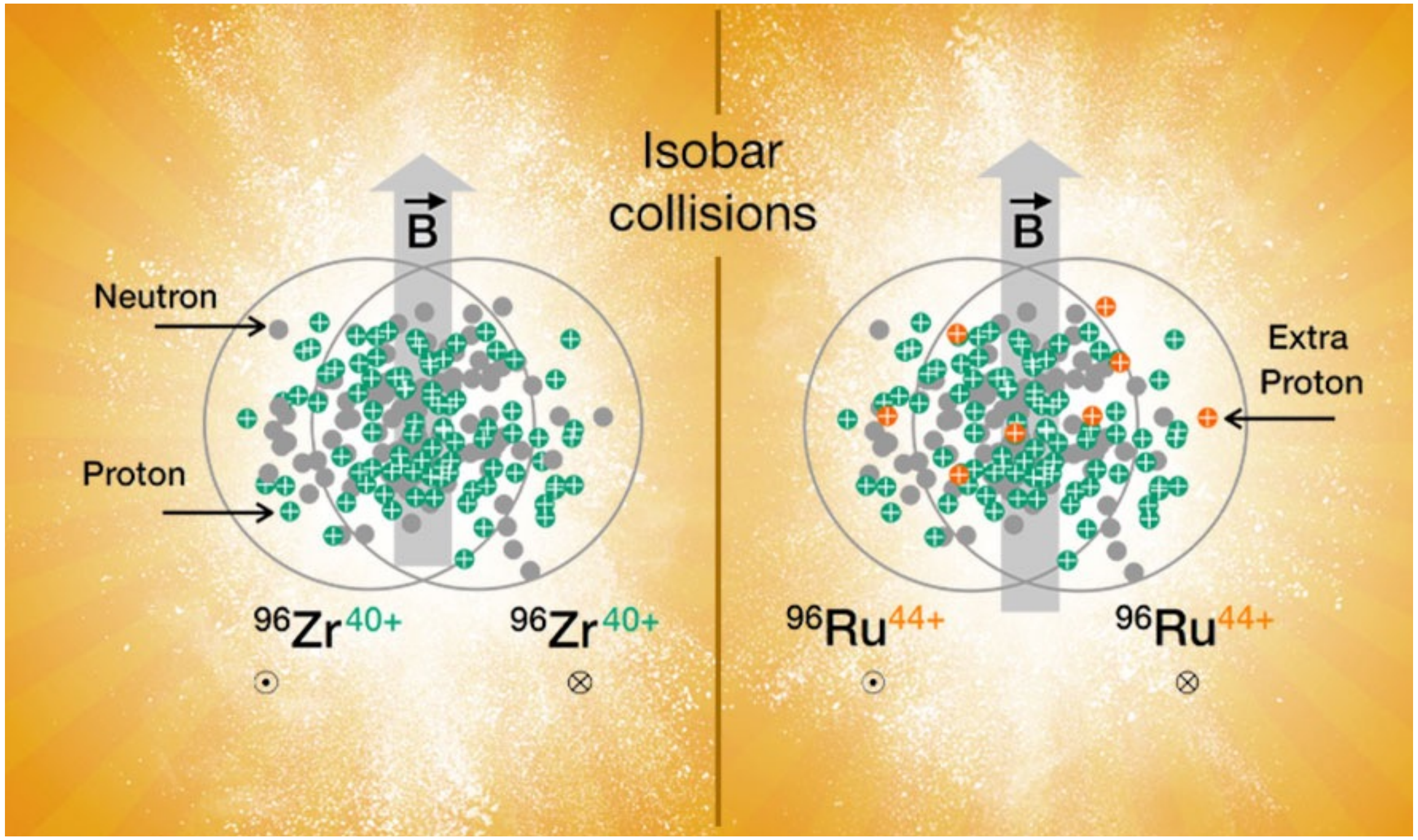
First STAR CME Results From the Isobar Run - An Overview

(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

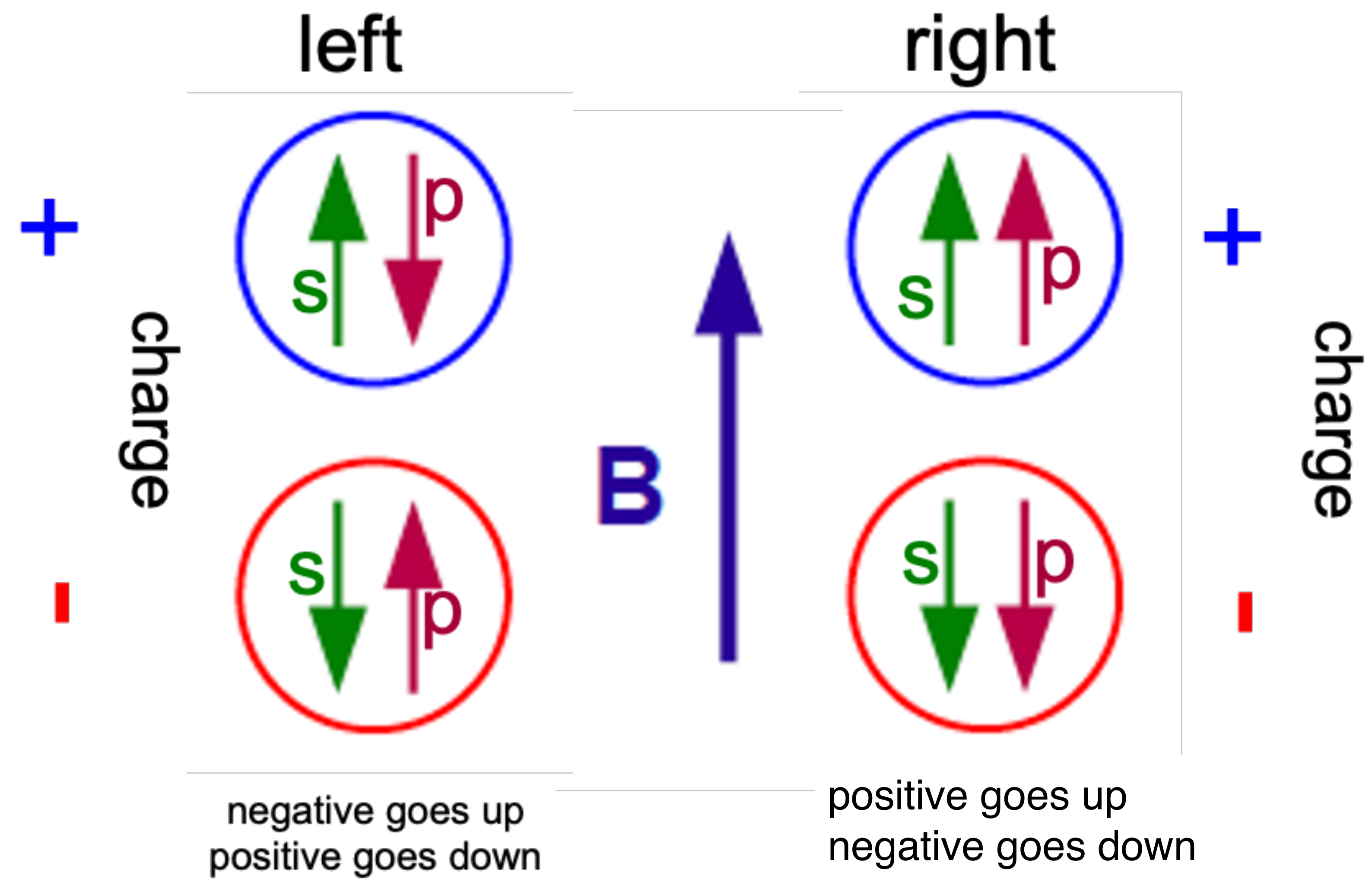
An excess of right/left handed quarks leads to current flow along B-field

Charge current

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

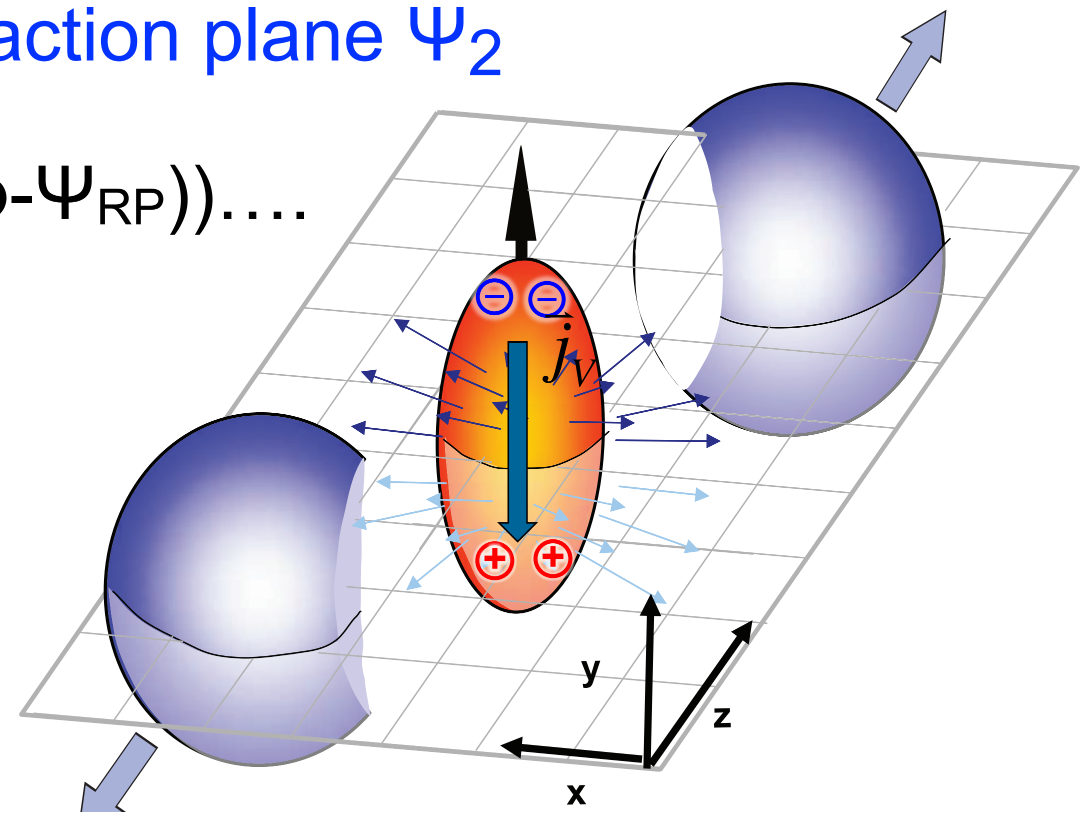
Chiral Magnetic Effect (CME)

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

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

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

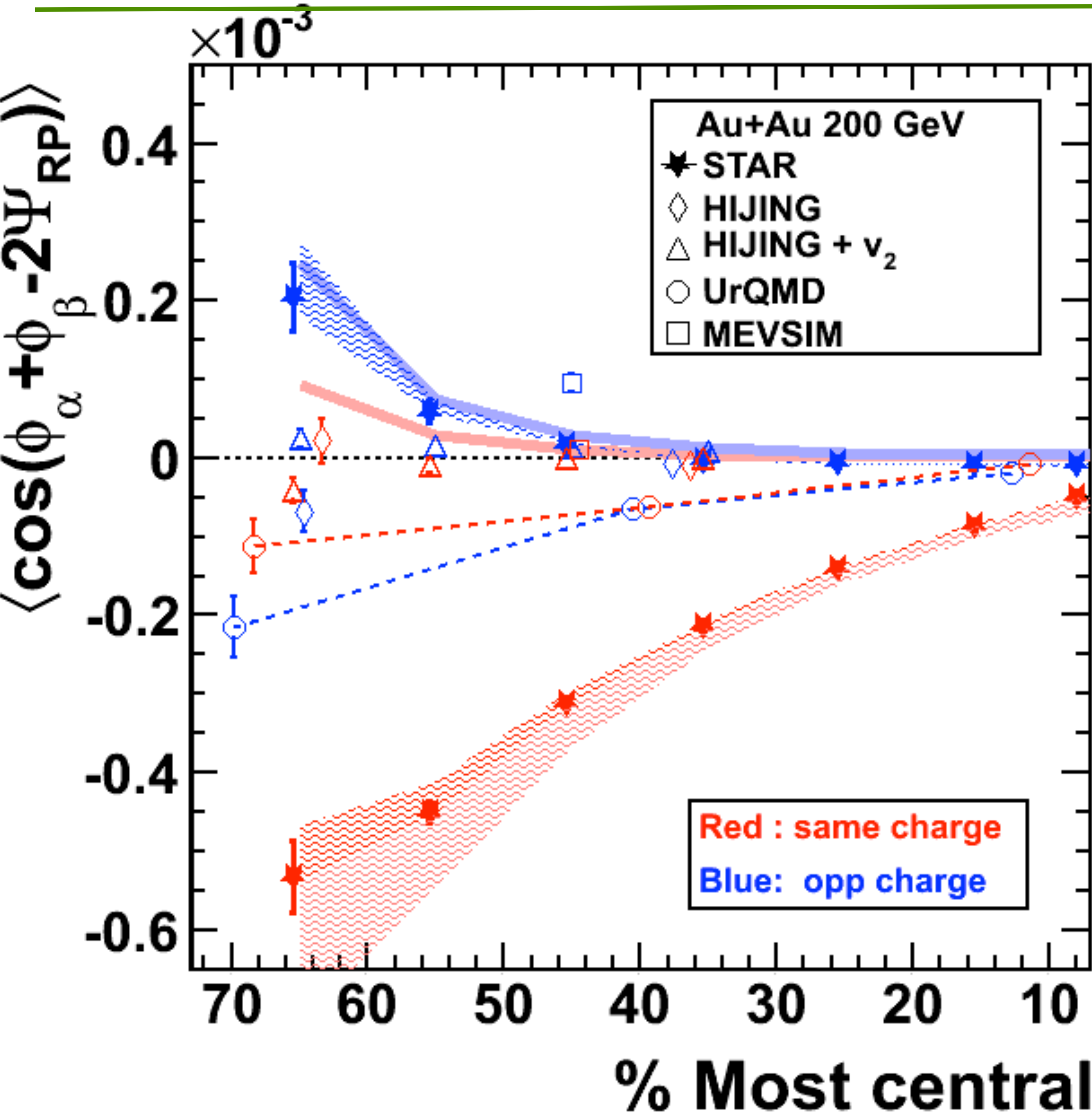
$$\gamma_{OS} = \langle \cos(\varphi_{\pm} + \varphi_{\mp} - 2\psi_{RP}) \rangle$$

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

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

Voloshin: hep-ph/0406311

First paper on CME from STAR



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

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

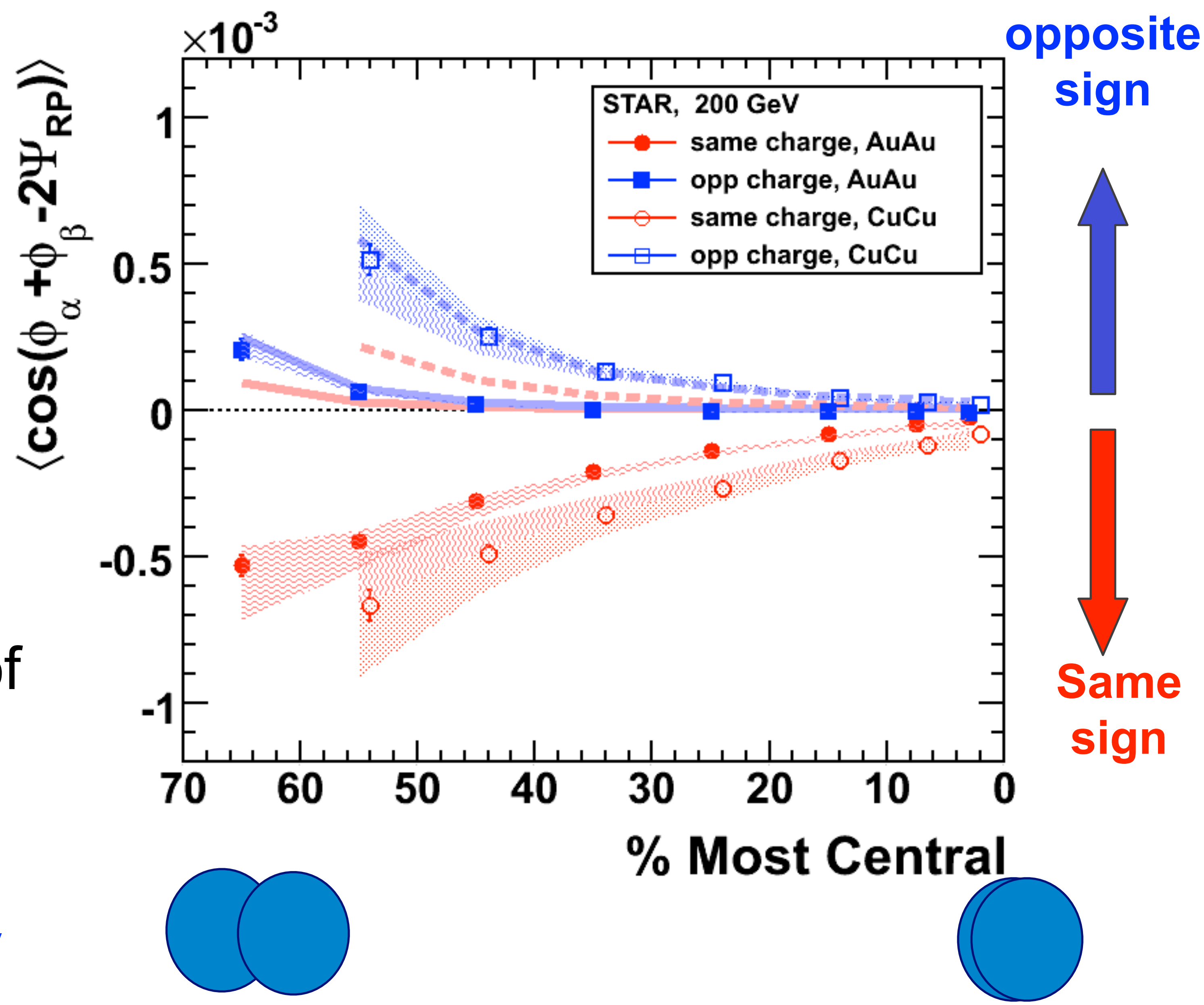
"…but the signal persists to higher transverse momentum than expected"

Recently became renowned >500 citations

STAR: PRL 103 251601 (2009)

CME - testing expectations in Cu+Cu

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



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

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

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

BG $\propto$ v_2

+ non-flow (jets, resonances)

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

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

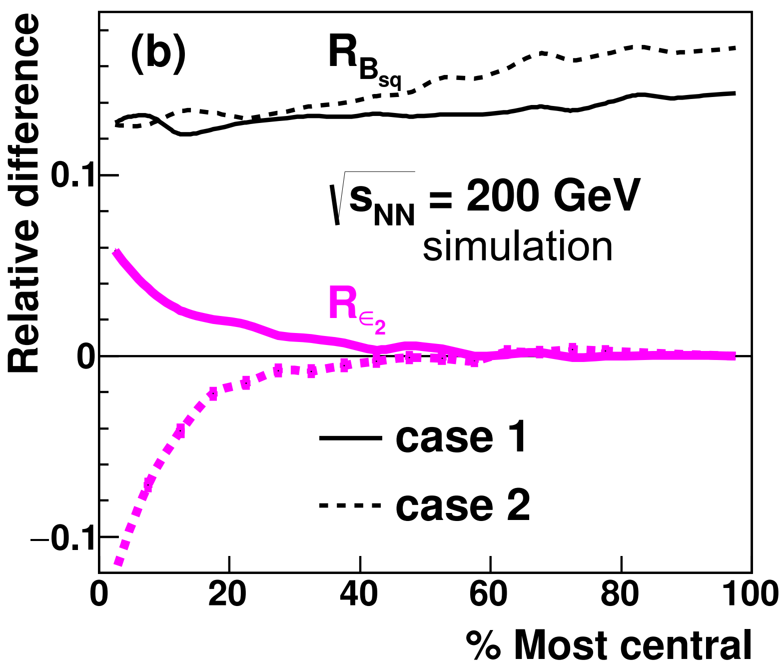
Vary B, signal driver

Use Isobars

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

R = 5.085 fm R = 5.02 fm

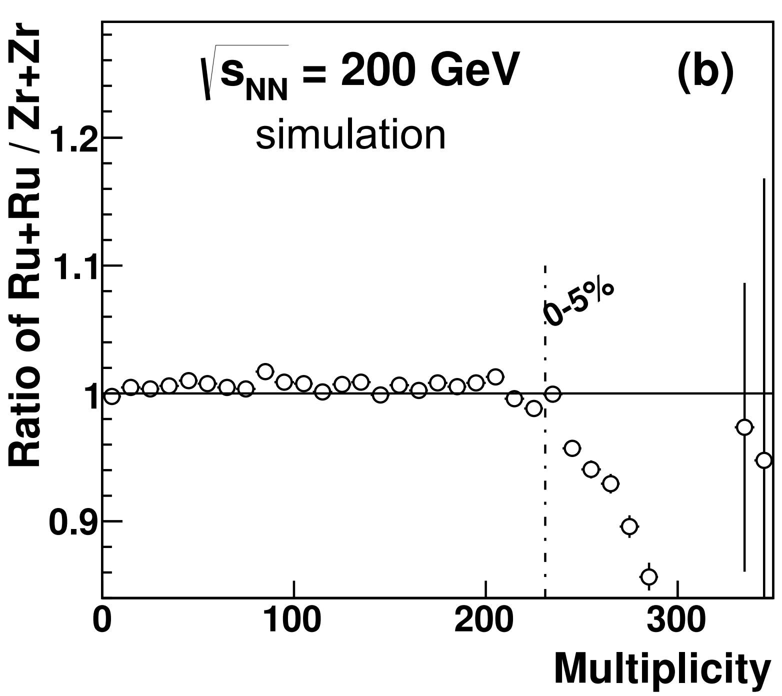
Nuclear deformity uncertain



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)

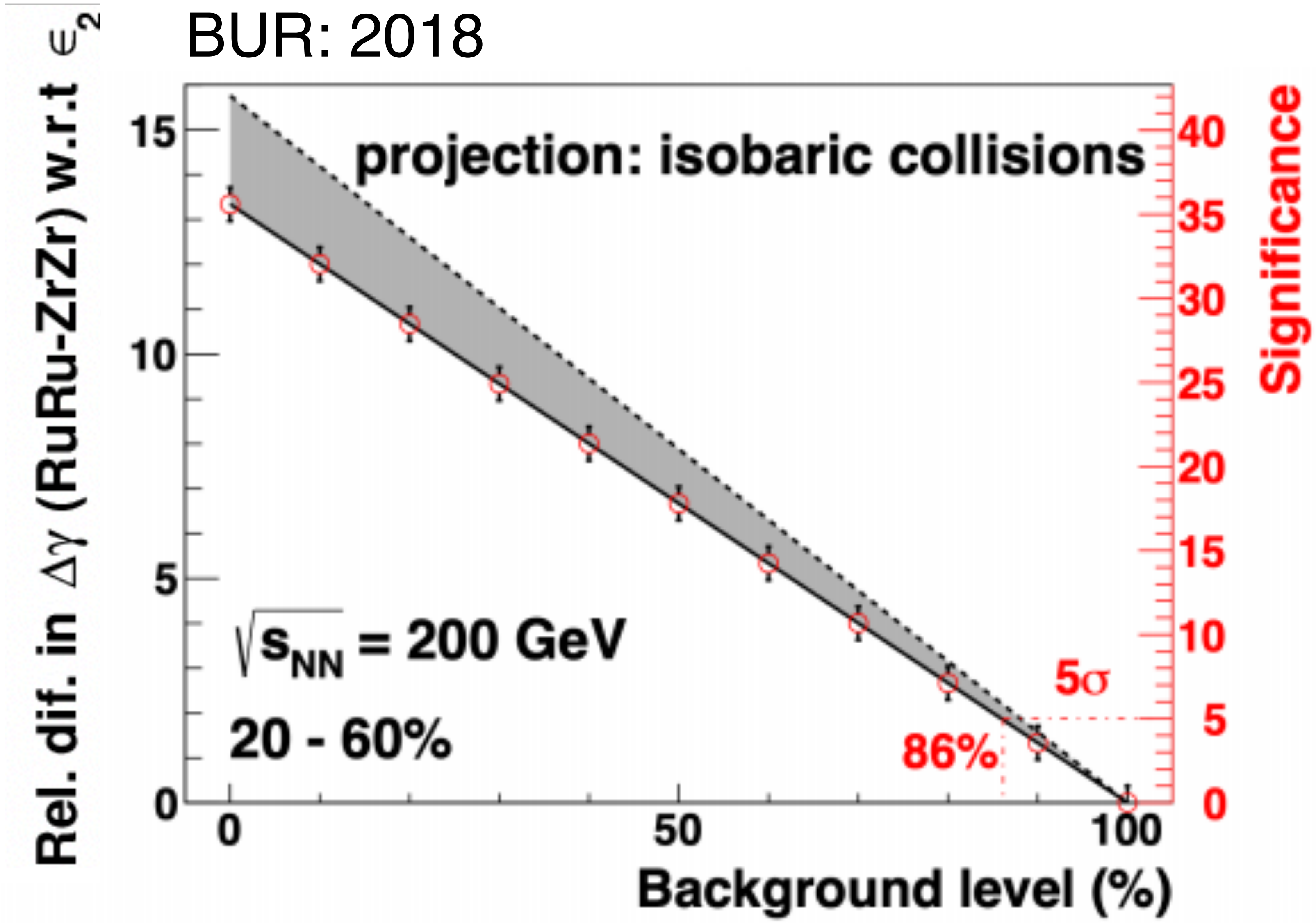
N_{ch}(Ru+Ru) ~ N_{ch}(Zr+Zr)

