

Measurements of azimuthal correlations with spectator and participant planes to search for the chiral magnetic effect in STAR

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(for the STAR Collaboration)



U.S. DEPARTMENT OF
ENERGY

Office of
Science

Why CME?

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PHYSICAL REVIEW LETTERS

20 JULY 1998

Possibility of Spontaneous Parity Violation in Hot QCD

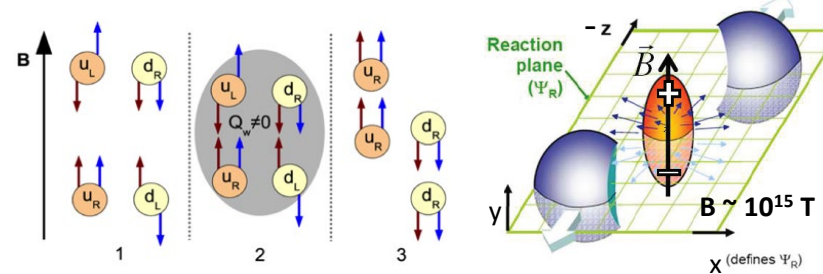
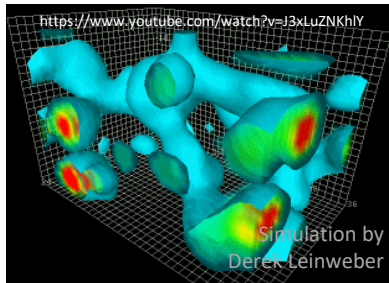
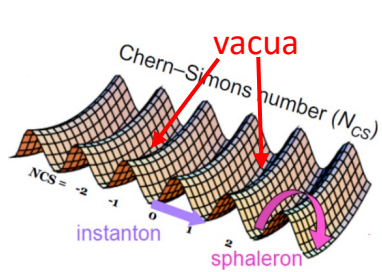
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(Received 3 April 1998)



QCD vacuum fluct.
Topological gluon field



Chiral anomaly
Chirality imbalance



Strong magnetic field
Charge separation

Fundamentally important
physics

Heavy ion collisions are a good
place to look for it

Outline:

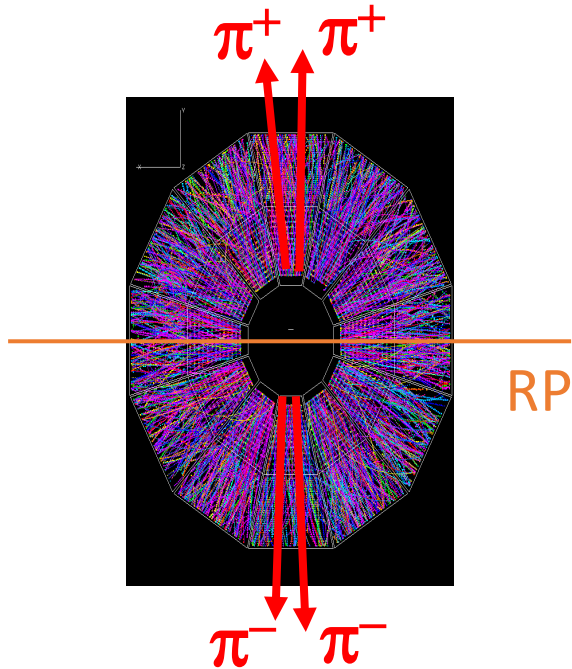
- The $\Delta\gamma$ observable
- Flow-induced background
- **Nonflow contamination**
- Results
- Summary

CME: Chiral symmetry restoration, Local P/CP violation, matter-antimatter asymmetry...

How to look for it?

Voloshin, PRC 2004
STAR, PRL 2009, PRC 2010

Look for charge separation

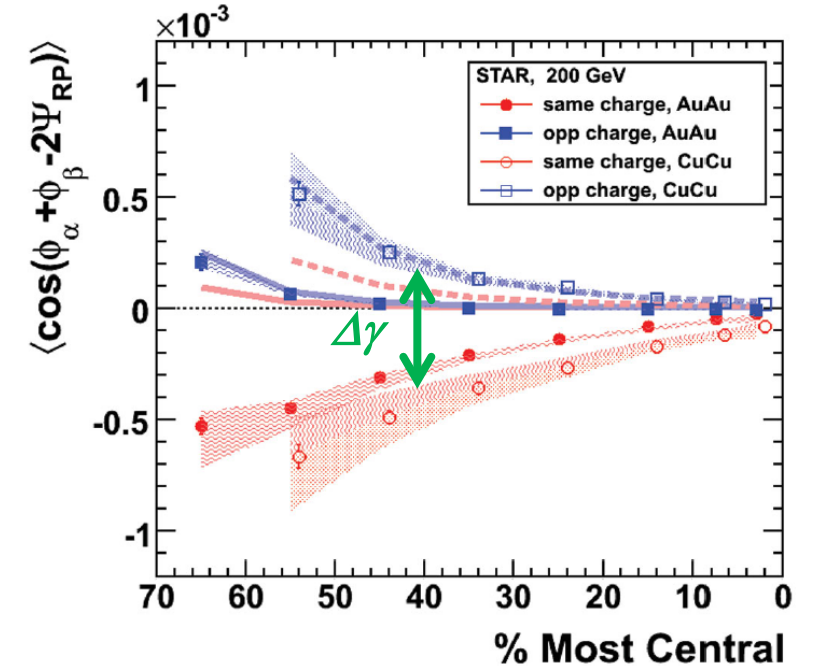


$\Delta\gamma$ correlator

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

$$\gamma_{+,-,+} > 0, \quad \gamma_{+,-,-} < 0$$

$$\Delta\gamma = \gamma_{\text{opposite-sign}} - \gamma_{\text{same-sign}} > 0$$



Significant $\Delta\gamma$ (charge separation across RP) observed

Flow-induced background is large

Voloshin 2004

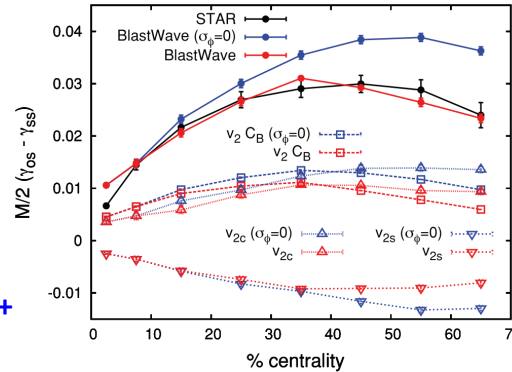
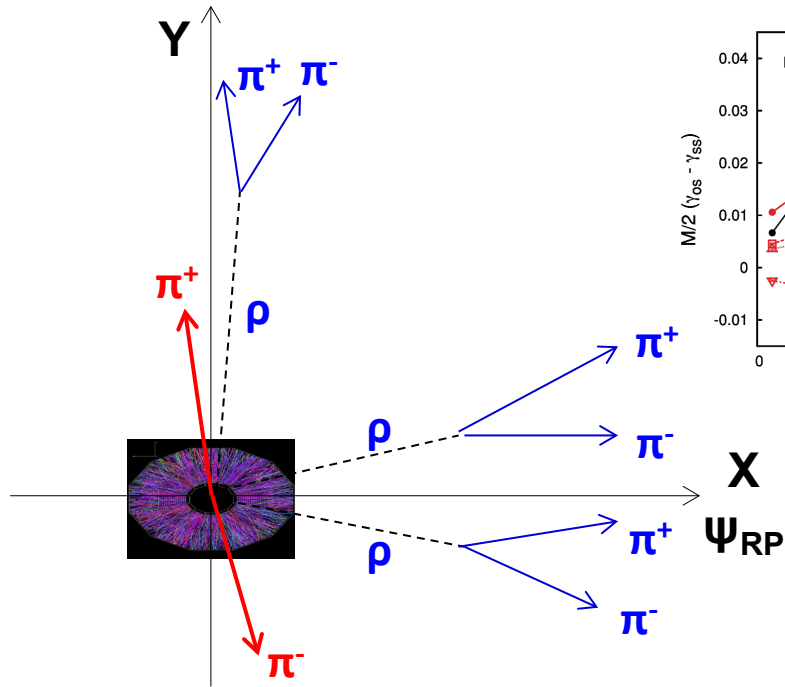
FW 2009

Bzdak, Koch, Liao 2010

Pratt, Schlichting 2010

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

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



$$dN_{\pm} / d\varphi \propto 1 + 2v_1 \cos \varphi^{\pm} + 2a_{\pm} \cdot \sin \varphi^{\pm} + 2v_2 \cos 2\varphi^{\pm} + \dots$$

$$\gamma_{\alpha\beta} = \left[\langle \cos(\varphi_\alpha - \psi_{RP}) \cos(\varphi_\beta - \psi_{RP}) \rangle - \langle \sin(\varphi_\alpha - \psi_{RP}) \sin(\varphi_\beta - \psi_{RP}) \rangle \right]$$

