Search for the QCD Critical Point -

Fluctuations of Conserved Quantities in High-Energy Nuclear Collisions at RHIC

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Standard Model

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

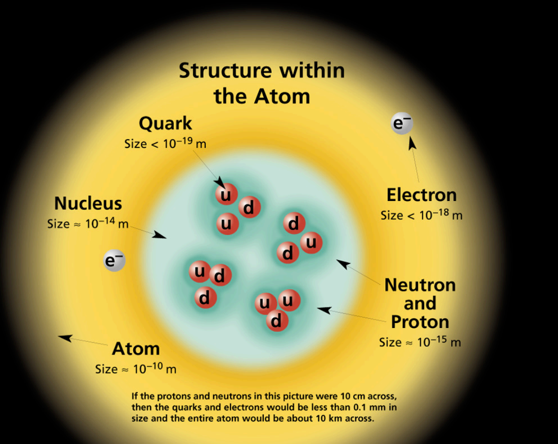
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV $= 10^9$ eV $= 1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 $= 1.67\times10^{-27}$ kg.



BOSONS
force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons
One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$
Mesons are bosonic hadrons.
There are about 140 types of mesons.

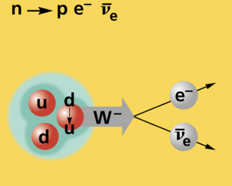
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Today

Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

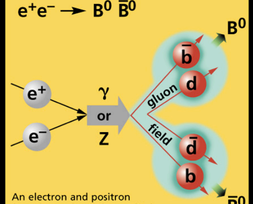
Figures
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p\, e^-\, \bar{\nu}_e$



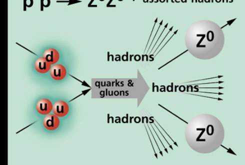
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\, \bar{B}^0$



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\, p \rightarrow Z^0 Z^0$ + assorted hadrons



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure
Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

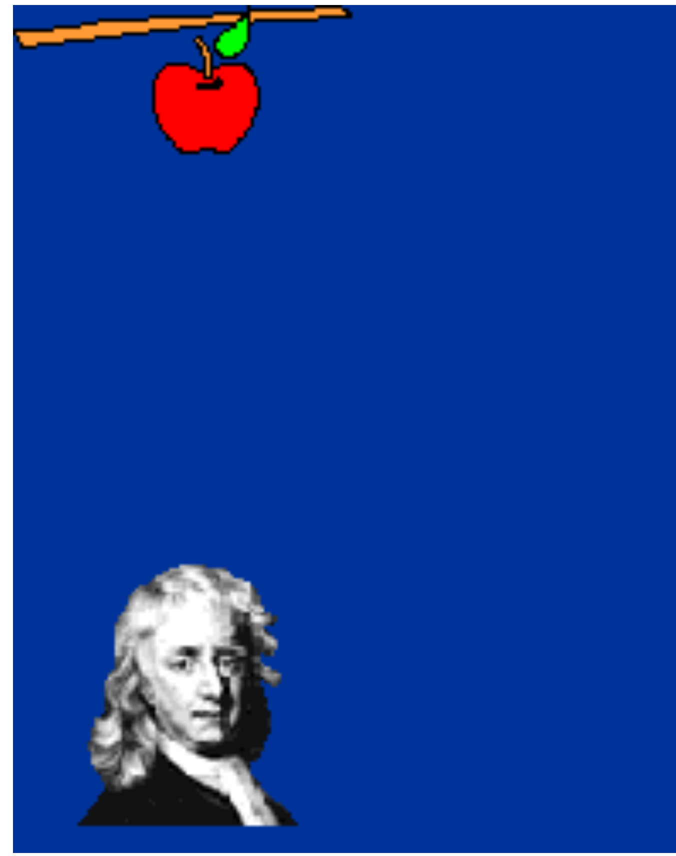
Strong Force – one of the four in nature

How those forces affect our life ?

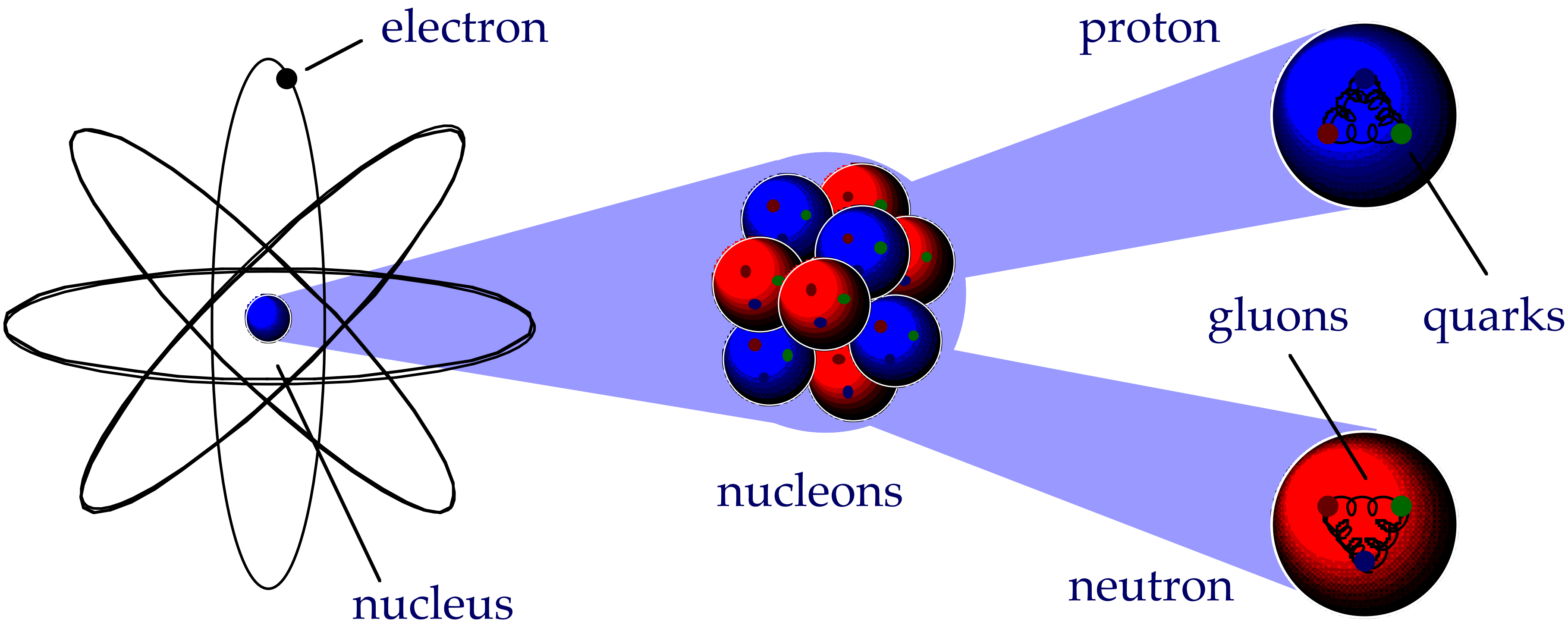
1. Gravity
   Makes apple fall to ground.

2. Electromagnetic+weak
   (2 unified forces)
   Bonds atoms together
   Makes apple red and tasty.

3. Strong force
   Generates 99% of apple's mass.



Structure of an atom

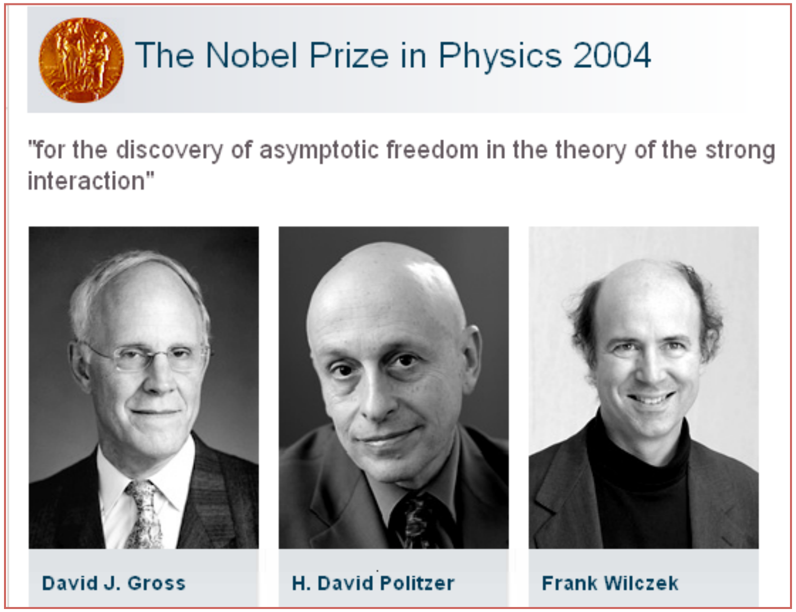


Atom>nucleus>proton/neutron>quarks/gluons

10^{-10}m 10^{-14}m 10^{-15}m (1fm) $<10^{-19}$m

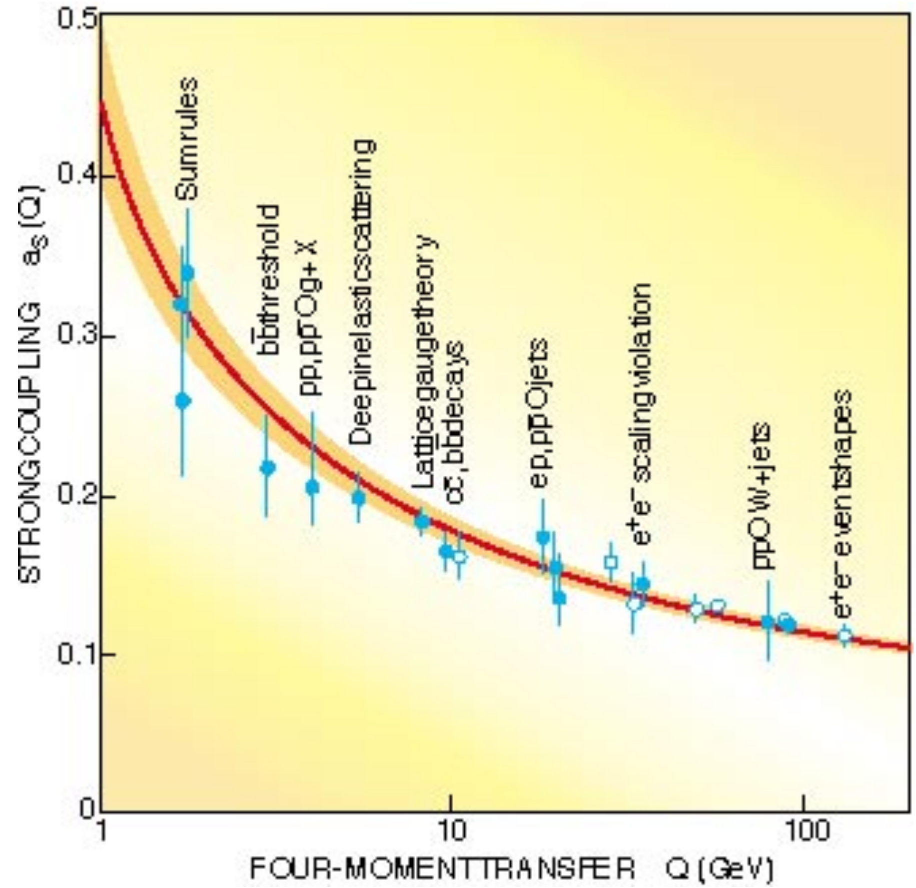
Where is the strong force most relevant ?

Theory of strong interaction : Quantum Chromodynamics (QCD)



- **Asymptotic freedom**: Quarks and Gluons weakly interacting
  1): when close together
  2): large momentum transfer.

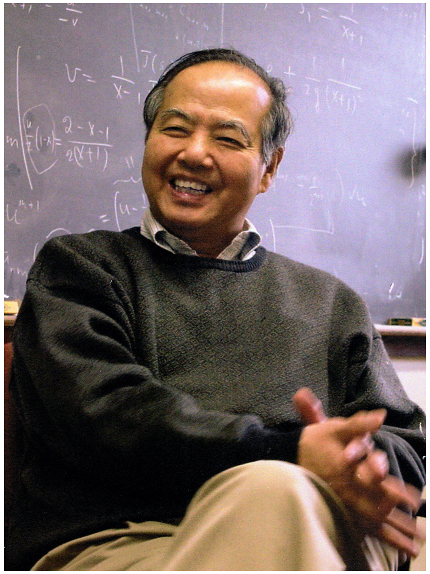
- **Confinement**: No free quarks and gluons observed in nature.



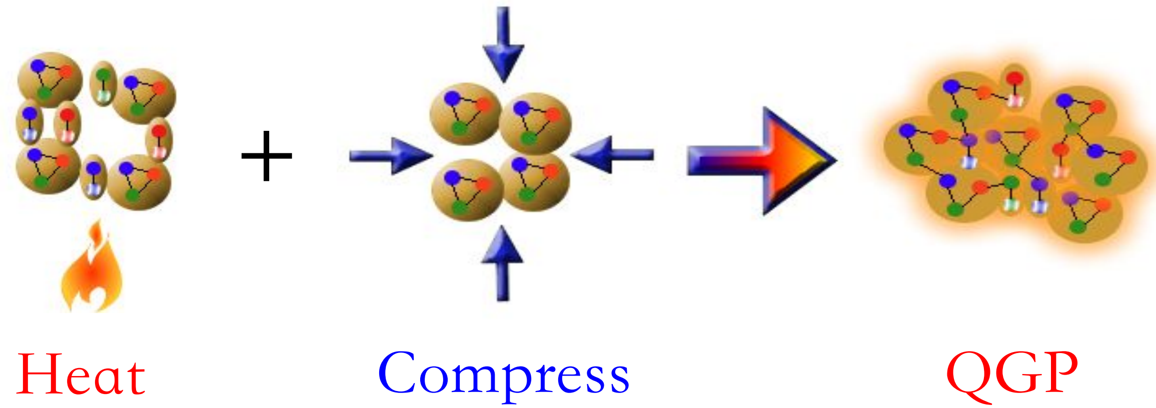
Running coupling constant

How to free the quarks and gluons from hadrons ?

Heavy-Ion Collisions: Free the Quarks and Gluons



T. D. Lee (1926-)



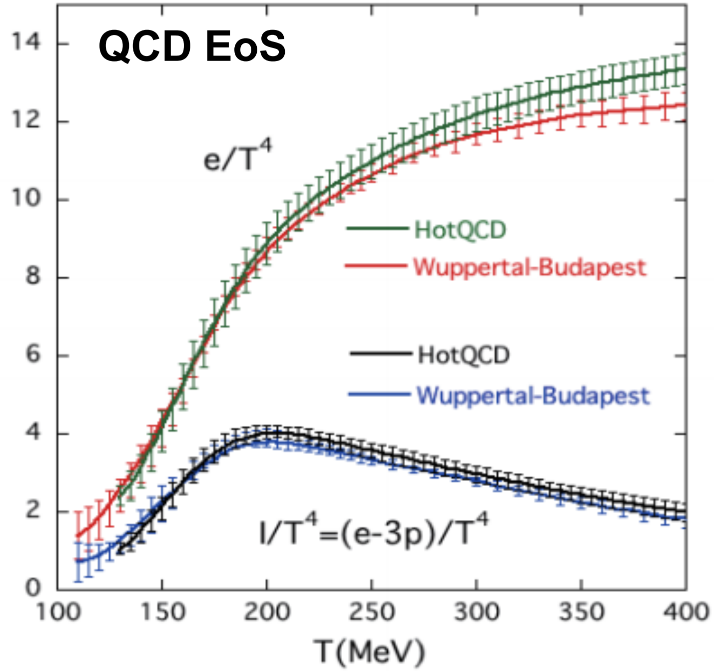
Create new form of matter： Quark-Gluon Plasma

T. D. Lee and G. C. Wick, Phys. Rev. D 9, 2291 (1974).
Vacuum stability and vacuum excitation in a spin-0 field theory.

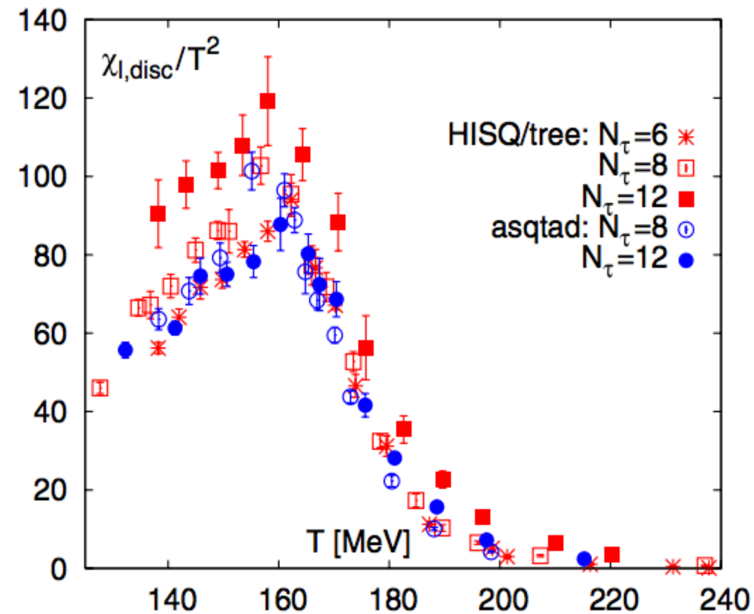
1) Study the formation and properties of QGP.
2) Study the phase structure of the QCD matter:
   Phase transition temperature, critical point and 1st order phase transition boundary

QCD Thermodynamics (μ_B=0)

Akira Ukawa, arXiv:1501.04215



WuppertalBudapest, JHEP 1009, 073 (2010).
HotQCD, Phys.Rev. D85, 054503 (2012).



