A Novel Approach to Search for the Chiral Magnetic Effect from STAR and the Future Prospect

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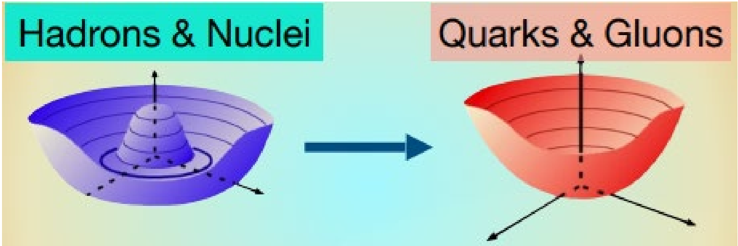
Thanks to Gang Wang, Zhiwan Xu, Jinfeng Liao, Jinhui Chen and Diyu Shen

Outline

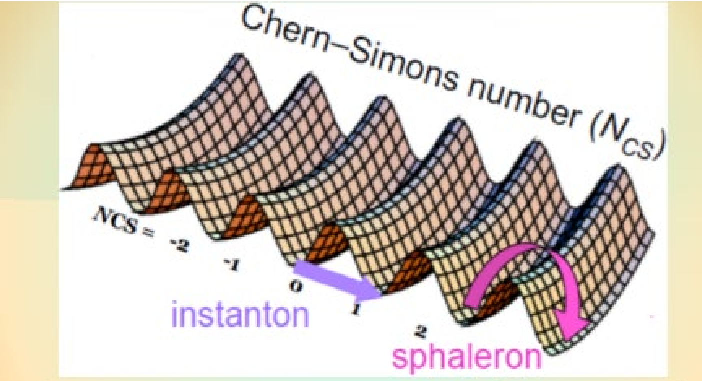
- Introduction
- Lessons from Previous Results
- Novel Approach of Event Shape Selection (ESS)
- STAR ESS Results from BES-II and 200 GeV Data
- Summary and Future Outlook

Chiral Magnetic Effect

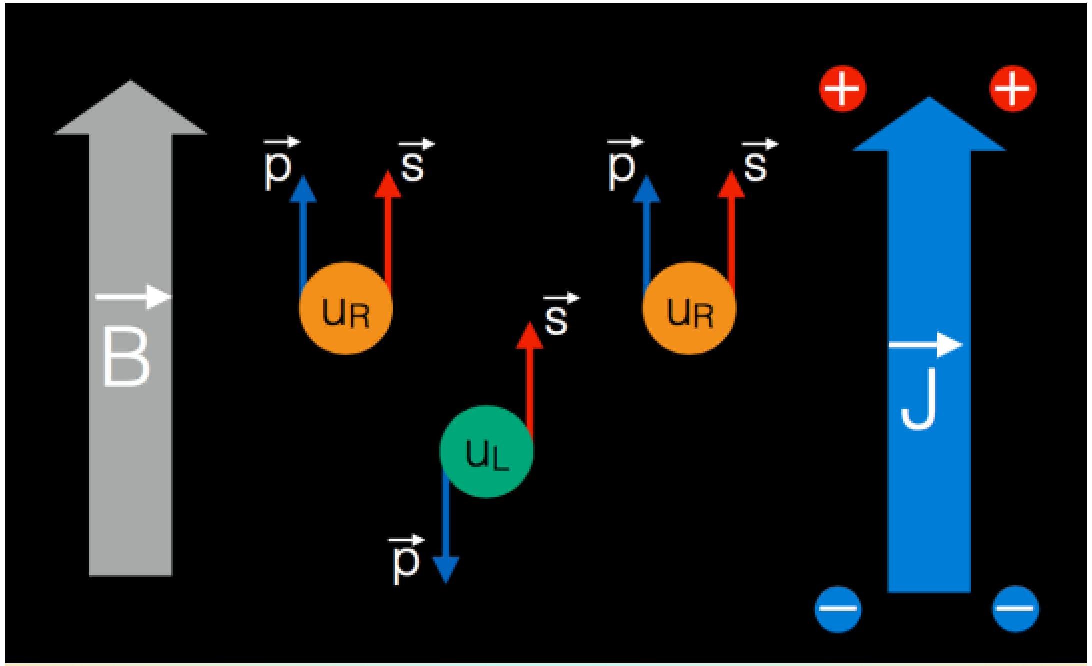
A Rare Opportunity to Experimentally Access Key Intrinsic Properties of the QCD



Chiral symmetry restoration (massless quarks)

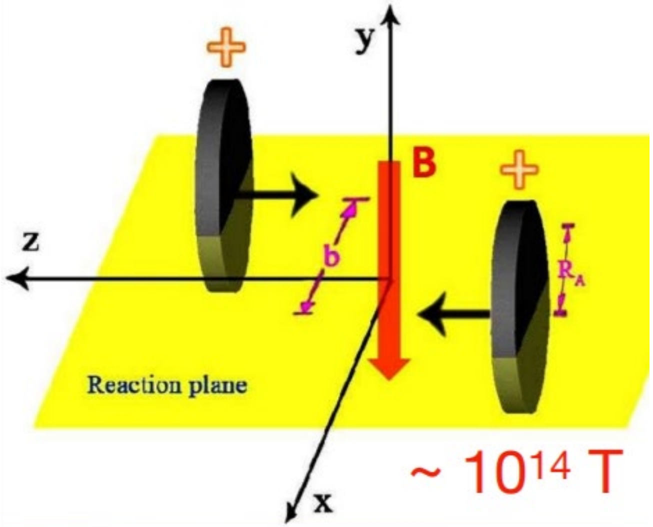


Chirality imbalance (finite μ_5)



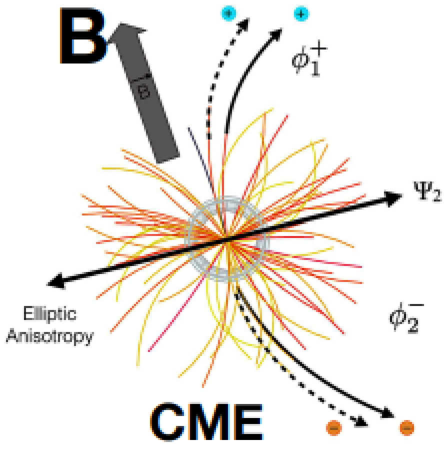
Chiral Magnetic Effect (J || B)

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



Strong magnetic field (B)

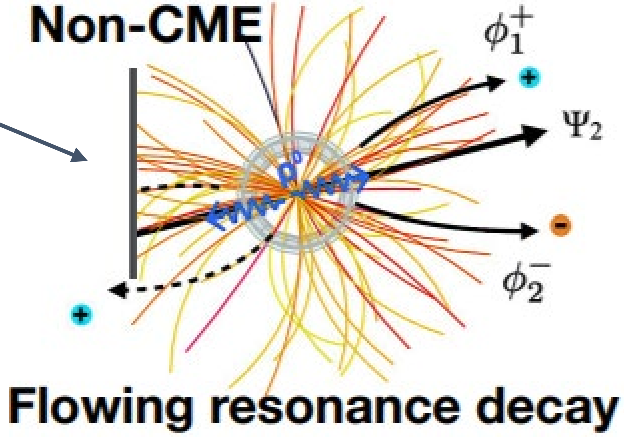
CME Observables



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

$$\propto \mu_5 B$$

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)

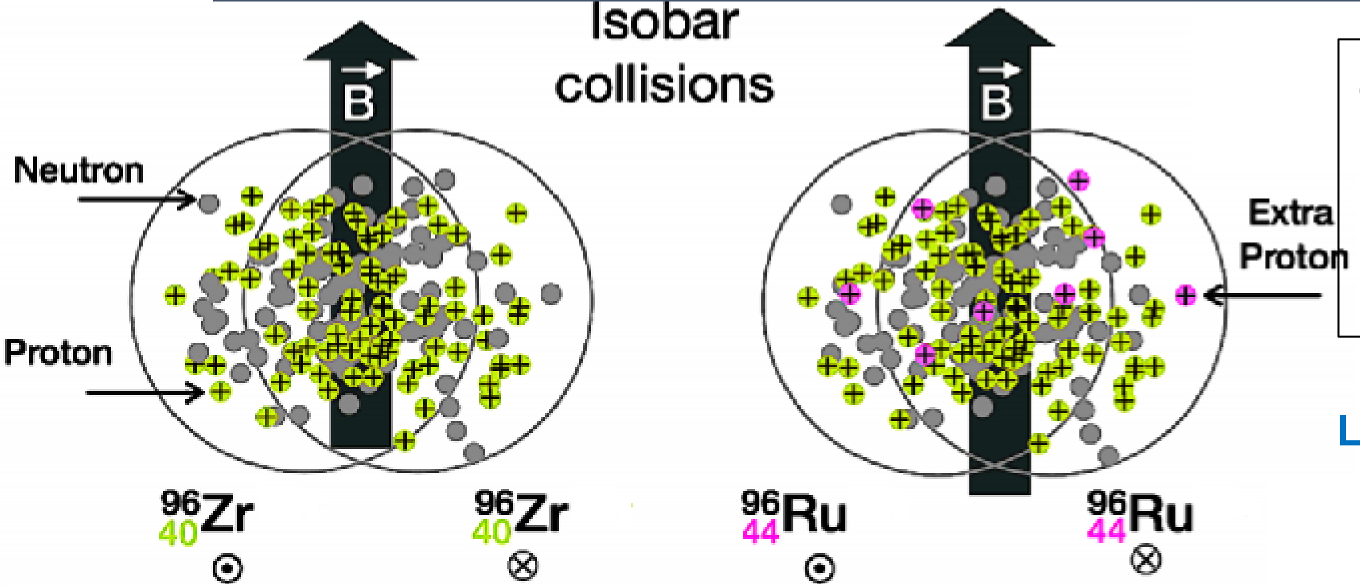
S. Choudhury et al.(STAR), Chin. Phys. C46(2022)014101

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

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

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

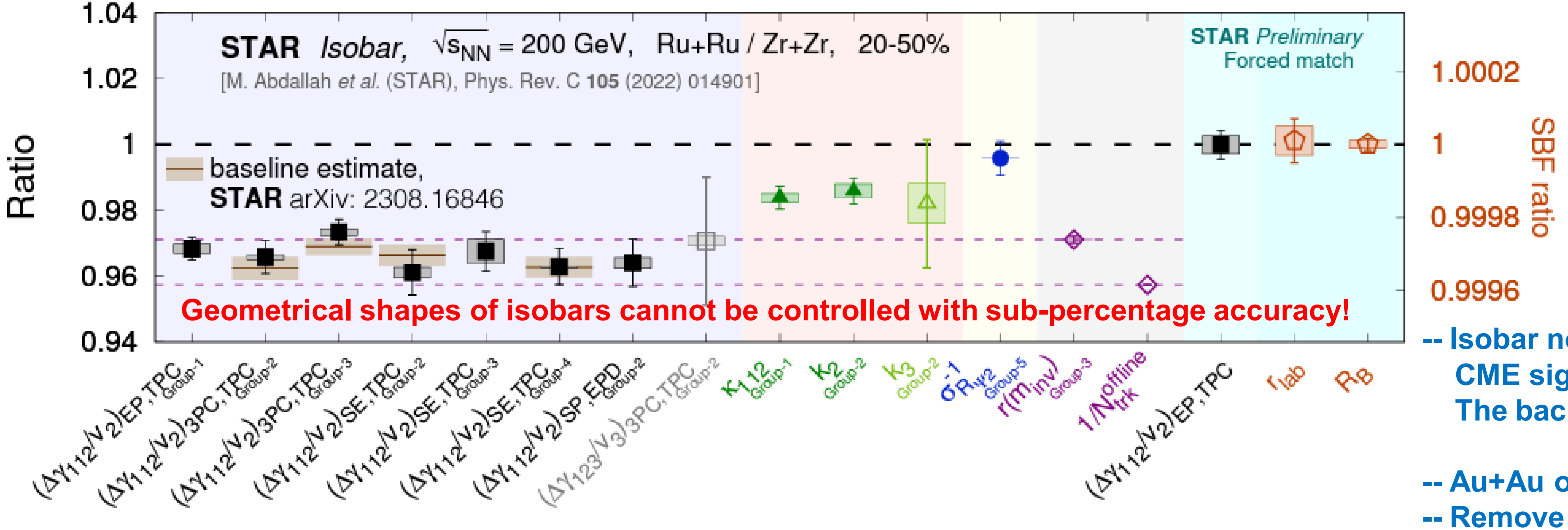
Lessons from Isobar Collisions



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 !



Geometrical shapes of isobars cannot be controlled with sub-percentage accuracy!