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

$$= \left[\langle v_{1,\alpha} v_{1,\beta} \rangle - \langle a_\alpha a_\beta \rangle \right] + \frac{N_{cluster}}{N_\alpha N_\beta} \langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{cluster}) \rangle v_{2,cluster}$$

$$\Delta\gamma = 2 \langle a_1^2 \rangle + \frac{N_\rho}{N_\alpha N_\beta} \langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_\rho) \rangle v_{2,\rho}$$

Flow-induced charge-dependent background:
nonflow coupled with flow

$$\Delta\gamma_{Bkg} \propto v_2 / N$$

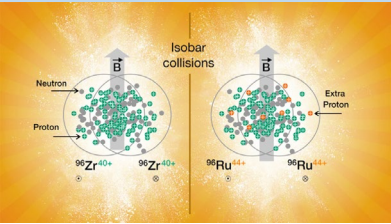
Isobars to handle flow background

Voloshin, PRL 105 (2010) 172301

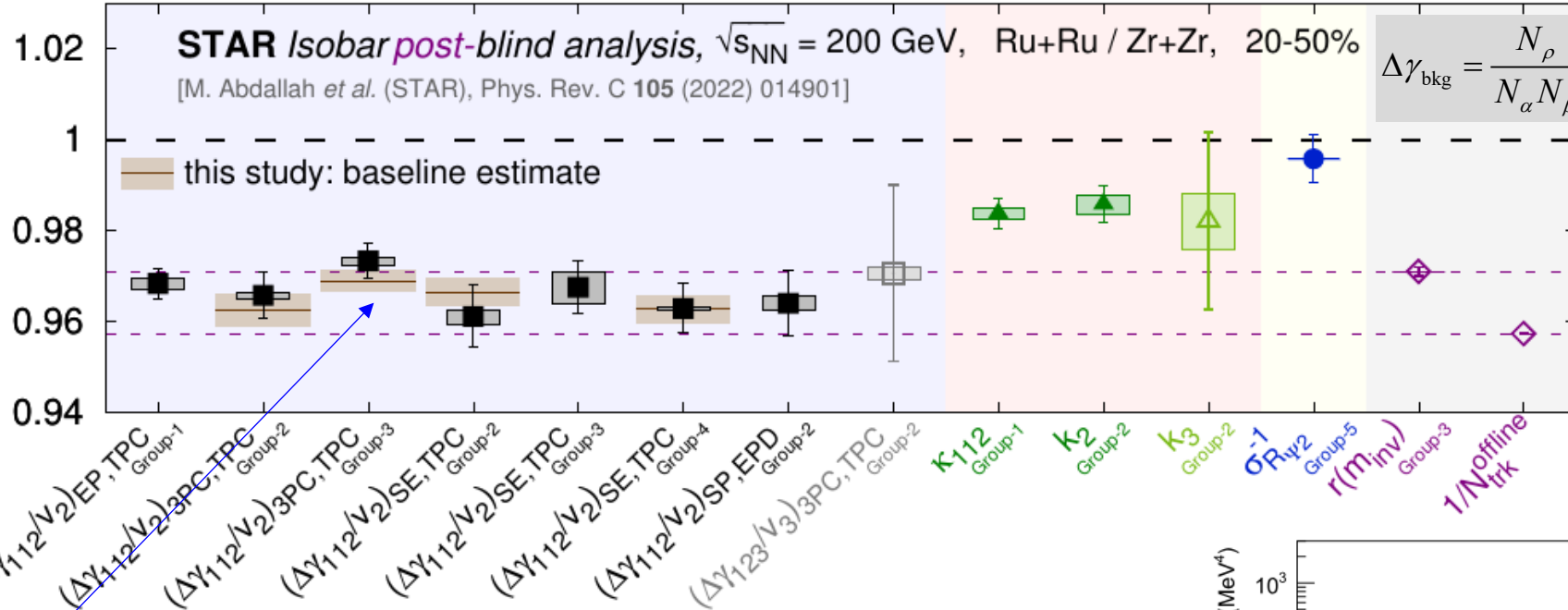
STAR, PRC 105 (2022) 014901

Haojie Xu et al. PRL 121 (2018) 022301

STAR, PRR 6 (2024) L032005, PRC 110 (2024) 014905



$\Delta\gamma/v_2$ Ratio



$$\Delta\gamma_{bkg} = \frac{N_p}{N_\alpha N_\beta} \langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_p) \rangle v_{2,p}$$

$$r = \frac{N_{os} - N_{ss}}{N_{os}}$$

$$N_{cluster} \propto N$$

0.4% precision is achieved!
But backgrounds not identical due to nuclear structure subtlety

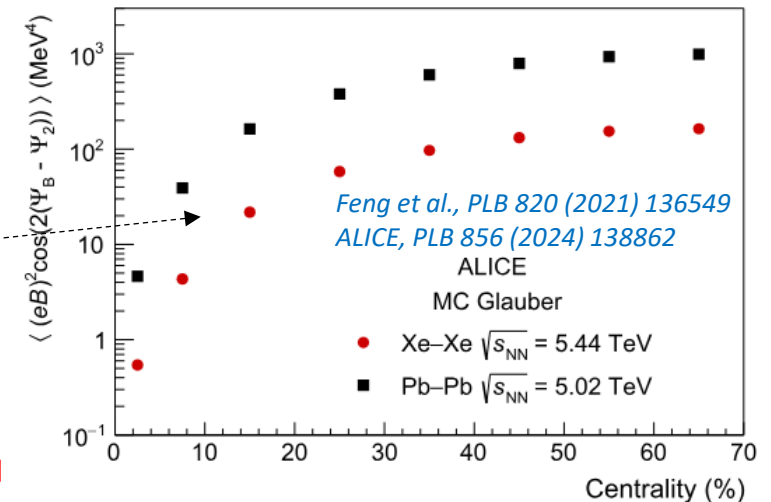
Additional contamination from nonflow estimated:

$$f_{CME} < 10\% \text{ at } 98\% \text{ CL}$$

Isobar signal/noise can be x10 smaller:

- ~2 from background
- ~1.5 from magnetic field strength
- ~several from de-correlation between magnetic field & EP

Isobar null signal does not necessarily mean no signal in larger systems -> Au+Au



