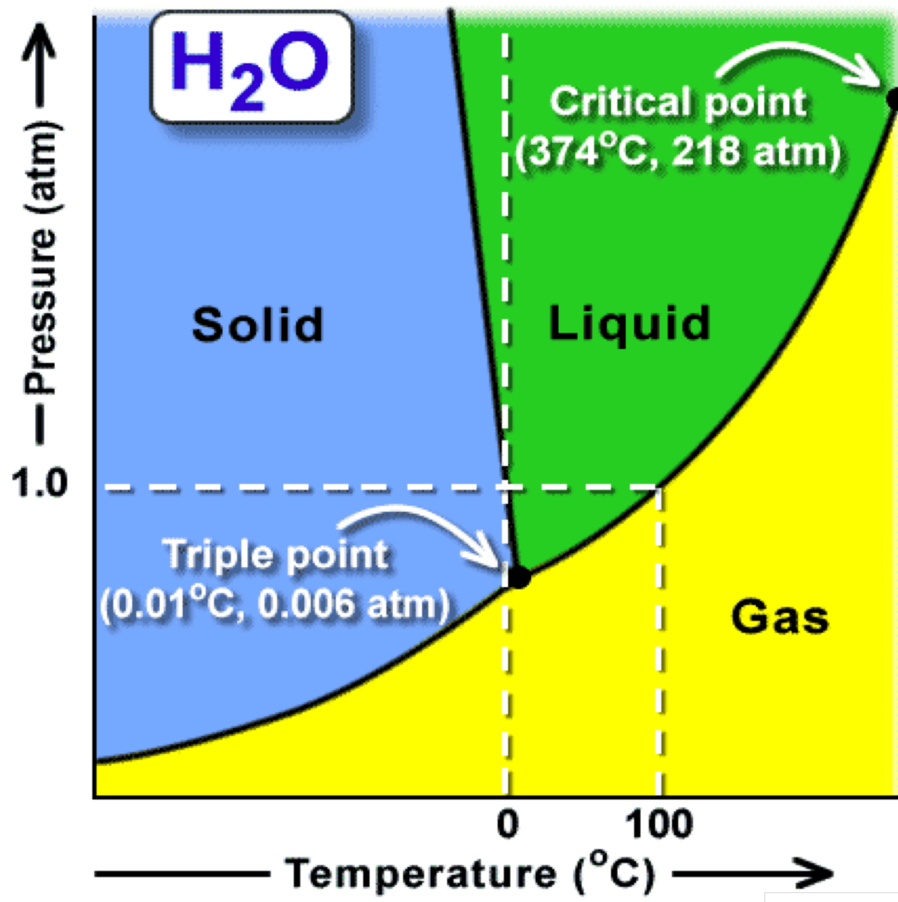
Search for the QCD Critical Point in High Energy Heavy-ion Collisions

Xiaofeng Luo (罗晓峰)

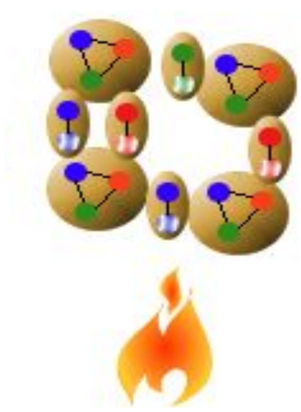
Central China Normal University

Water



Dominated by EM interactions

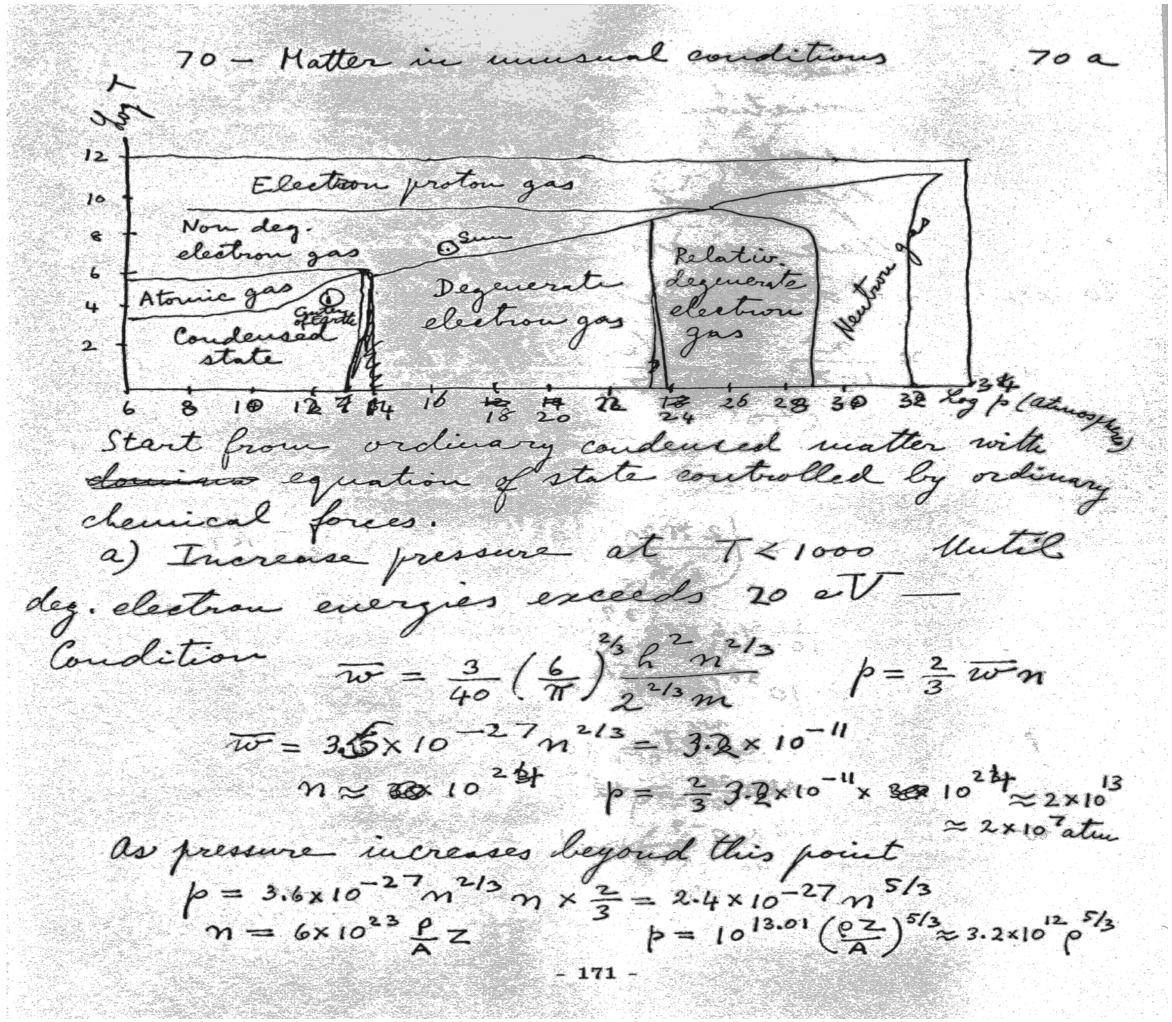
What will happen, if we
Heat matter to trillion (10^{12}) degree ?



Matter Under Extreme Condition (1953)

E. Fermi

E. Fermi: *"Notes on Thermodynamics and Statistics " (1953)*



70 — Matter in unusual conditions 70 a

Start from ordinary condensed matter with ~~domains~~ equation of state controlled by ordinary chemical forces.

a) Increase pressure at $T < 1000$ until deg. electron energies exceeds 20 eV — Condition

$$\overline{w} = \frac{3}{40}\left(\frac{6}{\pi}\right)^{2/3}\frac{h^2 n^{2/3}}{2^{2/3} m} \qquad p = \frac{2}{3}\overline{w} n$$

$$\overline{w} = 3.6\times 10^{-27} n^{2/3} = 3.2\times 10^{-11}$$

$$n \approx 30\times 10^{24} \qquad p = \frac{2}{3}\, 3.2\times 10^{-11}\times 30\, 10^{24} \approx 2\times 10^{13}$$

$$\approx 2\times 10^{7}\,\text{atm}$$

As pressure increases beyond this point

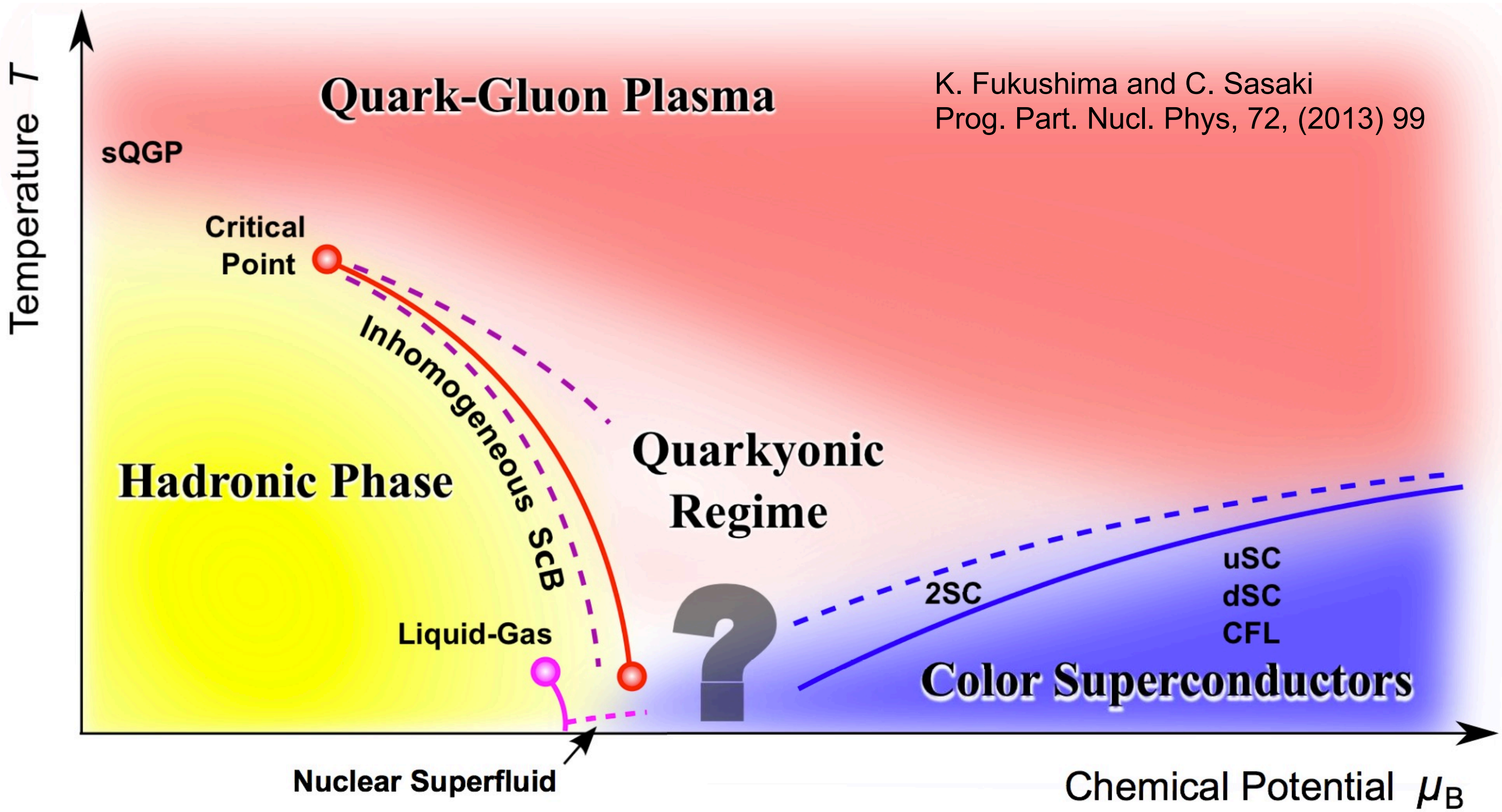
$$p = 3.6\times 10^{-27} n^{2/3}\, n \times \frac{2}{3} = 2.4\times 10^{-27} n^{5/3}$$

$$n = 6\times 10^{23}\frac{\rho}{A} Z \qquad p = 10^{13.01}\left(\frac{\rho Z}{A}\right)^{5/3} \approx 3.2\times 10^{12}\rho^{5/3}$$

- 171 -

QCD Phase Diagram (2013)

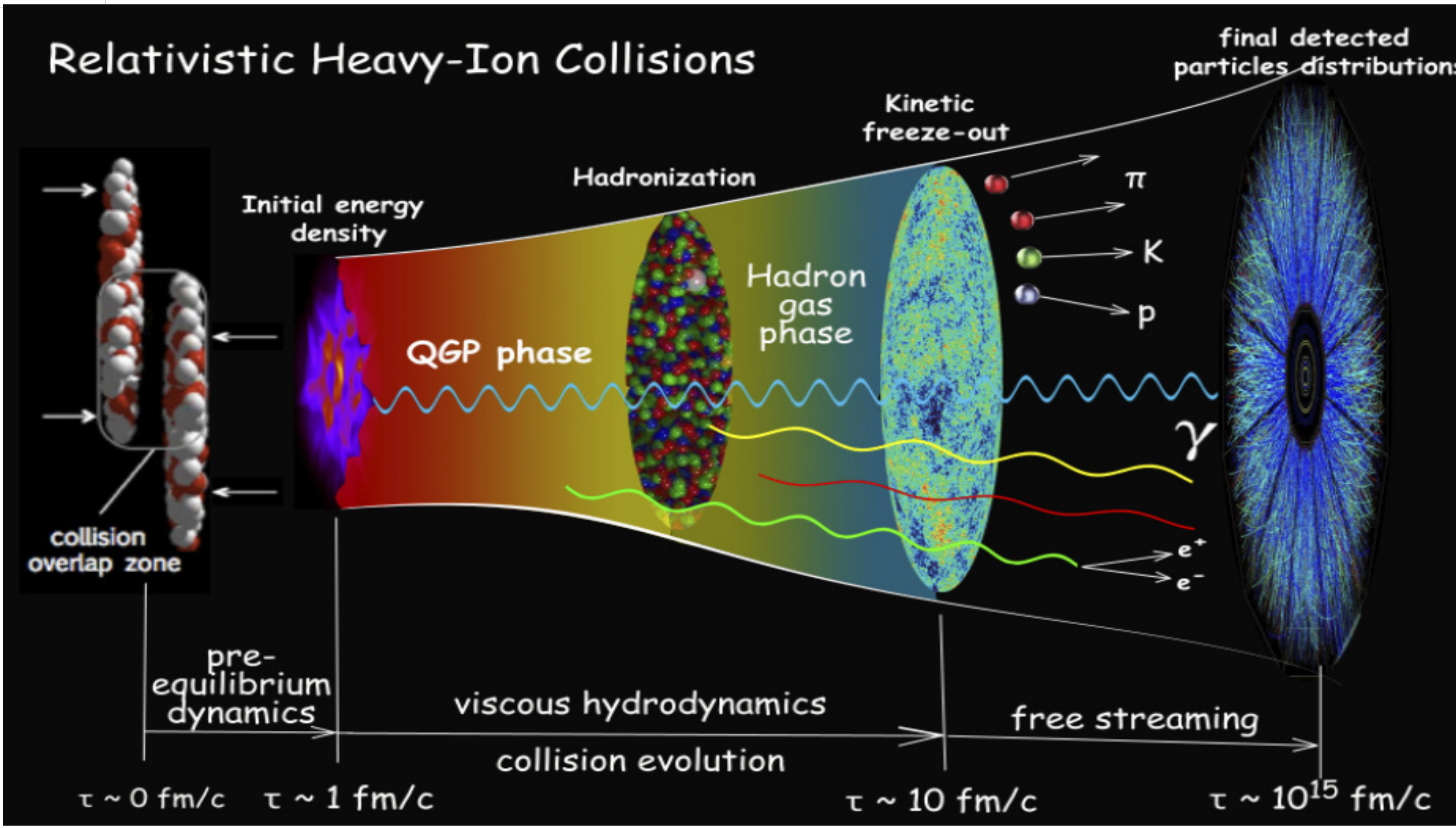
Very rich physics at high baryon density region.



