CELEBRATING NEW BEGINNINGS AT RHIC and EIC
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Overview of Chiral Magnetic Effect from RHIC Beam Energy Scan program

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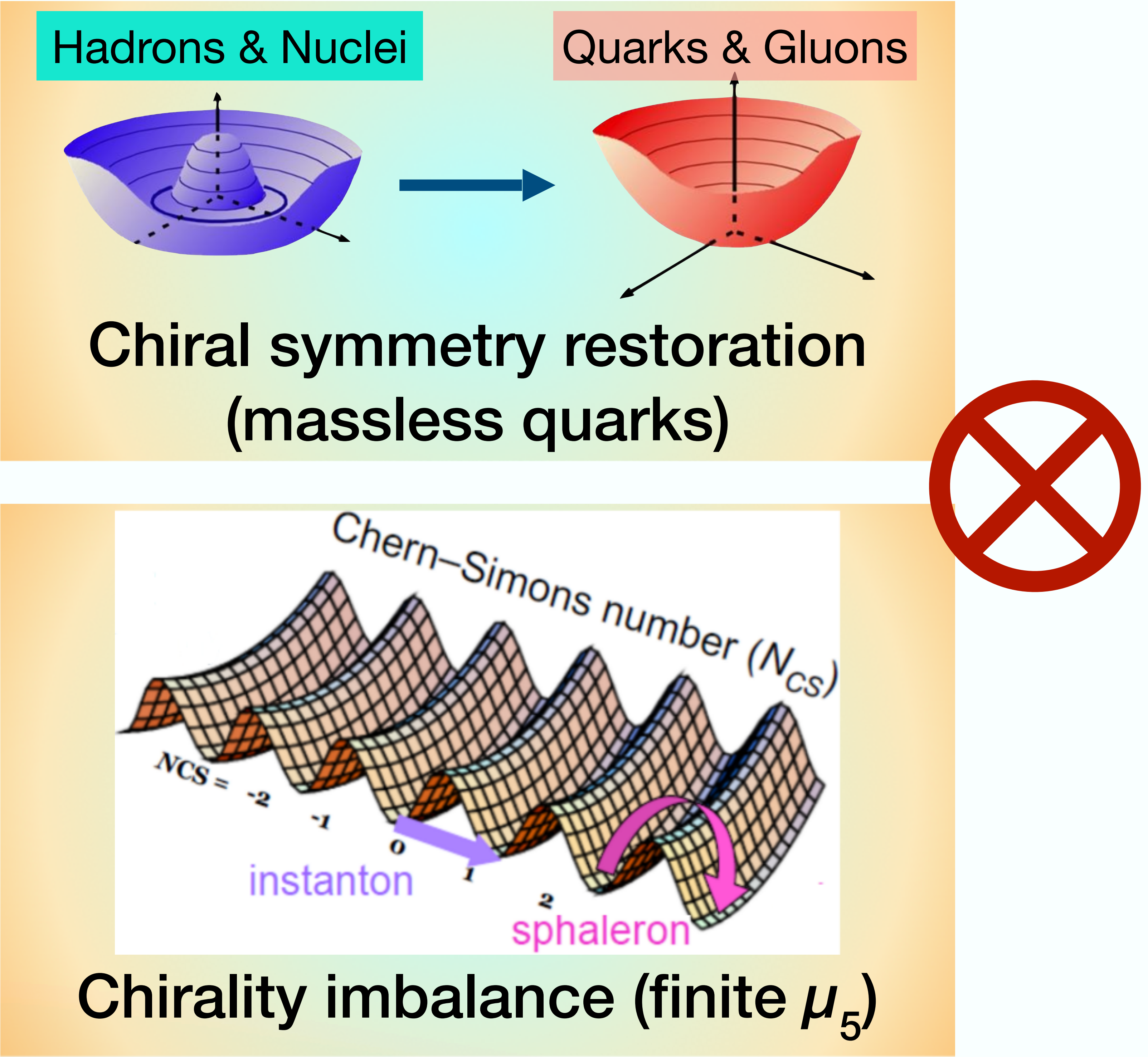
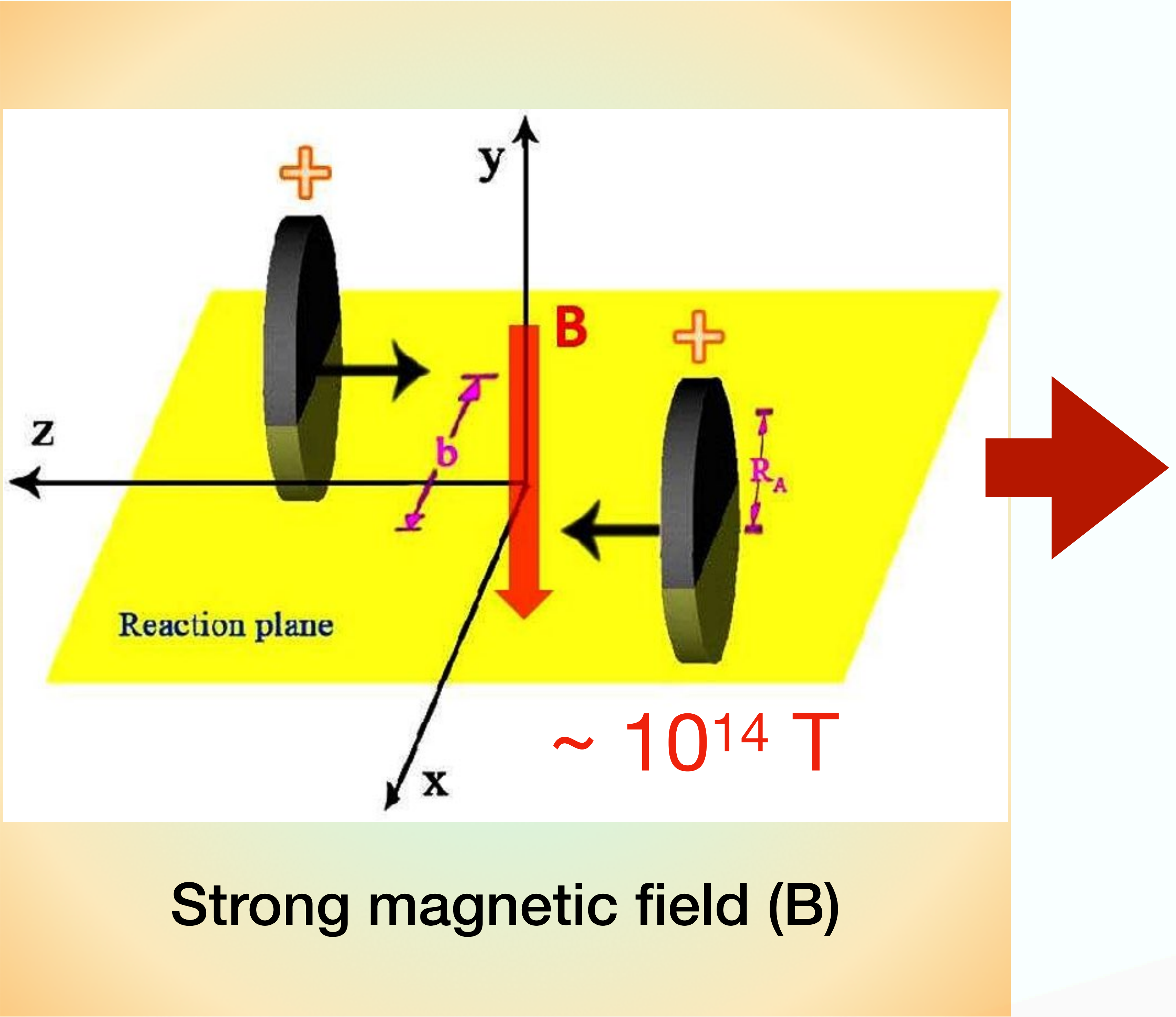
Aug 2, 2023

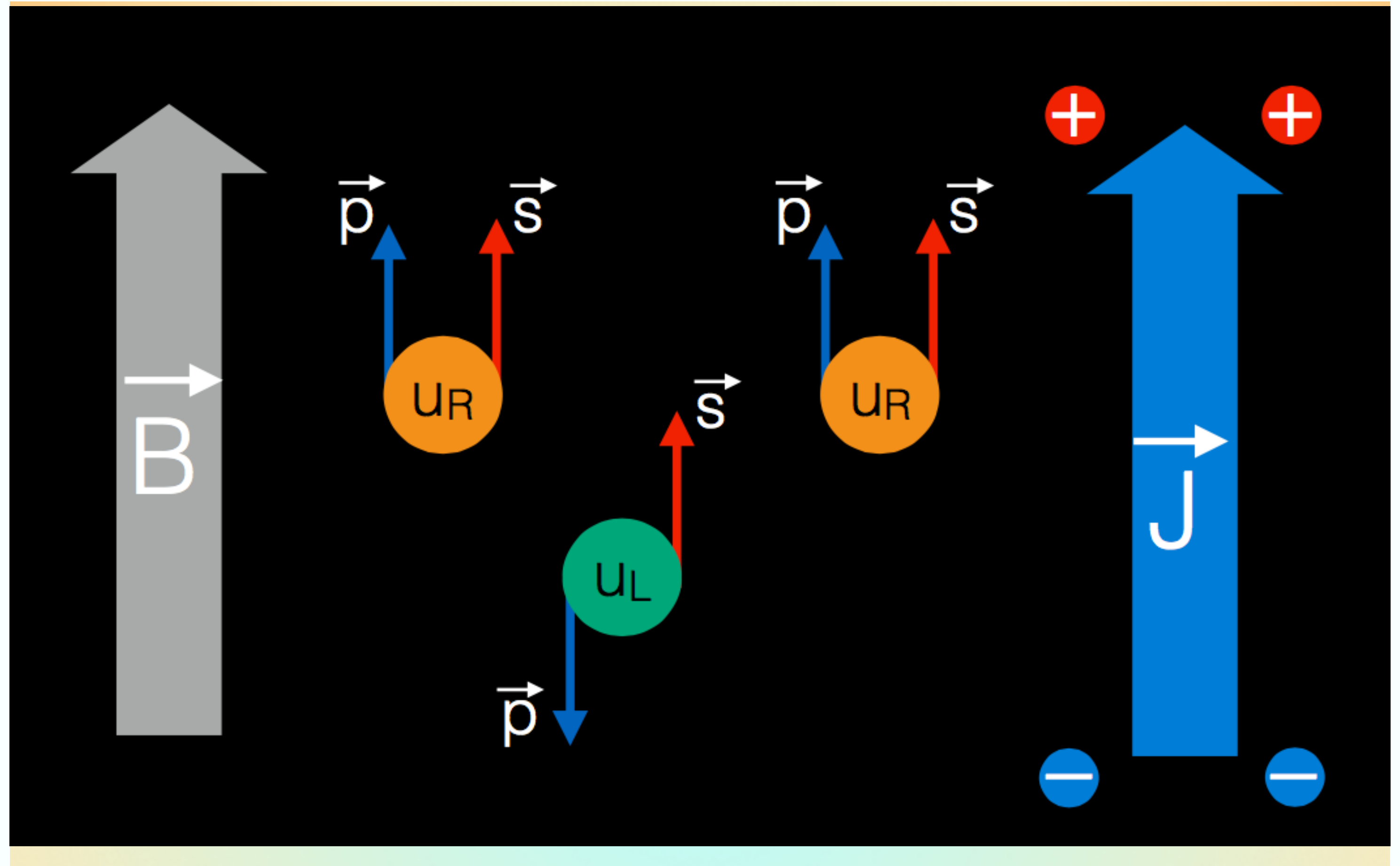
Thanks to the STAR CME focus group and many collaborators for discussions and insights!

Chiral Magnetic Effect

Kharzeev, Pisarski, Tytgat, PRL 81(1998) 512
Voloshin, PRC 70 (2004) 057901





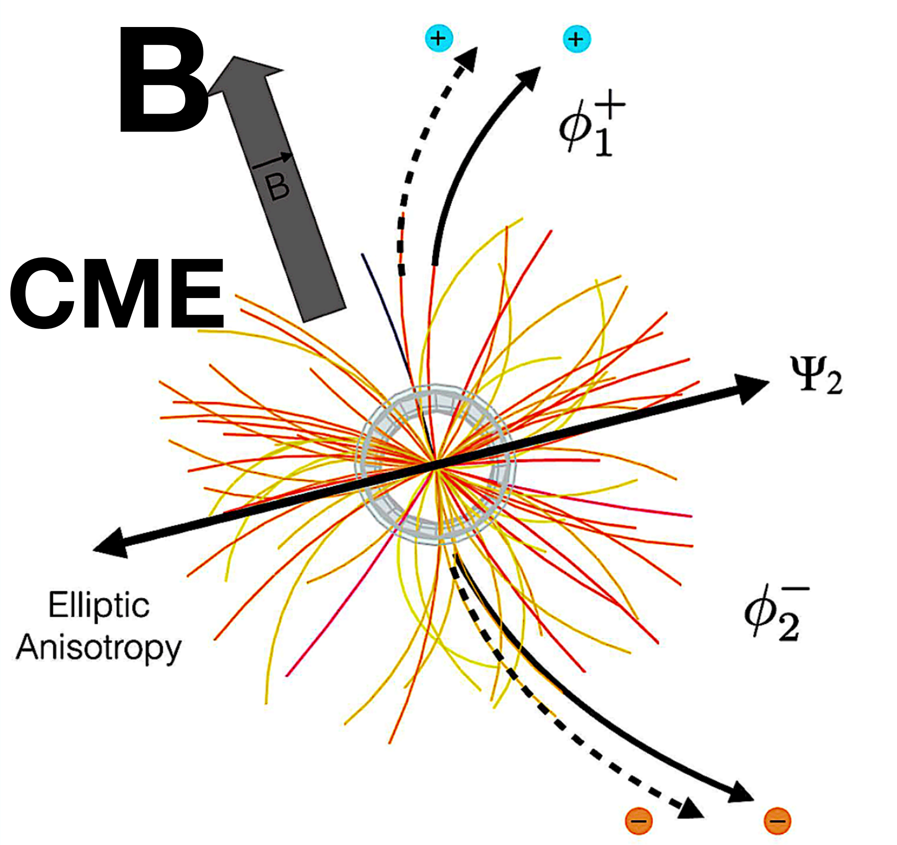


$$\vec{J} = \frac{e^2}{2\pi^2}\mu_5\vec{B}$$

- **QCD vacuum transition leads to nonzero topological charge.**
- **Chirality imbalance of quarks coupled with strong magnetic field induces an electric charge separation along the B field direction (violates local Parity Symmetry and CP Symmetry!)**

