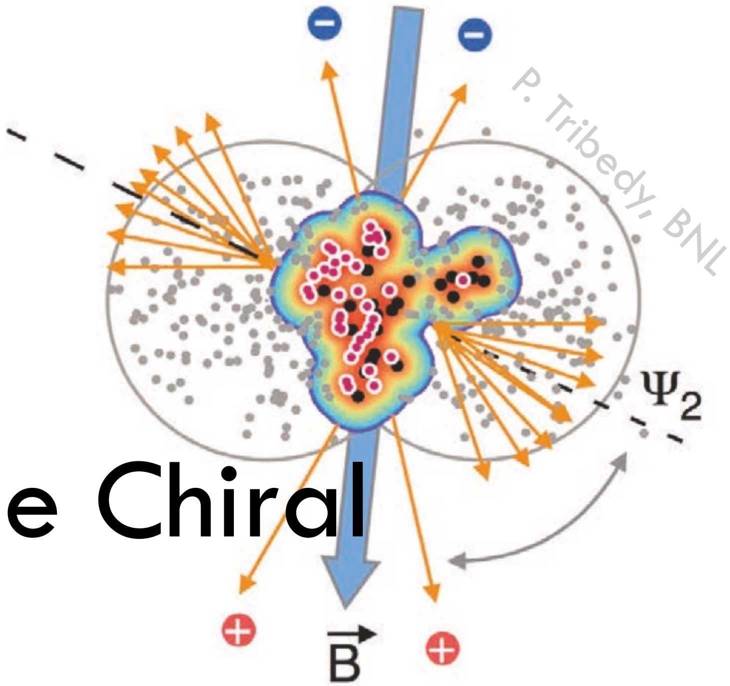
SQM2022
The 20th International Conference on Strangeness in Quark Matter
13-17 June 2022
Busan, Republic of Korea



Experimental Status of the Chiral Magnetic Effect

Evan Finch

Southern Connecticut State University

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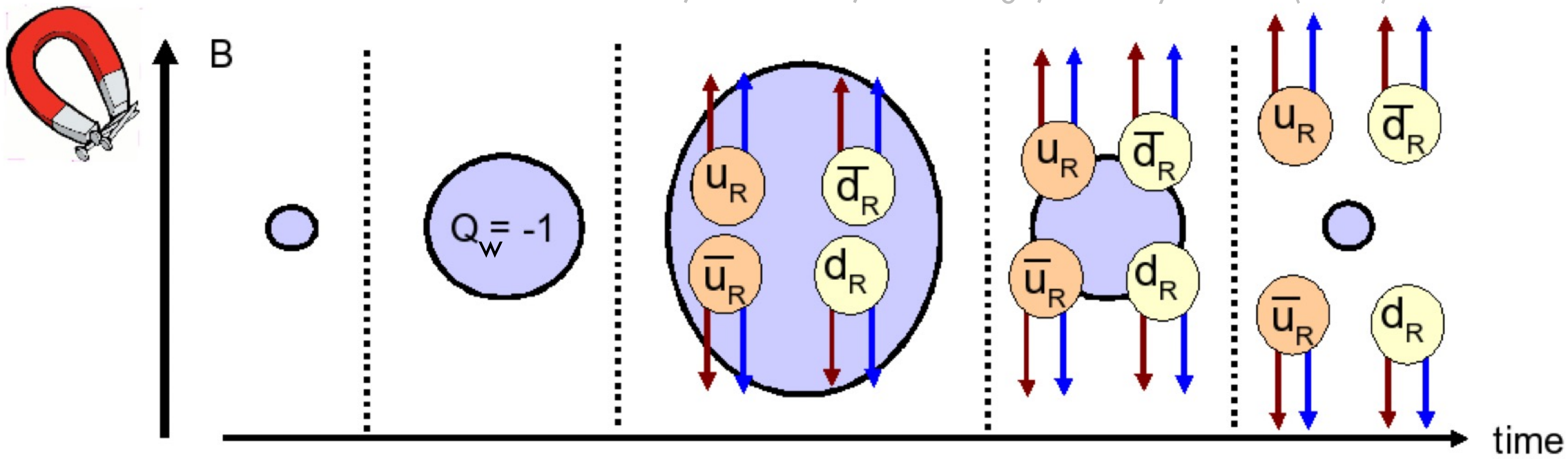
U.S. Department of Energy
Office of Science

SCSU

Chiral Magnetic Effect

D Kharzeev, L McLerran, H Warringa, Nucl Phys A 803 (2008)



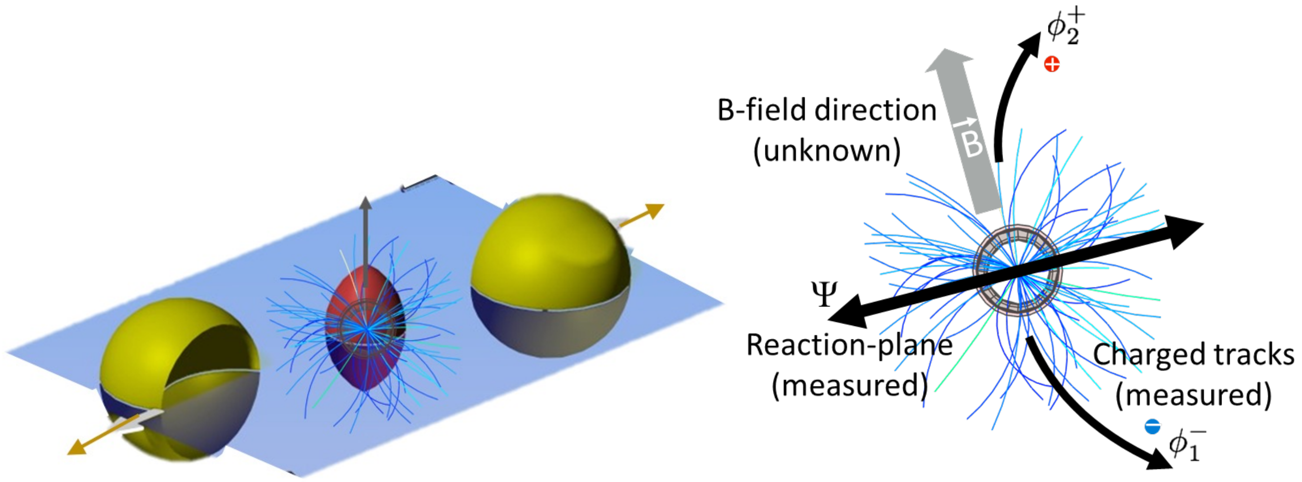
1) Chirality imbalance among all light quark flavor from topological fluctuations of gluon fields $(N_L^f - N_R^f) = 2Q_{\rm w}$ i.e. "Local Parity Violation"

D Kharzeev, R Pisarski, M Tytgat, PRL 81, 512 (1998)

2) Large magnetic field, generated mostly by spectator protons

Combine to give the CME: net electric charge flow along (or opposite to, depending on sign of Q_w in this event) the magnetic field direction

CME Sensitive Observables : $\Delta\gamma$

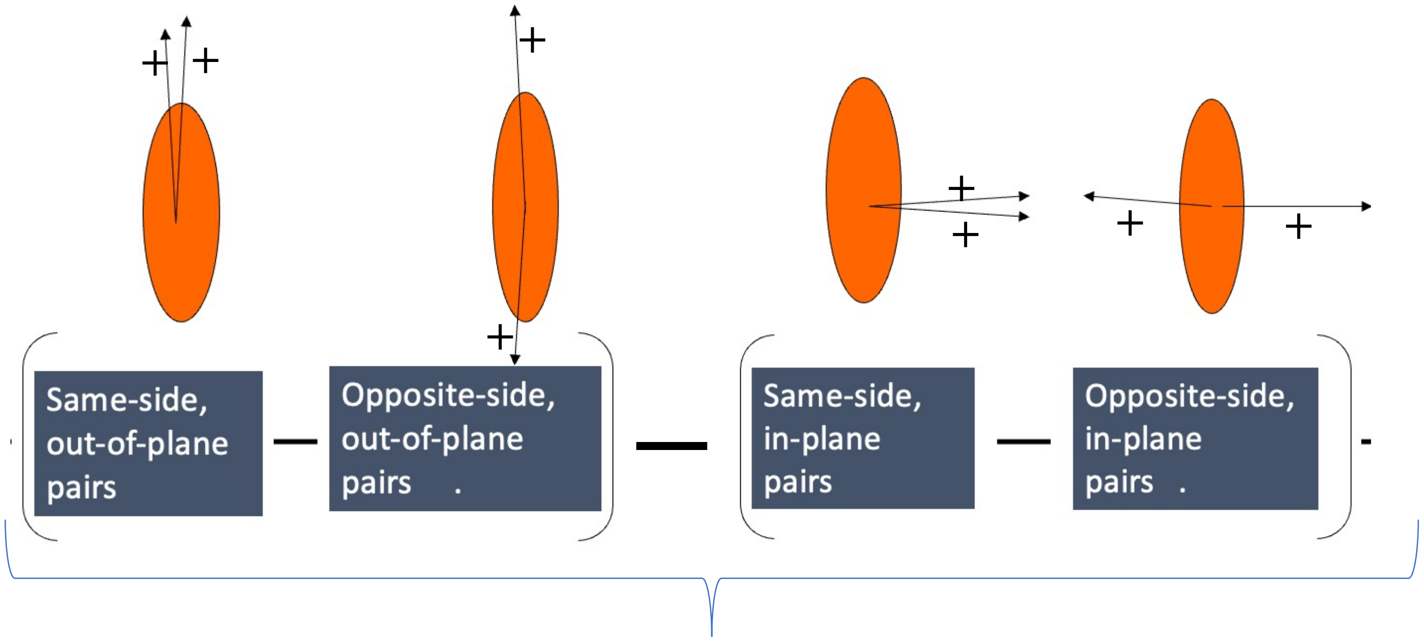


S. A. Voloshin, Phys. Rev. C 70, 057901 (2004)

$$\gamma^{\alpha,\beta} \equiv \langle cos(\phi^\alpha + \phi^\beta - 2\psi_2)\rangle$$

$$\Delta\gamma = \gamma^{OS} - \gamma^{SS}$$

2nd order event plane (1st order adds no more information here)!



