STAR Group-3 results on CME in isobar collisions

Jie Zhao (for the STAR collaboration)

Nov. 1 2021

Purdue University

Supported in part by U.S. DEPARTMENT OF ENERGY | Office of Science

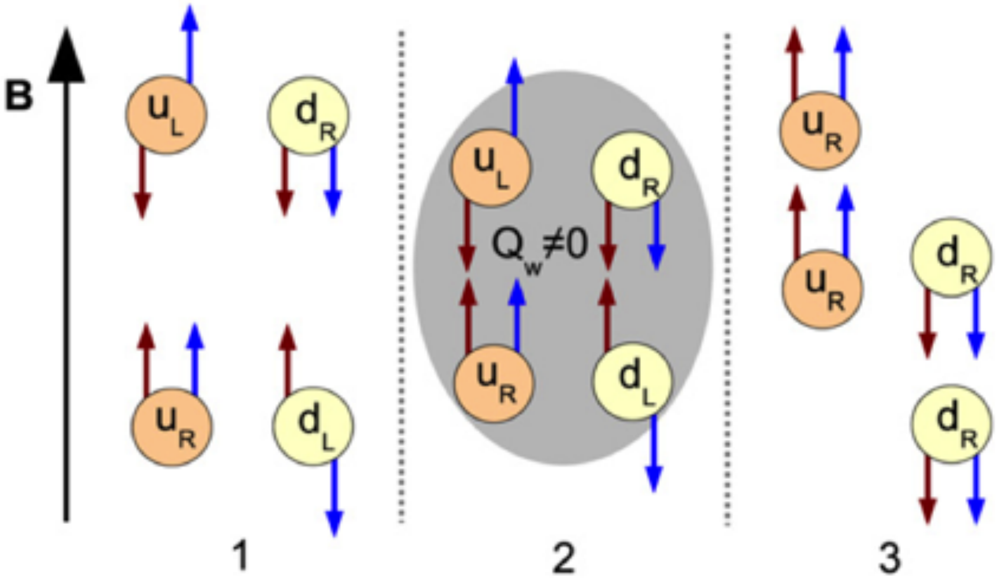
Outline

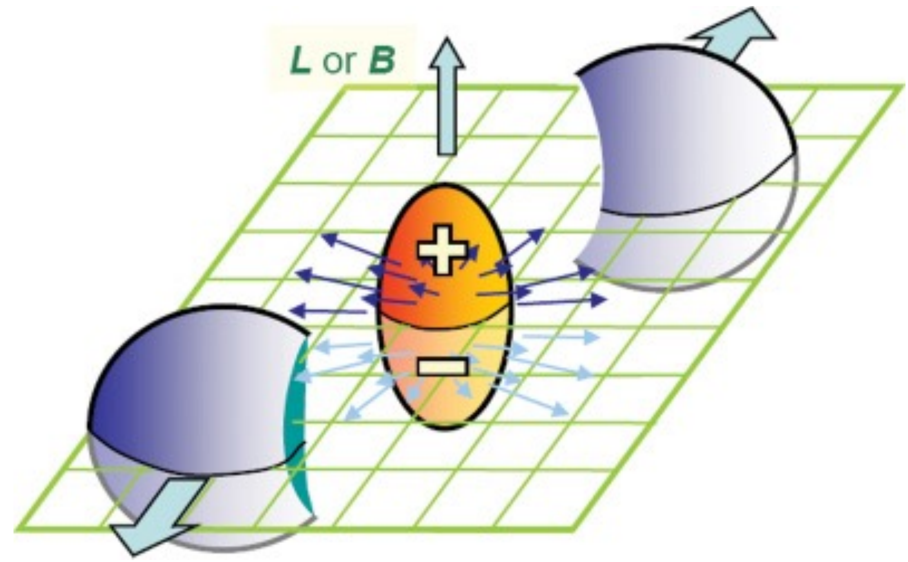
- **RHIC-STAR experiment**
- **Background issue**
- **Invariant mass dep. of the Δγ correlator**
- **Δγ with respect to Ψ_{RP} (ZDC) and Ψ_{PP} (TPC)**
- **Summary and outlook**

Ψ_{RP}: reaction plane ; Ψ_{PP}: participant plane

Chiral Magnetic Effect (CME)

Kharzeev, *et al*. NPA 803, 227 (2008)



