

基于RHIC和HIAF大科学装置 QCD相变临界点的研究

许 怒

华中师范大学

中国科学院近代物理研究所

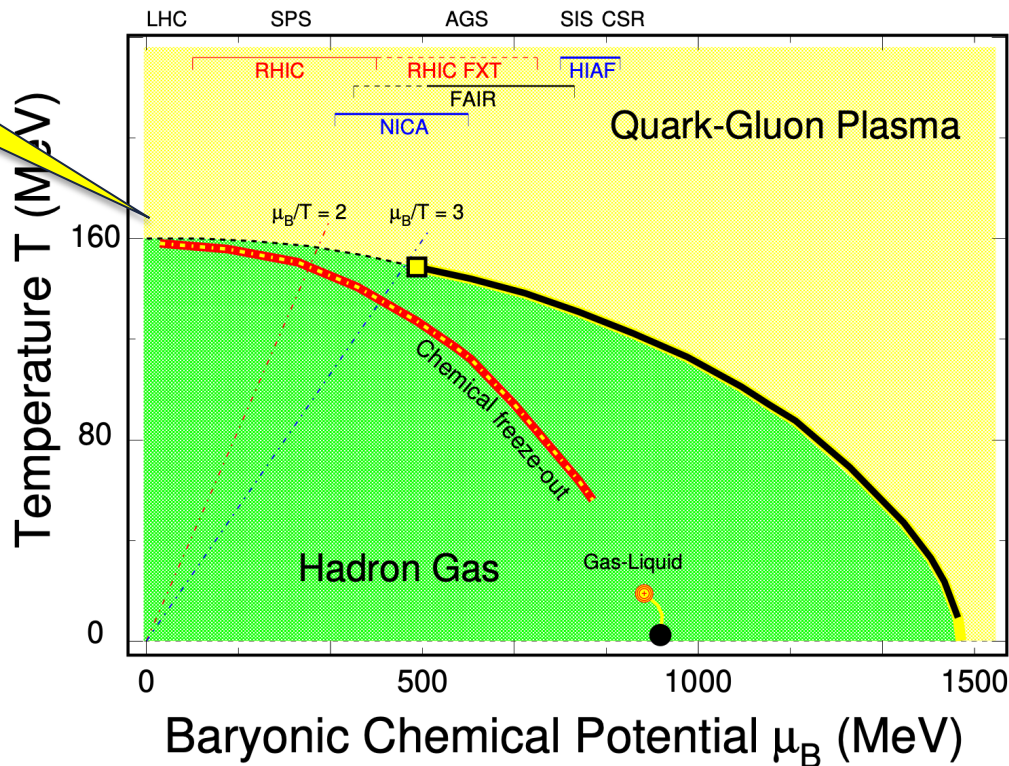


Major HI Accelerator Complexes

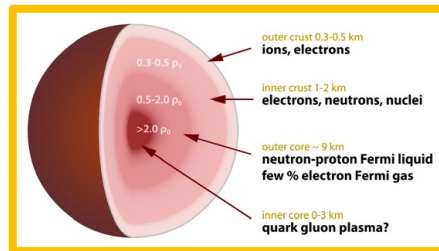


- 1) LHC: 2009 –
- 2) RHIC: 2000 – 2026
- 3) NICA: ?
- 4) HIAF: Starts in 2026
- 5) FAIR: Starts in 2029

Early
Universe

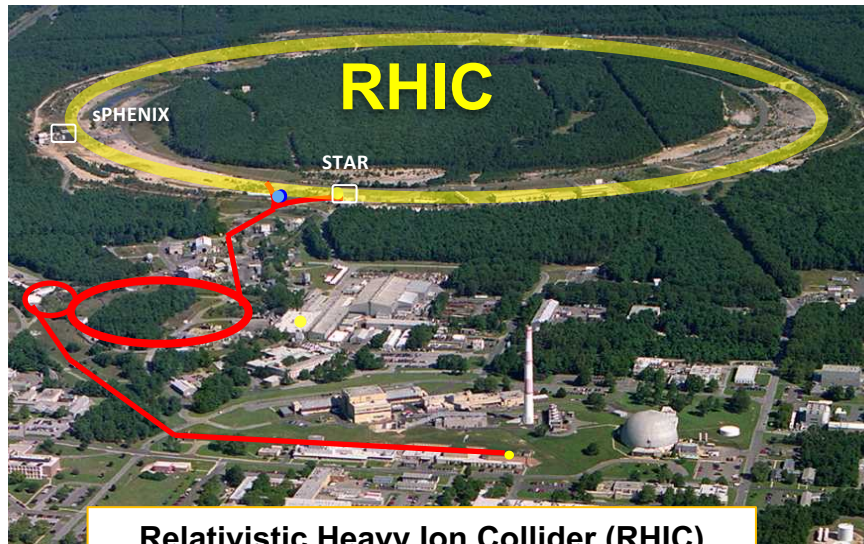


High baryon density:
Inner structure of
compact stars



RHIC BES: 2008 – 2026

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

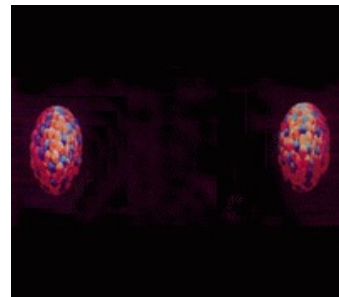


RHIC top collision energies:

- $\sqrt{s_{NN}} = 200$ GeV U+U / Au+Au / Zr+Zr / Ru+Ru / O+O
- $\sqrt{s} = 510$ GeV p+p

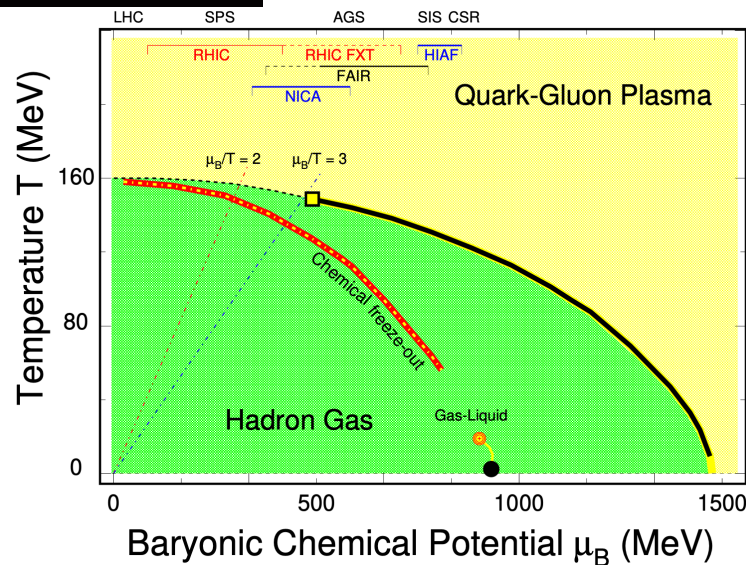
RHIC Beam Energy Scan (BES):

- $\sqrt{s_{NN}} = 200 - 7.7$ GeV (collider mode)
- $\sqrt{s_{NN}} = 17.3 - 3$ GeV (fixed-target mode)

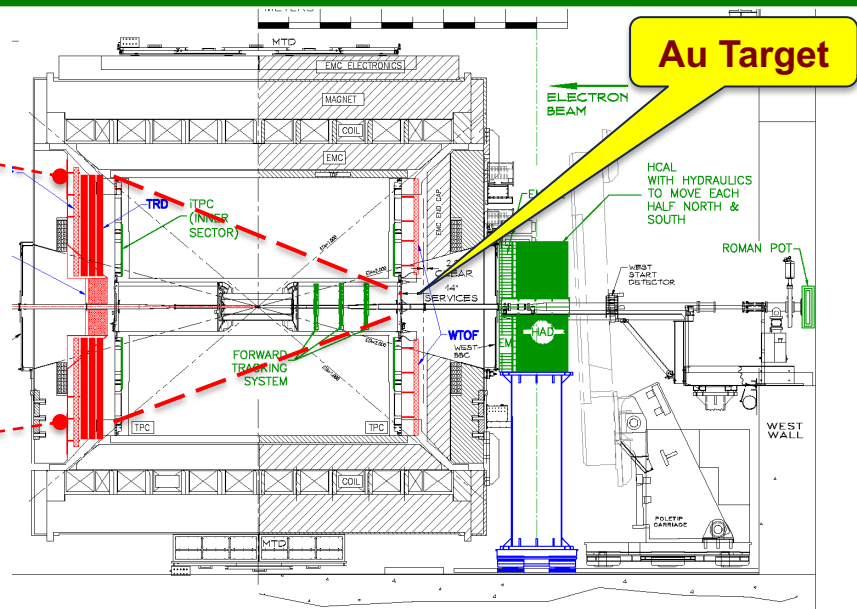
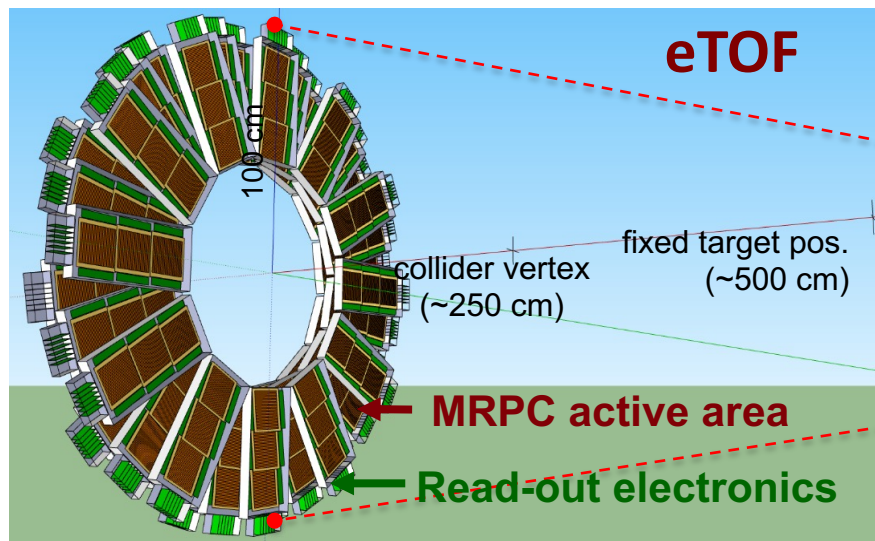


Quark-Gluon Plasma
(QGP)

QCD Phase Diagram



STAR Fixed Target Setup



CBM participates in RHIC BES-II in 2019 – 2021:

- Complementary to CBM program: $\sqrt{s_{NN}} = 3 - 7.2 \text{ GeV}$ ($760 \geq \mu_B \geq 420 \text{ MeV}$)
- Strange-hadron, hyper-nuclei and fluctuation at the high baryon density region

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	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	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	230 MeV		Run- 21	7	5.2 (13.5)	100+ 1000 M	540 MeV	-1.68	Run- 20, 25
8	14.6	340 M	262 MeV		Run-14, 19	8	4.5 (9.8)	110 + 2000 M	590 MeV	-1.52	Run- 20,25
9	11.5	57 M	316 MeV		Run-10, 20	9	4.2 (9.12)	1000 M	610 MeV	-1.41	Run- 25
10	9.2	160 M	372 MeV		Run-10, 20	10	3.9 (7.3)	120 M	633 MeV	-1.37	Run- 20
11	7.7	104 M	420 MeV		Run- 21	11	3.5 (5.75)	120 M	670 MeV	-1.2	Run- 20
						12	3.2 (4.59)	200 M	699 MeV	-1.13	Run- 19
						13	3.0 (3.85)	260 + 2000 M	760 MeV	-1.05	Run-18, 21

Most precise data to map the QCD phase diagram

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

Collectivity

$$\begin{aligned}\partial_\mu [(\varepsilon + p)u^\mu u^\nu - pg^{\mu\nu}] &= 0 \\ \partial_\mu [s u^\mu] &= 0\end{aligned}$$

$$\frac{d^2N}{p_T dp_T d\varphi} = \frac{1}{2\pi} \frac{dN}{p_T dp_T} \left\{ 1 + \sum_{n=1}^{\infty} 2v_n(p_T) \cos[n(\varphi - \Psi_R)] \right\}$$

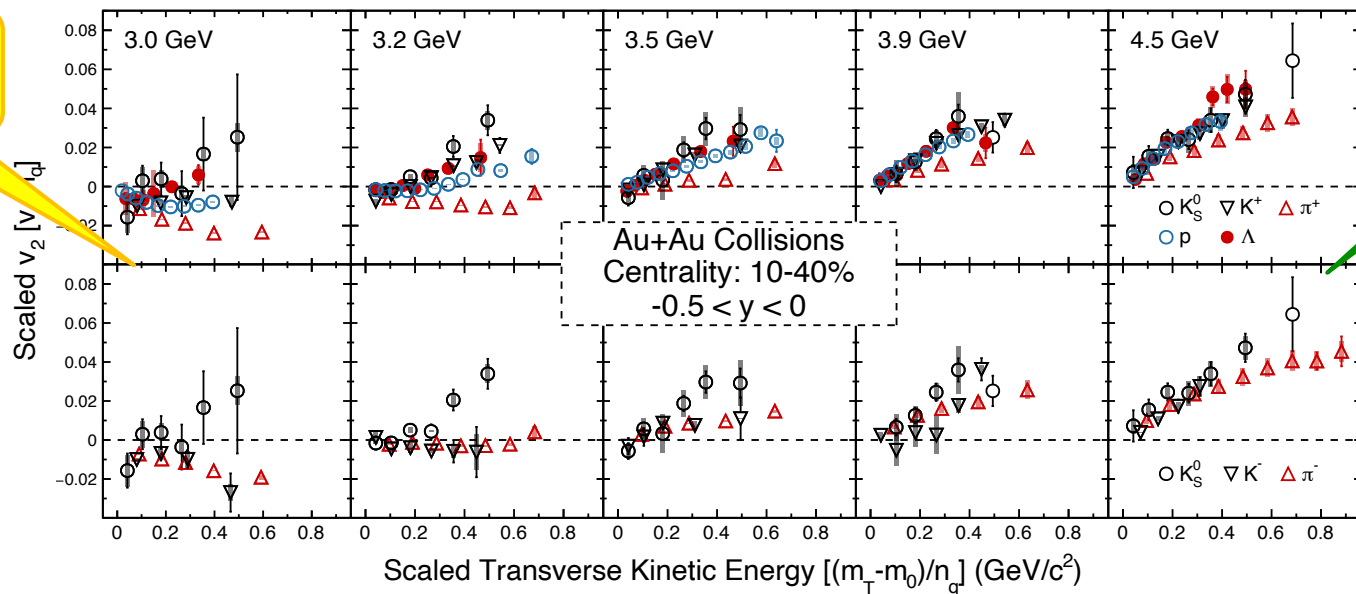
– v_1 Directed flow;

– v_2 Elliptic flow;

– v_3 Triangle flow

Onset of Partonic Collectivity

**Hadronic
Matter**

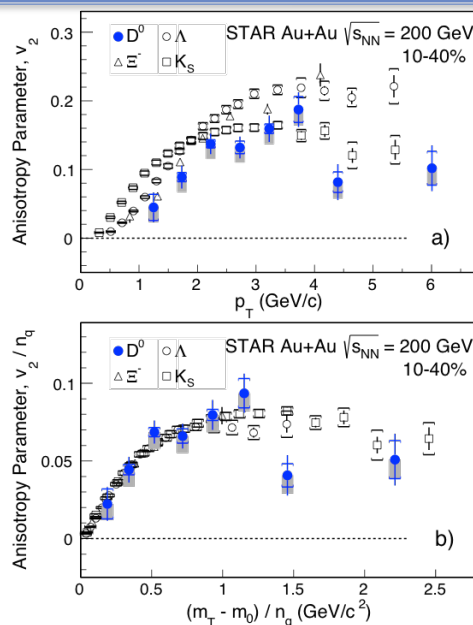
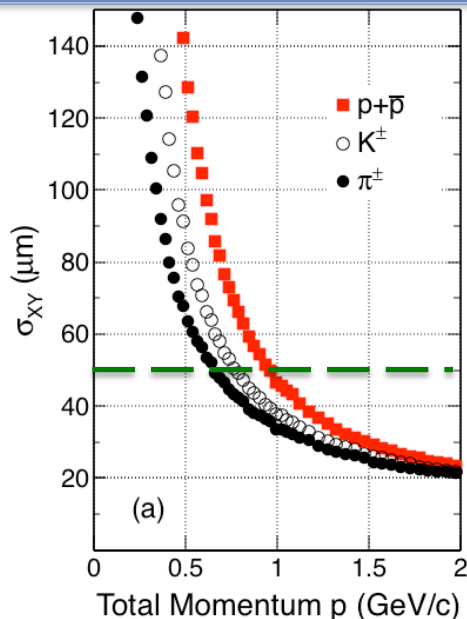


QGP

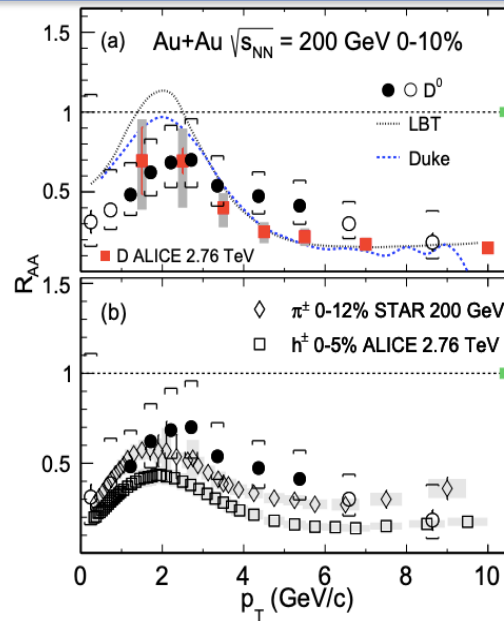
At **3 GeV**, NCQ scaling is absent, hadronic interactions dominant. But the scaling is gradually restored when energy increased to 4.5 GeV !

STAR: PLB827, 137003(2022)
PRL135, 072301(2025)

Heavy Flavor D^0 Collectivity at HRIC



PRL118, 212301 (2017)

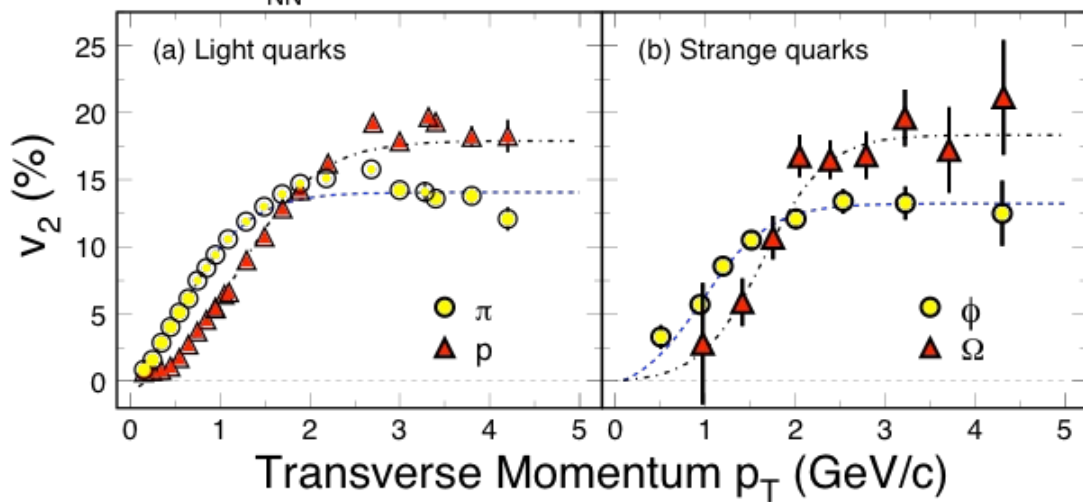


PRL113, 142301 (2014)
PRC99, 034908(2019)

- 1) First application of MAPS technology in high energy collisions, excellent position resolution;
 - “These results suggest that charm quarks have achieved **local thermal equilibrium** with the medium created in such (200GeV Au+Au) collisions”
 - Hadronization via **quark coalescence** process

STAR: PRL113, 142301(14); PRC99, 034908(19); PRL118, 212301(17); PRL123, 162301(19); PRL124, 172301(20)

$\sqrt{s_{NN}} = 200 \text{ GeV } ^{197}\text{Au} + ^{197}\text{Au} \text{ Collisions at RHIC}$