QCD EoS : Major goals in LQCD since 1980s, agreement from two different groups.

Rapid rise of the energy density:

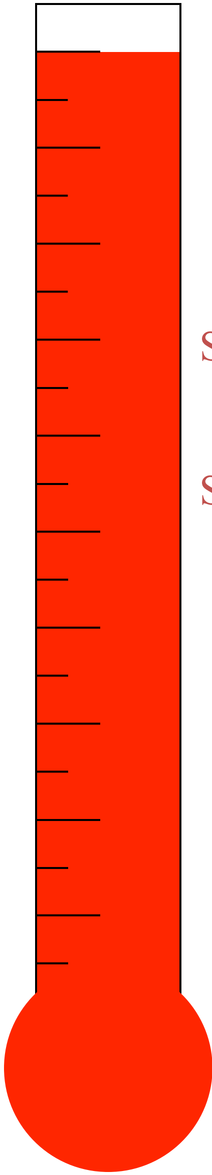
- Rapid increase in degrees of freedom due to transition from hadrons to quarks and gluons.
- Smooth crossover transition.

Chiral susceptibility peaks at T_c:

$$\chi_{\bar{\Psi}\Psi} = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial m^2}$$

Chiral phase transition T : T_c~155 MeV

Perspective on Temperature

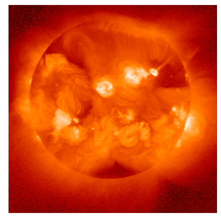


~10^{12} K — Nucleus-Nucleus collisions — ~ **120 MeV**

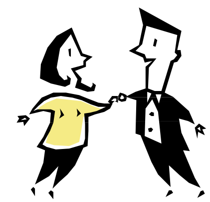
~10^{9} K — Neutron Star Thermonuclear Explosion

~10^{6} K — Solar Interior

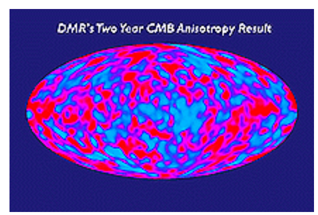
~6000 K — Solar Surface



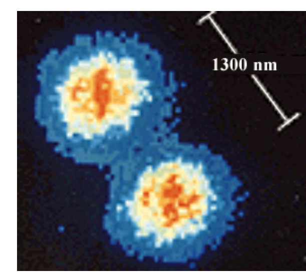
~300 K — Room Temperature ~ **1/40 eV**



~3 K — Cosmic Microwave Background



~10^{-6} K

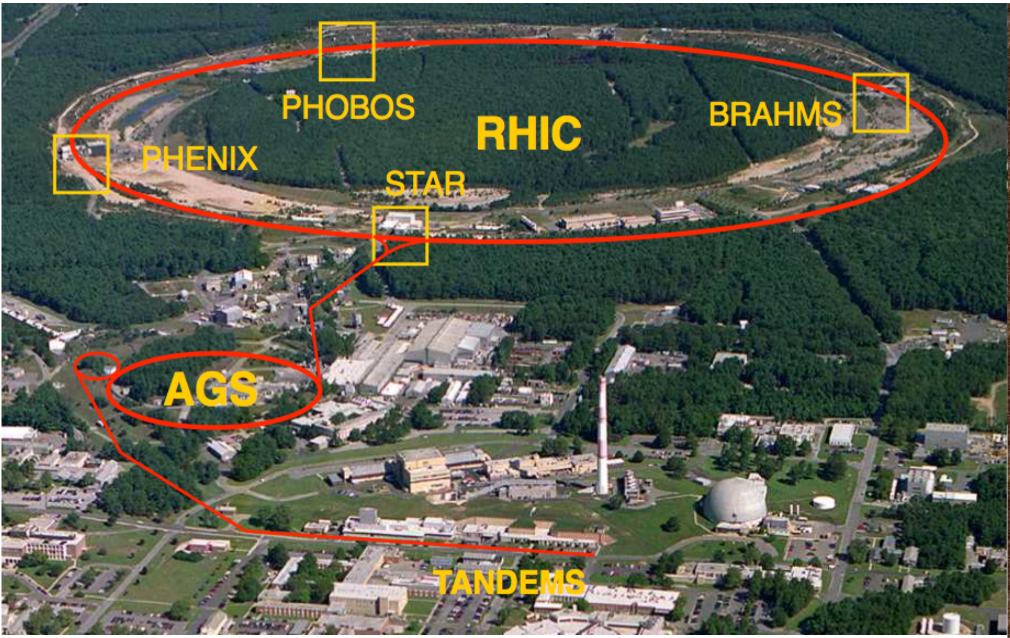


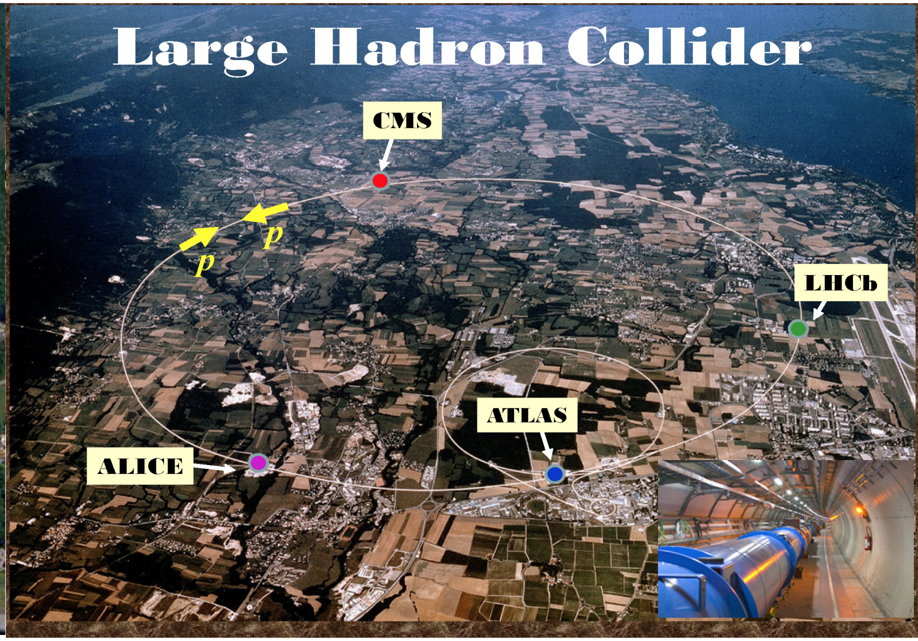
Trapped Ions

~10^{-10} K — Rhodium metal cooling (2000)

(Low-T World Record!)

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)

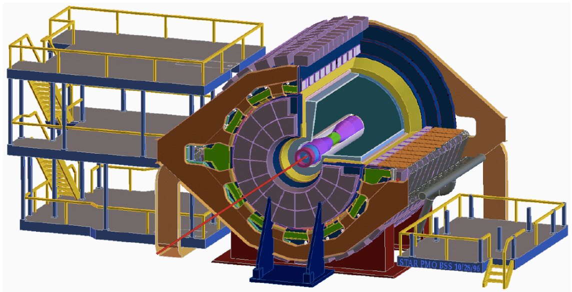
LHC@CERN,Geneva

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

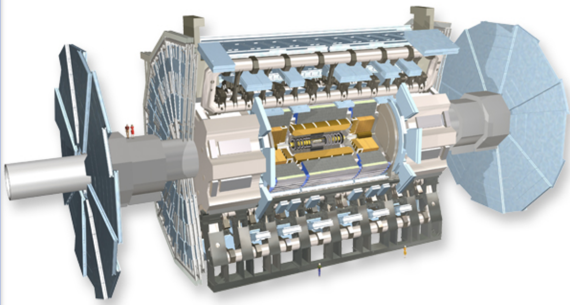
– LHC: The highest energy proton collider $\sqrt{s}$ = 14 TeV

High Energy Experiments at RHIC and LHC

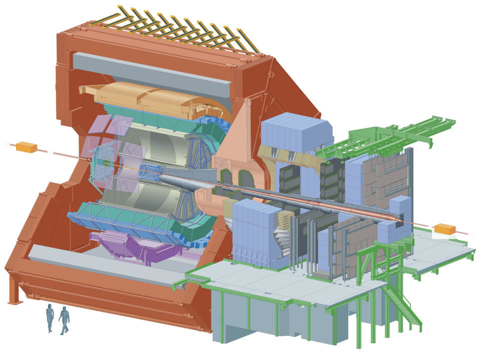
QCD Critical Point ?



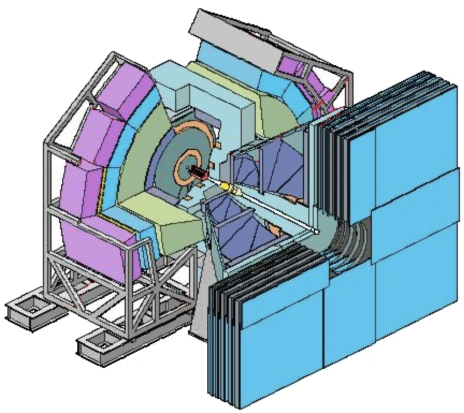
STAR



ATLAS

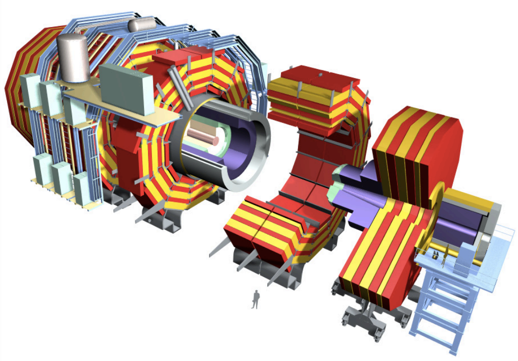


ALICE



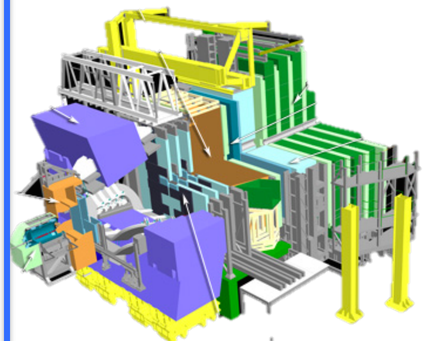
PHENIX

Higgs Discovery



CMS

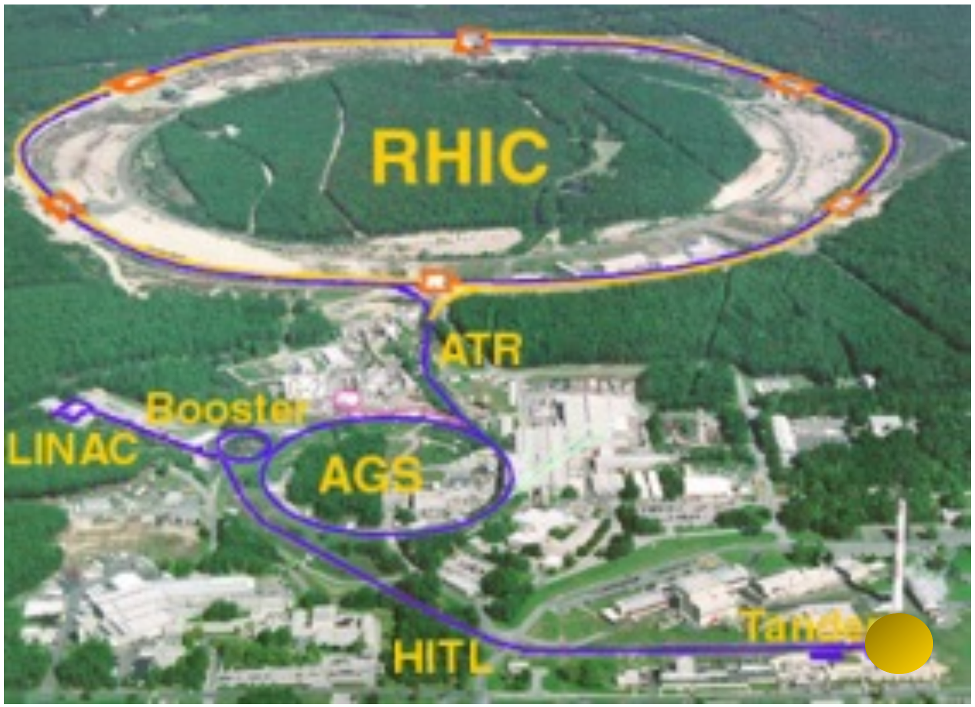
Pentaquark

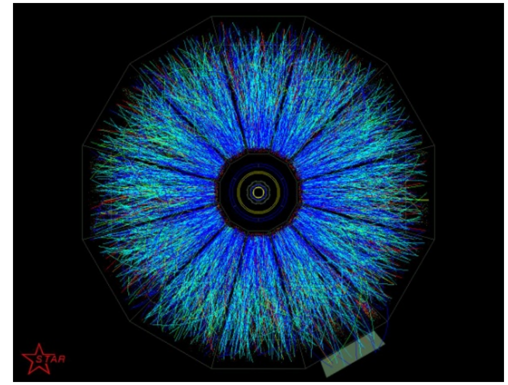


LHCb

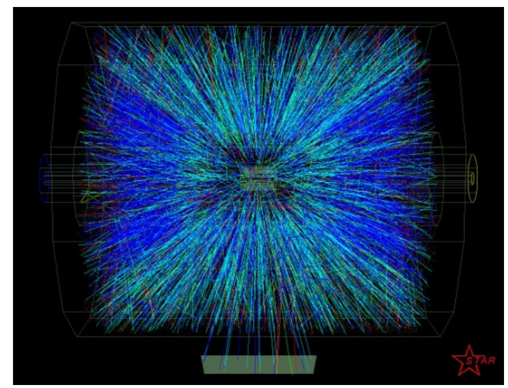
Heavy Ion Collisions at RHIC

Relativistic Heavy Ion Collider (2000-)





front view



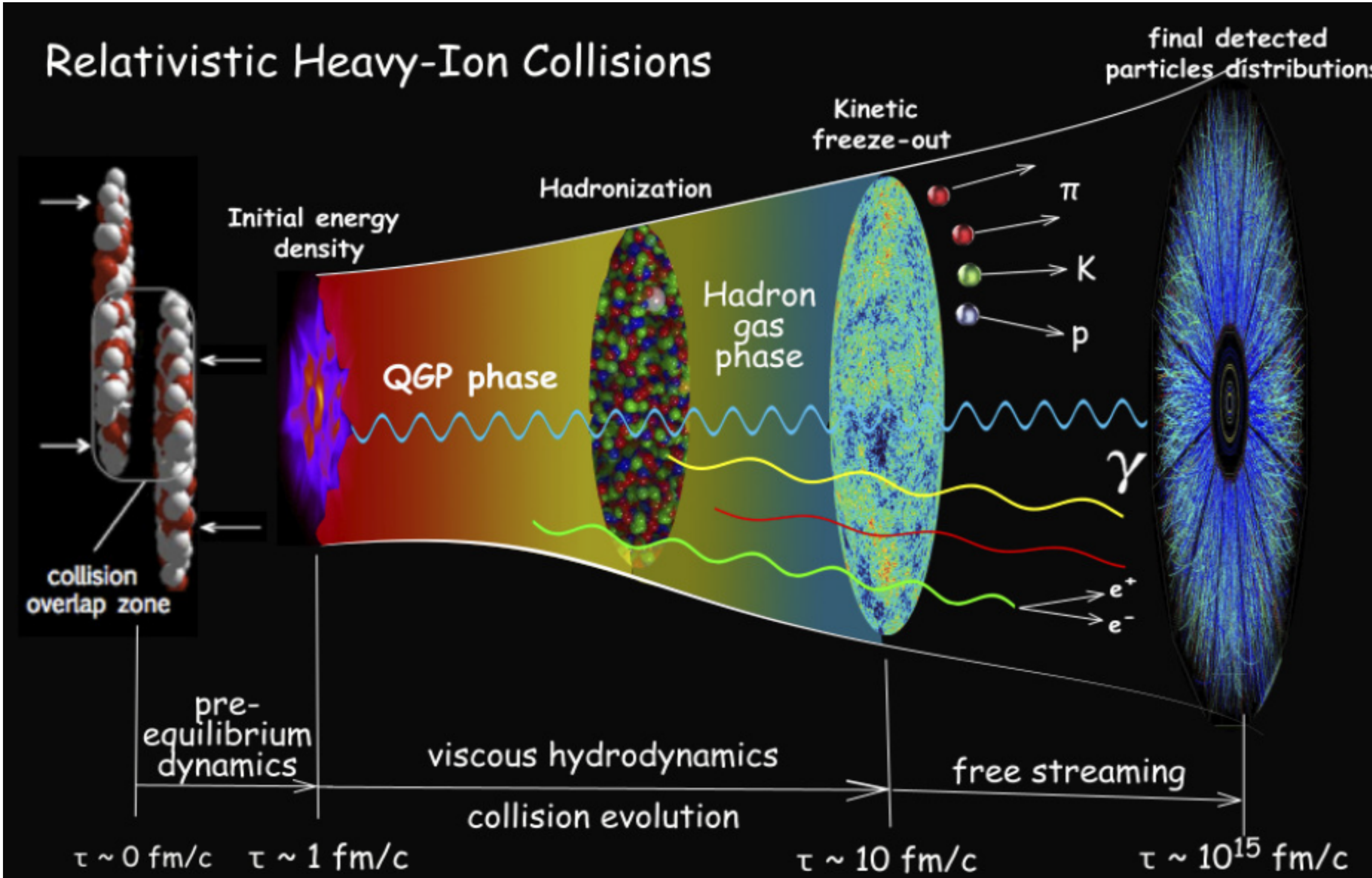
side view

Au+Au Collisions:
200 GeV per nucleon pair

Collision energy
⇩
Particle production
(N~5000)

