Search for the QCD Critical Point -

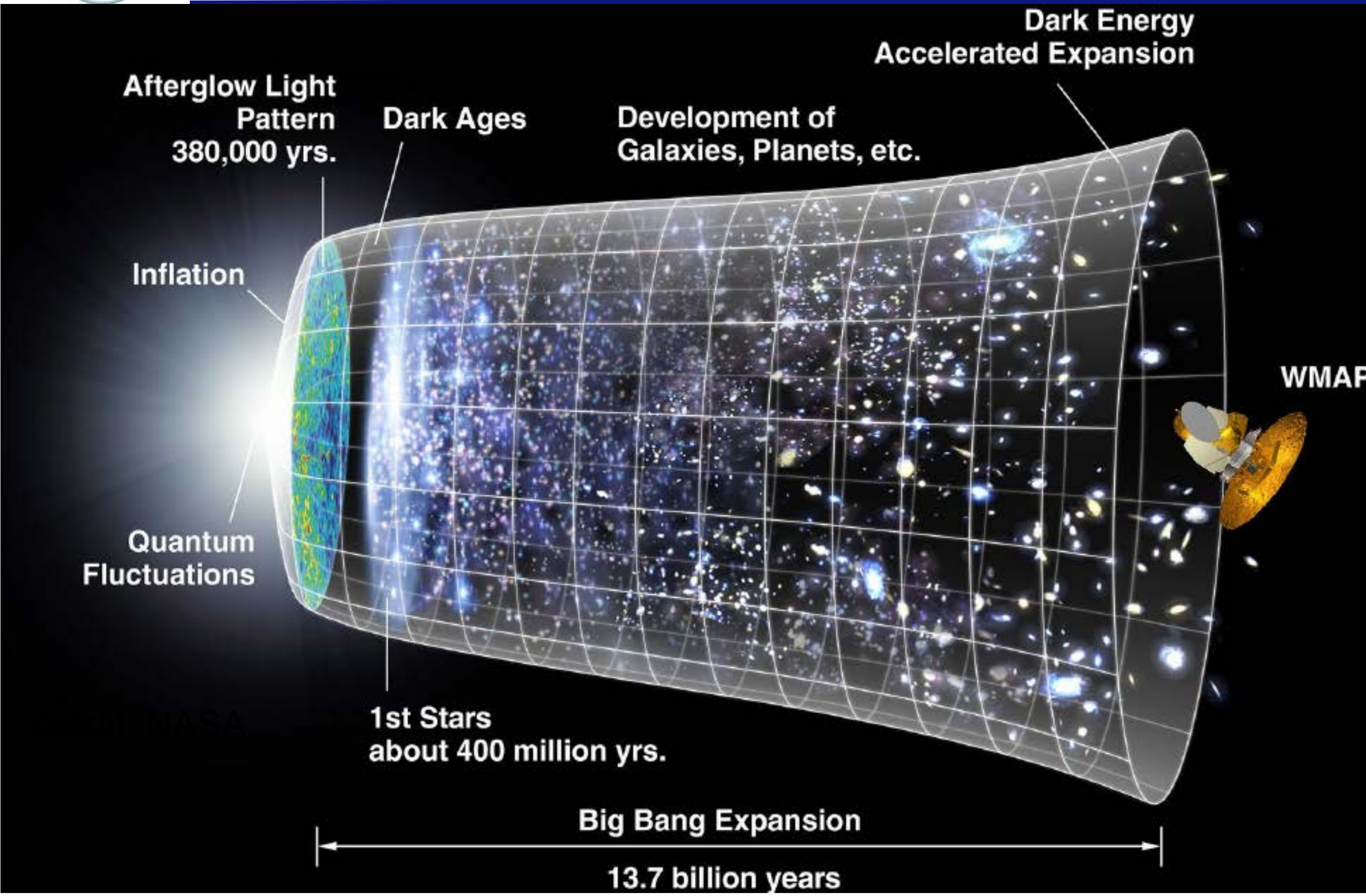
Fluctuations of Conserved Quantities in High Energy Nuclear Collisions at RHIC

Xiaofeng Luo (罗晓峰)

Central China Normal University (CCNU)

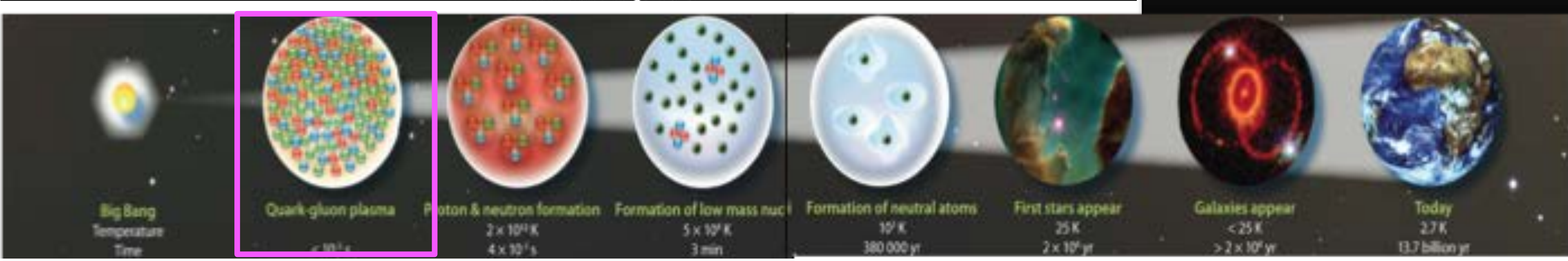
Jan. 19, 2016

Big bang

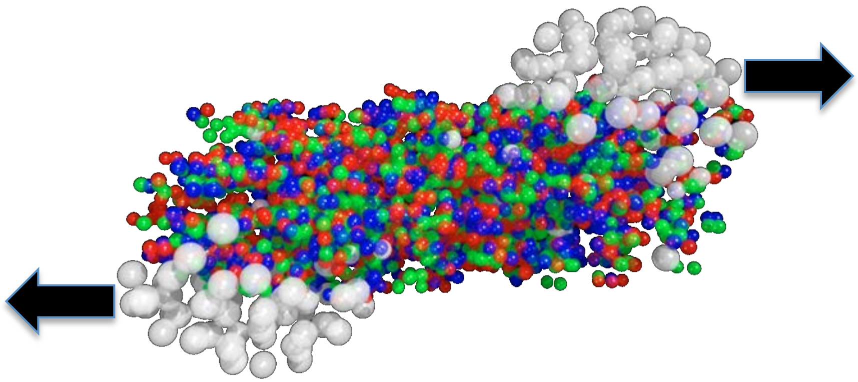


Quark-Gluon Plasma (***QGP***): a state of matter where the quarks and gluons are the relevant degrees of freedom

The universe after expanding and cooling down went through ***QGP*** phase few μs after the Big-Bang

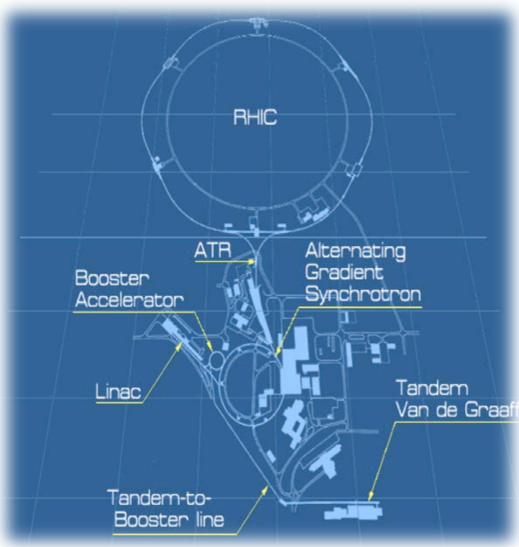


Experiments

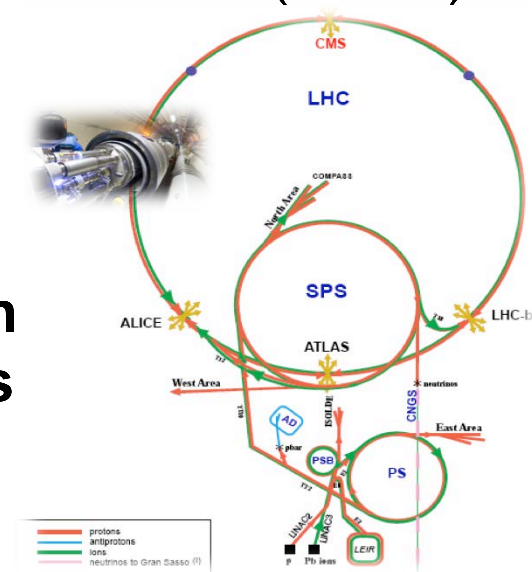


RHIC@BNL (2000-)

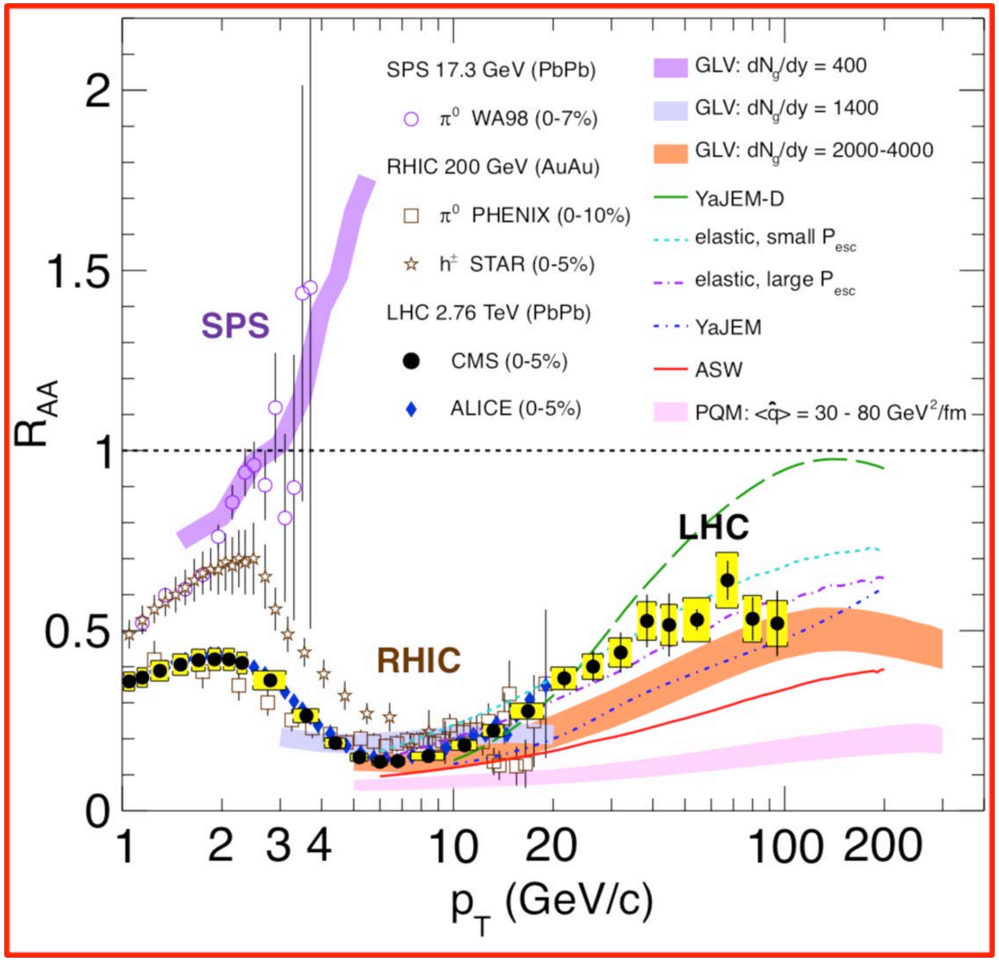
LHC@CERN (2008-)



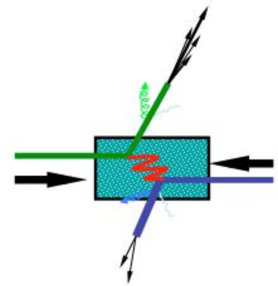
Study phase transition in controlled lab conditions by colliding heavy-ions



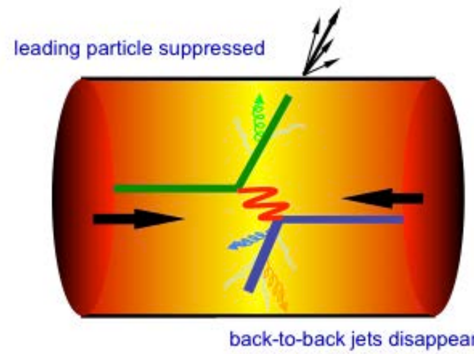
Establishing Quark Gluon Plasma (I): Jet quenching



Eur.Phys.J. C72 (2012) 1945



p+p



Au+Au

Nuclear Modification Factor：

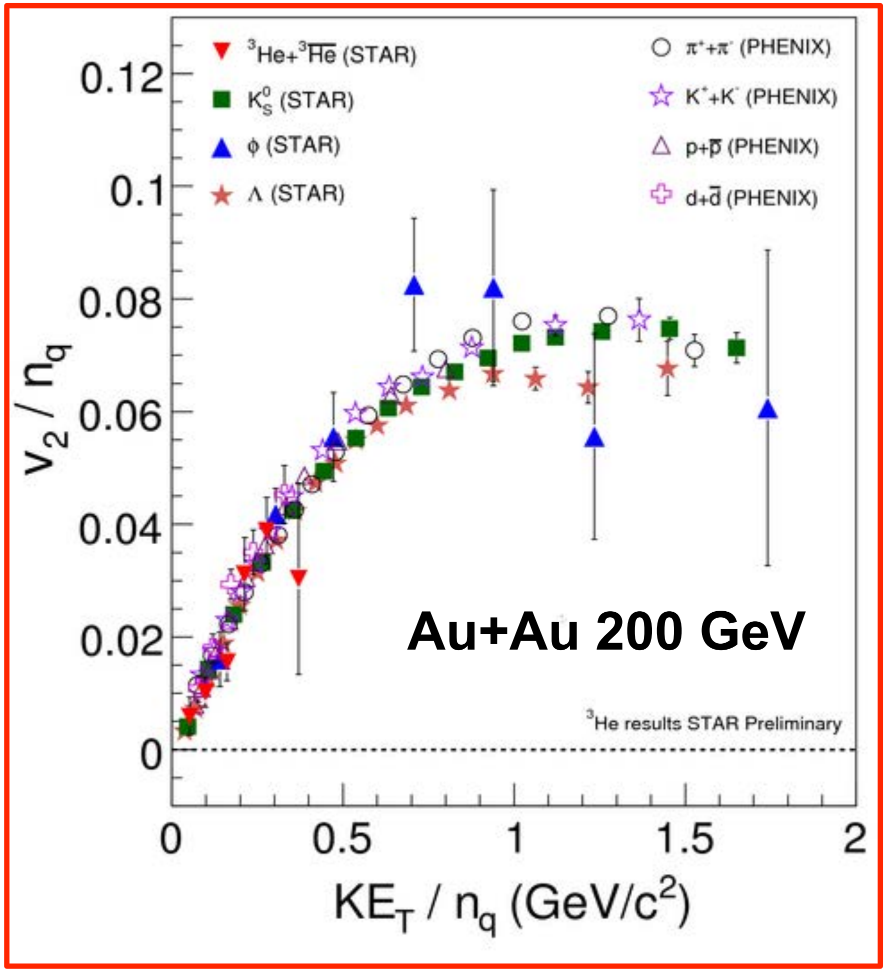
$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{d^2N^{AA}/dp_T d\eta}{d^2\sigma^{NN}/dp_T d\eta}$$

1992, Gyulassy, XNW:
Suppression of leading hadrons due to jet quenching.

