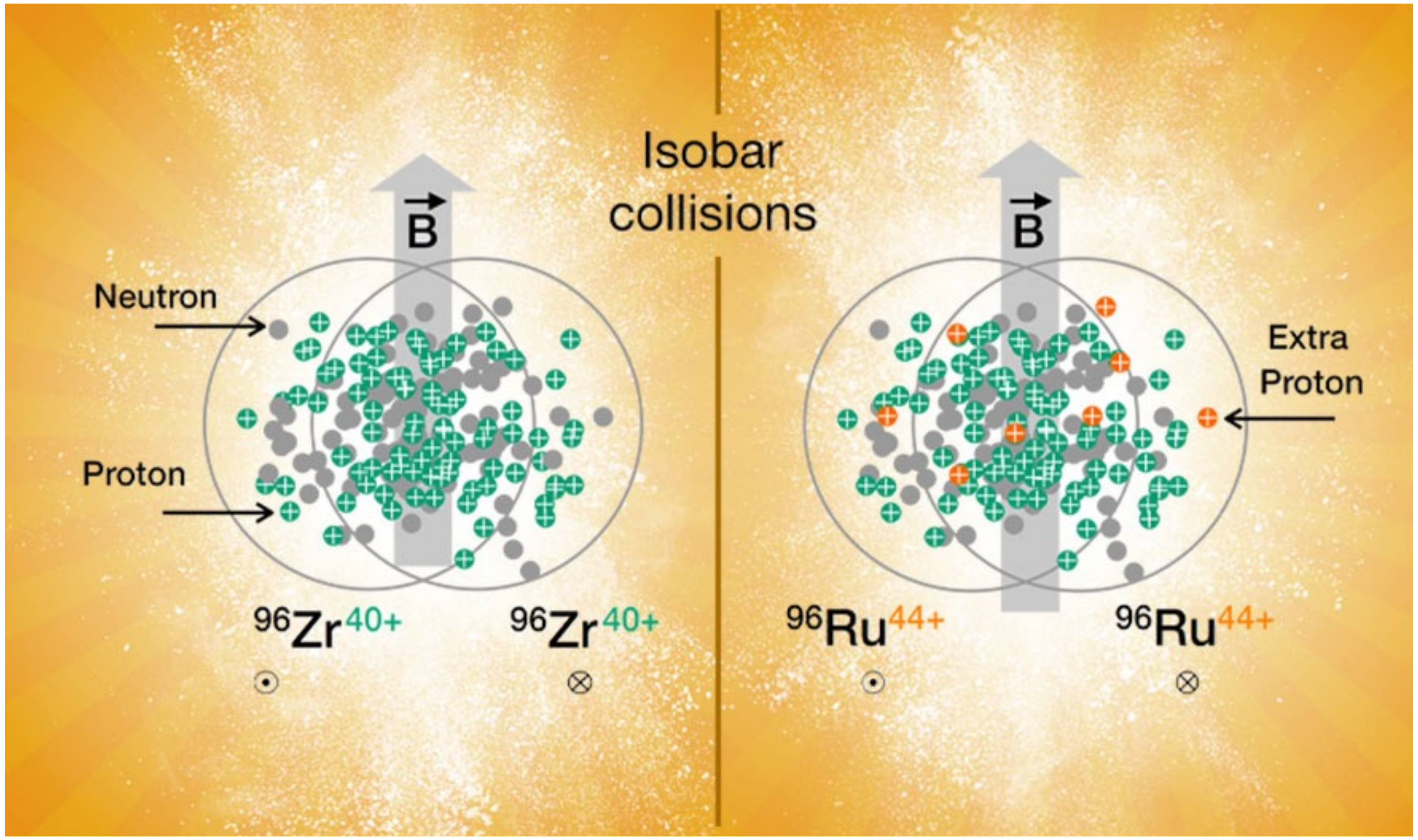
First STAR CME Results From the Isobar Run - An Overview

(based on arXiv:2109.00131)

Helen Caines - Yale



6th International Conference on Chirality, Vorticity and Magnetic Field in HIC

Hybrid meeting - Nov 1-5 2021

Wright Laboratory

Supported by: U.S. DEPARTMENT OF ENERGY | Office of Science

Chiral Magnetic Effect (CME)

QCD: chiral anomaly creates differences in number of left/right handed quarks

handedness : momentum and spin, aligned or anti-aligned

spin alignment in B-field : opposite direction for opposite charges

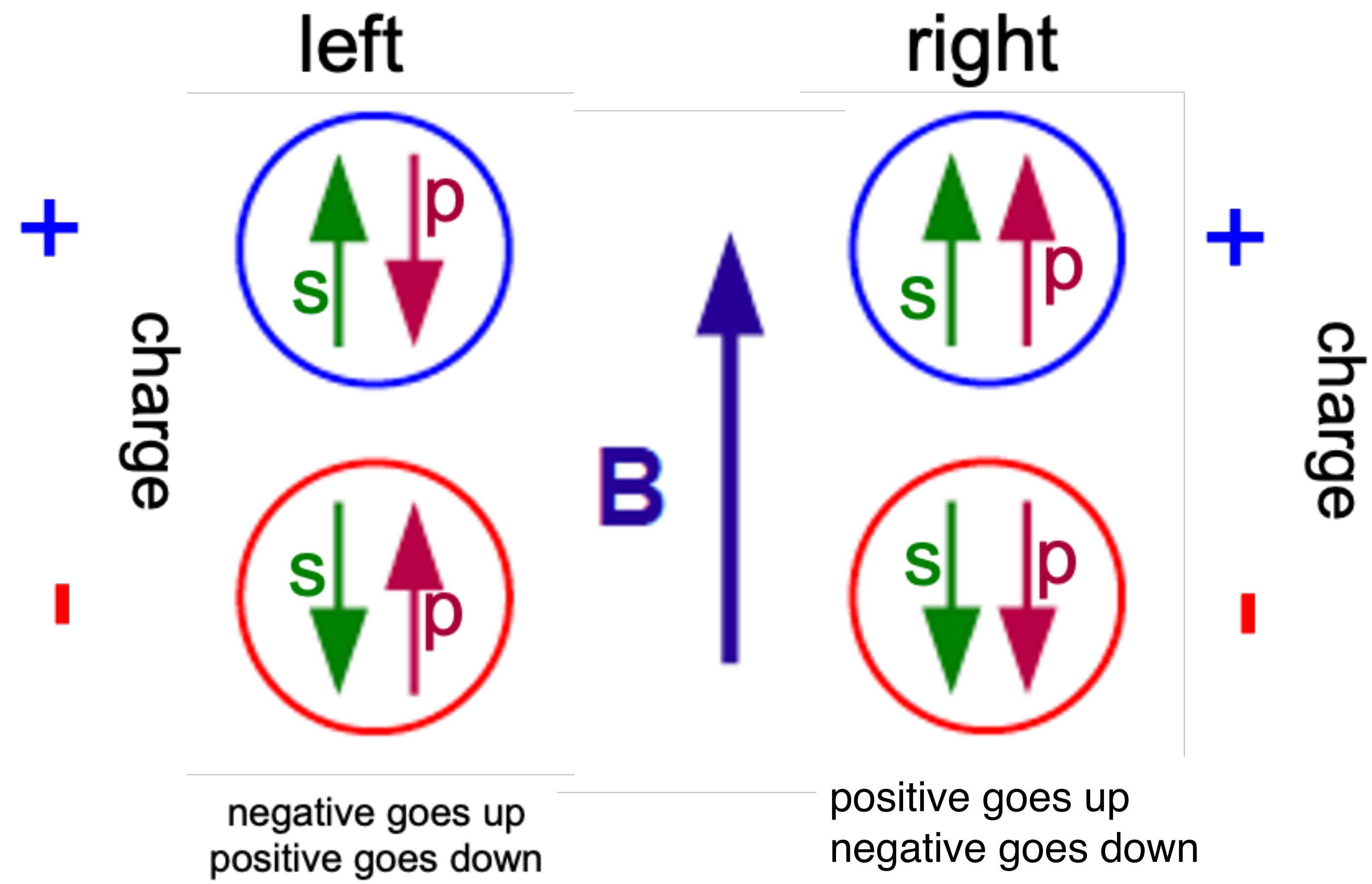
An excess of right/left handed quarks leads to current flow along B-field

Charge current

$$j_V = \frac{N_c e}{2\pi^2}\mu_A B$$

Chiral Magnetic Effect (CME)

Experimentally observe electric charge separation along the B-field



CME - making the measurement

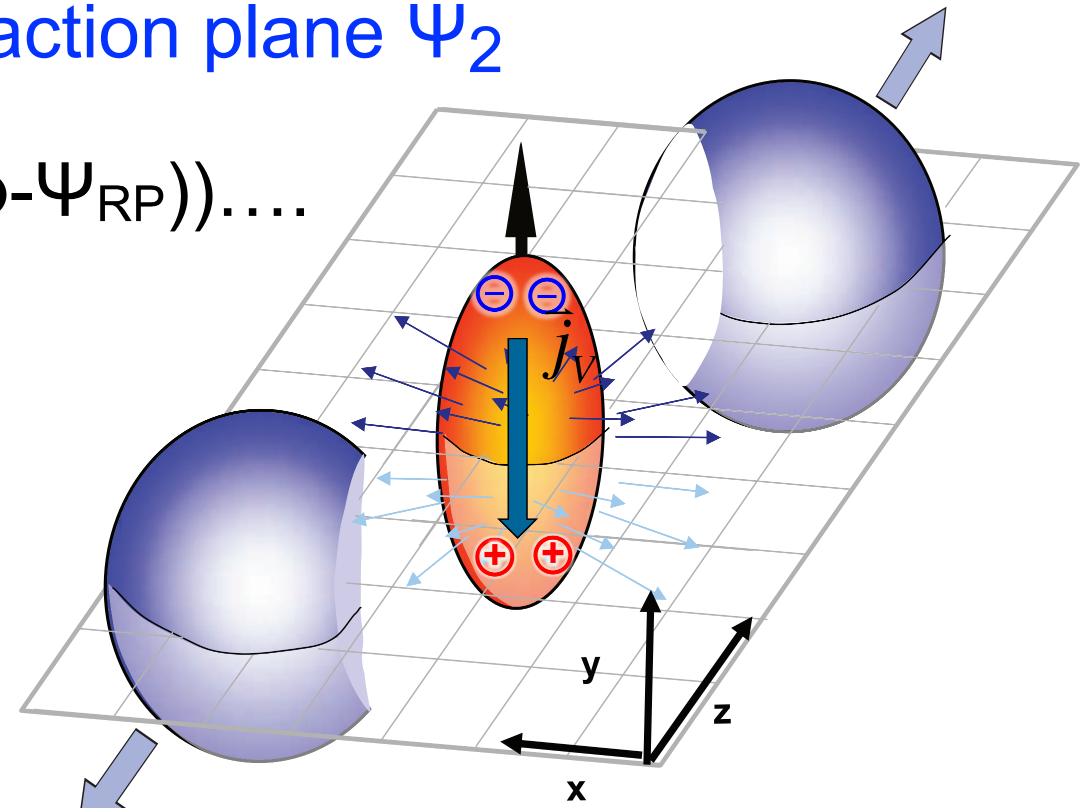
B-field aligned perpendicular to second-order reaction plane Ψ_2

$dN_{\pm}/d\varphi \propto 1+2\, v_1(p_T)\cos(\varphi-\Psi_{RP}) + 2\, v_2(p_T)\cos(2(\varphi-\Psi_{RP}))\ldots.$

$+2a_{\pm}\sin(\varphi-\Psi_{RP})$

the asymmetry $a_+ = -a_-$

Averages to zero due to random domains



instead measure

$$\gamma = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle \approx (v_{1,\alpha}, v_{1,\beta} - a_\alpha a_\beta)$$

Doesn't average to zero

$$\gamma_{SS} = \langle \cos(\varphi_{\pm} + \varphi_{\pm} - 2\psi_{RP}) \rangle$$

$$\gamma_{OS} = \langle \cos(\varphi_{\pm} + \varphi_{\mp} - 2\psi_{RP}) \rangle$$

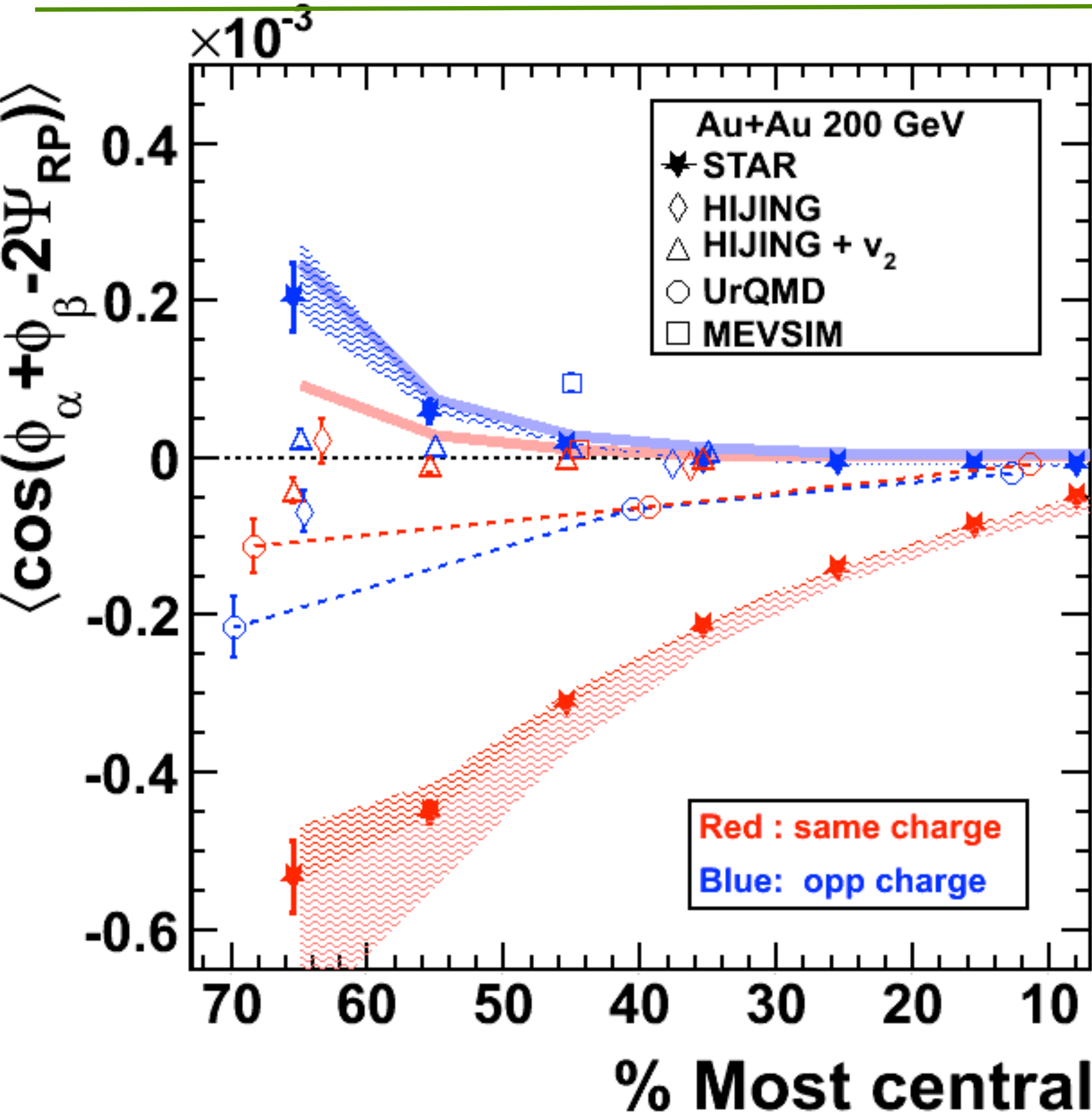
$$\Delta\gamma = \gamma_{OS} - \gamma_{SS}$$

- P-even so may contain other effects: such as resonances, jets - need to explore magnitude and centrality dependence of signal

$\gamma_{++} = \gamma_{--}$
$\gamma_{SS} < \gamma_{OS}$

Voloshin: hep-ph/0406311

First paper on CME from STAR



Paper concludes : "A signal consistent with several expectations from the [CME] theory is detected."