1. High Temperature : Early Universe
2. High Baryon density : Neutron star etc.

1. 1st order Phase Transition ?
2. Critical point ?

Relativistic Heavy-Ion Collisions



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

Location of CEP: Theoretical Prediction

- **Lattice QCD:**

1): Fodor&Katz, JHEP 0404,050 (2004):
(μ^E_B, T_E)= (360, 162) MeV (Reweighting)

2): Gavai&Gupta, NPA 904, 883c (2013)
(μ^E_B, T_E)= (279, 155) MeV (Taylor Expansion)

3): F. Karsch et al. NPA 956, 352 (2016).
(μ^E_B/ T_E >2)

- **Dyson-Schwinger Equation (DSE):**

1): Y. X. Liu, et al., PRD90, 076006 (2014); 94, 076009 (2016). PRL
(μ^E_B, T^E) = (372, 129) ; (262.3, 126.3) MeV
(330, 128), L=2fm (450, 109)

2): Hong-shi Zong et al., JHEP 07, 014 (2014).
(μ^E_B, T_E)= (405, 127) MeV

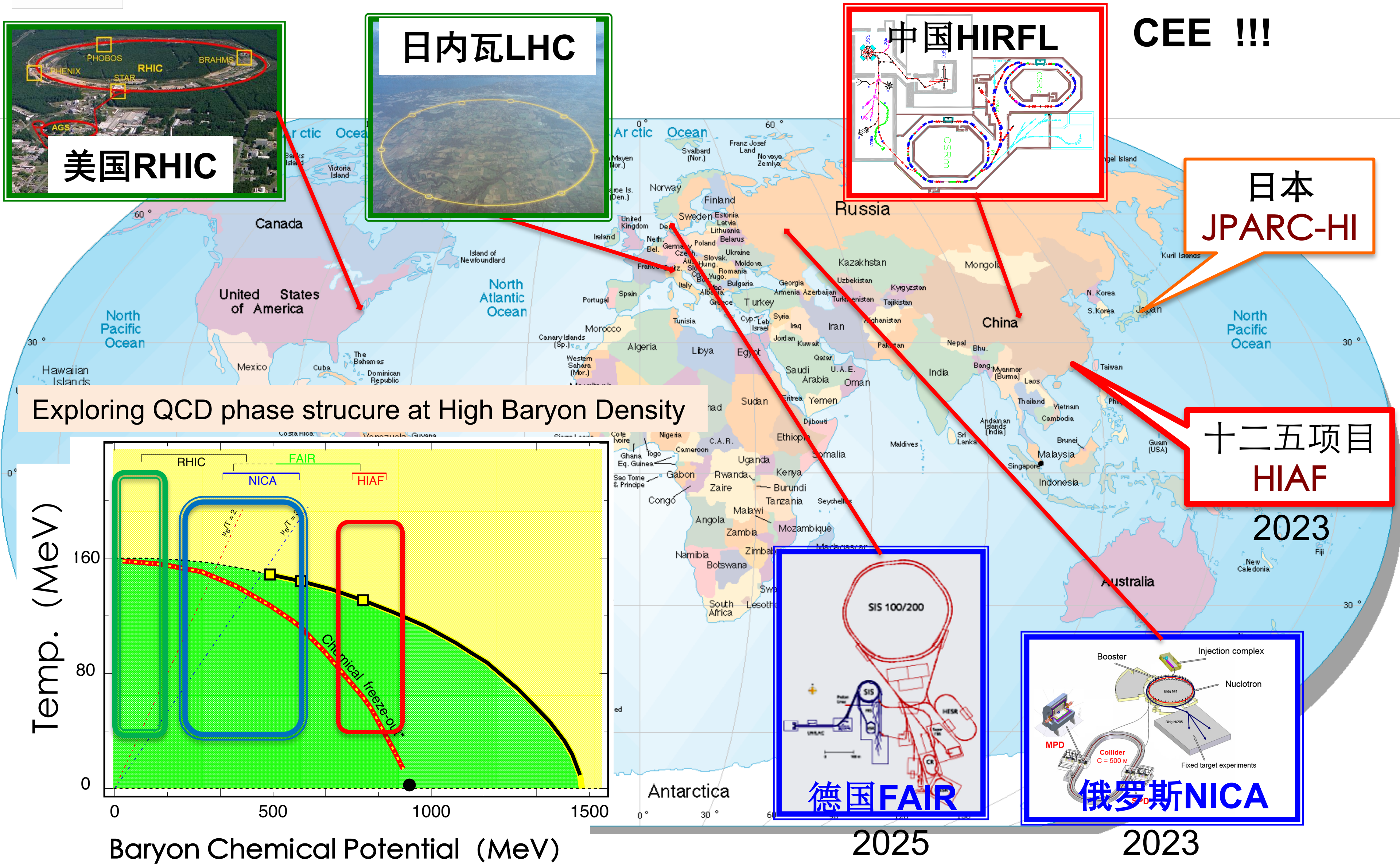
3): C. S. Fischer et al., PRD90, 034022 (2014).
(μ^E_B, T^E) = (504, 115) MeV

- **Functional Renormalization Group (FRG):**
(μ^E_B, T^E) = (635, 107) ; Weijie Fu et al.
(μ^E_B, T^E) = (780, 55); Defu Hou et al. PRD96 (2017)

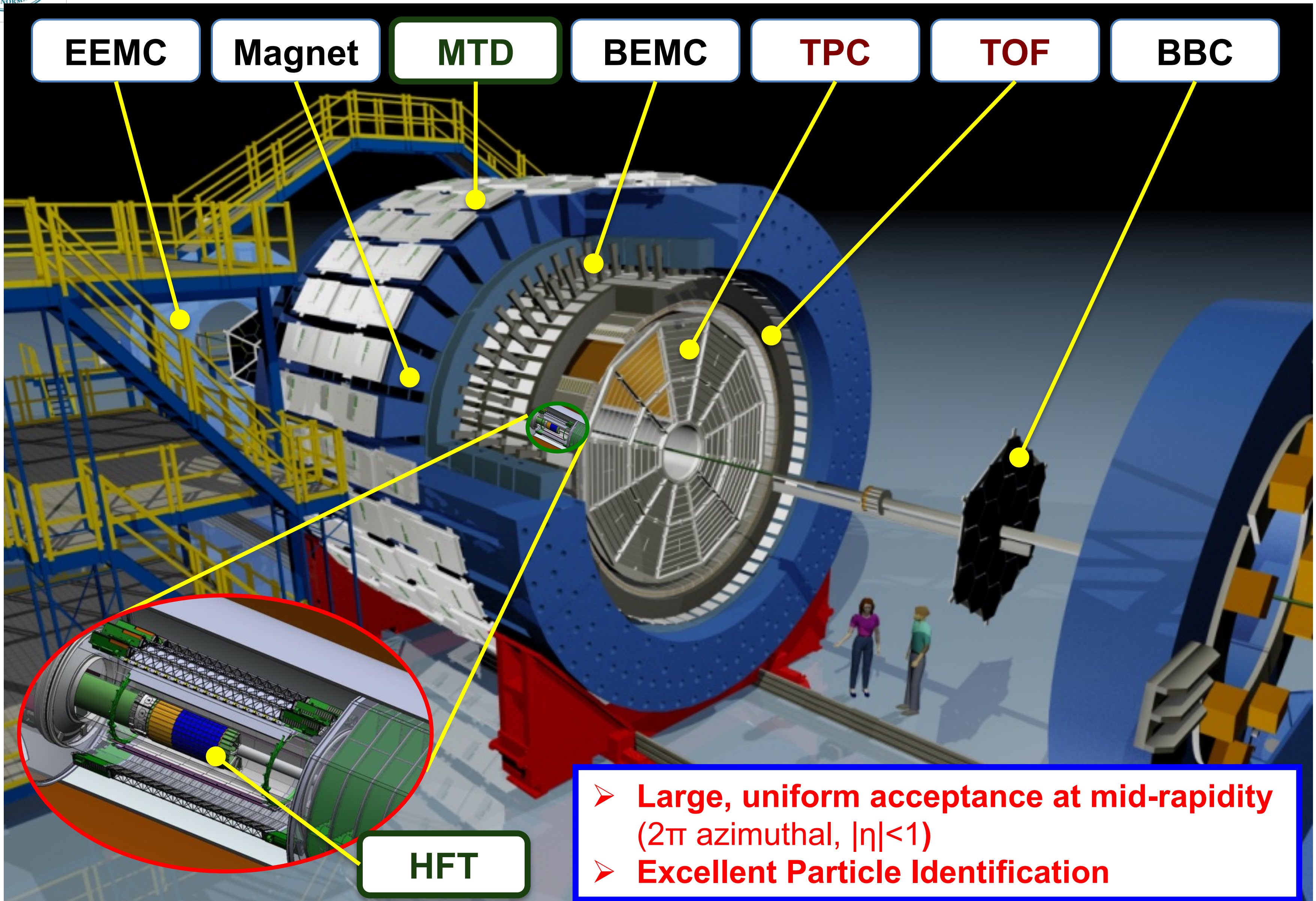
- **PNJL**, (μ^E_B, T^E) = (720, 90), Mei Huang, et al. EPJC 79, 245 (2019).

μ^E_B =262 ~ 780 MeV, T_E = 55~162 MeV

Exploring the QCD Phase Structure



STAR Detector System



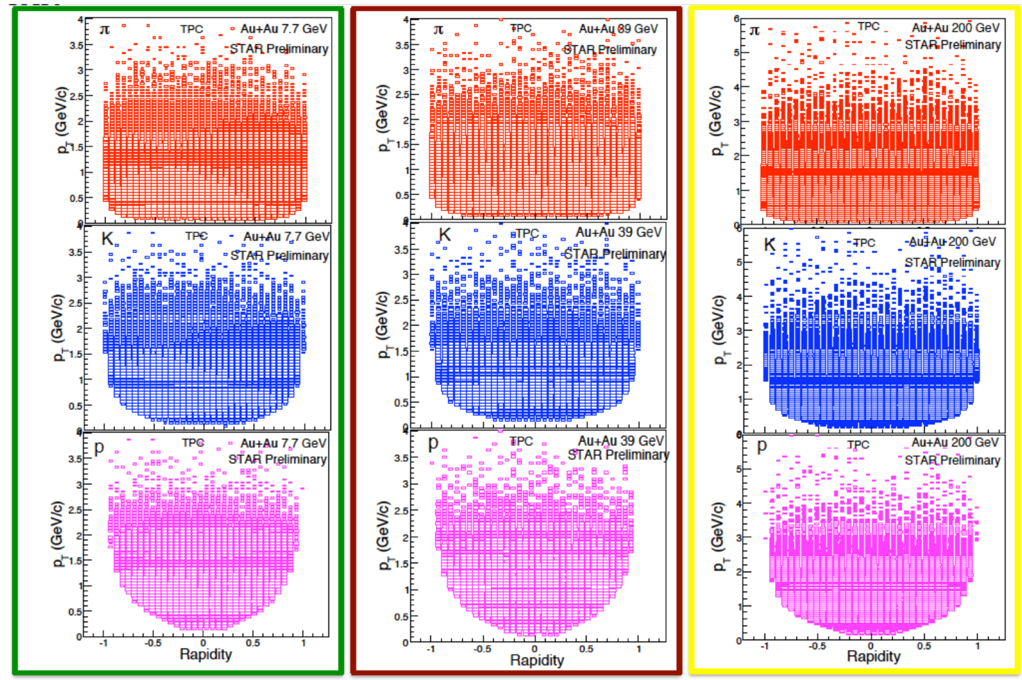
- **Large, uniform acceptance at mid-rapidity** (2π azimuthal, |η|<1)
- **Excellent Particle Identification**

RHIC Beam Energy Scan Phase I (2010-2017)

$\sqrt{s_{NN}}$ (GeV)	Year	Events (10^6)	*μ_B (MeV)	*T_{CH} (MeV)
200	2010	238	25	166
62.4	2010	45	73	165
54.4	2017	1200	83	165
39	2010	86	112	164
27	2011	32	156	162
19.6	2011	15	206	160
14.5	2014	13	264	156
11.5	2010	7	316	152
7.7	2010	3	422	140

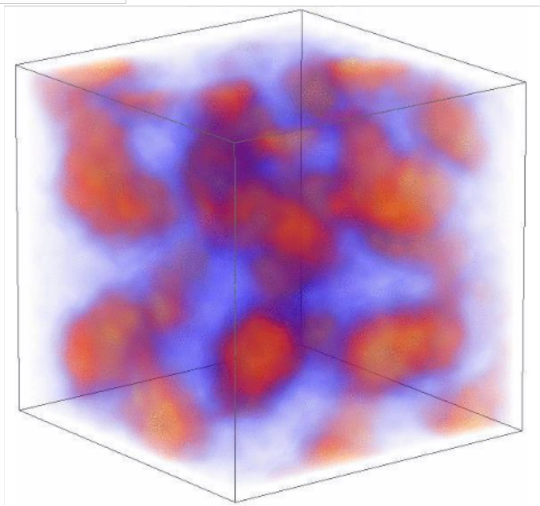
*(μ_B, T_{CH}) : J. Cleymans et al., PRC 73, 034905 (2006)

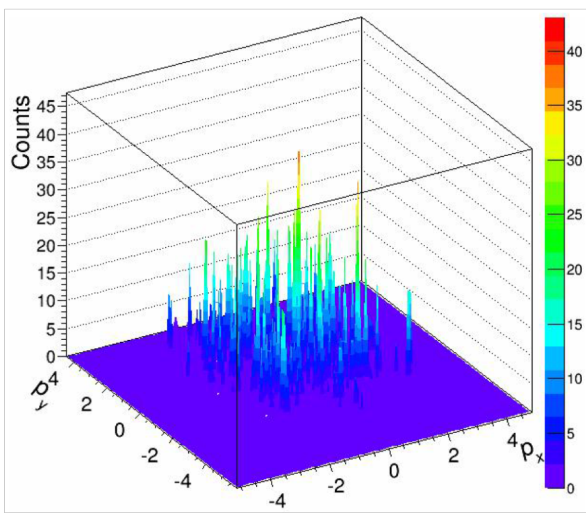
Uniform acceptance at Mid-rapidity



- Access the QCD phase diagram: vary collision energies/centralities.
  RHIC BES-I : 20 < μ_B < 420 MeV

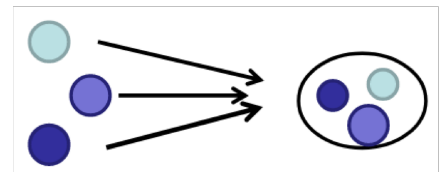
Search for the QCD critical point





In the vicinity of critical point

Large density fluctuations and long range corr.



