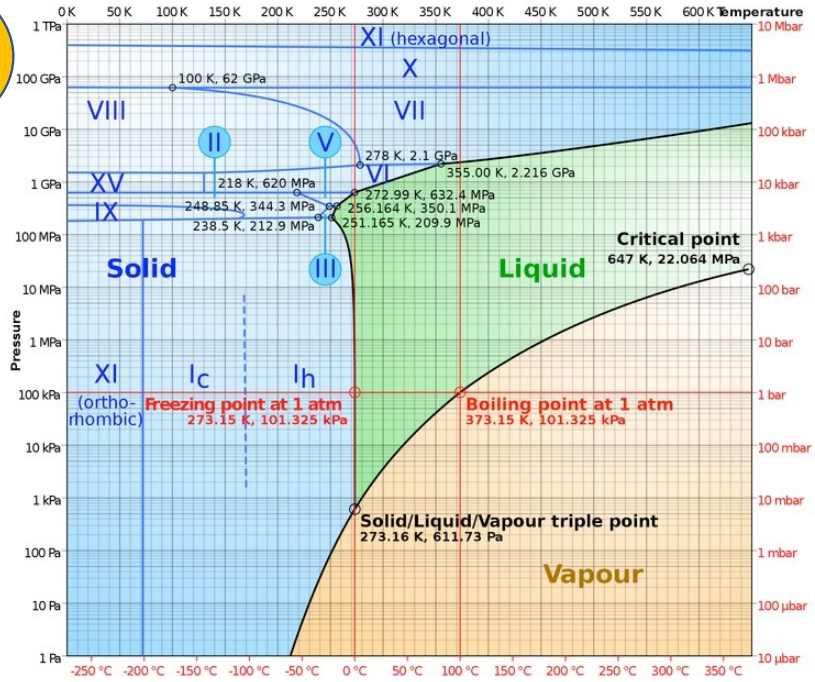
QCD Phase Structure and Relativistic Heavy-Ion Collisions

Bedanga Mohanty
National Institute of Science Education and Research
India

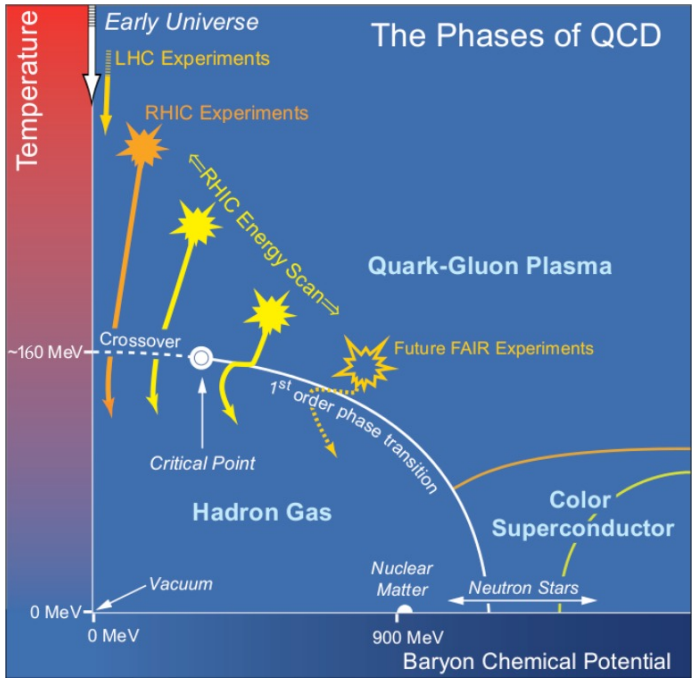
Tomonaga Center for the History of the Universe (TCHoU)

11th September 2021

QED



Wiki



US NP long range plan, 2015

QCD

QCD phase diagram

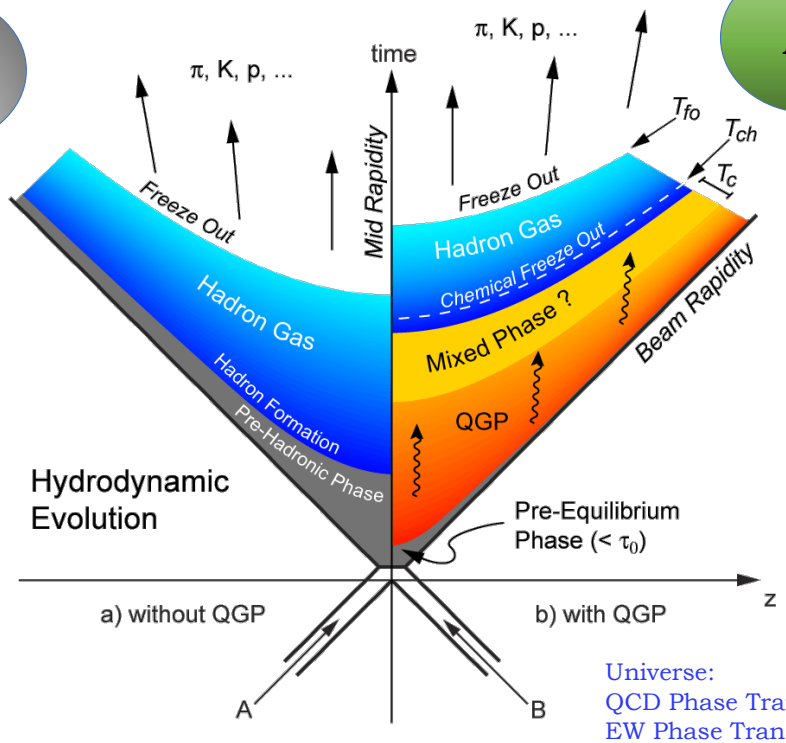
- Conserved quantities and temperature (T)
- Baryon number - μ_B
- Electric charge - μ_Q - small
- Strangeness ~ μ_S - small

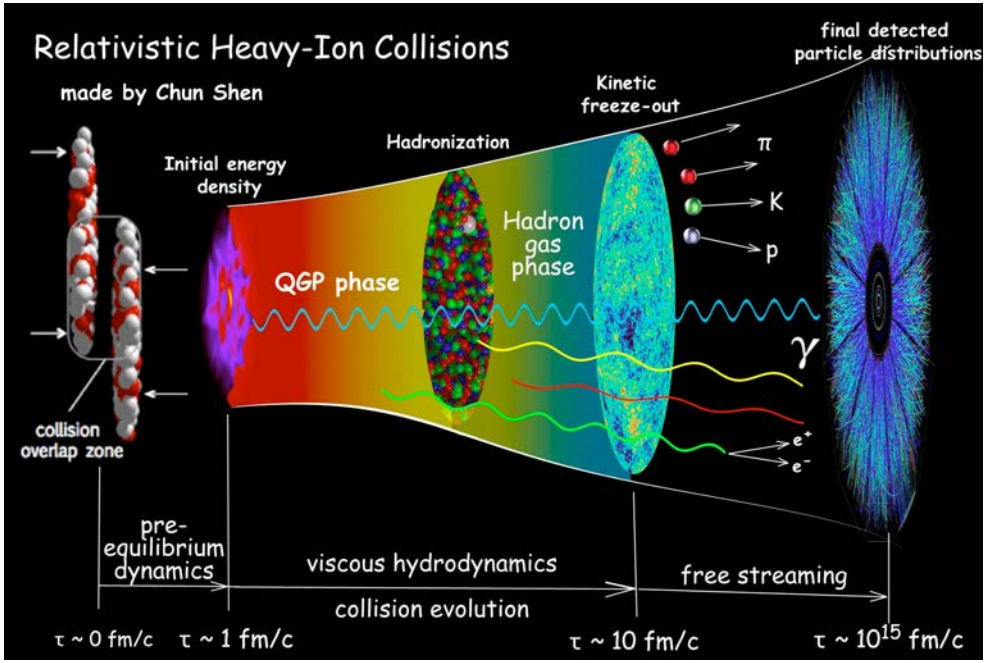
Relativistic Heavy Ion Collisions

J. D. Bjorken Physical Review D 27 (1983) 140

pp

AA

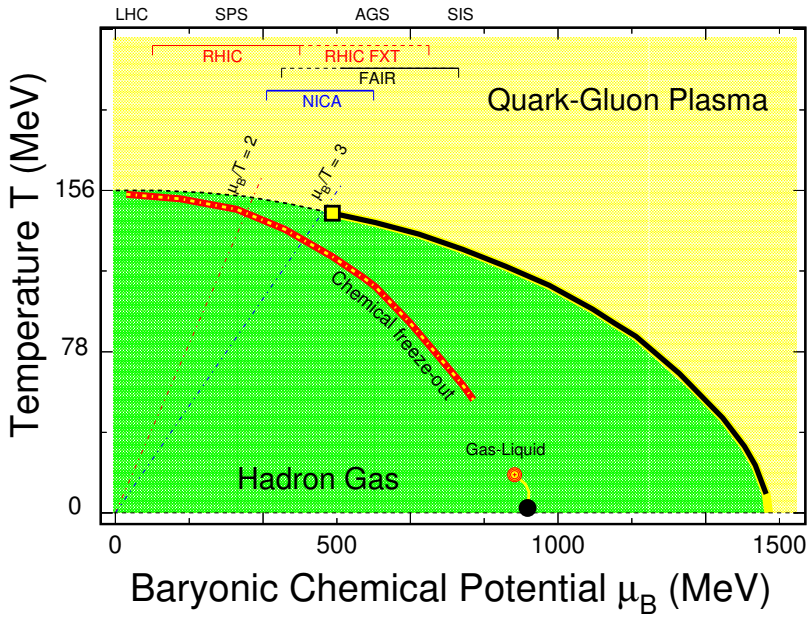




Universe:
QCD Phase Transition: T ~ 200MeV
EW Phase Transition: T ~ 150 GeV
GUT Phase Transition: T ~10^{16} GeV