"The observed signal cannot be described by the background models that we have studied (HIJING, HIJING+v2, UrQMD, MEVSIM), which span a broad range of hadronic physics."

but clearly a need to investigate other systems

"…but the signal persists to higher transverse momentum than expected"

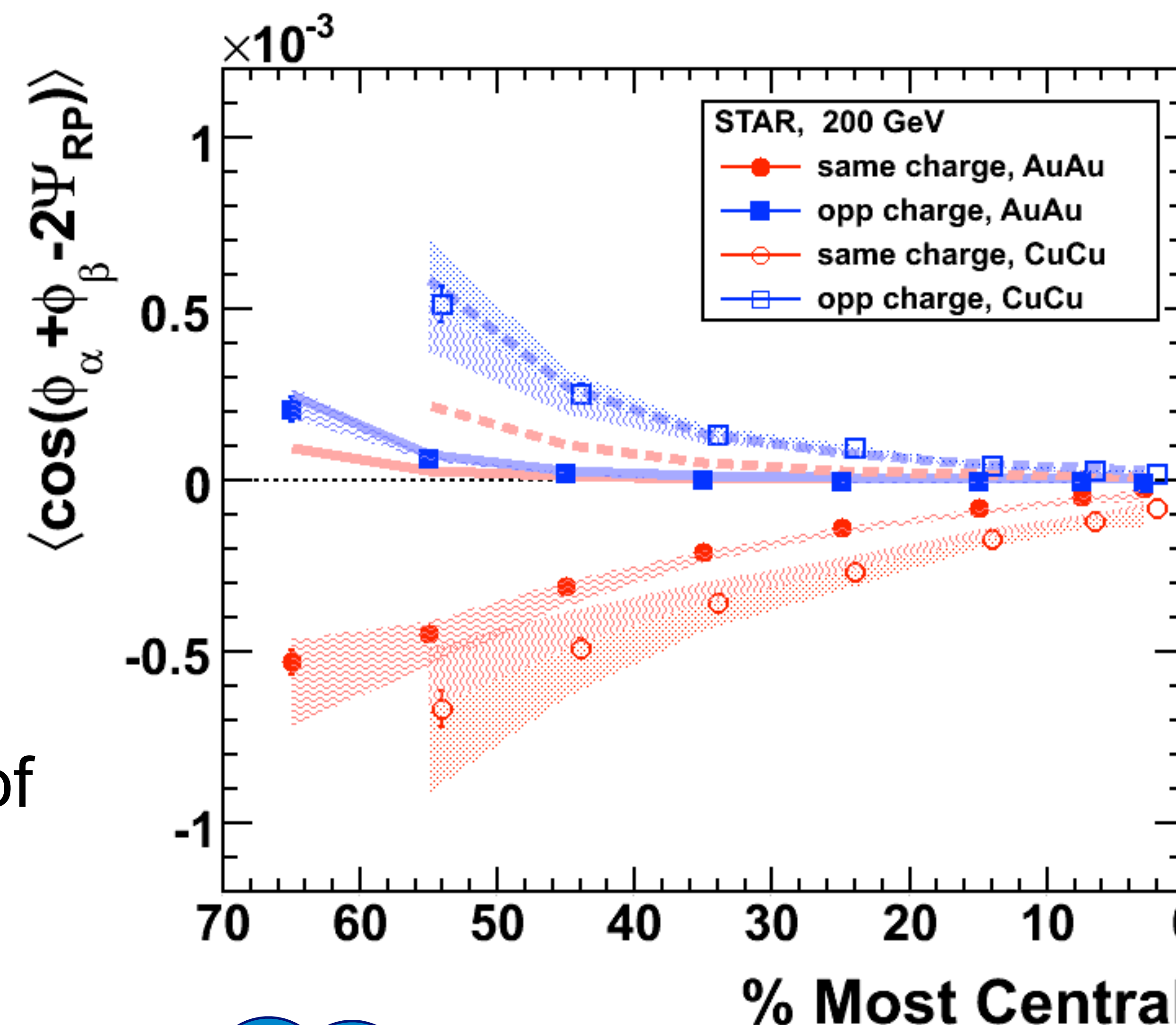
PAs: I. Selyuzhenkov, V. Dzordzhadze, R. Longacre, Y. Semertzidis, P. Sorensen, D. Gangadharan, G. Wang, J. Sandweiss, E. Finch, A. Chikanian, R. Majka, J. Thomas, S. Voloshin

Recently became renowned >500 citations

STAR: PRL 103 251601 (2009)

CME - testing expectations in Cu+Cu

$$\gamma = \langle cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP})\rangle \approx (v_{1,\alpha}, v_{1,\beta} - a_\alpha a_\beta)$$



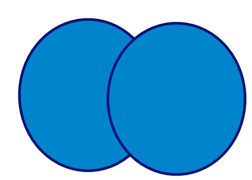
opposite sign

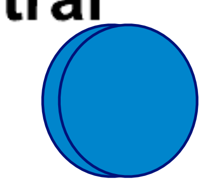
Same sign

$\gamma \propto B/N_{ch}$

$\gamma_{SS} < \gamma_{OS}$

Both same-sign and opposite-sign correlations have expected signs of correlation for charge separation





Cu+Cu > Au+Au at same centrality consistent with expected $1/N_{ch}$ dependence

Measurements at 200 GeV in Au+Au and Cu+Cu consistent with local parity violation

BG $\propto$ v_2

+ non-flow (jets, resonances)

STAR: PRC 81 054908 (2010)

Isobar program takes shape

First proposed by Sergei - PRL 105 172301

Initial further studies on U+U (body-body vs tip-tip) and BES data

STAR first proposes Isobar running in 2015 BUR

Summer 2016 - discussion of possible isobar pairs underway

- –considerations:
  - largest relative charge difference
  - similarity in shape
  - availability and price
  - ability to accelerate in RHIC

2017 Committee of theory and experiment called to review case for isobars
- case reported in CPC 14 072001 (2017)

2017 PAC approved Ru and Zr program

Isobar program: aims to disentangle signal

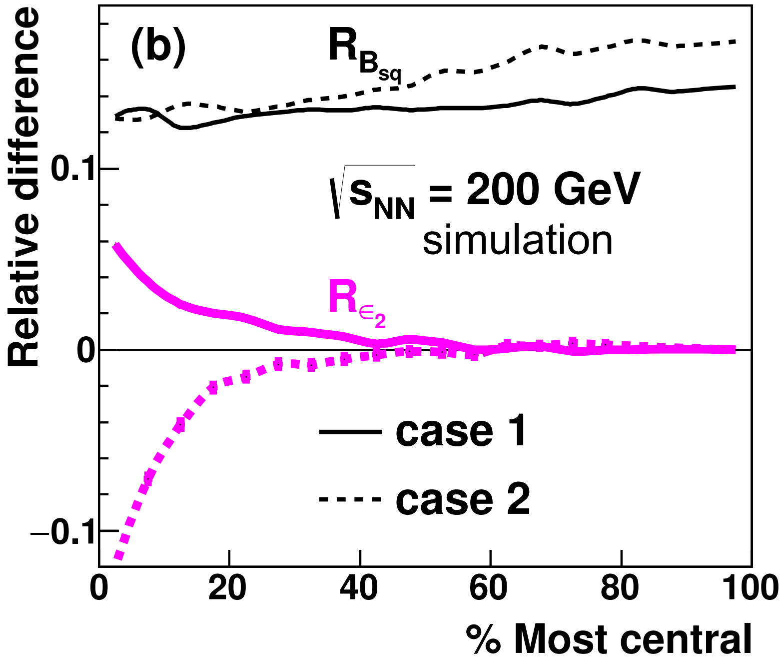
Goal to:
Keep constant v_2, background driver
Vary B, signal driver

Use Isobars

$^{96}_{44}Ru+^{96}_{44}Ru$ $^{96}_{40}Zr+^{96}_{40}Zr$

R = 5.085 fm R = 5.02 fm

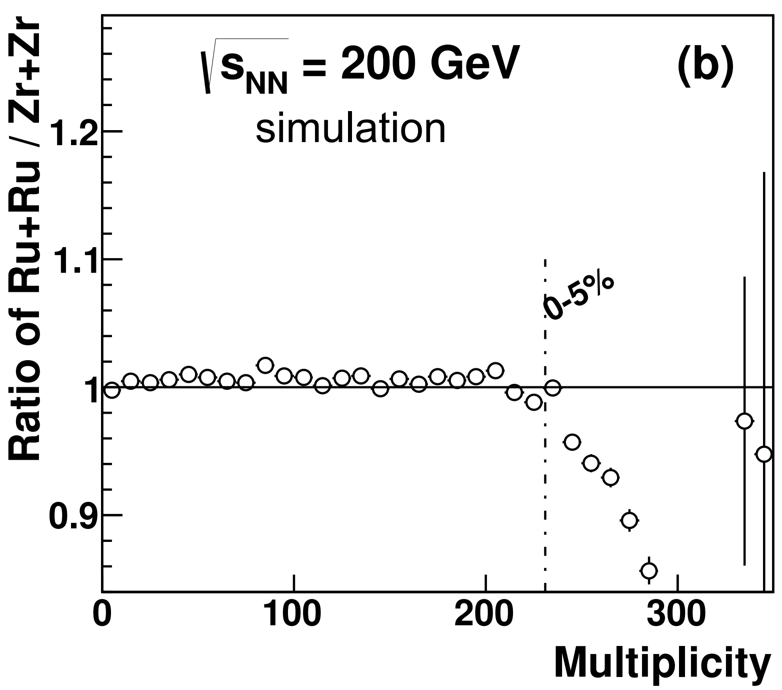
Nuclear deformity uncertain



Ru B-field squared 10-20% higher, 4 extra protons

Eccentricity similar (~4%) except for most central events v_2 expected to follow ϵ_2

Solid/dashed curves range in knowledge of shape of isobars from eA and theory



Multiplicities similar, except in most central events

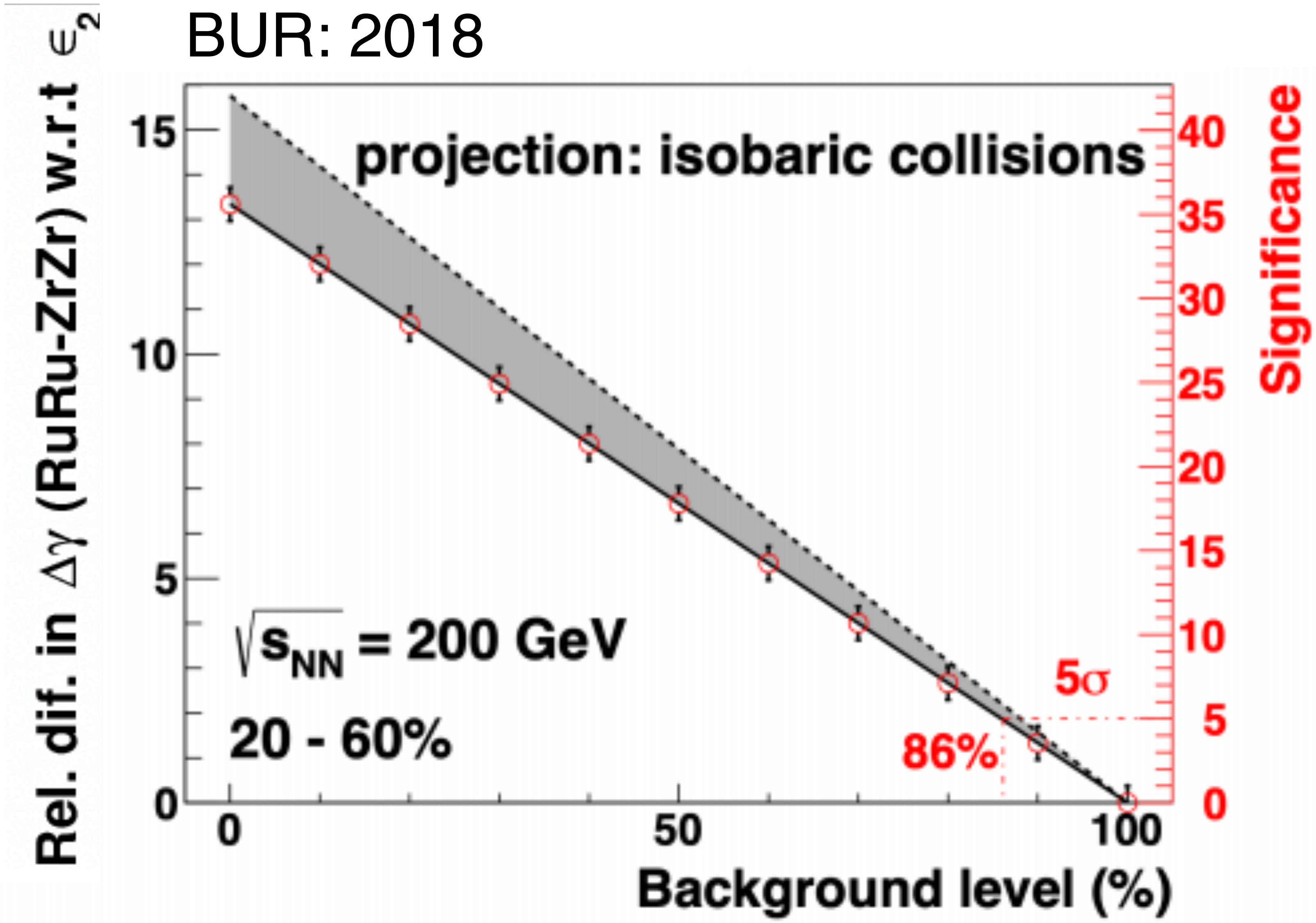
Study mid-central events
B field difference dominates

ϵ_2(Ru+Ru) ~ ϵ_2(Zr+Zr)
N_{ch}(Ru+Ru) ~ N_{ch}(Zr+Zr)
B(Ru+Ru) > B(Zr+Zr)

