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

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STAR

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Why CME?

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Possibility of Spontaneous Parity Violation in Hot QCD

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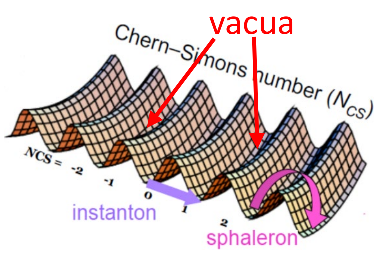
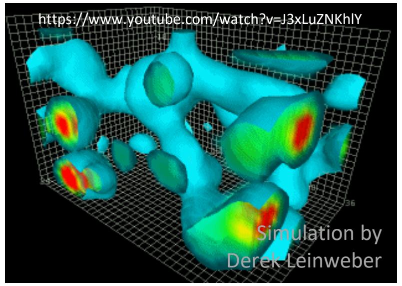
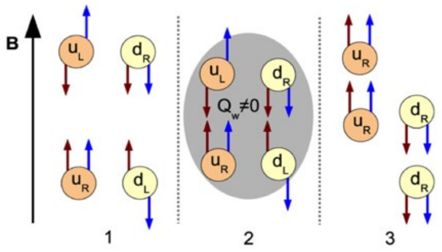
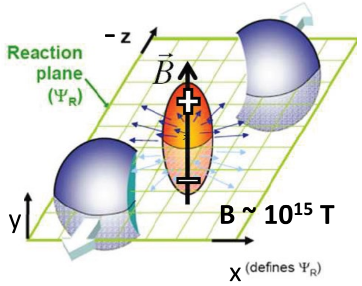








QCD vacuum fluct.
Topological gluon field

→

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

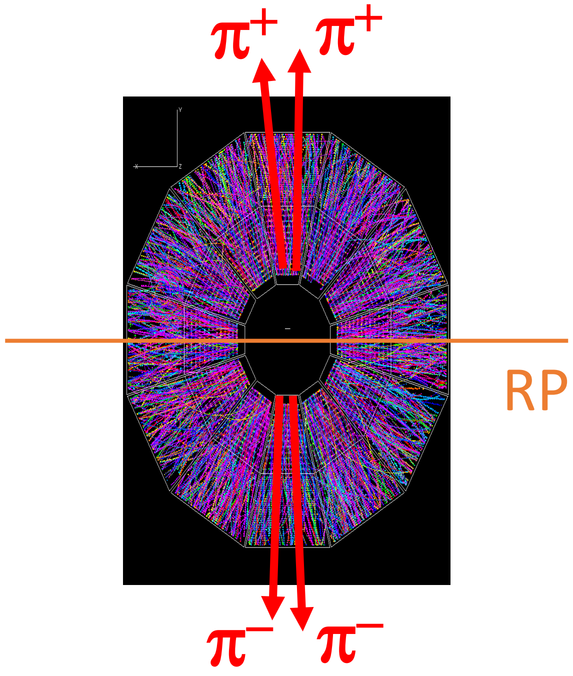
Outline:

- 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

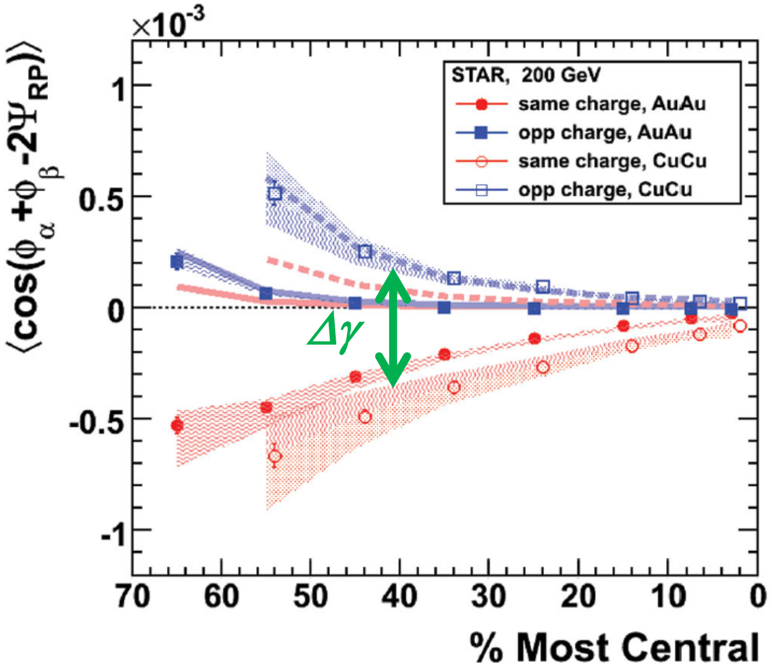


<u>Δγ correlator</u>

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

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

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



Significant Δγ (charge separation across RP) observed

Flow-induced background is large

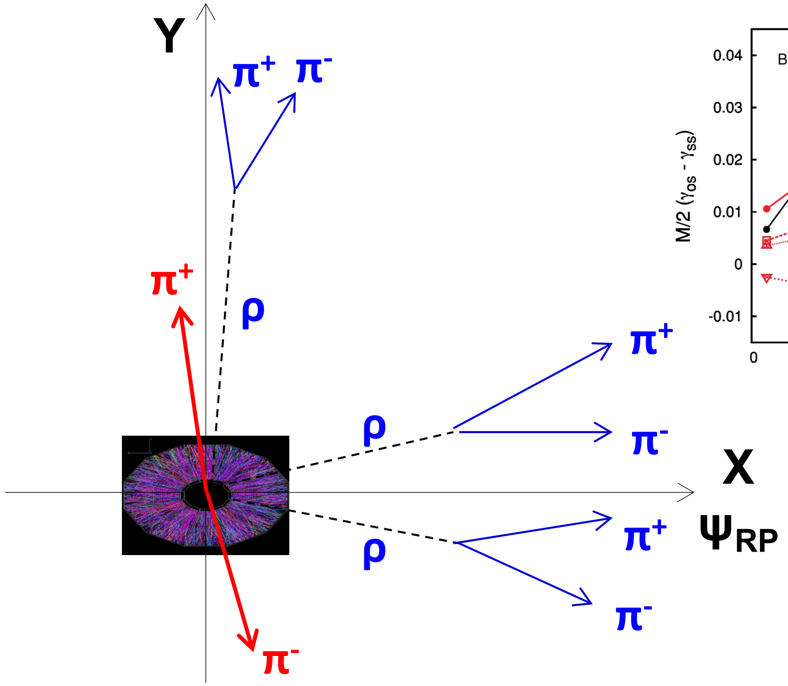
Voloshin 2004
FW 2009
Bzdak, Koch, Liao 2010
Pratt, Schlichting 2010