E-by-E conserved charge (B, Q, S) fluctuations

Baryon clustering: light nuclei production

Experimental Signatures:

Non-monotonic variation as a function of collision energy.

Higher Moments of Conserved Quantities

Cumulants of the event-by-event net-proton, net-charge and net-kaon distributions.

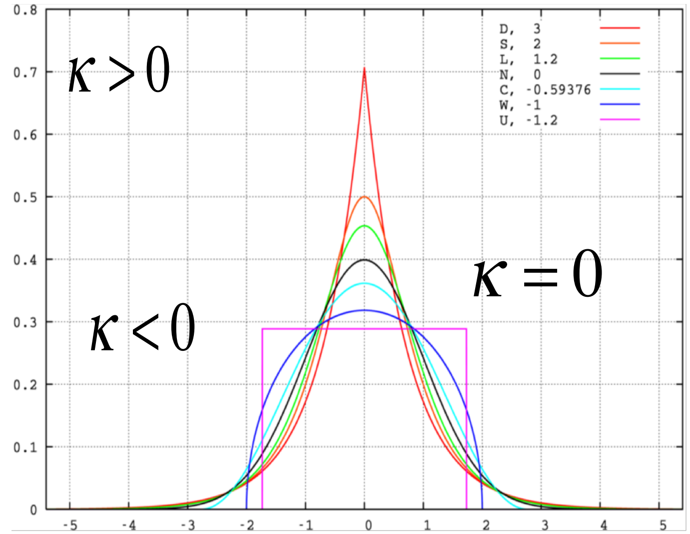
- **Net-Proton:** $N_p - N_{\bar{p}}$

  (Net-Baryon, *B*)

- **Net-Charge:** $N_{Q^+} - N_{Q^-}$

- **Net-Kaon:** $N_{K^+} - N_{K^-}$

  (Net-Strangeness, *S*)



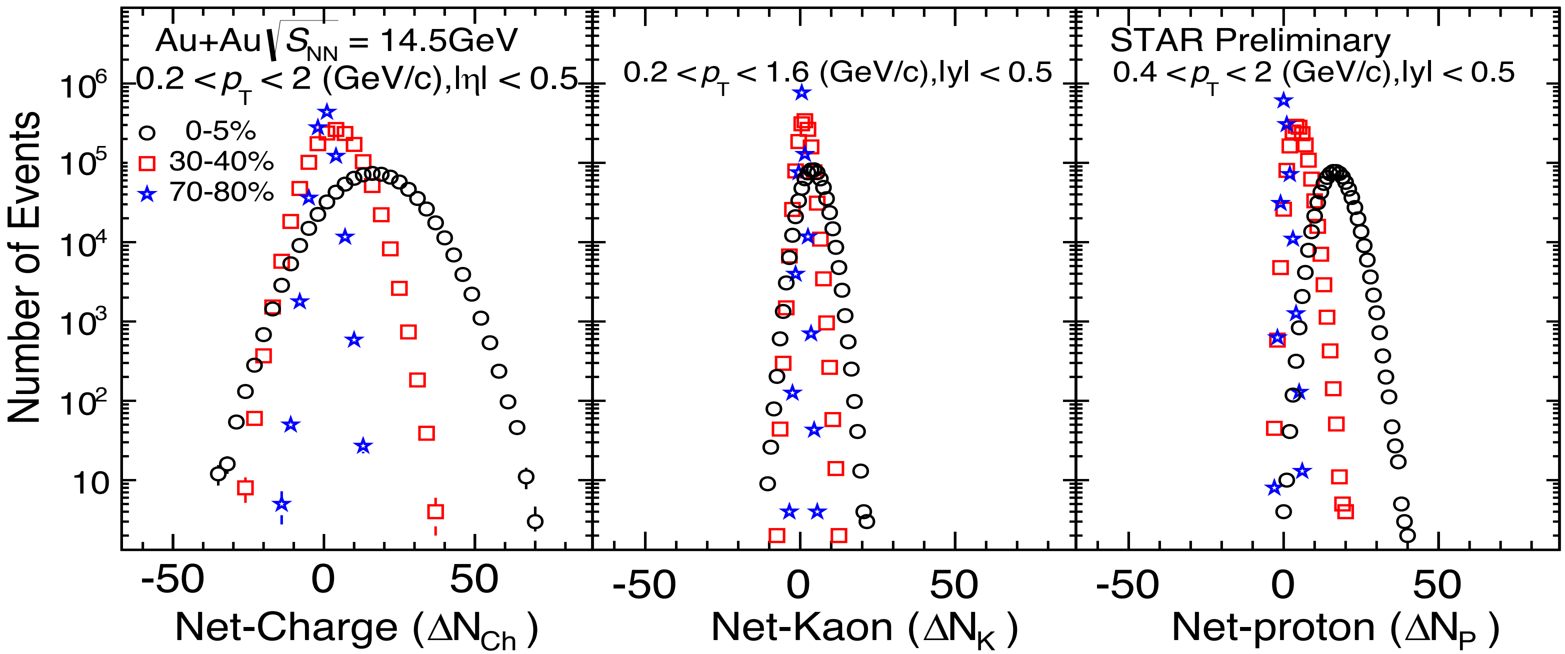
$$C_{2,q} \propto \xi^2, C_{3,q} \propto \xi^{4.5}, C_{4,q} \propto \xi^7$$

$$\frac{C_{4,q}}{C_{2,q}} = \kappa\sigma^2 \propto \xi^5$$

$$\frac{C_{3,q}}{C_{2,q}} = S\sigma \propto \xi^{9/4}$$

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

Data Analysis Methods



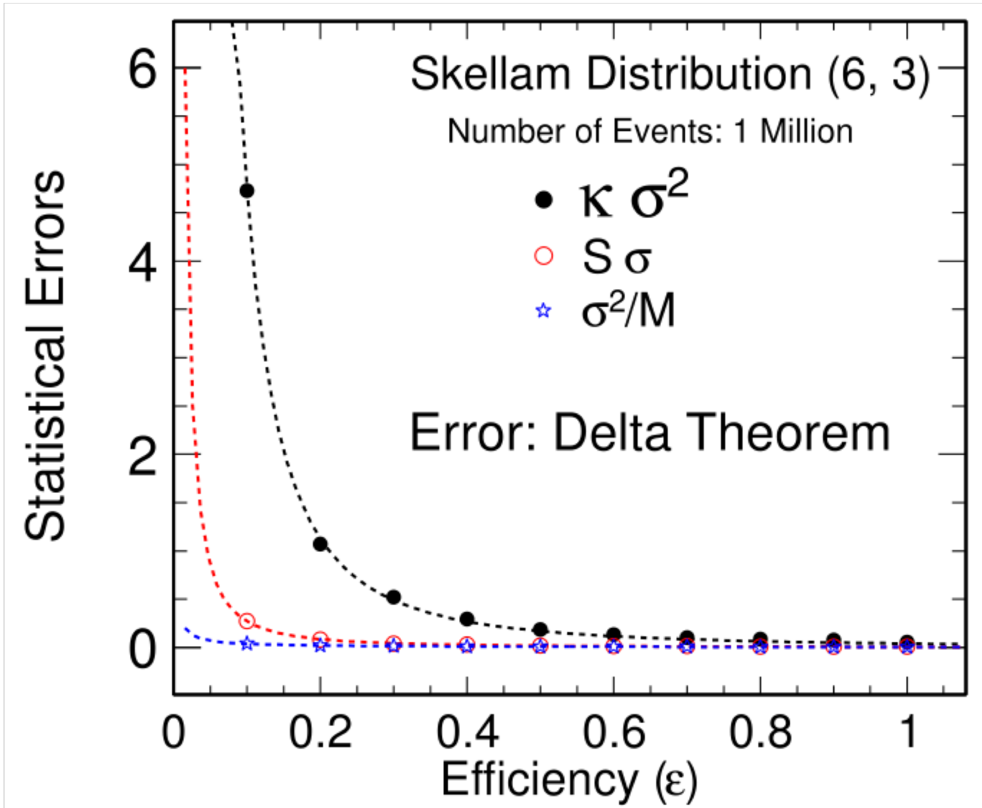
Analysis Methods used in the STAR coll.

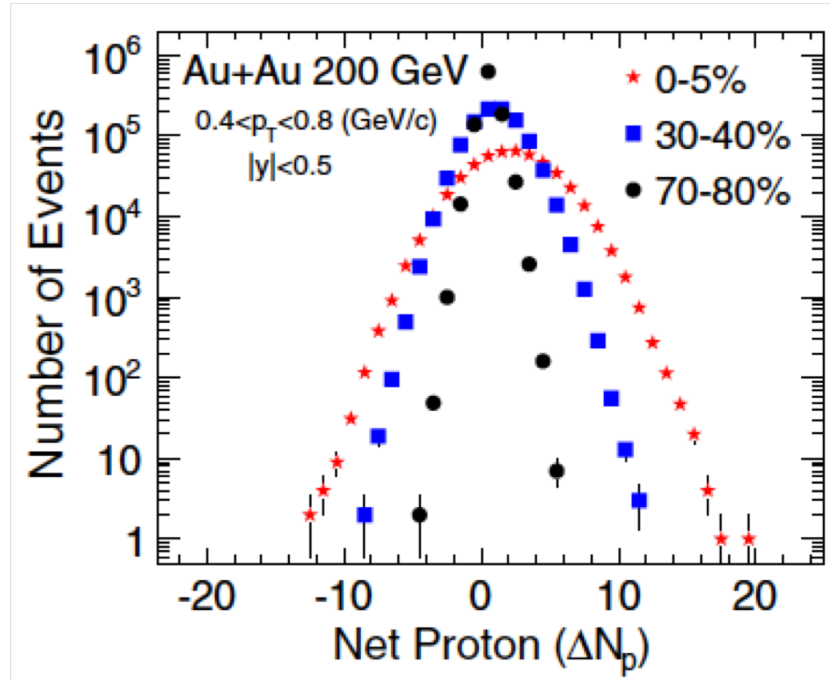
1. Statistical errors estimation : Delta theorem or bootstrap
2. Avoid auto-correlation effects: New centrality definition.
3. Suppress volume fluctuation：Centrality bin width correction
4. Finite detector efficiency correction (binomial response func.)

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

X.Luo, J. Phys. G 39, 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). X. Luo, T. Nonaka, PRC99, 044917 (2019);

Statistical Errors Estimation and Properties





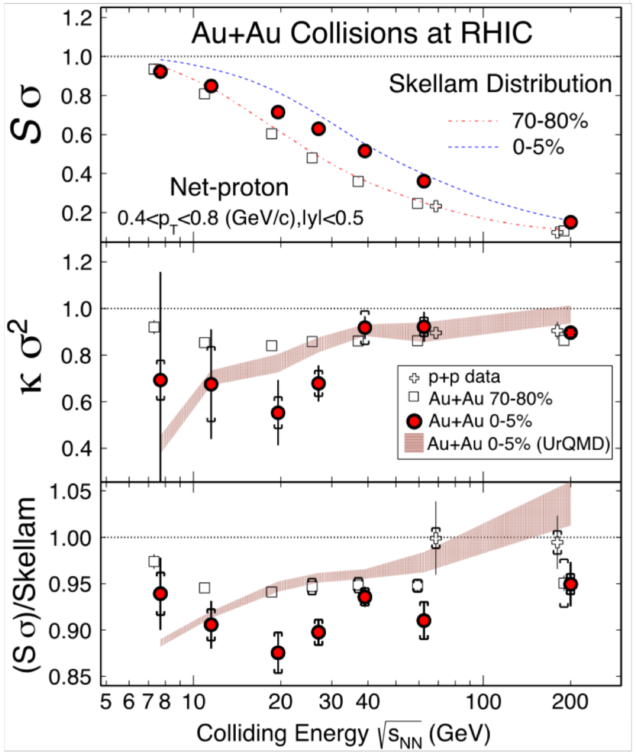
X. Luo, J. Phys. G 39, 025008 (2012);
X. Luo, Phys. Rev. C 91, 034907 (2015);
X. Luo, T. Nonaka, Phys. Rev. C 99, 044917 (2019);

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

Statistical errors strongly depend on the : Width of the measured distributions (σ) and the detector efficiency (ε).

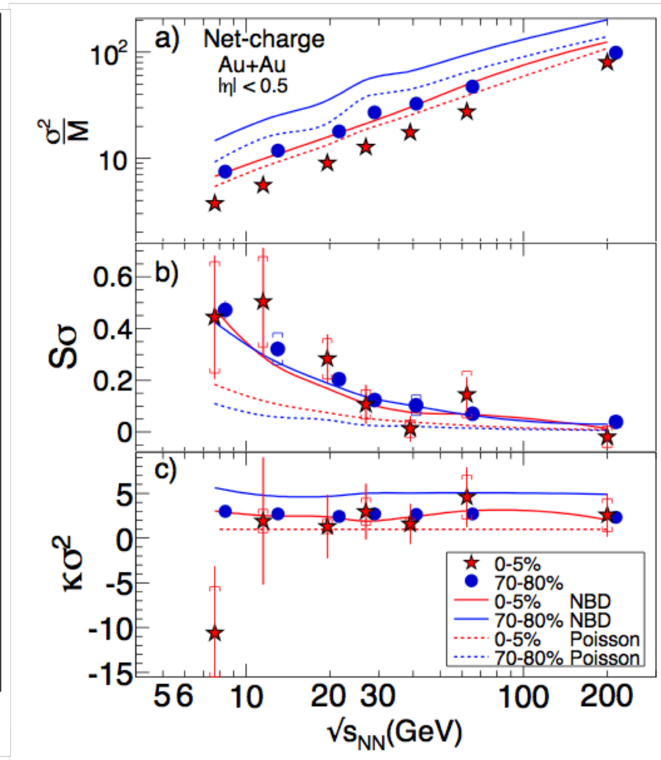
BES-I (2010-2014) : Net-Particle Fluctuation Measurements

Net-Proton



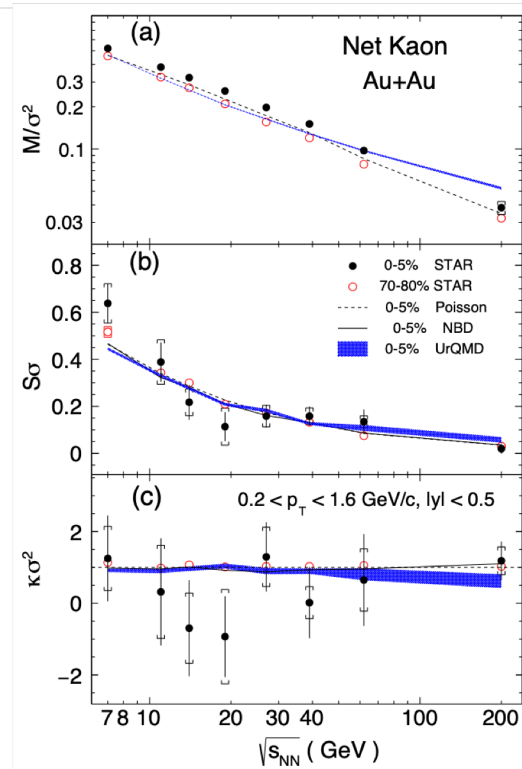
Phys. Rev. Lett. 105, 022302 (2010).
Phys. Rev. Lett. 112, 032302 (2014).

