Status on the Search for QCD Critical Point at RHIC and Lambda Polarization

许 怒

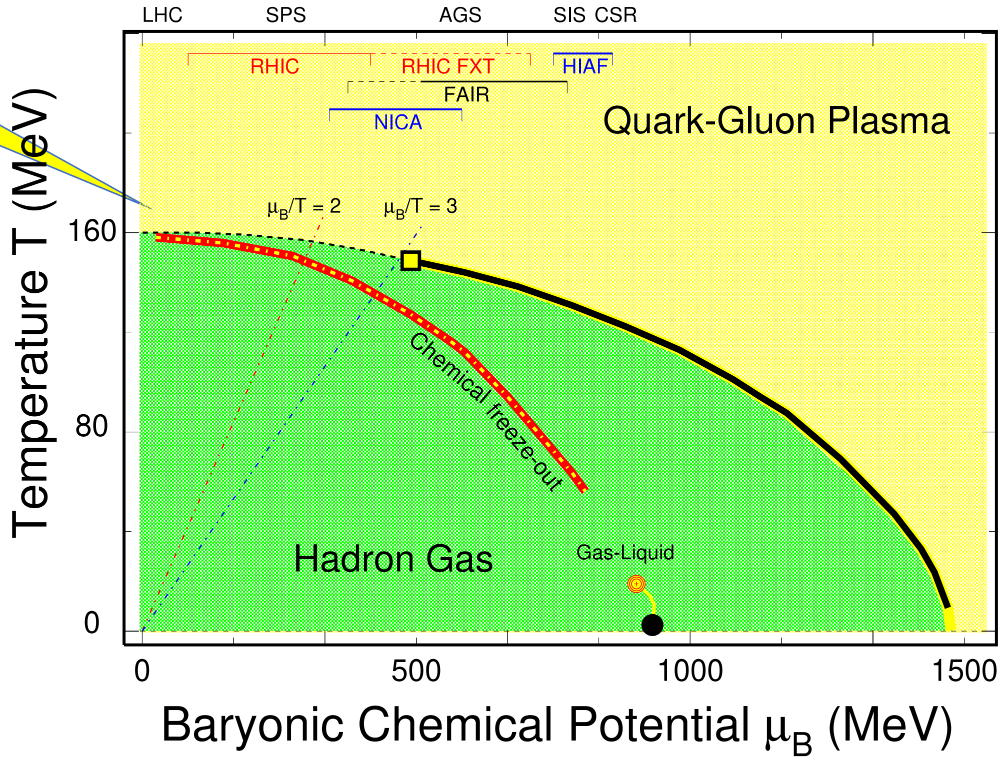
华中师范大学

中国科学院近代物理研究所

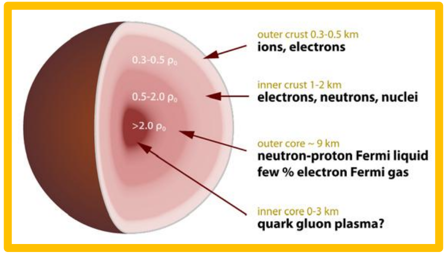
Outline

Nuclear Collisions and QCD Phase Diagram

Early Universe



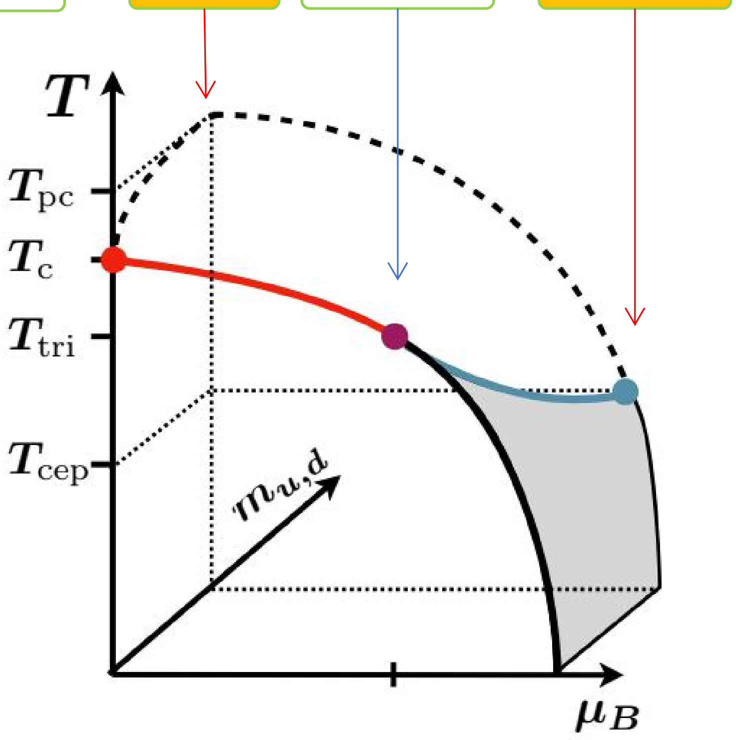
High baryon density: Inner structure of compact stars



1) RHIC BES: → search for 1st-order phase transition and **QCD critical point**;
2) Baryon interactions (*e.g.* $N - N$, $Y - N$) → inner structure of compact stars

LGT Calculation: QCD Phase Structure

T_C^0 | T_{PC} | T^{TC} | T^{CEP}



F. Karsch *et al.*, 2020

1) QCD transition temperature:

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

2) Chiral crossover line

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

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

3) Chiral transition temperature:

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

4) QCD critical end point:

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

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

Thermalization in Heavy-Ion Collisions

S. Gupta, **D. Mallick** *et al.* Phys. Lett. **B829**, (2022) 137021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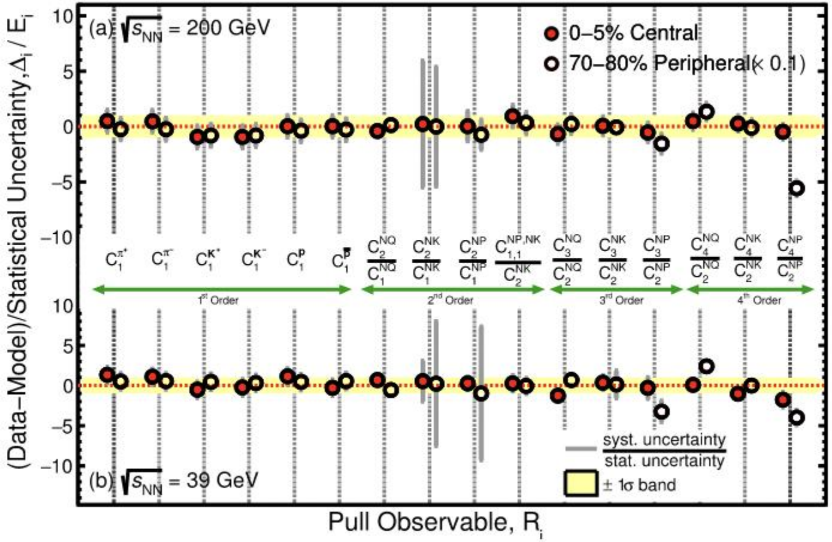
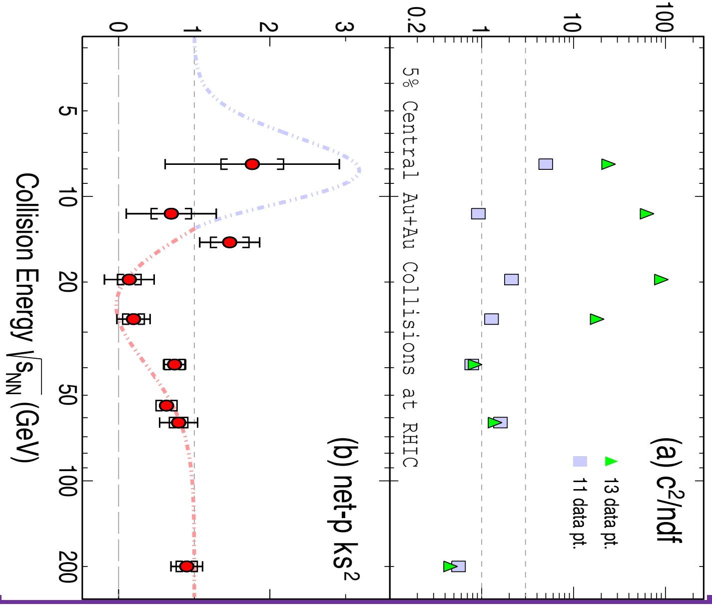
Limits of thermalization in relativistic heavy ion collisions

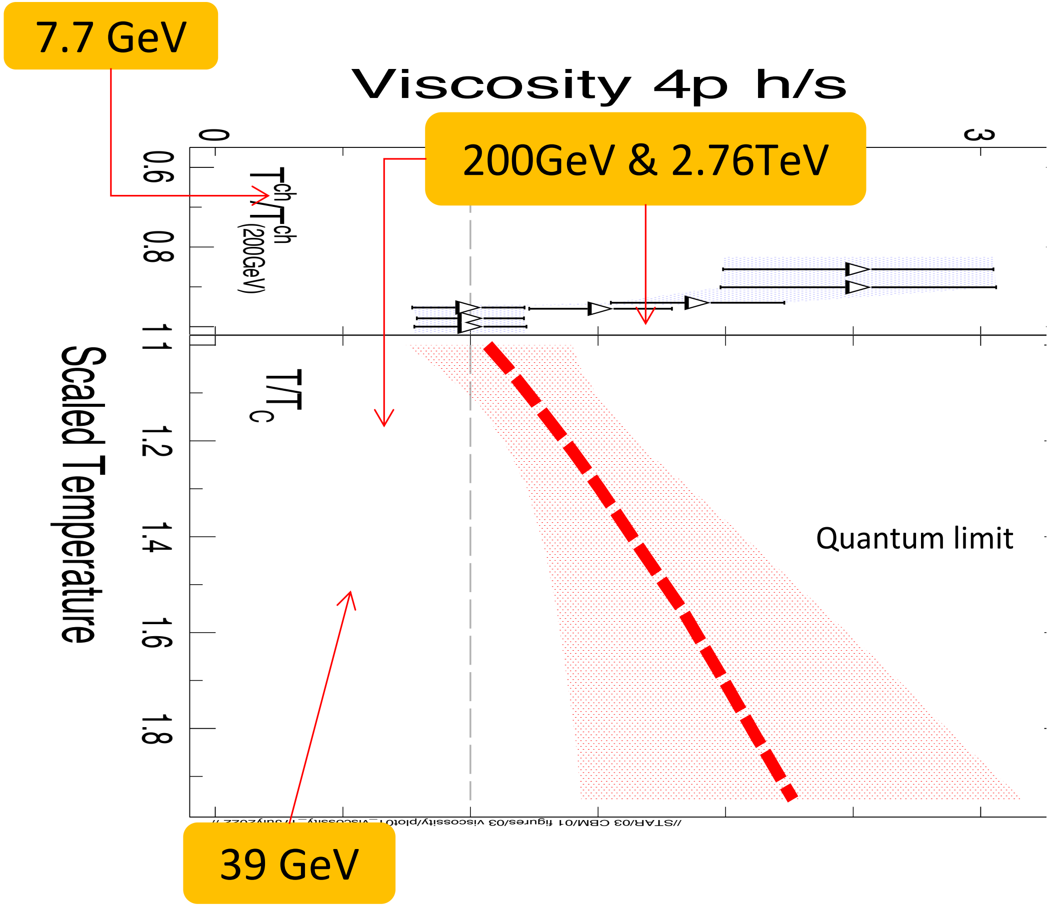
Sourendu Gupta[a], Debasish Mallick[b,c], Dipak Kumar Mishra[d], Bedangadas Mohanty[b,c,*], Nu Xu[e]