Major portion of beam energy goes in particle production

Little Bang



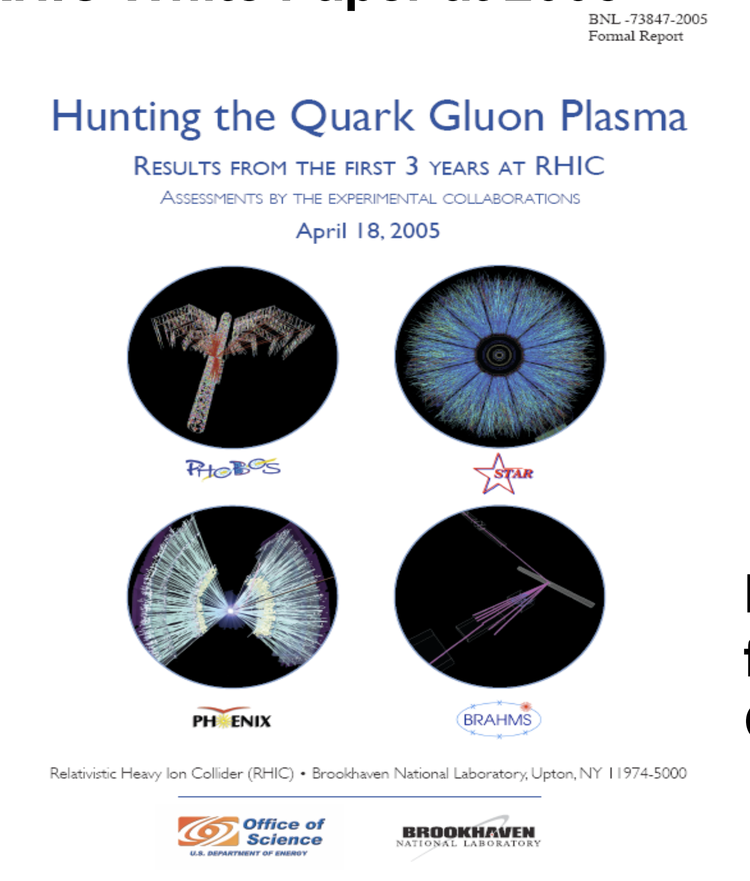
Relativistic Heavy-Ion Collisions
final detected particles distributions
Kinetic freeze-out
Hadronization
Initial energy density
π
K
p
Hadron gas phase
QGP phase
γ
e+
e−
collision overlap zone
pre-equilibrium dynamics
viscous hydrodynamics
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^15 fm/c

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

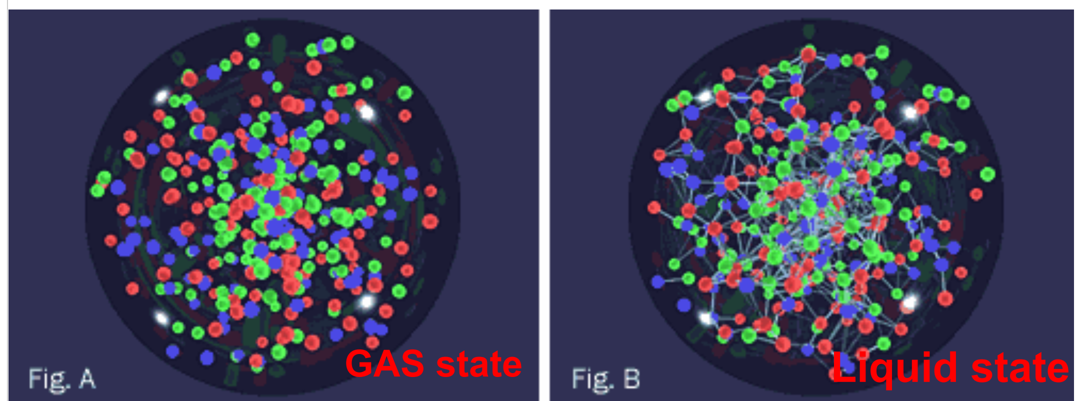
ASSESSMENTS BY THE EXPERIMENTAL COLLABORATIONS

April 18, 2005

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

Office of Science U.S. DEPARTMENT OF ENERGY

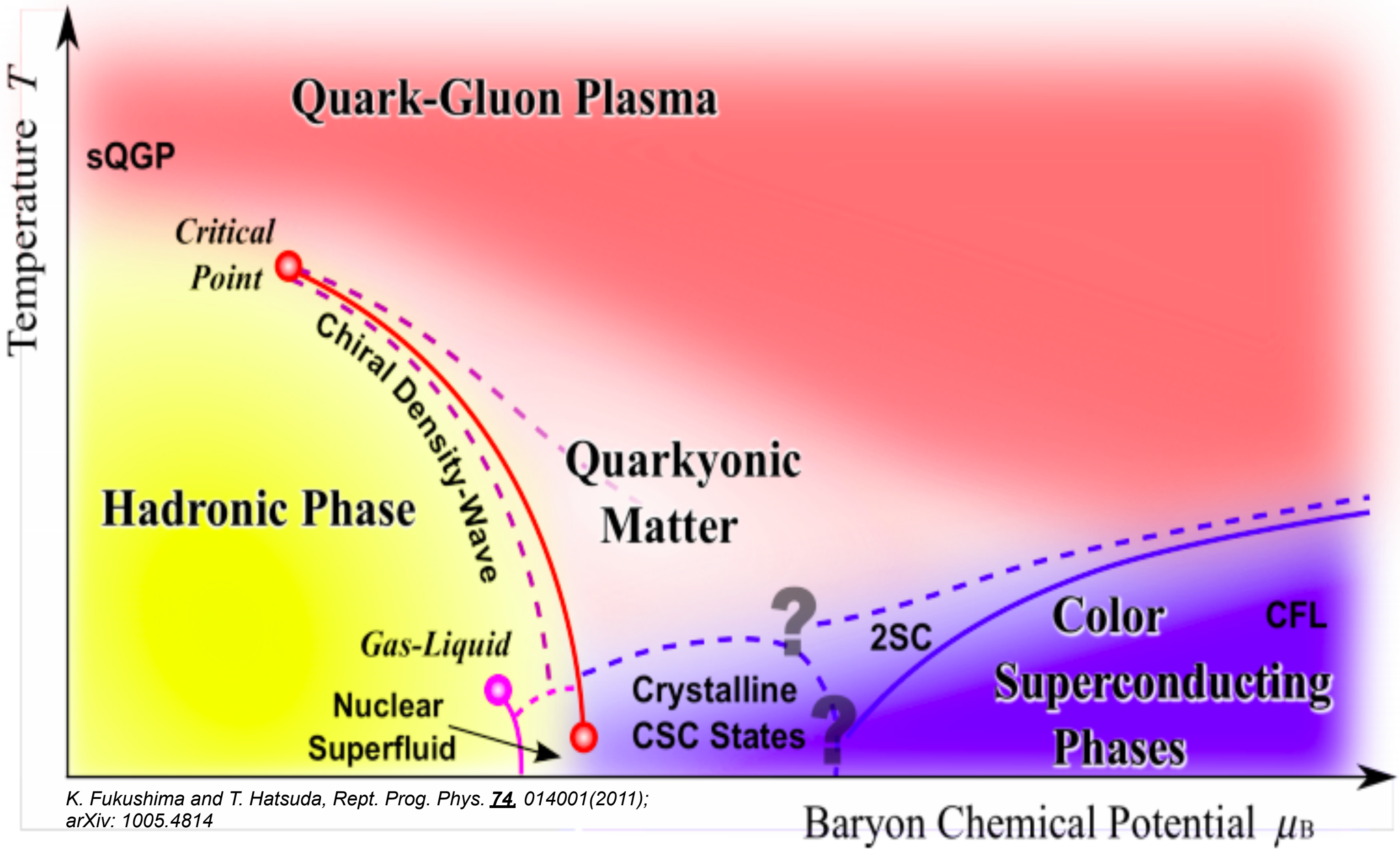
BROOKHAVEN NATIONAL LABORATORY



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

QCD Phase Diagram (Conjectured)

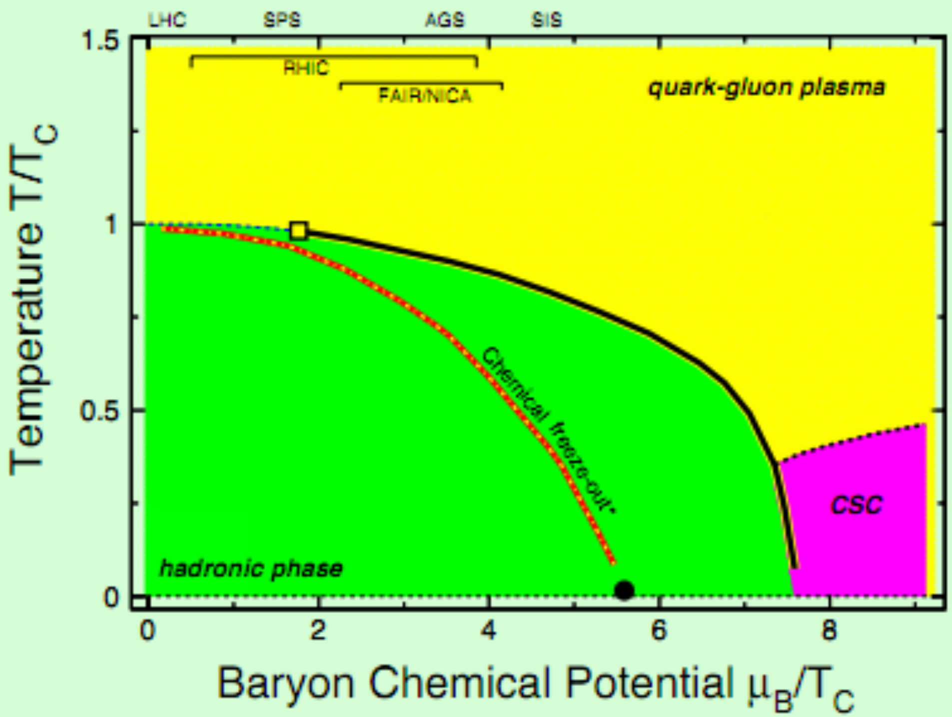
Very rich phase structure at high baryon density region.



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

1. *What's the phase transition temperature ?*
2. *Where is the location of the critical point ?*

Extract the transition temperature Tc at μ_B =0



Science June, 2011

"Scale for the Phase Diagram of Quantum Chromodynamics"

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

Science, 332, 1525(2011)

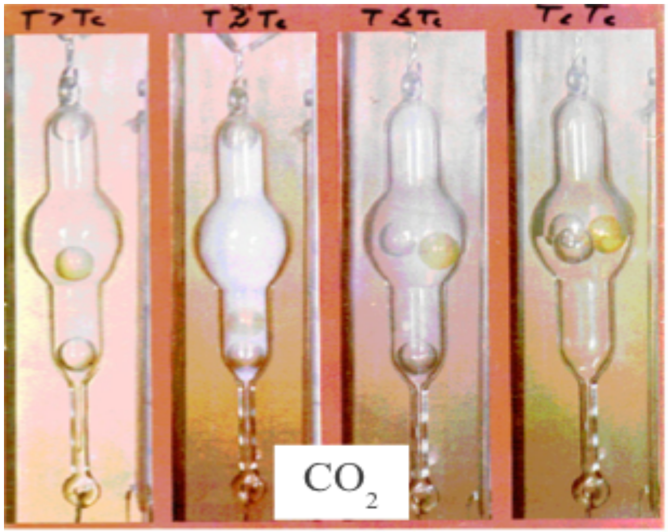
~2 trillion degree

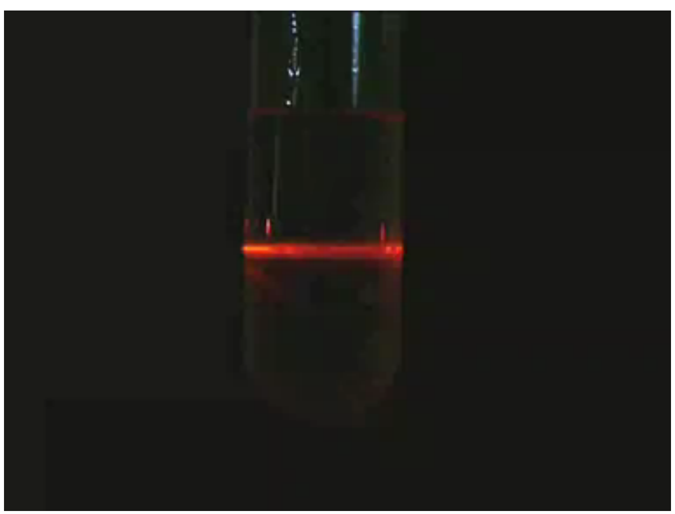
(2万亿摄氏度)

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

Critical Point and Critical Phenomena

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





Critical Phenomena :

- Density fluctuations and cluster formations.
- Divergence of Correlation length (ξ).

  Susceptibilities (χ), heat capacity (C_V) ,
  Compressibility (κ) etc.
  Critical opalescence.
- Universality and critical exponents determined by the symmetry and dimensions of underlying system.
- Finite Size and Finite time effects.

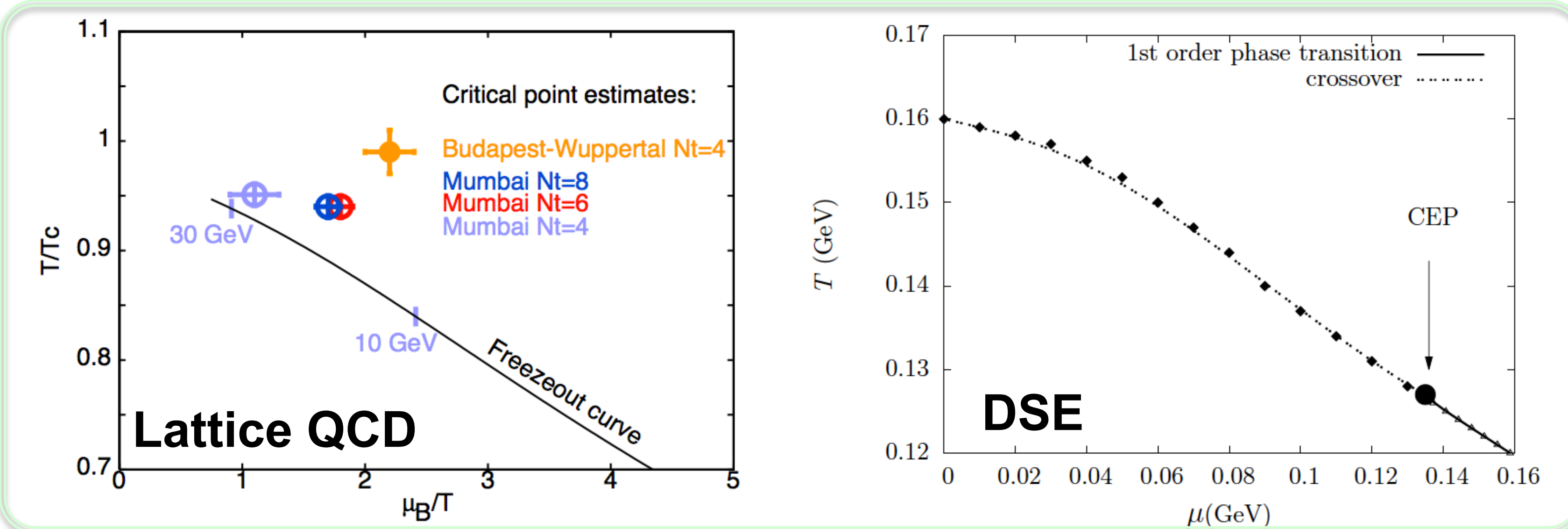
First CP is discovered in 1869 for CO_2 by Andrews.

