The 8th International Conference on Chirality, Vorticity and Magnetic Field in Quantum Matter

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

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for the STAR Collaboration

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STAR

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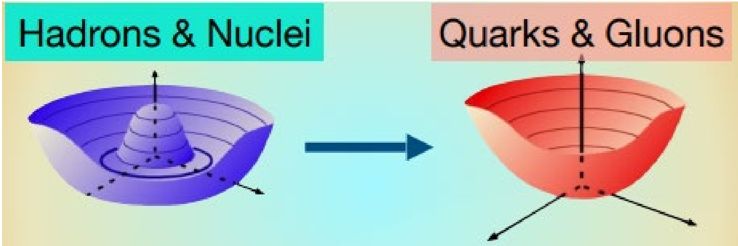
Outline

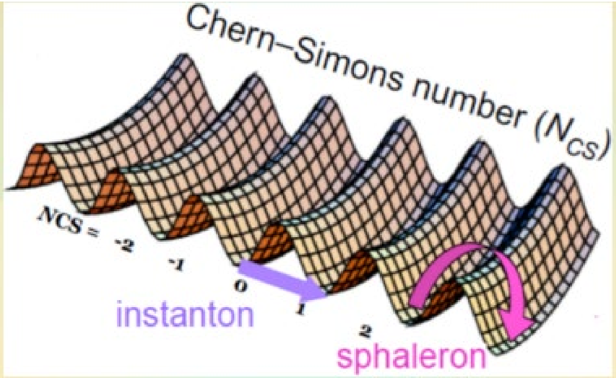
- ❖ Introduction
- ❖ Lessons from Previous Results
- ❖ Novel Approach of Event Shape Selection (ESS)
- ❖ STAR ESS Results from BES-II and 200 GeV Data
- ❖ Summary and Future Outlook

Chiral Magnetic Effect

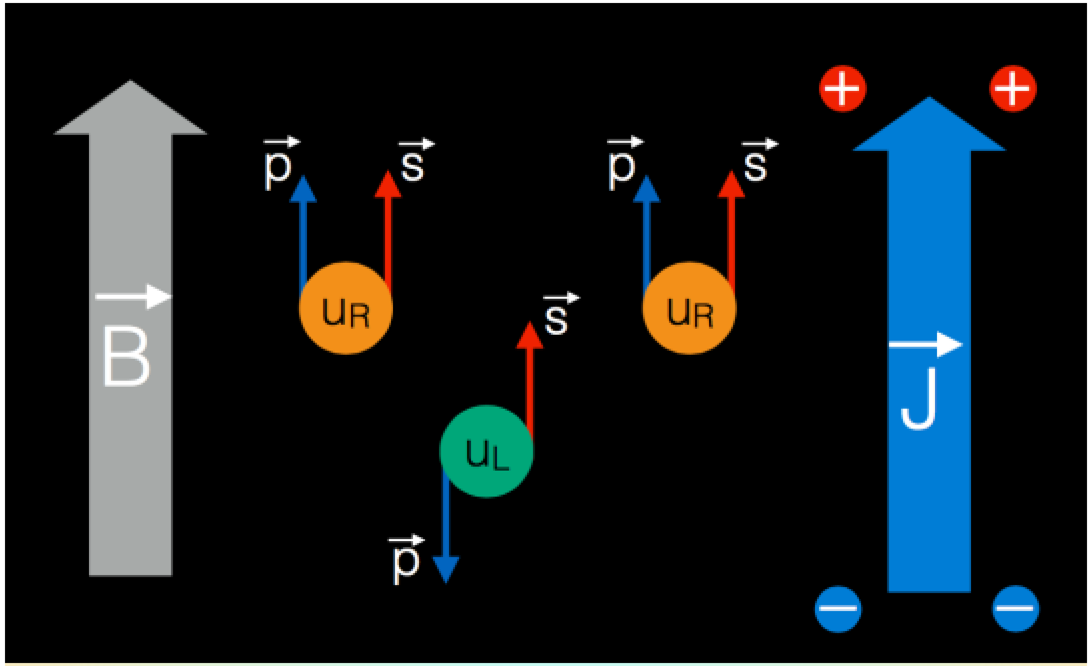
A Rare Opportunity to Experimentally Access Key Intrinsic Properties of the QCD



Chiral symmetry restoration (massless quarks)

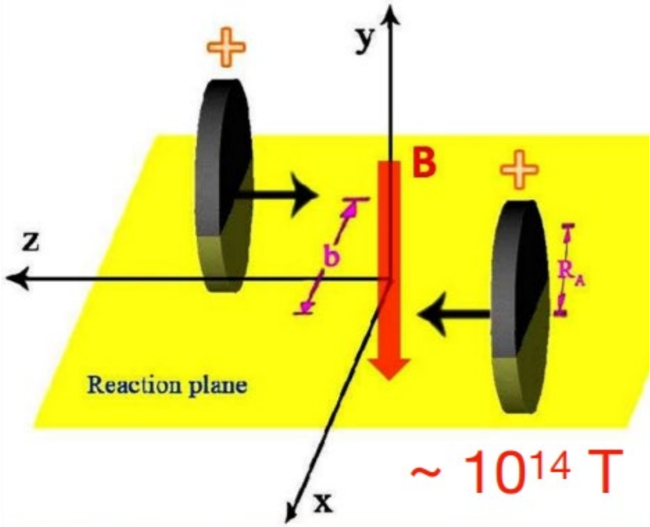


Chirality imbalance (finite μ_5)



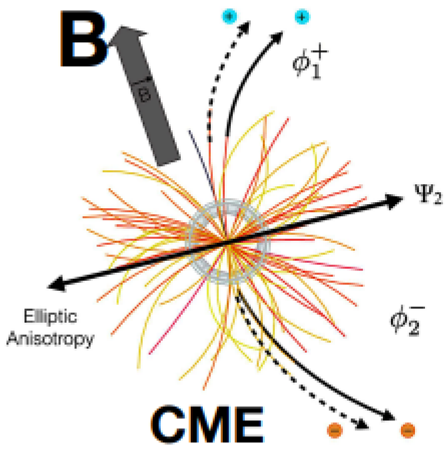
Chiral Magnetic Effect (J || B)

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



Strong magnetic field (B)

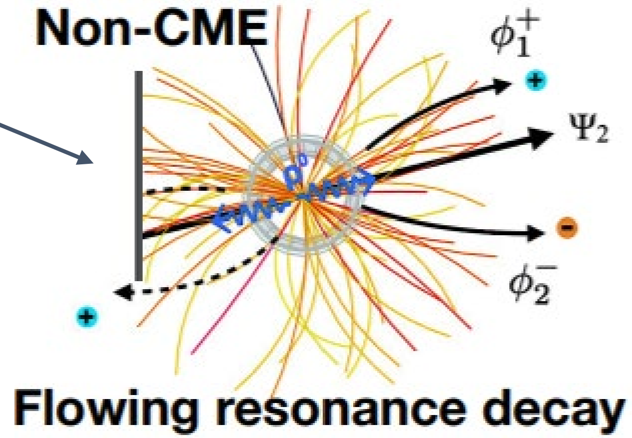
CME Observables



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

$\propto \mu_5 B$

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)

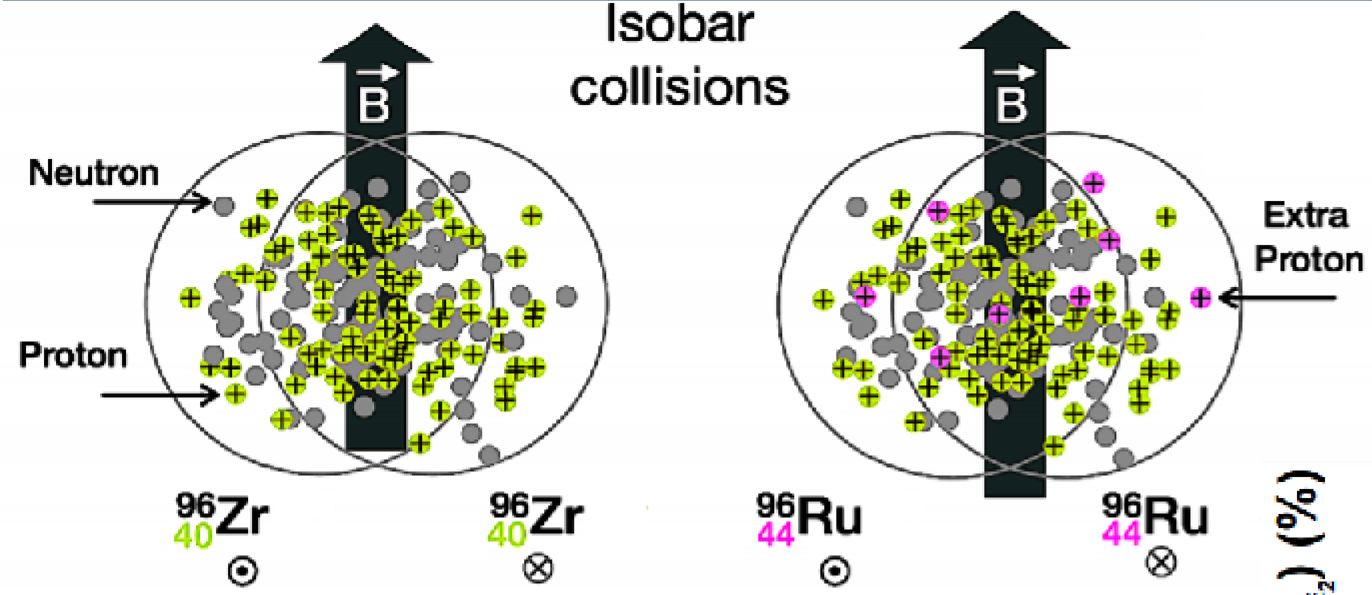
S. Choudhury et al.(STAR), Chin. Phys. C46(2022)014101