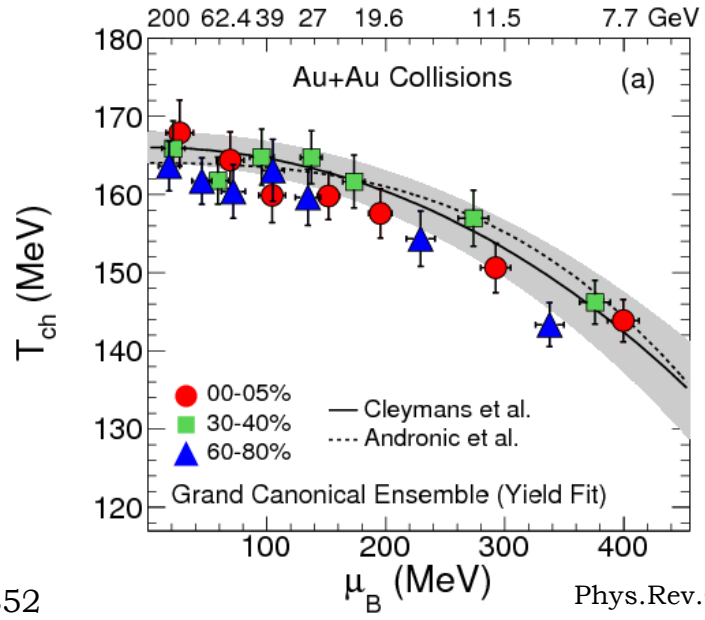
Mapping QCD phase diagram and Relativistic Heavy Ion Collisions

- Nature of transition
- Critical point
- Properties of the phases



STAR: arXiv: 2001.02852

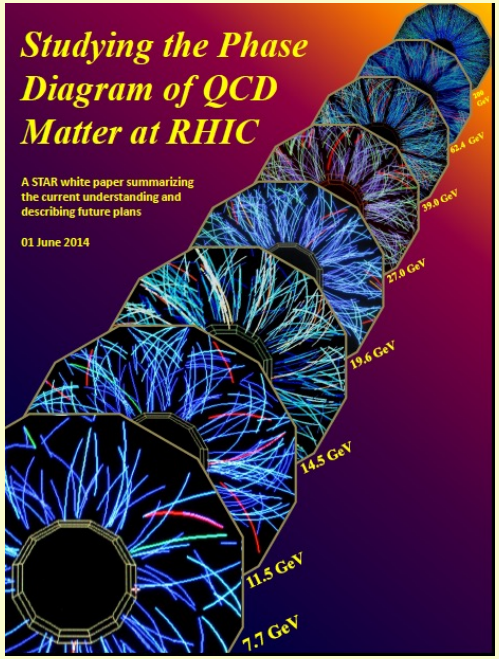
Collision energy

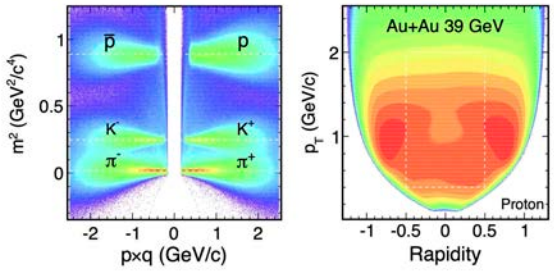


Phys.Rev.C 96 (2017) 4, 044904

Accessing phase diagram of QCD in heavy-ion collisions: varying collision energy changes the T and μ_B

Program: Beam Energy Scan





Requirements

- Uniform & wide acceptance
- Excellent particle identification
- Good momentum reconstruction
- Centrality with high resolution
- Large statistics

SN0493 : Experimental Study of the QCD Phase Diagram & Search for the Critical Point: Selected Arguments for the Run-10 Beam Energy Scan

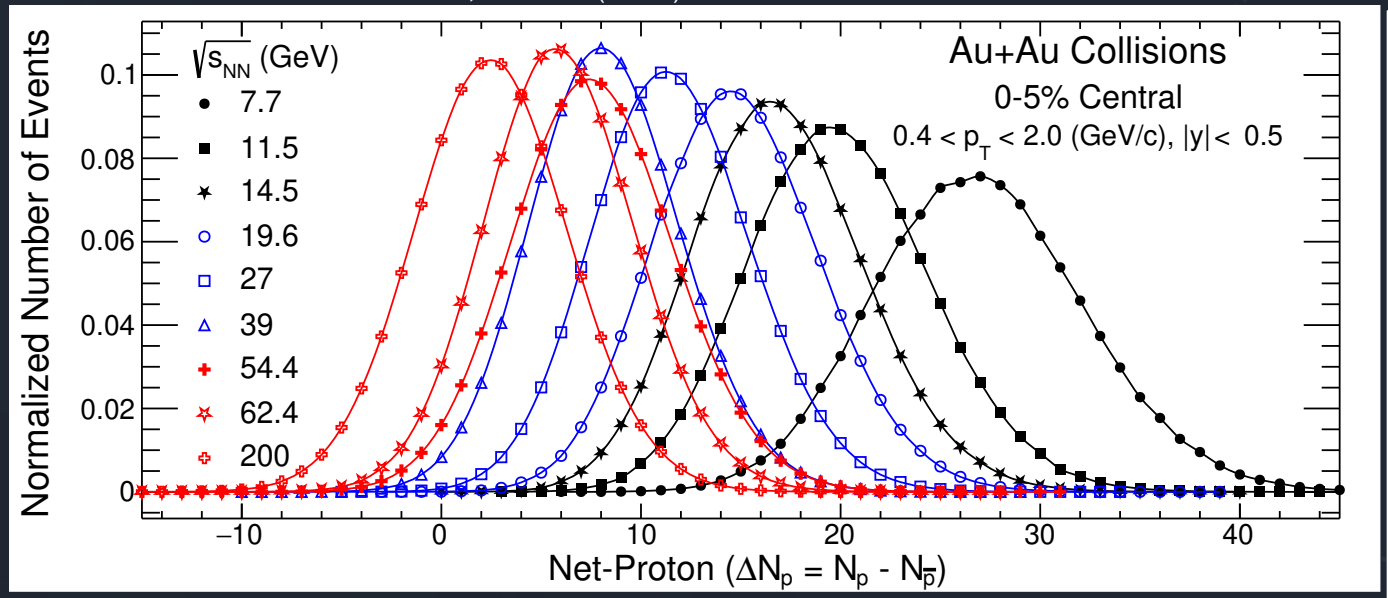
SN0598 : Studying the Phase Diagram of QCD Matter at RHIC

Tool - Higher moments

- $C_2 \sim \xi^2 \qquad C_4 \sim \xi^7$
- $\frac{\chi_q^{(4)}}{\chi_q^{(2)}} = \kappa\sigma^2 = \frac{C_{4,q}}{C_{2,q}} \qquad \frac{\chi_q^{(3)}}{\chi_q^{(2)}} = S\sigma = \frac{C_{3,q}}{C_{2,q}}$

*PRL*105, 22303(10); *ibid*, 112, 032302(14) *PLB633*, 275(06); *PRL*102, 032301(09); *PLB695*,136(11);*PLB696*, 459(11)

PHYSICAL REVIEW LETTERS 126, 092301 (2021)



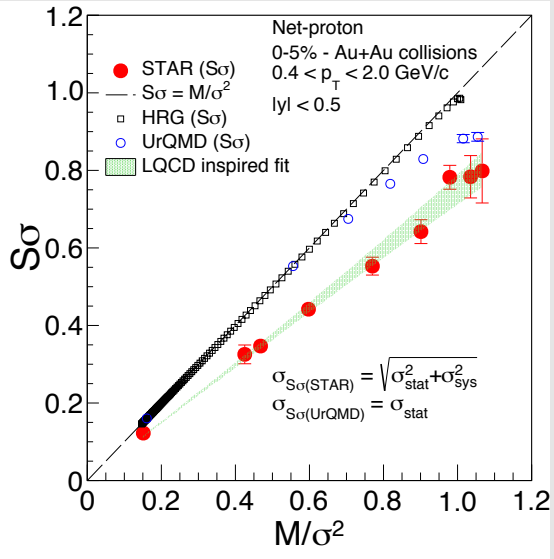
Connect to Theory. Correlation length & Susceptibility

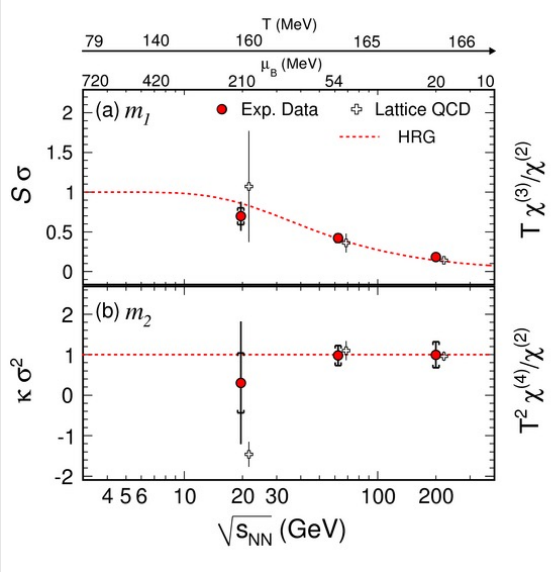
Sensitive to:

(1) Nature of transition
(2) Critical point
(3) Freeze-out
(4) Thermalization
(5) Initial EM fields

