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ENERGY

Search for the Chiral Magnetic Effect from STAR Beam Energy Scan-II data

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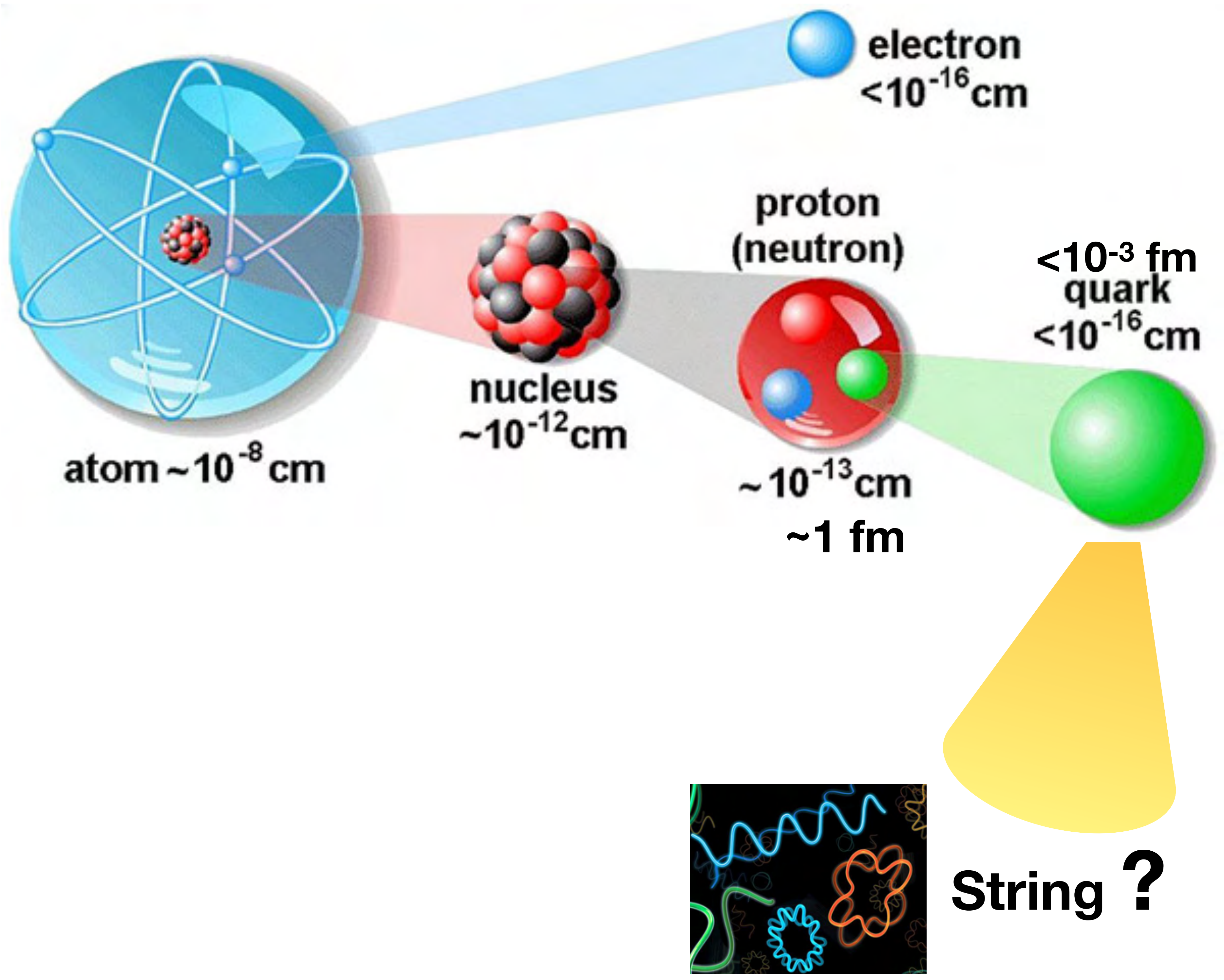
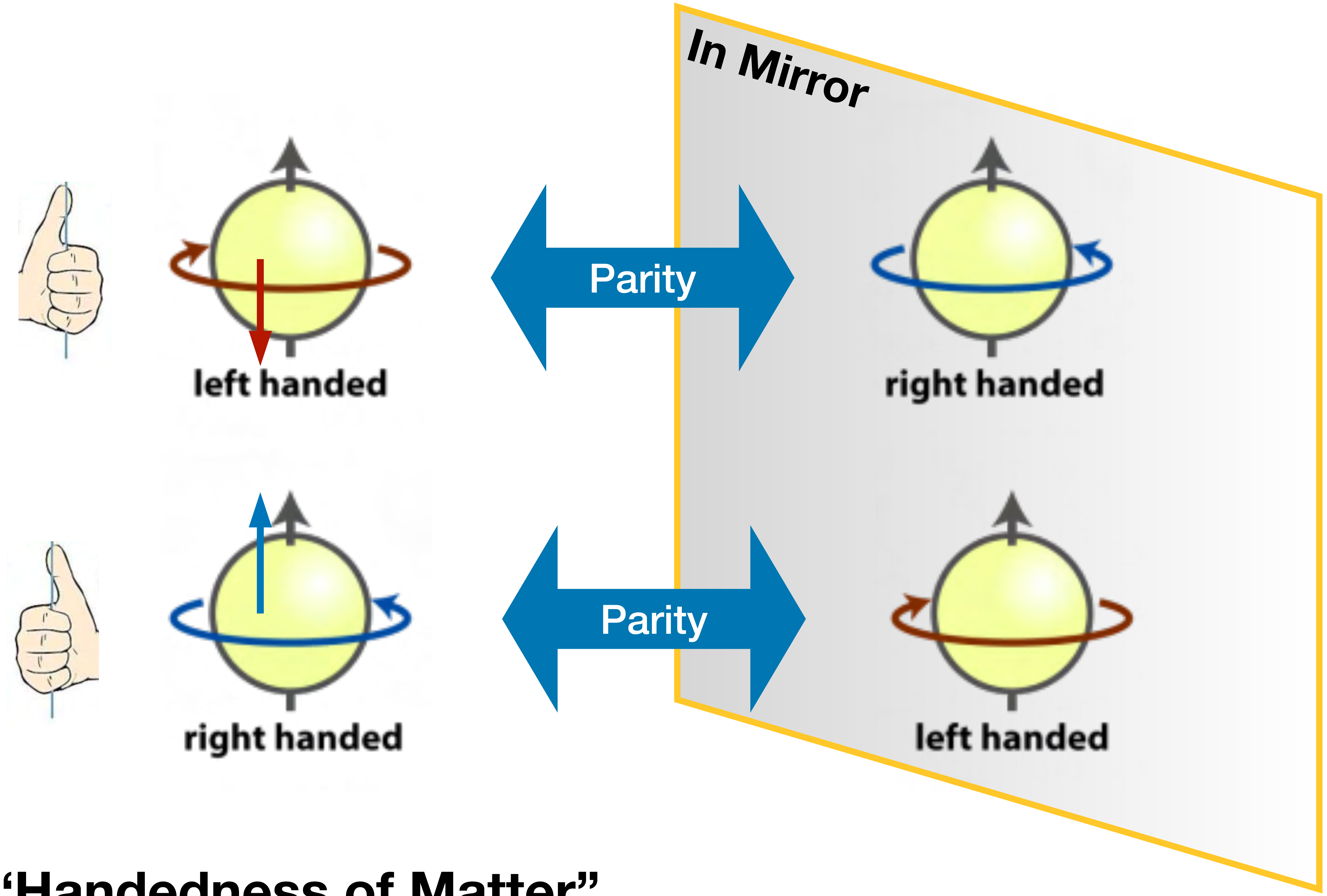
HENPIC seminar, Sept 19, 2024

Outline

- Introduction to CME
- Previous results at STAR
- New Method: Event Shape Selection
- Measurement with RHIC BES-II data
- Summary

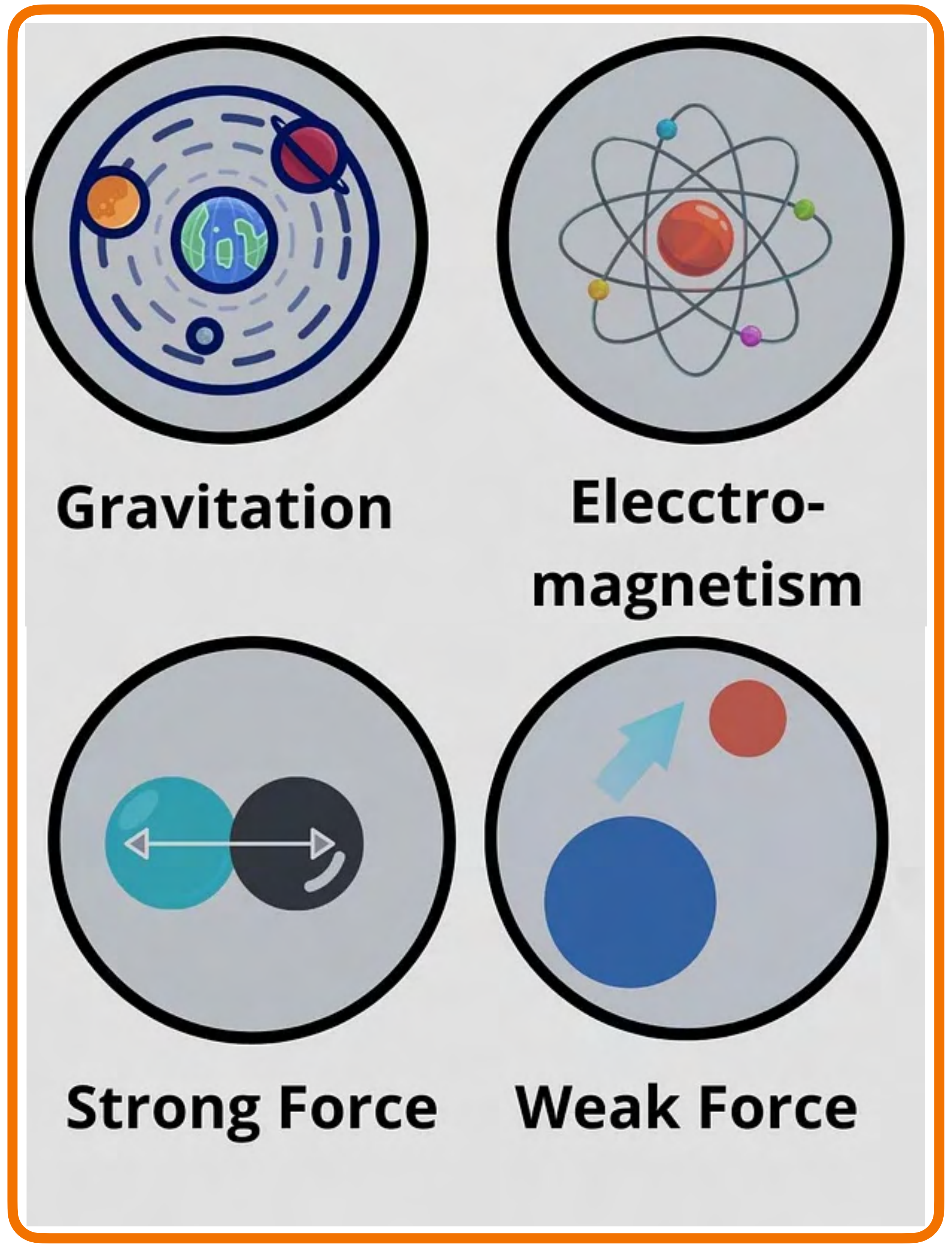
The Parity of Elementary Particles

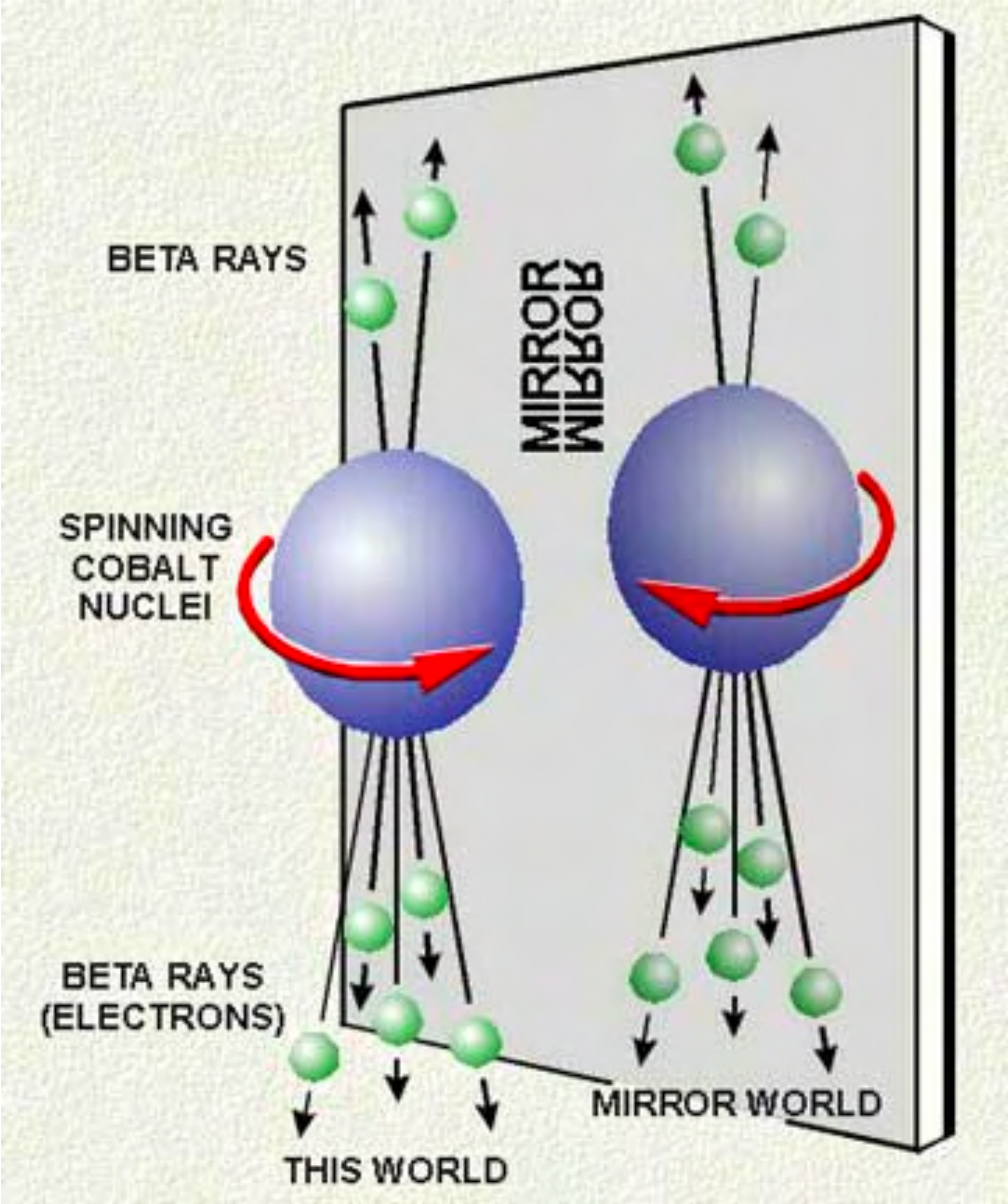




"Handedness of Matter"
~ Chirality

Discovery of Parity Violation in Weak Interaction






Chien-Shiung Wu

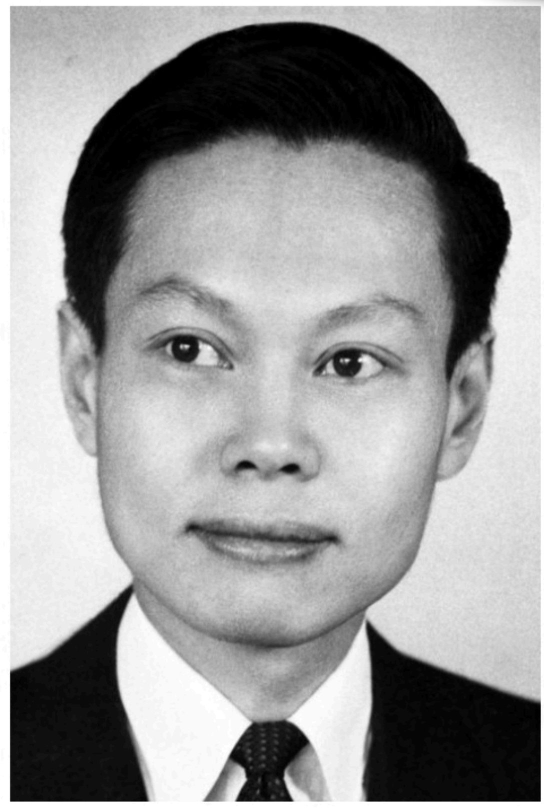


Photo from the Nobel Foundation archive.
Chen Ning Yang
Prize share: 1/2

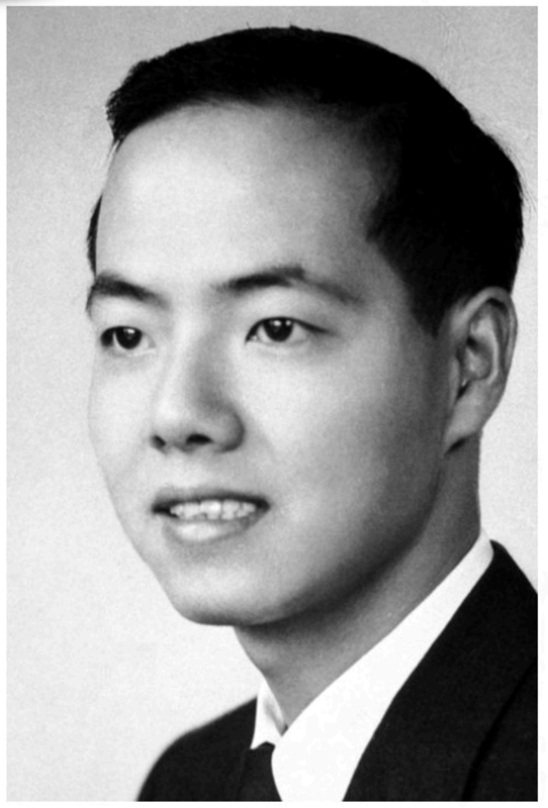
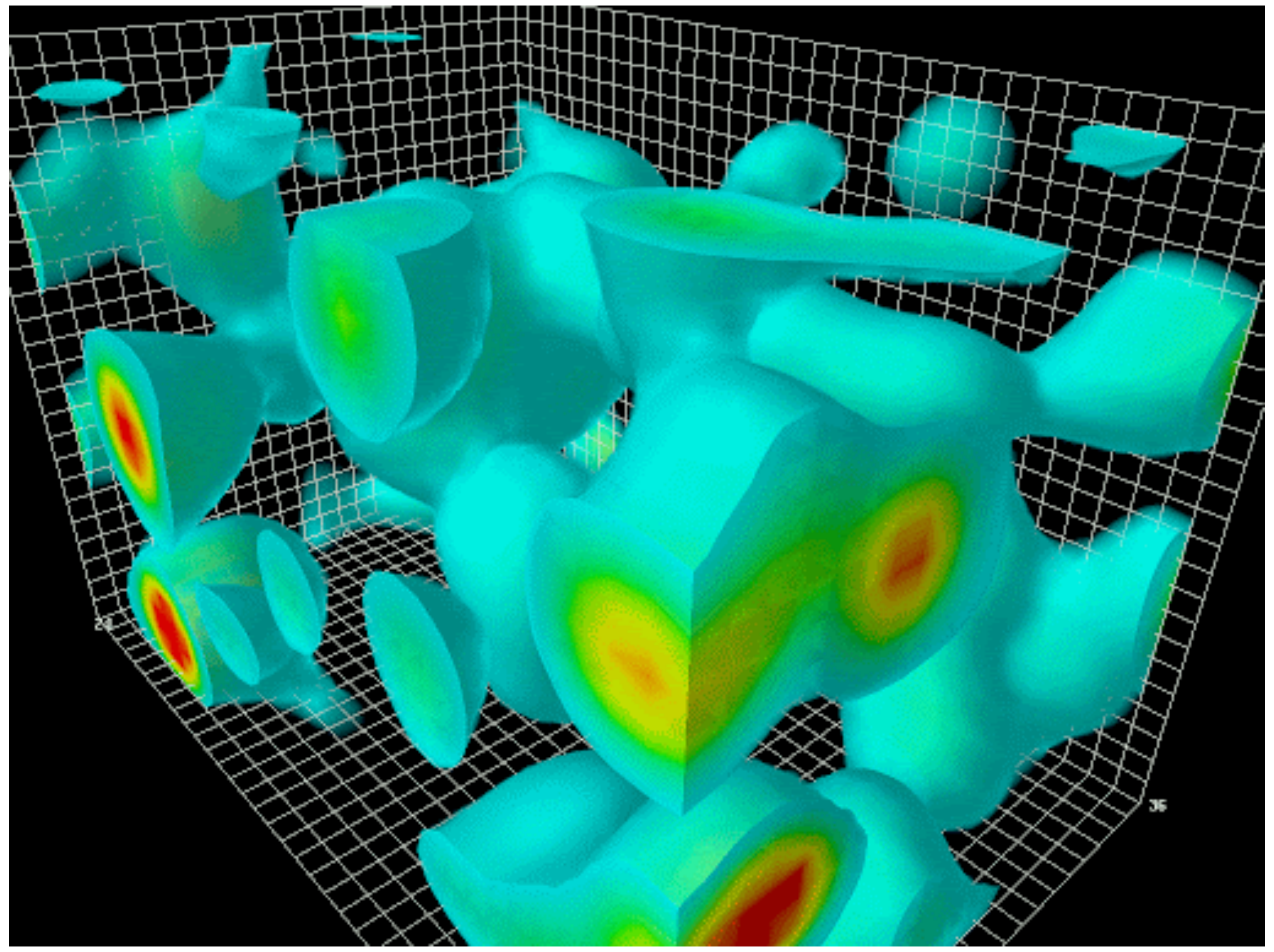


Photo from the Nobel Foundation archive.
Tsung-Dao (T.D.) Lee
Prize share: 1/2

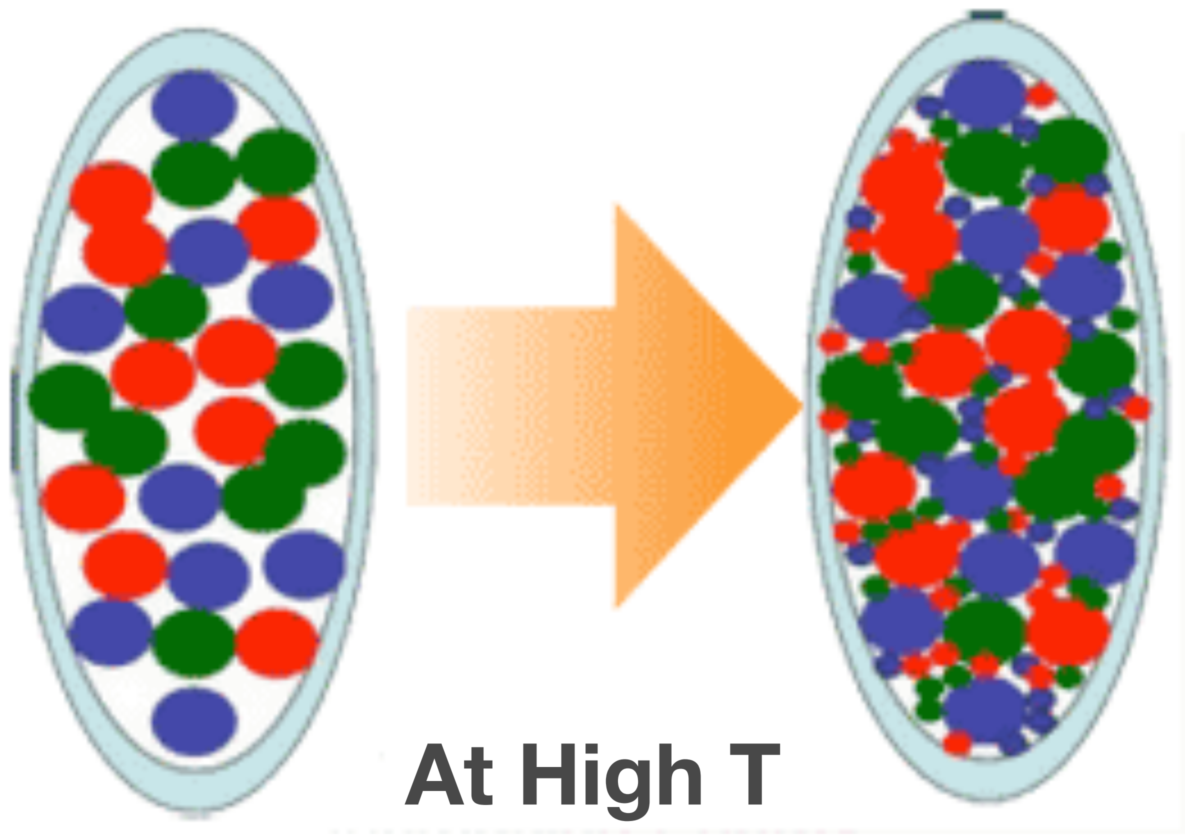
1956: **Co60 experiment (by Chien-Shiung Wu et al) discovered Parity symmetry breaking in the weak interaction.**

1957: **Nobel Prize for Yang and Lee**

Parity Violation in Strong Interaction?



QCD vacuum is not empty



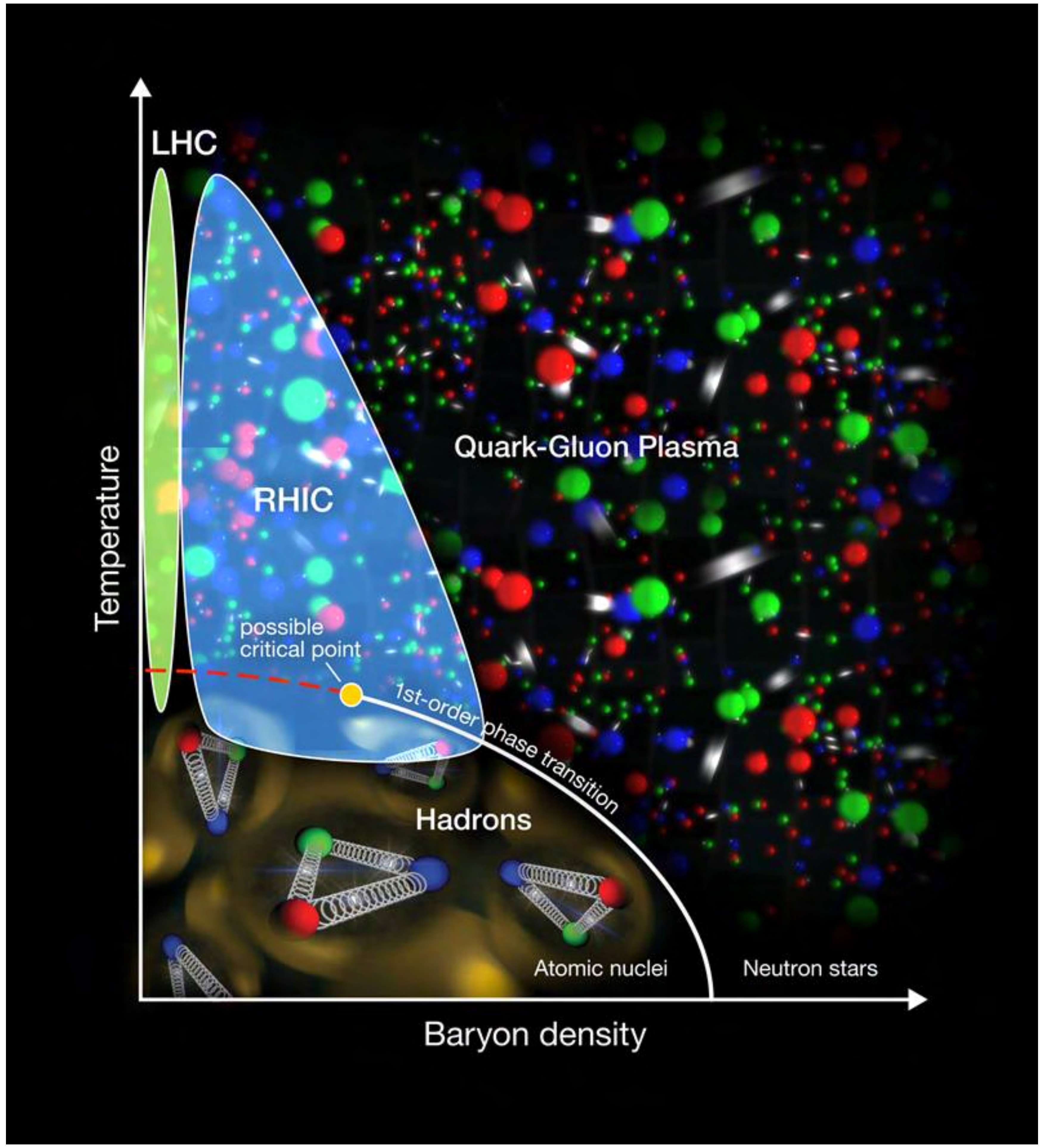
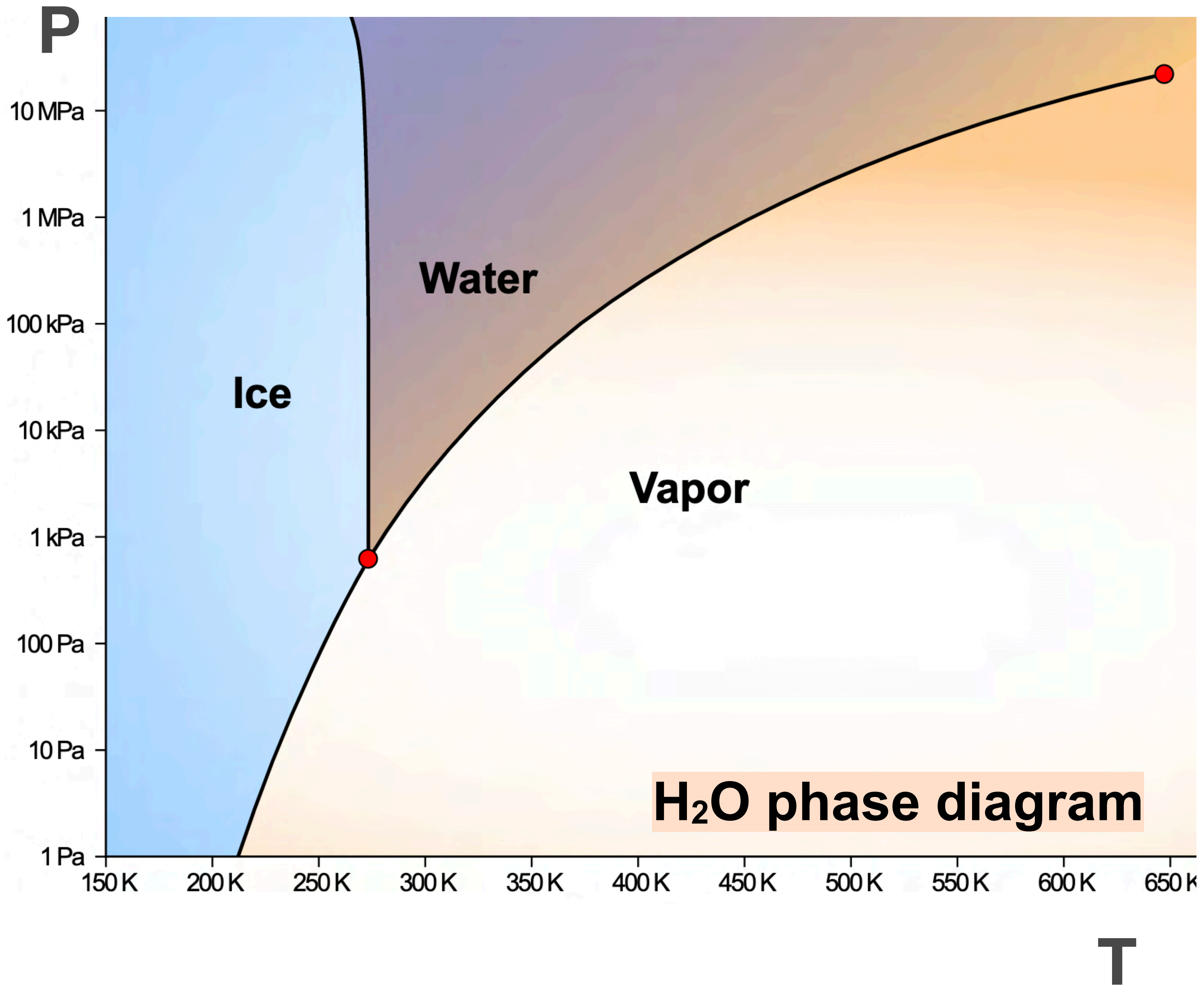


