9th Conference on Chirality, Vorticity and Magnetic Fields in Quantum Matter
ICTP-SAIFR, São Paulo, Brazil

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

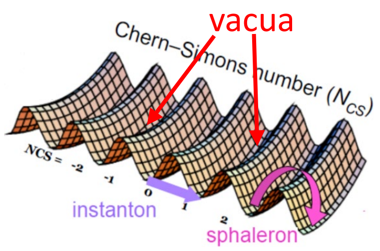
Fuqiang Wang
Purdue University
(for the STAR Collaboration)

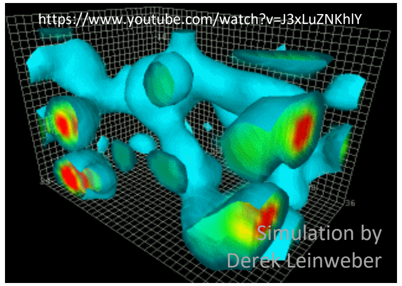
Why CME?

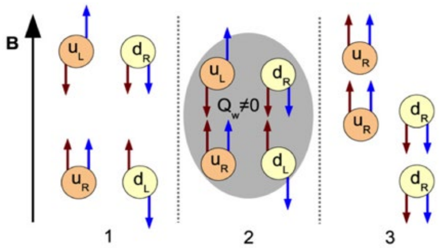
VOLUME 81, NUMBER 3 PHYSICAL REVIEW LETTERS 20 JULY 1998

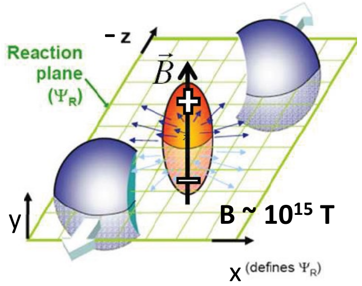
Possibility of Spontaneous Parity Violation in Hot QCD

Dmitri Kharzeev,[1] Robert D. Pisarski,[2] and Michel H. G. Tytgat[2,3]
[1]*RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973-5000*
[2]*Department of Physics, Brookhaven National Laboratory, Upton, New York 11973-5000*
[3]*Service de Physique Théorique, CP 225, Université Libre de Bruxelles, Boulevard du Triomphe, 1050 Bruxelles, Belgium*
(Received 3 April 1998)









QCD vacuum fluct. Topological gluon field → Chiral anomaly Chirality imbalance → Strong magnetic field Charge separation

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

Fundamentally important physics

Heavy ion collisions are a good place to look for it

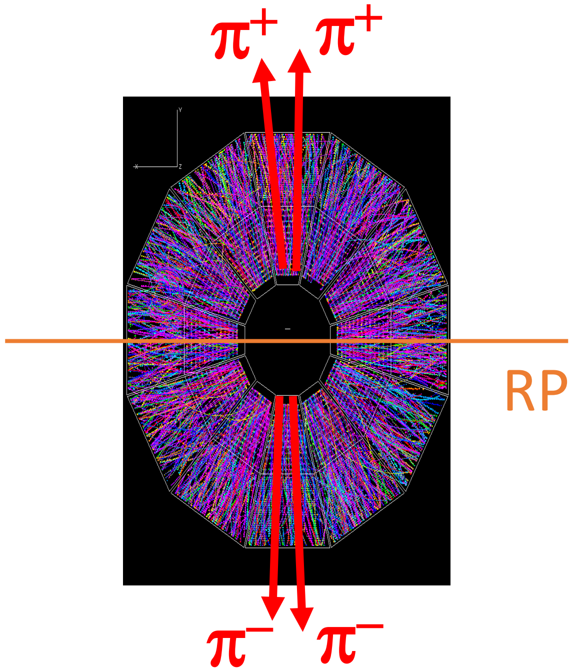
Outline:

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

How to look for it?