Net-Charge



Phys. Rev. Lett. 113 092301 (2014).

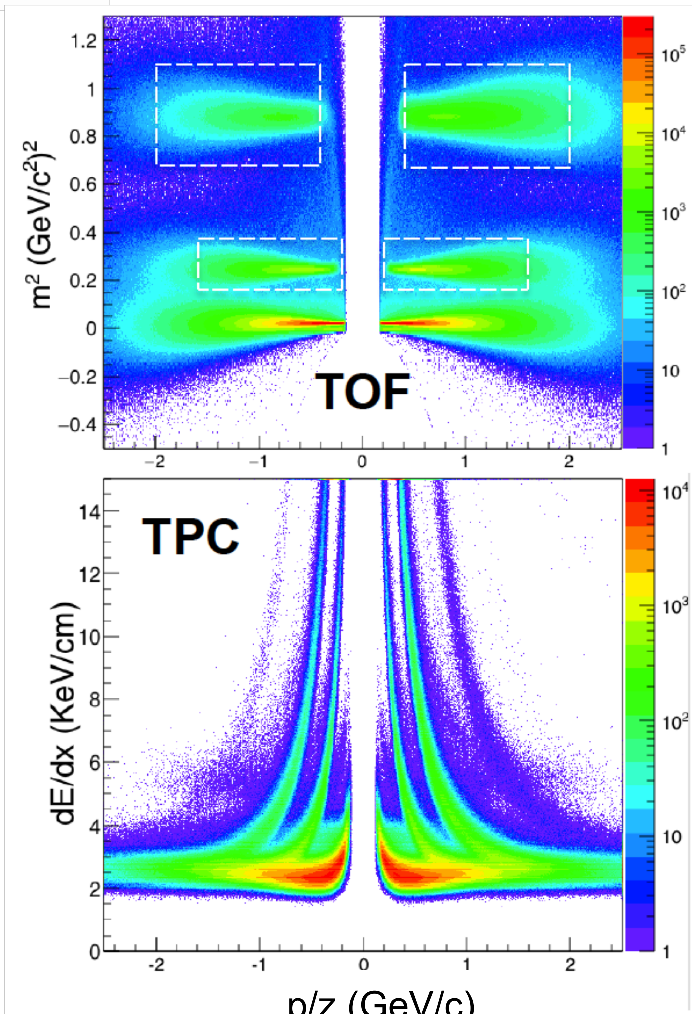
Net-Kaon



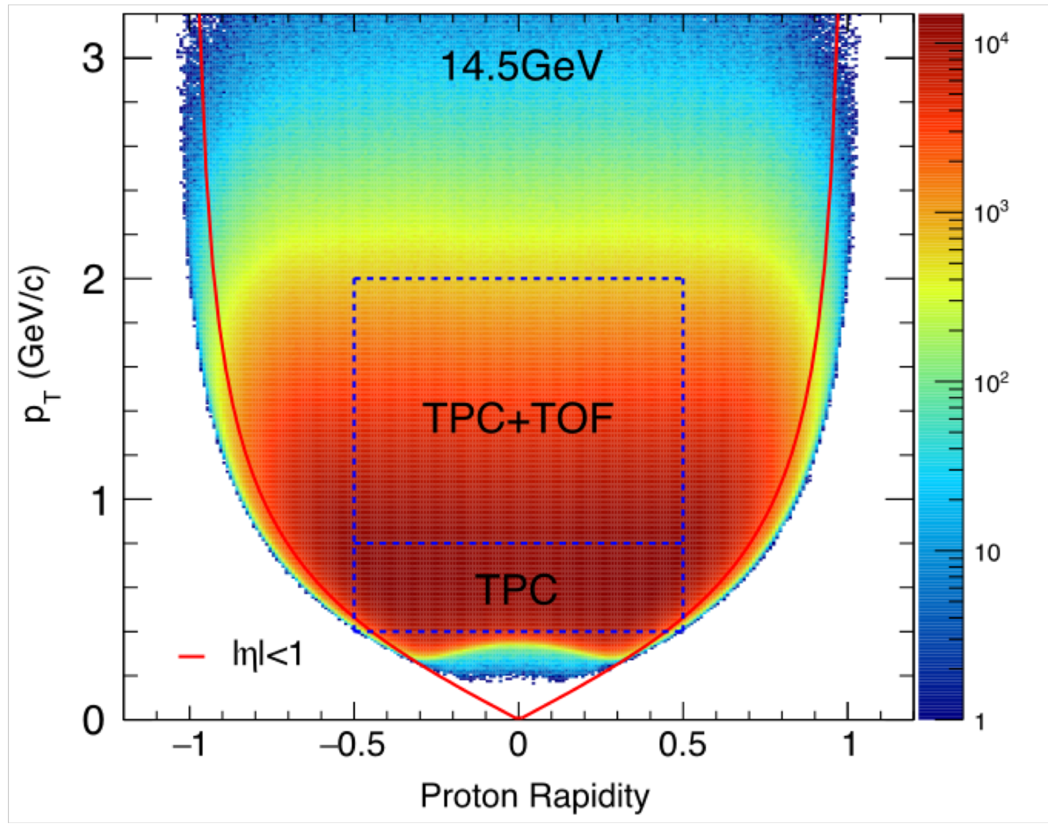
Phys. Lett. B 785, 551 (2018).

- ➢ Net-Proton :Both 3rd- and 4th-order fluctuations have their minima at $\sqrt{s}$ = 19.6 GeV.
- ➢ Net-charge and Net-kaon: large statistical errors, need more statistics.

Extend p_T coverage for (Anti-) Proton

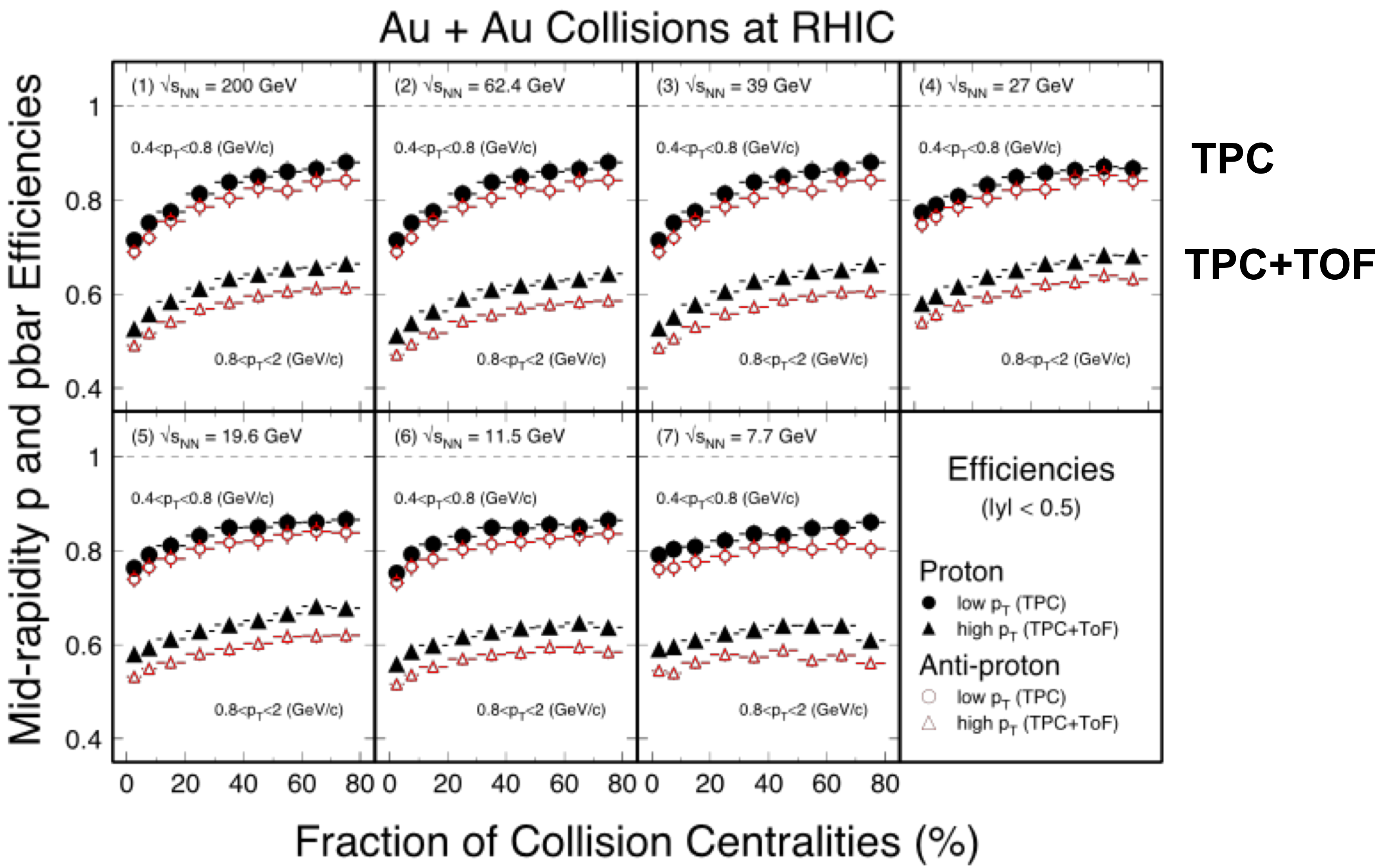


$|y|<0.5$, $0.4<p_T<0.8$ (TPC PID)
$0.8<p_T<2$ (TPC+TOF PID)



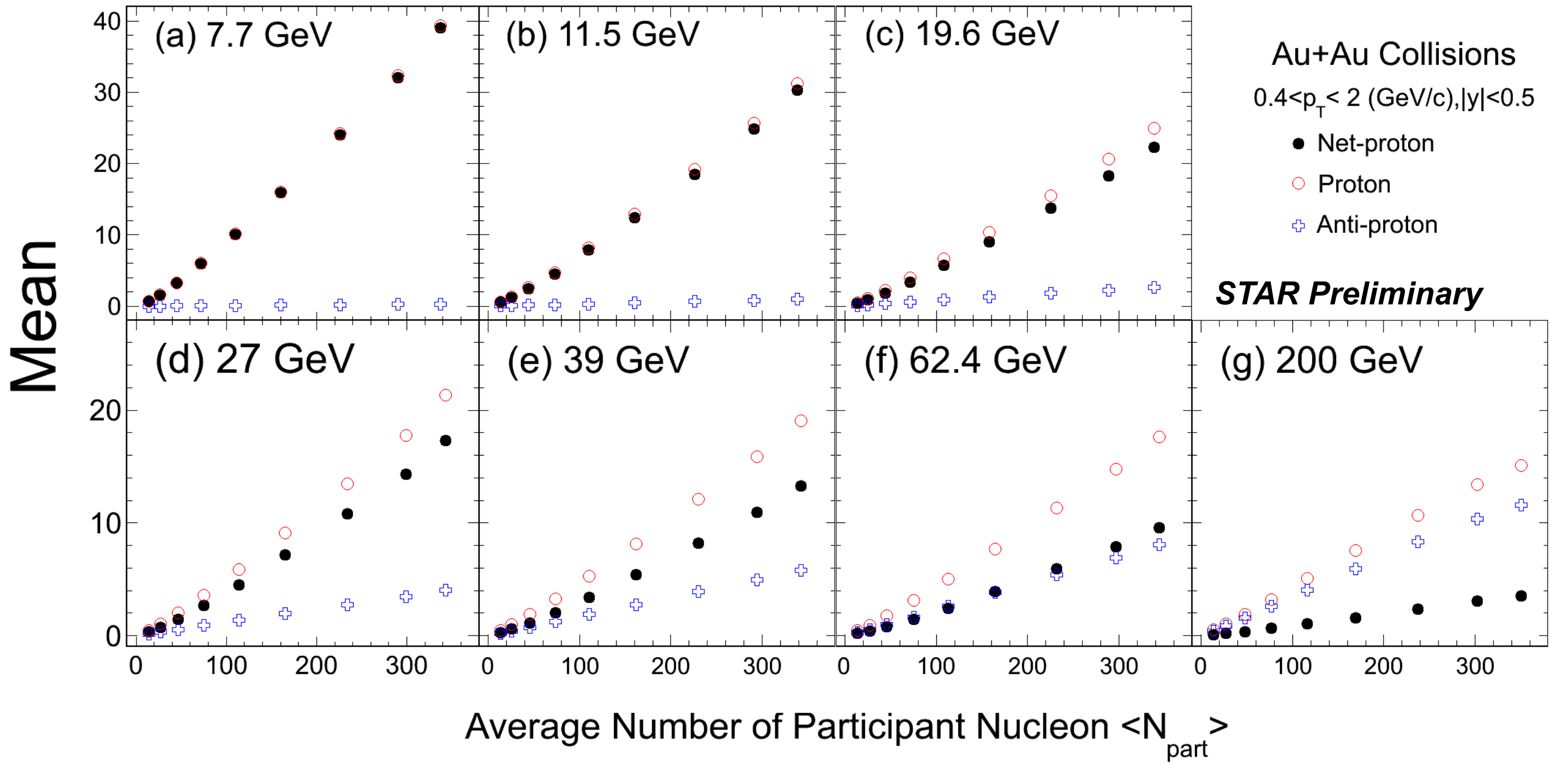
- p_T region can be extended up to 2.0 GeV by using TOF as well as TPC.
- (Anti)proton statistics is doubled with respect to the published results.