Interpretation : **Energy loss of parton in a hot dense medium.**

Establishing Quark Gluon Plasma (II): Partonic Collectivity

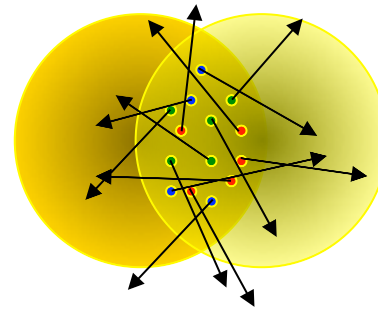
Number of constituent quark (NCQ) scaling



n_q = 2 for mesons
n_q = 3 for baryons

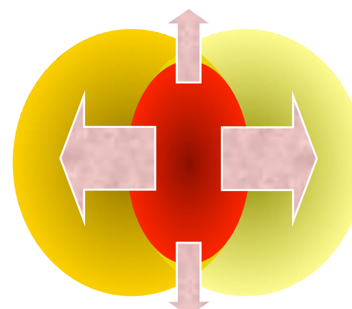
Initial spatial anisotropy

$$\varepsilon_x = \left\langle \frac{y^2 - x^2}{y^2 + x^2} \right\rangle$$



INPUT

Interaction among produced particles → Pressure Gradient



OUTPUT

Momentum Anisotropy

$$v_2 = \langle \cos 2\varphi \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

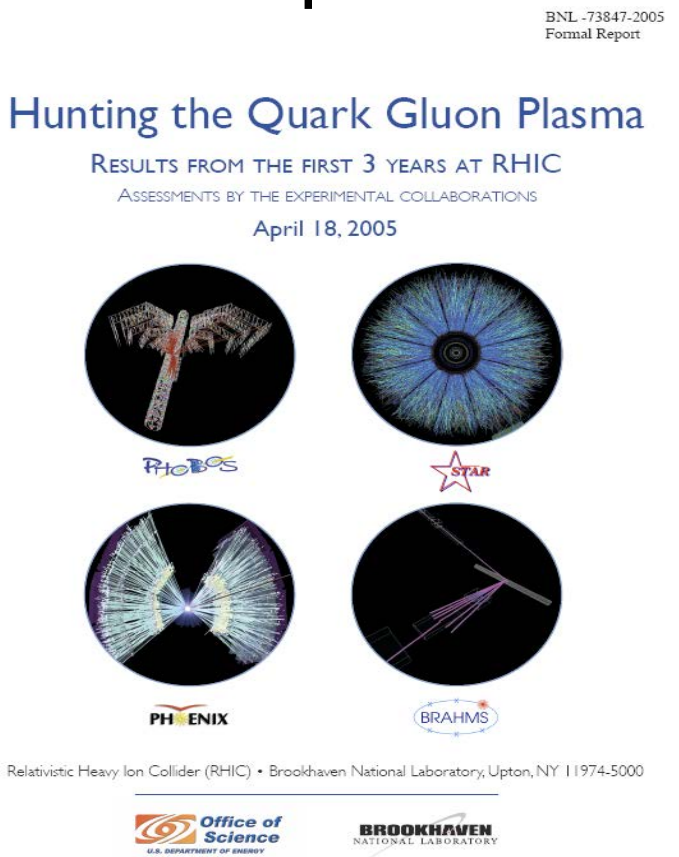
Partonic Collectivity at Early Stage.

RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

http://www.bnl.gov/rhic/news2/news.asp?a=303&t=pr

RHIC White Paper at 2005


BNL -73847-2005
Formal Report

Hunting the Quark Gluon Plasma

RESULTS FROM THE FIRST 3 YEARS AT RHIC

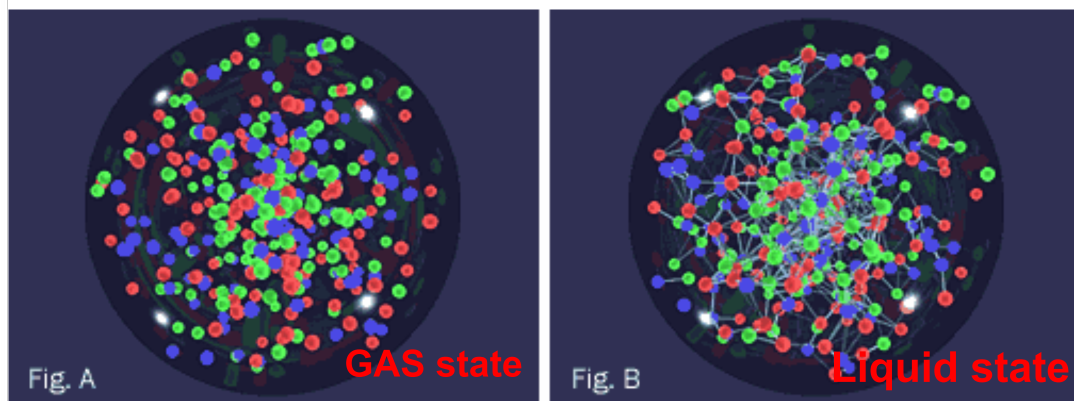
ASSESSMENTS BY THE EXPERIMENTAL COLLABORATIONS

April 18, 2005

Relativistic Heavy Ion Collider (RHIC) • Brookhaven National Laboratory, Upton, NY 11974-5000

Office of Science U.S. DEPARTMENT OF ENERGY

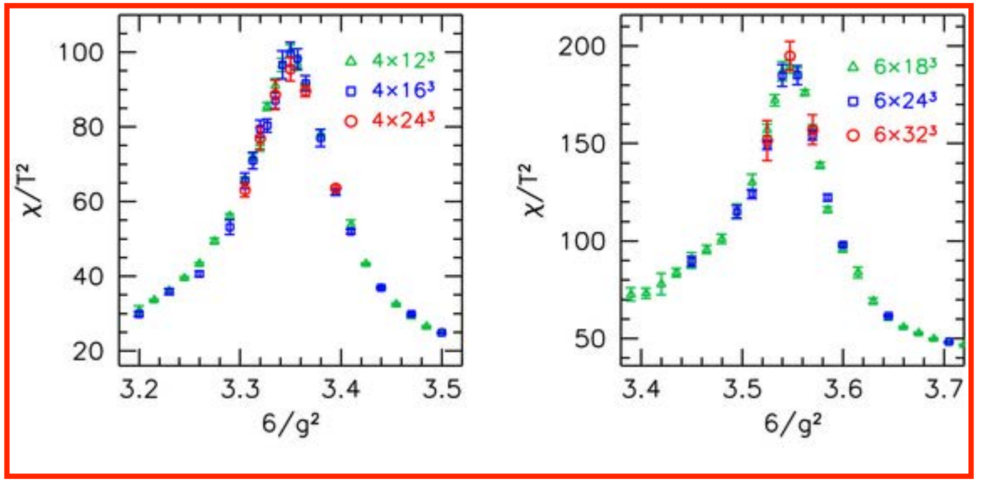
BROOKHAVEN NATIONAL LABORATORY



Experimental Observations support the formation of strongly interacting Quark Gluon Plasma at RHIC.

Nature of QCD Phase Transition (μ_B=0): Crossover

Y. Aoki et al., Nature 443:675-678, 2006



No significant volume dependence

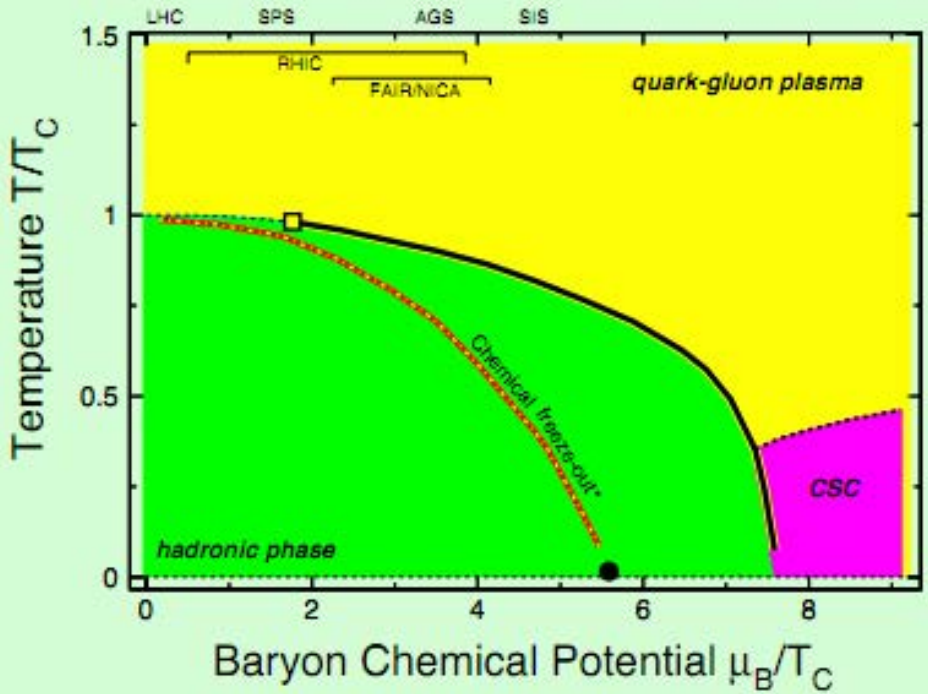
1^{st} order :
Peak height ~ V
Peak width ~ 1/V
Cross over :
Peak height ~ const.
Peak width ~ const.
2^{nd} order :
Peak height ~ V^{α}

hotQCD, Phys.Rev. D85, 054503 (2012).
Phys. Rev. D 74, 054507 (2006).

Tc (MeV)	HotQCD	Wuppertal-Budapest
Chiral Susceptibility	154 (9) (9)	151 (3) (3)
Polyakov loop Suscep.	192 (7) (4)	175 (2) (4)
S quark number suscep.	N/A	176 (3) (4)

- **For different lattice groups, they got agreement on Tc using chiral susceptibility, Tc≈154 MeV.**
- **Inconsistent results between two groups for Tc obtained from Polyakov loop susceptibility.**

How to make "Quark Soup"



June, 2011

"Scale for the Phase Diagram of Quantum Chromodynamics"

$\boldsymbol{T_c = 175^{+1}_{-7}}$ (MeV)

***Science*, <u>332</u>**, 1525(2011)

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

What we have learned ?

→ **Experiment: Strongly interacting hot dense nuclear matter of deconfined quarks and gluons is formed in the high energy heavy-ion collisions at RHIC and LHC.**

→ **Theory: At μ_B=0 the phase transition from hadronic to QGP is crossover.** Transition temperature using chiral condensates ~ **154 MeV,** using Susceptibilities and Polyakov loop ~ **175 MeV.**

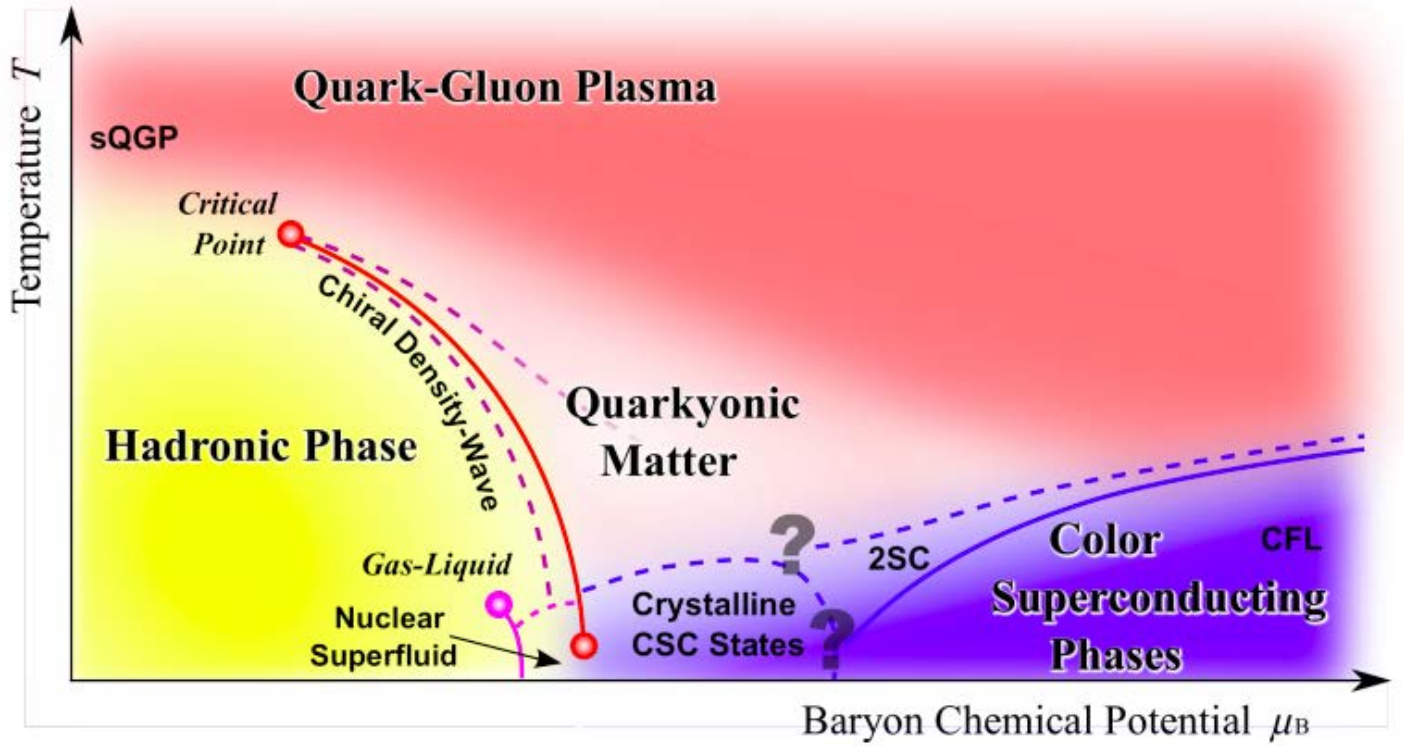
- **However, we know little about the phase structures of the hot dense nuclear matter at finite μ_B.**

Need to study the QCD Phase Structure !

QCD Phase Diagram (Conjectured)

Very rich phase structure in the QCD phase diagram.

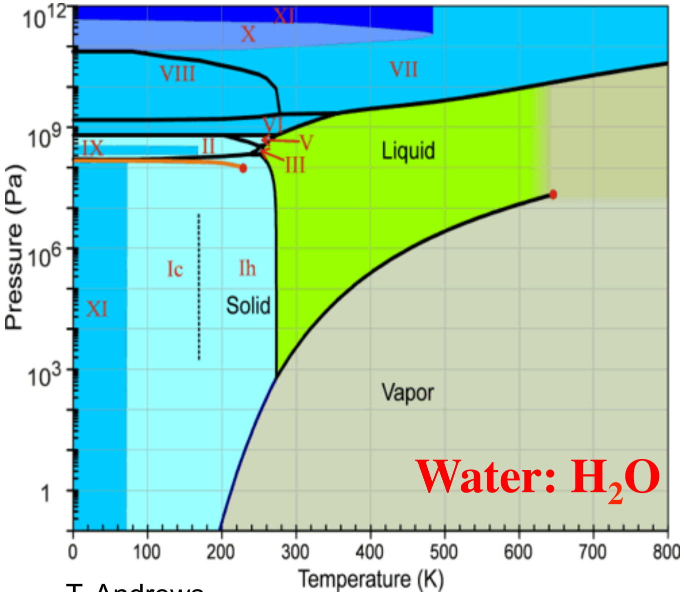
Hatsuda and Fukushima



K. Fukushima and T. Hatsuda, Rept. Prog. Phys. ***74,*** *014001(2011); arXiv: 1005.4814*

1. Is there a first order phase transition at large μ_B ?
2. Is there a QCD critical point ?
3. What's the T and μ_B dependence of the QGP properties ?
4. Can we see the QGP signals are turning off at low energies HIC ?

The QCD Critical Point



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

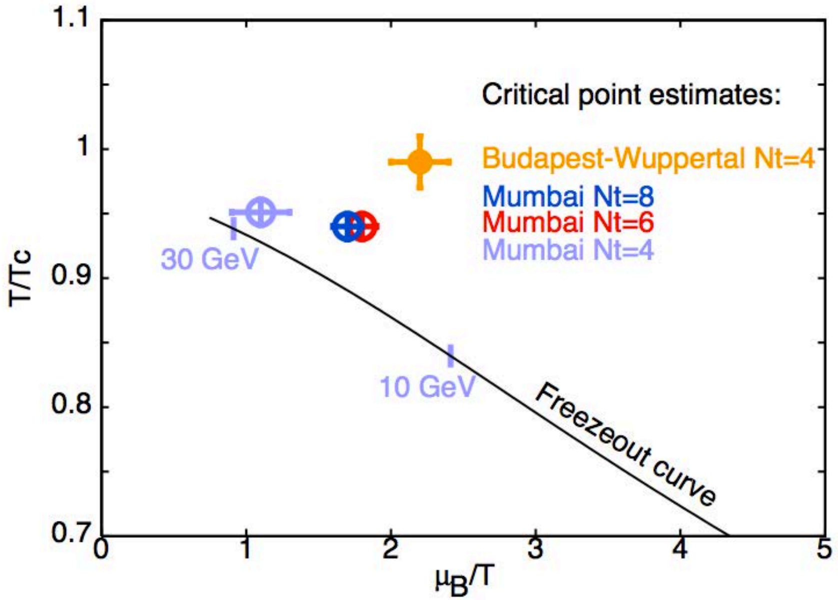
- Singularity of EoS: Diverges of the thermodynamics quantities, such as correlation length (ξ), Susceptibilities (χ), heat capacity (C_V).
- Long wavelength fluctuations of order parameter. Critical Opalescence. Z(2) universality class same as liquid-gas phase phase transiton.

