相对论重离子碰撞中QCD相图的实验研究

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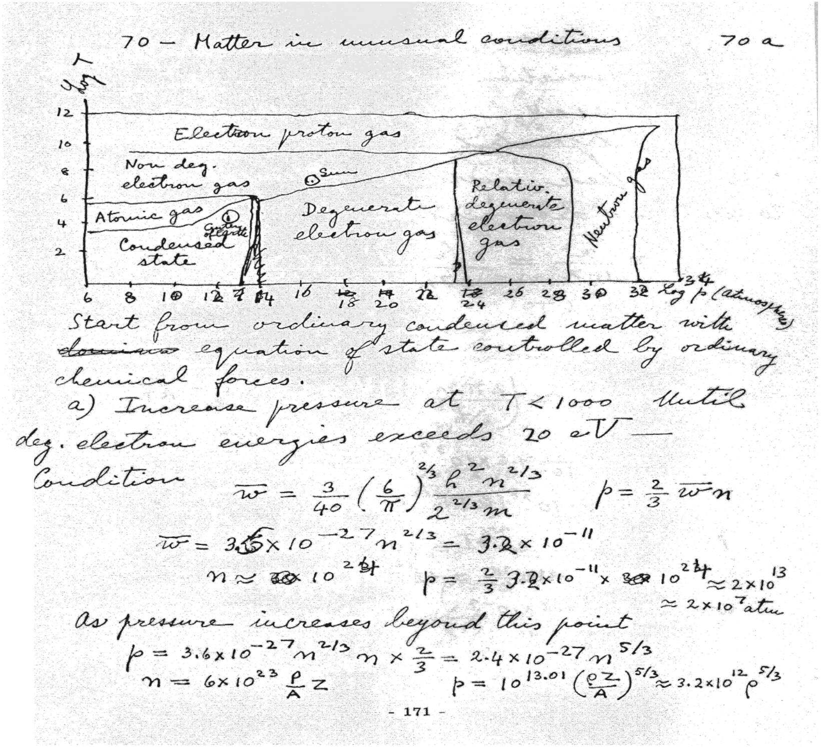
华中师范大学

2024年10月19日

极端物质形态

E. Fermi: *“Notes on Thermodynamics and Statistics ” (1953)*

E. Fermi


70 — Matter in unusual conditions 70 a

Start from ordinary condensed matter with equation of state controlled by ordinary chemical forces.

a) Increase pressure at $T < 1000$ until deg. electron energies exceeds 20 eV — Condition

$\bar{w} = \frac{3}{40}\left(\frac{6}{\pi}\right)^{2/3}\frac{h^2 n^{2/3}}{2^{2/3} m}$ $p = \frac{2}{3}\bar{w} n$

$\bar{w} = 3.5 \times 10^{-27} n^{2/3} = 3.2 \times 10^{-11}$

$n \approx 10^{24}$ $p = \frac{2}{3} 3.2\times10^{-11} \times 10^{24} \approx 2\times10^{13}$