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

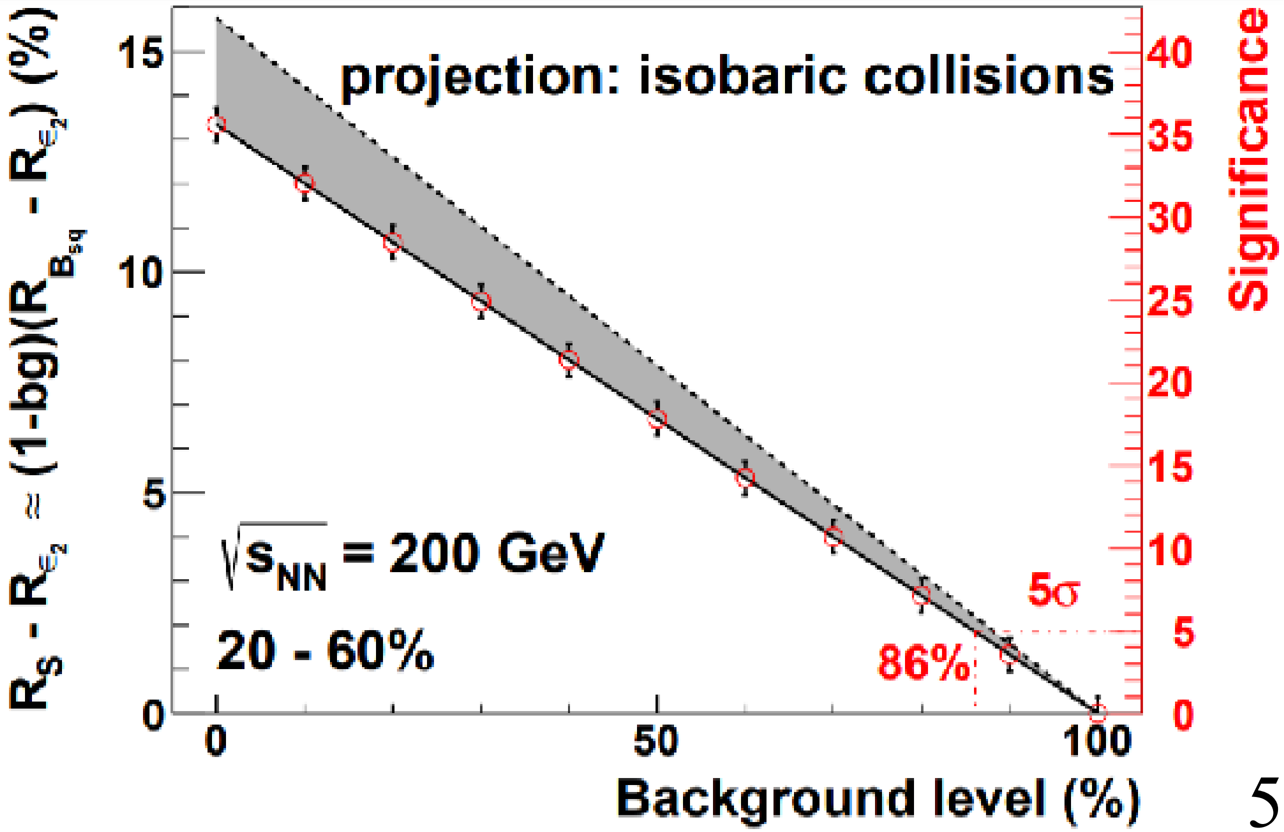
Isobar Collisions: An Excellent Idea



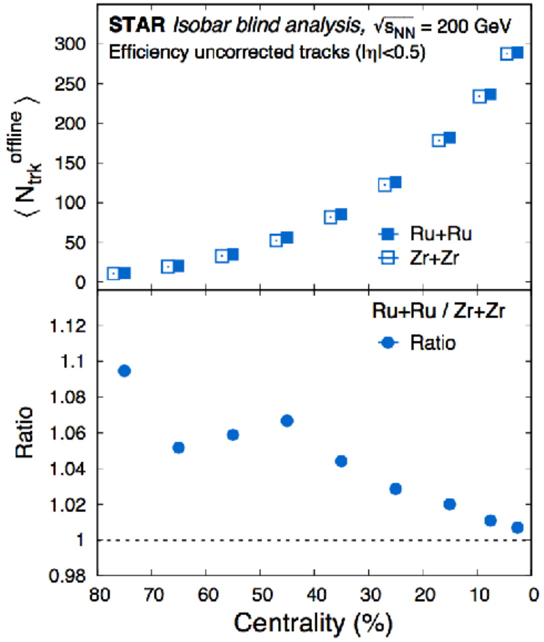
Compare the two isobaric systems:
- CME: B-field^2 is ~15% larger in Ru+Ru
- Flow-related BKG: utilize $\Delta\gamma_{112}/v_2$
- Nonflow-related BKG: almost same

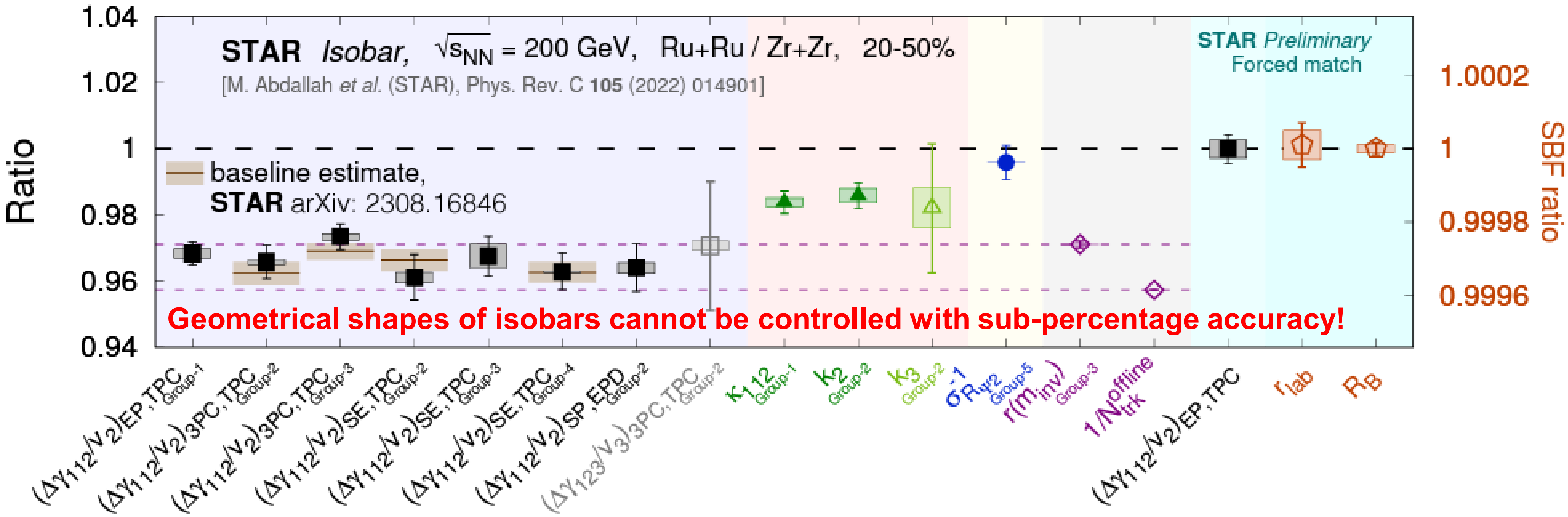
Isobar collisions provide a good control of signal and background.

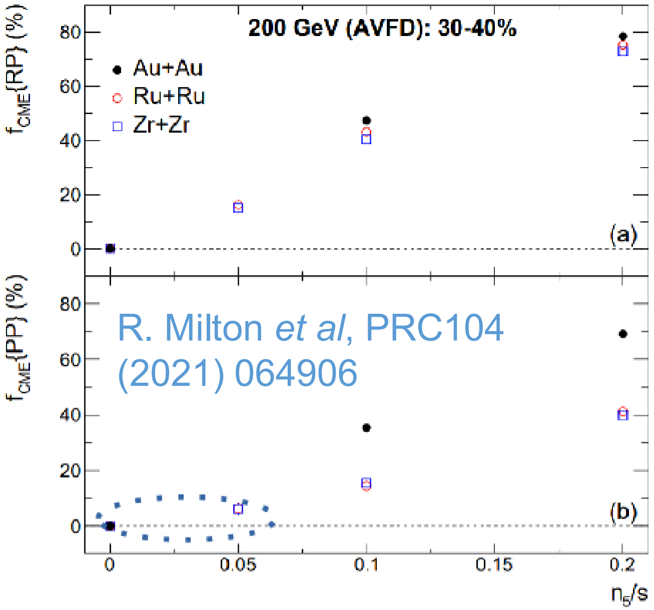
2.5 B events per species:
- uncertainty of 0.4% in the $\Delta\gamma_{112}/v_2$ ratio.
- if f_{CME} > 14%, $\Delta\gamma_{112}/v_2$ difference > 2%, yielding a 5σ significance.
- f_{CME} is the unknown CME fraction in $\Delta\gamma_{112}$.



Isobar Collision Results: Nature is Cruel







Why is f_{CME} so small?

AVFD simulations: f_{CME} is smaller in isobars than Au+Au, especially when using participant plane.

Smaller system → larger fluctuation
→ larger BKG & smaller CME signal → double-killed f_{CME}

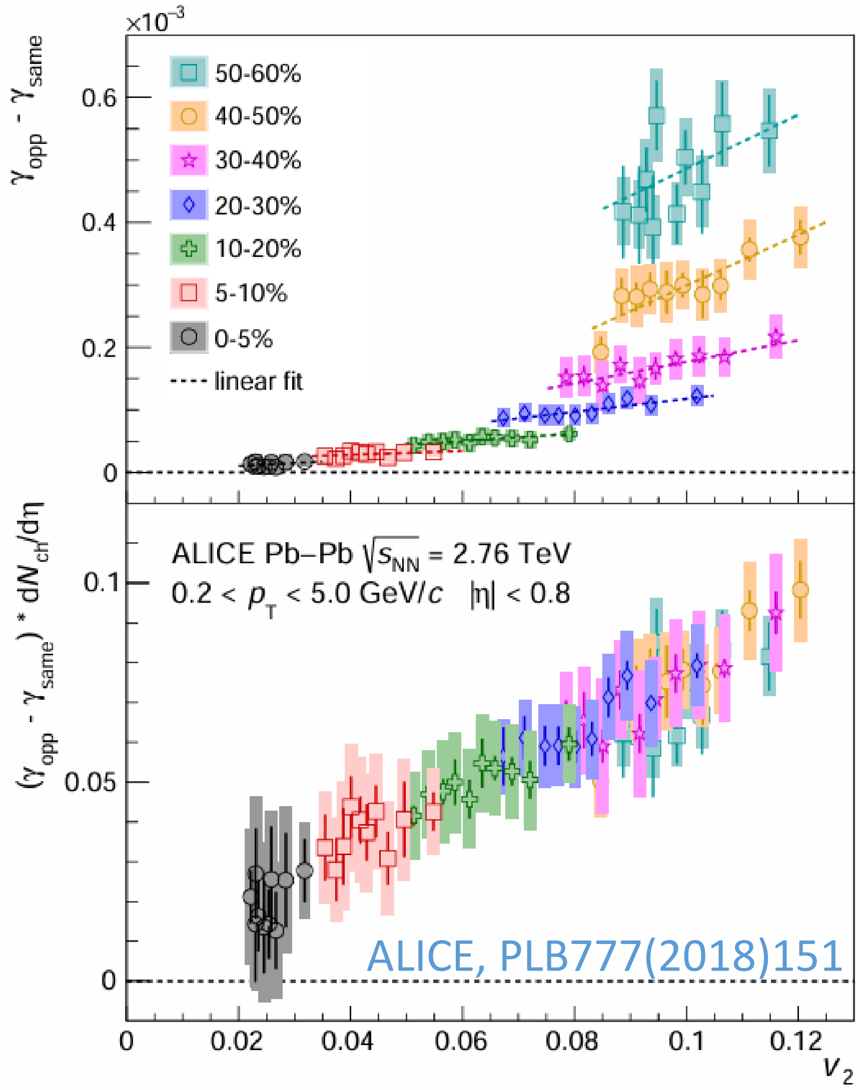
We need to focus on large systems like Au+Au, and directly suppress the background.

“Standard” Event Shape Engineering

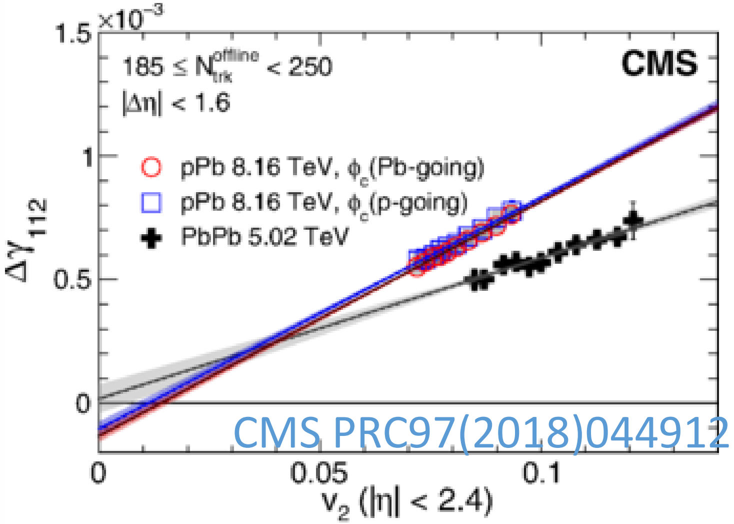
Three sub-events are used: one for POI, one for event plane, and one for event shape variable, q_2, the modulus of the flow vector.

