QCD Critical Point and Net-proton Number Fluctuations

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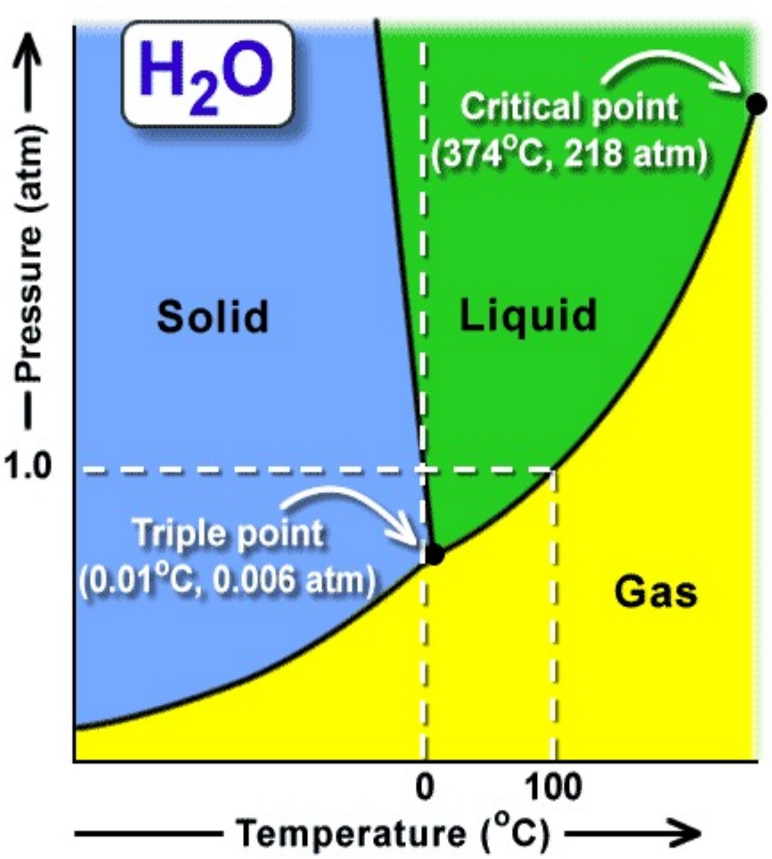
April 7th, 2021

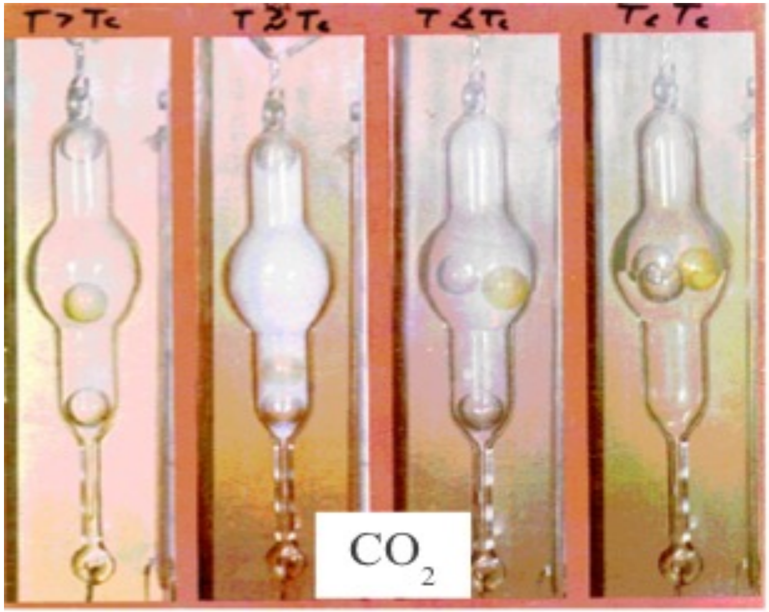
Phase Diagram: Water

How matter self-organized by varying external conditions.



Thermal motion Vs. Interactions
(Chaos) (Ordered)

Critical Point and Critical Phenomena



T. Andrews.Phil. Trans. Royal Soc., 159:575 (1869).

https://royalsocietypublishing.org/doi/pdf/10.1098/rstl.1869.0021

- First CP was discovered in 1869 for CO_2 by Andrews.

T_c = 31°C

Explained by Van der Waals (1873)

Nobel Prize 1910.

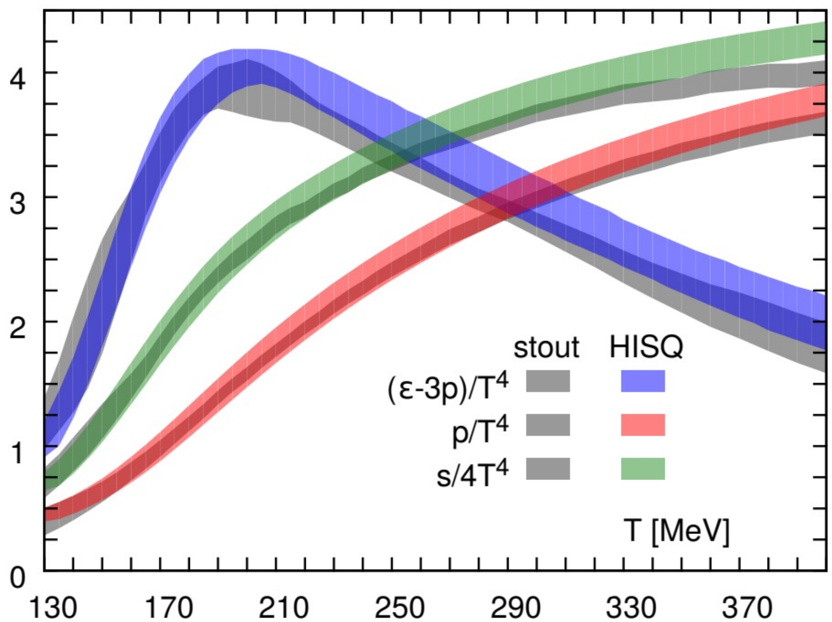
$$\left(P + a\frac{n^2}{V^2}\right)(V - nb) = nRT$$

Reviewed by : J. C. Maxwell, Nature 10, 477 (1874)

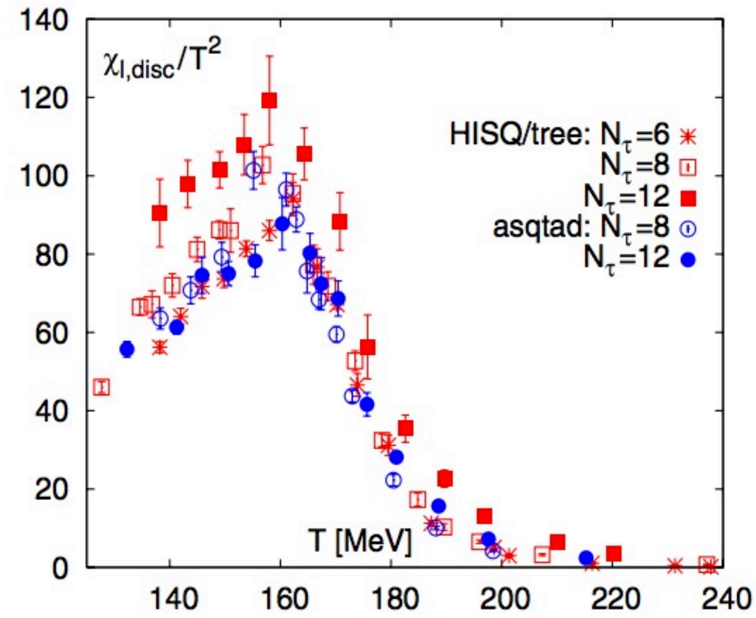
Critical Phenomena :

- Singularity of EoS : divergence of correlation length (ξ), susceptibilities (χ), heat capacity (C_V), critical opalescence.
- Universality and critical exponents : determined by degree of freedom and symmetry of system. (Landau mean field theory、renormalization group theory)
- Finite size/time effects.

QCD Thermodynamics (μ_B=0) : Lattice QCD



A. Bazavov, et al. (hotQCD), PRD 90, 094503 (2014)



S Borsanyi, et al. (WB), JHEP 1009, 073 (2010).
T. Bhattacharya, et al (hotQCD), PRL 113, 082001 (2014);
A. Bazavov (hotQCD), PRD 85,054503 (2012); PLB 795, 15 (2019)

Rapid rise of the energy density:

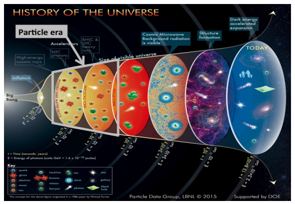
- Rapid increase in degrees of freedom due to transition from hadrons to quarks and gluons.

Chiral susceptibility peaks at T_c:

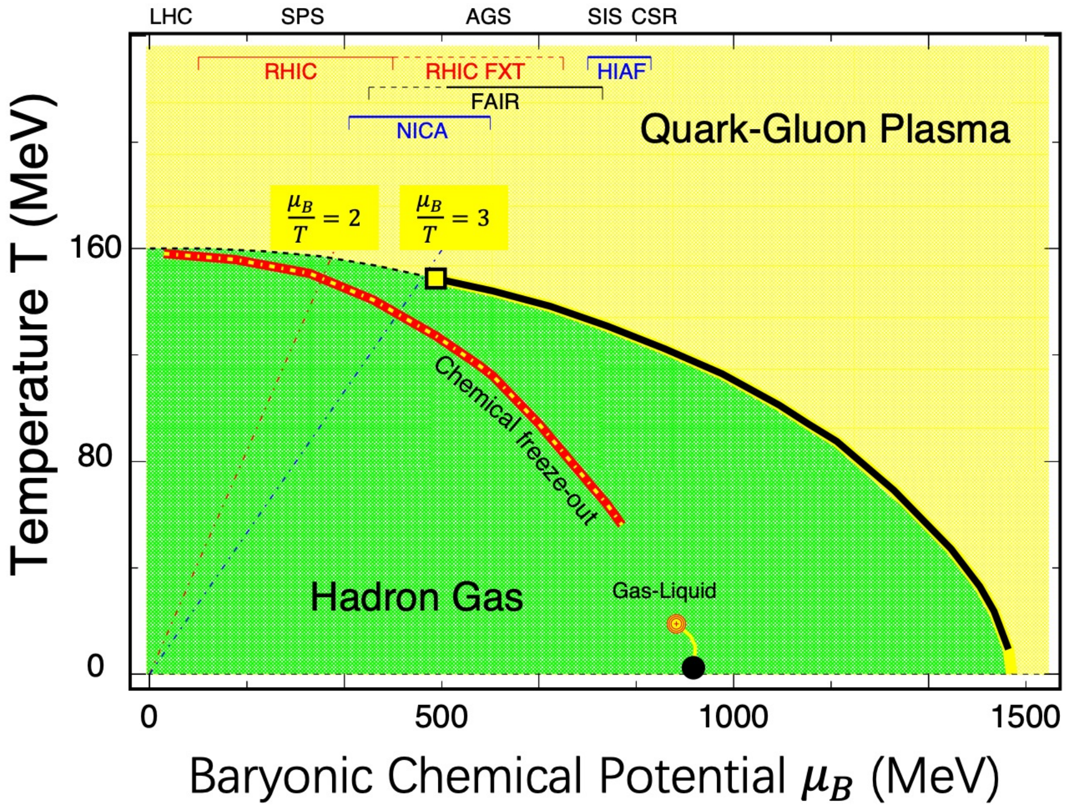
$$\chi_{\bar{\Psi}\Psi} = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial m^2}$$

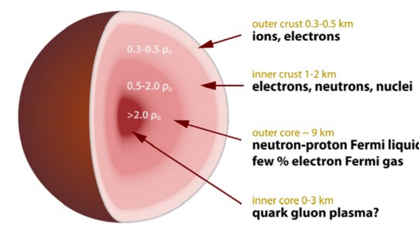
Transition at μ_B=0 with T_c ~ 156 MeV
~ trillion ℃ (10^{12})

QCD Phase Diagram



Emergent Properties of Strong Interactions : More is Different





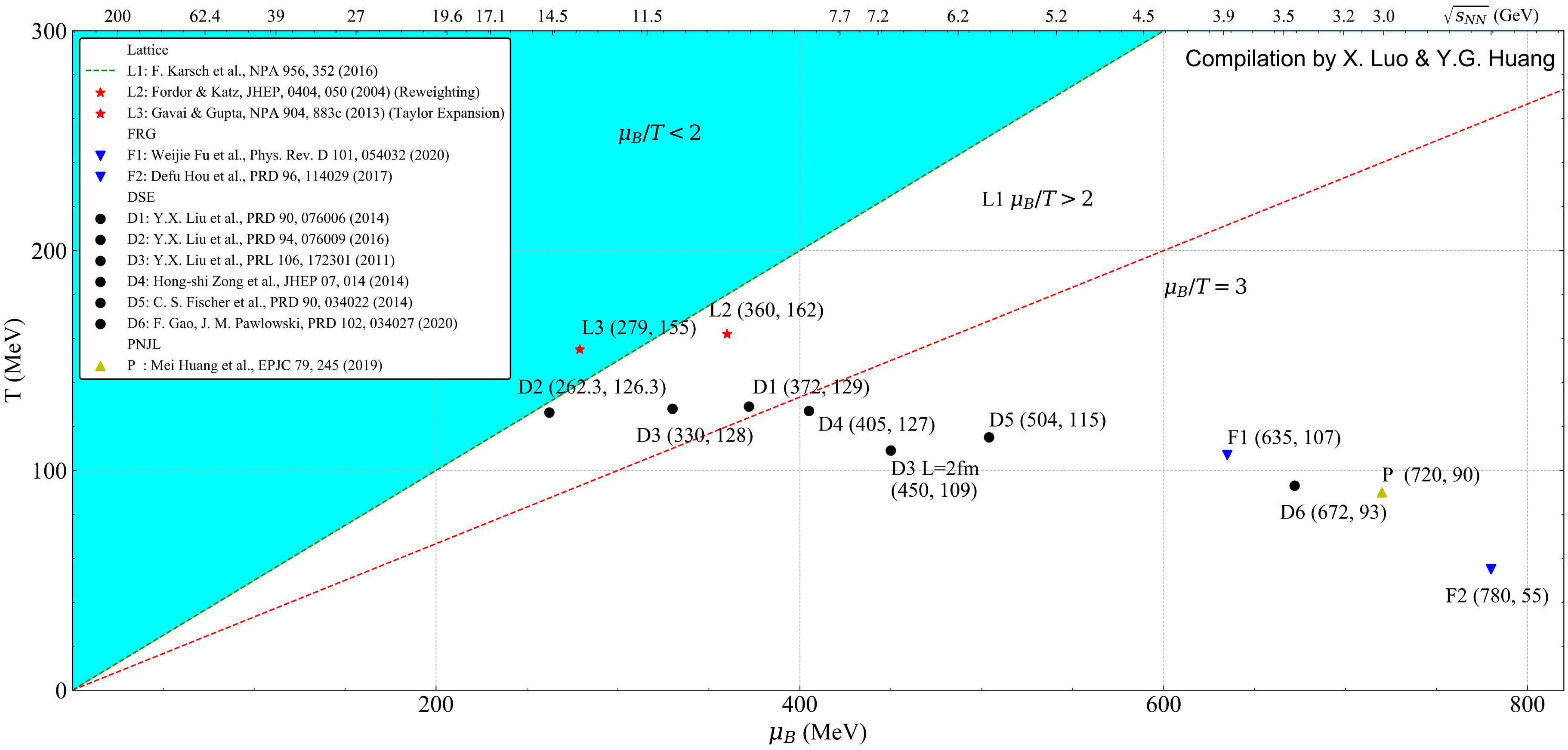
Y. Aoki et al., Nature 443, 675 (2006) ; A. Bazavov et al, PRD 85, 054503 (2012).
K. Fukushima and C. Sasaki, Prog. Part. Nucl. Phys, 72, 99 (2013).
A. Bzdak et al., Phys. Rep. 853, 1 (2020).

