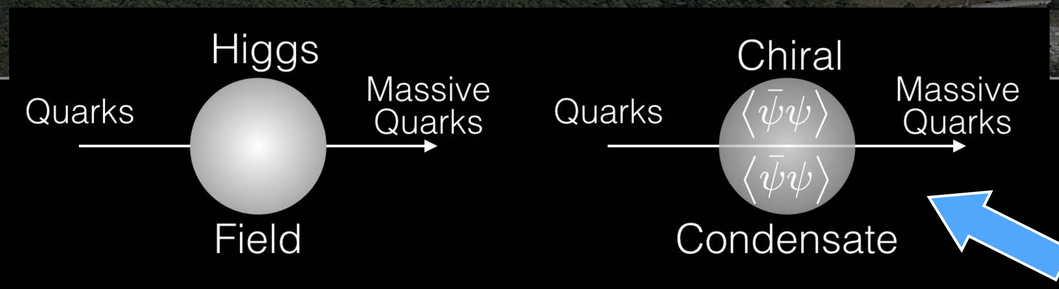
Wokshop on Chirality, Vorticity and Magnetic Field in Heavy Ion Collisions, Dec 2-4, UCLA

Chiral Properties of the medium

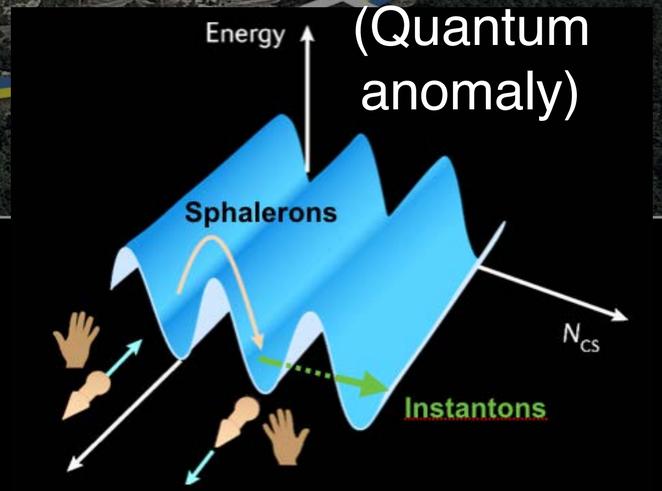
The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

Nuclear physicists have also played a pioneering role in elucidating the anomalous properties of chiral quantum systems. The chiral magnetic effect and the chiral vortical effect, which were first identified as dynamical properties of quark-gluon plasma, are particularly interesting because they can be understood as local violations of fundamental symmetries of space-time.



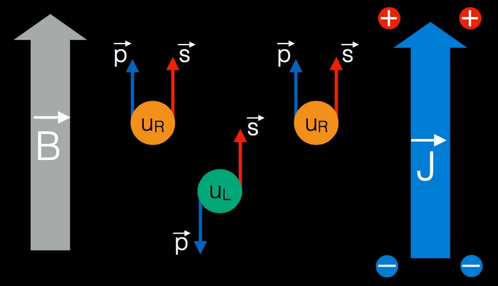


Turn this OFF



$$\mathcal{L}_{QCD} = \bar{\psi}_a \left(i(\gamma^\mu D_\mu)_{ab}\right)\psi_b - \cancel{m\delta_{ab}\bar{\psi}_a\psi_b} - \frac{1}{4}G^c_{\mu\nu}G^{\mu\nu}_c - \frac{\theta}{32\pi^2}g^2 F^{\mu\nu}_\alpha \tilde{F}_{\alpha\mu\nu}$$

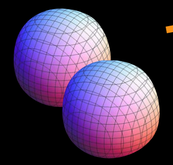
$$= -\frac{\theta}{8\pi^2}g^2 \vec{E}_\alpha . \vec{B}_\alpha$$

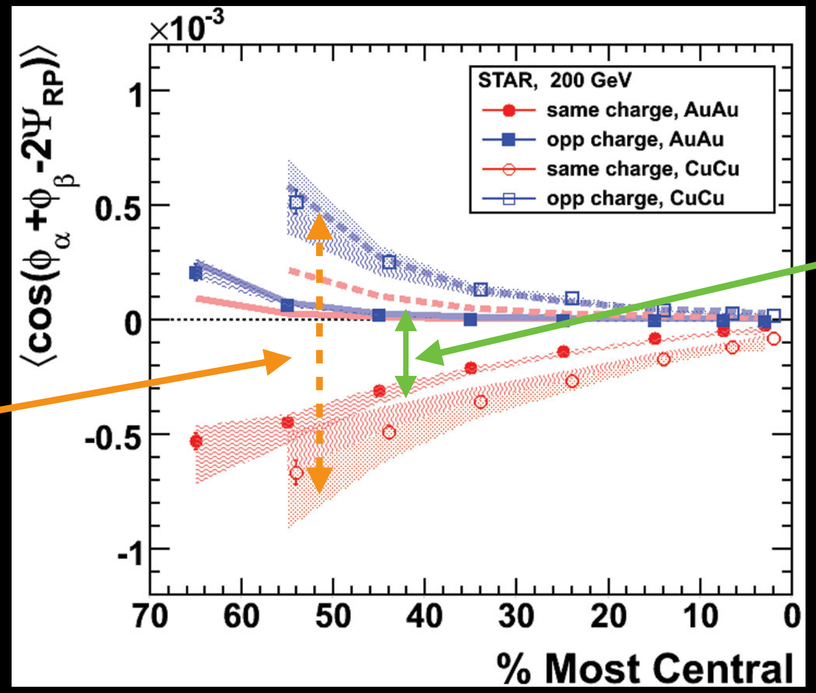


Chiral symmetry restoration ⟶ Chiral fermions
$U_A(1)$ symmetry breaking ⟶ Chirality imbalance
Strong B-field + Chirality imbalance ⟶ Chiral Magnetic Effect

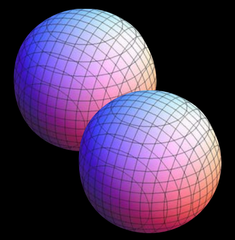
The first measurements at RHIC

Cu+Cu



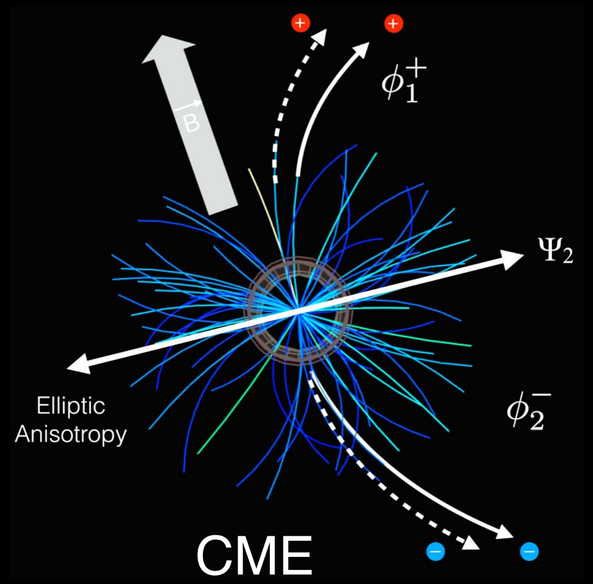


Au+Au



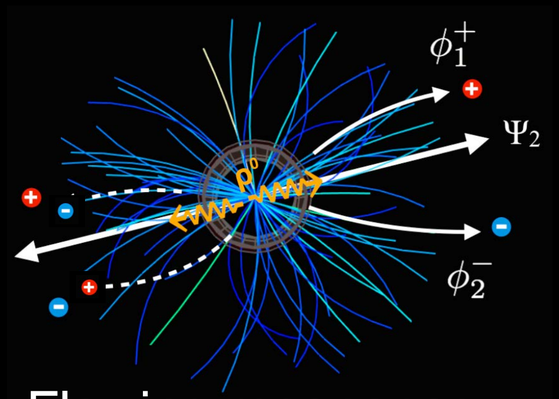
STAR collaboration, PRL 103, 251601 (2009

Three possible sources of charge separation



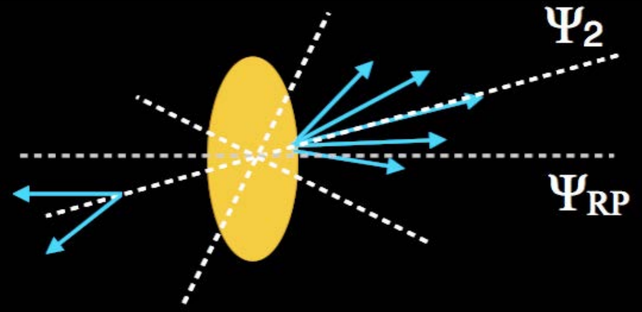
CME

+



Flowing resonance

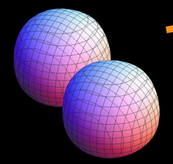
+

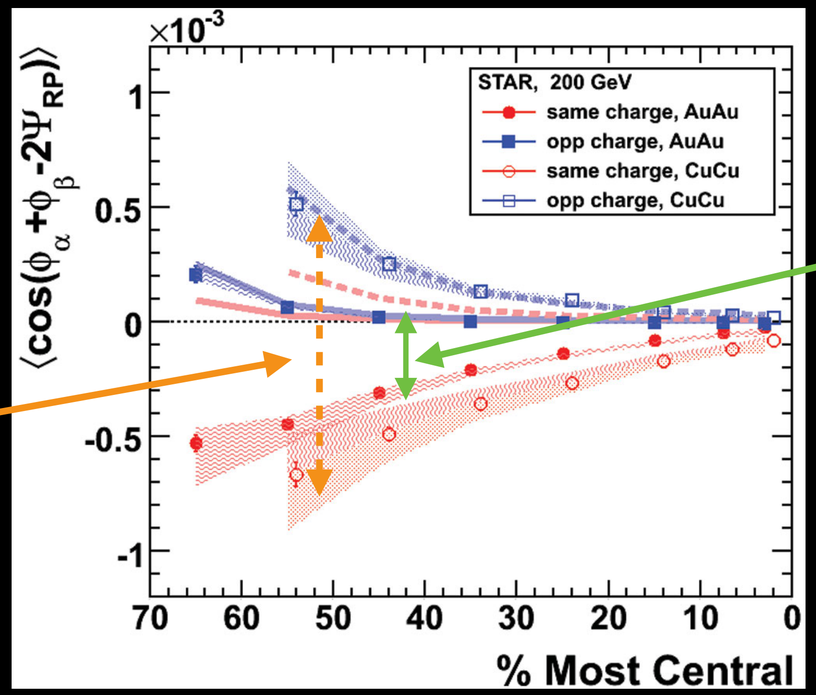


Di-jets (non-flow)

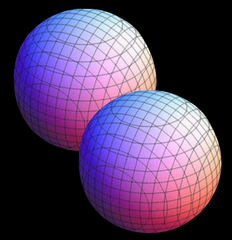
The first measurements at RHIC

Cu+Cu





Au+Au



STAR collaboration, PRL 103, 251601 (2009

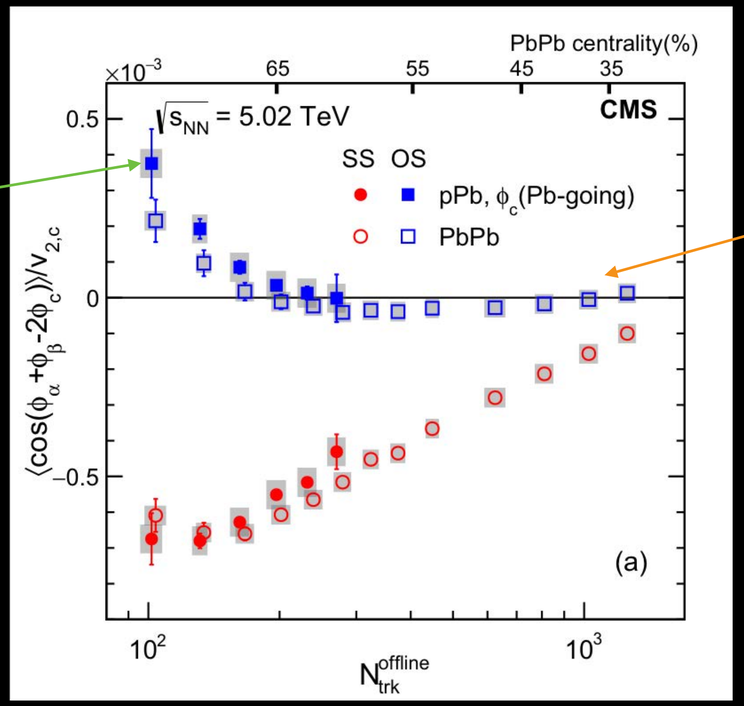
Significant charge separation observed, consistent with CME+ Background

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

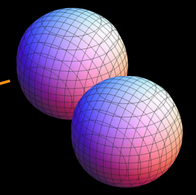
Measurement Signal Background-1 Background-2

Small system collisions to test CME

p+A



A+A



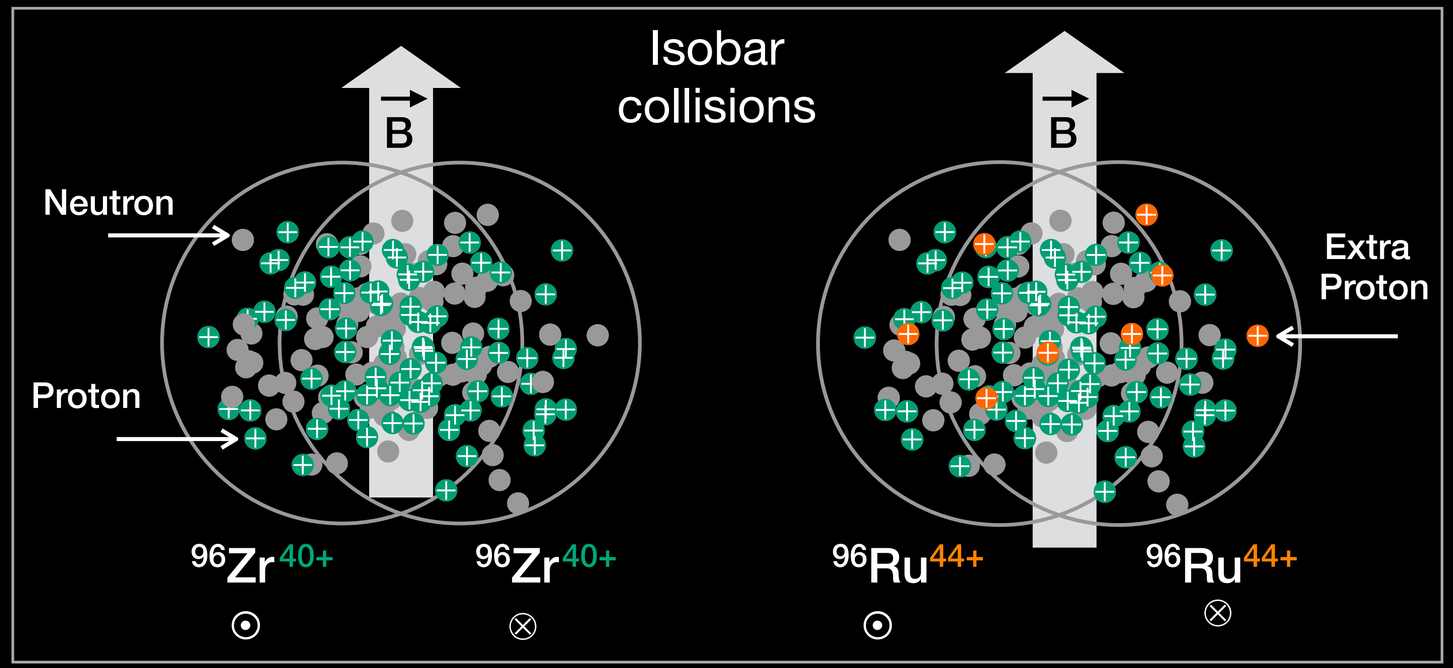
CMS collaboration, Phys. Rev Lett, 118 (2017) 122301