Key topics in the field

Measurements and Lattice QCD





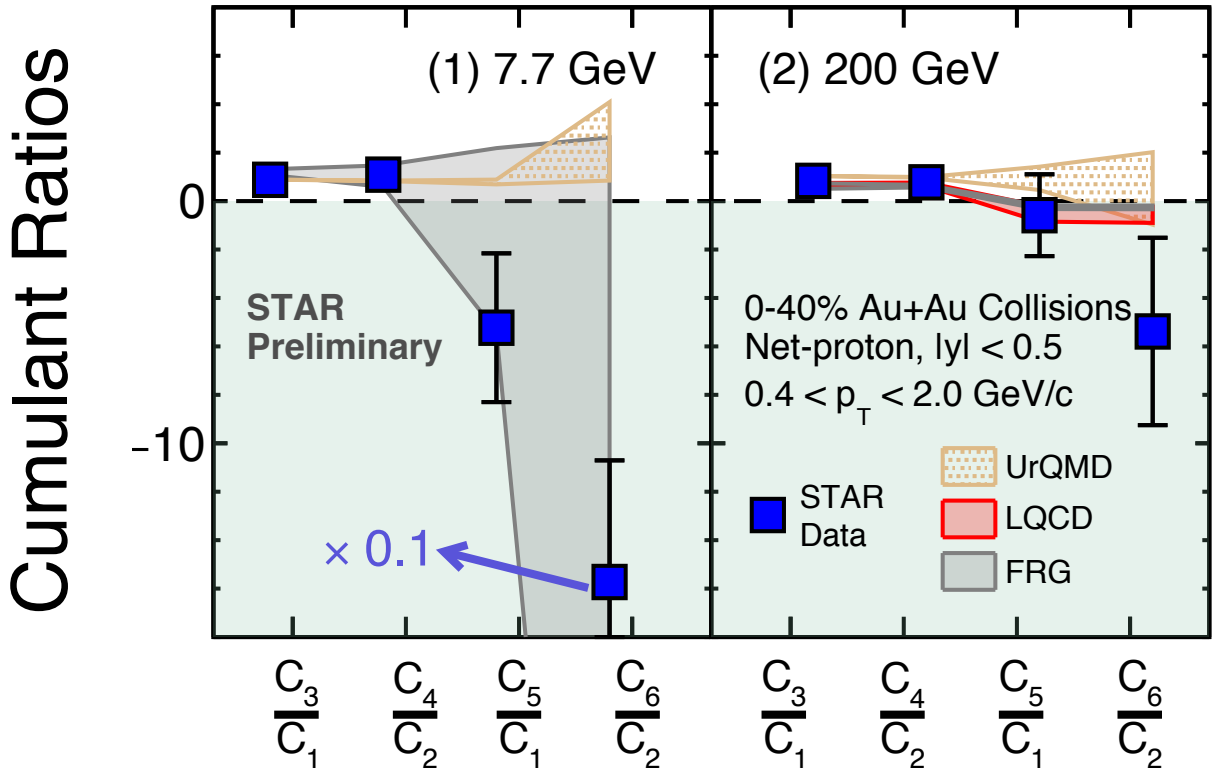
Science 332 (2011) 1525-1528

Assumptions

- Thermalization
- Grand Canonical Ensemble, $V/T^3 > 1$
- Net-proton ≡ Net-Baryon
- Acceptance
- Lattice artefacts: mass, volume, action, continuum limit, finite chemical potential

Measurements and QCD thermodynamics

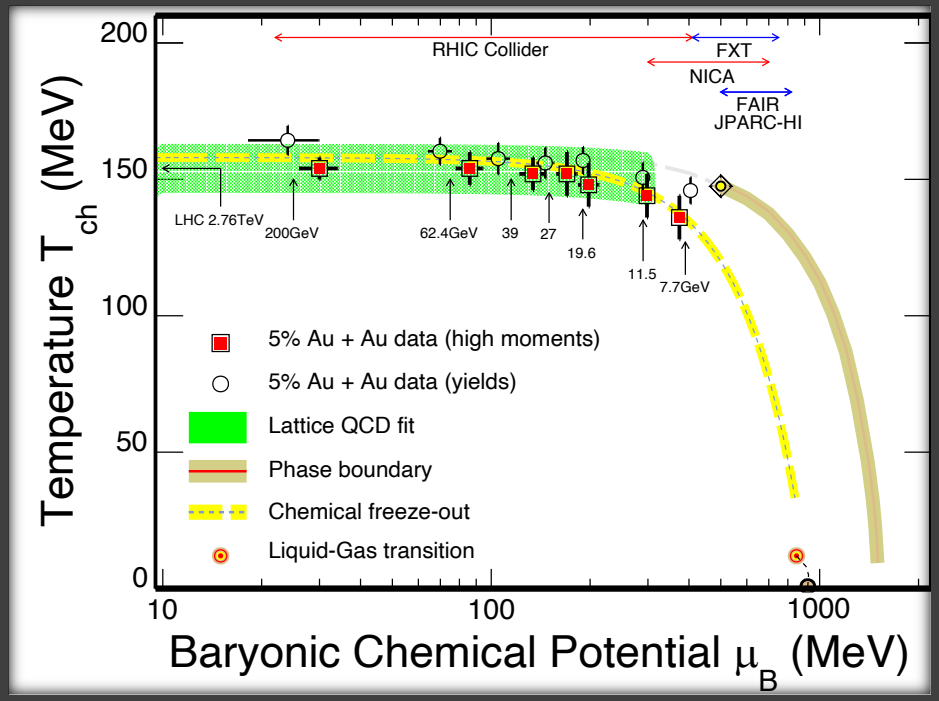
STAR@CPOD-2021



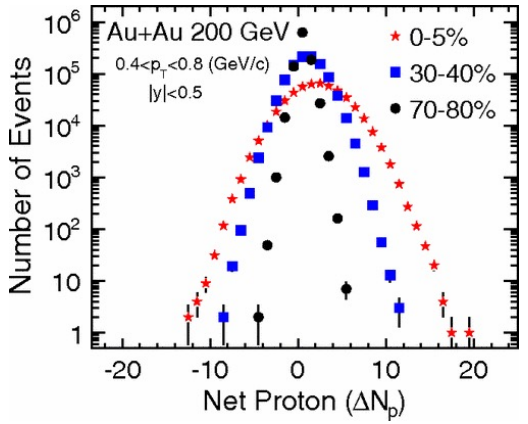
Susceptibility ratio ordering
PHYS. REV. D 101, 074502 (2020)

$$\frac{\chi_6^B(T,\vec{\mu})}{\chi_2^B(T,\vec{\mu})} < \frac{\chi_5^B(T,\vec{\mu})}{\chi_1^B(T,\vec{\mu})} < \frac{\chi_4^B(T,\vec{\mu})}{\chi_2^B(T,\vec{\mu})} < \frac{\chi_3^B(T,\vec{\mu})}{\chi_1^B(T,\vec{\mu})}$$

