Search for the QCD Critical Point :
Energy Dependence of Higher Moments of Net-proton and Net-charge Distributions at RHIC

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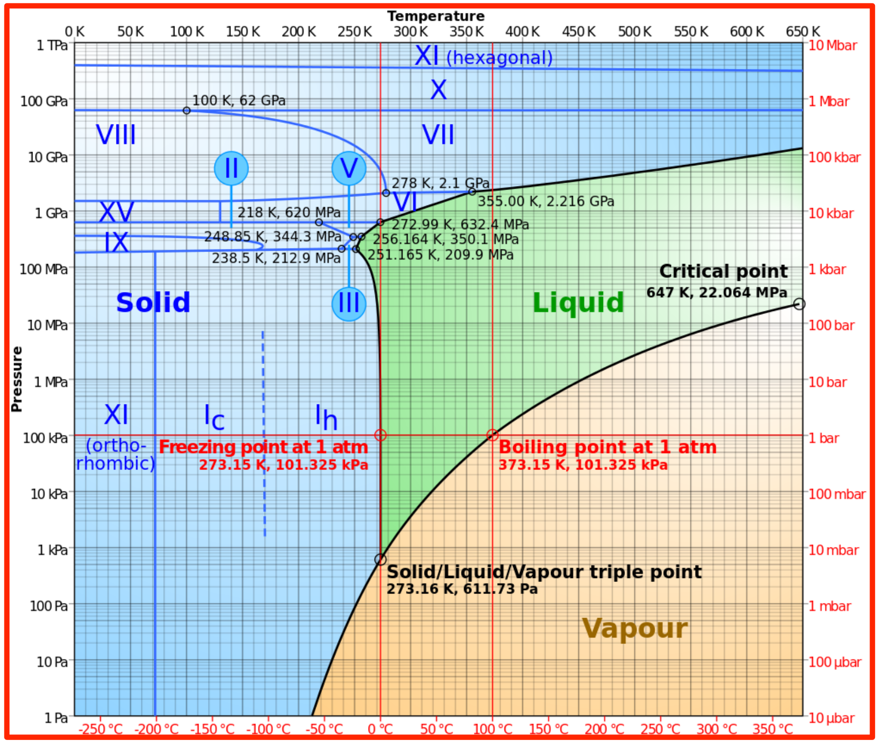
FAIRNESS

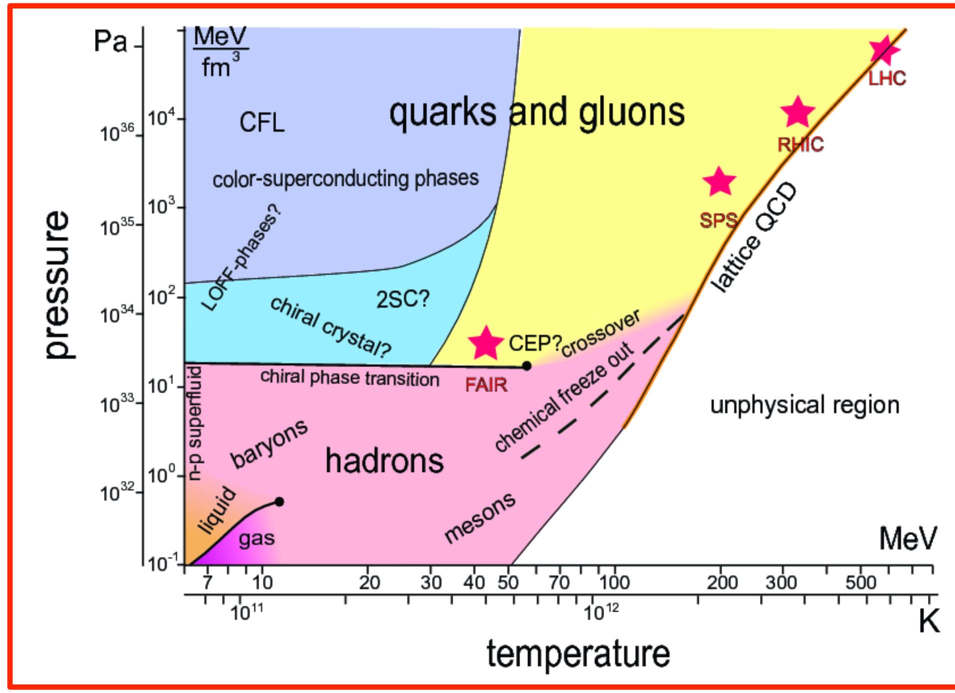
22 – 27 September 2014

Outline

- Introduction
- Results for Net-proton, Net-charge
- Outlook and Future Plan.
- Summary

Phase Diagram

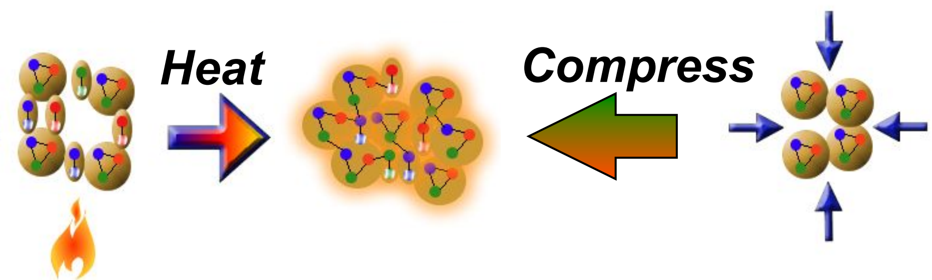




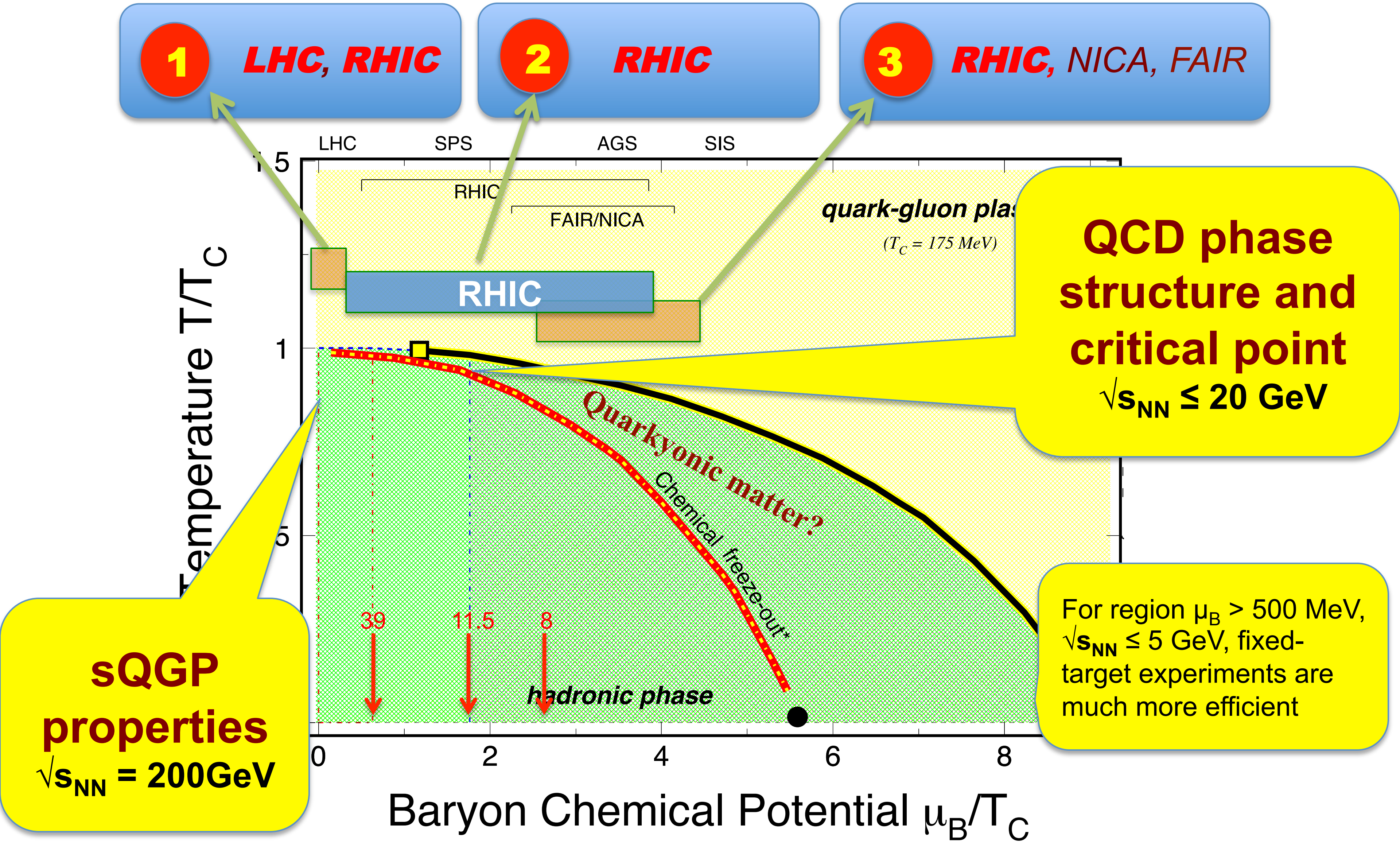
Water (EM Interaction)
(Preciously Known)

QCD Matter (Strong Interaction)
(Still Conjecture)

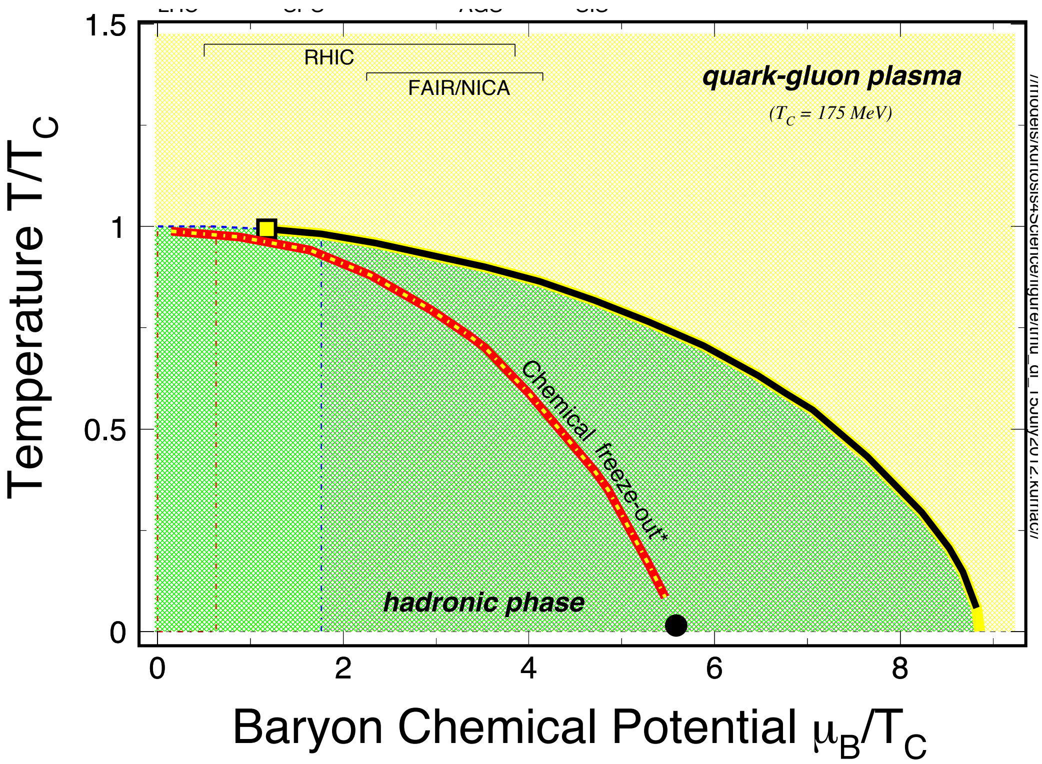
arXiv:1111.5475



Exploring the QCD Phase Structure



Search for the QCD Critical Point



S. Gupta, X. Luo, B. Mohanty, H.G. Ritter, and N. Xu, ***Science, 332, 1525 (2011).***

First time, using both experimental data and LGT results, fix the transition temperature at zero μ_B

Endpoint of the first order phase transition boundary.

