Search for the Chiral Magnetic Effect from the RHIC BES II
&
Implications and Future Perspective

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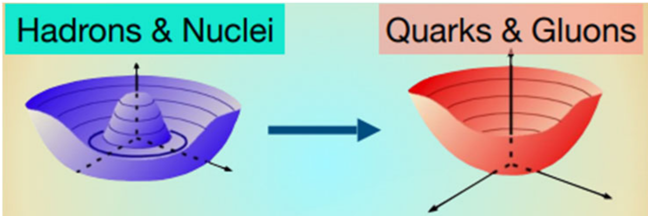
Thanks to Gang Wang, Zhiwan Xu, Jinfeng Liao, Jinhui Chen, Diyu Shen, Volker Koch and Agnieszka Sorensen

Outline

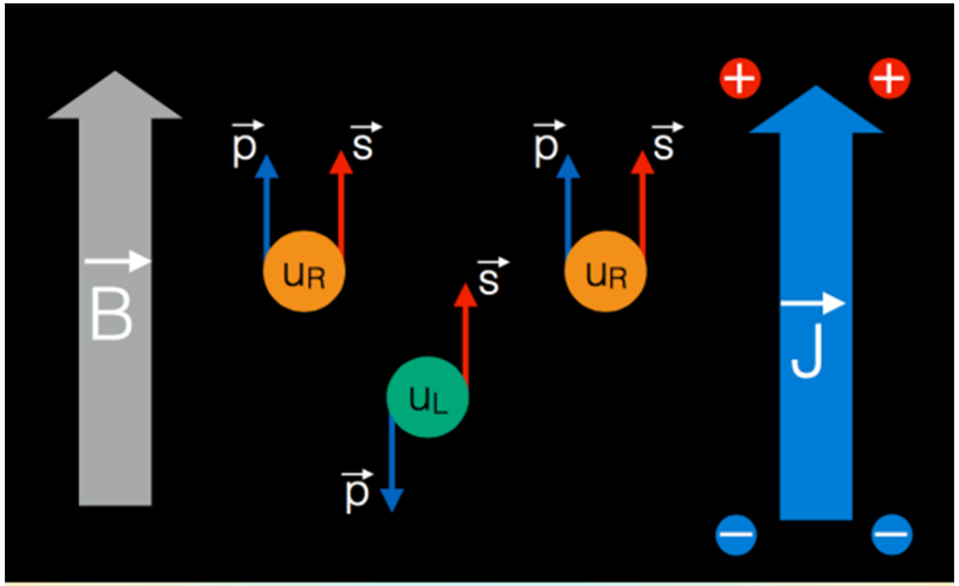
- ❖ Introduction
- ❖ Novel Approach of Event Shape Selection (ESS)
- ❖ STAR ESS Results from BES-II and 200 GeV Data
- ❖ Implications on Collision Dynamics
- ❖ Summary and Future Outlook

Chiral Magnetic Effect

A Rare Opportunity to Experimentally Access Key Intrinsic Properties of the QCD

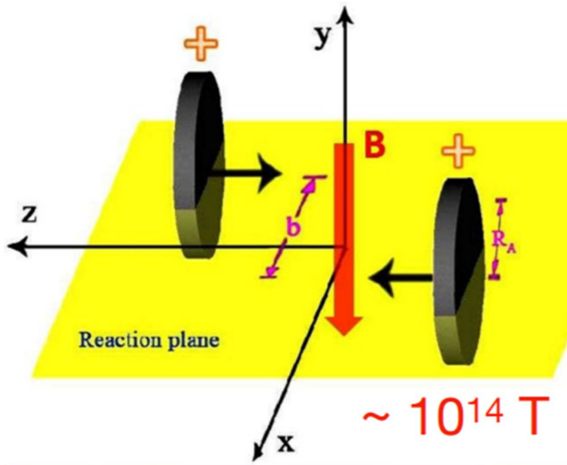


Chiral symmetry restoration (massless quarks)

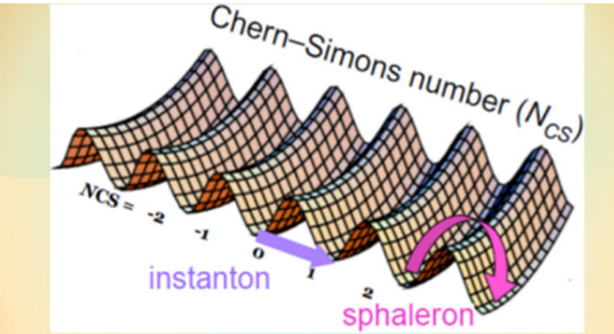


Chiral Magnetic Effect (J || B)

$$\vec{J} = \frac{e^2}{2\pi^2}\mu_5 \vec{B}$$

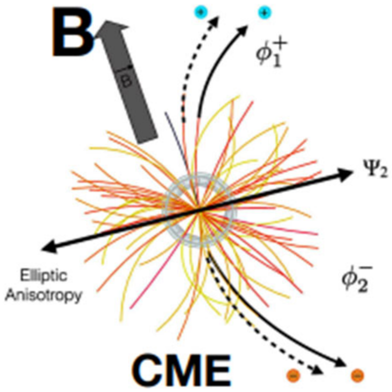


Strong magnetic field (B)



Chirality imbalance (finite μ_5)

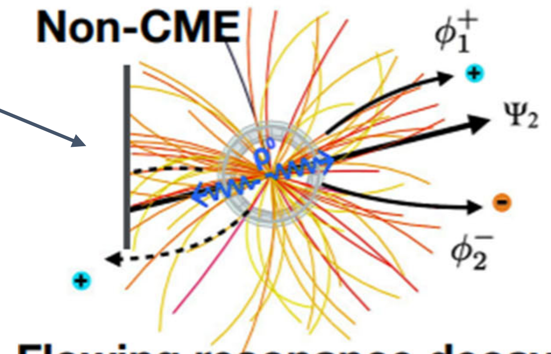
CME Observables



$$\frac{dN_\pm}{d\varphi} \propto 1 + 2v_1\cos(\varphi - \Psi_{RP}) + 2a_1^\pm \sin(\varphi - \Psi_{RP}) + 2v_2\cos(2\varphi - 2\Psi_{RP}) + \ldots$$

$2a_1^\pm \propto \mu_5 B$

Parity odd, can not directly observe



Popular CME-sensitive observables:

- γ correlator

S.A. Voloshin, Phys. Rev. C70(2004)057901

- *R* correlator

N. N. Ajitanand et al., Phys. Rev. C83(2011)011901(R)

- Signed balance functions

A. H. Tang, Chin. Phys. C44, No.5 (2020)054101

Model studies show that these methods have similar sensitivities to the CME signal and to the background. (Best Paper Award 2023 from Chin. Phys. C)

S. Choudhury et al.(STAR), Chin. Phys. C46(2022)014101

Here, we focus on $\gamma^{112} \equiv \langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP}) \rangle$

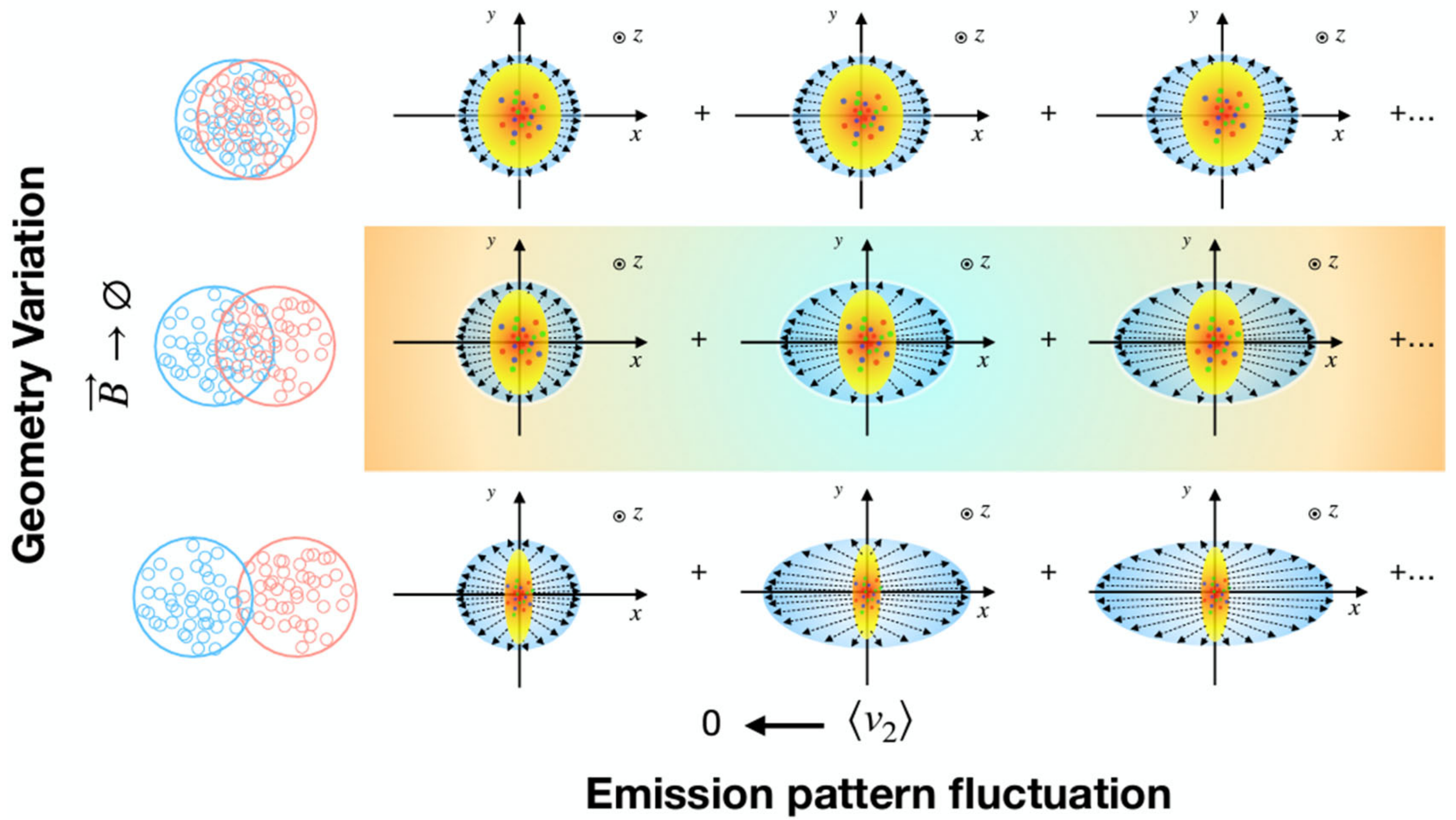
The CME causes $\Delta\gamma^{112} \equiv \gamma^{112}_{OS} - \gamma^{112}_{SS} > 0$

Background indicator $\gamma^{132} \equiv \langle \cos(\varphi_\alpha - 3\varphi_\beta + 2\Psi_{RP}) \rangle$

Event Shape Selection (ESS)

Ideally, if we control eccentricity, we control flow for everything.
But large event-by-event fluctuations could dominate the observable.

- participant zone geometry: expected to be long ranged in rapidity emission
- pattern fluctuations: more localized, less correlated over rapidity

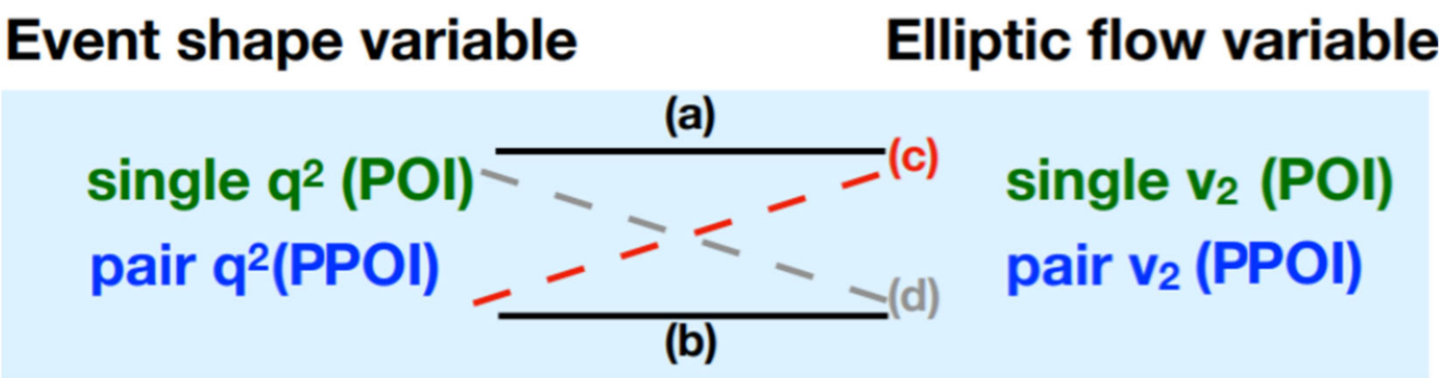


H. Petersen and B. Müller, Phys. Rev. C 88, 044918

Event shape variables based on **particles of interest (POI)** are sensitive to both geometry and emission pattern.