T_c = 31°C

Can we discovery the Critical Point of Quark Matter ? (Put a permanent mark in the QCD phase diagram in text book.)

T_c ~ Trillion (10^{12}) °C

Status on Predictions



Lattice QCD:

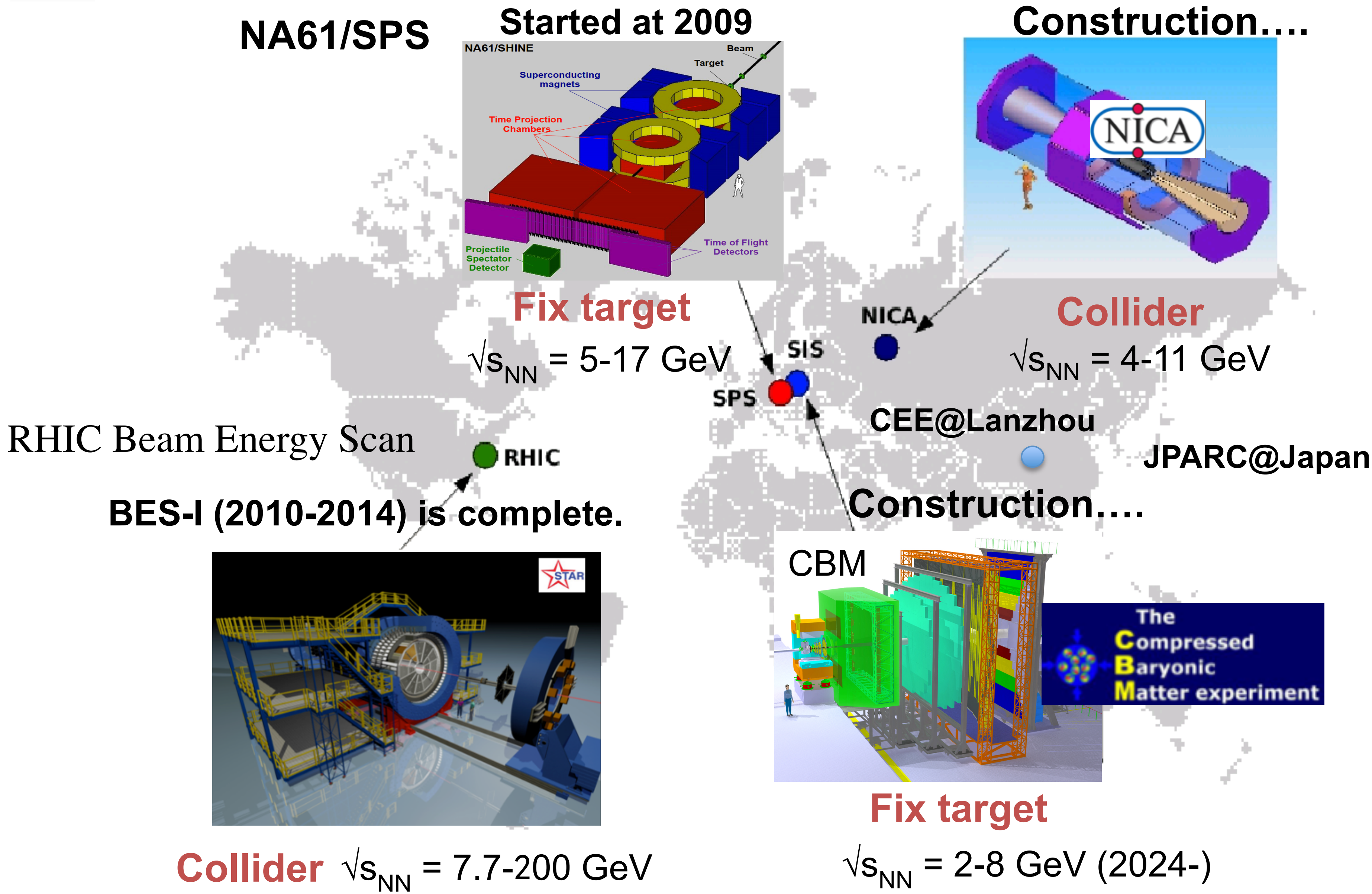
1) Fodor and Katz, JHEP 0404,050 (04)
   (μ^E_B, T_E)= (360, 162) MeV (Re.)
2) Gavai and Gupta, NPA 904, 883c (13)
   (μ^E_B, T_E)= (279, 155) MeV (Taylor)
3) F. Karsch (μ^E_B/ T_E >2, CPOD2016)

DSE:

1) Y. X. Liu, et al., PRD90, 076006(14)
   (μ^E_B, T^E) = (372, 129) MeV
2) H.S. Zong et al., JHEP 07, 014(14)
   (μ^E_B, T_E)= (405, 127) MeV
3) C.S. Fischer et al., PRD90, 034022(14)
   (μ^E_B, T^E) = (504, 115) MeV

μ^E_B =300 ~ 504 MeV, T_E =115~162 MeV, **μ^E_B/ T_E = 1.8-4.6**

Experiments to study high baryon density region



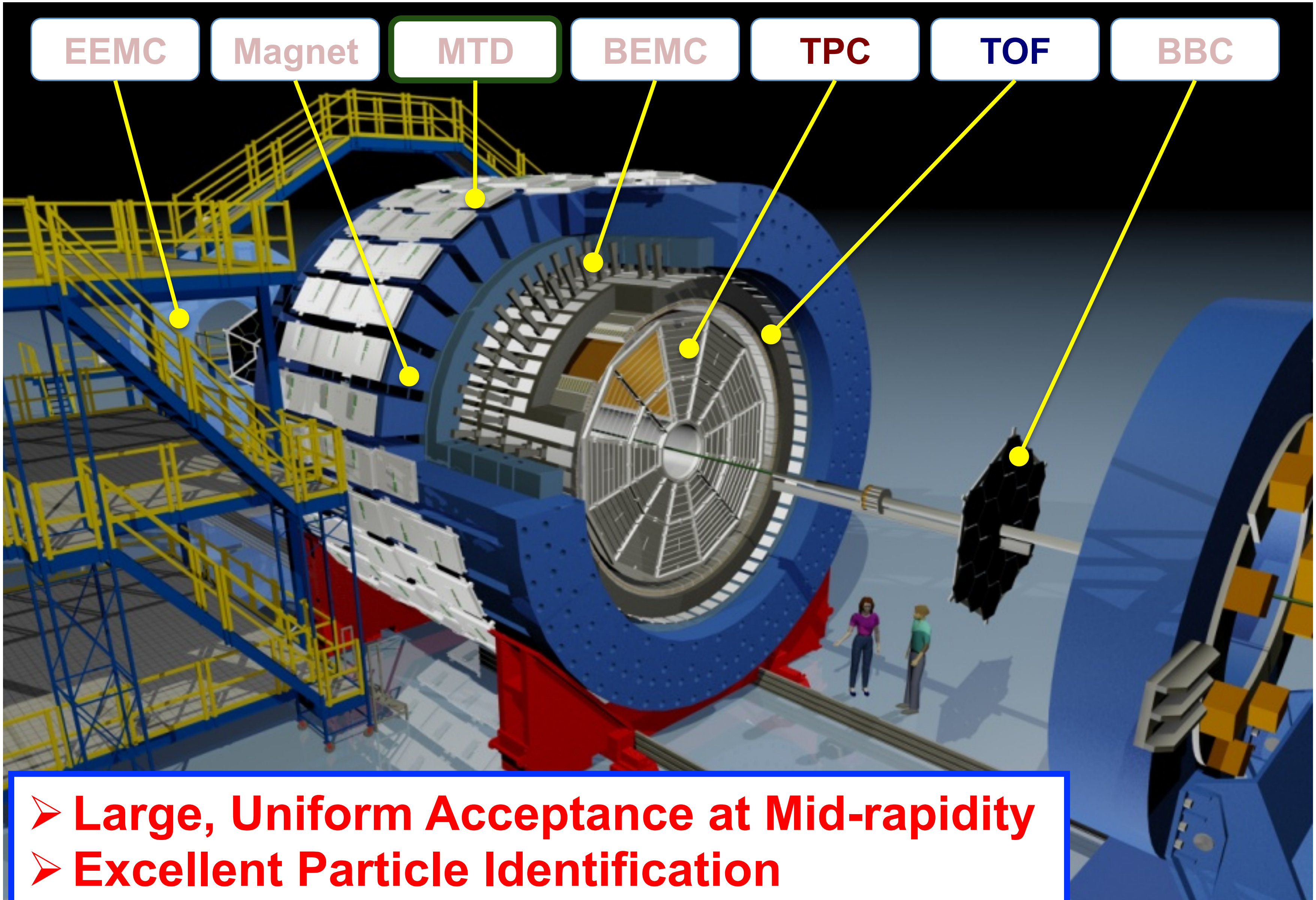
STAR Collaboration

Member #： 549

Institute #： 54

Ph. D： >100

STAR Detector

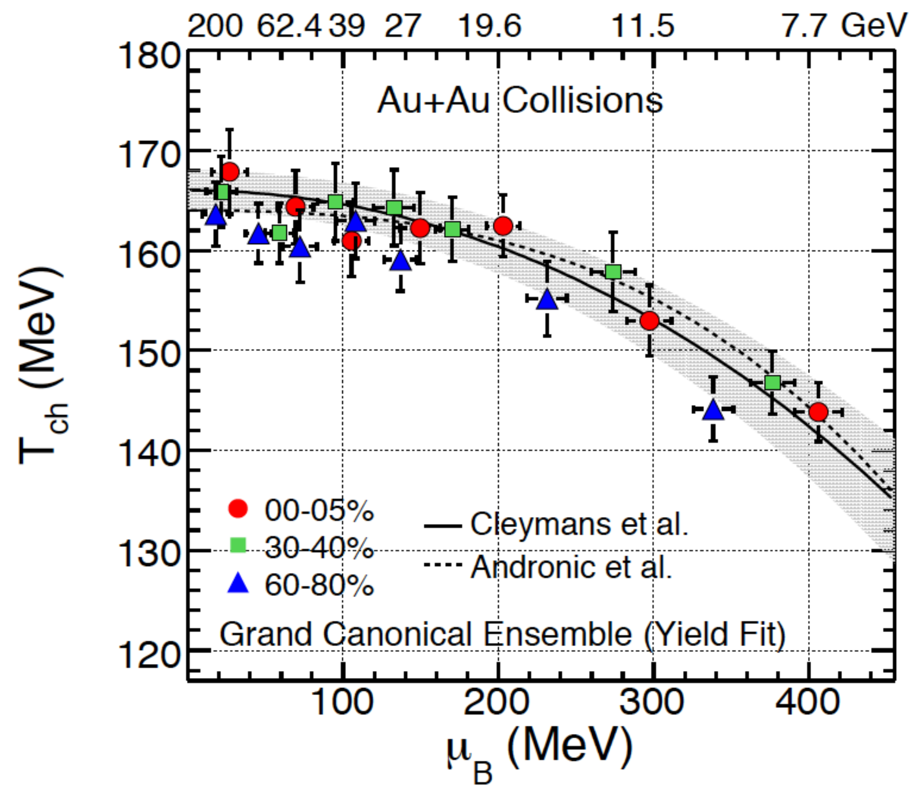


- ➢ **Large, Uniform Acceptance at Mid-rapidity**
- ➢ **Excellent Particle Identification**

Beam Energy Scan - I (2010-2017)

$\sqrt{s_{NN}}$ (GeV)	Events ($X10^6$)	Year	$*\mu_B$ (MeV)	$*T_{CH}$ (MeV)
200	350	2010	25	166
62.4	67	2010	73	165
54.4	~500	2017	83	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

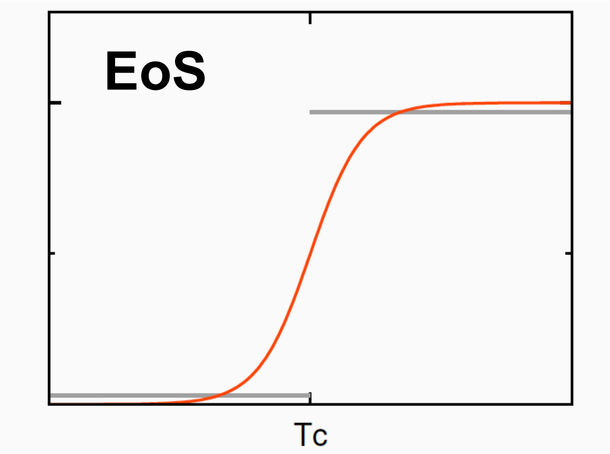
$*(\mu_B, T_{CH})$: J. Cleymans et al., PR**C73**, 034905 (2006)



STAR has good opportunity to explore the QCD phase structure by accessing broad region of phase diagram.

Fluctuations as Signature of Phase Transition

Fluctuations are sensitive to the phase transition and critical point.



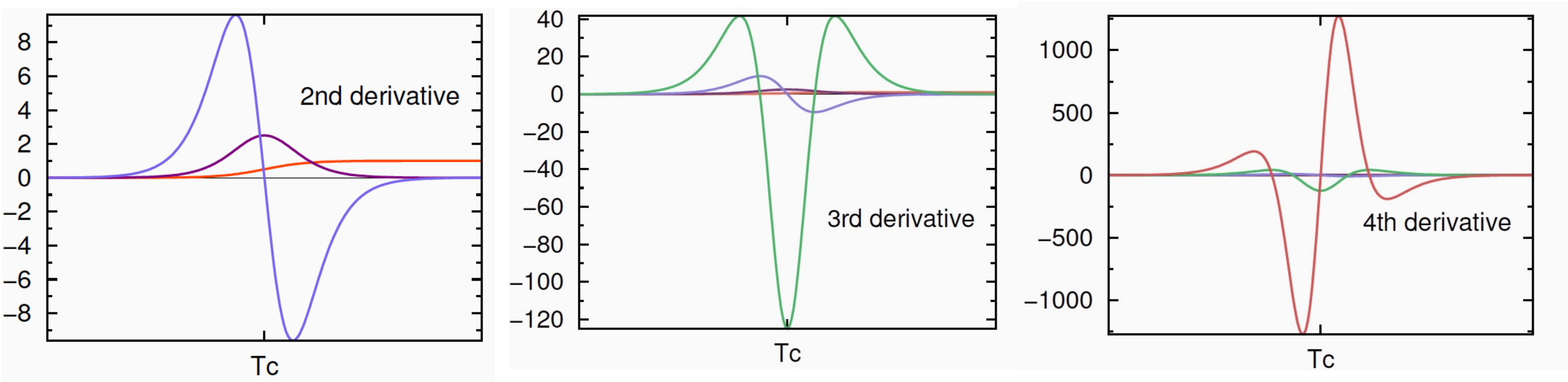
1. Derivations of thermodynamic quantities (EoS) are related to E-by-E fluctuations in HIC.

$$\chi_n = \frac{\partial^n (P/T^4)}{\partial(\mu/T)^n}\Big|_T$$

$$\chi_1 = \frac{1}{VT^3}\langle N \rangle, \quad \chi_2 = \frac{1}{VT^3}\langle (\Delta N)^2 \rangle, \quad \chi_3 = \frac{1}{VT^3}\langle (\Delta N)^3 \rangle,$$

$$\chi_4 = \frac{1}{VT^3}\langle (\Delta N)^4 \rangle_c \equiv \frac{1}{VT^3}\left(\langle (\Delta N)^4 \rangle - 3\langle (\Delta N)^2 \rangle^2\right).$$

2. It reveals more details: Sign change and diverge.



M. Stephanov, K. Rajagopal, E. Shuryak, Phys. Rev. Lett. 81, 4816 (1998). M. Stephanov, K. Rajagopal, E. Shuryak, Phys. Rev. D 60, 114028 (1999). S. Jeon and V. Koch, Phys. Rev. Lett. 83, 5435 (1999). S. Jeon and V. Koch, Phys. Rev. Lett. 85, 2076(2000). M. Asakawa, U. Heinz and B. Muller, Phys. Rev. Lett. 85, 2072 (2000). Y. Hatta, M. Stephanov, Phys. Rev. Lett. 91, 102003 (2003). V. Koch, A. Majumder, J. Randrup, Phys.Rev.Lett. 95, 182301 (2005). 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).

