Search for the QCD Critical Point -

Fluctuations of Conserved Quantities in High Energy Nuclear Collisions at STAR

Status and Future Plan

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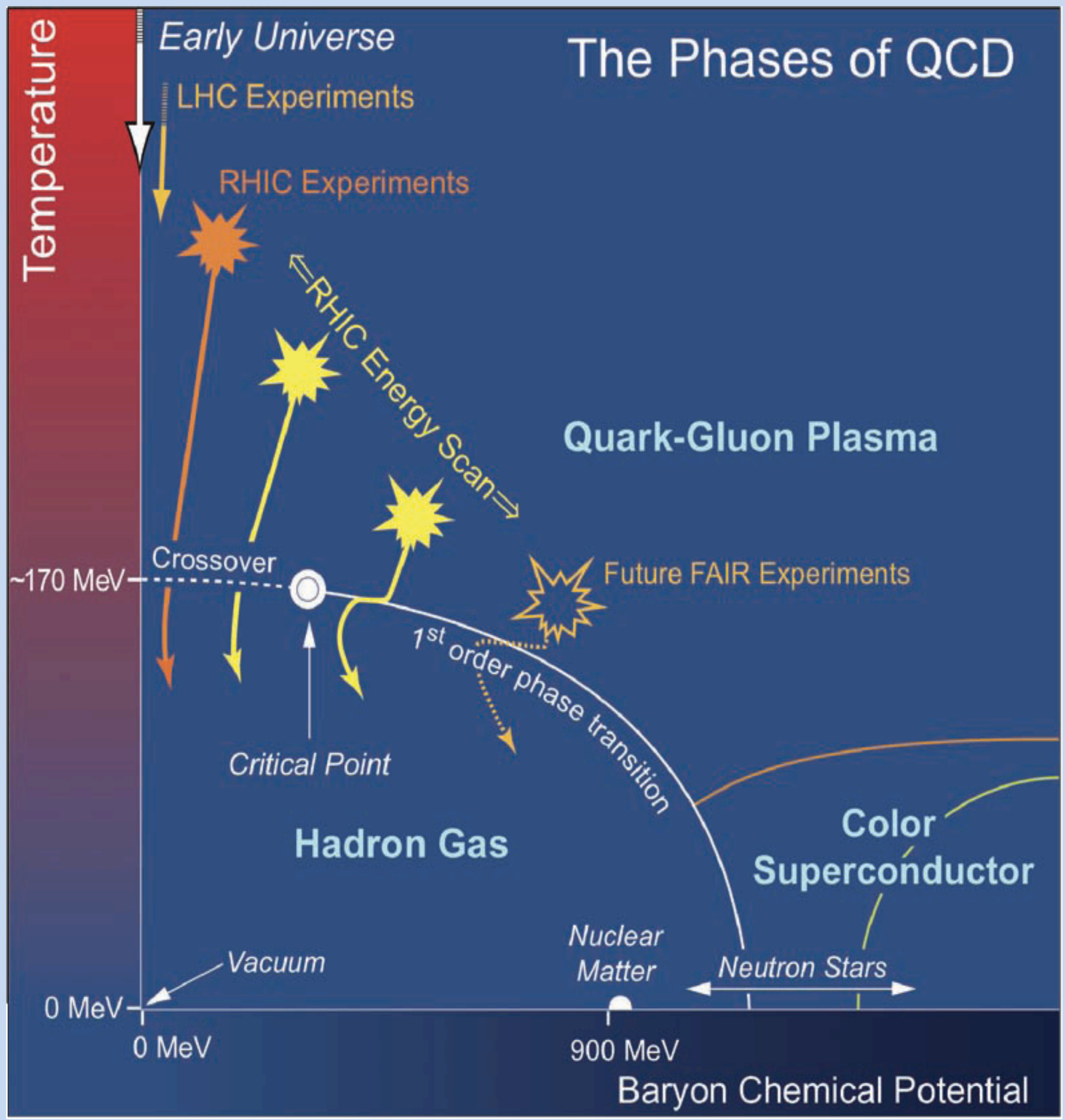
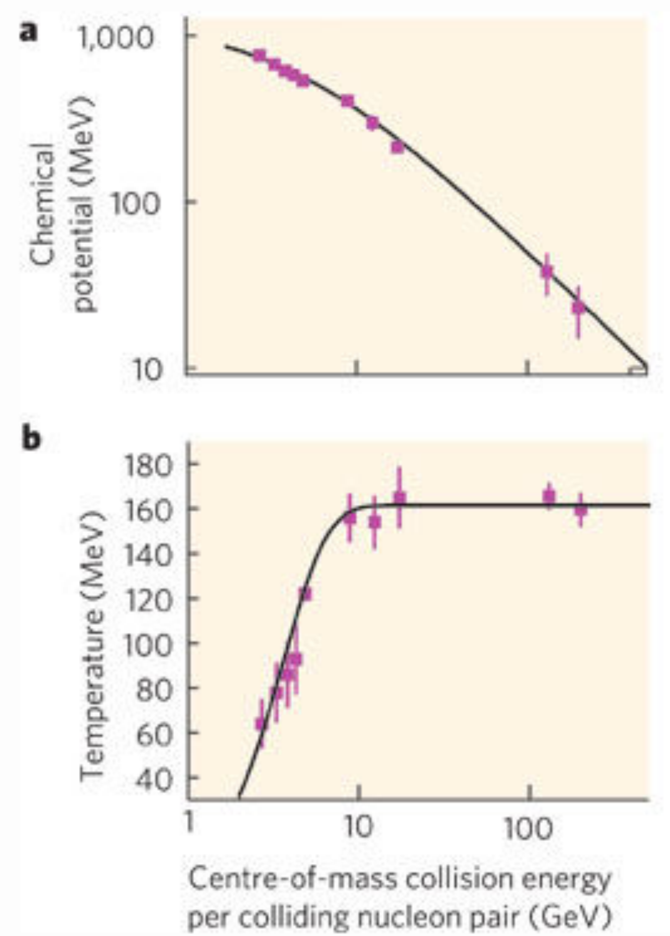
QCD Phase Structure and Beam Energy Scan

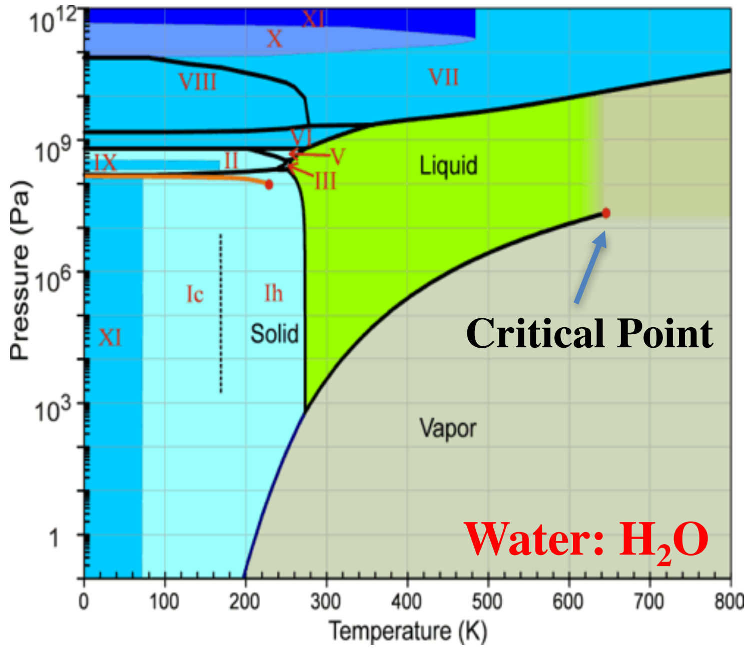




PBM&Johanna, Nature **448**, 302-309 (2007)

Scan the QCD phase diagram by varying the colliding energies in HIC.

Critical Phenomena and Critical Point



- Diverges of the thermodynamics quantities, such as correlation length (ξ), susceptibilities (χ), specific heat (C_V). Critical opalescence
- With the same Z(2) universality class as liquid-gas phase transition.

First CP is discovered in 1869 for CO_2

T_c = 31°C

Electromagnetic interaction

Can we discovery the Critical Point of Quark Matter ?

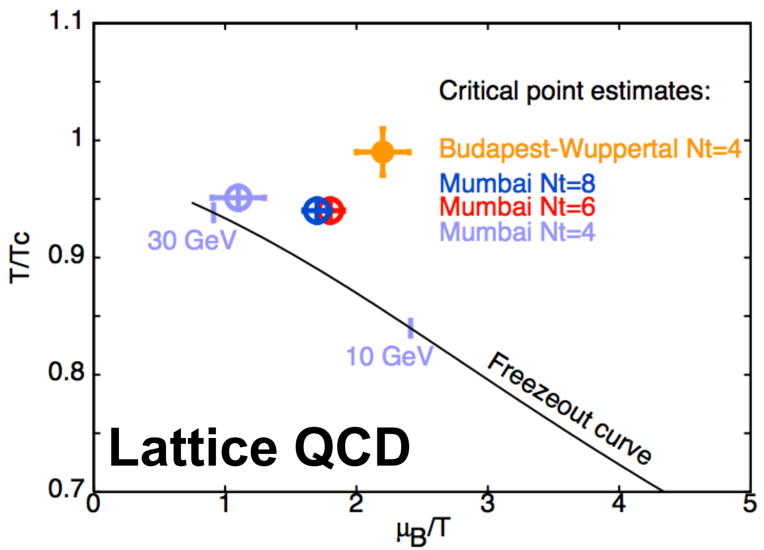
T_c ~ Trillion (10^{12}) °C

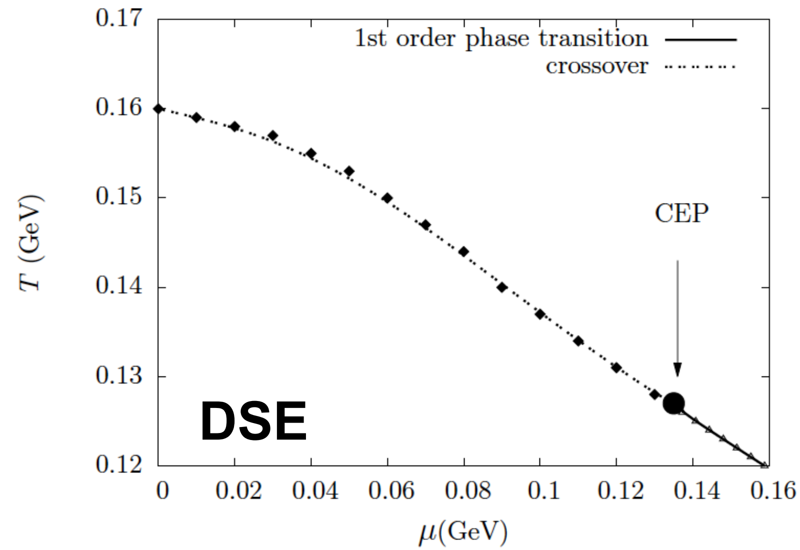
Strong interaction

Search for the QCD critical point in HIC, Challenges:

1. Finite size/time effects. (ξ=2~3 fm)
2. Non-equilibrium effects

Location of CEP: Theoretical Prediction





Lattice QCD:

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

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

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

Dyson-Schwinger Equation (DSE):

1): Y. X. Liu, et al., PRD90, 076006 (2014); 94, 076009 (2016).
$(\mu^E_B, T^E) = (372, 129)$; $(262.3, 126.3)$ MeV

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

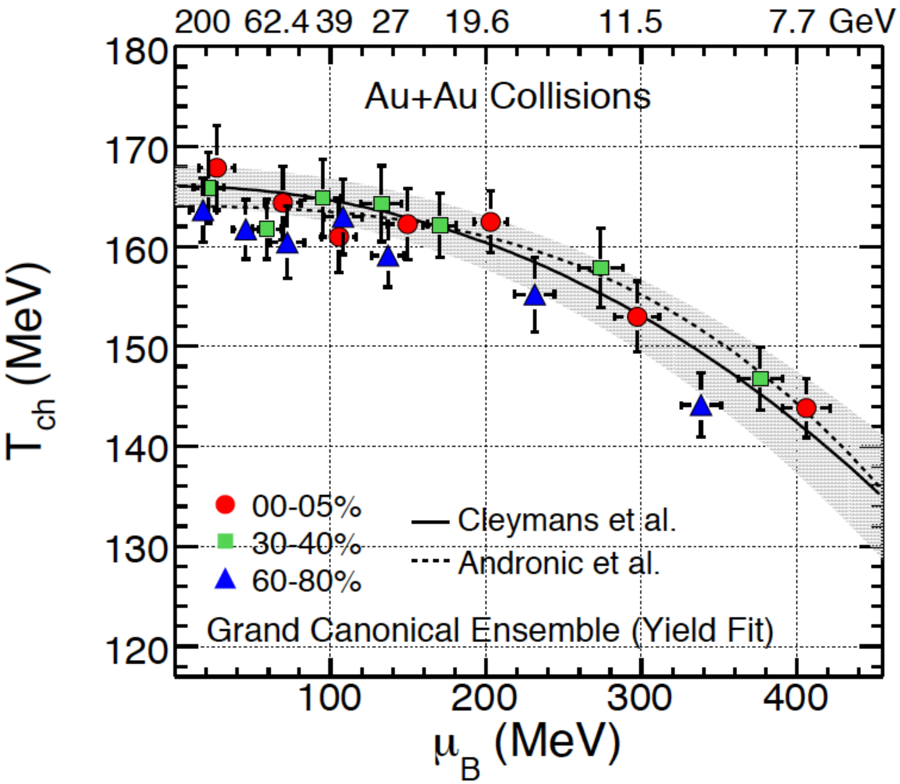
3): C. S. Fischer et al., PRD90, 034022 (2014).
$(\mu^E_B, T^E) = (504, 115)$ MeV

μ^E_B = 262 ~ 504 MeV, T_E = 115~162 MeV, μ^E_B / T_E = 1.74~4.38

RHIC Beam Energy Scan I (2010-2014)

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year	$^*\mu_B$ (MeV)	$^*T_{CH}$ (MeV)
200	350	2010	25	166
62.4	67	2010	73	165
39	39	2010	112	164
27	70	2011	156	162
19.6	36	2011	206	160
14.5	20	2014	264	156
11.5	12	2010	316	152
7.7	4	2010	422	140

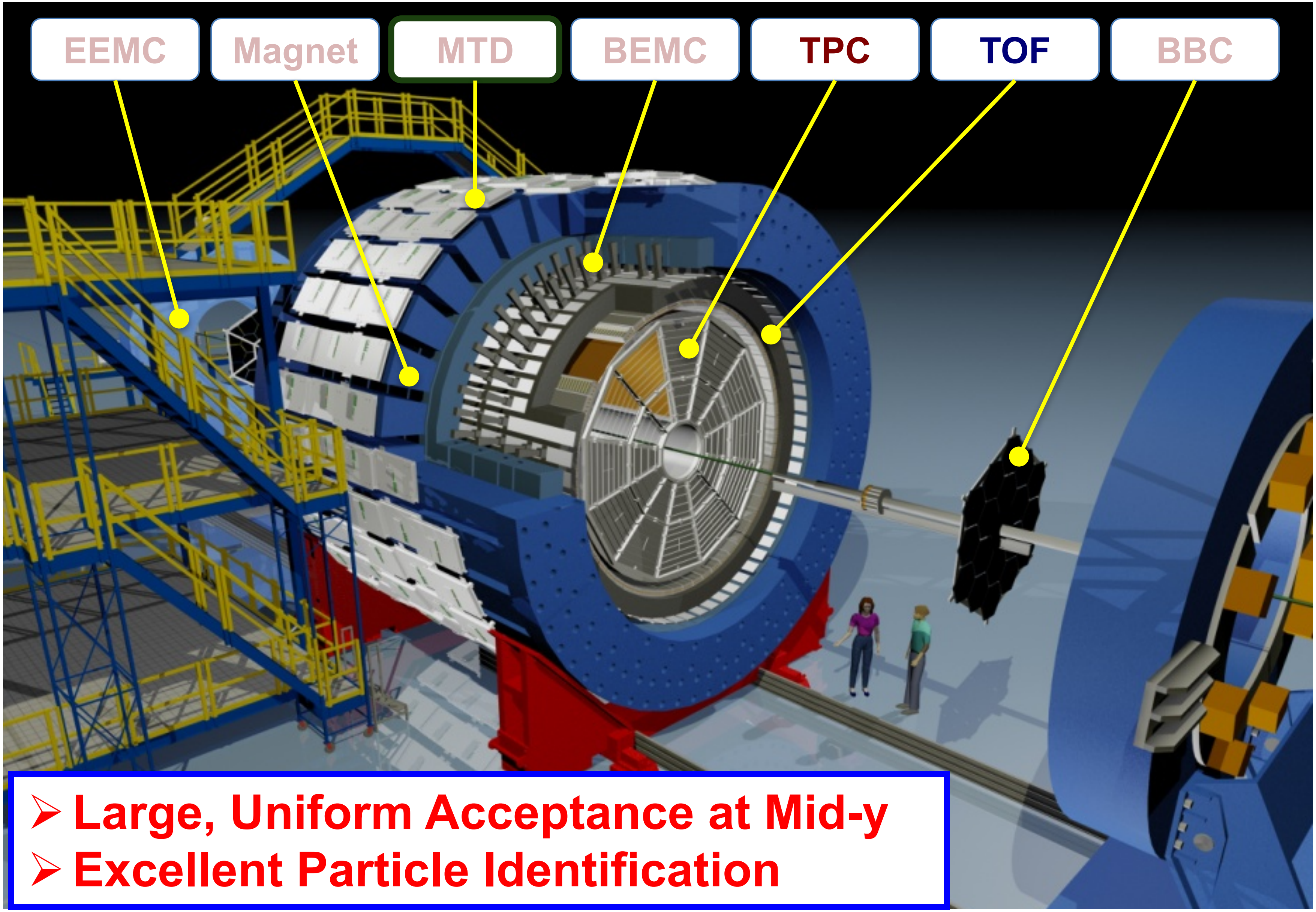
*(μ_B, T_{CH}) : J. Cleymans et al., PRC 73, 034905 (2006)



STAR: Phys. Rev. C 96, 044904 (2017).

1) Access the QCD phase diagram: vary collision energies/centralities.
2) Large and homogeneous acceptance: → crucial for fluctuation analysis.

The STAR Detector



- Large, Uniform Acceptance at Mid-y
- Excellent Particle Identification

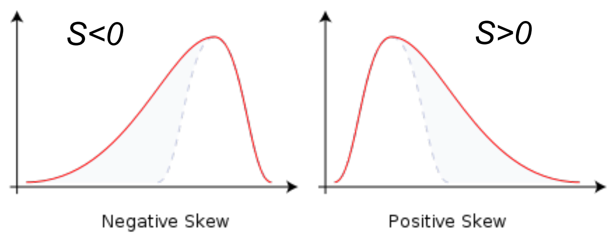
Fluctuations of Conserved Quantities (B, Q, S)

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

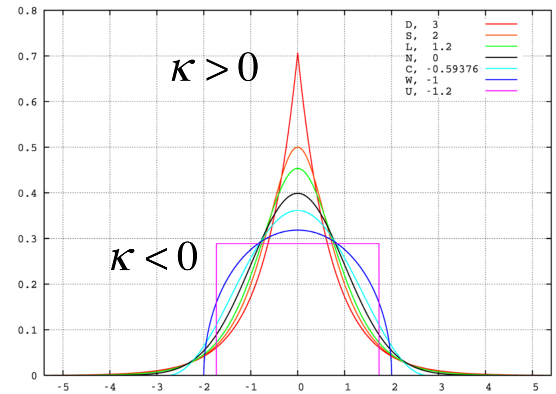
$$<\delta N> = N - <N>$$
$$C_1 = M = <N>$$
$$C_2 = \sigma^2 = <(\delta N)^2>$$
$$C_3 = S\sigma^3 = <(\delta N)^3>$$
$$C_4 = \kappa\sigma^4 = <(\delta N)^4> - 3<(\delta N)^2>^2$$

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

Skewness (S) → asymmetry



Kurtosis (κ) → Sharpness

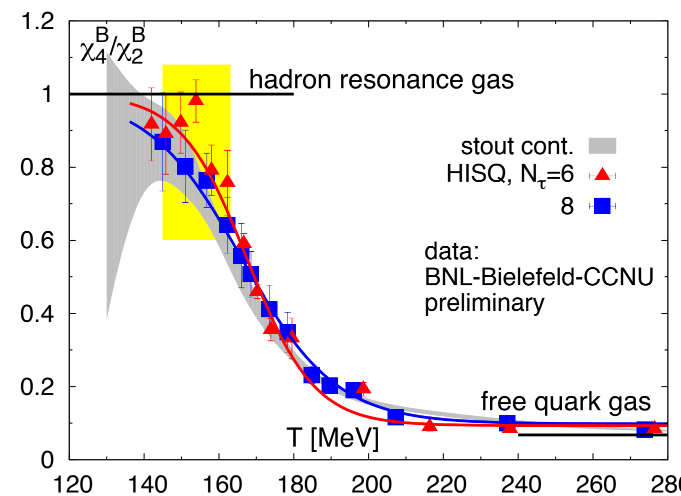


M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009).
M.Asakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009).
M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011).
Y. Hatta, M. Stephanov, Phys. Rev. Lett. 91, 102003 (2003).

