Challenges and Opportunities for Experimental Studies of QCD Chiral Magnetic Effect

黄焕中 （Huan Zhong Huang）
University of California Los Angeles

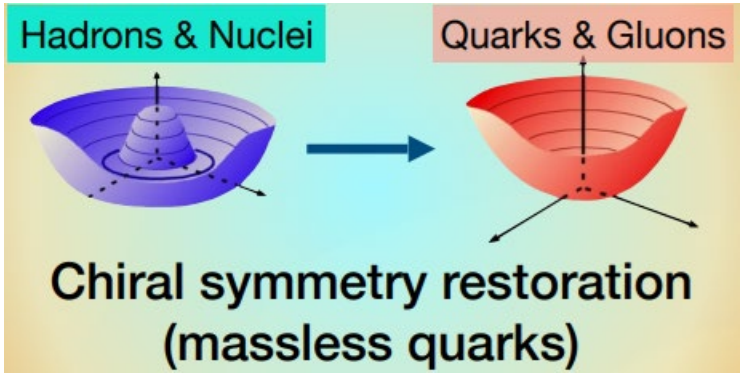
The 10th International Conference on Chirality, Vorticity and Magnetic Fields in Quantum Matter
(Chirality 2026)
Zhuhai, China
Nov. 16-20, 2026

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

Outline

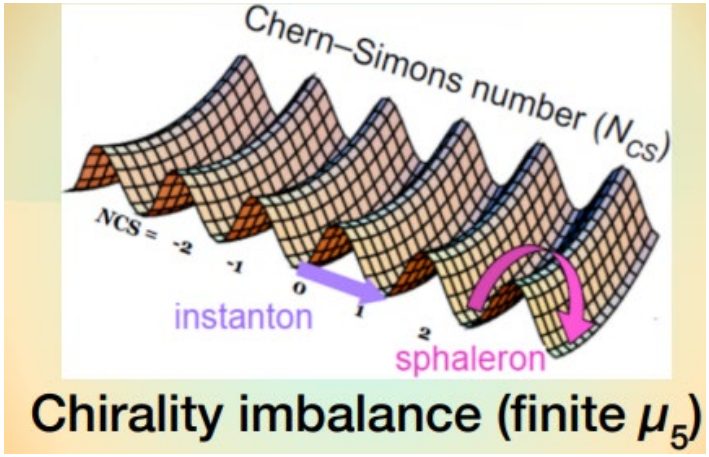
- Event Shape or Eccentricity Shape Approaches –
  Event Shape Engineering (ESE) and Event Shape Selection (ESS)
- STAR ESS Results from BES-II and 200 GeV Data
- Other Methods for CME Searches
- Magnetic Field and Beam Energy Dependence
- Future Perspective

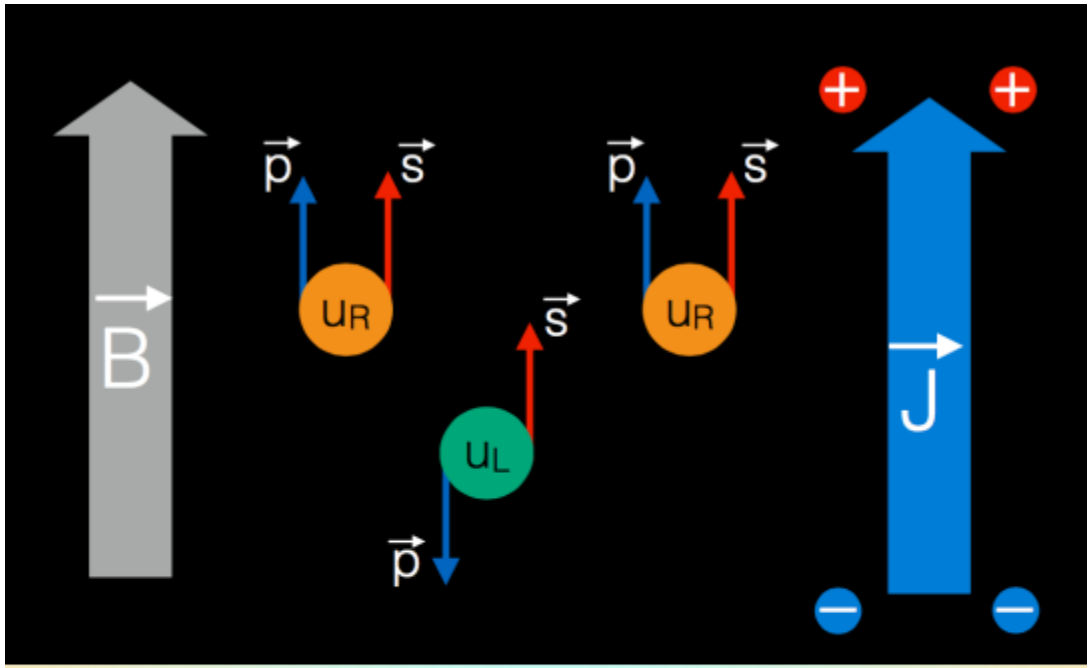
Chiral Magnetic Effect



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

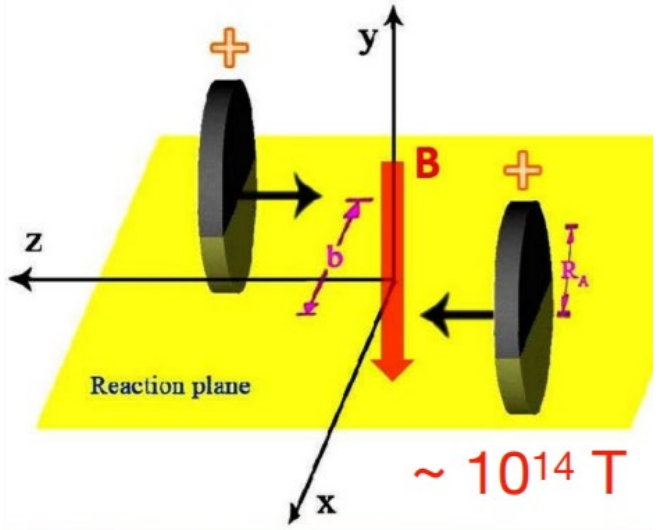
QCD Non-Abelian Nature → Collective Gluonic Excitations → Chirality Imbalance





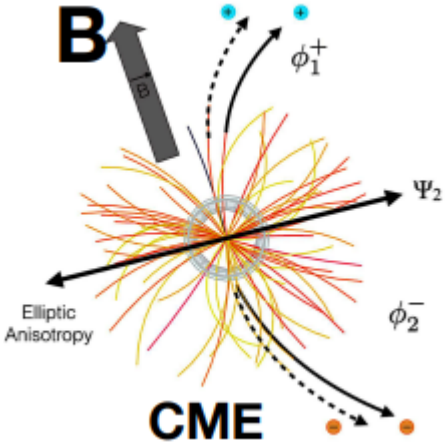
Chiral Magnetic Effect (J ∥ B)

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



Strong magnetic field (B)

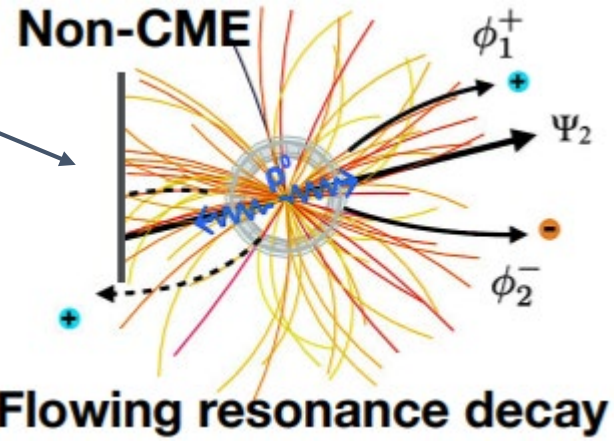
CME Observables



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

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

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)