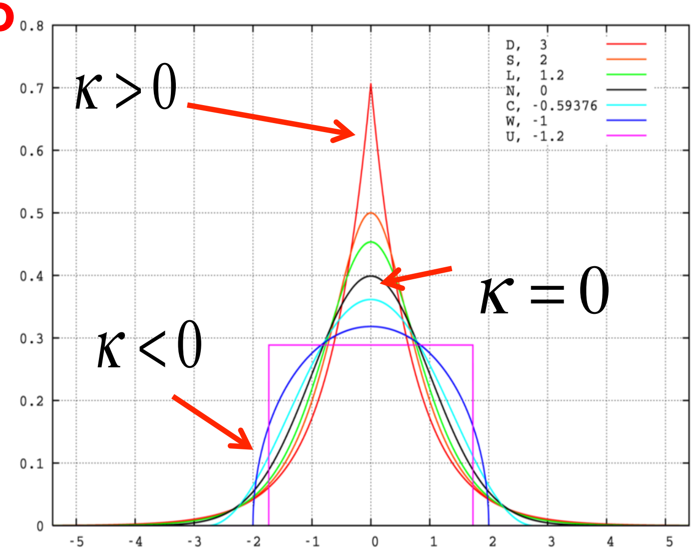
Higher Order Fluctuations of Conserved Quantities

1. **Higher order cumulants (C_n) are sensitive to the correlation length (ξ):**

$$C_{1,N} = \langle N \rangle, \quad C_{2,N} = \langle (\delta N)^2 \rangle$$

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

$$C_{3,N} \propto \xi^{4.5}, \quad C_{4,N} \propto \xi^{7}$$



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

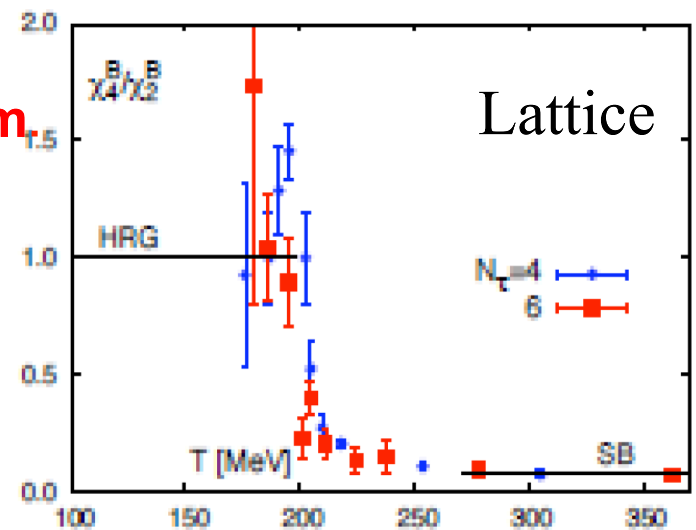
2. **Connection to the susceptibility of the system**

$$\frac{C_{4,q}}{C_{2,q}} = \kappa\sigma^2 = \frac{\chi_q^{(4)}}{\chi_q^{(2)}}$$

$$\frac{C_{3,q}}{C_{2,q}} = S\sigma = \frac{\chi_q^{(3)}}{\chi_q^{(2)}}$$

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

$$q = B, Q, S$$



S. Ejiri et al, Phys.Lett. B 633 (2006) 275. 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).

Three Questions to be addressed

1. Experimentally, how to precisely measure the fluctuations in heavy-ion collisions? (experimental methods)

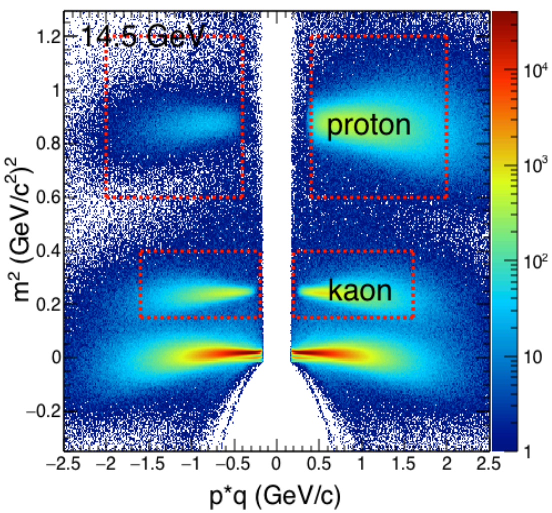
2. What's the characteristic signature (model independent) of the QCD critical point for the observable in heavy-in collisions ?

3. What's the background contributions (baseline) to the experimental observables ?

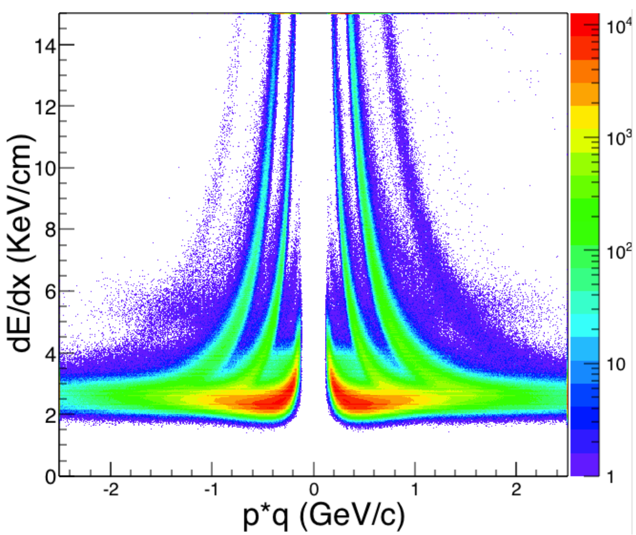
Analysis Details

	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
	$0.5 < \lvert\eta\rvert < 1.0$	$\lvert\eta\rvert < 1.0$	$\lvert\eta\rvert < 1.0$

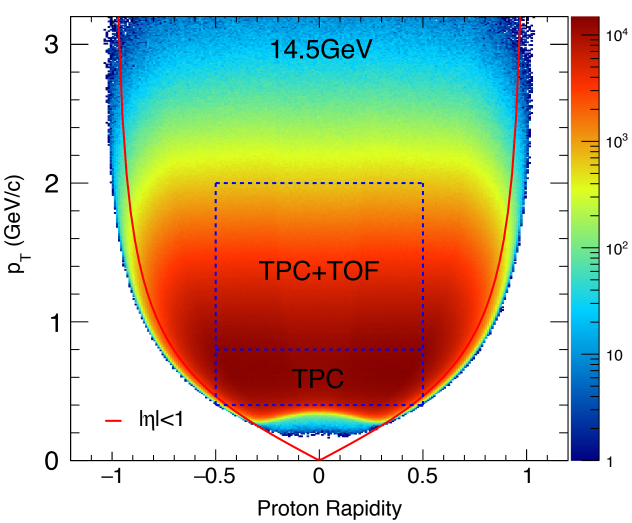
TOF PID



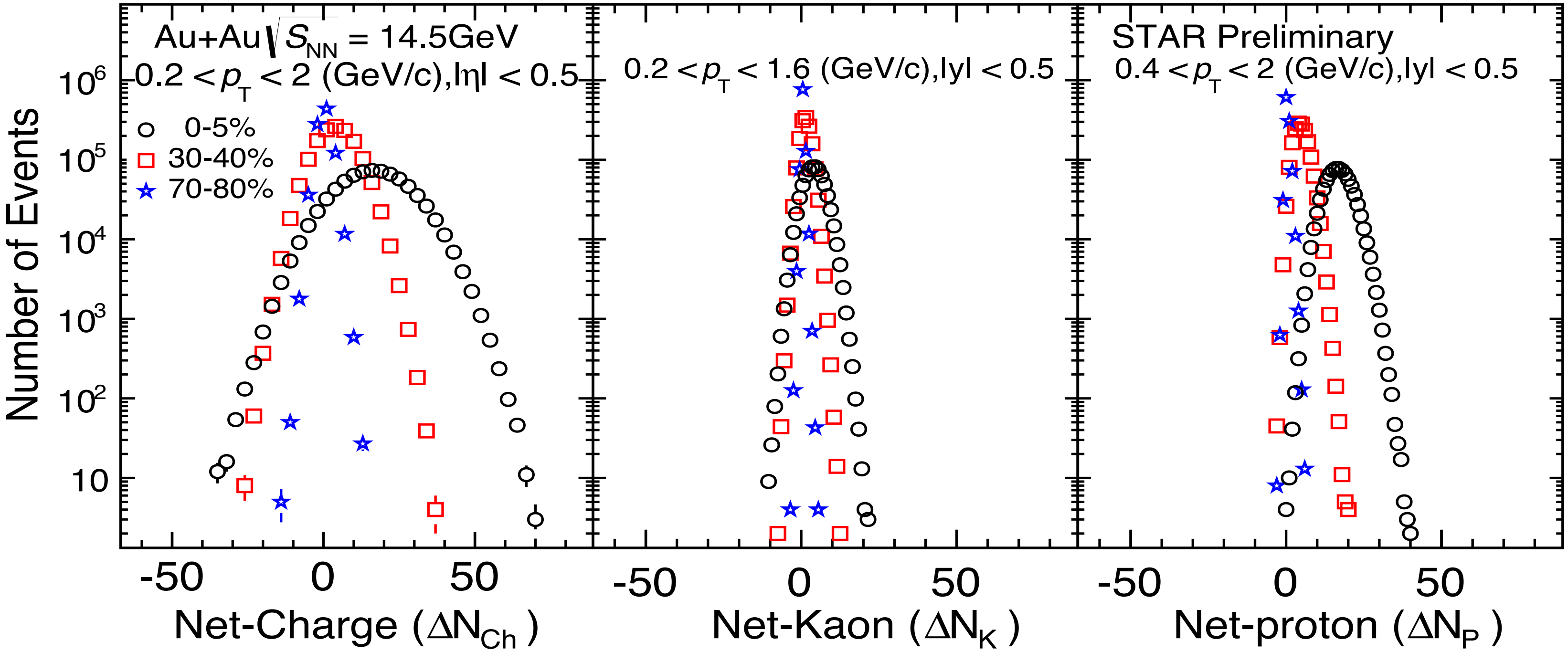
TPC PID



Phase Space



Raw Event-By-Event Net-Particle Multiplicity Distribution



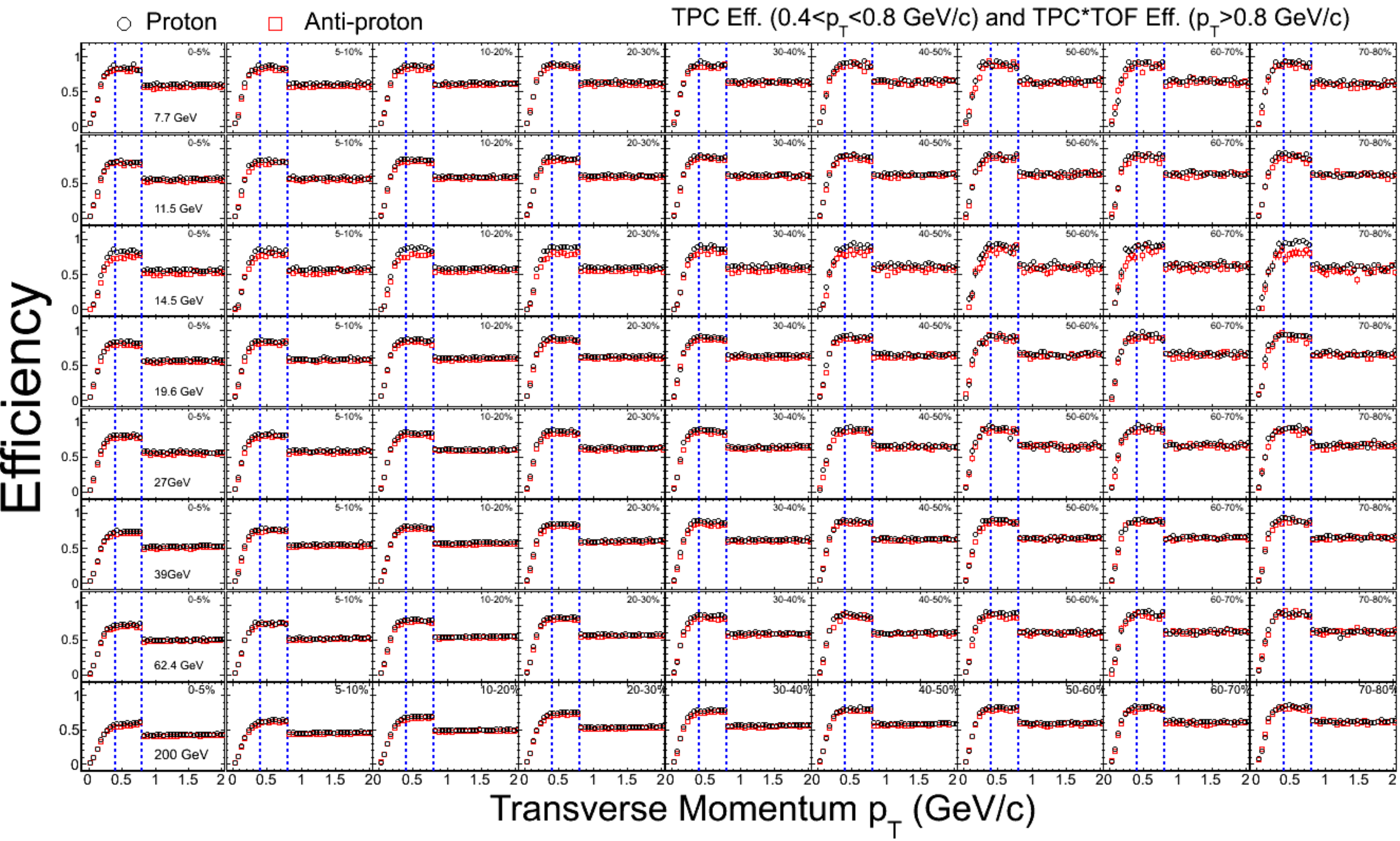
Effects needed to be addressed to get final moments/cumulants:

1. Eliminate auto-correlation effects: Centrality definition.
2. Suppress volume fluctuations：Centrality bin width correction
3. Efficiency correction: Use formula based on binomial efficiency

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).

Review article : X. Luo and N. Xu, Nucl. Sci. Tech. 28, 112 (2017). [arXiv: 1701.02105]

Efficiency for Proton and Anti-proton



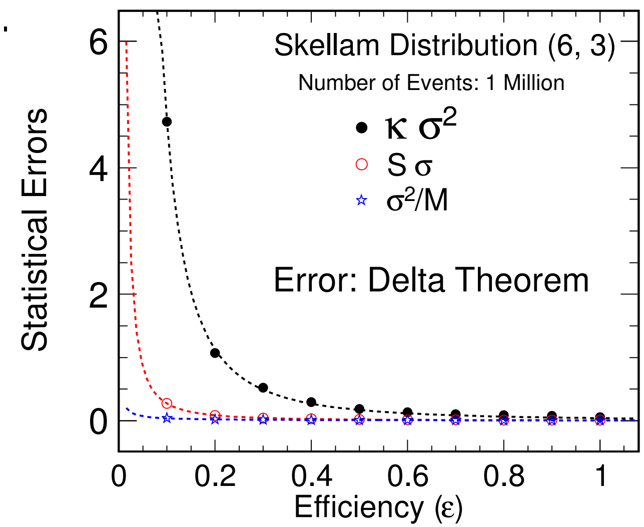
We provide a unified description of efficiency correction and error estimation for higher moments analysis in heavy-ion collisions.