Voloshin, PRC 2004
STAR, PRL 2009, PRC 2010

Look for charge separation

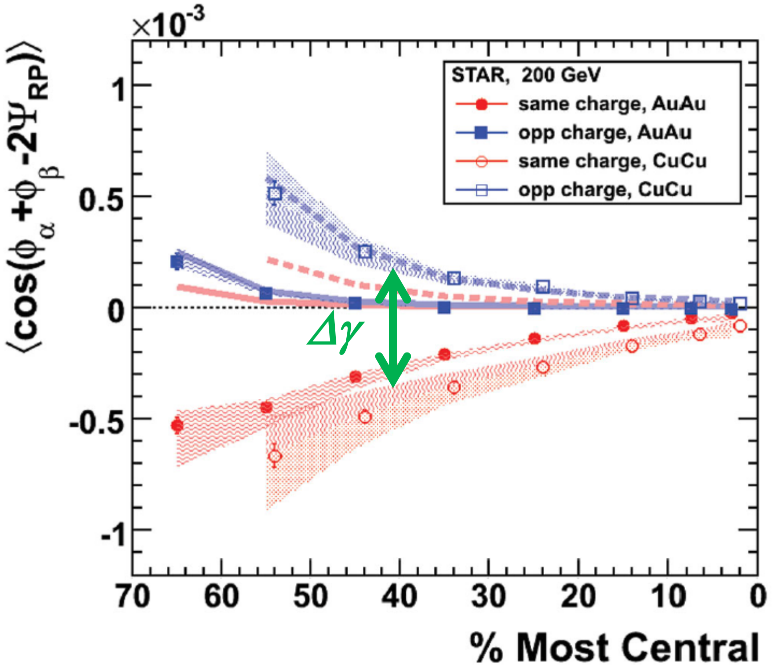


<u>$\Delta\gamma$ correlator</u>

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

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

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



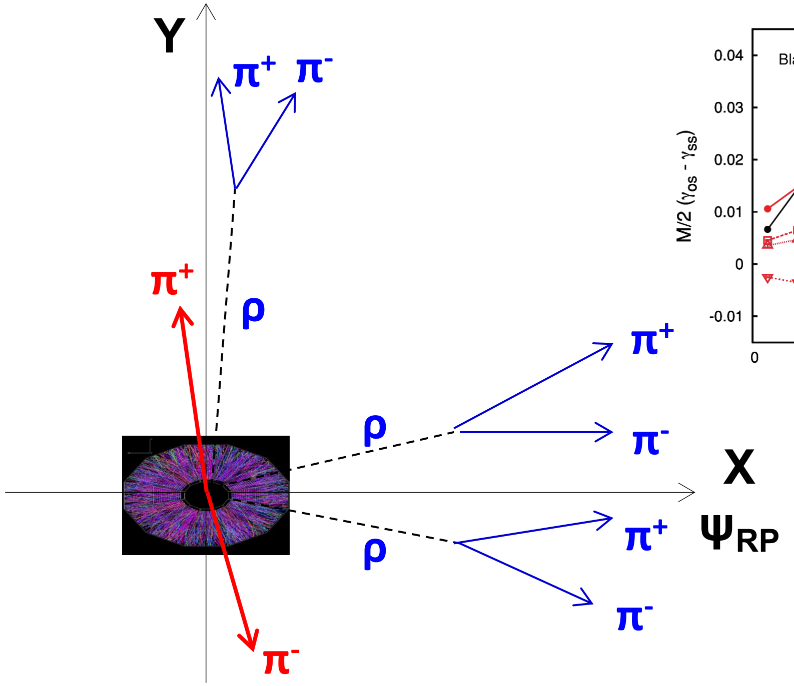
Significant $\Delta\gamma$ observed

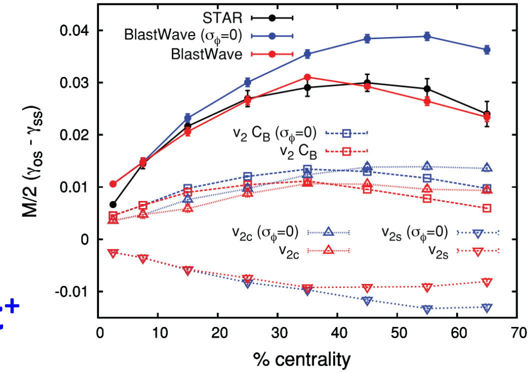
Flow-induced background is large

Voloshin 2004
FW 2009
Bzdak, Koch, Liao 2010
Pratt, Schlichting 2010

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

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





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

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

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

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

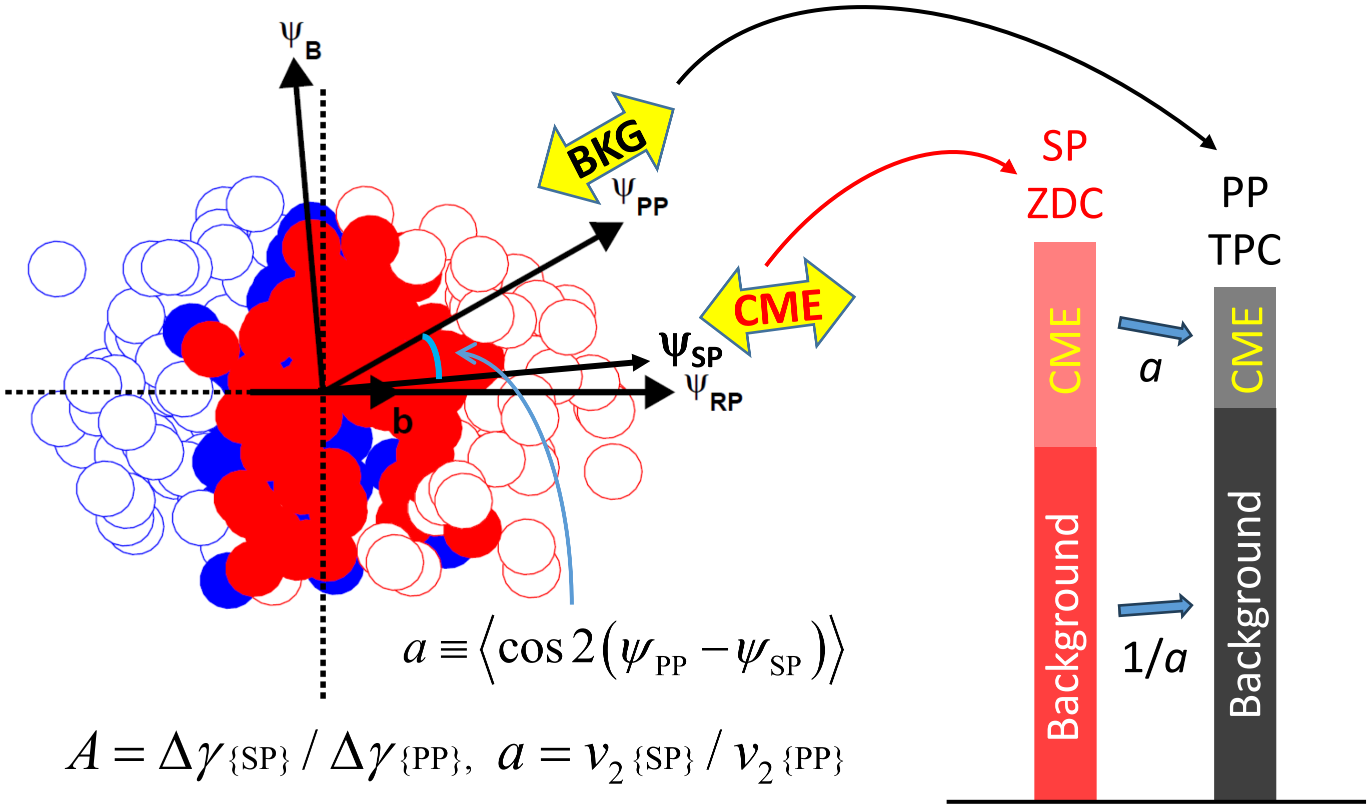
$$\Delta\gamma = 2\left\langle a_1^2 \right\rangle + \boxed{\frac{N_\rho}{N_\alpha N_\beta} \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_\rho) \right\rangle v_{2,\rho}}$$

