Study QCD Phase Structure in High-Energy Nuclear Collisions

- Selected results from RHIC beam energy scan program

Nu Xu

LBL

STAR: PRL**126**, 092301(2021); arXiv: 2101.12413

Outline

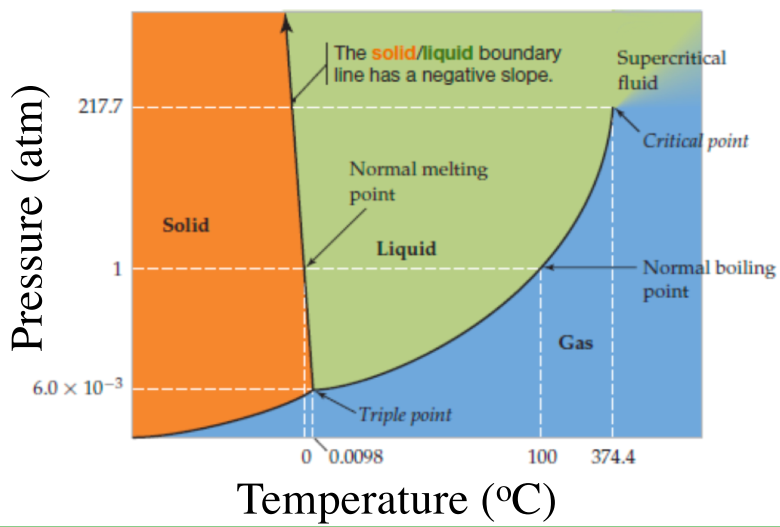
1) Introduction
2) STAR Experiment at RHIC
3) Selected Results from BES-I
   - Collectivity
   - Chirality
   - Criticality

   Emergent properties of Strong Interaction (QCD)
4) BES-II and Beyond

Phase Structure of Strong Interactions

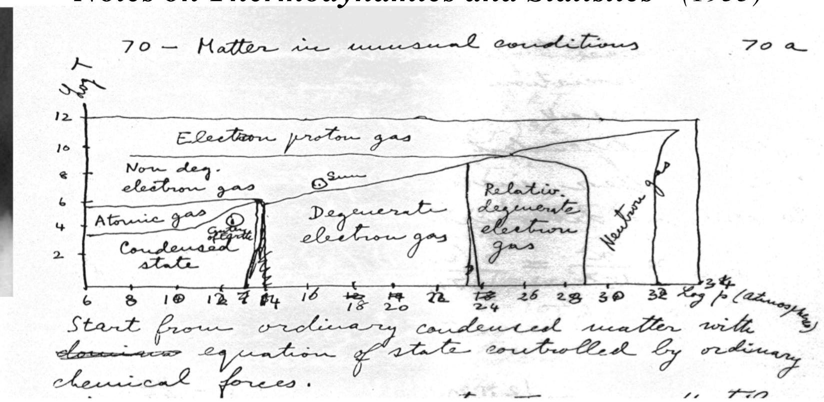
For given degrees of freedom, phase diagram tells us how matter (re)organized itself under external conditions.

Phase Diagram of Water: QED at Work



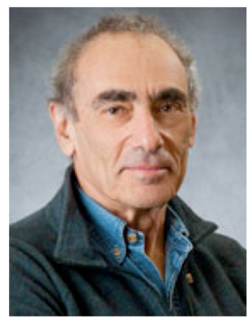
"Notes on Thermodynamics and Statistics" (1953)

E. Fermi

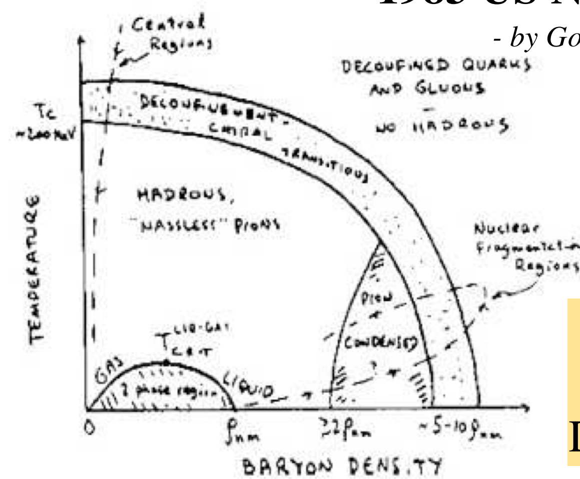


1983 US NP LRP

- by Gordon Baym



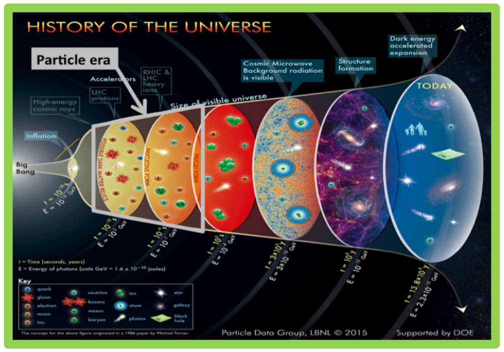
Gordon Baym



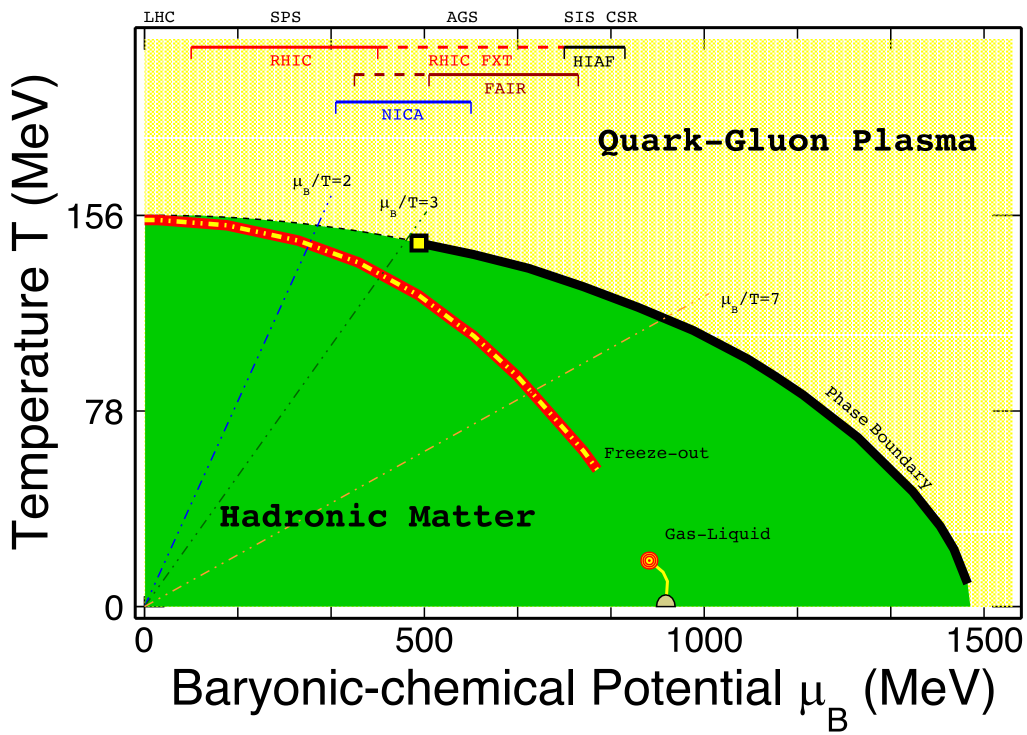
QCD Phase Diagram

High-Energy Nuclear Collisions and QCD Phase Diagram

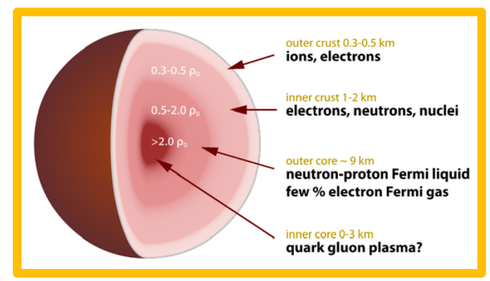
LHC | RHIC BES | FAIR, NICA, …



High temperature:
Early Universe evolution



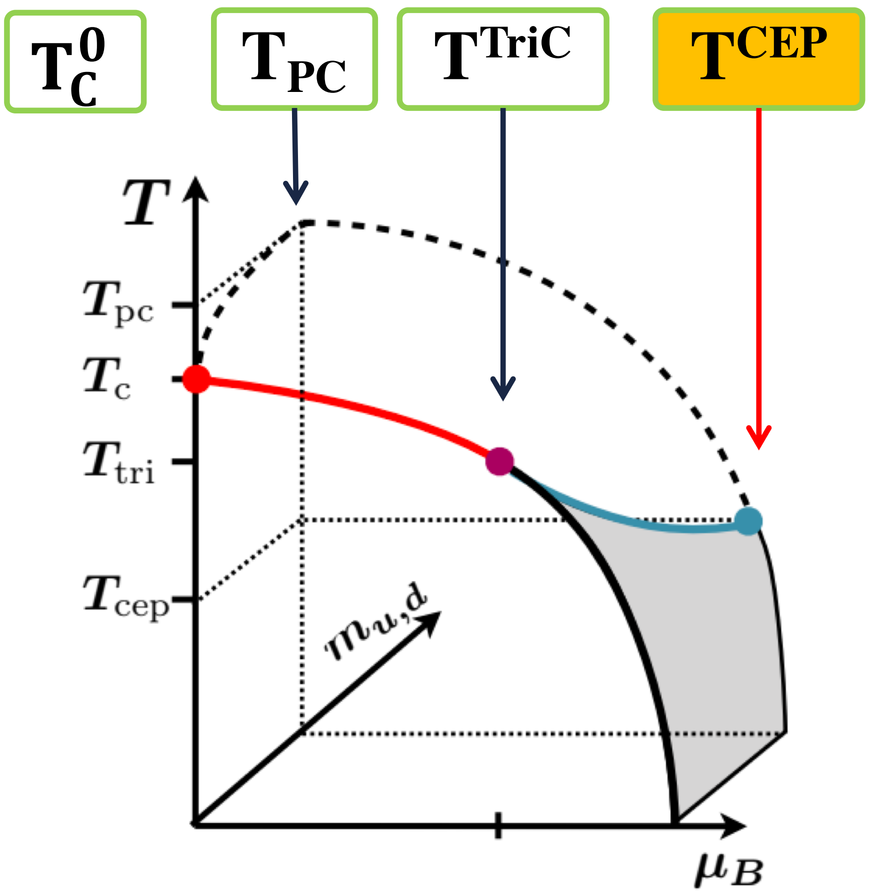
High baryon density:
Inner structure of
compact stars



1) At $\mu_B = 0$, smooth crossover (LGT);

2) Large μ_B, 1st order phase transition → **QCD critical point**

LGT Calculations: QCD Phase Structure



H.T. Ding, F. Karsch *et al.*, 2020

1) QCD transition temperature:
$\mathbf{T_{PC} = 156.5 \pm 1.5\ MeV}$

2) Chiral crossover line

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

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

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

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

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

RHIC sQGP paper:
NPA757, (2005) 3306

https://www.bnl.gov/riken/QCDRhic/default.asp

Organizers: T. Ludlam, H. Ritter, G. Stephans, M. Gazdzicki, B. Friman, F. Videbaek, T. Satogata, K. Rajagopal, L. McLerran

Motivation & Plans

The workshop is motivated by a growing body of theoretical and experimental evidence that the critical point on the QCD phase diagram, if it exists, should appear on the QGP transition boundary at baryo-chemical potential ~100 - 500 MeV, corresponding to heavy ion collisions with c.m. energy in the range 5 - 50 GeV/u. Identifying and pinning down this point with experimental measurements would be a major step forward in the world-wide effort to determine the properties of QCD at high temperature and density.

