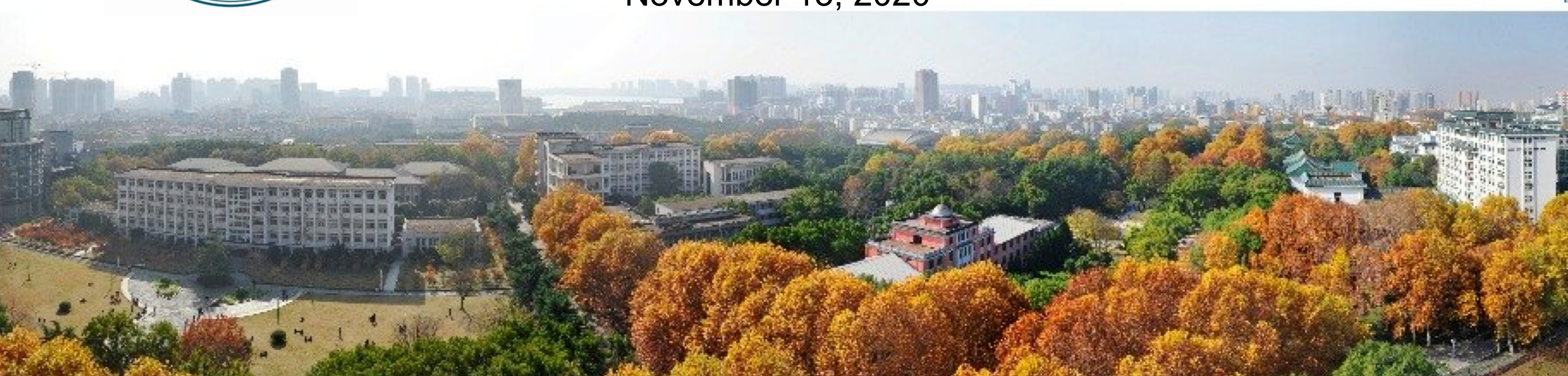
XXXII International Workshop on High Energy Physics “Hot problems of Strong Interactions”, November 9-13, 2020.

Search for the QCD Critical Point in Heavy-ion Collisions at RHIC

Xiaofeng Luo

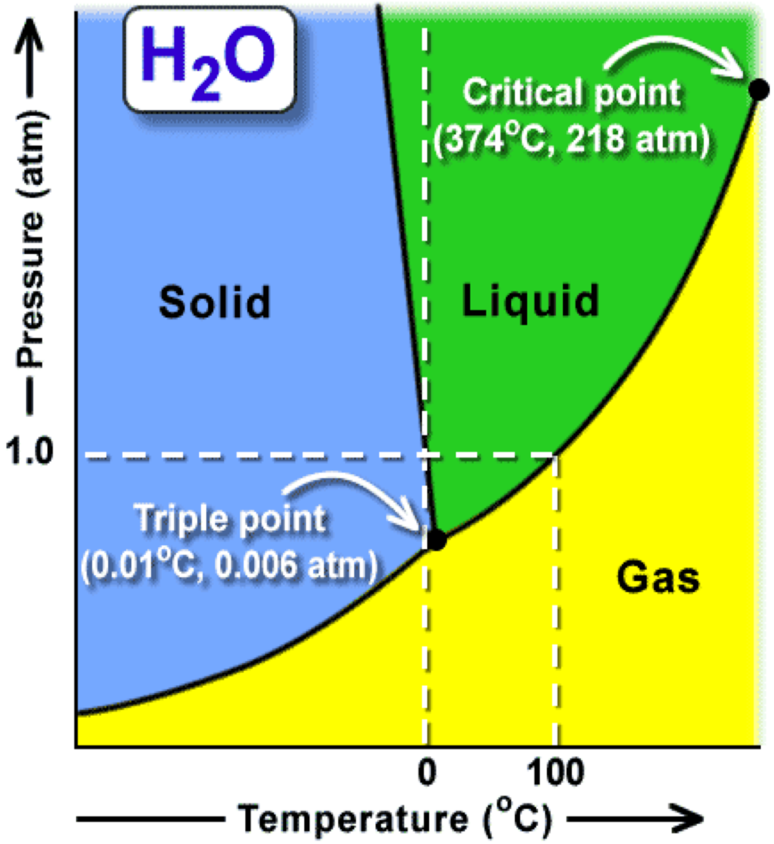
Central China Normal University

November 13, 2020



Phase Diagram: Water

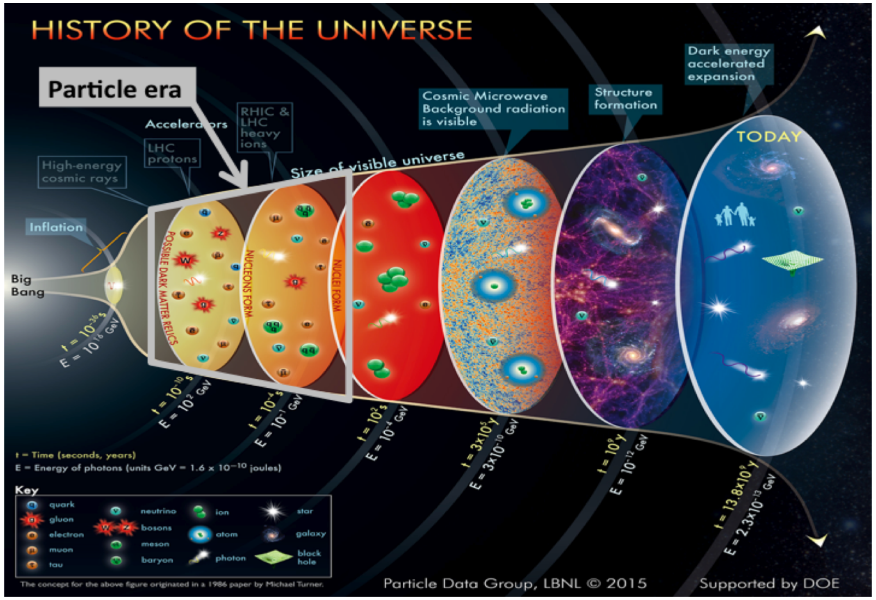
How matter self-organized by varying external conditions.



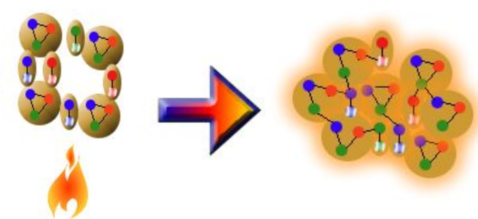
Thermal motion (Chaos) Vs. Interactions (Ordered)

Heat matter to trillion (10^{12}) ℃

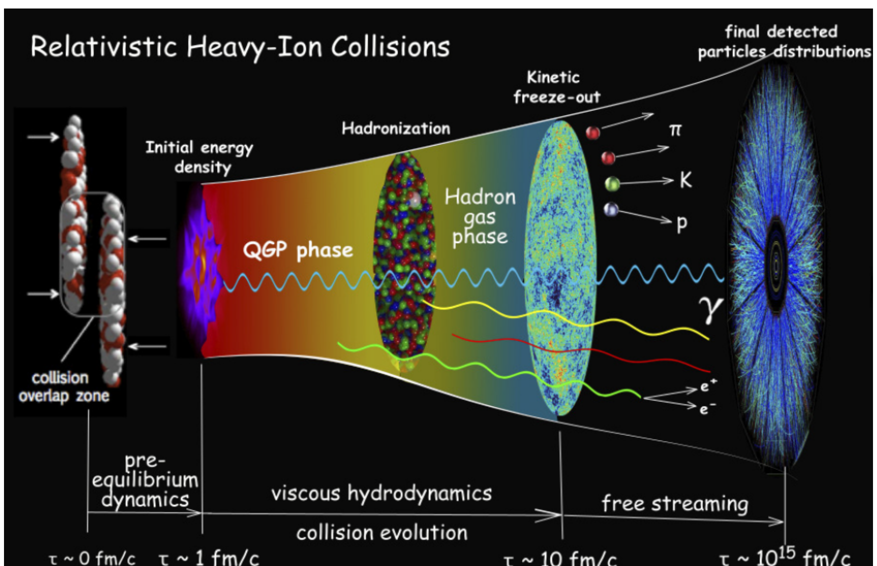
Big Bang



Quark-Gluon Plasma (**QGP**): a state of matter where the quarks and gluons are the relevant degrees of freedom, exist at few μs after the Big-Bang



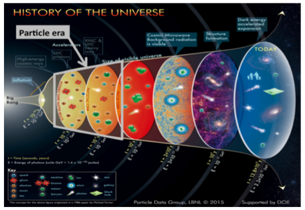
Little Bang

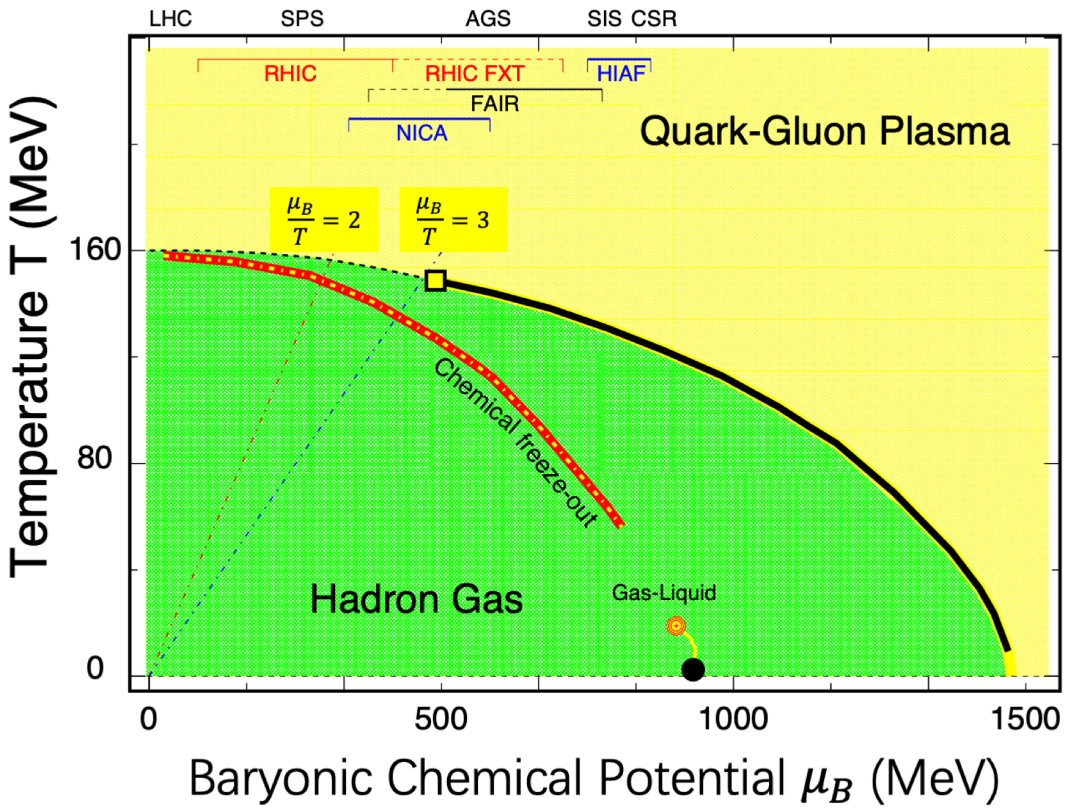


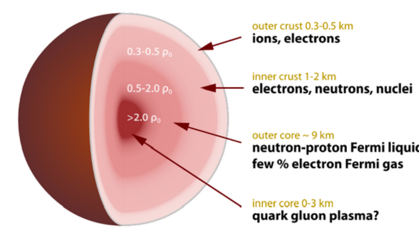
Relativistic heavy-ion collisions are a unique tool to create and study hot QCD matter and its phase transition under controlled conditions

T. D. Lee and G. C. Wick, Phys. Rev. D 9, 2291 (1974).
Vacuum stability and vacuum excitation in a spin-0 field theory.

QCD Phase Diagram







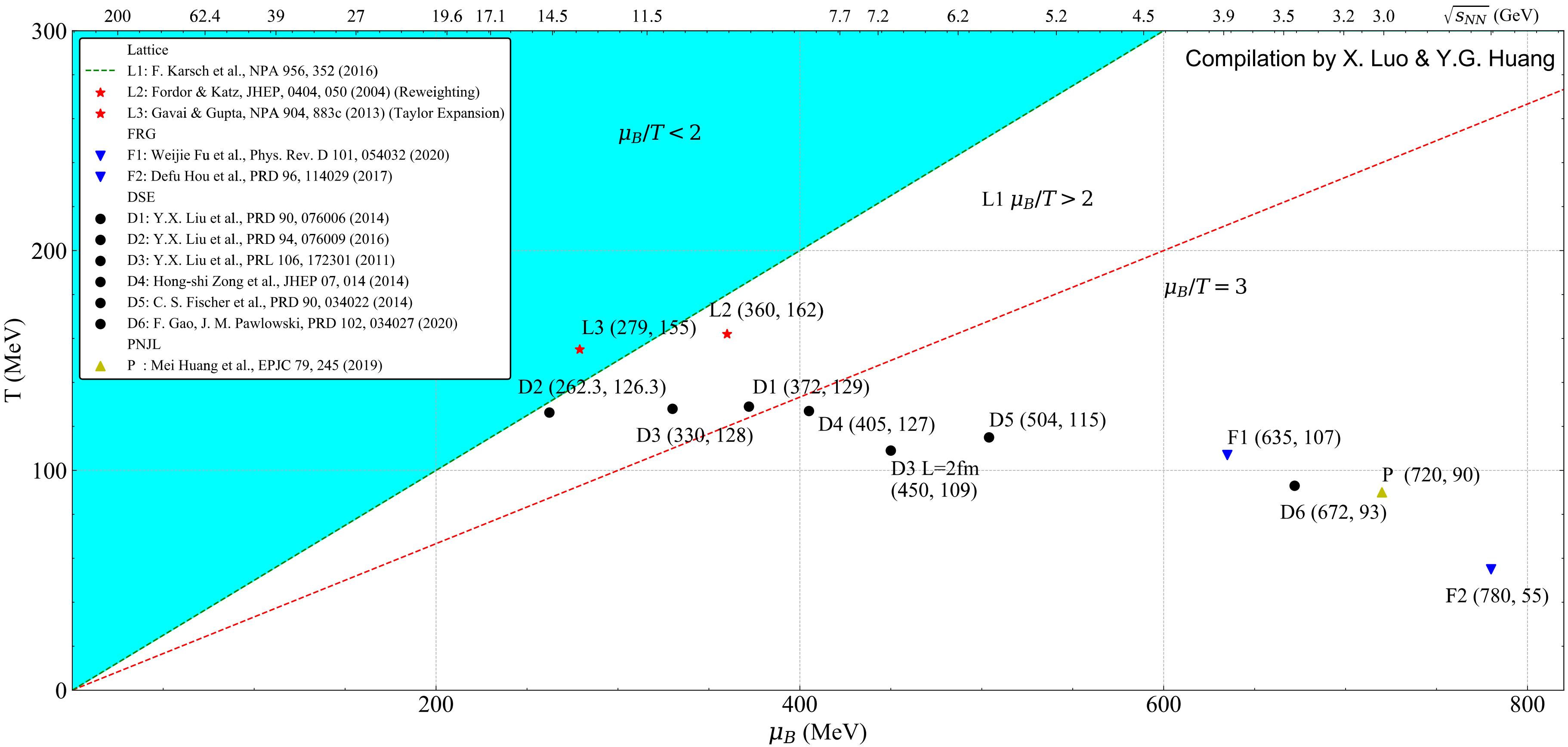
Y. Aoki et al., Nature 443, 675 (2006) ; A. Bazavov et al, PRD 85, 054503 (2012).
K. Fukushima and C. Sasaki, Prog. Part. Nucl. Phys, 72, 99 (2013).
A. Bzdak et al., Phys. Rep. 853, 1 (2020).