1) Test of the thermal model with high moments data: 4TH order;
2) Below 39 GeV, **data is not consistent with equilibrium.**



Strong Interaction Equation of State



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;

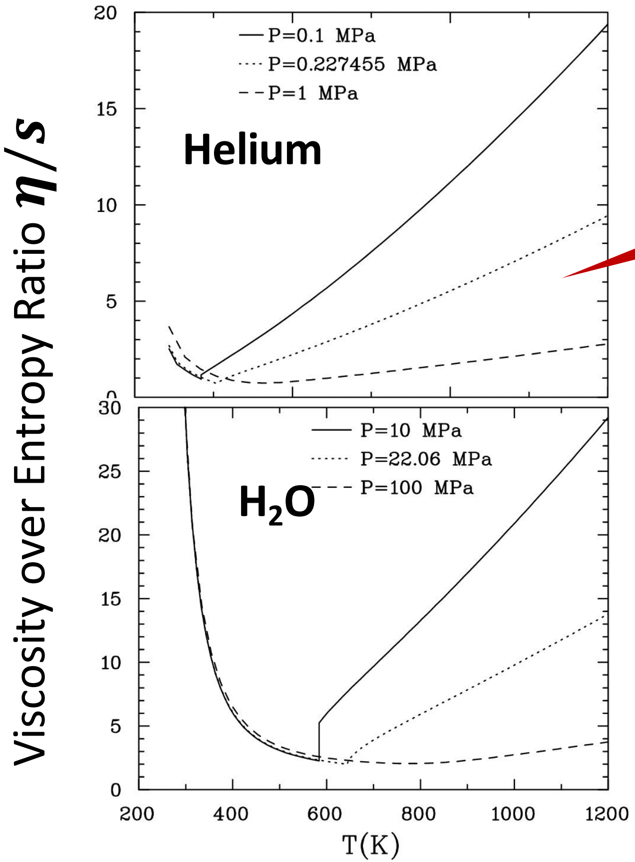
2) Both sides meet at the unity of the scaled temperature;