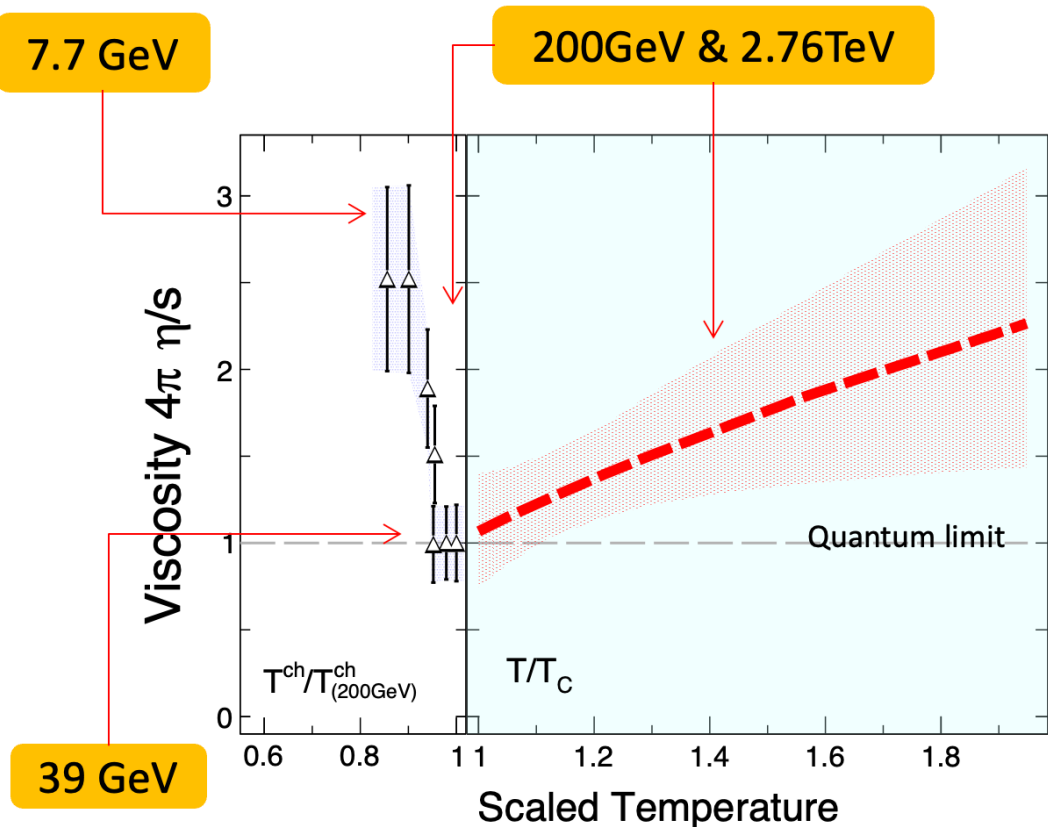
STAR: PRL116, 62301(2016)

- ✓ Low p_T ($\leq 2 \text{ GeV/c}$): hydrodynamic mass ordering
- ✓ High p_T ($> 2 \text{ GeV/c}$): **number of quarks scaling (NCQ)**

u-, d-, and s-quarks flow!

- **Partonic Collectivity!**
- **De-confinement Au+Au collisions at RHIC!**

STAR: PRL116, 62301(2016)



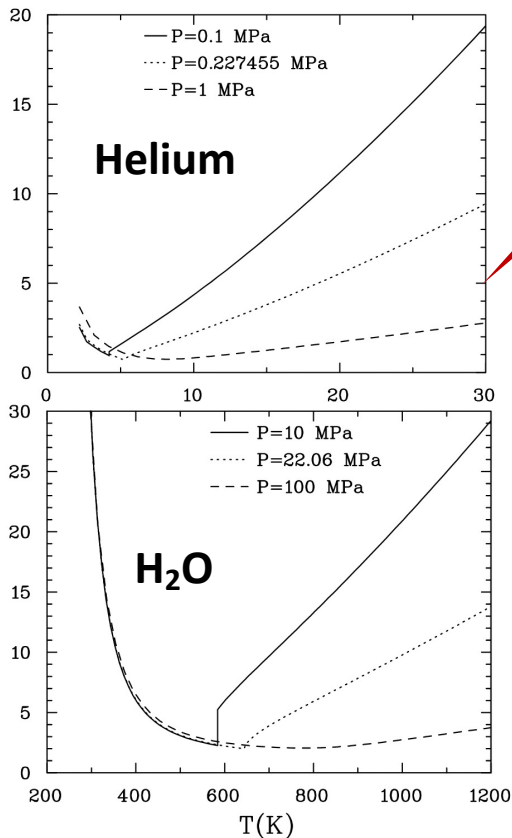
- 1) Left-plot: Energy dependence of η/s extracted from light-flavor hadron v_2 and v_3 . Right-plot: extracted from Bayesian fits to R_{AA} and v_2 at 200GeV collisions;
- 2) Both sides meet at the unity of the scaled temperature;
- 3) The values of η/s increase quickly below $\sqrt{s_{\text{NN}}} = 39 \text{ GeV} \rightarrow$ QGP dominants in higher energies;

→ **Evidence of the QCD transition!**

- 1) L.P. Csernai, J.I. Kapusta, L.D. McLerran, PRL **97** (2006) 152303
- 2) X.Dong, Y.J. Lee & R.Rapp, ARNPS, **69** (2019) 417
- 3) J.E.Bernhard, J.S.Moreland & S. Bass, Nat. Phys. **15** (2015) 1113
- 4) I. Karpenko, P. Huovinen, H. Petersen, and M. Bleicher, Phys.Rev. **C91**, 064901 (2015).
- 5) G.Nijs, W.van der Schee, U. Gürsoy and R. Snellings, PRL **126**, (2021) 202301
- 6) P. Braun-Munzinger, A. Rustamov, NX, arXiv: 2601.18666

武海斌老师报告

Viscosity over Entropy Ratio η/s

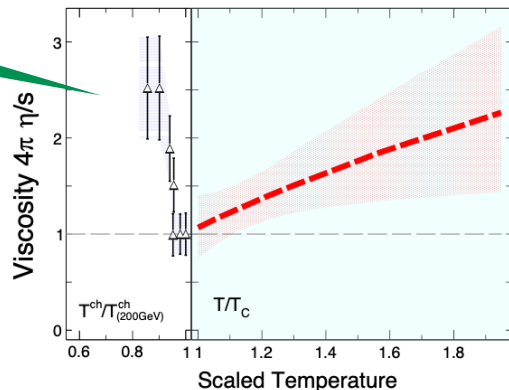
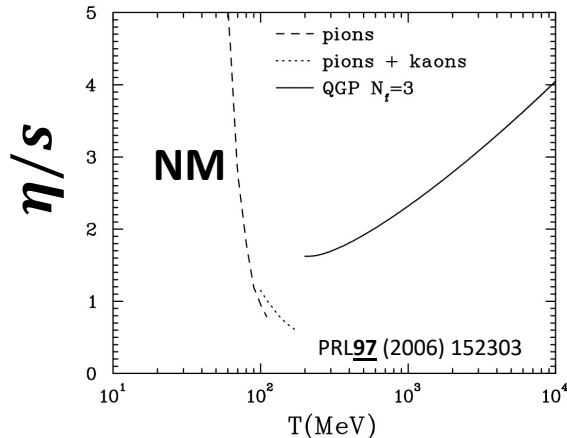


**EM
interaction**
 $\eta/s \sim 1$

L.P. Csernai, J.I. Kapusta, L.D. McLerran, PRL97 (2006) 152303

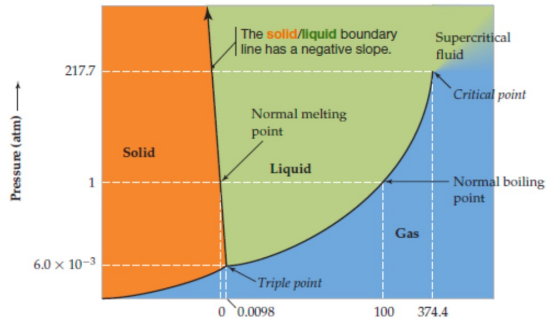
**Strong
Interaction**
 $\eta/s \sim 0.1$

- QGP matter in $\sqrt{s_{NN}} \geq 39$ GeV collisions!
- Universal behavior for phase transition!

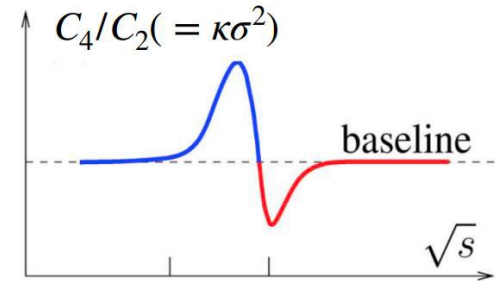
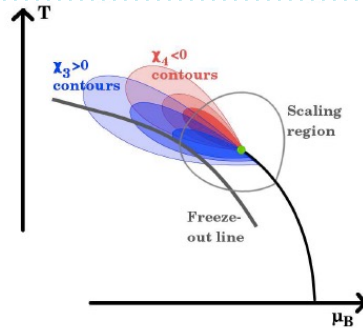