CME Observables

Chin. Phy. C 46 014101 (2022)
A. Bzdak, et.al, Euro. Phys. J. A 52 265 (2016)

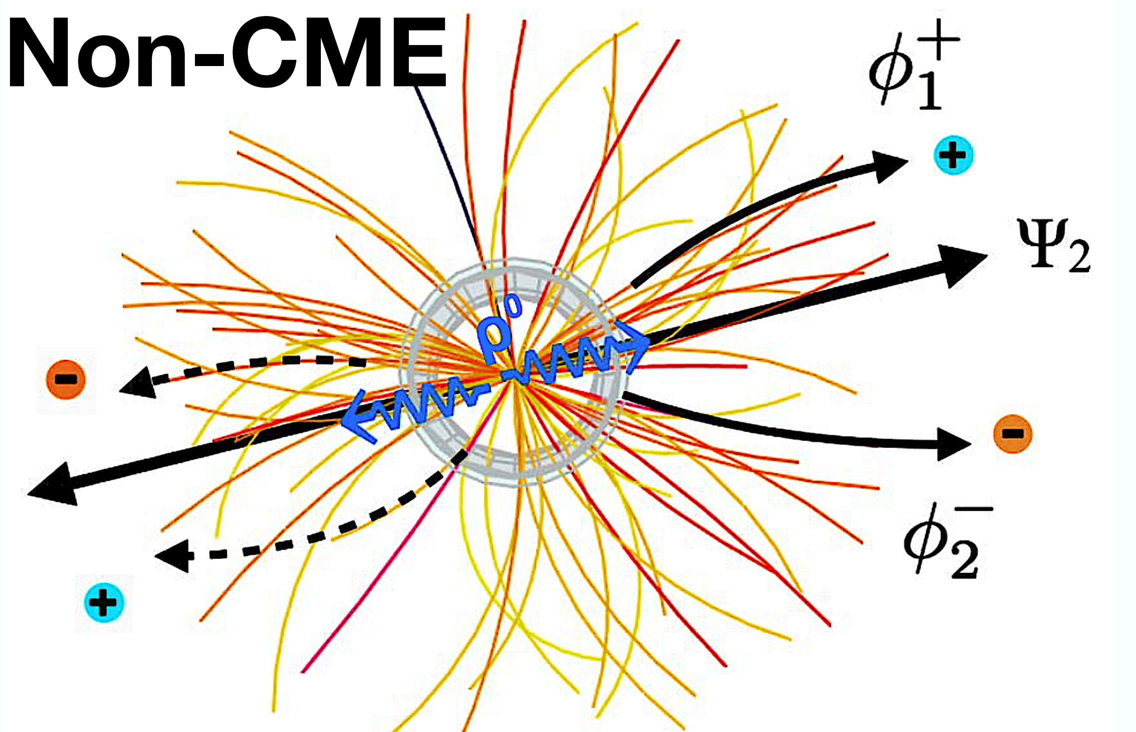


$$\frac{dN_\pm}{d\phi} \propto 1 + 2v_1\cos(\phi - \Psi_{RP}) + 2a_1^\pm \sin(\phi - \Psi_{RP}) + 2v_2\cos(2\phi - 2\Psi_{RP}) + \ldots$$

$\propto \mu_5 |\vec{B}|$

Parity Odd, can not directly observe

Parity Even, sensitive to charge separation



Flowing resonance decay

Common observables:

- **γ^{112} correlator**
  S.A. Voloshin, Phys. Rev. C,70, 057901 (2004)
- **R correlator**
  N. N. Ajitanand *et al.*, Phys. Rev. C83, 011901(R) (2011)
- **Signed balance functions**
  A.H. Tang, Chin. Phys. C,44, No.5 054101 (2020)

Core components of them are equivalent.

Here we focus on:

$$\gamma^{112} = \langle\cos(\phi_1 + \phi_2 - 2\psi_{RP})\rangle = \langle v_1 v_1\rangle - \langle a_1 a_1\rangle + \mathrm{BG}(v_2^{cl})$$

CME signal: $\Delta\gamma^{CME} = \gamma^{OS} - \gamma^{SS} > 0$

Variants of γ^{112} : To suppress $\Delta\gamma^{res} \propto v_2\delta > 0$

$\delta = \langle\cos(\varphi_1 - \varphi_2)\rangle$

- **H correlator**

$$H^k = (kv_2\delta - \gamma)/(1 + kv_2) \quad k = 1,\ 1.5\ \ldots$$

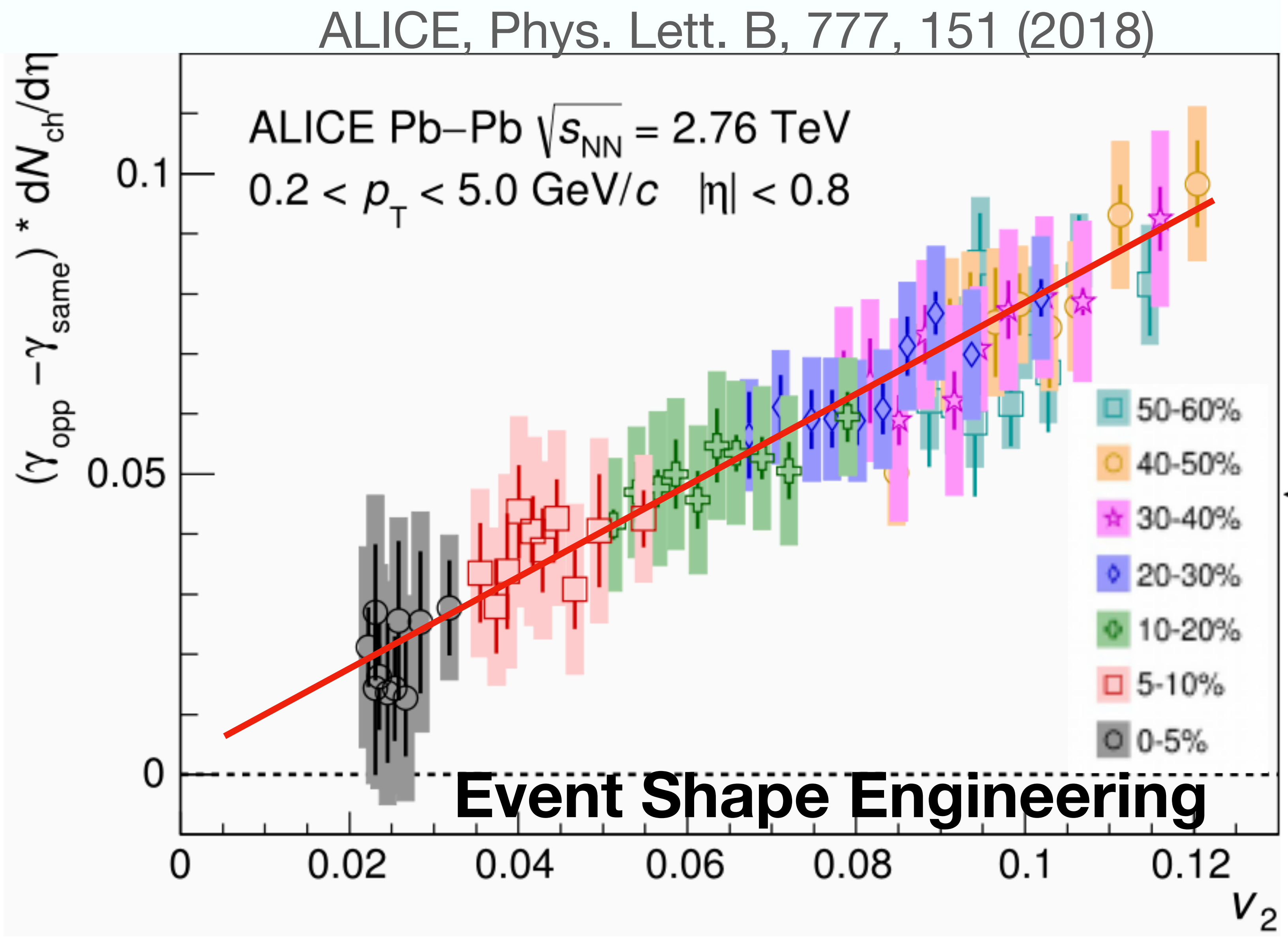
- **κ^{112} correlator**

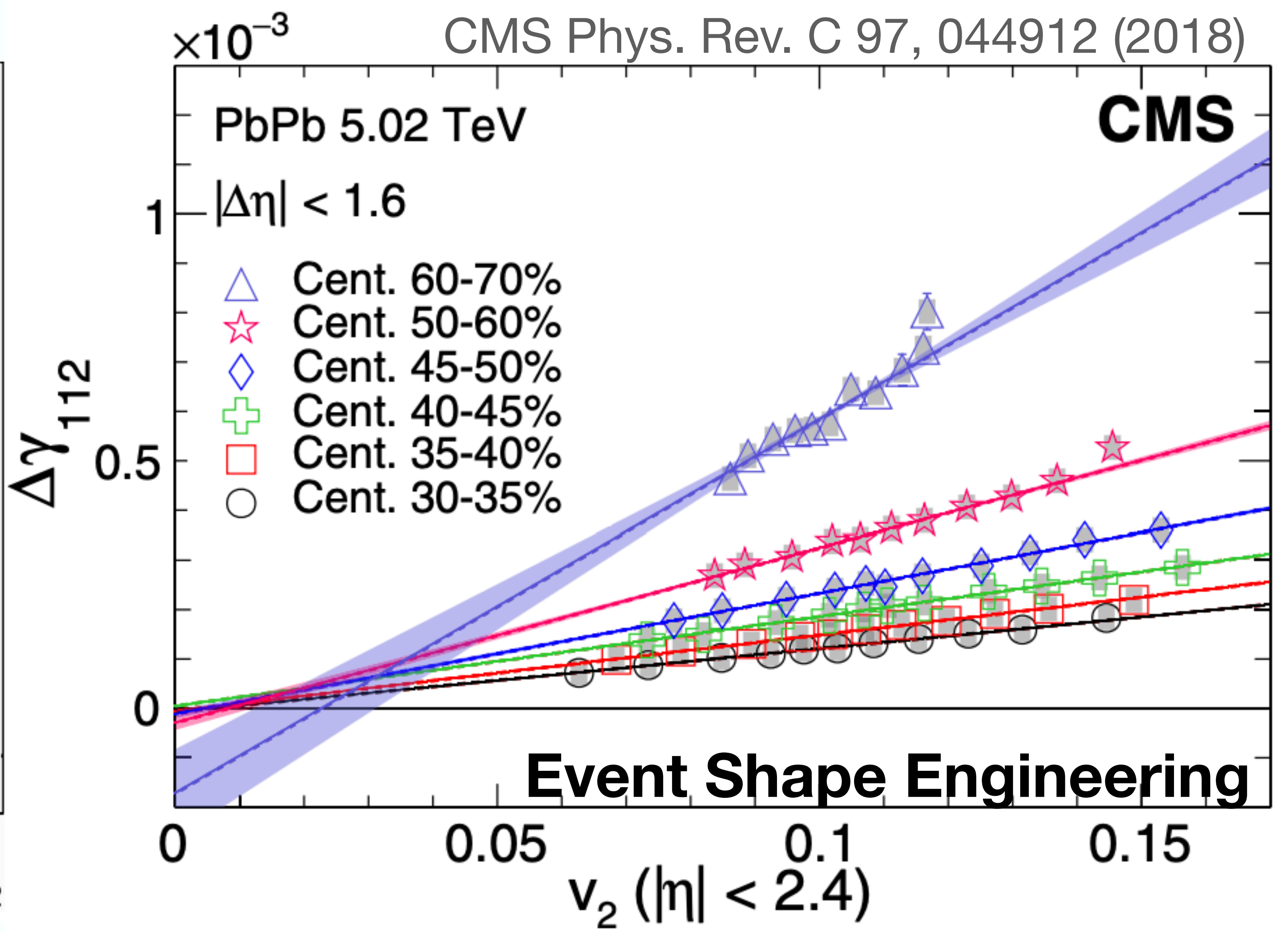
$$\kappa^{112} = \frac{\Delta\gamma^{112}}{v_2\Delta\delta}$$