Experimental Evidence ?

Lattice QCD : at $\mu_B = 0$, smooth crossover.
Large μ_B : 1st order phase transition and QCD critical point.

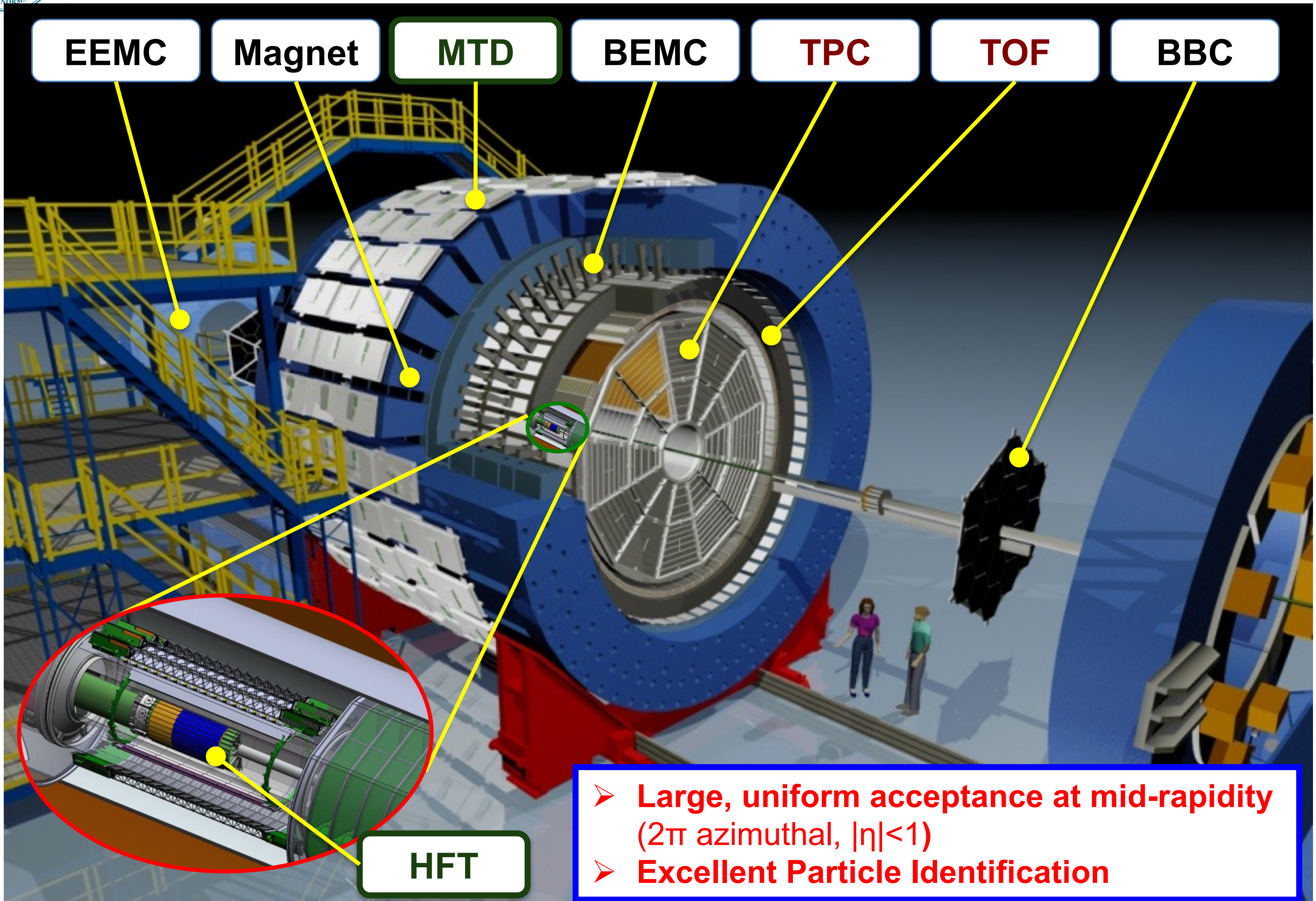
Location of CP : Theoretical Prediction

Preliminary collection from Lattice, DSE, FRG and PNJL (2004-2020)



Large uncertainties for the estimation of CP location.

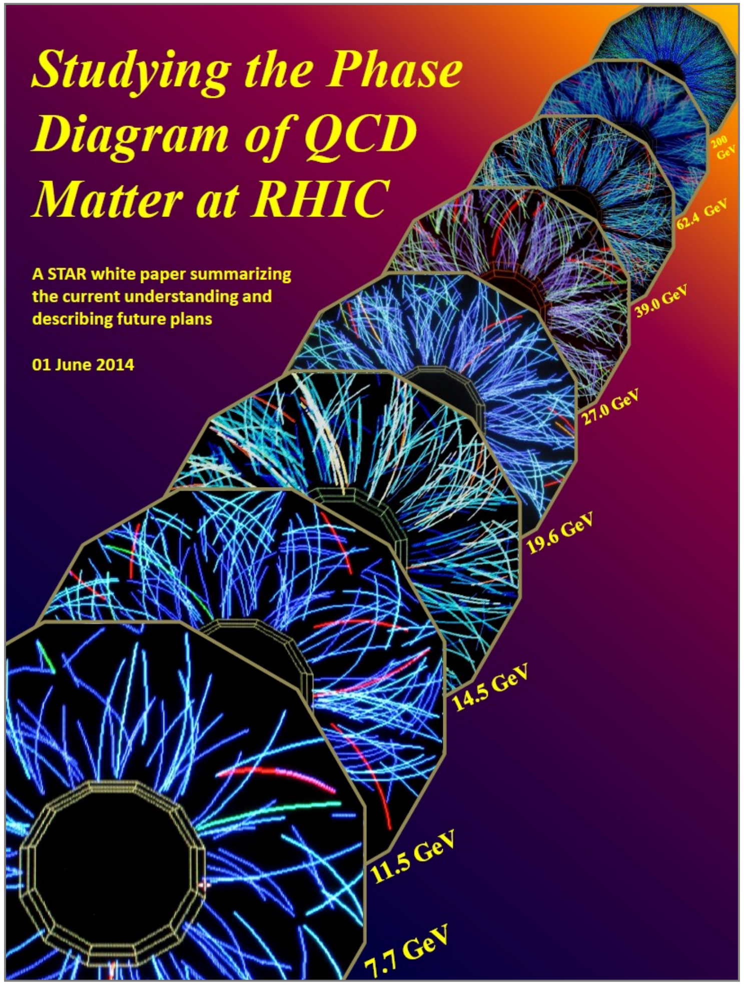
STAR Detector System



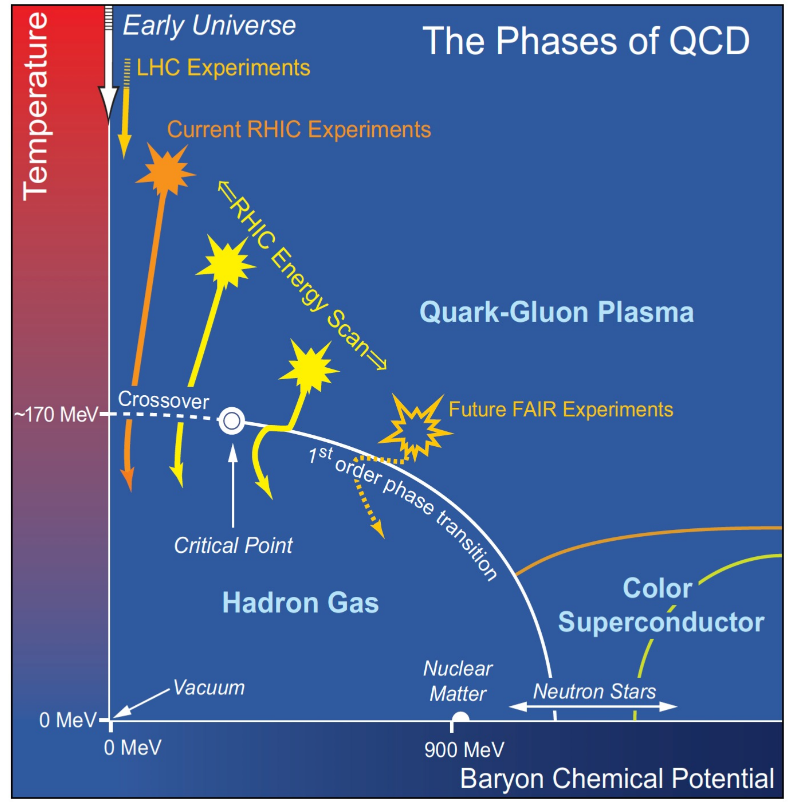
- **Large, uniform acceptance at mid-rapidity**
  (2π azimuthal, |η|<1)
- **Excellent Particle Identification**

STAR Beam Energy Scan Adventure

BES-II White Paper (2014)



- BES first proposed to PAC 2006,
- STAR BES campaign formally started in 2010
- BES-II officially requested in 2014, starts 2019(18)



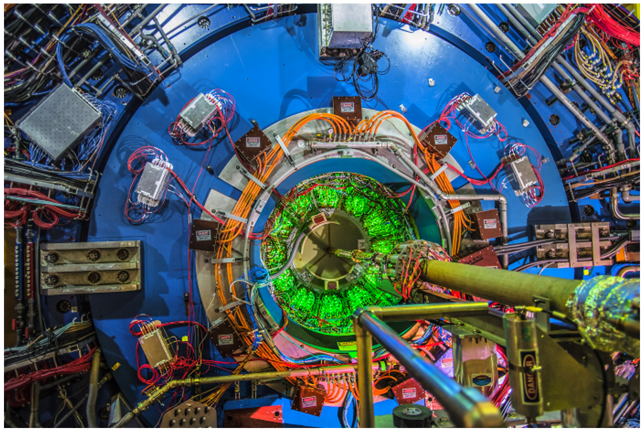
Main Motivation:

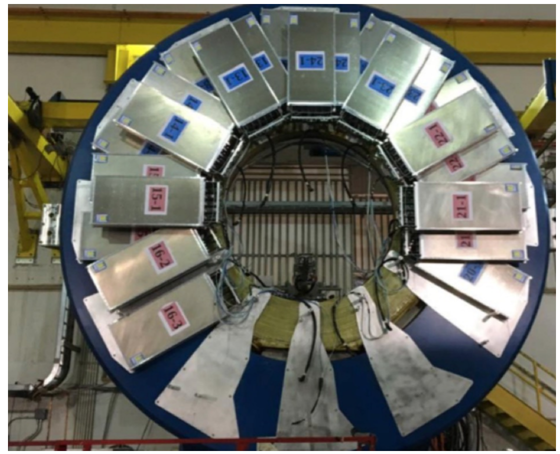
- Looking for turning off QGP signals observed at RHIC top energy.
- Mapping out the crossover and/or 1st order QCD phase boundary
- Search for the signatures of possible QCD critical point.

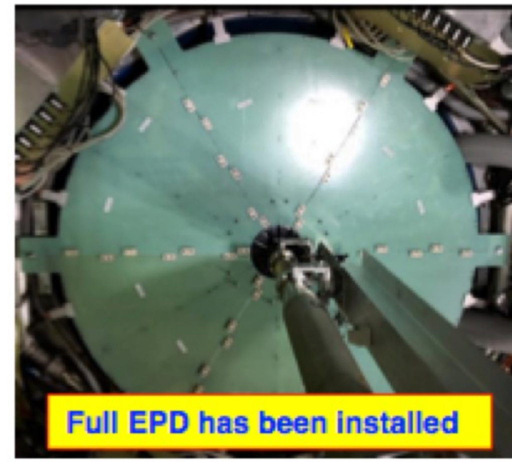
STAR, arXiv:1007.2613
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0493
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

Major Upgrades for BES-II

All 3 detectors fully installed prior to start of Run-19
Very successful and important for BES-II







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

EndCap TOF:
- Forward rapidity coverage is critical
- PID at η = 0.9 to 1.5
- Improves the fixed target program
- Provided by CBM-FAIR
- Ready in 2019

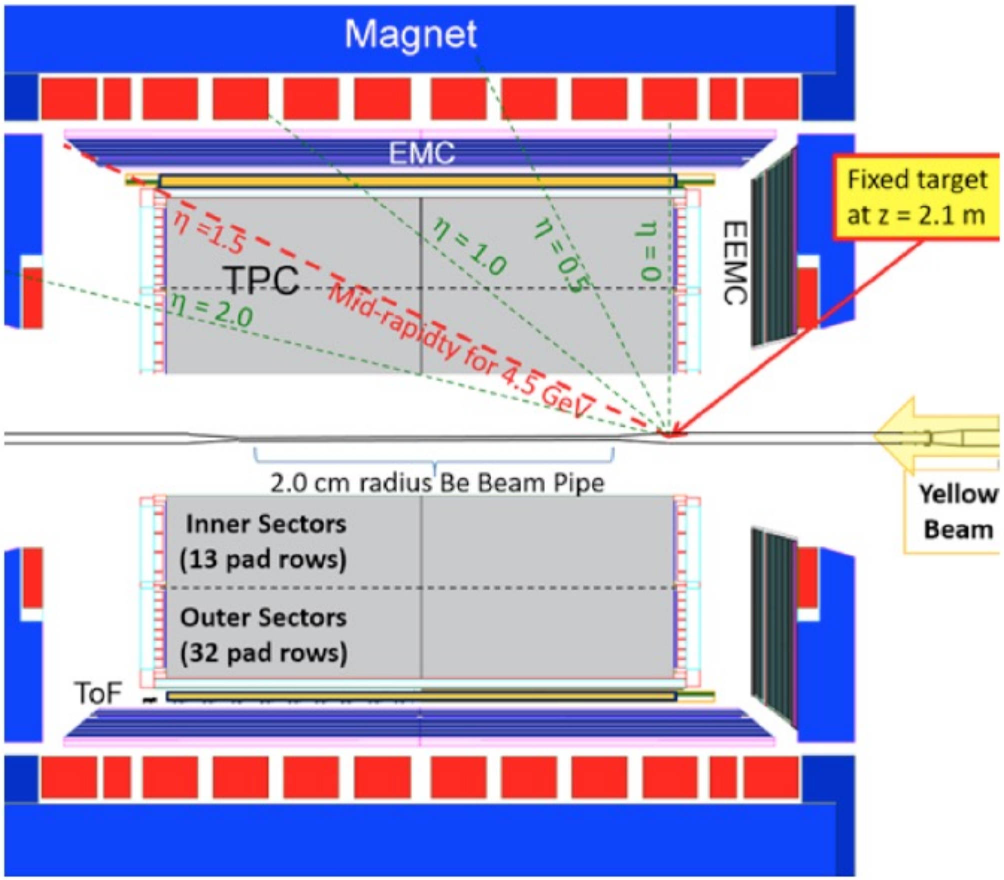
EPD:
- Improves trigger
- Reduces background
- Allows a better centrality and reaction plane measurement

