Recent Results from RHIC BES-II and Future Prospective

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Outline

1) **Introduction**

2) **Results from RHIC Beam Energy Scan-II**

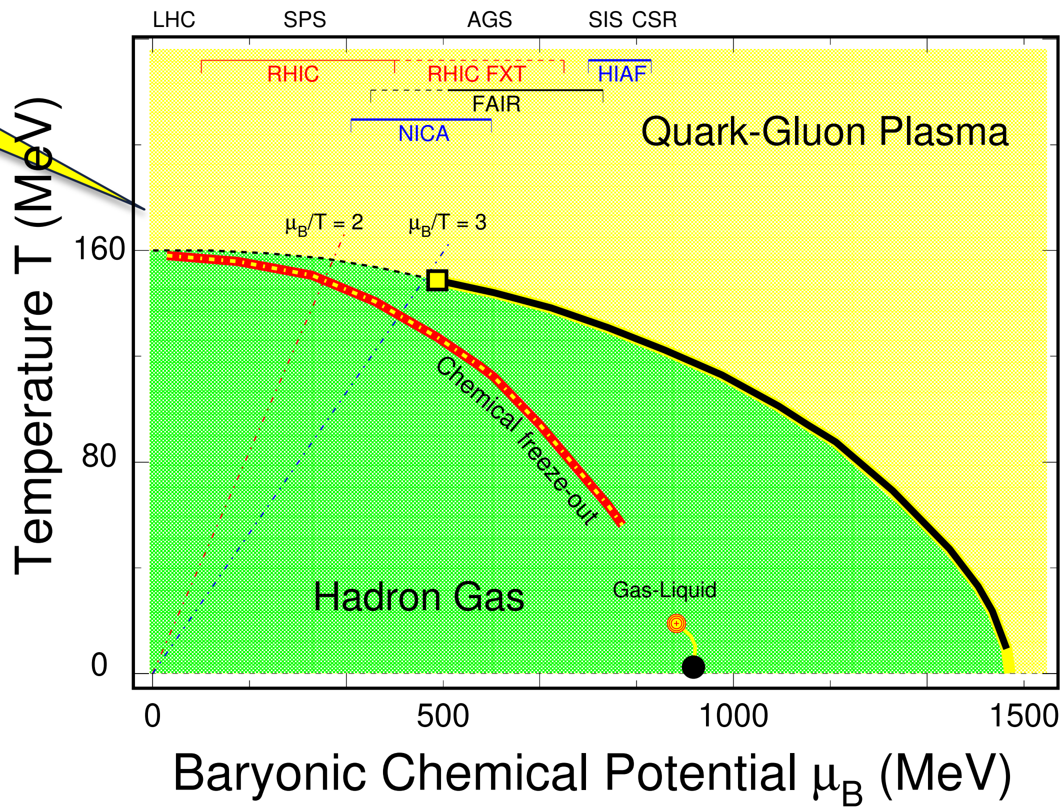
   - Chirality, Collectivity, Criticality
   - Polarization measurements

3) **Future Prospective**

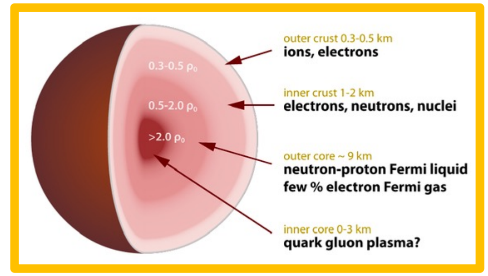
   - CBM at FAIR
   - H-NS at HIAF

Nuclear Collisions and QCD Phase Diagram

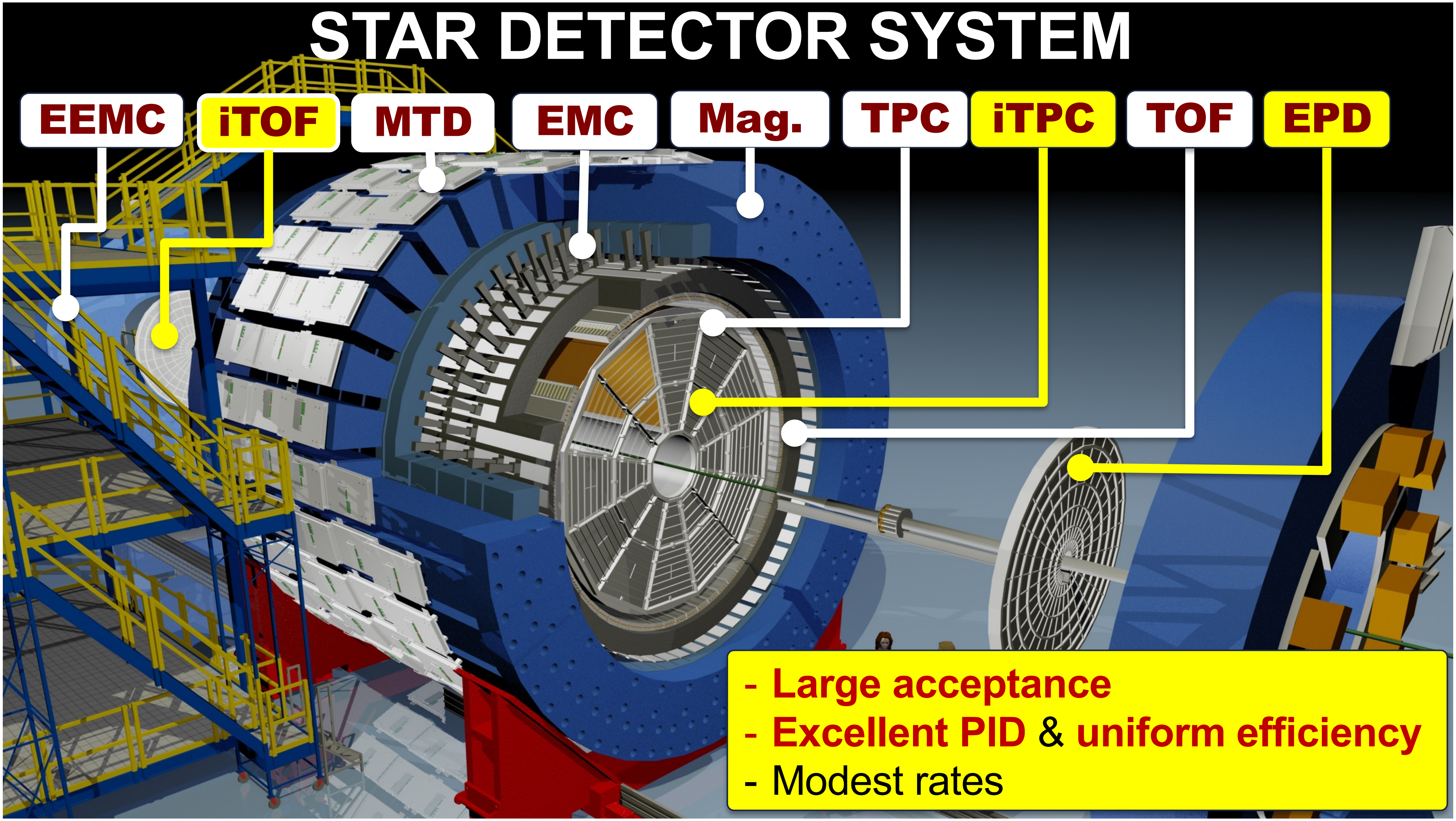
Early Universe



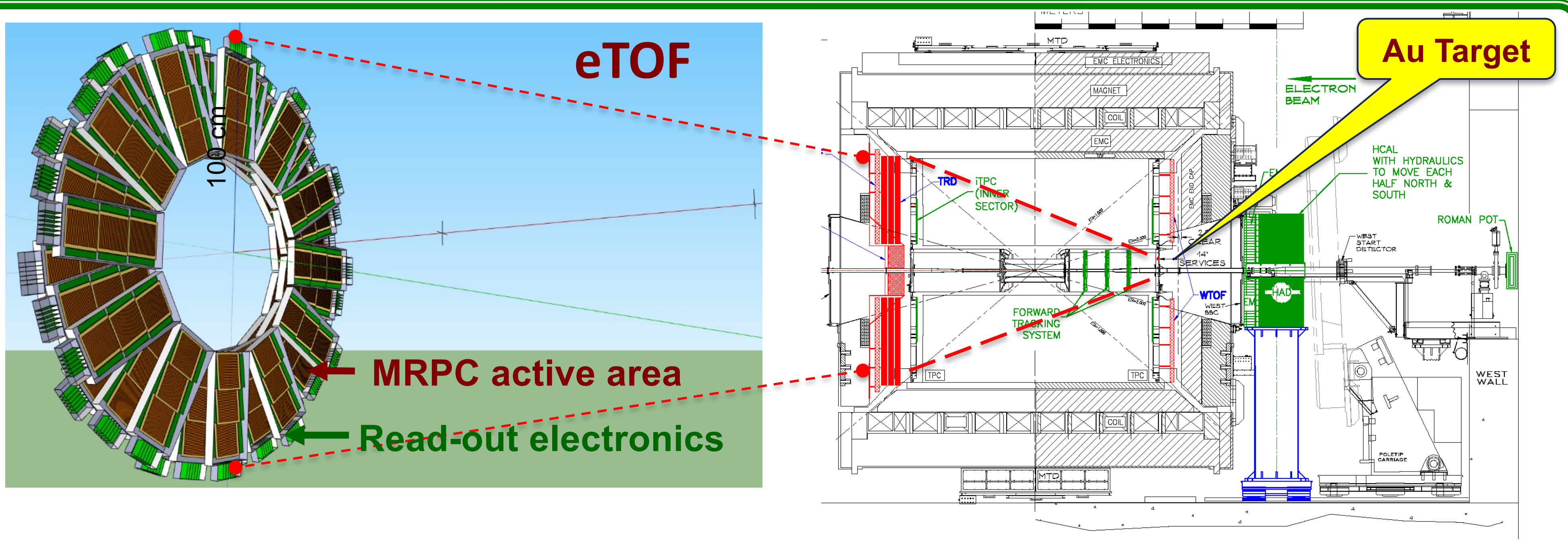
High baryon density: Inner structure of compact stars



1) RHIC BES: → search for 1st-order phase transition and **QCD critical point**;
2) Baryon interactions (*e.g.* $N-N$, $Y-N$) $\xrightarrow{?}$ EOS in compact stars


STAR DETECTOR SYSTEM
EEMC
iTOF
MTD
EMC
Mag.
TPC
iTPC
TOF
EPD
- Large acceptance
- Excellent PID & uniform efficiency
- Modest rates

STAR Fixed Target Setup



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

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

STAR BES-I and -II 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	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 M	540 MeV	-1.68	Run-20
8	14.6	340 M	262 MeV		Run-14, 19	8	4.5 (9.8)	110 M	590 MeV	-1.52	Run-20
9	11.5	57 M	316 MeV		Run-10, 20	9	3.9 (7.3)	120 M	633 MeV	-1.37	Run-20
10	9.2	160 M	372 MeV		Run-10, 20	10	3.5 (5.75)	120 M	670 MeV	-1.2	Run-20
11	7.7	104 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

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

Collectivity

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

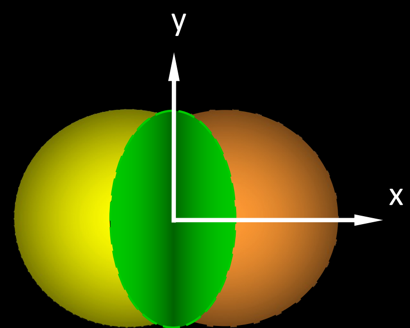
$$\frac{d^2N}{p_T dp_T d\varphi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T}\left\{1 + \sum_{n=1}^{\infty} 2v_n(p_T)cos[n(\varphi - \Psi_R)]\right\}$$

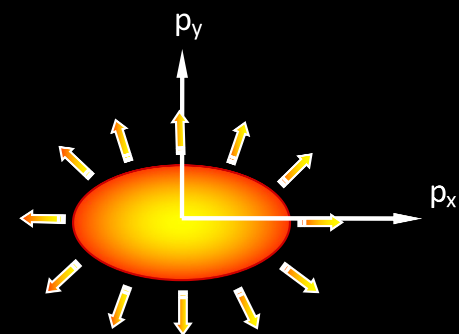
$- v_1$ Directed flow;

