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

Status and Prospect

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May 12, 2019

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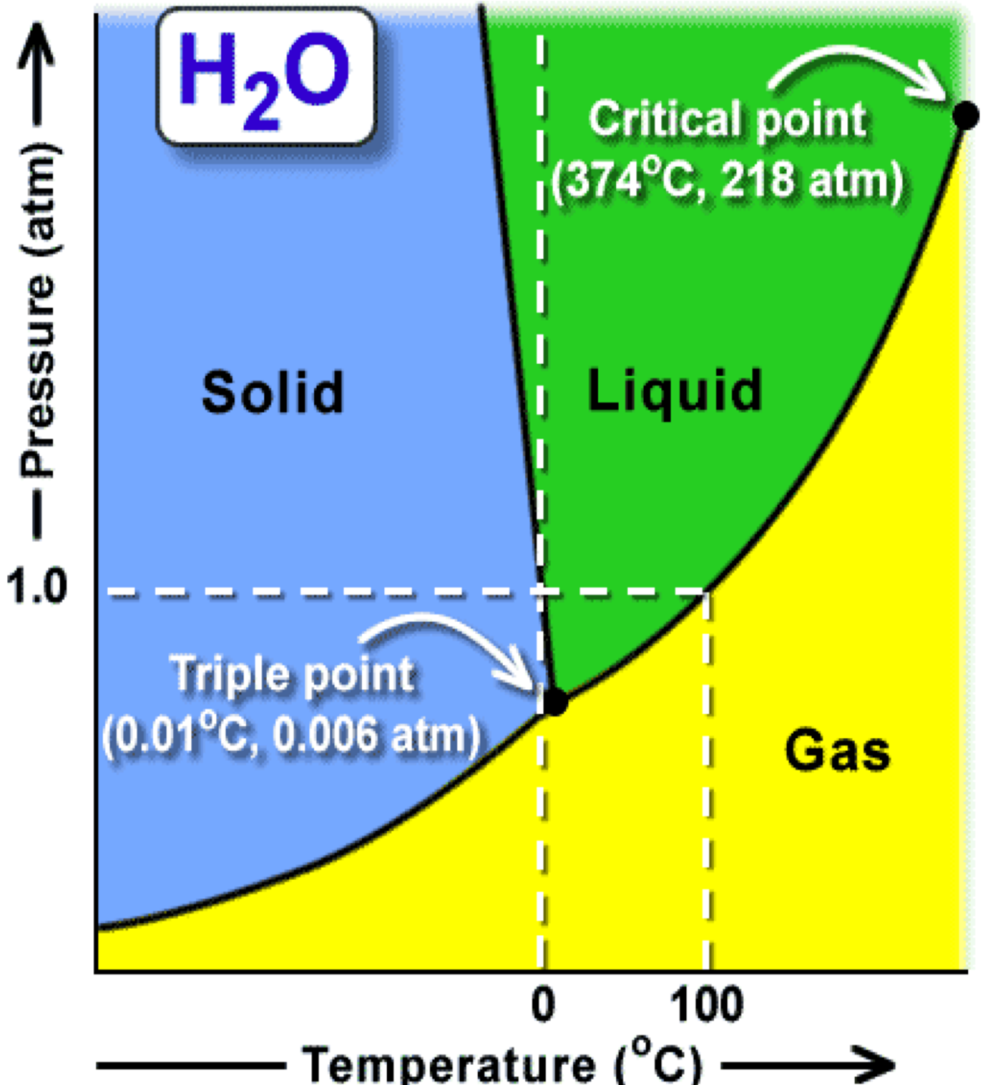
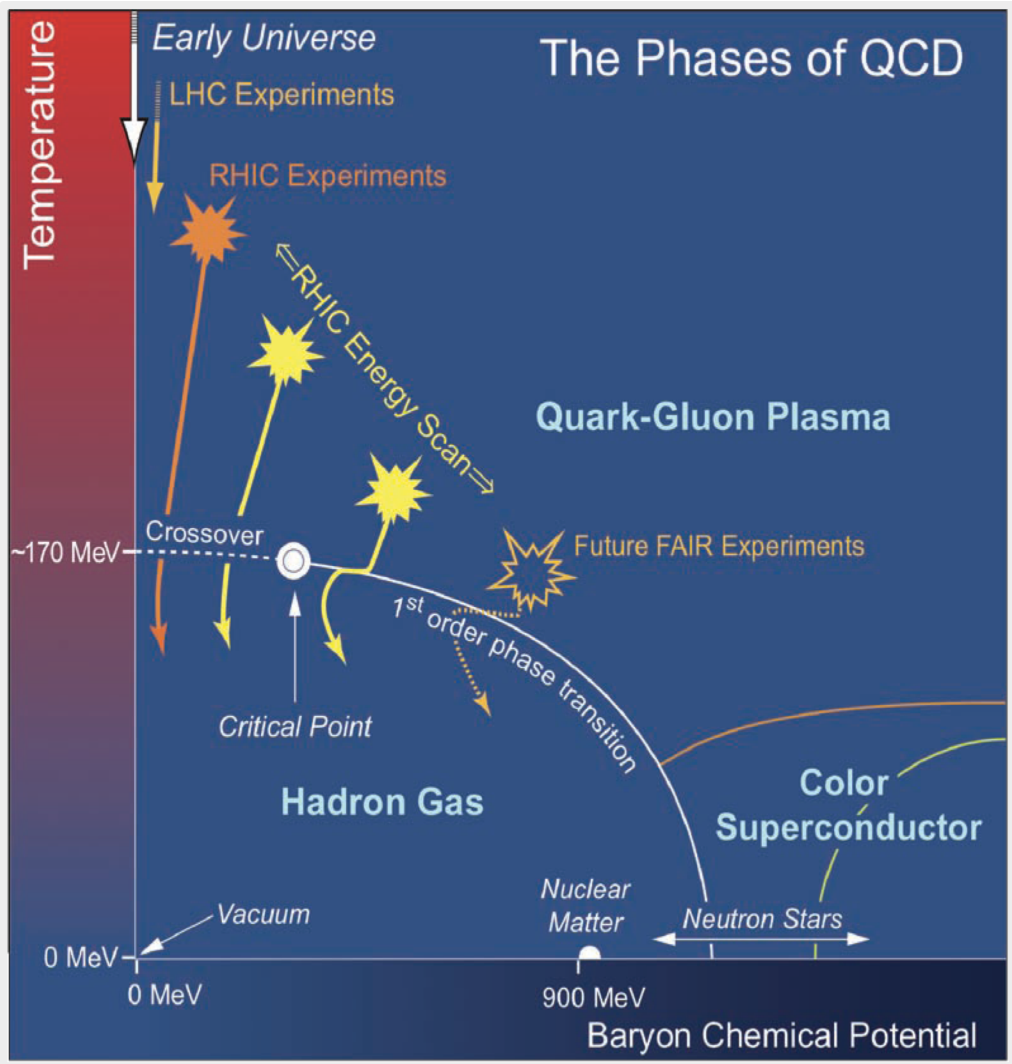
Phase Diagram of Water

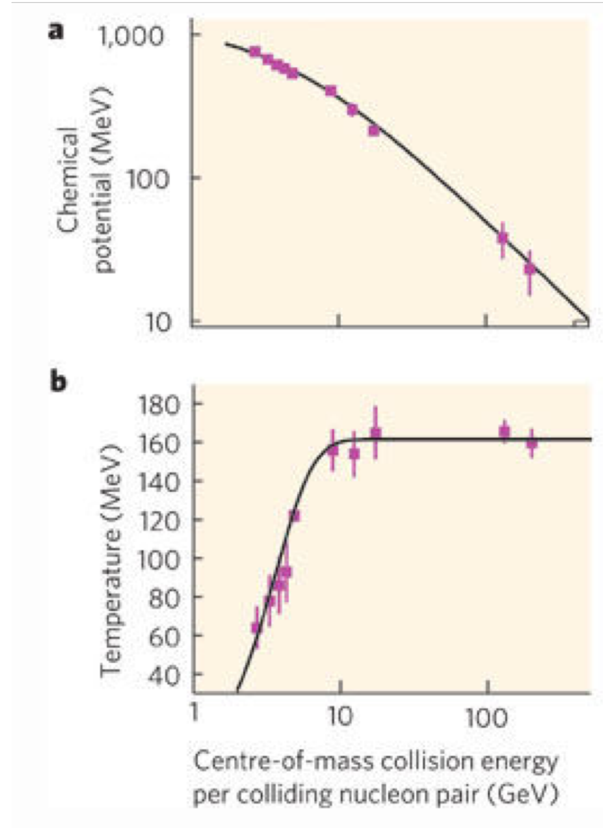


H_2O

EM Interaction

QCD Phase Diagram and Beam Energy Scan



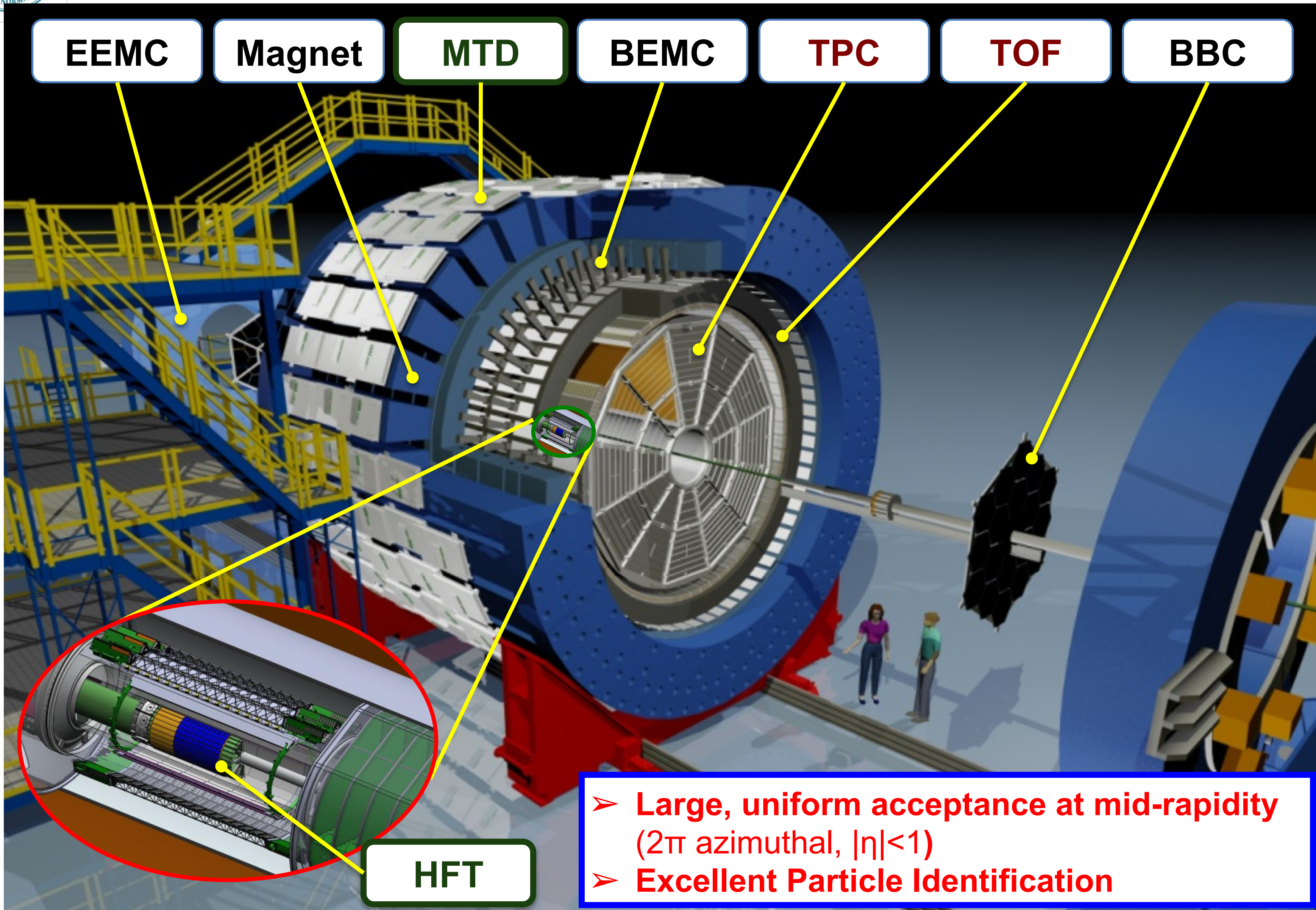


PBM&Johanna, Nature **448**, 302-309 (2007)

Search for signatures of QCD phase transition in heavy-ion collisions.