-- **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

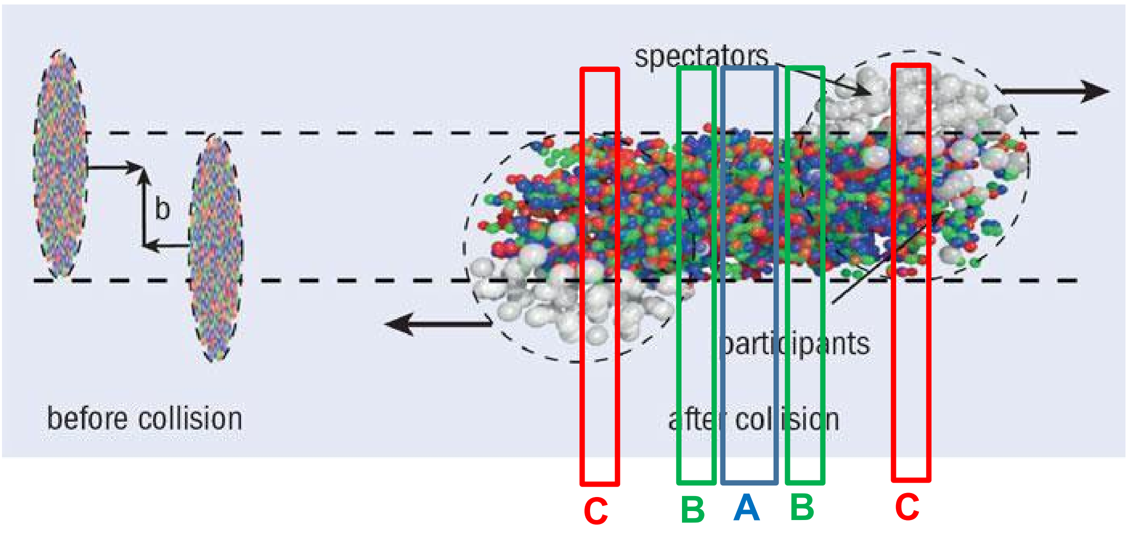
Previous Event Shape Engineering (ESE) Approach

"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

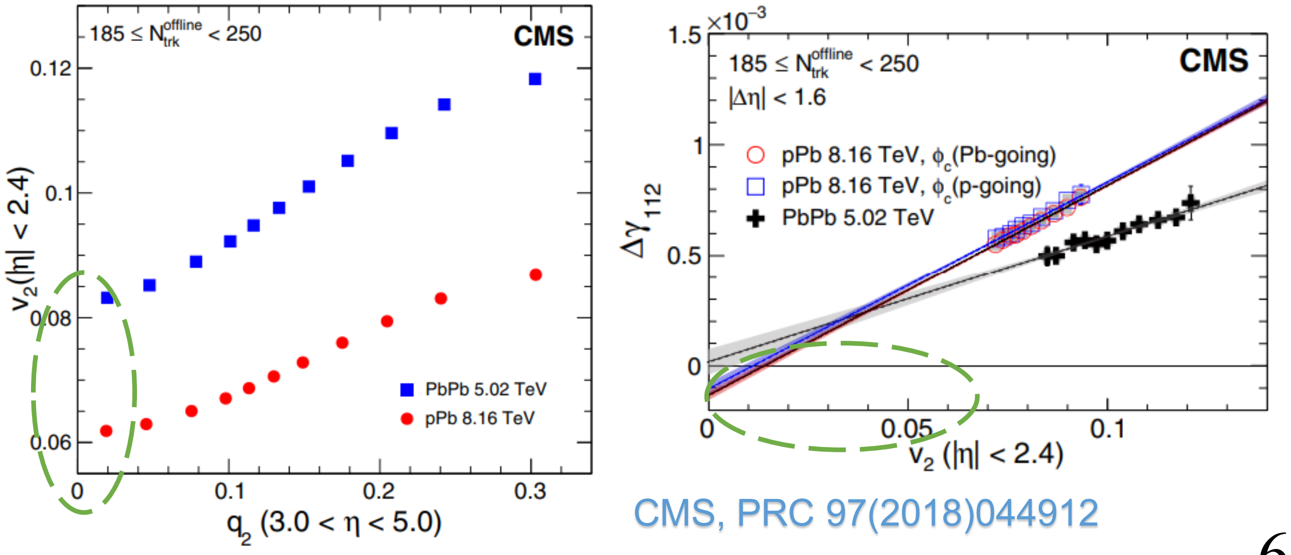


Sensitive to eccentricity which limited range of variation for a given centrality !
CME background – overall particle emission !

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!



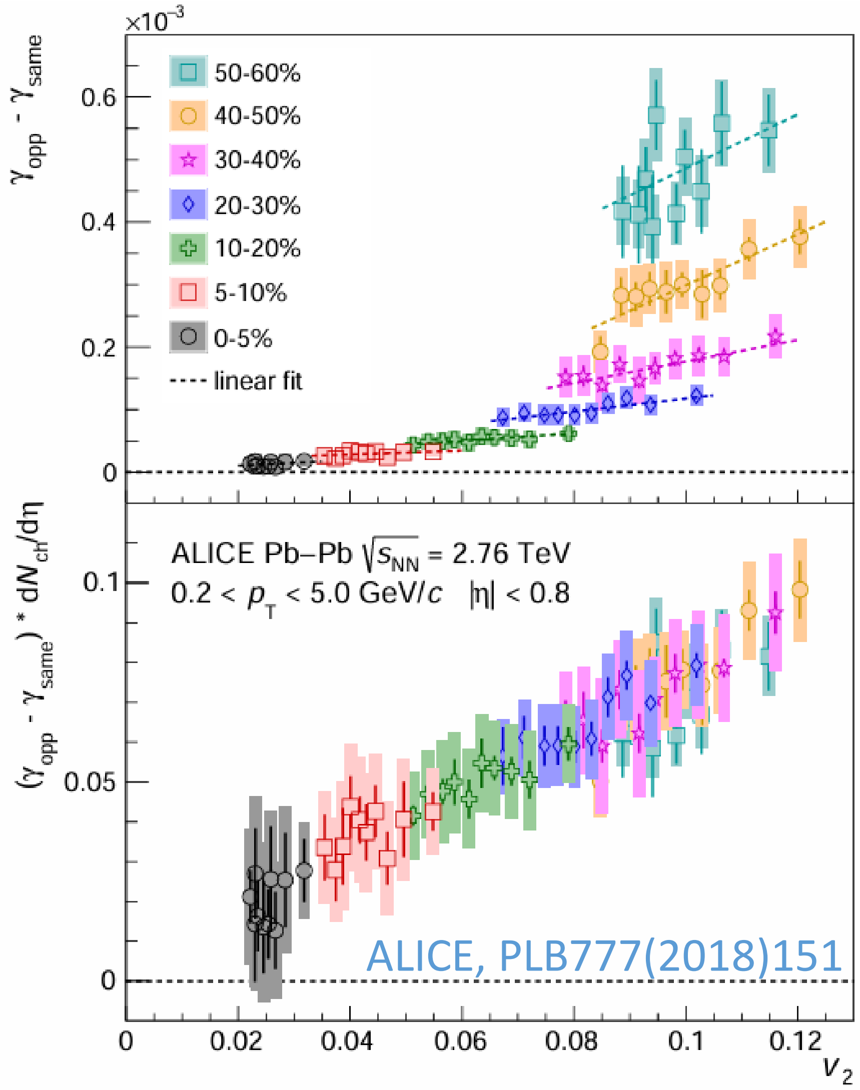
CMS, PRC 97(2018)044912

“Standard” Event Shape Engineering

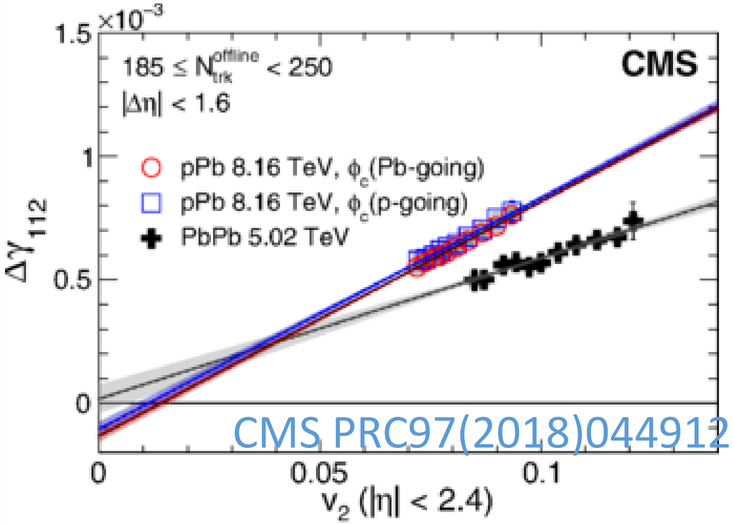
Three sub-events are used: one for POI, one for event plane, and one for event shape variable, q_2, the modulus of the flow vector.

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

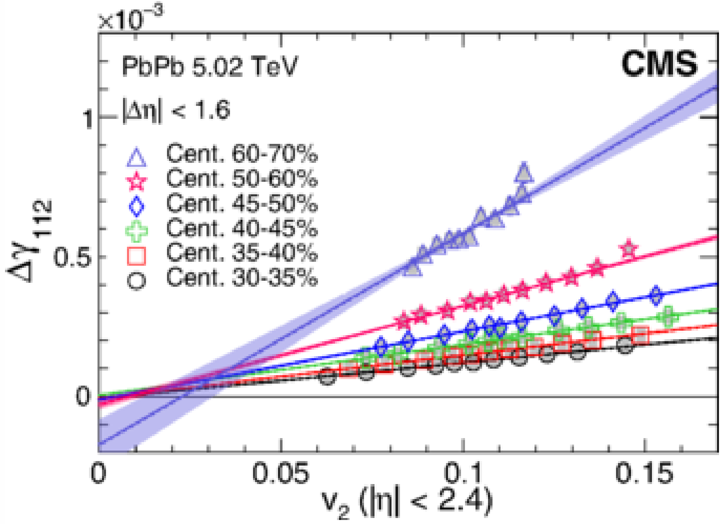
$$q_y \equiv \frac{1}{\sqrt{N}} \sum_i^N \sin(2\phi_i)$$



