Recent Results from RHIC Beam Energy Scan Program

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Outline

1) Introduction

2) Selected Recent Results

- Collectivity
- Criticality
- Hyper-nuclei Production (**new at high baryon density**)

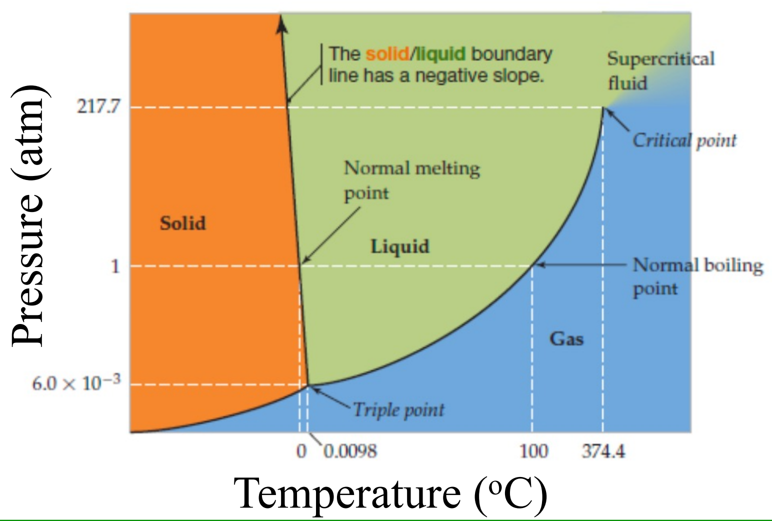
3) Future Physics at High Baryon Density

- CBM Experiment at FAIR

Phase Structure of Strong Interactions

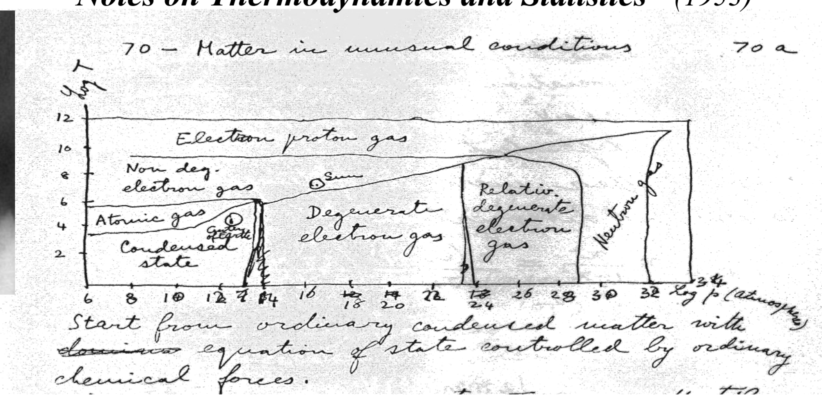
Phase Diagram: For given degrees of freedom, how matter (re)organizes itself under external conditions.

Phase Diagram of Water: QED at Work



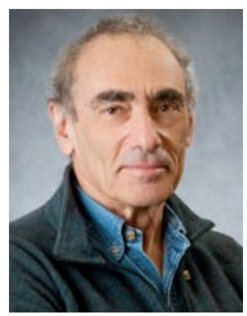
E. Fermi

"Notes on Thermodynamics and Statistics" (1953)

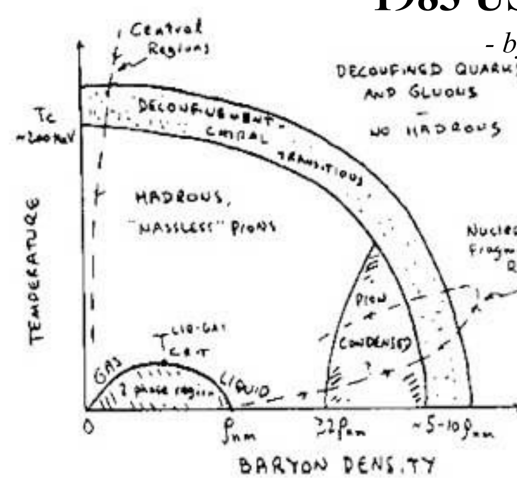


1983 US NP LRP

- by Gordon Baym

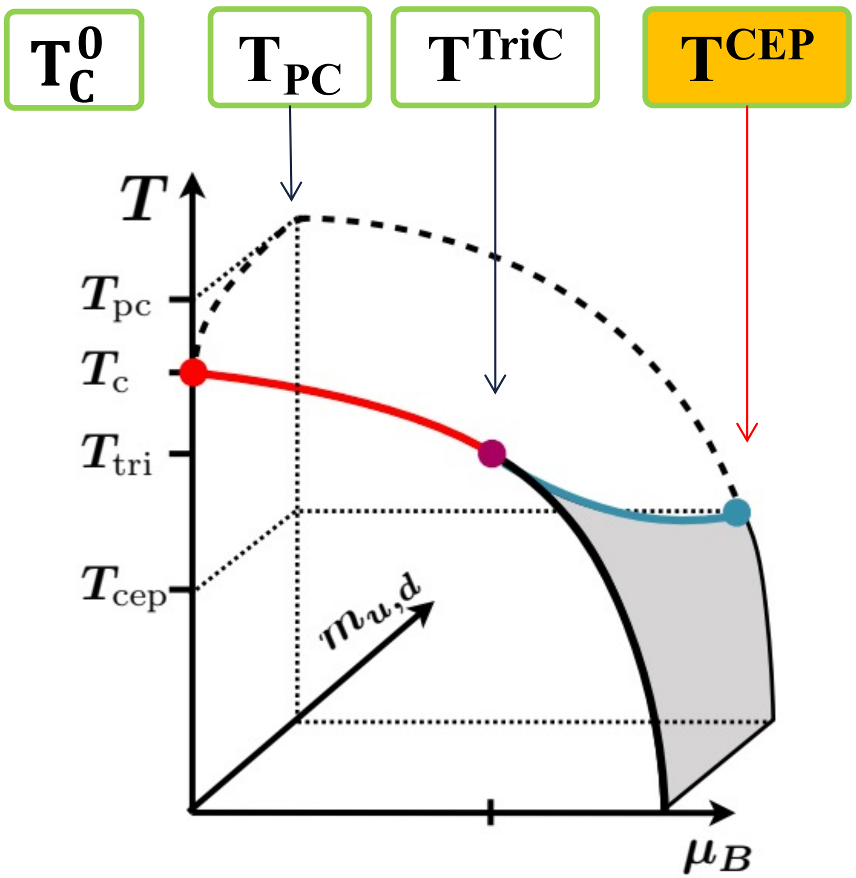


Gordon Baym



QCD Phase Diagram

LGT Calculation: QCD Phase Structure



F. Karsch *et al.*, 2020

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

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

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

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

High-Energy Nuclear Collisions and QCD Phase Diagram

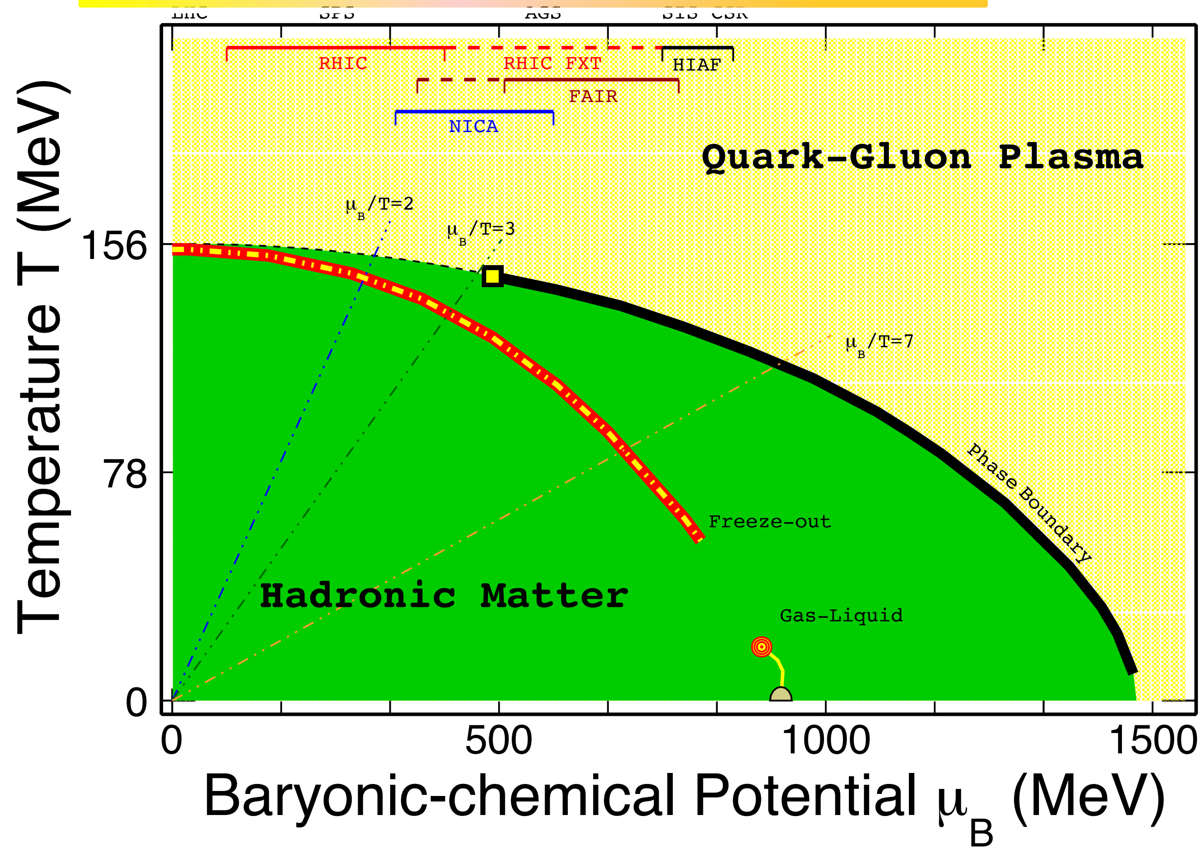
At LHC and RHIC top energy:

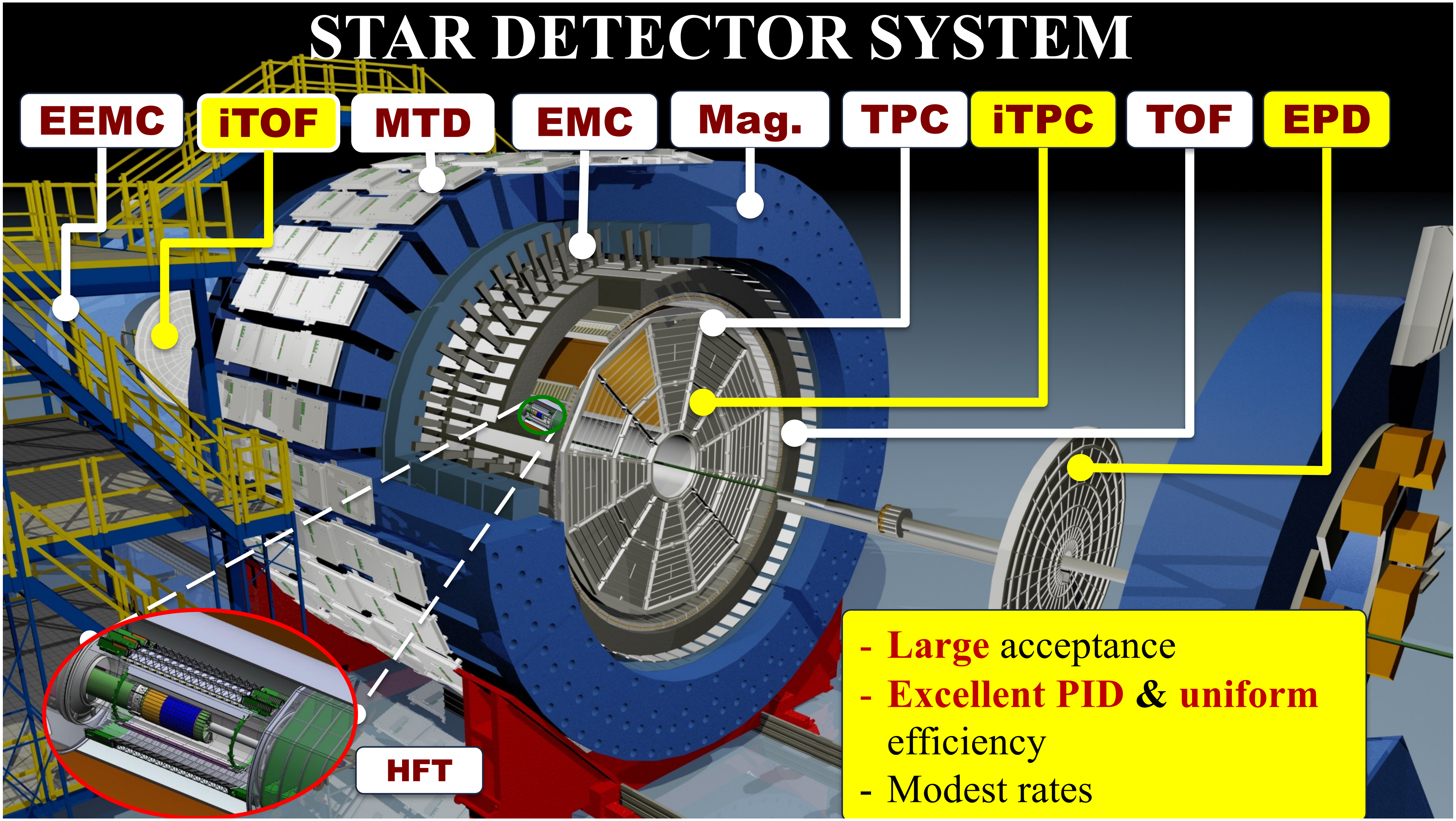
- Jet quenching;
- HF R_{AA} and v_2 data;
- Net-p C_6/C_2