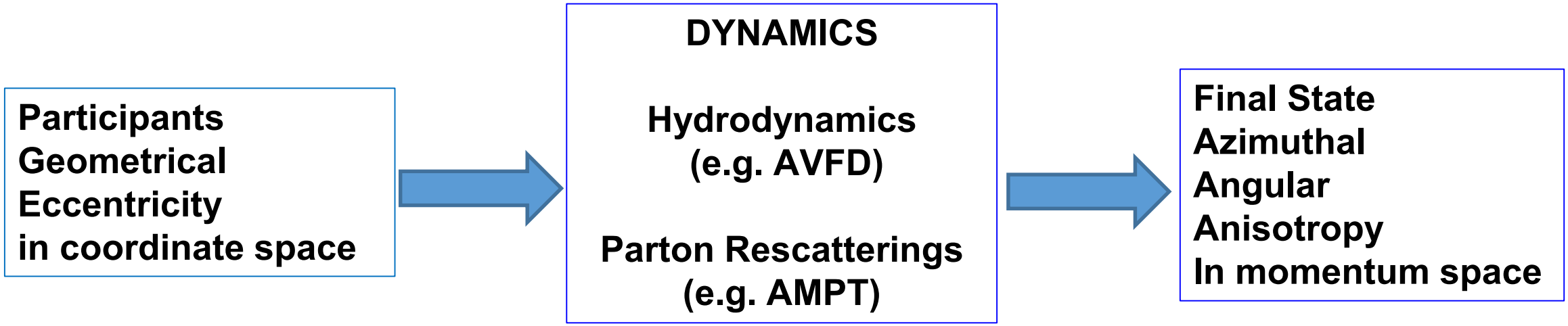
S. Choudhury et al.(STAR), Chin. Phys. C46(2022)014101

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 Approaches



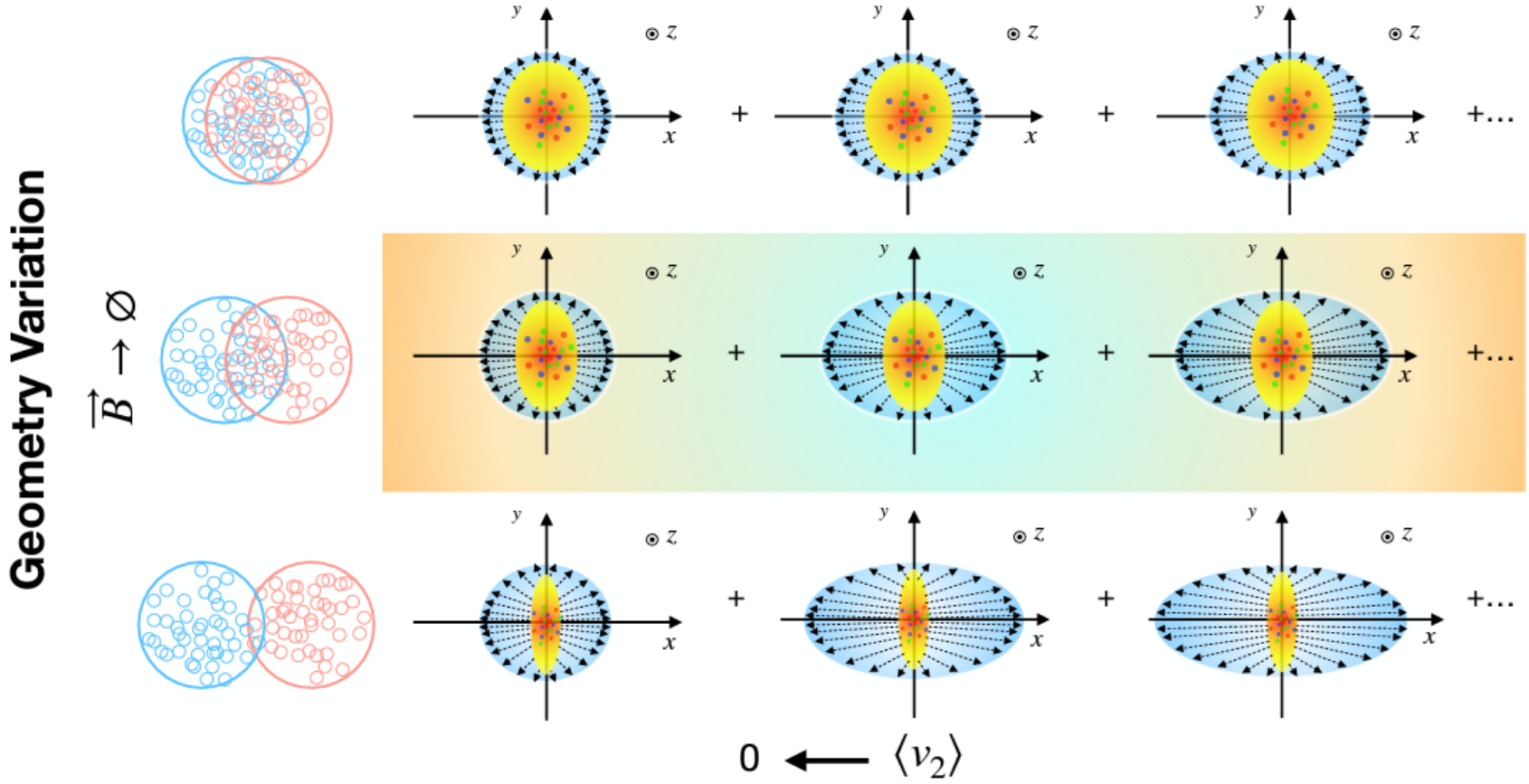
Not all models are useful to test event shape approaches

HIJING, uRQMD and EPOS without validation of v_n comparison with experimental data → does not add to our understanding of event shape based analyses !!

Toy models → needs to be treated with extreme cautions !

Event Shape (Final State Momentum Space) vs. Eccentricity Shape (Initial State Coordinate Space)

Event Shape Engineering Method → Focus on Geometrical eccentricity alone
Event Shape Selection Method → Final state anisotropic distribution arising from eccentricity and emission fluctuations while keeping Bfield unchanged – only useful for CME searches



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.

