Physics at High Baryon Density

– Recent Results from RHIC Beam Energy Scan Program

Nu Xu

Outline

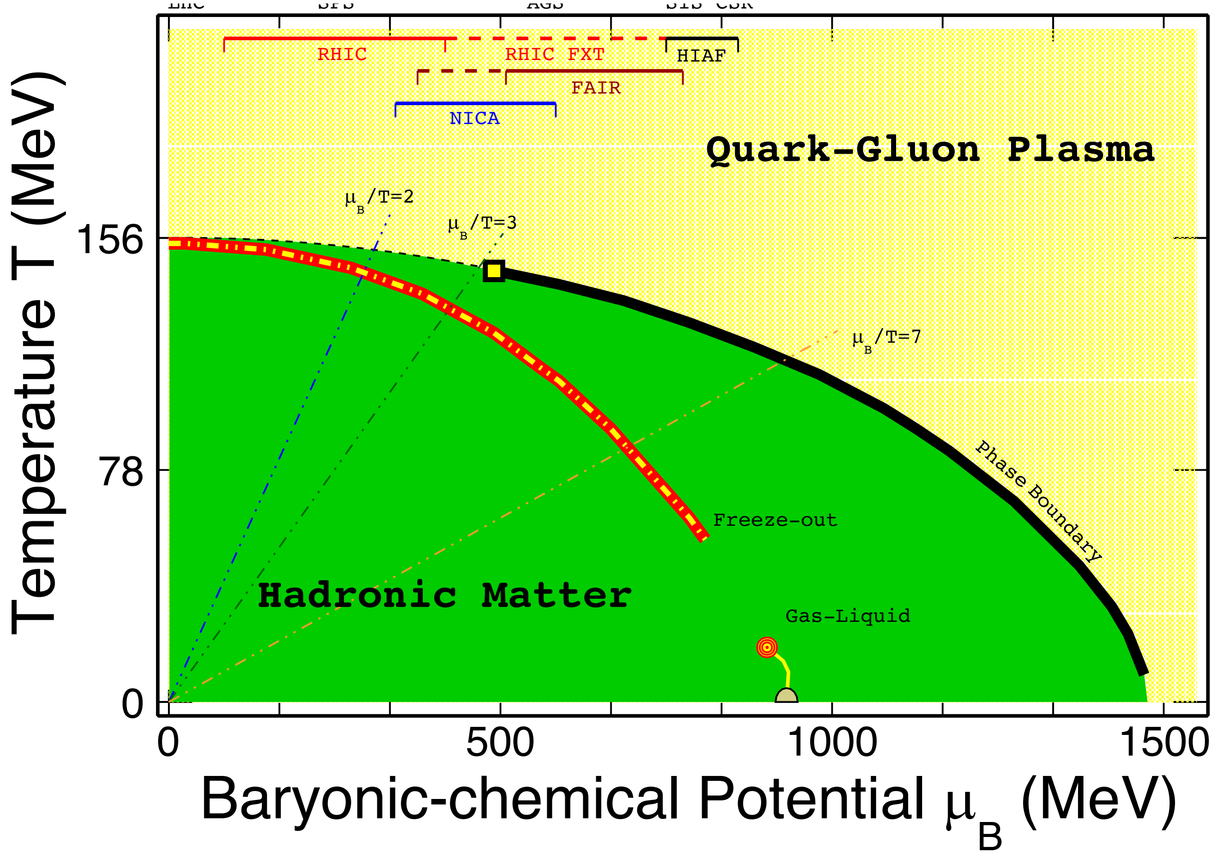
1) **Introduction**

2) **Selected Recent Results**
   - Collectivity
   - Criticality
   - Strangeness production: hyper-nuclei

3) **Future Physics at High Baryon Density**
   - CBM Experiment at FAIR

High-Energy Nuclear Collisions and QCD Phase Diagram

LHC RHIC & BES FAIR, …



At LHC and RHIC top energy:

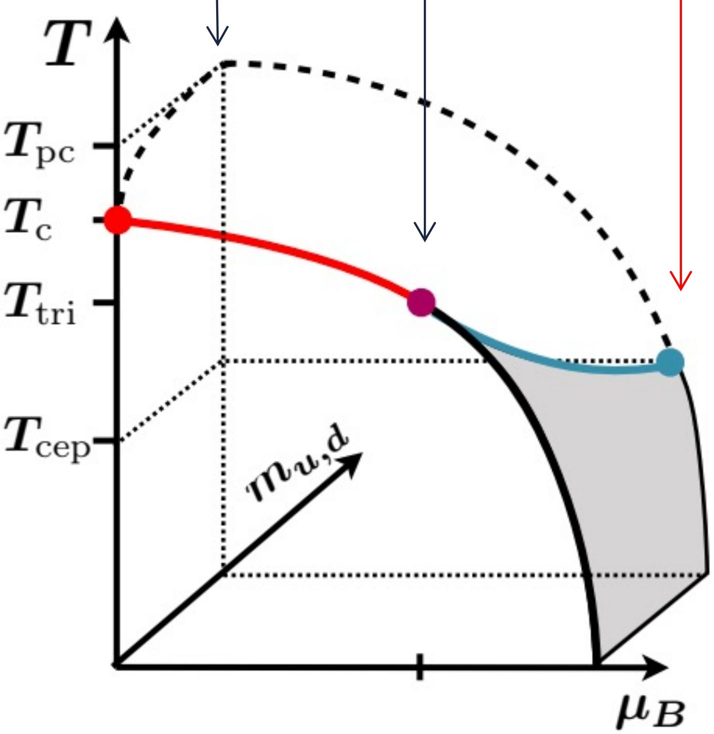
- Jet quenching;
- HF R_{AA} and v_2 data;
- Net-p C_6/C_2

→

1) **At $\mu_B \sim 0$, smooth crossover. μ_B/T ≤ 2 (LGT);**
2) **CP at μ_B/T > 3**

LGT Calculation: QCD Phase Structure

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



F. Karsch *et al*., 2020

1) QCD transition temperature:
$T_{PC} = 156.5 \pm 0.5$ MeV

2) Chiral crossover line

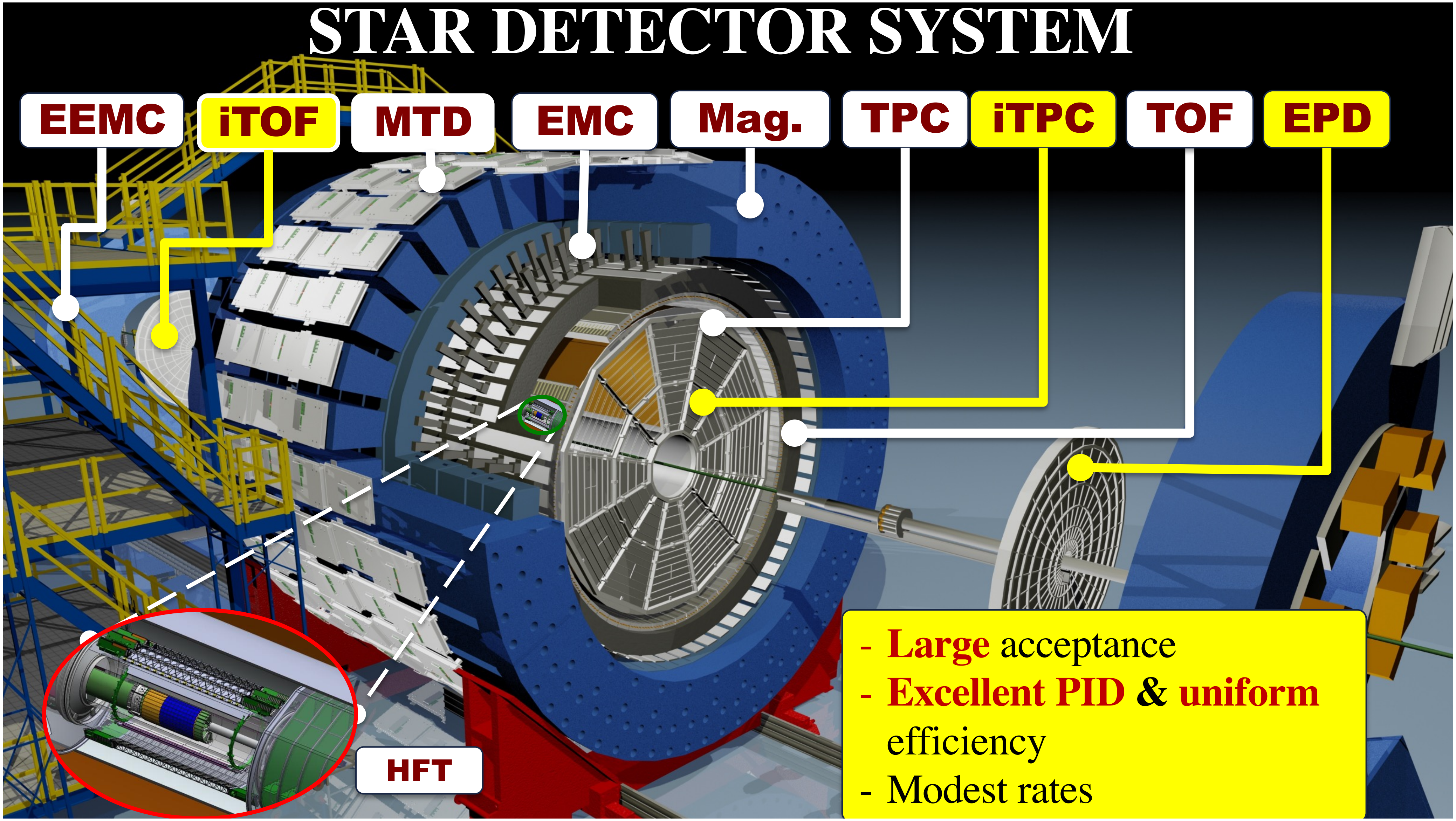
$$T_{PC}(\mu_B) = T_{PC}^0 \left[1 - \kappa_2 \left(\frac{\mu_B}{T_{PC}^0} \right)^2 - \kappa_4 \left(\frac{\mu_B}{T_{PC}^0} \right)^4 \right]$$