→

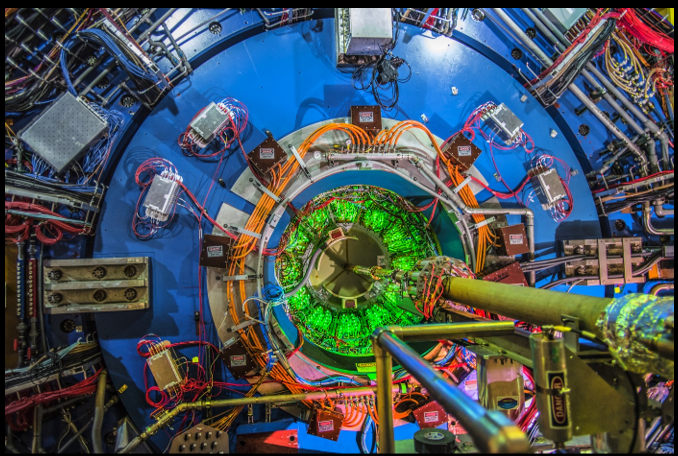
1) **At $\mu_B \sim 0$, smooth crossover. μ_B/T ≤ 2 (LGT);**
2) **CP at μ_B/T > 3**

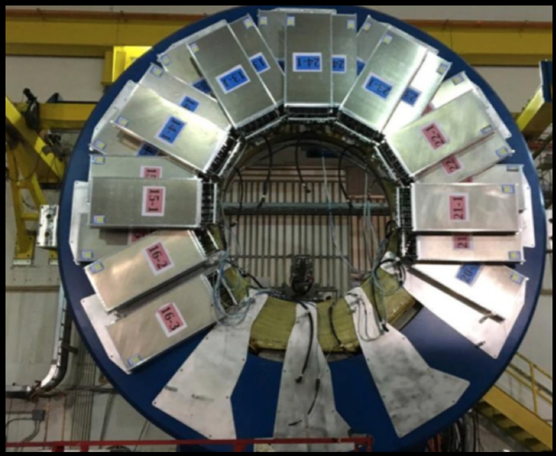
LHC RHIC & BES FAIR, …




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

Major Upgrades for BES-II





iTPC:
- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut-in from 125 to 60 MeV/c
- Ready in 2019

eTOF:
- Forward rapidity coverage
- PID at η = 0.9 to 1.5
- **Borrowed from CBM-FAIR**
- Ready in 2019

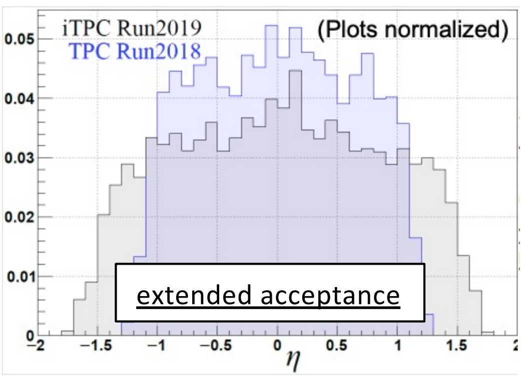
EPD:
- Improves trigger
- Better centrality & event plane measurements
- Ready in 2018

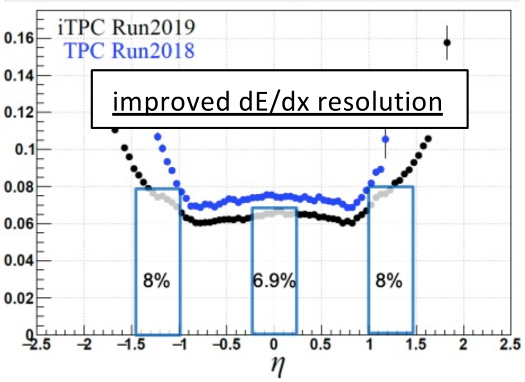
1) Enlarge rapidity acceptance
2) Improve particle identification
3) Enhance centrality/event plane resolution

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)

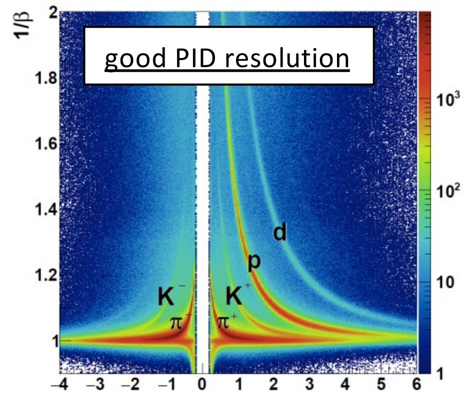
Upgraded Detector Performance

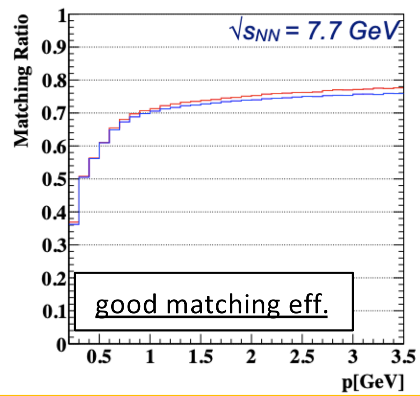
iTPC (2019+)



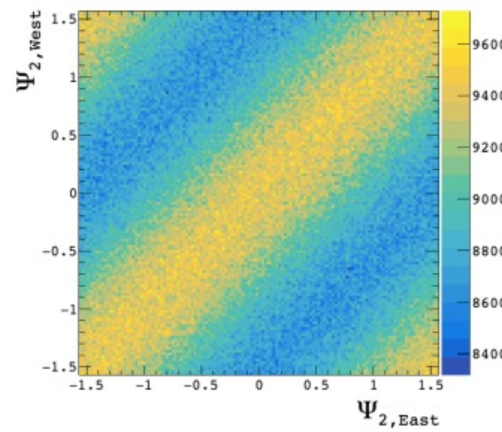


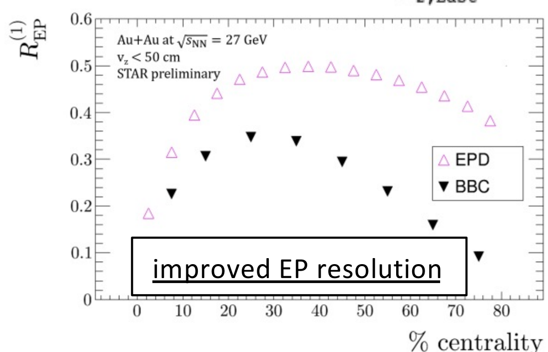
eTOF (2019+)



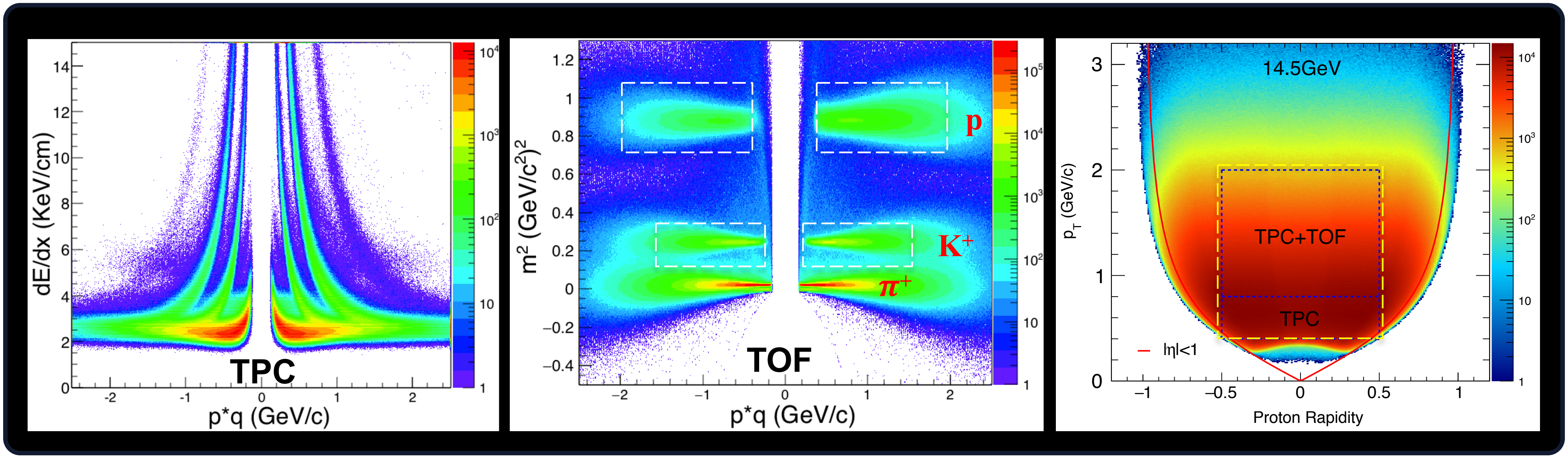


EPD (2018+)



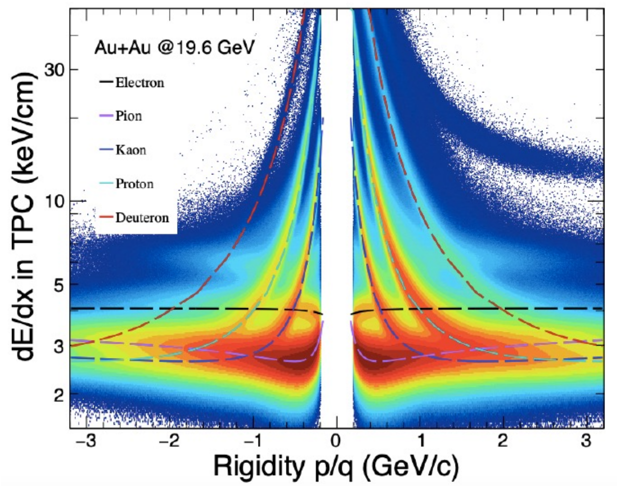


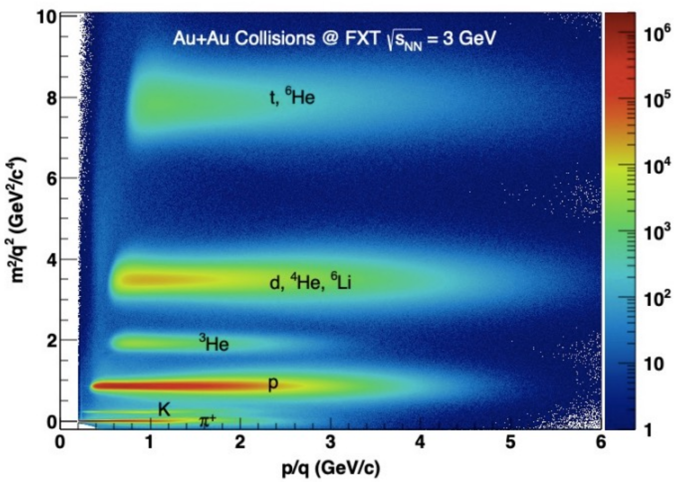
Particle Identification and Acceptance

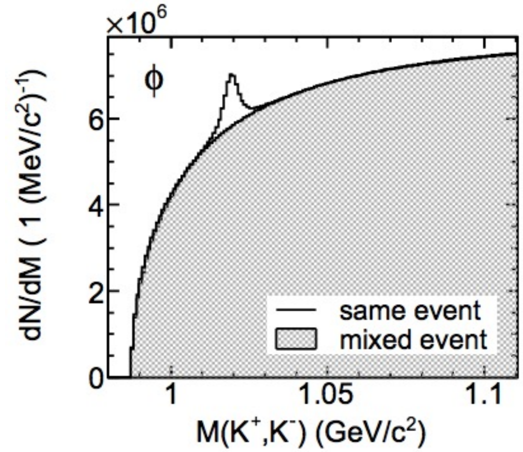


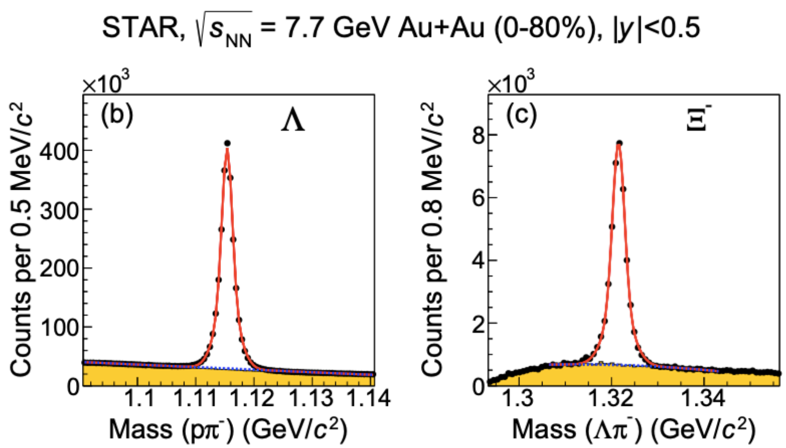
	Net-charge	**Net-Kaon**	**Net-proton**
Kinetic cuts	$0.2 < p_T < 2.0$ GeV/c, $\lvert\eta\rvert < 0.5$	$0.2 < p_T < 1.6$ GeV/c, $\lvert y_K\rvert < 0.5$	$0.2 < p_T < 1.6$ GeV/c, $\lvert y_p\rvert < 0.5$
Particle identifications	Reject spallation p at $p_T < 2.0$ GeV/c	TPC: $0.2 < p_T < 0.4$ GeV/c TPC/TOF: $0.4 < p_T < 1.6$ GeV/c	TPC: $0.4 < p_T < 0.8$ GeV/c TPC/TOF: $0.8 < p_T < 2.0$ GeV/c
Efficiency corrections		TPC: $\varepsilon_{TPC} \sim 0.8$; TPC+TOF: $\varepsilon_{TPC+TOF} \sim 0.5$	
Centrality Definitions	Un-corrected charge particles $0.5 < \lvert\eta\rvert < 1.0$	Un-corrected charge particles and reject Kaons, $\lvert\eta\rvert < 1.0$	Un-corrected charge particles and reject p and anti-p, $\lvert\eta\rvert < 1.0$

