Recent progress from STAR

GXNU involes

林裕富
广西师范大学(GXNU)

第八届粒子物理天问论坛

粒子物理团队基本情况（实验7+理论9）

实验：BESIII, STAR, STCF

魏代会（教授）

轻强子物理、重子谱学等研究

廖广睿（教授）

粲偶素及类粲偶素等

秦丽清（副教授）

轻强子物理、新型强子态等

林裕富（副教授）

QCD相结构、手征磁效应和自旋物理等

张宇（副教授）

QCD相结构和临界点，涨落和关联的研究

崔涵（副教授）

新型粒子/X射线探测领域

陈 倩（讲师）

基于输运模型研究QCD相变与相图结构

理论

梁伟红（教授）

强子物理理论，包括强相互作用有效理论、强子谱、强子结构等

郭云（教授）

高能核物理理论，包括夸克偶素物理、QCD相变与相图结构等

肖楮文（教授）

强相互作用、强子结构和强子谱、强衰变等

胡权宜（副教授）

重味物理与CP破坏、超出标准模型的新物理唯象

白楠（副教授）

引力/规范对偶在凝聚态系统中的应用以及超共形场论中的量子可积性等

牛娟娟（副教授）

重味物理产生机制的研究、新物理的唯象研究等

马鸿浩（副教授）

QCD状态方程、QCD相图、QCD微扰计算和重味物理方面的研究

史瑞祥（副教授）

味物理与强子物理，精确检验标准模型和寻找新物理

杜倩倩（副教授）

高能物理理论和唯象学

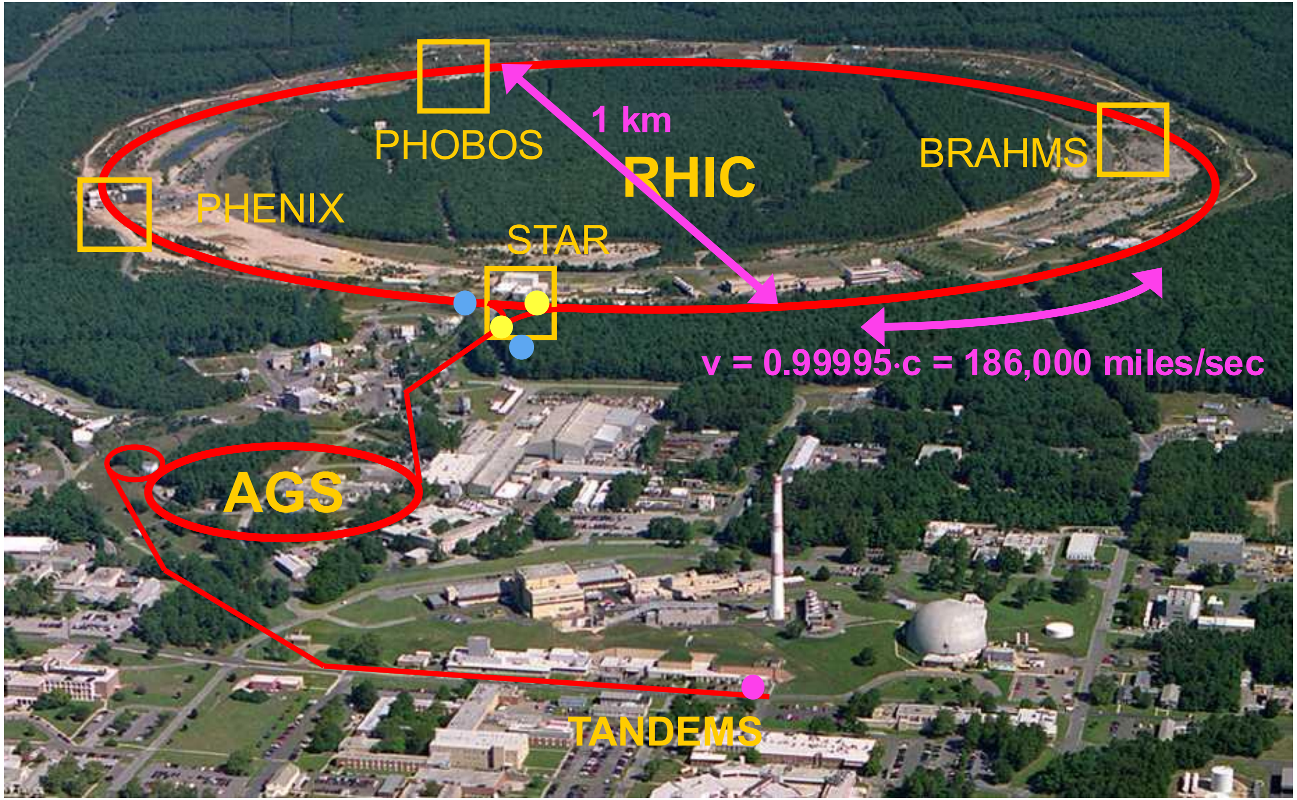
Outline

1) **Introduction**

2) Selected Results
   - Criticality from Beam Energy Scan(BES-II)
   - Directed Flow Splitting Between $\Lambda^0$and $\overline{\Lambda^0}$
   - Chiral Magnetic Effects(CME)

3) Summary and Outlook

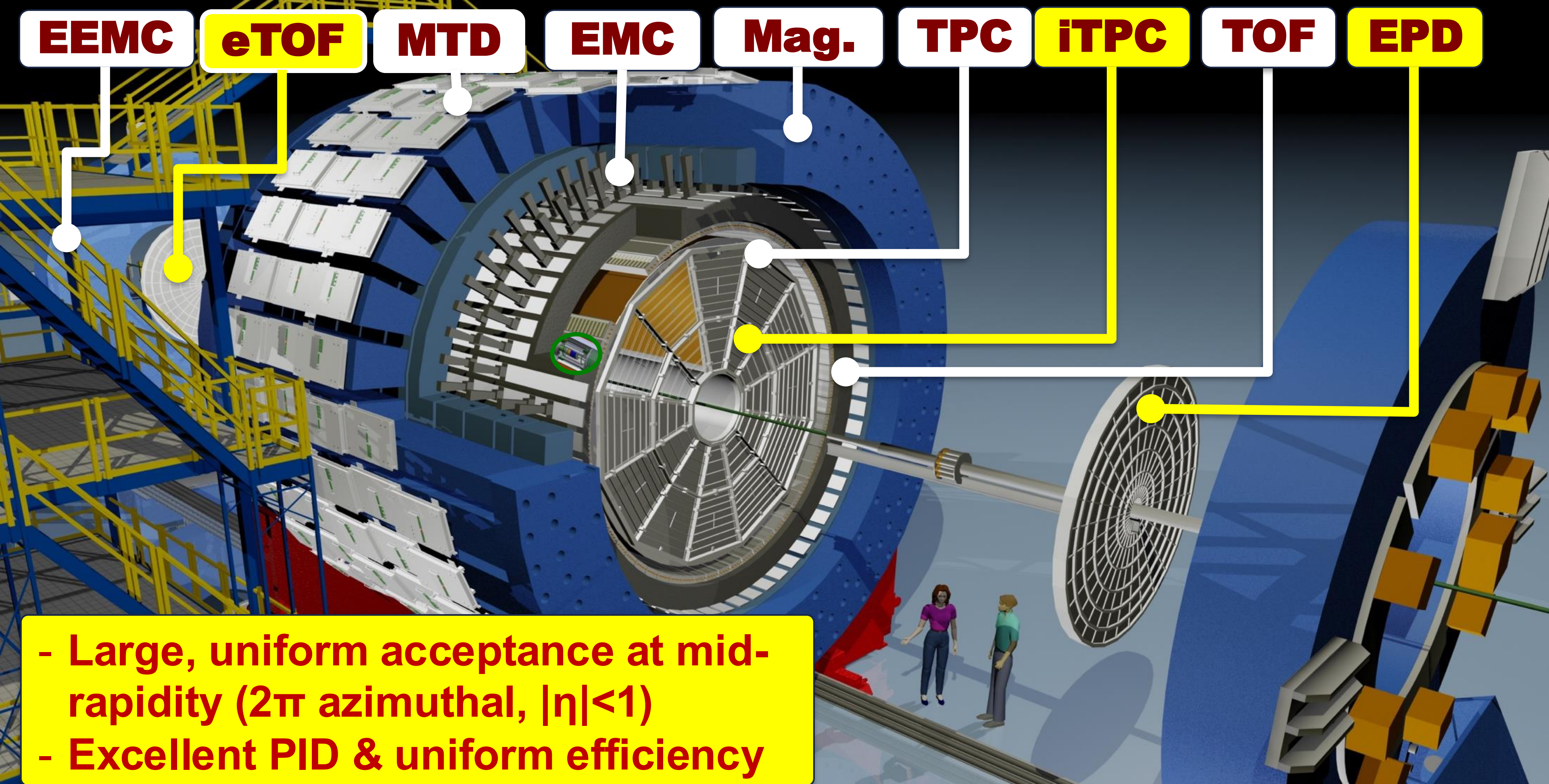
Relativistic Heavy Ion Collider



- The physics of star

The primary physics task of STAR is to study the formation and characteristics of the quark-gluon plasma (QGP), a state of matter believed to exist at sufficiently high energy densities.