1. **Crossover**
2. **Critical point**
3. **1st order phase transition**

STAR Detector System



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

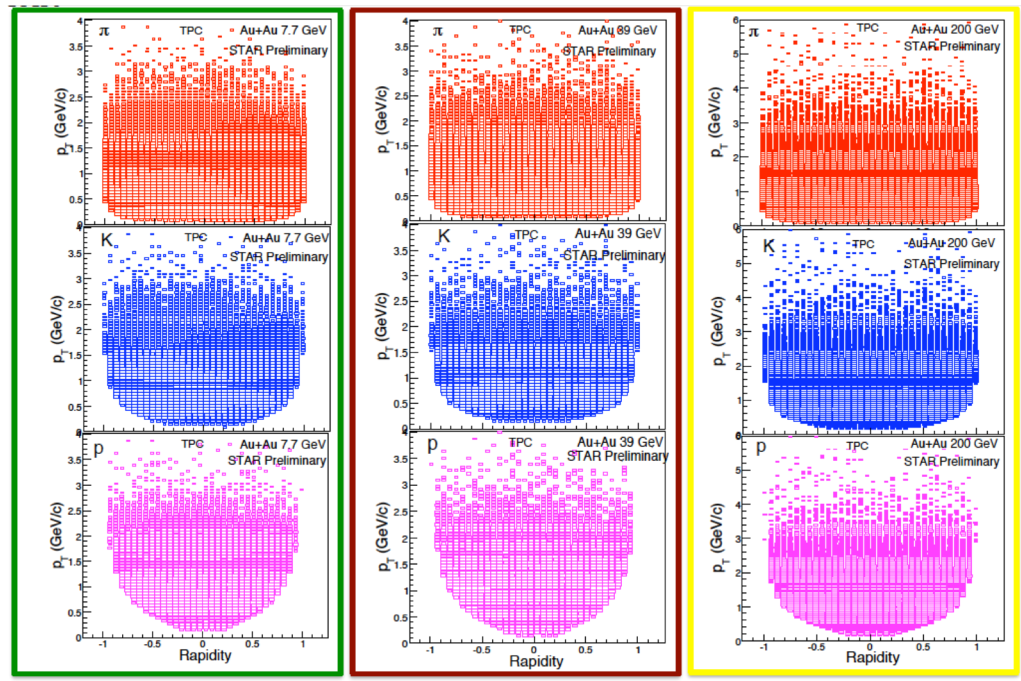
RHIC Beam Energy Scan-I (2010-2014)

Au+Au Collisions

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	*μ_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

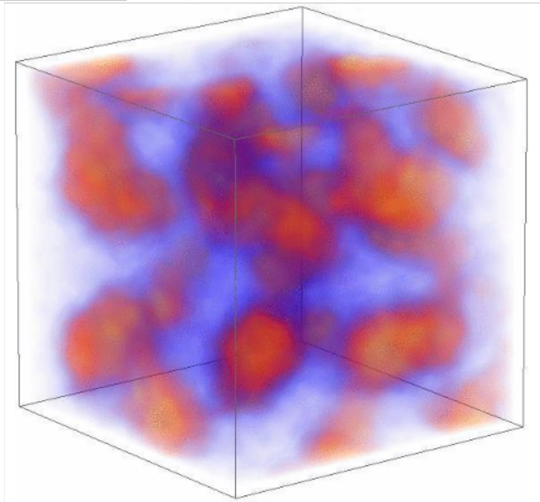
*(μ_B, T_{CH}) : J. Cleymans et al., PRC 73, 034905 (2006)

Uniform acceptance at Mid-rapidity



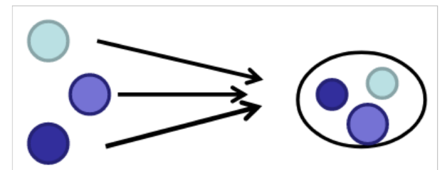
➢ Access the QCD phase diagram: vary collision energies/centralities.
RHIC BES-I : 20 < μ_B < 420 MeV

Sensitive observables !



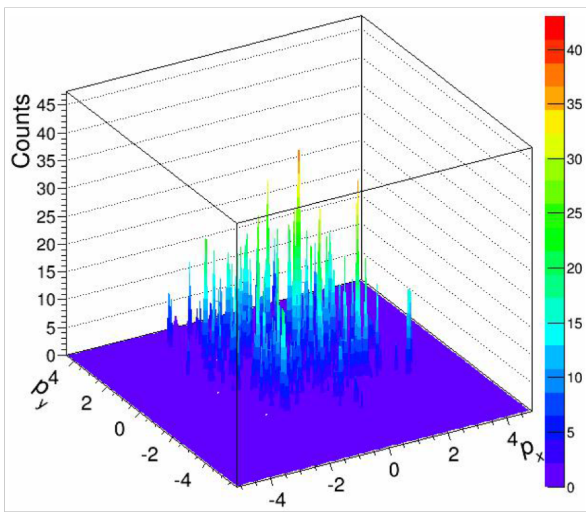
In the vicinity of critical point

Large density fluctuations and long range corr.



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

Baryon clustering: light nuclei production



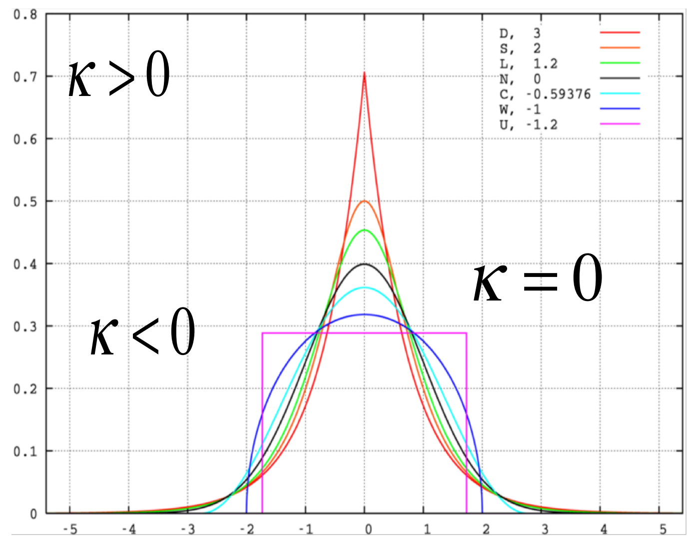
Experimental Signatures:

Non-monotonic variation as a function of collision energy.

Higher Moments of Conserved Quantities

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*)



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

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

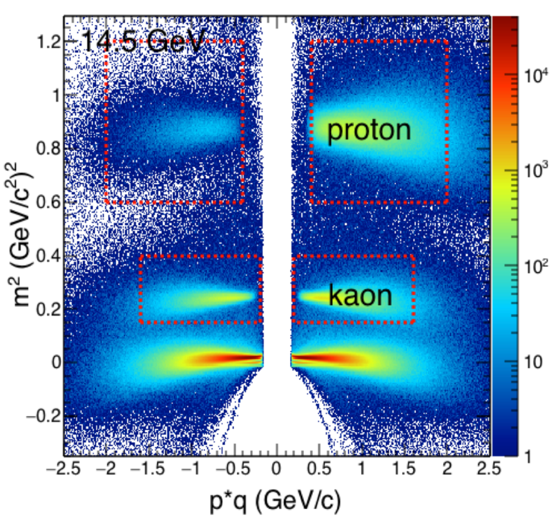
$$\frac{C_{3,q}}{C_{2,q}} = S\sigma \propto \xi^{9/4}$$

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

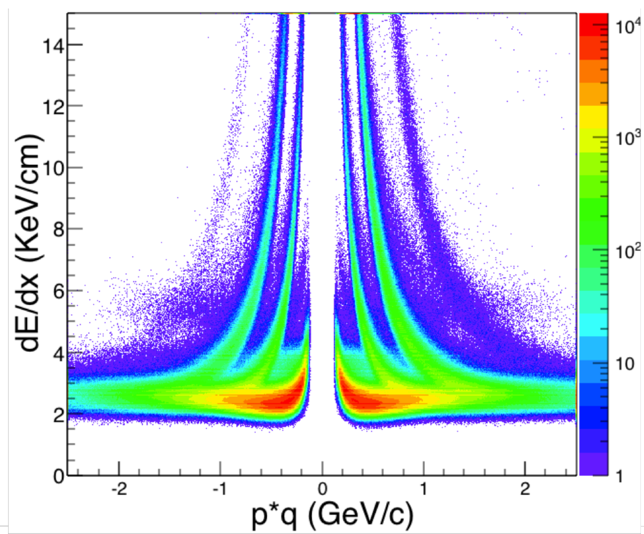
Analysis Details

	Net-Charge	Net-Proton	Net-Kaon
Kinematic cuts	$0.2 < p_T$ (GeV/c) < 2.0 $\lvert\eta\rvert < 0.5$	$0.4 < p_T$ (GeV/c) < 2.0 $\lvert y\rvert < 0.5$	$0.2 < p_T$ (GeV/c) < 1.6 $\lvert y\rvert < 0.5$
Particle Identification	Reject protons form spallation for $p_T < 0.4$ GeV/c	$0.4 < p_T$ (GeV/c) < 0.8 → TPC $0.8 < p_T$ (GeV/c) < 2.0 → TPC+TOF	$0.2 < p_T$ (GeV/c) < 0.4 → TPC $0.4 < p_T$ (GeV/c) < 1.6 → TPC+TOF
Centrality definition, → *to avoid auto-correlations*	Uncorrected charged primary particles multiplicity distribution	Uncorrected charged primary particles multiplicity distribution, without (anti-)protons	Uncorrected charged primary particles multiplicity distribution, without (anti-)kaons
	$0.5 < \lvert\eta\rvert < 1.0$	$\lvert\eta\rvert < 1.0$	$\lvert\eta\rvert < 1.0$