Particle Identifications

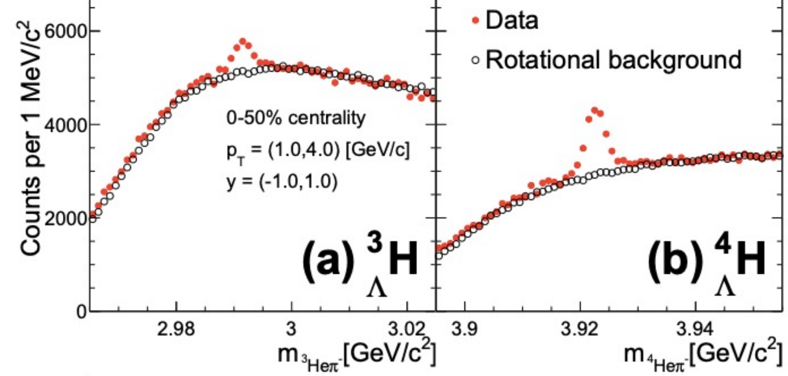




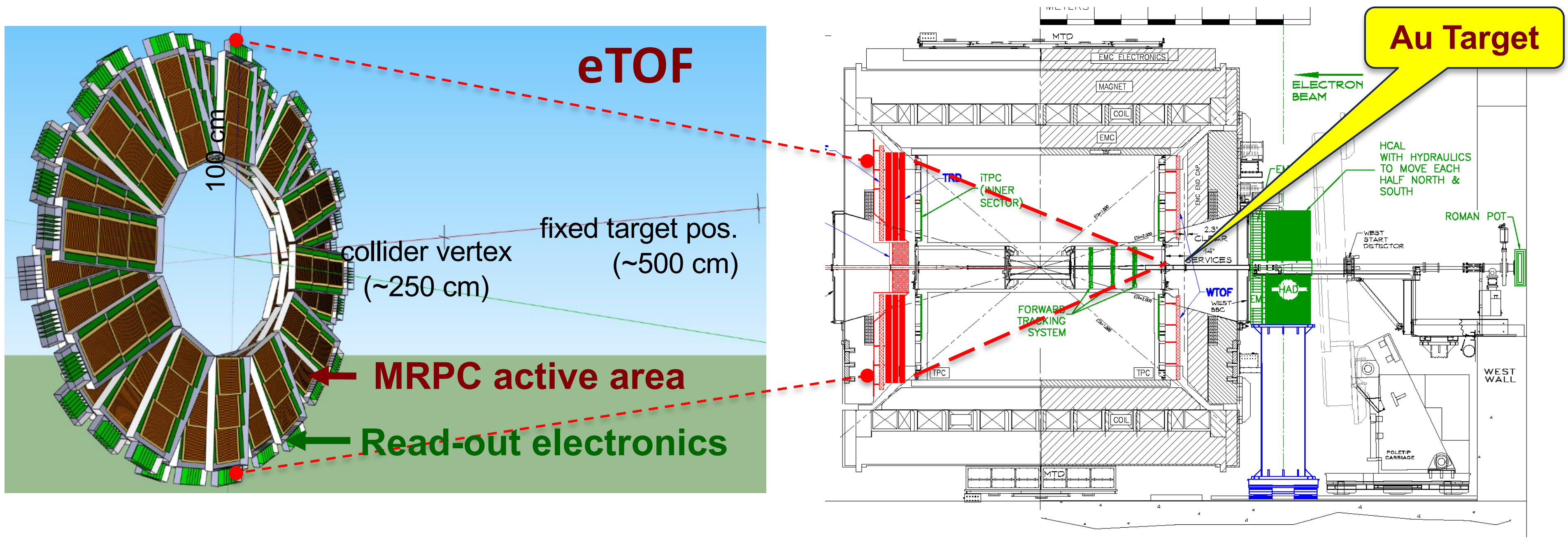




Au+Au Collisions at $\sqrt{s_{NN}}$ = 3.0 GeV



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

	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	**200**	380 M	**25** MeV	5.3	Run-10, 19
2	62.4	46 M	75 MeV		Run-10
3	54.4	1200 M	85 MeV		Run-17
4	39	86 M	112 MeV		Run-10
5	27	585 M	156 MeV	3.36	Run-11, 18
6	19.6	595 M	206 MeV	3.1	Run-11, 19
7	17.3	256 M	230 MeV		Run-21
8	14.6	340 M	262 MeV		Run-14, 19
9	11.5	57 M	316 MeV		Run-10, 20
10	9.2	160 M	372 MeV		Run-10, 20
11	7.7	104 M	420 MeV		Run-21

Fixed-Target Runs

	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	11.5 (70)	50 M	320 MeV	-2.51	Run-21
3	9.2 (44.5)	50 M	370 MeV	-2.28	Run-21
4	7.7 (31.2)	260 M	420 MeV	-2.1	Run-18, 19, 20
5	7.2 (26.5)	470 M	440 MeV	-2.02	Run-18, 20
6	6.2 (19.5)	120 M	490 MeV	1.87	Run-20
7	5.2 (13.5)	100 M	540 MeV	-1.68	Run-20
8	4.5 (9.8)	110 M	590 MeV	-1.52	Run-20
9	3.9 (7.3)	120 M	633 MeV	-1.37	Run-20
10	3.5 (5.75)	120 M	670 MeV	-1.2	Run-20
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

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

Outline

1) Introduction

2) Selected Recent Results

- Collectivity
- Criticality
- Strangeness production: hyper-nuclei

3) Future Physics at High Baryon Density

- CBM Experiment at FAIR

Collectivity

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

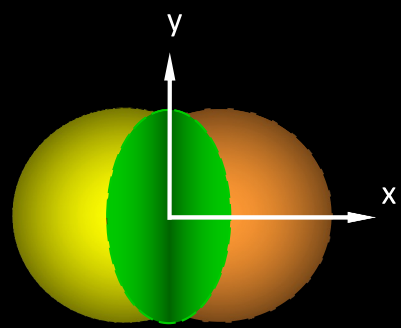
$$\frac{d^2N}{p_T dp_T d\varphi} = \frac{1}{2\pi} \frac{dN}{p_T dp_T} \left\{ 1 + \sum_{n=1}^{\infty} 2 v_n(p_T) cos[n(\varphi - \Psi_R)] \right\}$$

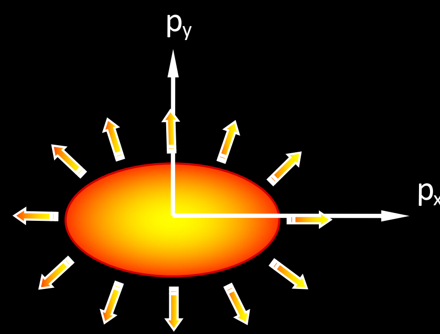
– v_1 Directed flow;

– v_2 Elliptic flow; – v_3 Triangle flow

Anisotropy Parameter v_2

coordinate-space-anisotropy ➡ momentum-space-anisotropy

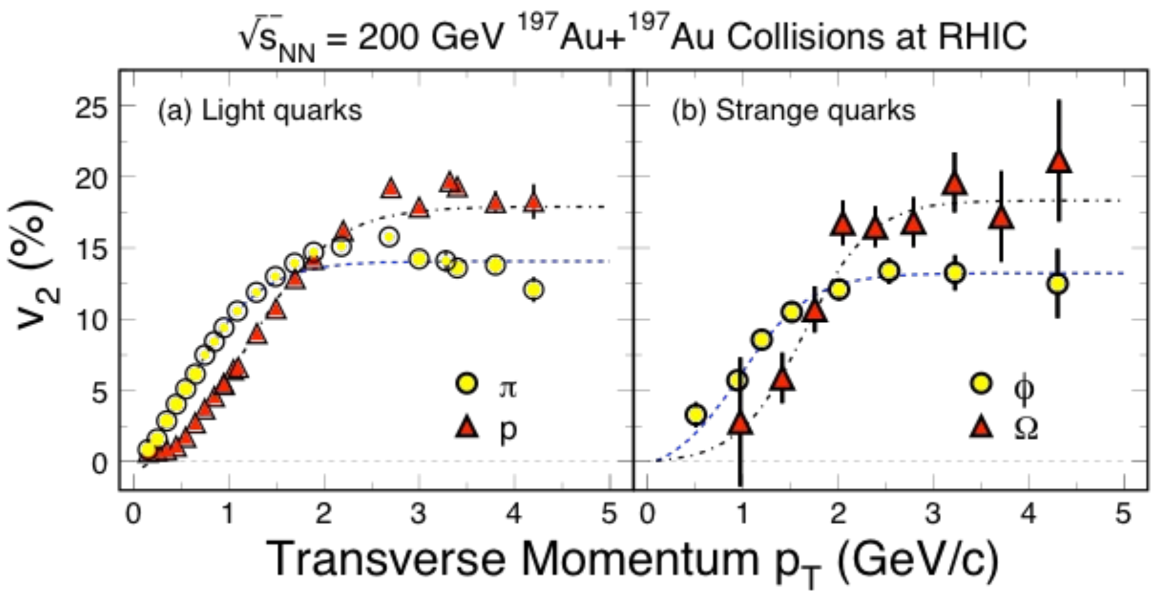




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle cos2\varphi \rangle, \qquad \varphi = tan^{-1}\left(\frac{p_y}{p_x}\right)$$

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

Partonic Collectivity at RHIC



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

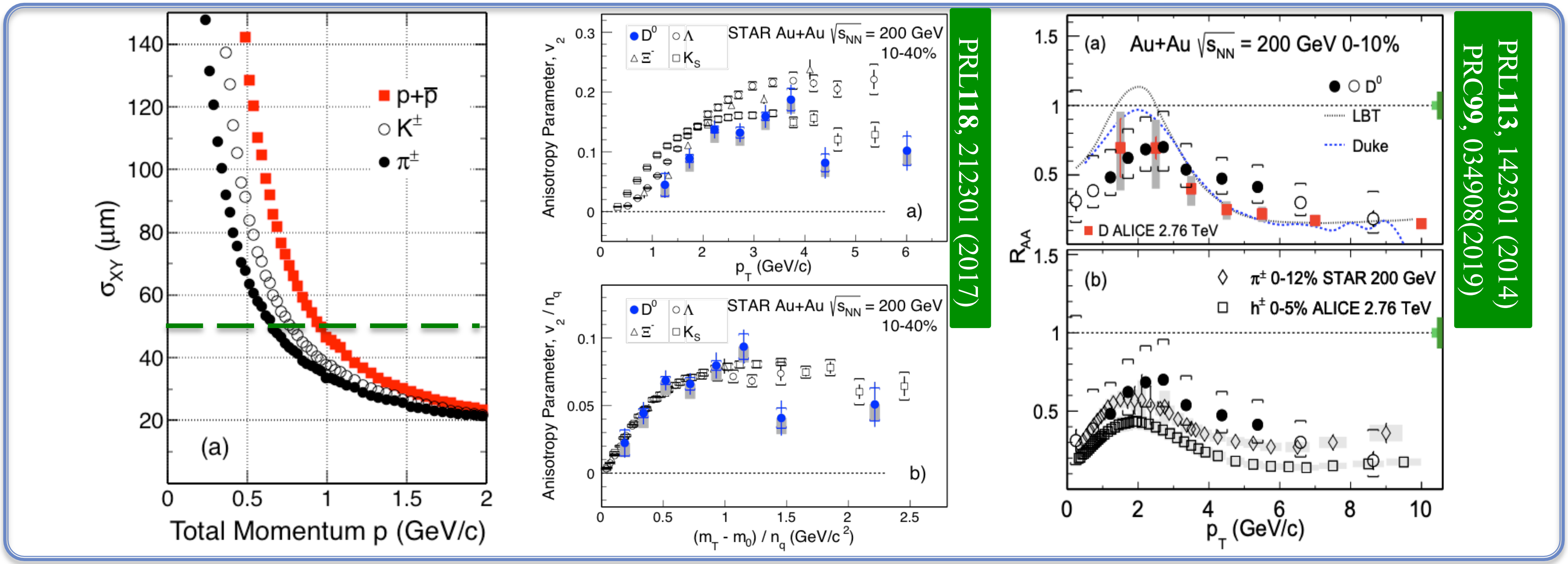
- ✓ Low p_T (≤ 2 GeV/c): hydrodynamic mass ordering
- ✓ High p_T (> 2 GeV/c): ***number of quarks scaling (NCQ)***