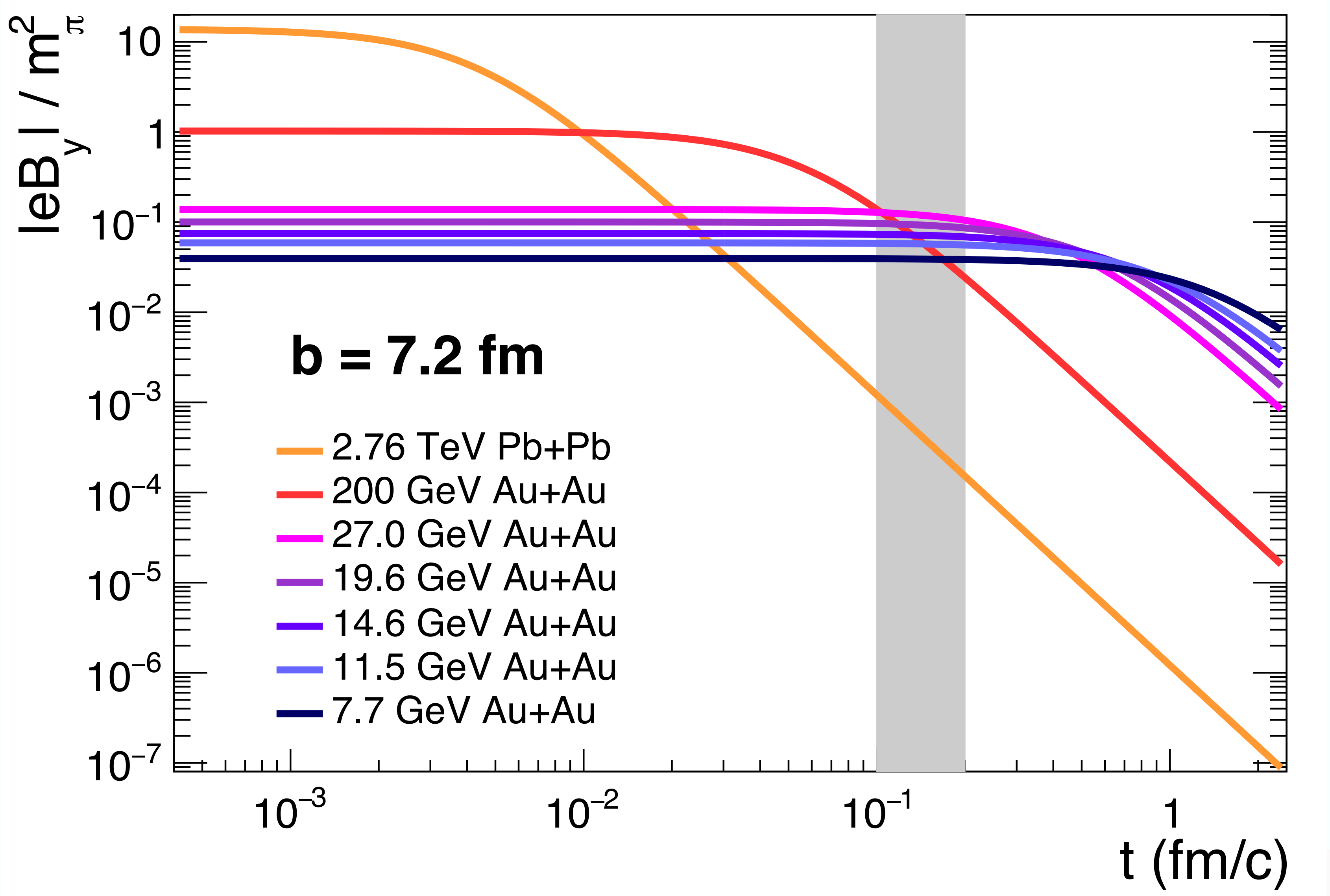
More Methods:

Participant Plane vs Spectator Plane,
Covariance between variables,
Event Shape Selection (Engineering), M_{inv} …

Why search CME in Beam Energy Scan?





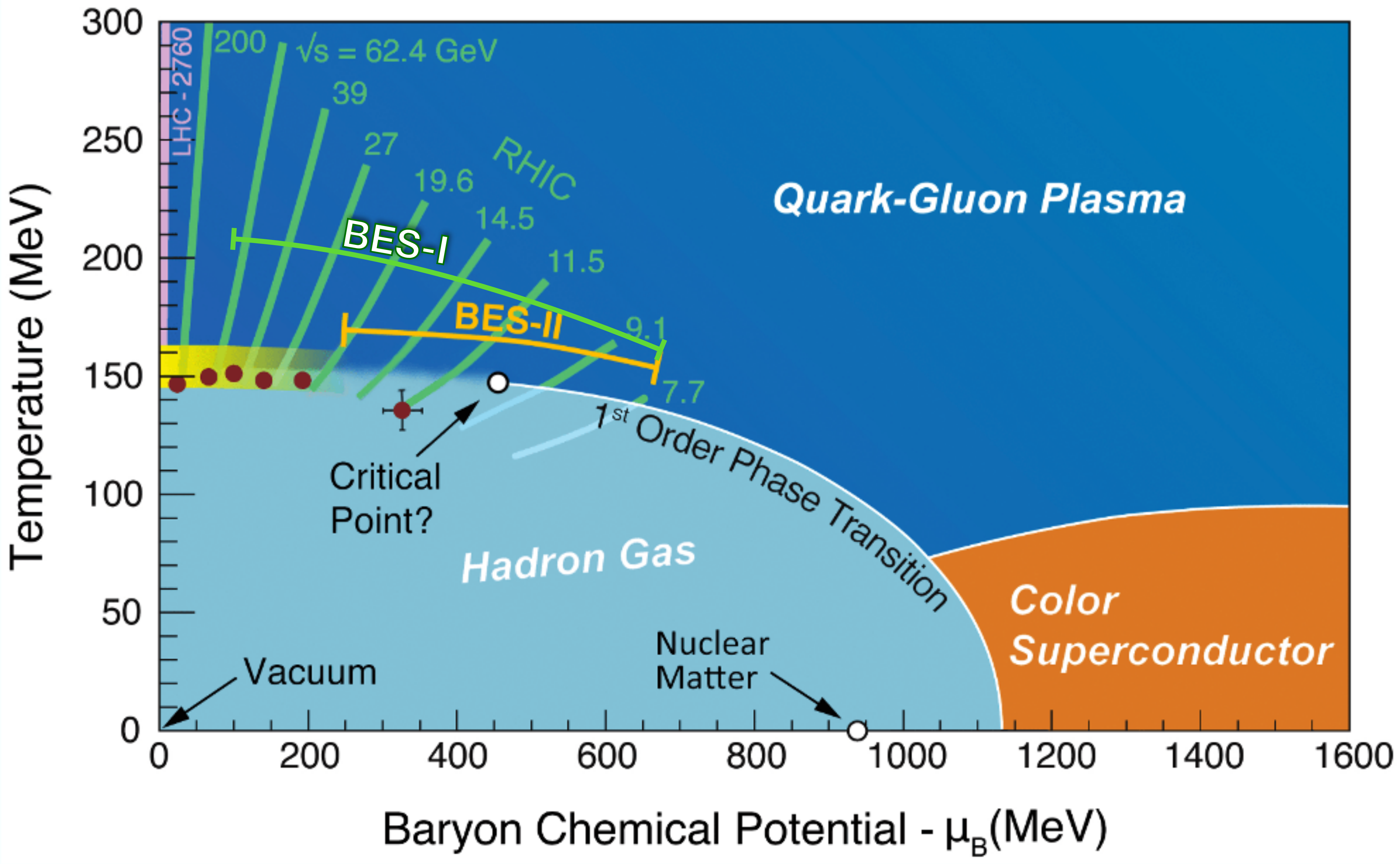


- **At LHC energies, $\Delta\gamma^{112}$ could be explained by v_2 related BKG.**
- **ESE based on variables excluding POI is unstable.**
- **We should focus on lower energy. Advantage: longer lasting B.**
- **Possible to see the turn-off effect near 7.7 GeV (where QGP is about to vanish!)**

Beam Energy Scan at RHIC

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

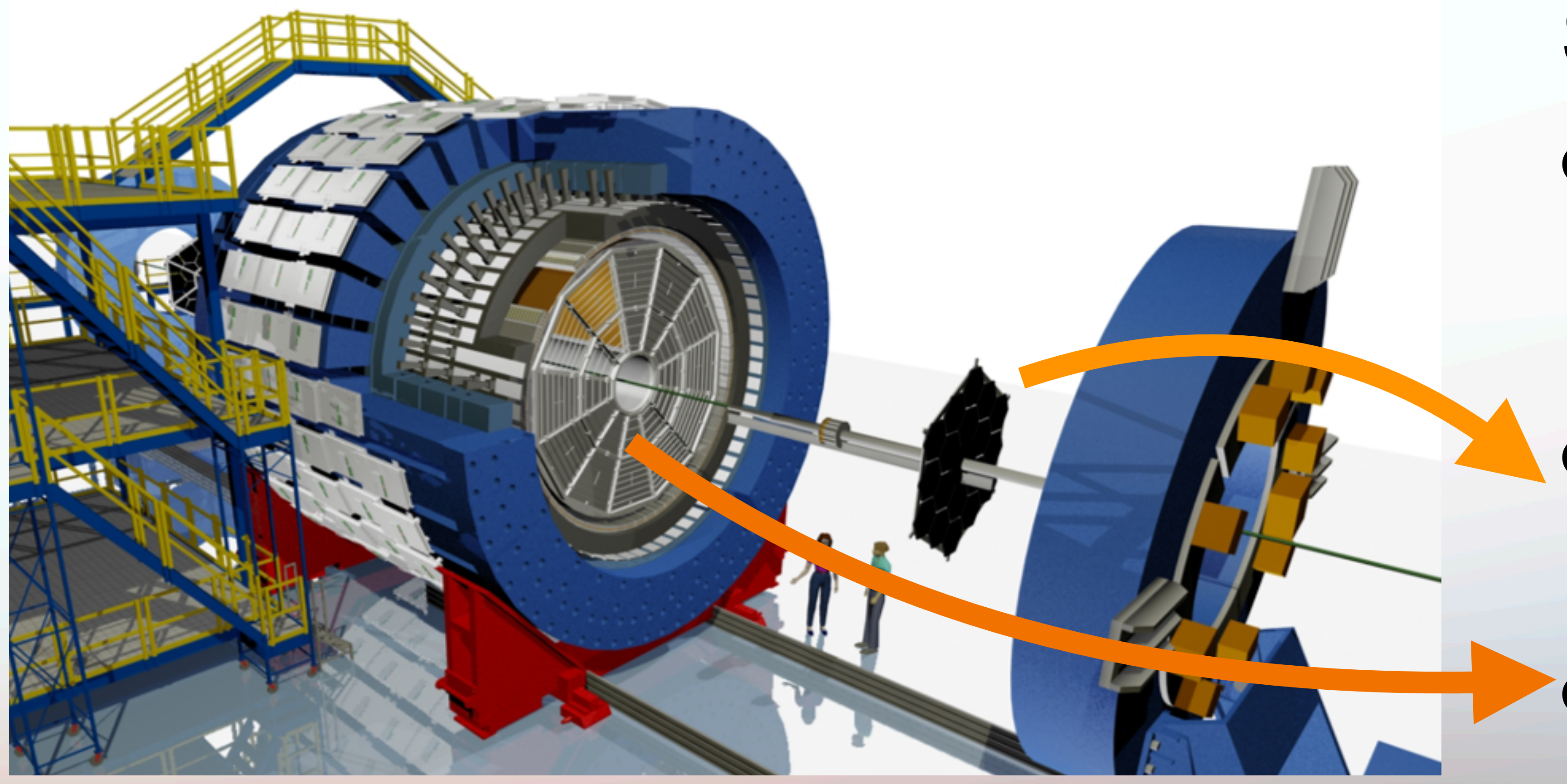
$\sqrt{S_{NN}}$(GeV)	Events (10^6)	Year
27	560	2018
19.6	538	2019
14.5	325	2019
11.5	230	2020
9.2	160	2020
7.7	100	2021

Publication on CME

BES-I: STAR, PRL 113 (2014) 052302

BES-II: STAR, PLB 839 (2023) 137779

STAR, PRC 108 (2023), 014909



Statistics:

- 20 times higher

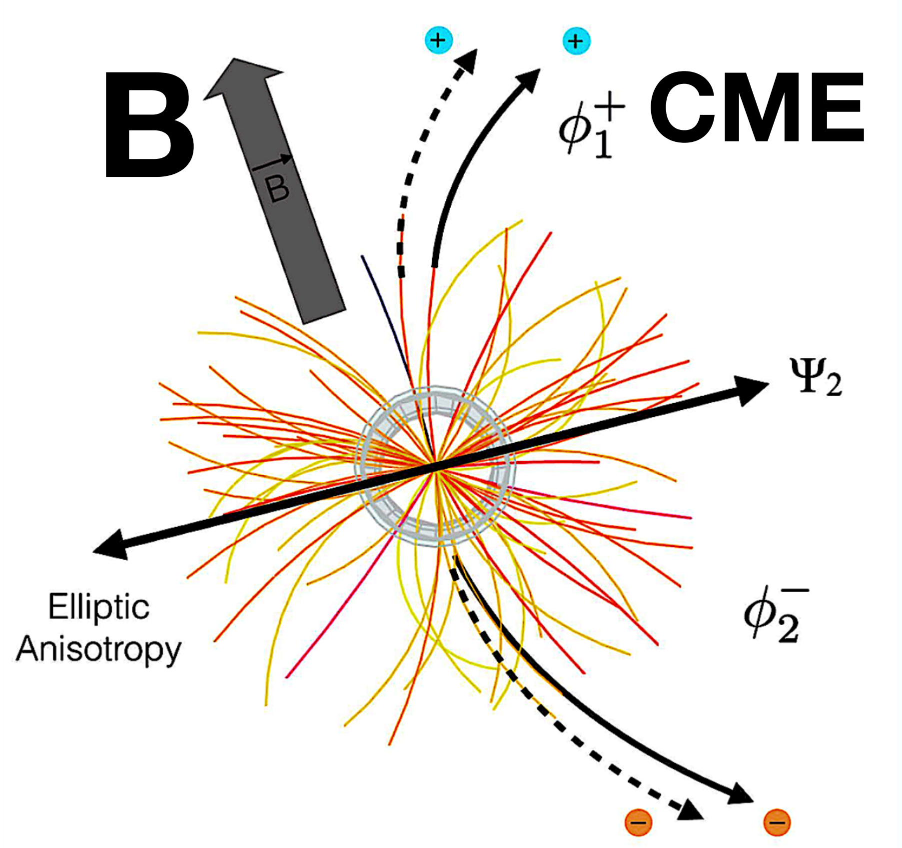
Detector Upgrades:

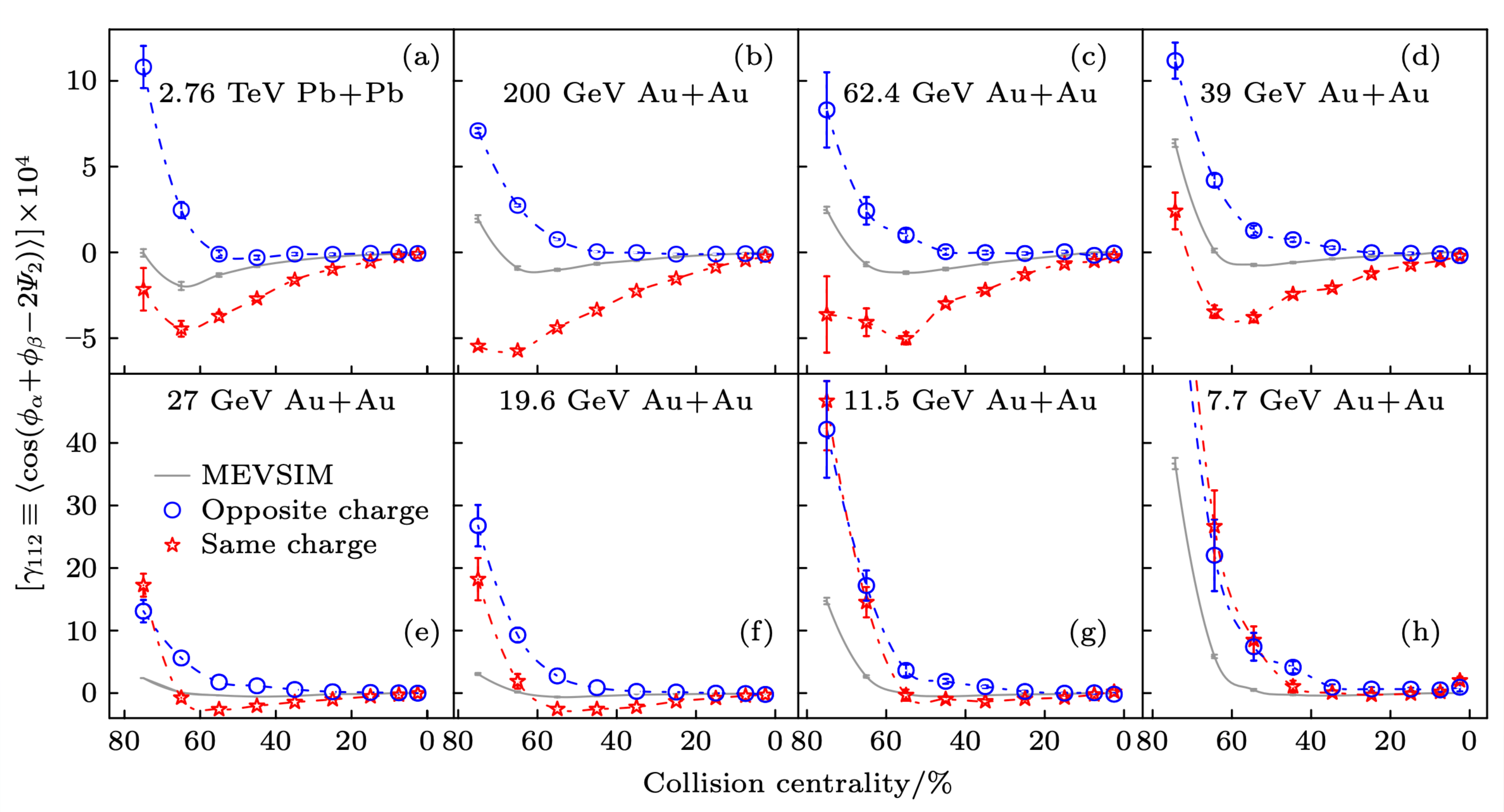
- 2018 EPD : high EP resolution into spectator region (2.1<η<5.1)
- 2019 iTPC: wider acceptance

Beam Energy Scan I

ALICE, Phys. Rev. Lett. 110, 012301 (2013)

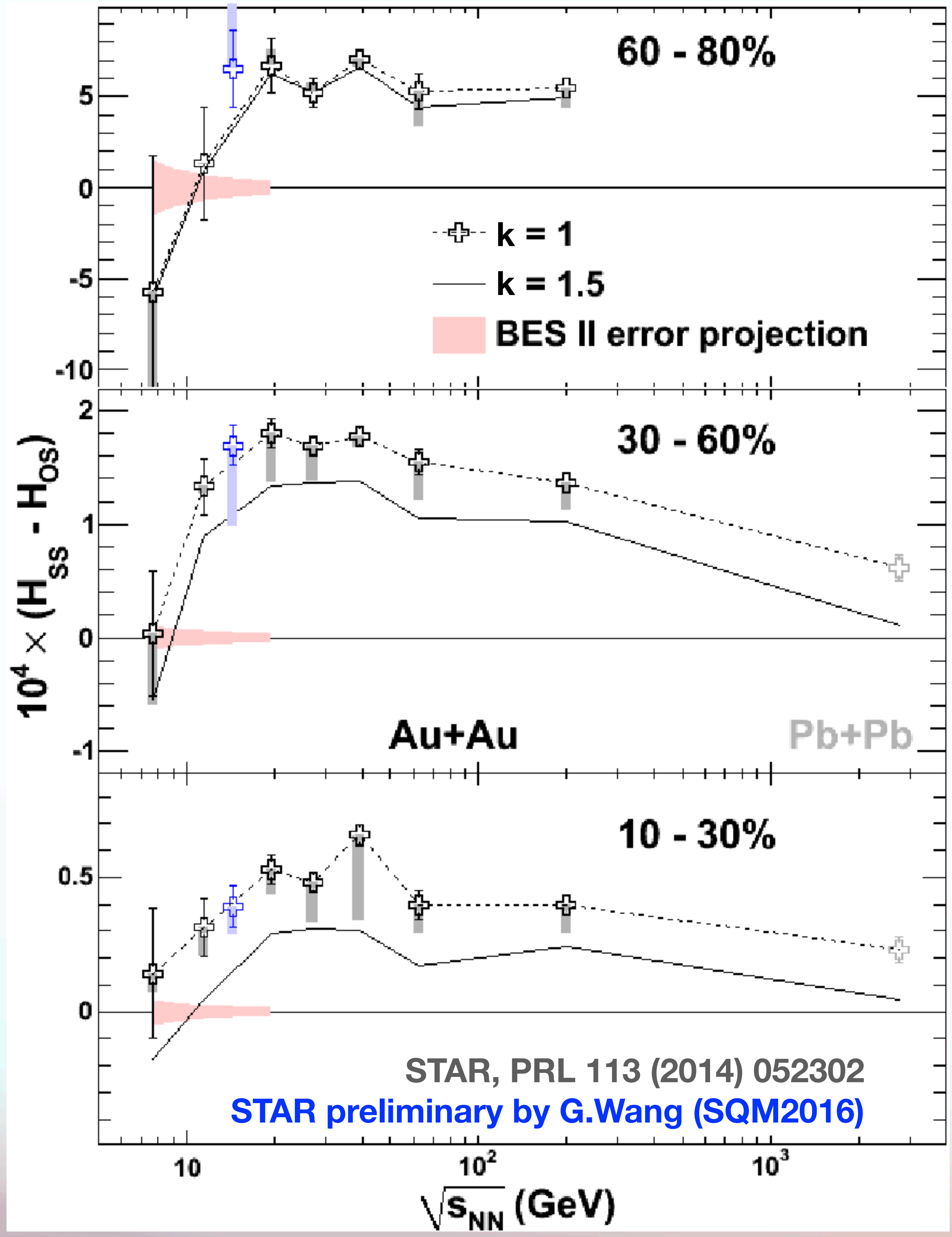
STAR, PRL 113 (2014) 052302





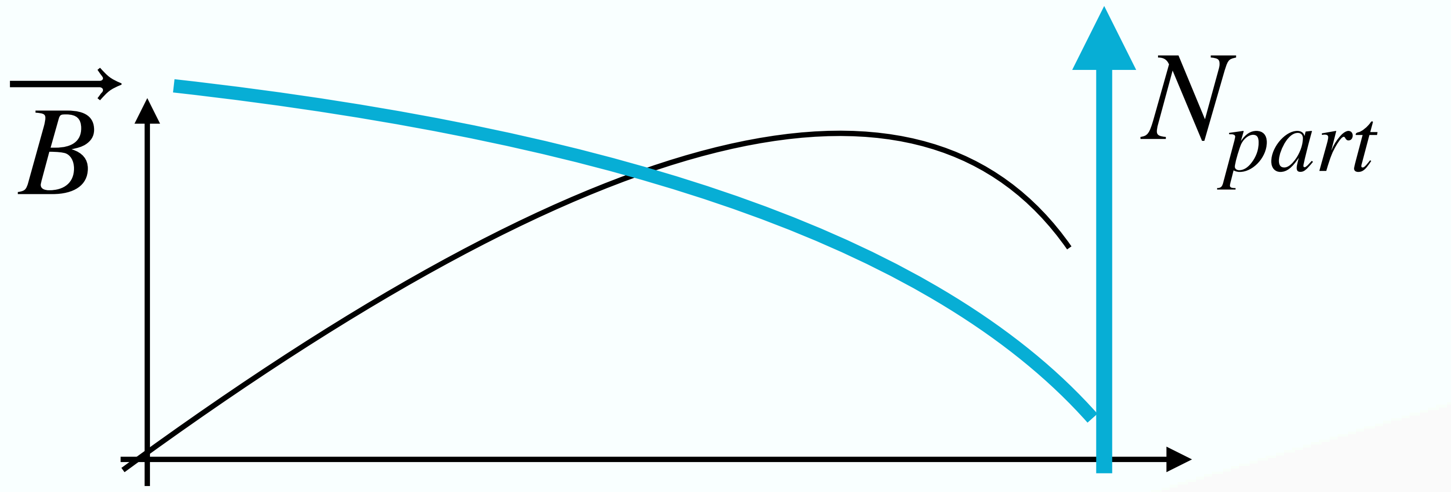
- Common BKG in γ^{OS} and γ^{SS} could be subtracted by $\Delta\gamma$
- In mid-central collisions, a finite charge separation is observed.
- However, $\Delta\gamma^{112}$ contains BKG contribution related to flow and nonflow.

Beam Energy Scan I



$$H^k = (kv_2\delta - \gamma)/(1 + kv_2) \quad k = 1,\ 1.5\ \ldots$$

- **ΔH disappears at the lowest and highest energies.**
- **The vanishing ΔH at 7.7 GeV indicates the domination of hadronic interactions over partonic ones.**
- **The B field may decay too fast at 2.76 TeV.**



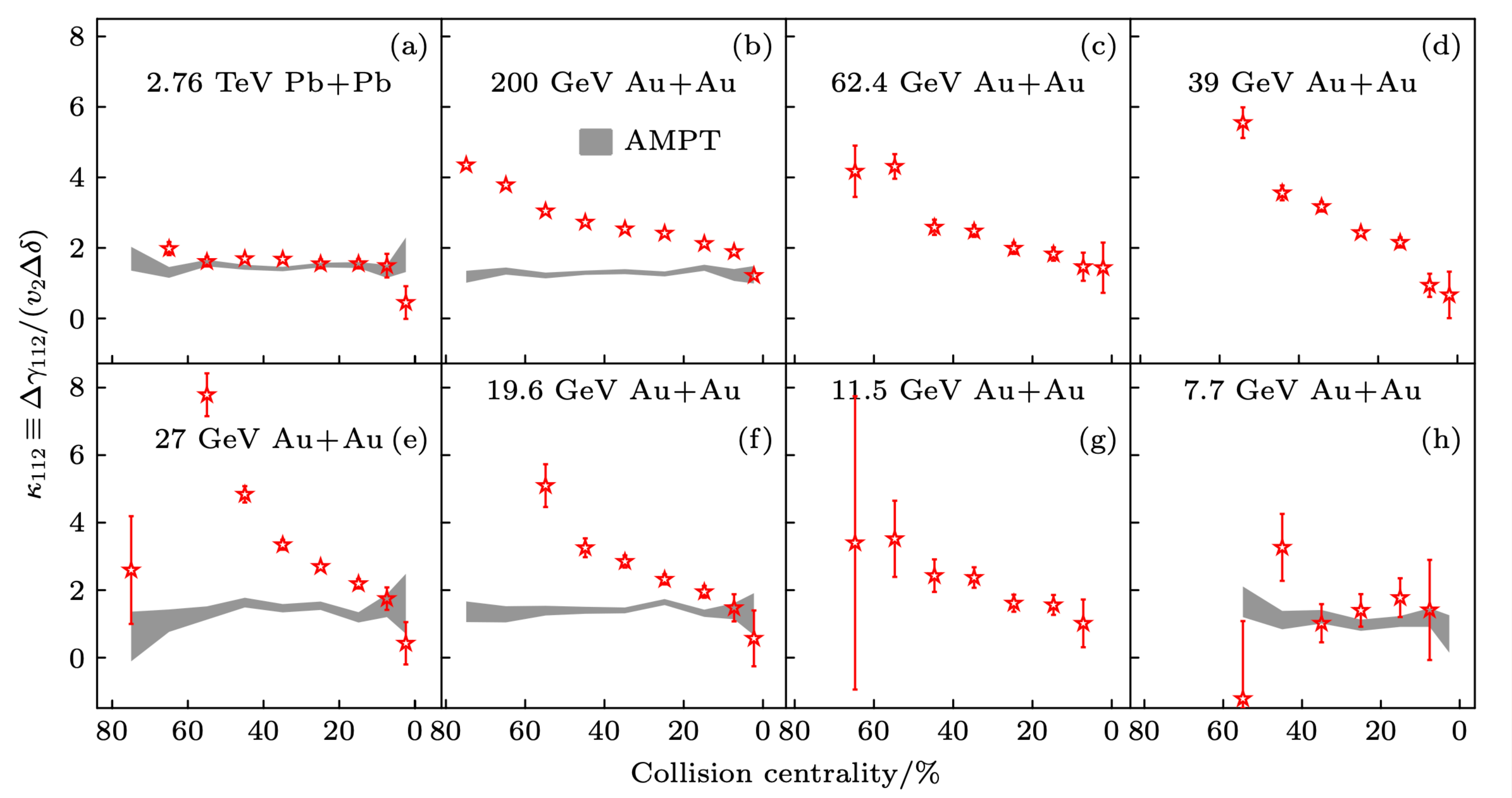
- **Mid-central collisions are preferred.**
  - **B field stronger than central events**
  - **More robust against nonflow ~ 1/N**

Beam Energy Scan I

ALICE, Phys. Rev. Lett. 110, 012301 (2013)
STAR, PRL 113 (2014) 052302
Acta Phys. Sin., 2023, 72(11): 112504.

$$\kappa^{112} = \frac{\Delta\gamma^{112}}{v_2 \Delta\delta}$$

Normalized observable κ^{112} allows better comparison between data and pure BKG model.