Theory：Lattice QCD et al.
Experiment：HIC et al.

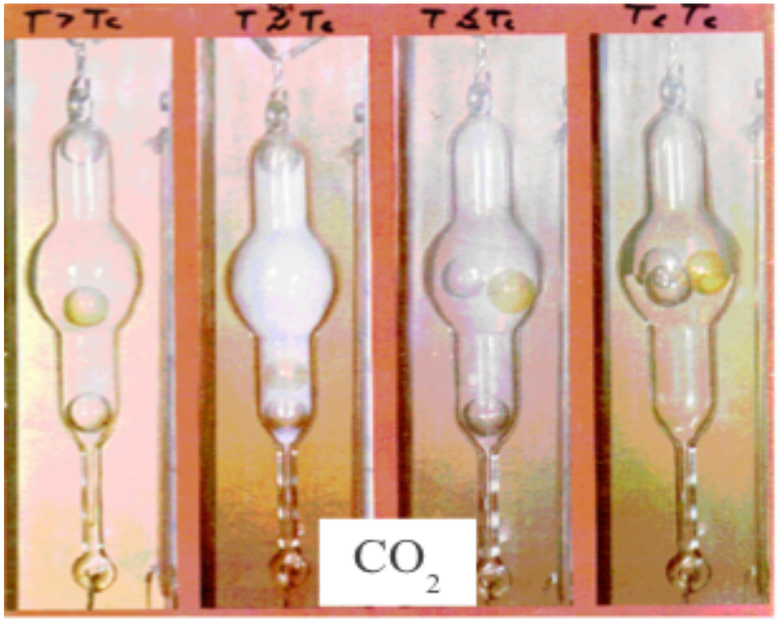
Create hot dense QCD matter. We have chance to find the CP experimentally.

Experimental discovery of the QCD critical point will be an excellent test of QCD theory in non-perturbative region and a landmark of the exploring the QCD phase structure.

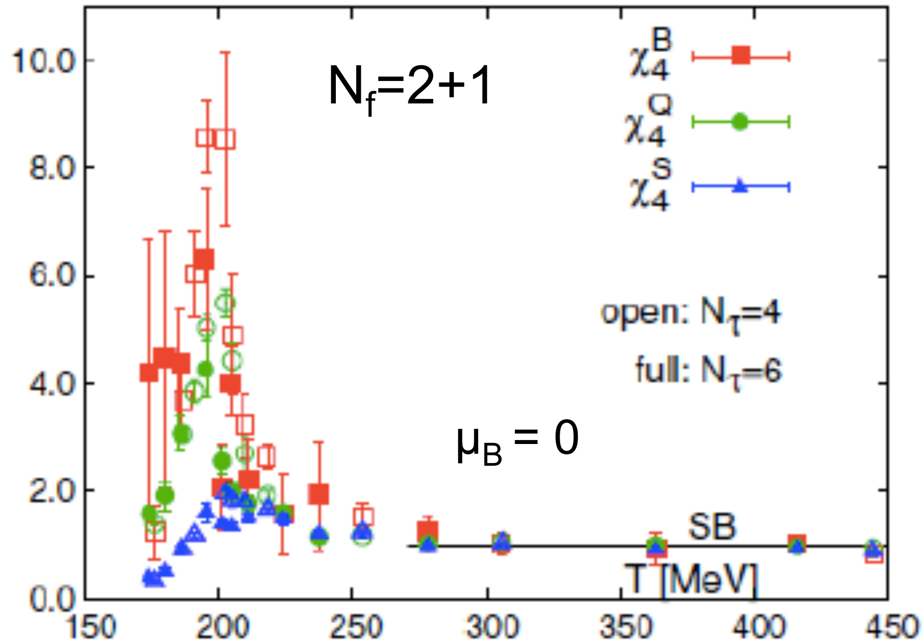
Critical Behavior near the Critical Point

At the Critical Point (CP): 2nd order phase transition.

Diverges of the correlation length (ξ), Susceptibilities (χ), etc.



Critical Opalescence :
"Cloudy" phenomena indicating long-range density fluctuations.



M. Cheng, et. al., PRD79, 074505 (2009).

Divergence of correlation length

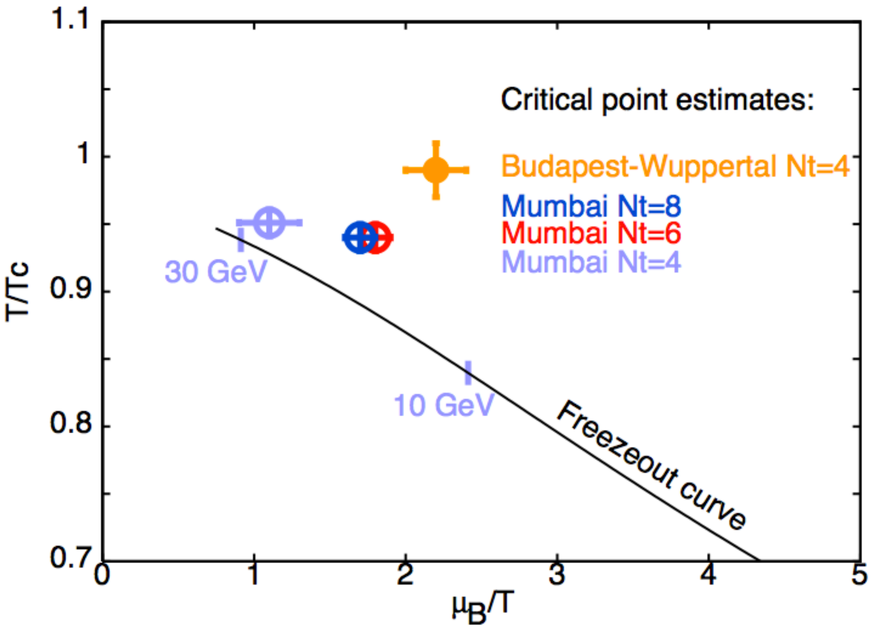
T. Andrews.
Phil. Trans. Royal Soc., 159:575, 1869.

Divergence of susceptibility.

(Affected by 2nd order chiral phase transition at vanishing baryon chemical potential.)

Location of CP：Recent Theory Prediction

Lattice QCD (N_f=2+1): Taylor Expansion

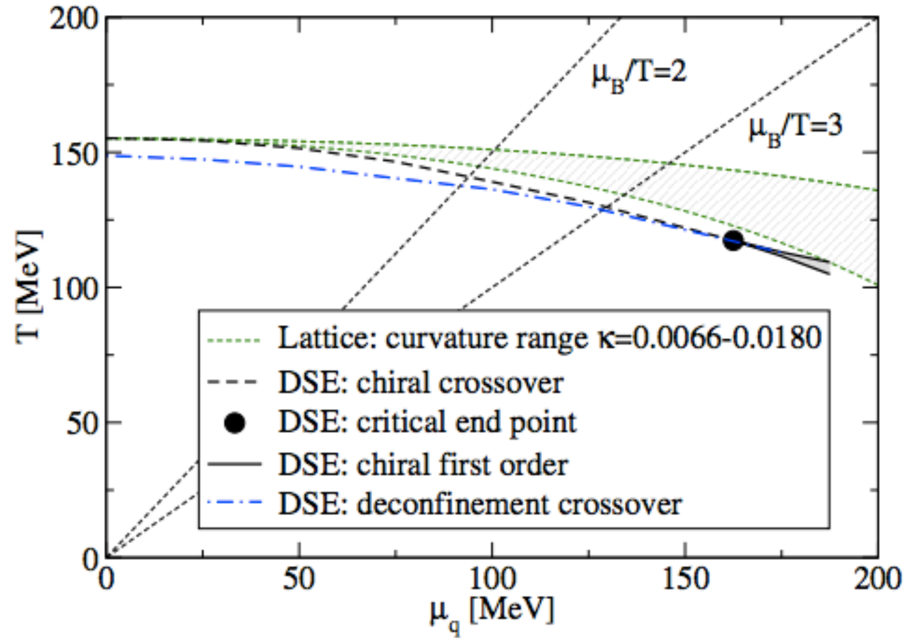


S. Datta, R. V. Gavai and S. Gupta, PoS (LATTICE 2013), 202 (2013).

$\mu^E_B/T^E \sim 1.7$

$\sqrt{s_{NN}}$ ~20 GeV

Dyson-Schwinger approach (N_f=2+1)



(Quark Chemical Potential)

arXiv:1405.4762

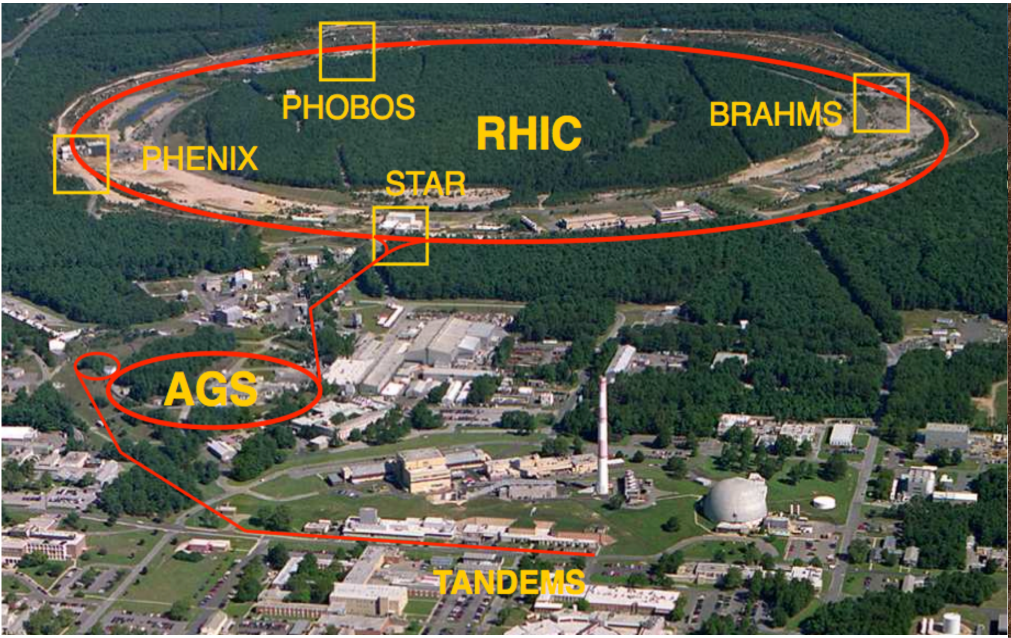
C. S. Fischer， Talk at QM 2014, Darmstadt

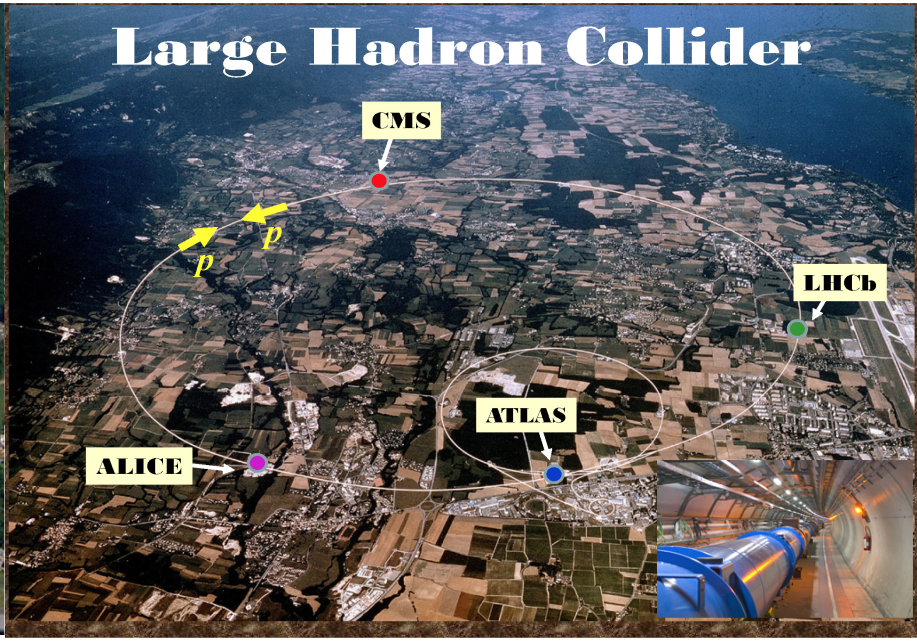
(μ^E_B = 504 MeV , T^E = 115 MeV) $\mu^E_B/T^E \sim 4.4$

$\sqrt{s_{NN}}$ ~ 6 GeV

Different Theory/Model gives very different CP location.