Thursday, March 9

8:30 – 9:00	*Registration*	
Chair: T. Ludlam		
9:00 – 9:10	Welcome	T. Ludlam (10)
9:10 – 9:50	Introduction and overview	K. Rajagopal (35+5)

Friday, March 10

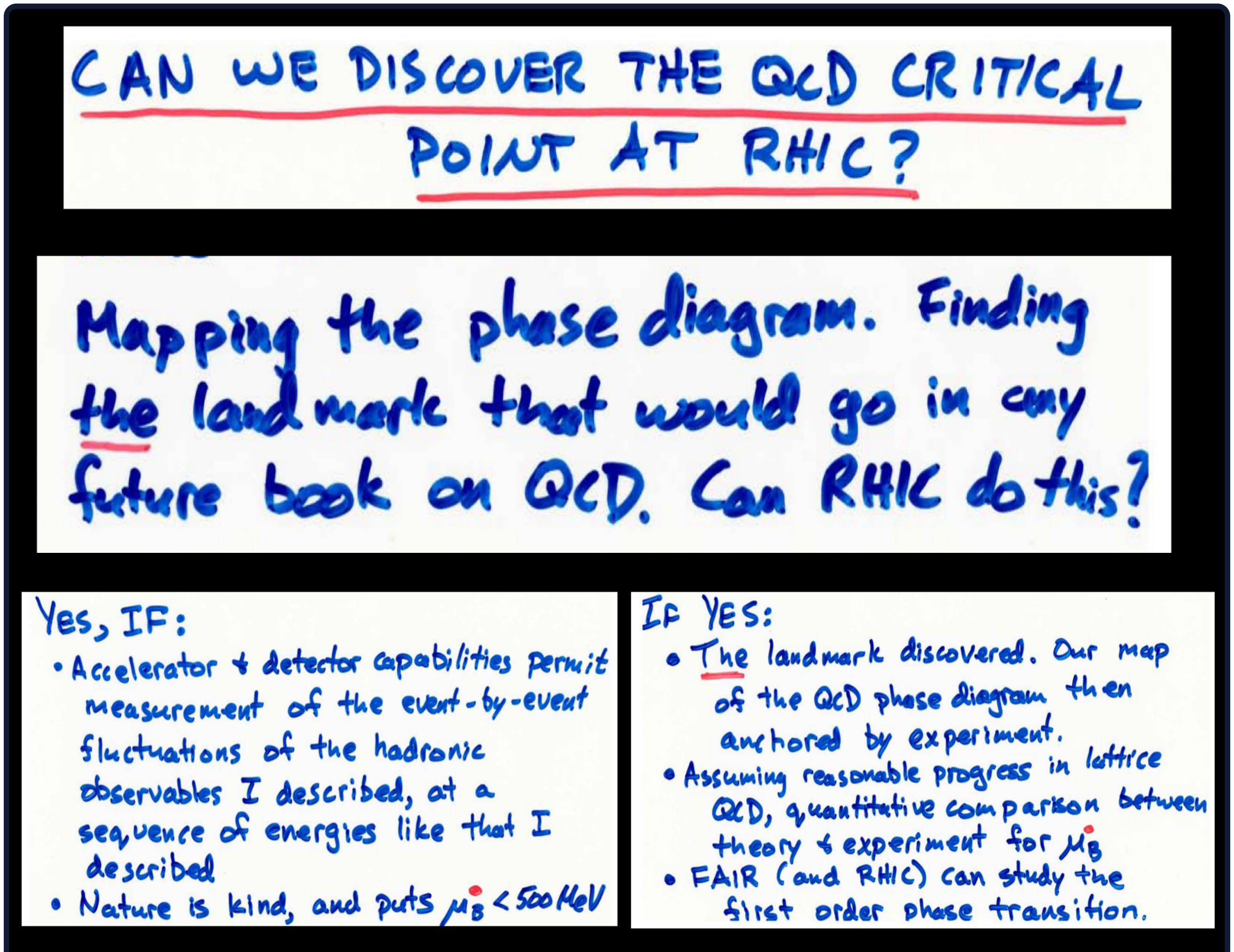
Chair: F. Videbaek		
8:30 – 9:30	Low energy operation of RHIC: AGS low energy extraction performance	N. Tsoupas (15+5)
	Luminosity monitoring issues	A. Drees (15+5)
	Low energy electron cooling	A. Fedotov (15+5)

Motivation & Plans

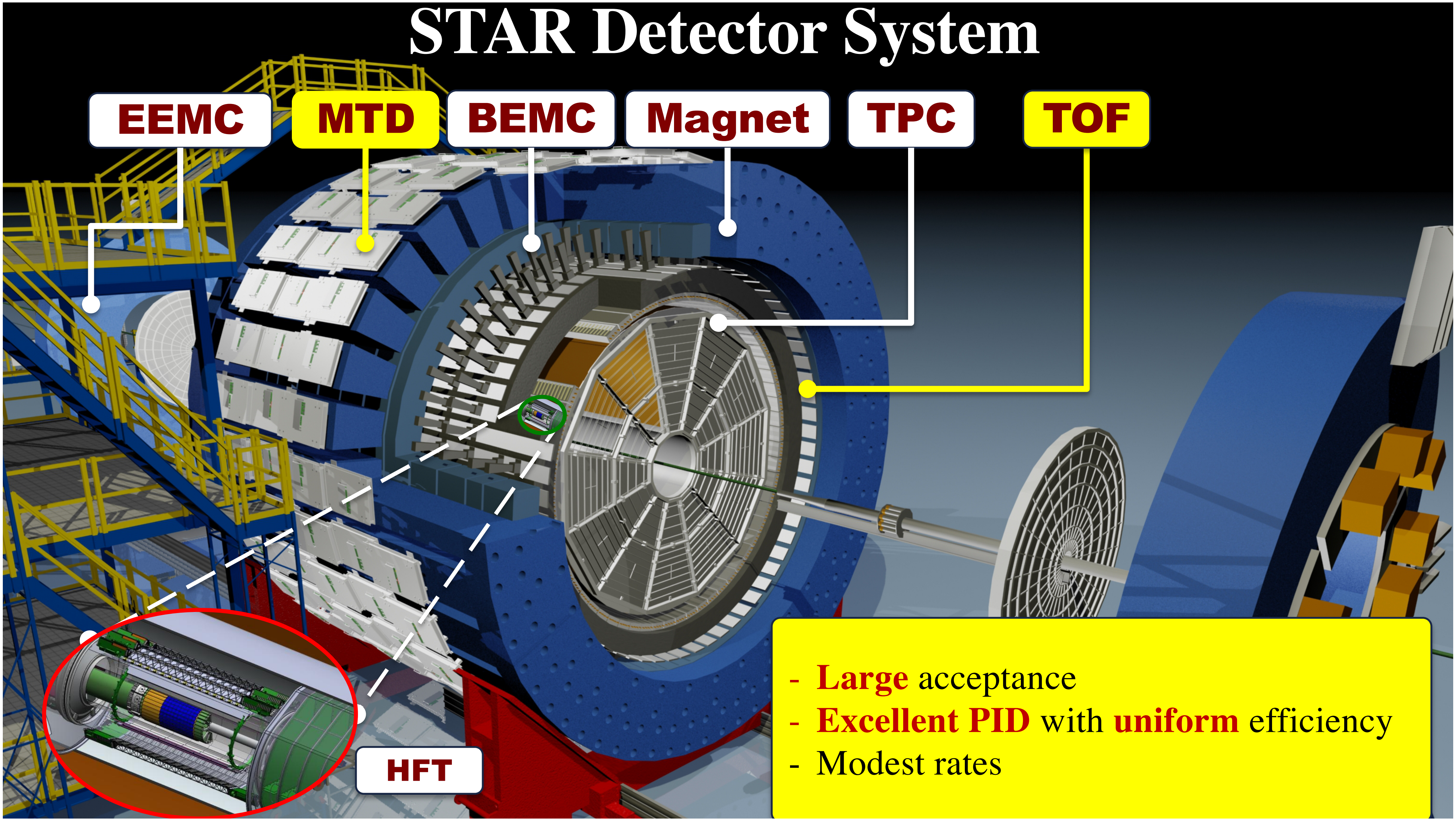
The workshop is motivated by a growing body of theoretical and experimental evidence that the critical point on the QCD phase diagram, if it exists, should appear on the QGP transition boundary at baryo-chemical potential ~100 - 500 MeV, corresponding to heavy ion collisions with c.m. energy in the range 5 - 50 GeV/u. Identifying and pinning down this point with experimental measurements would be a major step forward in the world-wide effort to determine the properties of QCD at high temperature and density.

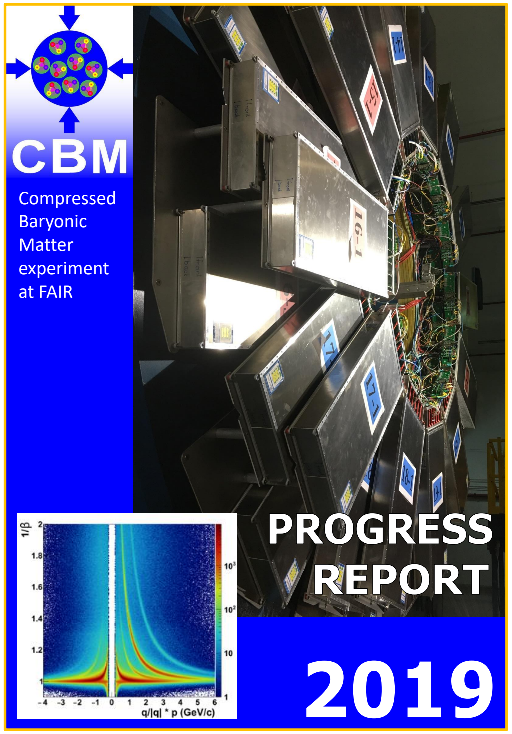
https://www.bnl.gov/riken/QCDRhic/default.asp

K. Rajagopal, https://www.bnl.gov/riken/QCDRhic/linked_files/talks/RHICQCD_rajagopal.pdf

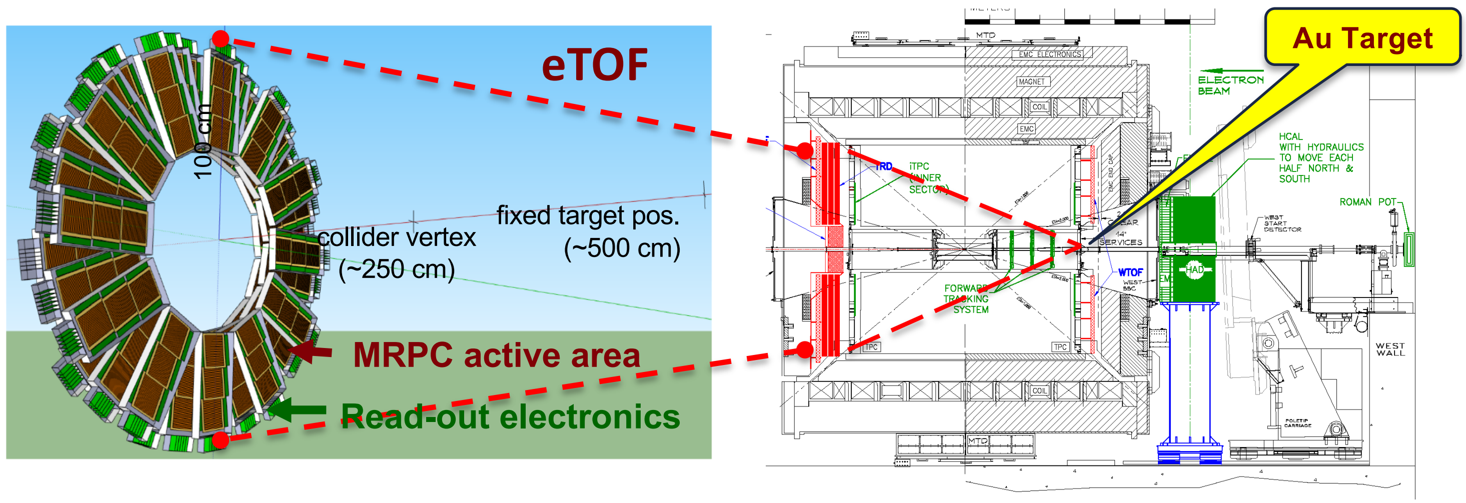


- **Collider upgrade;**
- **Detector upgrades;**
- **Theory efforts**


STAR Detector System
EEMC
MTD
BEMC
Magnet
TPC
TOF
HFT
- Large acceptance
- Excellent PID with uniform efficiency
- Modest rates



CBM Phase-0 Exp: eTOF at STAR

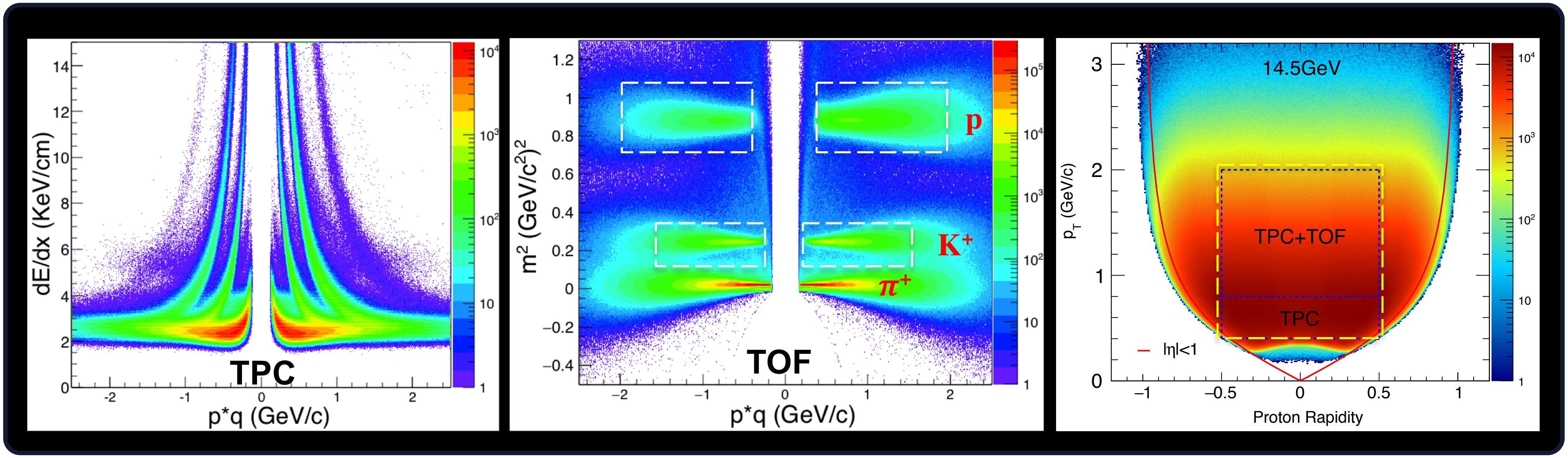


Install, commission and use 10% of the CBM TOF modules, including the read-out chains at STAR, started to work in 2019