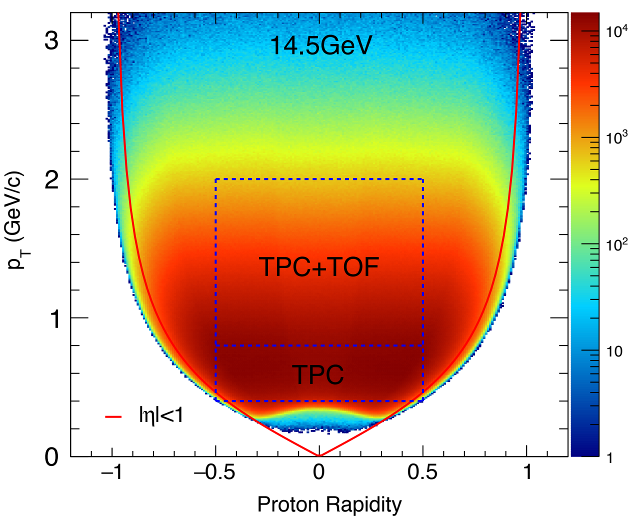
TOF PID



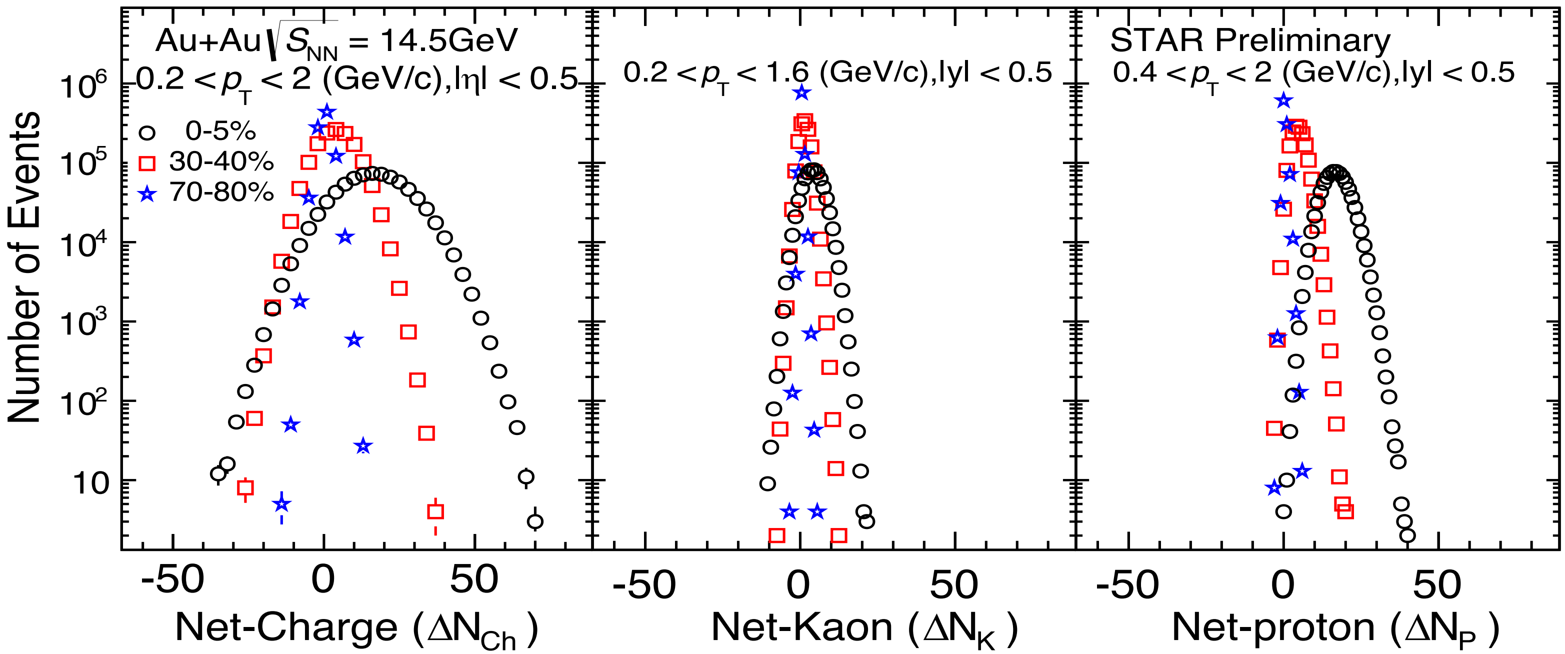
TPC PID



Phase Space



Data Analysis Methods



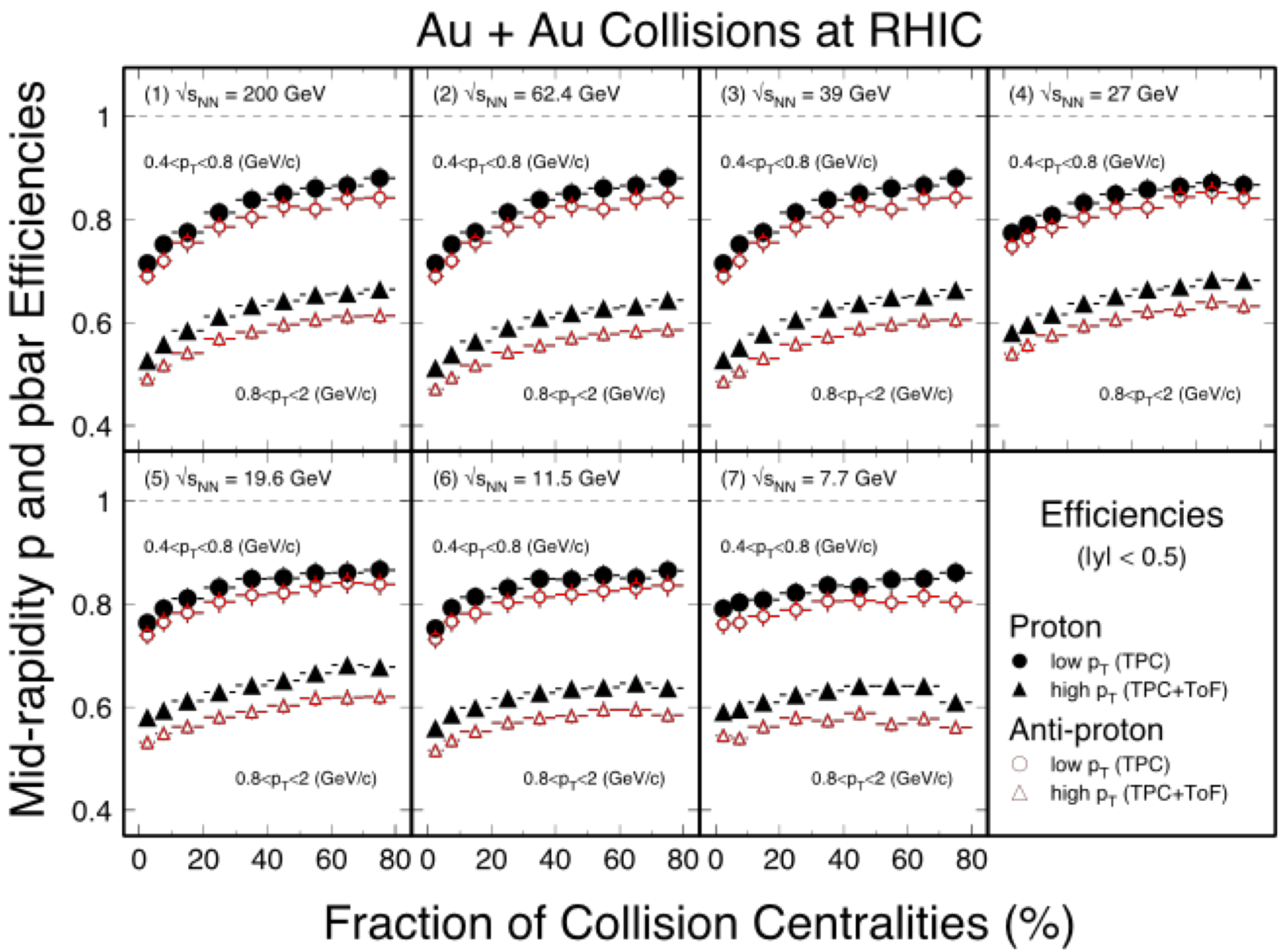
Analysis Methods used in the STAR coll.

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).

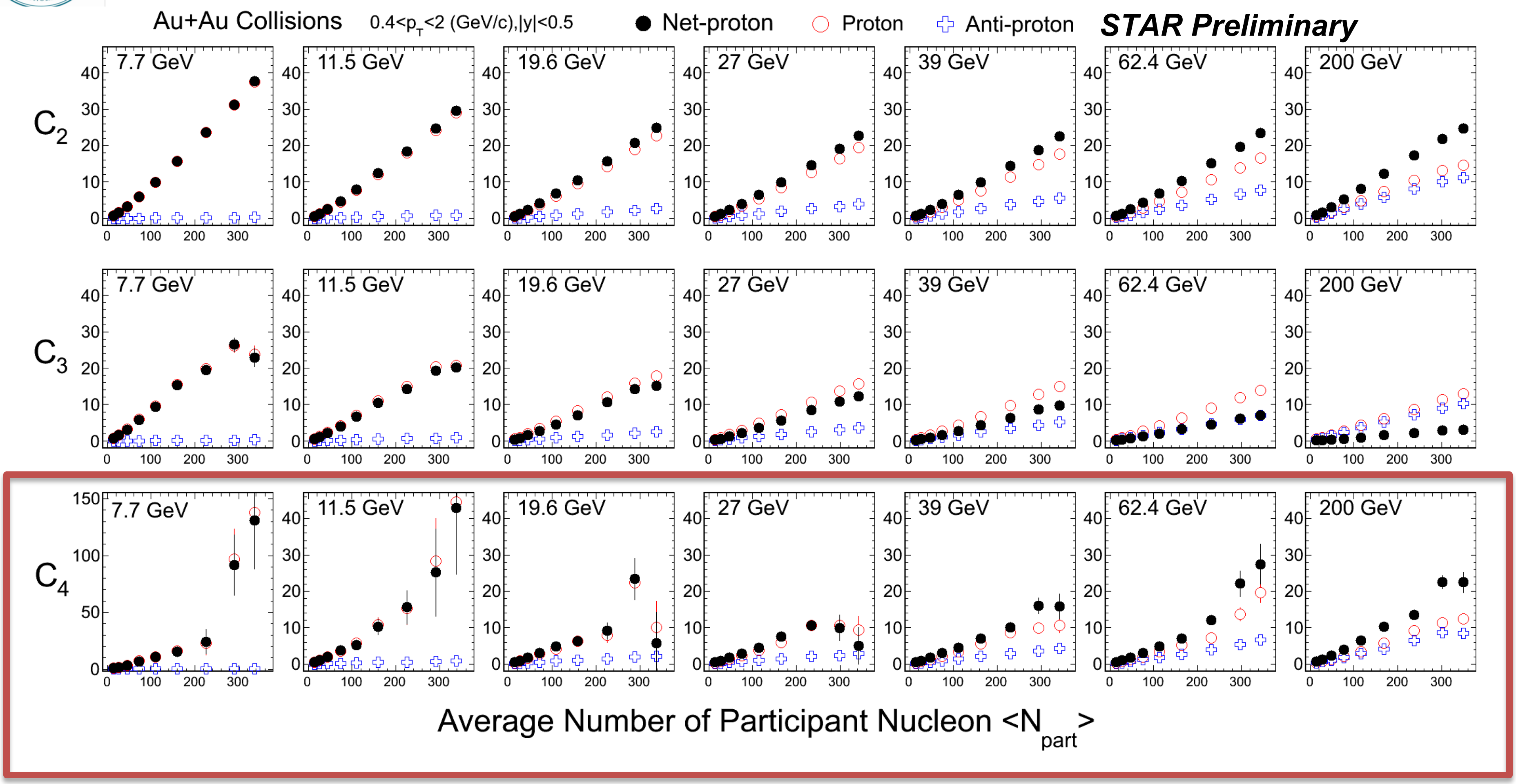
X.Luo, J. Phys. G 39, 025008 (2012); *A. Bzdak and V. Koch, PRC86, 044904 (2012); X.Luo, et al. J. Phys. G40,105104(2013); X.Luo, Phys. Rev. C 91, 034907 (2015); A . Bzdak and V. Koch, PRC91, 027901 (2015). T. Nonaka et al., PRC95, 064912 (2017). M. Kitazawa and X. Luo, PRC96, 024910 (2017). X. Luo, T. Nonaka, PRC99, 044917 (2019);*