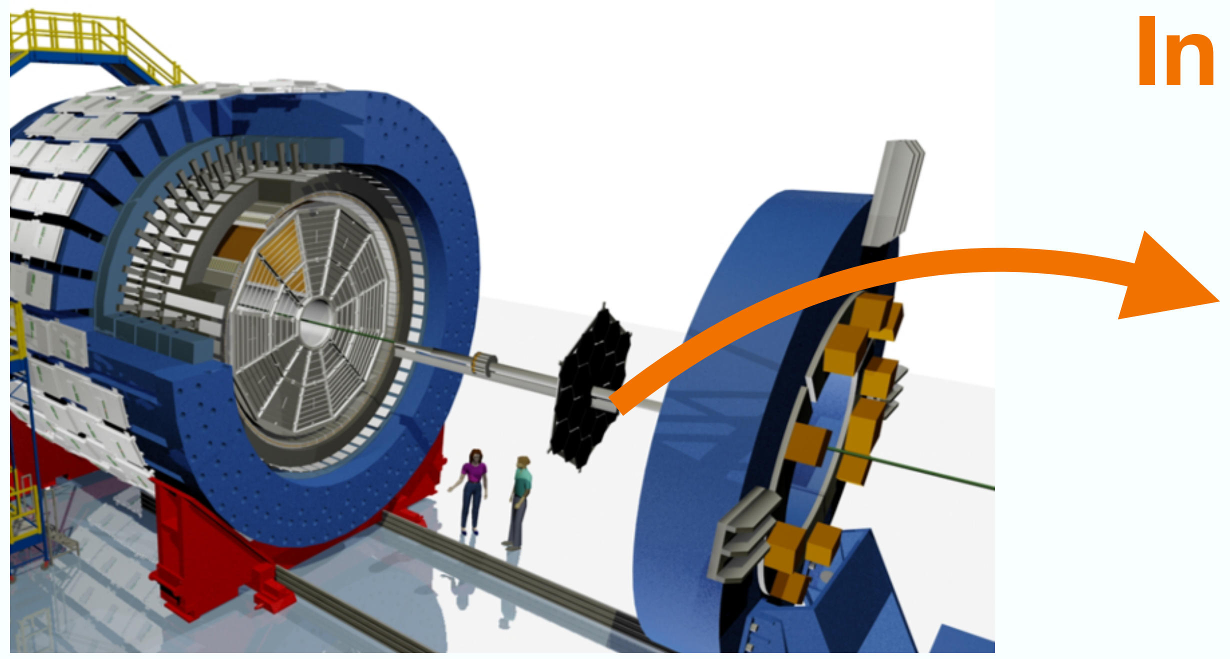
- **κ^{112} at highest and lowest energies are consistent with BKG prediction from AMPT.**
- **Nonflow in peripheral region may cause the enhancement of κ^{112}.**

The Lesson and Challenge from BES-I

	Beam rapidity	Year
27	3.36	2018
19.6	3.04	2019
14.5	2.75	2019
11.5	2.51	2020
9.2	2.28	2020
7.7	2.11	2021

In BES-I, we learned:

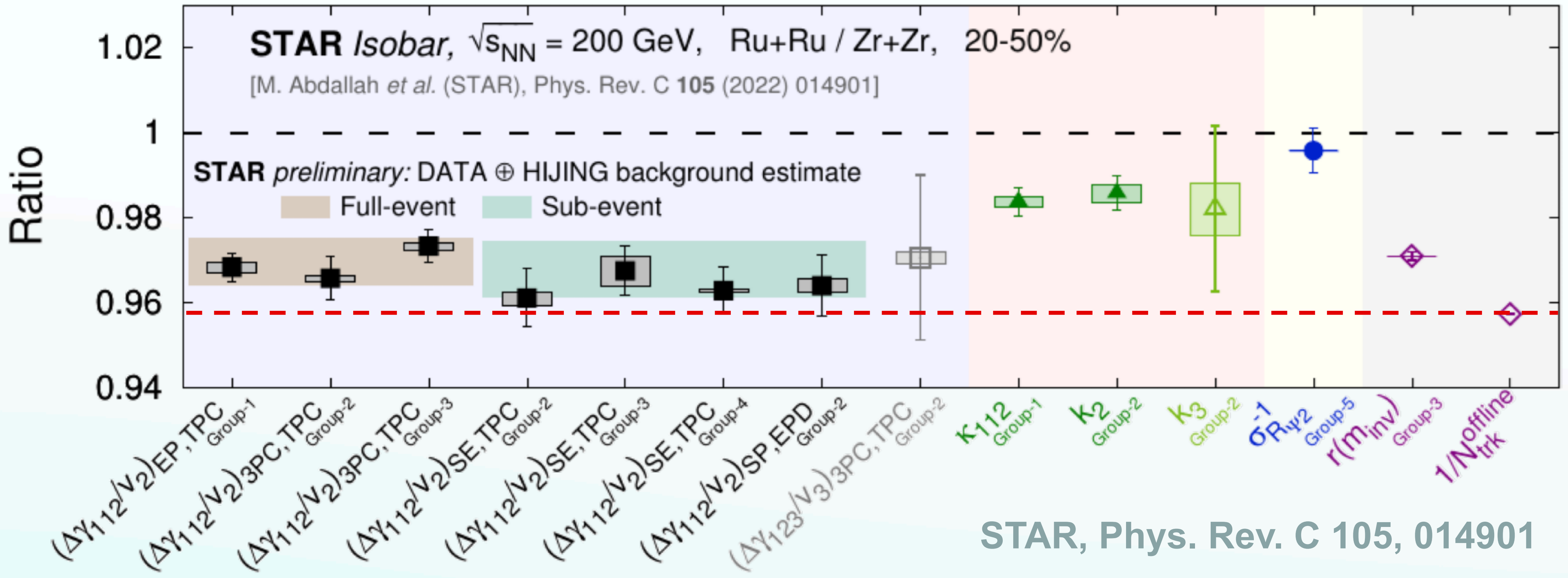
- **Using participant plane (TPC) entails large nonflow BKG (can be avoided with Ψ_1)**
- **Much Larger statistics needed!**
- **The large v_2-BKG requires better methods.**



In BES-II

- ✓ **EPD ($2.1<\eta<5.1$) covers spectator range**
- ✓ **x20 statistics**
- ✓ **New methods being developed**

Lesson from Recent Isobar Data:



STAR, Phys. Rev. C 105, 014901

Fraction of CME signal is not as large as expected
in smaller system: larger nuclei fluctuation and smaller B field;
in higher energy: shorter B life time.

BES-II provides unique opportunity to search for the CME!

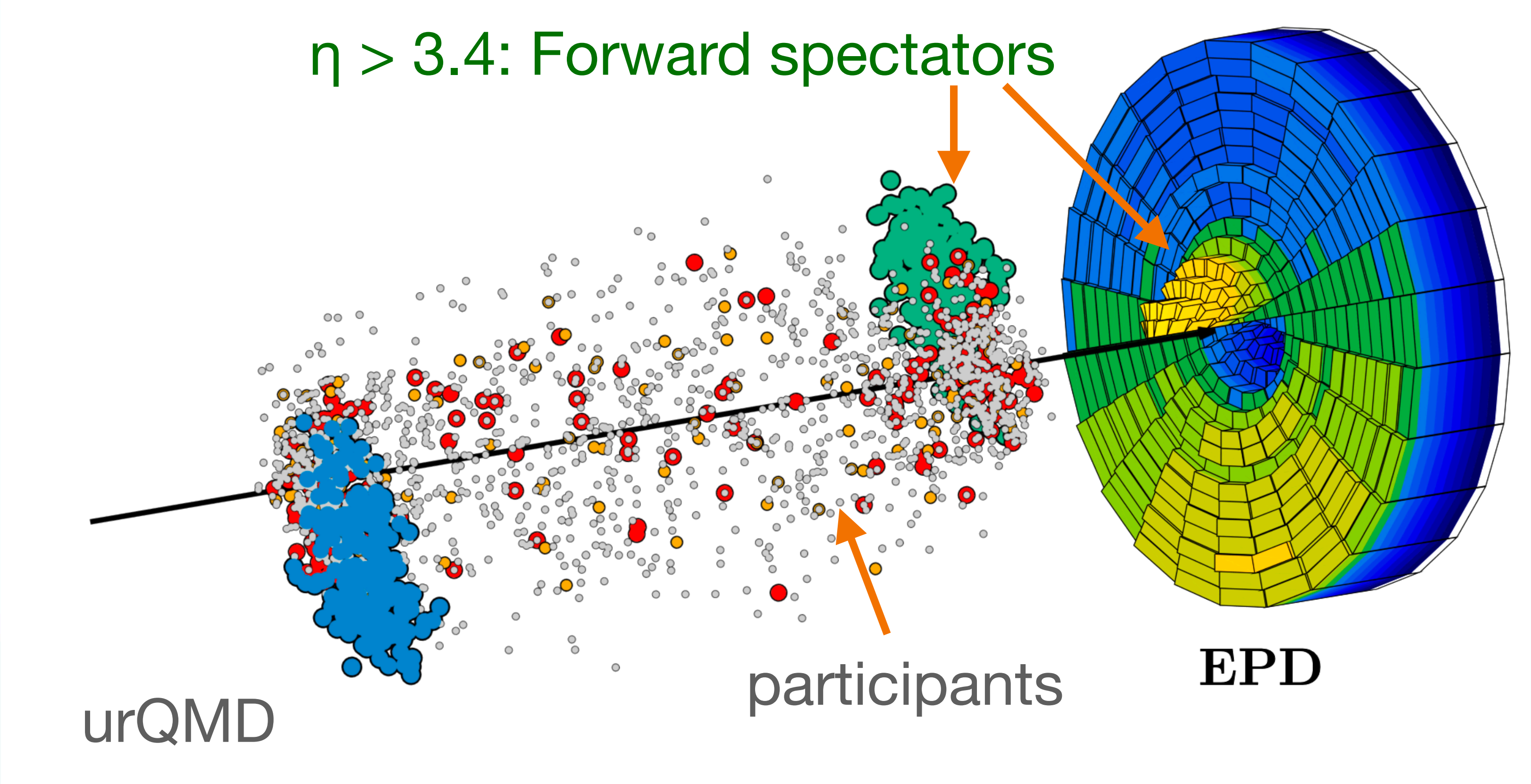
Beam Energy Scan II - P.P. vs S.P.

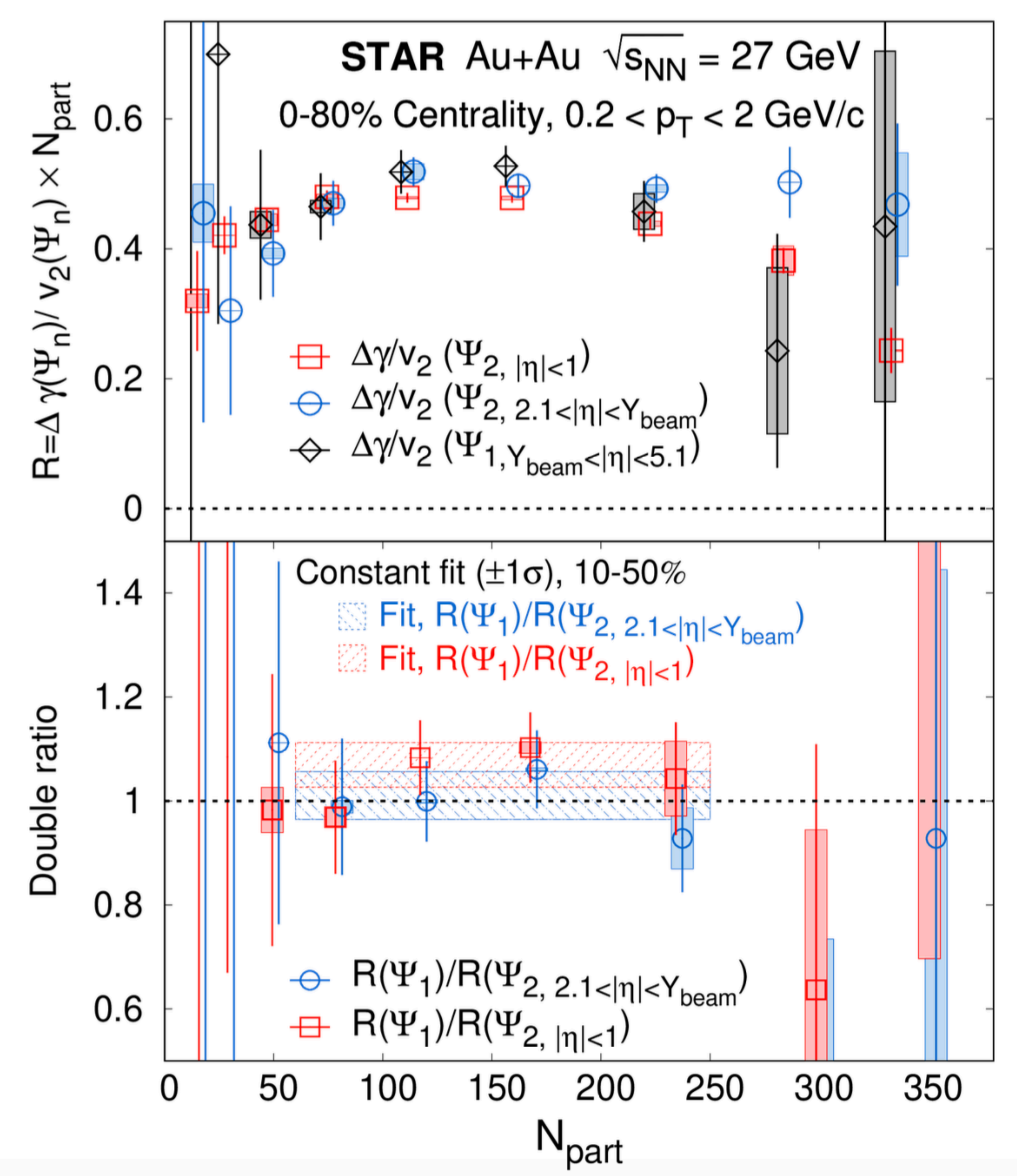
STAR PLB 839 (2023) 137779

Assumption: In a pure-BKG scenario driven by flow

$$\frac{\Delta\gamma}{v_2}(\Psi_{1,SP}) = \frac{\Delta\gamma}{v_2}(\Psi_{2,PP}) = \frac{\Delta\gamma}{v_2}(\Psi_{2,|\eta|<1})$$

$$R(\Psi_n) = \frac{\Delta\gamma(\Psi_n)}{v_2(\Psi_n)} \times N_{\text{part}} \qquad \frac{R(\Psi_1)}{R(\Psi_2)} \text{ would be unity}$$