Key question : is there a QCD critical point at finite baryon density region?

Its confirmation will greatly enhance our understanding of the universe evolution and structure of visible matter.

Location of CP : Theoretical Prediction

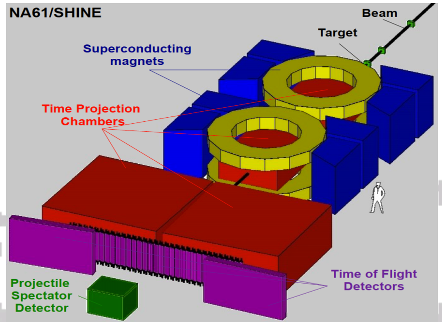
A preliminary collection from Lattice, DSE, FRG and PNJL (2004-2020)



Large uncertainties for the theoretical estimation of CP location.

Current and Future Facilities for exploring the QCD Phase Structure

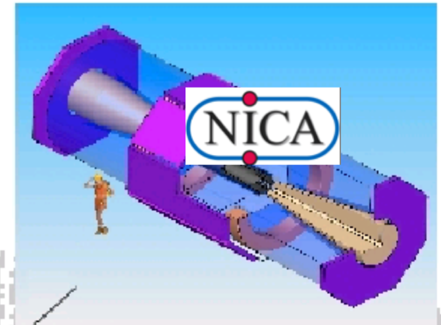
CERN SPS



Fix target

$\sqrt{s_{NN}}$ = 5-17 GeV

Construction….



Collider

$\sqrt{s_{NN}}$ = 4-11 GeV (2023-)

NICA

SIS

SPS

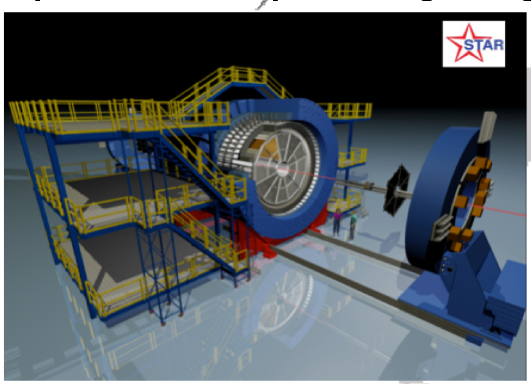
CEE@Lanzhou

JPARC@Japan

RHIC

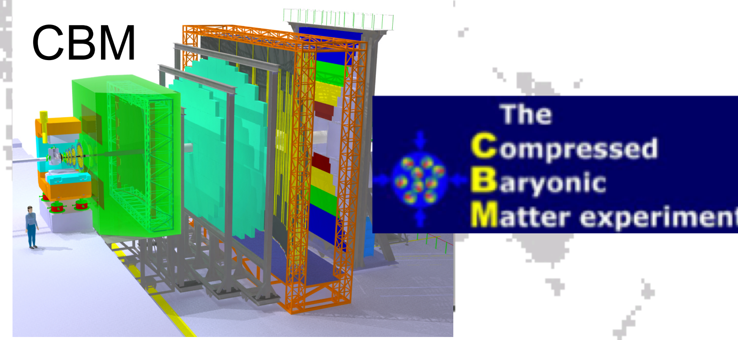
BNL/RHIC STAR

BES-I (2010-2017)
BES-II (2018-2021) is ongoing.



Collider $\sqrt{s_{NN}}$ = 7.7-200 GeV

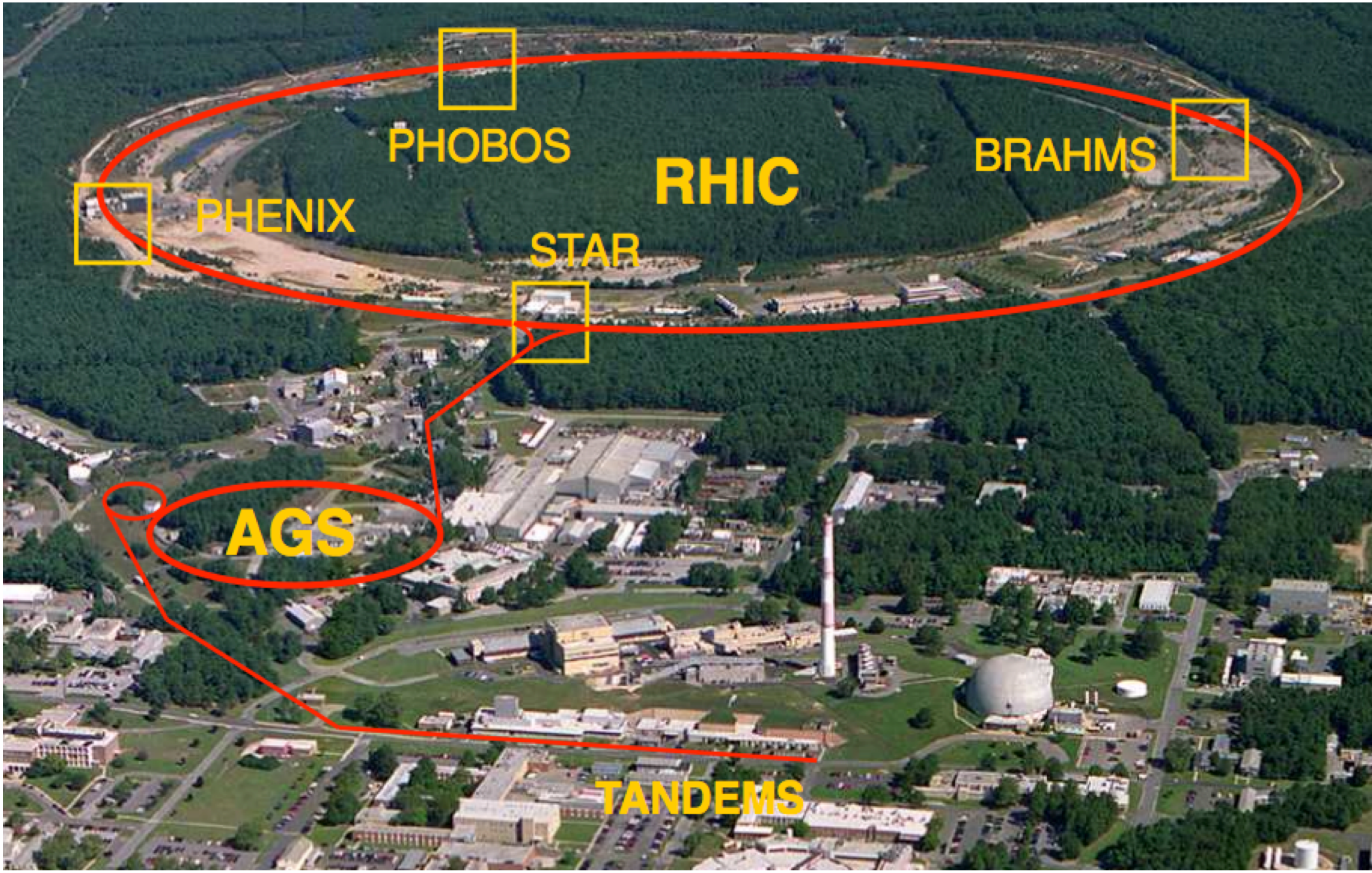
Construction….



Fix target

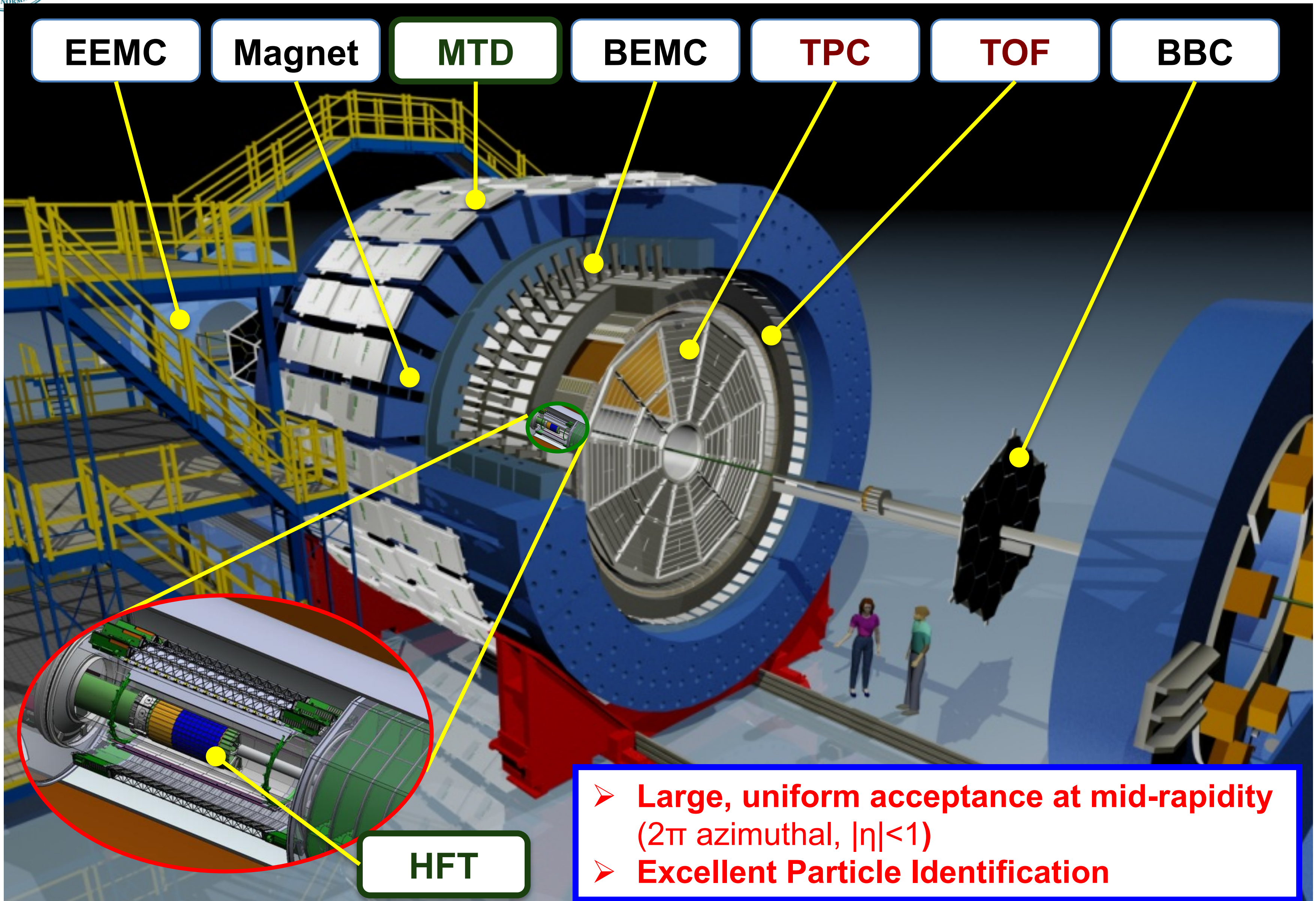
$\sqrt{s_{NN}}$ = 2-5 GeV (2025-)

Relativistic Heavy-ion Collider (RHIC)



- RHIC: The high energy heavy-ion collider $\sqrt{s}$ = 200 - 5 GeV
- RHIC: The highest energy polarized proton collider (500 GeV)

STAR Detector System



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

RHIC Beam Energy Scan - I (2010-2017)

Au+Au Collisions

$\sqrt{s_{NN}}$ (GeV)	Events (X10[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	3	2010	420	140

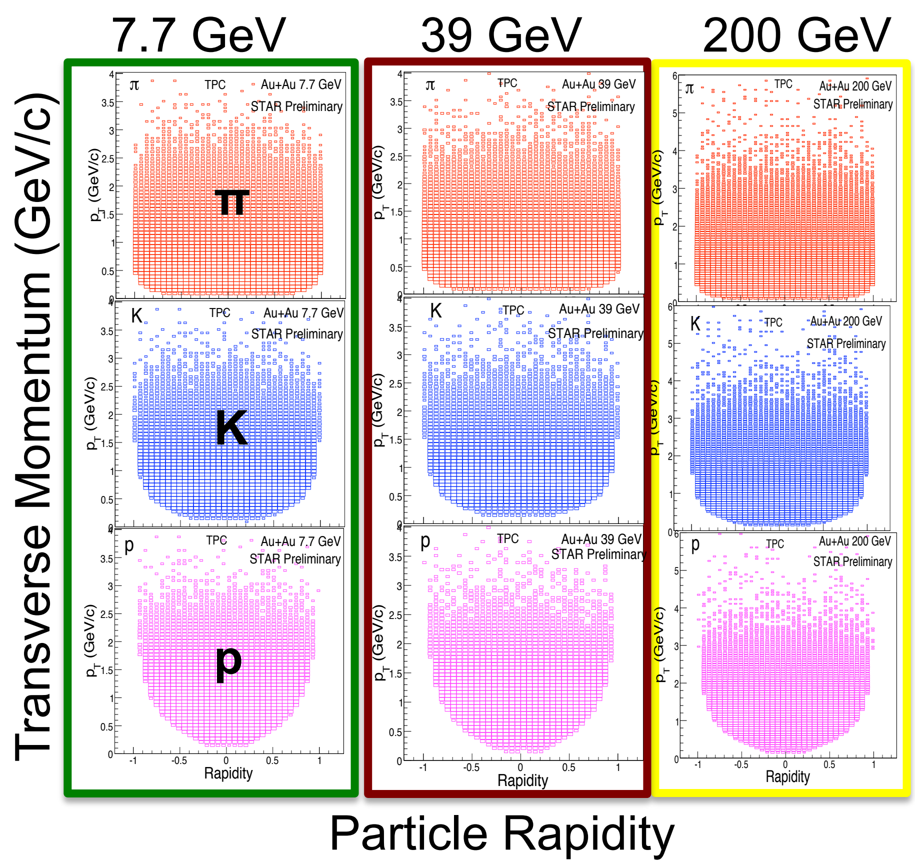
*(μ_B, T_{CH}) : J. Cleymans et al., PR**C73**, 034905 (2006)