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

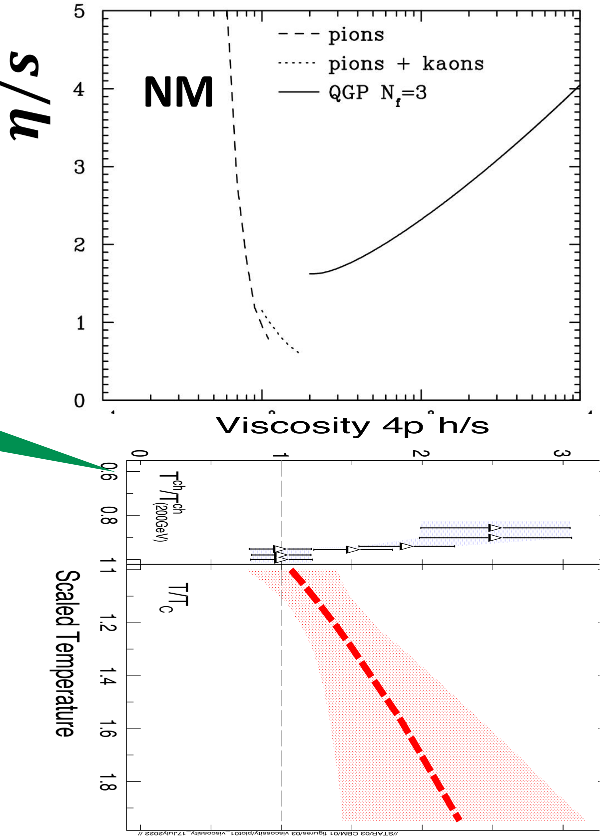


L.P. Csernai, J.I. Kapusta, L.D. McLerran, PRL**97** (2006) 152303

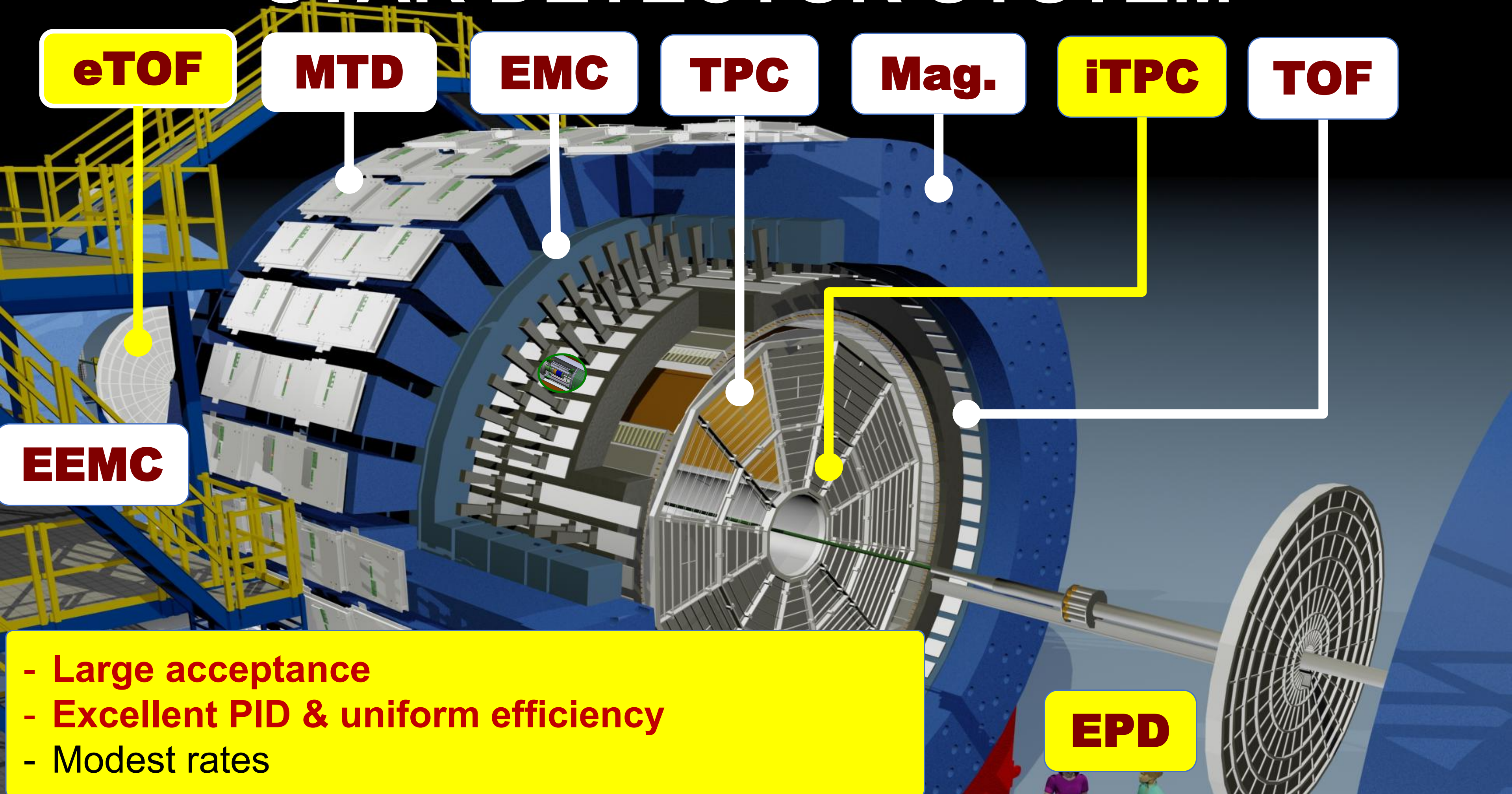
EM interaction
η/s ~ 1

Strong Interaction
η/s ~ 0.1

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

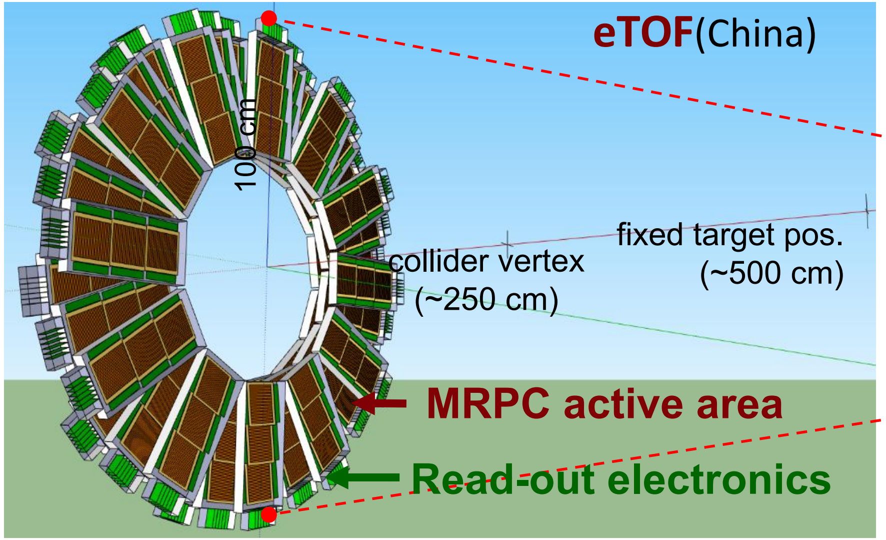


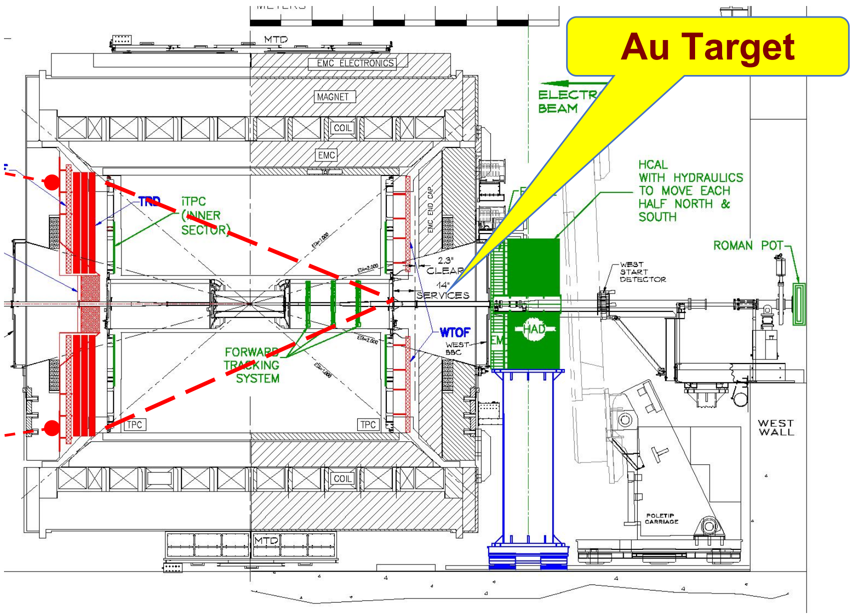
STAR DETECTOR SYSTEM



- **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 BES-II Data Sets

Au+Au Collisions at RHIC											
Collider Runs						Fixed-Target Runs					
	$\sqrt{s_{NN}}$	#Events	μ_B	y_{beam}	run		$\sqrt{s_{NN}}$	#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

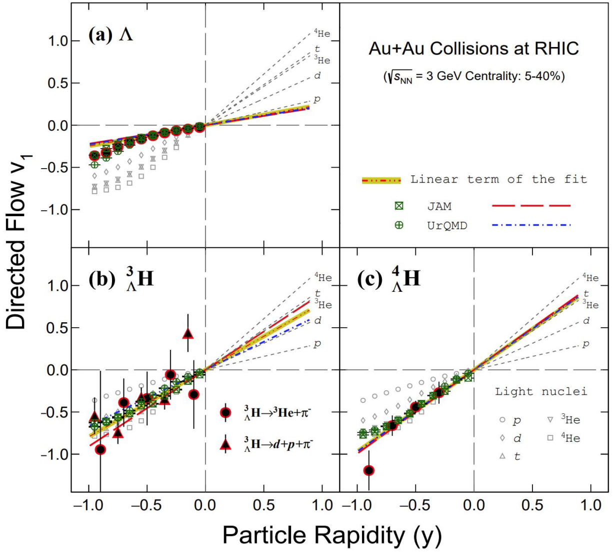
Most precise data to map the QCD phase diagram

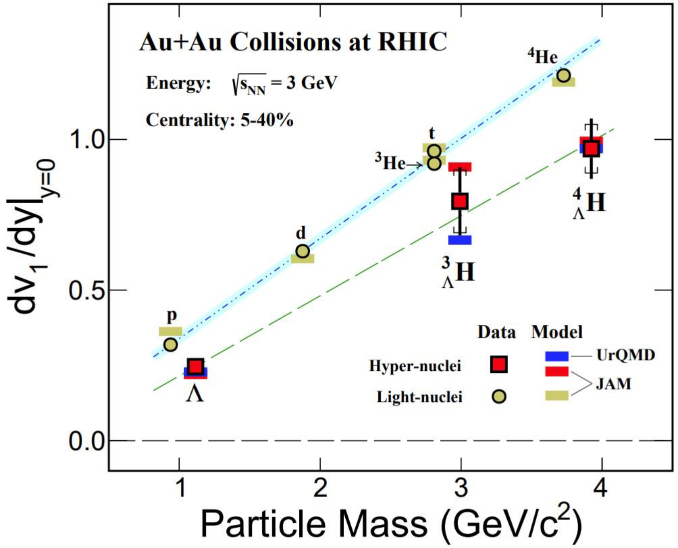
$$3 < \sqrt{s_{NN}} < 200 \text{ GeV}; \quad 760 > \mu_B > 25 \text{ MeV}$$

Outline

1) Introduction
2) Selected Recent Results from RHIC Beam Energy Scan
3) Lambda Hyperon Polarization and Hyperon-Nucleon Spectrometer (HNS)

Collectivity of Hyper-Nuclei

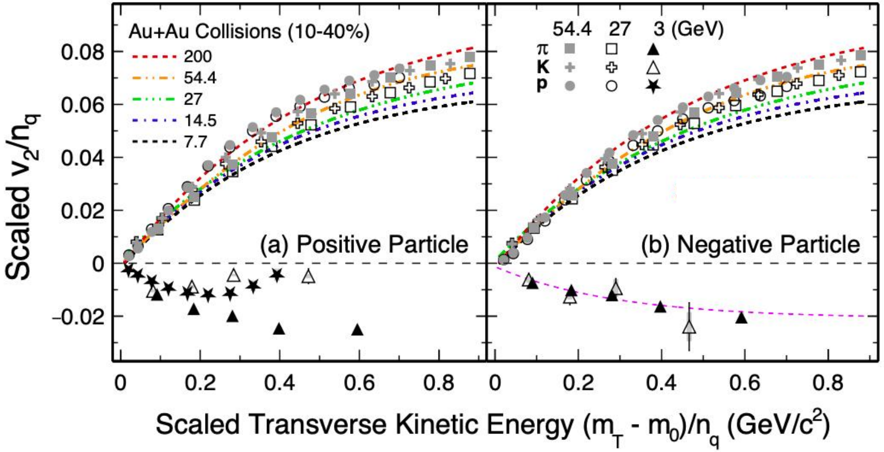


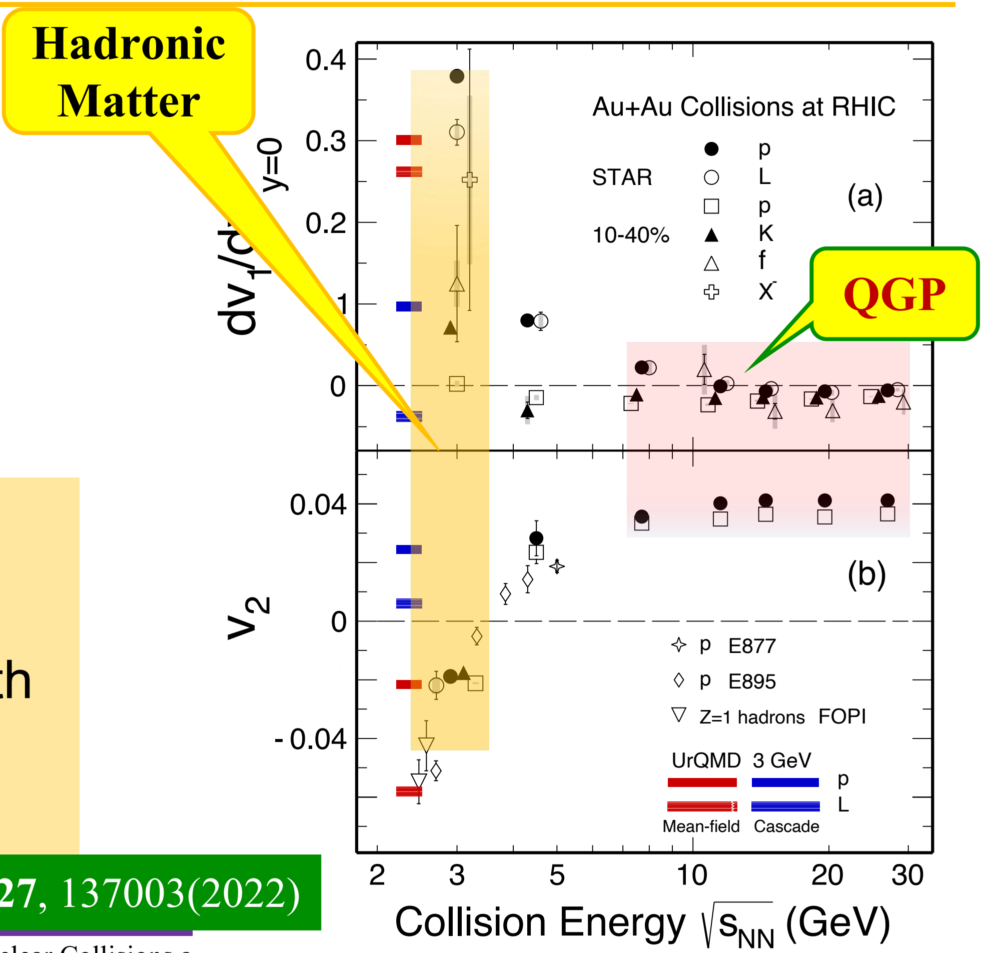


STAR: PRL 130, 212301(2023)

- Coalescence: the dominant procedure for hyper nuclei production;
- Hyper nuclei collectivity (e.g. v_1 and v_2) → ***Y-N*** and ***Y-Y*** interactions under finite pressure gradient;
- **Questions:** Connection to the EOS of compact stars? Effect of isospin?