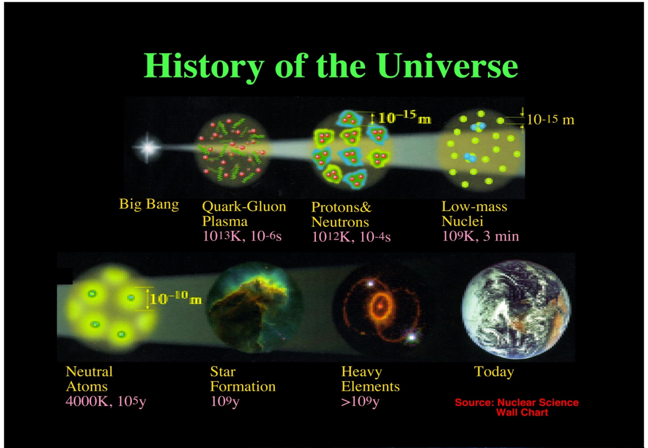
$\approx 2\times10^{7}$ atm

As pressure increases beyond this point

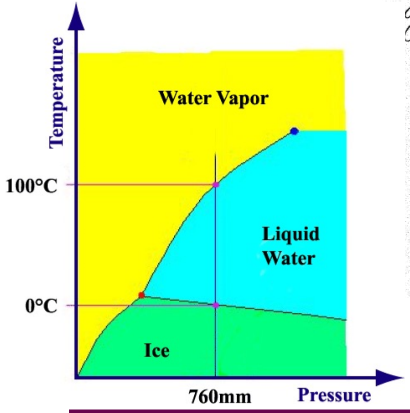
$p = 3.6\times10^{-27} n^{2/3} n \times \frac{2}{3} = 2.4\times10^{-27} n^{5/3}$

$n = 6\times10^{23}\frac{\rho}{A}Z$ $p = 10^{13.01}\left(\frac{\rho Z}{A}\right)^{5/3} \approx 3.2\times10^{12}\rho^{5/3}$

- 171 -

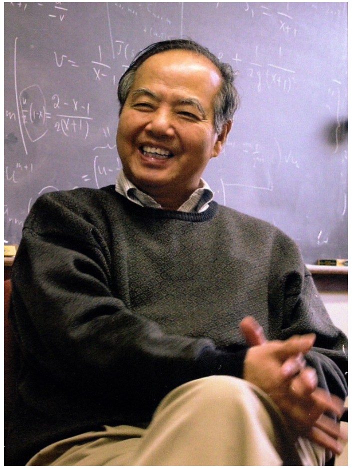


Water Phase Diagram



How to create extreme condition similar to early universe ?
What is the relevant degree of freedom and dominated interactions ?

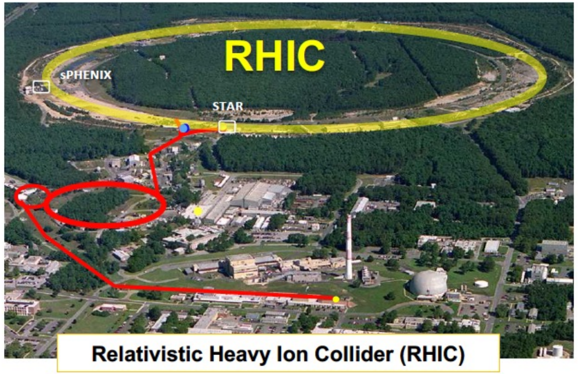
相对论重离子碰撞和夸克胶子等离子体(QGP)



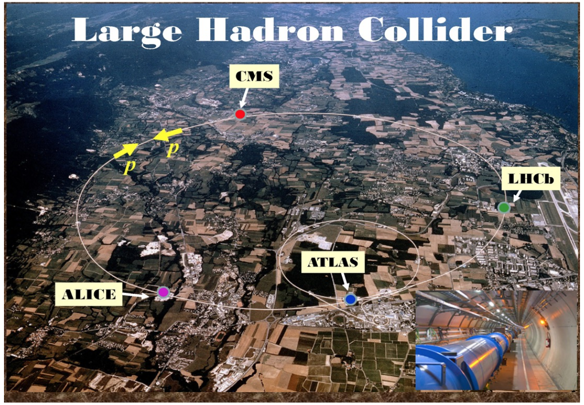
李政道先生

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

相对论重离子对撞机(RHIC)



大型强子对撞机(LHC)