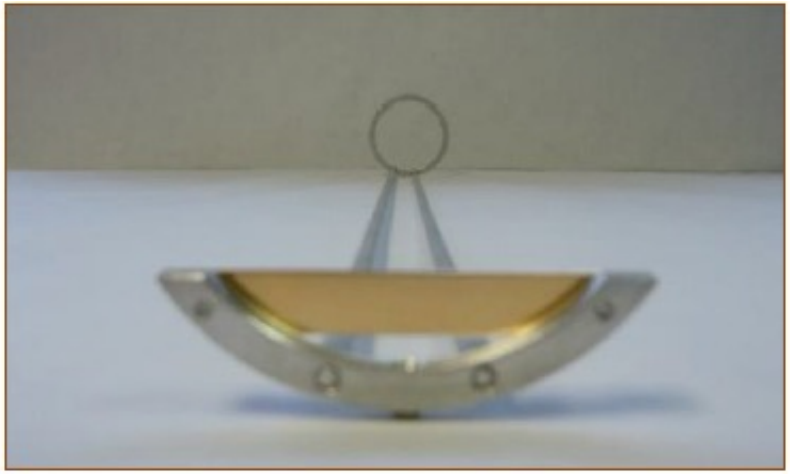
Ready in 2018

iTPC: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0619
eTOF: STAR and CBM eTOF group, arXiv: 1609.05102
EPD: J. Adams, et al. Nucl. Instr. Meth. A 968, 163970 (2020)

1) **Enlarge rapidity acceptance**
2) **Improve particle identification**
3) **Enhance centrality/EP resolution**

FXT Experiments at STAR (2018-2021)





Target design: Gold foil

1 mm Thick , ~1 cm High

~4 cm Wide, 210 cm from IR

FXT Data Taking Plan:
2015: Au+Au: 4.5 GeV (test Run)
2018: Au+Au :3 GeV (100 million events)
2019-2020: Au+Au: 6.2, 5, 4.5, 4, 3.5 GeV
2021: 3 GeV

Extend μ_B up to ~ 720 MeV
Explore High Baryon Density Region !

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

Collider mode   Au+Au Collisions   FXT mode

$\sqrt{s_{NN}}$ (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
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** / 3	**2021**/2010	420	140
17.1*	**250**	**2021**	230	158

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES II	μ_B (MeV)	T_{CH} (MeV)
7.7	**50+112**	**2019+2020**	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

T_{ch} and μ_B from J. Cleymans et al. PRC73, 034905 (2006)
*Newly Proposed Energy in Beam User Request 2021.

BES-II and FXT Program: data taking smoothly and reached the goal of statistics.

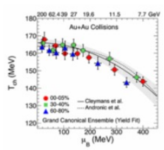
- Precisely map the QCD phase diagram **200 < μ_B < 720 MeV**

Particle Production and Freeze-out Dynamics

Bulk properties of the medium produced in relativistic heavy-ion collisions from the beam energy scan program

L. Adamczyk *et al.* (STAR Collaboration)

Phys. Rev. C **96**, 044904 (2017) – Published 13 October 2017



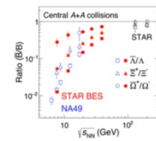
The beam-energy scan at RHIC aims to discover whether a critical point exists in the phase diagram of QCD. This paper reports on the most comprehensive measurement of single-particle spectra for a multitude of hadrons from the first run, taken with the STAR experiment. From these the authors infer the kinetic and chemical freeze-out temperatures and the baryon chemical potential as functions of beam energy and centrality. The results provide an opportunity for the beam-energy scan program at RHIC to enlarge the $(T, \mu B)$ region of the phase diagram to search for the QCD critical point.

Show Abstract +

Strange hadron production in Au + Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27,$ and 39 GeV

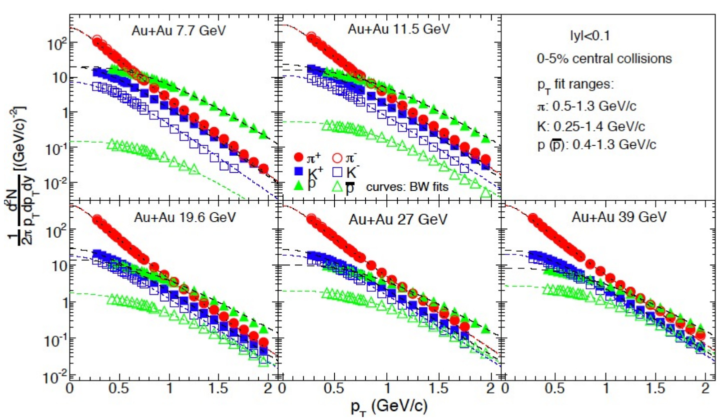
J. Adam *et al.* (STAR Collaboration)

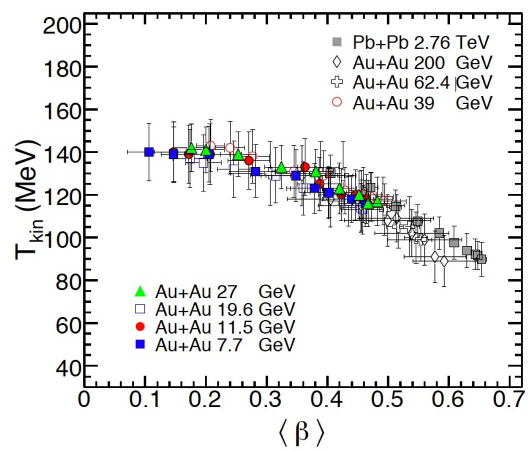
Phys. Rev. C **102**, 034909 (2020) – Published 29 September 2020

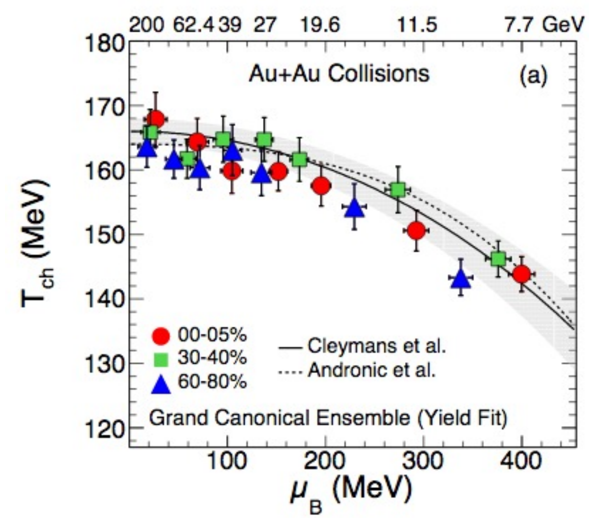


Strange hadrons are an excellent probe for identifying the phase boundary and onset of deconfinement in the QCD phase diagram. The STAR Collaboration has performed precision measurements of the abundances and transverse-momentum distributions for 8 species of strange mesons and baryons, as functions of centrality during a Au+Au beam-energy scan at RHIC. The results point to a possible change in strange-hadron production dynamics for $\sqrt{s_{NN}} < 20$ GeV. The results significantly improve the experimental knowledge in the energy range where key features of the QCD phase diagram are nowadays being studied.

Show Abstract +

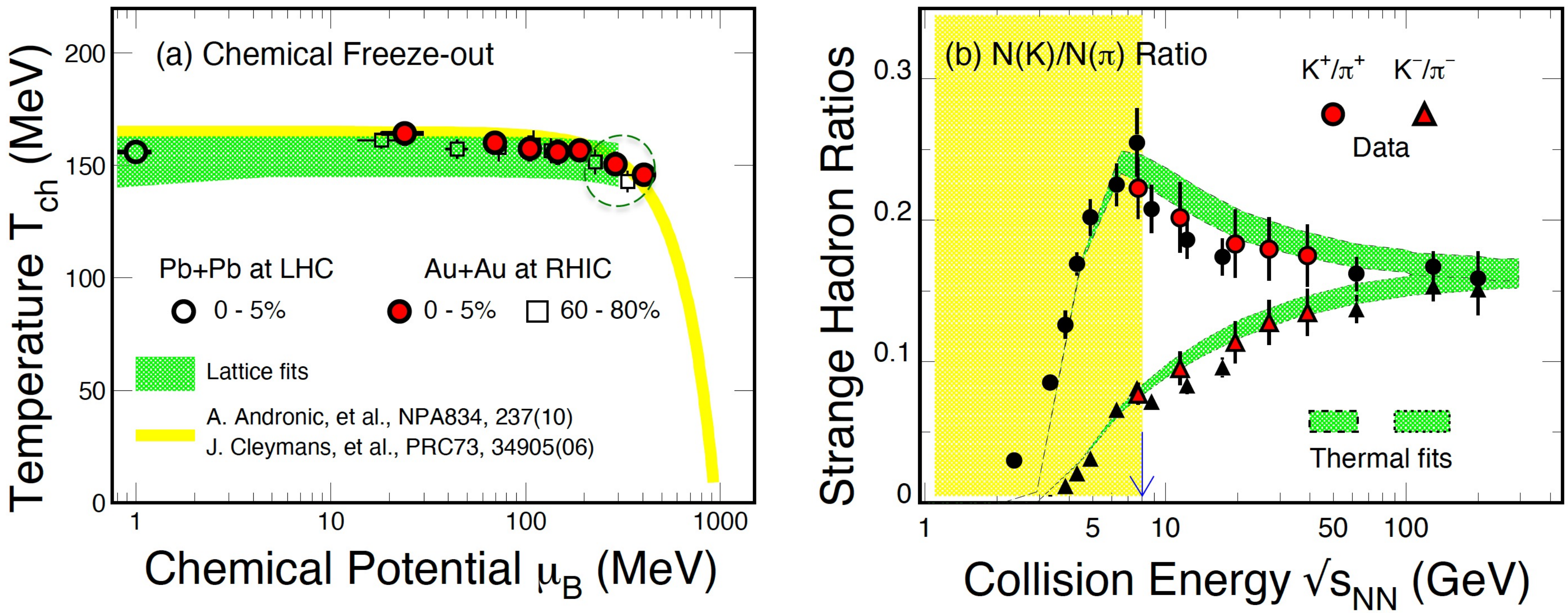






Chemical freeze-out and QCD phase boundary

By courtesy of Dr. N. Xu



- The chemical freeze-out T and μ_B (GCE) are close to the phase boundary determined from Lattice QCD with μ_B < 300 MeV.
- The peak of K^+/π^+ ratio around 8 GeV can be well described by thermal model, where the system start to enter into "high baryon density region". (< 8 GeV, μ_B> 420 MeV)

STAR : PRC96, 044904 (2017); PRC 102, 034909 (2020). ALICE : PRL 109, 252301 (2012), PRC 88, 044910 (2013). A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Nature 561, 321 (2018). X. Luo, S. Shi, N. Xu and Y. Zhang, Particle 3, 278 (2020); K. Fukushima, B. Mohanty, N. Xu, arXiv: 2009.03006; J. Randrup et al., Phys. Rev. C74, 047901(2006).

Fluctuations Probes the QCD Phase Transition

1. Fluctuations signals the QCD Critical Point.

M. Stephanov, K. Rajagopal, E. Shuryak, Phys. Rev. Lett. 81, 4816 (1998).
M. Stephanov, K. Rajagopal, E. Shuryak, Phys. Rev. D 60, 114028 (1999).

Probe singularity of the equation of state: Divergence of the fluctuations.

2. Fluctuations signals the Quark Deconfinement.

S. Jeon and V. Koch, Phys. Rev. Lett. 85, 2076(2000).
M. Asakawa, U. Heinz and B. Muller, Phys. Rev. Lett. 85, 2072 (2000).

Proposed experimental observables:

1. **Pion multiplicity fluctuations.**
2. **Mean p_T fluctuations.**
3. **Particle ratio fluctuations**

Higher Moments of Conserved Quantities (B, Q, S)

1. Higher order cumulants/moments: describe the shape of distributions and quantify fluctuations. (sensitive to the correlation length (ξ))

$$< \delta N >= N - < N >$$
$$C_1 = M =< N >$$
$$C_2 = \sigma^2 =< (\delta N)^2 >$$
$$C_3 = S\sigma^3 =< (\delta N)^3 >$$
$$C_4 = \kappa\sigma^4 =< (\delta N)^4 > -3 < (\delta N)^2 >^2$$

$$\left\langle (\delta N)^3 \right\rangle_c \approx \xi^{4.5}, \quad \left\langle (\delta N)^4 \right\rangle_c \approx \xi^7$$

M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009).
M.Asakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009).
M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011).

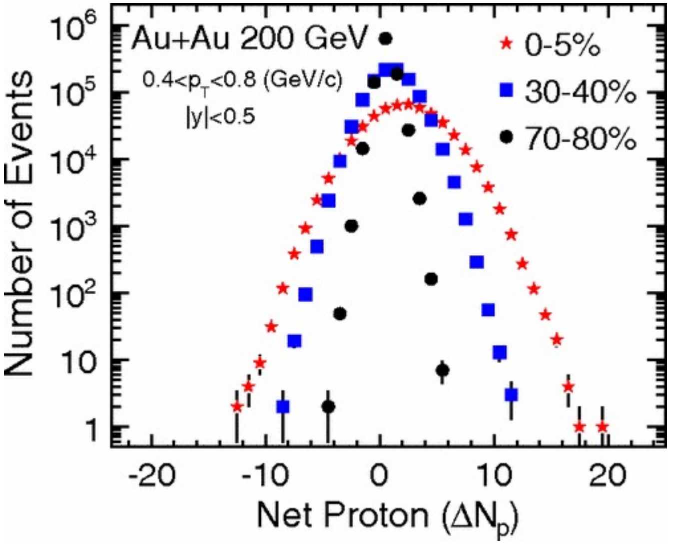
2. Direct connect to the susceptibility of the system.

$$\frac{\chi_q^4}{\chi_q^2} = \kappa\sigma^2 = \frac{C_{4,q}}{C_{2,q}} \qquad \frac{\chi_q^3}{\chi_q^2} = S\sigma = \frac{C_{3,q}}{C_{2,q}},$$

$$\chi_q^{(n)} = \frac{1}{VT^3} \times C_{n,q} = \frac{\partial^n (p/T^4)}{\partial (\mu_q)^n}, q = B,Q,S$$

S. Ejiri et al,Phys.Lett. B 633 (2006) 275. Cheng et al, PRD (2009) 074505. B. Friman et al., EPJC 71 (2011) 1694. F. Karsch and K. Redlich , PLB 695, 136 (2011).S. Gupta, et al., Science, 332, 1525(2012). A. Bazavov et al., PRL109, 192302(12) // S. Borsanyi et al., PRL111, 062005(13)

Event-by-Event Distribution



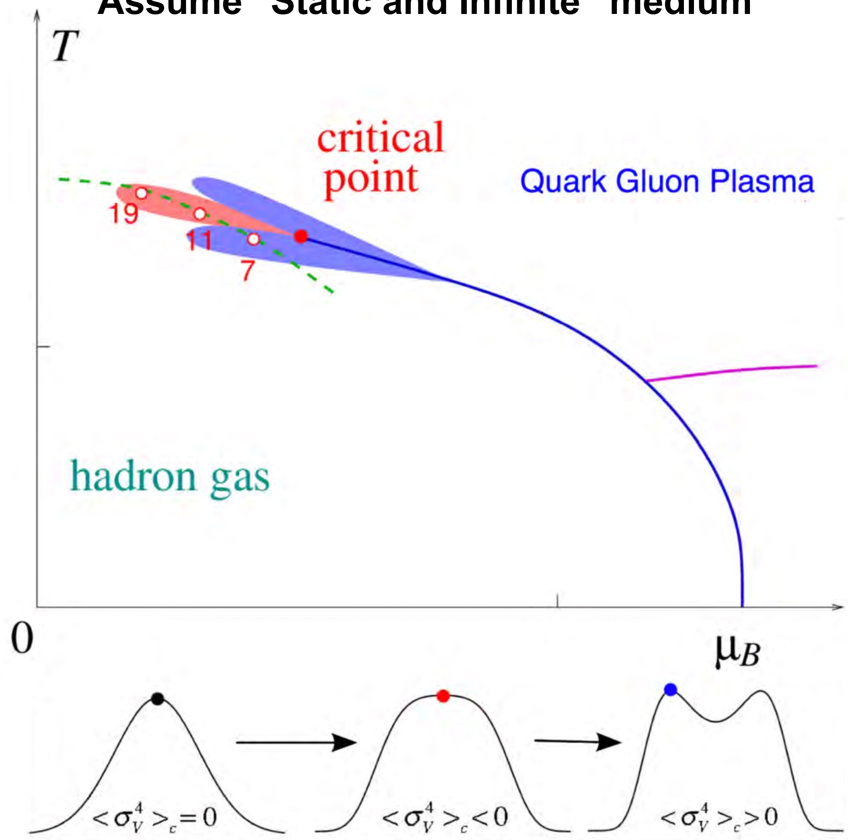
First Measurement : 2009-2010

STAR, PRL105, 022302 (2010).