CBM participating in RHIC Beam Energy BES-II in 2019-2021:

- Complementary to part of CBM physics program: Phase-0 CBM
  $\sqrt{s_{NN}} = 3 - 7.2$ GeV ($750 \geq \mu_B \geq 420$ MeV), especially for the study of strange hadrons, hyper-nuclei production and baryon-correlations

Particle Identification with TOF



	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, $\lvert\eta\rvert < 1.0$

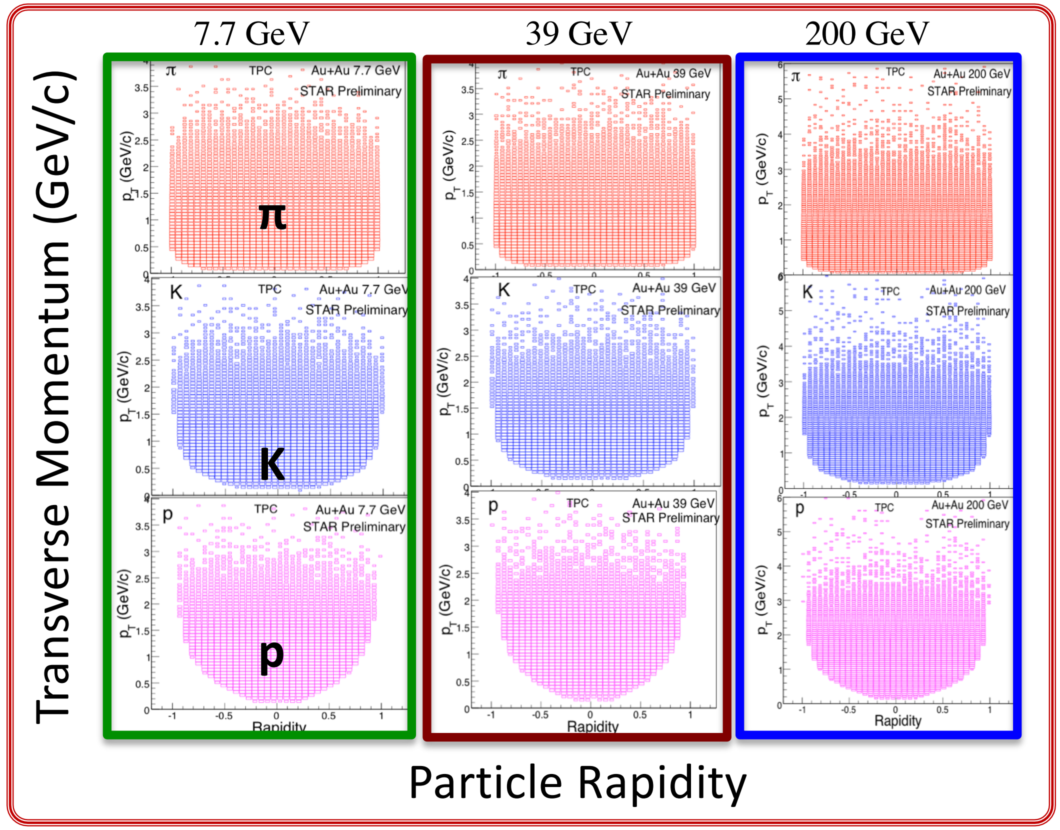
Data-sets for BES-I Program (2010 – 2017)

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year	*μ_B (MeV)	*T_{ch} (MeV)
200	238	2010	25	166
62.4	46	2010	73	165
54.4	1200	2017	83	165
39	86	2010	112	164
27	30	2011	156	162
19.6	15	2011	206	160
14.5	13	2014	264	156
11.5	7	2010	315	152
7.7	4	2010	420	140

*(μ_B, T_{ch}) : J. Cleymans et al., PR**C73**, 034905(2006)

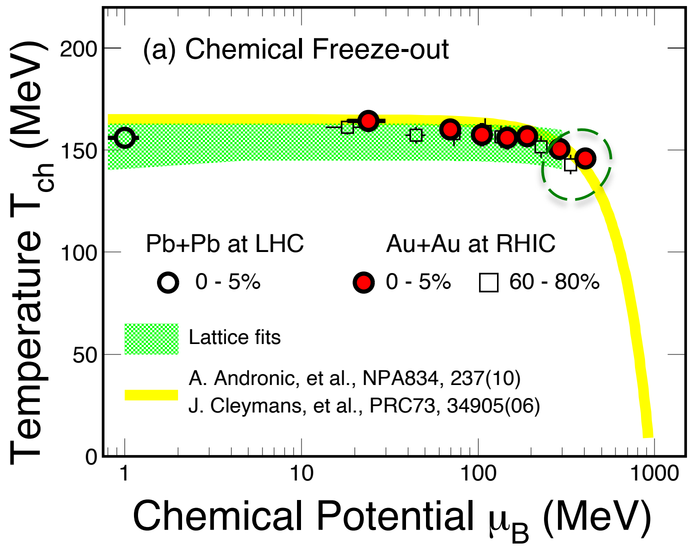
STAR, arXiv:1007.2613

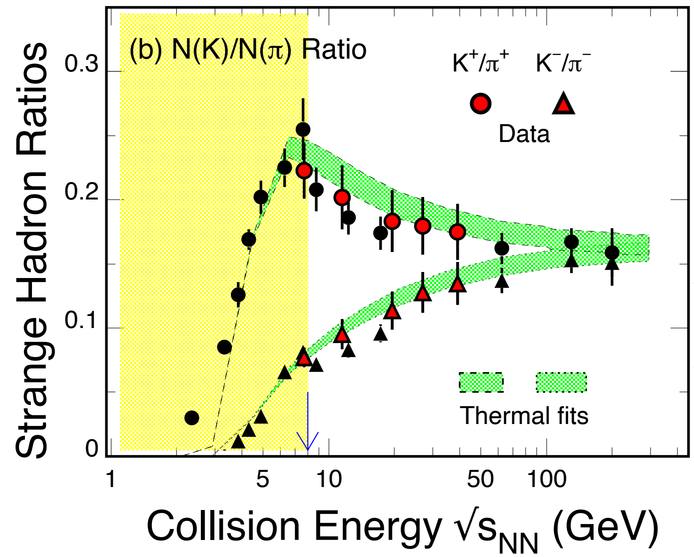
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0493,/sn0598



1) Largest data sets versus collision energy
2) STAR: Large and homogeneous acceptance, excellent particle identification capabilities. **Especially important for fluctuation analysis**

Bulk Properties at Freeze-out



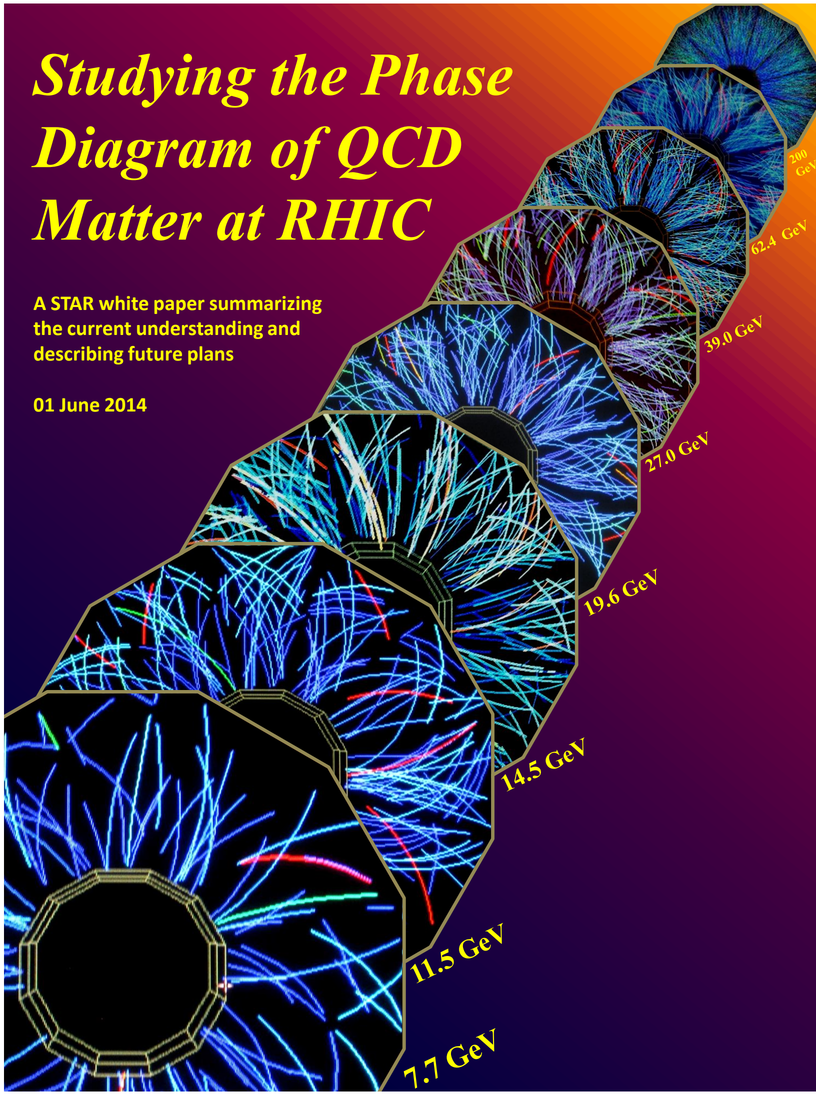


Chemical Freeze-out: (GCE)

- Weak temperature dependence
- Centrality dependence μ_B!
- LGT: **CP about $\mu_B \geq 500$ MeV?**

- The **K^+/π** ratio peaks at $\sqrt{s_{NN}} \sim 8$ GeV where model also predicted the peak of baryon density
- **HBDR**: ($\sqrt{s_{NN}} < 8$ GeV, $\mu_B \geq 420$ MeV)

- ALICE: B.Abelev et al., PRL **109**, 252301(12); PR **C88**, 044910(13).
- STAR: J. Adams, et al., **NPA757**, 102(05); PR **C96**, 044904(17); X.L. Zhu, **NPA931,** c1098(14); L. Kumar, **NPA931**, c1114(14).
- J. Randrup and J. Cleymans, PR **C74**, 047901(06)



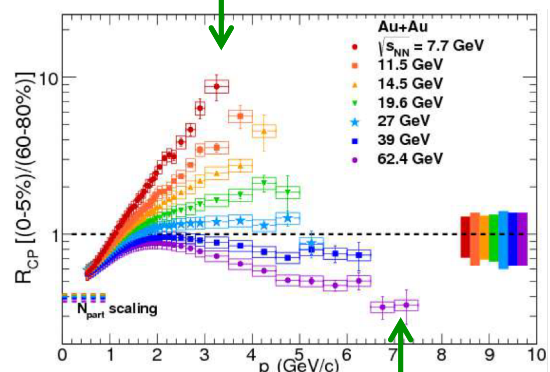
BES-II Whitepaper (2014)

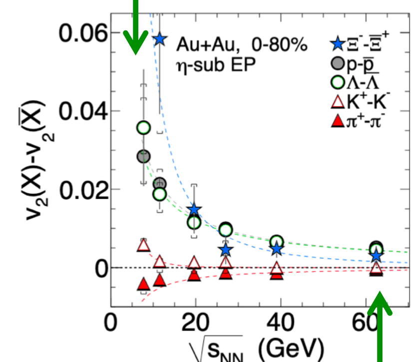
(3GeV) **7.7 GeV < $\sqrt{s_{NN}}$ < 19.6 GeV**

1) Accelerator upgrade → increase luminosity;
2) Detector upgrades → increase efficiency, improve precision and widen acceptance;
3) Main physics goal is to search for the illusive QCD critical point with Collectivity, Chirality and Criticality