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

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

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

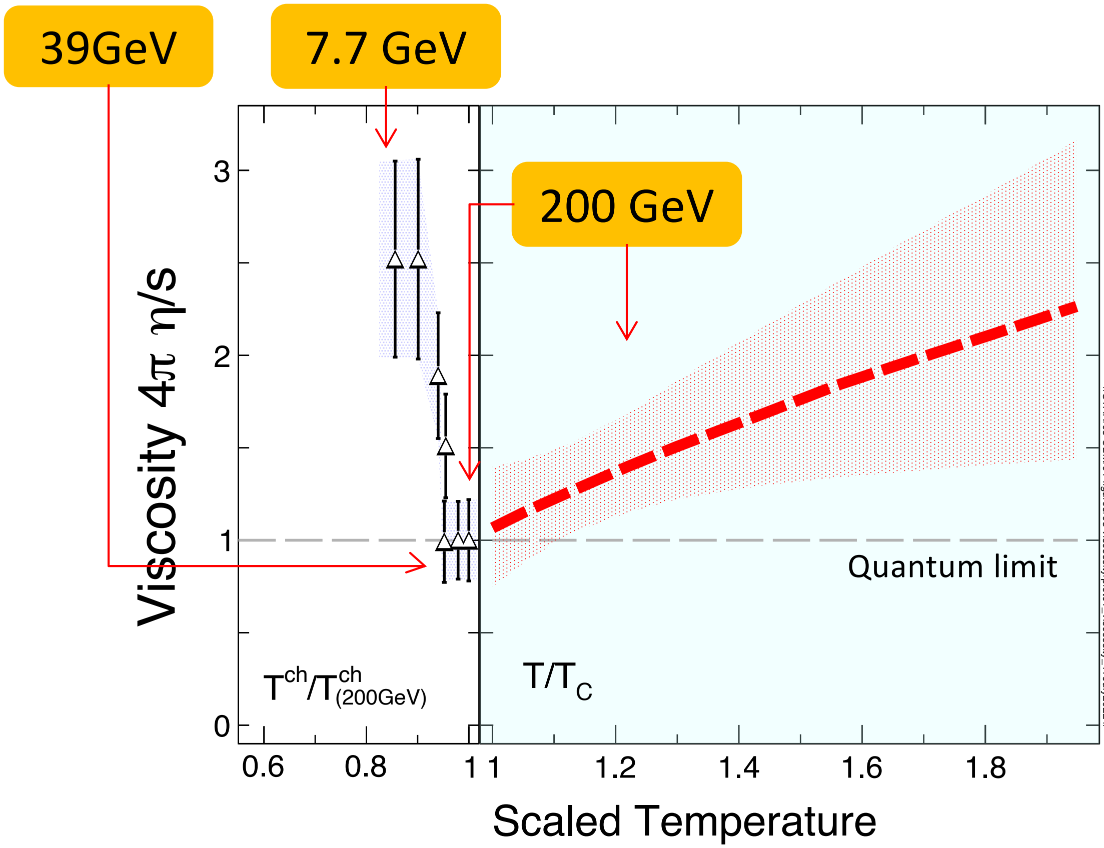
Heavy Flavor Hadron D^0 Collectivity at HRIC



1) First application of MAPS technology in high energy collisions, excellent position resolution;
   - "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.

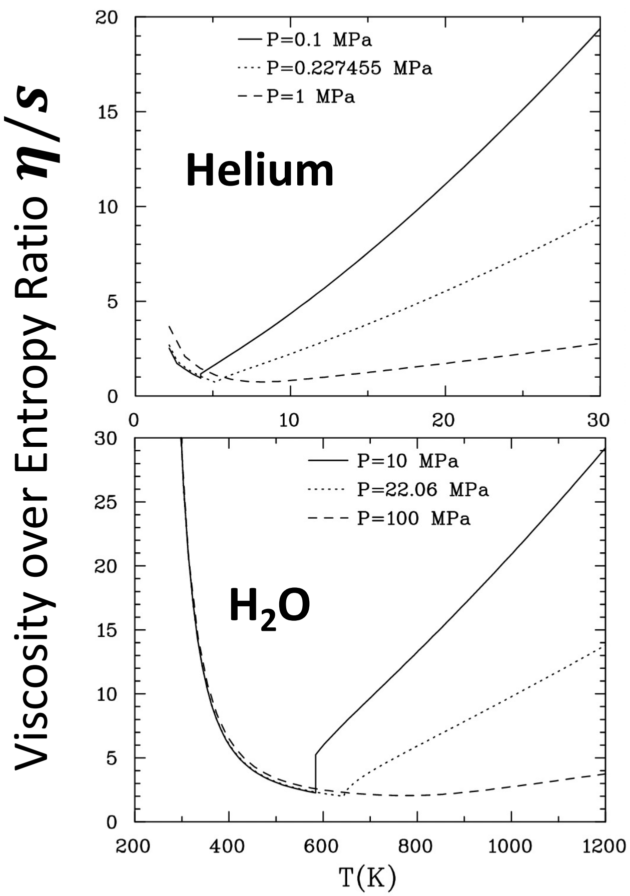
2) Both sides meet at the unity of the scaled temperature.

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).

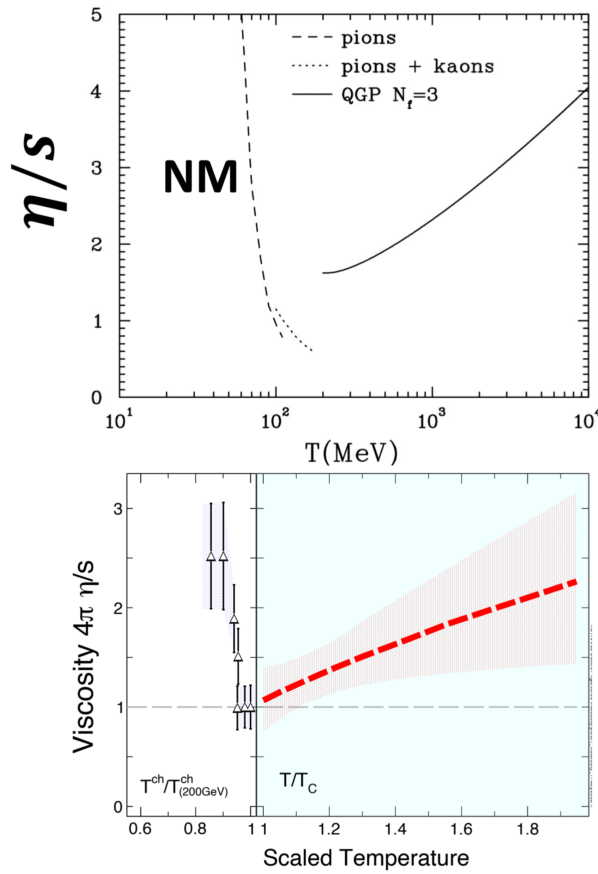
Strongly-Interacting Low-Viscosity Matter



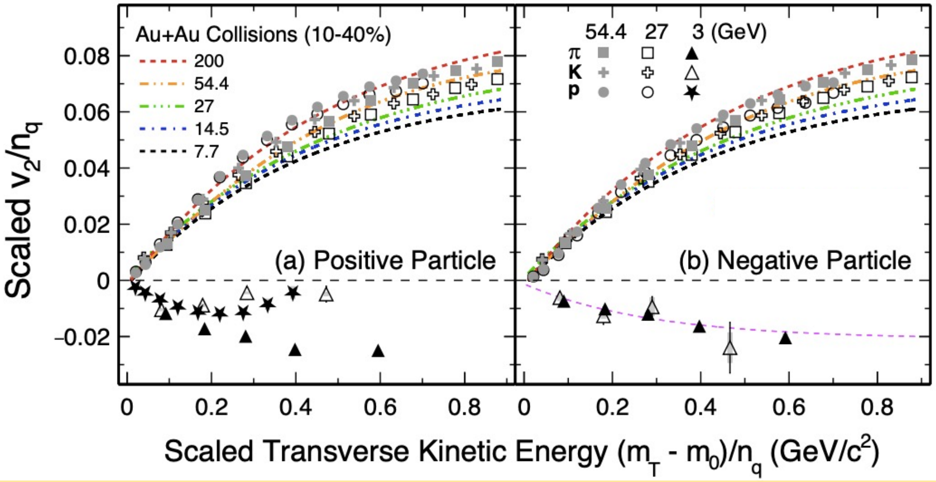
EM interaction
η/s ~ 1

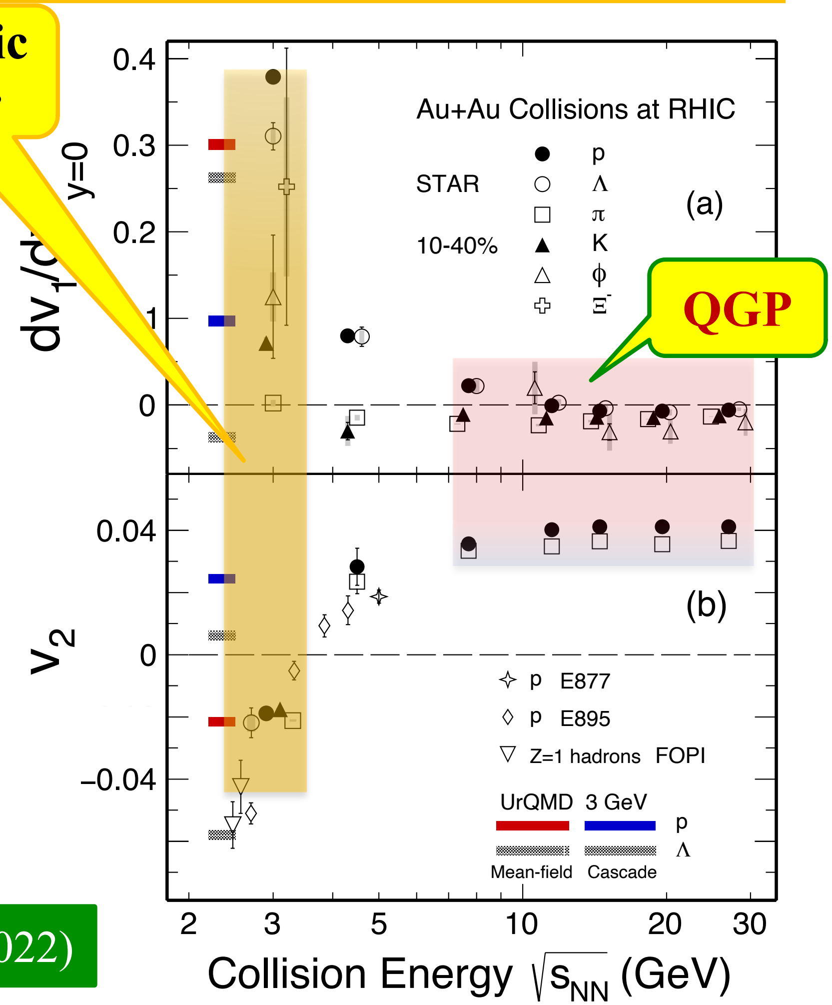
L.P. Csernai, J.I. Kapusta, L.D. McLerran, PRL**97** (2006) 152303

Strong Interaction
η/s ~ 0.1



Disappearance of Partonic Collectivity

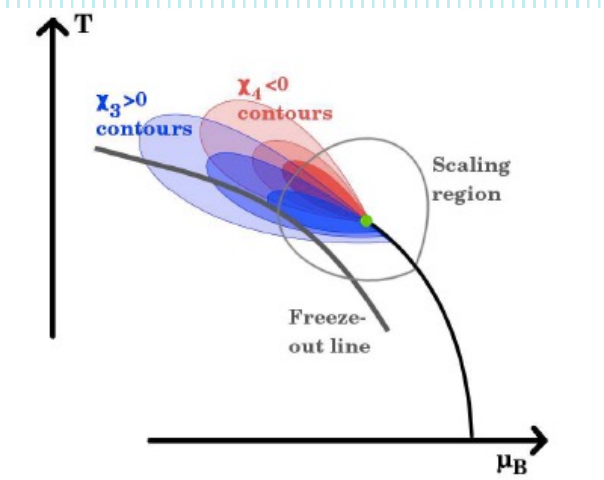




- At **3 GeV**, NCQ scaling is absent ;
- Transport model calculations, with baryonic mean field, reproduce both v_1 and v_2 results ;
- **hadronic interactions dominant!**