2. Direct connect to the susceptibility of the system.

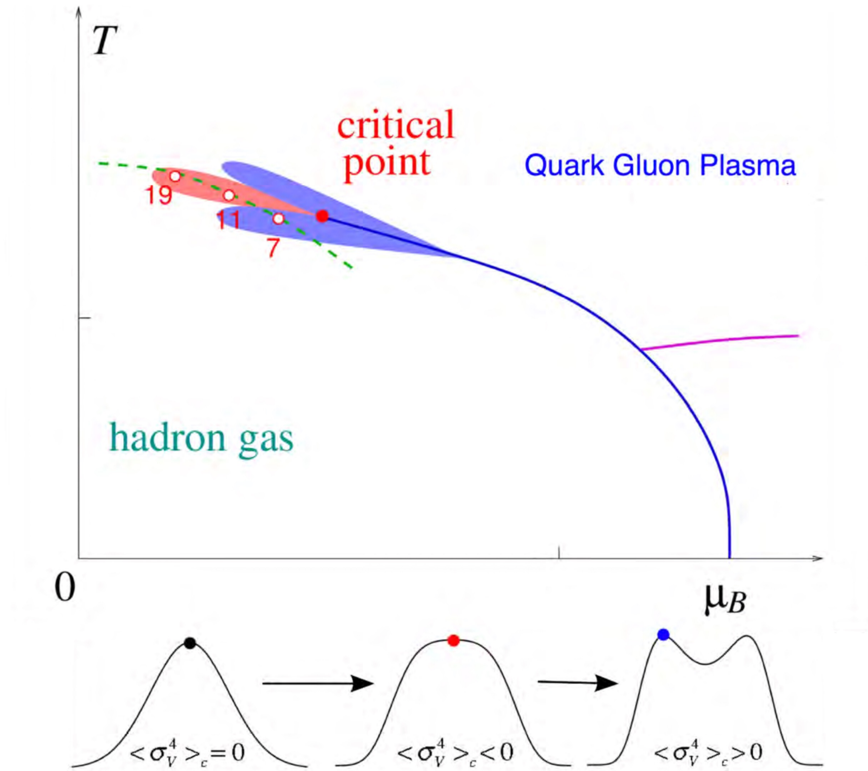
$$\frac{\chi_q^4}{\chi_q^2} = \kappa\sigma^2 = \frac{C_{4,q}}{C_{2,q}} \qquad \frac{\chi_q^3}{\chi_q^2} = S\sigma = \frac{C_{3,q}}{C_{2,q}},$$

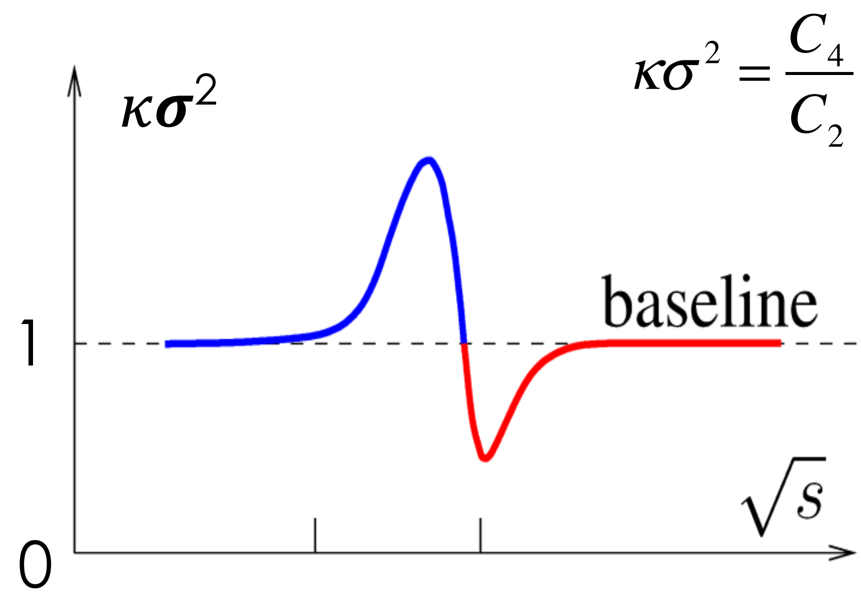
$$\chi_q^{(n)} = \frac{1}{VT^3} \times C_{n,q} = \frac{\partial^n (p/T^4)}{\partial(\mu_q)^n}, q = B, Q, S$$



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

Theoretical/Model Calculations: Signature of QCD Critical Point





$\kappa\sigma^2=1$ （Poisson Fluc.）

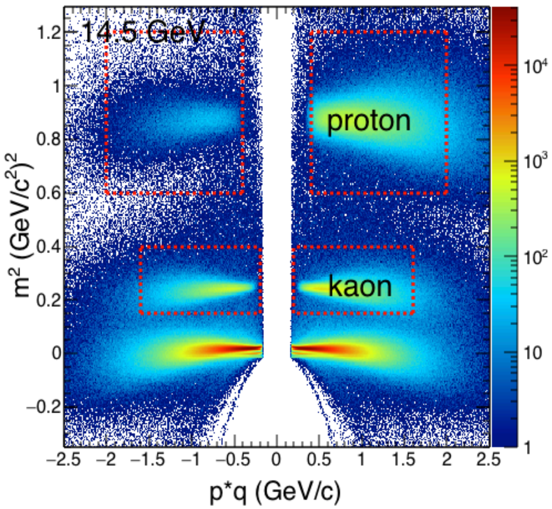
M.A. Stephanov, PRL107, 052301 (2011).
Schaefer, Wanger,PRD 85, 034027 (2012)
JW Chen， J. Deng et al., PRD93, 034037 (2016); PRD95, 014038 (2017).

The effect of CP could manifest as a non-monotonic dependence of the higher-moments of fluctuations as the critical point is passed by during the beam energy scan.

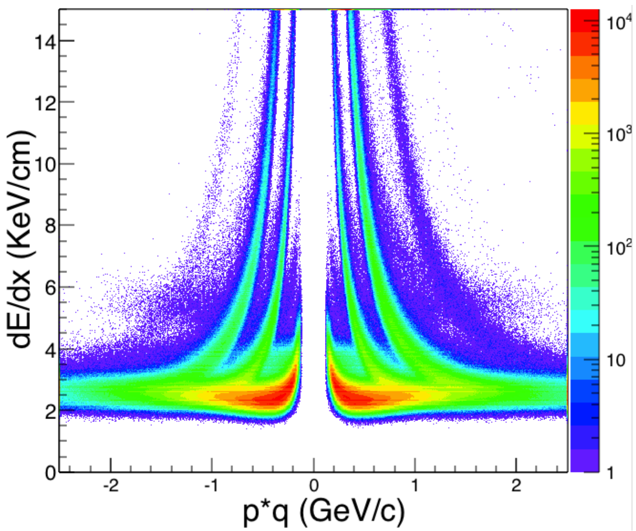
Analysis Details

	Net-Charge	Net-Proton	Net-Kaon
Kinematic cuts	$0.2 < p_T$ (GeV/c) < 2.0 $\|\eta\| < 0.5$	$0.4 < p_T$ (GeV/c) < 2.0 $\|y\| < 0.5$	$0.2 < p_T$ (GeV/c) < 1.6 $\|y\| < 0.5$
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
	$0.5 < \|\eta\| < 1.0$	$\|\eta\| < 1.0$	$\|\eta\| < 1.0$

