QCD与中高能核物理暑期学校,山东大学, July 10th - 25th, 2023

相对论重离子碰撞中QCD相图的实验研究

罗晓峰

华中师范大学

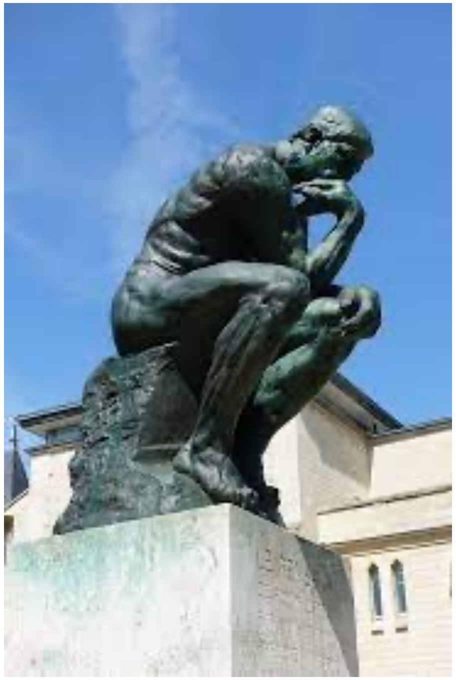
古希腊唯物主义哲学家：德谟克利特(~公元前370年)

率先提出原子论（万物由原子构成）

马克思和恩格斯赞美他是古希腊人中“第一个百科全书式的学者”

“一尺之棰，日取其半，万世不竭”《庄子–天下篇》

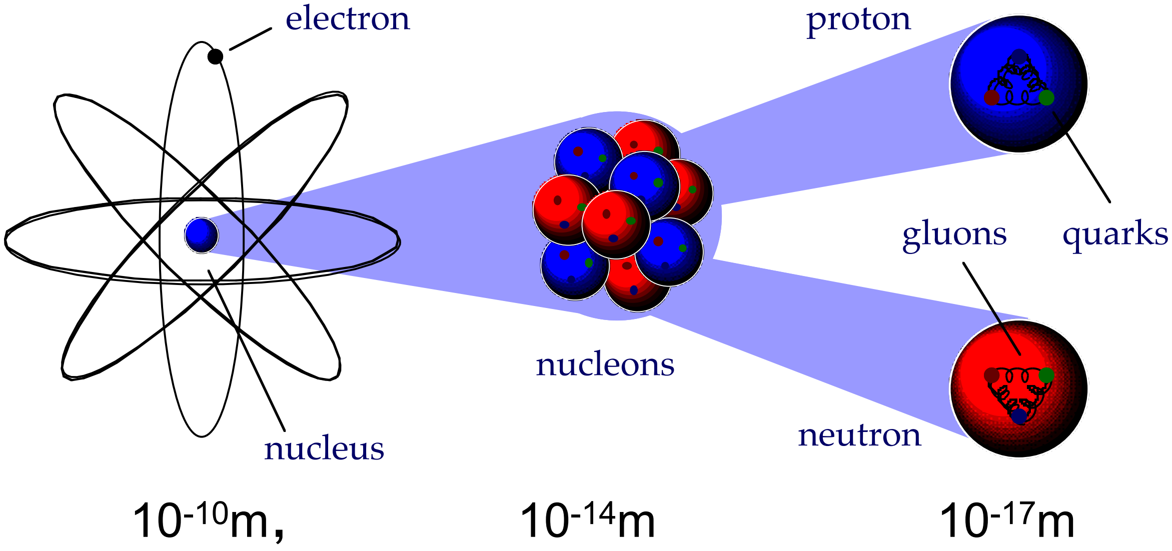
~ 公元前300年



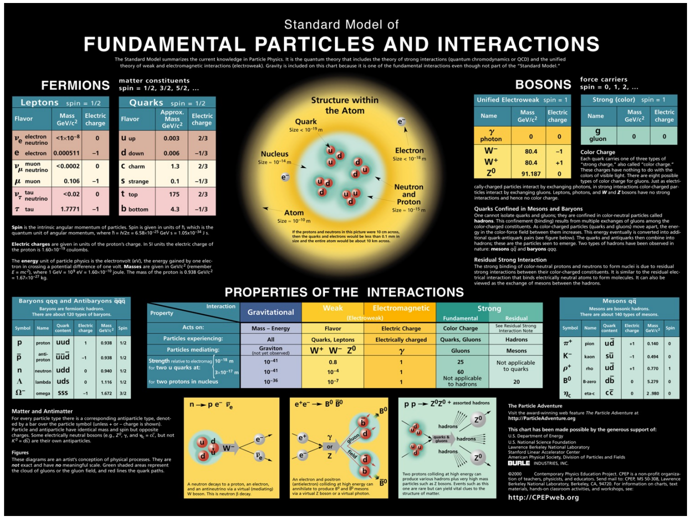
物质是否无限可分？
组成我们物质世界的基本单元是什么？

物质世界的基本单元和相互作用

- 1897年: 人类发现的第一个基本粒子：电子， J.J.汤姆森发现
- 1911年：卢瑟福散射实验发现原子具有内部结构，带正电的原子核
- 1967年：斯坦福直线加速器的电子-质子散射实验发现质子内部有结构



“标准模型”



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/c²	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/c²	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 = 1.05×10^{-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 = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.

Structure within the Atom

Quark Size < 10^{-19} m

Electron Size < 10^{-18} m

Nucleus Size ≈ 10^{-14} m

Neutron and Proton Size ≈ 10^{-15} m

Atom Size ≈ 10^{-10} m

If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

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

Unified Electroweak spin = 1		
Name	Mass GeV/c²	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/c²	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

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/c²	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

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

Mesons $q\bar{q}$ Mesons are bosonic hadrons. There are about 140 types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c²	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	eta-c	$c\bar{c}$	0	2 .980	0

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.

$p\, p \rightarrow Z^0Z^0$ + 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.

©2000 Contemporary Physics Education Project. CPEP is a non-profit organization of teachers, physicists, and educators. Send mail to: CPEP, MS 50-308, Lawrence Berkeley National Laboratory, Berkeley, CA, 94720. For information on charts, text materials, hands-on classroom activities, and workshops, see:

http://CPEPweb.org

- 四种基本相互作用力
- 61种基本粒子, 如三代夸克、轻子、中微子等

- 夸克是组成物质的基本单元，自然界没有发现自由的夸克：夸克禁闭
- 量子色动力学是较好描述强相互作用力的成功理论

More is different – 多即不同

http://science.sciencemag.org/content/177/4047/393

4 August 1972, Volume 177, Number 4047 **SCIENCE**

凝聚态物理的<<独立宣言>>

More Is Different

Broken symmetry and the nature of the hierarchical structure of science.

P. W. Anderson

The reductionist hypothesis may still be a topic for controversy among philosophers, but among the great majority of active scientists I think it is accepted without question. The workings of our minds and bodies, and of all the animate or inanimate matter of which we have any detailed knowledge, are assumed to be controlled by the same set of fundamental laws, which except under certain extreme conditions we feel we know pretty well.

It seems inevitable to go on uncritically to what appears at first sight to be an obvious corollary of reductionism: that if everything obeys the same fundamental laws, then the only scientists who are studying anything really fundamental are those who are working on those laws. In practice, that amounts to some astrophysicists, some elementary particle physicists, some logicians and other mathematicians, and few others. This point of view, which it is the main purpose of this article to oppose, is expressed in a rather well-known passage by Weisskopf (*1*):

> Looking at the development of science in the Twentieth Century one can distinguish two trends, which I will call "intensive" and "extensive" research, lacking a better terminology. In short: intensive research goes for the fundamental laws, extensive research goes for the explanation of phenomena in terms of known fundamental laws. As always, distinctions of this kind are not unambiguous, but they are clear in most cases. Solid state physics, plasma physics, and perhaps also biology are extensive. High energy physics and a good part of nuclear physics are intensive. There is always much less intensive research going on than extensive. Once new fundamental laws are discovered, a large and ever increasing activity begins in order to apply the discoveries to hitherto unexplained phenomena. Thus, there are two dimensions to basic research. The frontier of science extends all along a long line from the newest and most modern intensive research, over the extensive research recently spawned by the intensive research of yesterday, to the broad and well developed web of extensive research activities based on intensive research of past decades.

The effectiveness of this message may be indicated by the fact that I heard it quoted recently by a leader in the field of materials science, who urged the participants at a meeting dedicated to "fundamental problems in condensed matter physics" to accept that there were few or no such problems and that nothing was left but extensive science, which he seemed to equate with device engineering.

The main fallacy in this kind of thinking is that the reductionist hypothesis does not by any means imply a "constructionist" one: The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe. In fact, the more the elementary particle physicists tell us about the nature of the fundamental laws, the less relevance they seem to have to the very real problems of the rest of science, much less to those of society.

The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity. The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other. That is, it seems to me that one may array the sciences roughly linearly in a hierarchy, according to the idea: The elementary entities of science X obey the laws of science Y.

X	Y
solid state or many-body physics	elementary particle physics
chemistry	many-body physics
molecular biology	chemistry
cell biology	molecular biology
⋮	⋮
psychology	physiology
social sciences	psychology

But this hierarchy does not imply that science X is "just applied Y." At each stage entirely new laws, concepts, and generalizations are necessary, requiring inspiration and creativity to just as great a degree as in the previous one. Psychology is not applied biology, nor is biology applied chemistry.

In my own field of many-body physics, we are, perhaps, closer to our fundamental, intensive underpinnings than in any other science in which nontrivial complexities occur, and as a result we have begun to formulate a general theory of just how this shift from quantitative to qualitative differentiation takes place. This formulation, called the theory of "broken symmetry," may be of help in making more generally clear the breakdown of the constructionist converse of reductionism. I will give an elementary and incomplete explanation of these ideas, and then go on to some more general speculative comments about analogies at

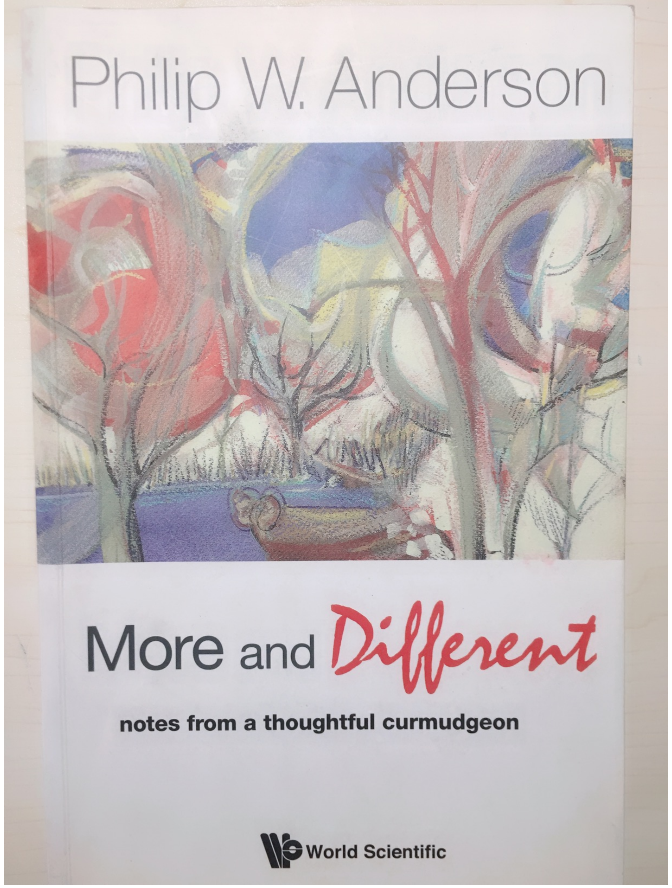
---

The author is a member of the technical staff of the Bell Telephone Laboratories, Murray Hill, New Jersey 07974, and visiting professor of theoretical physics at Cavendish Laboratory, Cambridge, England. This article is an expanded version of a Regents' Lecture given in 1967 at the University of California, La Jolla.

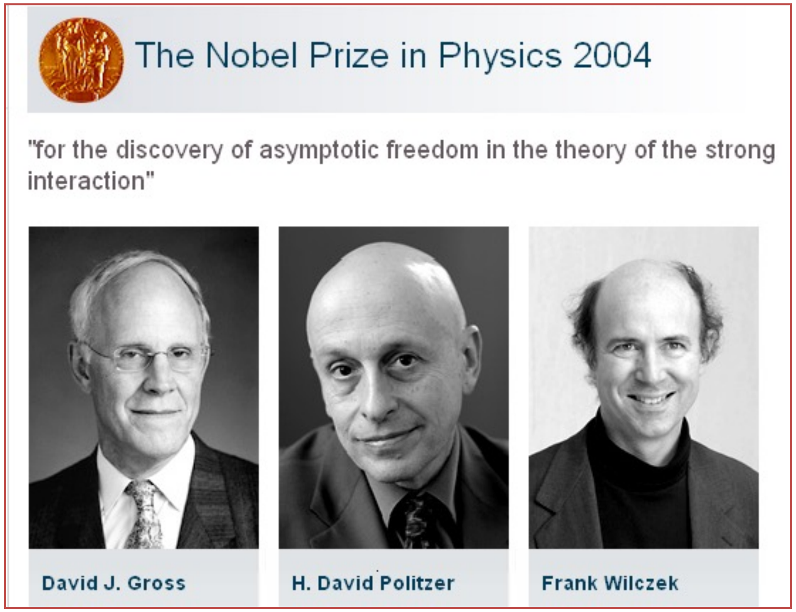
4 AUGUST 1972

393

安德森 (1923-)：美国理论物理学家
“对磁性和无序体系电子结构的基础理论研究”获1977年诺贝尔物理学奖



Quantum Chromodynamics (QCD)



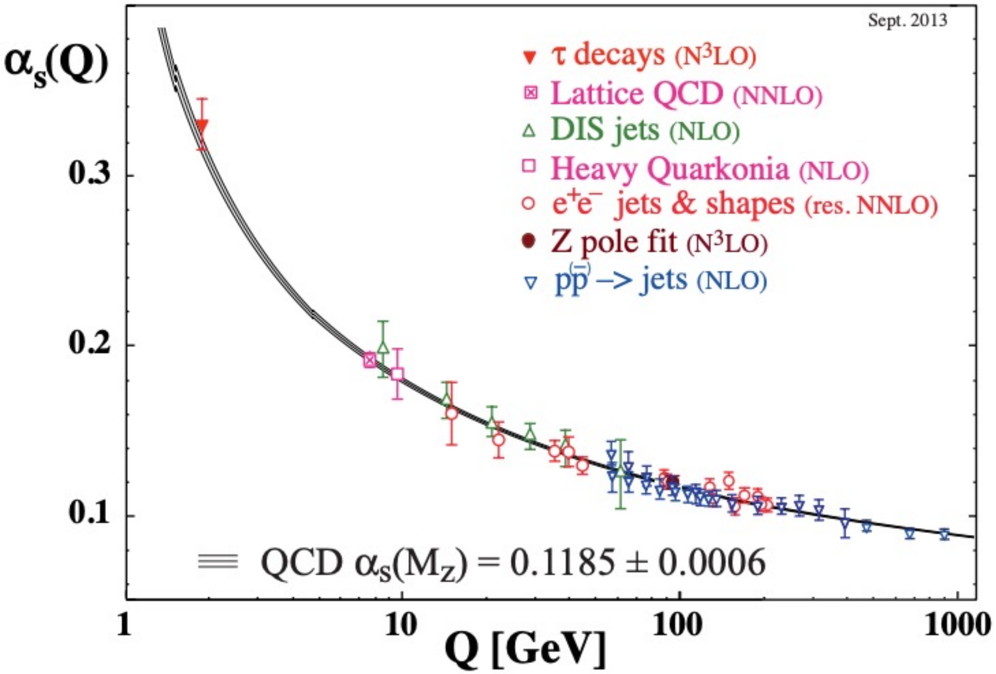
The Nobel Prize in Physics 2004

"for the discovery of asymptotic freedom in the theory of the strong interaction"

David J. Gross

H. David Politzer

Frank Wilczek



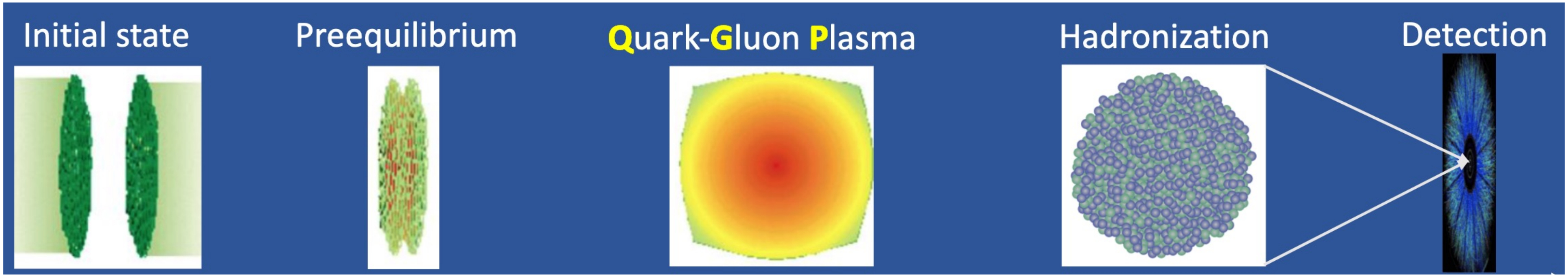
- **Asymptotic freedom**: Quarks and Gluons weakly interacting
  1): when getting close
  2): large momentum transfer.

- **Color Confinement**

如何研究夸克层次的凝聚态物理？

Free the quarks and gluons from hadrons !

相对论重离子碰撞：加热到万亿度(10^{12} ℃)！！

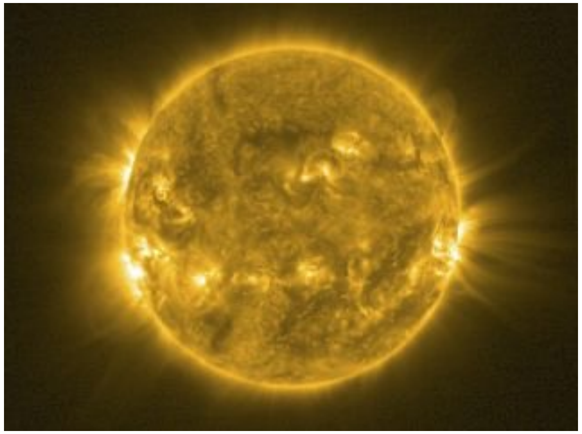


人类目前为止制造的最高温度：约为太阳中心温度的10万倍。

T. D. Lee (1926-)

获得1957年诺贝尔物理学奖

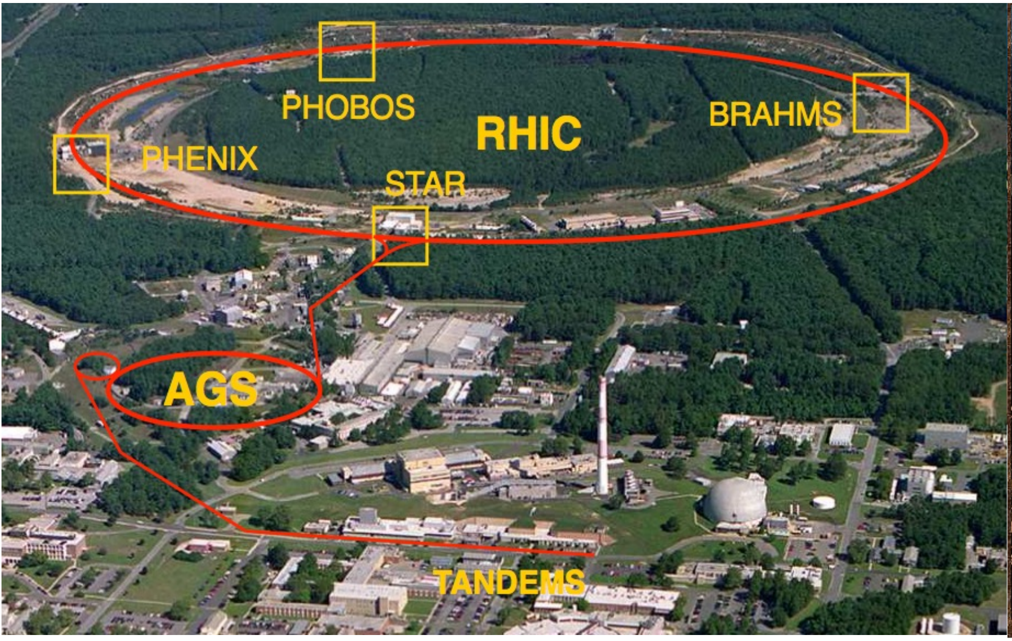
T. D. Lee and G. C. Wick, Phys. Rev. D 9, 2291 (1974).
Vacuum stability and vacuum excitation in a spin-0 field theory.