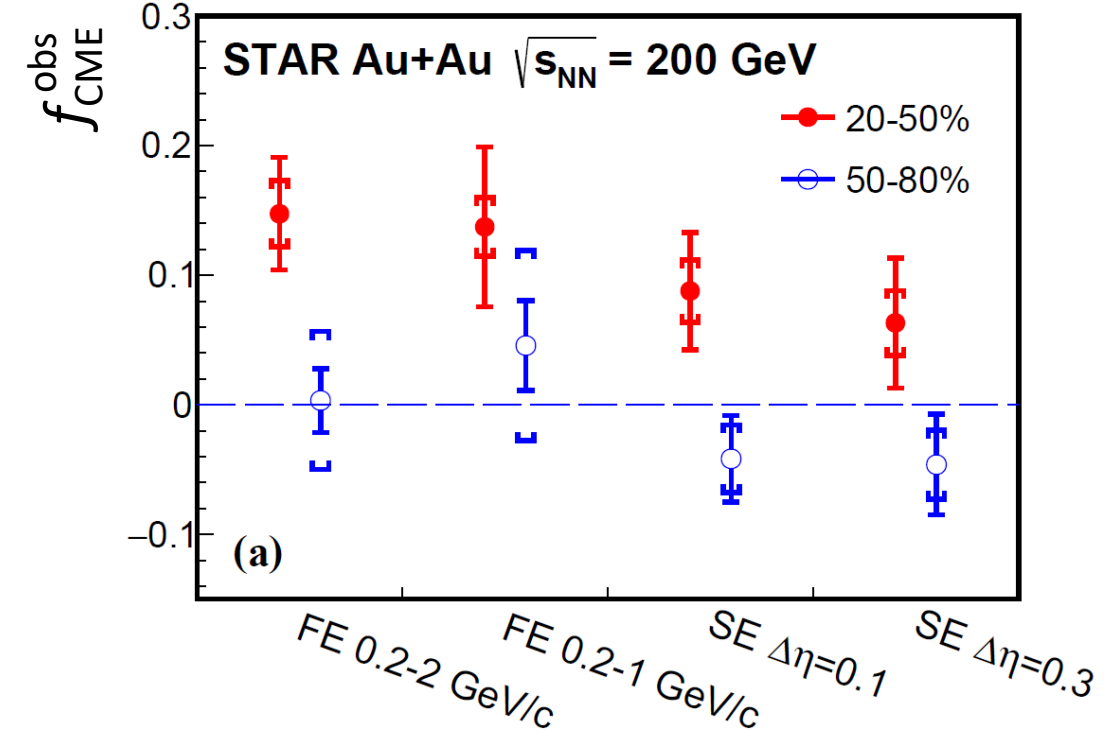
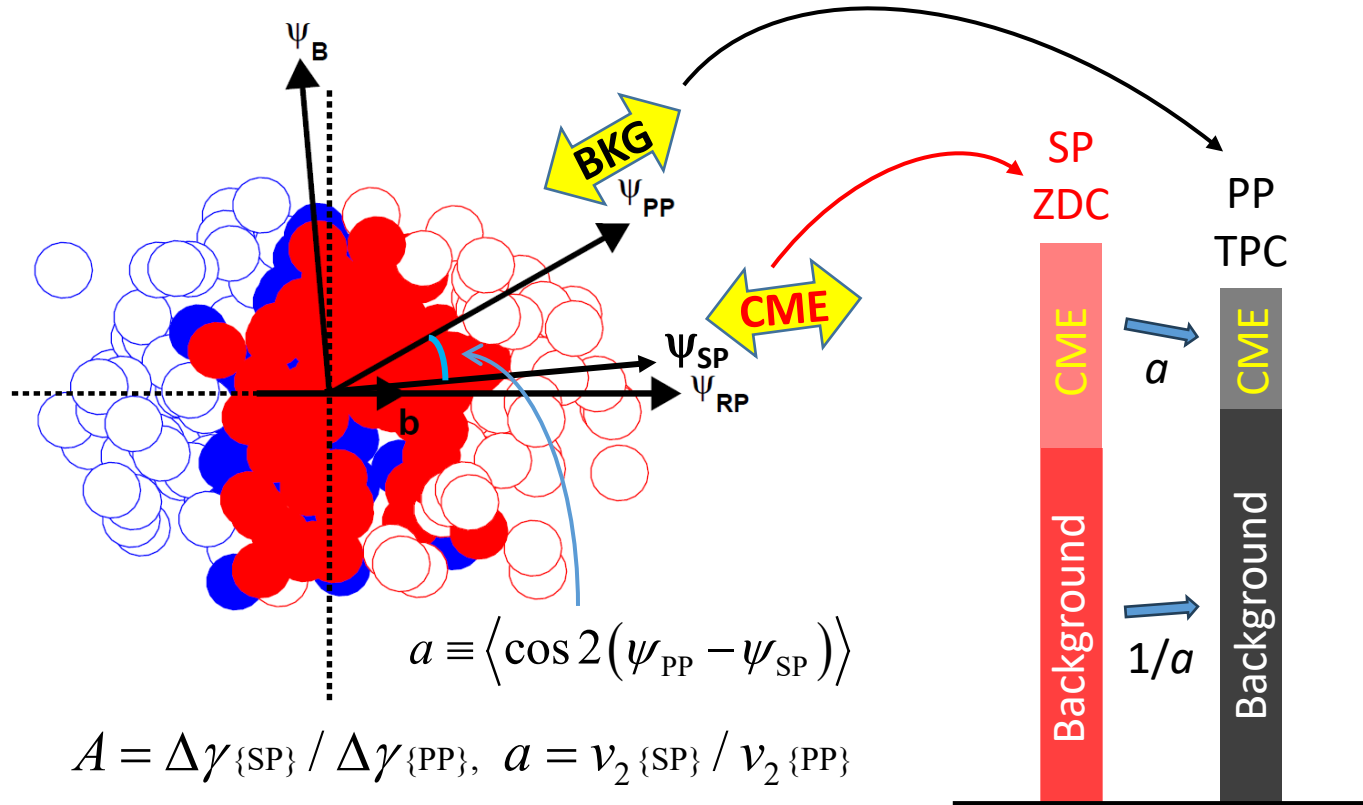
$f_{\text{CME}}^{\text{obs}}$ removing flow background

H.-j. Xu, et al., CPC 42 (2018) 084103

S.A. Voloshin, PRC 98 (2018) 054911

STAR, PRL 128 (2022) 092301

Spectator/participant planes comparative method



Flow-induced background is removed by the SP/PP method

- Peripheral 50-80%: consistent with zero
- Midcentral 20-50%: $\sim 2\text{-}3\sigma$ significance

Nonflow contamination

STAR, PRL 128 (2022) 092301
Feng et al., PRC 105 (2022) 024913

Assume: $\xi = C_{3p}/V_{2p}$ ratio in data = model
Ratio more robust than individual 3p, 2p correlations

CME signal is
this difference

$$\gamma = \langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_c) \rangle$$

intrinsic 3p correl.
makes f_{CME} smaller

$$f_{\text{CME}}^{\text{obs}} = \frac{\Delta\gamma_{\text{CME}}\{\text{TPC}\}}{\Delta\gamma\{\text{TPC}\}} = \frac{A/a - 1}{1/a^2 - 1}$$

$$f_{\text{CME}} \equiv \frac{\Delta\gamma_{\text{CME}}^{\text{PP}}}{\Delta\gamma\{\text{TPC}\}} = \frac{\sqrt{1 + \epsilon_{\text{nf}}}}{\frac{1}{a^2} - (1 + \epsilon_{\text{nf}})} \left[\left(\frac{A}{a} - 1 \right) + \epsilon_{\text{nf}} \left(\frac{C_{3p}/V_{2p}}{(N_3 C_3)/(N_2 V_2)} - 1 \right) \right]$$

$V_2\{2\}$ nonflow
contamination

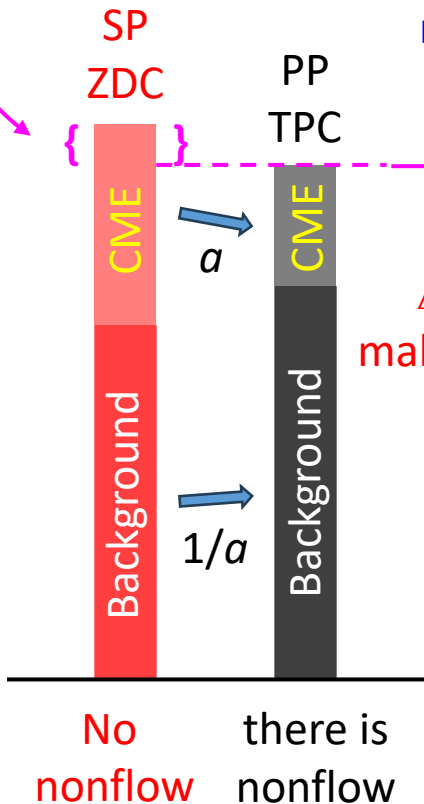
3p nonflow
2p nonflow

measurement
ZDC/TPC - 1

measurement
 $N\Delta\gamma/v_2$

$\Delta\gamma = C_3/v_2$
makes f_{CME} larger

3-particle correlations
primarily from (di-)jets



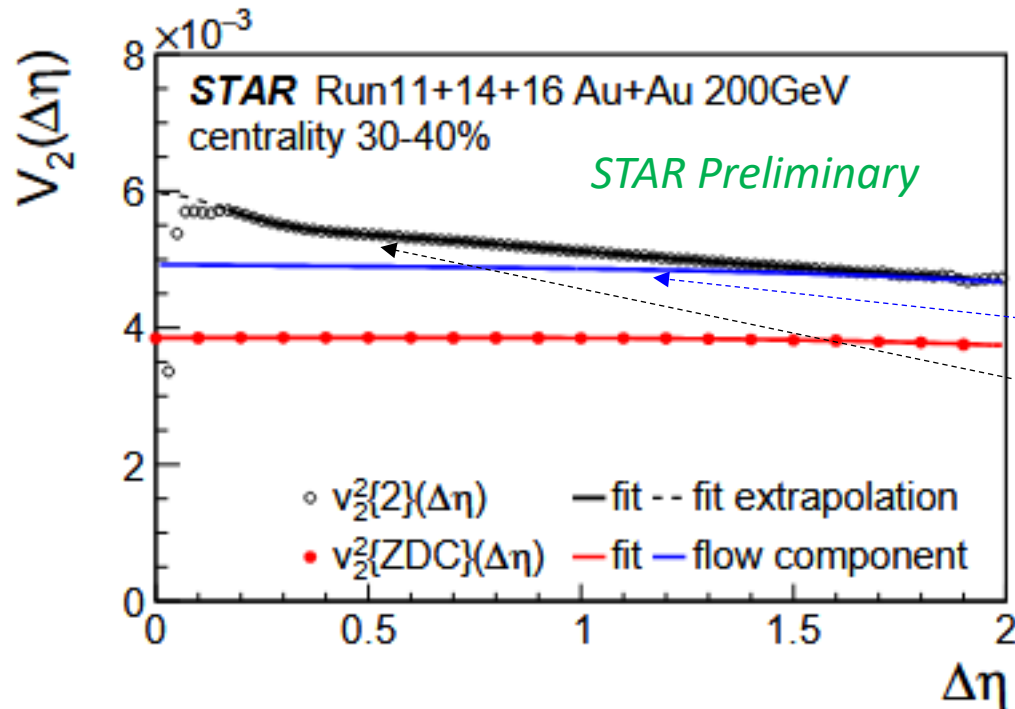
Stochastic jet fragmentation: fragment emission sampling an underlying distribution but otherwise uncorrelated

$$\langle \cos(\alpha + \beta - 2c) \rangle = \langle \cos(\alpha - c) \cos(\beta - c) - \sin(\alpha - c) \sin(\beta - c) \rangle \approx \langle \cos^2(\alpha - c) - \sin^2(\alpha - c) \rangle = \langle \cos 2(\alpha - c) \rangle$$