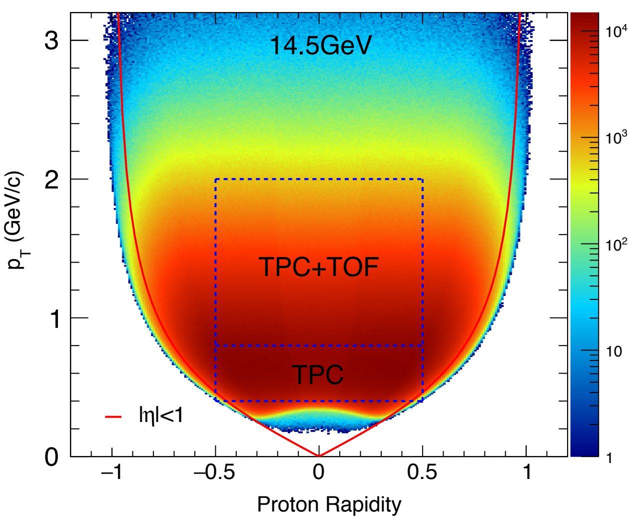
TOF PID



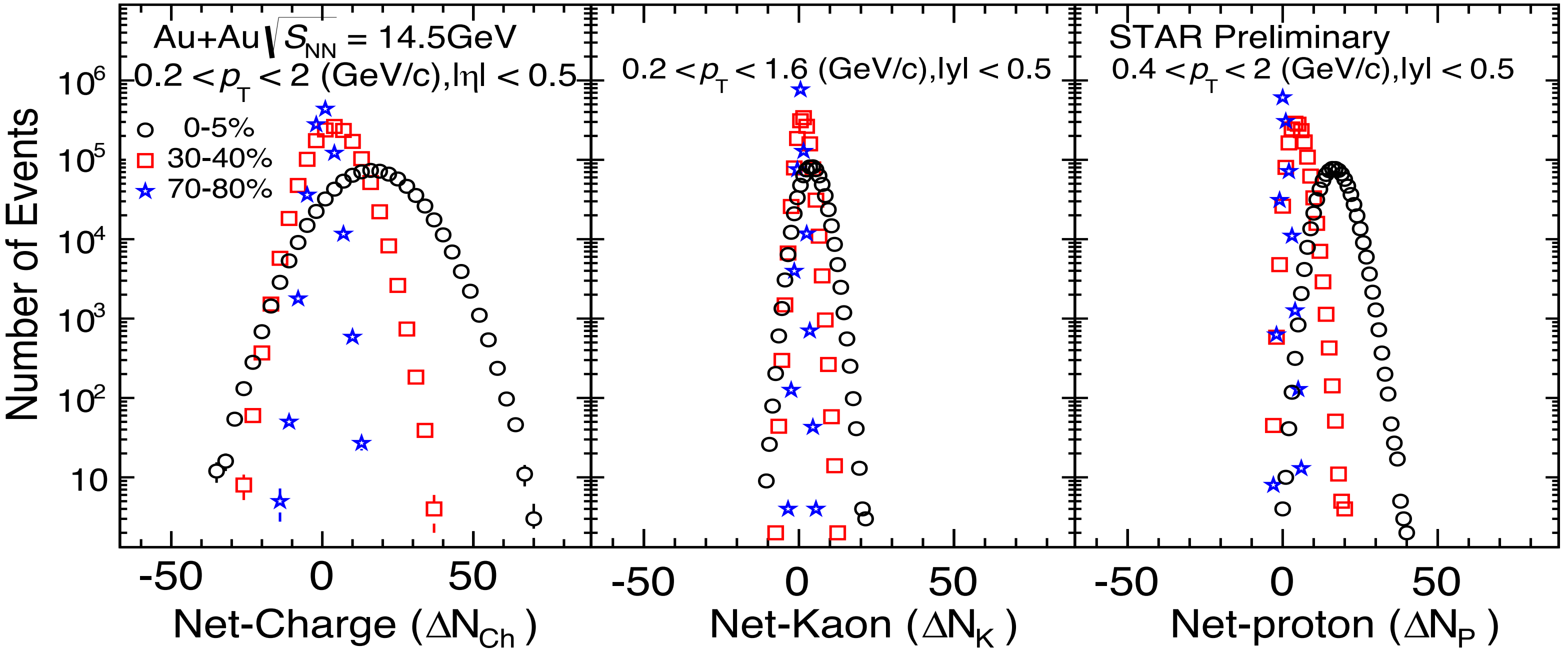
TPC PID



Phase Space



Data Analysis Methods



Effects needed to be addressed to get final moments/cumulants:

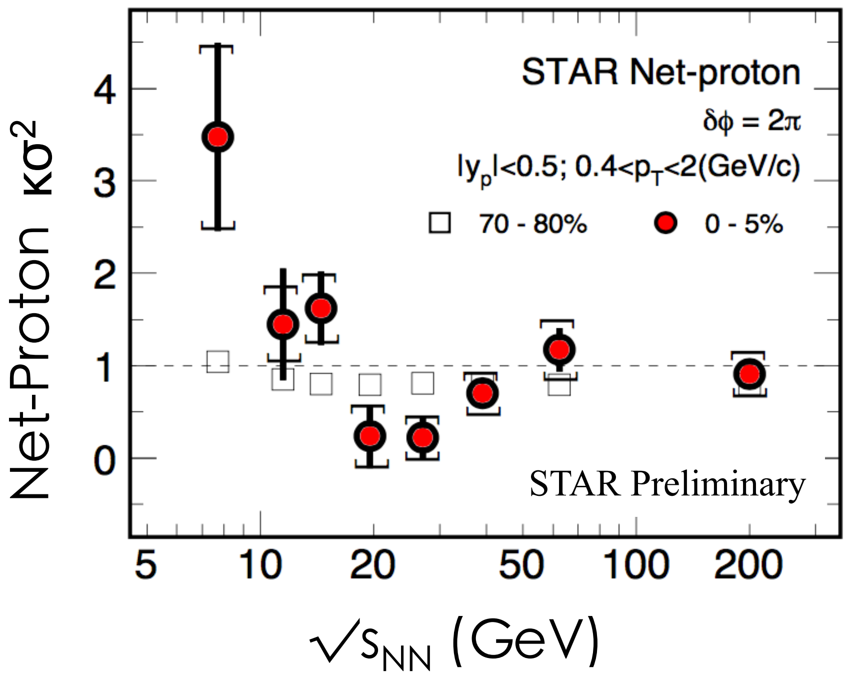
1. Avoid auto-correlation effects: New centrality definition.
2. Suppress volume fluctuation：Centrality bin width correction
3. Finite detector efficiency correction (binomial response func.)

(Possible non-binomial effect and unfolding method are under investigation.)

X.Luo, et al. J. Phys. G39, 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 and N. Xu, Nucl. Sci. Tech. 28, 112 (2017).

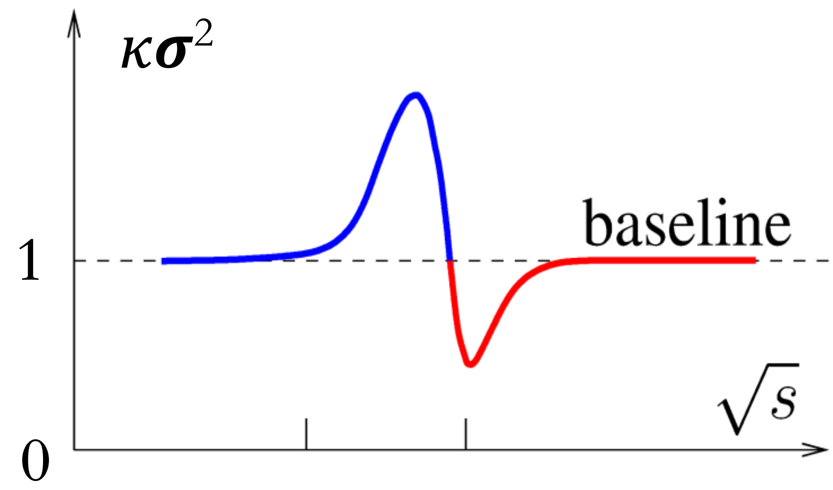
Net-Proton Fluctuations

Experimental Measure



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

Theoretical calculations

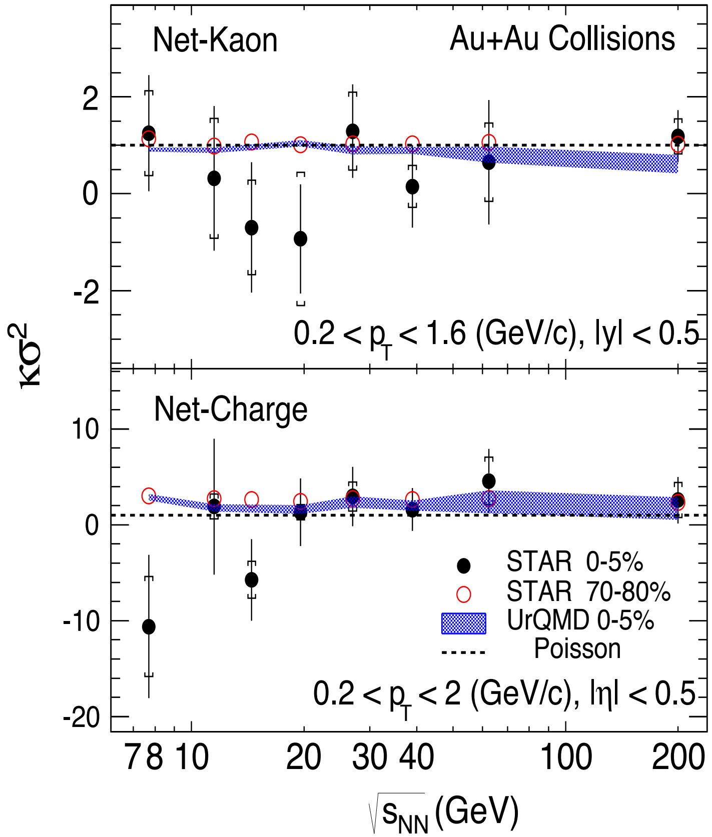


M. Stephanov, PRL107, 052301(2011)

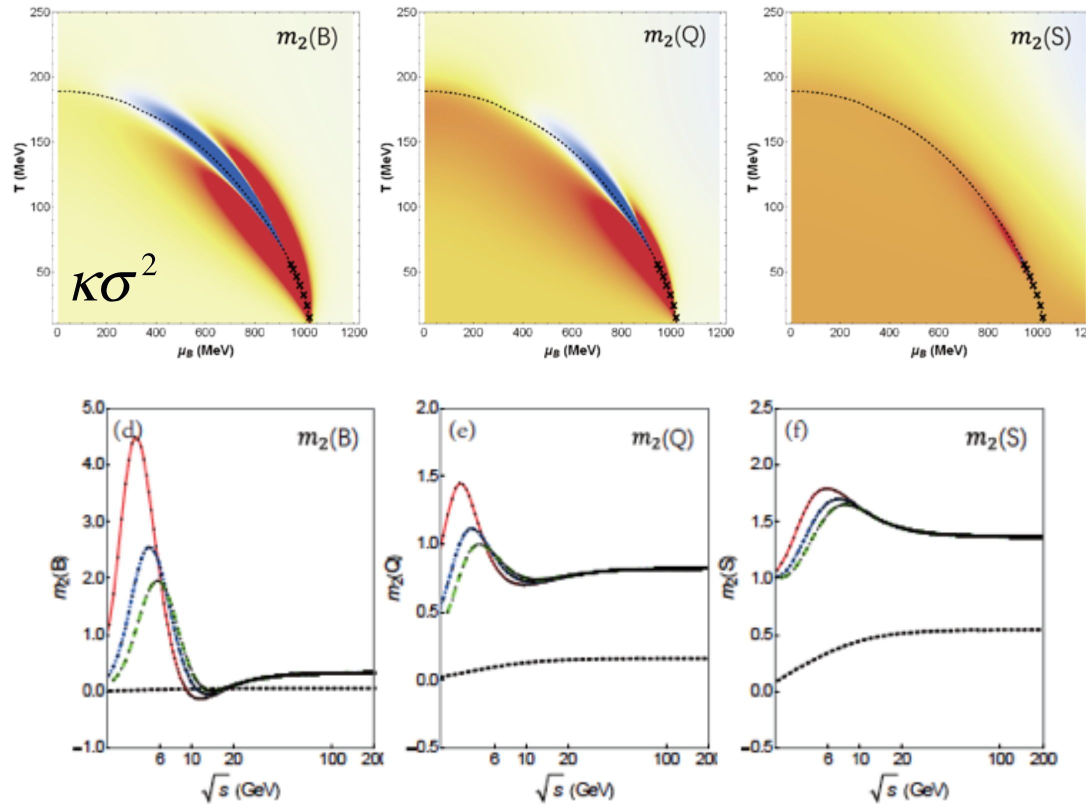
Observe non-monotonic energy dependence in 0-5% most central Au+Au collisions. A hint of entering the critical region.