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%

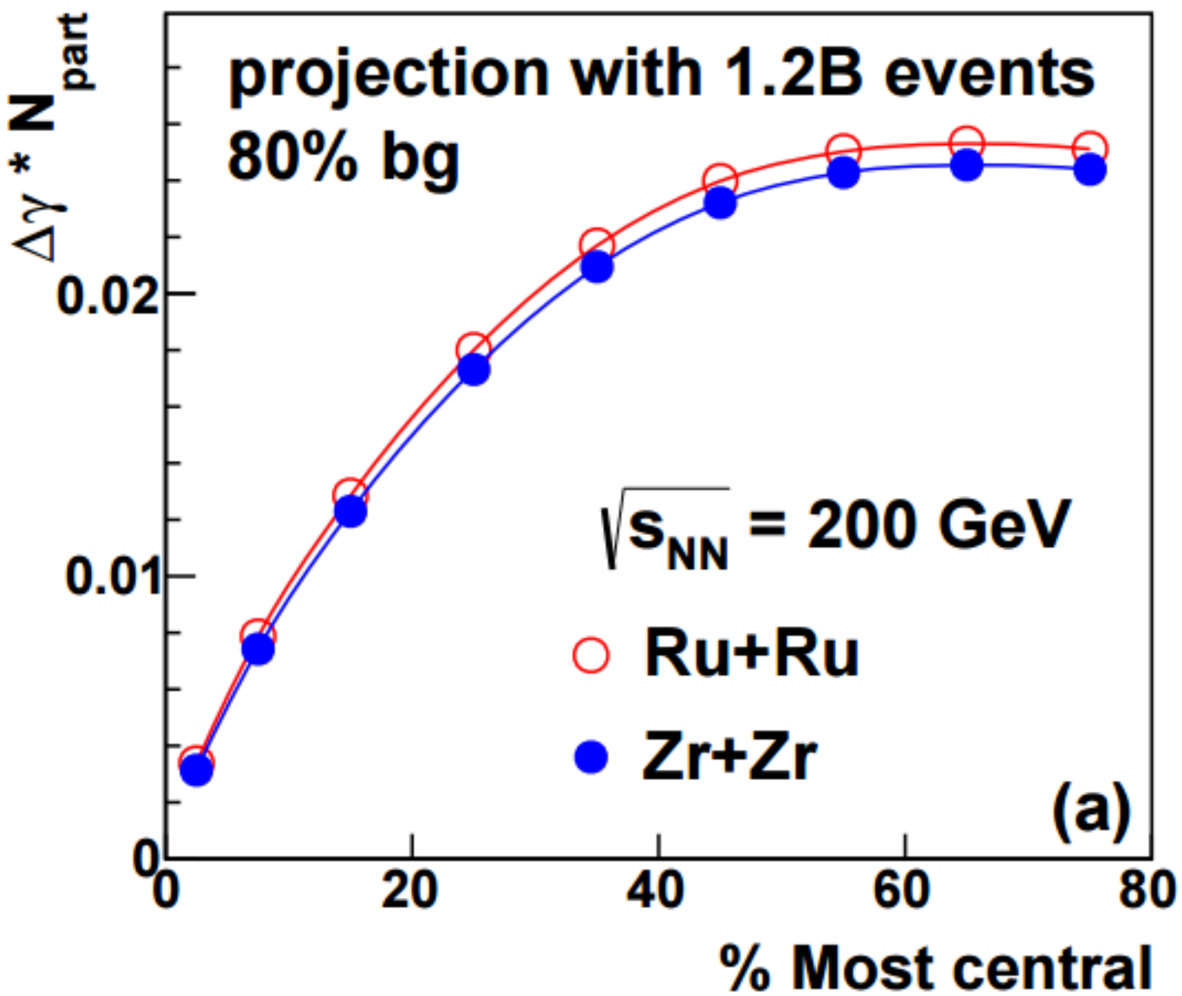
Estimates assume 1B events per species, actually collected ~2B for each species after QA cuts applied

Data should allow for ~5σ if BG ~80%

Potentially a definitive test!

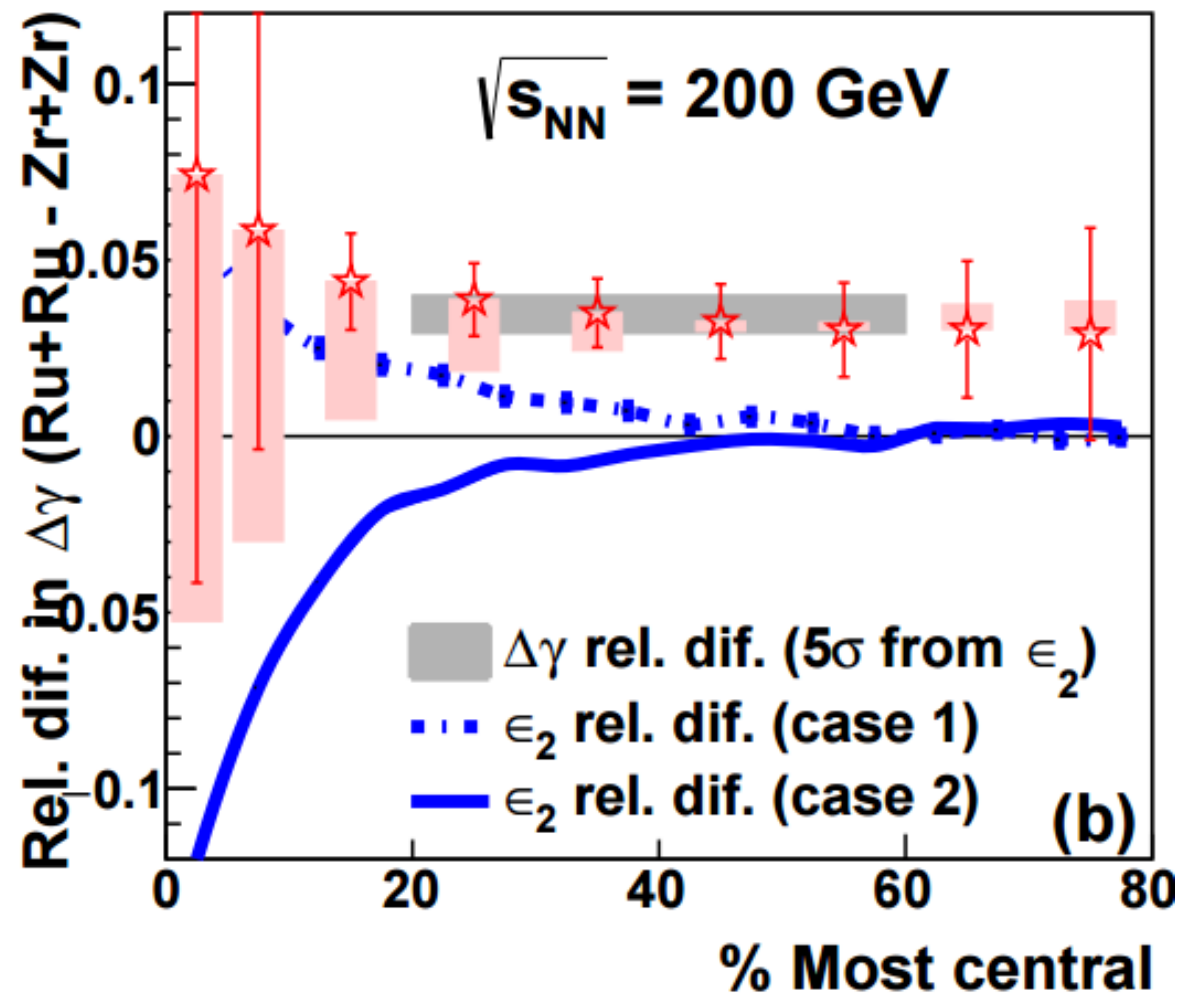
Isobar signal prediction

$\Delta\gamma \times N_{part}$



relative difference

relative difference - eccentricity



Estimate sensitive to details of:

- shape
- charge distribution
- neutron skin thickness

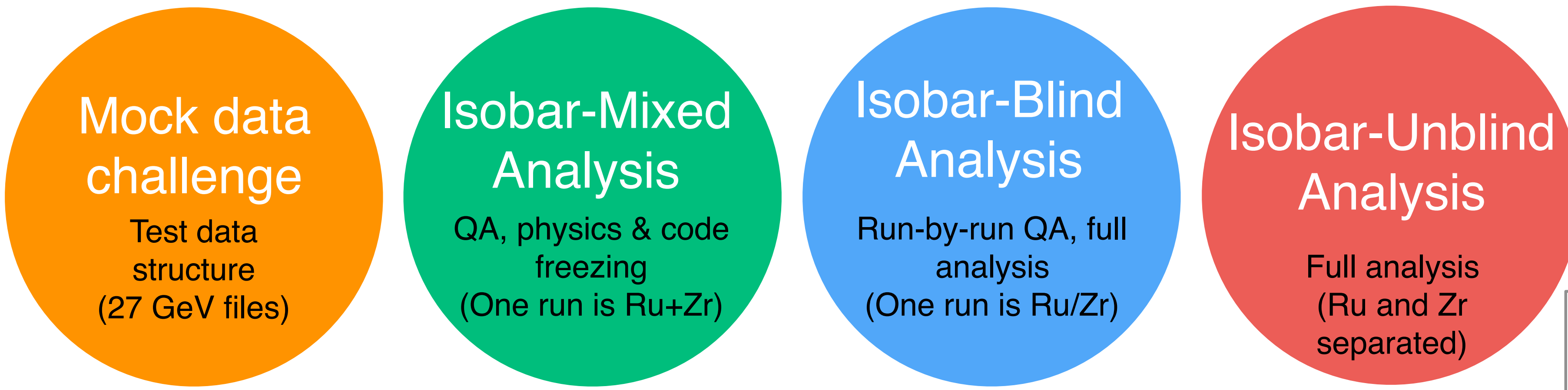
If collect at least 1.2B events for each species should have clear signal in mid-central events

Based on $\Delta\gamma$ 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

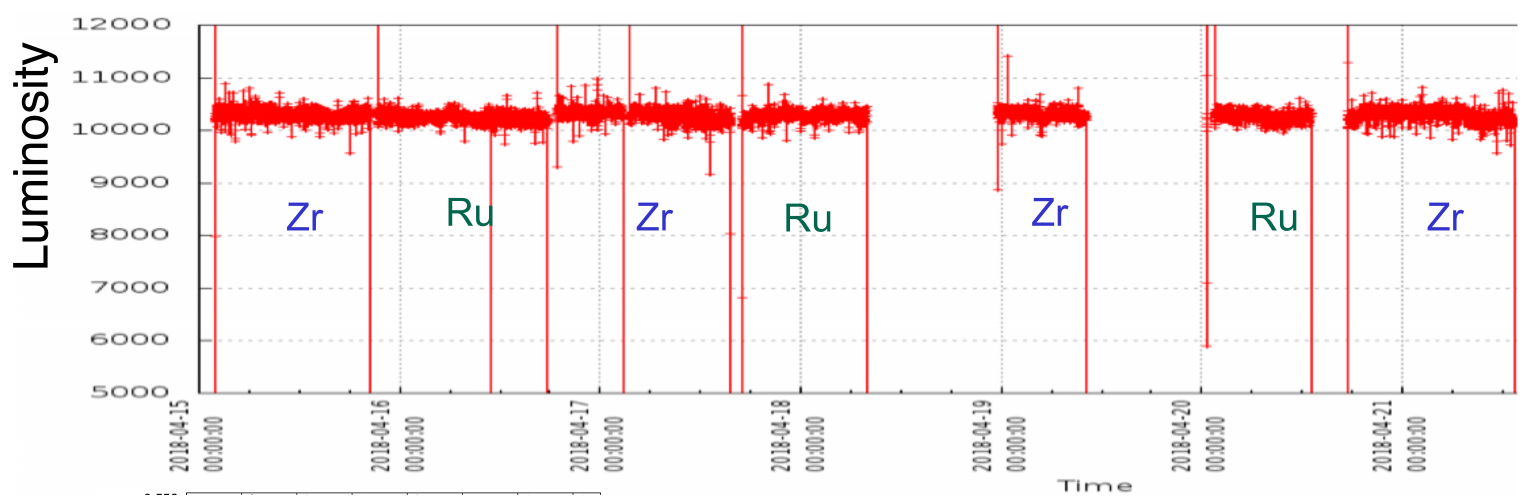
Large number of events to enable small statistical uncertainty -> long data collection period

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

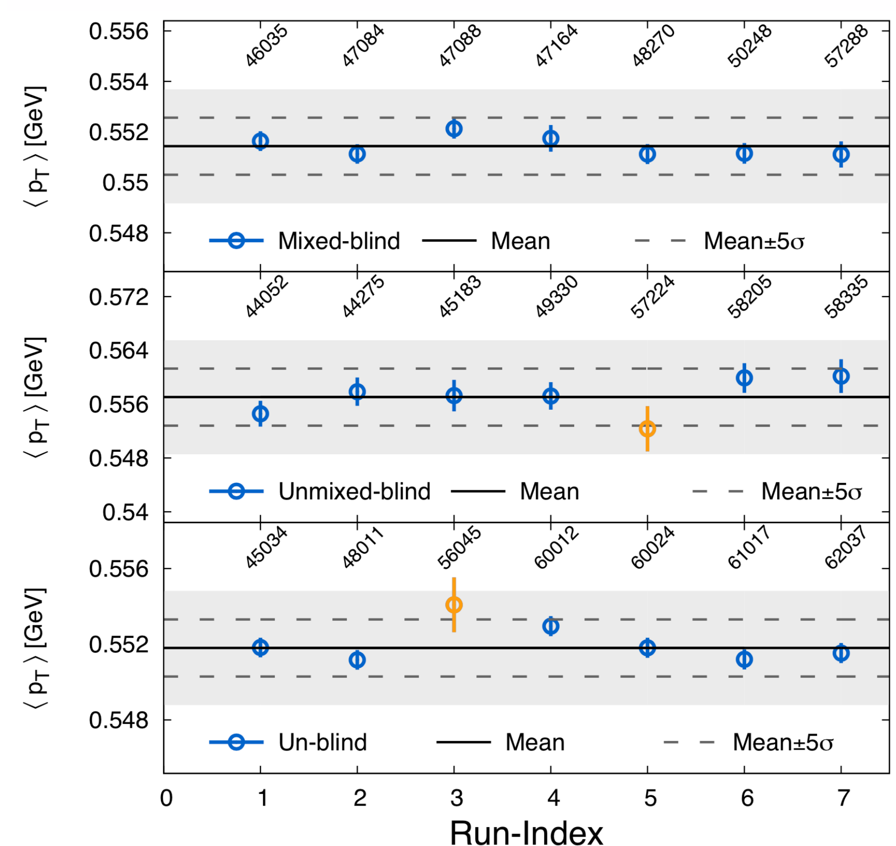
variation in beam luminosity



Determined to:

switch species each store

long stores with level low luminosity



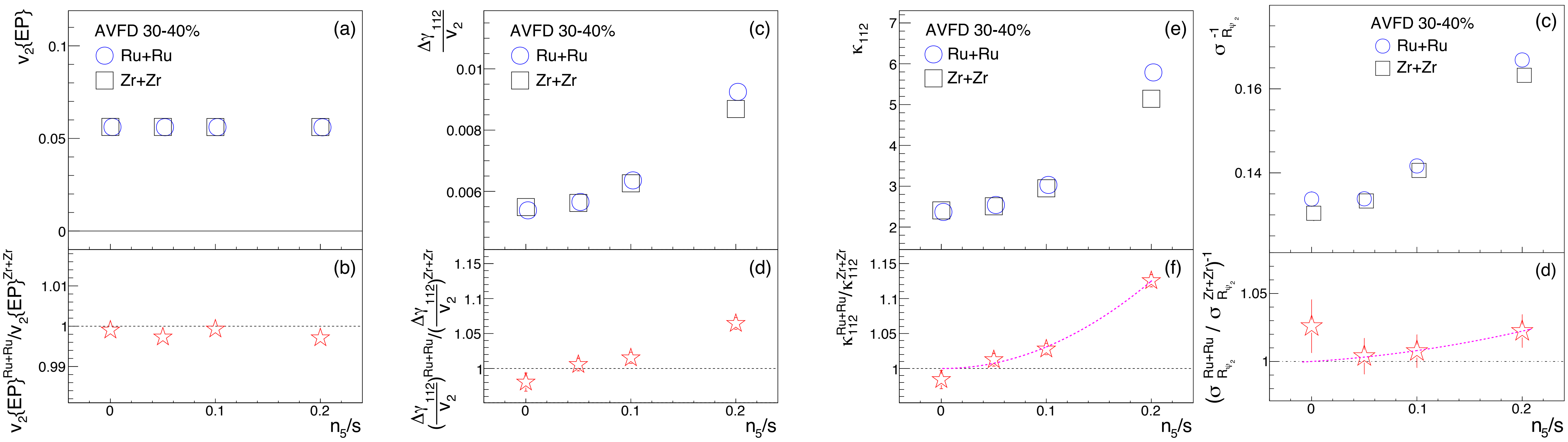
Data collection conditions “same” for both species

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

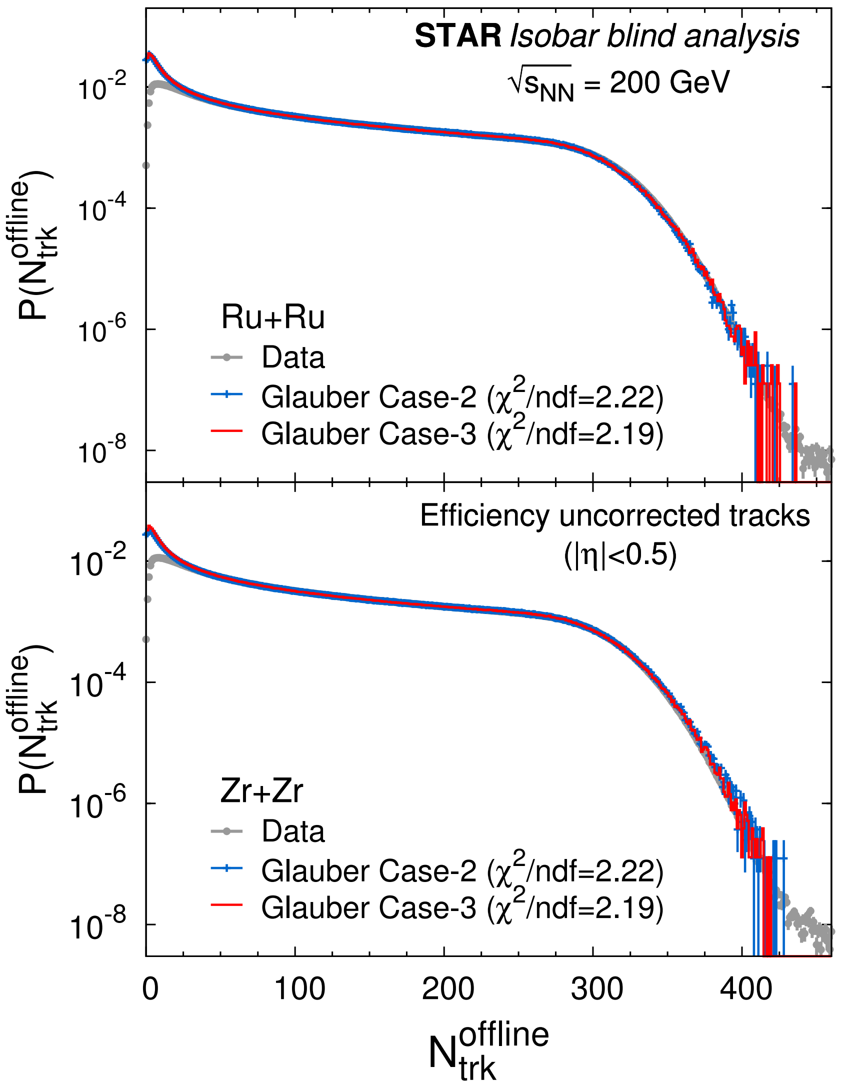
–n_5/s indicates CME signal strength

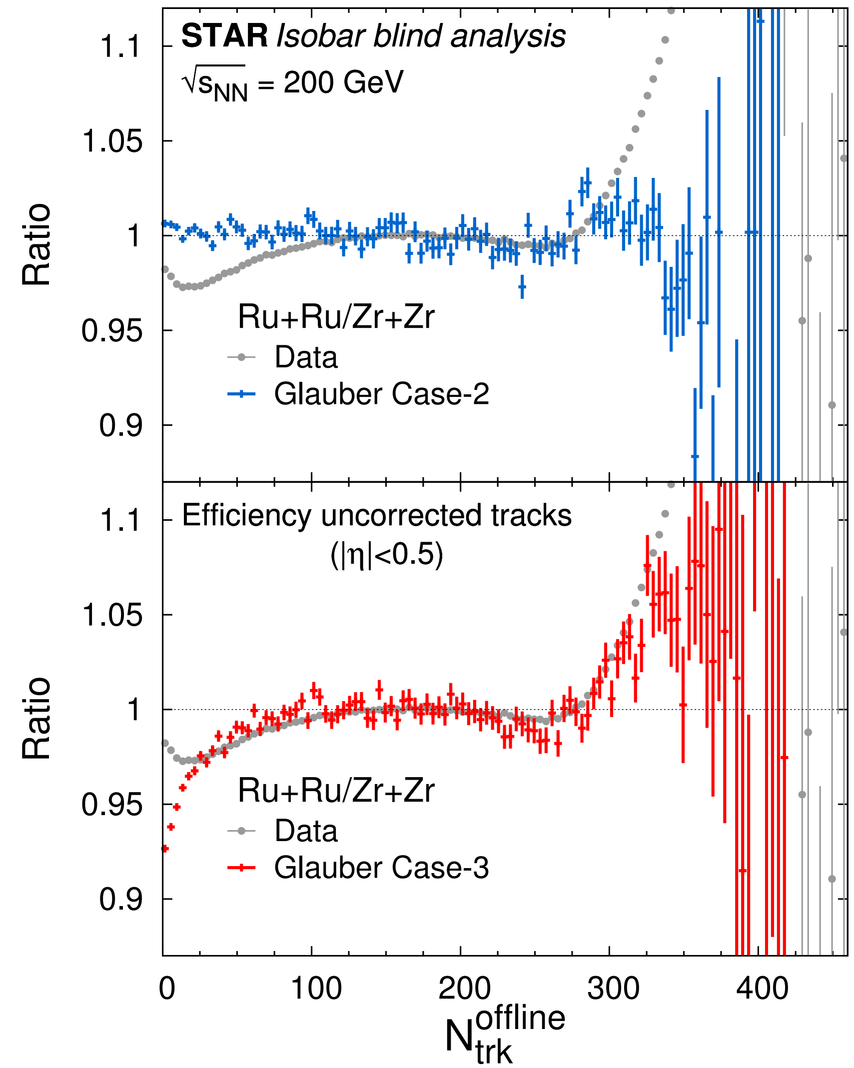
Variable believed sensitive to only background independent of CME strength