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

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

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

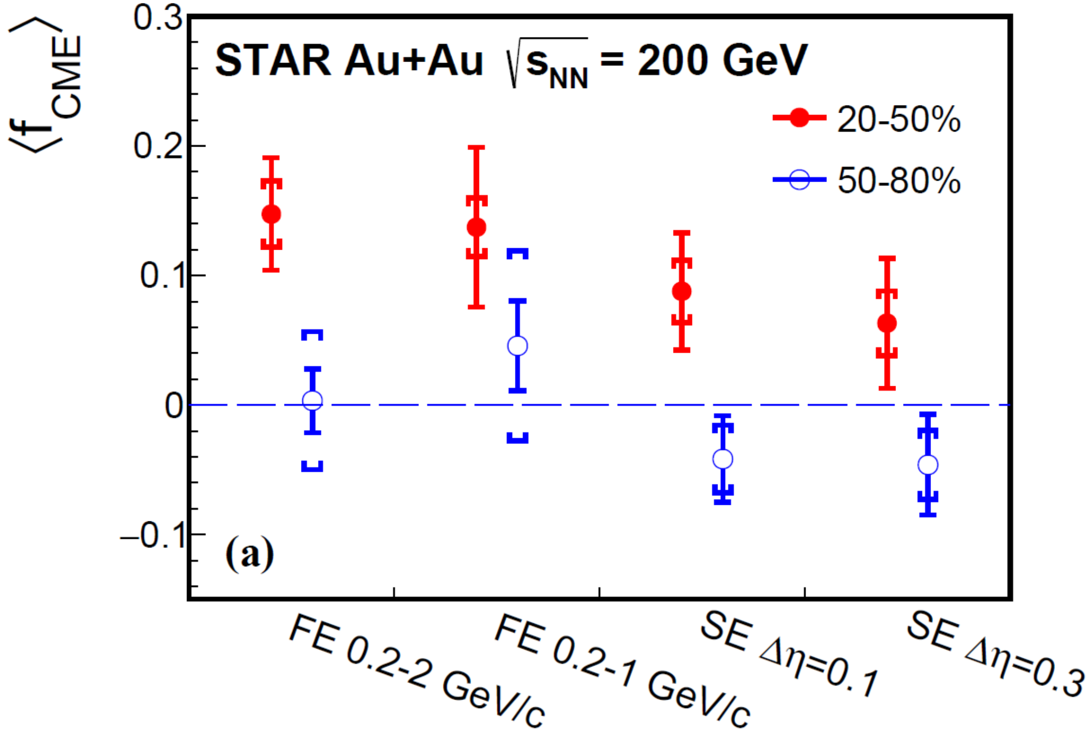
H.-j. Xu, et al., CPC 42 (2018) 084103
S.A. Voloshin, PRC 98 (2018) 054911
STAR, PRL 128 (2022) 092301



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

$$A = \Delta\gamma\{\rm SP\} / \Delta\gamma\{\rm PP\},\ \ a = v_2\{\rm SP\} / v_2\{\rm PP\}$$

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



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

- Peripheral 50-80%: consistent with zero
- Midcentral 20-50%: ~2-3σ significance