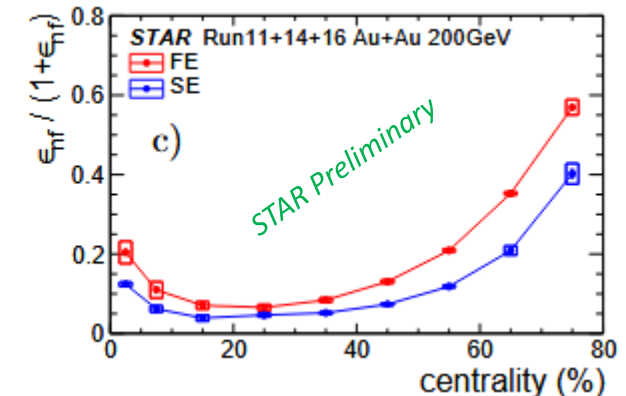
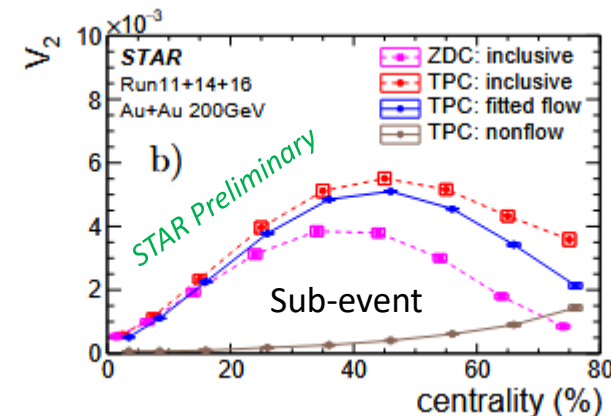
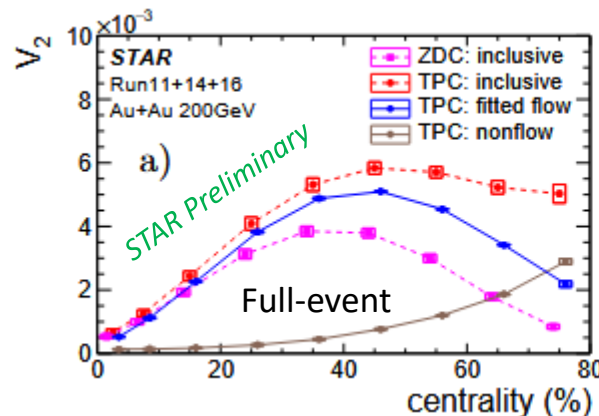
$$C_{3p} = \langle \cos(\alpha + \beta - 2c) \rangle N_{3p} / N, \quad V_{2p} = \langle \cos 2(\alpha - c) \rangle N_{2p} / N$$

$V_2\{2\}$ nonflow

STAR, PRes 6 (2024) L032005, PRC 110 (2024) 014905



- $V_2\{ZDC\}(\eta)$ measurement $\rightarrow V_2\{ZDC\}(\Delta\eta) \rightarrow$ fit
- Flow decorrelation $1-2F_2\Delta\eta$, $F_2=1.15\% \pm 50\%$ (syst)
- Flow fluctuations effect: assumed constant over η
- Nonflow modelled by two Gaussians
- Fit flow + nonflow to $V_2(\Delta\eta)$

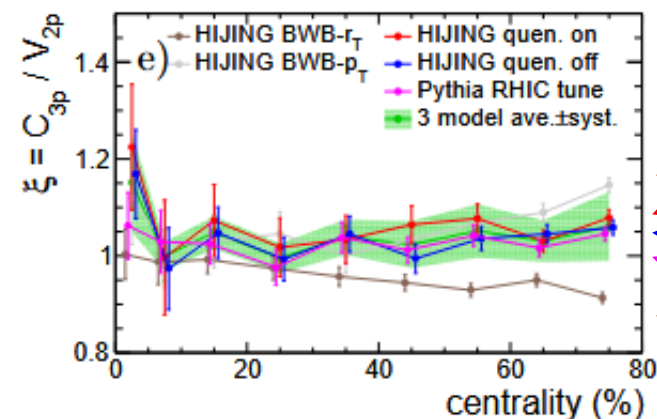
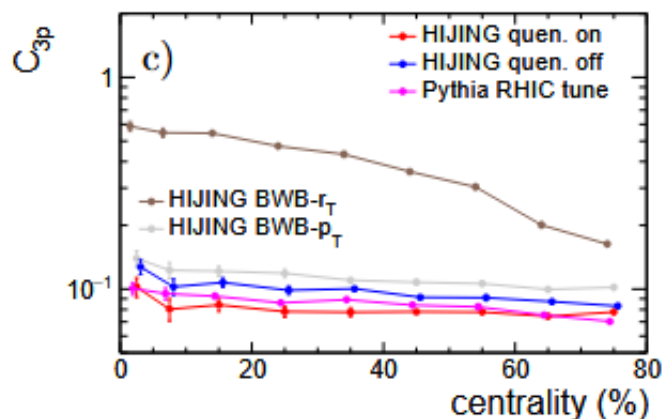
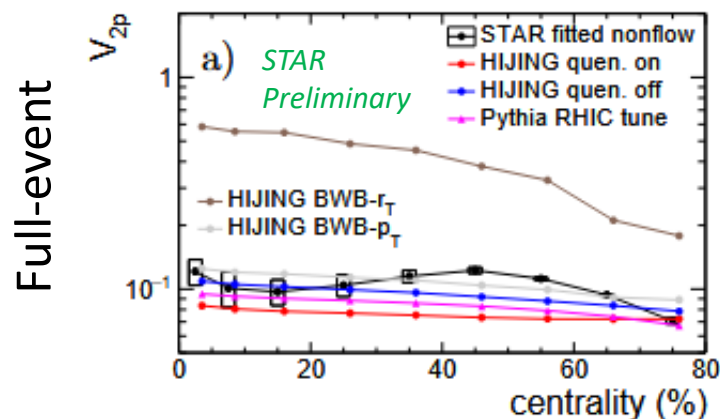