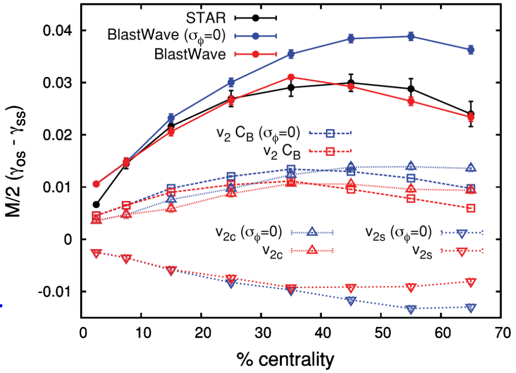
$$\gamma_{\alpha\beta} = \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\psi_{RP}) \right\rangle$$

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

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

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





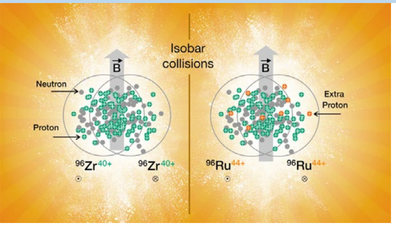
$$\Delta\gamma = 2\left\langle a_1^2 \right\rangle + \frac{N_\rho}{N_\alpha N_\beta} \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_\rho) \right\rangle v_{2,\rho}$$

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

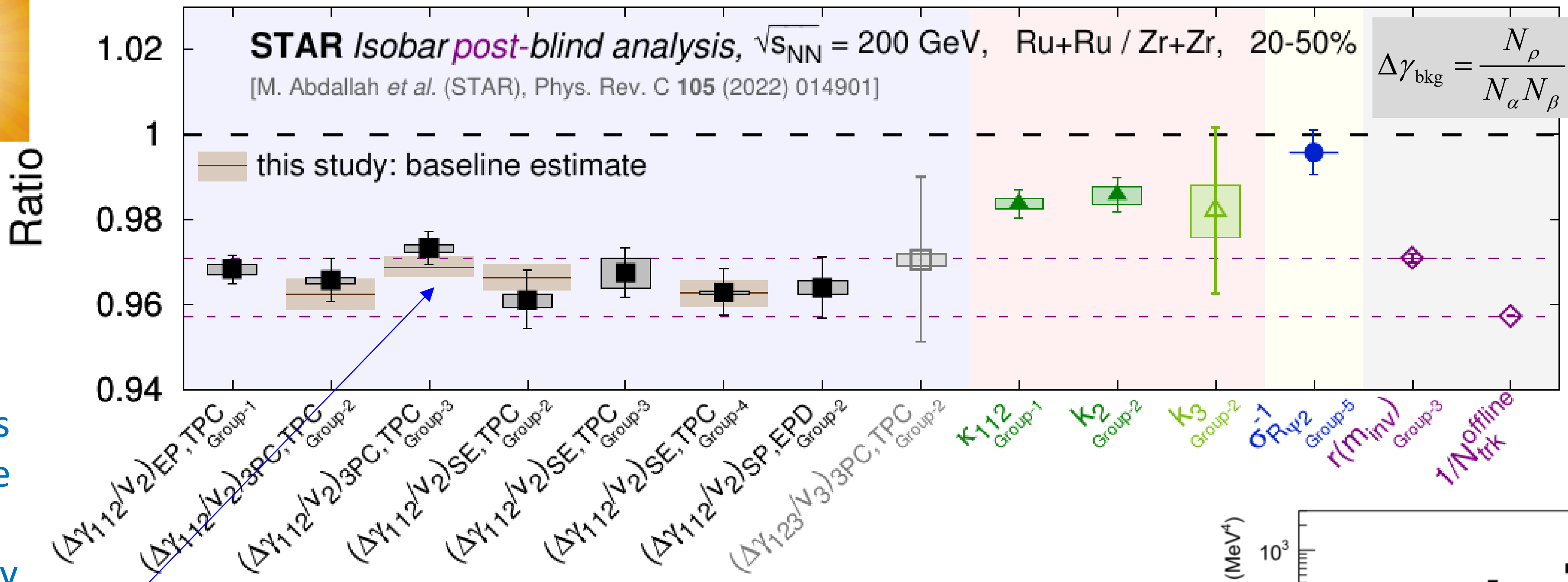
$$\Delta\gamma_{\mathrm{Bkg}} \propto v_2 / N$$

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



$\Delta\gamma/v_2$



$$\Delta\gamma_{\rm bkg} = \frac{N_\rho}{N_\alpha N_\beta}\left\langle\cos(\varphi_\alpha+\varphi_\beta-2\varphi_\rho)\right\rangle v_{2,\rho}$$

$$r = \frac{N_{\rm OS}-N_{\rm SS}}{N_{\rm OS}}$$

$$N_{\rm cluster} \propto N$$

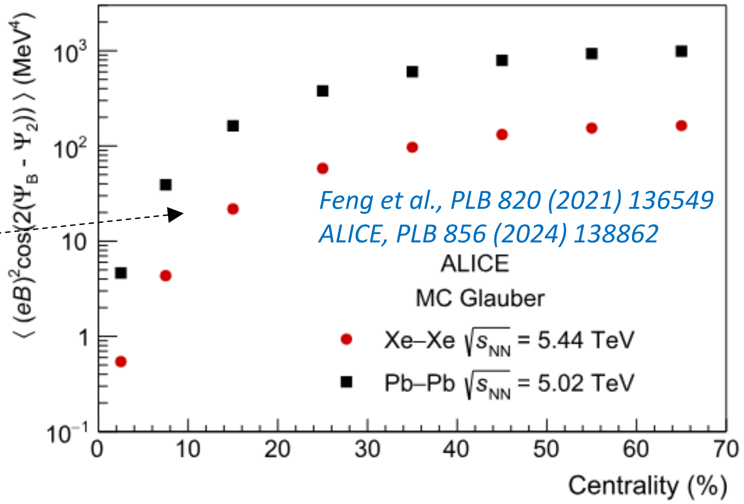
0.4% precision is achieved!
But backgrounds not identical due to nuclear structure subtlety

Additional contamination from nonflow estimated: $f_{\rm CME}$ < 10% at 98% 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