(Anti-) Proton Acceptance and Efficiencies



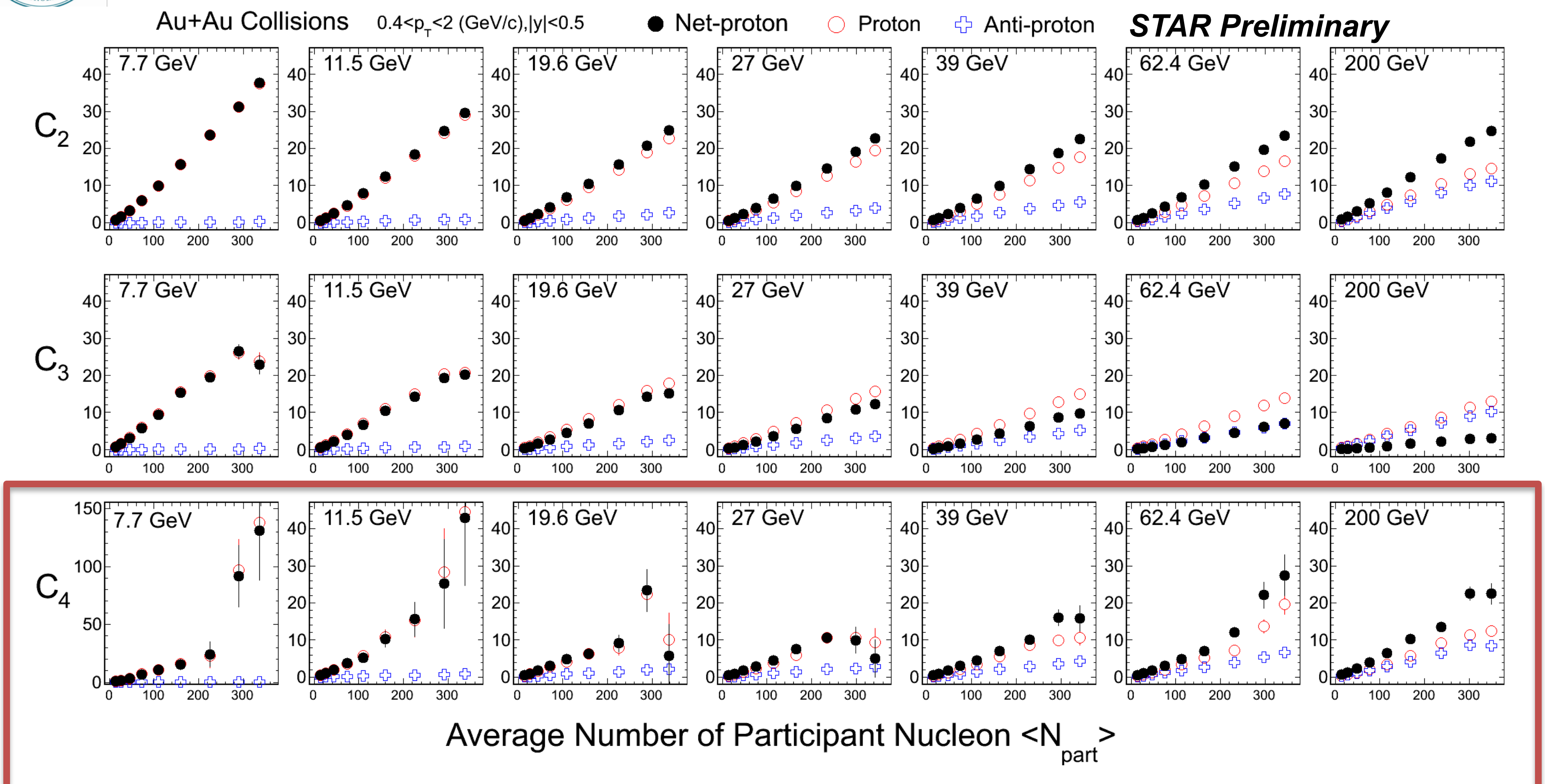
- Efficiency : Proton> Anti-proton, Low p_T > High p_T , low energy > High Energy, Peripheral > Central

Results: Mean Net-p, p and pbar



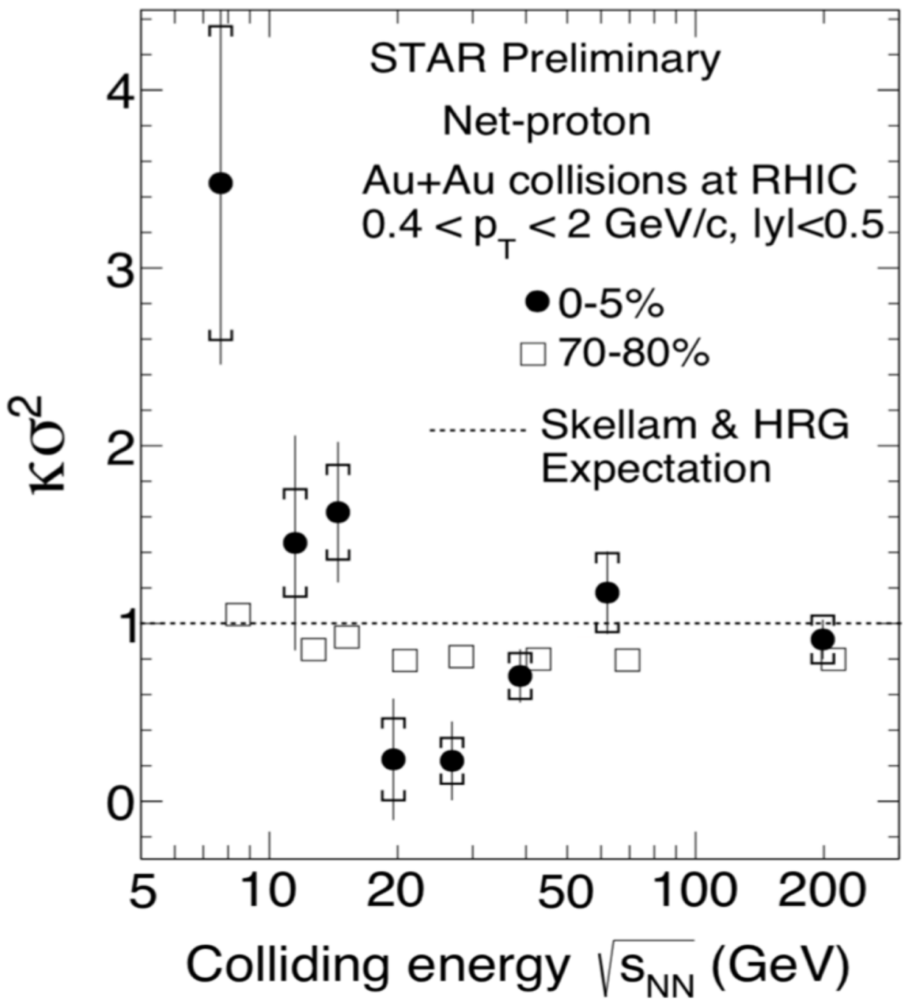
- Mean Net-proton, proton and anti-proton number increase with $\langle N_{part} \rangle$
- Net-proton number is dominated by protons at low energies and increases when energy decreases.
  (Interplay between baryon stopping and pair production)

Higher Order Cumulants for Net-p, p, pbar



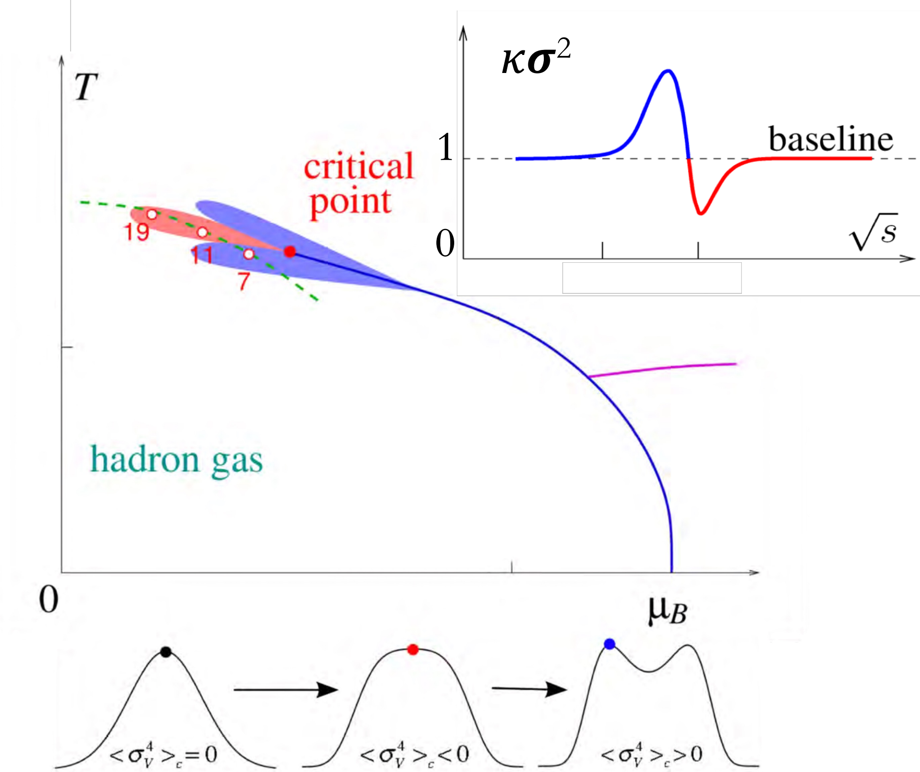
- In general, cumulants of Net-p, p and pbar are increasing with $<N_{part}>$.
- The cumulants of net-proton distributions closely follow the proton cumulants when the colliding energy is decreasing.

Fourth Order Net-Proton Fluctuations



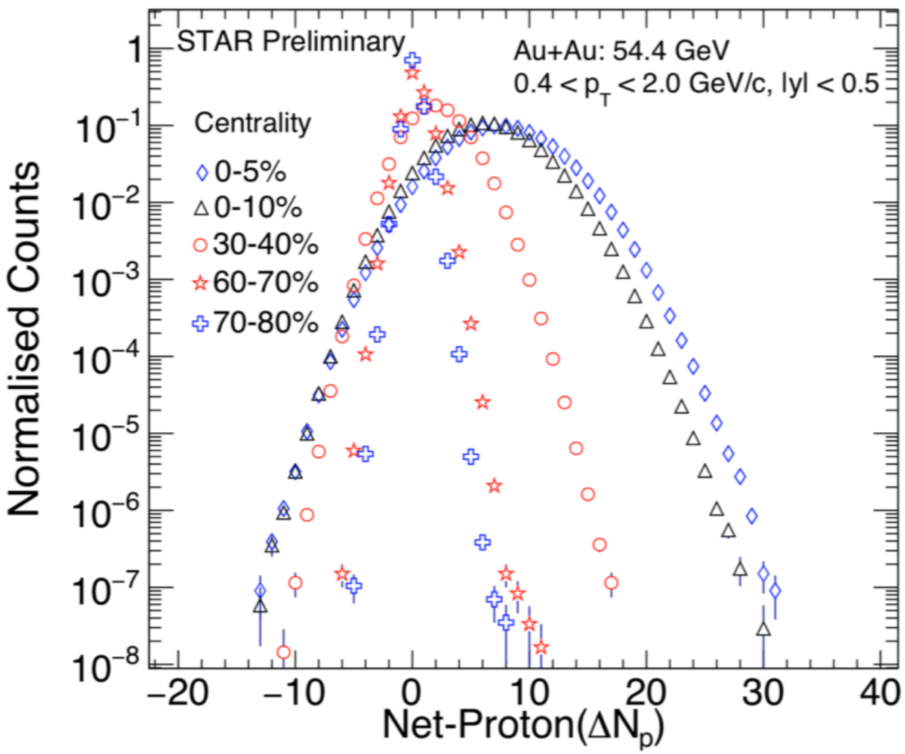
STAR: Phys. Rev. Lett. 105, 022302 (2010).
Phys. Rev. Lett. 112, 032302 (2014).
PoS CPOD2014 (2015) 019.

- First observation of the non-monotonic energy dependence of fourth order net-proton fluctuations. Hint of entering Critical Region ?

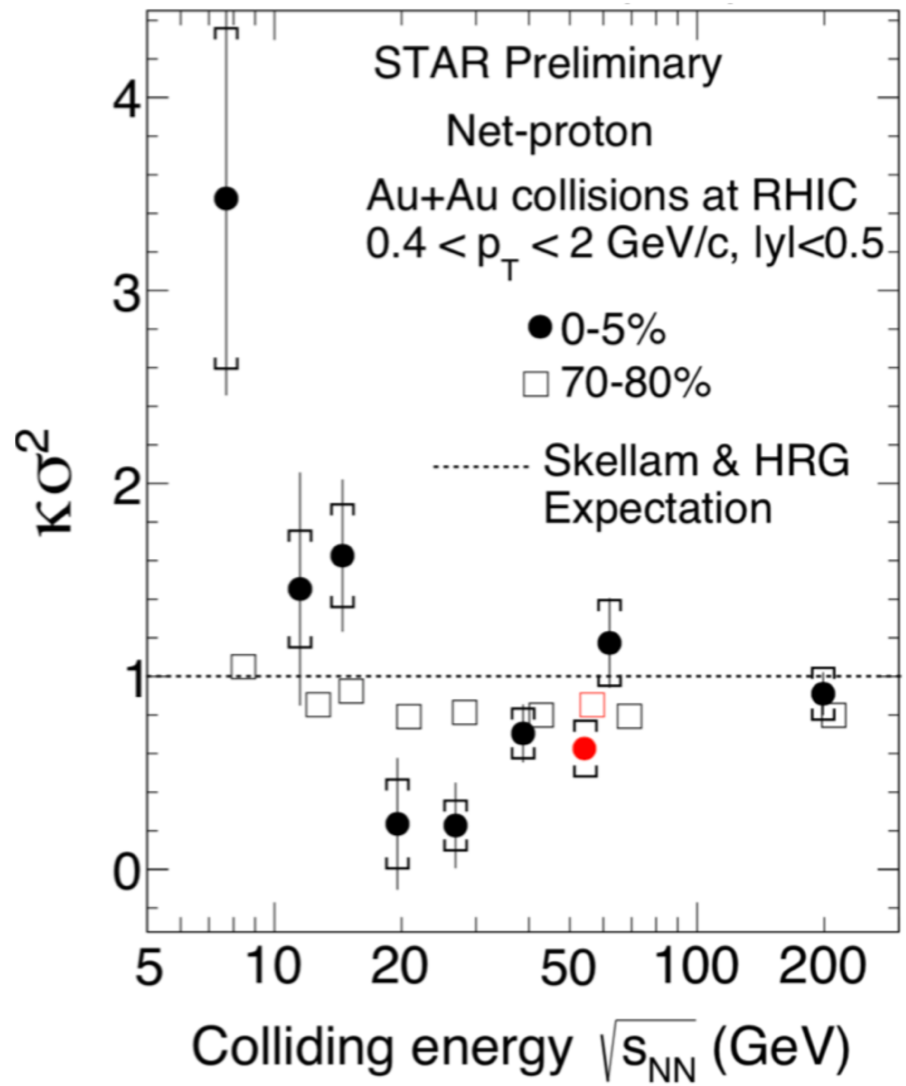


M. Stephanov, PRL107, 052301(2011)
J. Phys. G: 38, 124147 (2011).

New data set : 54.4 GeV (2017)