Disappearance of Partonic Collectivity

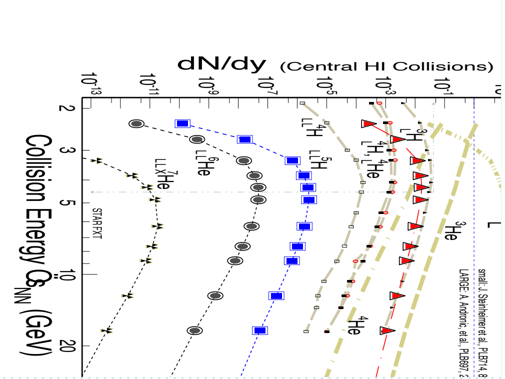


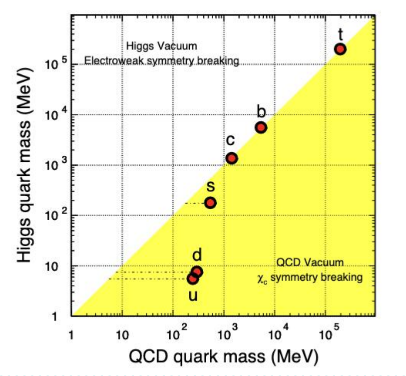


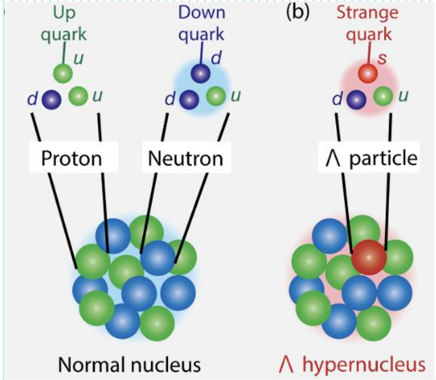
- ➢ At **3 GeV**, NCQ scaling is absent；
- ➢ Transport model calculations, with baryonic mean field, reproduce both v_1 and v_2 results；
- ➢ **Hadronic interactions dominant!**

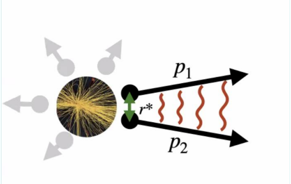
STAR: PLB**827**, 137003(2022)

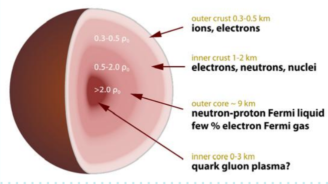
Strangeness， Hyper-Nuclei Baryon Correlations