Freeze-out



AAPPS Bull. 31 (2021) 1

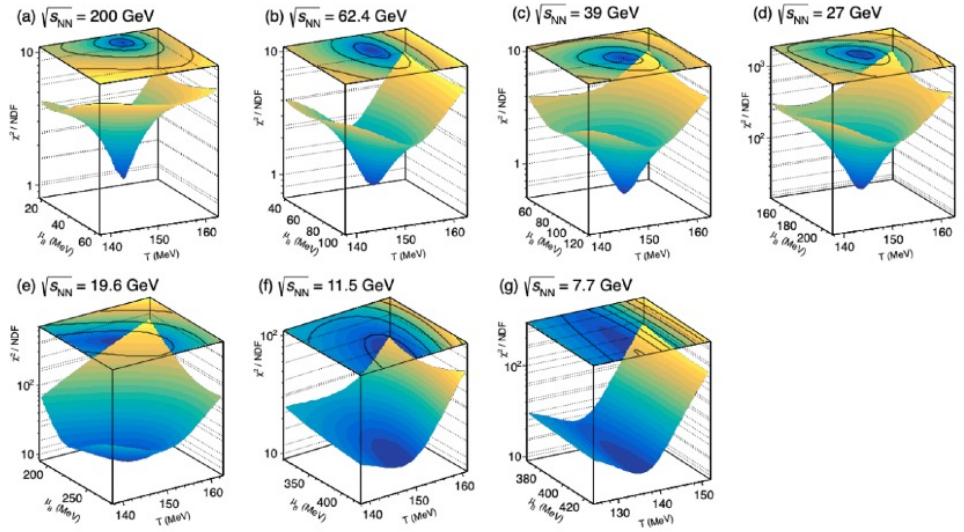


Idea

Mean of yields described by thermal statistical models

Distribution has several order moments

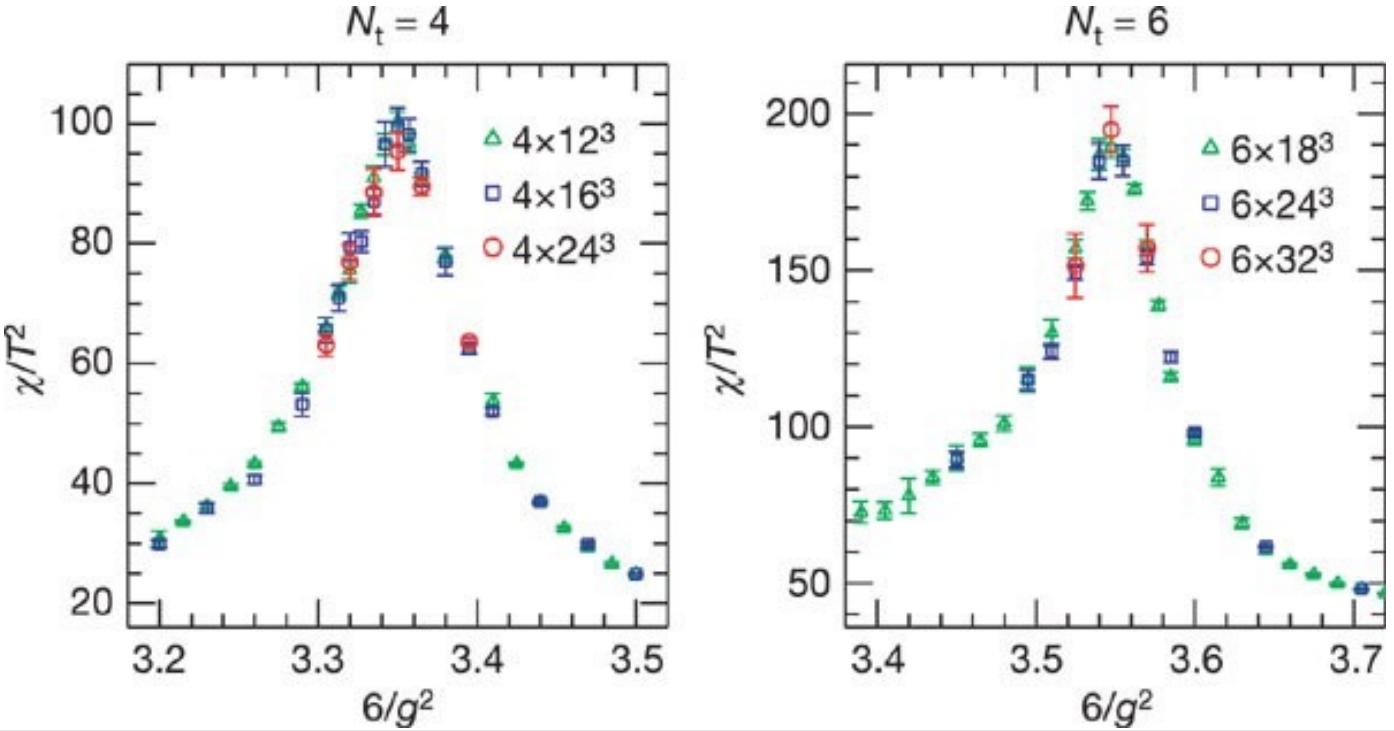
Are all orders thermal ?



e-Print: 2004.04681 [hep-ph]

Cross over at $\mu_B = 0$ MeV

Nature 443 (2006) 675-678



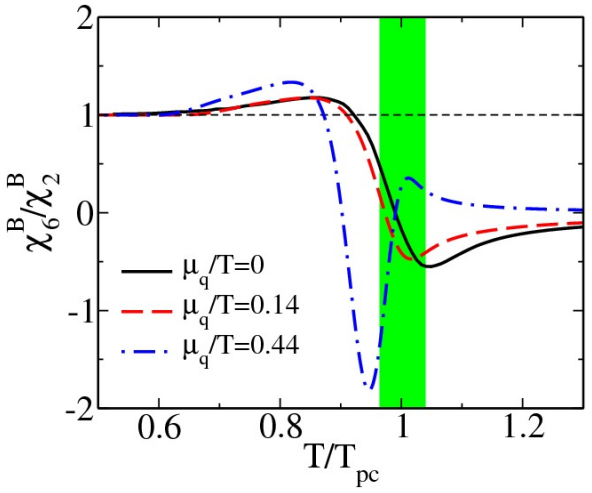
- T grows with $6/g^2$
- Largest volume is eight times bigger than the smallest one.
- First-order phase transition - susceptibility peak that is eight times higher
- Do not observe any volume dependence – cross over

Transition Temperature: ~ 154 MeV - Phys.Rev.D 85 (2012) 054503

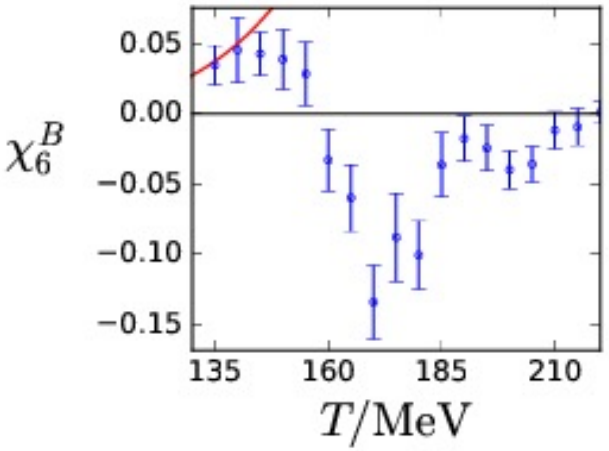
Cross over – theory expectation

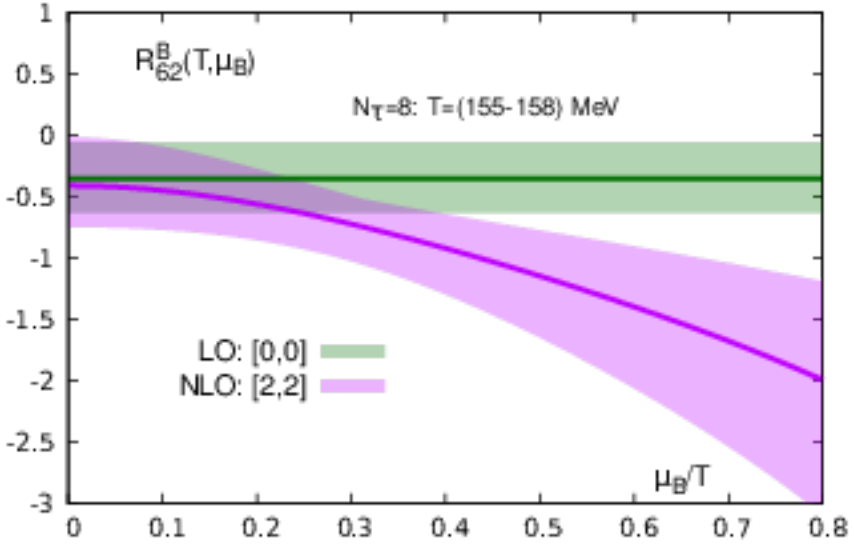
χ_6/χ_2 or $C_6/C_2 < 0$

Eur. Phys. J. C 71 1694 (2011)



JHEP 10 (2018) 205

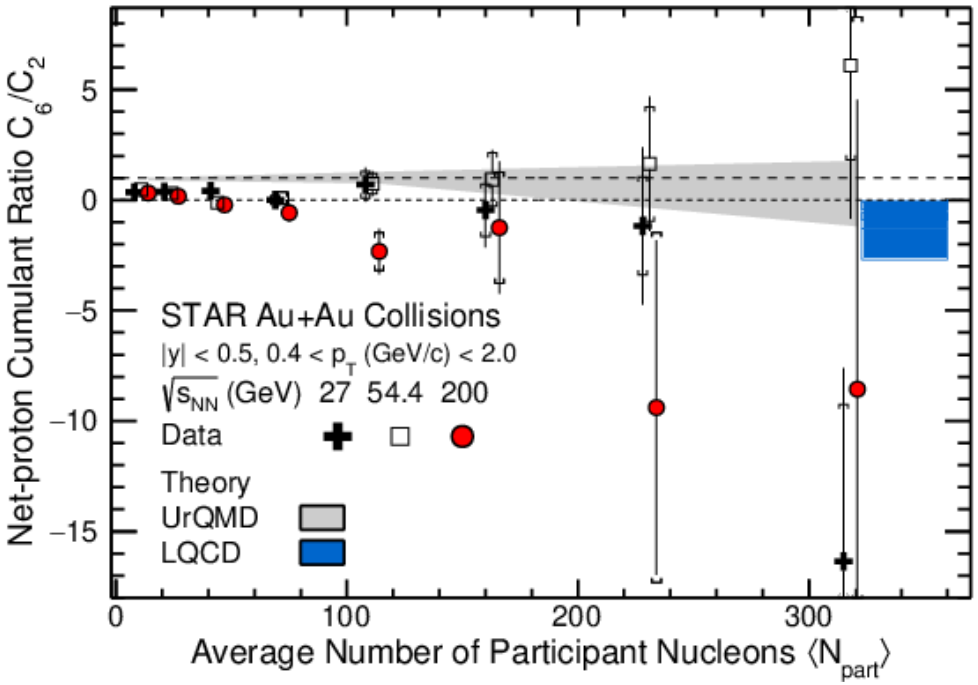


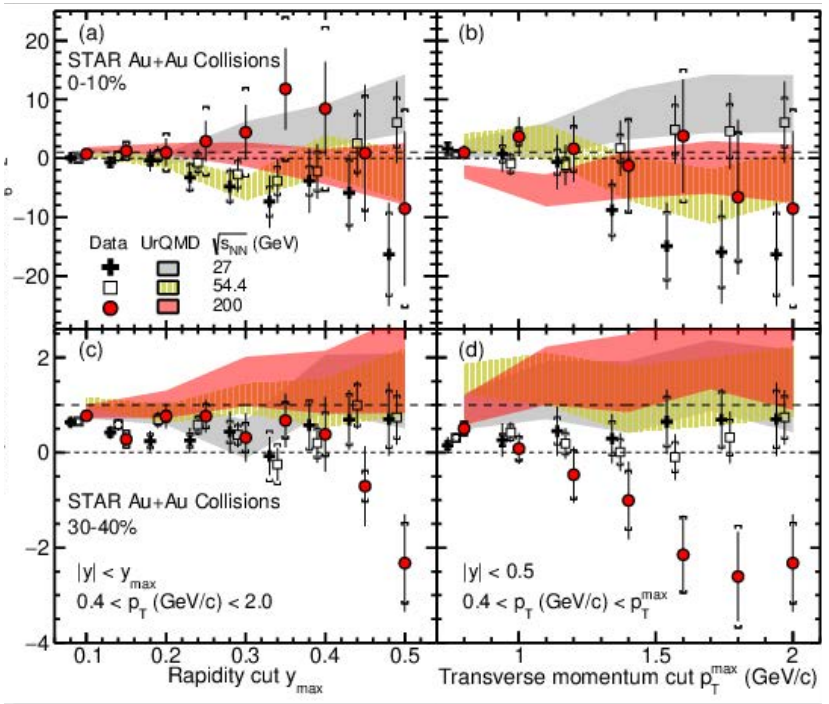


PHYSICAL REVIEW D 101, 074502 (2020)