W. Deng et al. PRC 94 041901 (2016)

Isobars: A unique test

BUR: 2018



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

? ≠ ≈ =

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

From B-field
10-18% different

Depending on background level different statistical significance

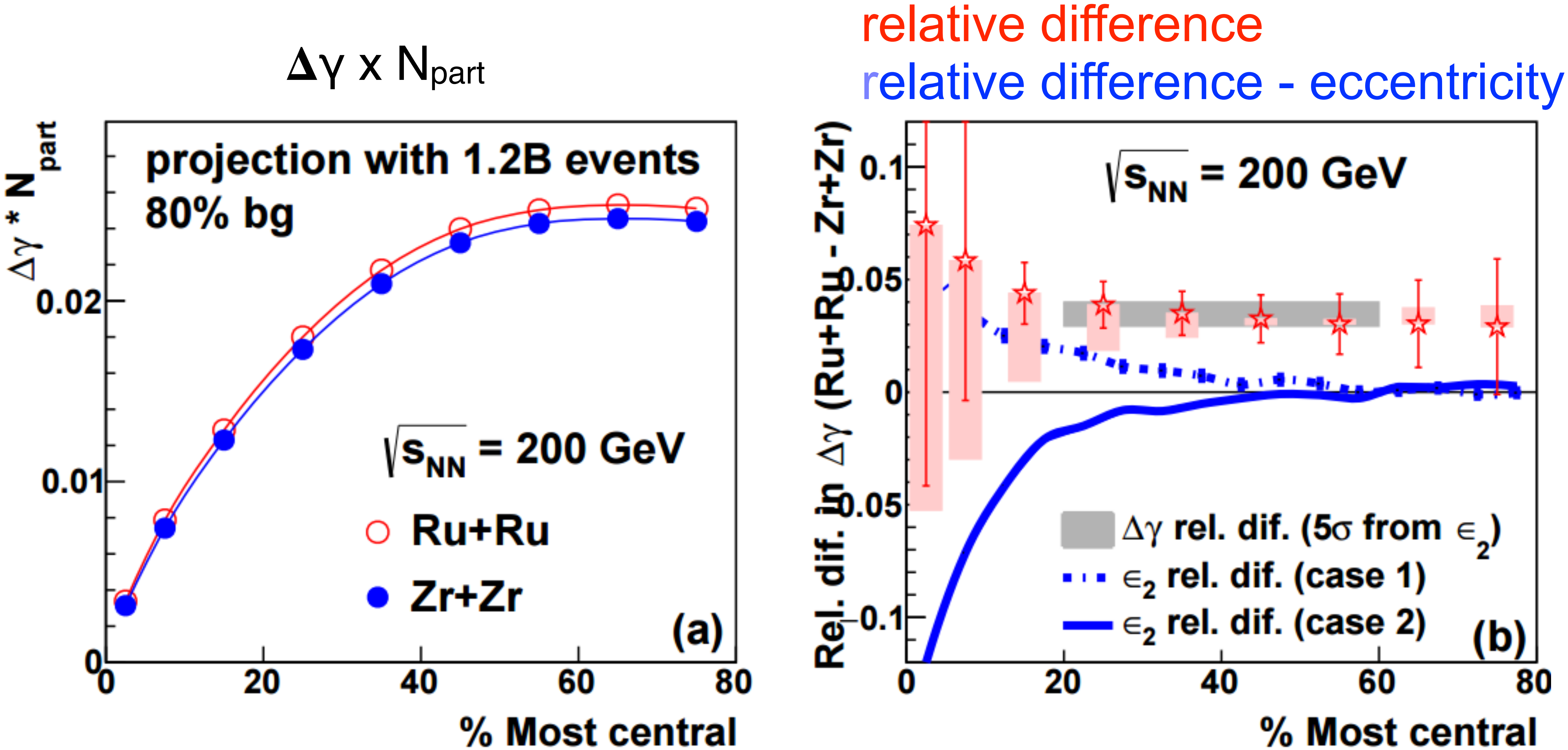
CMS and theory suggest BG ~80%

Estimates assume 1B events per species, actually collected ~2B for each species after QA cuts applied

Data should allow for ~5σ if BG ~80%

Potentially a definitive test!

Isobar signal prediction



Estimate sensitive to details of:

- shape
- charge distribution
- neutron skin thickness

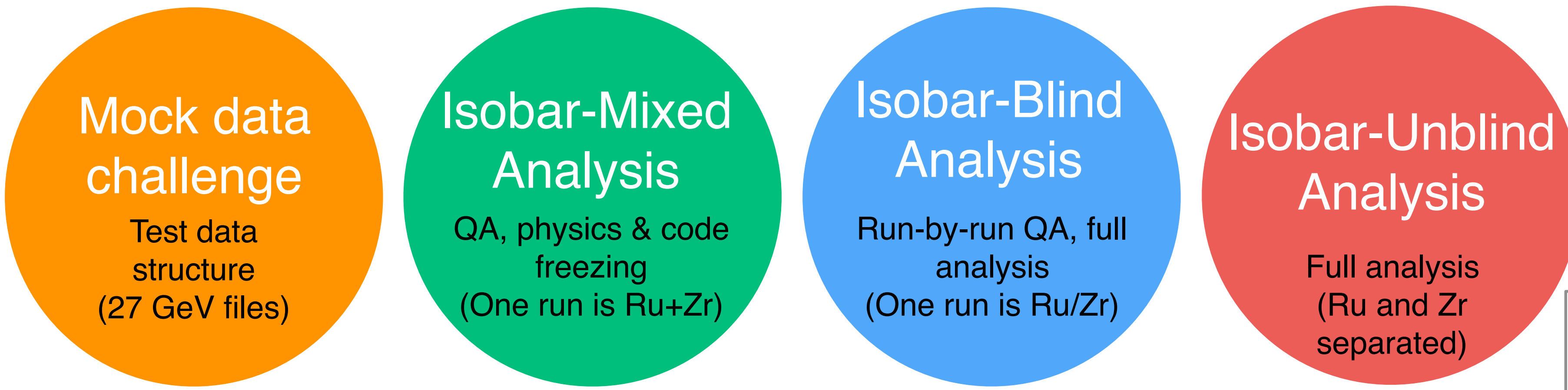
If collect at least 1.2B events for each species should have clear signal in mid-central events

Based on Δγ having 80% non-CME background

Decision to blind the analyses

2017 PAC recommended ***blind analyses*** of ***CME*** using Run-18 isobar data

Methods developed and accepted by collaboration in January 2018, well before 2018 data-taking



STAR, arXiv:1911.00596
Cartoon: arXiv:2009.01230

Step-1, "The Reference"

Provide output files composed of collision data from a ***mix*** of the two isobar species

As much as possible, order of collision "events" ***respects time-dependent changes in detector conditions***

Analysis code and **time-dependent QA** tuned and frozen

Step-2, "The run by run QA sample"

Provide files that blind the isobar species but do not "mix" data from different data acquisition runs

Only allow "run-by-run" corrections and code alteration directly resulting from these corrections

Step-3, Full un-blinding

Analysis completed and published as is

Combined effort of many many people in STAR

STAR: NST 32, 48 (2021)

Blinded analyses challenge accepted

Agreed that first paper would be based on predefined observables described in analysis notes frozen before analysis of data started

5 groups, each consisting of a few STAR collaborators, agreed to perform blind analyses

Each group focused on a specific analysis

Substantial overlap also exists for built-in cross-checks

Agreed on:

- A common and analysis-specific set of variables for data QA and data selection to use data with stable detector performance
- A common set of variations accepted for systematic uncertainty determination
- Calibration experts (recused from CME analyses) evaluate data quality “in real time”
- Restrict species-related information to those necessary for successful data-taking

Data taking considerations

Large number of events to enable small statistical uncertainty -> long data collection period

Need to keep systematics at few %, smaller than statistical uncertainty

Based on previous studies dominant systematics:

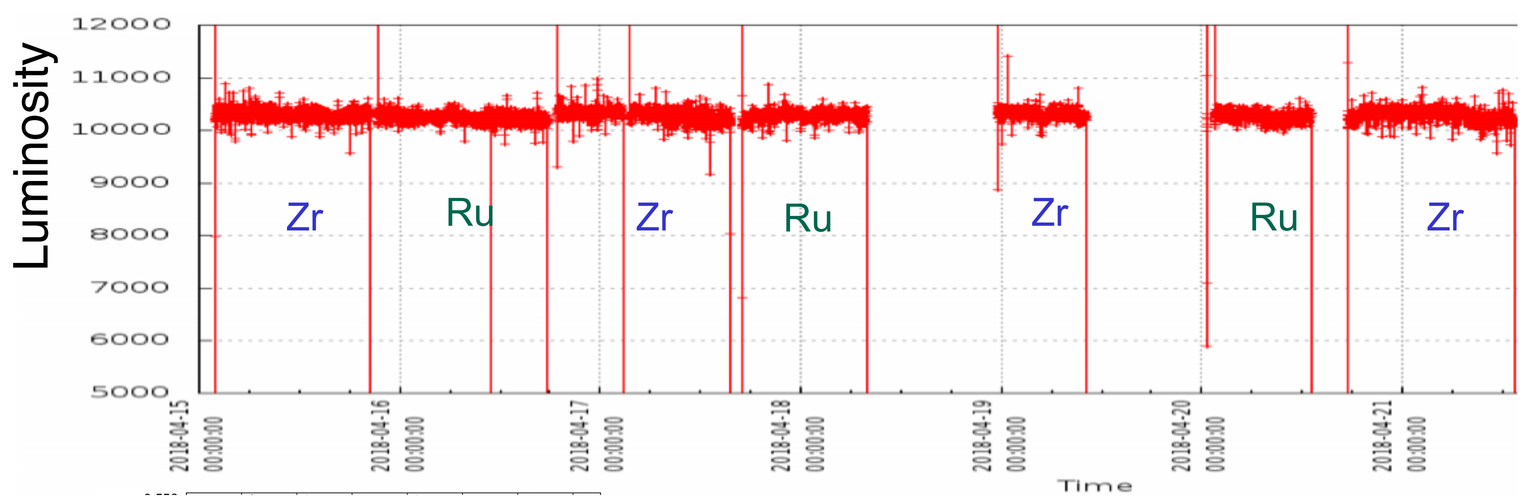
run-to-run variations of detector response - acceptance and efficiency

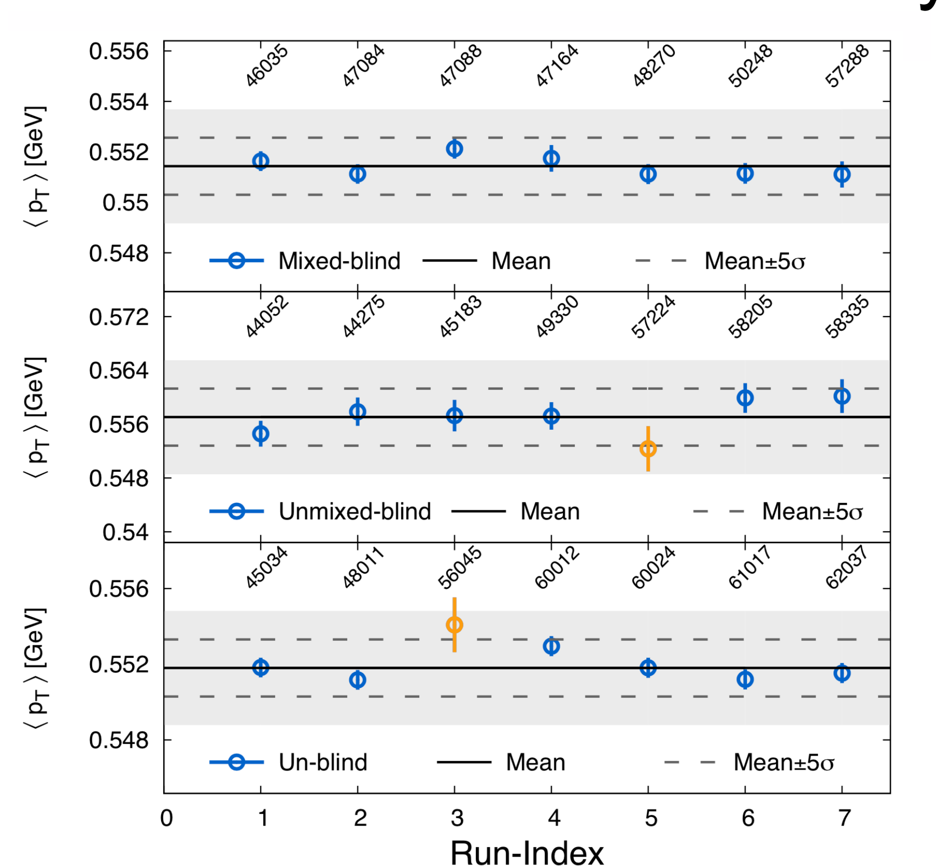
variation in beam luminosity

Determined to:

switch species each store

long stores with level low luminosity





Data collection conditions "same" for both species

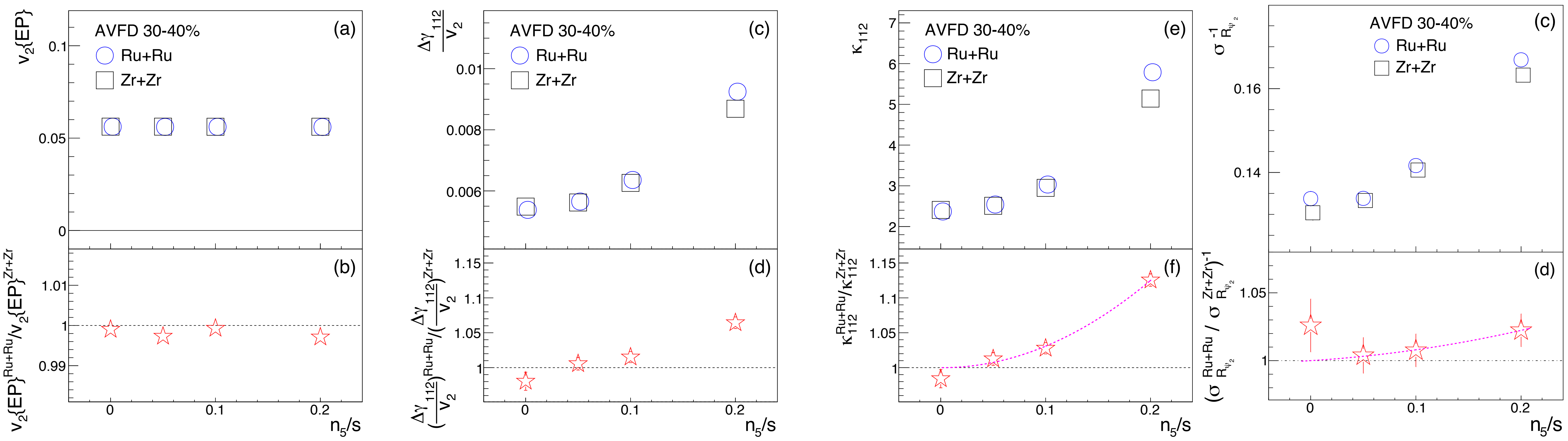
Special RHIC running conditions (G. Marr et al. 10th international particle accelerator conf (2019) 28-32)