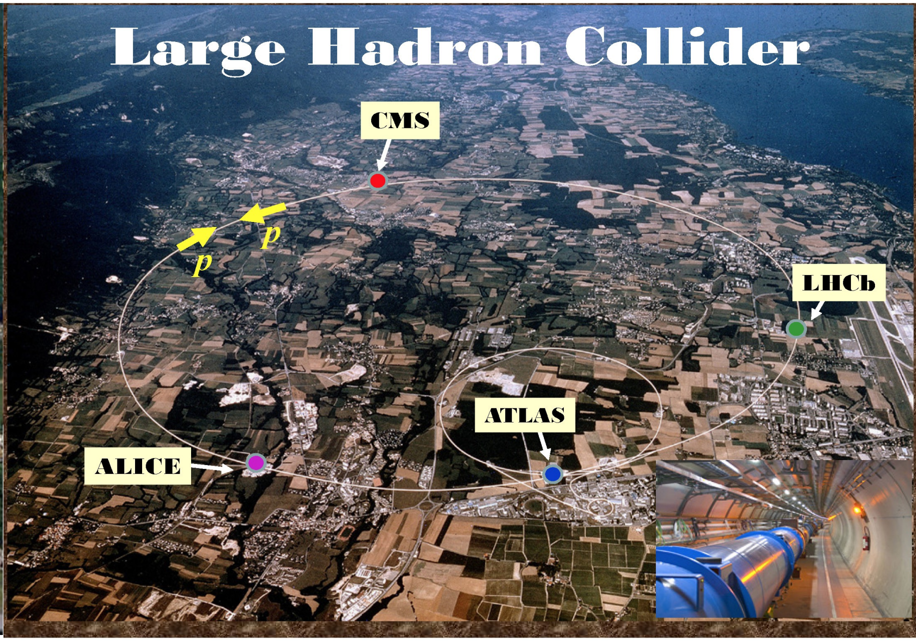


太阳核心温度：20000000 K (夸克仍被禁闭在强子中)

重离子被加速到接近光速发生对撞，创造出高温高密环境使夸克解禁闭形成夸克胶子等离子体。

High Energy Nuclear Collision Experiments





RHIC@BNL, USA

LHC@CERN, Geneva

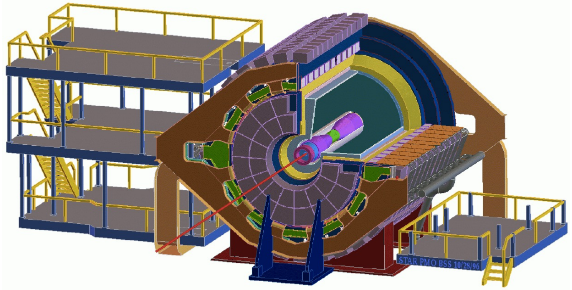
- RHIC: The high energy heavy-ion collider √s = 200 – 7.7 GeV

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

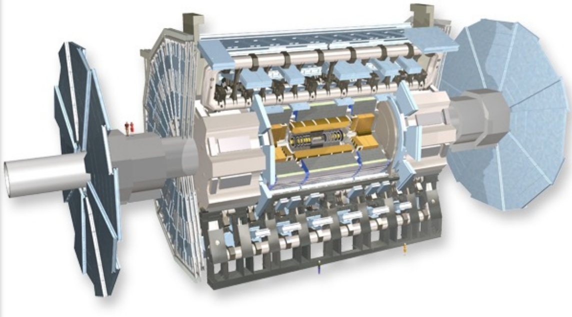
- LHC: The highest energy heavy-ion collider √s = 5.4 TeV

- LHC: The highest energy proton collider √s = 14 TeV

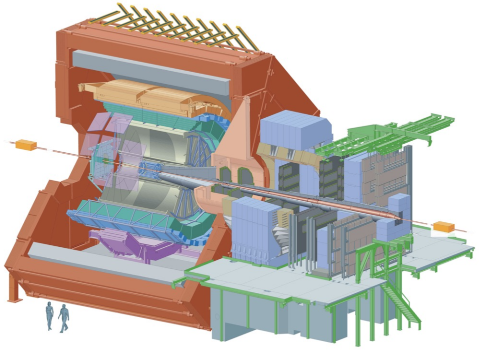
RHIC和LHC上的高能物理实验



STAR



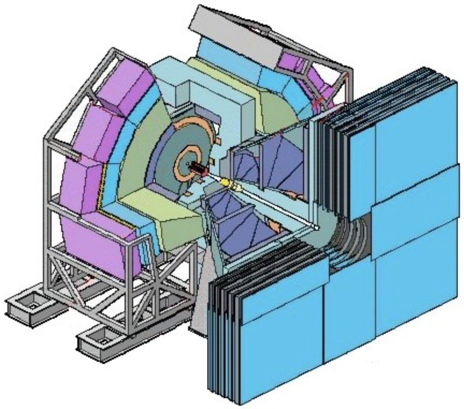
ATLAS



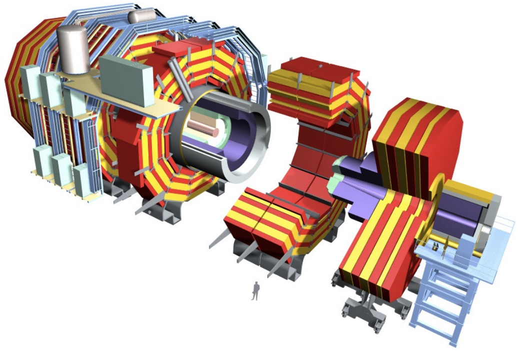
ALICE

Higgs Discovery

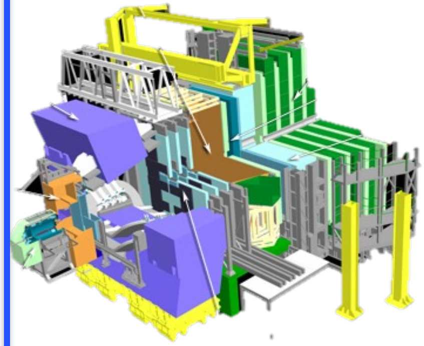
Pentaquark



PHENIX



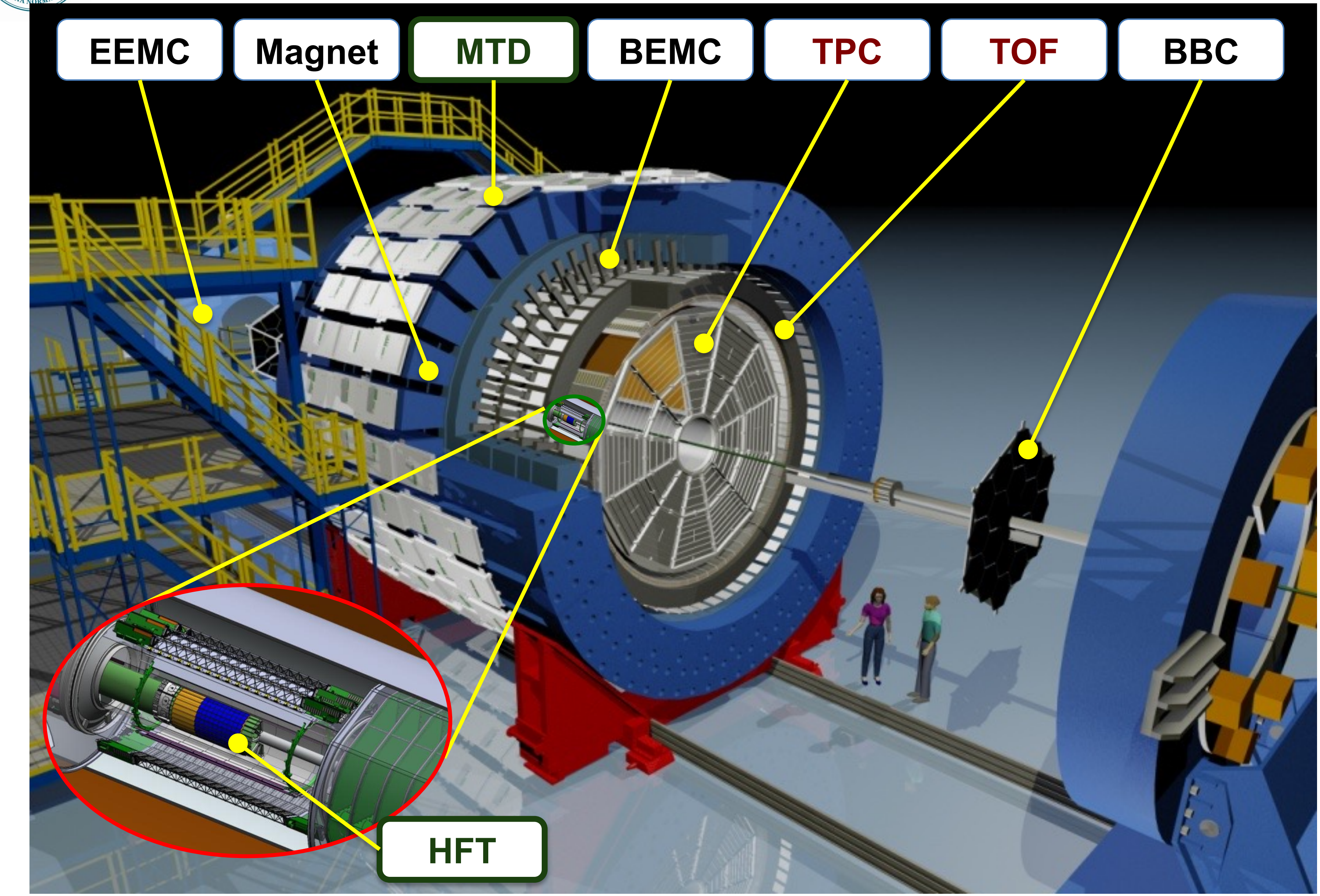
CMS



LHCb

STAR Collaboration

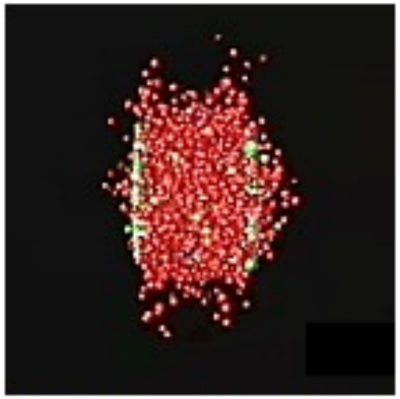
STAR Detector System

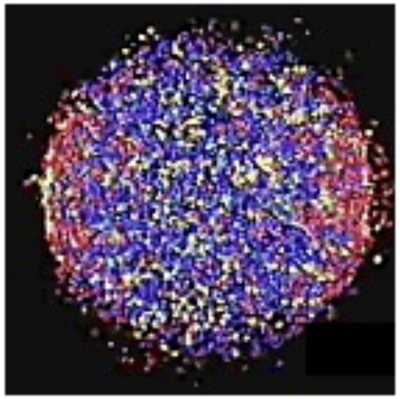


研究课题

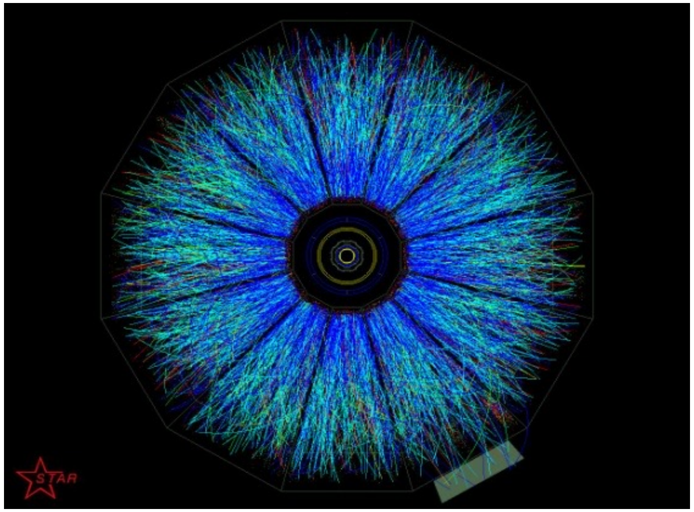

1. Ions about to collide*


2. Ion collision


3. Quarks, gluons freed


4. Plasma created

STAR时间投影室探测到的带电粒子径迹



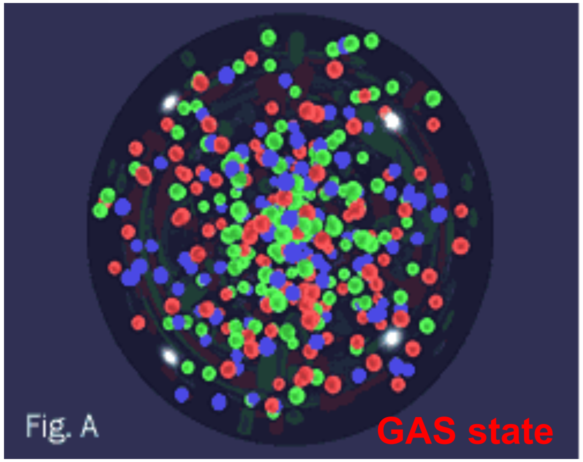
1、夸克胶子等离子体性质：集体流、奇异粒子产生、重味以及喷注、两粒子关联、双轻子产生等

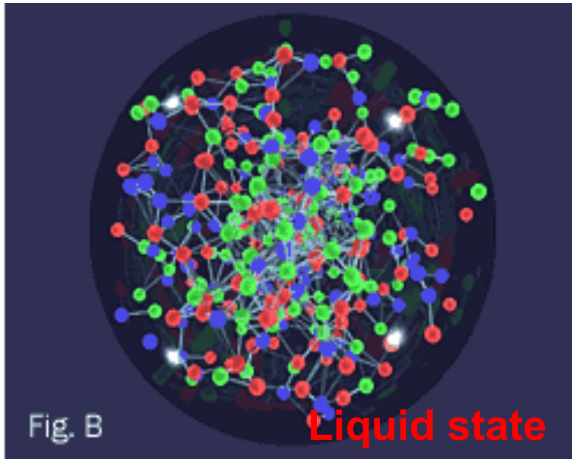
2、QCD相图结构、寻找QCD相变临界点：守恒荷涨落与关联、轻核产生、间歇等

3、新粒子以及奇异粒子态 ：超核、反物质等

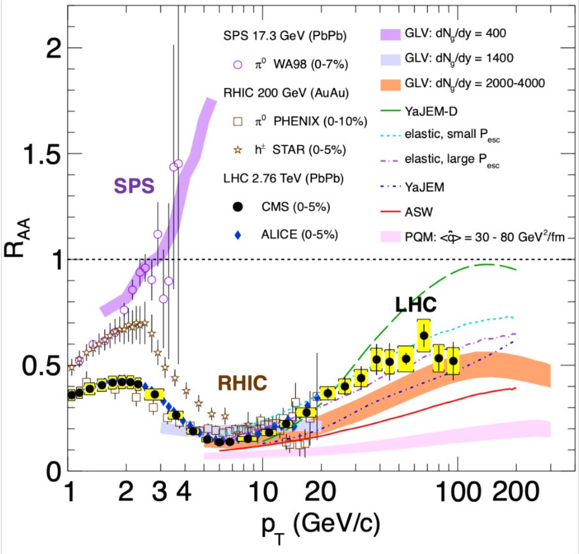
4、QCD真空性质与强电磁场：手征磁效应、手征磁波超子极化、UPC光光相互作用

Scientists Serve Up “Perfect” Liquid





Jet Quenching



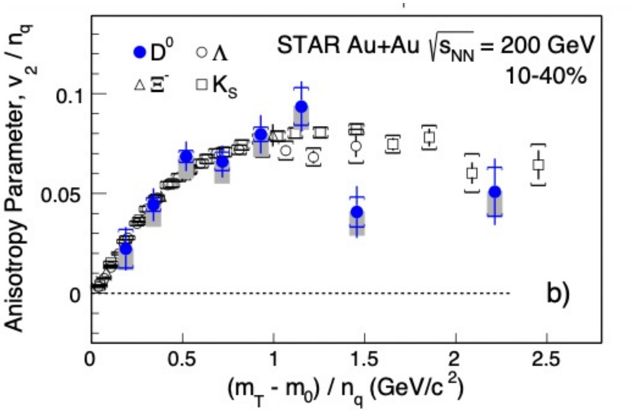
Eur.Phys.J. C72,1945 (2012).

Quark matter studied in nuclear collisions, since 1987 at BNL/AGS (2.7-4.8 GeV), 1996 at CERN/SPS (6.2-17.3 GeV), since 2000 at BNL/RHIC (7.7-200 GeV), since 2010 at the CERN/LHC at $\sqrt{s_{NN}}$ = 2.76-5.02 TeV.

Experimental observations support the formation of strongly couple and liquid like Quark-Gluon Plasma (sQGP) in Heavy-ion Collisions.

- Low viscosity
- Rapid thermalization
- Heavy quark suppression and Jet quenching
- Partonic collectivity
- Strong electromagnetic field and large vorticity

Partonic Collectivity v_2



Phys. Rev. Lett. **117**, 212301 (2017).

RHIC White Paper 2005 :

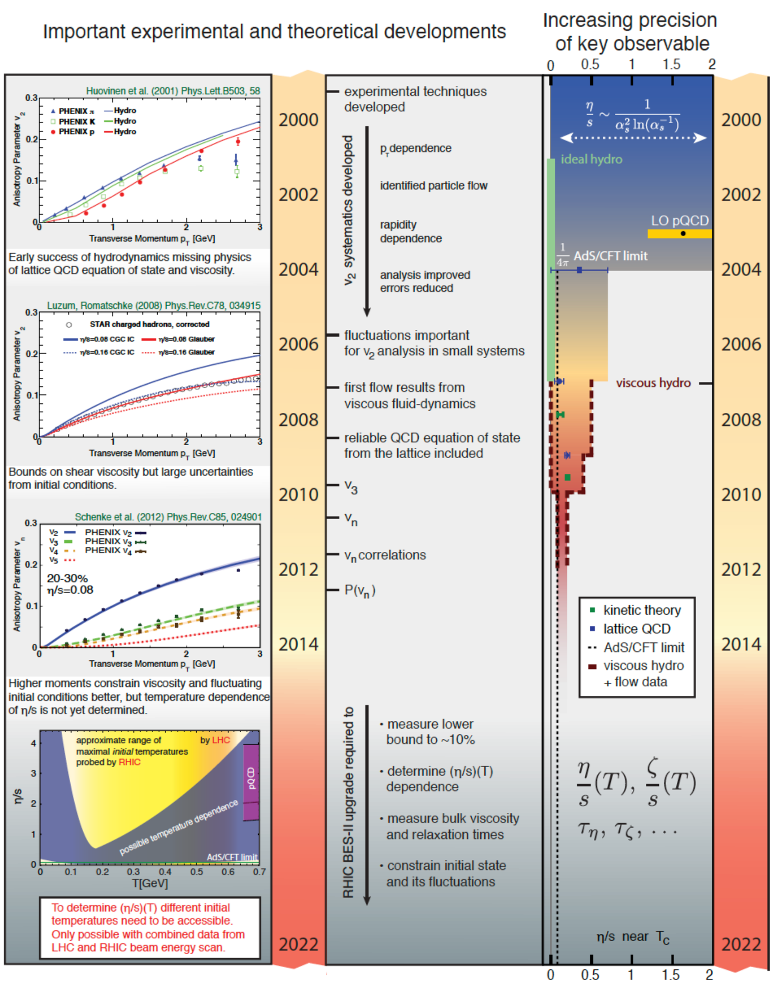
Hunting the Quark Gluon Plasma

RESULTS FROM THE FIRST 3 YEARS AT RHIC

ASSESSMENTS BY THE EXPERIMENTAL COLLABORATIONS

April 18, 2005

Quantifying the Properties of Hot and Dense QCD Matter



Important experimental and theoretical developments

Increasing precision of key observable

Huovinen et al. (2001) Phys.Lett.B503, 58

Early success of hydrodynamics missing physics of lattice QCD equation of state and viscosity.

Luzum, Romatschke (2008) Phys.Rev.C78, 034915

Bounds on shear viscosity but large uncertainties from initial conditions.

Schenke et al. (2012) Phys.Rev.C85, 024901

Higher moments constrain viscosity and fluctuating initial conditions better, but temperature dependence of η/s is not yet determined.

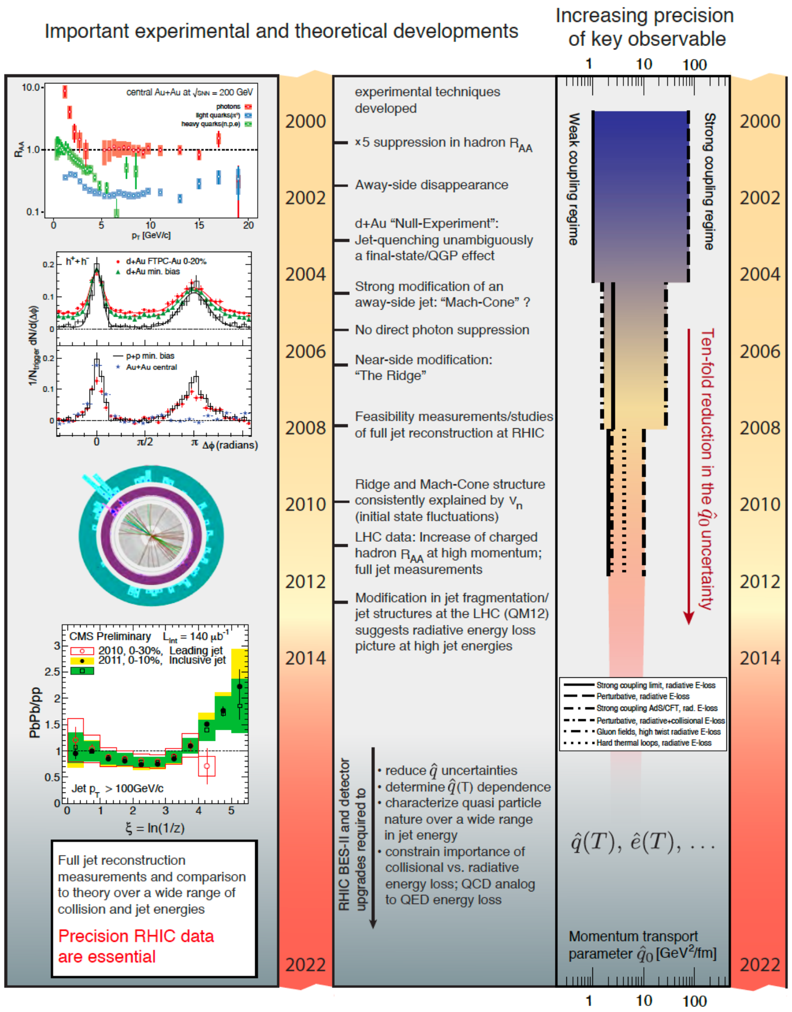
To determine $(\eta/s)(T)$ different initial temperatures need to be accessible. Only possible with combined data from LHC and RHIC beam energy scan.