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

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

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

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

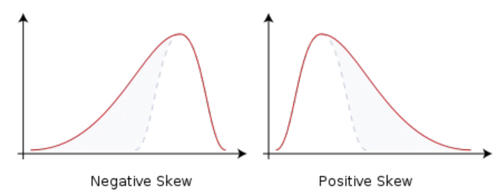
kurtosis: $\kappa = \langle (\delta N)^4 \rangle / \sigma^3 - 3 = C_4 / C_2^2$

Moments, cumulants and susceptibilities:

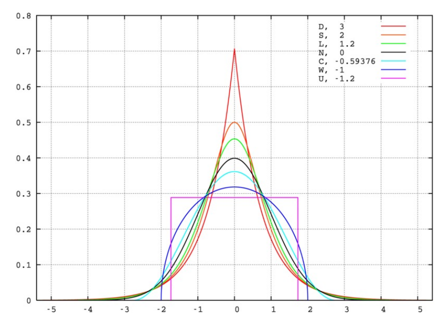
2^{nd} order: $\sigma^2/M \equiv C_2/C_1 = \chi_2/\chi_1$

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

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



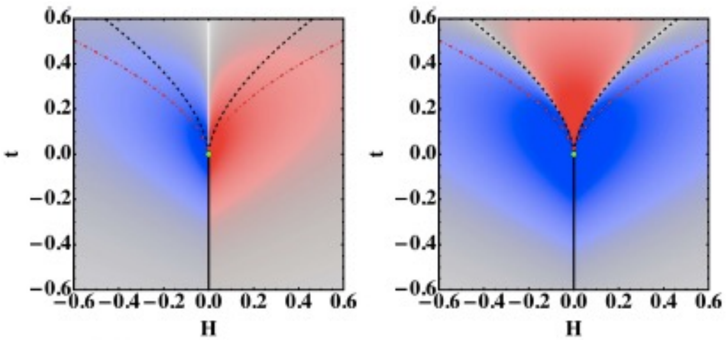
skewness (S) → asymmetry

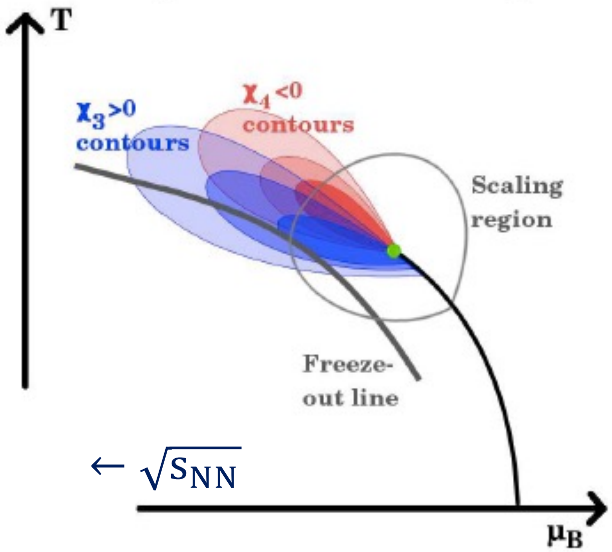


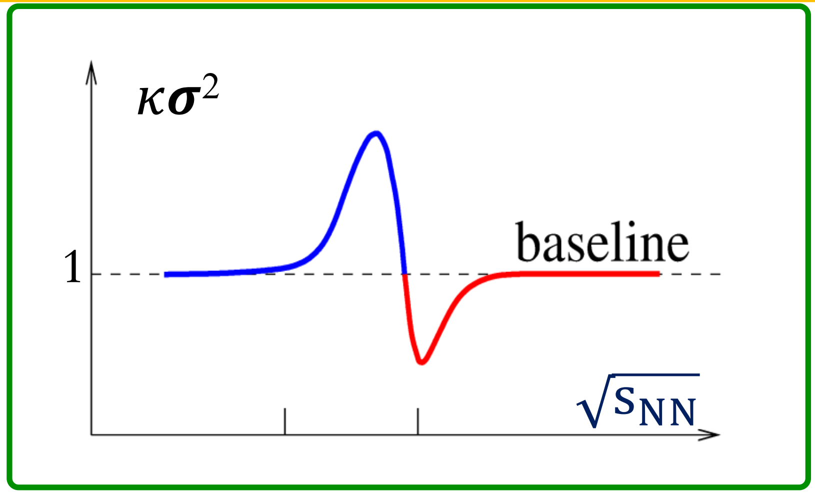
kurtosis (κ) → sharpness

INT 2008-2b : The QCD Critical Point

Expectations for Models





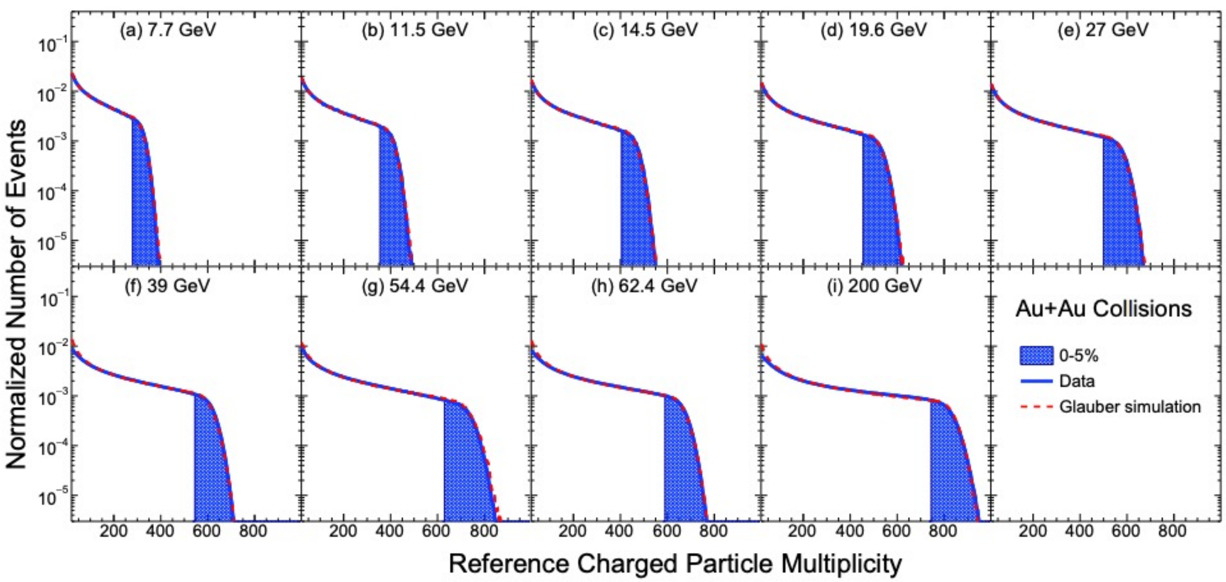


- Characteristic "Oscillating pattern" is expected for the QCD critical point but the exact shape depends on the location of freeze-out with respect to the location of CP
- Critical Region (CR)

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

Analysis Methods and Corrections

STAR: 2101.12413



1) Centrality bin correction;
2) Efficiency corrections;
3) Statistical uncertainty estimation;
4) Pileup correction (FXT)

-

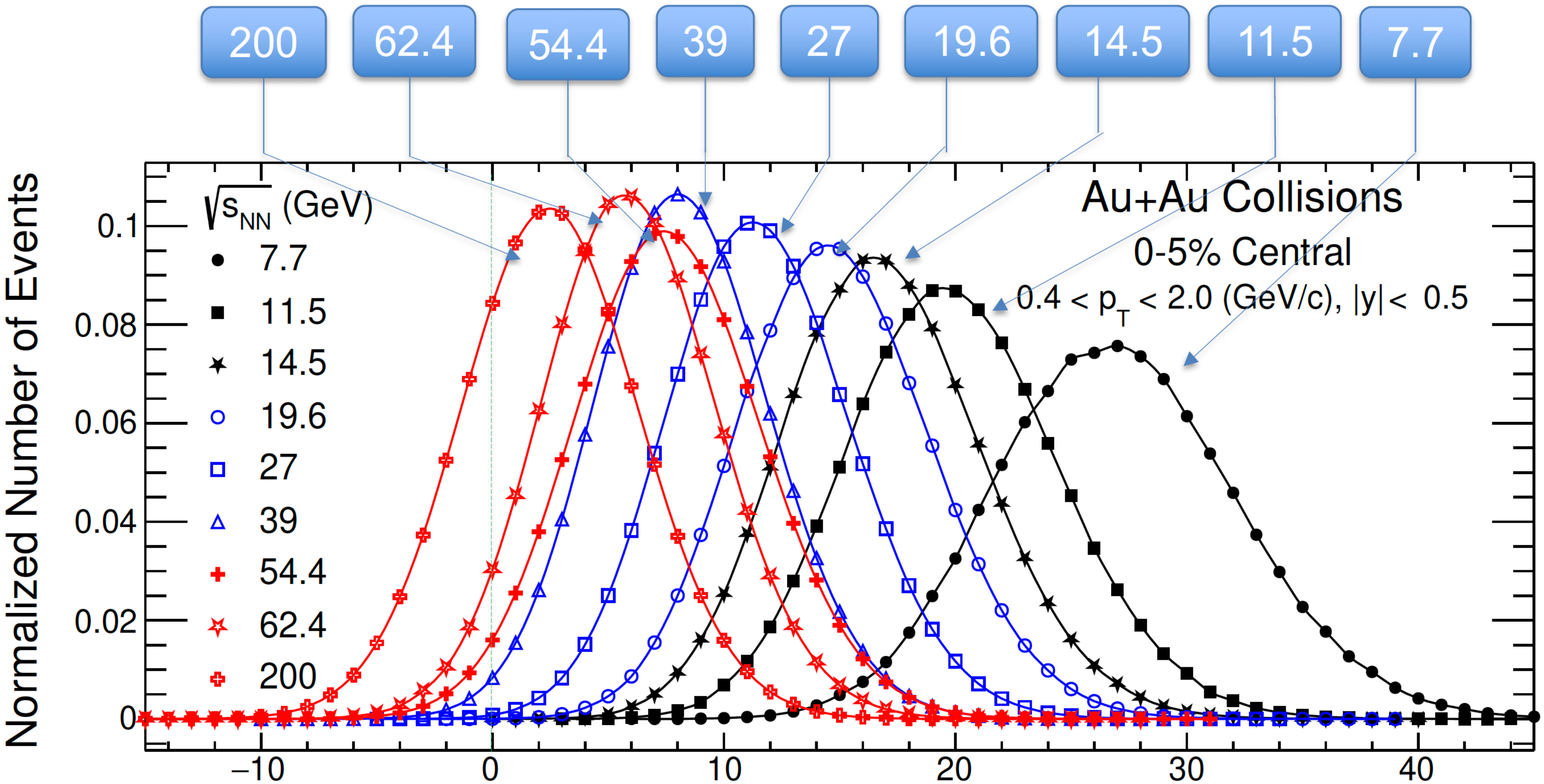
X.F. Luo, J.Phys.G Nucl.Part.Phys. **40,** 105104(13)

X.F. Luo, PRC**91**, 034907(15); T. Nonaka et al., PRC**95**, 044917(17); X.F. Luo et al., PRC**99**, 044917(19)

X.F. Luo, J.Phys.G Nucl.Part.Phys. **39**, 025008(12)

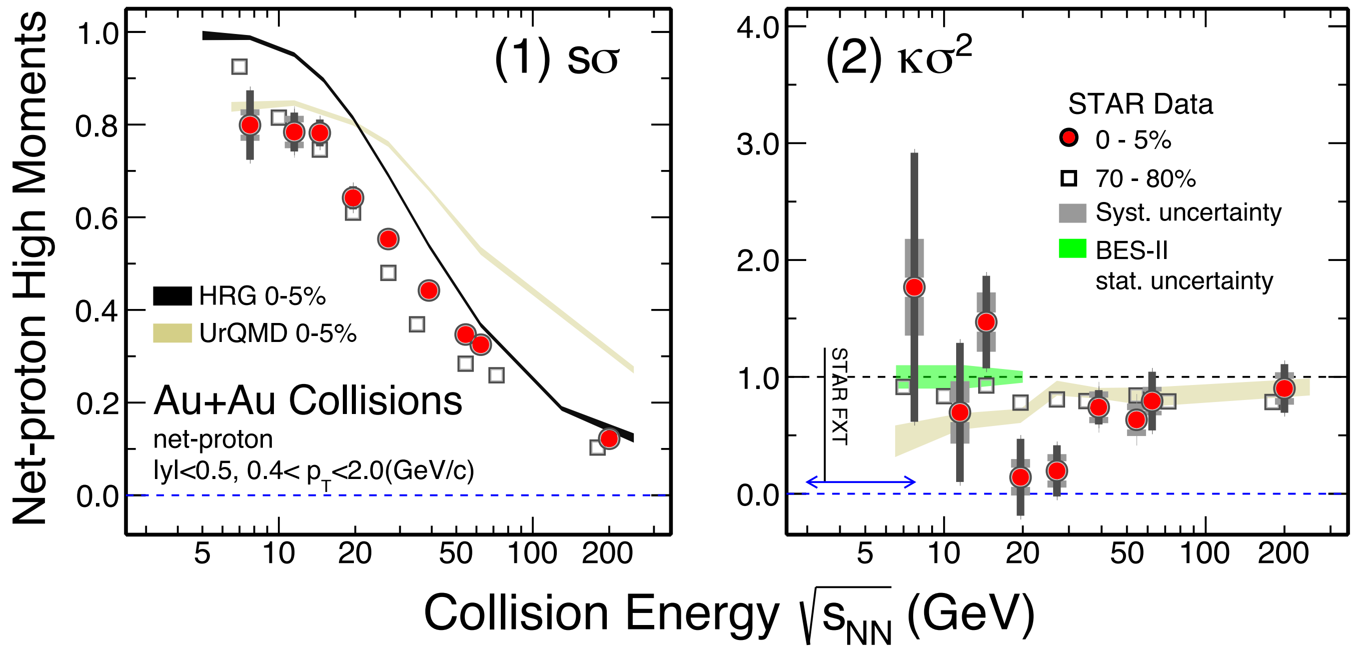
T. Nonaka et al., NIM**A984**, 164632(20)