7.7GeV: enhancement

PRL**110**, 142301(13), v_2
PRL**121**, 032301(18), R_{CP}





strong suppression due to QGP formation

Collectivity

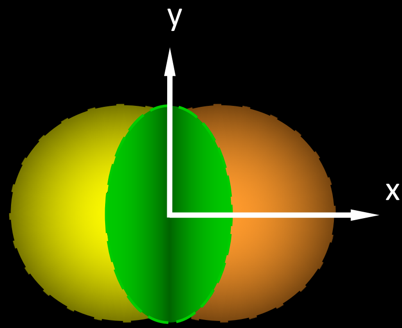
$\partial_\mu[(\varepsilon + p)u^\mu u^\nu - pg^{\mu\nu}] = 0$
$\partial_\mu[s\, u^\mu] = 0$

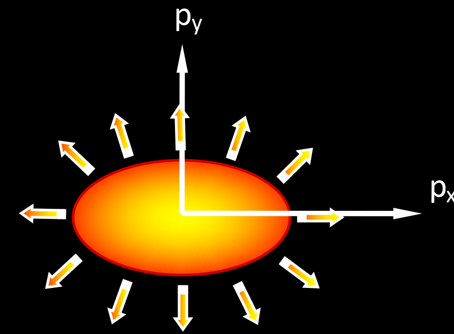
$$\frac{d^2N}{p_T dp_T d\varphi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T}\left\{1 + \sum_{n=1}^{\infty} 2v_n(p_T)cos[n(\varphi - \Psi_R)]\right\}$$

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

Anisotropy Parameter v_2

coordinate-space-anisotropy ➡ momentum-space-anisotropy

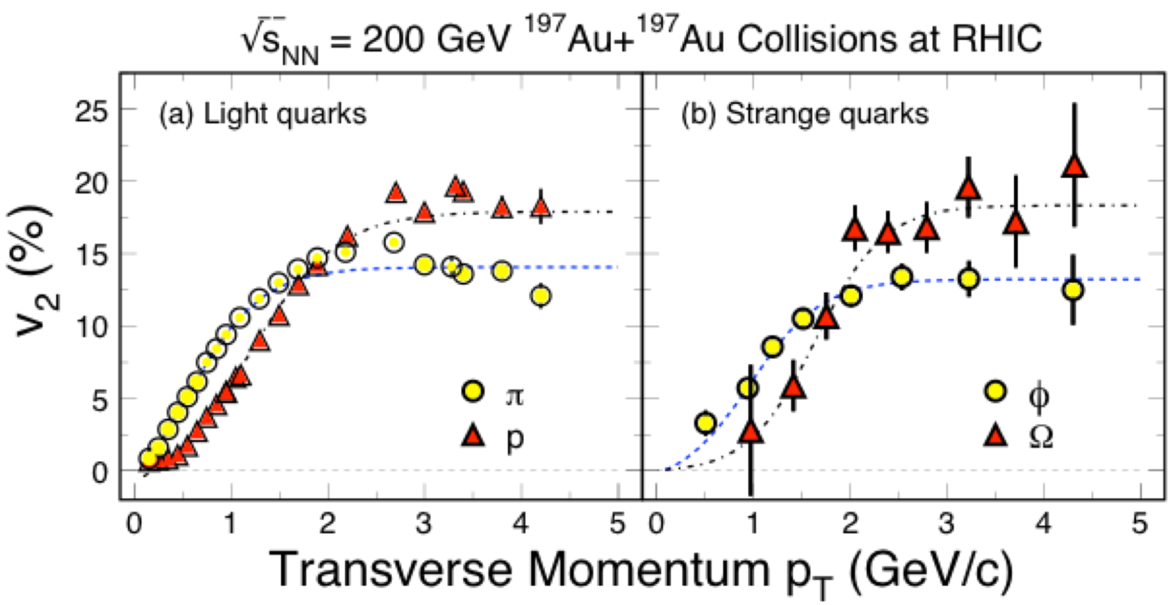




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle cos2\varphi \rangle, \qquad \varphi = tan^{-1}\left(\frac{p_y}{p_x}\right)$$

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

Partonic Collectivity at RHIC



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

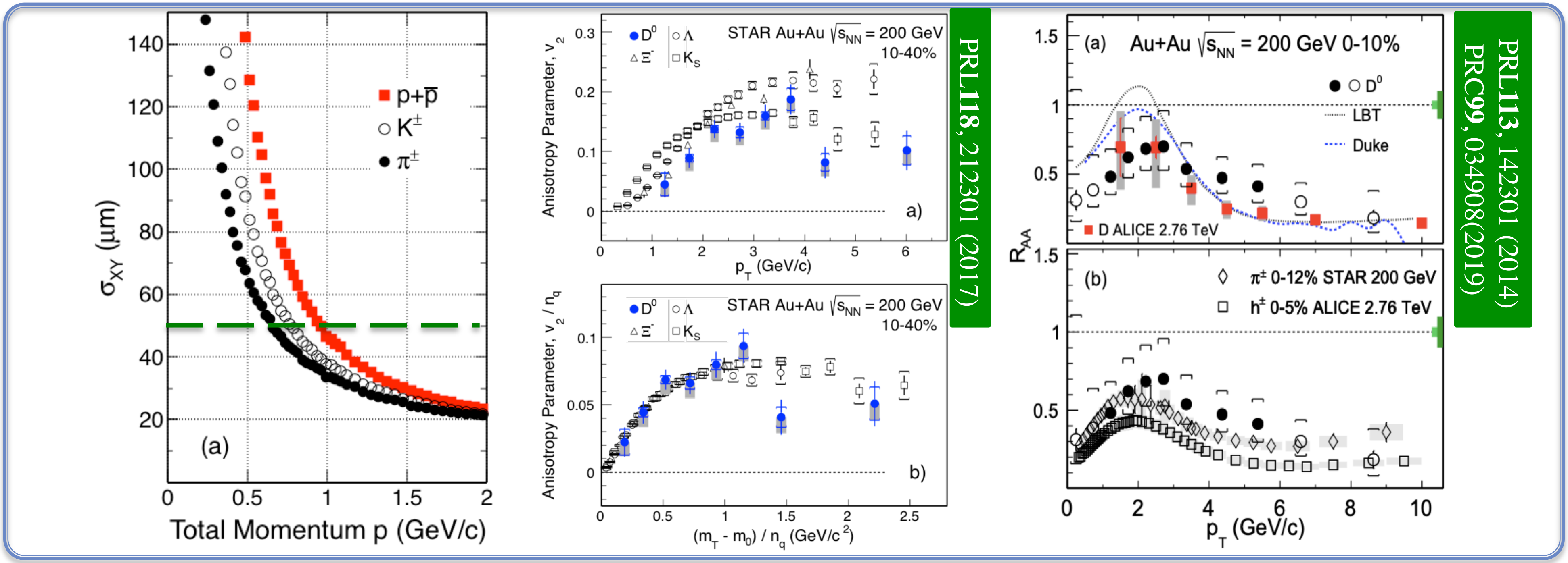
- ✓ Low p_T (≤ 2 GeV/c): hydrodynamic mass ordering
- ✓ High p_T (> 2 GeV/c): ***number of quarks scaling (NCQ)***

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

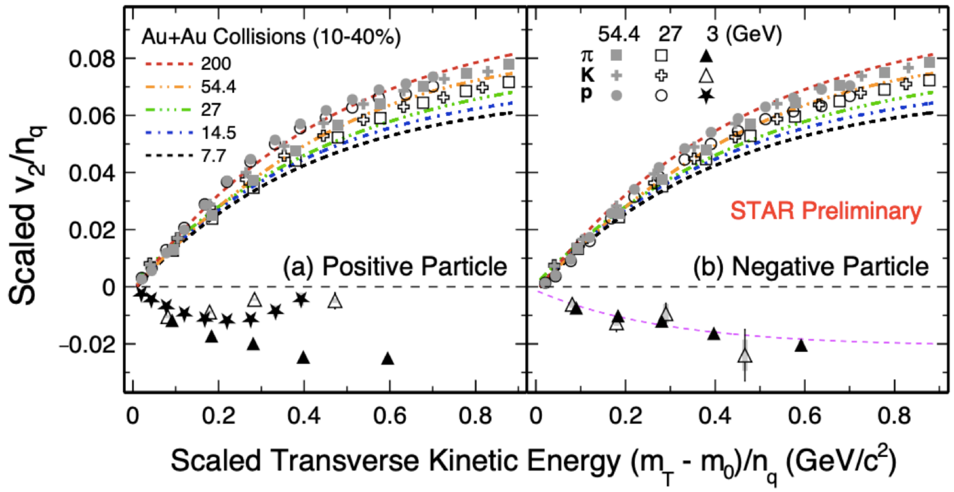


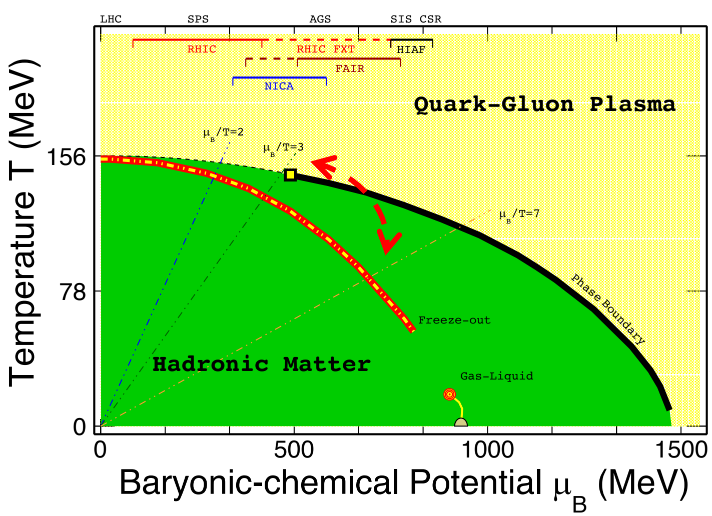
1) First application of MAPS technology in high energy collisions, excellent position resolution;
2) Measured $D^0, D^{\pm}, D_S^{\pm}, \Lambda_C$ and obtained two conclusions:
   - "These results suggest that charm quarks have achieved **local thermal equilibrium** with the medium created in such (200GeV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

$\sqrt{s_{NN}}$ = 3 GeV (FXT) Au+Au Collisions

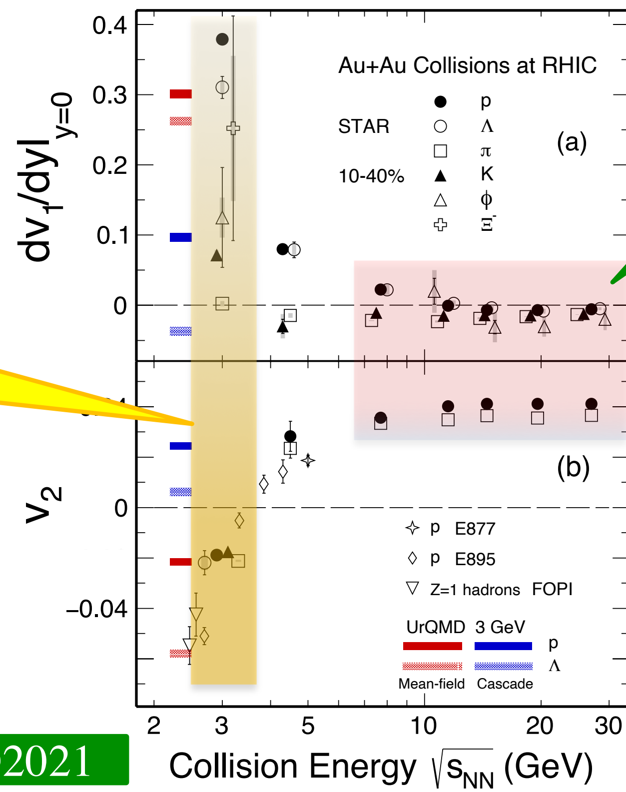
- At 3 GeV, NCQ scaling is absent, hadronic interactions dominant!
- Critical point searches focus in **3 - 20GeV** region





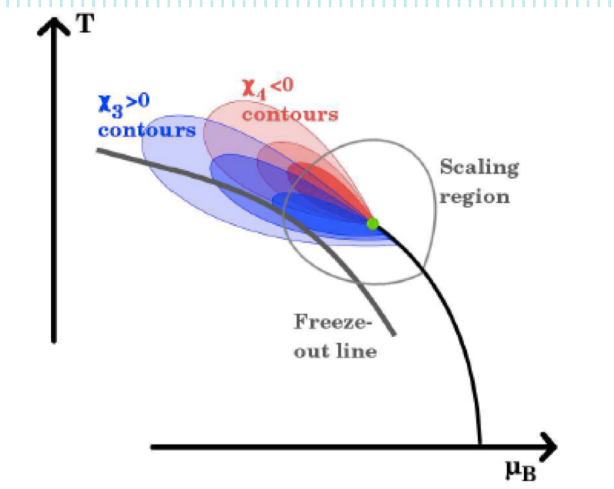
Hadronic Matter

QGP



STAR: CPOD2021

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

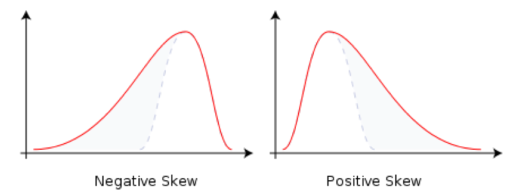
kurtosis: $\kappa = \langle (\delta N)^4 \rangle / \sigma^3 - 3 = C_4 / C_2^2$