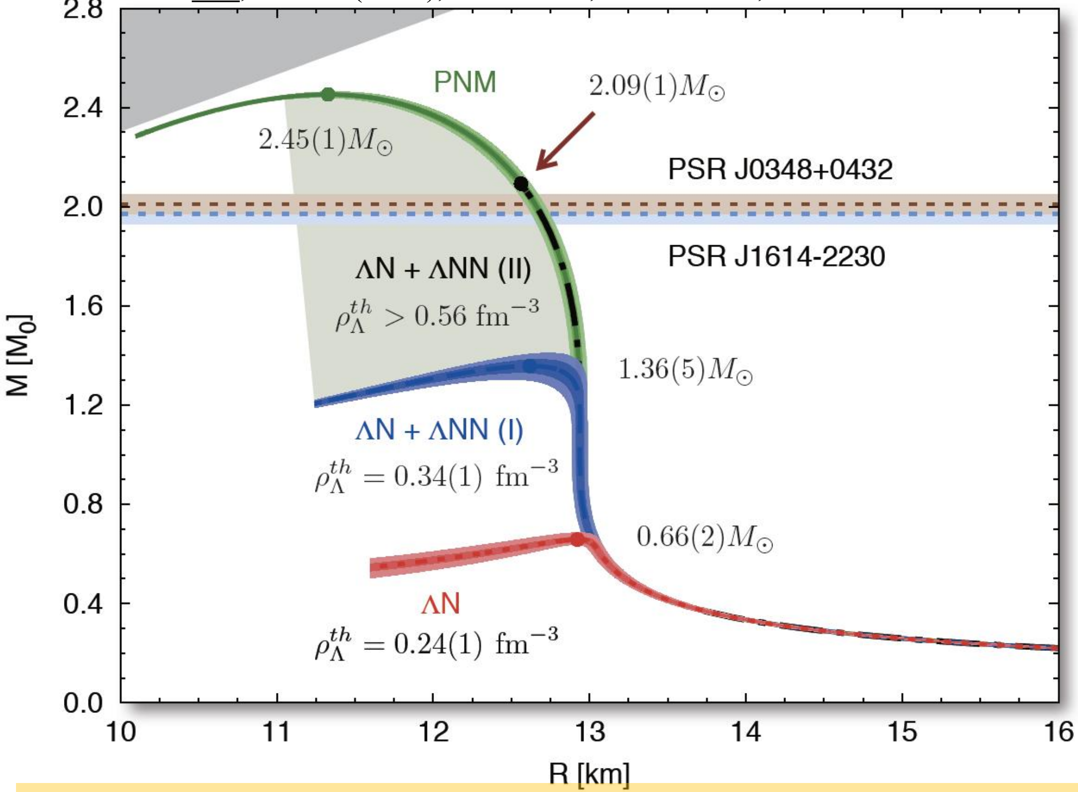


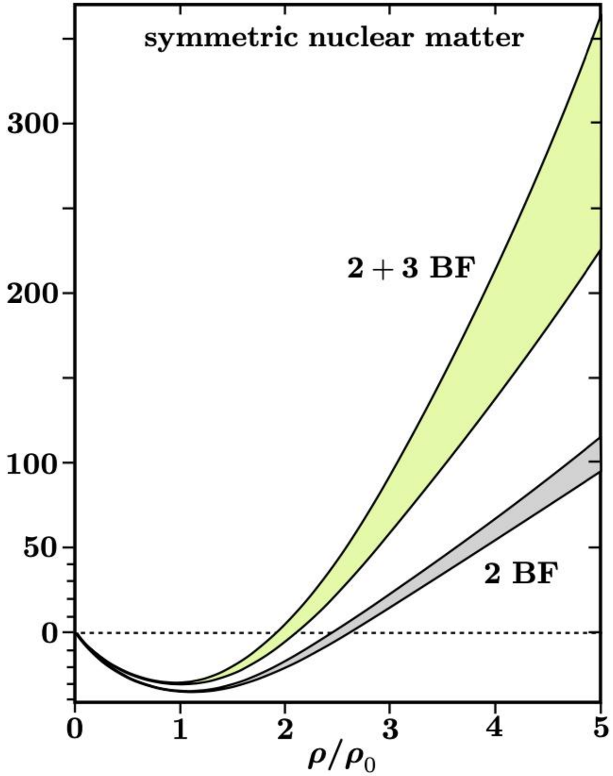




Λ-N Interaction inside Compact Stars

PRL**114**, 092301(2015), HYP2018, 1512.06832, 1711.07521

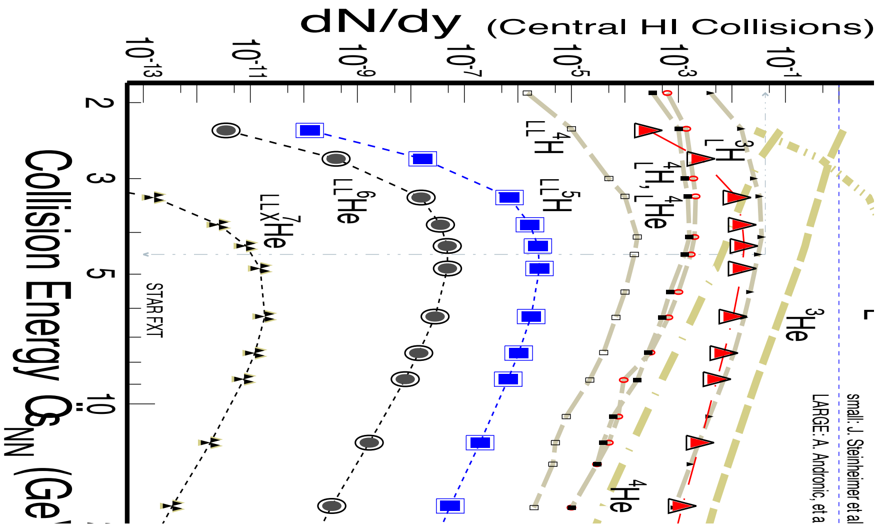




Y-N interaction: key to understand the inner structure of compact stars

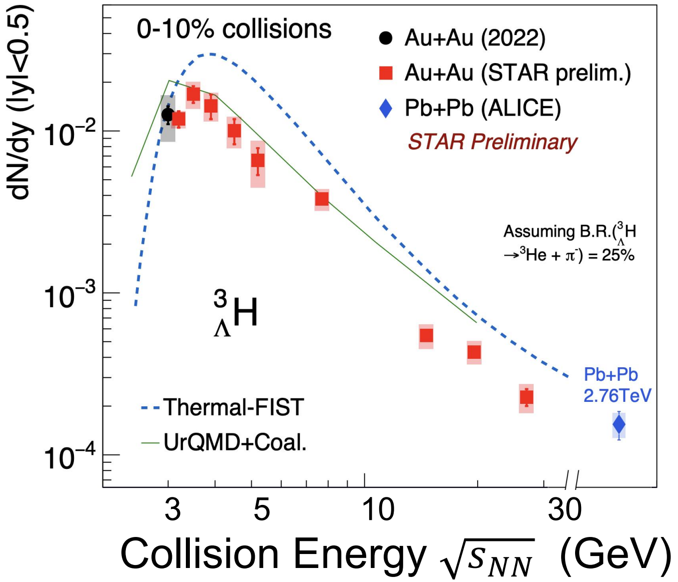
Hyper-Nuclei Production

A. Andronic *et al*. PL**B697**, 203(2011);
J. Steinheimer *et al*. PL**B714**, 85(2012)



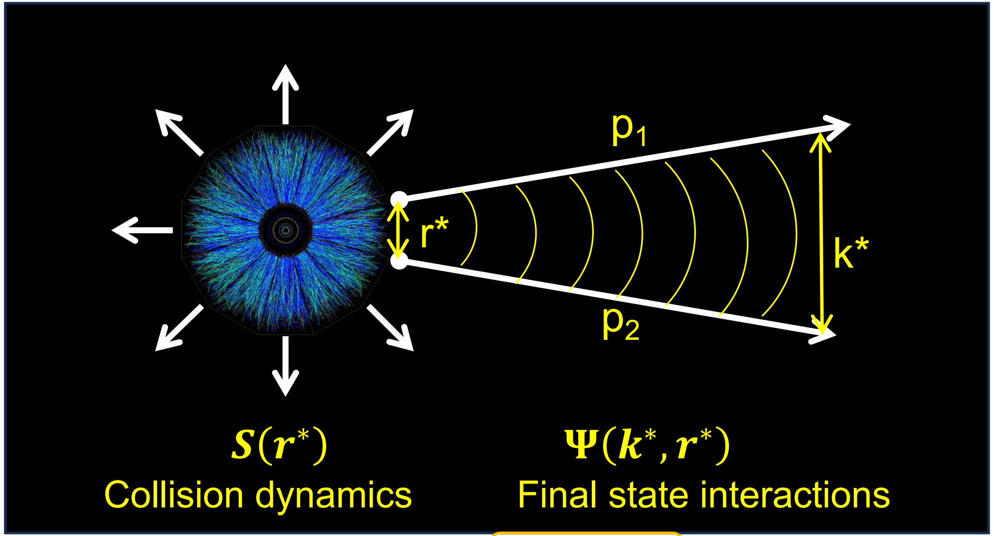
Collision Energy $\sqrt{s_{NN}}$ (GeV)

STAR: CPOD2024, SQM2024



1) Hypernucleus: $^3_\Lambda H$ yields versus energy: peaks at 3.2 GeV;
2) For $\sqrt{s_{NN}} < 10$ GeV, calculations from coalescence more consistent with data

Baryon Correlation Functions



Source

$$C_{the}(k^*) = \frac{1}{4\pi}\int \mathrm{d}^3 r^* S(r^*)|\Psi(r^*, k^*)|^2$$

Final State Interactions:
(1) Quantum statistics; (2) Coulomb; (3) Strong interaction

STAR:

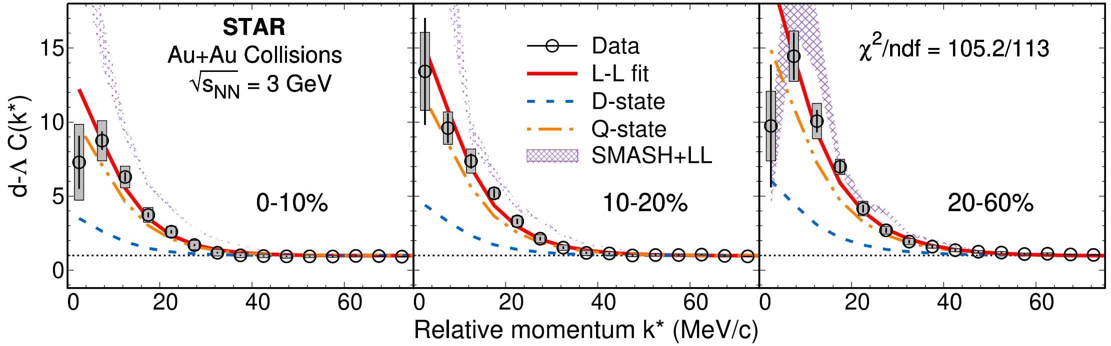
(1) Meson HBT: $\pi - \pi$, $K - K$;

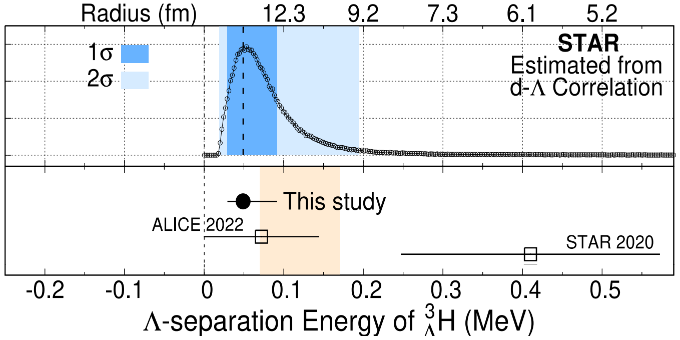
(2) **Baryon Correlations:**

$p - p$	reference	
$p - \Lambda$, $p - \Xi^-$, $p - \Omega$		Y-N
$p - \phi$		
$\Lambda - \Lambda$		Y-Y
$p - d$, $d - d$		N-N-N
$d - \Lambda$		Y-N-N

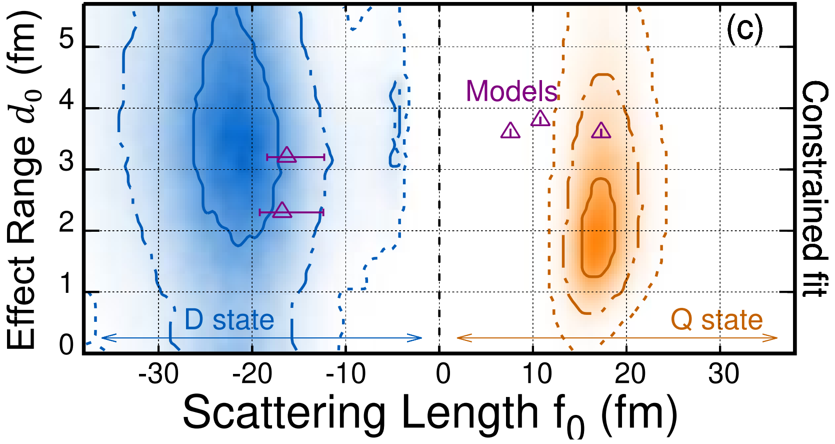
$$C_{exp}(k^*) = \lambda \frac{N_{same}(p_1, p_2)}{N(p_1)N(p_2)}$$

$d-\Lambda$ Correlation Functions 3.0 GeV





STAR: CPOD2024



1) Centrality dependence of the $d-\Lambda$ correlation functions from 3.0 GeV Au+Au collisions;

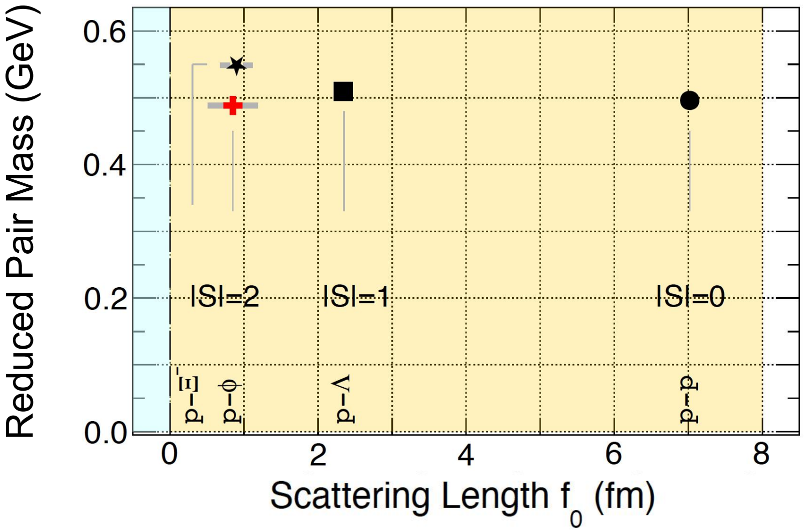
2) For the first time, spin dependent states, *D and Q*, identified experimentally!

→ **New window for studying 3-body interactions in the laboratory**

References:

(1) J.M. Lattimer and M. Prakash, Science **304**, 536 (2004);
(2) M. Kohno and H. Kamada, arXiv:2406.13899;
(3) H. W. Hammer, Nucl. Phys. **A705**,173 (2002)

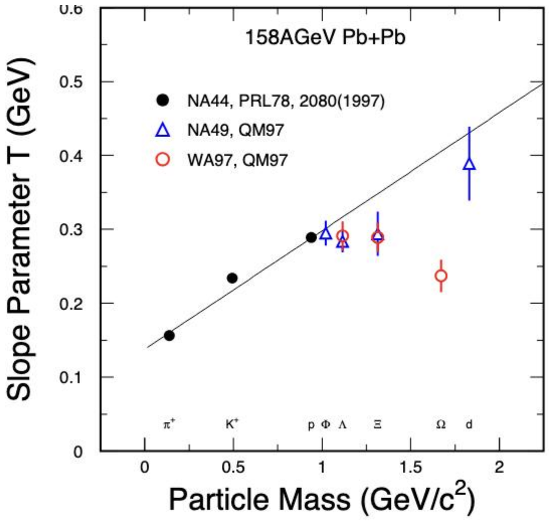
NN, NY, YY Interactions



H. van Hecke, H. Sorge NX, Phy.Rev.Lett. **81**, 5764(1998). *"Evidence of early multi-strange hadron freeze-out in high energy nuclear collisions"*

→ Rescatterings lead to collectivity

→ Collectivity is reduced as the strangeness content is increased

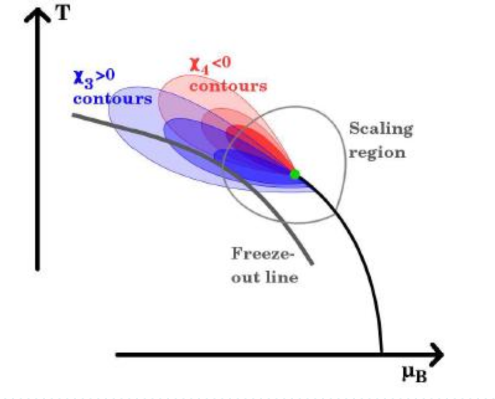


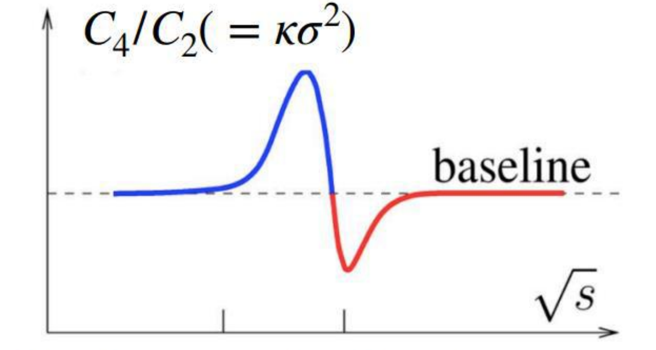
Hierarchy of strangeness content:

$$f_0(|s|=0) > f_0(|s|=1) > f_0(|s|=2) > 0 \;,\; f_0^2 \propto \sigma_{interaction}$$

- Interaction section is proportional to f_0^2, the observation implies that the *strength of the interaction depends on strangeness contents*;
- Important for understanding EOS of the medium in nuclear collisions and compact stars; In case of $f_0 < 0$, important for the search for di-baryons, such as $p\Omega^-$;
- Understand the strangeness hierarchy in QCD calculations?

