Search for the Chiral Magnetic Effect in Isobaric Collisions

- A Status Report

Aihong Tang (for the STAR Collaboration)
Brookhaven National Lab

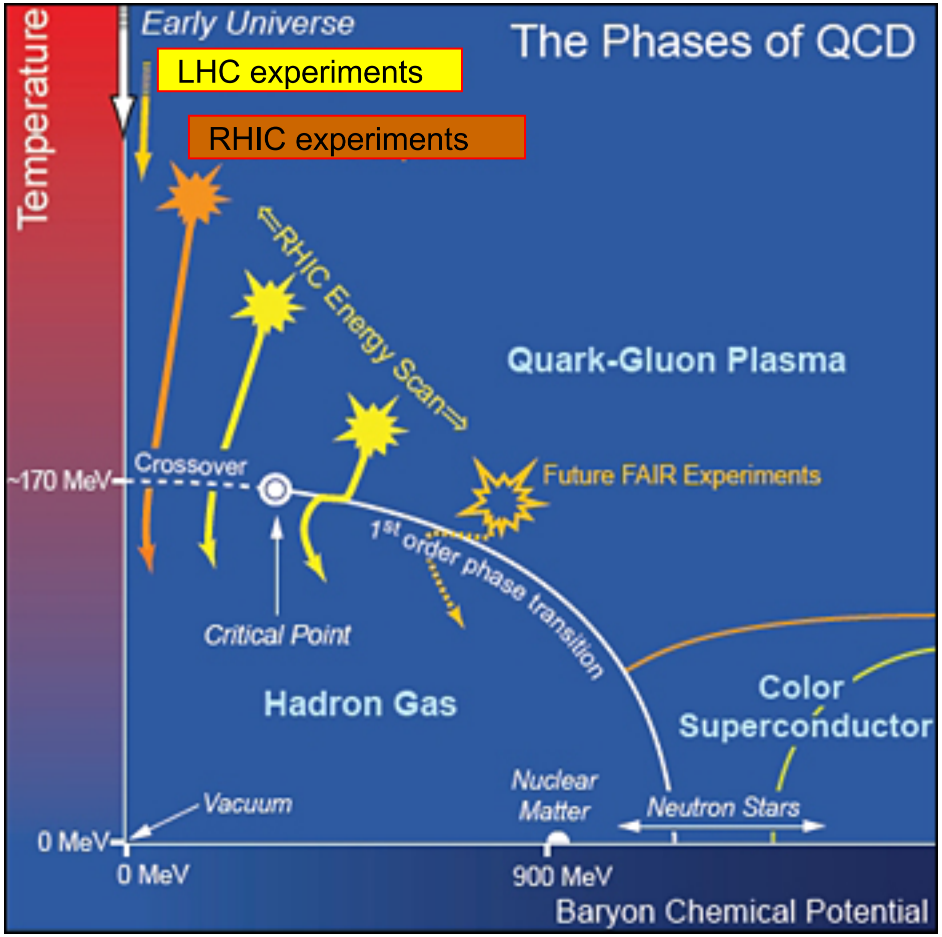
U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

Office of Science
U.S. DEPARTMENT OF ENERGY

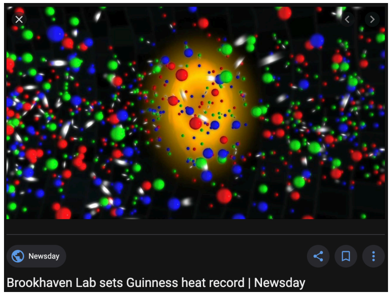
Heavy Ion Missions at RHIC and the LHC

1. QCD phase diagram

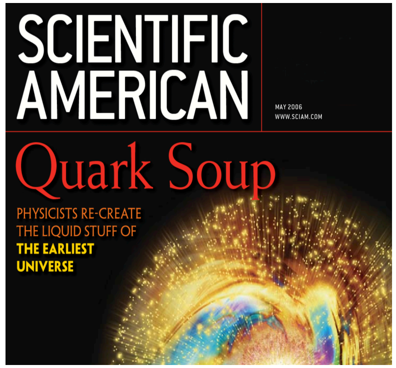


Relativistic Heavy Ion Collisions : Excellent QCD test ground

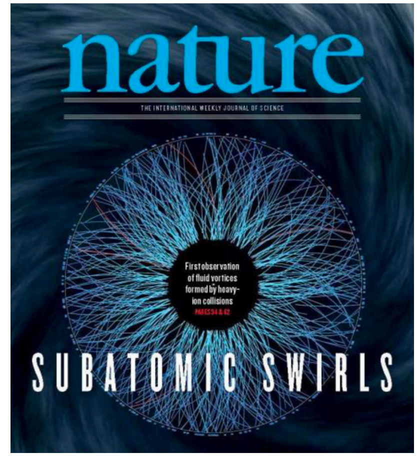
Heavy Ion Missions at RHIC and the LHC



Hottest



Least viscous



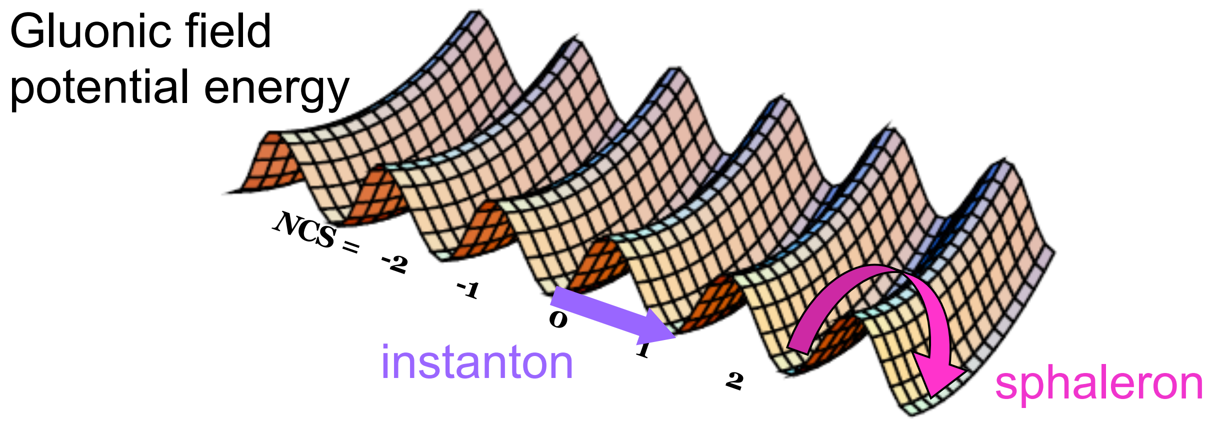
Most vortical

1. QCD phase diagram
2. Dynamic properties of QCD matter

???

Relativistic Heavy Ion Collisions : Excellent QCD test ground

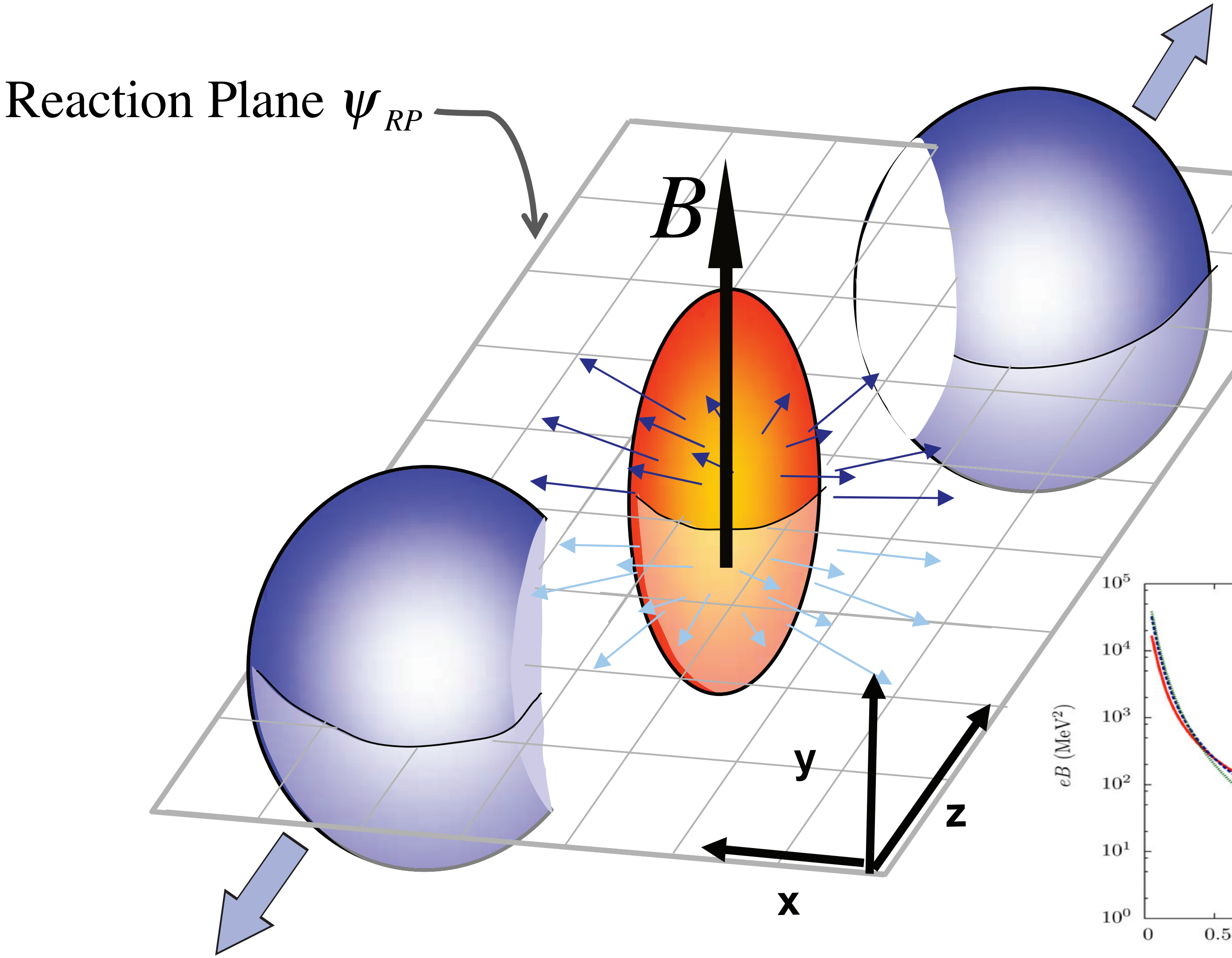
QCD Vacuum Transition

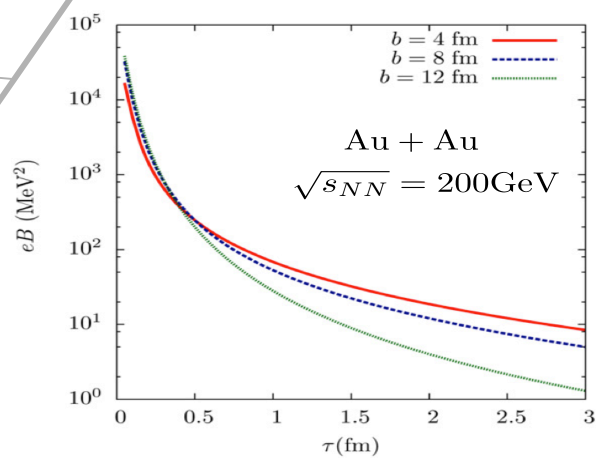


•QCD vacuum transition ➔ nonzero topological charge ➔ chirality imbalance

Local violations of fundamental symmetries of space-time in strong interaction

The Setup of Heavy Ion Collision





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

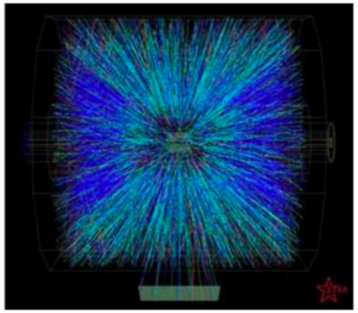
The Setup of Heavy Ion Collision

Earth

Magnet

Neutron star

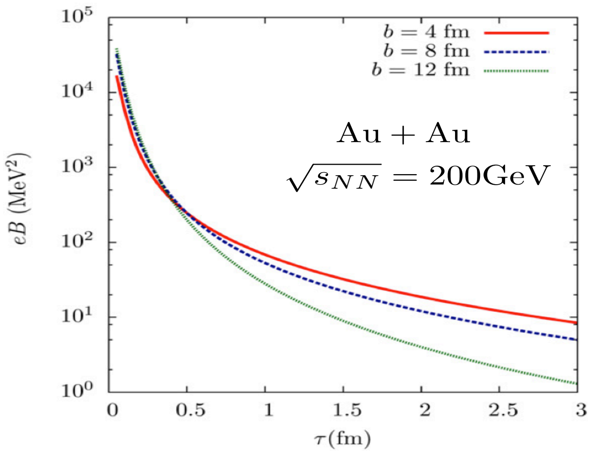
Heavy-ion collisions



B (Gauss)

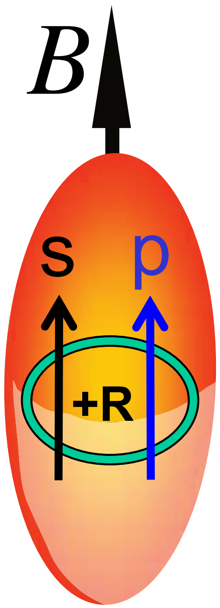
1 — $10^2 - 10^5$ — $10^{12} - 10^{15}$ — $10^{18} - 10^{20}$

Plot courtesy of X. Huang



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

Chiral Magnetic Effect

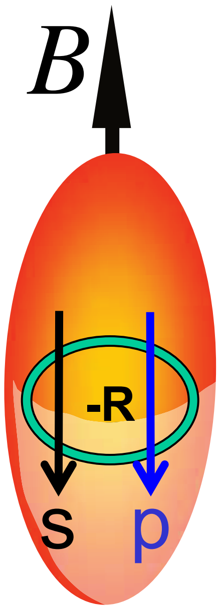


Positively charged particles moving upward.

$$\langle \vec{s} \rangle \propto (Qe)\vec{B}$$

$$\langle \vec{p} \rangle \propto \mu_A \langle \vec{s} \rangle$$

Chiral Magnetic Effect

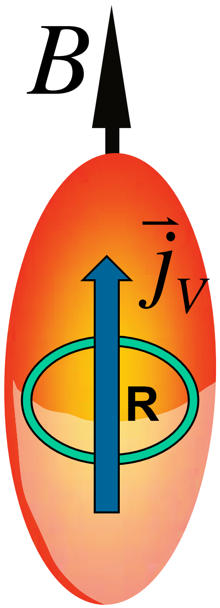


Negatively charged particles moving downward.

$$\langle \vec{s} \rangle \propto (Qe)\vec{B}$$

$$\langle \vec{p} \rangle \propto \mu_A \langle \vec{s} \rangle$$

Chiral Magnetic Effect



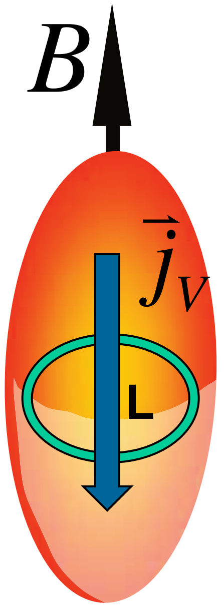
Charge current

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

Chiral Magnetic Effect (CME)

Charge separation along B direction.

Chiral Magnetic Effect



Charge current

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

Chiral Magnetic Effect (CME)

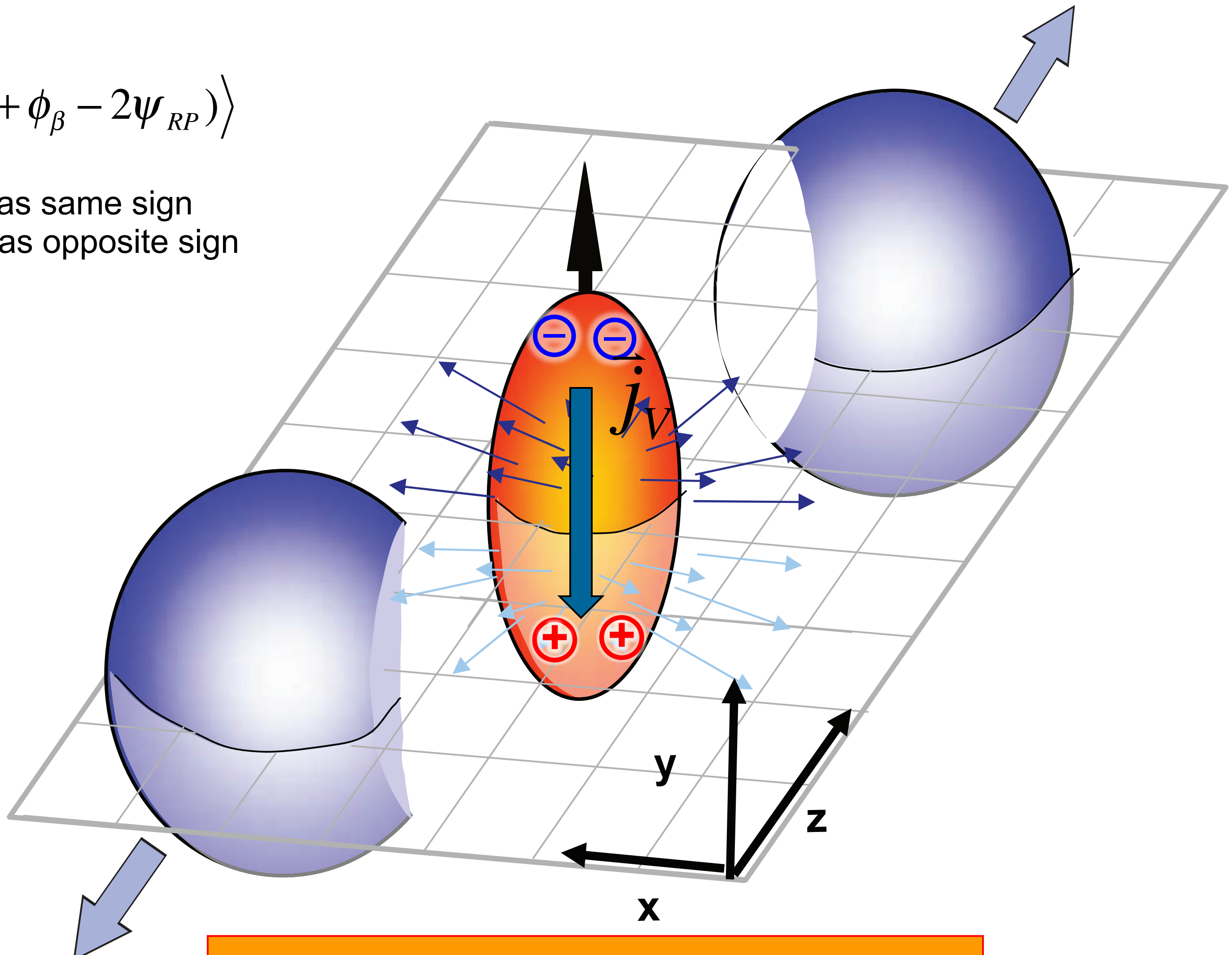
Charge separation along B direction.
Dipole effect, flips event by event.