Data monitored offline on run-by-run basis

Frozen codes tested on AVFD

Background

Examples of blind analysis variables



- note not real data

Members of CME group tested frozen code sensitivities with e-b-e AVFD

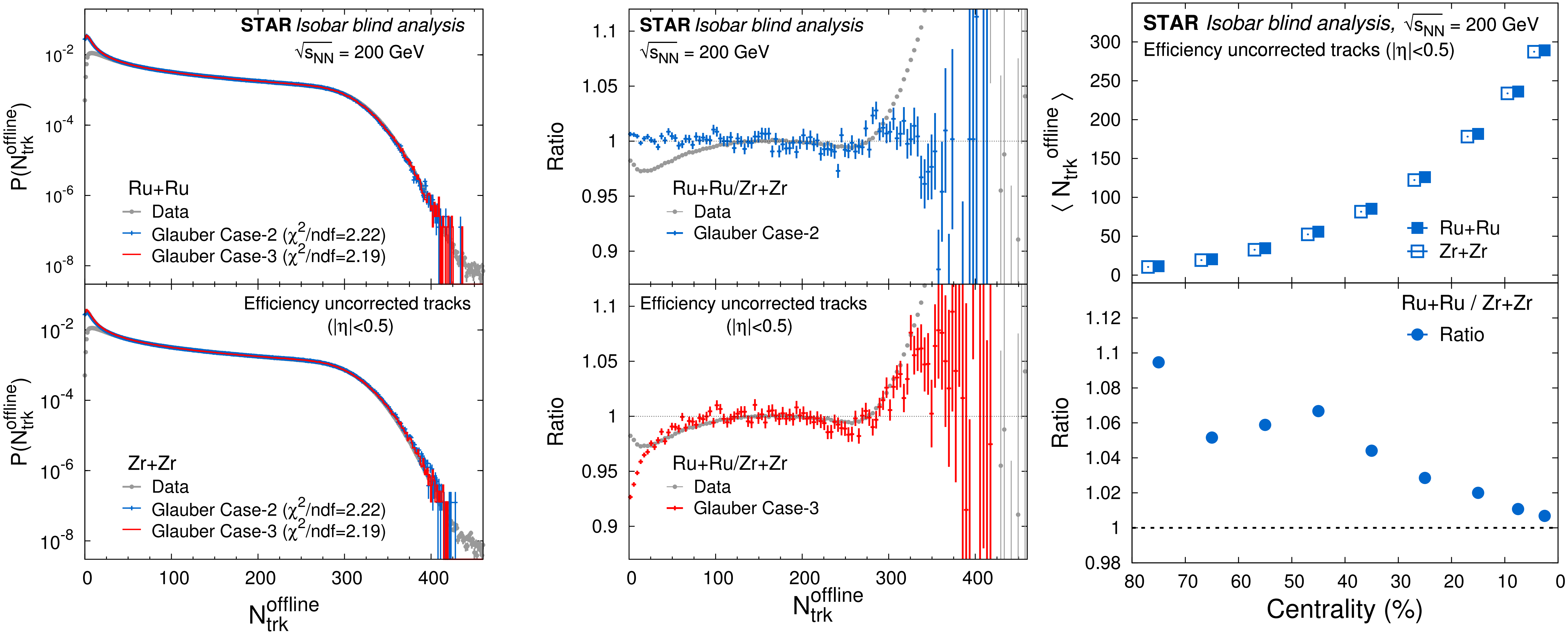
– n_5/s indicates CME signal strength

Variable believed sensitive to only background independent of CME strength

Good sensitivity of variables to signal

STAR CME Group:2105.06044

Centrality and multiplicity comparisons



3 Woods-Saxon parameter sets fit to multiplicity distributions

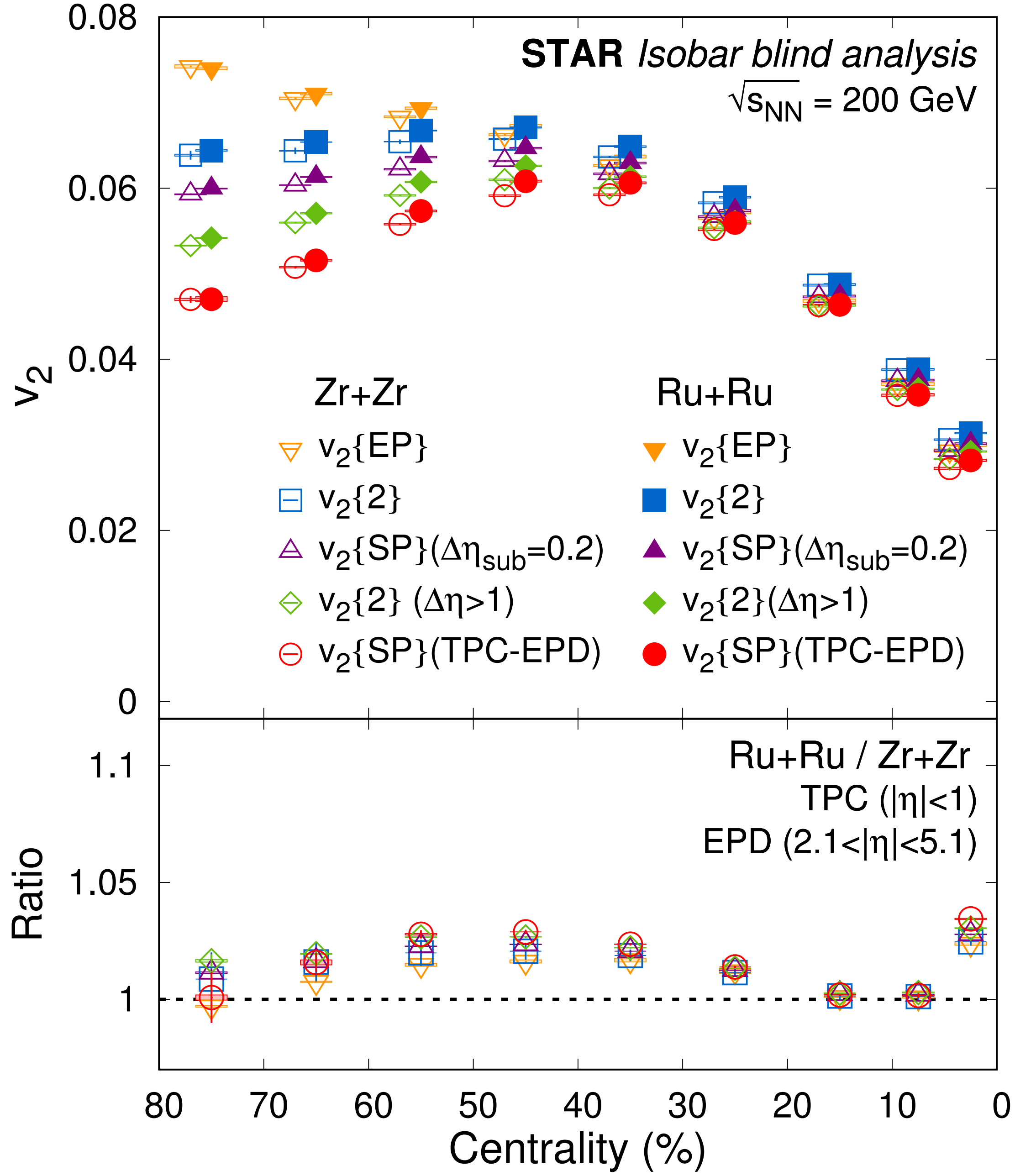
- 2-component nucleon-base MC Glauber
- Best fit (case-3) no quadrupole component, different neutron skin

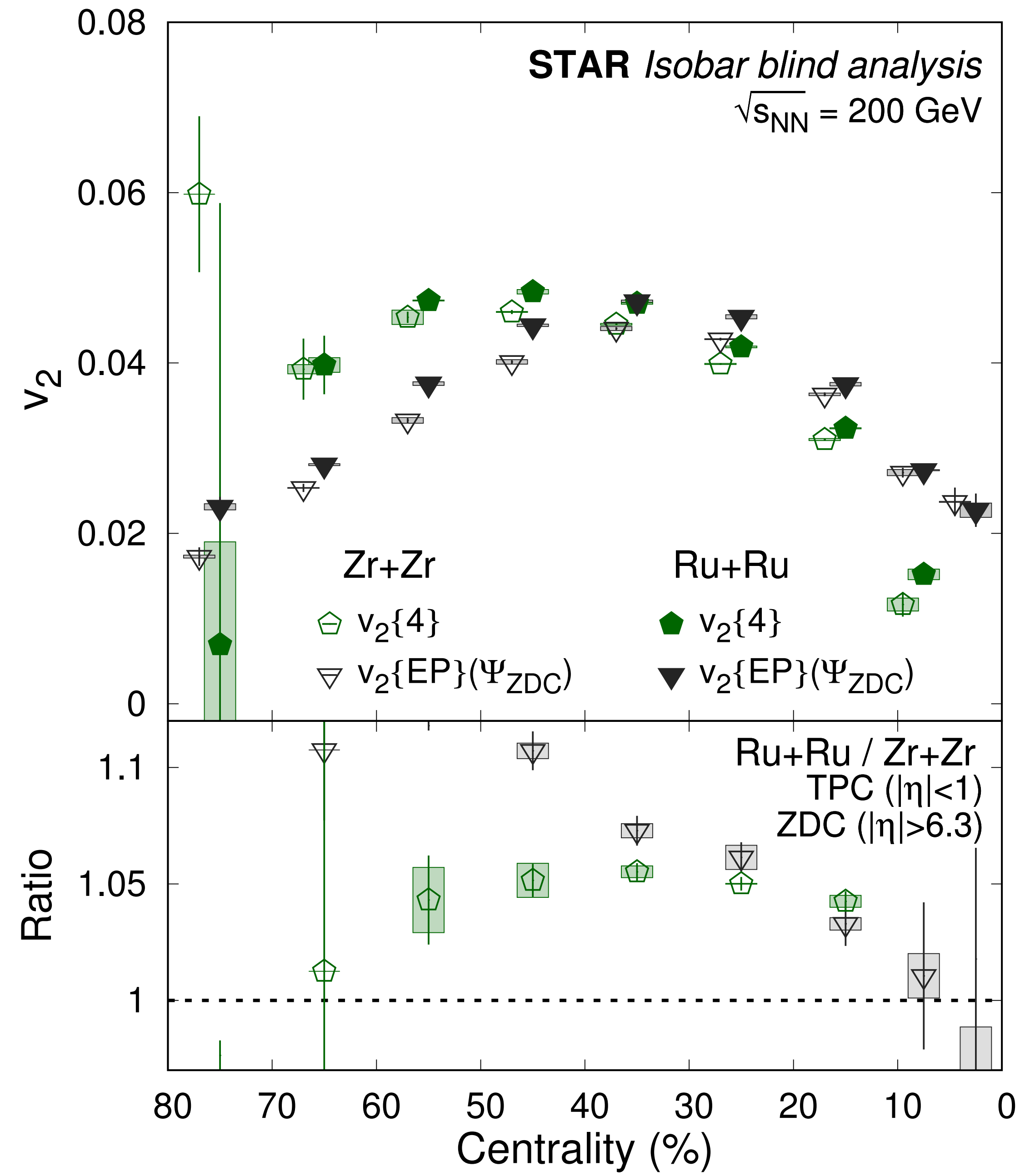
Future study: adjust WS parameters, different treatment of sub-nucleon fluctuations, better treatment of integer multiplicities in binning

	Case-1 [83]			Case-2 [83]			Case-3 [113]		
Nucleus	R (fm)	a (fm)	β_2	R (fm)	a (fm)	β_2	R (fm)	a (fm)	β_2
$^{96}_{44}$Ru	5.085	0.46	0.158	5.085	0.46	0.053	5.067	0.500	0
$^{96}_{40}$Zr	5.02	0.46	0.08	5.02	0.46	0.217	4.965	0.556	0