The Solenoidal Tracker at RHIC



- Large, uniform acceptance at mid-rapidity (2π azimuthal, |η|<1)
- Excellent PID & uniform efficiency

Major Upgrades for BES-II

iTPC:
- Improves dE/dx
- Extends η coverage from 1.0 to **1.6**
- Lowers p_T cut-in from 125 to 60 MeV/c
- Ready in 2019

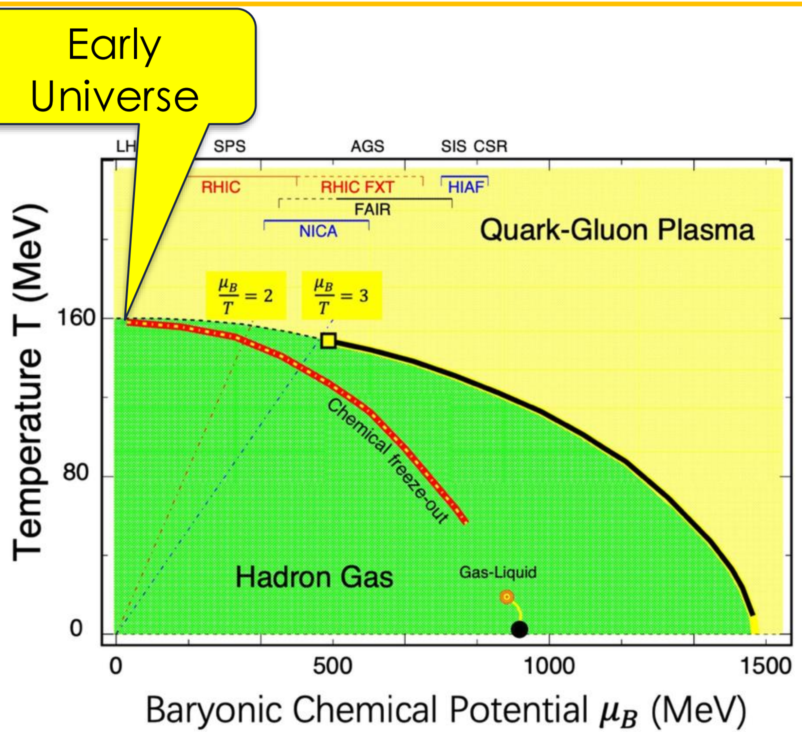
eTOF:
- Forward rapidity coverage
- PID at η = 0.9 to 1.6
- **Borrowed from CBM-FAIR**
- Ready in 2019

EPD:
- Improves trigger
- Better centrality & event plane measurements
- Ready in 2018

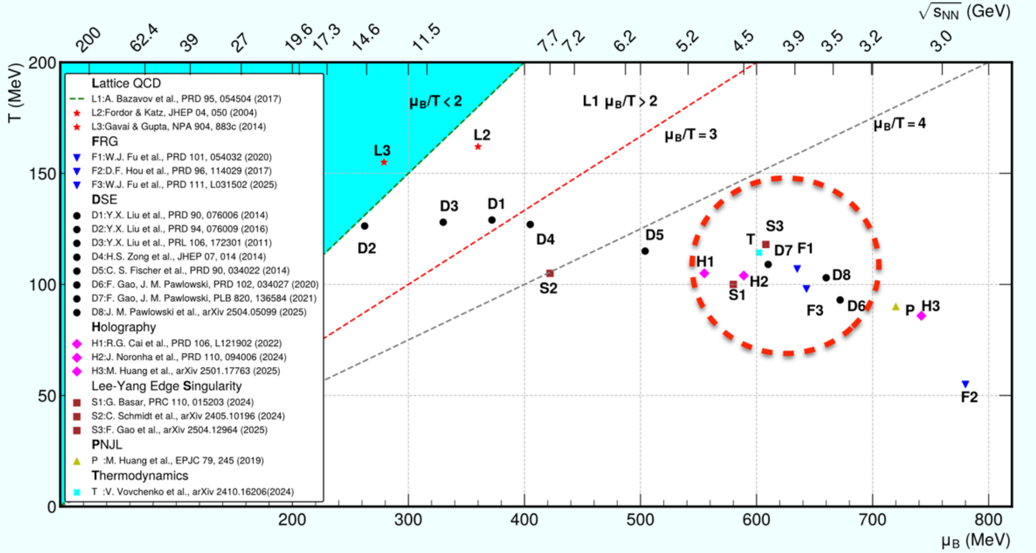
1) Enlarge rapidity acceptance
2) Improve particle identification
3) Enhance centrality/event plane resolution

iTPC: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0619
eTOF: STAR and CBM eTOF group, arXiv: 1609.05102
EPD: J. Adams, et al. NIM **A968**, 163970 (2020)

Nuclear Collisions and QCD Phase Diagram



CEP from different theoretical calculations



By courtesy of Xiaofeng Luo

RHIC BES: → search for 1st-order phase transition and **QCD critical point**

STAR BES Data Sets

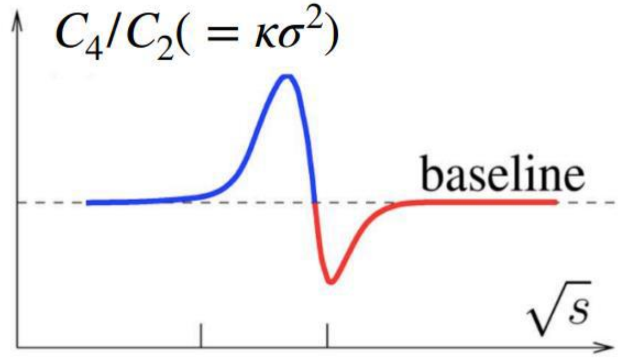
Au+Au Collisions at RHIC											
Collider Runs						**Fixed-Target Runs**					
	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run		$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	**200**	380 M	**25** MeV	5.3	Run-10, 19	1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	62.4	46 M	75 MeV		Run-10	2	11.5 (70)	50 M	320 MeV	-2.51	Run-21
3	54.4	1200 M	85 MeV		Run-17	3	9.2 (44.5)	50 M	370 MeV	-2.28	Run-21
4	39	86 M	112 MeV		Run-10	4	7.7 (31.2)	260 M	420 MeV	-2.1	Run-18, 19, 20
5	27	585 M / **220**	156 MeV	3.36	Run-11, 18	5	7.2 (26.5)	470 M	440 MeV	-2.02	Run-18, 20
6	19.6	595 M/ **270 M**	206 MeV	3.1	Run-11, 19	6	6.2 (19.5)	120 M	490 MeV	1.87	Run-20
7	17.3	256 M / **116 M**	230 MeV		Run-21	7	5.2 (13.5)	100 M	540 MeV	-1.68	Run-20
8	14.6	340 M/ **145 M**	262 MeV		Run-14, 19	8	4.5 (9.8)	110 M	590 MeV	-1.52	Run-20
9	11.5	257 M/ **110 M**	316 MeV		Run-10, 20	9	3.9 (7.3)	120 M	633 MeV	-1.37	Run-20
10	9.2	160 M/ **78 M**	372 MeV		Run-10, 20	10	3.5 (5.75)	120 M	670 MeV	-1.2	Run-20
11	7.7	104 M / **45 M**	420 MeV		Run-21	11	3.2 (4.59)	200 M	699 MeV	-1.13	Run-19
						12	**3.0** (3.85)	**260** + 2000 M	**760** MeV	-1.05	Run-18, 21

Most precise data to map the QCD phase diagram

$$3 < \sqrt{s_{NN}} < 200\ \text{GeV}; \quad 760 > \mu_B > 25\ \text{MeV}$$

Search for QCD Critical Point

Measurements of (Net-)Proton Number Fluctuations in Au+Au Collisions at RHIC (STAR Collaboration)



M. A. Stephanov, PRL 107 (2011) 052301

Signal for Critical Point:
Non-monotonical energy dependence

Conserved Quantities (***B***, ***Q***, ***S***)

1) In strong interactions, baryons (***B***), charges (***Q***) and strangeness (***S***) are conserved;
2) Higher order moments/cumulants describe the shape of distributions and quantify fluctuations. They are sensitive to the correlation length ξ, phase structure;
3) Direct connection to theoretical calculations of susceptibilities.

Measured multiplicity N, $\langle \delta N \rangle = \mathbf{N} - \langle N \rangle$

mean: $M = \langle N \rangle = C_1$

variance: $\sigma^2 = \langle (\delta N)^2 \rangle = C_2$

skewness: $S = \langle (\delta N)^3 \rangle / \sigma^3 = C_3 / C_2^{3/2}$

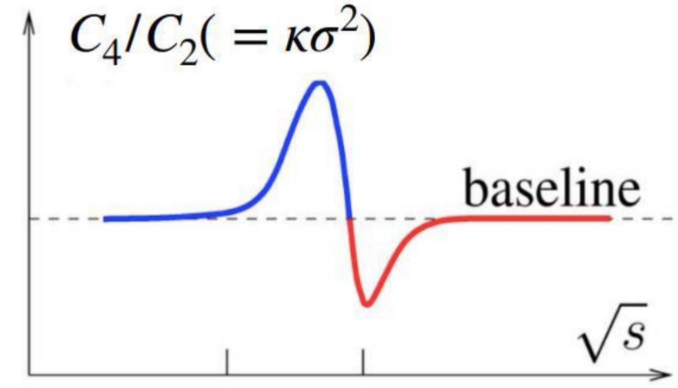
kurtosis: $\kappa = \langle (\delta N)^4 \rangle / \sigma^3 - 3 = C_4 / C_2^2$

Moments, cumulants and susceptibilities:

