Search for the QCD Critical Point with Beam Energy Scan at RHIC

Status and Prospective

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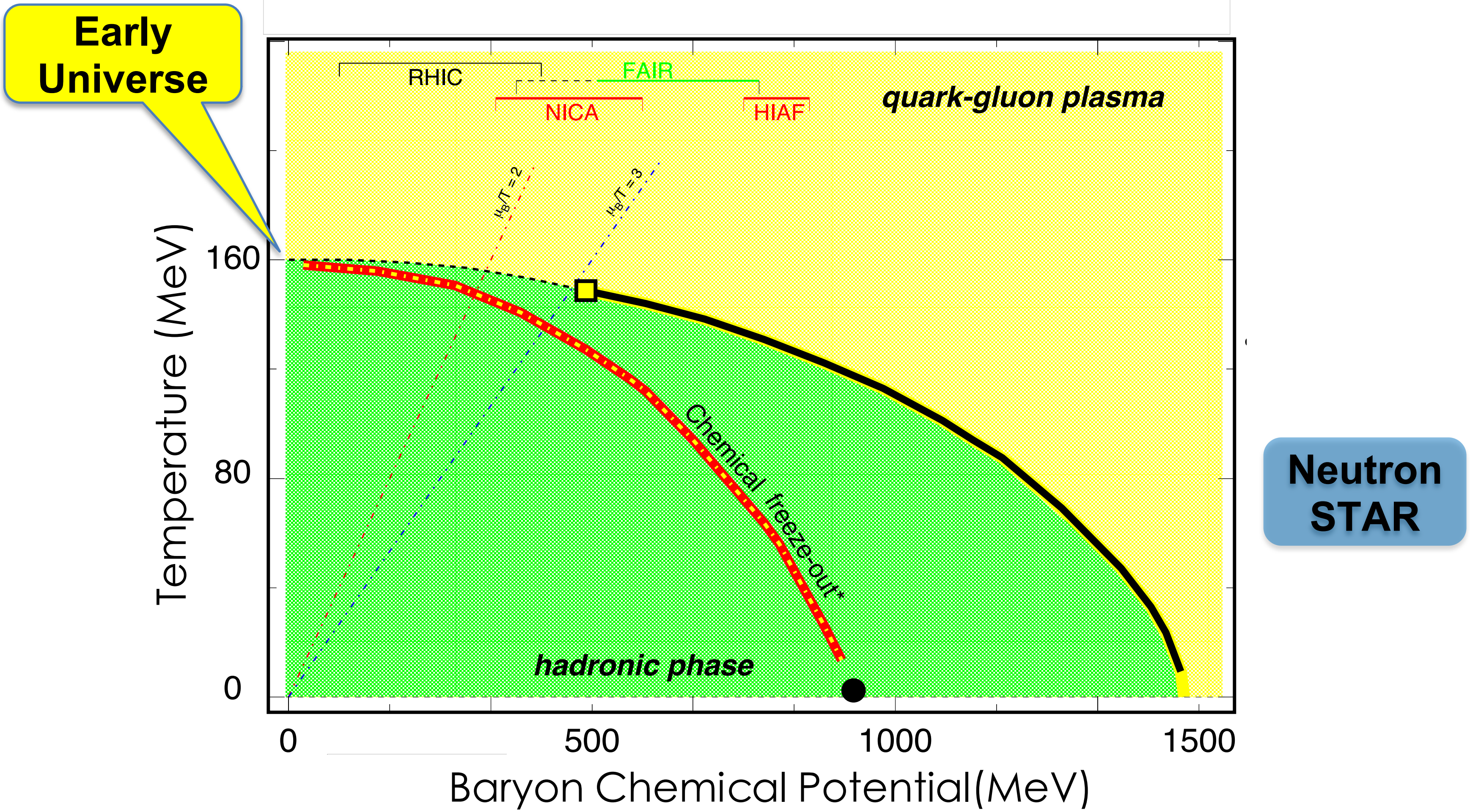
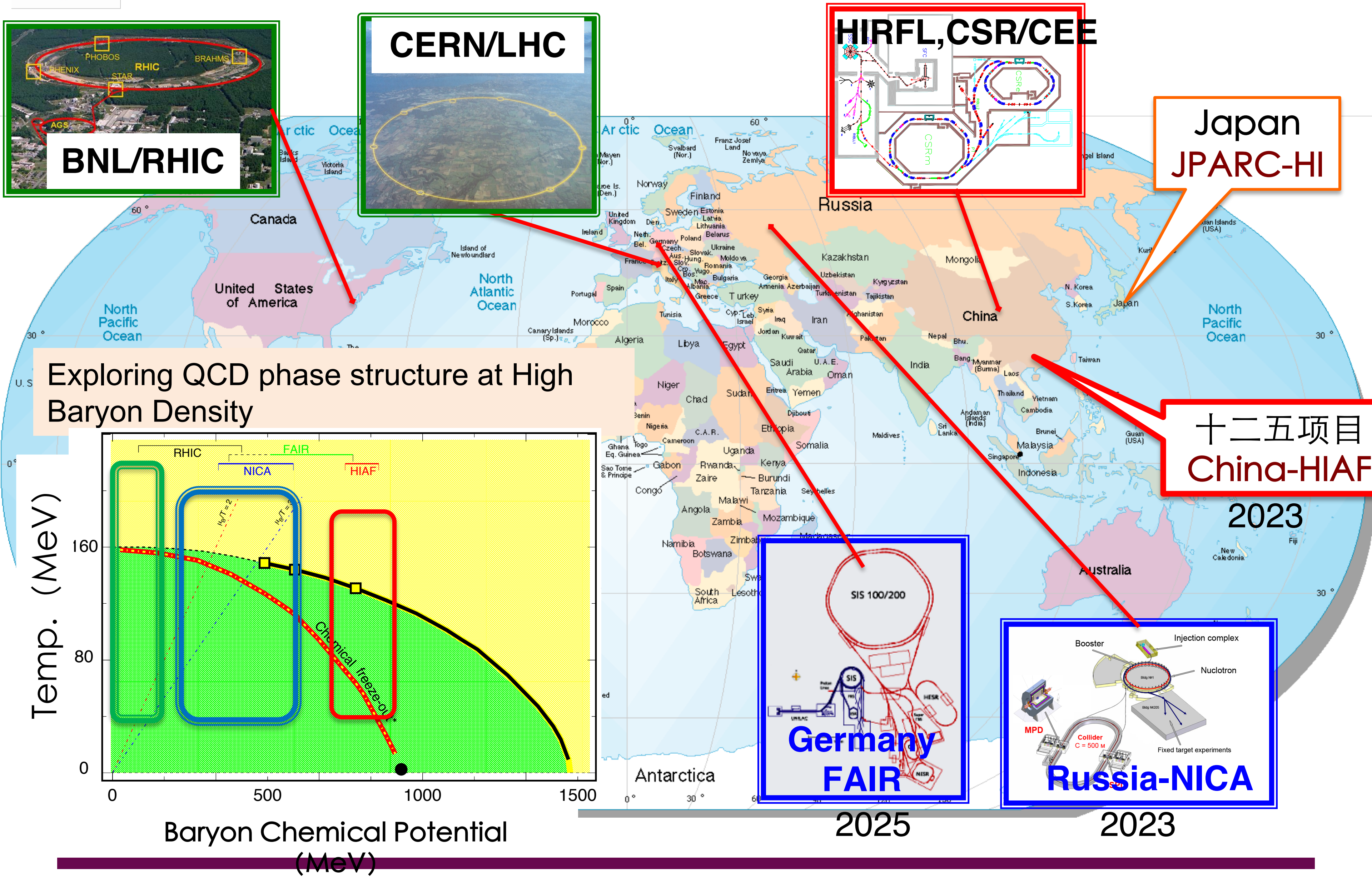
QCD Phase Diagram

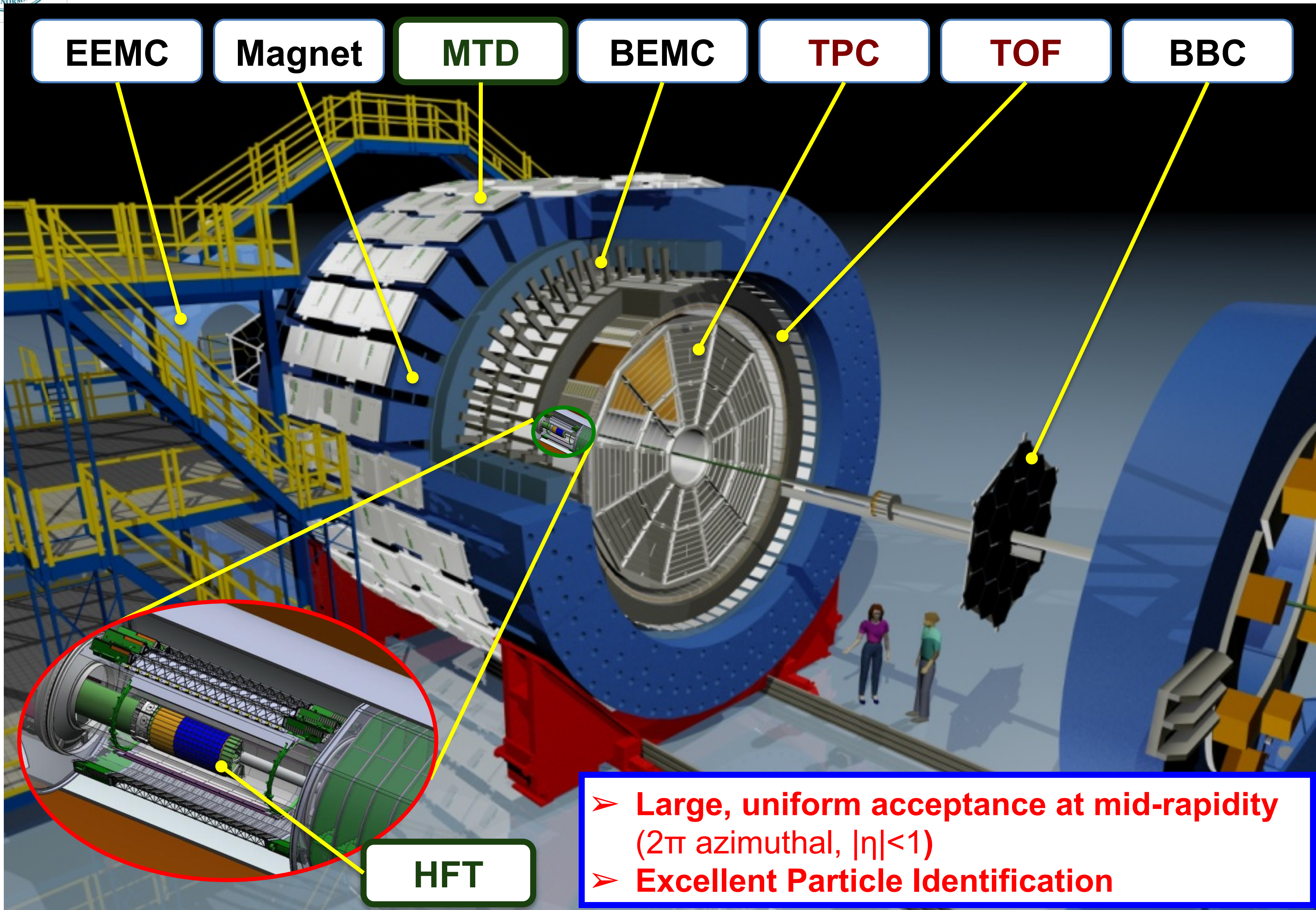


One of the Key Problems: Can we find the QCD critical point and its location ?