Cross over – experimental measurements

e-Print: 2105.14698 [nucl-ex]

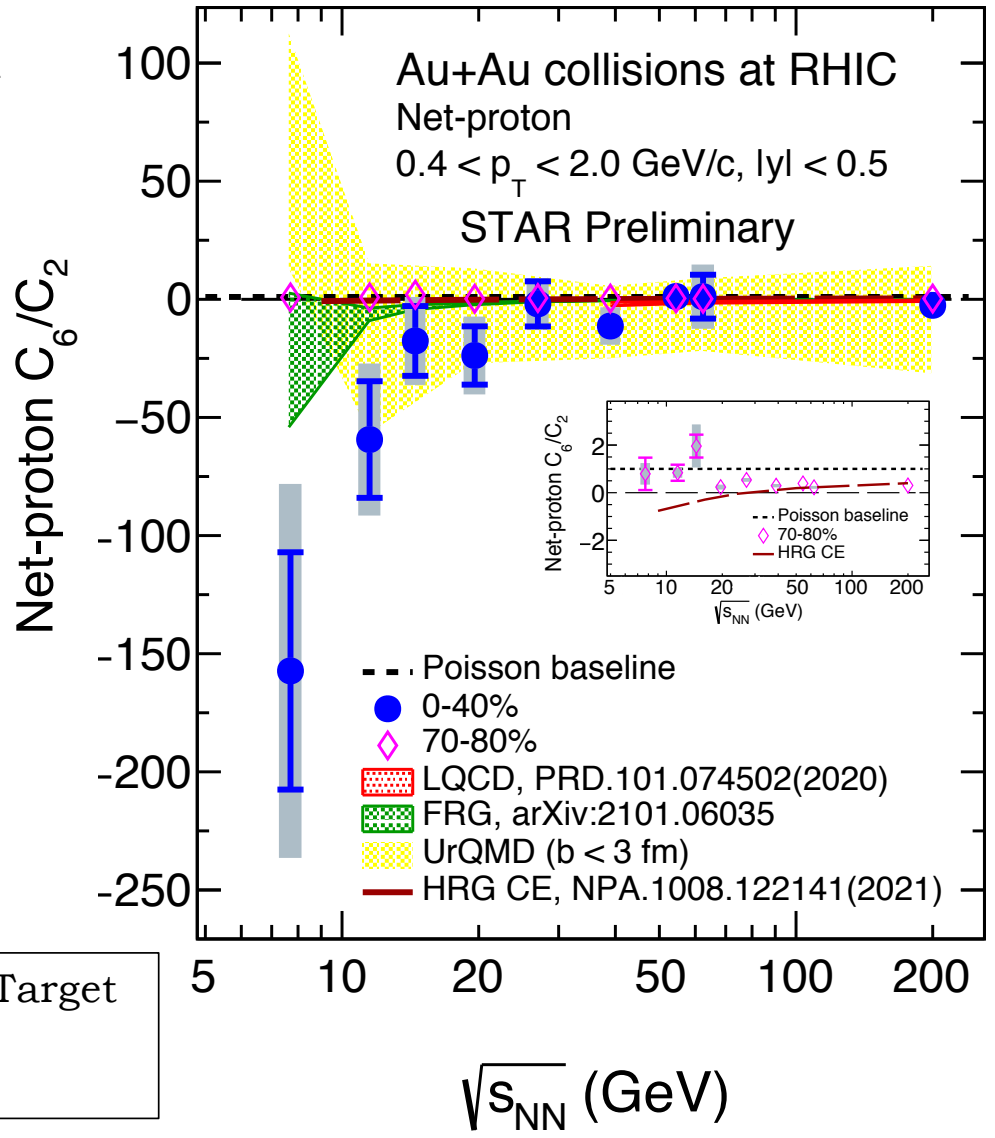




Systematic trends indicate $C_6/C_2 < 0$ at 200 GeV, uncertainties large

STAR@CPOD2021

Cross over – future measurements



High statistics data collected at BES-II and Fixed Target

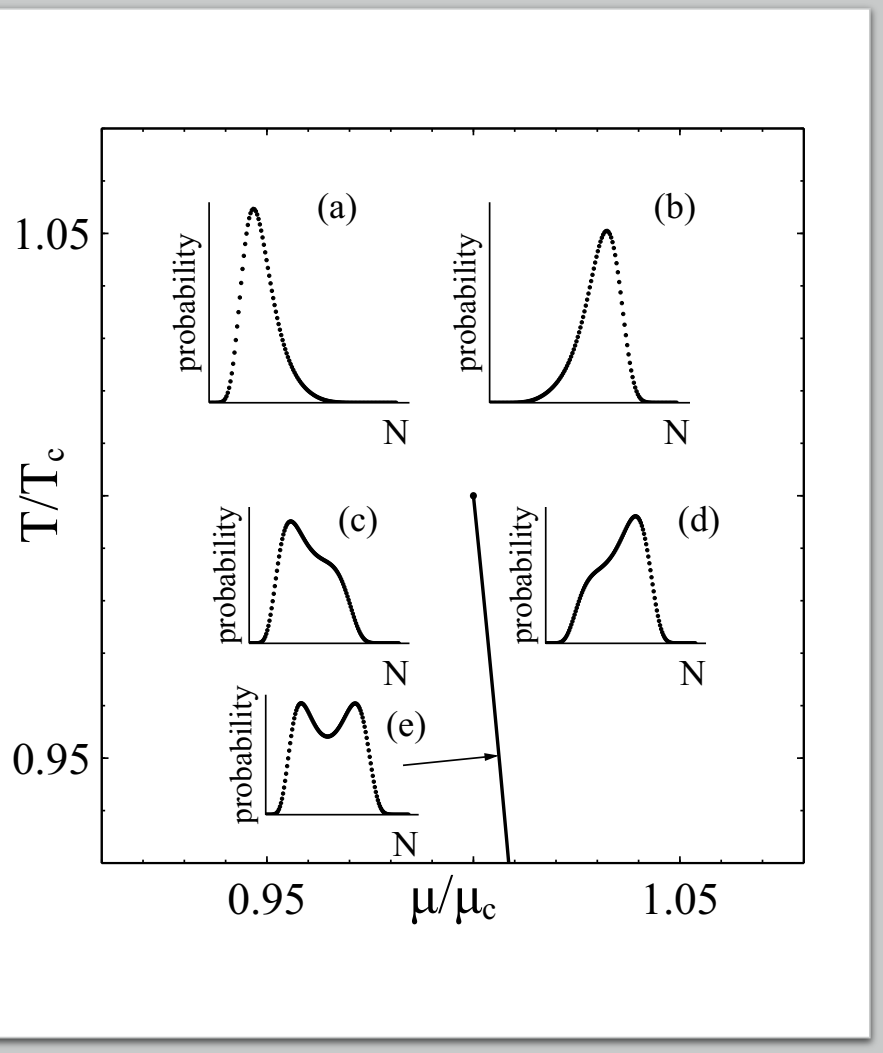
High statistics RHIC run at 200 GeV coming up

First order transition – theory expectation

(1) Multiplicity distribution bi-modal (contribution from two phases)

(2) Proton factorial cumulants ($\kappa_{n's}$) increases in magnitude with increasing order and flips sign

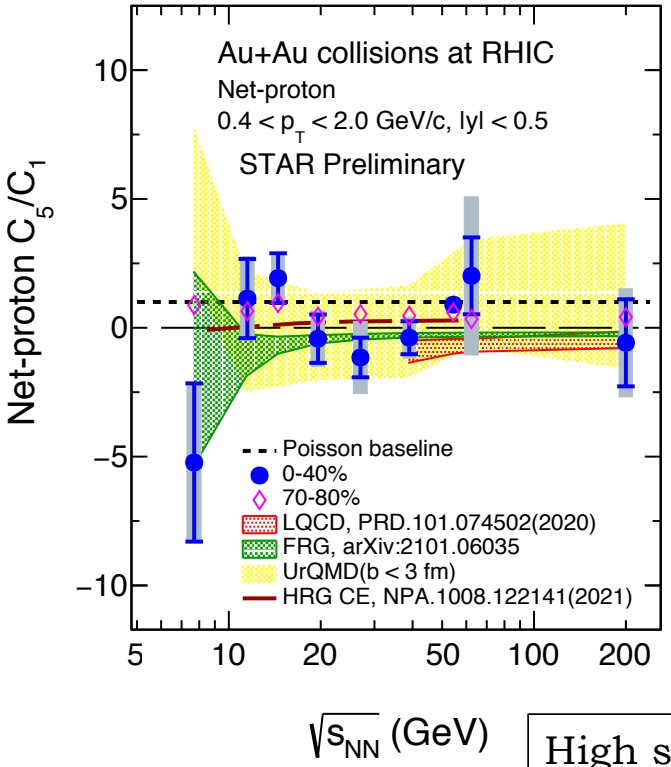
(3) $P(N) = (1-\alpha)P_a(N) + \alpha P_b(N)$