Moments, cumulants and susceptibilities:

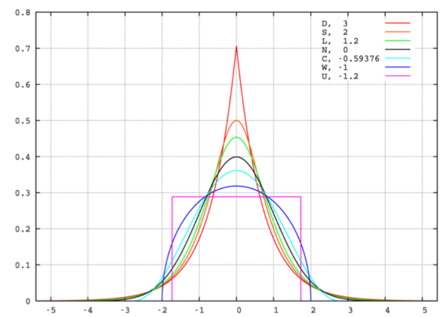
2^{nd} order: $\sigma^2/M \equiv C_2/C_1 = \chi_2/\chi_1$

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

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

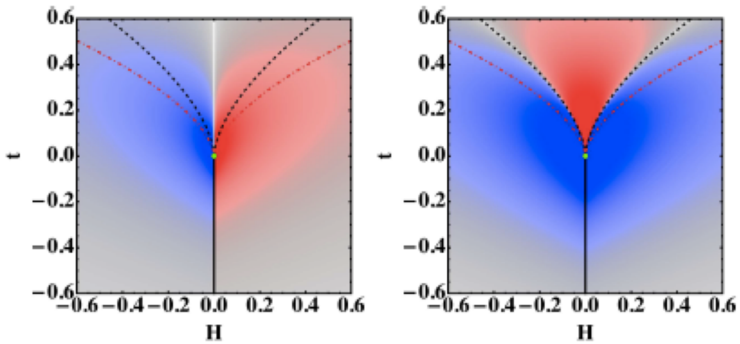


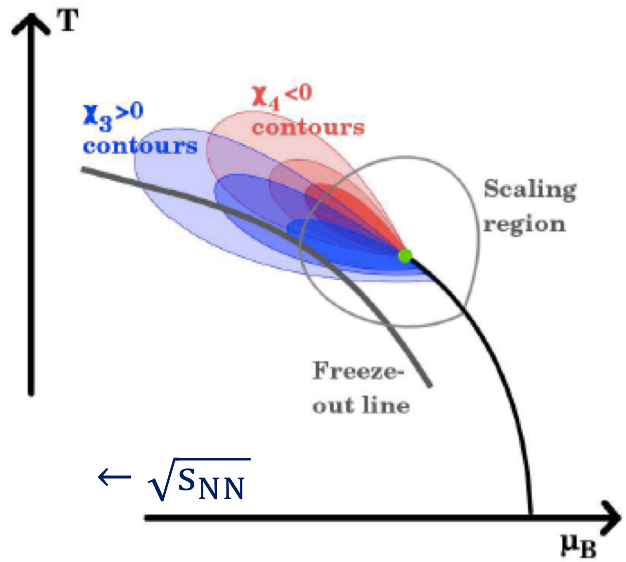
skewness (S)
→ asymmetry

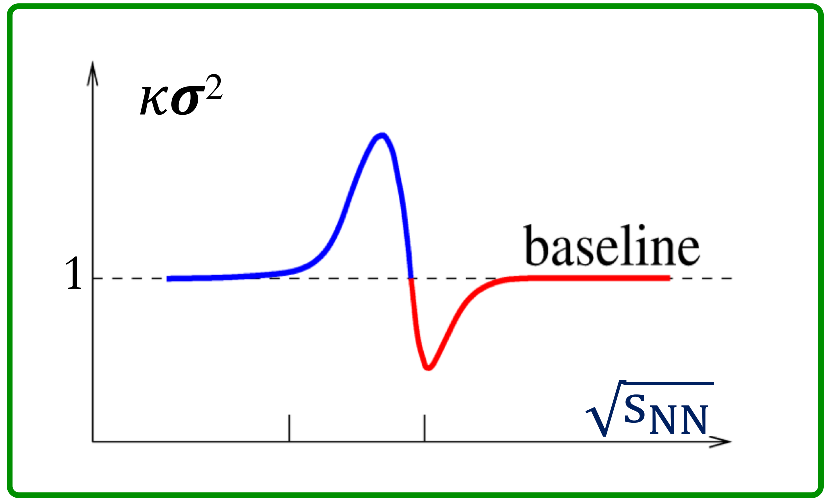


kurtosis (κ)
→ sharpness

Expectations for QCD Critical Point





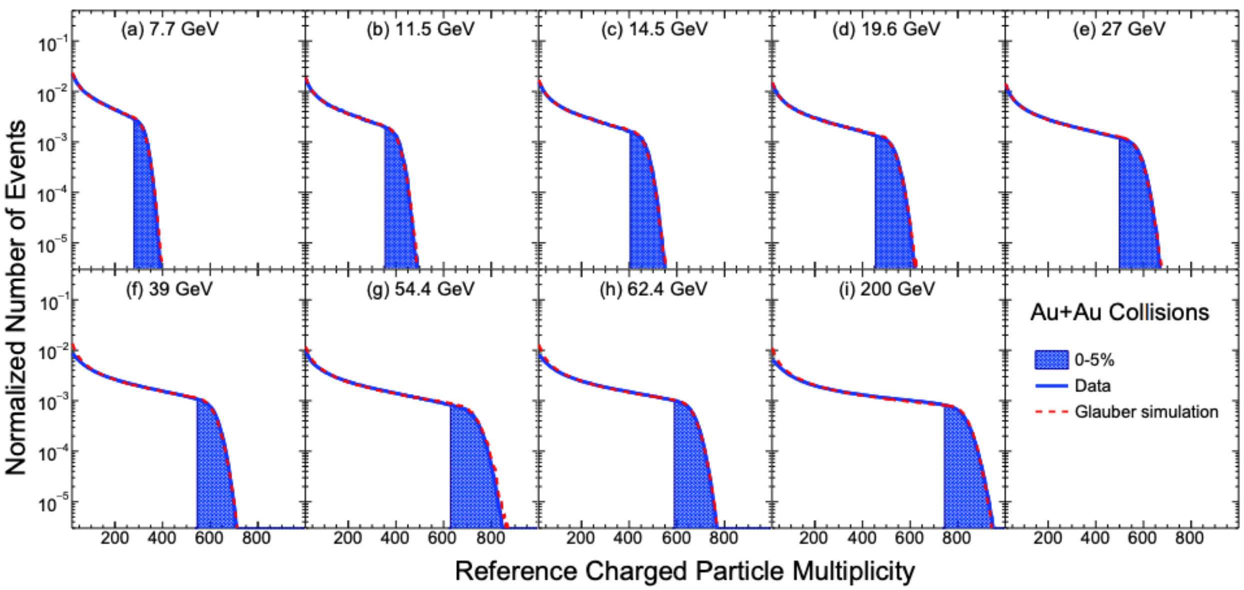


- Characteristic "Oscillating pattern" is expected for the QCD critical point but *the exact shape depends on the location of freeze-out with respect to the location of CP*
- Critical Region (CR)

- M. Stephanov, ***PRL107***, 052301(2011) - V. Skokov, Quark Matter 2012
- J.W. Chen, J. Deng, H. Kohyyama, Phys. Rev. **D93** (2016) 034037

Analysis Methods amd Corrections

STAR: 2101.12413



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

-

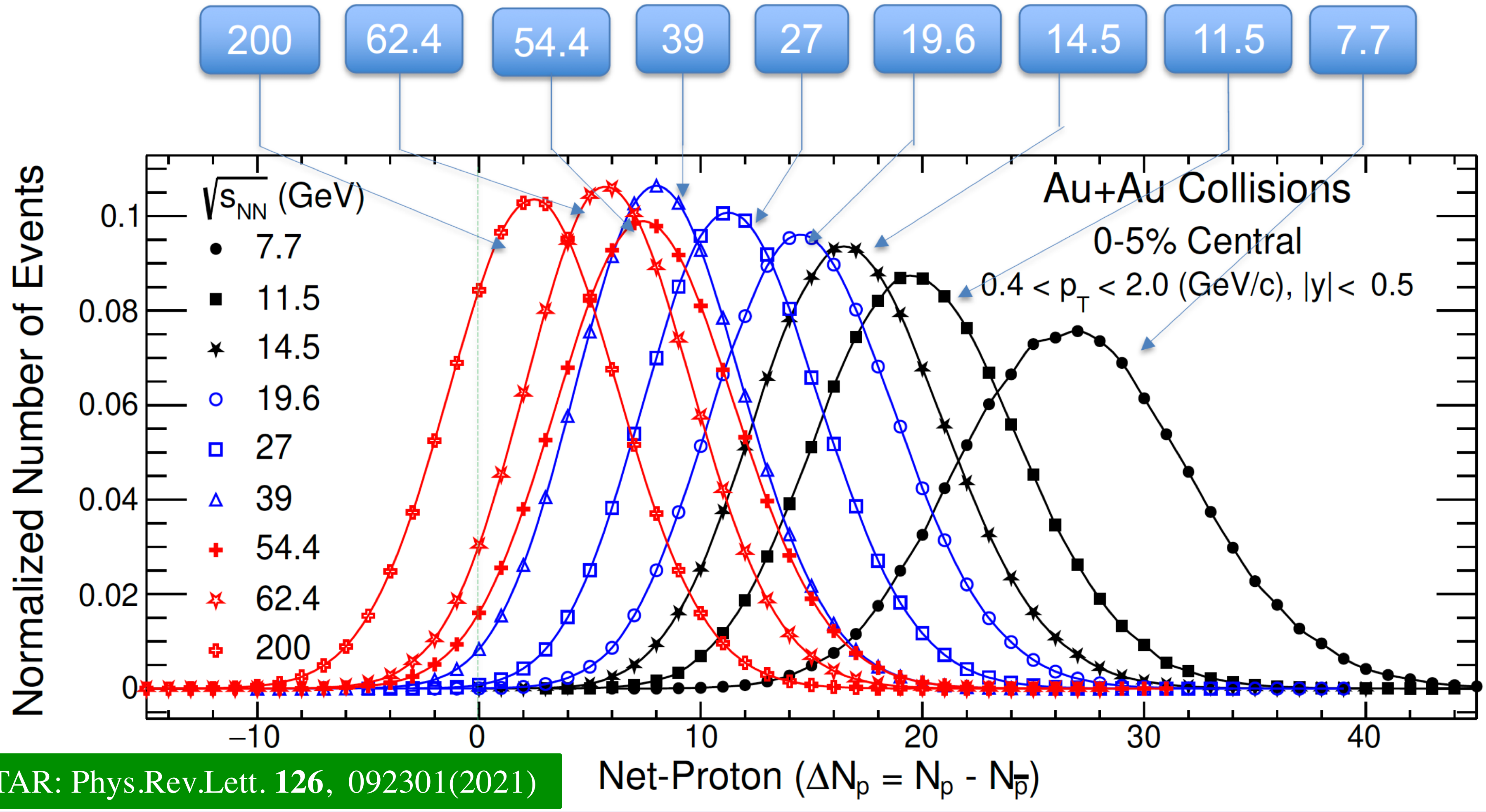
X.F. Luo, J.Phys.G Nucl.Part.Phys. **40,** 105104(13)

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., NIMA**984**, 164632(20)