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

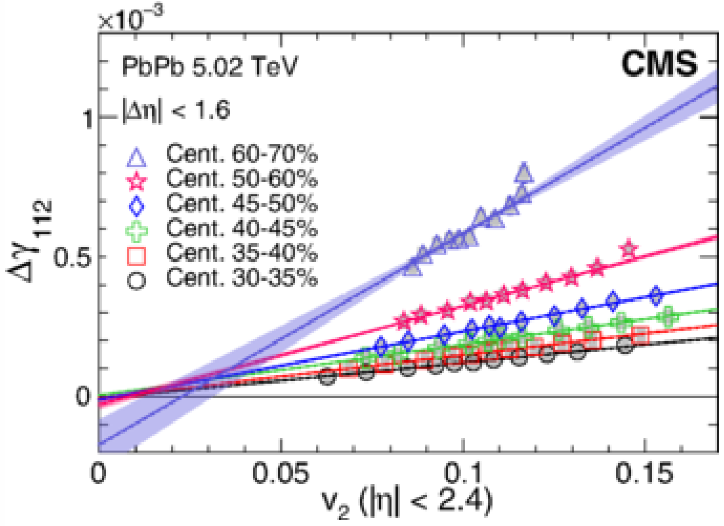
$$q_y \equiv \frac{1}{\sqrt{N}} \sum_i^N \sin(2\phi_i)$$



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.

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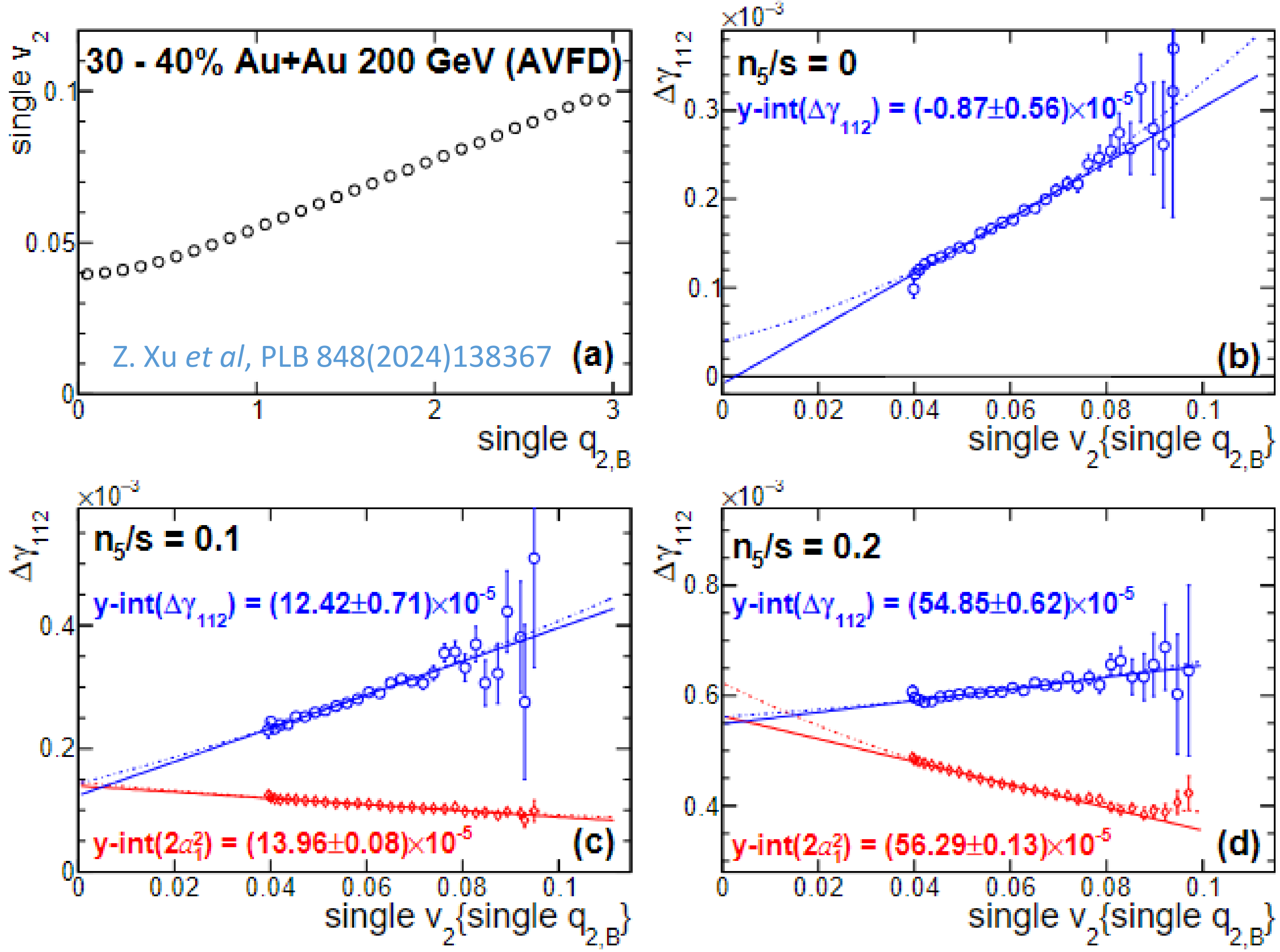

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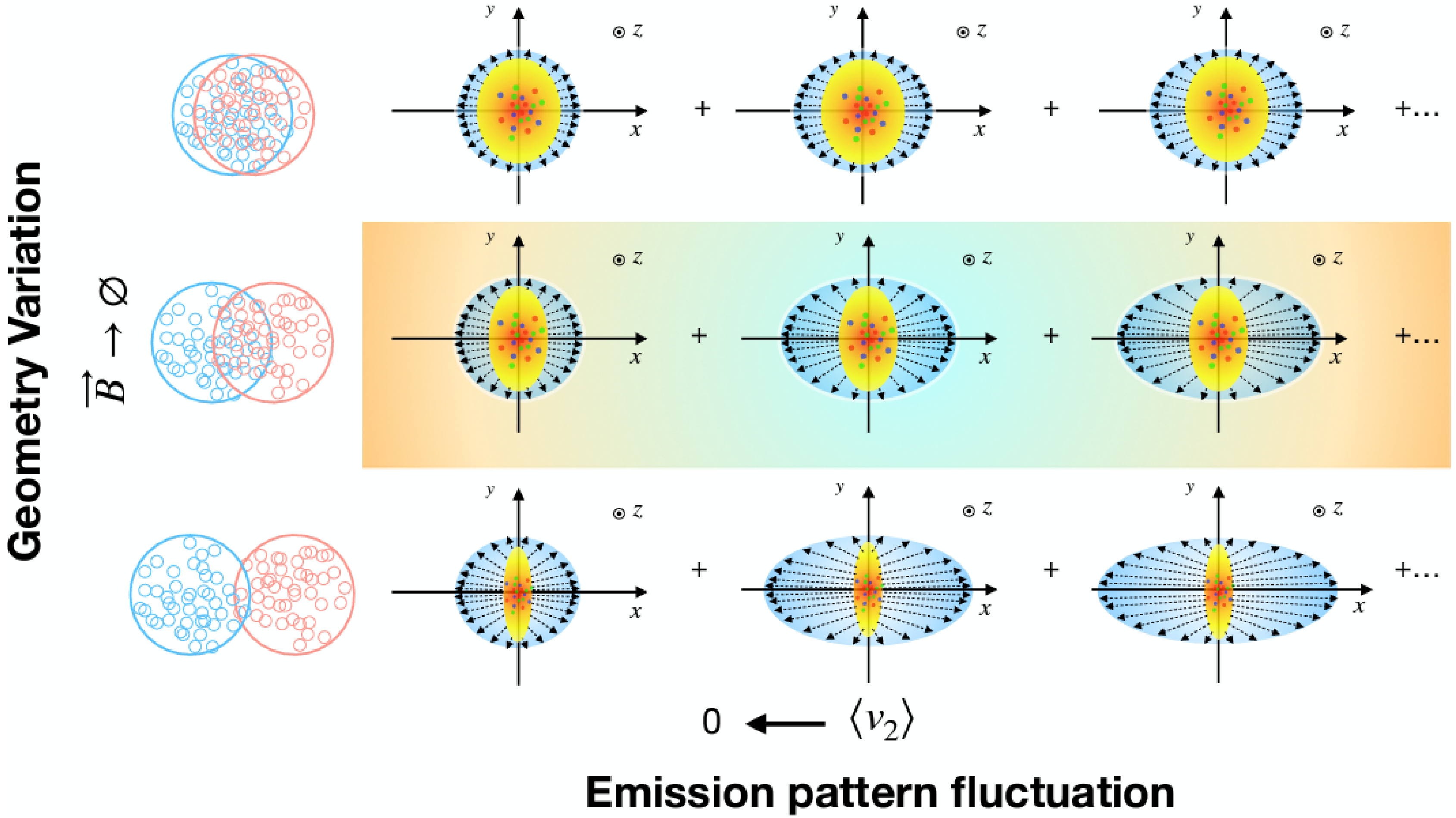
- At LHC energies, all the ESE results are consistent with zero. (too short duration of the *B* field?)
- Since particles of interest (POI) are excluded from q_2, the lever arm on v_2 is very weak, making the extrapolation unstable – **works if the signal is very large, no sensitivity for small signals**