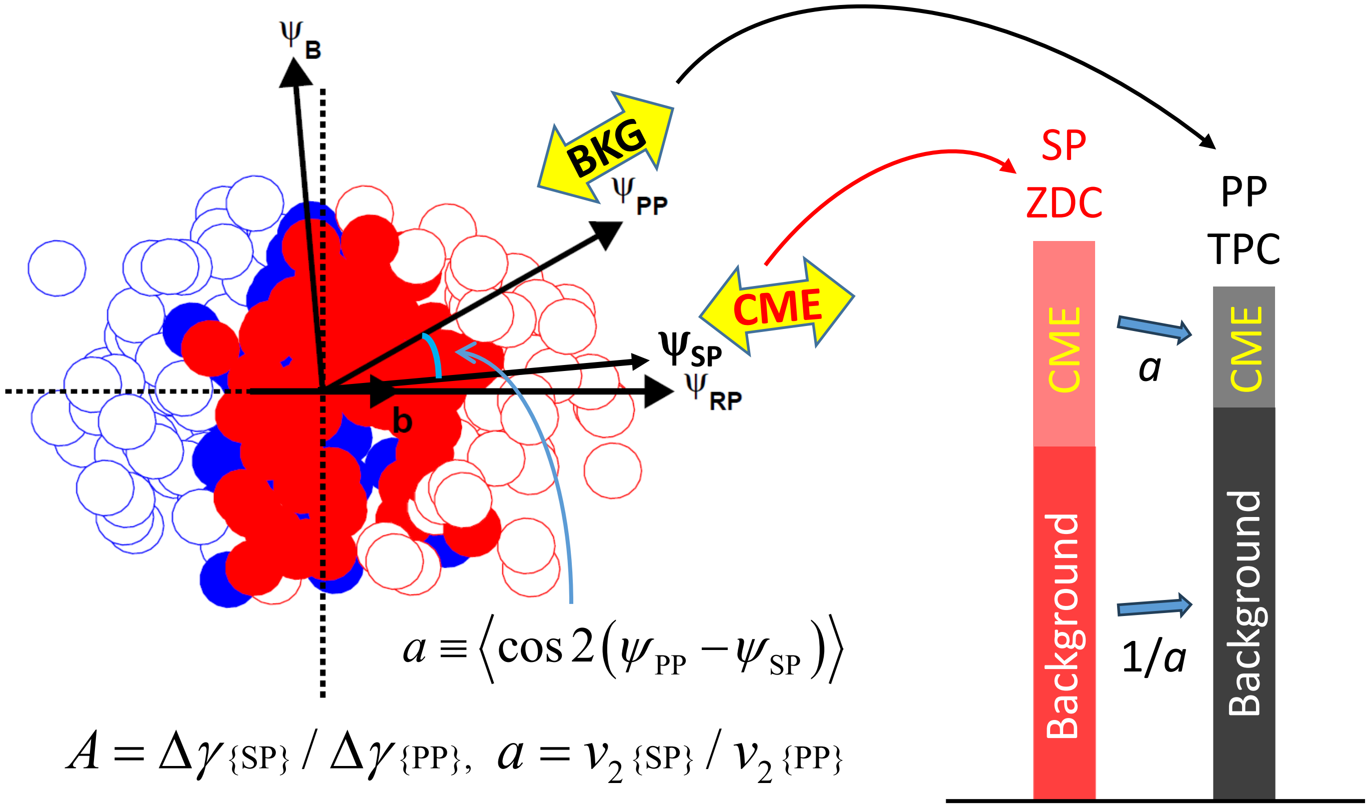
Isobar null signal does not necessarily mean no signal in larger systems -> Au+Au



f_{CME}^{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

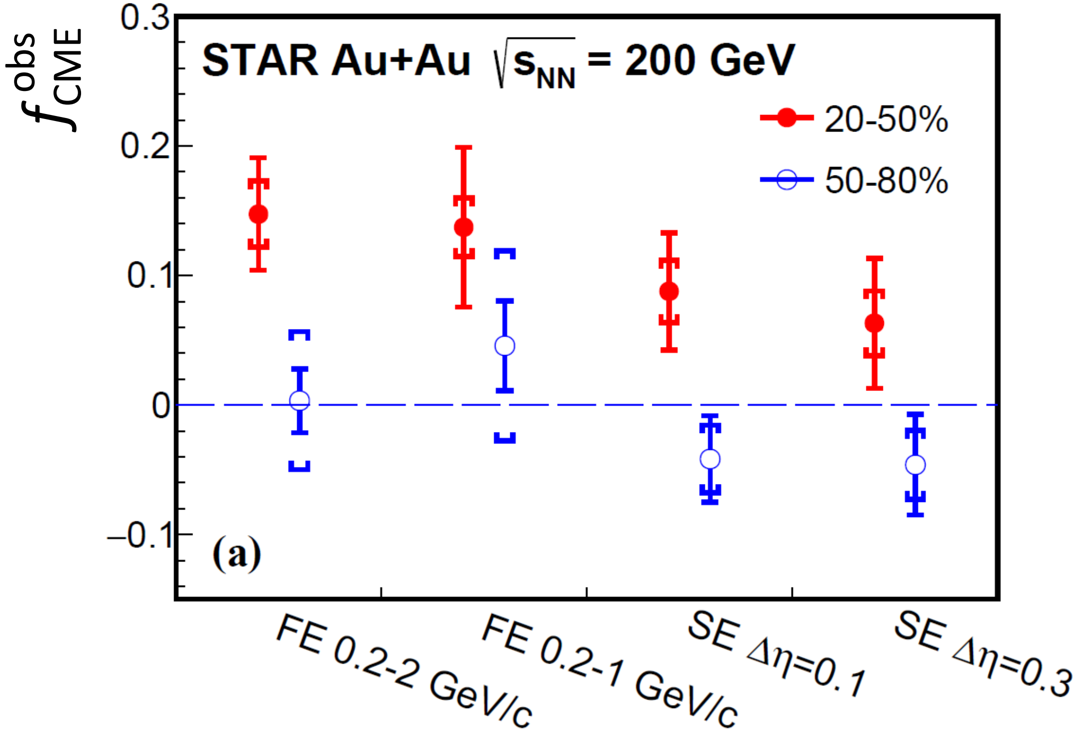


$$a \equiv \langle \cos 2(\psi_{PP} - \psi_{SP}) \rangle$$

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

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

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



Subevent (SE) reduces short-range nonflow; residual nonflow still present in data.