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



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

"Nonmonotonic Energy Dependence of Net-Proton Number"

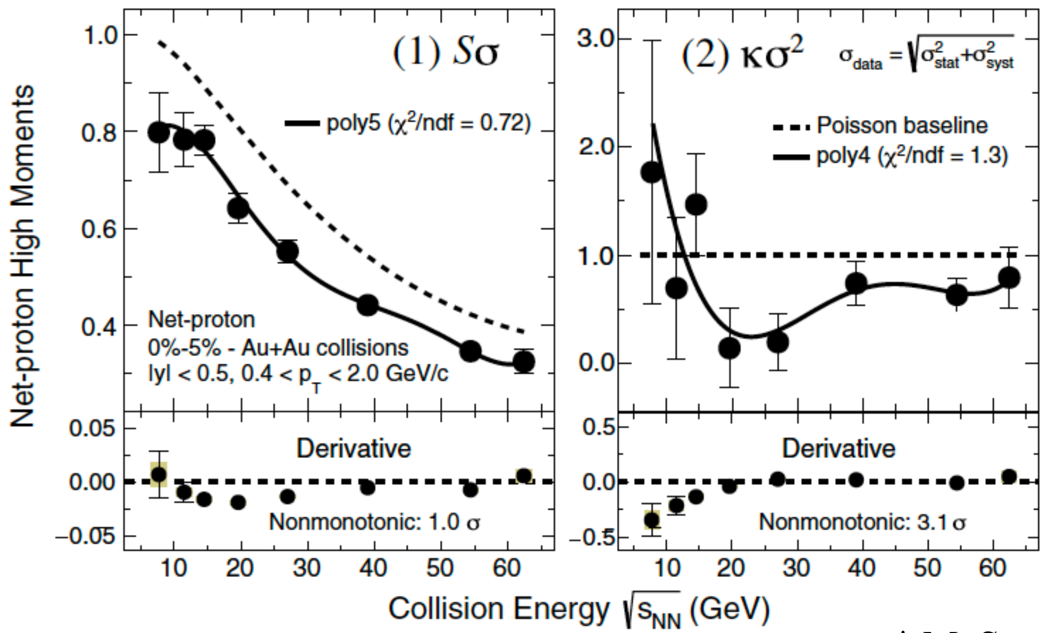


1) HRG and transport model predicted monotonical energy dependence: AMPT, JAM, UrQMD. Suppression at low energy due to conservation;

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

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

"Nonmonotonic Energy Dependence of Net-Proton Number Fluctuations"

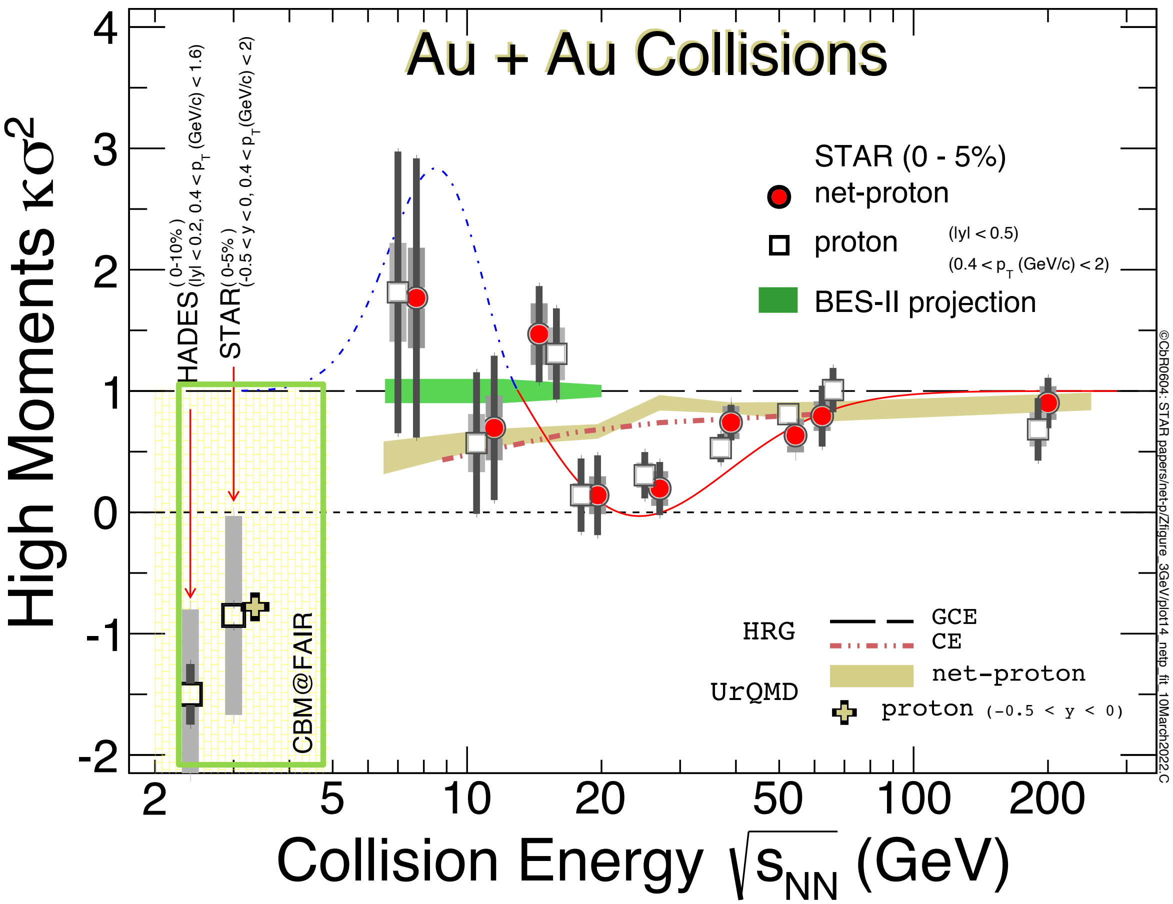


3.1σ

* M. Stephanov, PRL**102**, 022301(09)

	2ND order	3RD order	4TH order
Data	Monotonic, 3.4σ	Non-Monotonic, 1.0σ	Non-Monotonic, 3.1σ
Model*	$\langle(\delta N)^2\rangle \sim \xi^2$	$\langle(\delta N)^3\rangle \sim \xi^{4.5}$	$\langle(\delta N)^4\rangle \sim \xi^7$

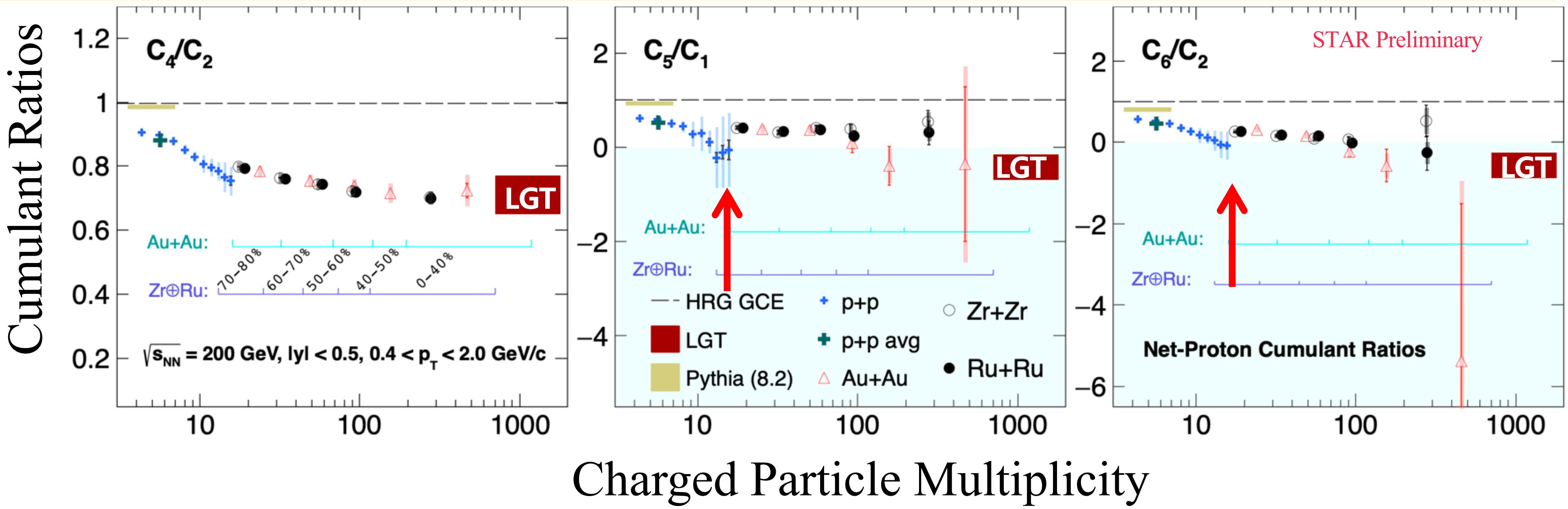
Net-p $\kappa\sigma^2$ Energy Dependence



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



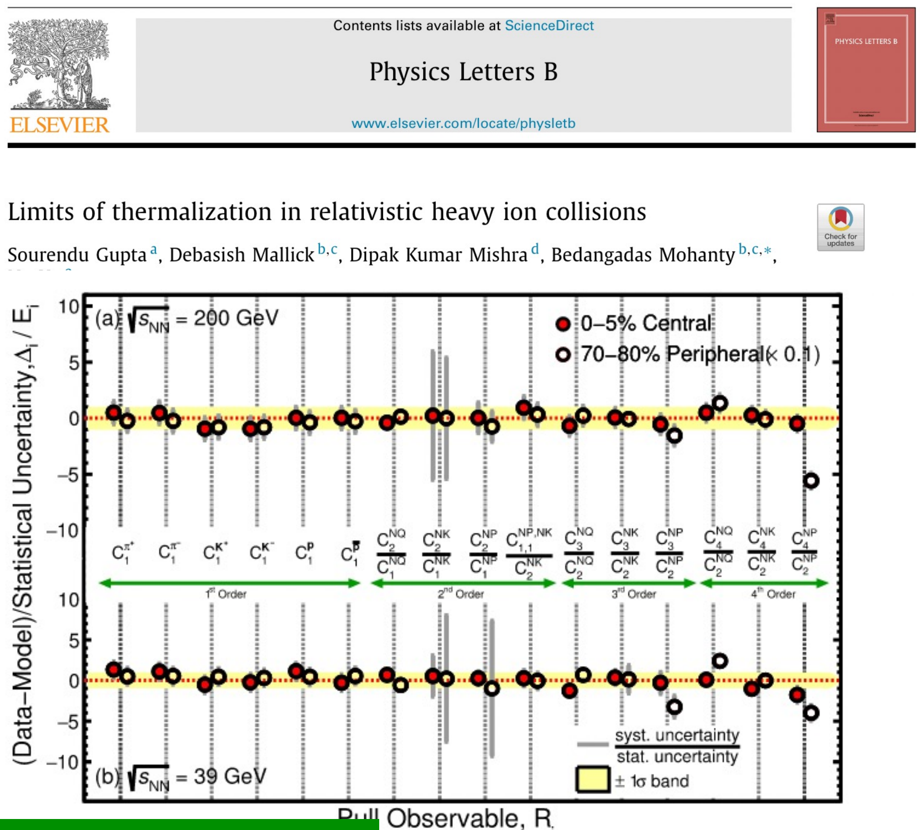
1) In 200GeV p+p collisions, at high multiplicity, C_5/C_2 and C_6/C_2 become negative as LGT predicted; *pp collisions are more efficient in producing QGP matter!*