Image courtesy of Brookhaven National Laboratory

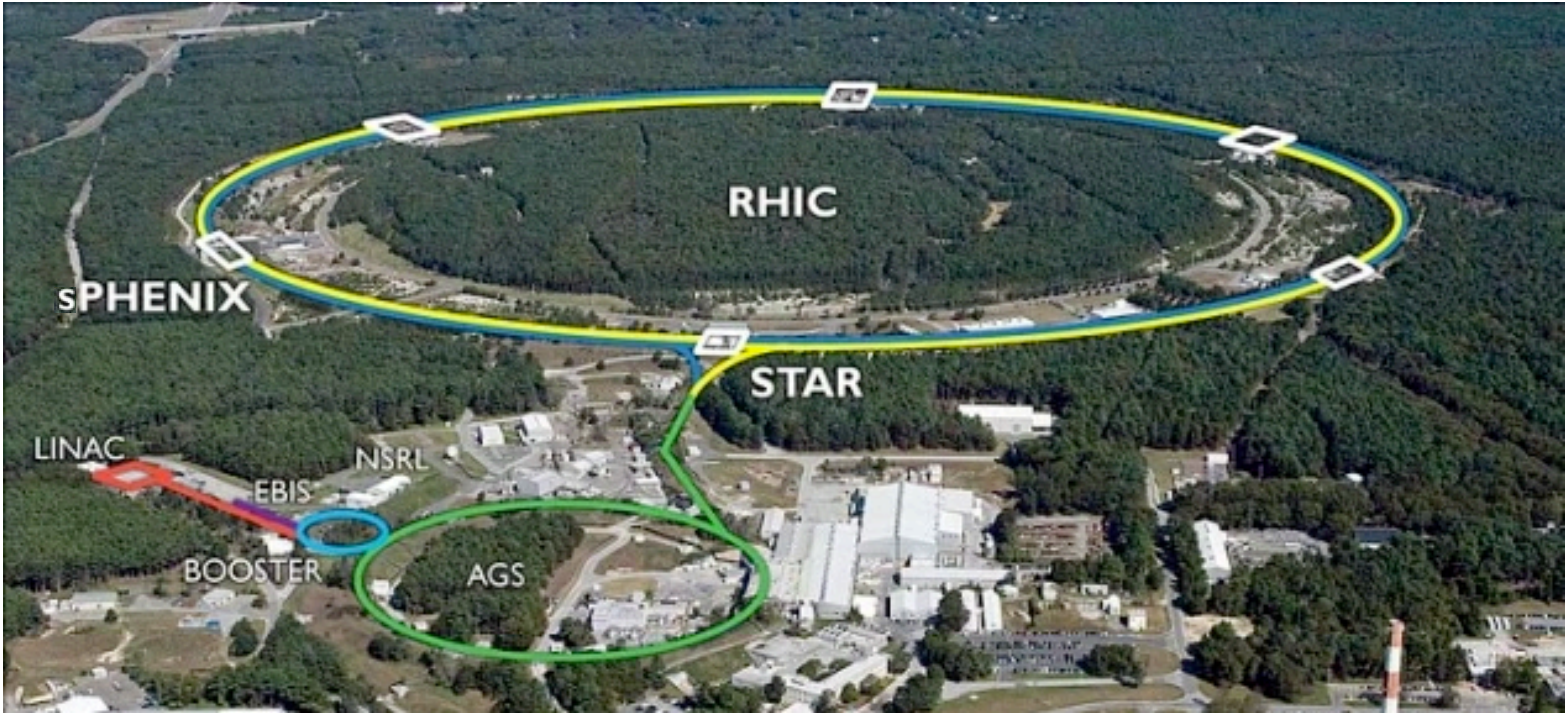
Phase change to Plasma



http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/

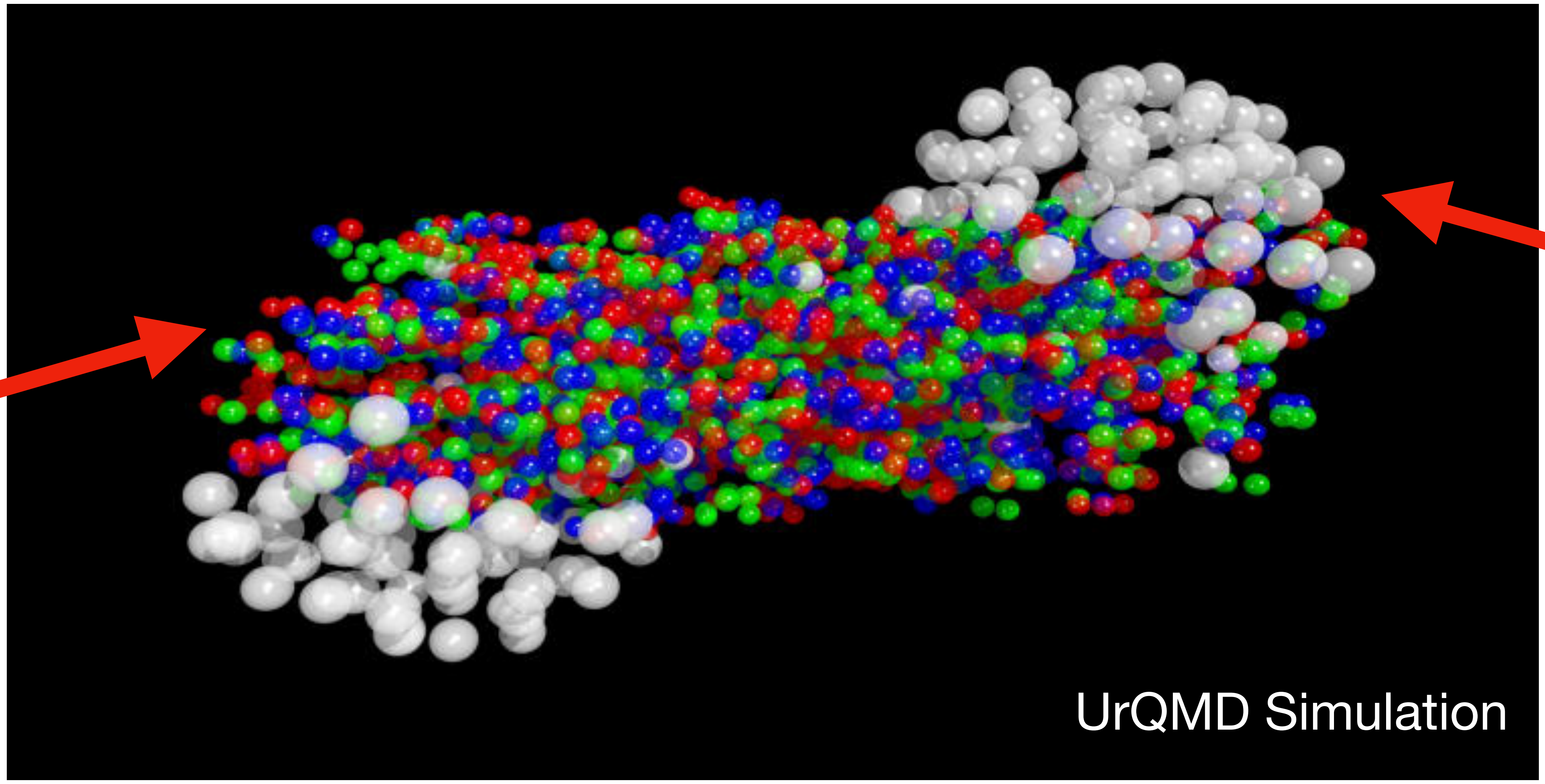
https://www.science.smith.edu/~jbrady/petrology/igrocks-diagrams/unary/H2O.php

Relativistic Heavy-Ion Collider



Heavy-Ion Collisions at RHIC

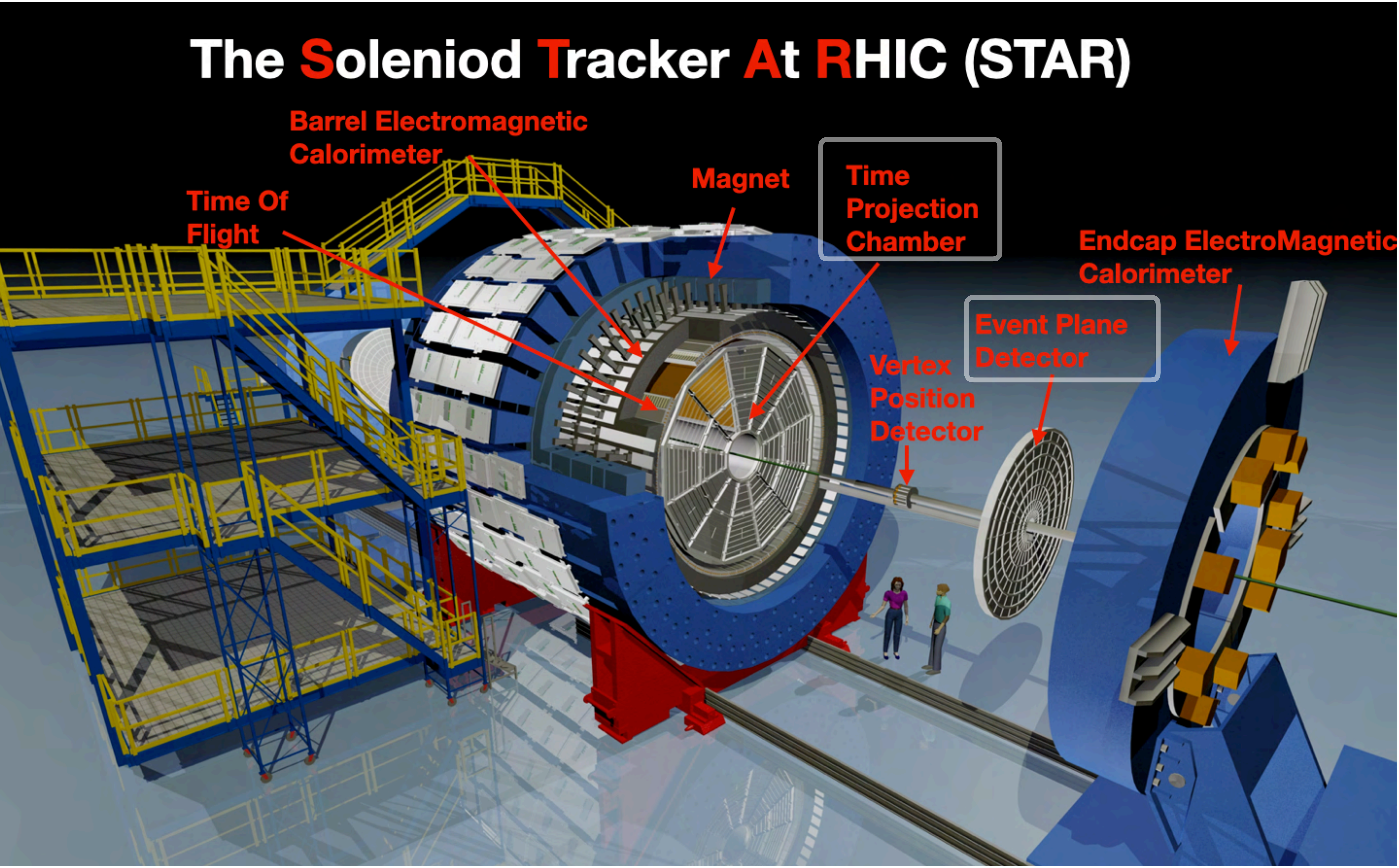
- Participants:
  - At high T: quarks are liberated
  - Excited gluons can probe QCD vacuum

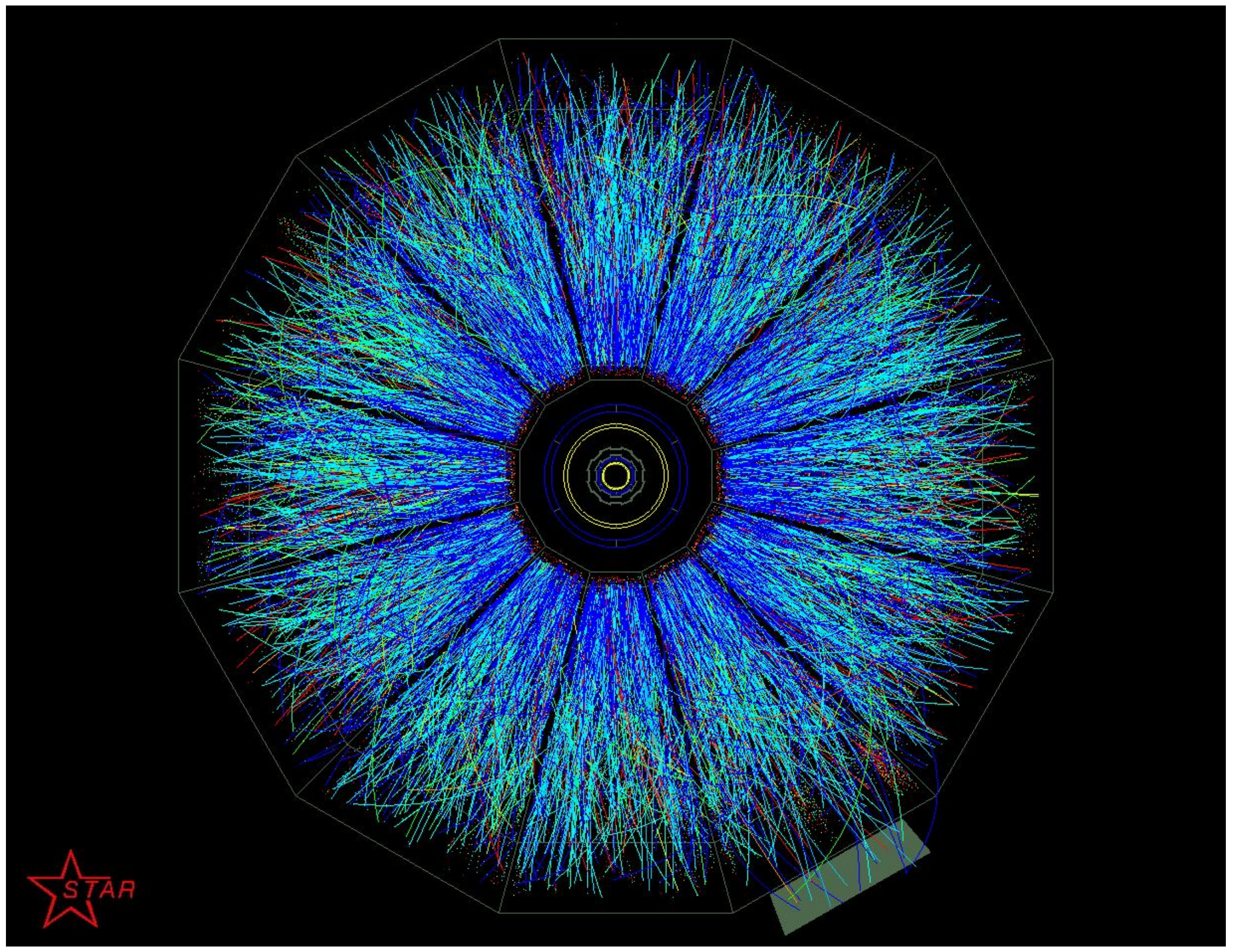


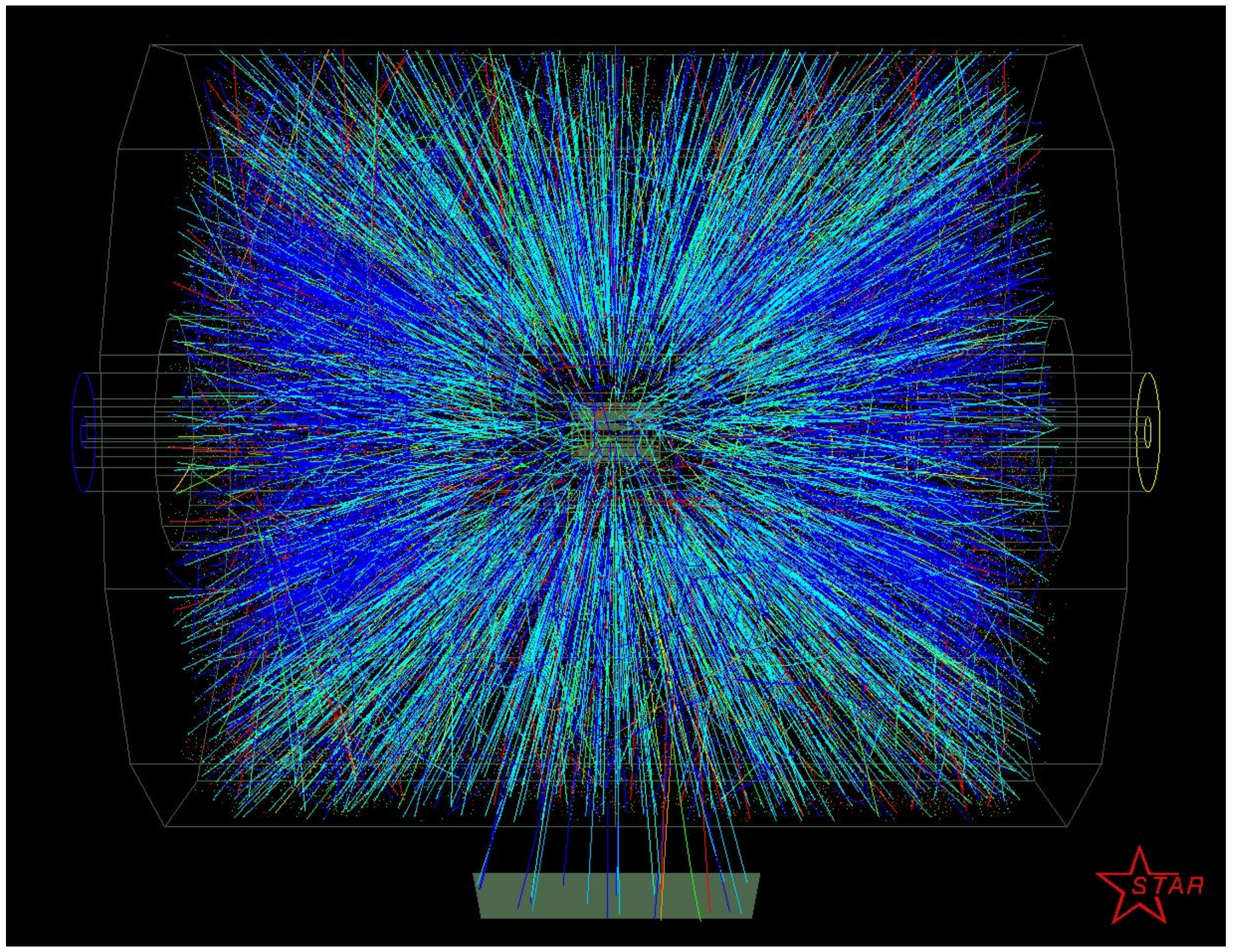
UrQMD Simulation

- Spectator protons carry “+” charges
  - Create B field

The STAR detector



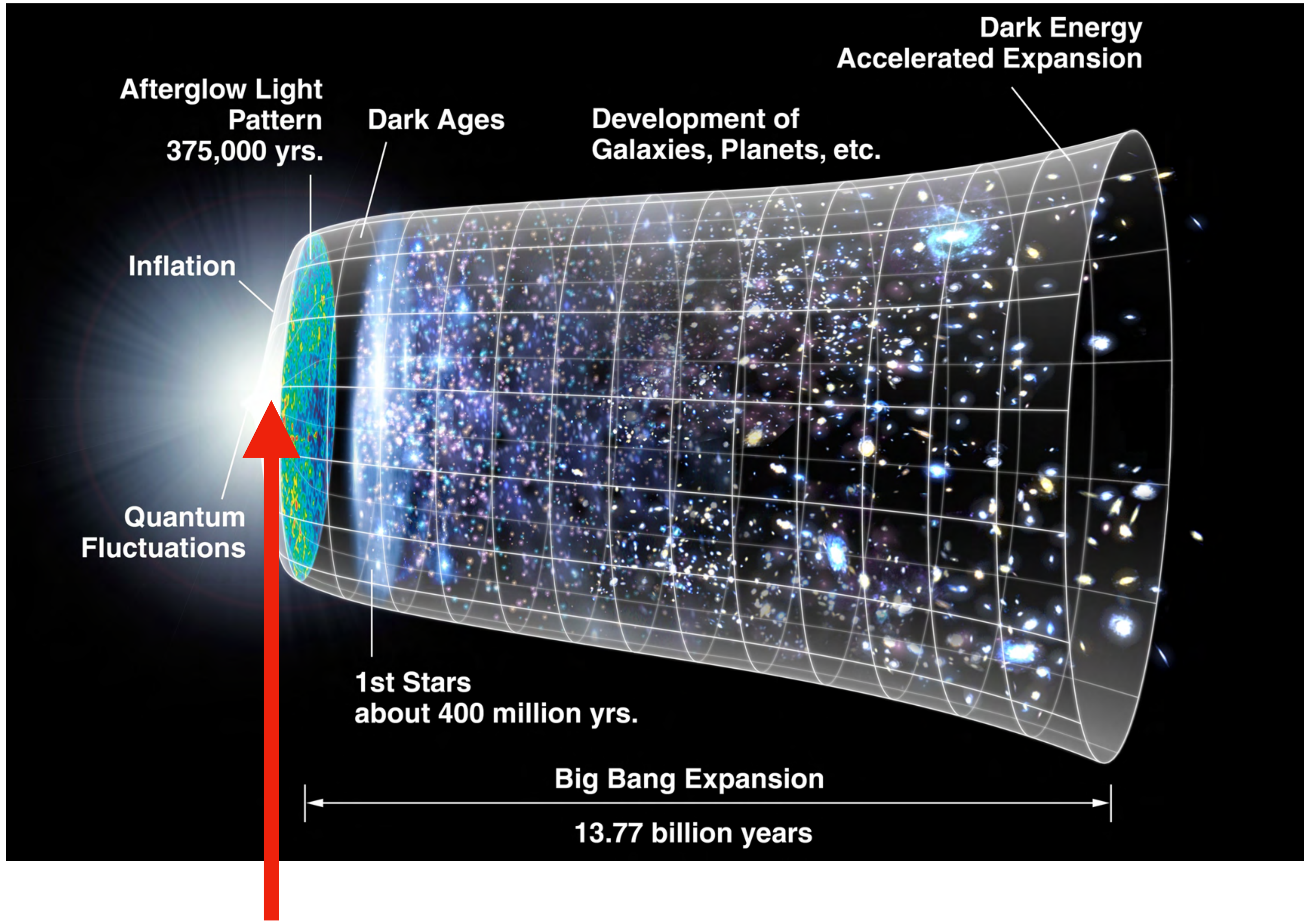




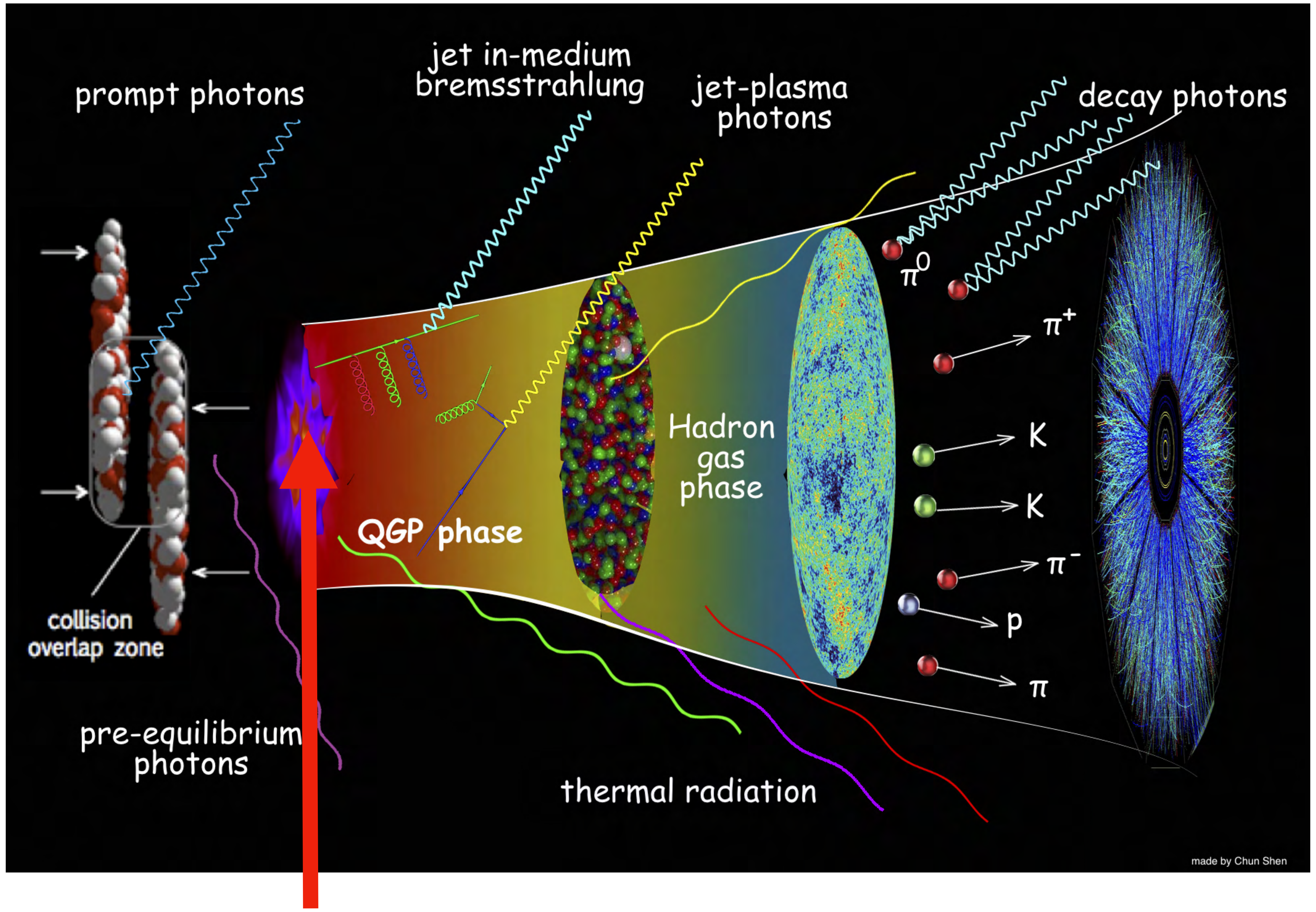
Front and Side View

Quark Gluon Plasma: the Small Bang

The Big Bang Theory



the "Small Bang" at RHIC



"Baryogengesis" Matter > Anti-matter

"Chirogenesis" More LH>RH (RH>LH) in local domain

https://www.bnl.gov/newsroom/news.php?a=11795

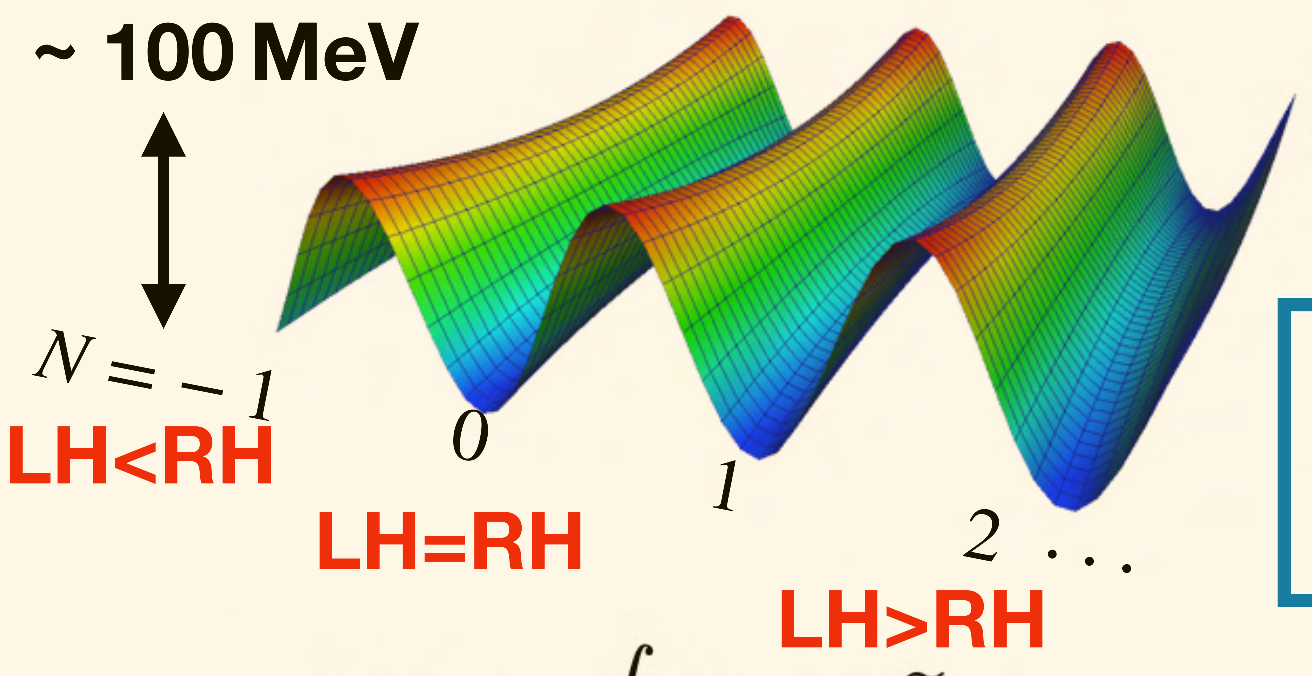
QCD Vacuum Topology and chirogenesis

QCD Lagrangian

$$\mathcal{L} = \bar{\psi}(i\not{D} - m)\psi - \frac{1}{4}(G^a_{\mu\nu})^2 + \frac{1}{2\xi}(\partial^\mu A^a_\mu)^2 + (\partial^\mu b^a)(D_\mu c)^a$$