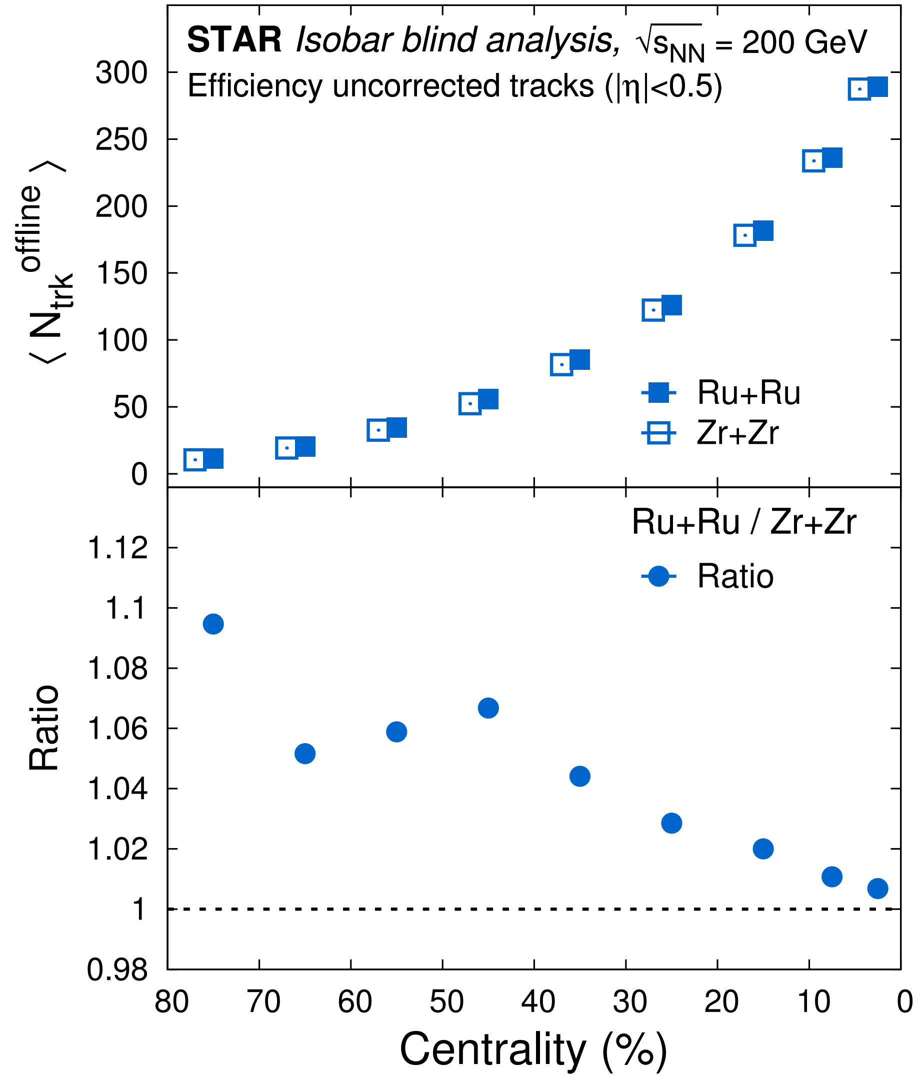
Good sensitivity of variables to signal

STAR CME Group:2105.06044

Centrality and multiplicity comparisons







3 Woods-Saxon parameter sets fit to multiplicity distributions

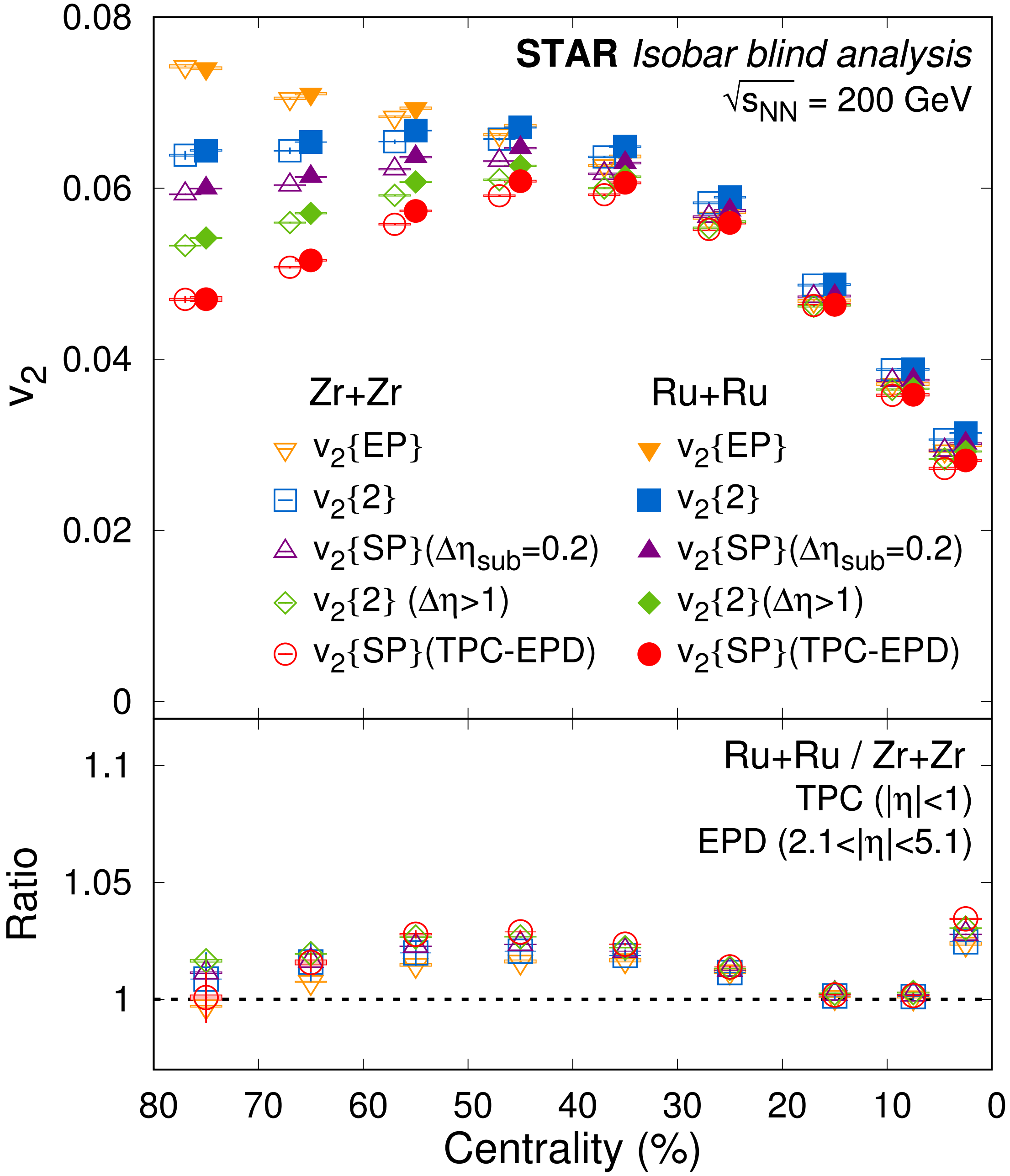
- 2-component nucleon-base MC Glauber
- Best fit (case-3) no quadrupole component, different neutron skin

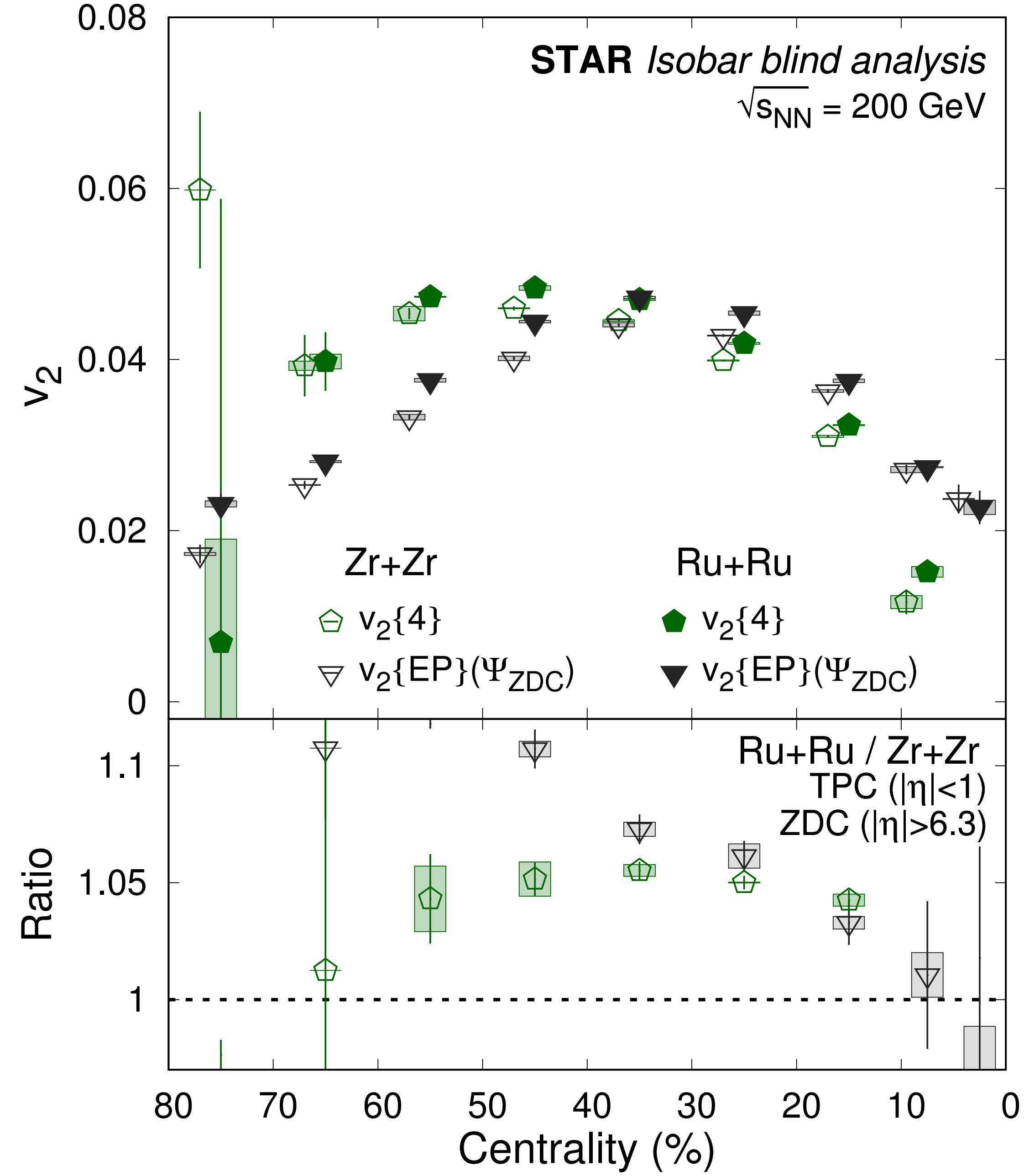
Future study: adjust WS parameters, different treatment of sub-nucleon fluctuations, better treatment of integer multiplicities in binning

Nucleus	Case-1 [83] R (fm)	a (fm)	β_2	Case-2 [83] R (fm)	a (fm)	β_2	Case-3 [113] 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





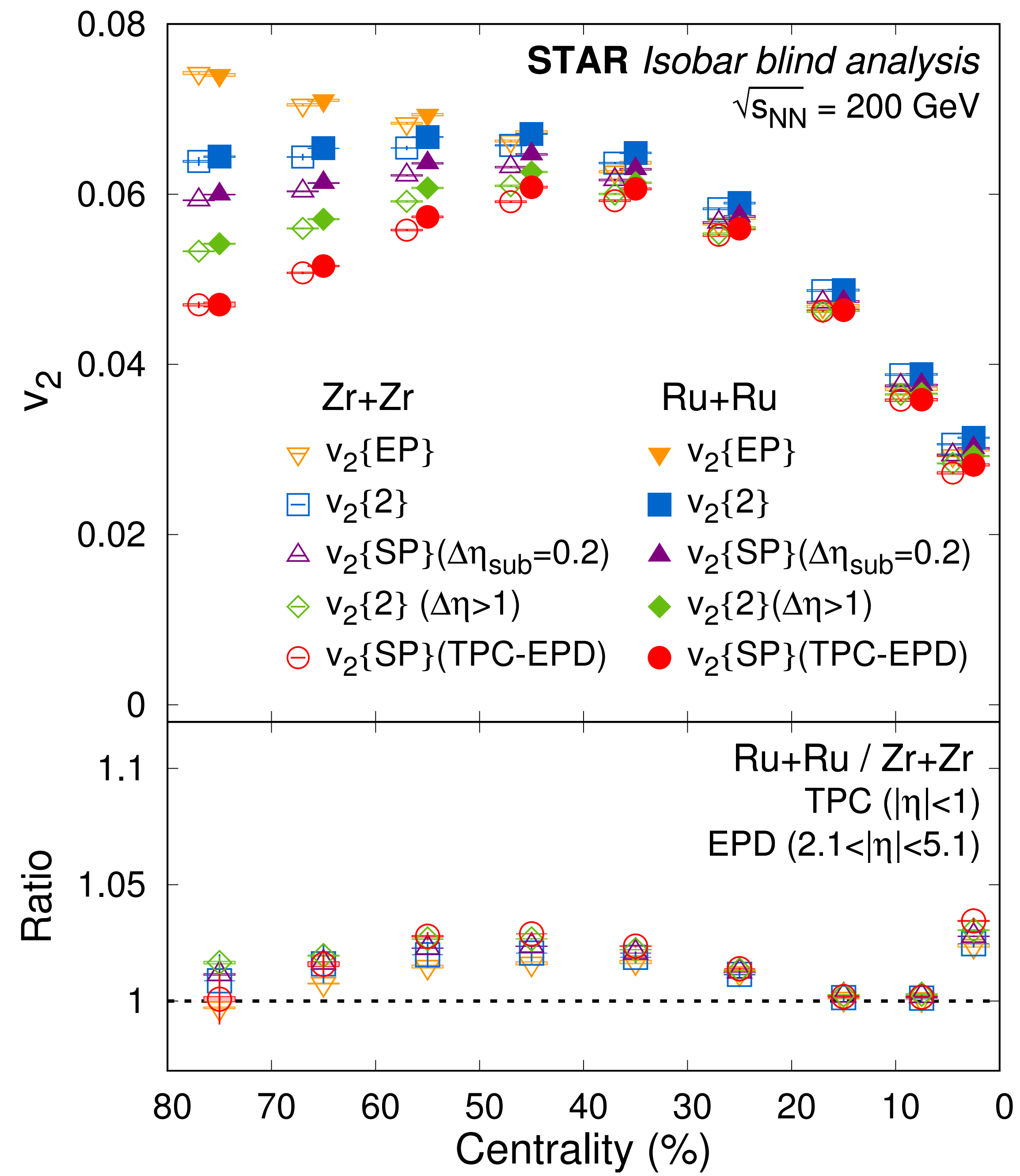
Different methods lead to different v_2

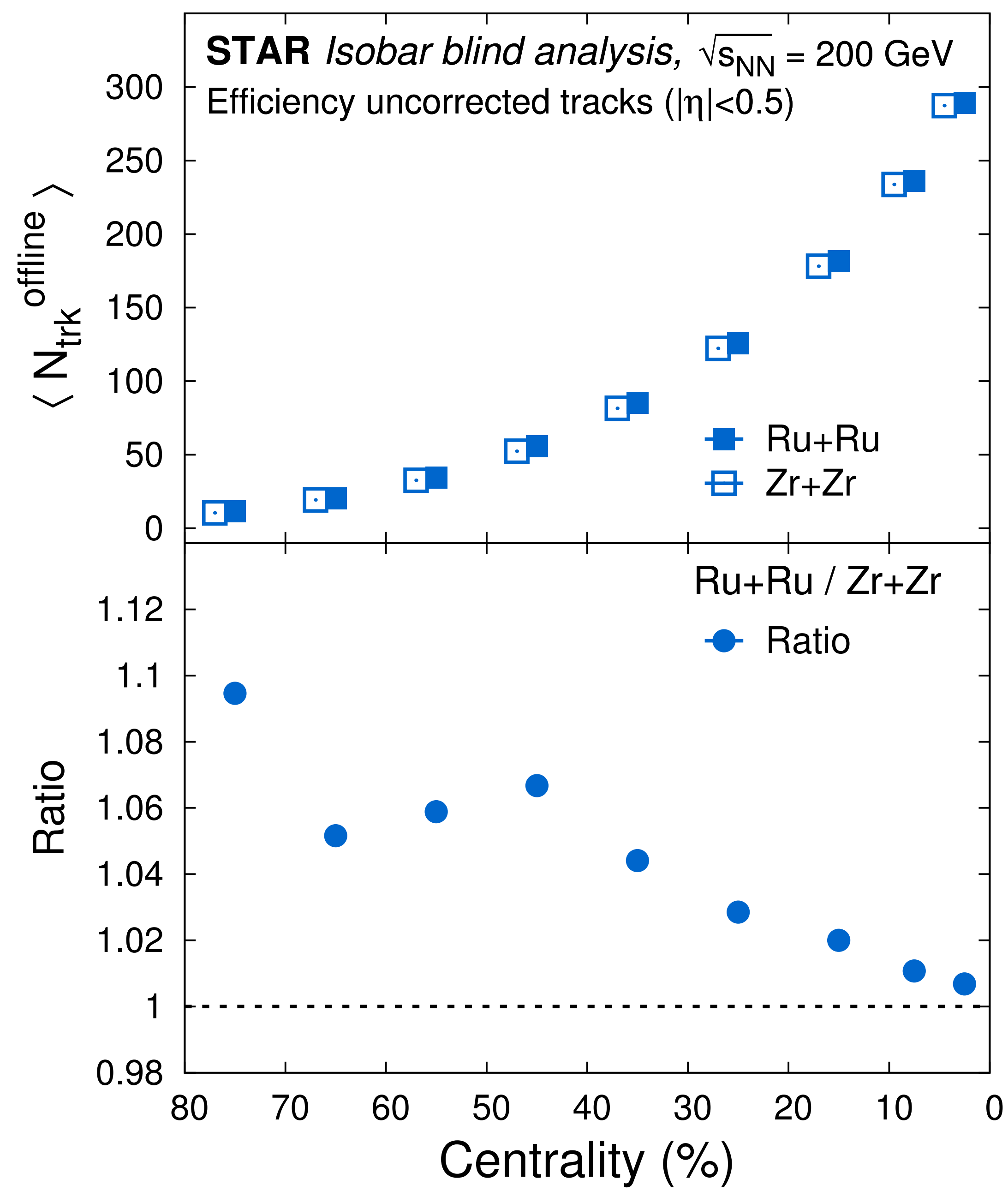
- expected due to differing sensitivities to non-flow contributions

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

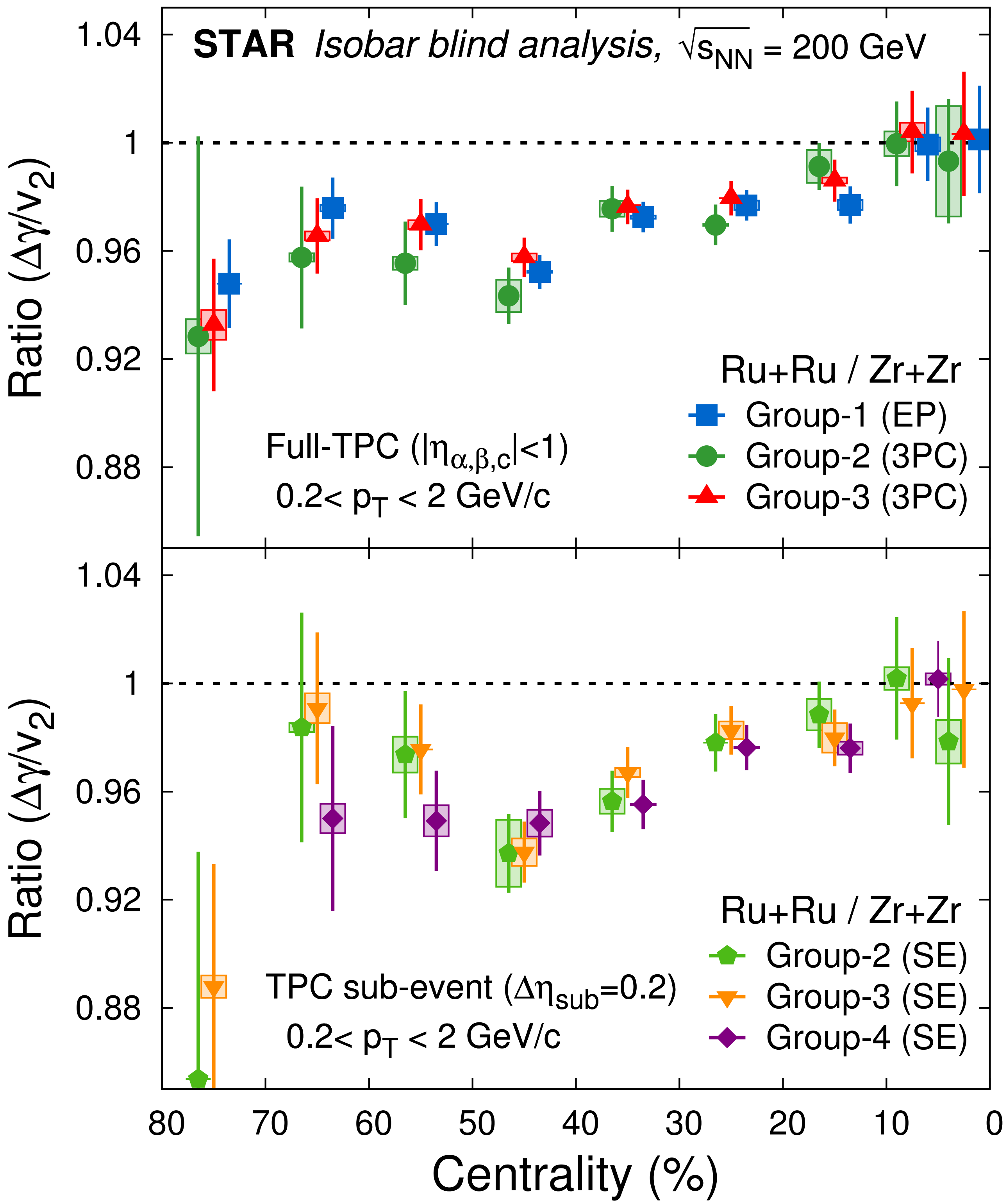
Affirmative observation of CME defined as 5σ (high significance) measurement

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:

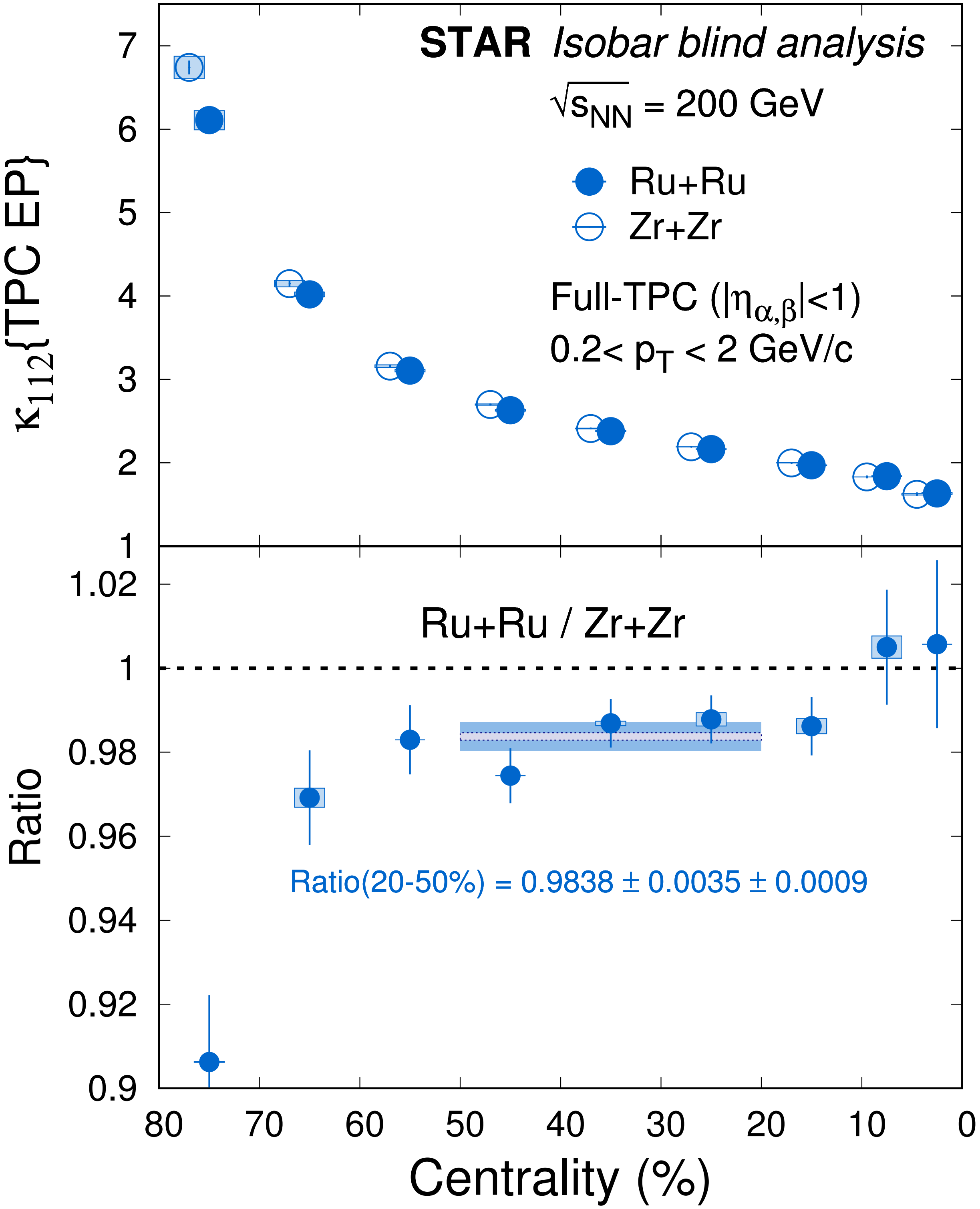
$$\frac{(\Delta\gamma/v_2)_{\mathrm{Ru+Ru}}}{(\Delta\gamma/v_2)_{\mathrm{Zr+Zr}}} = 1 + f_{\mathrm{CME}}^{\mathrm{Zr+Zr}}[(B_{\mathrm{Ru+Ru}}/B_{\mathrm{Zr+Zr}})^2 - 1],$$

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

Predefined signature criteria not observed

κ_{112}

Group 1



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

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

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

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:

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

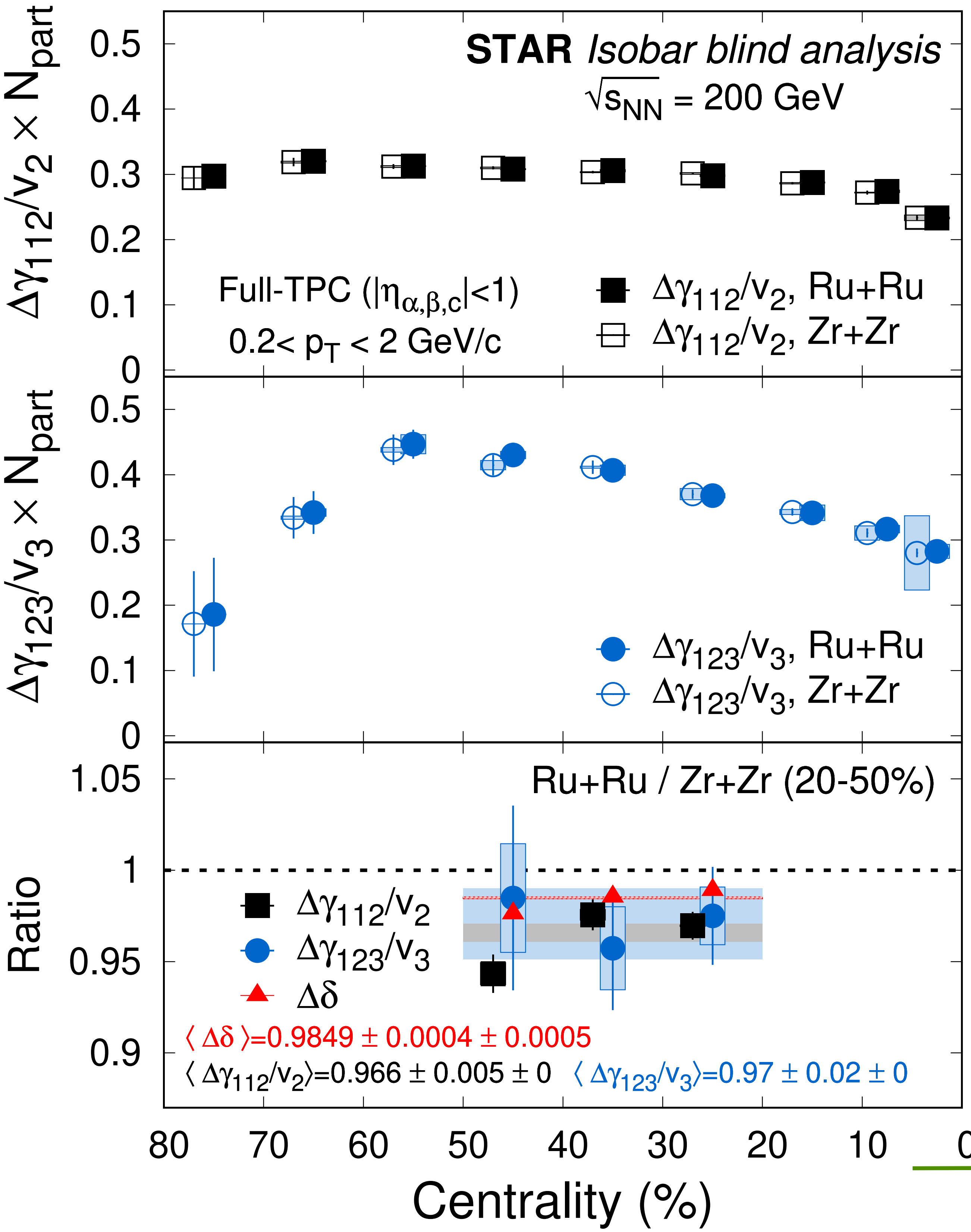
Predefined signature criteria not observed

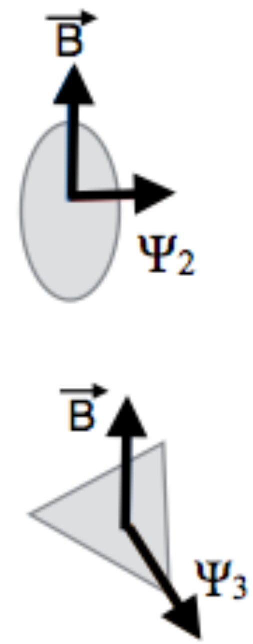
Precision down to 0.4% achieved

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_{113}* - BG only**

Predefined CME signature:

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

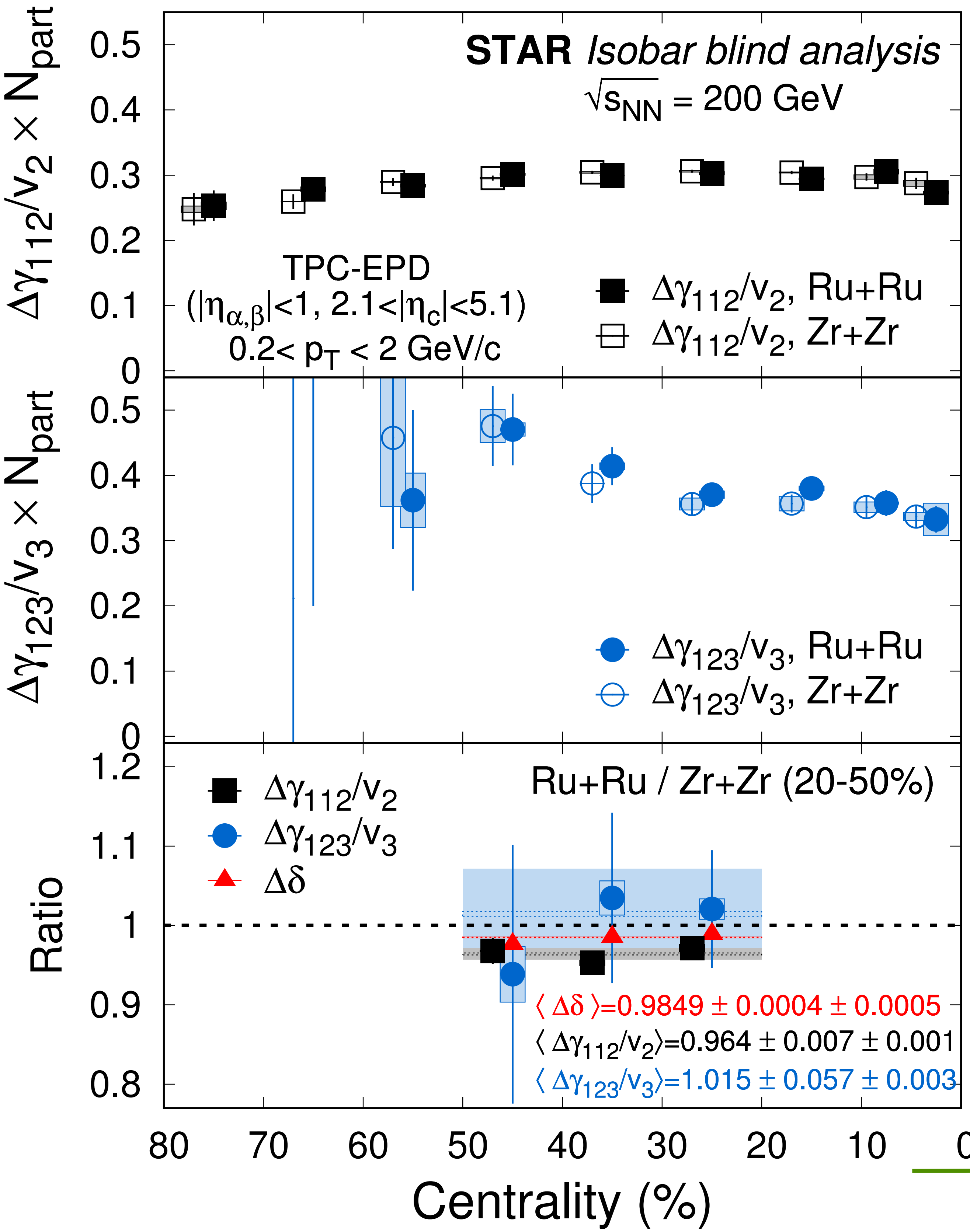
$$\frac{(\Delta\gamma_{112}/v_2)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{112}/v_2)^{\mathrm{Zr+Zr}}} > \frac{(\Delta\gamma_{123}/v_3)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{123}/v_3)^{\mathrm{Zr+Zr}}}\,,$$

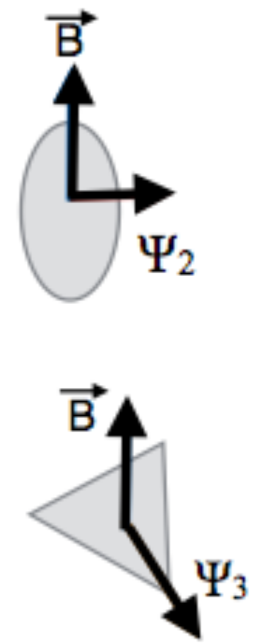
$$\frac{(\Delta\gamma_{112}/v_2)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{112}/v_2)^{\mathrm{Zr+Zr}}} > \frac{(\Delta\delta)^{\mathrm{Ru+Ru}}}{(\Delta\delta)^{\mathrm{Zr+Zr}}}.$$

Predefined signature criteria not observed

Mixed harmonics (TPC-EPD)

Group 2





Planes now from EPD - large eta gap

γ_{112} - CME + BG

3rd order Event Plane not correlated with Magnetic Field

γ_{113} - BG only

Predefined CME signature:

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

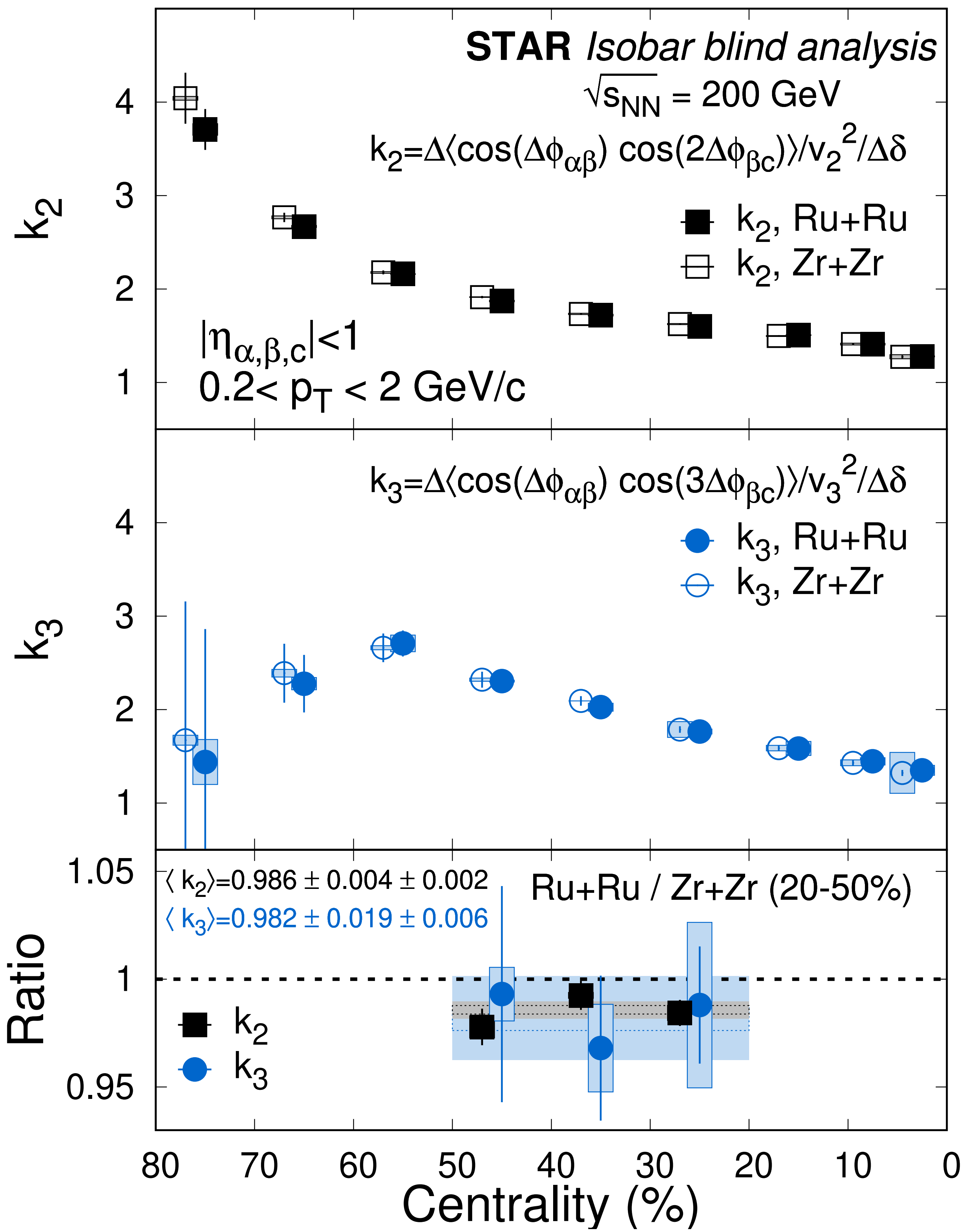
$$\frac{(\Delta\gamma_{112}/v_2)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{112}/v_2)^{\mathrm{Zr+Zr}}} > \frac{(\Delta\gamma_{123}/v_3)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{123}/v_3)^{\mathrm{Zr+Zr}}}\,,$$

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

Predefined signature criteria not observed

Factorization breaking

Group 2



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

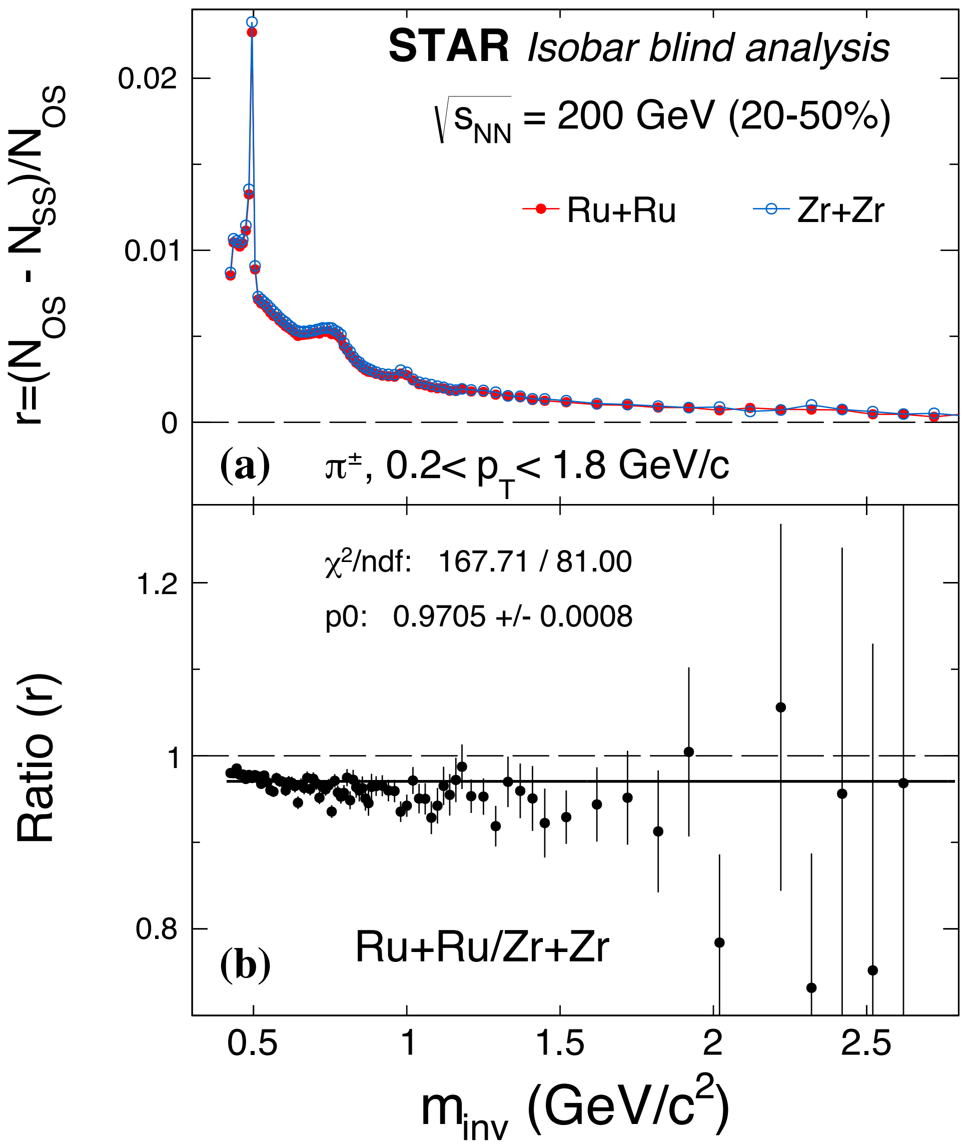
Predefined CME signature:

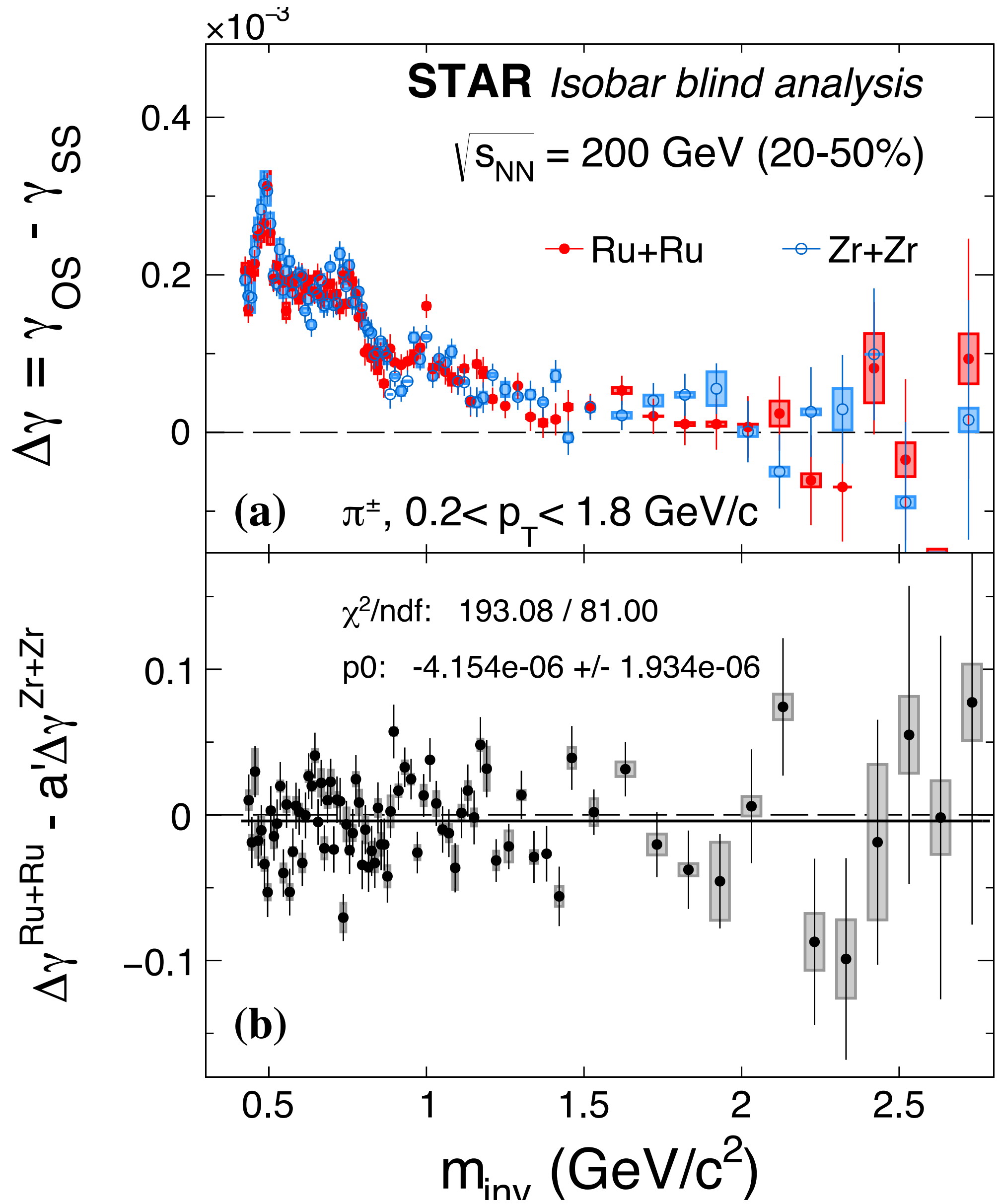
$$\frac{k_2^{\mathrm{Ru+Ru}}}{k_2^{\mathrm{Zr+Zr}}} > \frac{k_3^{\mathrm{Ru+Ru}}}{k_3^{\mathrm{Zr+Zr}}}$$

Predefined signature criteria not observed

Probing differentially in m_{inv}

Group 3





No obvious enhancements seen

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

Predefined CME signature:

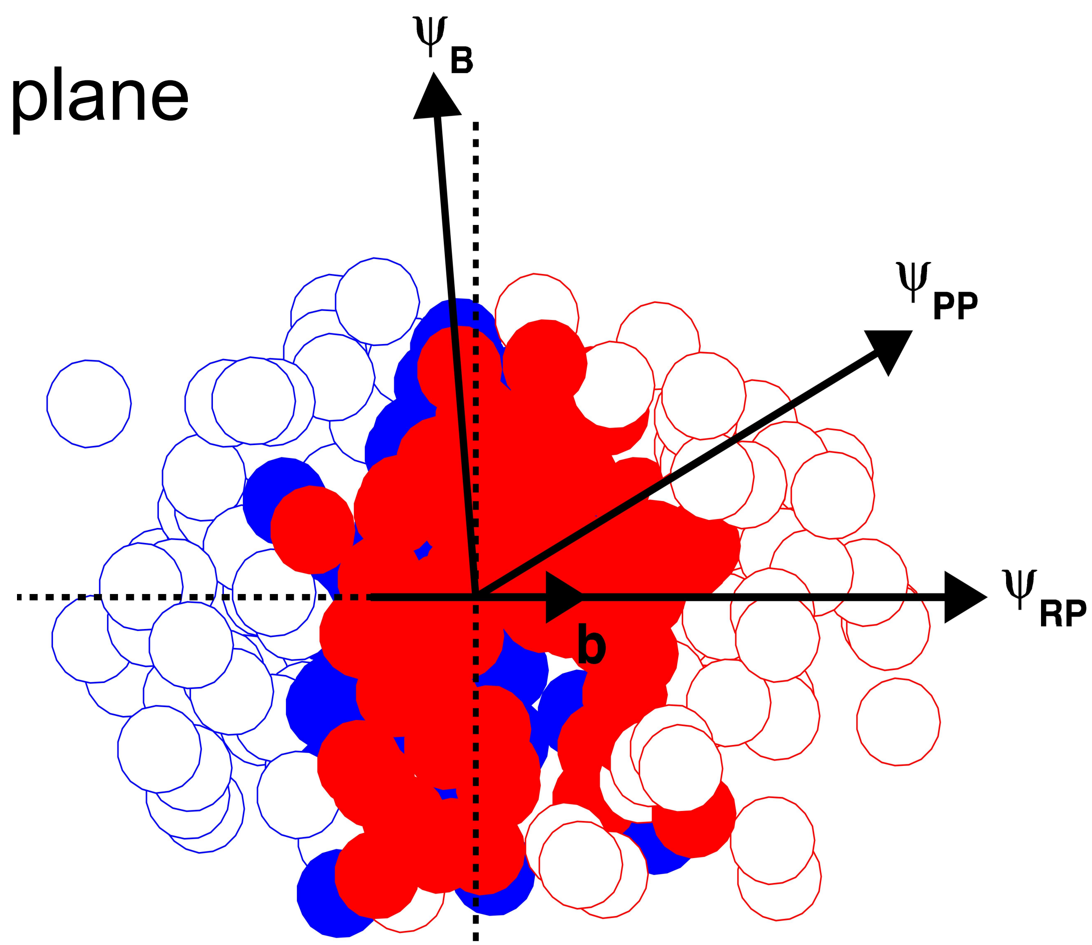
$$\Delta\gamma^{\mathrm{Ru+Ru}} - a'\Delta\gamma^{\mathrm{Zr+Zr}} > 0$$

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

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

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

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

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

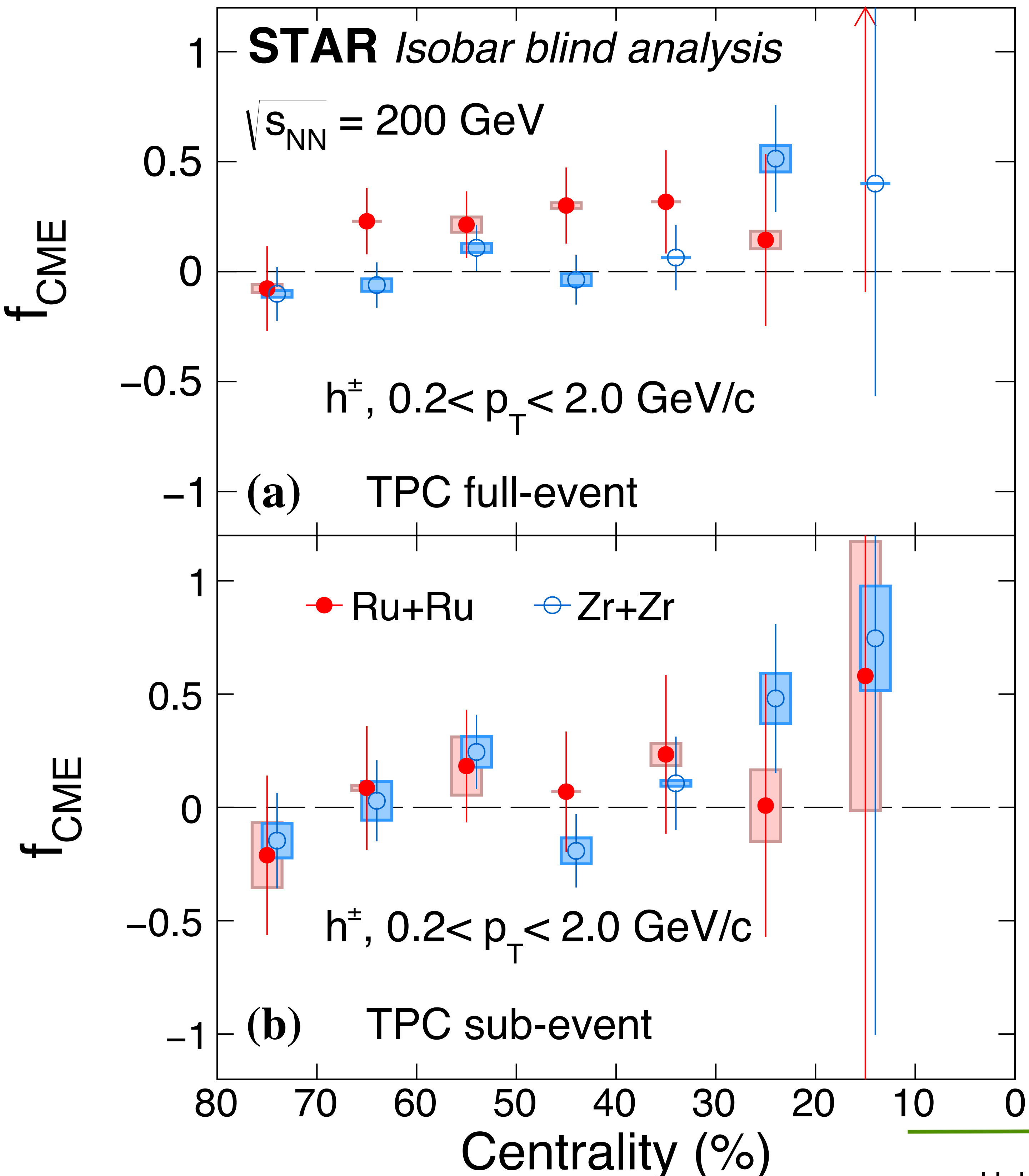
ZDC - spectator plane

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:

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

Average for 20-50% sub-event TPC

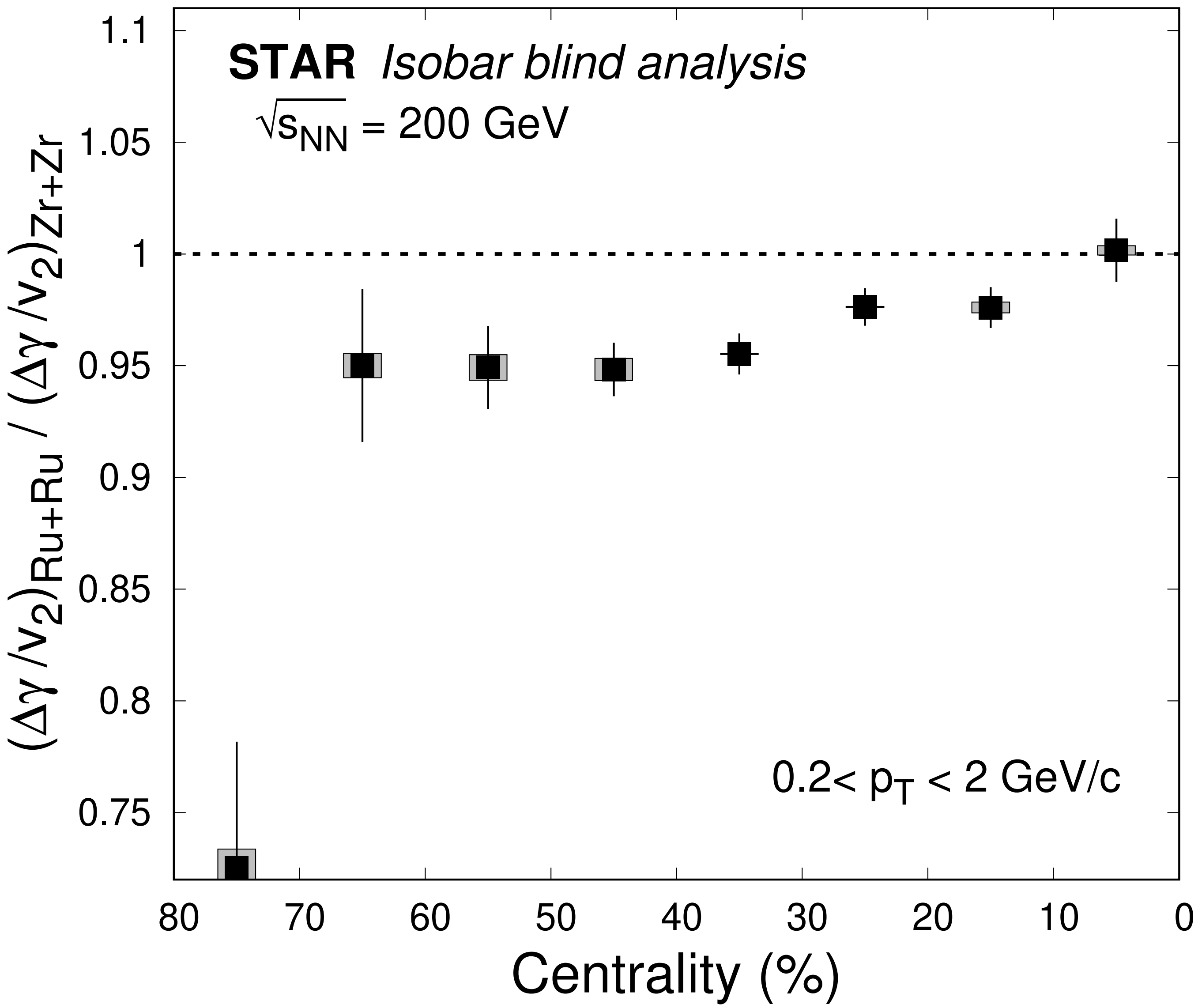
Ru:
f_{CME} 0.12 ± 0.20(stat) ± 0.00 (sys)

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

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

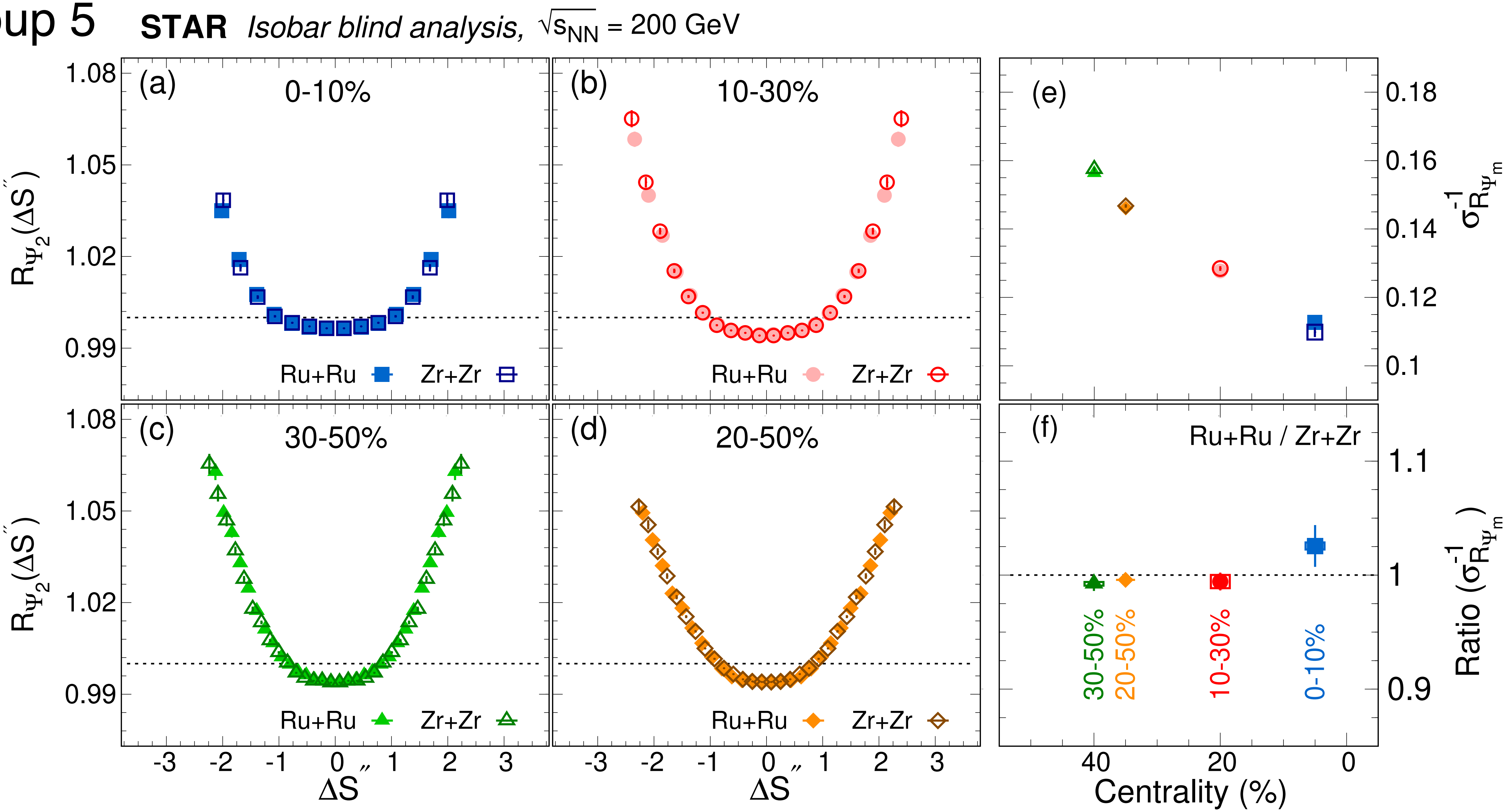
Predefined CME signature:

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

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

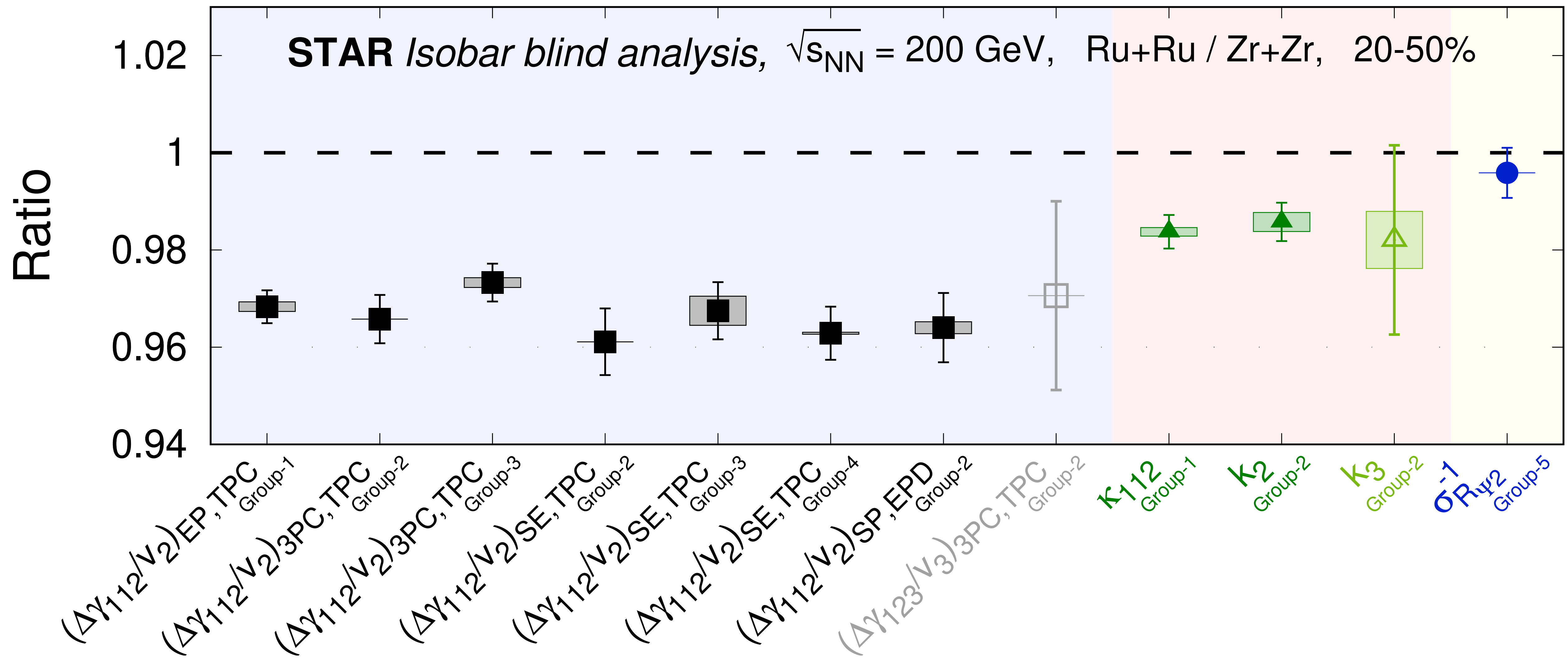
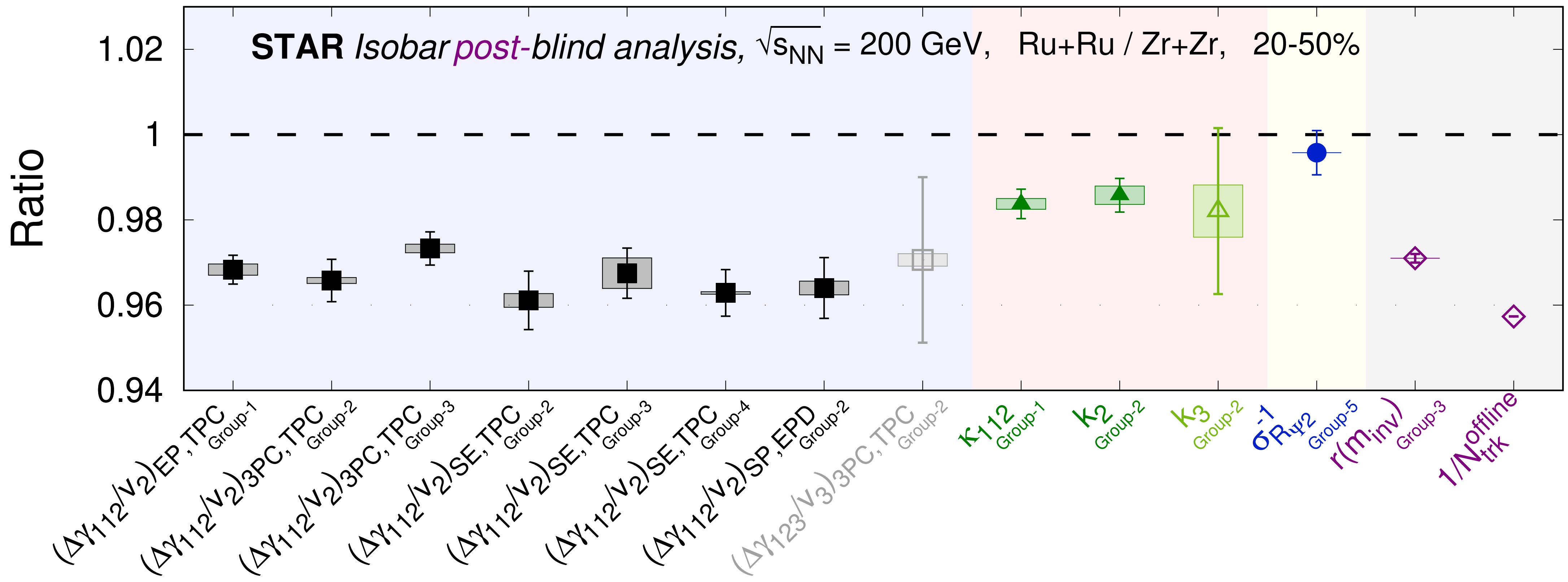


FIG. 26. Compilation of results from the blind analysis. Only results contrasting between the two isobar systems are shown. Results are shown in terms of the ratio of measures in Ru+Ru collisions over Zr+Zr collisions. Solid dark symbols show CME-sensitive measures whereas open light symbols show counterpart 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

Acknowledgments

We thank the RHIC Operations Group and RCF at BNL, the NERSC Center at LBNL, and the Open Science Grid consortium for providing resources and support. We are grateful to Oak Ridge National Laboratory for providing the Ru-96, enriched in a special run, and RIKEN, Japan, for providing critical technology for the Zr-96 beam source. This work was supported in part by the Office of Nuclear Physics within the U.S. DOE Office of Science, the U.S. National Science Foundation, the Ministry of Education and Science of the Russian Federation, National Natural Science Foundation of China, Chinese Academy of Science, the Ministry of Science and Technology of China and the Chinese Ministry of Education, the Higher Education Sprout Project by Ministry of Education at NCKU, the National Research Foundation of Korea, Czech Science Foundation and Ministry of Education, Youth and Sports of the Czech Republic, Hungarian National Research, Development and Innovation Office, New National Excellency Programme of the Hungarian Ministry of Human Capacities, Department of Atomic Energy and Department of Science and Technology of the Government of India, the National Science Centre of Poland, the Ministry of Science, Education and Sports of the Republic of Croatia, RosAtom of Russia and German Bundesministerium für Bildung, Wissenschaft, Forschung and Technologie (BMBF), Helmholtz Association, Ministry of Education Culture, Sports, Science, and Technology (MEXT) and Japan Society for the Promotion of Science (JSPS).

BACK UP

U+U collisions - vary BG, fix signal

Hard to isolate tip-tip (small v_2) from body-body (large v_2)

Not really able to manipulate v_2 contribution

0-1% most central events: dominated by BG
B-field minimal so any CME greatly suppressed
Results show CME consistent with zero, v_2 ~2.5%

Extrapolation to semi-central very model dependent
isolation of CME signal remains elusive

In both U+U and Au+Au signal scales with v2
suggests results dominated by BG

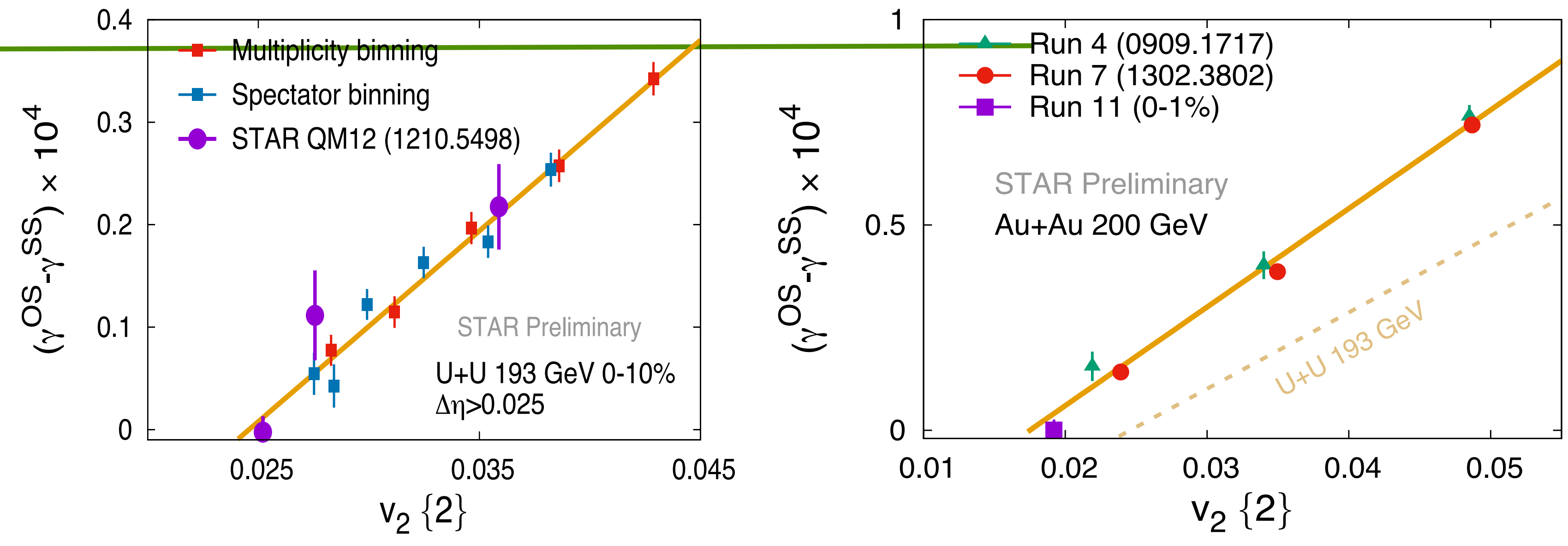
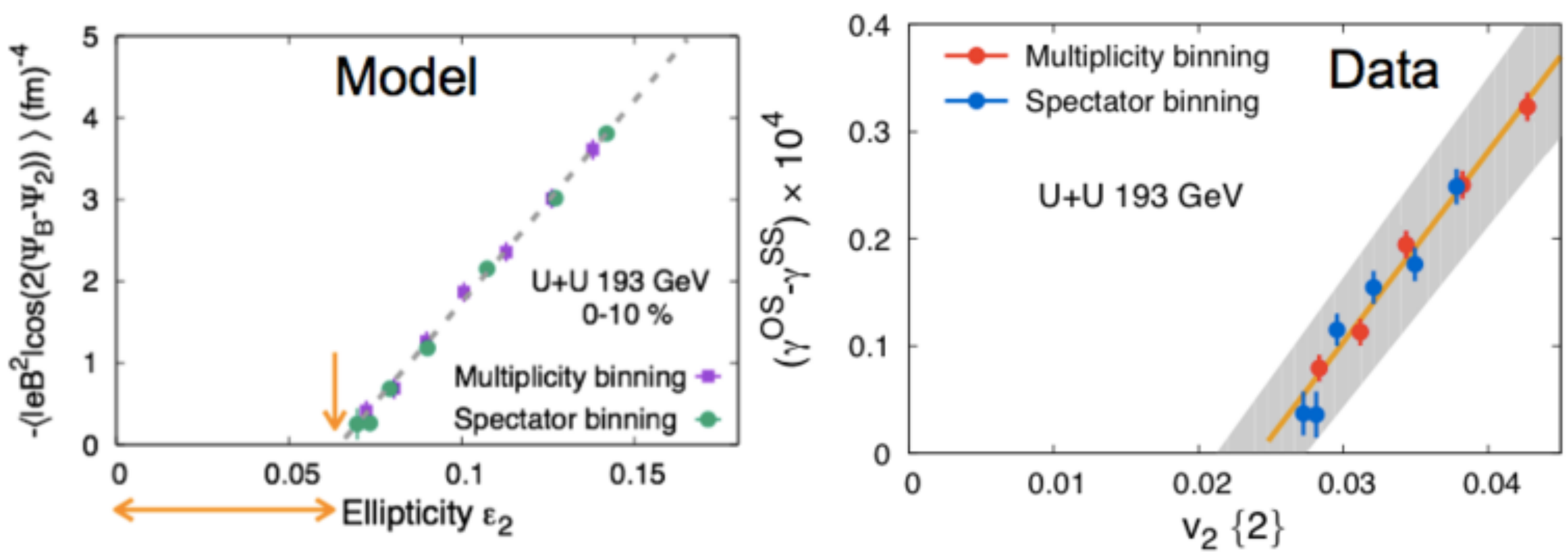
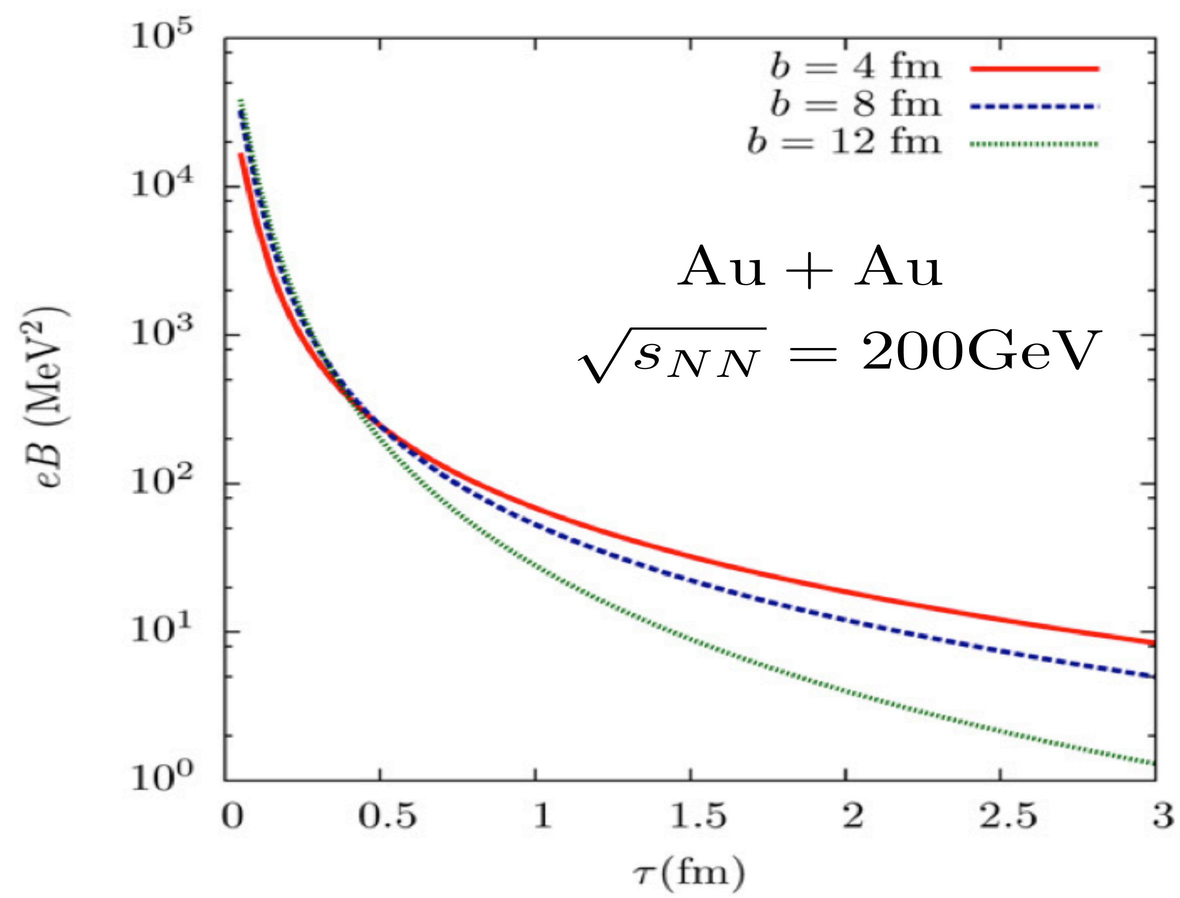