Chiral Magnetic Effect

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

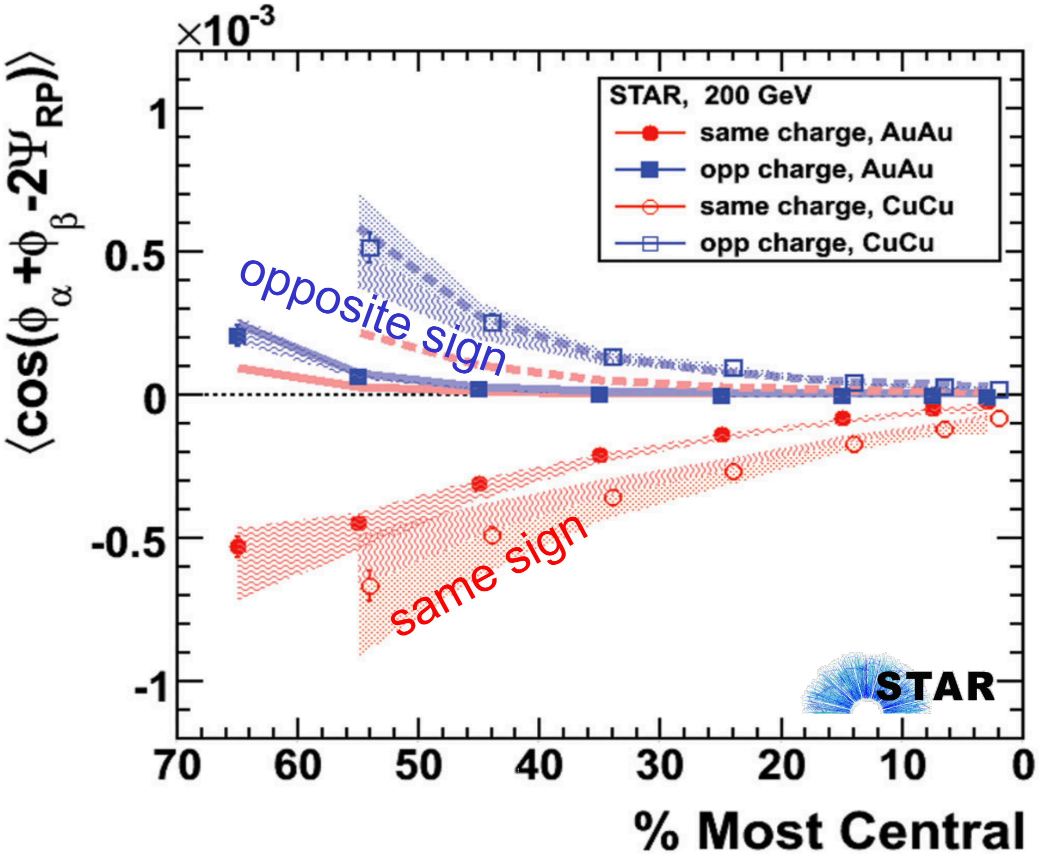
$\gamma \equiv \langle \cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \rangle$

ss : α and β has same sign
os : α and β has opposite sign



Charge separation along B direction.
Dipole effect, flips event by event.

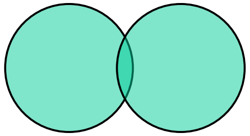
Chiral Magnetic Effect

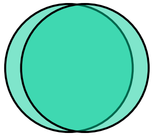


$$\gamma_{SS} < \gamma_{OS}$$

$$\gamma \equiv \langle \cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \rangle$$

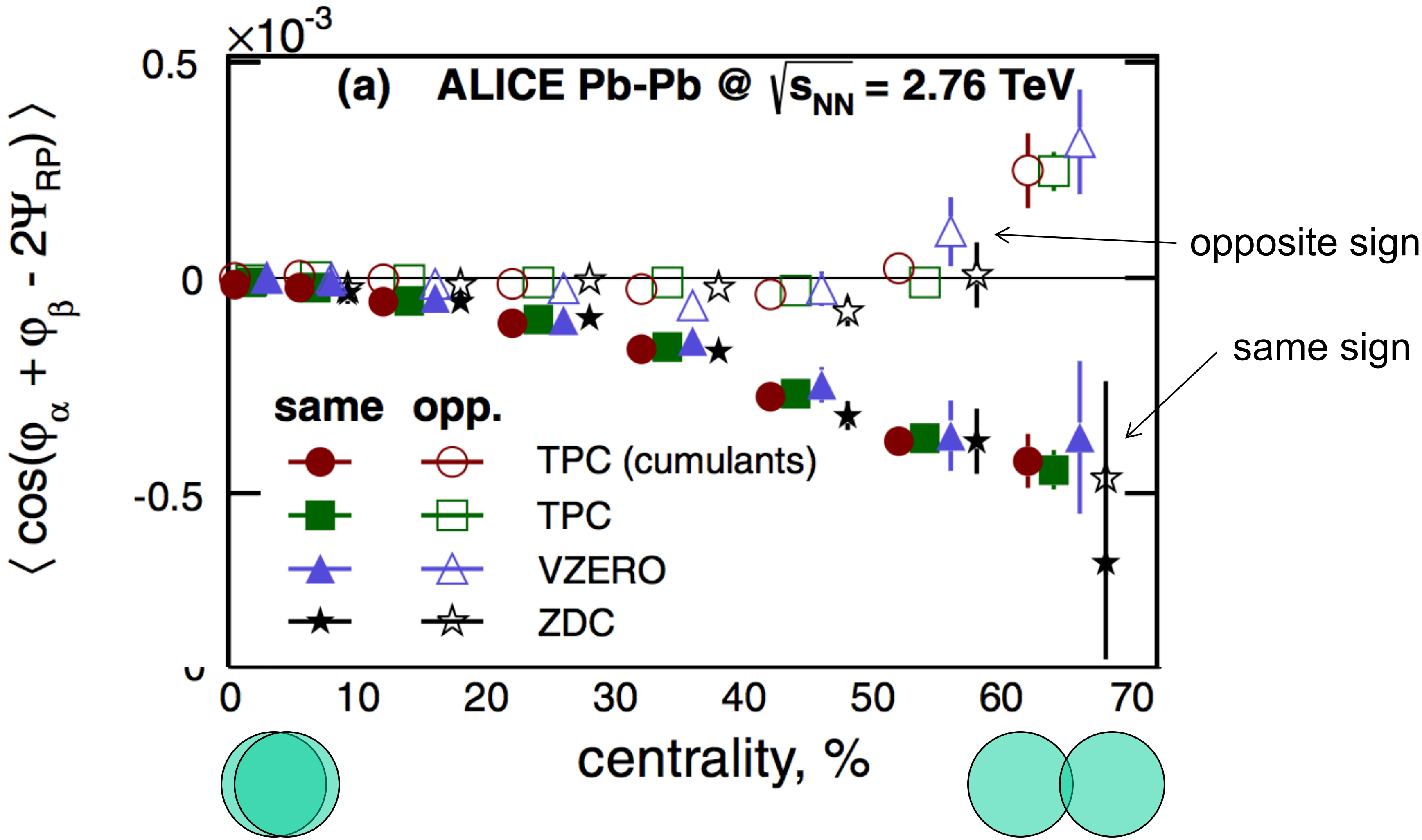
"A signal consistent with several expectations from the theory is detected."





STAR PRL103 251601 (2009)
STAR PRC 81 054908 (2010)

Chiral Magnetic Effect



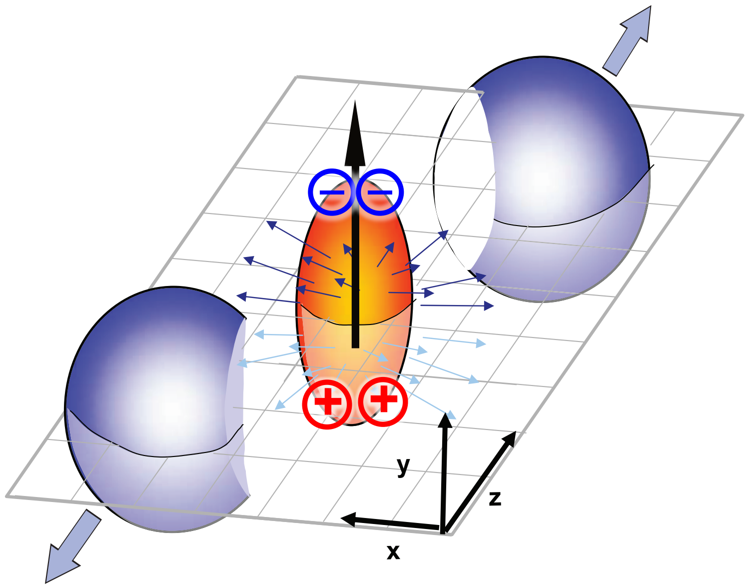
$\gamma_{SS} < \gamma_{OS}$

$\gamma \equiv \left\langle \cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \right\rangle$

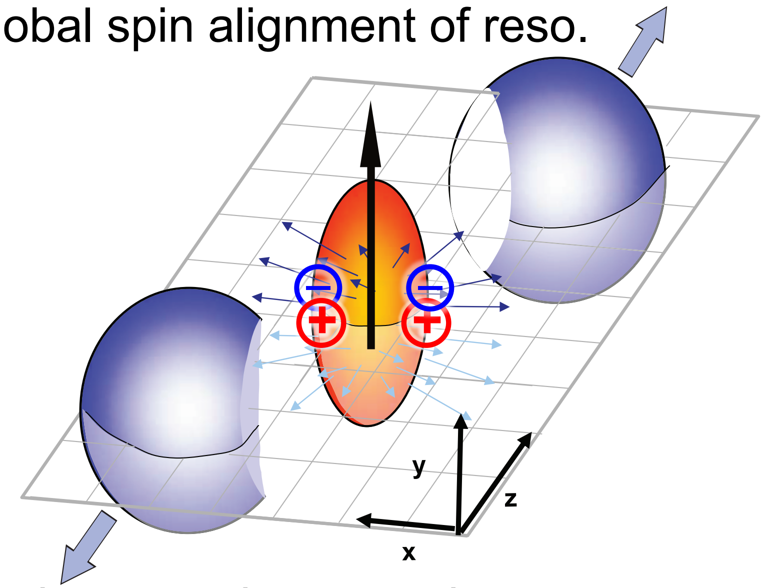
ALICE PRL110 012301 (2013)

Chiral Magnetic Effect : Backgrounds

Signal



Backgrounds:
Total Momentum Conservation (TMC)
Local Charge Conservation (LCC)
Flowing cluster in plane
Global spin alignment of reso.
…

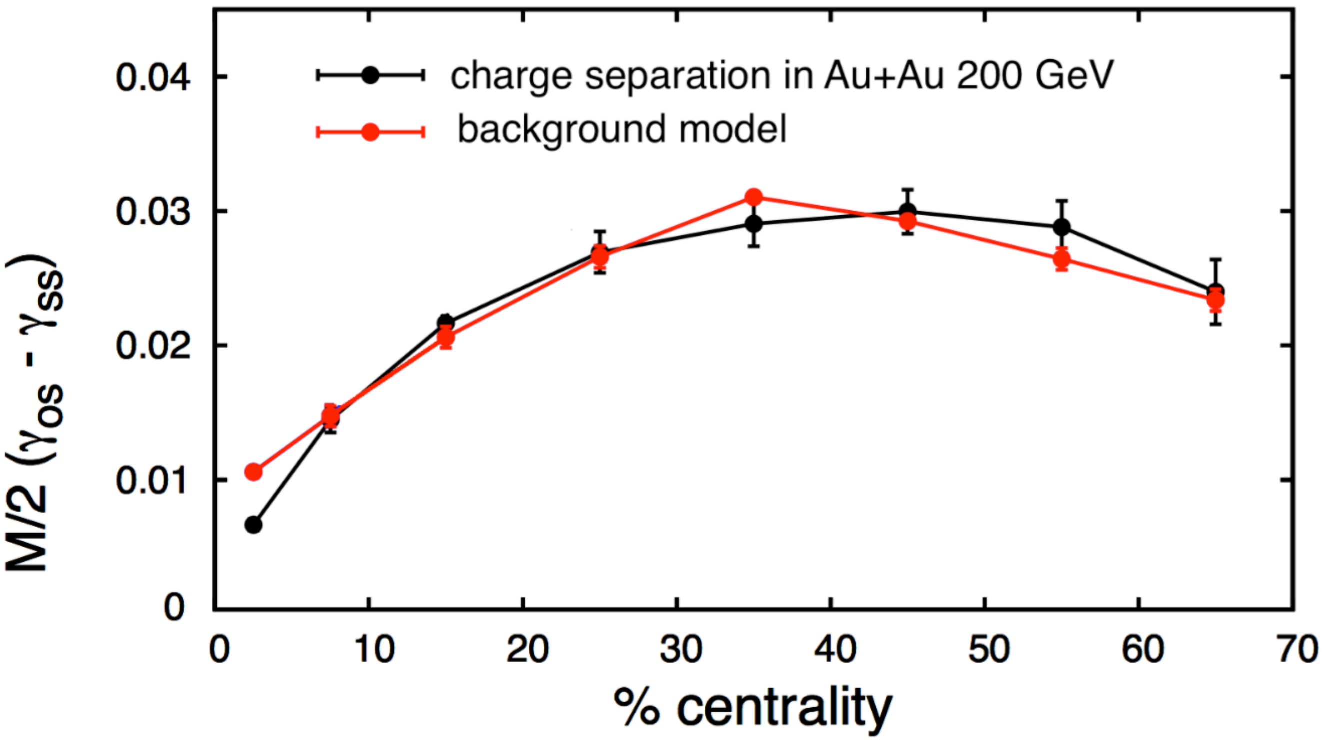


Flow boost collimates pairs more strongly in-plane than out of plane. Most background is driven by flow (v_2)

A. Bzdak, V. Koch, and J. Liao , Lect. Notes Phys. 871, 503 (2013)
S. Pratt, S. Shlichting and S. Gavin, PRC 84 024909 (2011)
S. Schlichting and S. Pratt, PRC 83 014913 (2011)
F. Wang PRC 81 064902 (2010)
A. Tang, Chin. Phys. C 44 No.5 054101 (2020)
…

Chiral Magnetic Effect : Backgrounds

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

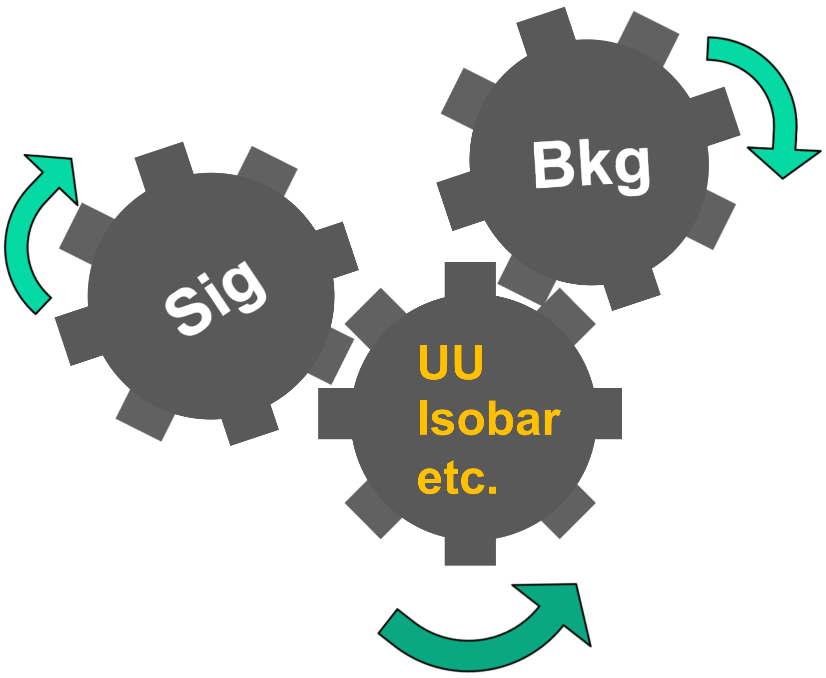


Backgrounds contributions could be comparable in magnitude to measured correlations

Understanding the Background

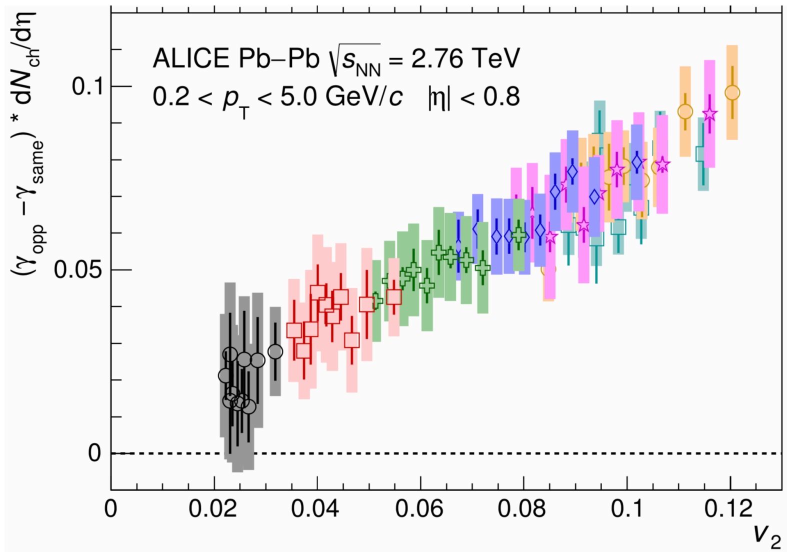
1. Turn off background (event shape engineering, $\Delta\gamma(M_{inv})$).
2. Turn off signal (small system).
3. Vary background only (Ultra-central U+U vs. Au + Au).
4. Vary signal only (Isobaric collisions).