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

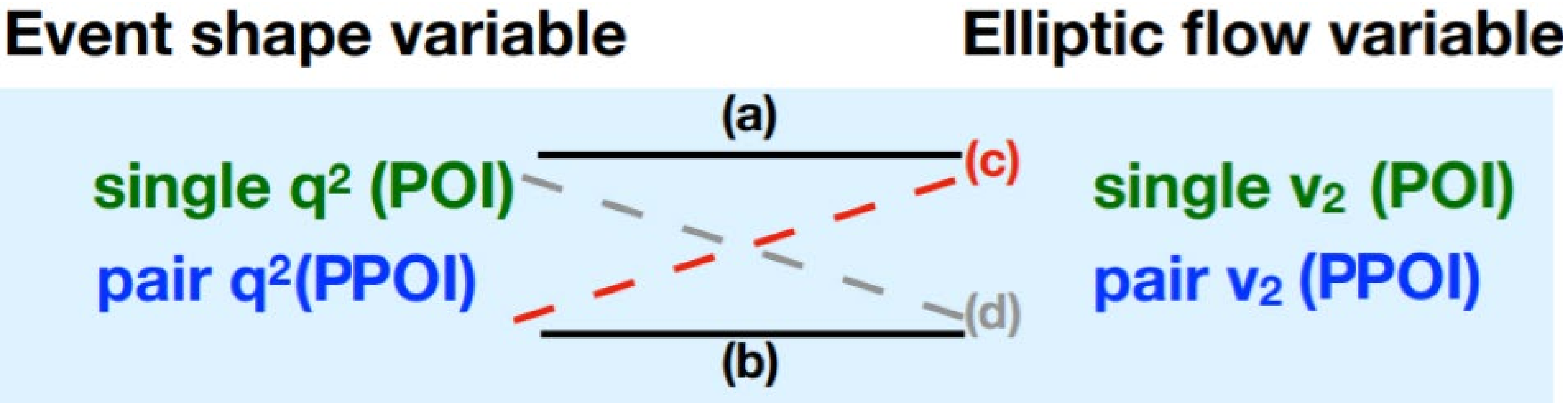


H. Petersen and B. Müller, Phys. Rev. C 88, 044918

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



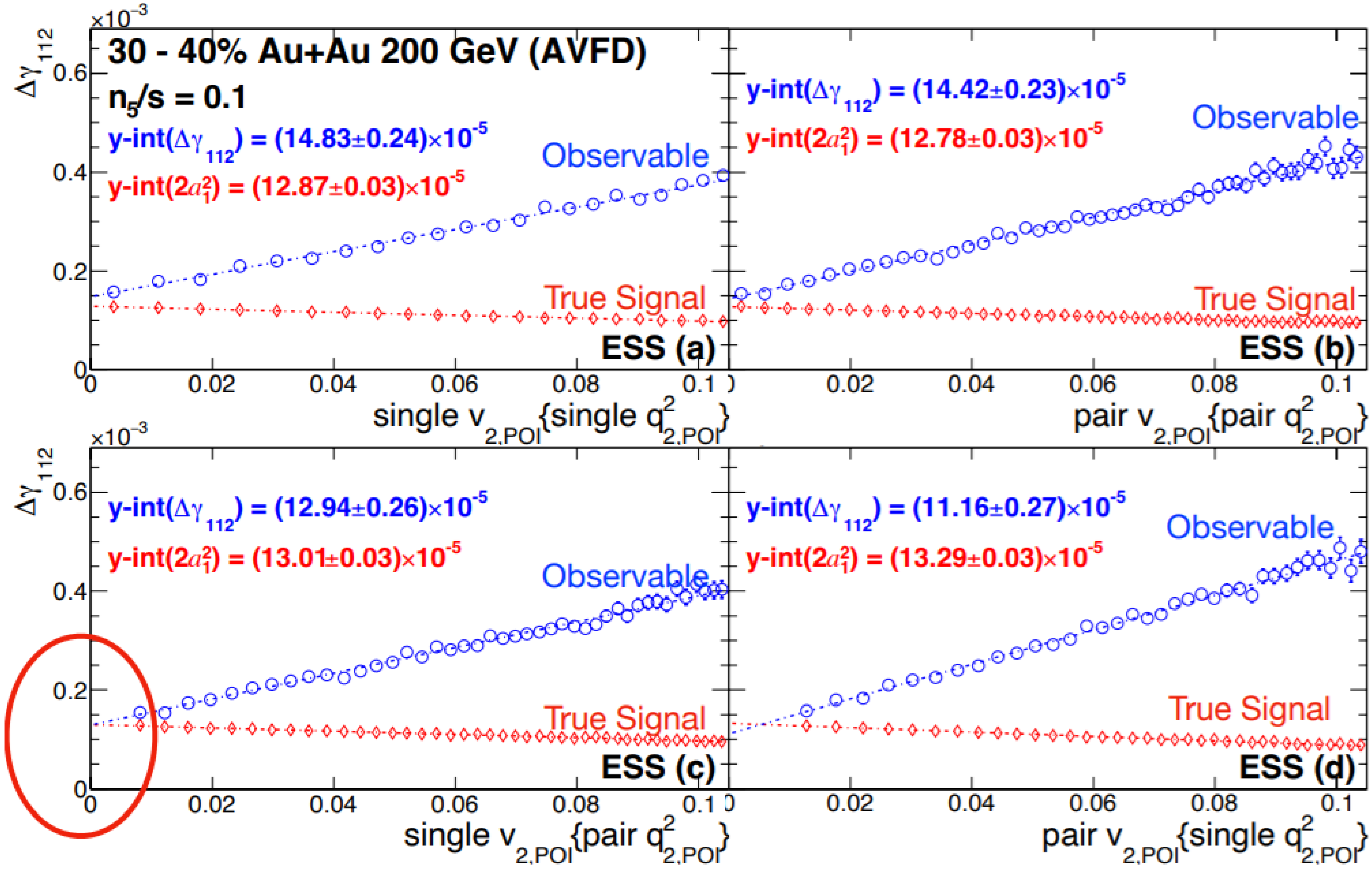
$$q_2^2 = \frac{1}{N}\left[\left(\sum_{i=1}^{N}\sin 2\varphi_i\right)^2 + \left(\sum_{i=1}^{N}\cos 2\varphi_i\right)^2\right]$$
$$= 1 + \frac{1}{N}\sum_{i\neq j}\cos[2(\varphi_i - \varphi_j)],$$

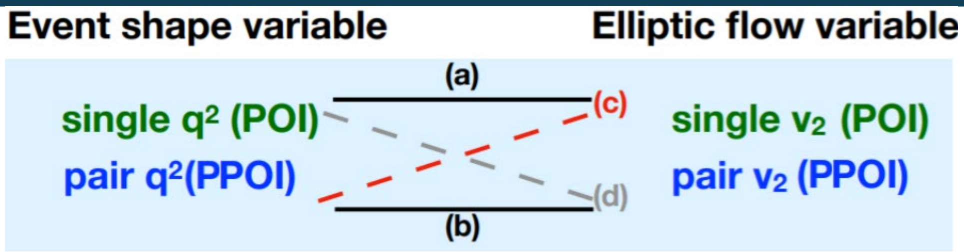
$$\langle q_2^2\rangle \approx 1 + N v_2^2\{2\}$$

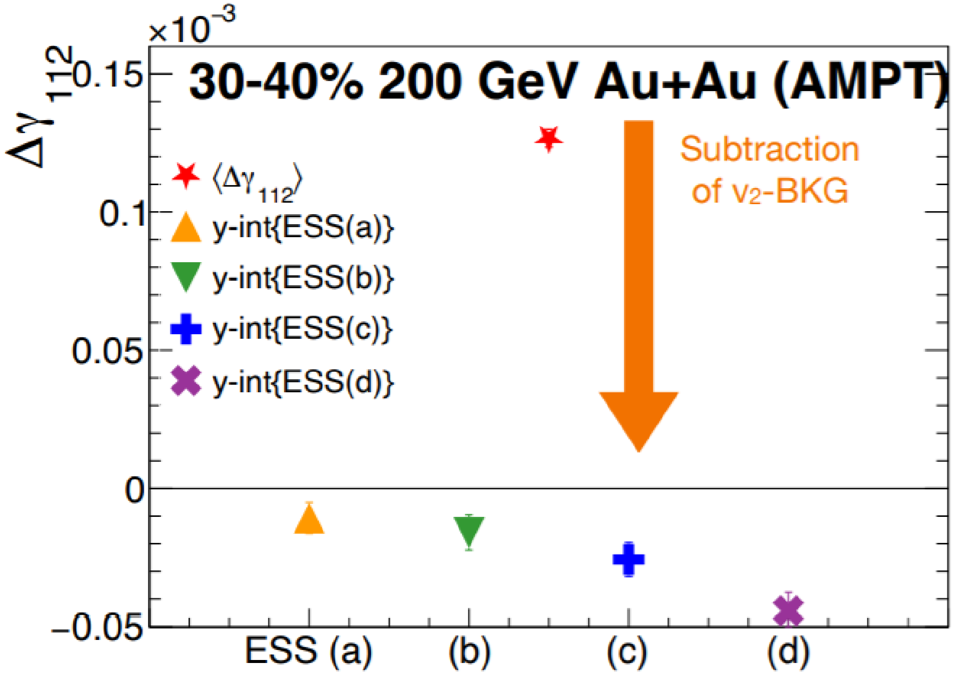
- ESS recipes (a) and (b) involve direct event-by-event correlations between $q_2{}^2$ and v_2, which will cause under-subtraction of background.
- We should use "mixed" recipes, (c) or (d).
- Redefine $q_2{}^2$ with an extra normalization.
- Pair $q_2{}^2$ and pair v_2 are based on $\boldsymbol{\varphi}_{\mathrm{p}}$.

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

Simulations







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).

ESS procedures

1. Categorize events Z. Xu et al, PLB 848(2024)138367

Flow vector with higher-order normalization

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

2. Measure the Δγ Observable & v_2 flow

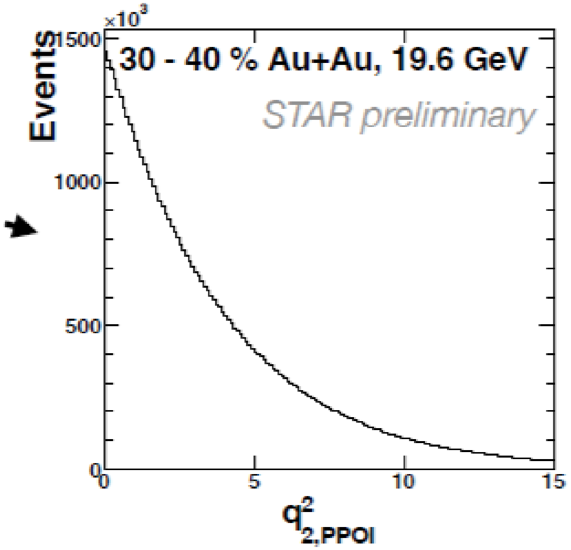
pair q_2 (PPOI) .... single v_2 (POI)

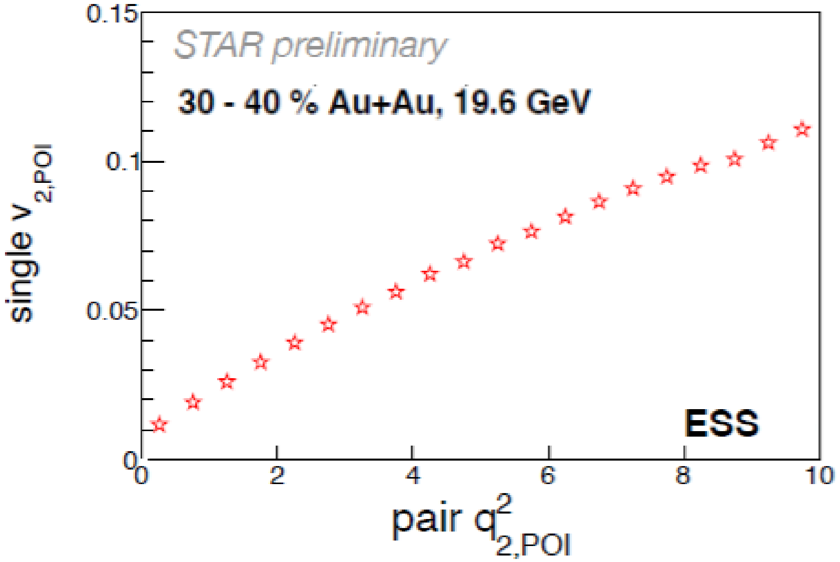
- **adding momenta of two POI particles ~ mimic resonance decay**