- **Net-Proton:** $N_p - N_{\bar{p}}$
  (proxy: Net-Baryon)
- **Net-Charge:** $N_{Q^+} - N_{Q^-}$
- **Net-Kaon:** $N_{K^+} - N_{K^-}$
  (proxy: Net-Strangeness)

Signals of QCD Critical Point : Theory/Model

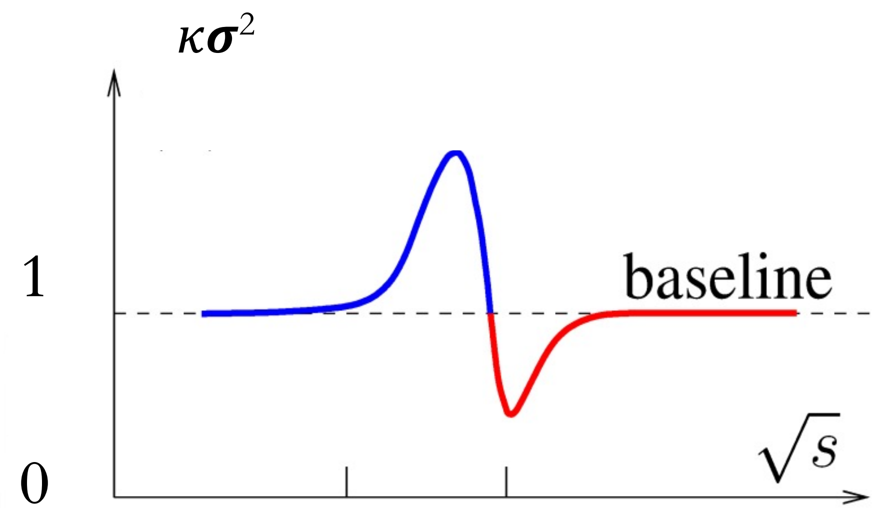
Assume "Static and Infinite" medium



M. Stephanov, PRL107, 052301 (2011); J. Phys. G 38, 124147 (2011).
Schaefer et al., PRD 85, 034027 (2012); W. Fu et al., PRD 94, 116020 (2016).
J.W. Chen, J. Deng, et al., PRD 93, 034037 (2016). PRD 95,014038 (2017).
W. K. Fan, X. Luo, H.S. Zong, IJMPA 32, 1750061 (2017);
G. Shao et al., EPJC 78, 138 (2018) ; Z. Li et al., EPJC 79, 245 (2019).
A. Bzdak et al., Phys. Rep. 853, 1(2020). D. Mroczek et al, arXiv: 2008.04022.

Caveats : Non-equilibrium, finite size/time effects

M. Asakawa, M. Kitazawa, B. Müller, PRC 101, 034913 (2020).
S Mukherjee, R. Venugopalan, Y Yin, PRL 117, 222301 (2016).
S. Wu, Z. Wu, H. Song, PRC 99, 064902 (2019).

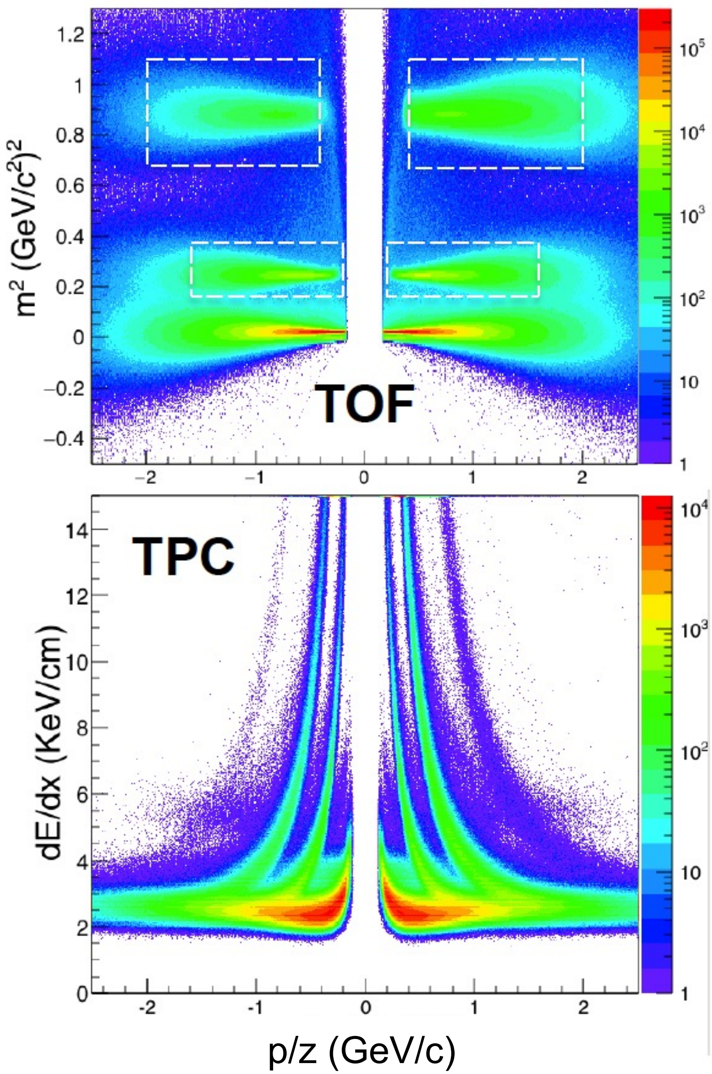


$\kappa\sigma^2 = 1$ (Poisson Fluctuations)

Characteristic signature of CP:
Non-monotonic energy dependence

"Oscillation Pattern"
Especially the Peak at low energies

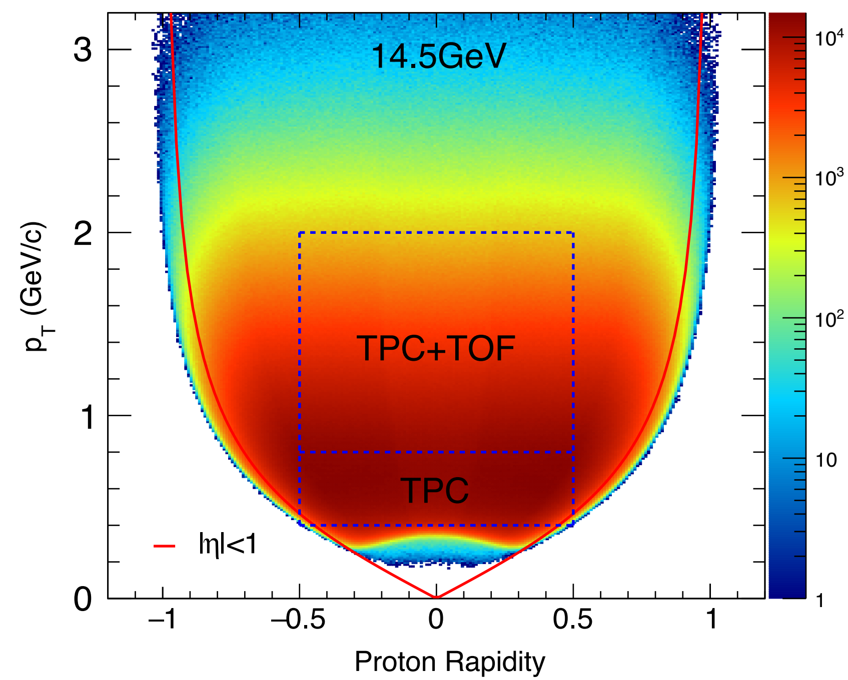
(Anti-) Proton PID and Acceptance



Extend the phase space coverage by TOF.

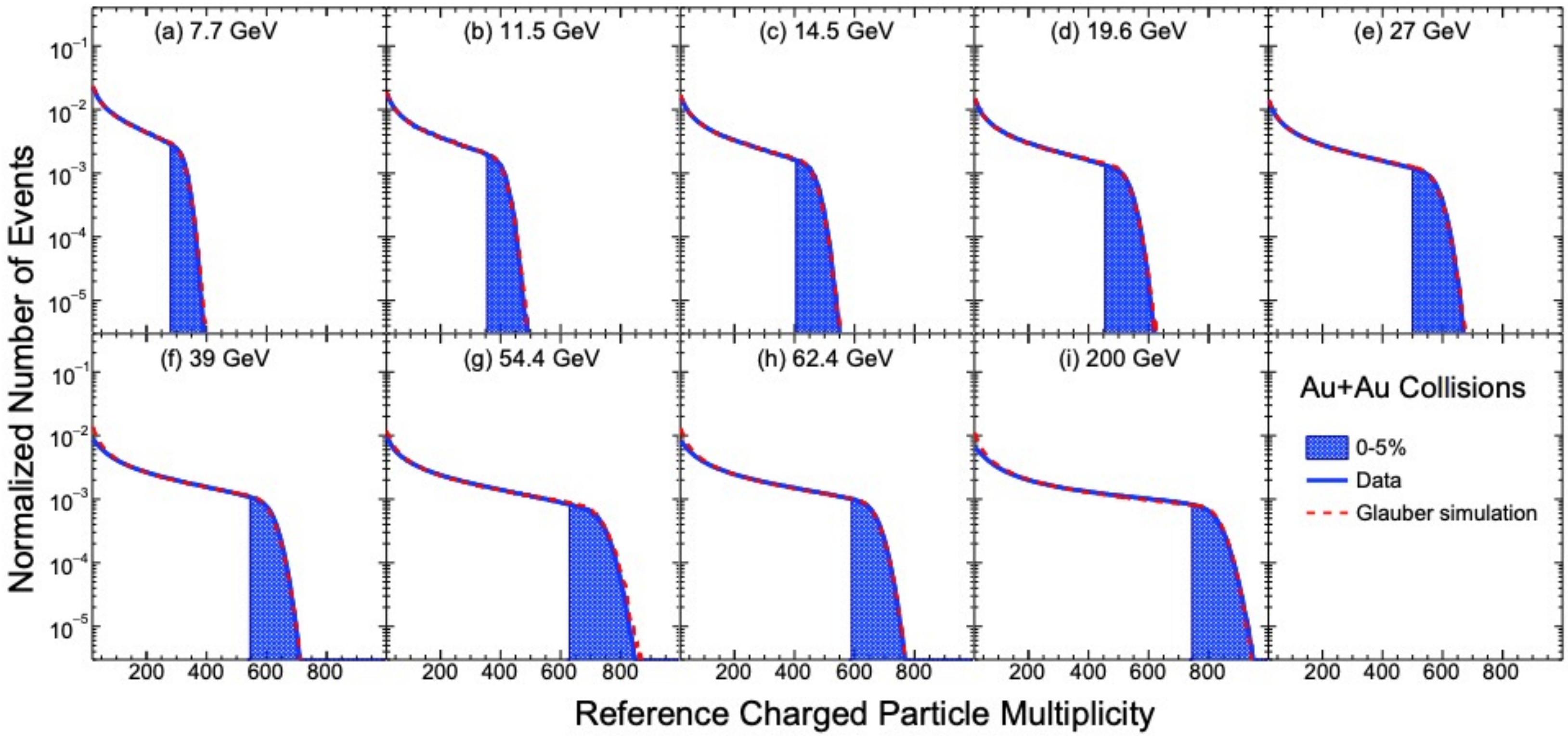
Doubled the accepted number of proton/anti-proton

$|y|<0.5$, $0.4 < p_T$ (GeV/c) < 0.8 (Low p_T, TPC PID)
$0.8 < p_T$ (GeV/c) < 2 (High p_T, TPC+TOF PID)



- Purity of proton and anti-proton identification > 97%.

Collision Centrality definitions



- Correlations between particles used in centrality definition and fluctuations. Methods to suppress/avoid self-correlations:

  1) kinematic separation : use particle in different kinematic regions to define centrality.