- **QCD Vacuum is not empty** $\langle q\bar{q}\rangle \sim -\Lambda^3_{QCD}$

- **Vacuum Topology structures, reflect the compact nature of non-Abelian groups**



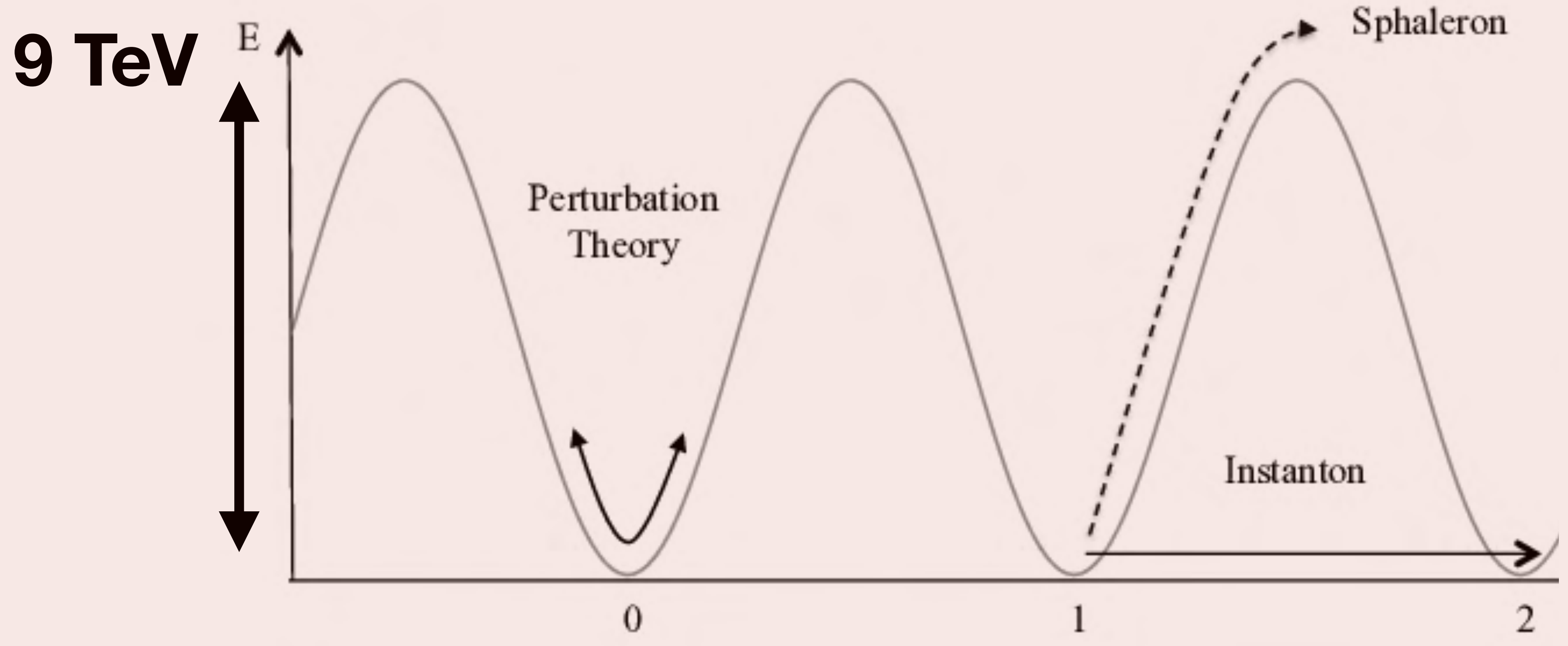
$$\Delta N_{CS} = \int d^4x G^{\mu\nu}\widetilde{G}_{\mu\nu}$$

$$\Sigma_n e^{in\theta_{QCD}}|n\rangle \rightarrow \Sigma_n|n\rangle$$

$$\mathcal{L}_\theta = -\frac{\theta}{32\pi^2} g^2 G^{\mu\nu}_a \widetilde{G}_{\mu\nu a}$$

$$\theta < 3 \times 10^{-10}$$

- **Analogy: EW vacuum SU(2)**

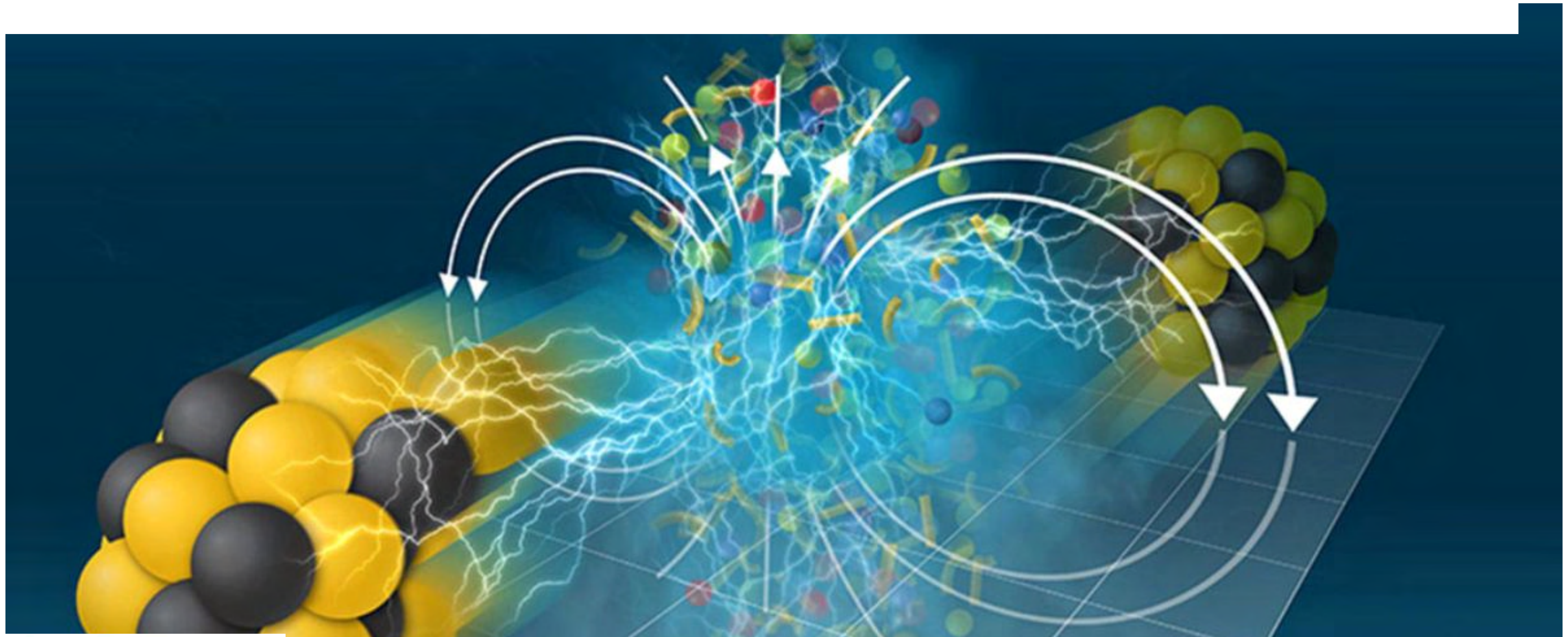


Baryogengesis: ΔN_{CS} = 2 of (L+B)

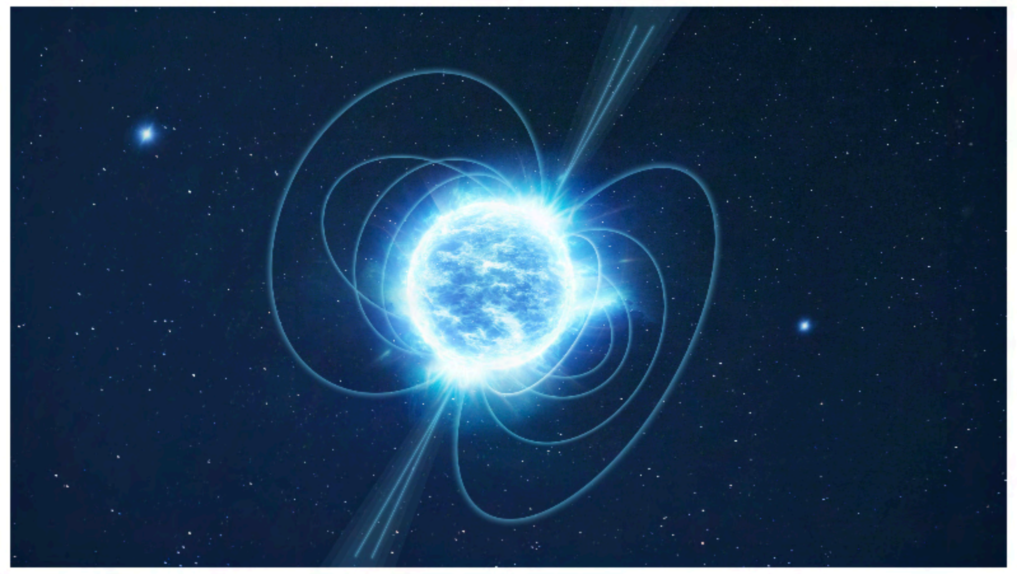
Amoroso, Simone & Kar, Deepak & Schott, Matthias. (2020). How to discover QCD Instantons at the LHC.

Strongest Magnetic Field on Earth

Brookhaven National Laboratory Newsroom Media & Communications Office



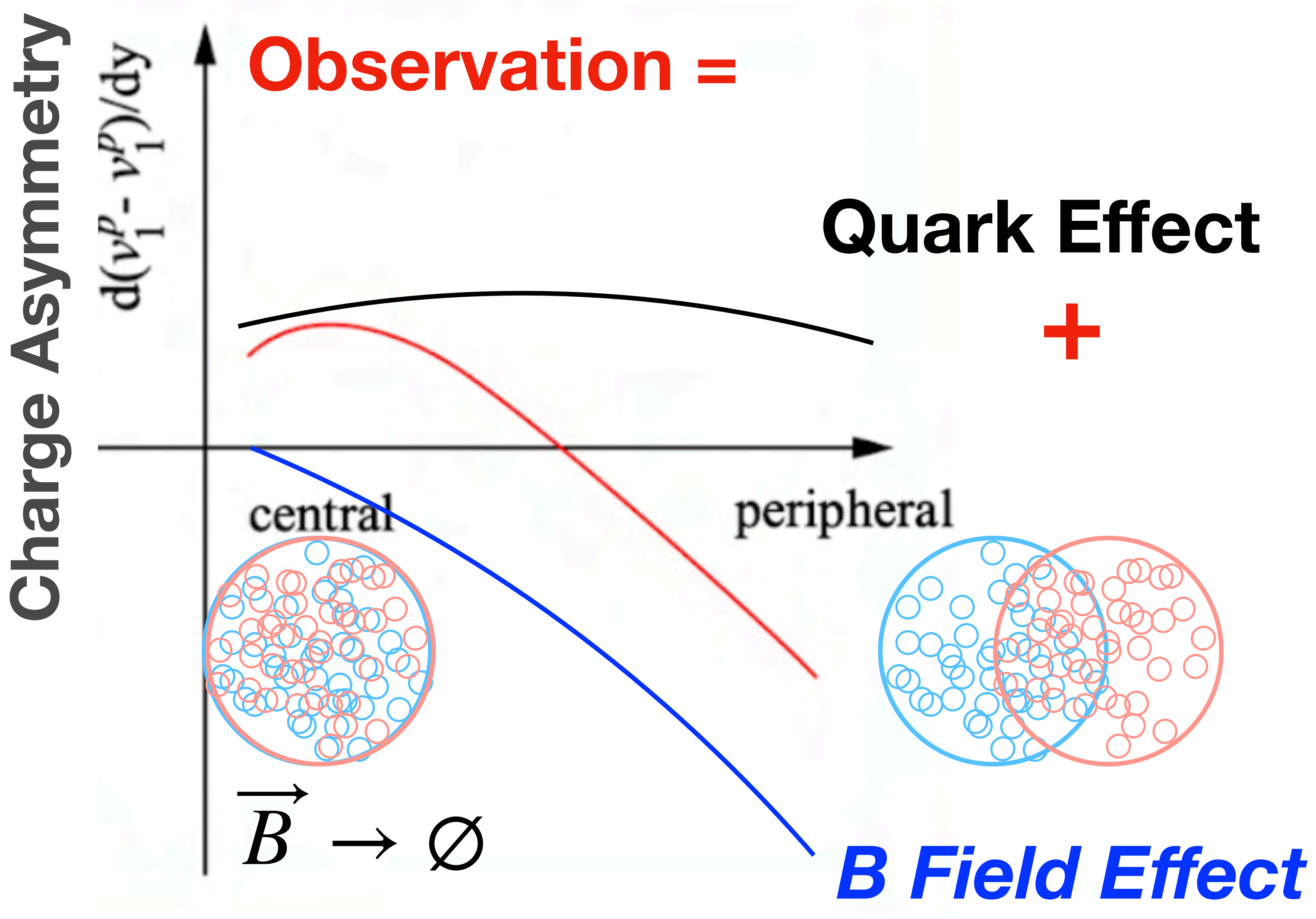
Earth' surface ~ 0.5 G

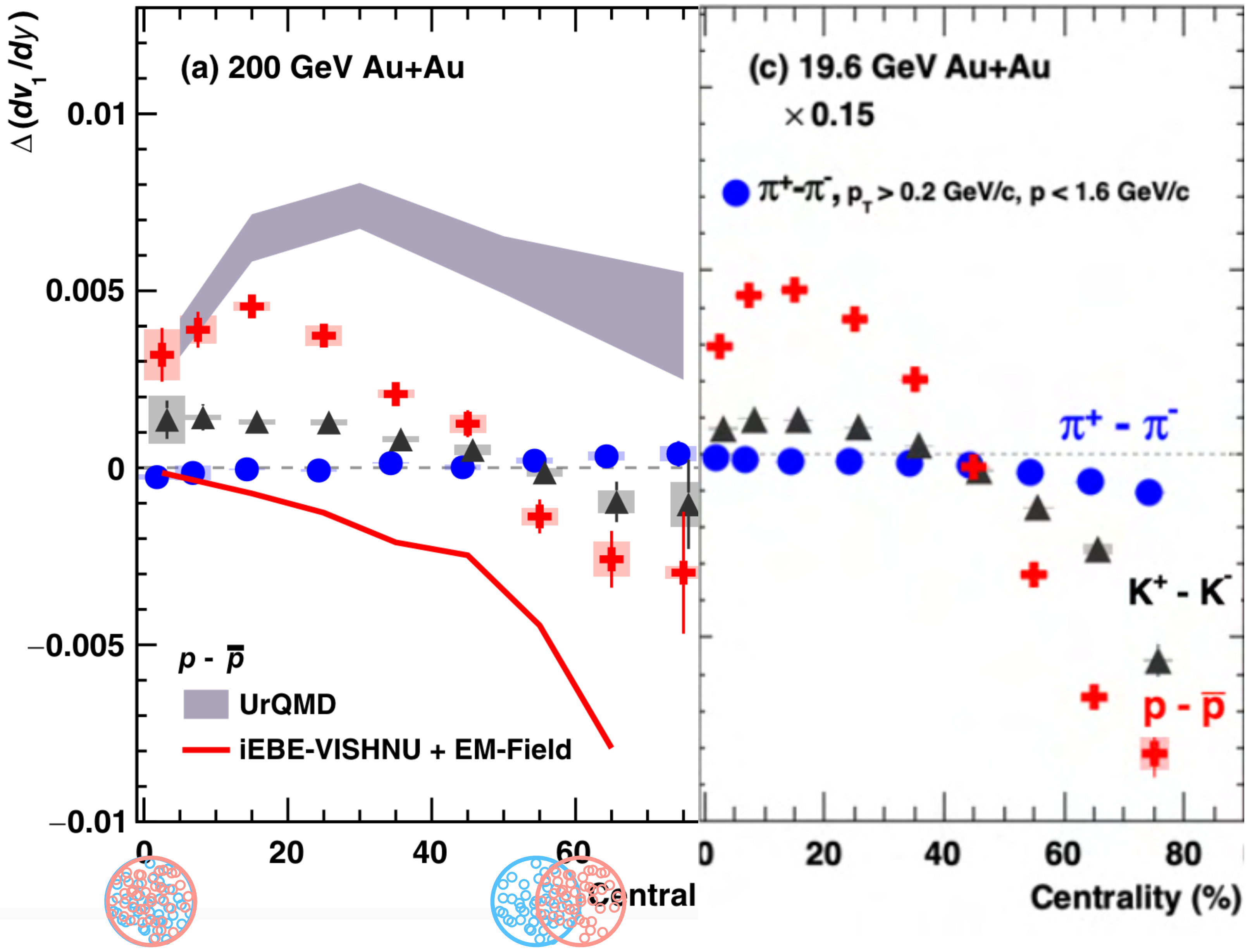


Neutron Star ~ 10^{14} G

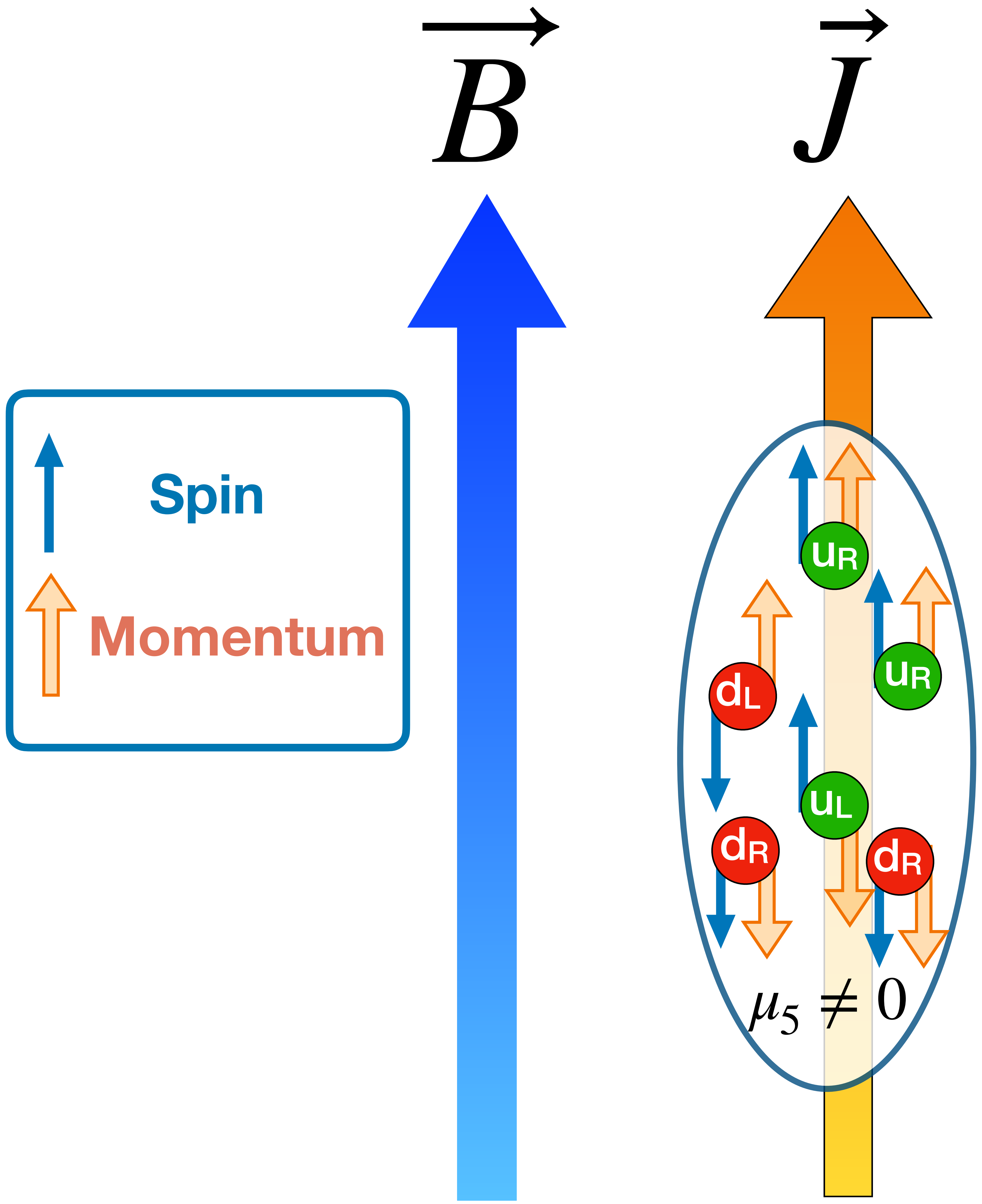
Heavy Ion Collisions ~ 10^{18} G

Phys. Rev. X 14, 011028
A. P. Dash QM 2023, arXiv:2401.04838





Chiral Magnetic Effect



Magnetic field (B) can induce charge separation (current J) for quarks at chirality imbalance (μ_5): CME.

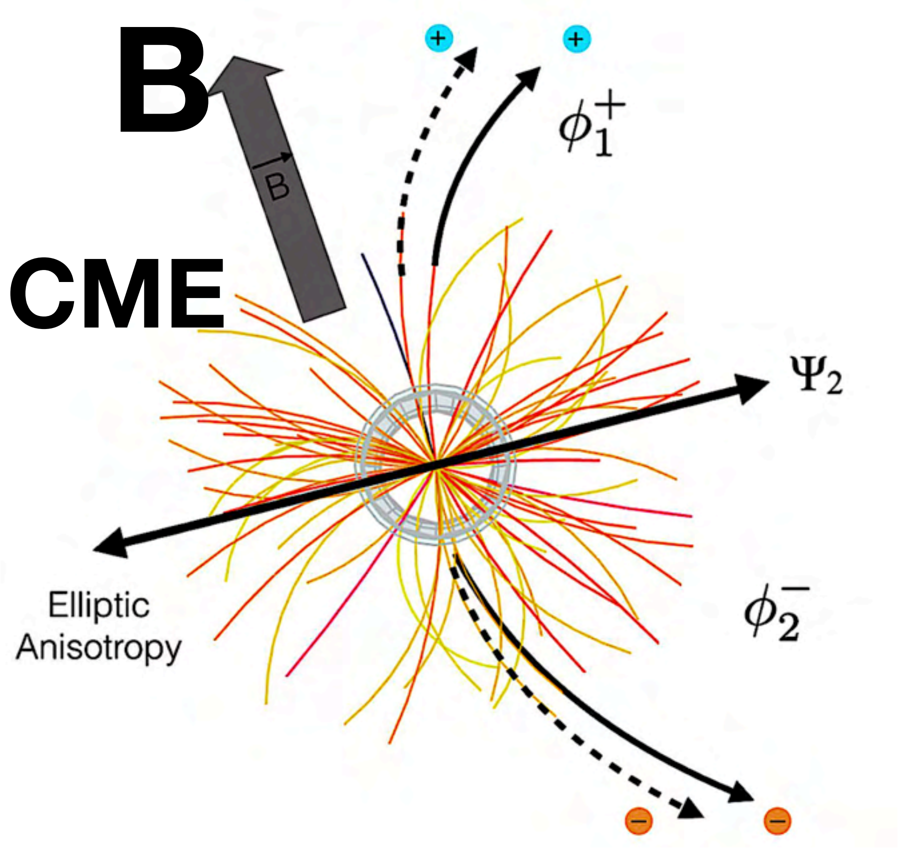
$$\underset{\text{odd parity}}{\underset{\uparrow}{\vec{J}}} \propto \mu_5 \underset{\text{even parity}}{\underset{\uparrow}{\overrightarrow{B}}}$$

Manifestly violate local P and CP symmetry.

3 conditions of CME

- **Chiral Symmetry Restoration**
- **Topological Vacuum Transition** $\mu_5 \neq 0$
- **A strong B field** **The key condition**

CME Observables in HEP



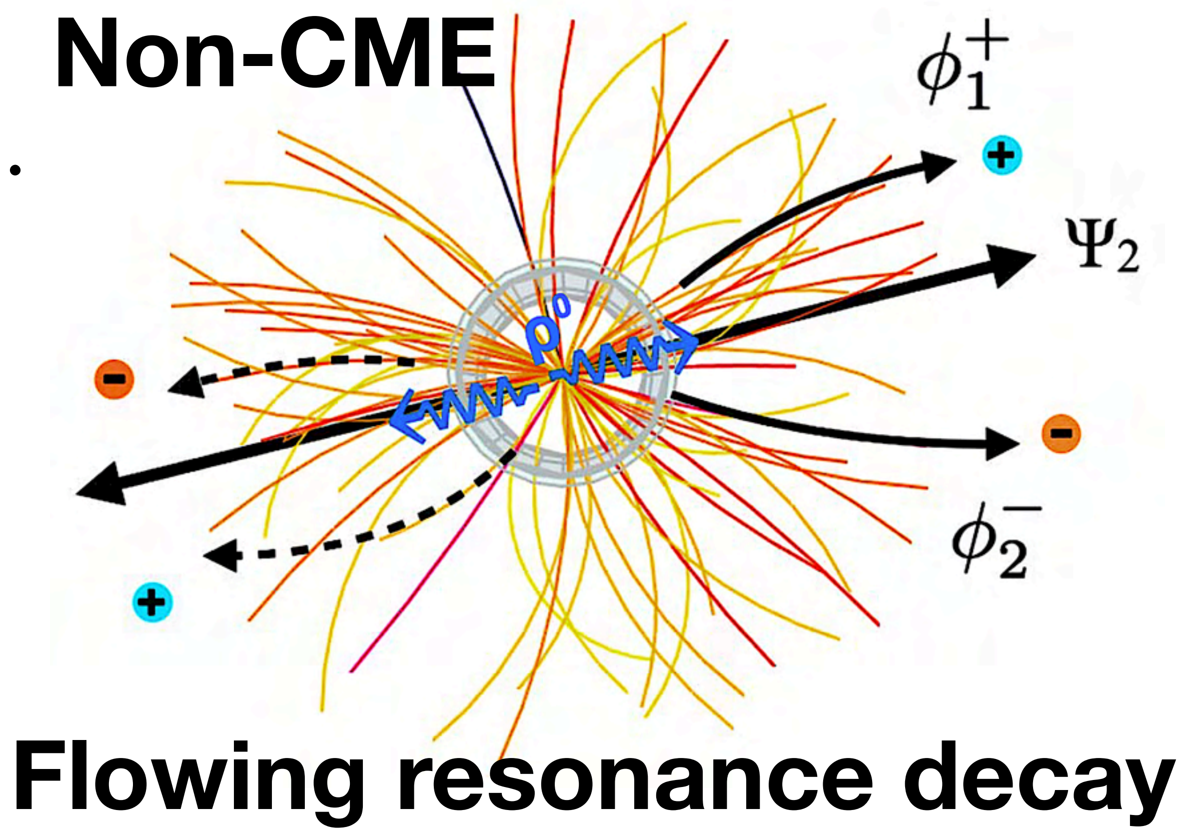
$$\frac{dN_\pm}{d\phi} \propto 1 + 2v_1\cos(\phi-\Psi_{\mathrm{RP}}) + \boxed{2a_1^\pm}\sin(\phi-\Psi_{\mathrm{RP}}) + \boxed{2v_2}\cos(2\phi-2\Psi_{\mathrm{RP}}) + \dots$$

$$\downarrow$$

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

Parity Odd, can not directly observe

Parity Even, sensitive to charge separation



Common CME 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)

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:

$$\gamma^{112} = \langle\cos(\phi_1+\phi_2-2\psi_{\mathrm{RP}})\rangle = \langle v_1 v_1\rangle - \langle a_1 a_1\rangle + \mathrm{BG}(\mathrm{v}_2^{\mathrm{cl}})$$

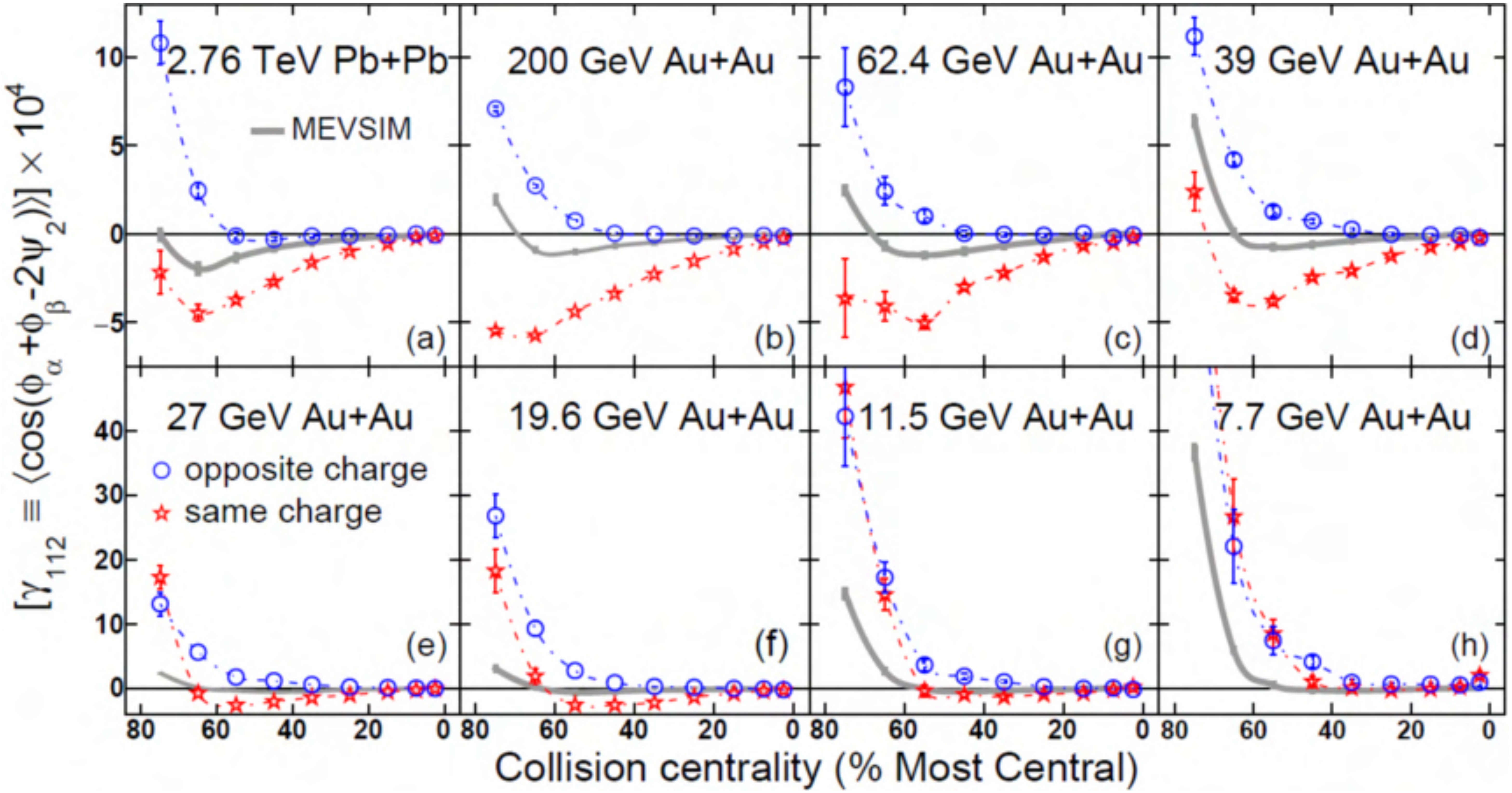
CME signal: $\boxed{\Delta\gamma^{\mathrm{CME}} = \gamma^{\mathrm{OS}} - \gamma^{\mathrm{SS}} > 0}$