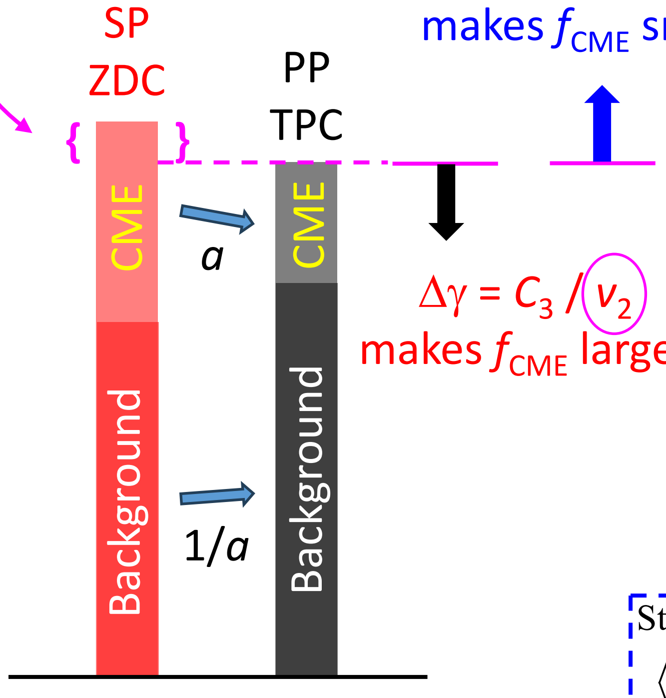
Nonflow contamination

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

CME signal is this difference

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

genuine 3p correl. makes f_{CME} smaller



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

Assume: $\xi = C_{3p}/V_{2p}$ data = model

$V_2\{2\}$ nonflow contamination

$\frac{\text{3p nonflow}}{\text{2p nonflow}}$

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

measurement ZDC/TPC - 1

measurement $N\Delta\gamma/v_2$

3-particle correlations primarily from (di-)jets

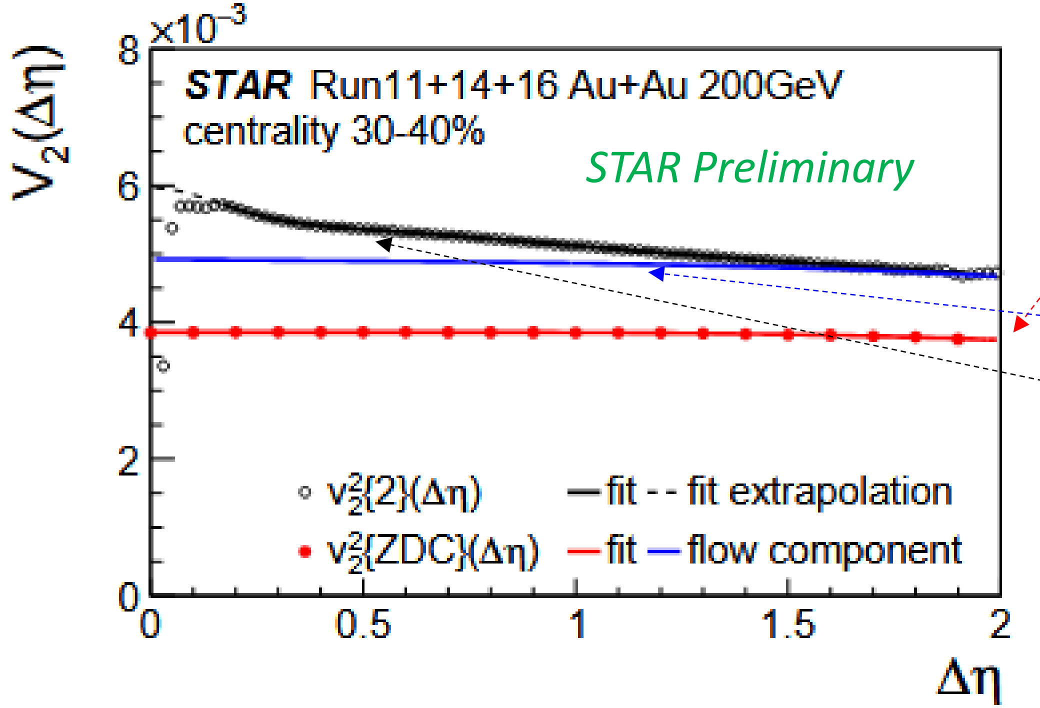
Stochastic jet fragmentation: fragment emission sampling an underlying distribution but otherwise uncorrelated

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

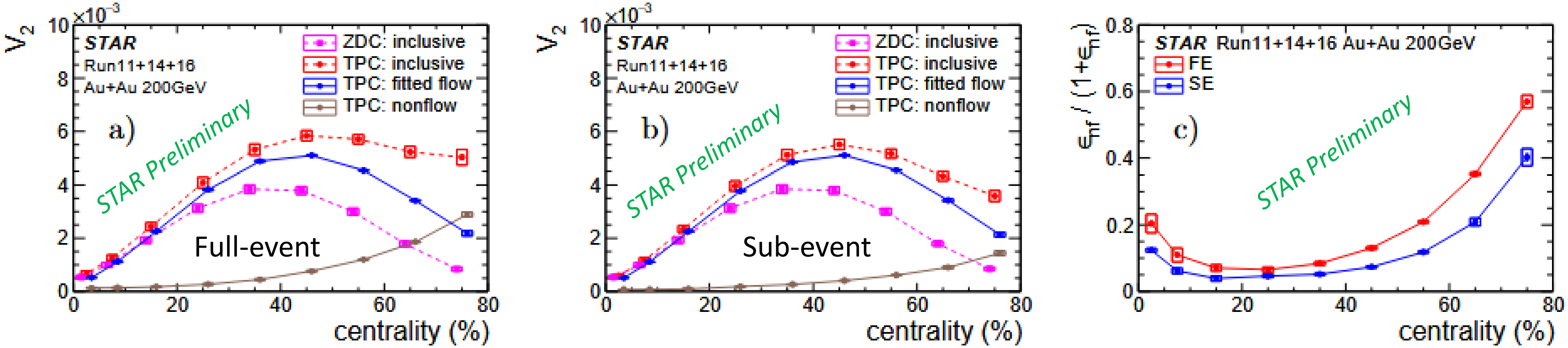
$$C_{3\mathrm{p}} = \langle \cos(\alpha+\beta-2c) \rangle N_{3\mathrm{p}} / N \quad , \quad V_{2\mathrm{p}} = \langle \cos 2(\alpha-c) \rangle N_{2\mathrm{p}} / N$$