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

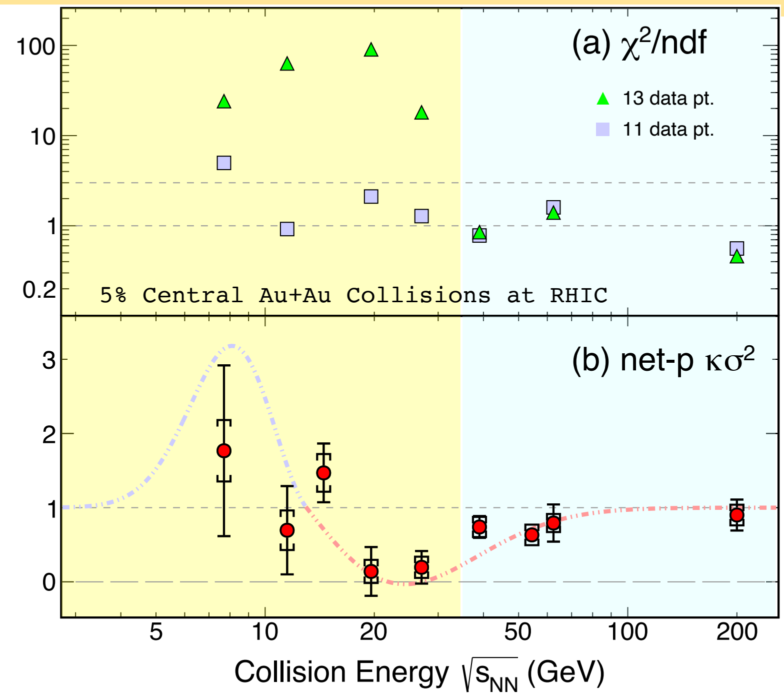
HotQCD Collaboration, PR**D101**, 074502 (2020)

Thermalization in Heavy-Ion Collisions

S. Gupta *et al.* Phys. Lett. **B829**, (2022) 137021

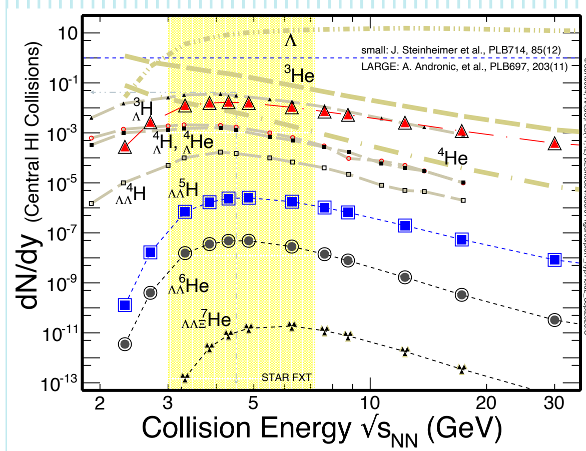


1) Test of the thermal model with high moments data: 4^{TH} order;
2) Below 39 GeV, **data is not consistent with equilibrium.**



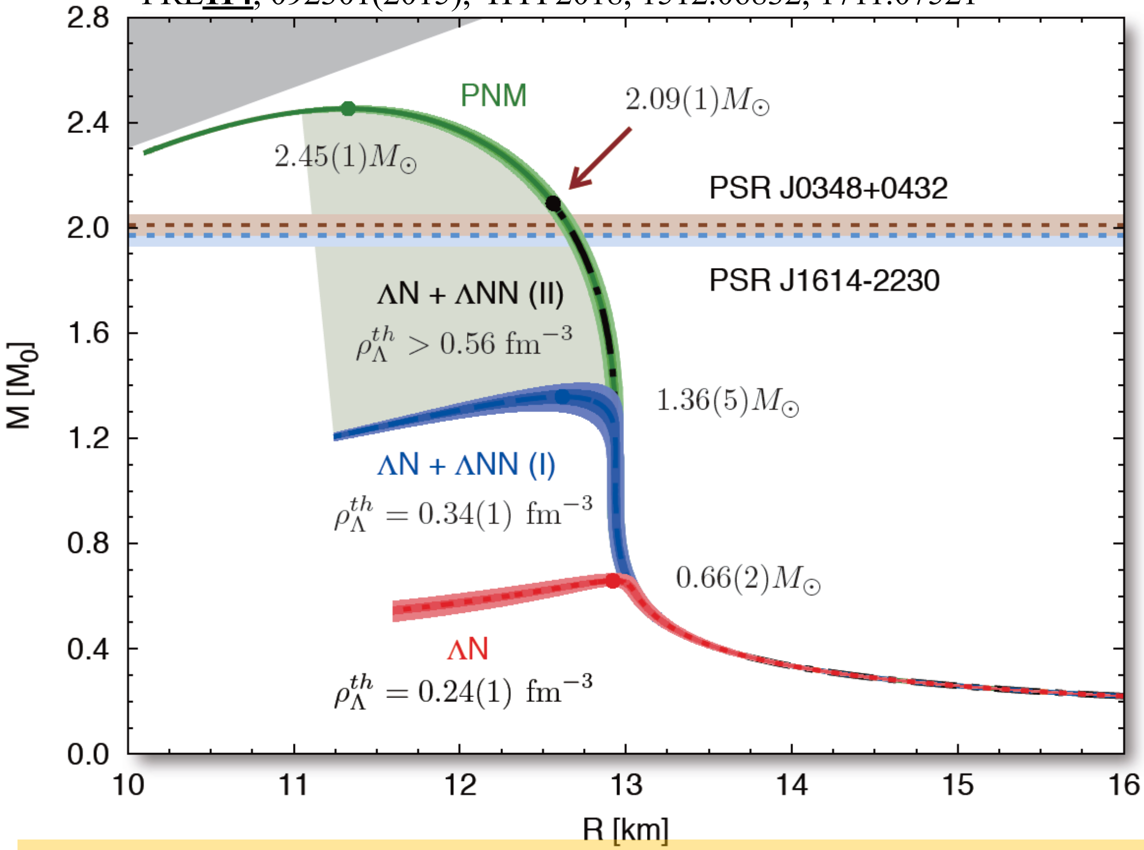
Debasish Mallick (NISER)

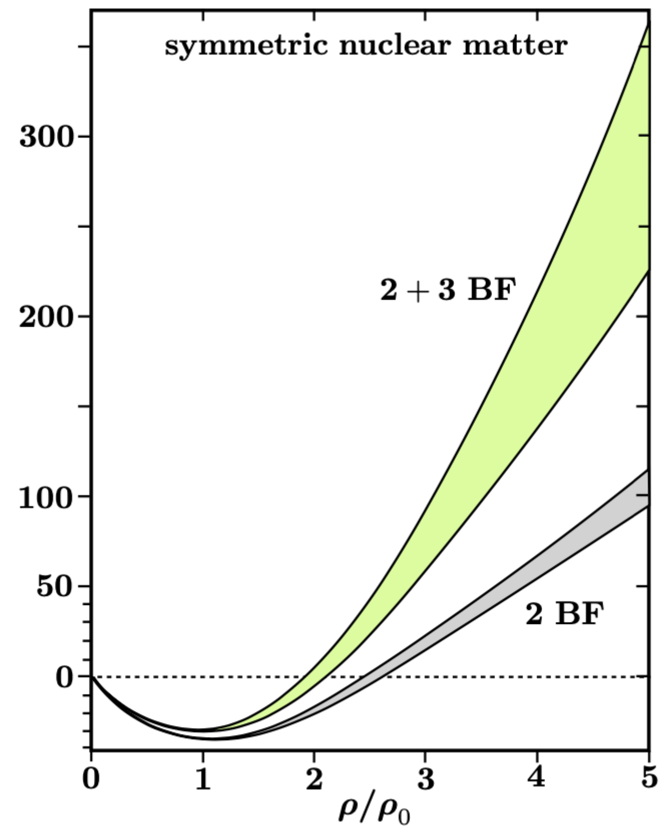
Strangeness and Hyper-Nuclei



Λ-N Interaction and Compact Star

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

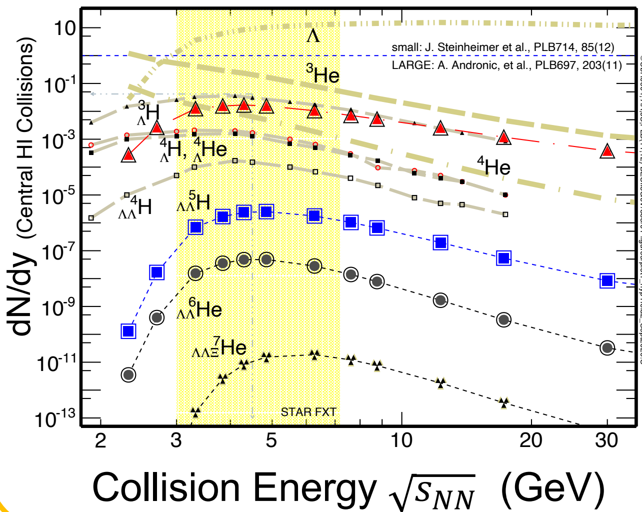




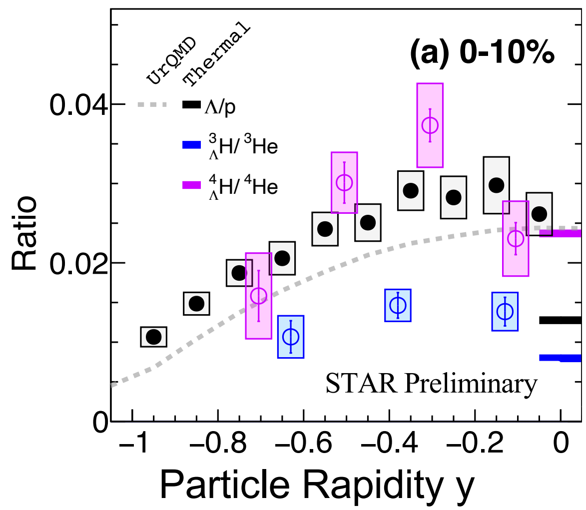
Y-N interaction: key to understand the inner structure of compact stars

Baryon Interactions and Hyper-Nuclei

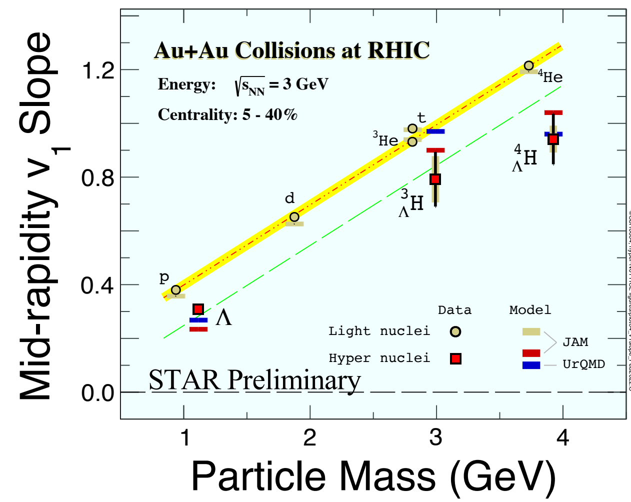
Yields



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: PRL**128** 202301(2022)
2211.16981(PRL)

Outline

1) **Introduction**

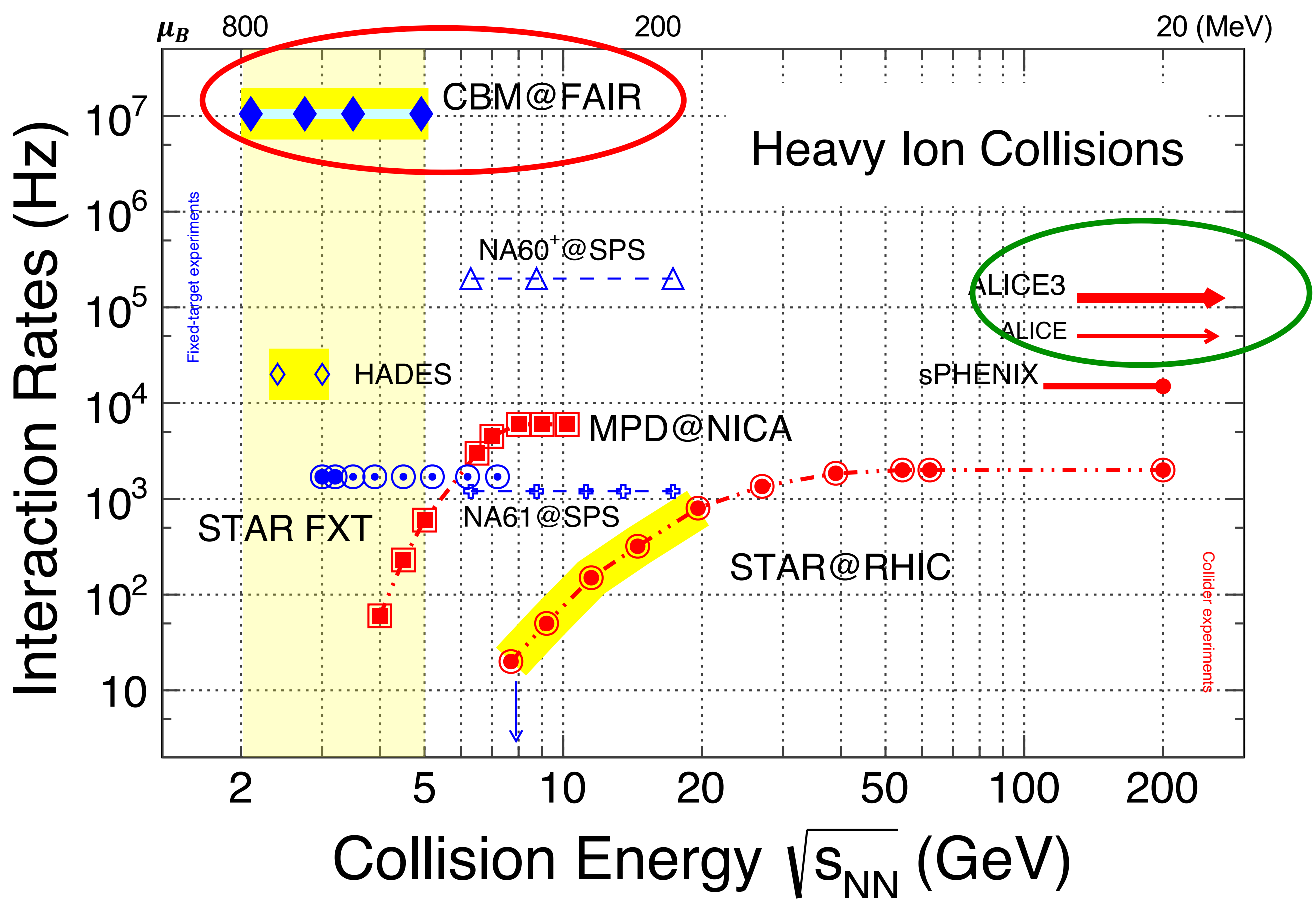
2) **Selected Recent Results**
   - Collectivity
   - Criticality
   - Strangeness production: hyper-nuclei