Play with it and learn !



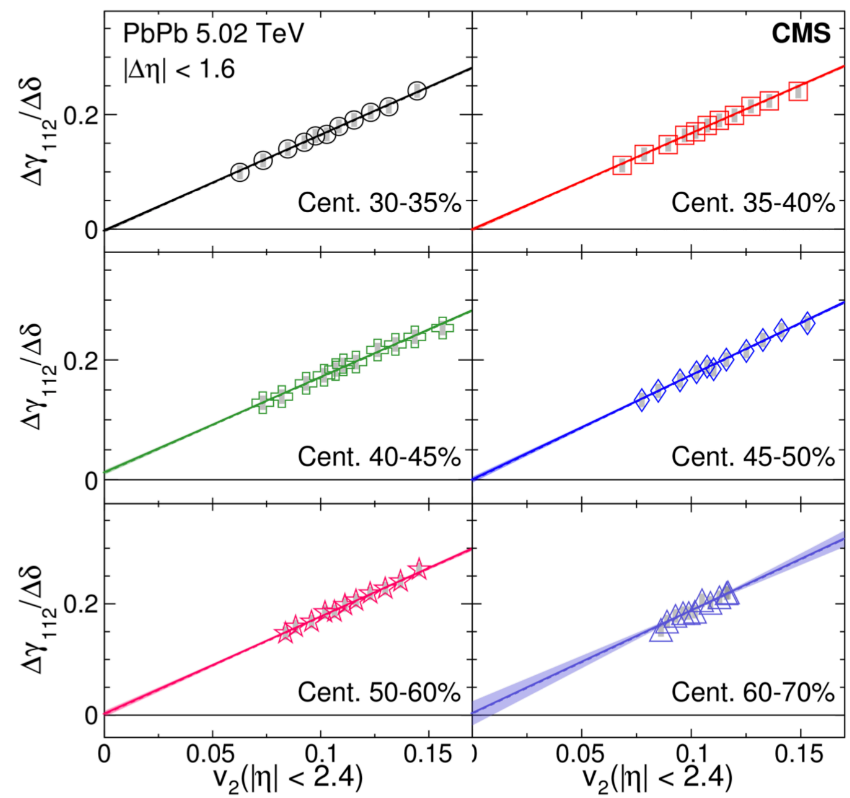
Understanding the Background : Turn off Background

Event Shape Engineering (ESE)



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

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



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

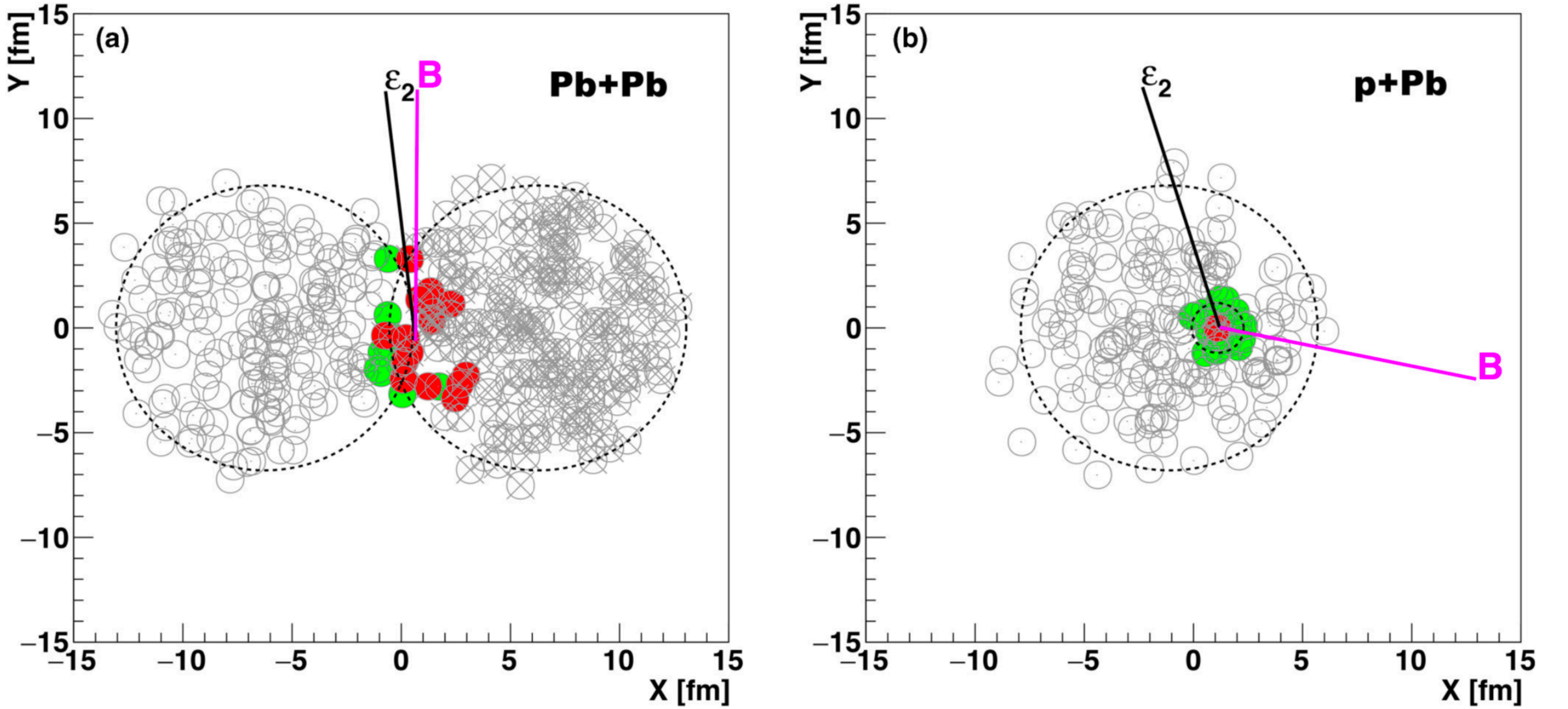
More ref. on ESE and EbyE v_2 method :
J. Schukraft, A. Timmins and S. Voloshin, Phys. Lett. B 719 394 (2013)
STAR, Phys. Rev. C 89 44908 (2014)
F. Wen, J. Bryon, L. Wen and G. Wang. Chin. Phys. C 42 No.. 1 014001 (2018)

Caveat : long projection over empty v_2 space.

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

Understanding the Background : Turn off Signal

Small System

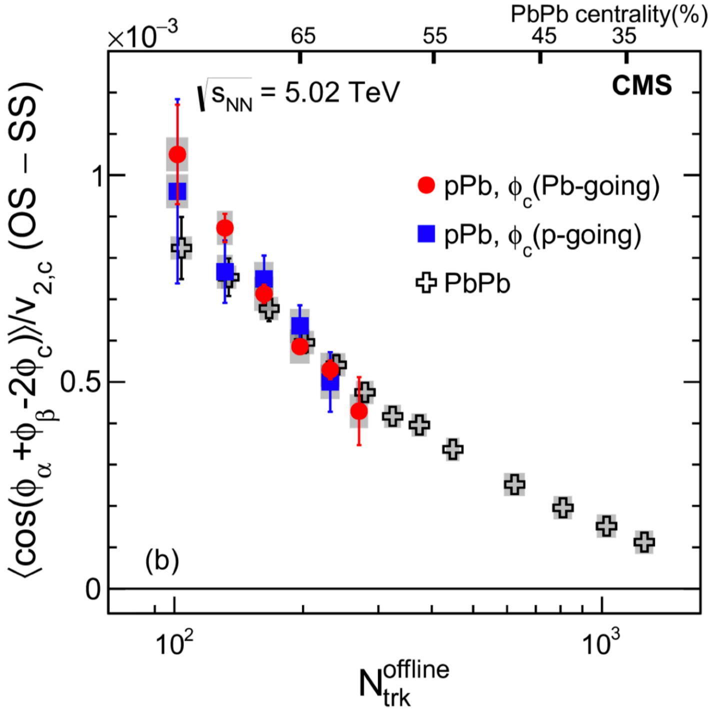


CMS, Phys. Rev. Lett. 118, 122301 (2017)
R. Belmont and J. Nagle, Phys. Rev. C 96 024901 (2017)

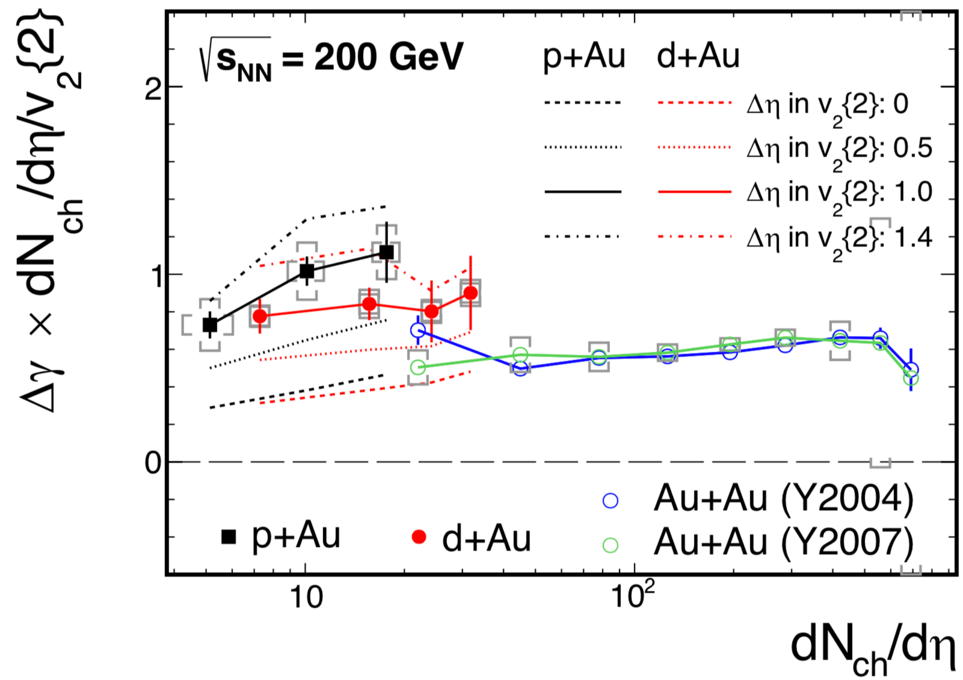
In small systems, B is not correlated with event plane, killing signal

Understanding the Background : Turn off Signal

Small System



CMS, Phys. Rev. Lett. 118, 122301 (2017)



STAR, Phys. Lett. B 798, 134975 (2019)

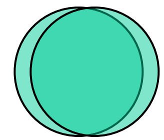
Similarity between large and small system at LHC suggests that background can dominate $\Delta\gamma$.

Open questions/issues remain :
Residual B field in pPb at LHC ? [PRC 97 024905]
RHIC and LHC have different $\Delta\eta$ gap.
Should RP independent background the same between small and large system ?

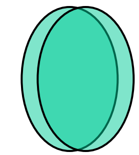
Understanding the Background : Vary Background

(Ultracentral collisions, **Au+Au vs U+U**)

Signal driver (B)	←	**Fixed at ~ 0**
Background driver (v_2)	←	**Vary**

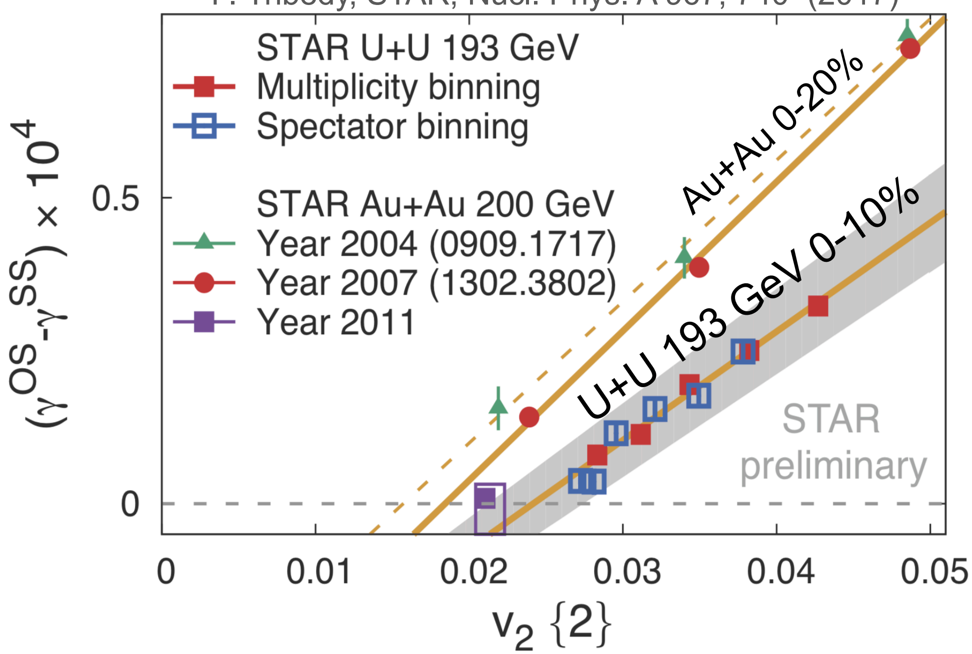


Au+Au (ultracentral)
$\varepsilon_2 \sim 0$, B ~ 0

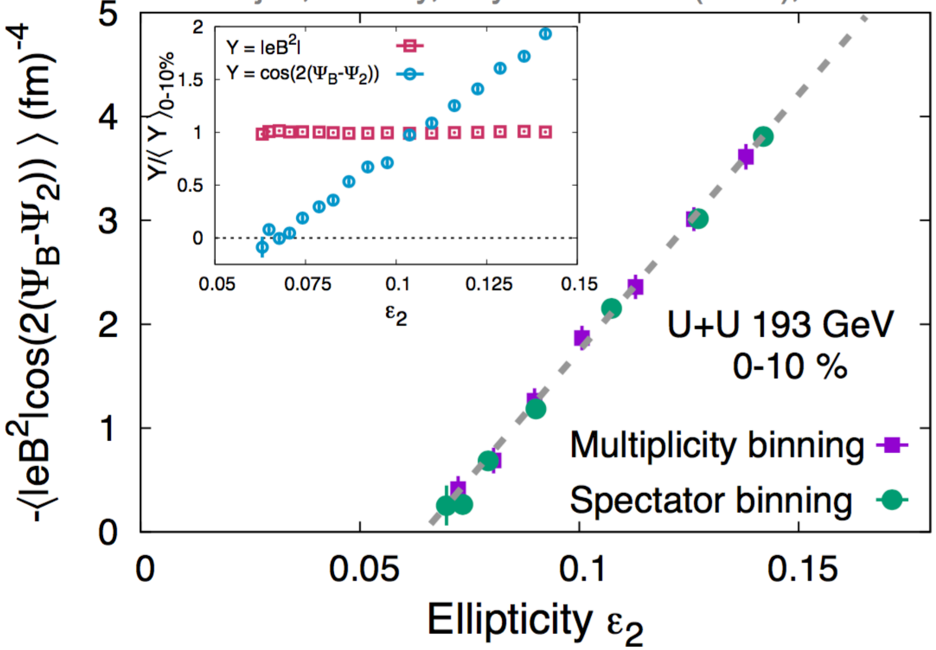


U+U (ultracentral)
$\varepsilon_2 \neq 0$, B ~ 0

P. Tribedy, STAR, Nucl. Phys. A 967, 740 (2017)



Chatterjee, Tribedy, Phys. Rev. C92 (2015), 011902



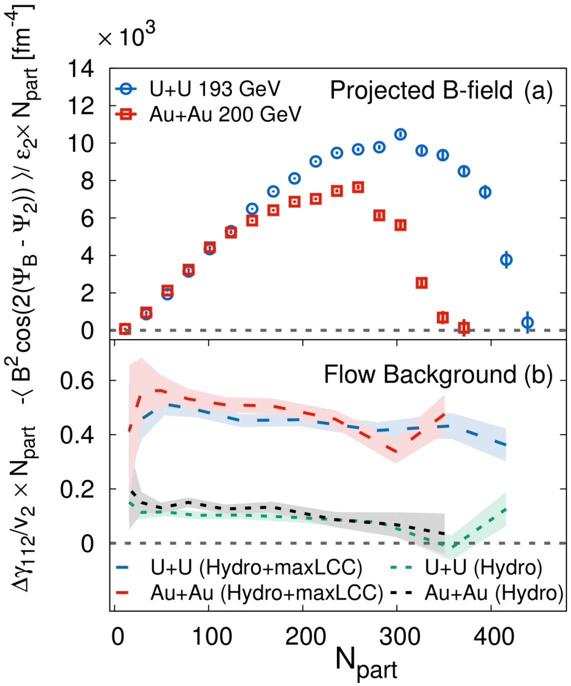
(γ_{os}-γ_{ss}) ~ 0 while v_2 is, 1) finite, and 2) larger in U+U than in Au+Au