ALICE, PLB777(2018)151



CMS PRC97(2018)044912

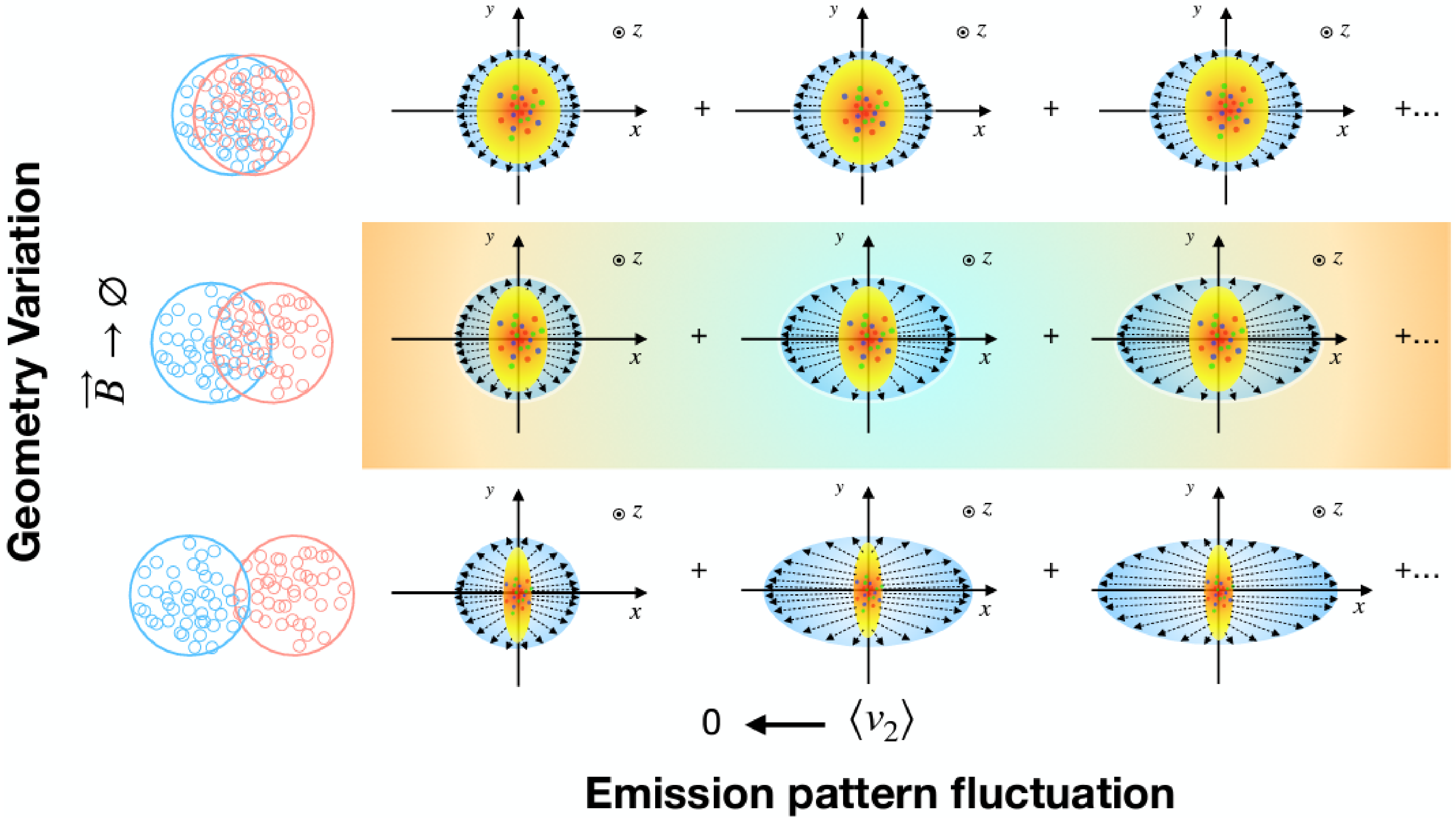


- Measure $\Delta\gamma_{112}$vs q_2 and v_2 vs q_2, then plot $\Delta\gamma_{112}$ vs v_2, and finally extrapolate $\Delta\gamma_{112}$ to zero v_2.
- At LHC energies, all the ESE results are consistent with zero. (too short duration of the *B* field?)
- Since particles of interest (POI) are excluded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

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



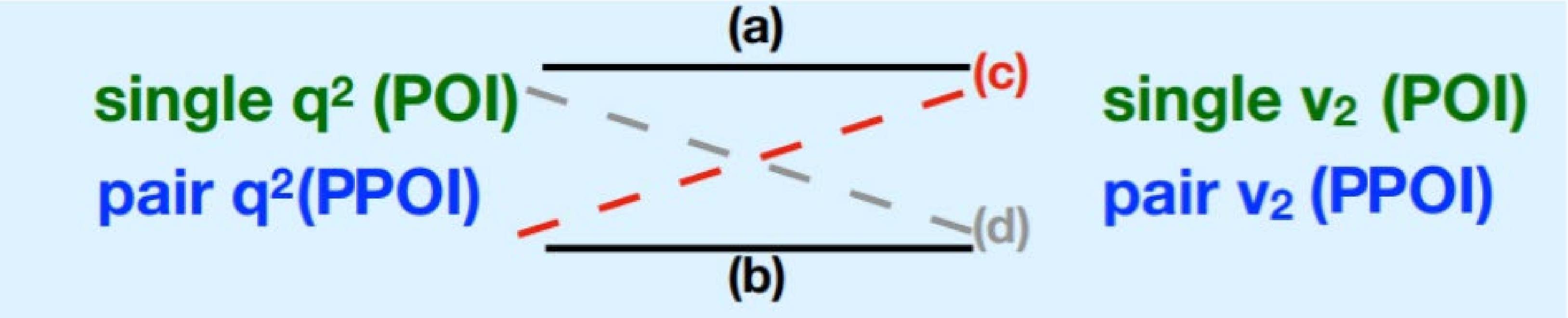
H. Petersen and B. Müller, Phys. Rev. C 88, 044918

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

Event shape variable **Elliptic flow variable**



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

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

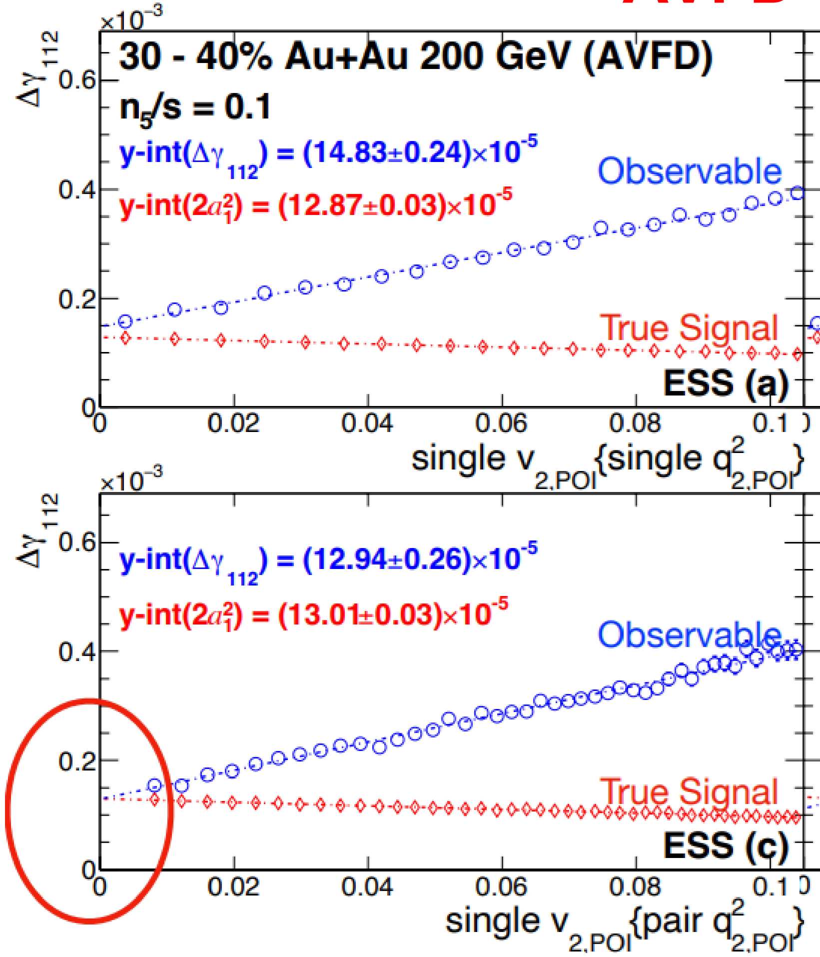
$$\langle q_2^2 \rangle \approx 1 + N v_2^2\{2\}$$

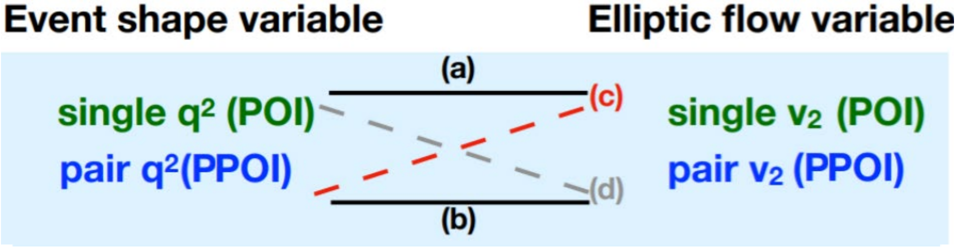
- ESS recipes (a) and (b) involve direct event-by-event correlations between $q_2{}^2$ and v_2, which will cause under-subtraction of background.
- We should use “mixed” recipes, (c) or (d).
- Redefine $q_2{}^2$ with an extra normalization.
- Pair $q_2{}^2$ and pair v_2 are based on $\boldsymbol{\varphi}_\mathrm{p}$.

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

Simulations

AVFD



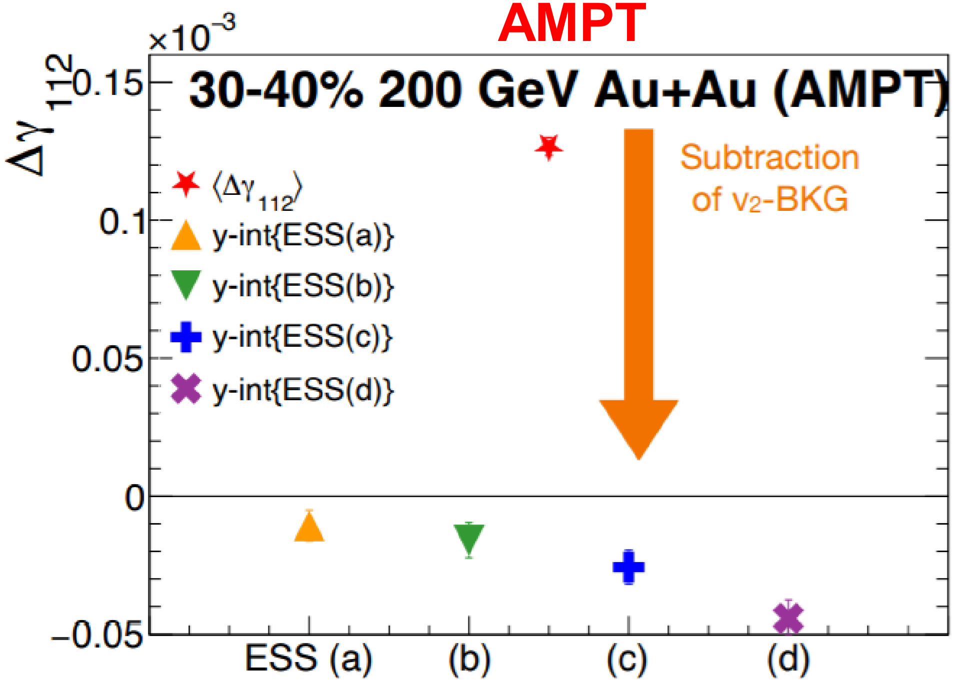


Event shape variable | **Elliptic flow variable**

single q^2 (POI) | single v_2 (POI)

pair q^2(PPOI) | pair v_2 (PPOI)

AMPT



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

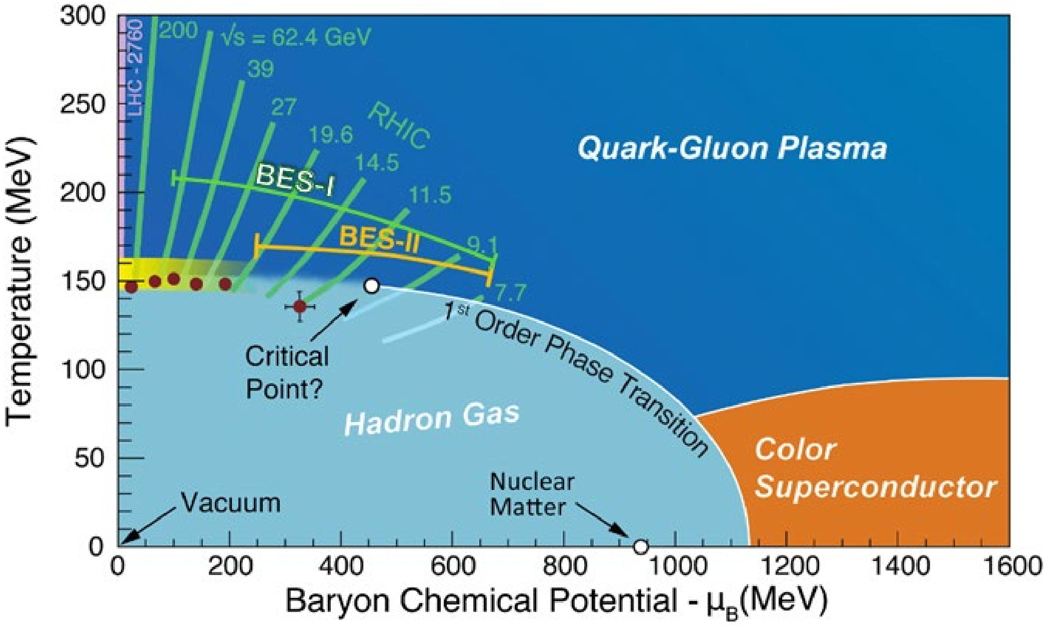
- AVFD: the optimal ESS recipe (c) accurately matches the input CME signal.
- Intercepts follow an ordering (a)>(b)>(c)>(d).
- AMPT: all ESS recipes over-estimate the BKG (with the same ordering as AVFD).

Application to Real Data

“Events” represents good events after quality cuts.