Double ratio is consistent with unity for 10-50%.

Flow decorrelation is a significant uncertainty yet to be understood in this approach.

Beam Energy Scan II - Inter-observable correlations

Phys. Rev. C 108 (2023), 014909

Assumption: Λ **and** $\bar{\Lambda}$ **hyperon global polarization is split by strong B field**

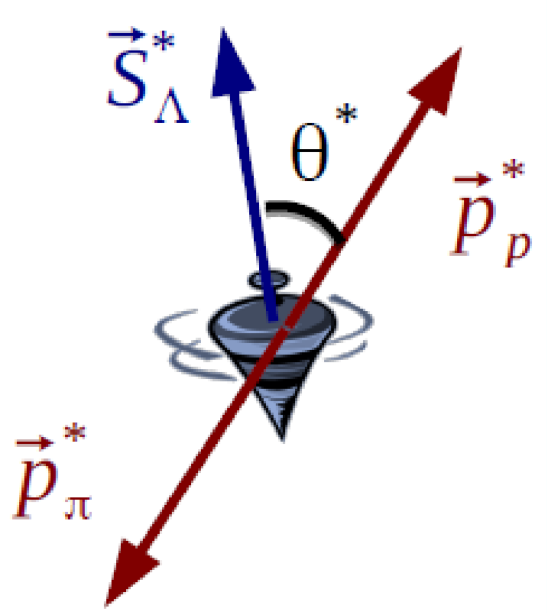
$$P(\Lambda) \approx \frac{\omega}{2T} + \frac{\mu_\Lambda}{T}B$$

$$P(\bar{\Lambda}) \approx \frac{\omega}{2T} - \frac{\mu_{\bar{\Lambda}}}{T}B \quad \Rightarrow \Delta P \propto B$$

Parity-even

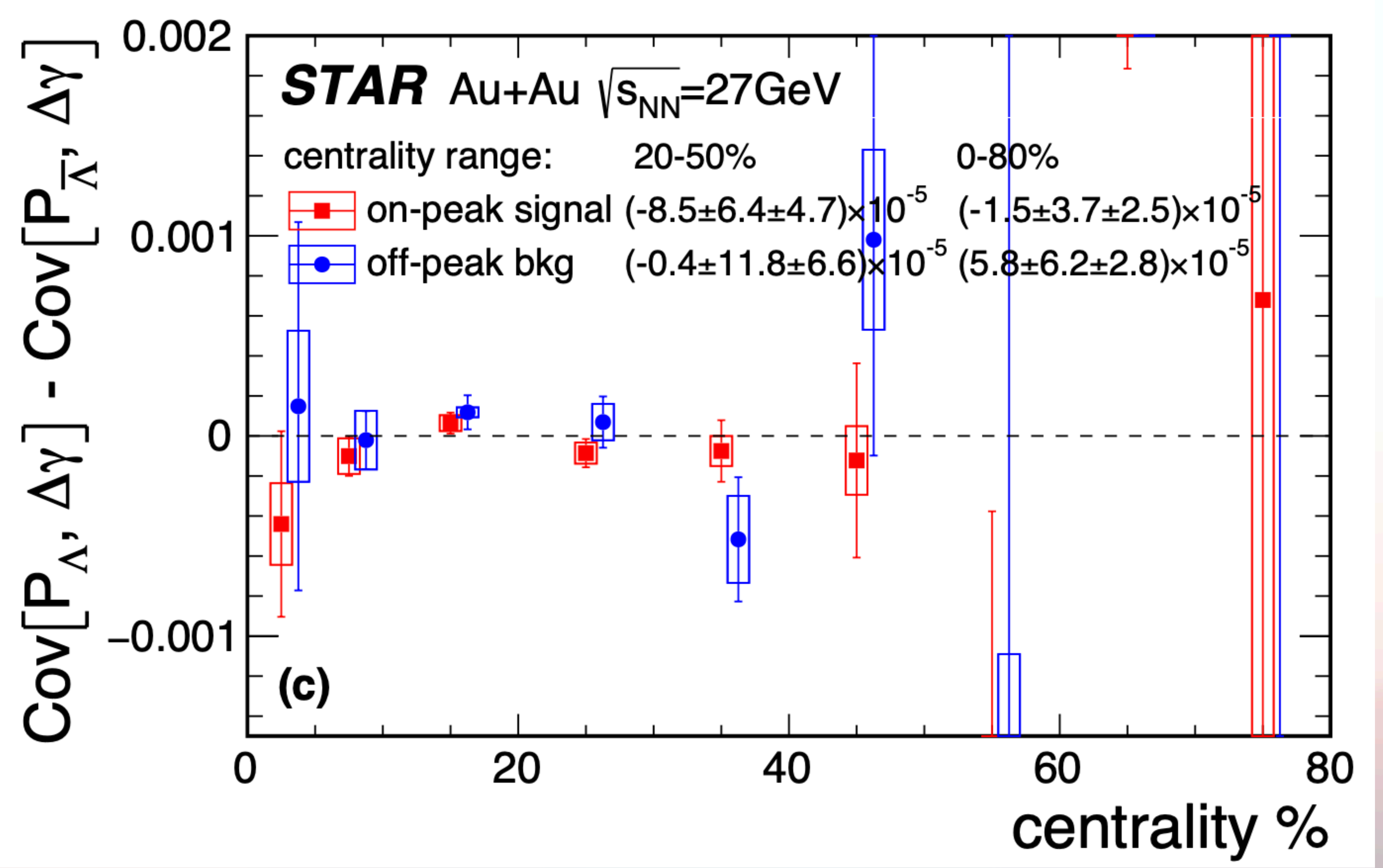
$$Cov[X, Y] = \langle XY \rangle - \langle X \rangle \langle Y \rangle$$

Cov(ΔP, $\Delta\gamma^{112}$) sensitive to B field, should be < 0



Limited by statistics, we are unable to use covariance to reach the required sensitivity.

At the hyperon formation time, the magnetic field may be much smaller than expected.



Beam Energy Scan II - Inter-observable correlations

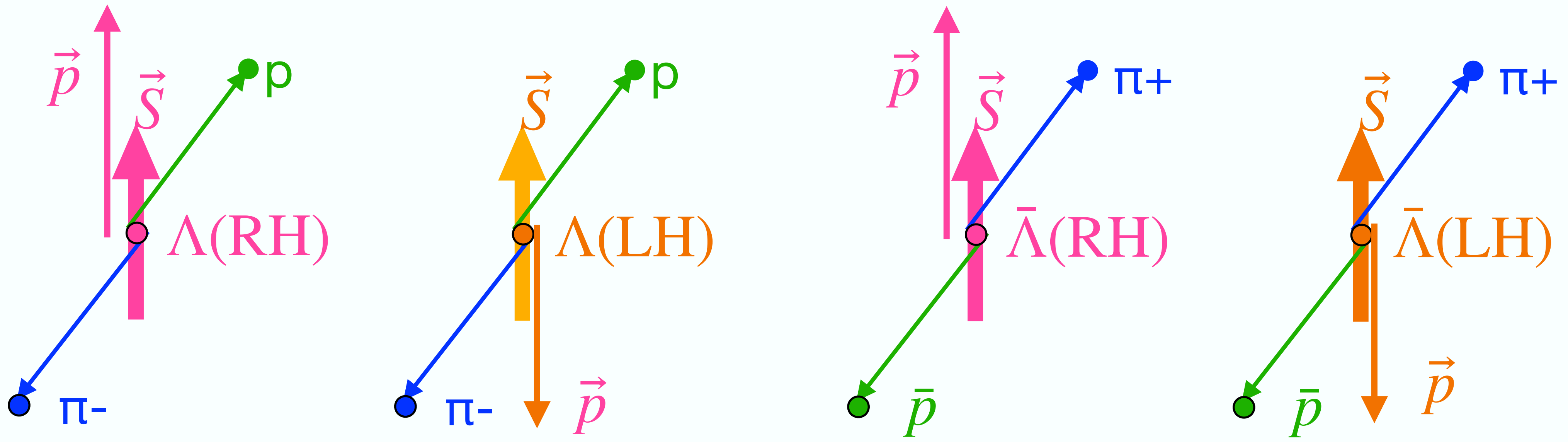
Phys. Rev. C 108 (2023), 014909

Assumption: Event by Event chirality (handness) fluctuation impacts the following covariance:

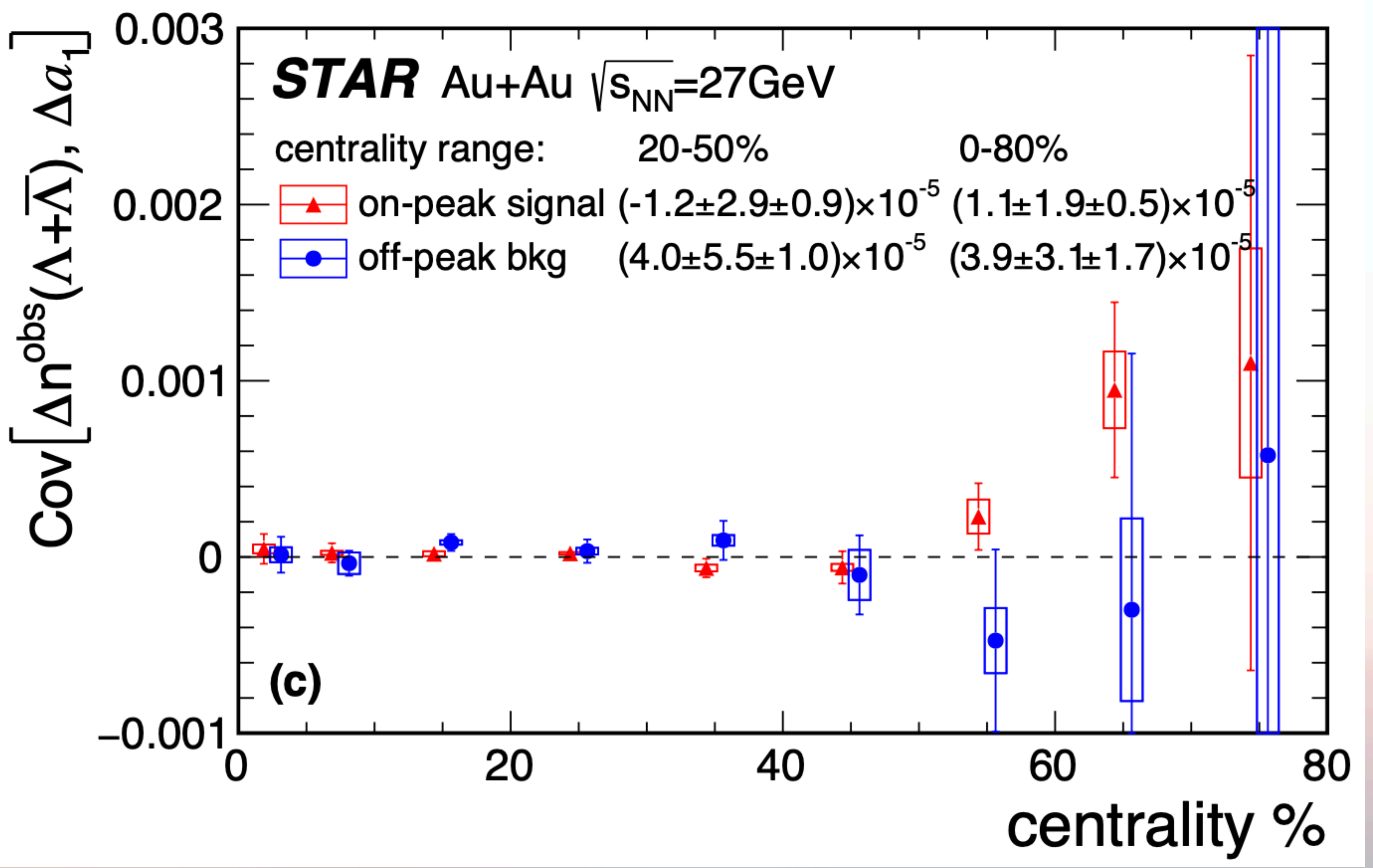
$$\Delta n = \frac{n_L - n_R}{n_L + n_R} \; ; \; \Delta a_1 = a_1^+ - a_1^- \qquad \textit{parity-odd}$$

$$Cov[X, Y] = \langle XY \rangle - \langle X \rangle \langle Y \rangle$$

Cov(Δn, Δa_1) sensitive to chirality fluctuations < 0



Both covariance method, even if they entail true signal, can not reach the statistical precision needed for observation.