Net-charge and Net-kaon Fluctuations

Experimental measure



NJL model calculation



Large statistical errors, need more data

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

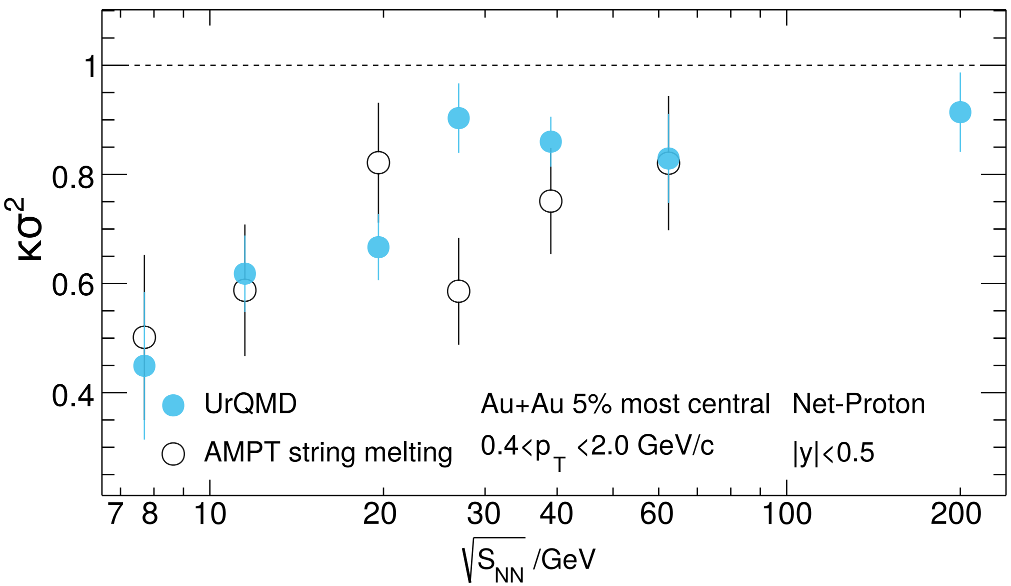
Net-Kaon : PLB in press.
Net-Charge: Phys. Rev. Lett. 113, 092301 (2014)

Signal strength：B>Q>S
(Due to large mass of s quark, $m_s >> m_{u,d}$)

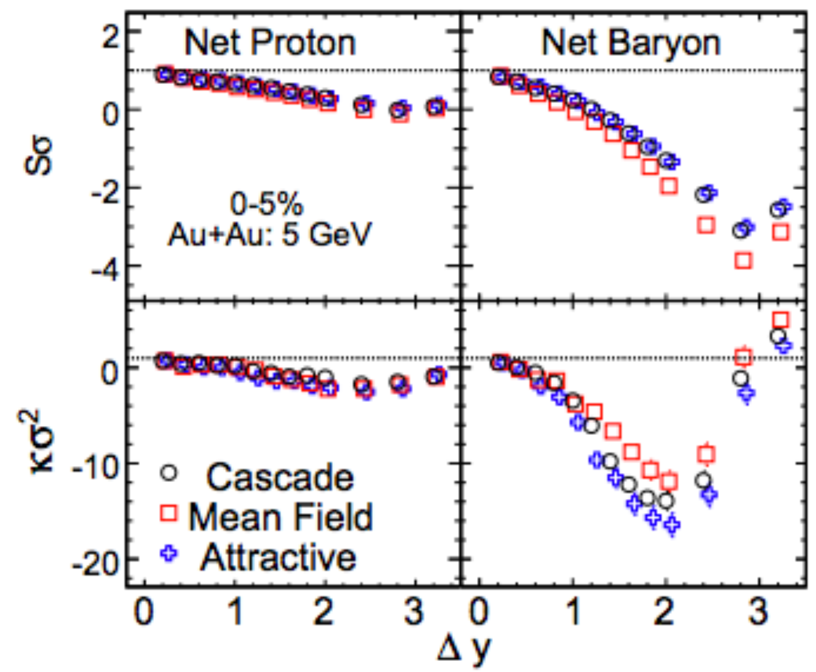
W. Fan, X. Luo, H.S. Zong, IJMPA 32, 1750061 (2017).

Non-critical Contributions: Transport Model Studies

UrQMD and AMPT models



JAM model

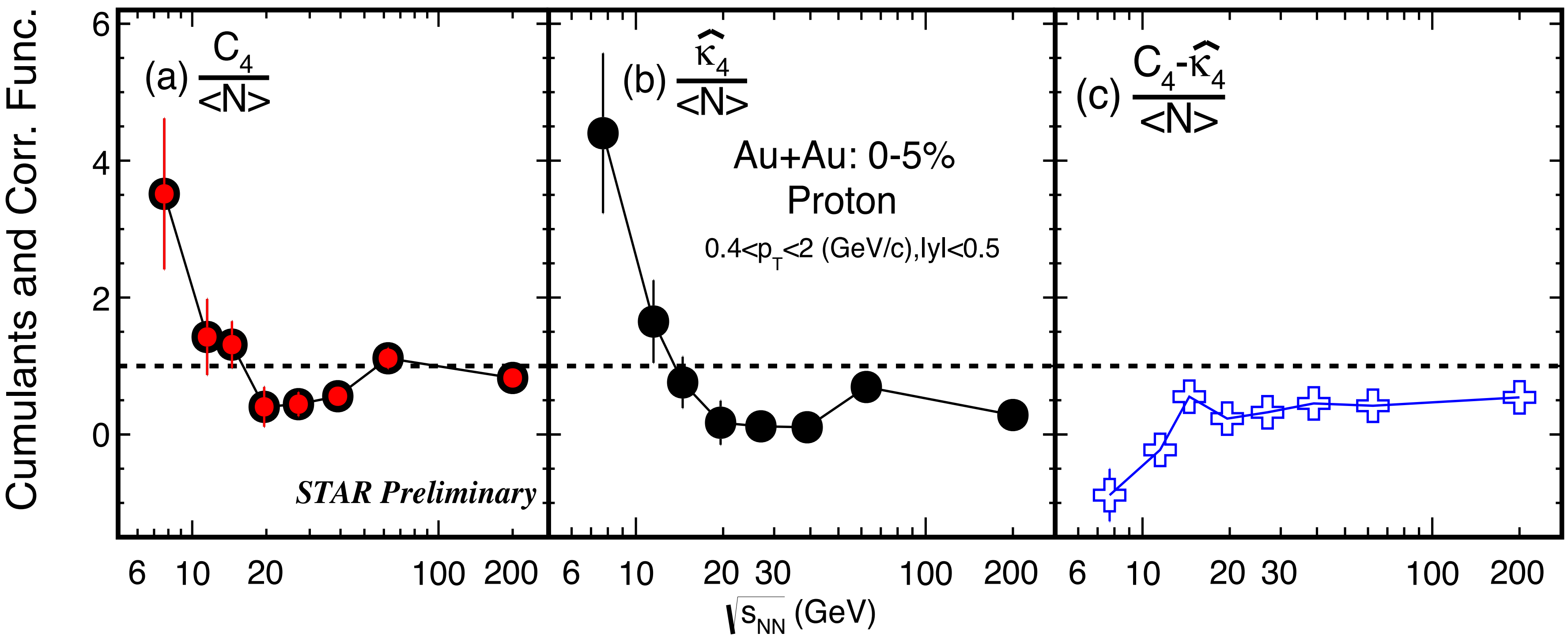


At $\sqrt{s_{NN}} \leq 10$ GeV: Data: **$\kappa\sigma^2 > 1$** Model: **$\kappa\sigma^2 < 1$**

➢ Model simulation : *suppress the net-proton fluctuations.*

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).

Proton Cumulants and Correlation Functions



Four-particle correlation dominated the non-monotonic behavior observed in forth order net-proton fluctuations.

$$C_2 =< N > + \hat{\kappa}_2$$

$$C_3 =< N > + 3\hat{\kappa}_2 + \hat{\kappa}_3$$

$$C_4 =< N > + 7\hat{\kappa}_2 + 6\hat{\kappa}_3 + \hat{\kappa}_4$$

$\hat{\kappa}_2, \hat{\kappa}_3, \hat{\kappa}_4$: 2,3,4-particle correlation function

Possible interpretation (cluster formation) :
A. Bzdak, V. Koch, V. Skokov, Eur. Phys. J., C77, 288(2017)

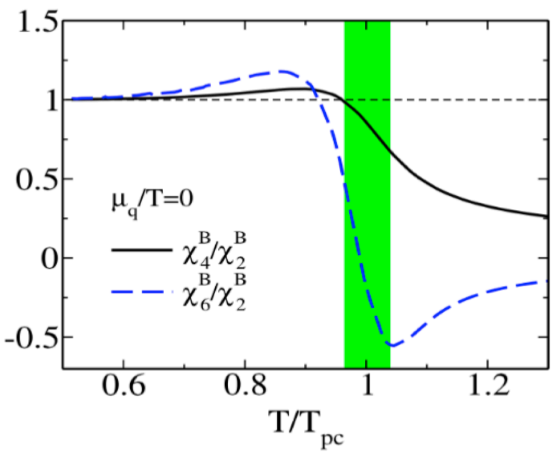
The sixth-order (C_6) fluctuation measurement

- The sixth-order cumulants of net-charge and net-baryon distributions are predicted to be negative if the chemical freeze-out is close enough to the phase transition.