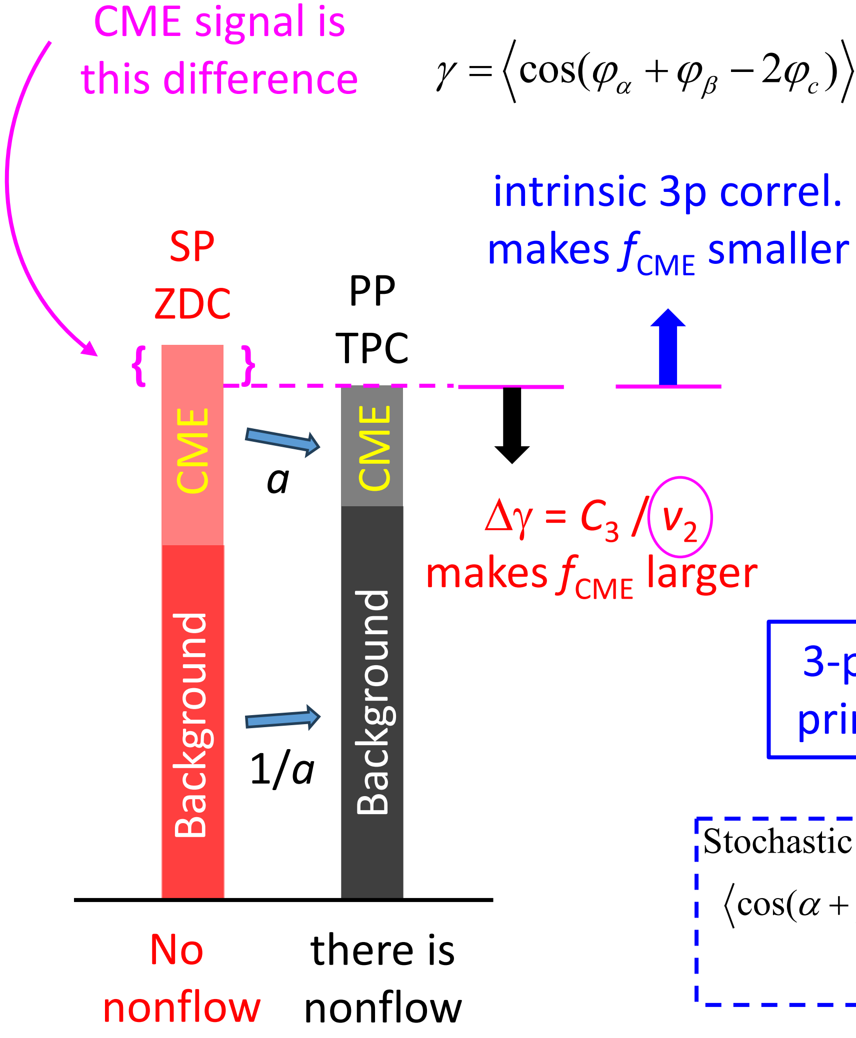
- Peripheral 50-80%: consistent with zero
- Midcentral 20-50%: ~2-3σ significance

Nonflow contamination

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

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

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



$$f^{\mathrm{obs}}_{\mathrm{CME}} = \frac{\Delta\gamma_{\mathrm{CME}}\{\mathrm{TPC}\}}{\Delta\gamma\{\mathrm{TPC}\}} = \frac{A/a - 1}{1/a^2 - 1}$$

V$_2${2} nonflow contamination

3p nonflow / 2p nonflow

$$f_{\mathrm{CME}} \equiv \frac{\Delta\gamma^{\mathrm{PP}}_{\mathrm{CME}}}{\Delta\gamma\{\mathrm{TPC}\}} = \frac{\sqrt{1+\varepsilon_{\mathrm{nf}}}}{\frac{1}{a^2} - (1+\varepsilon_{\mathrm{nf}})} \left[\left(\frac{A}{a} - 1 \right) + \varepsilon_{\mathrm{nf}} \left(\frac{C_{3p}/V_{2p}}{(N_3C_3)/(N_2V_2)} - 1 \right) \right]$$

measurement ZDC/TPC - 1

measurement $N\Delta\gamma/v_2$

3-particle correlations primarily from (di-)jets

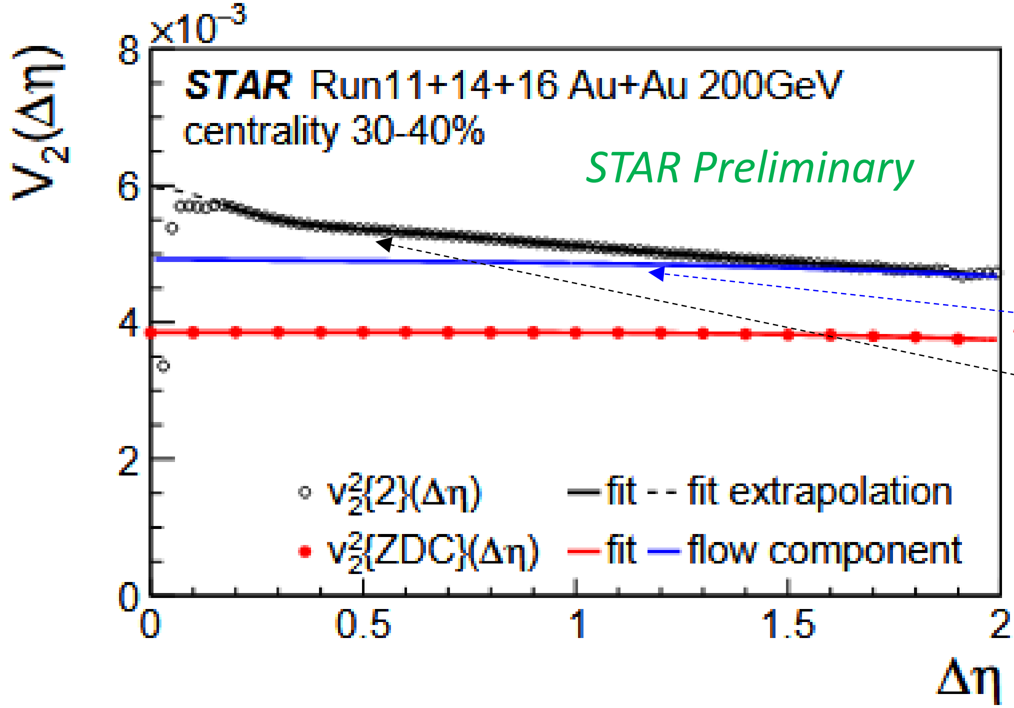
Stochastic jet fragmentation: fragment emission sampling an underlying distribution but otherwise uncorrelated

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

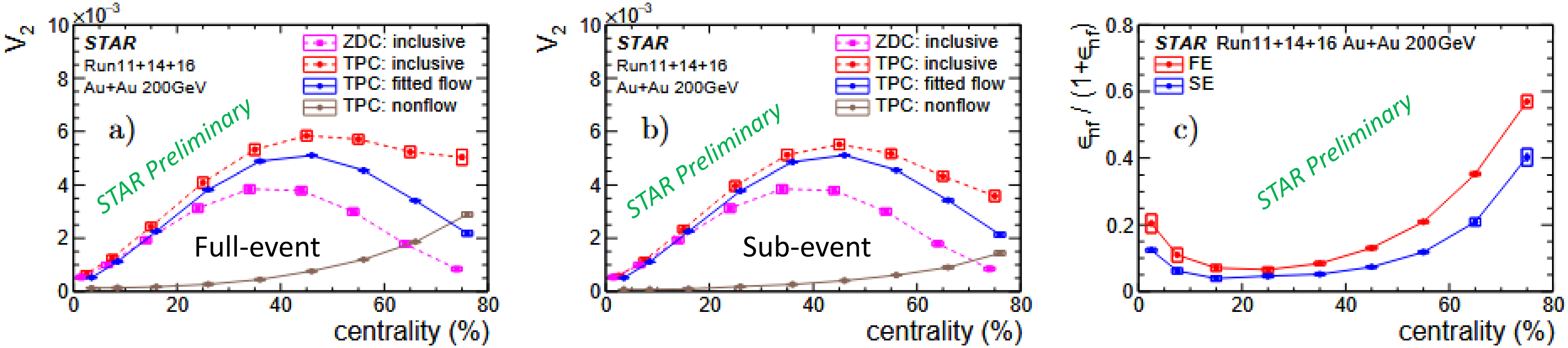
$$C_{3p} = \langle \cos(\alpha+\beta-2c) \rangle N_{3p}/N \quad , \quad V_{2p} = \langle \cos 2(\alpha-c) \rangle N_{2p}/N$$