(Anti-) Proton Acceptance and Efficiencies



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

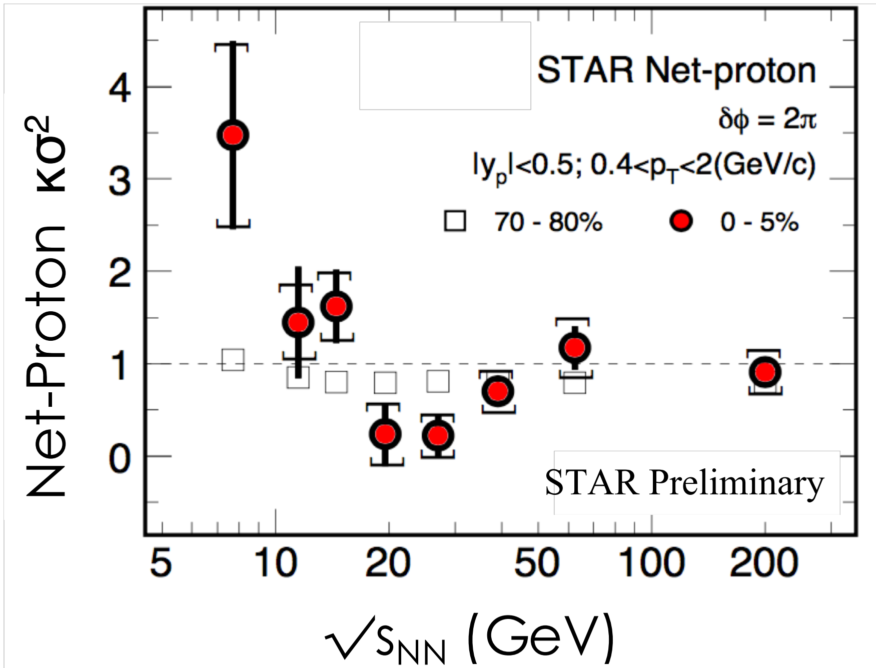
Higher Order Cumulants for Net-p, p, pbar



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

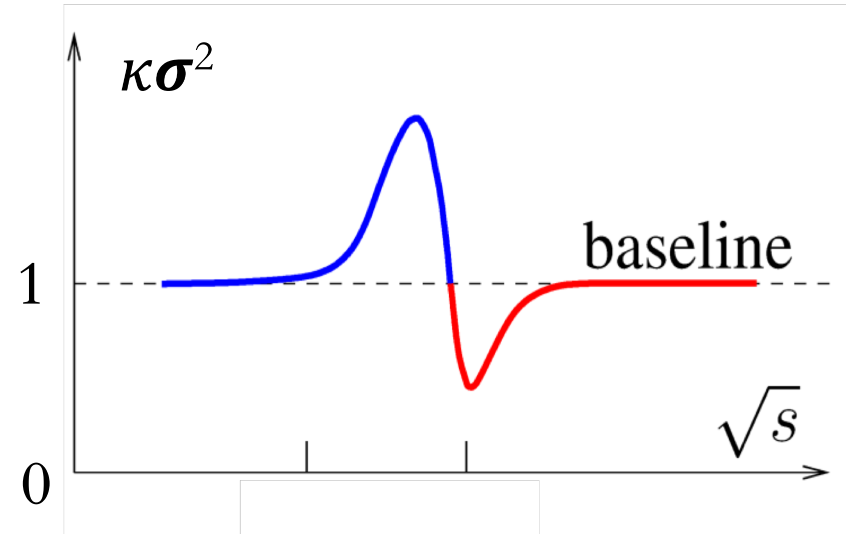
Net-Proton Fluctuations

Experimental Measure



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

Theoretical Prediction

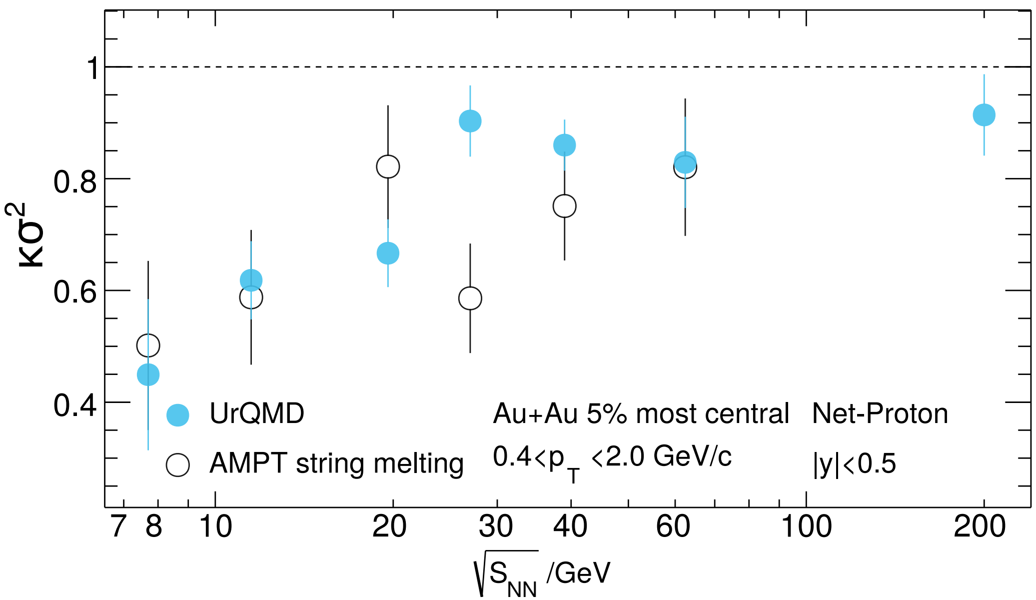


M. Stephanov, PRL107, 052301(2011)

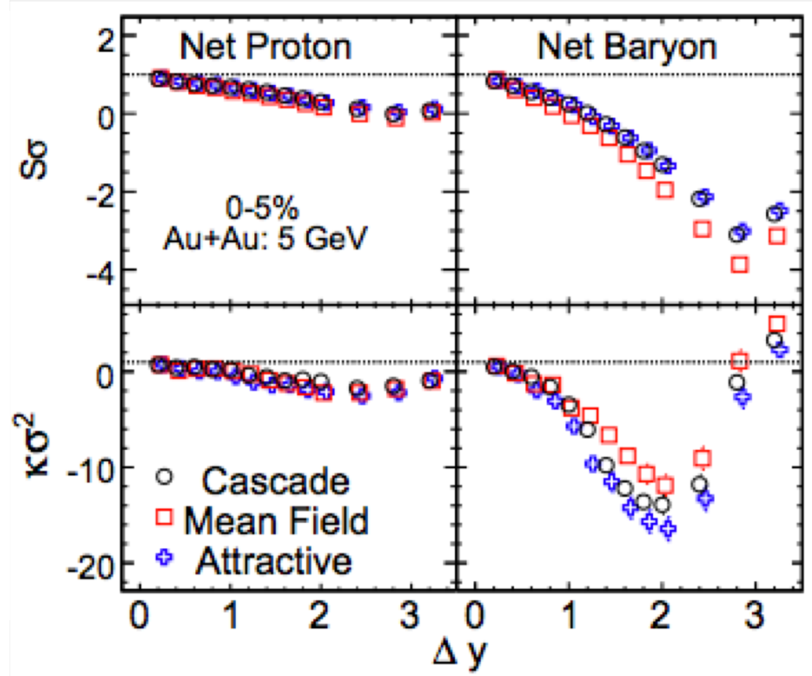
First observation of non-monotonic energy dependence.
Hint of entering critical region.

Non-critical Contributions: Transport Model Studies

UrQMD and AMPT models



JAM model



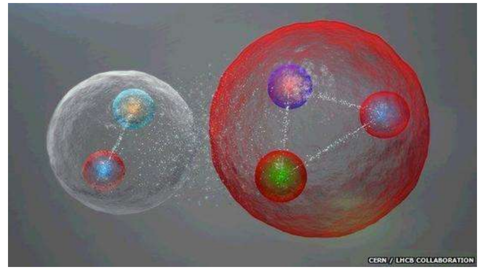
- Transport model (no CP physics) results show monotonic energy dependence: dominated by baryon number conservations

- 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).

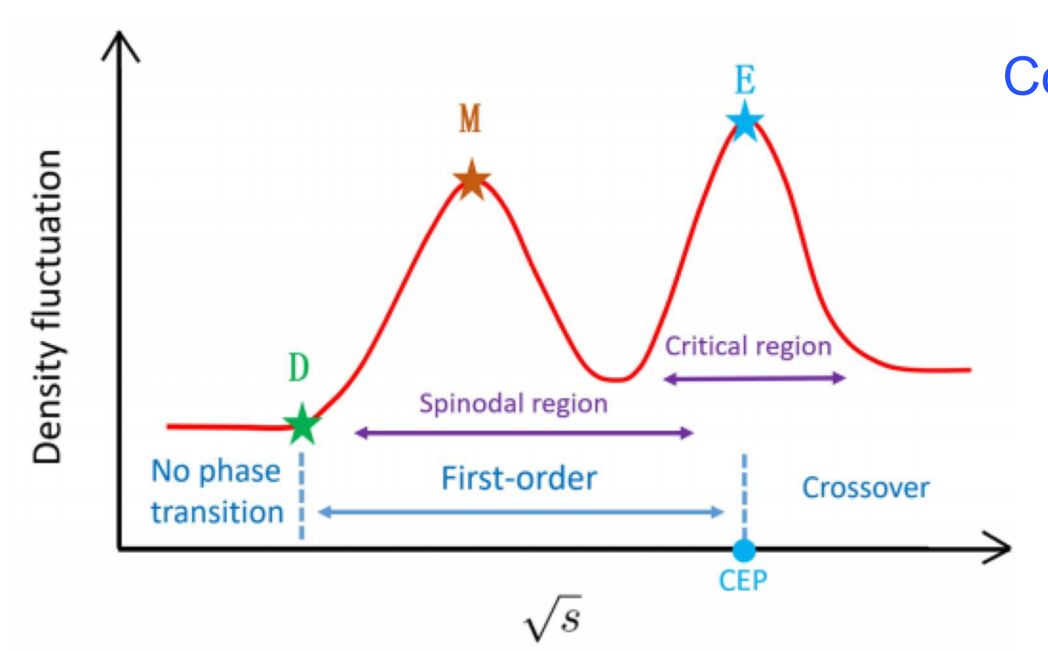
New Observable for CP: Light Nuclei Production

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



Light nuclei production

(Baryon Clustering)



Coalescence + nucleon density flu.