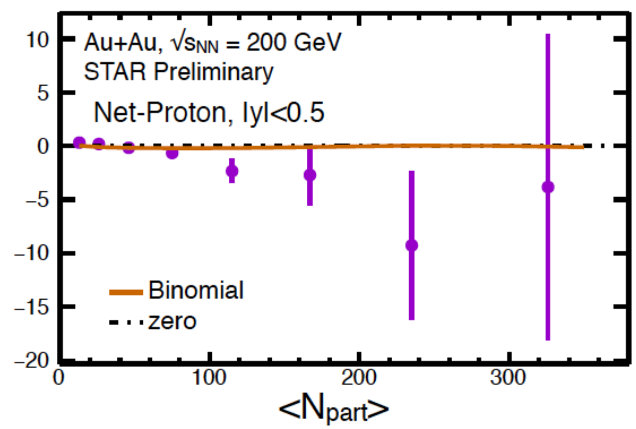
- In Au+Au collisions at 200 GeV, negative values are observed in net-proton C_6/C_2 systematically from peripheral to central. Results of net-charge C_6/C_2 are consistent with zero within large statistical errors.

$$error(C_n / C_2) \propto \frac{\sigma^{n-2}}{\sqrt{N_{evts}}}$$

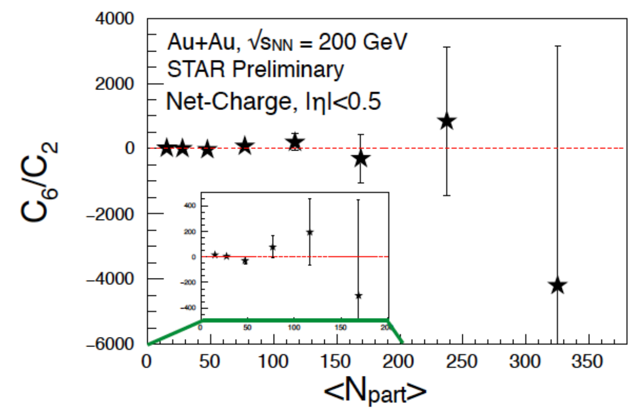
PQM model



Net-proton

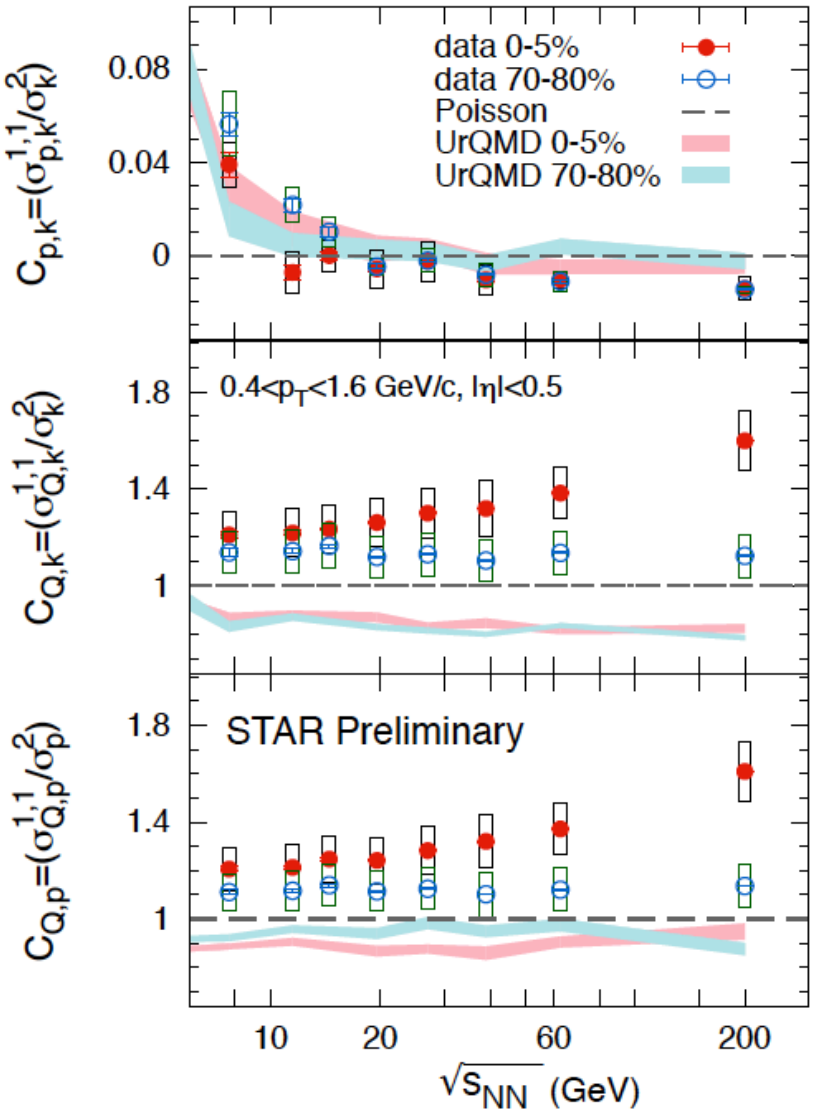


Net-charge



B. Friman et al., Eur. Phys. J. C 71 (2011) 1694

The 2nd-order Off-diagonal Cumulants

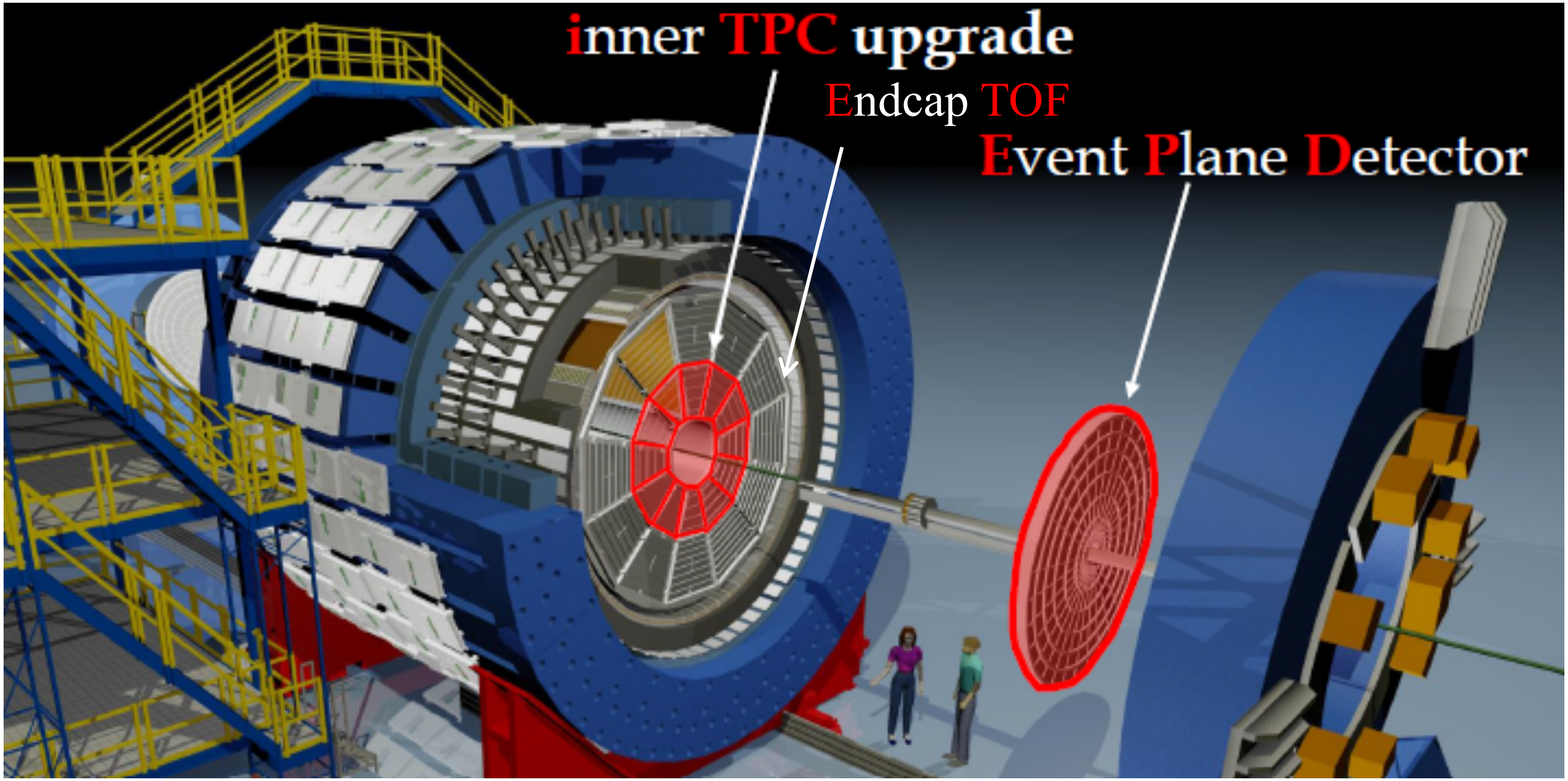


$$\sigma^2_{x,y} = \langle xy \rangle - \langle x \rangle \langle y \rangle$$

$$C_{x,y} = \frac{\sigma^{1,1}_{x,y}}{\sigma^2_y}$$

- Normalized p-k correlation is positive at low energies and negative at high energies, which are also consistent with UrQMD.
- Significant excess is observed in Q-k and Q-p with respect to the Poisson baseline and UrQMD.