$\Delta\gamma$: Same-sign pairs – Opposite-sign pairs

Key backgrounds:

- v_2+(clusters, local charge conservation)
- 3-particle correlations

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

If "flowing cluster" background dominates (it does!), $\Delta\gamma$ is "trivially" proportional to v_2 and 1/N .

CME Experimental “History”, 2009~2020

Initial CME measurements at RHIC, LHC

Significant signal in $\Delta\gamma$, goes away at lowest RHIC energies

STAR: PRL **103**, 251601 (2009), PRL **113**, 052302 (2014)
ALICE: PRL **110**, 012301 (2013)

Event shape engineering
ALICE: PLB777(2018)151
CMS: PRC97(2018)044912

Small systems
CMS: PRL 118 (2017) 122301
STAR: PLB 798 (2019) 134975

Higher harmonics comparisons
CMS: PRC 97 (2018) 044912

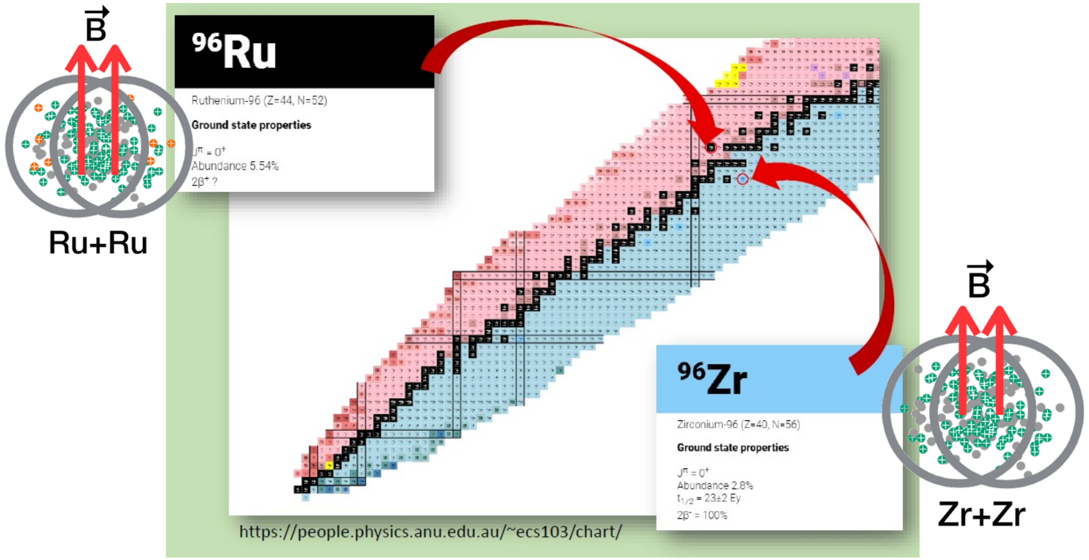
Theory work on “flowing clusters”

Local charge conservation backgrounds, models can reproduce signal reasonably well

S. Pratt, S. Schlichting and S. Gavin, PRC 84, 024909 (2011)
A. Bzdak, V. Koch and J. Liao, PRC 83, 014905 (2011)

In Mid-central Heavy Ions: $\Delta\gamma$ signal is dominated by “flowing clusters” background, at least at ~80% level

Experimental Search With Isobar Collisions



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

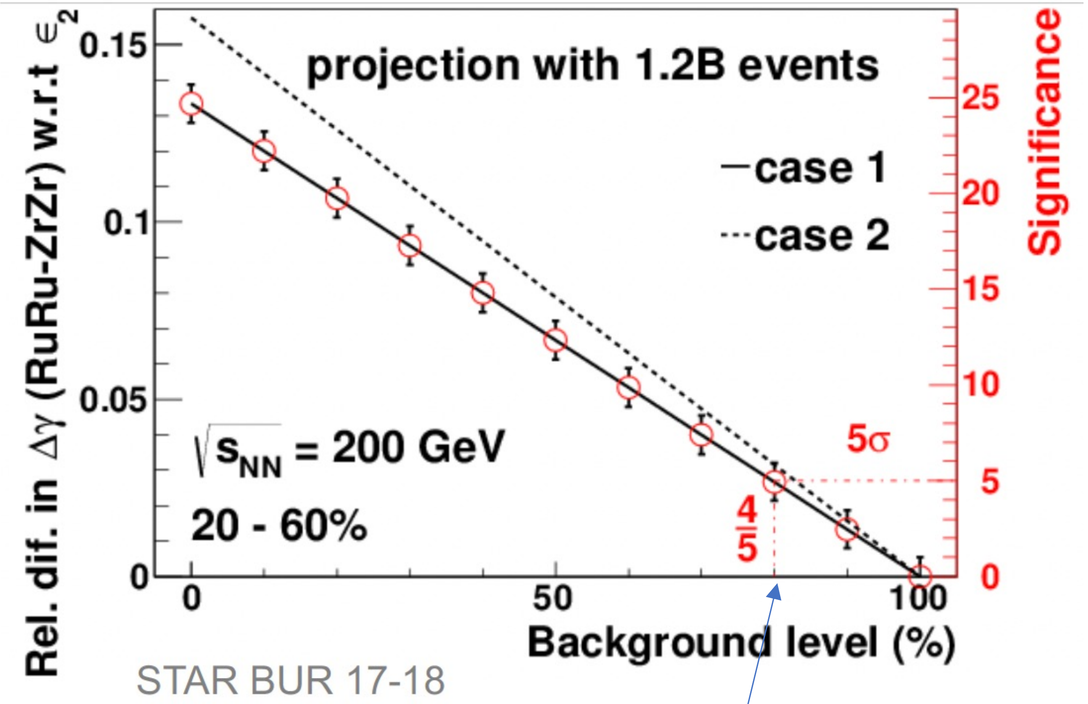
Measurement | Signal | "Flowing Clusters" Background | Smaller backgrounds