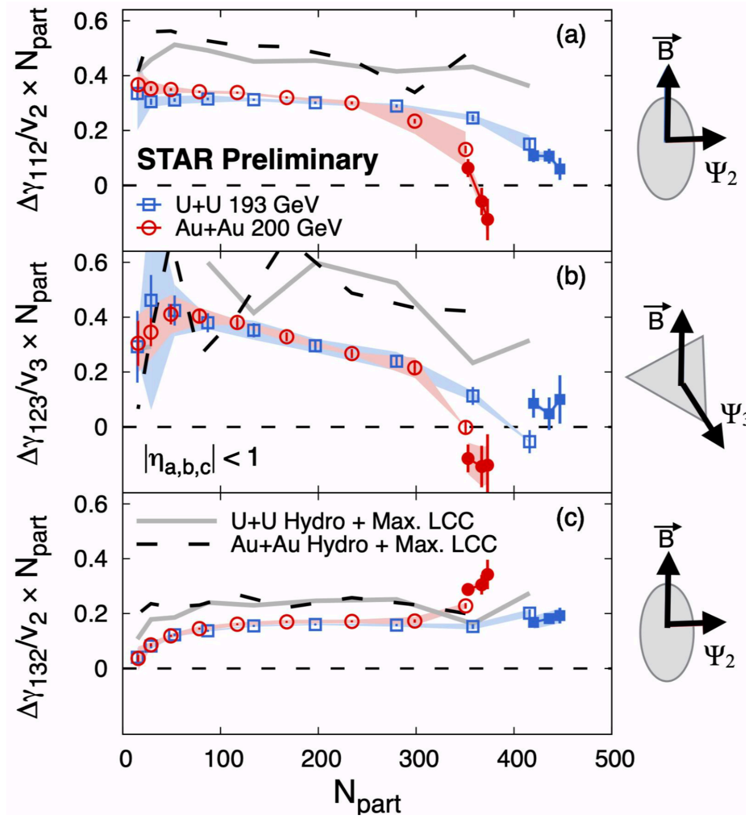
(γ_{os}-γ_{ss}) and the effective B has similar dependency on anisotropy

Not consistent with the existing understanding of background such as LCC

Note : The analysis depends on pseudorapidity separation of two particles.

More on U + U collisions





$\gamma_{112} = \langle \cos(1\phi_\alpha + 1\phi_\beta - 2\Psi_2) \rangle$

Sig + bkg.

$\gamma_{123} = \langle \cos(1\phi_\alpha + 2\phi_\beta - 3\Psi_3) \rangle$

Bkg. only

$\gamma_{132} = \langle \cos(1\phi_\alpha + 3\phi_\beta - 2\Psi_2) \rangle$

Bkg. dominant

B-fields : U + U ≠ Au + Au
Backgrounds : U + U ~ Au + Au

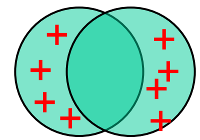
P. Tribedy for STAR, WWND 2020

Also not consistent with signal-only explanation.
Needs further investigations.

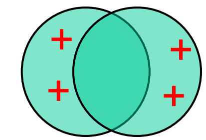
Understanding the Background : Vary signal

(**Isobar collisions**)

Signal driver (B)	←	**Vary**
Background driver (v_2)	←	**Fixed**

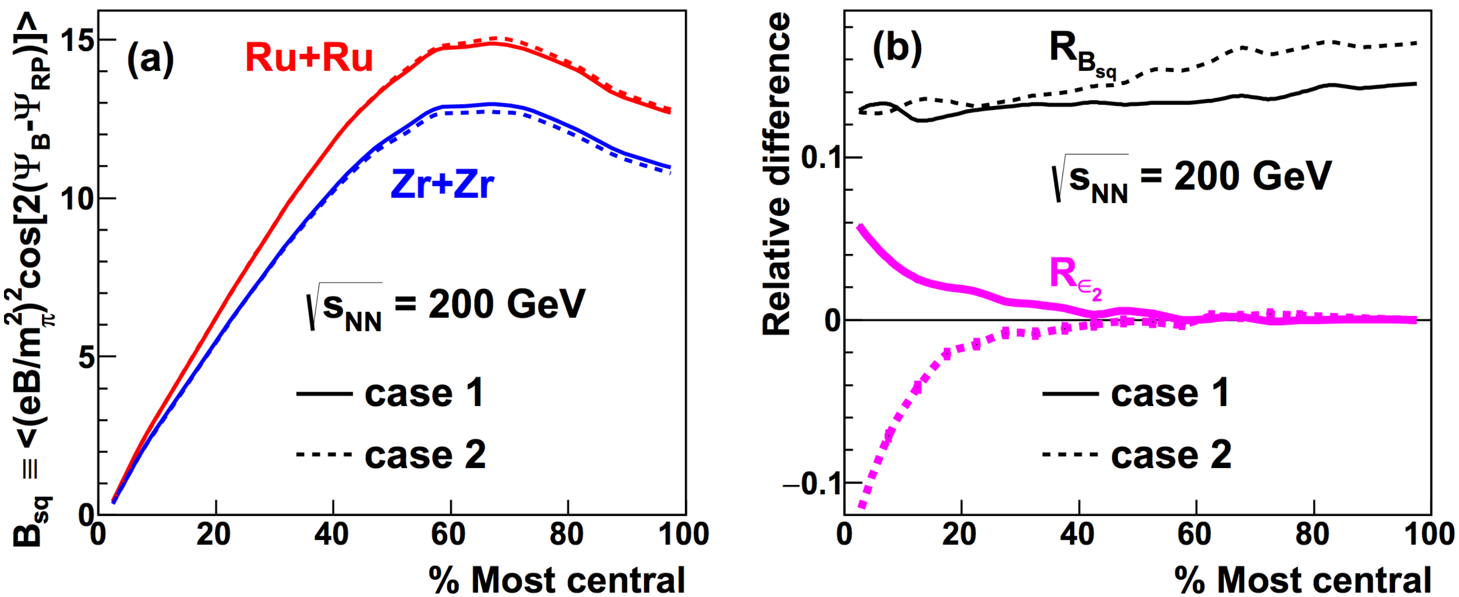


midcentral



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

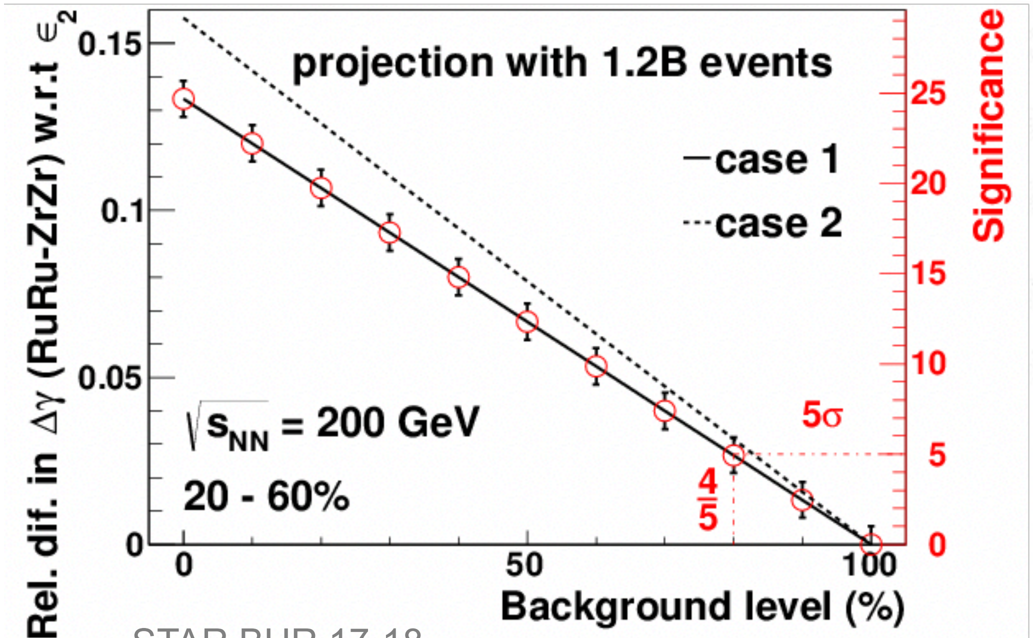
ε_2 (Ru+Ru) ~ ε_2 (Zr+Zr)
B (Ru+Ru) > B (Zr+Zr)



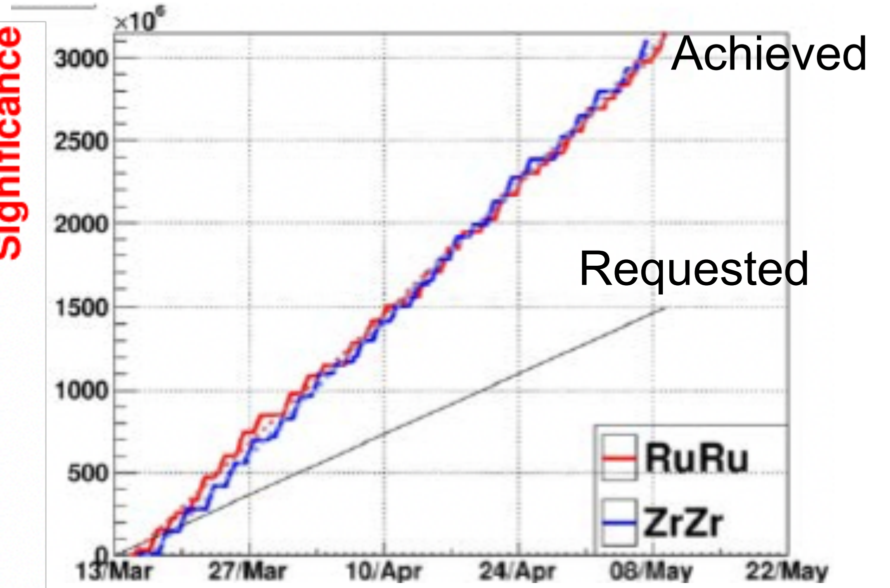
W. Deng, X-G. Huang G. Ma and G. Wang, PRC 94 041901 (2016)

Isobaric collisions : great potential for checking signal response.

Isobar Data Taking at RHIC



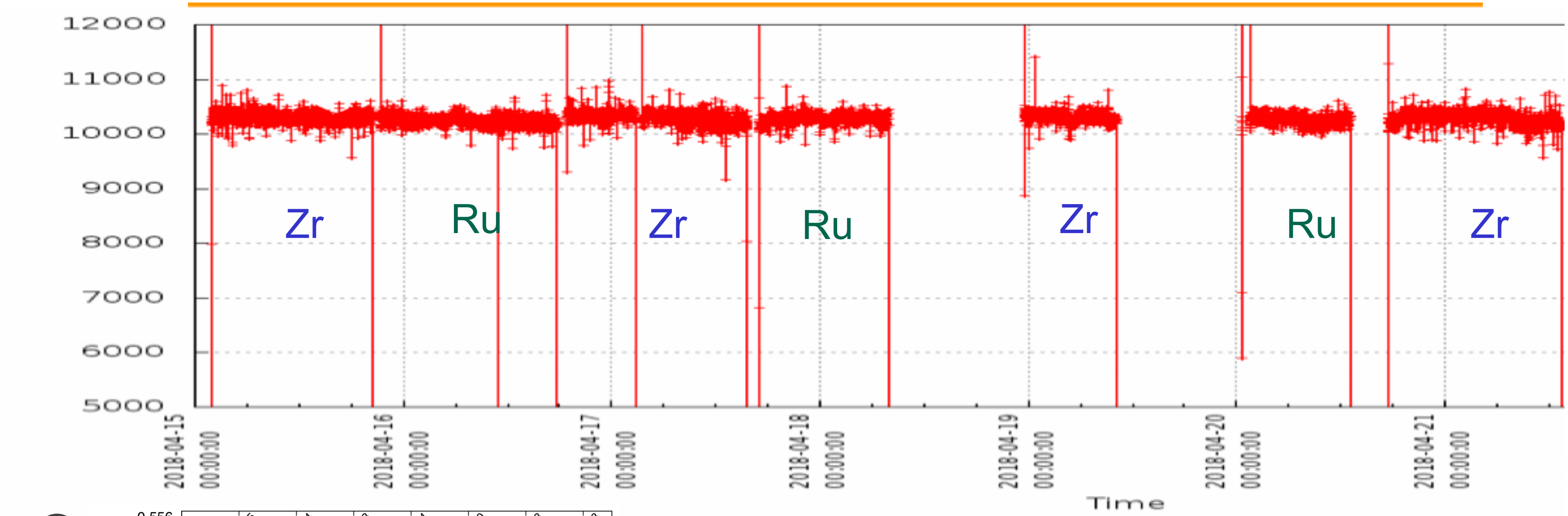
STAR BUR 17-18



5σ difference in $\Delta\gamma$ if bkg. is at ~80% level

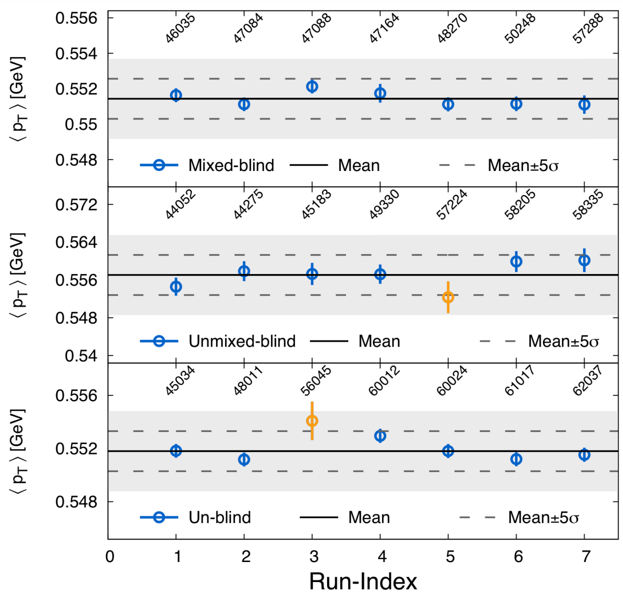
Took more than requested. (3B each)

Isobar Data Taking at RHIC



J-H Lee for STAR, RHIC/AGS Mtg 2018

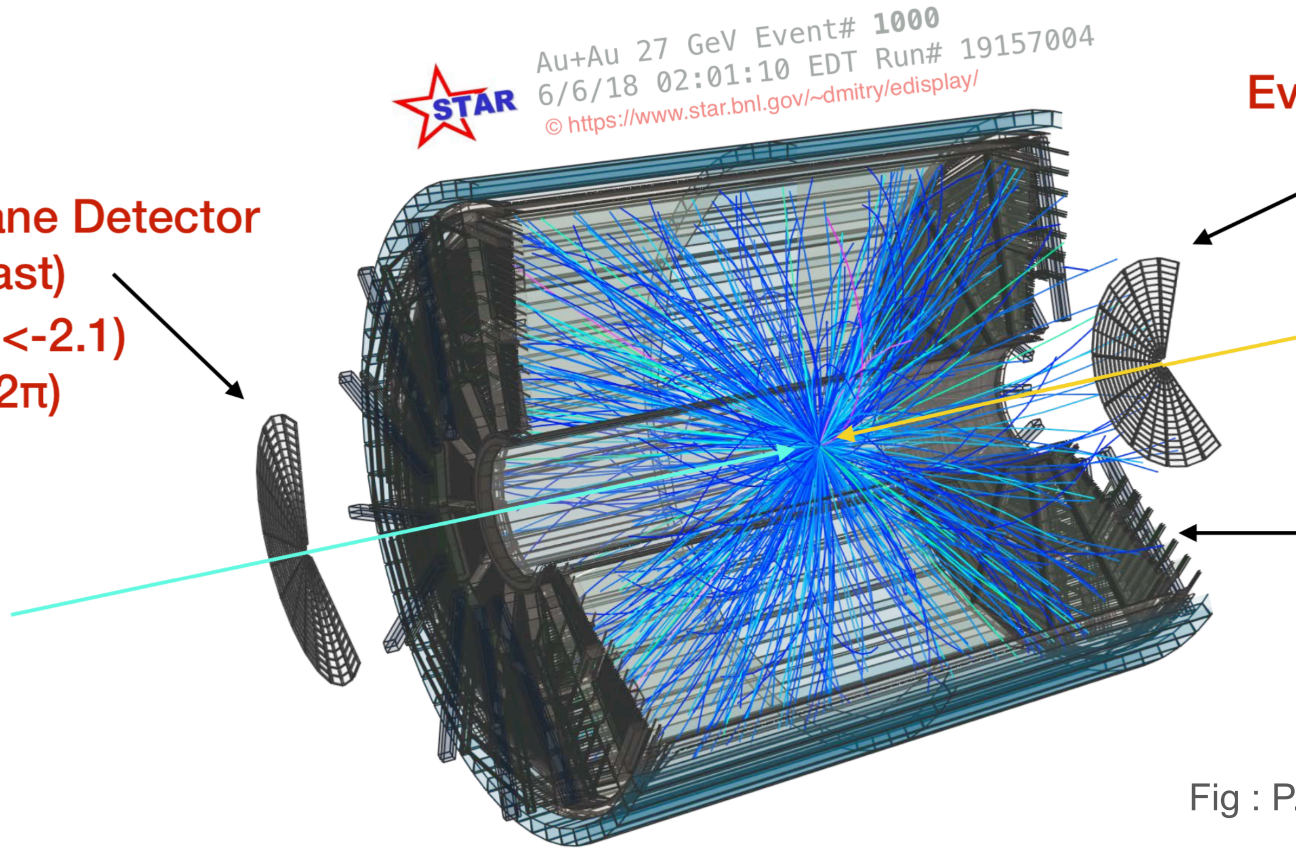
STAR, arXiv:1911.00596 (2019)



Interleaved fills for isobar species to minimize systematics.