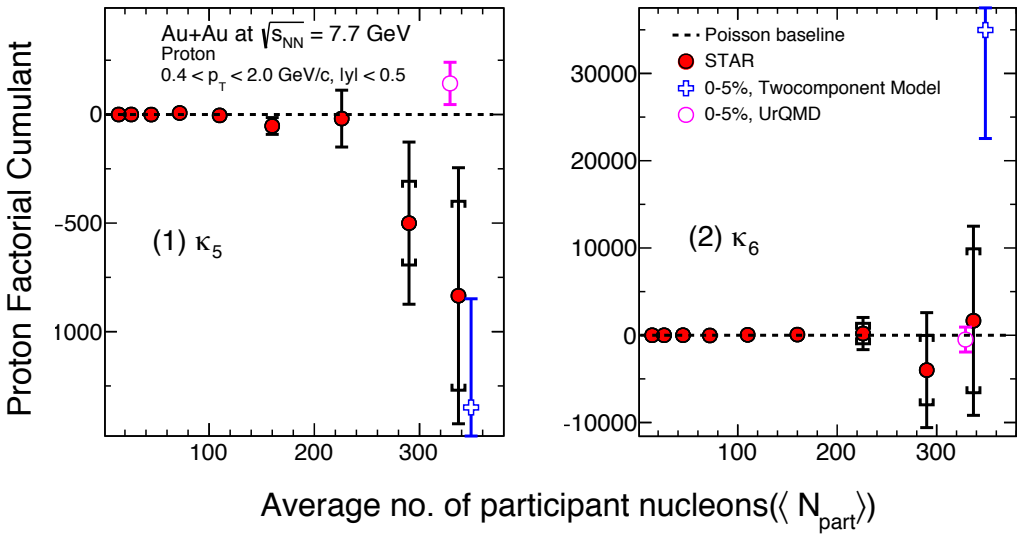


Phys. Rev. C 98 (2018) 5, 054901
Phys. Rev. C 100 (2019) 5, 051902

First order – experimental measurements and future

STAR@CPOD2021



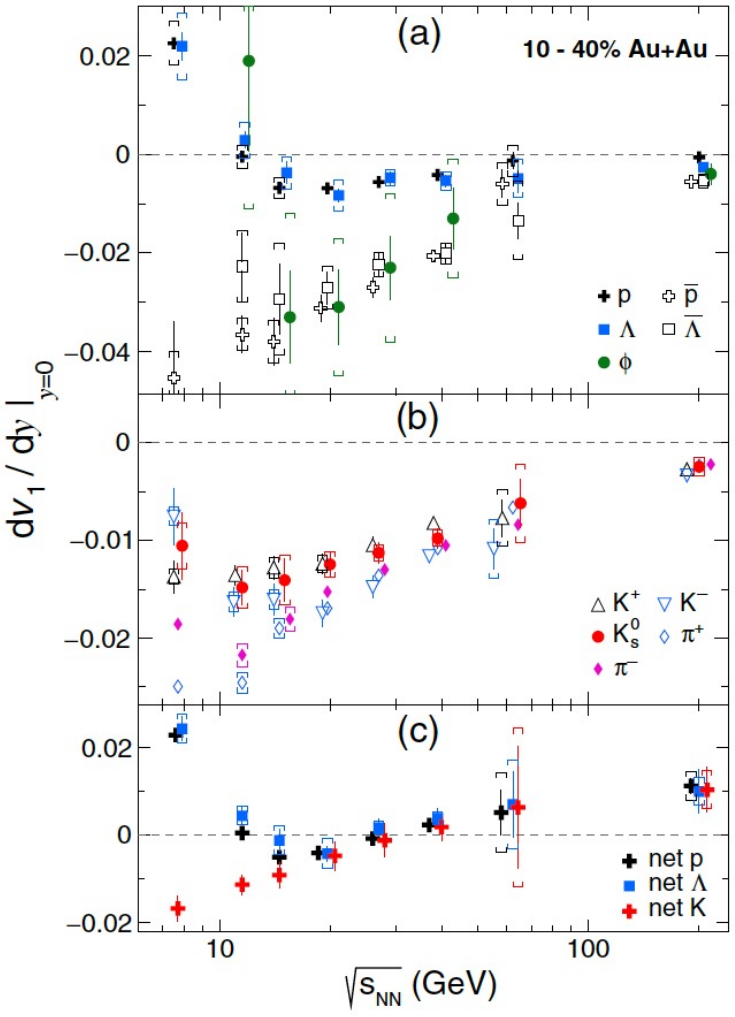


High statistics data collected at BES-II and Fixed target

First order transition – alternate measurements

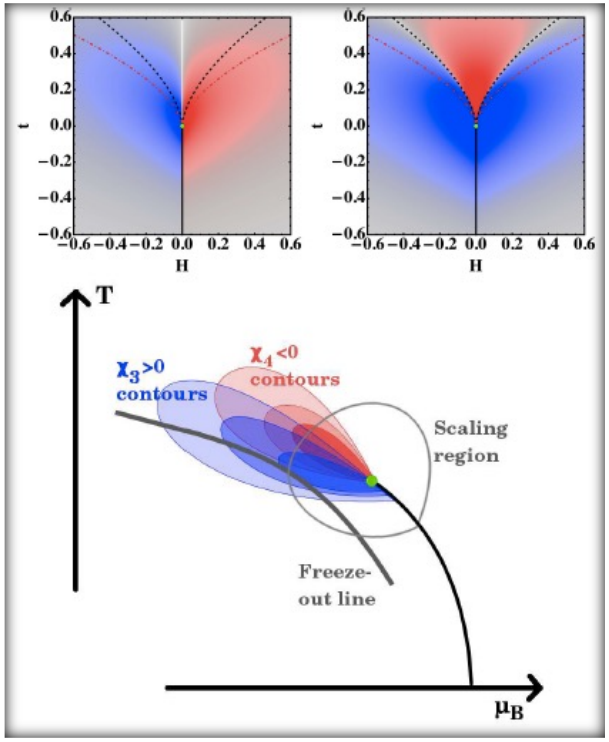
Nonmonotonic variation of dv_1/dy with collision energy

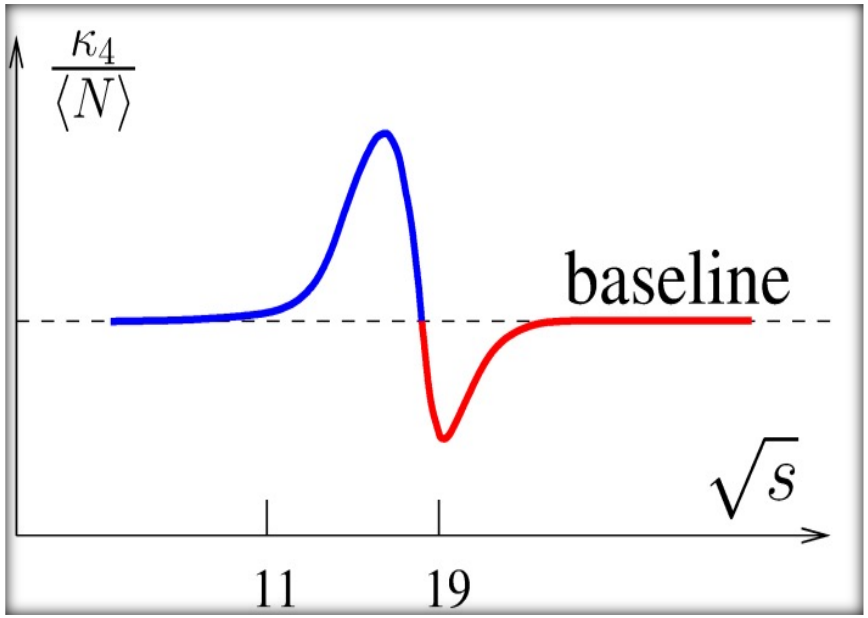
$$v_1 = \langle \cos(\phi - \Psi_{RP}) \rangle,$$



PHYSICAL REVIEW LETTERS 120, 062301 (2018)

QCD critical point – theory expectation





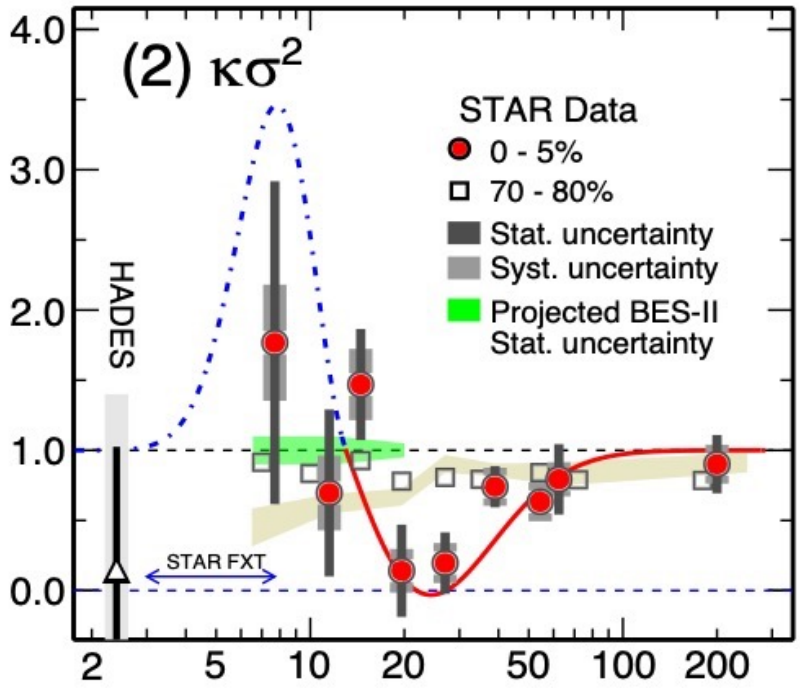
(1)QCD critical point - Characteristic "Oscillating pattern"