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

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

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

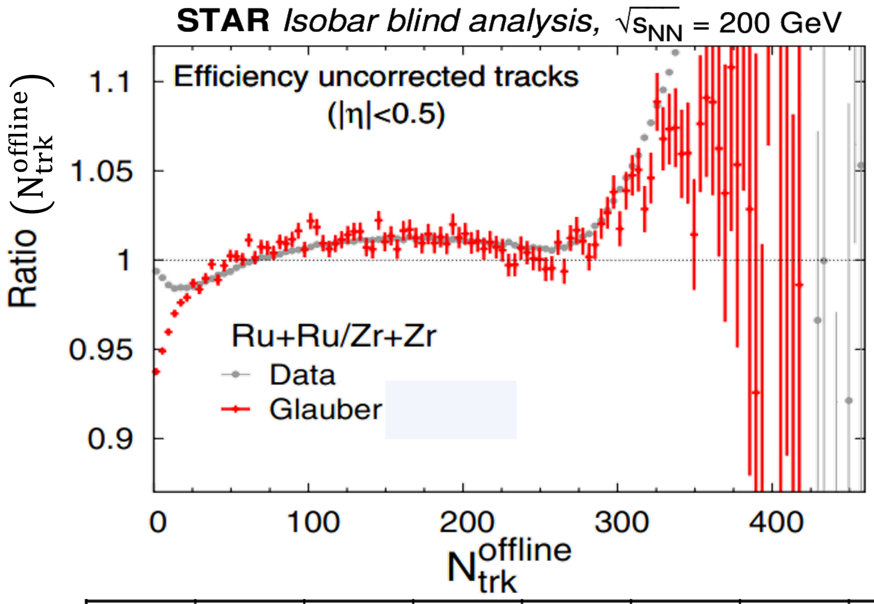
B^2 is ~15% different



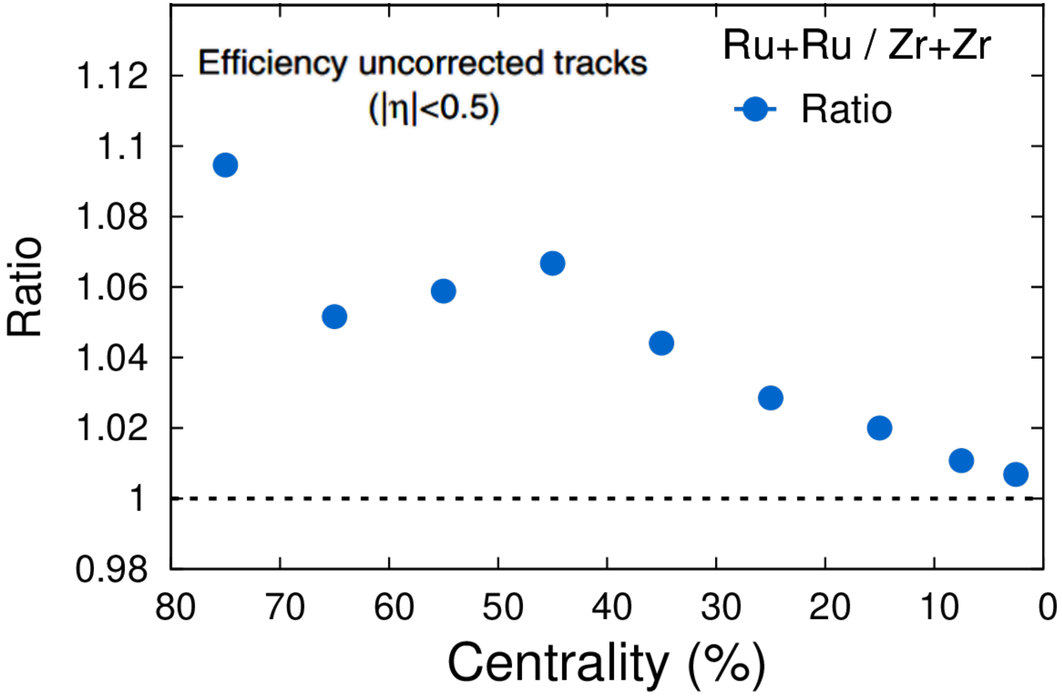
f_{CME}=20%

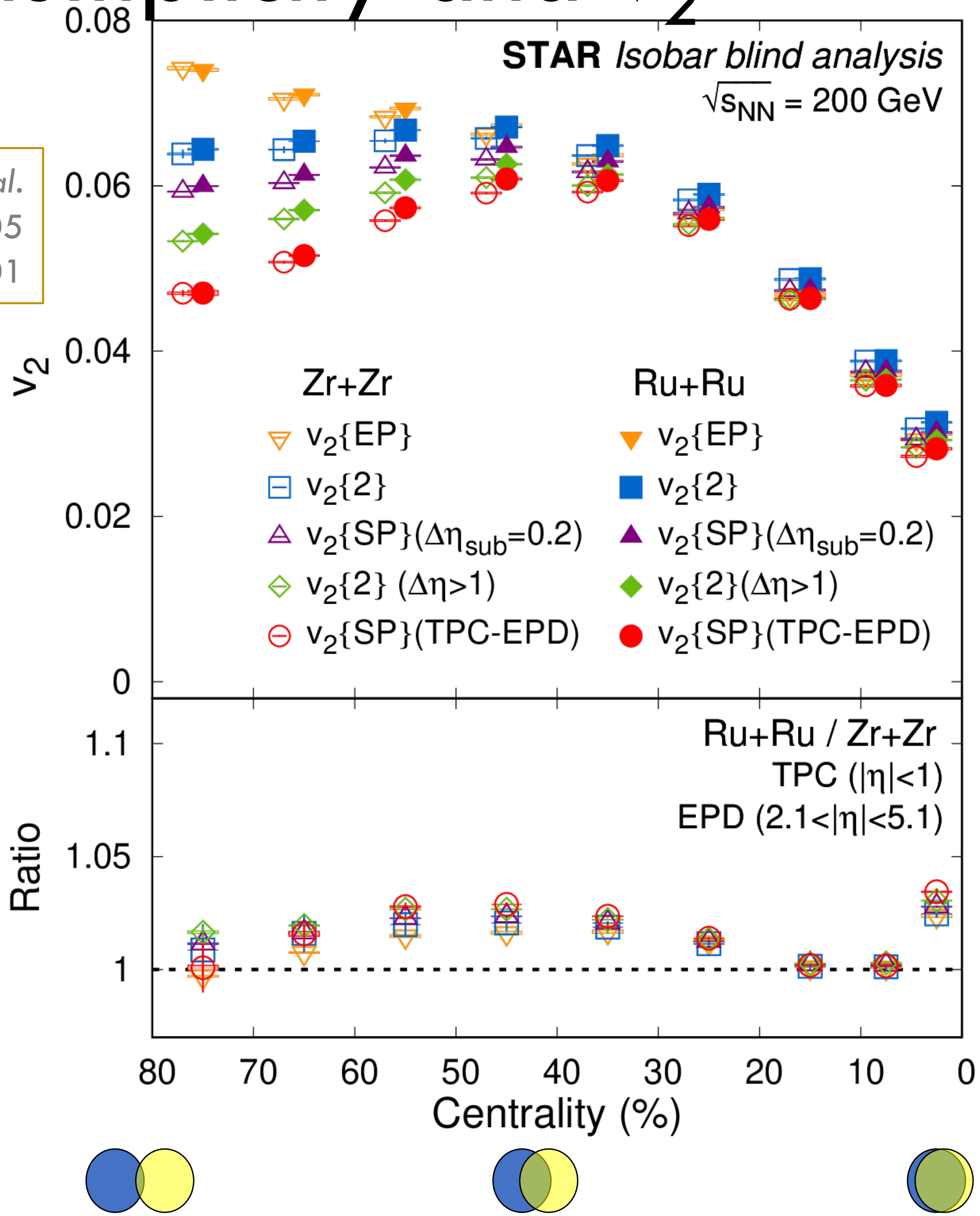
S. A. Voloshin, Phys. Rev. Lett. 105 (2010) 172301; W.-T. Deng, et al Phys. Rev. C94 (2016) 041901

STAR Isobar measurements: Multiplicity and v_2



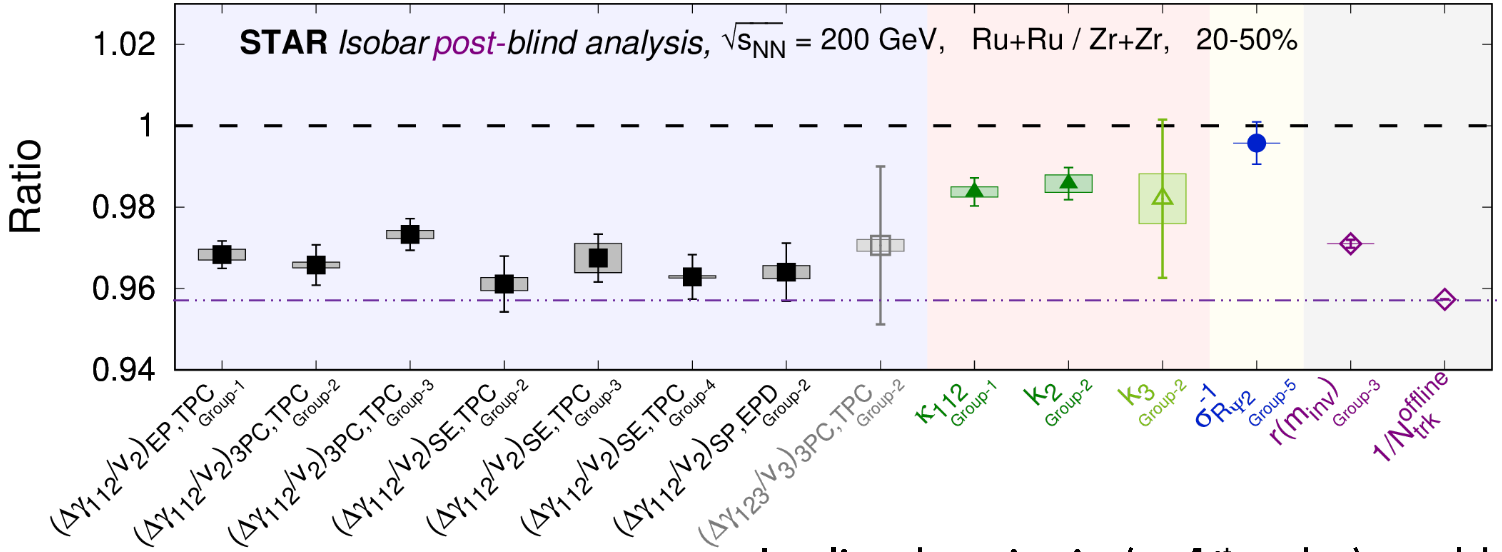
M. S. Abdallah *et al.* (STAR) PRC, 105 (2022) 014901





STAR Isobar Blind Analysis Results:

M. S. Abdallah *et al.* (STAR) Phys. Rev. C, 105 (2022) 014901



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

Implies the criteria (to 1st order) would instead be: $\frac{(\Delta\gamma/v_2)_{Ru}}{(\Delta\gamma/v_2)_{Zr}} > \frac{(1/N)_{Ru}}{(1/N)_{Zr}}$

See also:
D Kharzeev, J Liao, S Shi arXiv:2205.00120

J Jia, G Wang, C Zhang - arXiv:2203.12654

From the blind analysis

- STAR pre-defined criteria for CME observation: $(\Delta\gamma/v_2)_{Ru} > (\Delta\gamma/v_2)_{Zr}$. in mid-central collisions
  - NOT OBSERVED (nor were any other pre-defined criteria.)
- $\Delta\gamma/v_2$ ratios are below unity - mainly driven by the multiplicity difference between the two isobars