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

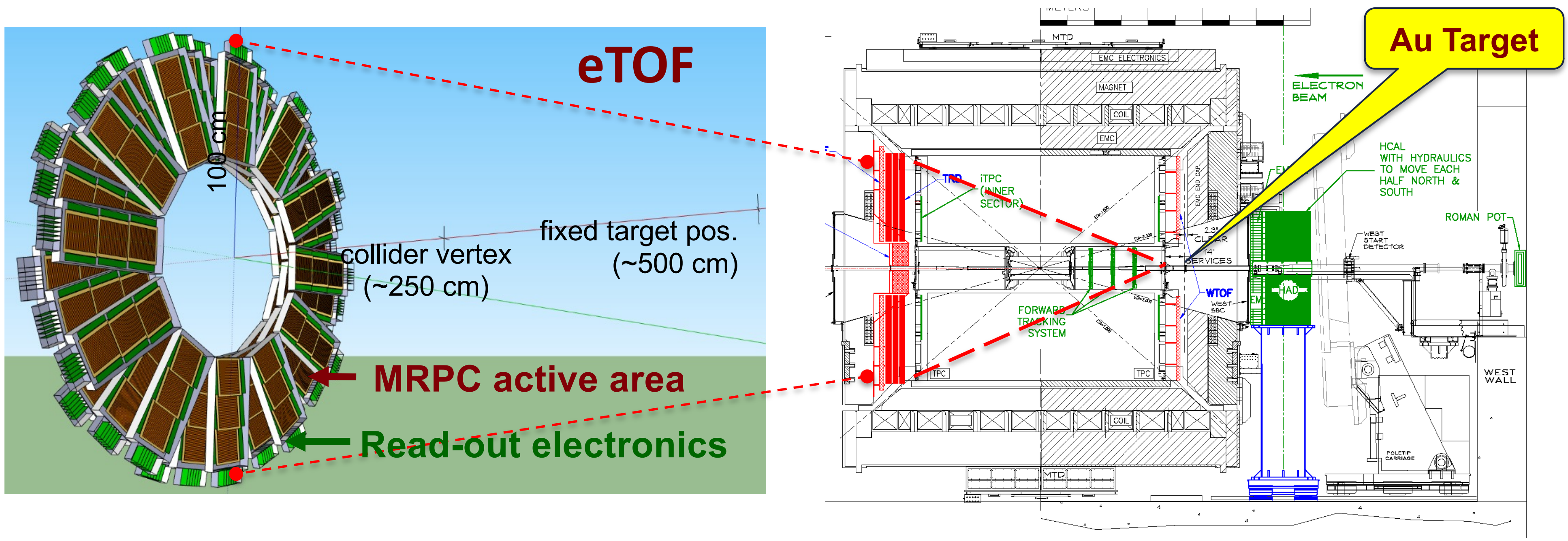
3) Chiral transition temperature:
$T_C = 132^{+3}_{-6}$ MeV

4) QCD critical end point:
$T^{CEP} < T_C$, $\mu_B^{CEP} \gtrsim 3T_C$

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


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

CBM TOF at STAR



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**					
	$\sqrt{s_{NN}}$ (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

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

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Collectivity

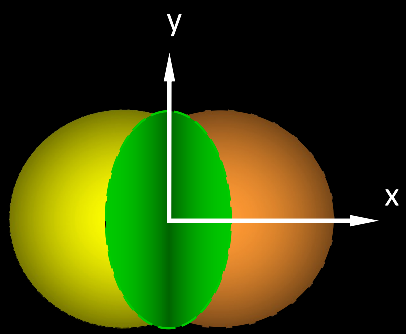
$$\partial_\mu[(\varepsilon + p)u^\mu u^\nu - pg^{\mu\nu}] = 0$$
$$\partial_\mu[s\, u^\mu] = 0$$

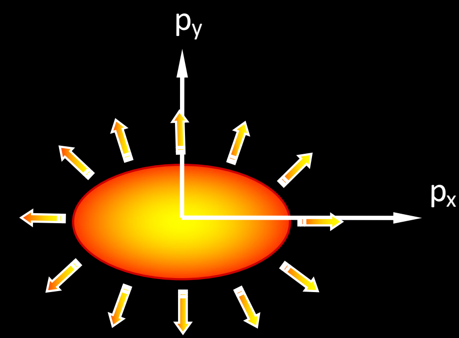
$$\frac{d^2N}{p_T dp_T d\varphi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T}\left\{1 + \sum_{n=1}^{\infty} 2v_n(p_T)cos[n(\varphi - \Psi_R)]\right\}$$

- v_1 Directed flow;
- v_2 Elliptic flow;
- v_3 Triangle flow

Anisotropy Parameter v_2

coordinate-space-anisotropy ➡ momentum-space-anisotropy

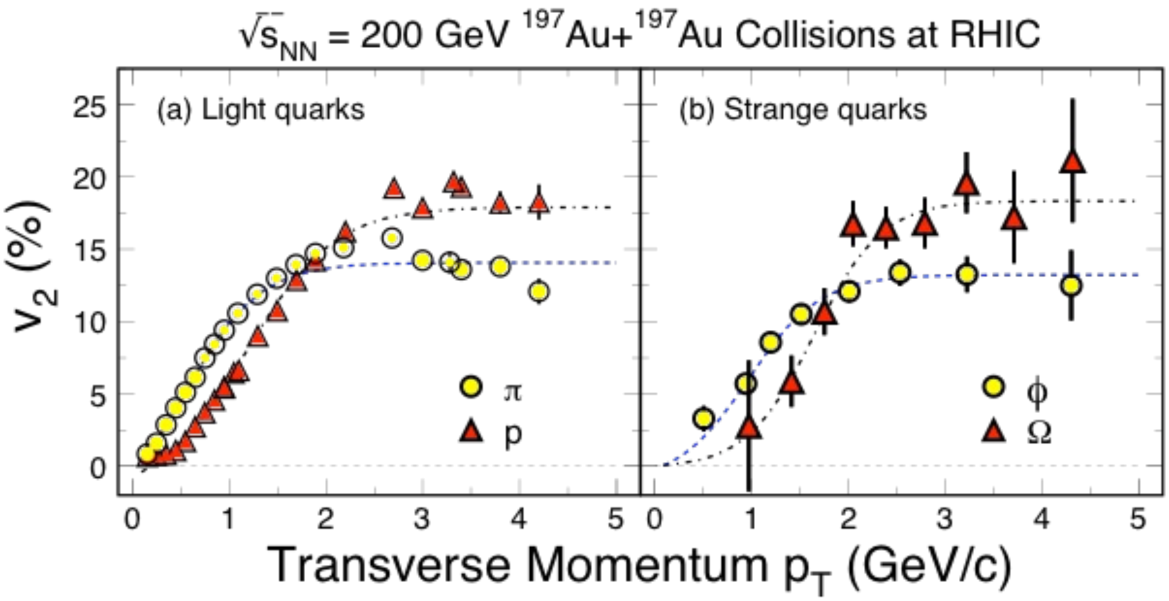




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle cos2\varphi \rangle, \qquad \varphi = tan^{-1}\left(\frac{p_y}{p_x}\right)$$

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

Partonic Collectivity at RHIC



STAR: PRL**116**, 62301(2016)

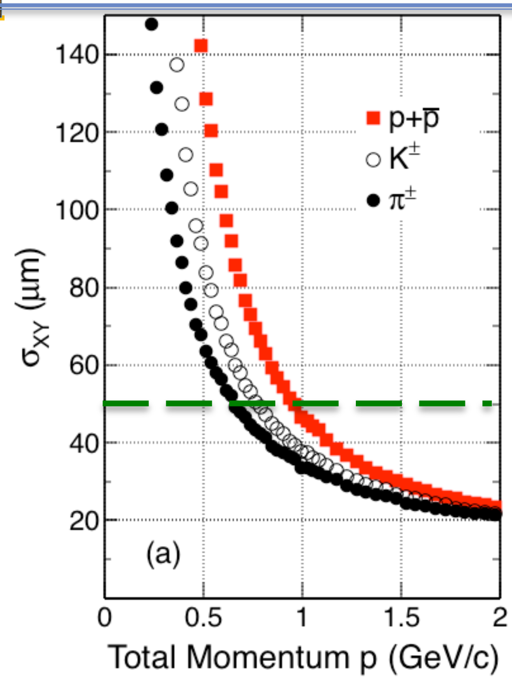
- ✓ Low p_T (≤ 2 GeV/c): hydrodynamic mass ordering
- ✓ High p_T (> 2 GeV/c): ***number of quarks scaling (NCQ)***

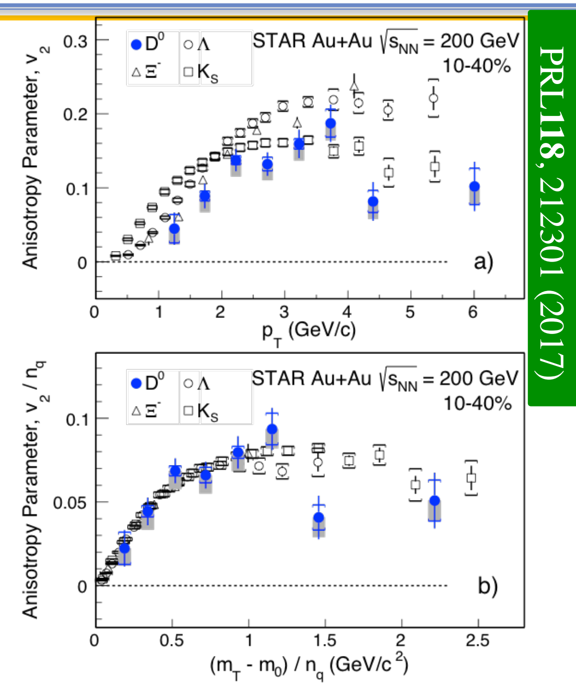
u- , d-, and s-quarks flow!