BKG indicator:

$$\gamma^{132} = \left\langle\cos(\varphi_1 - 3\varphi_2 + 2\Psi_{\mathrm{RP}})\right\rangle \rightarrow \Delta\gamma^{132}$$

Early CME γ^{112} Measurements

ALICE & STAR BES-I data



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

$\Delta\gamma^{OS} > \Delta\gamma^{SS}$

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

Signal? **Background?**

The 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)**

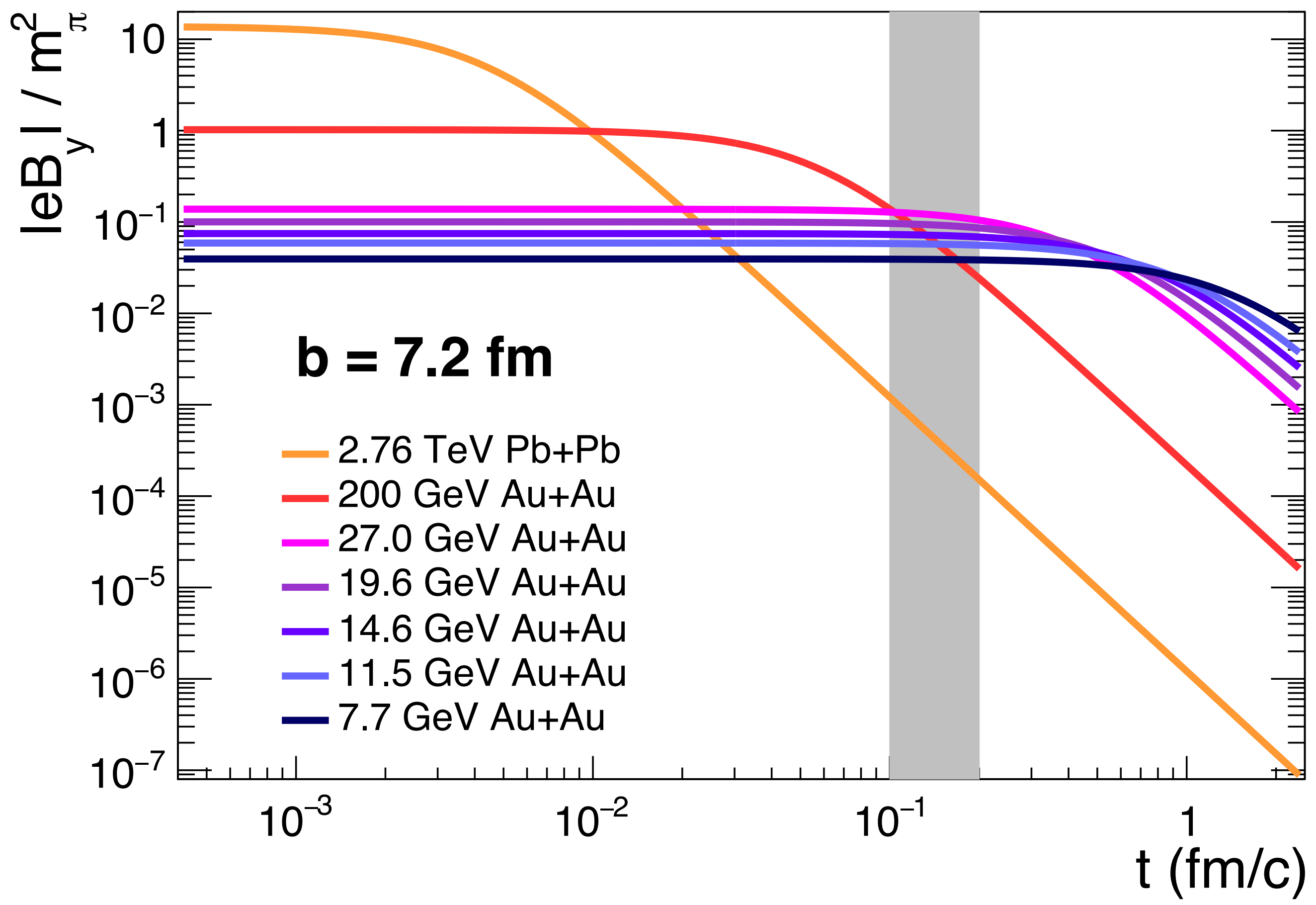
Rough Background Estimation

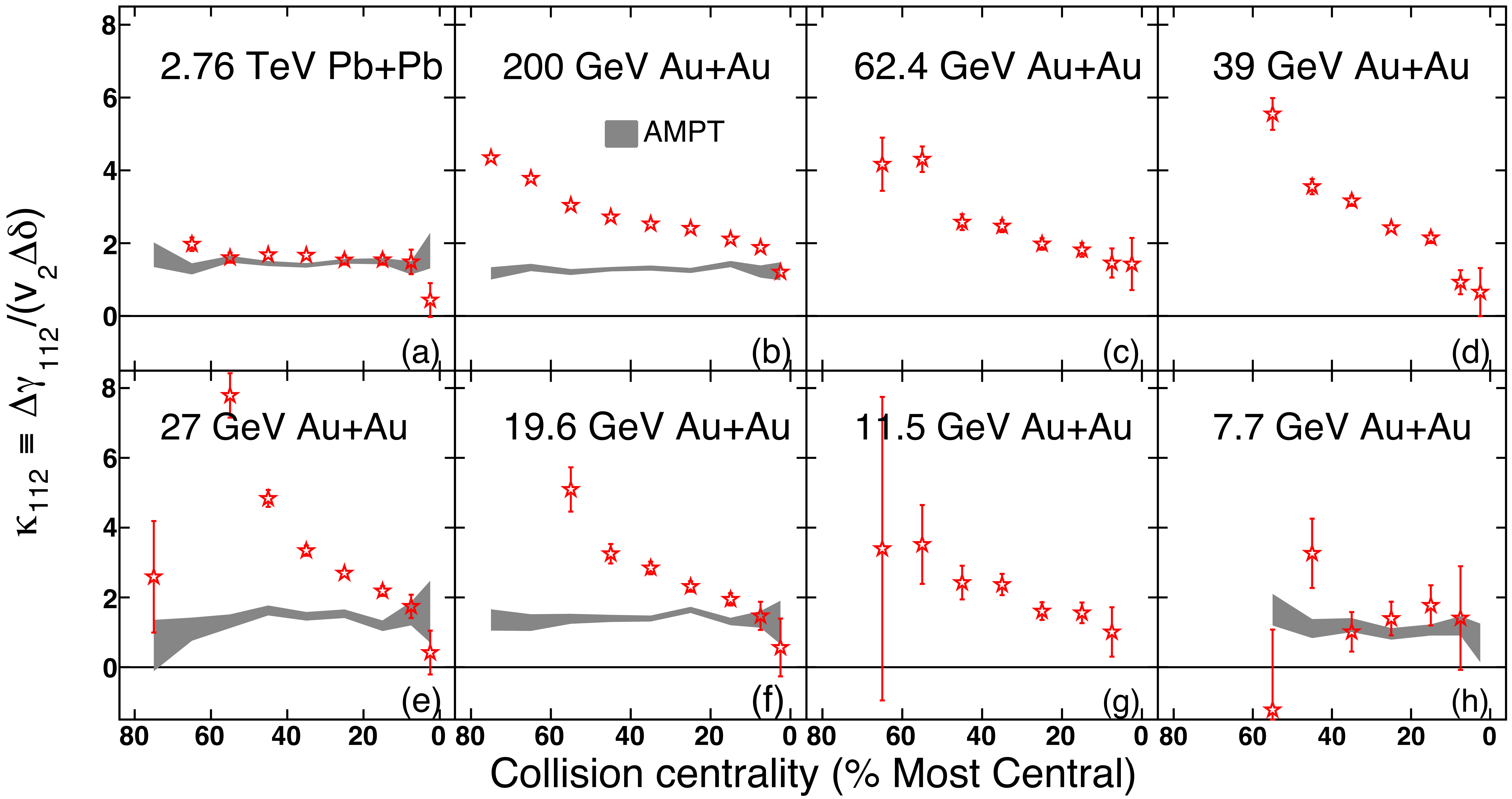
ALICE, Phys. Rev. Lett. 110(2013)012301
STAR, Phys. Rev. Lett. 113(2014)52302

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

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

Two-particle correlator to estimate background of decay, LCC, TMC



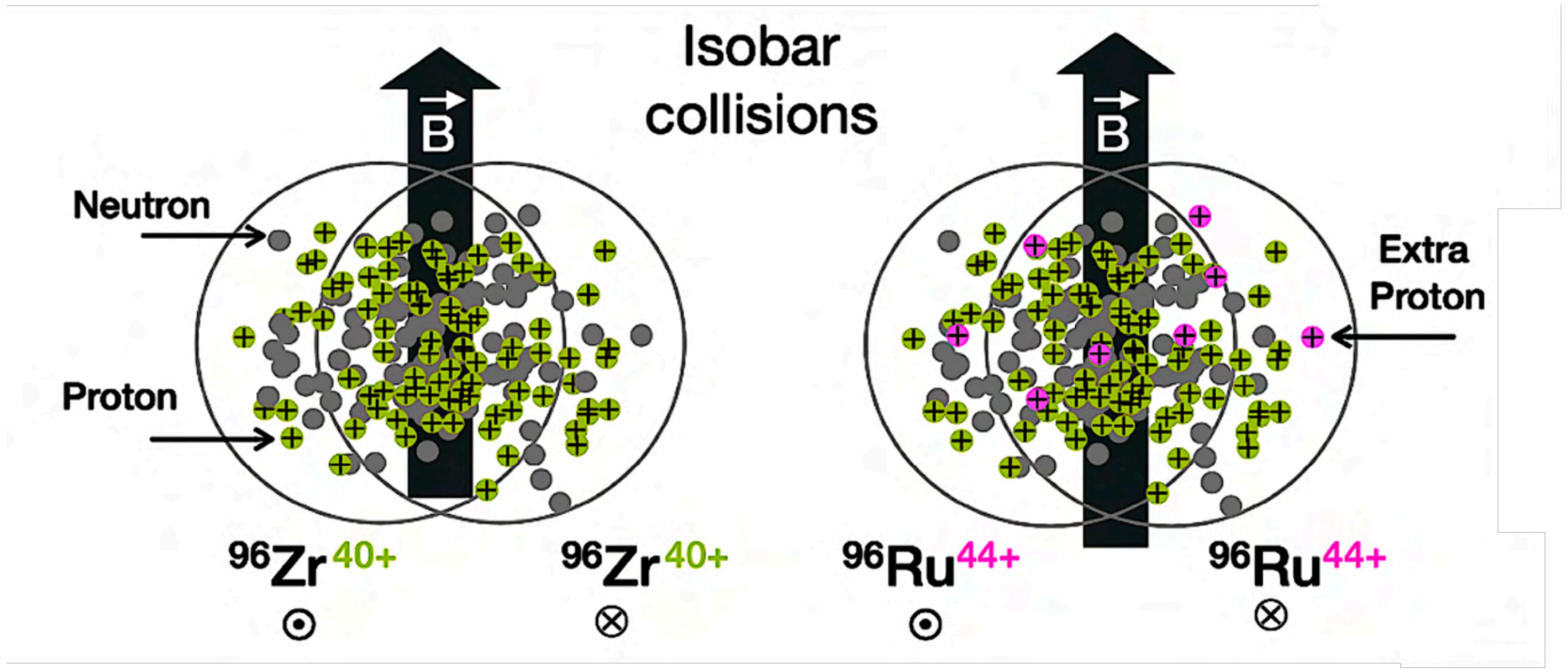


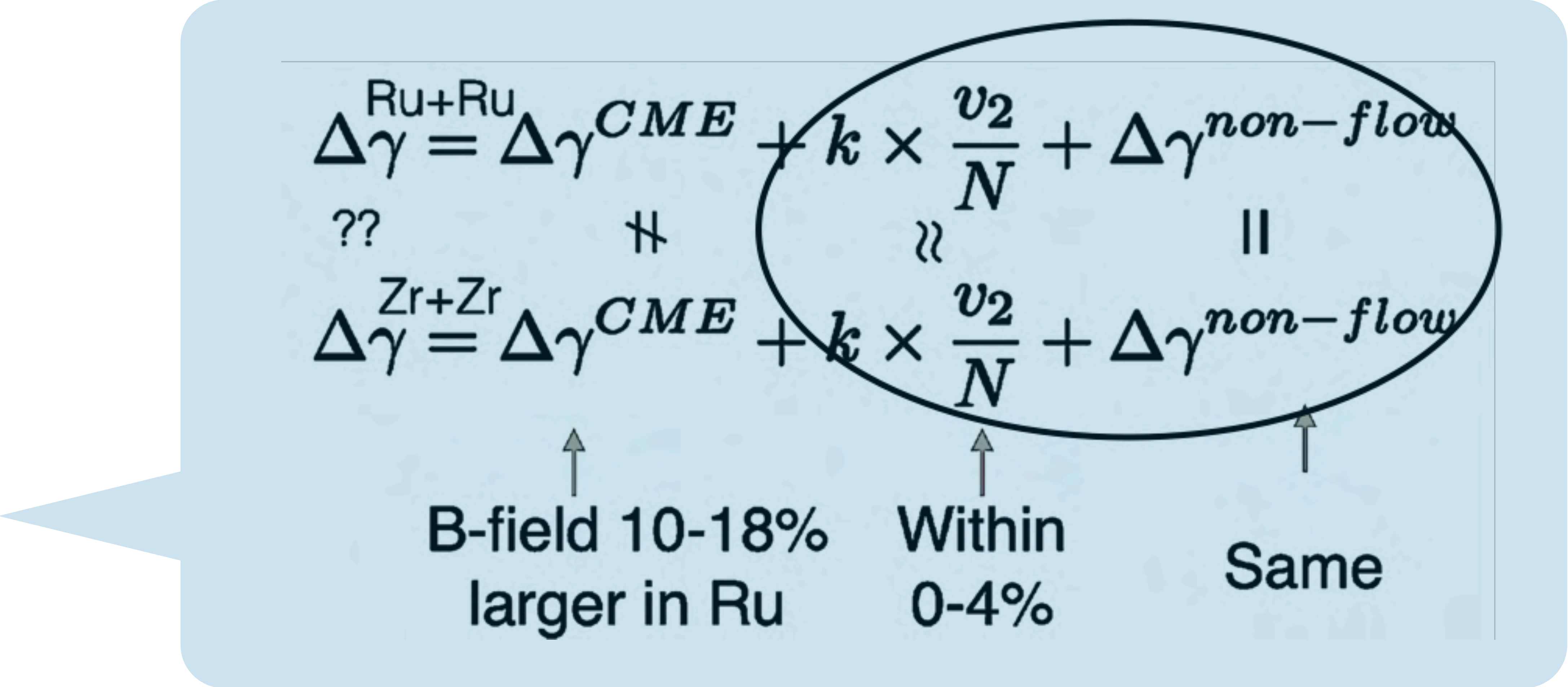
Compared with a pure-background model, the CME signal seems to disappear at 7.7 GeV and 2.76 TeV.

- **very low beam energies: chiral symmetry breaking?**
- **very high energies: no duration of the magnetic field?**
- **At energies in-between: AMPT could underestimate the background.**

Isobar Collisions

One approach is to look for signal difference in controlled experiment of two isobars:



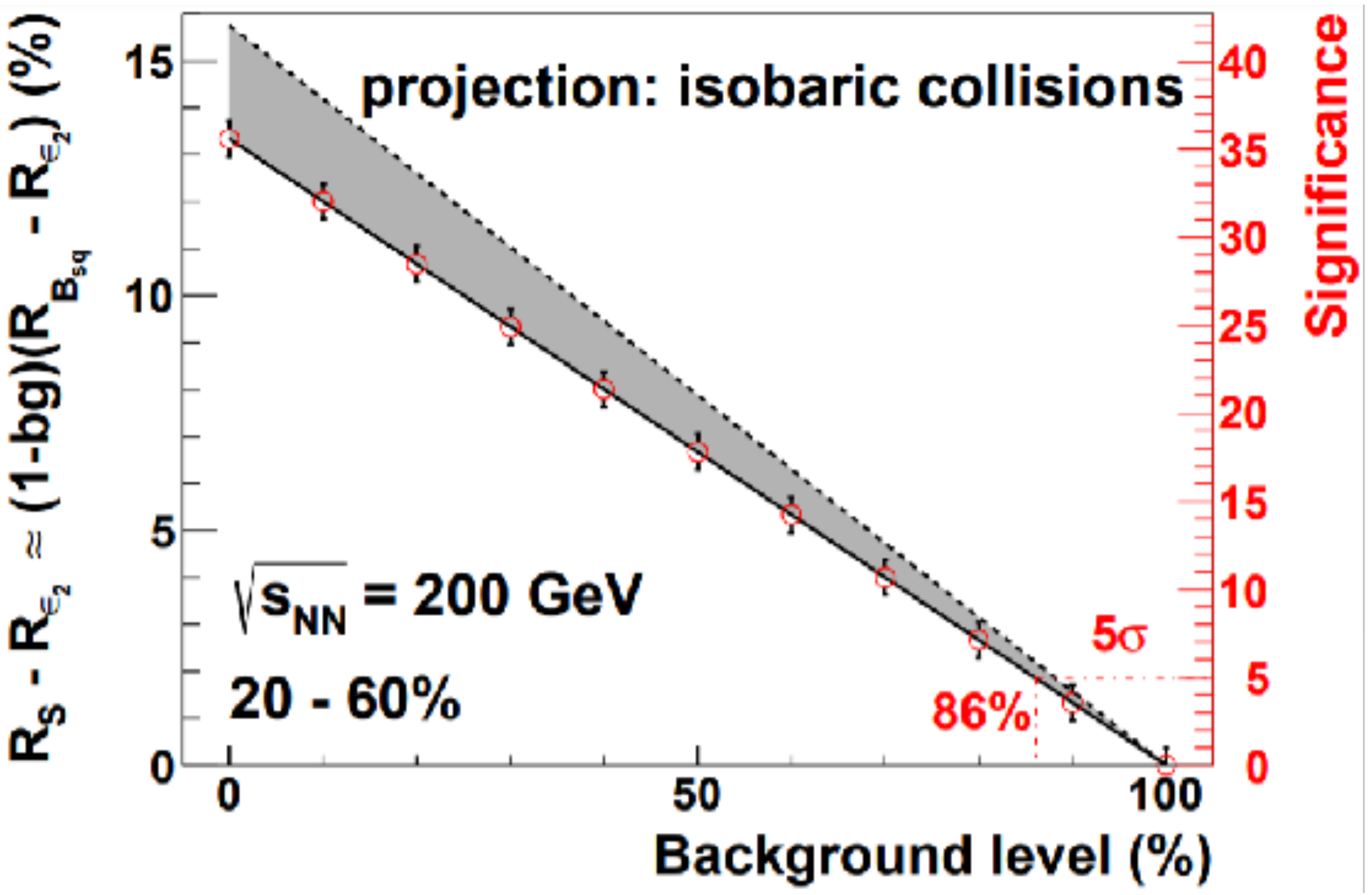


$$\begin{array}{ccccccc} \Delta\gamma^{\text{Ru+Ru}} & = & \Delta\gamma^{CME} & + & k \times \frac{v_2}{N} & + & \Delta\gamma^{non-flow} \\ ?? & & \nparallel & & \wr & & \| \\ \Delta\gamma^{\text{Zr+Zr}} & = & \Delta\gamma^{CME} & + & k \times \frac{v_2}{N} & + & \Delta\gamma^{non-flow} \\ & & \uparrow & & \uparrow & & \uparrow \\ & & \text{B-field 10-18\% larger in Ru} & & \text{Within 0-4\%} & & \text{Same} \end{array}$$

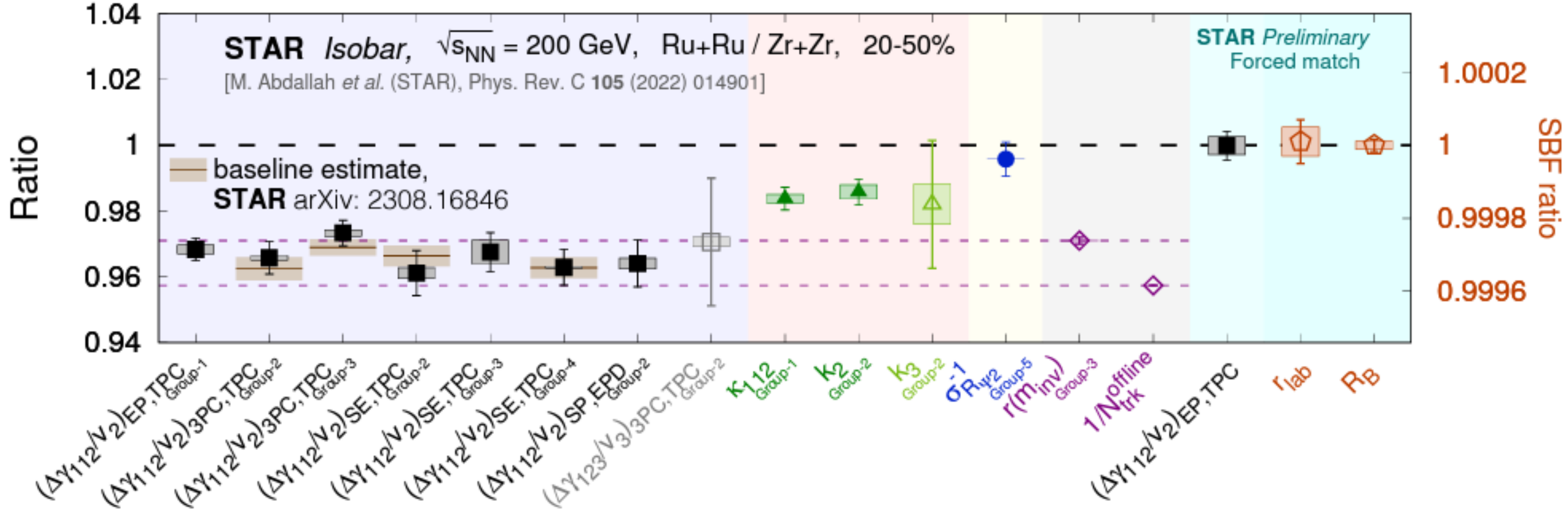
Expect $\Delta\gamma_{112}/v_2$ **double ratio** $\frac{\text{Ru} + \text{Ru}}{\text{Zr} + \text{Zr}} > 1$

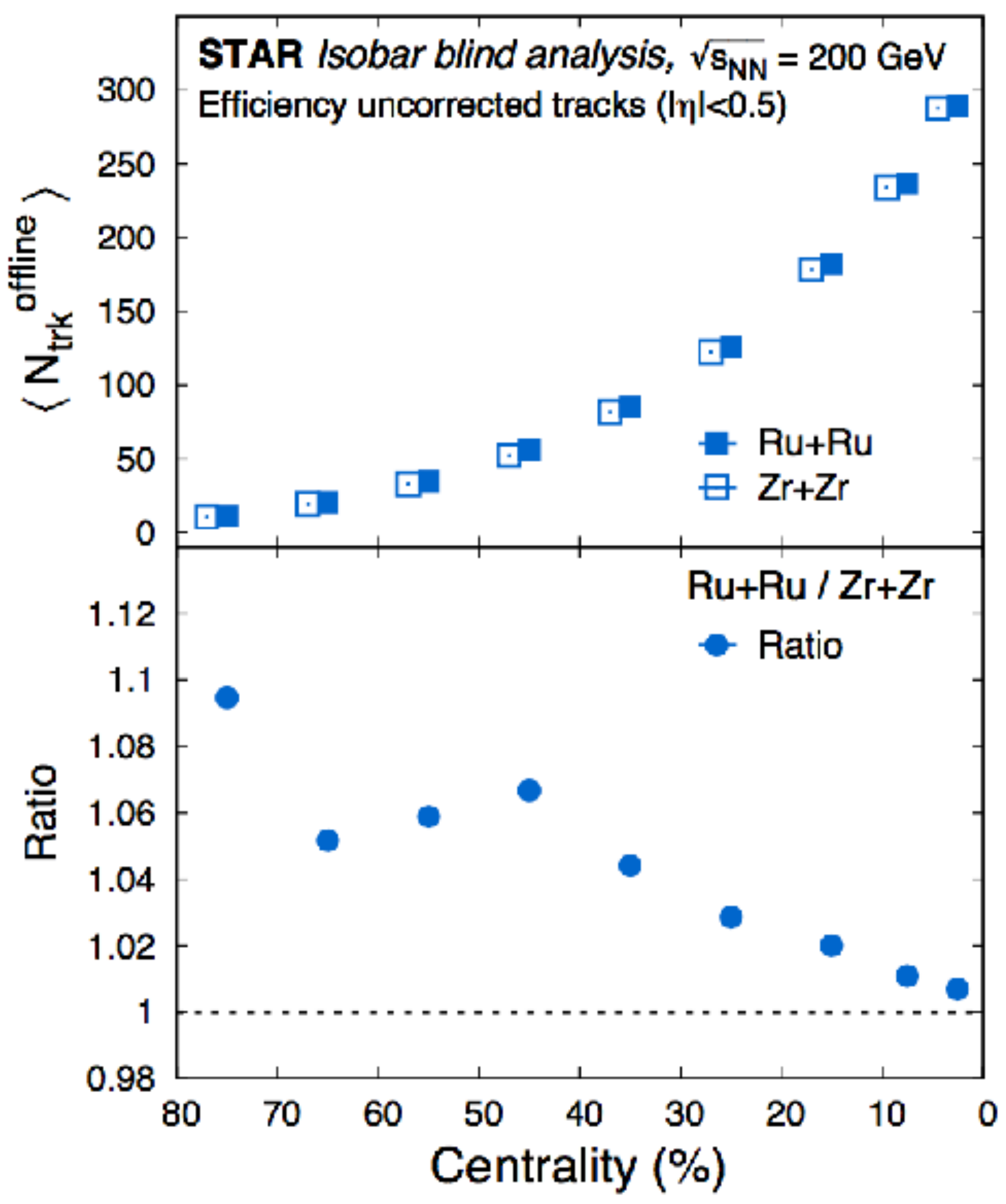
With 2.5 B events per species: uncertainty of 0.4% in the $\Delta\gamma_{112}/v_2$ ratio.

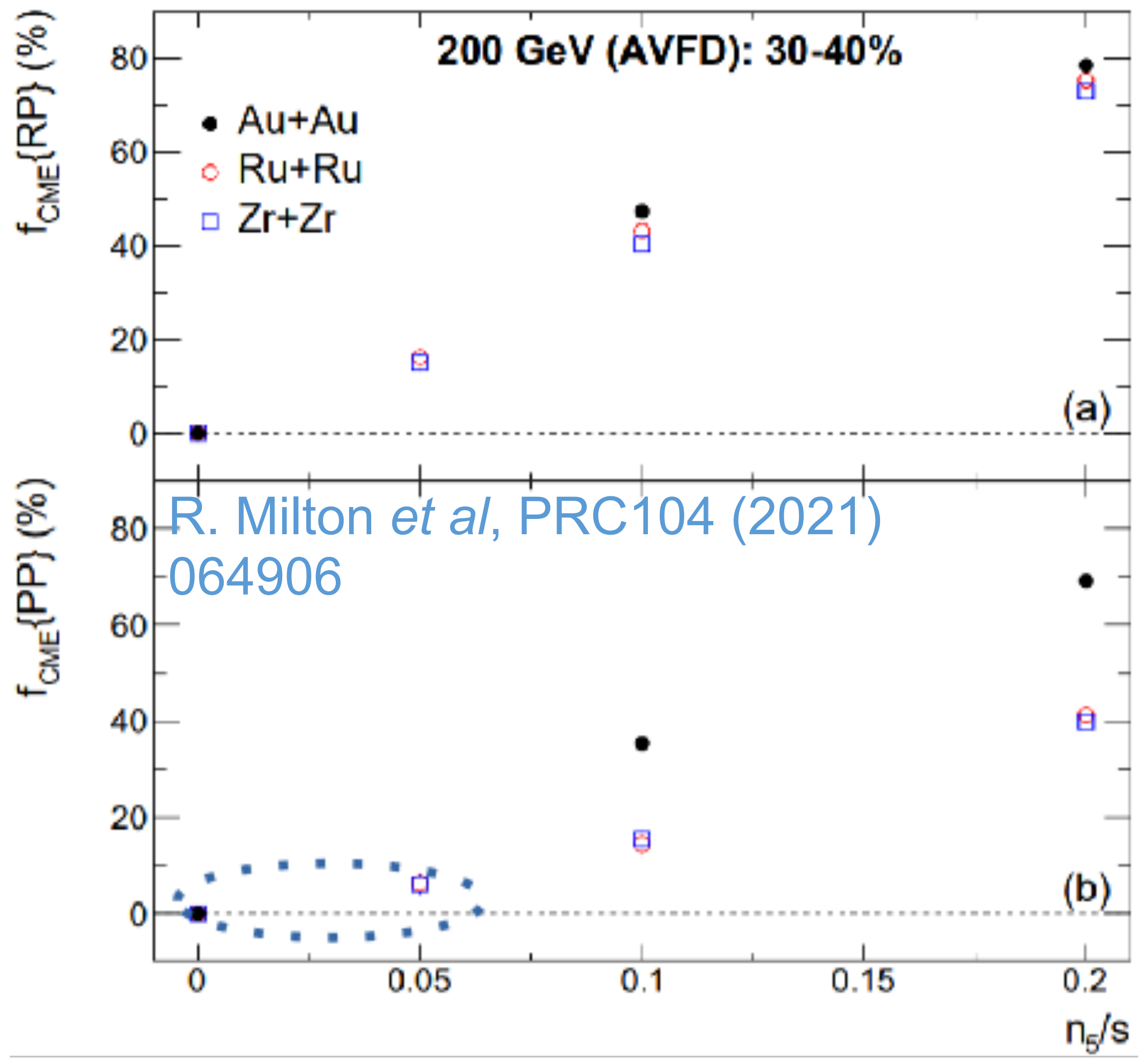
if f_{CME} > 14% in $\Delta\gamma_{112}$, difference > 2%, yielding a 5σ significance.