High Energy Nuclear Collisions Experiments



STAR Detector System



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

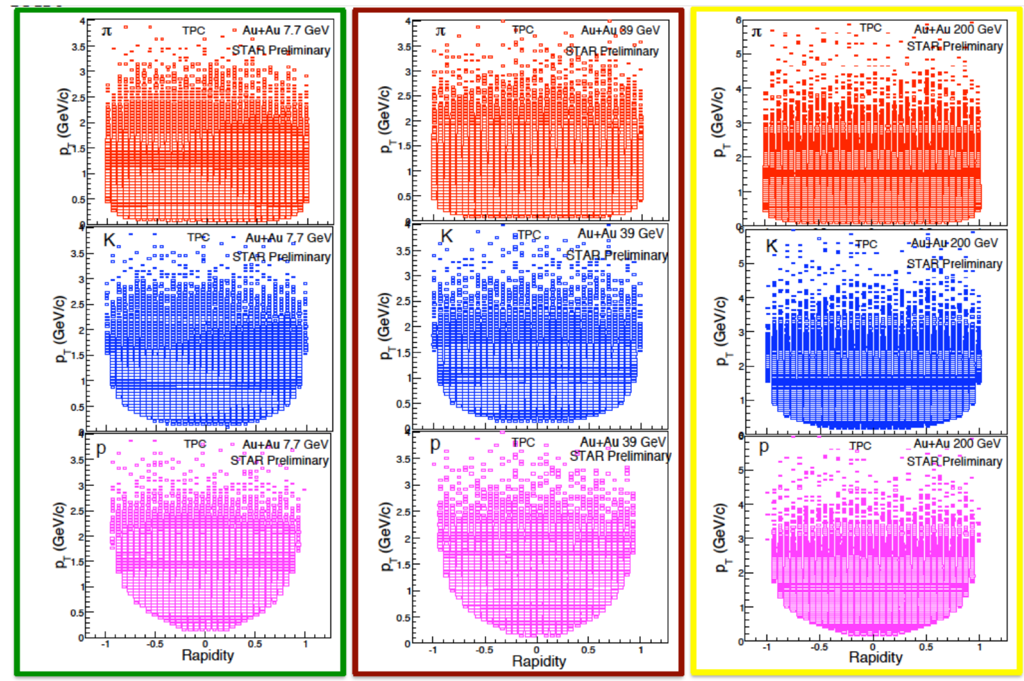
RHIC Beam Energy Scan-I (2010-2014)

Au+Au Collisions

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

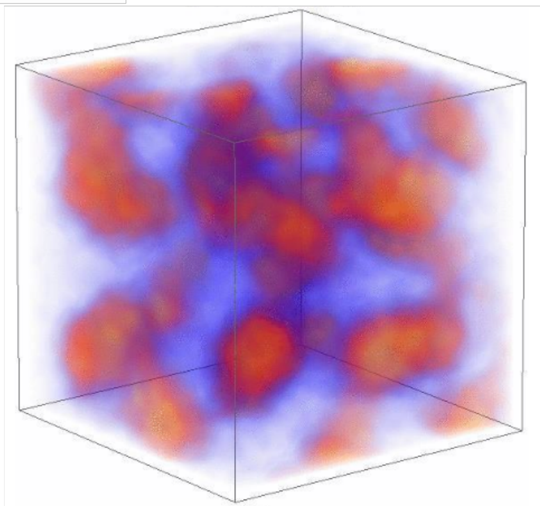
*(μ_B, T_{CH}) : J. Cleymans et al., PRC 73, 034905 (2006)

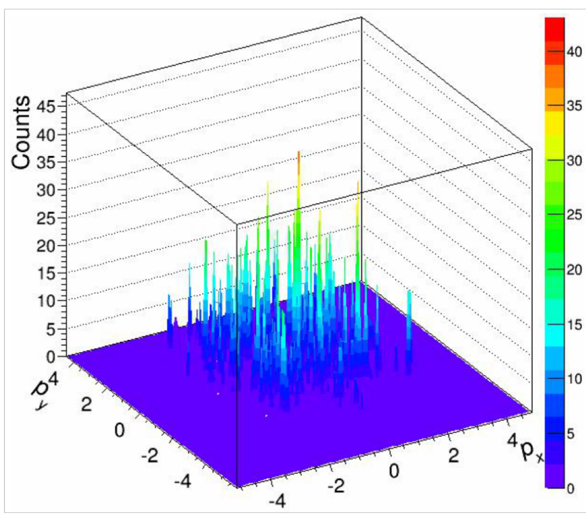
Uniform acceptance at Mid-rapidity



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

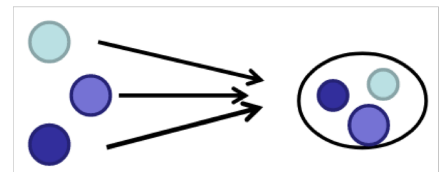
Sensitive observables !





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.

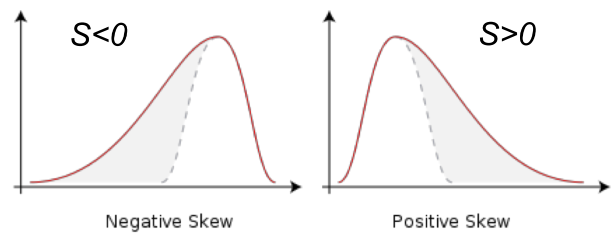
Higher Moments of Conserved Quantities (B, Q, S)

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

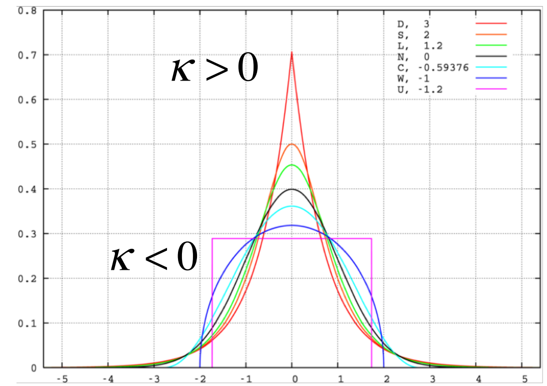
$$< \delta N >= N - < N >$$
$$C_1 = M =< N >$$
$$C_2 = \sigma^2 =< (\delta N)^2 >$$
$$C_3 = S\sigma^3 =< (\delta N)^3 >$$
$$C_4 = \kappa\sigma^4 =< (\delta N)^4 > -3 < (\delta N)^2 >^2$$

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

Skewness (S) → asymmetry



Kurtosis (κ) → Sharpness

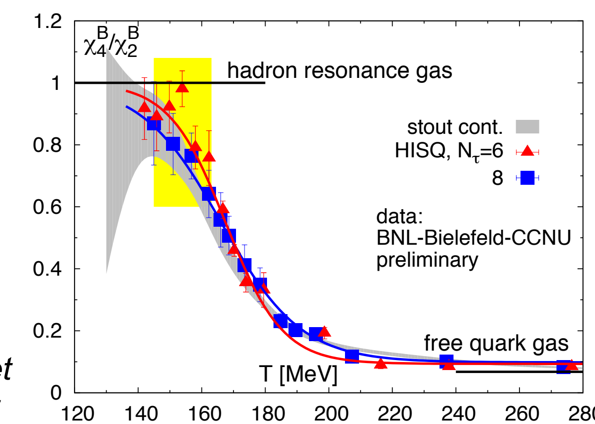


M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009); 107, 052301 (2011).
M.Asakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009).

2. Direct connect to the susceptibility of the system.

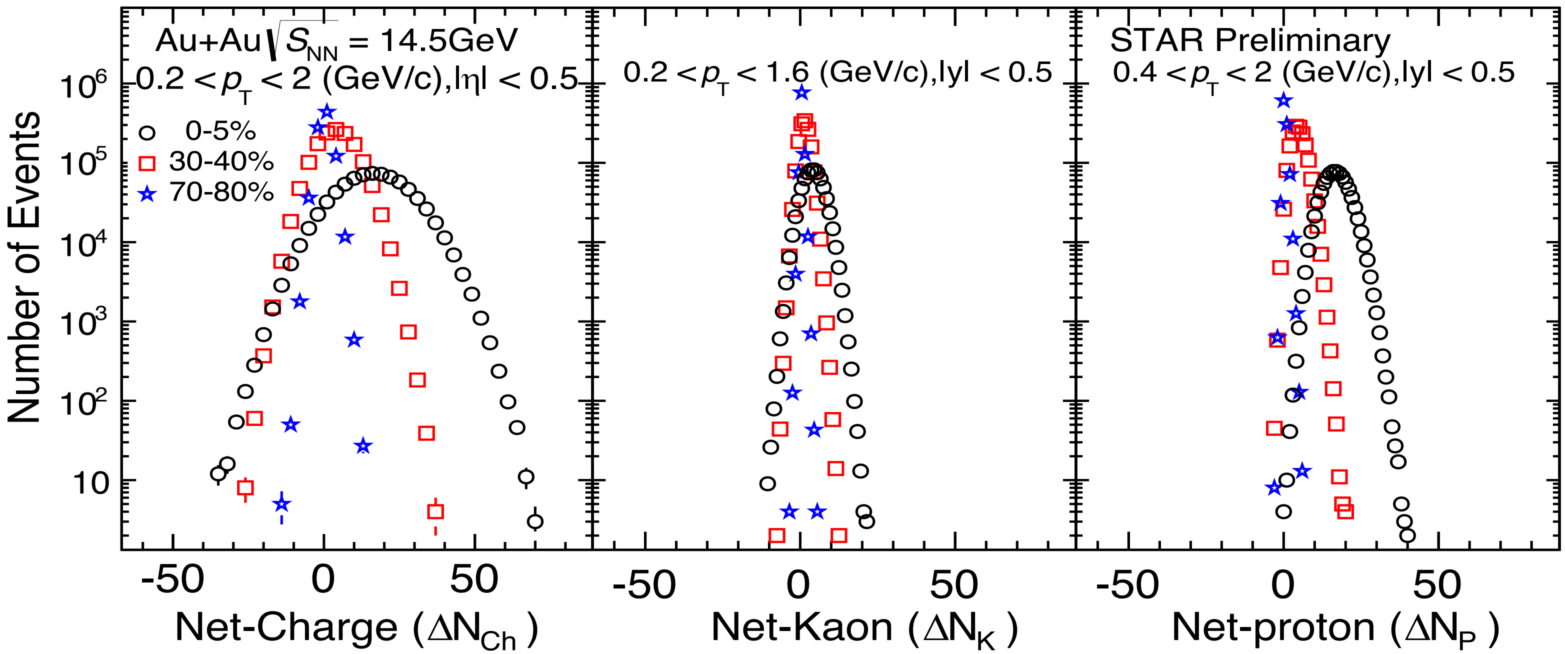
$$\frac{\chi_q^4}{\chi_q^2} = \kappa\sigma^2 = \frac{C_{4,q}}{C_{2,q}} \qquad \frac{\chi_q^3}{\chi_q^2} = S\sigma = \frac{C_{3,q}}{C_{2,q}},$$

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



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)

Data Analysis Methods



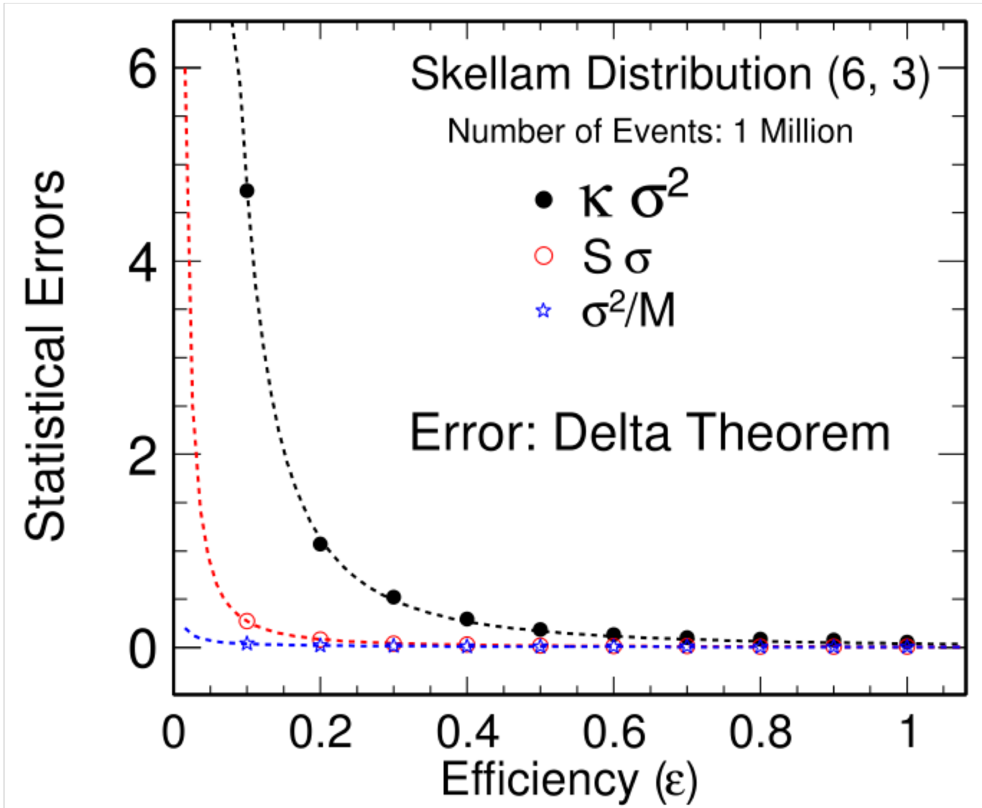
Analysis Methods used in the STAR coll.