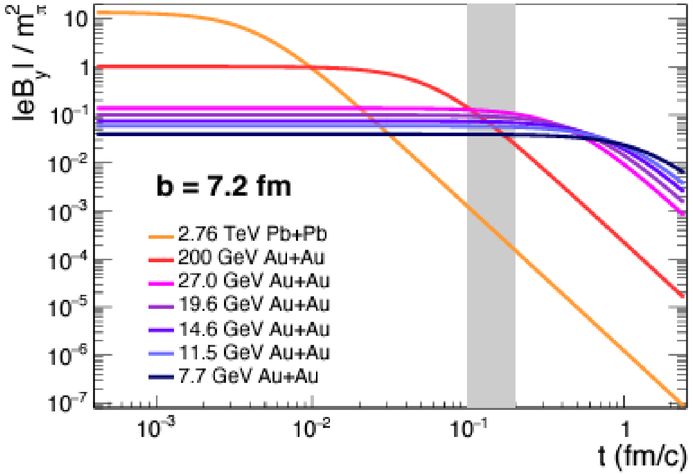
BES-I

$\sqrt{S_{NN}}$(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

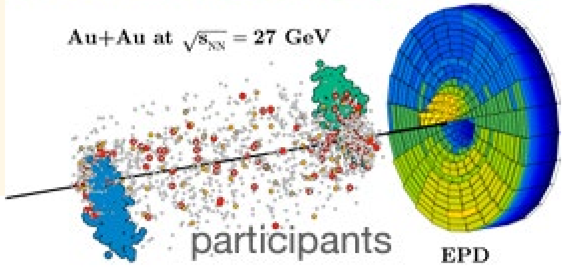
$\sqrt{S_{NN}}$(GeV)	Events (10^6)	Year
27	555	2018
19.6	478	2019
14.6	324	2019
11.5	230	2020
9.2	160	2020
7.7	101	2021



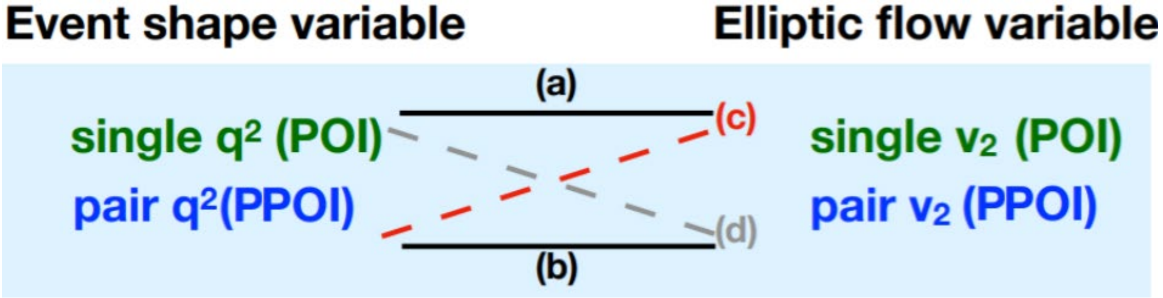
Event Shape Selection **Spectator Ψ_1**

$$\underset{\textbf{Measured}}{\Delta\gamma^{112}} = \underset{\textbf{Signal}}{\Delta\gamma^{\text{CME}}} + \underbrace{k\cancel{\frac{v_2}{N}} + \cancel{\Delta\gamma^{\text{non-flow}}}}_{\textbf{Backgrounds}}$$

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



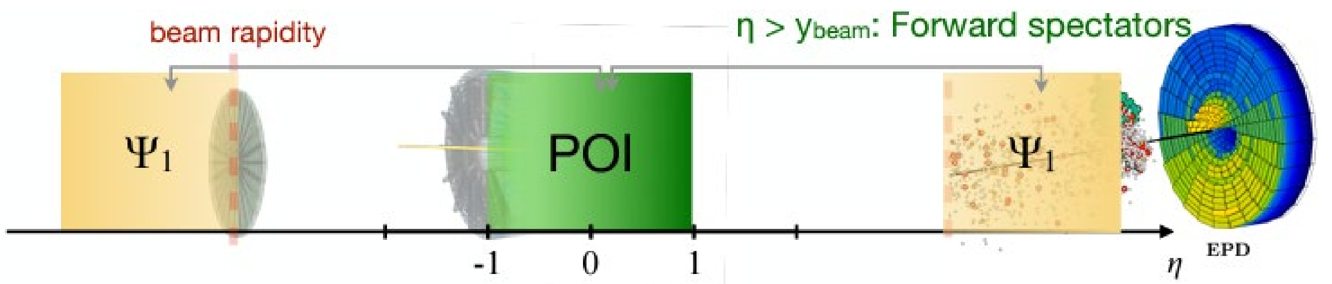
Au+Au at 19.6 GeV

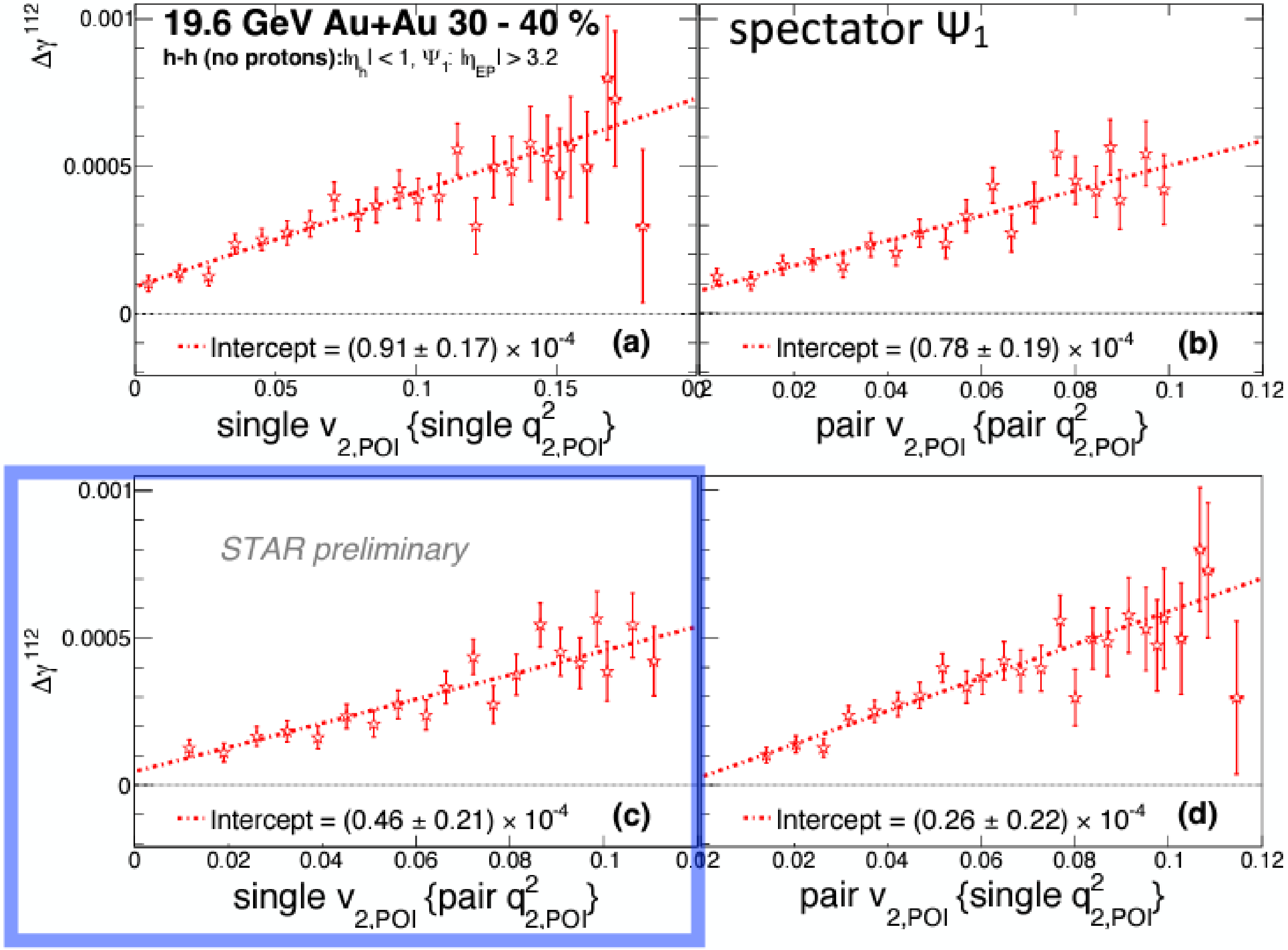


Event shape variable **Elliptic flow variable**

single q^2 (POI)
pair q^2(PPOI)

single v_2 (POI)
pair v_2 (PPOI)

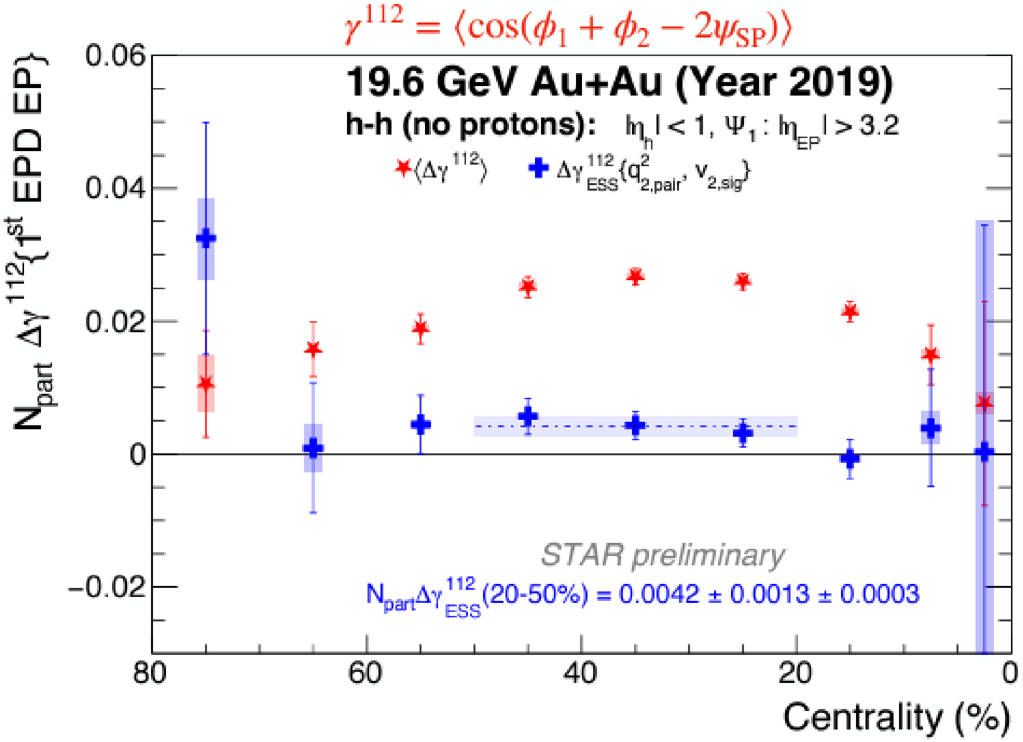




- **ESS using POI allows much shorter extrapolation to zero v_2.**
- **The ordering of y-intercepts follows predictions from both AVFD and AMPT.**
- **The y-intercept requires a small conversion to restore the unbiased signal:** $\Delta\gamma^{112}_{ESS} = Intercept \times (1 - v_2)^2$

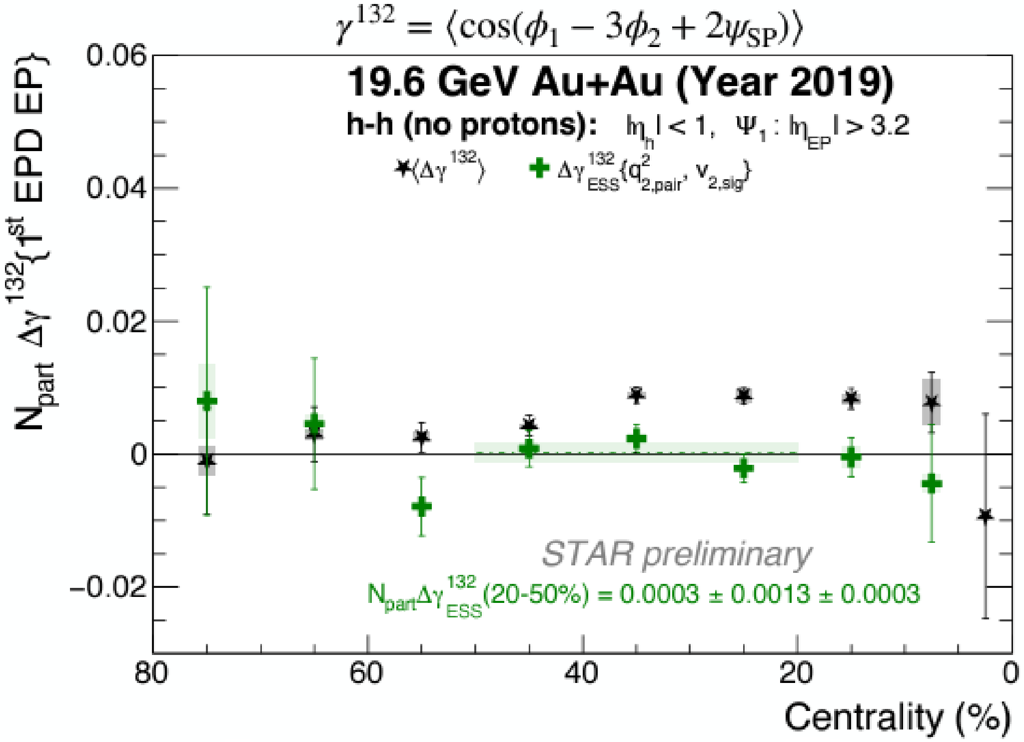
Z. Xu *et al.*, Phys. Rev. C 107, L061902