2^{nd} order: $\sigma^2/M \equiv C_2/C_1 = \chi_2/\chi_1$

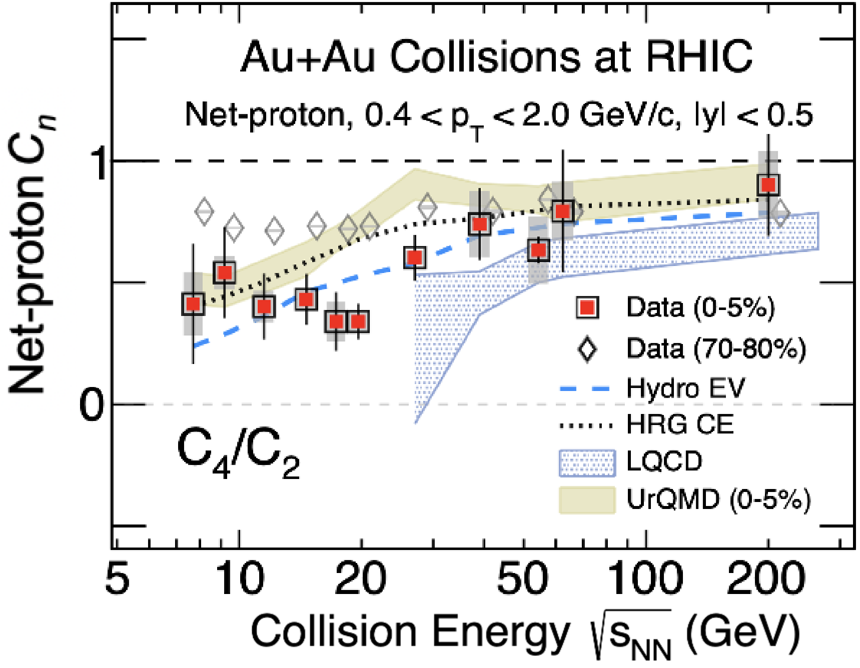
3^{rd} order: $S\sigma \equiv C_3/C_2 = \chi_3/\chi_2$

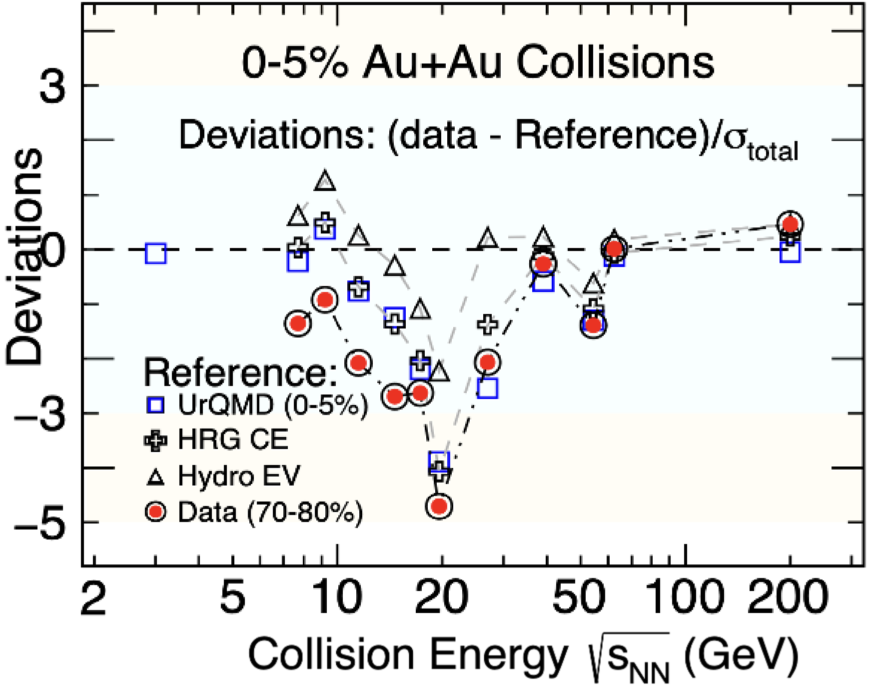
4^{th} order: $\kappa\sigma^2 \equiv C_4/C_2 = \chi_4/\chi_2$



M. A. Stephanov, PRL 107 (2011) 052301

Cumulants of Net-p from BES-II

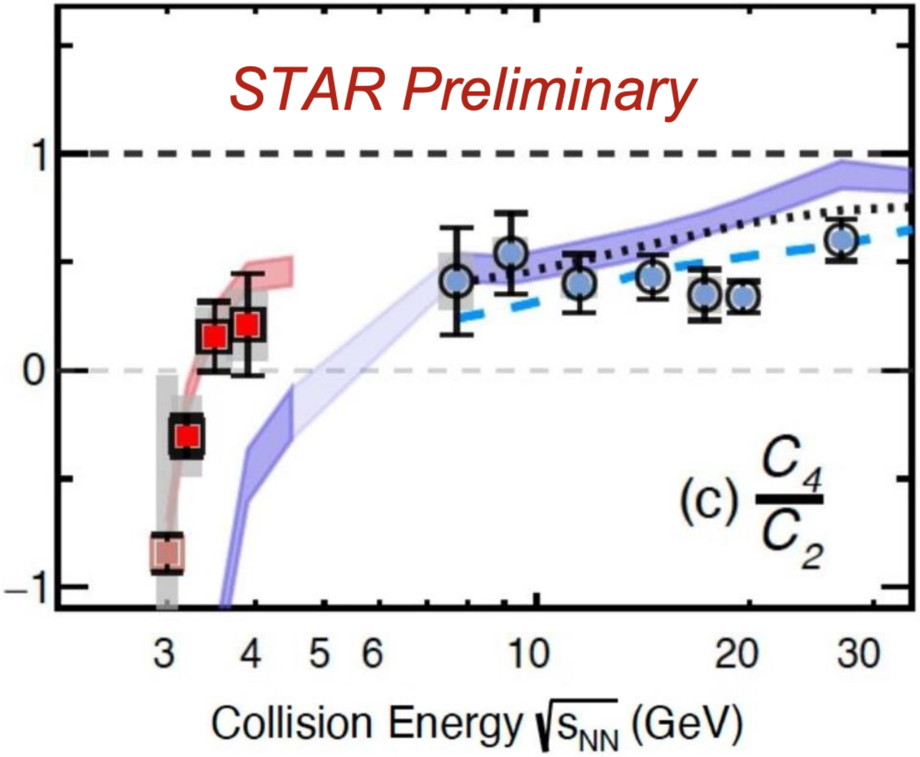




✓ In 0-5% central Au+Au collisions, net-proton C4 /C2 shows deviation from non-critical references at around 20 GeV.

STAR, PRL 135.142301(2025)

Cumulants of Net-p from FXT

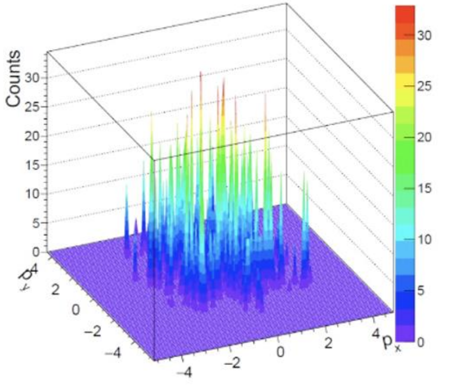


- ✓ C_4/C_2 seems to follow the decreasing trend from high energy

The analysis of 3.0 to 5.2 GeV data are still Ongoing.

Search for QCD Critical Point

Energy dependence of intermittency for charged hadrons in Au+Au collisions at RHIC
(STAR Collaboration)

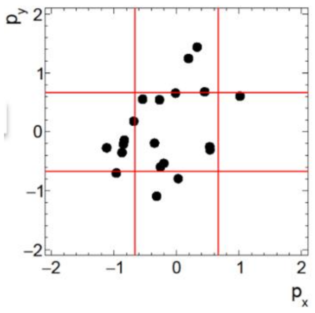


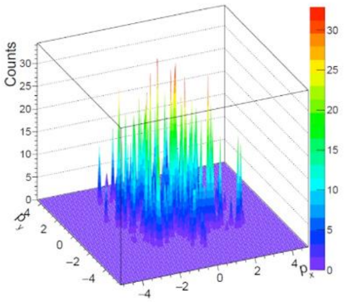
Signal for Critical Point:
Density fluctuations and long range correlations near the QCD critical point.

Intermittency for Charged Particle

STAR, Physics Letters B 845 (2023) 138165

Probing the density fluctuations and long range correlations near the QCD critical point via intermittency analysis in transverse momentum plane.