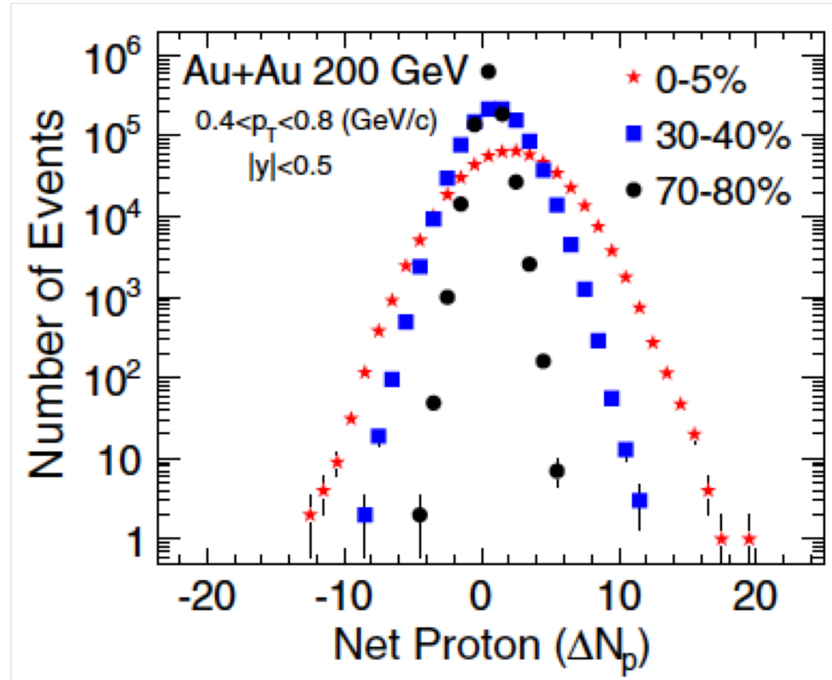
1. Statistical errors estimation : Delta theorem or bootstrap
2. Avoid auto-correlation effects: New centrality definition.
3. Suppress volume fluctuation：Centrality bin width correction
4. Finite detector efficiency correction (binomial response func.)

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, arXiv: 1812.10303*

Statistical Errors Estimation and Properties





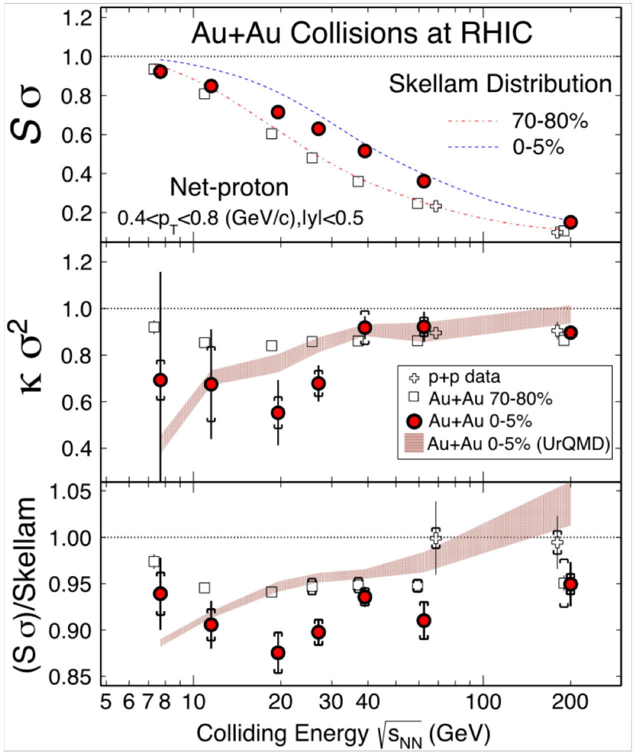
X. Luo, J. Phys. G 39, 025008 (2012);
X. Luo, Phys. Rev. C 91, 034907 (2015);
X. Luo, T. Nonaka, PRC in press [arXiv: 1812.10303]

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

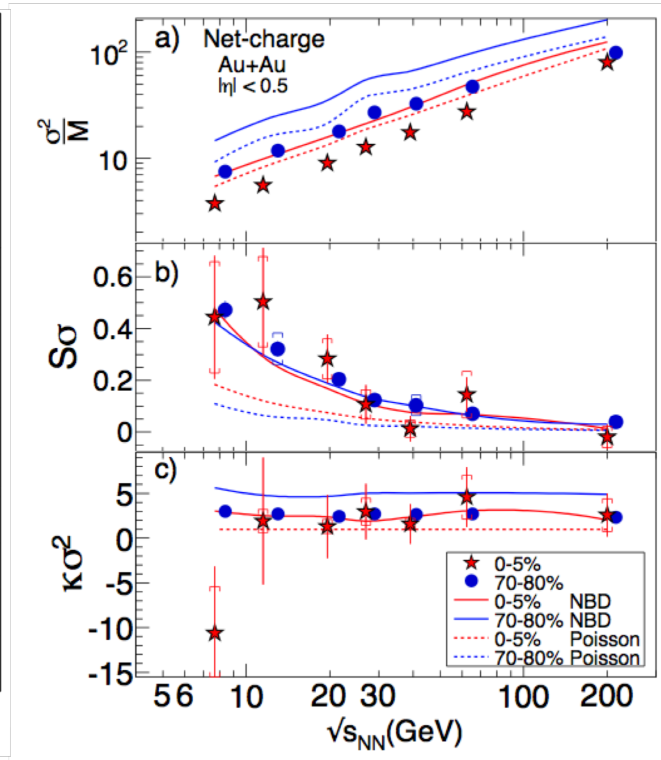
Statistical errors strongly depend on the : Width of the distributions and the detector efficiency (response function of).

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

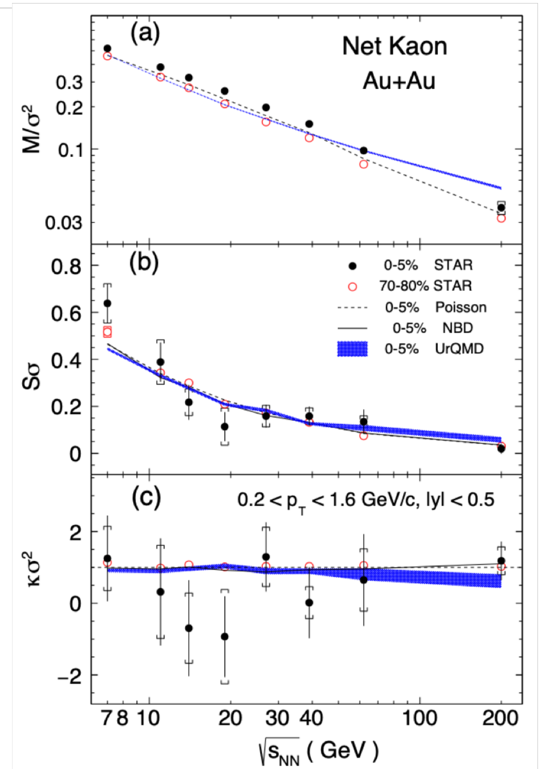
Net-Proton



Net-Charge



Net-Kaon

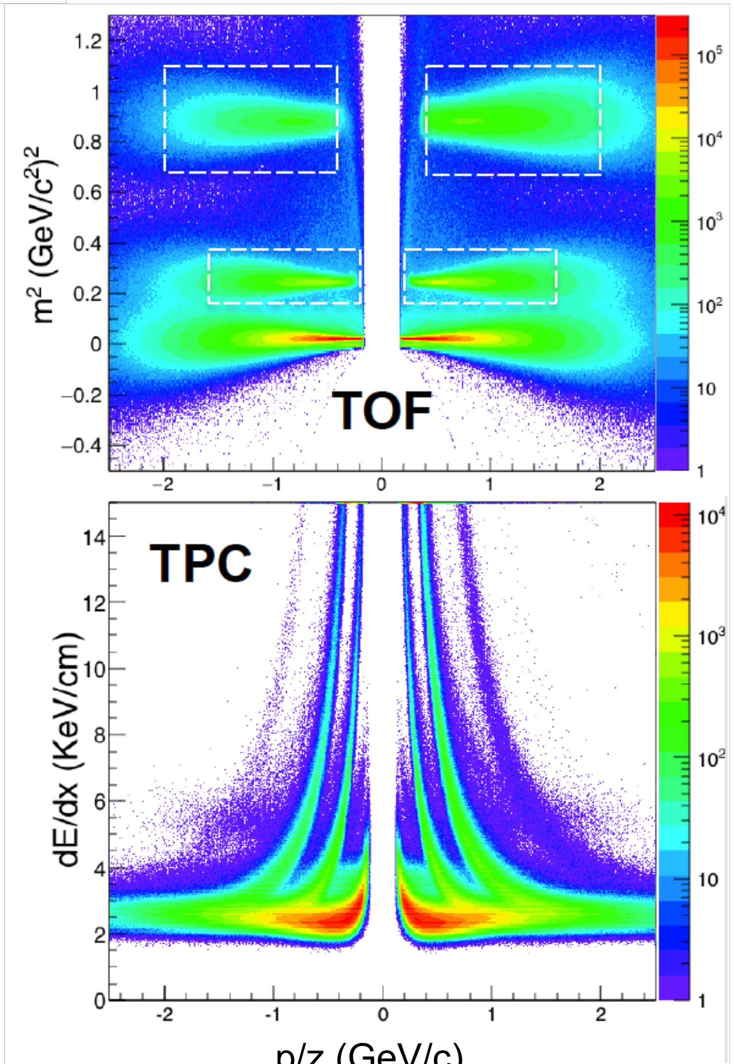


Phys. Rev. Lett. 105, 022302 (2010).
Phys. Rev. Lett. 112, 032302 (2014).

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

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

(Anti-) Proton PID and Acceptance

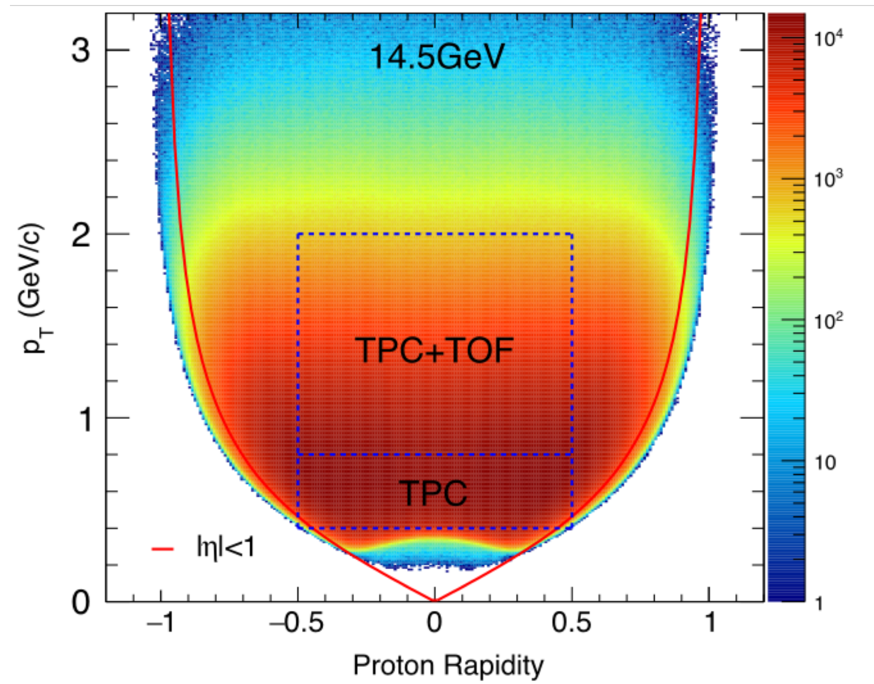


Extend the phase space coverage by TOF.