RP-independent 3-particle correlations

nonflow $V_{2p} = \cos 2(\phi_\alpha - \phi_c)$

RP-ind. $C_{3p} = \cos 2(\phi_\alpha + \phi_\beta - 2\phi_c)$

$\xi = C_{3p} / V_{2p}$



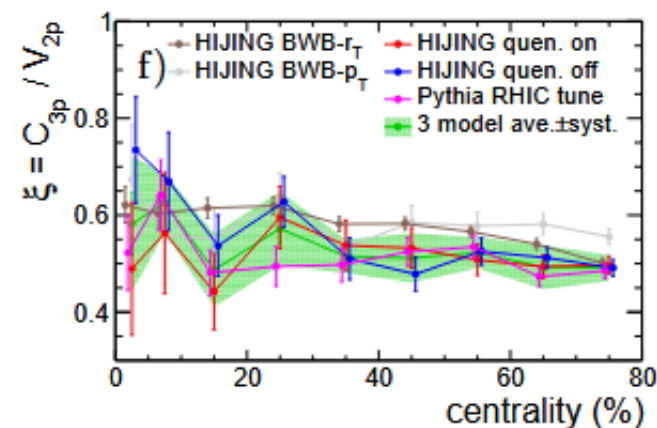
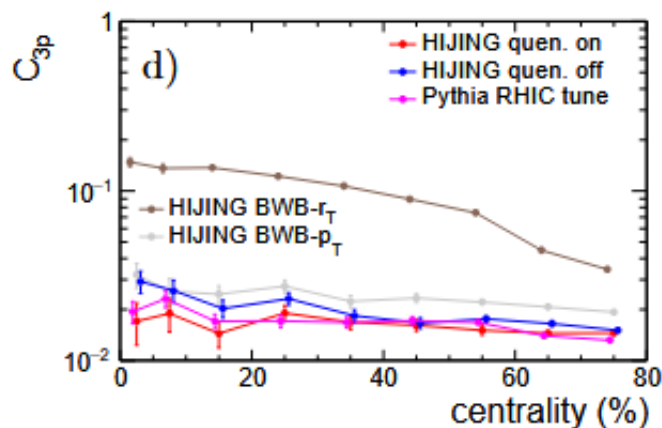
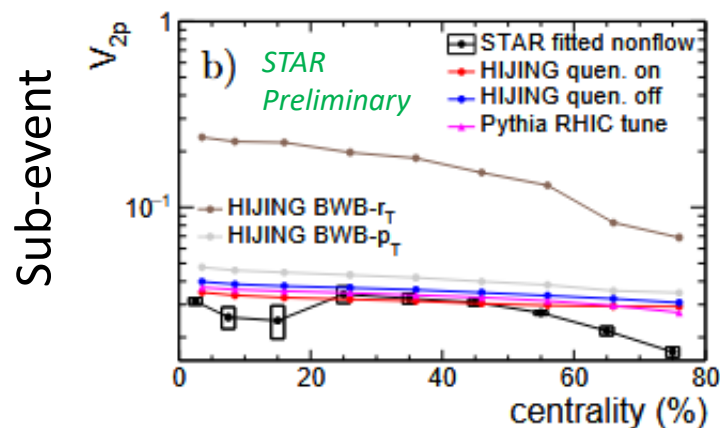
Hijing BWB-p_T

Hijing Q-on

Hijing Q-off

Pythia 8

Hijing BWB-r_T

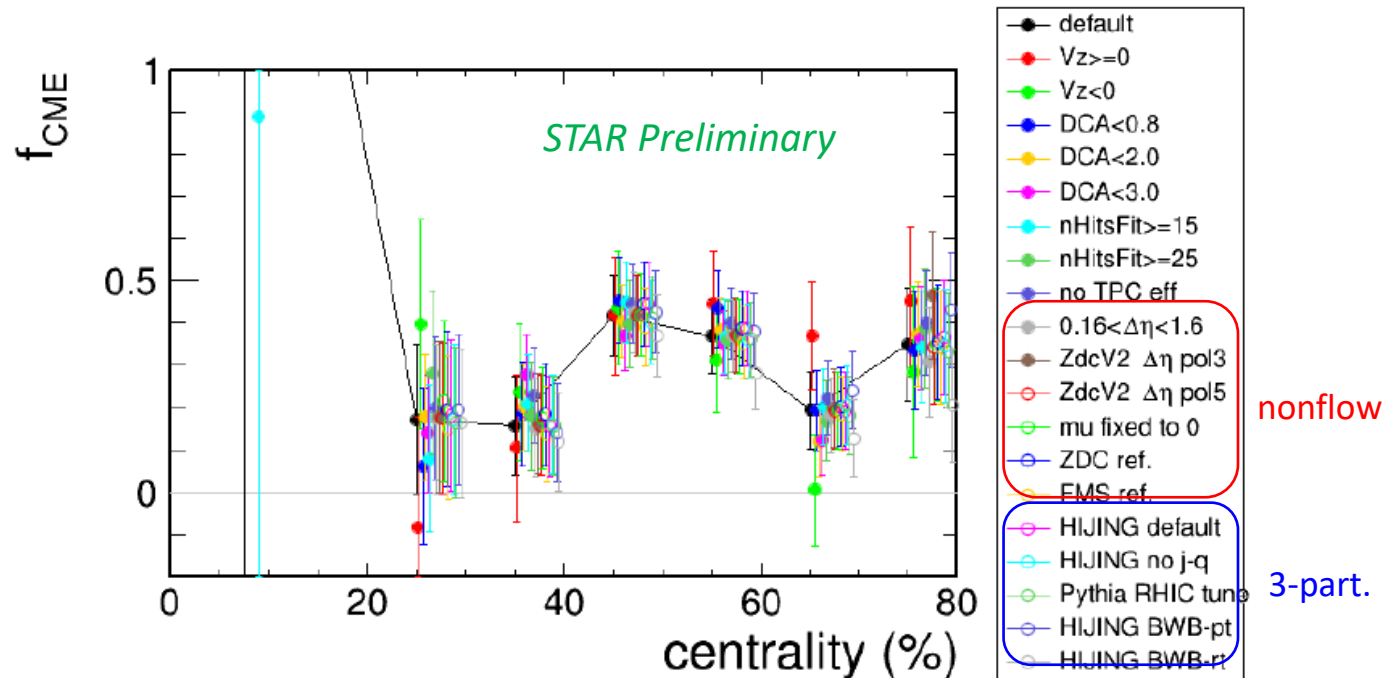


Continuing to investigate systematics

Systematic uncertainty assessment

Systematic variations in data analysis							
V_z [max]		DCA (cm)			Nhits		no eff.
≥ 0	< 0	< 0.8	< 2	< 3	≥ 15	≥ 25	[max]
Systematic variations in v_2 nonflow fit							
v_2^2 ZDC fit		fixed	fixed $\Delta\eta$	decorr. [max]			
poly3	poly5	$\mu_2 = 0$	0.16–1.6	ZDC	FMS		
Systematic variations in ξ							
HIJING	HIJING	Pythia	HIJING BWB [max]				
default	no quen.		BWB- p_T	BWB- r_T			

- Stat. fluctuations are removed from syst. uncertainties (Barlow's prescription)
- If multiple variations for a single systematic source, RMS is taken
- For [max] systematic ranges, take $\pm \text{RMS}/\sqrt{3}$
- Total syst uncertainty from quadrature sum of all sources



f_{CME} results

$$f_{\text{CME}} \equiv \frac{\Delta\gamma_{\text{CME}}^{\text{PP}}}{\Delta\gamma\{\text{TPC}\}} = \frac{\sqrt{1 + \epsilon_{\text{nf}}}}{\frac{1}{a^2} - (1 + \epsilon_{\text{nf}})} \left[\left(\frac{A}{a} - 1 \right) + \epsilon_{\text{nf}} \left(\frac{C_{3p}/V_{2p}}{(N_3 C_3)/(N_2 V_2)} - 1 \right) \right]$$

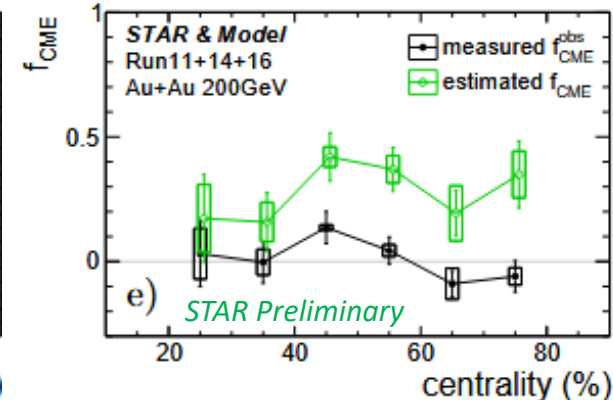
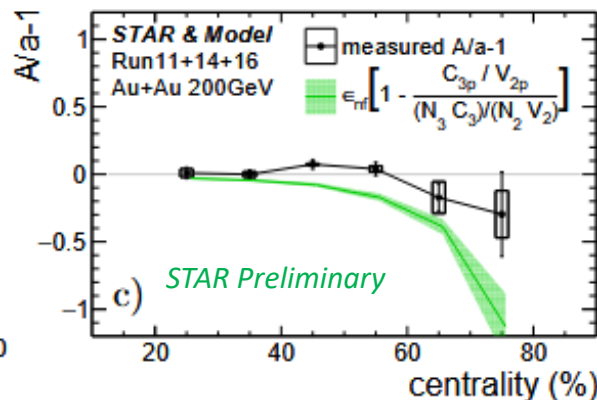
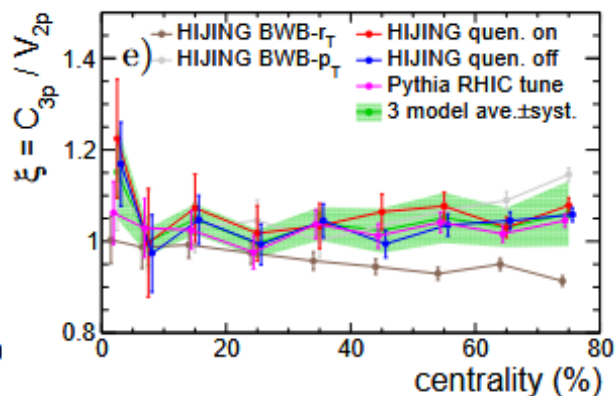
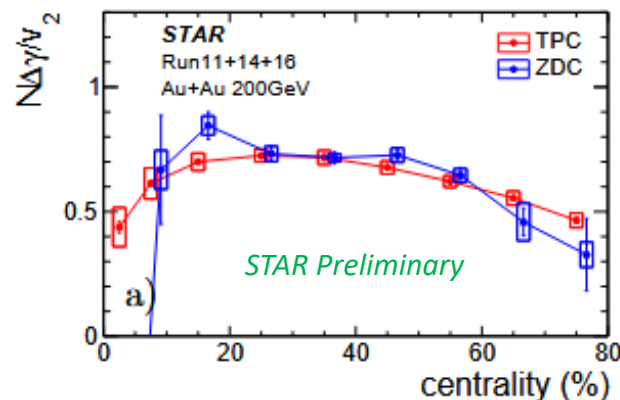
$N\Delta\gamma/v_2$
measurements

