CME Search at STAR

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for the STAR collaboration

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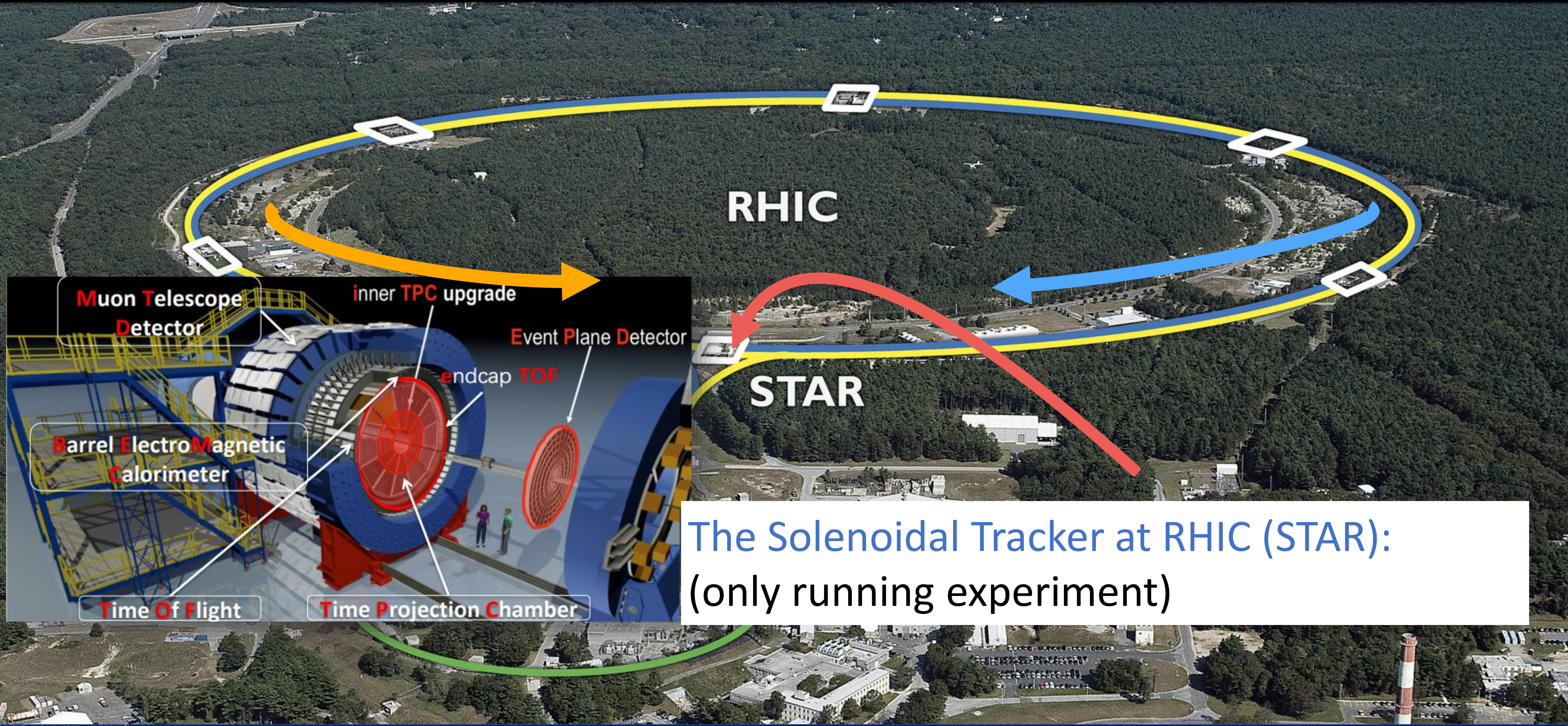
SQM2021

1.Fudan University; 2. Brookhaven National Laboratory

Supported in part by U.S. DEPARTMENT OF ENERGY

Introduction



The Solenoidal Tracker at RHIC (STAR):
(only running experiment)

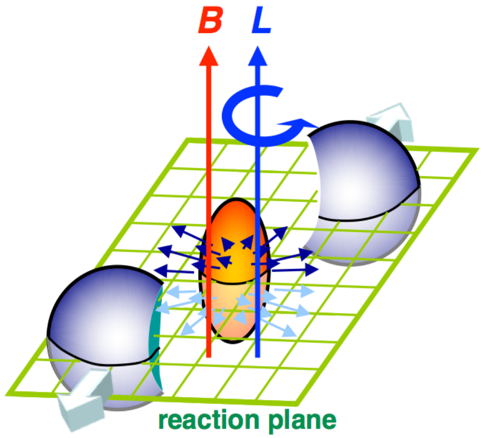
Strongest B-field in the Universe & Chiral Magnetic Effect

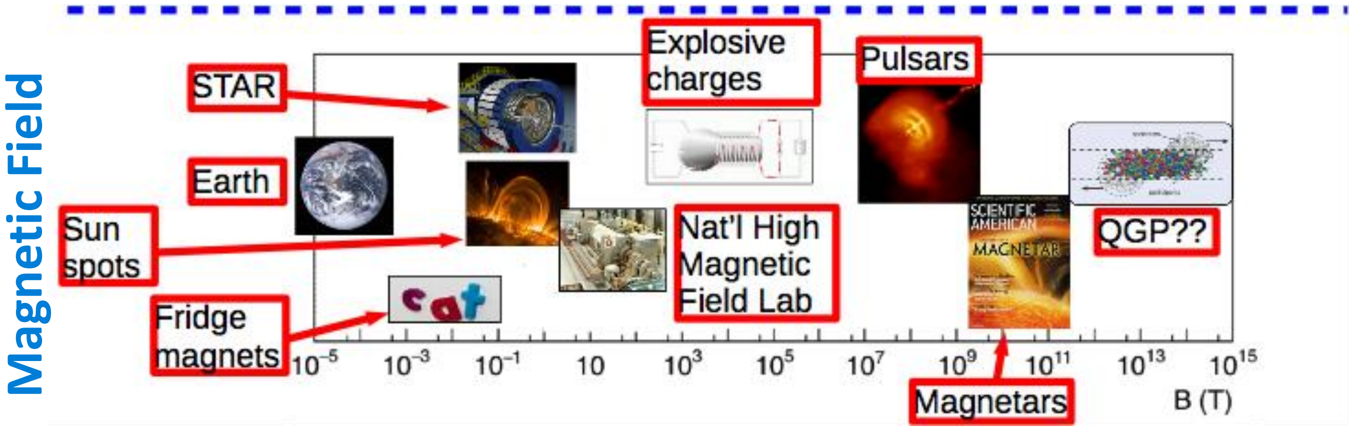
Collisions of two heavy ions create the strongest electromagnetic fields in the universe