High Energy Nuclear Collision Experiments





RHIC@BNL, USA

- RHIC: The high energy heavy-ion collider $\sqrt{s}$ = 200 - 5 GeV

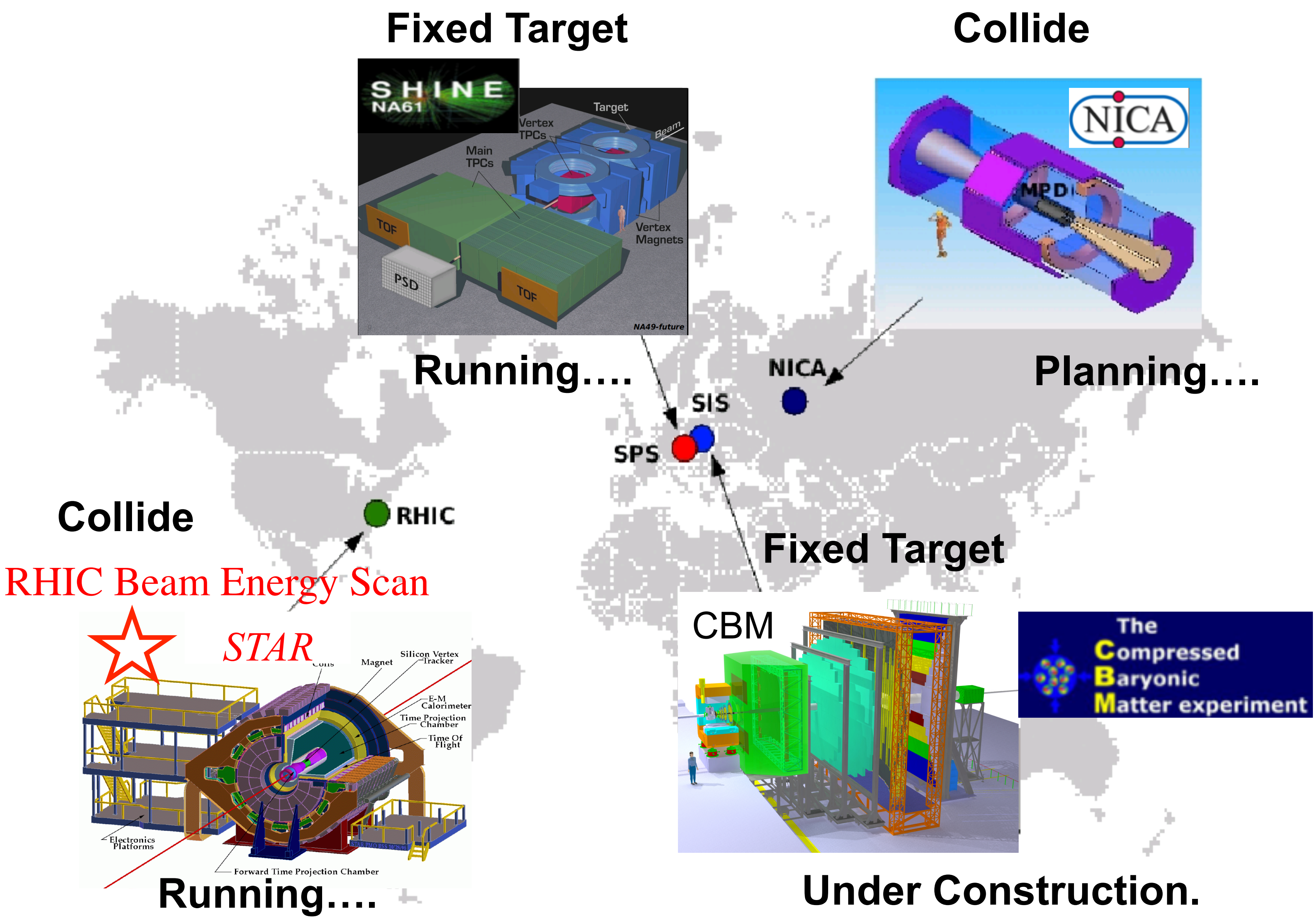
- RHIC: The highest energy polarized proton collider (500 GeV)

LHC@CERN,Geneva

– LHC: The highest energy heavy-ion collider $\sqrt{s}$ = 5.4 TeV

– LHC: The highest energy proton collider $\sqrt{s}$ = 14 TeV

Search for QCD Critical Point−Experiment



Strategy for the CP Search in Heavy−ion Collision

a) Establish observables that are sensitive to the critical behavior, such as fluctuations of conserved quantities (Q, B, S number) in heavy−ion collisions.

b) Vary external conditions, such as collision energy and centrality, to look for non-monotonic dependence of the observable.

c) Study the contribution of the non-critical behavior, such as statistics, acceptance, resonance decay, etc. Need transport and/or QCD based dynamical model studies.

Need efforts from experimentalist and theorist !

Experimental Observable: Higher Moments

Cumulants of E-by-E multiplicity distributions:

Event wise deviation: $\delta x = x - \langle x \rangle$

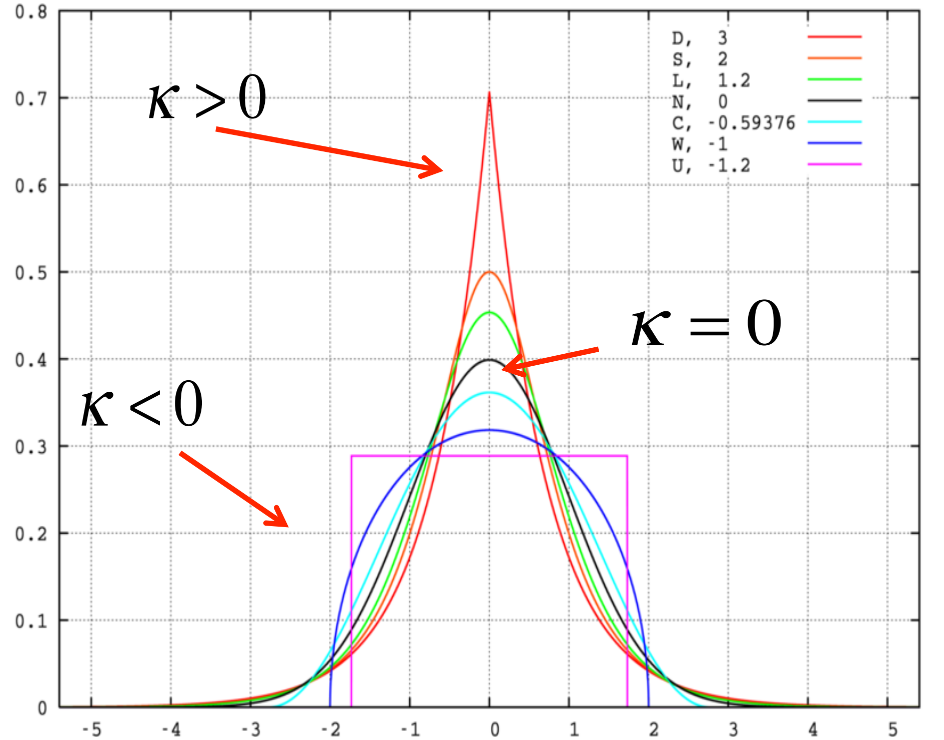
$$C_{1,x} = \langle x \rangle,$$

$$C_{2,x} = \langle (\delta x)^2 \rangle,$$

$$C_{3,x} = \langle (\delta x)^3 \rangle,$$

$$C_{4,x} = \langle (\delta x)^4 \rangle - 3 \langle (\delta x)^2 \rangle^2$$

$C_{2,x} \sim \xi^2$ $\quad C_{3,x} \sim \xi^{4.5}$ $\quad C_{4,x} \sim \xi^7$



Kurtosis and dis. shape, from Wiki.

- Ideal probe of non-gaussian fluctuations.
- Sensitive to the correlation length (ξ).

Main observables:

Volume Independent Cumulant Ratios:

$$\kappa\sigma^2 = \frac{C_{4,x}}{C_{2,x}}, S\sigma = \frac{C_{3,x}}{C_{2,x}}, \frac{\sigma^2}{M} = \frac{C_{2,x}}{C_{1,x}}$$

M. A. Stephanov, PRL102, 032301 (2009);
PRL107, 052301 (2011);
M. Akasawa, et al., PRL103,262301 (2009).

Connection to Susceptibility

Consider the Conserved Quantities : Baryon (B), Charge (C), Strangeness (S), Direct Connected to the particle number susceptibility:

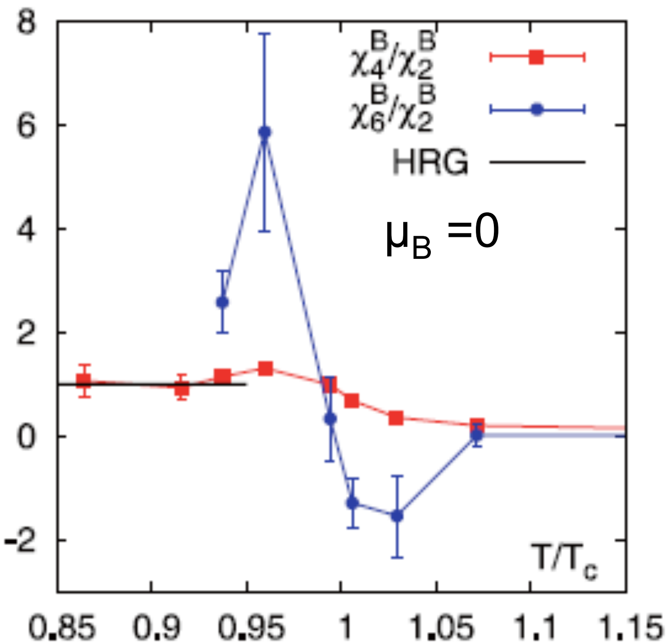
Susceptibility (Diverge at CP):

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

$$\chi_q^{(1)} = \frac{1}{VT^3}\langle \delta N_q \rangle, \chi_q^{(2)} = \frac{1}{VT^3}\langle (\delta N_q)^2 \rangle$$

$$\chi_q^{(3)} = \frac{1}{VT^3}\langle (\delta N_q)^3 \rangle, \chi_q^{(4)} = \frac{1}{VT^3}\left(\langle (\delta N_q)^4 \rangle - 3\langle (\delta N_q)^2 \rangle^2 \right)$$

Higher order – high sensitivity to criticality.