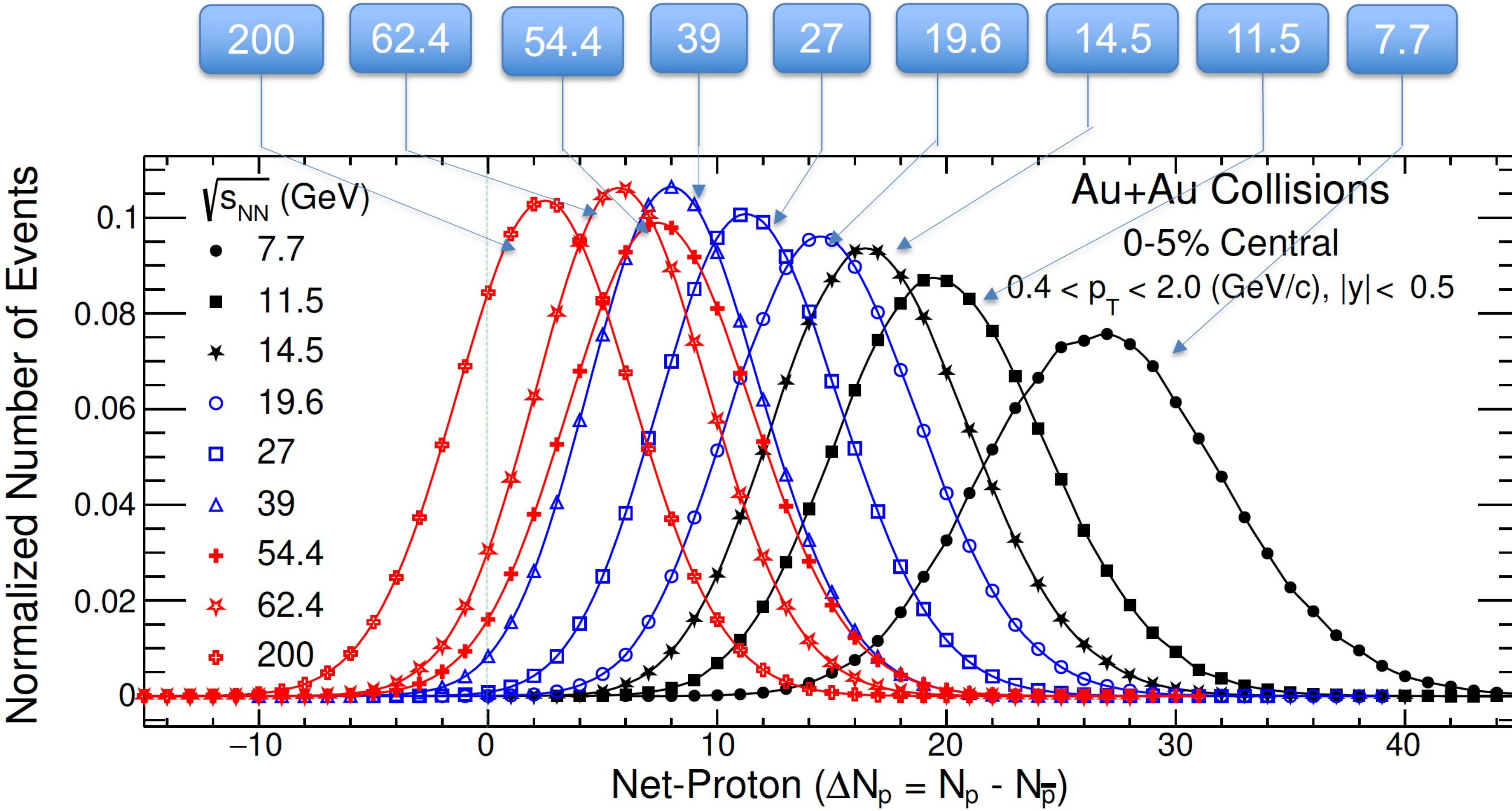
  Net-charge fluctuations: STAR, PRL 113, 092301 (2014).
  Off-diagonal 2nd order cumualnts: STAR, PRC100, 014902 (2019).
  Net-Lambda fluctuations : STAR, PRC102, 014903 (2020).

  2) Exclude particles used in fluctuation analysis from the centrality definition

  net-proton and net-kaon fluctuations : STAR, PRL 112, 032302 (2014); PRL 126, 092301 (2021); PLB 785, 551 (2018).

STAR, 2101.12413 (long paper)

Event-by-Event Net-Proton Distributions (0-5%)

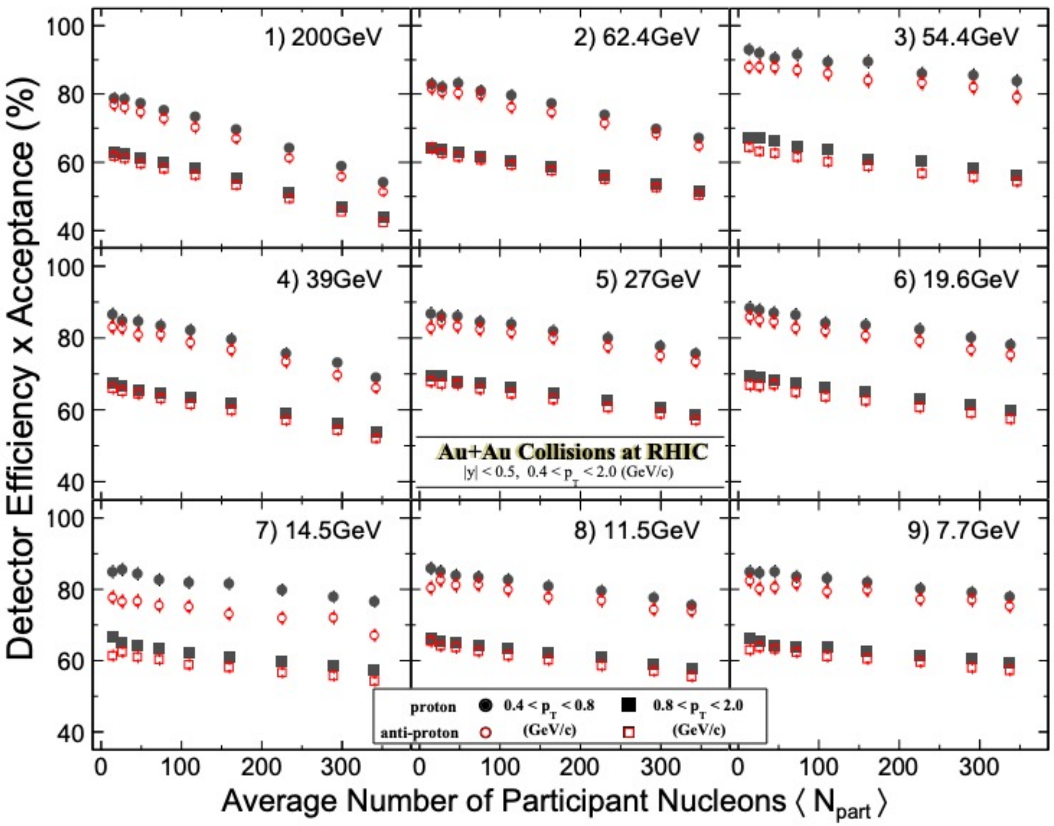


Efficiency uncorrected.

Mean values increase when decreasing energy:
Interplay between baryon stopping and pair production.

STAR, PRL 126, 092301 (2021)
STAR, 2101.12413 (long paper)

Efficiency Corrections for Proton and Anti-proton



STAR, PRL 126, 092301 (2021)
STAR, 2101.12413 (long paper)

Proton and anti-proton：

Factorial Moments -> Central Moments

$$m_n(N_p - N_{\bar{p}}) =< (N_p - N_{\bar{p}})^n >= \sum_{i=0}^{n} (-1)^i \binom{n}{i} < N_p^{n-i} N_{\bar{p}}^i >$$
$$= \sum_{i=0}^{n} (-1)^i \binom{n}{i} \left[\sum_{r_1=0}^{n-i} \sum_{r_2=0}^{i} s_2(n-i, r_1) s_2(i, r_2) F_{r_1,r_2}(N_p, N_{\bar{p}}) \right]$$
$$= \sum_{i=0}^{n} \sum_{r_1=0}^{n-i} \sum_{r_2=0}^{i} (-1)^i \binom{n}{i} s_2(n-i, r_1) s_2(i, r_2) F_{r_1,r_2}(N_p, N_{\bar{p}})$$

Central Moments -> Cumulant

$$C_r(N_p - N_{\bar{p}}) = m_r(N_p - N_{\bar{p}}) - \sum_{s=1}^{r-1} \binom{r-1}{s-1} C_s(N_p - N_{\bar{p}}) m_{r-s}(N_p - N_{\bar{p}})$$

A. Bzdak and V. Koch, PRC91, 027901 (2015)
X. Luo, Phys. Rev. C 91, 034907 (2015).

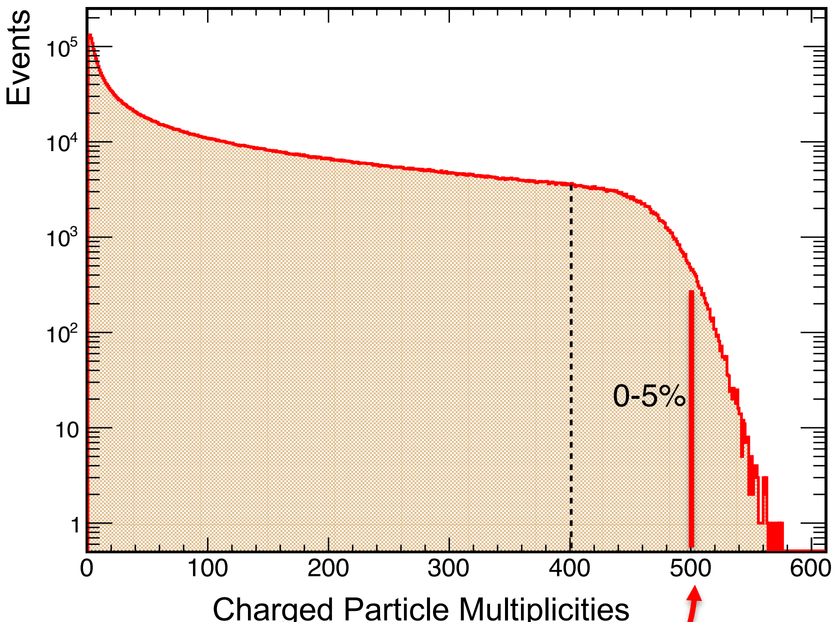
low p_T (TPC PID) > High p_T (TPC+TOF PID)
Central > Peripheral
Proton > Anti-proton

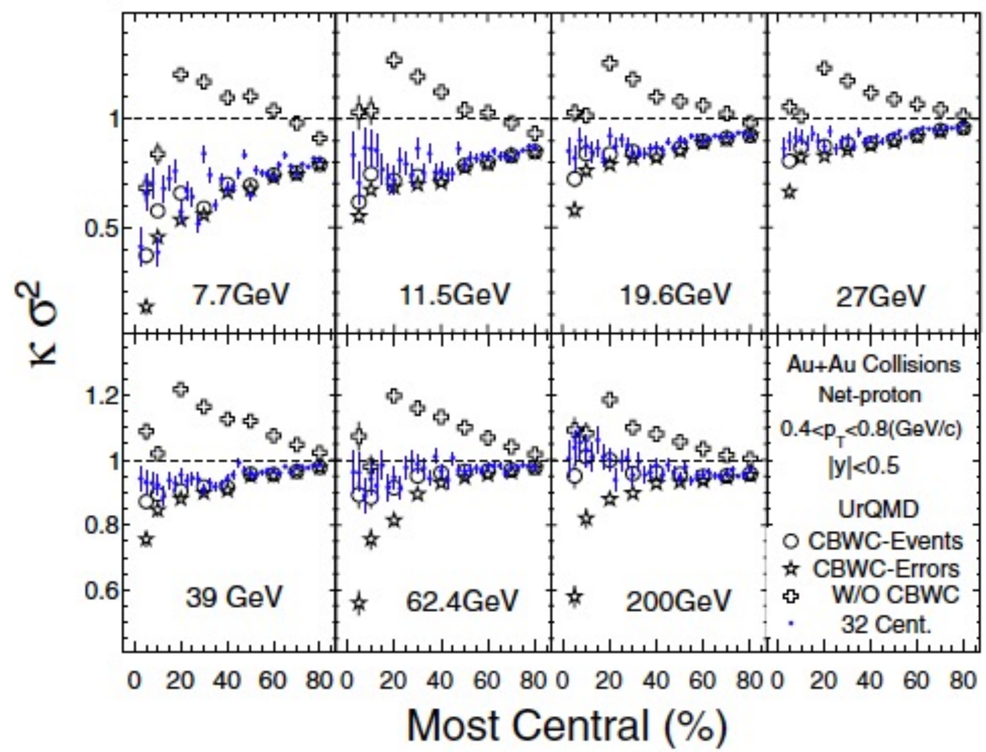
Track-by-track efficiency method (based on factorial cumulant):

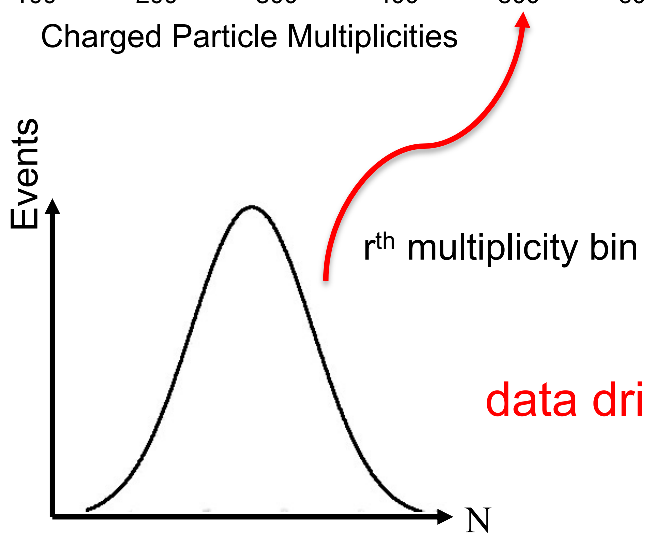
1. T. Nonaka et al., PRC95, 064912 (2017).
2. M. Kitazawa and X. Luo, PRC96, 024910 (2017).
3. X. Luo and T. Nonaka, PRC99, 044917 (2019).

Centrality Bin Width Correction (CBWC)

X.Luo, J. Xu, B. Mohanty and N. Xu. J. Phys. G 40,105104(2013).