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

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 collisions



Voloshin,

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

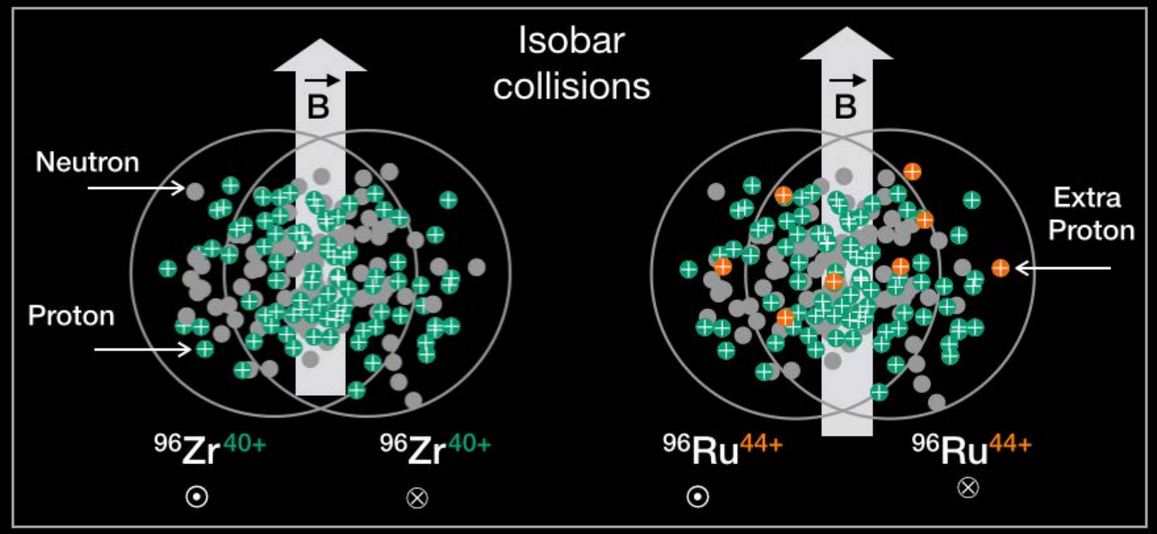
$$\Delta\gamma^{\text{Ru+Ru}} = \Delta\gamma^{CME} + k \times \frac{v_2}{N} + \Delta\gamma^{non-flow}$$

?? $\neq$ $\approx$ $=$

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

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

Isobar collisions



Voloshin,

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

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

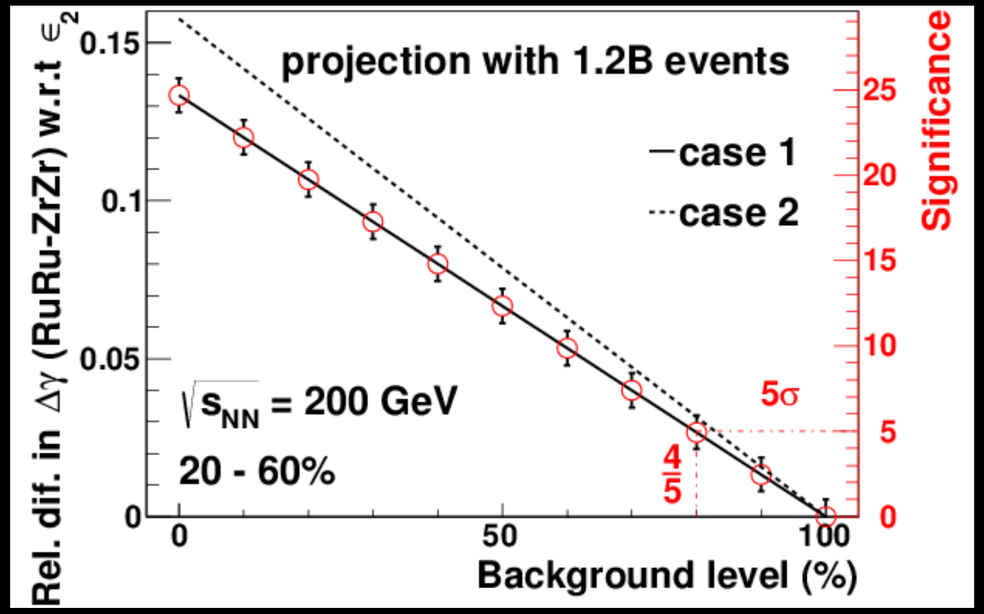
$$\frac{(\Delta\gamma/v_2)_{\mathrm{Ru+Ru}}}{(\Delta\gamma/v_2)_{\mathrm{Zr+Zr}}} \approx 1 + f_{\mathrm{CME}}^{\mathrm{Zr+Zr}}[\underbrace{(B_{\mathrm{Ru+Ru}}/B_{\mathrm{Zr+Zr}})^2 - 1}_{0.18}]$$

Unknown

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

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

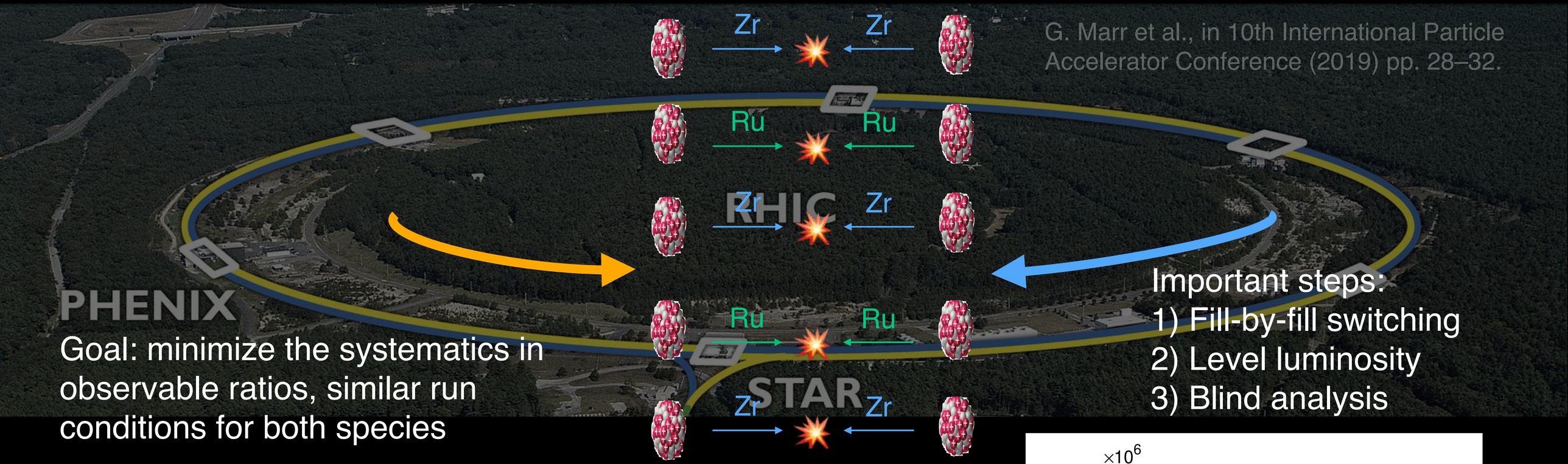
(A precision of 0.5% is needed !!)



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

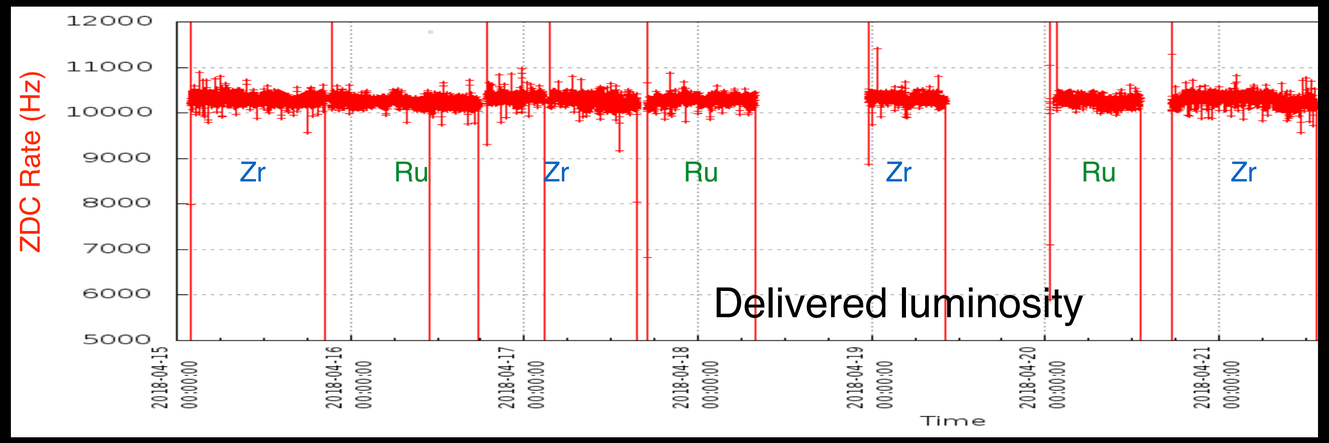
Details Of The Data Taking Of The Isobar Run

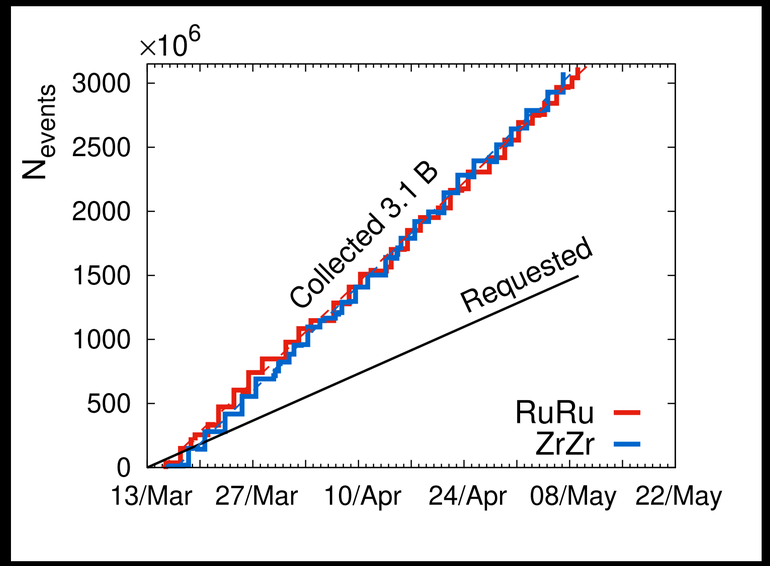
G. Marr et al., in 10th International Particle Accelerator Conference (2019) pp. 28–32.



Important steps:
1) Fill-by-fill switching
2) Level luminosity
3) Blind analysis

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



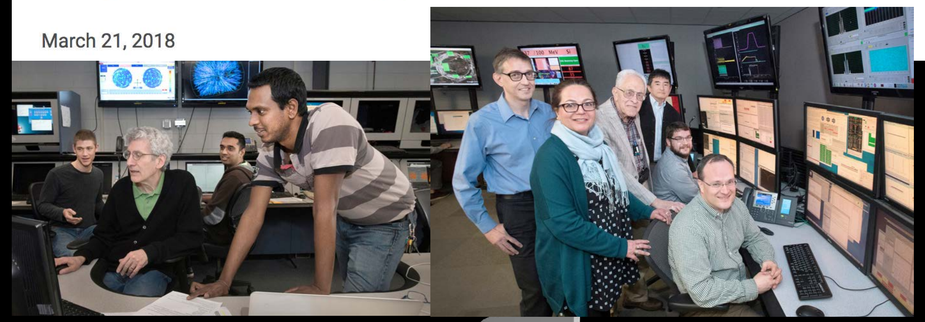


Isobar program at RHIC: journey since 2018

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

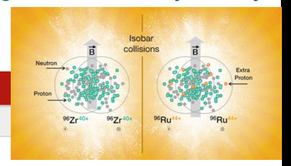


2018 2019 2020 2021

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

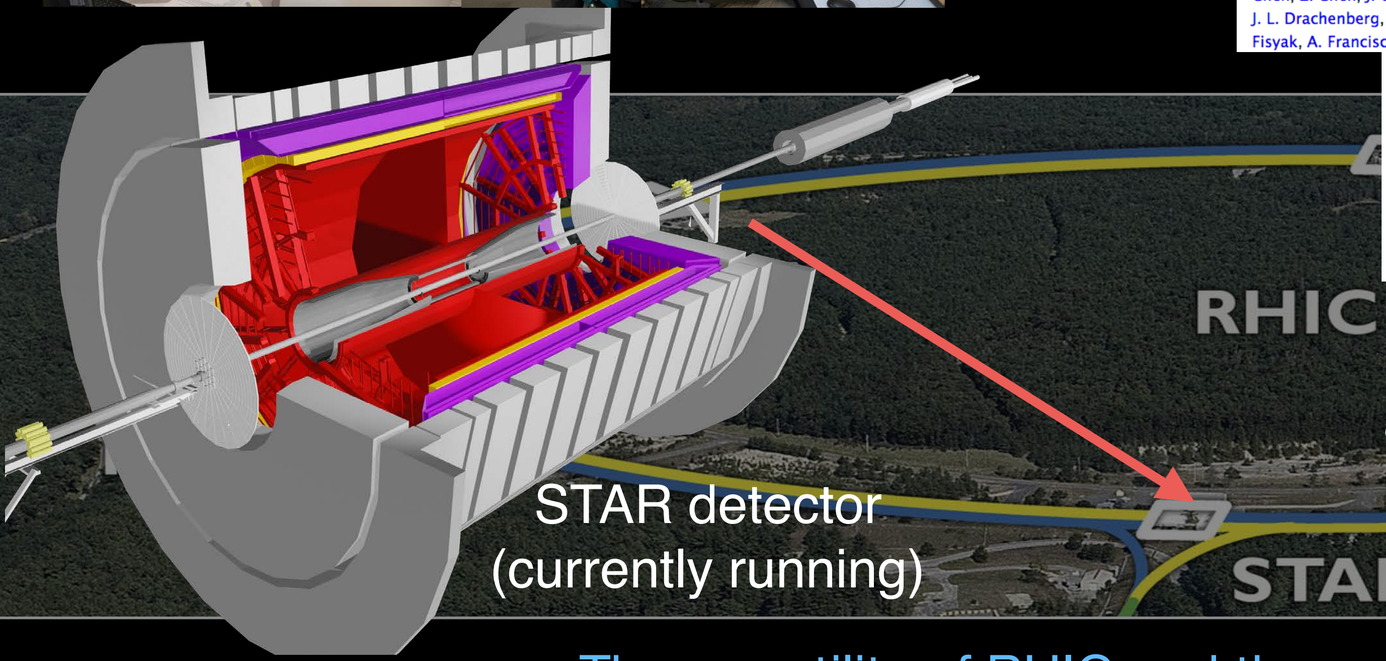
[Submitted on 1 Sep 2021]