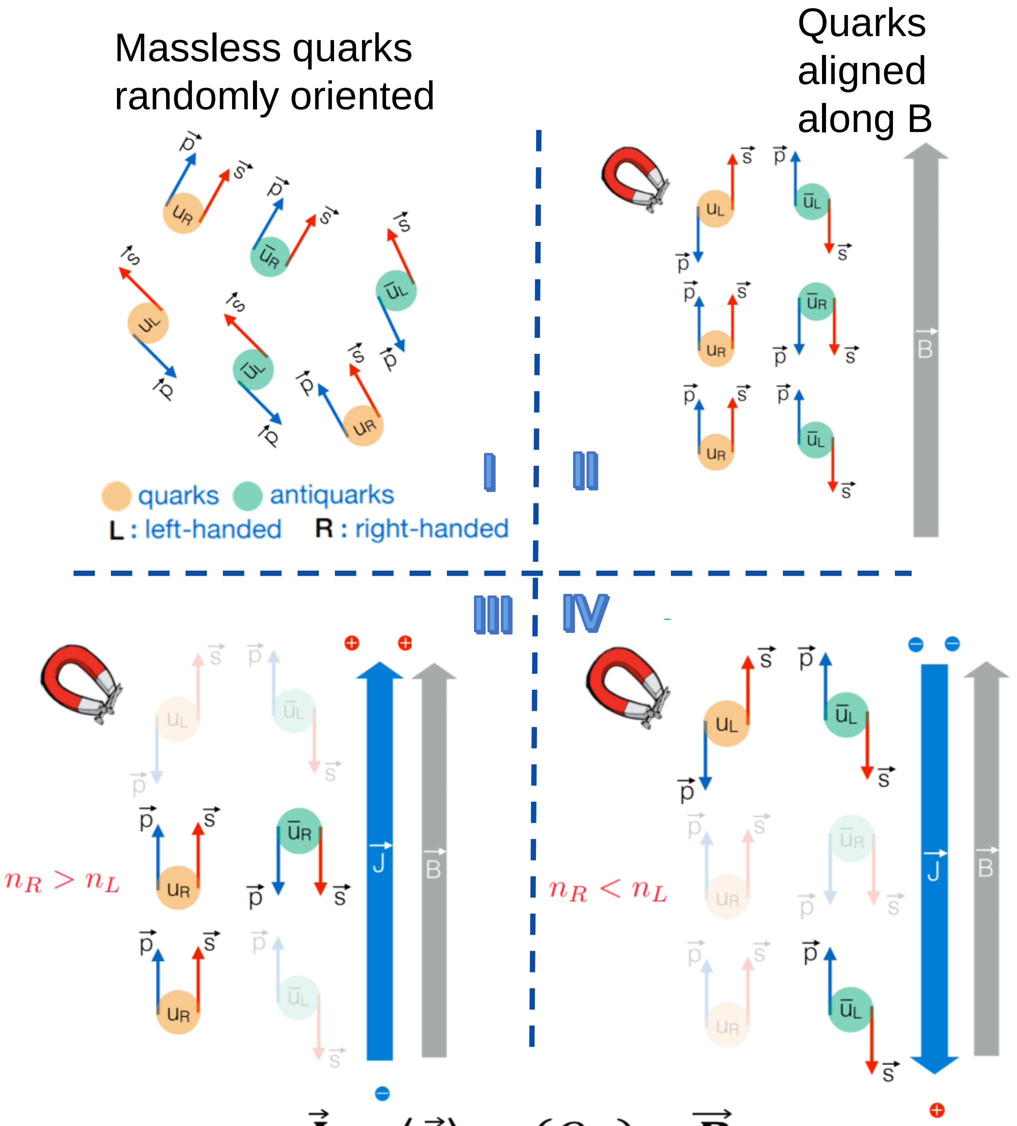
Strong magnetic field

B~10^{18} Gauss

D. Kharzeev, L. McLerran, and H. Warringa, Nucl.Phys.A803, 227 (2008)
McLerran and Skokov, Nucl. Phys. A929, 184 (2014)







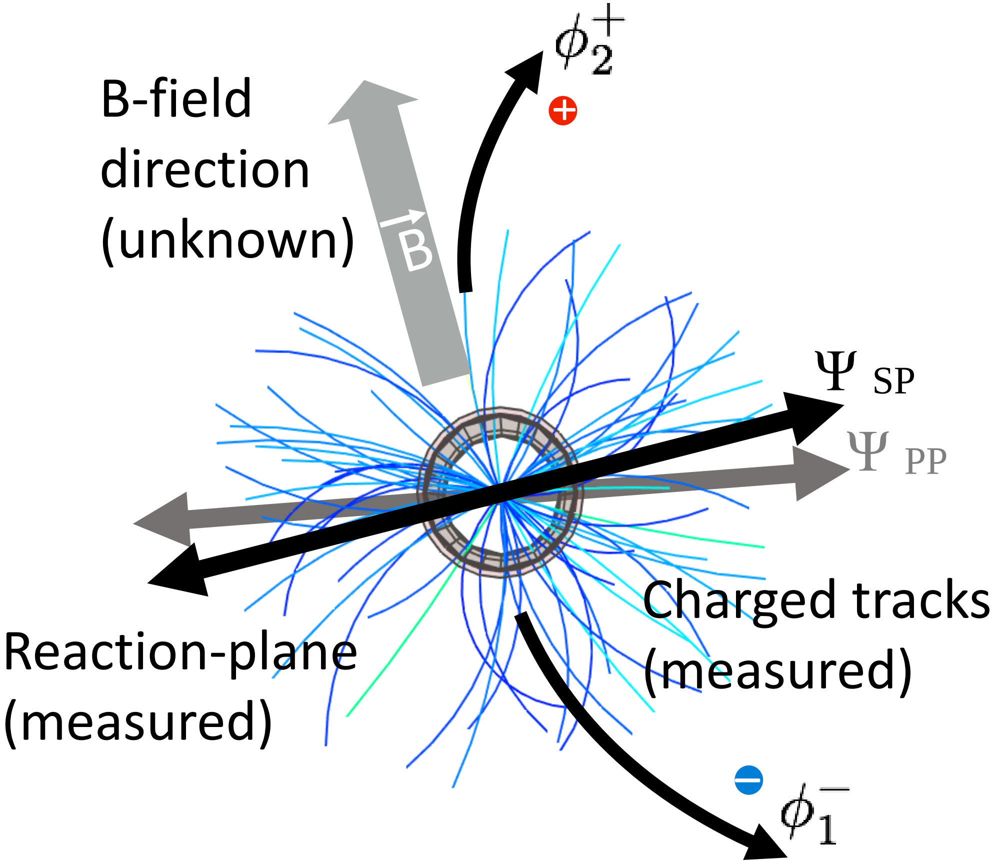
$$\vec{J} \propto \langle \vec{p} \rangle \propto (Qe)\mu_5 \vec{B}$$

Au + Au & U+U

@ Higher Energy

Charge Dependent Correlator & Event Plane

S. A. Voloshin, Phys. Rev. C70 (2004) 057901



RP, PP, SP…

$$\gamma_{\alpha\beta} = \cos(\phi_\alpha + \phi_\beta - 2\Psi)$$

$$\Delta\gamma = \gamma_{opposite} - \gamma_{same} \qquad \Delta\gamma = \Delta\gamma^{BG} + \Delta\gamma^{CME}$$

- TPC Ψ_{EP} → proxy of Ψ_{PP}
- ZDC Ψ_1 → proxy of Ψ_{RP}

$\Delta\gamma$ w.r.to TPC Ψ_{EP} and ZDC Ψ_1 contain different fractions of CME and Bkg.

$$\Delta\gamma(\Psi_{TPC}) = \Delta\gamma^{BG}(\Psi_{TPC}) + \Delta\gamma^{CME}(\Psi_{TPC}) \quad ①$$

$$\Delta\gamma(\Psi_{ZDC}) = \Delta\gamma^{BG}(\Psi_{ZDC}) + \Delta\gamma^{CME}(\Psi_{ZDC}) \quad ②$$

$$\frac{\Delta\gamma^{BG}(\Psi_{TPC})}{\Delta\gamma^{BG}(\Psi_{ZDC})} = \frac{v_2(\Psi_{TPC})}{v_2(\Psi_{ZDC})} \quad ③$$

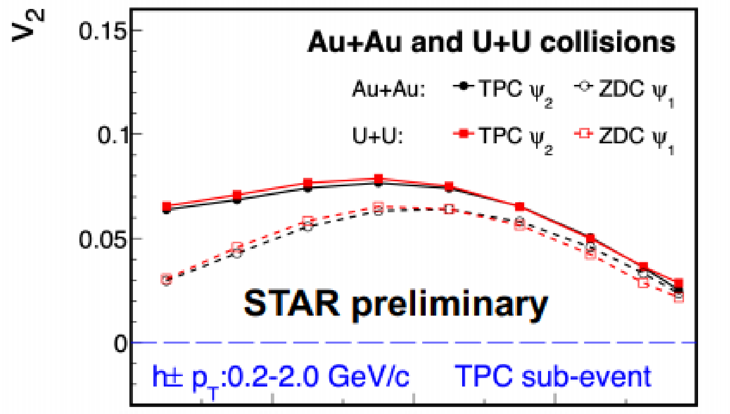
$$\frac{\Delta\gamma^{CME}(\Psi_{TPC})}{\Delta\gamma^{CME}(\Psi_{ZDC})} = \frac{v_2(\Psi_{ZDC})}{v_2(\Psi_{TPC})} \quad ④$$