Au+Au at 19.6 GeV



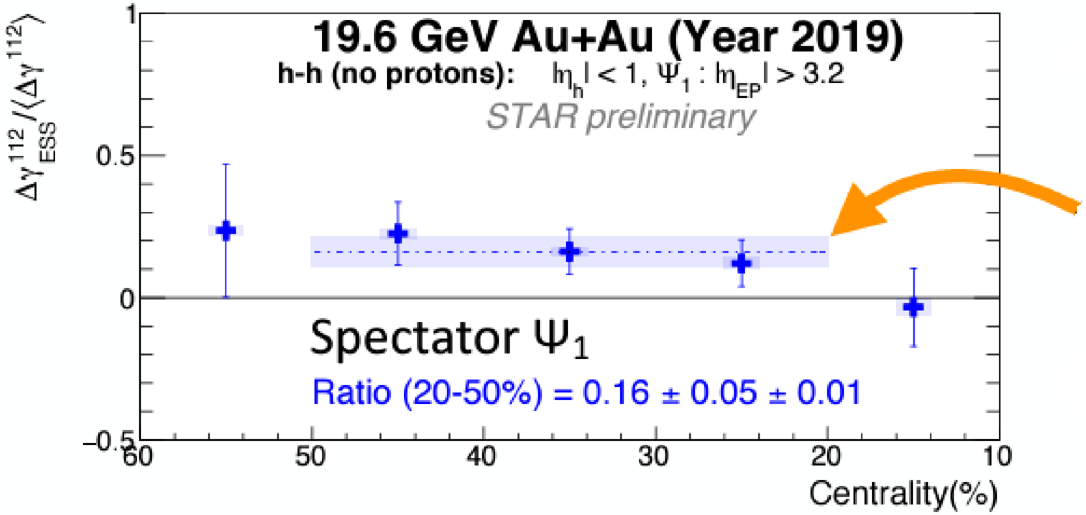
$\gamma^{112} = \langle \cos(\phi_1 + \phi_2 - 2\psi_{SP}) \rangle$

$\langle \Delta\gamma^{112} \rangle$ → $\Delta\gamma^{112}_{ESS}$



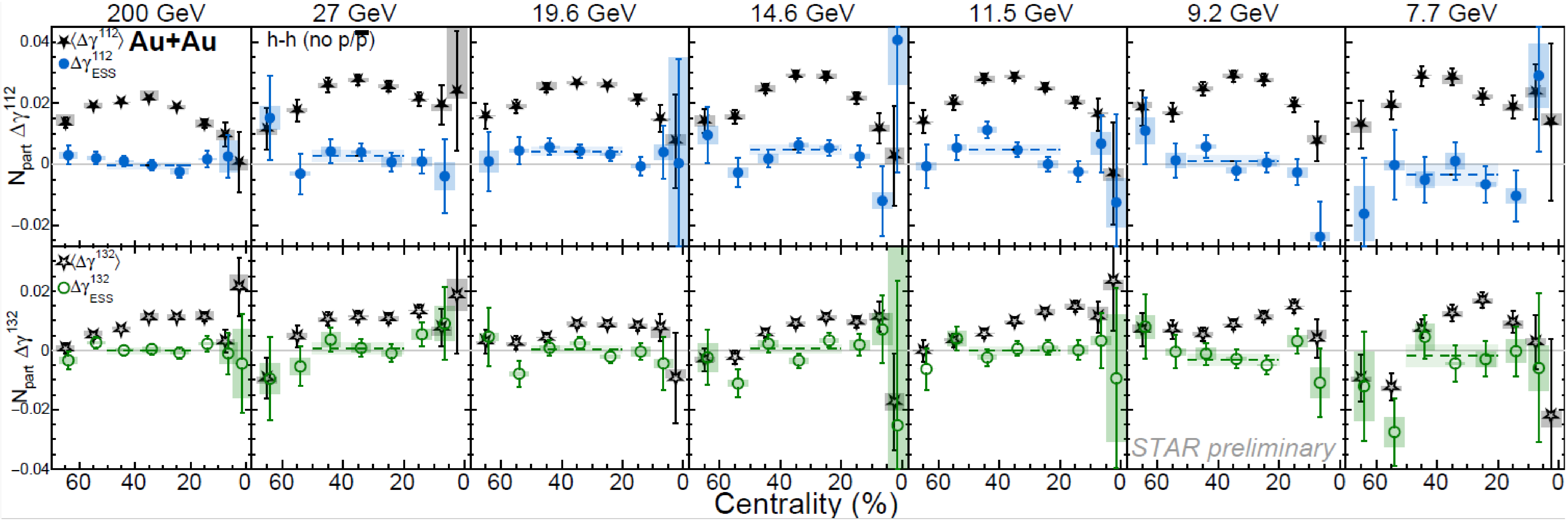
$\gamma^{132} = \langle \cos(\phi_1 - 3\phi_2 + 2\psi_{SP}) \rangle$

$\langle \Delta\gamma^{132} \rangle$ **BKG indicator** → $\Delta\gamma^{132}_{ESS}$ **BKG indicator**



- **After v_2-BKG subtraction, a finite signal in mid-central (20-50%) events.**
- **Ratio from the optimal ESS (c), pair q_2 and single v_2, yields a 3σ significance in the 20-50% centrality.**
- **From the BKG indicator $\Delta\gamma^{132}$, ESS successfully suppresses v_2-BKG.**

Au+Au at 7.7 -- 200 GeV

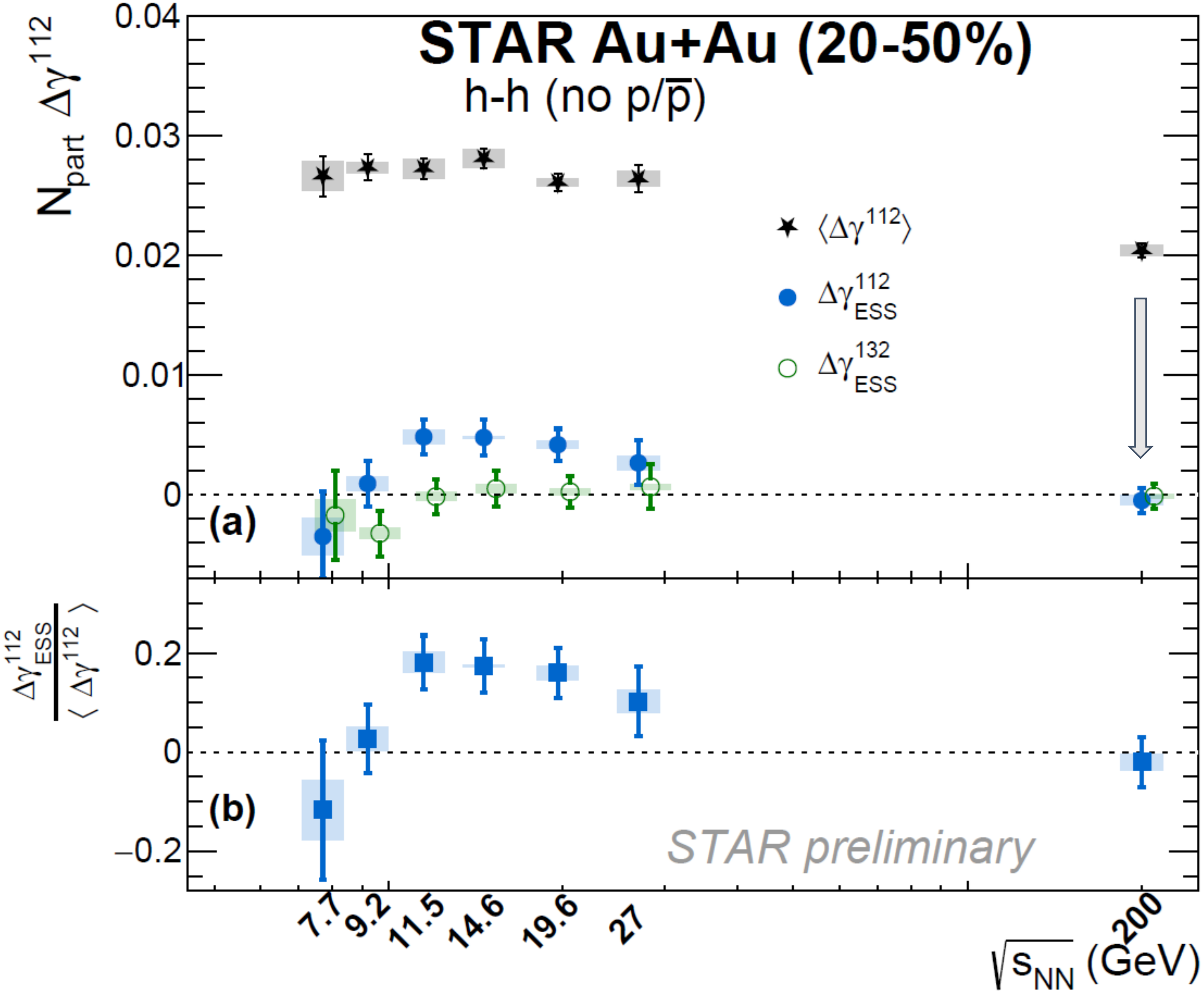


$\Delta\gamma^{112}_{ESS}$ from the optimal ESS (c), pair q_2 and single v_2:

- **At 200 GeV, using ZDC-SMD planes, no signal is observed.**
- **At 19.6, 14.6 and 11.5 GeV, a finite $\Delta\gamma^{112}_{ESS}$ (3σ significance) in the 20-50% centrality.**
- **At 9.2 and 7.7 GeV, data favor the zero-CME scenario.**

$\Delta\gamma^{132}_{ESS}$ is consistent with zero.

Beam Energy Dependence



- $\Delta\gamma^{132}{}_{ESS}$ consistent with zero.
- At least 80% of the measured $\Delta\gamma^{112}$ comes from BKG.
- 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!
- If we combine three points at 19.6, 14.6 and 11.5 GeV, the literal average of the ESS results reaches an over 5σ significance (assuming similar physics conditions between 10 and 20 GeV).
- The ESS results approach zero around 9.2 and 7.7 GeV.