Figure 2–18: γ_{OS}-γ_{SS} vs v_2 for different centralities in 193 GeV U+U collisions (left) and 200 GeV Au-Au collisions (right).[34]



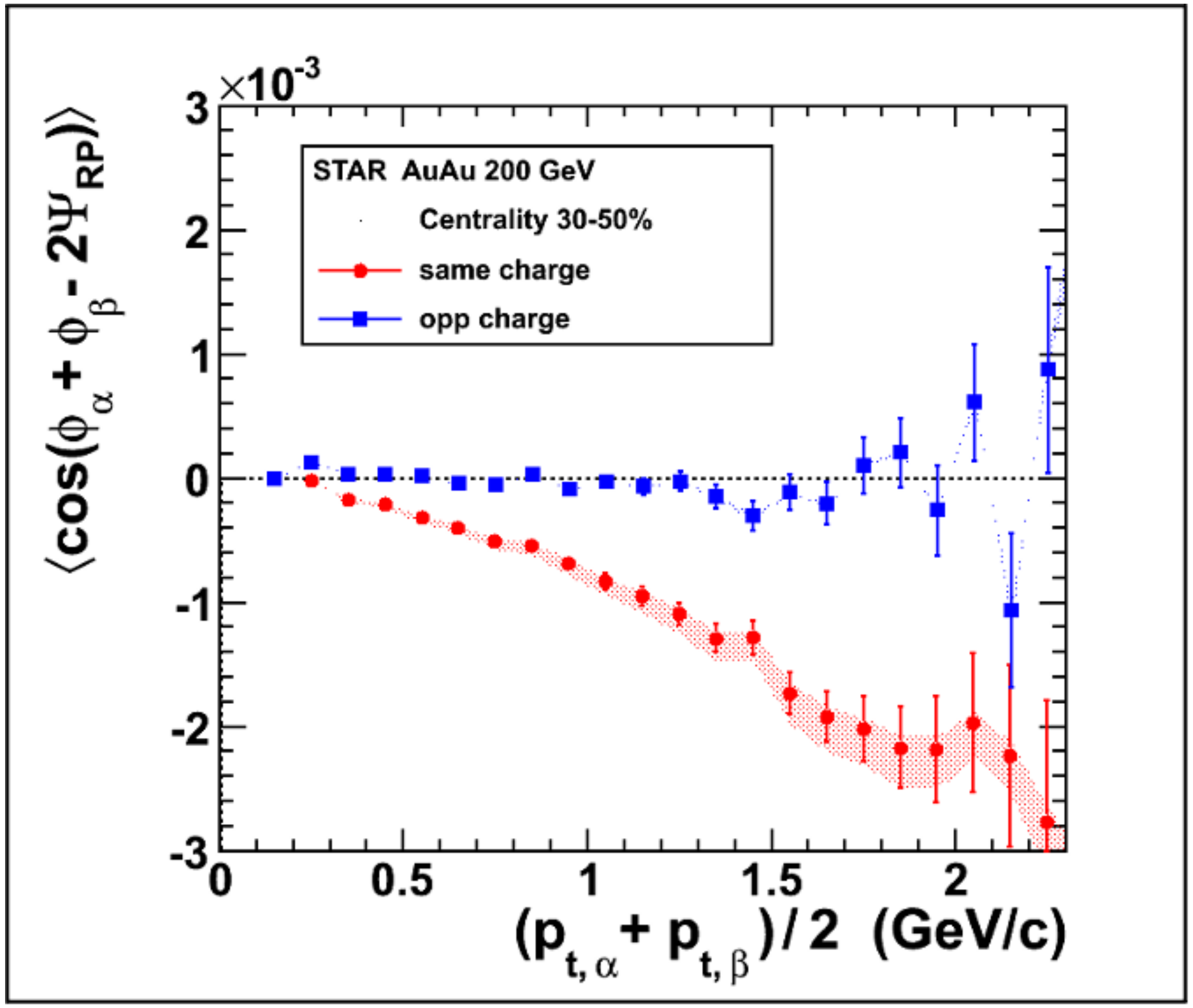
ciable v_2 but since models show that the magnetic field becomes oriented randomly with respect to the v_2 axis [17], no CME signal is expected. In a v_2 driven background scenario, we expect $\Delta\gamma$ to only reach zero when v_2 reaches zero. The data however contradicts this scenario and drops to zero while a large v_2 still persists. This is consistent with CME and contradicts the background models. This is the opposite of the conclusion one would naturally draw from the LHC data where the eventshape engineering data is consistent with a v_2 driven background and contradicts CME. Although much new data has appeared, the situation remains murky.

$-eB_y \sim 2Z_{Au}\gamma e_2 4\pi v_z (2b)_2 \approx 10 m_{2\pi} \approx 10_{19}$ Gauss,



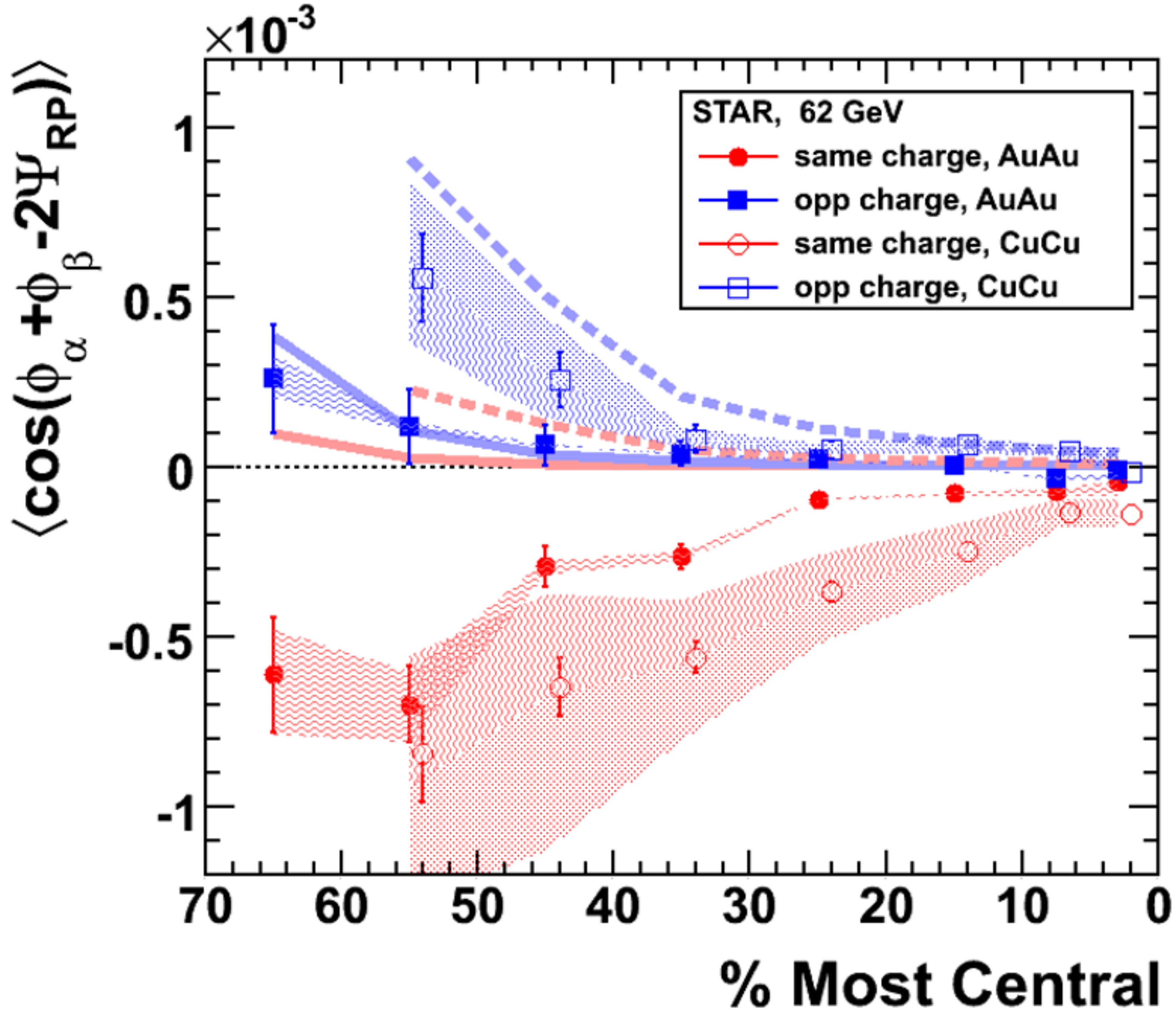
D. Kharzeev, L. McLerran and H. Warringa. Nuclear Physics A 803, 227 (2008).

Probing backgrounds



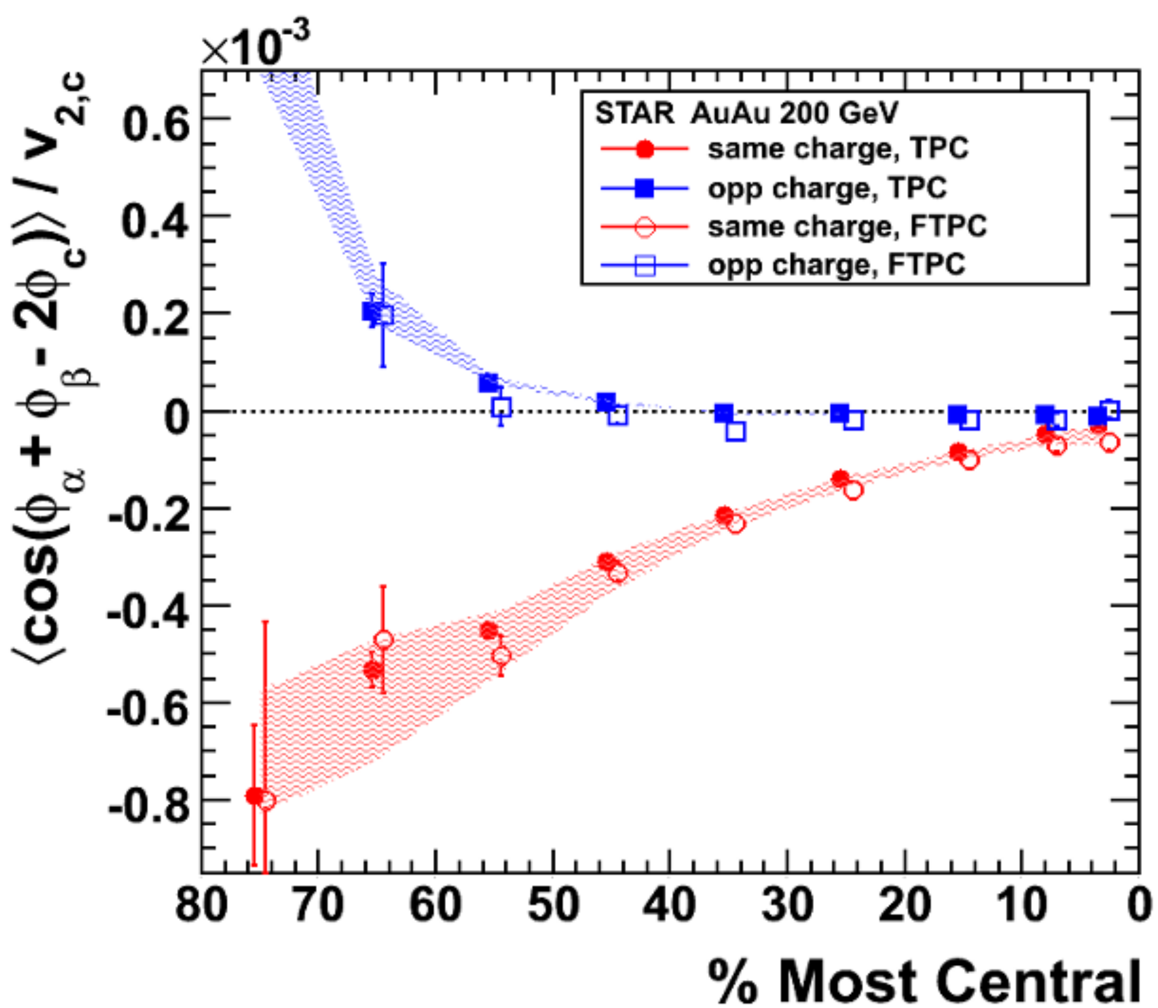
Average p_t : signal grows with p_t up to 2 GeV/c where the measurement runs out of steam. **Not as initially expected. (Can this be accommodated quantitatively by the C.M.E. theory?)**

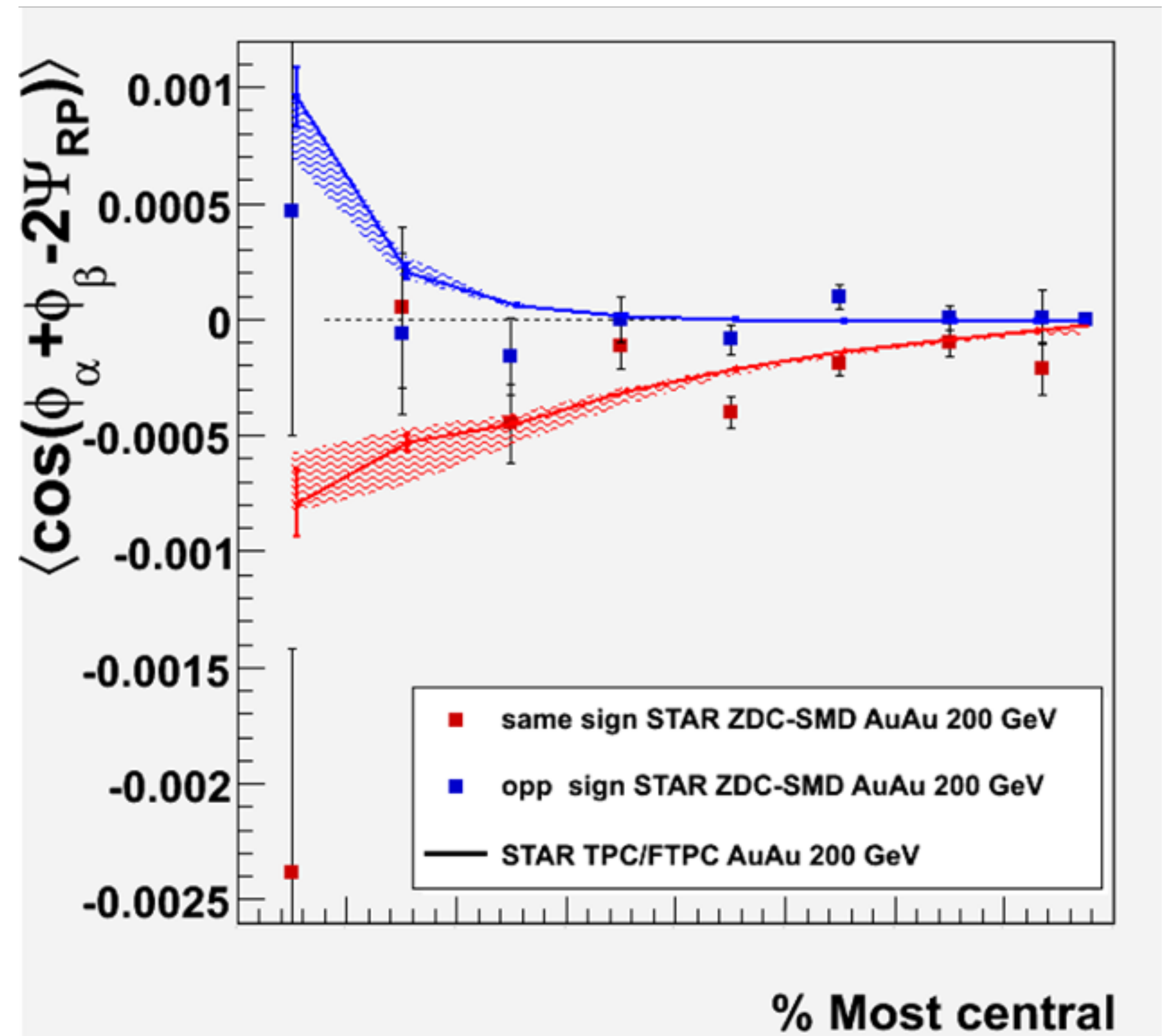
62 GeV



Nothing strikingly different from the 200 GeV results. Signal is somewhat larger (less combinatoric dilution) and again shows consistency with "less quenching in less dense systems"

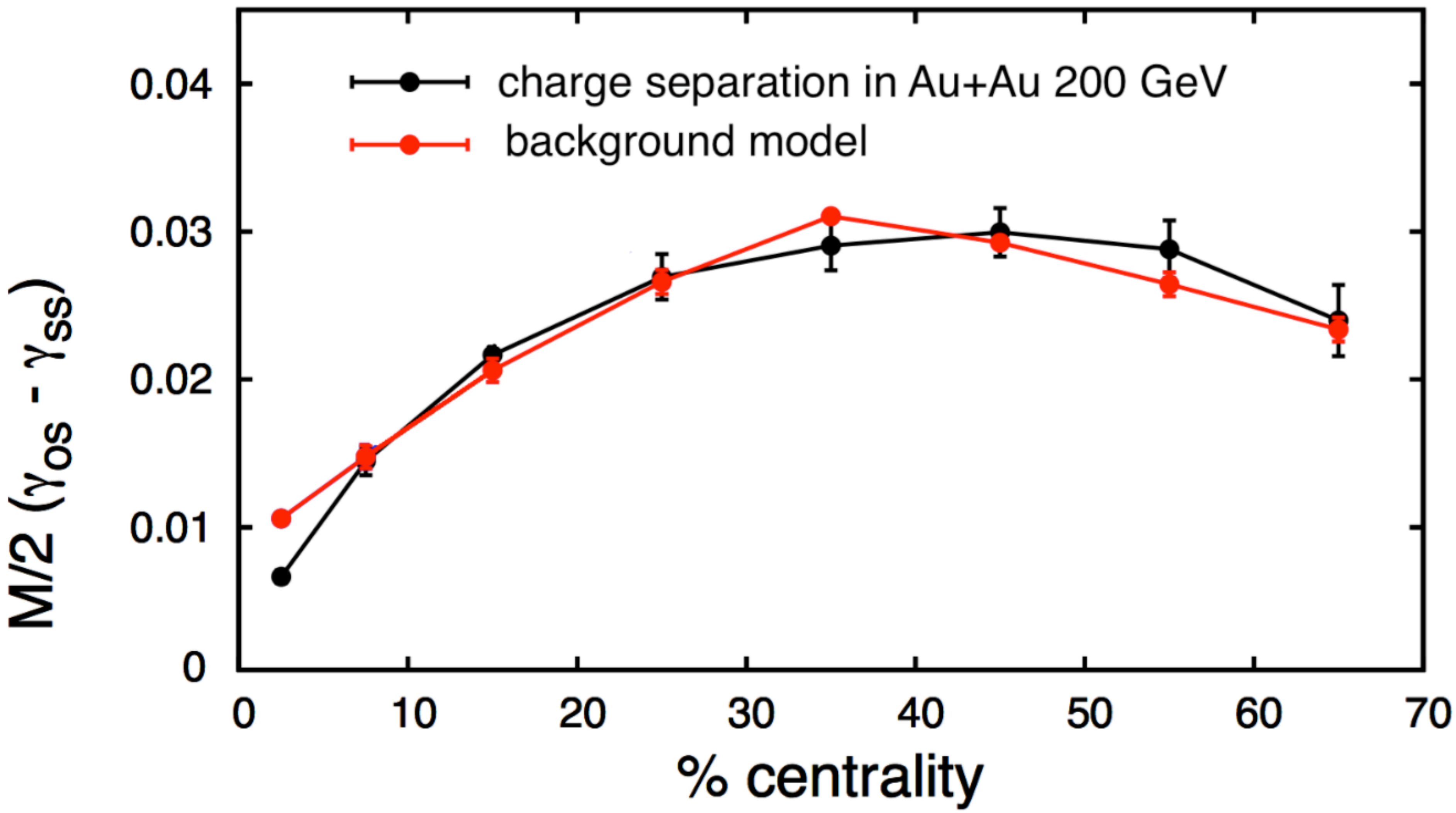
Checking with different event planes



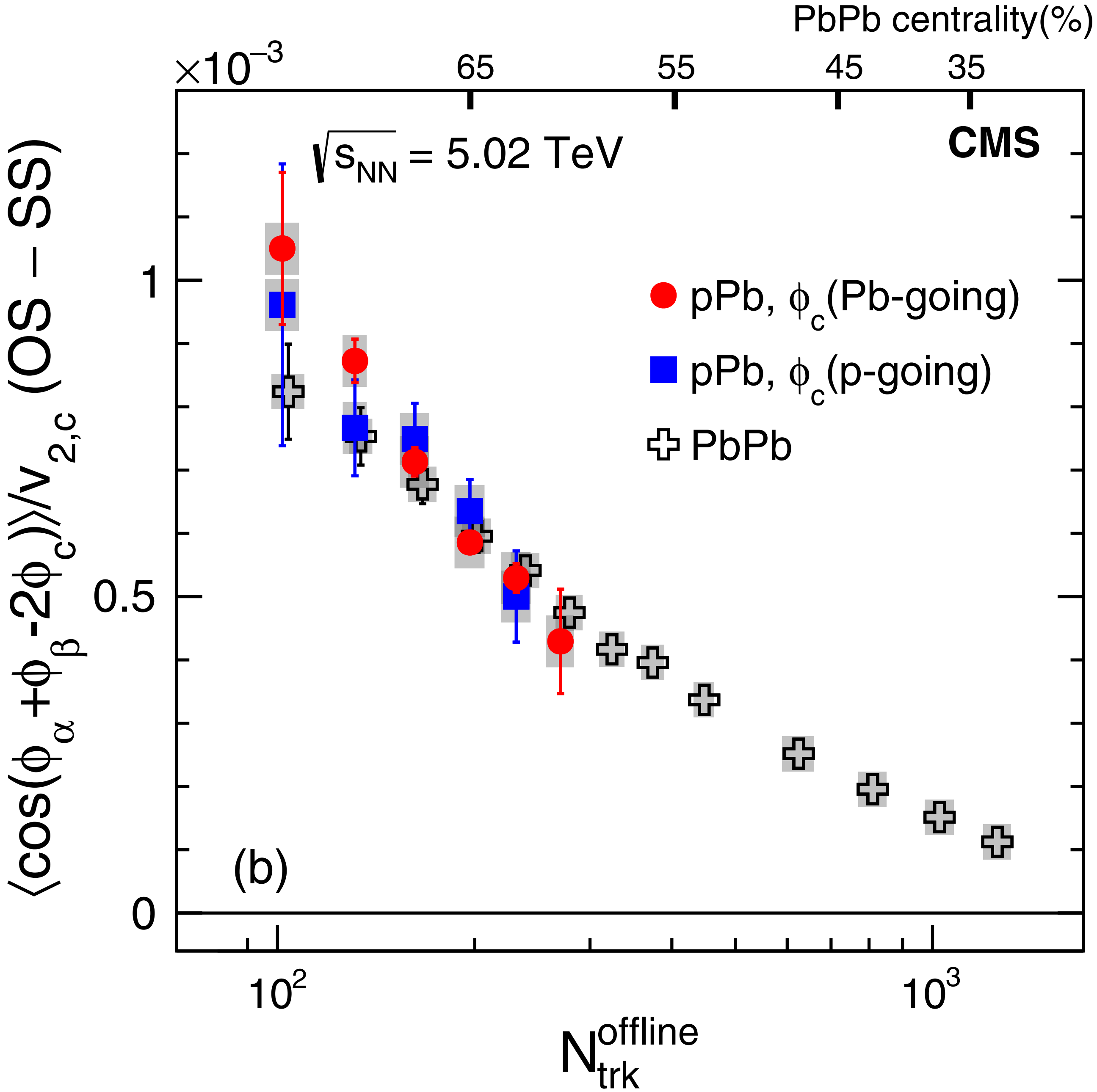


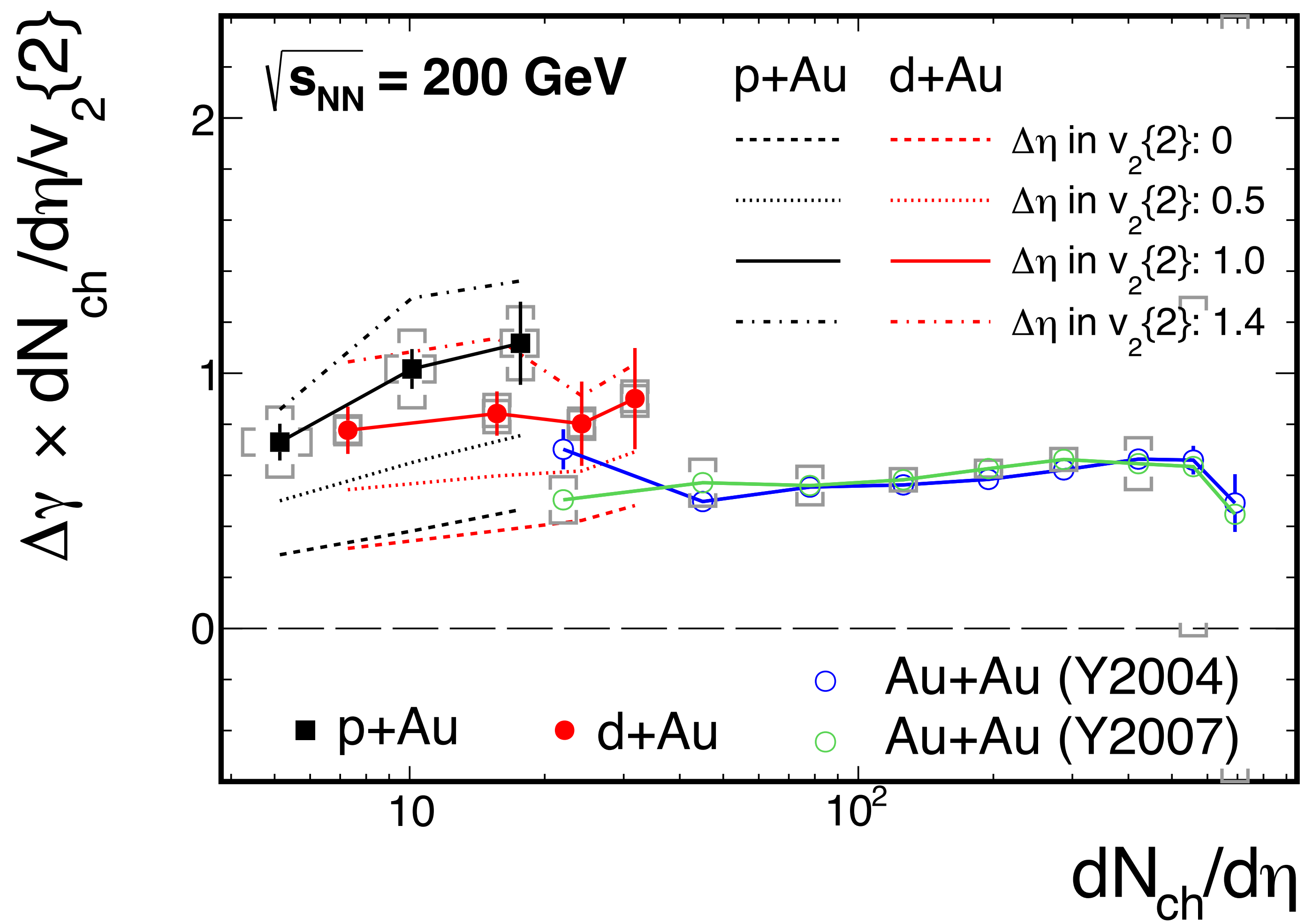
A test of factorization (i.e. can we assume $<\cos(\varphi_a+\varphi_b-2\Psi_{r.p.})>$ $=<\cos(\varphi_a+\varphi_b-2\varphi_c)>/v_{2,c}$) is that finding the reaction plane using different detectors gives consistent results.