$V_2\{2\}$ nonflow

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



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

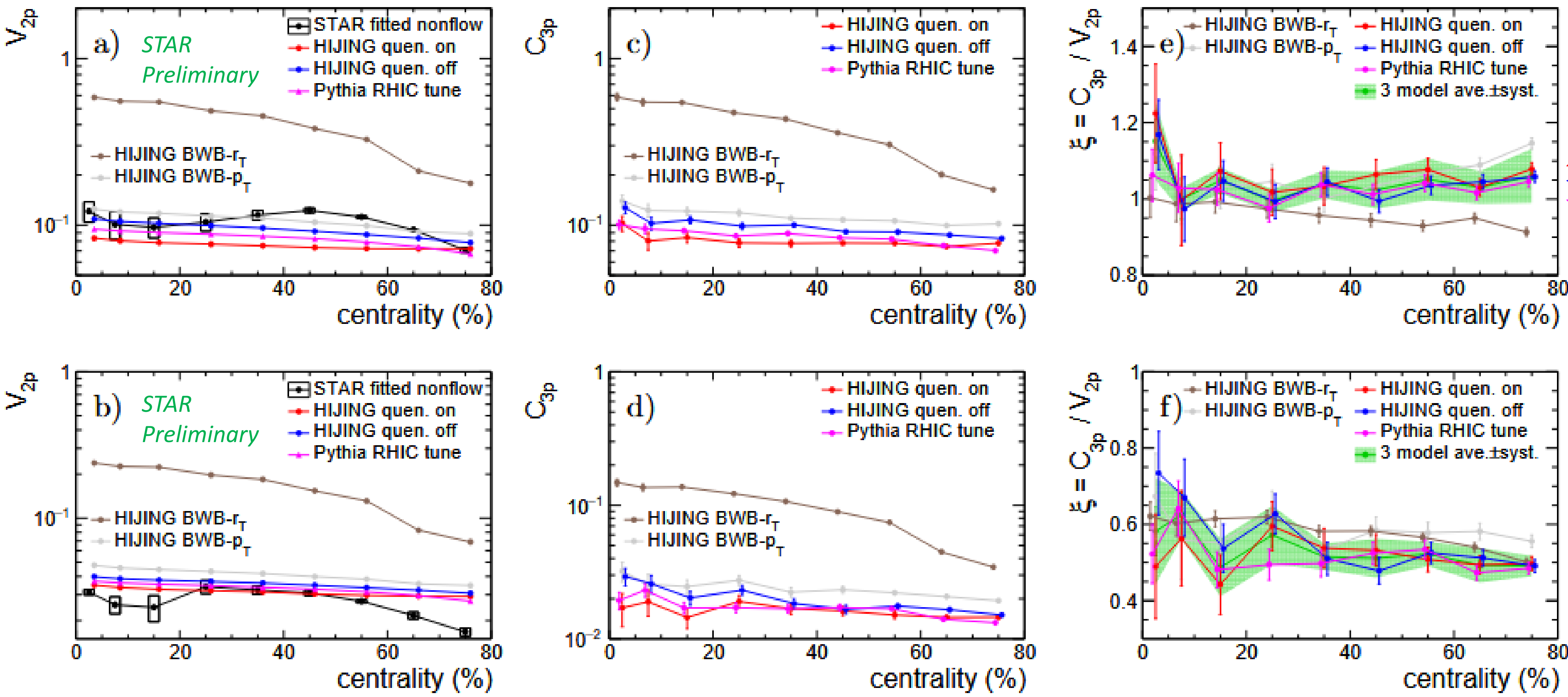


RP-independent 3-particle correlations

nonflow $V_{2p}=\cos2(\phi_\alpha-\phi_c)$ | RP-ind. $C_{3p}=\cos2(\phi_\alpha+\phi_\beta-2\phi_c)$ | $\xi = C_{3p}/V_{2p}$

Full-event

Sub-event



Hijing BWB-p_T

Hijing Q-on

Hijing Q-off

Pythia 8

Hijing BWB-r_T

Continuing to investigate systematics

Systematic uncertainty assessment

Systematic variations in data analysis

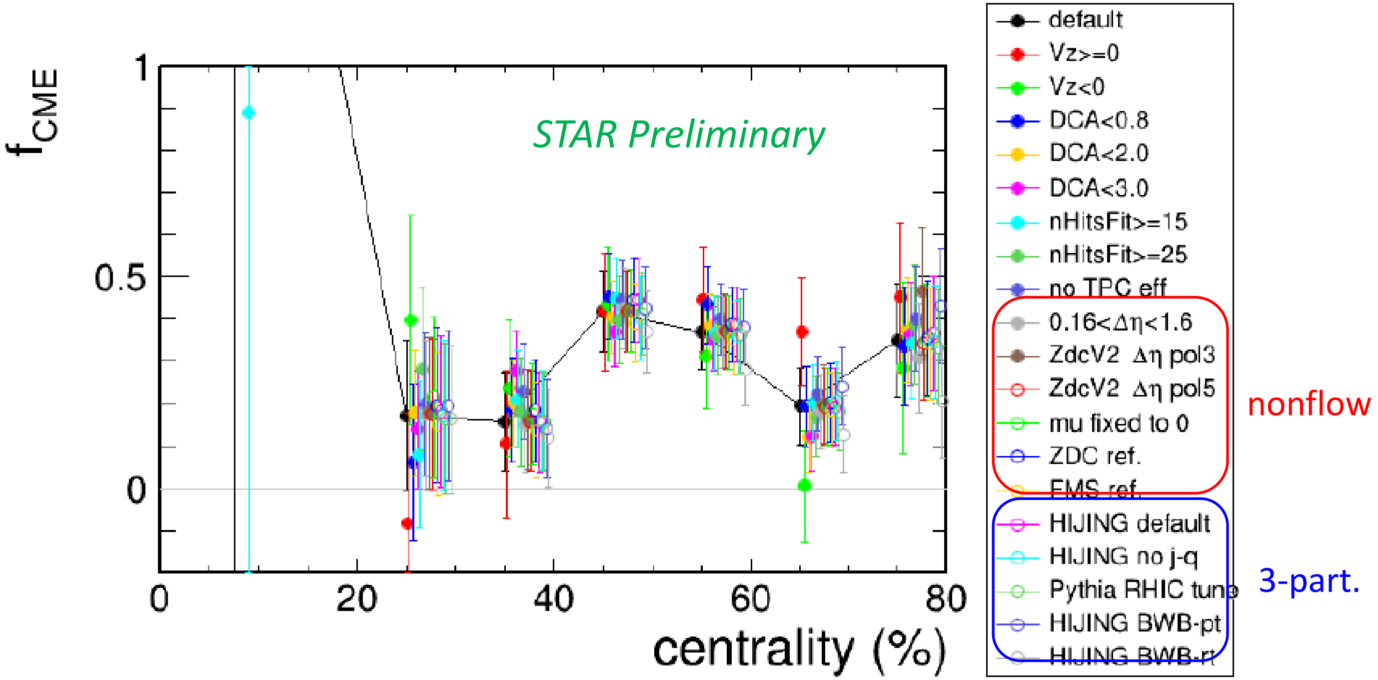
V_z [max]		DCA (cm)			Nhits		no eff.
≥ 0	< 0	< 0.8	< 2	< 3	≥ 15	≥ 25	[max]