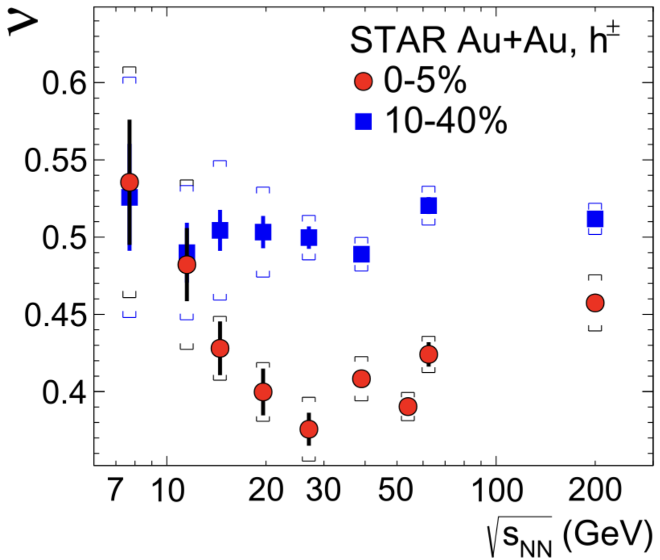


$$F_q(M) = \frac{< \frac{1}{M^D}\sum_{i=1}^{M^D} n_i(n_i-1)\ldots(n_i-q+1) >}{< \frac{1}{M^D}\sum_{i=1}^{M^D} n_i >^q}$$

$$\Delta F_q(M) = F_q^{data}(M) - F_q^{mix}(M)$$

$$\Delta F_q(M) \propto \Delta F_2(M)^{\beta_q}$$

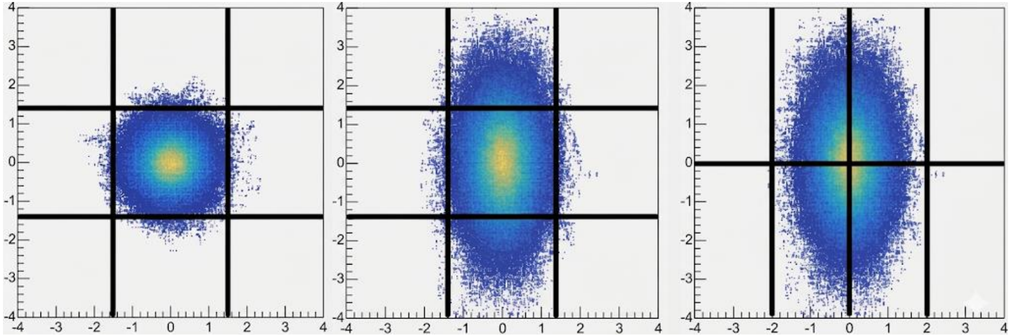
$$\boxed{\beta_q \propto (q-1)^{\nu}}$$



- **Scaling exponent exhibits a non-monotonic energy dependence in central collisions with a minimum around $\sqrt{s_{NN}}$ = 27 GeV.**

Self-affine analysis for anisotropy phase space

- ❑ Intermittency(self-similar) analysis ignore the anisotropy phase space in HIC evolution.



✓ Self-affine anlysis to taken into account the anisotropy of the nature.

VOLUME 70, NUMBER 21 PHYSICAL REVIEW LETTERS 24 MAY 1993

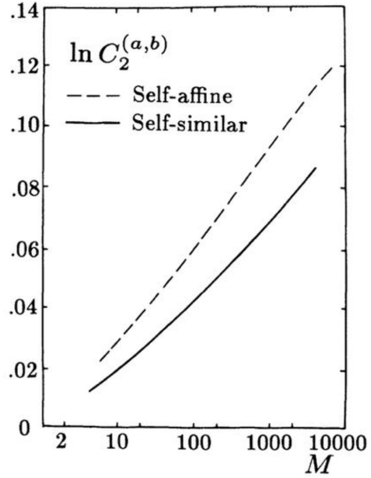
Self-Affinity of Multiplicity Fluctuation in the Phase Space of Multiparticle Production

Wu Yuanfang and Liu Lianshou

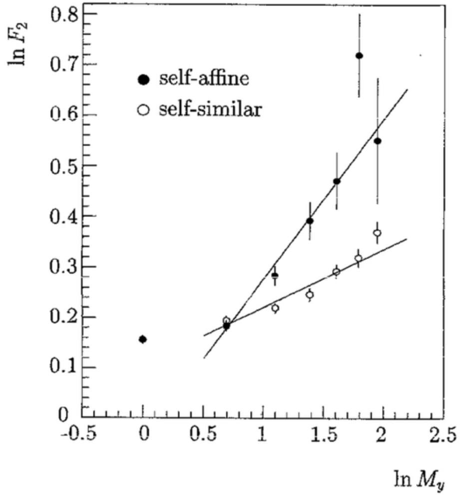
Institute of Particle Physics, Hua-Zhong Normal University, Wuhan 430070, China

(Received 11 December 1992; revised manuscript received 11 March 1993)

It is argued that, accounting for the anisotropy of phase space, the local fluctuations of multiplicity in high energy multiparticle production are self-affine rather than self-similar. Evidence is given confirming self-affinity in phase-space distributions. A method is proposed to extract the characteristic parameter of self-affinity, the Hurst exponent, from the experimental data iteratively.



NA22 Collaboration



Yuanfang Wu, Lianshou Liu., Phy. Rev. Lett. 70,3197 (1993)
EHS/NA22 Collaboration, Phy. Lett. B 382,305-311 (1996)

- ➢ Power-law scaling is more clearly and consistently realized in self-affine analysis than in self-similar analysis.

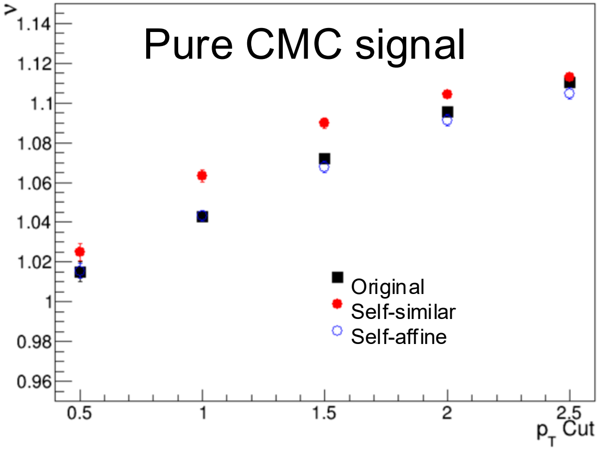
Self-affine Vs self-sinilar

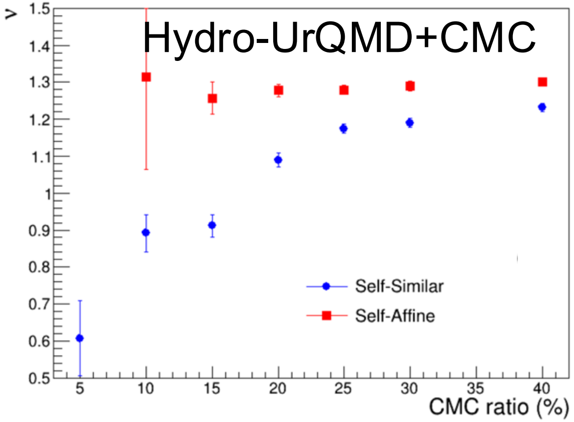
A Critical Monte-Carlo (CMC) with anisotropy:

Phy. Rev. Lett. 97,032002 (2006)
Physics Letters B 801 (2020) 135186

$$\rho(p)=\frac{\nu p_{\min}^{\nu}}{1-\left(p_{\min}/p_{\max}\right)^{\nu}}\,p^{-1-\nu}$$

Levy random walk method for local density fluctuations.



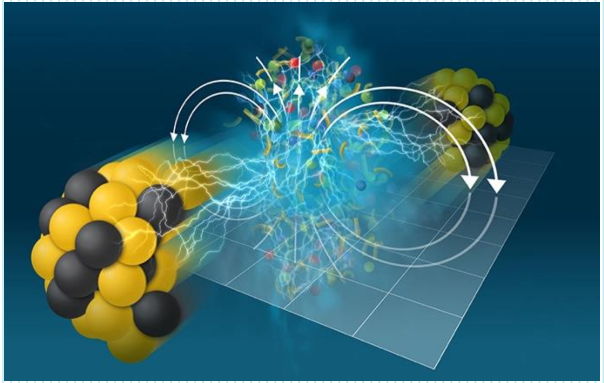


The methodology paper and data analysis are currently in progress. Stay tune!

- ➢ The original CMC signal can be produced when taken into account the anisotropy with self-affine analysis
- ➢ Compared with self-similar analysis, self-affine analysis is less affected by CMC signals.

Search for Electromagnetic(EM) Effects in HIC

Between Λ0 and Λ0-bar
(STAR Collaboration)

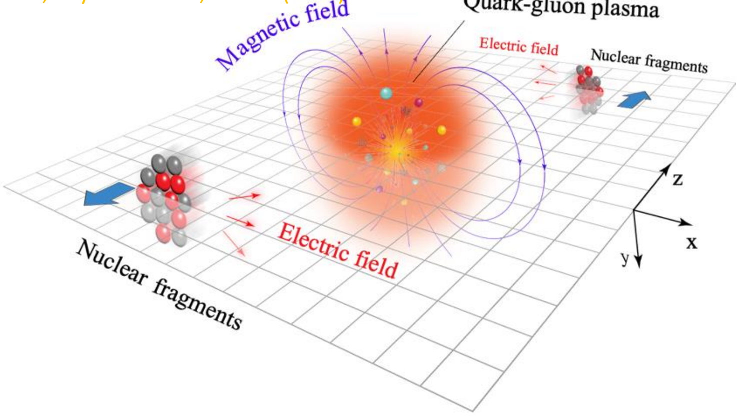


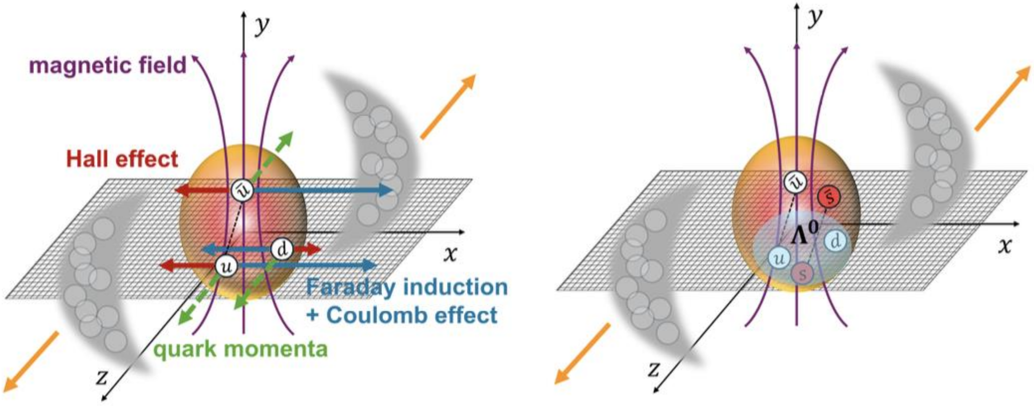
Signal for EM filed:

Directed Flow Splitting.