Isobar Results







R. Milton *et al*, PRC104 (2021) 064906

However, we found ratio $\frac{\mathrm{Ru+Ru}}{\mathrm{Zr+Zr}} < 1$

- **Explained by the multiplicity mismatch.**
- **Signal fraction f_{CME} is small in Isobar.**
- **Smaller system → BKG dominated → double-killed f_{CME}**

Lessons we learned from Isobar

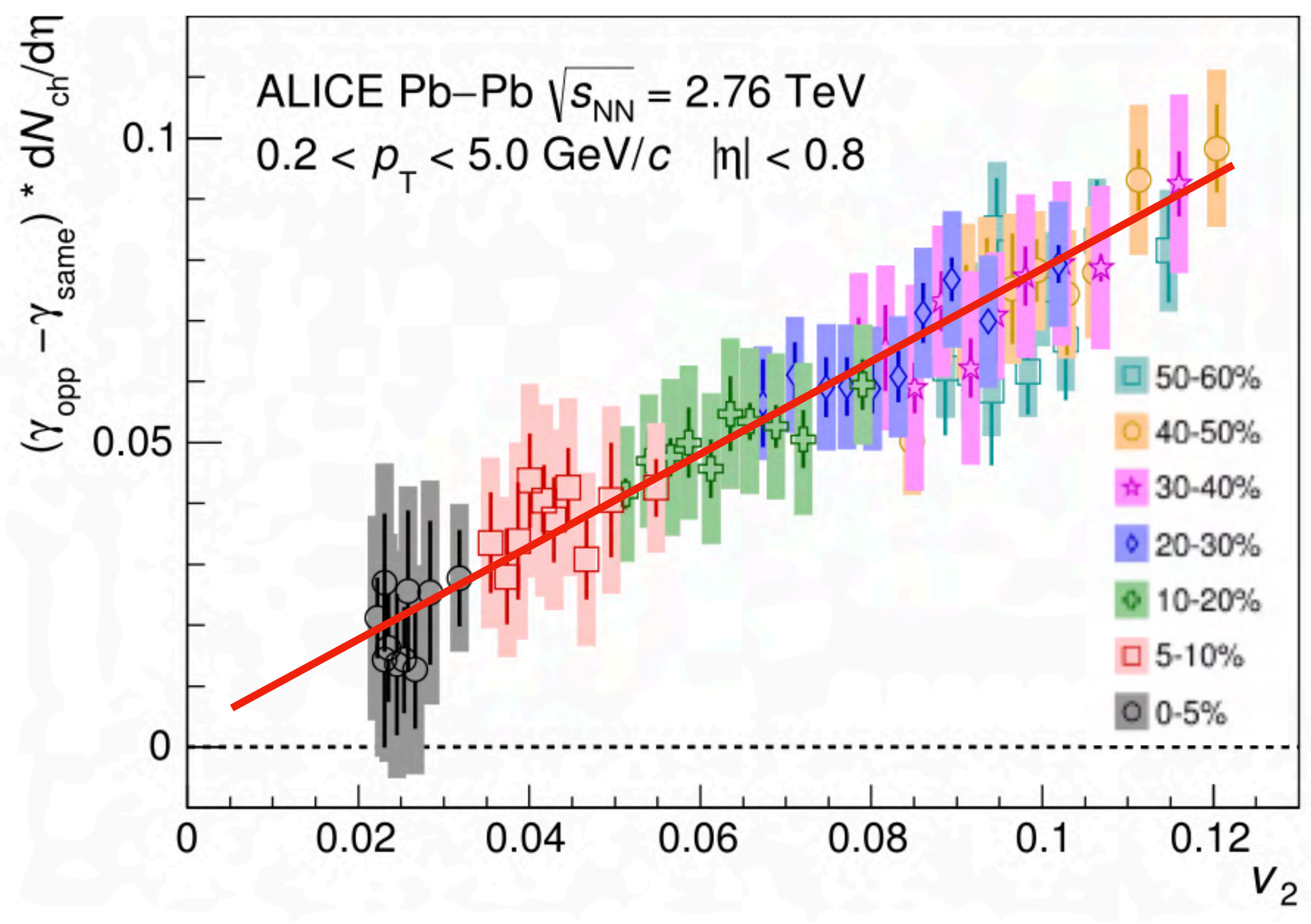
- **Need to investigate the BKG contribution**
- **Should go back to large collisions system**

"Traditional" Event Shape Engineering

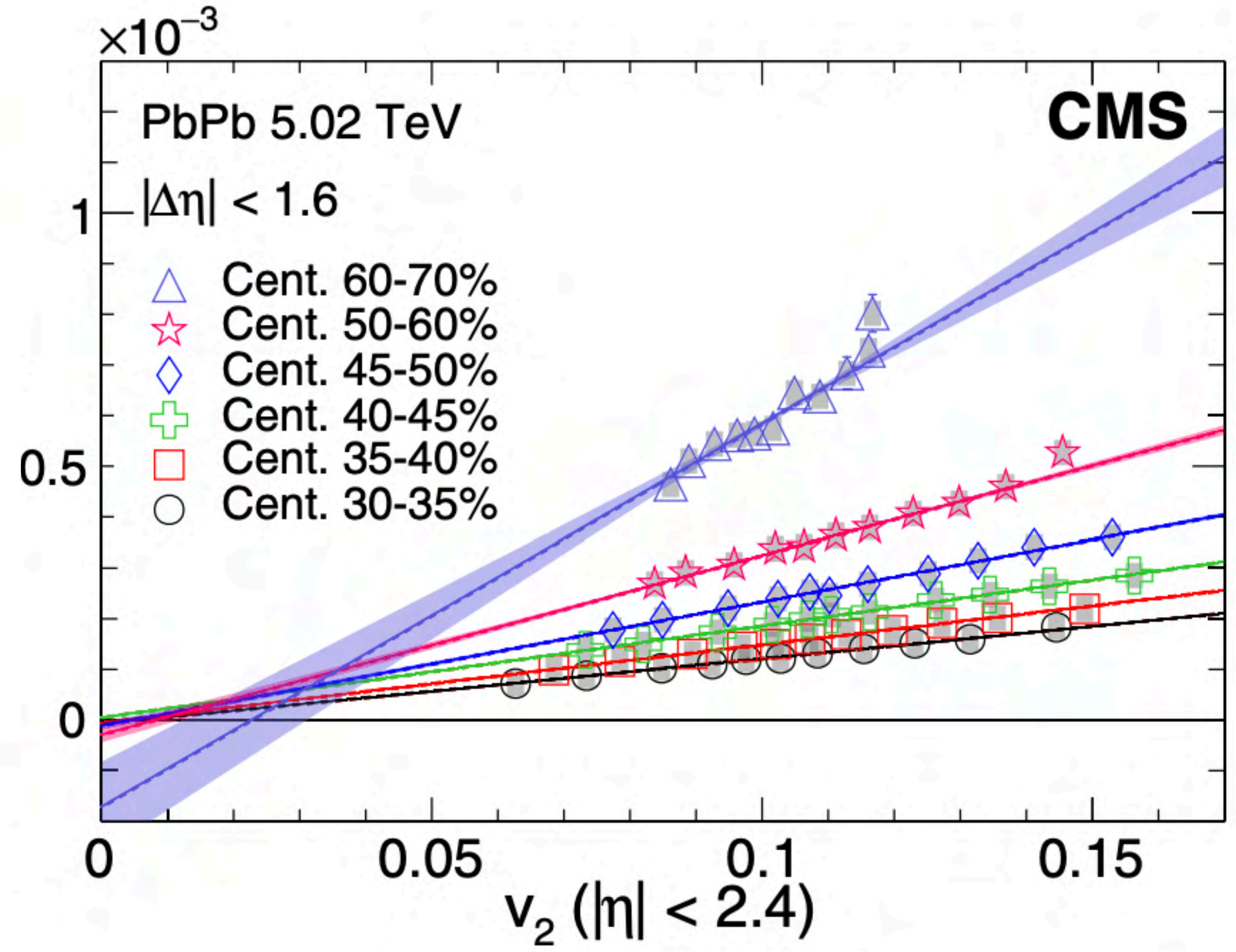
- Three sub-events are used: one for POI, one for event plane, and one for event shape variable, q_2, the modulus of the flow vector.

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

ALICE, Phys. Lett. B, 777, 151 (2018)



CMS Phys. Rev. C 97, 044912 (2018)



- Measure $\Delta\gamma^{112}$ vs q_2 and v_2 vs q_2, then plot $\Delta\gamma^{112}$ vs v_2 to extrapolate zero-v_2 intercept.
- At LHC energies, all the ESE results are consistent with zero. (no duration of the magnetic field?)
- Since POI are excluded from q_2, the extrapolation is long and unstable.

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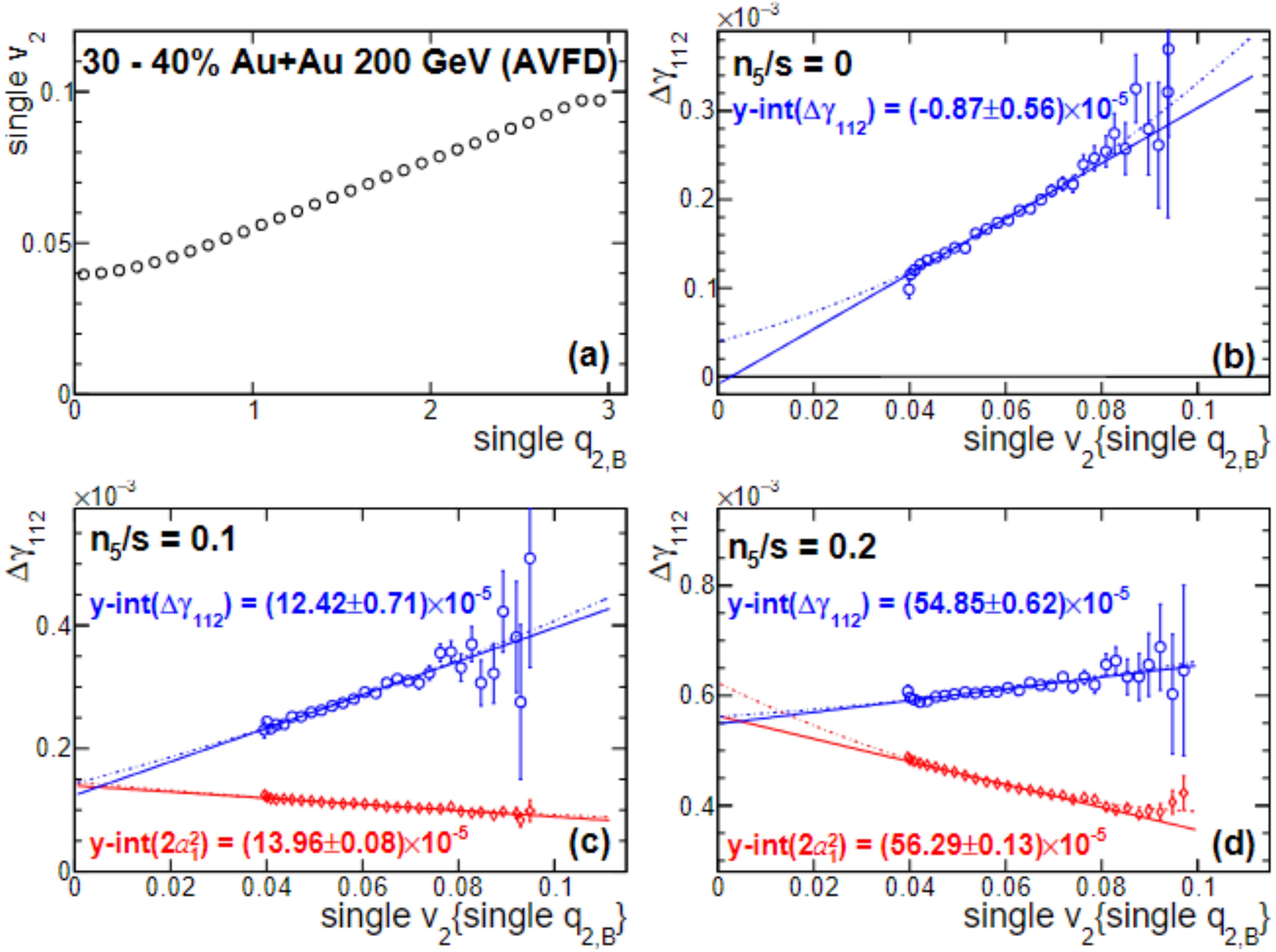

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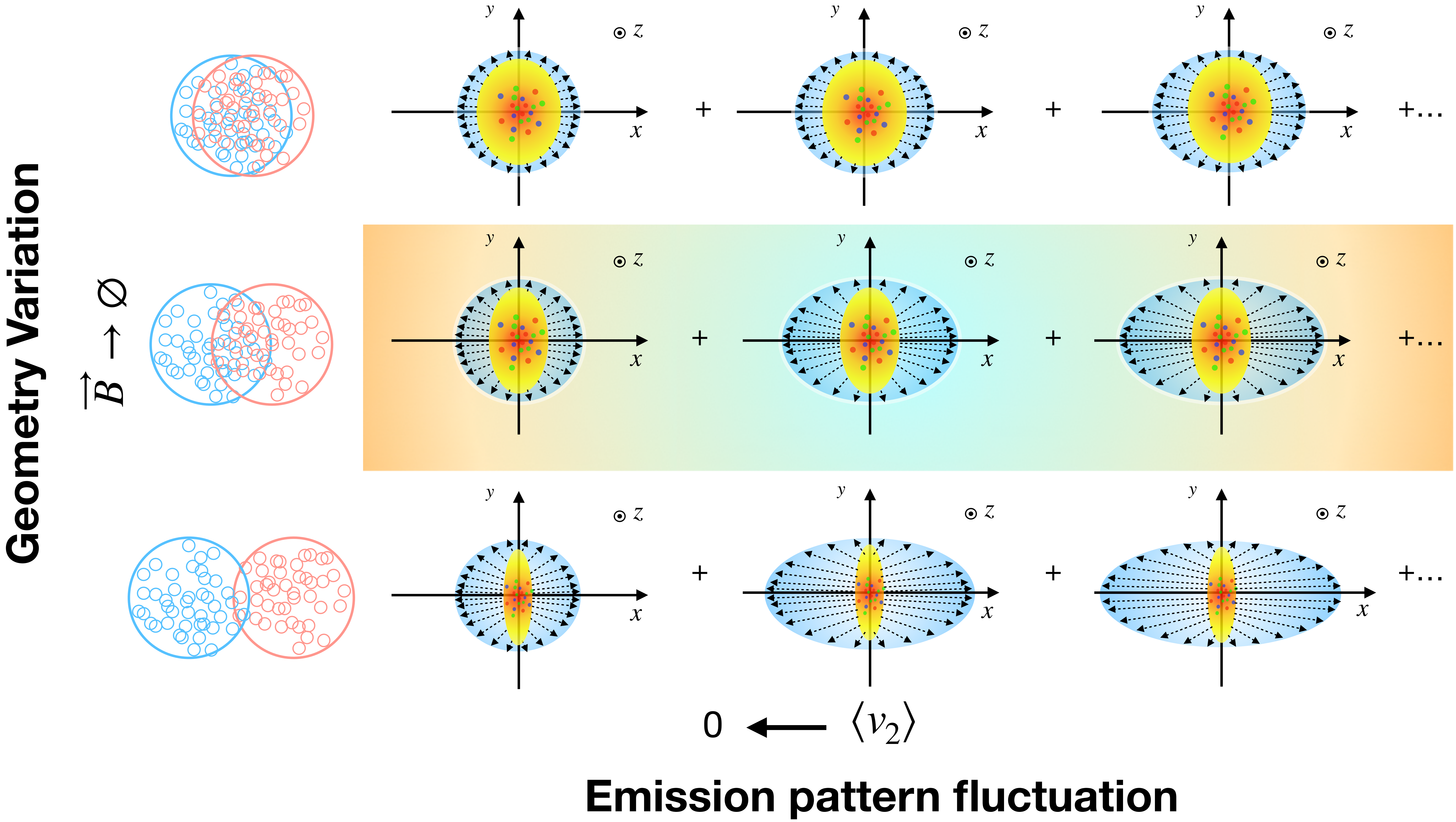
- **At LHC energies, all the ESE results are consistent with zero. (no duration of the magnetic field?)**
- **Since POI are excluded from q_2, the extrapolation is long and unstable – works if the signal is very large, while systematic uncertainties too large for small signals**

Schematic Diagram of Event Shape

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 range in rapidity
- emission pattern fluctuations – more localized, less correlated over rapidity

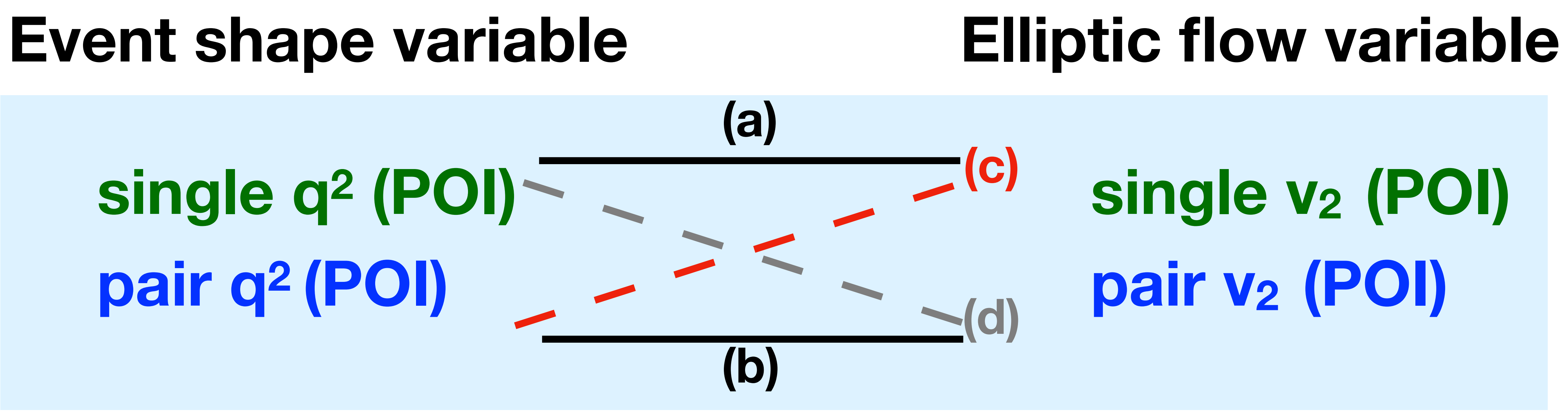
H. Petersen and B. Müller, Phys. Rev. C 88, 044918



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

CME background comes from combined eccentricity and emission patterns

Event Shape Selection and v_2 Control



Event shape variable

Elliptic flow variable

single q^2 (POI)

pair q^2 (POI)

(a)

(b)

(c)

(d)

single v_2 (POI)

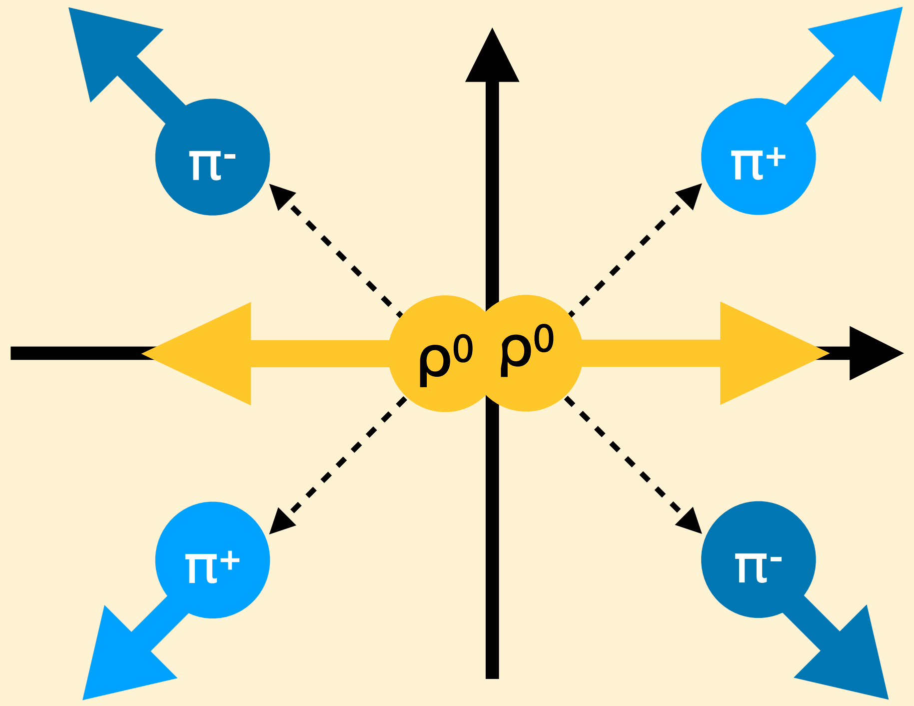
pair v_2 (POI)

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

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

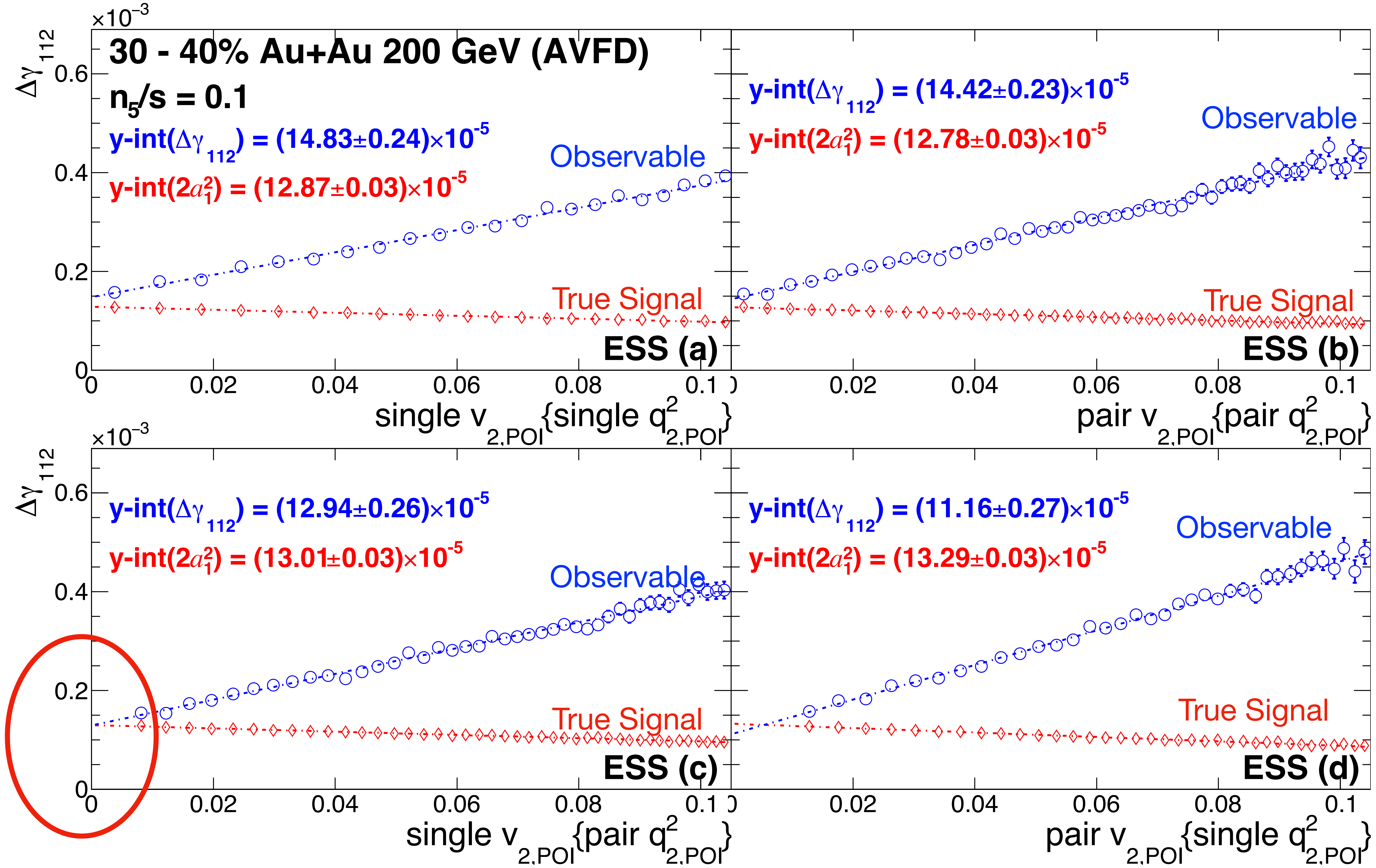
- **ESS recipes (a) and (b) involve direct event-by-event correlations between $q_2{}^2$ and v_2, which will cause under-subtraction of background.**
- **We should use "mixed" recipes, (c) or (d).**
- **Redefine $q_2{}^2$ with an extra normalization.**
- **Pair $q_2{}^2$ and pair v_2 are based on φ_p.**

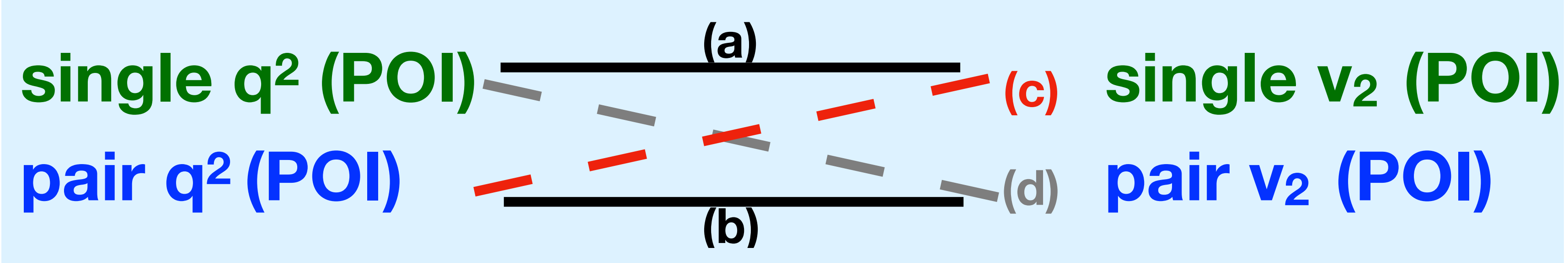
$$q_2^2 = \frac{\left(\sum_{i=1}^{N}\sin 2\varphi_i\right)^2 + \left(\sum_{i=1}^{N}\cos 2\varphi_i\right)^2}{N(1 + N\langle v_2\rangle^2)}$$

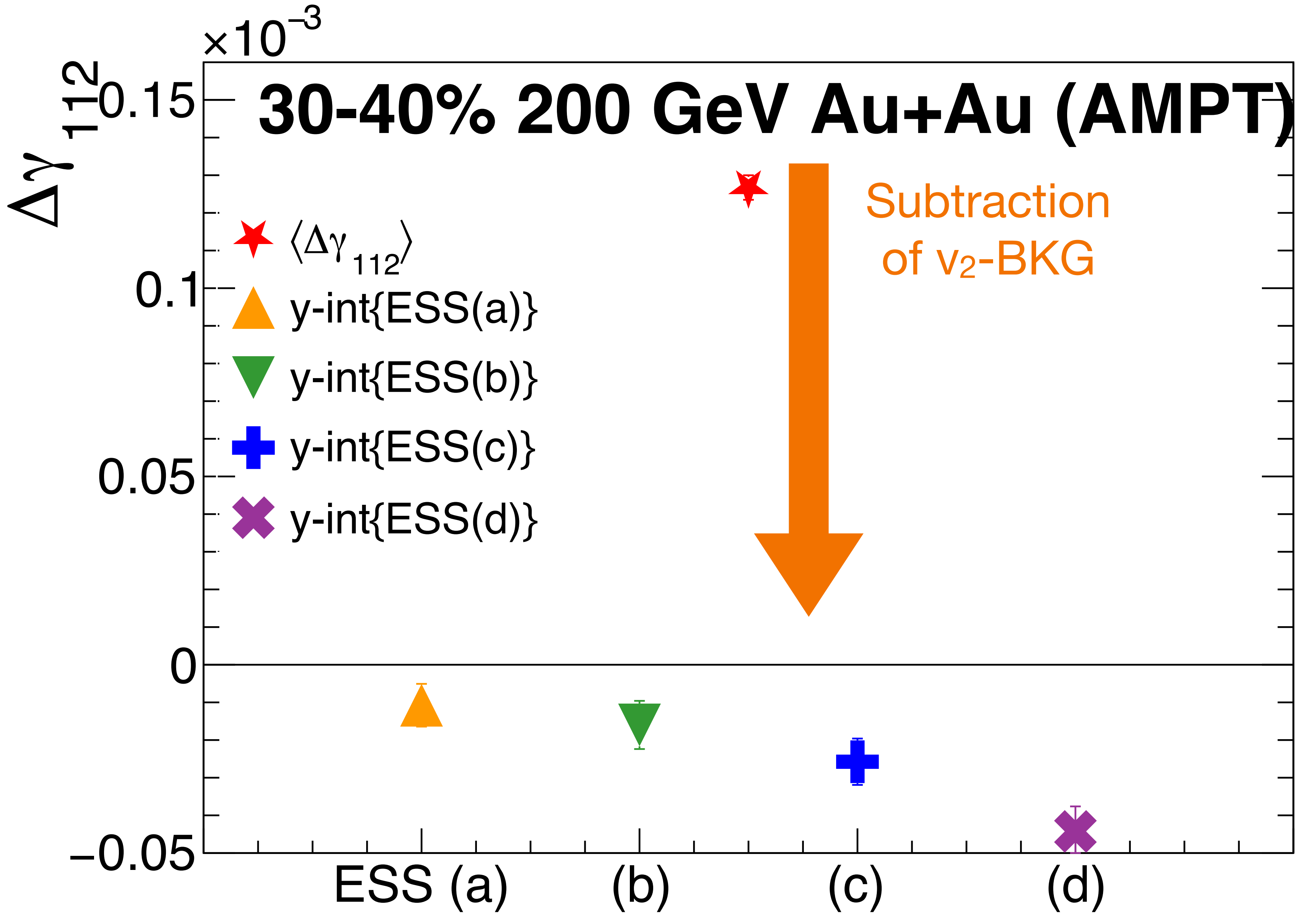


- $v_2\{\pi\} = 0; v_2\{\rho\} > 0$
- $\Delta\gamma^{112} = 1$ (pure-BKG)
- $q^2_{\mathrm{POI}} = 0$
- $q^2_{\mathrm{PPOI}} = 1$

Simulation







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

- In AVFD, the **optimal ESS recipe (c)** accurately matches the input true CME signal.
- Mixed combinations further suppress residual BKG: intercepts follow an ordering (a)>(b)>(c)>(d)
- With AMPT, all ESS schemes seem to over-estimate the BKG (same ordering as AVFD).