Doubled the accepted number of proton/anti-proton

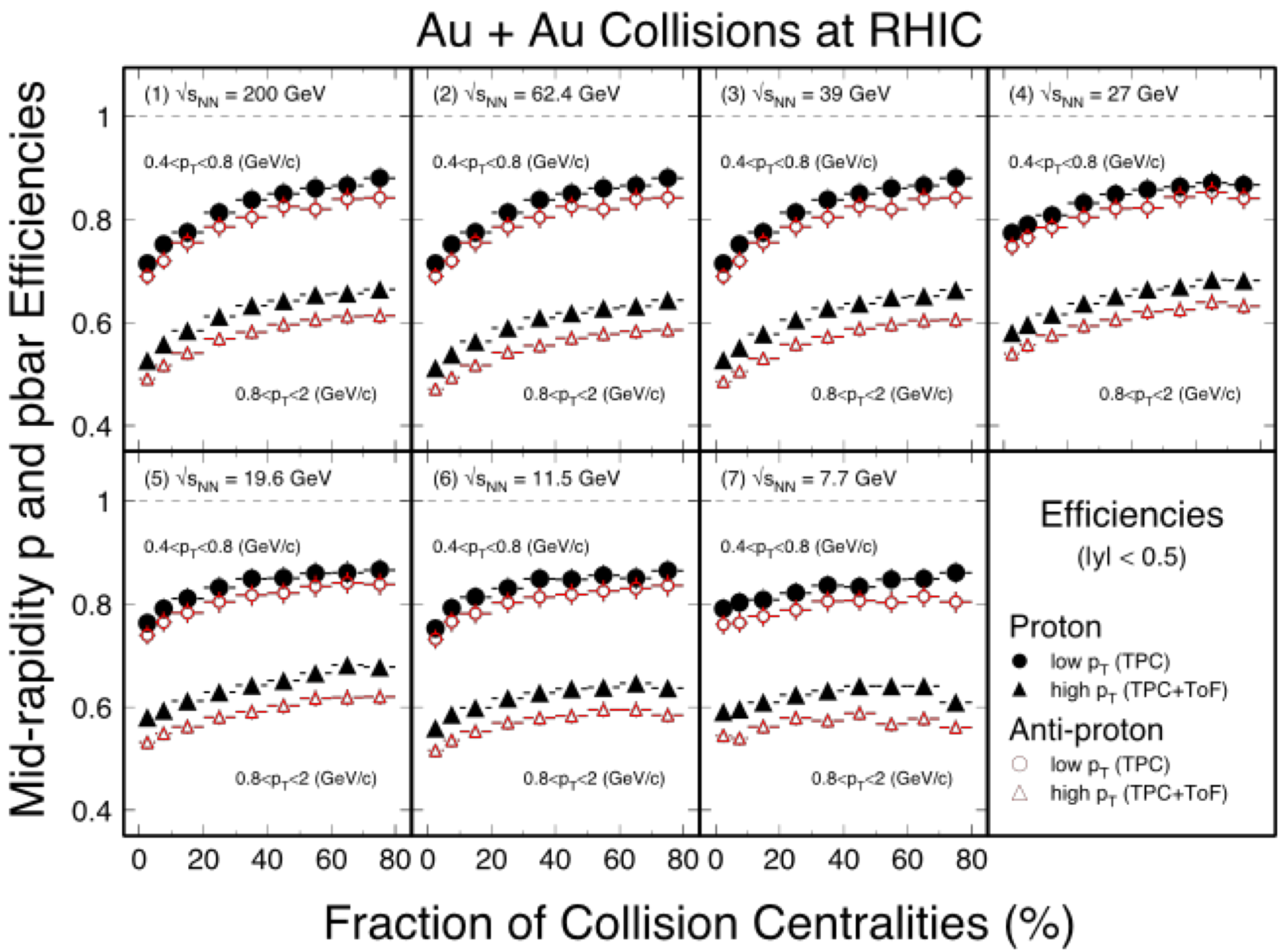
|y|<0.5, 0.4<p_T<0.8 (TPC PID)

0.8<p_T<2 (TPC+TOF PID)



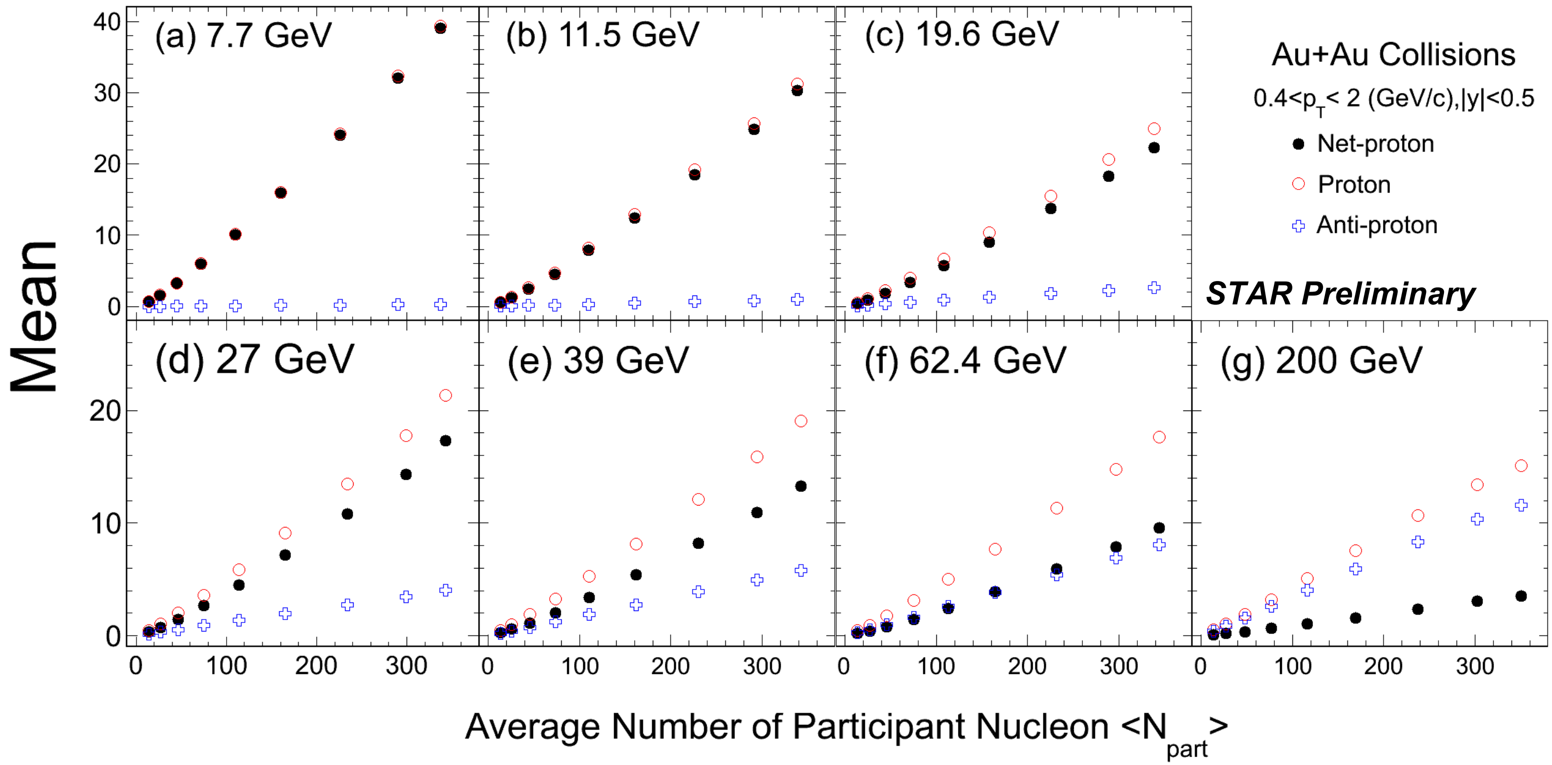
➢ Sufficiently large acceptance is important for fluctuation analysis

(Anti-) Proton Acceptance and Efficiencies



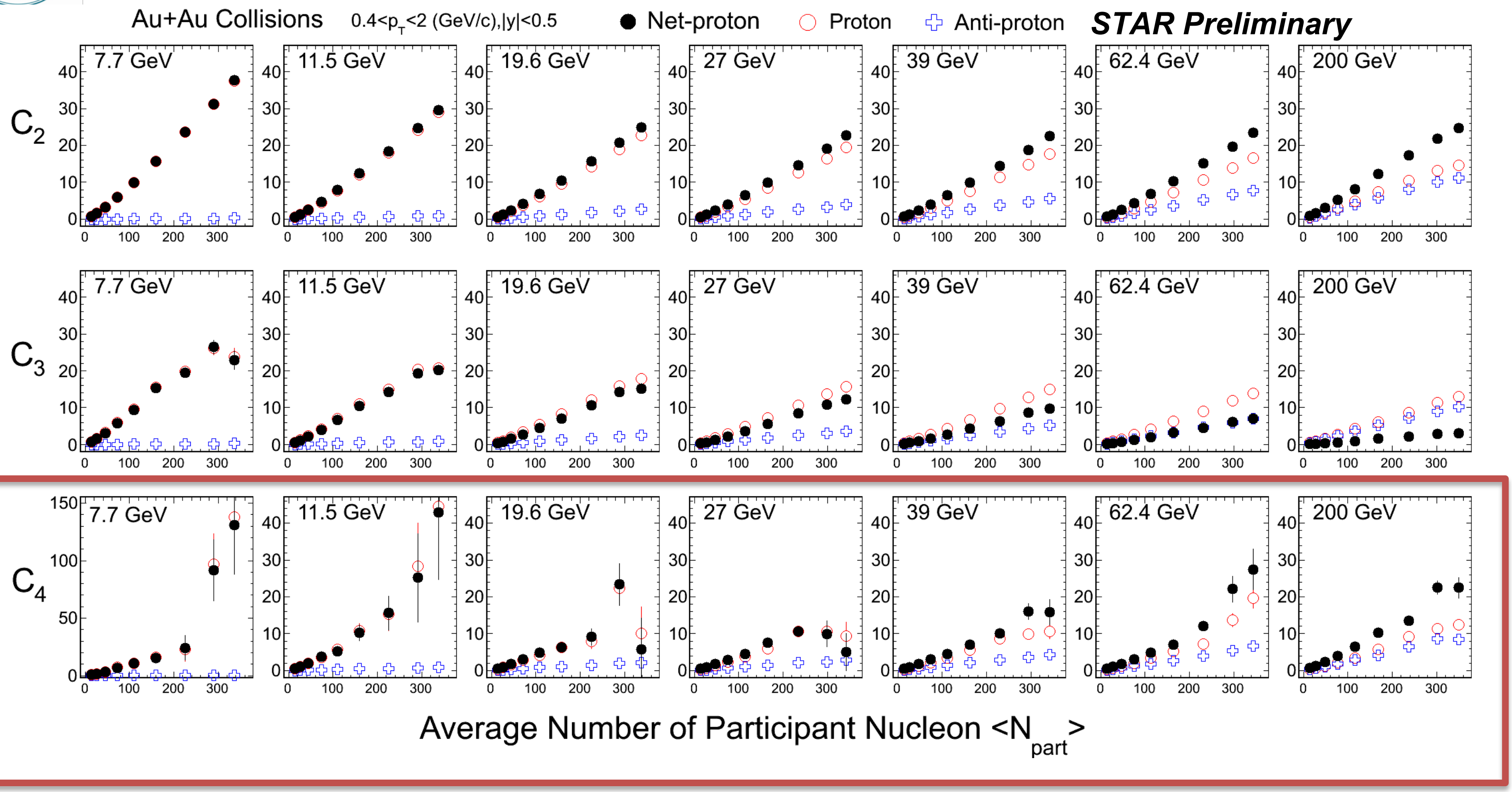
- Efficiency : Proton> Anti-proton, Low p_T > High p_T , low energy > High Energy, Peripheral > Central

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)

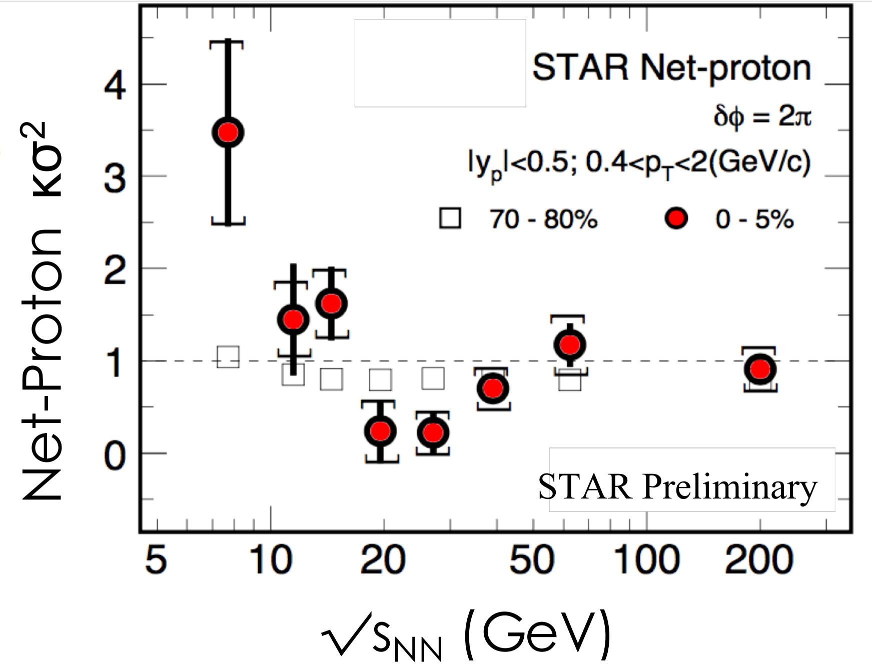
Higher Order Cumulants for Net-p, p, pbar



- ➢ 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.