M. S. Abdallah *et al.* (STAR) Phys. Rev. C, 105 (2022) 014901

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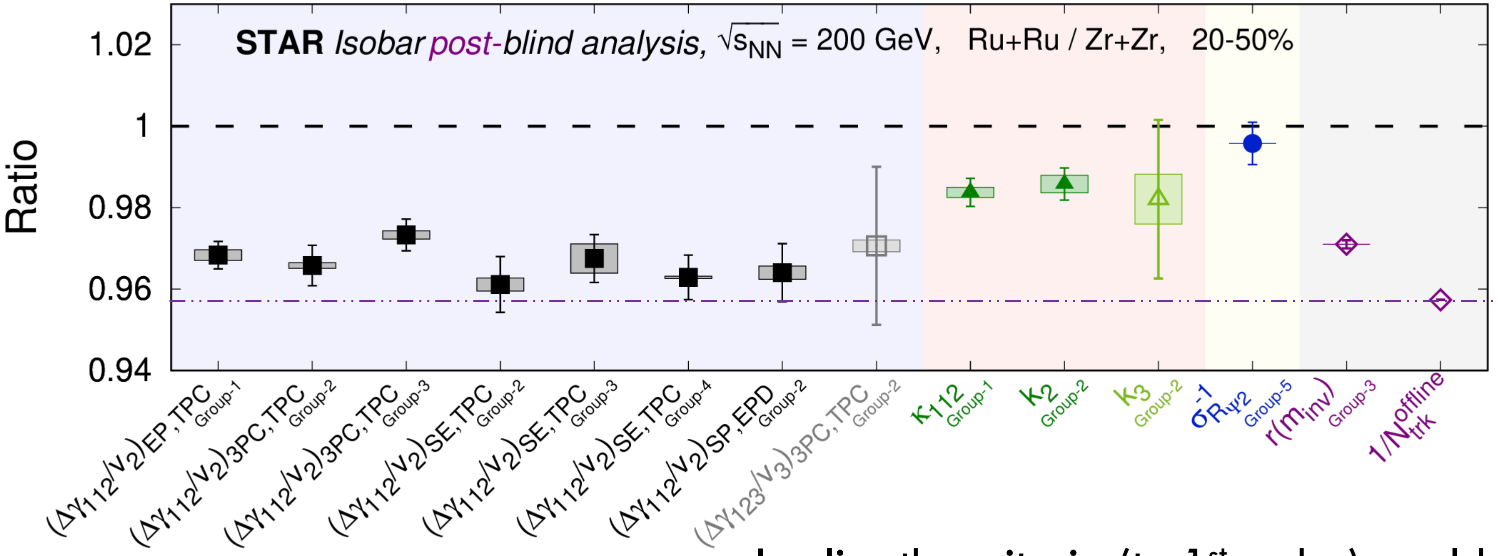

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Implies the criteria (to 1st order) would instead be: $\frac{(\Delta\gamma/v_2)_{Ru}}{(\Delta\gamma/v_2)_{Zr}} > \frac{(1/N)_{Ru}}{(1/N)_{Zr}}$

STAR Additional Correction: (PRELIMINARY)

$$\frac{(N\Delta\gamma/v_2^*)^{Ru}}{(N\Delta\gamma/v_2^*)^{Zr}} \approx 1 + \frac{\Delta\epsilon_2}{\epsilon_2} - \frac{\Delta\epsilon_{nf}}{1+\epsilon_{nf}} + \frac{\epsilon_3/\epsilon_2/(Nv_2^2)}{1+\epsilon_3/\epsilon_2/(Nv_2^2)}\left(\frac{\Delta\epsilon_3}{\epsilon_3} - \frac{\Delta\epsilon_2}{\epsilon_2} - \frac{\Delta N}{N} - \frac{\Delta v_2^2}{v_2^2}\right) = 1.012 \pm .003 \pm .005$$

$$\epsilon_2 = \langle\cos(\phi_a + \phi_b - 2\phi_{cluster})\rangle \frac{N_{2p} v_{2,2p}}{N v_2}$$

Flowing cluster background scales with N_{2p}/N^2

Estimated by measuring directly in data

$$\frac{\Delta\epsilon_2}{\epsilon_2} = (1.45 \pm .08)\%$$

$$\epsilon_{nf} = v_{2,nf}^2 / v_{2,true}^2$$

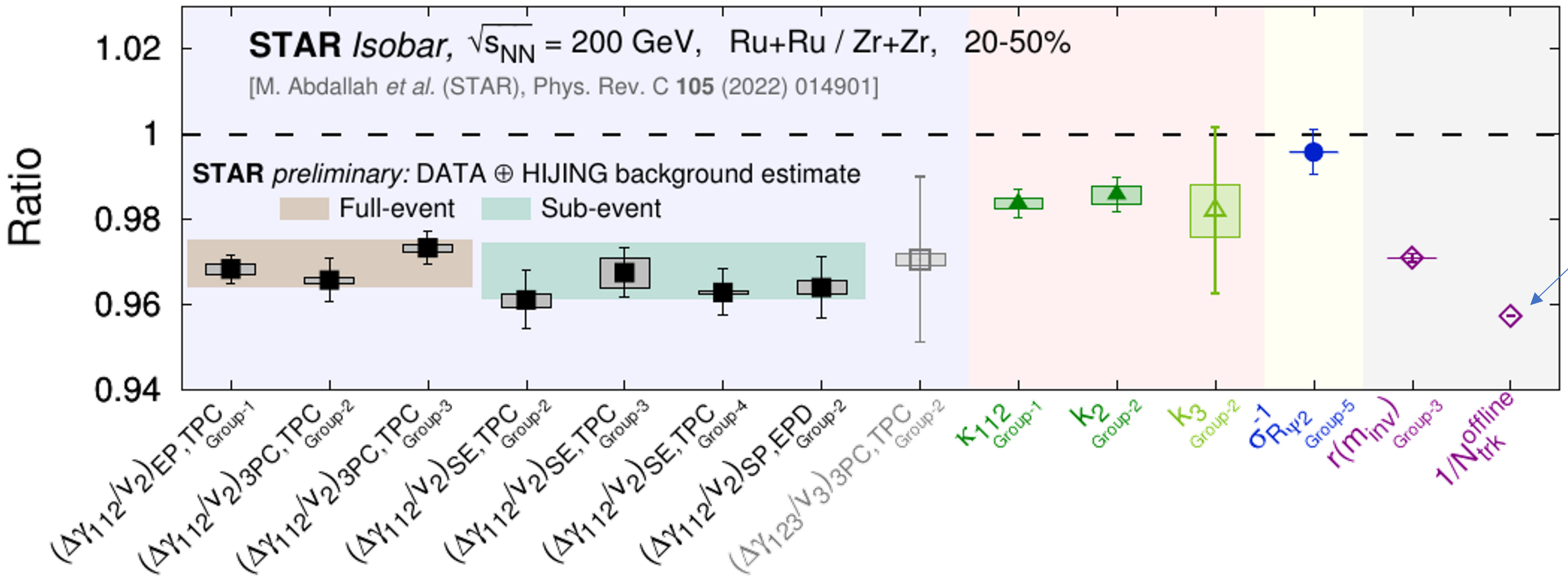
Estimation by 2-D decomposition of 2-particle correlations gives

$$\frac{-\Delta\epsilon_{nf}}{1+\epsilon_{nf}} = (0.65 \pm 0.11 \pm 0.22)\%.$$

Contribution of direct 3-particle correlations.

Estimation from HIJING gives $-(0.85 \pm 0.26 \pm 0.44)\%$

STAR Preliminary Isobar Background Estimate (Post-Blinding)



STAR preliminary: multiply this point by 1.0125 to give center of "full event" BG estimate band

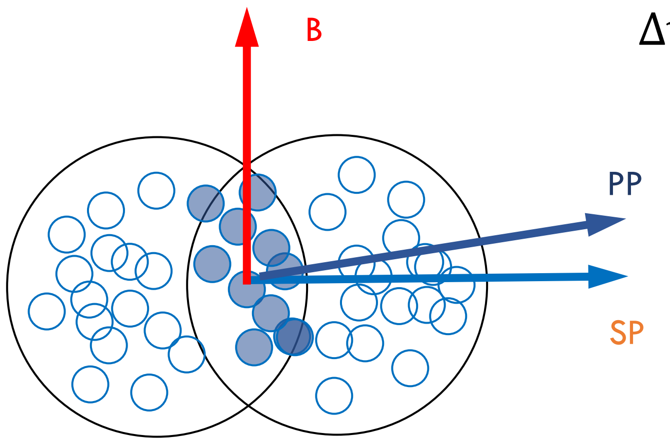
STAR preliminary background estimate:

$$\frac{(N\Delta\gamma/v_2^*)^{\text{Ru}}}{(N\Delta\gamma/v_2^*)^{\text{Zr}}} \approx 1.0125 \pm .003 \pm .005$$

$\Delta\gamma$ results consistent with STAR preliminary background estimate within current uncertainty.

Crucial to nail down this background estimate to make full use of isobar precision!