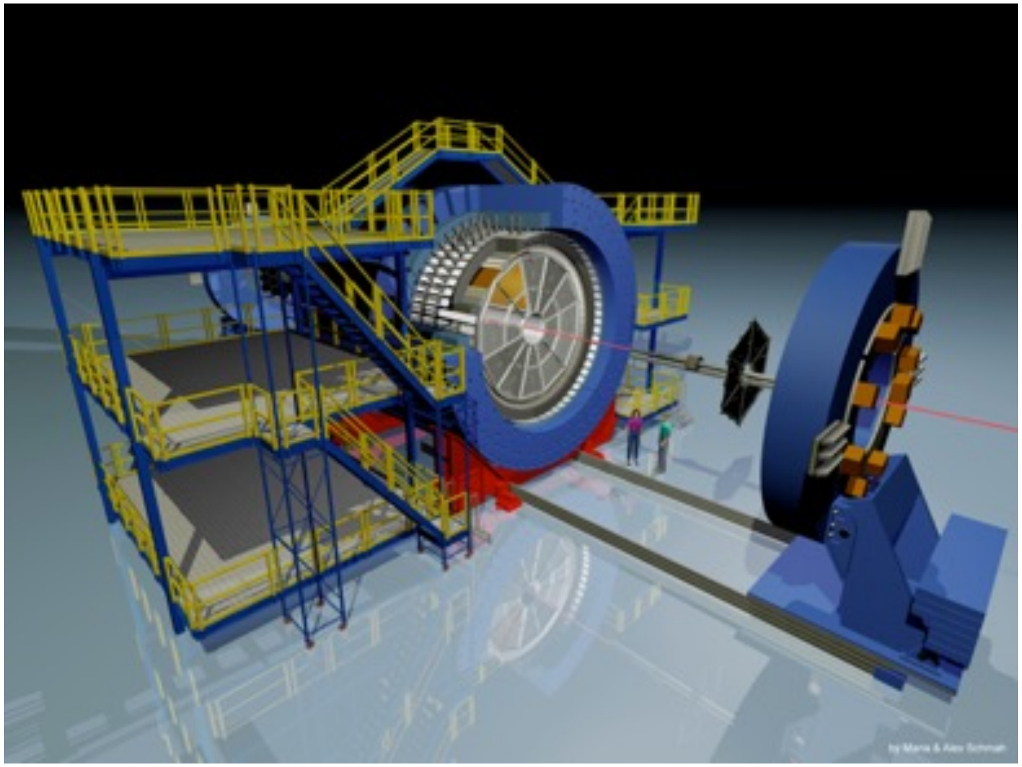


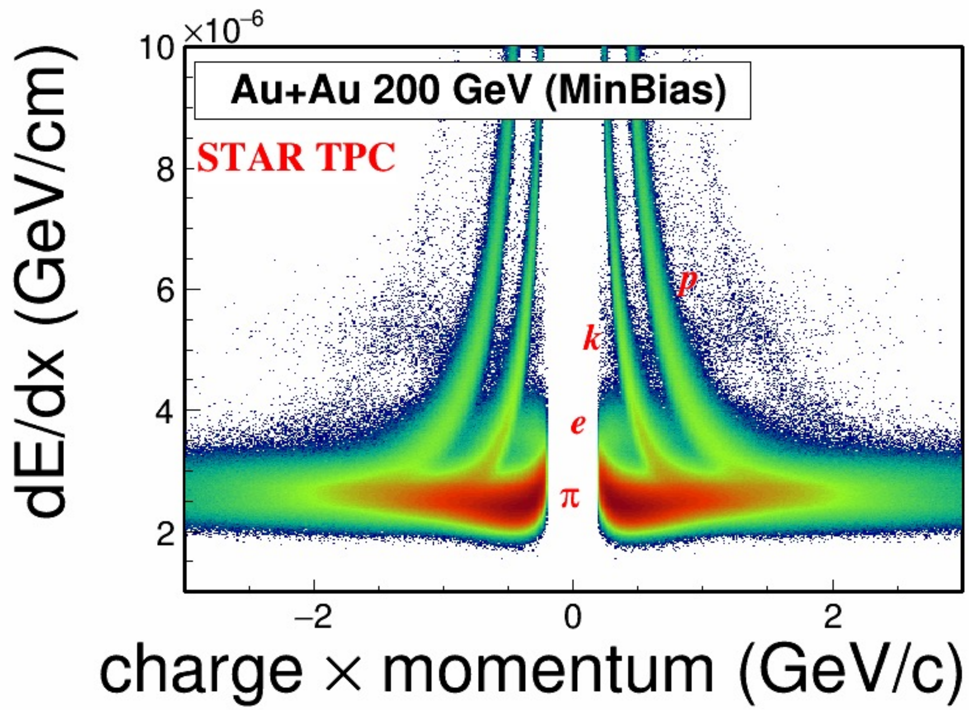
$$j_V = \frac{N_c e}{2\pi^2}\mu_A B,$$ ⇨ electric charge separation along the B field

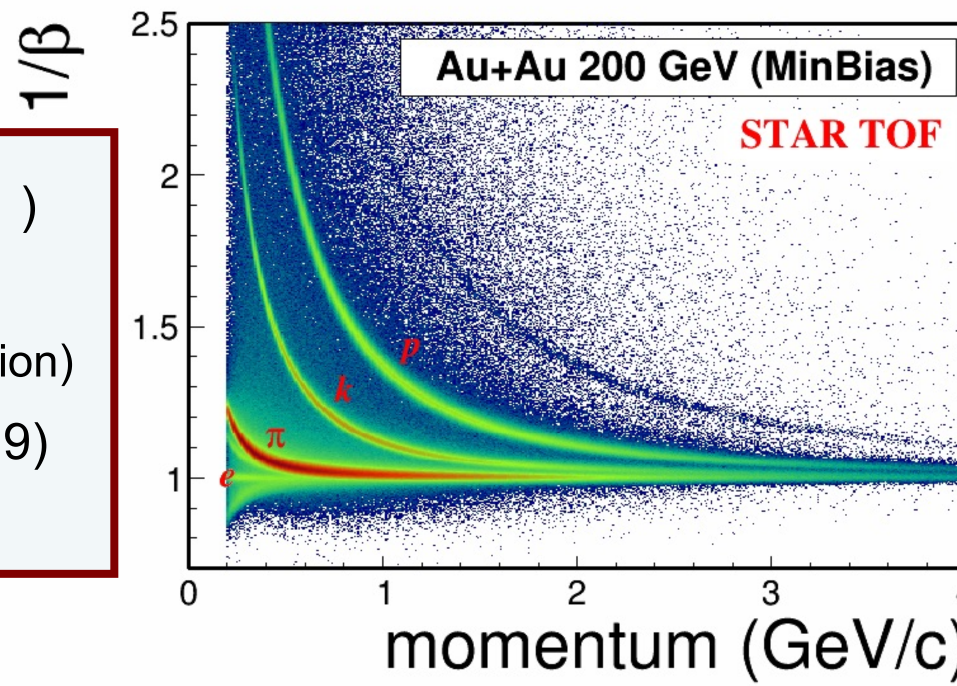
- ➢ Gluon configuration with non-zero topological charge (Q_w) converts left (right)-handed fermions to right (left)-handed fermions, generating electric current along B direction and leading to electric charge separation
- ➢ Experimentally, $\gamma = \cos(\phi_\alpha + \phi_\beta - 2\psi_{RP})$ used to search for the CME in heavy ion collisions

Voloshin, PRC 70, 057901 (2004)