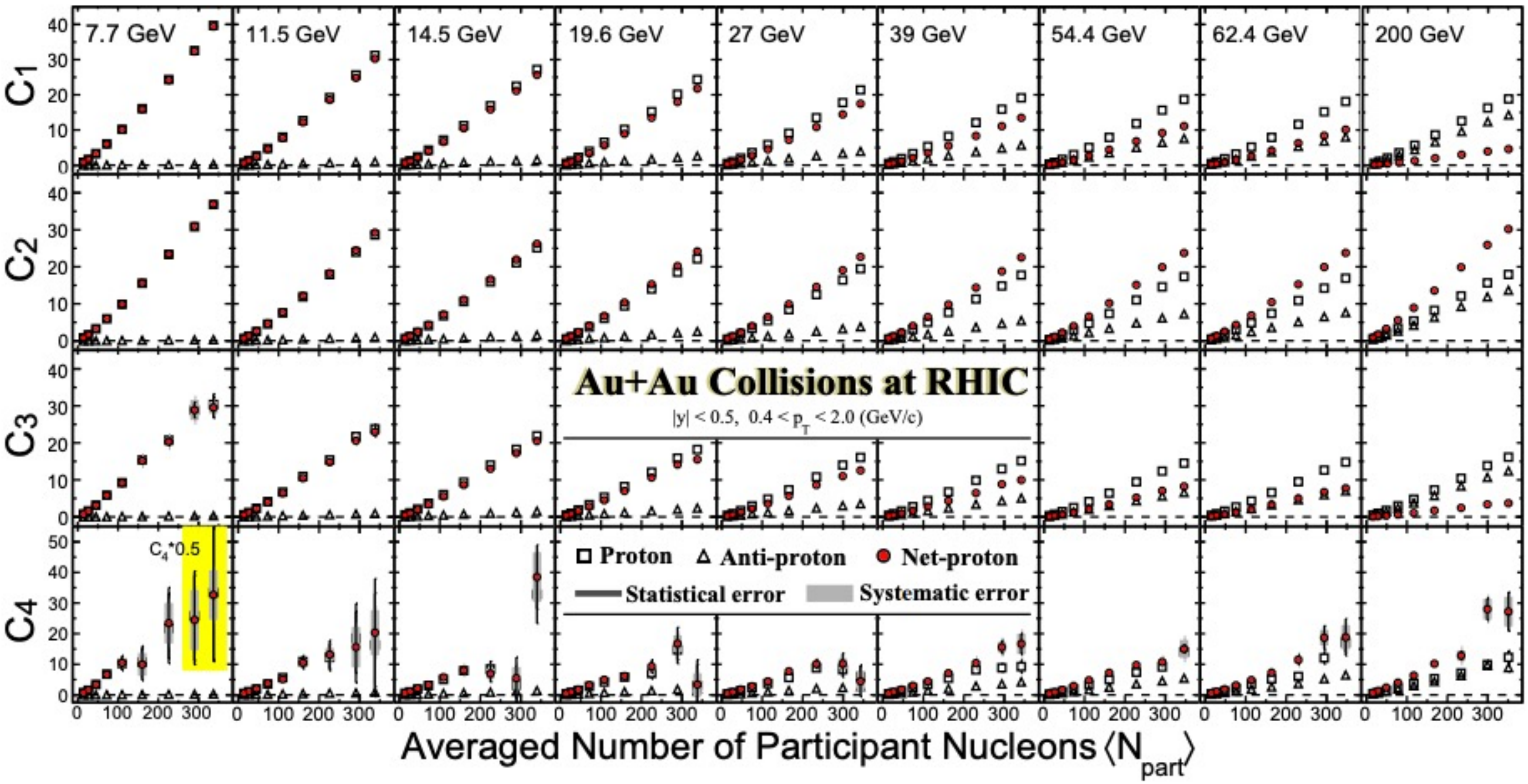


data driven approach

$$C_n = \frac{\sum_{r=N_1}^{N_2} n_r C_n^r}{\sum_{r=N_1}^{N_2} n_r} = \sum_{r=N_1}^{N_2} \omega_r C_n^r$$

r: r^{th} mul. bin, n_r : number of events in r^{th} bin

Centrality Dependence of Net-Proton Cumulant ($C_1 - C_4$)

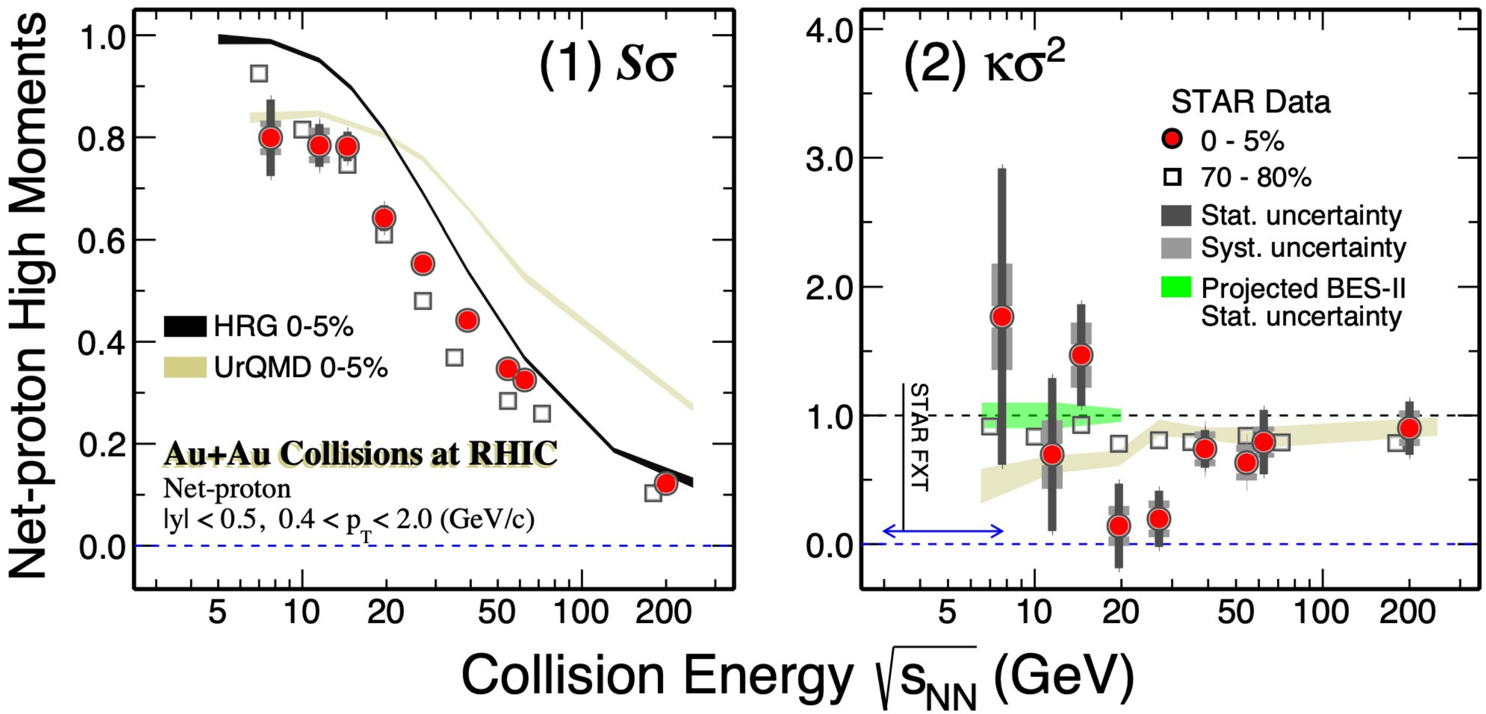


Efficiency and CBWC corrections applied.

- In general, cumulants are extensive quantity and proportional to the volume of system.
- Expecting sudden changes when passing through critical point/region.

STAR, PRL 126, 092301 (2021)
STAR, 2101.12413 (long paper)

Energy Dependence of Cumulant Ratios : $S\sigma$ and $\kappa\sigma^2$

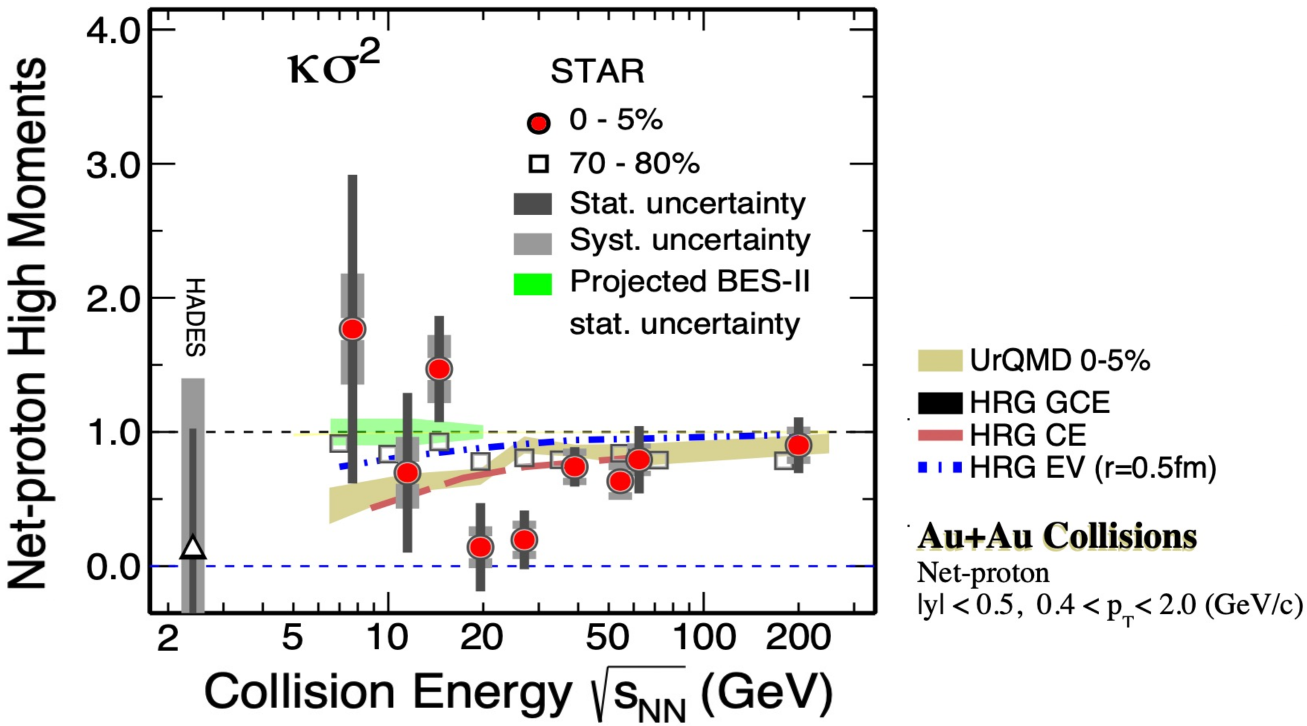


- HRG (GCE) and transport model predicted monotonical energy dependence. Suppression at low energy due to conservation.
- Observe a non-monotonic energy dependence in 0-5% net-proton $\kappa\sigma^2$ with a significant of 3.1σ

Is there a peak structure below 20 GeV ?
Need precise measurement at STAR (BES-II), CBM, NICA etc.

HADES, PRC 102, 024914 (2020)
STAR, PRL 126, 092301 (2021)
STAR, 2101.12413 (long paper)

Comparison between model calculations and exp. data

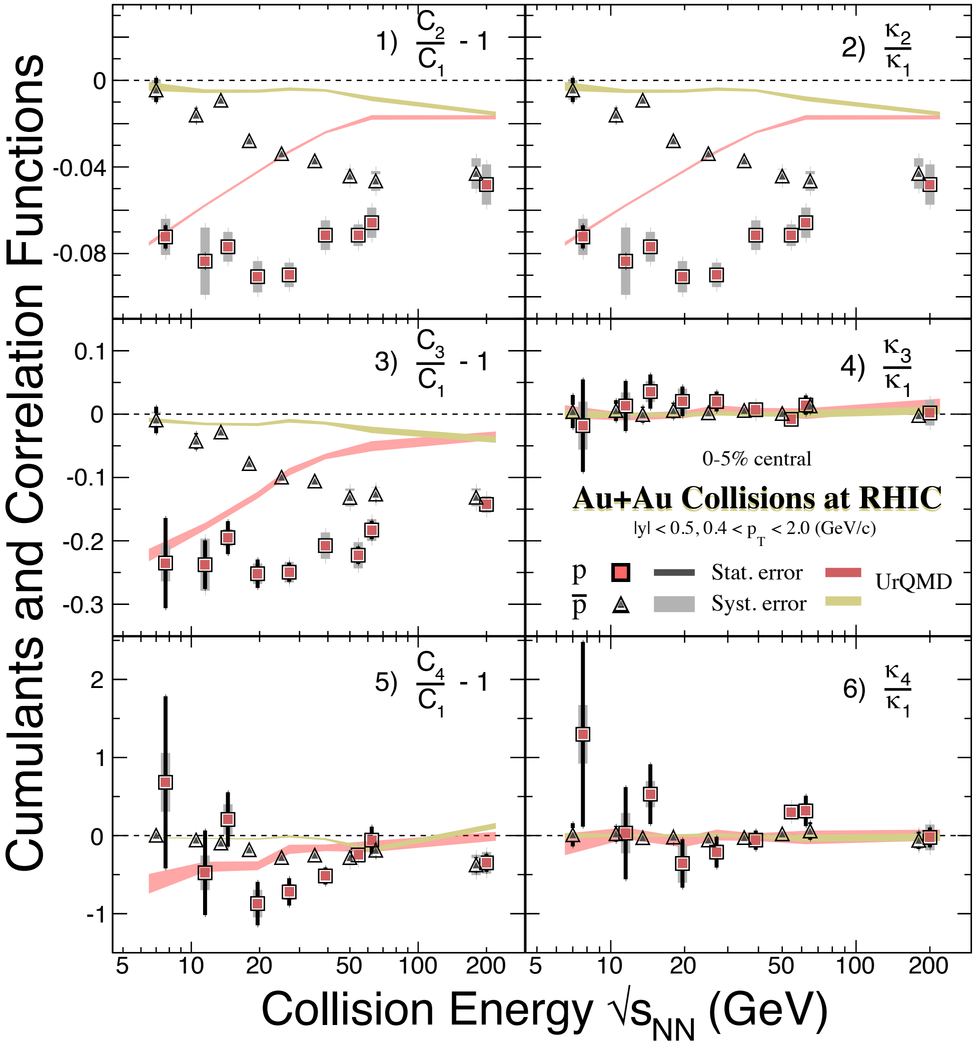


- Canonical Ensemble (CE) is used for describing the system at high baryon density (baryon number conservation). Their calculations are consistent with transport model results.
- Excluded volume (EV) approach also leads to suppression at high baryon region. 'repulsive force' suppress the fluctuations. 'Attractive' of protons at the 7.7 GeV collisions ?

PBM et al., arXiv: 2007.02463, S. He et al., PLB 762 296 (2016).
J.H. Fu, PLB 722, 144 (2013), A. Bhattacharyya et al., PRC 90, 034909(2014).
HRG+VDW: Vovchenko et al., PRC92,054901 (2015); PRL118,182301 (2017).
RMF: K. Fukushima, PRC91 044910 (2015)

STAR, PRL 126, 092301 (2021)
STAR, 2101.12413 (long paper)

Proton/Anti-Proton Cumulants and Factorial Cumulants



Factorial cumulants->
Help to understand the different contributions from underlying physics.

$$\kappa_1 = C_1 = \langle N \rangle,$$
$$\kappa_2 = -C_1 + C_2,$$
$$\kappa_3 = 2C_1 - 3C_2 + C_3,$$
$$\kappa_4 = -6C_1 + 11C_2 - 6C_3 + C_4,$$

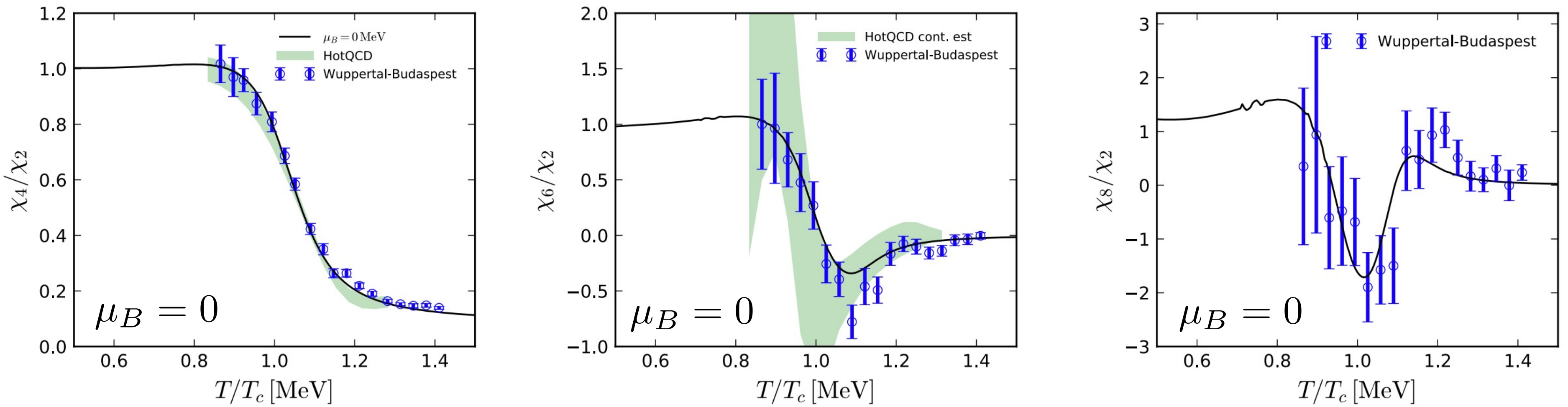
$$C_2 = \kappa_2 + \kappa_1,$$
$$C_3 = \kappa_3 + 3\kappa_2 + \kappa_1,$$
$$C_4 = \kappa_4 + 6\kappa_3 + 7\kappa_2 + \kappa_1,$$

- Negative K2 values are mainly due to the effects of baryon number conservations.
- No significant deviation of K3 and K4 from zero are observed. Need BES-II data to perform more precise measurements.