$- v_2$ Elliptic flow; $- v_3$ Triangle flow

Anisotropy Parameter v_2

coordinate-space-anisotropy ⇨ momentum-space-anisotropy

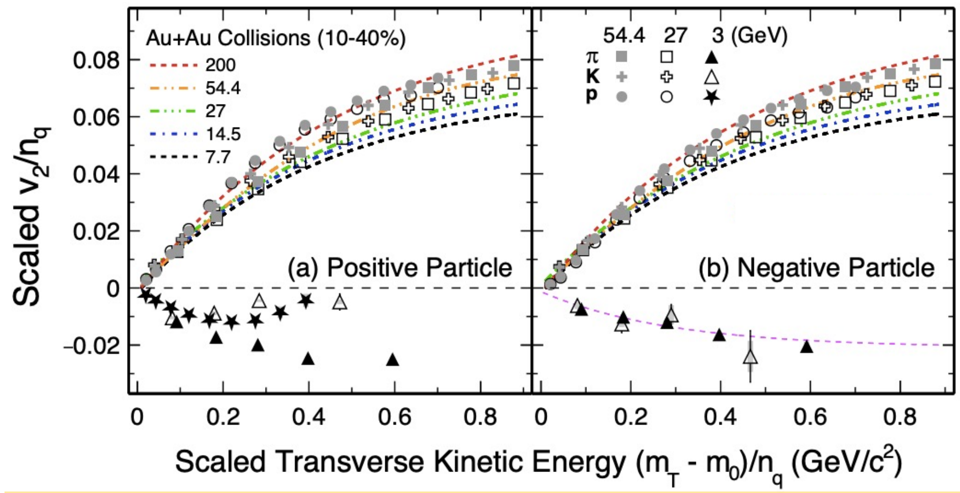


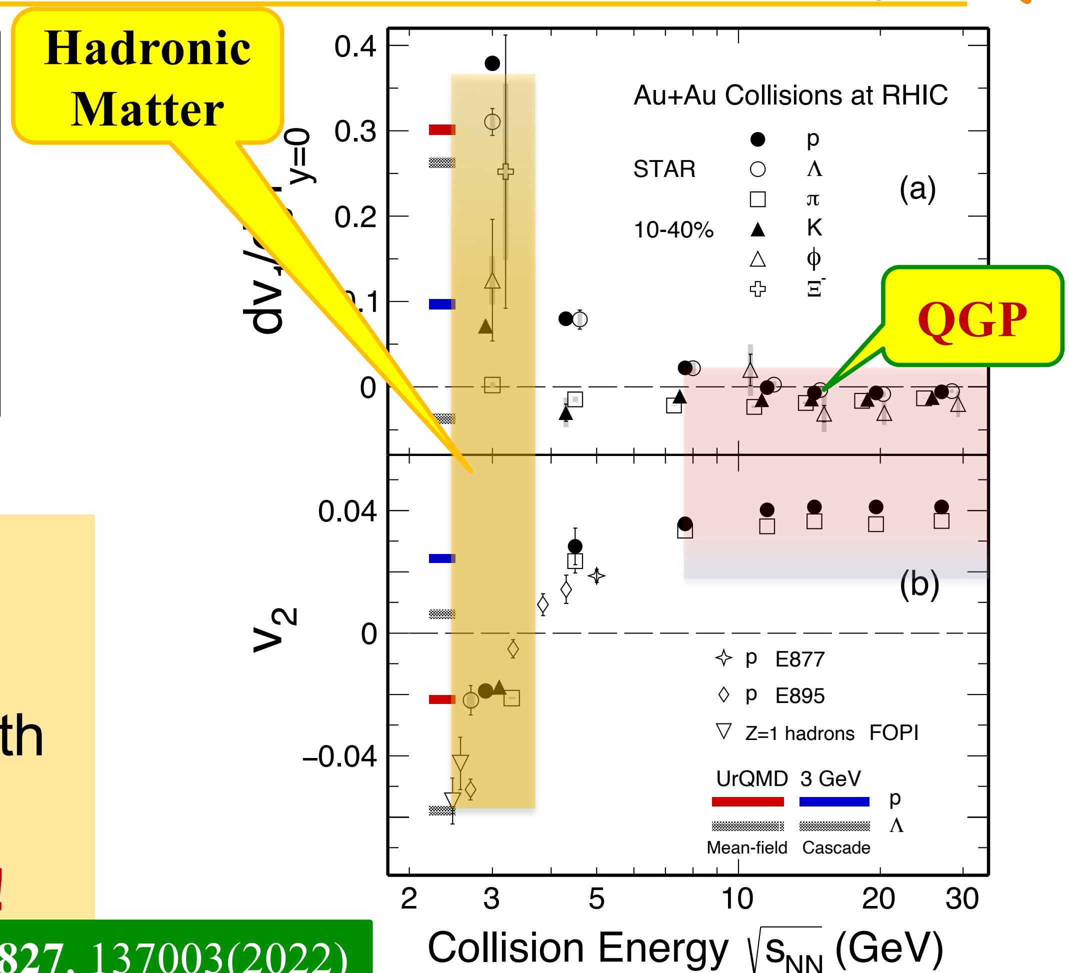


$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle cos2\varphi \rangle, \qquad \varphi = tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Sensitive to initial/final conditions, EoS and degrees of freedom

Disappearance of Partonic Collectivity

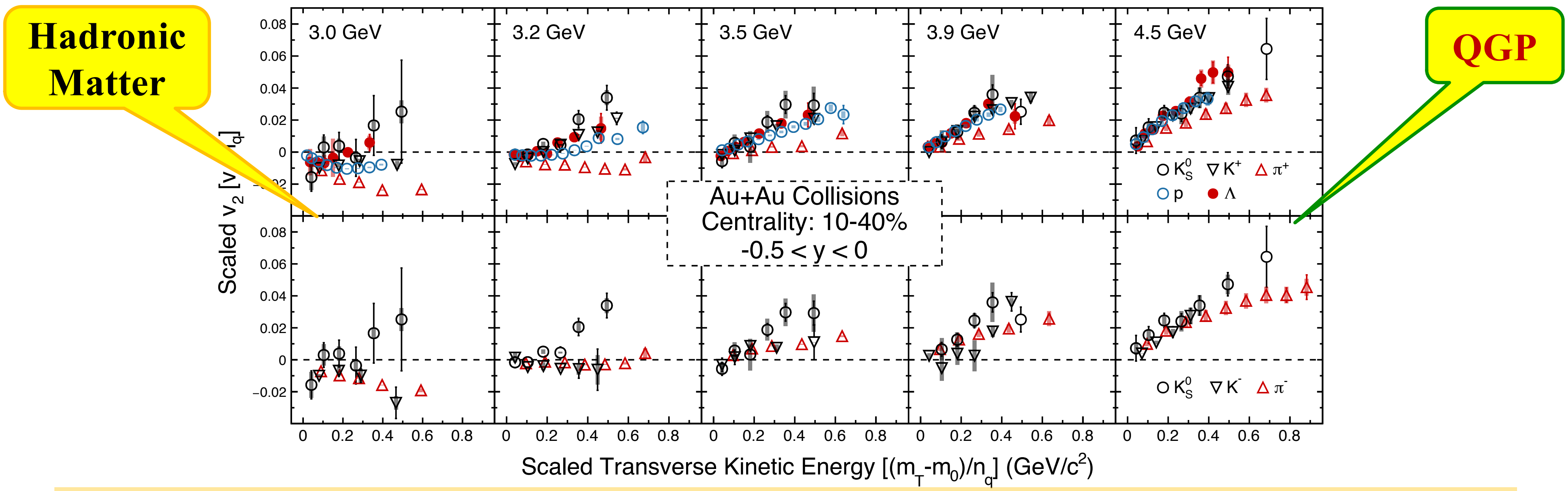




- At **3 GeV**, NCQ scaling is absent;
- Transport model calculations, with baryonic mean field, reproduce both v_1 and v_2 results;
- **hadronic interactions dominant!**

STAR: PLB**827**, 137003(2022)

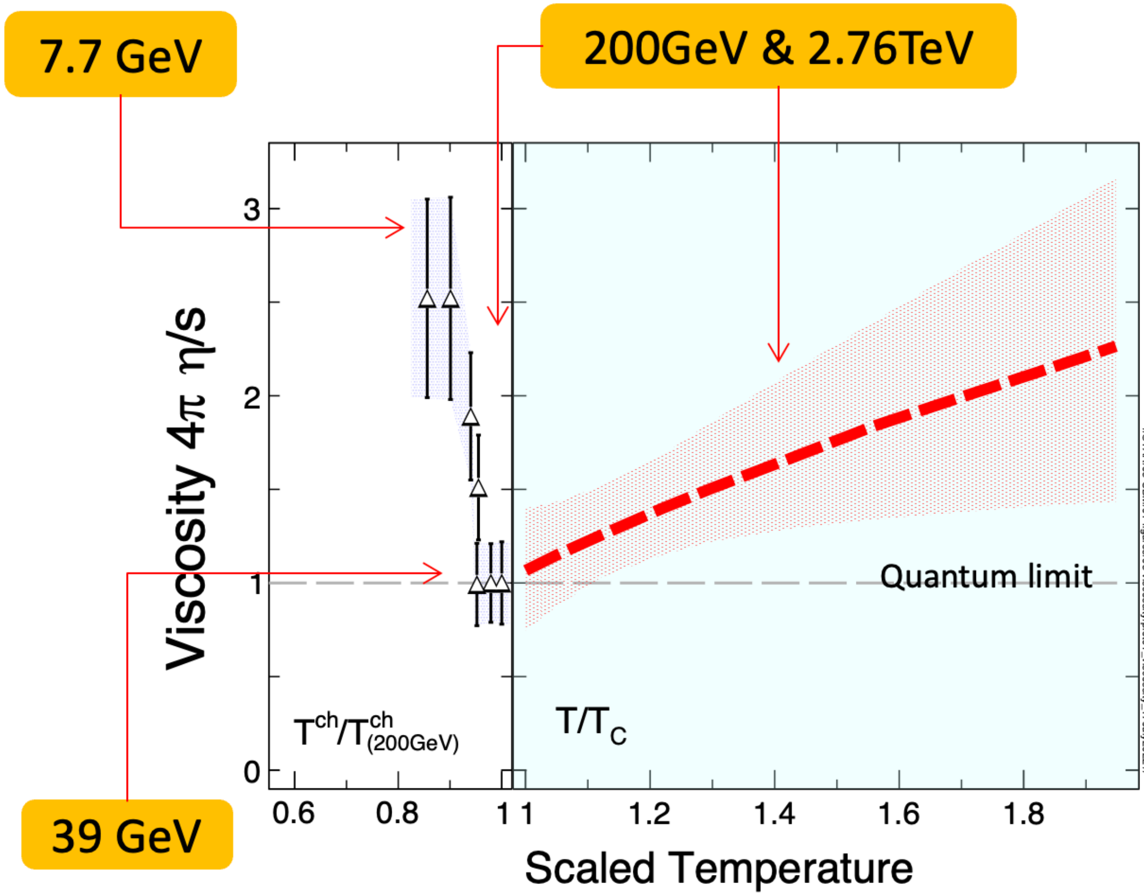
Onset of Partonic Collectivity



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

STAR: PLB**827**, 137003(2022)
PRL**135**, 072301(2025)

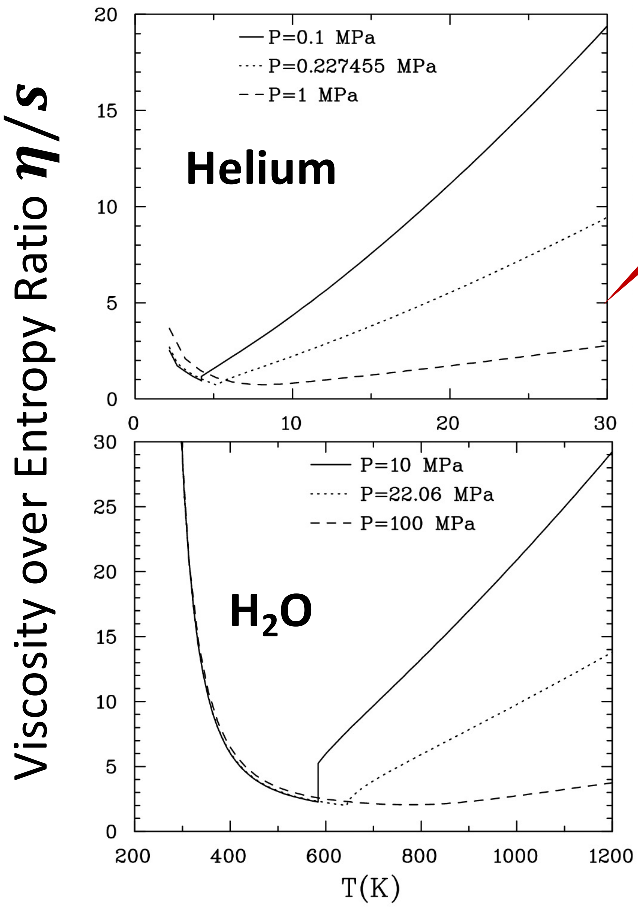
Equation of State for Strong Interaction