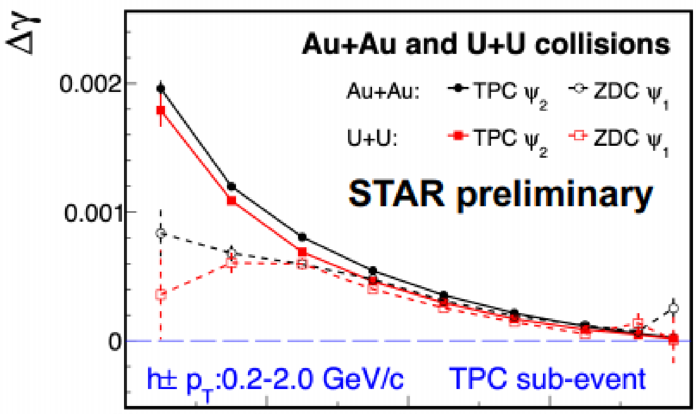
$$f_{EP}(CME) = \frac{\Delta\gamma^{CME}(\Psi_{TPC})}{\Delta\gamma(\Psi_{TPC})} \quad ⑤$$

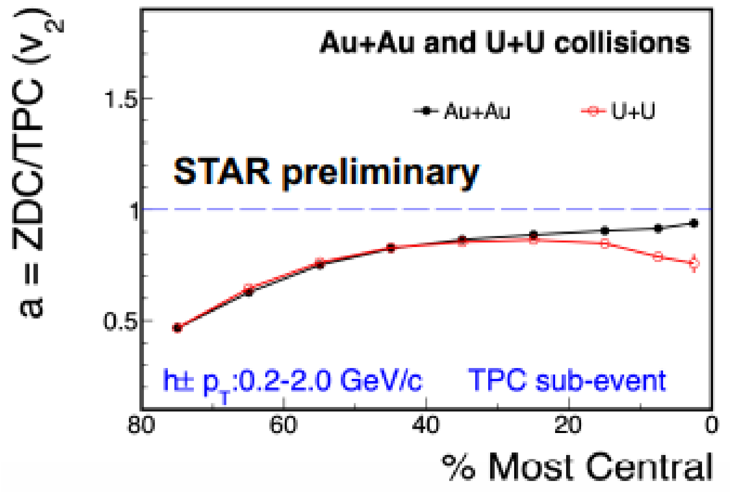
Known
Unknown

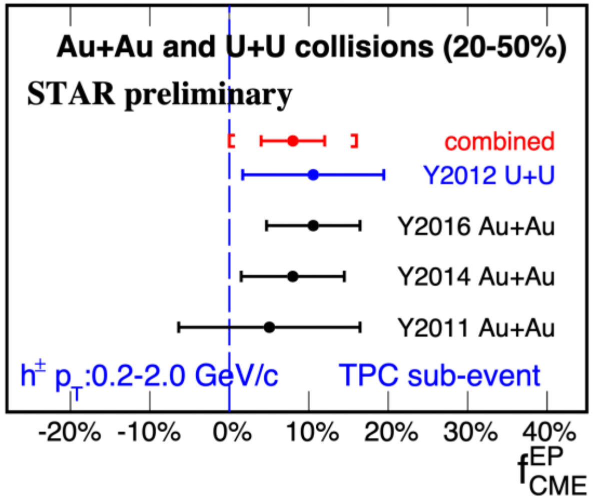
H-J. Xu, et al, CPC 42 (2018) 084103; S. A. Voloshin, Phys. Rev. C 98 (2018) 054911

$\Delta\gamma$ w.r.to different planes @ High Energy









$$\Delta\gamma(\Psi_{\mathrm{TPC}}) = \Delta\gamma^{BG}(\Psi_{\mathrm{TPC}}) + \Delta\gamma^{CME}(\Psi_{\mathrm{TPC}}) \quad ①$$

$$\Delta\gamma(\Psi_{\mathrm{ZDC}}) = \Delta\gamma^{BG}(\Psi_{\mathrm{ZDC}}) + \Delta\gamma^{CME}(\Psi_{\mathrm{ZDC}}) \quad ②$$

$$\frac{\Delta\gamma^{BG}(\Psi_{TPC})}{\Delta\gamma^{BG}(\Psi_{\mathrm{ZDC}})} = \frac{v_2(\Psi_{TPC})}{v_2(\Psi_{ZDC})} > 1 \quad ③$$

$$\frac{\Delta\gamma^{CME}(\Psi_{\mathrm{TPC}})}{\Delta\gamma^{CME}(\Psi_{\mathrm{ZDC}})} = \frac{v_2(\Psi_{\mathrm{ZDC}})}{v_2(\Psi_{\mathrm{TPC}})} < 1 \quad ④$$

$$f_{EP}(CME) = \frac{\Delta\gamma^{CME}(\Psi_{\mathrm{TPC}})}{\Delta\gamma(\Psi_{\mathrm{TPC}})} \quad ⑤$$

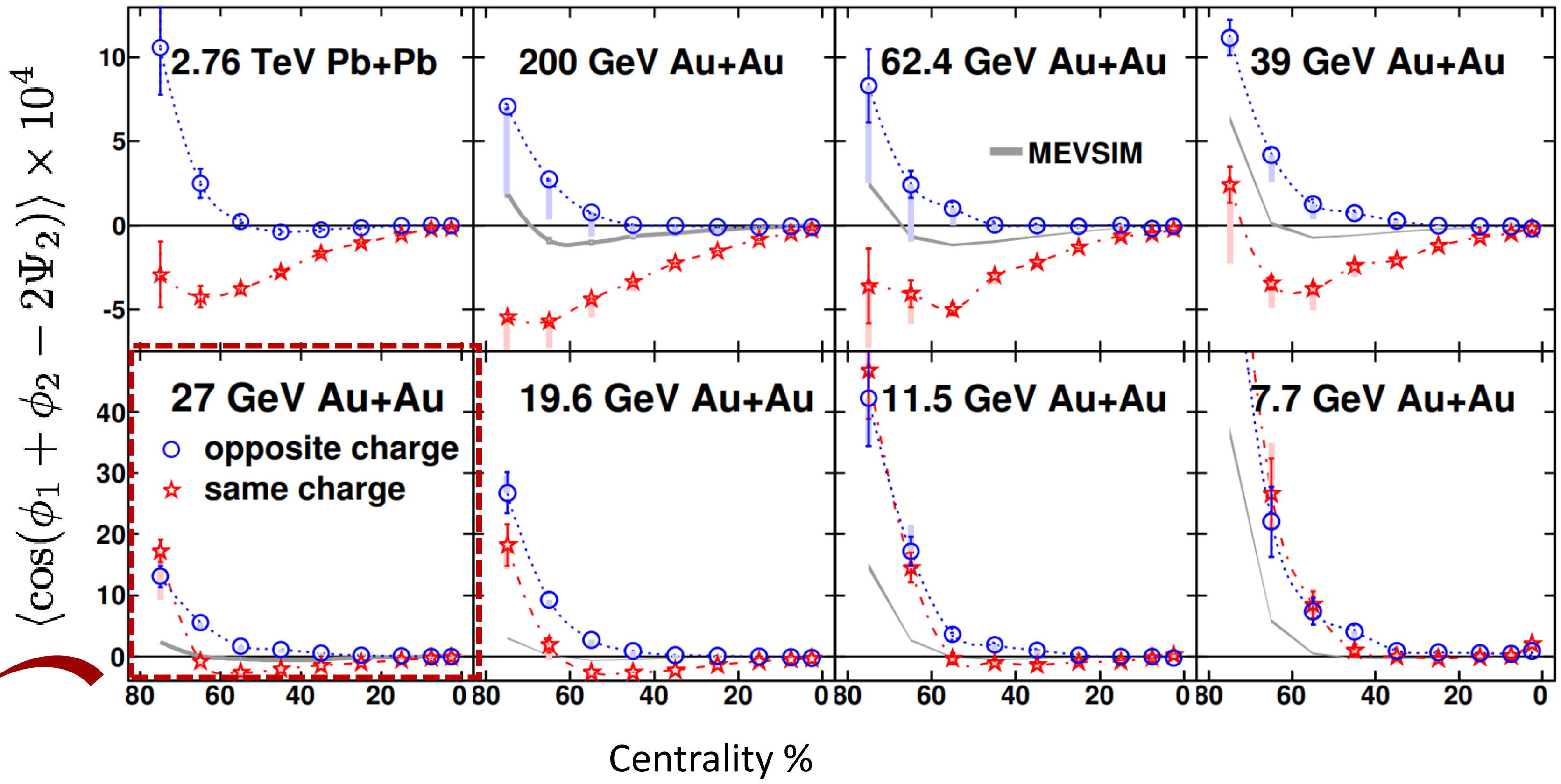
- CME fractions are extracted with $\Delta\gamma$ using Ψ_{PP} and Ψ_{RP} in U+U and Au+Au: the combined result is (8±4±8)%
- Current systematic uncertainties assessed by track quality cuts and η gap