- experimental techniques developed
- v_2 systematics developed
  - p_T dependence
  - identified particle flow
  - rapidity dependence
  - analysis improved errors reduced
- fluctuations important for v_2 analysis in small systems
- first flow results from viscous fluid-dynamics
- reliable QCD equation of state from the lattice included
- v_3
- v_n
- v_n correlations
- $P(v_n)$

RHIC BES-II upgrade required to

- measure lower bound to ~10%
- determine $(\eta/s)(T)$ dependence
- measure bulk viscosity and relaxation times
- constrain initial state and its fluctuations

η/s



Important experimental and theoretical developments

Increasing precision of key observable

- experimental techniques developed
- x5 suppression in hadron R_{AA}
- Away-side disappearance
- d+Au "Null-Experiment": Jet-quenching unambiguously a final-state/QGP effect
- Strong modification of an away-side jet: "Mach-Cone" ?
- No direct photon suppression
- Near-side modification: "The Ridge"
- Feasibility measurements/studies of full jet reconstruction at RHIC
- Ridge and Mach-Cone structure consistently explained by v_n (initial state fluctuations)
- LHC data: Increase of charged hadron R_{AA} at high momentum; full jet measurements
- Modification in jet fragmentation/ jet structures at the LHC (QM12) suggests radiative energy loss picture at high jet energies

Full jet reconstruction measurements and comparison to theory over a wide range of collision and jet energies

Precision RHIC data are essential

RHIC BES-II and detector upgrades required to

- reduce $\hat{q}$ uncertainties
- determine $\hat{q}(T)$ dependence
- characterize quasi particle nature over a wide range in jet energy
- constrain importance of collisional vs. radiative energy loss; QCD analog to QED energy loss

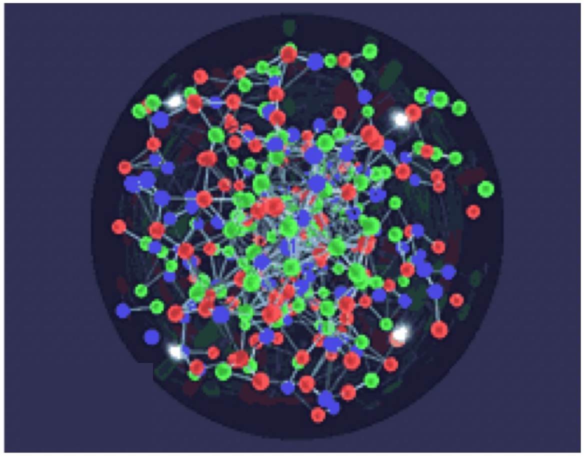
q^

Hot QCD White Paper, arXIv : 2303.17254

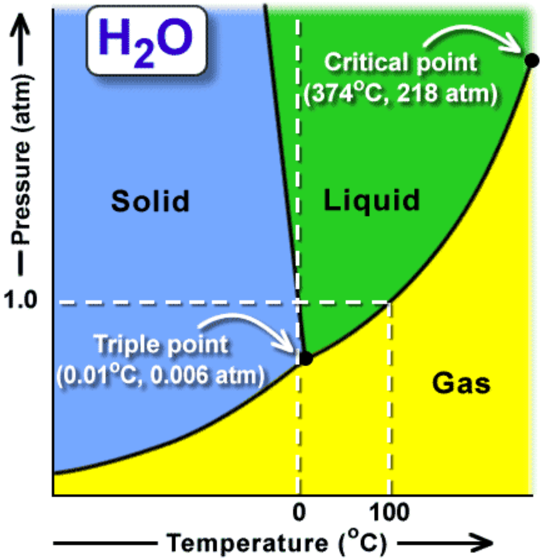
Hot and Dense QCD Matter : https://www.bnl.gov/npp/docs/bass_rhi_wp_final.pdf

QGP物质形态与相变

QGP新物态



水的相图



一定温度和密度下的热力学性质，如：

- ➢ 状态方程
- ➢ 粘滞系数
- ➢ 输运系数

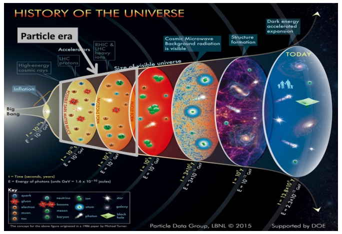
改变外部条件：研究发生相变形成QGP的条件和信号，探索相结构，一级相变边界、临界点？

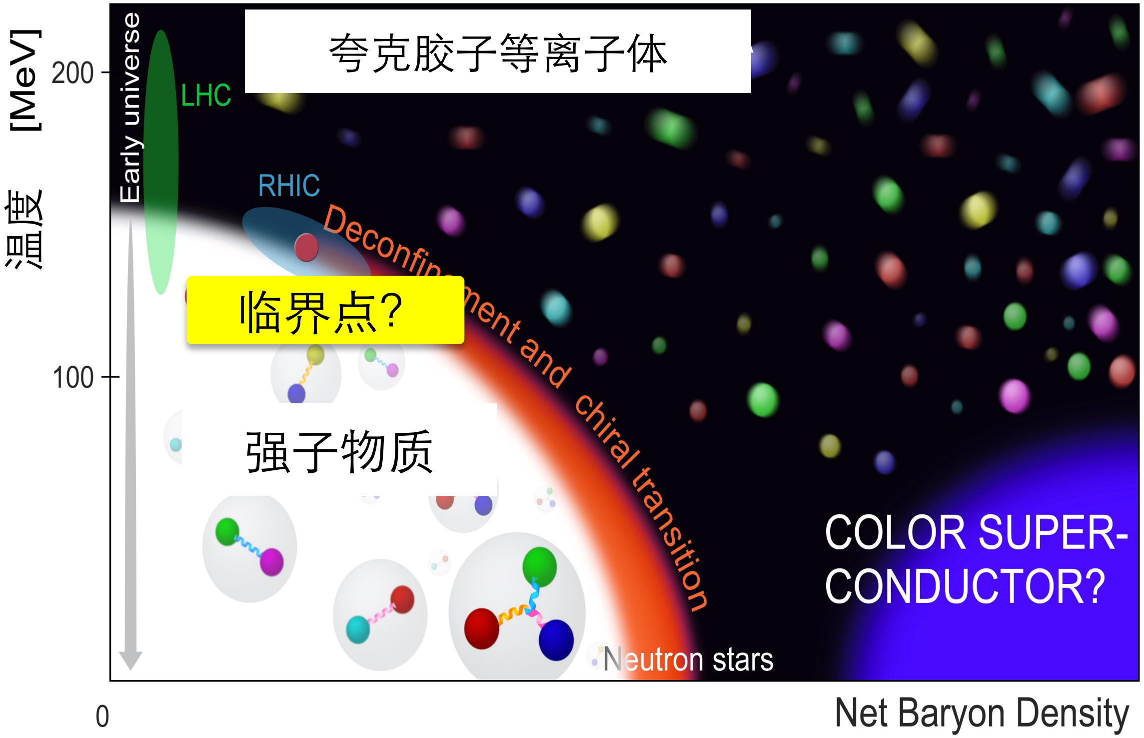
内因：相互作用、系统对称性
外因：外部条件的改变

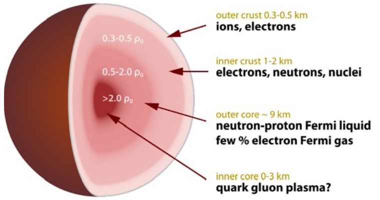
水的固液气相变：
电磁相互作用主导

强相互作用(QCD)物质相图

QCD相图结构被发现杂志评为：本世纪物理学11大未解决难题之一







Smooth Crossover at μ_B=0.
Transition Temperature : T_c ~ 156 MeV

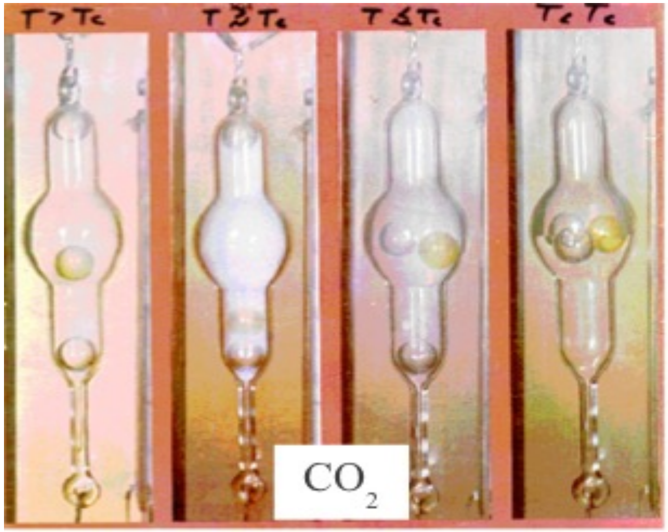
Y. Aoki, et al. Nature 443, 675 (2006).
A. Bazavov et al.(HotQCD)，Phys. Lett. B 795, 15 (2019)

关键科学问题：高重子密度区是否存在一级相变边界和对应的相变临界点。

马余刚、许怒、刘峰，基于HIAF集群的QCD相结构研究，中国科学:物理学 力学 天文学,2020,50(11):124

临界点和临界现象

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



First CP is discovered in 1869 for CO_2 by Andrews.

T_c = 31°C

Can we discover the critical point of quark matter ?

T_c ~ Trillion (10^{12}) °C

- **临界点：一级相变线终结点，**
  发生二级相变
- **密度涨落增强与关联长度增大：**
  临界乳光现象
- **系统的对称性决定临界指数：即热力学量的临界发散行为**
- **有限尺度效应.**

物理改变世界

边缘奇迹

相变和临界现象

Phase Transitions and Critical Phenomena

于 渌 郝柏林 陈晓松 著

科学出版社

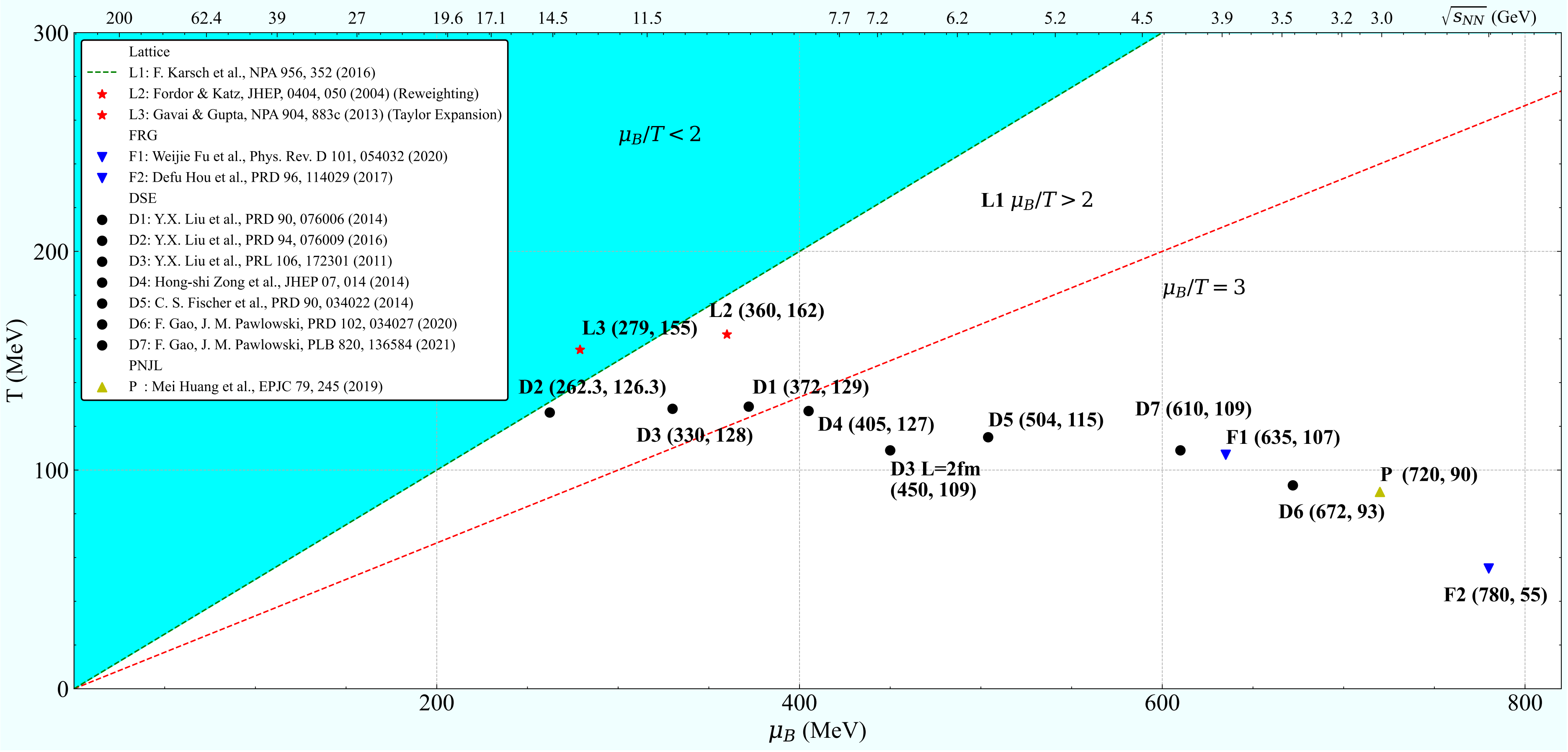
科普书(国家科技进步奖获奖丛书)

边缘奇迹：相变和临界现象

于渌，郝柏林，陈晓松 著

QCD临界点位置：理论模型计算

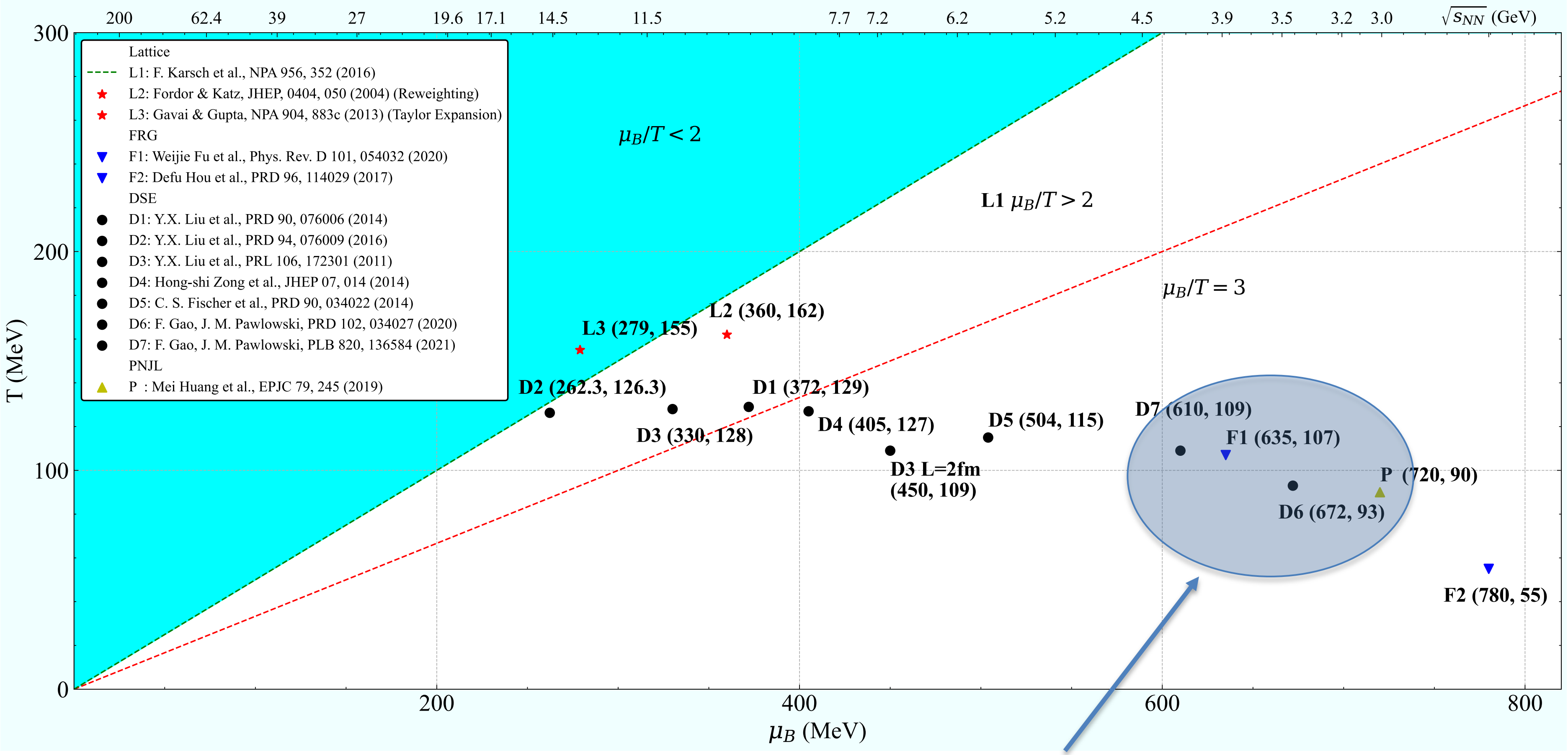
Preliminary collection from Lattice, DSE, FRG and PNJL (2004-2021)



理论上确定QCD相变临界点的位置有较大的不确定性。

QCD临界点位置：理论模型计算

Preliminary collection from Lattice, DSE, FRG and PNJL (2004-2021)



- ➢ 格点QCD: $\mu_B/T_c > 2$
- ➢ DSE、FRG (临界点重子化学势范围 $\mu_B \sim 600 - 670$ MeV).

Relativistic “Minds” Collisions (2006.03)


Can We Discover the QCD Critical Point at RHIC ?

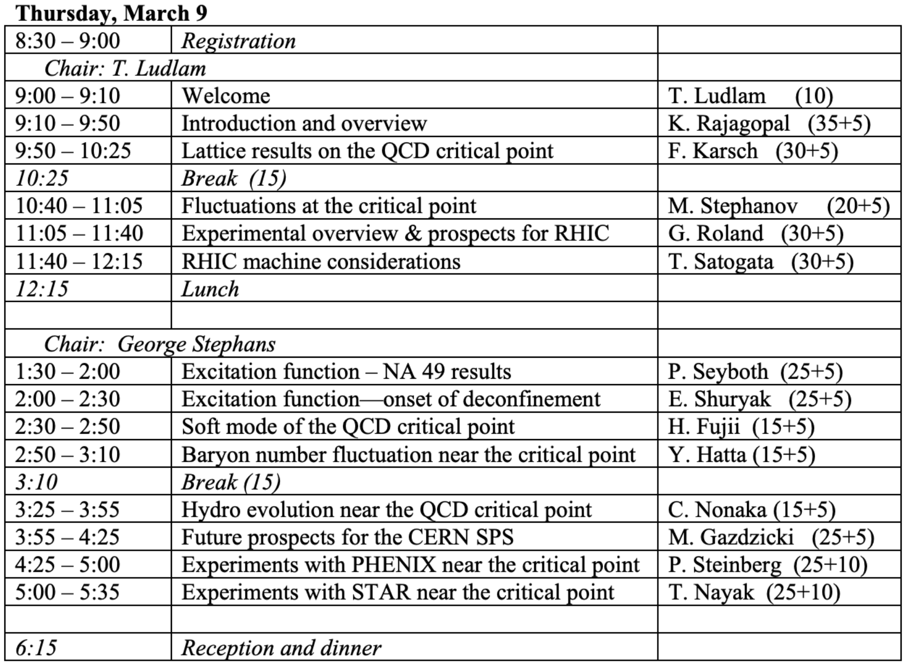
RIKEN BNL Research Center Workshop...

March 9-10, 2006 at Brookhaven National Laboratory

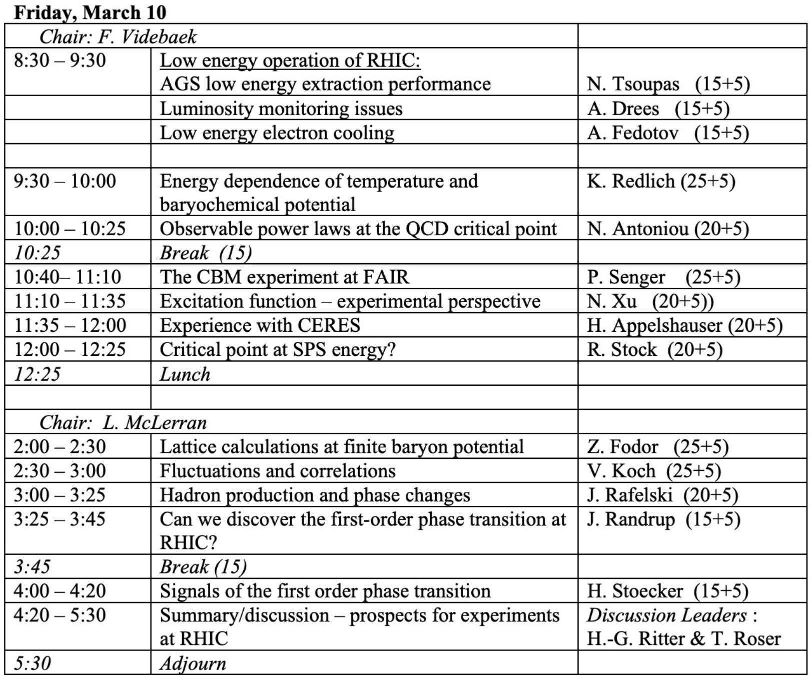
Organizers: T. Ludlam, H. Ritter, G. Stephans, M. Gazdzicki, B. Friman, F. Videbaek, T. Satogata, K. Rajagopal, L. McLerran
https://www.bnl.gov/riken/QCDRhic/default.asp

Motivation & Plans

The workshop is motivated by a growing body of theoretical and experimental evidence that the critical point on the QCD phase diagram, if it exists, should appear on the QGP transition boundary at baryo-chemical potential ~100 - 500 MeV, corresponding to heavy ion collisions with c.m. energy in the range 5 - 50 GeV/u. Identifying and pinning down this point with experimental measurements would be a major step forward in the world-wide effort to determine the properties of QCD at high temperature and density.


Thursday, March 9

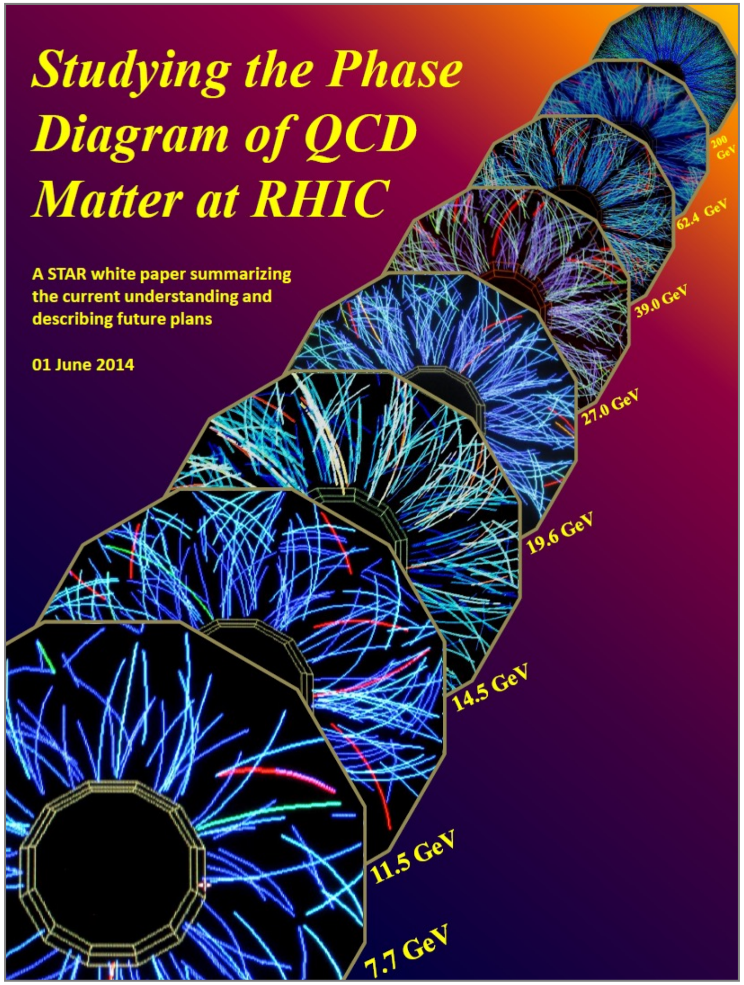
8:30 – 9:00	*Registration*	
Chair: T. Ludlam		
9:00 – 9:10	Welcome	T. Ludlam (10)
9:10 – 9:50	Introduction and overview	K. Rajagopal (35+5)
9:50 – 10:25	Lattice results on the QCD critical point	F. Karsch (30+5)
10:25	*Break (15)*	
10:40 – 11:05	Fluctuations at the critical point	M. Stephanov (20+5)
11:05 – 11:40	Experimental overview & prospects for RHIC	G. Roland (30+5)
11:40 – 12:15	RHIC machine considerations	T. Satogata (30+5)
12:15	*Lunch*	
Chair: George Stephans		
1:30 – 2:00	Excitation function – NA 49 results	P. Seyboth (25+5)
2:00 – 2:30	Excitation function—onset of deconfinement	E. Shuryak (25+5)
2:30 – 2:50	Soft mode of the QCD critical point	H. Fujii (15+5)
2:50 – 3:10	Baryon number fluctuation near the critical point	Y. Hatta (15+5)
3:10	*Break (15)*	
3:25 – 3:55	Hydro evolution near the QCD critical point	C. Nonaka (15+5)
3:55 – 4:25	Future prospects for the CERN SPS	M. Gazdzicki (25+5)
4:25 – 5:00	Experiments with PHENIX near the critical point	P. Steinberg (25+10)
5:00 – 5:35	Experiments with STAR near the critical point	T. Nayak (25+10)
6:15	*Reception and dinner*	