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

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

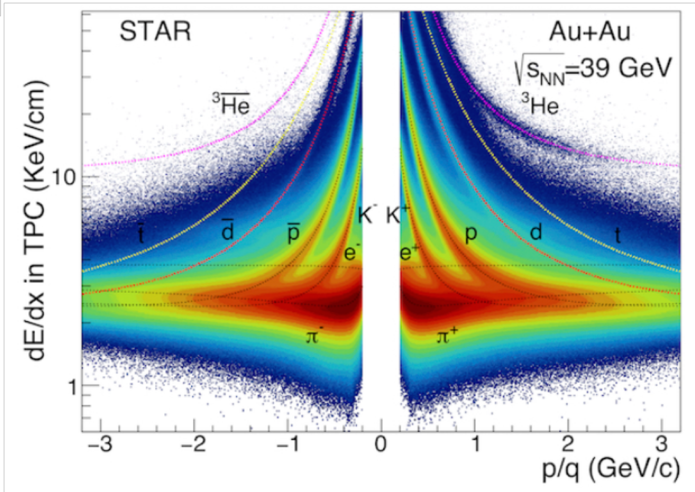
$$N_t \cdot N_p / N_d^2 \approx g(1+\Delta n)$$

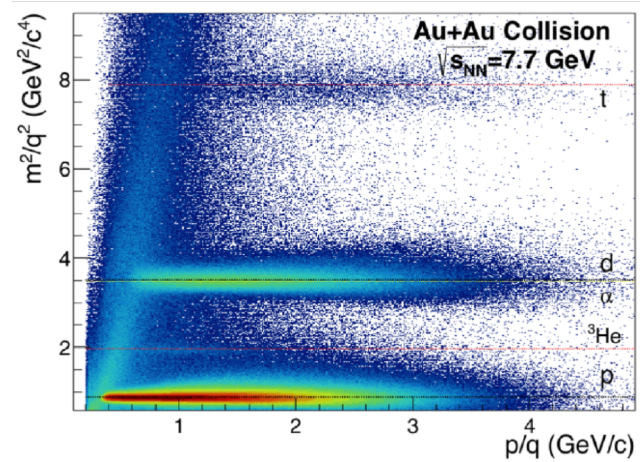
Neutron density fluctuations:

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

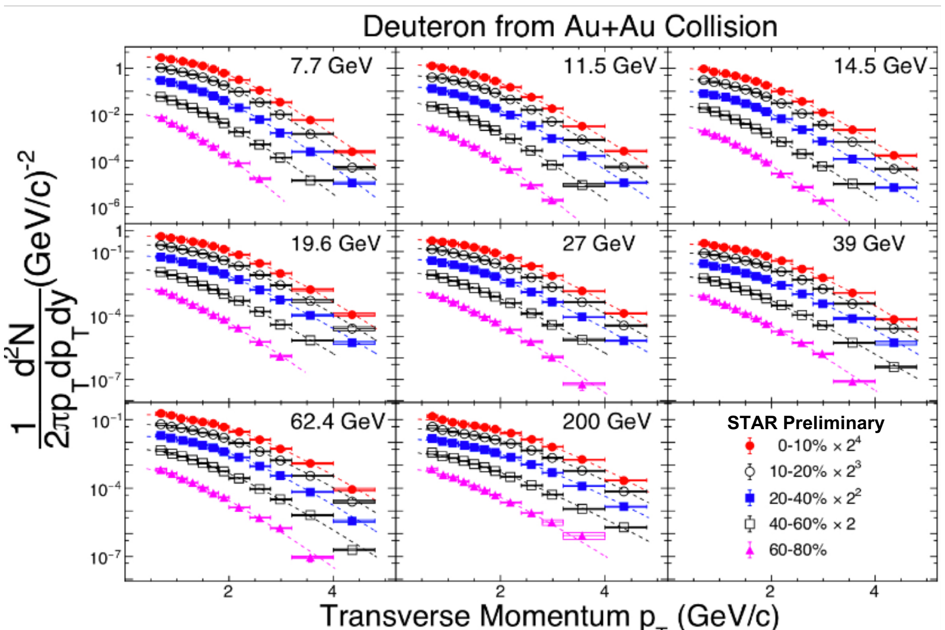
K. J. Sun，L. W. Chen, C. M. Ko, Z. Xu, Phys. Lett. B774, 103 (2017).
K. J. Sun，L. W. Chen, C. M. Ko, J. Pu, Z. Xu, Phys. Lett. B781, 499 (2018).
Edward Shuryak and Juan M. Torres-Rincon, arXiv:1805.04444

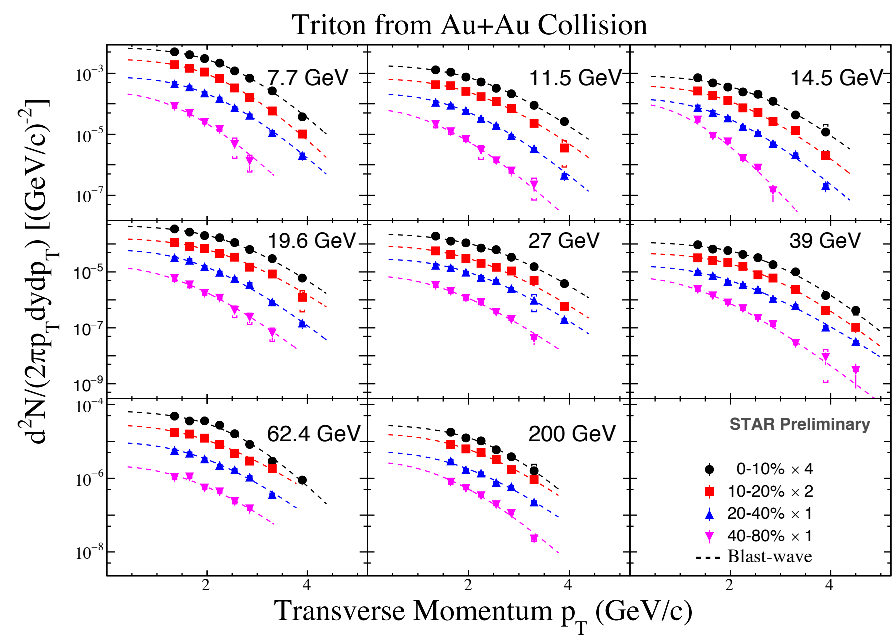
Deuteron and triton production from BES-I at RHIC



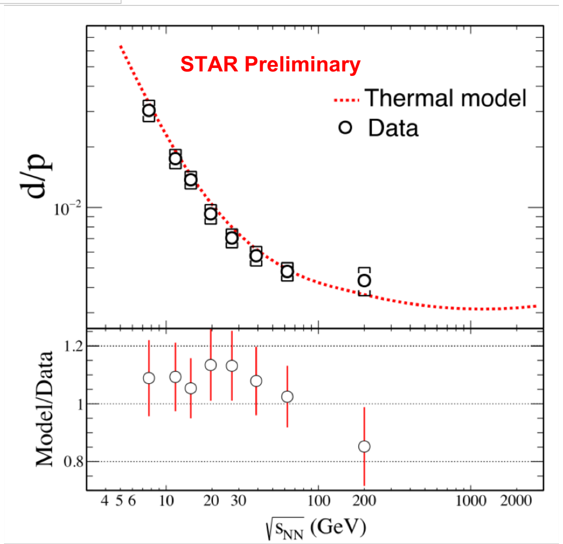


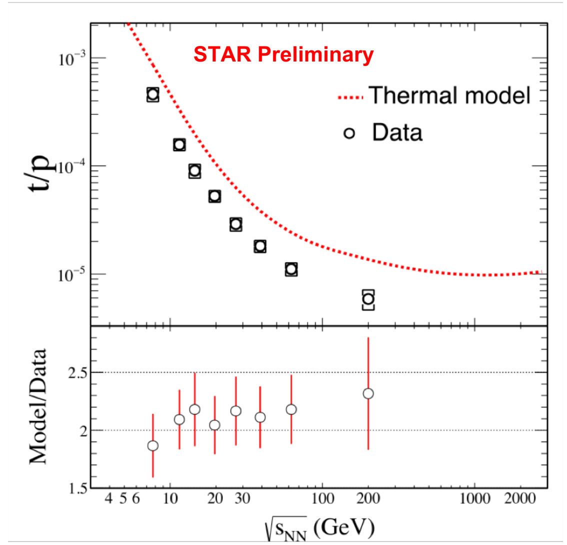
STAR, arXiv: 1903.11778

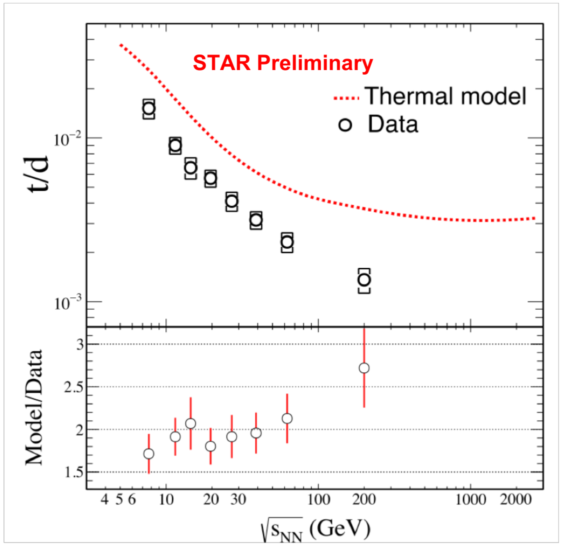




Light Nuclei Yield Ratio Vs. Thermal model







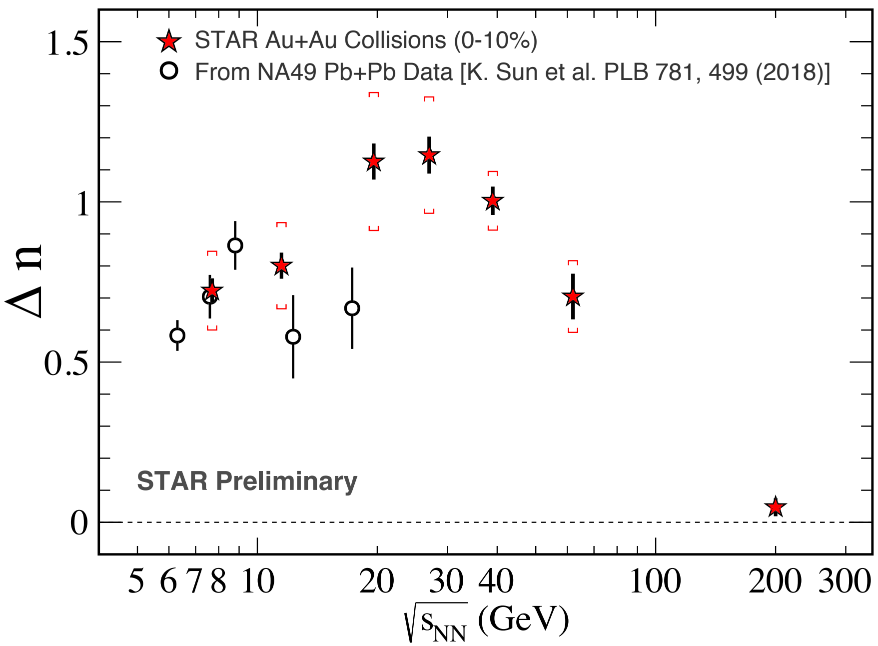
➢ At RHIC energies, thermal model can describe the d/p ratios, but can not describe the t/p, t/d ratios.

➢ If deuteron is formed at very late stage via nucleon cola., why it can be described by thermal model ?

Neutron 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.