Au + Au @ Lower Energy

Motivation: √s dependence & BES-I data

The STAR collaboration has measured charge separation over a wide range of collision energies

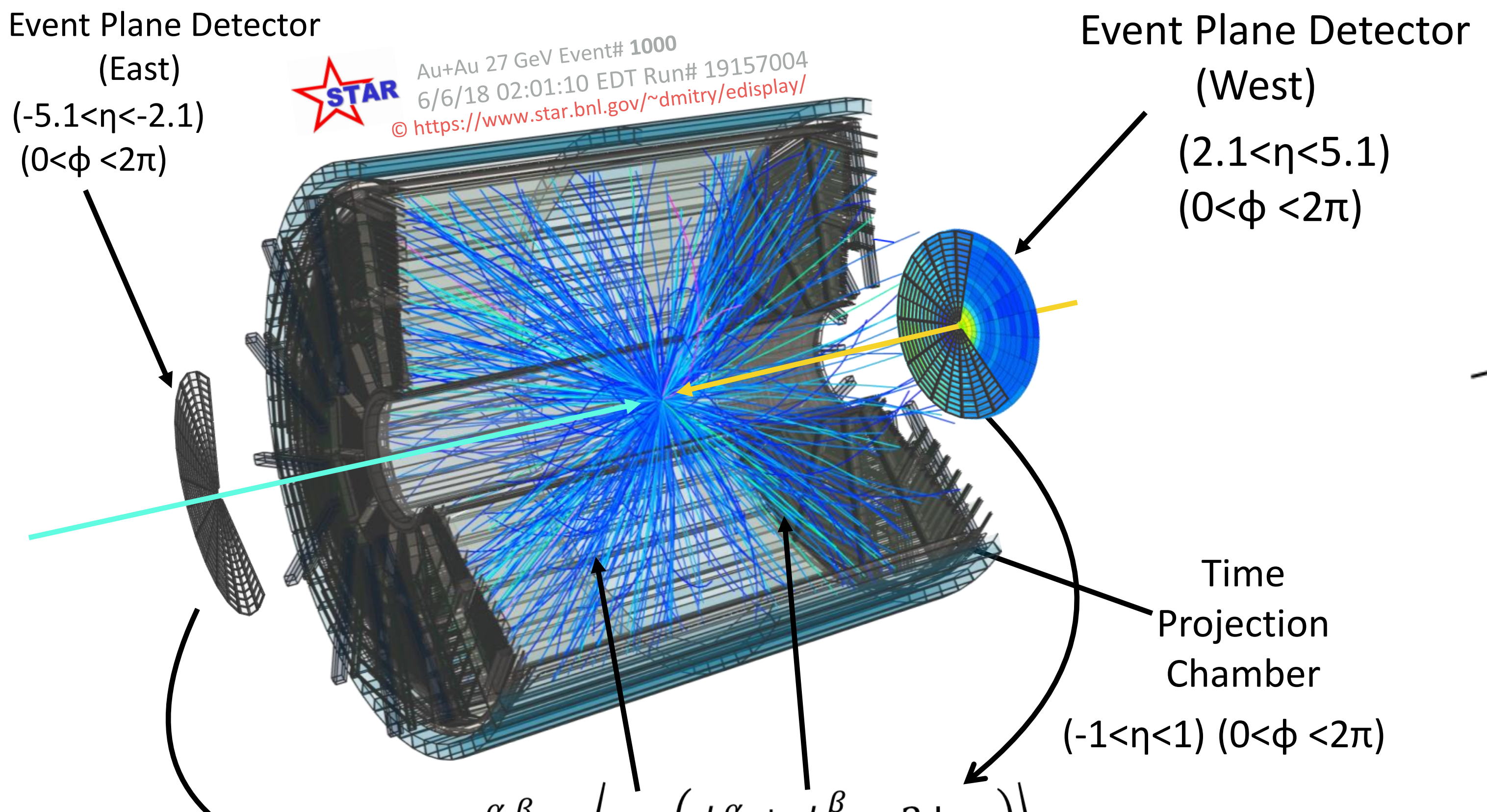
L. Adamczyk et al. (STAR Collaboration), PRL 113 (2014) 052302.



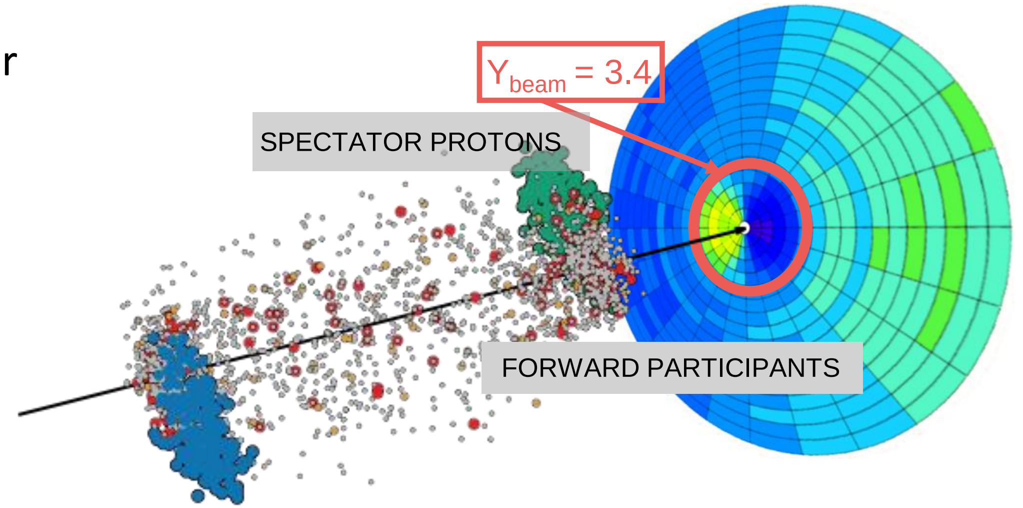
Interesting observation: charge separation disappears at lower energies

We revisit the 27 GeV analysis with new capabilities & high statistics data

STAR capability for CME search at low energies



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



The cartoon above shows that the inner region of EPD detects spectator protons, whose directed flow signal has an opposite direction compared to the outer sectors that are dominated by the participants.