Matching centrality bins leads to difference in multiplicities

Elliptic flow comparisons





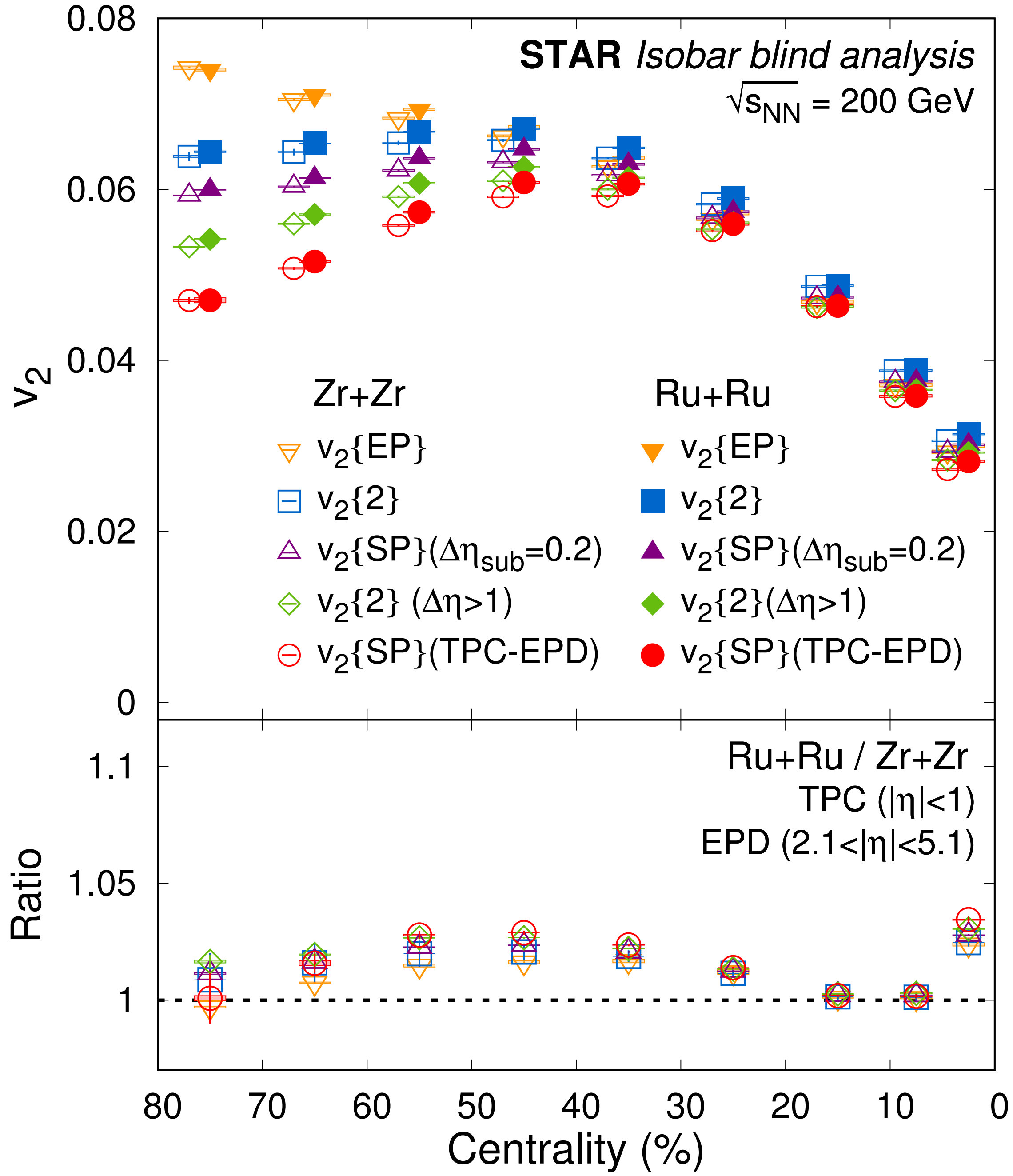
Different methods lead to different v_2

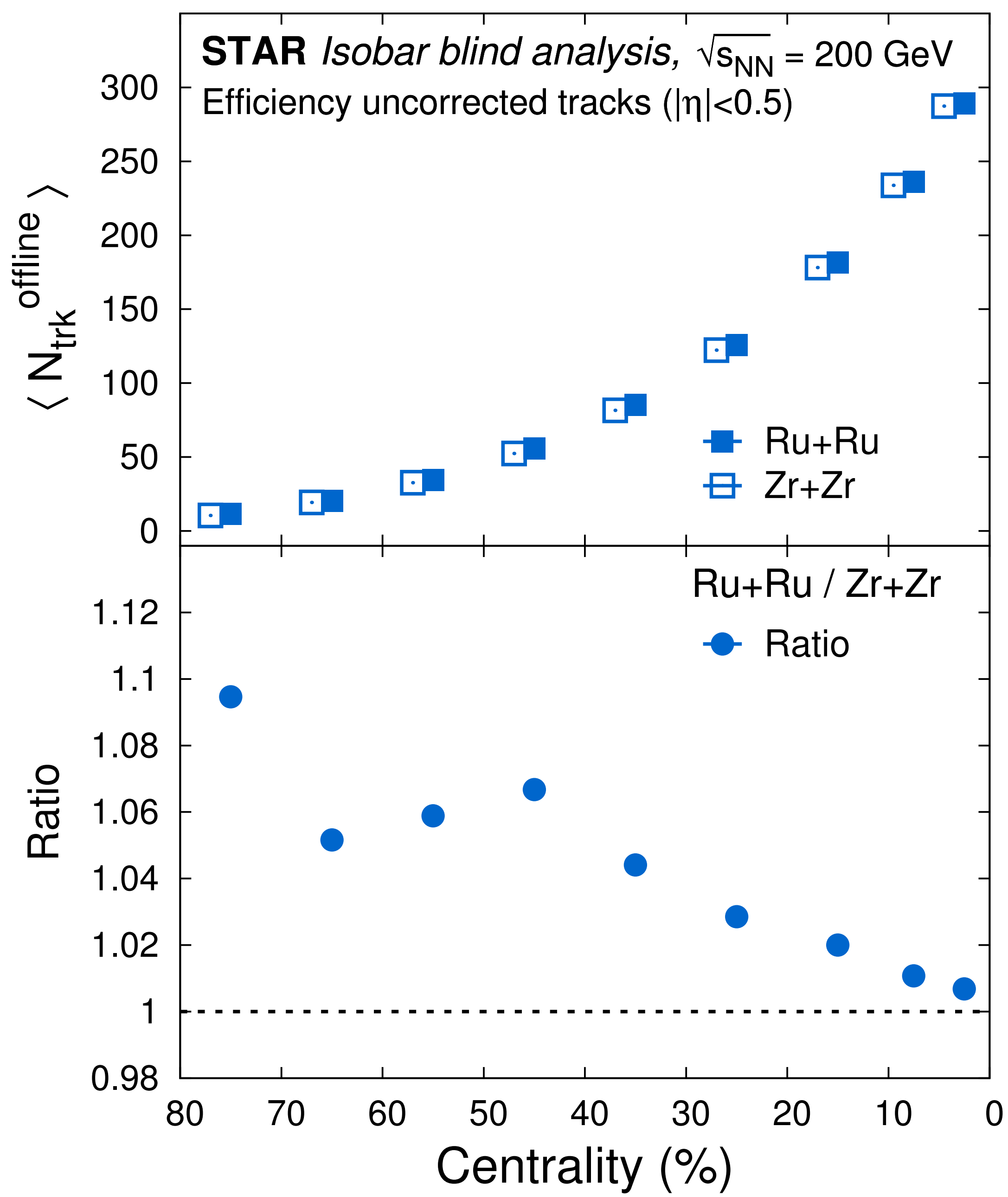
- expected due to differing sensitivities to non-flow contributions

Ratios all on common curve except $v_2\{4\}$ and $v_2(\psi_{ZDC})$

Differences on the multiple % scale

CME background appears different





Observed differences in both multiplicity and v_2 imply that CME background different for the two isobars at matching centralities

Expectations for CME signal

For each observable/approach, a set of CME signatures were predefined prior to the blind analysis

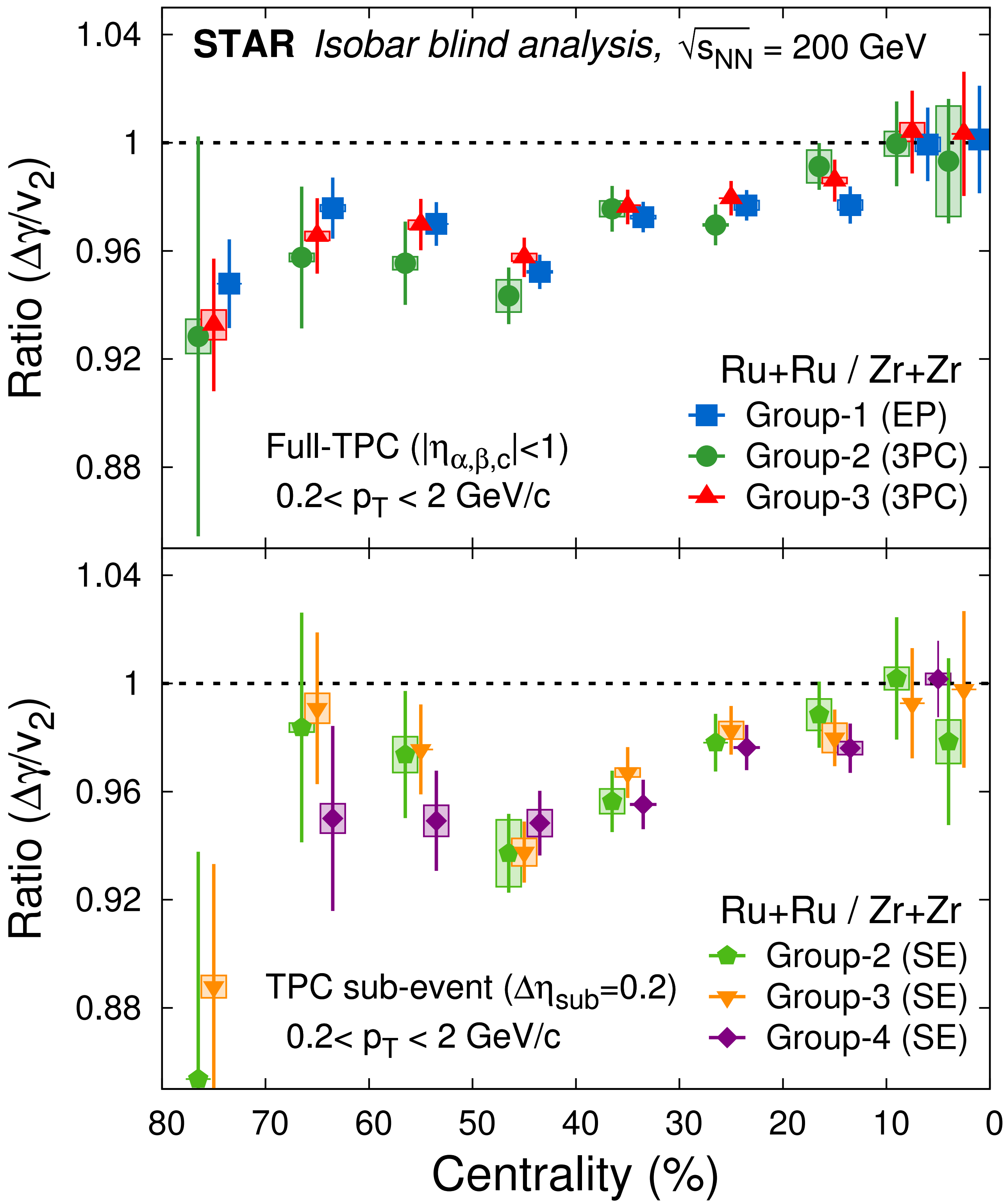
Affirmative observation of CME defined as 5σ (high significance) measurement

These CME signatures were defined as a significant excess of the CME-sensitive observables in Ru+Ru collisions over those in Zr+Zr collisions, owing to a larger magnetic field in the former

$$\frac{\mathrm{Measure(Ru+Ru)}}{\mathrm{Measure(Zr+Zr)}} > 1$$

$\Delta\gamma/v_2$

Groups 1-4



SE:sub-event

Verified results consistent within expected statistical fluctuations due to differing analysis-specific event selections and slightly different methods used

Stat uncertainties mostly (but not completely) correlated

Predefined CME signature:

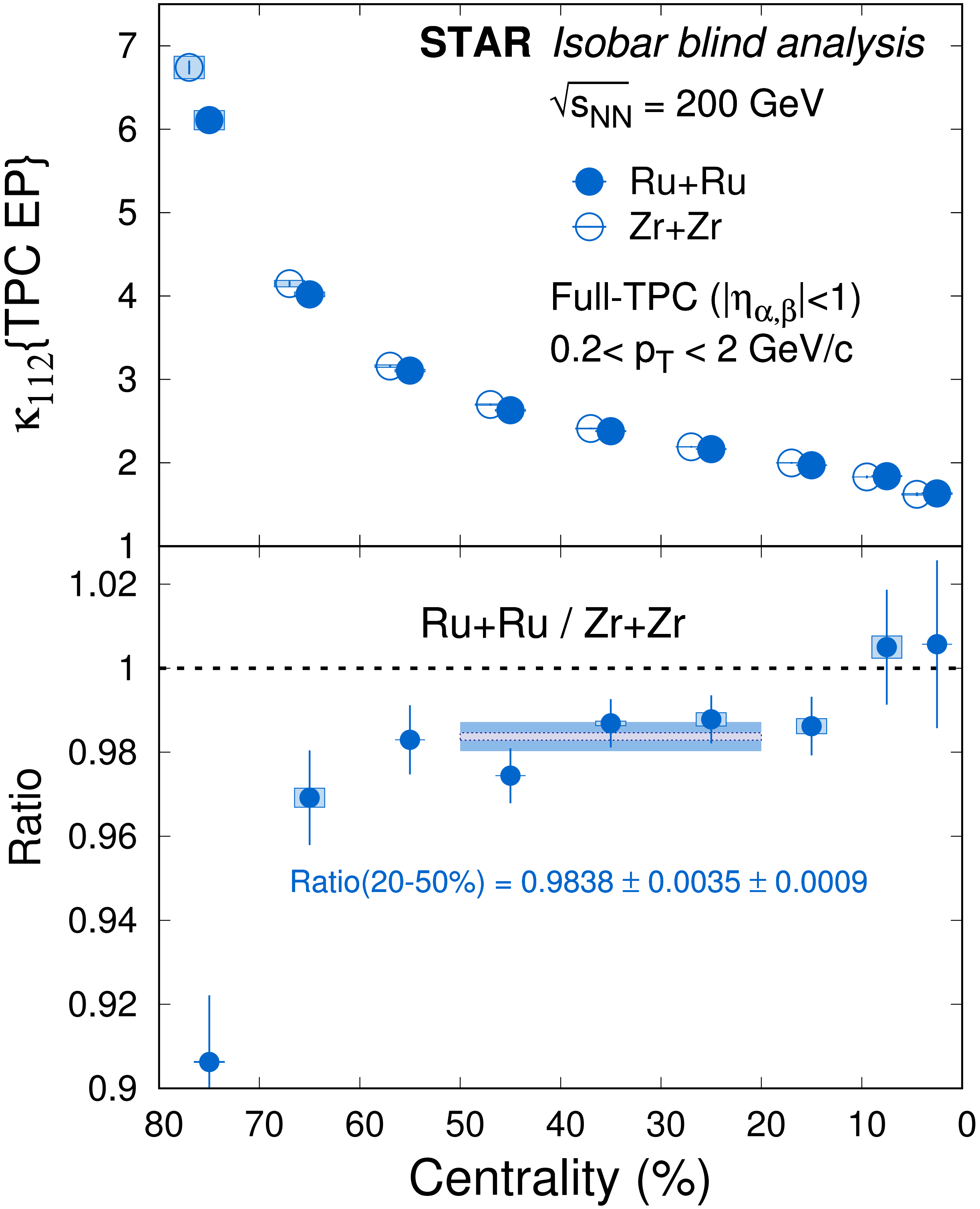
$$\frac{(\Delta\gamma/v_2)_{\rm Ru+Ru}}{(\Delta\gamma/v_2)_{\rm Zr+Zr}} = 1 + f_{\rm CME}^{\rm Zr+Zr}[(B_{\rm Ru+Ru}/B_{\rm Zr+Zr})^2 - 1],$$

$$\frac{(\Delta\gamma_{112}/v_2)^{\rm Ru+Ru}}{(\Delta\gamma_{112}/v_2)^{\rm Zr+Zr}} > 1$$

Predefined signature criteria not observed

κ_{112}

Group 1



$$\gamma_{112} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2) \rangle ,$$

$$\delta = \langle \cos(\phi_\alpha - \phi_\beta) \rangle$$
$$= (\langle v_{1,\alpha} v_{1,\beta} \rangle + B_{\rm IN}) + (\langle a_{1,\alpha} a_{1,\beta} \rangle + B_{\rm OUT})$$

$$\Delta\delta = \delta_{\rm OS} - \delta_{\rm SS}$$

Background contributions expected to have similar structure that involve coupling between v_2 and $\Delta\delta$

$$\kappa_{112} \equiv \frac{\Delta\gamma_{112}}{v_2\, \Delta\delta}$$

Predefined CME signature:

$$\frac{\kappa_{112}^{\rm Ru+Ru}}{\kappa_{112}^{\rm Zr+Zr}} > 1.$$

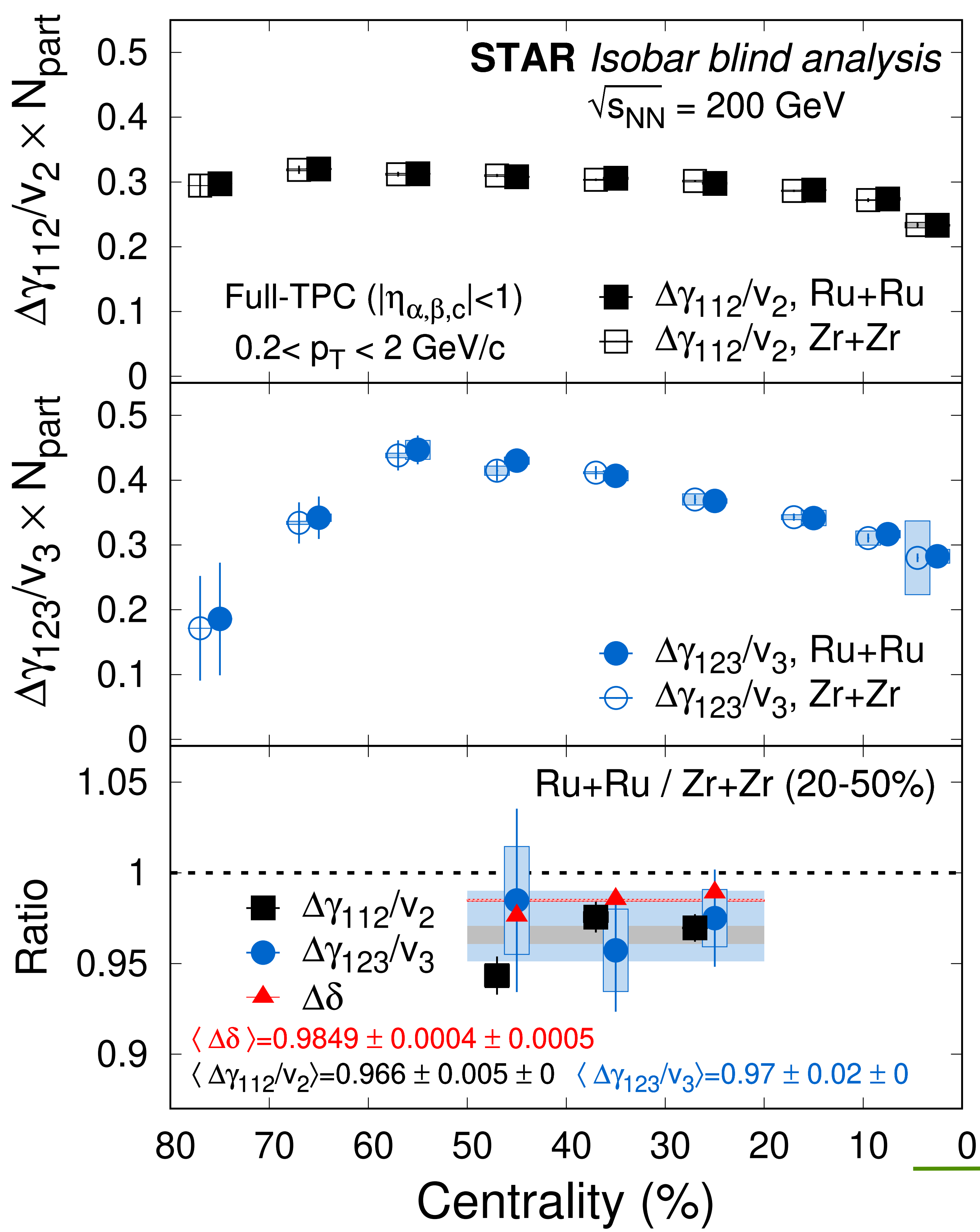
Predefined signature criteria not observed