$\xi = C_{3p}/V_{2p}$
RP-ind. 3p/2p ratio

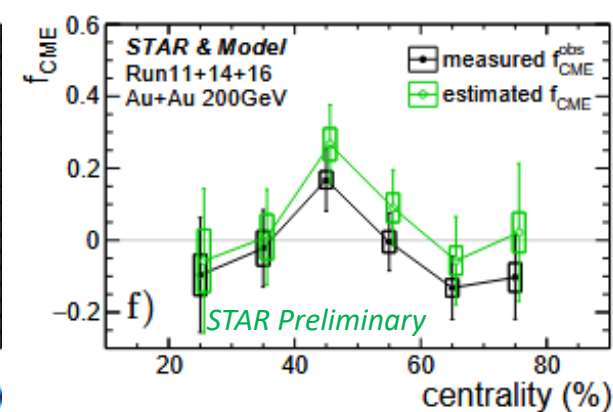
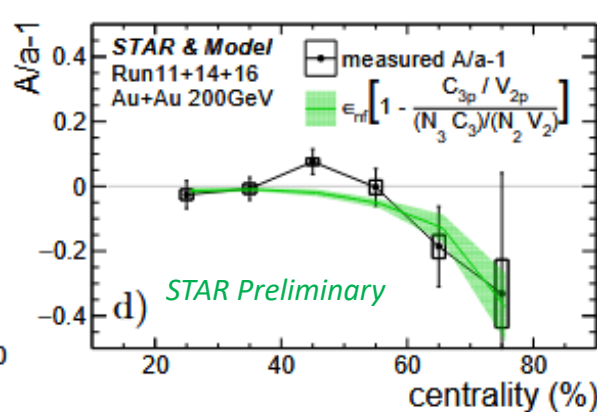
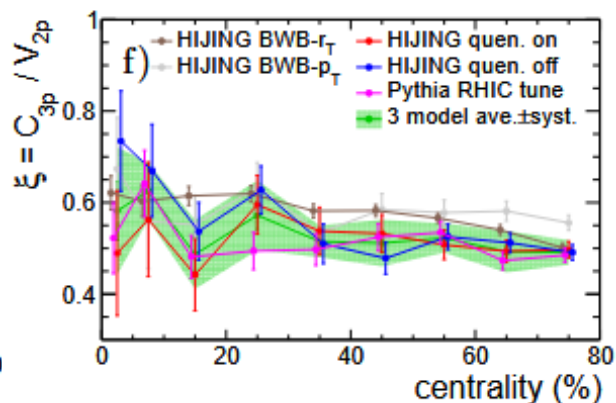
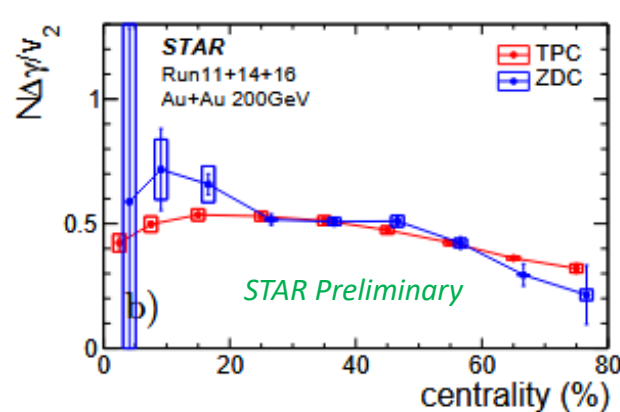
$A/a - 1$ measurements
and background estimates

Measured $f_{\text{CME}}^{\text{obs}}$ and
estimated f_{CME}

Full-event



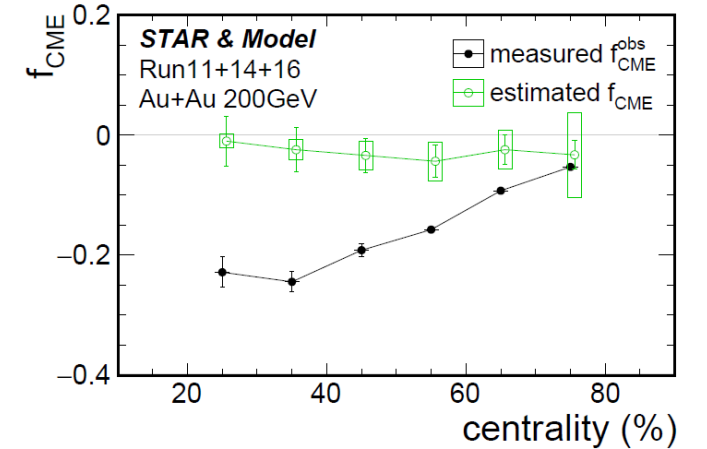
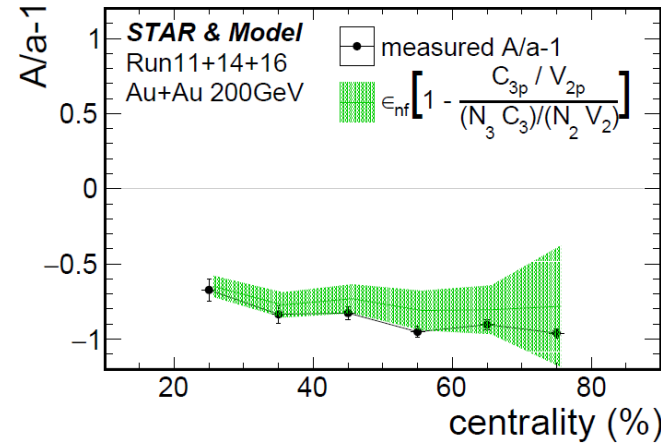
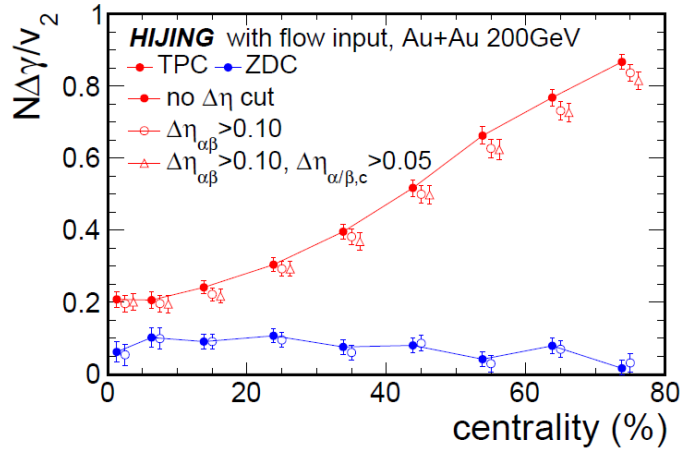
Sub-event