Systematic variations in v_2 nonflow fit

v_2^2ZDC 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

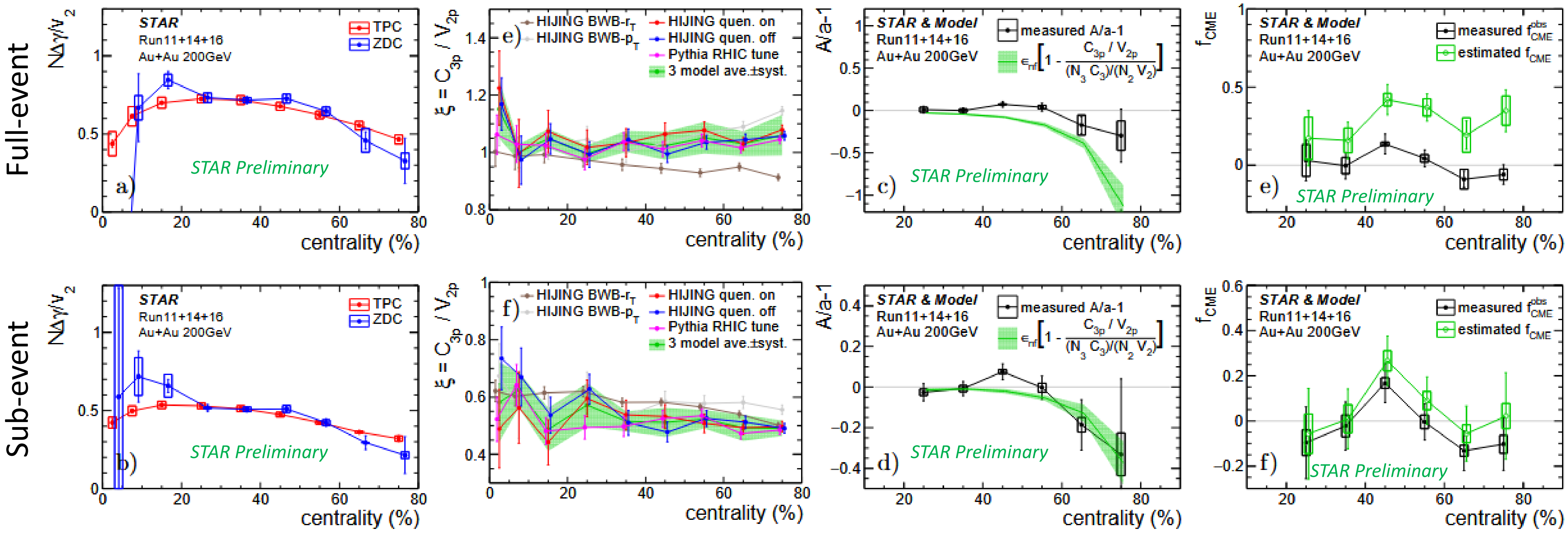


- Stat. fluctuations are removed from syst. uncertainties (Barlow's prescription)
- If multiple variations for a single systematic source, RMS is taken
- For [max] systematic ranges, take ±RMS/√3
- Total syst uncertainty from quadrature sum of all sources

f_{CME} results

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

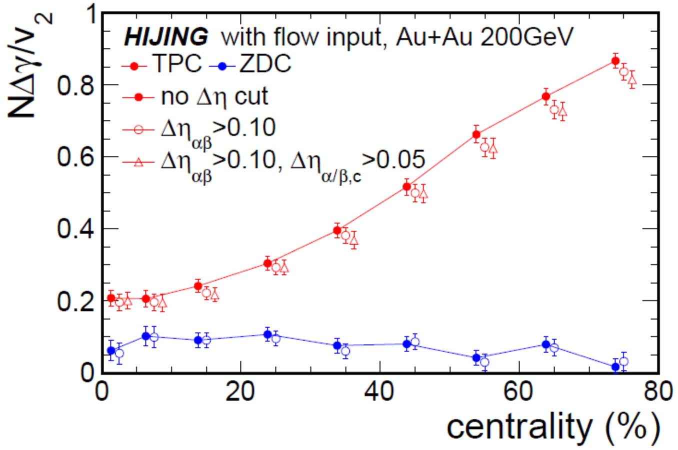
$N\Delta\gamma/v_2$ measurements	$\xi = C_{3p}/V_{2p}$ RP-ind. 3p/2p ratio	$A/a - 1$ measurements and background estimates	Measured $f^{\mathrm{obs}}_{\mathrm{CME}}$ and estimated f_{CME}

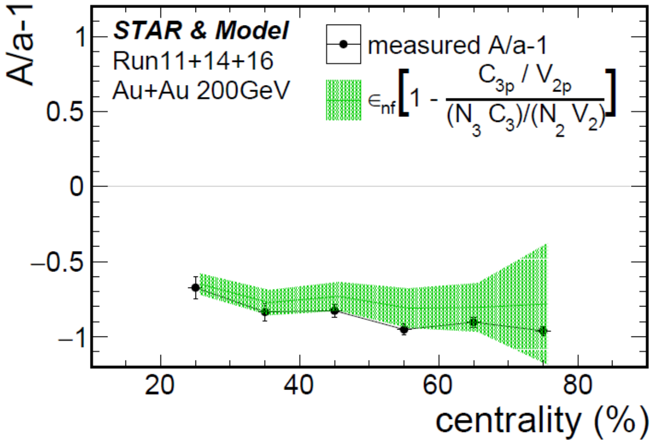


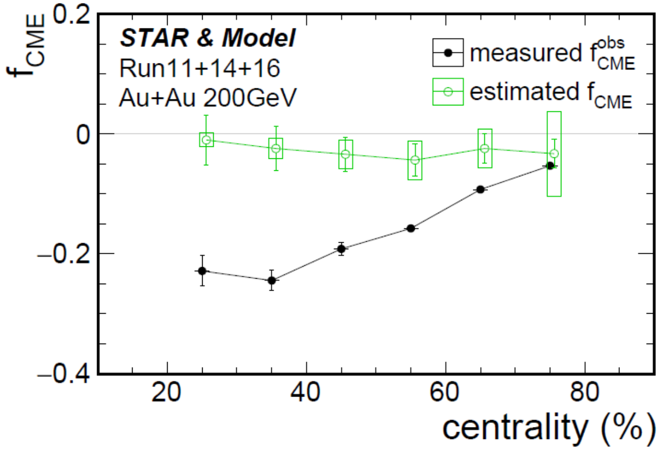
HIJING closure test checks out

- 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.