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 $\sqrt{s_{NN}}$ = 39 GeV → QGP dominants in higher energies;
4) **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

Strongly-Interacting Low-Viscosity Matter

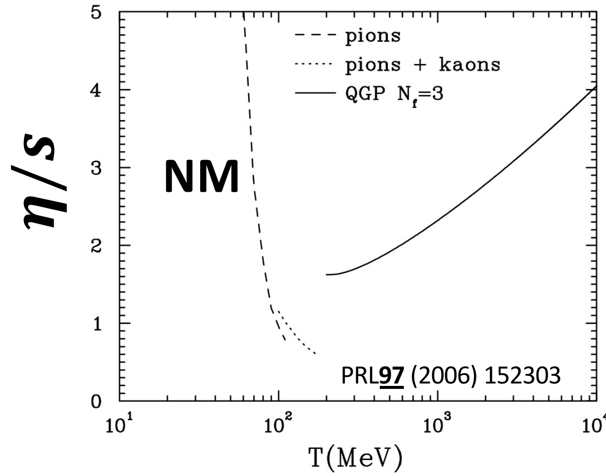


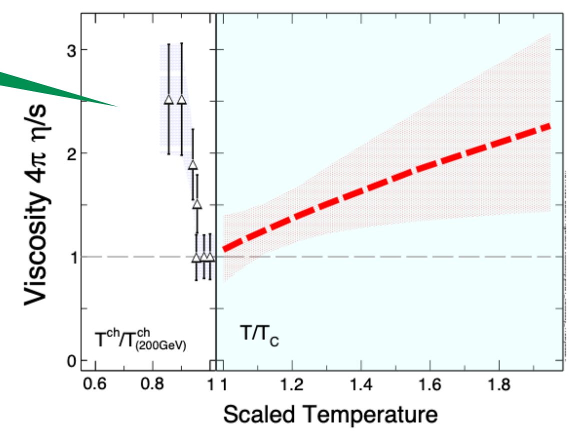
EM interaction
η/s ~ 1

L.P. Csernai, J.I. Kapusta, L.D. McLerran, PRL**97** (2006) 152303

Strong Interaction
η/s ~ 0.1

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

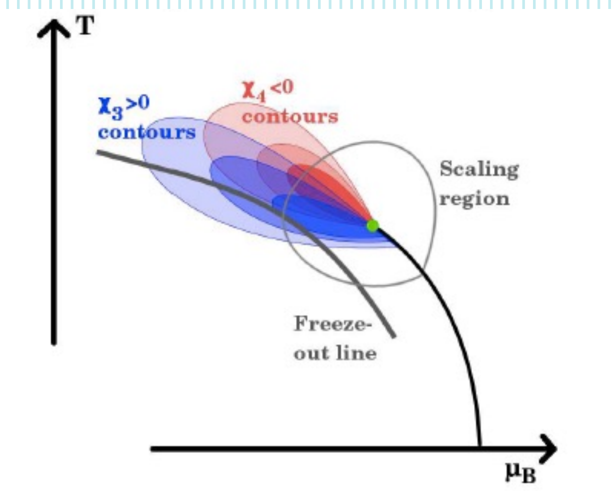




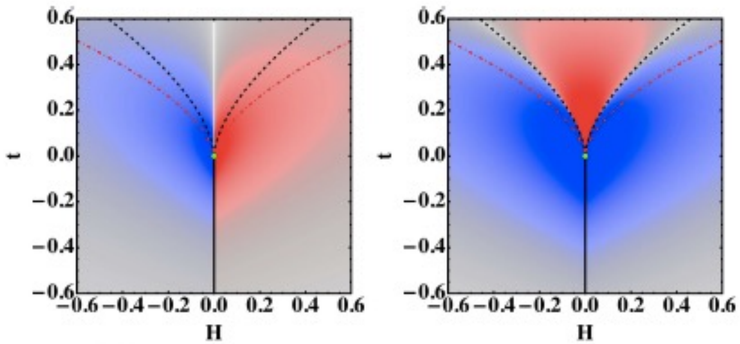
Collectivity: Summary

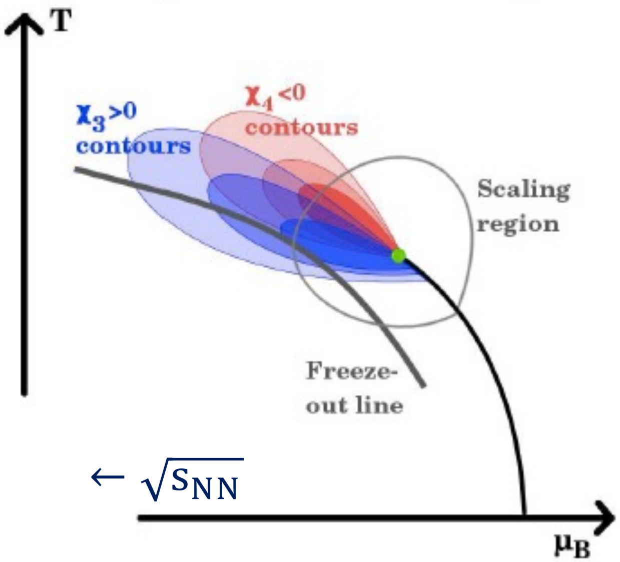
1) While at 3 GeV, hadronic interactions is dominant, partonic collectivity, a necessary condition for QGP formation in high-energy nuclear collisions, have been observed for collisions at $\sqrt{s_{NN}} \geq 30$ GeV;
2) Clear transition, or, onset of partonic collectivity observed in Au+Au collisions within 3 ~ 4.5 GeV;
3) Unique and universal phase transition, from hadronic to partonic medium, is seen in the Au+Au collisions at RHIC

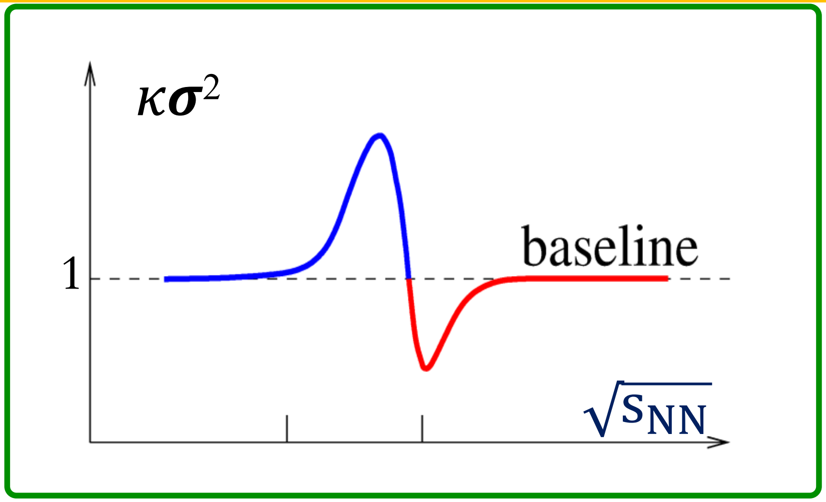
Criticality



Expectations







- 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. Kohyyama, Phys. Rev. **D93** (2016) 034037

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 as well as phase structure;
3) Cumulant ratios are direct connection to theoretical calculations of susceptibilities.

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

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

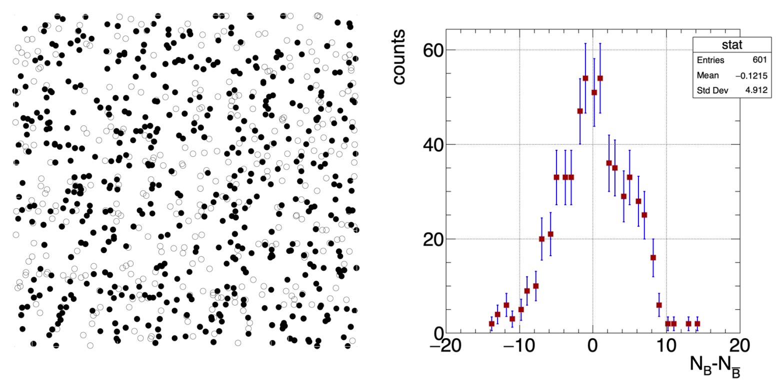
Moments, cumulants and susceptibilities:

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

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

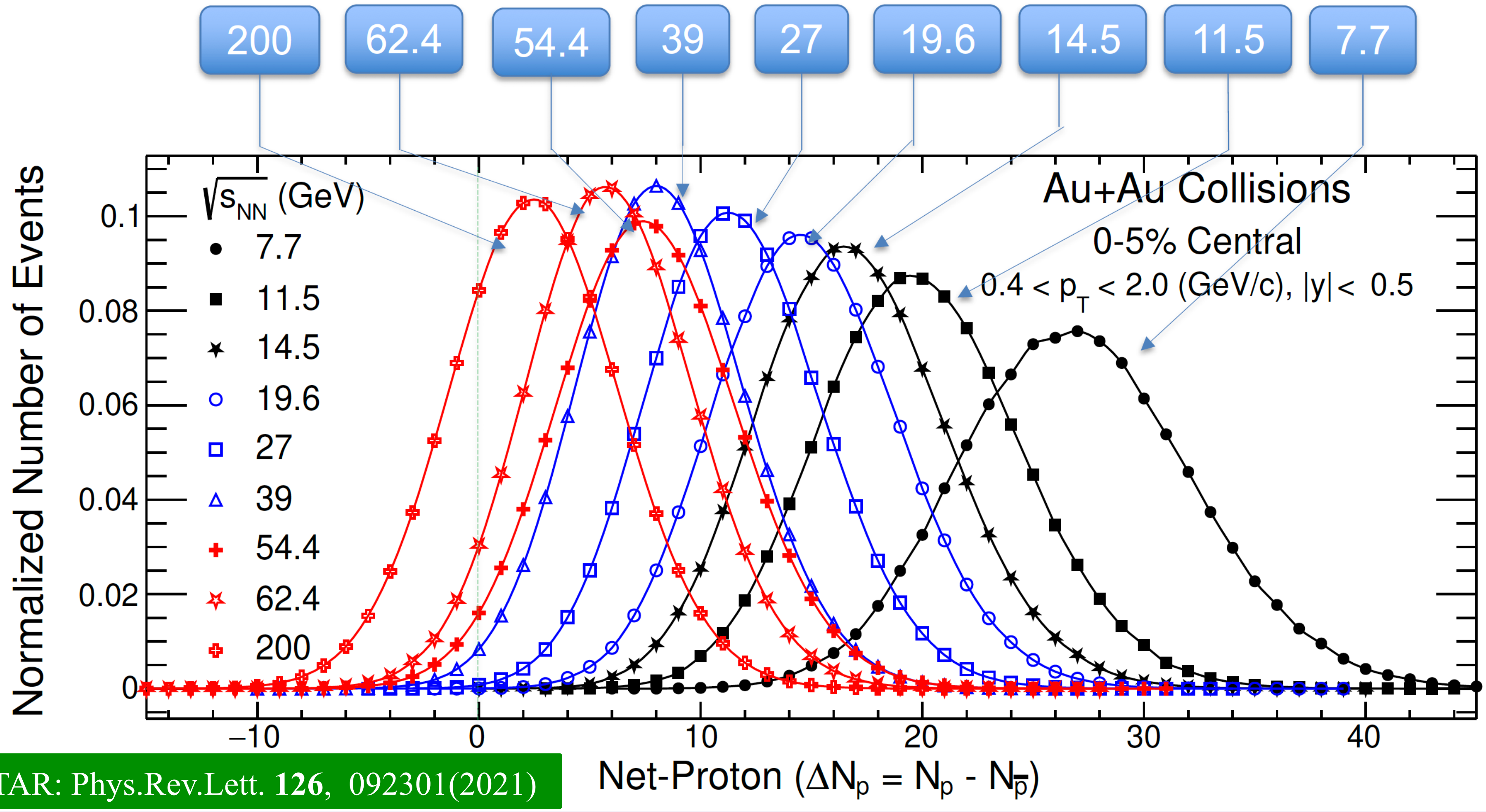
4th order: $\kappa\sigma^2 \equiv C_4/C_2 = \chi_4/\chi_2$