STAR ESS CME Search Summary

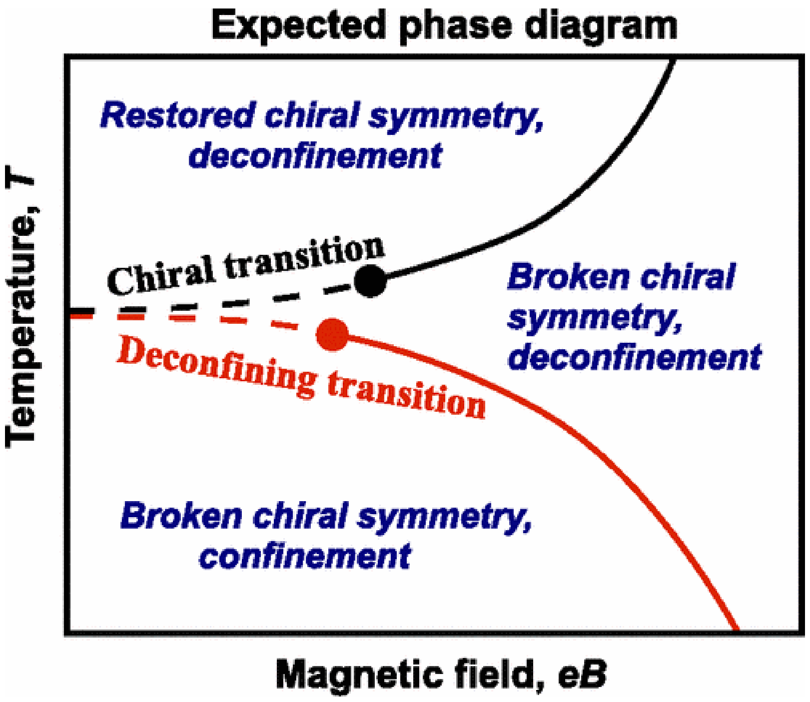
Event Shape Selection Spectator Ψ_1

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

Measured Signal Backgrounds

- **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 $\Delta\gamma^{112}_{\mathrm{ESS}}$ (>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?**

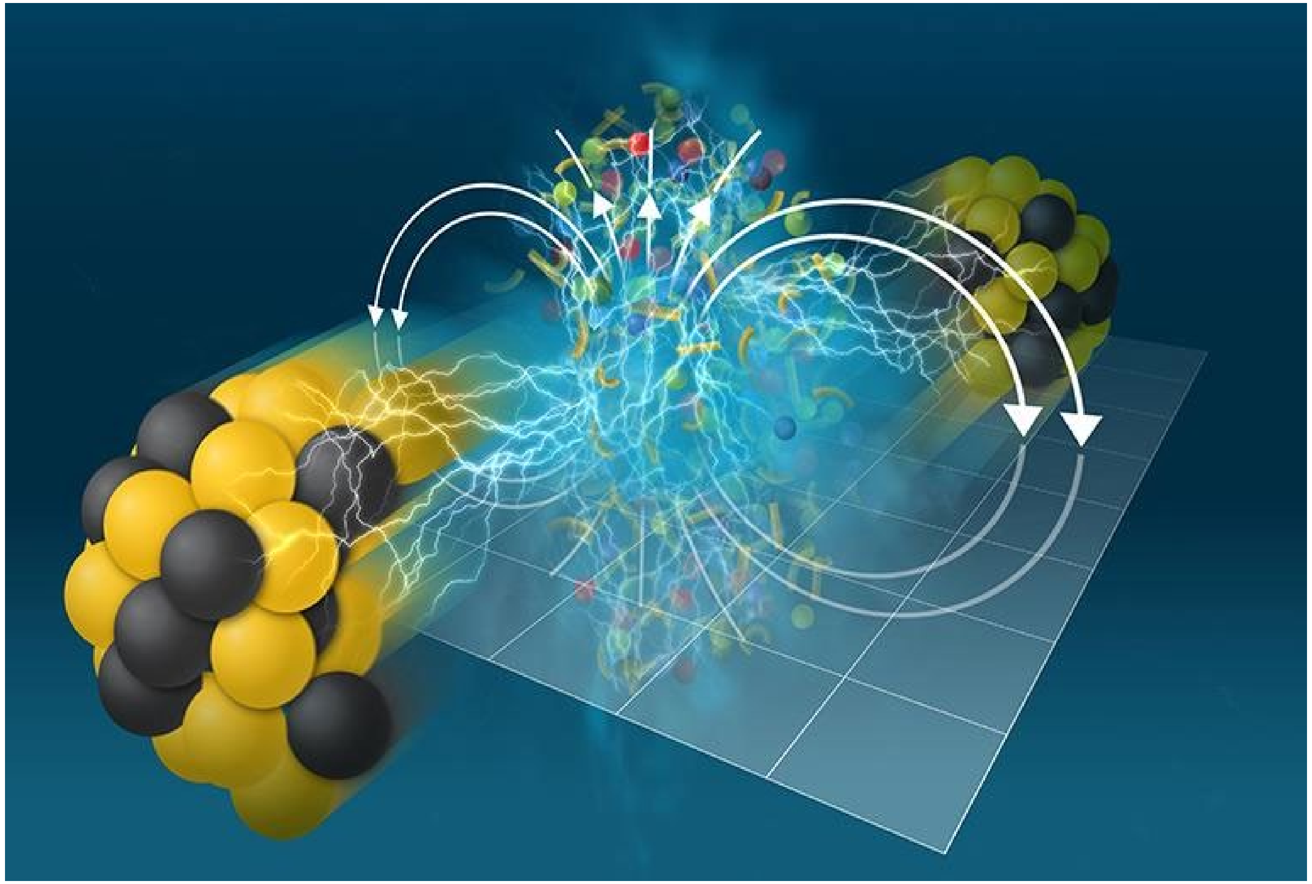
A. J. Mizher, M. N. Chernodub, and E. S. Fraga, PRD 82 (2010) 105016



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

Future Prospect

Impact of Model Dependence on Event Shape Approaches

All event shape mthods will have some model dependence –
event shape – observable measured from final state particles in momentum space
shape -- preferably in the coordinate system (initial eccentricity or emission source)

What shape selection most related to CME background contributions

Event-Shape Engineering (ESE) – more sensitive to initial collision eccentricity

Event-Shape Selection (ESS) – Sensitive to combination of eccentricity and particle emission pattern

For preferred mid-centrality for CME searches (20-50% for example)

ESE – limited range of eccentricity variation --- cannot reach the v_2 approach zero round shape to minimize CME bkgd
-- extrapolation to v_2 zero limit – model dependent
-- if the extrapolation follows the eccentricity variation, then initial eccentricity zero
corresponds to the most central collisions – small B field and no CME!

ESS – with limited range of eccentricity the approach to v_2 zero is mostly due to emission pattern fluctuations
What CME background at the v_2 approaches zero limit – the intercept point
Depends on shape observable versus v2 control method
For hydro-induced background, the optimized approach q_2(pair) vs v_2(single)

What 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 !!

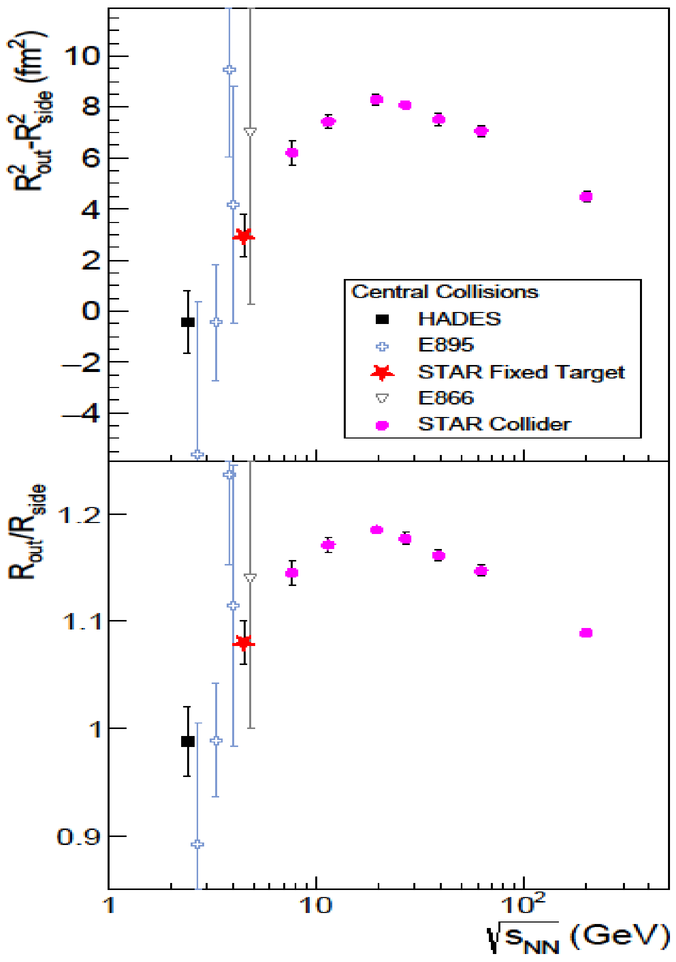
Why? (Professor Pengfei Zhuang gave an answer during his talk--
B field effect disappears at high Temperatures !)

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

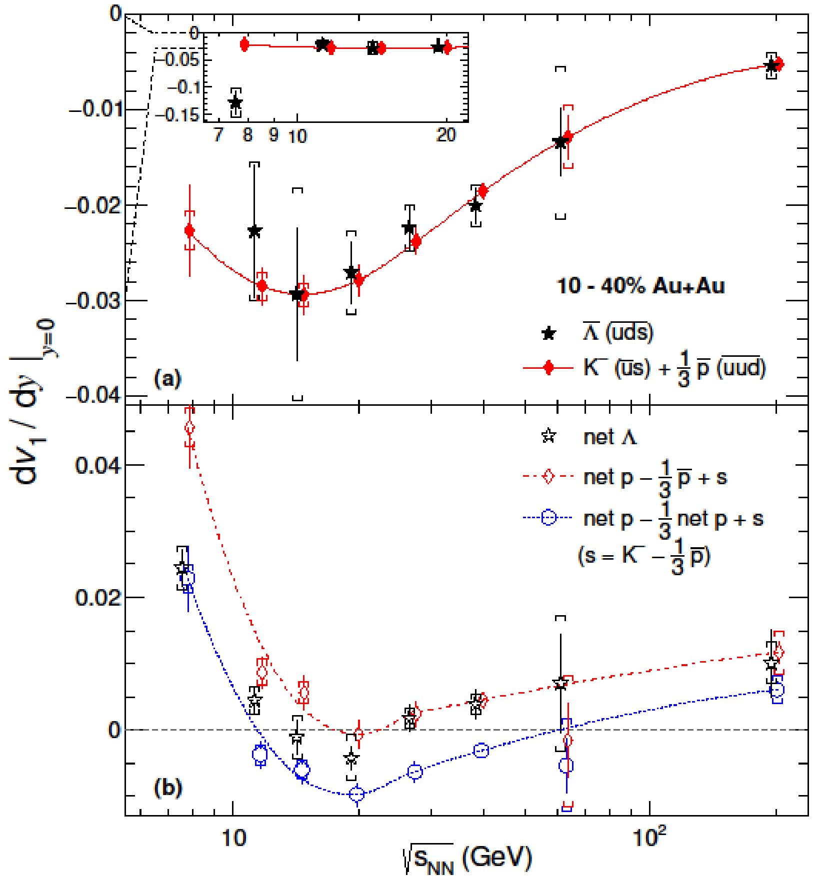
Please measure $v_2\delta$ background correlation as well !

What so Special for Collisions at 10-30 GeV

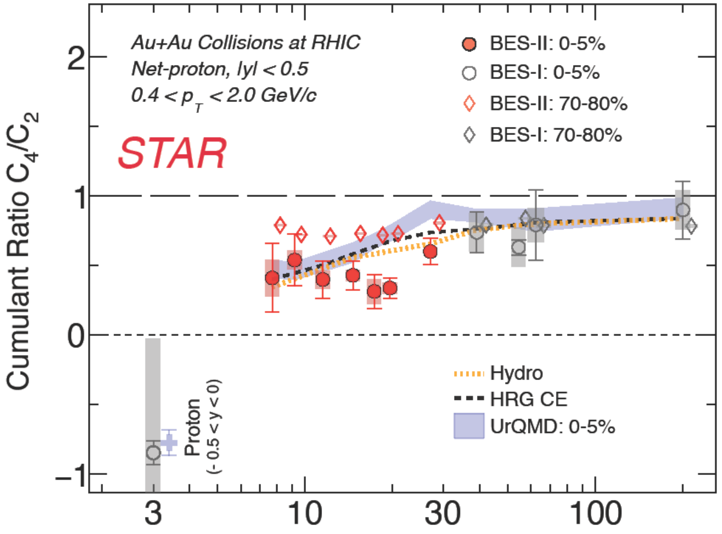
HBT Rout/Rside

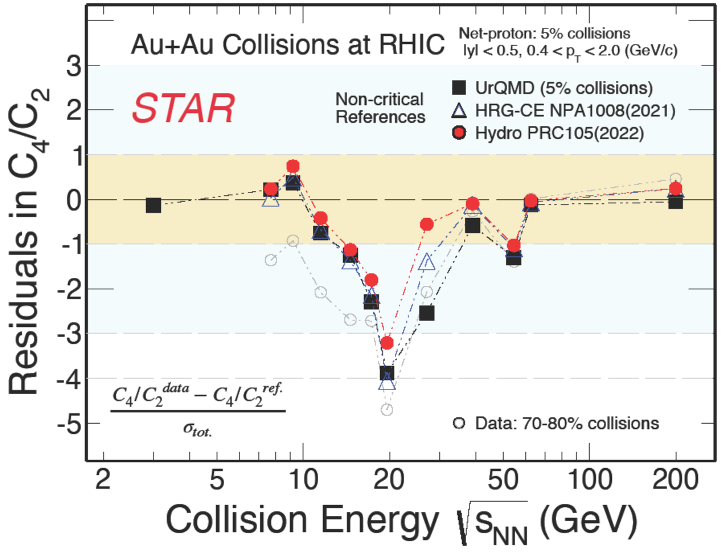


v_1 slope dv_1/dy



Critical Point: C_4/C_2





Future of Experimental CME Searches

Improve understanding background contributions !