- We use two planes from EPD as proxy for Ψ_{RP}
- Ψ_1 ($\eta > Y_{beam}$): 1st-order event plane enriched with spectator protons
- Ψ_2 ($\eta < Y_{beam}$): 2nd-order event plane for particles going in forward direction

We measure charge-dependent azimuthal correlator using TPC and EPD

Lower Energy Study with new installed EPD

$$\gamma_{\alpha\beta} = \cos\left(\phi_\alpha + \phi_\beta - 2\Psi\right)$$

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

If $\Delta\gamma^{BG} = b\, v_2$

$$\left(\frac{\Delta\gamma}{v_2}\right) = \frac{\langle\cos(\alpha+\beta-2\Psi)\rangle}{\langle\cos(2a-2\Psi)\rangle}$$

RP, PP, SP…

Under the background scenario, all these ratios equal one to another. If two different measurements yield different ratios, this would indicate the CME signal.

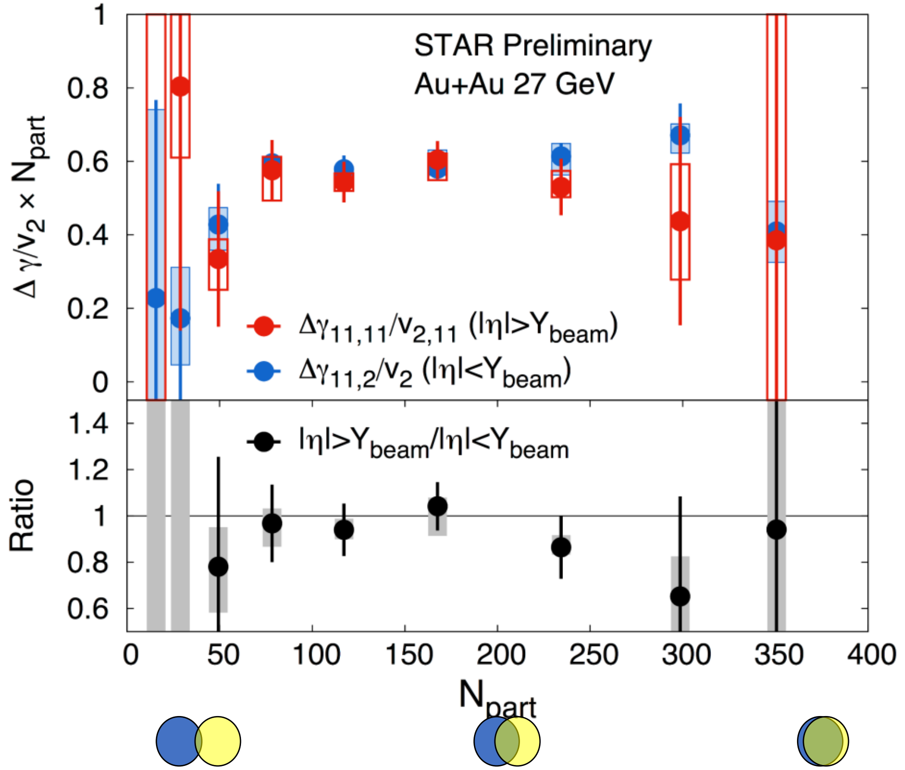
S. A. Voloshin, Phys. Rev. C 98 (2018) 054911

In a short word, under the background scenario, we should have:

$$\frac{\Delta\gamma}{v_2}(\Psi_A) = \frac{\Delta\gamma}{v_2}(\Psi_B) = \frac{\Delta\gamma}{v_2}(\Psi_C) = \cdots$$

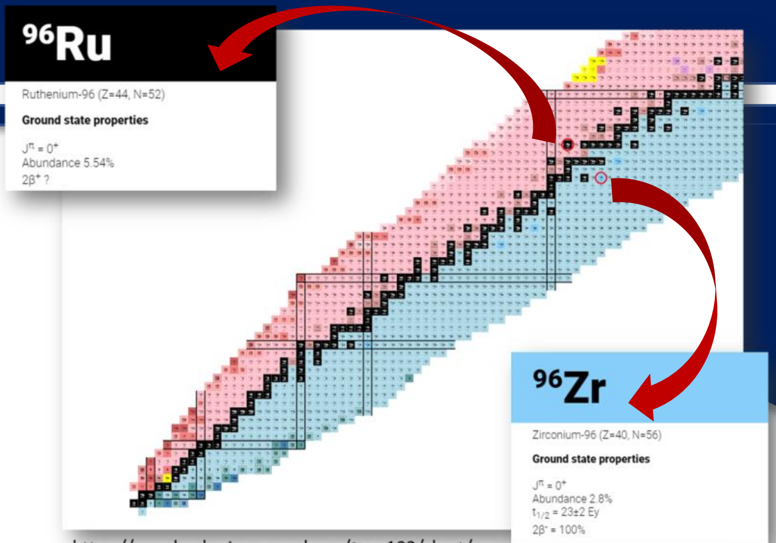
Where the Ψ_A, Ψ_B, Ψ_C… are different planes

We measure the elliptic flow and the charge separation, using γ correlator ($\Delta\gamma=\gamma(OS)-\gamma(SS)$), w.r.to **TPC-EPD-inner first harmonic planes** and the **TPC-EPD-outer second harmonic plane**.



The ratio of $\Delta\gamma/v_2$ between spectator proton rich EPD Ψ_1 plane and participant dominated Ψ_2 plane is presented — CME driven correlations will make this ratio >1.

Isobar Blind Analysis



https://people.physics.anu.edu.au/~ecs103/chart/

Why isobar?

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

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

Measurement

Signal

Background 1

Background 2

Is there a way to "see" the signal part "only"?

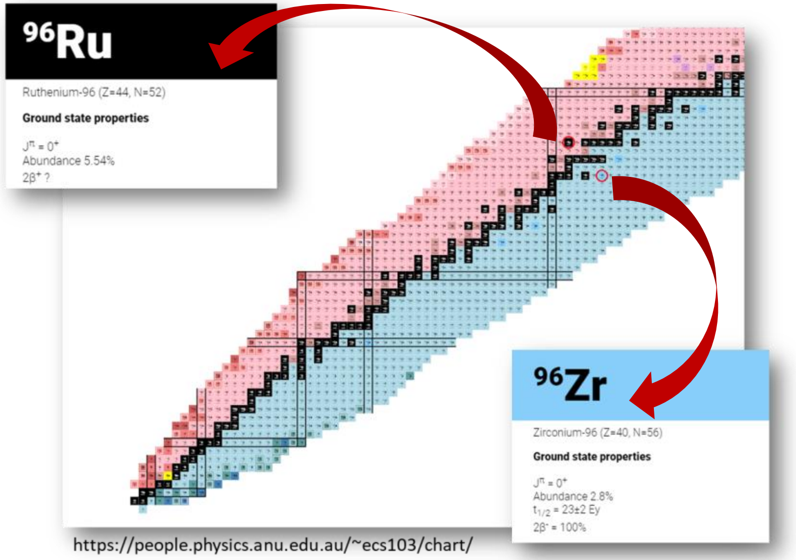
$$\Delta\gamma^{A+A} = \Delta\gamma^{CME} + k\frac{v_2}{N} + \Delta\gamma^{non-flow}$$

$? \quad \neq \quad \neq \quad \neq$

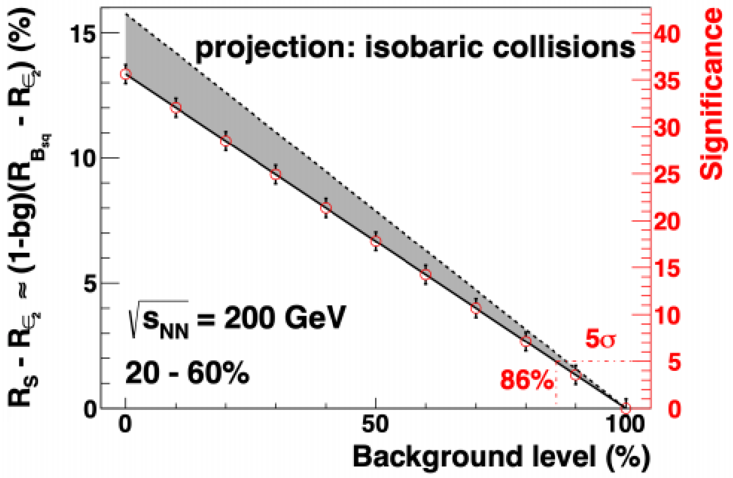
$$\Delta\gamma^{p+A} = \cancel{\Delta\gamma^{CME}} + k\frac{v_2}{N} + \Delta\gamma^{non-flow}$$

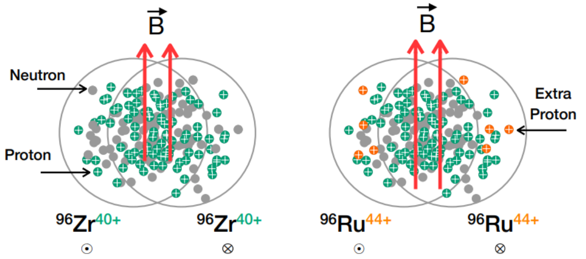
?