Good data set taken with very smooth running condition.

Event Plane Detector



Event Plane Detector (East)
($-5.1<\eta<-2.1$)
($0<\phi<2\pi$)

Event Plane Detector (West)
($2.1<\eta<5.1$)
($0<\phi<2\pi$)

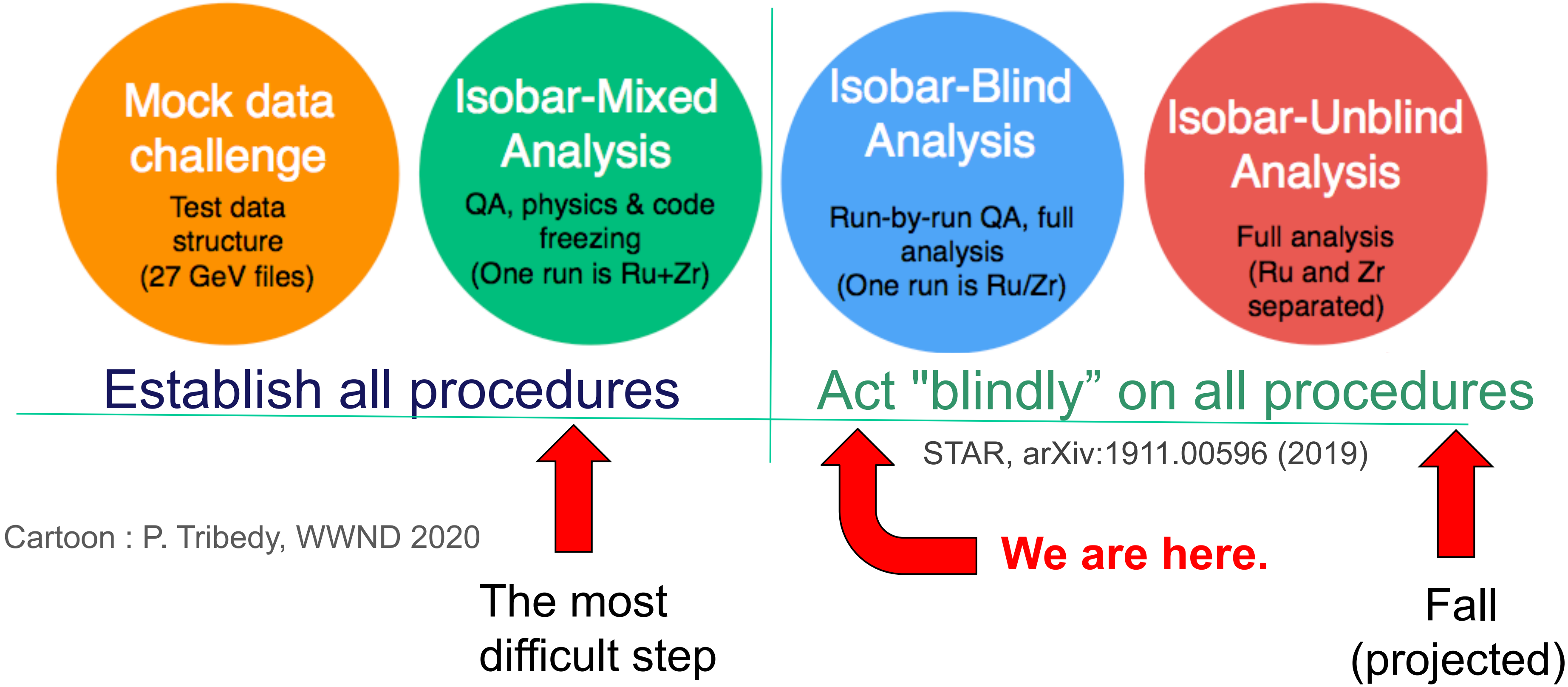
Time Projection Chamber
($-1<\eta<1$)
($0<\phi<2\pi$)

Fig : P. Tribedy, WWND 2020

Full azimuthal coverage
Large separation in η between TPC and EPD

J. Adams et al. Nucl. Instrum. Meth. A 968 (2020)

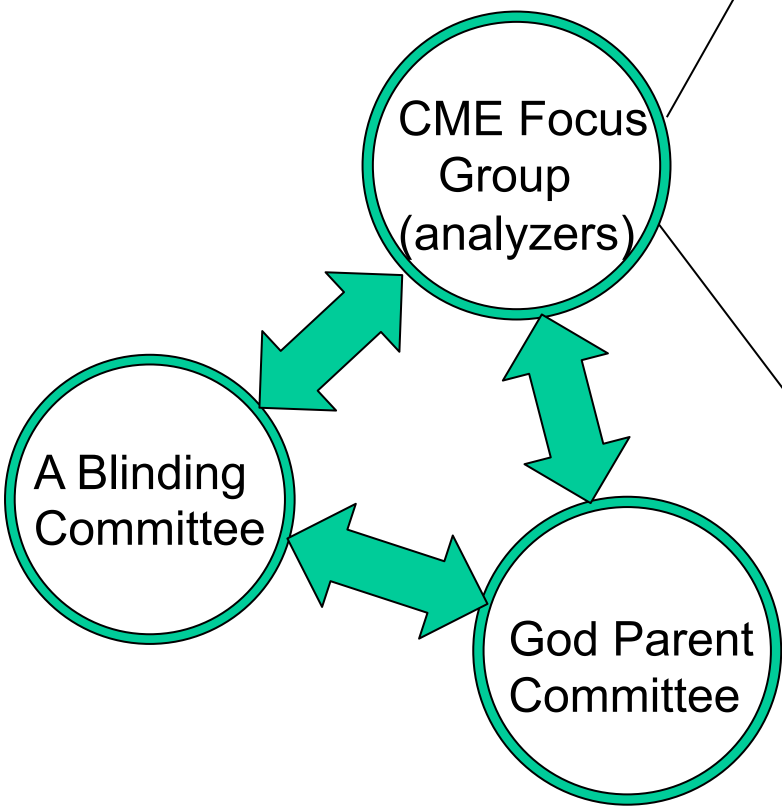
Isobar Blind Analysis : Procedure



- Program Advisory Committee Recommendation:
  - The PAC strongly recommends that any STAR publication regarding CME observables should contain the result after unblinding and without any additional corrections applied after unblinding that are deemed necessary by STAR. If such additional corrections are needed, then a paper containing both the unblinded and post-unblinded results should be published for reference in papers reporting the isobar data.

Isobar Analyses (5+1) in STAR

A large, collective effort



Blind analyses (5 groups):

- $\Delta\gamma$, $\Delta\delta$, and κ.
- $\Delta\gamma$, $\Delta\delta$, $\Delta\gamma(\Delta\eta)$.
- $\Delta\gamma$ in PP/SP, $\Delta\gamma(M_{inv})$.
- $\Delta\gamma$ in PP/SP.
- $R(\Delta S)$ Correlator.

No-Blind analysis (1 group):

- Signed Balance Function.

BNL, CCNU, Fudan, Huzhou, Purdue, SINAP, Stony Brook, Tsukuba, UCLA, UIC, Wayne State

Challenges :

- Coordination and synchronization. (among groups, as well as between groups and committees).
- Unify procedures in common.
- Identify run-by-run abnormalities before hand without actual seeing them.

……

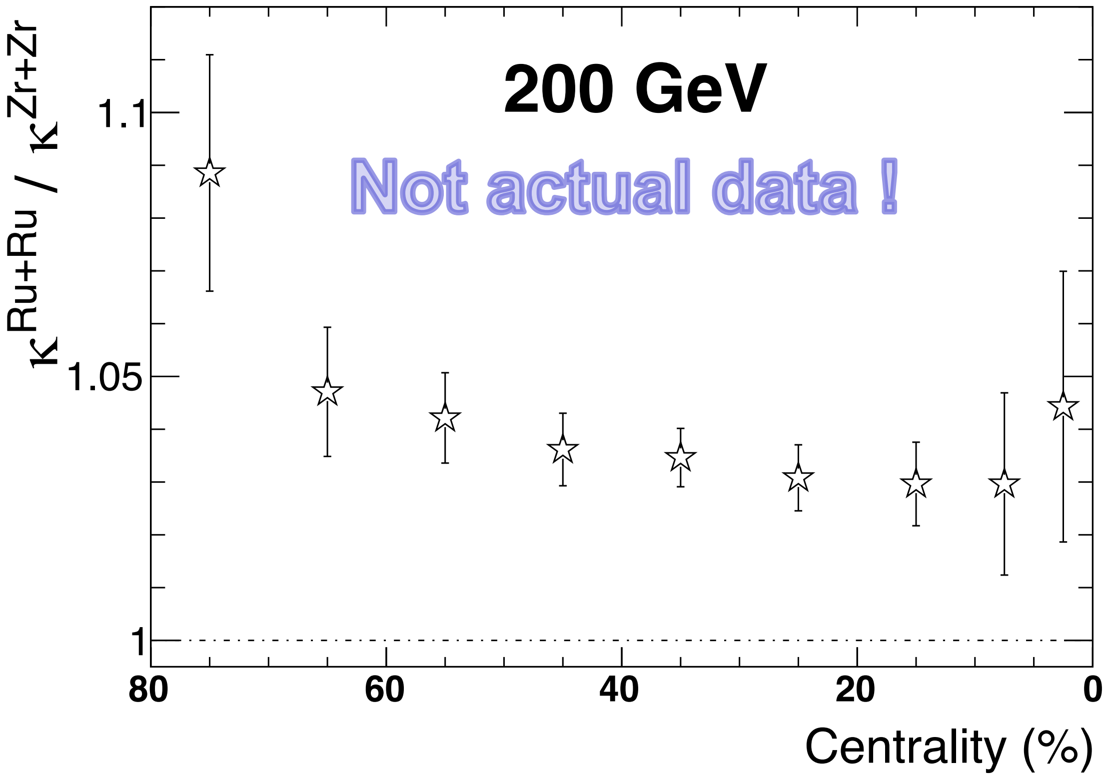
Isobar Analysis (Grp 1) : $\Delta\gamma$ and $\Delta\delta$

$\gamma = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$

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

When there is pure background, $\Delta\gamma \sim \Delta\delta \cdot v_2$,

motivates $\kappa \equiv \frac{\Delta\gamma}{\Delta\delta \cdot v_2}$



Case for CME :

κ (Ru / Zr) > 1

Test isobar systems with pure background assumption.

S. Voloshin, Phys. Rev. C 70 057901
A. Bzdak, V. Koch, J. Liao Lect. Notes Phys. 871 503 (2013)
S. Shi, H. Zhang, D. Hou, and J. Liao arXiv : 1910.1401
+ many others

Isobar Analysis (Grp 1) : $\Delta\gamma$ and $\Delta\delta$

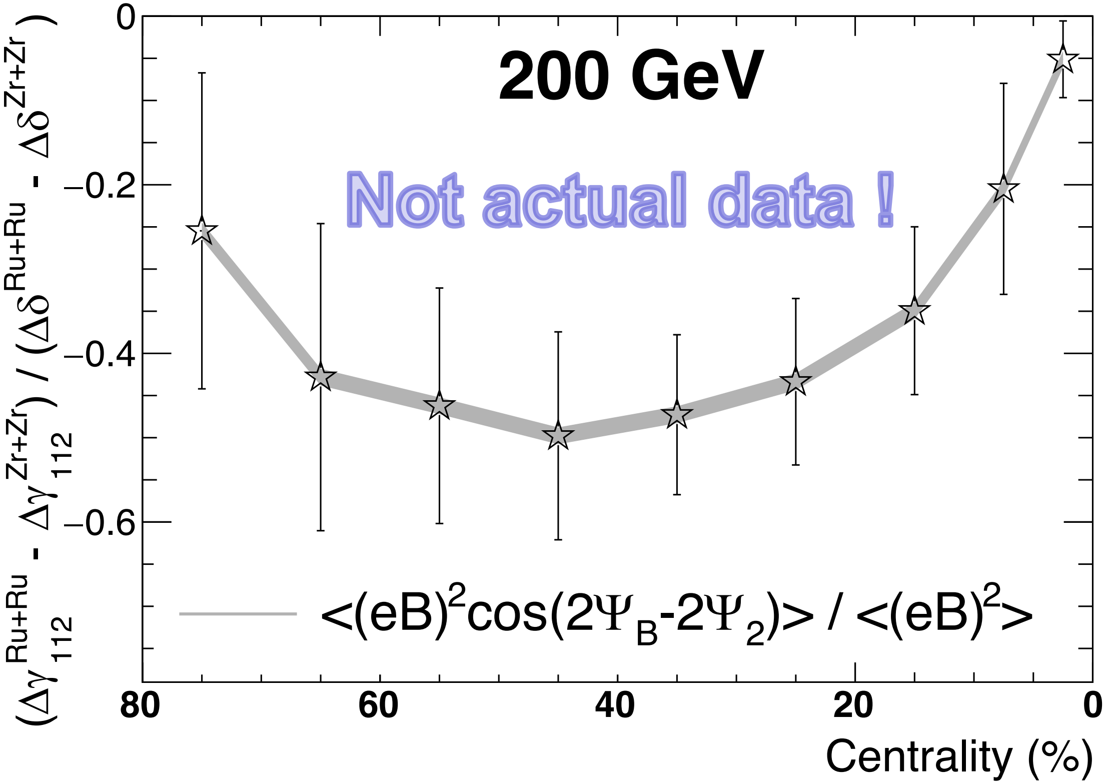
$\gamma = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$

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

When there is pure signal,

$\Delta\gamma \sim 2\langle a_1^2 \cos(2\Psi_B - 2\Psi_{EP}) \rangle$

$\Delta\delta \sim -2\langle a_1^2 \rangle$,



motivates $\rightarrow$ $\dfrac{\Delta\gamma\{Ru-Zr\}}{\Delta\delta\{Ru-Zr\}}$

$\left.\dfrac{\Delta\gamma\{Ru-Zr\}}{\Delta\delta\{Ru-Zr\}}\right|_{v_2} \approx \langle \cos(2\Psi_B - 2\Psi_{EP}) \rangle$ [1]

Case for CME :

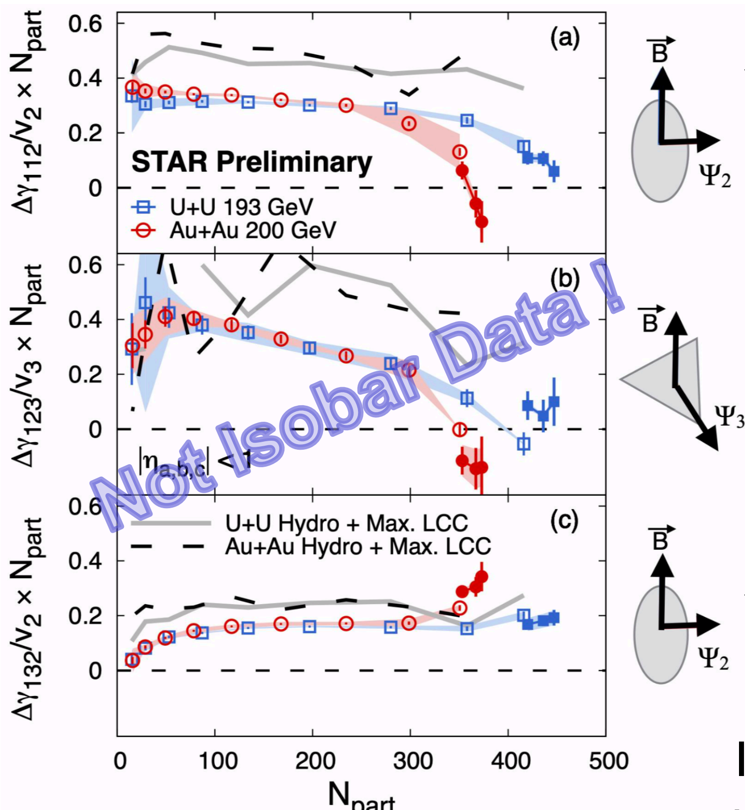
κ (Ru / Zr) > 1

Check isobar systems with a relatively clean ratio

S. Voloshin, Phys. Rev. C 70 057901
A. Bzdak, V. Koch, J. Liao Lect. Notes Phys. 871 503 (2013)
S. Shi, H. Zhang, D. Hou, and J. Liao arXiv : 1910.14010
+ many others

[1]Assume same v_2, which can be attempted by event shape selection.