Animation: A.Rustamov



INT 2008-2b : The QCD Critical Point

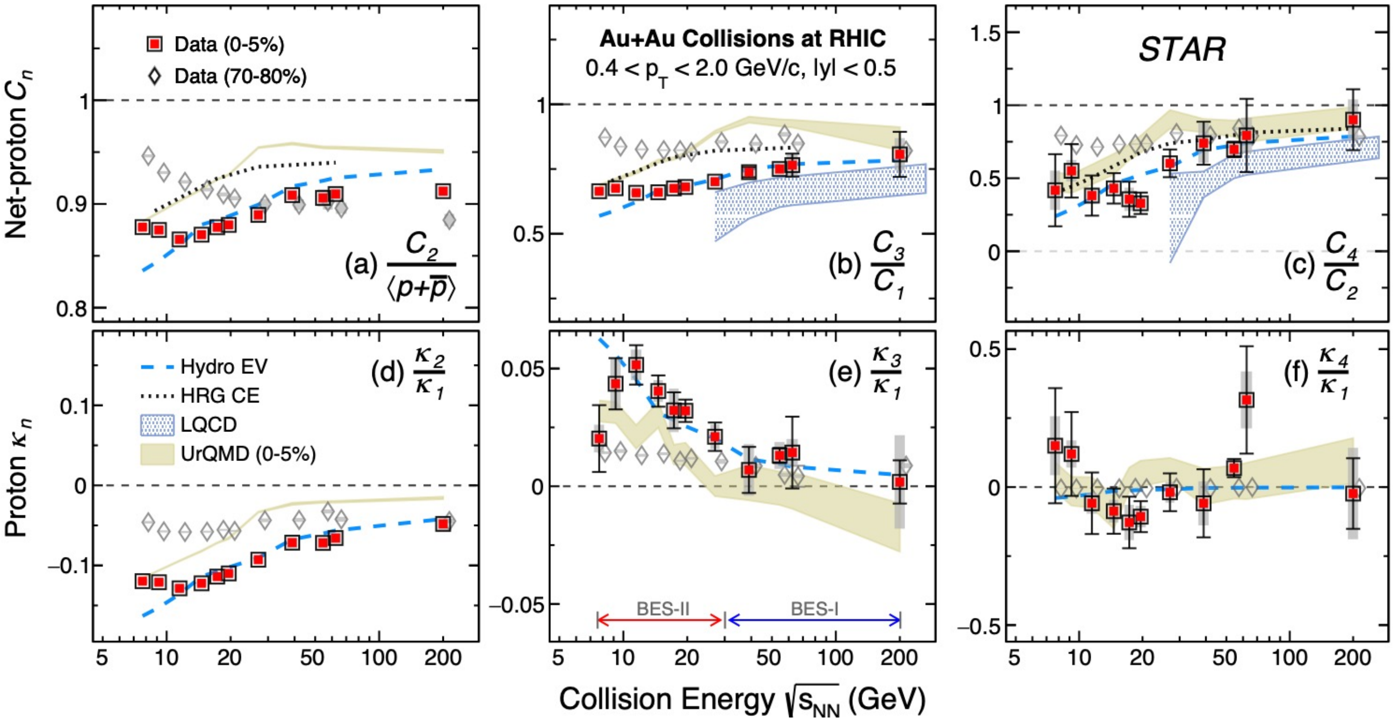
Event-by-Event Net-Proton Distributions (raw)



STAR: Phys.Rev.Lett. **126**, 092301(2021)

Energy Dependence

Au+Au Collisions at RHIC



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

STAR:
PRL**135,** 142305 (2025)

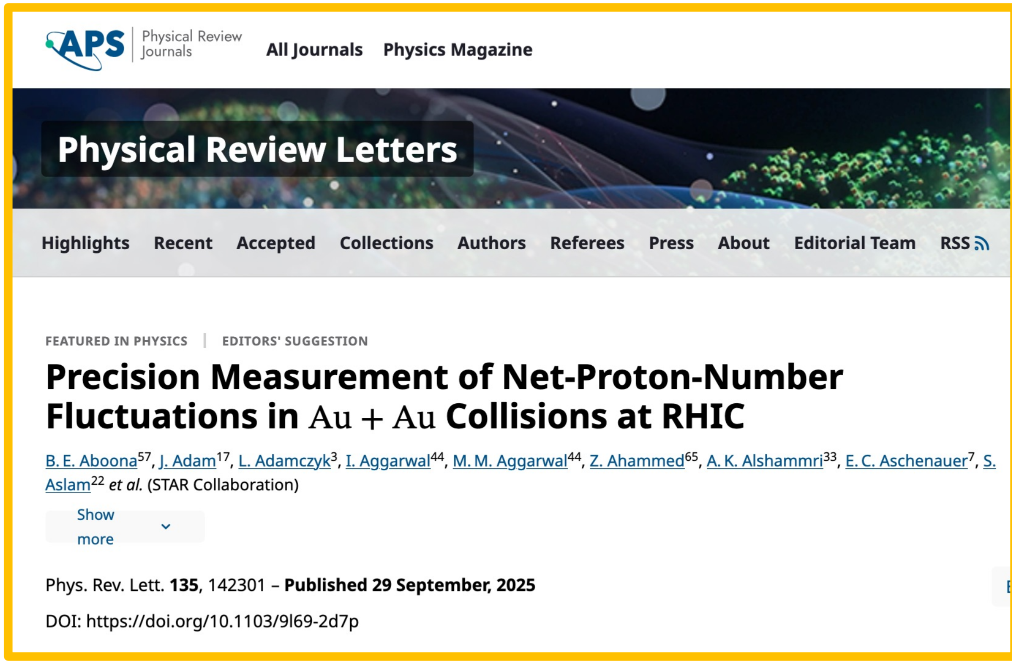
1) Results of LQCD and thermal model are consistent with data at high energy;
2) Deviations appear below $\sqrt{s_{NN}} < 35$ GeV

Search for the QCD CEP

STAR: PRL135, 142305(2025)

0-5% Au+Au Collisions at RHIC

STAR: QM2025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FEATURED IN PHYSICS | EDITORS' SUGGESTION

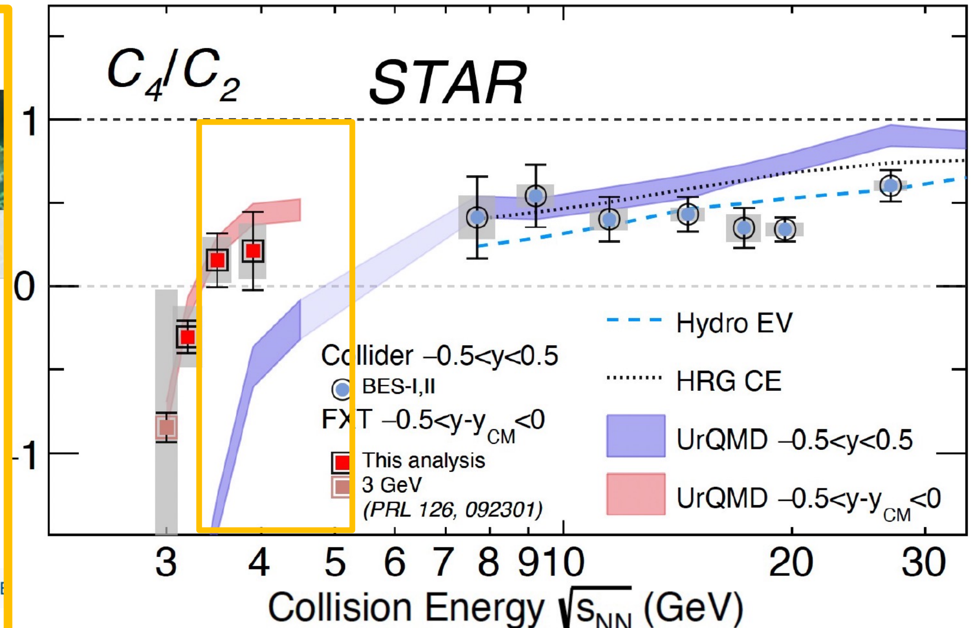
Precision Measurement of Net-Proton-Number Fluctuations in Au + Au Collisions at RHIC

B. E. Aboona[57], J. Adam[17], L. Adamczyk[3], I. Aggarwal[44], M. M. Aggarwal[44], Z. Ahammed[65], A. K. Alshammri[33], E. C. Aschenauer[7], S. Aslam[22] *et al.* (STAR Collaboration)

Show more

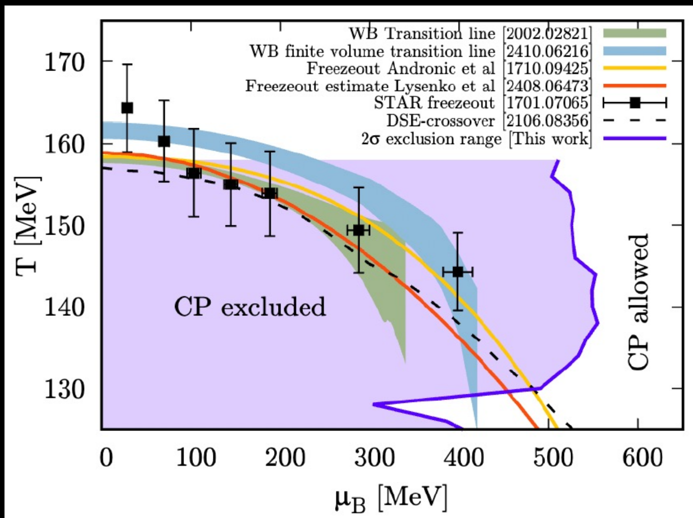
Phys. Rev. Lett. **135**, 142301 – **Published 29 September, 2025**

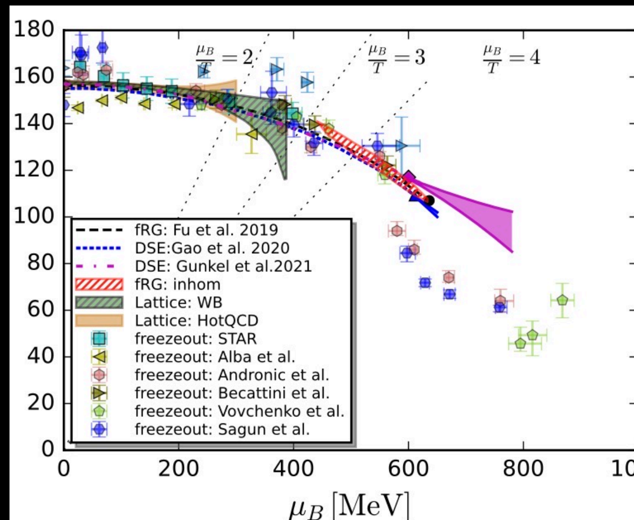
DOI: https://doi.org/10.1103/9l69-2d7p

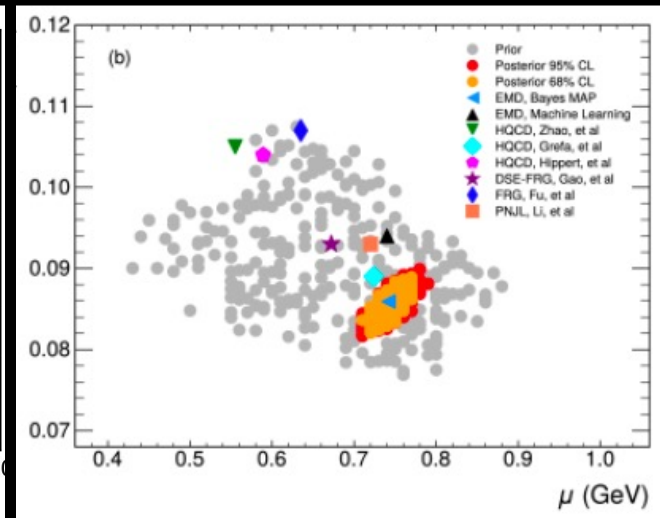


1) Experimental data between 3.5 – 8 GeV are crucial;
2) CBM at FAIR will play important role for the search of QCD critical point