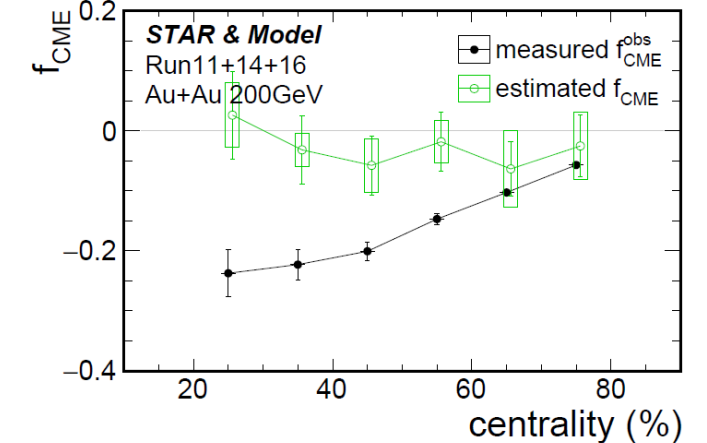
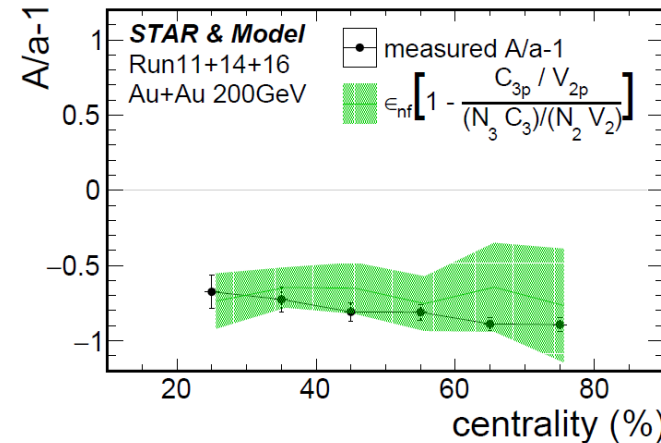
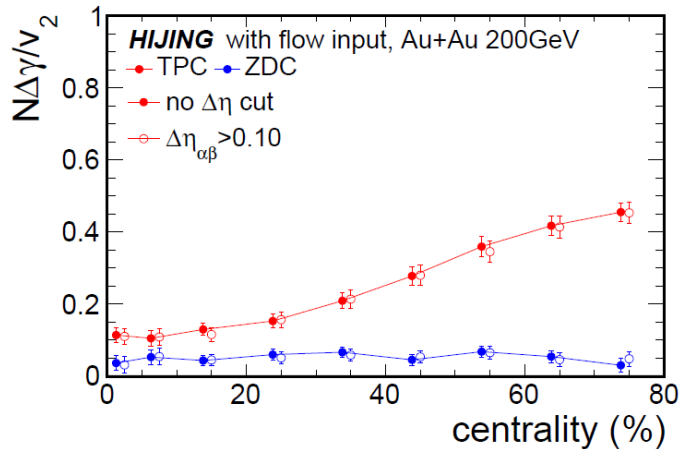
HIJING closure test checks out

- Apply v_2 -modulated weight. Input $v_2 = 0.05p_T$ for $p_T < 2$ GeV/c, saturate at $v_2 = 0.1$. No centrality dependence.
- PP fluctuates randomly about RP (=0) event by event, with Gaussian sampling of width $\pi/6$.
- The default HIJING (without flow input) is taken as nonflow.

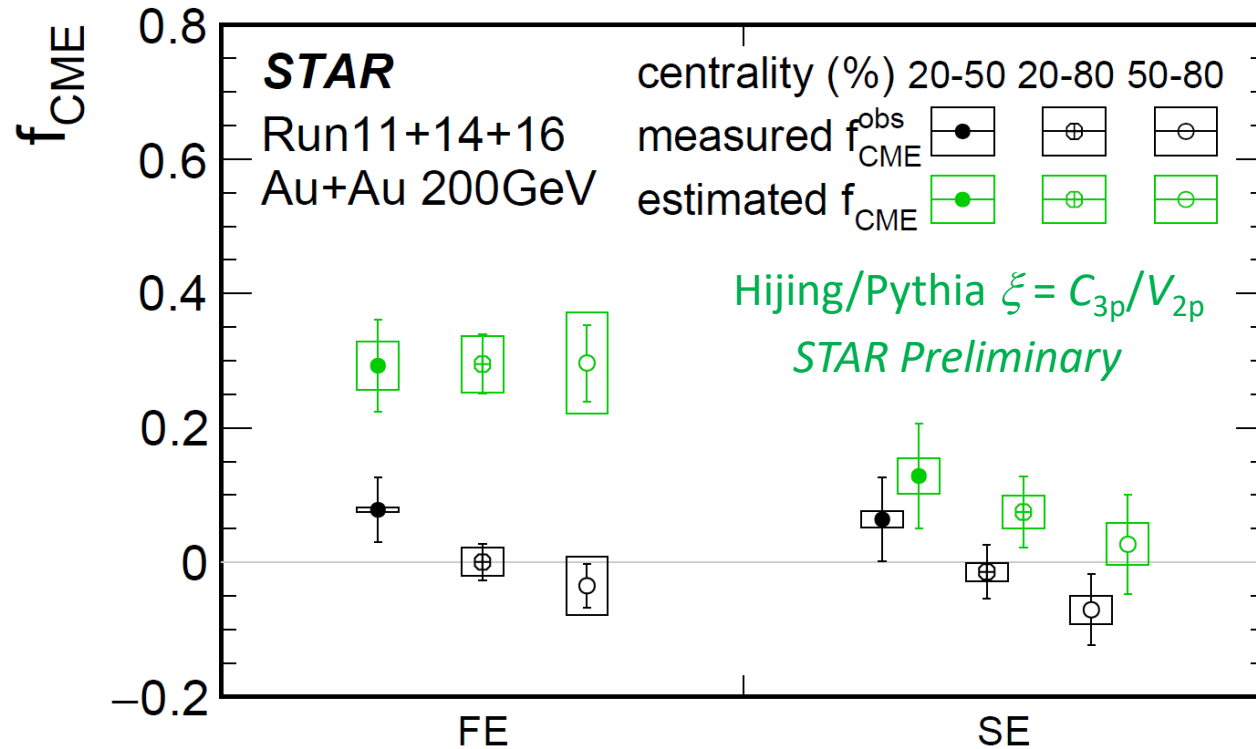
Full-event



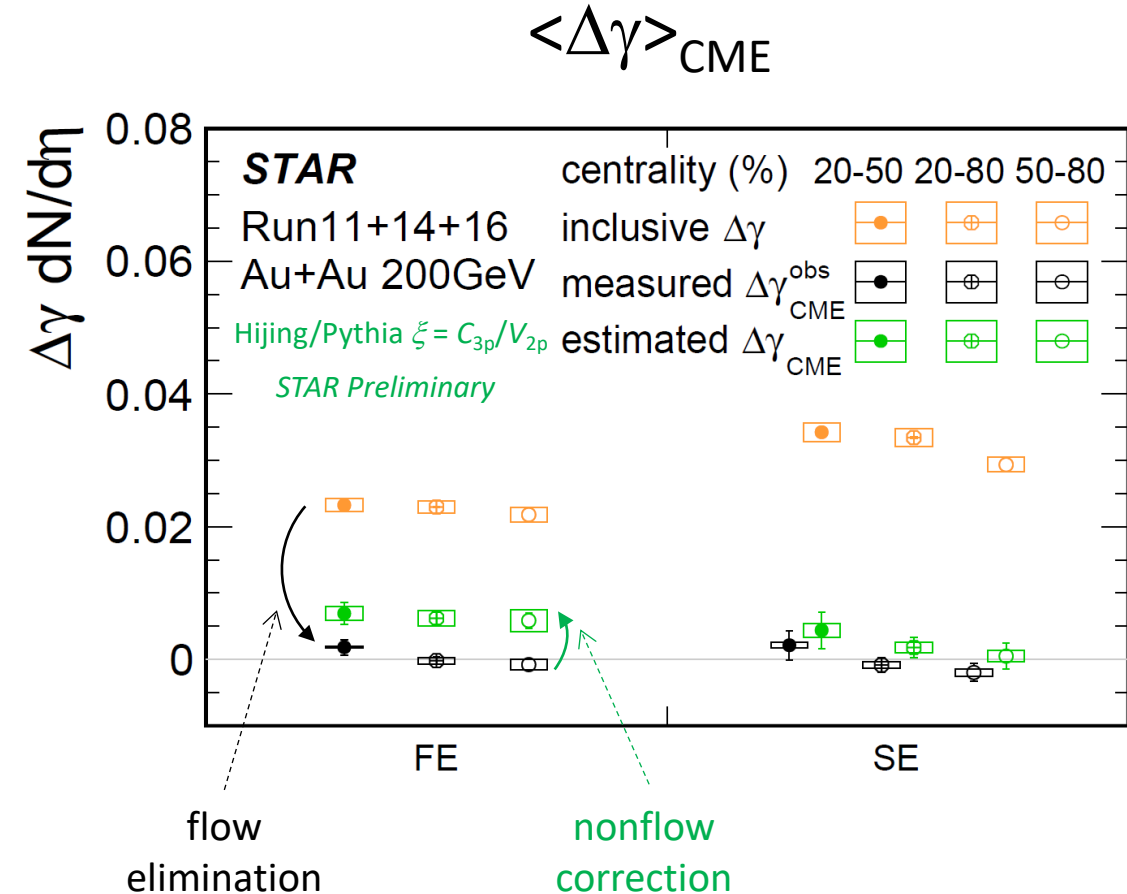
Sub-event



Centrality-averaged $\langle f_{\text{CME}} \rangle$



- Significant f_{CME} in full-event
- Weak centrality dependence
- f_{CME} full-event > sub-event; $\Delta\gamma_{\text{CME}}$ compatible in 20-50% centrality.