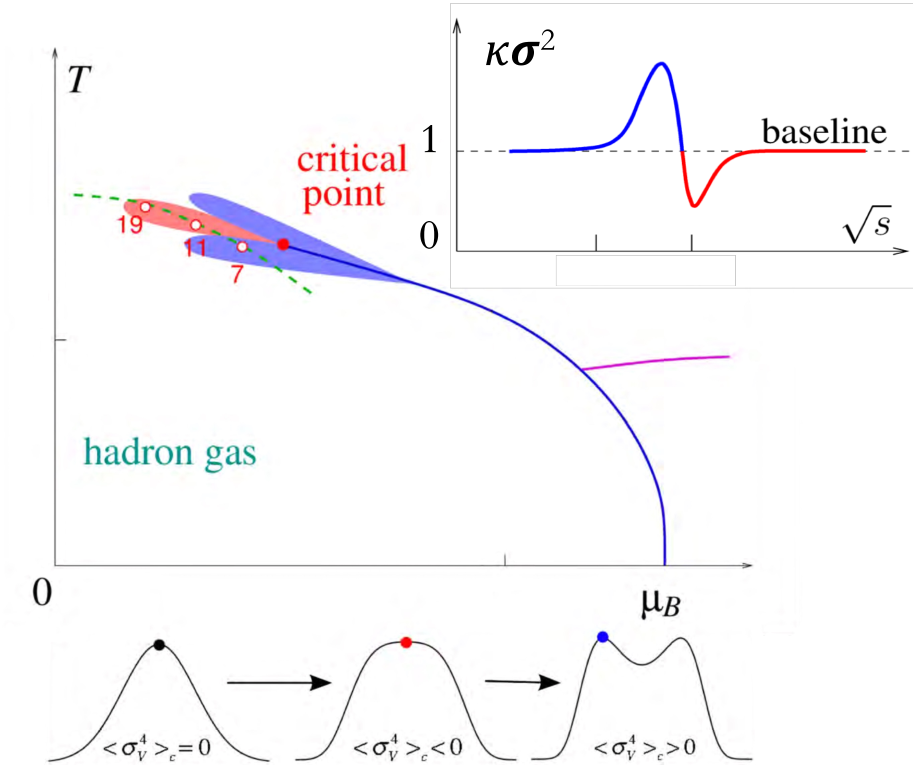
Net-Proton Fluctuations

Experimental Measure



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

Theoretical calculations

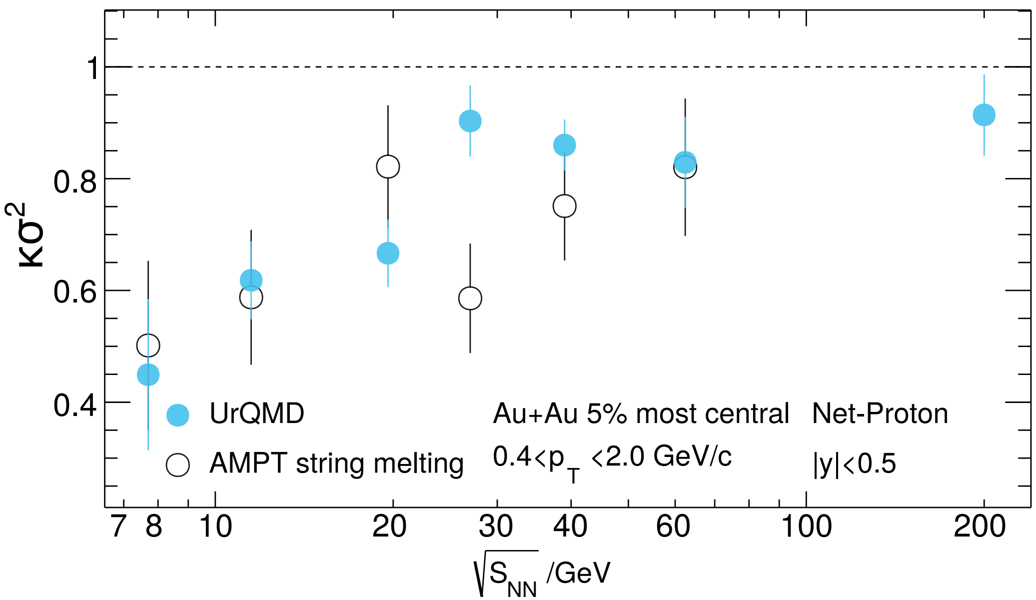


M. Stephanov, PRL107, 052301(2011)
J. Phys. G: 38, 124147 (2011).

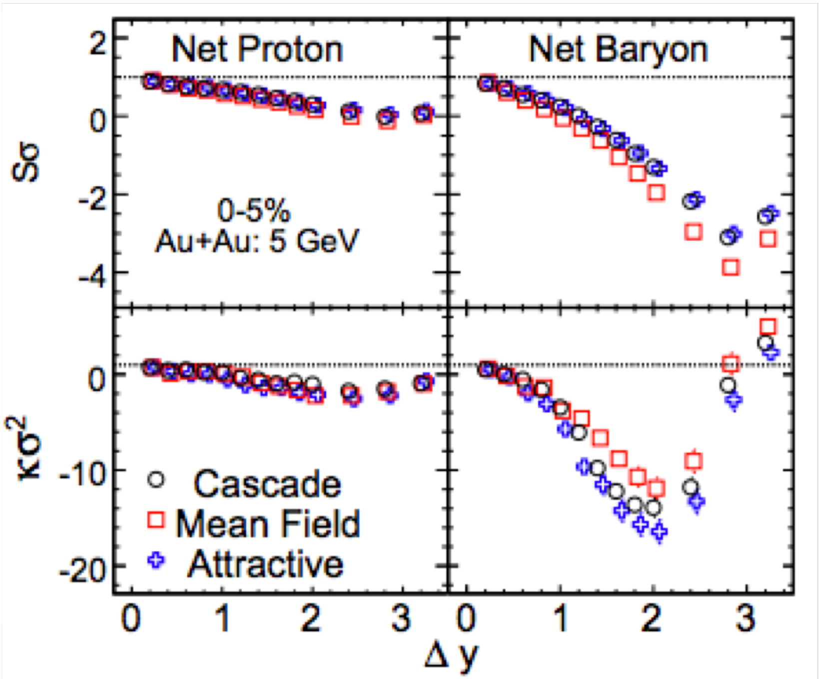
- First observation of the non-monotonic energy dependence of fourth order net-proton fluctuations. Hint of entering Critical Region ?

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).

Towards Understanding Experimental Data

1. **Effective model calculations (Static):** σ field Model, NJL, PNJL, PQM, FRG, VDW+HRG, Mean field

   M. A. Stephanov, PRL107, 052301 (2011). Schaefer&Wanger,PRD 85, 034027 (2012);
   JW Chen，JDeng et al., PRD93, 034037 (2016), PRD95, 014038 (2017)
   W. K. Fan, X. Luo, H.S. Zong, IJMPA 32, 1750061 (2017); arXiv: 1702.08674
   Vovchenko et al., PRC92,054901 (2015); PRL118,182301 (2017)
   K. Fukushima, Phys.Rev. C91 (2015) no.4, 044910; Weijie, Fu et al, Phys.Rev. D94 (2016) , 116020
   M. Huang et al., arXiv:1706.02238, Ju Xu et al, arXiv:1709.05178, Guoyun Shao et al.,arXiv:1708.04888
   Defu Hou, PRD 96 (2017) no.11, 114029,

2. **Dynamical evolution of critical fluctuations:** Study non-equilibrium effects

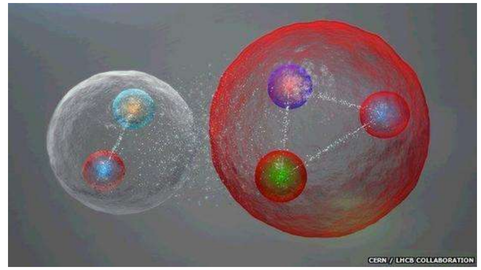
   Swagato et al, PRC92,034912 (2015). PRL117, 222301 (2016); M. Nahrgang, et al. EPJA 52, 240 (2016).
   C. herold Phys.Rev. C93 (2016) no.2, 021902 L. Jiang et al. arXiv: 1704.04765

3. **Non-critical background:** HRG, UrQMD, JAM, AMPT,Hydro+UrQMD

   Z. Feckova,et al., PRC92, 064908(2015). P.K. Netrakanti et al, NPA947, 248(2016), P. Garg et al. Phys. Lett. B726, 691(2013).J.H. Fu, arXiv: 1610.07138; Phys.Lett. B722 (2013) 144-150; M. Bluhm, EPJC77, 210 (2017). J. Xu, YSL, X. Luo, F. Liu, PRC94, 024901 (2016)； S. He, X. Luo, arXiv:1704.00423, C. Zhou, et al., PRC96, 014909 (2017). S. He, et al., PLB762, 296 (2016). L. Jiang et al., PRC94, 024918 (2016). H.J. Xu, PLB 2017.Huichao et al., arXiv:1707.09742

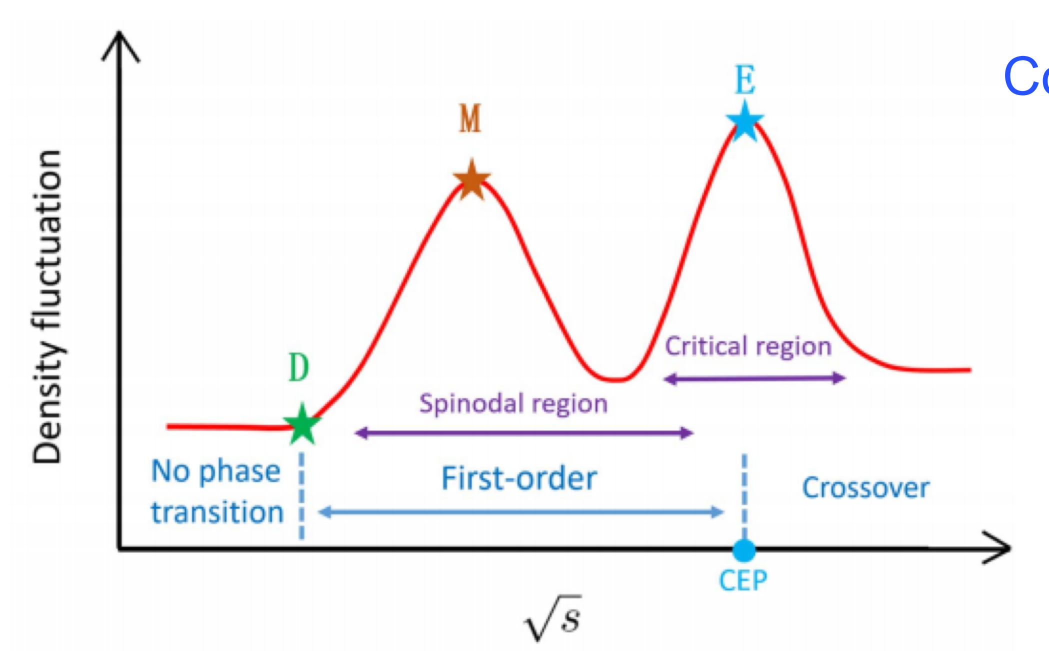
New Observable for CP: Light Nuclei Production

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



Light nuclei production

(Baryon Clustering)



Coalescence + nucleon density flu.