$V_2\{2\}$ nonflow

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



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

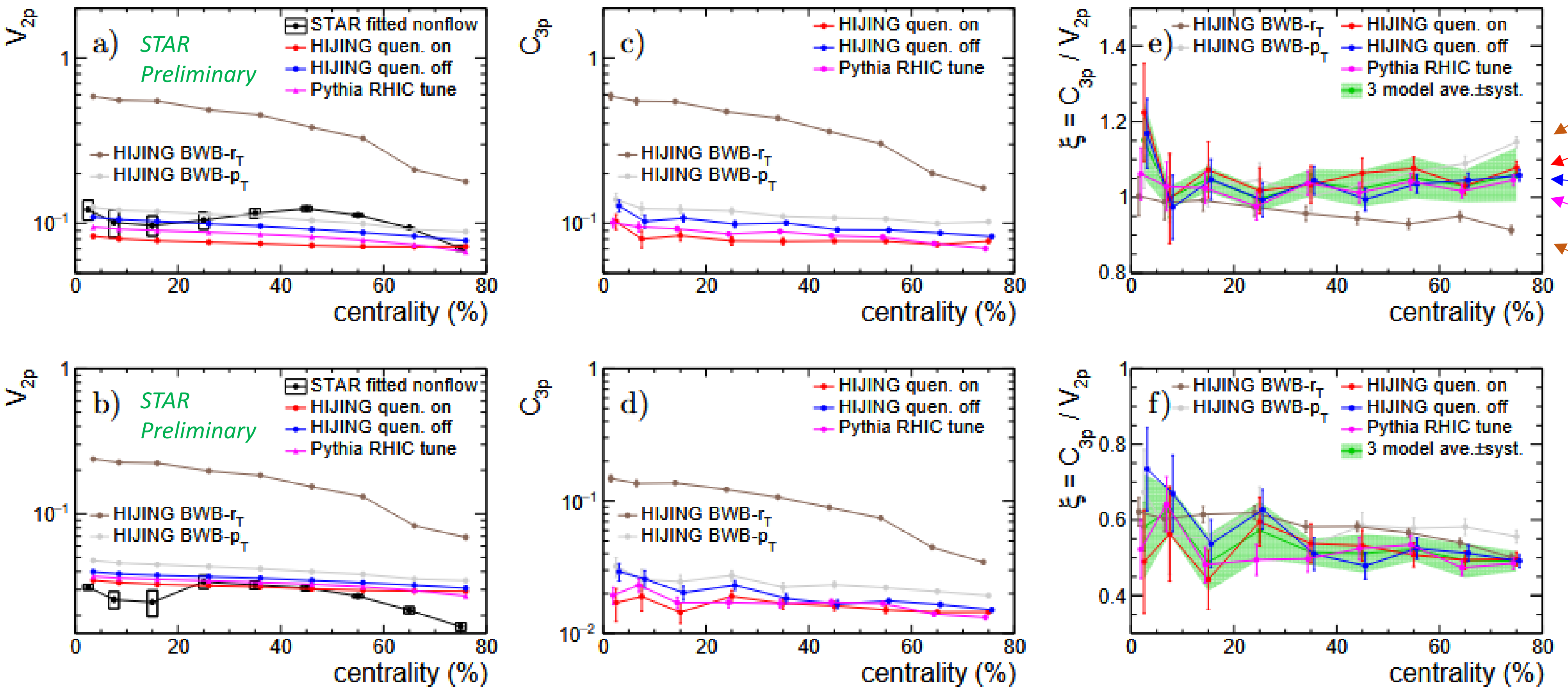


RP-independent 3-particle correlations

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

Full-event

Sub-event



Hijing BWB-p_T

Hijing Q-on

Hijing Q-off

Pythia 8

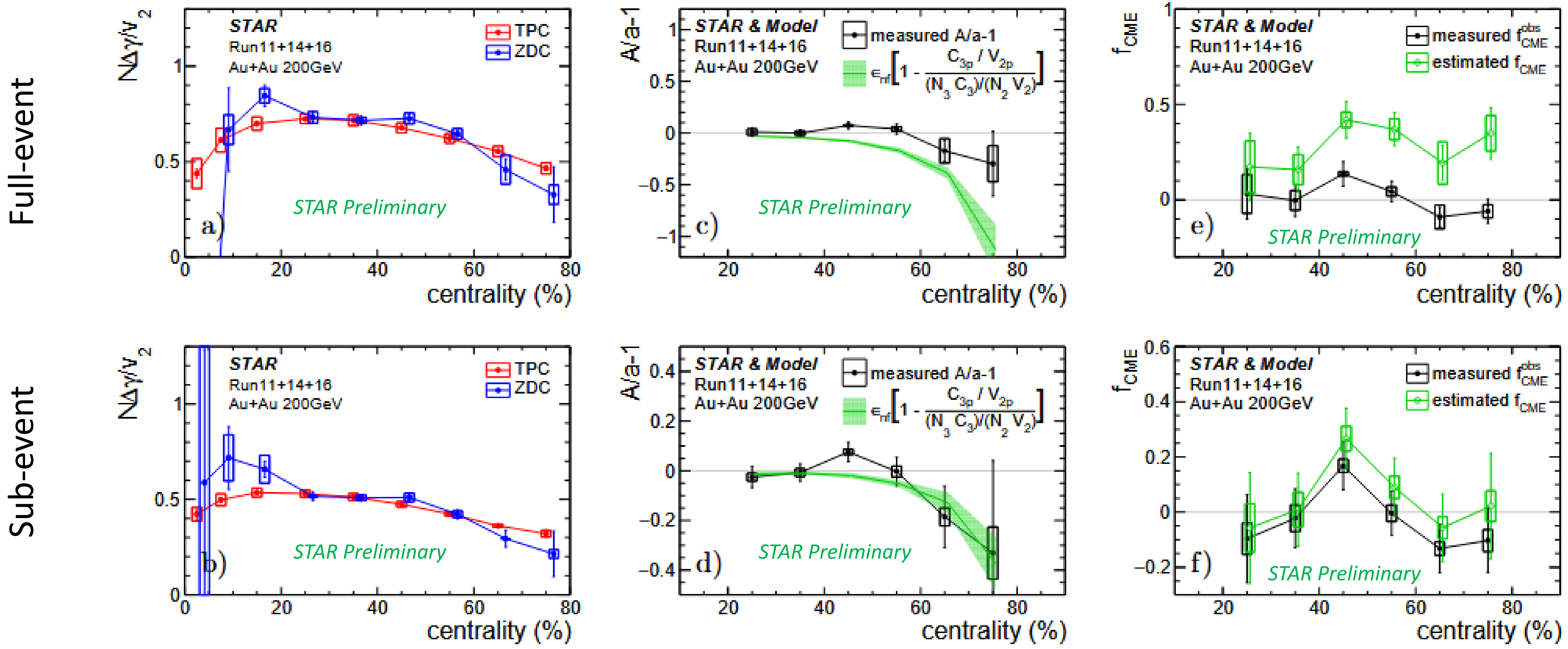
Hijing BWB-r_T

f_{CME} results

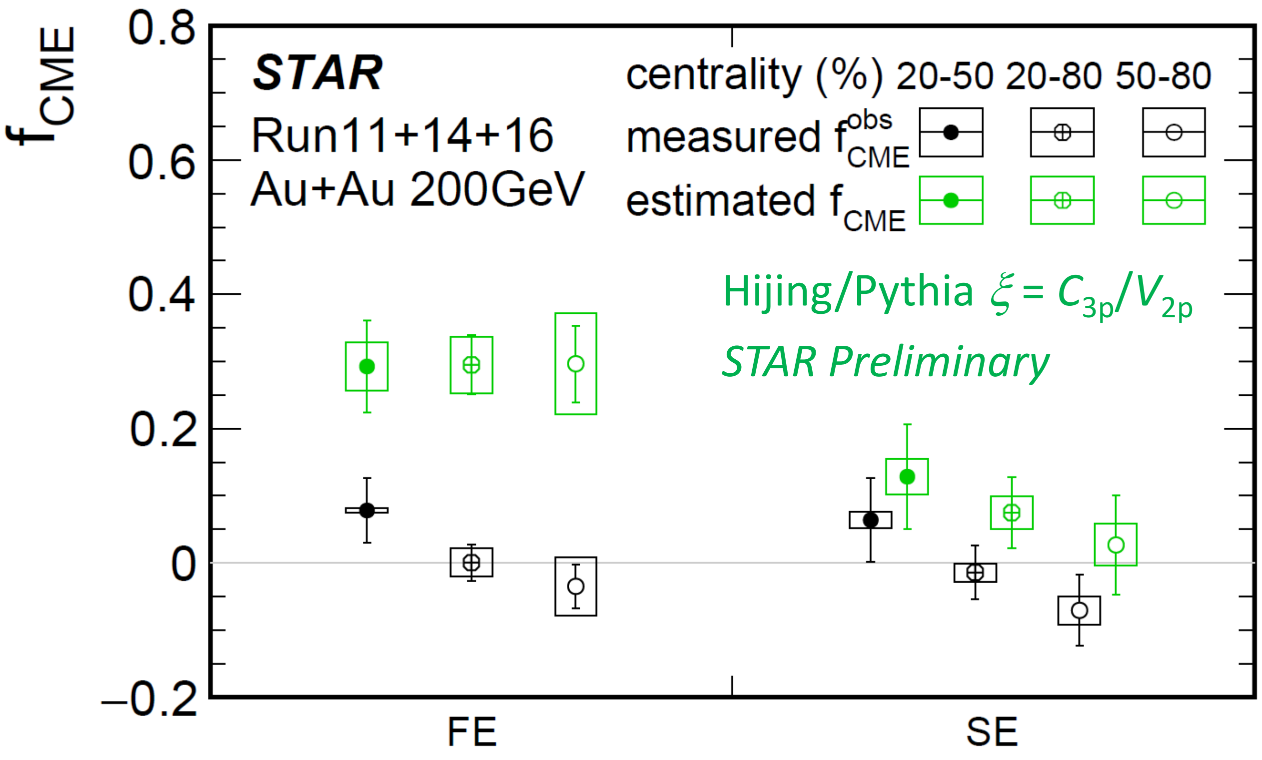
$N\Delta\gamma/v_2$ measurements

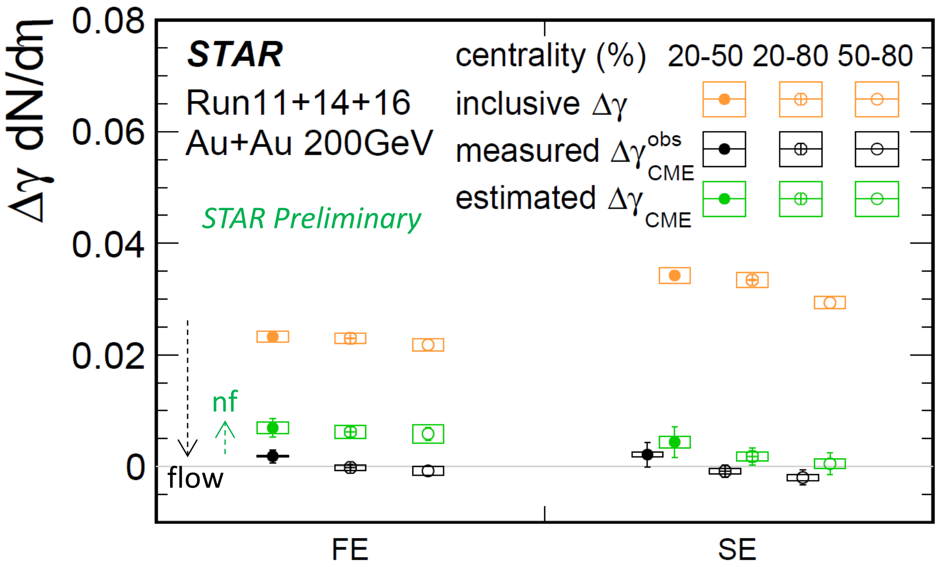