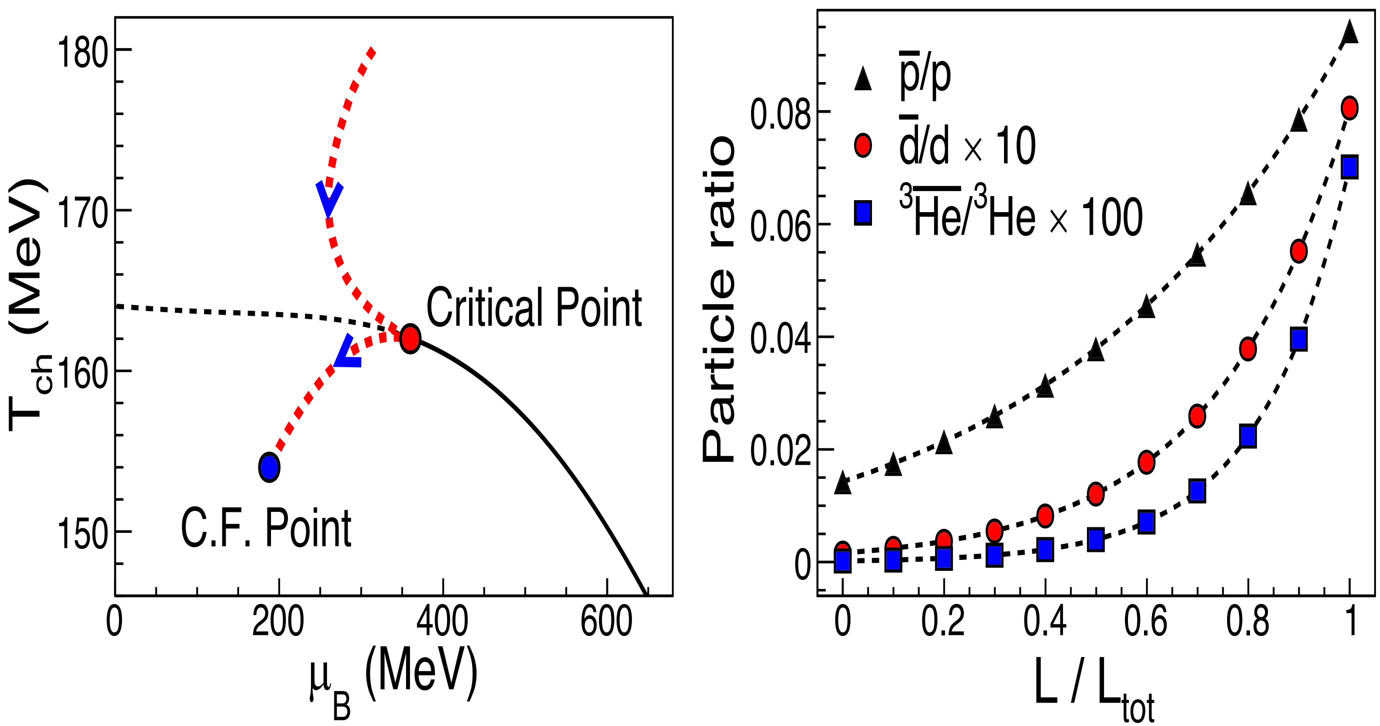
Peak around 20 GeV.

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)

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)



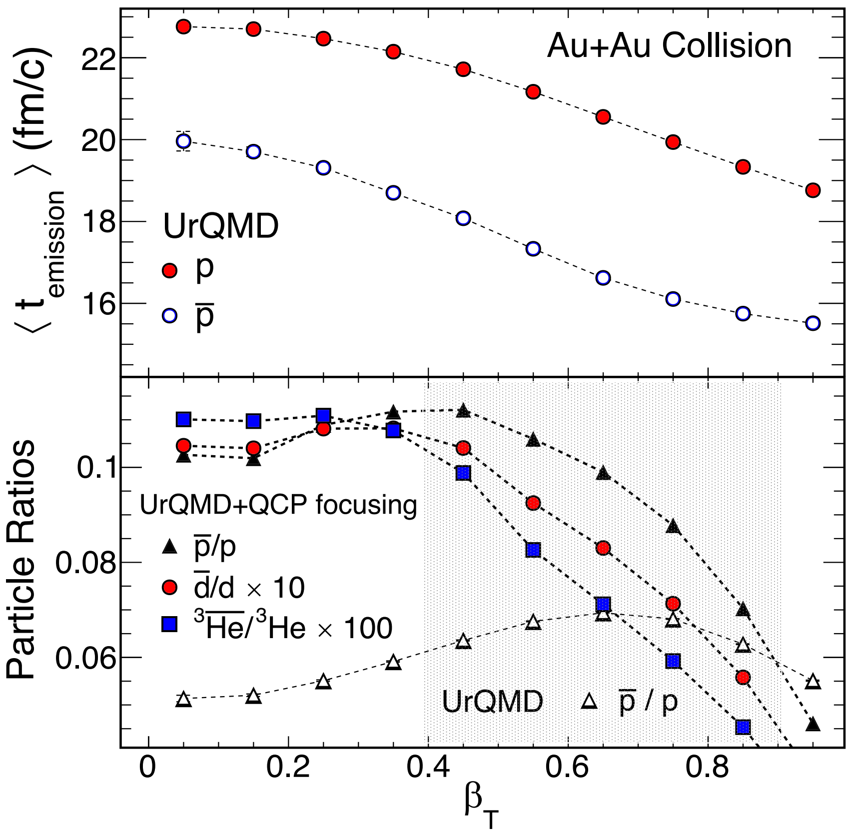
$t = L/L_{tot}$

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.

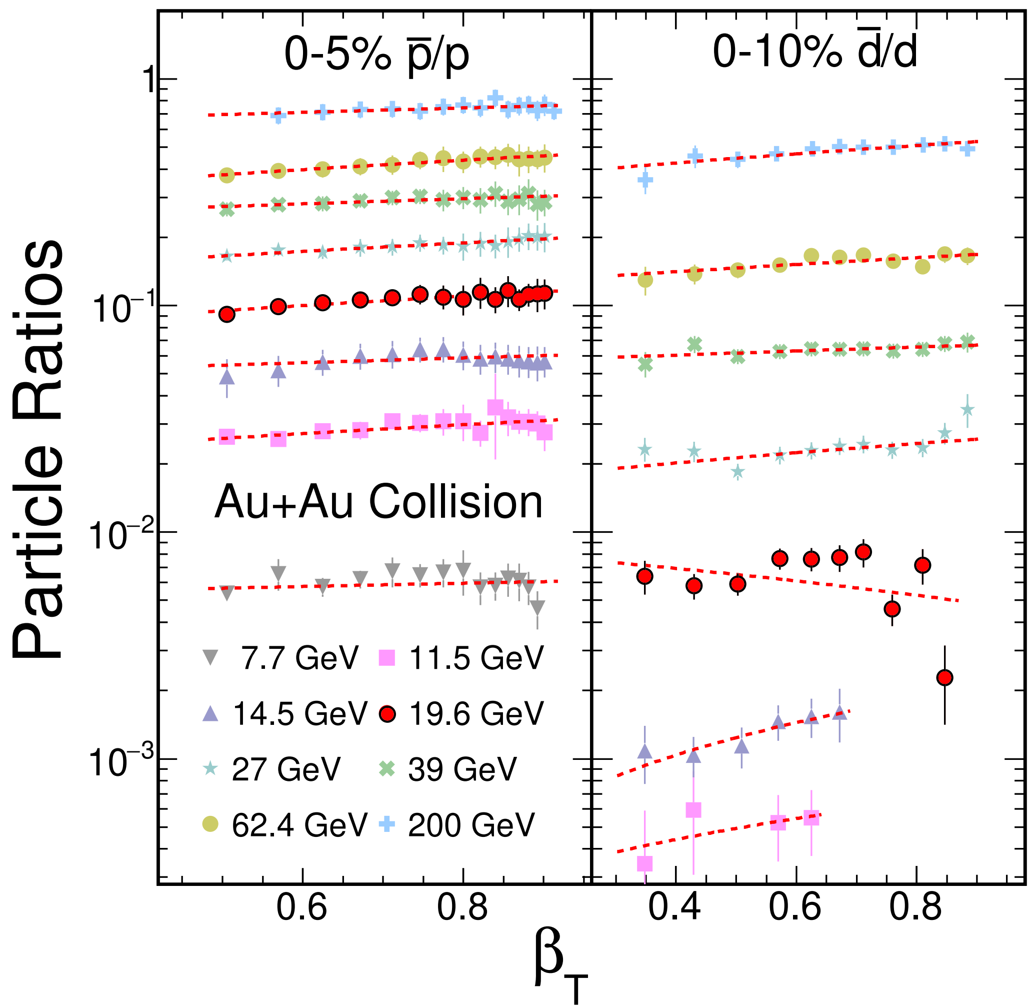


- ➢ The $\bar{p}/p$, $\bar{d}/d$, and $^3\overline{\mathrm{He}}/\mathrm{He}$ **decrease with increasing β_T** with QCP focusing effect.
- ➢ This behavior is more easier to be observed for heavier particles

Can we observe the QCP focusing effects in HIC experiment ?

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

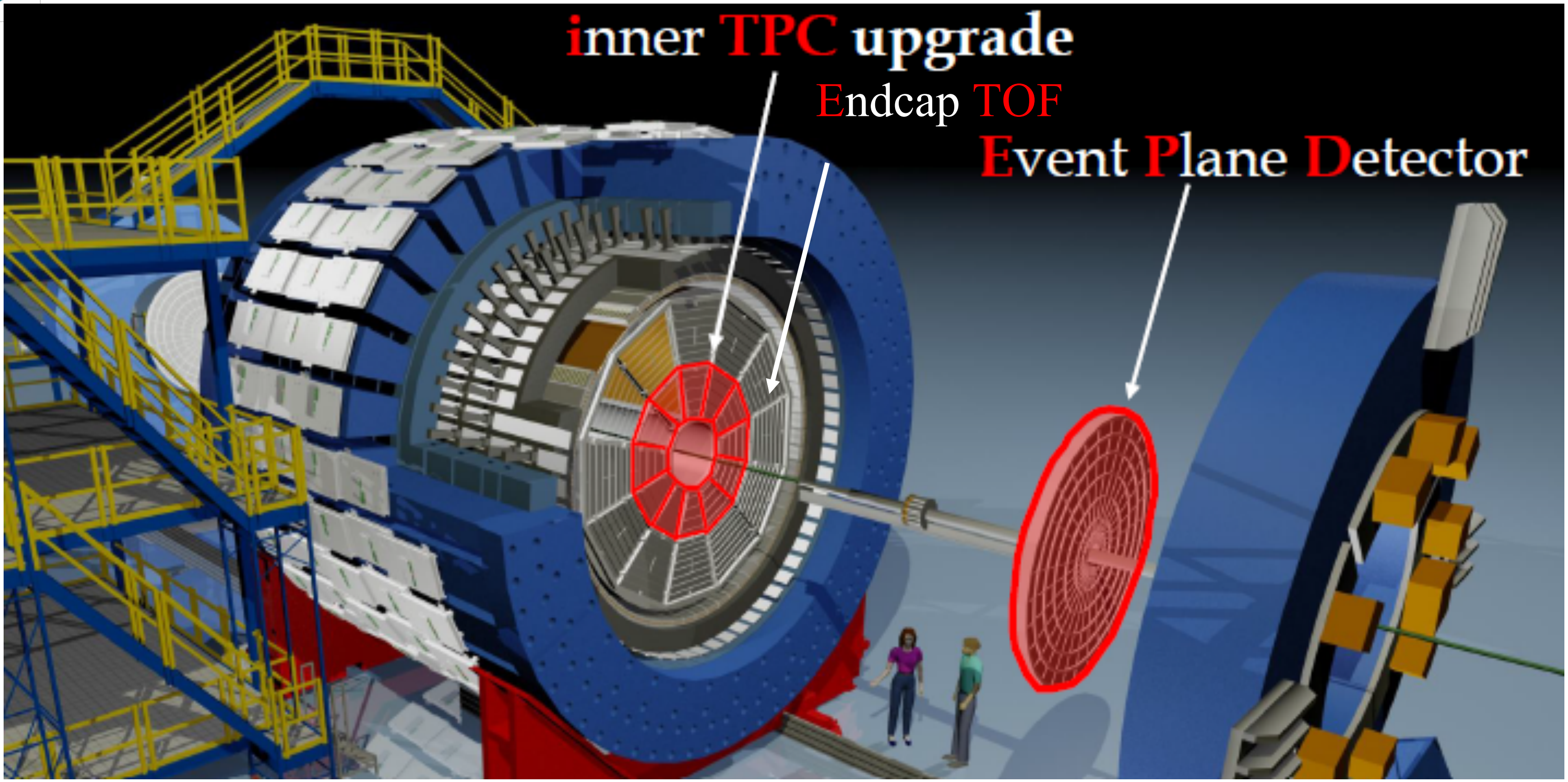
Transverse velocity dependence of dbar/d ratio



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

We observe anomalous for dbar/d ratio at 19.6 GeV measured by STAR.