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

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

Binomial response for efficiency:

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



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

X. Luo, PRC91, 034907 (2015).

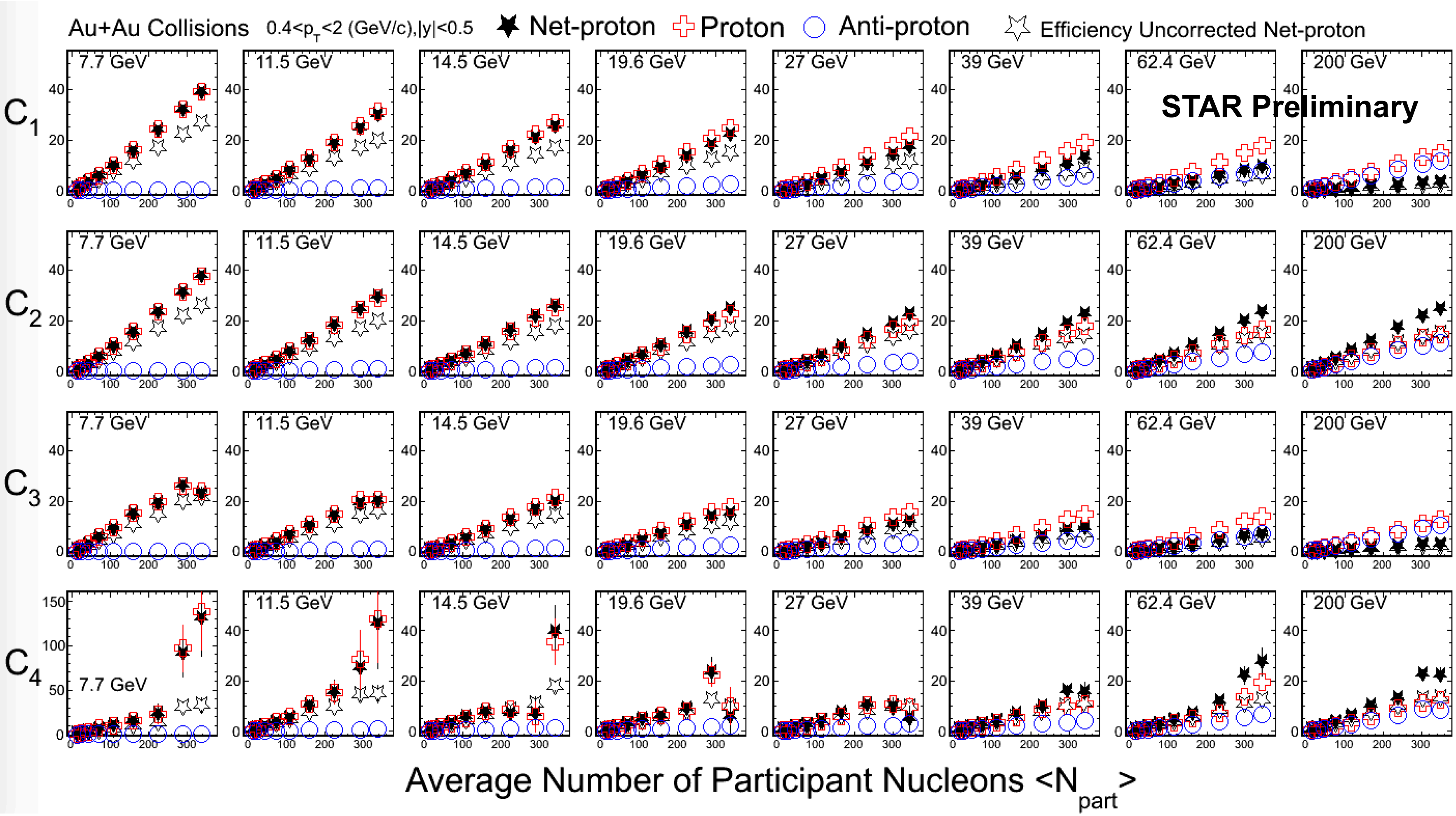
$$error(S\sigma) \propto \frac{\sigma}{\varepsilon^{3/2}}$$

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

Also see:

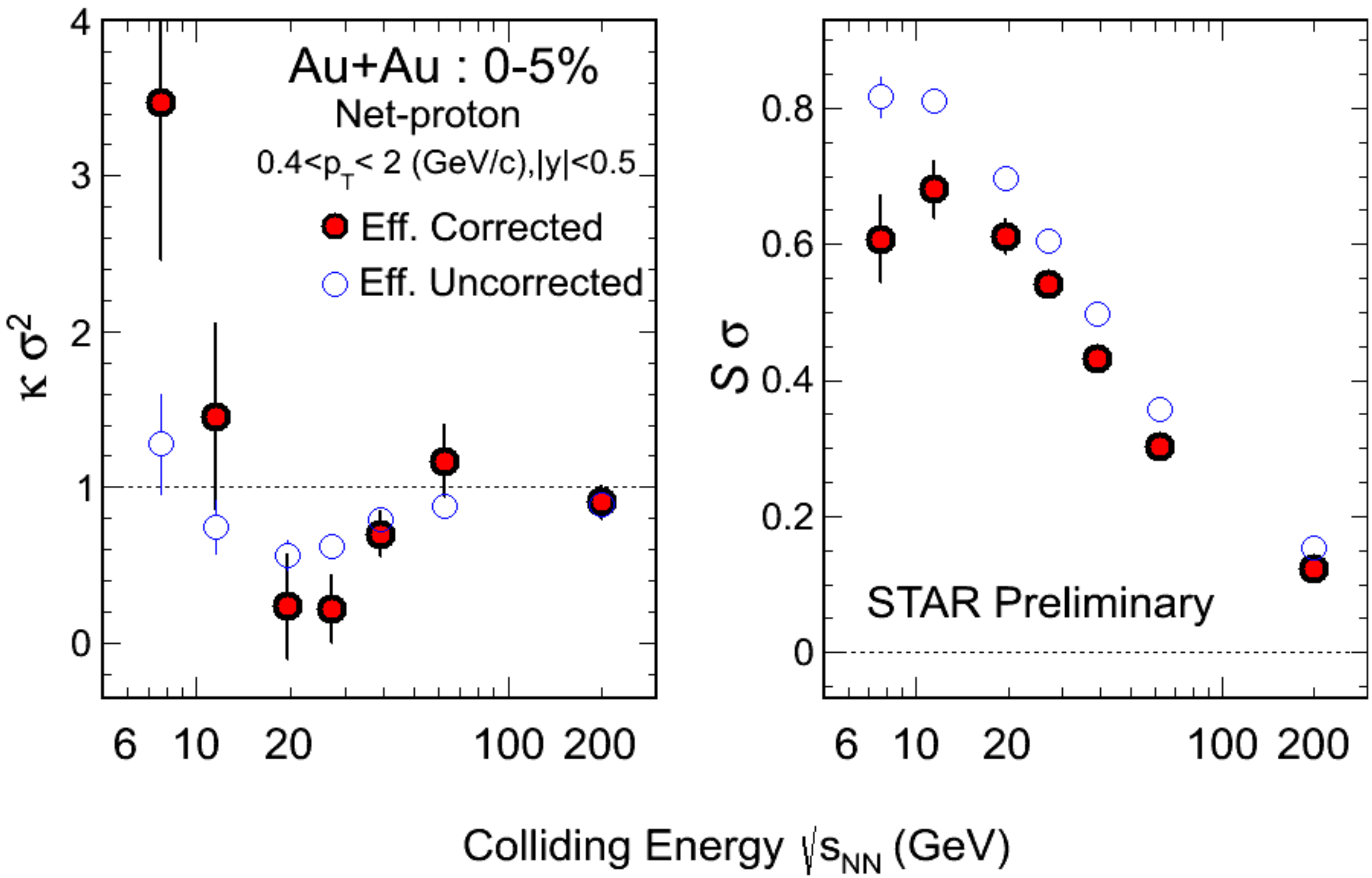
A. Bzdak and V. Koch, PRC91,027901(2015), PRC86, 044904(2012). T. Nonaka, et al., PRC95, 064912 (2017).

Net-Proton, Proton Cumulants ($C_1 \sim C_4$)



1. In general, cumulants are linearly increasing with $<N_{part}>$.
2. Efficiency corrections are important.
3. At low energies, the proton cumulants are close to net-proton.

Energy Dependence of Net-Proton Fluctuations



Clear non-monotonic energy dependence is observed in the fourth order net-proton fluctuations in 0-5% central Au+Au collisions.

Towards Understanding Experimental Data

Experiment : Signal (critical)+Bkgd. (non-critical)

1. **Effective model calculations (Static):** σ field Model, NJL, PNJL, PQM, 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

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

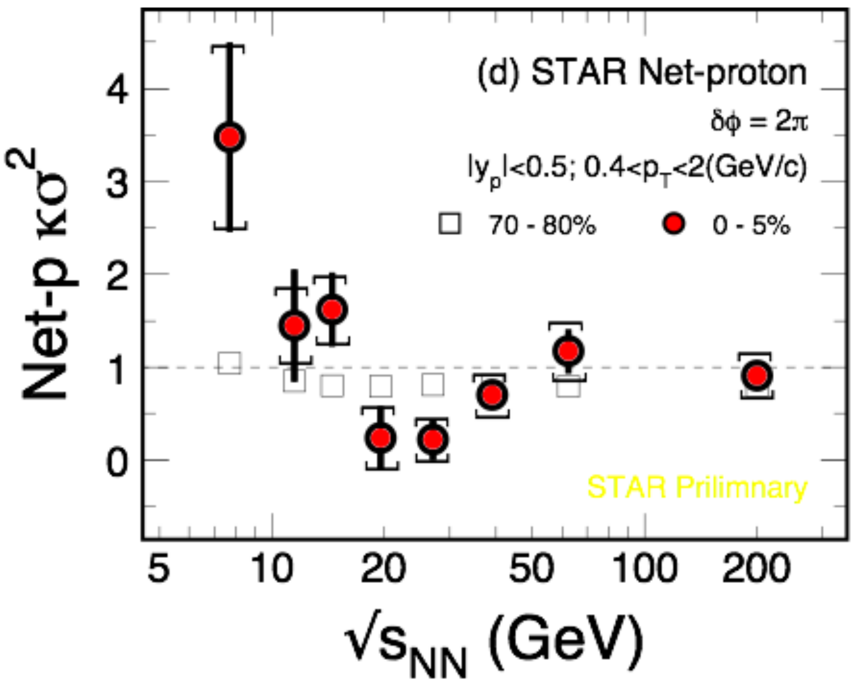
3. **Non-critical background:** HRG, UrQMD, JAM, AMPT, Hydro+UrQMD

   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)

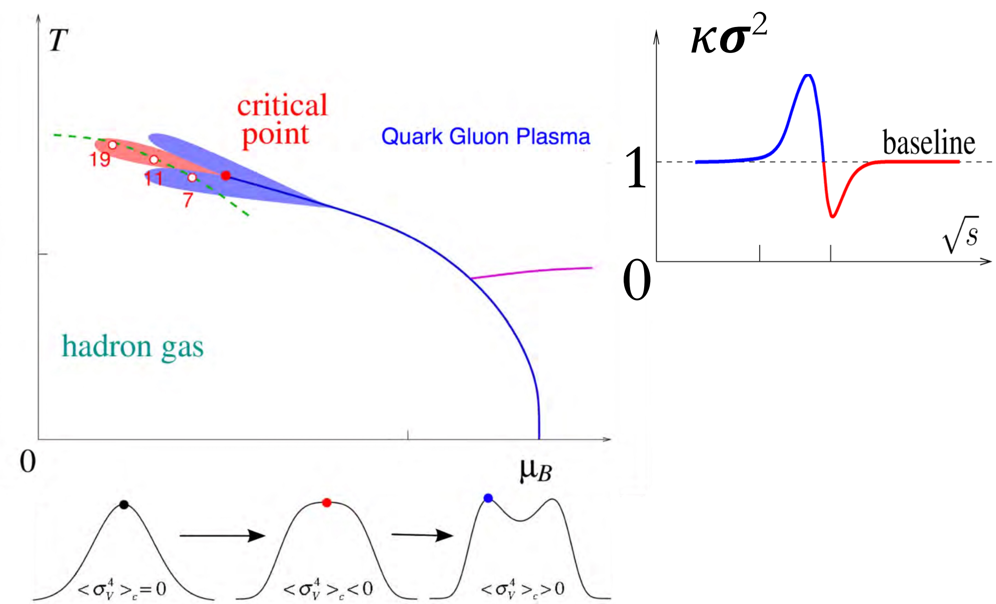
4th order Net-Proton Fluctuations $\kappa\sigma^2 = C_4/C_2$

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

STAR Data



σ field Model

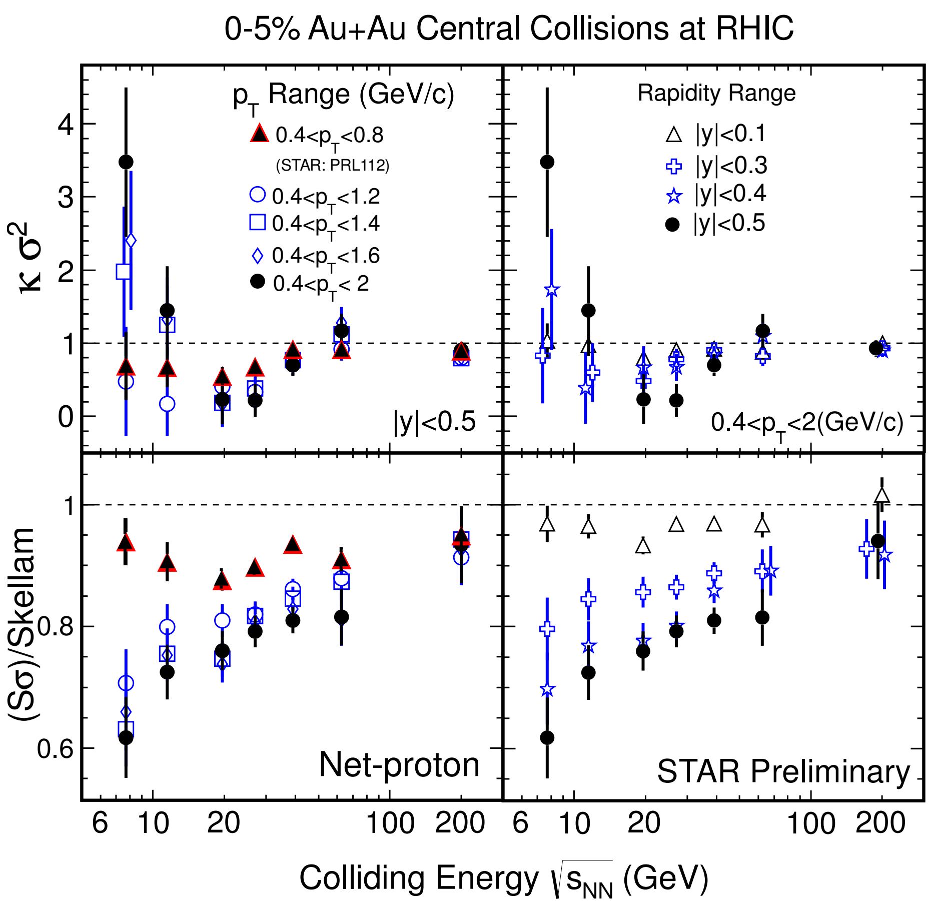


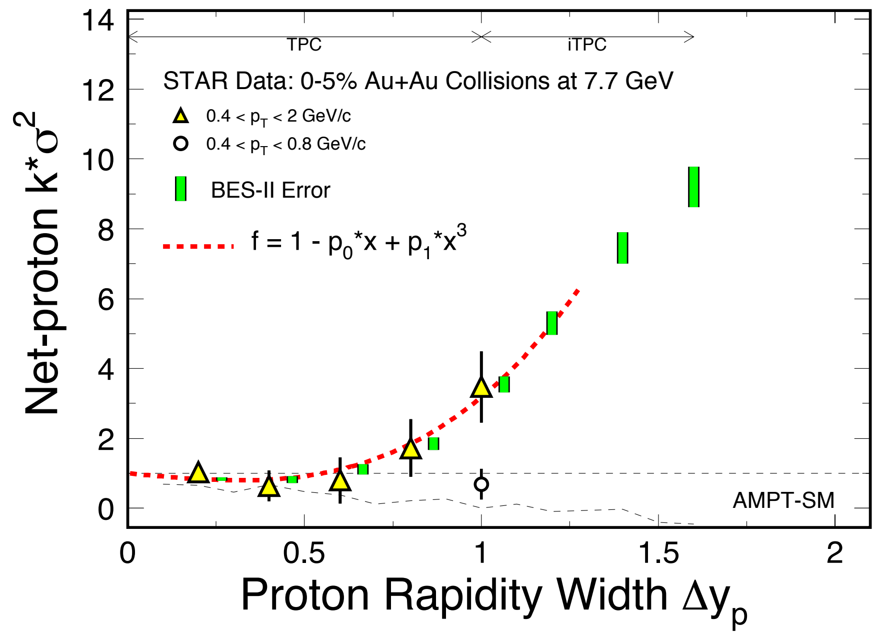
Critical signal: Oscillation Structure

STAR, PRL105,022302 (2010); PRL112,032302 (2014).
X. Luo (for STAR Coll.), PoS CPOD2014 (2015) 019
X. Luo, Plenary talk at QM15, Nucl. Phys. A956,75 (2016)