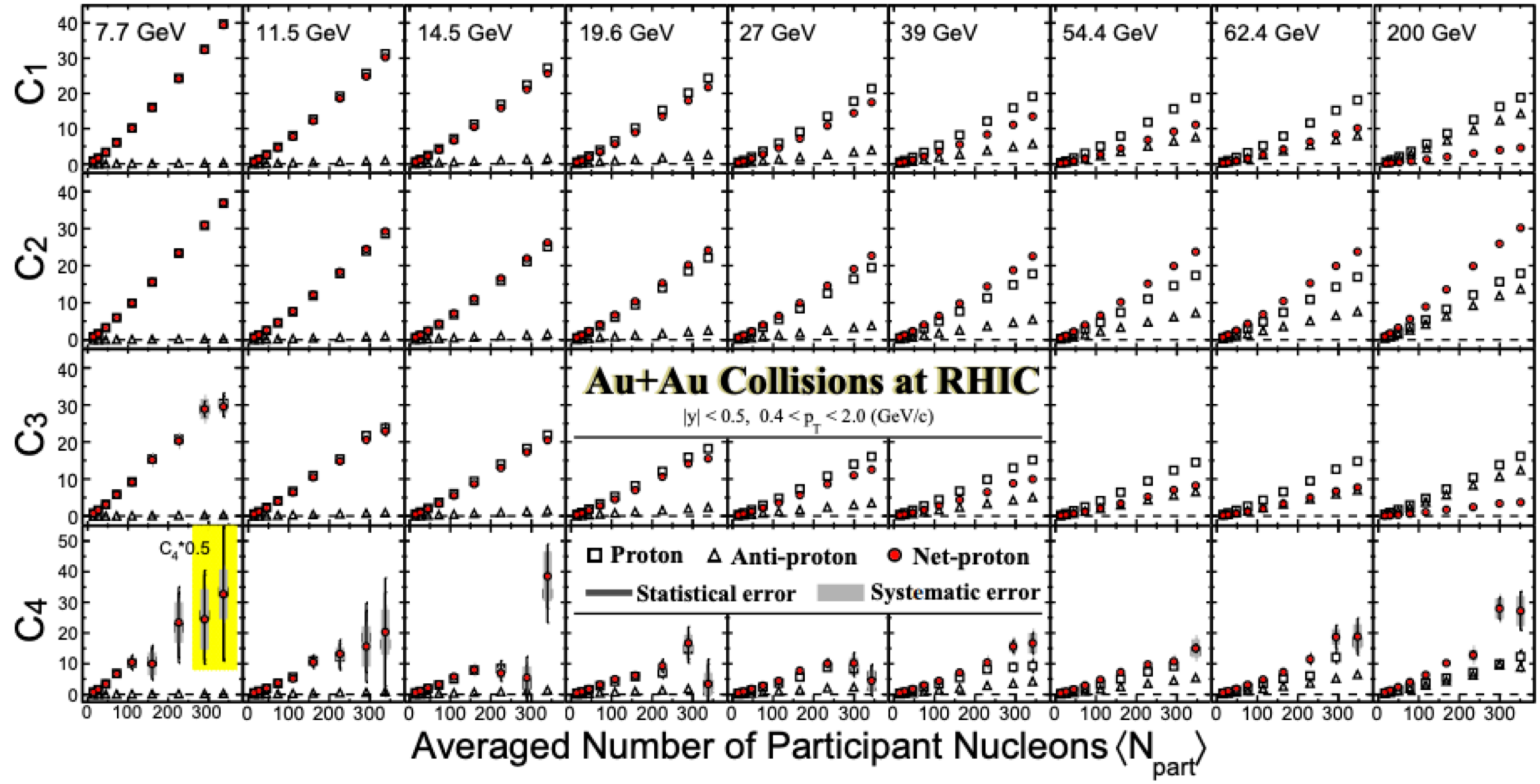
Event-by-Event Net-Proton Distributions (raw)



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

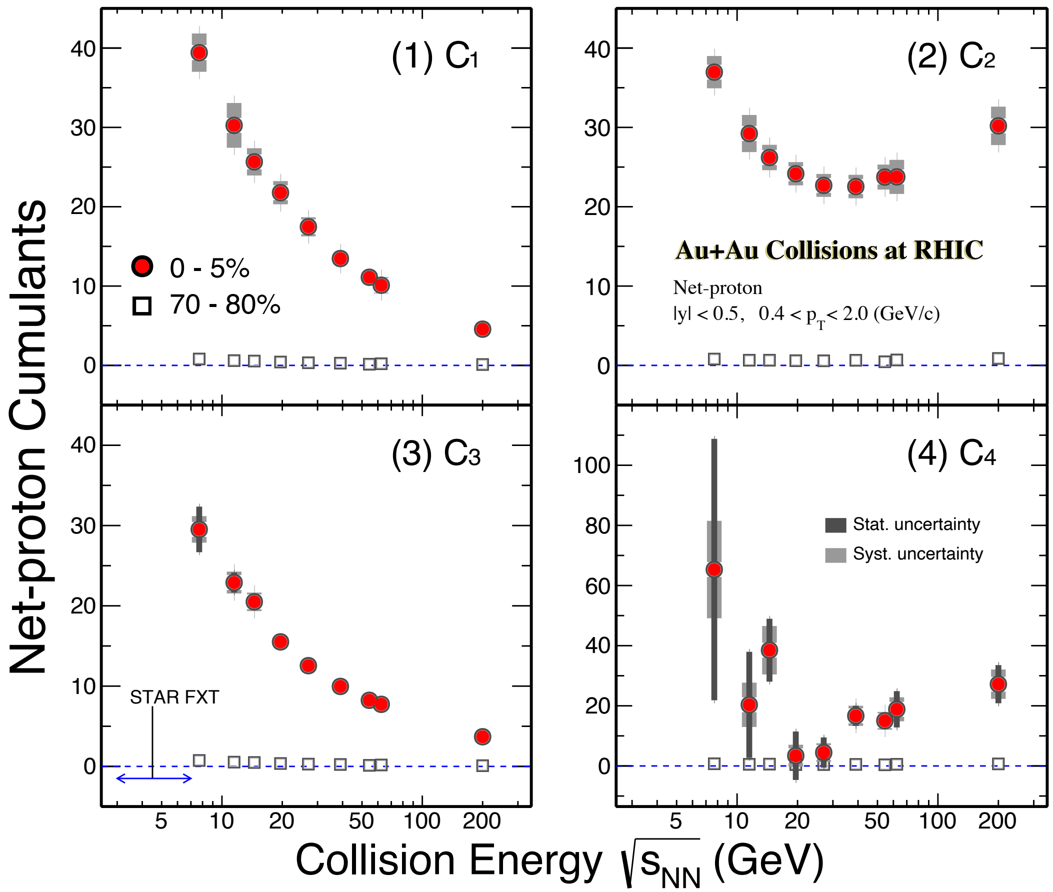
Net-proton Cumulants vs. Energy and Centrality

STAR: 2101.12413



Energy Dependence of Net-p Cumulants

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

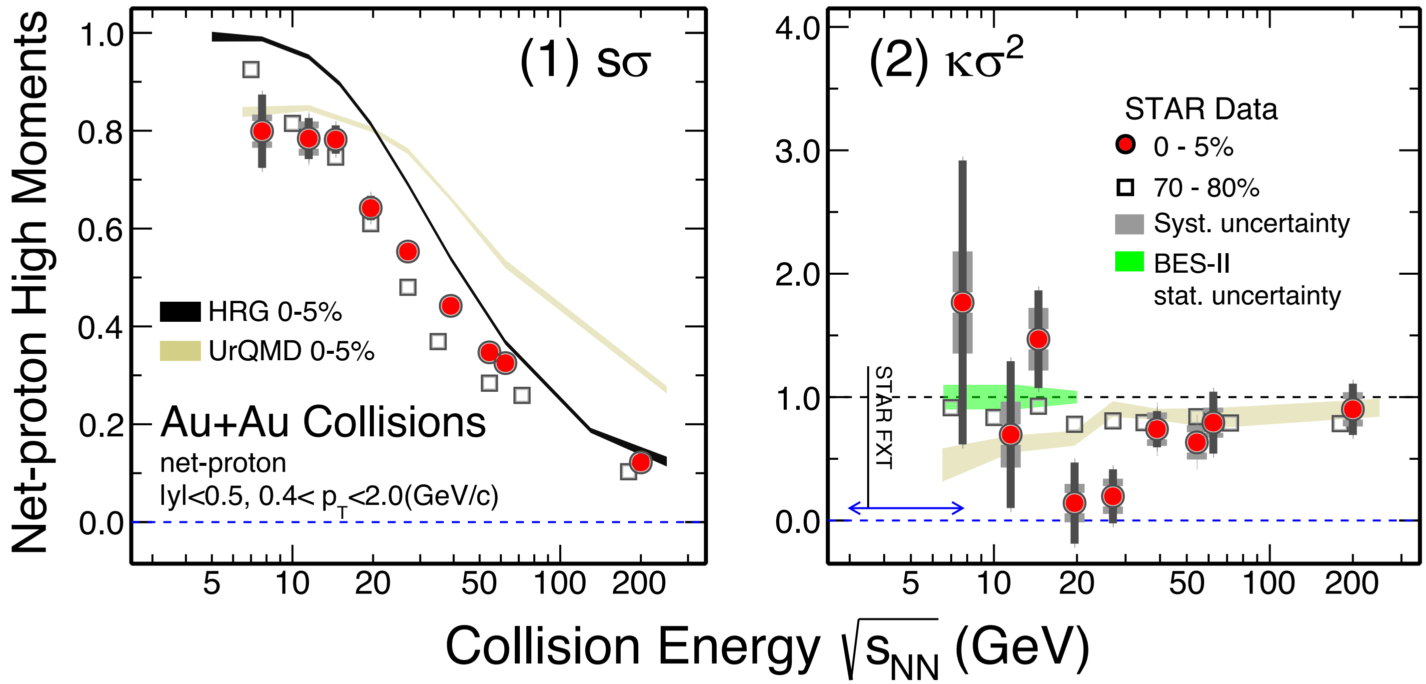


1) Cumulants of net-proton distributions, top 5% central and 70-80% peripheral collisions. Efficiency and acceptance correction applied

2) Value of mean increase as energy decreases, effect of baryon stopping

STAR: arXiv: 2001.02852

“Nonmonotonic Energy Dependence of Net-Proton Number Fluctuations”

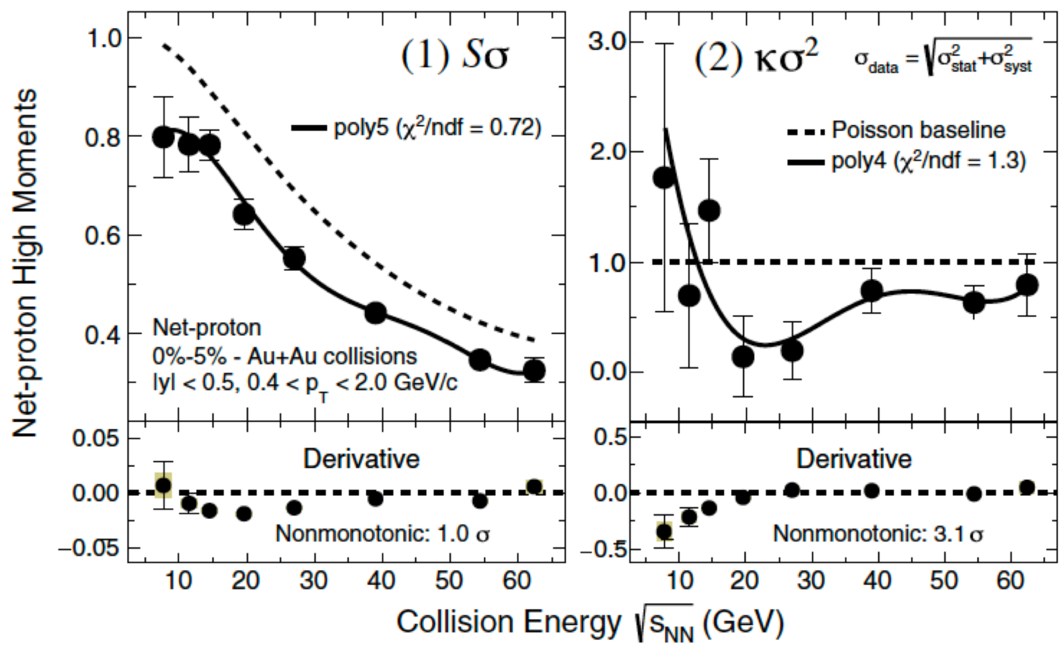


1) HRG and transport model predicted monotonical energy dependence: AMPT, JAM, UrQMD. Suppression at low energy due to conservation;

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

3) ‘**Attractive**’ of protons at the 7.7 GeV collisions? STAR: PRL**126**, 092301(21)

“Nonmonotonic Energy Dependence of Net-Proton Number Fluctuations”



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

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

Statistical Tests

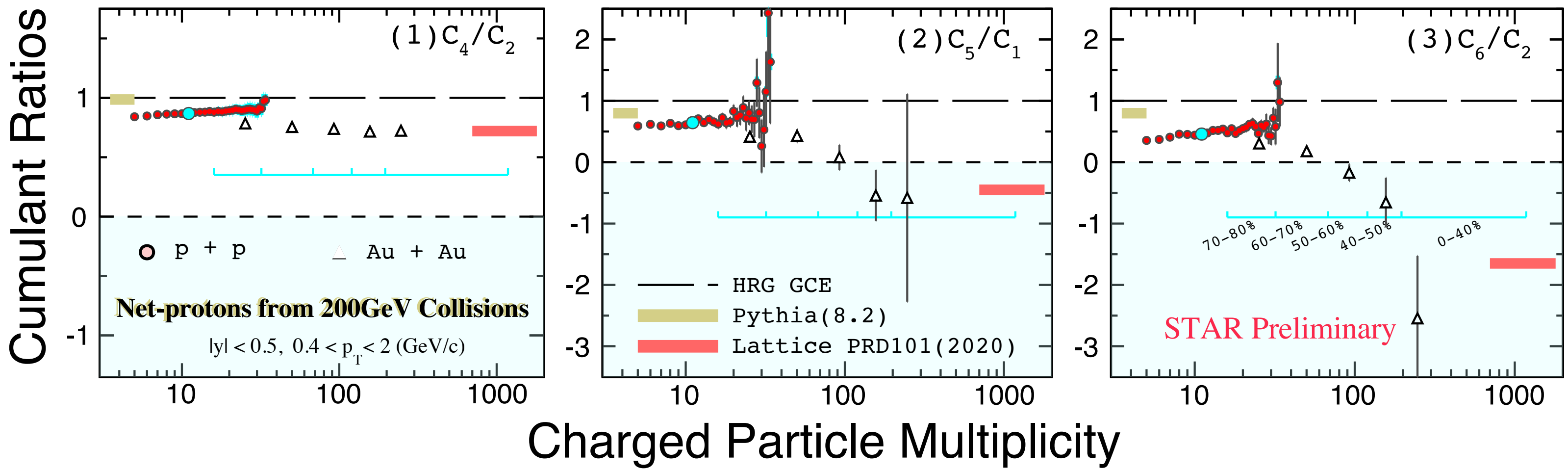
STAR: 2101.12413

Top 0 - 5% Au + Au Collisions at RHIC					
Energy Range	Cumulant Ratios	HRG GCE [4]	HRG CE [1]	HRG EV [3] (r = 0.5 fm)	UrQMD [2]
7.7 – 27 GeV	C_2/C_1	< 0.001	< 0.001	< 0.001	< 0.001
	C_3/C_2	< 0.001	$7.54e^{-3}$	< 0.001	< 0.001
	C_4/C_2	$5.53e^{-3}$	$4.50e^{-3}$	$1.45e^{-2}$	$2.21e^{-3}$
7.7 – 62.4 GeV	C_2/C_1	< 0.001	< 0.001	< 0.001	< 0.001
	C_3/C_2	< 0.001	< 0.001	< 0.001	< 0.001
	C_4/C_2	< 0.001	$1.28e^{-1}$	$1.07e^{-2}$	$5.77e^{-3}$