Criticality

QED



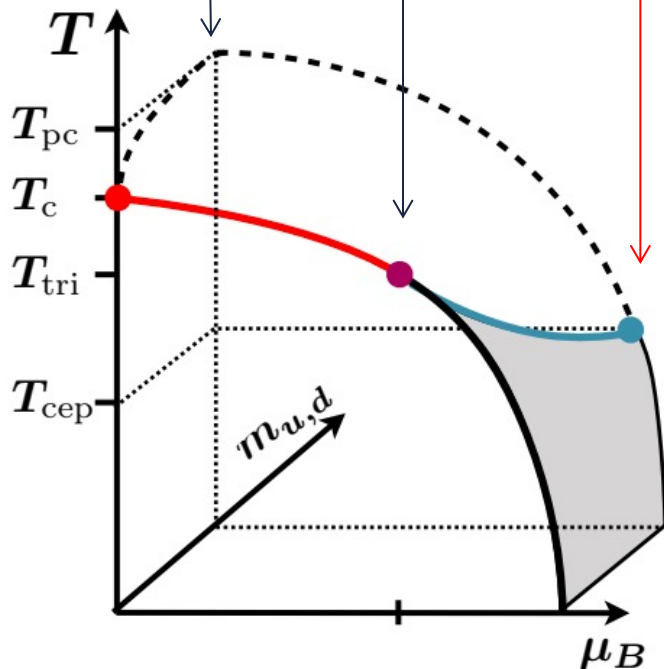
QCD



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

LGT Calculation: QCD Phase Structure

T_C^0 T_{PC} T_{TriC} T^{CEP}



F. Karsch *et al.*, 2020

1) QCD transition temperature:

$$T_{PC} = 156.5 \pm 1.5 \text{ MeV}$$

2) Chiral crossover line

$$T_{PC}(\mu_B) = T_{PC}^0 \left[1 - \kappa_2 \left(\frac{\mu_B}{T_{PC}^0} \right)^2 - \kappa_4 \left(\frac{\mu_B}{T_{PC}^0} \right)^4 \right]$$

$$\kappa_2 = 0.012(4), \quad \kappa_4 = 0.00(4)$$

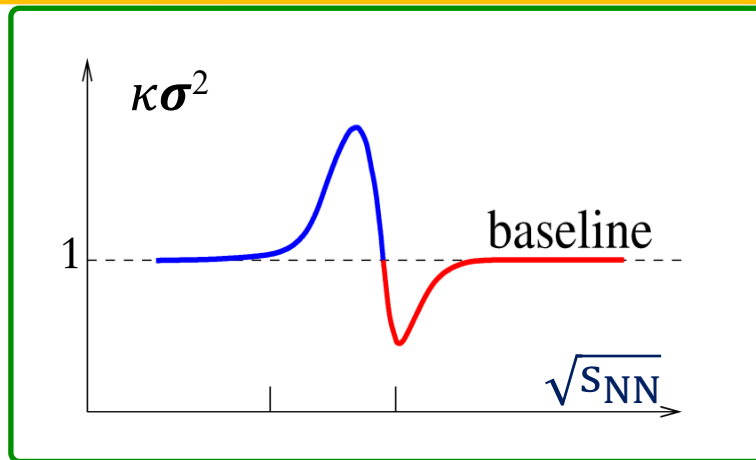
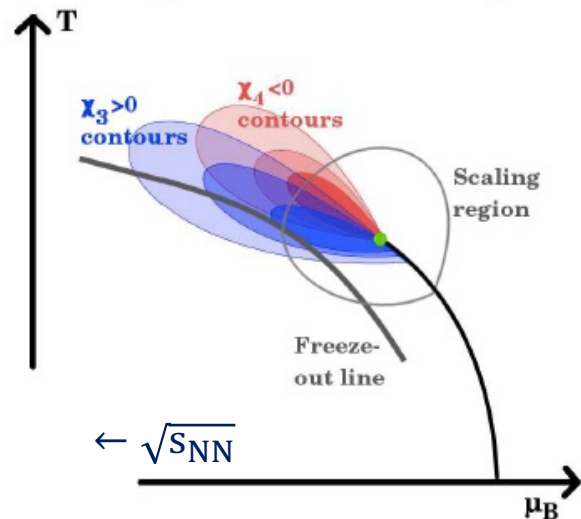
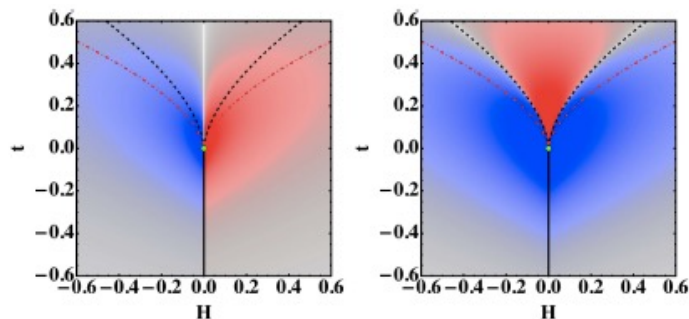
3) Chiral transition temperature:

$$T_C = 132_{-6}^{+3} \text{ MeV}$$

4) QCD critical end point, if exists:

$$T^{CEP} < T_C, \quad \mu_B^{CEP} / T_C \gtrsim 3$$

HotQCD: Phys.Lett.**B795**, 15(2019);
Phys. Rev. Lett. **123**, 062002(2019)

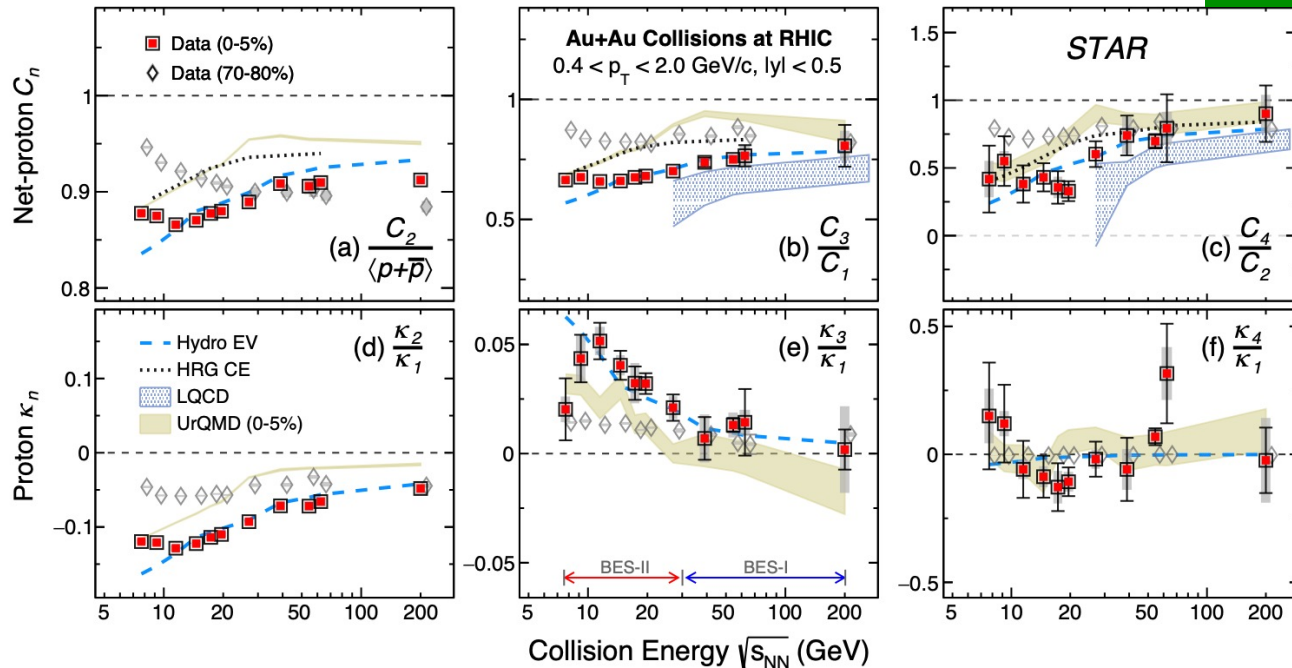


- Characteristic “Oscillating pattern” is expected for the QCD critical point but **the exact shape depends on the location of freeze-out with respect to the location of CP**
- Critical Region (CR)

- M. Stephanov, PRL **107**, 052301(2011) - V. Skokov, Quark Matter 2012
 - J.W. Chen, J. Deng, H. Kohyama, Phys. Rev. **D93** (2016) 034037

Au+Au Collisions at RHIC

STAR: PRL135, 142305(2025)

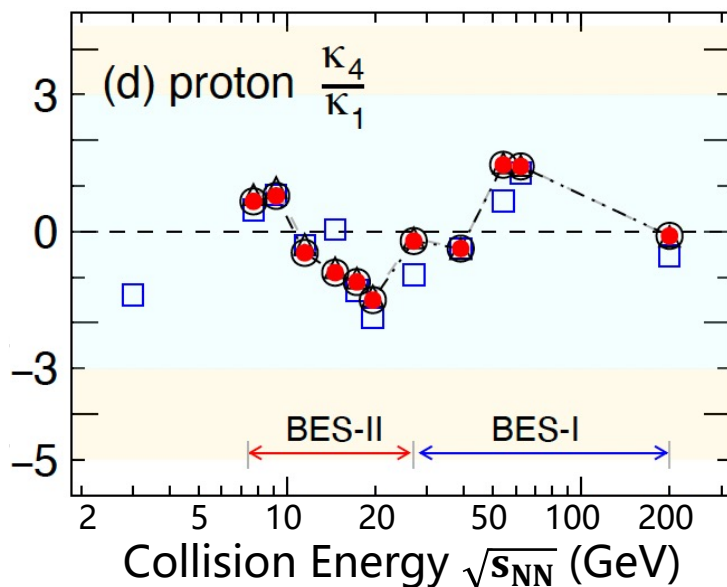
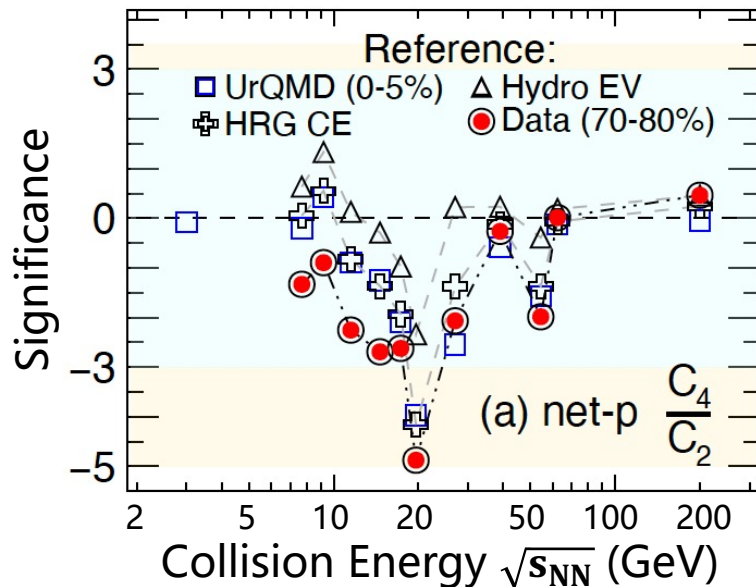


- 1) **UrQMD**: (hadronic transport calculations and the results are analyzed in the same way as data.) S. Bass *et al.*, Prog. Part. Nucl. Phys., **41**, 255 (1998);
- 2) **HRG CE**: P.B. Munzinger *et al.* Nucl. Phys. **A1008**, 122141(2021);
- 3) **Hydro**: HRG CE + EV, V. Vovchenko *et al.*, Phys. Rev. **C105**, 014904 (2022).
- 4) **LQCD**: (done for net-baryon) A. Bazavov *et al.*, Phys. Rev. D101, 074502 (2020). arXiv : 2407.09335

- 1) The energy dependence is reproduced by most calculations at high energy;
- 2) Deviations appear below $\sqrt{s_{NN}} < 35$ GeV