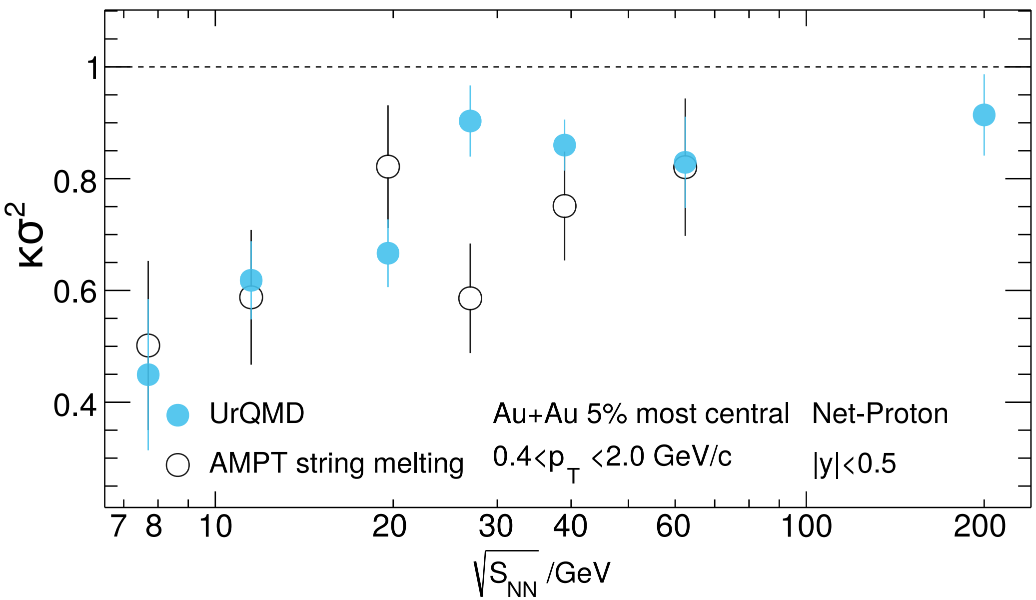
STAR, SQM 2019



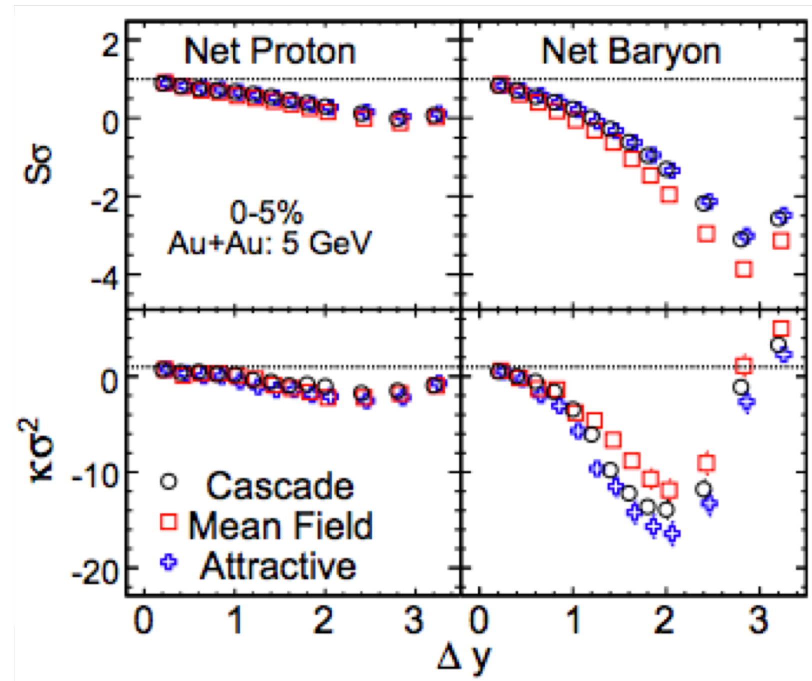
- **Results at 54.4 GeV follow the trend well.**

Non-critical Contributions: Transport Model Studies

UrQMD and AMPT models



JAM model



- Transport model (no CP physics) results show monotonic energy dependence: dominated by baryon number conservations
- Mean field potential can not explain the enhancement of $\kappa\sigma^2$ at low energy.

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. 1405.4617, NPA947, 248(2016), P. Garg et al. PLB 726, 691(2013). S. He, et. al., PLB762, 296 (2016). S. He, X. Luo, PLB 774, 623 (2017).

Net-Proton Fluctuation Paper Plan

Short Paper : Nature Physics

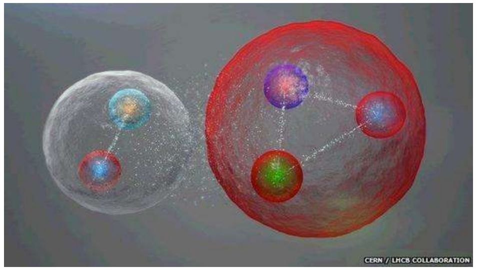
Long Paper : PRC

Paper draft are ready.
Going through collaboration process

The two papers will be submitted
to the journal simultaneously.

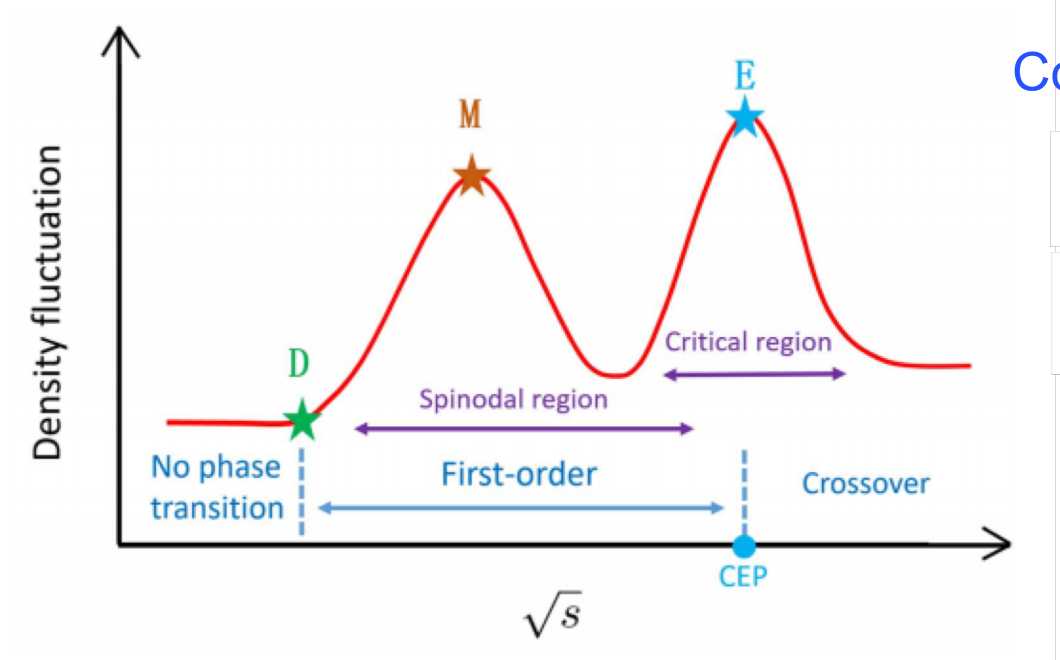
New Observable for CP: Light Nuclei Production

Near CP or 1st order phase transition, baryon density fluctuation become large.



Light nuclei production

(Baryon Clustering)



Coalescence + nucleon density flu.

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

$$N_{^3H} = \frac{3^{3/2}}{4}\left(\frac{2\pi}{m_0 T_{\rm eff}}\right)^{3} N_p \langle n \rangle^2 [1+(1+2\alpha)\Delta n],$$

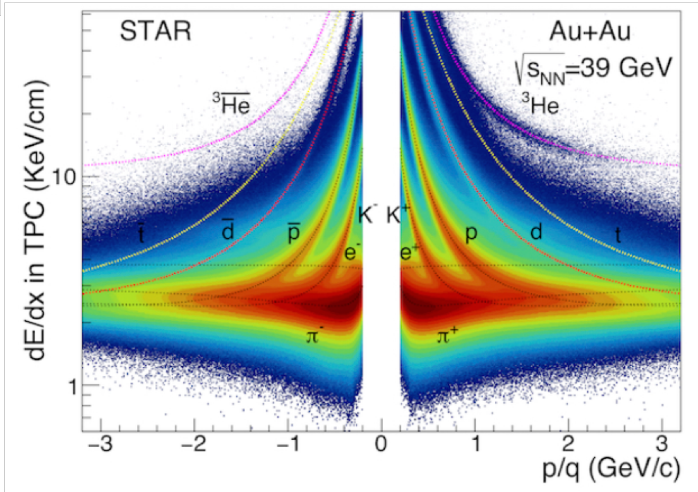
$$N_t \cdot N_p / N_d^2 \approx g(1+\Delta n)$$

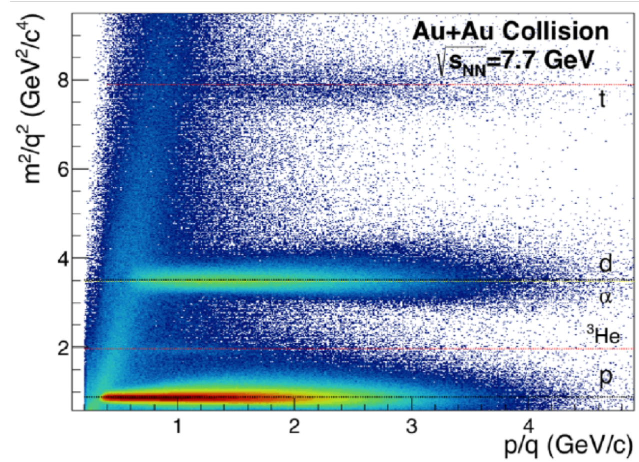
Neutron density fluctuations:

$$\Delta n = \langle (\delta n)^2 \rangle / \langle n \rangle^2$$

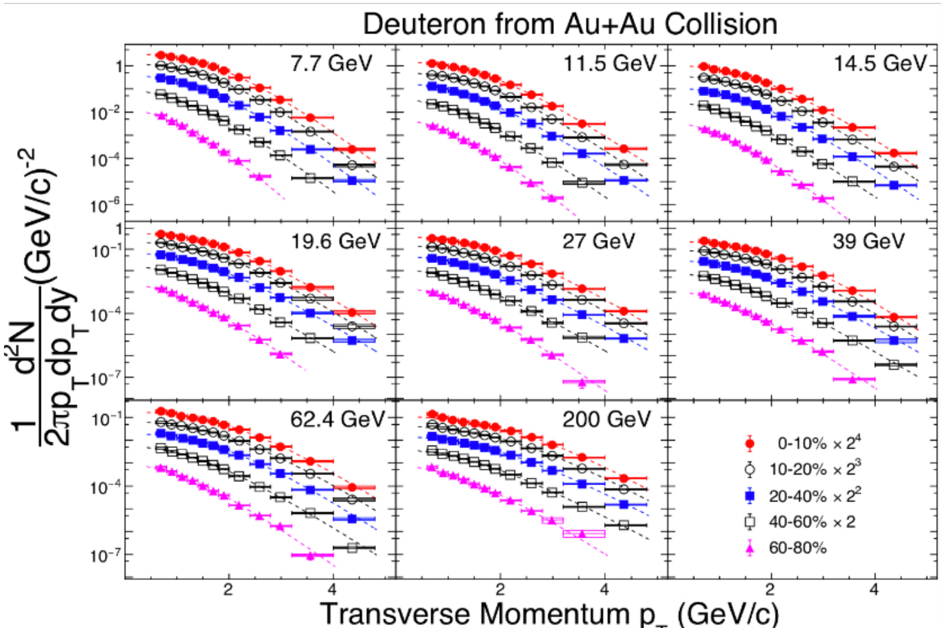
K. J. Sun, L. W. Chen, C. M. Ko, Z. Xu, Phys. Lett. B774, 103 (2017).
K. J. Sun, L. W. Chen, C. M. Ko, J. Pu, Z. Xu, Phys. Lett. B781, 499 (2018).
Edward Shuryak and Juan M. Torres-Rincon, arXiv:1805.04444

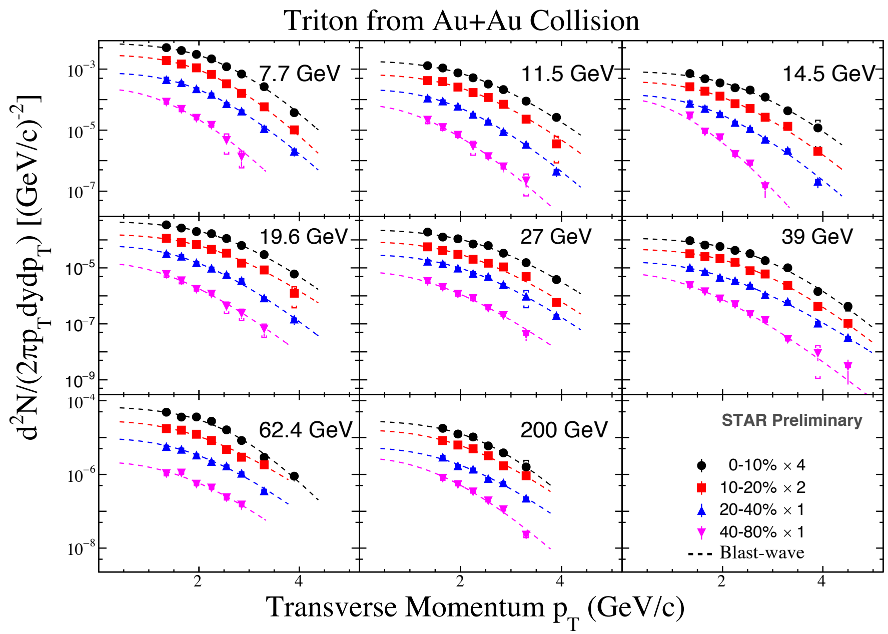
Deuteron and triton production from BES-I at RHIC





STAR, PRC99, 064905 (2019)



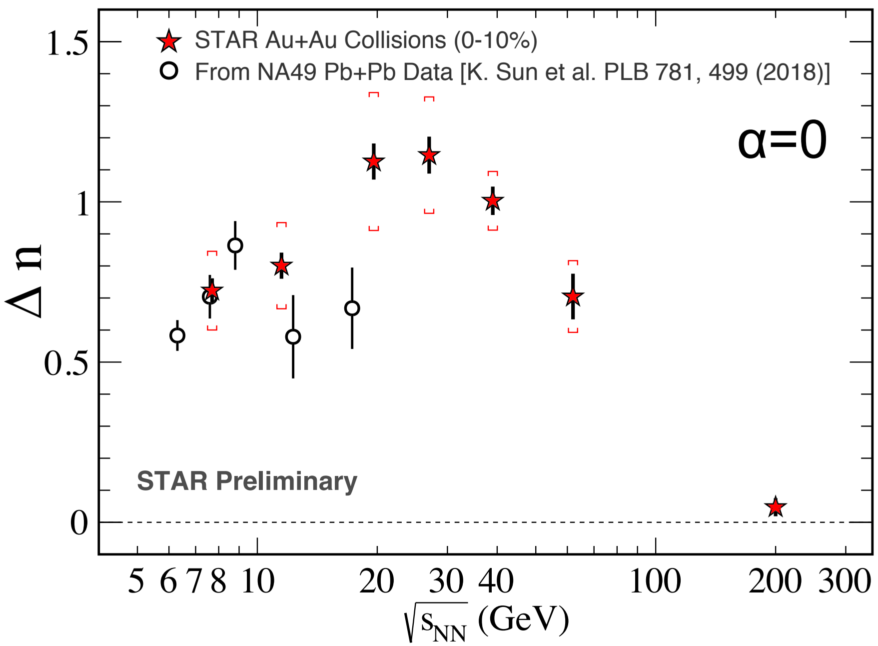


Nucleon Density Fluctuations

- The particle ratios of light nuclei is sensitive to the **nucleon density fluctuation** at kinetic freeze-out. This conclusion is based on **coalescence model.**

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

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



Dingwei Zhang, NN 2018

$$\frac{\langle(\delta n)^2\rangle}{\langle n\rangle^2} = \Delta n = \frac{1}{g}\frac{N_t N_p}{N_d^2} - 1$$