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

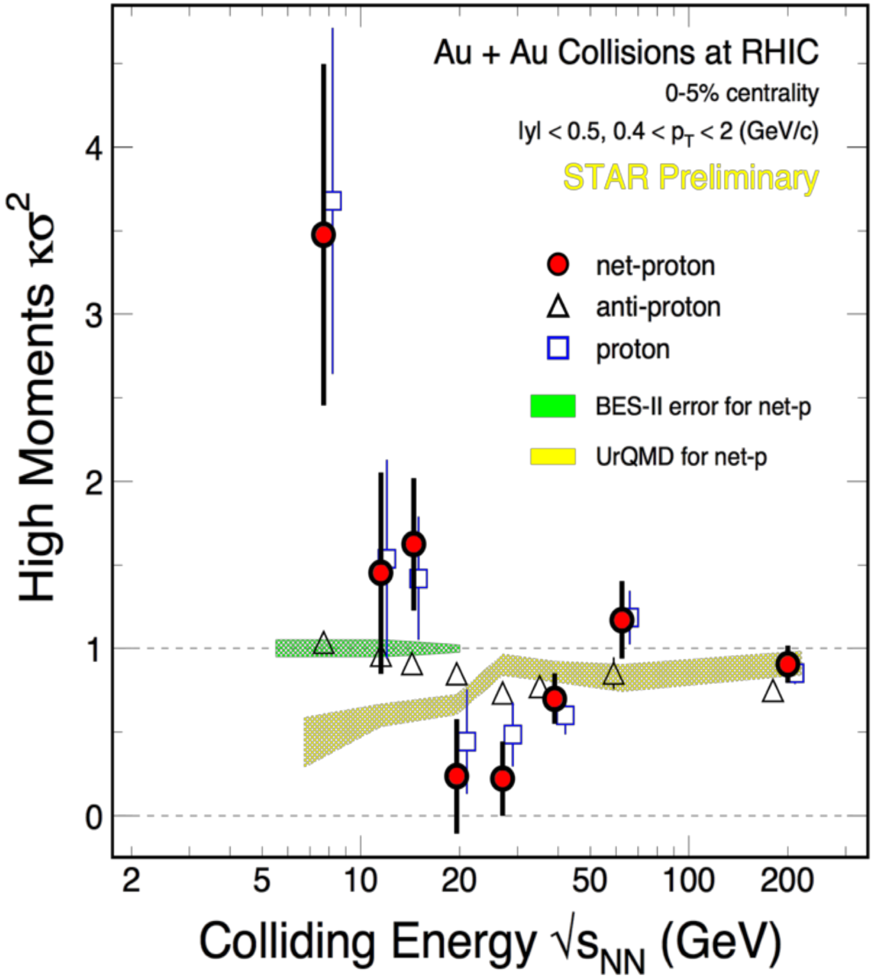


iTPC, EPD, eTOF Upgrade complete
Dedicated runs at : 2019-2021

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

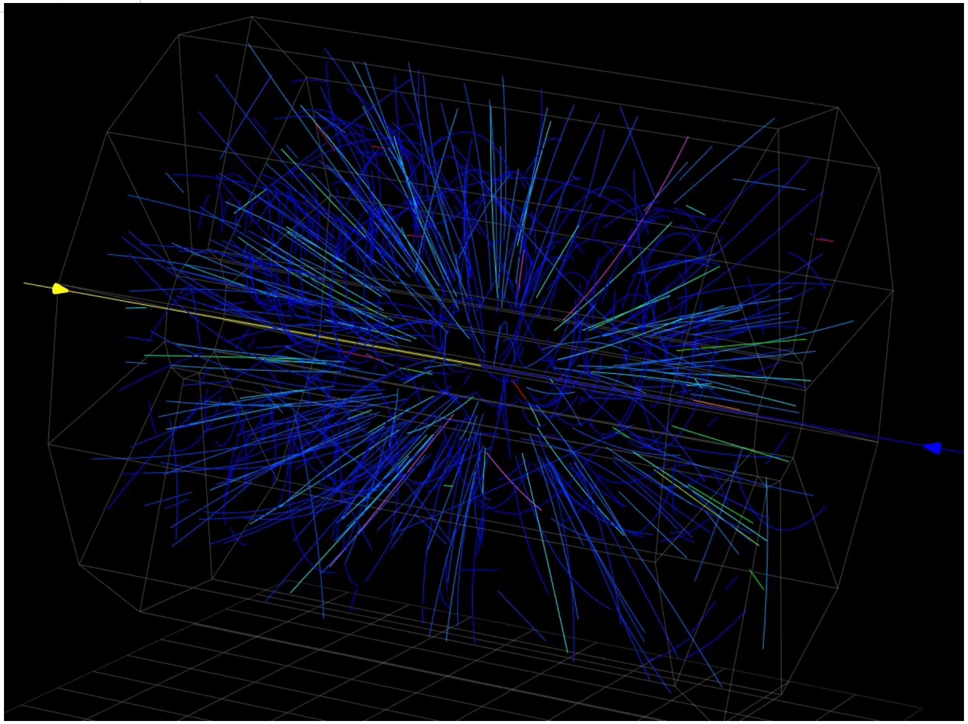
BES-II at RHIC (2019-2021)

$\sqrt{s_{NN}}$ (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

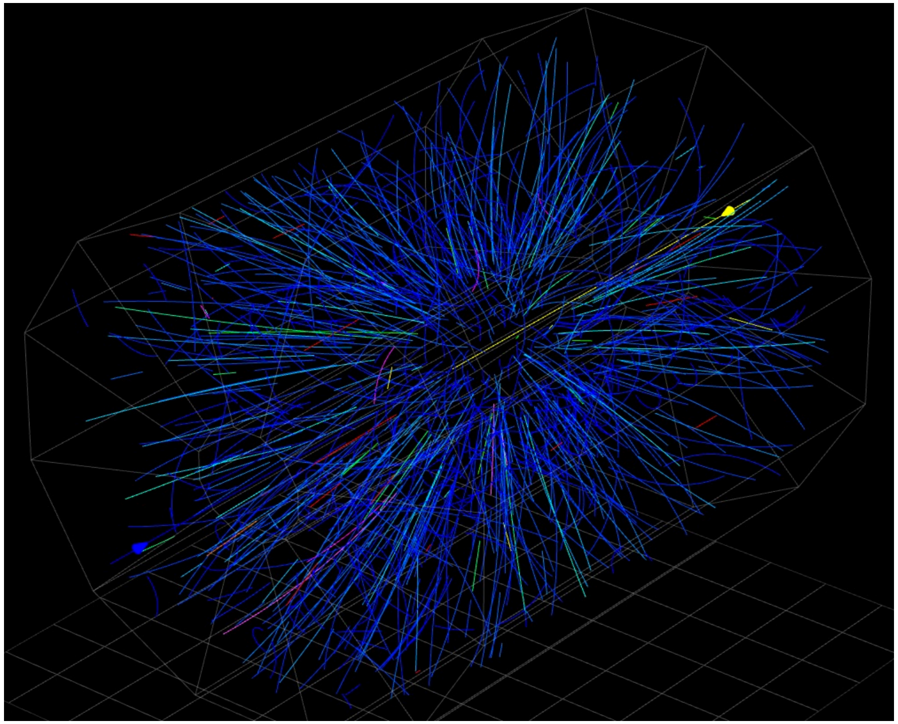


BES-II 19.6 GeV data taking is finished and now is taking 14.5 GeVdata.

3D Event Display in TPC at STAR



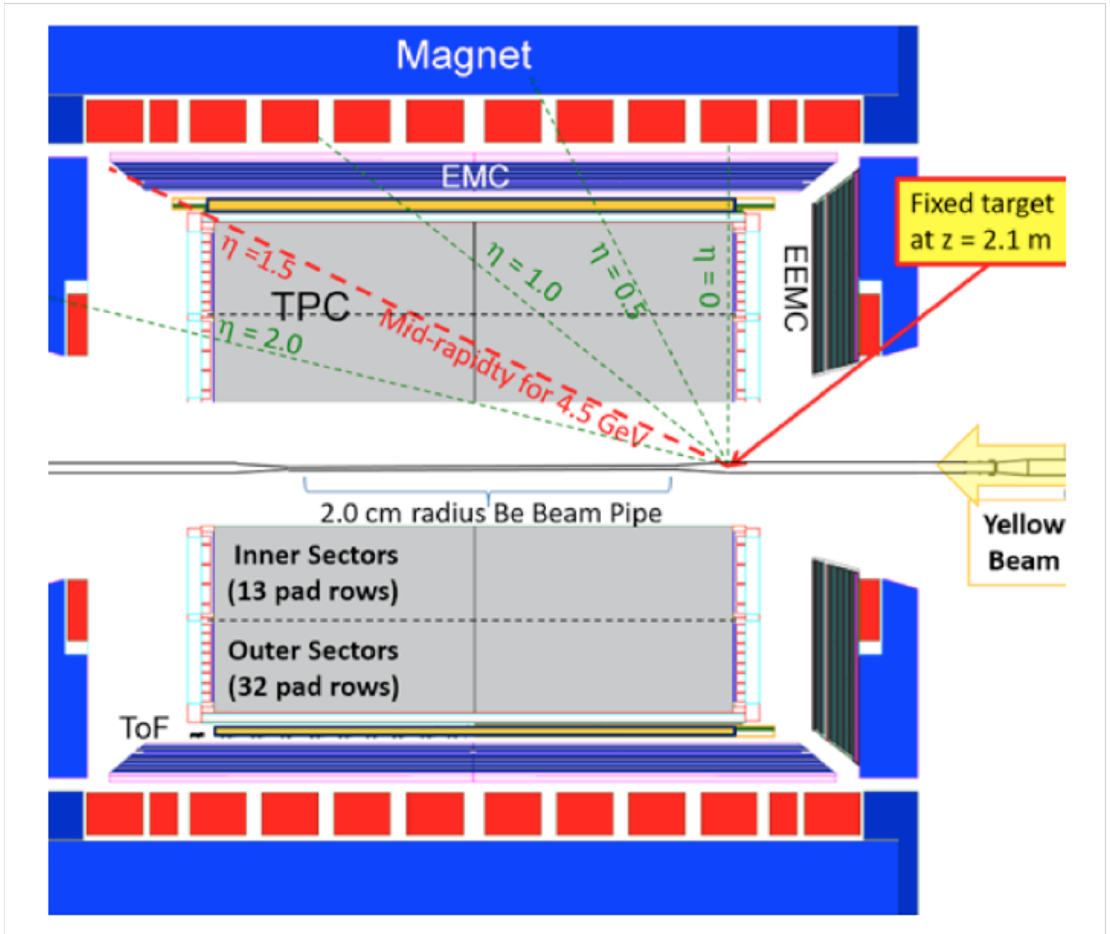
Au+Au collisions at 19.6 GeV.