Estimations on QCD Critical Point







Predictions: $T_C = 155$ MeV and $\kappa \sim 0.016$

$T \in (100, 120)$ MeV, $\mu_B \in (600, 700)$ MeV

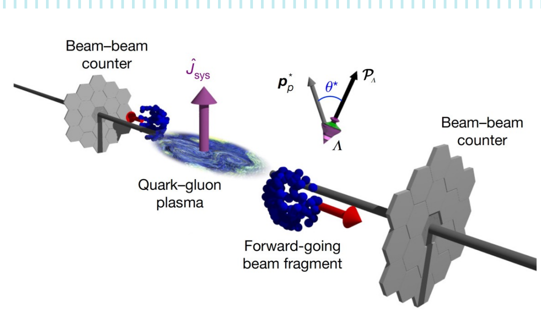
IF THERMALIZED, $\sqrt{s_{\mathrm{NN}}} \in (5, 3.5)$ GeV

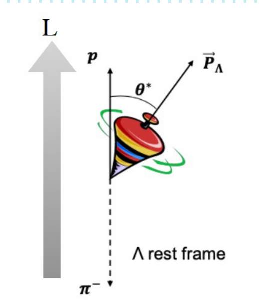
Criticality: Summary

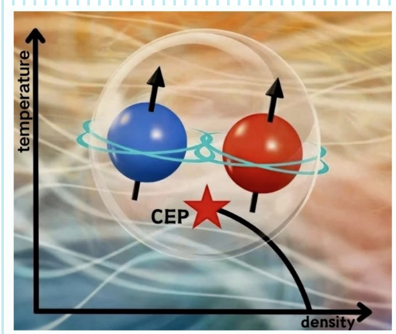
1) A $\boldsymbol{5\sigma}$ deviation from dynamic references observed at $\sqrt{s_{NN}}$~ 20 GeV;
2) At 3GeV, system seems back to hadronic interaction;
3) Energy region $4 < \sqrt{s_{NN}} < 8$ GeV is important for the QCD critical point search → CBM at FAIR and STAR is working on the FXT data of 3.0 – 4.5 GeV Au + Au collisions

The emergent properties of QCD matter

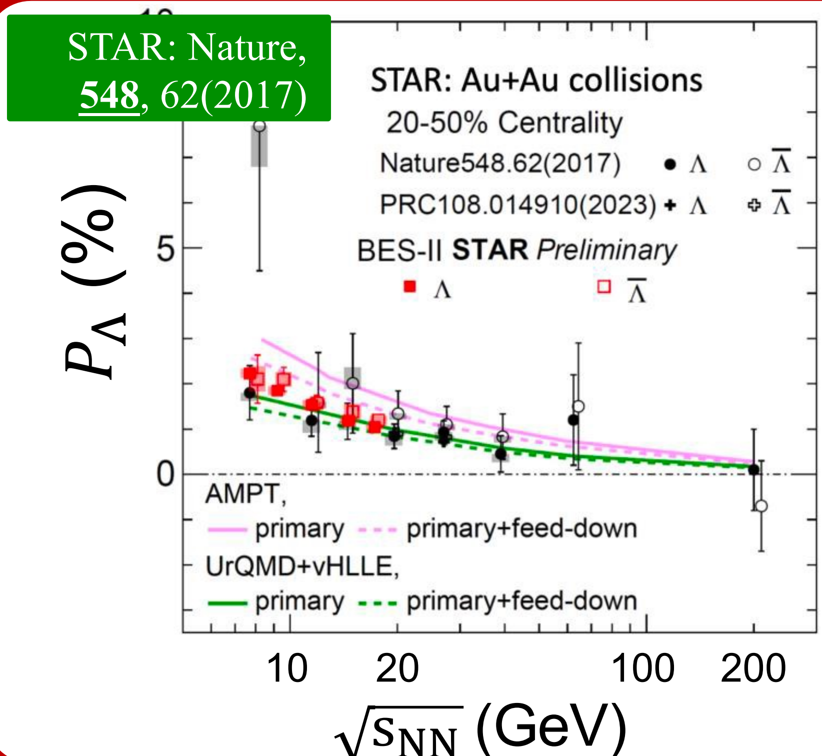
Polarizations

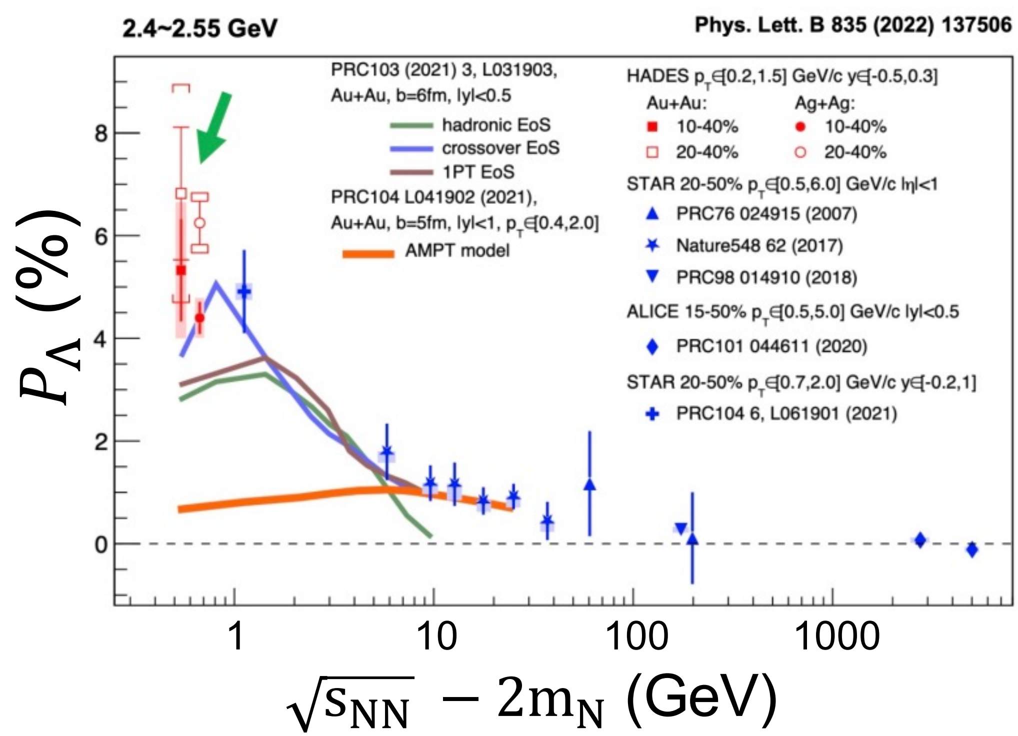






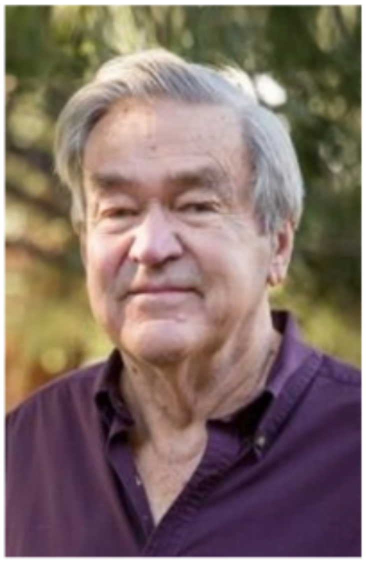
Results on Λ-Global Polarizations





1) Observed Λ-global polarization: along the direction of the total angular momentum and increased as collision energy decreases! $\propto \mu_B$?!
2) No theory explain these data! $\langle w \rangle \approx (9 \pm 1) \cdot 10^{21}/sec$ "The most vortical fluid"

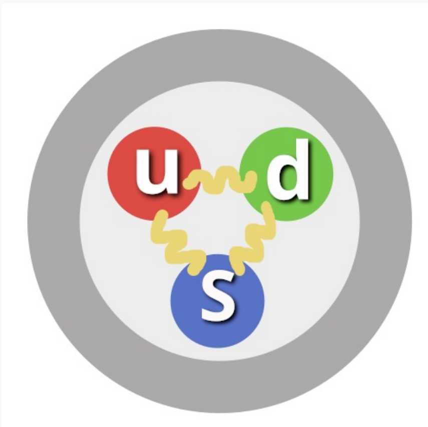
Spin and Strong Interactions



"Polarization data has often been the graveyard of fashionable theories. *If theorists had their way, they would ban all experiments involving spin."*

James D. Bjorken
Proc. Adv. Res. Workshop on QCD Hadronic Processes, St. Croix, Virgin Islands (1987)

Lambda baryon



Quark structure of the lambda baryon.

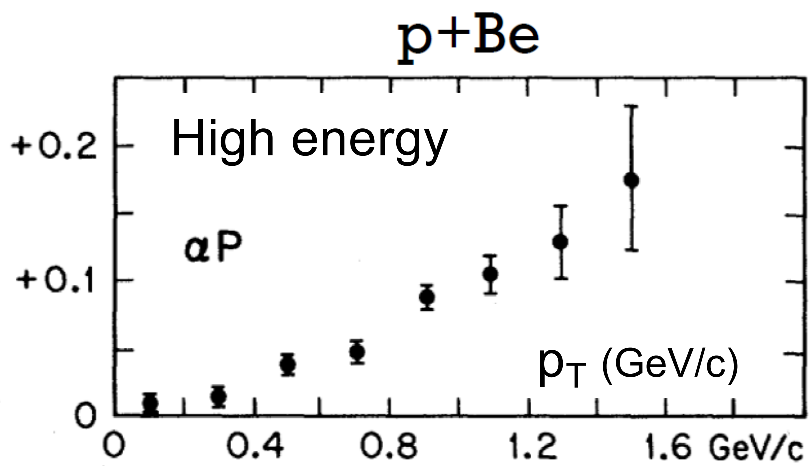
Composition	Λ^0: uds Λ_c^+: udc Λ_b^0: udb
Statistics	Fermionic
Family	Baryons
Interactions	Strong, weak, electromagnetic, and gravity
Types	3
Mass	Λ^0: 1 115.683 ± 0.006 MeV/c^2 [1] Λ_c^+: 2 286.46 ± 0.14 MeV/c^2 Λ_b^0: 5 619.60 ± 0.17 MeV/c^2
Spin	½
Isospin	0

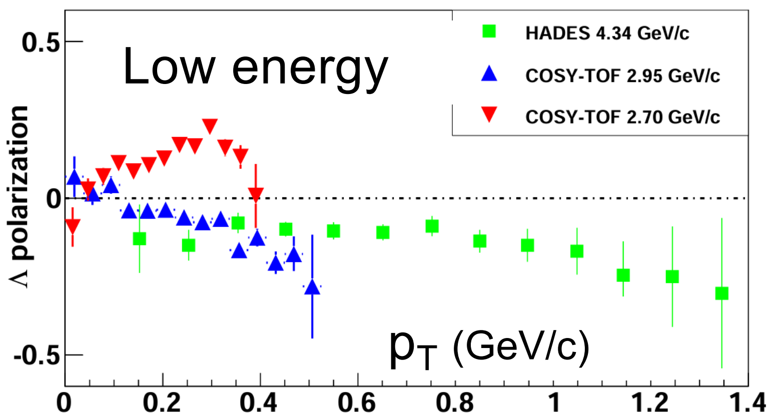
Spin and Strong Interactions

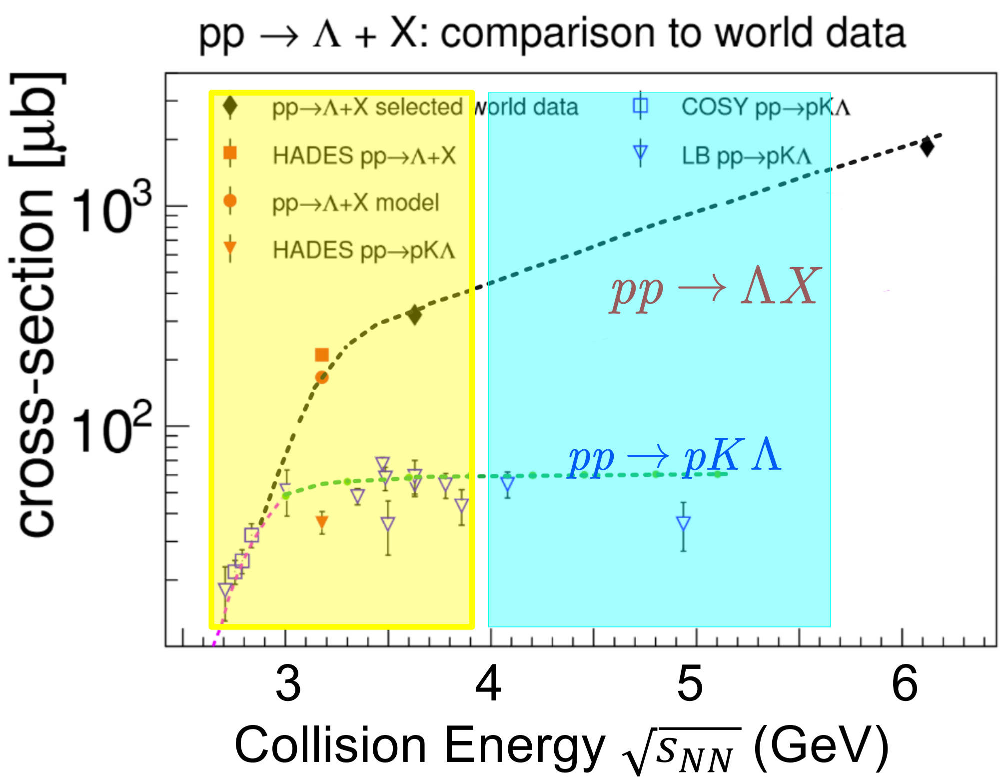
Chirality is the basic building block in strong interaction theory QCD. Experimental observables with spin, an intrinsic quantum number of any elementary particle, offer an important manifestation of chirality.