The STAR detector



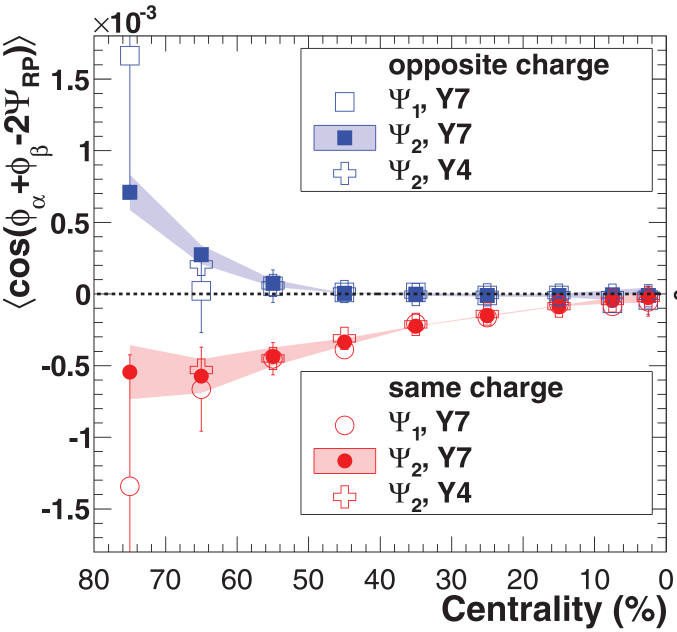


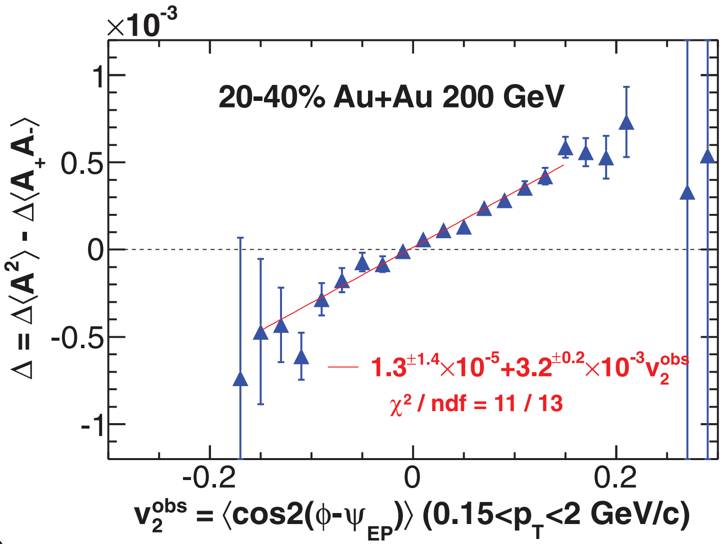


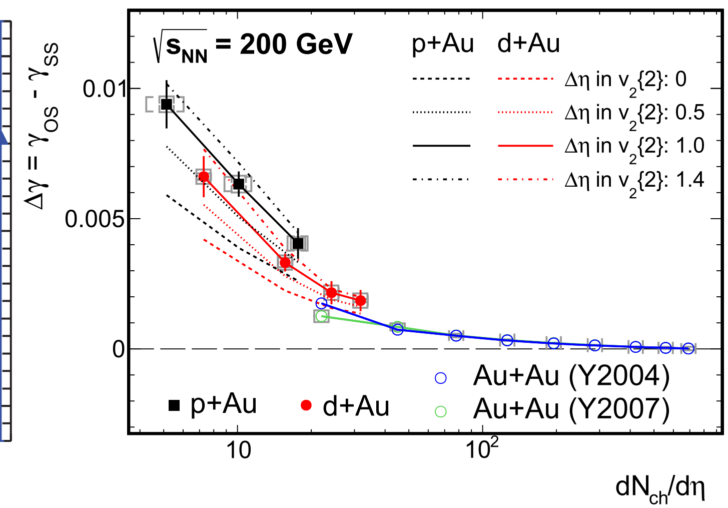
- **Time Projection Chamber** (ϕ=0-2π, |η|<1)
  - Tracking - momentum
  - Ionization energy loss - dE/dx (particle identification)
- **Time Of Flight detector** (ϕ=0-2π, |η|<0.9)
  - Timing resolution <100ps - PID improvement

Background issue

STAR, PRL 103,251601 (2009); PRC 81,54908 (2010); PRC 88,64911 (2013)







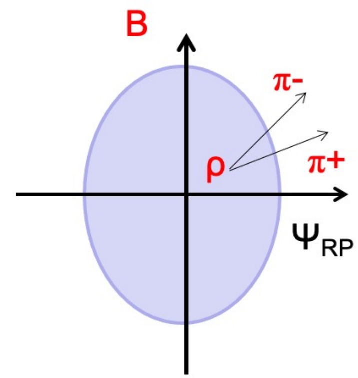
STAR, PRC 89,044908 (2014)

STAR, PLB 798 (2019) 134975

ϕ_α, ϕ_β, ϕ_c are the azimuthal angles of the charged particles measured by STAR TPC

- Large $\Delta\gamma = \gamma_{OS} - \gamma_{SS}$ correlator observed
- Measurements dominated by backgrounds
- How to address backgrounds?

Background



$$\Delta\gamma_{\mathrm{bkg}} = \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\psi_{RP}) \right\rangle$$

$$= \frac{N_{cluster}}{N_\alpha N_\beta} \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{cluster}) \cos(2\varphi_{cluster} - 2\psi_{RP}) \right\rangle$$

multiplicity "N" | two-particle correlation "2-p" | v_2

S. A. Voloshin, PRC 70, 057901 (2004)
F. Wang, PRC 81, 064902 (2010)
A. Bzdak, V. Koch and J. Liao, PRC 83, 014905 (2011)
S. Schlichting and S. Pratt, PRC 83, 014913 (2011)
F. Wang, J. Zhao, PRC 95,051901(R) (2017)

Background

J. Zhao, H. Li, F. Wang, Eur. Phys. J. C (2019) 79:168
H.-J. Xu, *et al*, CPC 42 (2018) 084103

- **Invariant mass dep. of the Δγ correlator**
- **Δγ with respect to Ψ_{RP} (ZDC) and Ψ_{PP} (TPC)**

$$\Delta\gamma_{\text{bkg}} = \langle \cos(\varphi_\alpha + \varphi_\beta - 2\psi_{RP}) \rangle$$

$$= \frac{N_{cluster}}{N_\alpha N_\beta} \langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{cluster}) \cos(2\varphi_{cluster} - 2\psi_{RP}) \rangle$$

multiplicity "N"

two-particle correlation "2-p"

v_2

Background

J. Zhao, H. Li, F. Wang, Eur. Phys. J. C (2019) 79:168
H.-J. Xu, *et al*, CPC 42 (2018) 084103

- **Invariant mass dep. of the $\Delta\gamma$ correlator**
- **$\Delta\gamma$ with respect to Ψ_{RP} (ZDC) and Ψ_{PP} (TPC)**

$$\Delta\gamma_{\mathrm{bkg}} = \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\psi_{RP}) \right\rangle$$

$$= \frac{N_{cluster}}{N_\alpha N_\beta} \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{cluster}) \cos(2\varphi_{cluster} - 2\psi_{RP}) \right\rangle$$

multiplicity "N" — two-particle correlation "2-p" — v_2

S. A. Voloshin, Phys. Rev. Lett. 105, 172301
W.T. Deng, *et al,* Phys. Rev. C 94, 041901(R)
H.J. Xu, *et al,* PRL 121 (2018) 022301
H.L. Li, *et al*, PRC 98, 054907 (2018)

- **Isobar collisions:**

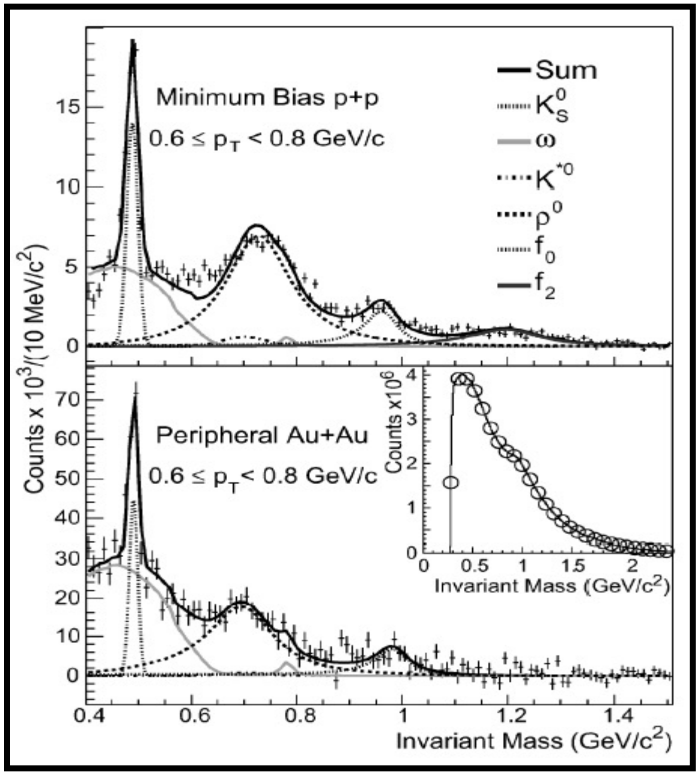
similar "N(~1% in MB)", "2-p", v_2 (~2-3%) ->

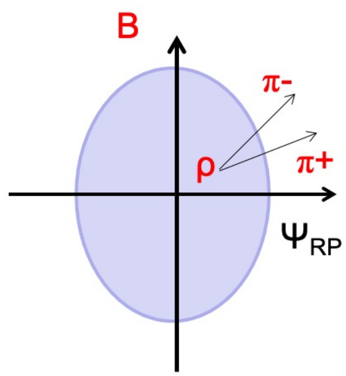
similar background (scaled ~v_2 and 1/N)

Invariant mass method

STAR, PRL 92,092301 (2004)