S. Schlichting and S. Pratt, Phys. Rev. C **83**, 014913 (2011)



Backgrounds contributions could be comparable in magnitude to measured correlations





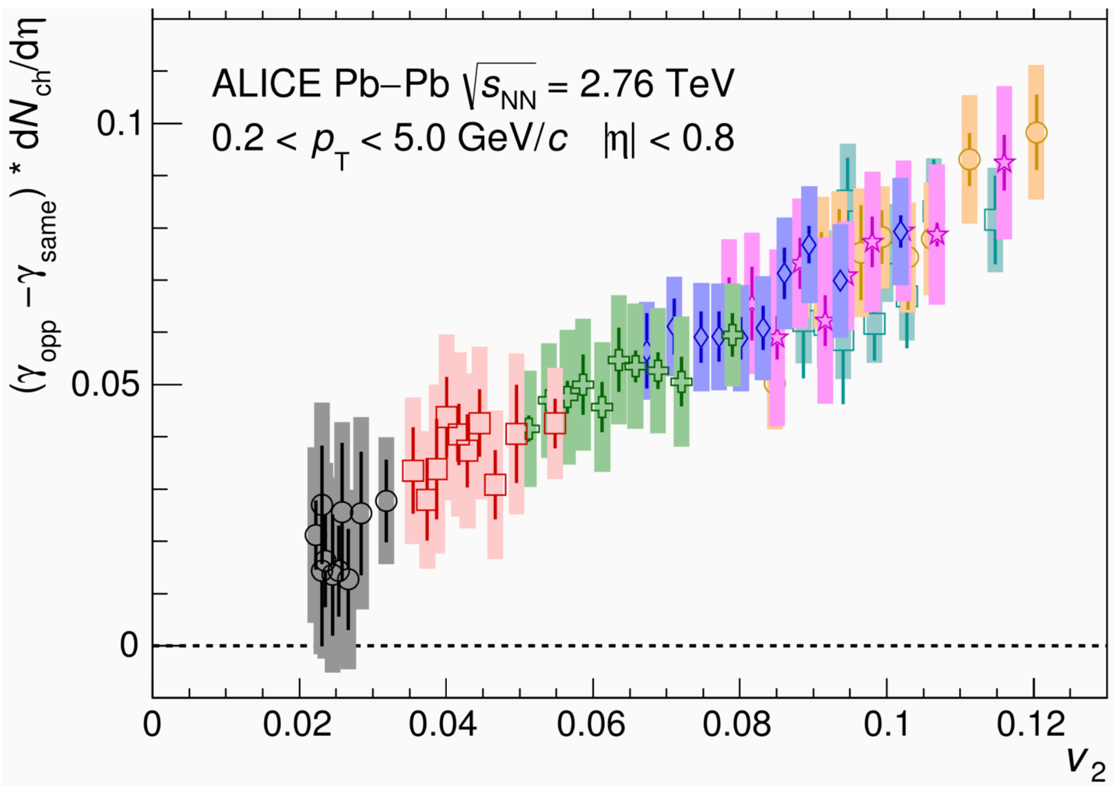
Small systems data confusing - suggest no CME

But why are backgrounds the same as in A+A?

STAR: PLB 798 134975 (2019)

CMS: PRL 118, 122301 (2017)

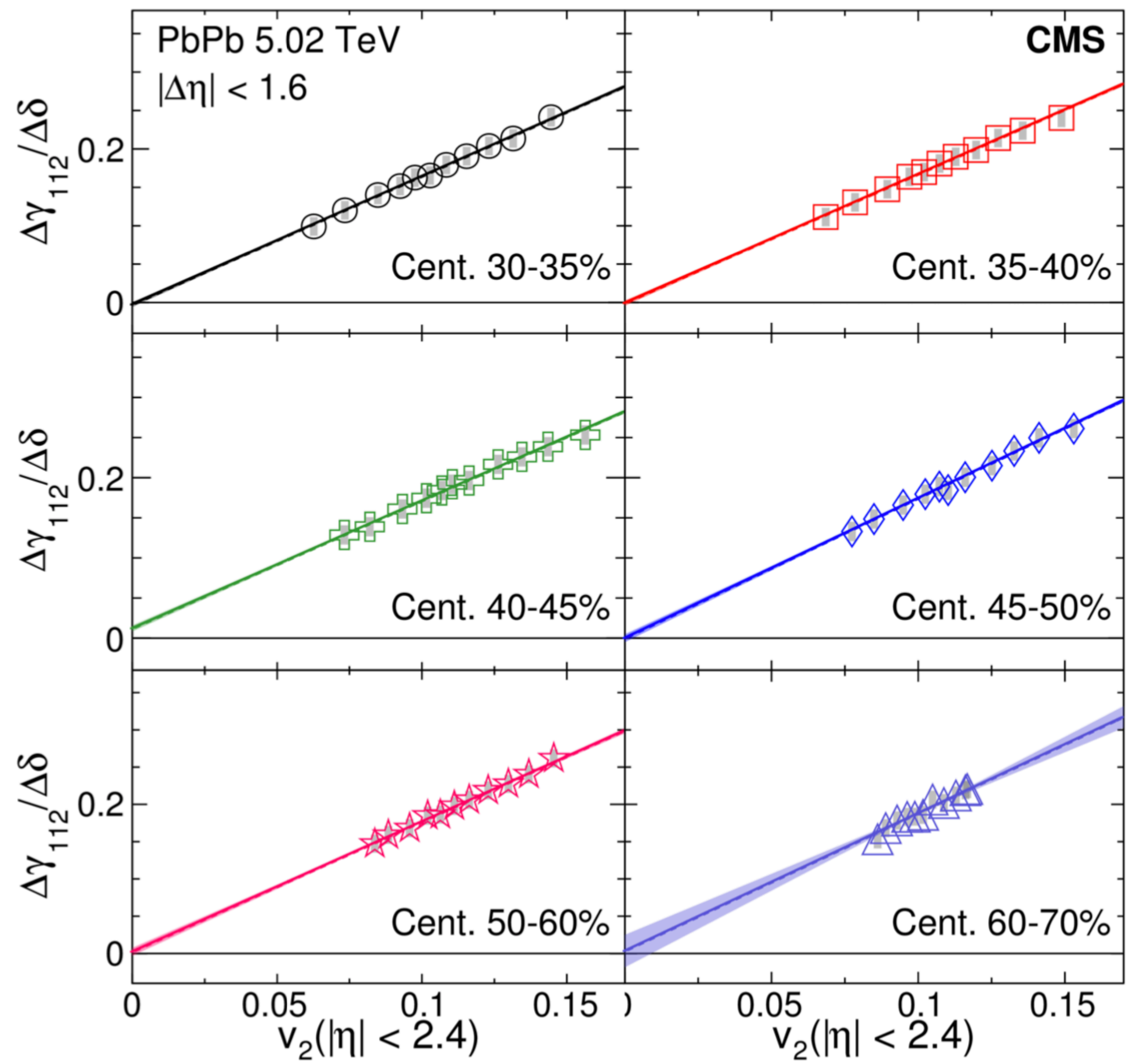
Event Shape Engineering (ESE)



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

$\Delta\gamma$ = background ($\propto v_2$) + signal

More ref. on ESE and EbyE v_2 method :
J. Schukraft, A. Timmins and S. Voloshin, Phys. Lett. B 719 394 (2013)
STAR, Phys. Rev. C 89 44908 (2014)
F. Wen, J. Bryon, L. Wen and G. Wang. Chin. Phys. C 42 No.. 1 014001 (2018)



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

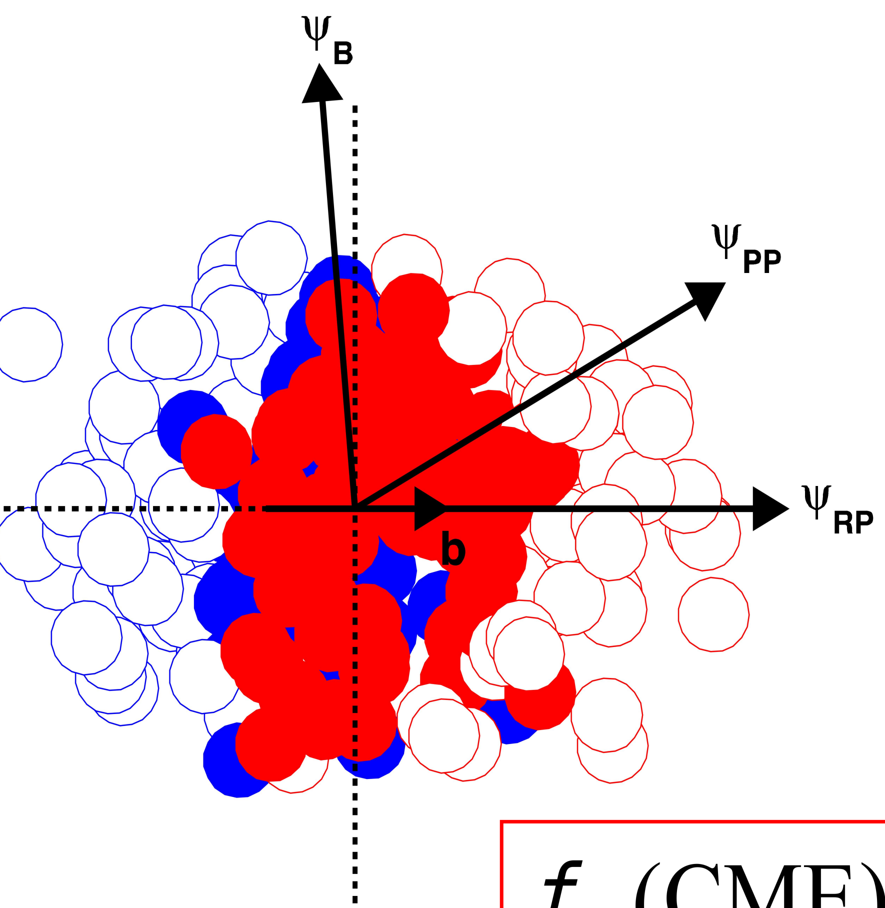
Caveat : long projection over empty v_2 space.

Signal in $\Delta\gamma$, if exists, should be very small at LHC energies.

Ψ_{PP} & Ψ_{RP} to resolve Bkg & CME

- Ψ_{PP} maximizes flow, ➔ flow background
- Ψ_{RP} maximizes the magnetic field (B), ➔ CME signal
- Ψ_{PP} and Ψ_{RP} are correlated, but not identical due to geometry fluctuations
- $\Delta\gamma$ w.r.t. TPC Ψ_{EP} (proxy of Ψ_{PP}) and ZDC Ψ_1 (proxy of Ψ_{RP}) contain different fractions of CME and Bkg

-J. Xu, *et al*, CPC 42 (2018) 084103, Xiv:1710.07265



$$\Delta\gamma\{\psi_{TPC}\} = \mathrm{CME}\{\psi_{TPC}\} + \mathrm{Bkg}\{\psi_{TPC}\}$$
$$\Delta\gamma\{\psi_{ZDC}\} = \mathrm{CME}\{\psi_{ZDC}\} + \mathrm{Bkg}\{\psi_{ZDC}\}$$

Two-component assumption

$$\mathrm{CME}\{\psi_{TPC}\} = a * \mathrm{CME}\{\psi_{ZDC}\},\ \mathrm{Bkg}\{\psi_{ZDC}\} = a * \mathrm{Bkg}\{\psi_{TPC}\}$$

assume $\mathrm{Bkg} \propto v_2$

$$a = v_2\{\psi_{ZDC}\} / v_2\{\psi_{TPC}\},\ A = \Delta\gamma\{\psi_{ZDC}\} / \Delta\gamma\{\psi_{TPC}\}$$

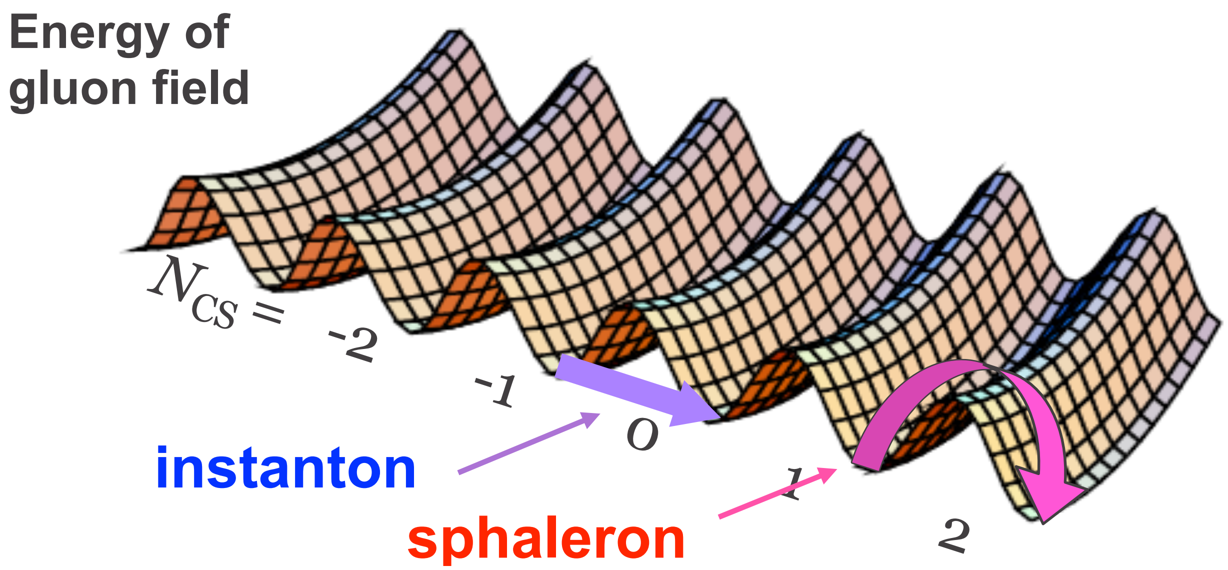
Both are experimental measurements

$$f_{EP}(\mathrm{CME}) = \mathrm{CME}\{\psi_{TPC}\} / \Delta\gamma\{\psi_{TPC}\} = (A/a - 1)/(1/a^2 - 1)$$

Local Strong Parity Violation

In QCD, chiral symmetry breaking is fundamental and due to nontrivial topological solutions; among the best evidence for this physics would be *event-by-event local strong parity violation*

Instantons and sphalerons are localized (in space and time) solutions describing transitions between different vacua via tunneling or go-over-barrier



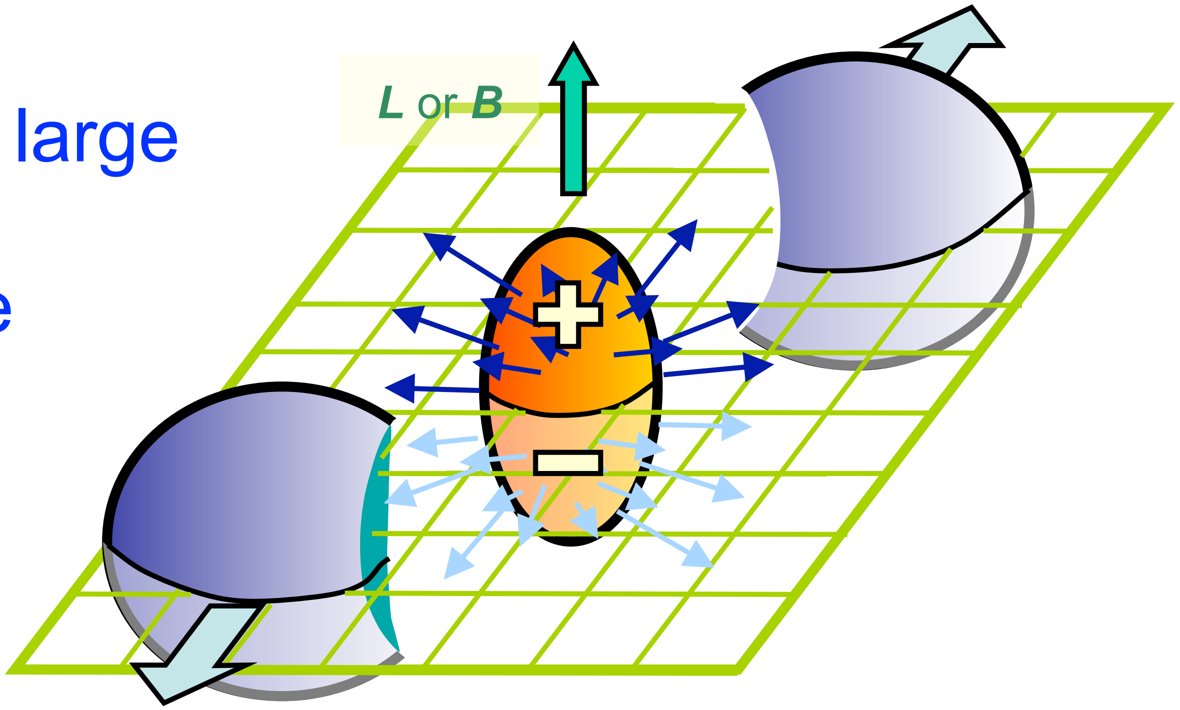
All non-Abelian gauge theories admit such non-trivial vacuum fluctuations – e.g., B- and CP-violating sphalerons frozen in at EW phase transition are (one) speculated origin of Baryon Asymmetry of the Universe!

How to potentially observe such an effect in the lab?

LSPV and the QGP

Usually this effect is confined within a nucleon and averages to zero over space and time

Heavy-Ion collision: deconfined partons over large volume + chiral symmetry restoration
: may enable metastable domains to be formed in which P, CP are locally violated



Experiment focus on non-central collisions:

large orbital angular momentum perp. to RP + large localized B fields
+ deconfined phase

⇒ strong P violating domains with diff. no. of left & right handed quarks

Kharzeev et al. PRL 81 (1998) 512, and PRD 61 (2000) 111901

⇒ Preferential emission of like-sign particles in the direction of B-field i.e. opposite sides of the reaction plane

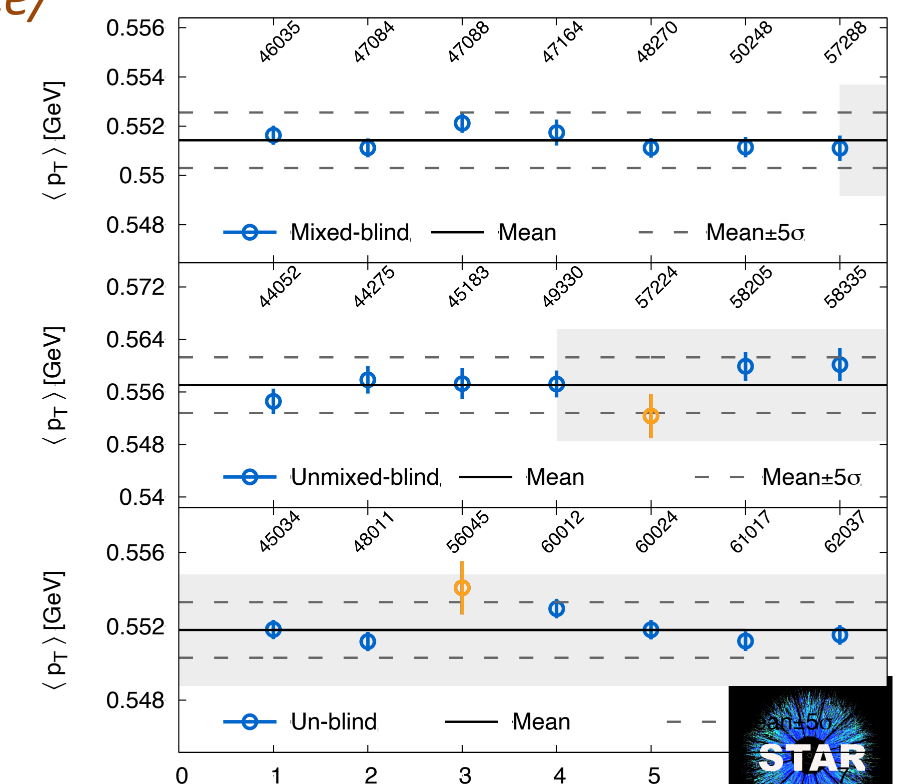
(Voloshin PRC 70 (2004) 057901)

This is termed the Chiral Magnetic Effect (CME)

Step-0: Initial Steps

“The Tune-up”

- Calibrations and quality run selection by un-blind experts
- Develop software infrastructure to implement the blinding procedure
  - Event mixing procedure and run-numbers encrypted
  - Additional information obfuscated in data
    - *Event ID, run ID, event timestamp, collision species, hit/coincidence/ background rates from certain detectors*
- “Mock data challenge”
  - *Sanity-check of feasibility and implementation*
  - Utilize blinding procedures on 2018 27 GeV Au+Au data
  - Analysts tune code on “mock data”
    - *Check that data blinding infrastructure works as intended*
    - *Verify the appropriate information is blinded as intended*
    - *Ensure appropriate information is accessible to analysts*
    - *Check that analysis codes run properly on “blind” data structures*
    - *Confirm “blind" and “unblind" results are the same*
      - *sanity check of procedures*



STAR, NST 32, 48 (2021)

Step-1: Isobar Blind and Mixed

"The Reference"

- Provide output files composed of events from a ***mix*** of the two isobar species
  - *Mixing procedure encrypted and known only by two computing experts (recused)*
- As much as possible, order of events ***respects time-dependent change in run conditions***
- **Analysis code** and **time-dependent QA** tuned
- Critical analysis needs enabled by this step:
  - Extraction of time-dependent spectra for quality assessment
  - Detection of time-dependent anomalies
  - Measurement of peak widths relevant to momentum resolution

Following completion of Step-1, analysis codes are frozen and committed to the repository
Before moving to Step-2, codes are documented and reviewed by the isobar paper review committee

Important Considerations

For STAR Chiral Magnetic Effect (CME) analyses:

- **Critical to account for**
  - ***Time-dependent*** detector fluctuations
  - Anomalies in the collection of 30-minute "runs" of the data acquisition system
- Do not randomize variables that may severely compromise analysis quality
  - *E.g., randomizing the sign of reconstructed charged-particle signals prevents charge-dependent efficiency corrections*
- 2018 data-taking used frequent switching of "isobar" species (and)
  - Species expected to have comparable behavior, e.g., luminosity, trigger, energy, vertex distribution, occupancy of tracks
  - *Possible to blind species by interleaving or "mixing" events from two species*
- Certain non-analyst experts need access to un-blind data
  - E.g.. STAR detector experts during RHIC running or offline calibration experts
  - ***All** must recuse themselves from blind physics analysis*
- Selection of high quality runs for analyses must proceed prior to mixing of events