CME background e-by-e comes from combined eccentricity and emission patterns

Shape Variable and v2 Control



$$q_2^2 = \frac{1}{N}\left[\left(\sum_{i=1}^{N}\sin 2\varphi_i\right)^2 + \left(\sum_{i=1}^{N}\cos 2\varphi_i\right)^2\right]$$

$$= 1 + \frac{1}{N}\sum_{i\neq j}\cos[2(\varphi_i - \varphi_j)],$$

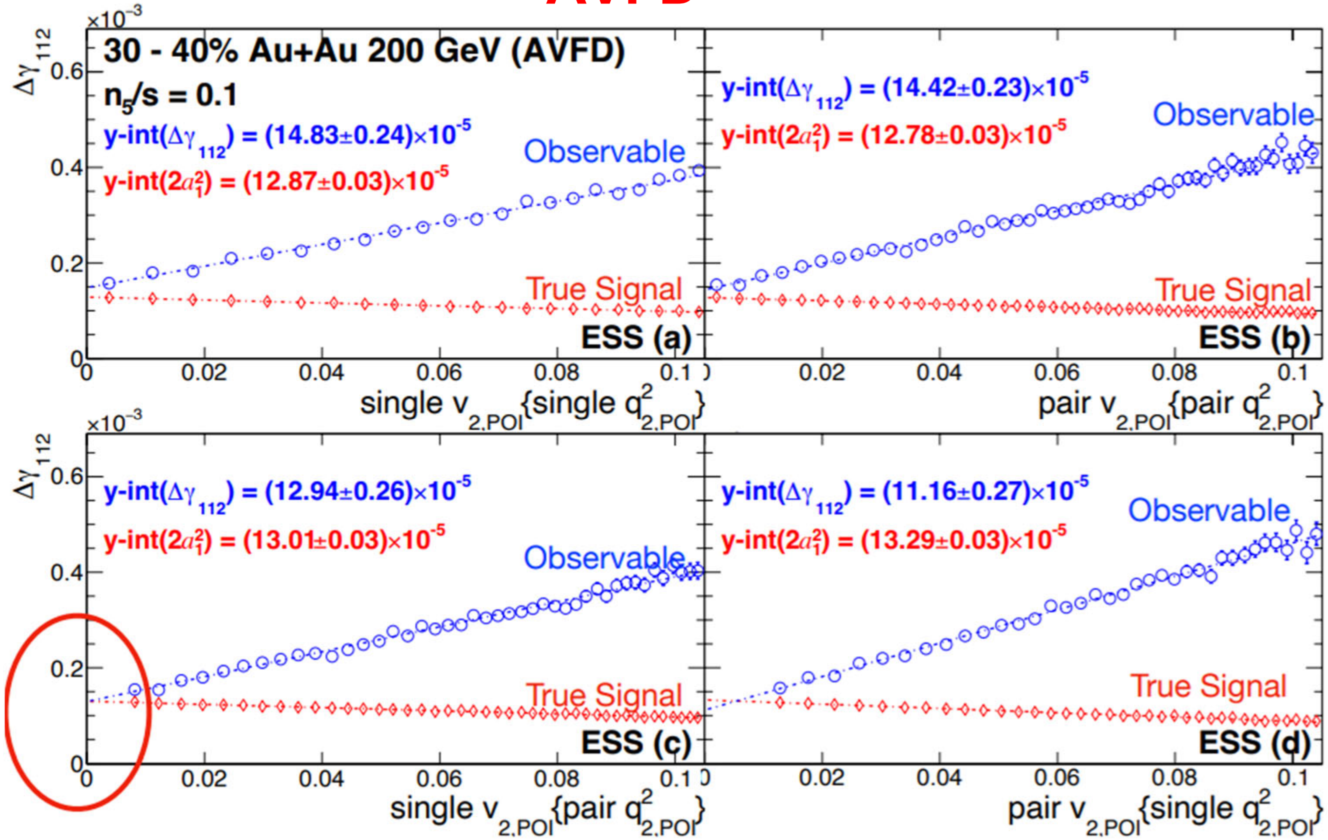
$$\langle q_2^2\rangle \approx 1 + N v_2^2\{2\}$$

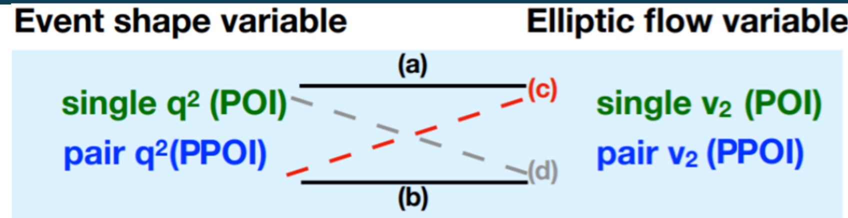
- ESS recipes (a) and (b) involve direct event-by-event correlations between $q_2{}^2$ and v_2, which will cause under-subtraction of background.
- We should use “mixed” recipes, (c) or (d).
- Redefine $q_2{}^2$ with an extra normalization.
- Pair $q_2{}^2$ and pair v_2 are based on $\boldsymbol{\varphi}_\mathrm{p}$.

$$q_2^2 = \frac{\left(\sum_{i=1}^{N}\sin 2\varphi_i\right)^2 + \left(\sum_{i=1}^{N}\cos 2\varphi_i\right)^2}{N(1 + N v_2^2\{2\})}$$

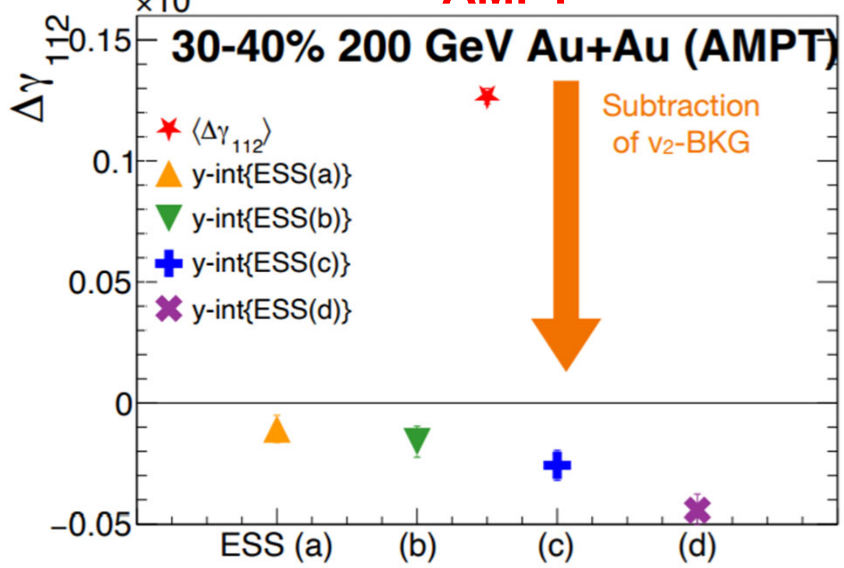
Simulations

AVFD





AMPT



Z. Xu *et al*, PLB 848(2024)138367

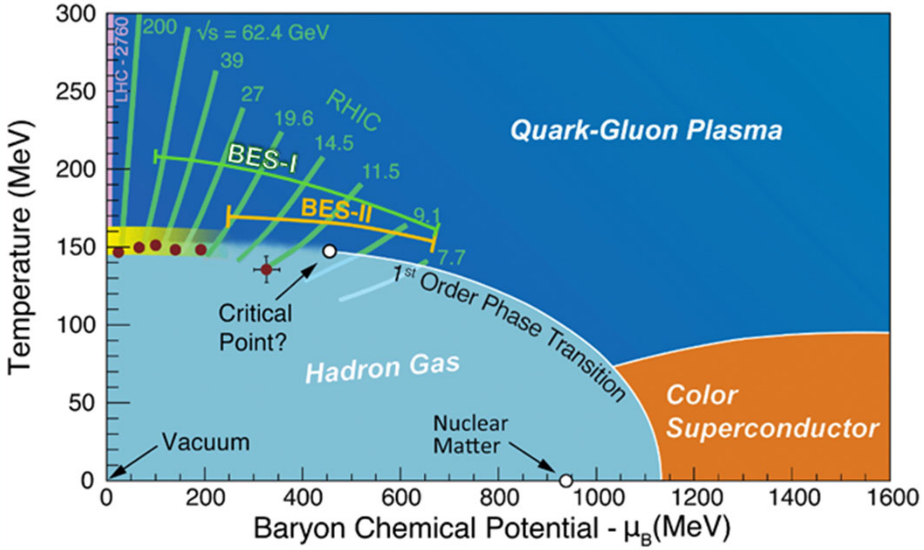
- **AVFD: the optimal ESS recipe (c) accurately matches the input CME signal.**
- **Intercepts follow an ordering (a)>(b)>(c)>(d).**
- **AMPT: all ESS recipes over-estimate the BKG (with the same ordering as AVFD).**

Application to Real Data

"Events" represents good events after quality cuts.

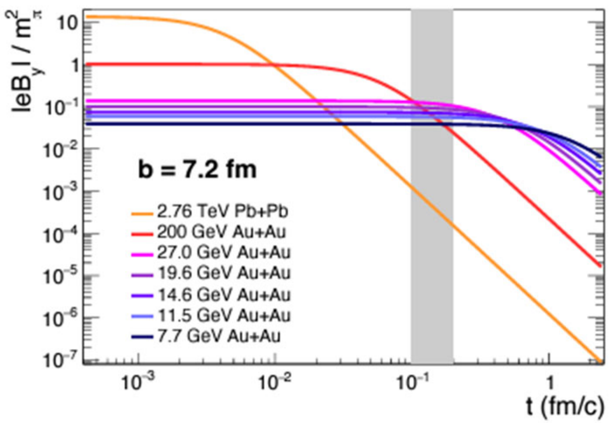
BES-I

$\sqrt{S_{NN}}$(GeV)	Events (10^6)	Year
62.4	46	2010
39	86	2010
27	30	2011
19.6	15	2011
14.6	13	2014
11.5	7	2010
9.2	0.3	2008
7.7	4	2010



BES-II

$\sqrt{S_{NN}}$(GeV)	Events (10^6)	Year
27	555	2018
19.6	478	2019
14.6	324	2019
11.5	230	2020
9.2	160	2020
7.7	101	2021

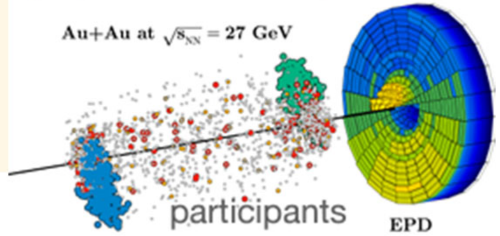


Event Shape Selection **Spectator Ψ_1**

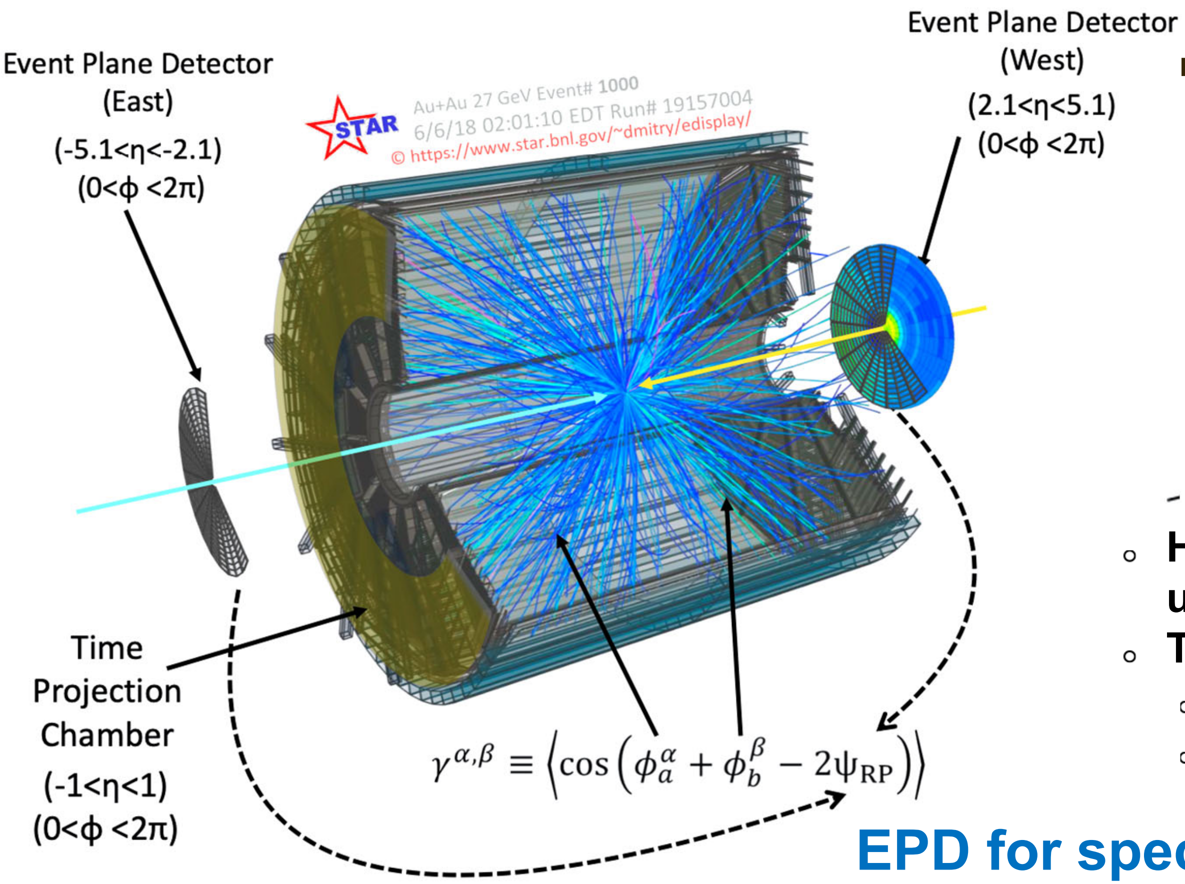
$$\Delta\gamma^{112} = \Delta\gamma^{CME} + k\frac{v_2}{N} + \Delta\gamma^{non-flow}$$