Cumulant Ratios: Experiment ⟺ Theory

$$\kappa\sigma^2 \sim \frac{\chi^{(4)}}{\chi^{(2)}}, S\sigma \sim \frac{\chi^{(3)}}{\chi^{(2)}}, \frac{\sigma^2}{M} \sim \frac{\chi^{(2)}}{\chi^{(1)}}$$

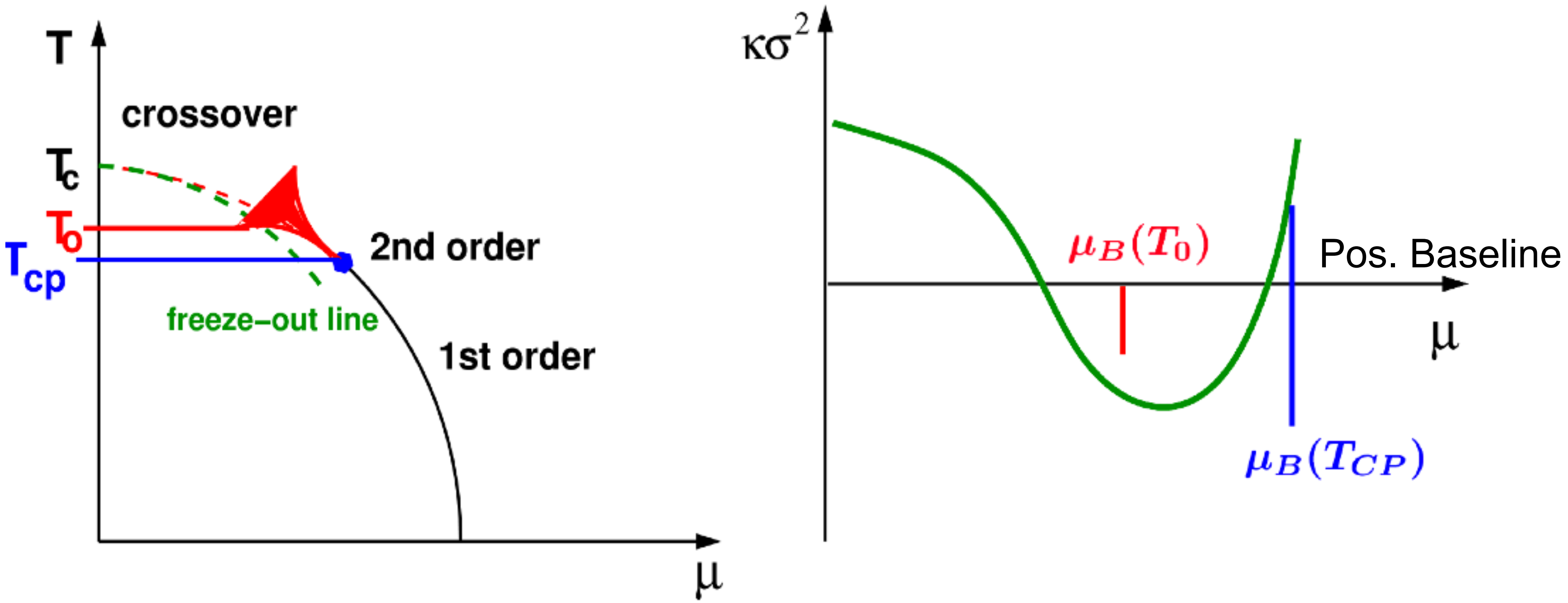
For e.g. : allowing us to determine the chemical freeze out parametsr in heavy-ion collisions.

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) // P. Alba et al., arXiv:1403.4903

Theoretical Prediction : Critical Point Induced Dip



Frithjof Karsch, Talk at NFQCD 2013, Japan.

A dip in the kurtosis*variance is likely to show up on the freeze-out line in the vicinity of a critical endpoint.

See also in Misha Stephanov, Phys. Rev. Lett. 107, 052301 (2011);

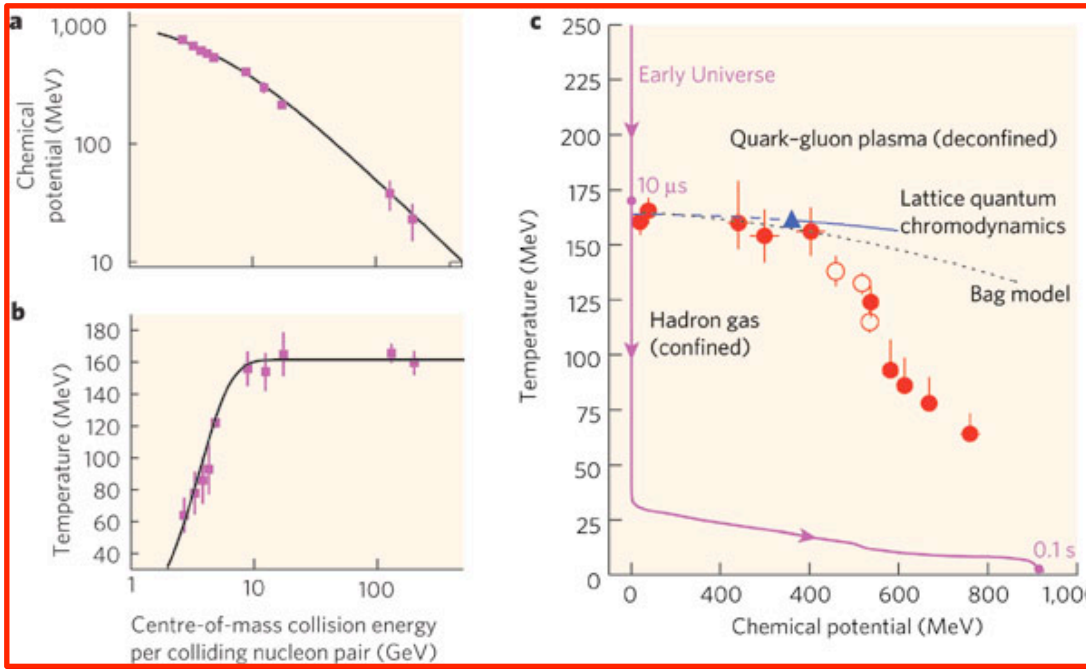
RHIC Beam Energy Scan–Phase I

In the first phase of the RHIC Beam Scan (BES), seven energies were surveyed in 2010 and 2011.

$\sqrt{s}$ (GeV)	μ_B (MeV)	T (MeV)
7.7	422	140
11.5	316	152
19.6	206	160
27	156	163
39	112	164
62.4	73	165
200	24	166

New Data: Year 2014
14.5 GeV, μ_B ~ 266 MeV

Fill in the large μ_B gap between 11.5 and 19.6 GeV



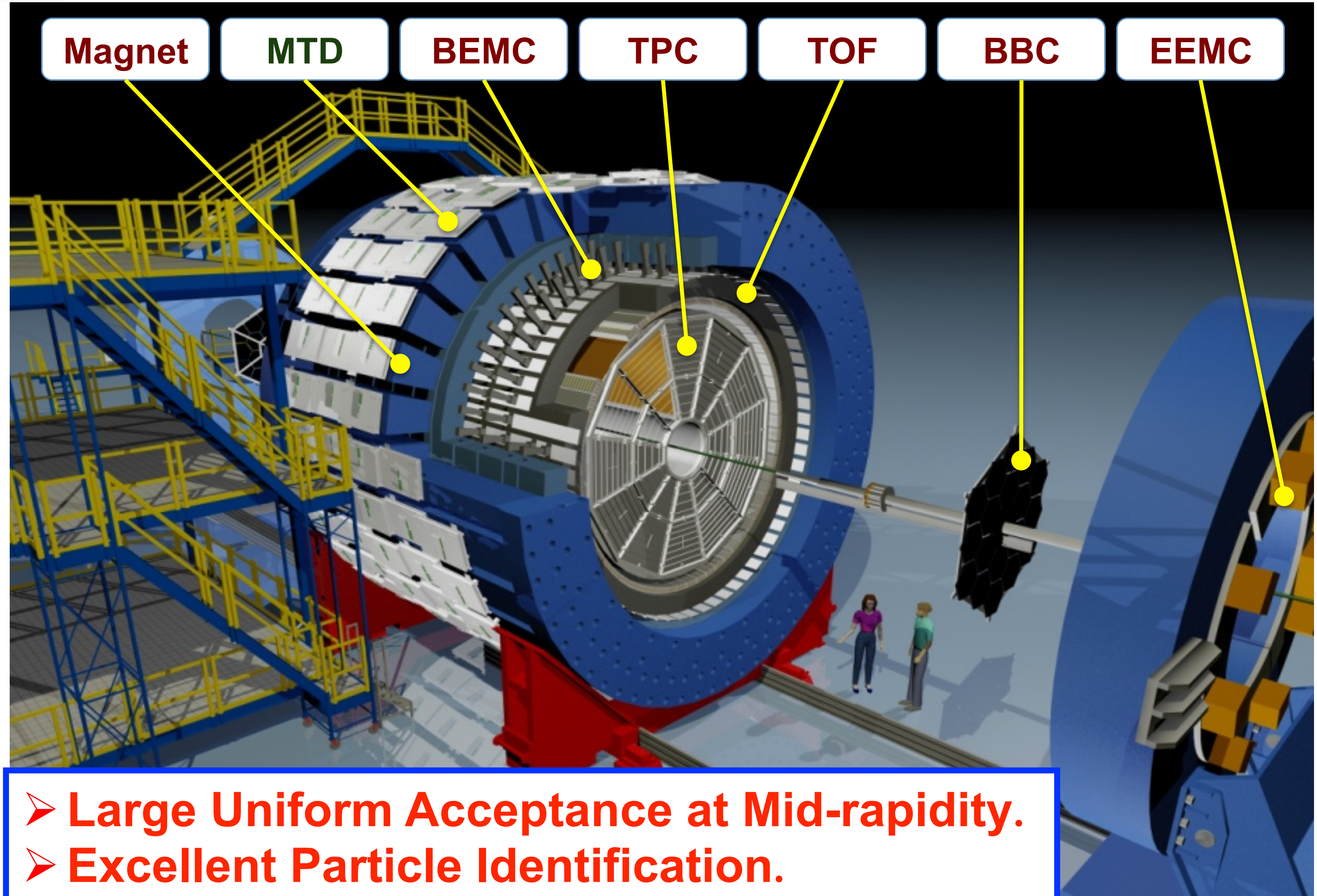
Nature 448 (2007) 302

The main goals of BES program:

- **Search for Onset of Deconfinement.**
- **Search for QCD critical point.**
- **Map the first order phase transition Boundary.**

Finite Size and time in HIC.
Need sensitive observable !

STAR Detector



- Large Uniform Acceptance at Mid-rapidity.
- Excellent Particle Identification.

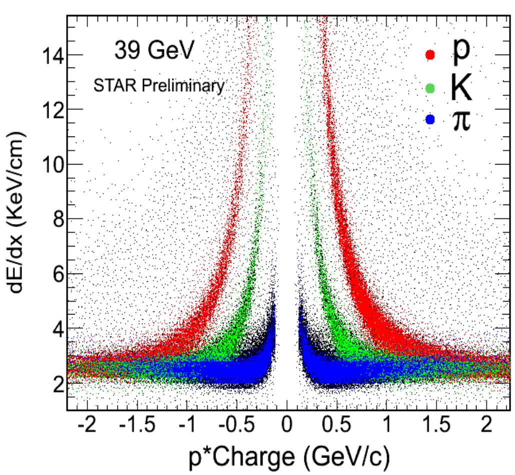
BES Data Analysis

Energy (GeV)	7.7	11.5	19.6	27	39	62.4	200
Statistics (Million), 0-80%	~3	~6.6	~15	~30	~87	~47	~238
Year	2010	2010	2011	2011	2010	2010	2010

- Events QA: Some quality cuts have been applied. (Bad Run/Events Removed)
- PID : Energy loss (dE/dx) in STAR TPC is used to identify protons with high purity within $0.4<p_T<0.8$ (GeV/c) and at mid-rapidity $|y|<0.5$.