Criticality





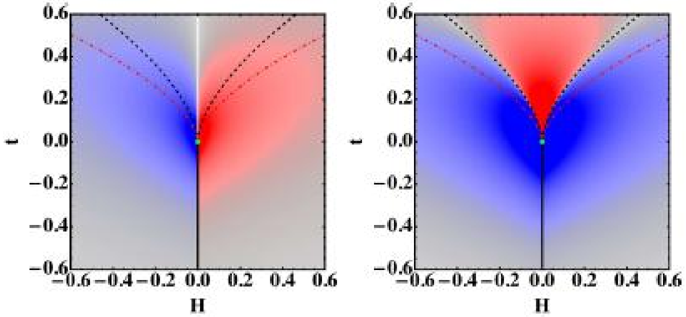
M. A. Stephanov, PRL 107 (2011) 052301

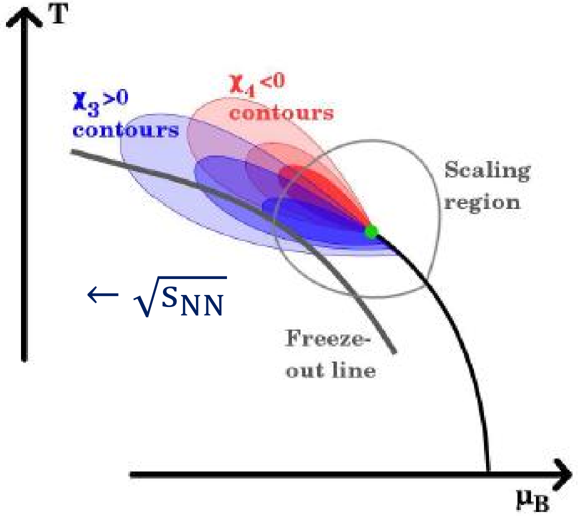
High Moments from BES-II

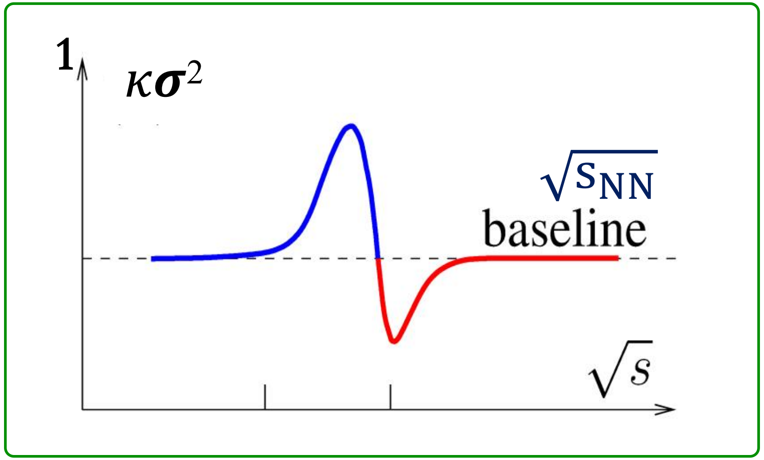
Precision Measurements of (Net-)Proton Number Fluctuations in Au+Au Collisions at RHIC (STAR Collaboration)

STAR: arXiv: 2503.xxxx

Expectations for Models







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

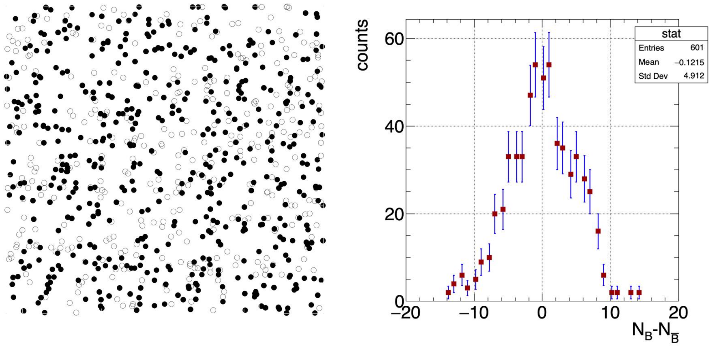
Moments, cumulants and susceptibilities:

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

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

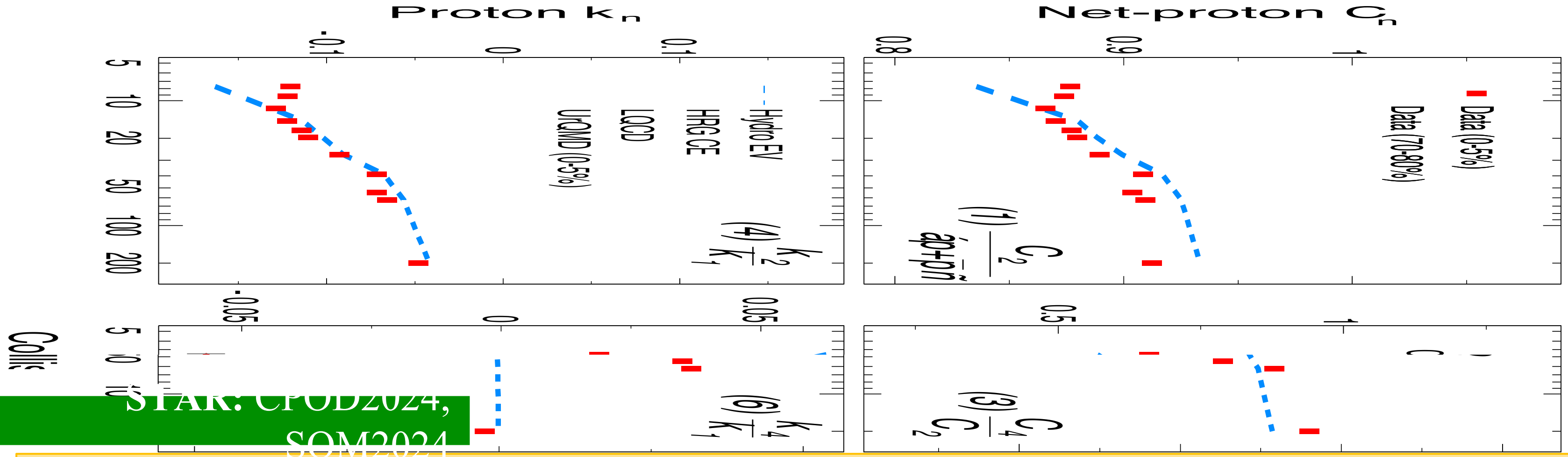
4th order: $\kappa\sigma^2 \equiv C_4 / C_2 = \chi_4 / \chi_2$

Animation: A.Rustamov



INT 2008-2b : The QCD Critical Point

Energy Dependence of Cumulant Ratios



STAR: CPOD2024, SQM2024

1) UrQMD: hadronic transport 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 collectivity. V. Vovchenko *et al.*, Phys. Rev. **C105**, 014904 (2022).
4) LQCD GCE: done for net-baryon A. Bazavov *et al.*, Phys. Rev. D101, 074502 (2020).

Baryon conservations applied in all model calculations except LQCD!

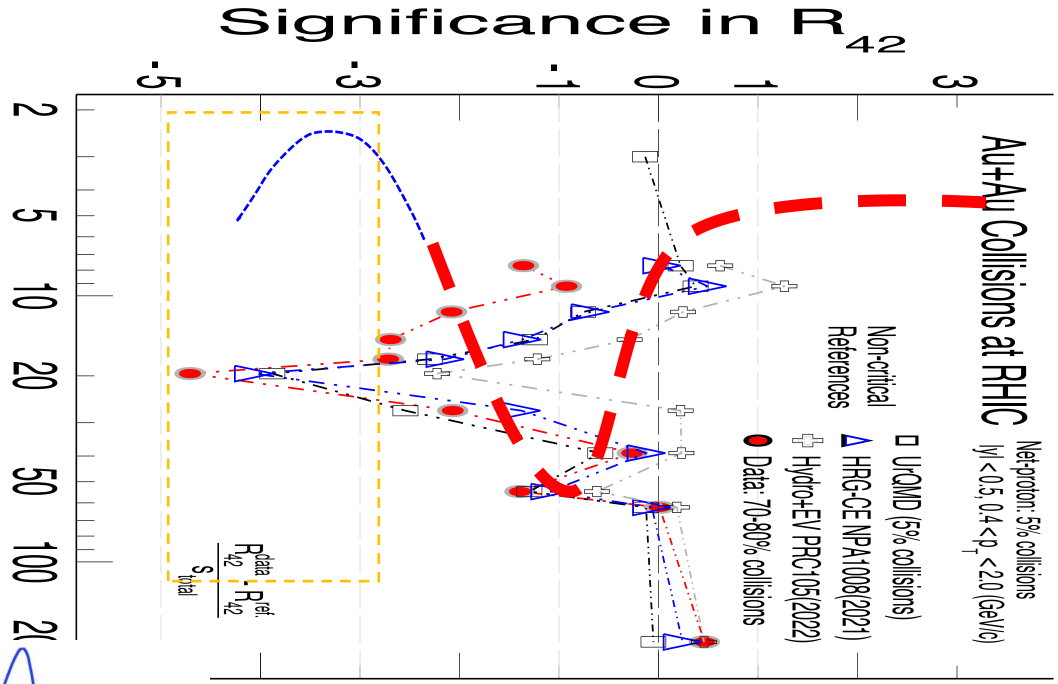
Deviations from Non-CP Models

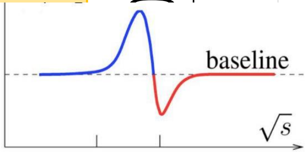
0-5% central collisions:

1) C_4/C_2 ratios: show minima at 19.6 GeV, **2-5σ effects**, depends on reference;

2) **Future data from**
   (i) STAR FXT;
   (ii) HADES at GSI and
   (iii) CBM experiment at FAIR (2028) will cover the energy region $\sqrt{s_{NN}}$ = 2.4 – 4.9 GeV

CP predictions at $\mu_B \sim 650$ MeV:
(1) M. Hippert, *et al.*, 2309.00579;
(2) X. An *et al.*, NP **A1017** (2022) 122343;
(3) W.J. Fu, *et al.*, 2308.15508;
(4) F. Gao *et al.*, PR **D104**, (2021) 054022

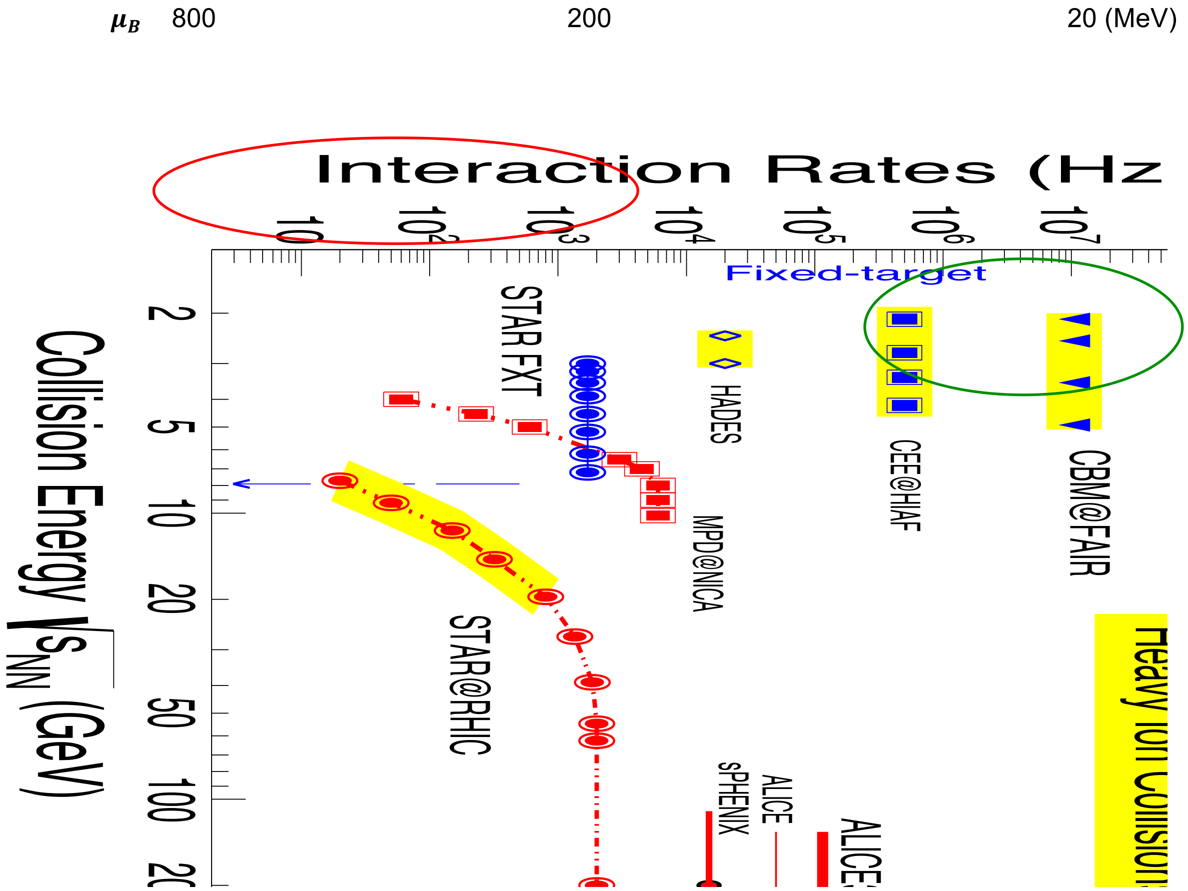




Future High Rates Experiments

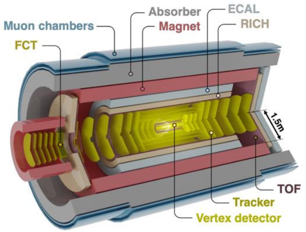
- **ALICE3:** μ_B ~ 0 Properties of QGP!
- **ALICE FoCAL:** small-x
- **CEE@HIRFAL**
- **CBM:** Unprecedented rate capability and μ_B ~ 800 MeV

1) High order baryon fluctuation and correlation;
2) 3D di-lepton spectra (collision centrality, pair mass and p_T) ;
3) Hyper-nuclei production and Y-N interactions

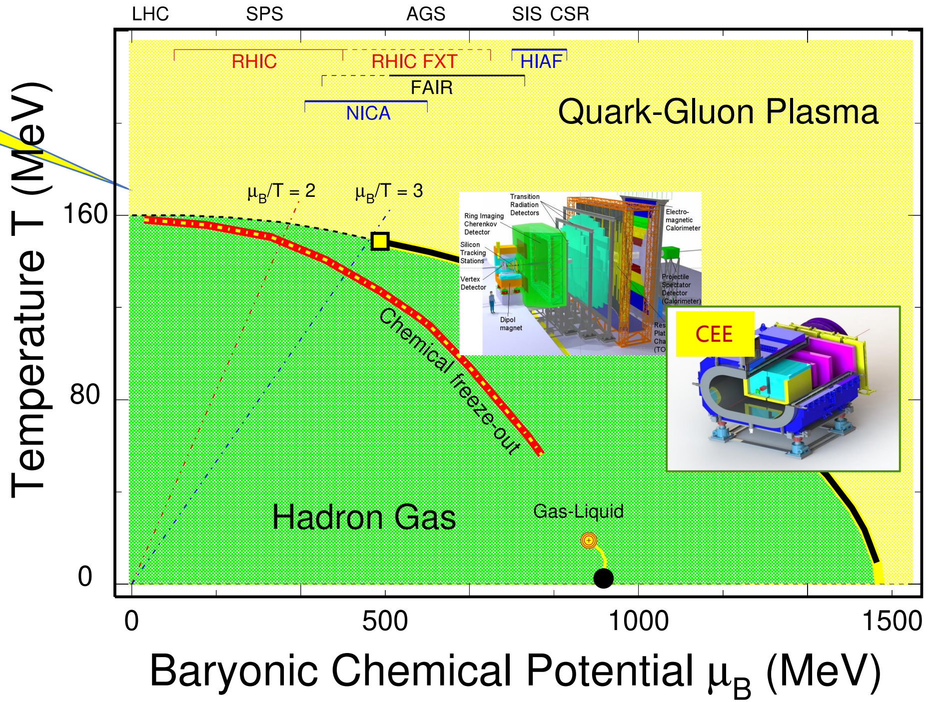


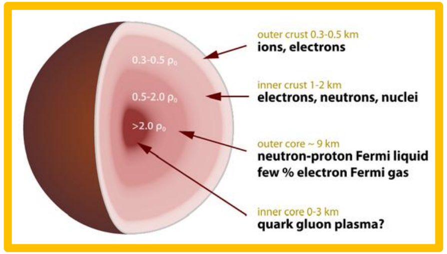
Nuclear Collisions and QCD Phase Diagram

Early Universe



- High order baryon fluctuation;
- 3D di-lepton spectra (collision centrality, pair mass and p_T);
- CGC





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

At $\mu_B = 0$: (i) Property of QGP, smooth crossover transition;
(ii) Small-x physics with ALICE FoCAL: → search for CGC;

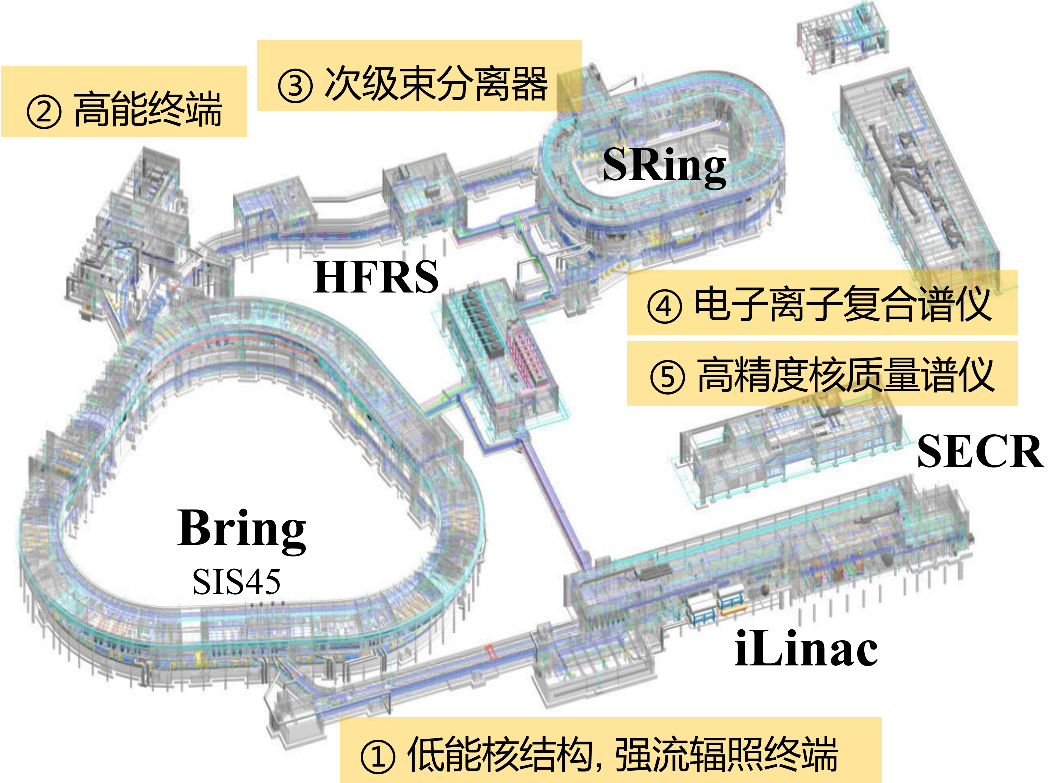
At large μ_B : (i) Search for 1st-order phase transition and **QCD critical point**;
(ii) Baryon interactions (*e.g.* $N-N$, $Y-N$) → inner structure of compact stars