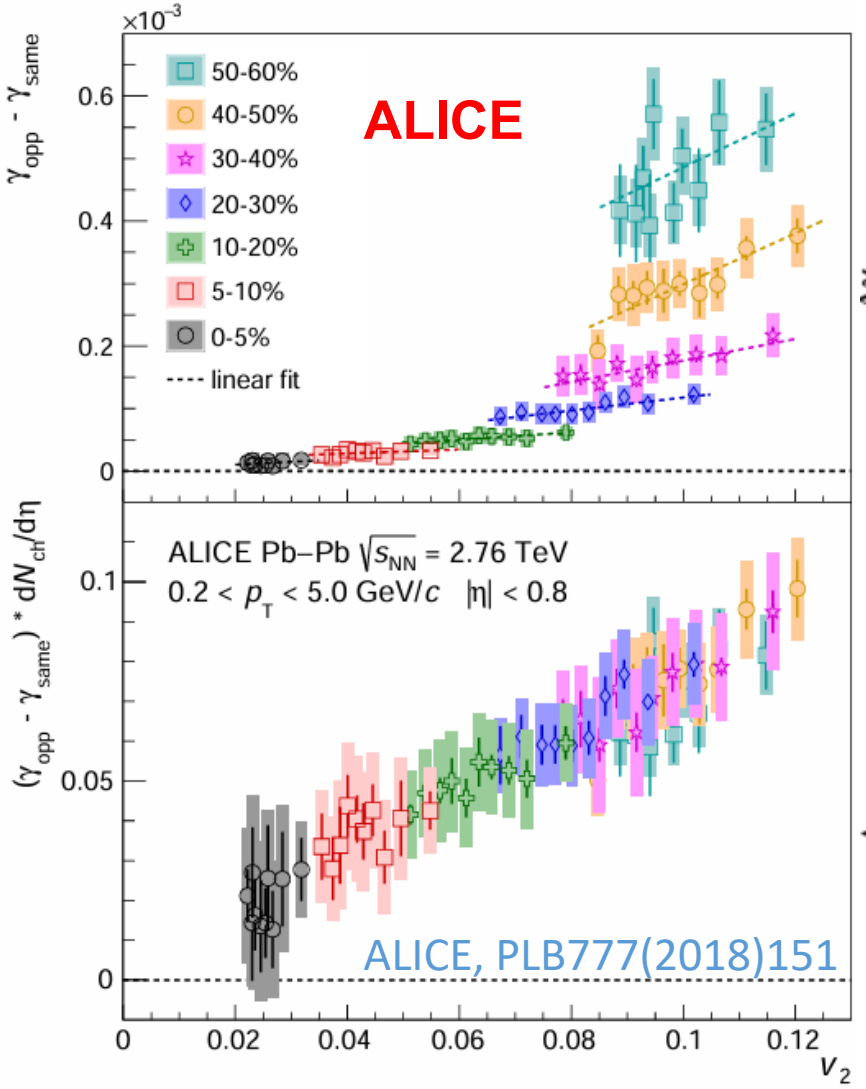
CME background e-by-e comes from combined eccentricity and emission patterns. validation by AVFD !

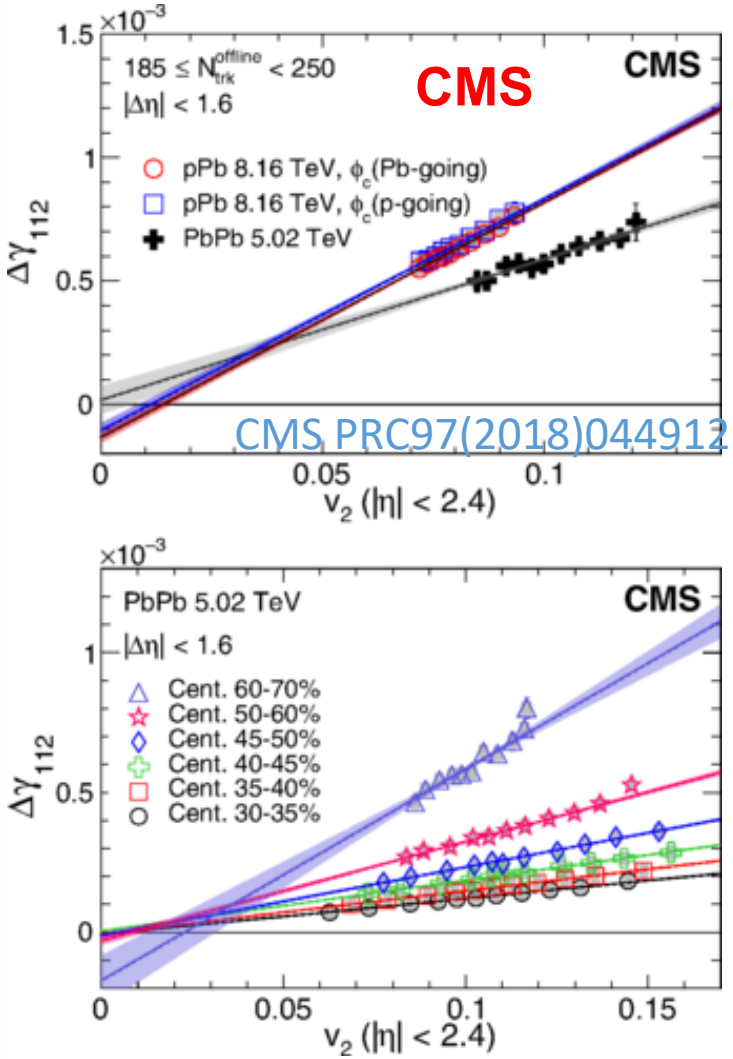
Eccentricity Shape (Event Shape Engineering)

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.

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

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



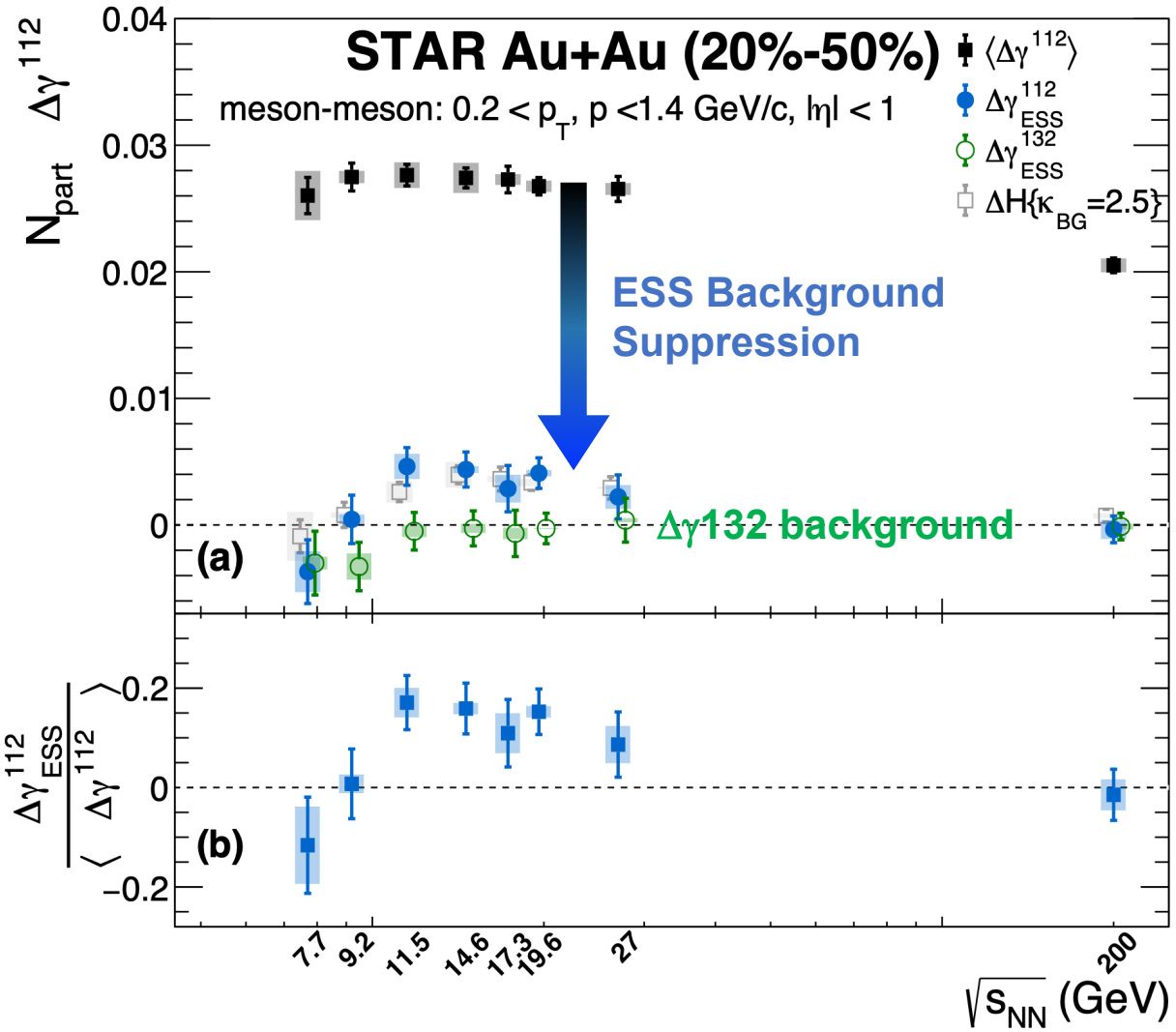


- Measure $\Delta\gamma_{112}$vs q_2 and v_2 vs q_2, then plot $\Delta\gamma_{112}$ vs v_2, and finally extrapolate $\Delta\gamma_{112}$ to zero v_2.
- At LHC energies, all the ESE results are consistent with zero. (too short duration of the *B* field?)
- For middle centralities participant shapes do not fluctuate close to round shape, making the extrapolation to v_2 ZERO unstable.