Significances at the 4TH Orders

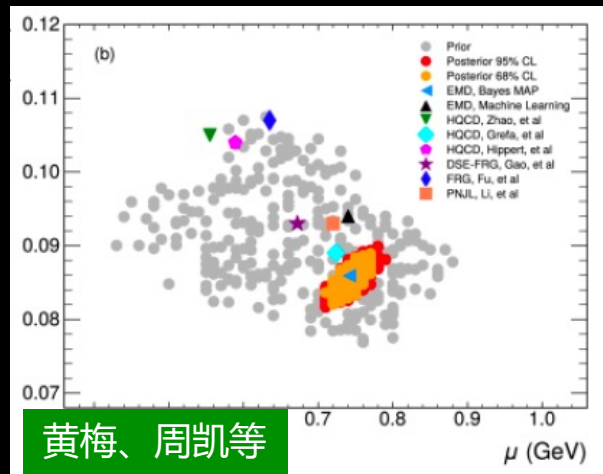
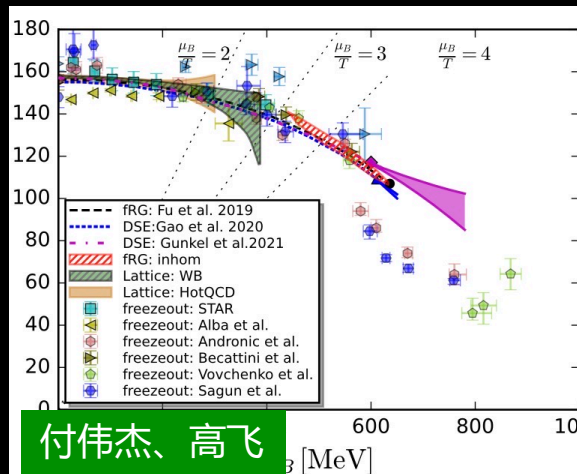
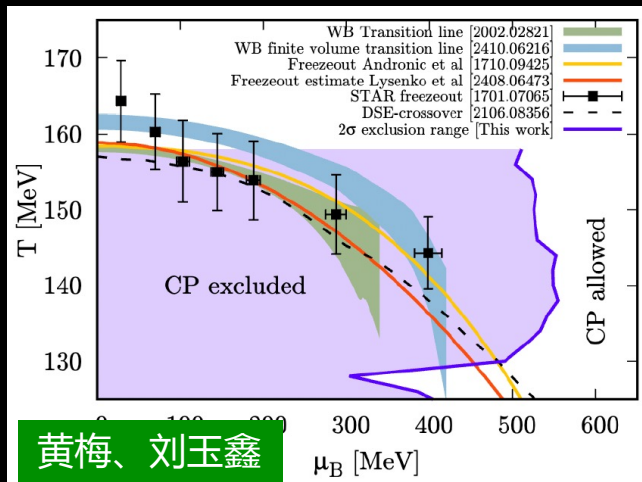
0-5% Au+Au Collisions at RHIC



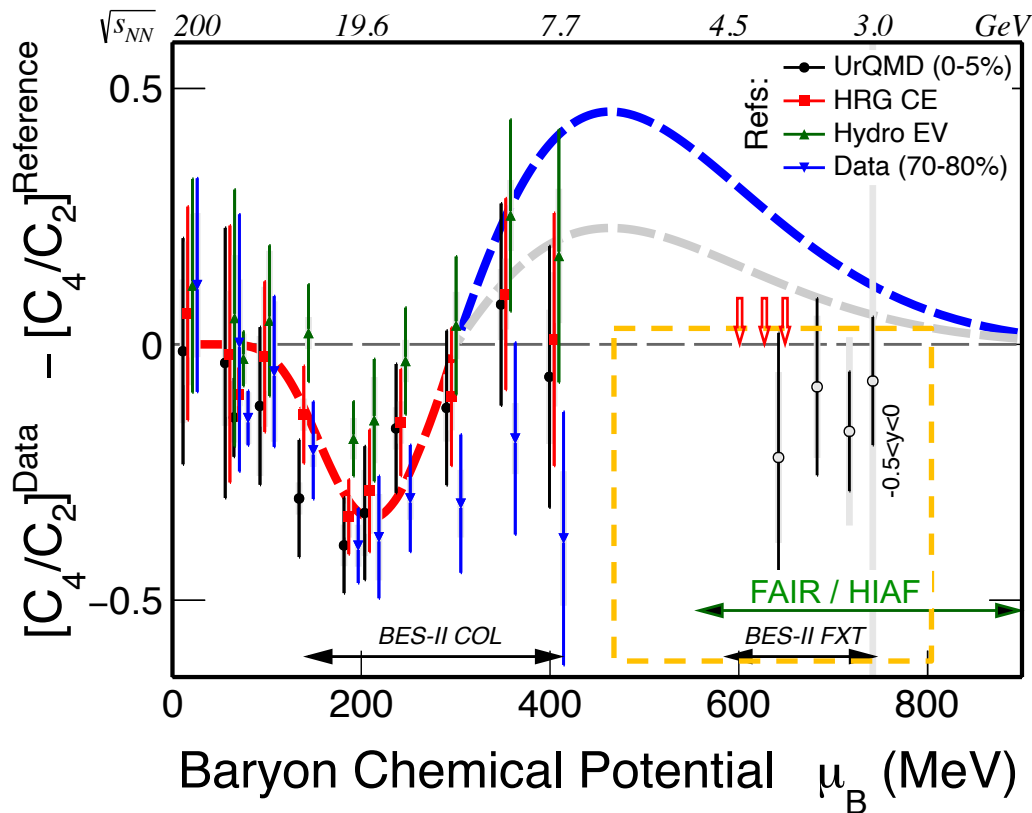
Significant deviations from non-critical references are observed!

STAR: PRL135, 142305(2025)

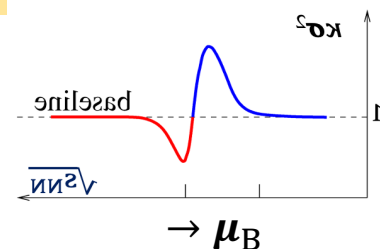
P. Braun-Munzinger, A. Rustamov, NX, arXiv: 2601.18666



Predictions: $T_c = 155$ MeV and $\kappa \sim 0.016$
 $T \in (100, 120)$ MeV, $\mu_B \in (600, 700)$ MeV
如果热化, QCD CP $\sqrt{s_{NN}} \in (5, 3.5)$ GeV



- 1) Experimental data between 3.5 – 8 GeV are crucial;
- 2) CBM@FAIR, H-NS@HIAF will play important role for the search of QCD critical point

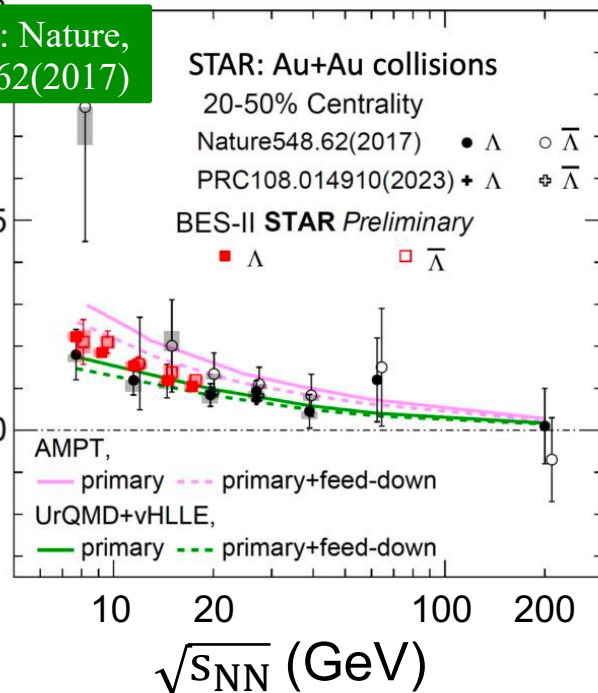


M. Stephanov: Phys.Rev.Lett. 107, 052301 (2011)
 P. Braun-Munzinger et al. Nucl.Phys. A1008, 122141 (2021)

Results on Λ -Global Polarizations

STAR: Nature,
548, 62(2017)

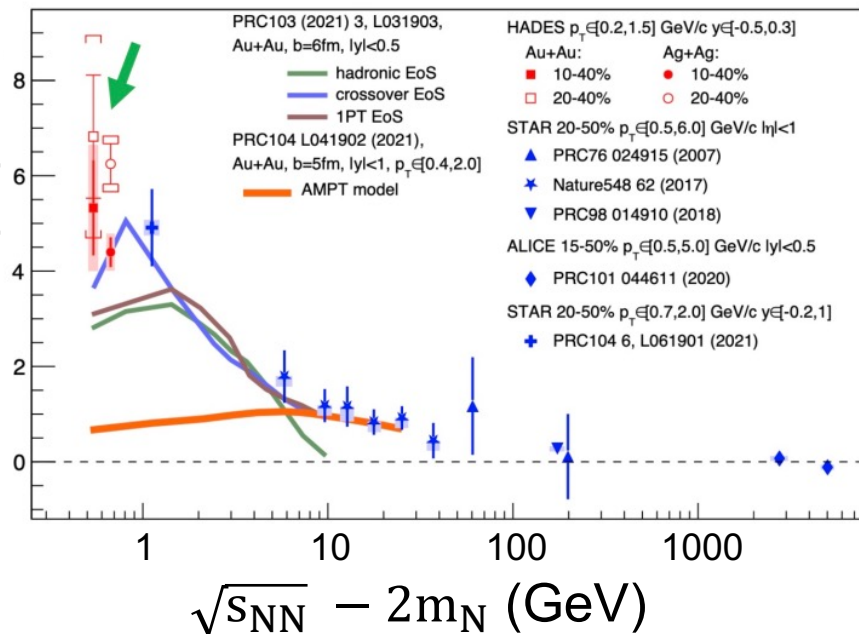
P_{Λ} (%)



2.4~2.55 GeV

Phys. Lett. B 835 (2022) 137506

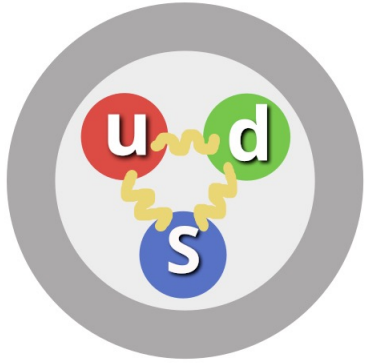
P_{Λ} (%)



- 1) Observed Λ -global polarization: along the direction of the total angular momentum and increased as collision energy decreases!
- 2) No theory explain these data, especially at low energies!