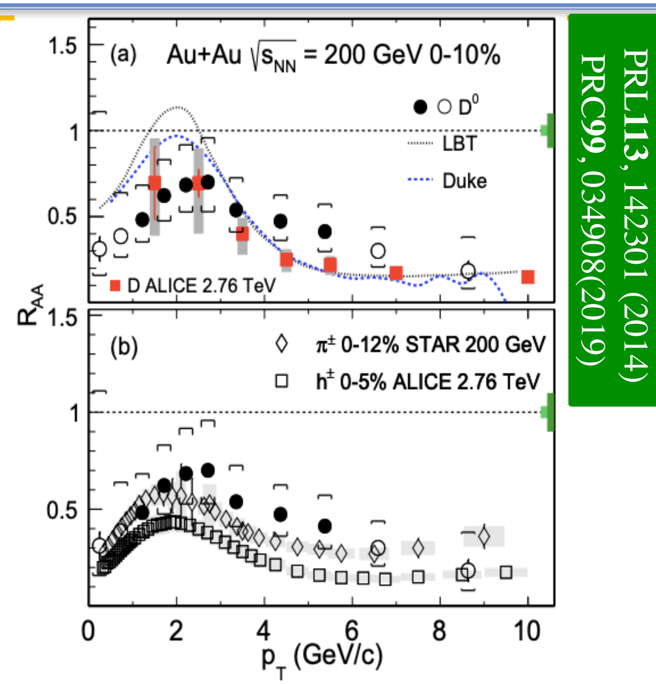
- ➢ **Partonic Collectivity!**
- ➢ **De-confinement Au+Au collisions at RHIC!**

STAR: PRL**116**, 62301(2016)

Heavy Flavor Hadron D^0 Collectivity at HRIC



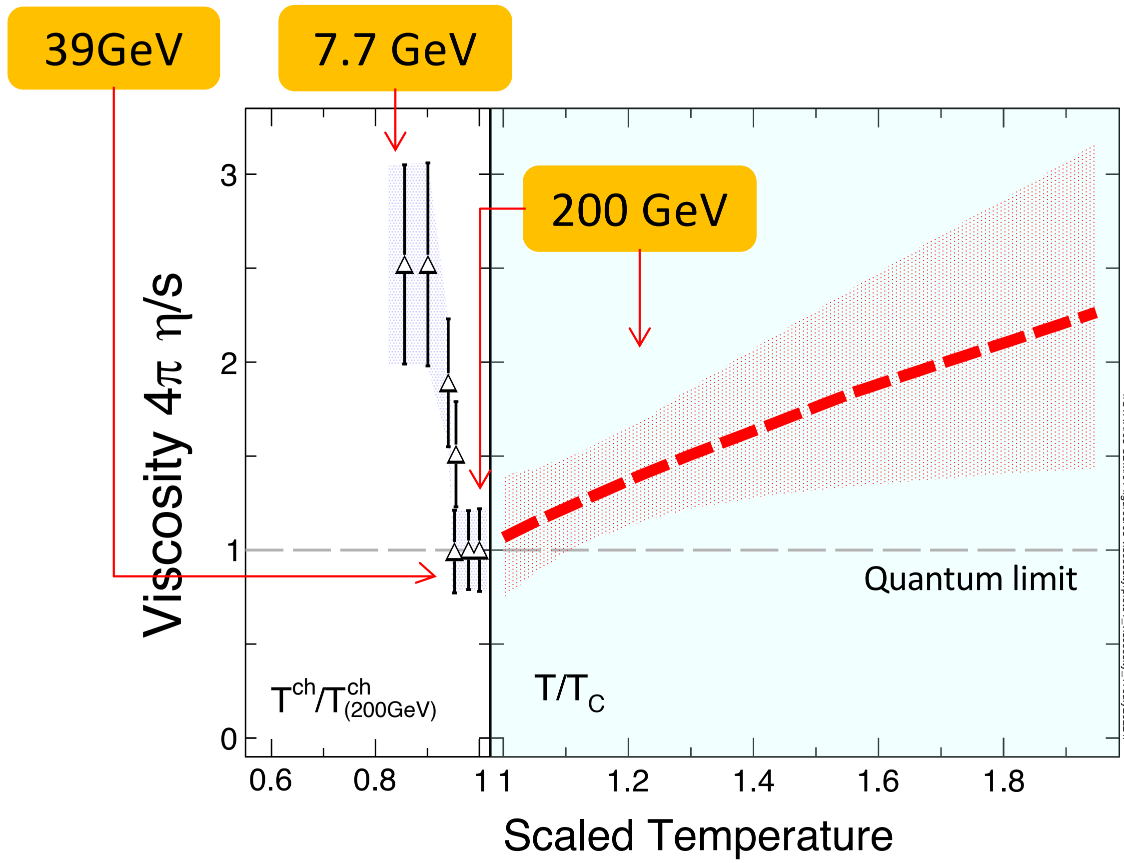




1) First application of MAPS technology in high energy collisions, excellent position resolution;
2) Measured $\boldsymbol{D^0, D^{\pm}, D_S^{\pm}, \Lambda_C}$ and achieved two conclusions:
   - "These results suggest that charm quarks have achieved **local thermal equilibrium** with the medium created in such (200GeV Au+Au) collisions"
   - Hadronization via **quark coalescence** process

STAR: PRL**113**, 142301(14); PRC**99**, 034908(19); PRL**118**, 212301(17); PRL**123**, 162301(19); PRL**124**, 172301(20)

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.

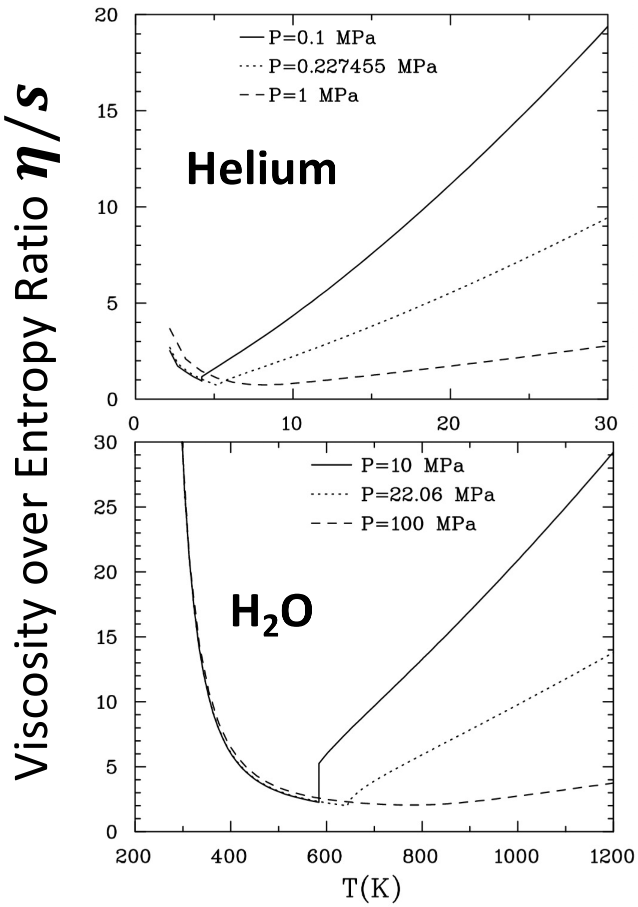
2) Both sides meet at the unity of the scaled temperature.

3) The values of η/s increase quickly below $\sqrt{s_{NN}}$ = 39 GeV → QGP dominants in higher collision energies.

4) Exp. evidence of the QCD transition

- L.P. Csernai, J.I. Kapusta, L.D. McLerran, PRL**97** (2006) 152303
- X.Dong, Y.J. Lee & R.Rapp, ARNPS, **69** (2019) 417
- J.E.Bernhard, J.S.Moreland & S. Bass, Nat. Phys. **15** (2015) 1113
- I. Karpenko, P. Huovinen, H. Petersen, and M. Bleicher, Phys.Rev.**C91**, 064901 (2015).

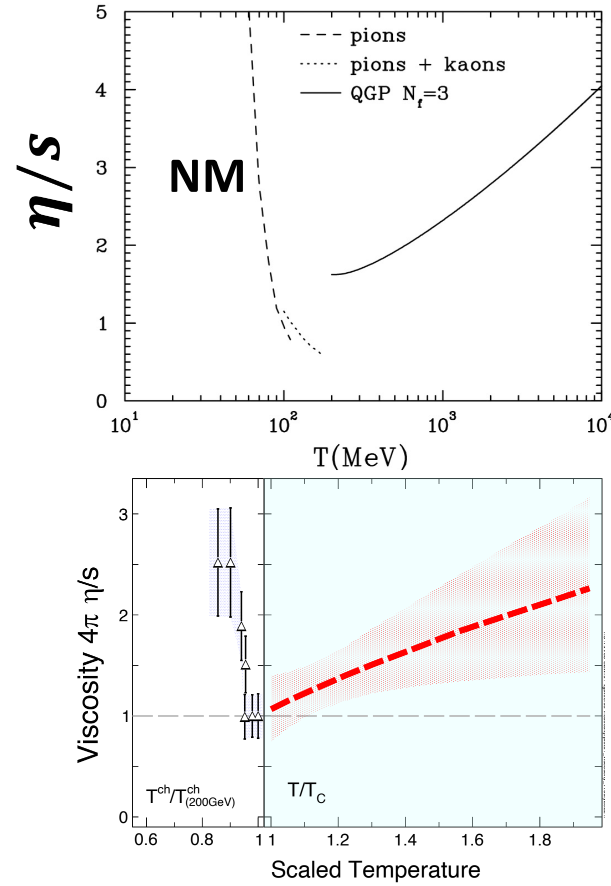
Strongly-Interacting Low-Viscosity Matter