Challenges:

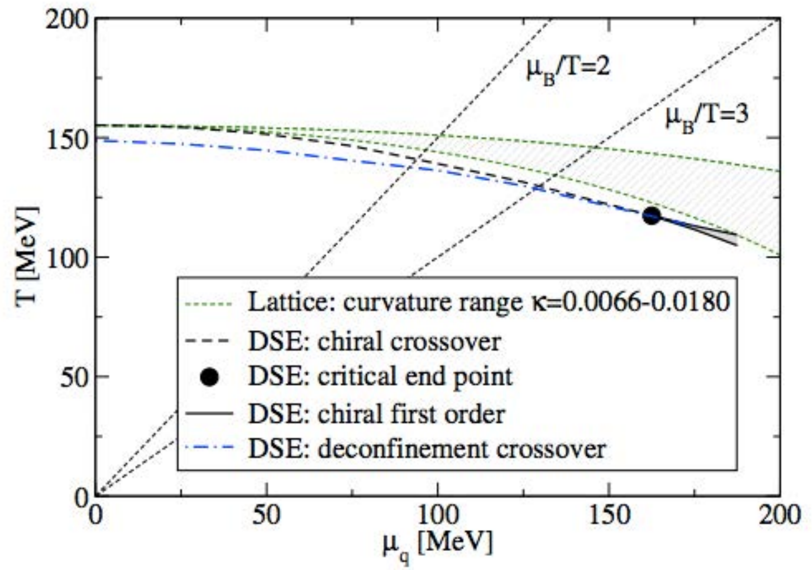
1. finite size/time. ξ=2 ~ 3 fm
2. Non-CP physics background.
3. Signal isn't washed out after expansion.

Location of QCD Critical Point: Theory

Lattice QCD:



DES:



Lattice QCD:

1): Reweighting: Fodor&Katz,2004:

$\mu^E_B/T^E \sim 2.2 \rightarrow \sqrt{s_{NN}} \sim 9.5$ GeV

2): Tylor Expansion: Gavai&Gupta 2013

$\mu^E_B/T^E \sim 1.7 \rightarrow \sqrt{s_{NN}} \sim 14.5$ GeV

DSE:

1): Y. X. Liu, et al., PRD90, 076006 (2014).

$\mu^E_B/T^E \sim 2.88 \rightarrow \sqrt{s_{NN}} \sim 8$ GeV

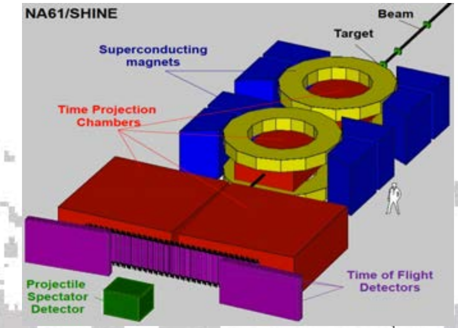
2): C. S. Fischer et al., PRD90, 034022 (2014).

$\mu^E_B/T^E \sim 4.4 \rightarrow \sqrt{s_{NN}} \sim 6$ GeV

$\sqrt{s_{NN}} =$ 6 ~ 14.5 GeV, $\mu^E_B =$ 266 ~ 496 MeV

Experimental Facility for the Beam Energy Scan

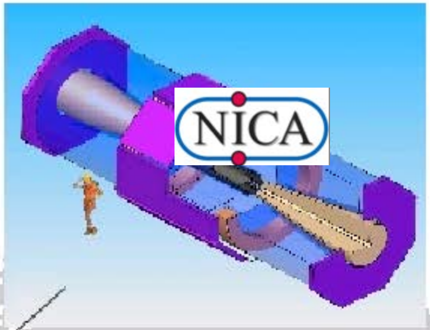
NA61/SPS — Started at 2009



Fix target

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

Construction….



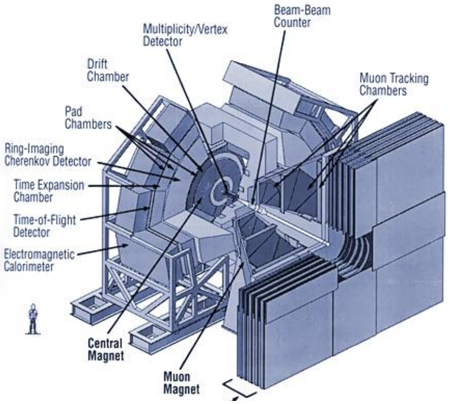
Collider

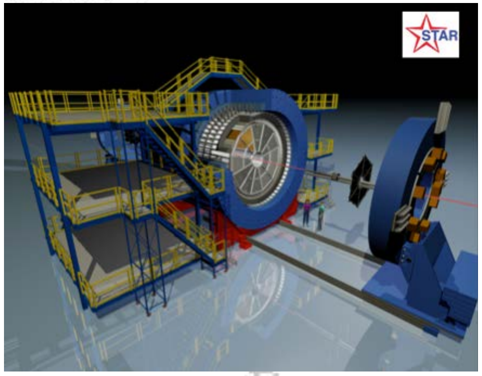
$\sqrt{s_{NN}}$ = 4-11 GeV

NICA
SIS
SPS
RHIC

RHIC Beam Energy Scan

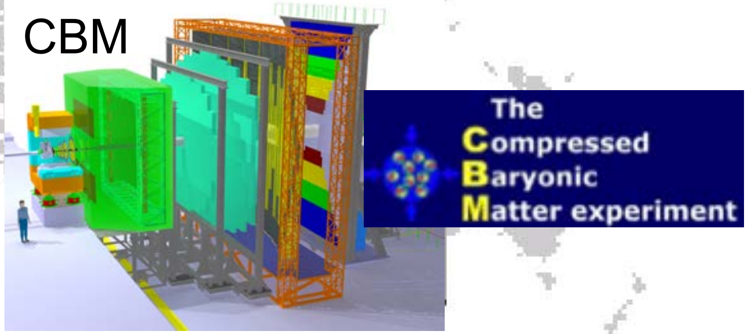
BES-I (2010-2014) is complete.





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

Construction….



Fix target

$\sqrt{s_{NN}}$ = 2-8 GeV

Fluctuations Probes the QCD Phase Transition

Fluctuations are sensitive to the thermodynamic properties of the system and can be used to probe the QCD phase transition.

1. Fluctuations signals the QCD Critical Point.

M. Stephanov, K. Rajagopal, E. Shuryak, Phys. Rev. Lett. 81, 4816 (1998). Cited:928
M. Stephanov, K. Rajagopal, E. Shuryak, Phys. Rev. D 60, 114028 (1999). Cited:708

Probe singularity of the equation of state: Divergence of the fluctuations.

2. Fluctuations signals the Quark Deconfinement.

S. Jeon and V. Koch, Phys. Rev. Lett. 83, 5435 (1999). Cited: 193.
M. Asakawa, U. Heinz and B. Muller, Phys. Rev. Lett. 85, 2072 (2000). Cited:443

Proposed experimental observables:

1. **Pion multiplicity fluctuations.**
2. **Mean p_T fluctuations.**
3. **Particle ratio fluctuations**
4. **Fluctuations of conserved quantities.**

Fluctuations Measure: During last 20 years

Observable	Definition	Non-dynamical	Experiments
ω_x	$\sigma_x^2/\langle N\rangle$ Scaled variance	Beyond poissionian (>1) Other models without PT	WA98, NA49, PHENIX
Φp_T	$z_{pT} = (p_{Ti} - \langle p_T\rangle)$; $Z_{pT} = \Sigma\ z_{pT}$ $\mathrm{Sqrt}(\langle Z_{pT}^2\rangle/\langle N\rangle) - \mathrm{Sqrt}(z_{pT}^2)$	= 0 by construction	NA49,PHENIX
ν_{dyn}	$\langle N_x (N_x - 1)\rangle/\langle N_x\rangle^2 + \langle N_y (N_y - 1)\rangle/\langle N_y\rangle^2 - 2 \langle N_x N_y\rangle/\langle N_x\rangle\langle N_y\rangle$	= 0 by construction	STAR
F_{pT}	$(\omega_{data} - \omega_{baseline})/\ \omega_{baseline}$	Baseline : Mixed events	PHENIX
Σ_{pT}	$X^2_{dyn} = \omega(\text{data}) - \omega(\text{inclusive single particle})$ $= \mathrm{sgn}(X^2_{dyn})\ \mathrm{Sqrt}(\lvert X^2_{dyn}\rvert)/\langle p_T\rangle$	= 0 by construction	CERES
$\langle \Delta p_{T,i} \Delta p_{T,j}\rangle$	$\frac{1}{\sum_{k=1}^{n_{ev}} N_k^{\text{pairs}}} \cdot \sum_{k=1}^{n_{ev}} \sum_{i=1}^{N_k} \sum_{j=i+1}^{N_k} (p_{ti} - \overline{p_t})(p_{tj} - \overline{p_t}).$	= 0 by construction	STAR, CERES
$\sigma_{x,dyn}$ $\Delta\sigma_{pt}$	$\sim \mathrm{sign}(\sigma^2(\text{data}) - \sigma^2(\text{mixed}))\mathrm{Sqrt}(\lvert\sigma^2(\text{data}) - \sigma^2(\text{mixed})\rvert)$	Mixed events	STAR

Most of those observables are looking at dynamical fluctuations with second order moment and non-conserved quantities.

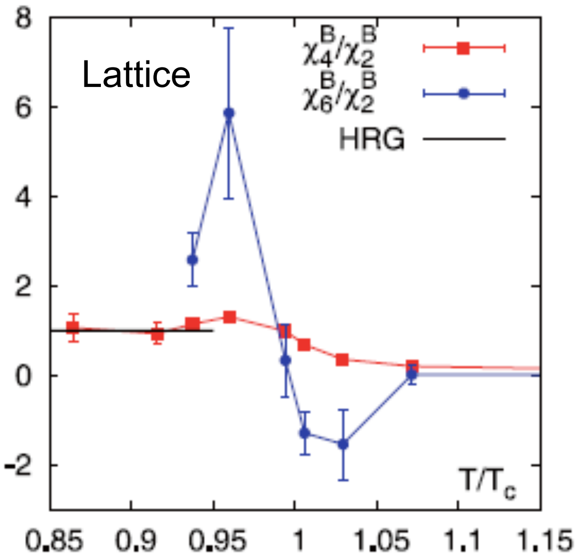
Higher Order Fluctuations of Conserved Quantities

1. Higher sensitivity to correlation length (ξ) and probe non-gaussian fluctuations near the Critical Point.

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

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

2. Direct connection to the susceptibility of the system.



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

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

Observables: Higher Moments (fluctuations)

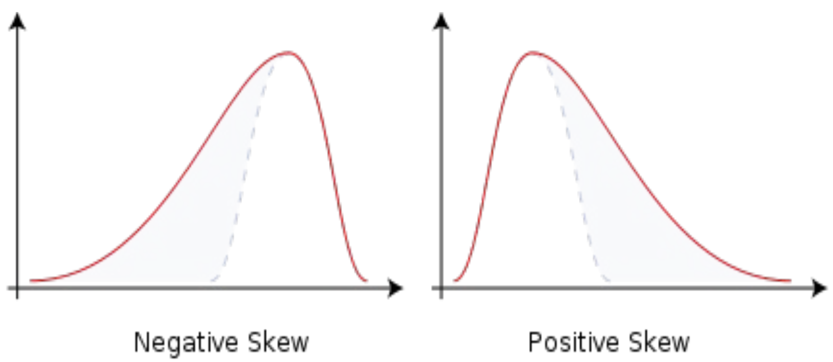
"Shape" of the fluctuations can be measured: non-Gaussian moments.

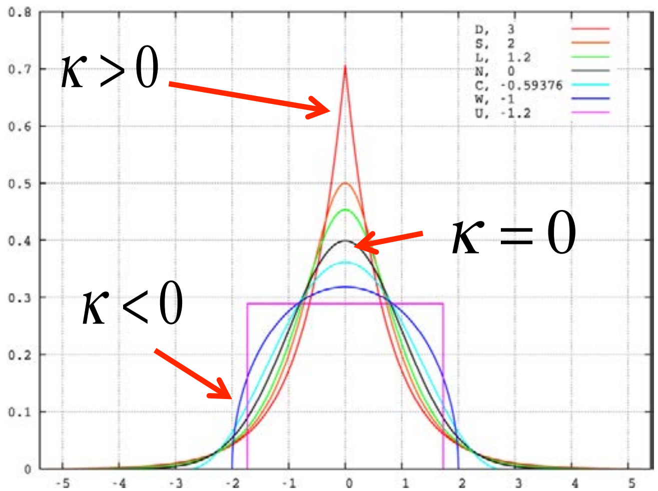
$$C_{1,x} = < x >, C_{2,x} = < (\delta x)^2 >,$$

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

$$S = \frac{C_{3,N}}{(C_{2,N})^{3/2}} = \frac{< (N - < N >)^3 >}{\sigma^3}$$

$$\kappa = \frac{C_{4,N}}{(C_{2,N})^2} = \frac{< (N - < N >)^4 >}{\sigma^4} - 3$$



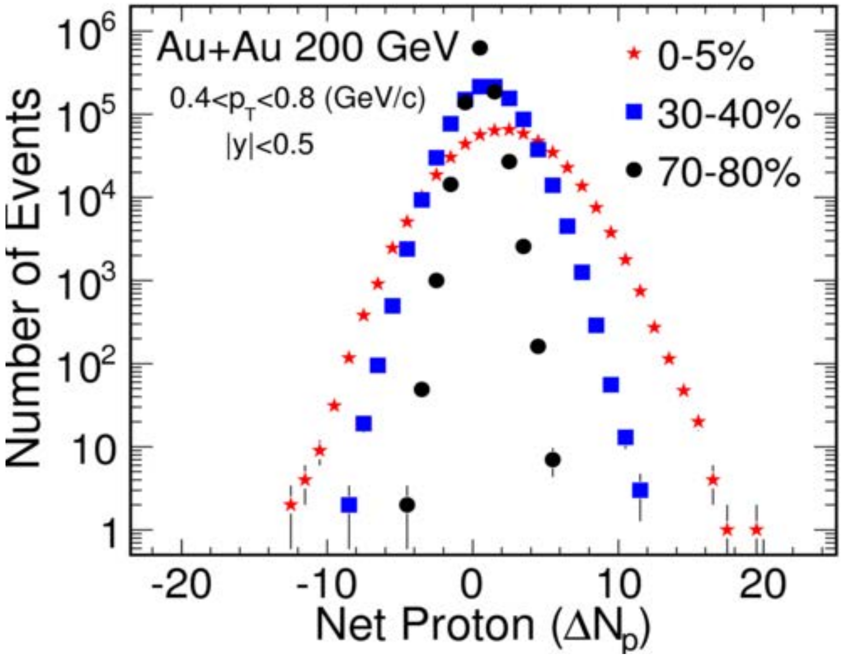


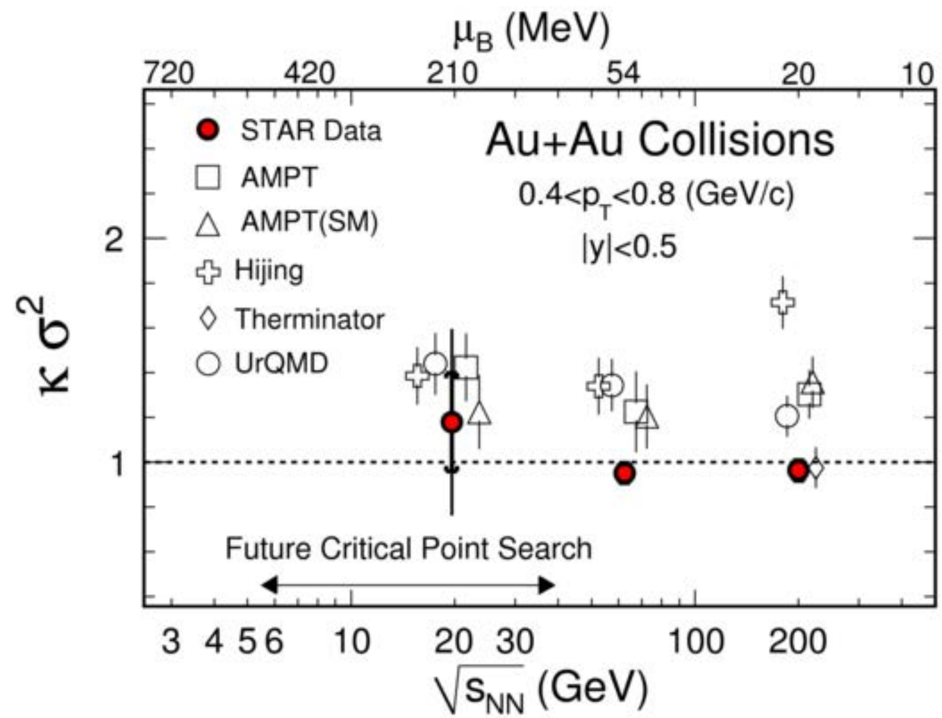
➢ **Susceptibility ratios ⇔ Cumulant Ratios (Cancel V dependence)**