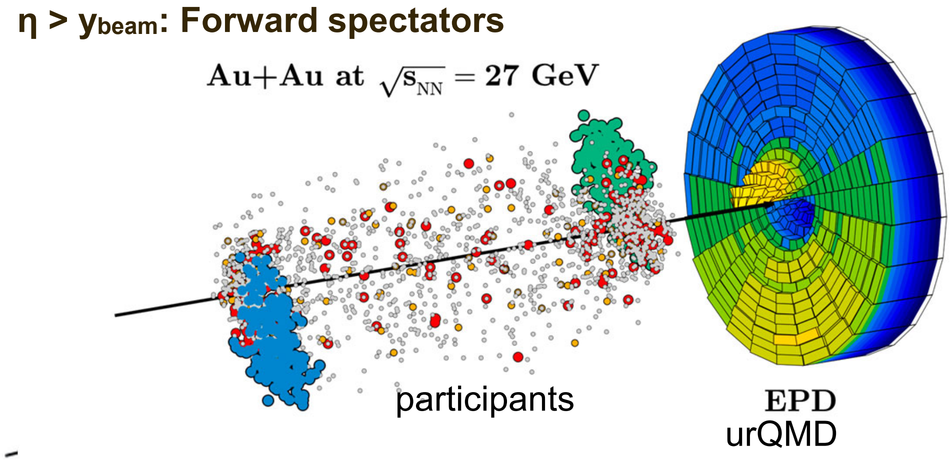
Measured **Signal** **Backgrounds**

$\eta > y_{beam}$: Forward spectators



The Event Plane Detector at STAR

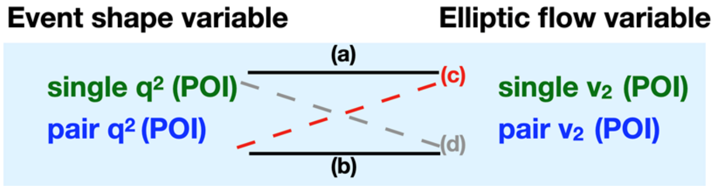


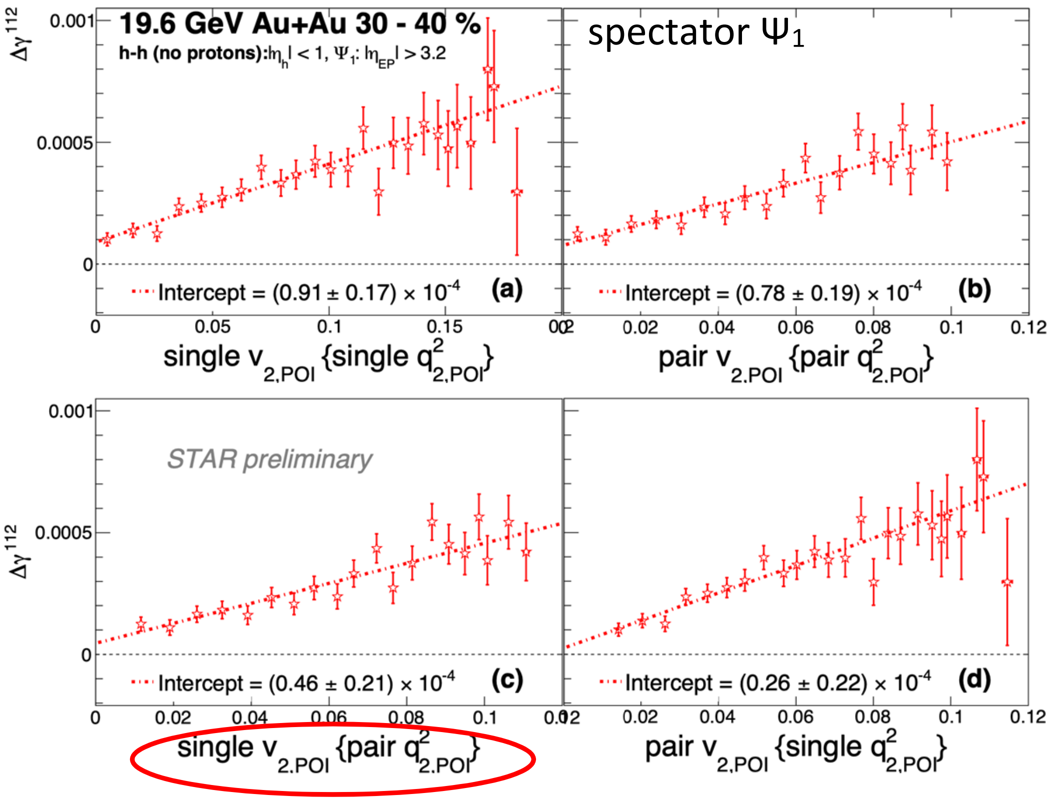


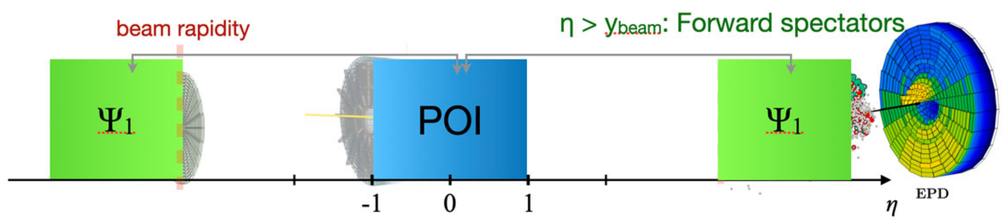
- Higher resolution, BES-II new detector (EPD) upgraded in 2018
- The inner EPD detects first-order spectator plane
  - Targeting the spectator regions for B field
  - Suppressing non-flow background

EPD for spectator proton plane measurement works for low beam energies

ESS applied to Au+Au at 19.6 GeV







Event Shape Selection **Spectator Ψ_1**

$$\Delta\gamma^{112} = \Delta\gamma^{CME} + k\frac{v_2}{N} + \Delta\gamma^{nonflow}$$

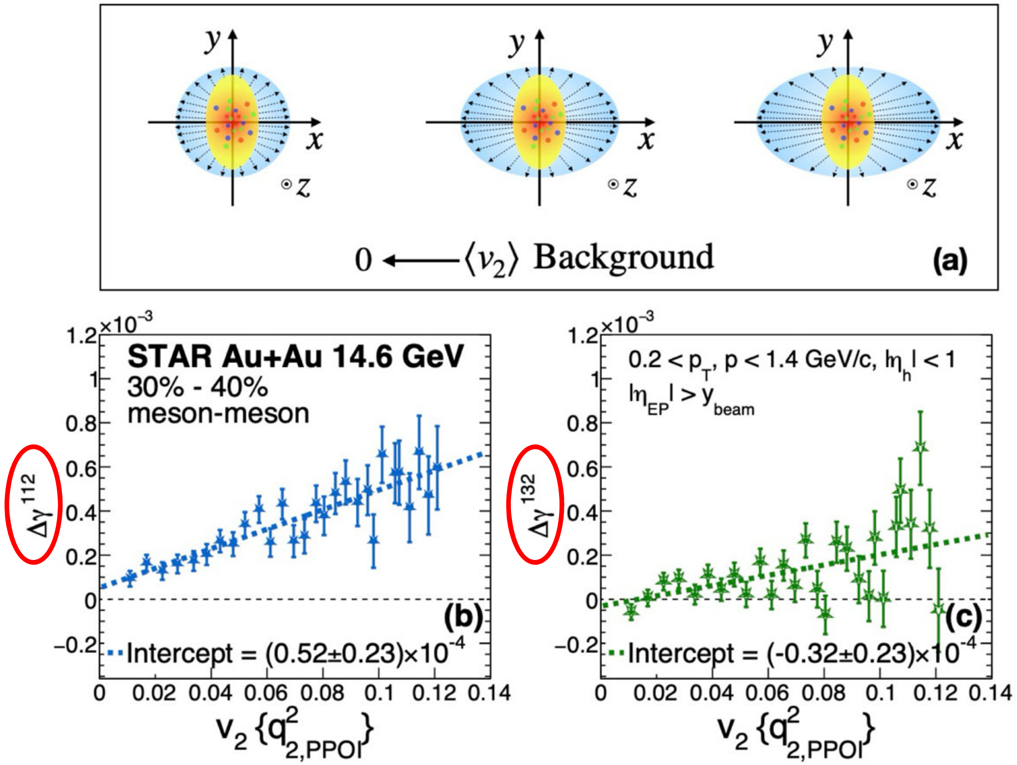
Signal ***Background***

- **ESS using POI allows much shorter extrapolation to zero v_2.**
- **The ordering of y-intercepts follows predictions from both AVFD and AMPT**
- **The y-intercept requires a small correction to restore the unbiased CME signal:**

$$\Delta\gamma^{112}_{ESS} = Intercept \times (1 - v_2)^2$$

Z.Xu et al Phys. Rev. C 107, L061902

ESS applied to $\Delta\gamma^{112}$ and $\Delta\gamma^{132}$



arXiv:2506.00275

$$\Delta\gamma^{112} = \Delta\gamma^{\mathrm{CME}} + \kappa^{112} v_2 \Delta\delta + \Delta\gamma^{\mathrm{nonflow}}$$

$$\Delta\gamma^{132} = \kappa^{132} v_2 \Delta\delta + \Delta\gamma^{\mathrm{nonflow}}$$

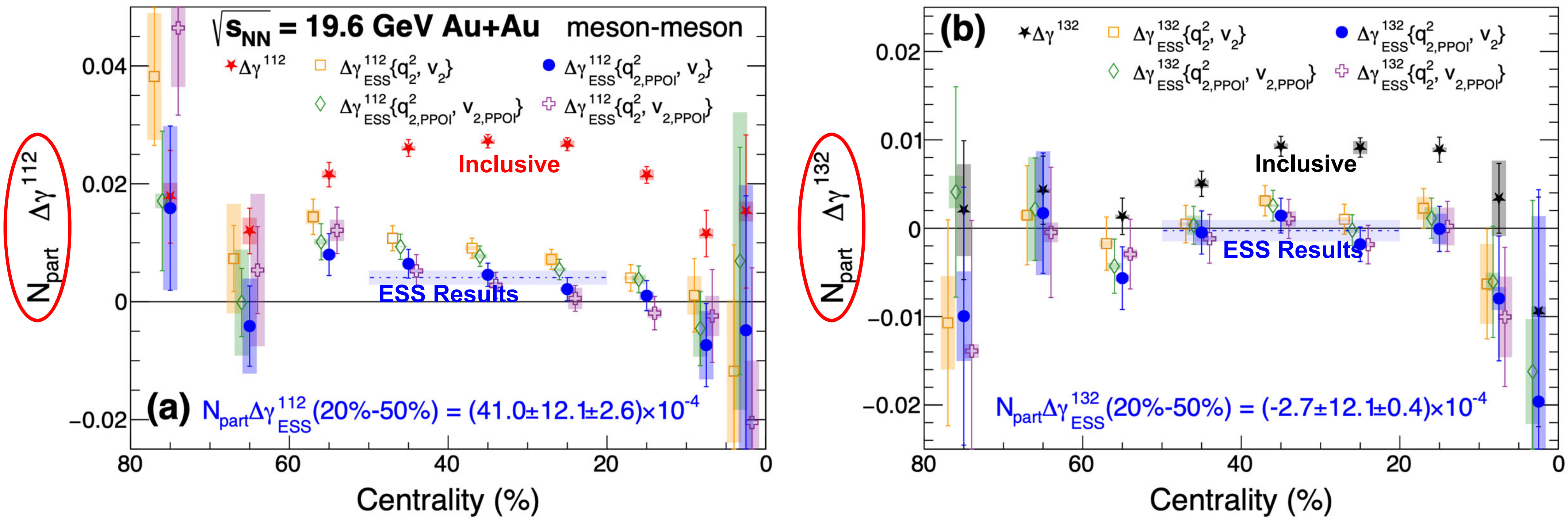
Flow background suppressed by ESS method.
Non-flow backgrounds suppressed by spectator Ψ_1

With optimal ESS we can suppress all known background in our charge separation observable.

Phys. J. C 80, 383 (2020)

Au+Au at 19.6 GeV

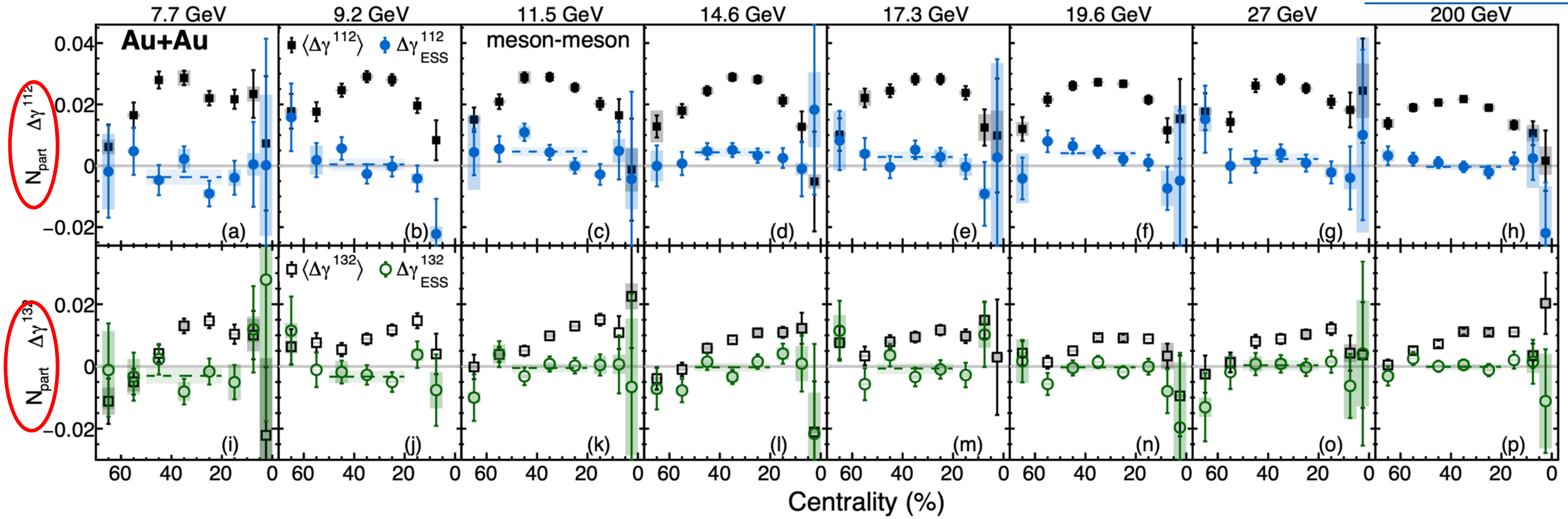
arXiv:2506.00278



- After v_2-BKG subtraction, a finite signal in mid-central (20-50%) events with the optimal ESS (c), pair q^2 and single v_2, a 3σ significance for 20-50% centrality.
- For BKG indicator $\Delta\gamma^{132}$, ESS results consistent with ZERO -- v_2-BKG suppressed.