Isobar Analysis (Grp 2) : $\Delta\gamma$ and $\Delta\delta$



P. Tribedy for STAR, WWND 2020

$\gamma_{112} = \langle \cos(1\phi_\alpha + 1\phi_\beta - 2\Psi_2) \rangle$

Sig + bkg.

$\gamma_{123} = \langle \cos(1\phi_\alpha + 2\phi_\beta - 3\Psi_3) \rangle$

Bkg. only

$\gamma_{132} = \langle \cos(1\phi_\alpha + 3\phi_\beta - 2\Psi_2) \rangle$

Bkg. dominant

In addition the $\Delta\boldsymbol{\eta}$ dependence of $\Delta\boldsymbol{\gamma}$ will be explored.

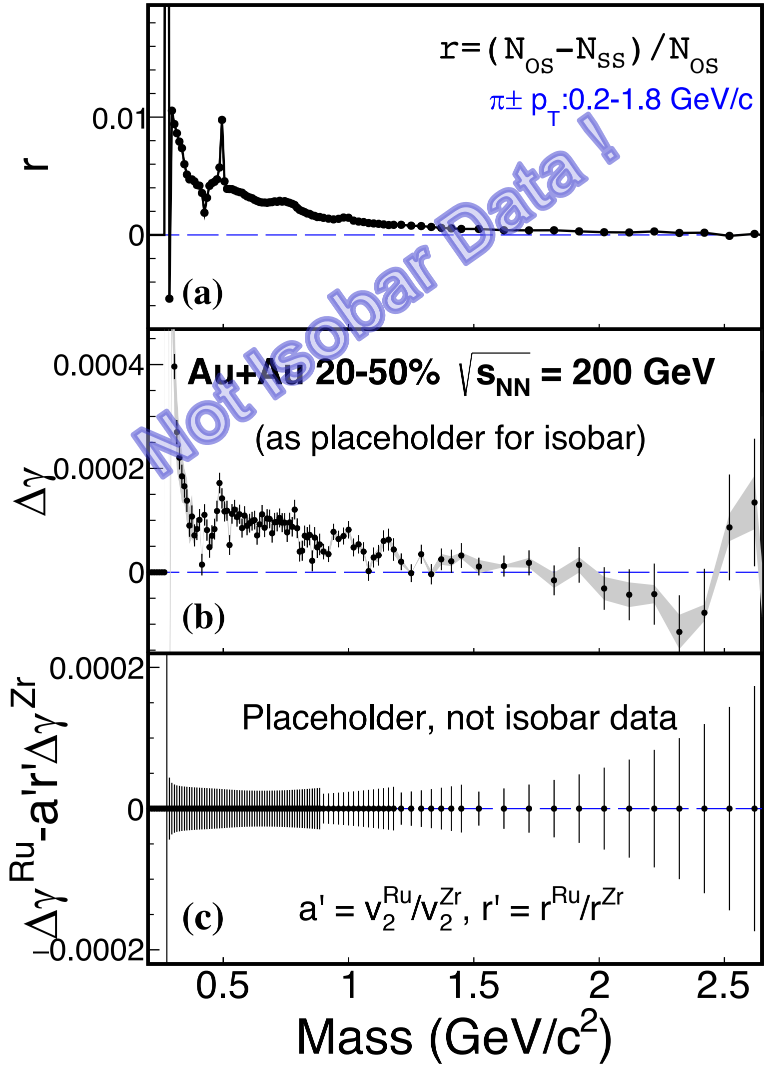
Case for CME :

$\Delta\gamma_{112}/v_2$ (Ru / Zr) > 1

$\Delta\gamma_{112}/v_2$ (Ru / Zr) > $\Delta\gamma_{123}/v_3$ (Ru / Zr)

$\Delta\gamma_{112}/v_2$ (Ru / Zr) > $\Delta\delta$ (Ru / Zr)

Isobar Analysis (Grp 3) : $\Delta\gamma(M_{inv})$



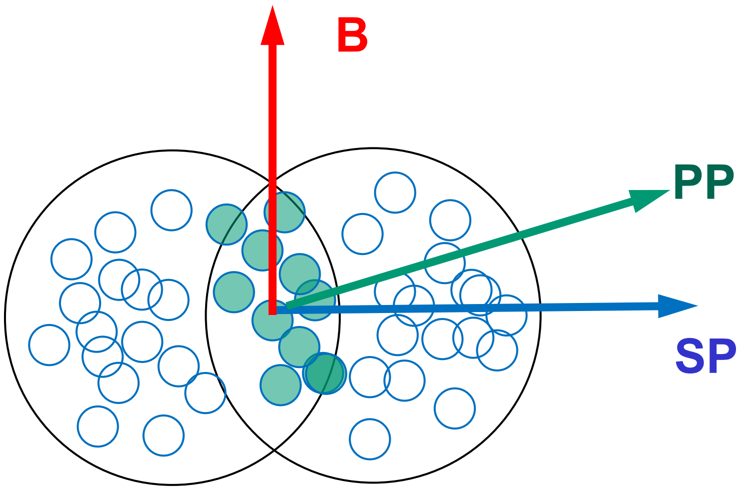
$$\Delta\gamma\,(m_{inv}) = r(m_{inv})\langle\cos(\phi_\alpha + \phi_\beta - 2\phi_{reso.})\rangle\, v_{2,reso.} + \Delta\gamma_{\,CME}$$

Case for CME :

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

Different shape from inclusive $\Delta\gamma$

Isobar Analysis (Grp 3) : Participant Plane (PP) / Spectator Plane (SP)



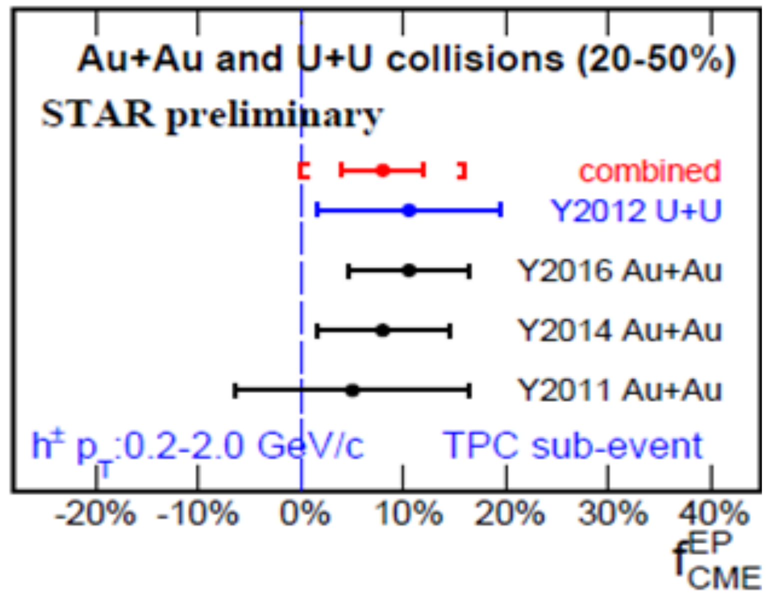
$$\Delta\gamma = \Delta\gamma^{sig} + \Delta\gamma^{bg}$$

PP : maximum background

$$\Delta\gamma^{bg}\{PP\} = \frac{\Delta\gamma^{bg}\{SP\}}{a}$$

SP : maximum signal

$$\Delta\gamma^{sig}\{SP\} = \frac{\Delta\gamma^{sig}\{PP\}}{a}$$



J. Zhao for STAR, QM 2019
arXiv:2002:09410

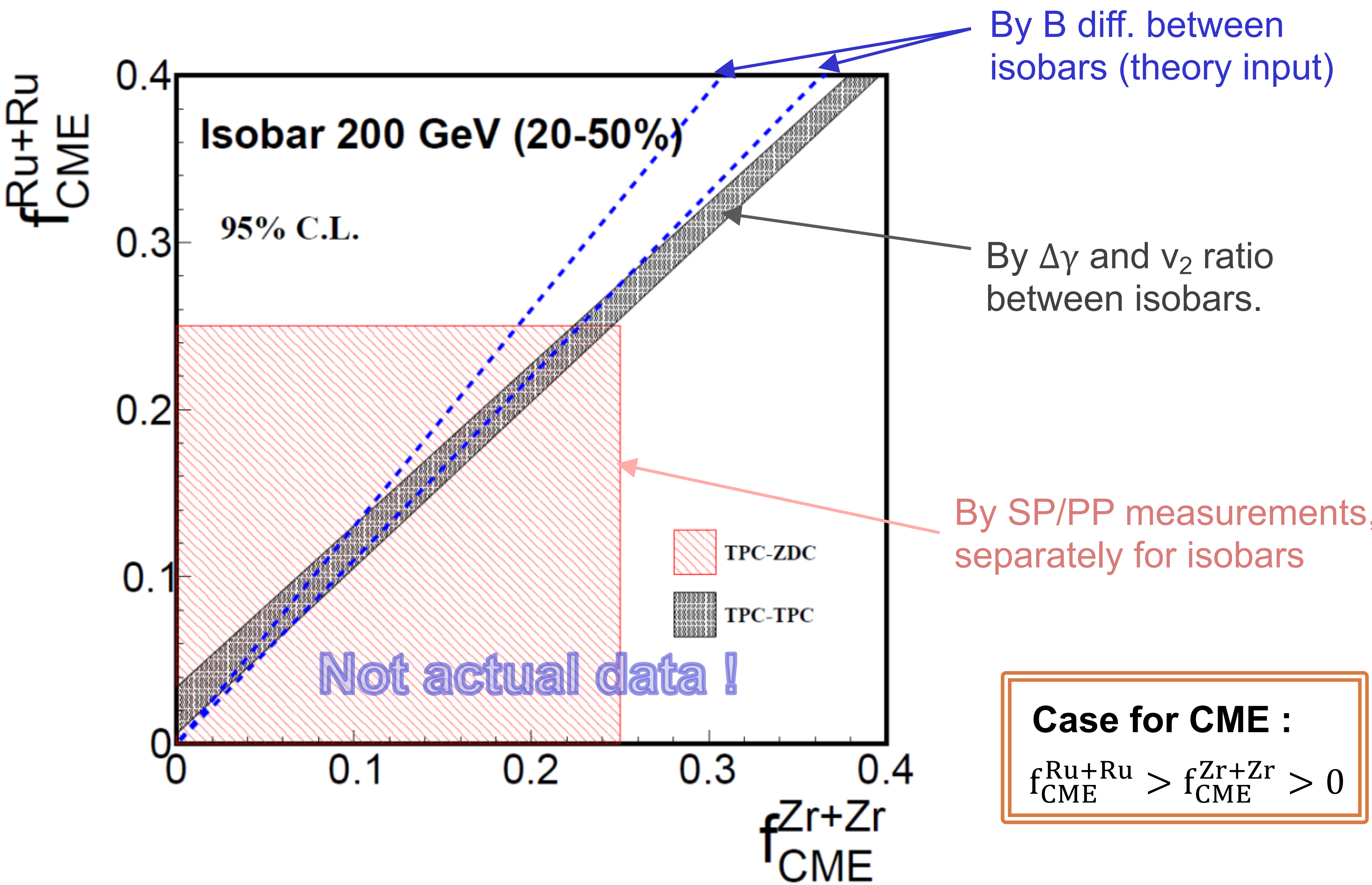
$$f_{CME}^{PP} = \frac{\frac{\Delta\gamma\{SP\}}{\Delta\gamma\{PP\}}/a - 1}{1/a^2 - 1}$$

$$a = \langle\cos 2(\Psi_{PP} - \Psi_{SP})\rangle \approx \frac{v_2^{ZDC}}{v_2^{TPC}} < 1$$

H-J. Xu et al., Chin. Phys. C 42 084103 (2018)

Flow bkg is usually positively correlated with signal ➡ Difficult to disentangle.
This troublesome pattern can be broken by switching between PP and SP.

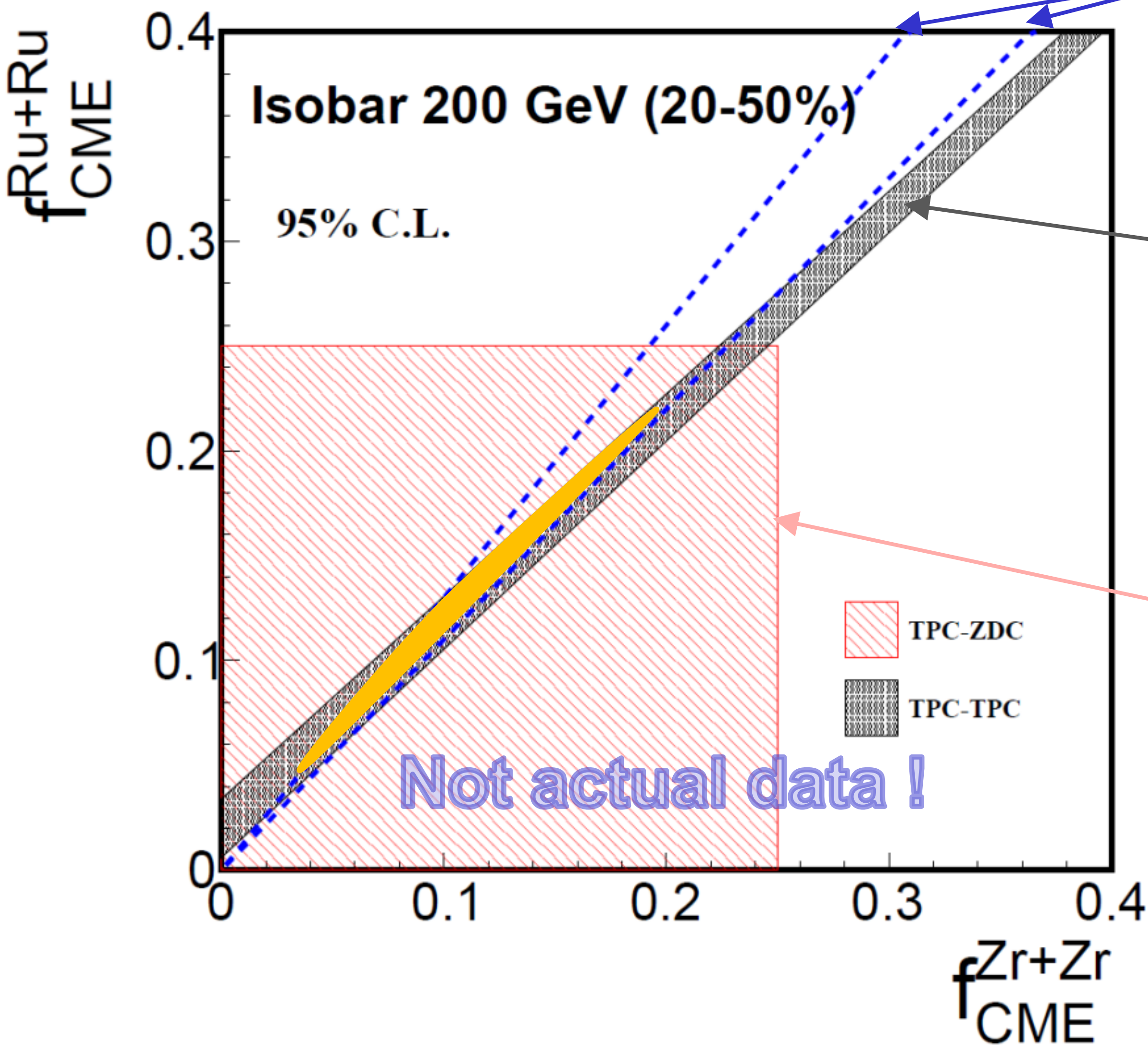
Isobar Analysis (Grp 3) : Participant Plane (PP) / Spectator Plane (SP)



Case for CME :

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

Isobar Analysis (Grp 3) : Participant Plane (PP) / Spectator Plane (SP)



By B diff. between isobars (theory input)

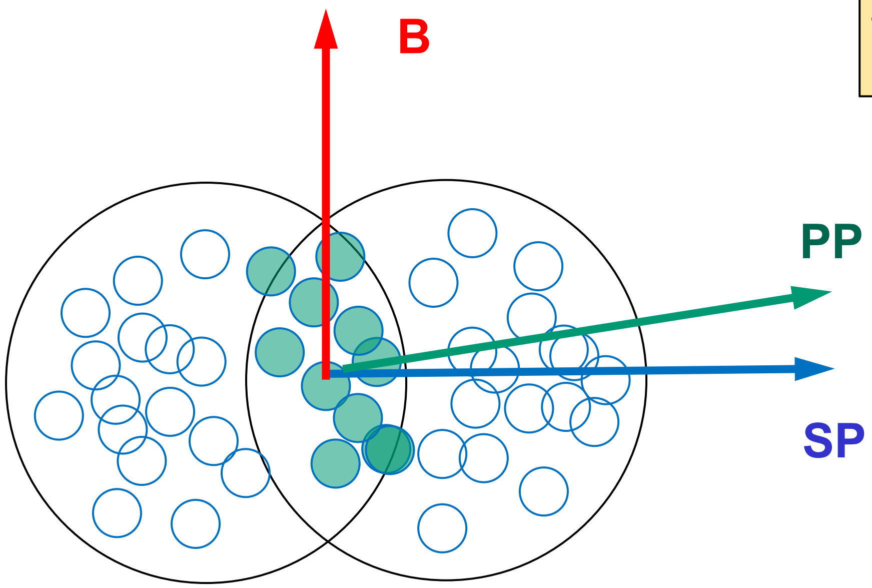
By $\Delta\gamma$ and v_2 ratio between isobars.