2. Plot Δγ against v_2 to extrapolate $\Delta\gamma_{ESS}^{112}$

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

Non-interdependent Flow, Z.Xu et al Phys. Rev. C 107, L061902





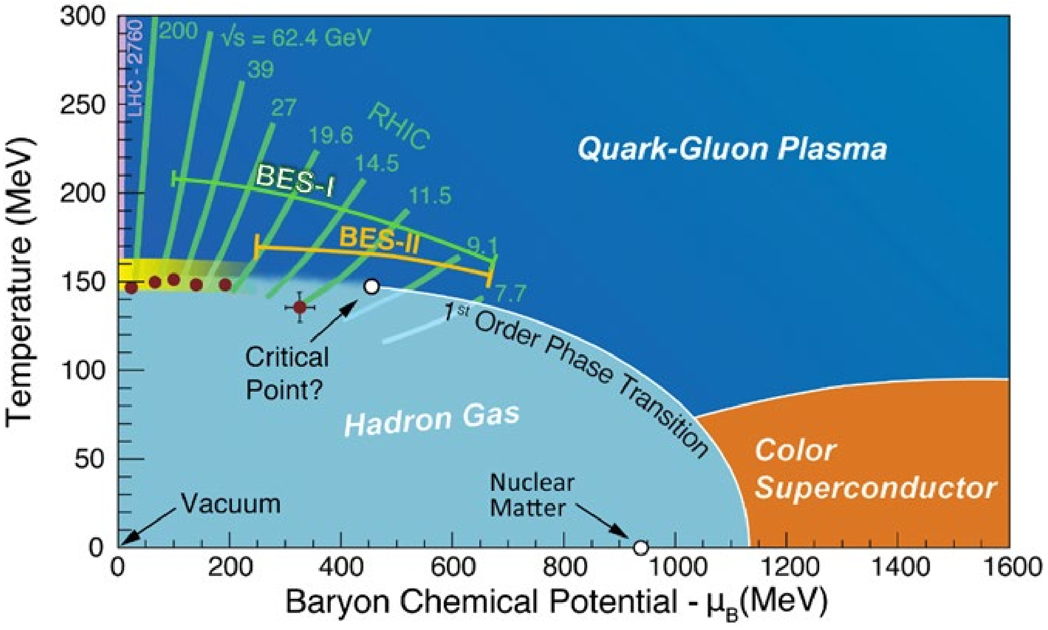
Application to Real Data

BES-I

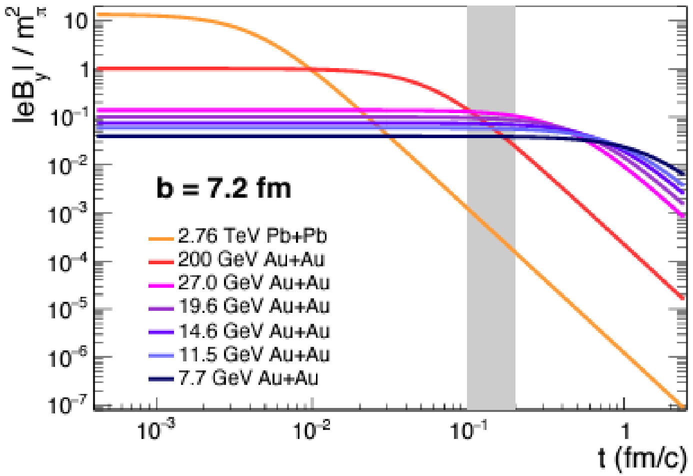
"Events" represents good events after quality cuts.

BES-II

$\sqrt{S_{NN}}$(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



$\sqrt{S_{NN}}$(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

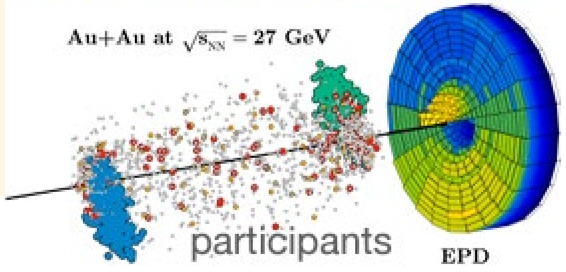


Event Shape Selection **Spectator Ψ_1**

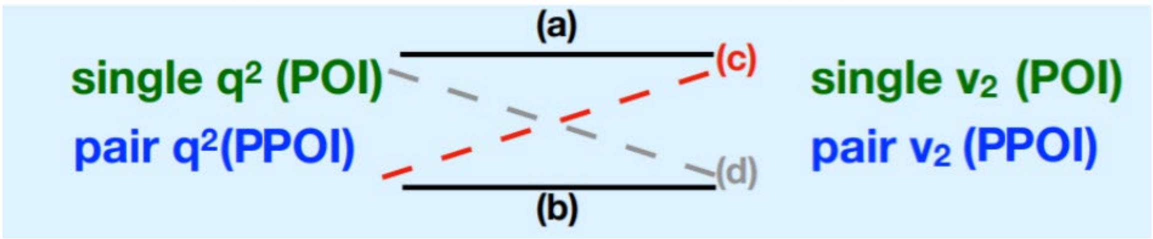
$$\Delta\gamma^{112} = \Delta\gamma^{\mathrm{CME}} + k\frac{v_2}{N} + \Delta\gamma^{\mathrm{non-flow}}$$