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

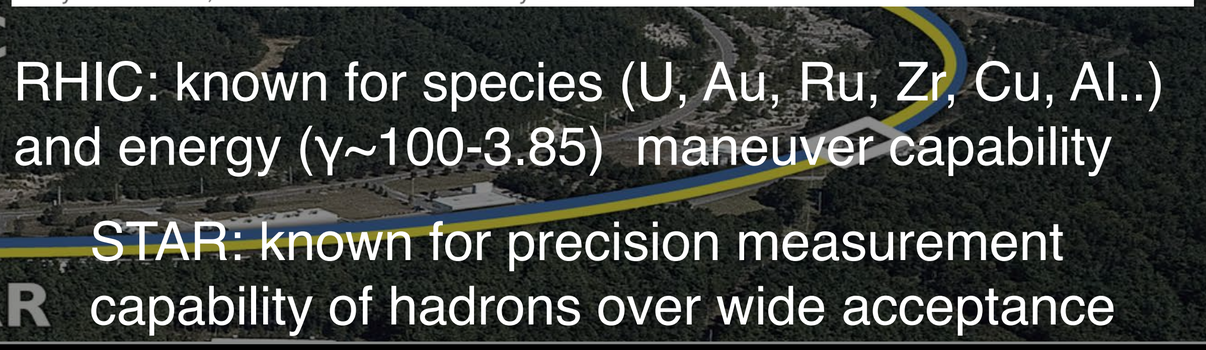
STAR Collaboration: M. S. Abdallah, B. E. Aboona, J. Adam, L. Adamczyk, J. R. Adams, J. K. Adkins, G. Agakishiev, I. Aggarwal, M. M. Aggarwal, Z. Ahammed, I. Alekseev, D. M. An Ashraf, F. G. Atetalla, A. Attri, G. S. Averichev, V. Bairathi, W. Baker, J. G. Ball Cap, K. Barish, A. Behera, R. Bellwied, 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 additi

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)



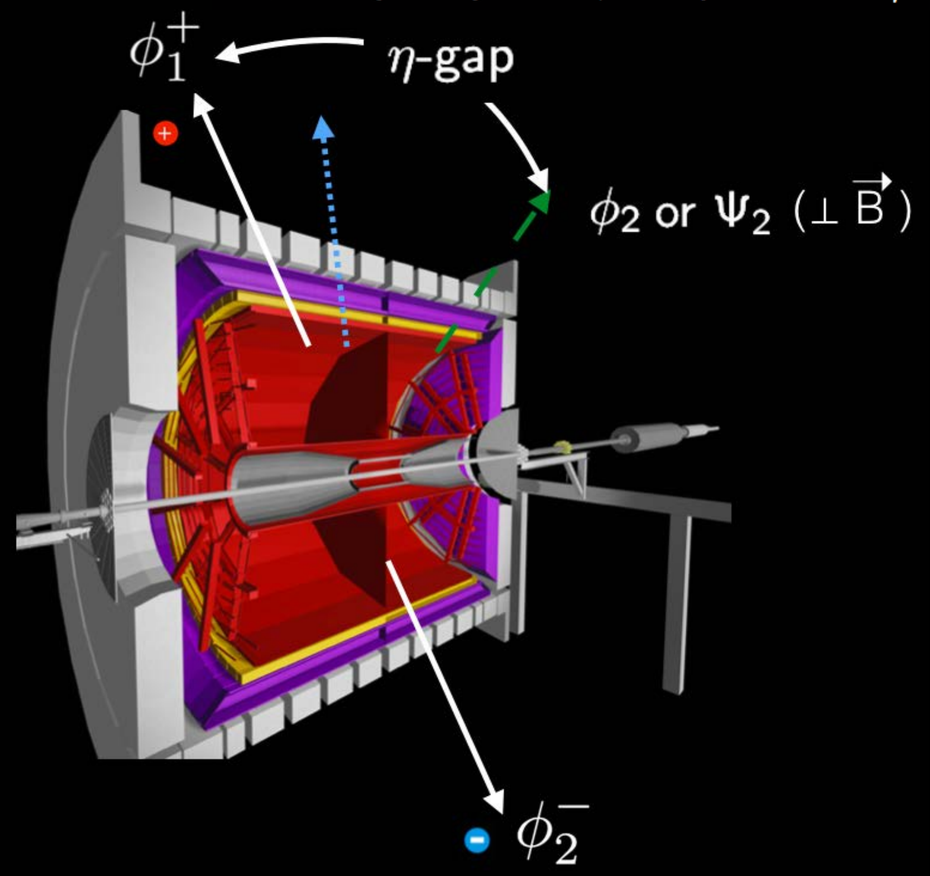
RHIC: known for species (U, Au, Ru, Zr, Cu, Al..) and energy (γ~100-3.85) maneuver capability

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

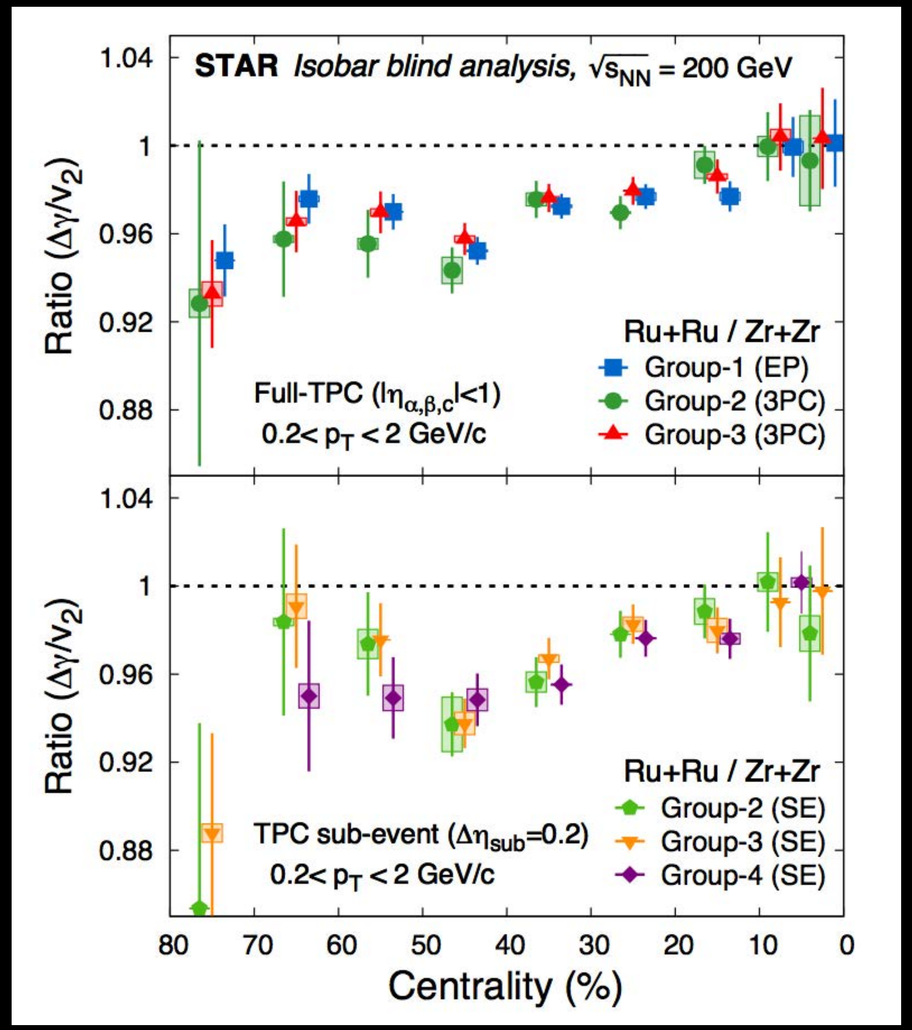
The versatility of RHIC and the unique capabilities of the STAR detector were crucial to the success of our program

Charge separation scaled by elliptic flow

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



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



Pre-defined criteria for CME

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

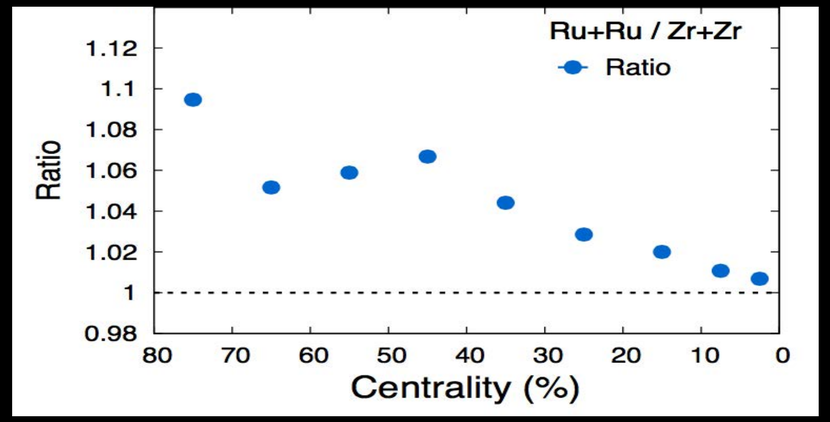
NOT seen!!

Limited Post-blind analysis: modified CME baseline

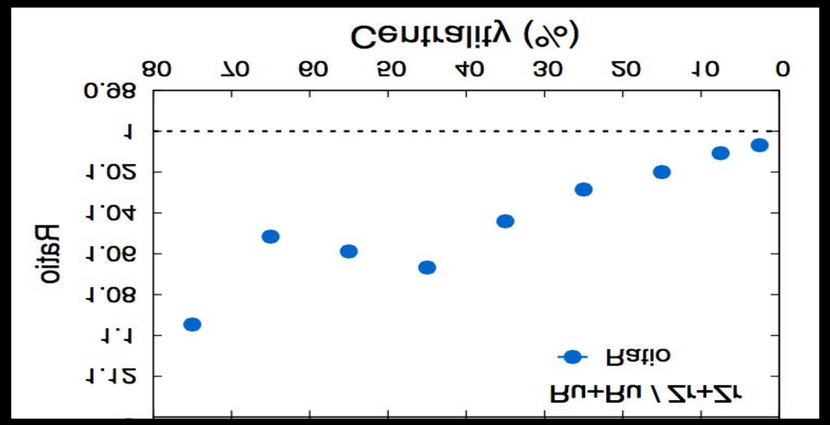
Voloshin for STAR, DNP 2021

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

Multiplicity is larger in Ru+Ru



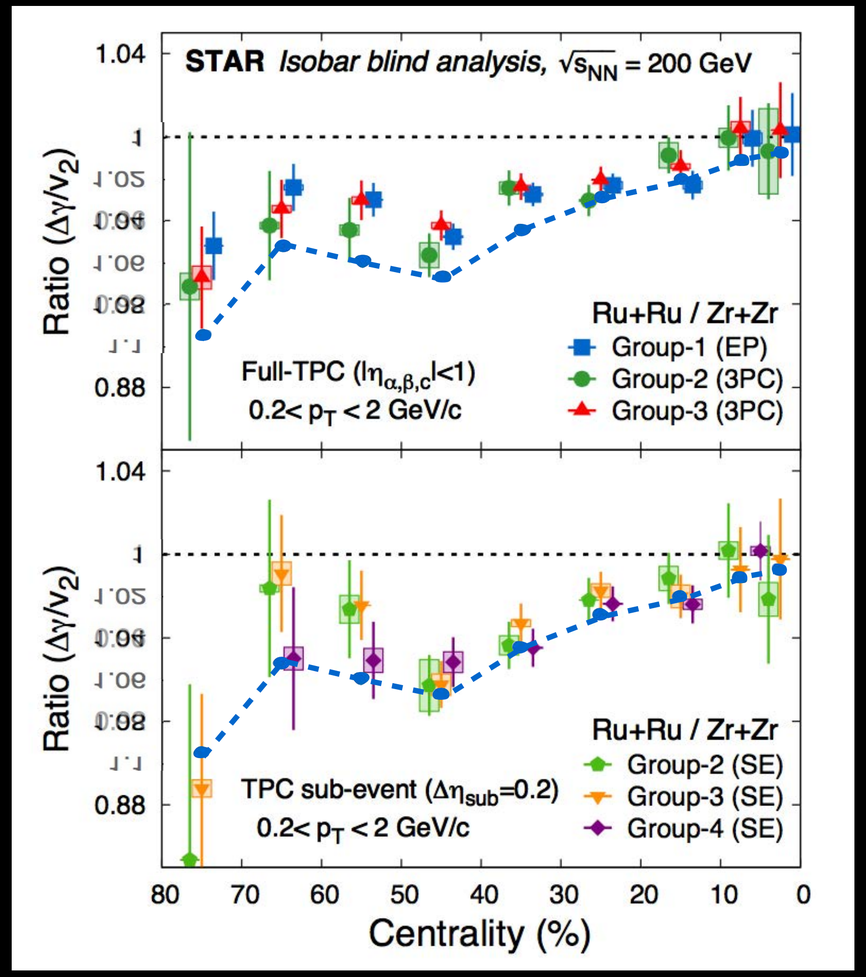
Flip



overlay

Change of baseline from "1" to 1/multiplicity

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



Dilution ~ 1/multiplicity is more in Ru+Ru

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

Inverse of multiplicity ratio explain the qualitative trend

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

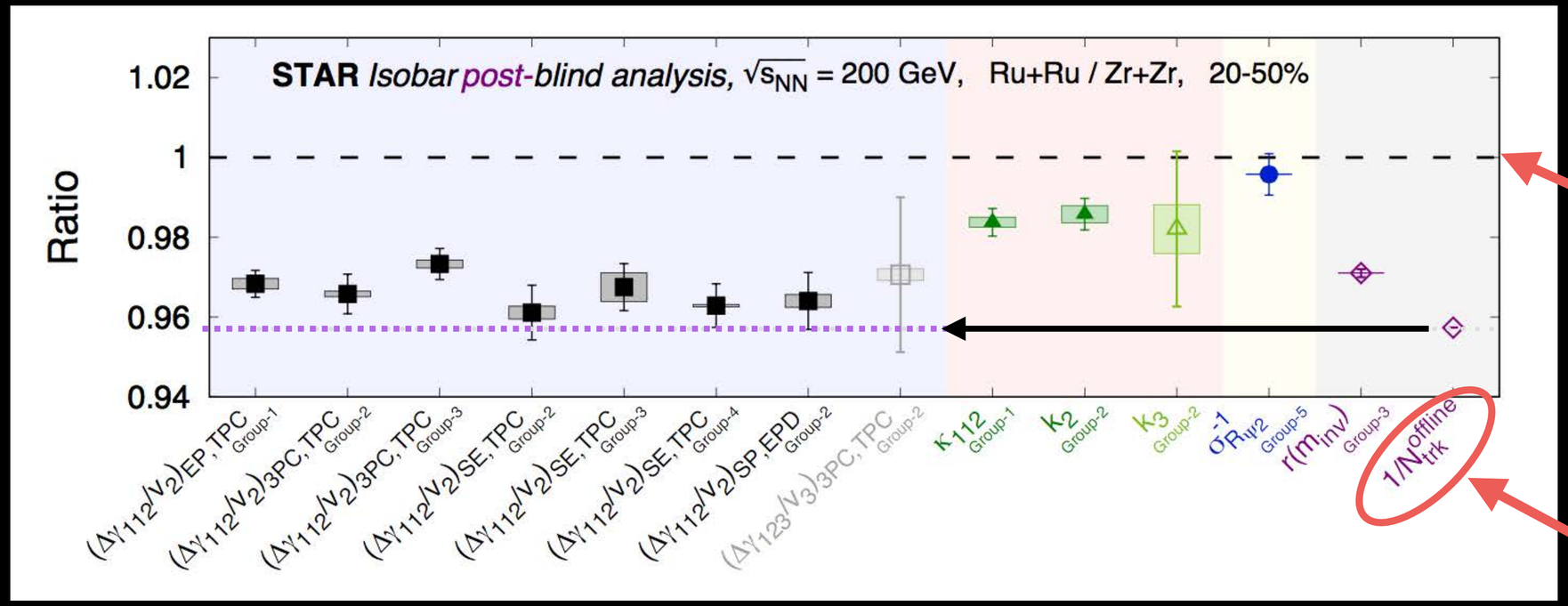
$$\Delta\gamma^{\mathrm{Ru+Ru}} = \Delta\gamma^{CME} + k \times \frac{v_2}{N}$$

$$\overset{??}{\neq} \qquad \approx$$

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

Post-blinding criterion for CME:

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



Blind analysis baseline

Post-blinding modified baseline

Latest update including the multiplicity dependence

M. Abdallah et al. (STAR Collaboration), Phys. Rev. C 105 (2022) 1, 014901

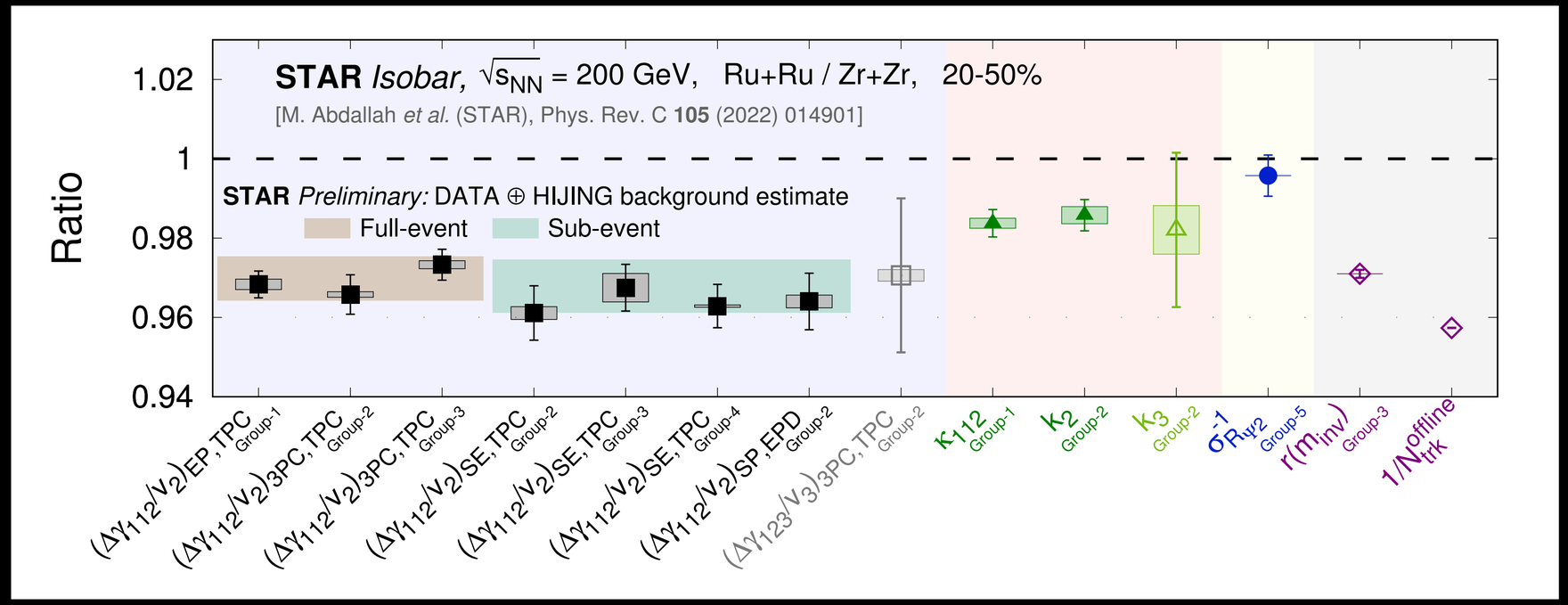
Blind analysis performed with pre-defined criteria for primary CME sensitive observable:

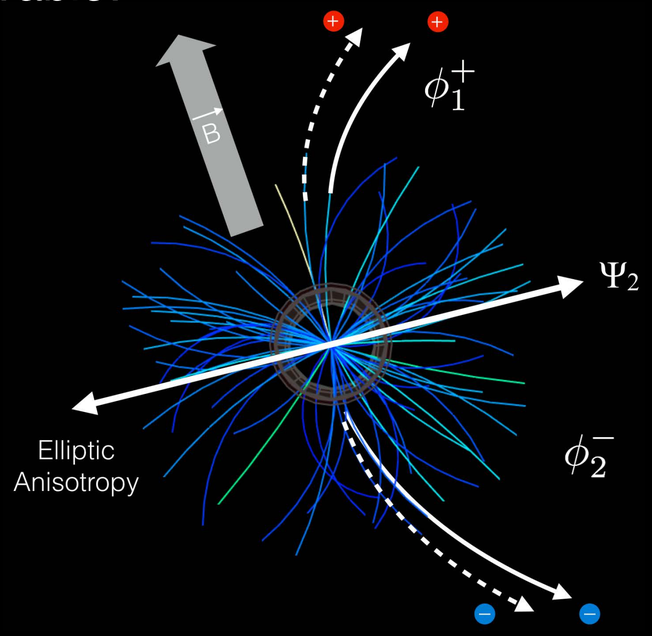
$$\frac{(\Delta\gamma/v_2)_{\mathrm{Ru+Ru}}}{(\Delta\gamma/v_2)_{\mathrm{Zr+Zr}}} \approx 1 + f_{\mathrm{CME}}^{\mathrm{Zr+Zr}}\left[\left(B_{\mathrm{Ru+Ru}}/B_{\mathrm{Zr+Zr}}\right)^2 - 1\right] > 1 \text{ (for CME)}$$

Unknown

0.1-0.15

Precision of 0.4% achieved





Yicheng Feng (STAR Collaboration), QM 2022

No pre-defined signature of CME is observed in isobar collisions, possible residual signal due to change of baseline & non-flow effects are under study

Remaining signal estimates

1. STAR isobar blind analysis (most precision measurement):

M. Abdallah et al. (STAR Collaboration), Phys. Rev. C 105 (2022) 1, 014901

$$R = \frac{(\Delta\gamma/v_2)_{\mathrm{Ru+Ru}}}{(\Delta\gamma/v_2)_{\mathrm{Zr+Zr}}} = 0.9683 \pm 0.0034 \pm 0.0013$$

$$\frac{(1/N_{\mathrm{ch}})_{\mathrm{Ru+Ru}}}{(1/N_{\mathrm{ch}})_{\mathrm{Zr+Zr}}} = 0.957337 \pm 0.000017$$

2. STAR background estimate including non-flow:

Yicheng Feng, STAR collaboration, QM 2022

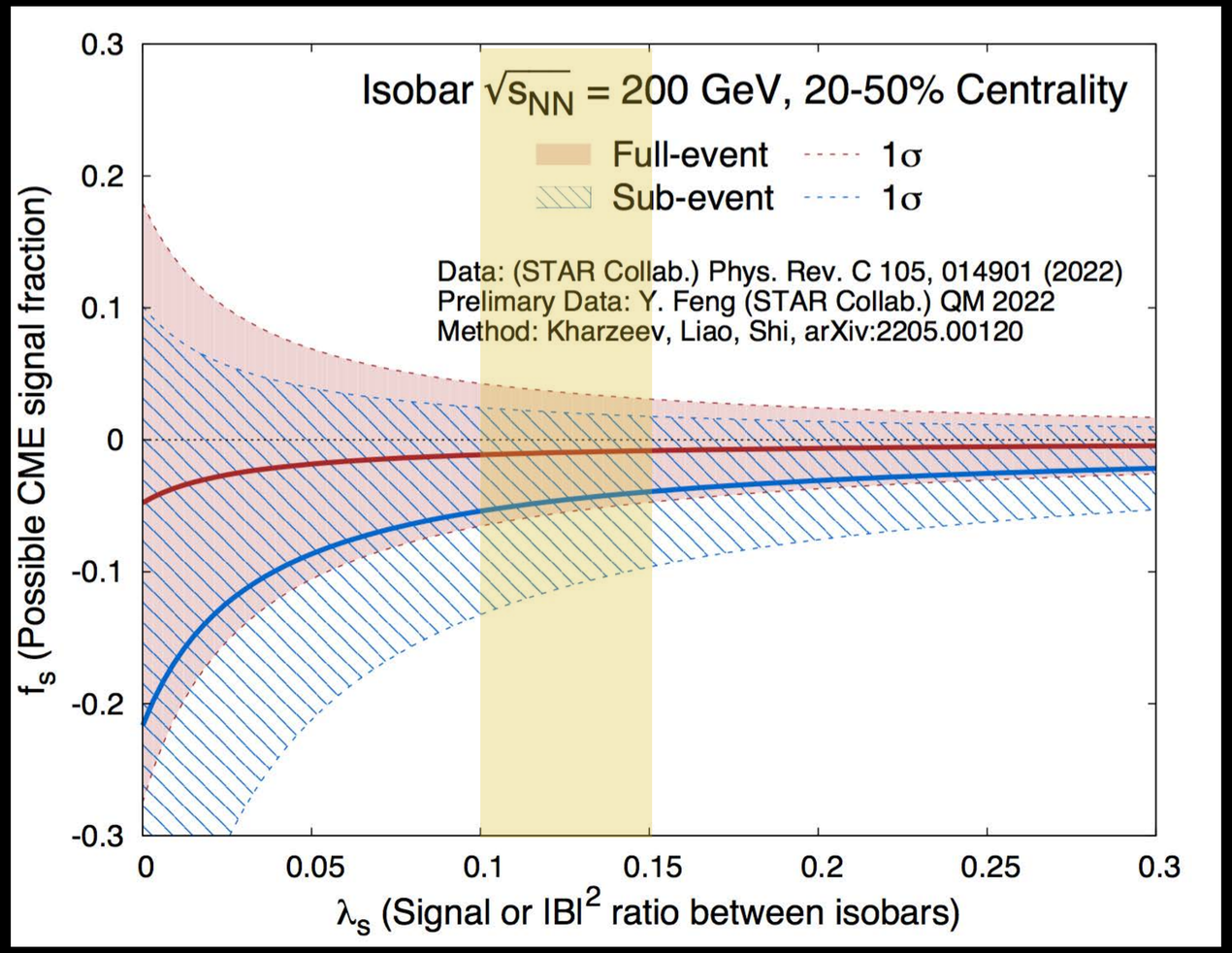
$$\frac{(N_{\mathrm{ch}}\,\Delta\gamma/v_2)^{\mathrm{bkg}}_{\mathrm{Ru+Ru}}}{(N_{\mathrm{ch}}\,\Delta\gamma/v_2)^{\mathrm{bkg}}_{\mathrm{Zr+Zr}}} = 1.013 \pm 0.003 \pm 0.005$$

$$R^{\mathrm{bkg}} = \frac{(\Delta\gamma/v_2)_{\mathrm{Ru+Ru}}}{(\Delta\gamma/v_2)_{\mathrm{Zr+Zr}}} = 0.9698 \pm 0.003 \pm 0.005$$

3. Estimates of Possible CME signal:

Kharzeev, Liao, Shi, 2205.00120 [nucl-th]

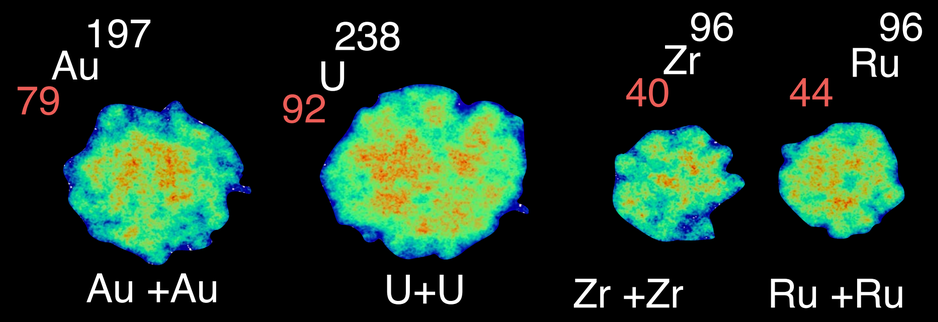
$$f_s = \frac{1/R^{\mathrm{bkg}} - 1/R}{\lambda_s + 1/R^{\mathrm{bkg}} - 1}$$