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

(q=B, Q, S)

First measure: Higher moments of net-proton distributions





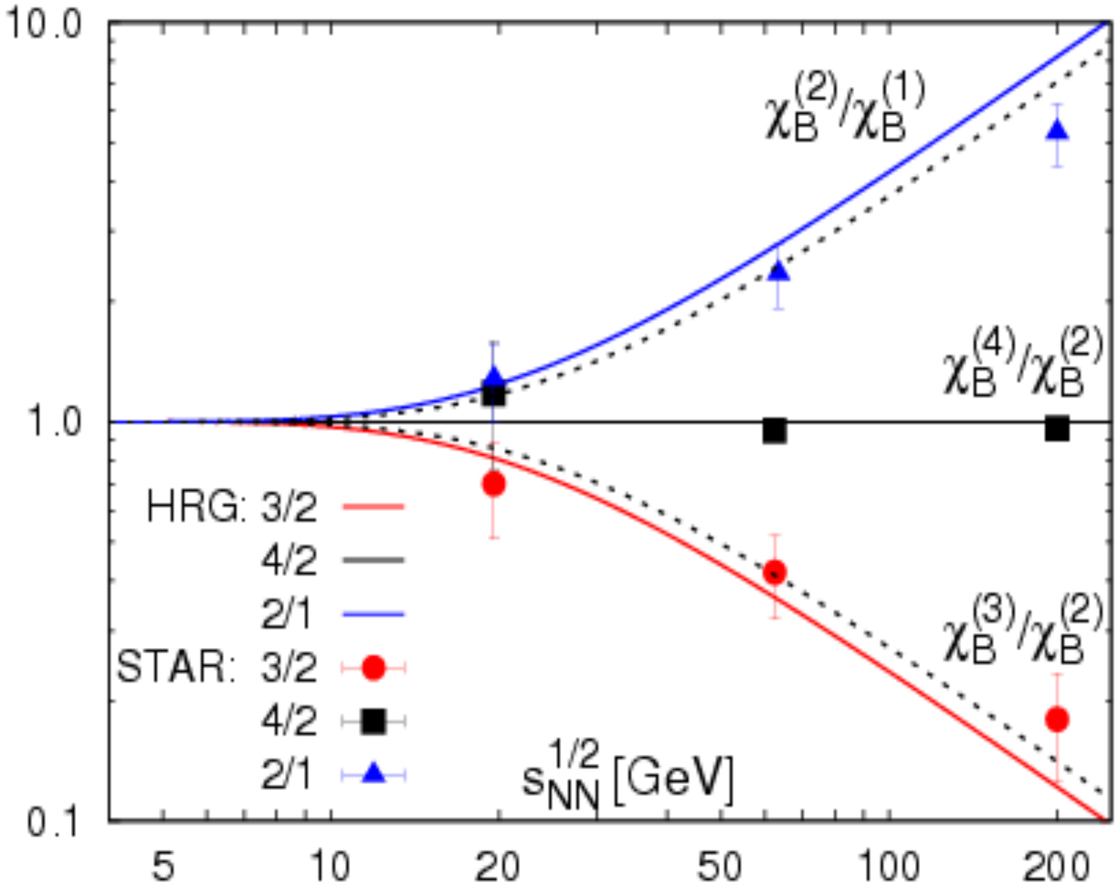
STAR: PRL105, 022302 (2010).

Net-proton fluctuations can reflect the diverges of baryon number fluctuations at CP and can be used to search for the CP.

Y. Hatta, Misha Stephanov, PRL 91, 102003 (2003).

- **There has no evidence for the existence of QCD critical point with μ_B <200 MeV.**

Hadron Resonance Model Calculation



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

χ_q^n n^th order susceptibility for conserved quantity q.

Baryon number fluctuation from thermal model. **Poisson statistics**

$$\kappa\sigma^2 = 1, S\sigma = \tanh(\mu_B / T)$$

F. Karsch et al, PLB695,136 (2011)

RHIC Beam Energy Scan- I (2010-2014)

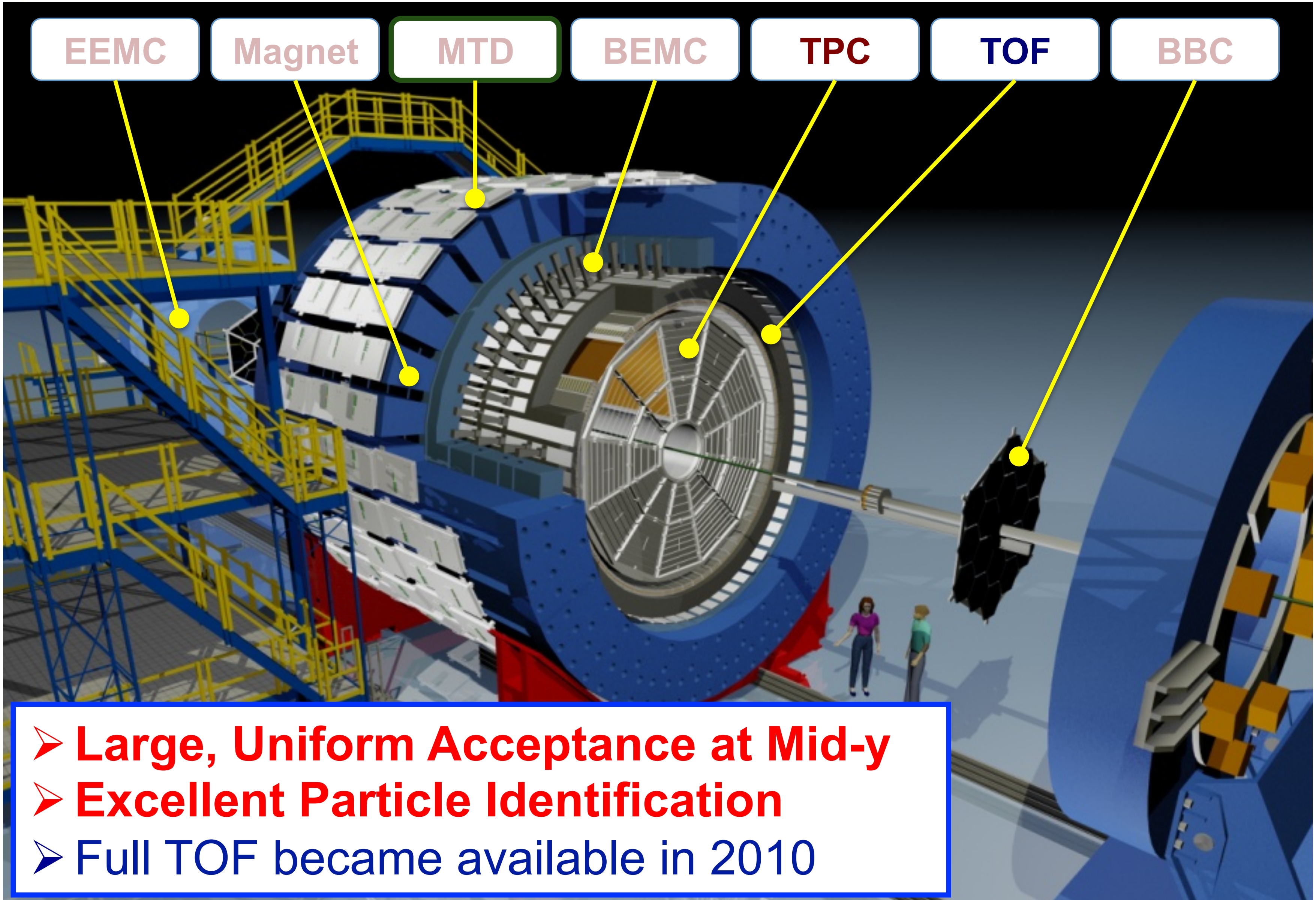
$\sqrt{s}$ (GeV)	Statistics(Millions) (0-80%)	Year	μ_B (MeV)	T (MeV)	μ_B /T
7.7	~4	2010	420	140	3.020
11.5	~12	2010	315	152	2.084
14.5	~ 20	2014	266	156	1.705
19.6	~36	2011	205	160	1.287
27	~70	2011	155	163	0.961
39	~130	2010	115	164	0.684
62.4	~67	2010	70	165	0.439
200	~350	2010	20	166	0.142

μ_B , T : J. Cleymans et al., Phys. Rev. C 73, 034905 (2006).

Study QCD Phase Structure

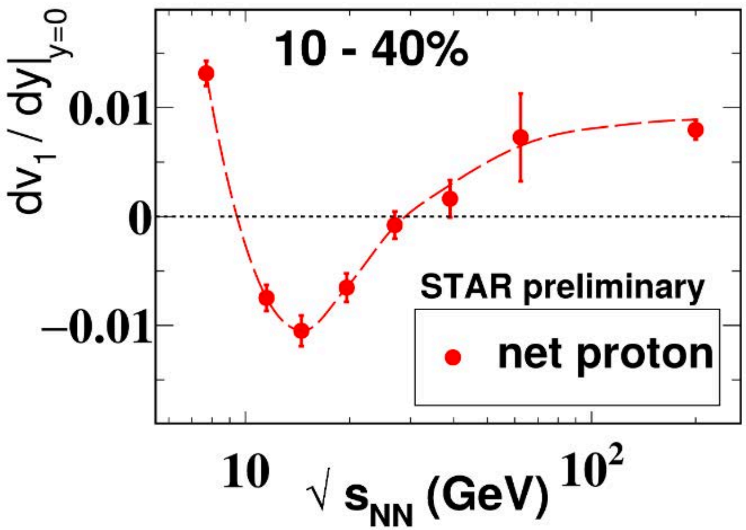
- Onset of sQGP
- Phase boundary and **critical point**

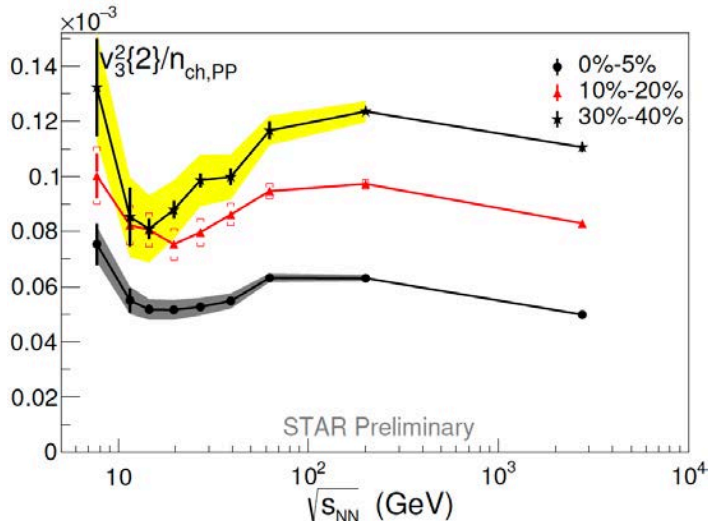
STAR Detector System

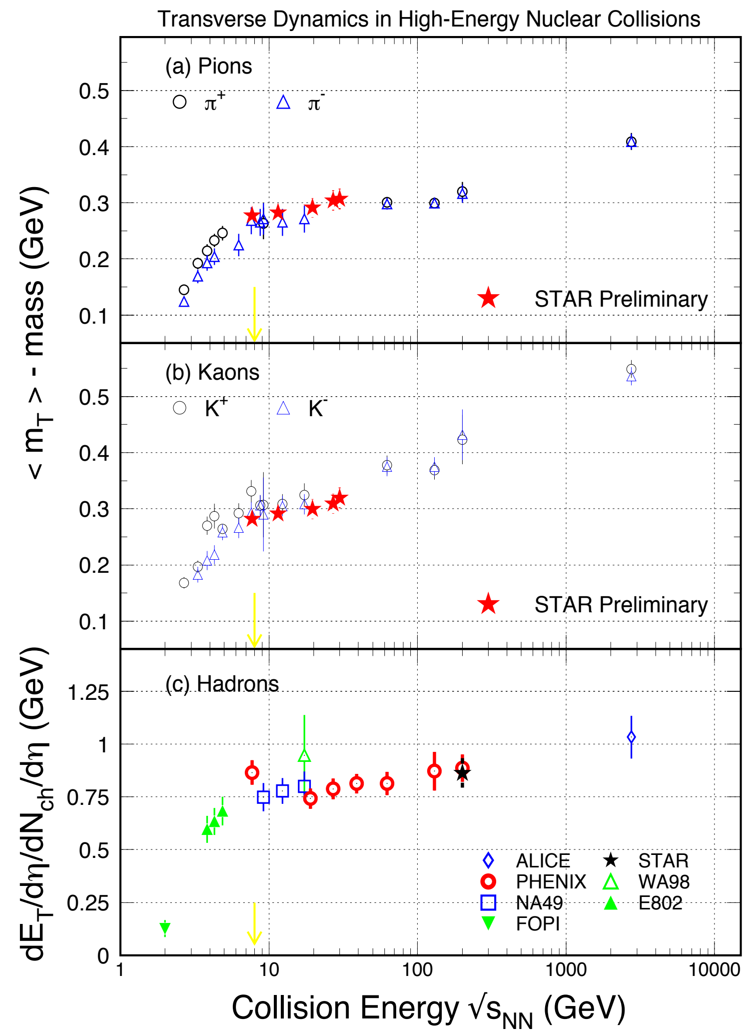


- Large, Uniform Acceptance at Mid-y
- Excellent Particle Identification
- Full TOF became available in 2010

First Order Phase Transition ?





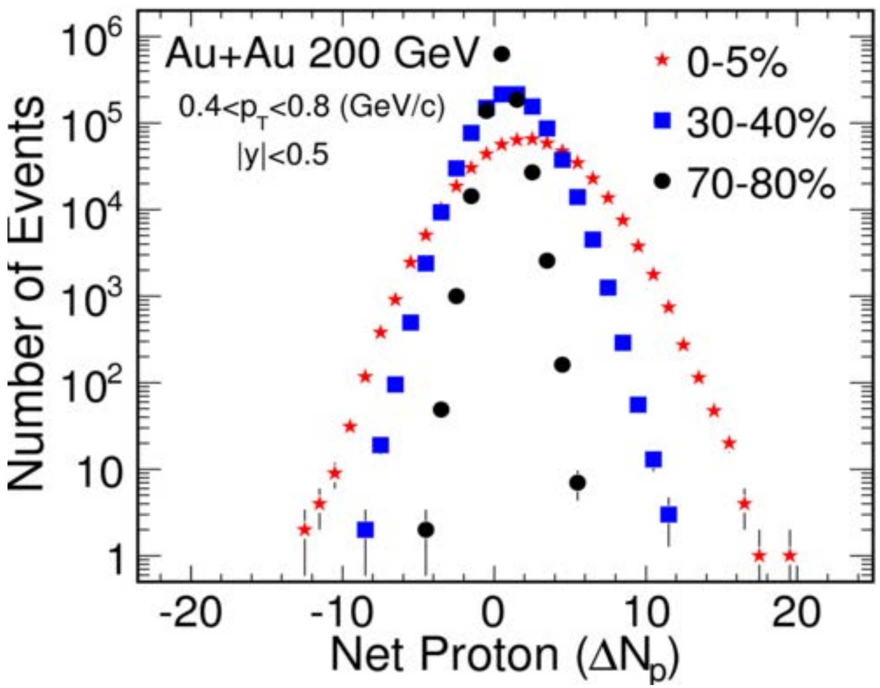


Indication of a First Order Phase Transition between 10-20 GeV ??