Directed Flow Splitting Between Λ^0 and $\overline{\Lambda^0}$

STAR, Phys. Rev. X 14, 011028(2024)

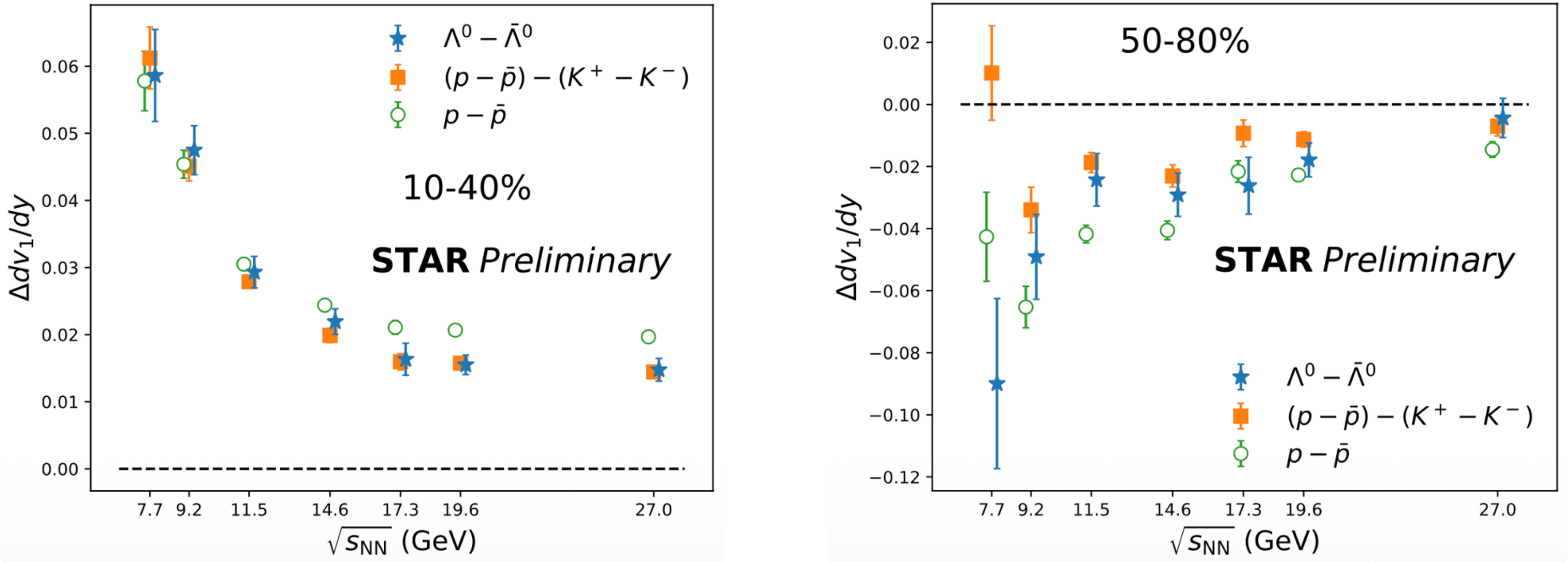




- Electromagnetic(EM) field effects can act on quarks before hadronization $v_1\left(\sum_{quark} q_i\right) = \sum_{quark} v_1(q_i)$
- $\Delta dv_1/dy$ of quark can impact to hardon through coalescence：

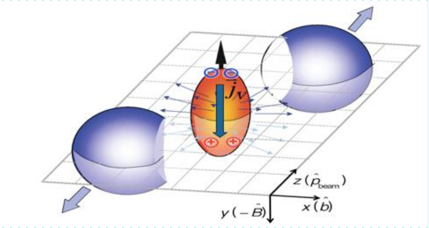
$$\Delta\left(\frac{dv_1}{dy}\right)_{[\Lambda^0(uds)-\overline{\Lambda^0}(\overline{uds})]} \sim \left(\Delta\left(\frac{dv_1}{dy}\right)_{[p(uud)-\bar{p}(\overline{uud})]} - \Delta\left(\frac{dv_1}{dy}\right)_{[K^+(u\bar{s})-K^-(\bar{u}s)]}\right)$$

Directed Flow Splitting Between Λ^0 and $\overline{\Lambda^0}$

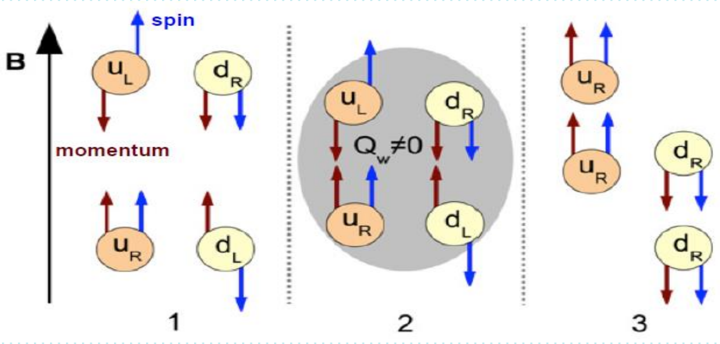


➢ Lambda $\Delta dv_1/dy$ consistent with difference between proton and kaon, agreeing with coalescence expectation.

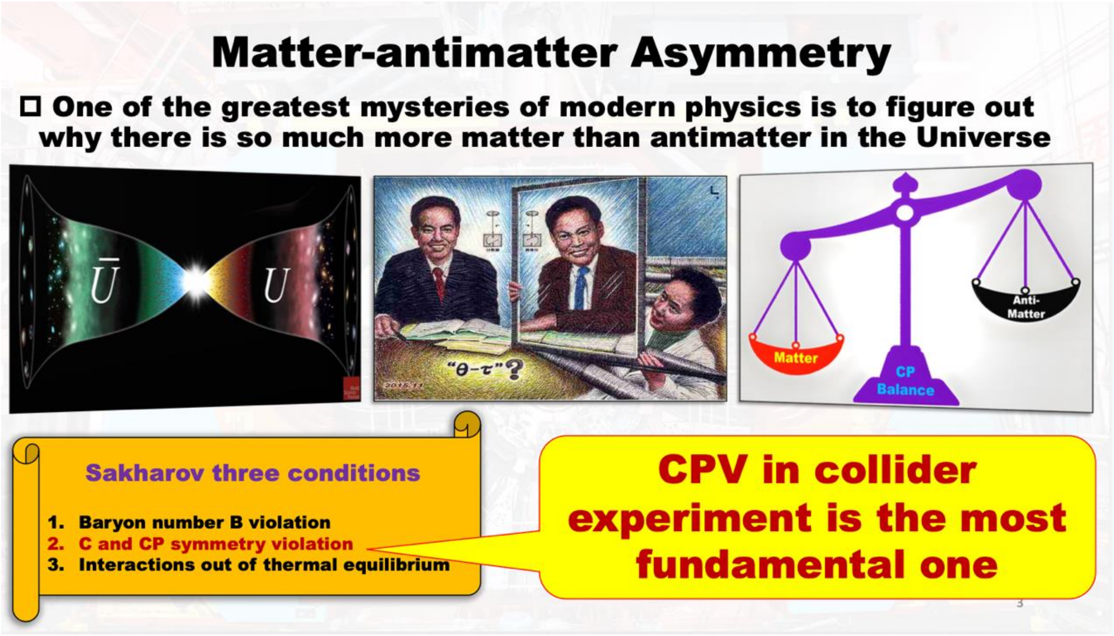
Search for Chiral Magnetic Effect in isobar collisions

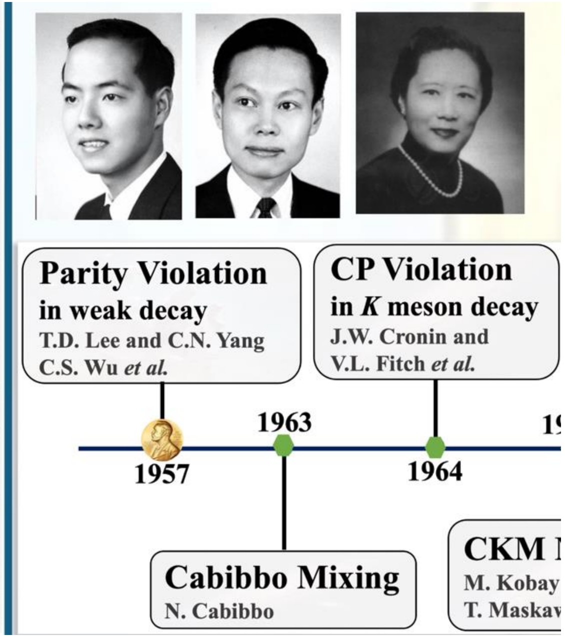


(STAR Collaboration)



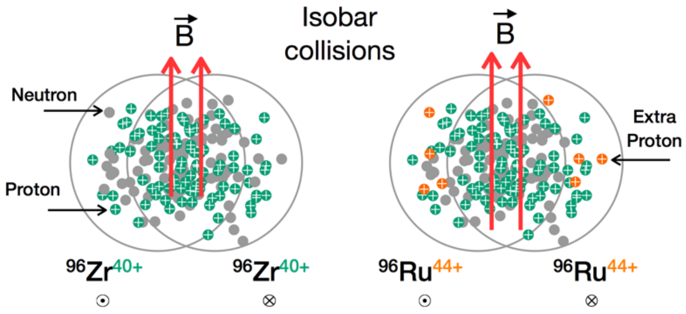
Signal for CME: charge separation of positively and negatively





- The chiral magnetic effect (CME) is predicted to occur as a consequence of a local violation of P and CP symmetries of the strong interaction amidst a strong electromagnetic field.