Improve CME search approach !
    We improved ESS approach and we are open to more optimizations

Understand magnetic field effect !

Theoretical insights !

Be Critical, but also Be Truthful !

2407.14489v1

The goal of the ESE was to approach v2 = 0 limit, it is clear that the ESE method has a problem here !

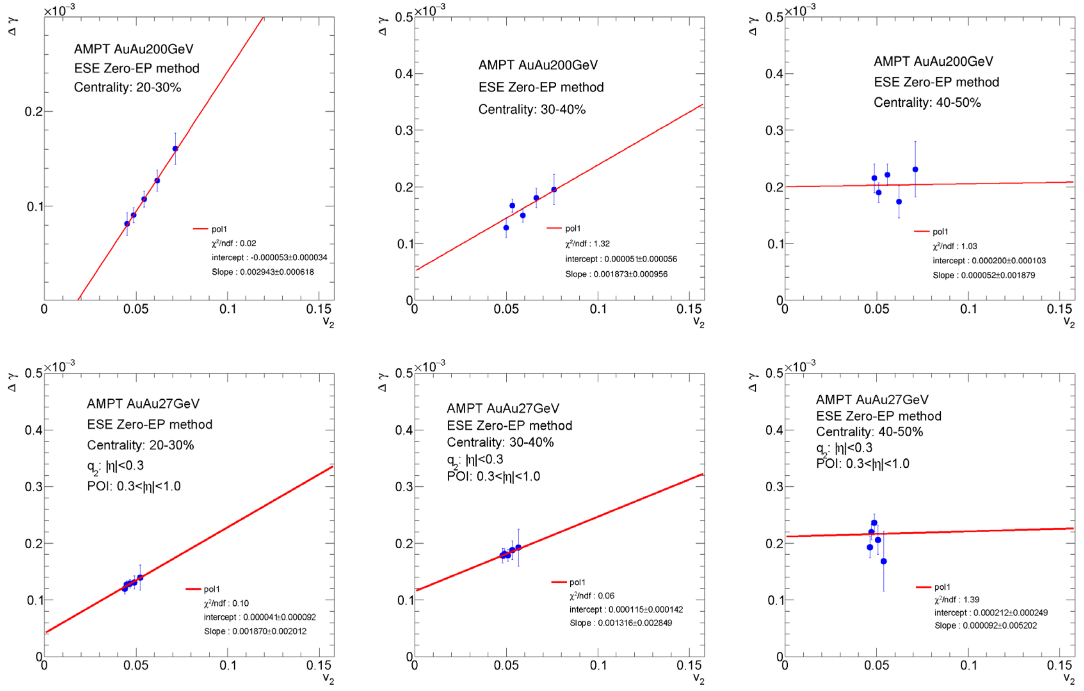


FIG. A.4. AMPT ESE results. Shown are three centralities of Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV (upper panels) and at 27 GeV (lower panels) simulated by AMPT, with approximately 5×10^6 events for each centrality at each energy. The $\Delta\gamma$ is plotted as a function of v_2 in events binned in $\hat{q}_2^2\{2\}$ (Eqs. 5,6). POIs are from acceptance $0.3 < |\eta| < 1$, and the event selection variable $\hat{q}_2^2\{2\}$ is computed from particles in $|\eta| < 0.3$, both with $0.2 < p_T < 2$ GeV/c. The model's known impact parameter direction $\psi = 0$ is taken as the EP in calculating $\Delta\gamma$ (Eqs. 2,3) and $\langle v_2 \rangle$ (Eq. 10).

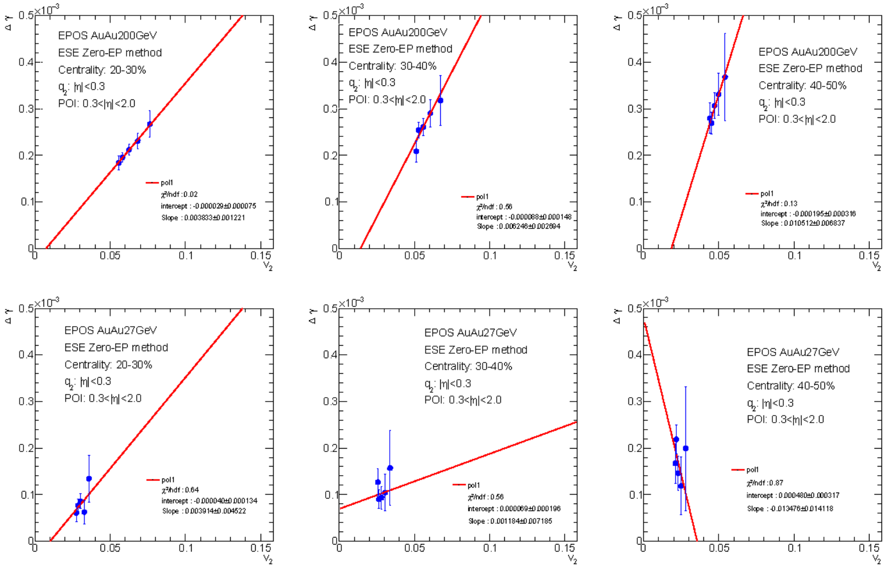


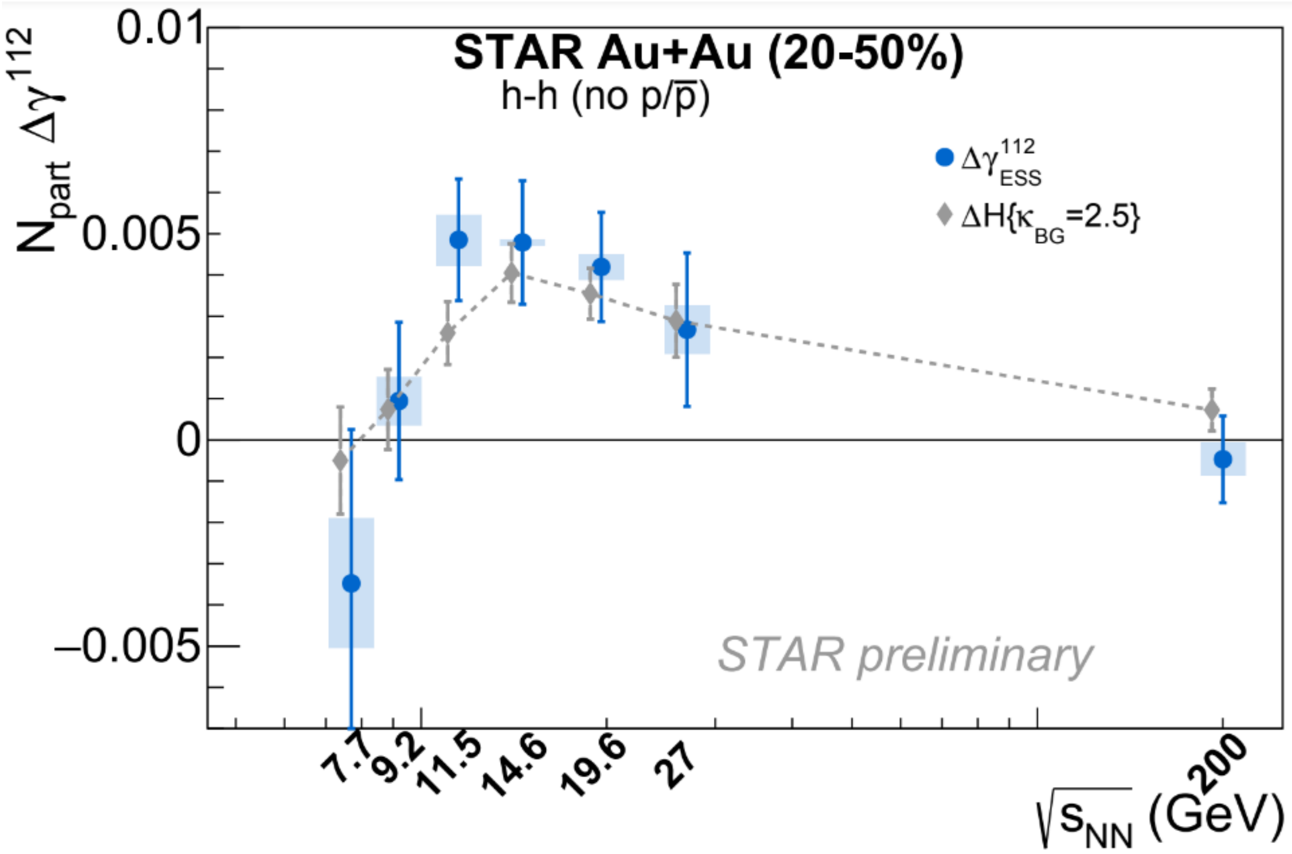
FIG. A.6. EPOS ESE results. Shown are three centralities of Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV (upper panels) and at 27 GeV (lower panels) simulated by EPOS4, with approximately 1.6×10^6 and 8×10^5 events for each centrality, respectively. The $\Delta\gamma$ is plotted as a function of v_2 in events binned in $\hat{q}_2^2\{2\}$ (Eqs. 5,6). POIs are from acceptance $0.3 < |\eta| < 2$ and $0.2 < p_T < 2$ GeV/c, and the event selection variable $\hat{q}_2^2\{2\}$ is computed from particles in $|\eta| < 0.3$, both with $0.2 < p_T < 2$ GeV/c. The model's known impact parameter direction $\psi = 0$ is taken as the EP in calculating $\Delta\gamma$ (Eqs. 2,3) and $\langle v_2 \rangle$ (Eq. 10).

Event Shape Analysis cannot solve all our physics problems – need to find the best approach for your particular physics

1) **Some toy models are indeed just toys, avoid playing "garbage in, garbage out" game !**
2) **Respect statistics: when you get 1+-1, result is consistent with zero, but is also consistent with many other scenarios -- it does not mean your method working, it could also mean that your method does not have sensitivity**

Thank You !

Connection between ESS and the *H* correlator



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

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

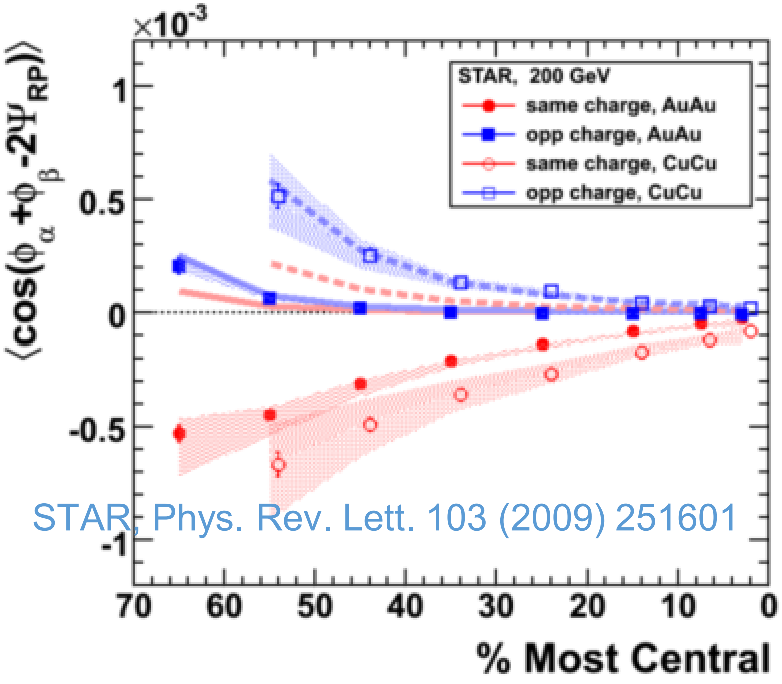
$$\Delta H \equiv H_{SS} - H_{OS} \qquad \delta = \cos(\phi_1 - \phi_2)$$

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

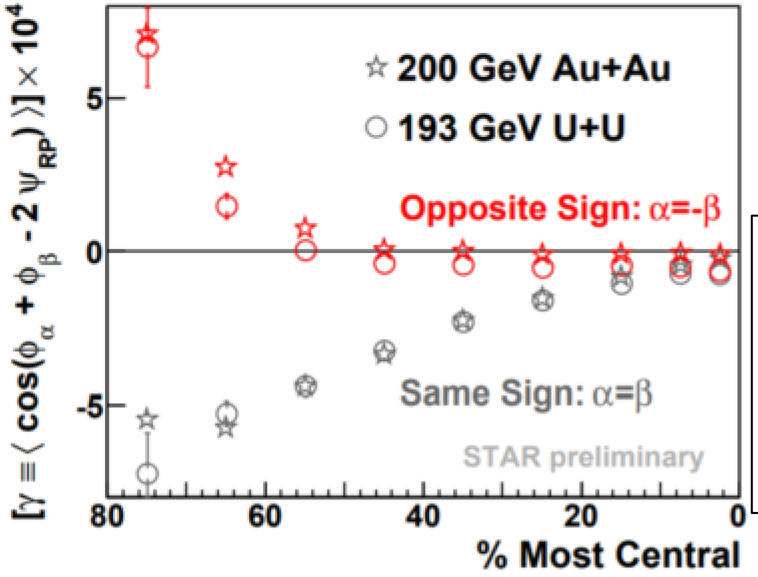
- κ_{bg} is an adjustable parameter, unknown a priori. It quantifies the coupling between elliptic flow and other mechanisms manifested in the two-particle correlation.