$\langle \mathbf{w} \rangle \approx (9 \pm 1) \cdot 10^{21} / \text{sec}$
"The most vortical fluid"

Lambda baryon



Quark structure of the lambda baryon.

Composition	Λ^0 : uds Λ_c^+ : udc Λ_b^0 : udb
Statistics	Fermionic
Family	Baryons
Interactions	Strong, weak, electromagnetic, and gravity
Types	3
Mass	Λ^0 : $1\,115.683 \pm 0.006 \text{ MeV}/c^2$ ^[1] Λ_c^+ : $2\,286.46 \pm 0.14 \text{ MeV}/c^2$ Λ_b^0 : $5\,619.60 \pm 0.17 \text{ MeV}/c^2$
Spin	$\frac{1}{2}$
Isospin	0

Spin and Strong Interactions

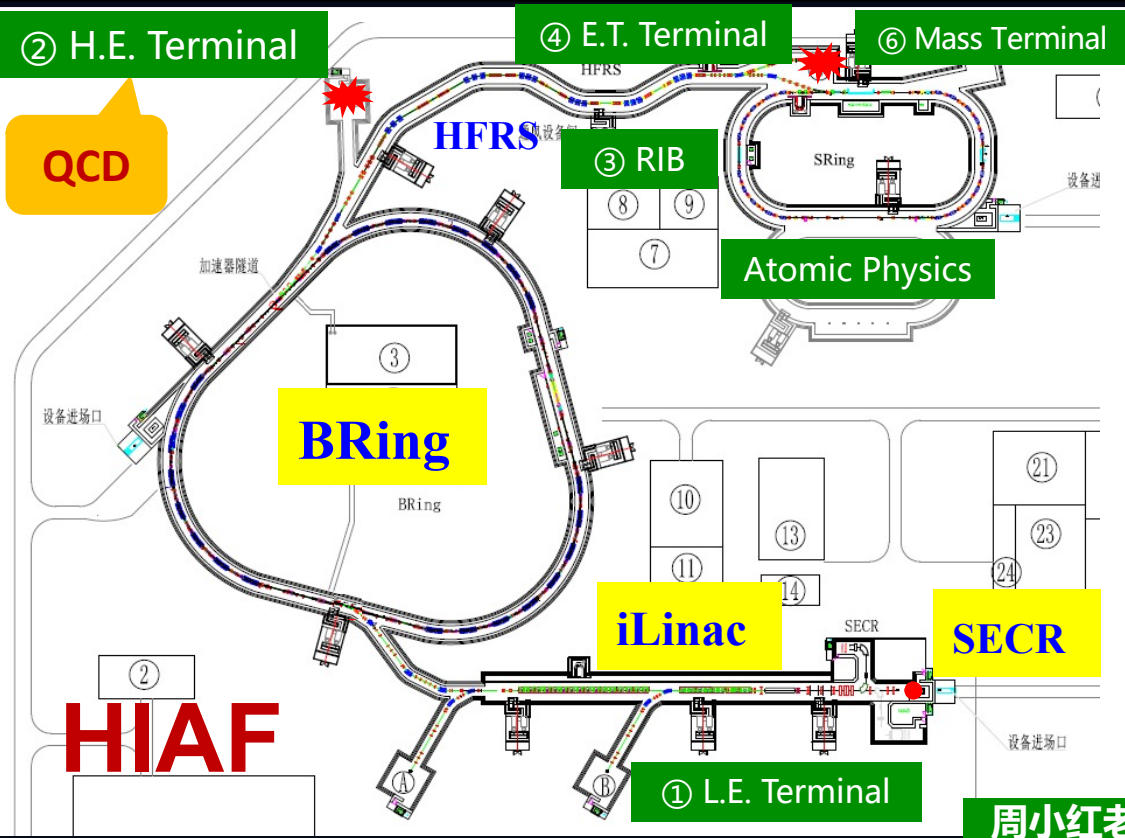
“Chirality is the basic building block in strong interaction theory QCD. Experimental observables with spin, an intrinsic quantum number of any elementary particle, offer an important manifestation of chirality.”

— *H-NS* *whitepaper*

- Λ polarization and its spin structure?
- Polarization of other hadrons, p ?
- The relation between Λ -local, global polarizations and its spin?
- ...

High Intensity heavy-ion Accelerator Facility

(HIAF, Huizhou, China)



HIAF Physics:

- (i) Atomic physics;
- (ii) Nuclear physics;
- (iii) Applied research in biology and material science etc.

低能综合研究终端

HIAF Commission started in 2025



Science
Volume 390, Issue 6773
Nov 2025

周小红老师报告

HIAF Beam Parameters

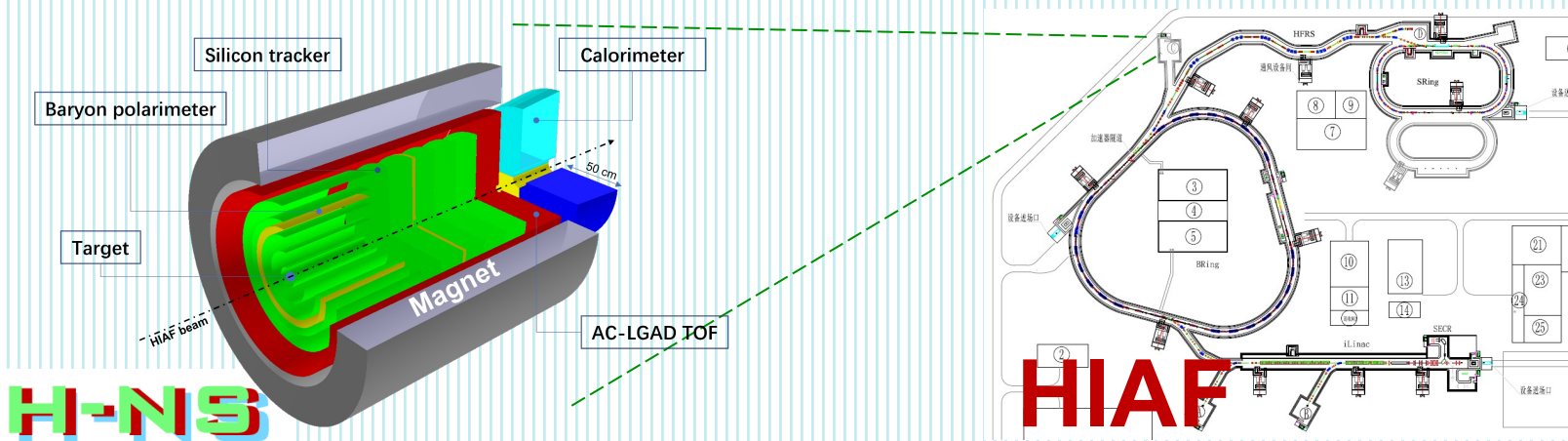
Ion	Intensity (ppp)	Kinetic Energy
$^{238}\text{U}^{35+}$	2.0×10^{11}	0.84 (GeV/u)
$^{238}\text{U}^{76+}$	5.0×10^{10}	2.5 (GeV/u)
$^{129}\text{Xe}^{27+}$	3.6×10^{11}	1.4 (GeV/u)
$^{78}\text{Kr}^{19+}$	5.0×10^{11}	1.7 (GeV/u)
$^{40}\text{Ar}^{12+}$	7.0×10^{11}	2.3 (GeV/u)
$^{18}\text{O}^{6+}$	8.0×10^{11}	2.6 (GeV/u)
protons	6.0×10^{12}	9.3 (GeV/u)
	4.0×10^{14} (HIAF-U, EicC)	32 (GeV/u)

The emergent properties of QCD matter

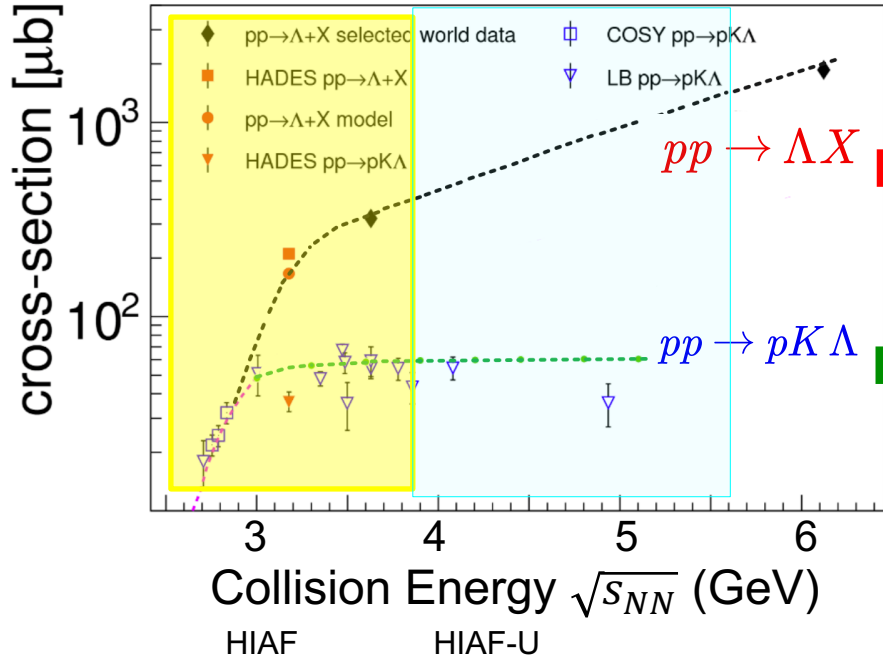
New Physics Opportunities

H-NS@HIAF

(超子-核子谱仪)



Λ Production and Polarization



(1) $p + p (\mathbf{A}) \rightarrow \Lambda + X$

Polarization puzzle:

ZT Liang, and C. Boros, PRL**79**, 3608 (1997);
PRD**61**, 117503 (2000). H Dong and ZT Liang,
PRD**70**, 014019 (2004); PRD**72**, 033006 (2005).