$A/a-1$ measurements and background estimates

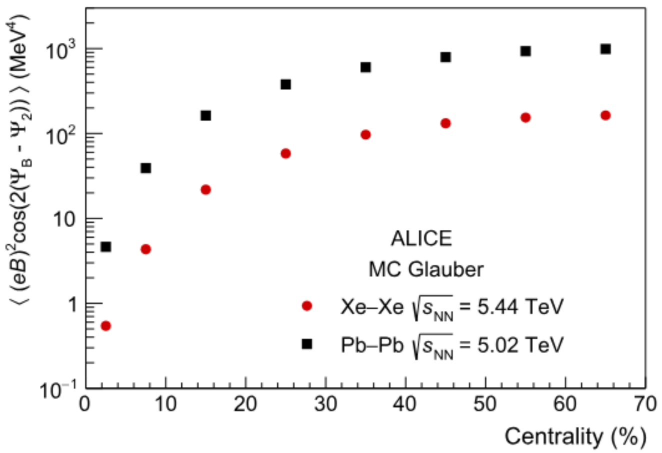
Measured $f_{\mathrm{CME}}^{\mathrm{obs}}$ and estimated f_{CME}



Average <f_{CME}>







- Significant f_{CME} in full-event
- Little centrality dependence
- f_{CME} full-event > sub-event; $\Delta\gamma_{CME}$ compatible

STAR, PRC 105 (2022) 014901
Feng et al., PLB 820 (2021) 136549
ALICE, PLB 856 (2024) 138862

Isobar signal/noise ratio can be x10 smaller:

- ~3 net effect of magn. field strength and background