STAR, arXiv:1007.2613

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

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

Uniform acceptance at Mid-rapidity

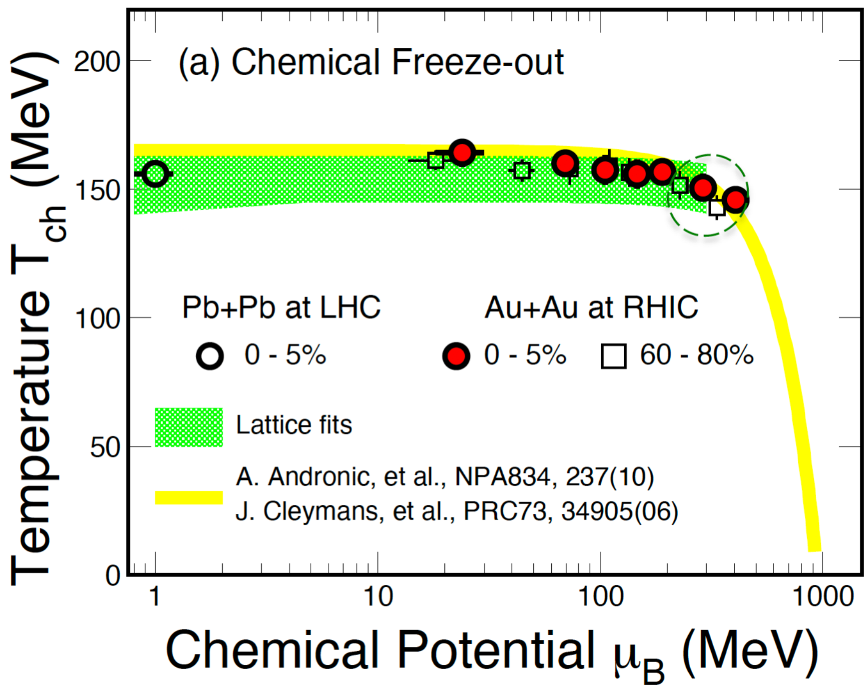


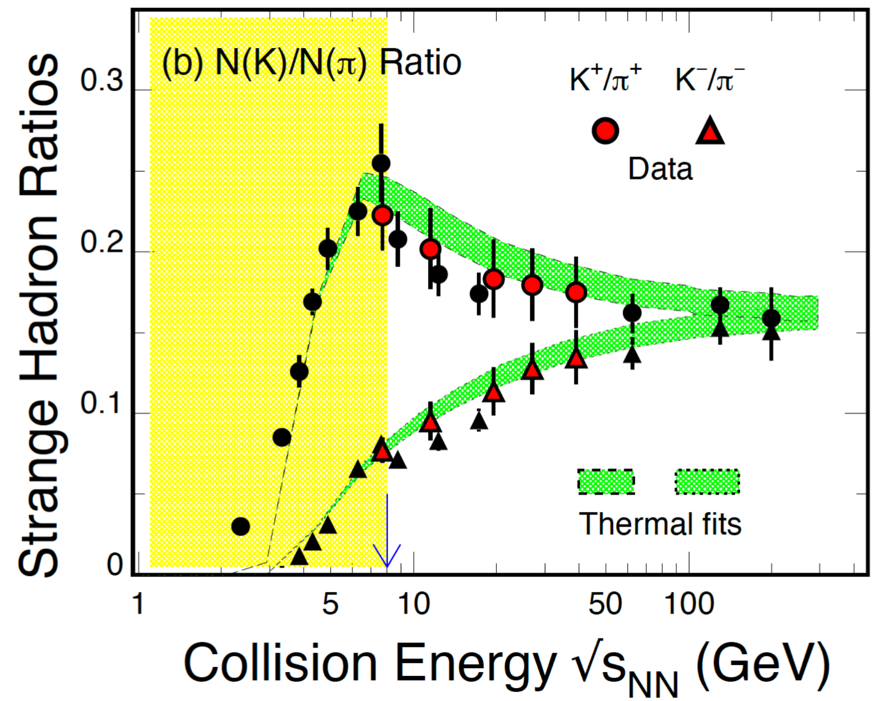
- ➢ Access the QCD phase diagram: vary collision energies and/or system size.

RHIC BES-I : 25 < μ_B < 420 MeV

Chemical freeze-out and QCD phase boundary

By courtesy of Dr. N. Xu

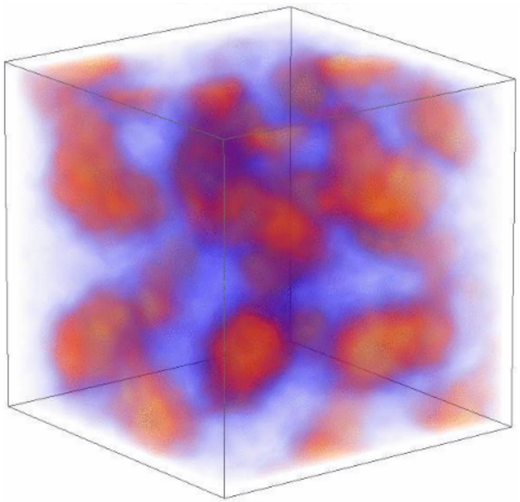




- The chemical freeze-out T and μ_B (GCE) are close to the phase boundary determined from Lattice QCD with μ_B < 300 MeV.
- The peak of K^+/π^+ ratio around 8 GeV can be well described by thermal model, where the system start to enter into "high baryon density region". (< 8 GeV, μ_B> 420 MeV)

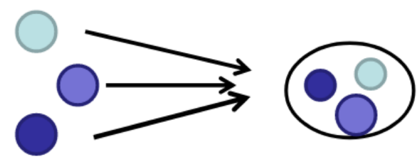
STAR : PRC96, 044904 (2017); PRC 102, 034909 (2020). ALICE : PRL 109, 252301 (2012), PRC 88, 044910 (2013). A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Nature 561, 321 (2018). X. Luo, S. Shi, N. Xu and Y. Zhang, Particle 3, 278 (2020); K. Fukushima, B. Mohanty, N. Xu, arXiv: 2009.03006;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

Sensitive observables for QCD phase transition



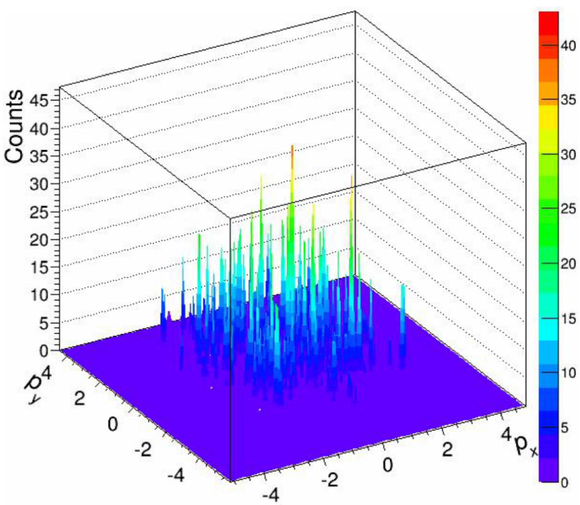
In the vicinity of critical point and/or 1st order phase transition

Large density fluctuations and Baryon clustering



Higher moments of conserved charge (B, Q, S) distributions

light nuclei production

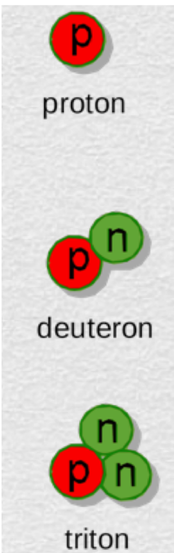


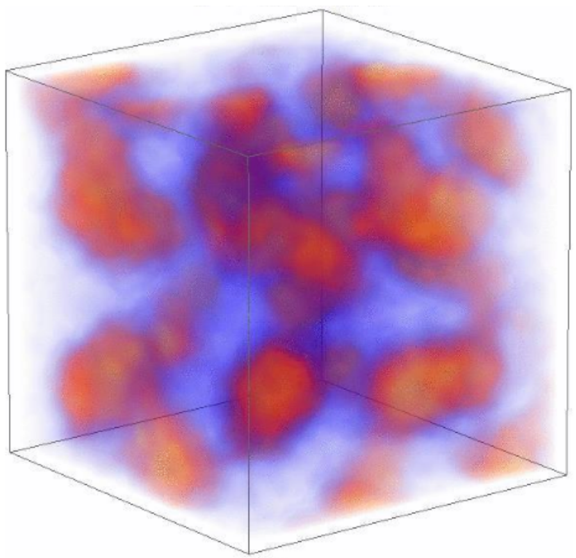
Experimental Signatures:

Non-monotonic variation as a function of collision energy.

Light nuclei production as probes of QCD phase structure

Near first order P.T. or critical point ：
large density fluctuations and baryon clustering





Based on coalescence model:

$$N_d = \frac{3}{2^{1/2}}\left(\frac{2\pi}{m_0 T_{eff}}\right)^{3/2} N_p\langle n\rangle(1 + C_{np})$$

$$N_t = \frac{3^{\frac{3}{2}}}{4}\left(\frac{2\pi}{m_0 T_{eff}}\right)^{3} N_p\langle n\rangle^2(1 + \Delta n + 2C_{np})$$

New observable : Yield ratio of light nuclei

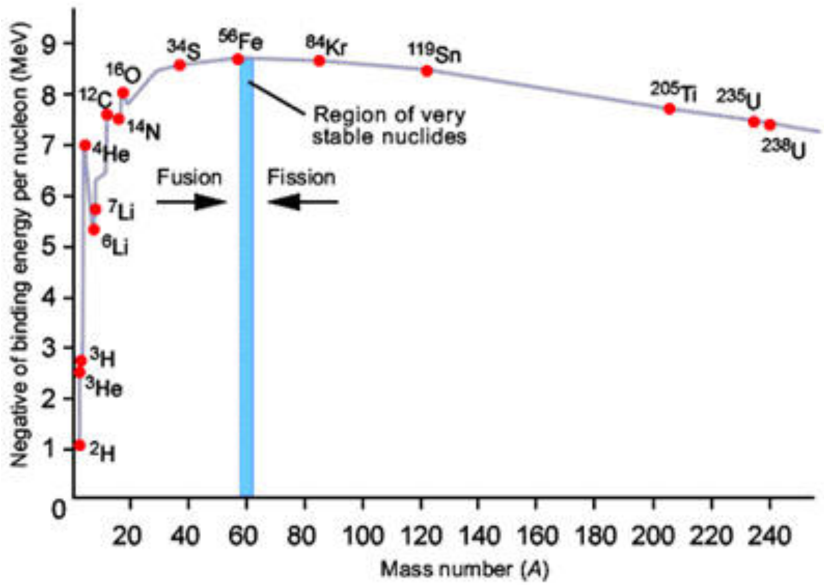
$$\mathrm{N_t \cdot N_p / N_d^2 \approx g(1 + \Delta n)}$$

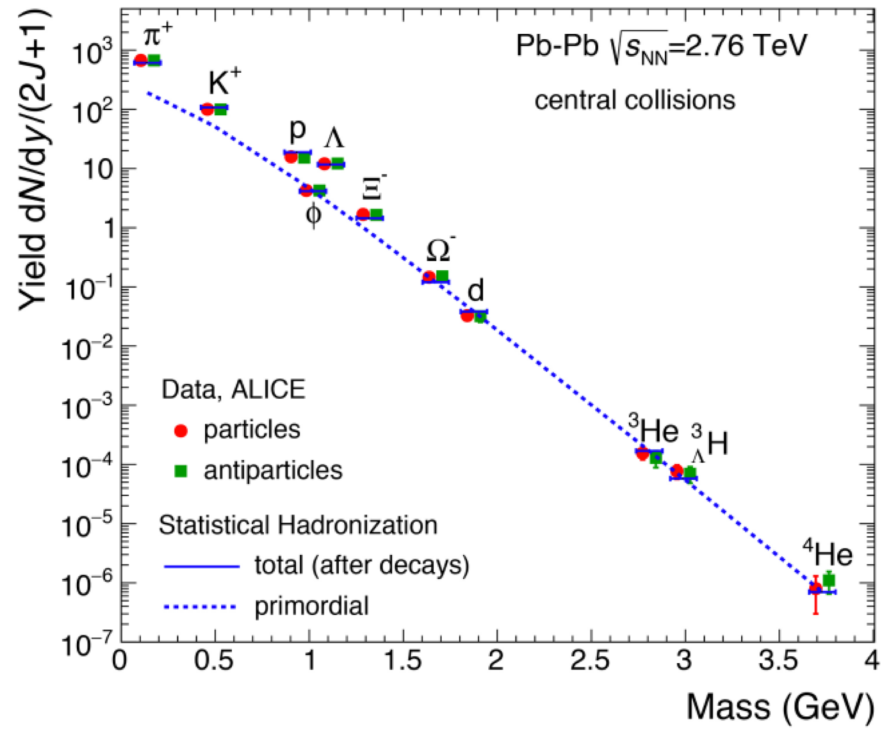
Neutron density fluctuations $\Delta \mathrm{n} = \langle(\delta \mathrm{n})^2\rangle / \langle \mathrm{n}\rangle^2$
g=0.29

Yield ratio of light nuclei is sensitive to the baryon density fluctuations and can be used to probe the signature of 1st order phase transition and/or critical point in heavy-ion collisions.

K.J. Sun, L.W. Chen, C.M. Ko, and Z.B. Xu, PLB 774, 103 (2017);
K.J. Sun, L.W. Chen, C.M. Ko, J. Pu, and Z.B. Xu, PLB781, 499 (2018)
Edward Shuryak, Juan M. Torres-Rincon, PRC 100, 024903 (2019); PRC 101, 034914 (2020); EPJA 56, 241 (2020).

Light Nuclei production in high energy nuclear collisions





nucleus	rms radius (fm)
deuteron	2.1421±0.0088
triton	1.7591±0.0363
^{3}He	1.9661±0.0030
^{4}He	1.6755±0.0028
$^{3}_{\Lambda}$H	4.9

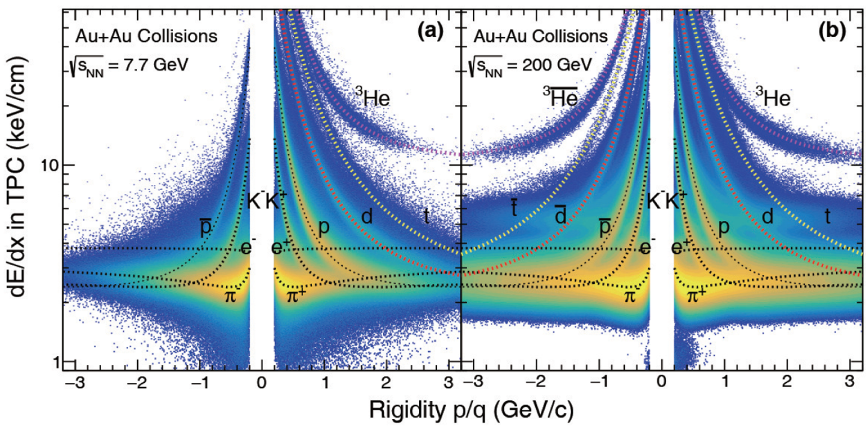
“Snowball in hell” ?