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

Λ Production and Polarization



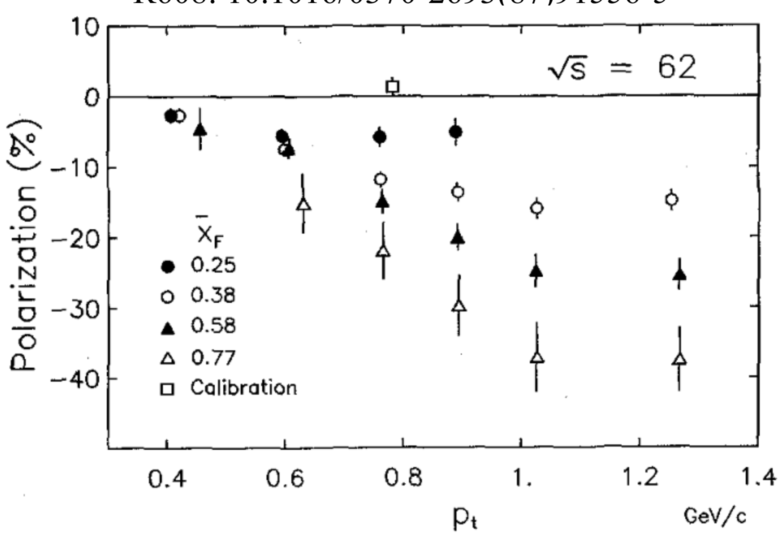




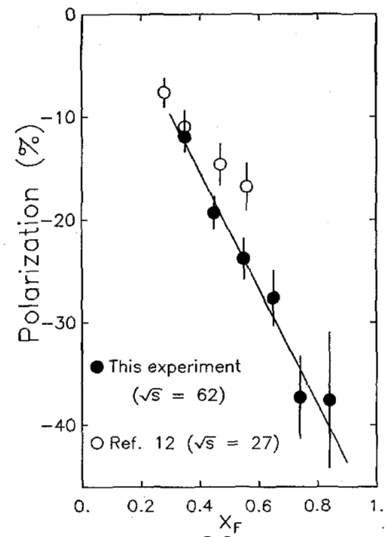
HIAF HIAF-U

Λ –Polarization: x_f- anf p_T-scaling (?)

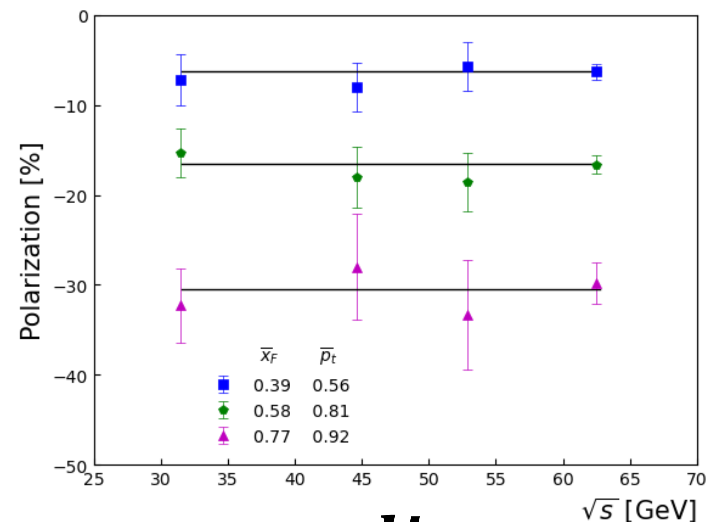
R608: 10.1016/0370-2693(87)91556-5



p_T



x_f



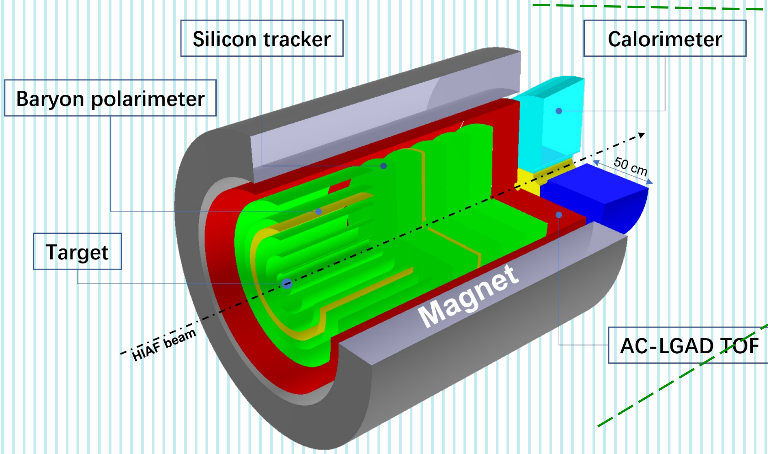
$scaling$

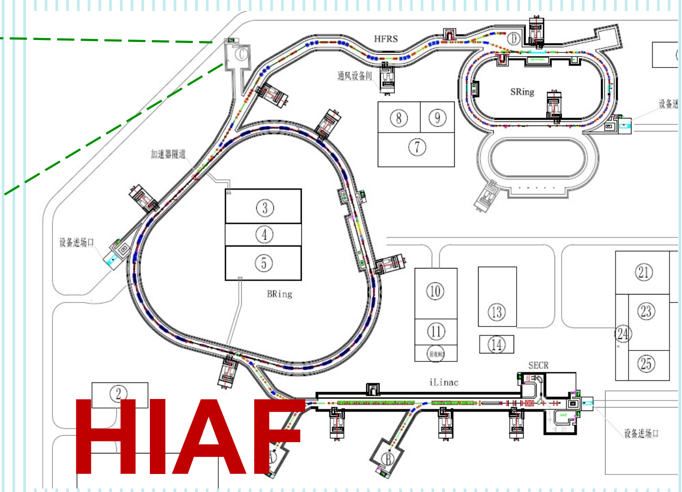
Questions:

1) Origin of the Λ polarization: **Collision dynamics? Intrinsic spin structure?**
2) In p+A and A+A collisions, Λ –global polarization, Λ –local polarization have been observed. What is the relation between those and Λ polarization?

Future Experimental Opportunities

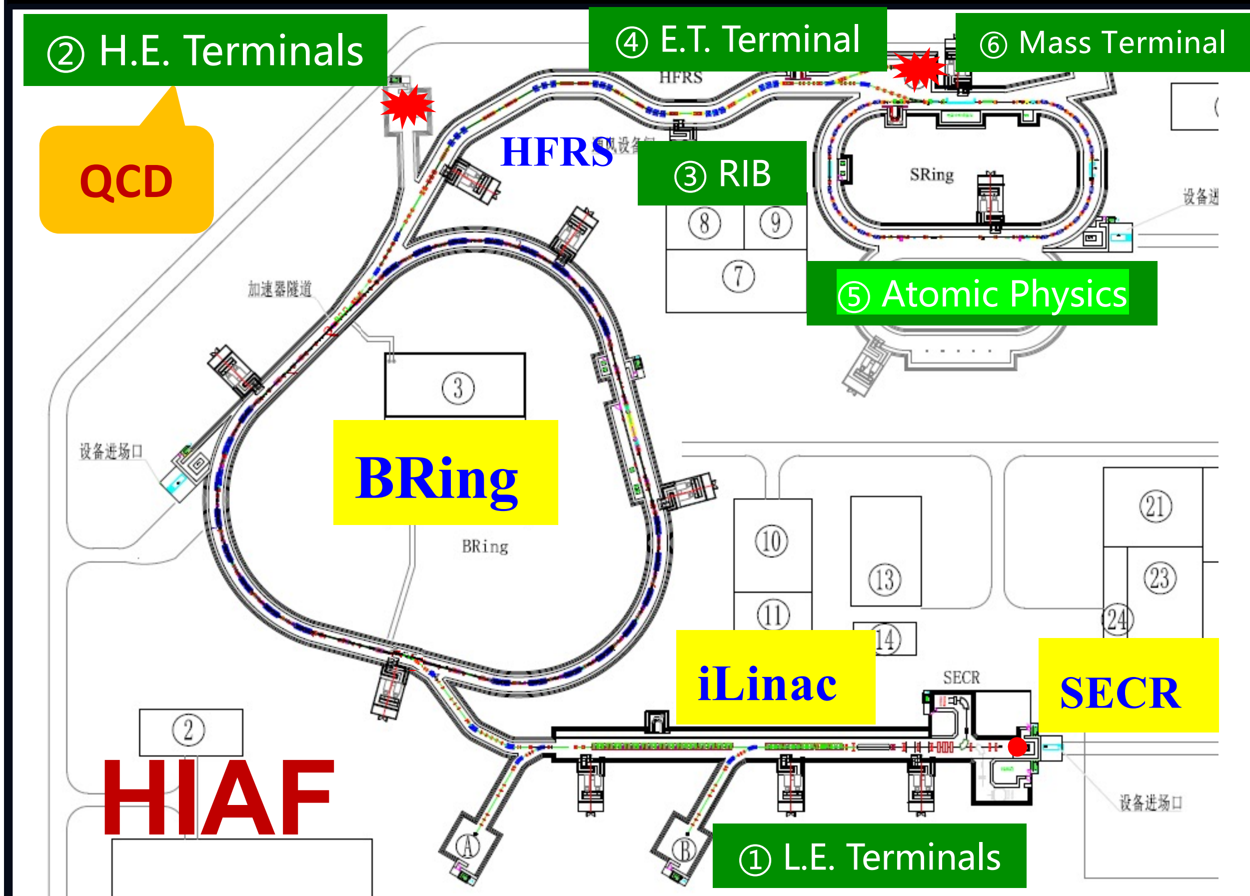
H-NS@HIAF





High Intensity heavy-ion Accelerator Facility

(HIAF, Huizhou, China)