M. A. Stephanov, PRL102, 032301 (2009).
M. A. Stephanov, PRL107, 052301 (2011).

Acceptance Dependence: STAR Data

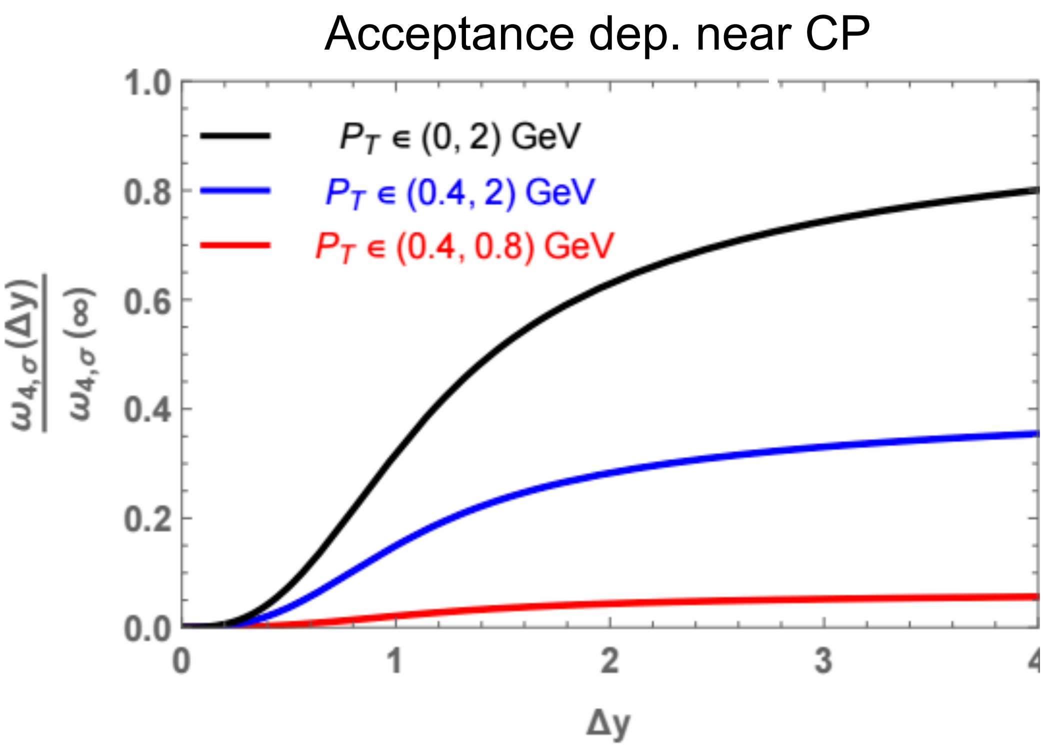


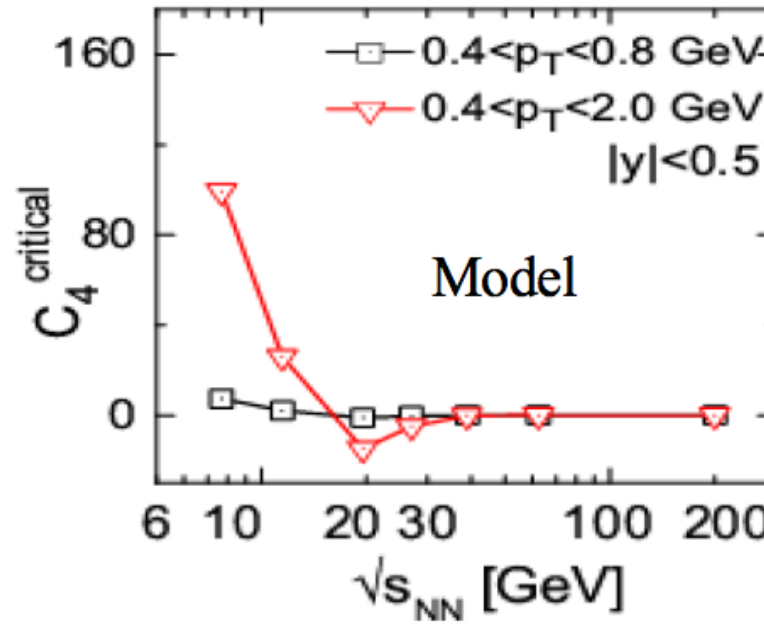


Enhance the fluctuation signals by enlarge the acceptance.

- ➢ The smaller the acceptance window the closer to the Poisson values.
- ➢ The acceptance needs to be large enough to capture the critical fluctuations.

Acceptance Dependence: Theoretical Calculations

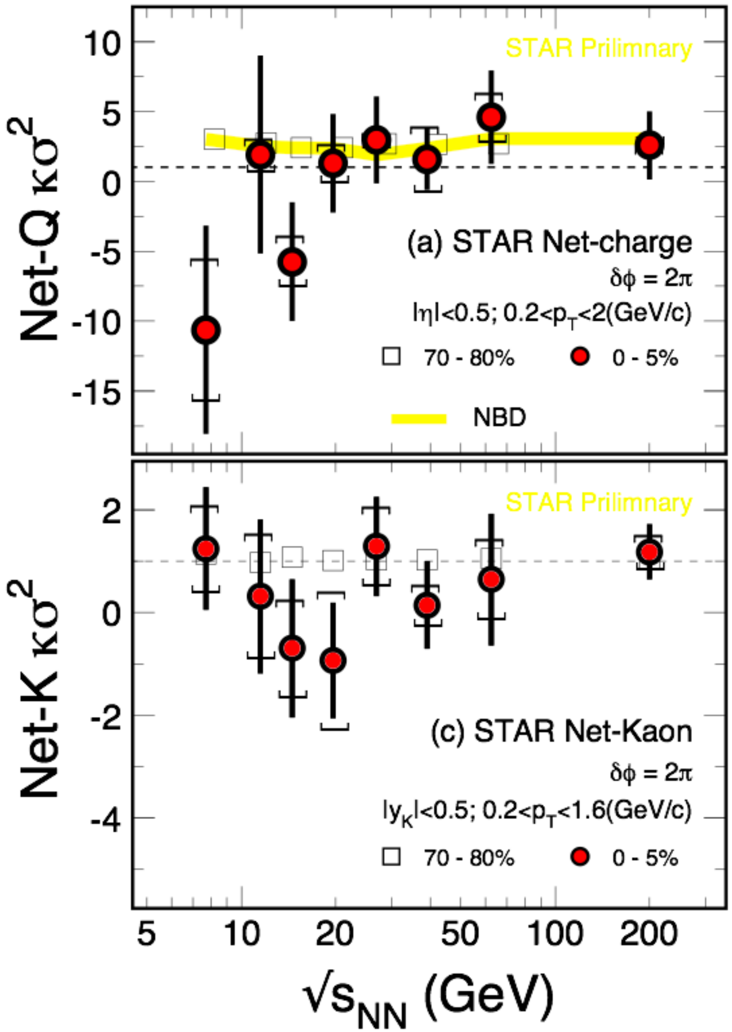




B. Ling, M. Stephanov, Phys. Rev. C 93, 034915 (2016).
A. Bzdak, V. Koch, Phys.Rev. C95, 054906 (2017)
H. Song et al., PRC94, 024918 (2016)
M. Kitazawa, X. Luo, PRC in press. [arXiv: 1704.04909]

Signals can be enlarged by extending the acceptance.

Net-charge and Net-kaon Fluctuations



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

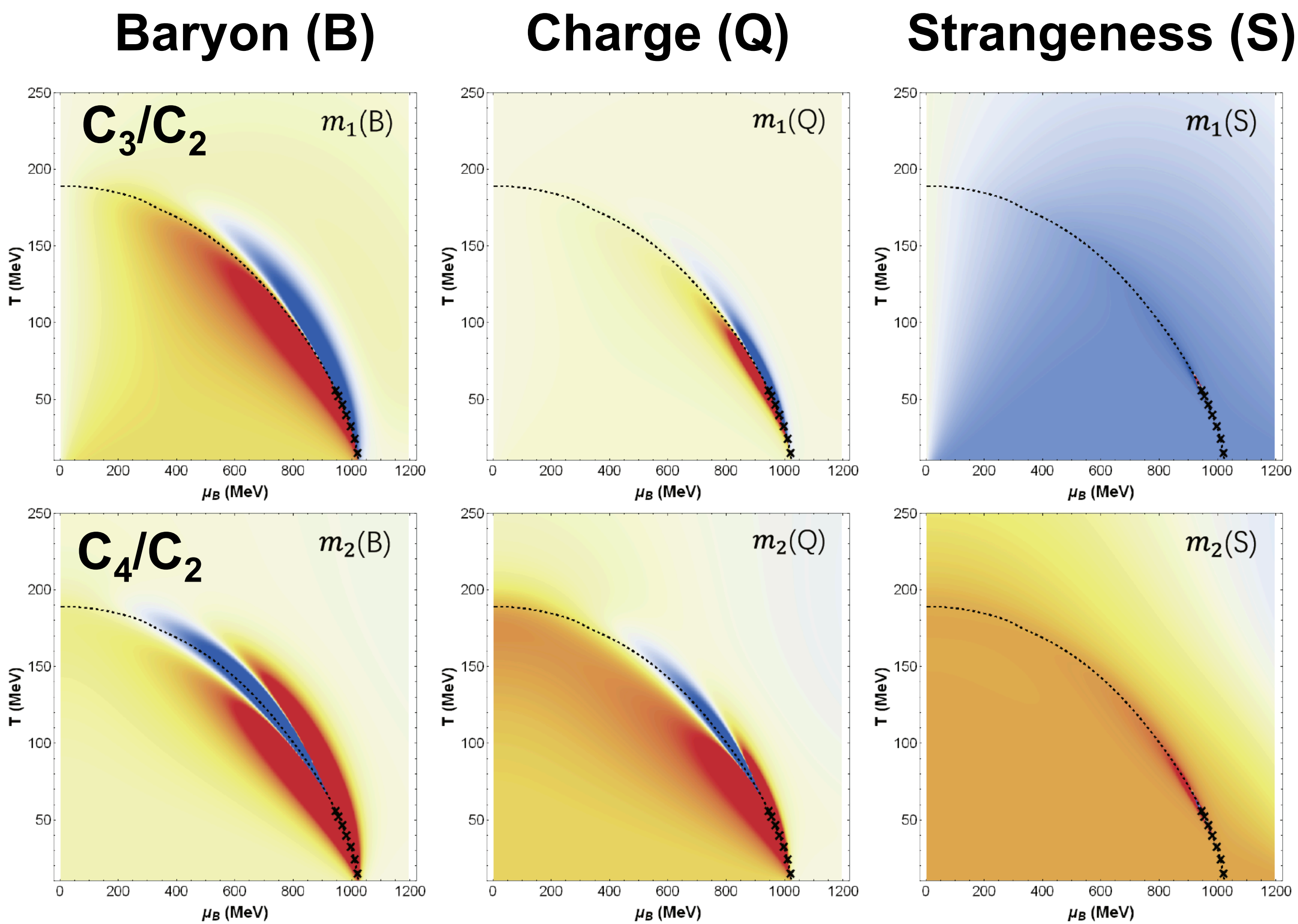
σ: Width of the distribution

ε: Efficiency

Net-Charge: Phys.Rev.Lett. 113 (2014) 092301
Net-Kaon: Submitted to PLB [arXiv: 1709.00773]

1) Within errors, the results of net-Q and net-Kaon show flat energy dependence.
2) More statistics are needed at low energies.

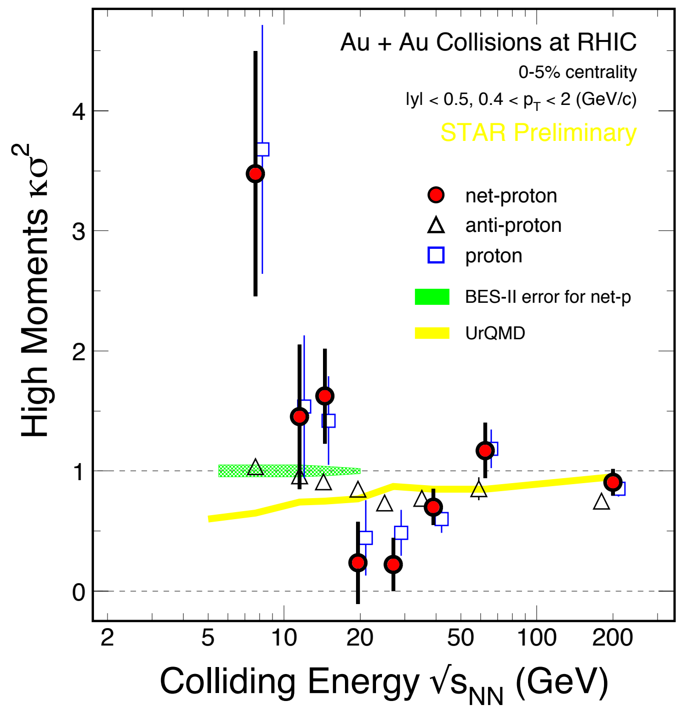
NJL Model Calculations

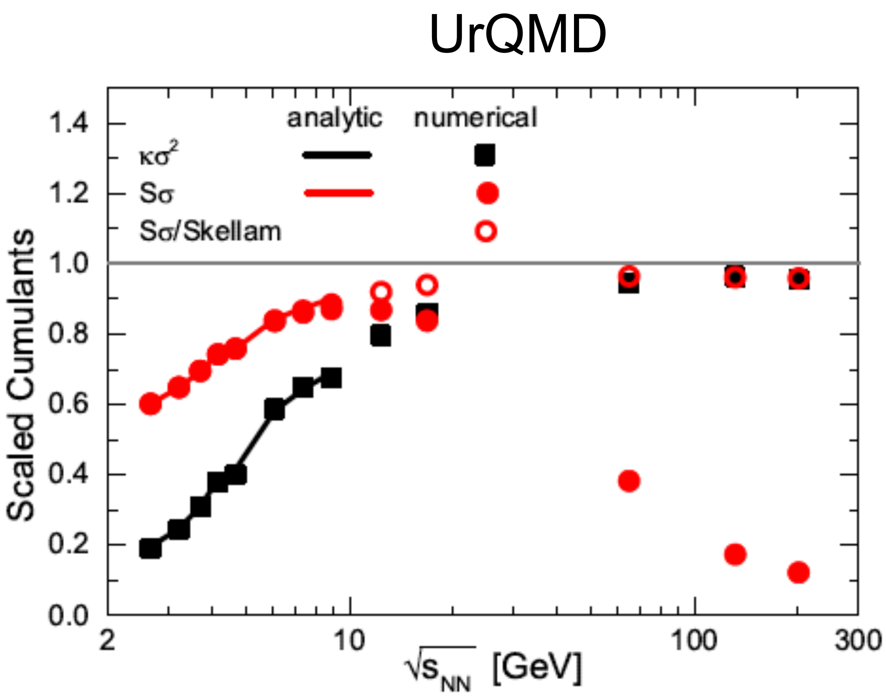


1) CP Signals from baryon fluctuations are much stronger than Q and S.
2): Forth and third order fluctuations have very different behavior.