(2) $p + p \rightarrow \Lambda + K + p$

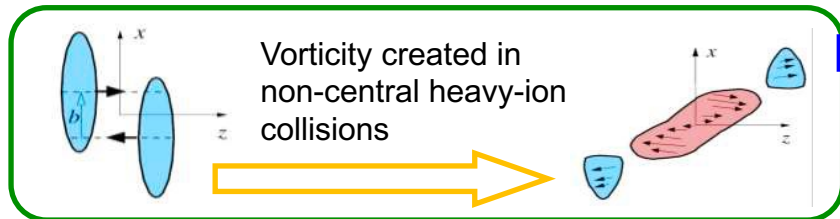
Exclusive Process:

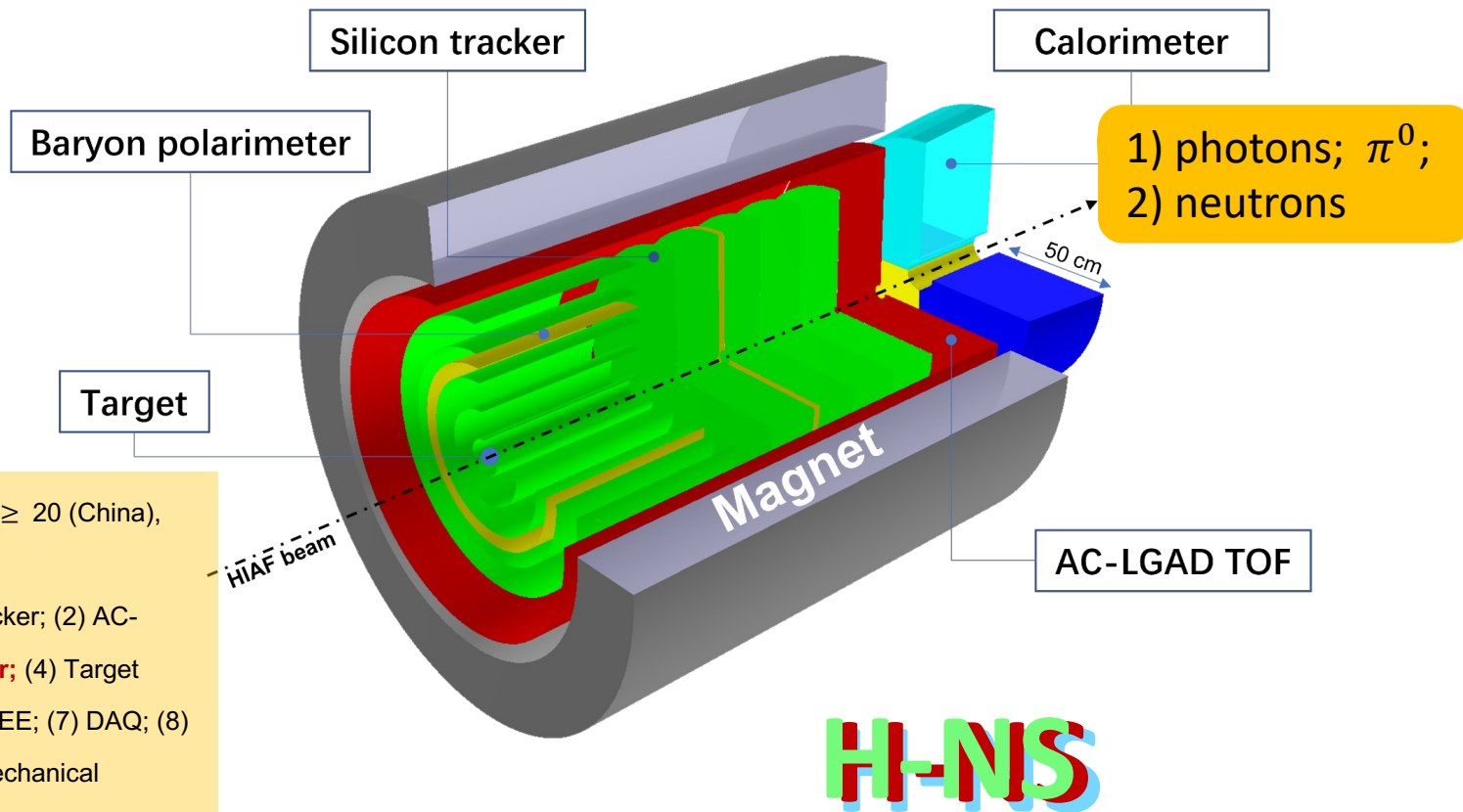
R Machleidt, K Holinde and C Elster, Phys.
Rept.**149**, 1 (1987). BC Liu, BS Zou, PRL**96**,
042002 (2006).

(3) $\mathbf{A} + \mathbf{A} \rightarrow \Lambda + X$

Global Polarizations:

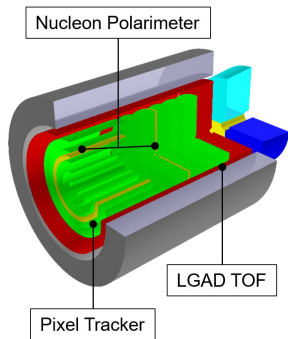
ZT Liang, XN Wang, PRL**94**, 102301 (2005);
PLB**629**, 20 (2005). JH Gao, *et al.*, PRC**77**, 044902
(2008).





Participating Institutes: ≥ 20 (China),
more are welcome!

R&D Efforts: (1) Pixel tracker; (2) AC-LGAD; (3) **Baryon Polarimeter**; (4) Target systems; (5) Calorimeter; (6) FEE; (7) DAQ; (8) Magnet; (9) Beam line; (10) Mechanical structure design



H-NS

Reaction: $p+p$

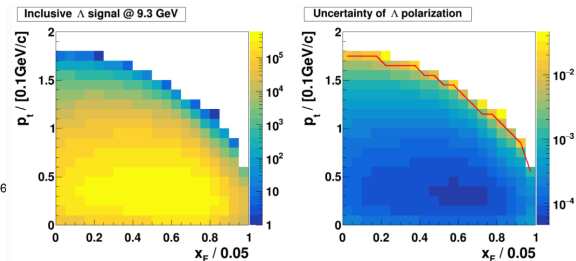
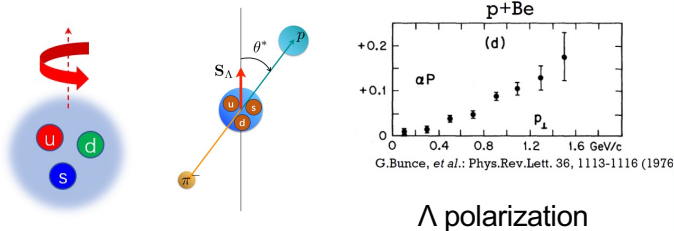
Event rate: 1MHz

Time: 3 months

- $pp \rightarrow \Lambda + X$ $N \sim 10^{11}$
- $pp \rightarrow p + X$ $N \sim 10^{13}$
- $pp \rightarrow pK\Lambda$ $N \sim 10^{10}$

$$p p \rightarrow \Lambda + X$$

$$\sigma_{\text{stat.}} < 0.01 \quad 2\text{D:400 bins}$$

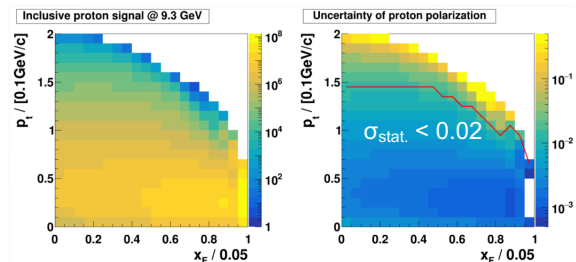
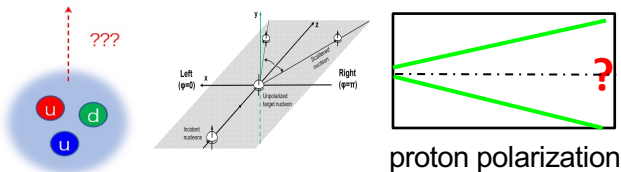


Projection @ H-NS

$$p p \rightarrow p + X$$

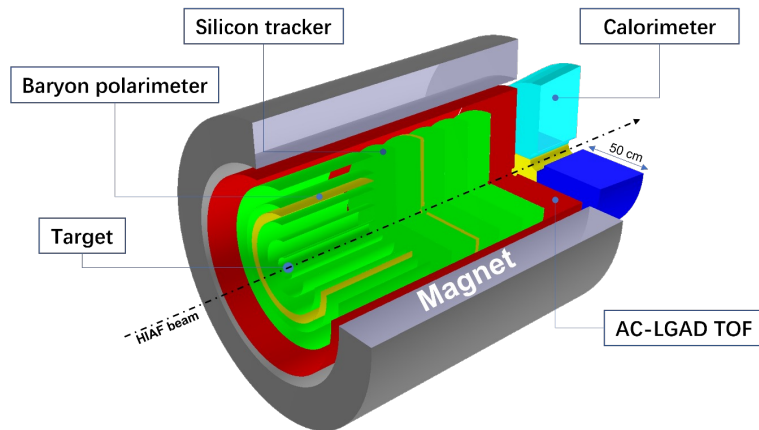
$$\sigma_{\text{stat.}} < 0.02 \quad 2\text{D:400 bins}$$

$$pC \text{ scattering} \sim 10^{13} \times 4 \times 10^{-4} = 4 \times 10^9$$



Projection @ H-NS

超子-核子谱仪 (H-NS)



Participating Institute (21): 北京航空航天大学、北京师范大学、复旦大学、高能物理研究所、国科大、河南师范大学、湖州师范学院、华东师范大学、华南师范大学、华中师范大学、近代物理研究所、理论物理研究所、南开大学、清华大学、山东大学、香港中文大学 (深圳)、原子能研究院、郑州大学、中科大、中山大学

Subsystems: Silicon tracker, AC-LGAD, Target, Baryon polarimeter, Calorimeter, Electronics, DAQ, Magnet, Beamline, Mechanics + Engineering

I. Physics:

- Λ production and polarization ($p+p$)
 - ◆ Medium effect ($p+A$)
 - ◆ Global polarization of Λ ($A+A$)
- Hadron physics via $p+p$
- QCD Phase Structure at High Baryon Density

II. Community:

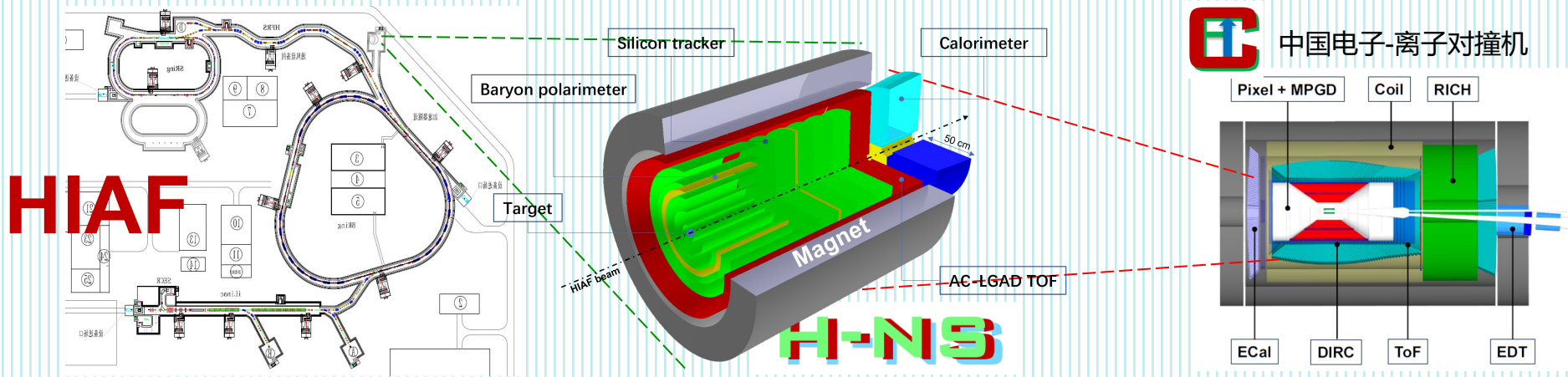
- Supports both communities of hadron structure and heavy-ion physics
- International participations are welcome!