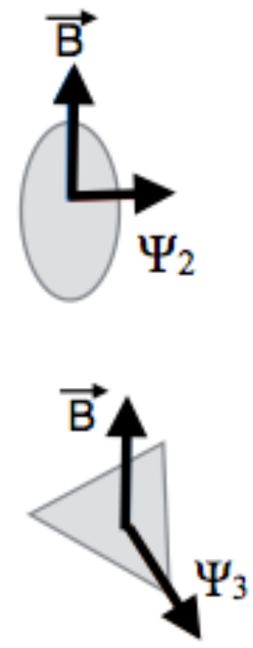
Precision down to 0.4% achieved

Mixed harmonics (full TPC)

Group 2

$$\gamma_{123} \equiv \langle \cos(\phi_\alpha + 2\phi_\beta - 3\Psi_3) \rangle$$





3rd order Event Plane not correlated with Magnetic Field

γ_{112} - CME + BG

γ_{123} - BG only

Predefined CME signature:

$$\frac{(\Delta\gamma_{112}/v_2)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{112}/v_2)^{\mathrm{Zr+Zr}}} > 1\,,$$

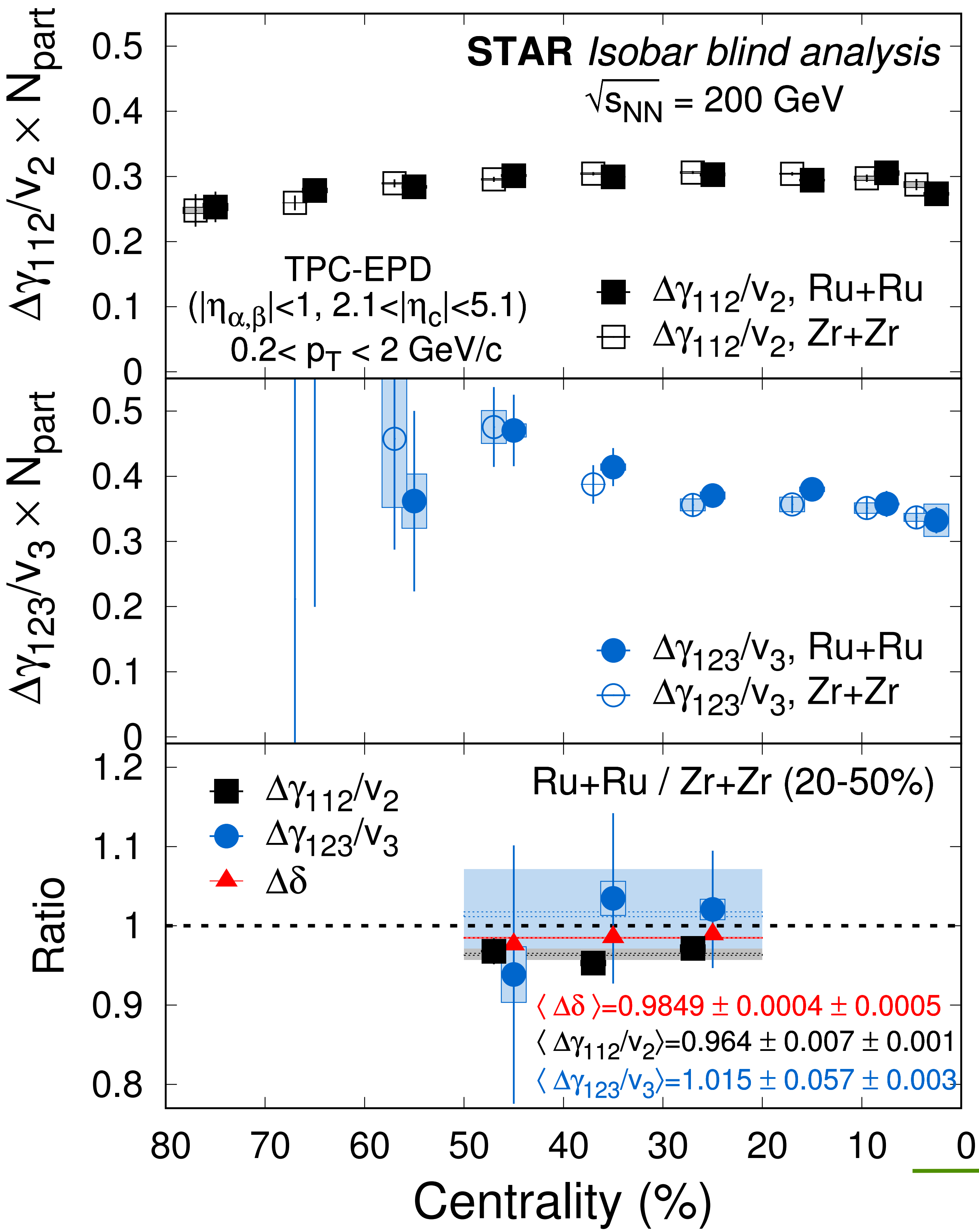
$$\frac{(\Delta\gamma_{112}/v_2)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{112}/v_2)^{\mathrm{Zr+Zr}}} > \frac{(\Delta\gamma_{123}/v_3)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{123}/v_3)^{\mathrm{Zr+Zr}}}\,,$$

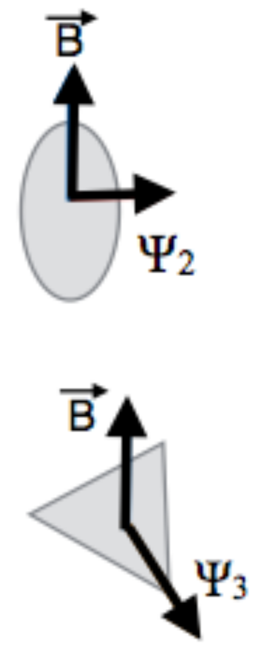
$$\frac{(\Delta\gamma_{112}/v_2)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{112}/v_2)^{\mathrm{Zr+Zr}}} > \frac{(\Delta\delta)^{\mathrm{Ru+Ru}}}{(\Delta\delta)^{\mathrm{Zr+Zr}}}.$$

Predefined signature criteria not observed

Mixed harmonics (TPC-EPD)

Group 2





Planes now from EPD - large eta gap

γ_{112} - CME + BG

3[rd] order Event Plane not correlated with Magnetic Field

γ_{113} - BG only

Predefined CME signature:

$$\frac{(\Delta\gamma_{112}/v_2)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{112}/v_2)^{\mathrm{Zr+Zr}}} > 1\,,$$

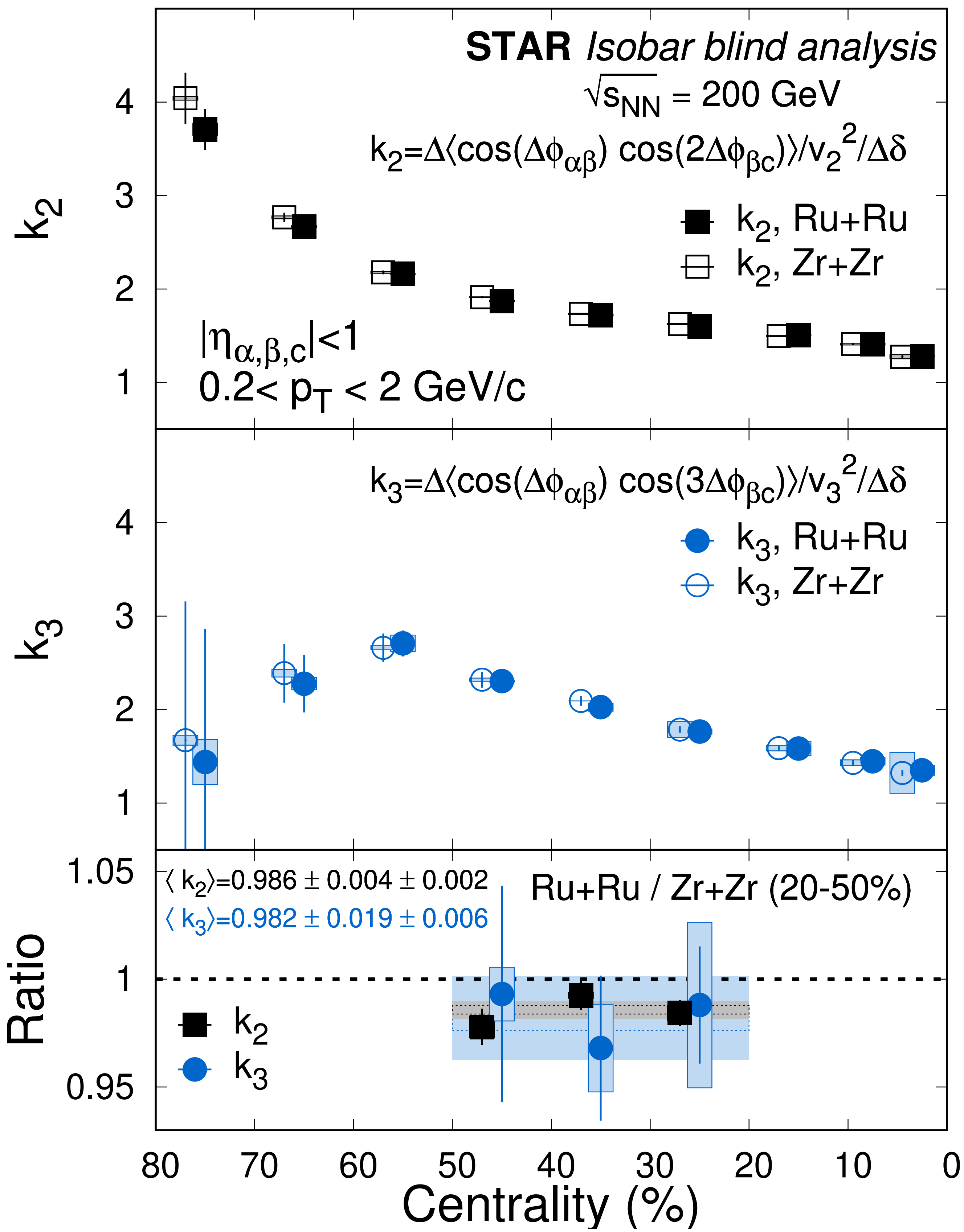
$$\frac{(\Delta\gamma_{112}/v_2)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{112}/v_2)^{\mathrm{Zr+Zr}}} > \frac{(\Delta\gamma_{123}/v_3)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{123}/v_3)^{\mathrm{Zr+Zr}}}\,,$$

$$\frac{(\Delta\gamma_{112}/v_2)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{112}/v_2)^{\mathrm{Zr+Zr}}} > \frac{(\Delta\delta)^{\mathrm{Ru+Ru}}}{(\Delta\delta)^{\mathrm{Zr+Zr}}}\,.$$

Predefined signature criteria not observed

Factorization breaking

Group 2



$$k_n = \frac{\Delta\langle\cos(\Delta\phi_{\alpha\beta})\cos(n\Delta\phi_{\beta c})\rangle}{v_n^2\{2\}\Delta\delta_{\alpha\beta}}$$

k_2 sensitive to CME + v_2

k_3 sensitive to v_3

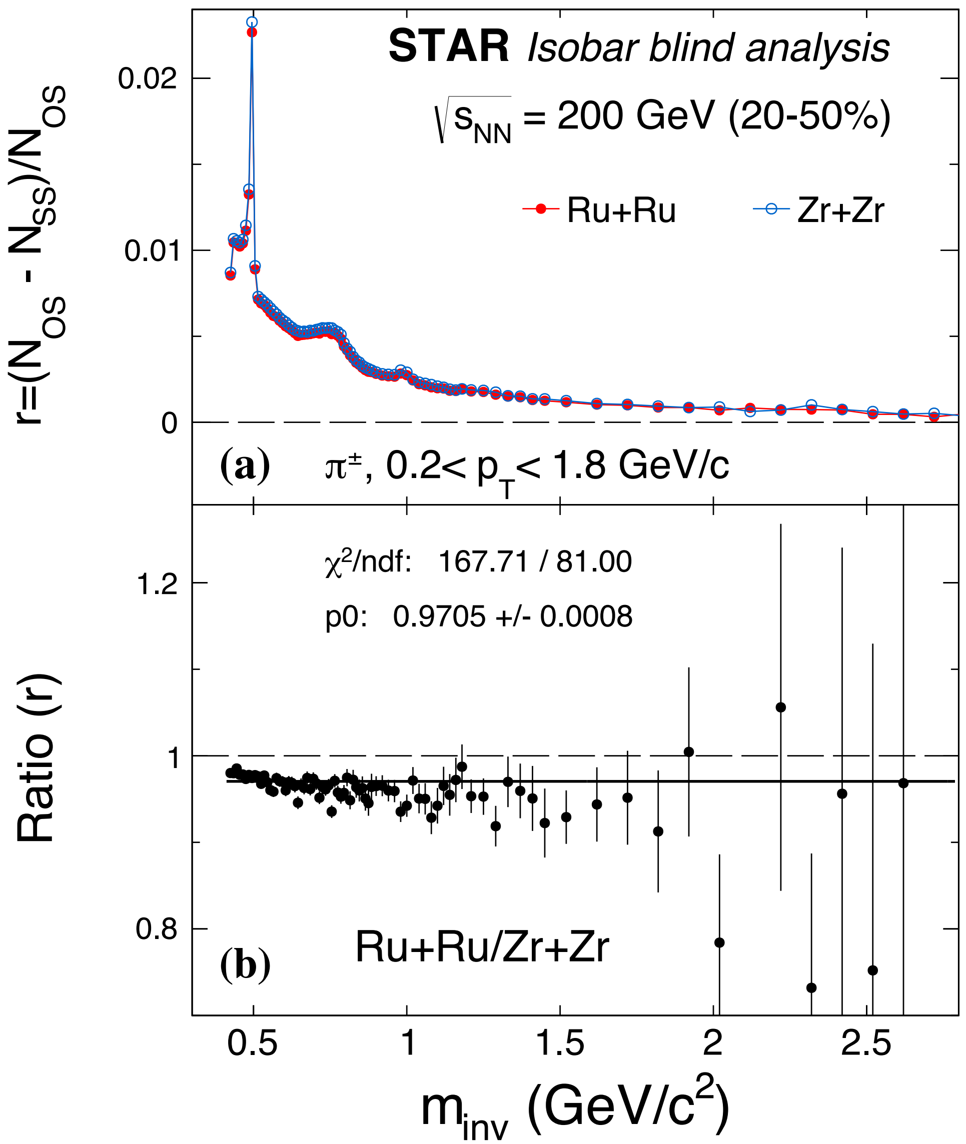
Predefined CME signature:

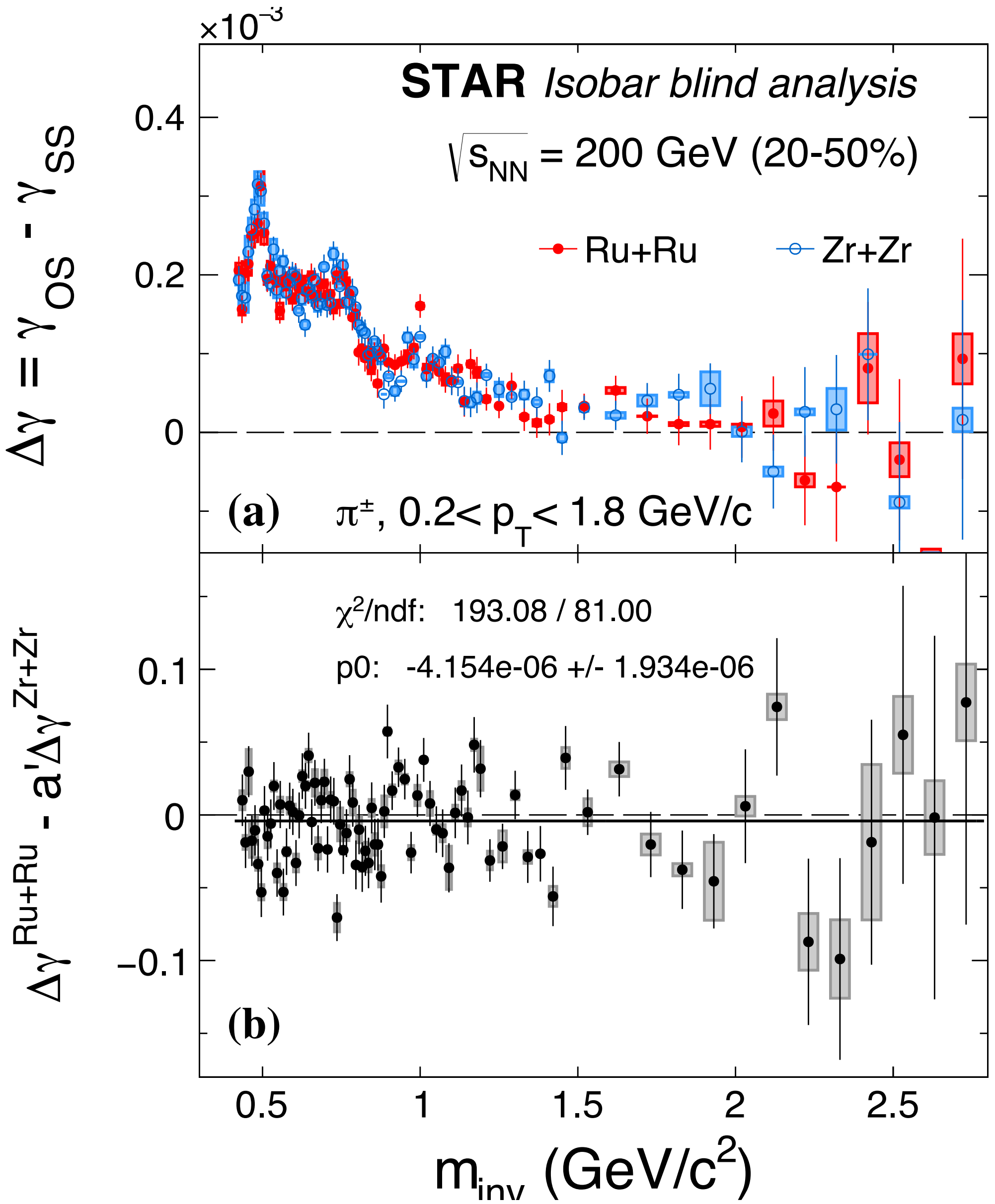
$$\frac{k_2^{\mathrm{Ru+Ru}}}{k_2^{\mathrm{Zr+Zr}}} > \frac{k_3^{\mathrm{Ru+Ru}}}{k_3^{\mathrm{Zr+Zr}}}$$

Predefined signature criteria not observed

Probing differentially in m_{inv}

Group 3





Probe using pion pairs

No obvious enhancements seen

$$a' = v_2^{\mathrm{Ru+Ru}} / v_2^{\mathrm{Zr+Zr}}$$

Predefined CME signature:

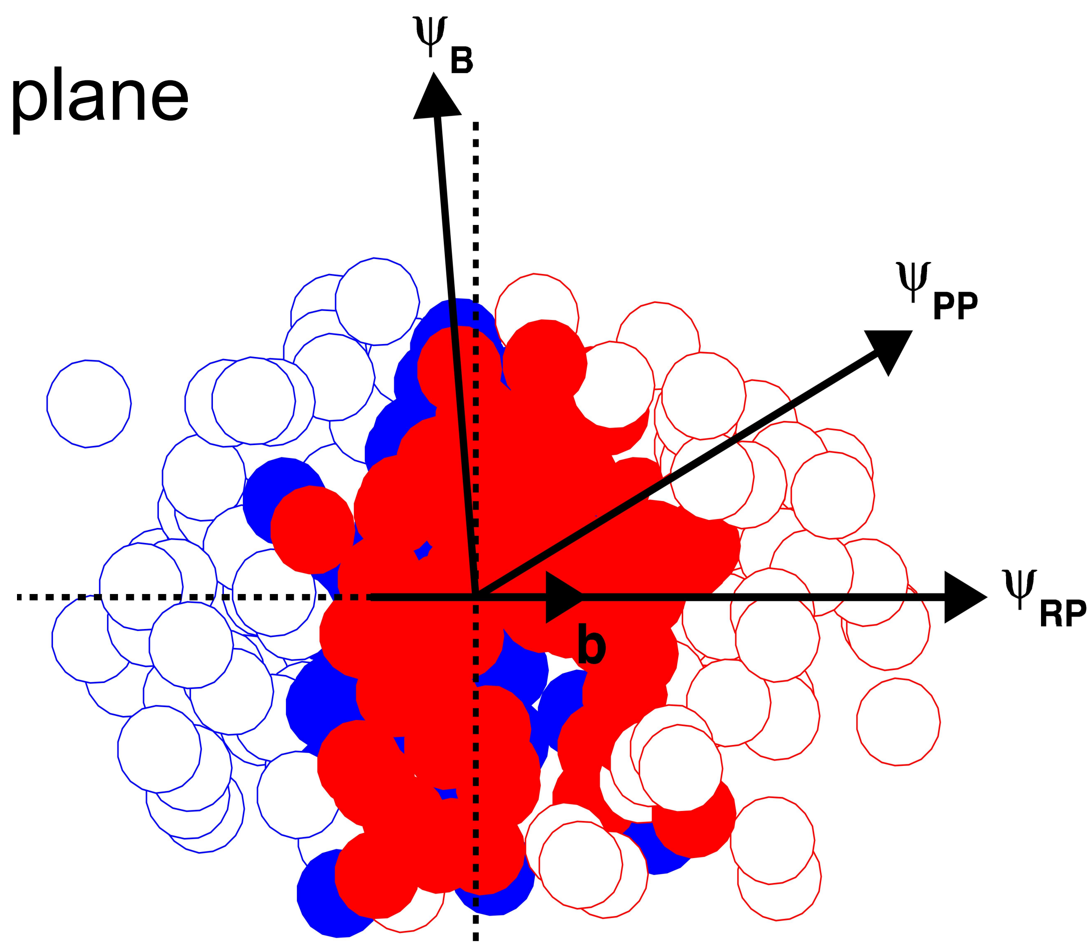
$$\Delta\gamma^{\mathrm{Ru+Ru}} - a'\Delta\gamma^{\mathrm{Zr+Zr}} > 0$$

Predefined signature criteria not observed

Comparing spectator to participant plane

N.B. B-field correlated with spectator (reaction) plane

Flow correlated with participant plane



Assume $\Delta\gamma$ can be decomposed:

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

$\Delta\gamma^{CME}\{PP\} = a\,\Delta\gamma^{CME}\{SP\}$

a = projection factor from one plane to the other
= $\langle\cos[2(\psi_{PP} - \psi_{SP})]\rangle$

$\Delta\gamma^{BG}$ driven by v_2 so maximal when measured with respect to PP

$\Delta\gamma^{BG}\{SP\} = a\,\Delta\gamma^{BG}\{PP\}$

$a = v_2\{SP\} / v_2\{PP\}$

$f_{CME} = \Delta\gamma^{CME}\{PP\} / \Delta\gamma\{PP\}$
$= [A/a - 1] / [1/a^2 - 1]$

$A = \Delta\gamma\{SP\} / \Delta\gamma\{PP\}$

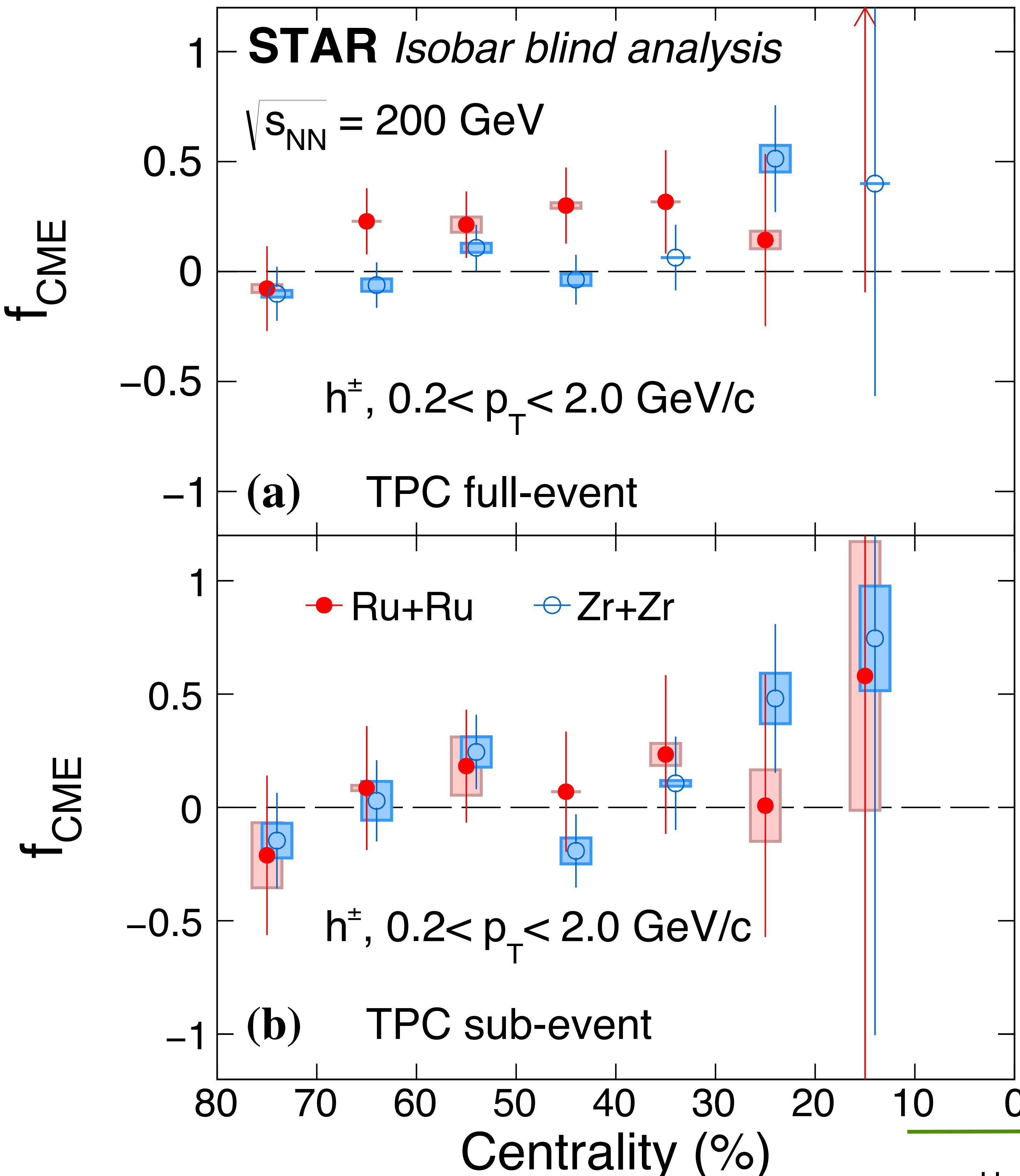
ZDC - spectator plane

TPC - participant plane

STAR: arXiv:2106.09243

Extracting f_{CME}

Group 3 (also Group 4, slightly different)



Performed in full and sub-event TPC

Predefined CME signature:

$$f_{\text{CME}}^{\text{Ru+Ru}} > f_{\text{CME}}^{\text{Zr+Zr}} > 0$$

Average for 20-50% sub-event TPC

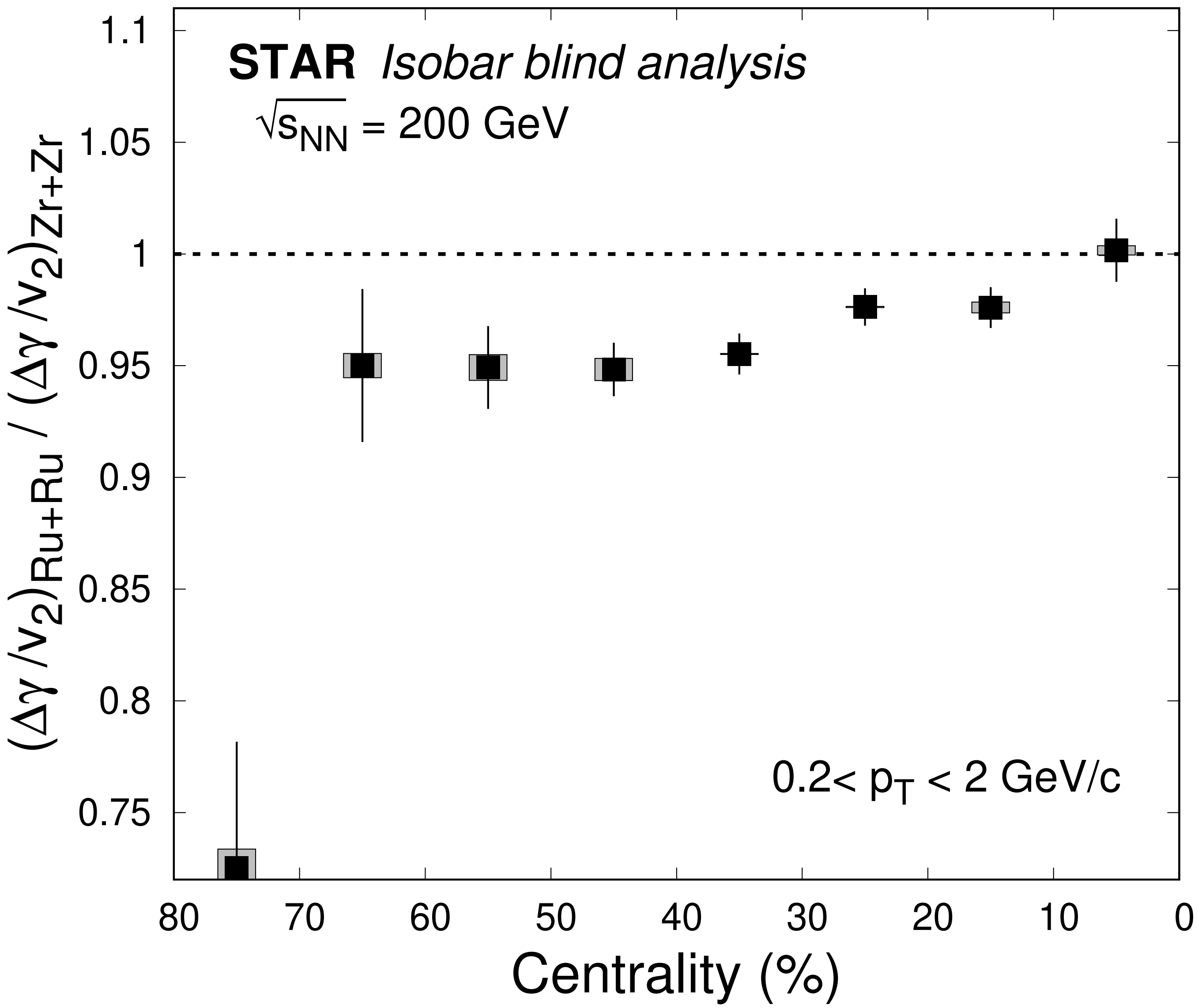
Ru:
f_{CME} 0.12 ± 0.20(stat) ± 0.00 (sys)