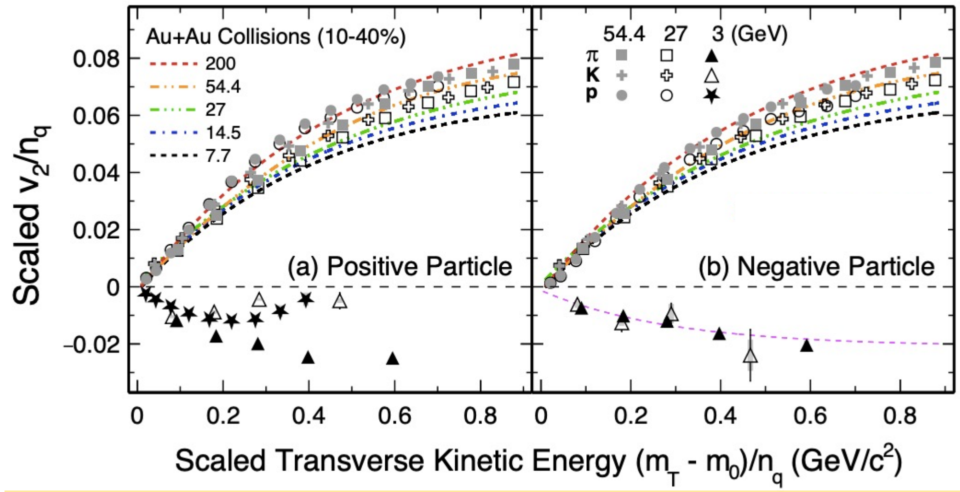
EM interaction
η/s ~ 1

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

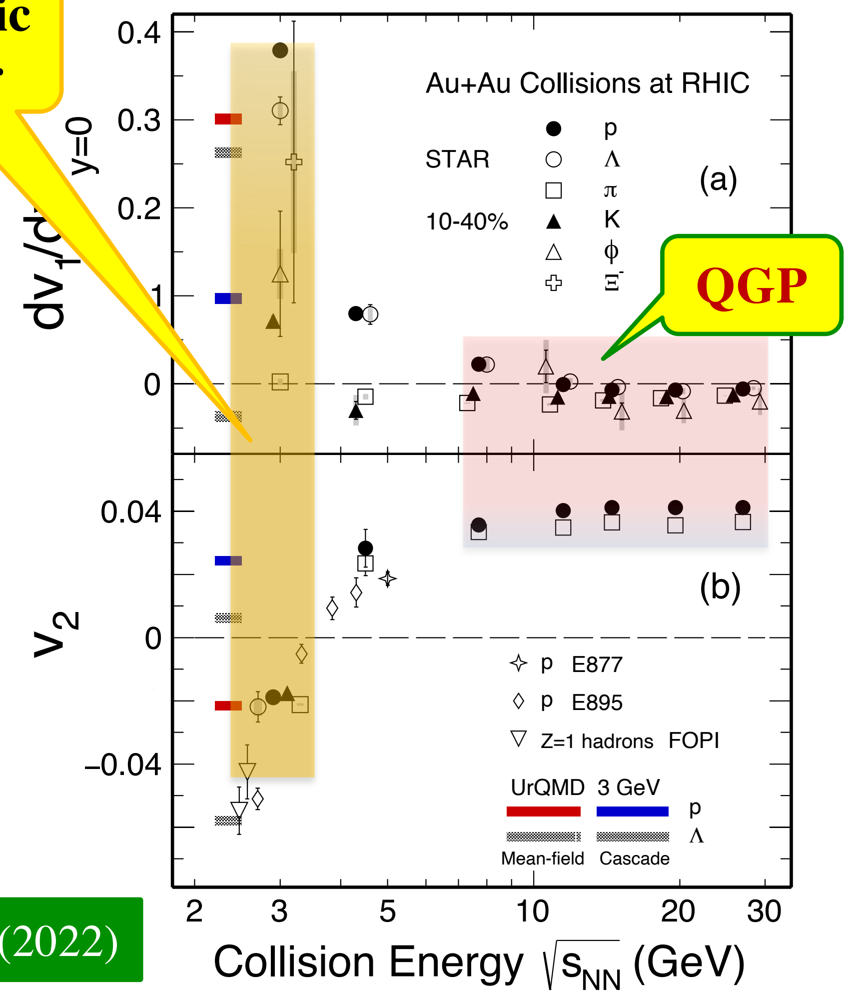
Strong Interaction
η/s ~ 0.1



Disappearance of Partonic Collectivity



Hadronic Matter

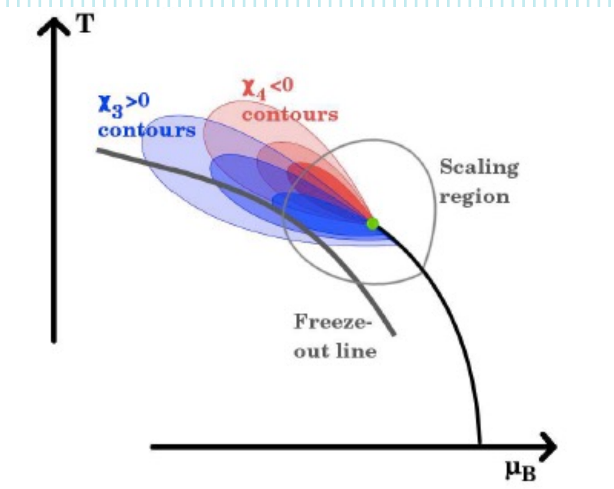


QGP

- 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)

Criticality



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

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

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

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

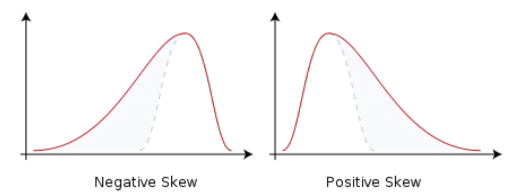
kurtosis: $\kappa = \langle (\delta N)^4 \rangle / \sigma^3 - 3 = C_4 / C_2^2$

Moments, cumulants and susceptibilities:

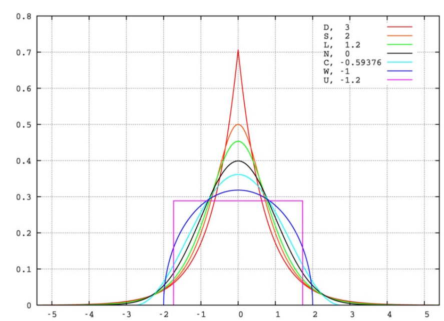
2nd order: $\sigma^2/M \equiv C_2/C_1 = \chi_2/\chi_1$