STAR, 2101.12413 (long paper)

Baryon number fluctuations at μ_B =0 from Lattice and FRG

4th order　　6th order　　8th order



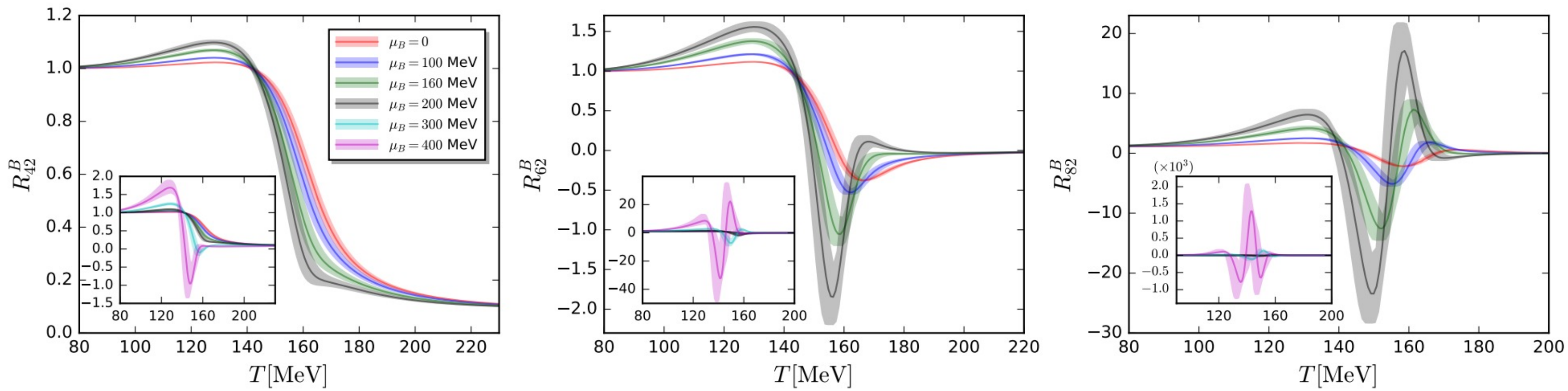
Wei-jie Fu et al. arXiv: 2101.06035

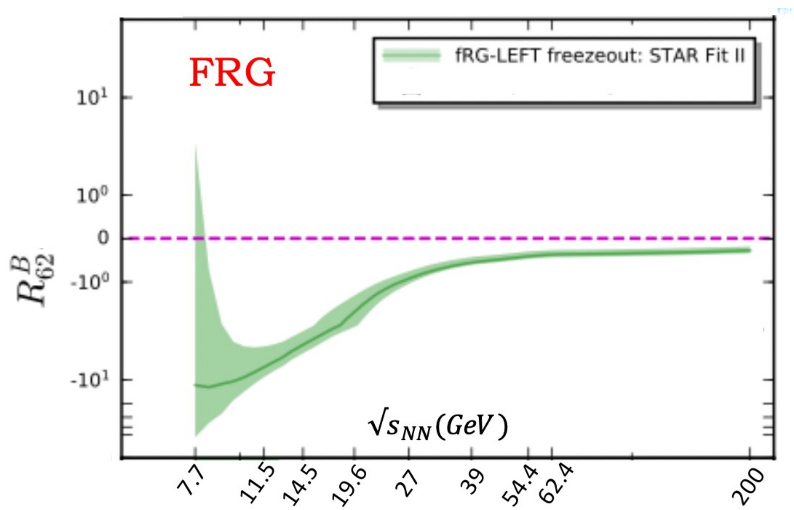
$$C_6 = \mu_6 - 10\mu_3^2 - 15\mu_4\mu_2 + 30\mu_2^3 \qquad \mu_n : \text{Central Moments}$$

Lines : numerical results from the functional renormalization group (FRG) approach at $\mu_B = 0$

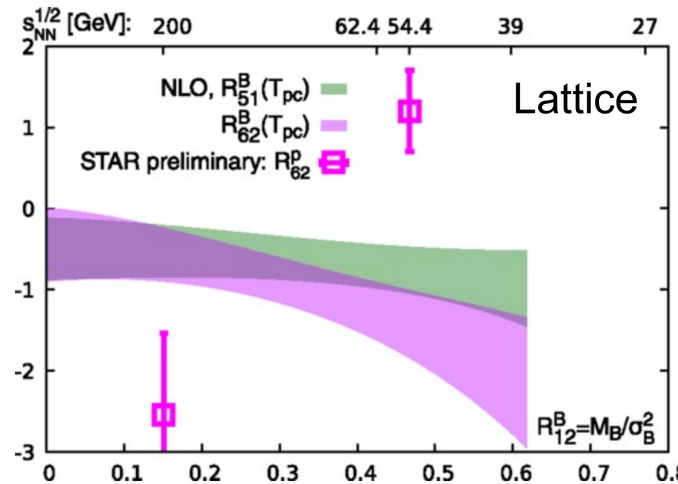
- Higher order fluctuations are more sensitive to crossover transition.
- At $\mu_B = 0$, C_6 and C_8 become negative when freeze-out temperature close to Tc.
  -> could serve as experimental evidence of chiral crossover.

Baryon number fluctuations at $\mu_B > 0$ from Lattice and FRG





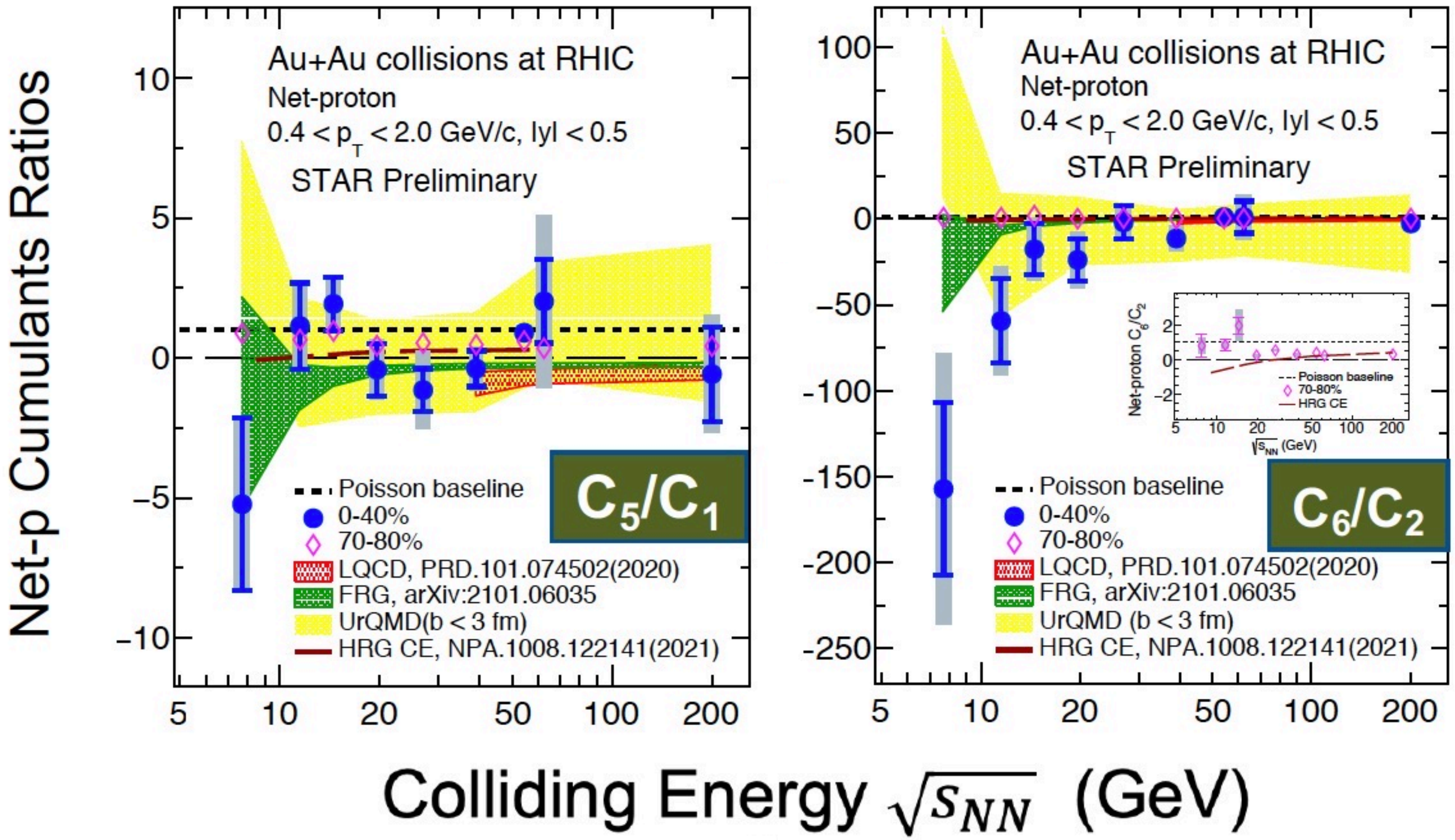
Wei-jie Fu et. al,arXiv:2101.06035



A. Bazavov et al. Phys. Rev. D **101**, 074502

➢ Along the crossover line, the larger the μ_B values, the stronger fluctuations.

Net-Proton fifth (C_5/C_1) and sixth (C_6/C_2) order from BES-I



- C_5/C_1 and C_6/C_2 data:

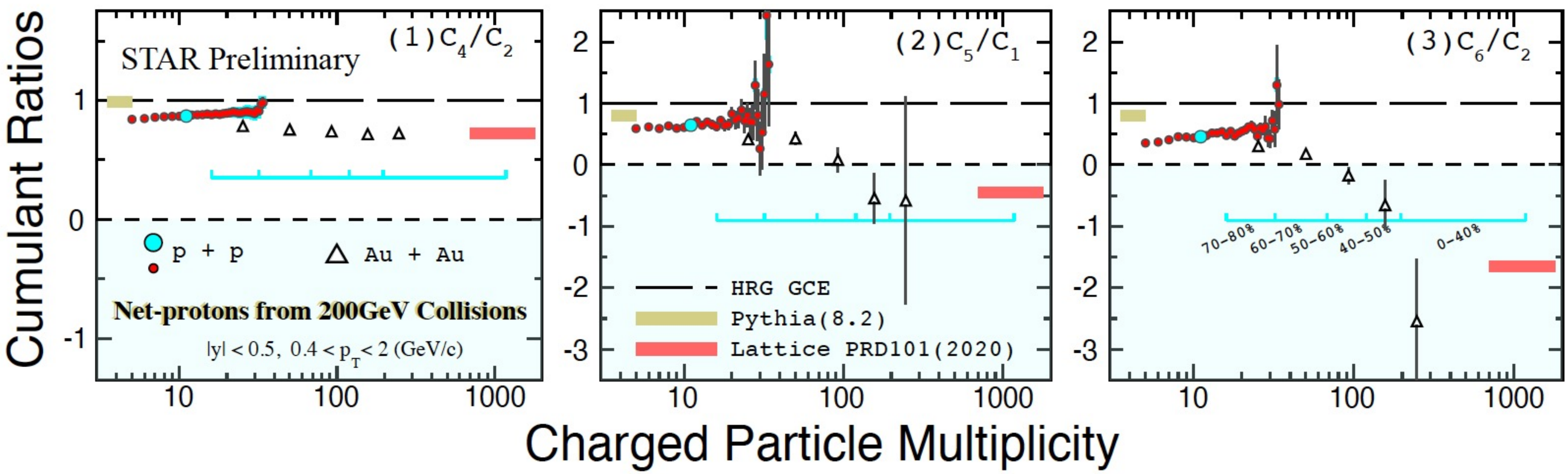
(i) > 0 for 70-80% peripheral collisions; (ii) mostly < 0 for 0-40% central collisions

- LQCD and FRG calculations predict < 0 due to the transition between partonic and hadronic phases.

$$error(C_n/C_2) \propto \frac{\sigma^{n-2}}{\sqrt{N}\varepsilon^{\alpha}}$$

STAR, CPOD, Moriond 2021

Net-proton fluctuations from 200 GeV p+p collisions

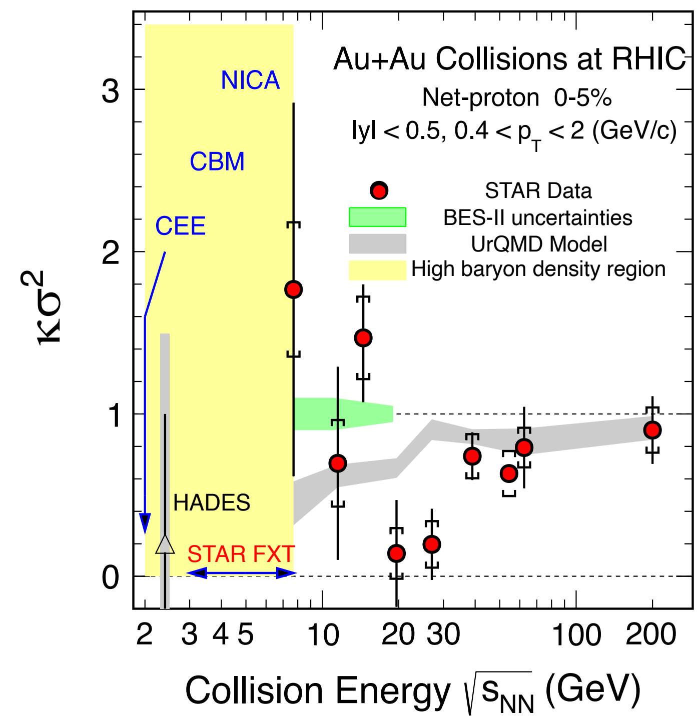


- Results of the net-p cumulant ratios from p+p collisions fit in the multiplicity dependence of C_4/C_2, C_5/C_1 and C_6/C_2 in Au+Au collisions
- C_5/C_1 and C_6/C_1 are found to be negative in central Au+Au collisions
- LQCD calculations predict < 0 due to the transition between partonic and hadronic phase

STAR, CPOD, Moriond 2021

BES-II at RHIC (2019-2021)

STAR, PRL 126, 092301 (2021)

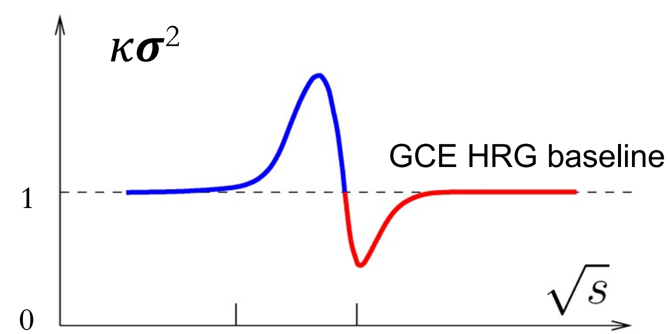


- ➢ BES-II data taking are very successful.