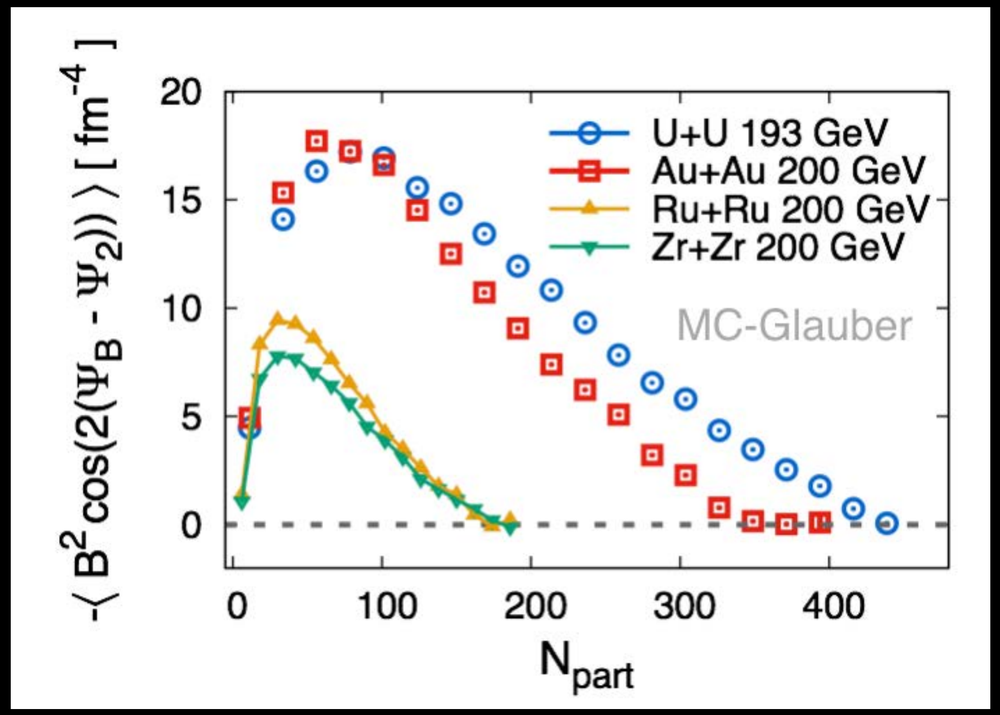


More work from STAR collaboration is underway

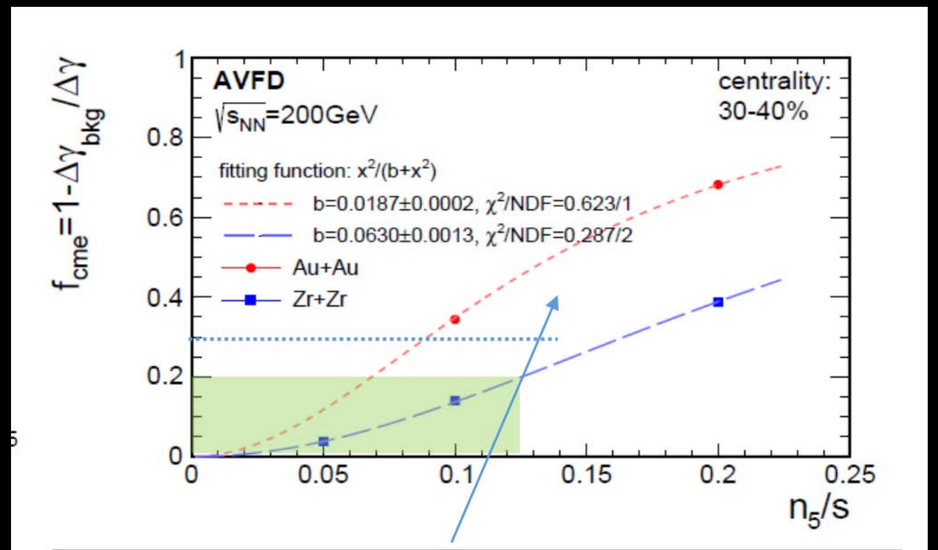
Going back to larger systems

How to understand the system dependence of CME signal





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

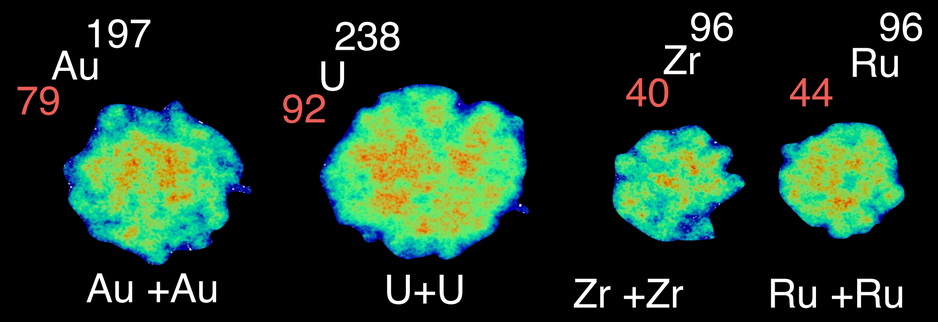


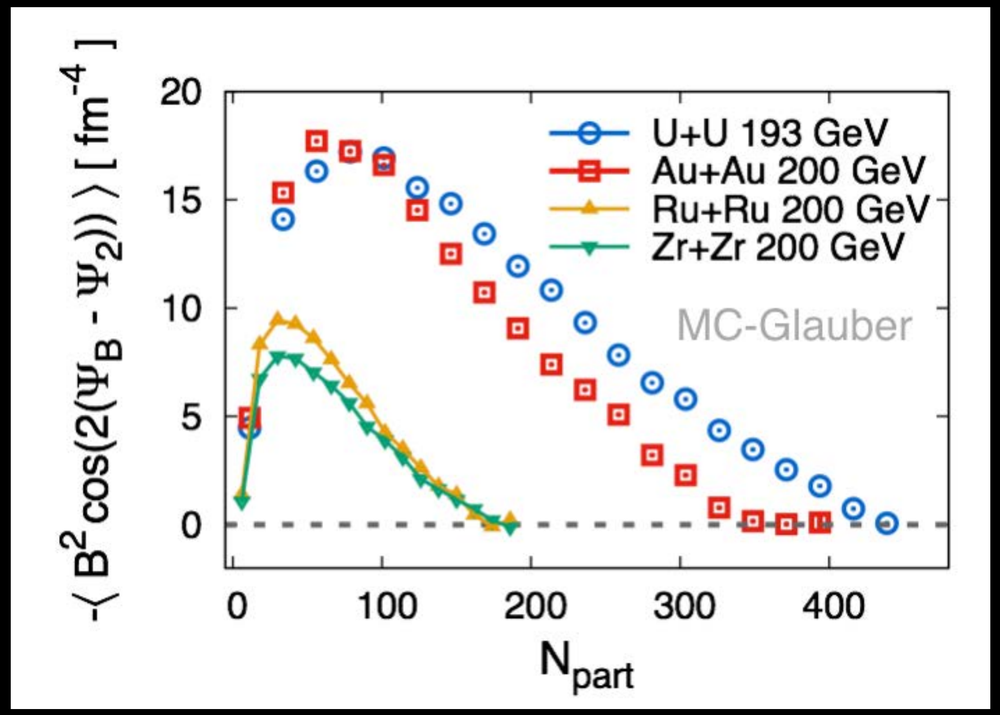
Could be x3 reduction in f_{CME} at the same n_5/s
If AuAu f_{CME}=10%, then isobar 3% (1σ effect)
Ru/Zr = 1 + 15%*3% = 1.005 (±0.004)

Reduction of signal in isobar system

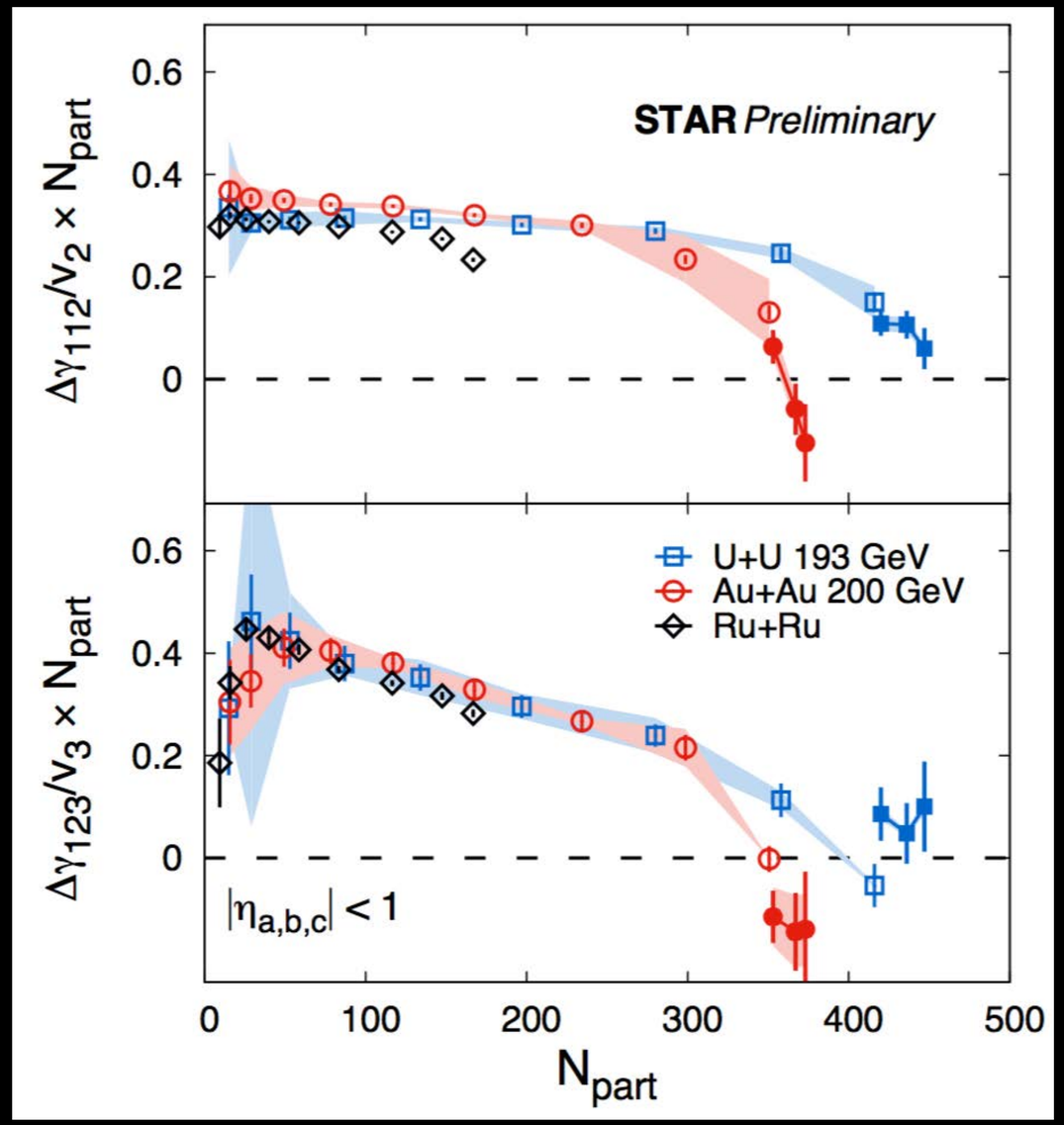
Y. Feng et. al., Phys. Lett. B 820, 136549 (2021), arXiv:2103.10378 [nucl-ex].

How to understand the system dependence of CME signal





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



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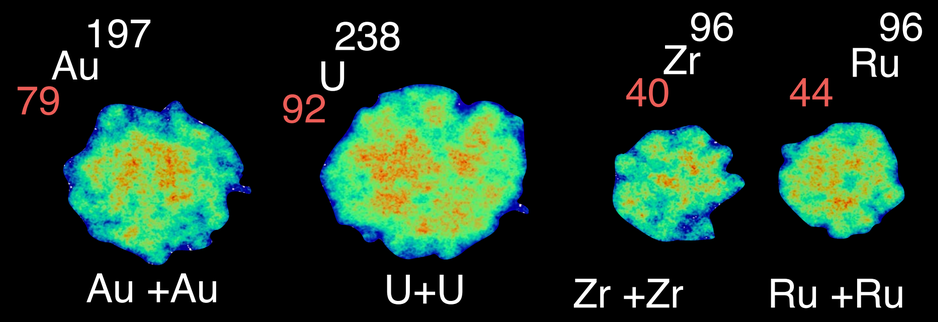