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

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



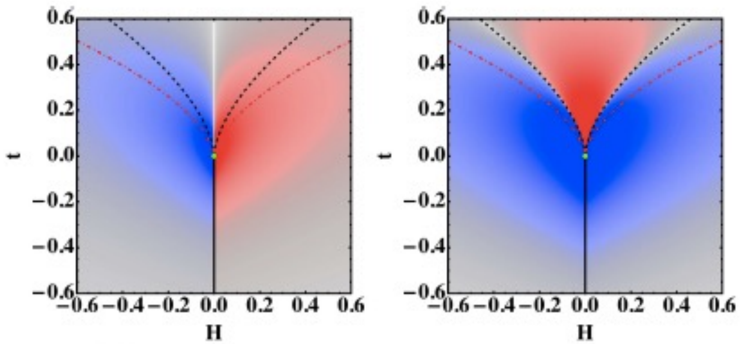
skewness (S)
→ asymmetry

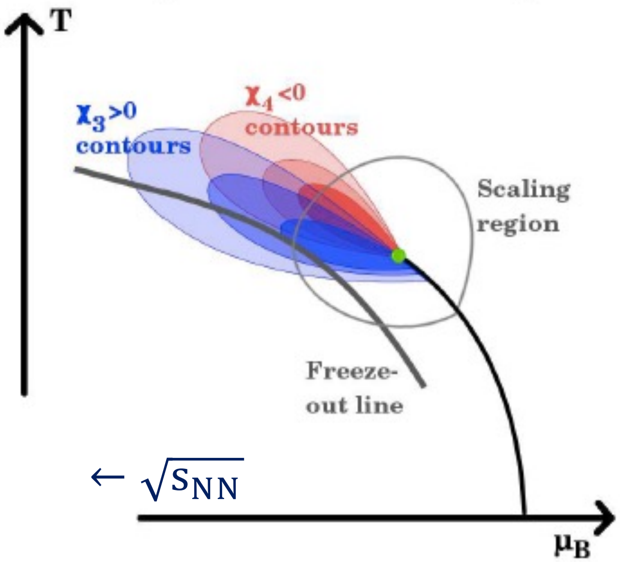


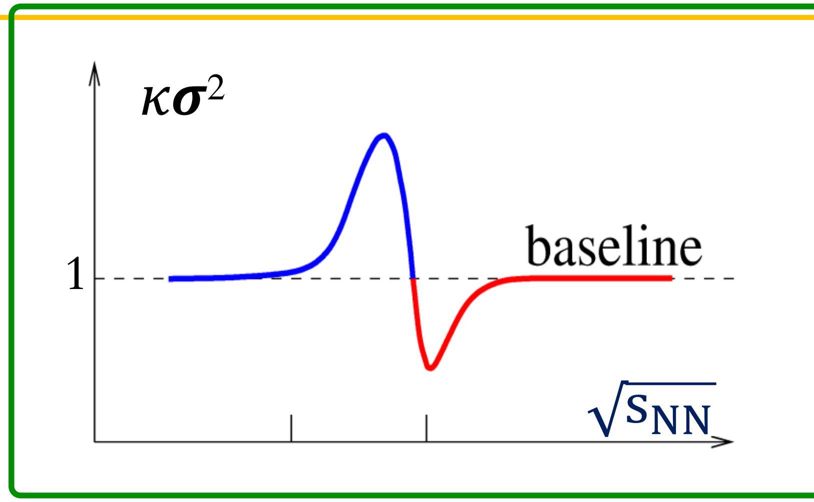
kurtosis (κ)
→ sharpness

INT 2008-2b : The QCD Critical Point

Expectations for Models



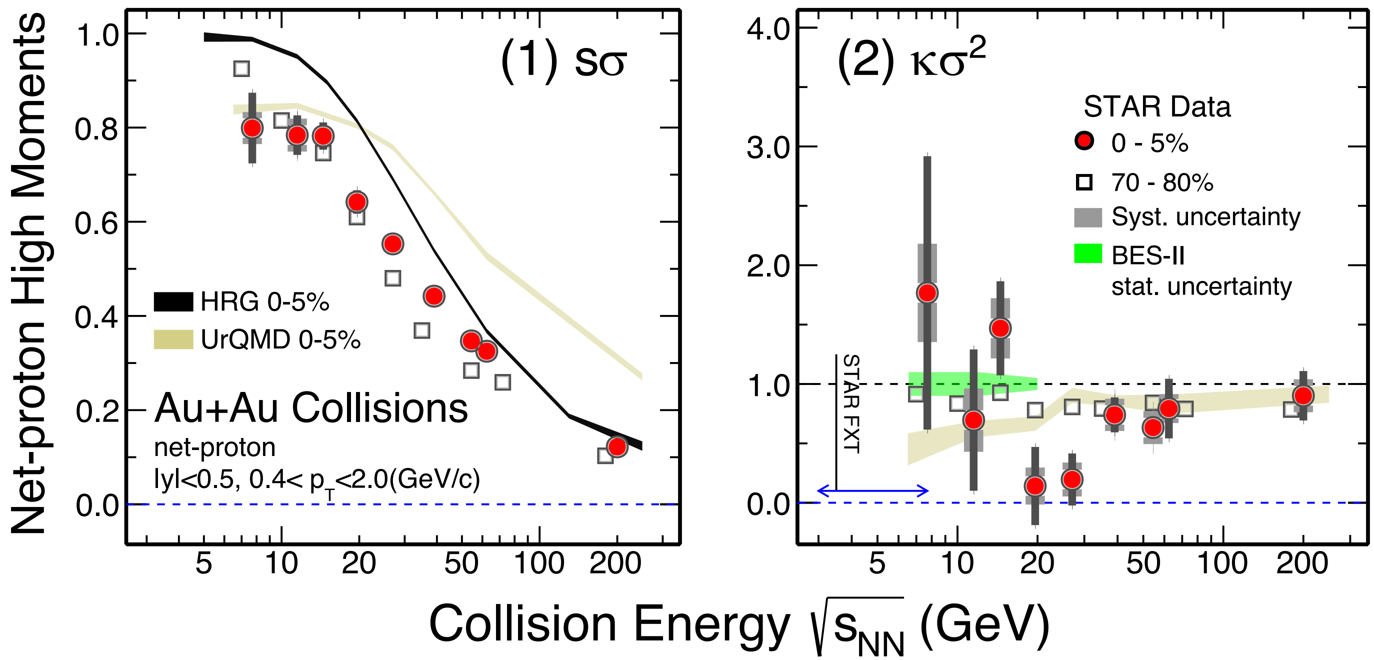




- Characteristic "Oscillating pattern" is expected for the QCD critical point but the exact shape depends on the location of freeze-out with respect to the location of CP
- Critical Region (CR)

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

"Nonmonotonic Energy Dependence of Net-Proton Number"

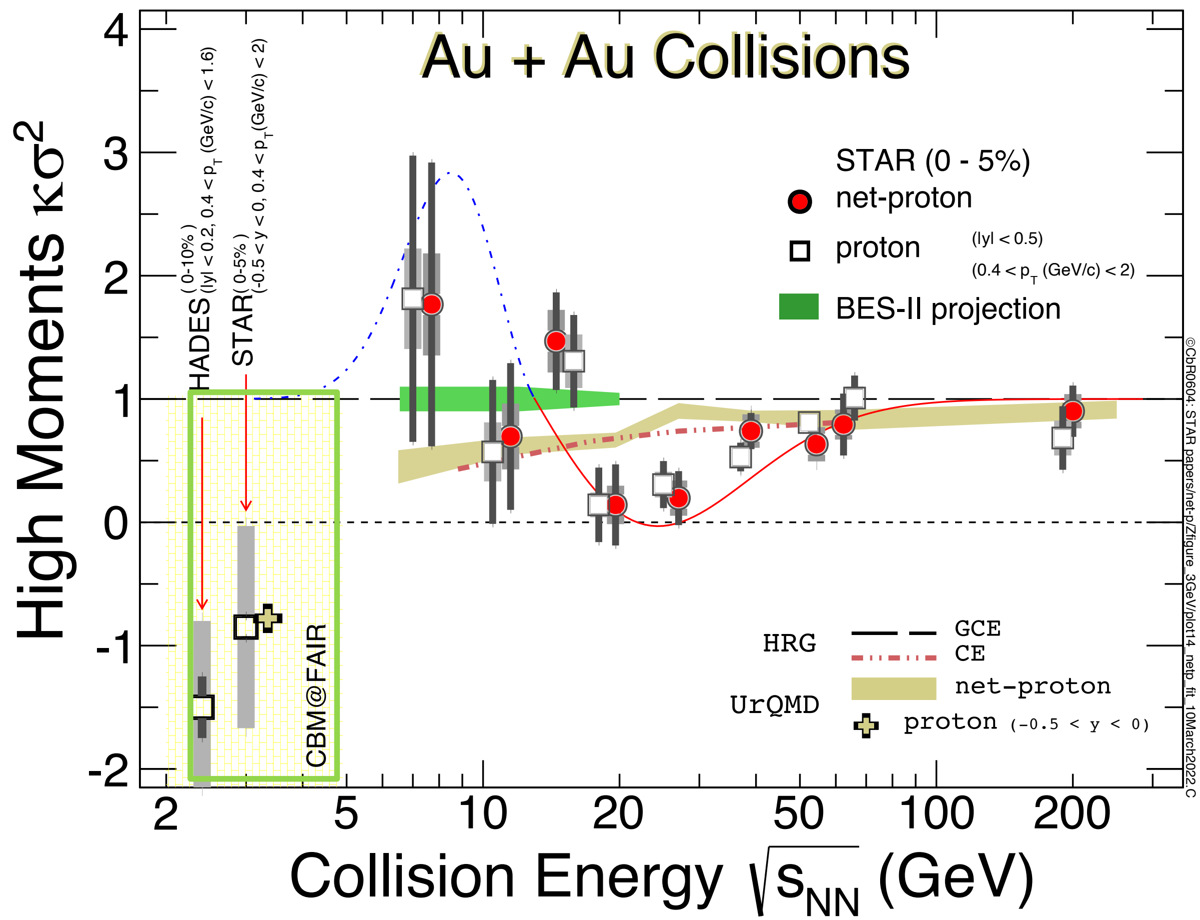


1) HRG and transport model predicted monotonical energy dependence: AMPT, JAM, UrQMD. Suppression at low energy due to conservation;

2) The 3rd and 4th orders: **deviate from the Poisson limit** in the most central collisions!

STAR: PRL**126**, 092301(21)

Net-p $\kappa\sigma^2$ Energy Dependence



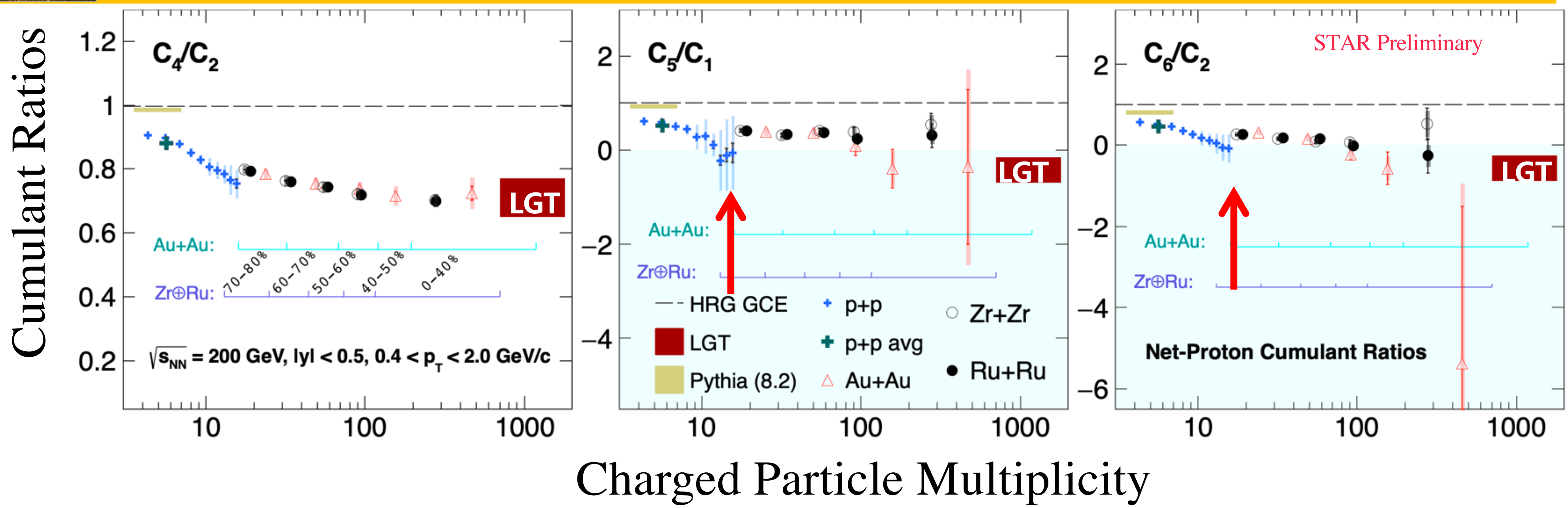
1) Non-monotonic energy dependence;

2) 3 GeV proton high moments data → **Hadronic interaction dominant!**

3) Energy gap between 3 and 7.7 GeV, important for **Critical Point search**

STAR: PRL**126**, 92301(2021)
PRL**128**, 202303(2022)
HADES: PRC**102**, 024914(2020)

Net-p in 200 GeV p+p and Au+Au Collisions

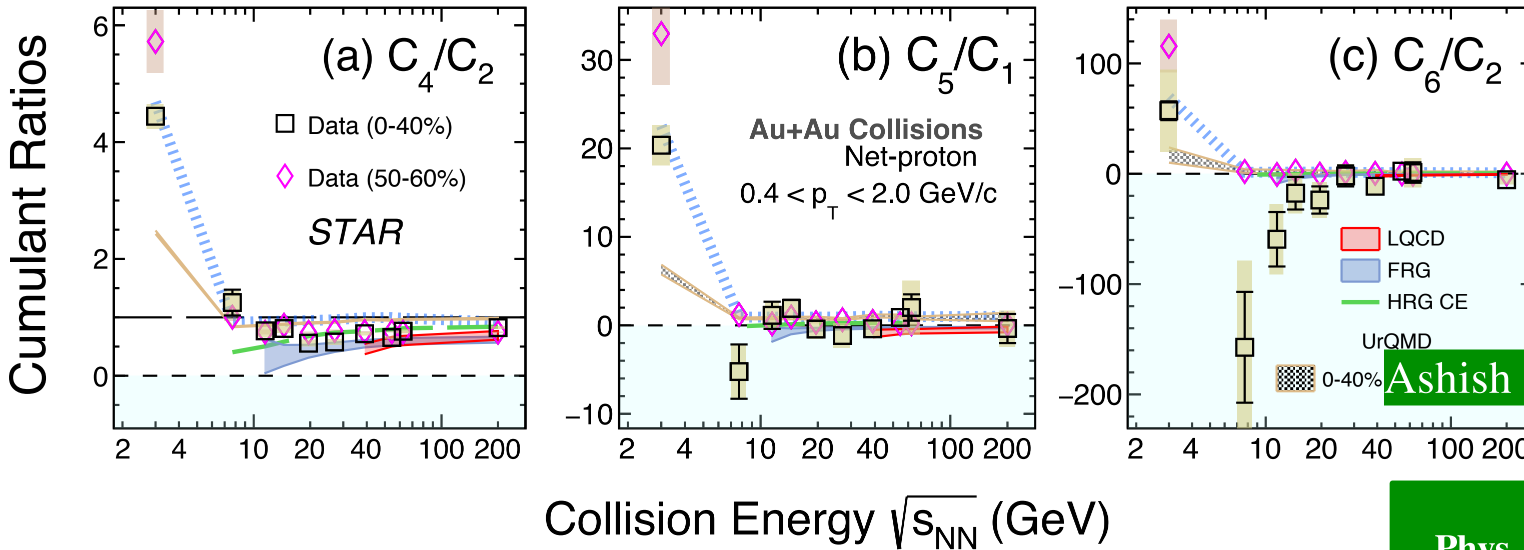


1) In 200GeV p+p collisions, at high multiplicity, C_5/C_2 and C_6/C_2 become negative as LGT predicted; LHC p+p collisions!