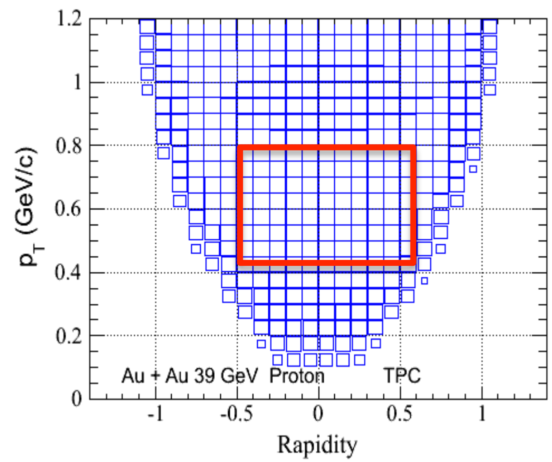
$$Z_p = \frac{\ln((dE/dx)_{exp.}/(dE/dx)_{theory})}{\sigma_{TPC}}$$

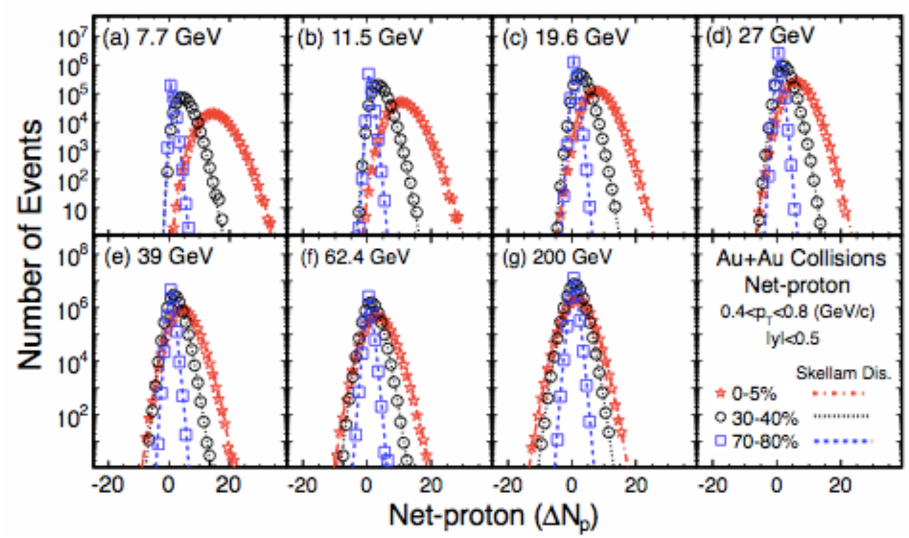
STAR TPC dE/dx PID

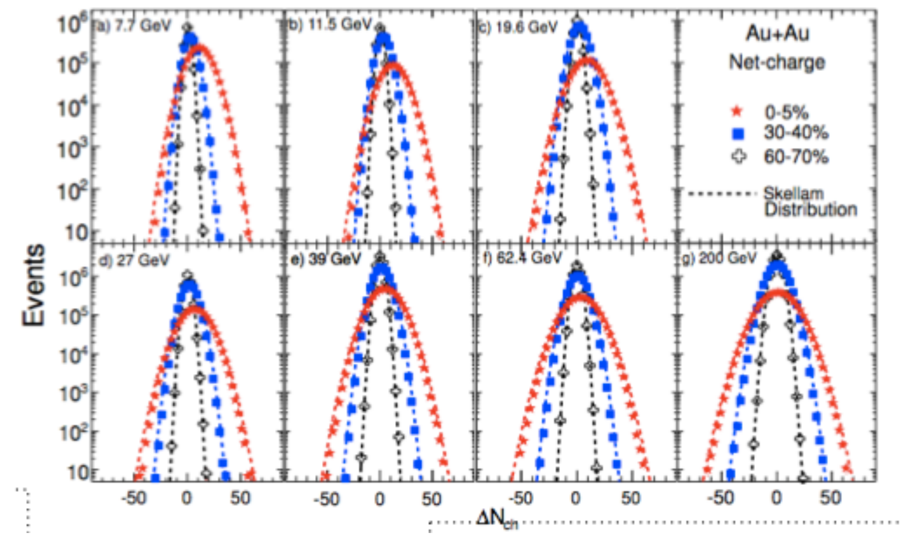


$|Z_p| < 2$

Proton Phase Space







Net-proton **Net-charge**

STAR, PRL 112, 032302 (2014). STAR, PRL113 092301 (2014).

At given energy and centrality, the width of the net-charge distribution is wider than net-proton. The statistical errors of moments will be larger for net-charge than net-proton:

e.g.:

$$Error(S\sigma) \propto \frac{\sigma}{\sqrt{N}}, Error(\kappa\sigma^2) \propto \frac{\sigma^2}{\sqrt{N}}$$

X. Luo, J. Phys. G 39, 025008 (2012).

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

Analysis Techniques

Background/artifacts effects.

- Auto-correlation effects.
- Volume fluctuation effects.
- Detector efficiency effects.

Initial volume fluctuation

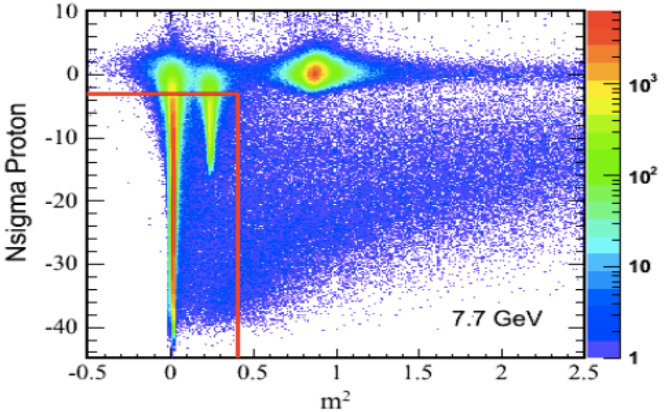
Volume flu. within centrality

Techniques:

1. Define the centrality without p and pbar
2. Define the centrality with large η window.
3. Centrality Bin Width Correction (CBWC).
4. Efficiency Correction

STAR Collaboration: Phys. Rev. Lett. 112, 032302 (2014).

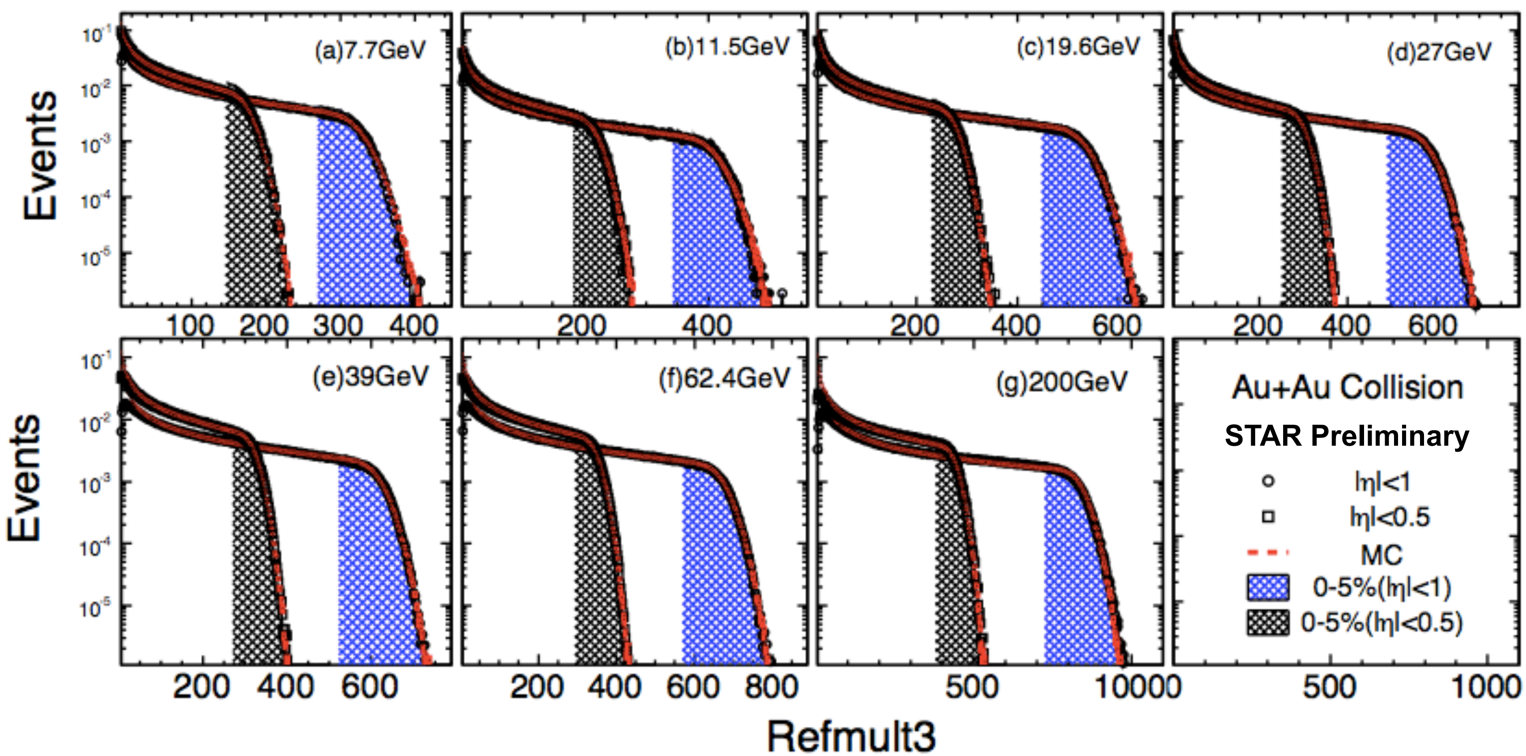
New Centrality Definition for Net-proton Analysis



Refmult3 (Charged Pion+Kaon)

|η|<1, Current TPC Acceptance Limit.

To address the auto-correlation and volume fluctuations.



Detector Efficiency Correction

Treat the detector efficiency as constant and the response function of detection efficiency is modeled as a binomial distribution.

$$C_2(X-Y)=\frac{C_2(x-y)+(\varepsilon-1)(\langle x\rangle+\langle y\rangle)}{\varepsilon^2}$$

$$C_3(X-Y)=\frac{C_3(x-y)+3(\varepsilon-1)(C_2(x)-C_2(y))+(\varepsilon-1)(\varepsilon-2)(\langle x\rangle-\langle y\rangle)}{\varepsilon^3}$$

X: Input Proton,
Y: Input Anti-proton,
x: measured proton
y: measured anti-proton
C_2, C_3, C_4: 2nd, 3rd 4th order cumulants.

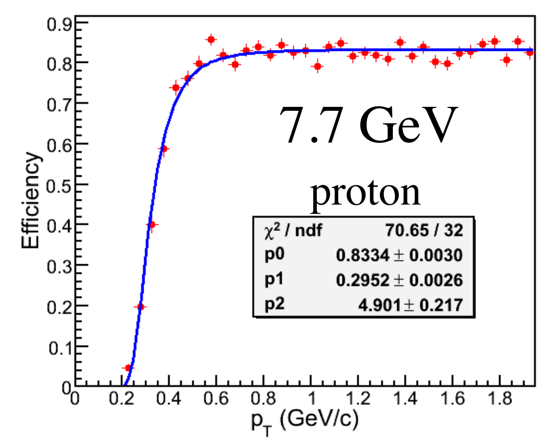
$$\varepsilon=\frac{\varepsilon_p+\varepsilon_{\bar{p}}}{2}$$

$$C_4(X-Y)=\frac{C_4(x-y)-2(\varepsilon-1)C_3(x+y)+8(\varepsilon-1)(C_3(x)+C_3(y))+(5-\varepsilon)(\varepsilon-1)C_2(x+y)+8(\varepsilon-2)(\varepsilon-1)(C_2(x)+C_2(y))+(\varepsilon^2-6\varepsilon+6)(\varepsilon-1)(\langle x\rangle+\langle y\rangle)}{\varepsilon^4}$$