Beam Energy Scan II - Event Shape Selection

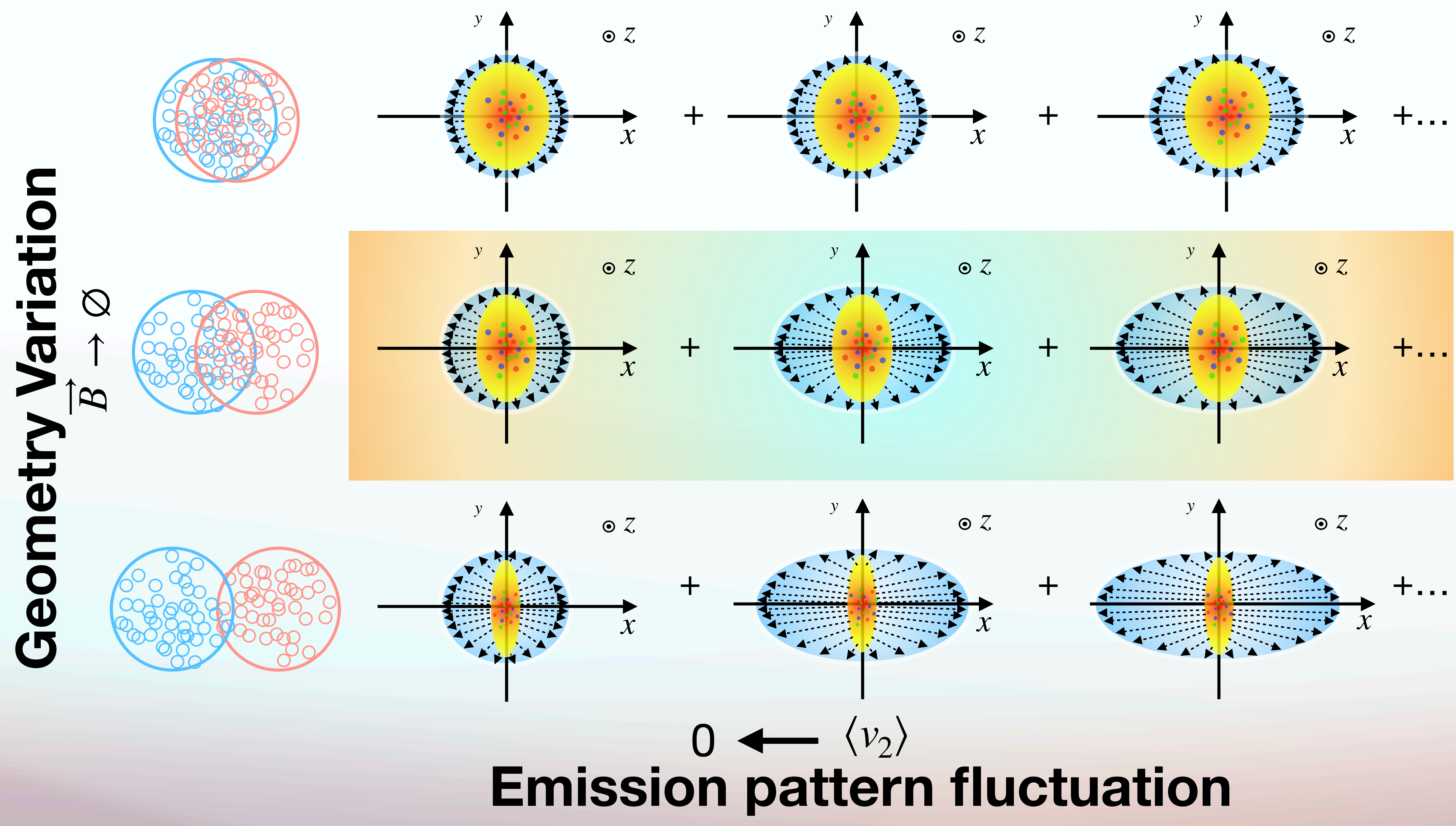
Assumption: ESS Spectator Ψ_1

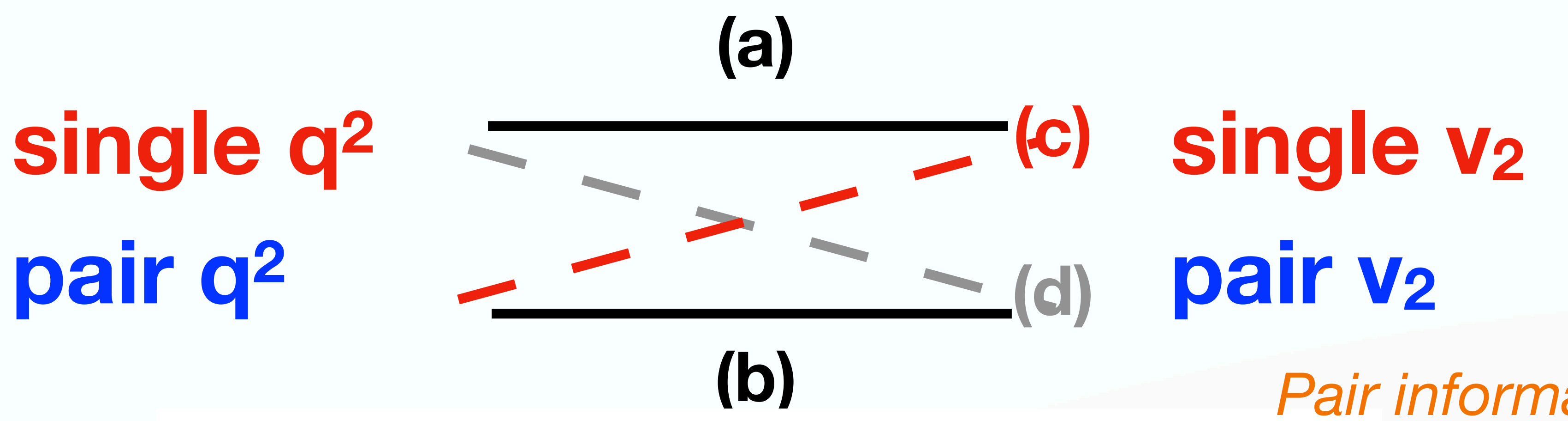
$$\Delta\gamma^{112} = \Delta\gamma^{\text{CME}} + k\frac{v_2}{N} + \Delta\gamma^{\text{non-flow}}$$

Measured — Signal — Backgrounds

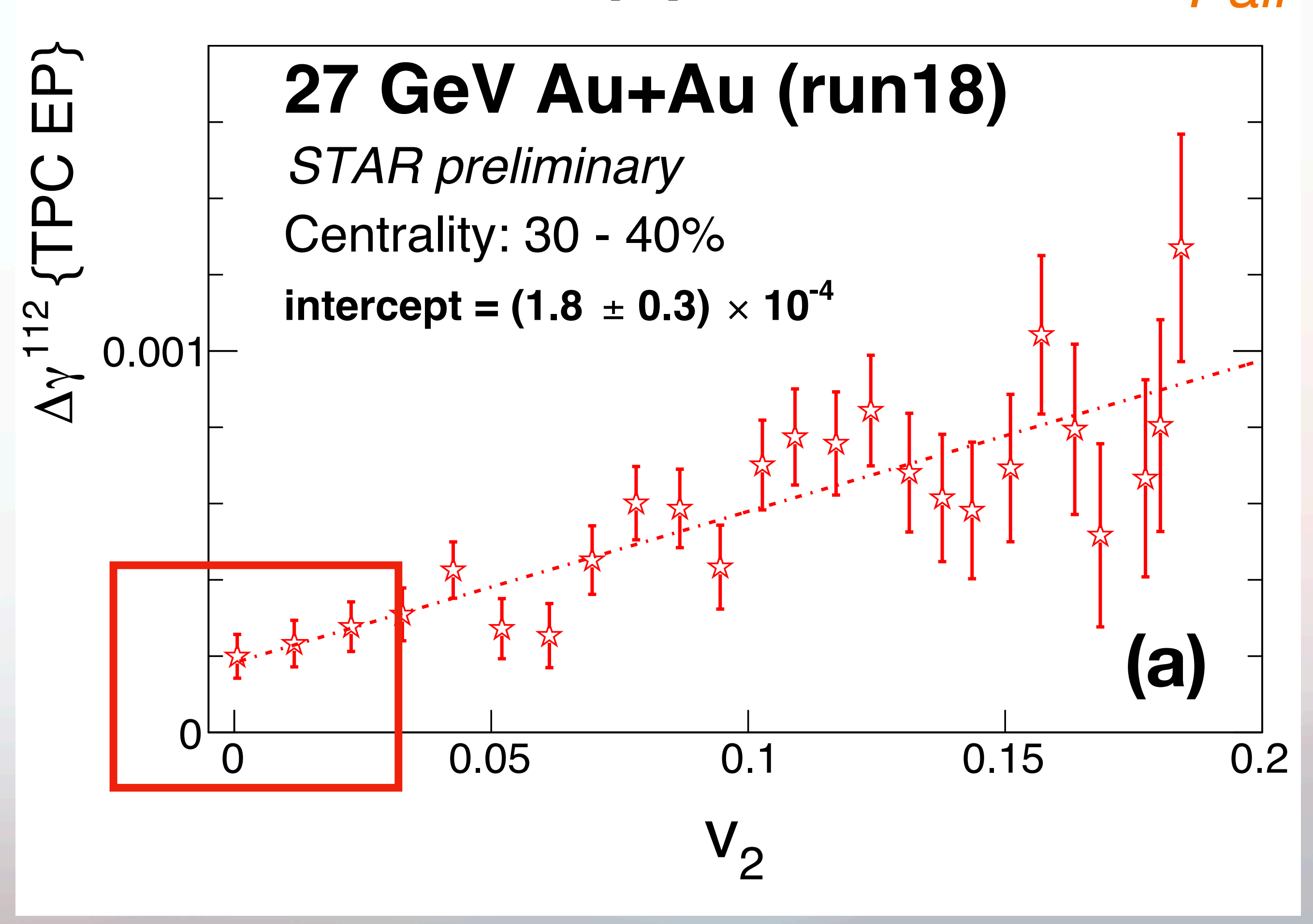
Flow vector $q_2^2 = \frac{(\sum \sin 2\varphi)^2 + (\sum \cos 2\varphi)^2}{N(1+Nv_2^2)}$ **(event binning) or v_2 (BKG control) has contributions from:**

- **participant shape distribution – likely long range and correlated over large η gaps**
- **emission pattern fluctuations – short range, uncorrelated for different η regions**