S. A. Voloshin, Phys. Rev. C70 (2004) 057901
S. A. Voloshin, Phys. Rev. Lett. 105 (2010) 172301
W.-T. Deng, et al Phys. Rev. C94 (2016) 041901.
Khachatryan Vet al.(CMS) Phys. Rev. Lett.118 (2017) 122301
Adam J et al.(STAR) Phys. Lett. B 798 (2019) 134975



https://people.physics.anu.edu.au/~ecs103/chart/





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

$? \quad \neq \quad \approx \quad =$

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

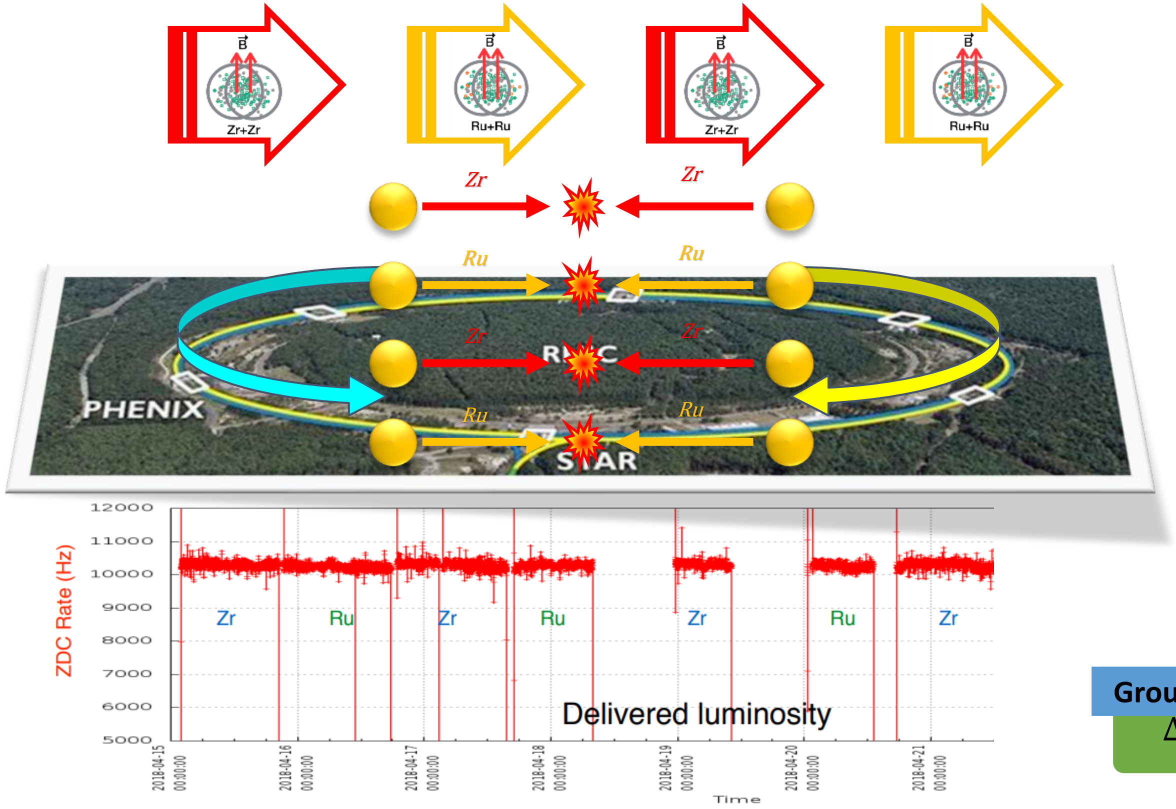
B-field are 10-18% different

Within 4%

- ~2 B events can give five sigma significance for 14% signal level.
- Only if the systematics error is very small.

Minimize the Systematics

How to run?



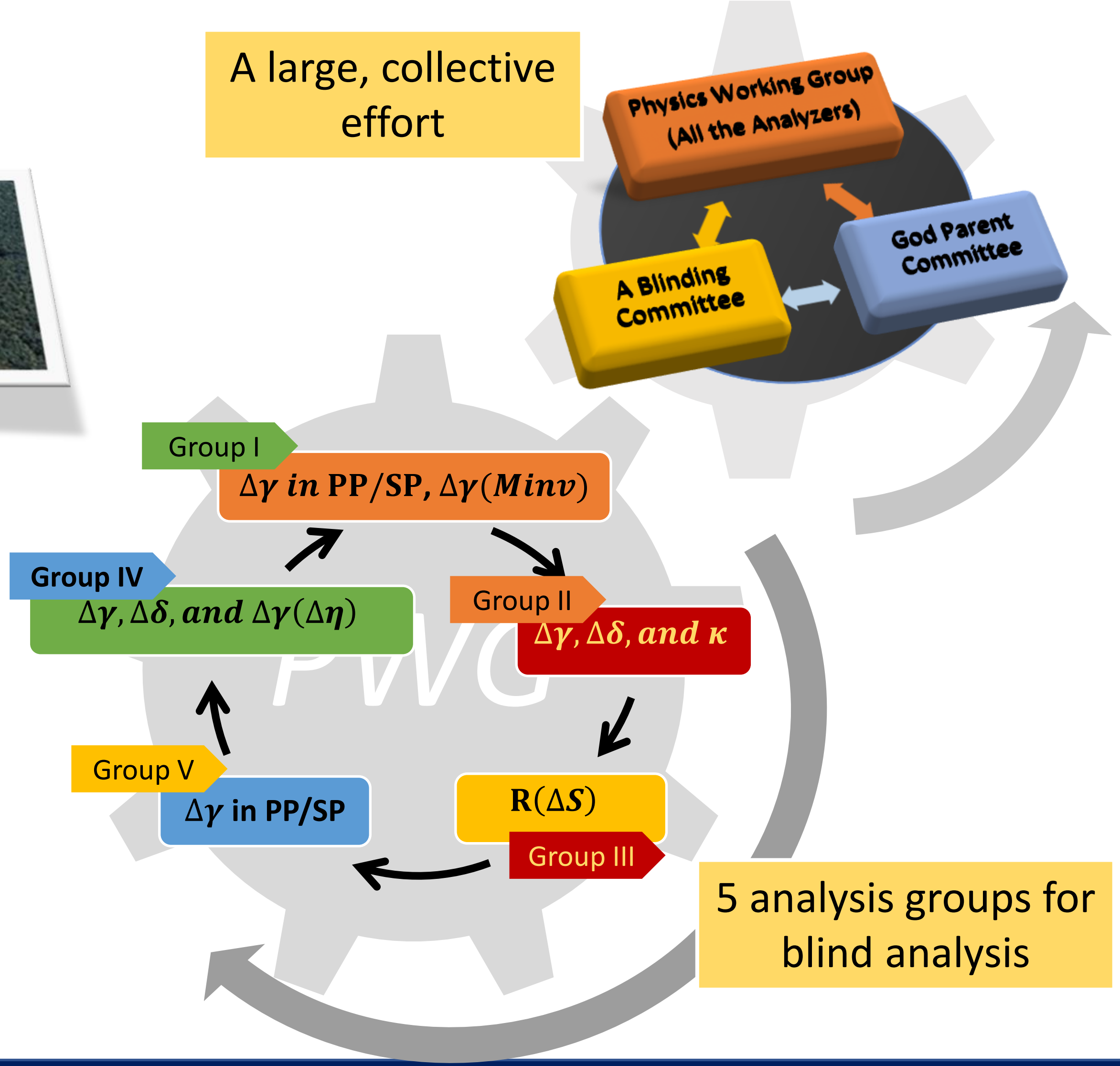
Minimize the Systematics:

Similar run conditions for both species

Eliminate Pre-determined bias:

Perform blind analysis of data

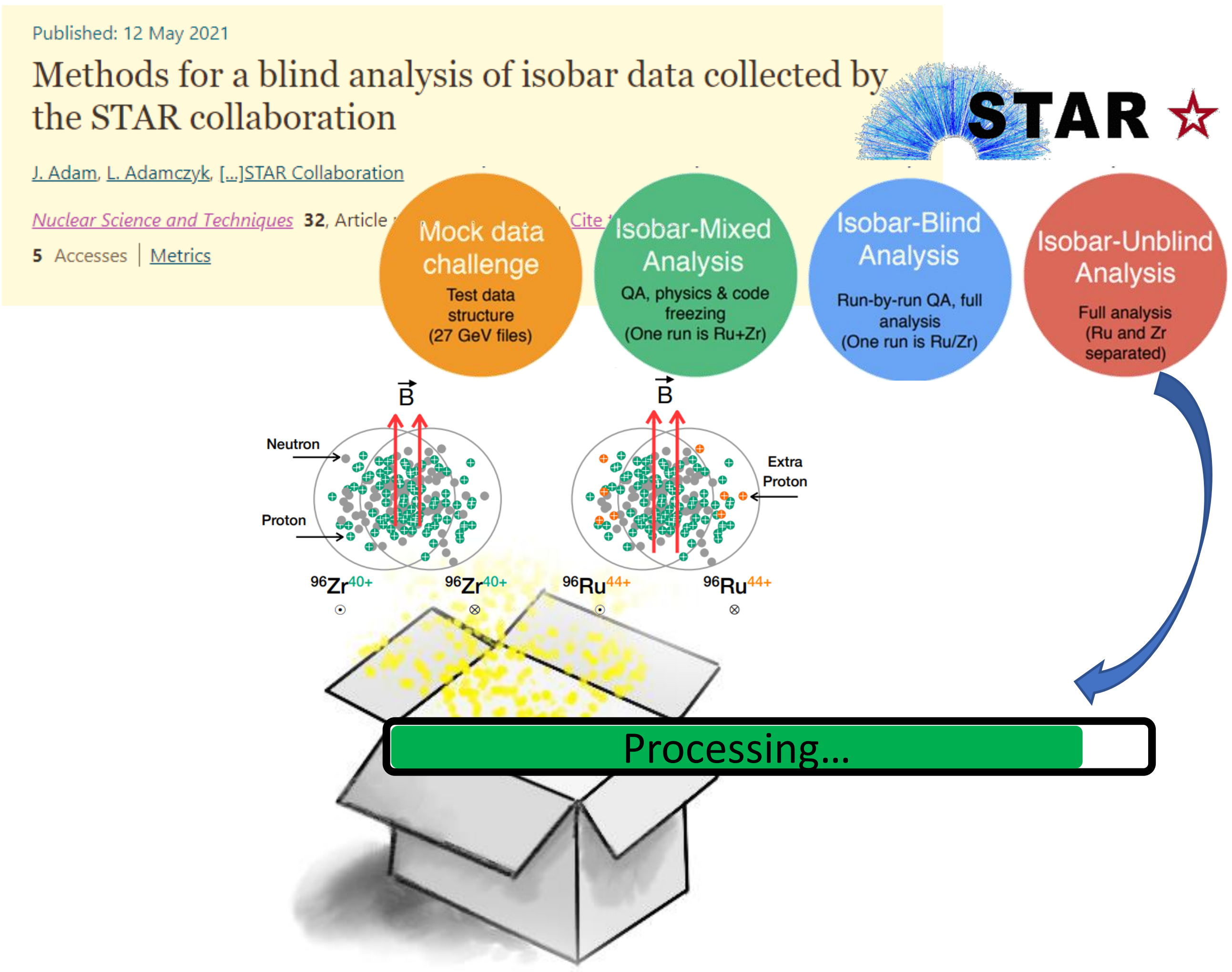
A large, collective effort



5 analysis groups for blind analysis

Procedure for blinding

Adam, J. et al. (STAR) NUCL SCI TECH 32, 48 (2021)



<100 Runs	A fraction of Events	Mixed-Analysis

1	Freeze Event Level Cuts
2	Freeze Track Level Cuts
3	Freeze Analysis Method
4	Freeze Procedure for QA
5	Freeze Analysis Code

~2k Runs	A fraction of Events	Blind-Analysis

1	Do Run-by-Run QA
2	Freeze Run-by-run Cuts

~2k Runs	All events	Prior-to-Unblinding

1	Fix Acceptance Correction Factor
2	Estimate all Observables
3	Statistical Uncertainty
4	Systematic Uncertainty

~2k Runs	All events	Unblinding

1	Re-group the run Ids
2	Ratios, confidence limit

P. Tribedy for the STAR Collaboration, J. Phys. Conf. Ser. 1602, 1, 012002 (2020)

Final cross check with model

- Try to measure signal for each isobar...
- Try to estimate the background...
- Measure the difference between 2 spices..
- ...

arXiv.org > nucl-ex > arXiv:2105.06044

A STAR technical Paper

Nuclear Experiment

https://arxiv.org/abs/2105.06044

[Submitted on 13 May 2021]

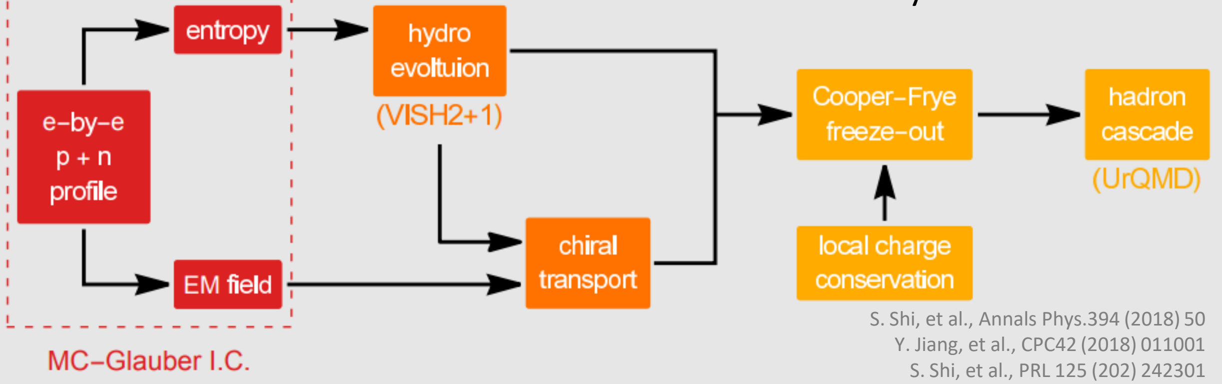
Investigation of Experimental Observables in Search of the Chiral Magnetic Effect in Heavy-ion Collisions in the STAR experiment

Subikash Choudhury, Xin Dong, Jim Drachenberg, James Dunlop, ShinIchi Esumi, Yicheng Feng, Evan Finch, Yu Hu, Jiangyong Jia, Jerome Lauret, Wei Li, Jinfeng Liao, Yufu Lin, Mike Lisa, Takafumi Niida, Robert Lanny Ray, Masha Sergeeva, Diyu Shen, Shuzhe Shi, Paul Sorensen, Aihong Tang, Prithwish Tribedy, Gene Van Buren, Sergei Voloshin, Fuqiang Wang, Gang Wang, Haojie Xu, Zhiwan Xu, Nanxi Yao, Jie Zhao