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

Transport Model Calculations





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

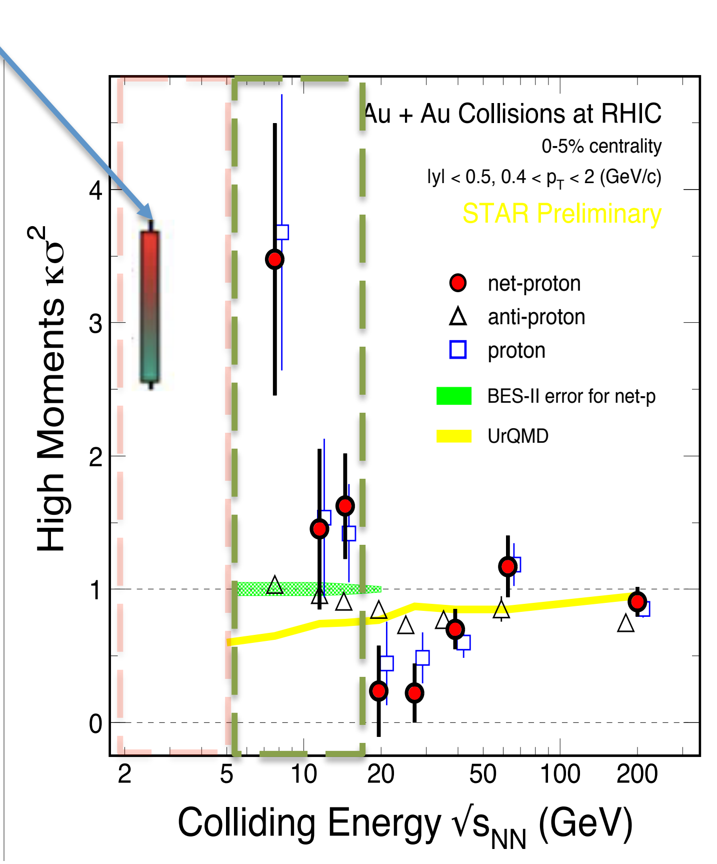
*All models: **suppress higher order net-proton fluctuations***

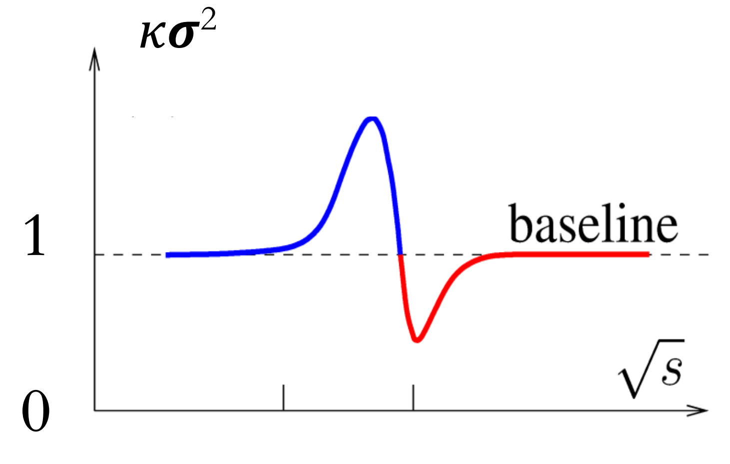
(UrQMD, AMPT, HRG and JAM do not reproduce data)

1) Z. Feckova, J. Steonheimer, B. Tomasik, M. Bleicher, 1510.05519, PRC92, 064908(15)
2) X.F. Luo et al, NP A931, 808(14); P.K. Netrakanti et al., NP A947, 248(16); P. Garg et al. Phys. Lett. B726, 691(13)
3) J. Xu, YSL, X. Luo, F. Liu, PRC94, 024901 (2016)
4) Baryon mean-field (attractive): Shu He et al., Phys. Lett. B762, 296(2016).
5) Proton clusters: A. Bzdak, V. Koch, V. Sokokov, Eur. Phys. J., C77, 288(2017)

Future Plan for Critical Point Search

Preliminary HADES Results (QM2017)





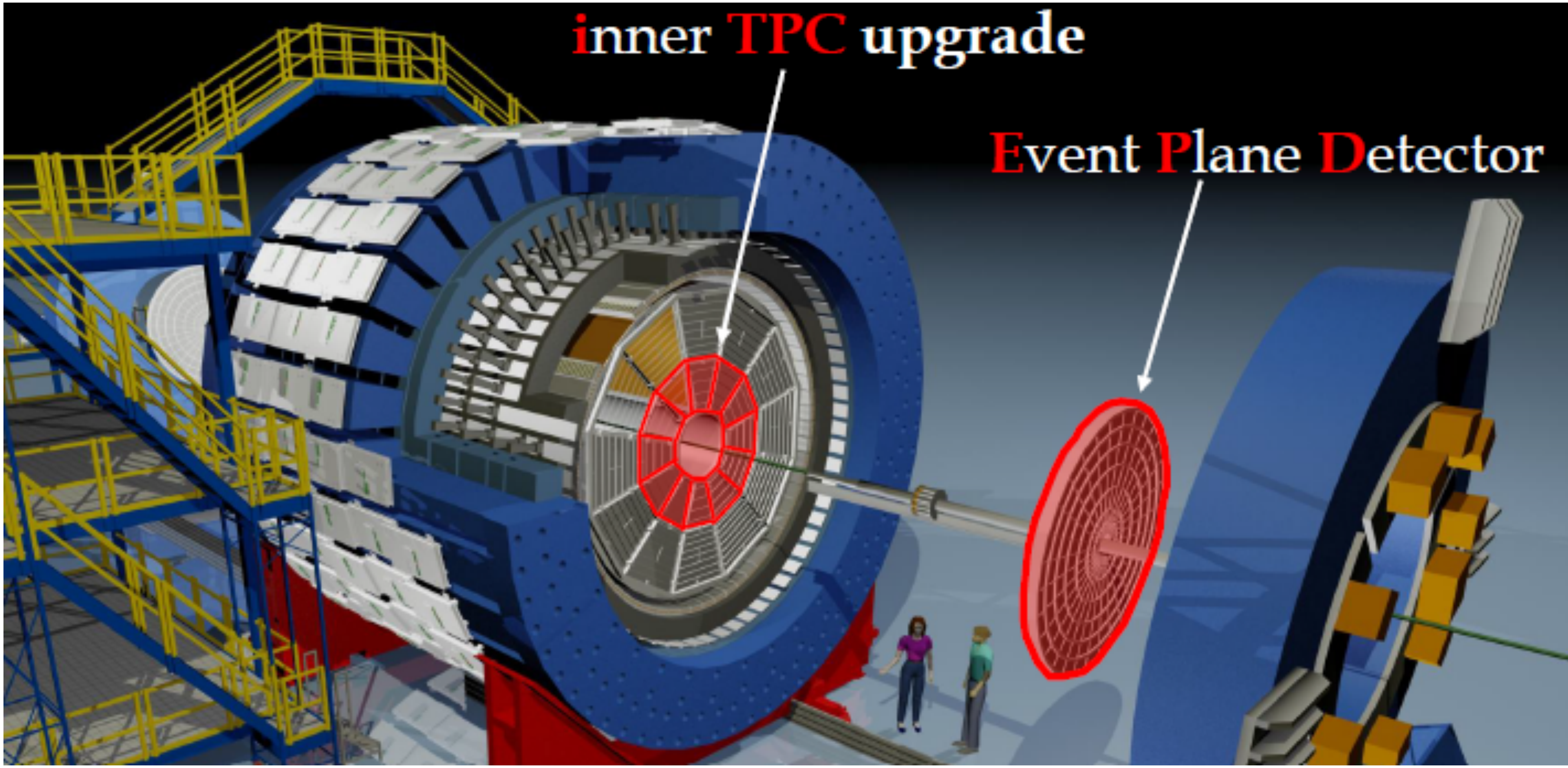
Need precision measurement between 7.7 to 20 GeV (BES-II, 2019-2020)

CBM/STAR FXT/HADES/NICA Experiments (**2.5 < $\sqrt{s_{NN}}$ < 8** GeV) :

Key region for Critical Point search

STAR Data: X.F. Luo *et al*, CPOD2014, QM2015; PRL**112** (2014) 32302

STAR Upgrades for BES Phase-II



1) Enlarge rapidity acceptance
2) Improve particle identification
3) Enhance centrality/EP resolution

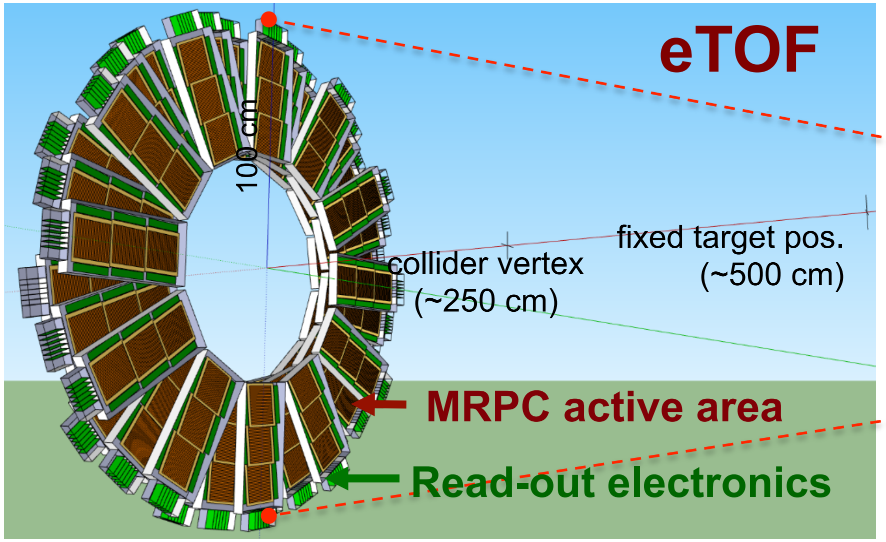
iTPC, EPD, eTOF
Dedicated two runs at RHIC: 2019 & 2020

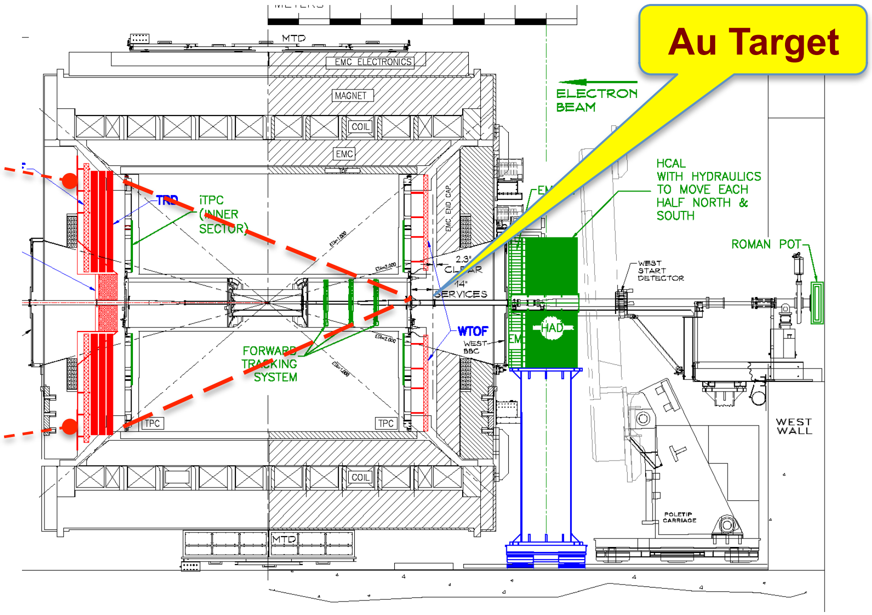
2019-2020: BES II at RHIC

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES II / BES I	Weeks	μ_B (MeV)	T_{CH} (MeV)
200	350	2010		25	166
62.4	67	2010		73	165
54.4	**1200**	**2017**			
39	39	2010		112	164
27	70	2011		156	162
19.6	**400** / 36	**2019-20** / 2011	**3**	206	160
14.5	**300** / 20	**2019-20** / 2014	**2.5**	264	156
11.5	**230** / 12	**2019-20** / 2010	**5**	315	152
9.2	**160** / 0.3	**2019-20** / 2008	**9.5**	355	140
7.7	**100** / 4	**2019-20** / 2010	**14**	420	140

Precision measurements, map the QCD phase diagram **$200 < \mu_B < 420$MeV**

CBM Phase-0 Exp: eTOF at STAR





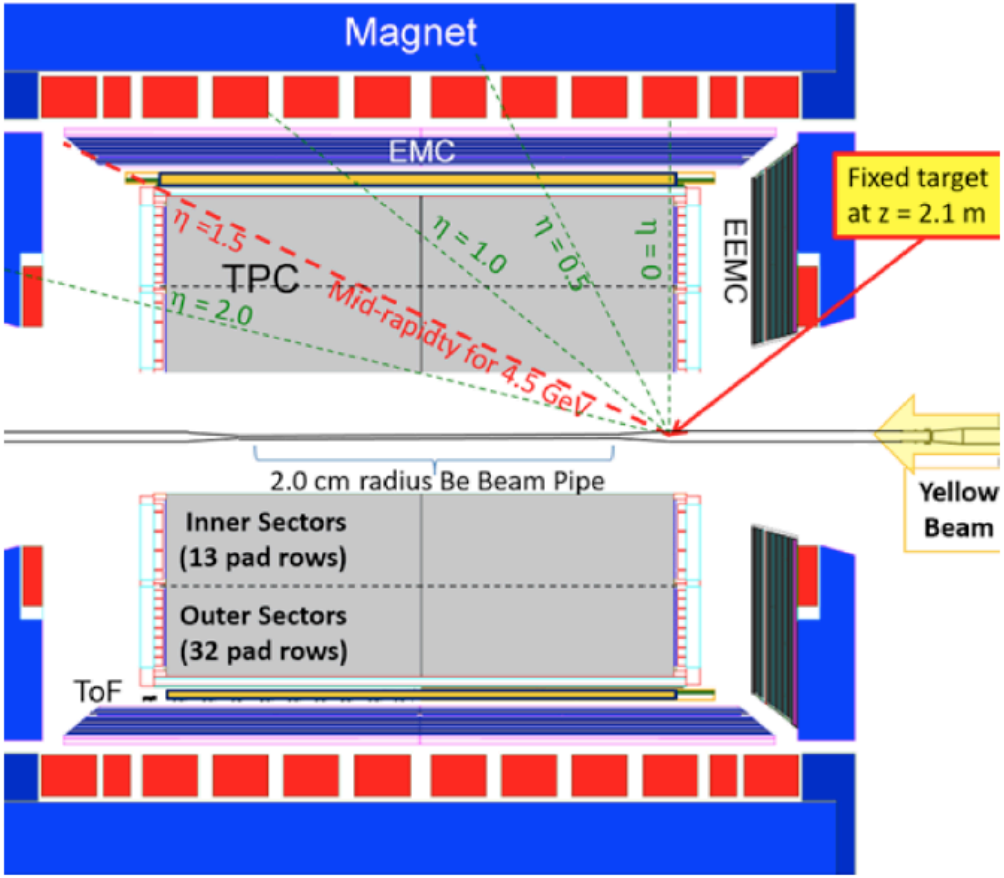
FAIR (CBM) construction starts 17, beam on target in 2025!

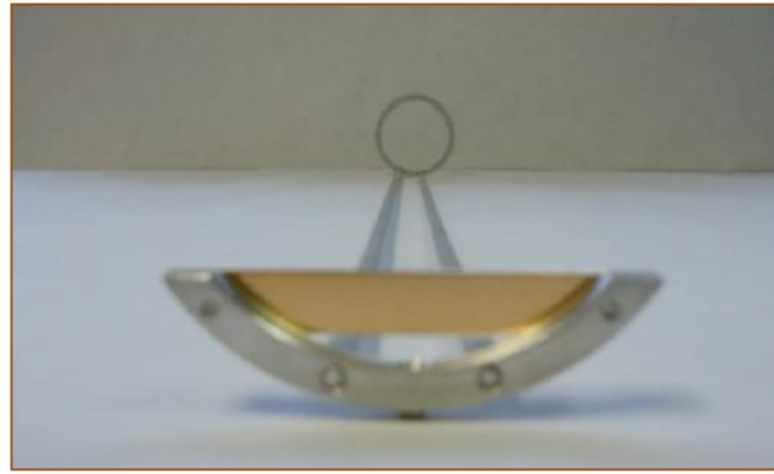
CBM participating in RHIC Beam Energy BES-II in 2019-2020:

Two prototype modules with readout installed in run 17
Run 18 plans on one full Sector
Complete installation in 11/2018

Install, commission and use 10% of the CBM TOF modules, including the read-out chains at STAR, starting in 2019

FXT Experiments at STAR (2018-2019)





Target design:
Gold foil
1 mm Thick
~1 cm High
~4 cm Wide
210 cm from IR

FXT Data Taking Plan：
2015: Au+Au: 4.5 GeV (test Run)
2018: Au+Au :3 GeV (100 million events)
2019-2020: Au+Au: 6.2, 5, 4.5, 4, 3.5 GeV

Summary

- Clear non-monotonic energy dependence is observed in the net-proton kurtosis at most central Au+Au collision.
  A hint of entering critical region.
  Need to confirm with more statistics and lower energies data.

- Model simulation (No CP) indicates: *Baryon conservations, Mean-field potential, hadronic scattering, Deuteron formation.*
  All suppress the net-proton fluctuations.

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

- Study the QCD phase structure at high baryon density with high precision:
  (1) BES-II at RHIC (2019-2020, both collider and fix target mode).
  (2) Future Fix-target at low energies: FAIR/CBM, CSR/HIAF etc.

A journey of a thousand miles begins with a single step.

---Lao-tzu 《Tao Te Ching》

千里之行，始于足下 --- 老子·《道德经》