ESS procedure

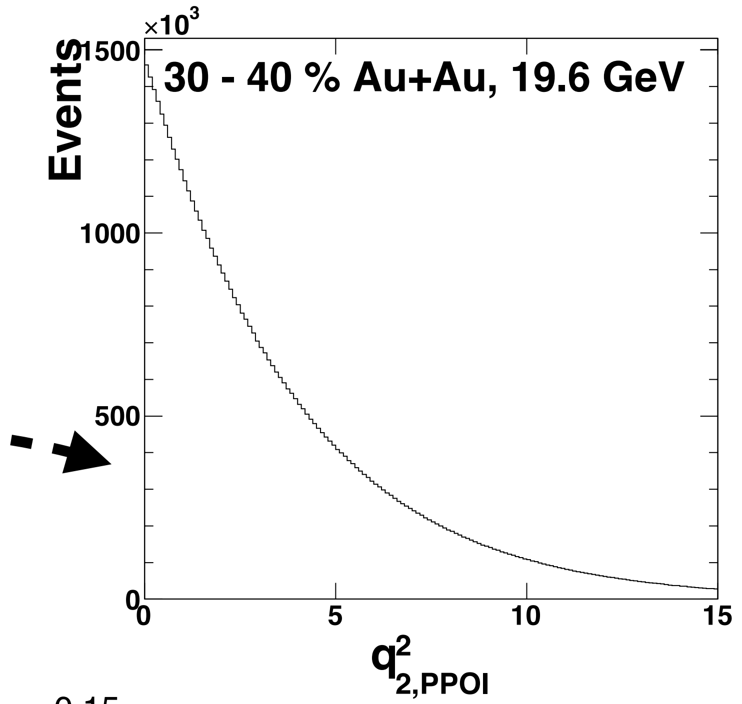
- A novel method to control emission pattern: utilize **event shapes** of **POI kinematic region**

1. Categorize events

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

Flow vector with higher-order normalization

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



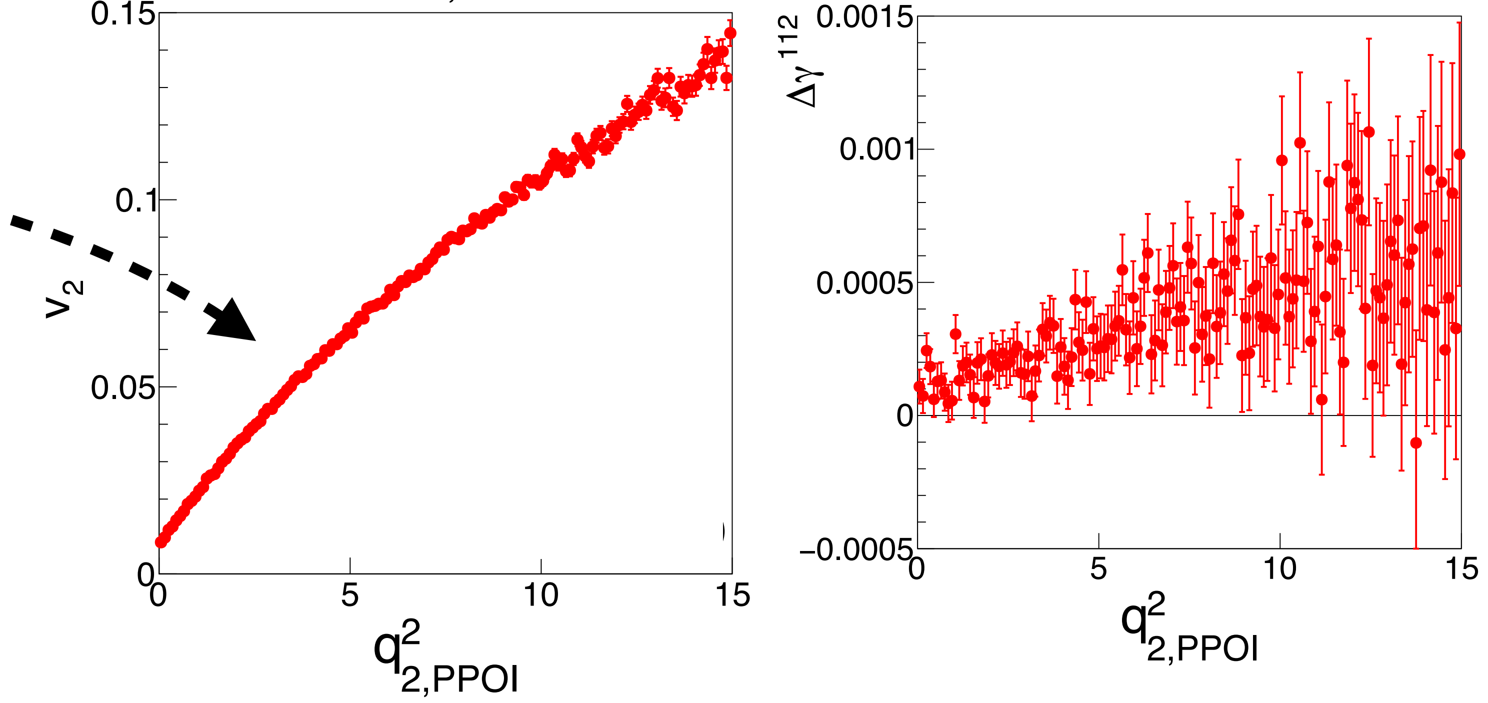
2. Measure the Δγ Observable & v_2 flow

Optimal Solution

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

- **adding momenta of two POI particles**

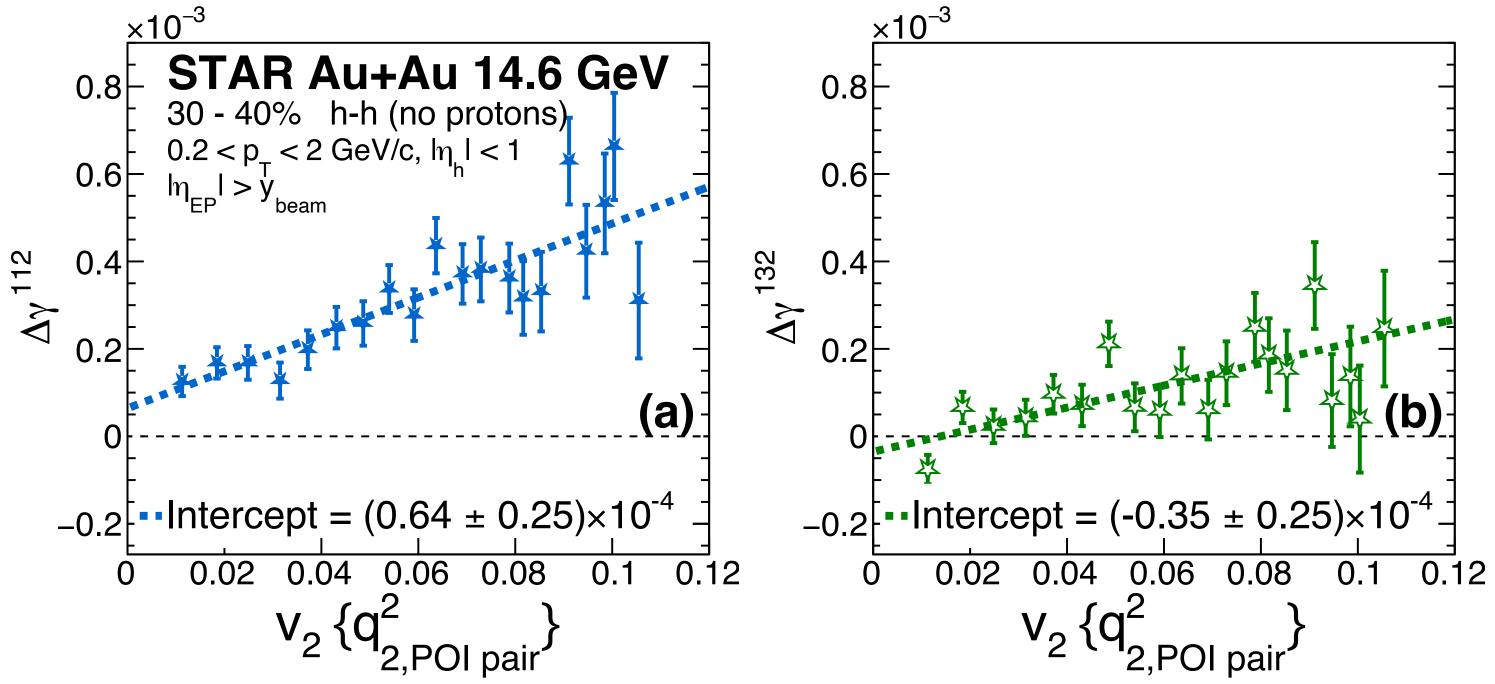
~ mimic resonance decay.



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

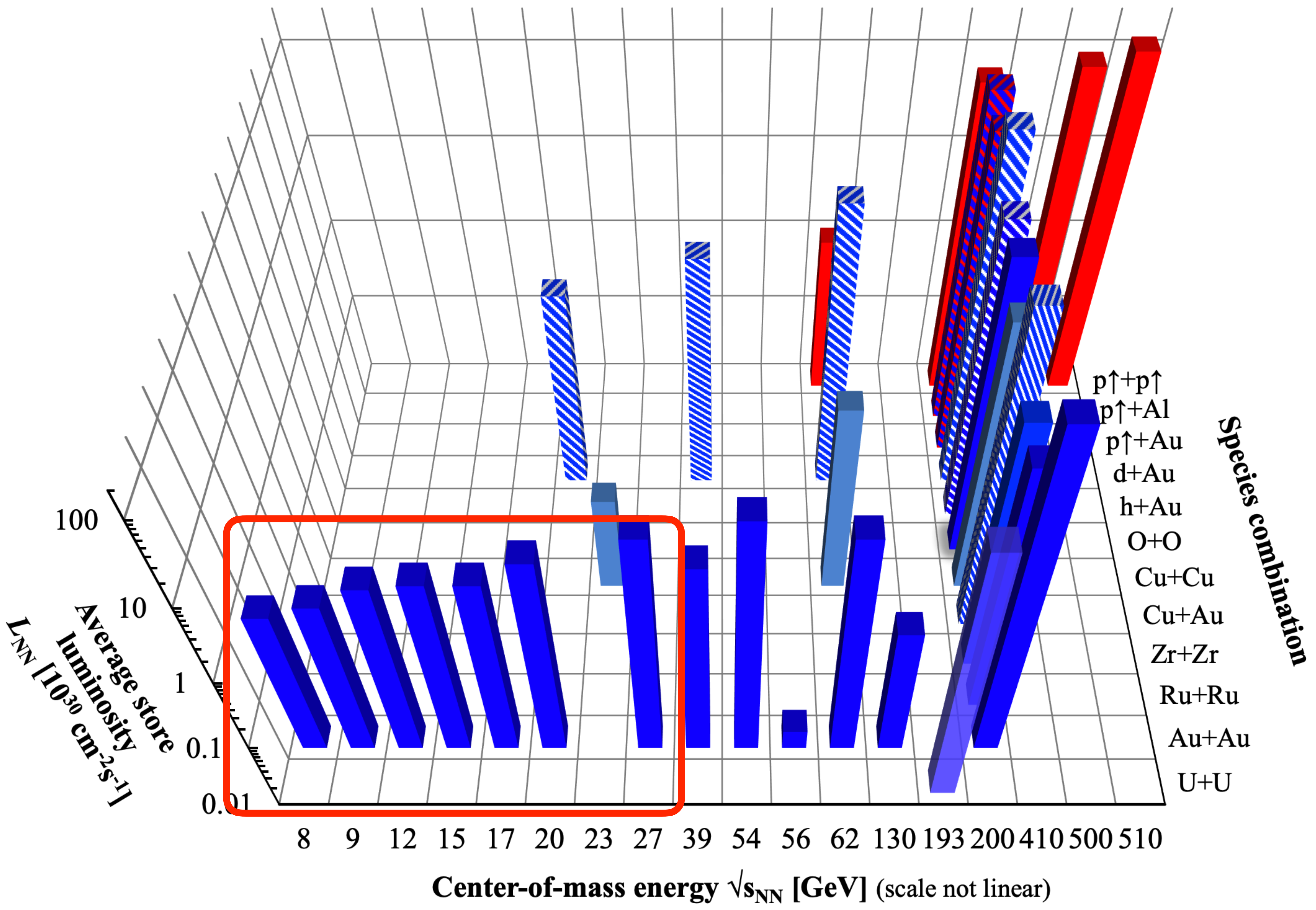
$$\Delta\gamma_{ESS}^{112} = Intercept \times (1 - v_2)^2$$

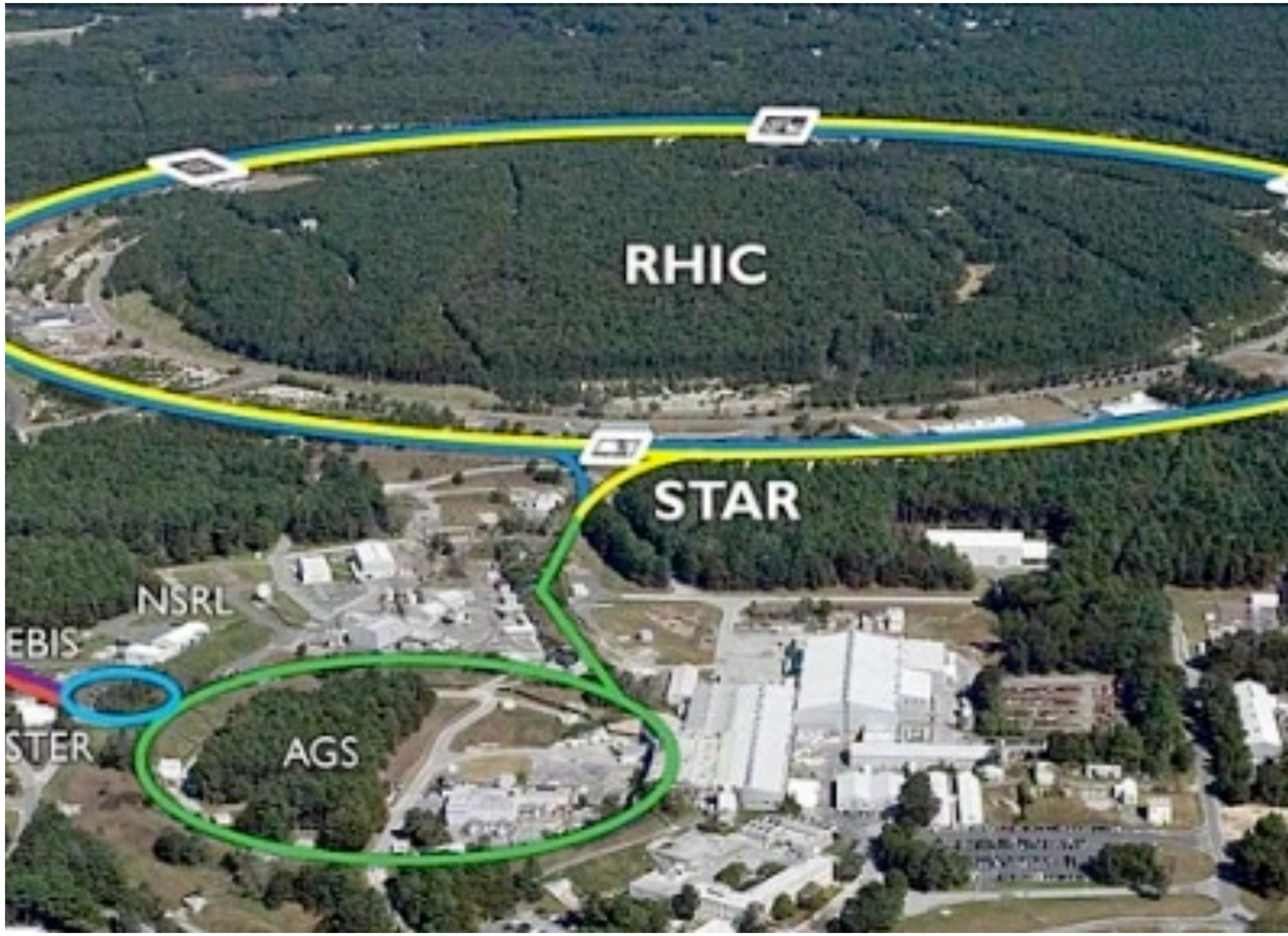
Non-interdependent Flow, Z.Xu et al Phys. Rev. C 107, L061902



Beam Energy Scan at RHIC

RHIC energies, species combinations and luminosities (Run-1 to 22)



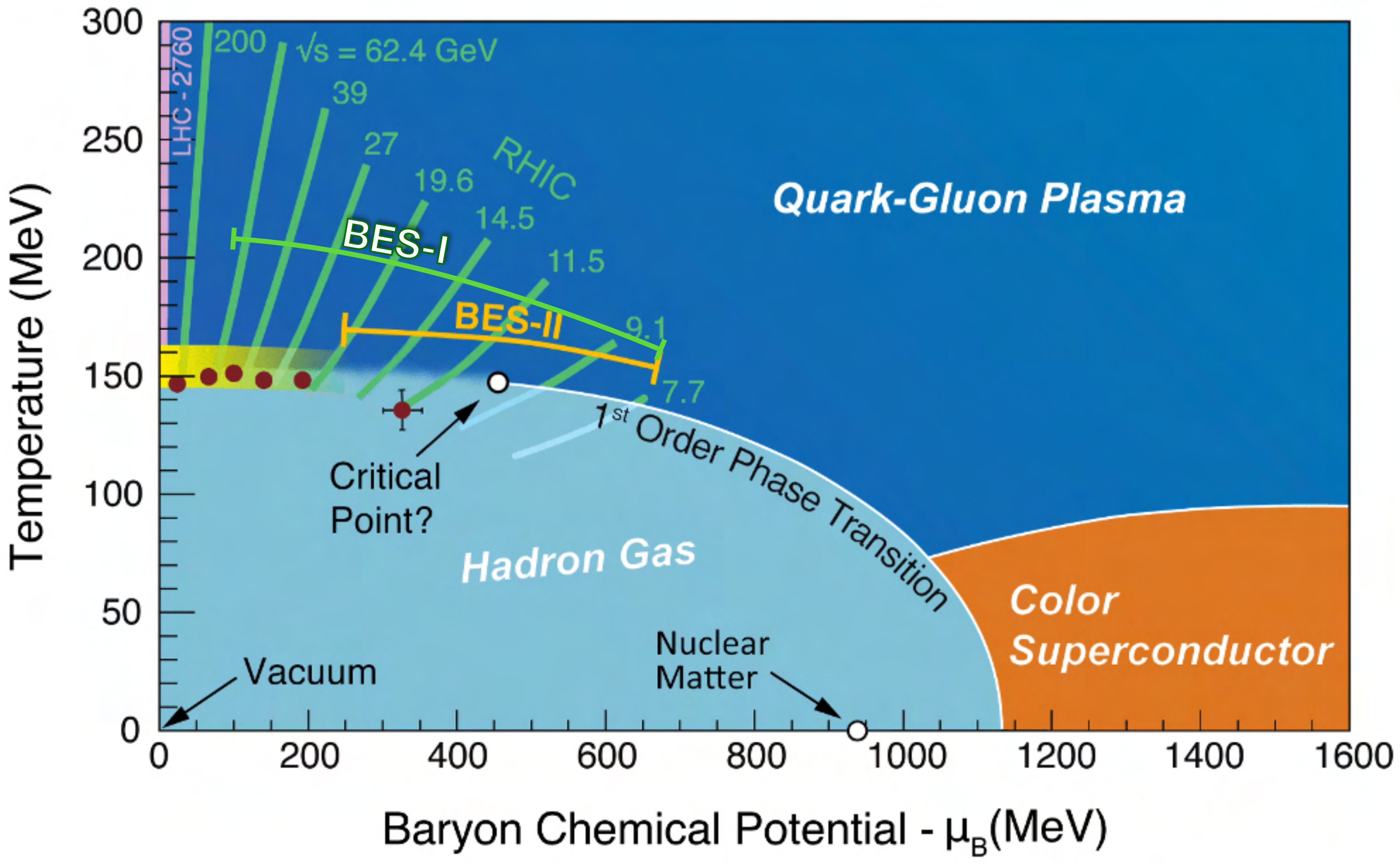


Beam Energy Scan

Beam Energy Scan at RHIC

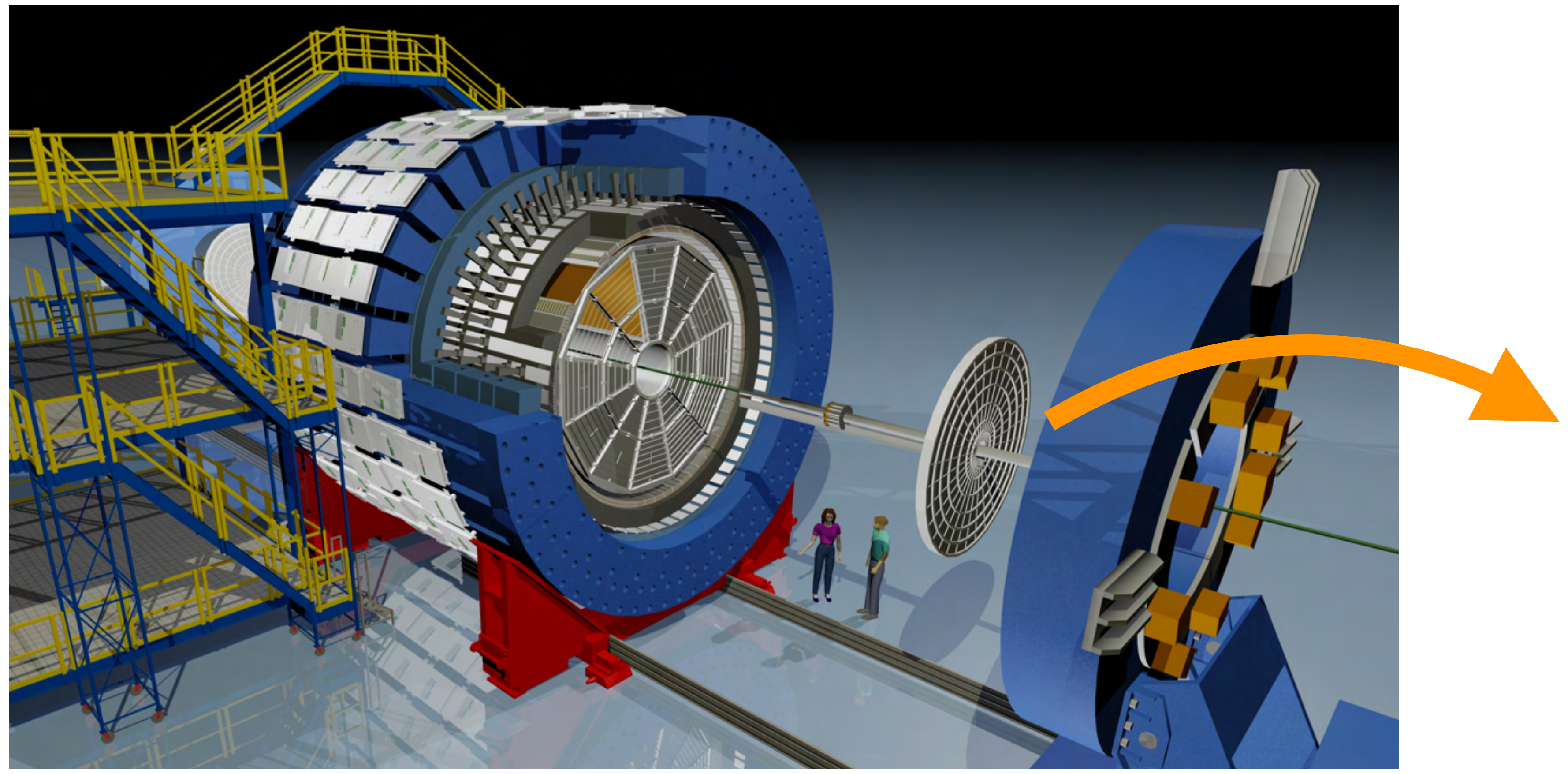
BES-I

$\sqrt{S_{NN}}$(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	555	2018
19.6	478	2019
14.6	324	2019
11.5	230	2020
9.2	160	2020
7.7	101	2021



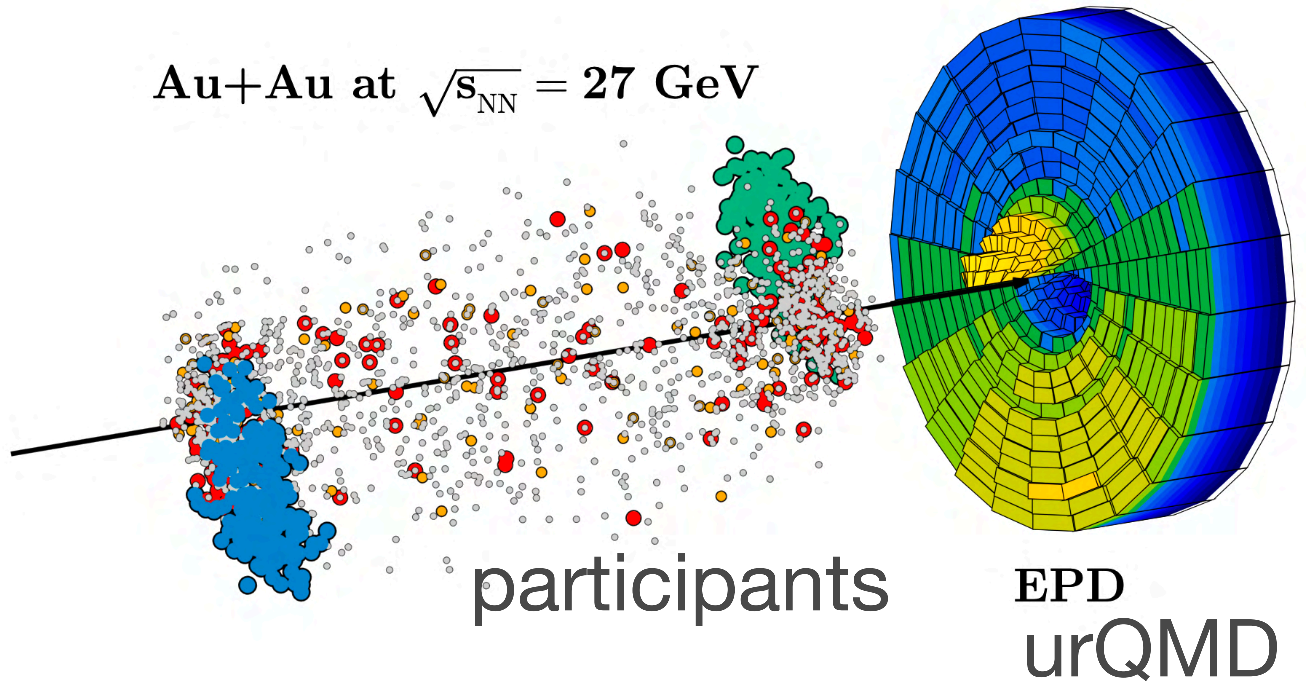
BES-II Statistics:

- **10-20 times higher.**

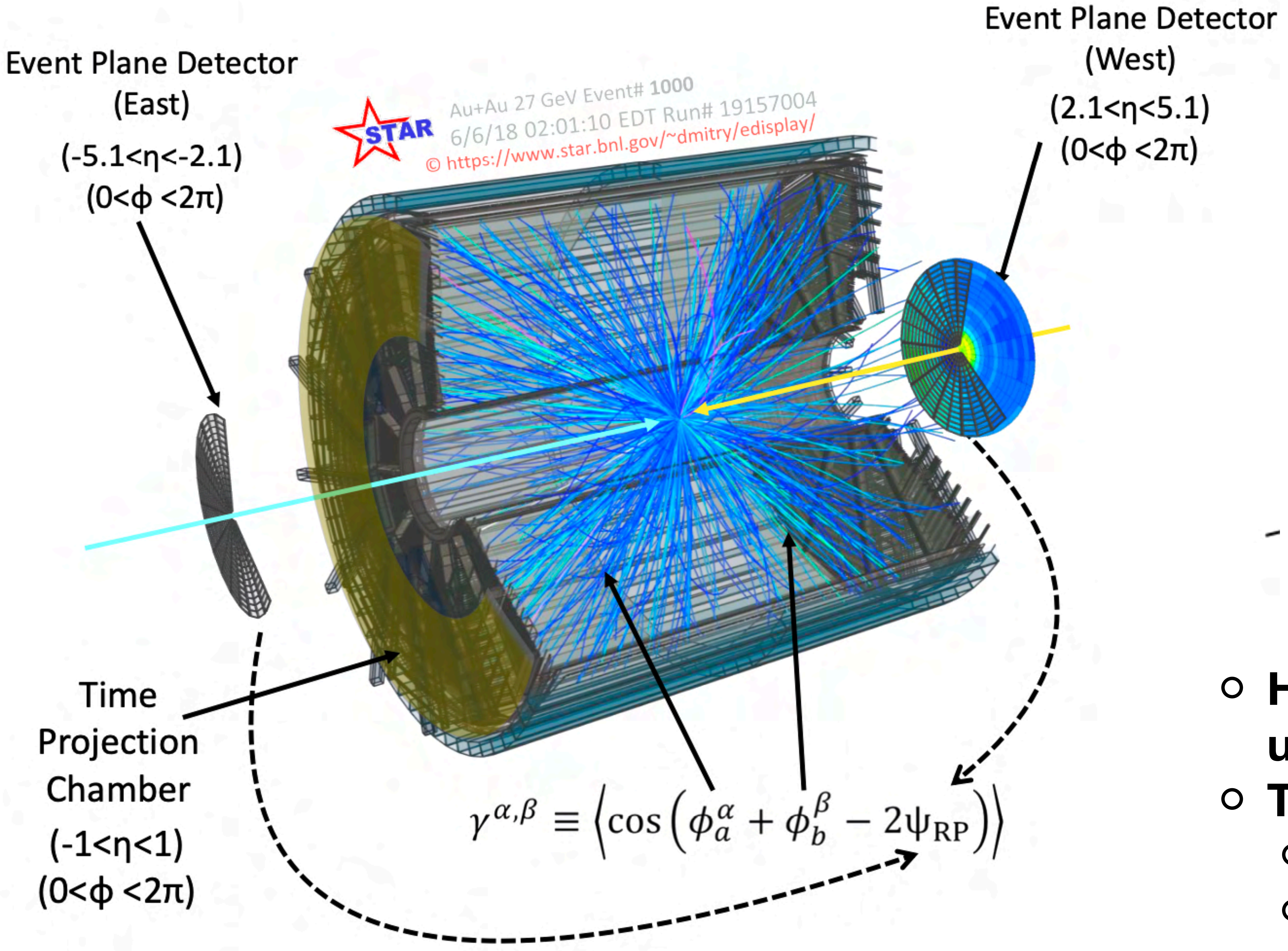
Detector Upgrades:

- **2018 EPD : high EP resolution into spectator region (2.1<η<5.1)**

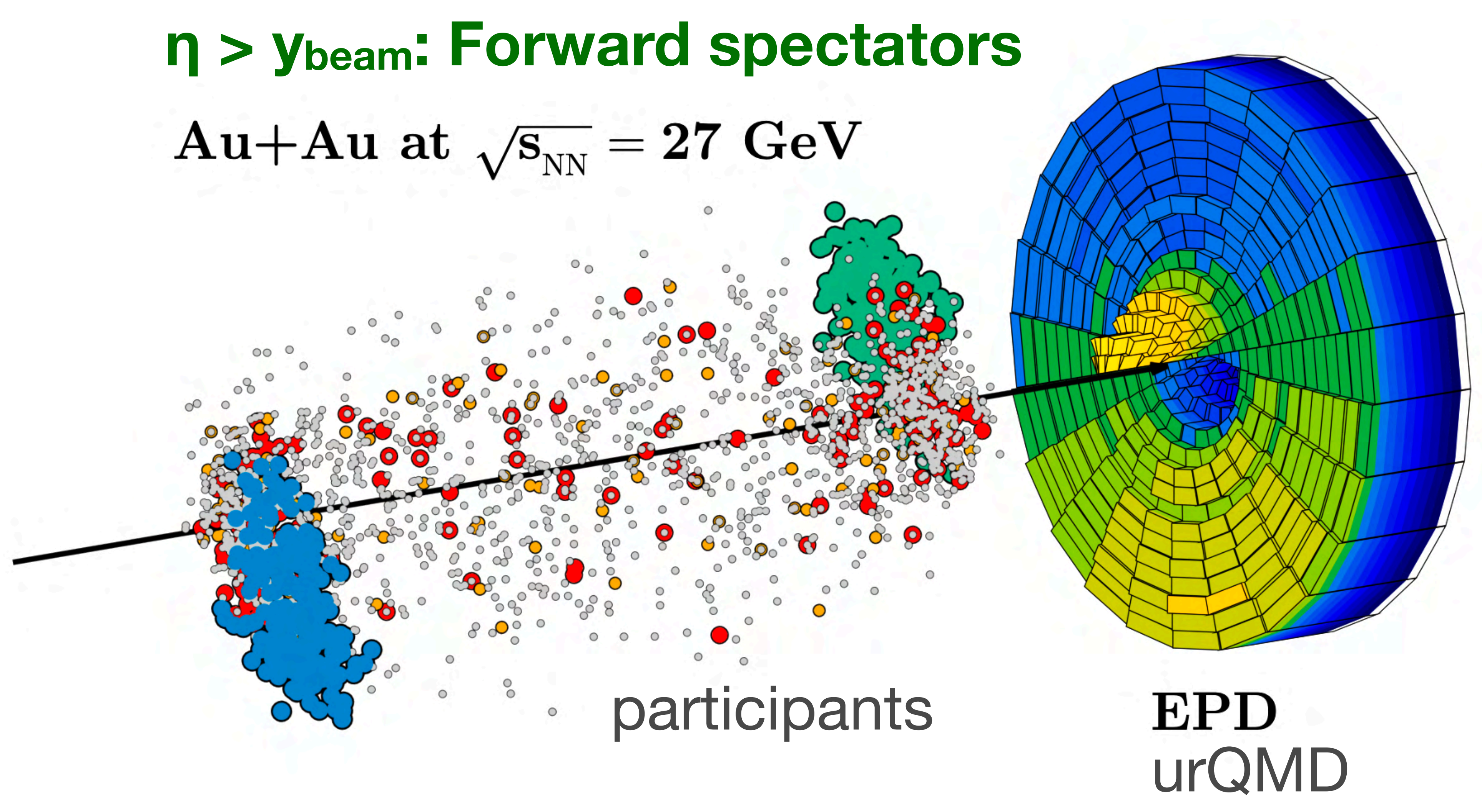
$\eta > y_{beam}$: Forward spectators



The Event Plane Detector at STAR

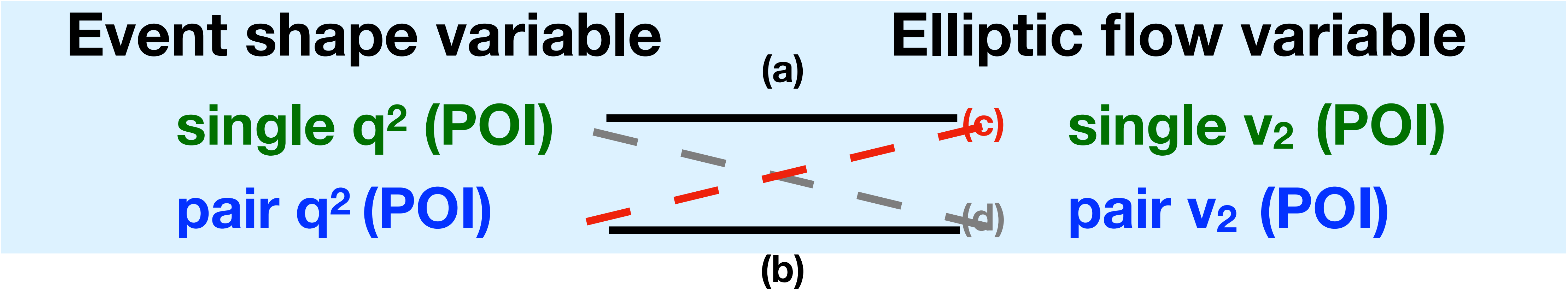


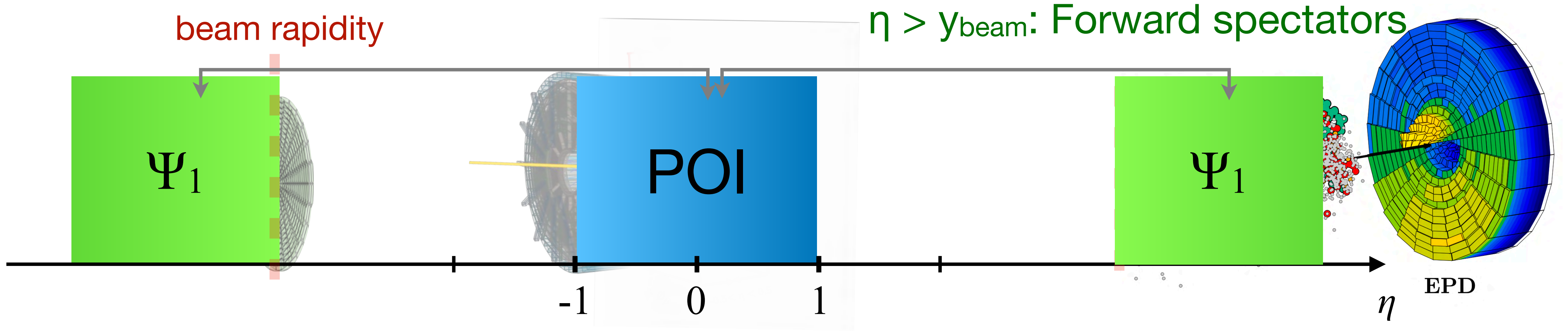
$$\gamma^{\alpha,\beta} \equiv \left\langle \cos\left(\phi_a^\alpha + \phi_b^\beta - 2\psi_{\mathrm{RP}}\right)\right\rangle$$

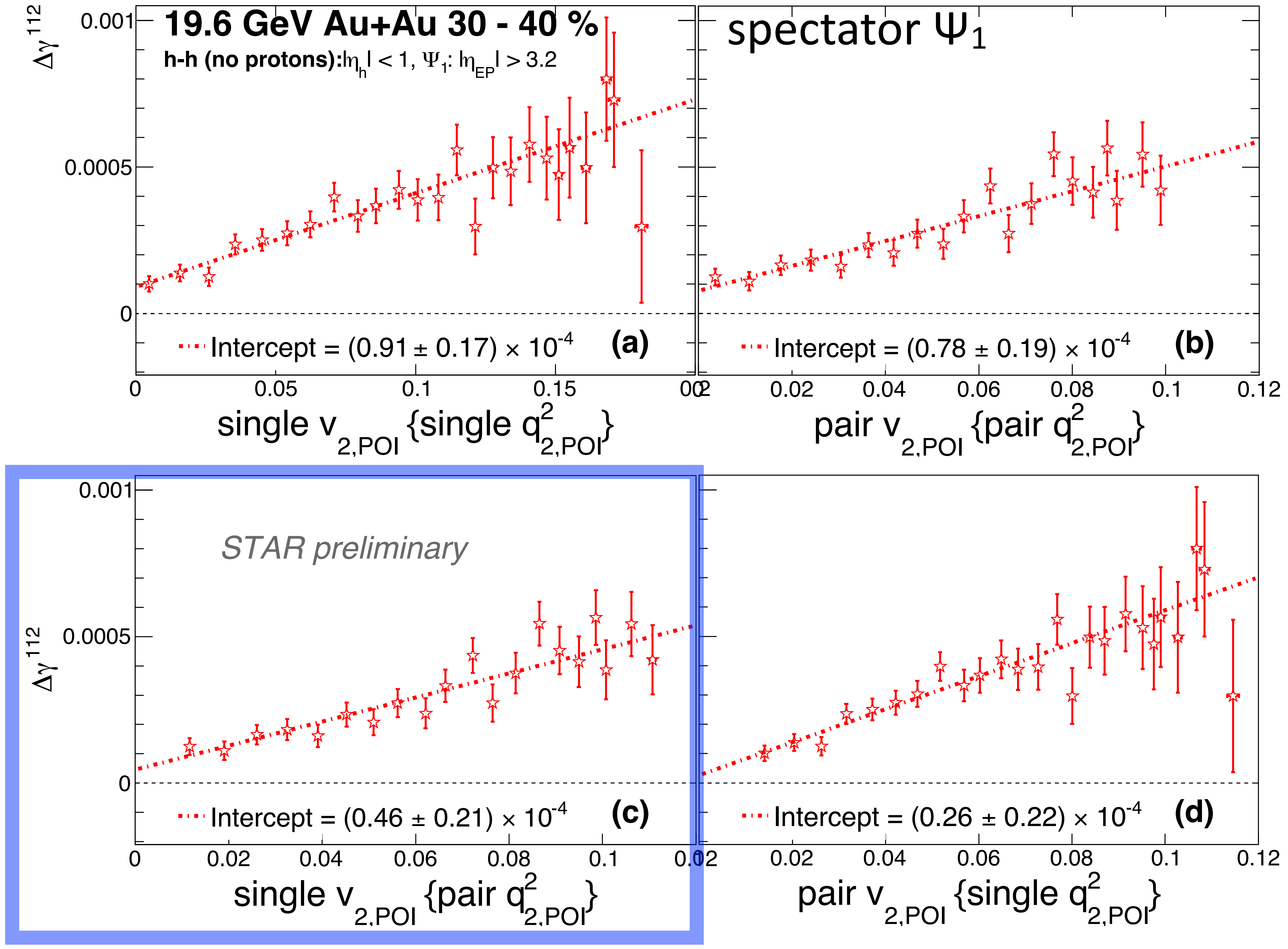


- Higher resolution, BES-II new detector (EPD) upgraded in 2018
- The inner EPD detects first-order spectator plane
  - Targeting the spectator regions for B field
  - Suppressing non-flow background

ESS applied to Au+Au at 19.6 GeV







Event Shape Selection **Spectator Ψ_1**

$$\Delta\gamma^{112} = \underbrace{\Delta\gamma^{CME}}_{\text{Signal}} + \underbrace{\cancel{k\frac{v_2}{N}}}_{\text{Background}} + \cancel{\Delta\gamma^{nonflow}}$$

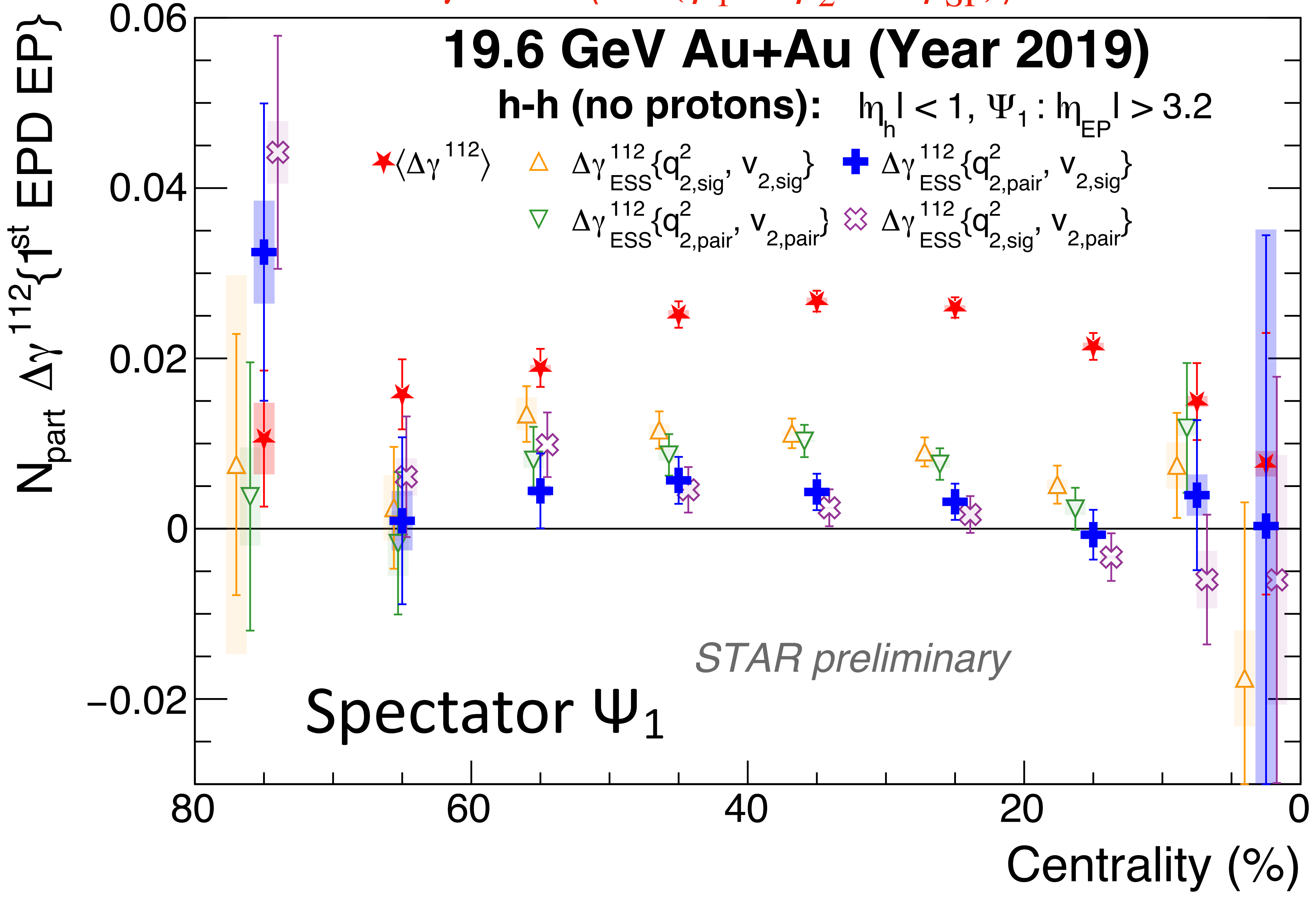
- **ESS using POI allows much shorter extrapolation to zero v_2.**
- **The ordering of y-intercepts follows predictions from both AVFD and AMPT**
- **The y-intercept requires a small correction to restore the unbiased CME signal:**

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

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

Au+Au at 19.6 GeV

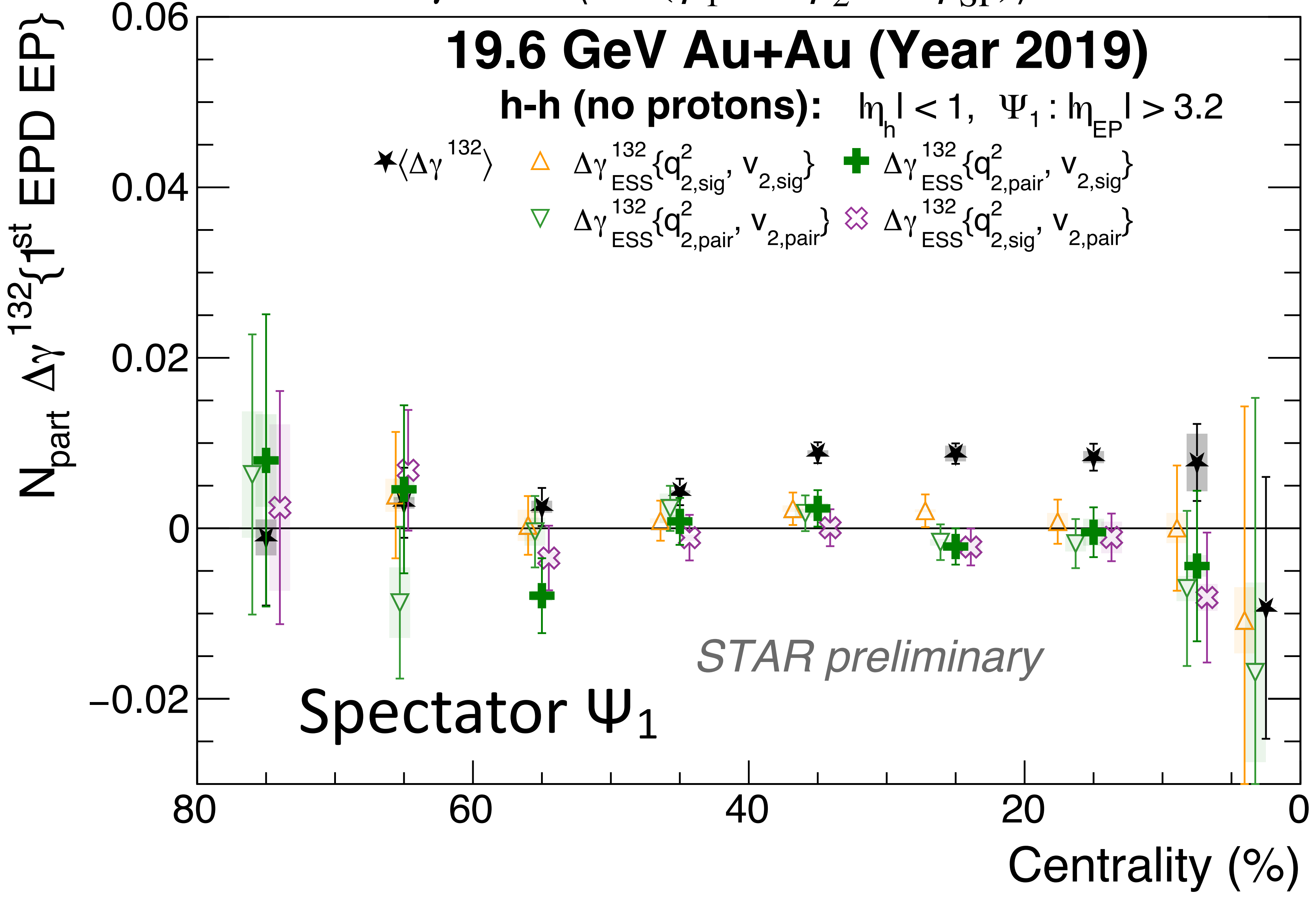
$\gamma^{112} = \langle \cos(\phi_1 + \phi_2 - 2\psi_{\rm SP}) \rangle$



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

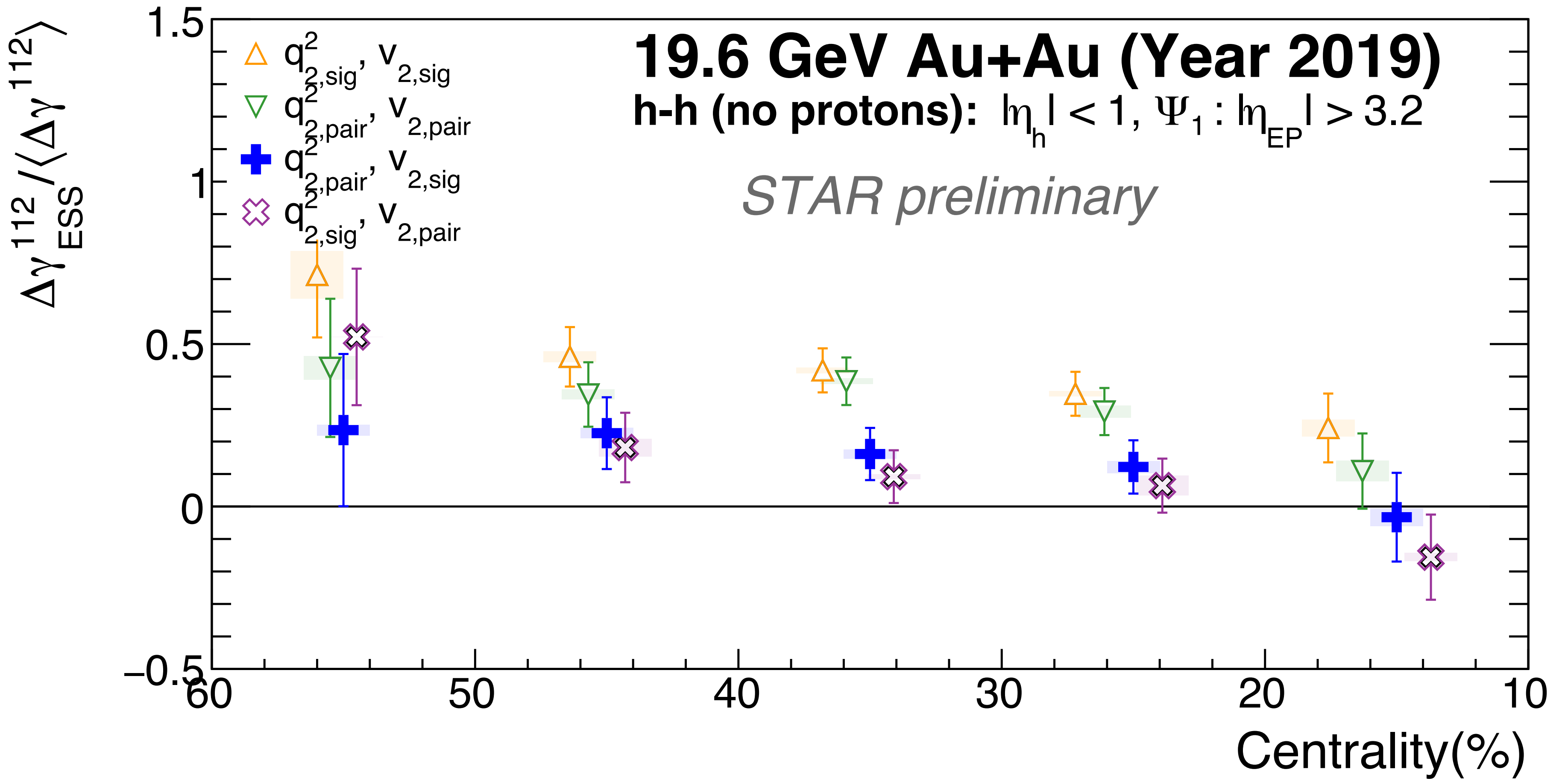
$\Delta\gamma^{112}_{ESS}$

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



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

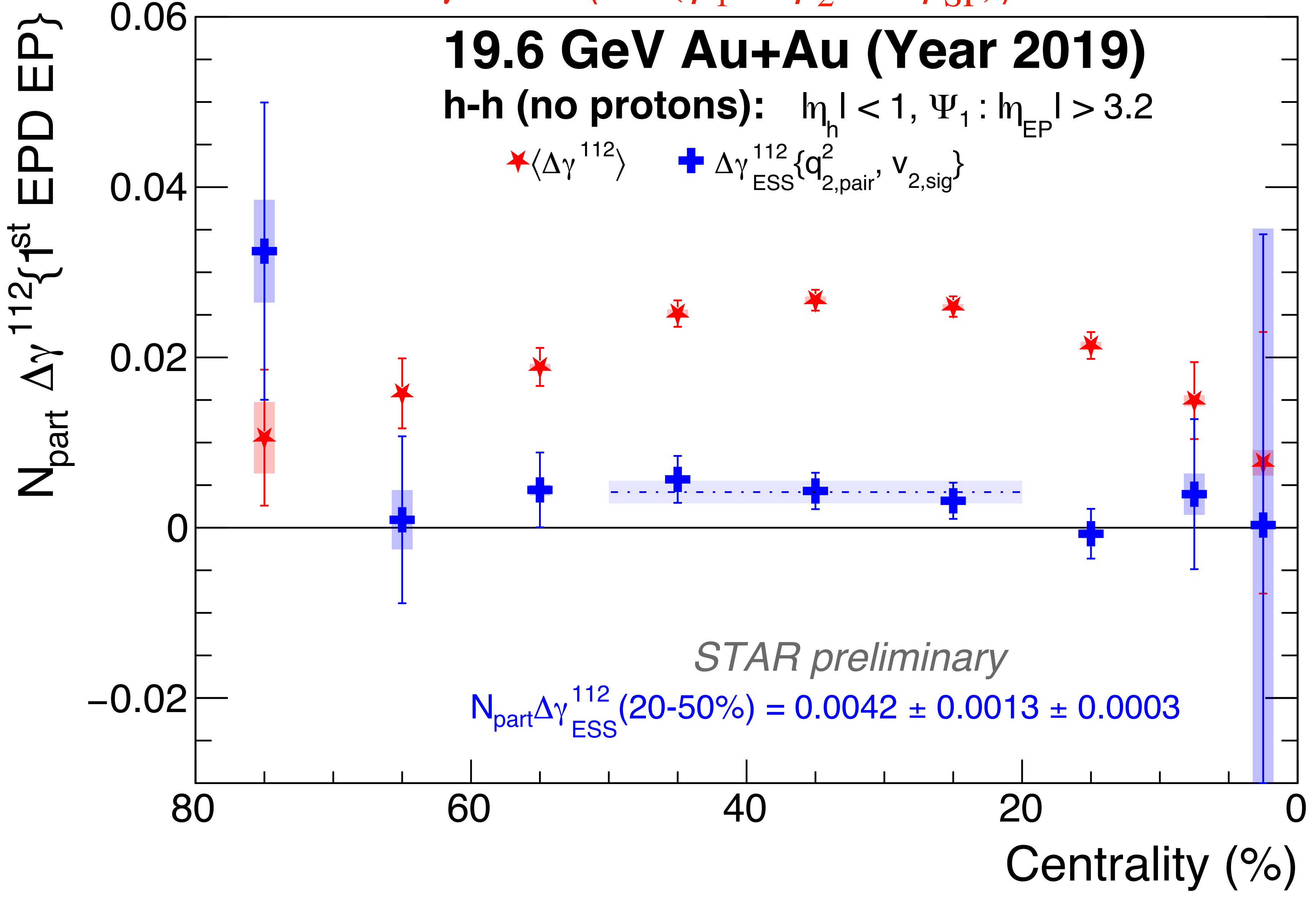
$\Delta\gamma^{132}_{ESS}$ **BKG indicator**



- **The ESS is applied to different centralities.**
- **The ordering of four intercept $\Delta\gamma^{112}_{ESS}$ follows prediction from both AMPT and AVFD model.**

Au+Au at 19.6 GeV

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

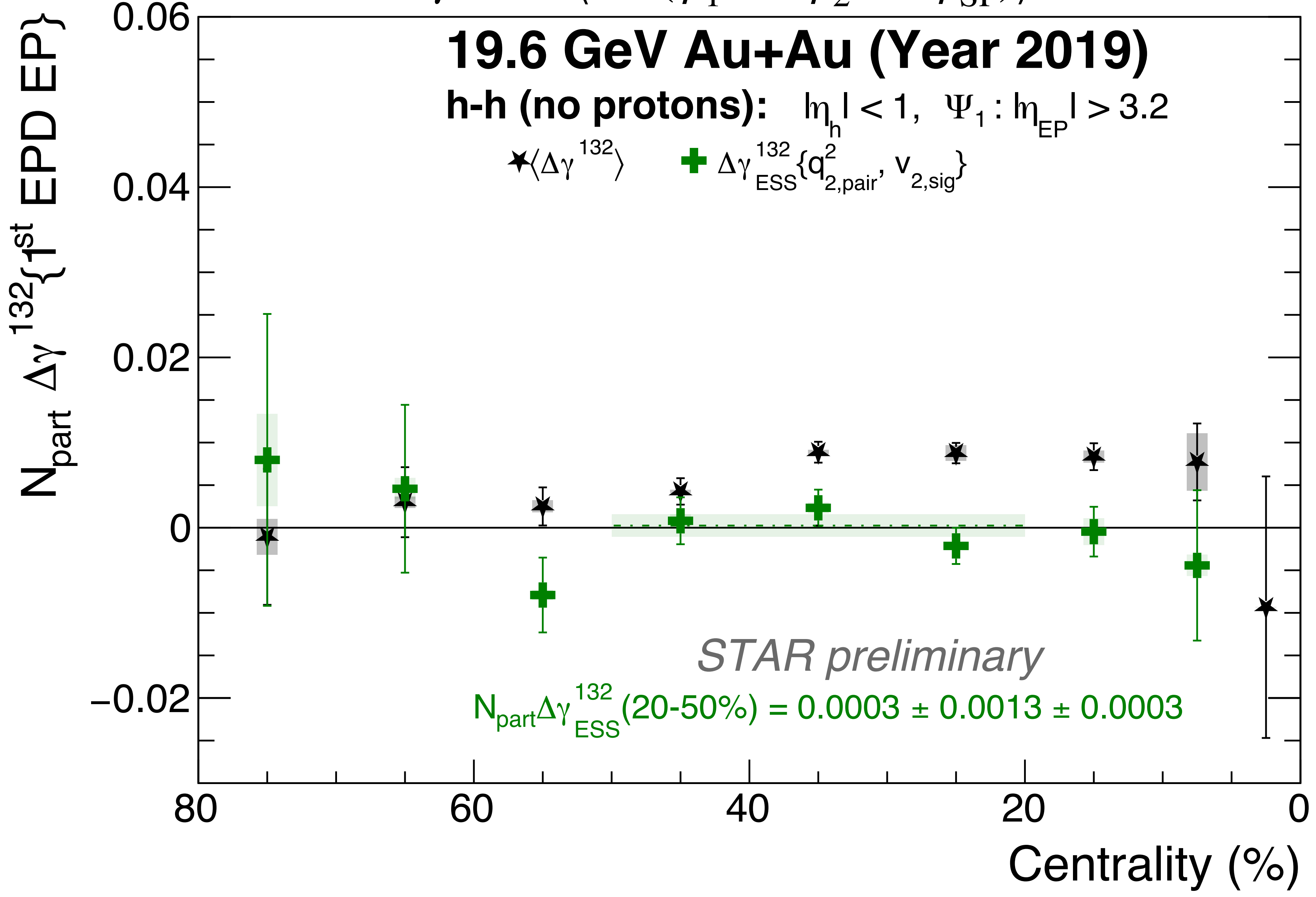


$\langle\Delta\gamma^{112}\rangle$

↓

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

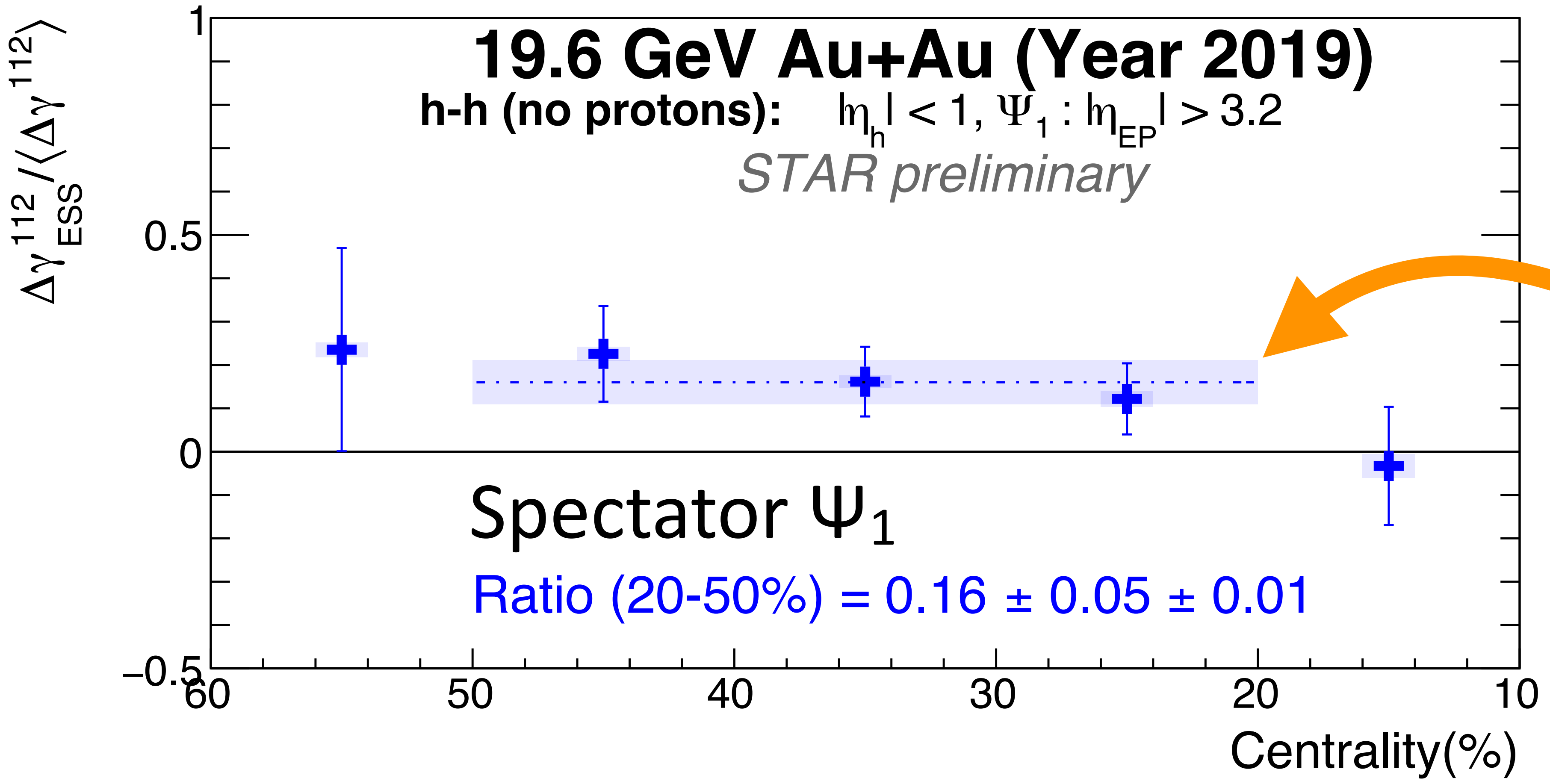
$\gamma^{132} = \langle\cos(\phi_1 - 3\phi_2 + 2\psi_{SP})\rangle$