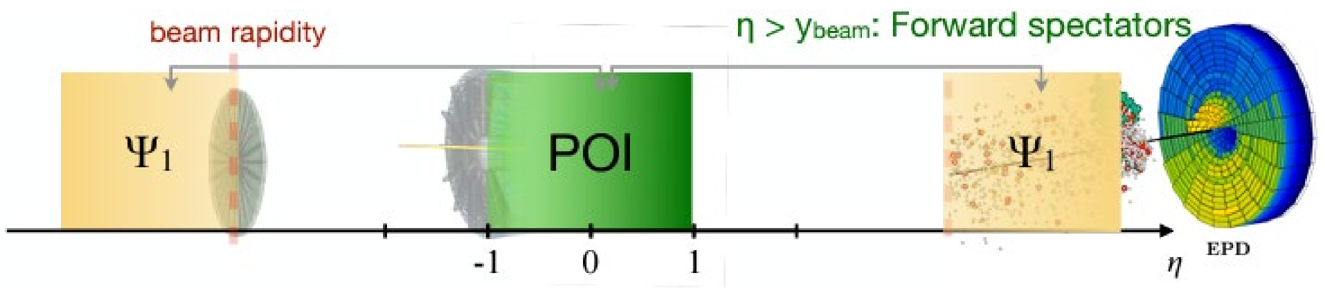
Measured **Signal** **Backgrounds**

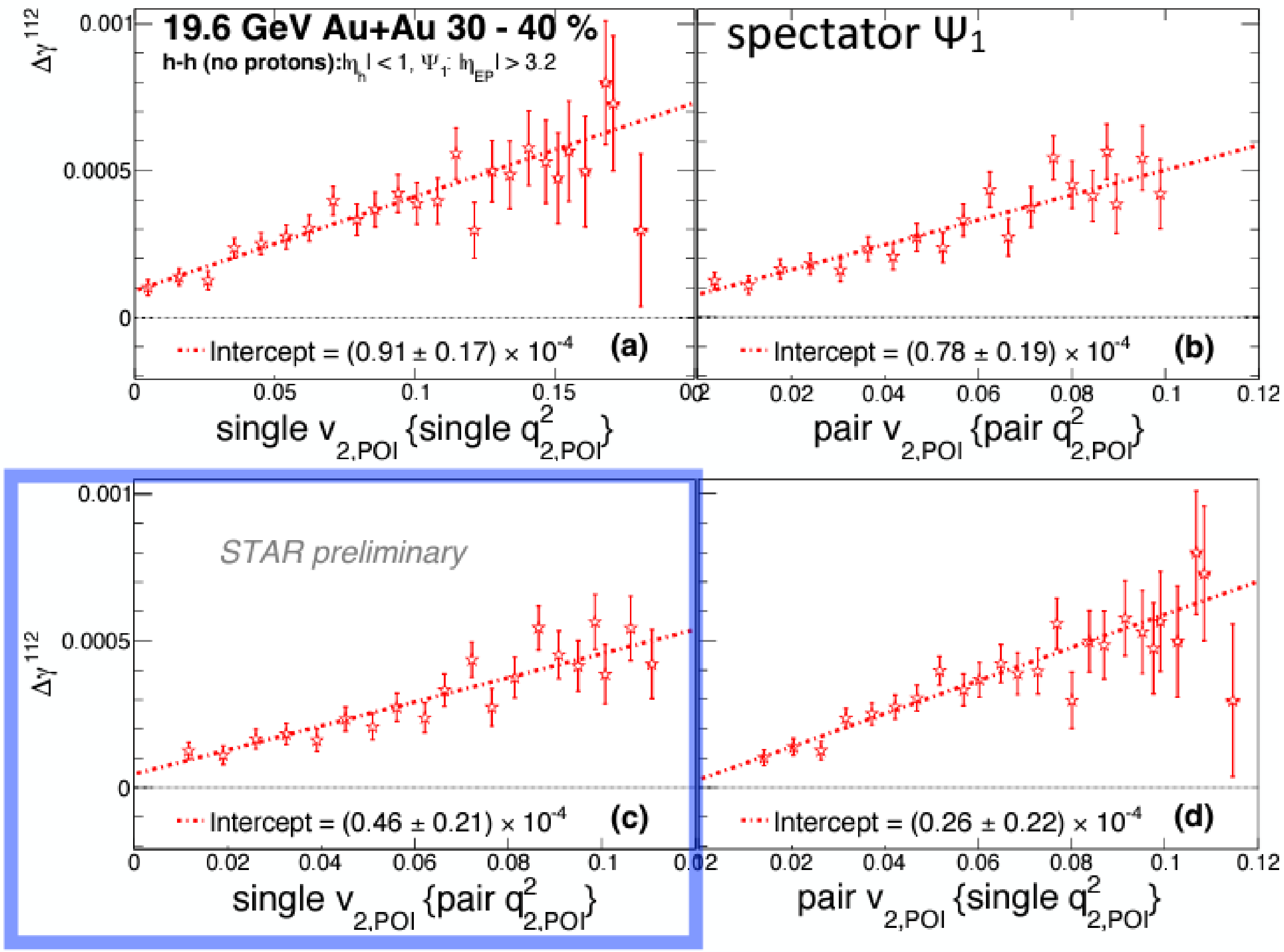
$\eta > y_{beam}$: Forward spectators



Au+Au at 19.6 GeV



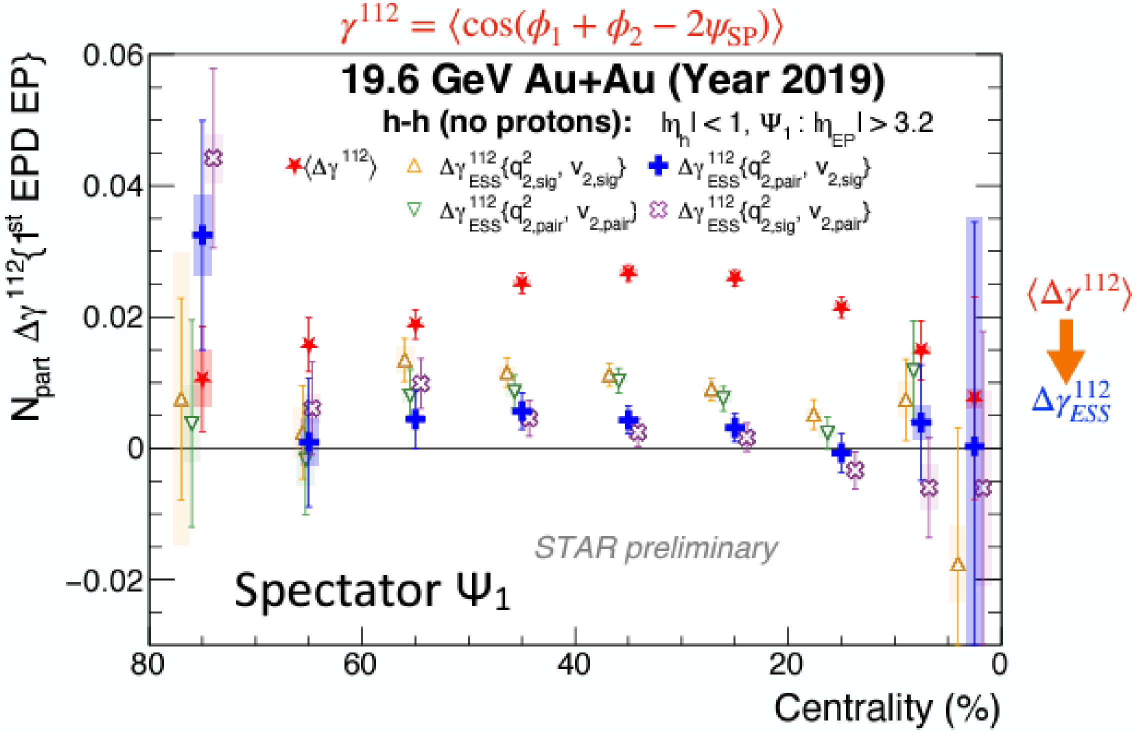


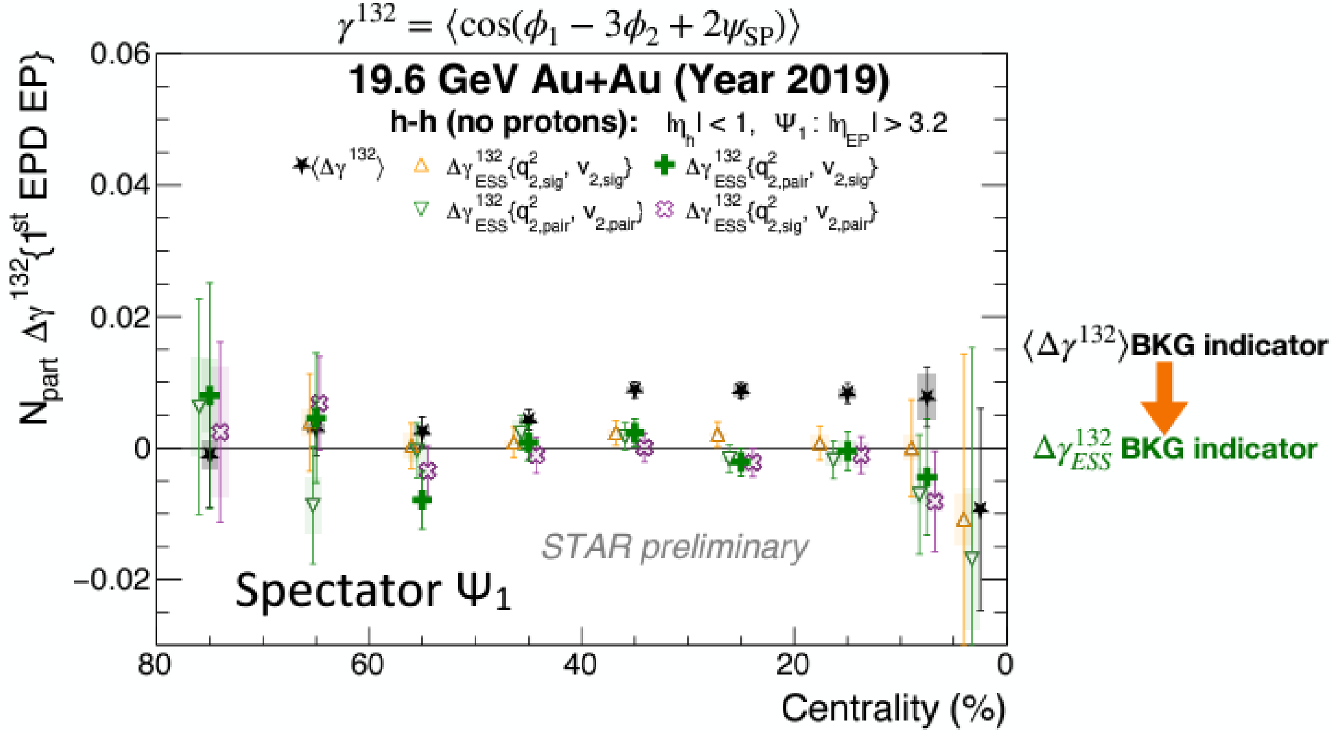


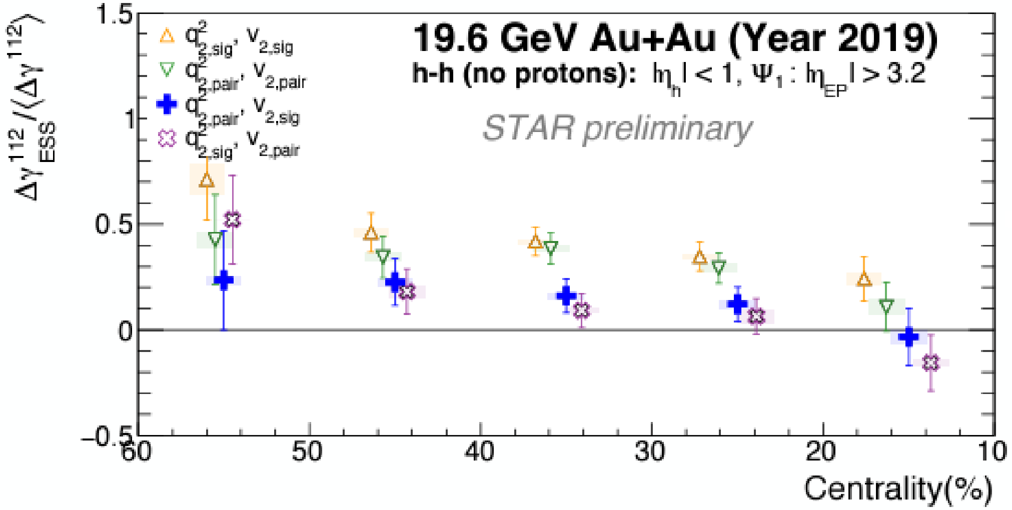
- **ESS using POI allows much shorter extrapolation to zero v_2.**
- **The ordering of y-intercepts follows predictions from both AVFD and AMPT.**
- **The y-intercept requires a small conversion to restore the unbiased signal:** $\Delta\gamma^{112}_{ESS} = Intercept \times (1 - v_2)^2$

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

Au+Au at 19.6 GeV





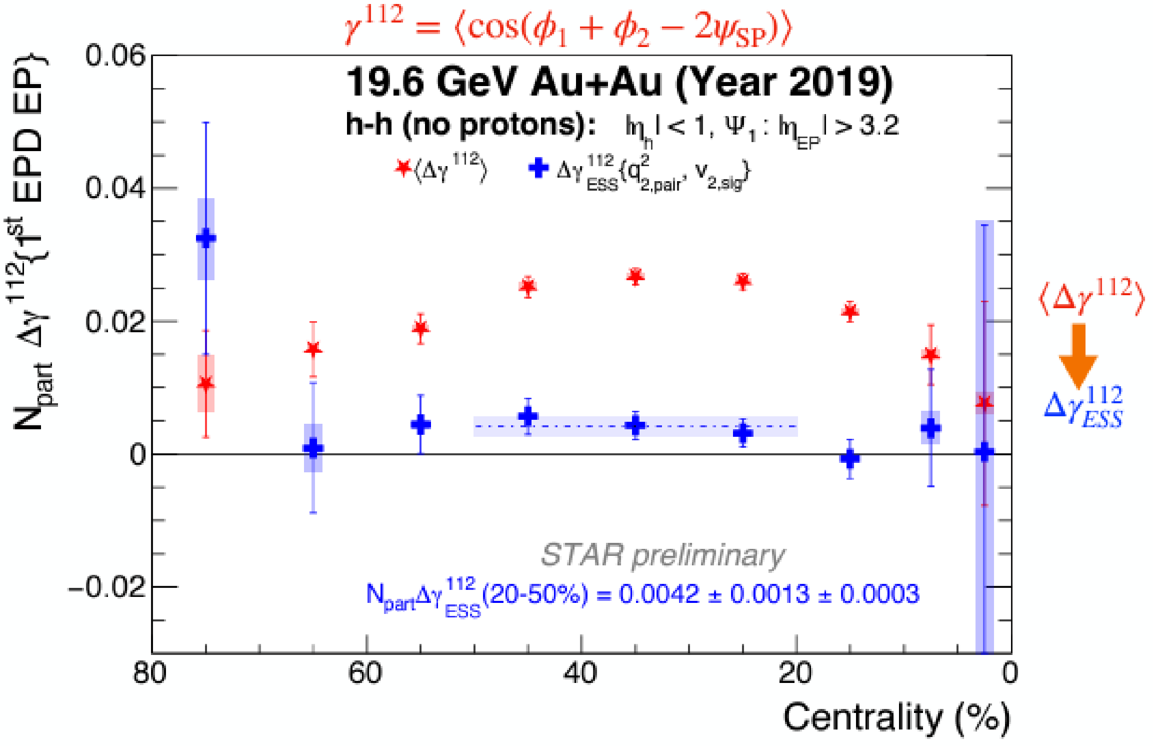


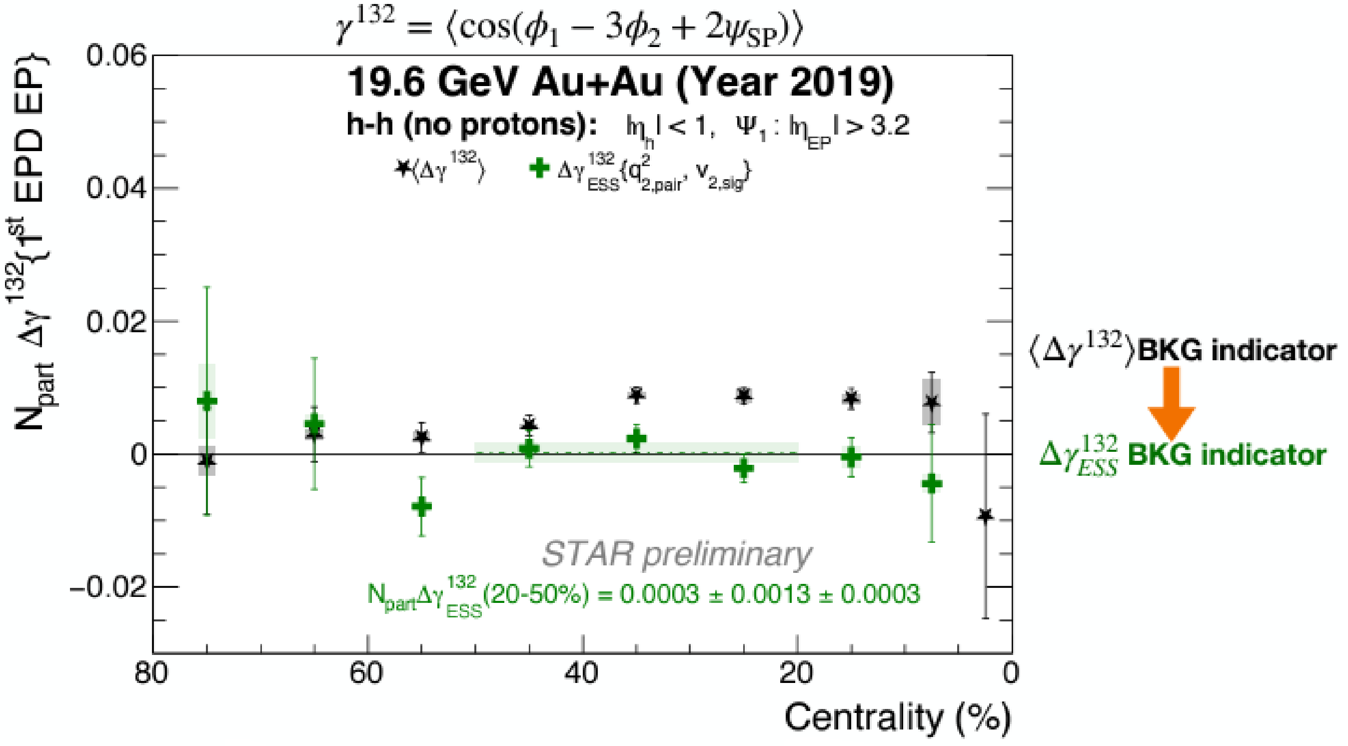
- **The ordering of y-intercepts follows predictions from both AVFD and AMPT.**