- ~several from de-correl. between magn. field & EP

Summary

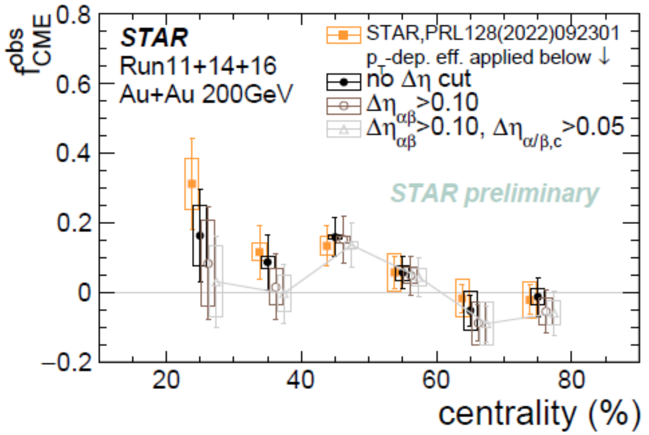
- Flow-induced background is well understood and under control by SP/PP comparison measurements

- Additional backgrounds from nonflow v2 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 model dependency and is robust against collective radial flow
  - **Assume model ξ to correct for RP-independent 3-particle correlations**

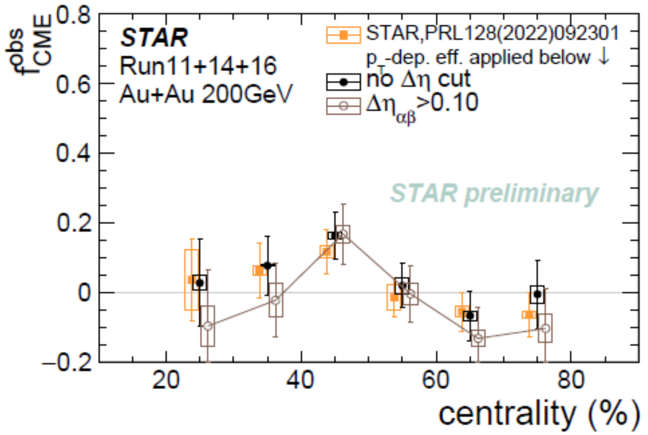
- f_{CME} extracted. Further scrutiny, e.g. MC closure.