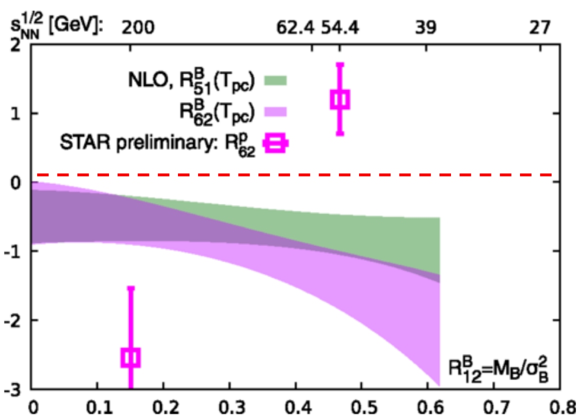
- Models predict monotonical energy dependence: Statistically do not agree with data, especially at finite baryon density region
- Statistical analysis → **non-monotonic energy dependence**

[1] P. Braun-Munzinger et al., Nucl.Phys. **A1008**, 122141(2021); [2] S. He et al., Phys. Lett. **B762**, 296(2016)
[3] J.H. Fu, Phys. Lett. **B722**, 144(2013); [4] A. Bhattacharyya et al., Phys. Rev. **C90**, 034909(2014)

Comparison Between 200 GeV p+p and Au+Au Collisions



STAR: CPOD2021



1) In 200GeV p+p collisions, high order cumulants ratios of net-protons are found to be positive for , C_4/C_2, C_5/C_2 and C_6/C_2;

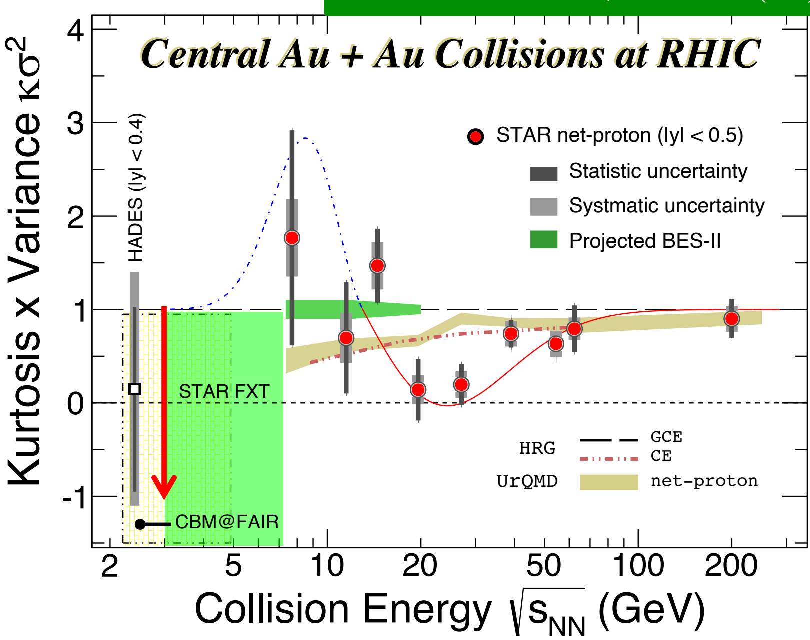
2) For QCD matter, LGT predicted negative net-baryon C_5/C_2 and C_6/C_2;

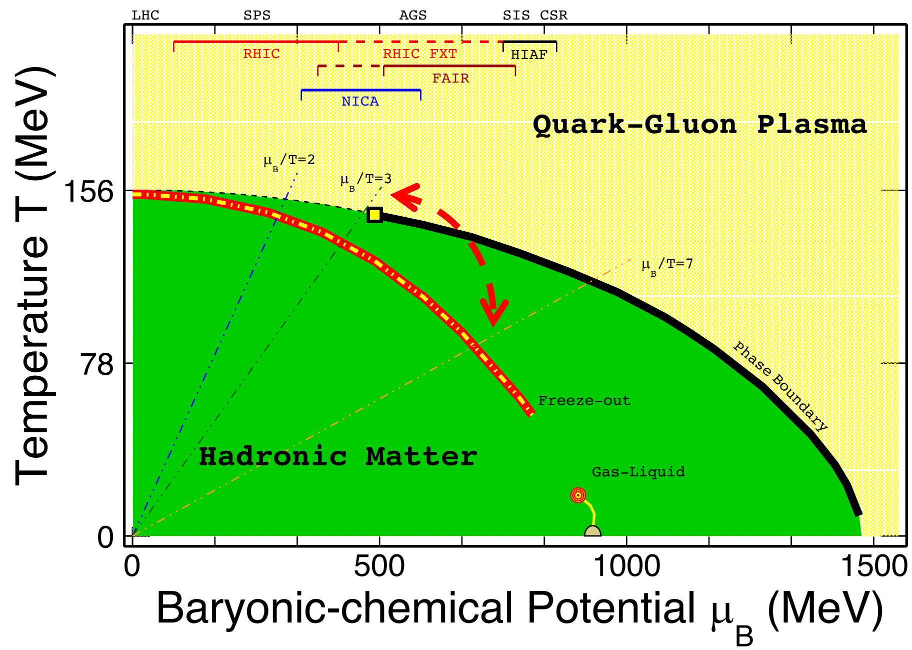
3) Direct **evidence for the QGP formation in 200GeV Au+Au central collisions!**

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

Proton High Moments at High Baryon Density Region

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

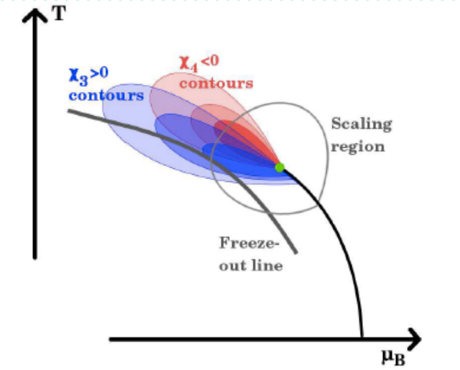


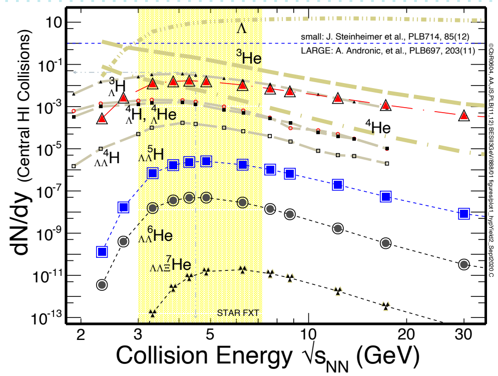


1) HADES data and hadronic transport model UrQMD predicted negative C_4/C_2 at 3 GeV → **Hadronic interactions dominant**;
2) Fill the gap $2 < \sqrt{s_{NN}} < 7.7$ GeV and pin down QCD critical point → CBM Experiment at FAIR

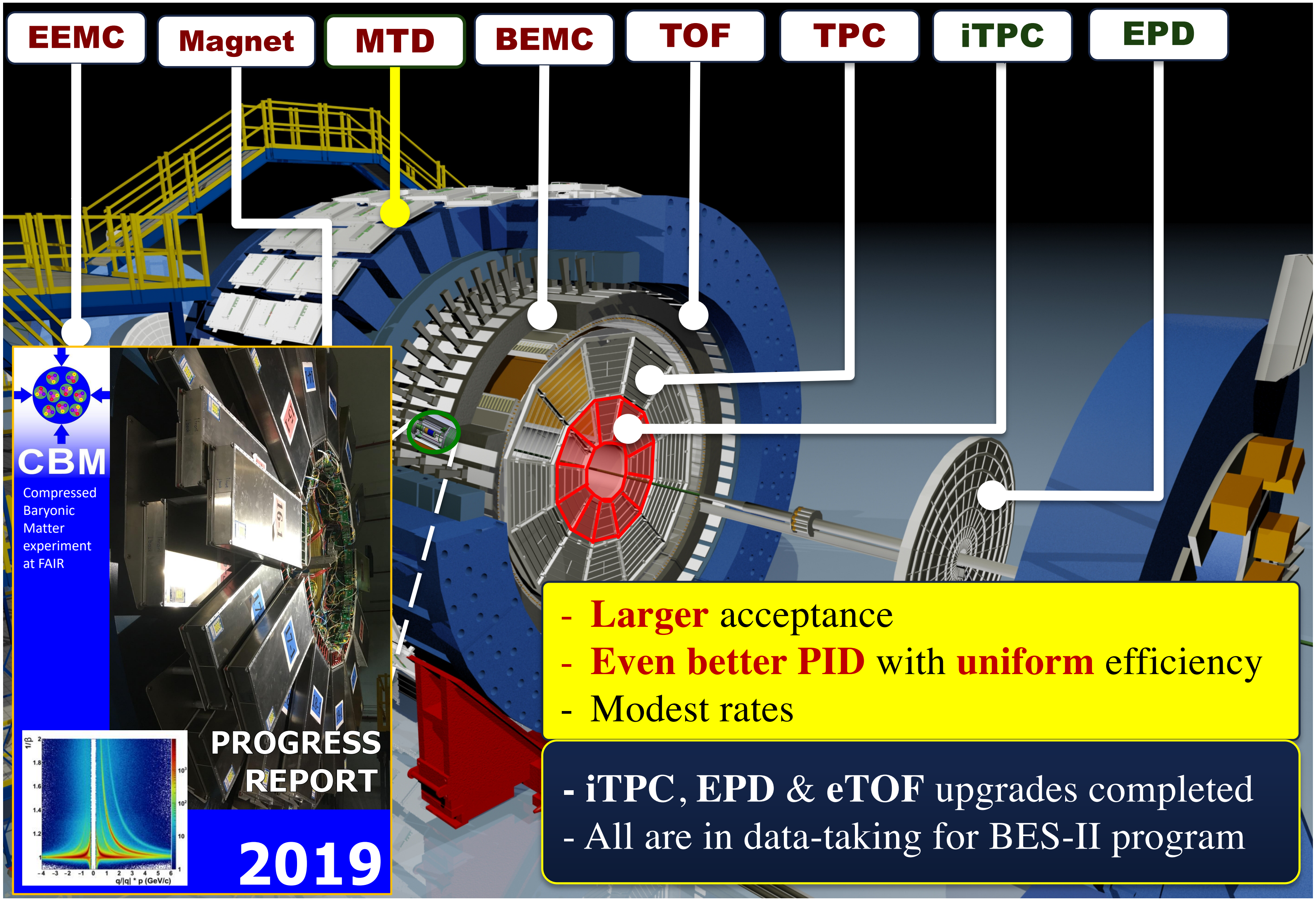
HADES: PRC**102**, 024914(20)