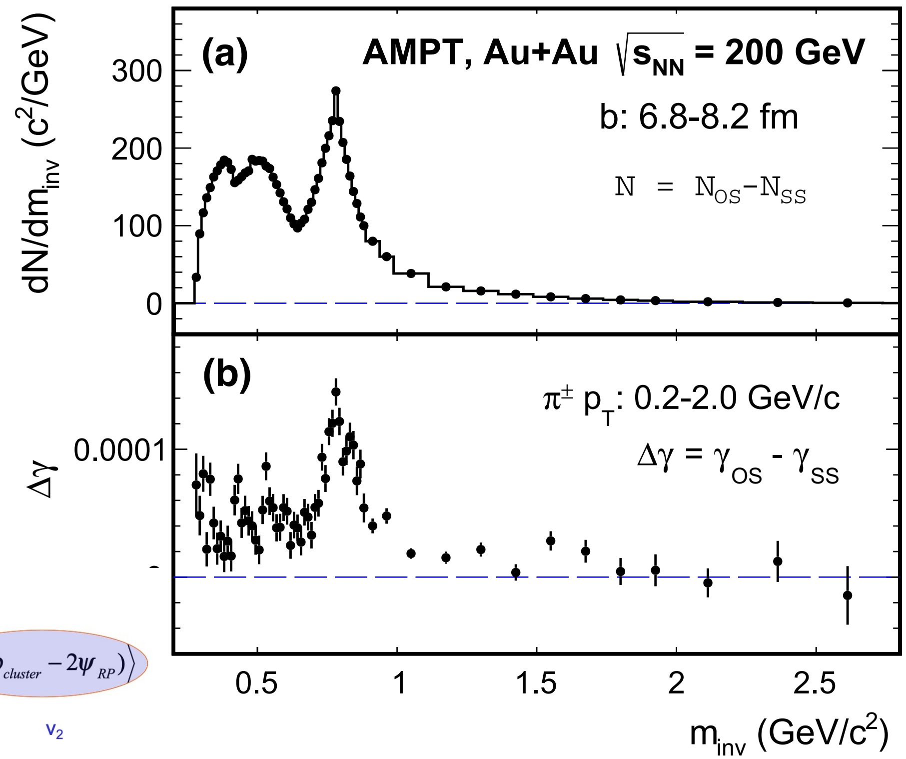
F. Wang, J. Zhao, PRC 95,051901(R) (2017)
J. Zhao, *et al*, Eur. Phys. J. C (2019) 79:168





$$\Delta\gamma_{bkg} = \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\psi_{RP}) \right\rangle = \frac{N_{cluster}}{N_\alpha N_\beta} \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{cluster}) \cos(2\varphi_{cluster} - 2\psi_{RP}) \right\rangle$$

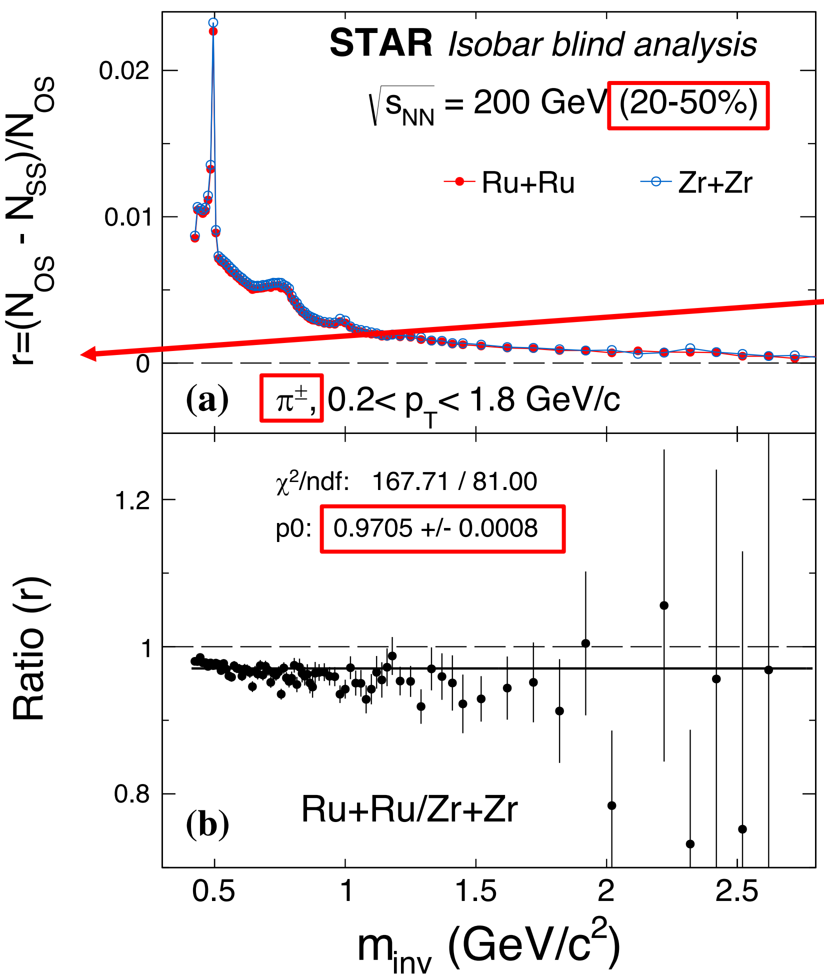
decays ... v_2



- Resonance background: resonance decay + v_2 ➔ CME-like Δγ
- Can we remove/isolate the background?
- Exploiting invariant mass dependence of Δγ

Invariant mass method

STAR, arXiv:2109.00131



expect:

$$\Delta\gamma_{bkg} = \langle \cos(\varphi_\alpha + \varphi_\beta - 2\psi_{RP}) \rangle$$

$$= \frac{N_{cluster}}{N_\alpha N_\beta} \langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{cluster}) \cos(2\varphi_{cluster} - 2\psi_{RP}) \rangle$$

multiplicity "N" | two-particle correlation "2-p" | v_2

S. A. Voloshin, Phys. Rev. Lett. 105, 172301
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- **Isobar collisions:**

  similar "N(~1% in MB)", "2-p", v_2 (~2-3%) ->

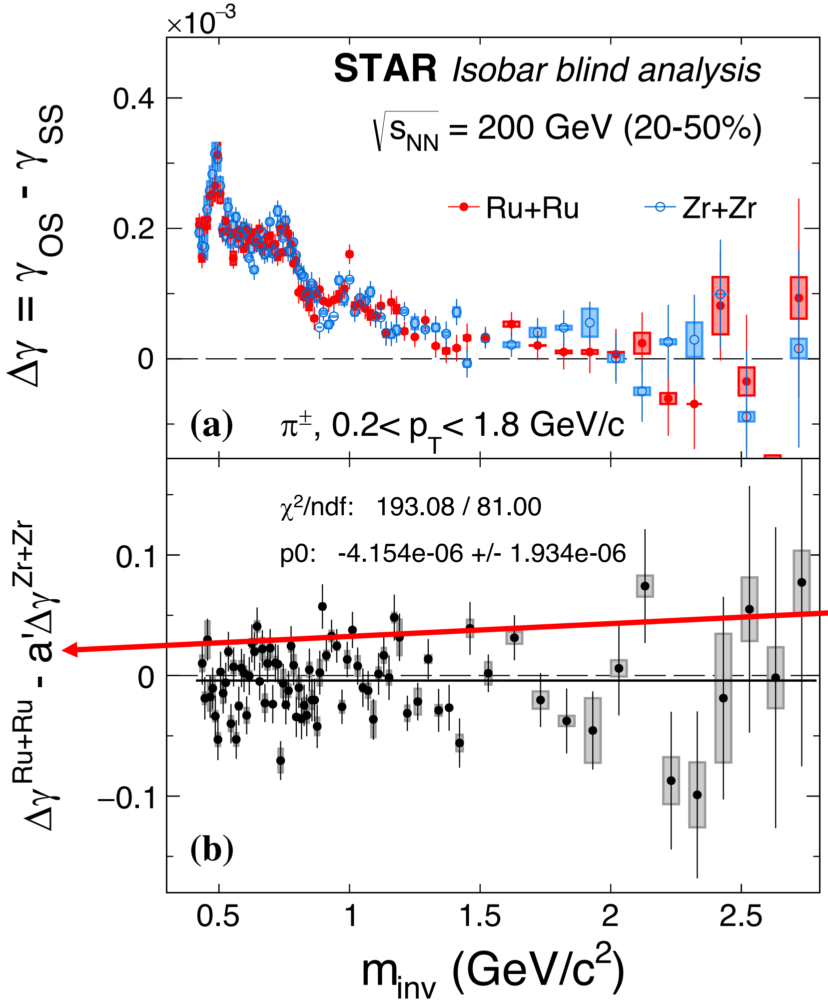
  similar background (scaled ~v_2 and 1/N)