Isobaric Collision and Blind-analysis at STAR



Charge Asymmetry Correlation Measurement

Background | Signal **RuRu**

Background | Signal **ZrZr**

✓ Expectations for CME signal:

$$\frac{\boldsymbol{Observable(Ru+Ru)}}{\boldsymbol{Observable(Zr+Zr)}} > 1$$

✓ The two isobaric systems: Difference in the CME signal but same flow backgrounds.

STAR, NUCL SCI TECH 32, 48 (2021)

Phase-I Blinding

- Mock data challenge
  Test data Structure (27 GeV files)
- Isobar-Mixed Analysis
  QA, physics & code freezing (One run is Ru+Zr)

Establish all procedures

Phase-II Blinding

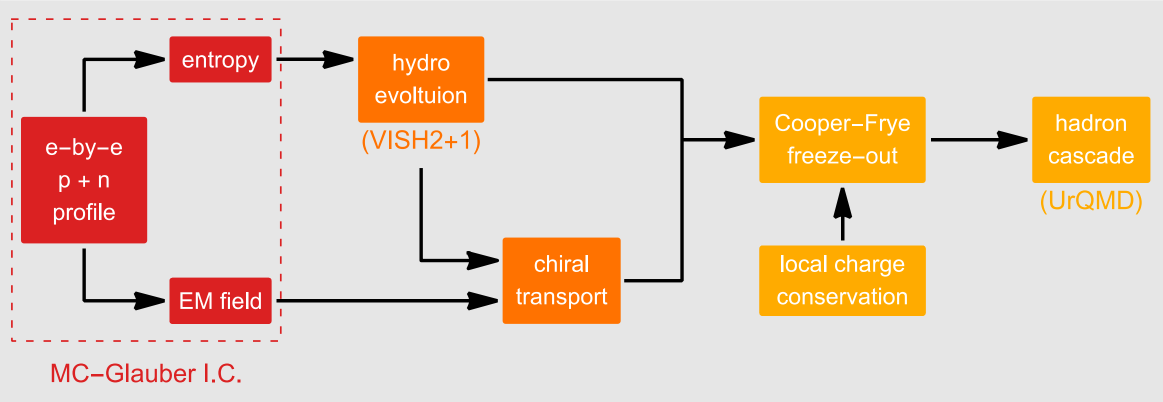
- Isobar-Blind Analysis
  Run-by-run QA, Full analysis (One run is Ru/Zr)
- Isobar-Unblind Analysis
  Full analysis (Ru and Zr Separated)

Act "blindly" on all procedures

- The STAR Collaboration has implemented a blind-analysis recipe to eliminate unintentional biases in data analyses, and currently all the analysis codes have been frozen as part of the blinding procedure. (Five institutional groups participated with various observables)
- Desirable to study the connection and difference between various observables, and their sensitivities to the CME signals.

EBE-AVFD Beta1.0 with Isobars

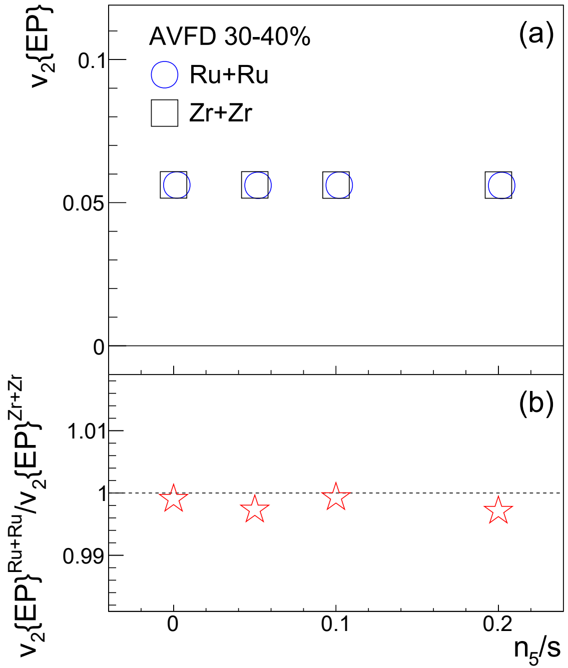
EBE-AVFD: event-by-event anomalous-viscous fluid dynamics



Y. Jiang, S. Shi, Y. Yin and J. Liao, Chin. Phys. C 42 No. 1 011001 (2018)
S. Shi, Y. Jiang, E. Lilleskov and J. Liao. Annals of Physics 394 50-72 (2018)
S. Shi, H. Zhang, D. Hou, and J. Liao. Phys. Rev. Lett. 125, 242301 (2020)

n_5/s	$a_{1,+}$ (%)		$a_{1,-}$ (%)	
	Ru+Ru	Zr+Zr	Ru+Ru	Zr+Zr
0	0	0	0	0
0.05	0.37	0.35	0.35	0.33
0.10	0.74	0.69	0.71	0.66
0.20	1.48	1.38	1.42	1.32

✓ a_1 (Ru) > a_1 (Zr)



✓ The major background (v_2) is identical.

Significance Study for Isobaric Collision with AVFD

With frozen code.

n_5/s	N_{event}	$\Delta\gamma_{112}$	κ_{112}	r_{lab}	σ_{R2}^{-1}	$\Delta\gamma_{112}\{\text{RP}\}$	$\sigma_{R2}^{-1}\{\text{RP}\}$
0	2×10^8	-1.50	-1.21	-0.77	1.33	0.67	0.56
0.05	4×10^8	0.62	1.37	0.47	0.29	2.84	3.33
0.10	4×10^8	1.91	3.43	3.11	0.62	11.78	10.85
0.20	2×10^8	7.73	14.07	5.96	1.84	37.48	27.90

The O_{RP}: True RP and same kinematic cuts.

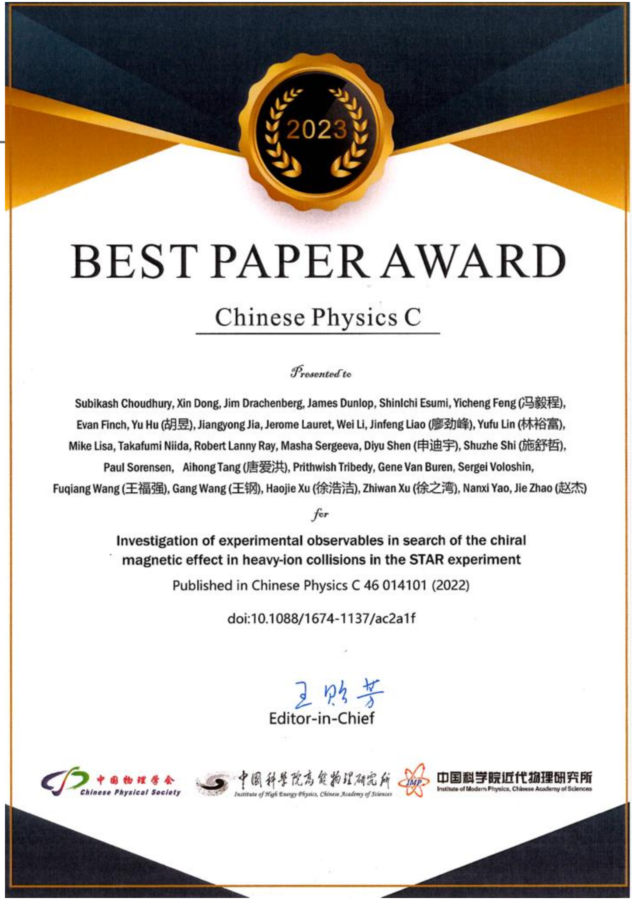
- The ratios of two isobars, $\Delta\gamma$ and r_{lab} show compatible and decent sensitivity.