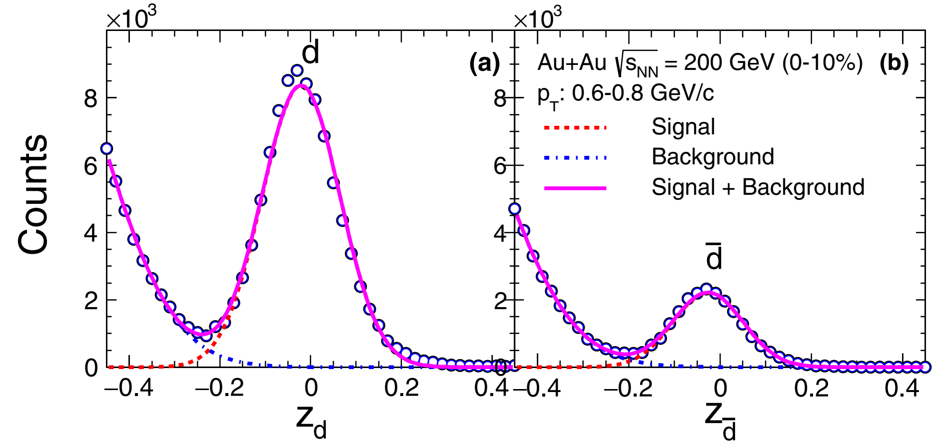
Braun-Munzinger, Dönigus, NPA 987, 144 (2019).
Benjamin Dönigus, IJMPE 29, 2040001 (2020).
J. Chen, et al., Phys. Rep. 760, 1 (2018)
D. Oliinychenko, et al., Phys. Rev. C 99, 044907 (2019).
Y. Oh, Z.W. Lin, C.M. Ko, Phys. Rev. C 80, 064902 (2009).
S. Sombun et al., Phys. Rev. C 99,014901 (2019).

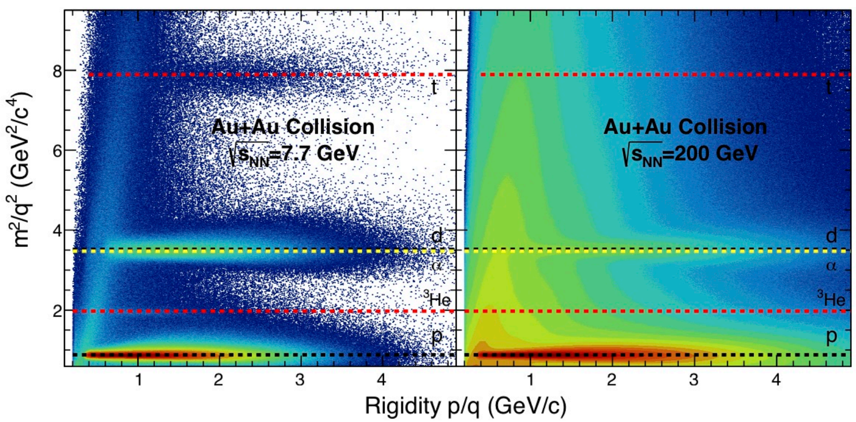
- Light nuclei (d, t, ^{3}He): loosely bond object with few MeV binding energies can be produced in HIC.
- Understanding the production mechanism of light nuclei in HIC will provide baseline to map the QCD phase boundary. coalescence、microscopic interactions、 thermal production ?

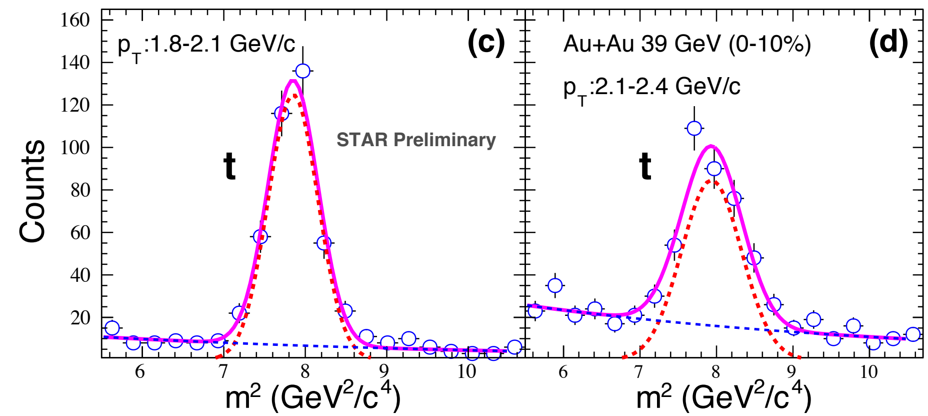
Particle Identification

TPC : Low p_T TPC+TOF : High p_T



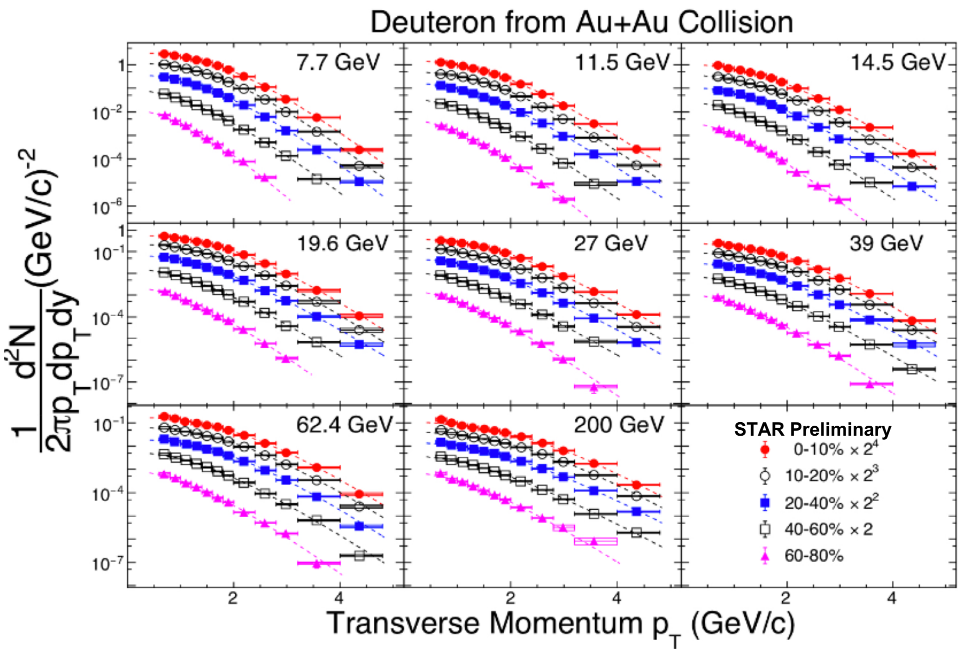


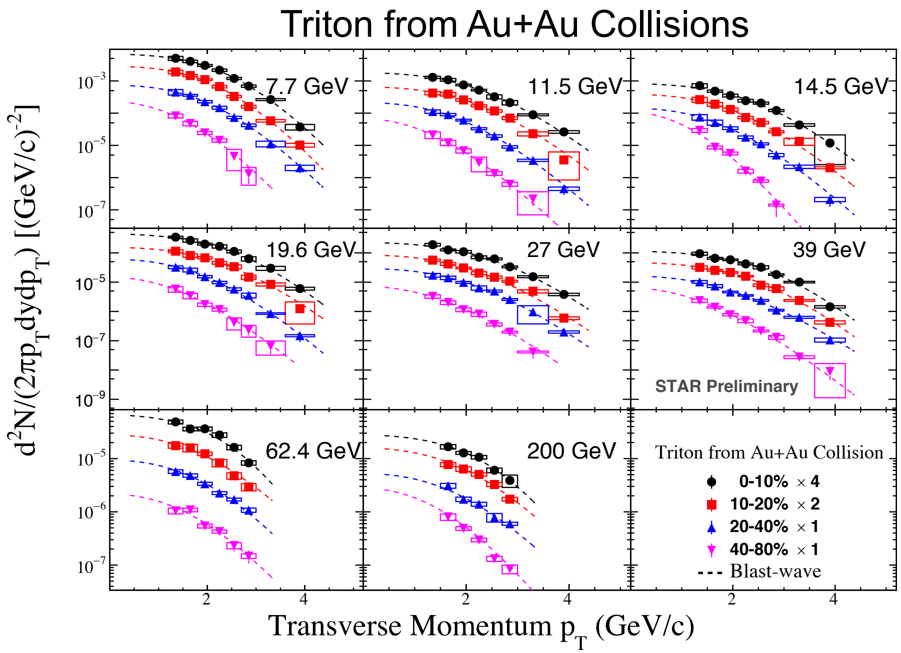




1) TPC and TOF efficiency correction
2) Energy loss corrections
3) Absorption corrections
4) Background subtraction

Deuteron and triton production from BES-I at RHIC



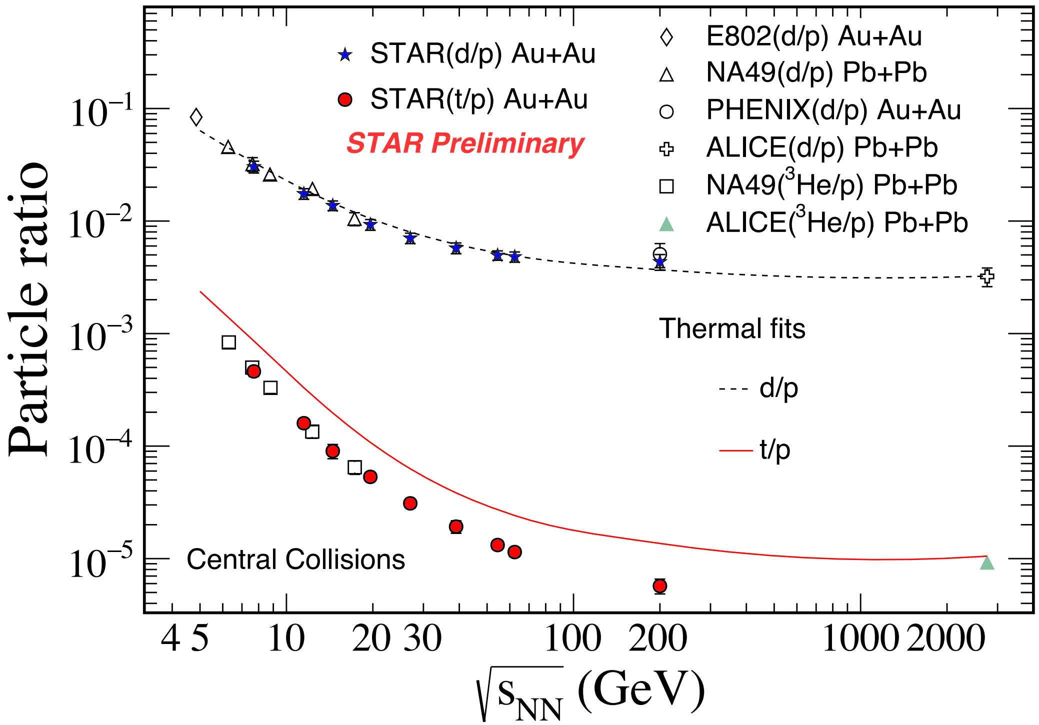


Dash lines (blast-wave function fits) : $\frac{d^2N}{p_T dp_T d_y} \propto \int_0^R r dr m_T I_0\left(\frac{p_T sinh\rho}{T}\right) K_1\left(\frac{m_T cosh\rho}{T}\right)$

E. Schnedermann, J. Sollfrank, and U. Heinz, PRC 48,2462 (1993).

STAR BES-I data :
Deuteron, Phys. Rev. C 99, 064905 (2019).
Triton : Dingwei Zhang (for STAR), QM2019 [arXiv : 2002.10677]; Hui Liu, Poster, QM2019.

Energy dependence of d/p and t/p ratios



Thermal model inputs:

$$T_{CF} = T_{CF}^{lim}/(1 + \exp(2.60 - \ln(\sqrt{s_{NN}})/0.45))$$

$$\mu_B = a/(1 + 0.288\sqrt{s_{NN}})$$

With $\sqrt{s_{NN}}$ in GeV

$T_{CF}^{lim} = 158.4$ MeV and a = 1307.5 MeV

A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stöcker, PLB 697 (2011) 203.

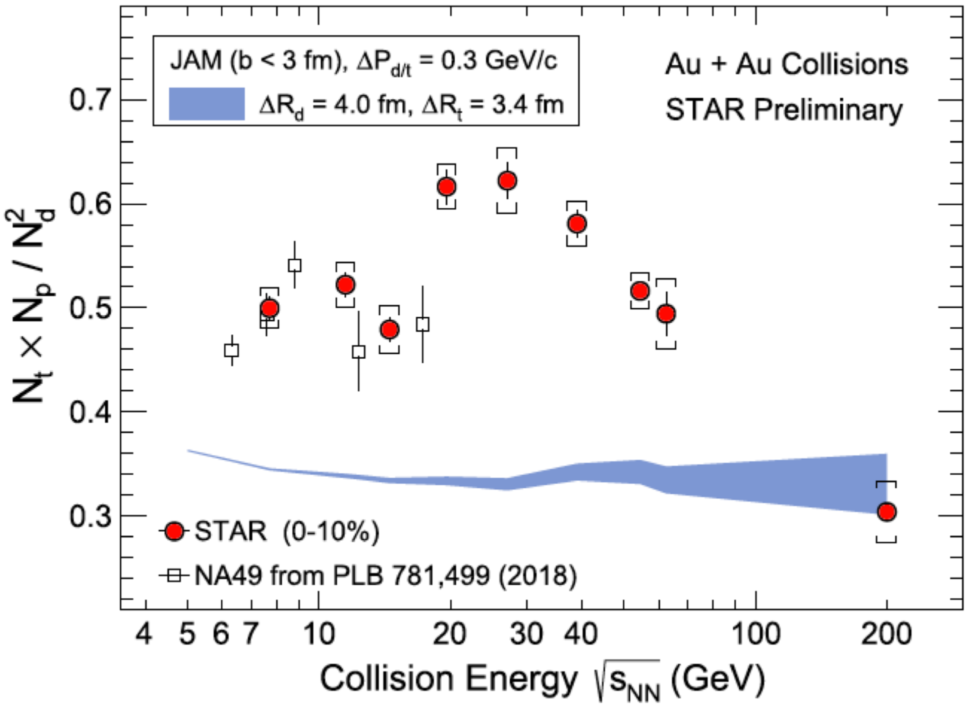
Proton yield corrected for weak decay feed down based on a STAR paper using UrQMD + GEANT simulation : https://journals.aps.org/prl/supplemental/10.1103/PhysRevLett.121.032301

- The d/p ratios from LHC、RHIC down to AGS energies can be well described by thermal model.
- t/p and ^{3}He/p ratios are significant deviation and below the thermal model expectations at RHIC and SPS energies.

ALICE data : Phys. Rev. C 93, 024917 (2016)
STAR data : Deuteron, Phys. Rev. C 99, 064905 (2019).
Triton : Dingwei Zhang (for STAR), QM2019 [arXiv : 2002.10677]; Hui Liu, Poster, QM2019.

Energy Dependence of Light Nuclei Yield Ratio

Dingwei Zhang (STAR), QM2019 [arXiv: 2002.10677]



The yield ratio is related to neutron density fluctuations.

$$N_t \cdot N_p / N_d^2 = g(1 + \Delta n),$$
$$\text{with } g = 0.29$$

Proton yield corrected for weak decay feed down used in the left plot based on a STAR paper using UrQMD + GEANT simulation :
https://journals.aps.org/prl/supplemental/10.1103/PhysRevLett.121.032301

- Yield ratio shows a non-monotonic dependence on collision energy in 0-10% Au + Au collisions, with a peak around 20-30 GeV.
- Flat energy dependence of yield ratio observed in JAM, AMPT, UrQMD, hybrid model.