200 GeV Au-Au Data, Using Participant and Spectator Planes



PP(TPC) : maximum background
SP(ZDC-SMD) : maximum signal

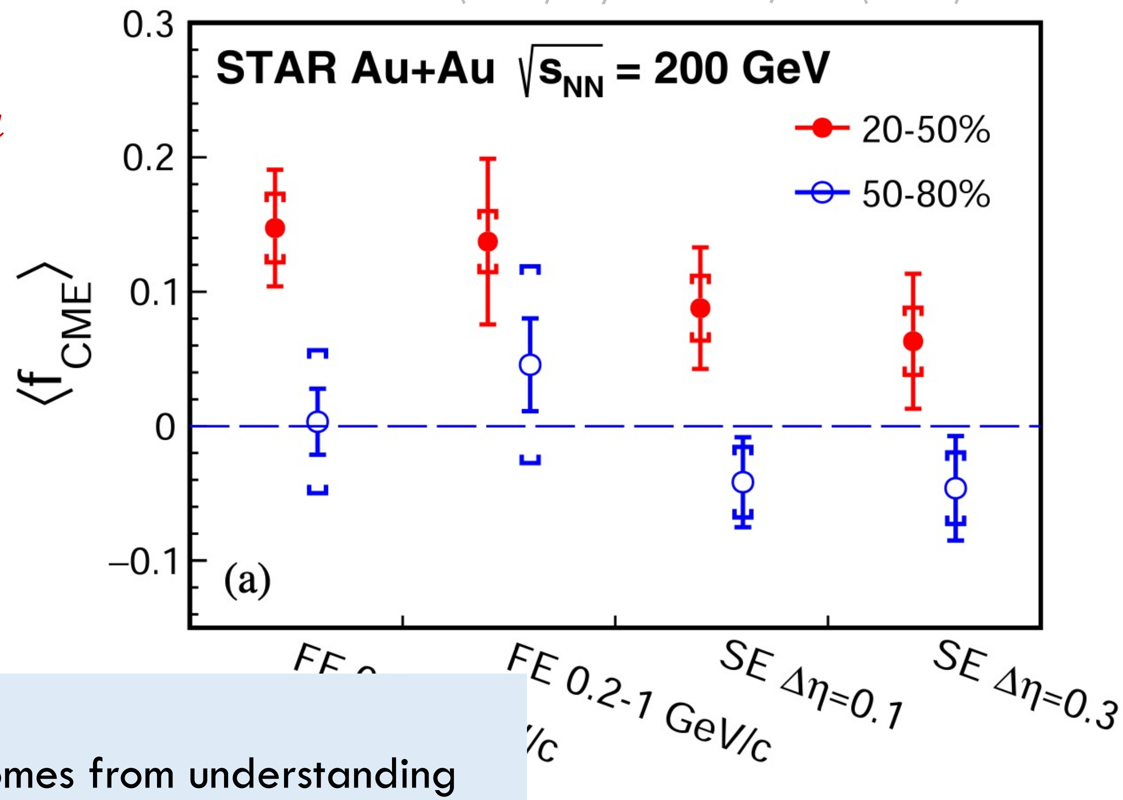
$$\Delta\gamma\{PP\} = \Delta\gamma_{CME}\{PP\} + \Delta\gamma_{BKG}\{PP\}$$
$$\Delta\gamma\{SP\} = \Delta\gamma_{CME}\{PP\}/a + \Delta\gamma_{BKG}\{PP\}a$$

$$a = \langle \cos 2(\Psi_{PP} - \Psi_{SP}) \rangle$$

$$f^{PP}_{CME} = \frac{\frac{\Delta\gamma\{SP\}}{\Delta\gamma\{PP\}}/a - 1}{1/a^2 - 1}$$

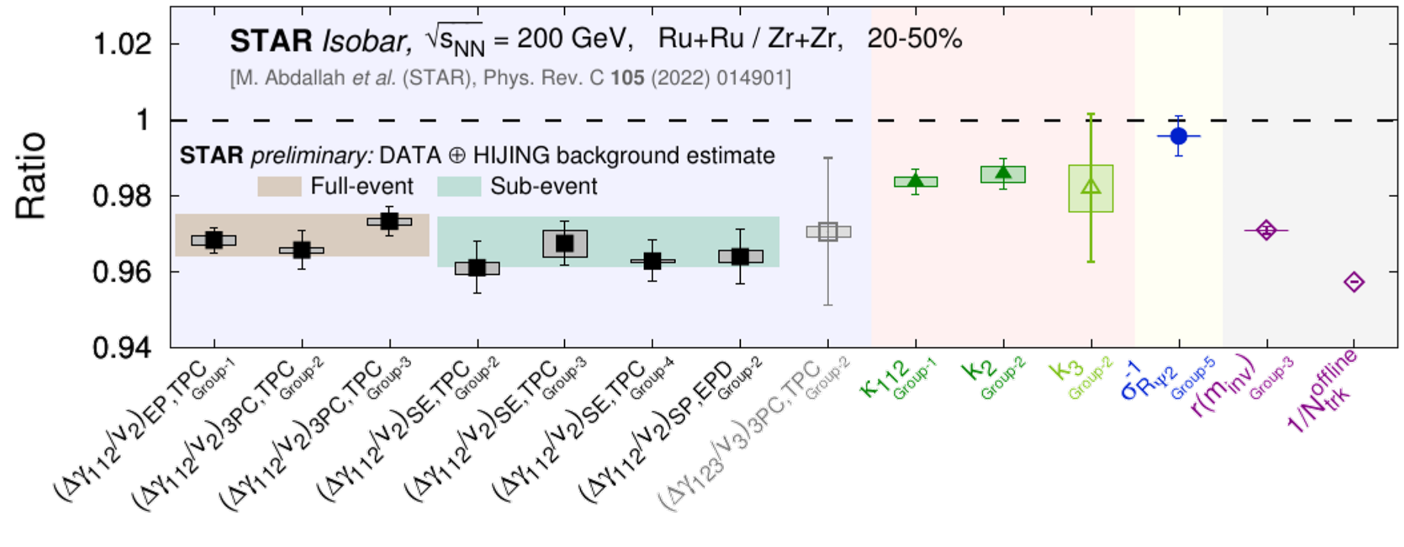
H-J. Xu, et al, CPC 42 (2018) 084103; S. A. Voloshin, Phys. Rev. C 98 (2018) 054911

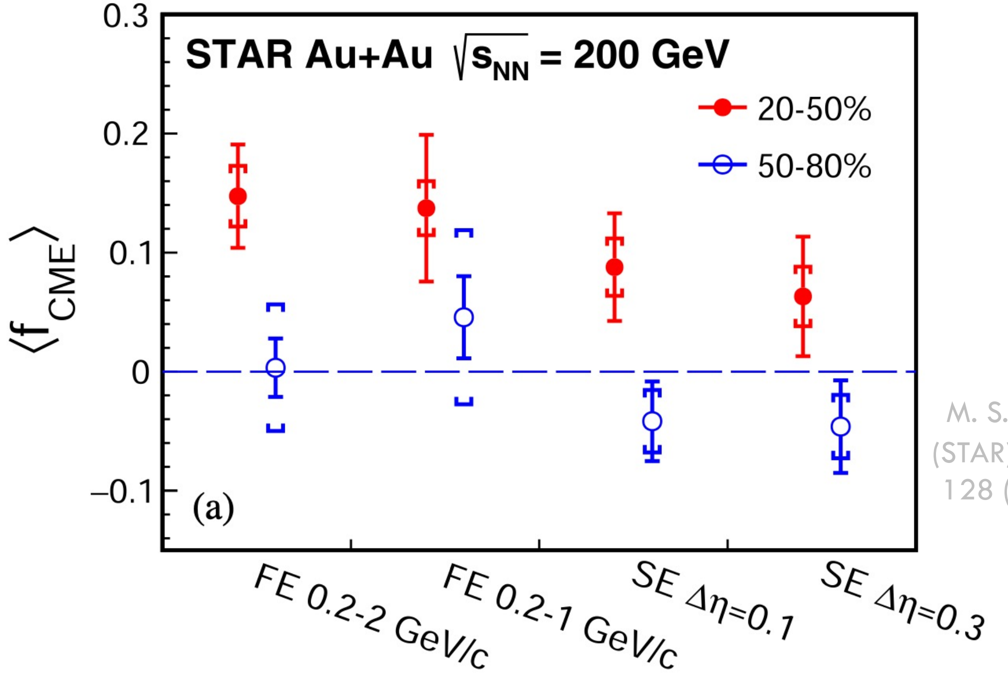
M. S. Abdallah *et al.* (STAR) Phys. Rev. Lett, 128 (2022) 092301



- As with isobar result, we're at the level where quantitative progress comes from understanding non-flow background.
- If we takes this as $f_{CME} \approx 10\%$ can we reconcile this f_{CME} in Au-Au with isobar results? In isobar system, smaller B-field ($\sim A^{1/3}$), larger $\Delta\gamma$ "flowing clusters" background ($\sim 1/A$) , would argue for a smaller f_{CME} in isobar compared to Au-Au. Y. Feng et. al., Phys. Lett. B820 (2021) 136549
- This method is an important target for future high-statistics AuAu RHIC runs.

Mid-Talk Summary: Current Experimental Status of CME





M. S. Abdallah et al. (STAR) Phys. Rev. Lett, 128 (2022) 092301

Isobar post-blinding: $\Delta\gamma$ results consistent with STAR preliminary background estimate within current uncertainty.

In 200GeV Au+Au data, spectator versus participant plane analysis shows signal 1-3σ above zero, fCME $\approx 10\%$

In both of these cases, crucial to understand non-flow effects.