HIAF Physics：

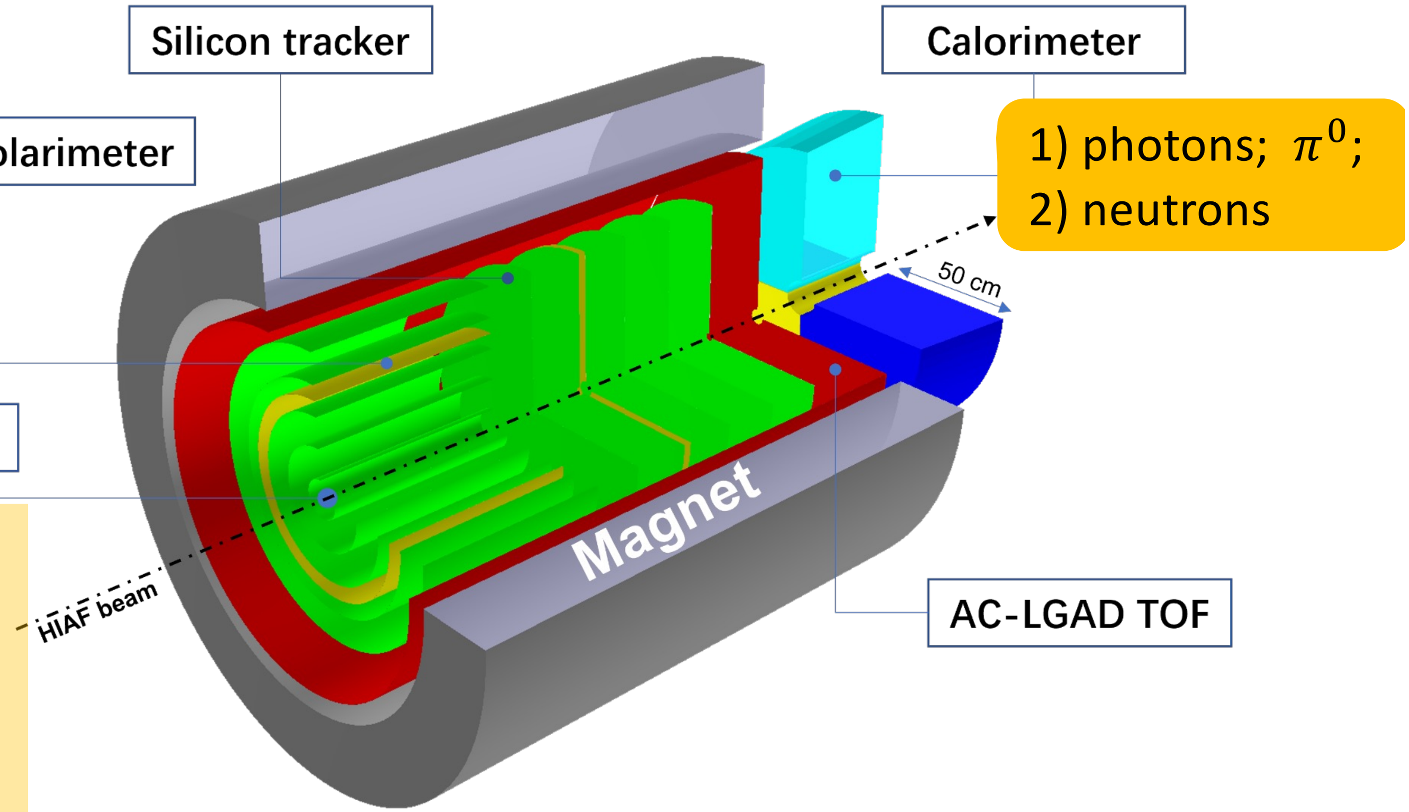
(i) Atomic physics;
(ii) Nuclear physics;
(iii) Applied research in biology and material science etc.

HIAF Commission will start in December of 2025

HIAF Beam Parameters

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

Hyperon-Nucleon Spectrometer Concept



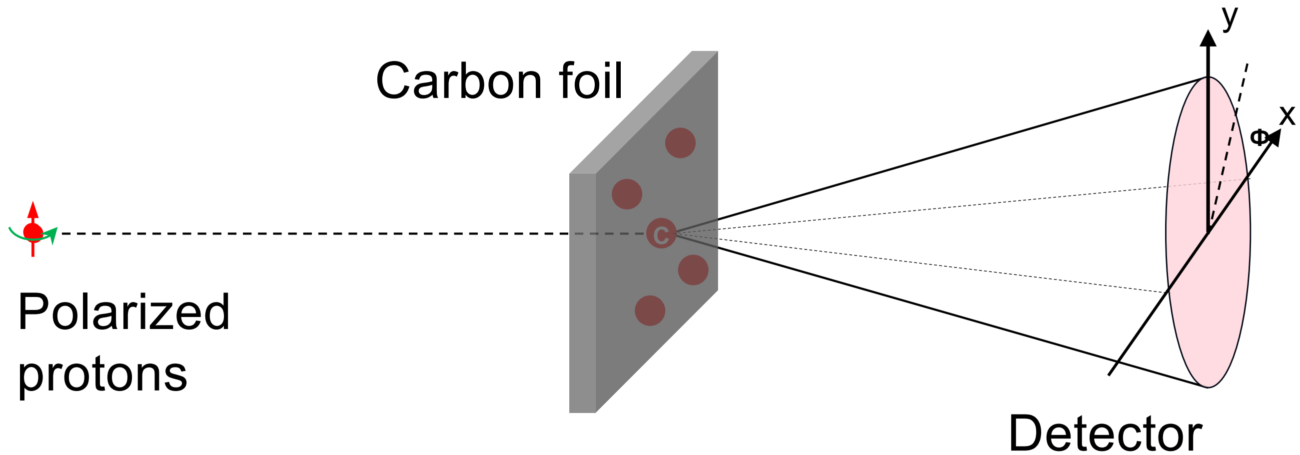
Participating Institutes: ≥ 10 (China), more are welcome!

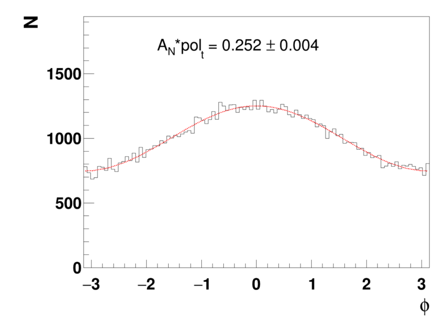
R&D Efforts: (1) Pixel tracker; (2) AC-LGAD; (3) **Baryon Polarimeter;** (4) Target systems; (5) Calorimeter; (6) FEE; (7) DAQ; (8) Magnet; (9) Beam line; (10) Mechanical structure design

Proton Polarimeter

Spin-dependent cross-section of p + p/C scattering:

$$\frac{d\sigma}{d\phi d\cos\theta} = \frac{1}{2\pi}\frac{d\sigma_0}{d\cos\theta}\left[1 + P_y A_N(\theta)\cos\phi\right]$$



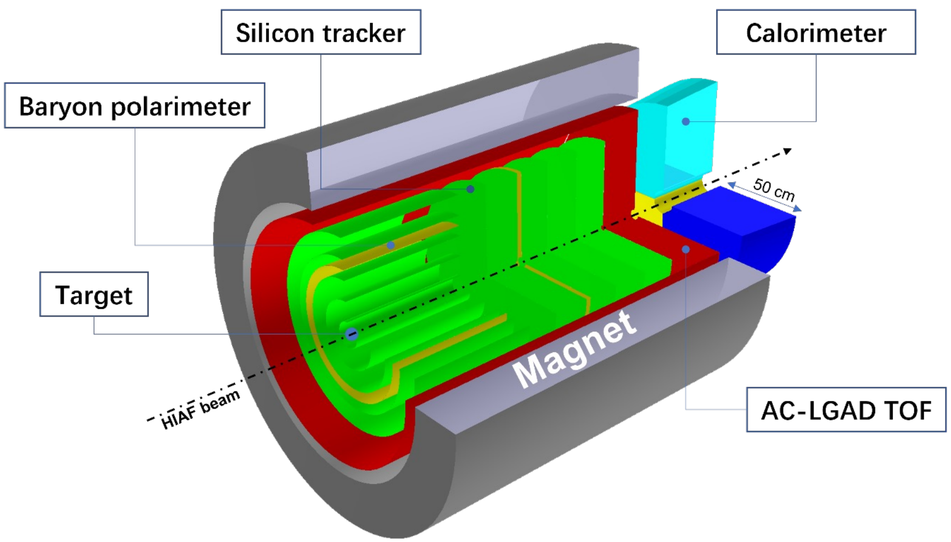


More protons to the left:
Left-right asymmetry

Widely used to measure polarized proton beam (PSI, TRIUMF, LAMPF, COSY, SATURNE, ZGS, KEK-PS, AGS, RHIC …)

Proton Polarimeter:
Yutie Liang: PRD**112**, L031502(2025)

Hyperon-Nucleon Spectrometer (H-NS)



Participating Institute: 近代物理研究所、清华大学、山东大学、北京航空航天大学、复旦大学、国科大、华中师范大学、华南师范大学、北京师范大学、香港中文大学（深圳）、中科大、 中国原子能研究院、湖师、 …

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 hyperon (*A*+*A*)
- Hadron physics via *p*+*p*

II. Community:

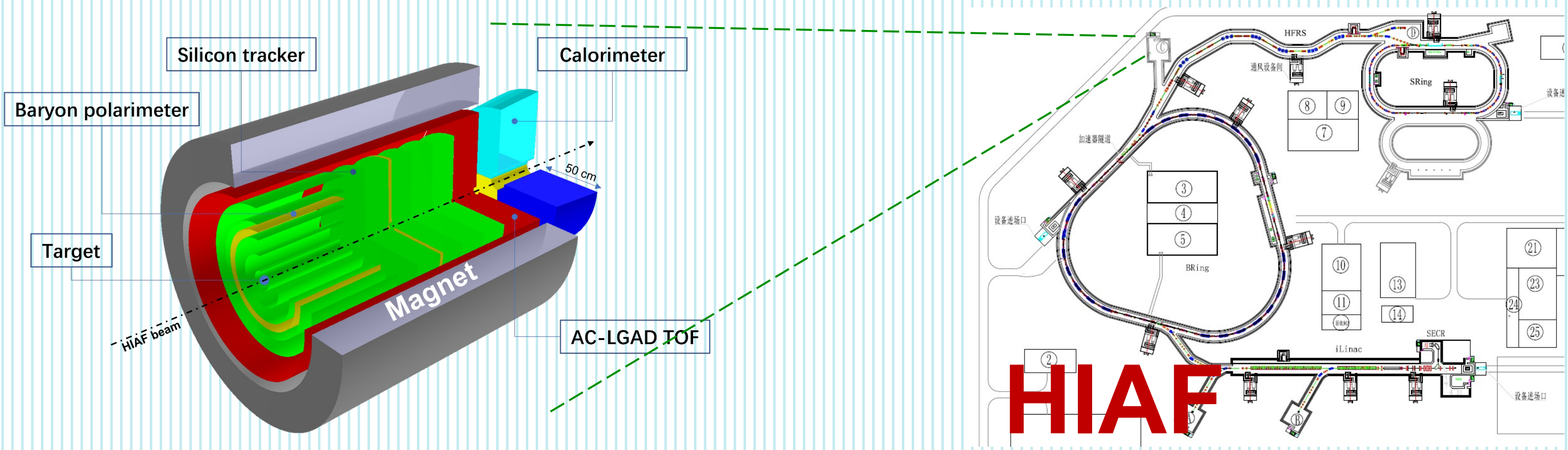
- Supports both communities of hadron structure and heavy-ion physics
- International participations are welcome!