observed:

- pion pair r (~1/N) different by ~3% with 20-50% centrality
- v_2 diff by ~1.5% (data v_2 contain nonflow)

Invariant mass method

STAR, arXiv:2109.00131



- **Isobar collisions:**

similar "N (~1% in MB)", "2-p", v_2 (~2-3%) ->
similar background (scaled ~v_2 and 1/N)

$$\Delta\gamma^{Zr} = CME^{Zr} + Bkg^{Zr}$$

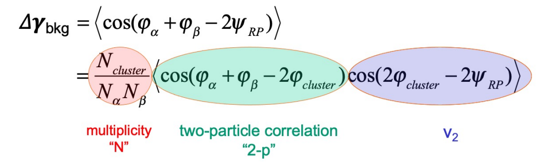
$$\Delta\gamma^{Ru} = CME^{Ru} + Bkg^{Ru}$$

with:

$$A' = \Delta\gamma^{Ru}/\Delta\gamma^{Zr}$$

$$a' = r^{Ru}/r^{Zr} \cdot v_2^{Ru}/v_2^{Zr}$$

$$= Bkg^{Ru}/Bkg^{Zr}$$



The "N" (r) diff. not corrected in the blind analysis due to an overlook

$$\Delta\gamma^{Ru} - a'\Delta\gamma^{Zr} = CME^{Ru} - a'CME^{Zr}$$

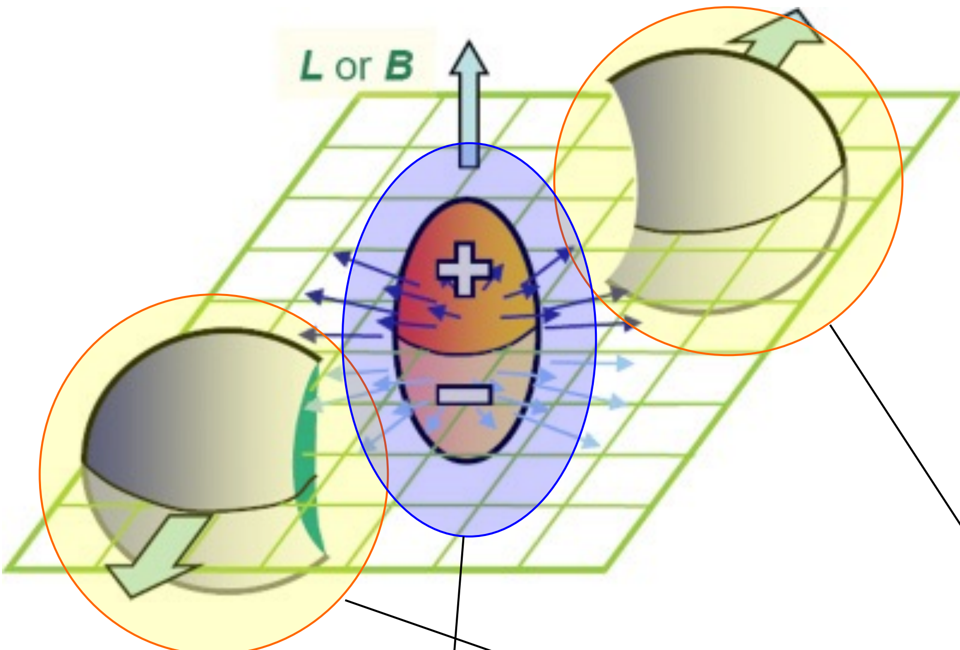
mass dependent CME signal

- **No evidence of difference observed**

Ψ_{PP} & Ψ_{RP} to resolve CME & Bkg

H-J. Xu, *et al*, CPC 42 (2018) 084103, arXiv:1710.07265

B. Alver *et al.* (PHOBOS) , PRL **98**, 242302 (2007).



- **Ψ_{PP}** maximizes v_2
  - ➔ v_2 background
- **Ψ_{RP}** maximizes magnetic field strength
  - ➔ CME signal
- **Ψ_{PP}** and **Ψ_{RP}** are correlated, but not identical due to geometry fluctuations

spectator

participant

$$a \equiv \langle \cos 2(\psi_{PP} - \psi_{RP}) \rangle$$

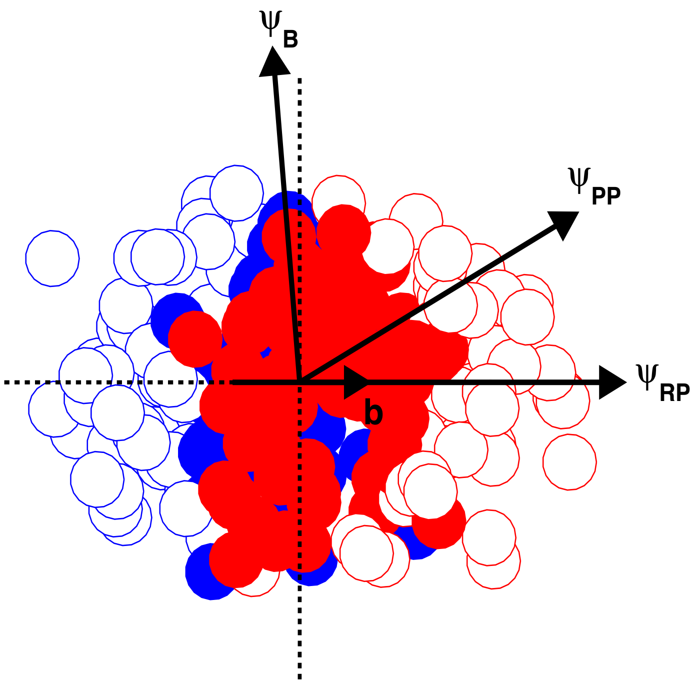
- $\Delta\gamma$ w.r.t. TPC Ψ_{EP} (proxy of Ψ_{PP}) and ZDC Ψ_1 (proxy of Ψ_{RP}) contain different fractions of CME and background (Bkg)

Ψ_{PP} & Ψ_{RP} to resolve CME & Bkg

- Ψ_{PP} maximizes flow, ➔ flow background
- Ψ_{RP} maximizes the magnetic field (B) strength, ➔ CME signal