2) Direct evidence for the QGP formation in 200GeV central collisions!

HotQCD Collaboration, PR**D101**, 074502 (2020)

C_4, C_5 and C_6 in Au+Au Collisions



Ashish Pandav (NISER)

STAR: 2207.09837
Phys. Rev. Lett., accepted

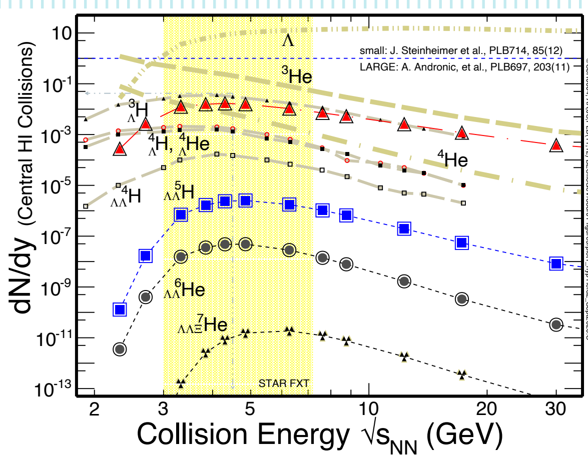
1) **C6/C2 < 0** from 200 GeV to 7.7 GeV consistent with LGT prediction for C_5/C_2 and C_6/C_2! HotQCD Collaboration, PR**D101**, 074502 (2020)

2) **Direct evidence for QGP formation in central Au+Au collisions 200-39GeV!**

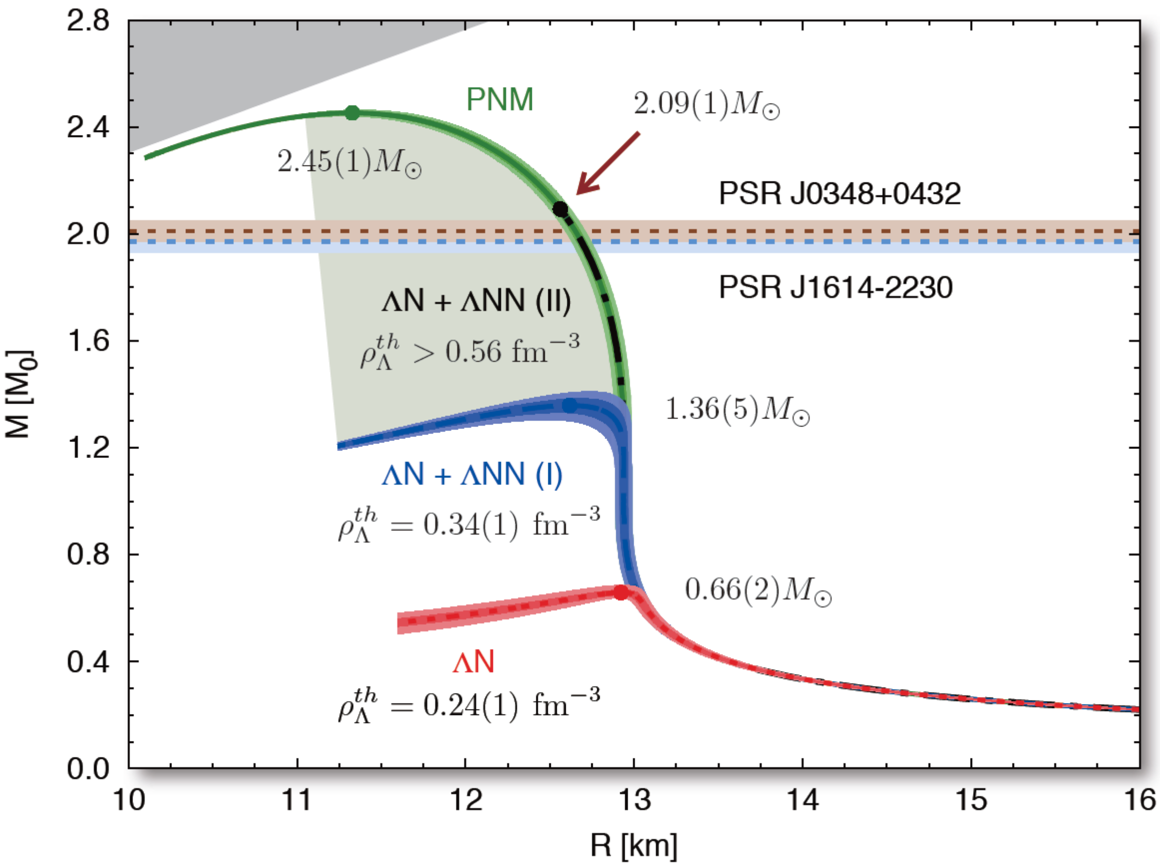
3) At 3 GeV: hadronic interactions dominant!

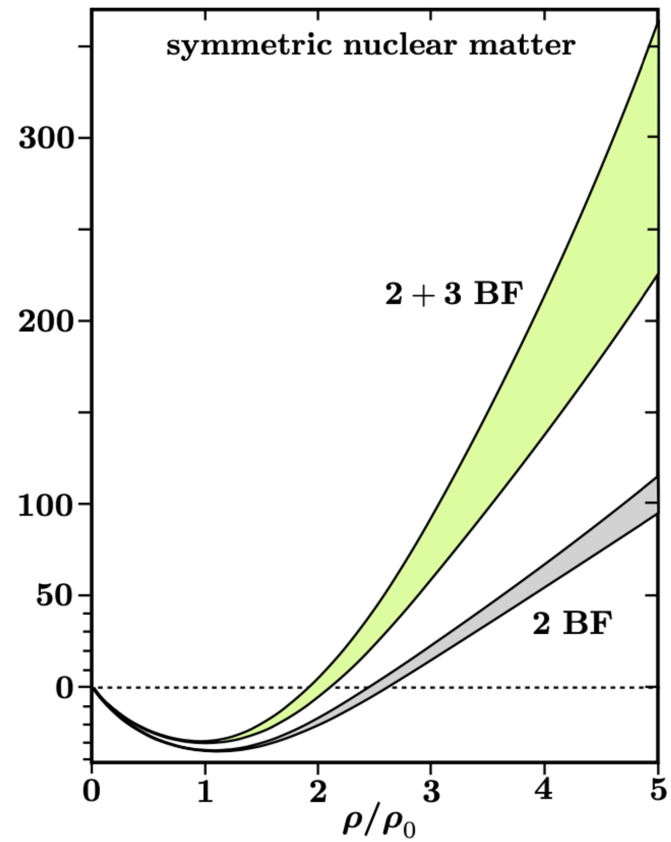
STAR: Phys. Rev. Lett., 128, 202303 (2022)

Strangeness and Hyper-Nuclei



Λ-N Interactions and Compact Stars

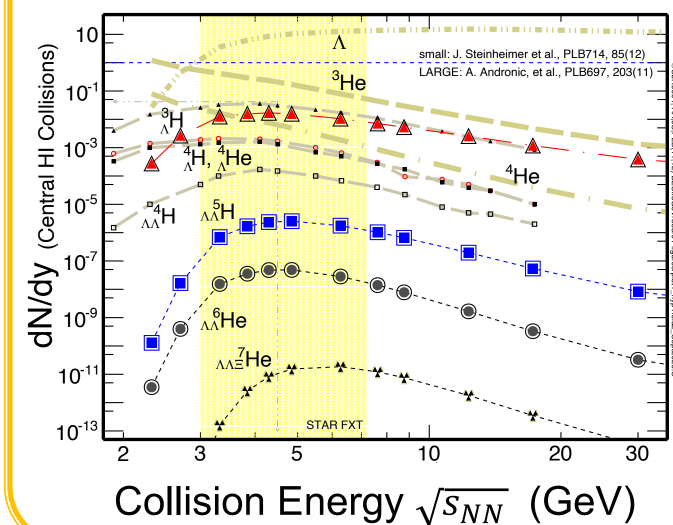




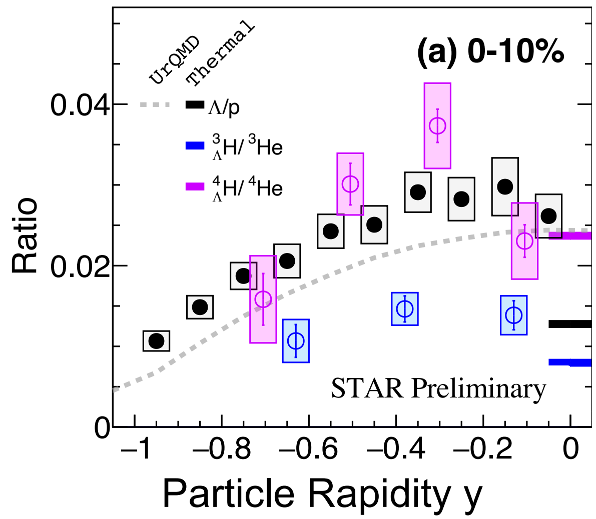
PRL114, 092301(2015), HYP2018, 1512.06832, 1711.07521