Step-2: Isobar Blind

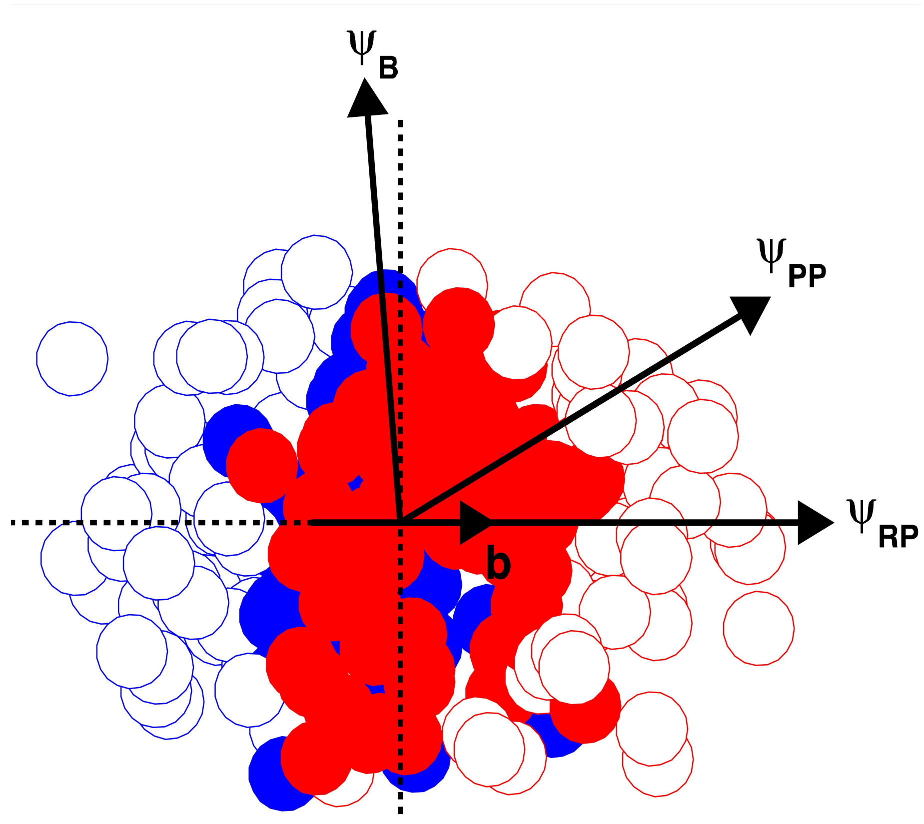
"The run by run QA sample"

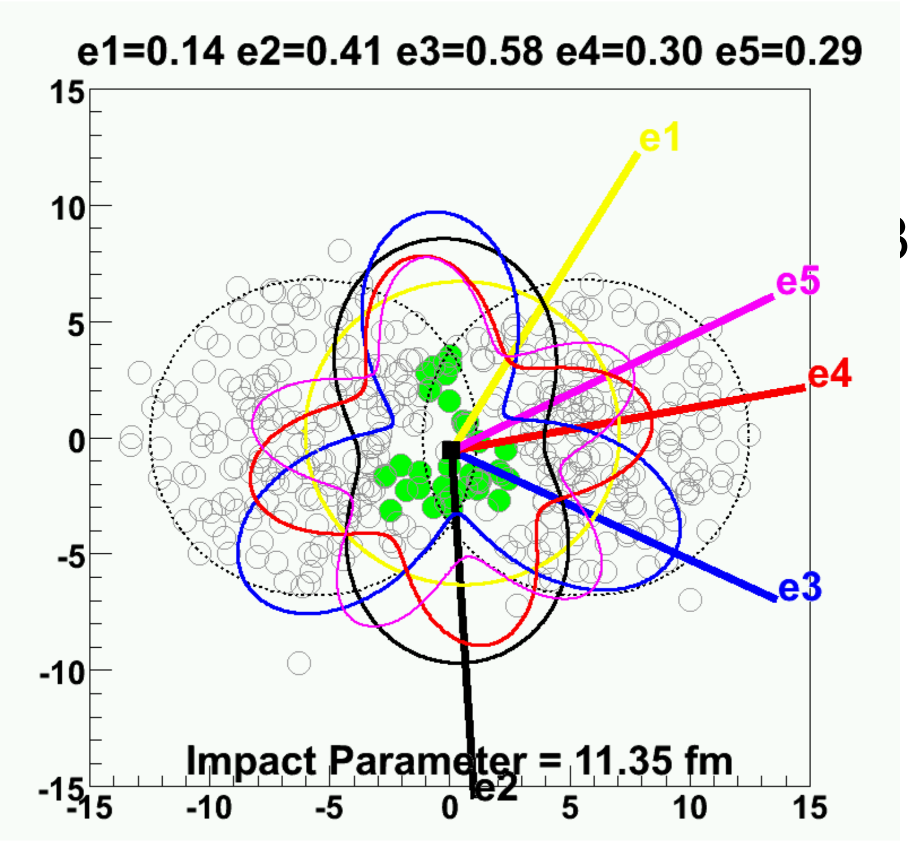
- Provide data files that obscure the species but do ***not*** mix events across different runs
  - *Limit the number of events to prevent deciphering species by simple counting*
- ***Only run-by-run corrections and code alteration directly resulting from these corrections are allowed at this stage***
- Additional bad runs identified based on physics quantities and discarded
  - *Analysts perform run-by-run QA using a predefined and frozen algorithm*
- This step enables analysts to perform QA using quantities relevant to their specific analysis

Following completion of Step-2…

- ***Analysis codes are reviewed, frozen, and committed to the repository***
- ***Fully un-blind data are released and analyzed with the frozen codes***
- Only changes to correct "mistakes" are allowed after unblinding
  - Errors in arithmetic
  - Unintended departures from ***documented and approved*** procedures, cuts, corrections, and systematic uncertainty estimates

Defining planes - fluctuations matter





Spectator or Reaction plane:
- Assumes hard sphere geometry
- Correlated with B field

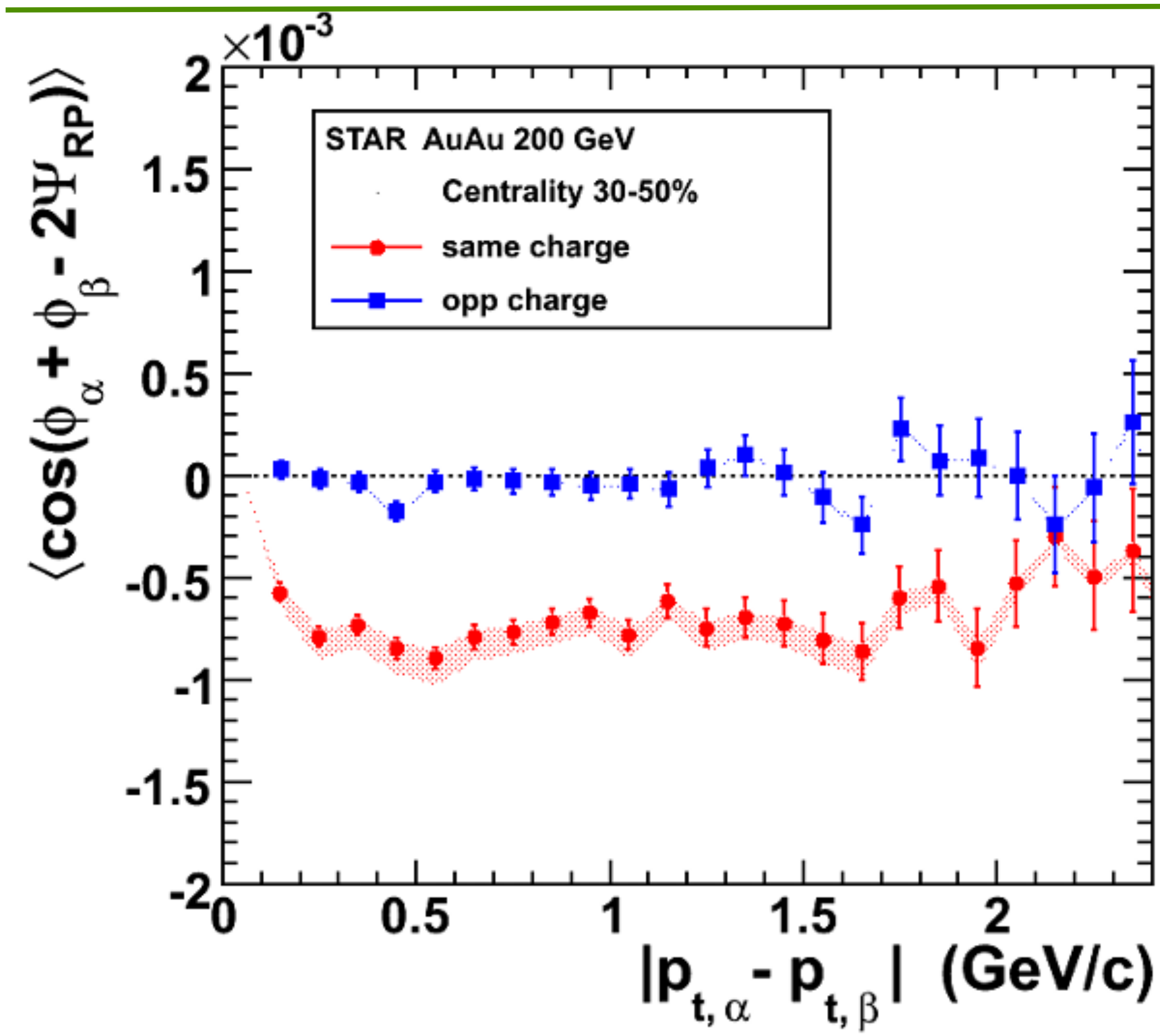
Participant plane:
- Defined by nuclei actually involved in the collision
- Maximizes elliptic flow component

Triangular plane:
- Plane which maximizes triangular shape of participants
- Largely uncorrelated with spectator or participant planes

Higher order planes:
- Fluctuations make all orders possible

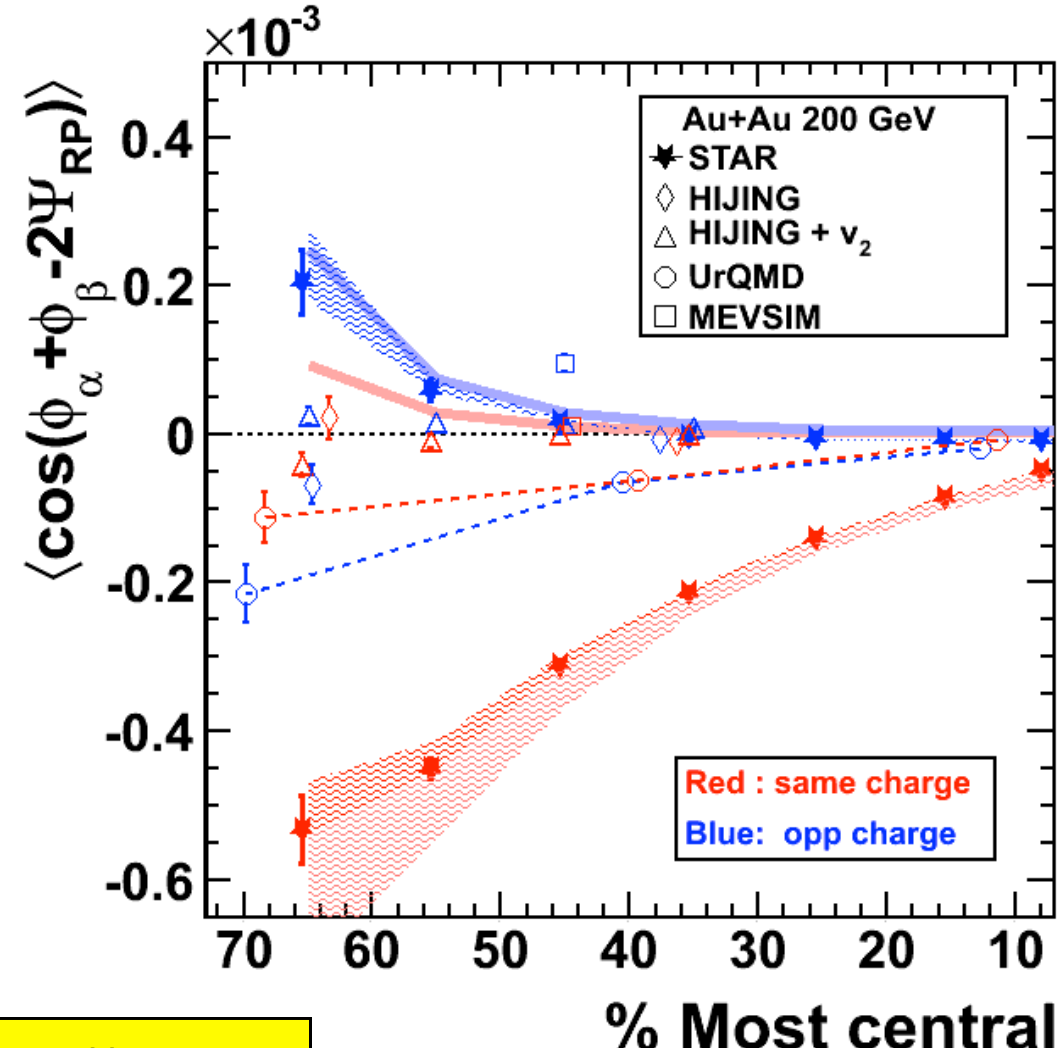
Will take advantage of this later

Probing background contributions



Signal roughly independent of p_T difference

- rules out causes like HBT, Coulomb



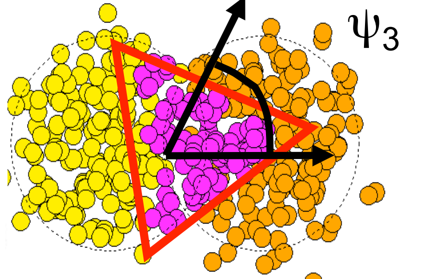
Models with no CME but effects such as

- elliptic flow
- resonances
- jets

don't reproduce SS and OS signals

SS signal not solely from trivial non-CME effects

Probing the background some more



Ψ_3 plane, unlike Ψ_2, is not correlated to B-field direction so measurement made with respect to Ψ_3 should not reveal any CME signal

$$\gamma = \langle cos(\phi_1 + \phi_2 - 2\Psi_R)\rangle = \kappa v_2 F - H$$

$$\delta = \langle cos(\phi_1 - \phi_2)\rangle = \langle cos(\Delta\phi_1)cos(\Delta\phi_2) + sin(\Delta\phi_1)sin(\Delta\phi_2)\rangle = F + H$$

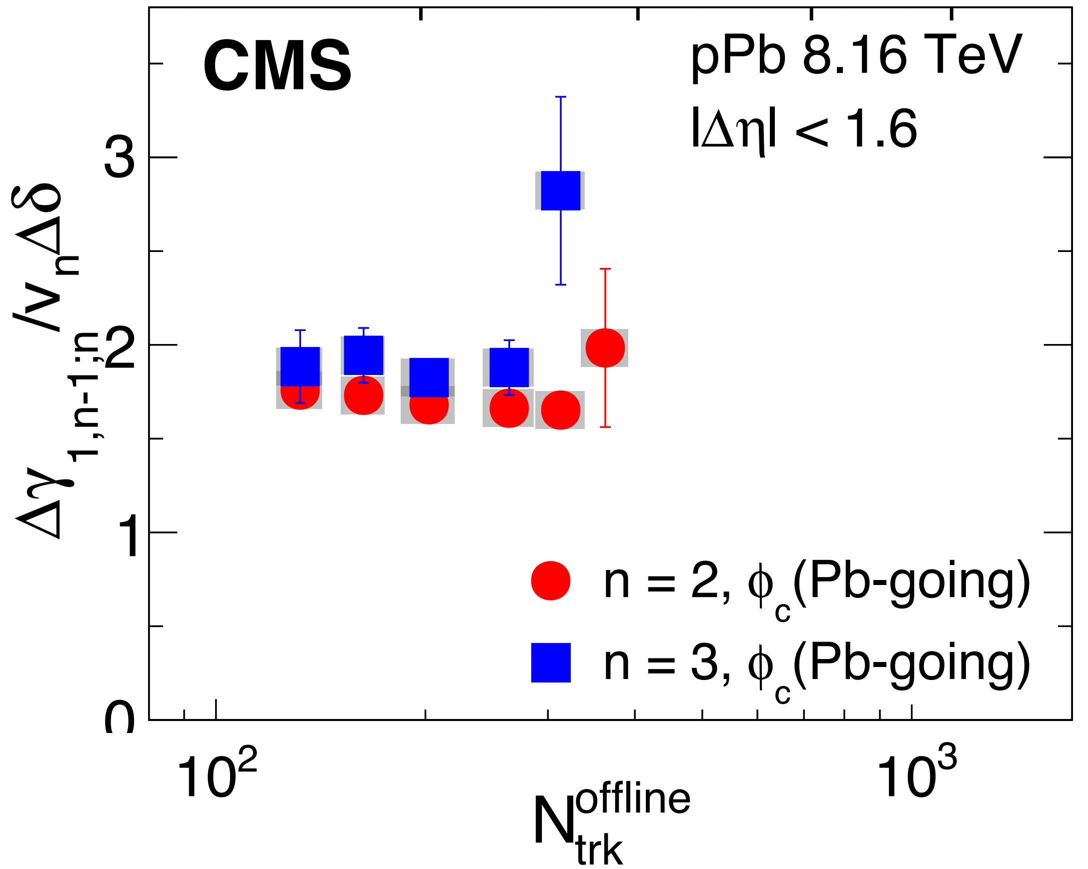
H - CME signal, F - Background, κ - scaling factor ~1

Introducing: $\gamma_{123} = \langle \cos(\varphi_a - 2\varphi_b - 3\Psi_3)\rangle = \kappa v_3 F$

If data only contains background

$$\frac{\Delta\gamma_{112}}{v_2\Delta\delta} \approx \frac{\Delta\gamma_{123}}{v_3\Delta\delta}$$

p+Pb consistent with 100% BG

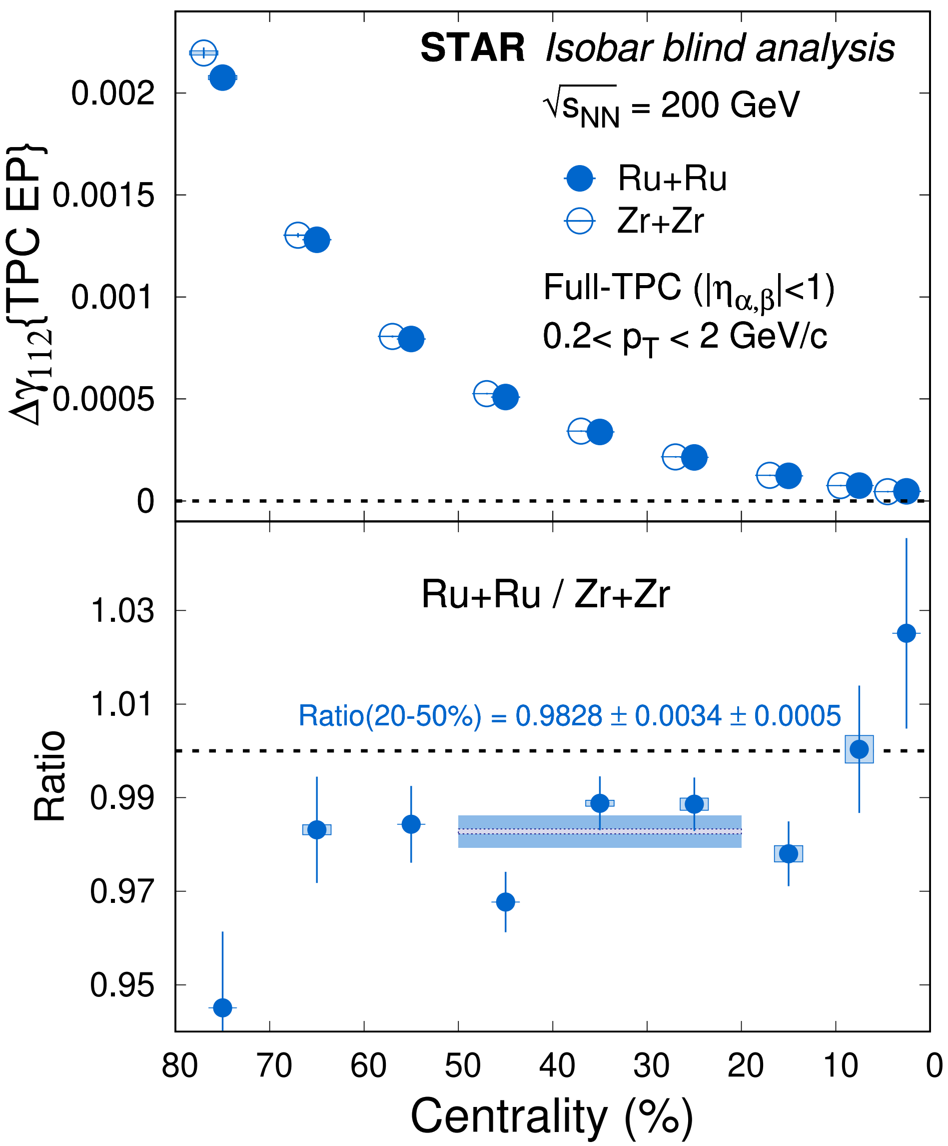


p+Au and d+Au at RHIC give similar results

CMS: PRC 97 044912 (2018)
STAR: PLB 798 134975 (2019)

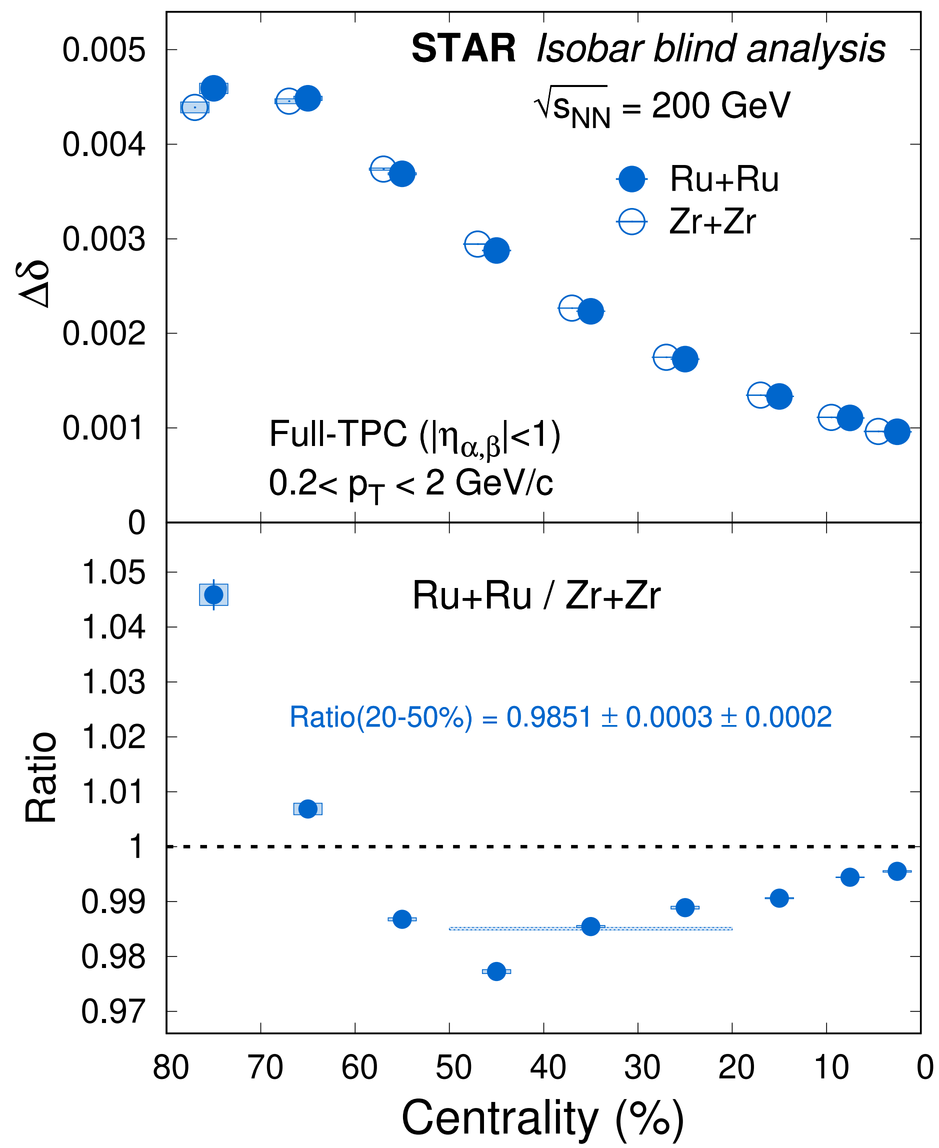
$\gamma_{112}\{\mathrm{EP}\} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2^{\mathrm{TPC}}) \rangle$

$\Delta\gamma = \gamma_{112}(OS) - \gamma_{112}(SS)$



$\delta \equiv \langle \cos(\phi_\alpha - \phi_\beta) \rangle$

$\Delta\delta = \delta(OS) - \delta(SS)$



Group 1: Focus on full TPC event plane to maximize statistical precision

Tested: Ratios insensitive to short-range correlations

Anticipated precision down to 0.4% achieved