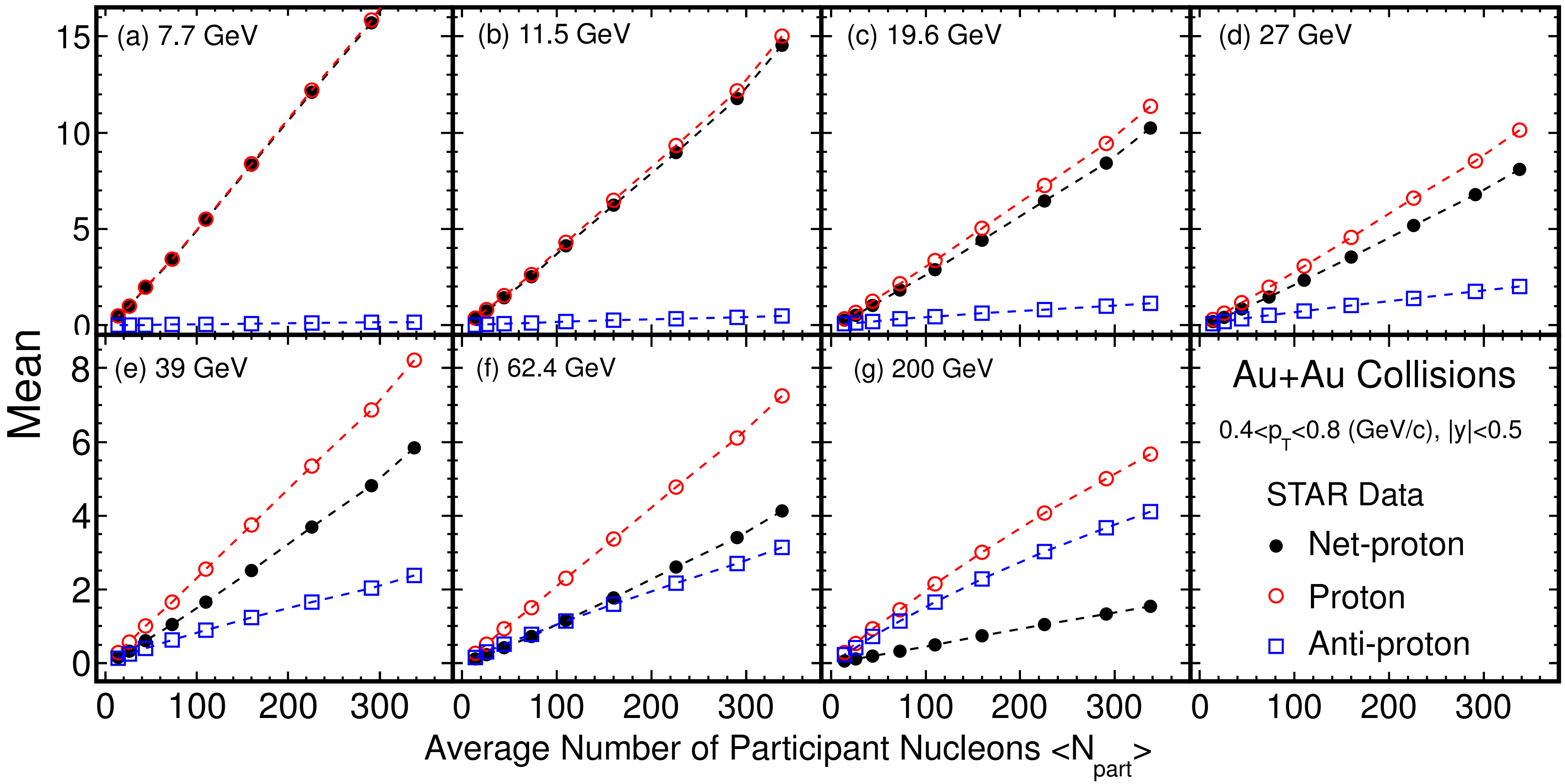
Average Efficiency within transverse momentum range (a,b): Embedding efficiency weighted by p_T spectra.

$$\varepsilon(p\ \ or\ \ \bar{p})=\frac{\int_a^b \varepsilon'(p_T)f(p_T)p_T\,\mathrm{dp_T}}{\int_a^b f(p_T)p_T\,\mathrm{dp_T}}$$

$\varepsilon'(p_T)$: embedding p_T dependent efficiency for proton or anti-proton.



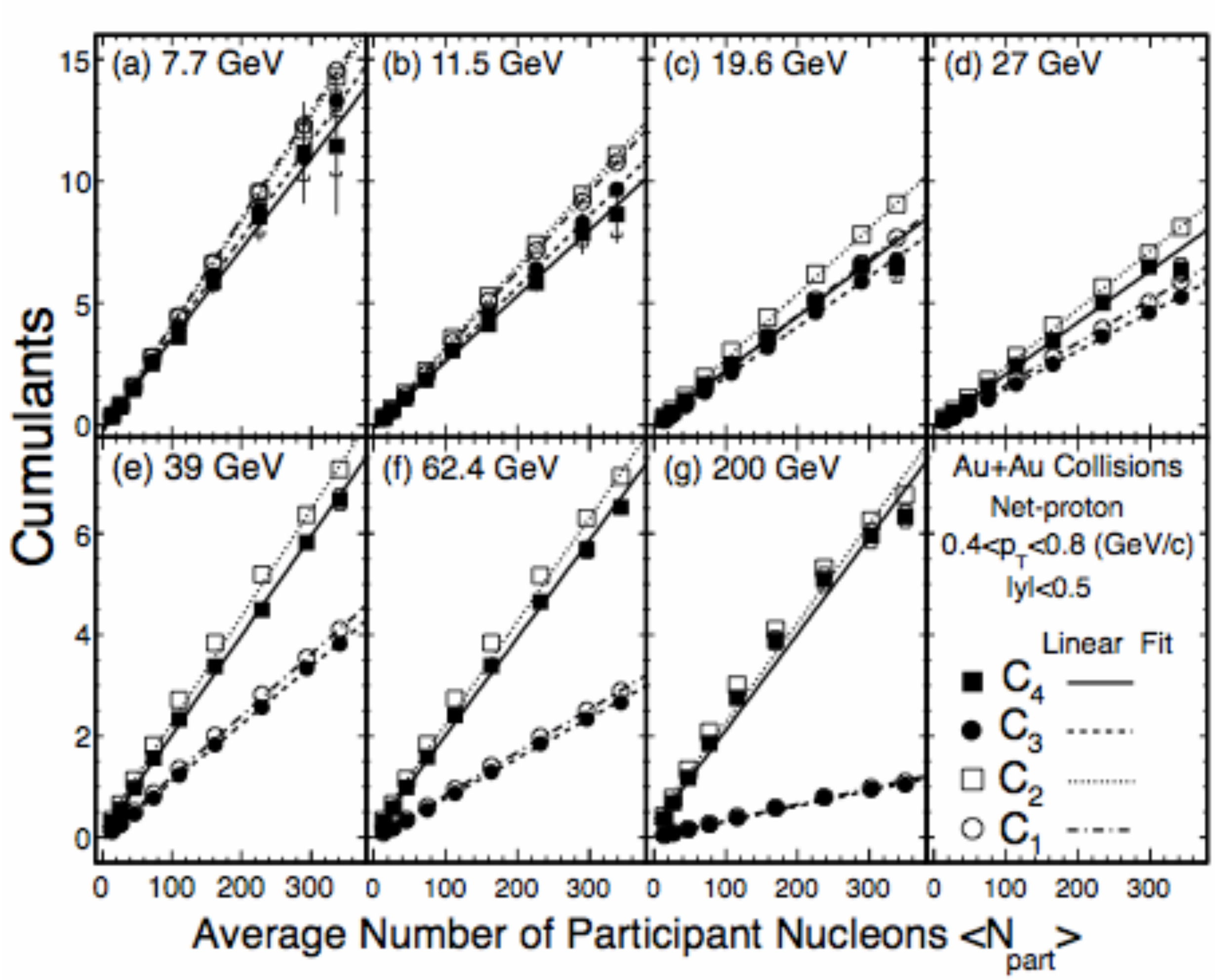
Mean net-proton, proton and anti-proton Number



X. Luo, B. Mohanty, N. Xu, arXiv: 1408.0495;

- Mean Net-proton, proton and anti-proton number increase with N_{part}.
- Net-proton Number increase when energy decrease and dominated by protons at low energies. (Interplay between baryon stopping and pair production)

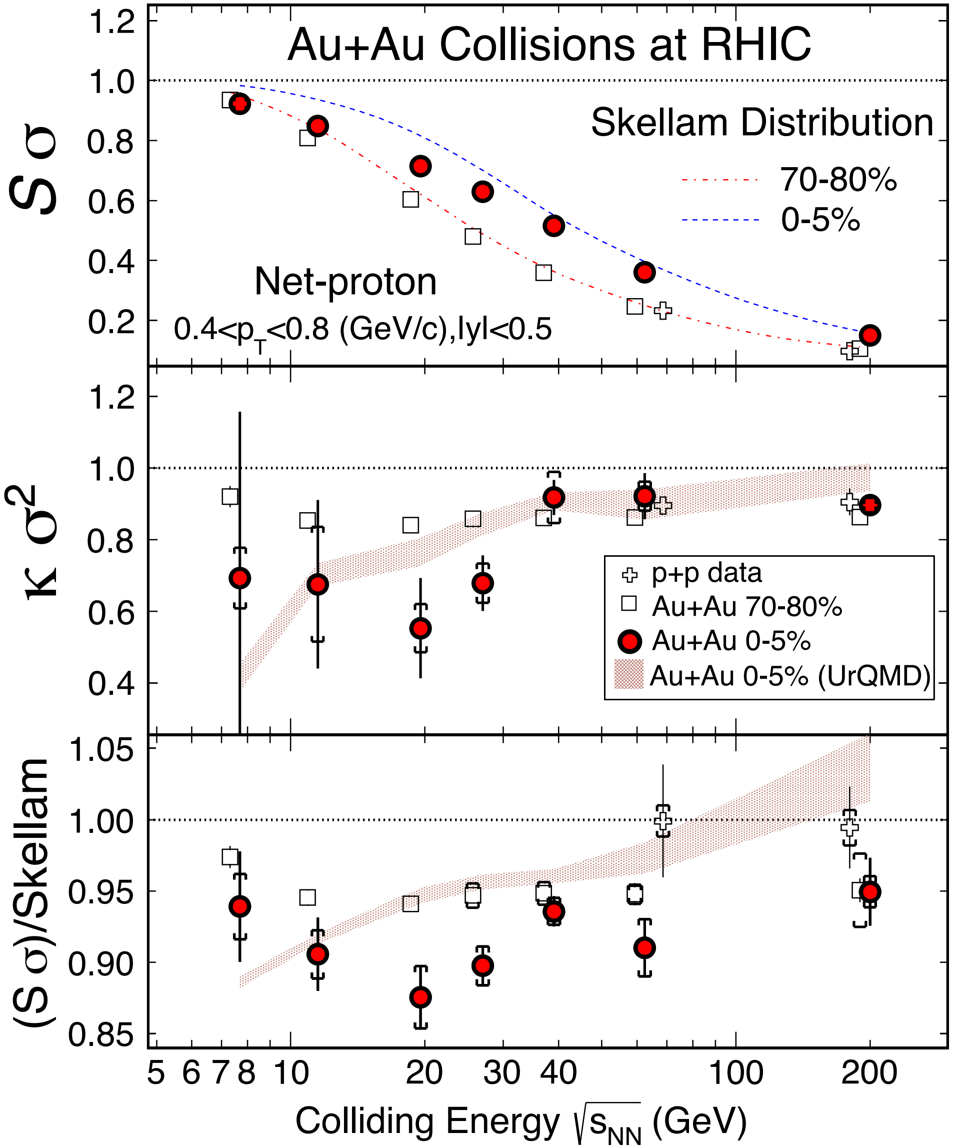
Cumulants of Net-proton Distributions: Efficiency Uncorrected



STAR, PRL112, 032302 (2014).

- Linear increase with N_{part}.
- C1~C3 and C2~C4 for all energies.