Beam Energy Scan II - Event Shape Selection

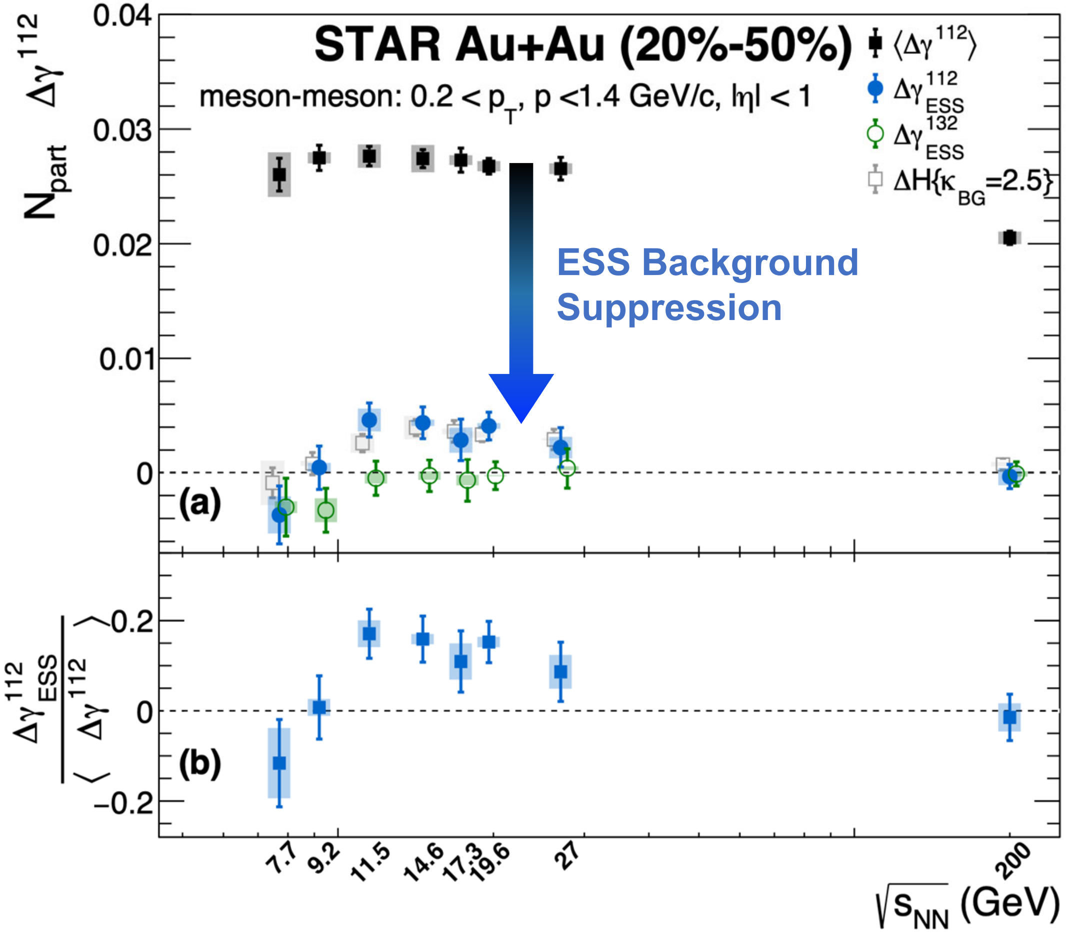
arXiv:2506.00275



- Charge separation signal after applying ESS:
  - At 200 GeV, using ZDC-SMD planes, no signal is observed.
  - At 19.6, 14.6 and 11.5 GeV, a finite charge separation (around 3σ) in the 20-50% centrality.
  - At 9.2 and 7.7 GeV, data favor the zero-CME scenario.
- Background indicator after ESS is consistent with zero at all energies.

Beam Energy Dependence of CME observable

arXiv:2506.00275



ESS BKG-indicator consistent with zero.

At least 80% of $\Delta\gamma^{112}$ is from the background.
At 200 GeV, ratio is (-2 ± 5.1 ± 1.6)%

- **upper limit of f_{CME}~10% in Au+Au**
- **upper limit of f_{CME}~ 5% in isobars using participant planes: 0.7% difference, too small to detect with the current isobar data !**

Between 11.5 - 19.6 GeV, the average reaches > 5σ significance (assuming similar physics conditions).

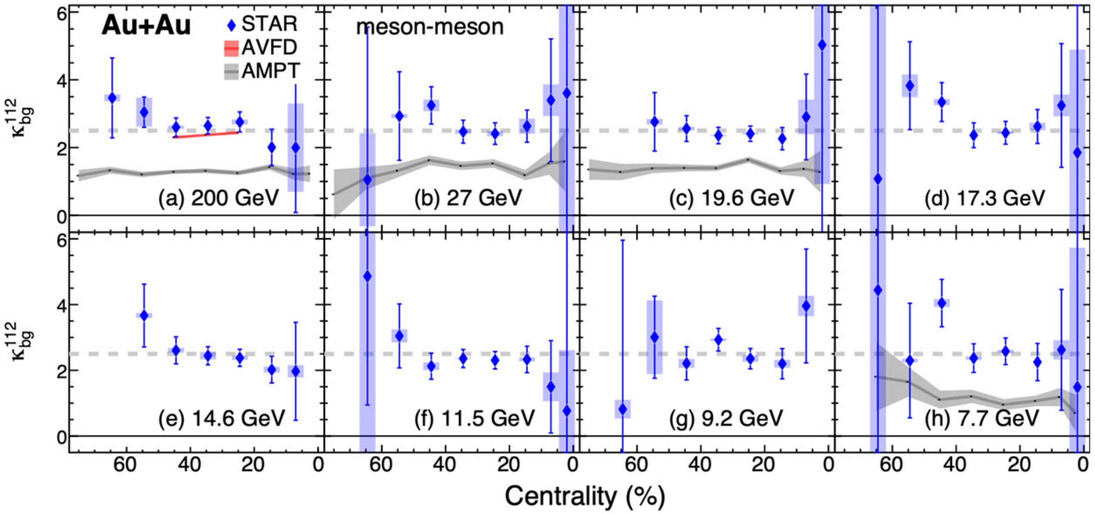
The ESS results approach zero around 9.2 and 7.7 GeV.

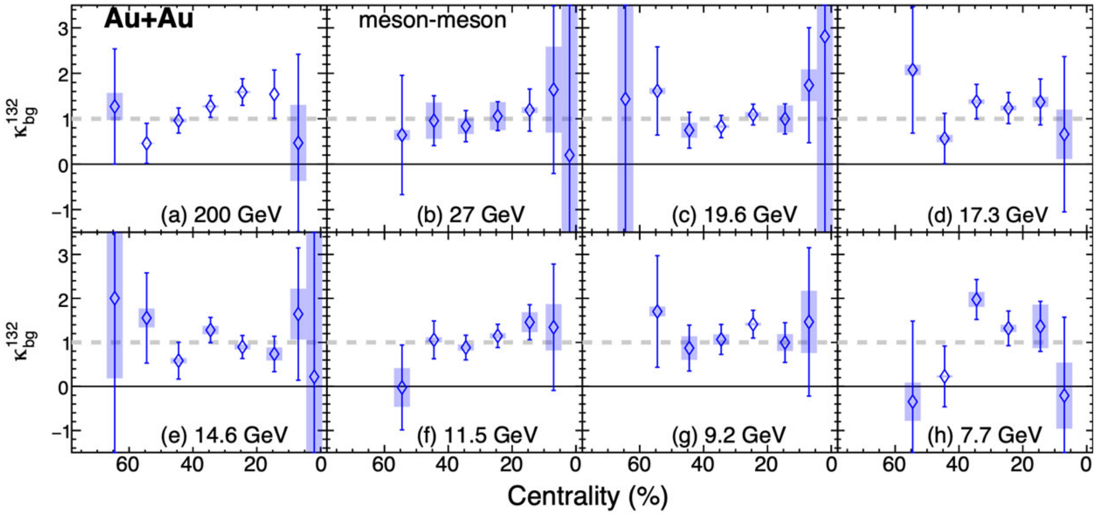
The background in $\Delta\gamma^{112}$ and $\Delta\gamma^{132}$

$$\kappa^{112} = \frac{\Delta\gamma^{112} - \Delta\gamma^{112}_{ESS}}{v_2(\Delta\delta + \Delta\gamma^{112}_{ESS})}$$

$$\kappa^{132} = \frac{\Delta\gamma^{132} - \Delta\gamma^{132}_{ESS}}{v_2(\Delta\delta + \Delta\gamma^{132}_{ESS})}$$

arXiv:2506.00278





- **The background in $\Delta\gamma^{112}$ and $\Delta\gamma^{132}$ arise from an universal coupling between elliptic flow and 2-particle correlation: $\kappa^{112} \sim 2.5$, $\kappa^{132} \sim 1$**
- **AMPT failed to describe data, while AVFD model is consistent with data at 200 GeV.**

The background is indeed flow induced, an unified description of the dynamics is needed !

STAR ESS CME Search Summary

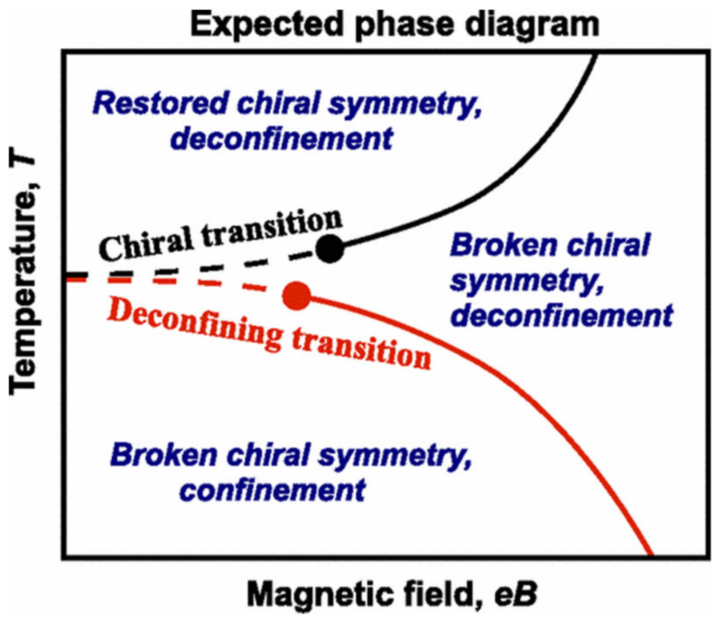
Event Shape Selection   Spectator Ψ_1

$$\Delta\gamma^{112} = \Delta\gamma^{\text{CME}} + k\frac{v_2}{N} + \Delta\gamma^{\text{non-flow}}$$

Measured → $\Delta\gamma^{112}$; Signal → $\Delta\gamma^{\text{CME}}$; Backgrounds → $k\frac{v_2}{N}$, $\Delta\gamma^{\text{non-flow}}$

- **The novel Event Shape Selection effectively suppresses flow-related backgrounds.**
  - **At 200 GeV, upper limit of f_{CME}~10%.**
  - **At each of 11.5, 14.6 and 19.6 GeV, a positively finite $\Delta\gamma^{112}_{\text{ESS}}$ (>3σ). Over 5σ if combined.**
  - **Around 7.7 GeV, approaches zero CME limited with large uncertainties.**
- **More theoretical insights are needed:**
  - **The remaining B field effect too weak at 200 GeV?**
  - **Chiral symmetry breaking around 7.7 GeV?**
  - **The chance of the CME occurrence is enhanced near the critical point?**

A. J. Mizher, M. N. Chernodub, and E. S. Fraga, PRD 82 (2010) 105016



Dynamics at RHIC 200 GeV and LHC

With ESS method we found the $\Delta\gamma^{112}_{ESS}$ close to ZERO in Au+Au 200 GeV !!
Expect $\Delta\gamma^{112}_{ESS}$ to be small or near ZERO at the LHC energy ?!

The magnetic field B magnitude at these energies are certainly larger at the initial collision t = 0 !!

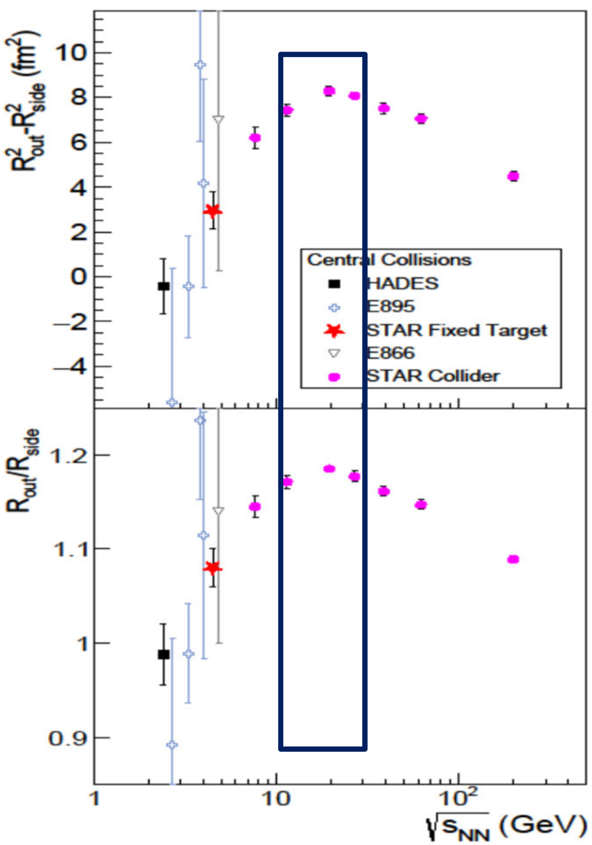
How do we understand these phenomena ?

Please measure $\Delta\gamma^{112}_{ESS}$ at the LHC energy !

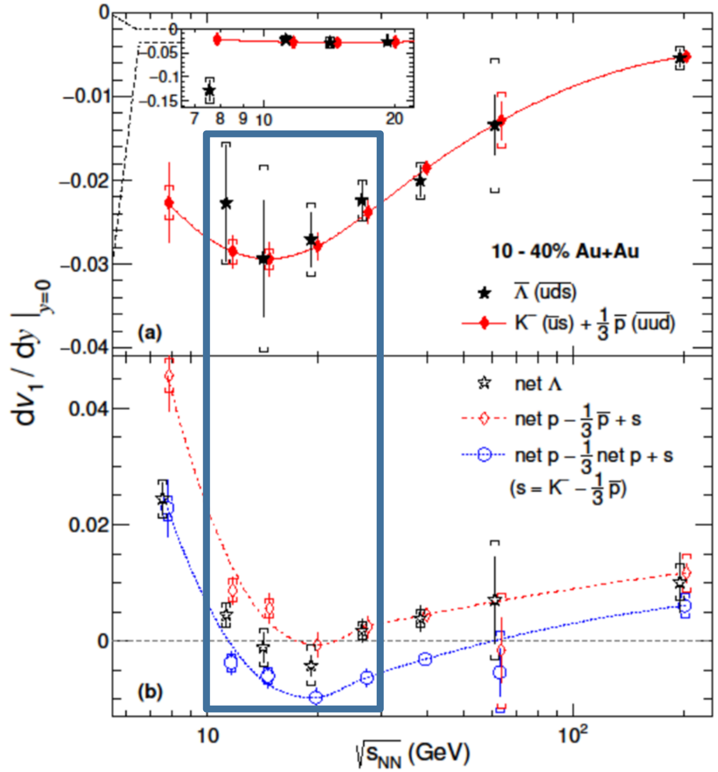
Please measure $v_2\delta$ background correlation as well !