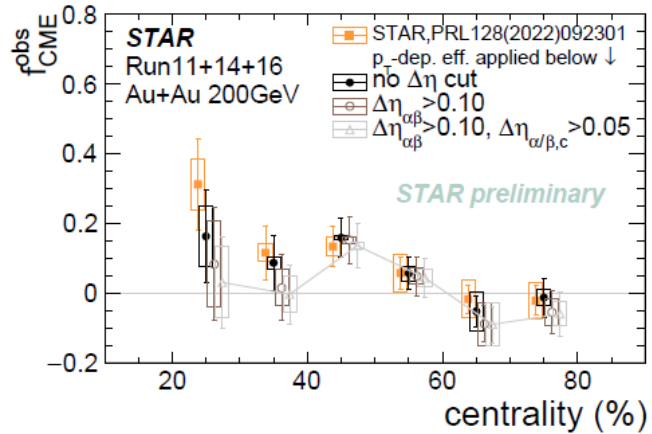


Summary

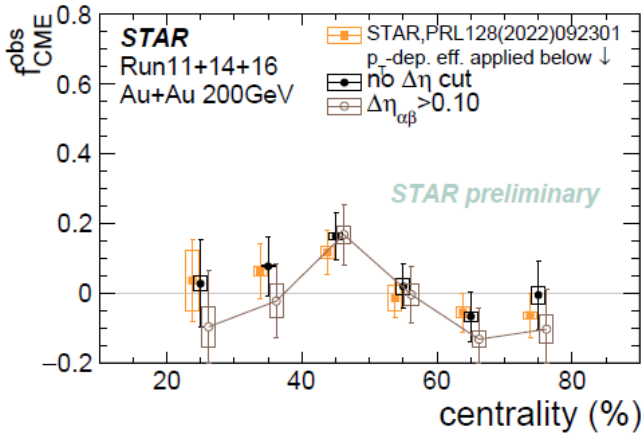
- Flow-induced background is well understood and under control by SP/PP comparison measurements. CME fraction in Au+Au 200 GeV data revisited.
- Additional backgrounds from nonflow v_2 contamination and RP-independent 3-particle correlations
 - Decomposition of flow and nonflow via a fitting procedure
 - The genuine 3-particle/2-particle correlation ratio ($\xi = C_{3p}/V_{2p}$) has weak dependency on the QCD-inspired models studied and is robust against collective radial flow
 - Assume model ξ to correct for RP-independent 3-particle correlations
- f_{CME} extracted. Further scrutiny, e.g. MC/model closure underway.

$f_{\text{CME}}^{\text{obs}}$ results

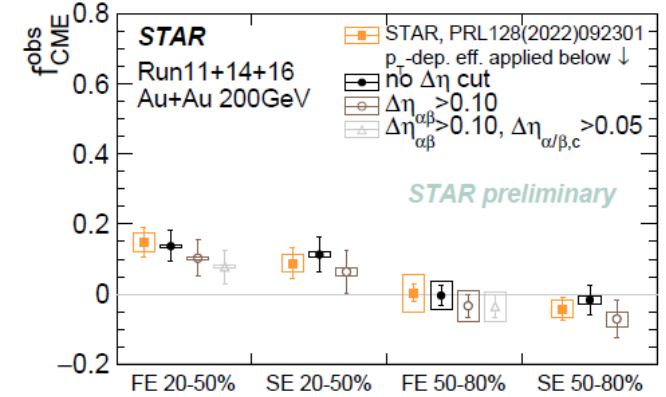
full-event $f_{\text{CME}}^{\text{obs}}$



sub-event $f_{\text{CME}}^{\text{obs}}$



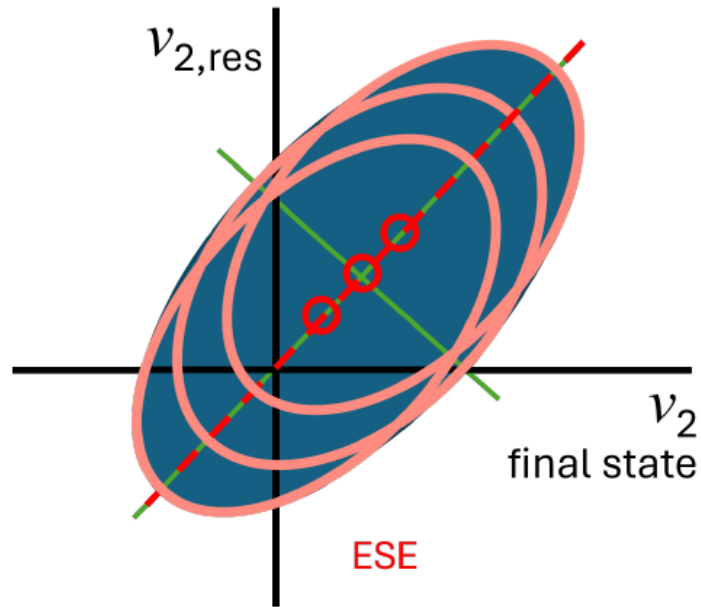
centrality-averaged $\langle f_{\text{CME}}^{\text{obs}} \rangle$



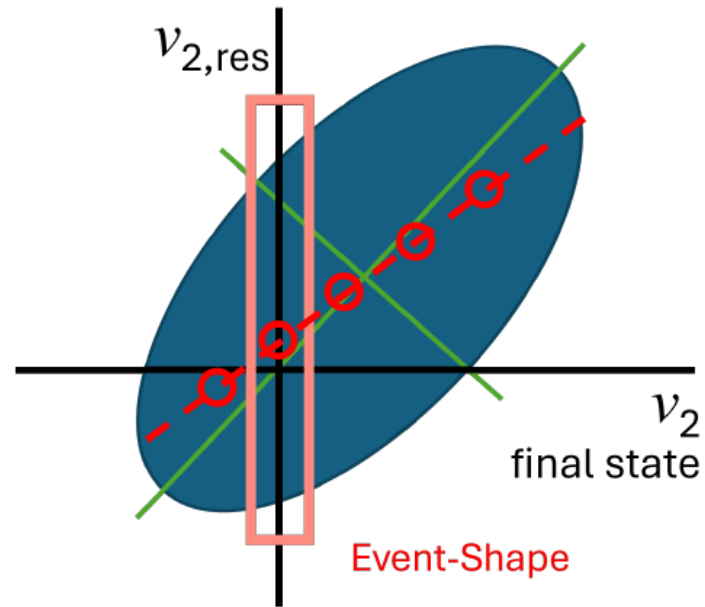
- $f_{\text{CME}}^{\text{obs}}$ published previously by STAR [PRL 128 \(2022\) 092301](#)
- This analysis used the same data, with improved analysis cuts and systematic studies:
 - p_{T} -dependent efficiency correction is applied
 - $\Delta\eta$ cuts between POIs and between POI and particle c are applied
 - Systematic uncertainties are assessed with corresponding efficiency corrections
- Results are $\sim$ consistent given the p_{T} -dependent efficiency correction and $\Delta\eta$ cuts

Event-shape engineering methods

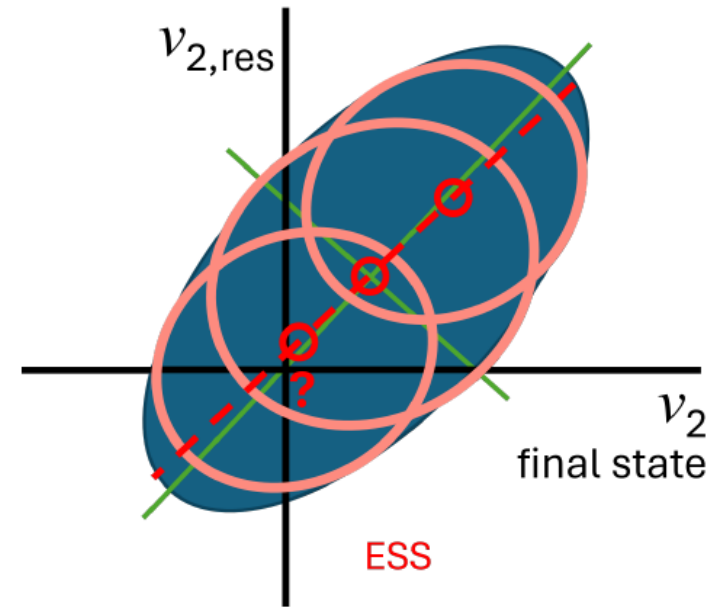
H.-S. Li, Y. Feng, FW, arXiv:2407.14489



LHC method



STAR, PRC 89 (2014) 044908



STAR, arXiv:2506.00278