Energy Dependence of Moments of Net-proton Distribution

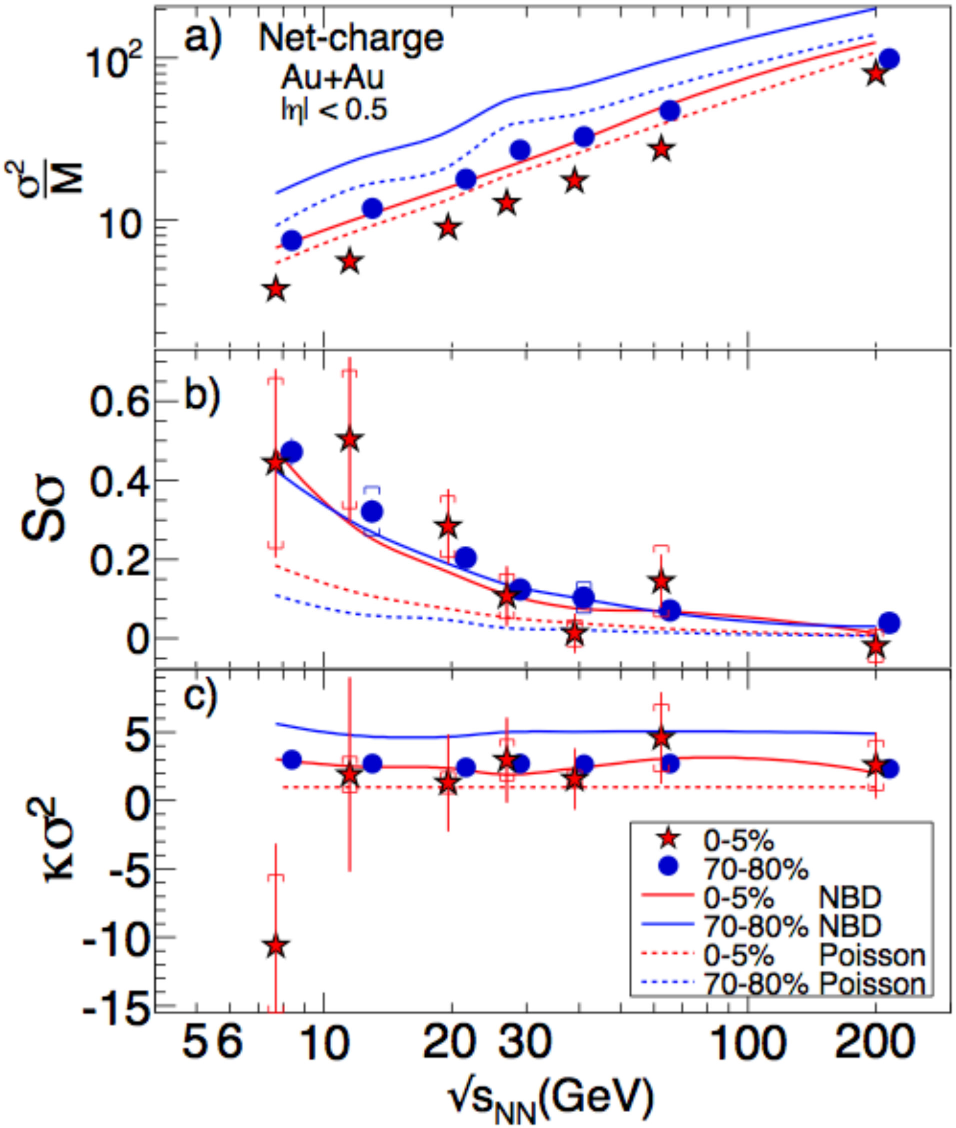


- Largest deviation fromPoisson statistics in the 0-5% most central collisions for $\kappa\sigma^2$ and Sσ is observed at $\sqrt{s_{NN}}$ ~ 20GeV.
- UrQMD show monotonic decrease with decreasing colliding energies.
- Higher statistics needed for collisions at $\sqrt{s_{NN}}$ < *20 GeV.* **BES-II is needed.**

Non-monotonic energy dependence in the most central collisions.
Hint of the QCD Critical Point ?

STAR, PRL 112, 032302 (2014).

Moments of Net-charge Distribution at RHIC



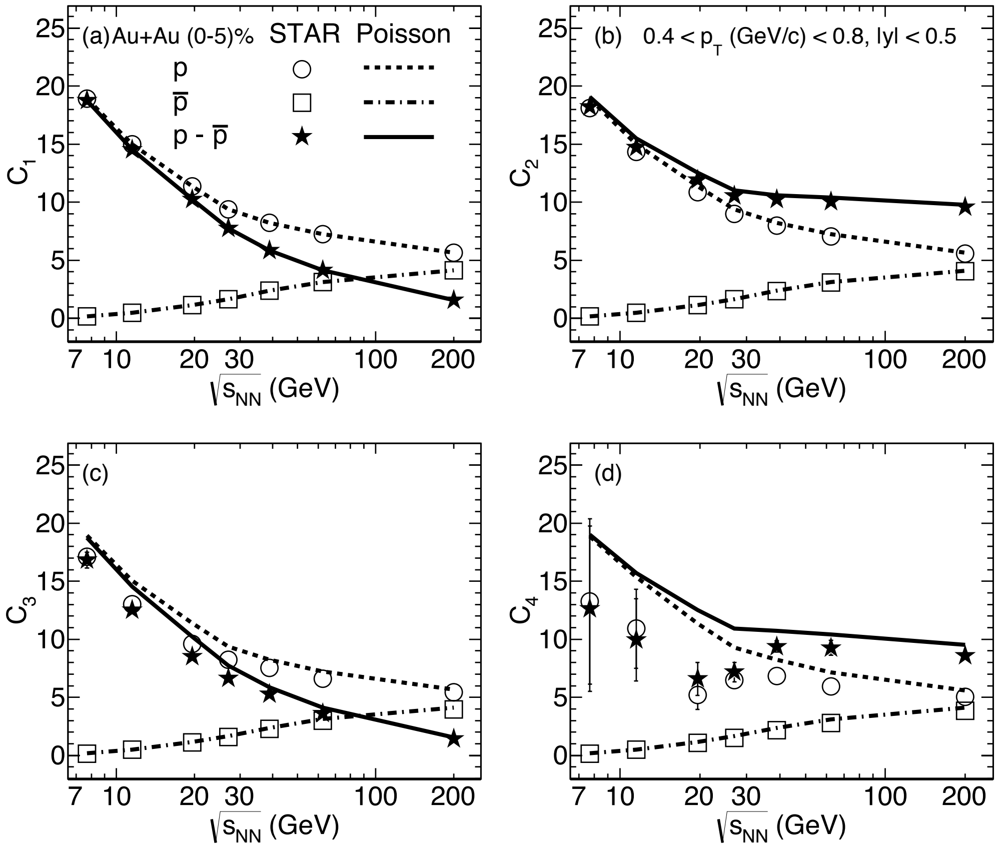
- ➢ Within the current statistics, no non-monotonic behavior is observed as a function of beam energy.

Comparing to net-proton fluctutions
The net-charge
1. Large Resonance decay effects.
2. Weaker coupling to critical mode for pion than proton.

- ➢ NBD has better description of the data than Poisson at 3rd and 4th order moments.

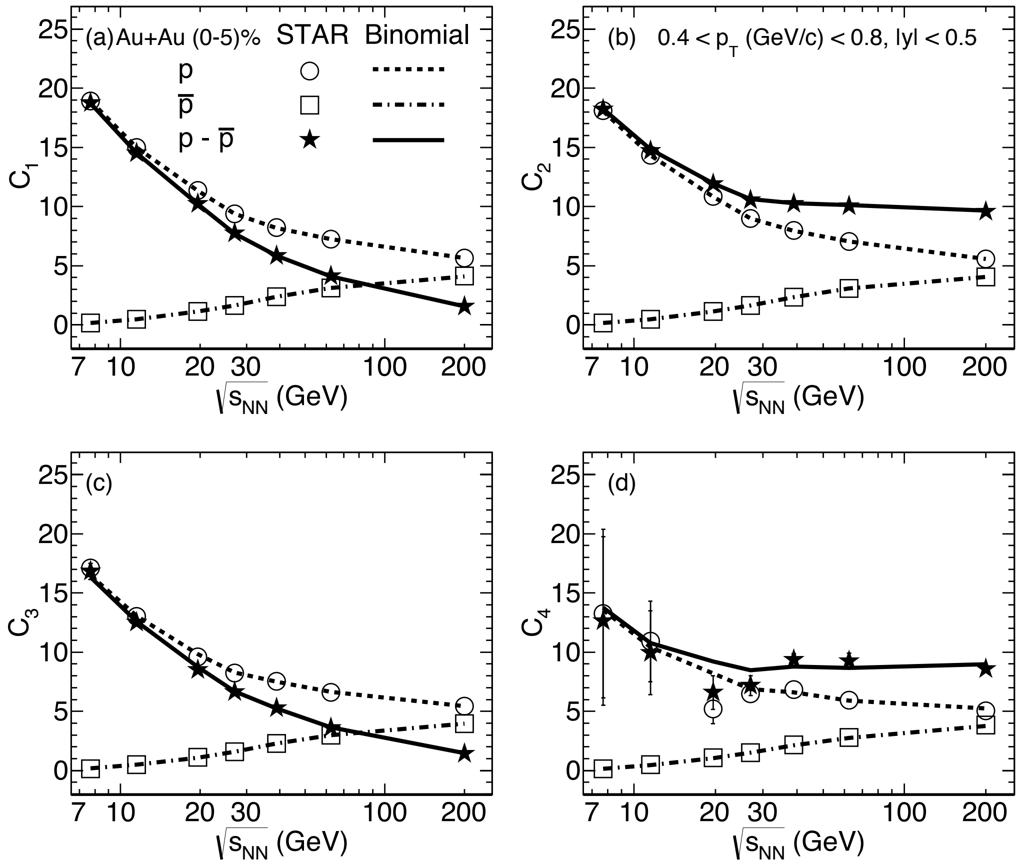
STAR, PRL113 092301 (2014).

Baseline (I): Poisson



- The mean proton and anti-proton number are used to construct high order cumulants.
- The order of cumulant increases the deviations of the data from the Poisson expectations for net-proton and proton increase.
- Largest deviation is found for C4 at 19.6 and 27 GeV.

Baseline (II): Binomial



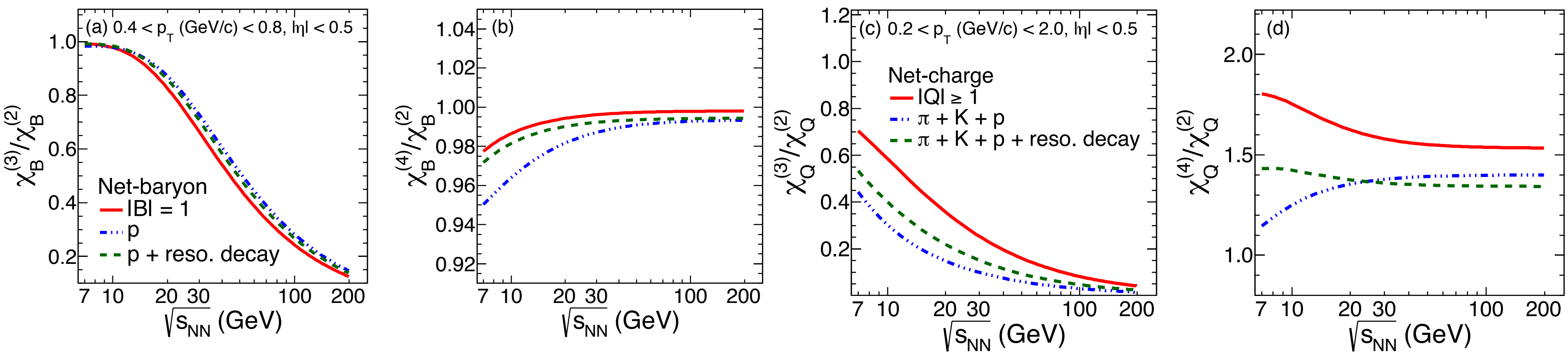
X. Luo, B. Mohanty, N. Xu, arXiv: 1408.0495; P. K. Netrakanti et al., arXiv: 1405.4617.