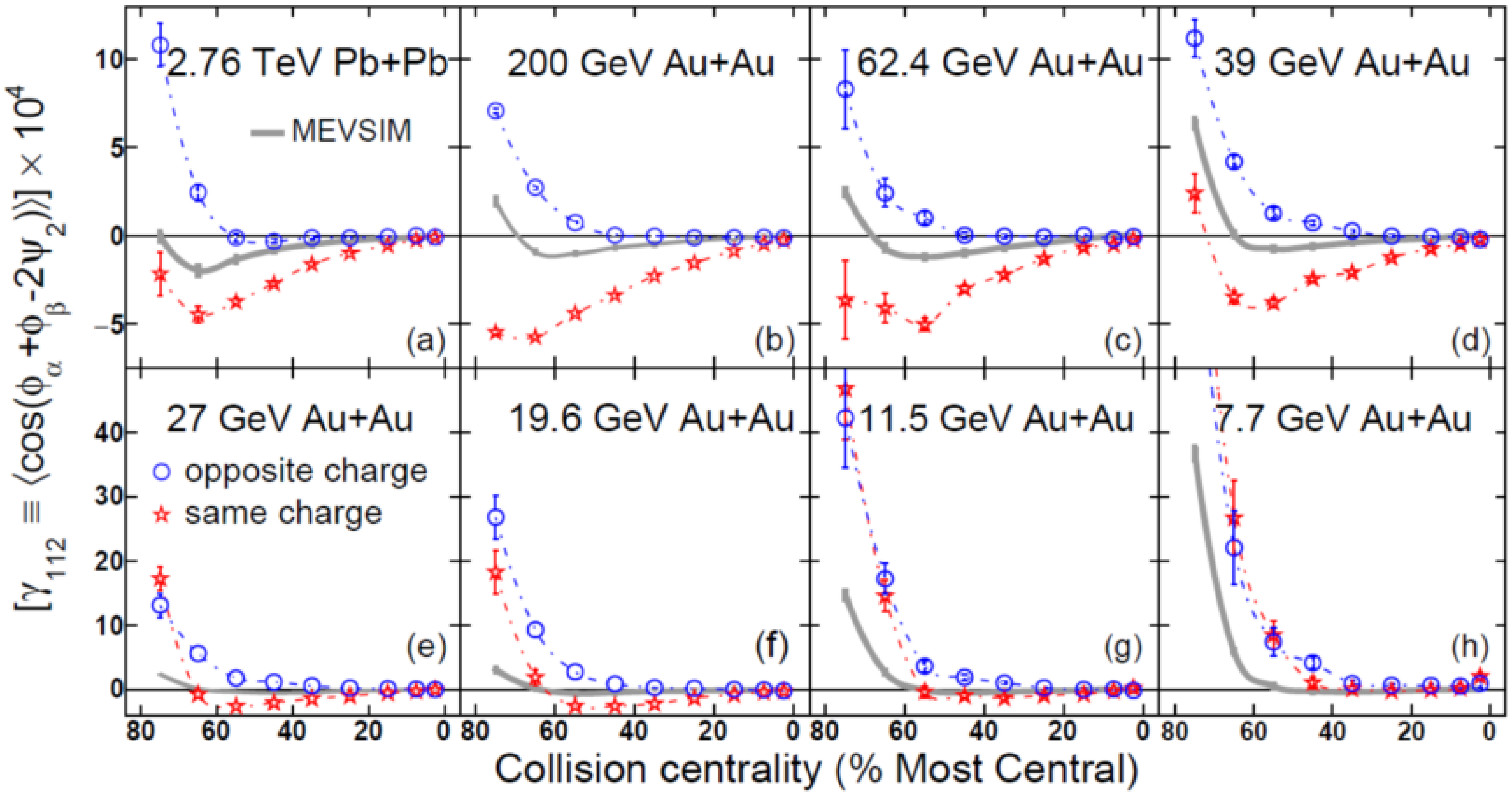
- **With κ_{bg} set to 2.5, ΔH agrees with the ESS result at all beam energies under study.**
- **The flow background can be reasonably well described by a universal coupling between v_2 and the two-particle correlation.**

Initial Evidence



STAR, Phys. Rev. Lett. 103 (2009) 251601





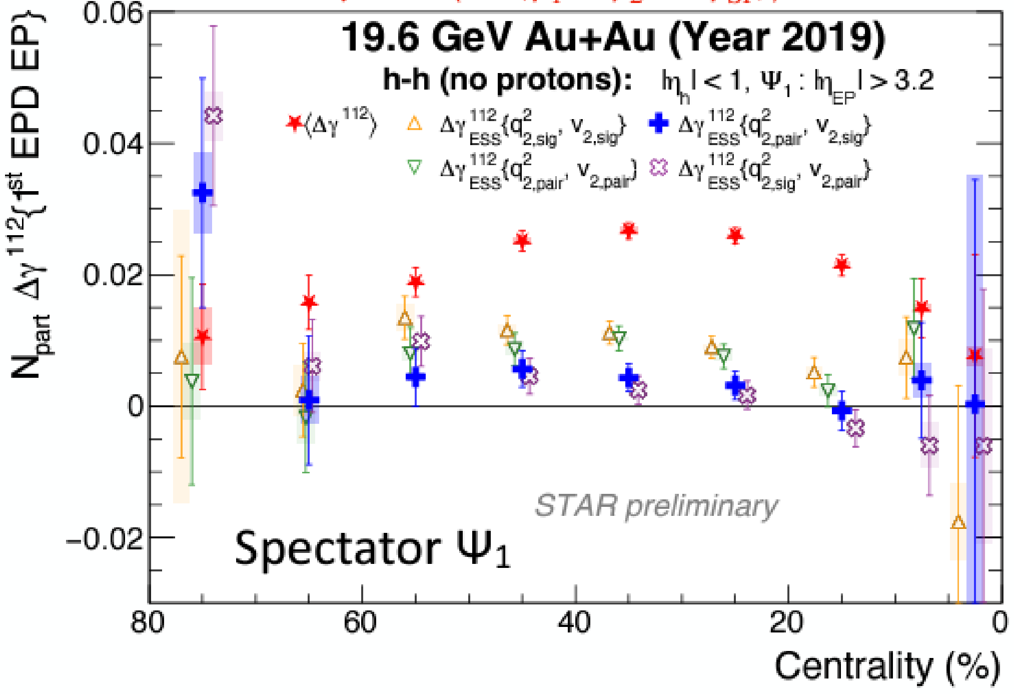
ALICE, Phys. Rev. Lett. 110(2013)012301. STAR, Phys. Rev. Lett. 113(2014)52302

In various collision systems and at different beam energies, positively finite $\Delta\gamma_{112}$ meets the CME expectation, but could contain contributions from:

- Flow-related background $\propto v_2$ (elliptic flow)
- Nonflow-related background (di-jets)

Au+Au at 19.6 GeV

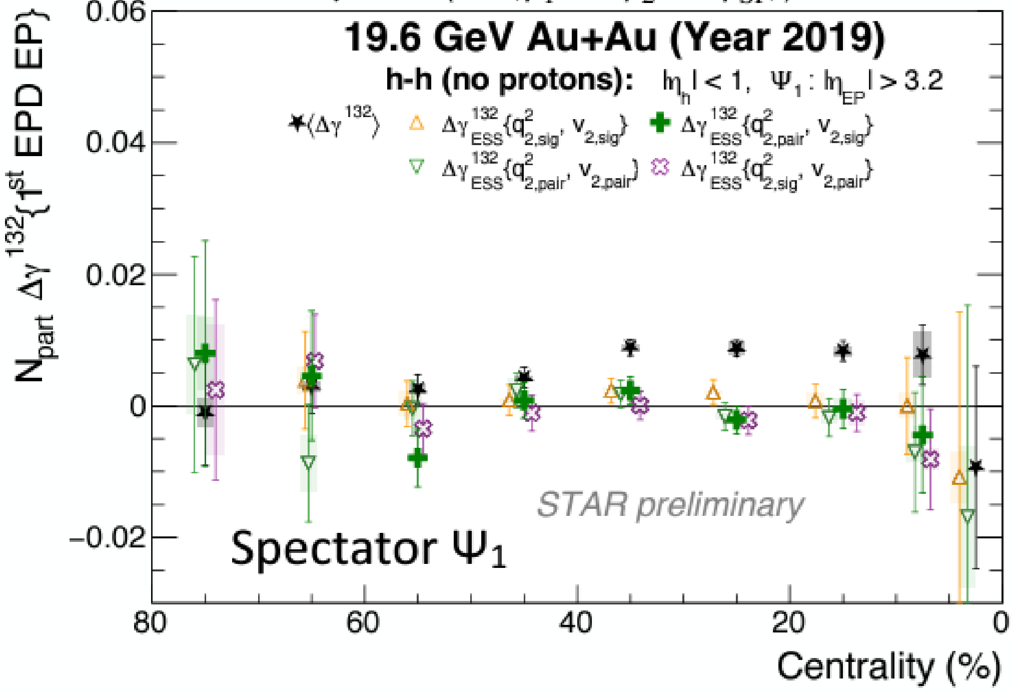
$\gamma^{112} = \langle \cos(\phi_1 + \phi_2 - 2\psi_{SP}) \rangle$



$\langle \Delta\gamma^{112} \rangle$

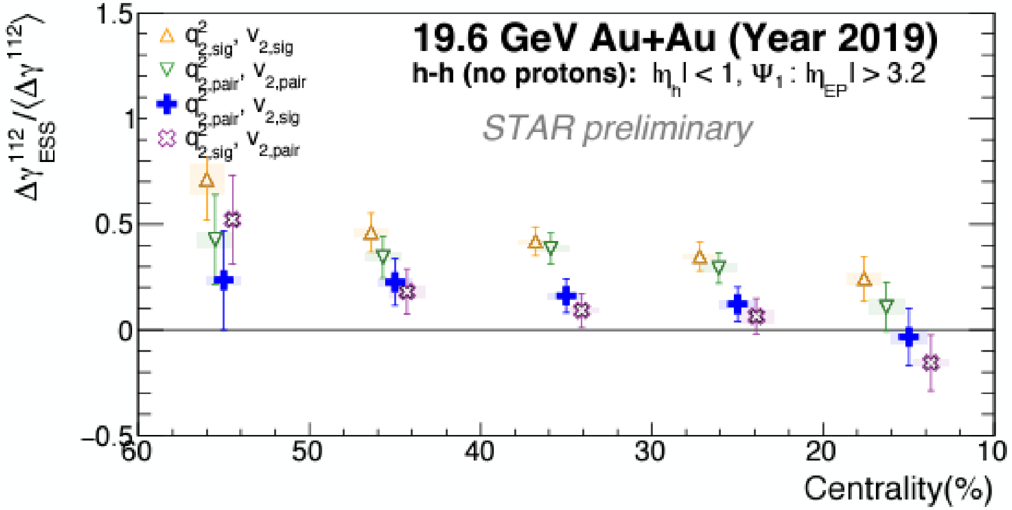
$\Delta\gamma^{112}_{ESS}$

$\gamma^{132} = \langle \cos(\phi_1 - 3\phi_2 + 2\psi_{SP}) \rangle$



$\langle \Delta\gamma^{132} \rangle$**BKG indicator**

$\Delta\gamma^{132}_{ESS}$ **BKG indicator**



- **The ordering of y-intercepts follows predictions from both AVFD and AMPT.**

Not all event shape selections are equal, there is some model dependence
We need to optimize the method to suppress the hydro-related CME background

Also event shape selection optimized for CME search only, is not universally best !
Approach for hydro comparisons, for example, the ESE method would be better !