Residual Charge Separation Signal from ESS

PRC 113, 014912 (2026)

(Jinhui Chen's Talk)



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).

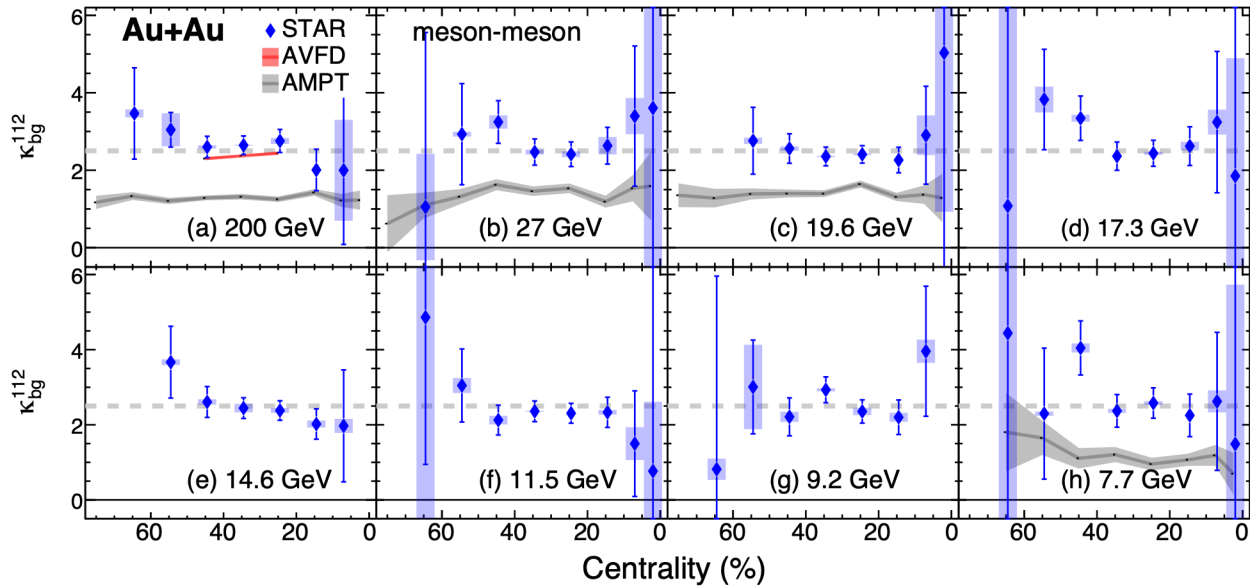
The ESS results approach zero around 9.2 and 7.7 GeV.

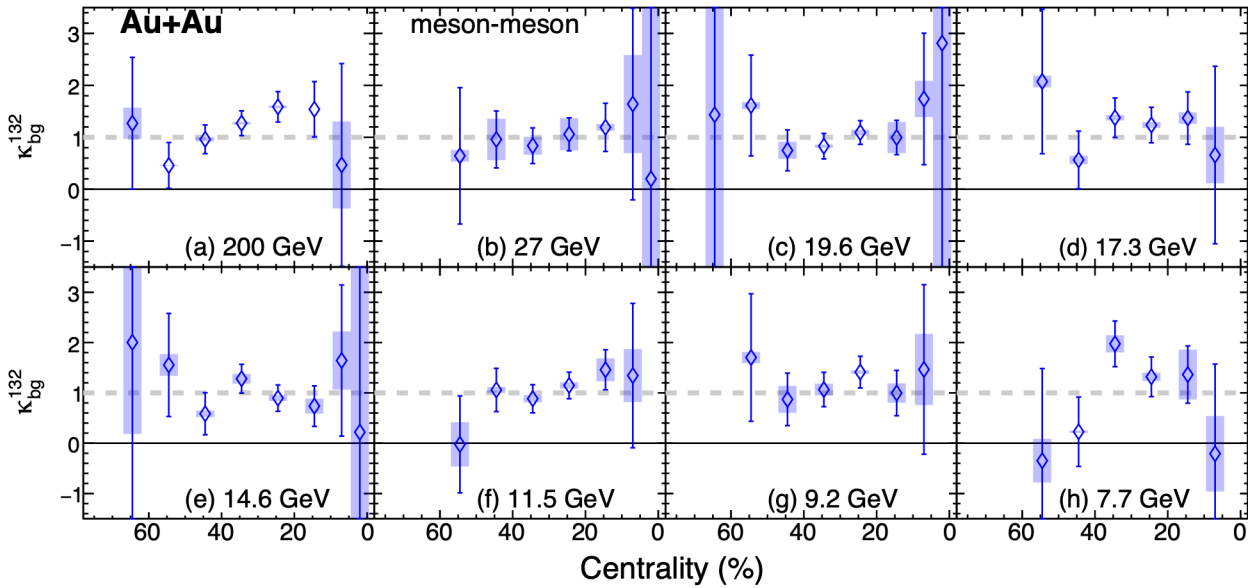
The Background in $\Delta\gamma^{112}$ and $\Delta\gamma^{132}$

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

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

PRC 113, 014912 (2026)





- 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 !

Clarification on Model Dependence of ESS

1) The STAR Event Shape Selection (ESS) procedure does not depend on any theoretical models.

2) The interpretation of the ESS analysis results, like many other results from HIC, will always be model-dependent and will take many experimental and theoretical investigations to understand the dynamical physical picture.

3) The interpretation of ESS results in CME search depends on your model-biased perspective:

   Hydrodynamics – IF correct for pT< 1.4 GeV/c – ESS removes v2-background;
   AMPT – IF correct – ESS over-subtracted the v2-background;
   HIJING – IF correct – ESS not applicable for v2-related shape selection at all;
   Non-hydro toy models – IF correct – ESS anything "garbage in, garbage out".

4) Do some basic model comparisons with experimental measurements of v_2, v_3, $\Delta\gamma^{112}$ and $\Delta\gamma^{132}$ before trashing the STAR ESS procedure!

Intriguing Aspects of the ESS Results on Charge Separation

1) No, STAR has not claimed discovery of CME yet!

2) We have observed a charge-separation signal along the B field direction at the v_2 close to zero limit in Au+Au collisions at 10-20 GeV energies using the ESS method and the ESS method can be validated with Anomalous Viscous Fluid Dynamics (AVFD) model with 200 GeV simulations.

3) The background in $\Delta\gamma^{112}$ seems to be flow-related and has an universal coupling with two-particle correlations.

4) The beam energy range 10-20 GeV seems to be a favored region for the residual charge separation signal.