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

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

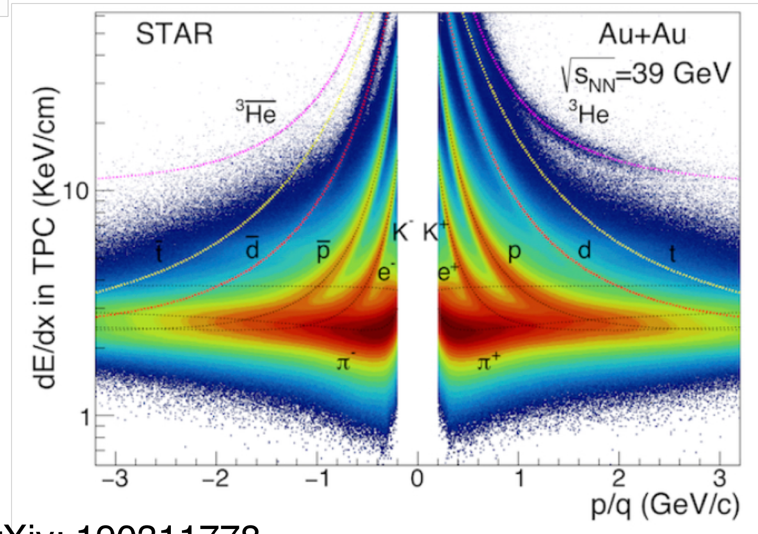
$$N_t \cdot N_p / N_d^2 \approx g(1+\Delta n)$$

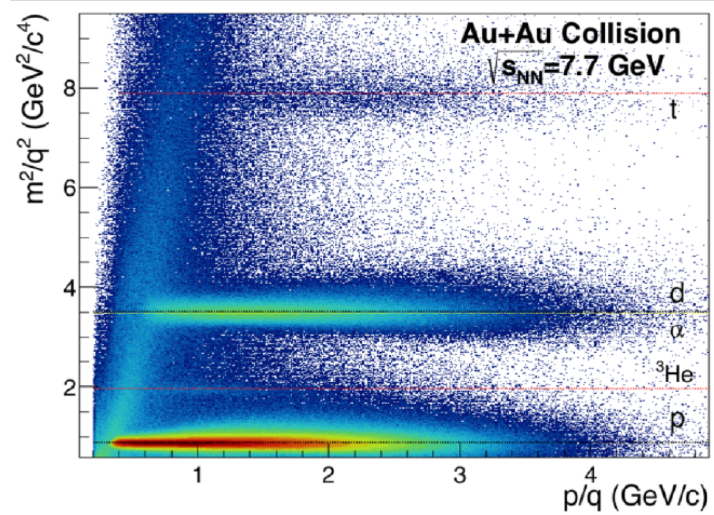
Neutron density fluctuations:

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

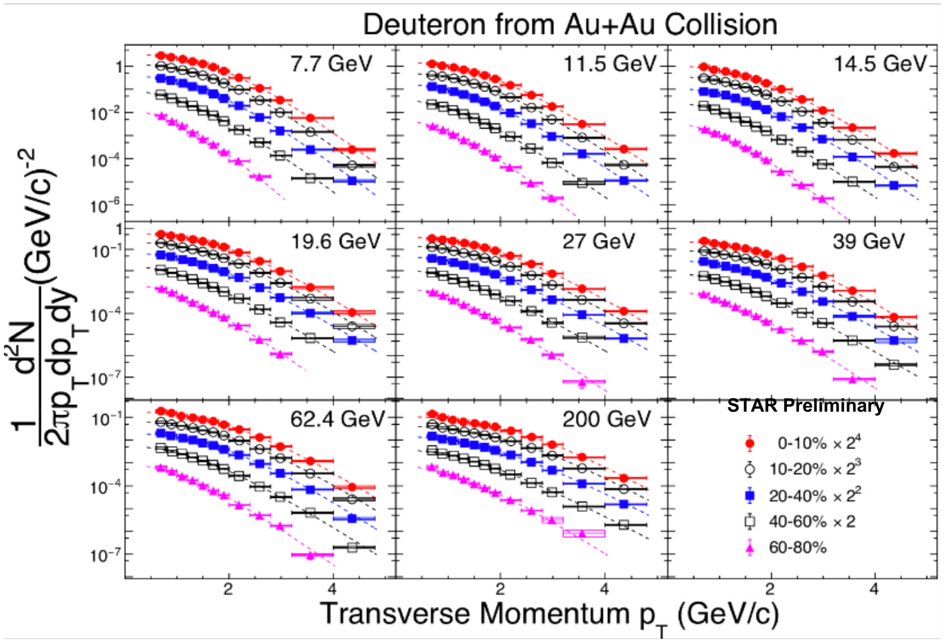
K. J. Sun, L. W. Chen, C. M. Ko, Z. Xu, Phys. Lett. B774, 103 (2017).
K. J. Sun, L. W. Chen, C. M. Ko, J. Pu, Z. Xu, Phys. Lett. B781, 499 (2018).
Edward Shuryak and Juan M. Torres-Rincon, arXiv:1805.04444

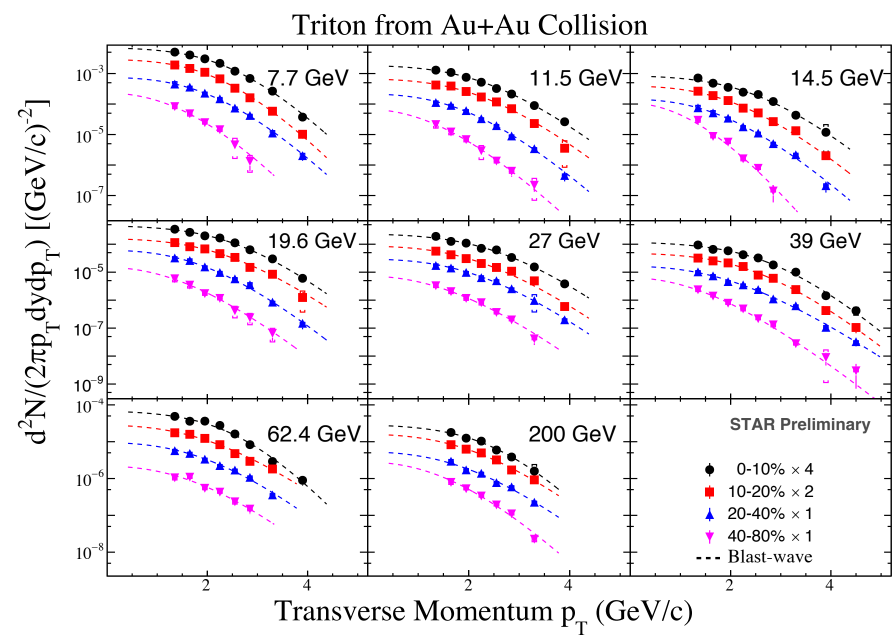
Deuteron and triton production from BES-I at RHIC



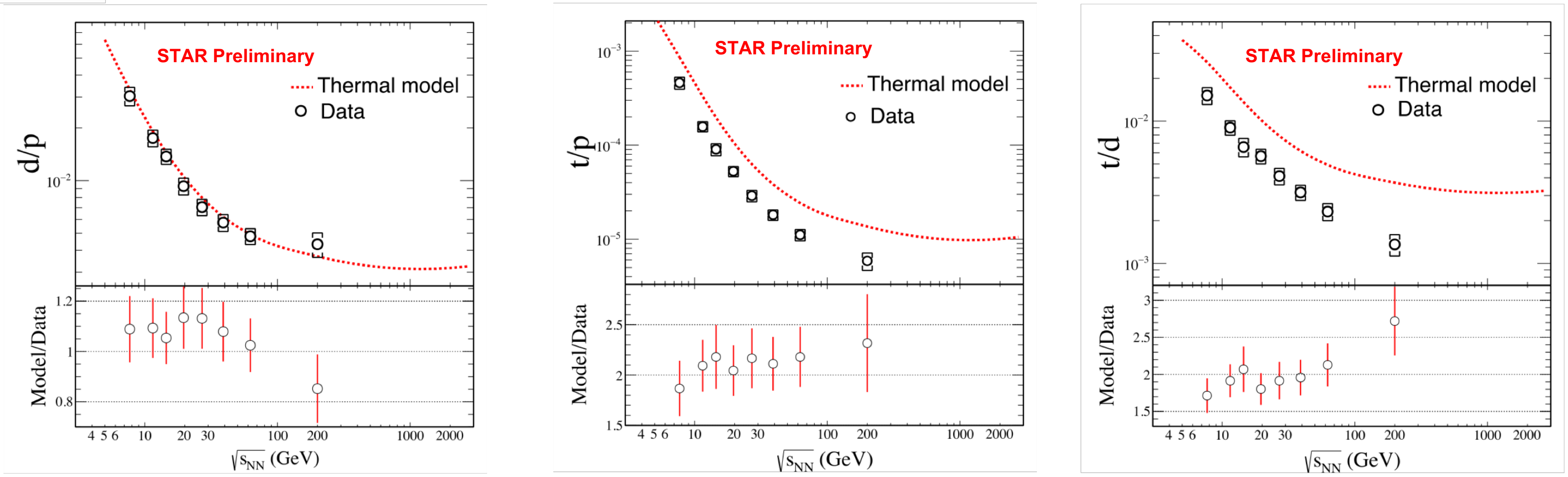


STAR: arXiv: 190311778



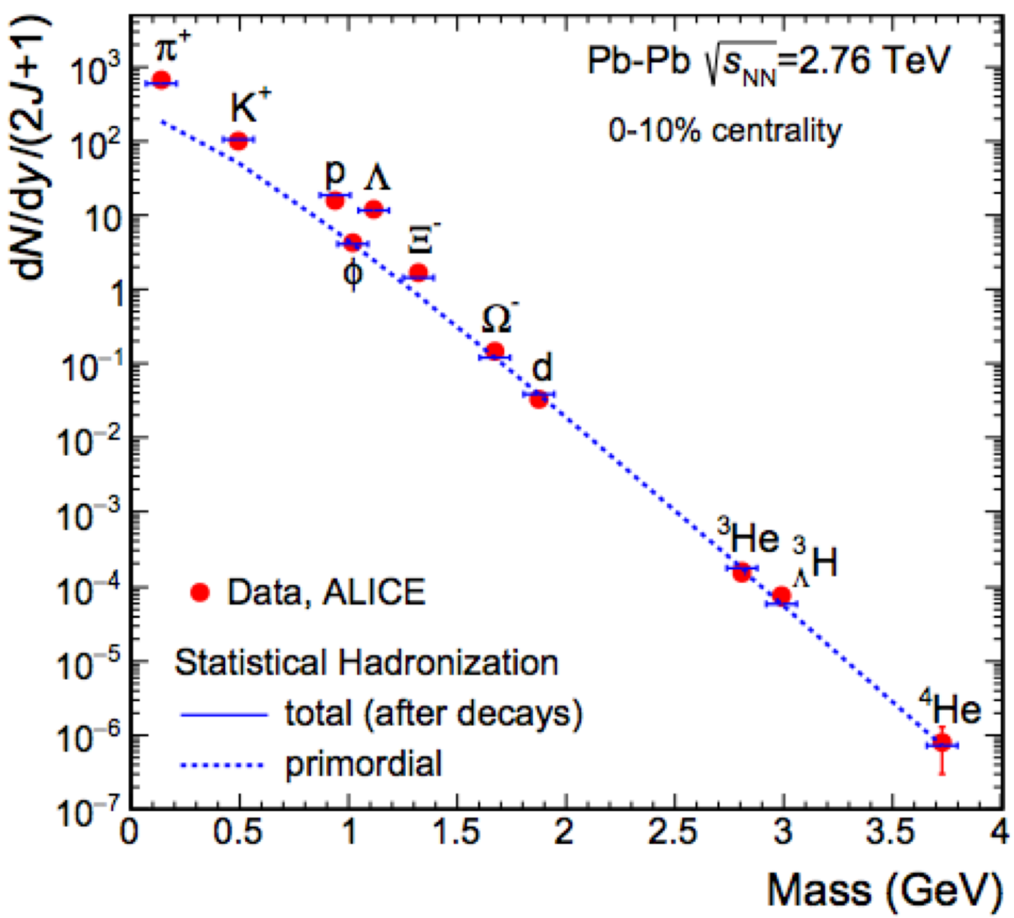


Light Nuclei Yield Ratio Vs. Thermal model



- ➢ At RHIC energies, thermal model can describe the d/p ratios, but can not describe the t/p, t/d ratios.
- ➢ If deuteron is formed at very late stage via nucleon cola., why it can be described by thermal model ?

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 ?

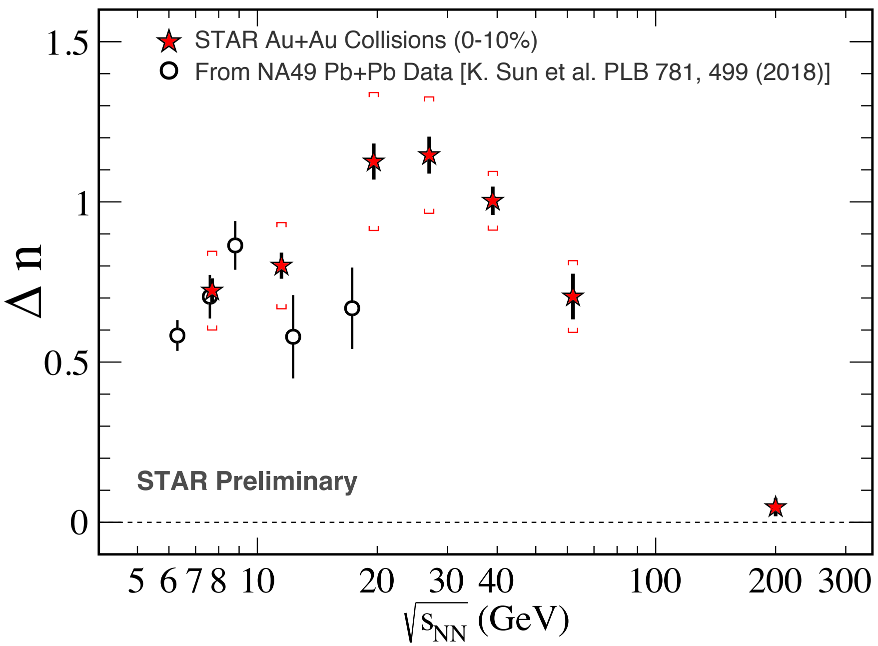
Different production mechanism of light nuclei at RHIC and LHC energies ??