What so Special for Collisions at 10-30 GeV

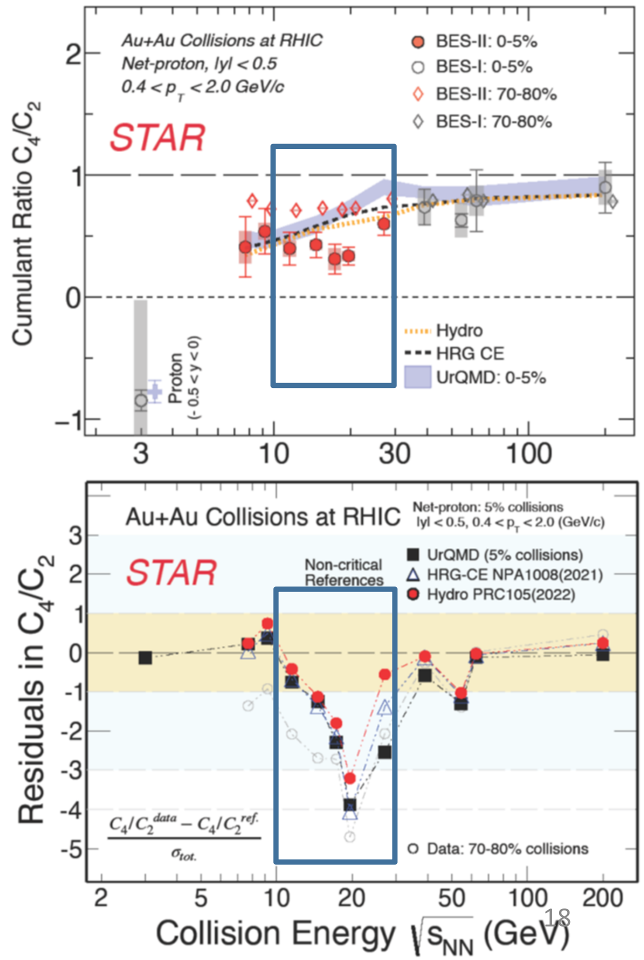
HBT Rout/Rside



v_1 slope dv_1/dy



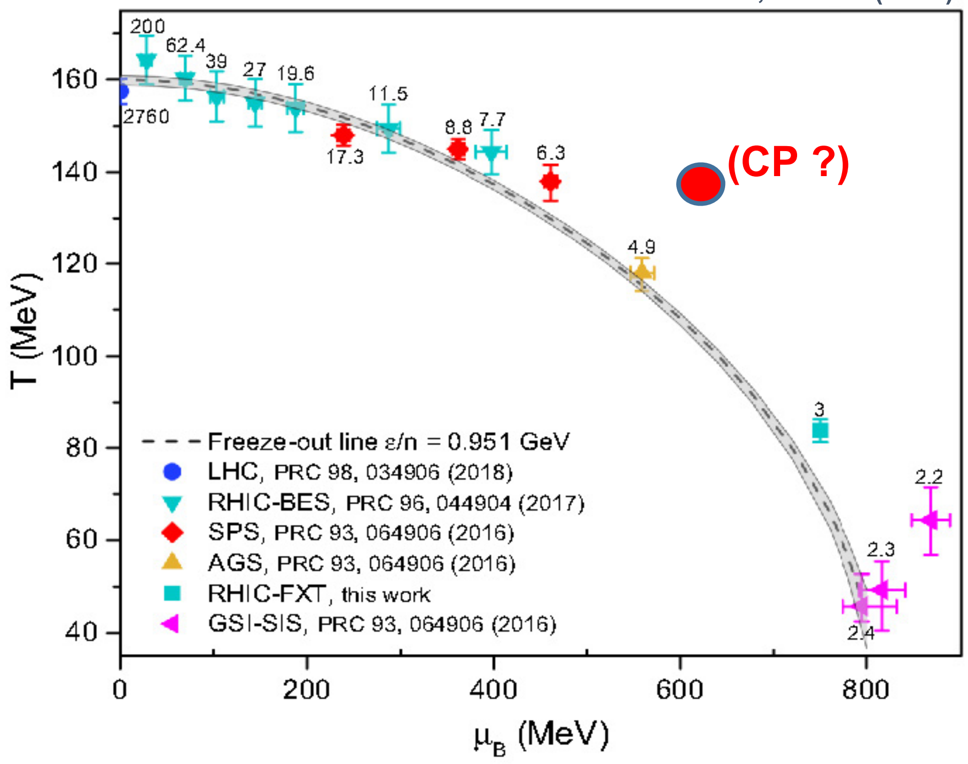
Critical Point: C_4/C_2



Can we approach the possible critical point (region) based on chemical freeze-out conditions?

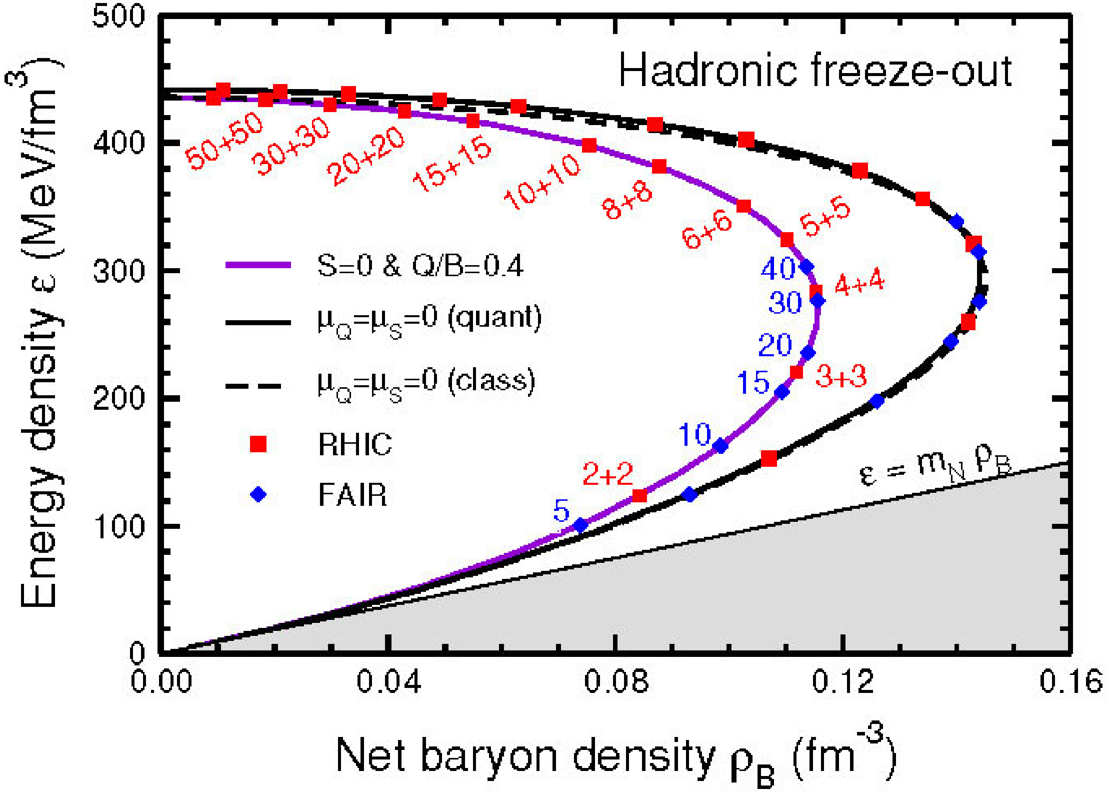
Chemical Freeze-out Curve

PHYSICAL REVIEW C 111, 054903 (2025)

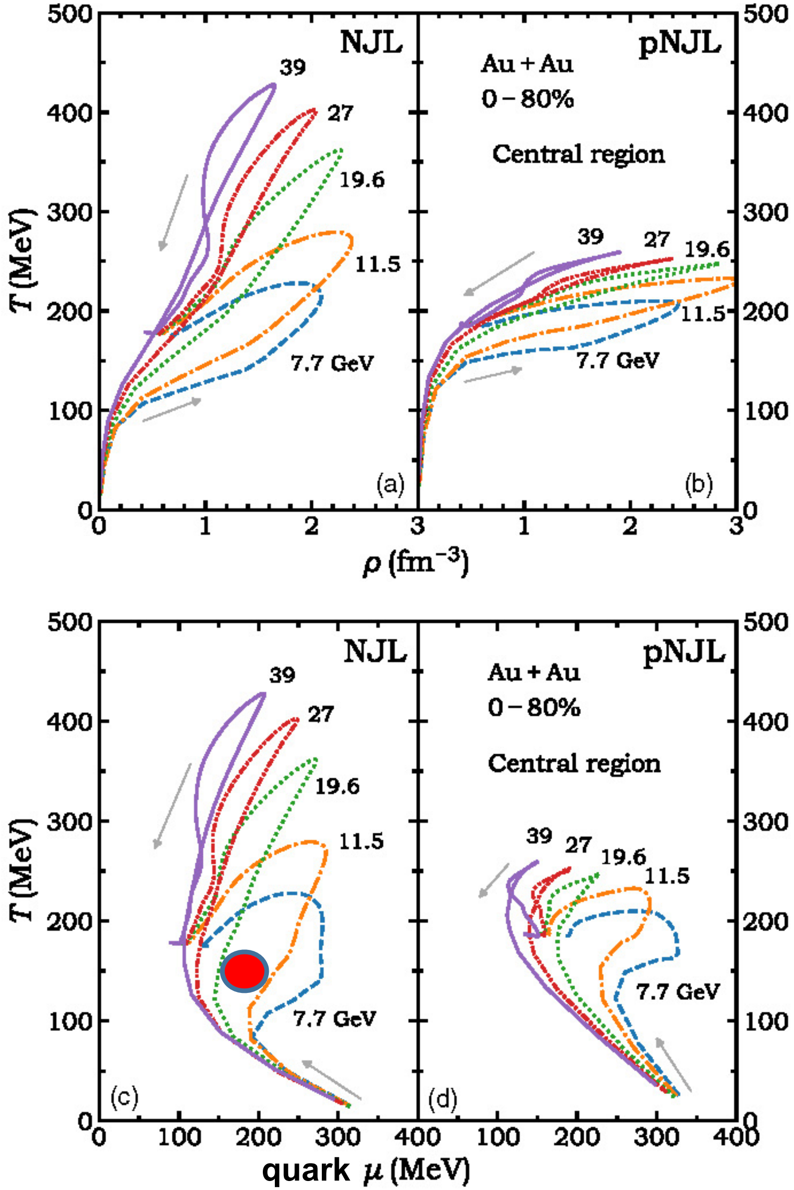


Max baryon density at freeze-out

PHYSICAL REVIEW C 74, 047901 (2006)



Where is the critical point (region)? What is the corresponding net baryon density?



Dynamical Approach towards Critical Region ?!

W. Zhou et al, PRC 104, 044901 (2021)

Nambu-Jona-Lasinio Model does not describe the critical phenomenon ($T_{C,}$ μ_C) correctly !

These models provide empirical mapping from AMPT based (energy density, baryon numbers) to (T, μ);

Detail numbers may vary, but the overall scenario is very intriguing !

How do we map the (en, n_B) to (T, μ) better than NJL or pNJL models ?

Future of Experimental CME Searches

Improve understanding background contributions !

Improve CME search approach !

- **We improved Event Shape Selection approach:**
  - **remove flow-induced background (hydro-like);**
  - **remove non-flow background – spectator proton plane from EPD!**
- **We are open to more optimizations if we have better understanding of background dynamics !**
  (comparison of background with real data background important! Some toy models are just toys, Nothing More !)

Relating charge-separation signal with magnetic field effect !

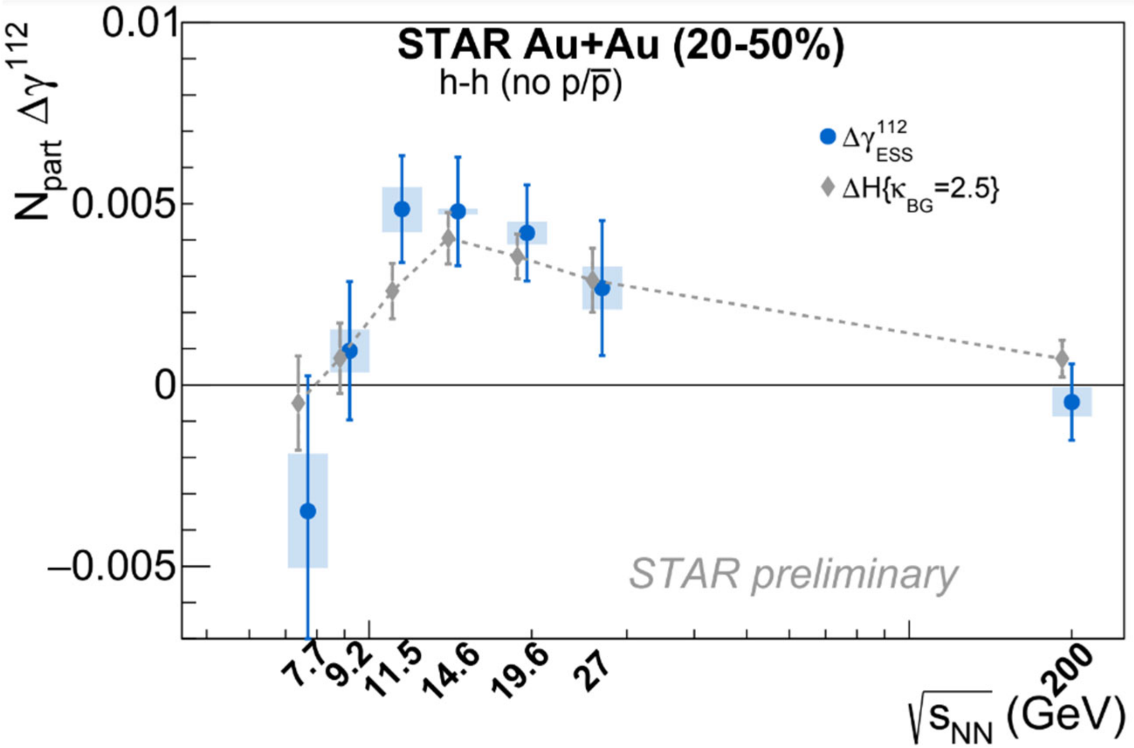
- **Important physics message in the beam energy dependence !**

Theoretical insights !