The best paper award

Chinese Physics C Vol. 46, No. 1 (2022) 014101

Investigation of experimental observables in search of the chiral magnetic effect in heavy-ion collisions in the STAR experiment*

Subikash Choudhury[1] Xin Dong[2] Jim Drachenberg[3] James Dunlop[4] ShinIchi Esumi[5] Yicheng Feng(冯毅程)[6] Evan Finch[7] Yu Hu(胡昱)[1,4] Jiangyong Jia[4,8] Jerome Lauret[4] Wei Li[9] Jinfeng Liao(廖劲峰)[10] Yufu Lin(林裕富)[11,12†] Mike Lisa[13] Takafumi Niida[5] Robert Lanny Ray[14] Masha Sergeeva[15] Diyu Shen(申迪宇)[1‡] Shuzhe Shi(施舒哲)[16] Paul Sorensen[4] Aihong Tang(唐爱洪)[4] Prithwish Tribedy[4] Gene Van Buren[4] Sergei Voloshin[17] Fuqiang Wang(王福强)[6] Gang Wang(王钢)[15] Haojie Xu(徐浩洁)[18] Zhiwan Xu(徐之湾)[15] Nanxi Yao[15§] Jie Zhao(赵杰)[6]


2023

BEST PAPER AWARD

Chinese Physics C

Presented to

Subikash Choudhury, Xin Dong, Jim Drachenberg, James Dunlop, ShinIchi Esumi, Yicheng Feng (冯毅程), Evan Finch, Yu Hu (胡昱), Jiangyong Jia, Jerome Lauret, Wei Li, Jinfeng Liao (廖劲峰), Yufu Lin (林裕富), Mike Lisa, Takafumi Niida, Robert Lanny Ray, Masha Sergeeva, Diyu Shen (申迪宇), Shuzhe Shi (施舒哲), Paul Sorensen, Aihong Tang (唐爱洪), Prithwish Tribedy, Gene Van Buren, Sergei Voloshin, Fuqiang Wang (王福强), Gang Wang (王钢), Haojie Xu (徐浩洁), Zhiwan Xu (徐之湾), Nanxi Yao, Jie Zhao (赵杰)

for

Investigation of experimental observables in search of the chiral magnetic effect in heavy-ion collisions in the STAR experiment

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王贻芳

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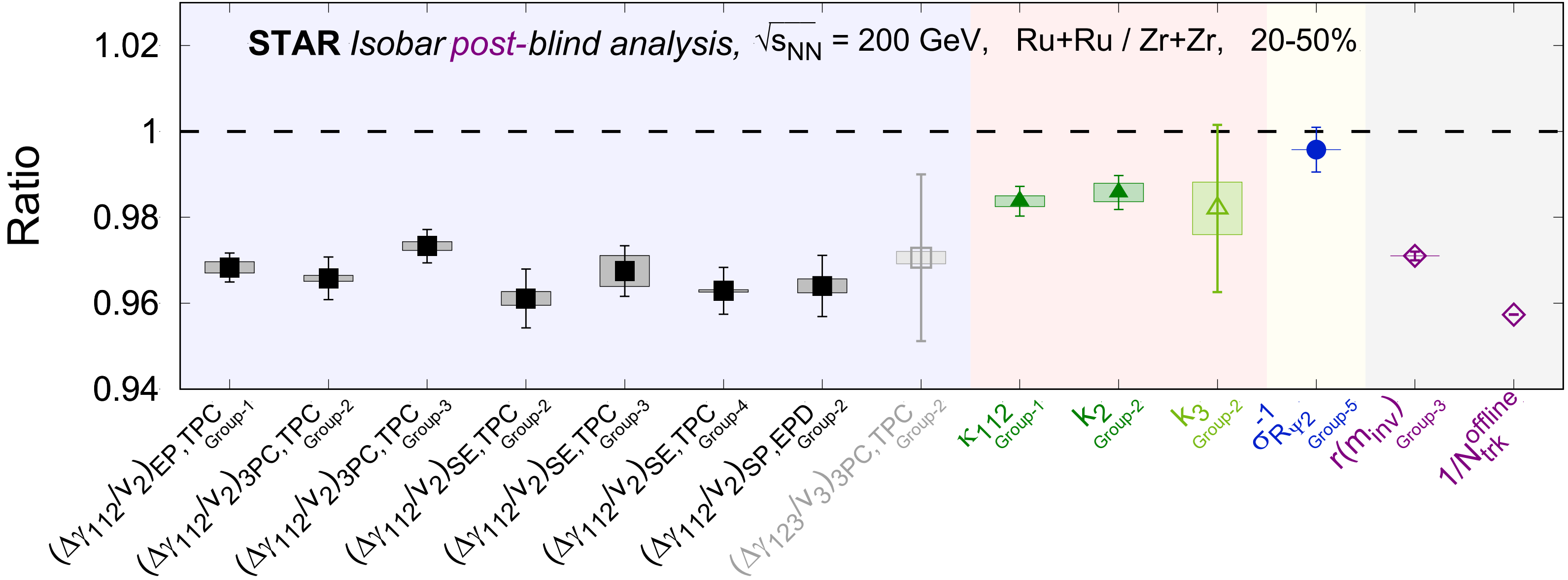
Blind-analysis at STAR

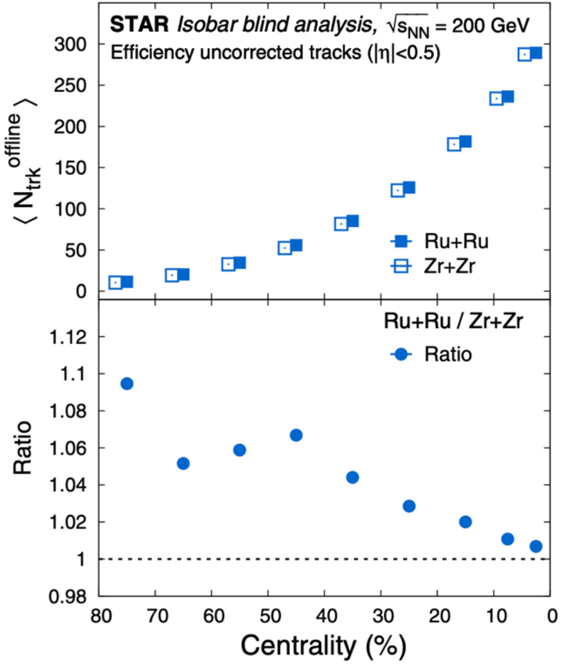
STAR Isobar blind analysis, PRC 105, 014901 (2022)

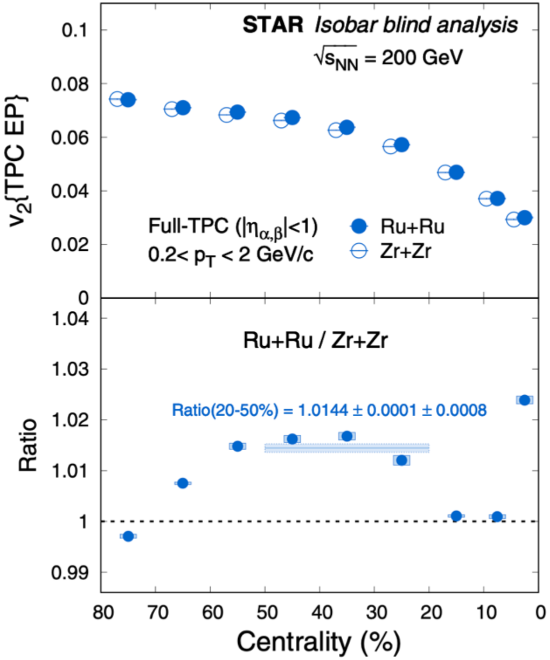


❖ Pre-defined signature ($Ratio > 1$) of CME is not observed.

Blind-analysis at STAR

STAR Isobar blind analysis, PRC 105, 014901 (2022)





❖ Differences in the multiplicity and v_2 is observed between the two species.

✓ The BKG difference should be deal with.

Forced match!

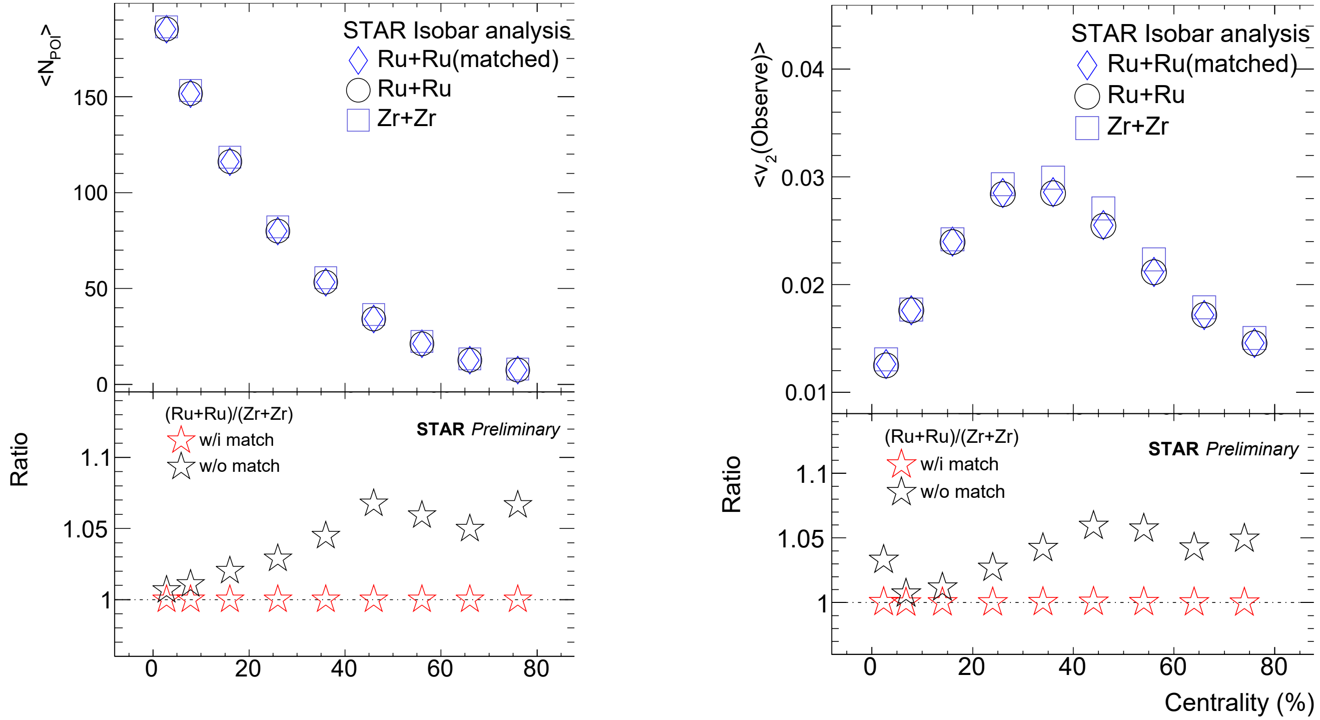
Keep the Zr+Zr original and then match the Ru+Ru Distribution to Zr+Zr.