D.H. Rischke et al. HIP1, 309(1995) H. Stoecker, NPA750, 121(2005)
J. Steinheimer et al., arXiv:1402.7236 P. Konchakovski et al., arXiv:1404.276

Methodology

Raw net-p prob. distribution



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

1. Efficiency Correction.

Binomial efficiency response

2. Initial Volume Fluctuations.

centrality bin width correction.

3. Remove auto-correlation.

New centrality definition.

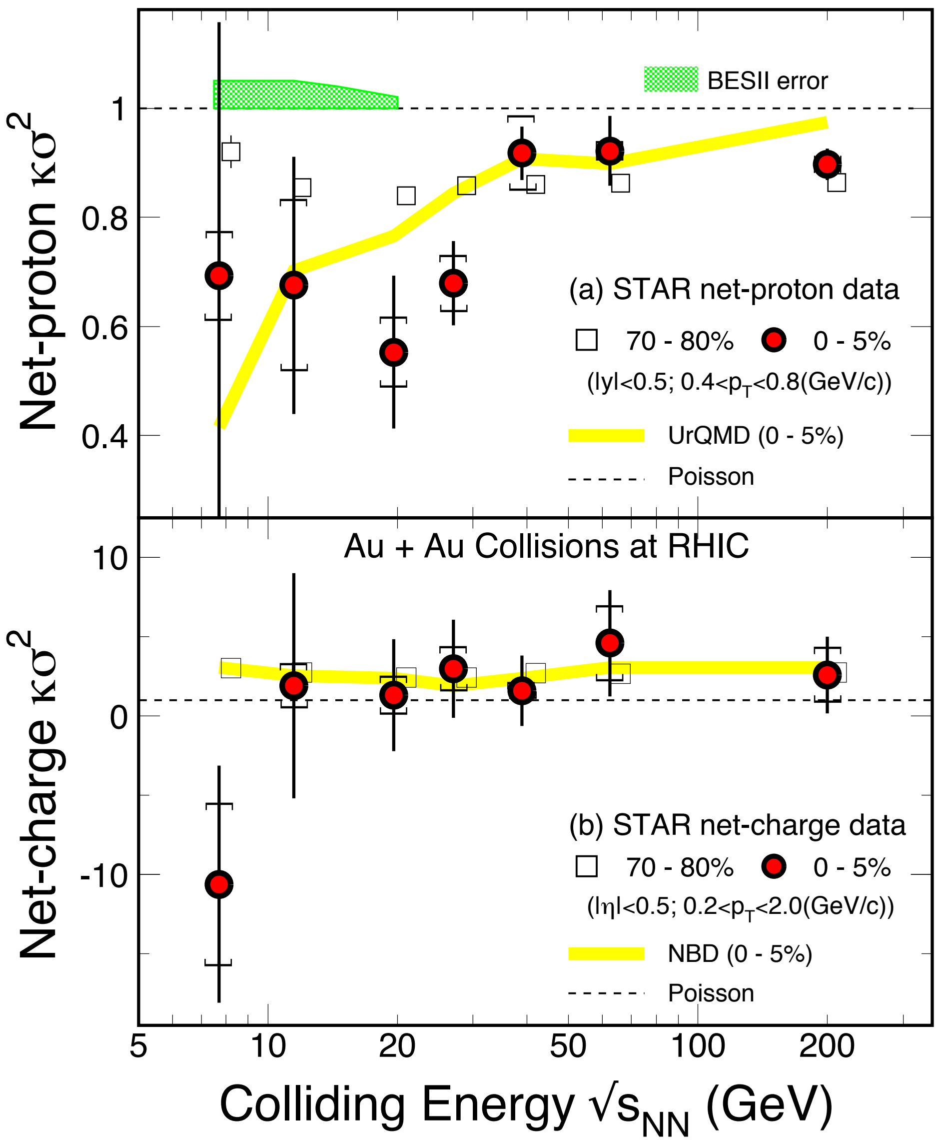
4. Statistical Error Estimation.

Delta theorem and Bootstrap

$$error \propto O\left(\sigma^n / \varepsilon^\alpha\right)$$

STAR: **PRL112**, 32302(14) ; **113**,092301(14).
X. Luo, J. Phys.: Conf. Ser. 316 012003 (2011); JPG 39, 025008 (2012); JPG 40, 105104 (2013); PRC 91, 043907 (2015).
A. Bzdak and V. Koch, PRC91,027901(2015), PRC86，044904(2012).

Results Published in 2014



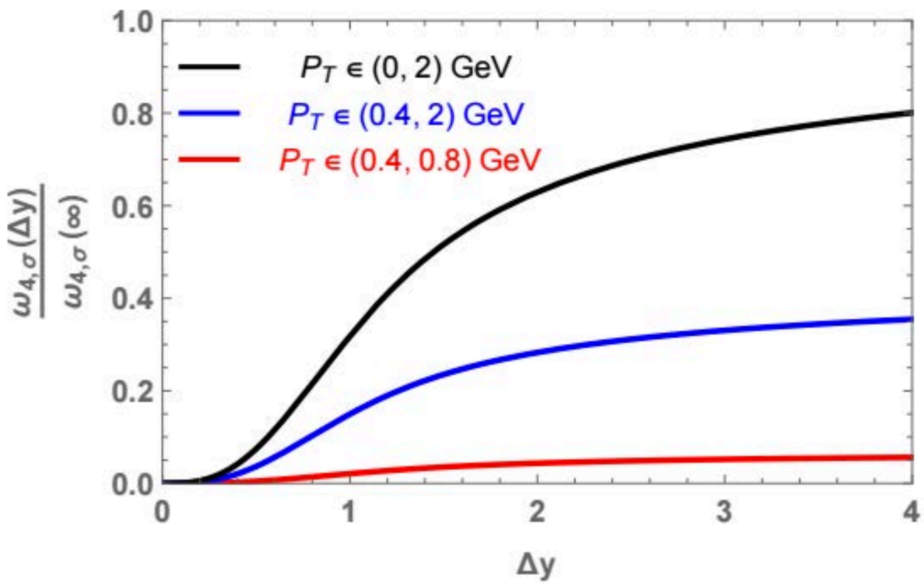
Net-proton ($0.4<p_T<0.8$ GeV/c):
All data show deviations below Poisson for $\kappa\sigma^2$ at all energies. Larger deviation at $\sqrt{s_{NN}} \sim 20$ GeV

Net-charge ($0.4<pT<2$ GeV/c) Need more statistics.

Poisson: $\kappa\sigma^2=1$

Net-proton: STAR: **PRL112**, 32302(2014)
Net-charge: STAR: **PRL113**,092301(2014)

Acceptance Dependence Study



Δy_{corr} : The correlation range in rapidity.
is determined by the momentum distribution of the particles at freezeout.
-- Diffusion + thermal Blurring effects.

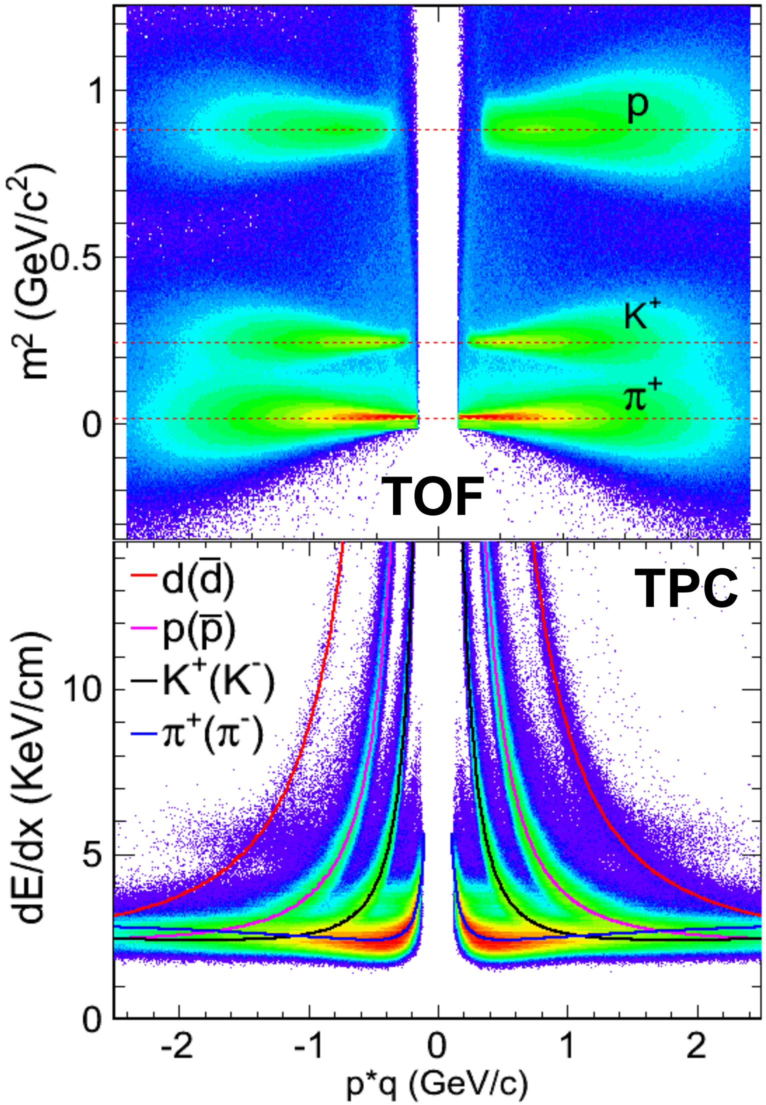
Critical contribution to fluctuations of proton number strongly depends on acceptance in both p_T and rapidity.

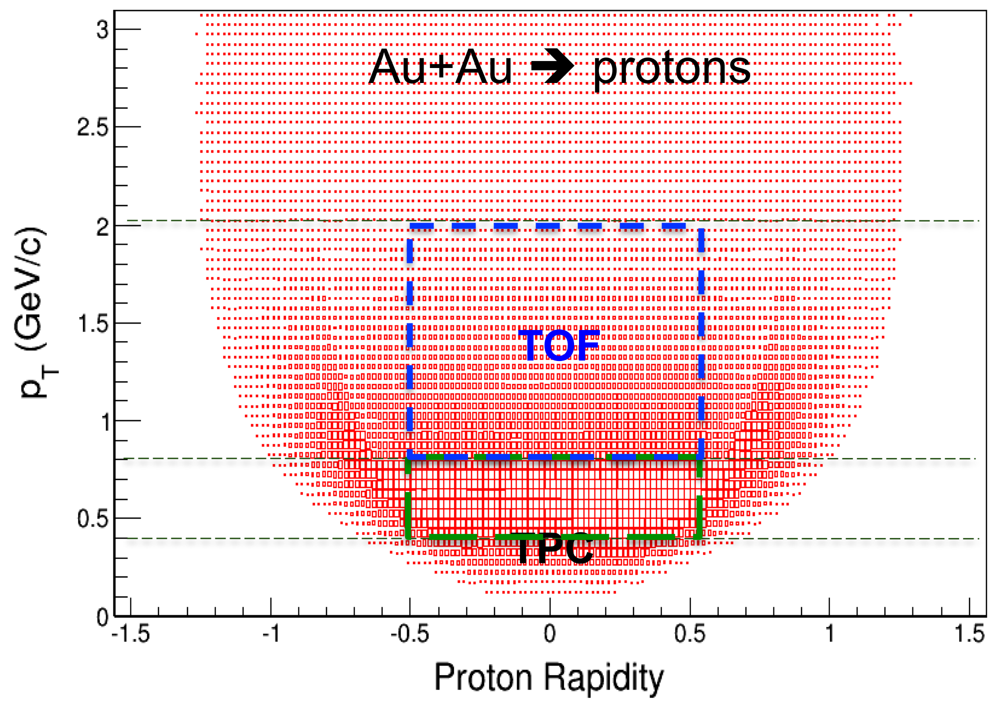
It is important to explore the acceptance dependence of the fluctuation measures.

V. Koch, arXiv: 0810. 2520; B. Ling, M. Stephanov, arXiv: 1512. 09125. M. Asakawa and M. Kitazawa, arXiv:1512.05038; MK, NPA942，65 (2015). M. Sakaida et al, PRC90 (2014) 6, 064911

New Net-proton Analysis: Larger p_T Acceptance

TOF is used for Identify p/pbar in addition with TPC to extend the p_T coverage.





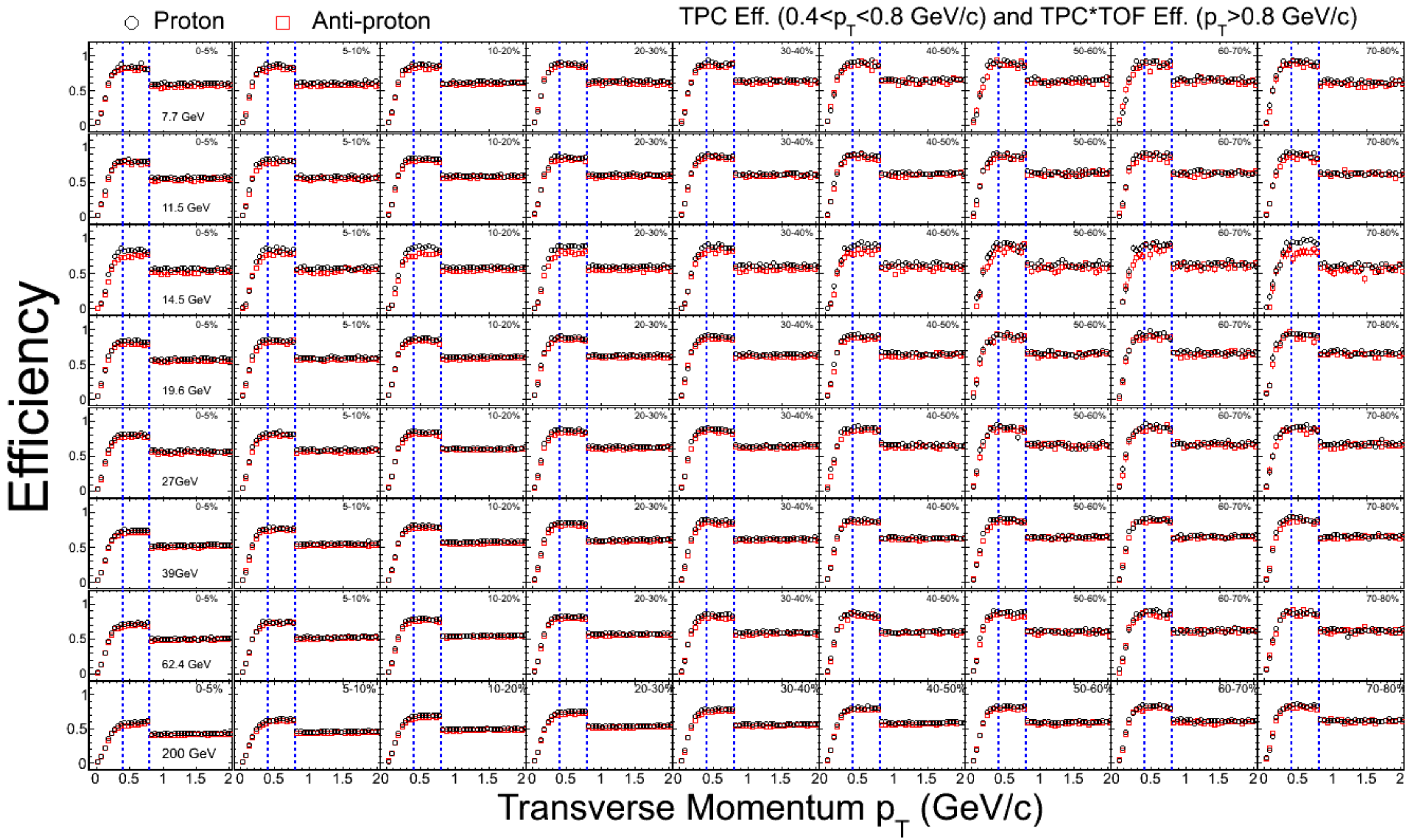
Acceptance: $|y| \leq 0.5$, $0.4 \leq p_T \leq 2$ GeV/c

Efficiency corrections:

TPC ($0.4 \leq p_T \leq 0.8$ GeV/c): **$\varepsilon_{TPC} \sim 0.8$**

TPC+TOF ($0.8 \leq p_T \leq 2$ GeV/c): **$\varepsilon_{TPC} * \varepsilon_{TOF} \sim 0.5$**

Efficiency for Proton and Anti-proton



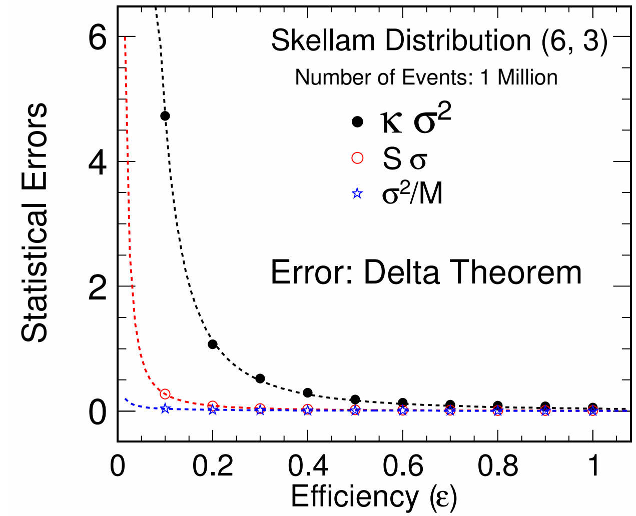
Efficiency are nearly constant for p and pbar within two different p_T region.