Baryon Interactions and Hyper-Nuclei

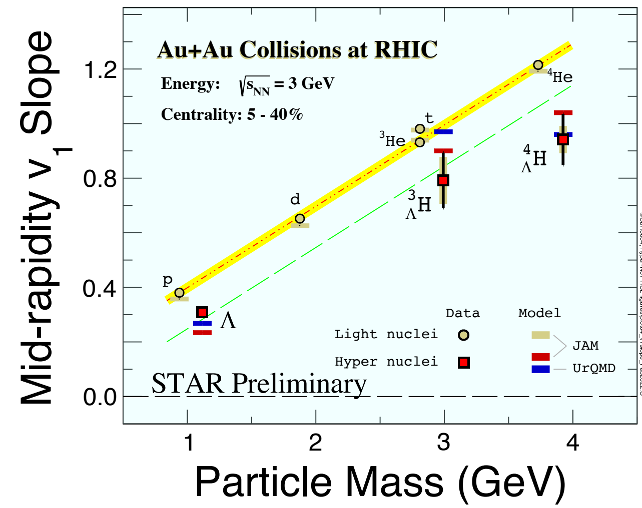
Yields



Rapidity Density



Collectivity



1) Hyper nuclei and double-Λ hyper-nuclei productions
2) Hyper nuclei collectivity (e.g. v_1 and v_2) → ***Y-N*** and ***Y-Y*** interactions under finite pressure

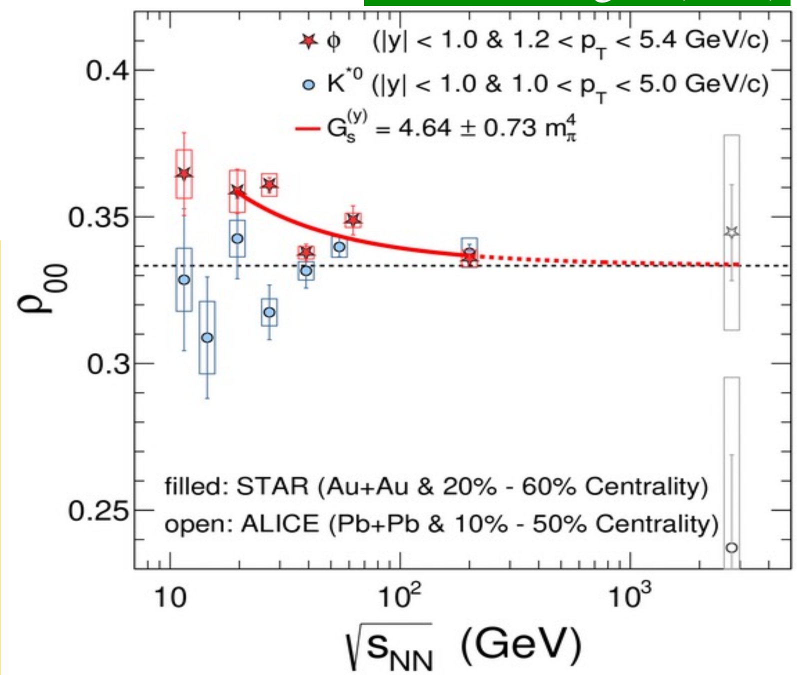
STAR: CPOD21, SQM22, SYP22

Article

Pattern of global spin alignment of ϕ and K*0 mesons in heavy-ion collisions

https://doi.org/10.1038/s41586-022-05557-5
STAR Collaboration*
Received: 4 April 2022

Subhash Singha (IMP)



Unexpected large ρ_{00} for ϕ-meson:
"*'Unbelievable' Spinning Particles Probe Nature's Most Mysterious Force*" – ***SCIENTIFIC AMERICAN*** February 2, 2023

Important for understanding initial strong external fields

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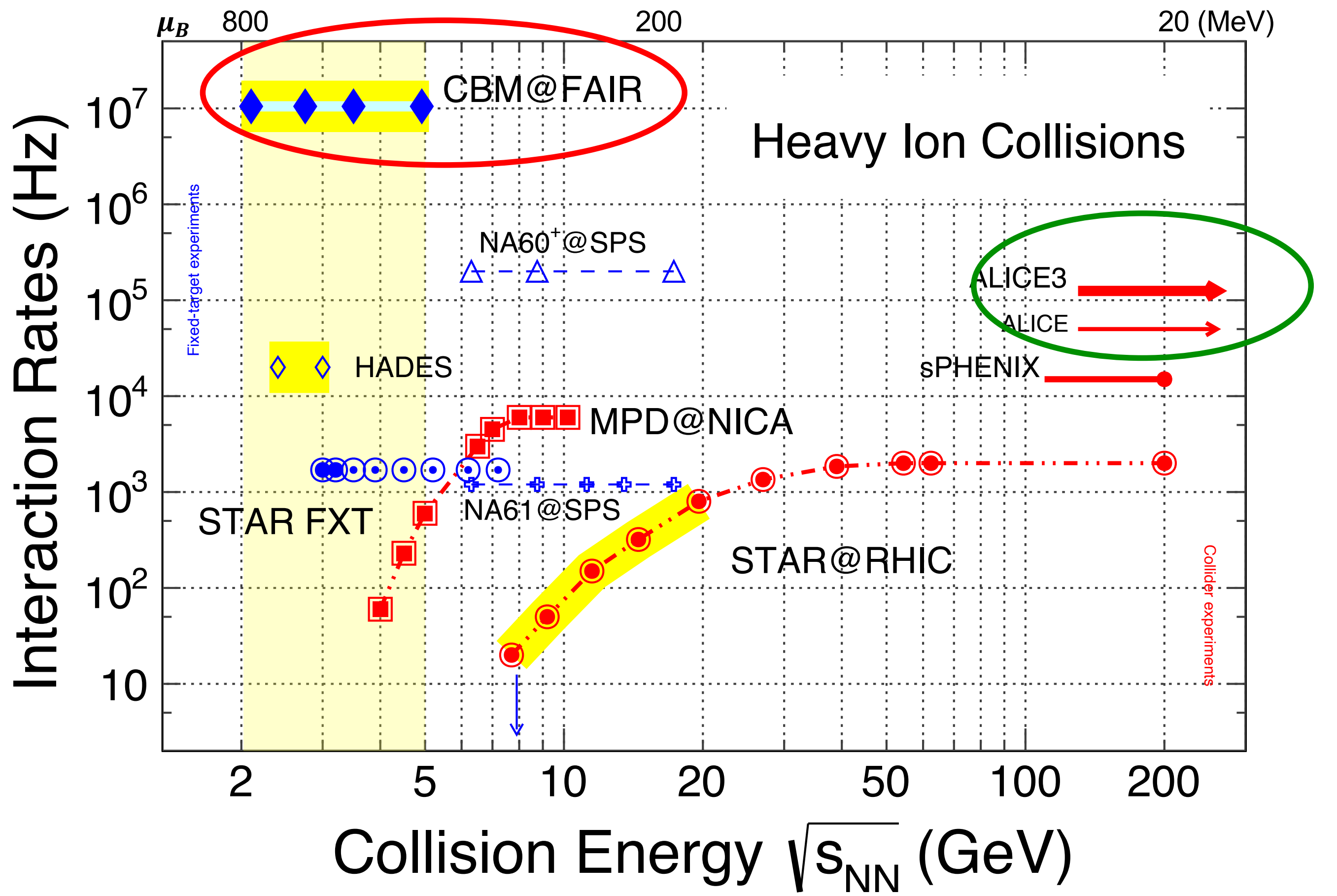
Future High Rates Experiments

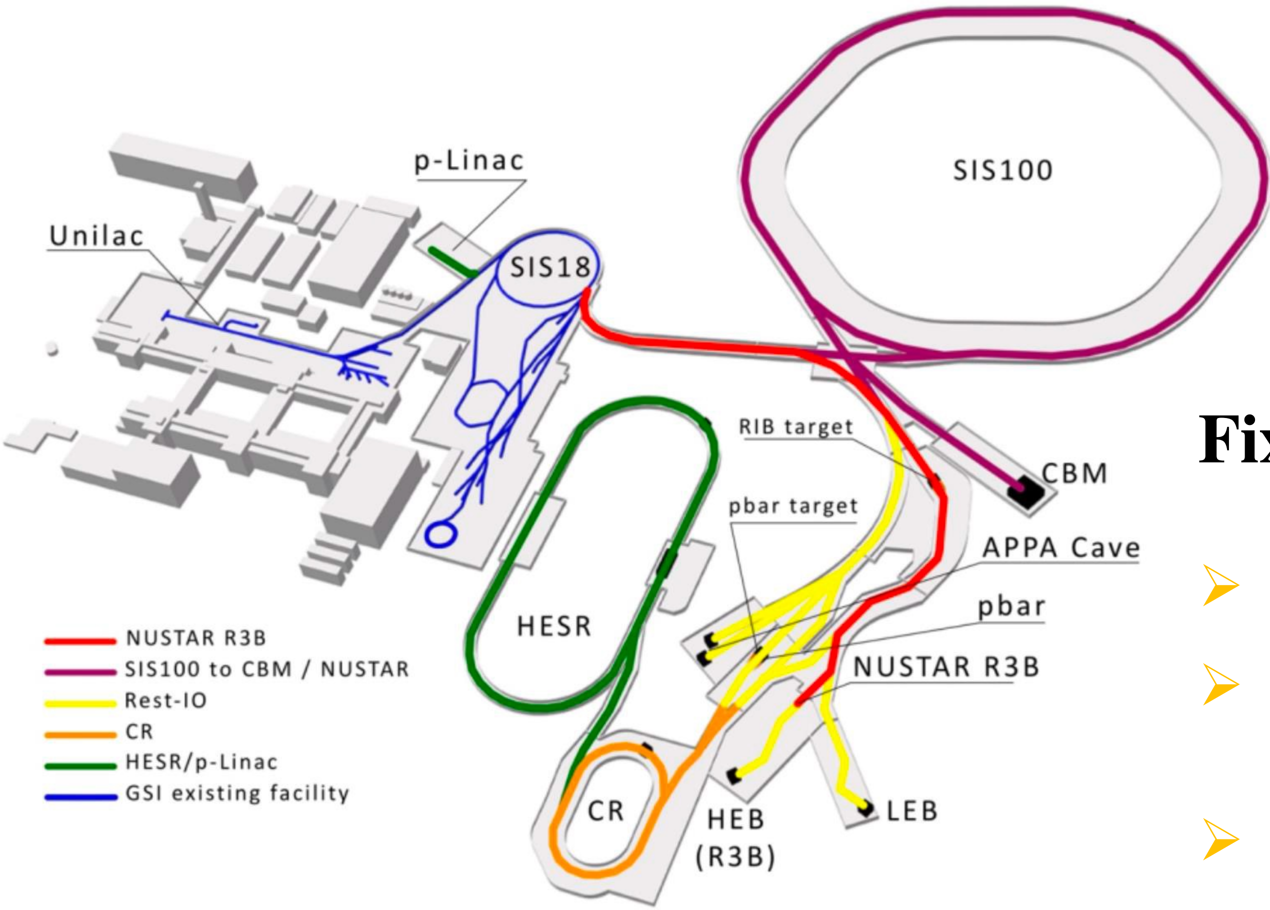
- **ALICE3:** μ_B ~ 0 Properties of QGP!