STAR Upgrades for BES-II (2019-2020)

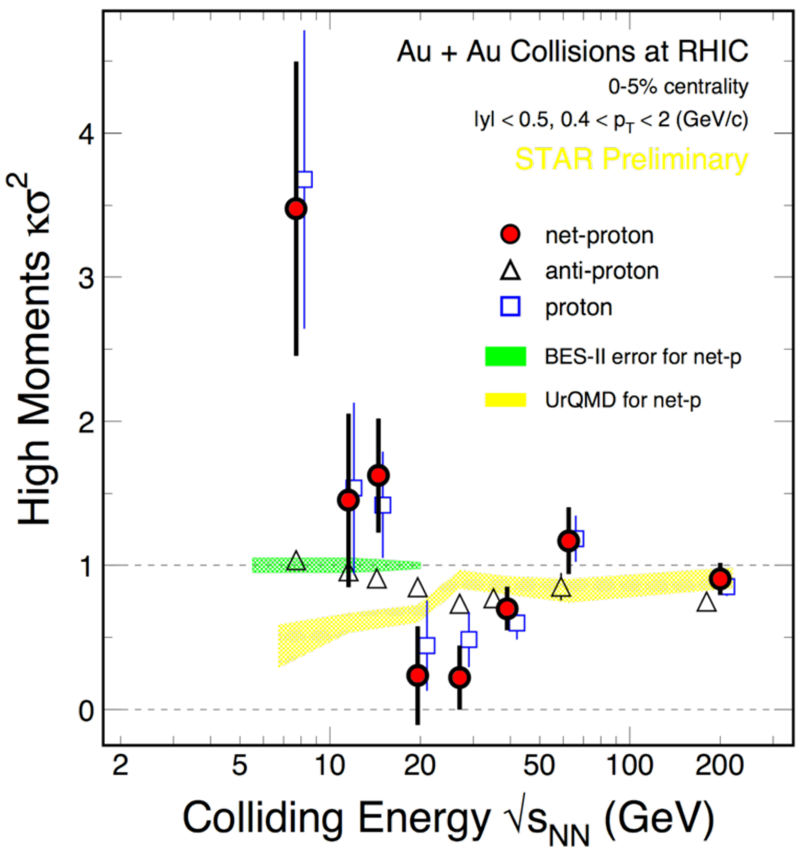


1) Enlarge rapidity acceptance
2) Improve particle identification
3) Better centrality and reaction plane measurement

EPD: Ready in 2018
iTPC&eTOF: Ready in 2019

BES-II at RHIC (2019-2020)

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES II / BES I
200	350	2010
62.4	67	2010
54.4	1200	2017
39	39	2010
27	70	2011
19.6	**400** / 36	**2019-20** / 2011
14.5	**300** / 20	**2019-20** / 2014
11.5	**230** / 12	**2019-20** / 2010
9.2	**160** / 0.3	**2019-20** / 2008
7.7	**100** / 4	**2019-20** / 2010



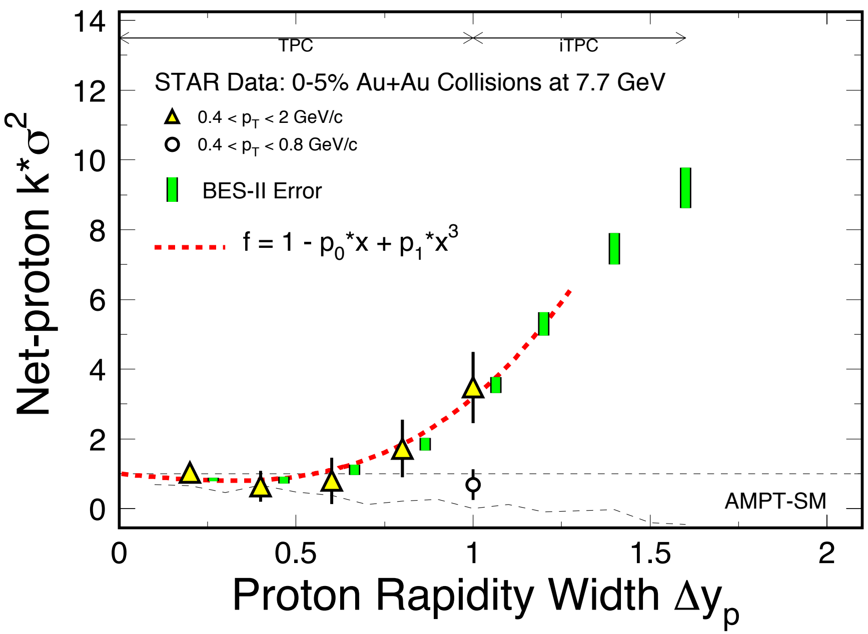
BES-II / BES-I: Precise mapping the QCD phase diagram

200 < μ_B < 420 MeV

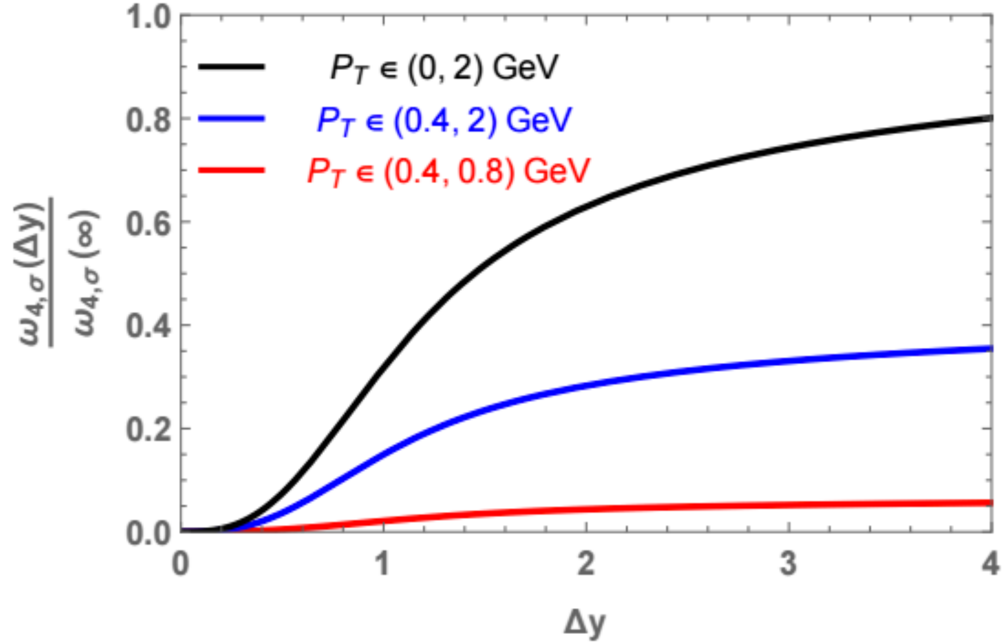
Acceptance Dependence

Acceptance dep. near CP

STAR Data



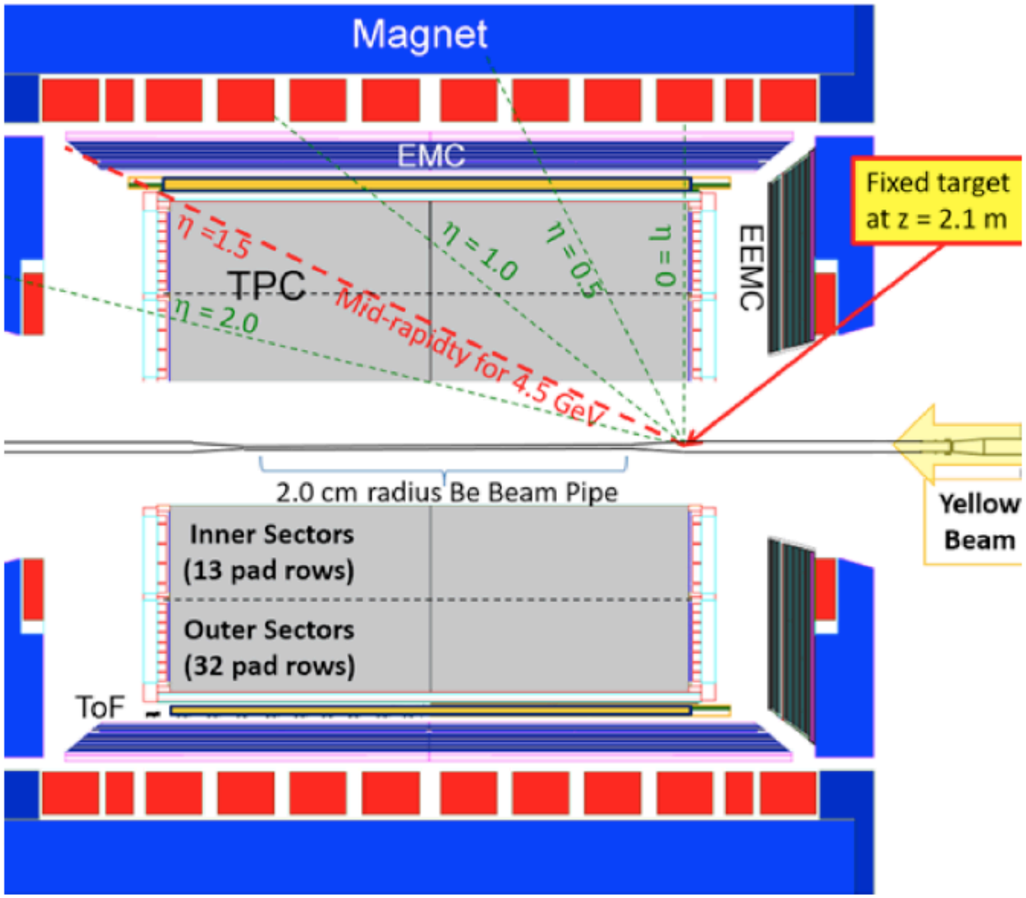
Model

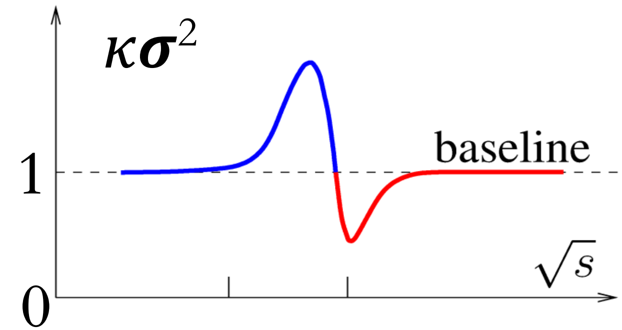


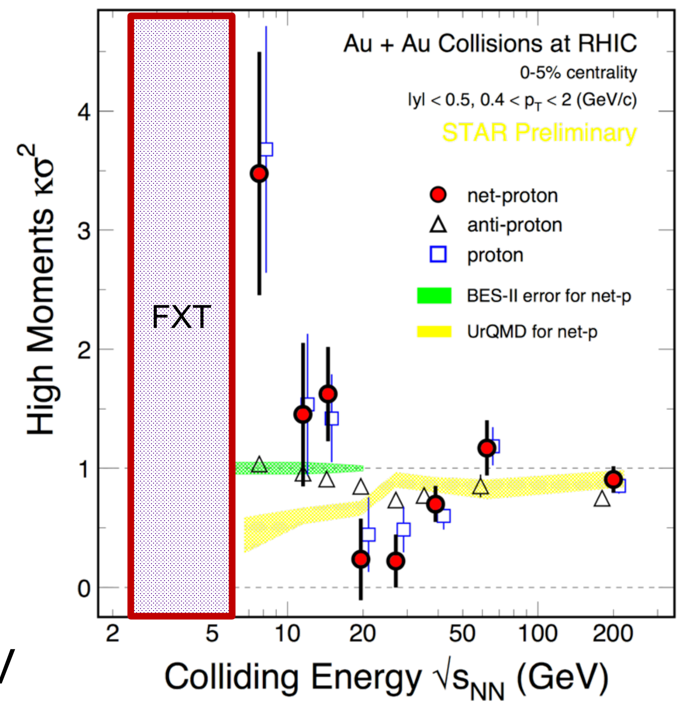
Signals can be enhanced by enlarging the acceptance.