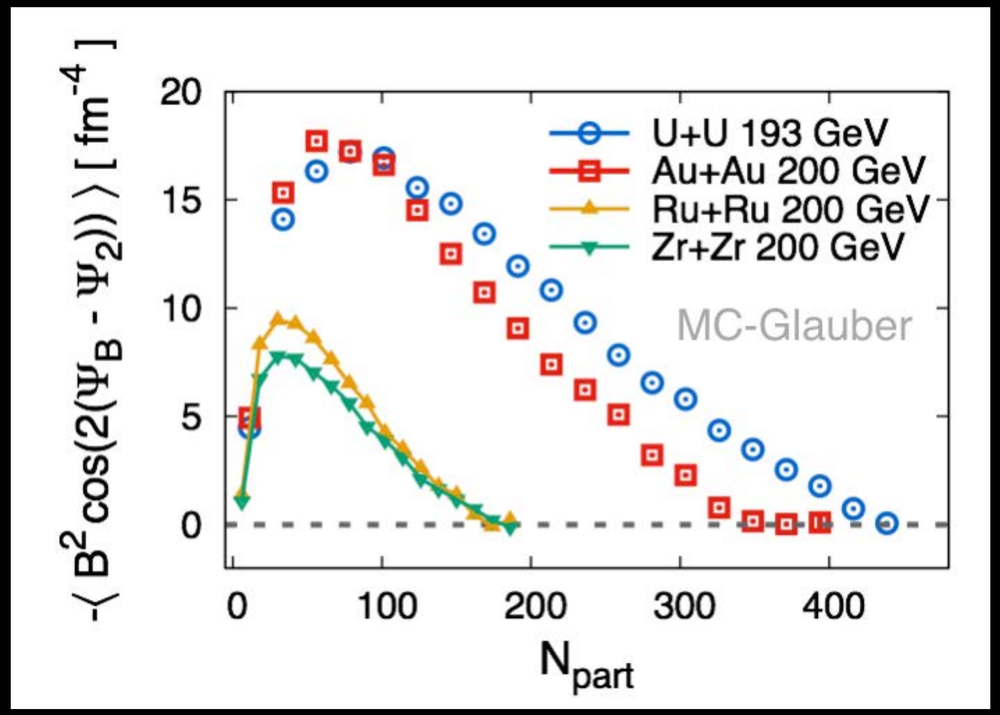

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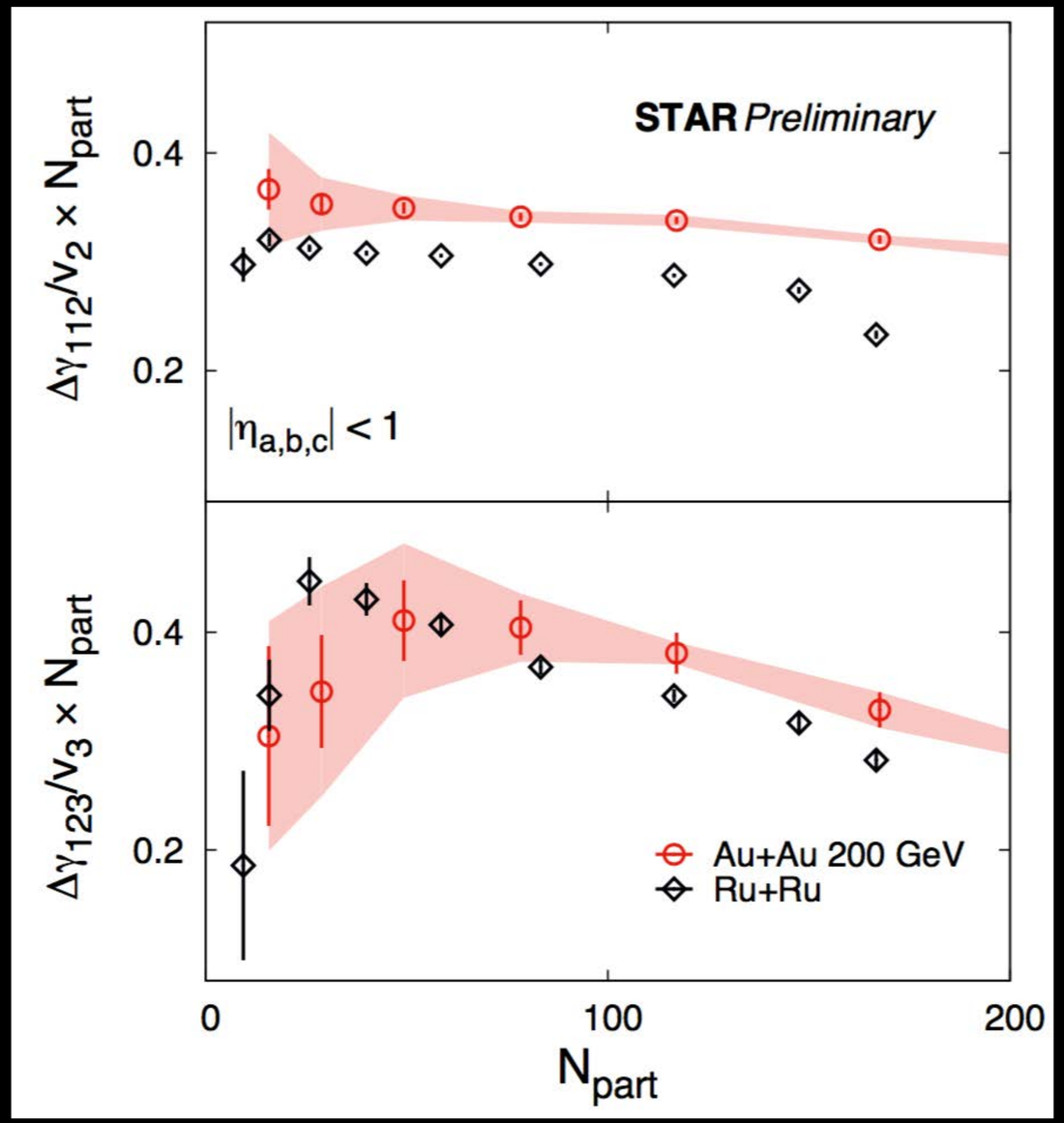
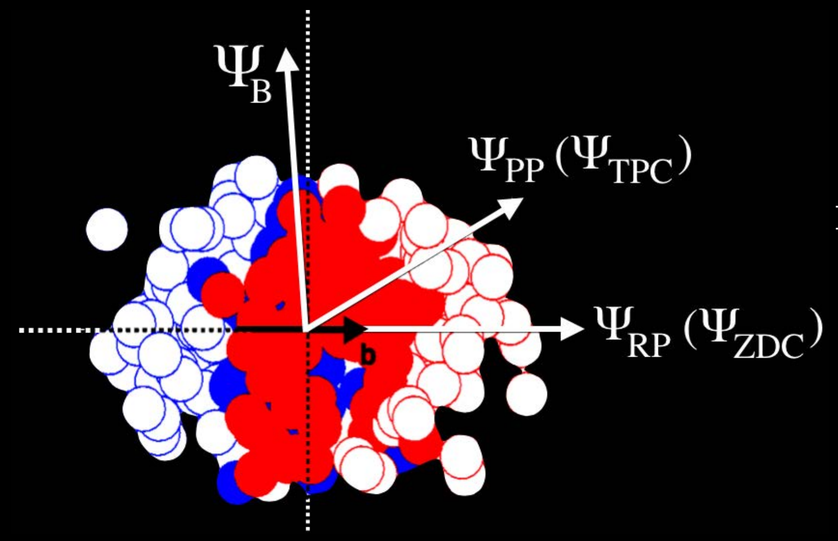
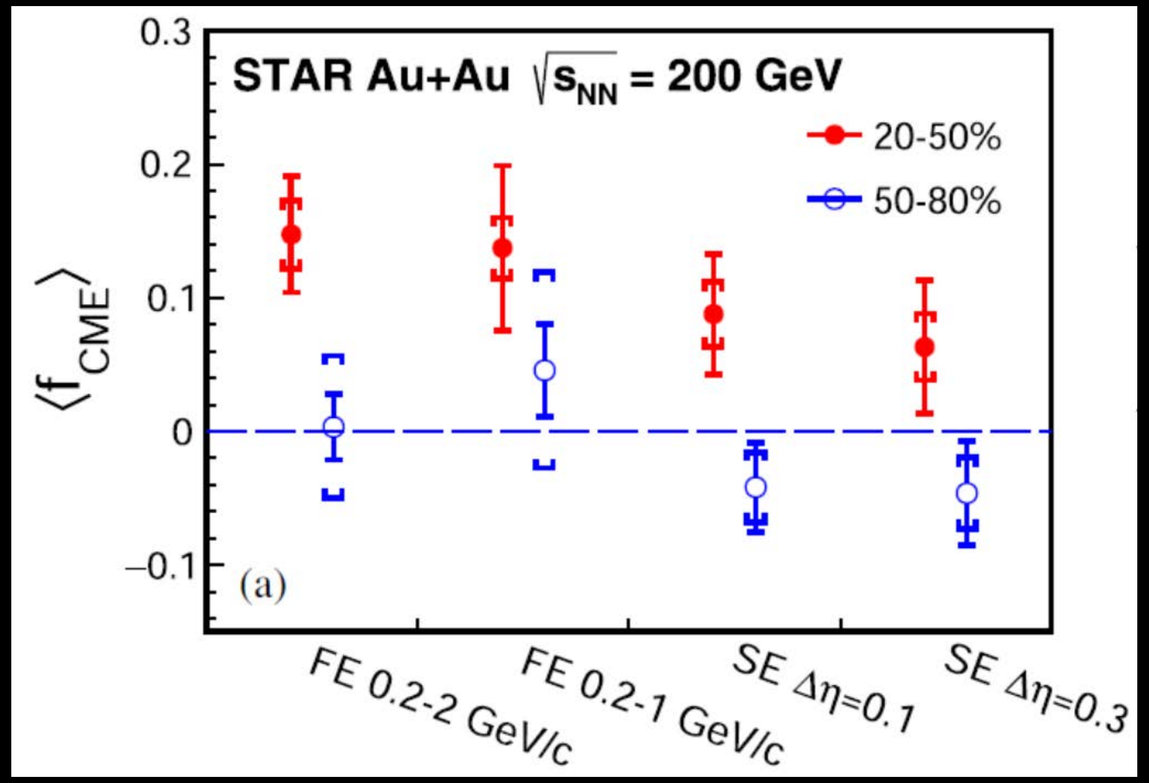


CME search using spectator/participant plane



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

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



Four equations, four unknowns:

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

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

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

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

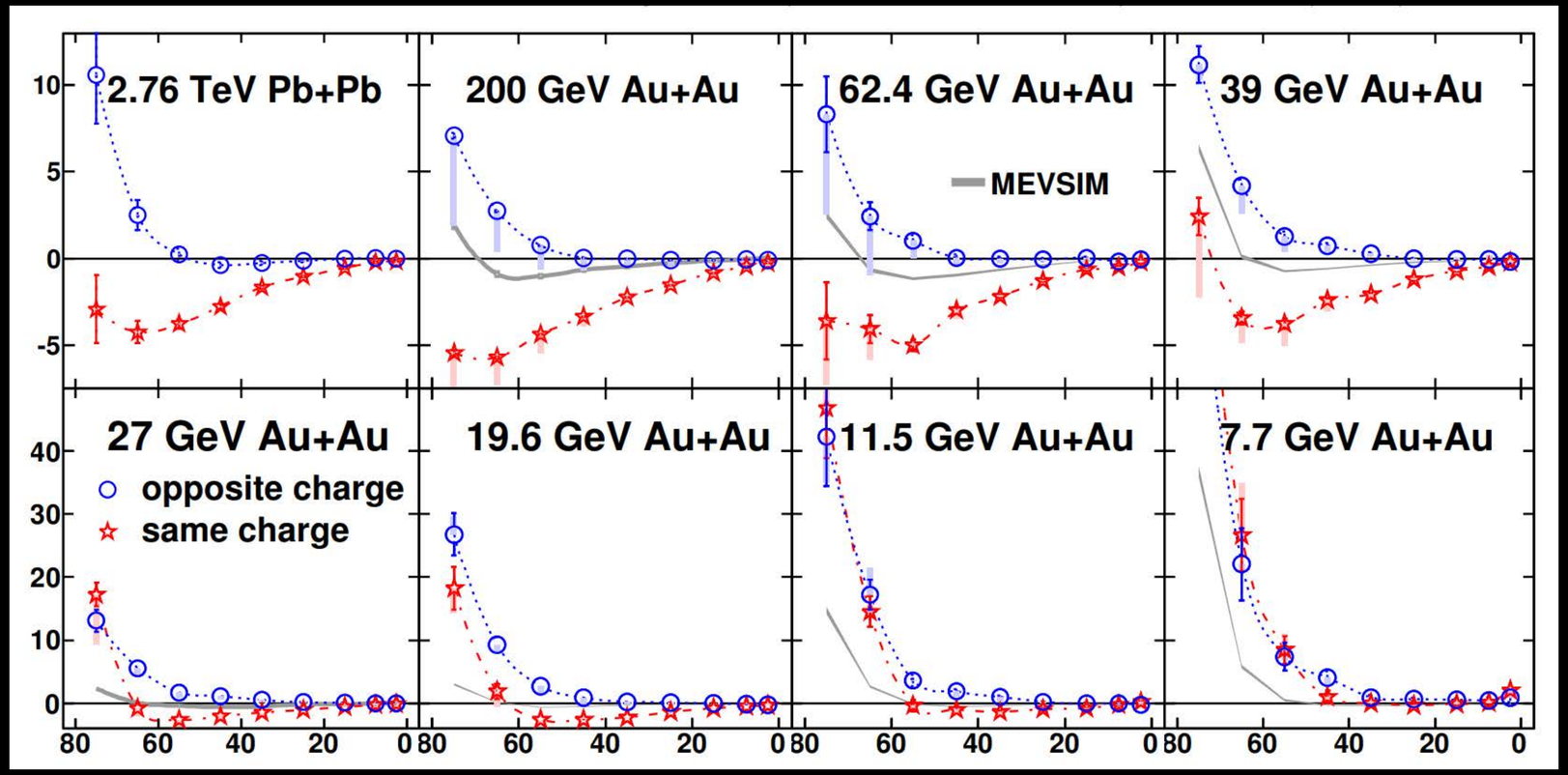
2σ significance of CME fraction using 2.4 Billion events

Going lower collision energy

CME search at low energies

The prerequisites for CME change as we change the collisions energy

L. Adamczyk *et al.* (STAR), Phys. Rev. Lett., 113 (2014) 052302
B. Abelev *et al.* (ALICE), Phys. Rev. Lett., 110 (2013) 012301



arXiv > hep-ph > arXiv:2012.02926

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High Energy Physics – Phenomenology

[Submitted on 5 Dec 2020 (v1), last revised 26 Feb 2021 (this version, v2)]

Real-time dynamics of Chern-Simons fluctuations near a critical point

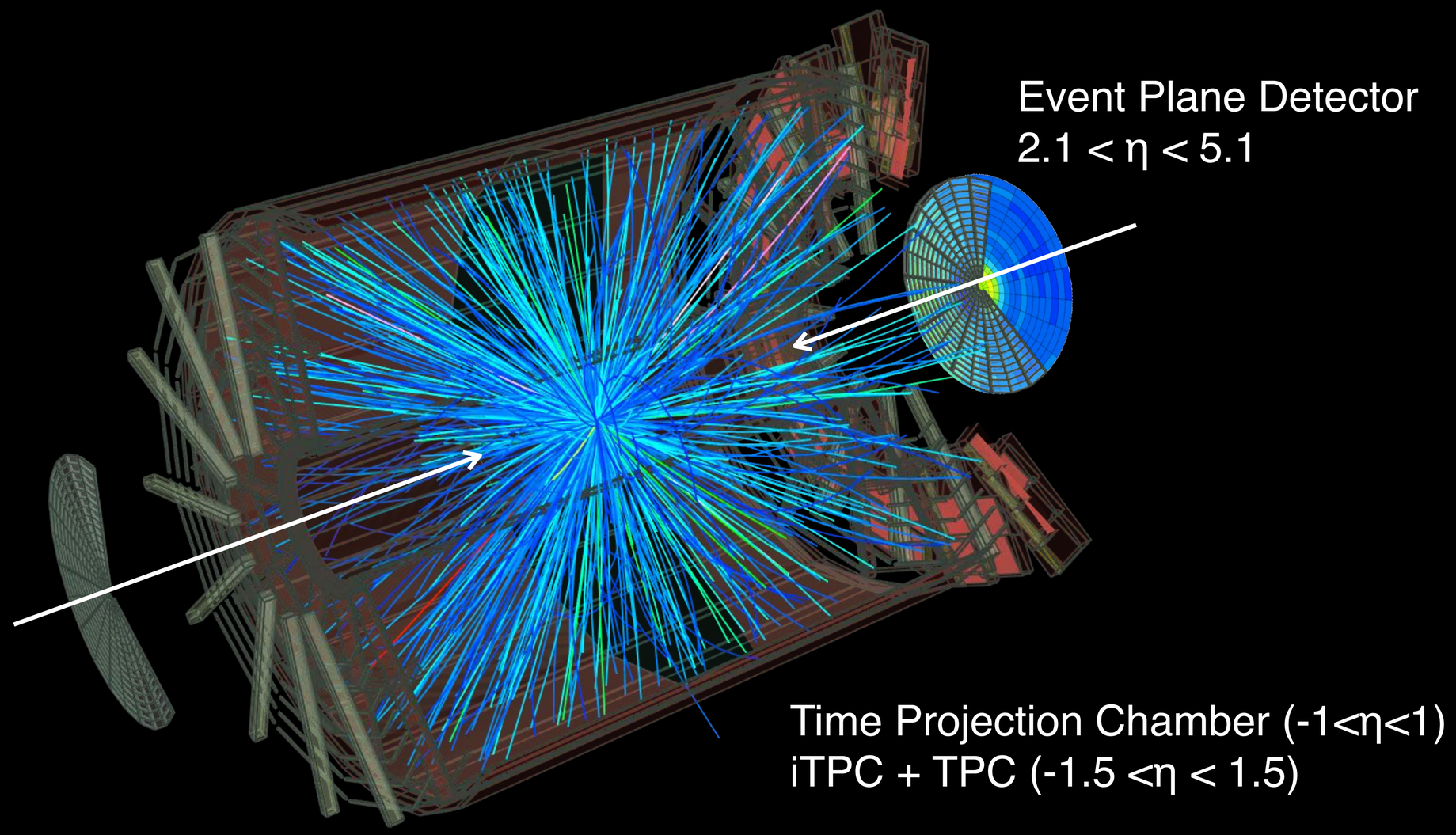
Kazuki Ikeda, Dmitri E. Kharzeev, Yuta Kikuchi

With the BES-II data

- New capabilities
  the new installed Event Plane Detectors
- ~10 times statistics
  the Event Shape Engineering technique

Previous measurement with BES-I data show interesting trend, BES-II provide additional capabilities

CME search at low energies: Participant Spectator Plane

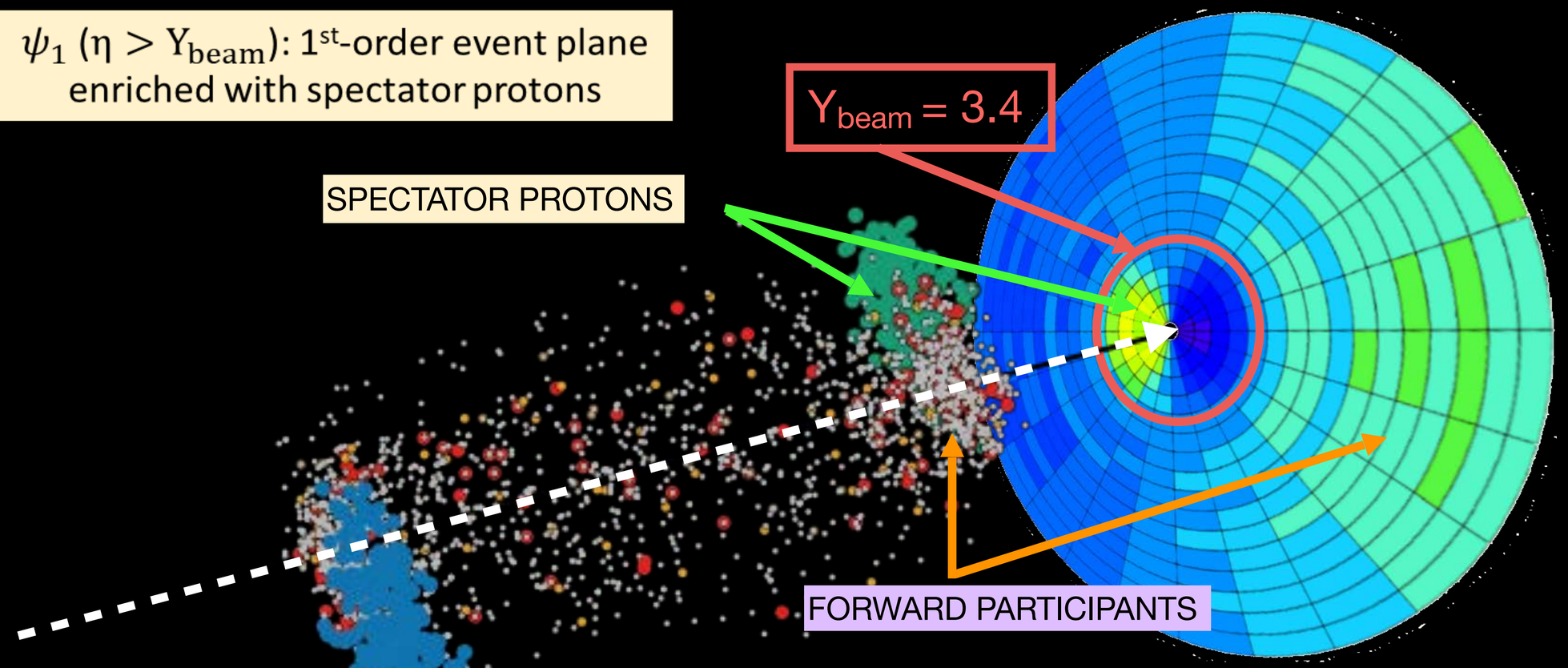


CME search at low energies

STAR Collaboration, arXiv: 2209.03467 [nucl-ex]