$$f_{w,bin} = N_{bin(Zr)} \,/\, N_{bin(Ru)}$$
$$S_O \mathrel{+}= O_{bin(Ru)} \cdot N_{bin(Ru)} \cdot f_{w,bin}$$

$$S_w \mathrel{+}= N_{bin(Ru)} \cdot f_{w,bin}$$

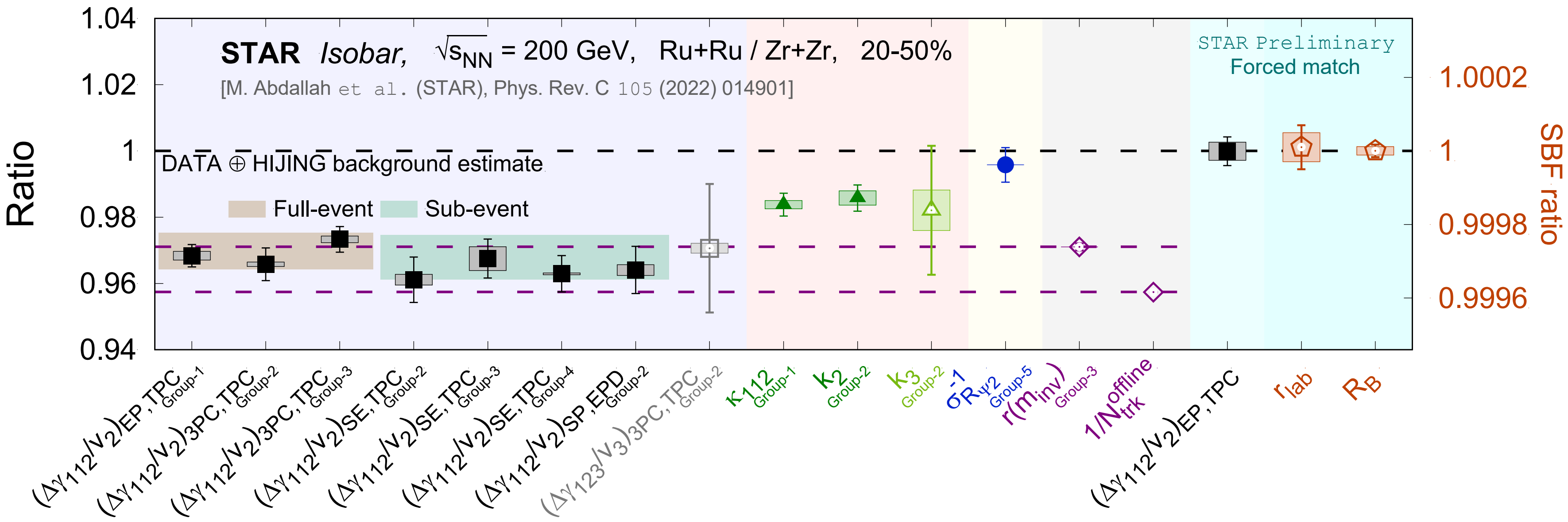
$$\boldsymbol{O_{Ru(matched)} = S_O \,/\, S_w}$$

Isobar collision with forced match



➤ The different backgrounds have been removed with forced match.

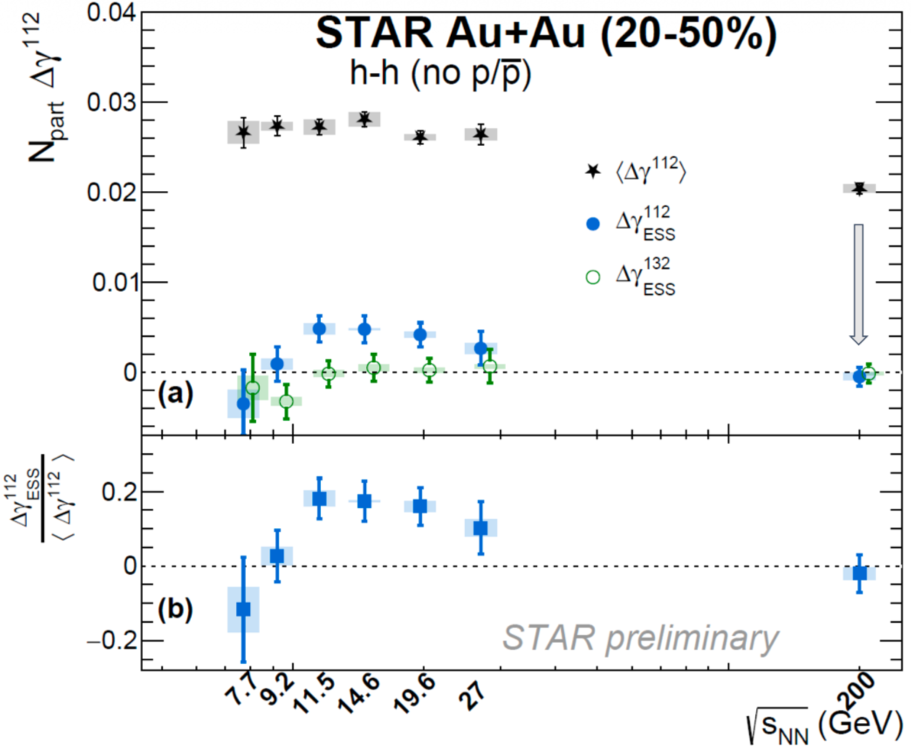
Isobar collision with forced match



➢ No obvious CME signal has been observed in Isobar collisions.

Either with SBF method or γ correlator method, when the differences of the multiplicity and v_2 have been removed with forced match.

Event Shape Selection for CME



- $\Delta\gamma^{132}_{ESS}$ **consistent with zero.**
- **At least 80% of the measured $\Delta\gamma^{112}$ comes from BKG.**
- **At 200 GeV,**
  - **ratio is (-2 ± 5.1 ± 1.6)%**
  - **upper limit of f_{CME}~10% in Au+Au**
  - **upper limit of f_{CME}~ 5% in isobars using participant planes: 0.7% difference, too small to detect!**
- **If we combine three points at 19.6, 14.6 and 11.5 GeV, the literal average of the ESS results reaches an over 5σ significance (assuming similar physics conditions between 10 and 20 GeV).**
- **The ESS results approach zero around 9.2 and 7.7 GeV.**

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New measurements for CME?

- Shear-induced anomalous transport and charge asymmetry of triangular flow in heavy-ion collisions, Matteo Buzzegoli, Dmitri E. Kharzeev, Yu-Chen Liu, Shuzhe Shi, Sergei A. Voloshin, Ho-Ung Yee, Physical Review C 106, L051902 (2022)
- Detecting anomalous CP violation in heavy-ion collisions through baryon-electric charge correlations, David Frenklakh, Dmitri E. Kharzeev and Andrea Palermo, PHYSICAL REVIEW D 110, 114007 (2024)
- New method to clarify the contribution of the chiral magnetic effect in small collision systems $p{\uparrow}+A$ involving a transversely polarized proton. Gui-Zhen Wu (吴桂珍), Zong-Wei Zhang (张宗炜), Chen Gao (高晨), Yi Xu (许易) and Wei-Tian Deng (邓维天)， PHYSICAL REVIEW C **110**, L061901 (2024)
- Studying Effects of Evolution on Charge Separation in Small Collision System with A MultiPhase Transport model， Yi Xu, Chen Gao, Shi-Xue Zhang, Wei-Tian Deng， arXiv:2502.17232
- Event-by-event analysis of chiral charge separation in p↑+Au collisions within an improved AMPT model Chen Gao, Gui-Zhen Wu, Yi Xu, Wei-Tian Deng, arXiv:2608.10496

- **AI**
- Search for CME with Transformers, Aihong Tang, Chirality workshop 2025
- Optimal observables for the chiral magnetic effect from machine learning, Yuji Hirono, Kazuki Ikeda, Dmitri E. Kharzeev, Ziyi Liu, Shuzhe Shi, Phys.Rev.C 112 (2025) 5, L051904

Summary and outlook

- **Search for QCD critical point:**
  - Known model calculations **Do Not** reproduce the energy dependence ($\sqrt{s_{\mathrm{NN}}}$ = 7.7 – 200 GeV)
  - The observed non-monotonic behavior of ν in central collisions needs to be understood with more theoretical inputs.

- **No CME signal has been observed in Isobar collision.**

Outlook:

- ❑ Complete FXT data analysis at $\sqrt{s_{\mathrm{NN}}}$ = 3 – 3.9 GeV
- ❑ Self-affine analysis in BES-II data
- ❑ New measurements for CME study

谢谢大家的聆听！

STAR shut down on Feb.6, 2026