By SP/PP measurements, separately for isobars

Case for CME :

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

Isobar Analysis (Grp 4) : Participant Plane (PP) / Spectator Plane (SP)



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

f is the fraction of CME signal

PP : maximum background

SP : maximum signal

Case for CME : $\Delta\gamma/v_2$ (Ru / Zr) > 1

Flow bkg is usually positively correlated with signal ➡ Difficult to disentangle.
This troublesome pattern can be broken by switching between PP and SP.

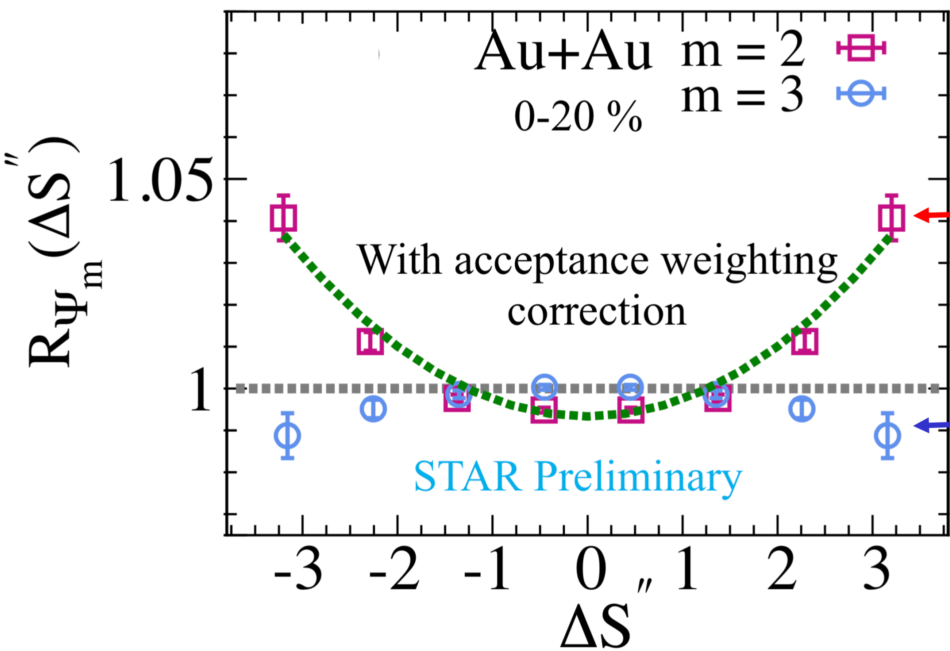
S. Voloshin, Phys. Rev. C 98 054911 (2018)

Isobar Analysis (Grp 5) : R(ΔS) Correlator

1) EbyE out-of-plane v_1 difference between +/- charge ΔS.

2) Removal of trivial contribution $C(\Delta S) = \frac{N_{real}(\Delta S)}{N_{shuffled}(\Delta S)}$

3) Look for out-of-plane excess $R(\Delta S) = \frac{C^{\perp}(\Delta S)}{C(\Delta S)}$



4) Repeat with Ψ_3 EP for baseline.

Signal, U-shape

Background

N. Magdy, S. Shi, J. Liao, N. Ajitanand and R. Lacey Phys. Rev. C 97 061901 (2018)

N. Magdy for STAR, WWND 2019

Isobar Analysis (Grp 5) : R(ΔS) Correlator

1) EbyE out-of-plane v_1 difference between +/- charge ΔS.

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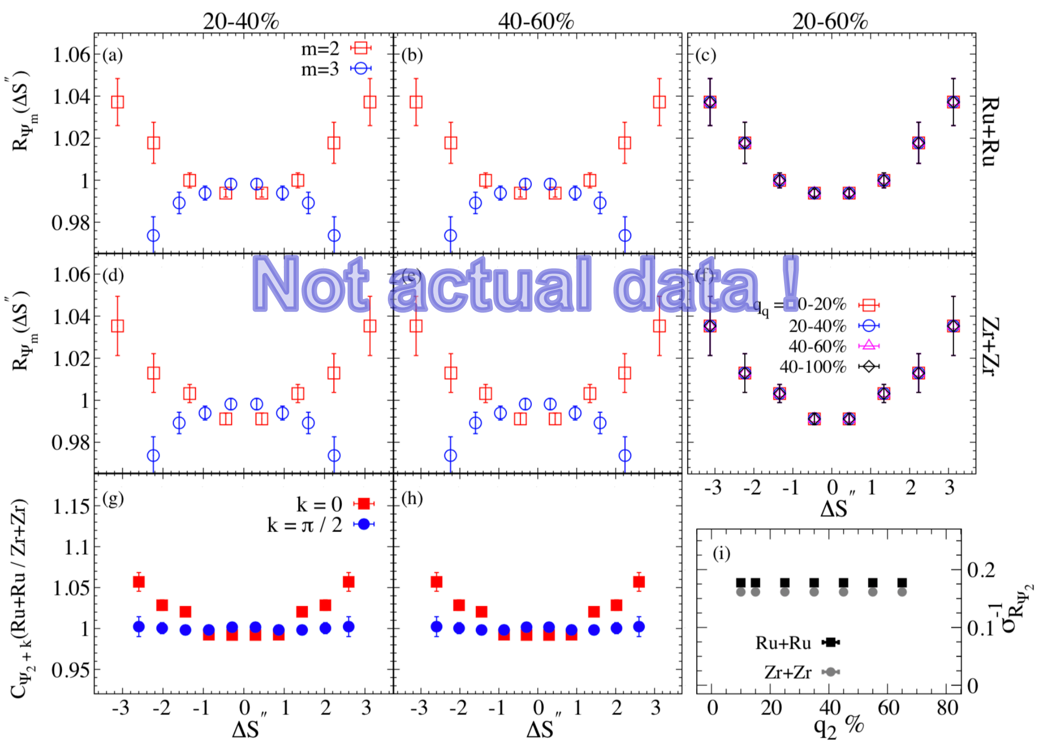


4) Repeat with Ψ_3 EP for baseline.

Intend to measure :
Sig. & bkg from each isobar.
Difference in sig. & bkg between isobars.

Case for CME :
R (Ru / Zr) concave shape

N. Magdy, S. Shi, J. Liao, N. Ajitanand and R. Lacey Phys. Rev. C 97 061901 (2018)

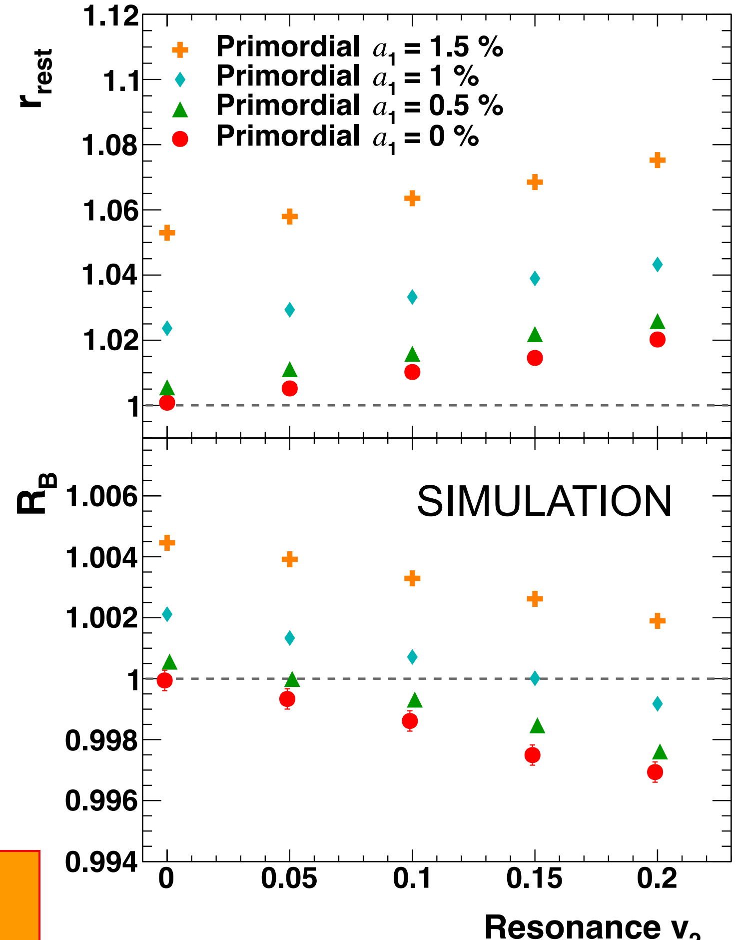
Isobar Analysis (Grp 6) : Signed Balance Function

1) EbyE count +/- pair's momentum ordering in in- and out-of-plane direction.

2) EbyE count net-ordering ΔB.

3) Excess ΔB fluct. out-of-plane $r = \frac{\sigma_{\Delta B}^{\perp}}{\sigma_{\Delta B}}$

4) Rest frame enhancement $R_B = \frac{r_{rest}}{r_{lab}}$



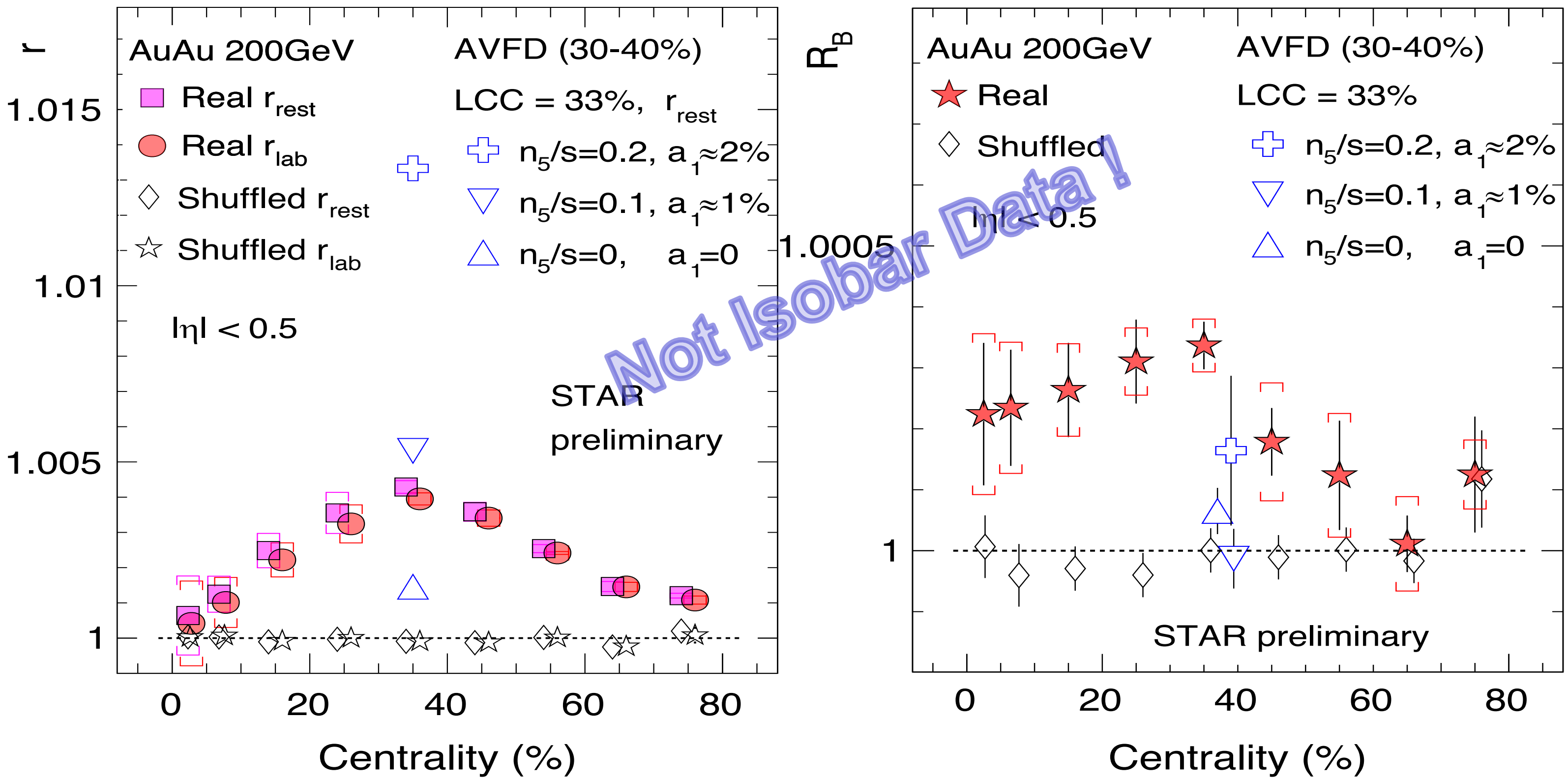
A. Tang, Chin. Phys. C 44 No.5 054101 (2020)

Resonance daughters have no v_2 in rest frame ➡ r_{rest} tends to closer to 1 than r_{lab}.

r and R_B : Similar response to signal, opposite response to bkg.

Not participated in blind analyses

Isobar Analysis (Grp 6) : Signed Balance Function

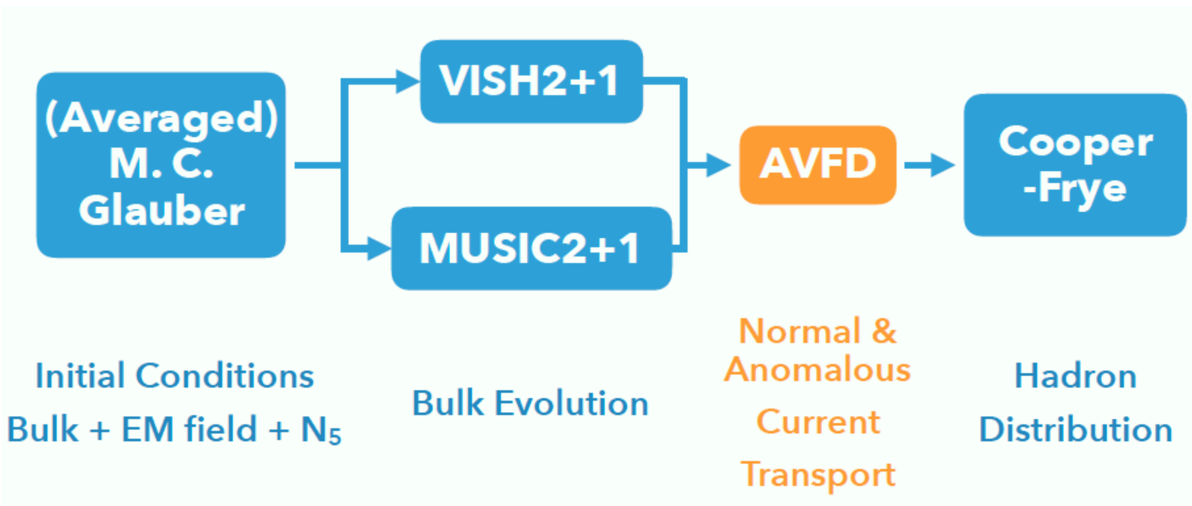


Y. Lin for STAR, QM 2019

Case for CME : $r > 1$, $R_B > 1$
r (Ru / Zr) > 1
R_B (Ru / Zr) > 1

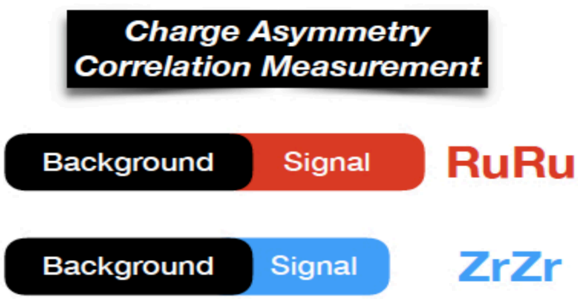
Not participated in blind analyses

Observable's Response to Signal in AVFD



AVFD Version Beta 1.0

The initial state fluctuations are fully accounted for by event-wise sampling for bulk entropy density and the fermion axial charge density (n_5/s).

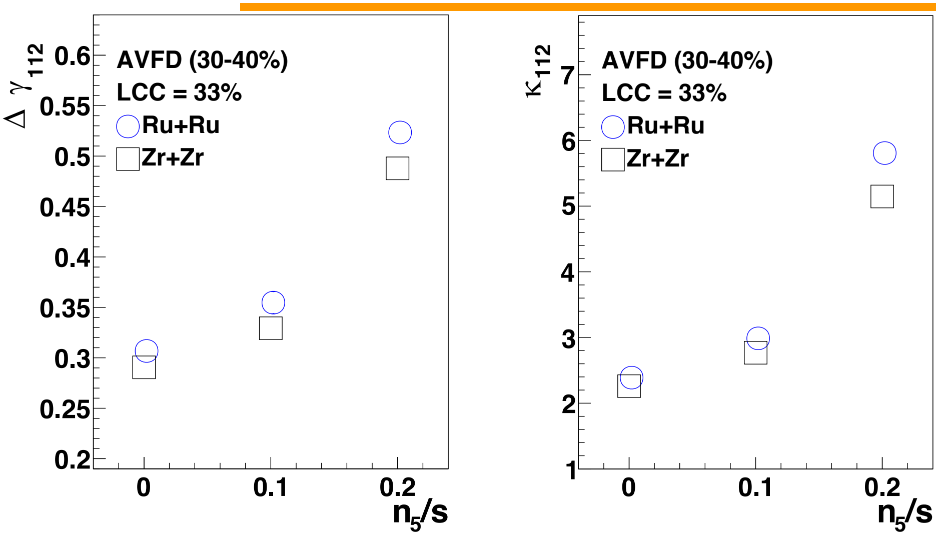


	$n_5/s=0$	$n_5/s=0.10$	$n_5/s=0.2$
Ru	$a_1 = 0$	$a_1 \approx 0.75\%$	$a_1 \approx 1.49\%$
Zr	$a_1 = 0$	$a_1 \approx 0.69\%$	$a_1 \approx 1.38\%$

Three cases of AVFD evts are generated for each isobar.