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

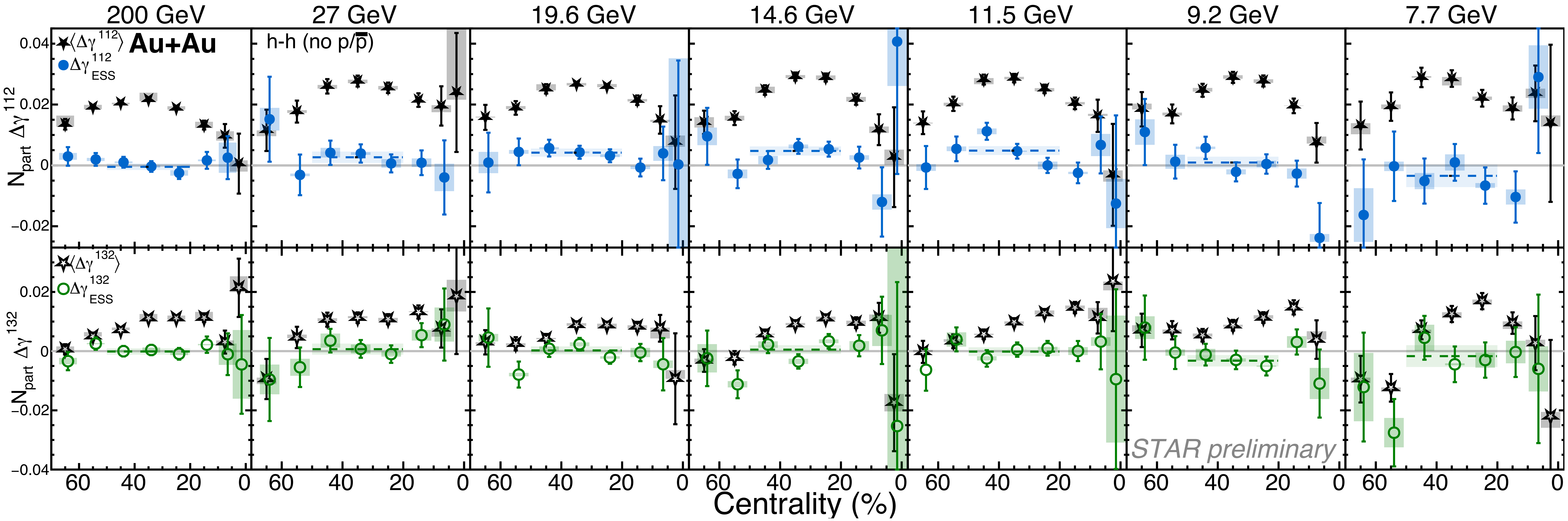
↓

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



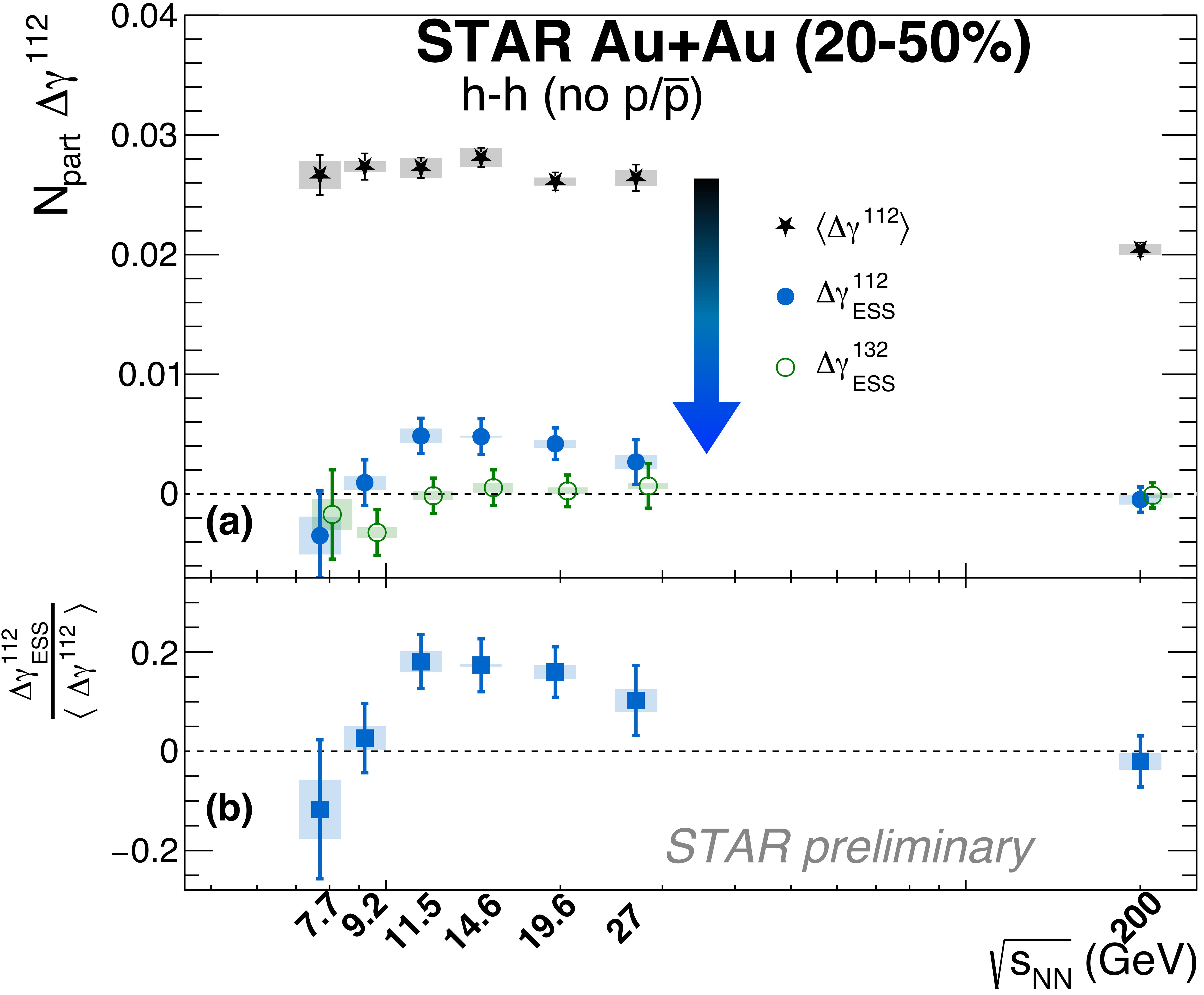
- **After v_2-BKG subtraction, a finite signal in mid-central (20-50%) events.**
- **Ratio from the optimal ESS (c), pair q^2 and single v_2, yields a 3σ significance for 20-50% centrality.**
- **From BKG indicator $\Delta\gamma^{132}$, ESS successfully suppressed v_2-BKG.**

Beam Energy Scan II - Event Shape Selection



- $\Delta\gamma^{112}_{ESS}$ from the optimal ESS (c), pair q2 and single v2:
  - 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 of CME observable



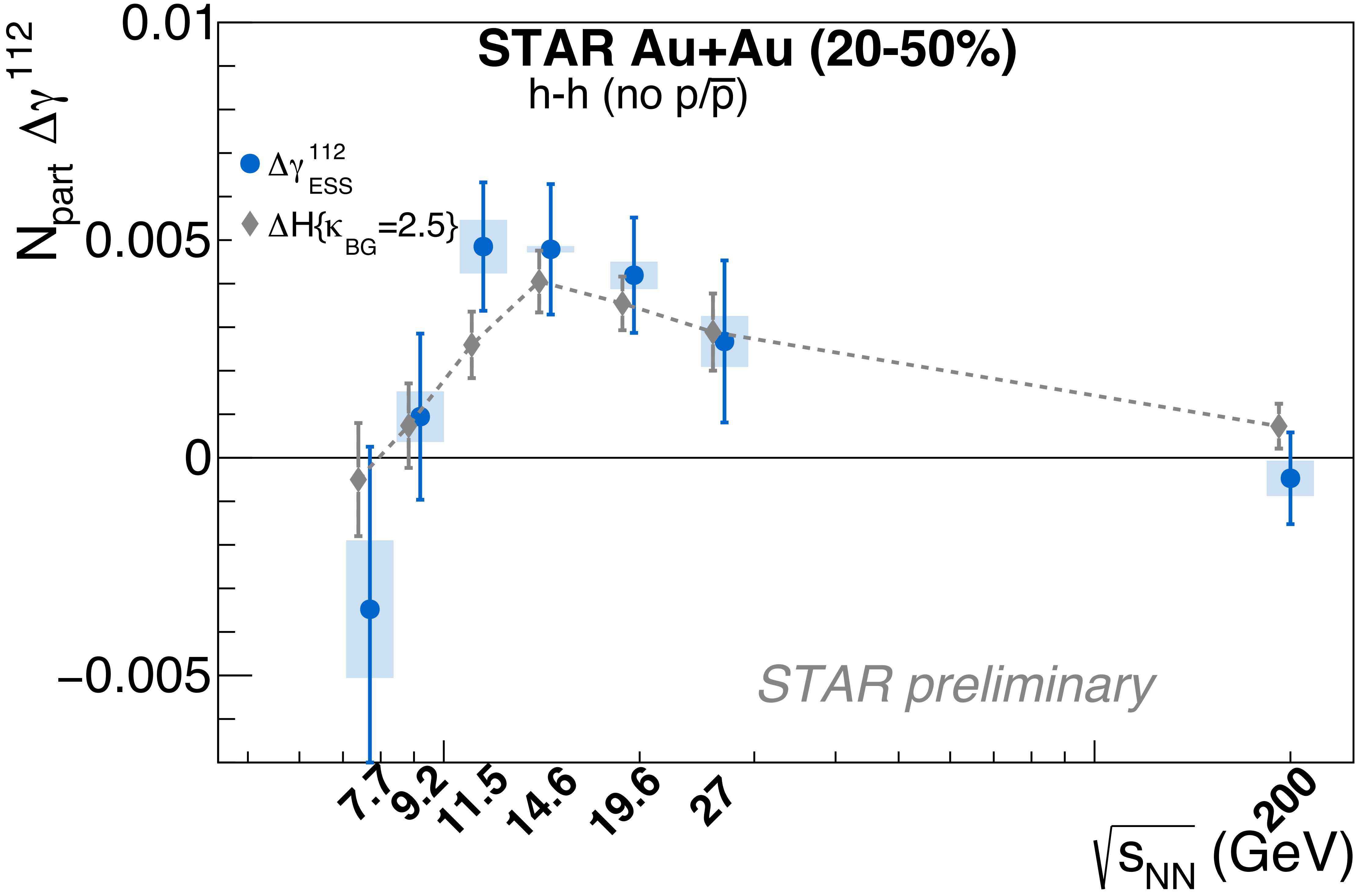
- BKG-indicator $\Delta\gamma^{132}_{ESS}$ consistent with zero

- At least 80% of $\langle\Delta\gamma^{112}\rangle$ is from the background.
- At 200 GeV, ratio is (-2 ± 5.1 ± 1.6)%
  - upper limit of fCME~10% in Au+Au
  - upper limit of fCME~ 5% in isobars using participant planes: 0.7% difference, too small to detect

- 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 from ESS to H-correlator



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

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

$$\Delta H \equiv H_{\mathrm{SS}} - H_{\mathrm{OS}}$$

$\gamma = \kappa v_2 B - H$

$\delta = B + H$

$\delta = \cos(\phi_1 - \phi_2)$

A. Bzdak, V. Koch and J. Liao, Lect. Notes Phys. 871, 503 (2013).

- κ_{bg} is an adjustable parameter, unknown priori.

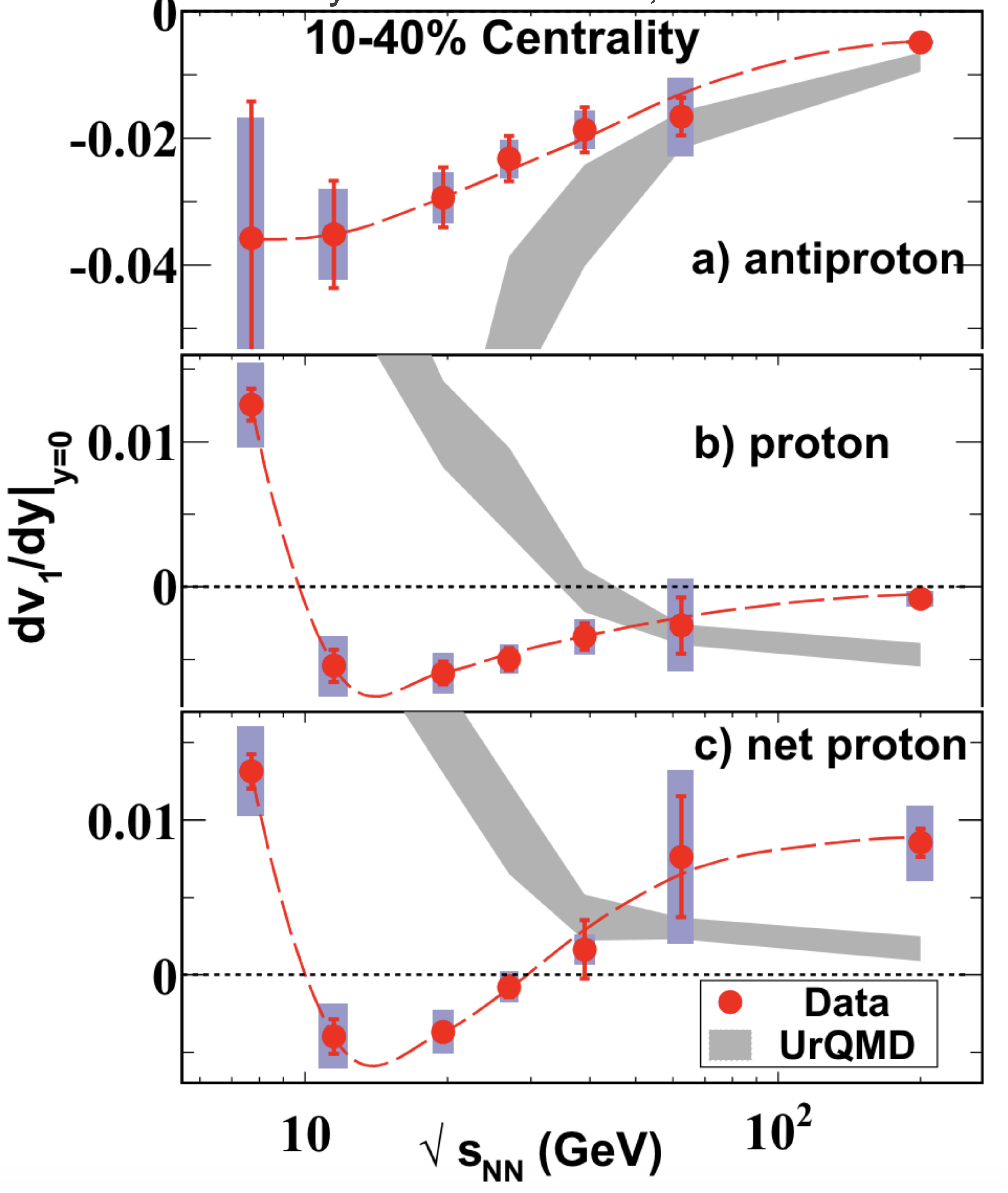
  It quantifies the coupling between elliptic flow and other mechanisms manifested in the two-particle correlation.

- 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.

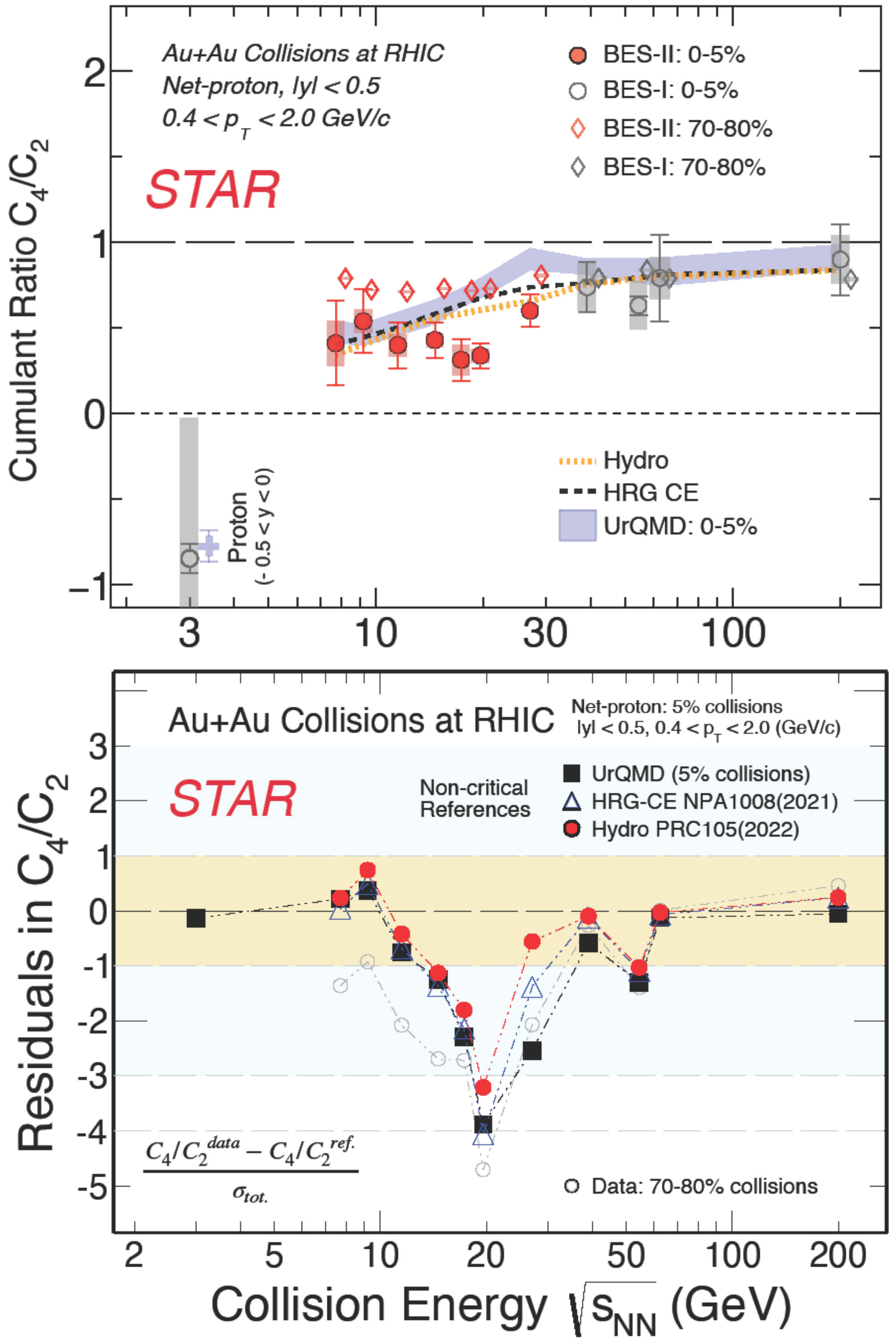
A sweet-zone: 10-30 GeV?

v_1 slope dv_1/dy

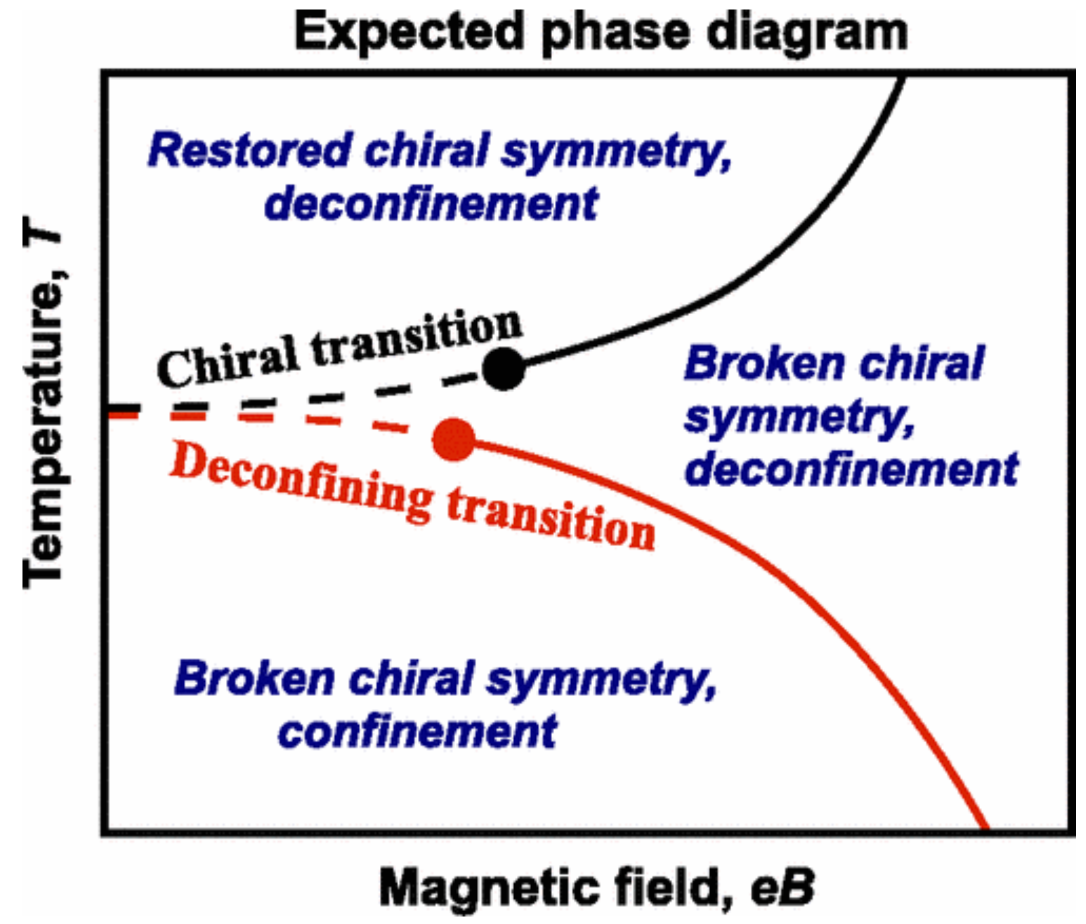
Phys. Rev. Lett. 101, 252301



Critical Point: C_4/C_2



- **dv₁/dy is sensitive to the EOS: “softest point collapse” of flow.**
- **Near critical point region, the topological fluctuation will be enhanced.**
- **STAR net-proton cumulant measured a significant deviation from model.**
- **At large B, the chiral symmetry breaking (split from deconfiment)?**



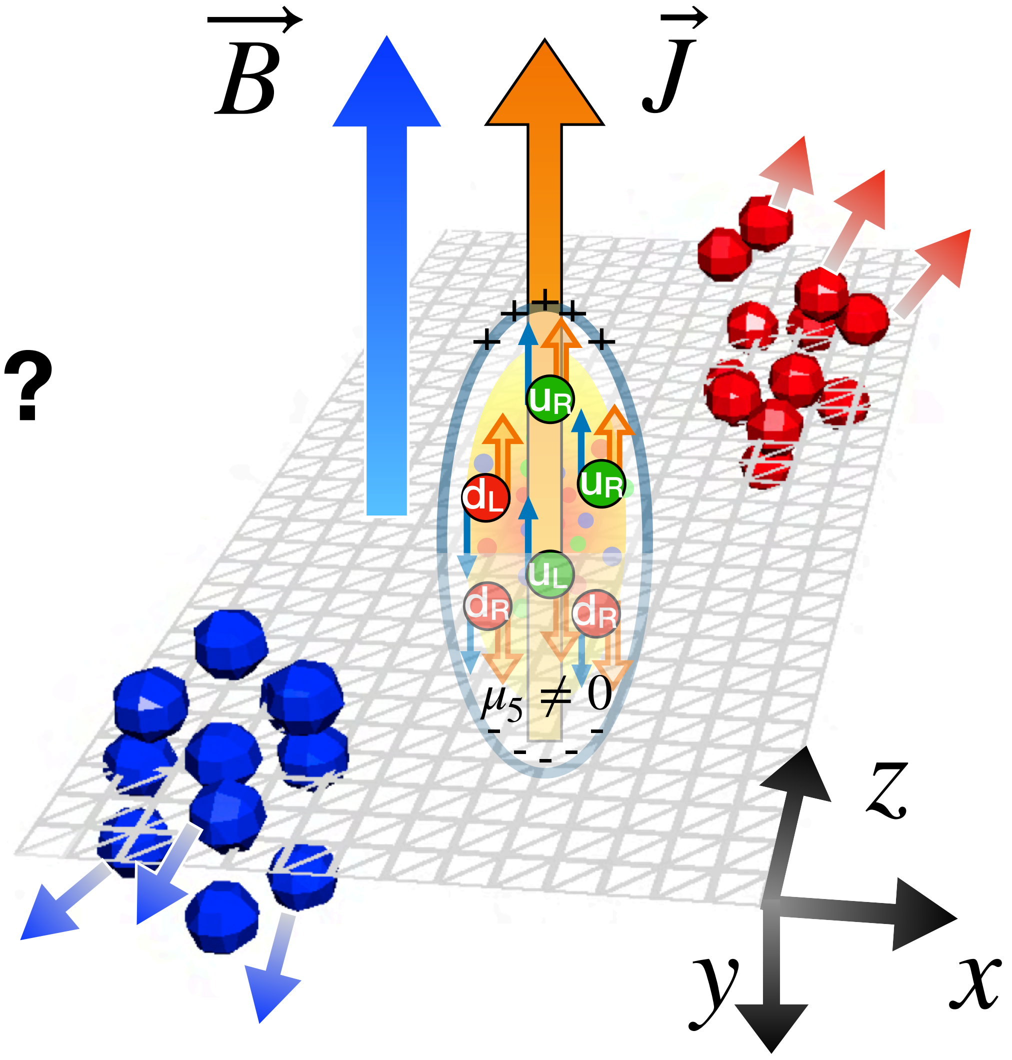
A. J. Mizher, M. N. Chernodub, and E. S. Fraga, PRD 82 (2010) 105016

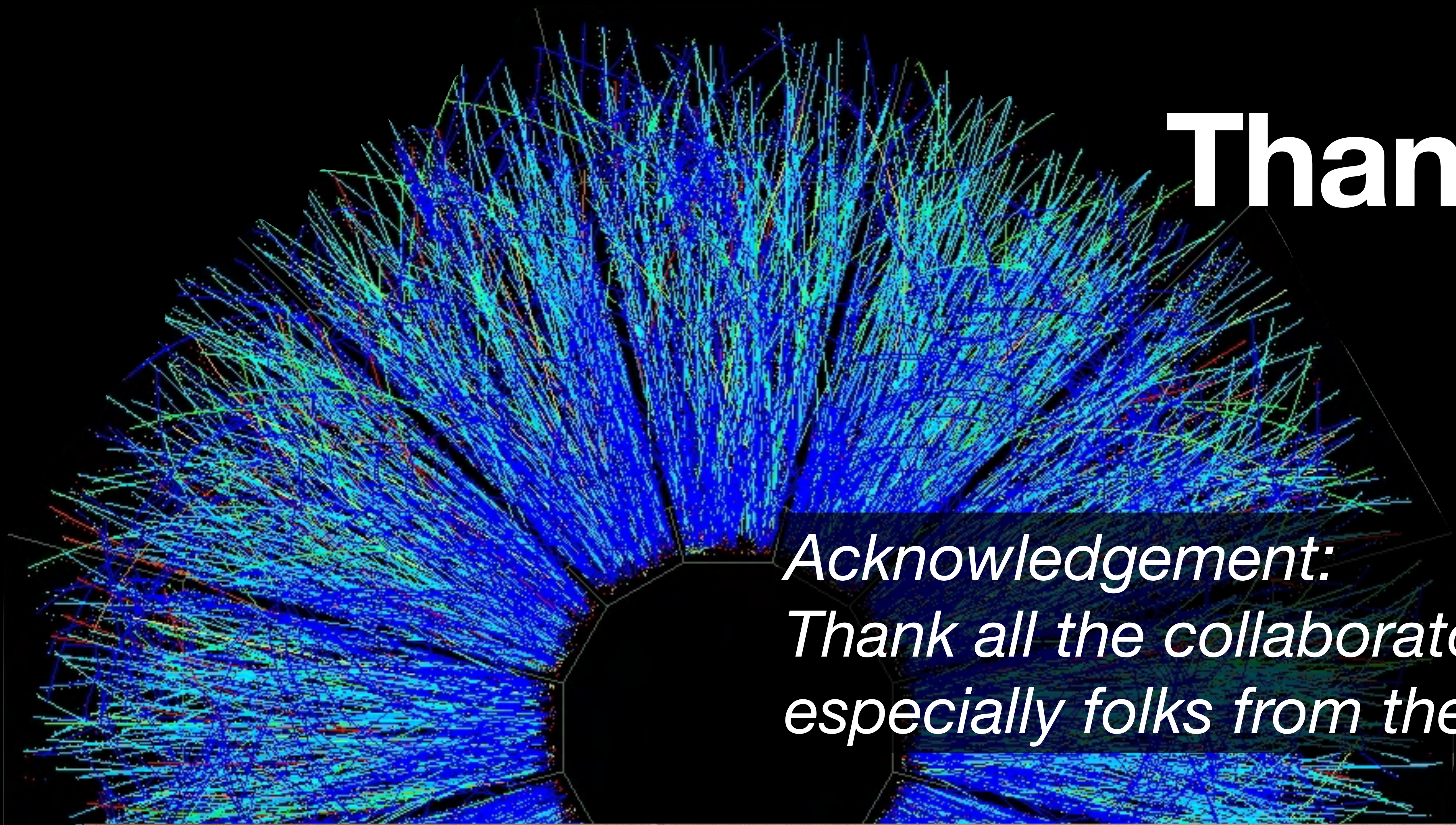
Summary

- **The search for the CME in heavy-ion collision probes the intrinsic properties of QCD.**

- **STAR latest CME searches use the novel Event Shape Selection to effectively suppress 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 $\Delta\gamma^{112}_{ESS}$ (>3σ). Over 5σ if combined.**
  - **Around 7.7 GeV, approaches zero CME with large uncertainties.**

- **More theoretical insights are needed:**
  - **The remaining B field may be too weak at 200 GeV?**
  - **Chiral symmetry breaking/QGP disappering around 7.7 GeV?**
  - **The chance of the CME occurrence is enhanced near the critical point?**





Thank you.

Acknowledgement:
Thank all the collaborators at STAR,
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