BES-II and Beyond

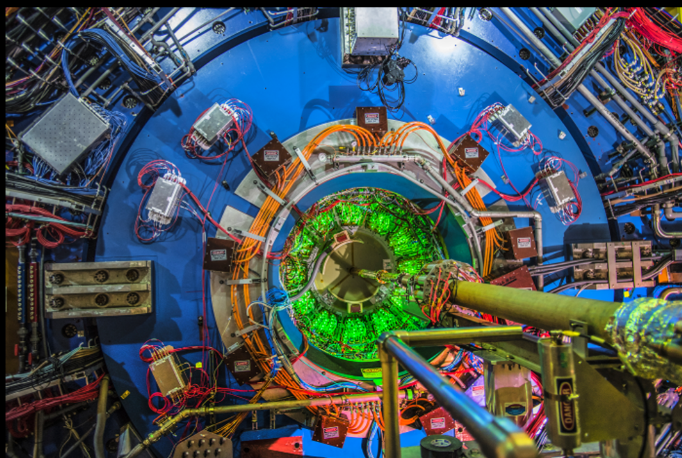


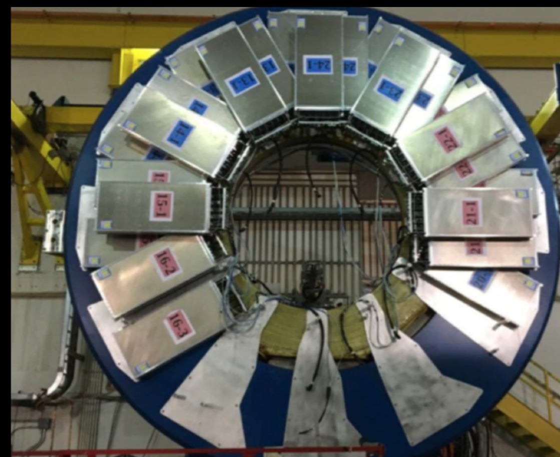


STAR Detector System for BES-II



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 $\eta = 0.9$ to 1.5
- Provided by CBM-FAIR
- Ready in 2019

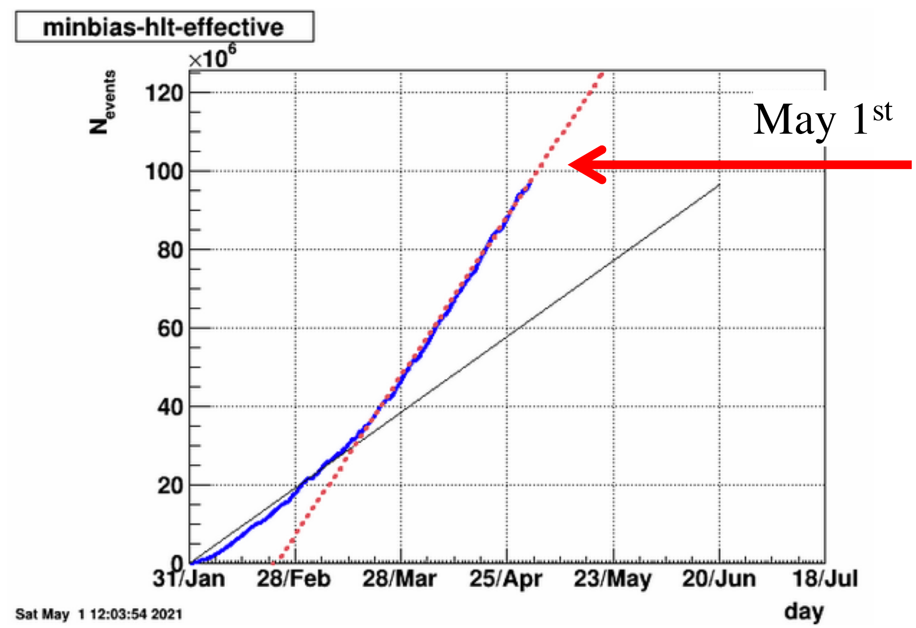
EPD:
- Improves trigger
- Better centrality & event plane measurements
- Ready in 2018

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)

RHIC BES-I & II (2010-2017, 2019-2021)

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES II / BES I	μ_B (MeV)	T_{ch} (MeV)
200	238	2010	25	166
62.4	46	2010	73	165
54.4	1200	2017	83	165
39	86	2010	112	164
27	30 (560)	2011 / 2018	156	162
19.6	**538** / 15	**2019** / 2011	206	160
17.3	**250**	**2021**	~227	~158
14.5	**325** / 13	**2019** / 2014	264	156
11.5	**230** / 7	**2020** / 2010	315	152
9.2	**160** / 0.3	**2020** / 2008	355	140
7.7	**100** / 4	**2021** / 2010	420	140
3.0 (FXT)	**250 +** 2B	**2021**	~720	~80



7.7GeV data goal, 100M, reached on May 1st
World largest data set!

https://www.bnl.gov/riken/QCDRhic/default.asp

K. Rajagopal, https://www.bnl.gov/riken/QCDRhic/linked_files/talks/RHICQCD_rajagopal.pdf

CAN WE DISCOVER THE QCD CRITICAL POINT AT RHIC?

Mapping the phase diagram. Finding the landmark that would go in any future book on QCD. Can RHIC do this?

Yes, IF:

- Accelerator + detector capabilities permit measurement of the event-by-event fluctuations of the hadronic observables I described, at a sequence of energies like that I described
- Nature is kind, and puts $\mu_B < 500$ MeV

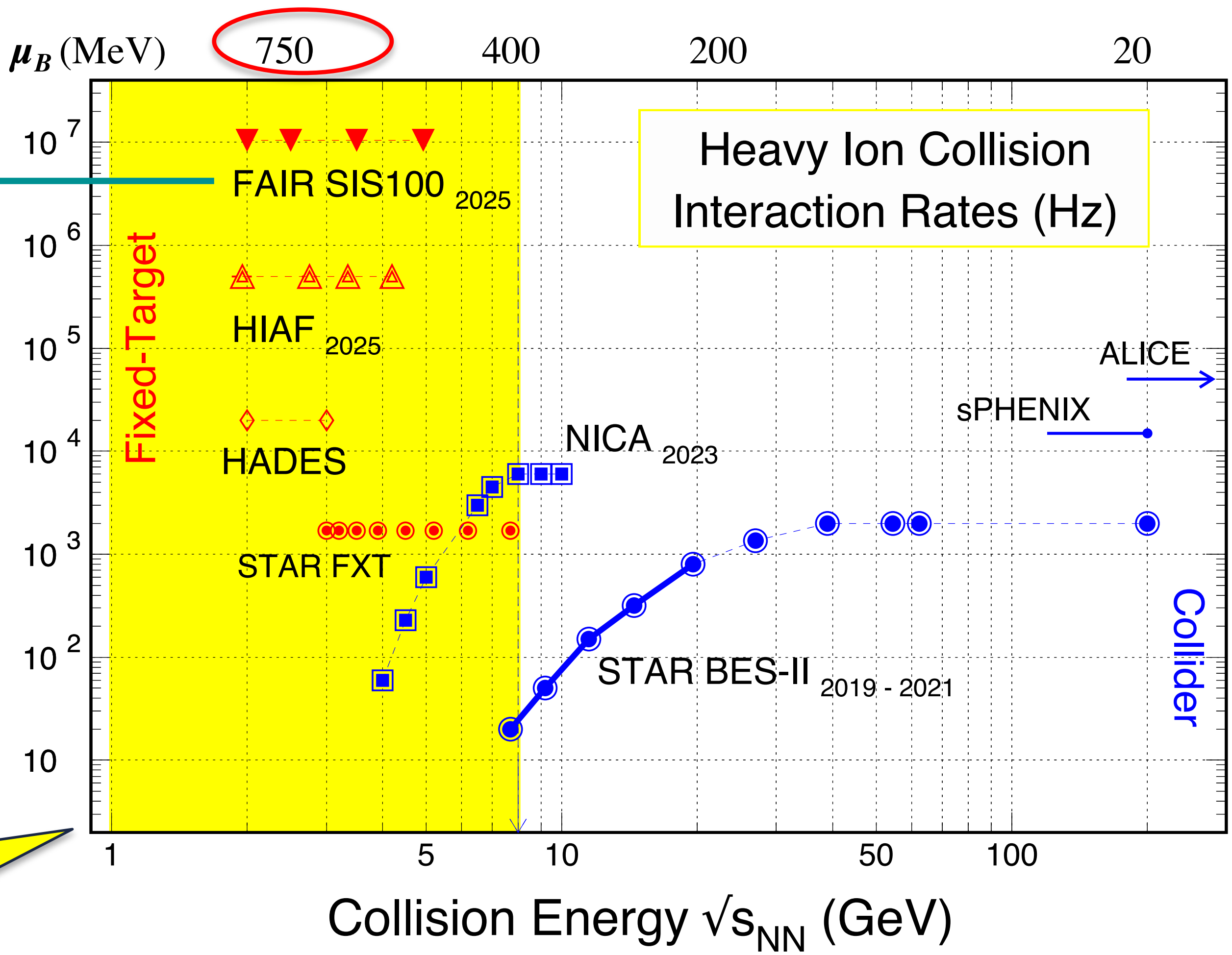
If YES:

- The landmark discovered. Our map of the QCD phase diagram then anchored by experiment.
- Assuming reasonable progress in lattice QCD, quantitative comparison between theory + experiment for μ_B
- FAIR (and RHIC) can study the first order phase transition.

- **YES! Since 2010, RHIC and STAR have completed upgrades successfully and carried out the beam energy scan.**
- **World largest data sets from heavy ion collisions have been collected**
- **BEST: theory collaboration**
- **Is Nature kind?**

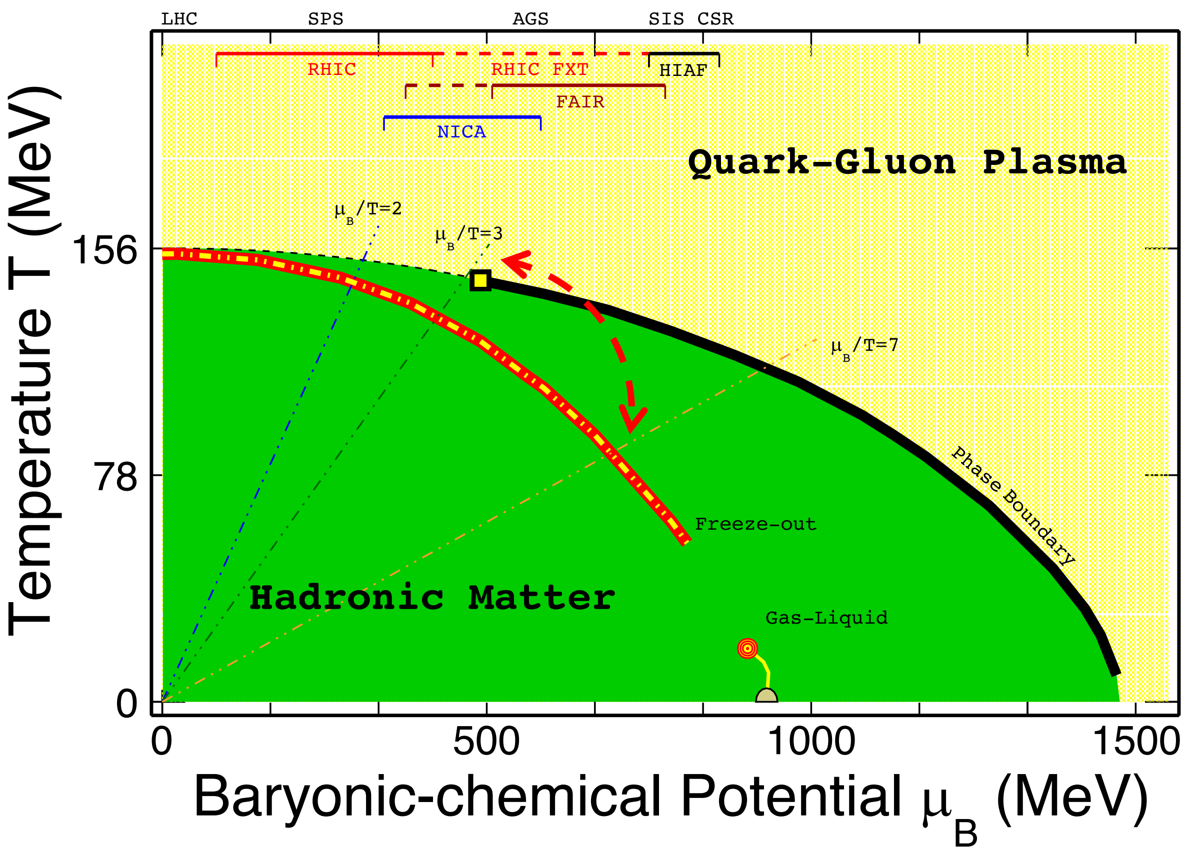
Future Facilities for Heavy Ion Collisions

CBM
High rates, FXT experiment at FAIR



Region of high baryon density

The QCD Phase Diagram



<u>2000 – 2021</u> BES-I & -II: search for the QCD CP at RHIC

- Lattice: CP may exist at $\frac{\mu_B}{T} \geq 3$
- 3σ effect: non-monotonic collision energy dependence $\sqrt{s_{NN}} \leq 20$ GeV

<u>2021 – 2033</u> BES-III:

- fixed-target experiments at $2 \leq \sqrt{s_{NN}} \leq 5$ GeV
- **Confirm** first-order phase boundary and the QCD CP

Acknowledgements

STAR Collaboration and RHIC Operation

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* *students*

Drs. S. Gupta**, F. Karsch**, V. Koch**, JF. Liao, S. Mukherjee**, K. Rajagopal**, K. Redlich**, M. Stephanov**, PF. Zhuang

**INT 2008

Thank you for your attention!