5) Dynamical modeling and more experimental measurements are needed to relate the charge separation signal with CME or any other physical dynamics – Recent theoretical calculations from Jinfeng Liao et al on AVFD, Kharzeev et al on CME and critical phenomenon, and STAR on Magnetic B field imprints……

More experimental works towards CME signal discovery

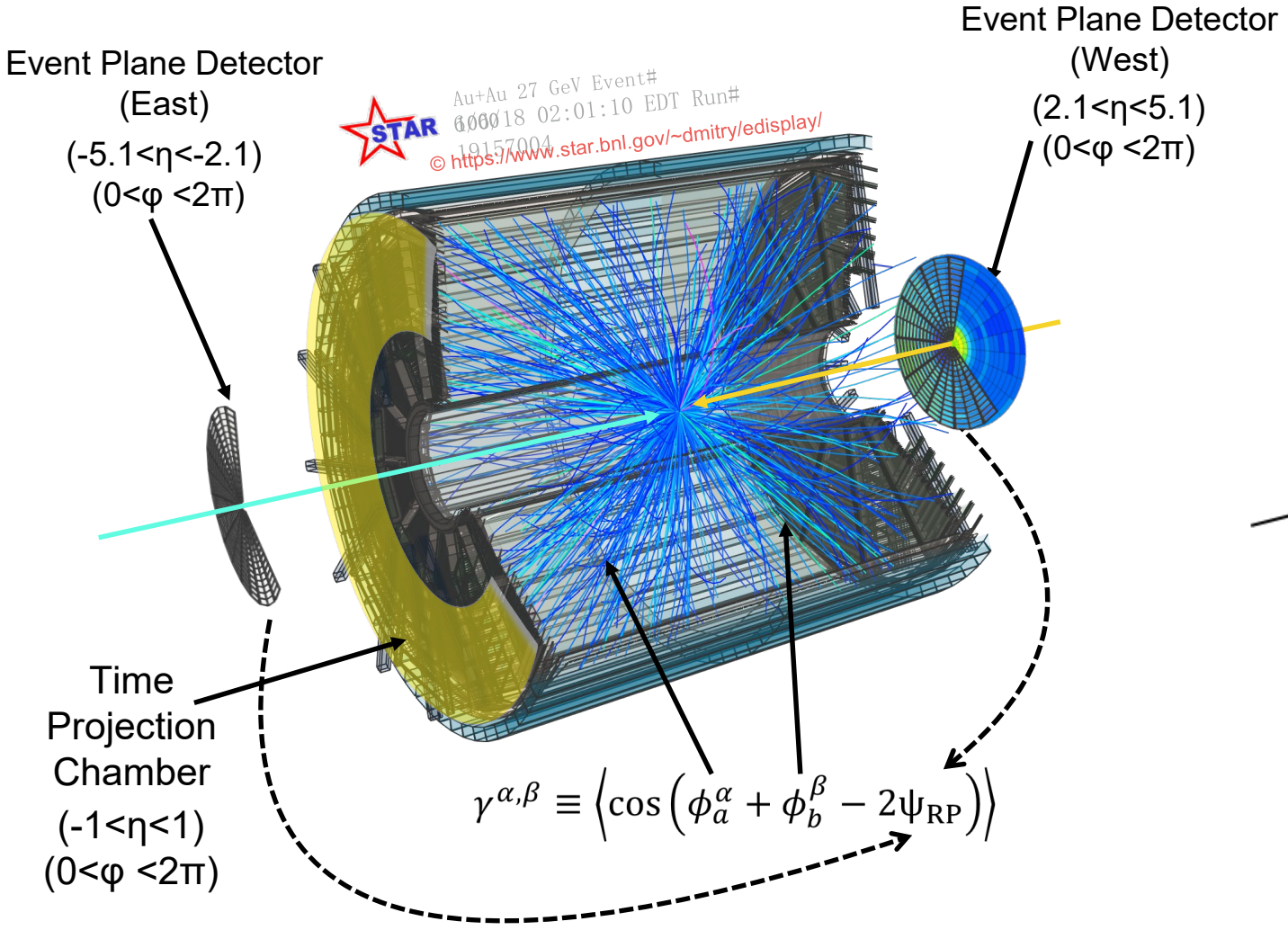
1) Test flow-induced background understanding – measure $\kappa^{112} = \frac{\Delta\gamma^{112} - \Delta\gamma^{112}_{ESS}}{v_2(\Delta\delta + \Delta\gamma^{112}_{ESS})}$ and $\kappa^{132} = \frac{\Delta\gamma^{132} - \Delta\gamma^{132}_{ESS}}{v_2(\Delta\delta + \Delta\gamma^{132}_{ESS})}$ at LHC

2) More analysis approaches sensitive to CME

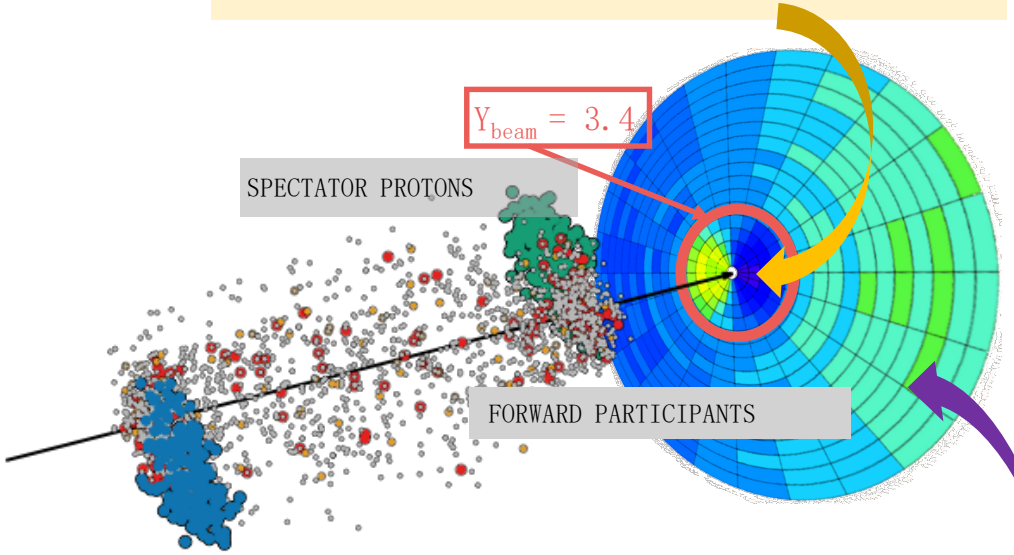
3) Find imprints of magnetic field effect and beam energy dependence

4) Chiral Magnetic Wave and Chiral Vortical Effect searches

Two Plane Method for CME Searches



ψ_1 ($\eta > Y_{beam}$): 1st-order event plane enriched with spectator protons



The inner region of EPD detects spectator protons, whose directed flow signal has an opposite direction compared to the outer sectors that are dominated by the participants.

ψ_2 ($\eta < Y_{beam}$): 2nd-order event plane for particles going in forward direction

We measure charge-dependent azimuthal correlator using TPC and EPD

Scaled γ correlator and double ratio

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

$$\Delta\gamma = \Delta\gamma^{BG} + \Delta\gamma^{CME}$$

If $\Delta\gamma^{BG} = b\, v_2$

$$\left(\frac{\Delta\gamma}{v_2}\right) = \frac{\langle\cos(\alpha + \beta - 2\Psi)\rangle}{\langle\cos(2a - 2\Psi)\rangle}$$

RP, PP, SP…

Under the background scenario, all these ratios equal one to another. If two different measurements yield different ratios, this would indicate the CME signal.