Efficiency correction and error estimation methods : X. Luo, PRC91, 034907 (2015).

Efficiency Correlation and Error Estimation

We provide a unified description of efficiency correction and error estimation for higher moments analysis in heavy-ion collisions.

$$F_{r_1,r_2}(N_p,N_{\bar{p}}) = F_{r_1,r_2}(N_{p_1}+N_{p_2}, N_{\bar{p}_1}+N_{\bar{p}_2})$$
$$= \sum_{i_1=0}^{r_1}\sum_{i_2=0}^{r_2} s_1(r_1,i_1)s_1(r_2,i_2) < (N_{p_1}+N_{p_2})^{i_1}(N_{\bar{p}_1}+N_{\bar{p}_2})^{i_2} >$$
$$= \sum_{i_1=0}^{r_1}\sum_{i_2=0}^{r_2} s_1(r_1,i_1)s_1(r_2,i_2) < \sum_{s=0}^{i_1}\binom{i_1}{s} N_{p_1}^{i_1-s}N_{p_2}^{s} \sum_{t=0}^{i_2}\binom{i_2}{t} N_{\bar{p}_1}^{i_2-t}N_{\bar{p}_2}^{t} >$$
$$= \sum_{i_1=0}^{r_1}\sum_{i_2=0}^{r_2}\sum_{s=0}^{i_1}\sum_{t=0}^{i_2} s_1(r_1,i_1)s_1(r_2,i_2)\binom{i_1}{s}\binom{i_2}{t} < N_{p_1}^{i_1-s}N_{p_2}^{s}N_{\bar{p}_1}^{i_2-t}N_{\bar{p}_2}^{t} >$$
$$= \sum_{i_1=0}^{r_1}\sum_{i_2=0}^{r_2}\sum_{s=0}^{i_1}\sum_{t=0}^{i_2}\sum_{u=0}^{i_1-s}\sum_{v=0}^{s}\sum_{j=0}^{i_2-t}\sum_{k=0}^{t} s_1(r_1,i_1)s_1(r_2,i_2)\binom{i_1}{s}\binom{i_2}{t}$$
$$\times s_2(i_1-s,u)s_2(s,v)s_2(i_2-t,j)s_2(t,k) \times F_{u,v,j,k}(N_{p_1},N_{p_2},N_{\bar{p}_1},N_{\bar{p}_2})$$



Fitting formula: $f(\varepsilon) = \frac{1}{\sqrt{n}}\frac{a}{\varepsilon^b}$

X. Luo, PRC91, 043907 (2015).

We can express the moments and cumulants in terms of the factorial moments, which can be easily efficiency corrected.

Assume Binomial response for efficiency

$$F_{u,v,j,k}(N_{p_1},N_{p_2},N_{\bar{p}_1},N_{\bar{p}_2}) = \frac{f_{u,v,j,k}(n_{p_1},n_{p_2},n_{\bar{p}_1},n_{\bar{p}_2})}{(\varepsilon_{p_1})^u(\varepsilon_{p_2})^v(\varepsilon_{\bar{p}_1})^j(\varepsilon_{\bar{p}_2})^k}$$

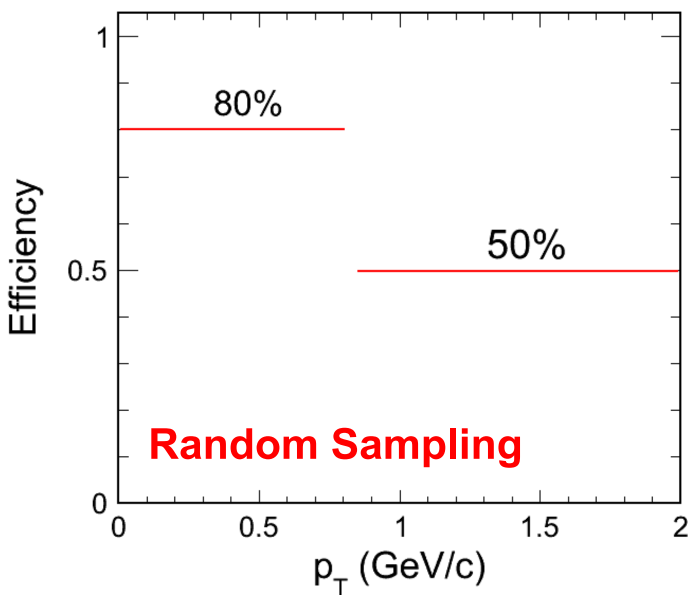
Also see:
A. Bzdak and V. Koch, PRC91,027901(2015), PRC86，044904(2012).

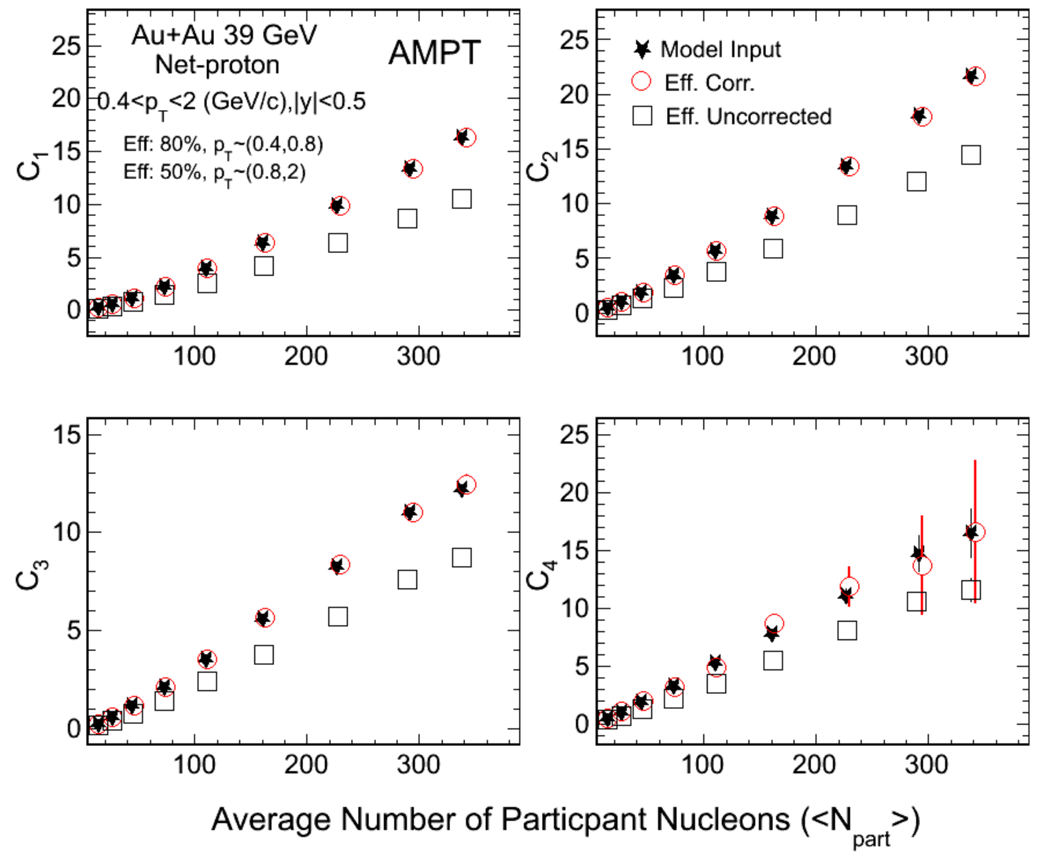
Verification of the Eff. Correction Method with Model

AMPT model: Au+Au 39 GeV.

X. Luo, PRC91, 043907 (2015).

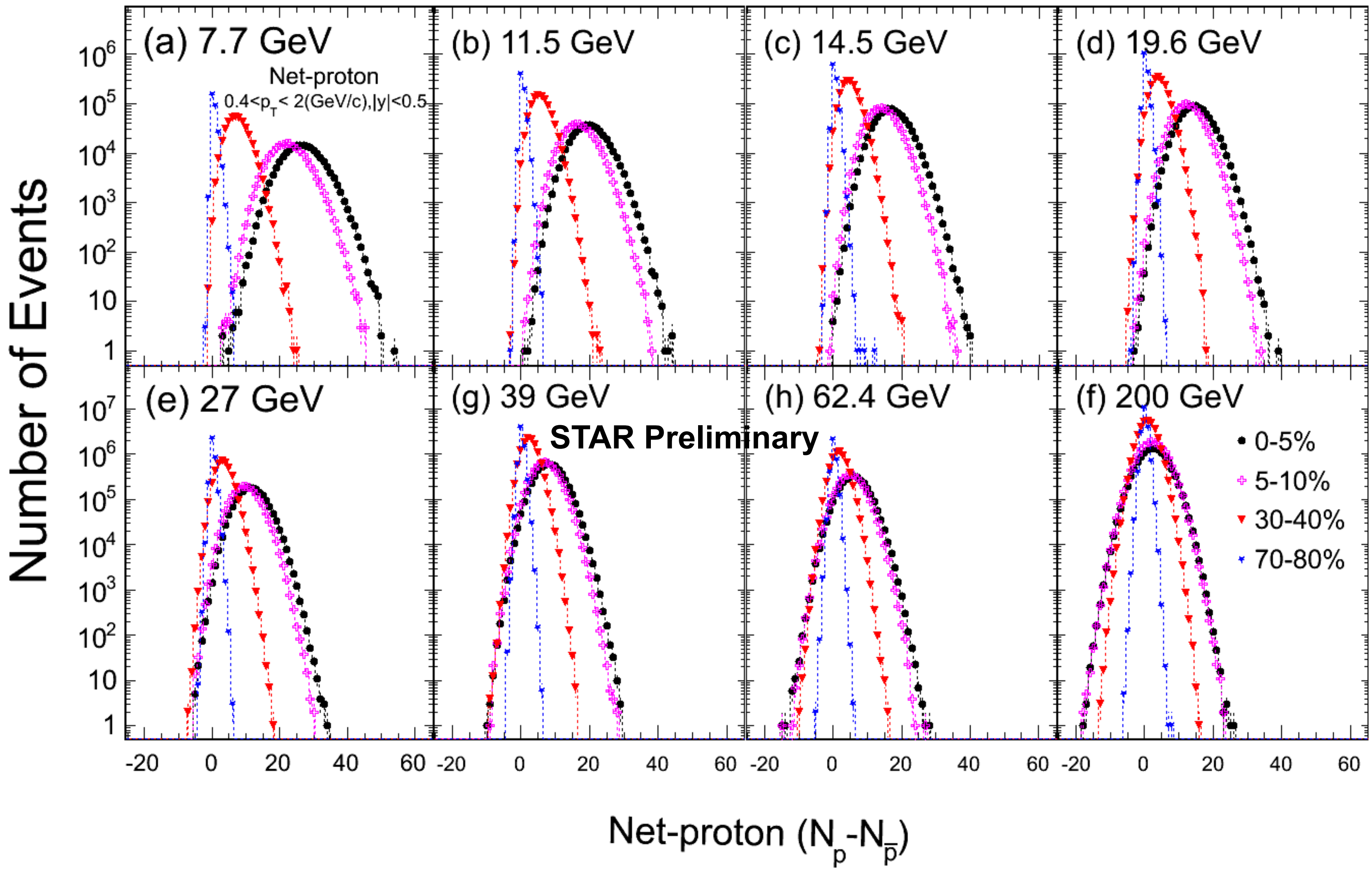
Set different efficiency for two p_T range.
(0.4, 0.8) : 80%, (0.8, 2): 50% for p and pbar.



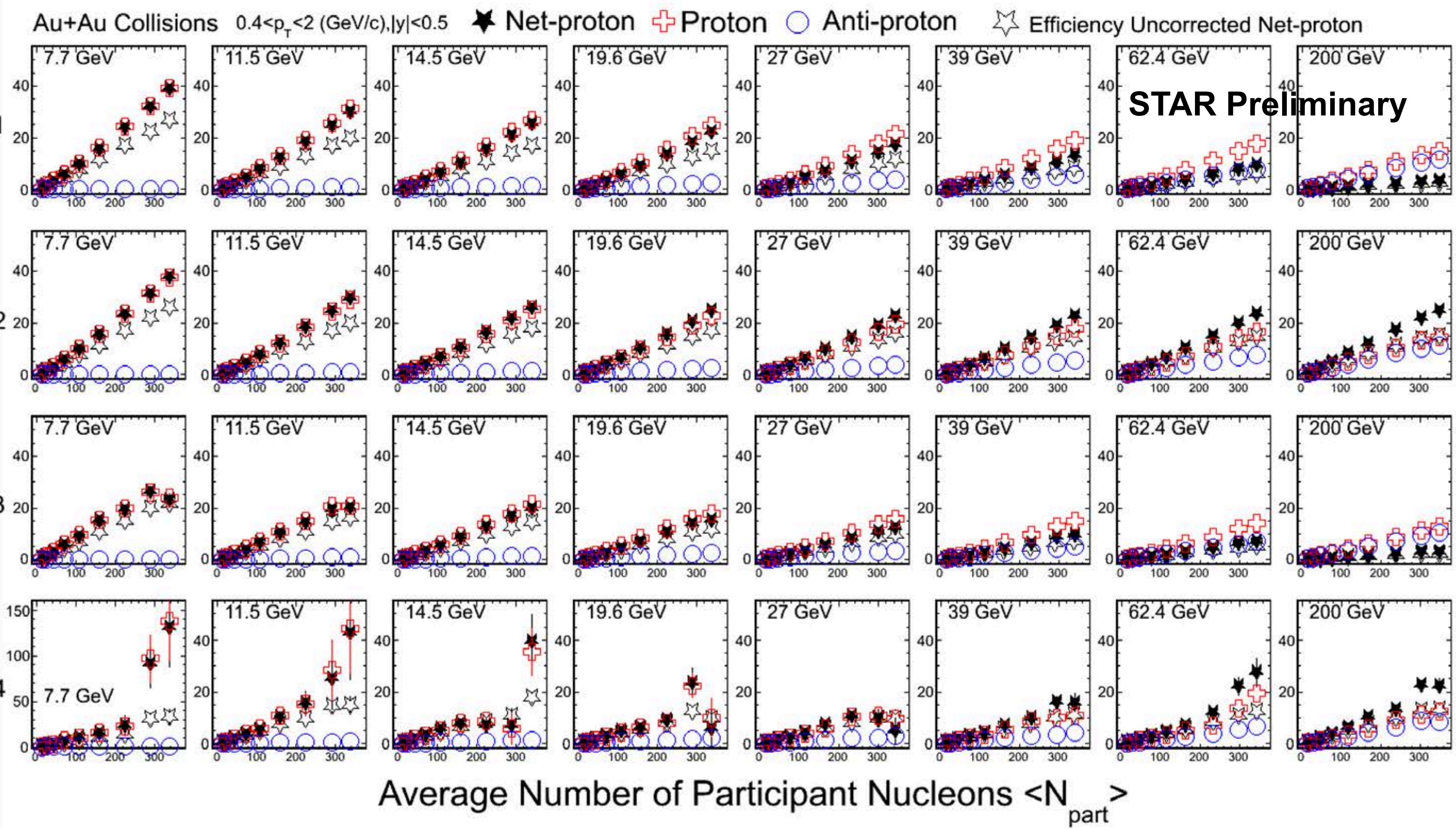


1. The eff. corrected results match the model inputs very well, which indicate the efficiency correction method works well.
2. The error estimation for eff. corrected results are based on the Delta theorem.