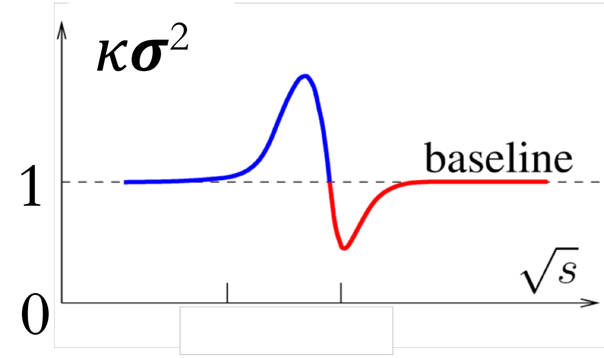


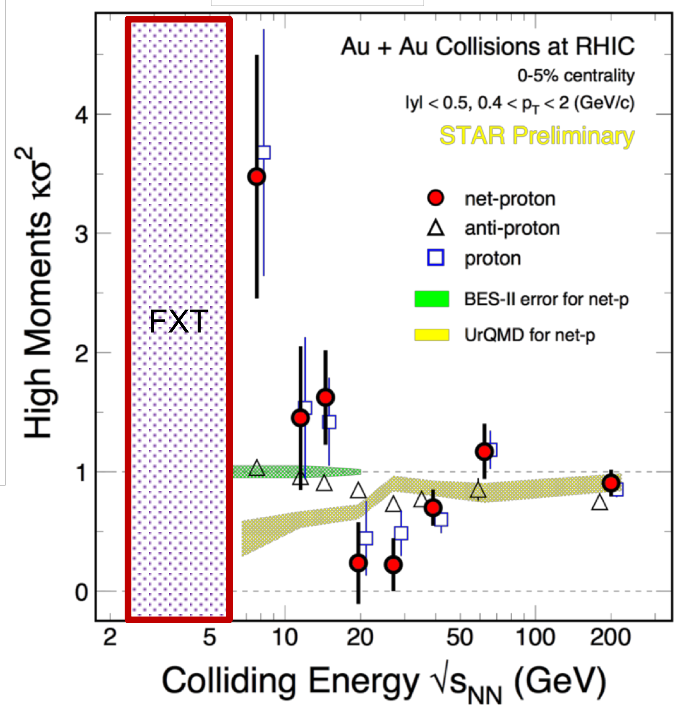
Au+Au collisions at 14.5 GeV.

BES-II data taking is ongoing !

FXT Experiments at STAR (2018-2020)







FXT Data Taking Plan：
2018: Au+Au :3 GeV (>100 million events)
2019-2020: Au+Au: 7.3, 6.2, 5, 4.5, 4, 3.5 GeV

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.

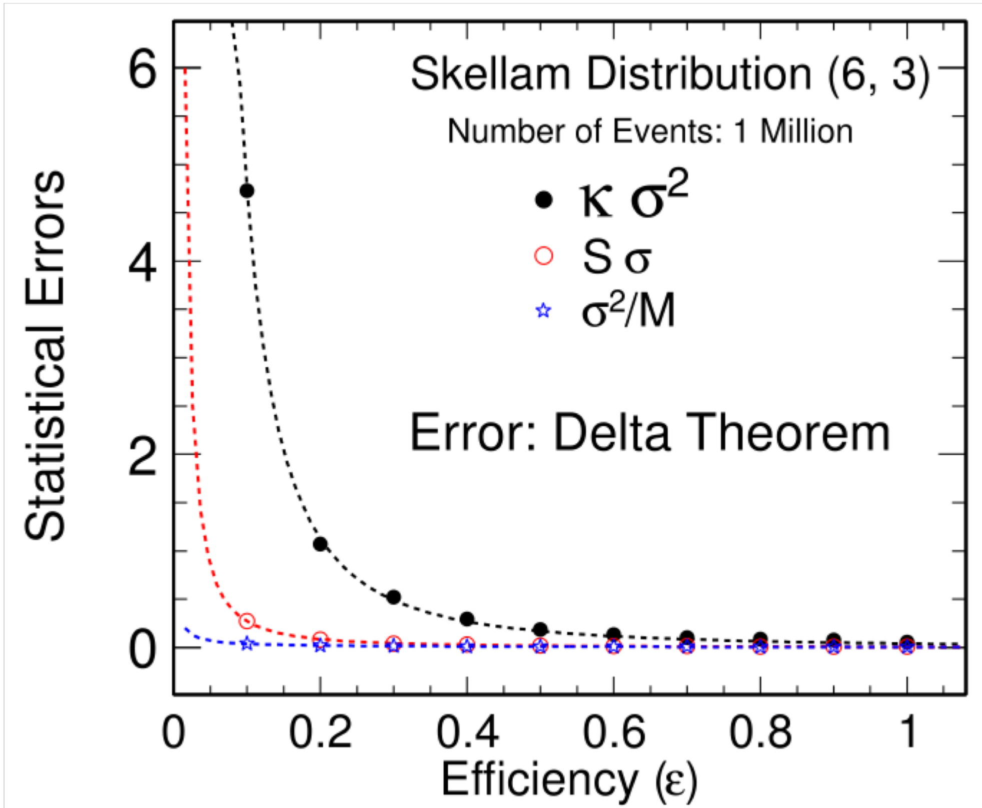
- Neutron density fluctuations in 0-10% central Au+Au collisions shows non-monotonic energy dependence with a peak around 20-30 GeV. Hint of entering the critical region.

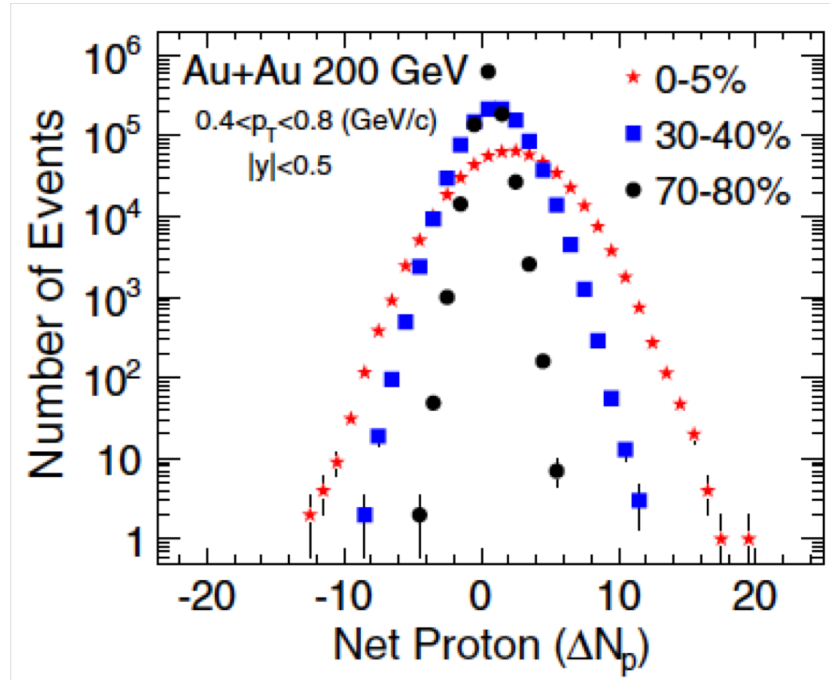
- In BES-II, we can study the QCD phase structure with high precision at $\sqrt{s_{NN}}$ = 7.7-19.6 GeV (collider mode) and 3-7.3 GeV (Fix-target mode)

Stay tuned for RHIC BES-II !!

Thank you and congratulations to Prof. Che-Ming Ke for 50-year scientific career !

Statistical Errors Estimation and Properties



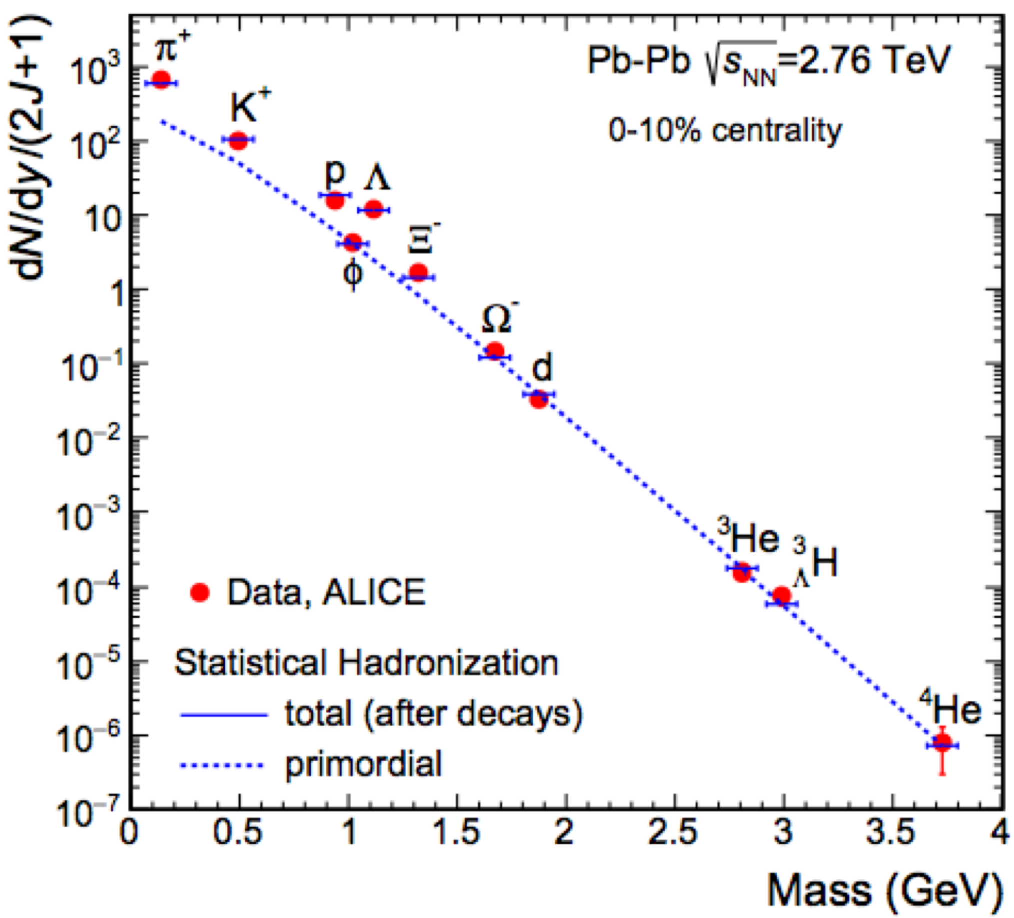


X. Luo, J. Phys. G 39, 025008 (2012);
X. Luo, Phys. Rev. C 91, 034907 (2015);
X. Luo, T. Nonaka, Phys. Rev. C 99, 044917 (2019);

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

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

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).