Ideas for further analysis of isobars:
D Kharzeev, J Liao, S Shi arXiv:2205.00120

J Jia, G Wang, C Zhang - arXiv:2203.12654

R_{Ψ_2} correlator

N. Magdy *et al.* Phys. Rev. C, 97 (2018) 061901

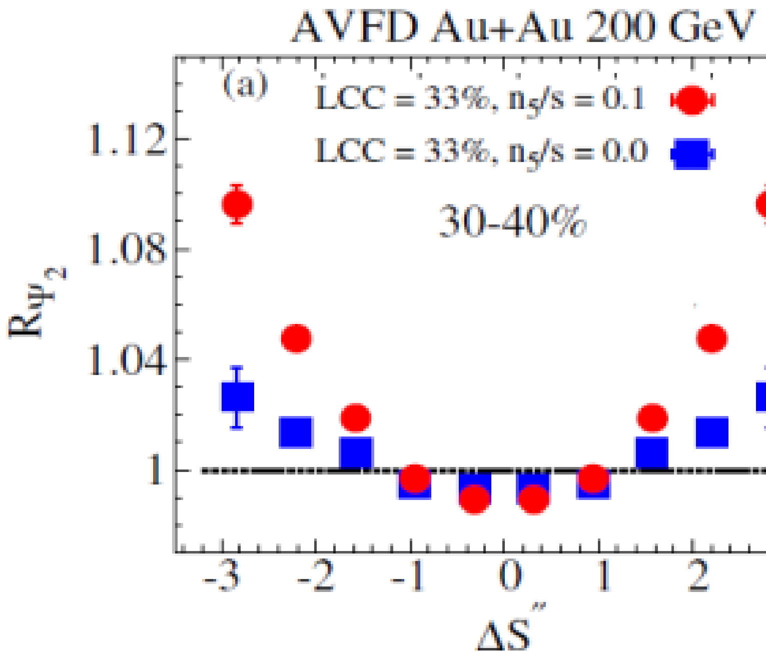
$$R_{\Psi_2}(\Delta S) = C_{\Psi_2}(\Delta S)/C^{\perp}_{\Psi_2}(\Delta S)$$

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

$$\Delta S = \left\{ \frac{\sum_{i=1}^{n+} w_i^+ \sin(\phi_i - \psi_2)}{\sum_{i=1}^{n+} w_i^+} - \frac{\sum_{i=1}^{n-} w_i^- \sin(\phi_i - \psi_2)}{\sum_{i=1}^{n-} w_i^-} \right\}$$

σ_{Ψ_2} is the Gaussian width of the respective $R(\Delta S'')$

Measurement of the in-plane and out-of-plane distributions of the dipole separation event-by-event



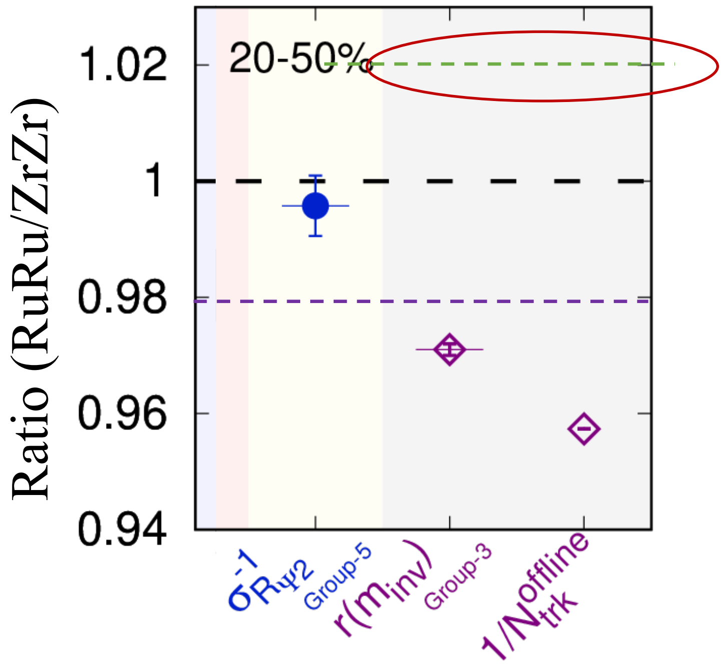
R. Lacey, SQM 2022

In studies with STAR frozen code for blind analysis, R_{Ψ_2} and $\Delta\gamma$ have similar sensitivities to CME signal and background.

Also determined algebraically: $1/\sigma^2_{R_{\Psi_2}} \approx N\Delta\gamma$

S. Choudhury *et al.* Chin. Phys. C, 46 (2022) 014101

STAR: R_{ψ_2} isobar measurement, how to interpret?



Pre-defined CME criterion in blind analysis:

$1/\sigma_{\psi_2}^{\mathrm{Ru+Ru}} > 1/\sigma_{\psi_2}^{\mathrm{Zr+Zr}}$ Not observed

1st order correction to background estimate for trivial v_2 and N dependence ?

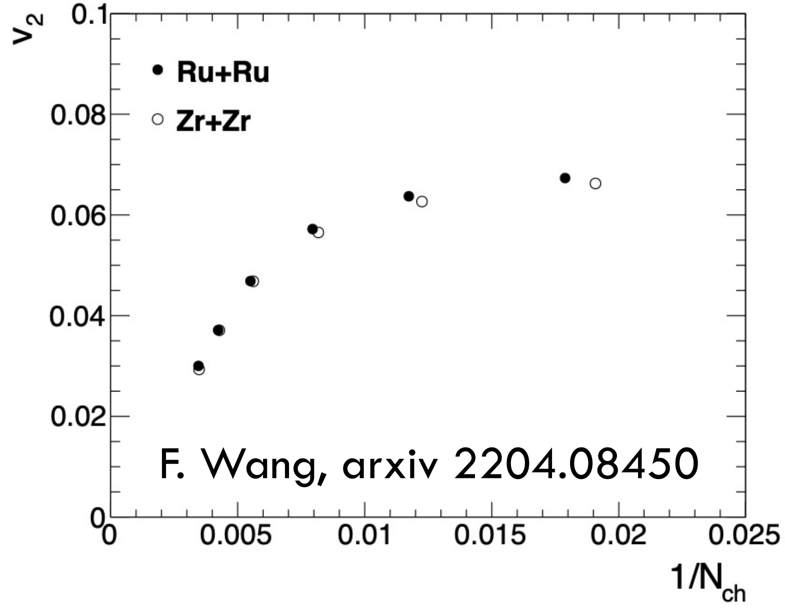
S. Choudhury *et al.* Chin. Phys. C, 46 (2022) 014101:

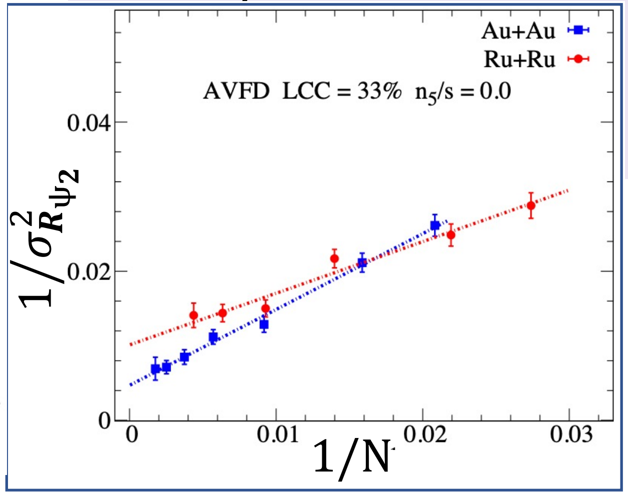
$$1/\sigma^2_{R_{\psi_2}} \approx N\Delta\gamma \longrightarrow 1/\sigma^2_{R_{\psi_2}}\ \alpha\ v_2 \longrightarrow \text{"background level"} = 1.02$$

"Correct" 1st-order background estimate. Can we determine non-flow contribution?

R. Lacey et. al. arXiv:2203.10029 :

$$1/\sigma^2_{R_{\psi_2}}\ \alpha\ 1/N \longrightarrow \text{"background level"} = 0.98$$





STAR Isobar: κ_{112} and γ_{123}

M. S. Abdallah *et al.* (STAR) Phys. Rev. C, 105 (2022) 014901

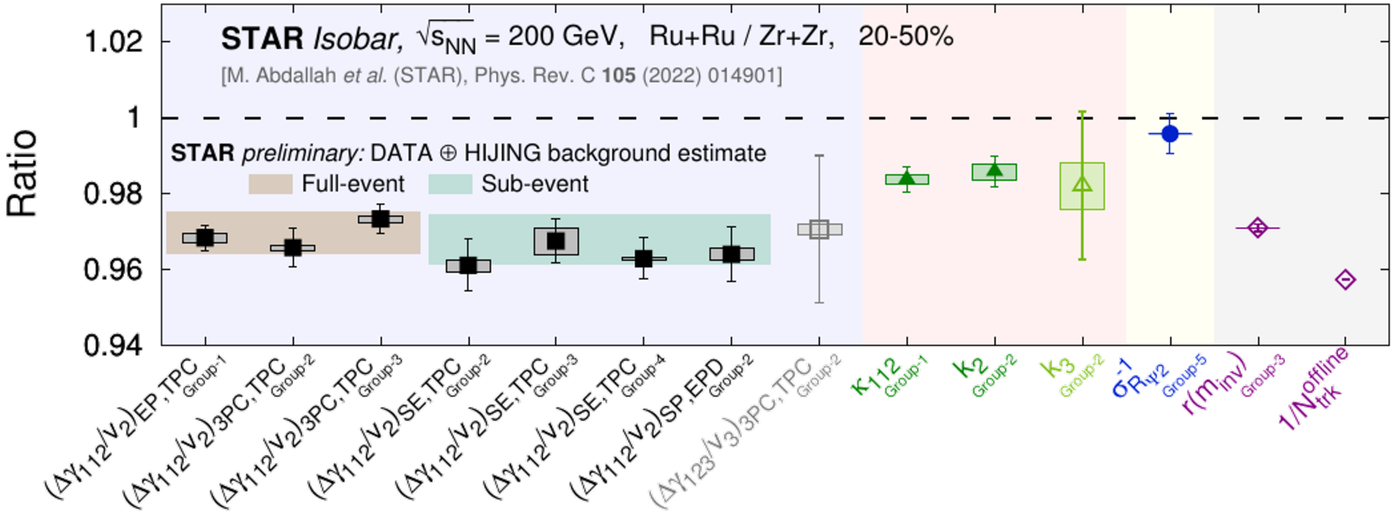
Pre-defined CME criteria:

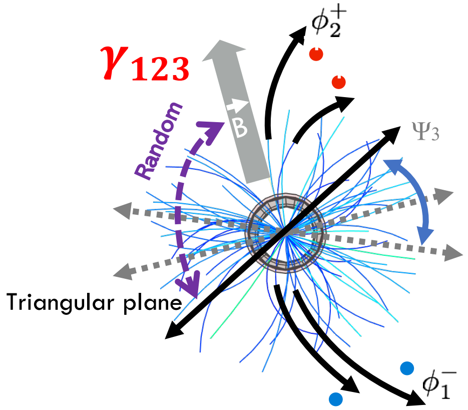
$$\frac{(\Delta\gamma_{112}/v_2)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{112}/v_2)^{\mathrm{Zr+Zr}}} > \frac{(\Delta\delta)^{\mathrm{Ru+Ru}}}{(\Delta\delta)^{\mathrm{Zr+Zr}}}$$

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

Pre-defined CME criterion:

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



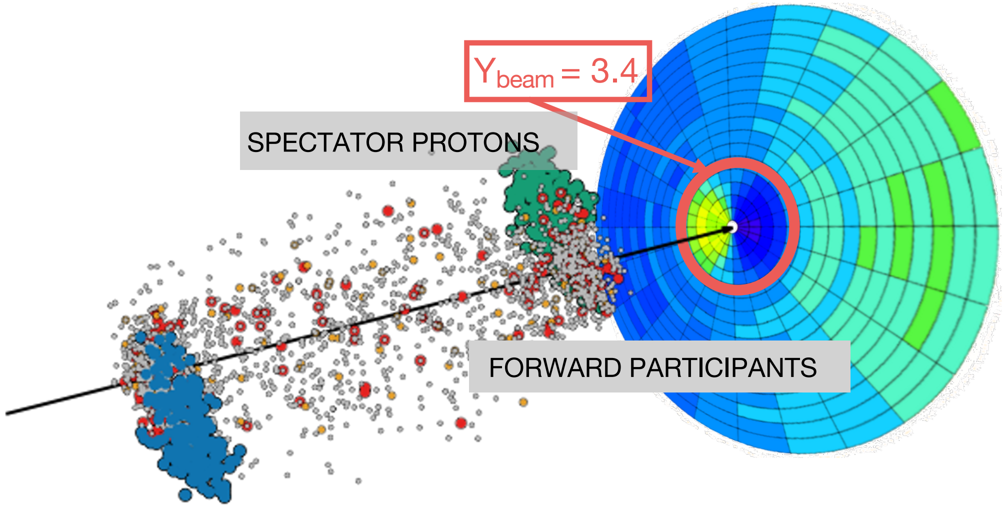


Pre-defined CME criterion:

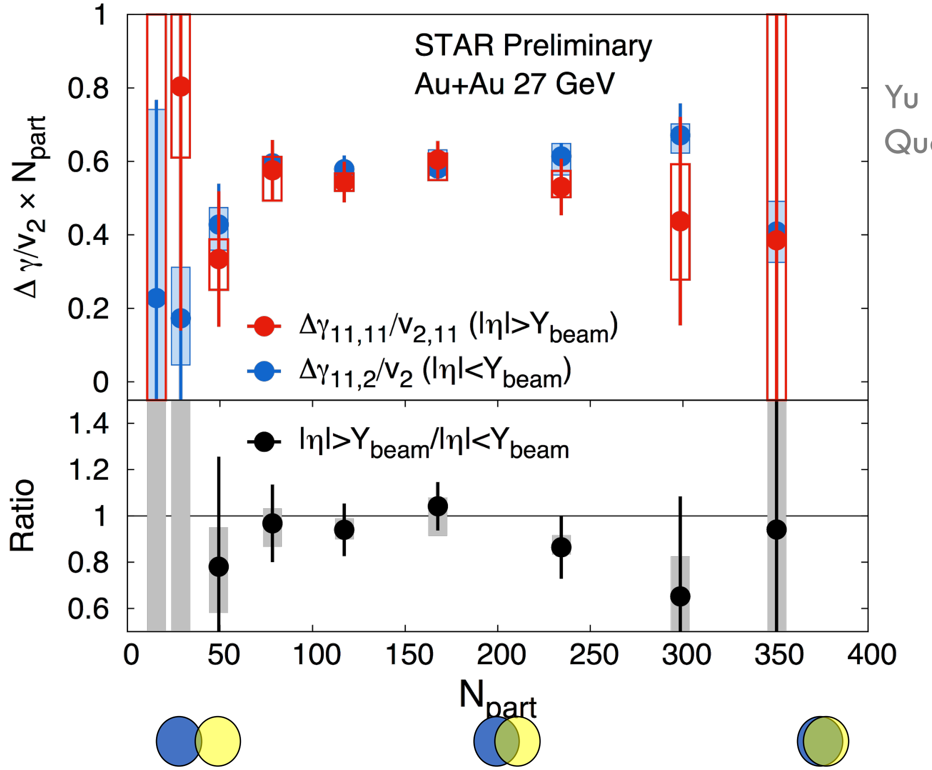
$$\frac{(\Delta\gamma_{112}/v_2)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{112}/v_2)^{\mathrm{Zr+Zr}}} > \frac{(\Delta\gamma_{123}/v_3)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{123}/v_3)^{\mathrm{Zr+Zr}}}$$

IN both cases: Data not compatible with pre-defined CME criterion
No 1st-order corrections for multiplicity difference

New Work: Measurement with STAR EPD @ 27 GeV



We measure the elliptic flow and the charge separation, using $\Delta\gamma$ w.r.t. **EPD-inner first harmonic plane** and the **EPD-outer second harmonic plane**.



Yu Hu (STAR)
Quark Matter 2022

$$\Delta\gamma = \Delta\gamma^{BG} + \Delta\gamma^{CME}$$

If $\Delta\gamma^{BG} = b\, v_2$

$$\left(\frac{\Delta\gamma}{v_2}\right) = \frac{\langle cos(\alpha + \beta - 2\Psi)\rangle}{\langle cos(2a - 2\Psi)\rangle}$$

RP, PP, SP…

Under a 'pure background' scenario, all these ratios are equal. If different measurements yield different ratios, this would indicate a CME signal.

The ratio of $\Delta\gamma/v_2$ between spectator-proton rich EPD Ψ_1 plane and participant-dominated Ψ_2 plane. CME-driven correlations will make this ratio >1.

S. A. Voloshin, Phys. Rev. C 98 (2018) 054911

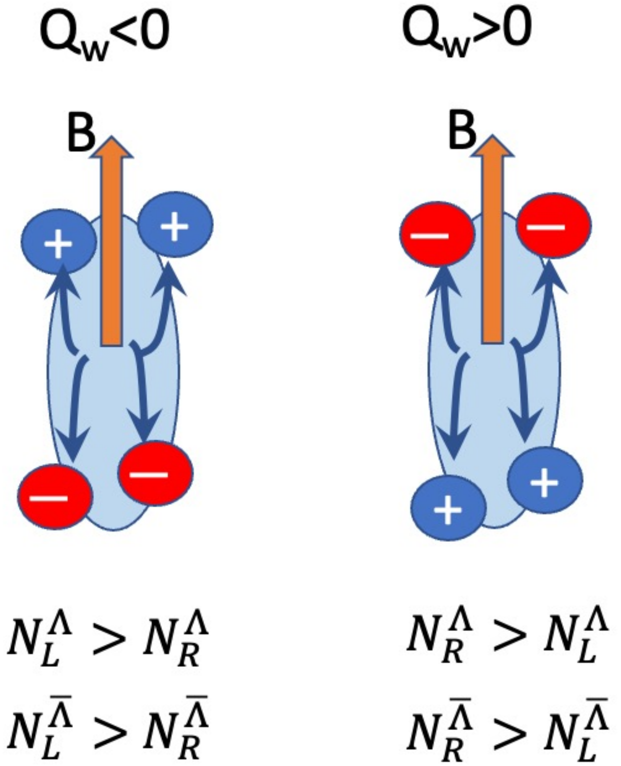
New Work: Correlations with Other Parity-Odd Signals (Λ helicity)

Another observable sensitive to Local Parity Violation is net helicity of Λs in each event.