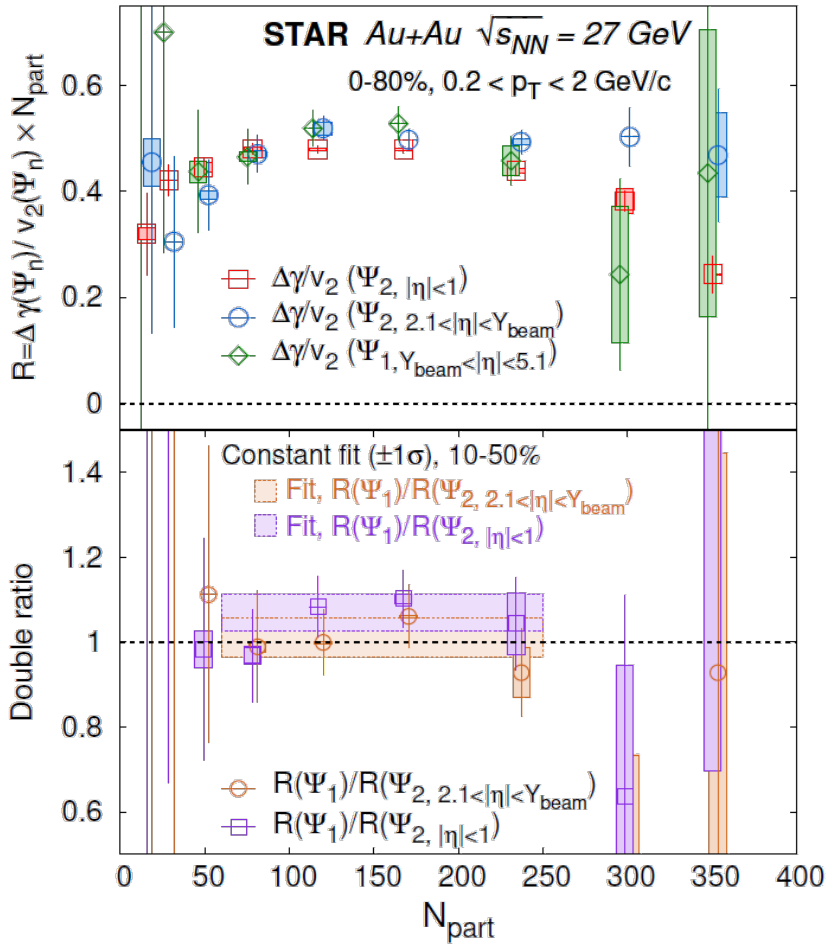
S. A. Voloshin, Phys. Rev. C 98 (2018) 054911

In a short word, under the background scenario, we should have:

$$\frac{\Delta\gamma}{v_2}(\Psi_A) = \frac{\Delta\gamma}{v_2}(\Psi_B) = \frac{\Delta\gamma}{v_2}(\Psi_C) = \cdots$$

Where the Ψ_A, Ψ_B, Ψ_C… are different planes

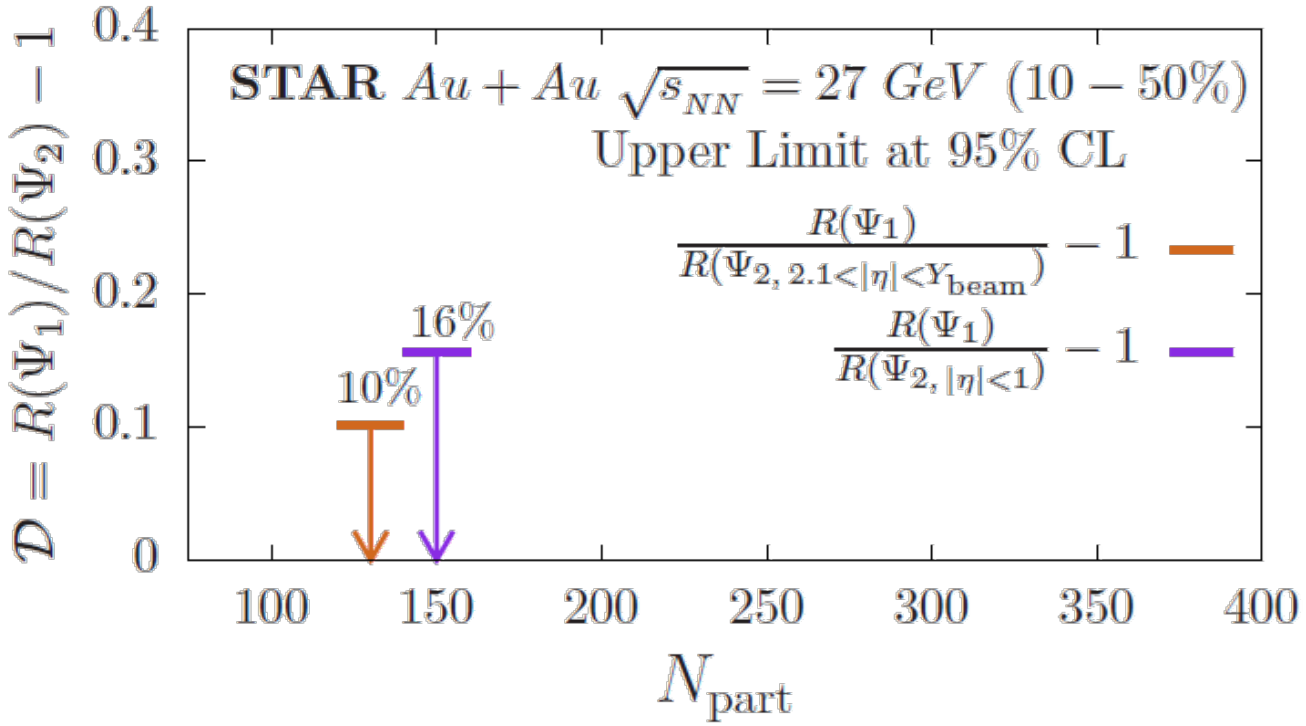
We measure the elliptic flow and the charge separation, using γ correlator (Δγ=γ(OS)-γ(SS)), w.r.to TPC-EPD-inner first harmonic planes and the TPC-EPD-outer second harmonic plane.



- CME driven correlations will make this ratio >1
- The results show the double ratios are consistent with unity

The observed difference is not statistically significant

STAR Collaboration, PLB 839, 13777 (2023)



In 10-50% centrality we find the upper limits of $\mathcal{D}$ to be 10% and 16% using Ψ_2 at forward and mid-rapidity, respectively.

Conservative approach, says nothing about CME !

Two Plane Method for Quantitative CME Estimate

To derive quantitative CME estimate one needs to know non-flow contributions to v2 and three particle correlations !

The devil is in the details !

1) Estimate non-flow contributions from small systems !

2) Estimate non-flow contributions to two particle and three particle correlations from theoretical models !

- **HIJING**
- **AMPT**
- **AVFD**

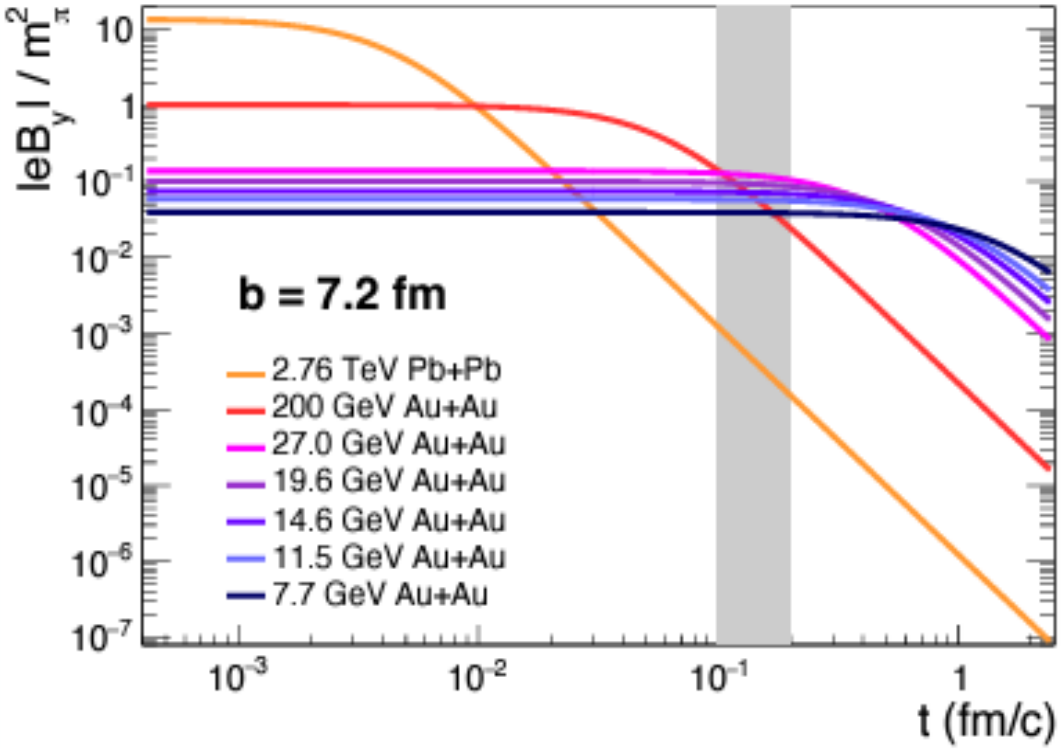
NONE is satisfactory and fully justified !!