Zr:
f_{CME} =-0.01 ± 0.12(stat) ± 0.03(sys)

Predefined signature criteria not observed

Double ratio to cancel resolution

Group 4



Plane resolution canceled by direct calculation of ratio

Systematics also reduces

$$(\Delta\gamma/v_2)_{\mathrm{TPC}} = \frac{\Delta\langle\cos(\phi_\alpha + \phi_\beta - 2\phi_c)\rangle}{\langle\cos(2\phi_\alpha - 2\phi_c)\rangle}$$

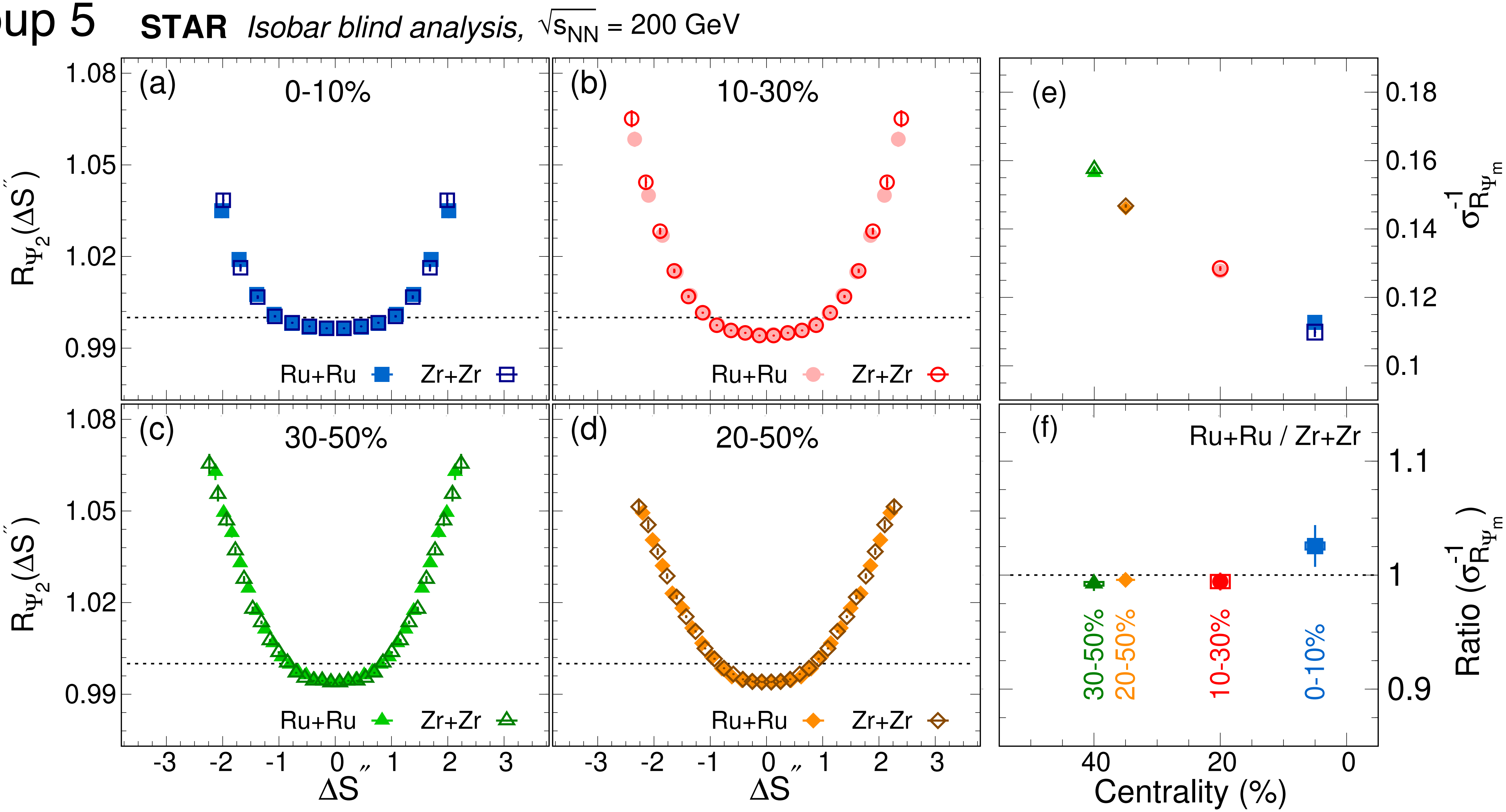
Predefined CME signature:

$$\frac{(\Delta\gamma_{112}/v_2)^{RuRu}}{(\Delta\gamma_{112}/v_2)^{ZrZr}} > 1$$

Predefined signature criteria not observed

R variable

Group 5



$$R_{\Psi_2}(\Delta S) = C_{\Psi_2}(\Delta S)/C^{\perp}_{\Psi_2}(\Delta S),$$

$$C_{\Psi_2}(\Delta S) = \frac{N_{\text{real}}(\Delta S)}{N_{\text{shuffled}}(\Delta S)},$$

$$\Delta S = \frac{\sum_1^{n^+} w_i^+ \sin(\Delta\varphi_2)}{\sum_1^{n^+} w_i^+} - \frac{\sum_1^{n^-} w_i^- \sin(\Delta\varphi_2)}{\sum_1^{n^-} w_i^-},$$

Predefined CME signature:

$$1/\sigma_{R_{\Psi_2}}(\mathrm{Ru+Ru}) > 1/\sigma_{R_{\Psi_2}}(\mathrm{Zr+Zr})$$

Predefined signature criteria not observed

Putting it all together

Predefined CME signatures: ratios involving Ψ_2 > those involving Ψ_3 , and > 1

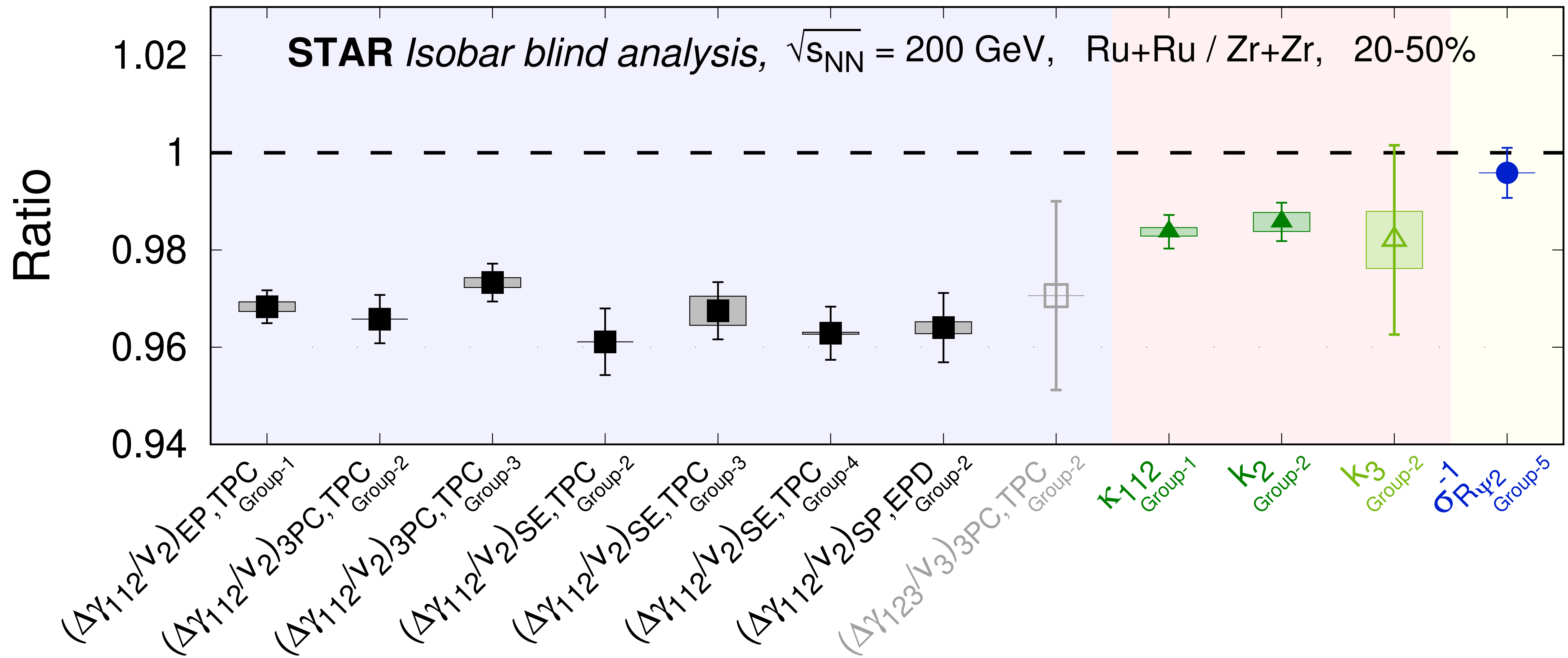
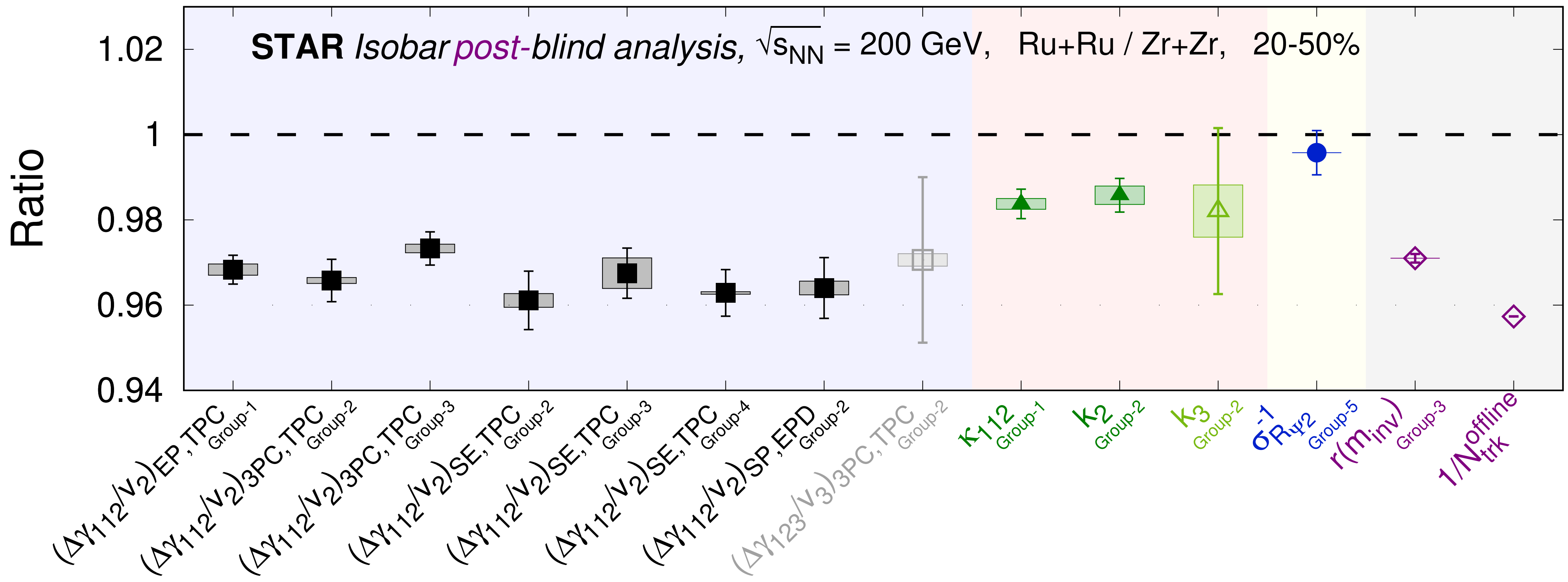


FIG. 26. Compilation of results from the blind analysis. Only results contrasting between the two isobar systems are shown. Results are shown in terms of the ratio of measures in Ru+Ru collisions over Zr+Zr collisions. Solid dark symbols show CME-sensitive measures whereas open light symbols show counterpart measures that are supposed to be insensitive to CME. The vertical lines indicate statistical uncertainties whereas boxes indicate systematic uncertainties. The colors in the background are intended to separate different types of measures. The fact that CME-sensitive observable ratios lie below unity leads to the conclusion that no predefined CME signatures are observed in this blind analysis.

No predefined signature criteria observed

Post-blinding analysis



2-particle correlations due to small clusters scale approximately with 1/mult
Potentially therefore more correct to define a CME signal as:

$$\frac{(\Delta\gamma/v_2)_{Ru+Ru}}{(\Delta\gamma/v_2)_{Zr+Zr}} > \frac{N_{ch}^{Zr}}{N_{ch}^{Ru}}$$

But it could also be $r = (N_{os}-N_{ss})/N_{os}$

Need better understanding of the baseline

Summary

- CME analyses of STAR's Isobar data:
  - signatures of the CME were defined prior to analyzing the blinded data
  - more details and blind analysis results are in the paper (arXiv:2109.00131)
  - more unblinded results to come
- Backgrounds are reduced by comparing differences between the isobar datasets
- Consistent results are obtained by the 5 independent analyses groups
- A precision down to 0.4% has been demonstrated, as anticipated, in the relative magnitudes of pertinent observables between the two isobar systems
- Differences in multiplicity and flow variables at matching centralities indicate that CME backgrounds differs between Zr and Ru
- No CME signature that satisfies the pre-defined criteria has been observed in the blind analysis

Next step: to establish exact limits need to understand systematics driving the ratio

$$\frac{(\Delta\gamma/v_2)_{Ru+Ru}}{(\Delta\gamma/v_2)_{Zr+Zr}}$$

to sub-percent level. Smaller than current differences between groups and Full vs SE

"By hand" replotting not sufficient

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