B. Ling, M. Stephanov, Phys. Rev. C 93, 034915 (2016).
A. Bzdak, V. Koch, Phys.Rev. C95, 054906 (2017)
M. Kitazawa, X. Luo, PRC96, 024910 (2017).

Fixed-target (FXT) Experiments at STAR







2018: Au+Au :3 GeV (~250 million events taken)

FXT data taking plan：

2019-2020: Au+Au: 7.7, 6.2, 5.2, 4.5, 3.9, 3.5 GeV

Summary and Outlook

- Non-monotonic energy dependence is observed in net-proton C_4/C_2 at most central Au+Au collisions. *A hint of entering the critical region. Need to confirm with more statistics and lower energies data.*

- Within current uncertainties, net-charge and net-kaon fluctuations show flat energy dependent. *Need more statistics.*

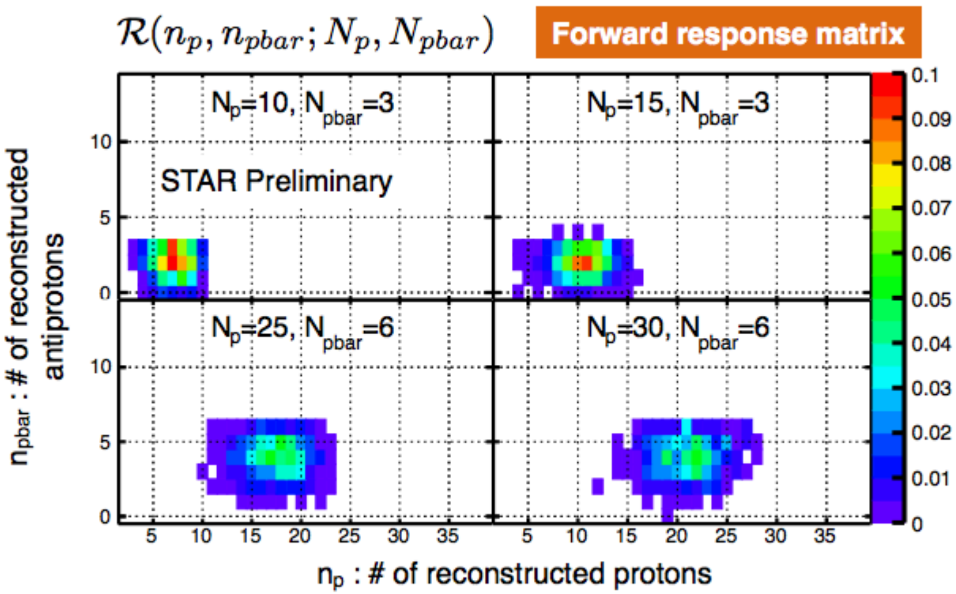
- Negative values are observed in net-proton C_6/C_2 from peripheral to central Au+Au collisions at 200 GeV.

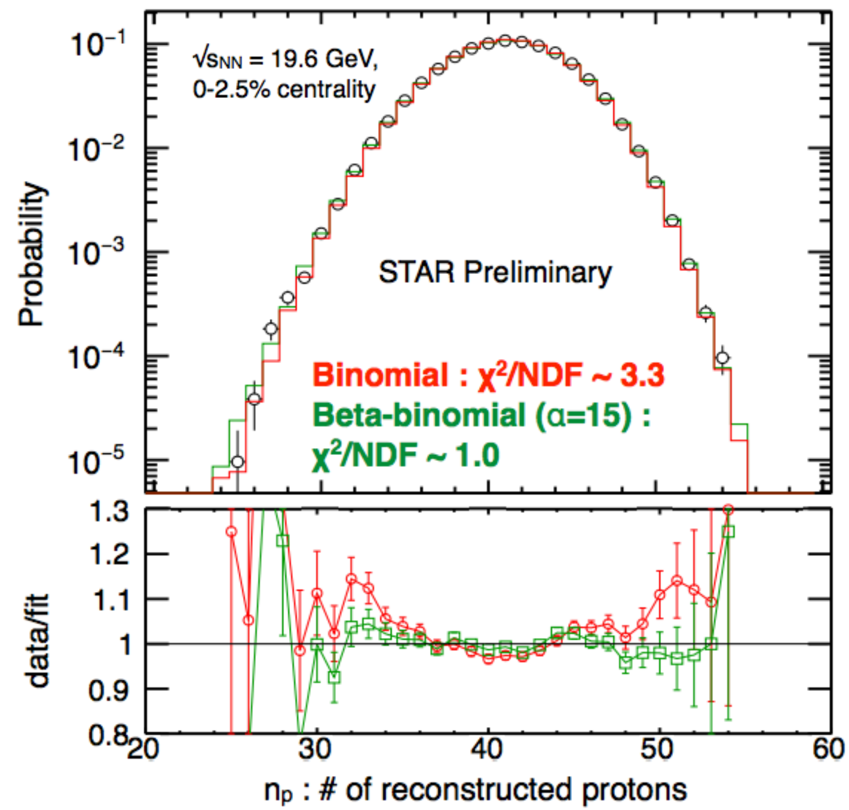
- Study the QCD phase structure with high precision: BES-II at RHIC (2019-2020, both collider and fixed-target mode).

Thank you !

Back up slides

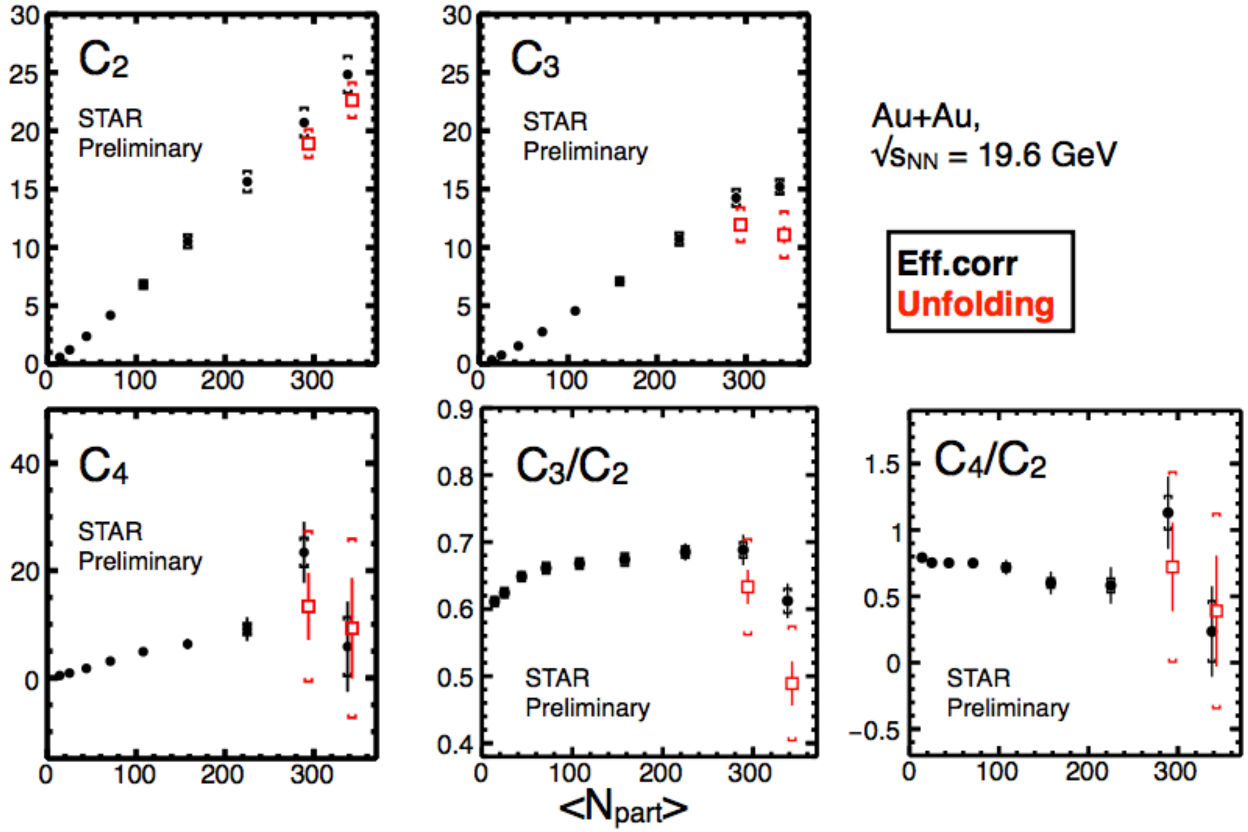
Study Non-Binomial Effects from Embedding Simulation





- We perform simulation to construct response matrix by embedding MC tracks of protons and antiprotons into real events, which will be used for unfolding.
- When embed 60 protons (an extreme case), the response matrix is close to beta-binomial, which is wider than binomial (right plot). The deviation from binomial would depend on the # of embedded protons and antiprotons.

Results of Unfolding



- For unfolding, 2.5% centrality width averaging has been done.
- Systematic suppression is observed for C_2 and C_3 with respect to the results of efficiency correction assuming binomial efficiencies.
- C_4, C_3/C_2 and C_4/C_2 are consistent within large systematic uncertainties limited by embedding samples.