The procedure depends on model-based correction parameters – totally changes the analysis output if different model is used !!

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 !!

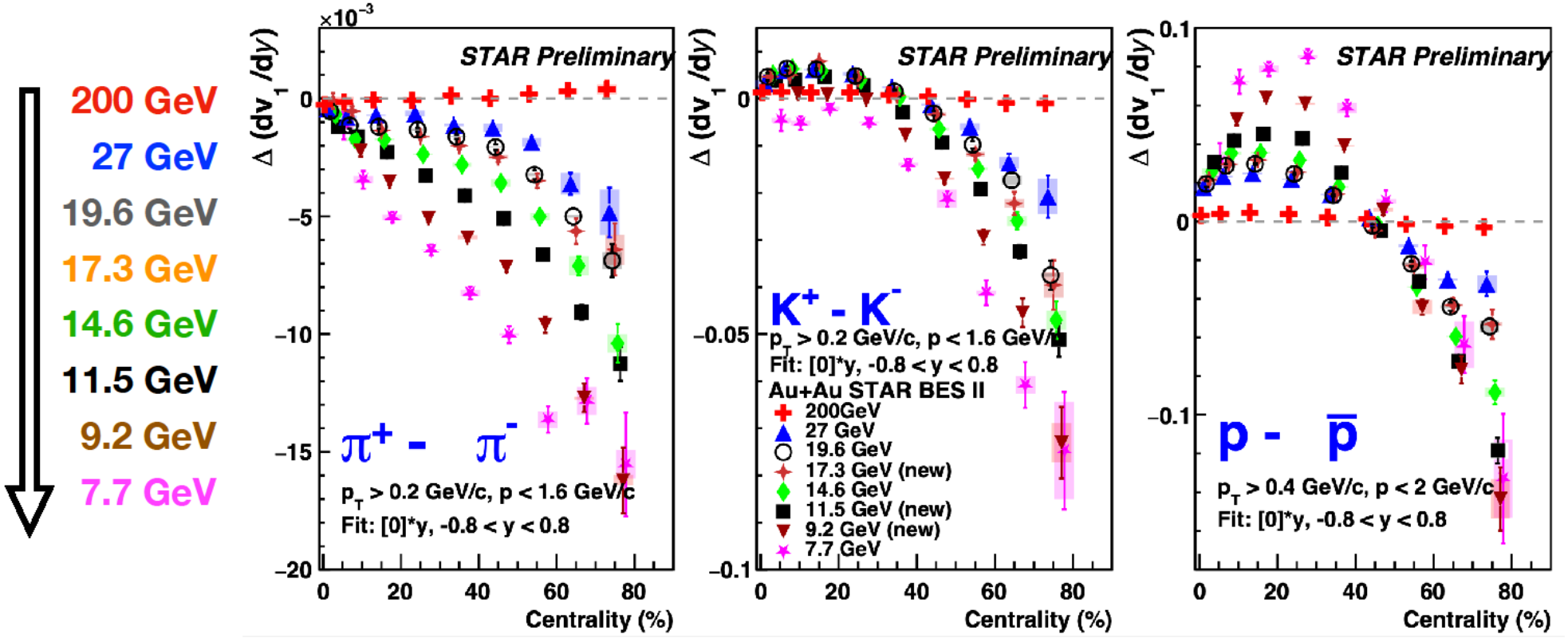


How do we understand these phenomena ?

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

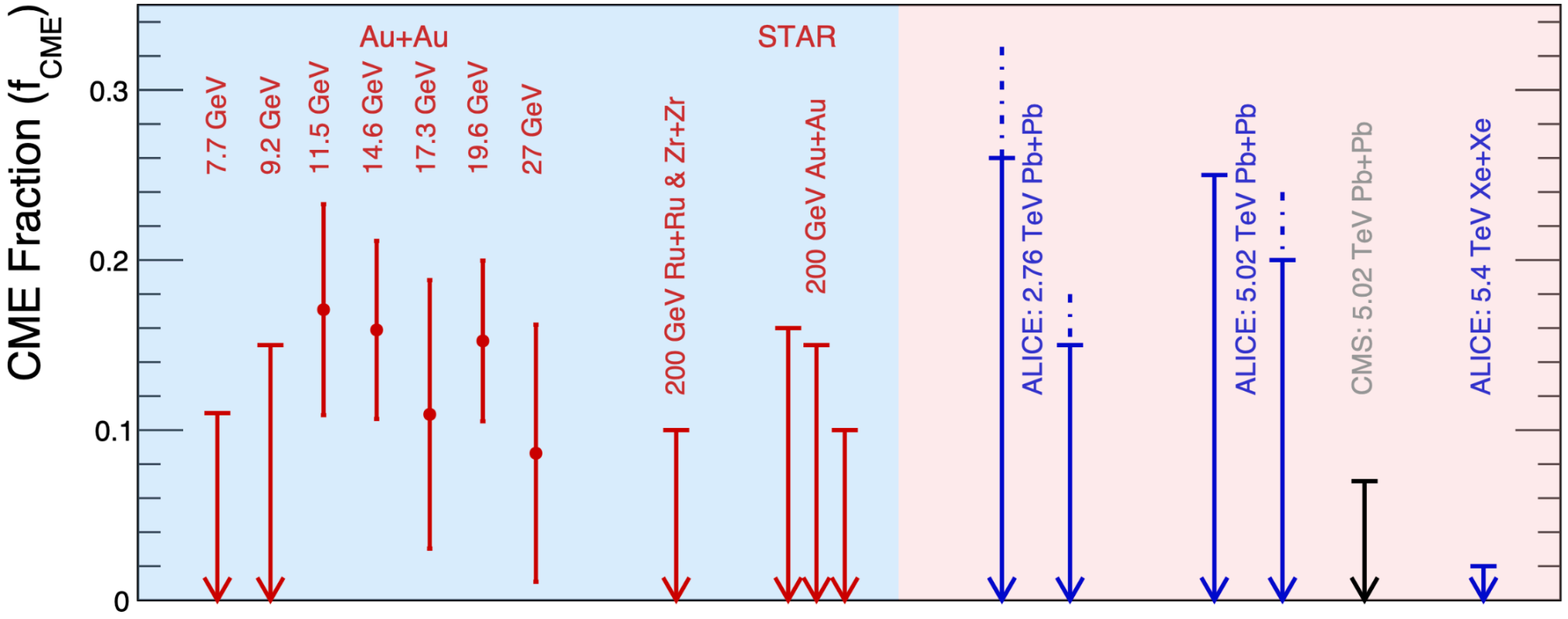
& the $v_2\delta$ background correlation !