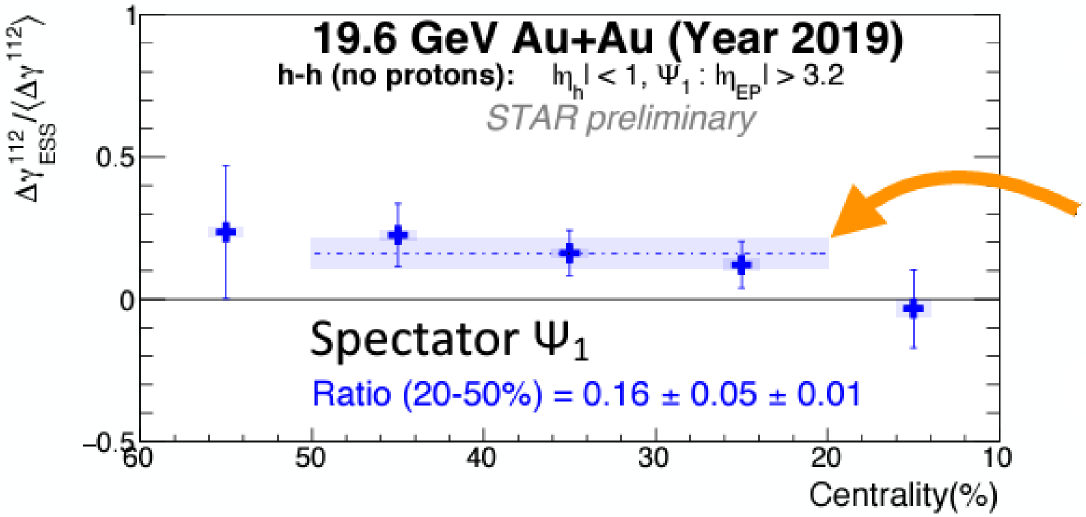
Not all event shape selections are equal, there is some model dependence
We need to optimize the method to suppress the hydro-related CME background

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 !

Au+Au at 19.6 GeV

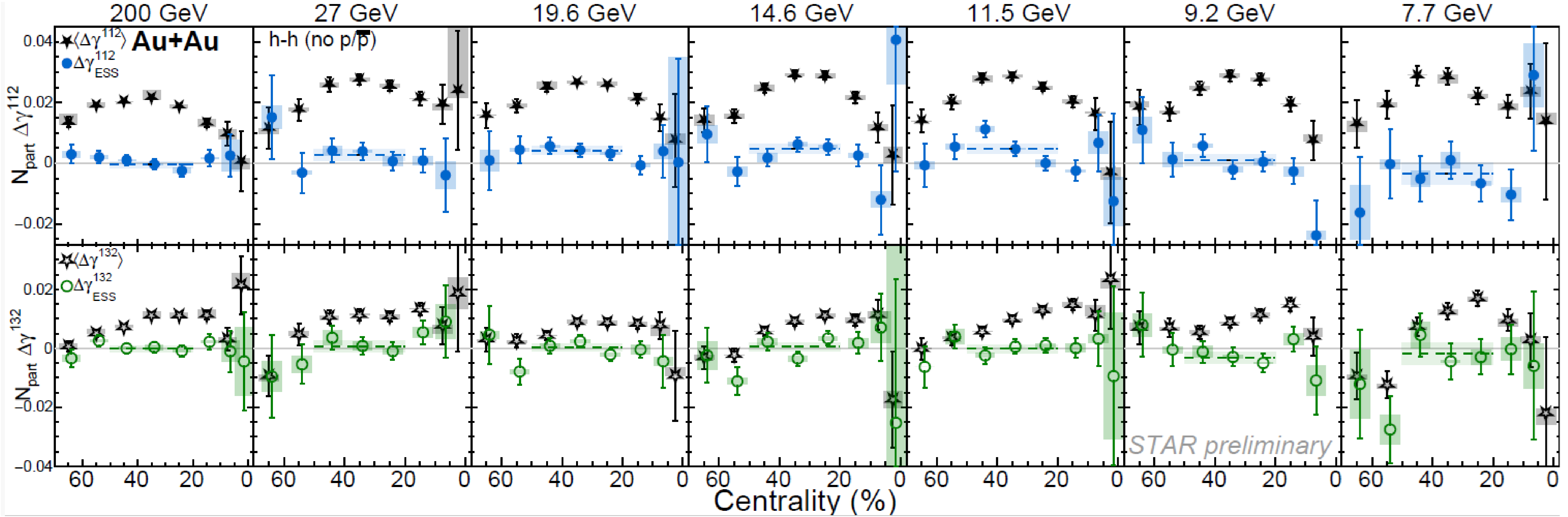






- **After v_2-BKG subtraction, a finite signal in mid-central (20-50%) events.**
- **Ratio from the optimal ESS (c), pair q_2 and single v_2, yields a 3σ significance in the 20-50% centrality.**
- **From the BKG indicator $\Delta\gamma^{132}$, ESS successfully suppresses v_2-BKG.**

Au+Au at 7.7 -- 200 GeV

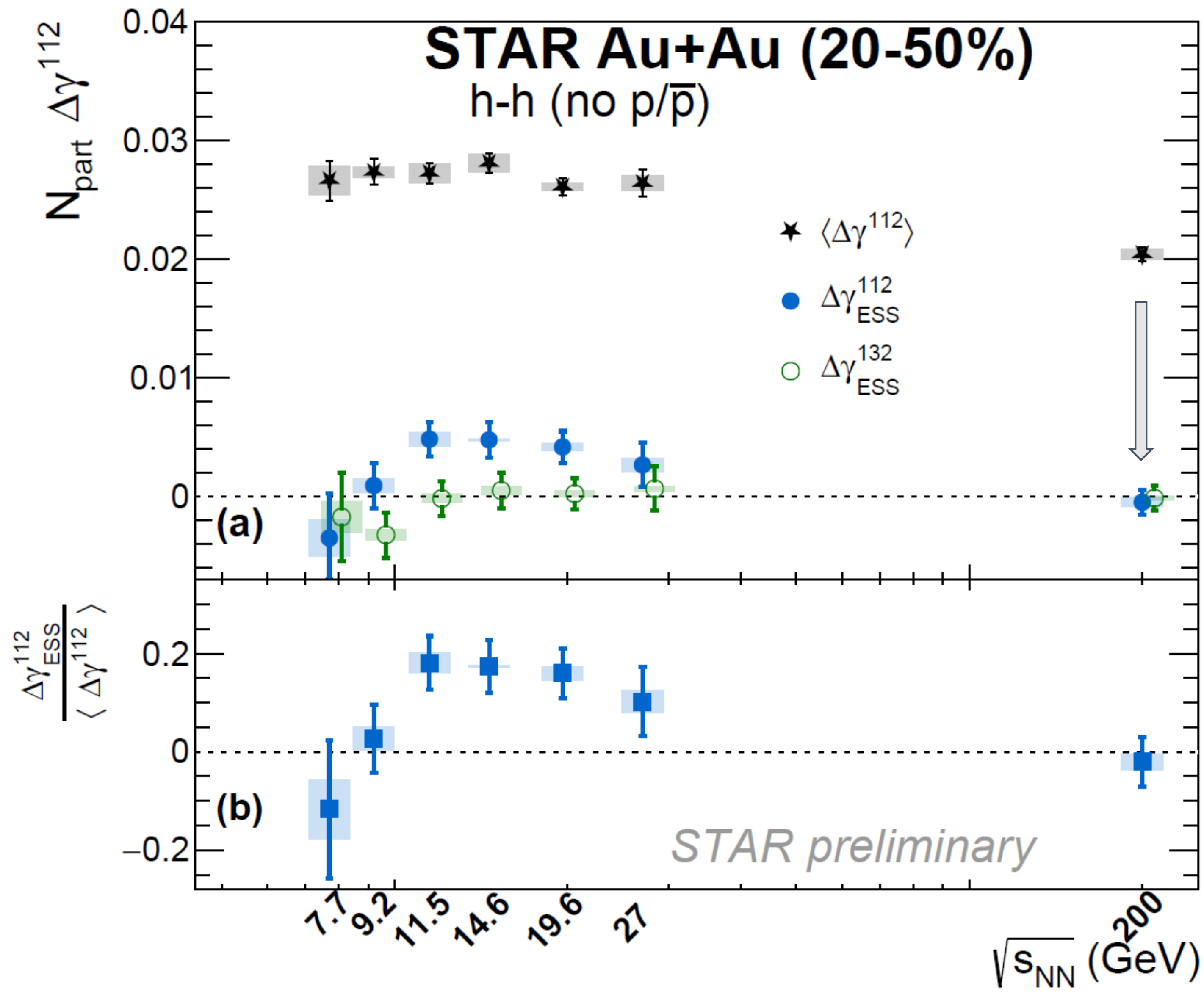


$\Delta\gamma^{112}_{ESS}$ from the optimal ESS (c), pair q_2 and single v_2:

- **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.**

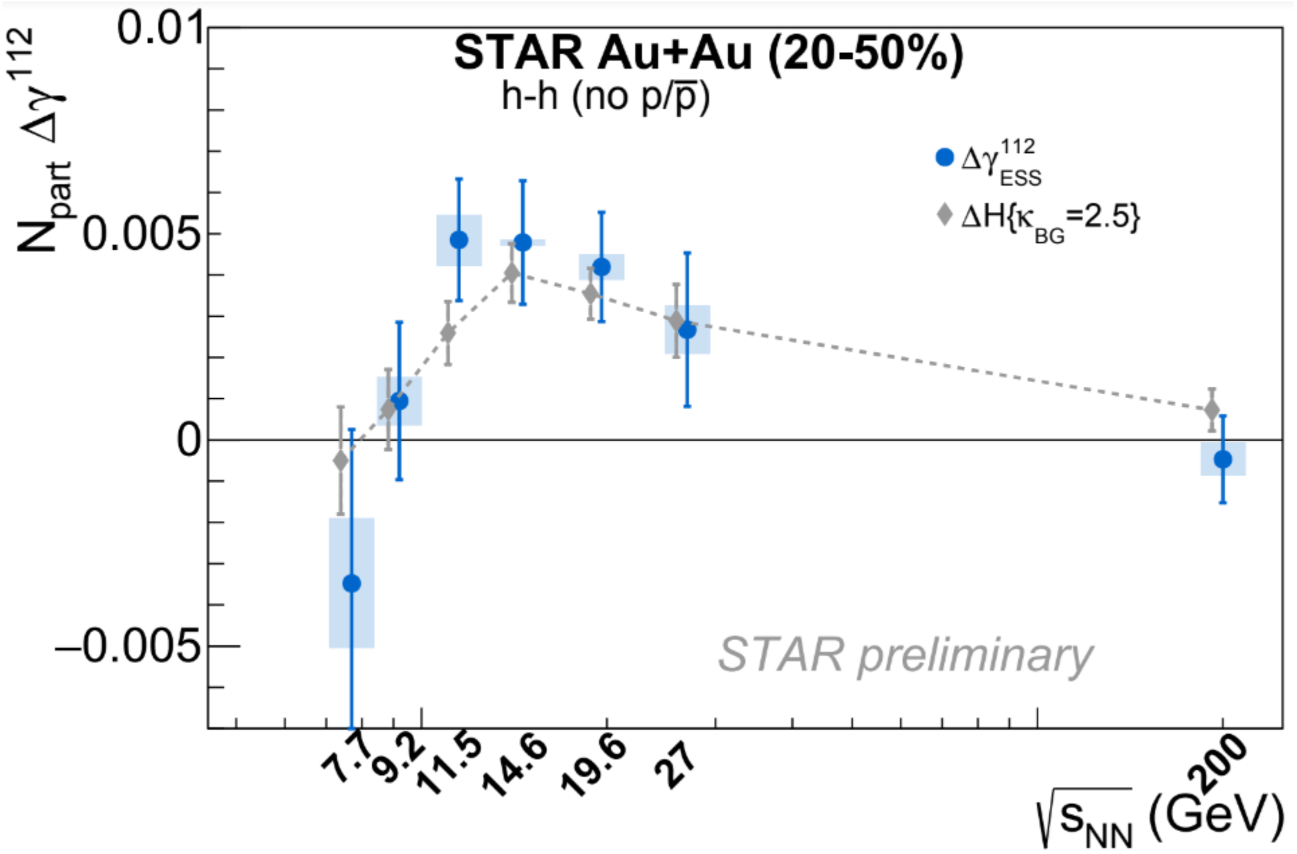
$\Delta\gamma^{132}_{ESS}$ is consistent with zero.