Raw Net-proton Multiplicity Distributions



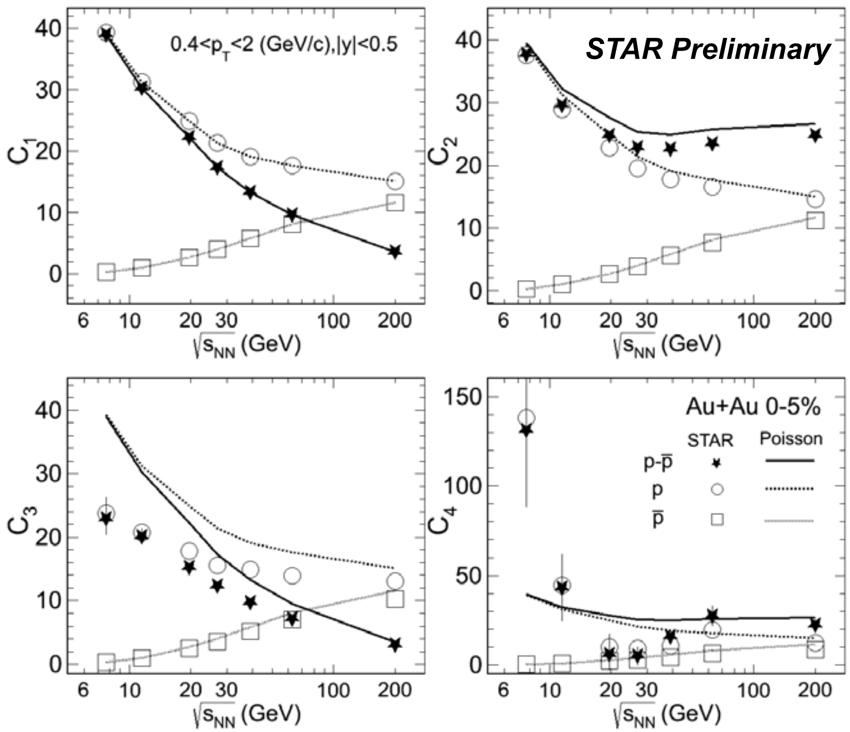
Cumulants: C1~C4



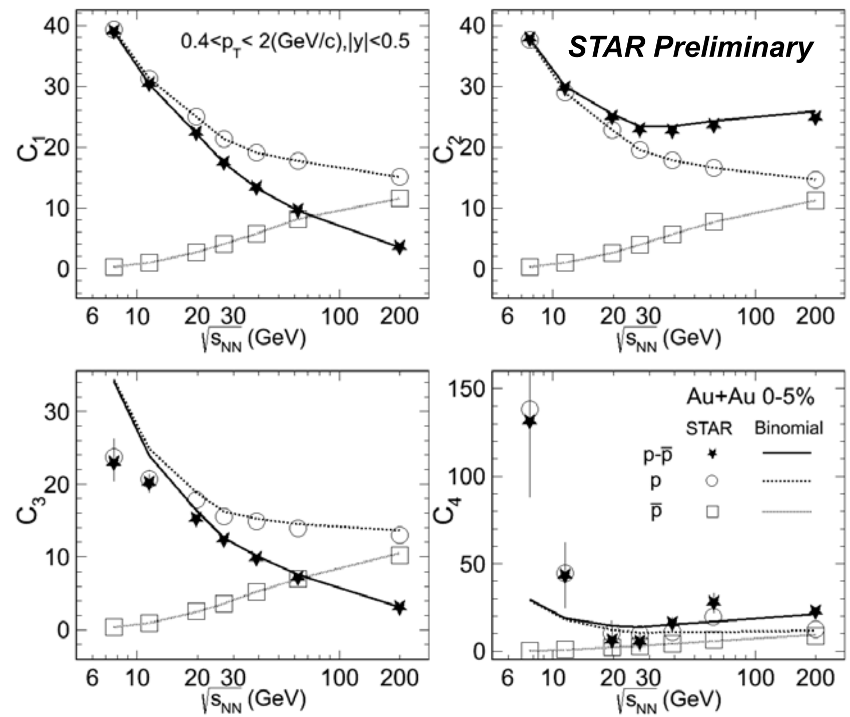
In general, cumulants are increasing with $\langle N_{part} \rangle$.
Significant increase for C4 at most two central bin at 7.7 GeV.

Cumulants vs. Baselines

Cumulants vs. Poissonn(M)

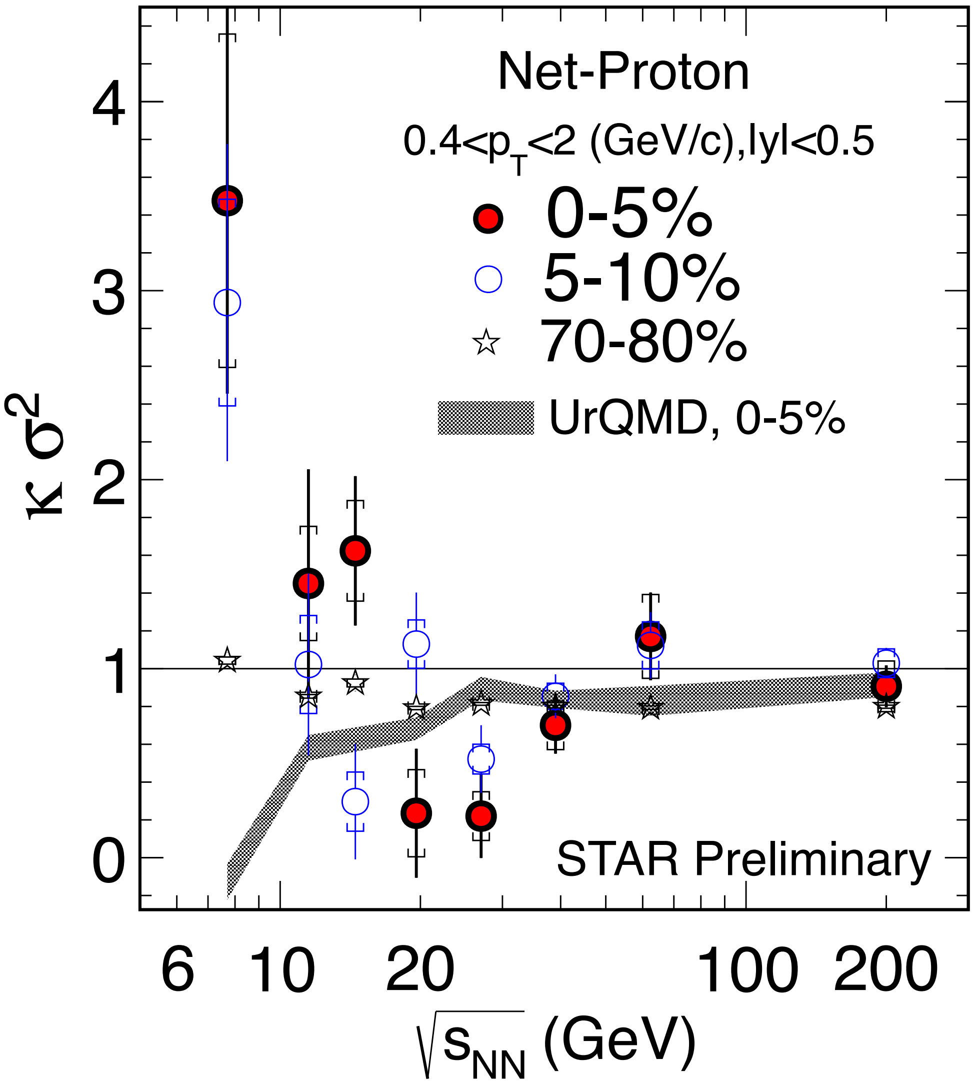


Cumulants vs. Binomial (M,σ)



- The higher the order of cumulants the larger deviations from Poisson expectations for net-proton and proton.
- The binomial distribution (BD) better described the data than Poisson. But large deviations seen in C_3 and C_4.

Forth Order Fluctuations: Net-proton



$$\kappa\sigma^2 = C_4/C_2$$

- Non-monotonic trend is observed for the 0-5% most central Au+Au collisions. Dip structure is observed around 19.6 GeV.

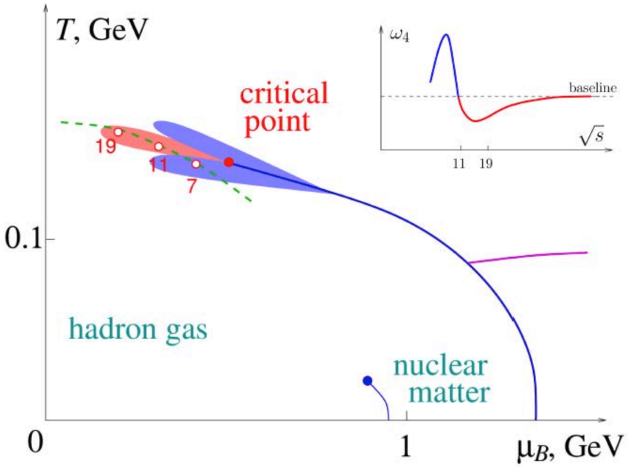
- Separating and flipping for the results of 0-5% and 5-10% centrality are observed at 14.5 and 19.6 GeV. (**Oscillation Pattern observed !**)

- UrQMD (no CP) results show suppression at low energies. Consistent with the effects of baryon number conservation.

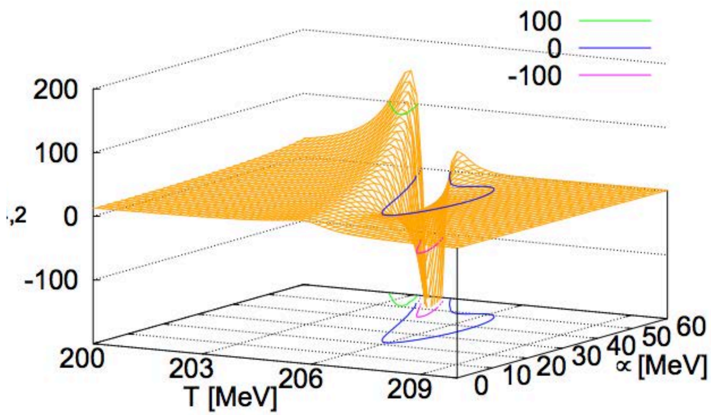
Systematic errors: 1) Uncertainties on efficiency, 2) PID, 3) Track Cuts.

Sign of Kurtosis :Model and Theoretical Calculations

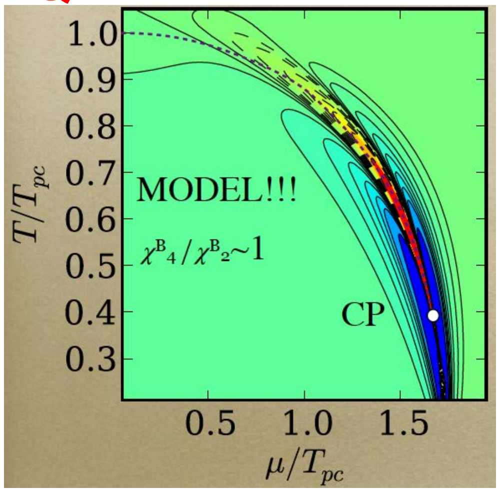
σ model M.A. Stephanov, PRL107, 052301 (2011).



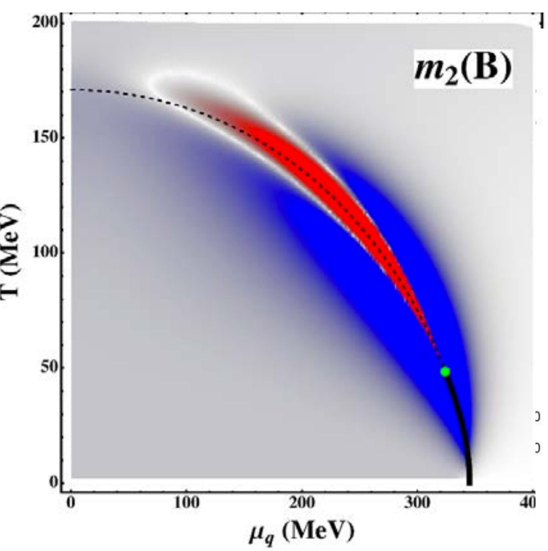
PQM Schaefer&Wanger, PRD 85, 034027 (2012)