JAM : H. Liu et al, Phys. Lett. B 805, 135452 (2020).
AMPT : K. Sun, C. M. Ko, arXiv: 2005.00182.
Hydro + transport + coal. : W. Zhao et al., arXiv: 2009.06959
UrQMD: X. G. Deng, Y. G. Ma, Phys. Lett. B 808, 135668 (2020)

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).

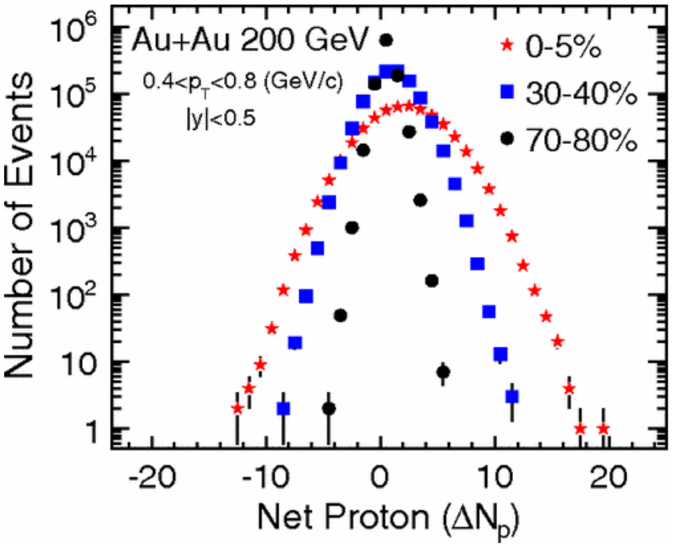
2. Direct connect to the susceptibility of the system.

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

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

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



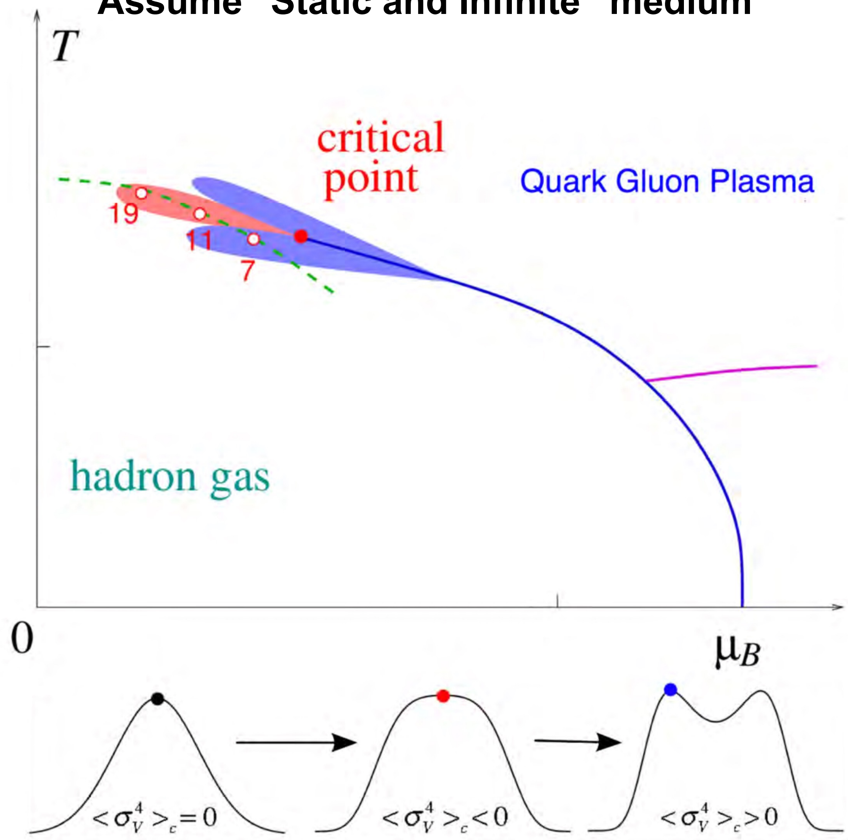
First Measurement : 2009-2010

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)

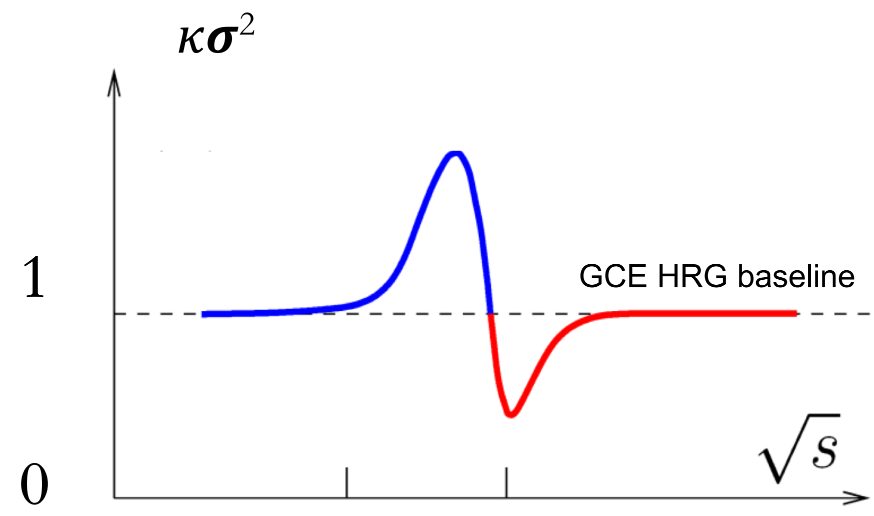
Signals of QCD Critical Point : Theory/Model

Assume "Static and Infinite" medium



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).



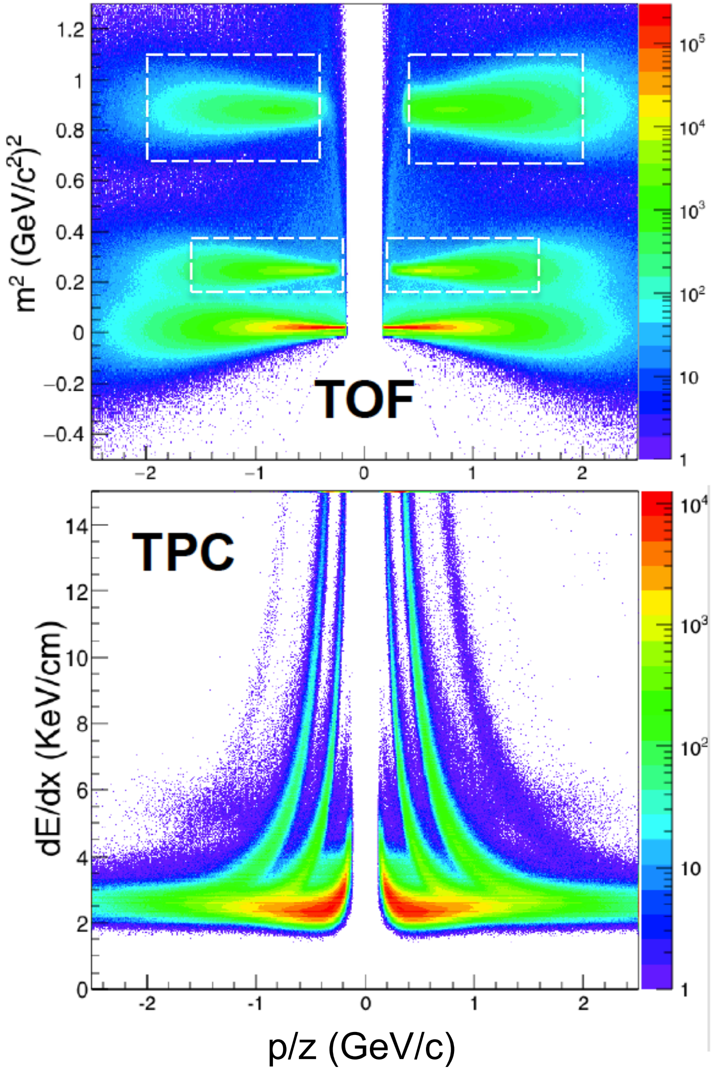
$\kappa\sigma^2 = 1$ (Poisson Fluctuations)

Characteristic signature of CP:
Non-monotonic energy dependence

"Oscillation Pattern"
Especially the Peak at low energies

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.

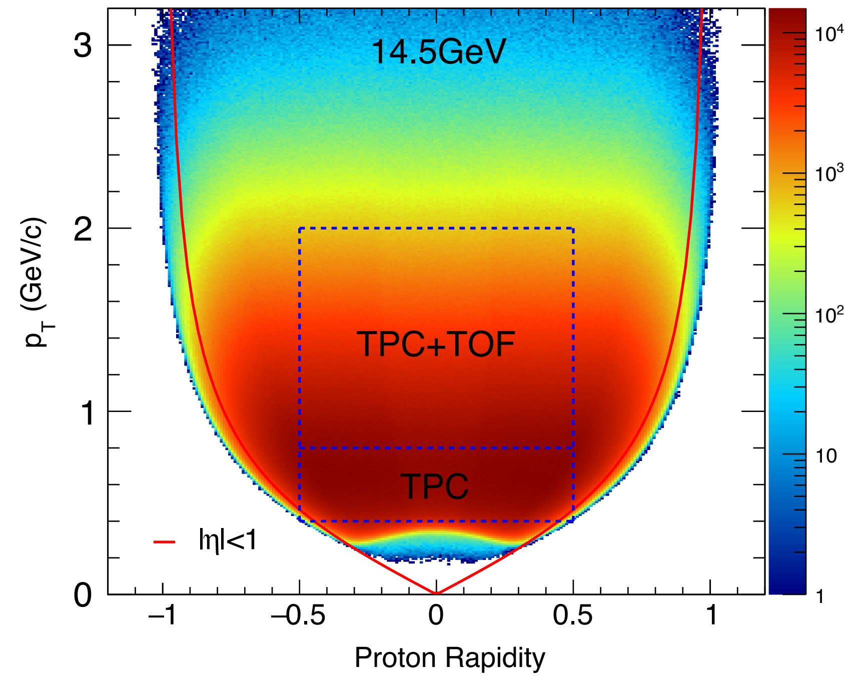
(Anti-) Proton PID and Acceptance



Extend the phase space coverage by TOF.

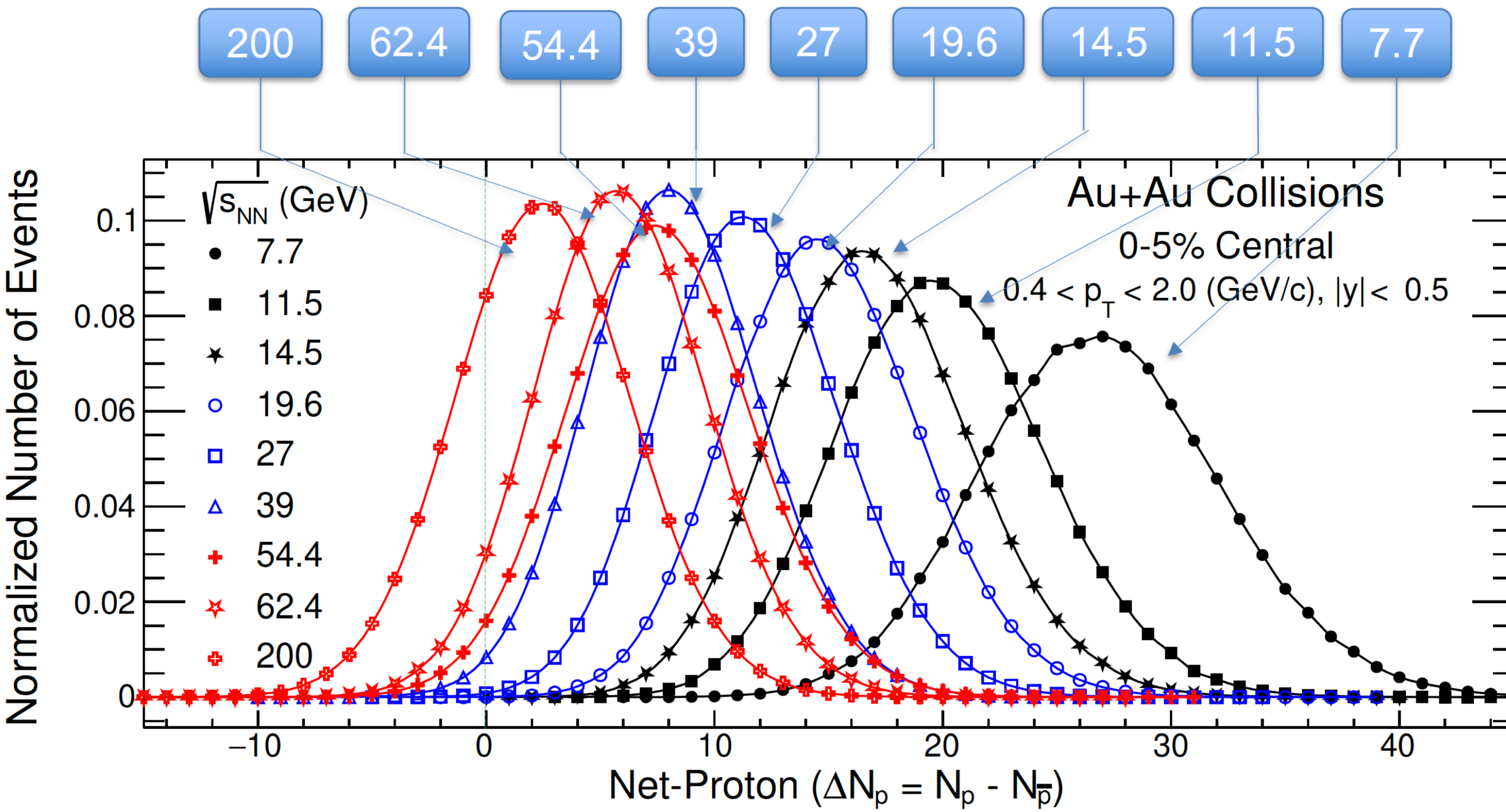
Doubled the accepted number of proton/anti-proton

$|y|<0.5$, $0.4 < p_T$ (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%.