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.

Connection between ESS and the H correlator



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

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

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

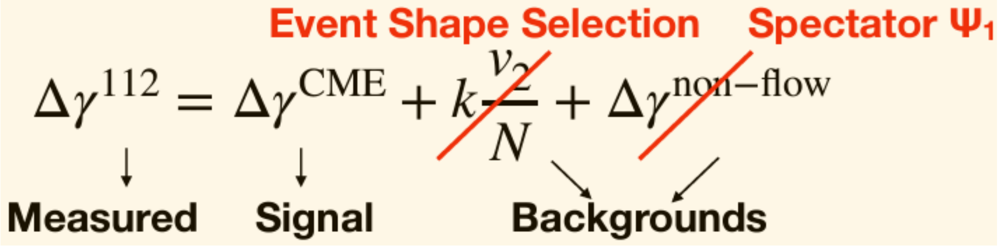
$$\gamma = \kappa v_2 B - H$$
$$\delta = B + H$$

- 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.

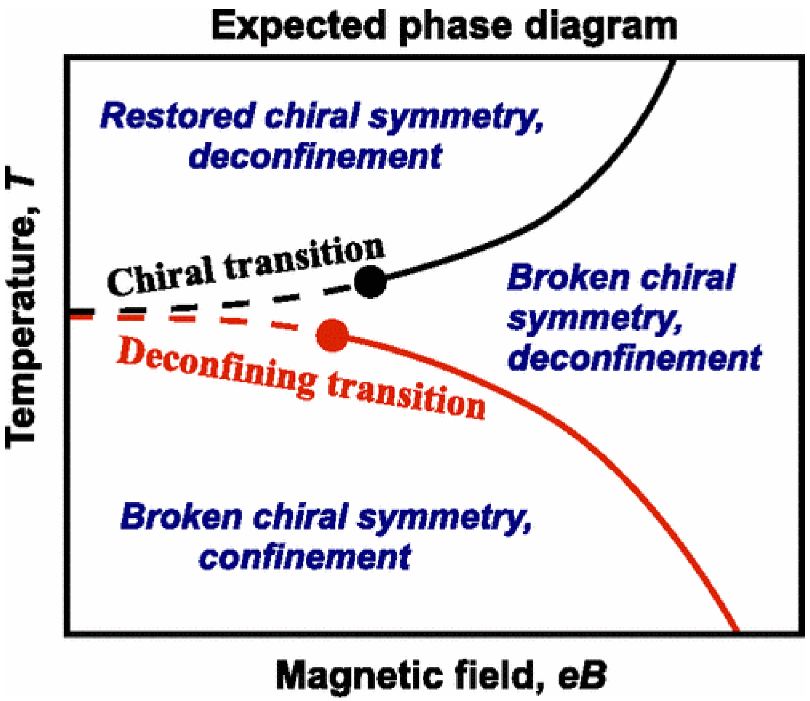
- **With κ_{bg} set to 2.5, ΔH agrees with the ESS result at all beam energies under study.**
- **The flow background can be reasonably well described by a universal coupling between v_2 and the two-particle correlation.**

STAR ESS CME Search Summary

- 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 too weak at 200 GeV?
  - Chiral symmetry breaking around 7.7 GeV?
  - The chance of the CME occurrence is enhanced near the critical point?
- We urge our LHC colleagues to try the ESS method with LHC data



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



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 at the LHC energy ?!

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

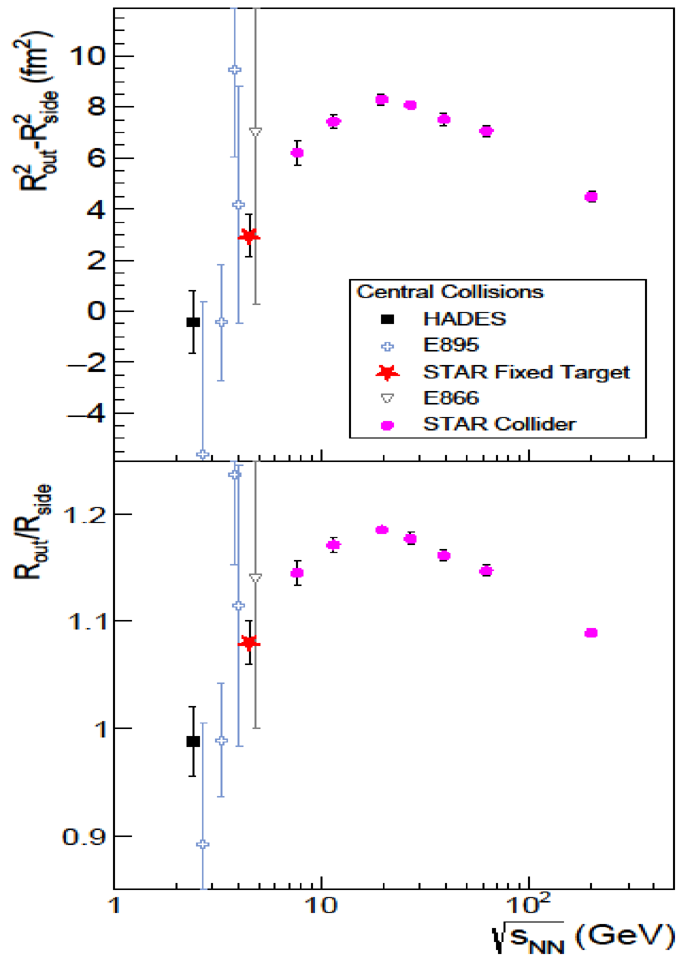
Why?

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

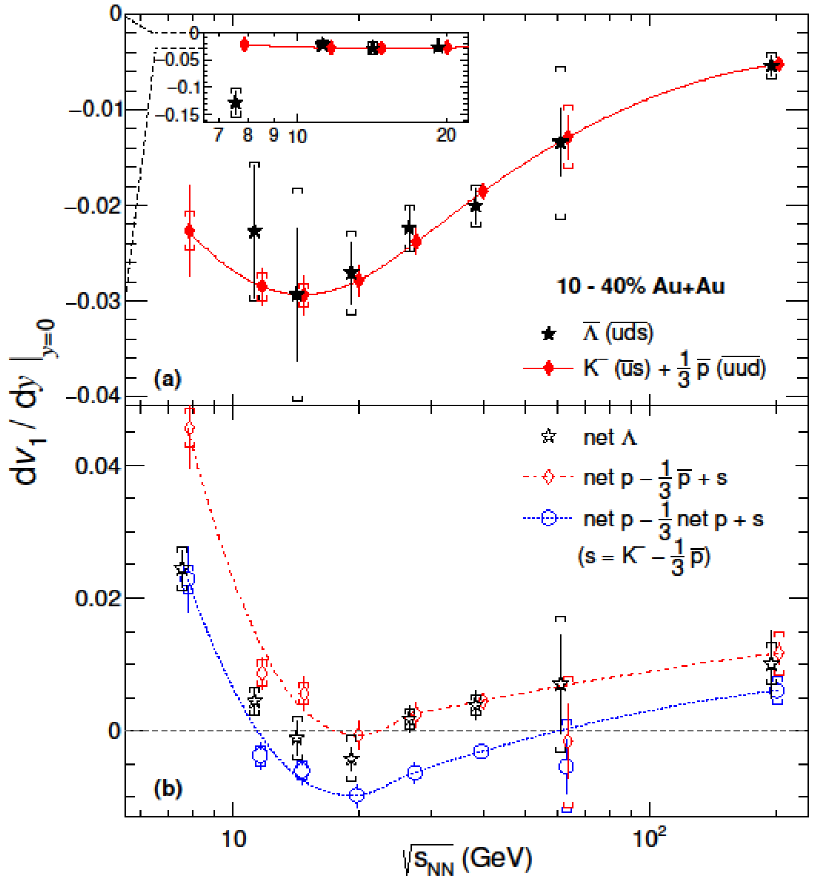
Please measure $v_2\delta$ background correlation as well !

What so Special for Collisions at 10-30 GeV

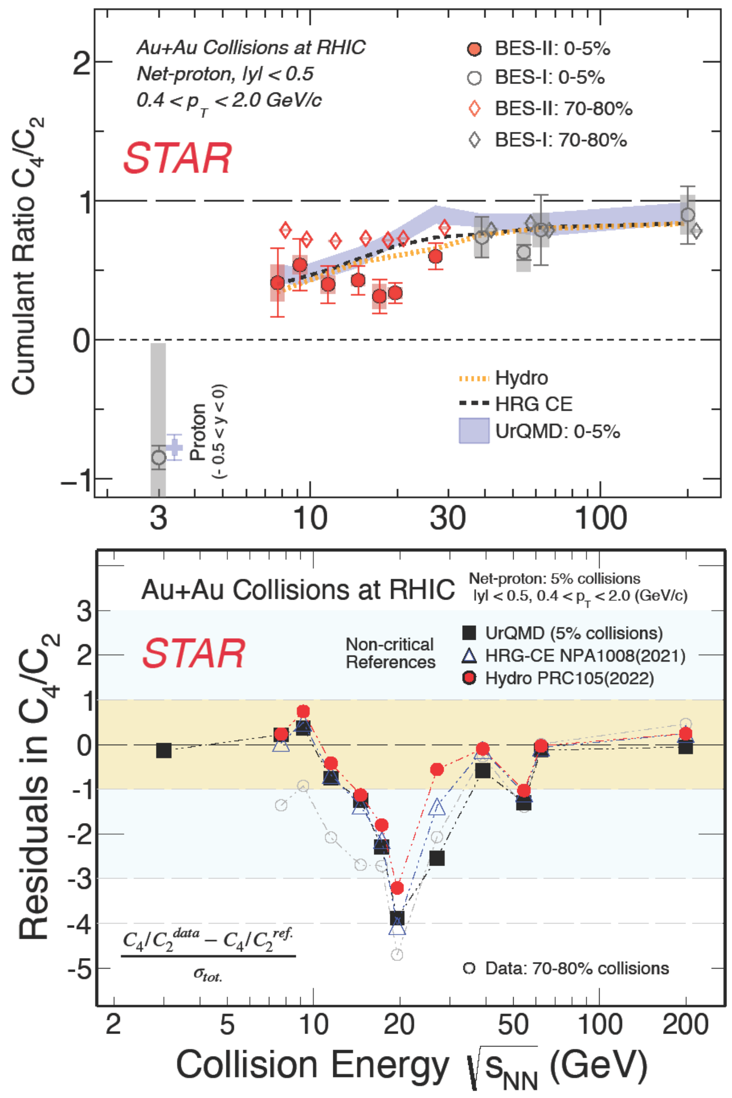
HBT Rout/Rside



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 !

Stay hungry Stay foolish !

Thank You !