Friday, March 10

Chair: F. Videbaek		
8:30 – 9:30	Low energy operation of RHIC: AGS low energy extraction performance	N. Tsoupas (15+5)
	Luminosity monitoring issues	A. Drees (15+5)
	Low energy electron cooling	A. Fedotov (15+5)
9:30 – 10:00	Energy dependence of temperature and baryochemical potential	K. Redlich (25+5)
10:00 – 10:25	Observable power laws at the QCD critical point	N. Antoniou (20+5)
10:25	*Break (15)*	
10:40– 11:10	The CBM experiment at FAIR	P. Senger (25+5)
11:10 – 11:35	Excitation function – experimental perspective	N. Xu (20+5))
11:35 – 12:00	Experience with CERES	H. Appelshauser (20+5)
12:00 – 12:25	Critical point at SPS energy?	R. Stock (20+5)
12:25	*Lunch*	
Chair: L. McLerran		
2:00 – 2:30	Lattice calculations at finite baryon potential	Z. Fodor (25+5)
2:30 – 3:00	Fluctuations and correlations	V. Koch (25+5)
3:00 – 3:25	Hadron production and phase changes	J. Rafelski (20+5)
3:25 – 3:45	Can we discover the first-order phase transition at RHIC?	J. Randrup (15+5)
3:45	*Break (15)*	
4:00 – 4:20	Signals of the first order phase transition	H. Stoecker (15+5)
4:20 – 5:30	Summary/discussion – prospects for experiments at RHIC	*Discussion Leaders* : H.-G. Ritter & T. Roser
5:30	*Adjourn*	

STAR Beam Energy Scan Adventure

BES-II White Paper (2014)



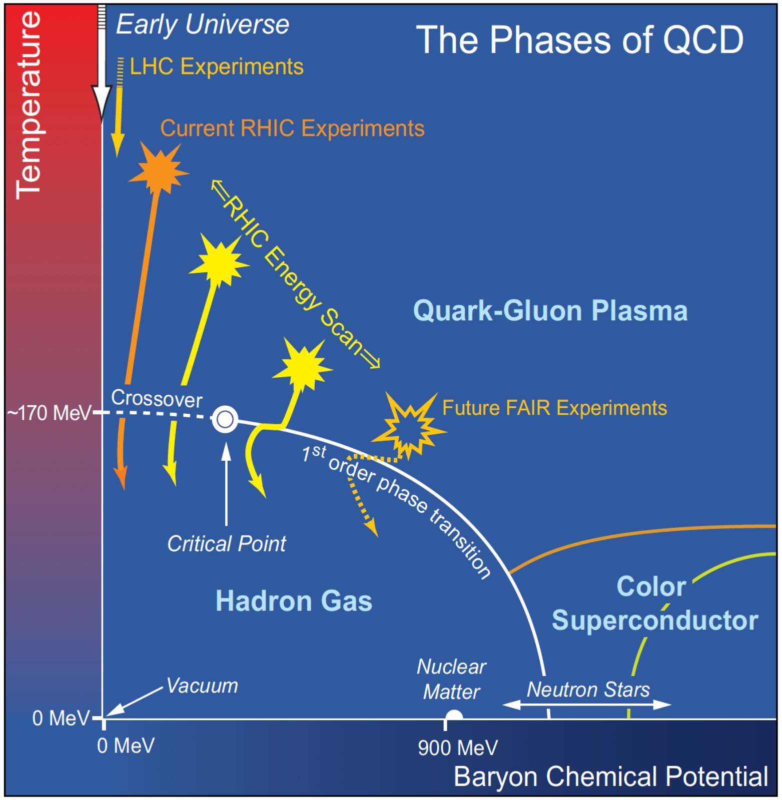
Studying the Phase Diagram of QCD Matter at RHIC

A STAR white paper summarizing the current understanding and describing future plans

01 June 2014

STAR, arXiv:1007.2613
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0493
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

- BES first proposed to PAC 2006.
- STAR BES campaign formally started in 2010
- BES-II officially requested in 2014, starts 2019(18)



Main Motivation:

- Looking for turning off QGP signals observed at RHIC top energy.
- Mapping out the crossover and/or 1^{st} order QCD phase boundary
- Search for the signatures of possible QCD critical point.

Fluctuations Probes the QCD Phase Transition

1. Fluctuations signals the QCD Critical Point.

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

热力学强度量与延展量的涨落相关

比热 -> 能量涨落
不可压缩系数->粒子数涨落

2. Fluctuations signals the Quark Deconfinement.

S. Jeon and V. Koch, Phys. Rev. Lett. 85, 2076(2000).
M. Asakawa, U. Heinz and B. Muller, Phys. Rev. Lett. 85, 2072 (2000).

系统关联长度

Two-point correlation functions of magnetic moment:

$$G(\vec{r}) = \langle S(\vec{r})S(0)\rangle - \langle S(\vec{r})\rangle\langle S(0)\rangle$$

In 3D case: $$G(\vec{r}) \propto \frac{1}{r} e^{-r/\xi(t)}$$

$$\xi(t) = \xi_0 \,|\, t \,|^{-1/2}$$

t : reduced temperature

Susceptibility
(2^{nd} fluctuations)

$$\chi \propto \int G(\vec{r})d\vec{r} \propto \xi^2(t)$$

Correlation length

Fluctuations Probes the QCD Phase Transition

1. Fluctuations signals the QCD Critical Point.

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

热力学强度量与延展量的涨落相关

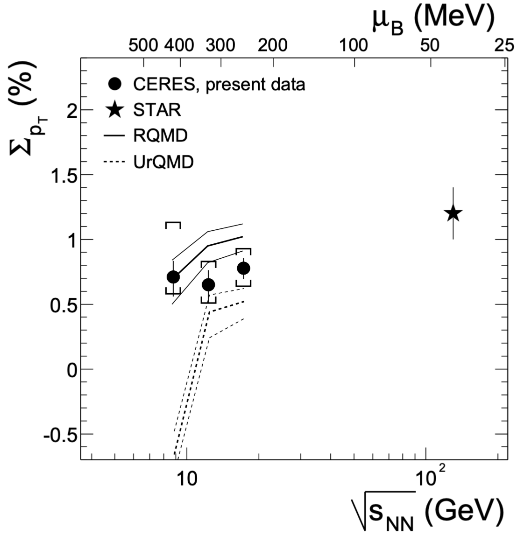
比热 -> 能量涨落
不可压缩系数->粒子数涨落

2. Fluctuations signals the Quark Deconfinement.

S. Jeon and V. Koch, Phys. Rev. Lett. 85, 2076(2000).
M. Asakawa, U. Heinz and B. Muller, Phys. Rev. Lett. 85, 2072 (2000).

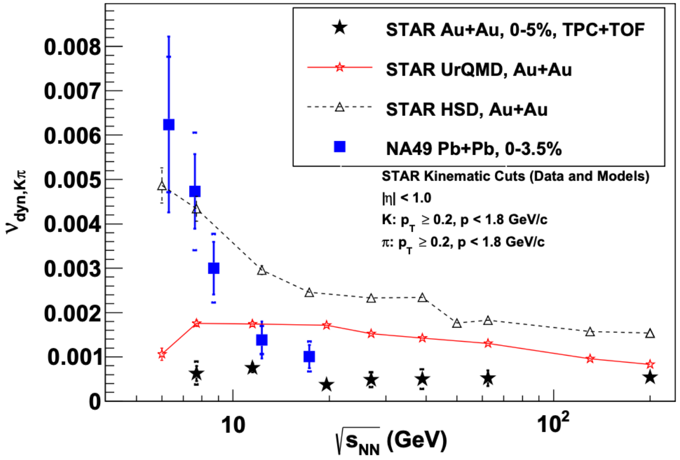
系统关联长度

Mean p_T fluctuations



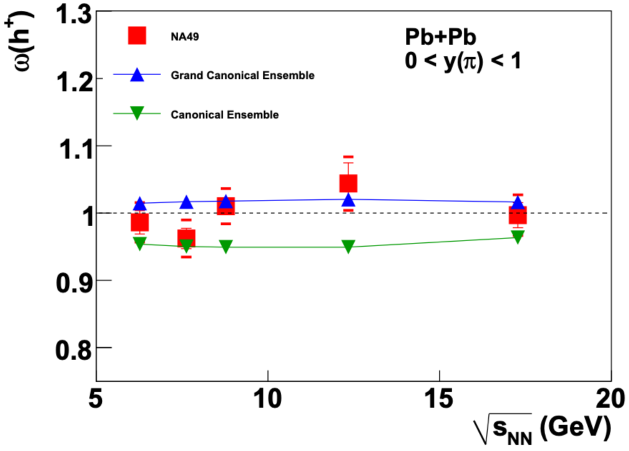
CERES, Nucl. Phys. A 727:97,2003
STAR, Phys. Rev. C 99 (2019) 44918

Particle ratio fluctuations



STAR, Phys. Rev. C 92 (2015) 21901
NA49, Phys. Rev. Lett. 86 (2001) 1965

Multiplicity fluctuations



NA49, Phys. Rev. C 78 (2008) 034914

INT 2008-2b : The QCD Critical Point

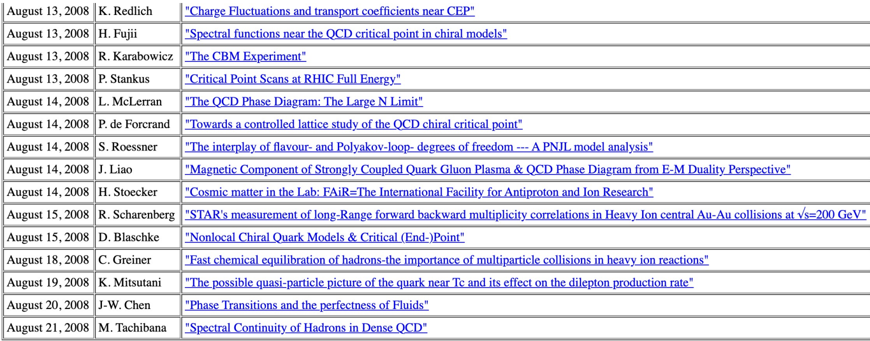
Organizer: https://www.int.washington.edu/PROGRAMS/08-2b.html

Volker Koch
Lawrence Berkeley National Laboratory
vkoch@lbl.gov

Gunther Roland
Massachusetts Institute of Technology
rolandg@mit.edu

Mikhail Stephanov
University of Illinois at Chicago
misha@uic.edu

July 28, 2008	S. Gupta	"New results in QCD at finite μ"
July 29, 2008	M.P. Lombardo	"The QCD critical point at imaginary mu"
July 29, 2008	S. Ejiri	"Numerical study of the critical point in lattice QCD at high temperature and density"
July 30, 2008	K. Fukushima	"What can we learn from model studies on the chiral critical end-point?"
July 30, 2008	B. Klein	"Scaling and Finite-Size Scaling Analysis of Critical Behavior in Lattice QCD"
July 31, 2008	J. Braun	"Chiral Phase Boundary from Quark-Gluon Dynamics"
July 31, 2008	C. Ratti	"A quasiparticle model for QCD thermodynamics"
August 4, 2008	J. Verbaarschot	"Phase of the Fermion Determinant and the Phase Diagram of QCD"
August 5, 2008	R. Lacey	"The Role of Energy Scans at RHIC"
August 5, 2008	L. Ferroni	"Space and Phase Space saturation: a simple Bag-Model-inspired picture for a smooth transition to QGP"
August 6, 2008	M. Asakawa	"QCD Critical Point and its Effect on Physical Observables"
August 6, 2008	T. Hell	"Thermodynamics of a Nonlocal PNJL Model for Two and Three Flavors"
August 7, 2008	C. Miao	"QCD Equation of State and Fluctuations on the Lattice"
August 11, 2008	K. Rajagopal	"The Search for the QCD Critical Point Using Lattice QCD Calculations-Part I" Part 2
August 11, 2008	F. Karsch	"Lattice results on the QCD critical point"
August 11, 2008	J. Randrup	"Spinodal decomposition: A tool for seeing the phase transition?"
August 11, 2008	H. Caines	"STAR and the RHIC Energy Scan"
August 11, 2008	K. Homma	"Fluctuations and Search for the QCD Critical Point"
August 12, 2008	G. Stephans	"Experimental Exploration of the QCD Phase Diagram"
August 12, 2008	K.F. Liu	"Finite Density Phase Transition with Canonical Ensemble Approach"
August 12, 2008	C. Nonaka	"Hydrodynamic Expansion with the QCD Critical Point in Heavy Ion Collisions"
August 12, 2008	M. Mitrovski	"Energy and System Size Dependence of Hadron Production from NA49"
August 12, 2008	T. Schuster	"Energy and System Size Dependence of Fluctuations: NA49 results and NA61 plans"
August 12, 2008	G. Westfall	"K/pi Fluctuations and the Balance Function-Part 1" Part 2 Part 3

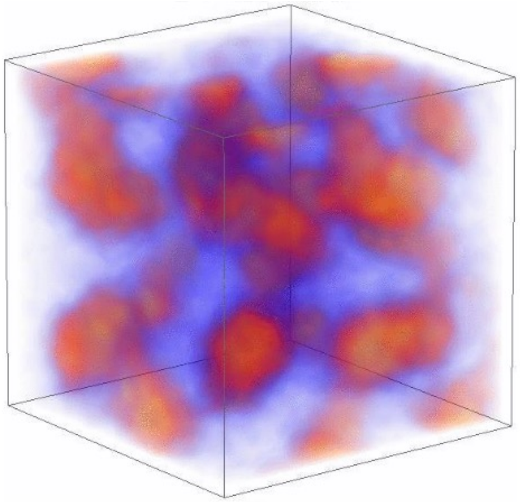


August 13, 2008	K. Redlich	"Charge Fluctuations and transport coefficients near CEP"
August 13, 2008	H. Fujii	"Spectral functions near the QCD critical point in chiral models"
August 13, 2008	R. Karabowicz	"The CBM Experiment"
August 13, 2008	P. Stankus	"Critical Point Scans at RHIC Full Energy"
August 14, 2008	L. McLerran	"The QCD Phase Diagram: The Large N Limit"
August 14, 2008	P. de Forcrand	"Towards a controlled lattice study of the QCD chiral critical point"
August 14, 2008	S. Roessner	"The interplay of flavour- and Polyakov-loop- degrees of freedom --- A PNJL model analysis"
August 14, 2008	J. Liao	"Magnetic Component of Strongly Coupled Quark Gluon Plasma & QCD Phase Diagram from E-M Duality Perspective"
August 14, 2008	H. Stoecker	"Cosmic matter in the Lab: FAiR=The International Facility for Antiproton and Ion Research"
August 15, 2008	R. Scharenberg	"STAR's measurement of long-Range forward backward multiplicity correlations in Heavy Ion central Au-Au collisions at $\sqrt{s}$=200 GeV"
August 15, 2008	D. Blaschke	"Nonlocal Chiral Quark Models & Critical (End-)Point"
August 18, 2008	C. Greiner	"Fast chemical equilibration of hadrons-the importance of multiparticle collisions in heavy ion reactions"
August 19, 2008	K. Mitsutani	"The possible quasi-particle picture of the quark near Tc and its effect on the dilepton production rate"
August 20, 2008	J-W. Chen	"Phase Transitions and the perfectness of Fluids"
August 21, 2008	M. Tachibana	"Spectral Continuity of Hadrons in Dense QCD"

https://www.int.washington.edu/talks/WorkShops/int_08_2b/

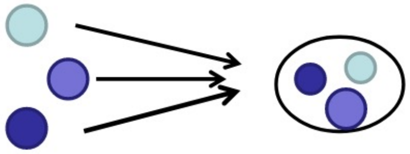
Need sensitive experimental observable !!

QCD临界点灵敏观测量：守恒荷高阶矩和轻核产生



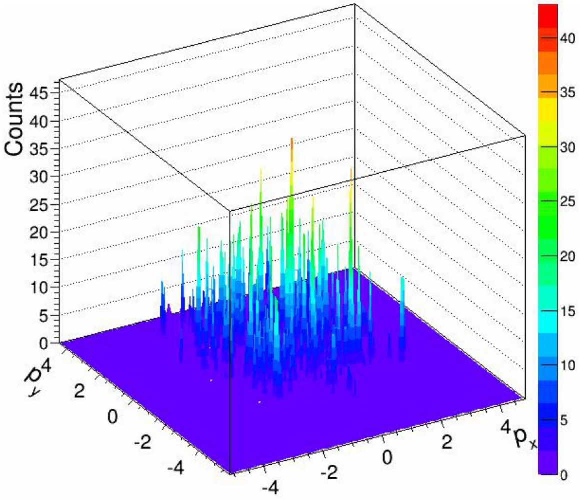
In the vicinity of critical point and/or 1st order phase transition

Large density fluctuations and Baryon clustering



Higher moments of conserved charge (B, Q, S) distributions

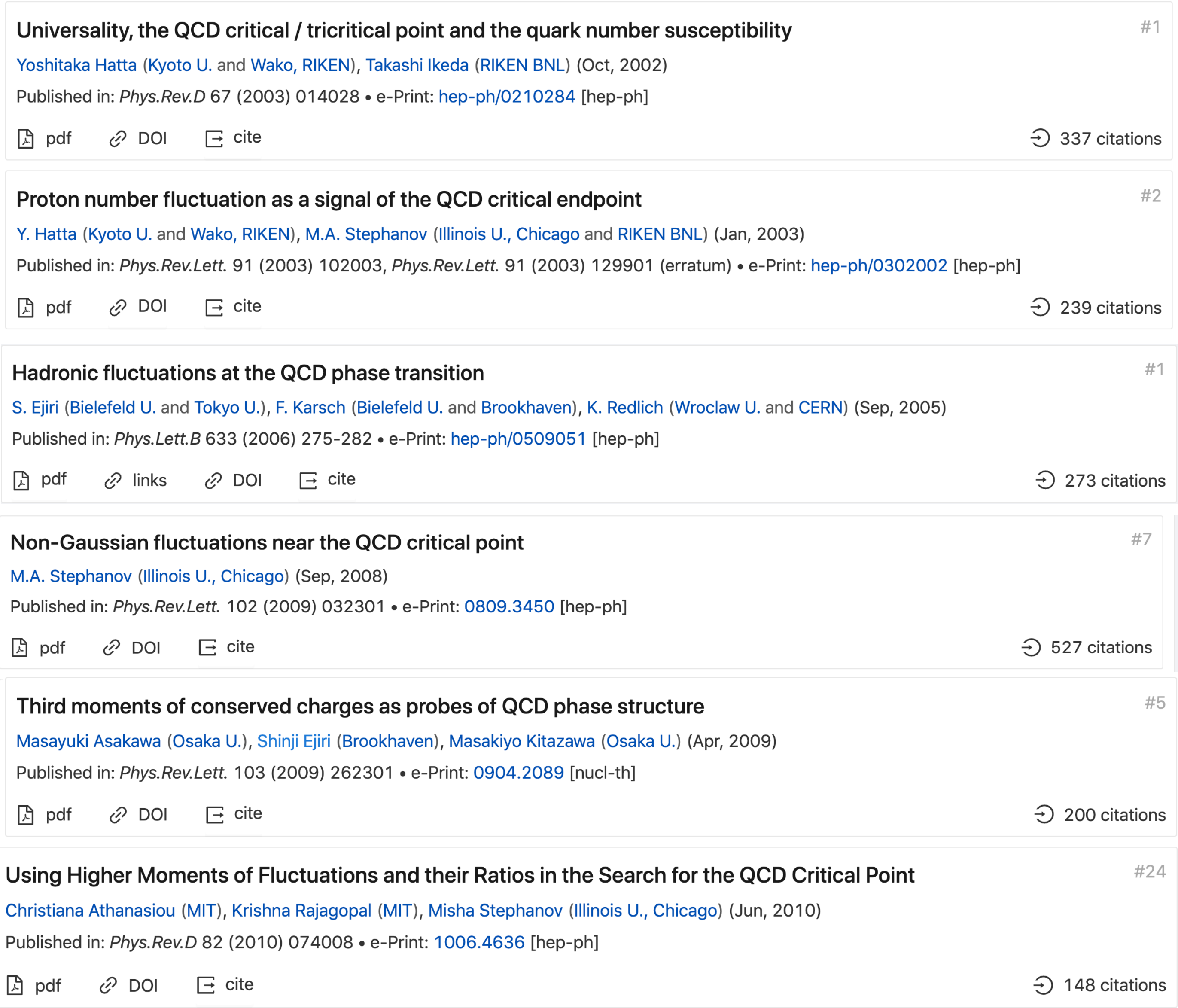
light nuclei production



Experimental Signatures:

Non-monotonic variation as a function of collision energy.

The history of higher-order fluctuations observables



Universality, the QCD critical / tricritical point and the quark number susceptibility #1

Yoshitaka Hatta (Kyoto U. and Wako, RIKEN), Takashi Ikeda (RIKEN BNL) (Oct, 2002)

Published in: *Phys.Rev.D* 67 (2003) 014028 • e-Print: hep-ph/0210284 [hep-ph]

pdf DOI cite 337 citations

Proton number fluctuation as a signal of the QCD critical endpoint #2

Y. Hatta (Kyoto U. and Wako, RIKEN), M.A. Stephanov (Illinois U., Chicago and RIKEN BNL) (Jan, 2003)

Published in: *Phys.Rev.Lett.* 91 (2003) 102003, *Phys.Rev.Lett.* 91 (2003) 129901 (erratum) • e-Print: hep-ph/0302002 [hep-ph]

pdf DOI cite 239 citations

Hadronic fluctuations at the QCD phase transition #1

S. Ejiri (Bielefeld U. and Tokyo U.), F. Karsch (Bielefeld U. and Brookhaven), K. Redlich (Wroclaw U. and CERN) (Sep, 2005)

Published in: *Phys.Lett.B* 633 (2006) 275-282 • e-Print: hep-ph/0509051 [hep-ph]

pdf links DOI cite 273 citations

Non-Gaussian fluctuations near the QCD critical point #7

M.A. Stephanov (Illinois U., Chicago) (Sep, 2008)

Published in: *Phys.Rev.Lett.* 102 (2009) 032301 • e-Print: 0809.3450 [hep-ph]

pdf DOI cite 527 citations

Third moments of conserved charges as probes of QCD phase structure #5

Masayuki Asakawa (Osaka U.), Shinji Ejiri (Brookhaven), Masakiyo Kitazawa (Osaka U.) (Apr, 2009)

Published in: *Phys.Rev.Lett.* 103 (2009) 262301 • e-Print: 0904.2089 [nucl-th]

pdf DOI cite 200 citations

Using Higher Moments of Fluctuations and their Ratios in the Search for the QCD Critical Point #24

Christiana Athanasiou (MIT), Krishna Rajagopal (MIT), Misha Stephanov (Illinois U., Chicago) (Jun, 2010)

Published in: *Phys.Rev.D* 82 (2010) 074008 • e-Print: 1006.4636 [hep-ph]

pdf DOI cite 148 citations

2002

2003

2005

2008

2009

2010

Higher Moments 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))

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

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

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).

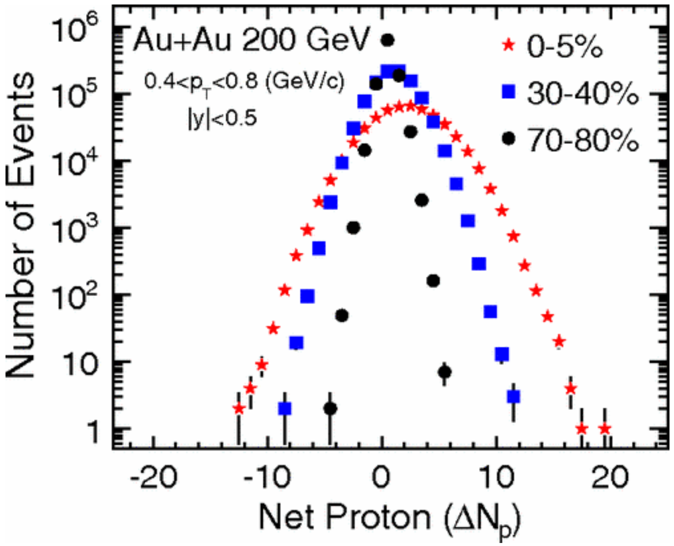
2. Direct connect to the susceptibility of the system.