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

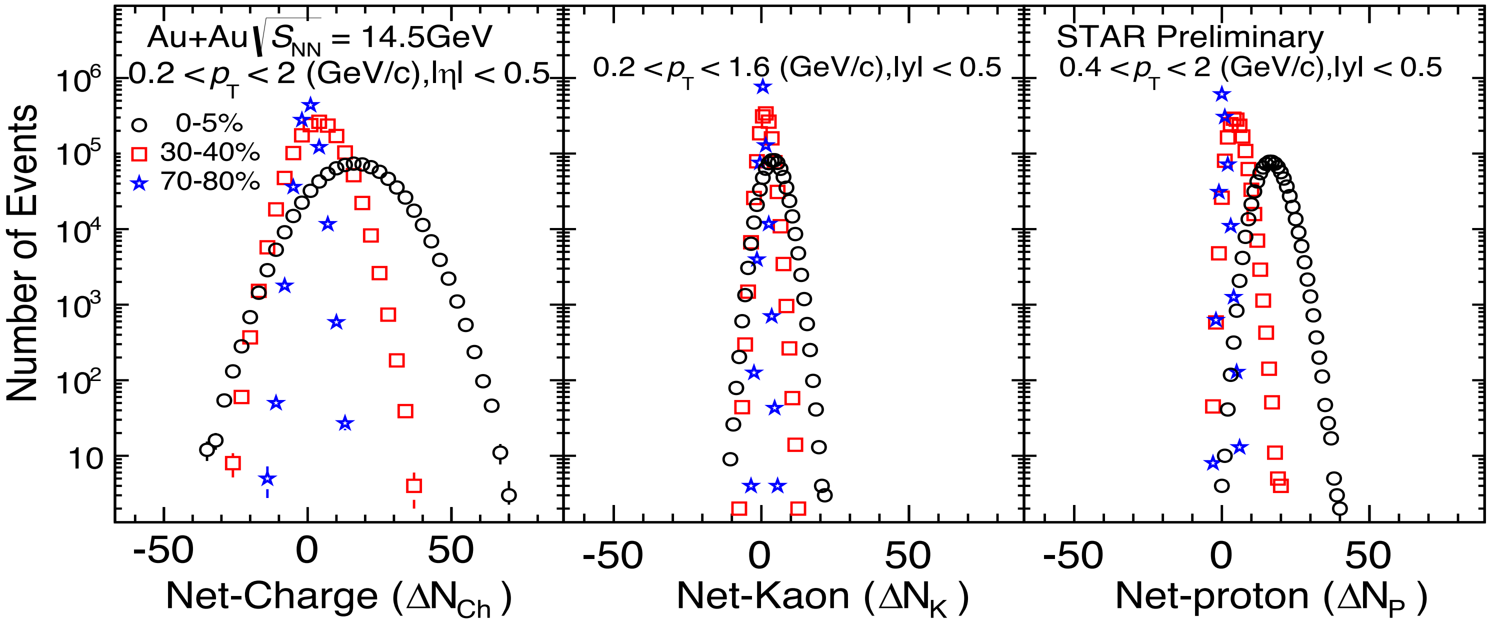


Efficiency uncorrected.

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

STAR, arXiv: 2001.02852

Analysis Details

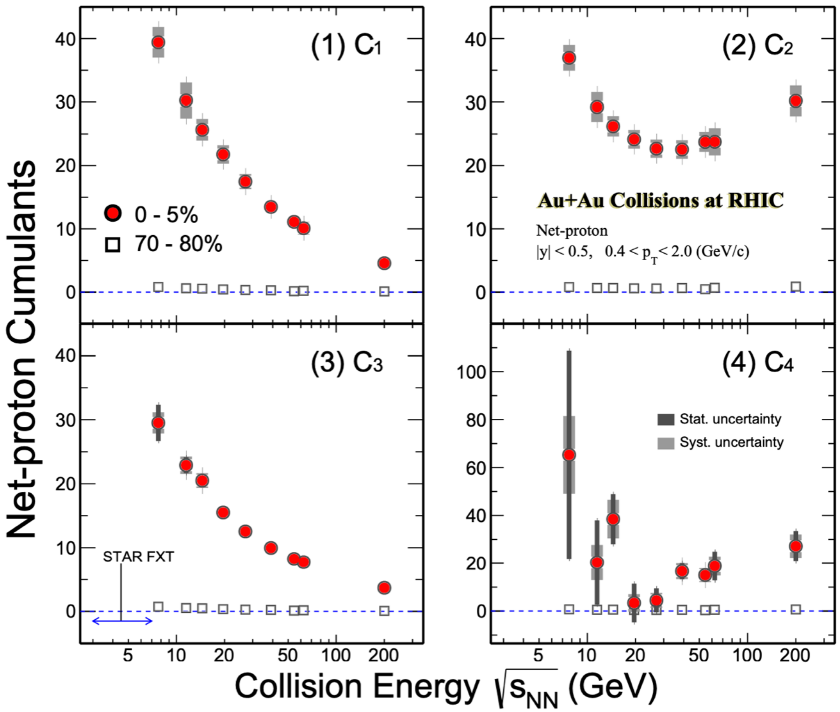


1. Statistical errors estimation : Delta theorem or bootstrap
2. Avoid auto-correlation effects: New centrality definition.
3. Suppress volume fluctuation： Centrality bin width correction (CBWC)
4. Detector efficiency correction : Binomial model

Review Article : X. Luo and N. Xu, Nucl. Sci. Tech. 28, 112 (2017).

X.Luo, J. Phys. G39, 025008 (2012); A. Bzdak and V. Koch, PRC86, 044904 (2012); X.Luo, et al. J. Phys. G40,105104(2013); X.Luo, Phys. Rev. C 91, 034907 (2015); A . Bzdak and V. Koch, PRC91, 027901 (2015). T. Nonaka et al., PRC95, 064912 (2017). M. Kitazawa and X. Luo, PRC96, 024910 (2017). S. He, X. Luo, Chin. Phys. C43, 104001 (2018), X. Luo and T. Nonaka, PRC99, 044917 (2019); Arghya Chatterjee, et al. PRC 101,034902 (2020)

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



Efficiency and CBWC corrections applied.

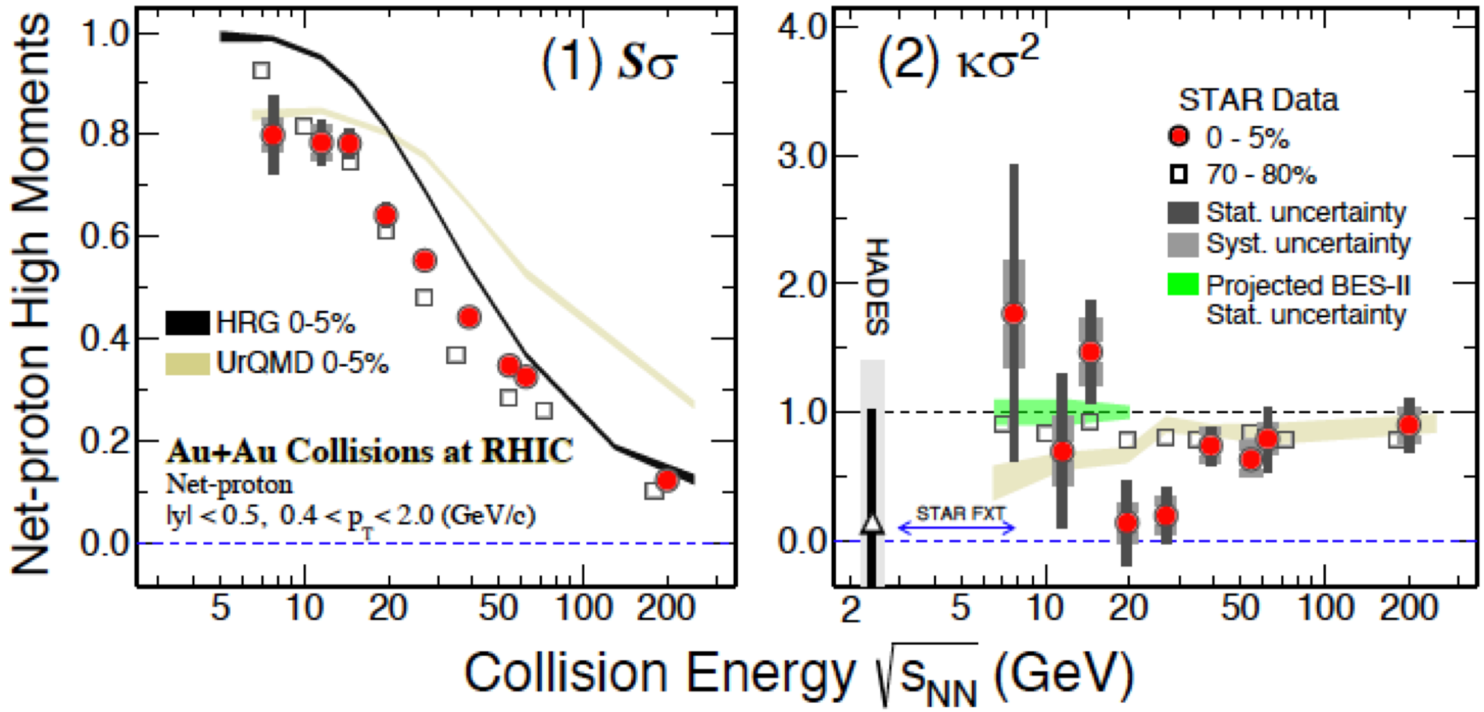
STAR: arXiv: 2001.02852 (short version)

A long paper is prepared and under review process within collaboration.

1) Net-p, proton and anti-proton cumulants
2) Correlation functions of protons and anti-protons
3) Energy, Centrality, acceptance dependence (p_T, y).
4) Compare the data with various model results .

- Cumulants of net-proton distributions from 0-5% central and 70-80% peripheral collisions.
- Mean values increase when energy decreases due to baryon stopping.
- Cumulants can be decomposed into various order correlation functions, which will provide additional information for underlying physics.

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

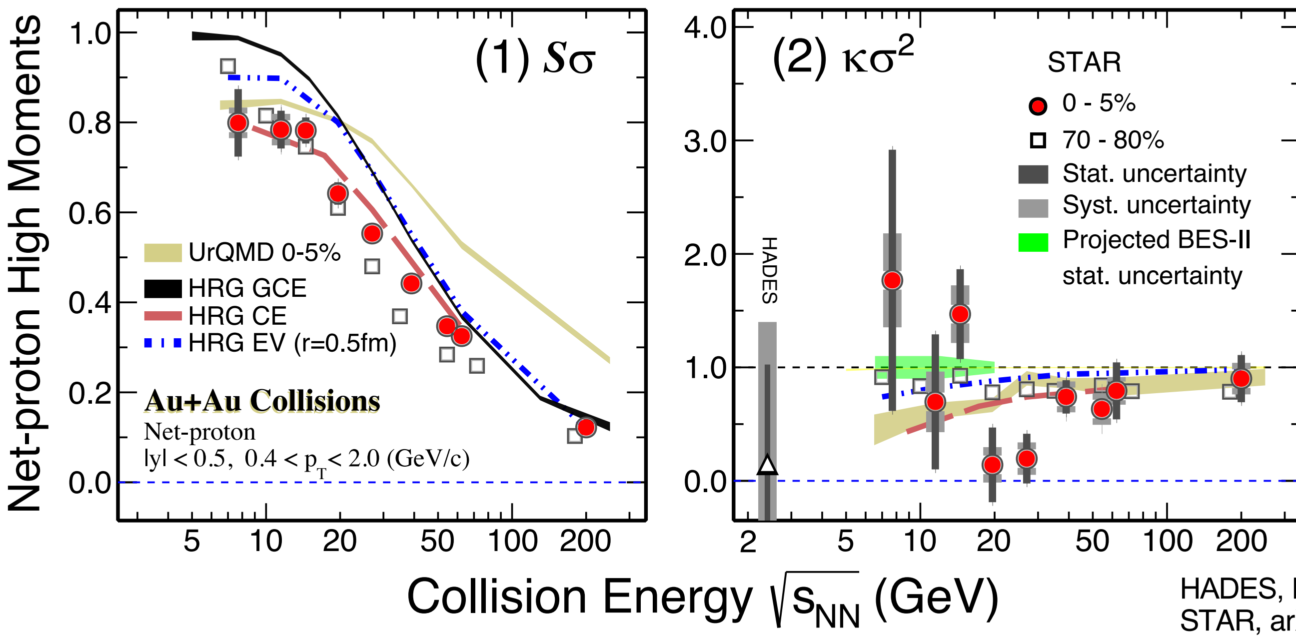


- HRG (GCE) and transport model predicted monotonical energy dependence. Suppression at low energy due to conservation.
- Observe a non-monotonic energy dependence (7.7-62.4 GeV) in 0-5% net-proton $\kappa\sigma^2$ with a significant of 3.1σ

HADES, PRC 102, 024914 (2020)
STAR, arXiv: 2001.02852

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

Comparison between model calculations and exp. data



HADES, PRC 102, 024914 (2020)
STAR, arXiv: 2001.02852

- PBM et al. proposed the Canonical Ensemble (CE) 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 ?

- Goodness of the description between data and model results are evaluated with the p values obtained from χ^2 test.

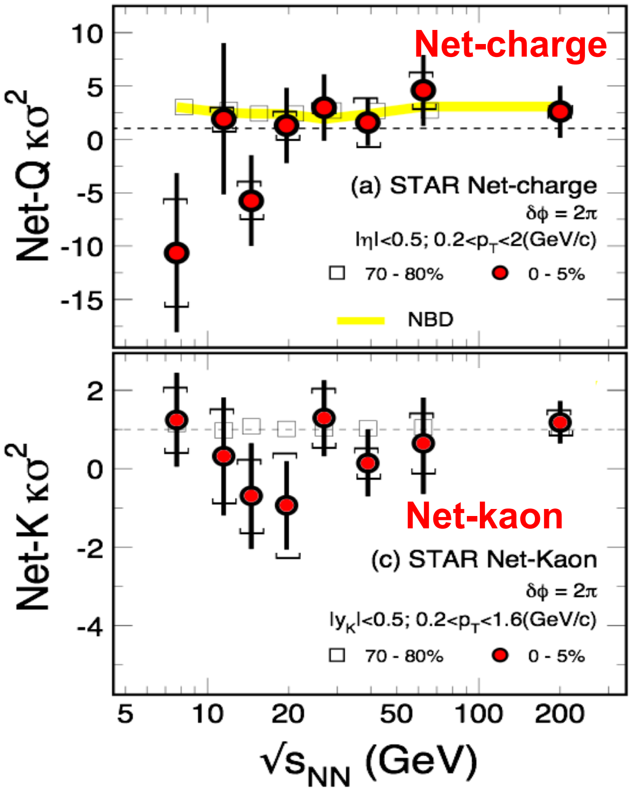
p values from χ^2 test below 27 GeV

Moments	HRG GCE	HRG EV (r = 0.5 fm)	HRG CE	UrQMD
$S\sigma$	< 0.001	< 0.001	0.0754	< 0.001
$\kappa\sigma^2$	0.00553	0.0450	0.0145	0.0221

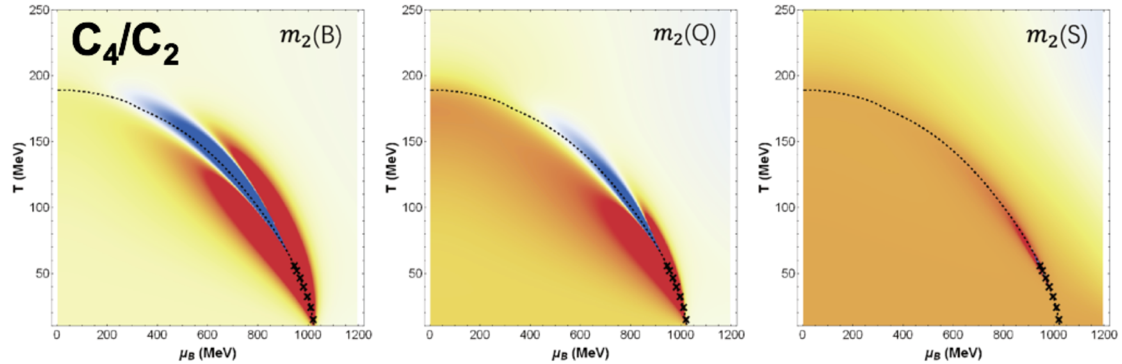
PBM et al., arXiv: 2007.02463, S. He et al., PLB 762 296 (2016).
J.H. Fu, PLB 722, 144 (2013), A. Bhattacharyya et al., PRC 90, 034909(2014).
HRG+VDW: Vovchenko et al., PRC92,054901 (2015); PRL118,182301 (2017).
RMF: K. Fukushima, PRC91 044910 (2015)