Thank You !

Backup slides

Connection between ESS and the *H* correlator



- In dealing with the BES-I data, we introduced the *H* correlator to subtract the flow BKG:

$$H(\kappa_{bg}) \equiv (\kappa_{bg} v_2 \delta - \gamma^{112})/(1 + \kappa_{bg} v_2)$$

$$\Delta H \equiv H_{SS} - H_{OS} \qquad \delta = \cos(\phi_1 - \phi_2)$$

$$\gamma = \kappa v_2 B - H$$
$$\delta = B + H$$

- κ_{bg} is an adjustable parameter, unknown a priori. It quantifies the coupling between elliptic flow and other mechanisms manifested in the two-particle correlation.

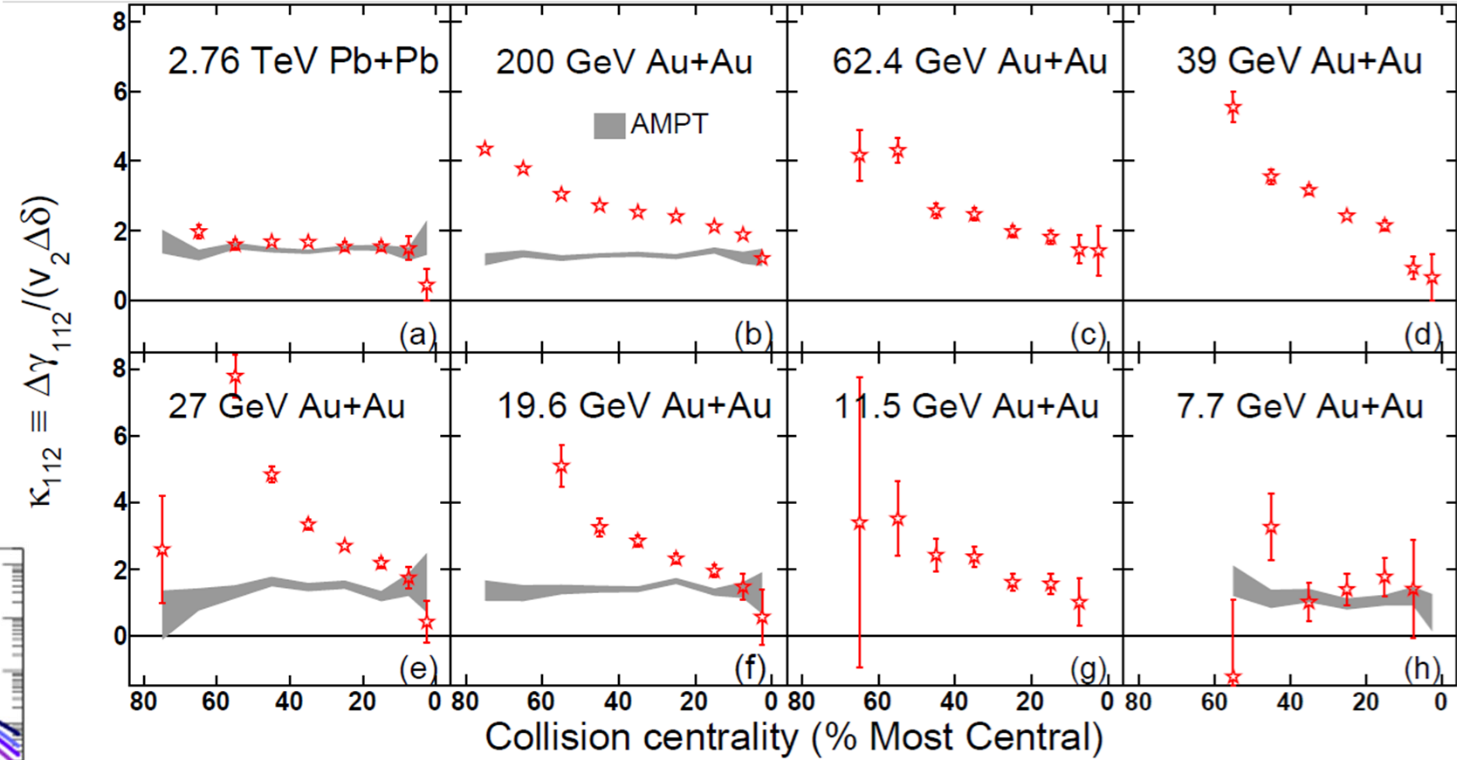
- **With κ_{bg} set to 2.5, ΔH agrees with the ESS result at all beam energies under study.**
- **The flow background can be reasonably well described by a universal coupling between v_2 and the two-particle correlation.**

Rough Background Estimate

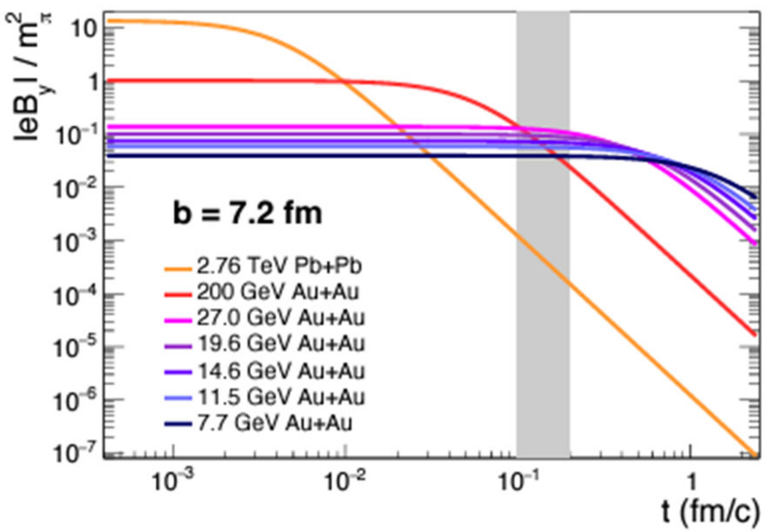
$$\kappa_{112} \equiv \Delta\gamma_{112}/(v_2\Delta\delta)$$

$$\delta \equiv \langle\cos(\phi_\alpha - \phi_\beta)\rangle$$

Normalized quantity facilitates comparison between data and model calculations (AMPT).



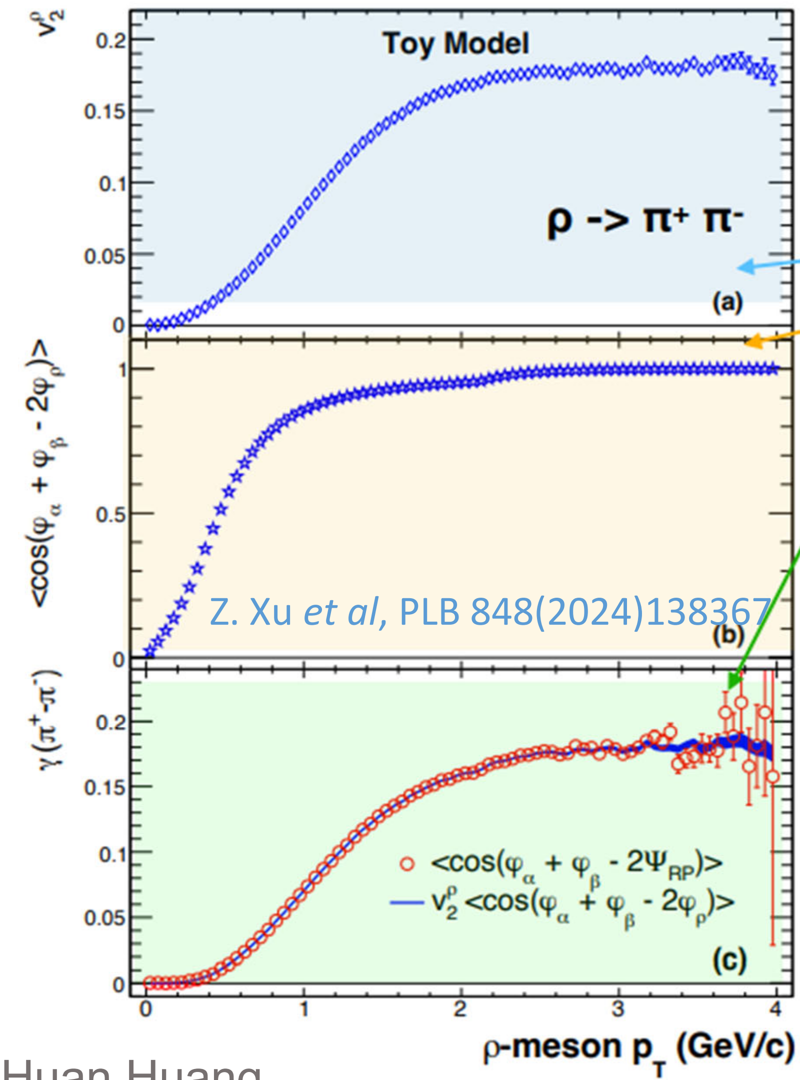
ALICE, Phys. Rev. Lett. 110(2013)012301. STAR, Phys. Rev. Lett. 113(2014)52302



Compared with a pure-background model, the CME signal seems to disappear at 7.7 GeV and 2.76 TeV.

- very low beam energies: chiral symmetry breaking?
- very high energies: no duration of the magnetic field?

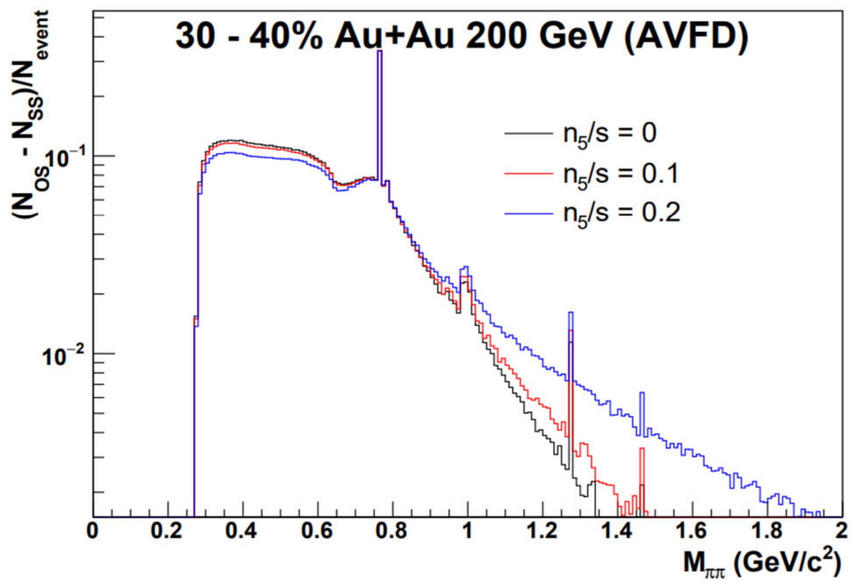
Flowing Resonance Background

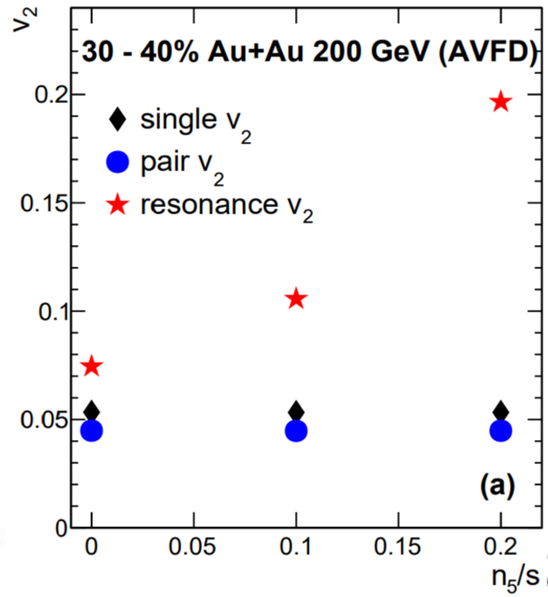


BKG due to flowing resonance decay can be well represented by

$$\Delta\gamma\{BG\} = v_2^{res}\langle\cos(\varphi_\alpha + \varphi_\beta - 2\varphi_\rho)\rangle$$

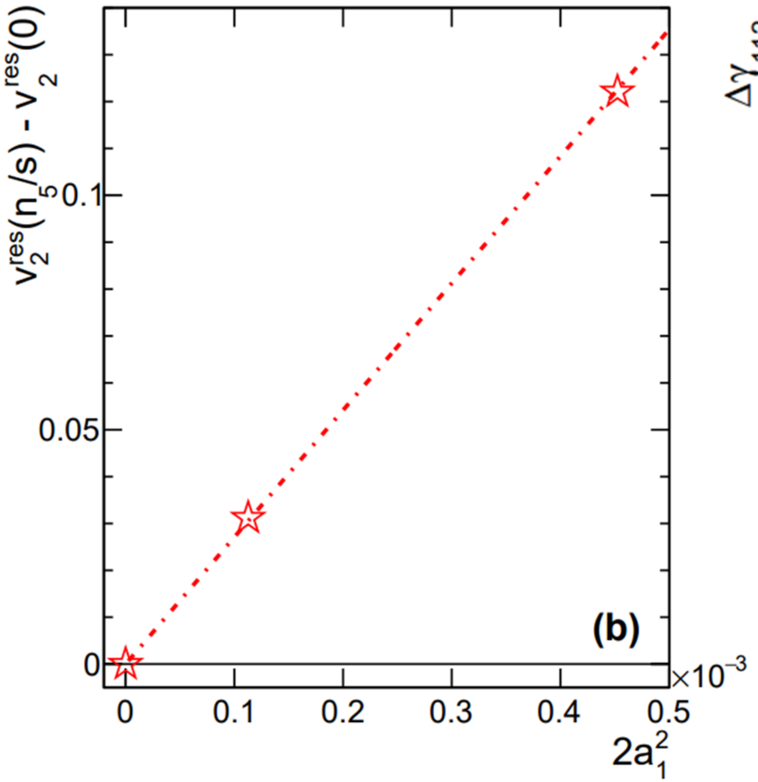
- However, v_2^{res} itself is sensitive to the CME.
- Invariant mass is modified under the CME existence.
- Single and pair v_2 values are relatively constant.