Event Plane Detector
$2.1 < \eta < 5.1$

ψ_1 ($\eta > Y_{beam}$): 1st-order event plane enriched with spectator protons



ψ_2 ($\eta < Y_{beam}$): 2nd-order event plane for particles going in forward direction

Measurement Au+Au √s=27 GeV

STAR Collaboration, arXiv: 2209.03467 [nucl-ex]

In flow driven background scenario, we should have:

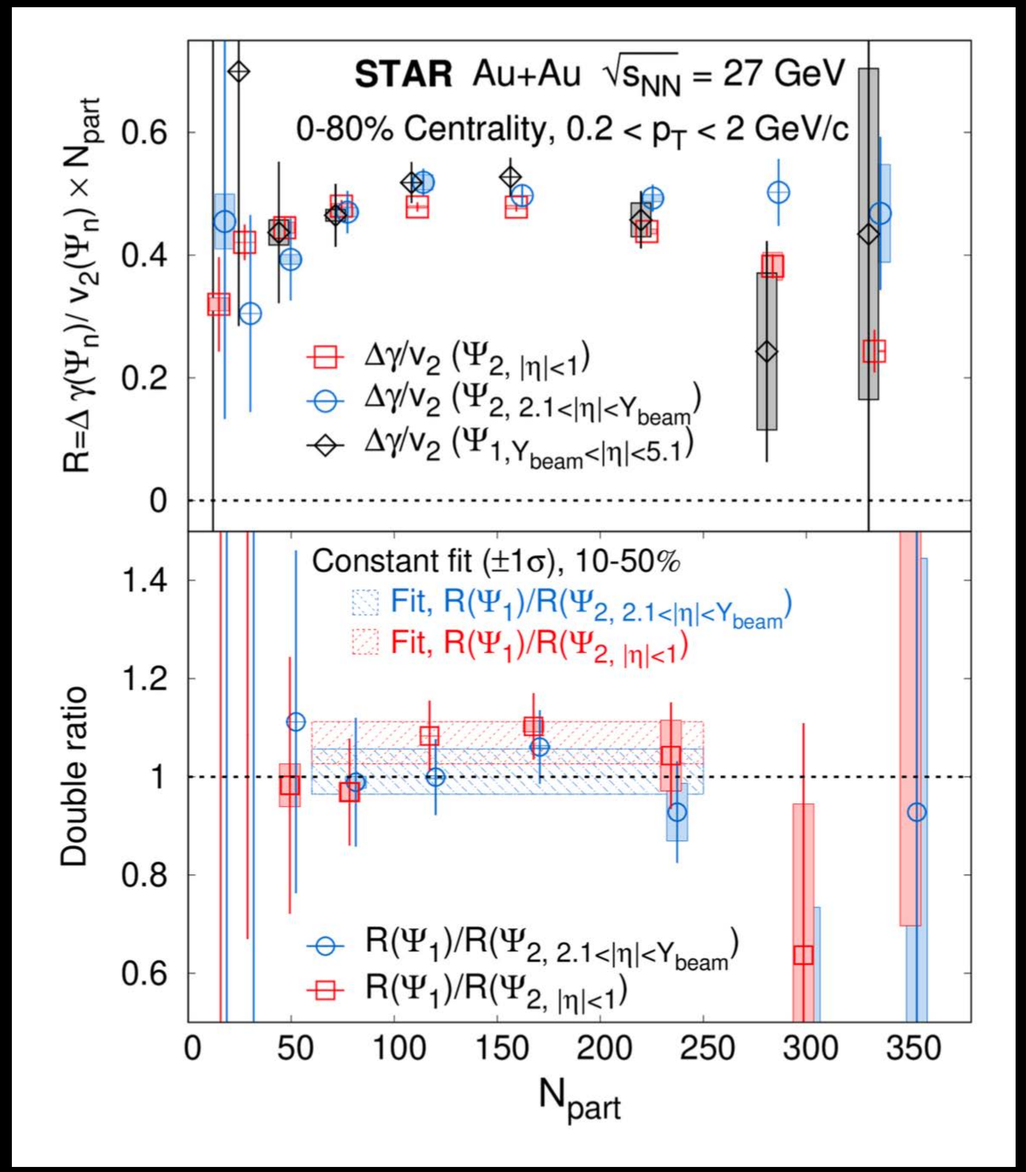
$$\Delta\gamma/v_2(\Psi_A) = \Delta\gamma/v_2(\Psi_B) = \Delta\gamma/v_2(\Psi_C)\cdots$$

B-field is more correlated to forward directed-flow plane, CME scenario would lead to:

SPECTATOR-RICH

$$\frac{\Delta\gamma/v_2(\Psi_1)}{\Delta\gamma/v_2(\Psi_2)} > 1$$

PARTICIPANT-RHIC



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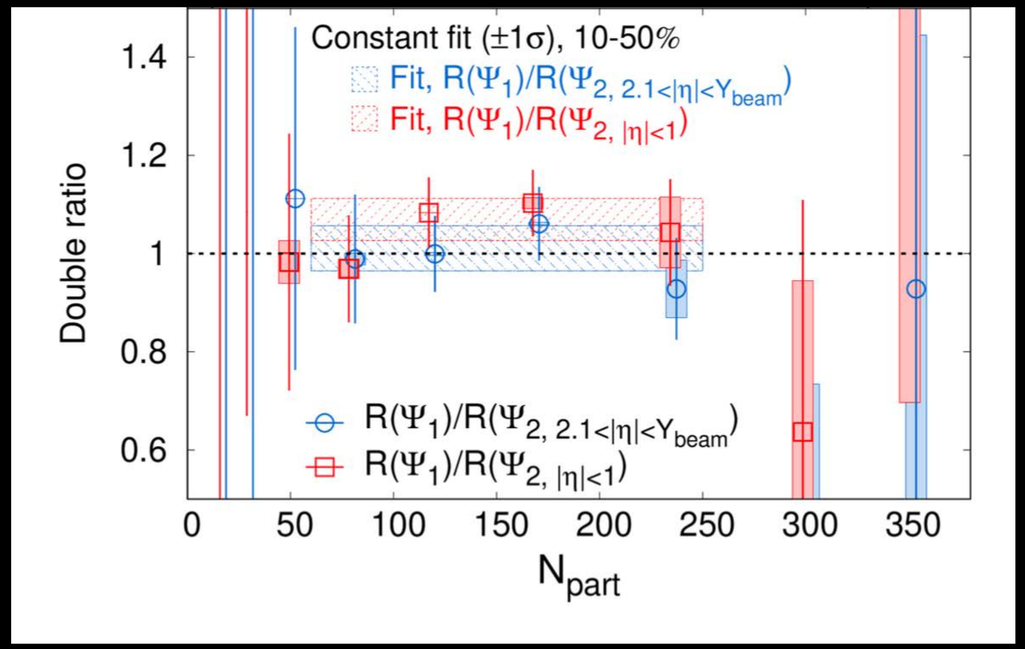
SPECTATOR-RICH

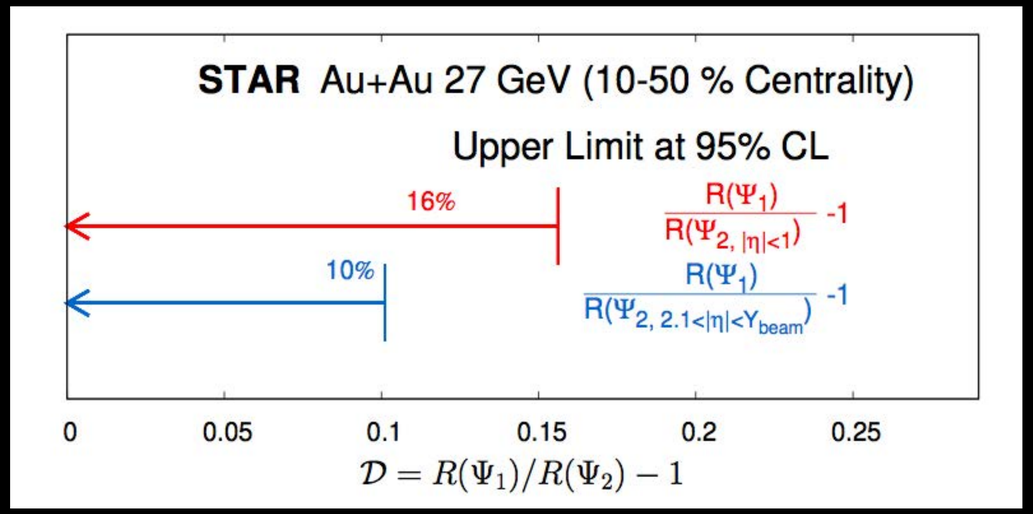
PARTICIPANT-RICH

$$\frac{\Delta\gamma/v_2(\Psi_1)}{\Delta\gamma/v_2(\Psi_2)} > 1$$

Deviation from background scenario:

$$\mathcal{D} = \frac{\Delta\gamma/v_2(\Psi_1)}{\Delta\gamma/v_2(\Psi_2)} - 1$$



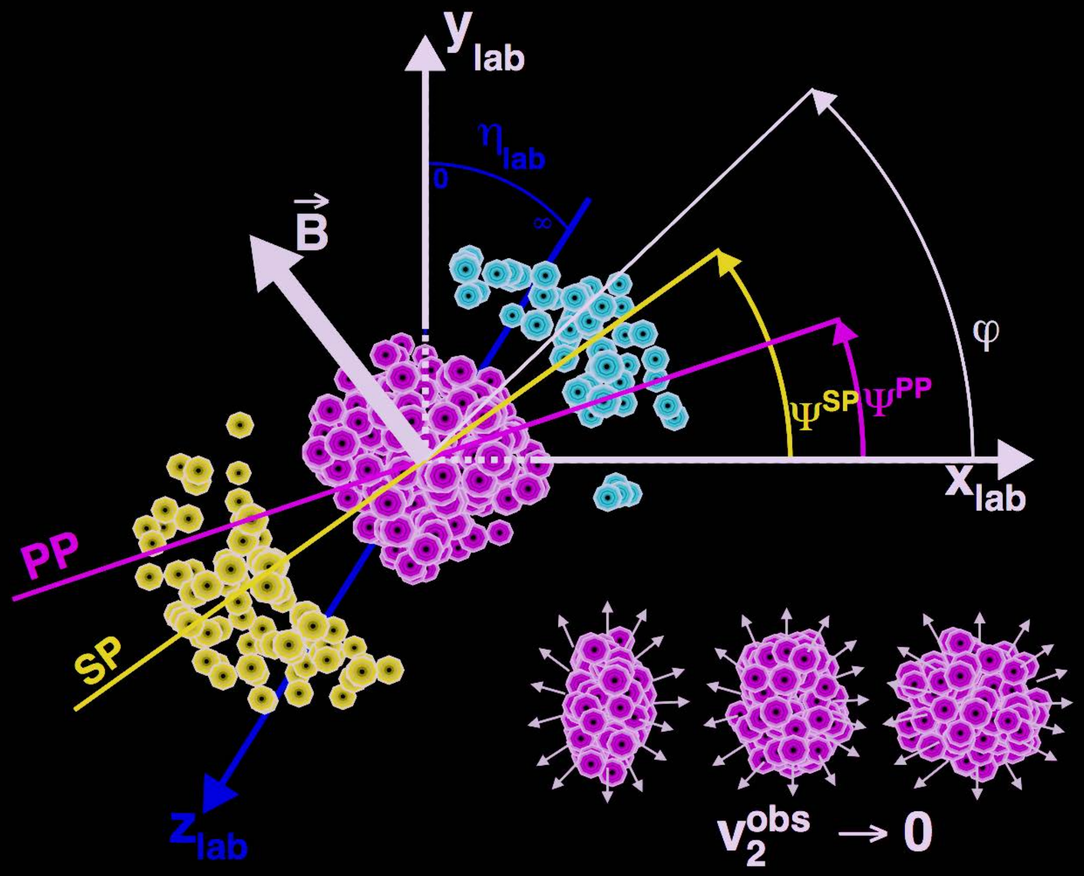


10-16% deviation from the background scenario observed, CME-fraction estimation require more work

CME search at low energies: Event Shape Selection (ESS)

Zhiwan Xu, DNP 2022

R. Milton et al. Phys. Rev. C 104, 064906 (2021)



- **Flow vector to control the event shape:**

$$\vec{q_n}^{A} = (q^{A}_{n,x}, q^{A}_{n,y})$$

$$q^{A}_{n,x} = \frac{1}{\sqrt{N}} \sum_{i}^{N} \cos(n\phi_i^{A}),$$

$$q^{A}_{n,y} = \frac{1}{\sqrt{N}} \sum_{i}^{N} \sin(n\phi_i^{A}),$$

- **For events in each q^A class, v_2 and $\Delta\gamma$ are measured using POIs in sub-event (A), and EP estimated from independent sub-event (B).**
  - $\Delta\gamma(q_2^2)$ **and** $v_2(q_2^2) \rightarrow \Delta\gamma(v_2)$
- **Event Shape Selection (ESS) approach**