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

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.**

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



Dingwei Zhang, NN2018

If assume α=0.

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

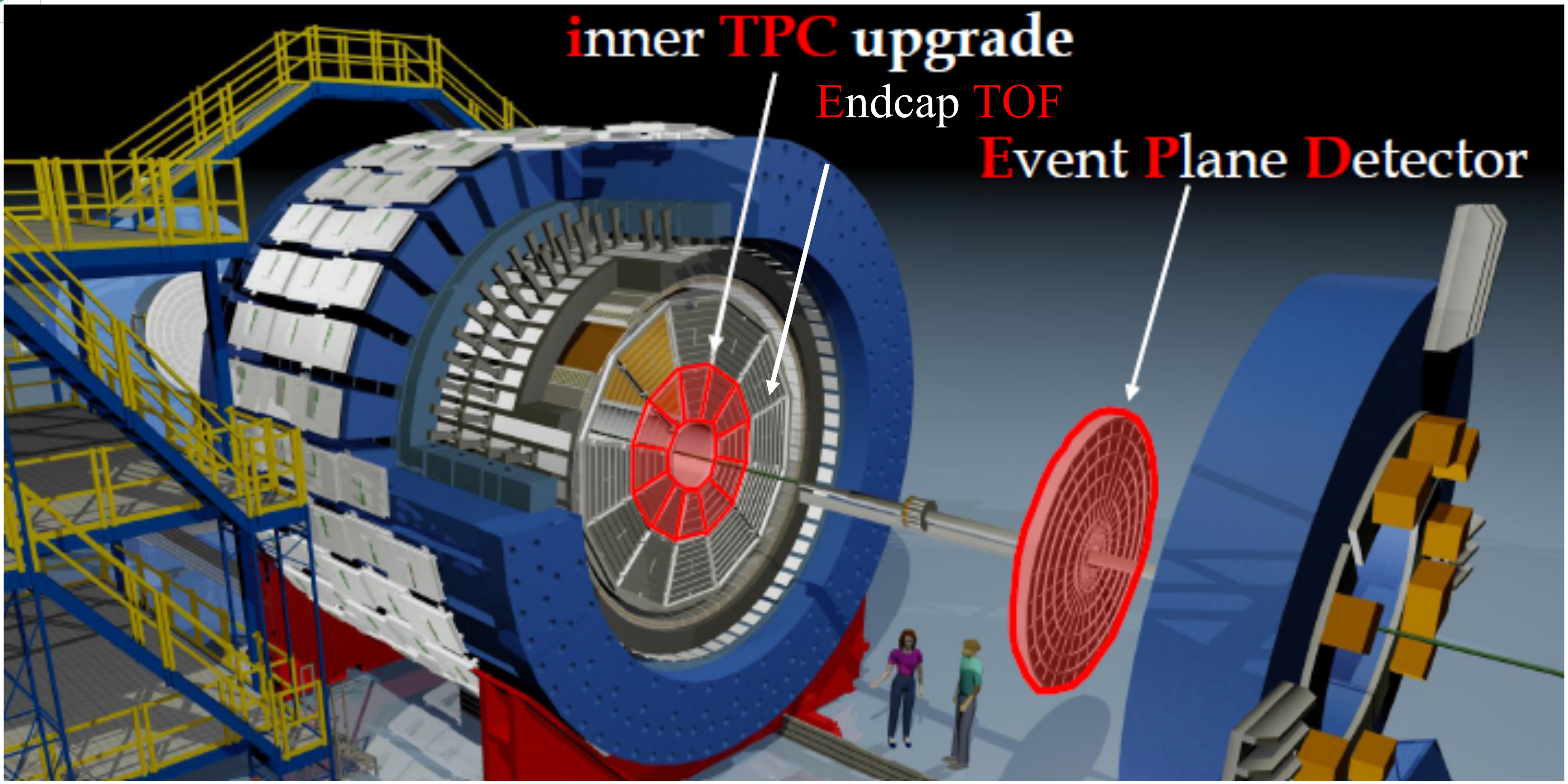
N_t : Triton yield, N_d : Deuteron yield
N_p : Proton yield

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)

STAR Upgrades for BES Phase-II (2019-2021)

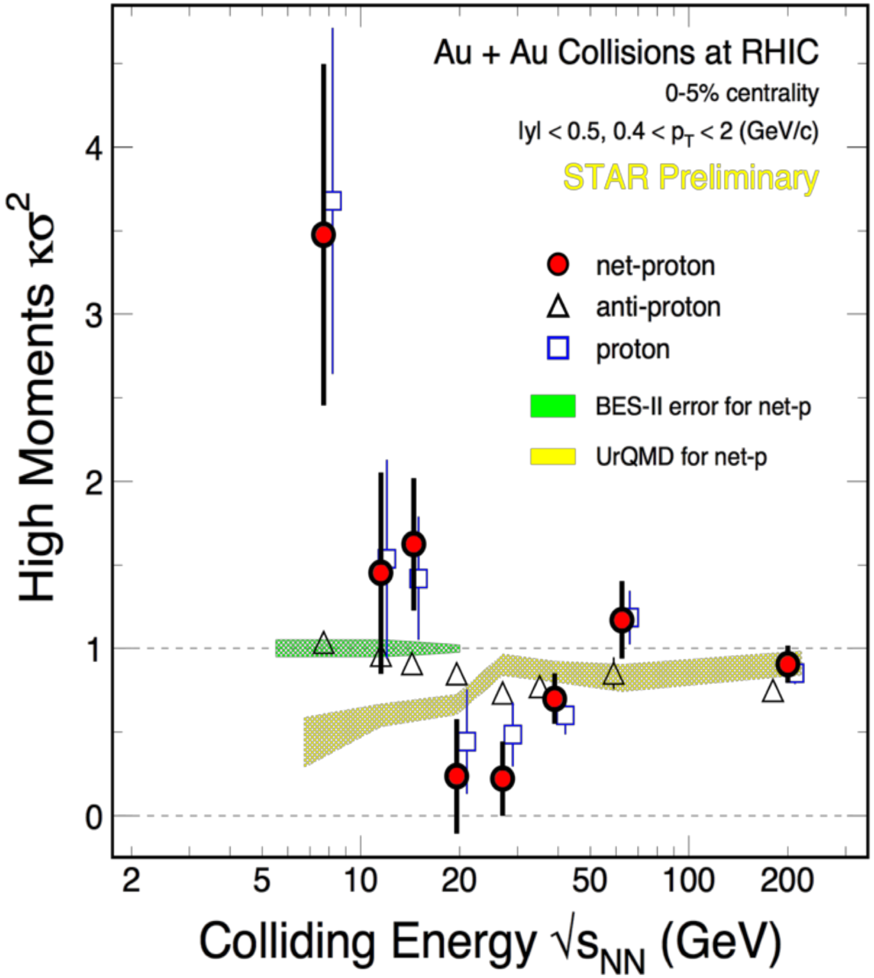


- Enlarge Acceptance : η coverage from 1.0 to 1.5
- Improve dE/dx and forward PID
- Improve centrality/event plane determination

iTPC, EPD, eTOF Upgrade complete
Dedicated runs at : 2019-2021

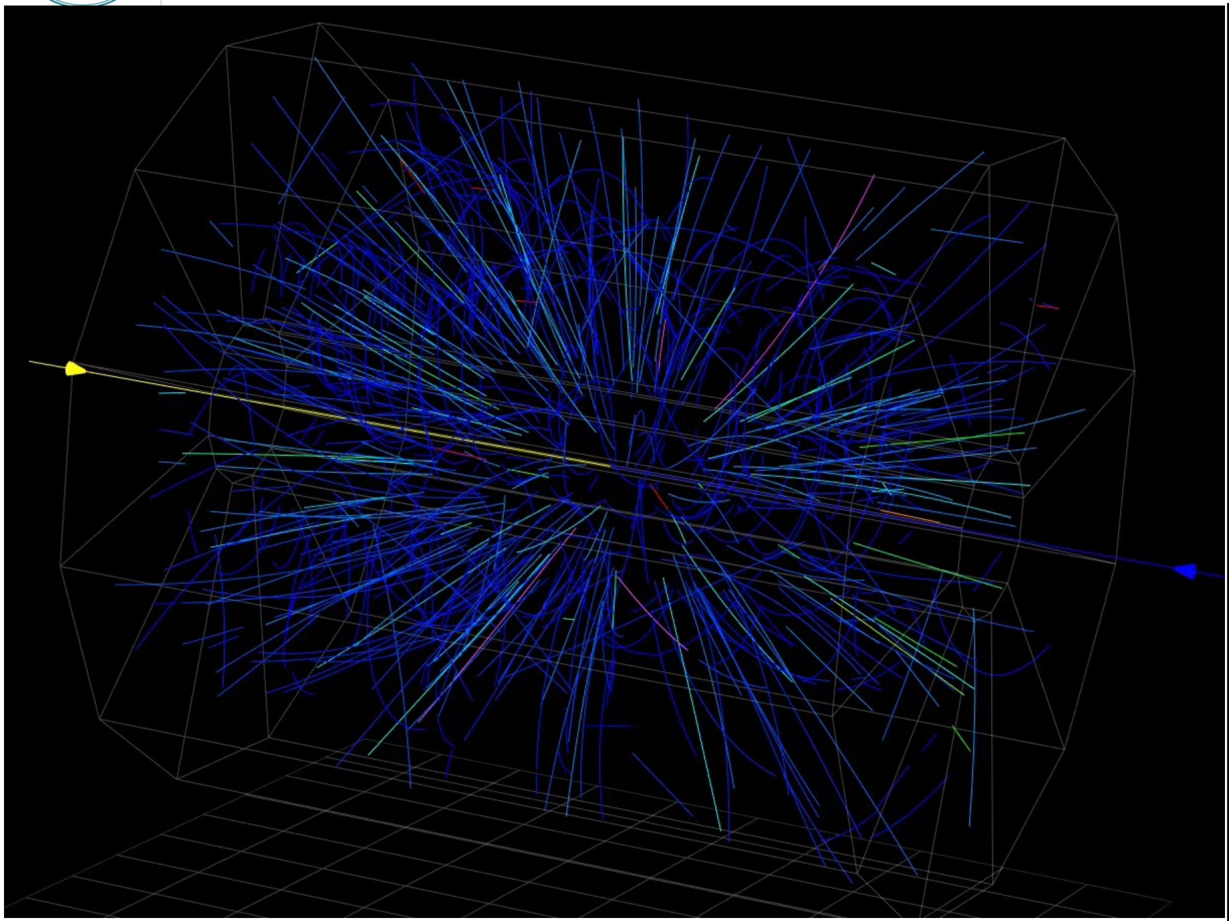
BES-II at RHIC (2019-2021)

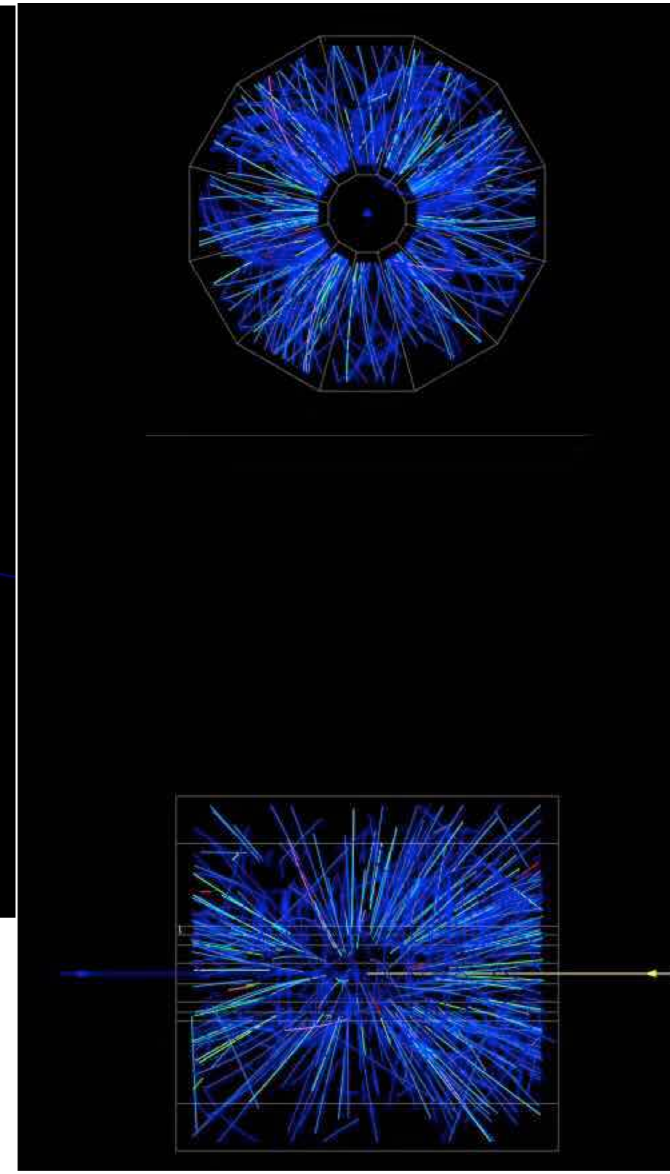
$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES II / BES I
200	238	2010
62.4	45	2010
54.4	1200	2017
39	86	2010
27	32	2011
19.6	**400** / 15	**2019** / 2011
14.5	**300** / 13	**2019** / 2014
11.5	**230** / 7	**2020** / 2010
9.2	**160** / 0.3	**2020** / 2008
7.7	**100** / 3	**2020-202** / 2010



BES-II 19.6 GeV data taking is finished and now is taking 14.5 GeVdata.