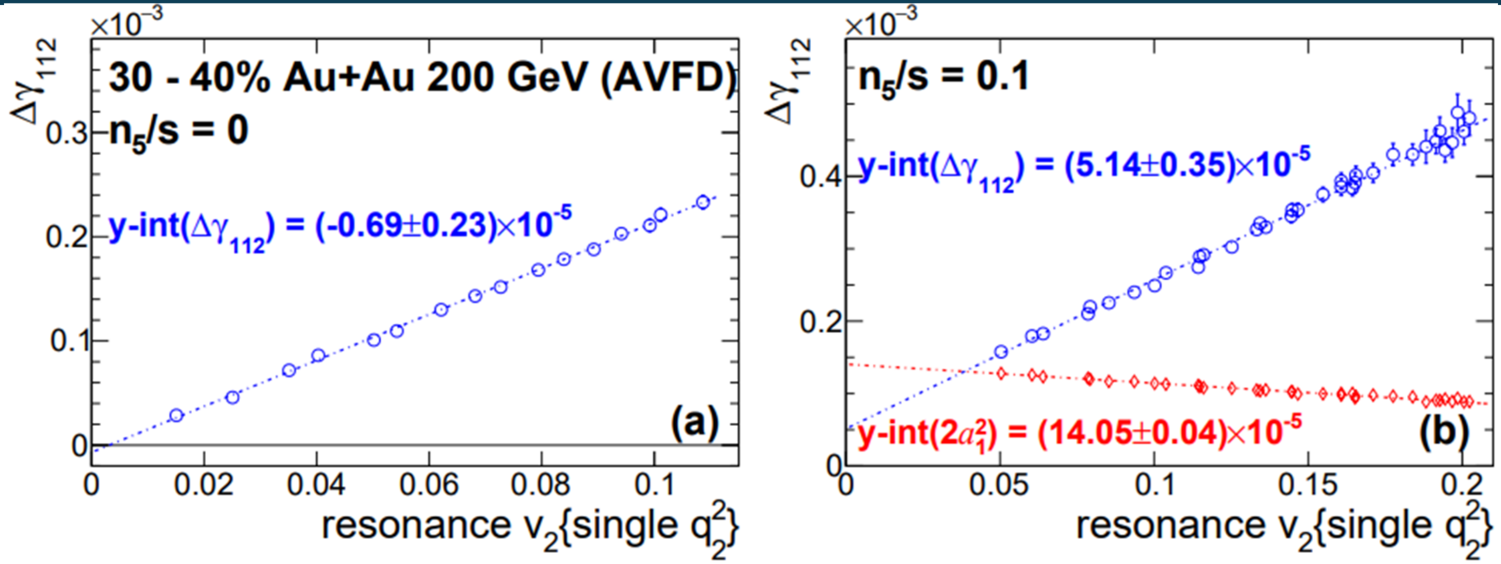




Huan Huang

Flowing Resonance Background





- v_2^{res} itself is sensitive to CME.
- Single and pair v_2 values are relatively constant.
- Using v_2^{res} for ESS will cause severe over-subtraction.
- Using pair v_2 will also cause slight over-subtractoin.

$$v_2^{res} \approx v_2^\pi + \frac{1}{2}(\gamma^{OS} + \gamma^{SS}) - \frac{v_2^\pi}{2}(\delta^{OS} + \delta^{SS}) + \frac{N_{OS} + N_{SS}}{2(N_{OS} - N_{SS})}(\Delta\gamma_{112} - v_2^\pi \Delta\delta)$$

$$v_{2,pair} \approx v_2^\pi + \frac{1}{2}(\gamma^{OS} + \gamma^{SS}) - \frac{v_2^\pi}{2}(\delta^{OS} + \delta^{SS}) + \frac{N_{OS} - N_{SS}}{2(N_{OS} + N_{SS})}(\Delta\gamma_{112} - v_2^\pi \Delta\delta)$$

comparable

Z. Xu *et al*, PLB 848(2024)138367

dominant

Non-interdependent Collective Motions

$$\frac{2\pi}{N^{\pm}}\frac{dN^{\pm}}{d\varphi} = 1+\sum_{n=1}^{\infty} 2a_n^{\pm}\sin n\Delta\varphi+\sum_{n=1}^{\infty} 2v_n^{\pm}\cos n\Delta\varphi$$

$$\frac{2\pi}{N^{\pm}}\frac{dN^{\pm}}{d\varphi} = \prod_{n=1}^{\infty}(1+2\tilde{a}_n^{\pm}\sin n\Delta\varphi)\prod_{n=1}^{\infty}(1+2\tilde{v}_n^{\pm}\cos n\Delta\varphi)$$

$$4\tilde{a}_1\tilde{v}_2\sin\Delta\varphi\cos 2\Delta\varphi = -2\tilde{a}_1\tilde{v}_2\sin\Delta\varphi + 2\tilde{a}_1\tilde{v}_2\sin 3\Delta\varphi.$$

Noumenon

$$\tilde{a}_1 = \frac{a_1 - a_3 v_2}{1 - v_2 - v_2^2}$$

$$\tilde{a}_3 = \frac{a_3 - a_1 v_2 - a_3 v_2}{1 - v_2 - v_2^2}$$

$$\tilde{v}_1 = \frac{v_1 - v_3 v_2}{1 + v_2 - v_2^2}$$

$$\tilde{v}_3 = \frac{v_3 - v_1 v_2 + v_3 v_2}{1 + v_2 - v_2^2}$$

Phenomena

$$a_1 = \tilde{a}_1 - \tilde{a}_1\tilde{v}_2 + \tilde{a}_3\tilde{v}_2$$

$$a_3 = \tilde{a}_3 + \tilde{a}_1\tilde{v}_2$$

$$v_2 = \tilde{v}_2 + \tilde{a}_1\tilde{a}_3$$

$$v_1 = \tilde{v}_1 + \tilde{v}_1\tilde{v}_2 + \tilde{v}_3\tilde{v}_2$$

$$v_2 = \tilde{v}_2 + \tilde{v}_1\tilde{v}_3$$

$$v_3 = \tilde{v}_3 + \tilde{v}_1\tilde{v}_2$$

We introduce new sets of non-interdependent Fourier coefficients $\tilde{a}_n$ and $\tilde{v}_n$ to better represent the physics, and takes factorized form in azimuthal distribution.

The mapping between old and new sets reveals inter-dependency between conventional coefficients.

Z. Xu *et al*, Phys. Rev. C 107, L061902

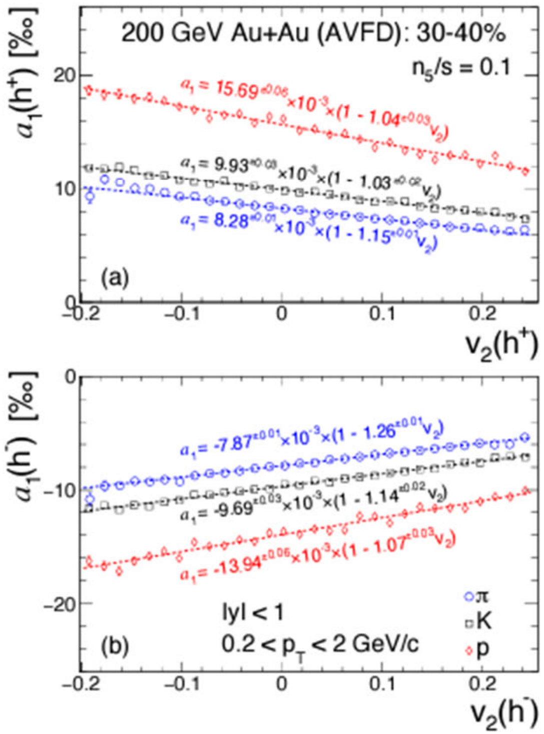
Assuming the prominent elliptic flow magnitude is almost unchanged, $v_2 \approx \tilde{v}_2$, we study the relation among (a_1, v_2, a_3) and (v_1, v_2, v_3) with model simulations.

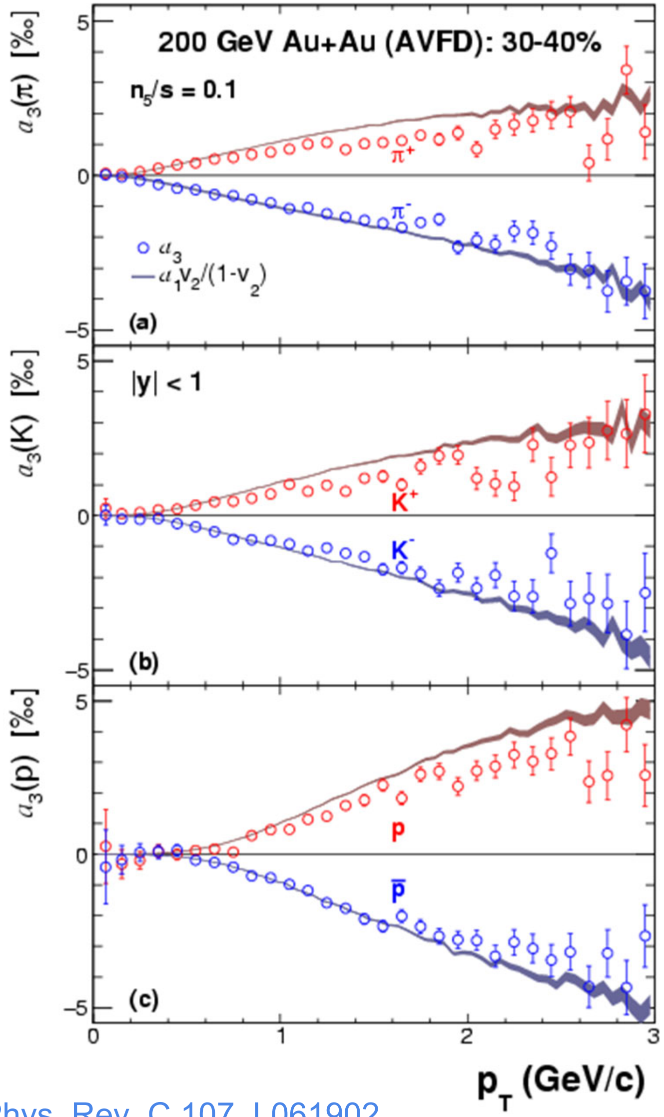
Model Evidence: AVFD

Event-by-Event Anomalous-Viscous Fluid Dynamics (AVFD)[2] model simulates the dynamical CME transport for *u*, *d* and *s* quarks in addition to the hydrodynamic expansion, and further handles local charge conservation and resonance decays.

$$\tilde{a}_3 = 0\ ;\ v_2 \approx \tilde{v}_2$$
$$a_1 = \tilde{a}_1(1 - v_2)$$
$$a_3 = \tilde{a}_1 v_2$$

- Correlations between a_1 and v_2 may contain trigonometric identity in addition to the math relation we look for.
- The observed a_3 as a function of p_T can be described by $a_1v_2/(1-v_2)$ (shaded bands) as predicted.



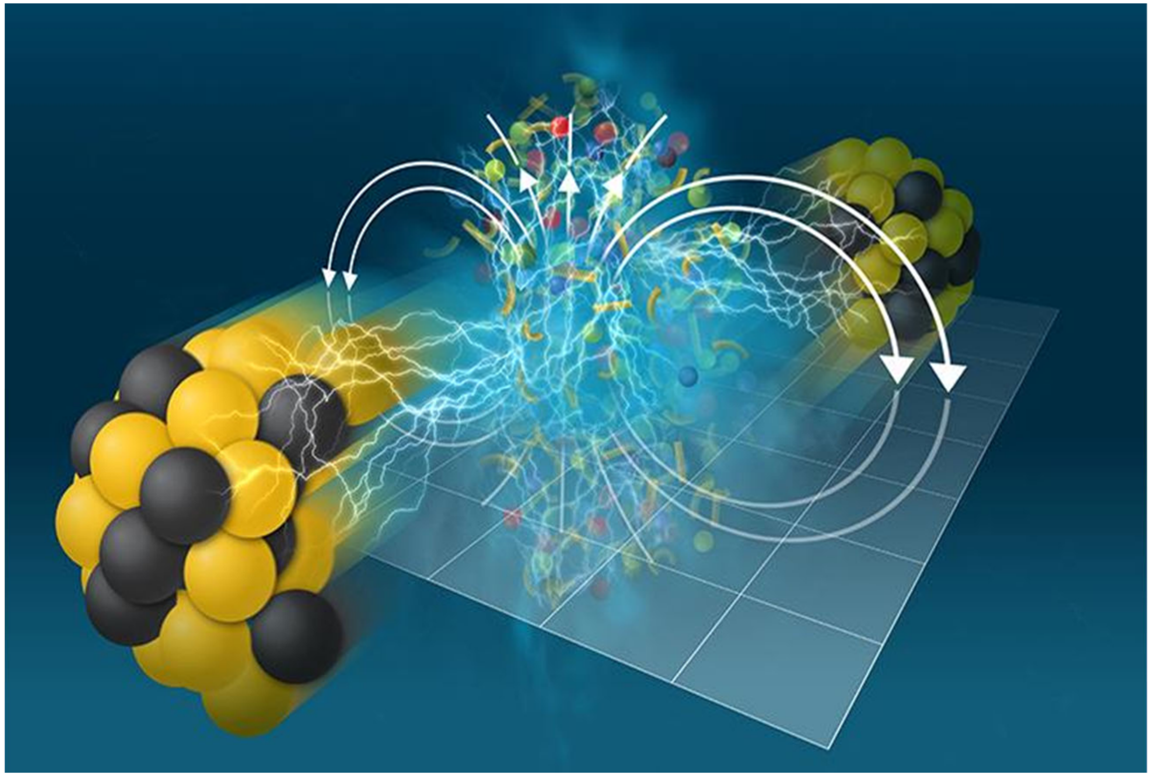


Z. Xu *et al*, Phys. Rev. C 107, L061902

Super Strong Magnetic fields’ Imprint

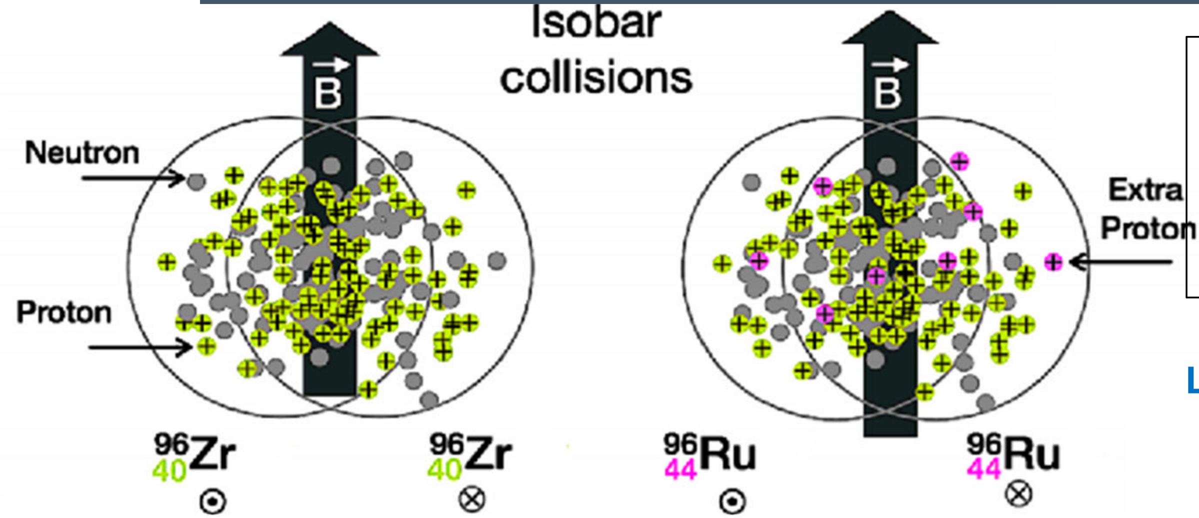
Analysis of electrical charge dependent deflections in quark-gluon plasma by the STAR Collaboration at the BNL Relativistic Heavy Ion Collider(RHIC)