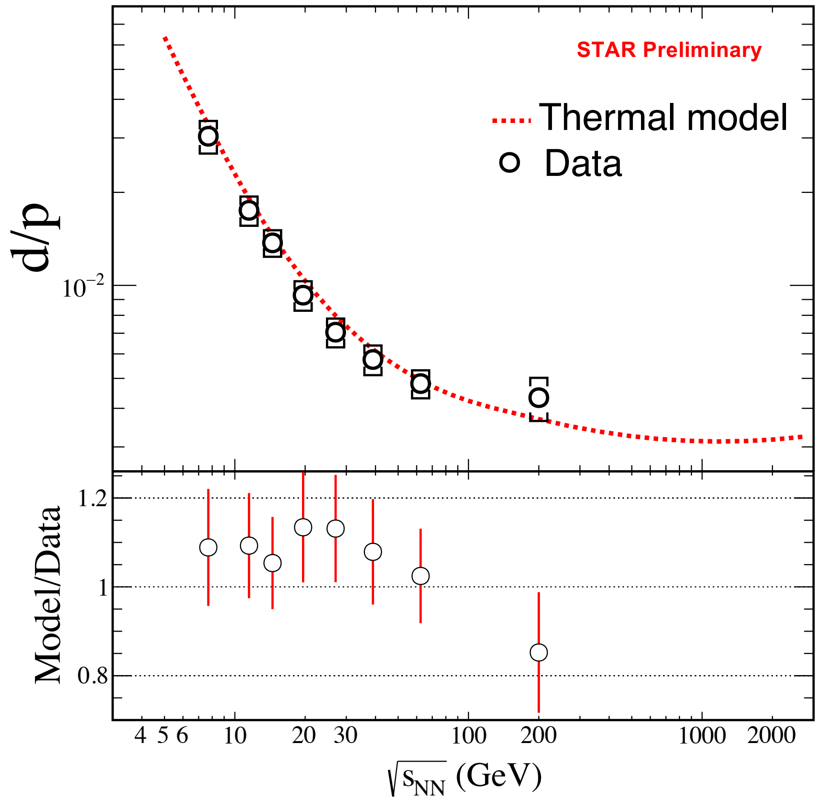
N_t : Triton yield, N_d : Deuteron yield
N_p : Proton yield

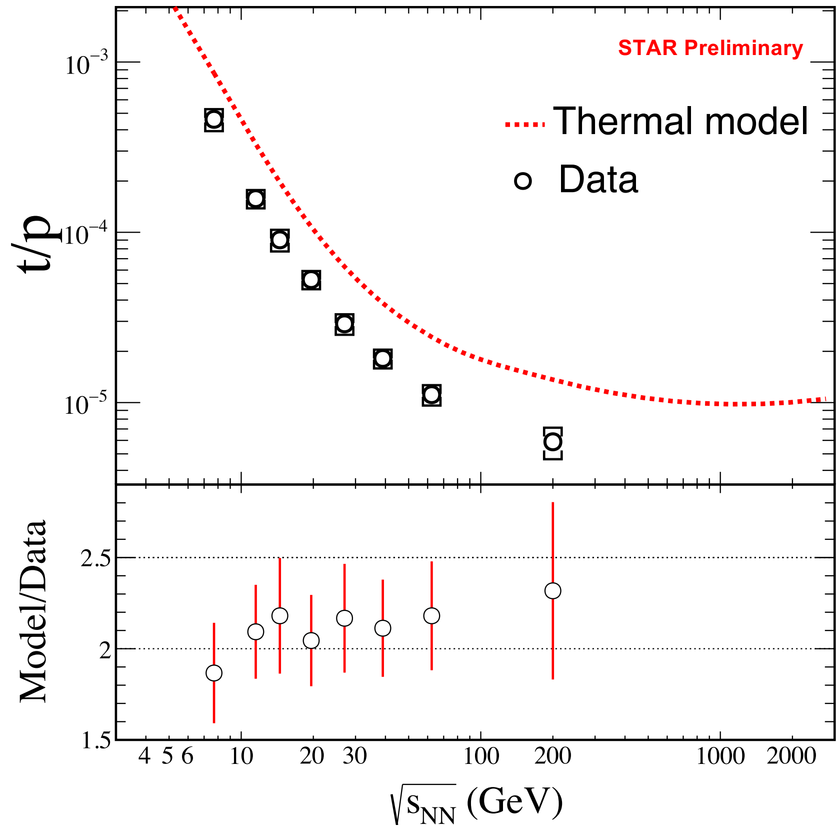
Neutron density fluctuation Δn shows a non-monotonic behavior on collision energy.

Peak around 20 GeV.

K. J. Sun, L. W. Chen, C. M. Ko, Z. Xu, Phys. Lett. B774, 103 (2017).
K. J. Sun, L. W. Chen, C. M. Ko, J. Pu, Z. Xu, Phys. Lett. B781, 499 (2018).
Edward Shuryak and Juan M. Torres-Rincon, NPA 982, 831 (2019)

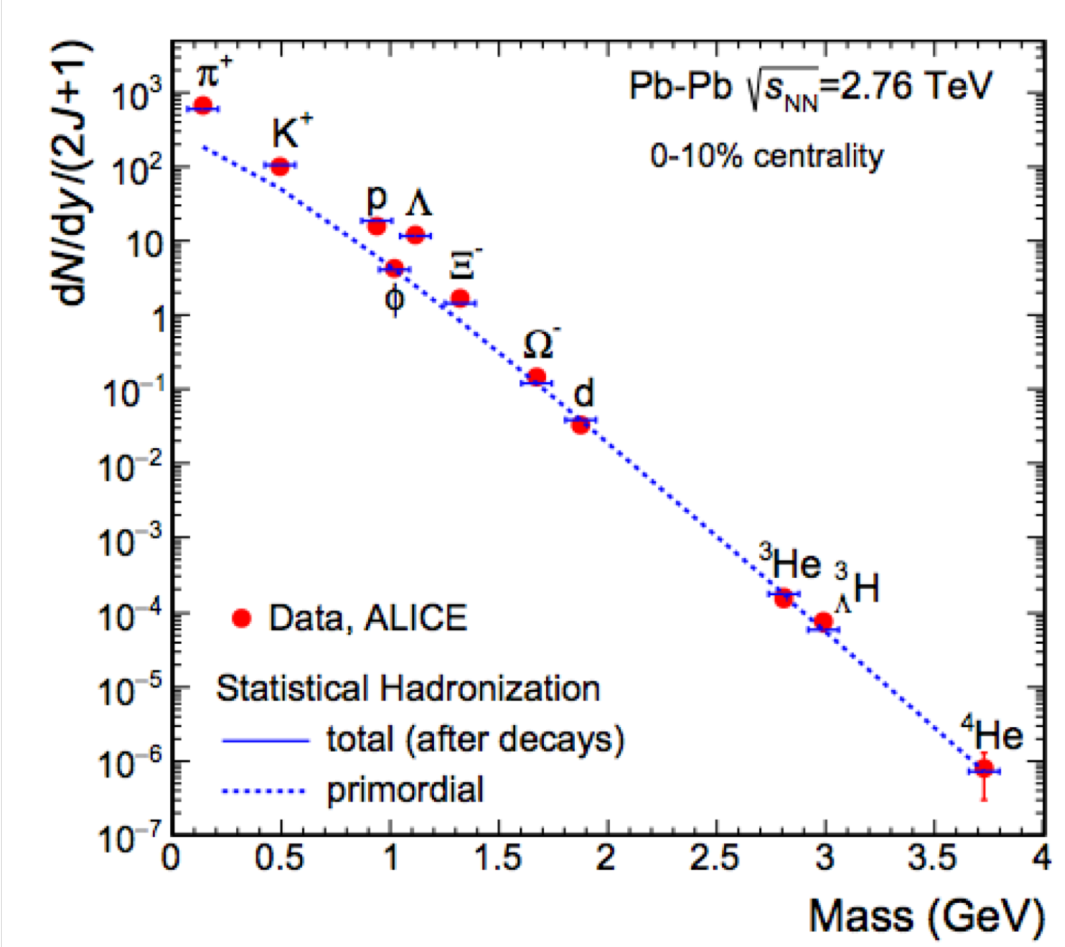
Light Nuclei Yield Ratio Vs. Thermal model





- At RHIC energies, thermal model can describe the d/p ratios, but can not describe the t/p ratios.

ALICE Data Vs. Thermal Model

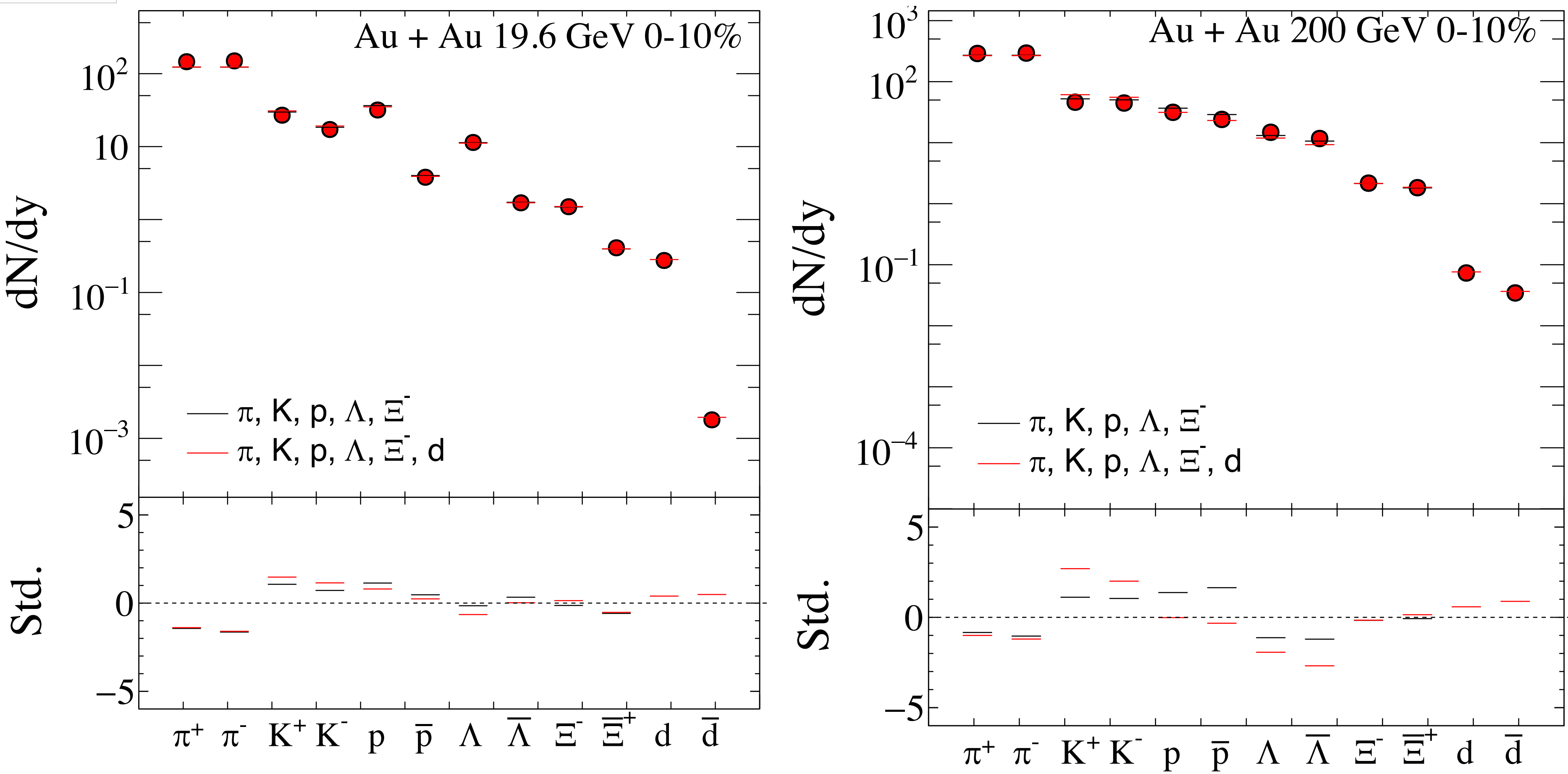


Why the yield of triton and even alpha can be well described by thermal model at LHC energies But not at RHIC energies ?

Different production mechanism of light nuclei at RHIC and LHC energies ??

A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Nature 561, 321 (2018).

Statistical thermal fit including light nuclei



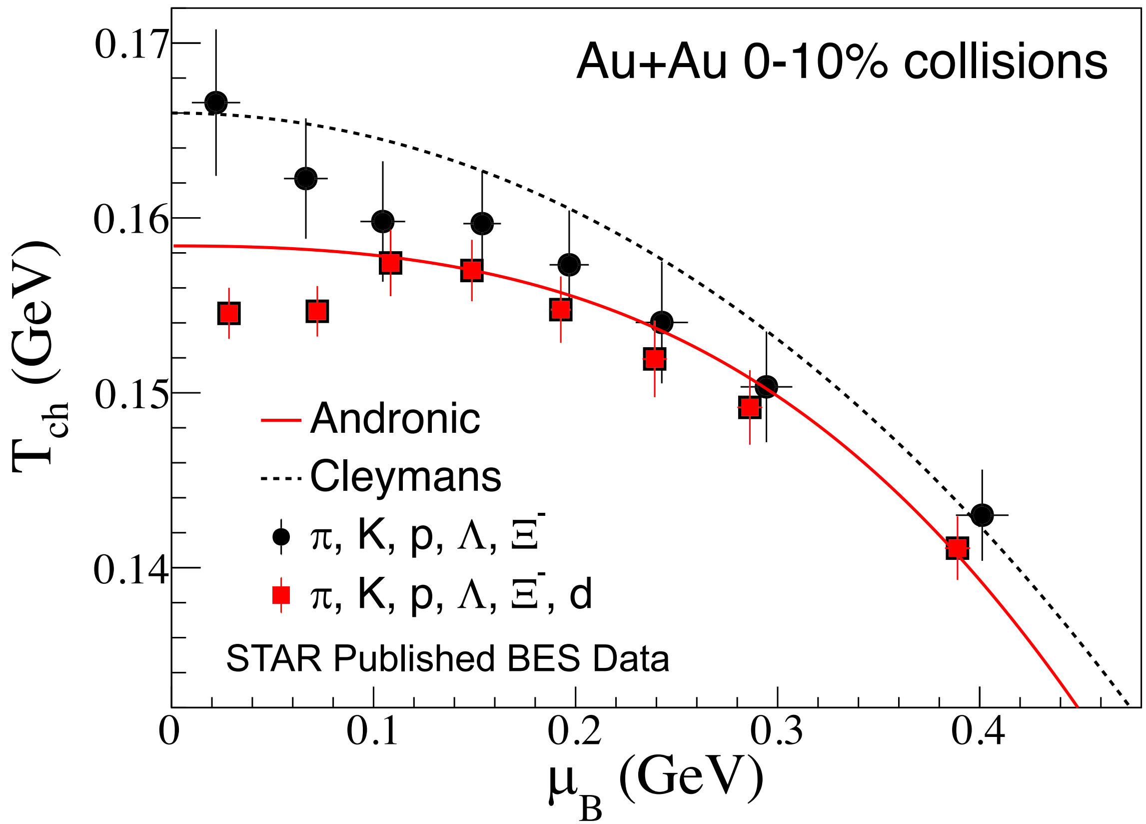
Data are taken from :

STAR, PRC 96,044904 (2017). (BES light hadrons)

STAR, PRC 99, 064905 (2019) (BES deuteron production)

STAR, arXiv:1906.03732, submitted to PRC (BES strangeness)