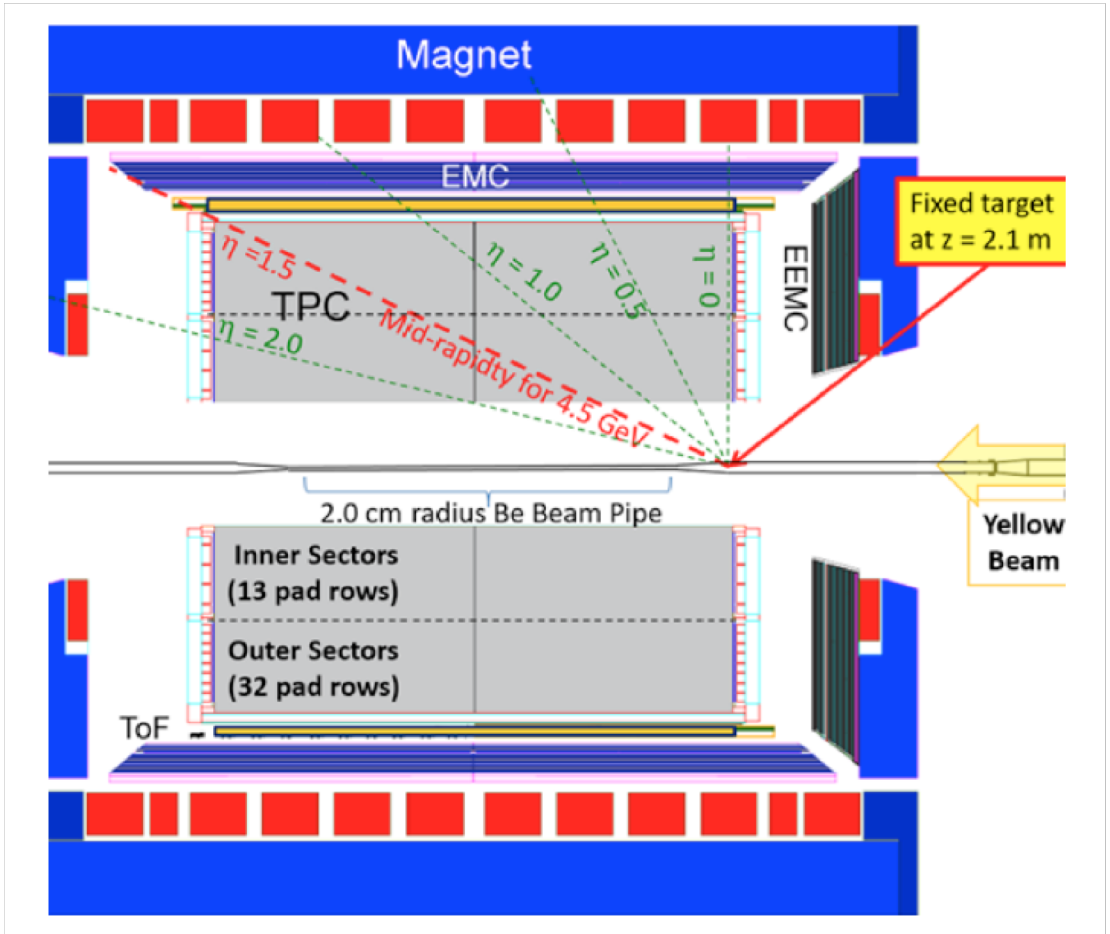
3D Event Display at STAR

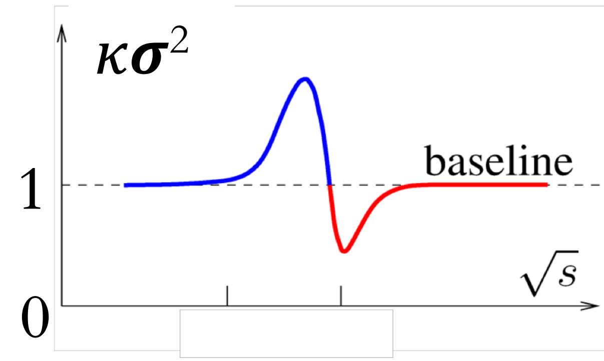


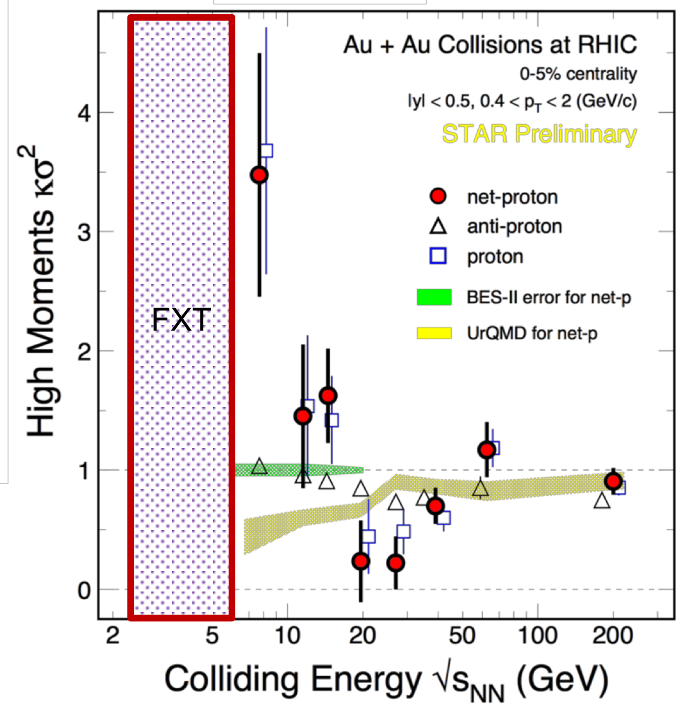


BES-II, real Au+Au collisions at 19.6 GeV.

FXT Experiments at STAR (2018-2020)







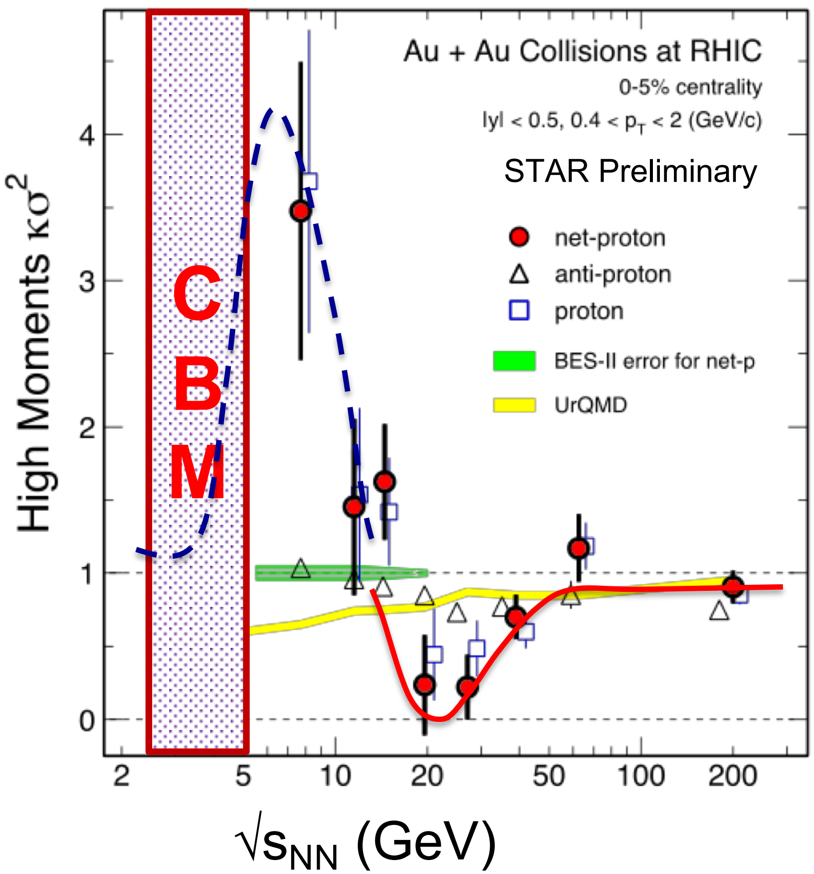
FXT Data Taking Plan：
2018: Au+Au :3 GeV (>100 million events)
2019-2020: Au+Au: 6.2, 5, 4.5, 4, 3.5 GeV

Future CBM experiment

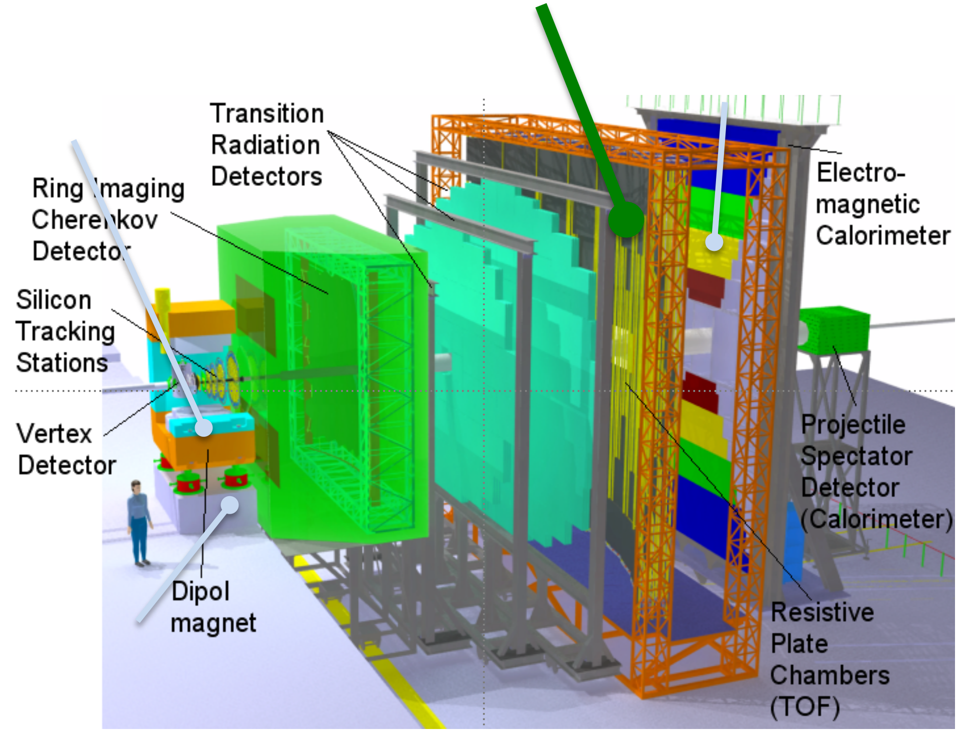
FAIR/CBM Fix target experiment：

Energy：2.7 – 5 GeV

Starting ： 2025 –



Time of flight Wall



Explore QCD phase structure at higher baryon density region with high precision

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. Hint of entering the critical region.

- Neutron density fluctuations in 0-10% central Au+Au collisions shows non-monotonic energy dependence with a peak around 20-30 GeV.
  Hint of entering the critical region.

- 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 !!

Thank you !