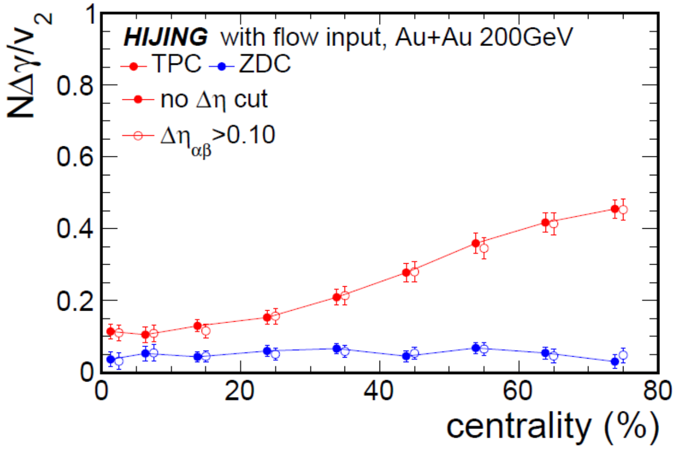
Full-event

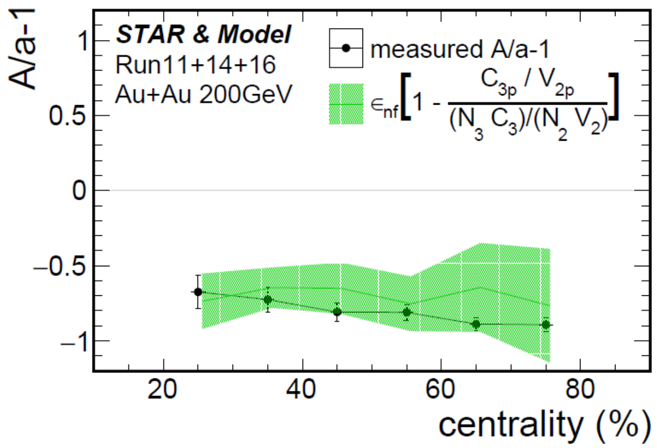


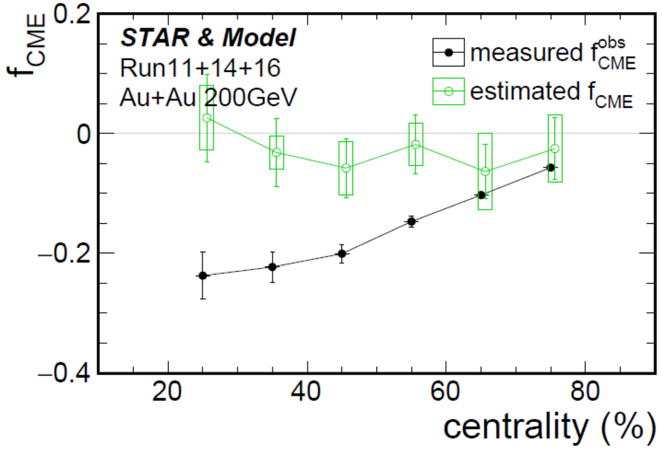




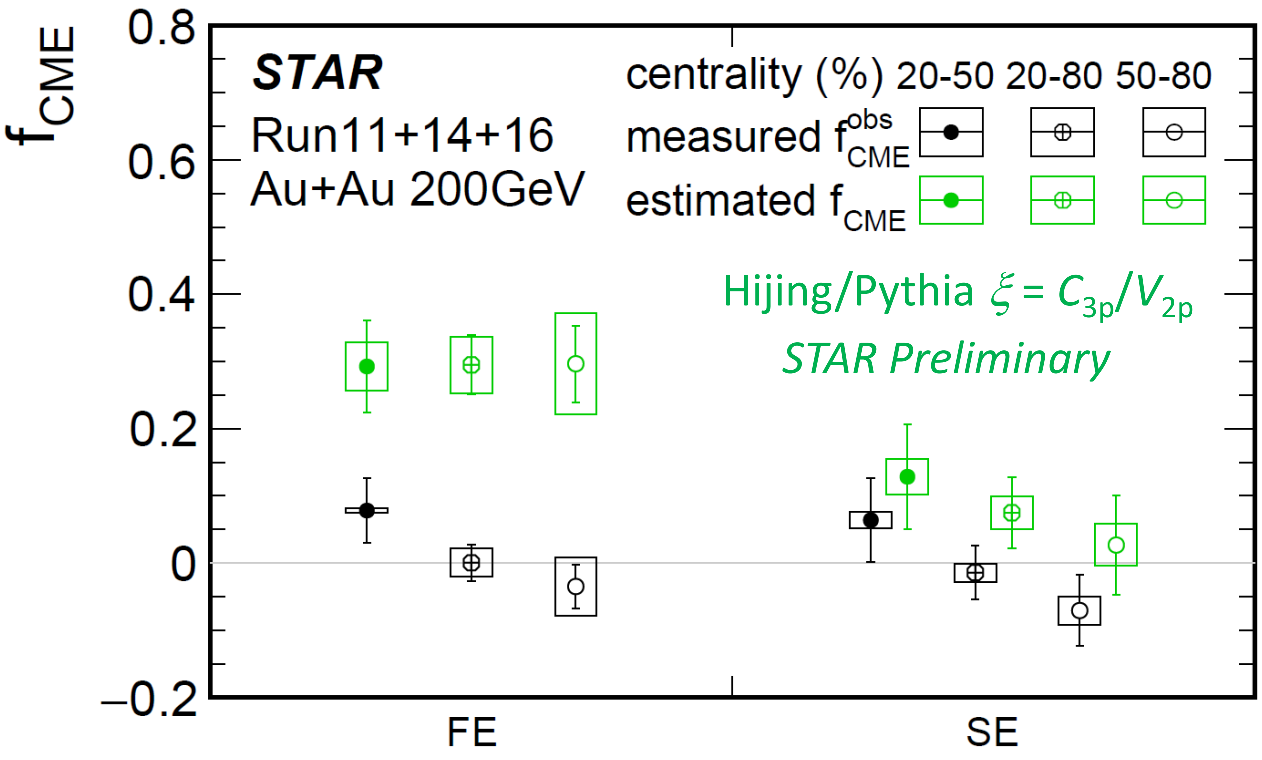
Sub-event

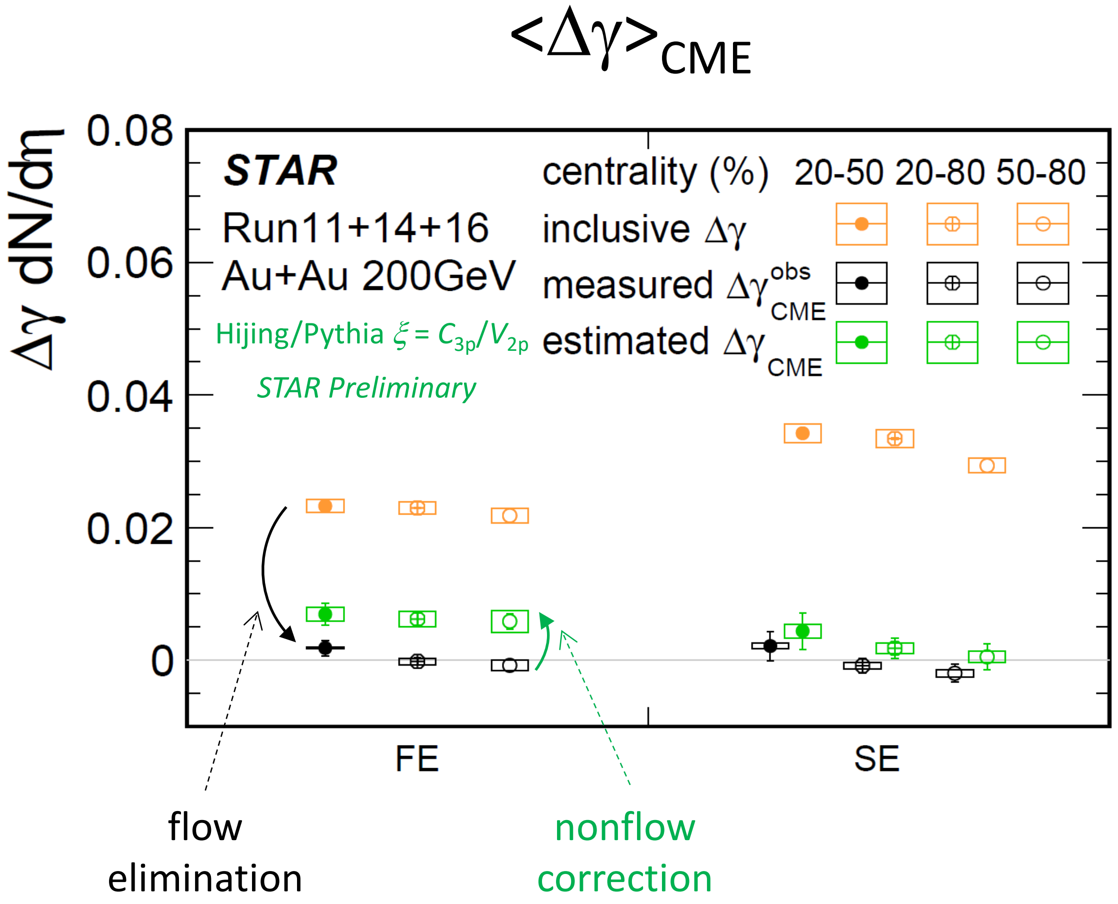






Centrality-averaged <f_{CME}>





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

Summary

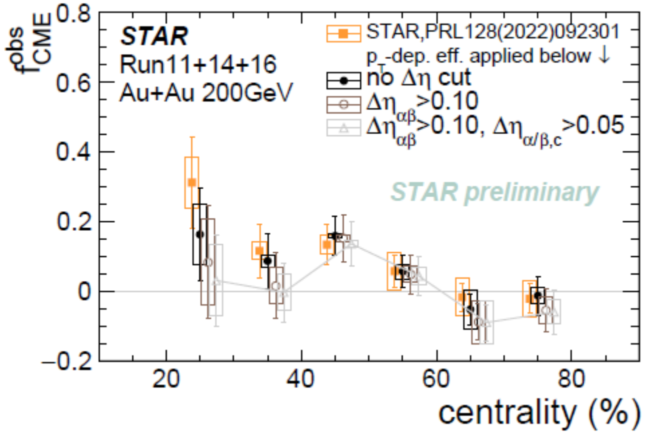
- Flow-induced background is well understood and under control by SP/PP comparison measurements. CME fraction in Au+Au 200 GeV data revisited.