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

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

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)

Event-by-Event Distribution



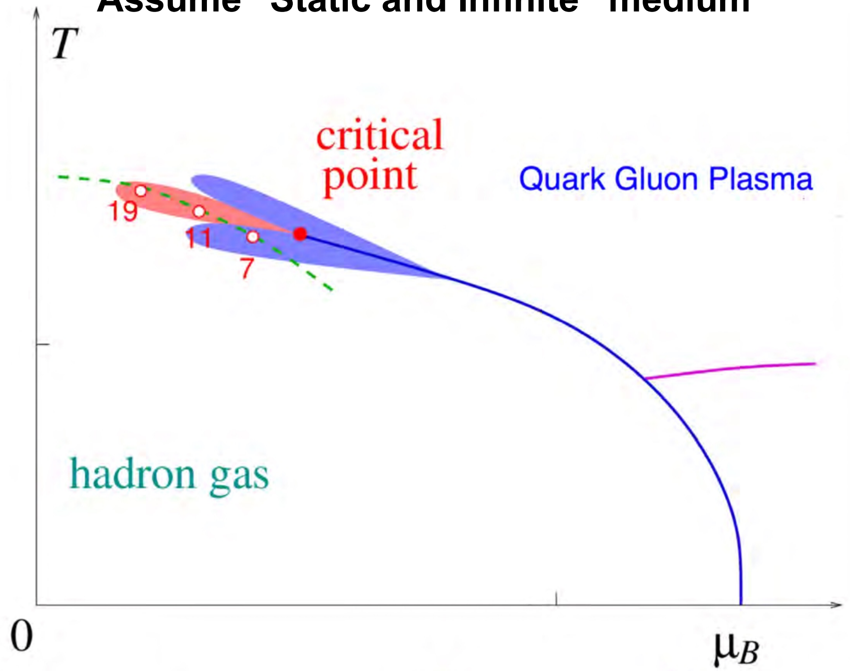
First Measurement : 2009-2010

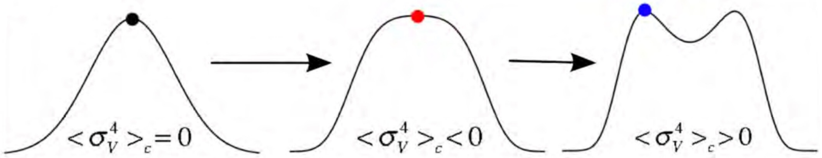
STAR, PRL105, 022302 (2010).

- **Net-Proton:** $N_p - N_{\bar{p}}$
  （**proxy: Net-Baryon**）
- **Net-Charge:** $N_{Q^+} - N_{Q^-}$
- **Net-Kaon:** $N_{K^+} - N_{K^-}$
  （**proxy: Net-Strangeness**）

Signals of QCD Critical Point : Theory/Model

Assume "Static and Infinite" medium

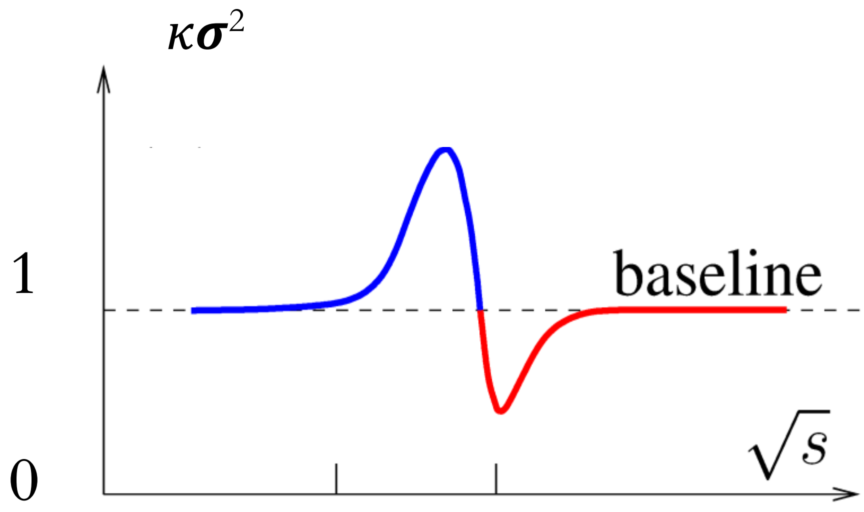




M. Stephanov, PRL107, 052301 (2011); J. Phys. G 38, 124147 (2011).
Schaefer et al., PRD 85, 034027 (2012); W. Fu et al., PRD 94, 116020 (2016).
J.W. Chen, J. Deng, et al., PRD 93, 034037 (2016). PRD 95,014038 (2017).
W. K. Fan, X. Luo, H.S. Zong, IJMPA 32, 1750061 (2017);
G. Shao et al., EPJC 78, 138 (2018) ; Z. Li et al., EPJC 79, 245 (2019).
A. Bzdak et al., Phys. Rep. 853, 1(2020). D. Mroczek et al, arXiv: 2008.04022.

Caveats : Non-equilibrium, finite size/time effects

M. Asakawa, M. Kitazawa, B. Müller, PRC 101, 034913 (2020).
S Mukherjee, R. Venugopalan, Y Yin, PRL 117, 222301 (2016).
S. Wu, Z. Wu, H. Song, PRC 99, 064902 (2019).



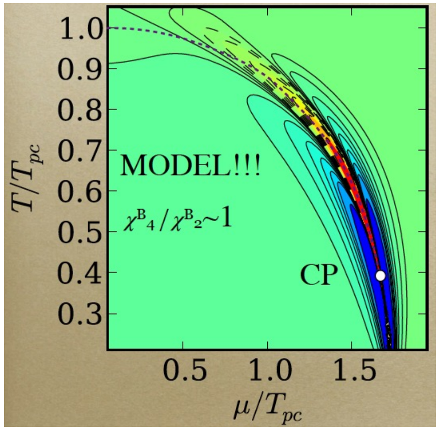
$\kappa\sigma^2 = 1$ (Poisson Fluctuations)

Characteristic signature of CP:
Non-monotonic energy dependence

"Oscillation Pattern"
Especially the Peak at low energies

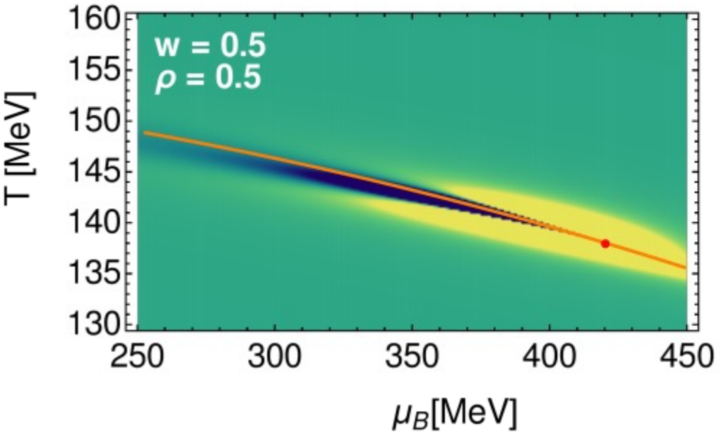
Critical Contributions to Fourth-order Fluctuations ($\kappa\sigma^2$)

PQM V. Skokov, QM2012



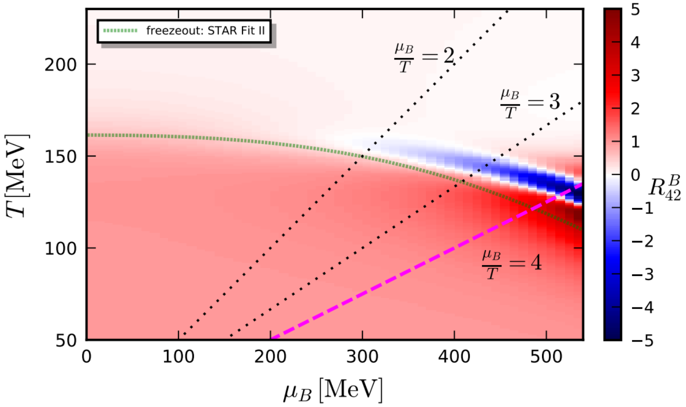
3D Ising Mapping

D. Mroczek et al, PRC 103, 034901 (2021)



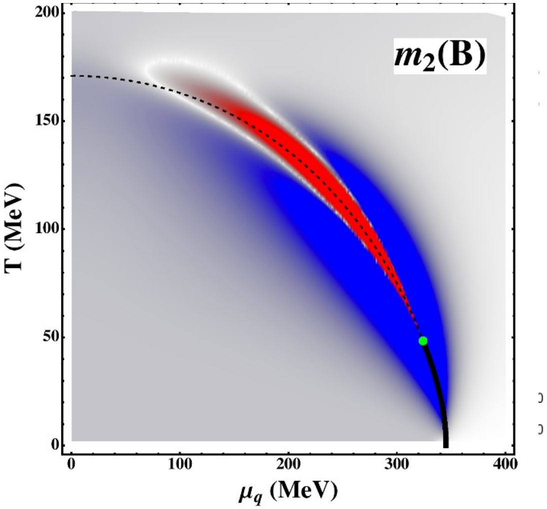
FRG

付伟杰等 PRD 104 (2021) 9, 094047



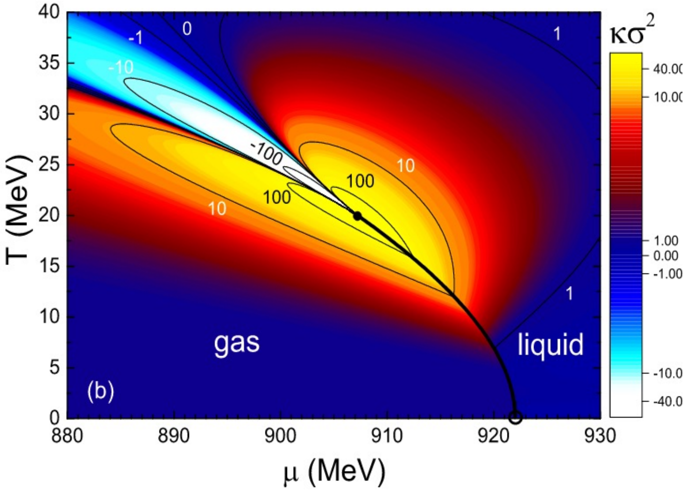
Symmetry and Universality

NJL



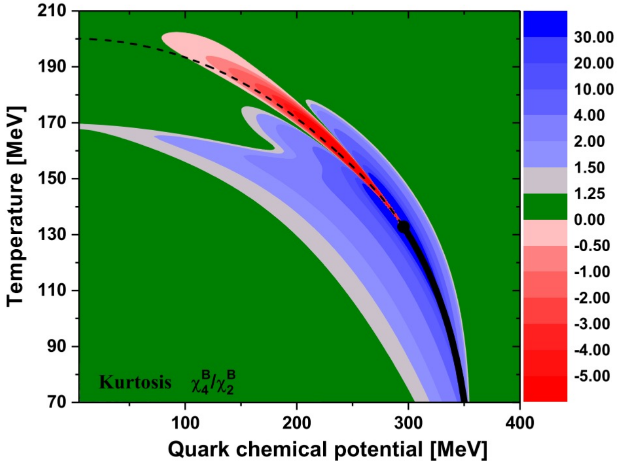
邓建等, PRD93, 034037 (2016)

van der Waals (VDW)



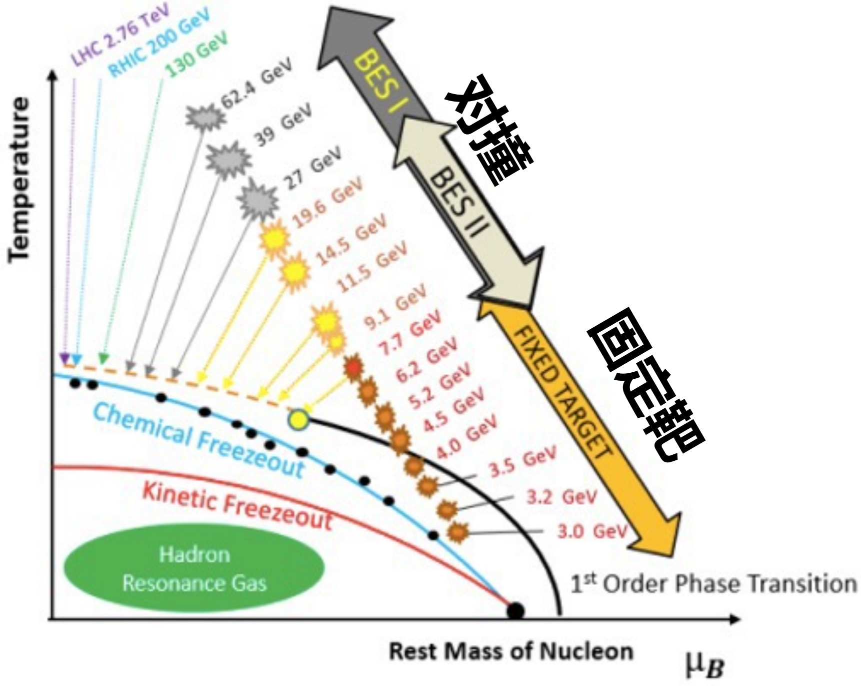
Vovchenko et al., PRC92, 054901 (2015)

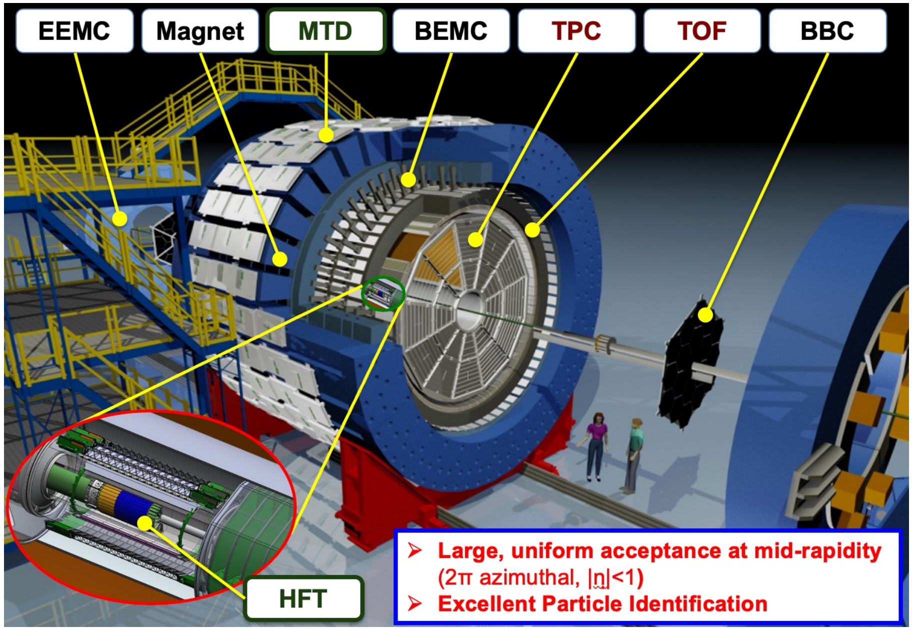
PNJL



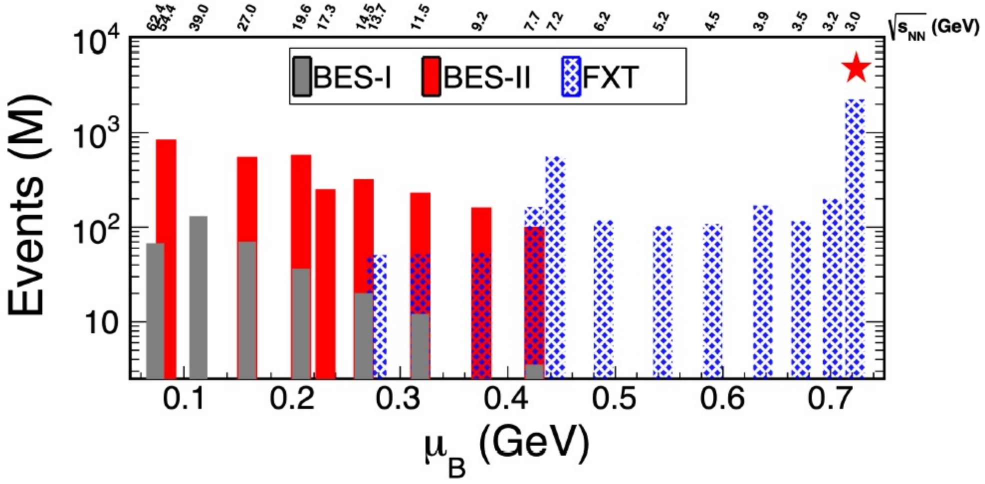
邵国运等, EPJC 78, 138 (2018)
黄梅等, EPJC 79, 245 (2019).

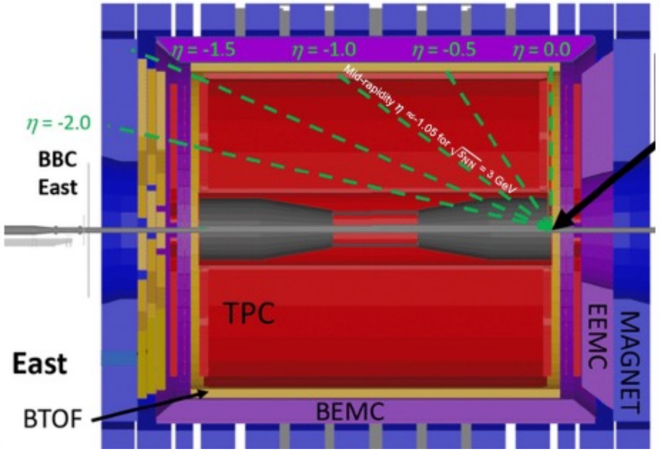
RHIC Beam Energy Scan (BES) Program (2010-2021)





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





STAR实验固定靶模式

RHIC能量扫描数据统计表

Au+Au Collisions at RHIC （RHIC 金核-金核碰撞）

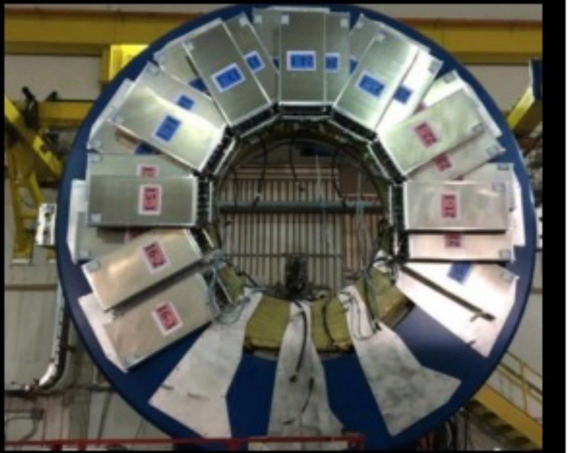
Collider Runs （对撞模式）					**Fixed-Target Runs （固定靶模式）**				
	$\sqrt{s_{NN}}$ (GeV) 碰撞能量	#Events 事例率	μ_B(MeV) 重子化学势	Run 采集时间		$\sqrt{s_{NN}}$ (GeV) 碰撞能量	#Events 事例率	μ_B(MeV) 重子化学势	Run 采集时间
1	200	380 M	25	Run-10,19	1	13.7 (100)	50 M	280	Run-21
2	62.4	46 M	75	Run-10	2	11.5 (70)	50 M	320	Run-21
3	54.4	1200 M	85	Run-17	3	9.2 (44.5)	50 M	370	Run-21
4	39	86 M	112	Run-10	4	7.7 (31.2)	260 M	420	Run-18,19,20
5	27	585 M	156	Run-11,18	5	7.2 (26.5)	470 M	440	Run-18,20
6	19.6	595 M	206	Run-11,19	6	6.2 (19.5)	120 M	490	Run-20
7	17.3	256 M	230	Run-21	7	5.2 (13.5)	100 M	540	Run-20
8	14.6	340 M	262	Run-14,19	8	4.5 (9.8)	110 M	590	Run-20
9	11.5	57 M	316	Run-10,20	9	3.9 (7.3)	120 M	633	Run-20
10	9.2	160 M	372	Run-10,20	10	3.5 (5.75)	120 M	670	Run-20
11	7.7	104 M	420	Run-21	11	3.2 (4.59)	200 M	699	Run-19
					12	3.0 (3.85)	2300 M	750	Run-18,21

STAR, arXiv:1007.2613
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0493
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

- x10-20 more statistics in BES-II compared to BES-I at collider energies
- BES-II: 8 collider energies (7.7 – 54.4GeV) / 12 FXT energies (3.0 - 13.7 GeV)
- μ_B coverage : $25 < \mu_B < 750$ MeV.

Major Upgrades for BES-II

All 3 detectors fully installed prior to start of Run-19
Very successful and important for BES-II



iTPC:
- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut-in from 125 to 60 MeV/c
- Ready in 2019

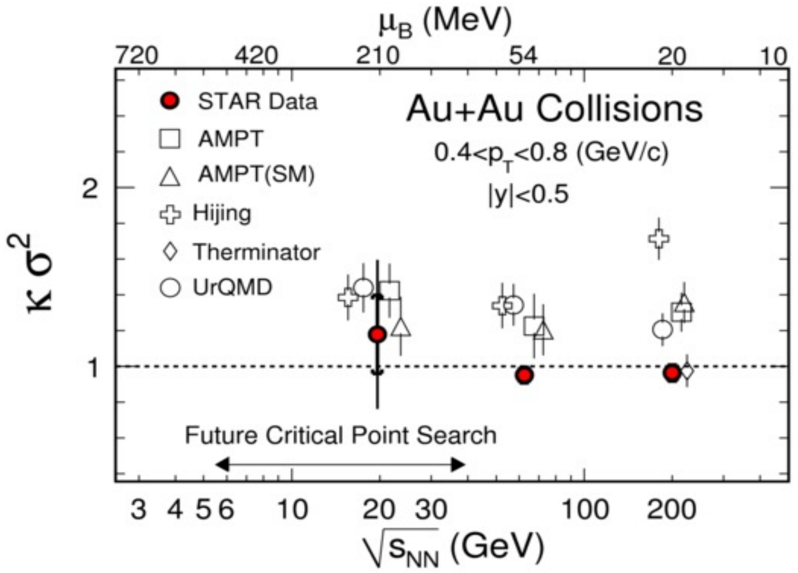
eTOF:
- Forward rapidity coverage
- PID at $\eta = 0.9$ to 1.5
- **Borrowed from CBM-FAIR**
- Ready in 2019

EPD:
- Improves trigger
- Better centrality & event plane measurements
- Ready in 2018

1) **Enlarge rapidity acceptance**
2) **Improve particle identification**
3) **Enhance centrality/event plane resolution**

iTPC: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0619
eTOF: STAR and CBM eTOF group, arXiv: 1609.05102
EPD: J. Adams, et al. Nucl. Instr. Meth. A 968, 163970 (2020)

第一阶段能量扫描高阶矩测量结果

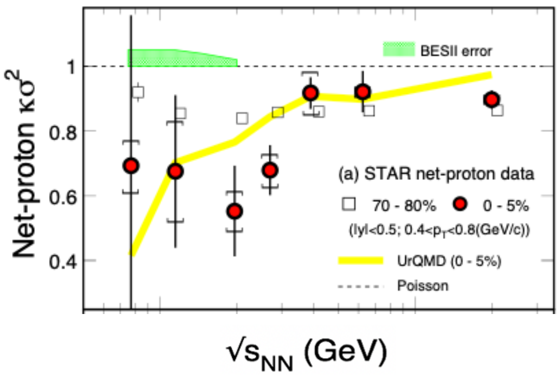


2010年首次测量：验证了该观测量在STAR重离子碰撞实验中的可行性

STAR, Phys. Rev. Lett. 105, 022302(2010).