(2) Exact shape depends on the location of freeze-out with respect to the location of CP - Critical Region (CR)

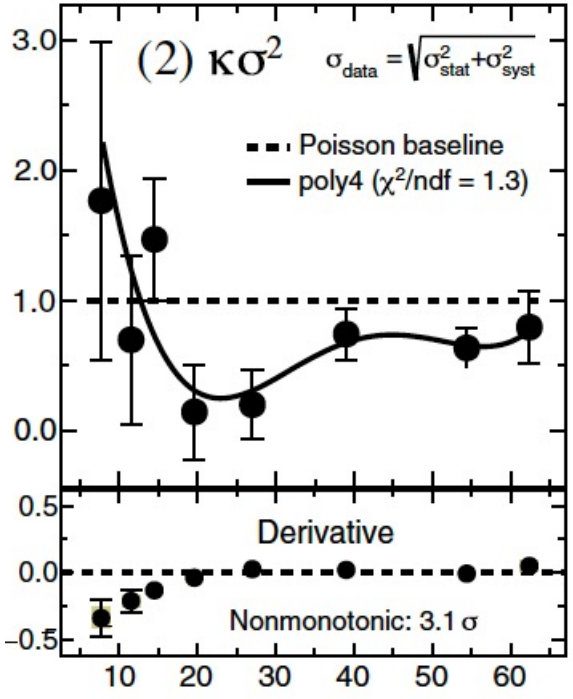
PRL 102, 032301 (2009) PRL 107, 052301 (2011)

QCD critical point – experimental measurement

PHYSICAL REVIEW LETTERS 126, 092301 (2021)



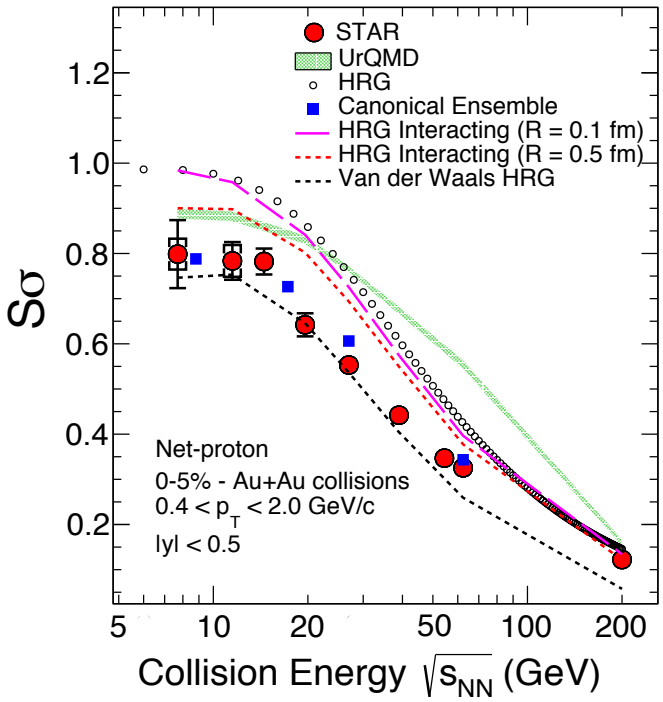
Collision energy (GeV)

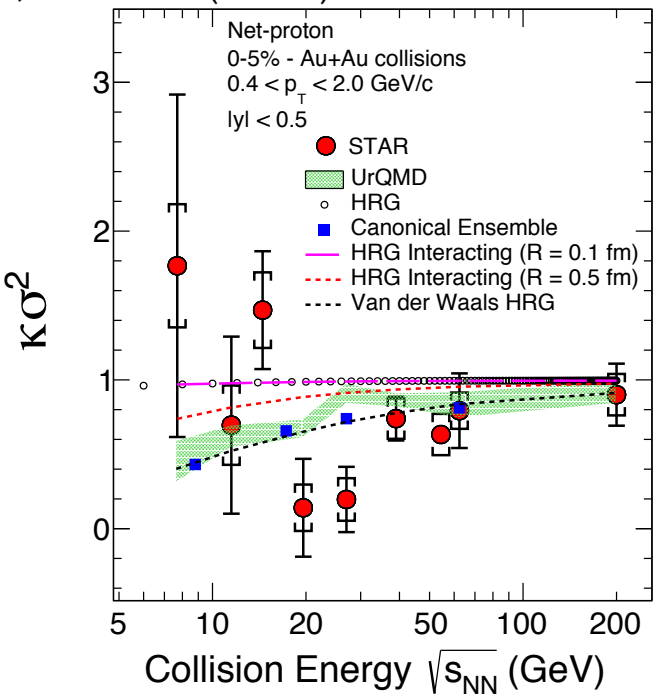


Collision energy (GeV)

QCD critical point – experiment vs. non-CP models

PHYSICAL REVIEW LETTERS 126, 092301 (2021)





Phys.Lett.B 726 (2013) 691-696, e-Print: 1905.09311
Phys.Rev.C 90 (2014) 3, 034909, e-Print: 2007.02463 [nucl-th]

QCD critical point – future measurements

STAR@RHIC collider mode				
Energy (GeV)	Events (10^6)	**BES II** / BES I 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	**560**/30	**2018**/2011	156	162
19.6	**538**/15	**2019**/2011	206	160
14.5	**325**/13	**2019**/2014	264	156
*17.3**	*250*	*2021*	*227*	*158*
11.5	**230**/7	**2020**/2010	315	152
7.7	**100**/3	**2021**/2010	420	140

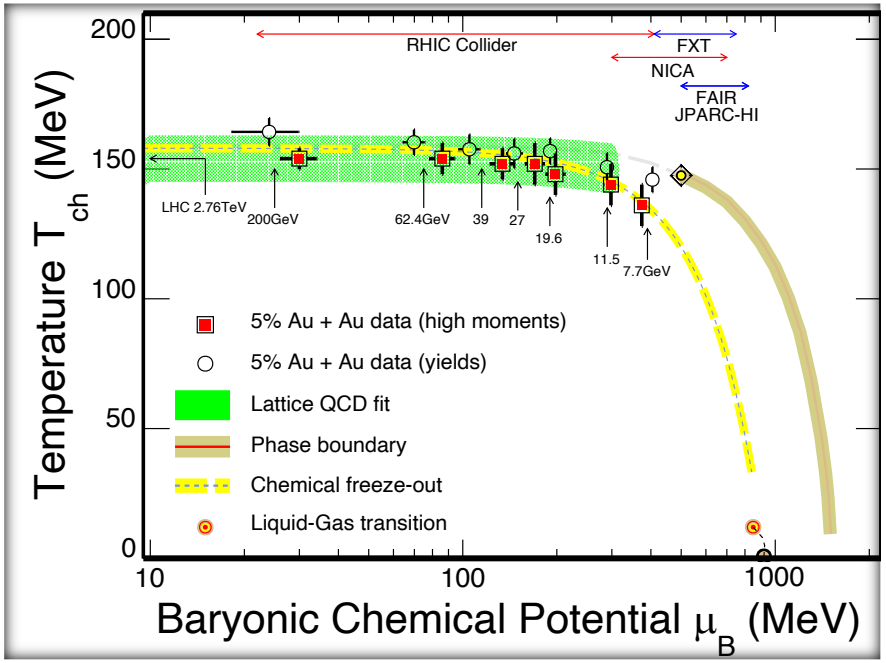
STAR@RHIC fixed target mode				
Energy (GeV)	Events (10^6)	BES II	μ_B (MeV)	T_{ch} (MeV)
7.7	112/50	2020/ 2019	420	140
6.2	118	2020	487	130
5.2	103	2020	541	121
4.5	108	2020	589	112
3.9	117	2020	633	102
3.5	116	2020	666	93
3.2	200	2019	699	86
3.0	259	2018	720	80
*3.0**	*2000*	*2021*	*720*	*80*

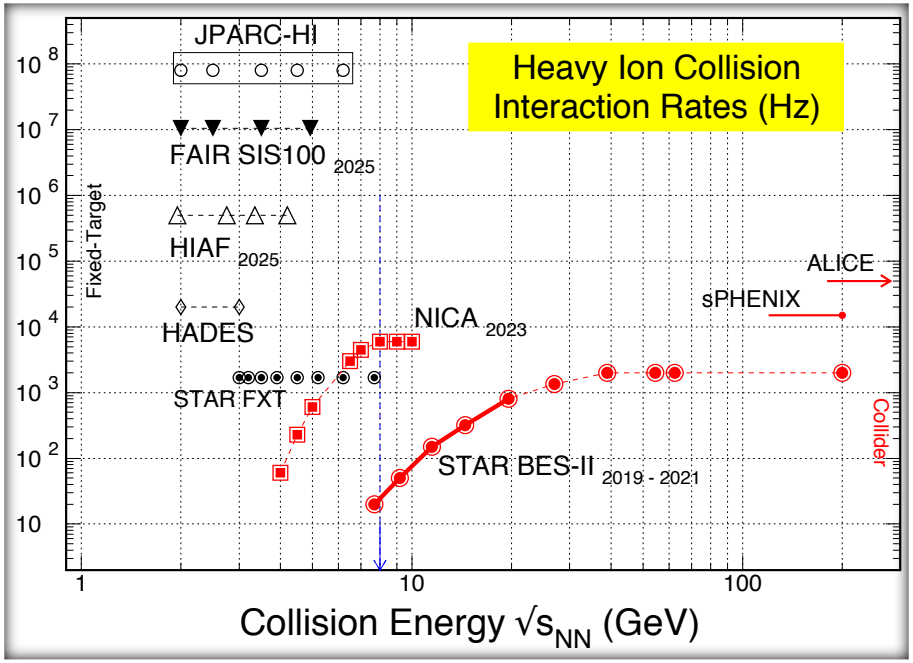
*Proposed

T_{ch} and μ_B:Phys. Rev. C 73 (2006) , 034905

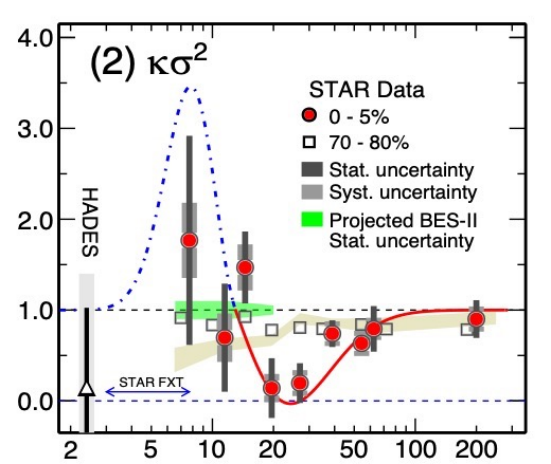
High statistics data has been collected over a wide μ_B range