- **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



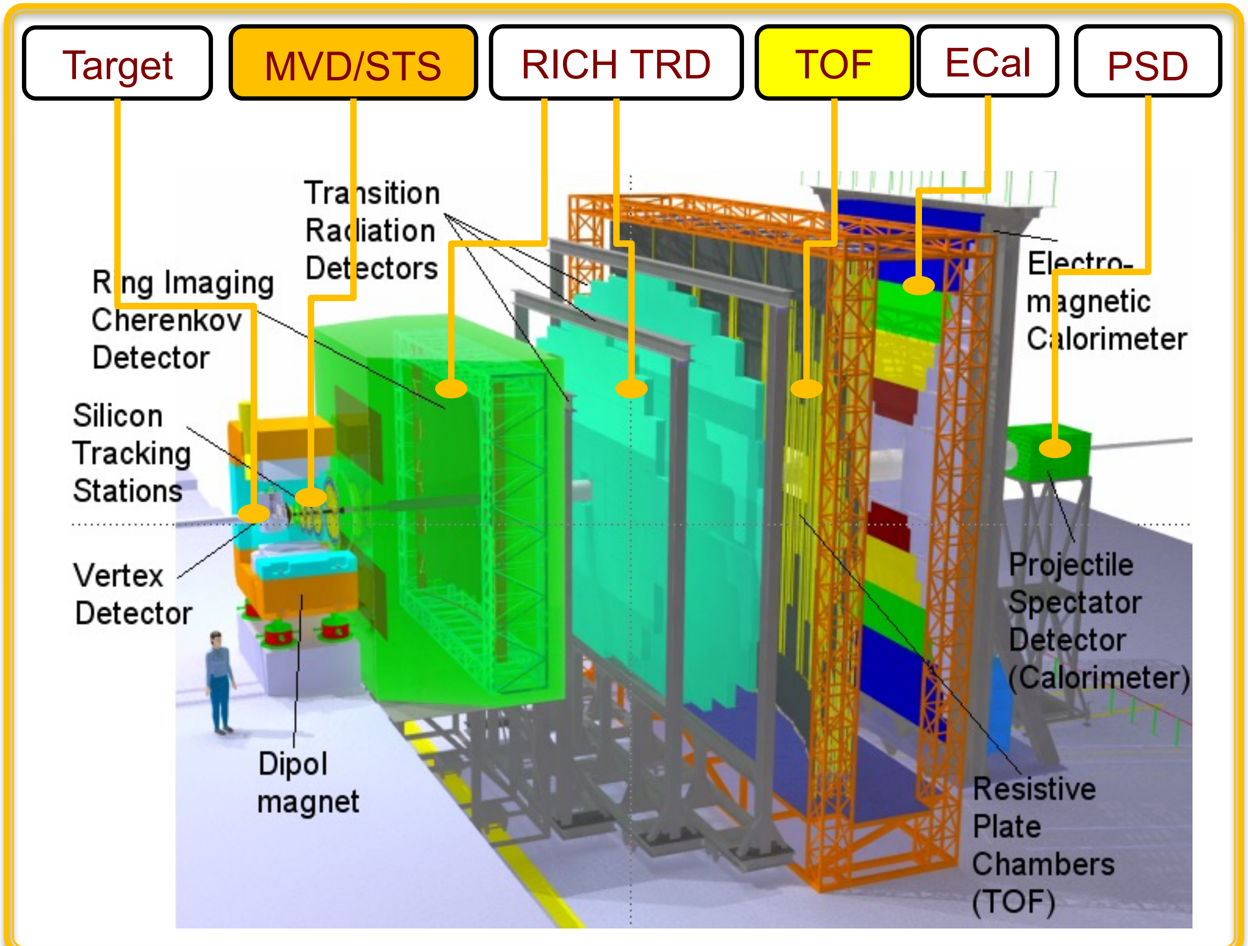
CBM Experiment at FAIR



Fixed-target experiment:

- **$2.4 < \sqrt{s_{NN}} < 4.9$ GeV**
- **High intensity & collision rates up to 10MHz**
- **Operation stars 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) and hyper-nuclei

Beam on target in 2028

US-CBM Whitepaper

QCD Phase Structure and Baryonic Interactions at High Baryon Density

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(Dated: July 23, 2022)

QCD Phase Structure and Baryonic Interactions at High Baryon Density

BNL, Duke, INT, IU, KSU, LBNL, MSU, NCSU, OSU, PU, Purdue, RICE, StonyBrook, Texas A&M, UC Davis, UCLA, UC Riverside, UH, UIC, UIUC, UNC, WSU

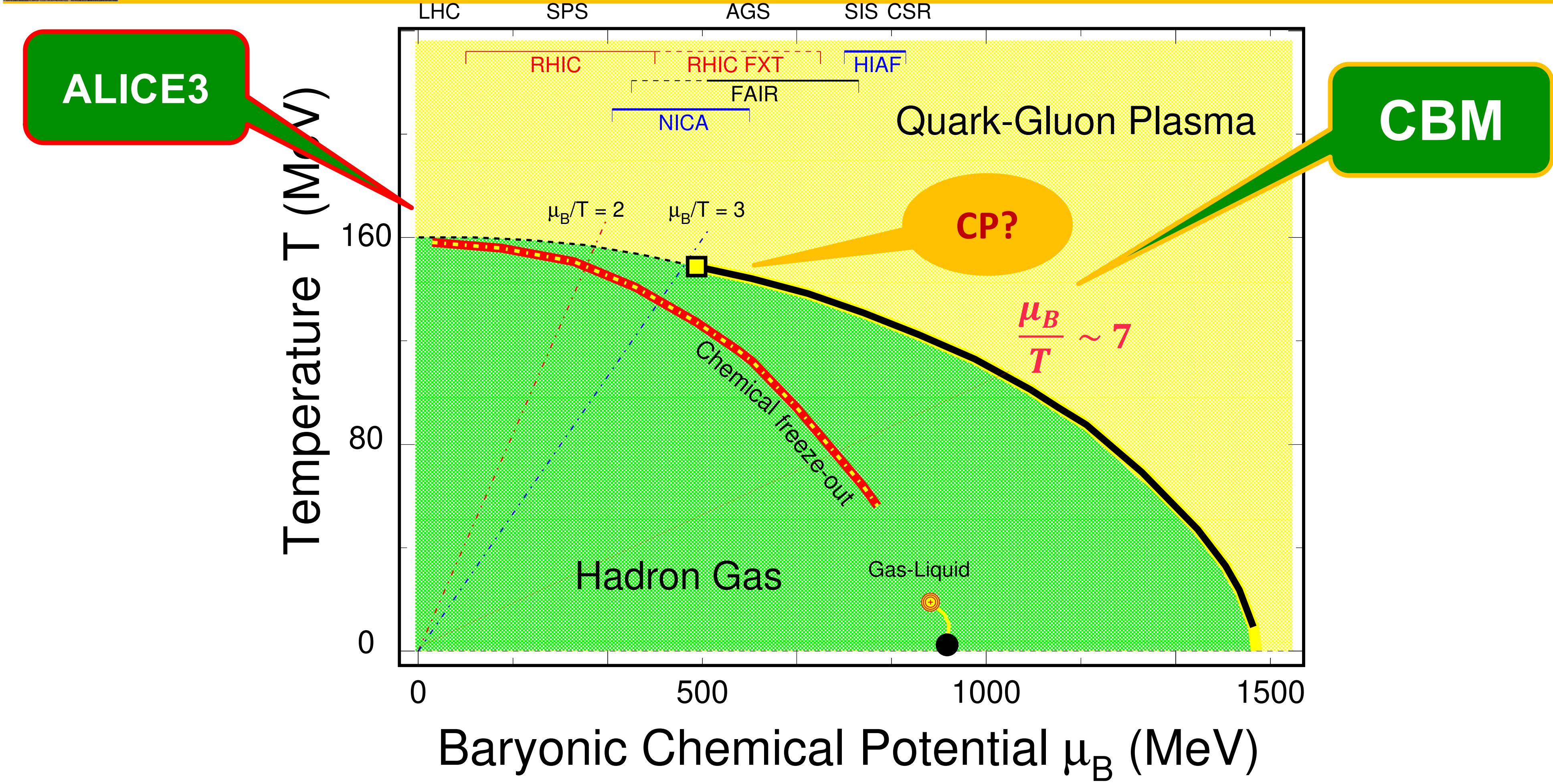
US-CBM Whitepaper

QCD Phase Structure and Baryonic Interactions at High Baryon Density

Executive Summary

We review recent key results from the Beam Energy Scan (BES) program at RHIC. In order to complete the BES physics program including the search for the QCD critical point, the extraction of hyperon-nucleon interaction and the nuclear matter equation of state at high baryon density, the participation in the international collaboration of the CBM Experiment at FAIR is scientifically necessary and cost effective.

Summary


LHC
SPS
AGS
SIS CSR
ALICE3
CBM
RHIC
RHIC FXT
HIAF
FAIR
NICA
Quark-Gluon Plasma
CP?
$\mu_B/T = 2$
$\mu_B/T = 3$
$\frac{\mu_B}{T} \sim 7$
Chemical freeze-out
Hadron Gas
Gas-Liquid
Temperature T (MeV)
160
80
0
0
500
1000
1500
Baryonic Chemical Potential μ_B (MeV)

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// BLUE: Theory // **RED**: Exp., high moment //

Thanks for you attention!