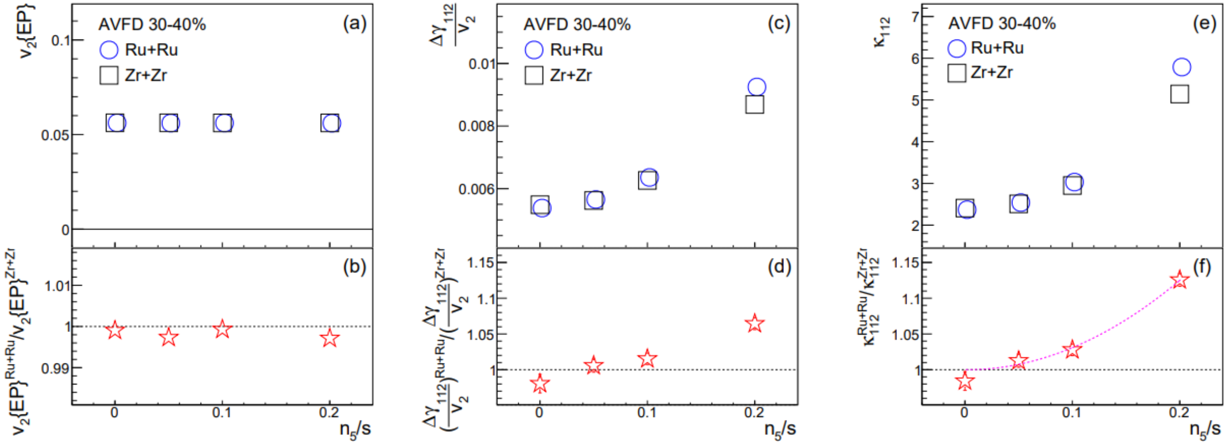
The chiral magnetic effect (CME) is a novel transport phenom
energy nuclear collisions, the CME may survive the expansio
searches for the CME have aroused extensive interest at the
investigate three pertinent experimental approaches: the γ c
realistic event generator (EBE-AVFD) to verify the equivalen
the isobaric collisions at RHIC.

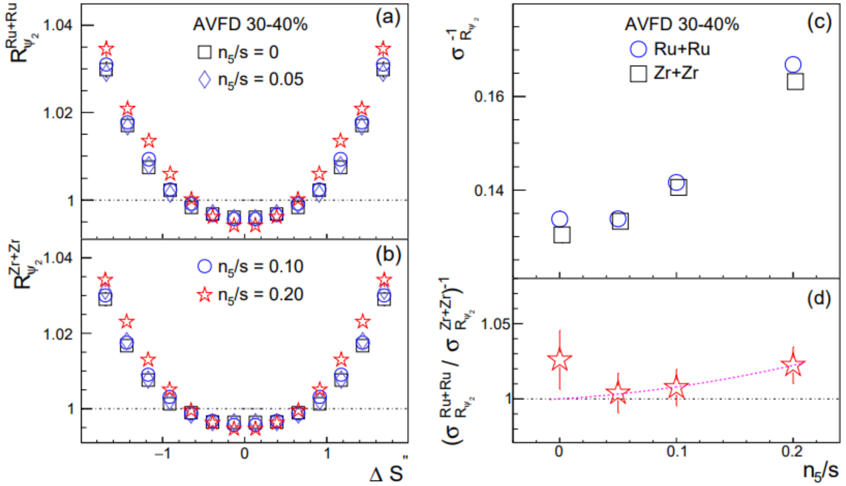
Frozen code from STAR to check the sensitivity of different observables between Ru+Ru and Zr+Zr.

Flow chart for an Event-by-Event AVFD model



S. Shi, et al., Annals Phys.394 (2018) 50
Y. Jiang, et al., CPC42 (2018) 011001
S. Shi, et al., PRL 125 (202) 242301





Test response of different observables in frozen code to CME signal and difference between Ru+Ru and Zr+Zr using the event-by-event AVFD model,
– n_5/s indicates CME signal strength
- Same sensitivity (inclusive $\Delta\gamma$, R_2) when put on same footing

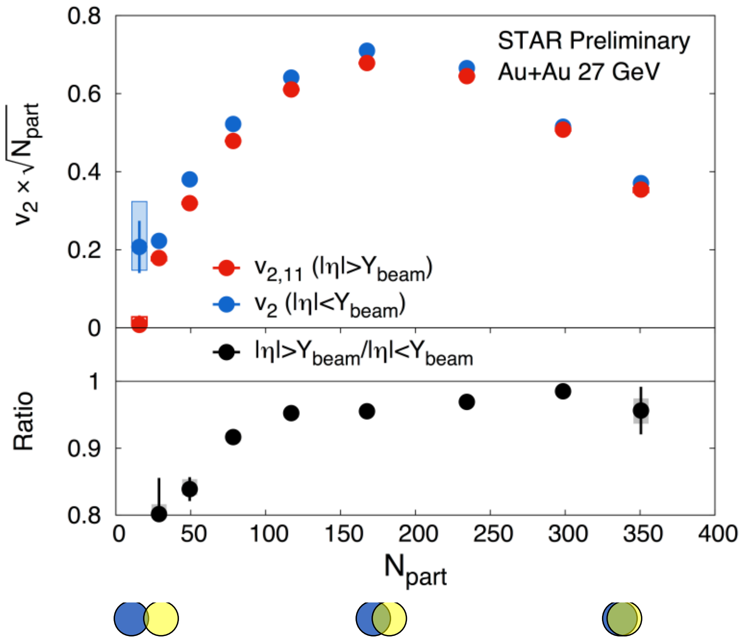
Summary

- We measured the possible CME fraction beyond the flow background by using the $\Delta\gamma$ w.r.to TPC and ZDC planes. At Au+Au 200 GeV and U+U 193 GeV, the combined result shows (8±4±8)% CME fraction in 20%-50% centrality.
- We did the background scenario test at Au+Au 27 GeV by using $\Delta\gamma$ w.r.to TPC and the new installed EPD, the result shows that it is consistent with zero in the current statistics.
- We introduced the method of the ongoing isobar blind analysis, and the latest sensitivity check with the Event-by-Event AVFD model on the different observables between Ru+Ru and Zr+Zr.

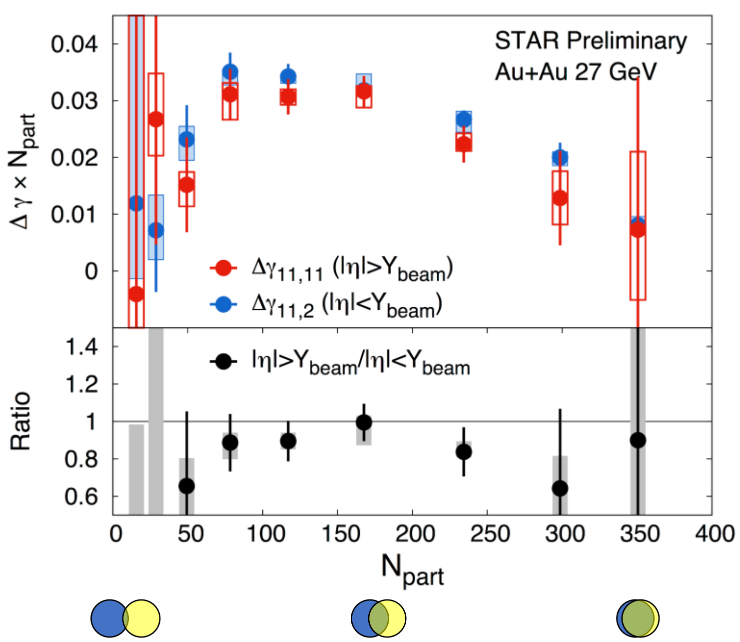
Thank you!

BACKUP

$\Delta\gamma$ and v_2 at Au+Au 27 GeV



the elliptic anisotropy drops due to reduction in non-flow, de-correlation & change in flow fluctuations with pseudorapidity.



In mid-central events the charge separation w.r.t different planes are consistent with each other.