F. Becattini *et al.* Phys.Lett.B 822 (2021) 136706
F. Du *et al.* Phys.Rev.C 78 (2008) 044908

In each event, sign of charge separation dipole and net helicity are both determined by same Q_w ! $(N_L^f - N_R^f) = 2Q_w$

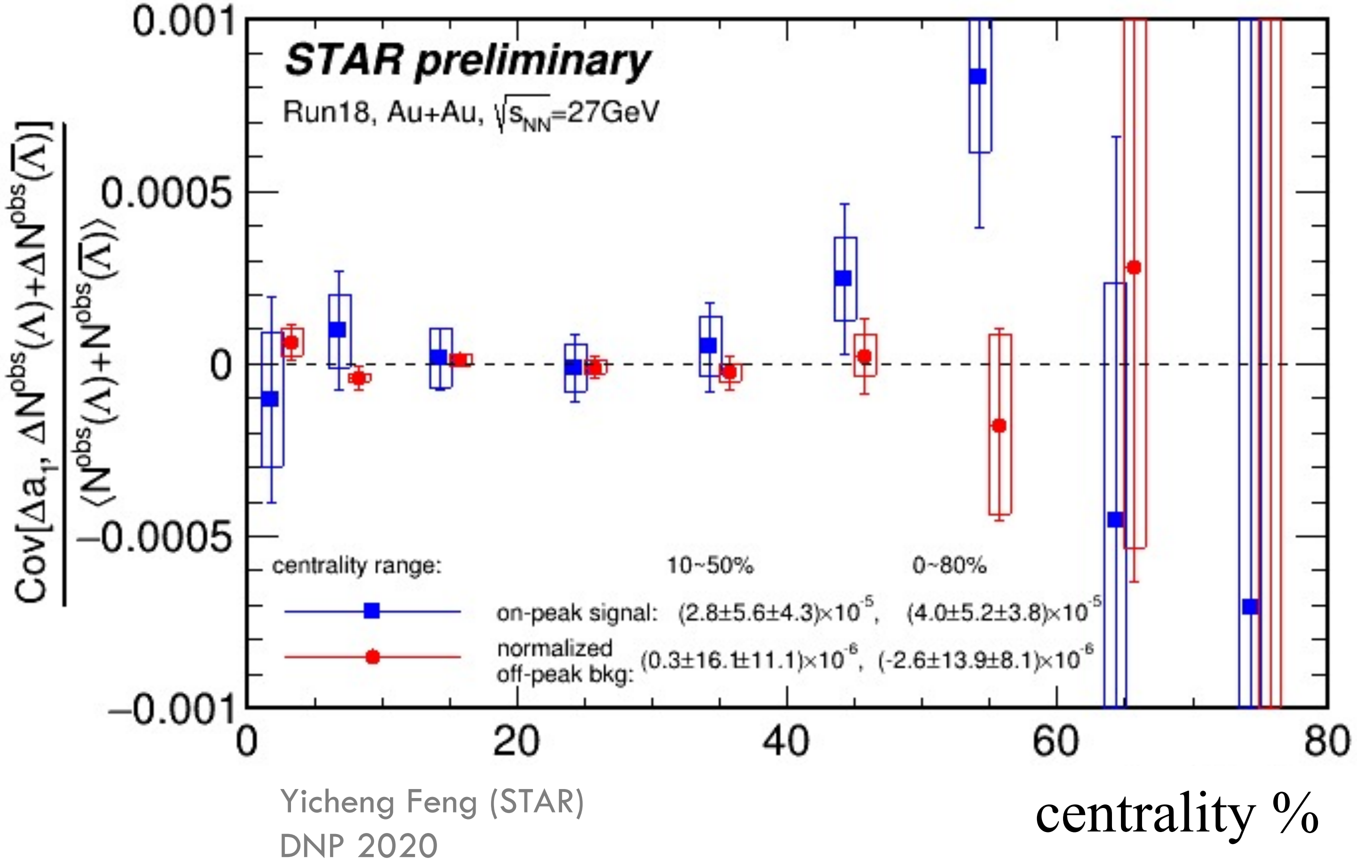
→In events where positive charges flow in B-field direction, expect $N_L^\Lambda - N_R^\Lambda > 0$



Can look for a correlation between sign of CME in each event and net handedness of Λ in that event. Two parity-odd observables with very different background sources (can also observe $\bar{\Lambda}$ as further systematics check and/or to increase statistical power)

Need 1st order event plane (STAR EPD or ZDC/SMD)

New Work: Correlations with Other Parity-Odd Signals (Λ helicity)



Yicheng Feng (STAR)
DNP 2020

$$a_1^{\pm} = \langle \sin(\phi_{\pm} - \Psi_{\mathrm{RP}}) \rangle \qquad \Delta N = N_L^{\Lambda} > N_R^{\Lambda}$$

$$\Delta a_1 = \frac{N_+}{N_+ + N_-} a_1^+ - \frac{N_-}{N_+ + N_-} a_1^-$$

In 27GeV Au+Au data, we use EPD for ψ_1

Measure covariance between

$a_1^+ - a_1^-$ and $N_L^{\Lambda} > N_R^{\Lambda}$

"positive charge flow along B-field"

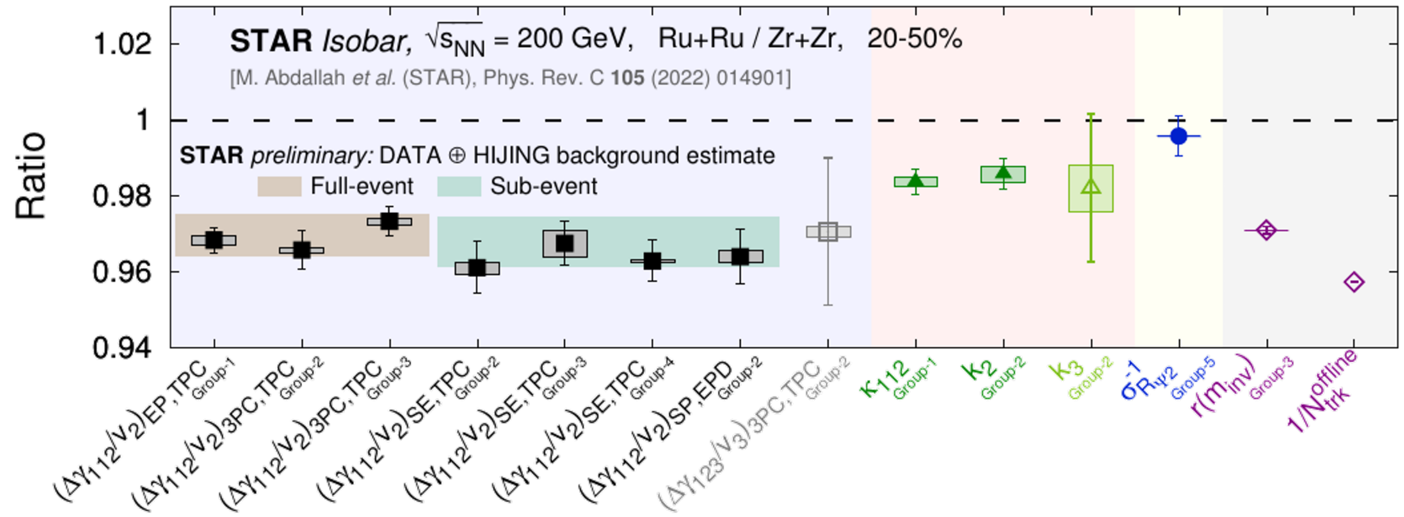
"Excess of left-helicity Λ"

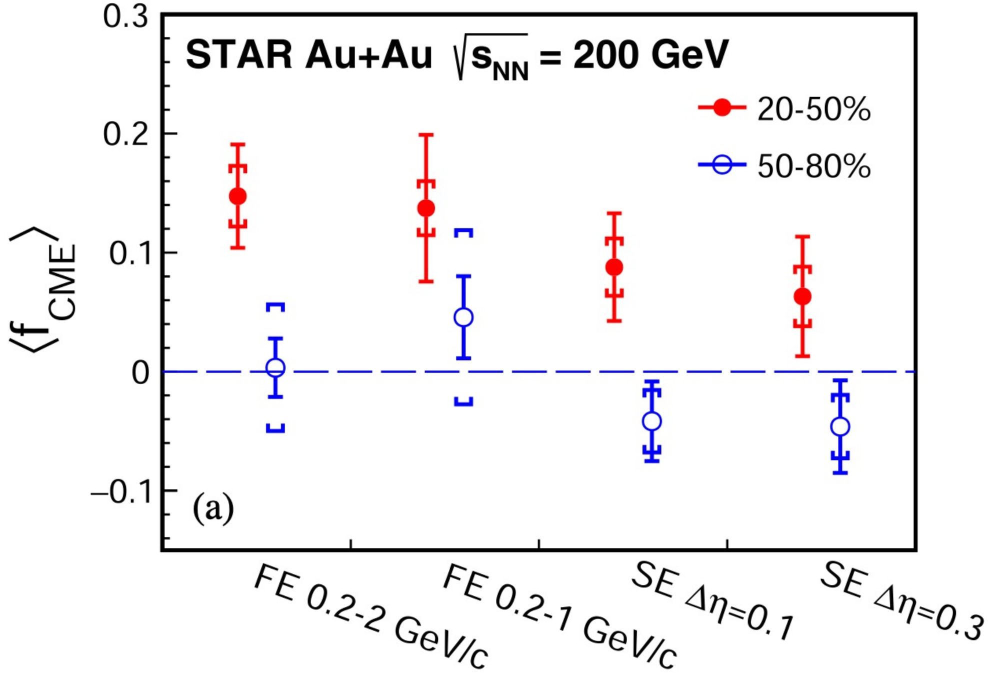
Positive covariance (blue points above zero, 20-60% centrality) would indicate presence of two parity-odd effects tied to local parity violation

In 27GeV run 18 data, signal consistent with zero within uncertainty

2022 STAR BUR: This method will be target for future high-statistics Au-Au runs.

Summary: Current Experimental Status of CME





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In 200GeV Au+Au data, spectator versus participant plane analysis shows signal 1-3σ above zero, $f_{CME} \approx 10\%$

In both of these cases, crucial to continue working on non-flow effects.

New methods in progress, including correlations with other local parity violation signals (net hyperon helicity)