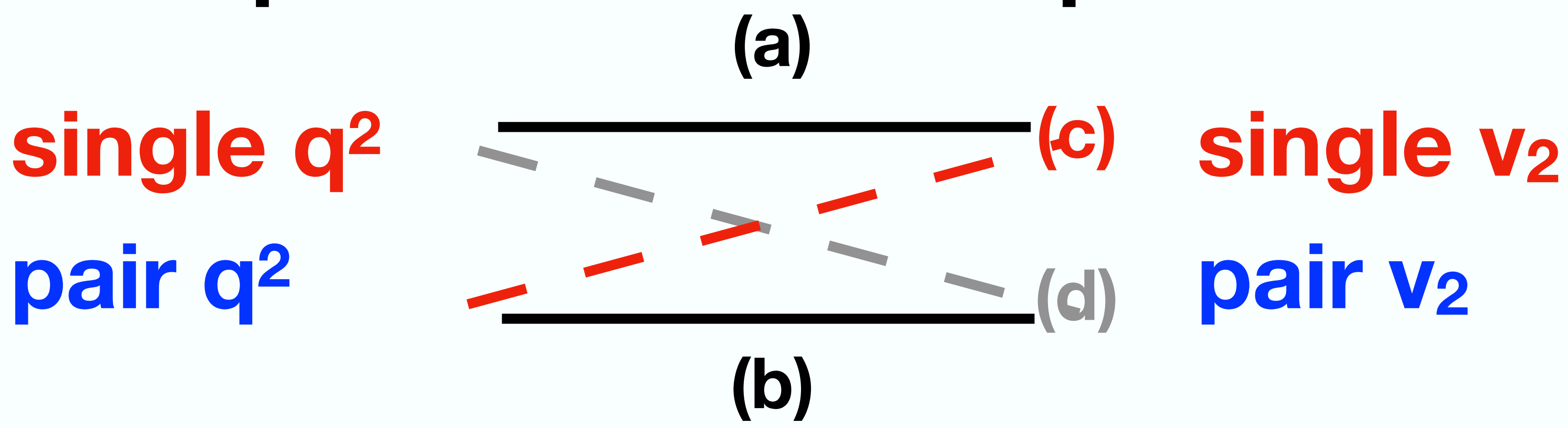
Pair information used

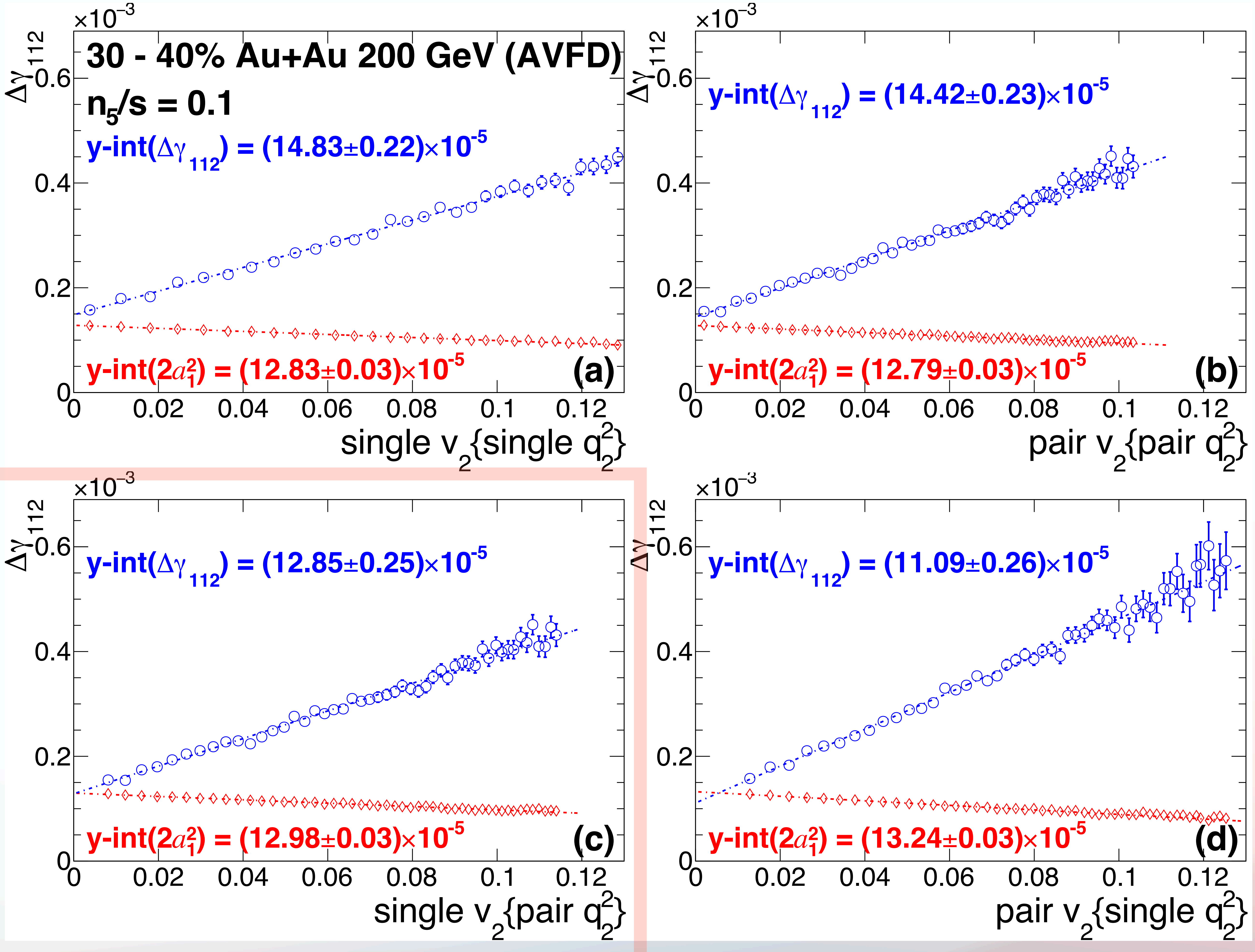


Beam Energy Scan II - Event Shape Selection

More coming soon: arXiv:2307.14997

Event shape variables **Elliptic flow variables**

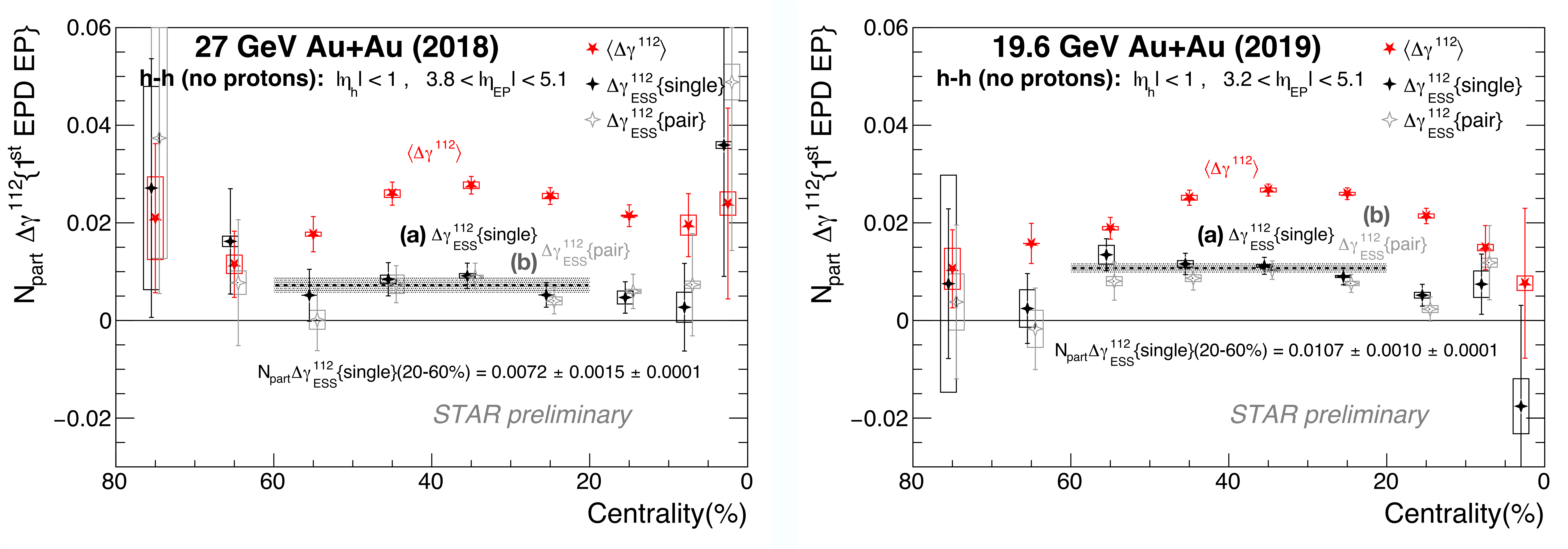




- **From AVFD study, we settled the optimal ESS recipe (c) that can accurately match the input true CME signal.**
- **ESS recipe (a) and (b) under-subtract the BKG.**
- **Recipe (d) over-subtracts the BKG.**

Beam Energy Scan II - Event Shape Selection

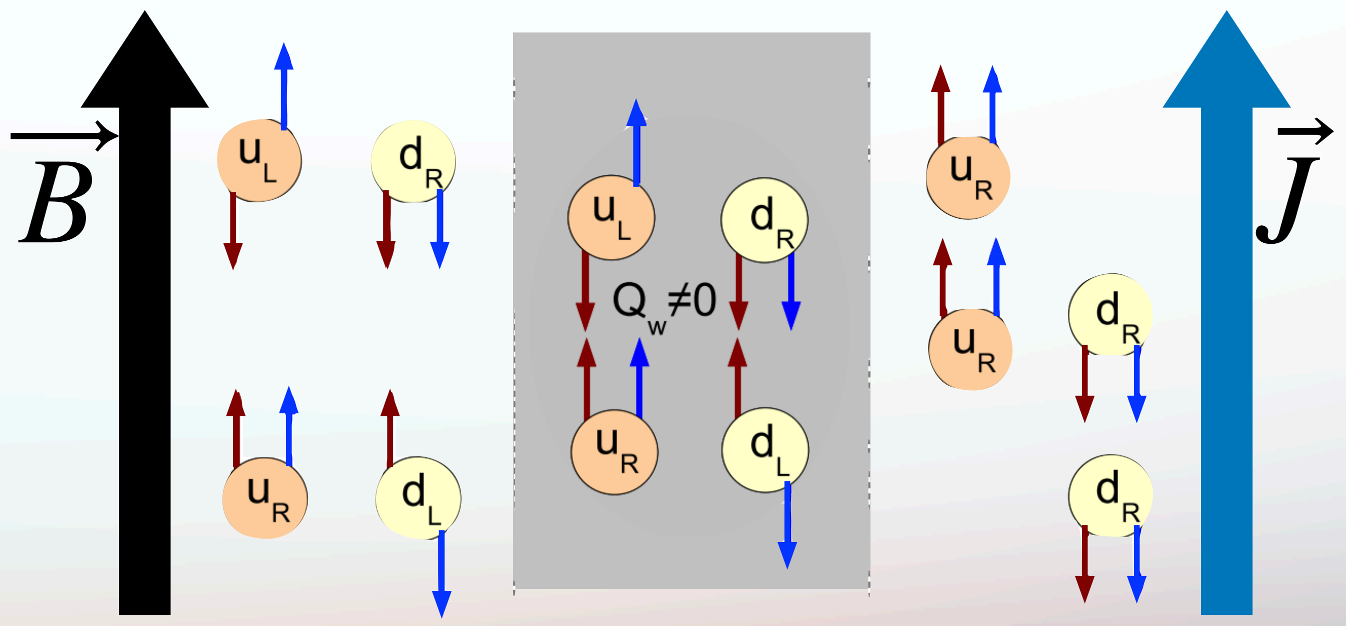
Z.Xu DNP 2022

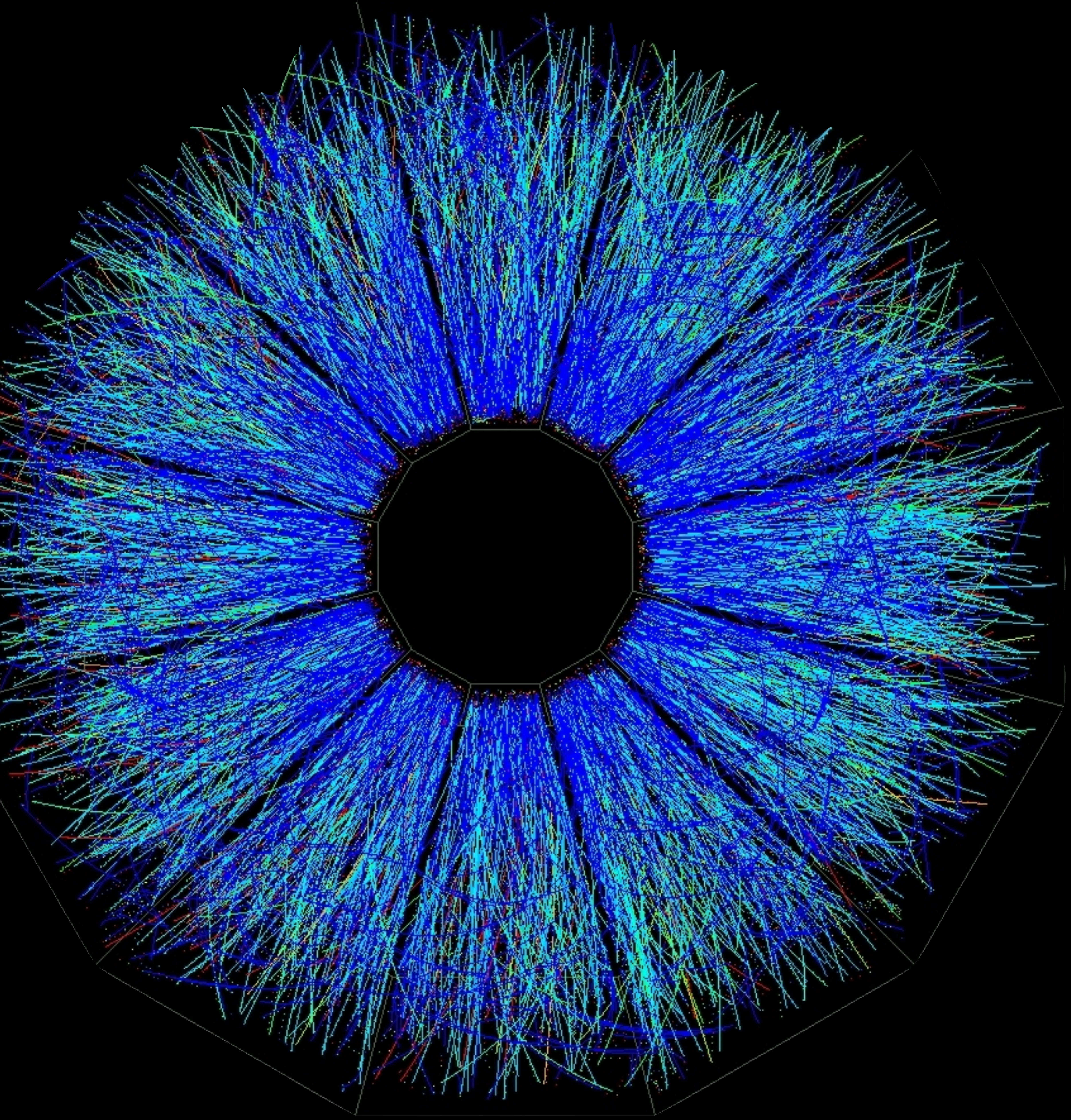


- Spectator plane Ψ_1 is more correlated to the magnetic field direction.
- ESS (a) and (b) present finite $\Delta\gamma^{112}_{ESS}$ in mid central events with effectively more than 70% of v_2 BKG removed.
- The precision of STAR measurement after ESS is controlled to be 5.4% (3.6%) of ensembled average $\Delta\gamma^{112}$ at BES-II 27 (19.6) GeV.
- We will report the new findings of BES-II result (7.7 to 27 GeV) in the upcoming QM2023.

Summary

- The search for the CME addresses an intrinsic topological property of QCD.
- We have learned many new insight for the v_2-related BKG in the CME observables
  - H-correlator, κ^{112}, double ratio of S.P./P.P, and inter-observable covariance.
- We have developed new Event Shape Selection utilizing pair information to select events, and single v_2 to control BKG.
- New BES-II $\Delta\gamma$ measurements will be presented in QM2023.





Thank you!