f_{CME}^{obs} results

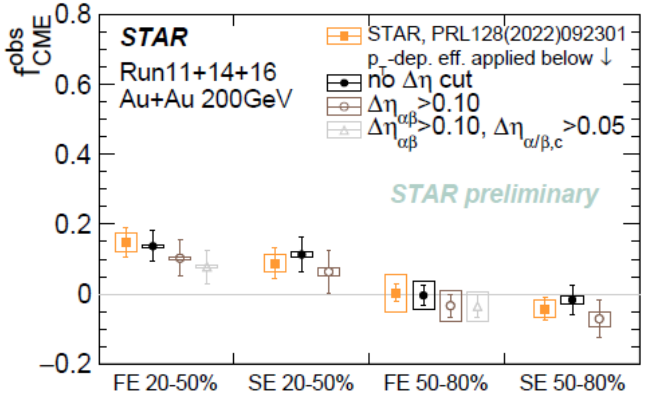
full-event



sub-event



$< f_{CME}^{obs} >$



- f_{CME}^{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
  - Δη cuts between POIs and between POI and particle *c* are applied
  - Systematic uncertainties are assessed with corresponding efficiency corrections
- Results are ~consistent given the p_T-dependent efficiency correction and Δη cuts

Systematic uncertainty assessment

Systematic variations in data analysis								
V_z [max]		DCA (cm)			Nhits		no eff. [max]	
≥ 0	< 0	< 0.8	< 2	< 3	≥ 15	≥ 25		

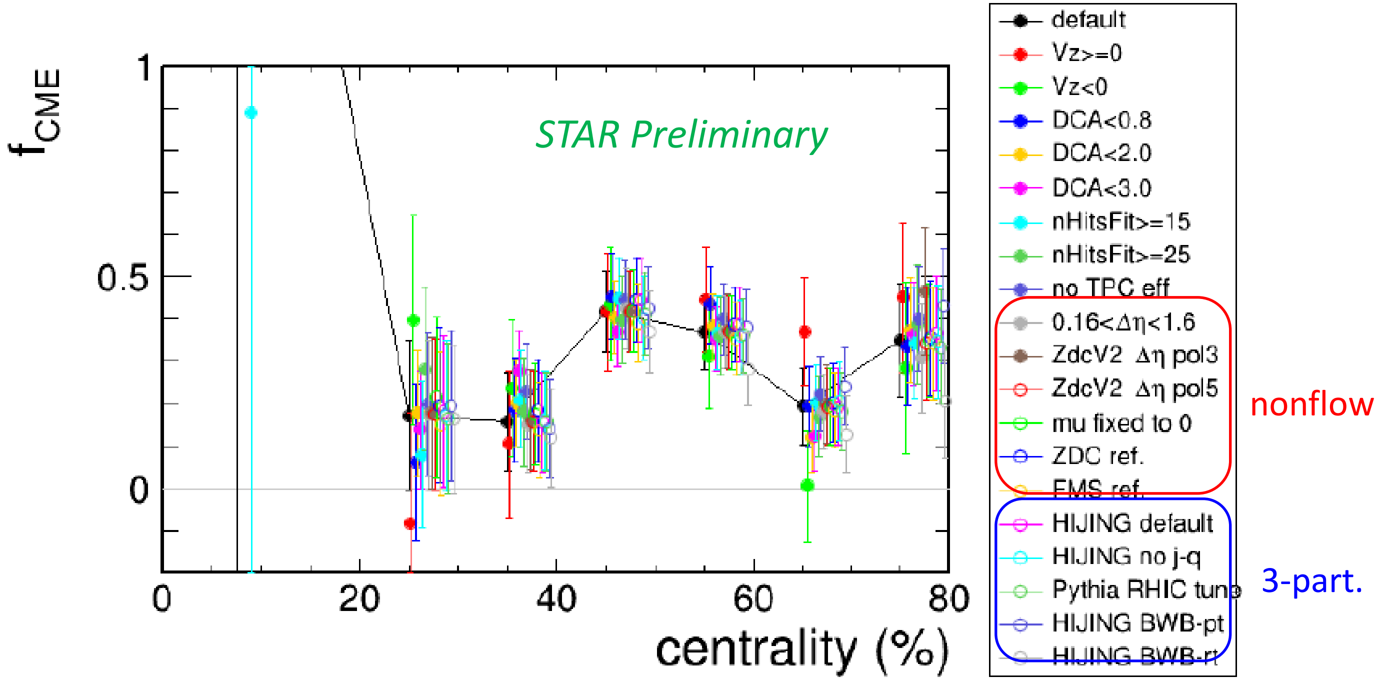
Systematic variations in v_2 nonflow fit					
v_2^2ZDC fit		fixed	fixed $\Delta\eta$	decorr. [max]	
poly3	poly5	$\mu_2 = 0$	0.16–1.6	ZDC	FMS

Systematic variations in ξ				
HIJING default	HIJING no quen.	Pythia	HIJING BWB [max]	
			BWB-p_T	BWB-r_T

- For a quantity x, its default measurement is x_0 with statistical uncertainty e_0, and it has systematic variations $x_i \pm e_i$.
- The differences are $d_i = x_i - x_0$.
- The systematic uncertainty from each variation is s_i. If we use Barlow's check

$$\text{if } d_i \geq \sqrt{|e_i^2 - e_0^2|}, \text{ then } s_i = \sqrt{d_i^2 - |e_i^2 - e_0^2|}$$
$$\text{else } s_i = 0$$

- For n_j variations from the same sources (e.g., multiple cuts on one quantity, set Q_j) $s_{i \in Q_j}$, RMS is used by default.
- Combining all those variations in quadrature



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