- In addition to the mean value, the variance of proton/anti-proton distributions are used also used to construct high order cumulants.The agreement persist up to 3rd order.
- But fails to describe the data for C4 at 19.6 and 27 GeV.

Towards Understanding non-CP Physics Effects

Non-CP effects, such as:
Resonance decay, hadronic scattering , quantum statistics, conservation of baryon number/charges etc.

Based on Hadron Resonance Gas Model (HRG) P. Garg, et al, PLB 726, 691 (2013)



Net-Baryon **Net-Charge**

Resonance decay and two charge states has much larger effects in net-charge cumulant ratios than in net-proton (within 5%).

Other HRG studies:
F. Karsch and K. Redlich , PLB695, 136 (2011). J. Fu, PLB722, 144 (2013).
Marlene Nahrgang et al, arXiv: 1402.1238.

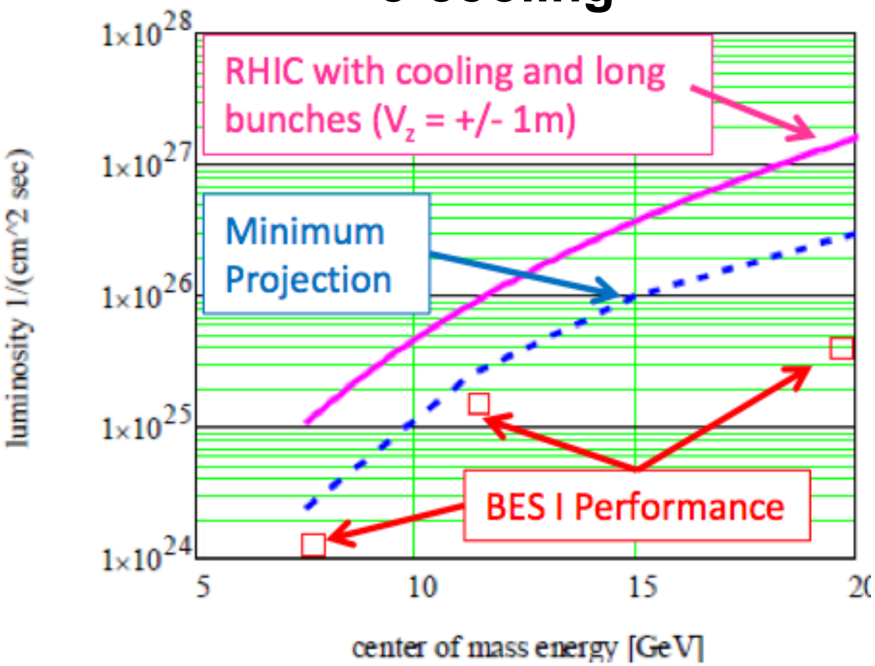
Future Critical Point Search

- **High Luminosity.**
- **High Baryon Density.**
- **High Sensitive Observable.**
- **Large Acceptance.**

The STAR Upgrades and BES Phase-II

- Fine energy scan at $\sqrt{s_{NN}}$ <~ 20 GeV
- Electron cooling will provide increased luminosity ~ 3-10 times
- STAR iTPC upgrade extend mid-rapidity coverage – beneficial to many crucial measurements

e-cooling



iTPC Upgrade

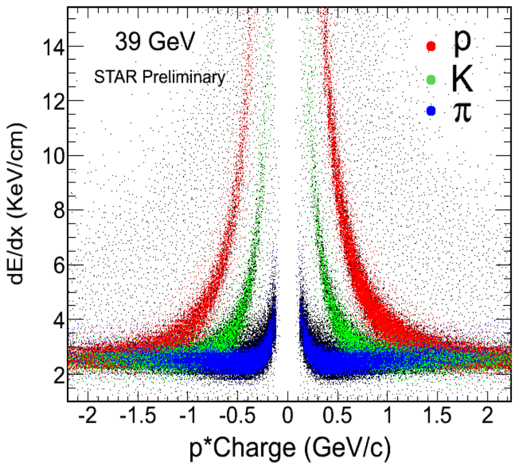
China : USTC, SDU, SINAP

For moment analysis, iTPC upgrade will improve tracking efficiency and centrality resolution.

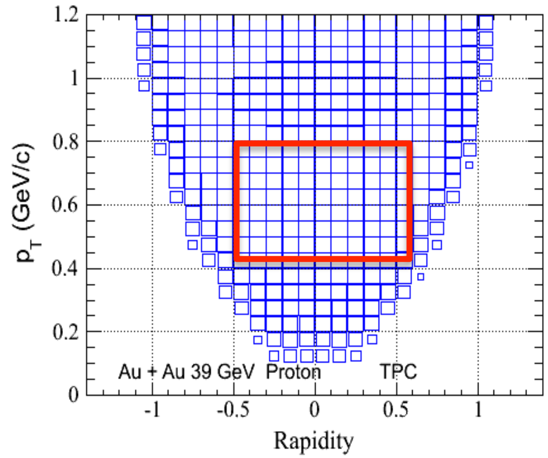
Extend Phase Space Coverage with TOF PID

Published Results: only TPC was used for proton/anti-proton PID. Currently, we use TOF detector to extend the phase space coverage for net-proton moment analysis.

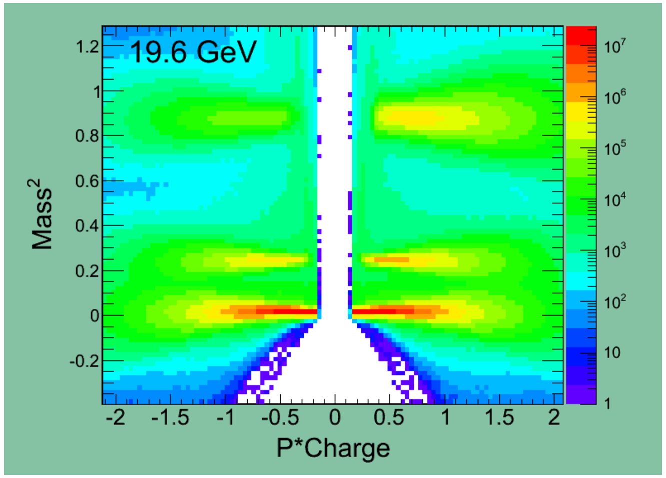
TPC PID:



Proton Phase Space



TOF PID:



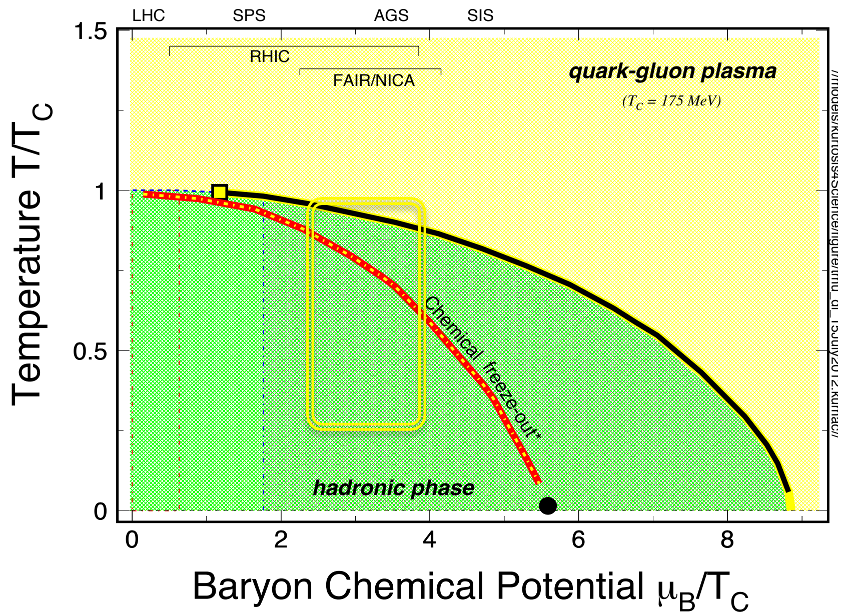
$0.4<p_T<0.8$ (GeV/c)

~ Doubled the accepted number of proton/anti-proton.

$0.4<p_T<3$ (GeV/c)

Sufficiently large acceptance is crucial for fluctuation analysis and critical point search.

Experimental Study on Highly Compressed Baryonic Matter

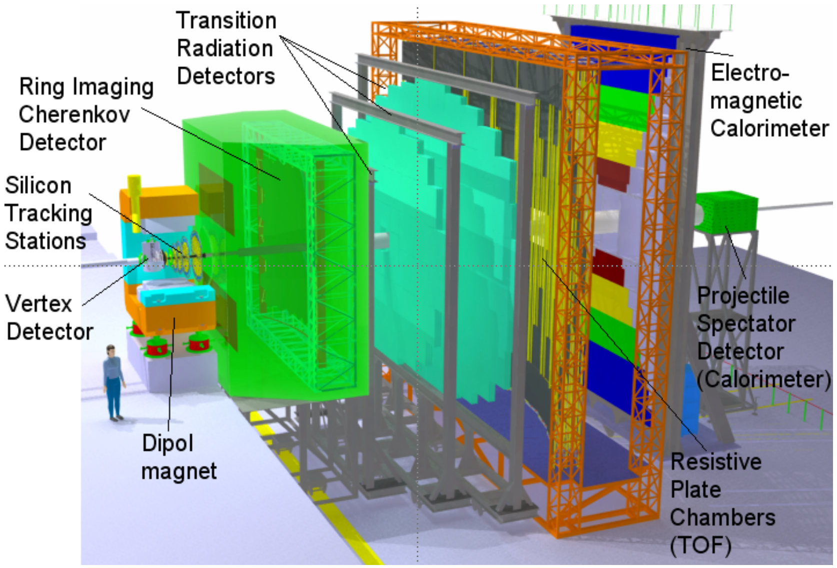


Exploring Phase Structure at High Baryon Density

（1） Quarkyonic

（2） QCD Critical Point/Phase Boundary

Fixed Target Detector, CBM@FAIR



Center of Mass Energy $\sqrt{s_{NN}} \leqslant 12$ GeV per nucleon pair.

It allows us to explore the QCD phase structure at high baryon density region with high precision !

Summary

Measurements:

- We present the moments of net-proton/net-charge cumulants in Au+Au collisions at RHIC BES-Phase I energies (7.7, 11.5, 19.6, 27, 39, 62.4 and 200 GeV).

Comparisons with Various Baselines and Models:

- We observe in the net-proton fluctuations, the most significant deviation below various baselines around 19.6 and 27 GeV.

Hint of QCD Critical Point ?

- Within current statistics, the net-Q results show monotonic variation as a function of energy and are consistent with NBD baseline.

- Higher statistics are needed at low energies to explore the QCD phase structure: RHIC BES-II (from 2018). Fixed target experiment, CBM@FAIR.

Future Physics Opportunities:

Discover the CP: It is crucial to understand non-CP physics effects on the experimental observables. Need QCD based modeling of the heavy-ion collision dynamics.

- keep the money in a safe place and only a little amount in you wallets;

- don't travel with expensive jewels or watches;

- don't walk around with an expensive camera hanging from your neck or a fancy phone in your hands;

- don't go into dark, remote streets;

Thank you for your attention !

- don't leave your luggage unattended;

- be careful on very crowded public transportation: keep an eye or a hand on the luggage all the time;

- don't carry your purse in your hand on the outter side of the street (pickpockets on small motorbikes slowing down next to you pulling your purse away from you and disappearing to the horizon are very typical).

Facility for Antiproton and Ion Research: FAIR

Get Beam at Year 2018，～€1.5 Billion

Primary Beam

- 10^{12}/s; 1.5 GeV/u; $^{238}U^{28+}$
- **10^{10}/s $^{238}U^{73+}$** up to 35 GeV/u
- **3x10^{13}/s 30 GeV protons**

Secondary Beam

- range of radioactive beams up to 1.5 - 2 GeV/u; up to factor 10 000 higher in intensity than presently
- antiprotons 3 - 30 GeV

Cooling Storage Ring

- radioactive beams
- 10^{11} antiprotons 1.5 - 15 GeV/c, stored and cooled