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(½ EicC)

H-NS@HIAF:

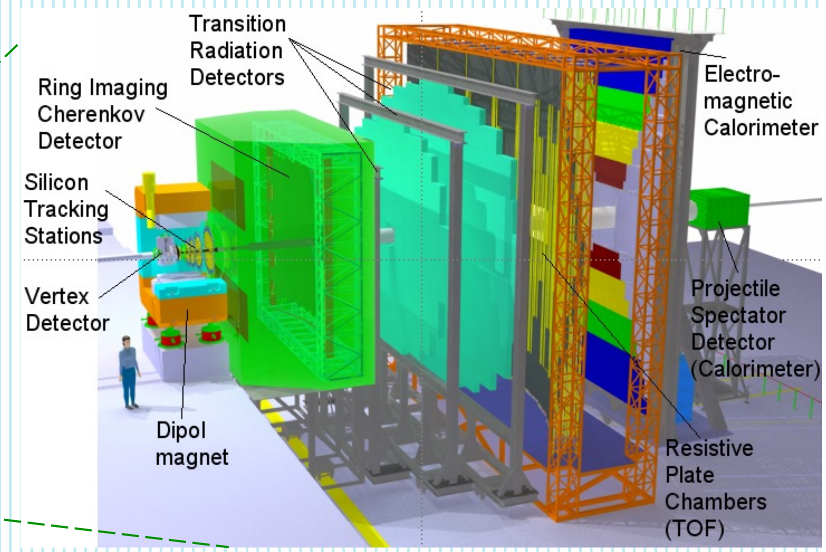
1) H-NS: **Large acceptance with full azimuthal coverage, High efficiency, Fast DAQ** (~1M Hz). **Energy scan within 3 – 9.3 – 31 GeV/u is planned …**
2) In p+p and p+A collisions: **Λ (p) polarization, Hadron spectra, Spin structure, Spin-spin correlations, Hyper-nuclei, …;**
3) In A+A collisions: **High μ_B properties, QCD critical point, …**



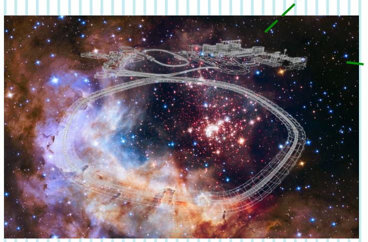
Future Experimental Opportunities

CBM@FAIR

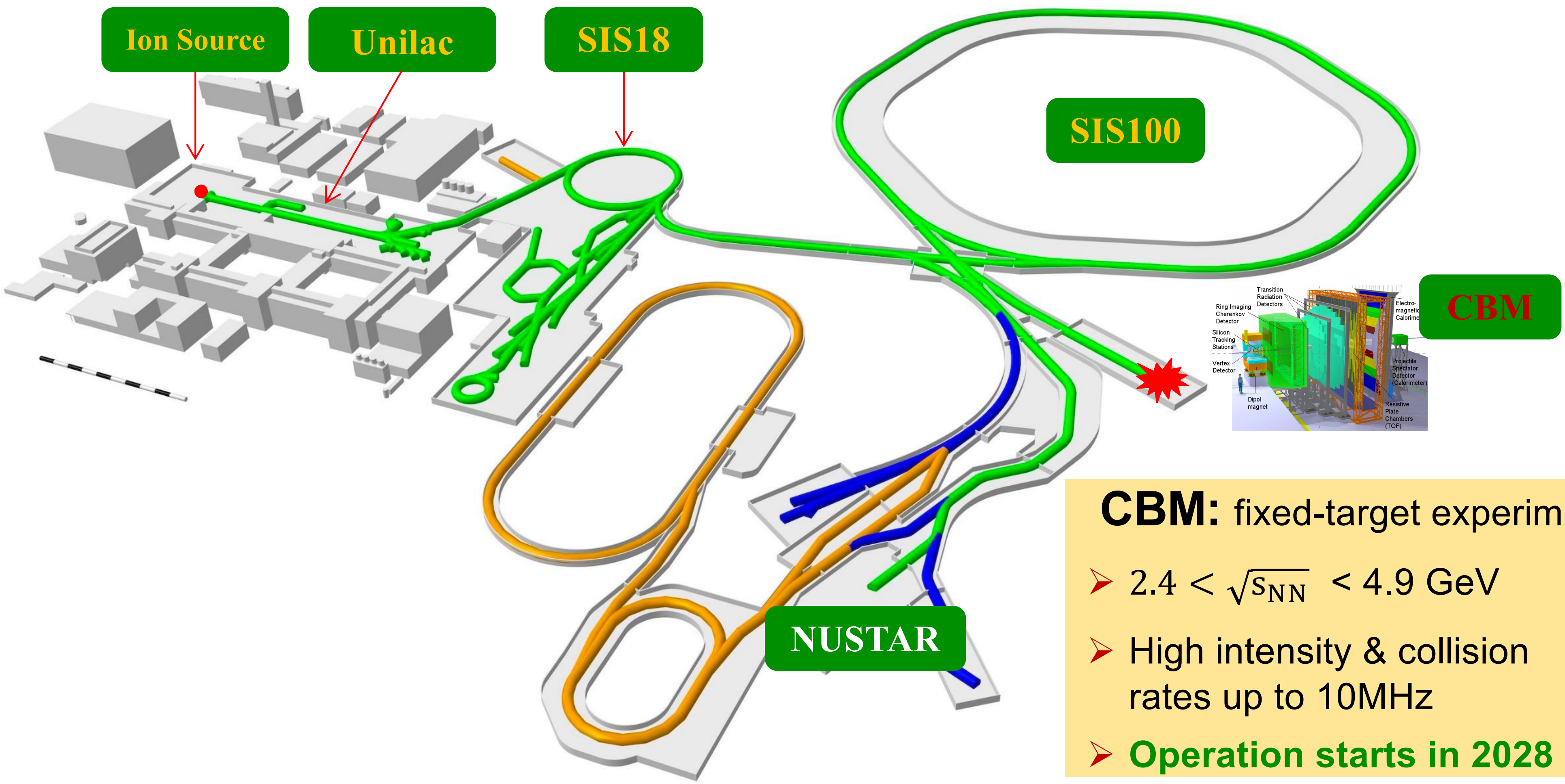
1) **QCD critical point**
2) **High μ_B properties**



FAIR



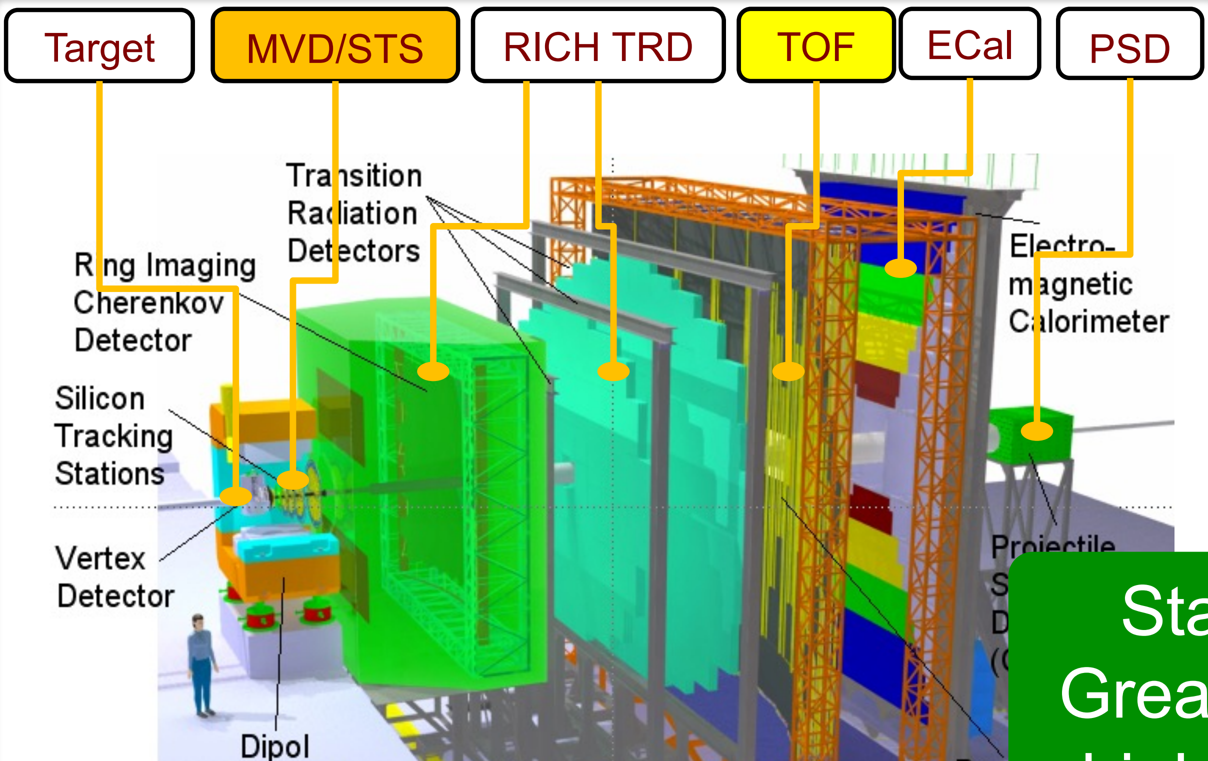
Compressed Baryonic Matter Experiment at FAIR



CBM: fixed-target experiment

- $2.4 < \sqrt{s_{NN}} < 4.9$ GeV
- High intensity & collision rates up to 10MHz
- **Operation starts in 2028**

CBM Experiment at FAIR



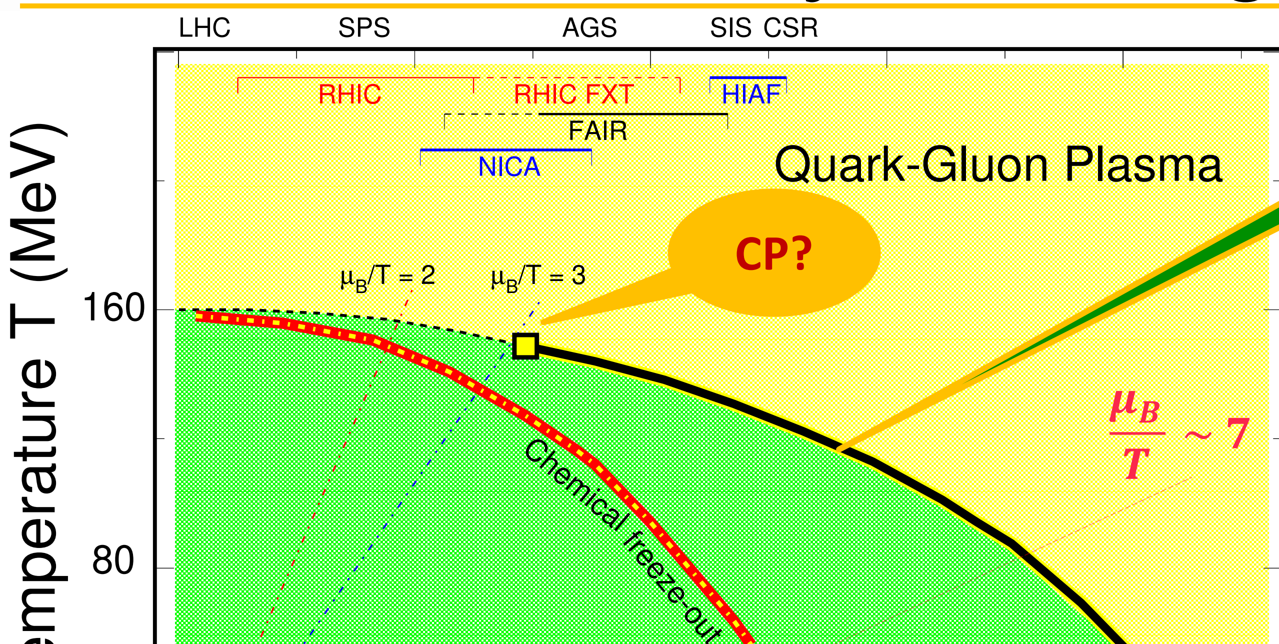
- **FAIR:** One of the brightest accelerator complexes
- **Precision measurements** at high baryon density region:
  (i) Dileptons (*e*, μ);
  (ii) High order correlations;
  (iii) Flavor productions (s, c)

State-of-the-art detector!
Great discovery potentials at high baryon density region!

A dream experiment!

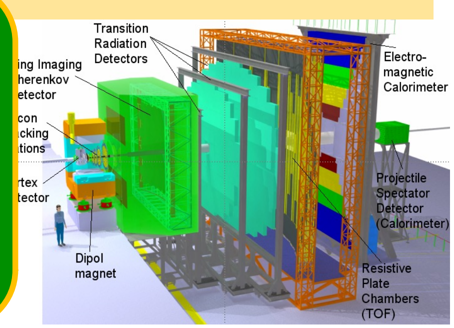
1) "The CBM Physics Book", B. Friman *et al.*, Lect.Notes Phys. **814**, 1 (2011)
2) "Challenges in QCD Matter Physics – The Scientific Program of the Compressed Baryonic Matter Experiment at FAIR", T. Ablyazimov *et al.* Eur.Phys. J. **A53**, 3 (2017).

Future Physics Programs



BES-III
CBM

- Critical point and phase boundary;
- Nuclear matter EOS at high baryon density;
- Y-N interactions, inner structure of compact



Key Physics in CBM:

- QCD critical point, EOS at high μ_B
- Heavy-Ion Collisions⇔ Astro-Nuclear Physics

Summary

1) High-energy nuclear collisions: CCC

- Thermalization and smooth crossover transition
- At 3 GeV, hadronic interaction dominant

2) Outlook: polarization

- **CBM** at FAIR
- **H-NS** at HIAF

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A.Q. Guo, *X.G. Huang*, Y.T. Liang, *J.F. Liao, Z.T. Laing, J.J. Wu*, Q.H. Xu, Y.X. Zhao, *B.S. Zou*

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

Thank you for your attention!