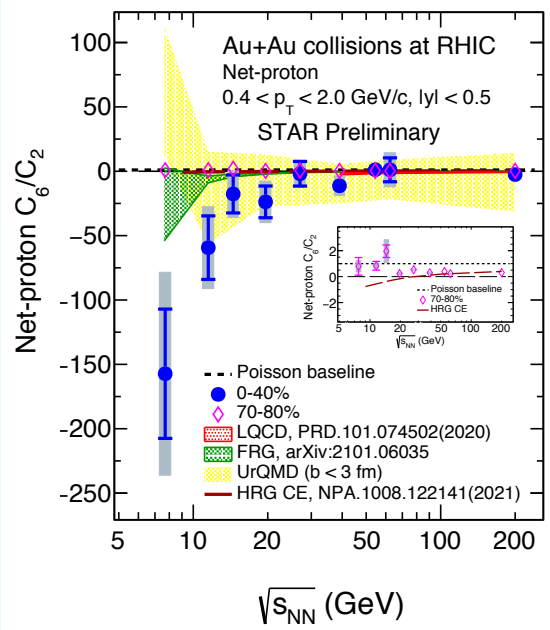
Experimental program for high baryon density matter





Summary





- Programs to carry out systematic study of the phase structure of QCD phase diagram through relativistic heavy ion collisions underway

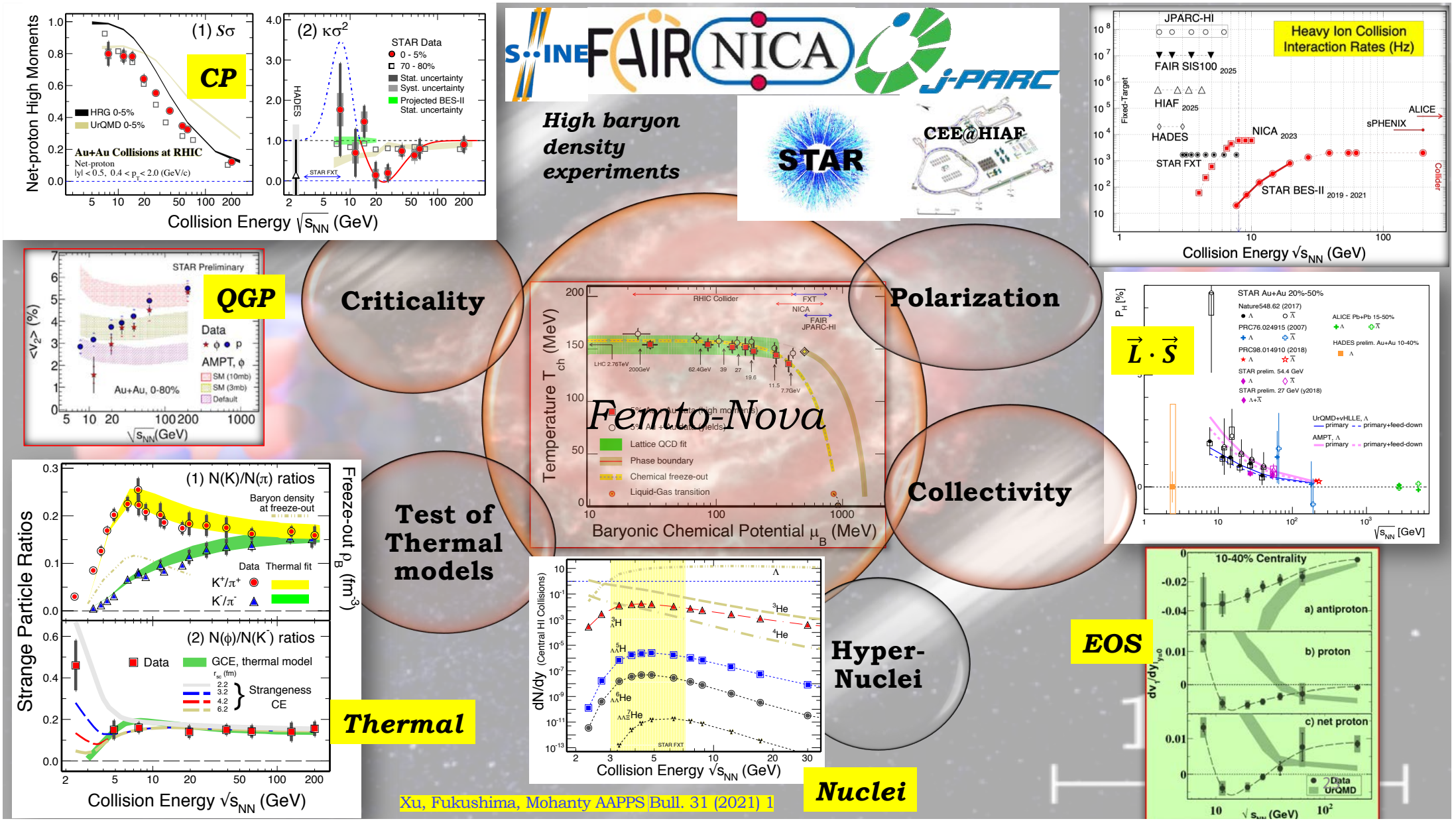
- Higher moments measurements seem to follow QCD thermodynamics

- Experimental evidences of signatures related to critical point observed at a 3 σ level

- Lattice QCD clearly shows cross over at $\mu_B = 0$.
- Experimental indications of cross over at μ_B = 20 MeV observed at < 2 σ level

- Hints of change of equation of state at high μ_B
- Need to continue the dedicated programs in the high baryon density regime to unfold the QCD phase diagram.

- Experiments: STAR@RHIC BES-II, CBM@FAIR, NICA@JNIR, SHINE@CERN-SPS, J-PARC-HI and CEE-HIAF complementary to each other


CP
(1) Sσ
(2) κσ²
HRG 0-5%
UrQMD 0-5%
Au+Au Collisions at RHIC
Net-proton
|y| < 0.5, 0.4 < p_T < 2.0 (GeV/c)
Net-proton High Moments
Collision Energy √s_NN (GeV)
STAR Data
0 - 5%
70 - 80%
Stat. uncertainty
Syst. uncertainty
Projected BES-II Stat. uncertainty
HADES
STAR FXT
High baryon density experiments
SIS100
FAIR
NICA
J-PARC
STAR
CEE@HIAF
JPARC-HI
FAIR SIS100 2025
HIAF 2025
HADES
NICA 2023
STAR FXT
STAR BES-II 2019 - 2021
ALICE
sPHENIX
Collider
Fixed-Target
Heavy Ion Collision Interaction Rates (Hz)
QGP
STAR Preliminary
Data
AMPT, φ
SM (10mb)
SM (3mb)
Default
Au+Au, 0-80%
<v2> (%)
Criticality
Polarization
Femto-Nova
RHIC Collider
FXT
NICA
FAIR
JPARC-HI
LHC 2.76TeV
200GeV
62.4GeV
39
27
19.6
11.5
7.7GeV
Lattice QCD fit
Phase boundary
Chemical freeze-out
Liquid-Gas transition
Temperature T_ch (MeV)
Baryonic Chemical Potential μ_B (MeV)
L · S
STAR Au+Au 20%-50%
Nature548.62 (2017)
PRC76.024915 (2007)
PRC98.014910 (2018)
STAR prelim. 54.4 GeV
STAR prelim. 27 GeV (y2018)
ALICE Pb+Pb 15-50%
HADES prelim. Au+Au 10-40%
UrQMD+vHLLE, Λ
AMPT, Λ
primary
primary+feed-down
P_H [%]
√s_NN [GeV]
Test of Thermal models
Collectivity
(1) N(K)/N(π) ratios
Baryon density at freeze-out
Data Thermal fit
K⁺/π⁺
K⁻/π⁻
(2) N(φ)/N(K⁻) ratios
Data
GCE, thermal model
r_sc (fm)
2.2
3.2
4.2
6.2
Strangeness CE
Strange Particle Ratios
Freeze-out ρ_B (fm⁻³)
Collision Energy √s_NN (GeV)
Thermal
dN/dy (Central HI Collisions)
Λ
³He
⁴He
³ΛH
⁵ΛΛH
⁶ΛΛHe
⁷ΛΛ²He
STAR FXT
Collision Energy √s_NN (GeV)
Hyper-Nuclei
EOS
10-40% Centrality
a) antiproton
b) proton
c) net proton
Data
UrQMD
dv1/dy|y=0
√s_NN (GeV)
Nuclei
Xu, Fukushima, Mohanty AAPPS Bull. 31 (2021) 1

Acknowledgements

All members of the STAR Collaboration, F. Karsch & S. Gupta.
Thanks to the organizers for the invitation.