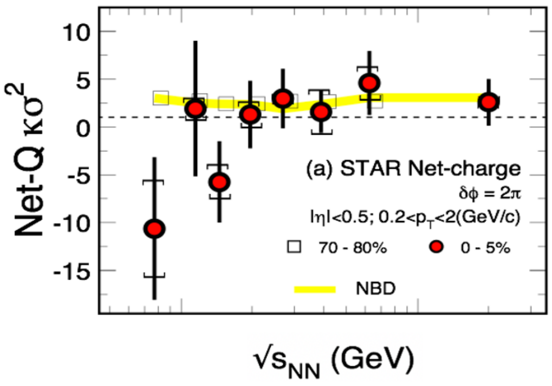
寻找QCD临界点信号：非单调能量依赖

净质子数



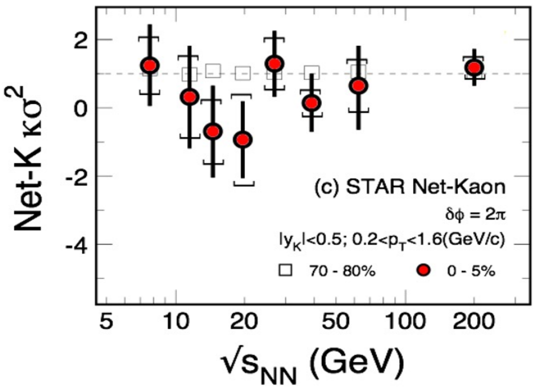
STAR, PRL 112, 032302 (2014).

净电荷数



STAR, PRL113, 092301 (2014).

净K介子数

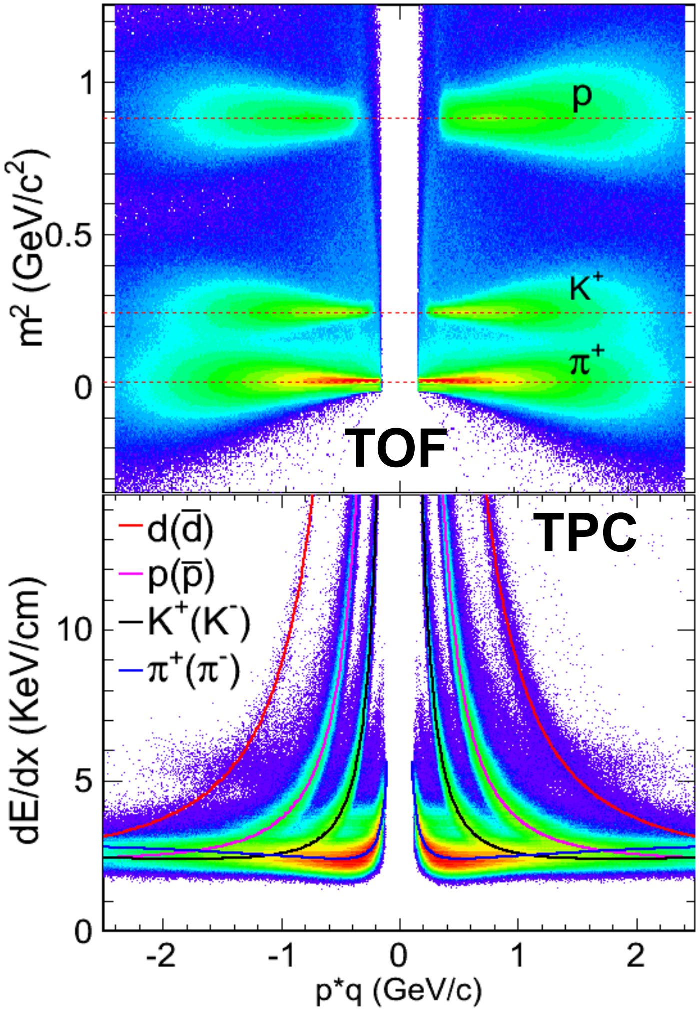


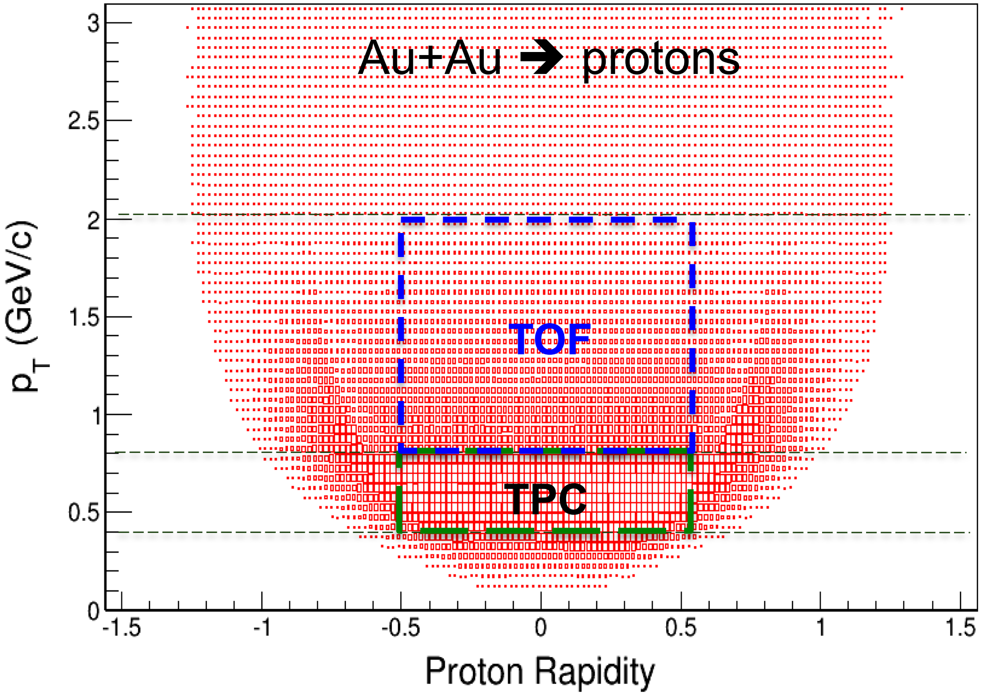
STAR, PLB 785, 551 (2018).

Extend p_T Acceptance

Multi-Particle Correlations : Larger acceptance -> Larger signal

B. Ling, M. Stephanov, Phys. Rev. C 93, 034915 (2016)
姜丽佳, 李鹏飞, 宋慧超, Phys. Rev. C 94, 024918 (2016)



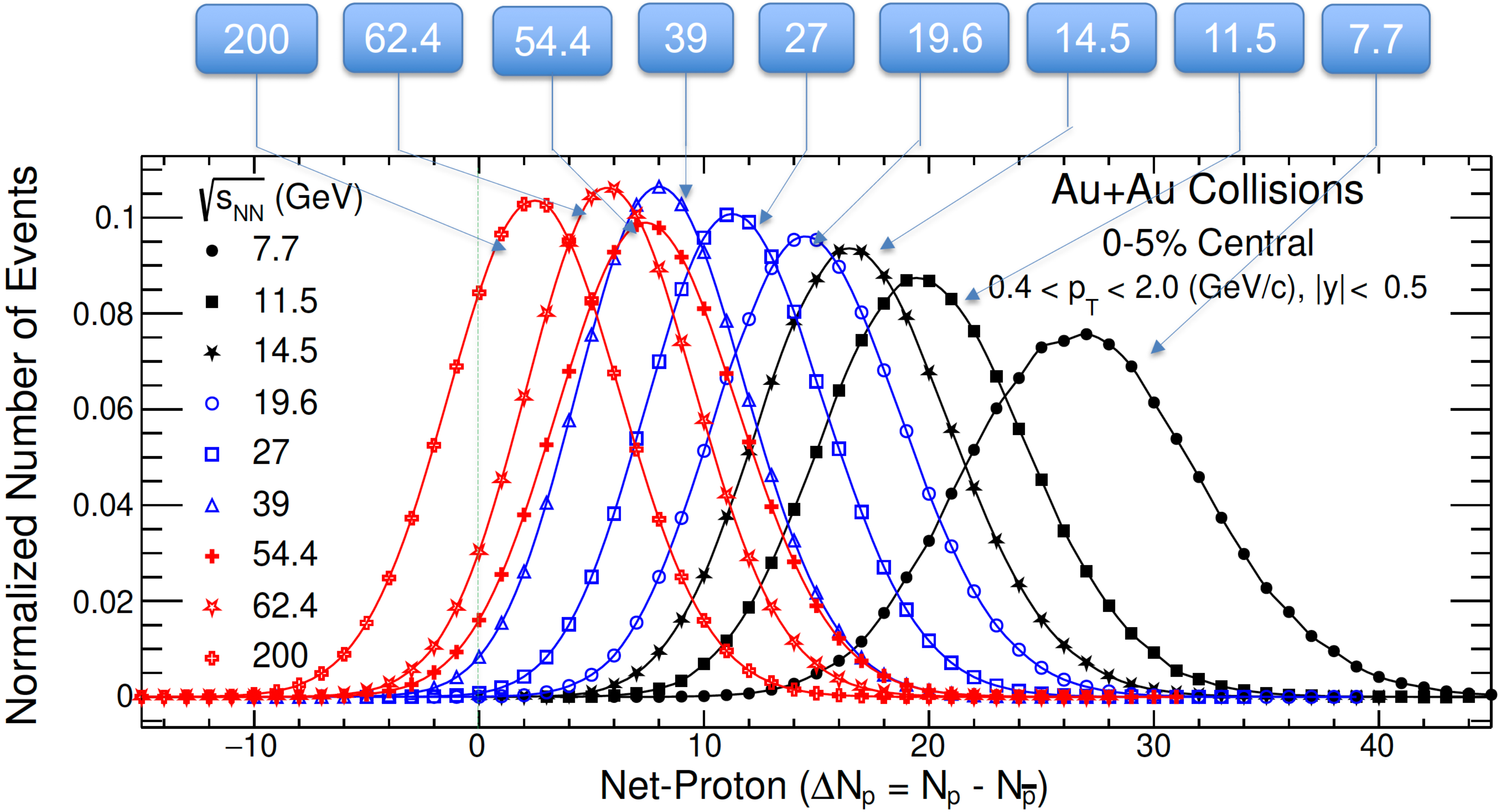


Acceptance: $|y| \leq 0.5$, $0.4 \leq p_T \leq 2$ GeV/c
Efficiency corrections:

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): $\varepsilon_{TPC} * \varepsilon_{TOF} \sim 0.5$

XFL, Phys. Rev. C 91, 034907 (2015).

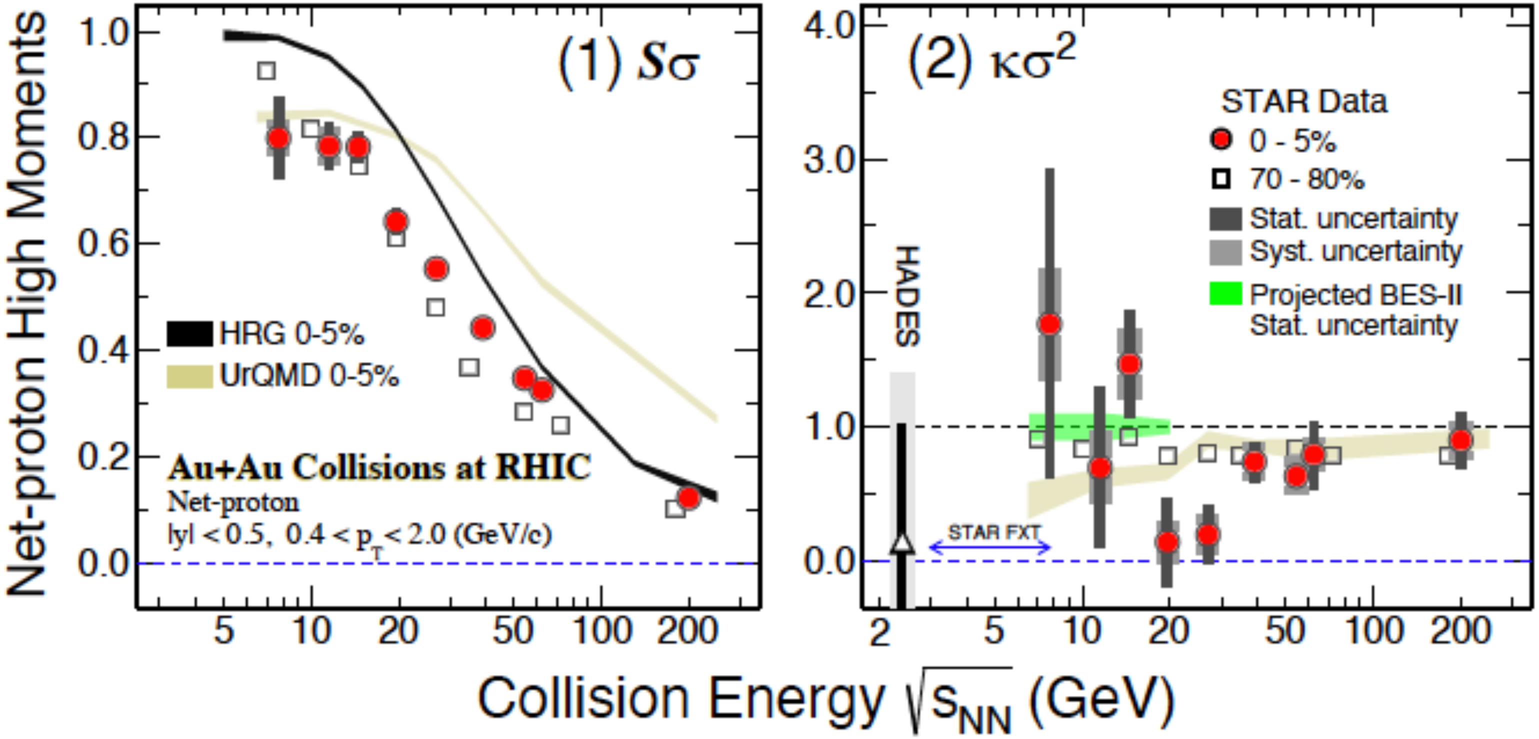
Raw Event-by-Event Net-Proton Distributions



Mean values increase when decreasing energy:
Interplay between baryon stopping and pair production.

STAR, PRL 126, 092301 (2021)
STAR, PRC104, 024902 (2021)

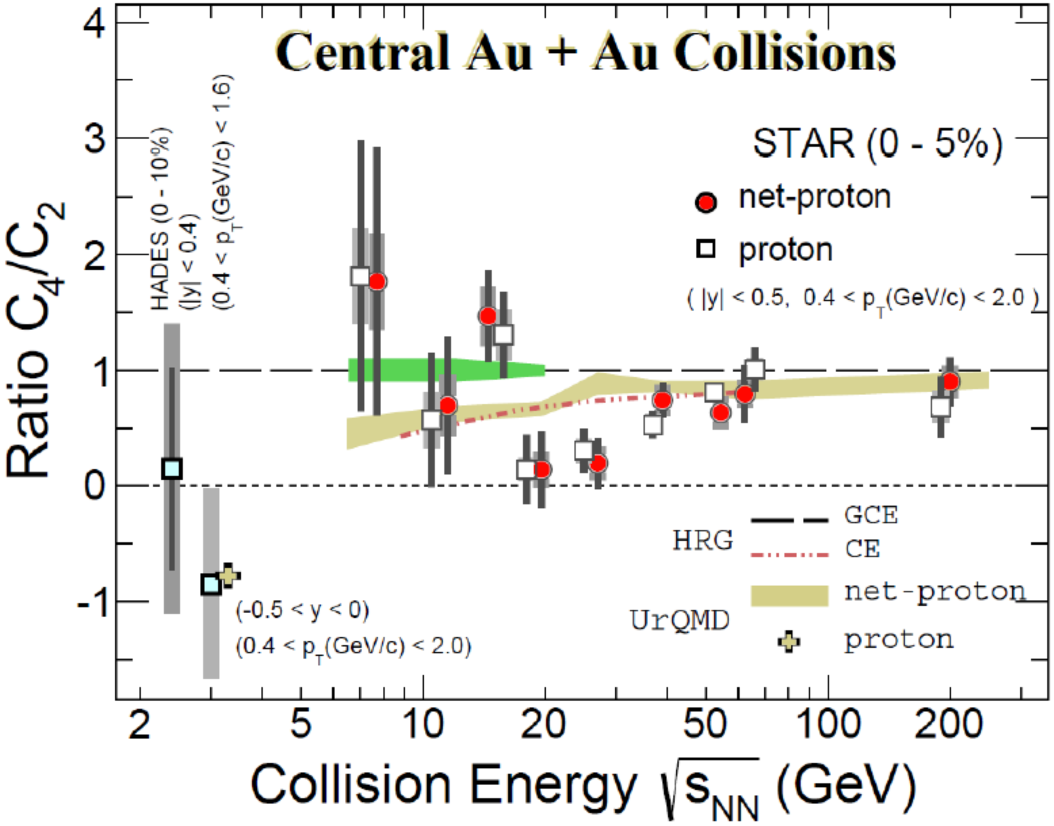
Energy Dependence of Cumulant Ratios : $S\sigma$ and $\kappa\sigma^2$

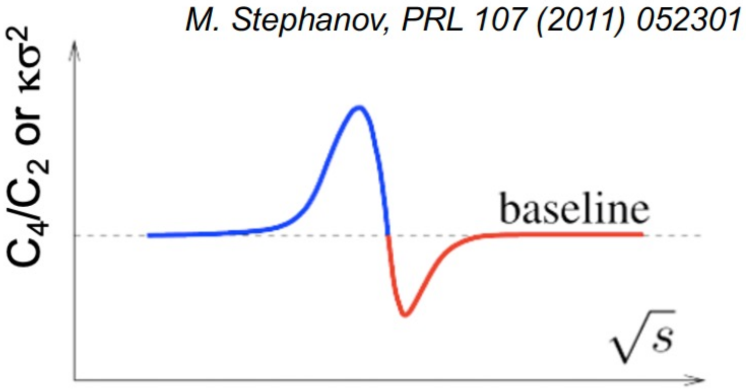


- ➢ HRG (GCE) and transport model predicted monotonical energy dependence. Suppression at low energy due to conservation.
- ➢ Observe a non-monotonic energy dependence (7.7-62.4 GeV) in 0-5% net-proton $\kappa\sigma^2$ with a significant of 3.1σ

STAR, Phys. Rev. Lett. 126, 092301 (2021)
STAR, Phys. Rev. C 104, 024902 (2021)
HADES, Phys. Rev. C 102, 024914 (2020)

Energy Dependence of (Net-) Proton Fourth-order Fluctuations



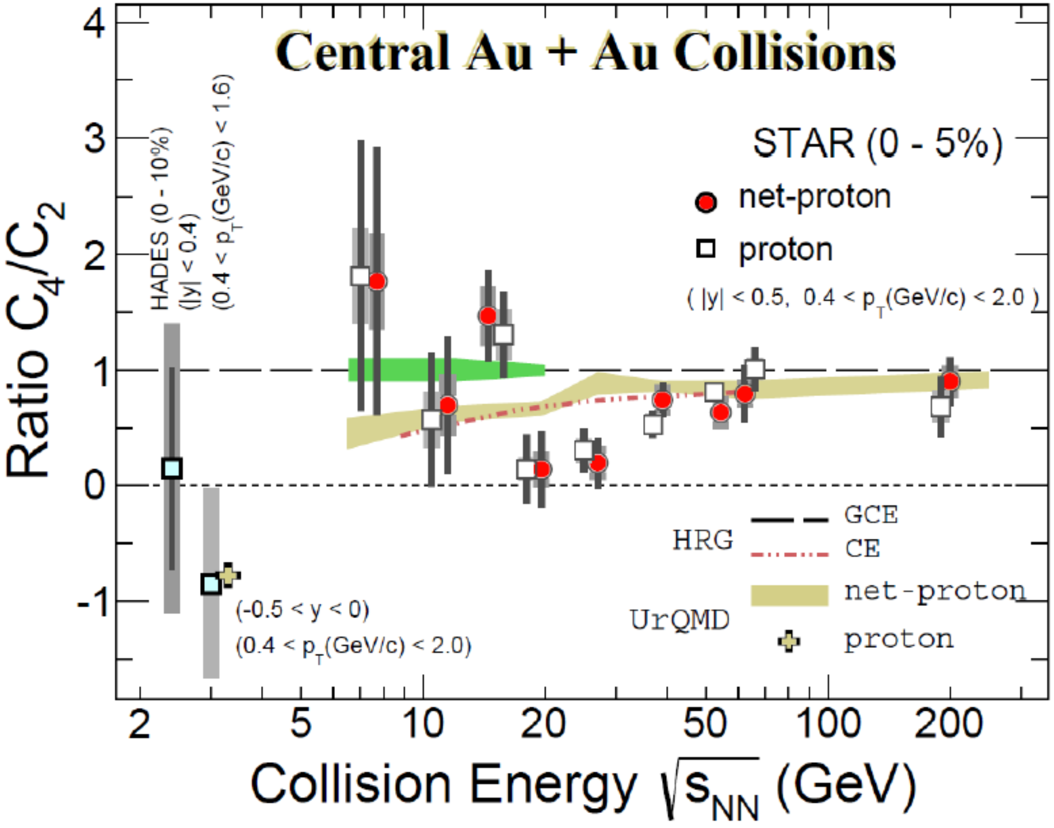


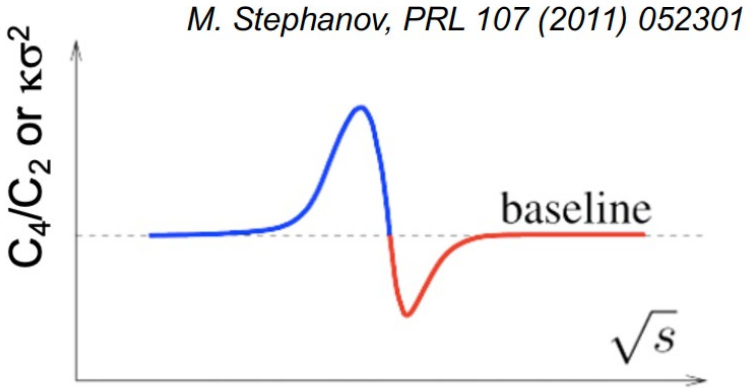
- Non-monotonic energy dependence in central Au+Au collisions (3.1σ)
- The suppression of C_4/C_2 at 3 GeV is consistent with UrQMD. Hadronic dominated.
- The QCD critical point, if exists in heavy ion collisions, could likely be at energy higher than 3 GeV.