- Additional backgrounds from nonflow 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 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**

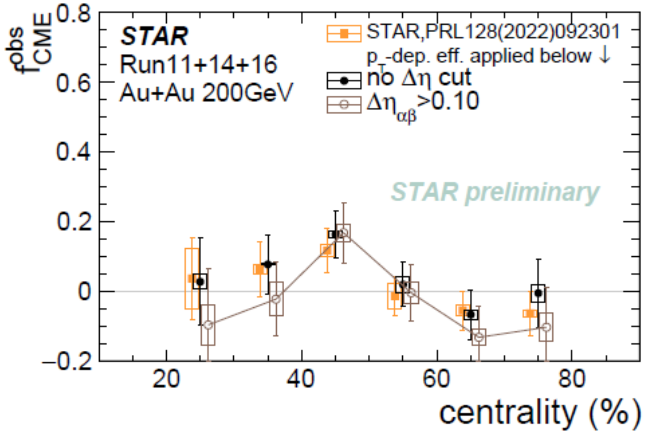
- f_{CME} extracted. Further scrutiny, e.g. MC/model closure underway.

f_{CME}^{obs} results

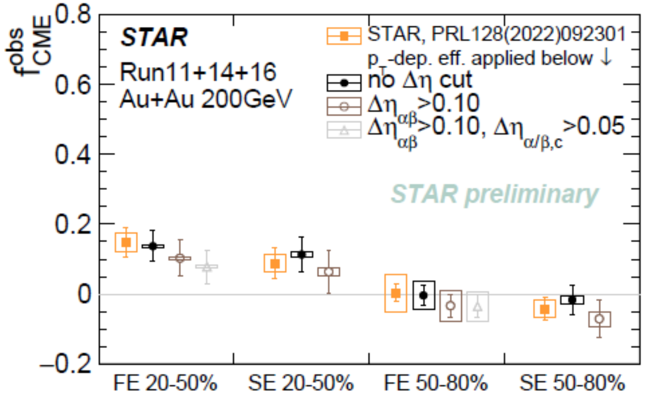
full-event f_{CME}^{obs}



sub-event f_{CME}^{obs}



centrality-averaged $< f_{CME}^{obs} >$



- 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
  - $\Delta\eta$ 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 $\Delta\eta$ cuts

Event-shape engineering methods

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