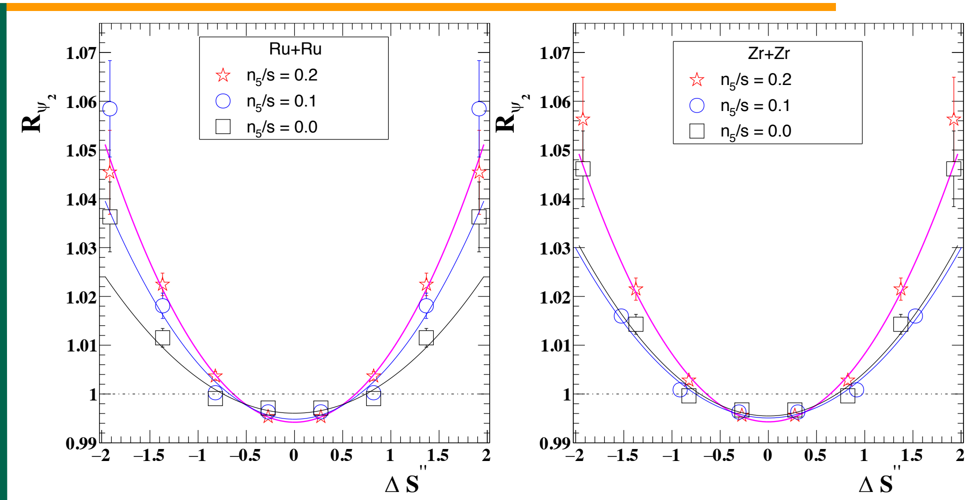
1st generation (smooth initial condition, no bkg.):
S. Shi, Y. Jiang, E. Lilleskov and J. Liao. Annals of Physics 394 *50-72 (2018)*
Y. Jiang, S. Shi, Y. Yin and J. Liao, Chin. Phys. C 42, No.1, 011001 (2018)
2nd genefation (ebye initial cond., LCC and hadron cascade. Used in this work):
S. Shi, H. Zhang, D. Hou, and J. Liao. arXiv:1910.14010

Observable's Response to Signal in AVFD



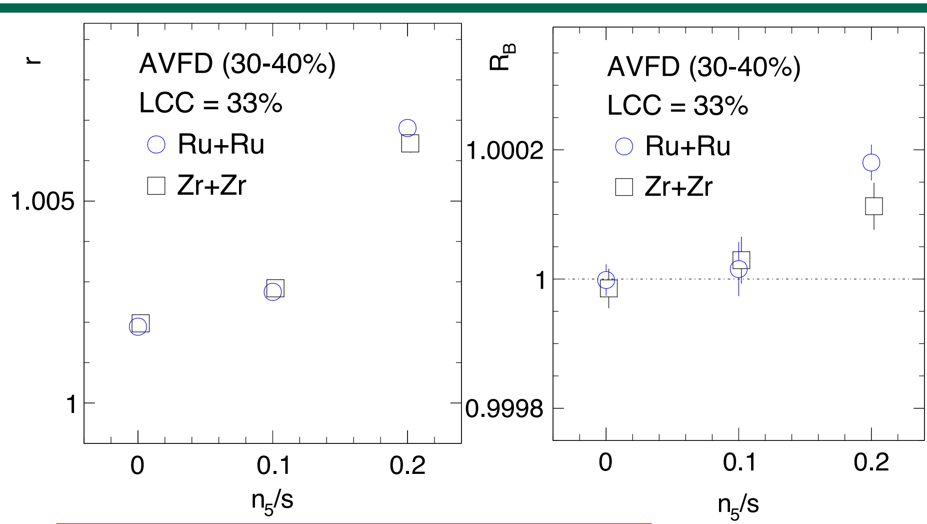
γ -correlator

20 M evts



R(ΔS)-correlator

20 M evts



Signed Balance Function

50 M evts

Frozen codes are being tested with AVFD events (still accumulating/analyzing more evts).

Working in progress, independent of blind analyses.

- Connection between observables can be made with realistic CME model.
- Serve as guidance when comparing results across different methods.

Summary

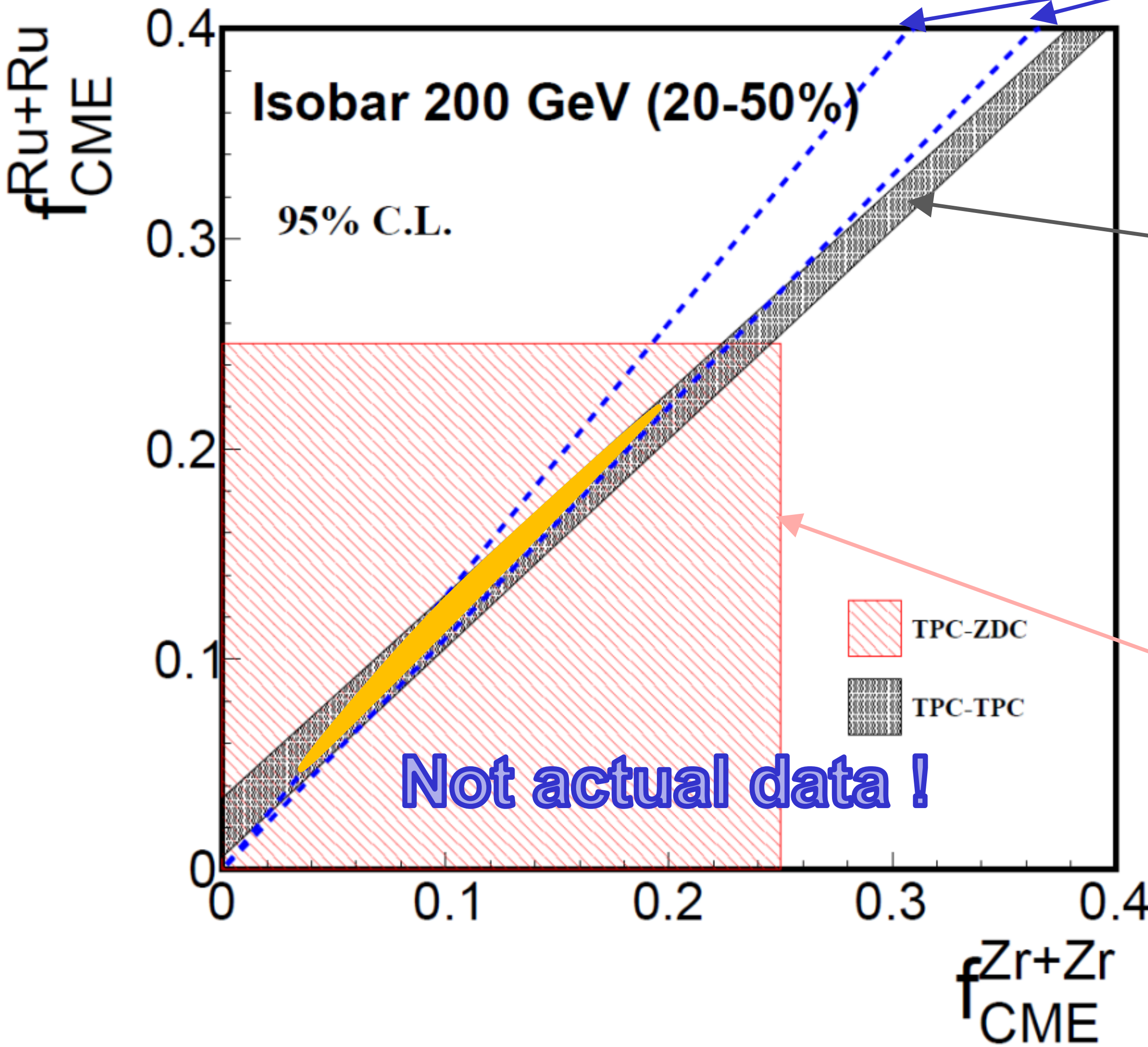
The CME sub-field keeps evolving with new methods and innovations. Although a conclusion on the existence of CME cannot be made for now, a lot of progress have been made in terms of understanding the background and its interplay with signal.

STAR’s blind analysis of isobar data has passed a critical step, expect relatively smooth sailing ahead.

We are getting close, stay tuned !

Backup Slides

Isobar Analysis (Grp 3) : Participant Plane (PP) / Spectator Plane (SP)



By B diff. between isobars (theory input)

$$f_{CME}^{Ru} \approx (1 + \Delta B^2) f_{CME}^{Zr}$$

By $\Delta\gamma$ and v_2 ratio between isobars.

$$f_{CME}^{Ru} = \left(1 - \frac{a\prime}{A\prime}\right) + \frac{a\prime}{A\prime} f_{CME}^{Zr}$$

$$A' = \frac{\Delta\gamma^{Ru}}{\Delta\gamma^{Zr}}, \quad a' = \frac{v_2^{Ru}}{v_2^{Zr}}$$

By SP/PP measurements, separately for isobars

Case for CME :

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

Isobar Analysis (Grp +1) : Signed Balance Function

$$B_p(S) = \frac{N_{+-}(S) - N_{++}(S)}{N_+}$$

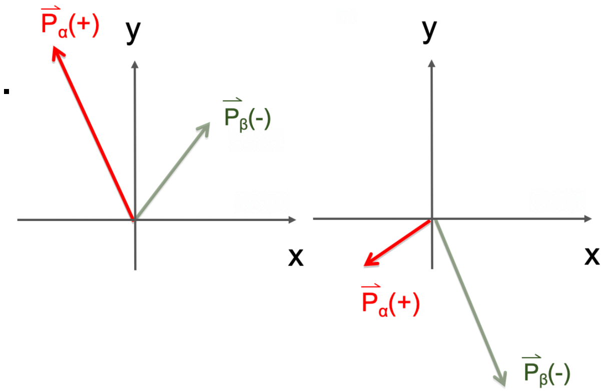
$$B_N(S) = \frac{N_{-+}(S) - N_{--}(S)}{N_-}$$

⟵ 1) Pair's mtm ordering. ($S = \pm 1$)

$$\delta B_p(\pm 1) = B_p(\pm 1) - B_N(\pm 1)$$

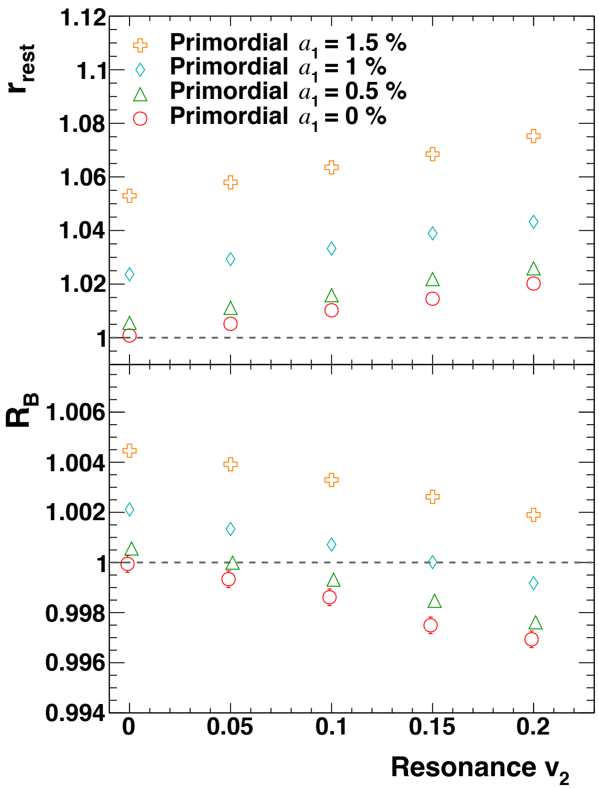
$$\Delta B = \delta B(+1) - \delta B(-1)$$

⟵ 2) Count net ordering.



Two examples of α leading β in p_y ($S = +1$)

A. Tang, Chin. Phys. C 44 No.5 054101 (2020)



$$r = \frac{\sigma_{\Delta B}^{\perp}}{\sigma_{\Delta B}}$$

⟵ 3) Excess ΔB fluct. out-of-plane.

$$R_B = \frac{r_{rest}}{r_{lab}}$$

⟵ 4) Rest frame enhancement.

⟵ Resonance daughters have no v_2 in rest frame ➡ r_{rest} tends to closer to 1 than r_{lab}.

r and R_B : Similar response to signal, opposite response to bkg.

Not participated in blind analyses

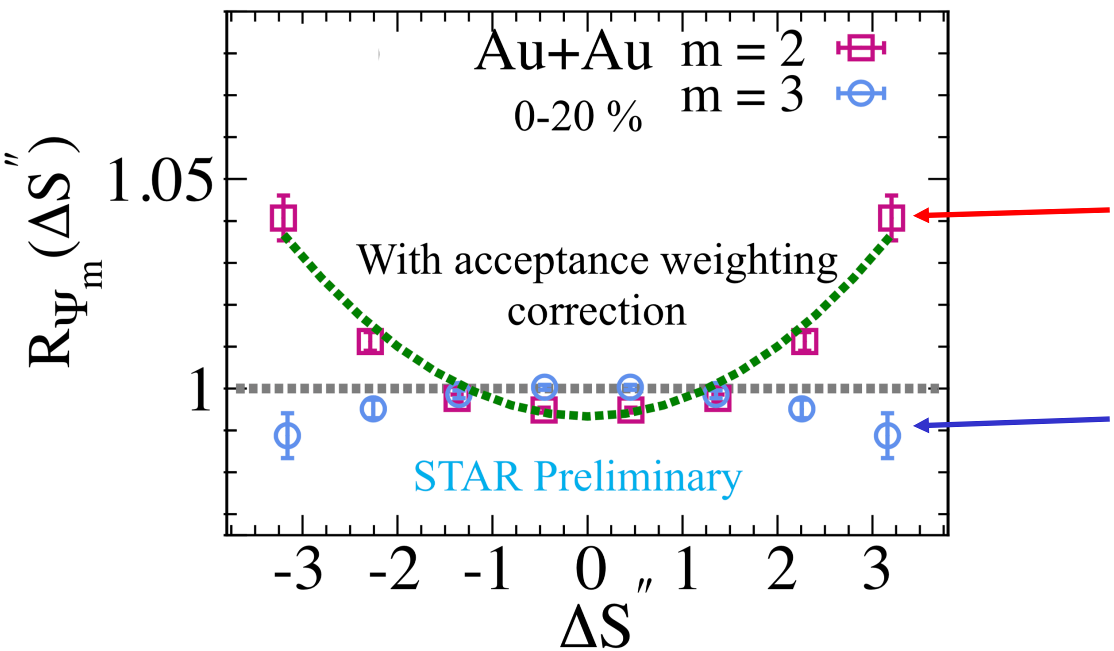
Isobar Analysis (Grp 5) : R(ΔS) Correlator

$$\Delta S = \langle \sin \Delta\phi \rangle_+ - \langle \sin \Delta\phi \rangle_-$$ ← 1) EbyE out-of-plane v_1 diff.

$$C(\Delta S) = \frac{N_{real}(\Delta S)}{N_{shuffled}(\Delta S)}$$ ← 2) Removal of trivial contribution.

$$R(\Delta S) = \frac{C^{\perp}(\Delta S)}{C(\Delta S)}$$ ← 3) Look for out-of-plane excess.

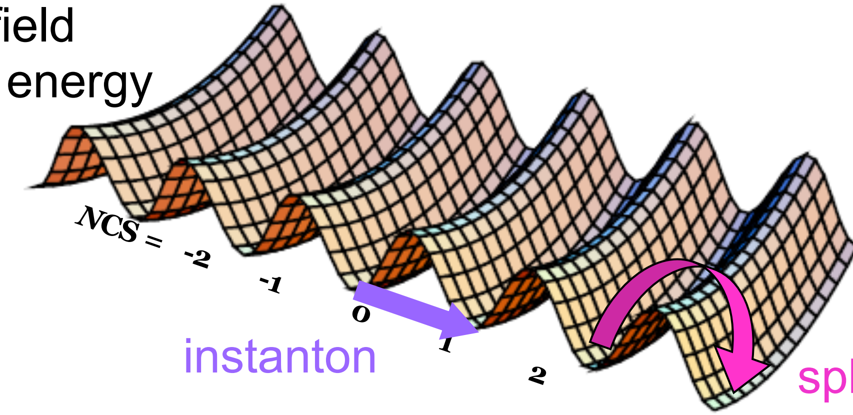
4) Repeat with Ψ_3 EP for baseline.



N. Magdy for STAR, WWND 2019

N. Magdy, S. Shi, J. Liao, N. Ajitanand and R. Lacey Phys. Rev. C 97 061901 (2018)

QCD Vacuum Transition



- Gluonic field energy is periodic in Chern–Simons number (N_{CS}) direction
- Winding number: N_{CS} difference between initial and final states

$$Q_W = \boxed{\frac{g^2}{32\pi^2}\int \mathrm{d}^4x\, F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a}$$

- Axial current j^5_μ : net handedness flow

$$\partial^\mu j^5_\mu = 2\sum_f m_f \langle \bar{\psi}_f i\gamma_5 \psi_f \rangle_A \boxed{-\frac{N_f g^2}{16\pi^2} F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a}$$

- Nonzero topological charge generates chirality imbalance

$$N^f_L - N^f_R = 2Q_W,\ Q_W \neq 0 \rightarrow \mu_A \neq 0$$

- QCD vacuum transition ➔ nonzero topological charge ➔ chirality imbalance