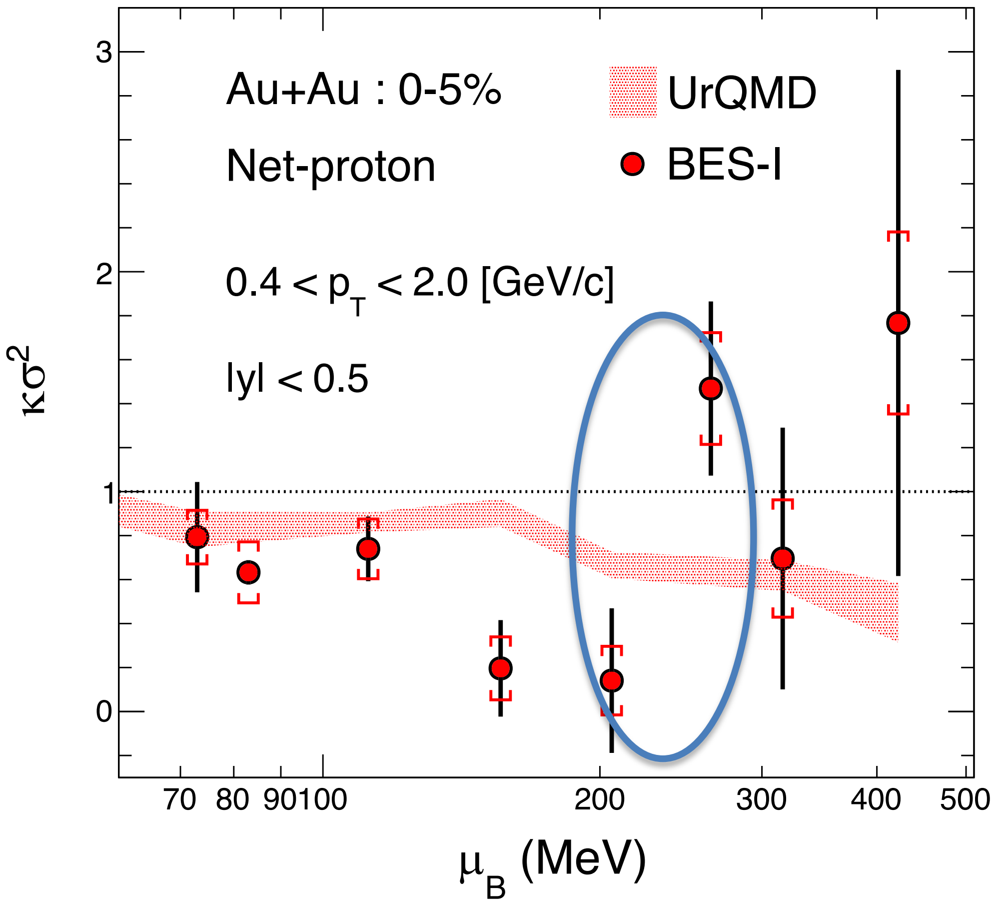
The data taking of 9.2, 11.5, 14.6, 19.6 GeV are completed.

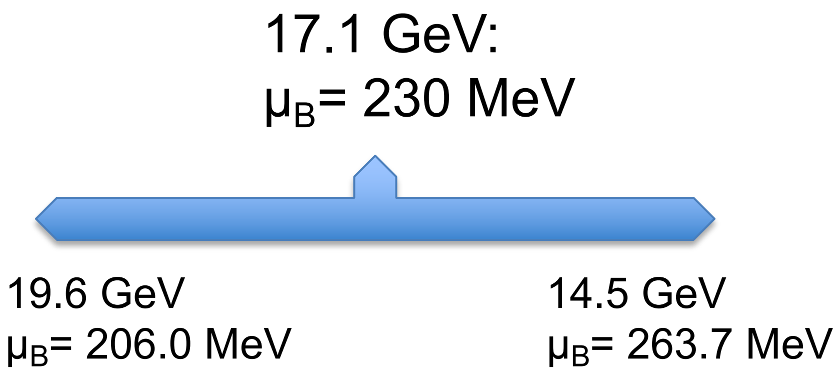
7.7 GeV data taking is ongoing， will reach goal around beginning of the May.

- ➢ FIX-target mode : $\sqrt{s_{NN}}$ = 3-7.7 GeV (2018-2021).



Propose to take the data of Au+Au collisions at 17.1 GeV



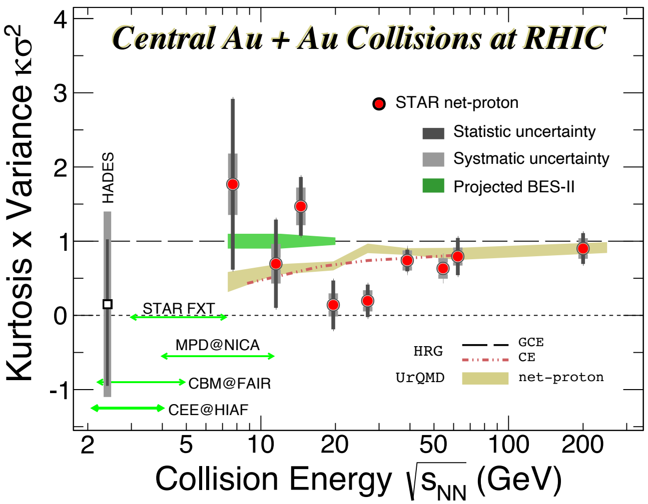


17.1 GeV will be taken after 7.7 GeV.

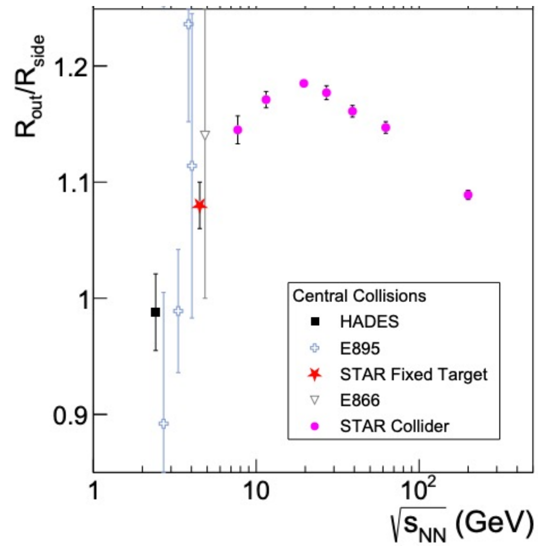
- Sudden change between 19.6 and 14.5 GeV.
- Still large μ_B gap ~ 60 MeV between 19.6 and 14.5 GeV.

Summary

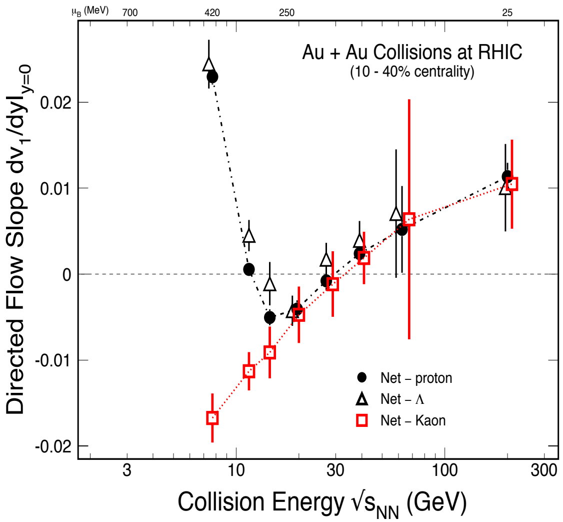
STAR, Phys. Rev. Lett. 126, 092301 (2021)

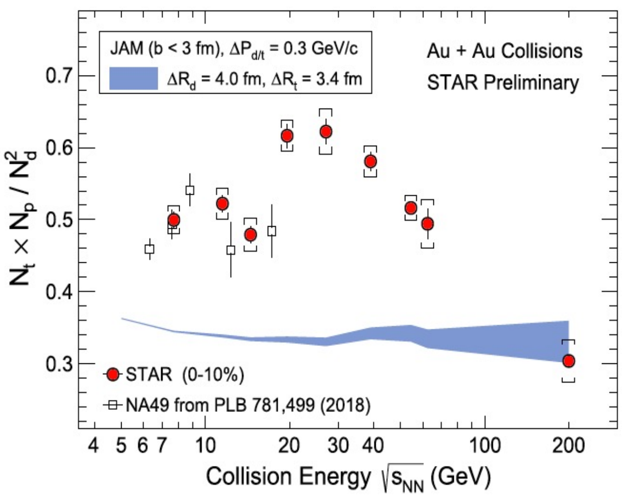


STAR: Phys. Rev. C 103, 034908 (2021)



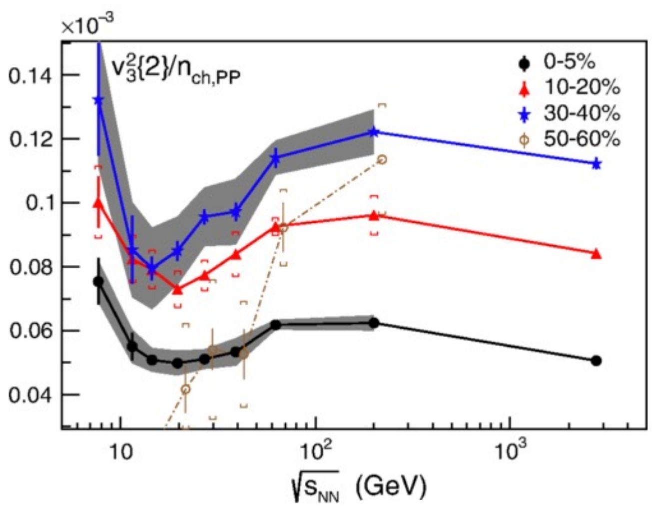
STAR: Phys. Rev. Lett. 112, 162301(2014)





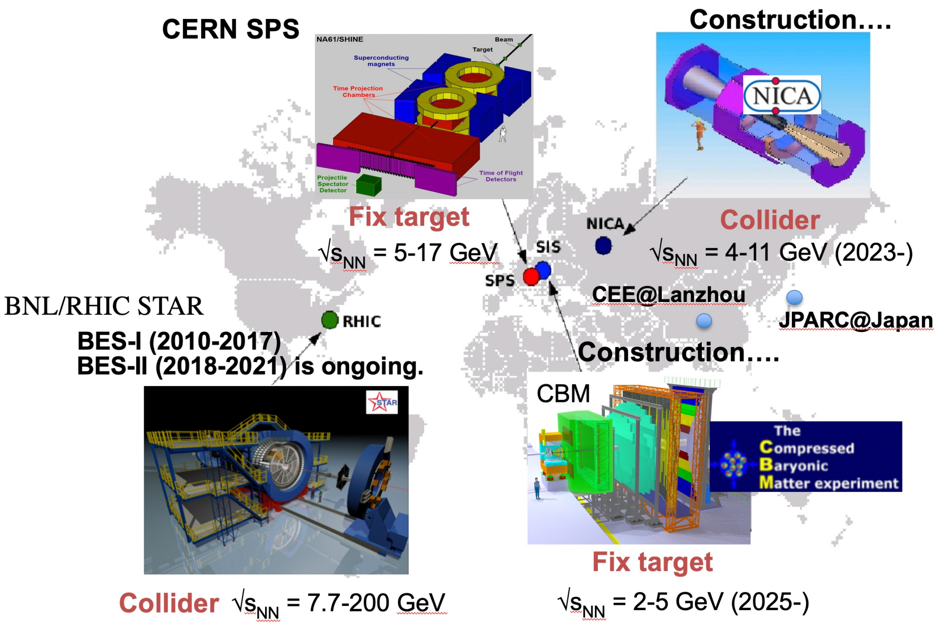
Dingwei Zhang (STAR), QM2019

STAR, Phys. Rev. Lett. 116, 112302 (2016)

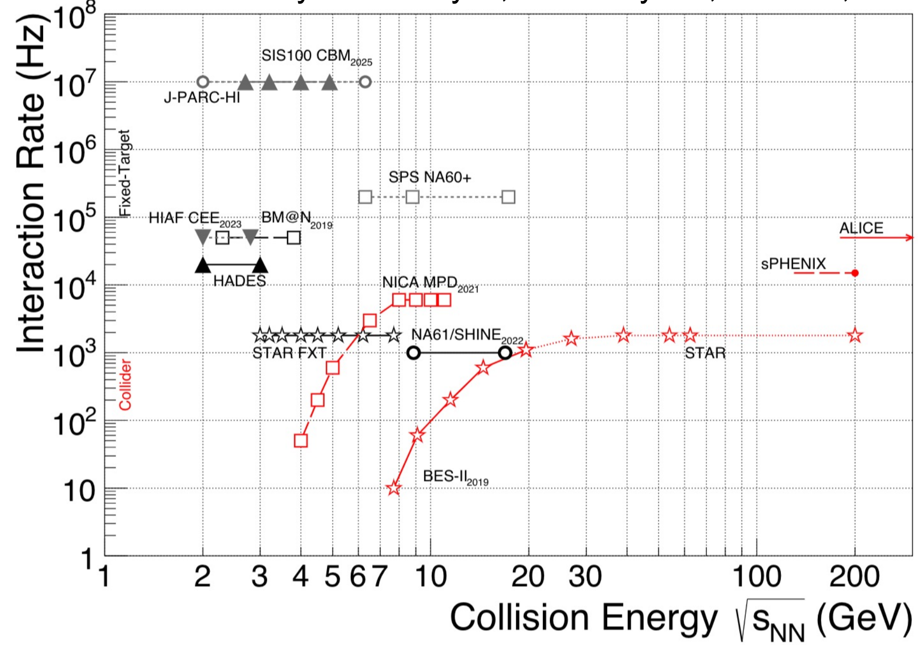


Intriguing structures around **20-30 GeV** for many observables : What's the underlying physics ?

Outlook



Tetyana Galatyuk, Nucl. Phys. A, 982:163,2019



Explore the QCD phase structure at high baryon density with high precision:

(1) RHIC BES-II : Collider ($\sqrt{s_{NN}}$ =7.7 - 19.6 GeV) and FXT ($\sqrt{s_{NN}}$ = 3 - 7.7 GeV) mode.

(2) Future Facilities ($\sqrt{s_{NN}}$ =2 - 11 GeV) : FAIR/CBM, NICA/MPD, HIAF/CEE, JPARC-HI.

Stay tune for exciting physics !!!

Acknowledgements :

Thanks to the members of the STAR Collaboration and the kind invitation from the organizers.

Thank you for your attention !