$\Delta\gamma$ w.r.t. TPC Ψ_{EP} (proxy of Ψ_{PP}) and ZDC Ψ_1 (proxy of Ψ_{RP}) contain different fractions of CME and Bkg

H-J. Xu, *et al*, CPC 42 (2018) 084103, arXiv:1710.07265



$$\Delta\gamma\{\psi_{TPC}\} = \mathrm{CME}\{\psi_{TPC}\} + \mathrm{Bkg}\{\psi_{TPC}\}$$

$$\Delta\gamma\{\psi_{ZDC}\} = \mathrm{CME}\{\psi_{ZDC}\} + \mathrm{Bkg}\{\psi_{ZDC}\}$$

Two-component assumption

$$\mathrm{CME}\{\psi_{TPC}\} = a * \mathrm{CME}\{\psi_{ZDC}\},\ \mathrm{Bkg}\{\psi_{ZDC}\} = a * \mathrm{Bkg}\{\psi_{TPC}\}$$

assume $\mathrm{Bkg} \propto v_2$

$$a = v_2\{\psi_{ZDC}\} / v_2\{\psi_{TPC}\},\ A = \Delta\gamma\{\psi_{ZDC}\} / \Delta\gamma\{\psi_{TPC}\}$$

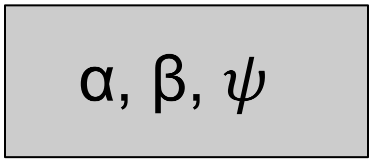
Both are experimental measurements

$$f_{CME} = \mathrm{CME}\{\psi_{TPC}\}/\Delta\gamma\{\psi_{TPC}\} = (A/a-1)/(1/a^2-1)$$

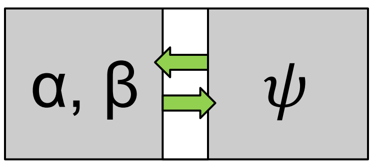
f_{CME} in Ru+Ru and Zr+Zr

STAR, arXiv:2109.00131

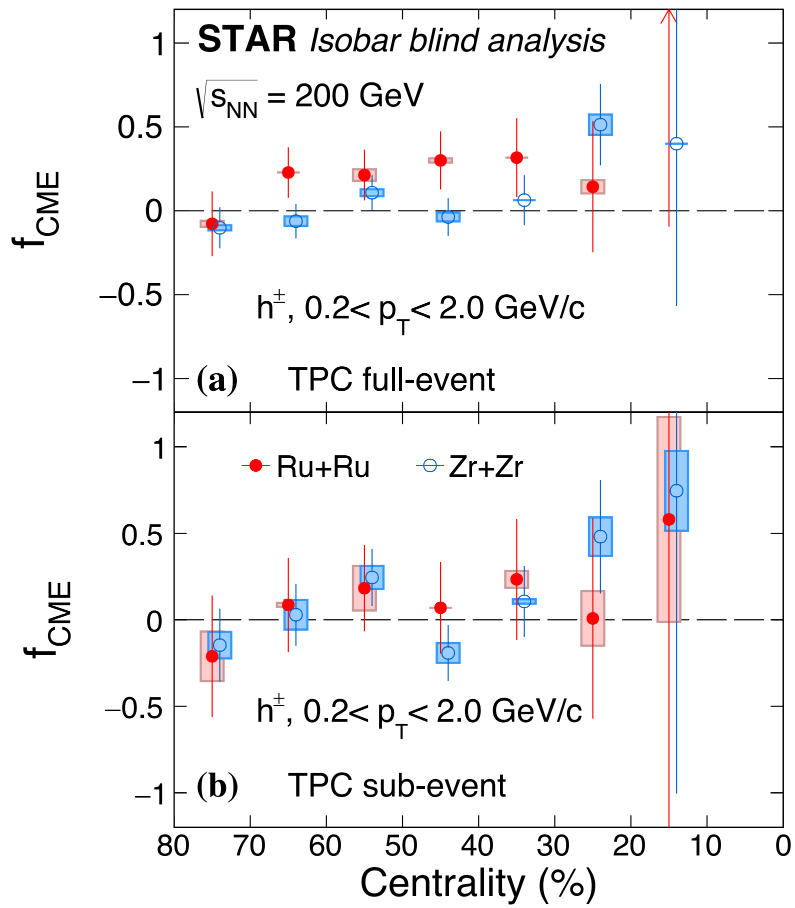
Full-event



$$\cos(\phi_\alpha + \phi_\beta - 2\psi)$$



Sub-event



$$f_{\rm CME} = \frac{\Delta\gamma_{CME}\{\psi_{\rm TPC}\}}{\Delta\gamma\{\psi_{\rm TPC}\}} = \frac{A/a - 1}{1/a^2 - 1},$$

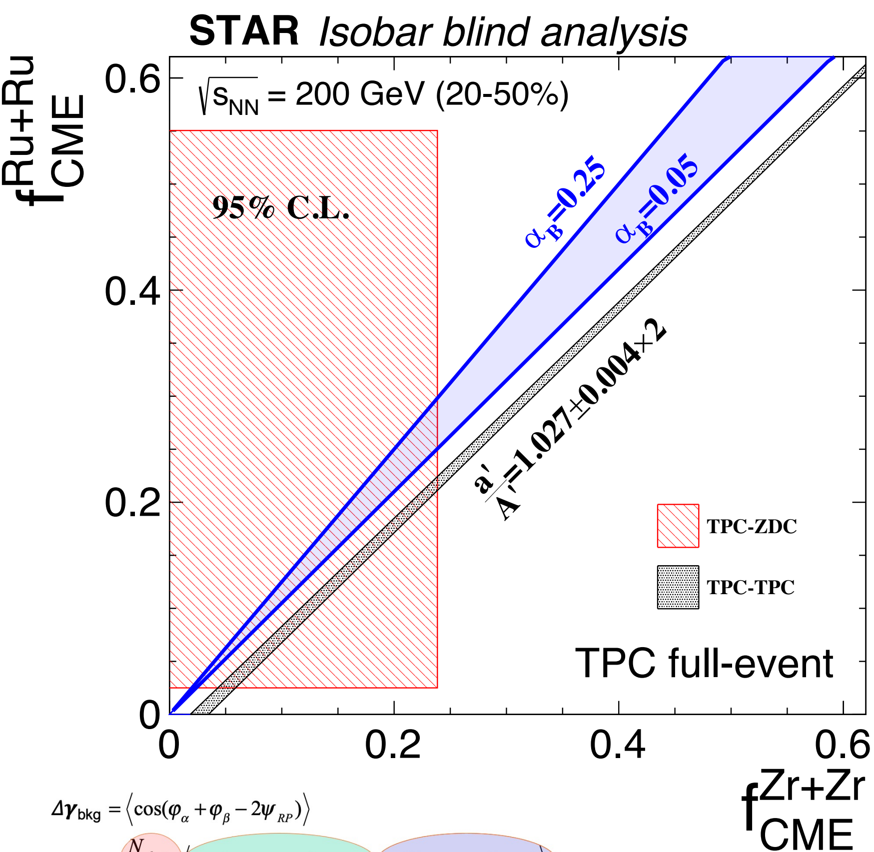
$$a = v_2\{\psi_{\rm ZDC}\}/v_2\{\psi_{\rm TPC}\}.$$