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

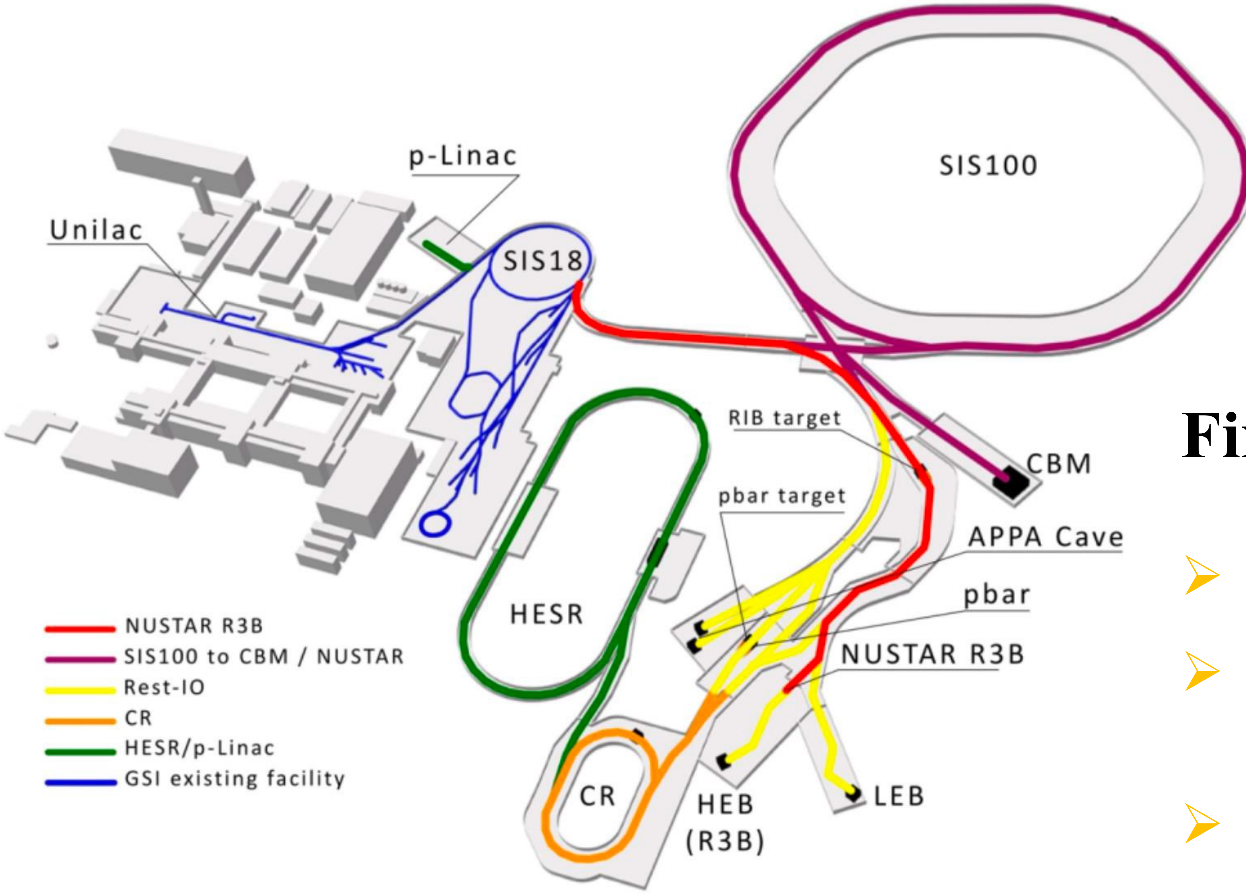
Future High Rates Experiments

- **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



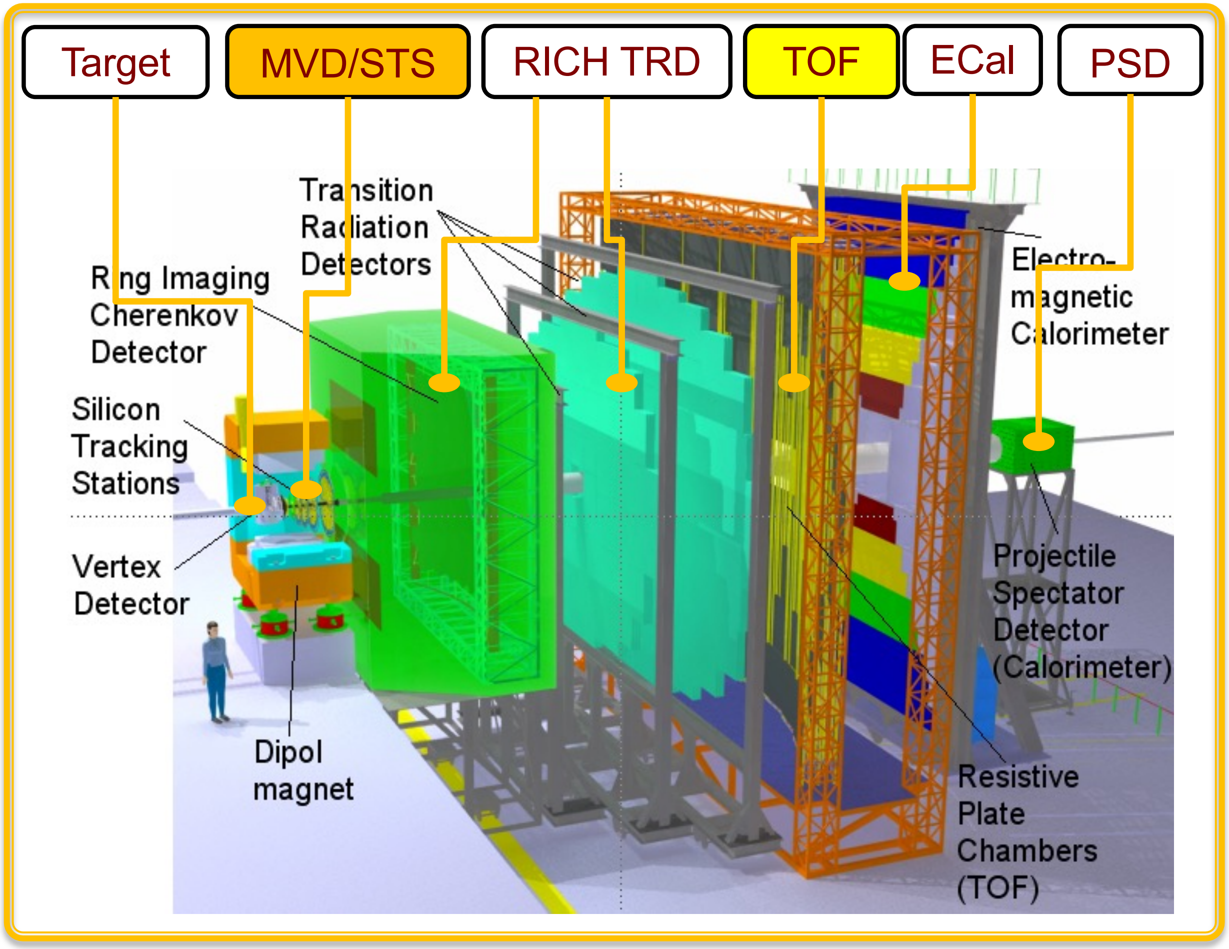
CBM Experiment at FAIR



Fixed-target experiment:

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

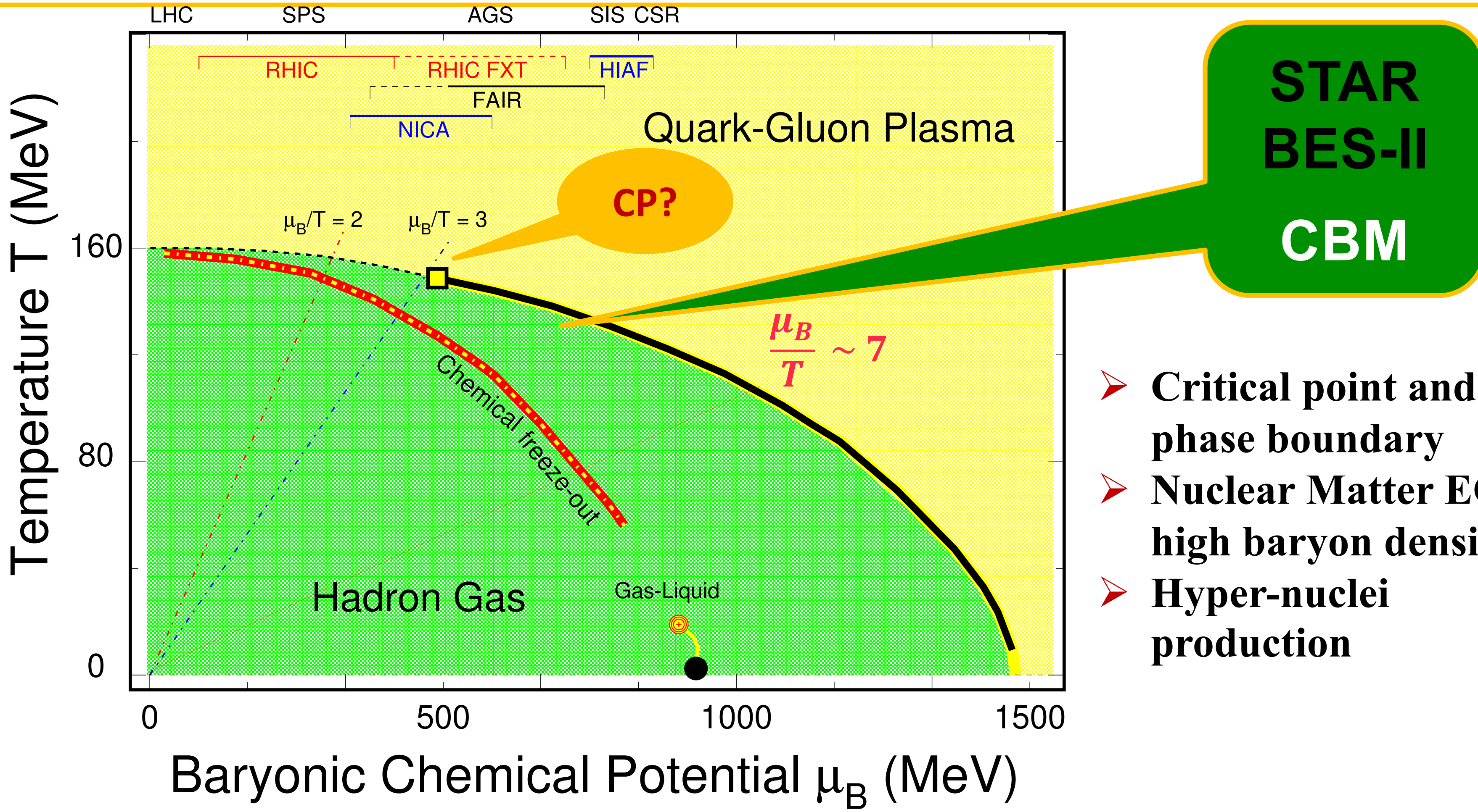
CBM Experiment at FAIR



- 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) and hyper-nuclei

Beam on target in 2028

Summary



- **Critical point and phase boundary**
- **Nuclear Matter EOS at high baryon density**
- **Hyper-nuclei production**

Acknowledgements:

P. Braun-Munzinger, X. Dong, S. Esumi, V. Koch, XF. Luo, B. Mohanty, T. Nonaka, A. Rustamov, K. Redlich, M. Stephanov, J. Stachel, J. Stroth, V. Vovchenko // BLUE: Theory // **RED**: Exp. //

Humboldt Foundation

Thank you for your attention!