Net-charge and Net-kaon Fluctuations

STAR Data



NJL Model calculations



Baryon (B) Charge (Q) Strangeness (S)

W. Fan, X. Luo, H.S. Zong, IJMPA 32, 1750061 (2017).

Critical signals: B>Q>S

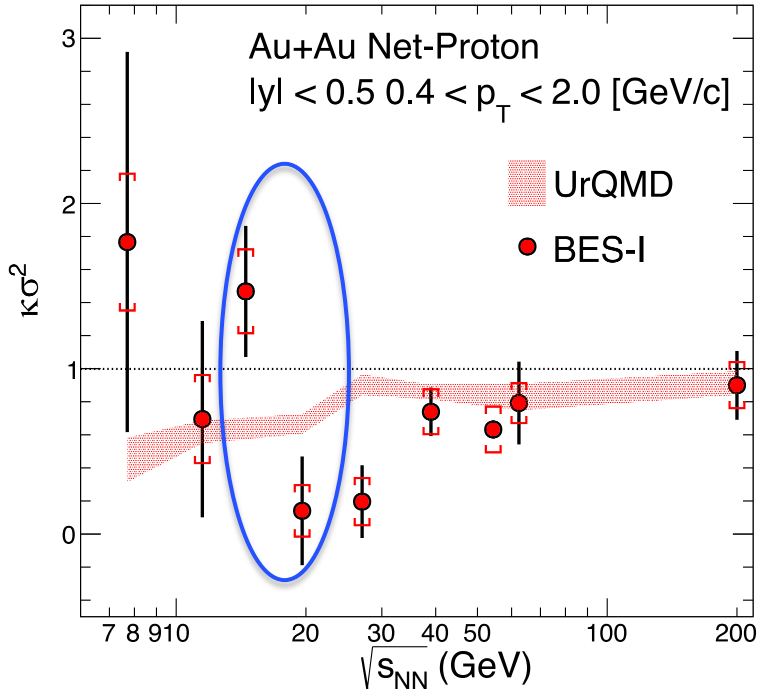
(Due to the mass of strange quark is much larger than u,d quarks， $m_s >> m_{u,d}$)

STAR : Phys. Rev. Lett. 113 092301 (2014).
Phys. Lett. B 785, 551 (2018).

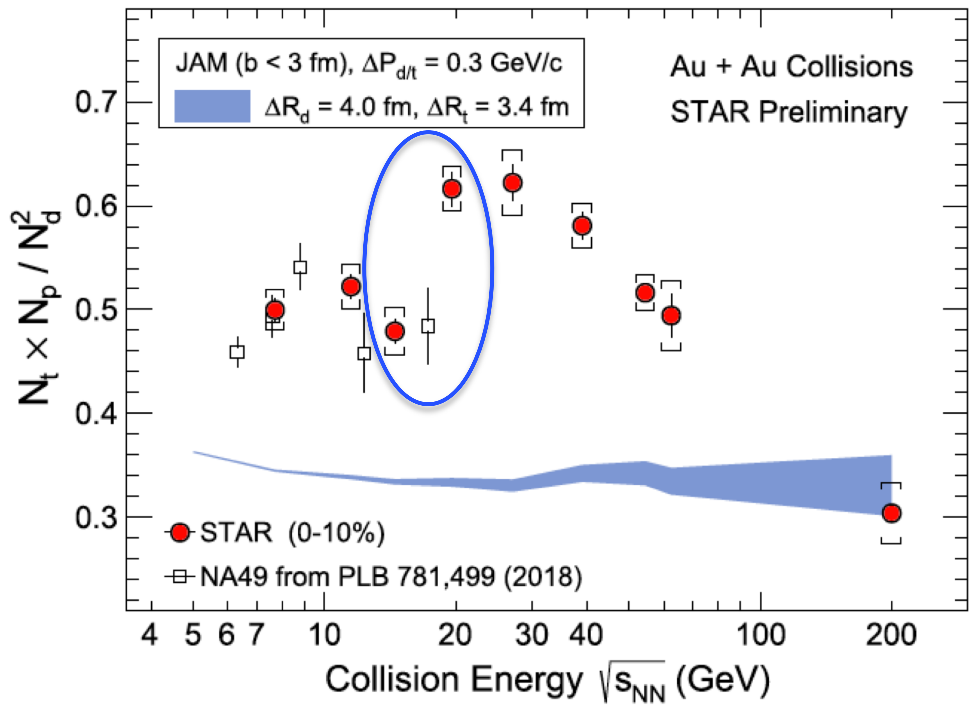
$$error(\kappa\sigma^2) \propto \frac{\sigma^2}{\varepsilon^2}\frac{1}{\sqrt{N_{evts}}}$$

1) Within errors, the results of net-Q and net-Kaon show flat energy dependence.
2) More statistics are needed, especially at low energies (BES-II will help).

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



STAR: arXiv: 2001.02852



Dingwei Zhang (STAR), QM2019 [arXiv: 2002.10677]

1. Value jumps between 19.6 and 14.5 GeV in both net-proton flu. and light nuclei yield ratio.
2. STAR has proposed to take a new energy point in 2021 (Run 21) : 17.1 GeV (μ_B ~ 235 MeV) with μ_B lie between 14.5 (μ_B ~ 266 MeV) and 19.6 GeV (μ_B ~ 205 MeV).

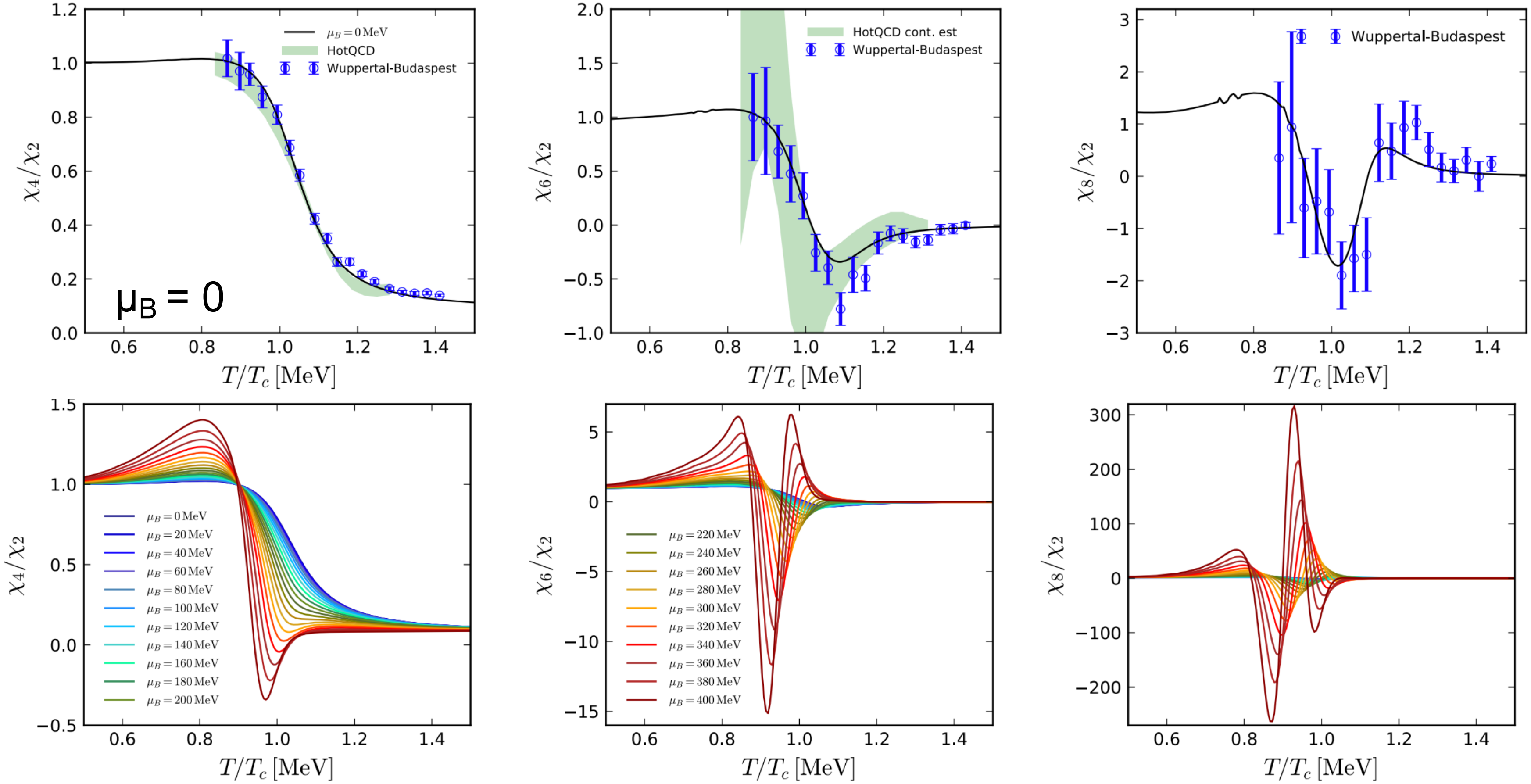
Model calculations trying to explain both observations :

Pre-cluster at chemical freeze-out due to attractive *NN* potential :
Edward Shuryak, Juan M. Torres-Rincon, PRC 100, 024903 (2019); PRC 101, 034914 (2020); EPJA 56, 241 (2020).

Propose to take data of Au+Au 17.1 GeV in Run 21 : 2.5 Weeks with ~250 million events.

Higher-order baryon number fluctuations: PQM+FRG Model

4th order **6th order** **8th order**

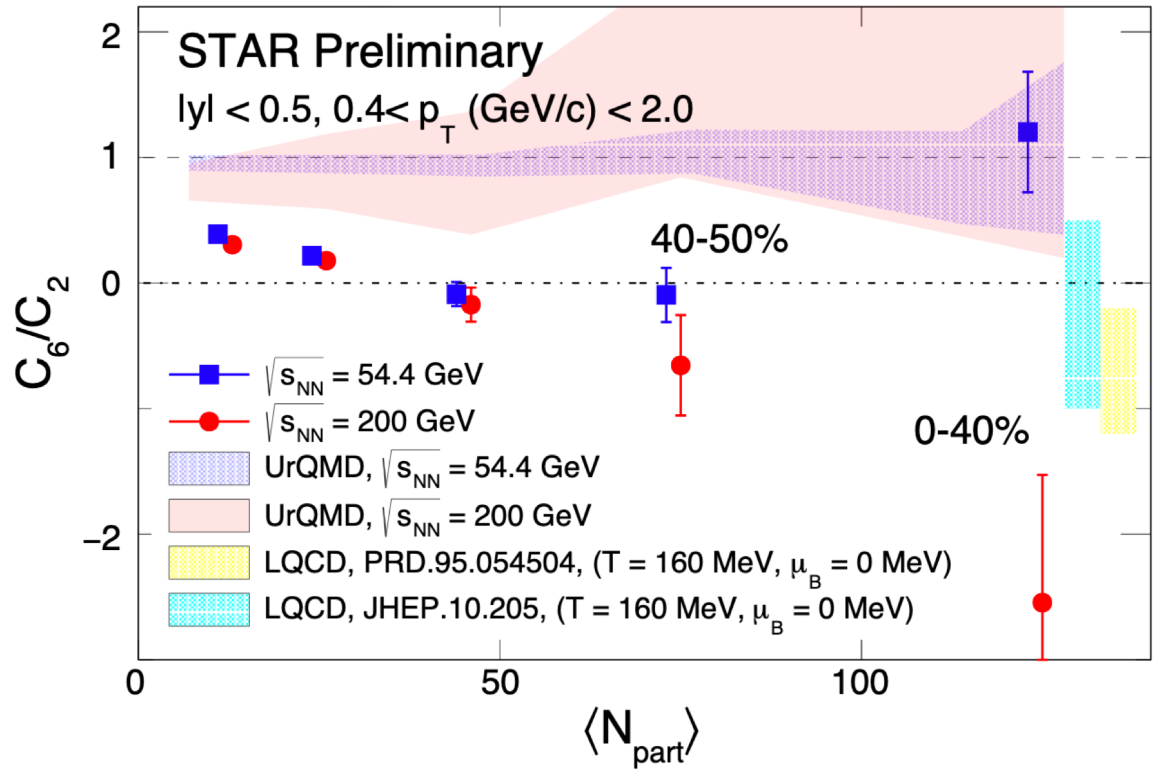


- Higher-order fluctuations are more sensitive to QCD phase transition.
- At μ_B = 0, C_6 ~ 0 or negative, and C_8 become negative when chemical freeze-out temperature close to Tc.

-> could serve as experimental evidence of chiral crossover.

Wei-jie Fu et al., In preparation.

Net-proton C_6 measurement



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

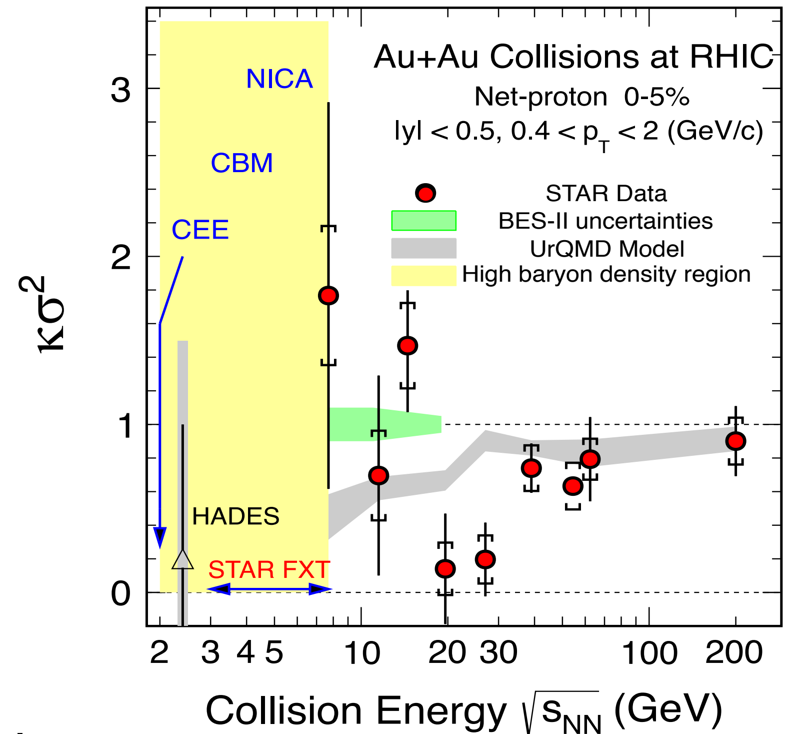
- Results from three energies are consistent in peripheral collisions.
- $C_6/C_2 > 0$ at 54.4 GeV and $C_6/C_2 < 0$ at 200 GeV in 0-40% central collisions.