$$A = \Delta\gamma\{\psi_{\rm ZDC}\}/\Delta\gamma\{\psi_{\rm TPC}\}.$$

Full-event:	sub-event:
f_{CME}(Ru+Ru) = 0.29 ± 0.13 ± 0.01;	(f_{CME}(Ru+Ru) = 0.12 ± 0.20 ± 0.00)
f_{CME}(Zr+Zr) = 0.06 ± 0.08 ± 0.02;	(f_{CME}(Zr+Zr) =-0.01 ± 0.12 ± 0.03)

additional constraint using TPC

STAR, arXiv:2109.00131



$$\Delta\gamma_{bkg} = \langle \cos(\varphi_\alpha + \varphi_\beta - 2\psi_{RP}) \rangle = \frac{N_{cluster}}{N_\alpha N_\beta} \langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{cluster}) \rangle \langle \cos(2\varphi_{cluster} - 2\psi_{RP}) \rangle$$

multiplicity "N" | two-particle correlation "2-p" | v_2

Background scales with v_2 and 1/N:

$$\frac{(1 - f_{\rm CME}^{\rm Ru+Ru})\Delta\gamma^{\rm Ru+Ru}}{v_2^{\rm Ru+Ru}/N^{\rm Ru+Ru}} = \frac{(1 - f_{\rm CME}^{\rm Zr+Zr})\Delta\gamma^{\rm Zr+Zr}}{v_2^{\rm Zr+Zr}/N^{\rm Zr+Zr}}$$

$$f_{\rm CME}^{\rm Ru+Ru} = \left(\frac{a'}{A'}\right) f_{\rm CME}^{\rm Zr+Zr} + \left(1 - \frac{a'}{A'}\right)$$

$$A' = \Delta\gamma^{\rm Ru+Ru}/\Delta\gamma^{\rm Zr+Zr}$$

$$a' = (v_2^{\rm Ru+Ru}/N^{\rm Ru+Ru})/(v_2^{\rm Zr+Zr}/N^{\rm Zr+Zr})$$

$$a'/A' = \frac{\Delta\gamma^{\rm Zr+Zr}/(v_2^{\rm Zr+Zr}/N^{\rm Zr+Zr})}{\Delta\gamma^{\rm Ru+Ru}/(v_2^{\rm Ru+Ru}/N^{\rm Ru+Ru})}$$

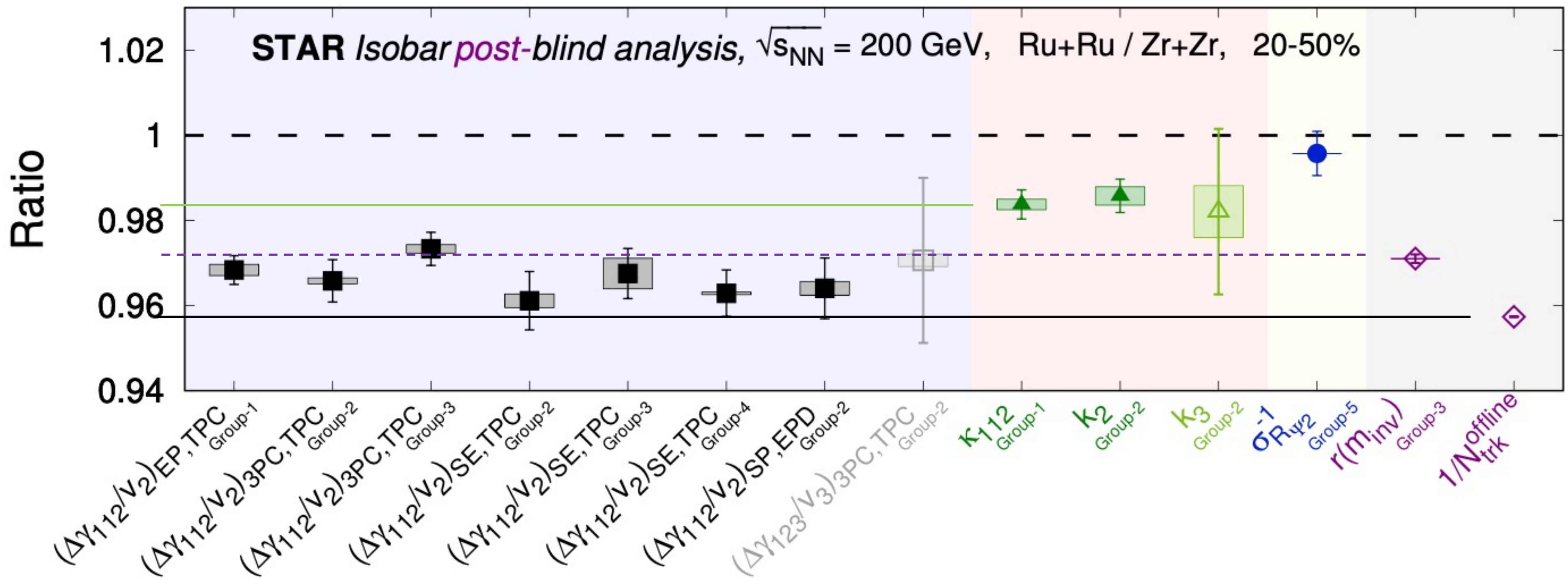
The "N" diff. not corrected in the blind analysis

B-field expectation:
$f_{CME}^{Ru+Ru}/f_{CME}^{Zr+Zr}$ = 1+α_B
where α_B =0.15$\pm$0.05

No overlap with allowed CME region, but "N" ratio not included in the predefined a'. Including it, a'/A' = 0.990 $\pm$ 0.007, there would be overlap with allowed CME region (including f_{CME}=0)

Compilation of all the results

STAR, arXiv:2109.00131, 1 Sep 2021



$$\Delta\gamma_{\mathrm{bkg}} = \langle \cos(\varphi_\alpha + \varphi_\beta - 2\psi_{RP}) \rangle = \frac{N_{cluster}}{N_\alpha N_\beta} \langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{cluster}) \rangle \langle \cos(2\varphi_{cluster} - 2\psi_{RP}) \rangle$$

multiplicity "N" — two-particle correlation "2-p" — v_2

Δγ/v2

$\kappa = \Delta\gamma/(\Delta\delta^* v_2)$:

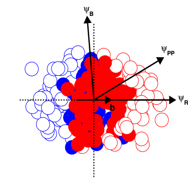
- None of the predefined signatures have been observed in the blind analysis
- Blind analysis assumes background ~ v_2 only. Multiplicity effect should and will be taken into account
- Nonflow effect can affect the CME baseline and will be studied