III. Detector R&D

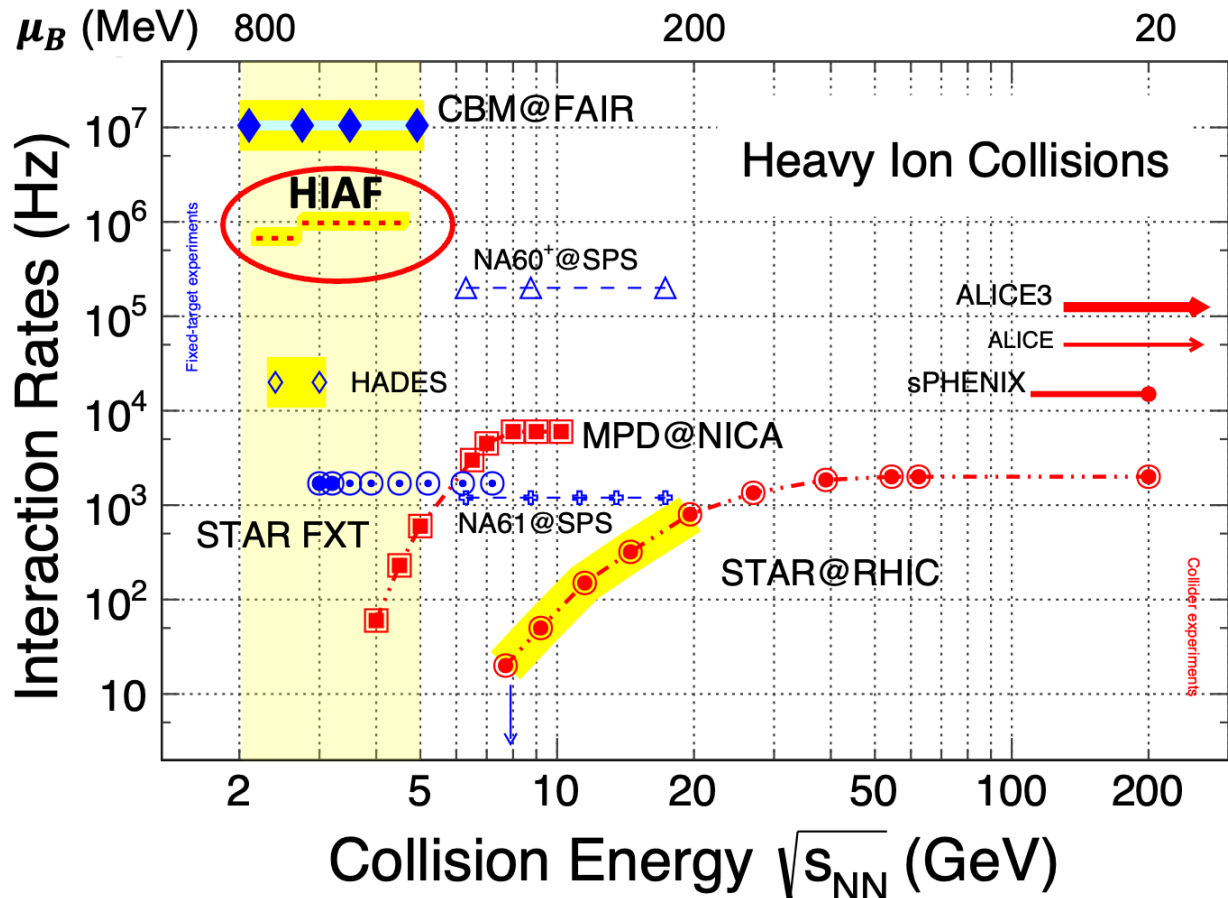
- Many parts are similar for CEPC, H-NS, EicC, and STCF: Save resources!
- H-NS: a detector R&D platform for EicC(1/2 EicC)

高能强子与核物理@HIAF:

- 1) **H-NS:** Large acceptance with full azimuthal coverage, High efficiency, Fast DAQ ($\sim 1\text{M Hz}$). Energy scan within $3 - 9.3\text{ GeV/u}$...
- 2) **p+p and p+A collisions:** Λ and p polarization, Hadron spectra, Spin structure, Spin-spin correlations, Hyper-nuclei production, BS, ...;
- 3) **A+A collisions:** High μ_B properties: QCD critical point, Global polarizations, ...



Future High Rates Experiments



Heavy-ion accelerator fires up

An accelerator that will produce the world's most intense pulses of heavy ions generated its first beam on 28 October. When fully operational, China's High

<https://www.science.org/doi/pdf/10.1126/science.aed6538>

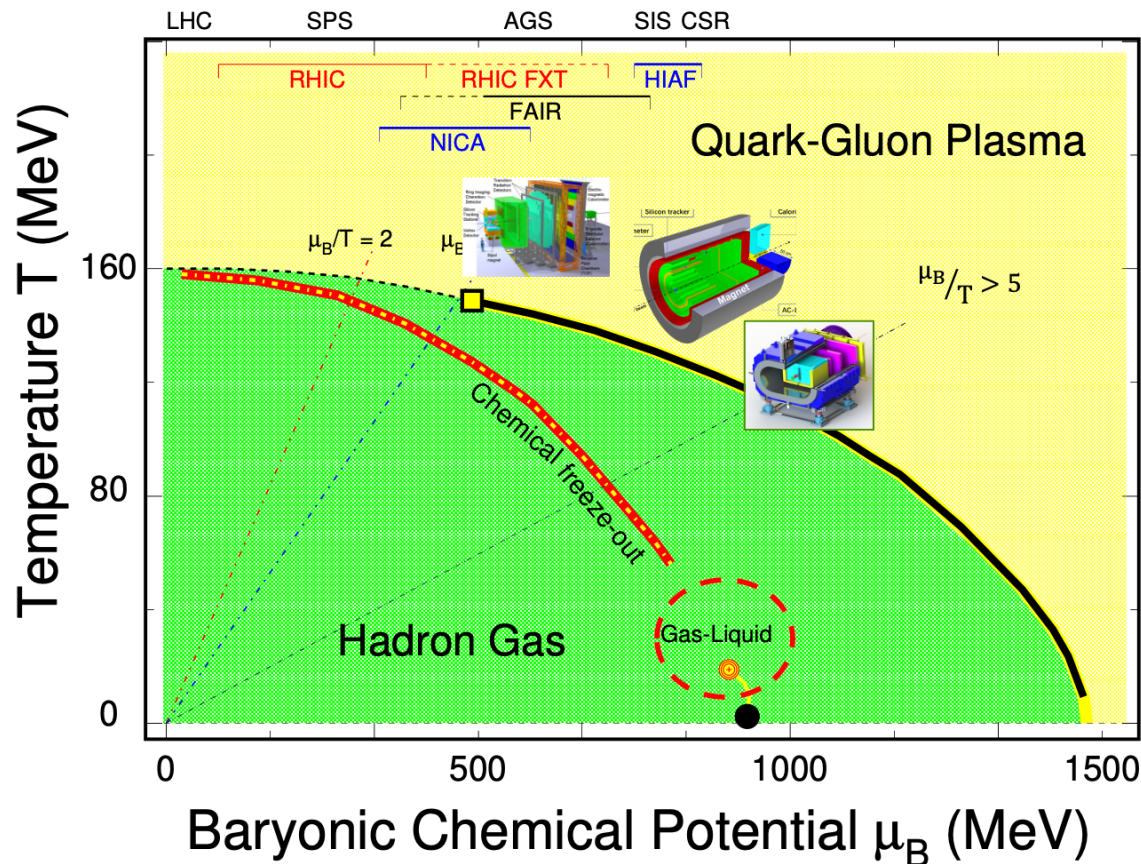


Science

Volume 390, Issue 6773

Nov 2025

重离子碰撞与核物质相结构



At $\mu_B = 0$

(*ALICE, ATLAS, CMS, LHCb*):

- 1) Property of QGP, smooth crossover transition;
- 2) Small-x physics: $\rightarrow$ search for **CGC**

At large μ_B (*CBM, H-NS, CEE*)

precision measurements:

- 1) Search for 1st-order phase transition and QCD critical point;
- 2) Spin structure of p & Λ ;
- 3) **EOS with spin degree of freedom**;
- 4) The fate of the liquid-gas transition;
- 5) Baryon interactions $\rightarrow$ NN, NY, ...;
- 6) Nuclear structure studies at high baryon density!

Acknowledgements:

QCD CP: P. Braun-Munzinger, 董昕, 高飞、付伟杰, S. Esumi, 黄梅、F. Karsch, V. Koch, 刘峰、刘玉鑫、罗晓峰, B. Mohanty, A. Pandav, A. Rustamov, K. Redlich, 施梳苏、M. Stephanov, J. Stachel, J. Stroth, V. Vovchenko, 王恩科、张亚鹏、张宇、庄鹏飞

H-NS: 郭爱强、梁羽铁、梁作堂、刘天博、吴佳俊、邢宏喜、徐庆华、王群、赵强、赵宇翔、邹冰松

// BLUE: Theory // RED: Exp. //

Thank you for your attention!