BES-I : Phys. Rev. Lett. 126, 092301 (2021)
Phys. Rev. C 104, 024902 (2021)

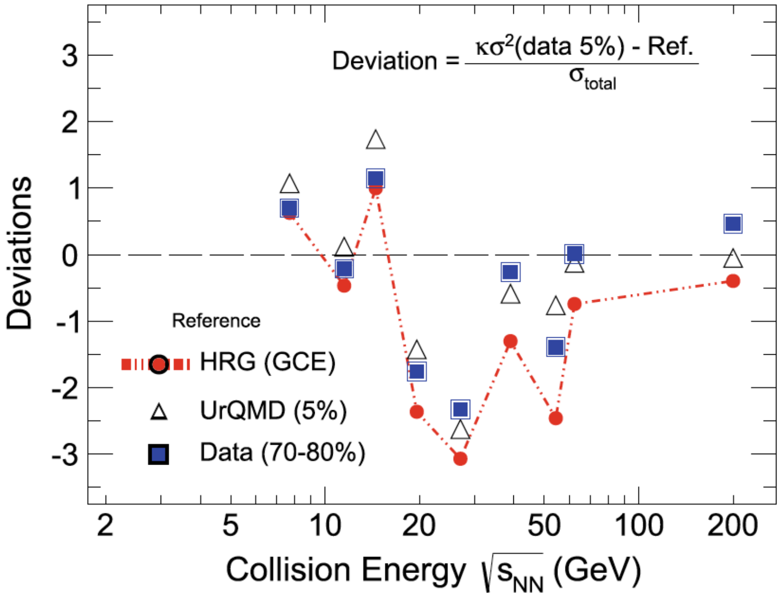
3 GeV: Phys. Rev. Lett. 128, 202303 (2022)
Phys. Rev. C 107, 024908 (2023)

Energy Dependence of (Net-) Proton Fourth-order Fluctuations





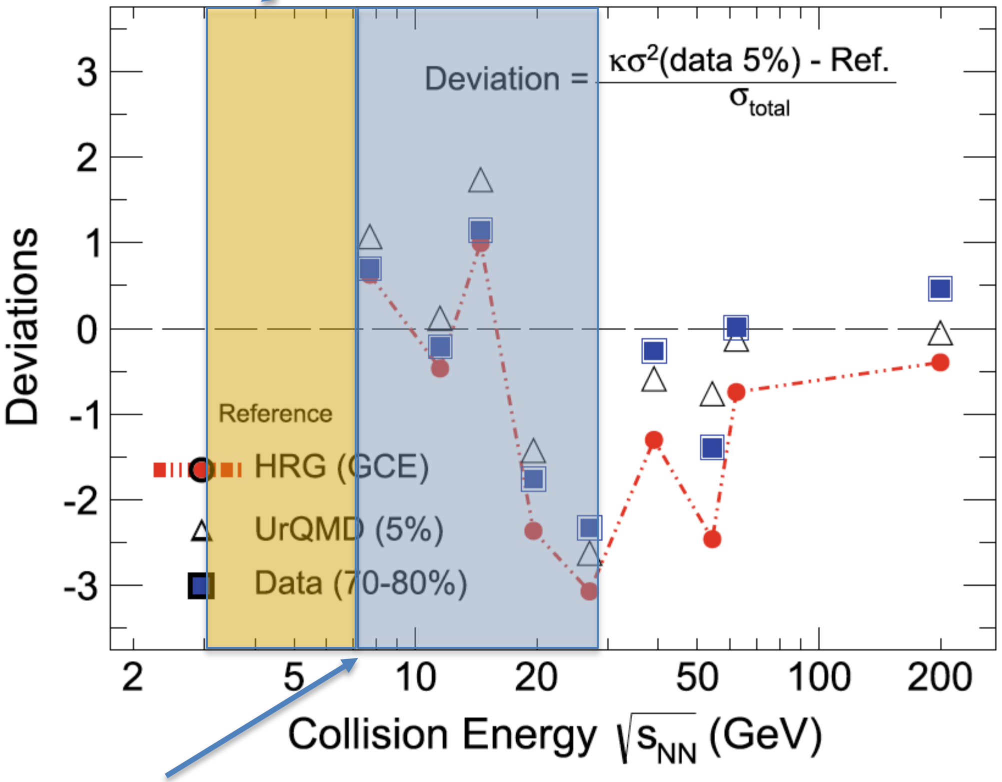
M. Stephanov, PRL 107 (2011) 052301



BES-I : Phys. Rev. Lett. 126, 092301 (2021)
Phys. Rev. C 104, 024902 (2021)

3 GeV: Phys. Rev. Lett. 128, 202303 (2022)
Phys. Rev. C 107, 024908 (2023)

Prospects from BES-II

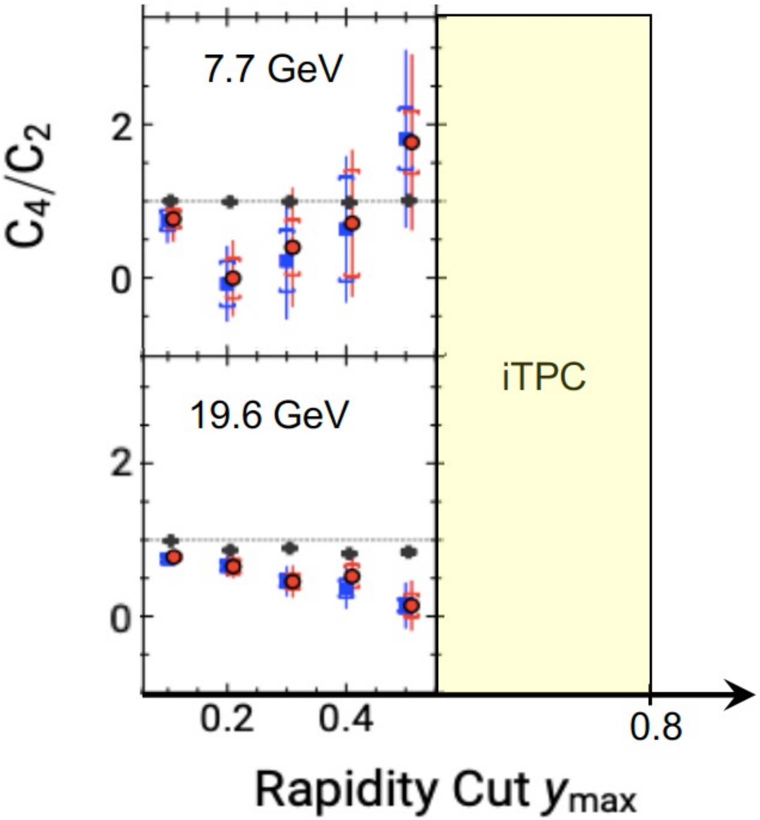


Fixed-target energies

(3 - 7.7 GeV)

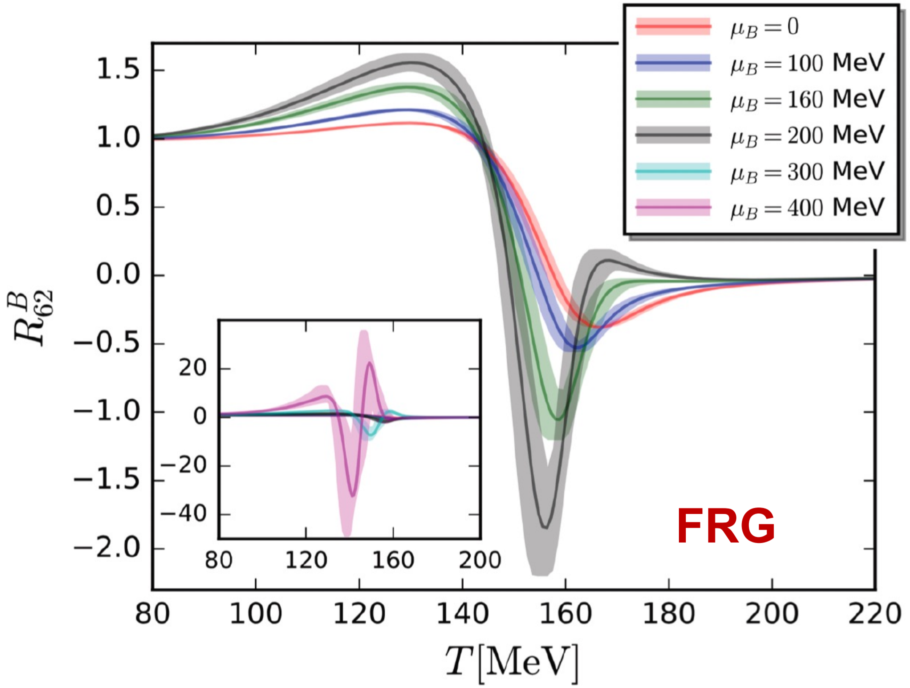
BES-II Collider Energies :
10-20 times more statistics
Extended acceptance and PID

STAR, PRC 104 (2021) 024902

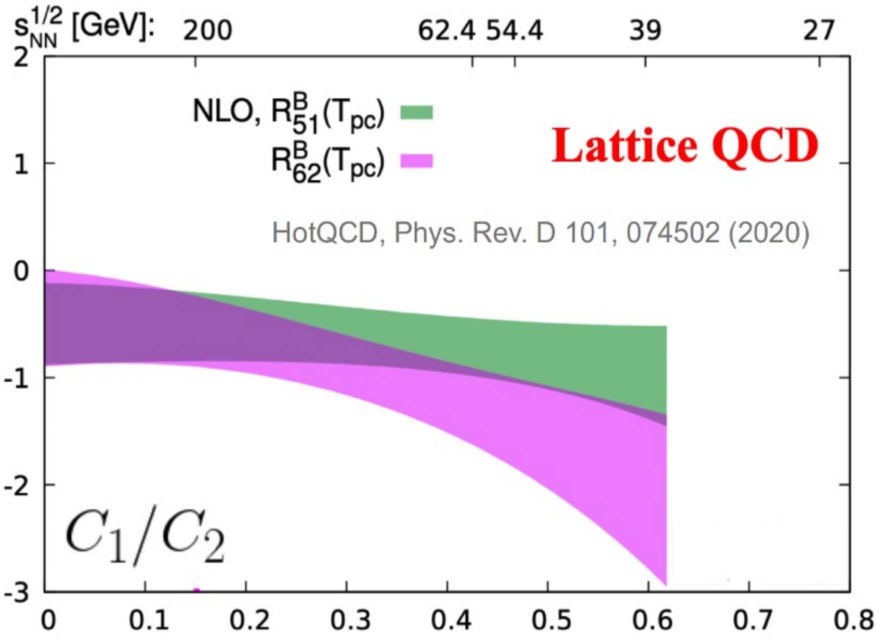


Rapidity coverages at BES-II
Collider: |y|<y_{max}=0.8
FXT: -1.0<y<0.5 @ 3 GeV

Higher-order baryon number fluctuations



付伟杰, XFL等，Phys. Rev. D 104, (2021) 094047 (Editor Suggestion)



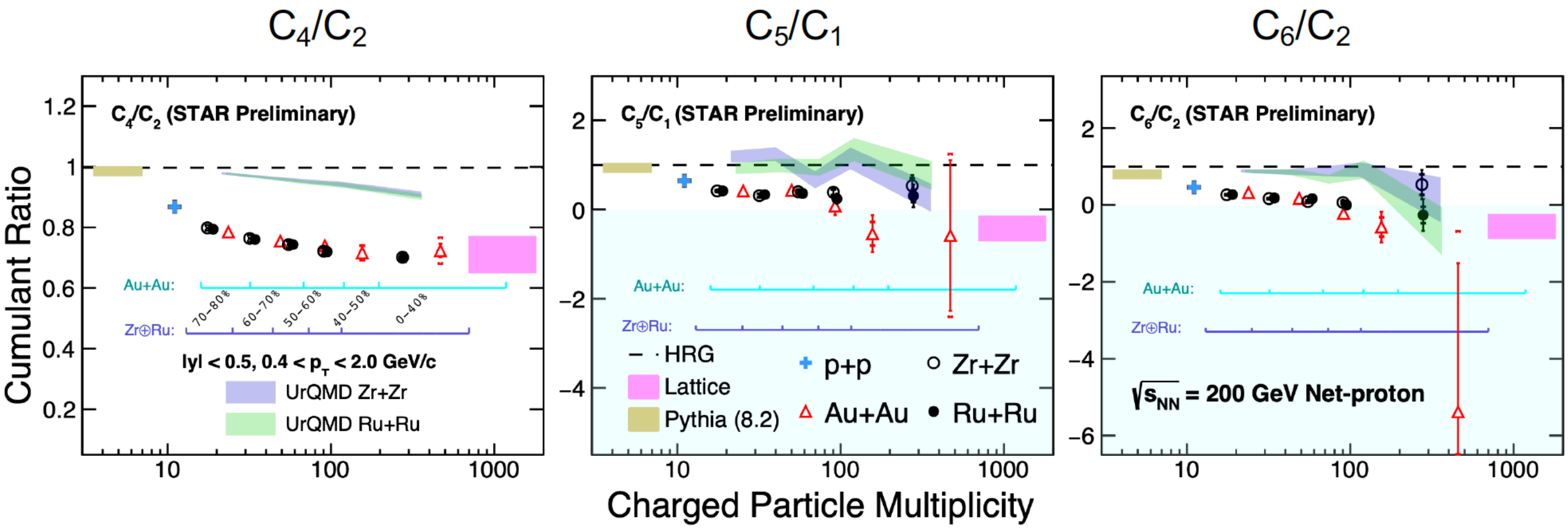
A. Bazavov, et al. (hotQCD), Phys. Rev. D 101, 074502 (2020);

- Higher-order fluctuations are more sensitive to QCD phase transition.
- Negative C_n (n>4) near Tc due to chiral crossover.

-> Serve as experimental evidence for the formation of thermalized QGP and smooth crossover transition ！

C_5/C_1 and C_6/C_2 : System Size Dependence

200 GeV : p+p, Ru+Ru, Zr+Zr and Au+Au



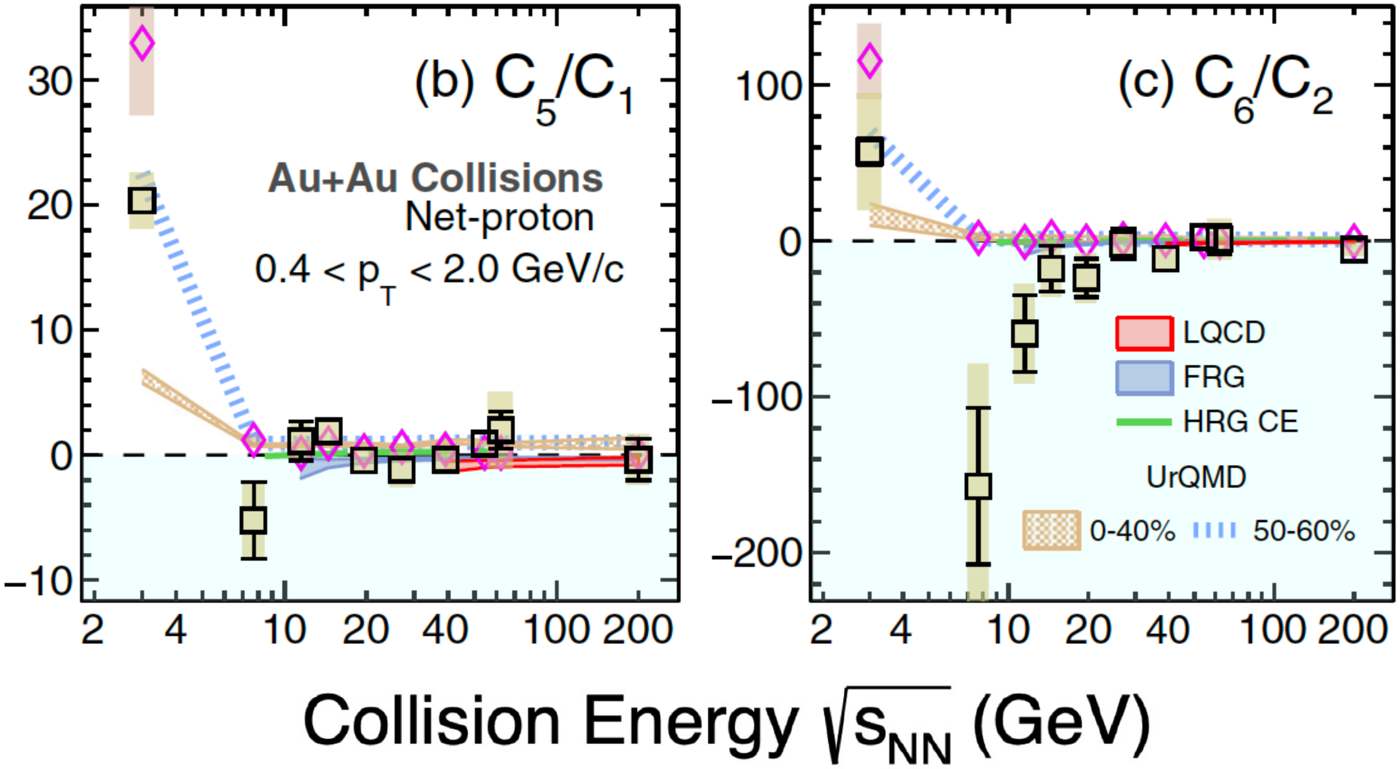
Isobar and *p+p* : under collaboration review

200 GeV Au+Au: PRC 104 (2021) 024902; PRL 126.092301 (2021), PRL 127, 262301 (2021).

- Cumulant ratios (up to C6) of net-proton from p+p, Au+Au and isobar data, systematic decreasing trend with multiplicity, approaching LQCD calculations

- Most central Au+Au collision results become consistent with Lattice QCD prediction for the formation of thermalized QCD matter and smooth crossover transition.

C_5/C_1 and C_6/C_2 : Energy Dependence

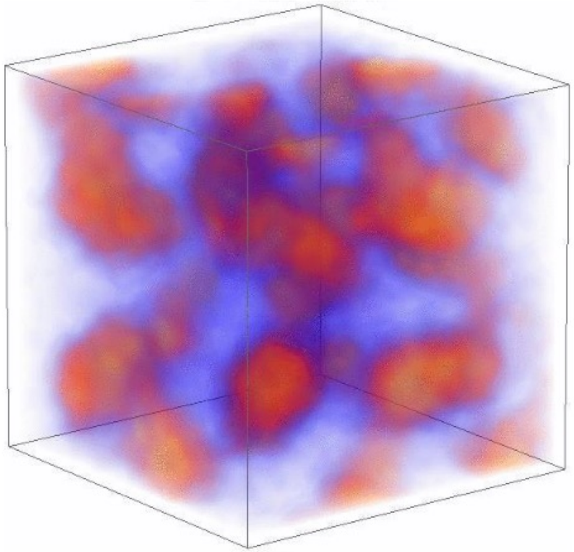


1. C_5/C_1 and C_6/C_2 (0-40%): Consistent with Lattice QCD with $\mu_B < 110$ MeV. (> 39 GeV)
2. C_6/C_2 progressively negative with decreasing collision energy down to 7.7 GeV.
~ 1.7 sigma to be negative sign.
3. 3 GeV 0-40% results : large initial volume fluctuations and consistent with UrQMD.

STAR, Phys. Rev. Lett. 130, 082301 (2023)

Light nuclei production as probes of QCD phase structure

Near first order P.T. or critical point ：
large density fluctuations and baryon clustering



Based on coalescence model:

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

$$N_t = \frac{3^{\frac{3}{2}}}{4}\left(\frac{2\pi}{m_0 T_{eff}}\right)^{3} N_p\langle n\rangle^2\left(1 + \Delta n + 2C_{np}\right)$$

New observable : Yield ratio of light nuclei

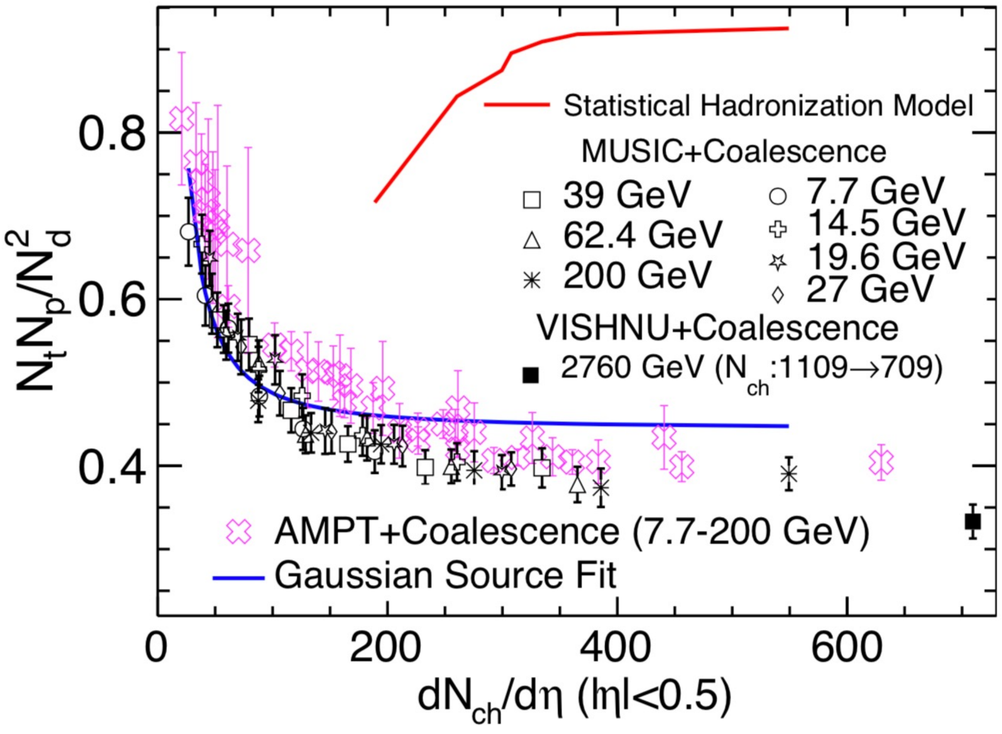
$$\mathrm{N_t \cdot N_p / N_d^2 \approx g(1 + \Delta n)}$$

Neutron density fluctuations $\Delta n = \langle(\delta n)^2\rangle/\langle n\rangle^2$
g=0.29

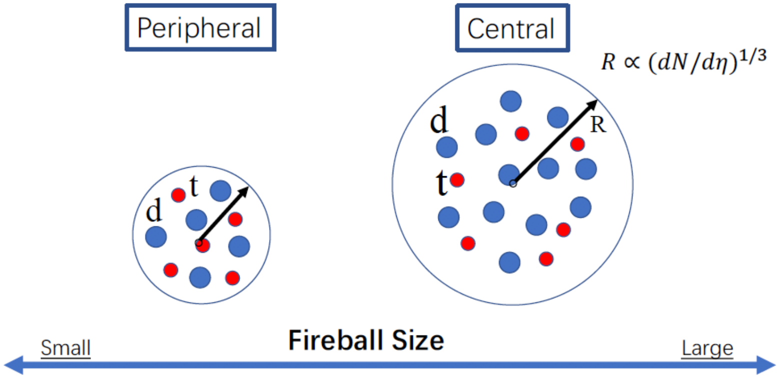
Yield ratio of light nuclei is sensitive to the baryon density fluctuations and can be used to probe the signature of 1st order phase transition and/or critical point in heavy-ion collisions.