Ashish and Toshihiro, QM2019

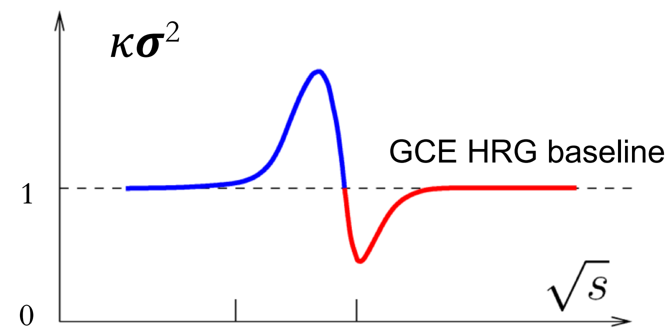
BES-II at RHIC (2019-2021)

STAR, arXiv: 2001.02852

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES II / BES I
19.6	538	2019 / 2011
14.6	325	2019 / 2014
11.5	230	2020 / 2010
9.2	160	2020 / 2008
7.7	100	2021 / 2010
17.1	250	2021 (proposed)



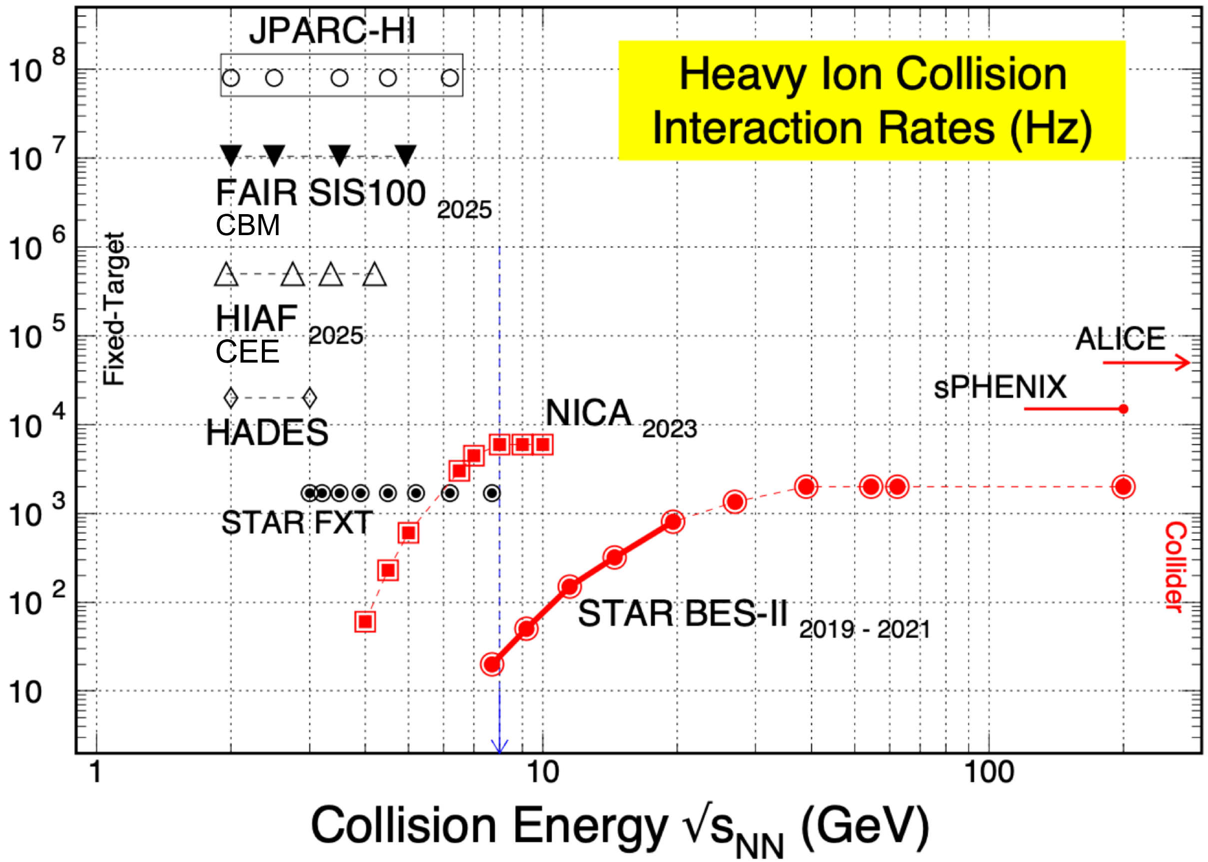
- BES-II: 10-20 times higher statistics than BES-I.
- FIX-target mode : $\sqrt{s_{NN}}$ = 3-7.7 GeV (2018-2021).



iTPC, ETOF, EPD upgrade completed.

- Enlarge Acceptance : η coverage from 1.0 to 1.5
- Improve dE/dx and forward PID
- Improve centrality/event plane determination

Future Facilities for Heavy-Ion Collisions



X. Luo, N. Xu, Nucl. Sci. Tech. 28, 112 (2017).
X. Luo, S. Shi, N. Xu and Y. Zhang, Particle 3, 278 (2020)
A. Bzdak, S. Esumi, V. Koch, J. Liao, M. Stephanov, N. Xu Phys. Rep. 853, 1 (2020).
K. Fukushima, B. Mohanty, N. Xu, arXiv: 2009. 03006

Exploring the QCD phase structure at high baryon density region

Summary and Outlook

Higher moments of conserved quantities and light nuclei production are sensitive observables of CP (large density fluctuations and long range correlations)

- Yield ratio of light nuclei and fourth order net-proton fluctuations (C_4/C_2) in central Au+Au collisions shows non-monotonic energy dependence, which could serve as important experimental basis for critical point search.

- C_6 and C_8 can be used to probe the chiral crossover at μ_B=0. Large statistics are needed to conduct precise measurements.

- Need to study the background/non-equilibrium contributions carefully and build-up dynamical modeling of heavy-ion collisions with critical fluctuations.

- 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.

Acknowledgements :

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

Thank you for your attention !!

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

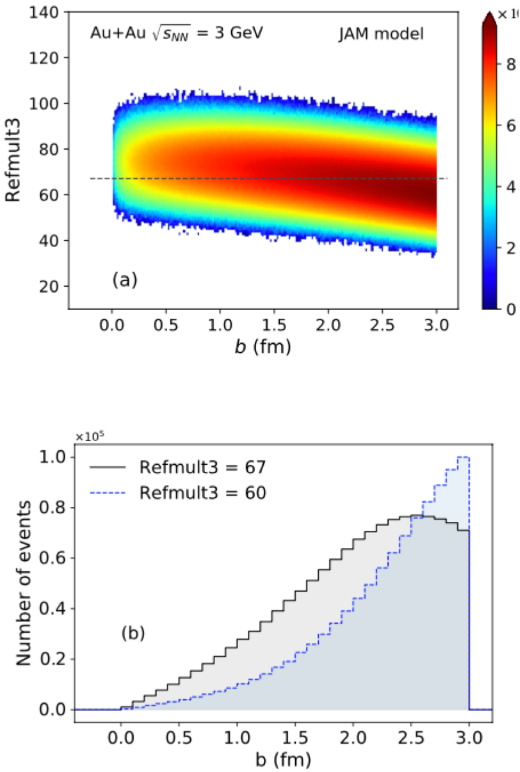
$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES II / BES I	μ_B (MeV)	T_{CH} (MeV)
7.7	50+112	2019+2020	420	140
6.2	118	2020	487	130
5.2	103	2020	541	121
4.5	108	2020	589	112
3.9	117	2020	633	102
3.5	116	2020	666	93
3.2	200	2019	699	86
3.0	259	2018	720	80
3.0*	**2000**	**2021**	720	80

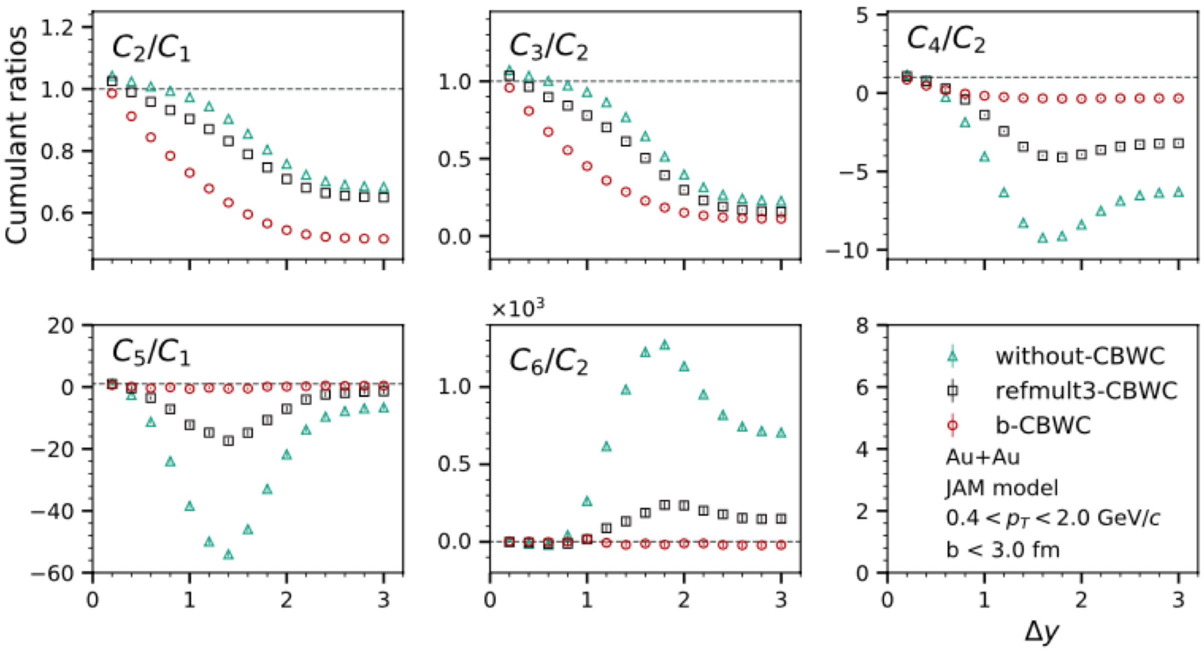
T_{ch} and μ_B from J. Cleymans et al. PRC73, 034905 (2006)
*New Proposed Energy in Beam User Request 2020/2021.

BES-II Program:

- Precisely map the QCD phase diagram **200 < μ_B < 420 MeV**
- The FXT program extends **μ_B coverage up to 720 MeV (3 GeV)**

Centrality determination at lower energies





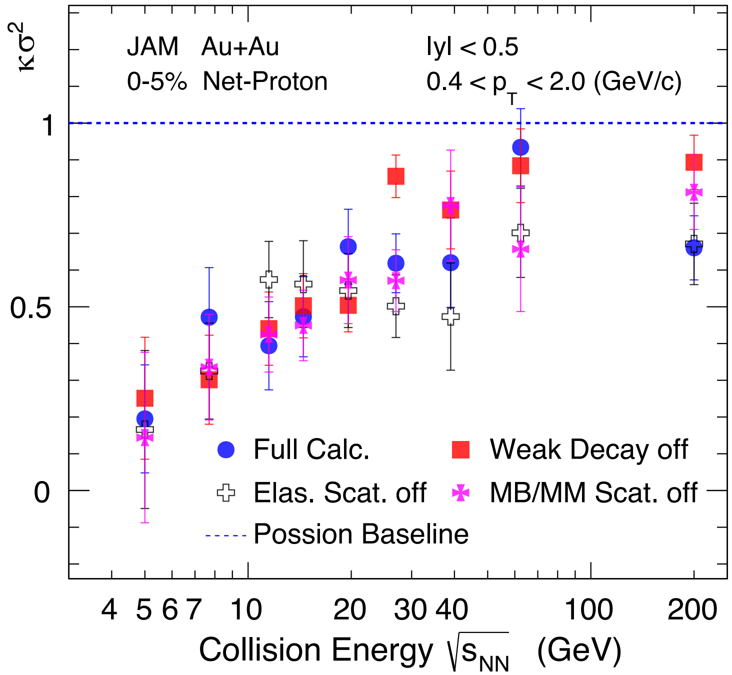
A. Chatterjee et al., arXiv:2009.03755

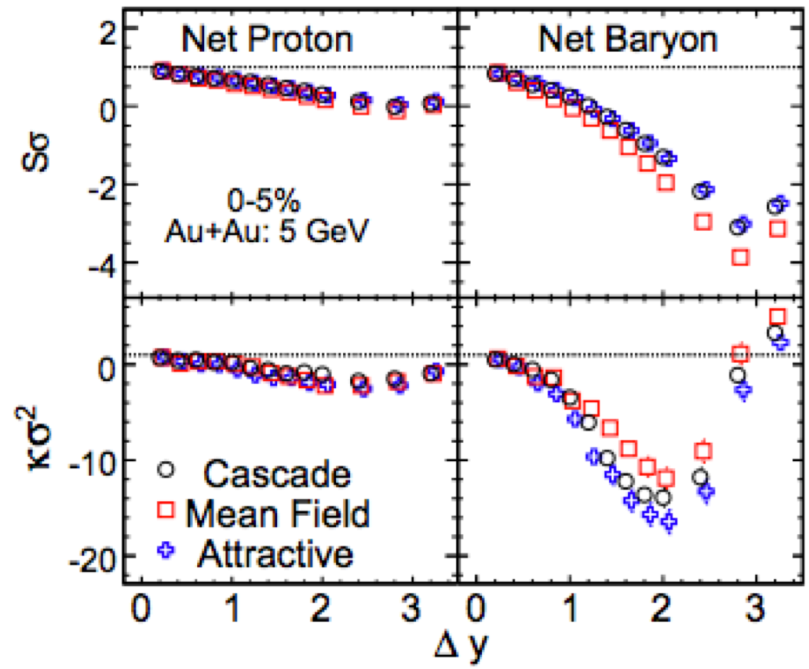
- At low energies, centrality resolution obtained from charge particle multiplicities is very poor and CBWC is not efficient.
- New methods, such as machine learning technique could be helpful.

  F. P. Li et al., J. Phys. G 47, 115104 (2020). M. O. Kuttan et al., arXiv : 2009.01584
- Volume fluctuations corrections ?

T. Sugiura et al., Phys. Rev. C 100, (2019) 044904; Braun-Munzinger et al., Nucl. Phys. A 960 (2017)114-130
Skokov et al., Phys. Rev. C88 (2013) 034911; HADES, PRC 102, 024914 (2020)

Non-critical contributions: transport model studies





UrQMD, JAM, AMPT : Dominated by baryon number conservations at low energies

- Effects of weak decay and hadronic scattering are not significant within uncertainties.
- No significant effects observed for mean field potential and attractive scattering (to simulate softening of EoS)

Z. Feckova, et al., PRC92, 064908(2015); J. Xu, et. al., PRC94, 024901(2016); X. Luo et al., NPA931, 808(14), P.K. Netrakanti et al., NPA947, 248(2016), P. Garg et al. PLB 726, 691(2013). S. He, et. al., PLB762, 296 (2016); PLB 774, 623 (2017).
J. Li et al, PRC 97,014902 (2018). H. J. Xu, PLB 765, 188 (2017); Y. X. Ye et al., PRC 98, 054620 (2018). C. Zhou, et al., PRC 96, 014909 (2017). Y. Zhang, et al. PRC101, 034909 (2020). L. Jiang et al., PRC94, 024918 (2016); M. Bluhm, EPJC77, 210 (2017).