- Data confirm that super strong magnetic fields (~10^{18} Gauss) generated in off-center collisions could induce an electric current in the quark-gluon plasma
- The findings offer a measure that could relate to the electrical conductivity of the quark-gluon plasma to learn about nature’s fundamental building blocks



Observation of the Electromagnetic Field Effect via Charge-Dependent Directed Flow in Heavy-Ion Collisions at the Relativistic Heavy Ion Collider, Phys. Rev. X 14 (2024) 011028

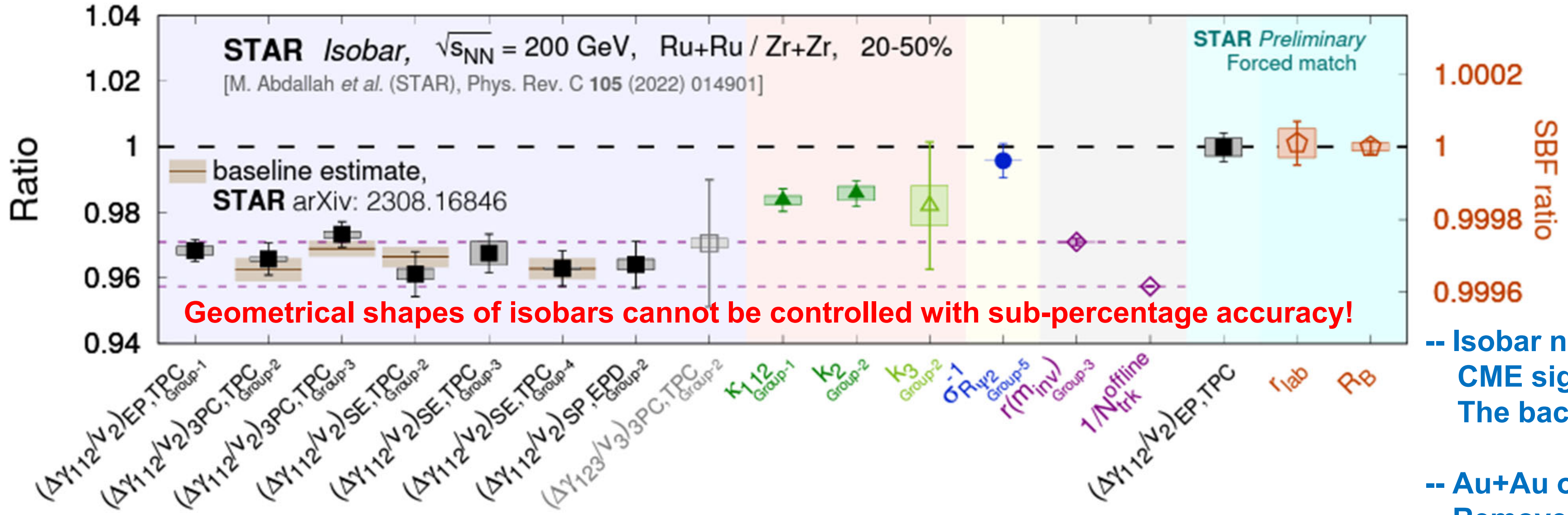
Lessons from Isobar Collisions



Compare the two isobaric systems:

- CME: B-field^2 is ~15% larger in Ru+Ru
- Flow-related Background: utilize $\Delta\gamma_{112}/v_2$
- Nonflow-related Background: almost same

Looking for difference in the signal due to Z difference < 15% of the signal strength !



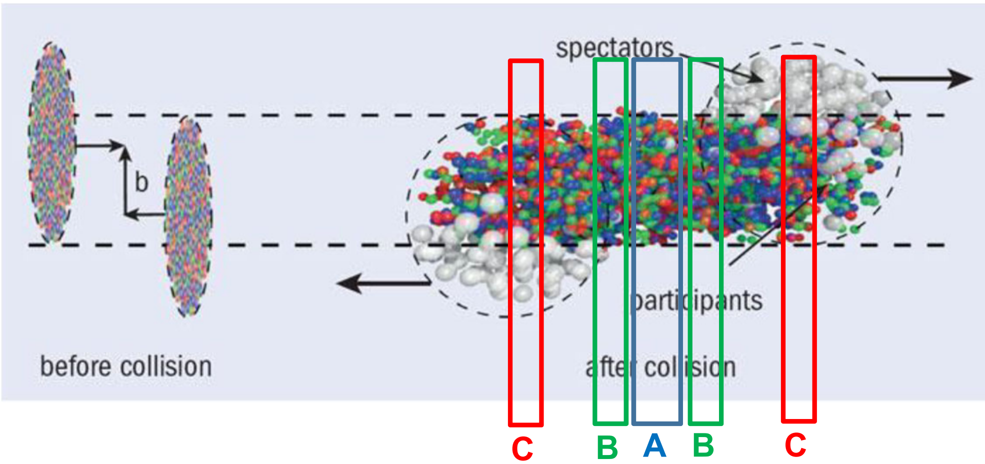
-- Isobar not sensitive enough
CME signal is smaller than expected
The background fluctuation cannot be controlled well
-- Au+Au or Pb+Pb better system
-- Remove background essential

Previous Event Shape Method

Previous Event Shape Engineering (ESE) Approach

"Standard" ESE splits an event into 3 sub-events

- (A) particles of interest (POI)
- (B) particles to construct q_n shape
- (C) particles to reconstruct EP

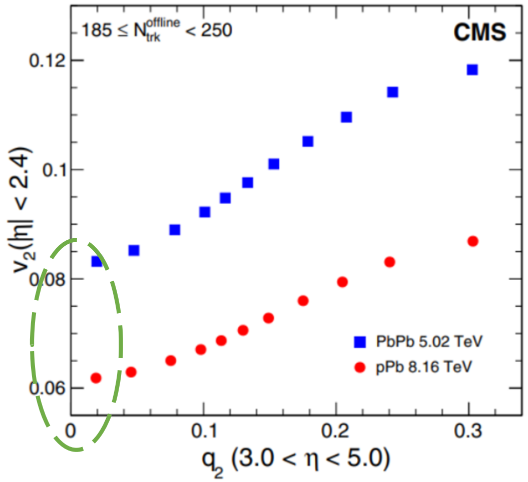


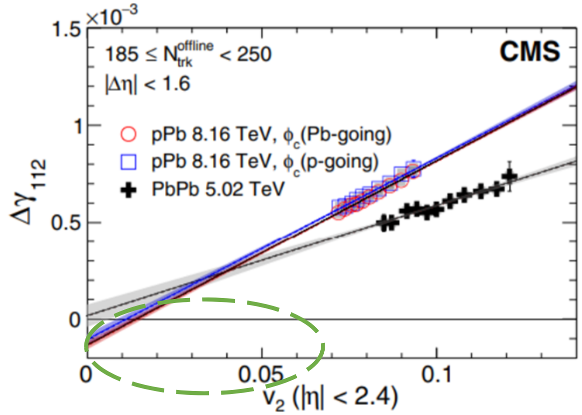
Sensitive to eccentricity which limited range of variation for a given centrality !
CME background – overall particle emission !

We found
Shape Observable flow vector q_n in region B not effective in selecting shape for particles A

Flow vector q from B correlated to <v_2>

Extreme shape fluctuations are largely local, not global feature!





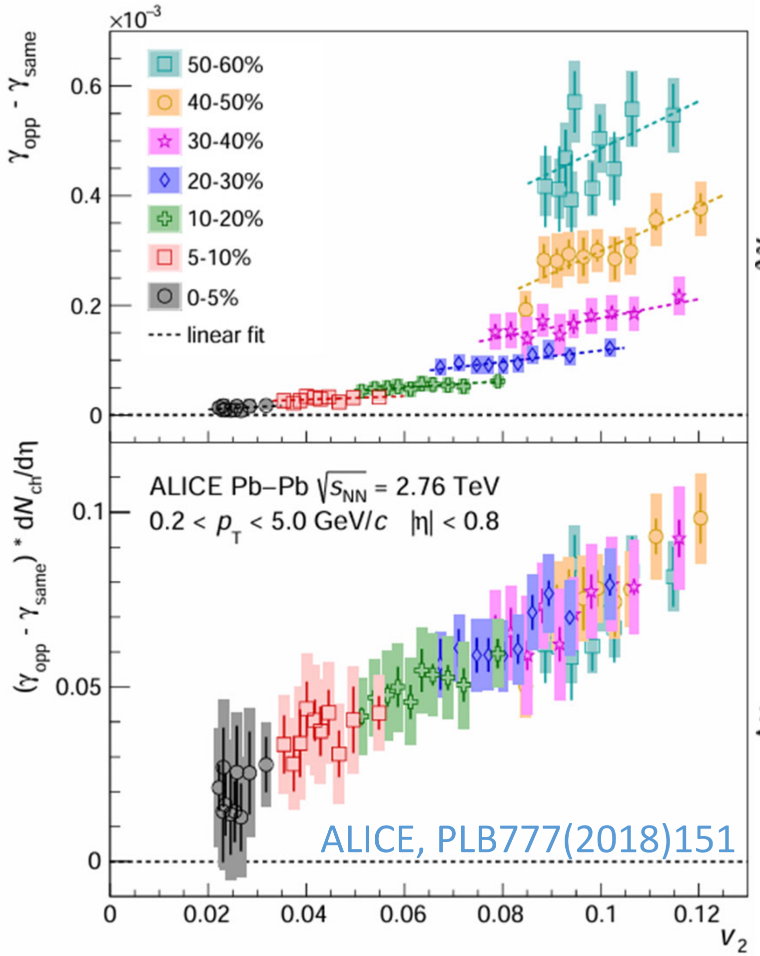
CMS, PRC 97(2018)044912

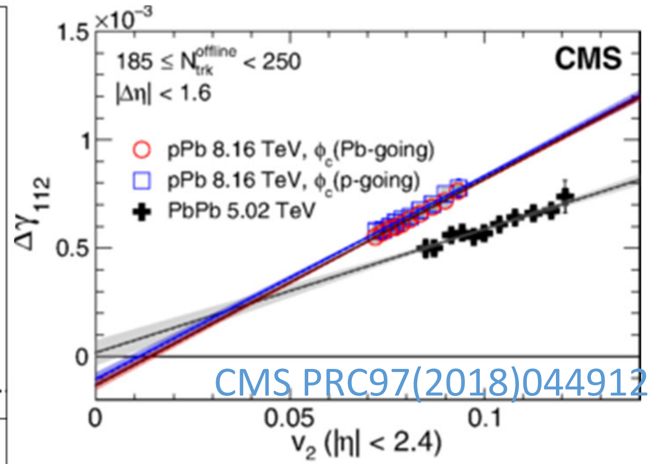
“Standard” Event Shape Engineering

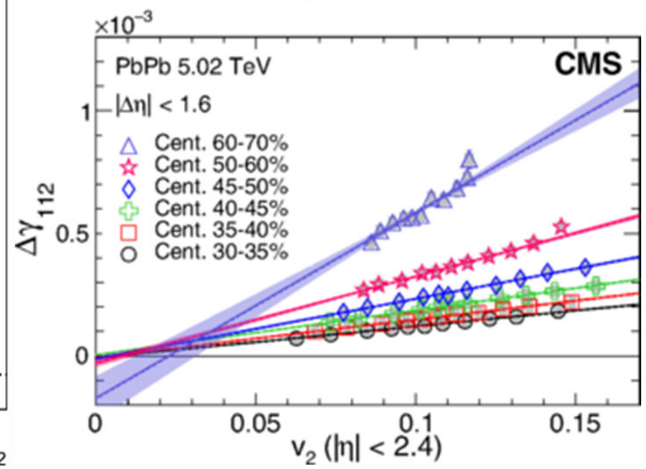
Three sub-events are used: one for POI, one for event plane, and one for event shape variable, q_2, the modulus of the flow vector.

$$q_x \equiv \frac{1}{\sqrt{N}} \sum_i^N \cos(2\phi_i)$$

$$q_y \equiv \frac{1}{\sqrt{N}} \sum_i^N \sin(2\phi_i)$$







- Measure $\Delta\gamma_{112}$ vs q_2 and v_2 vs q_2, then plot $\Delta\gamma_{112}$ vs v_2, and finally extrapolate $\Delta\gamma_{112}$ to zero v_2.
- At LHC energies, all the ESE results are consistent with zero. (too short duration of the *B* field?)
- Since particles of interest (POI) are excluded from q_2, the lever arm on v_2 is very weak, making the extrapolation unstable.