PQM V. Skokov, QM2012

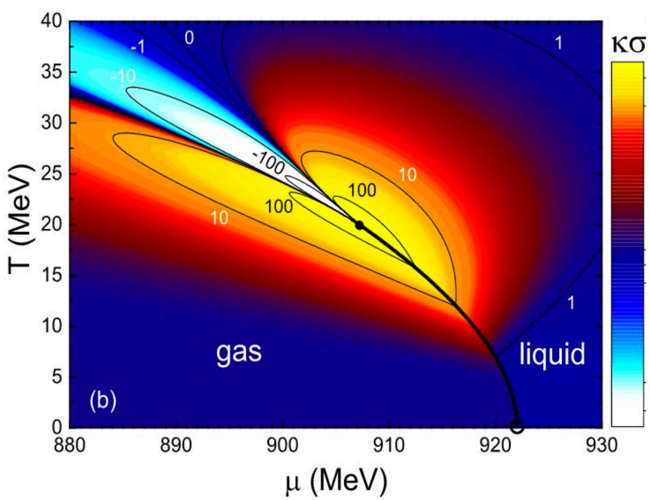


NJL



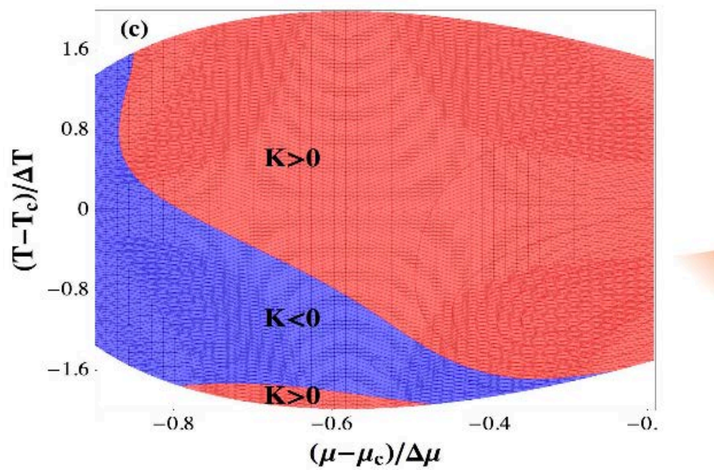
JW Chen et al., arXiv:1509.04968

VDW



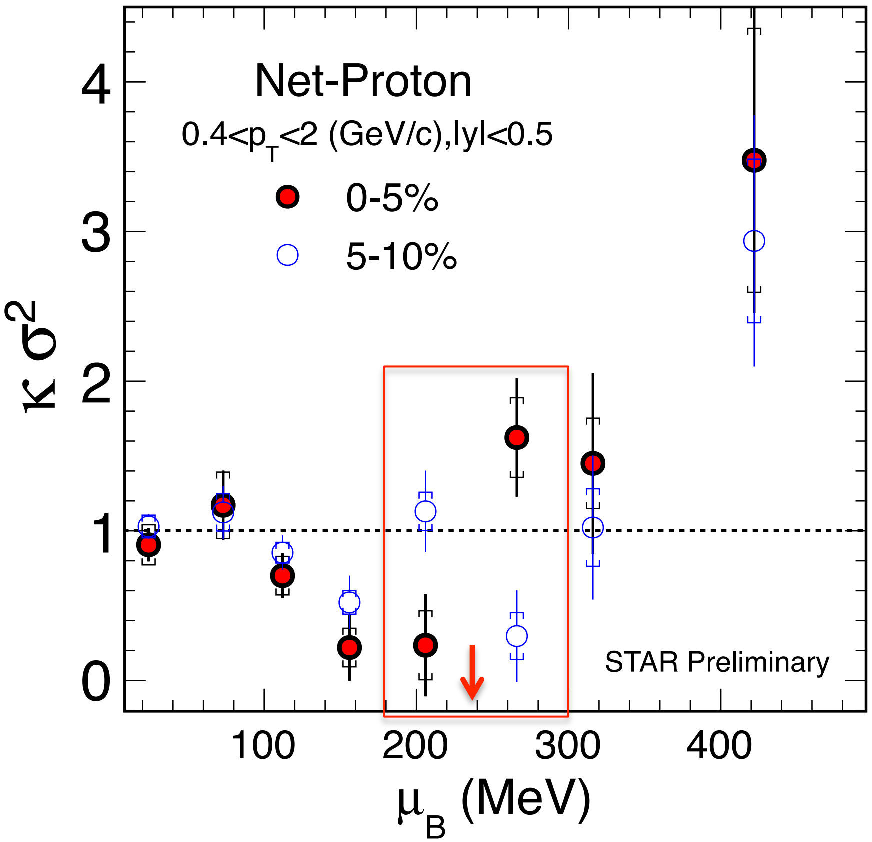
Vovchenko et al., arXiv:1506.05763

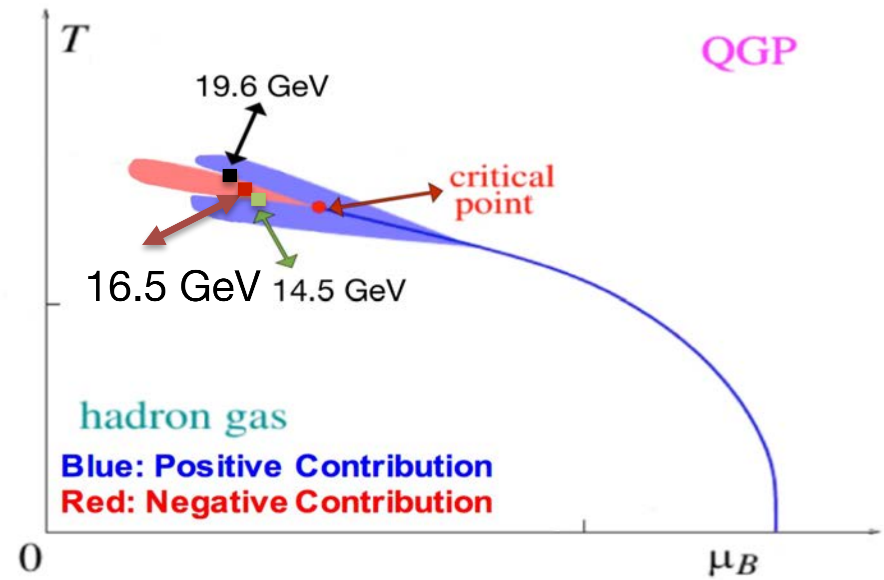
Memory Effects



Swagato, et al, PRC92,034912 (2015).

Oscillation Pattern: Signature of Critical Region ?





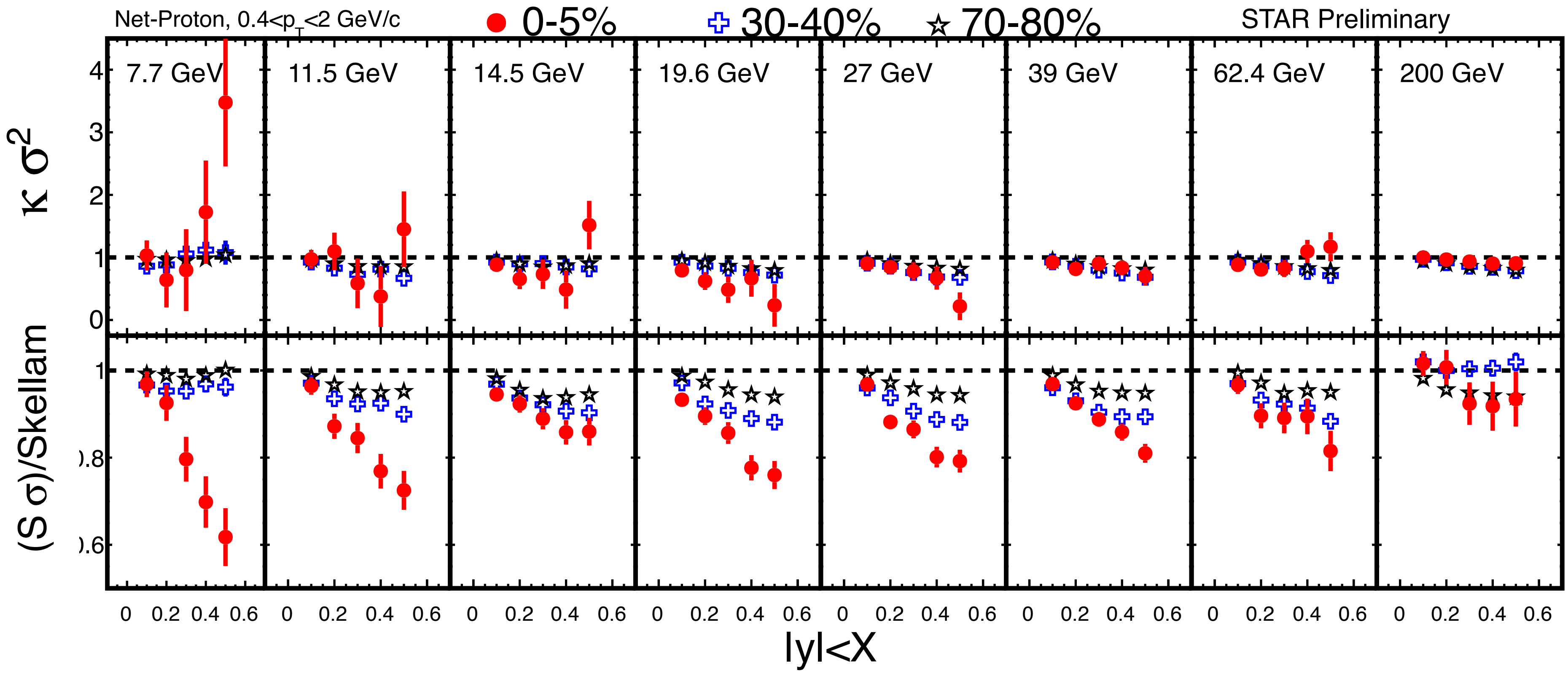
Depending on relative position between reaction trajectories/freeze out position and critical region.

"Oscillation pattern" around baseline for Kurtosis **may indicate a signature of critical region.**

$\kappa\sigma^2$	0-5%	5-10%
14.5 GeV	**1+Pos.**	**1+Neg.**
19.6 GeV	**1+Neg.**	**1+Pos.**

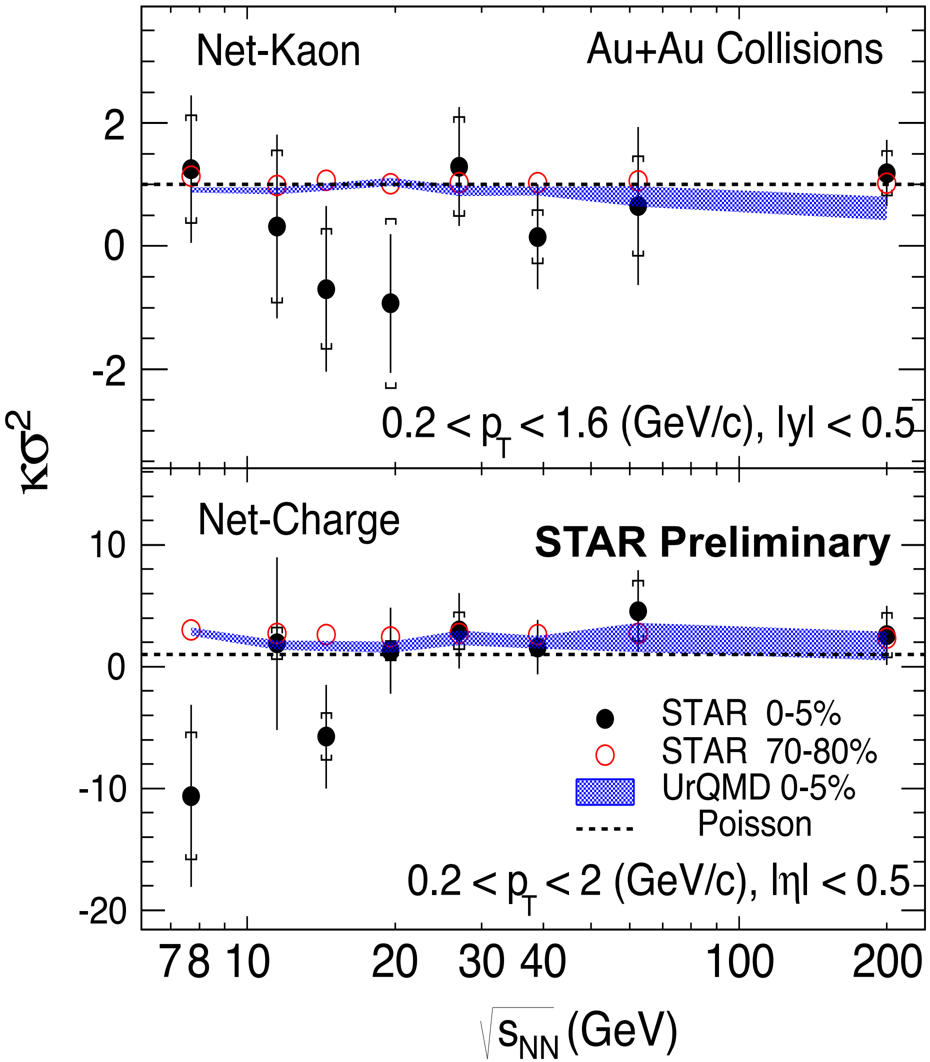
Propose to scan **16.5 GeV (μ_B =238 MeV)** or even finer step between 14.5 and 19.6 GeV, expect to see bigger dip and no separation for the results of the 0-5% and 5-10%.

Rapidity Window Dependence



Significant rapidity window dependence are observed.
Large acceptance is crucial for the fluctuation measurement.

Moments of Net-Charge and Net-Kaon Distributions



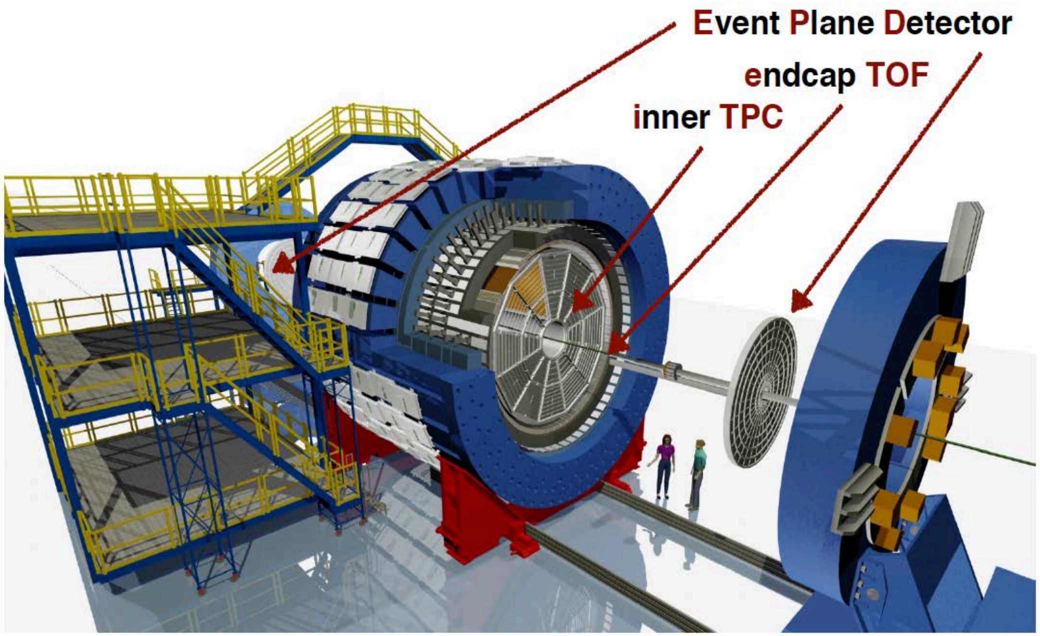
- Within current errors, Net-Kaon and Net-Charge $\kappa\sigma^2$ are consistent with unity.
- More statistics are needed to make a conclusion.
- UrQMD (no CP), show no energy dependent.

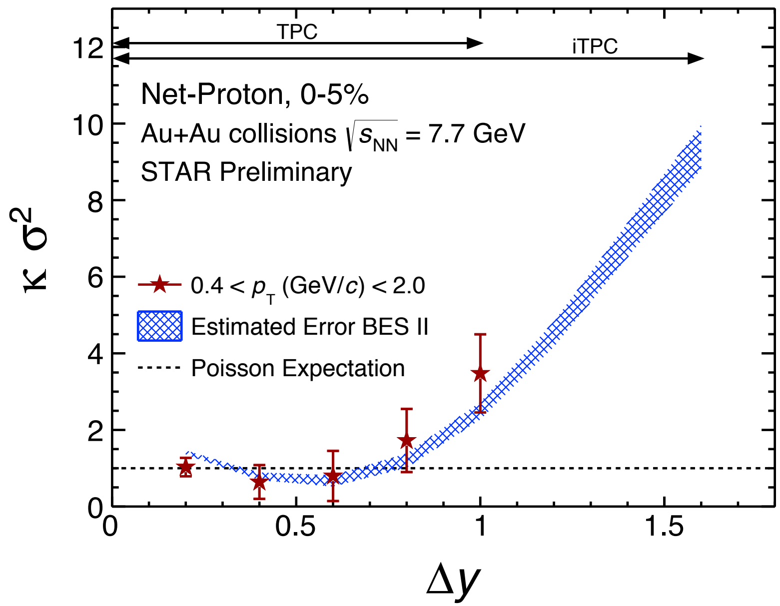
$$error(\kappa\sigma^2) \propto \frac{1}{\sqrt{N}} \frac{\sigma^2}{\varepsilon^2}$$

σ : Measured width of distributions.
ε : Efficiency.

In STAR, with the same # of events: error(Net-Q) > error(Net-K) > error (Net-P)

STAR Upgrades and BES Phase-II (2019-2020)





iTPC proposal: http://drupal.star.bnl.gov/STAR/starnotes/public/sn0619
BES-II whitepaper: http://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

Larger rapidity acceptance crucial for further critical point search with net-protons

- Electron cooling upgrade will provide increased luminosity ~ 3-10 times.
- Inner TPC(iTPC) upgrade : |η| < 1 to | η |< 1.5. Better dE/dx resolution.
- Forward Event Plane Detector (EPD)：Centrality and Event Plane Determination. 1.8 < |η| < 4.5

Summary

- We present centrality and energy dependence of cumulants and cumulant ratios for proton, anti-proton and net-proton at mid-rapidity (|y|<0.5) and p_T coverage up to 2 GeV/c for Au+Au collisions at 7.7,11.5, 14.5, 19.6, 27, 39, 62.4 and 200 GeV.

- Non-monotonic behavior is observed at most central collisions. Oscillation pattern are observed at 0-5% and 5-10% for 14.5 and 19.6 GeV, which could be indication of critical region. Propose to scan 16.5 GeV, could see bigger dip and no oscillation.

- Acceptance (p_T and y) studies indicate large acceptance is crucial for fluctuation measurements.

Discovery Potential at High Baryon Density

It is time to discover the QCD Critical Point !

Welcome to the STAR !