Outline

1) Introduction
2) Selected Recent Results from RHIC Beam Energy Scan
3) Lambda Hyperon Polarization and Hyperon-Nucleon Spectrometer (HNS)

强流重离子加速器装置-HIAF

High Intensity heavy ion Accelerator Facility



HIAF关键物理目标：

1) 研究原子核存在极限，寻找超重新元素119，120；
2) 研究宇宙中重元素起源；
3) 研究核物质相结构，理解中子星内部结构，寻找QCD相变临界点；
4) 升级建造中国电子-离子对撞机 **EicC**

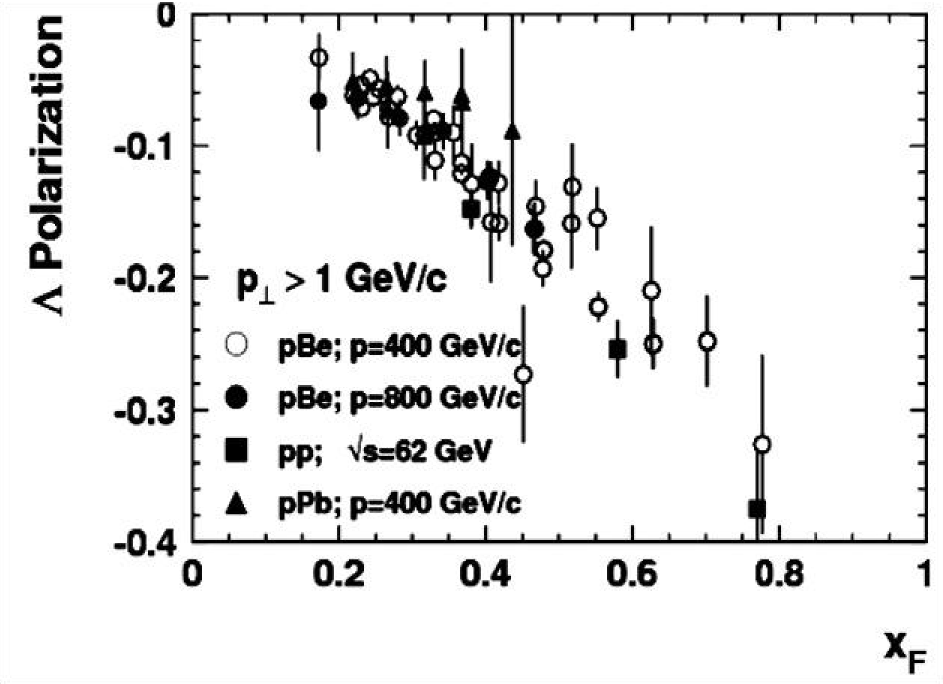
HIAF 束流和未来计划

研究机构	加速器	建成时间	离子束 (GeV/u)		束流强度
IMP	HIAF	2025	$^{238}U^{35+}$	0.8	1.0-2. 0×10^{11} ppp
			$^{238}U^{76+}$	2.45	0.5-1.0×10^{11} ppp
			p	**9.3**	5 × 10^{13}
IMP	HIAF-U	2027 – 2032	$^{238}U^{35+}$	2.95	2. 0×10^{12} ppp
			$^{238}U^{76+}$	7.3	1.0×10^{12} ppp
			$^{238}U^{92+}$	9.1	1.0×10^{12} ppp
			p	25.0	4.0 × 10^{14}
GSI	FAIR SIS100	2028	$^{238}U^{28+}$	2.7	5×10^{11} ppp

Hyperon-Nucleon Spectrometer

HNS

Λ-Polarization: Unknown to pQCD



I. p+p collisions：

1) Negatively polarized in its helicity plane in unpolarized collisions, x_F-scaling observed;
2) Left-right asymmetric of pion production in polarized p↑+p collisions;

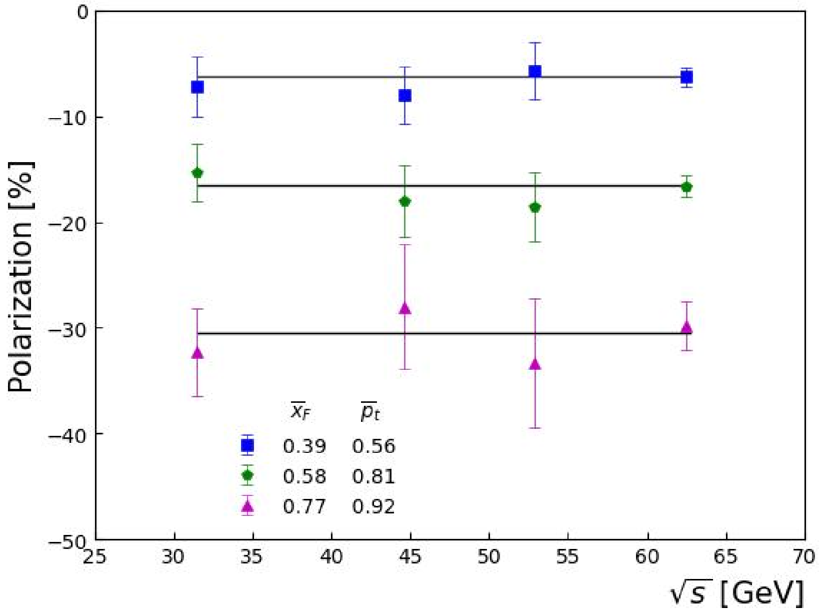
No pQCD predictions even for high energy elementary p+p collisions!

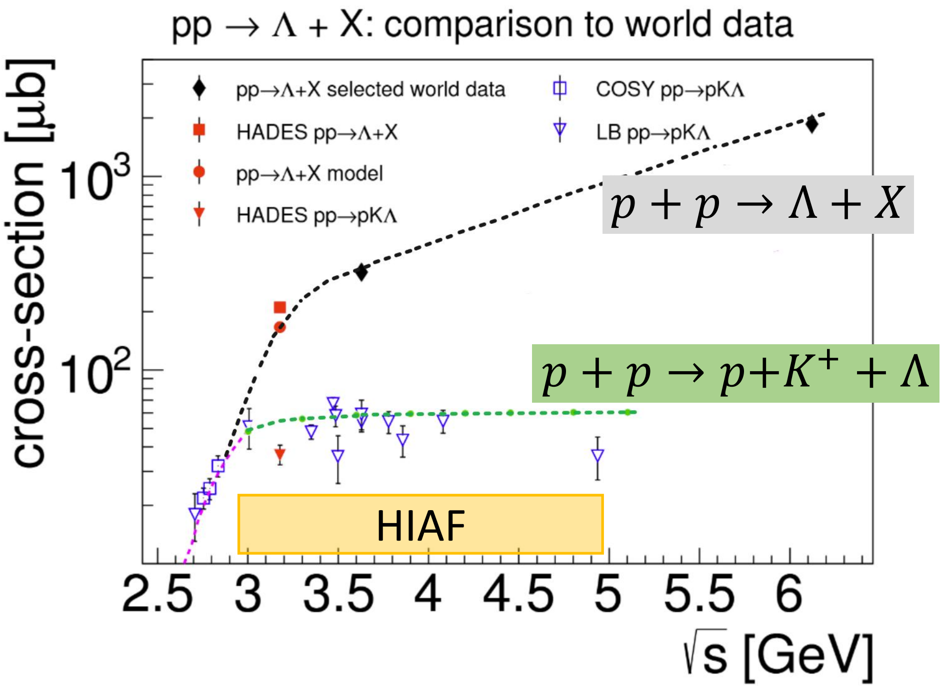
II. Heavy-ion collisions

Global polarizations have been observed in event plane: signature of baryon vorticity especially at *high baryon density*

HIAF proton beam 3 – 9.3 GeV for energy scan and understand the x_F-scaling

Λ-Polarization: Scaling?





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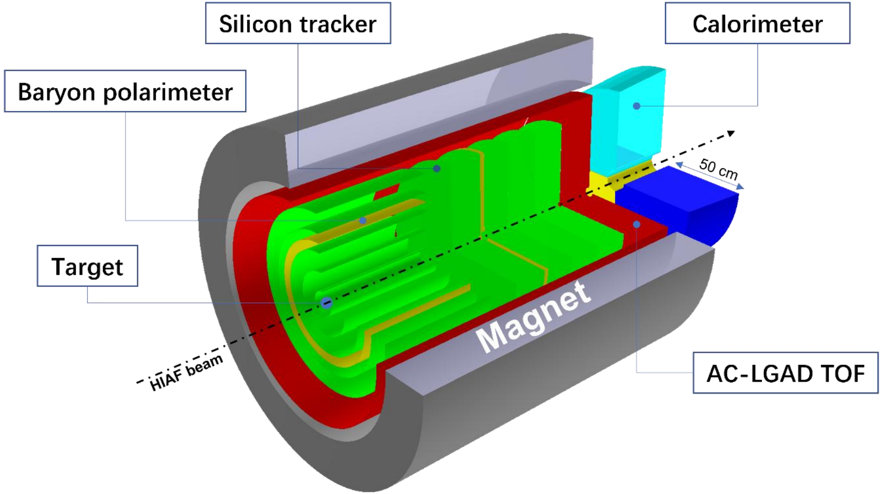
Hyperon-Nucleon Spectrometer (HNS)



Costs: ≤ \$45M

Participating Institutes: ≥ 15 (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

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 interests are expected: Japan

III. Detector R&D

- Many parts are similar for CEPC, *HNS*, EicC, and STCF. Save resources.
- HNS: a detector R&D platform for EicC (½ EicC)

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

Thank you for your attention!