Experimental Imprints of Magnetic Fields



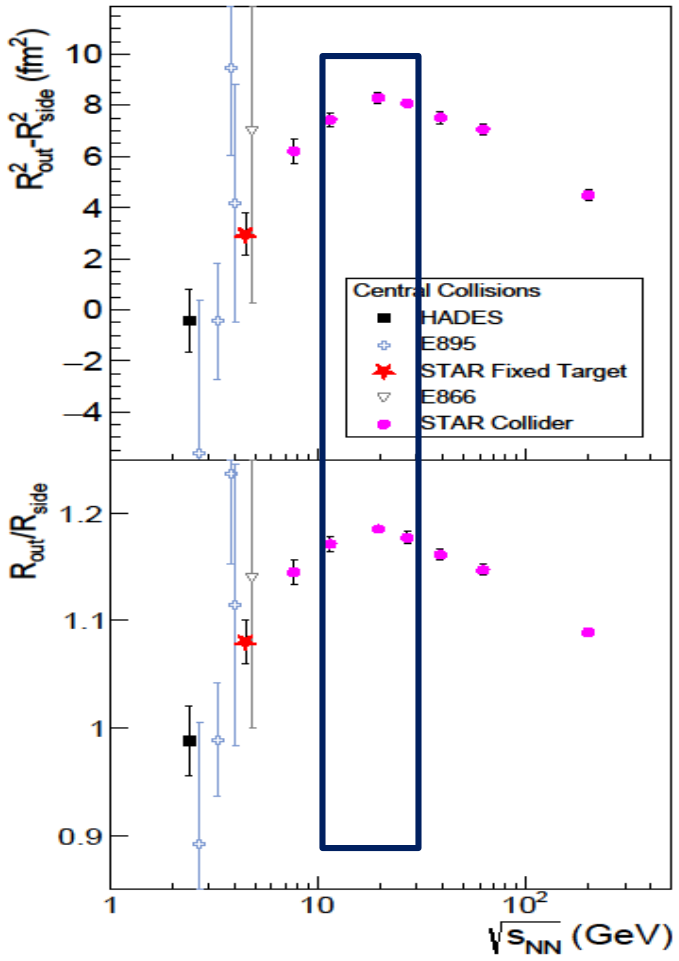
- At lower energy, the v_1 splitting also supports magnetic field picture.
- Indicate EM effects are significantly stronger at lower energy.

Where more progresses can be made?

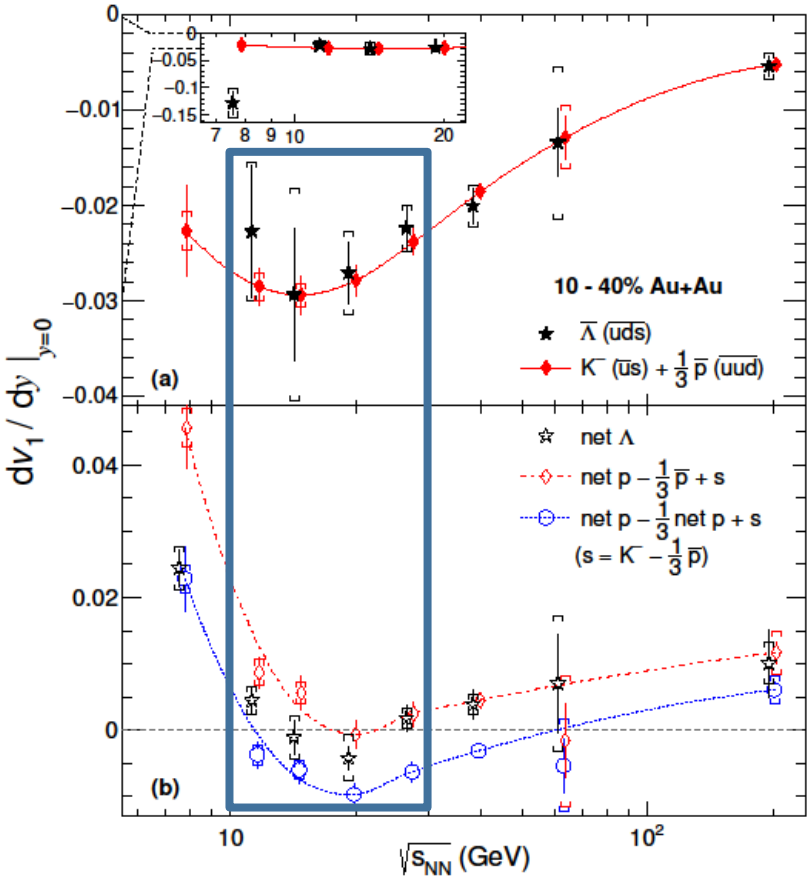


What so Special for Collisions at 10-30 GeV

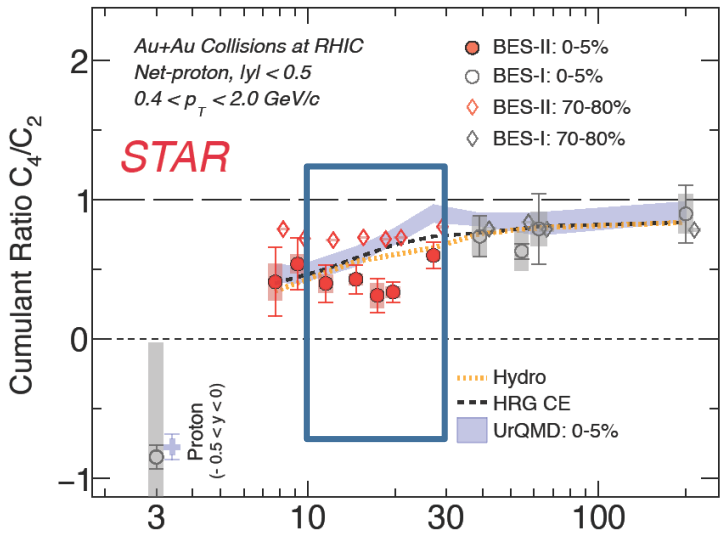
HBT Rout/Rside

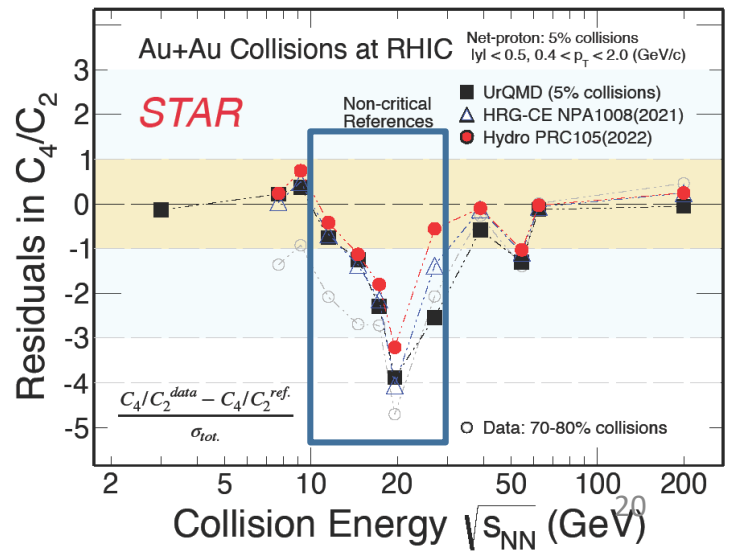


v_1 slope dv_1/dy



Critical Point: C_4/C_2





Future of Experimental CME Searches

Improve understanding background contributions !

Improve CME search approach and more innovative analysis approaches !

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 !

Understanding important physics message in the beam energy dependence !

Theoretical insights !

Thank You !