ESS

EPD plane

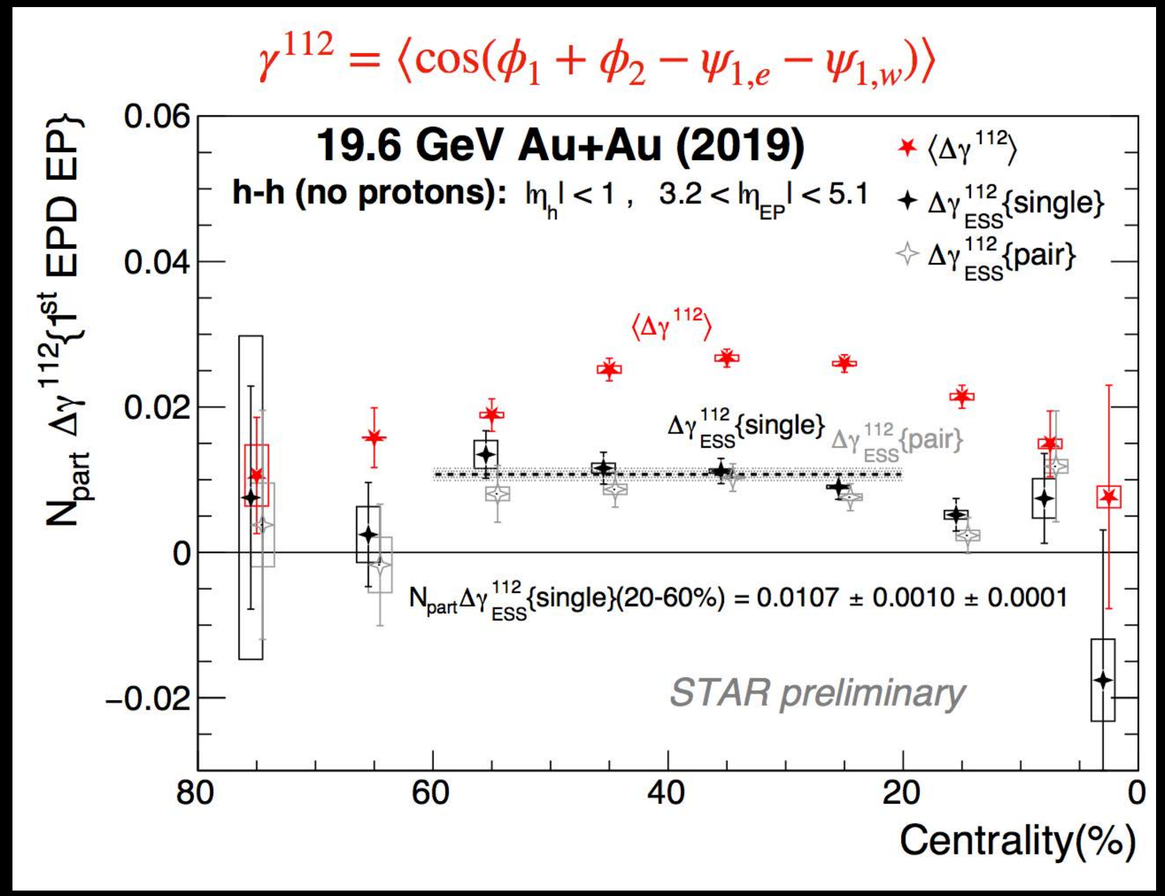
$$\Delta\gamma^{112} = \Delta\gamma^{\mathrm{CME}} + k\frac{v_2}{N} + \Delta\gamma^{\mathrm{non-flow}}$$

Measured Signal Backgrounds

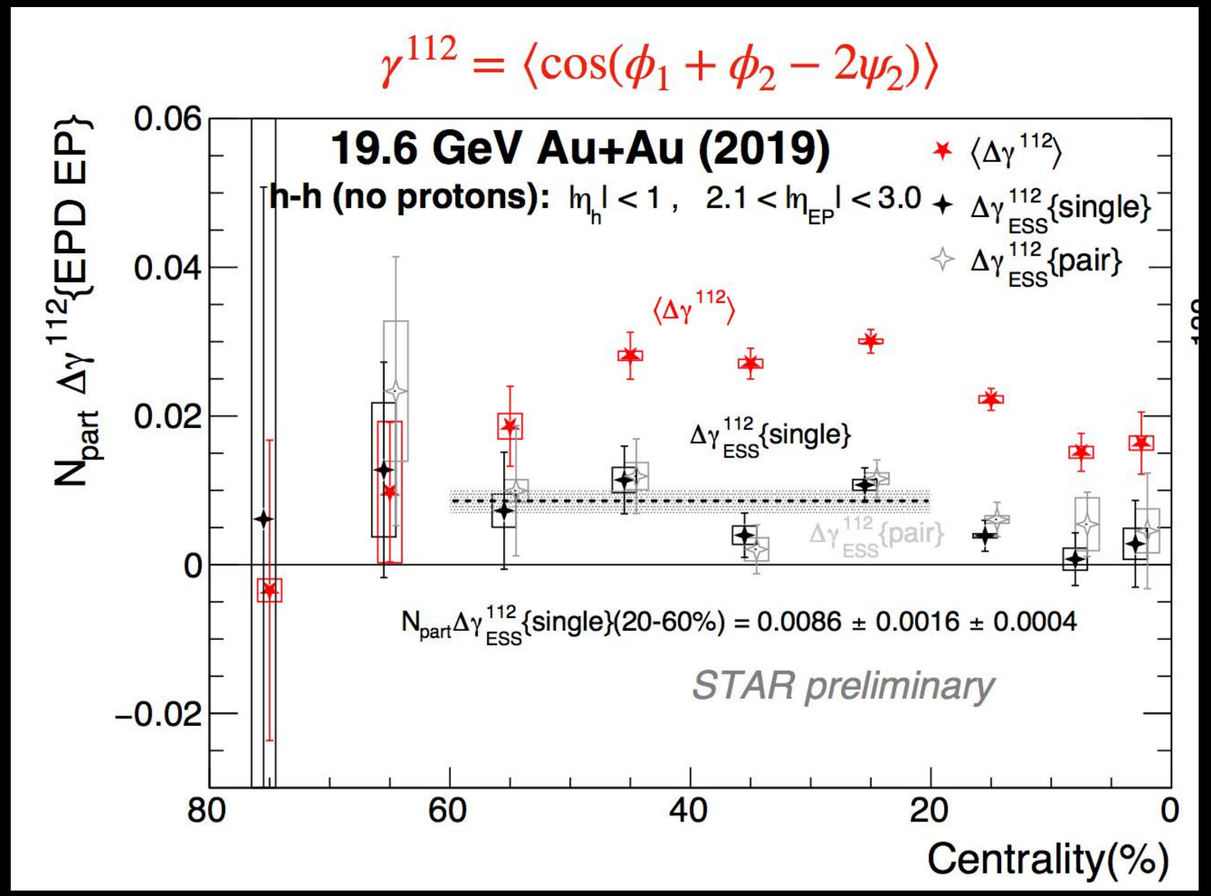
Measurement Au+Au √s=19 GeV using ESS approach

Zhiwan Xu, DNP 2022

EPD spectator-rich plane



EPD participant-rich plane



Substantial reduction of flow and non-flow related background demonstrated using ESS approach, important step towards CME search at low energy collisions

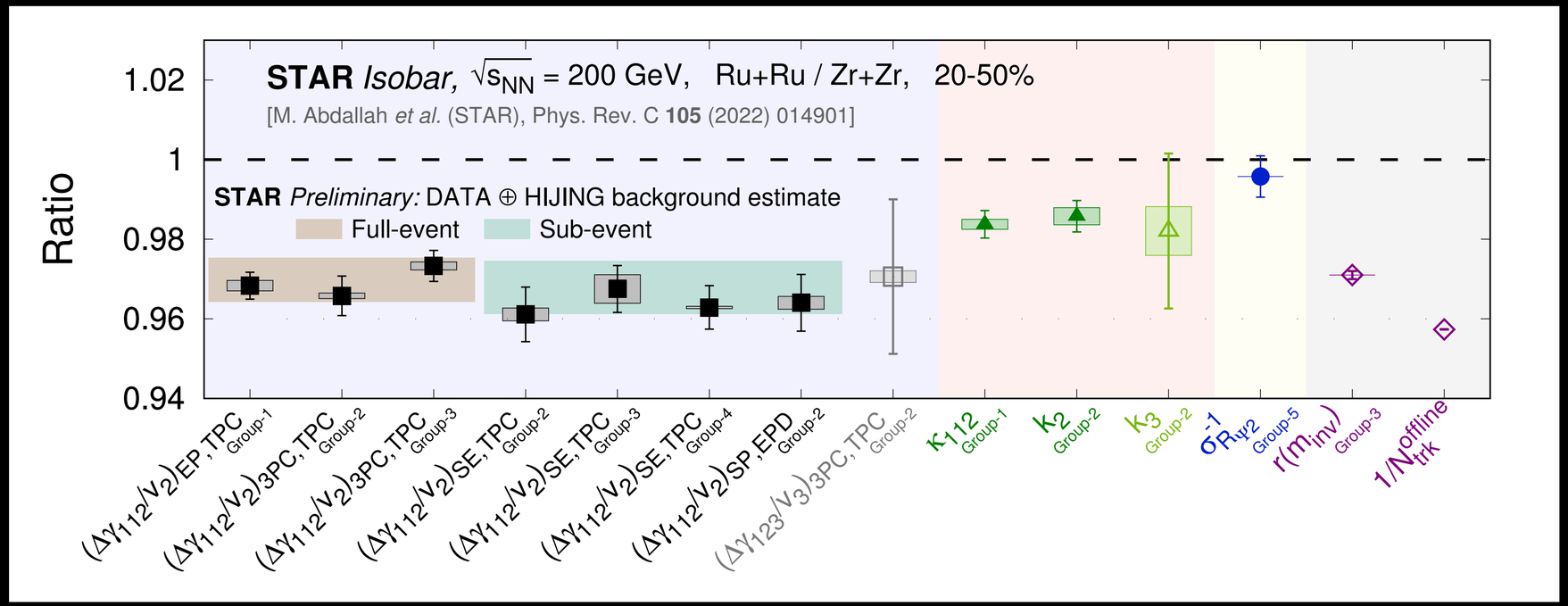
Summary

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

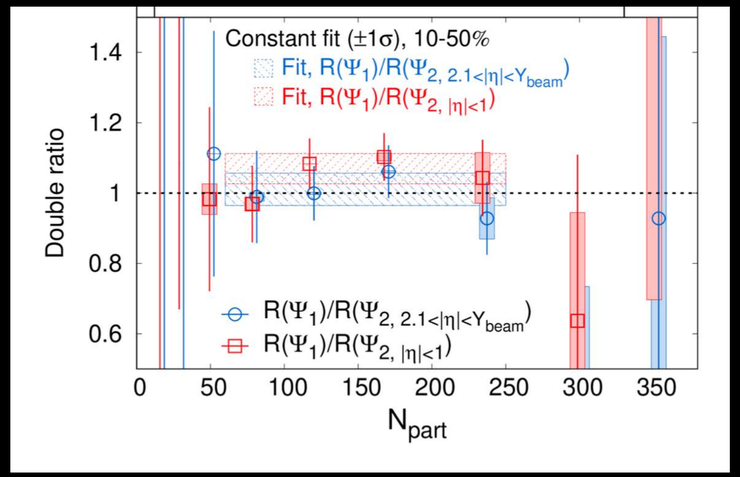
Primary CME observable $\Delta\gamma/v_2$ baseline is affected by the multiplicity difference (4% in 20-50%), post-blind analysis is needed to search for residual CME signal

Possible residual signal due to change of baseline & non-flow effects are under study

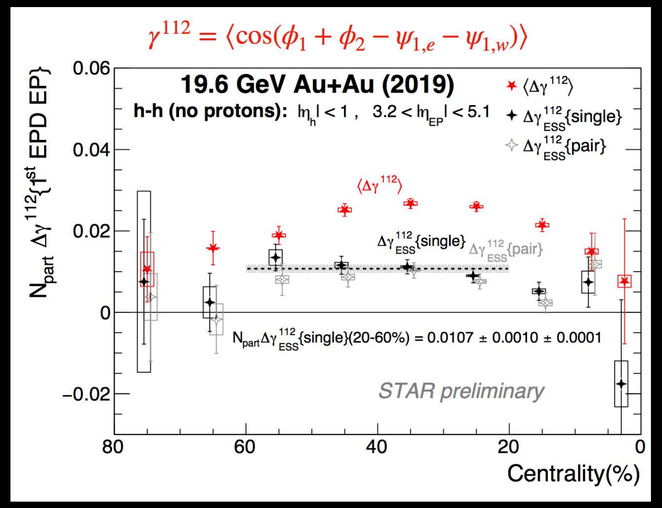


What is the future of CME search?

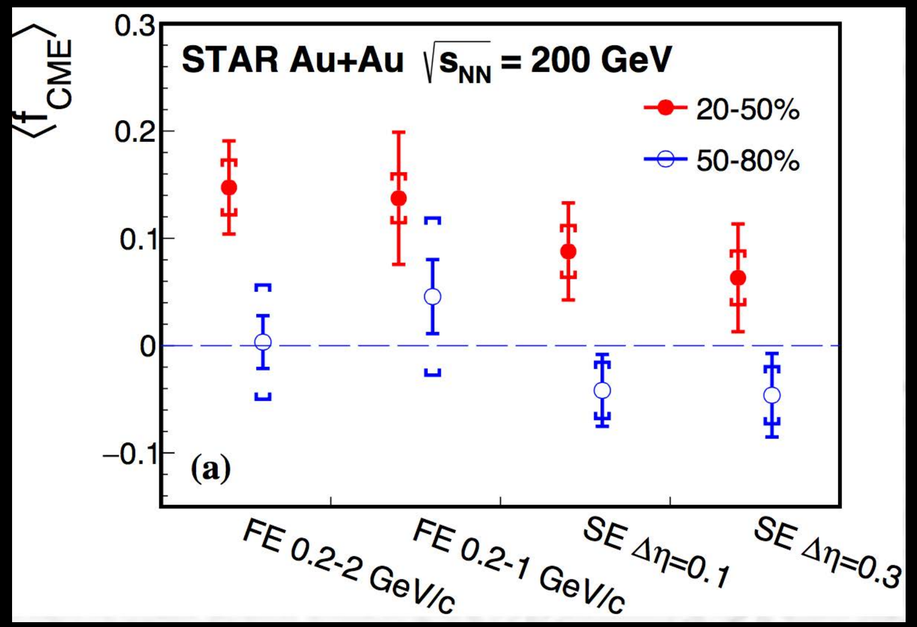
STAR EPD: better handle on B-field direction (2209.03467)



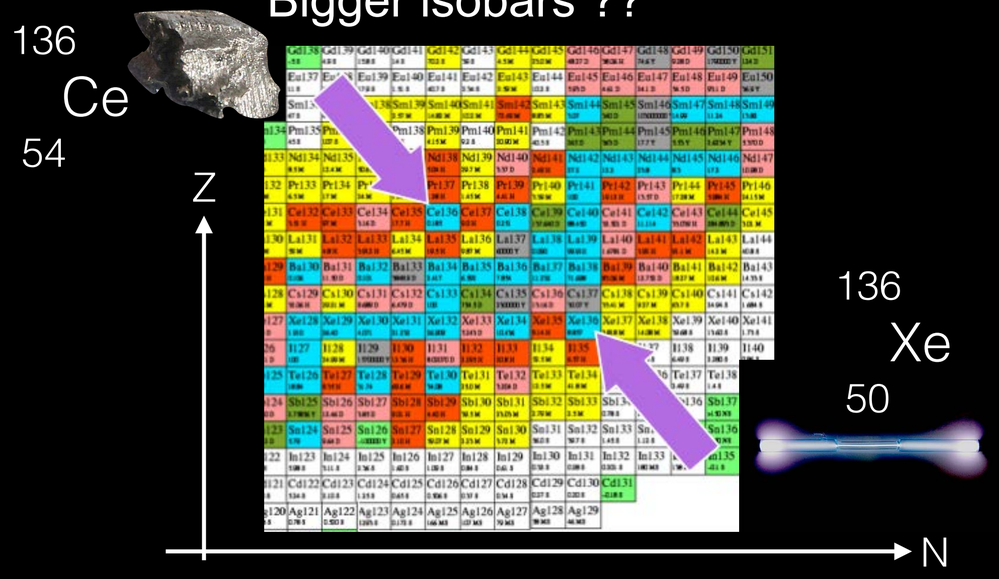
Event Shape Selection



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



Bigger isobars ??



CME search with AIML (2105.13761)