Chemical freeze-out T_{ch} Vs. μ_B



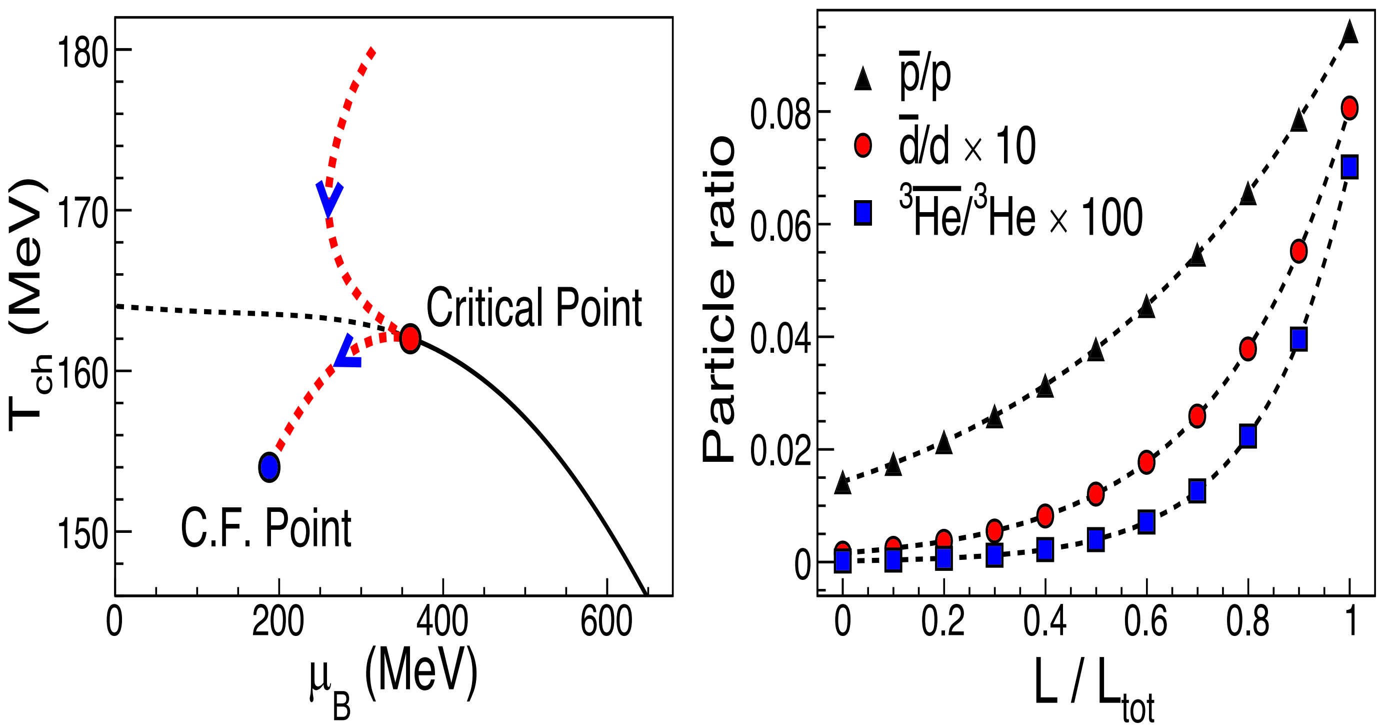
Cleymans: J. Cleymans et al., PRC 73, 034905 (2006)
Andronic: A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Nature 561, 321 (2018).

- Obtain lower chemical freeze-out temperature if we include the deuteron yield into the fitting.
- At 200 GeV, T_{ch} ~ 155 MeV.

QCD Critical Point Focusing Effects

QCD critical point focusing effect : critical point will serve as an attractor of the trajectory evolution in the $T - \mu_B$ plane.

M. Asakawa, S. A. Bass B. Muller, C. Nonaka PRL 101, 122302 (2008)



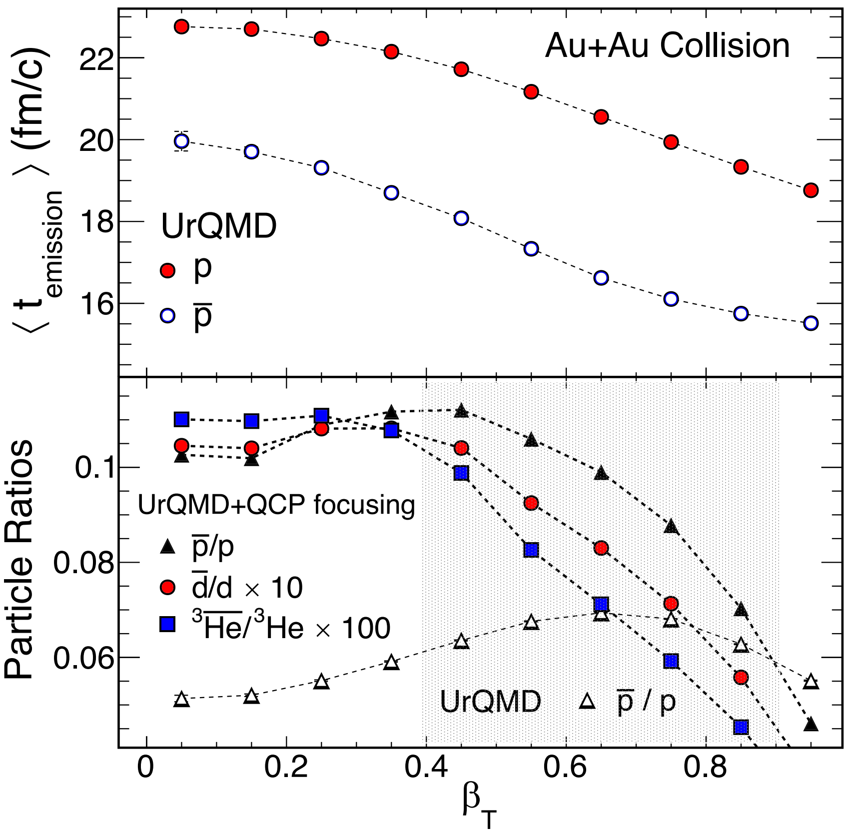
$t = L/L_{tot}$

N. Yu, D. Zhang, and X. Luo arXiv:1812.04291

The particle emitting probability along the trajectory is assumed to be proportional to the particle density calculated from the thermal model with corresponding T and μ_B.

QCP Focusing Effects : Model Implementation

- $\beta_T - t$ distribution is from UrQMD central Au+Au collision at $\sqrt{s_{NN}} = 19.6$ GeV.

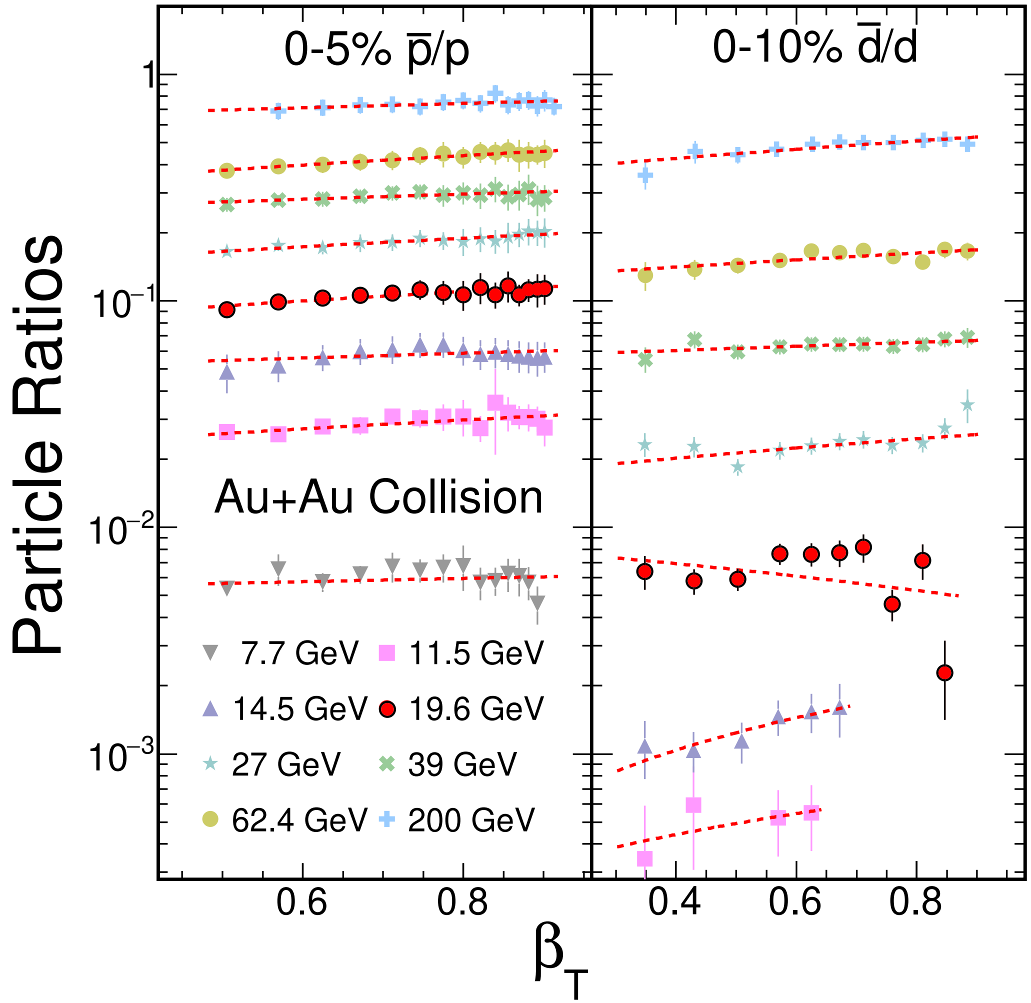


- The $\bar{p}/p$, $\bar{d}/d$, and $^{3}\overline{\mathrm{He}}/\mathrm{He}$ **decrease with increasing β_T** with QCP focusing effect.
- This behavior is more easier to be observed for heavier particles

Can we observe the QCP focusing effects in HIC experiment ?

N. Yu, D. Zhang, and X. Luo arXiv:1812.04291

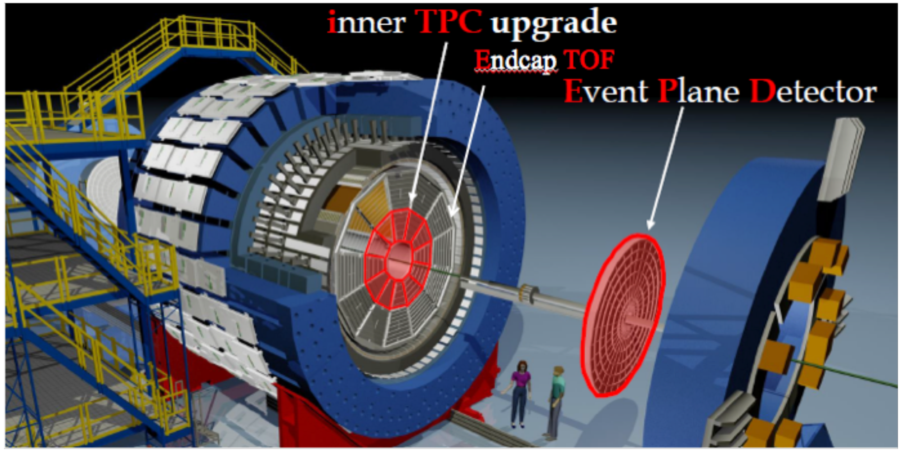
Transverse velocity dependence of dbar/d ratio



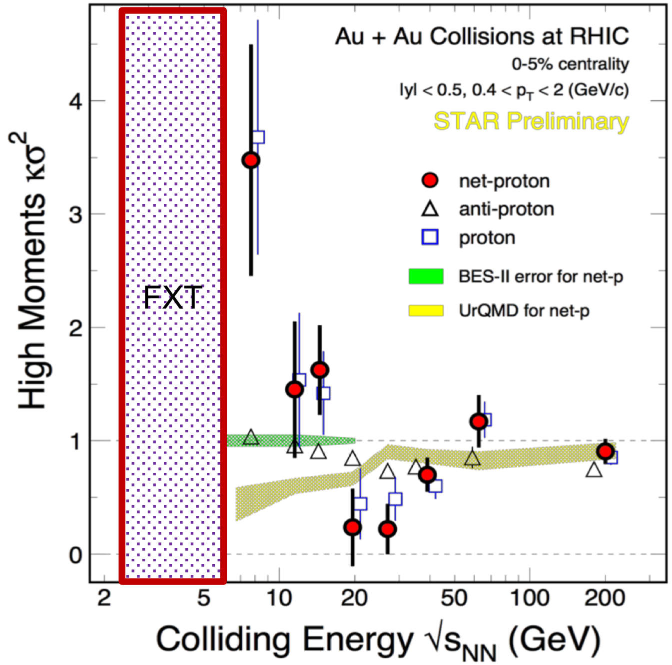
We indeed observe anomalous for dbar/d ratio at 19.6 GeV measured by STAR. Will make more precise measurements in RHIC-BES-II.

BES-II at RHIC (2019-2021)

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES II / BES I
19.6	400	**2019** / 2011
14.5	300	**2019** / 2014
11.5	230	**2020** / 2010
9.2	160	**2020** / 2008
7.7	100	**2021** / 2010
17.1	250	**2021**



- BES-II : 10-20 times higher statistics than BES-I.
- FIX-target mode : $\sqrt{s_{NN}}$ = 3-7.7 GeV (2018-2020).
- 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**

Summary

Explore the QCD phase structure with Beam Energy Scan

- Fourth order net-proton fluctuations (C_4/C_2) in central Au+Au collisions shows non-monotonic energy dependence, with a minimum around 20-30 GeV.
- Neutron density fluctuations in 0-10% central Au+Au collisions shows non-monotonic energy dependence with a peak around 20-30 GeV.
- dbar/d vs. beta_t show anomaly around 19.6 GeV.
- In BES-II, we can study the QCD phase structure with high precision at $\sqrt{s_{NN}}$ = 7.7-19.6 GeV (collider mode) and 3-7.7 GeV (Fix-target mode)

Stay tuned for RHIC BES-II (2019-2021) !

Workshop on the QCD Phase Structure at High Baryon Density Region

12-14 November 2019
Central China Normal University
Asia/Shanghai timezone

Search

- Overview
- Scientific Programme
- Timetable
- Author List
- Participant List
- Registration
  - Registration Form
- Travel Information

Support
maya@mail.ccnu.edu....
+86-27-67867975

In this workshop, we will focus on discussing the physics of QCD phase structure at high baryon density. It will cover recent experimental and theoretical developments and the perspective for future low energy heavy-ion collision experiments.

No registration fee is collected.

Topics:

1. Search for the QCD critical point and Beam Energy Scan
2. Equation of state at high baryon density
3. Future low energy heavy-ion collision experiments

Local Organizing Committee:

Xiaofeng Luo (CCNU), Co-chair

Nu Xu (CCNU/IMP/LBNL), Co-chair

Feng Liu (CCNU)

Shusu Shi (CCNU)

Yaping Wang (CCNU)

QM Satellite Meeting, Nov. 12-14, 2019

Truth buried in the sands.
Need to dig it out.

Thank you !

2019-2021: BES II at RHIC

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	**BES II** / BES I	μ_B (MeV)	T_{CH} (MeV)
200	238	2010	25	166
62.4	45	2010	73	165
54.4	1000	2017	90	165
39	86	2010	112	164
27	32 (1000)	2011(2018)	156	162
19.6	**400** / 36	**2019**/ 2011	206	160
14.5	**300** / 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**	235	

Precise mapping the QCD phase diagram **$200 < \mu_B < 420$MeV**