K.J. Sun, L.W. Chen, C.M. Ko, and Z.B. Xu, PLB 774, 103 (2017);
K.J. Sun, L.W. Chen, C.M. Ko, J. Pu, and Z.B. Xu, PLB781, 499 (2018)
Edward Shuryak，Juan M. Torres-Rincon, PRC 100, 024903 (2019); PRC 101, 034914 (2020); EPJA 56, 241 (2020).

Size effect in coalescence production of light nuclei



W. Zhao, K.-j. Sun, C. M. Ko, and X. Luo, Phys. Lett. B 820, 136571 (2021);
K.-J. Sun, C. M. Ko, and B. Dönigus, Phys. Lett. B 792, 132 (2019)



$$\frac{N_tN_p}{N_d^2} = \frac{4}{9}\left(\frac{1+\frac{2r_d^2}{3R^2}}{1+\frac{r_t^2}{2R^2}}\right)^3 = \frac{4}{9}\left(1+\frac{\frac{4}{3}r_d^2 - r_t^2}{2R^2+r_t^2}\right)^3$$

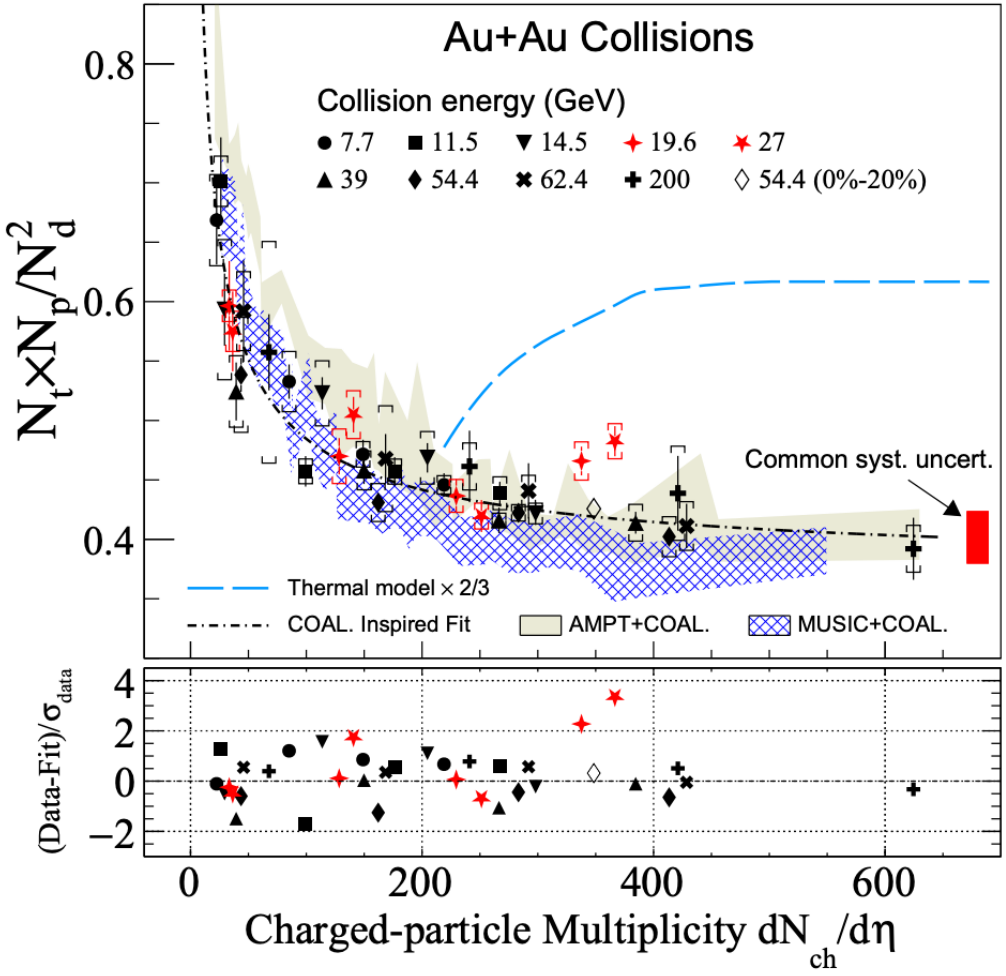
r_t and r_d: matter radius of Triton and deuteron.

$$R \propto (dN_{\mathrm{ch}}/d\eta)^{1/3}$$

R: Radius of spherical Gaussian emission source

- Due to size effect in coalescence, yield ratio shows scaling behavior and decreasing with increasing the charged particle multiplicity.
- This multiplicity scaling can be used to validate the production mechanism of light nuclei and serve as a baseline to search for the critical point in heavy-ion collisions

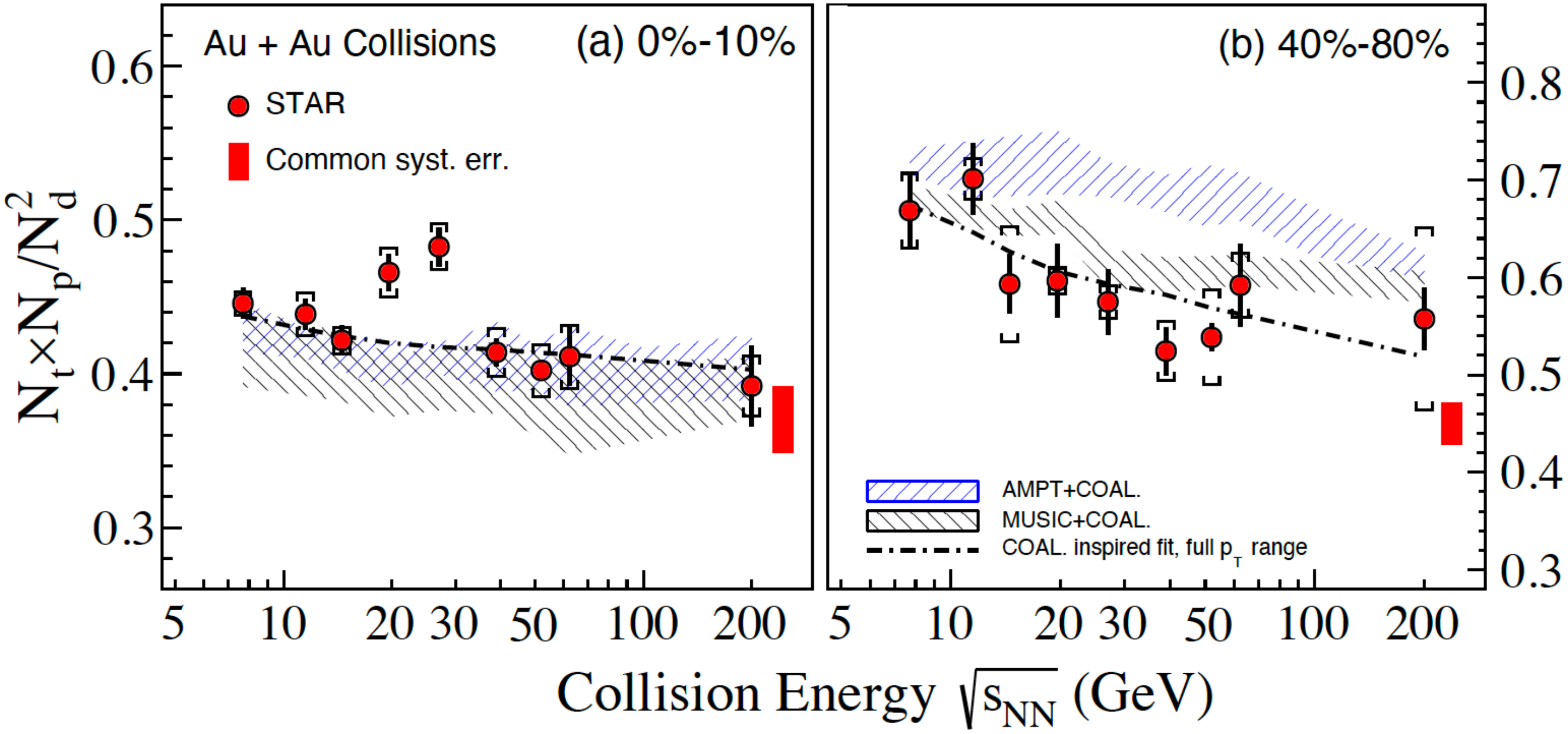
Charged-particle Multiplicity Dependence of Light Nuclei Yield Ratio



STAR, Phys. Rev. Lett. 130, 202301 (2023)

- The yield ratio exhibits a scaling behavior: Trend driven by interplay between the size of light nuclei and the size of fireball created in HIC
- The ratio of 19.6 and 27 GeV from 0% - 10% centrality show enhancements to the coalescence baseline with a combined significance of 4.1 σ
- The thermal model overestimates the experimental data, shows clear difference compared to coalescence model

Energy Dependence of Light Nuclei Yield Ratio

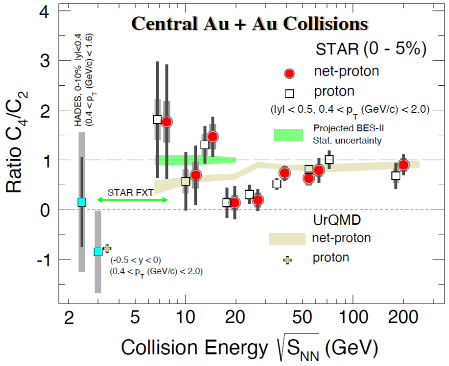


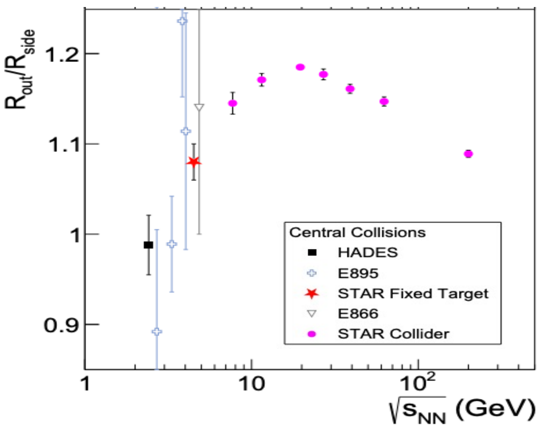
STAR, Phys. Rev. Lett. 130, 202301 (2023)

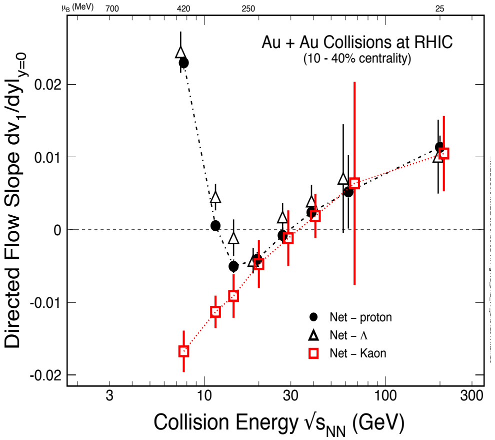
- Yield ratio shows a non-monotonic dependence on collision energy in 0-10% Au + Au collisions, with a peak around 20-30 GeV.
- Flat energy dependence of yield ratio observed in JAM, AMPT, UrQMD, hybrid model.

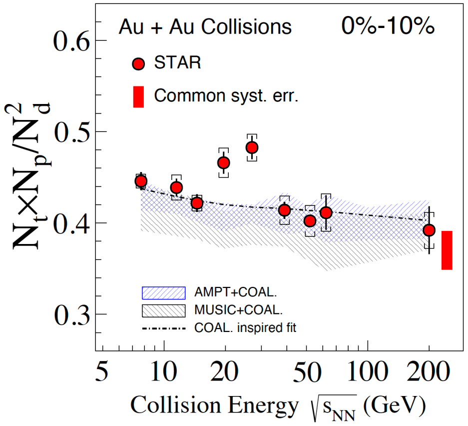
JAM : H. Liu et al, Phys. Lett. B 805, 135452 (2020).
AMPT : K. Sun, C. M. Ko, PRC 103,064909 (2021).
Hydro + transport + coal. : W. Zhao et al., PRC 102,044912 (2020)
UrQMD: X. G. Deng, Y. G. Ma, Phys. Lett. B 808, 135668 (2020)

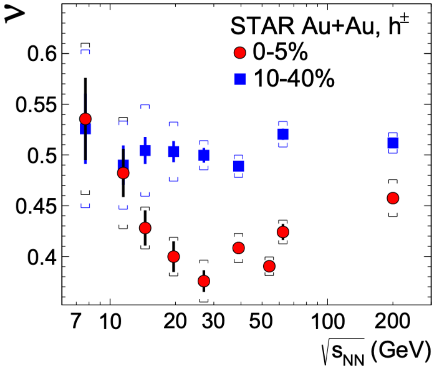
Summary











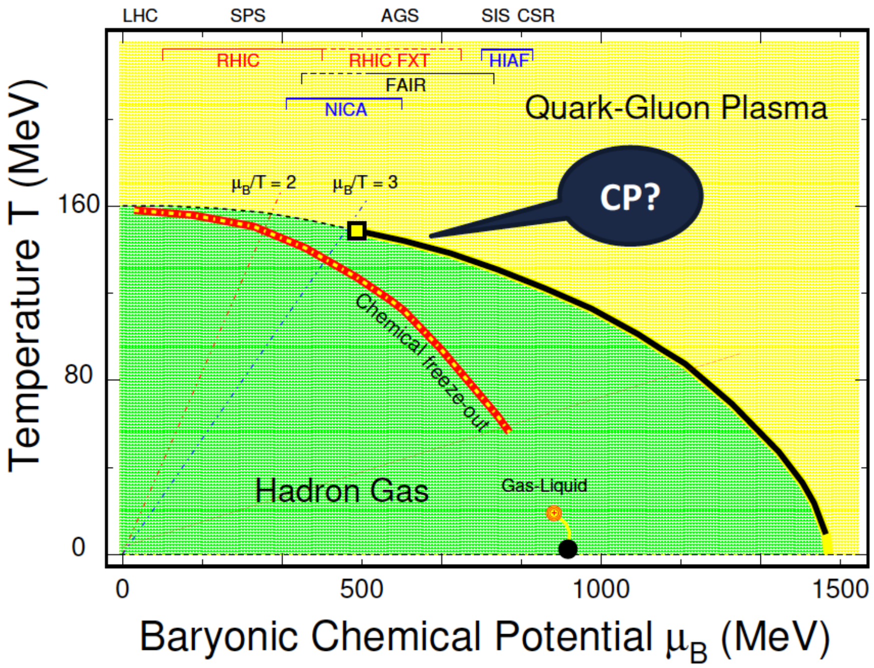
1) Au+Au collisions at 39-200 GeV, $\mu_B < 110$ MeV
QGP EOS dominant, smooth crossover transition.

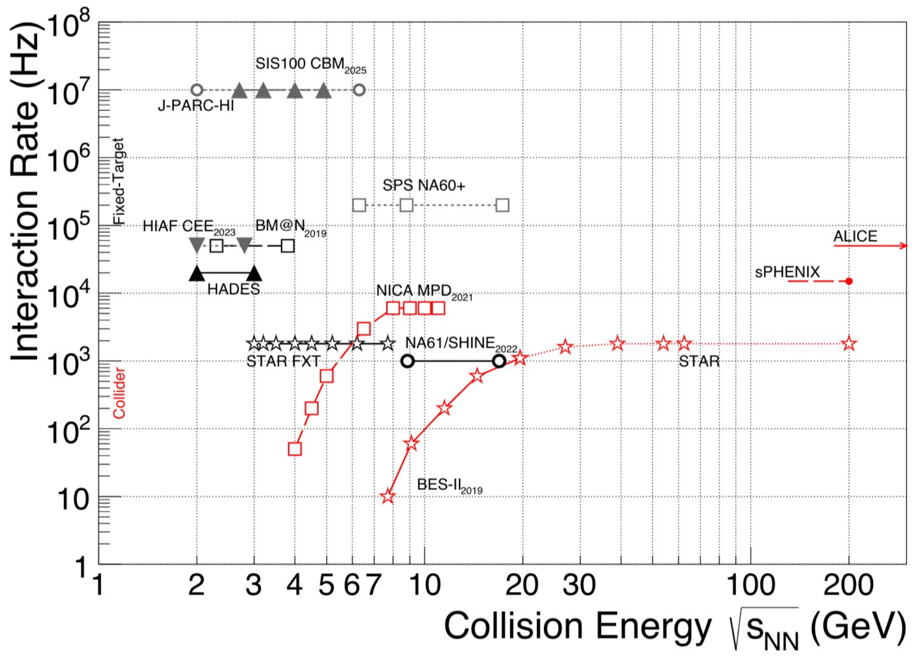
2) At 3 GeV collisions, $\mu_B \sim 750$ MeV, different EOS comparing to high energy.
hadronic dominated !

3) BES-I : QCD critical point between 3 – 39 GeV??
What is the physics behind the structure around 20 ~ 27 GeV ?

4) BES-II (data taken completed !), analysis ongoing:
7.7 ~ 19.6 GeV (collider)
3 ~ 7.7 GeV (FXT)

Outlook





万亿摄氏度下烹煮夸克汤：核物质相结构和量子色动力学相变临界点的实验研究

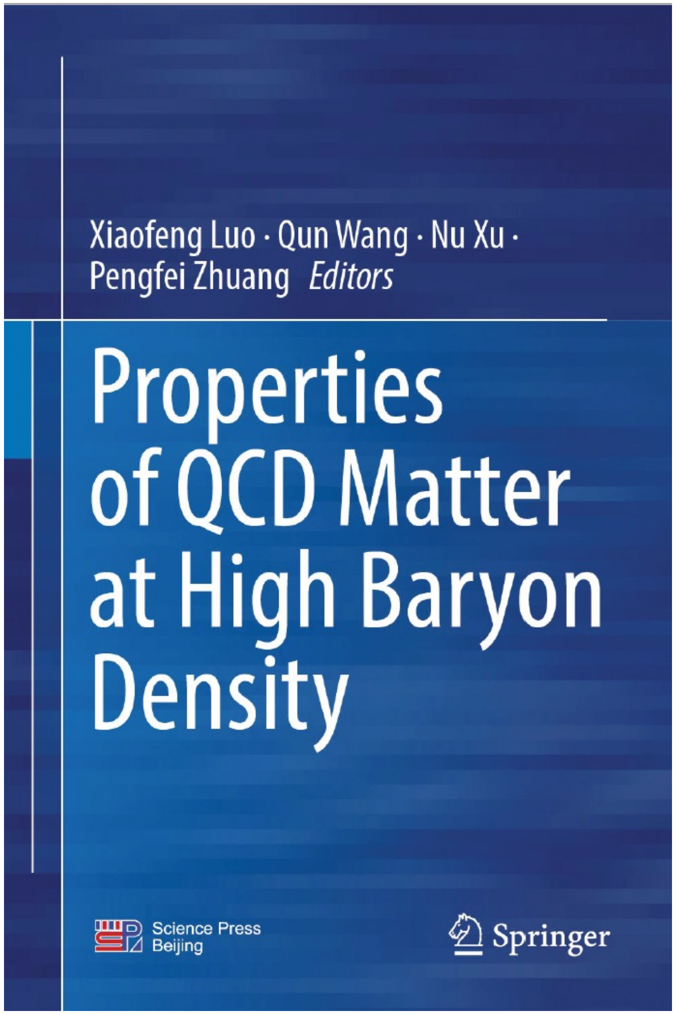
科普(前沿进展)：
XFL、刘峰、许怒,《物理》50(2), (2021)

Mapping out the QCD phase structure at high baryon density with high precision:

(1) RHIC BES-II : Collider ($\sqrt{s_{NN}}$ =7.7 - 19.6 GeV) and FXT ($\sqrt{s_{NN}}$ = 3 - 7.7 GeV) mode.

(2) Future Facilities ($\sqrt{s_{NN}}$ =2 - 11 GeV) : FAIR/CBM, NICA/MPD, HIAF/CEE, JPARC-HI.

Stay tuned for the exciting physics from High Baryon Density !

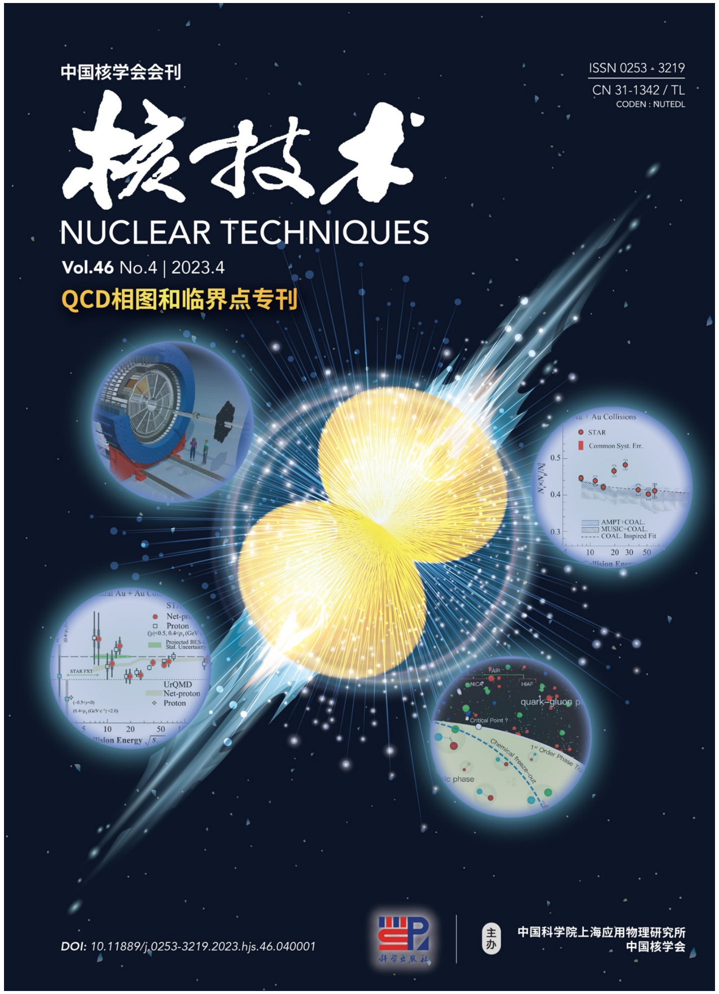


Xiaofeng Luo · Qun Wang · Nu Xu ·
Pengfei Zhuang *Editors*

Properties of QCD Matter at High Baryon Density

Science Press Beijing

Springer



中国核学会会刊

核技术

NUCLEAR TECHNIQUES

Vol.46 No.4 | 2023.4

QCD相图和临界点专刊

ISSN 0253 - 3219
CN 31-1342 / TL
CODEN : NUTEDL

DOI: 10.11889/j.0253-3219.2023.hjs.46.040001

主办
中国科学院上海应用物理研究所
中国核学会

“高重子密度区QCD物质的性质” (2022)

https://inspirehep.net/literature/2611423

https://link.springer.com/book/10.1007/978-981-19-4441-3

核技术“QCD相图和临界点专刊”(2023)

客座编辑：陈列文、黄梅、刘玉鑫、罗晓峰

主编：马余刚

谢谢大家！