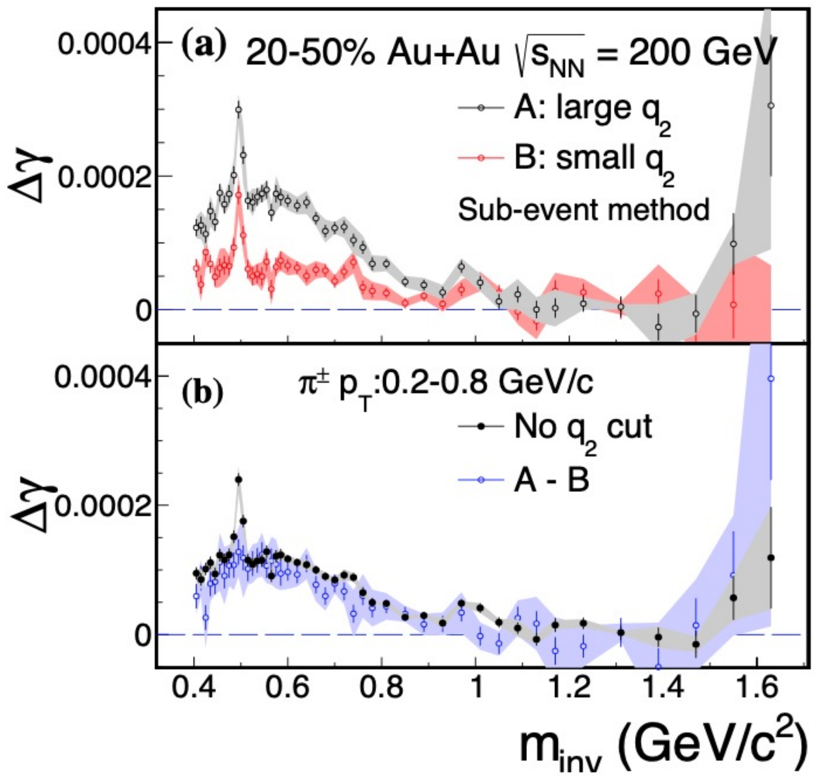
Results from Au+Au

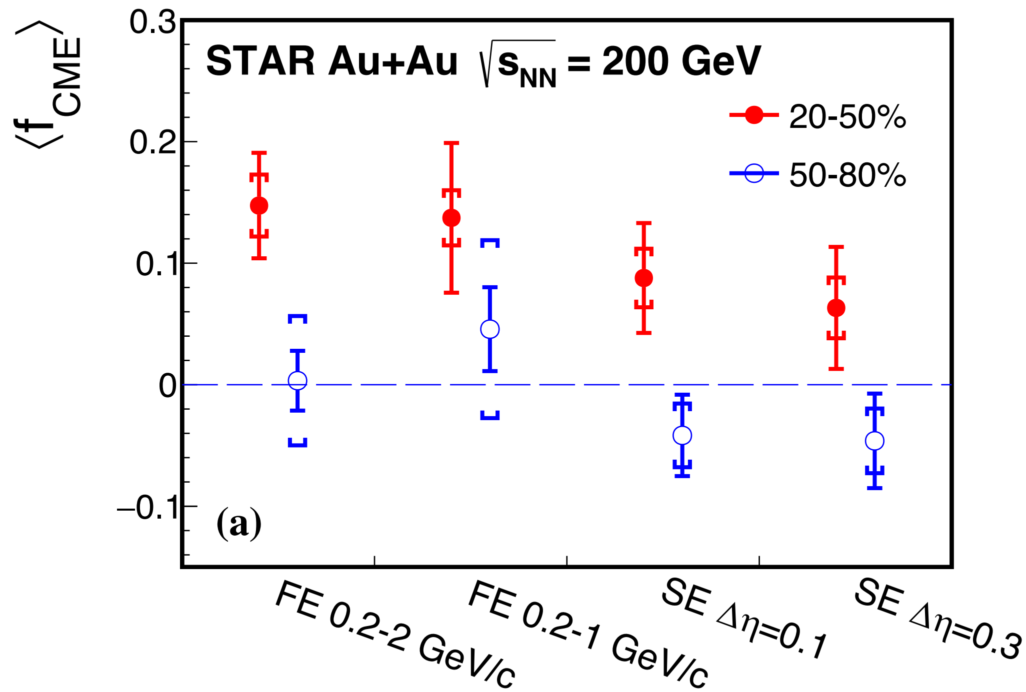
STAR, arXiv:2006.05035, 9 Jun 2020

STAR, arXiv:2106.09243, 17 Jun 2021

F. Wang's talk @Nov. 2







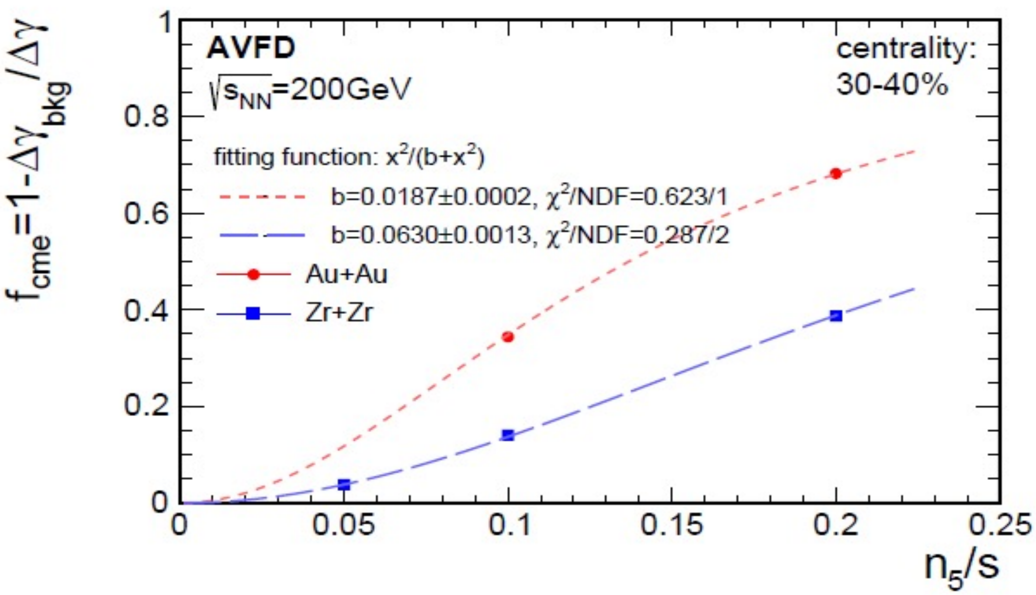
Upper limit ~15%

Indications of finite signal in 20-50%, 1-3σ
possible remaining nonflow effects

Y. Feng et al., arXiv:2106.15595

Connection between isobar and Au+Au

Y. Feng, Y. Lin, J. Zhao, and F. Wang, Phys. Lett. B 820, 136549 (2021)



Bkg. ~ 1/N ~ 1/A
B. field ~ $A/A^{2/3}$ ~ $A^{1/3}$
$\Delta\gamma_{CME}$ ~ B^2 ~ $A^{2/3}$
Background: isobar/AuAu ~ 2
Signal: AuAu/isobar ~ 1.5
f_{cme} possibly a factor of ~3 reduction

Caveats: axial charge density μ_5/s, temperature dependent sphaleron transition can be different between isobar and AuAu

- **AVFD simulation:** indicates smaller signal in isobar than Au+Au
- **Isobar blind analysis**: no predefined CME signatures have been observed
- **STAR Au+Au data:** (2.4B MB events) indicate a finite CME signal with 1-3σ significance; Expect 20B from 2023+25 runs
- Isobar data and Au+Au data are not inconsistent

Summary and outlook

- STAR Group-3 carried out the invariant mass and spectator plane/participant plane analyses in the isobar blind analysis
- No predefined CME signatures have been observed in the isobar blind analysis
- For better understanding of the isobar data: multiplicity ("N") effect will be taken into account. Nonflow effect on baseline will be studied
- STAR Au+Au data (2.4B MB events) indicate a finite CME signal with 1-3σ significance; Expect 20B from 2023+25 runs
- Isobar data and Au+Au data are generally understood/expected under the same overall picture

Thanks to BNL, RHIC operation and RCF, ORNL, RIKEN, and everyone involved in the isobar program !