- **夸克胶子等离子体性质：**

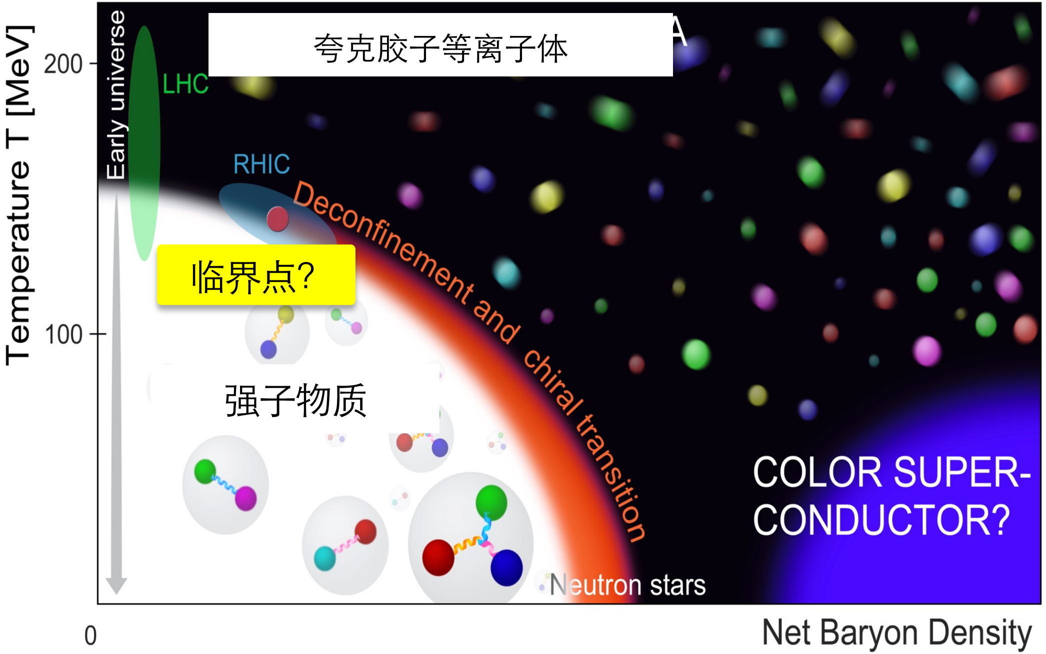
  sQGP： 强耦合理想流体
  强耦合低粘滞
  强涡旋场
  强电磁场

人类制造的最高温度：~2万亿度
太阳中心温度：~2000万度

RHIC White Paper :nucl-ex/0501009
Hot QCD White Paper：2303.17254
ALICE: 2211.04384 (review)

- **强相互作用物质相结构**

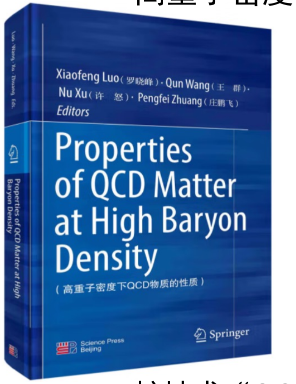
强相互作用(QCD)相图

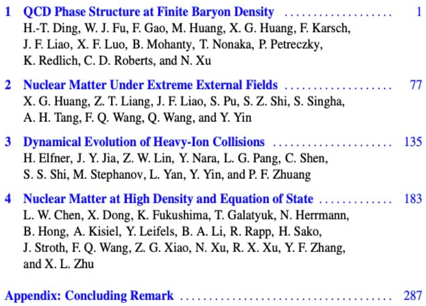


Smooth Crossover at μ_B=0.
QCDTransition Temperature : T_c ~ 156 MeV

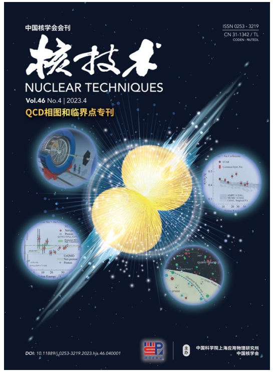
Y. Aoki, et al. Nature 443, 675 (2006).
A. Bazavov, H.-T. Ding et al.(HotQCD),
B. Phys. Lett. B 795, 15 (2019)

高重子密度下QCD物质的性质 (2022)

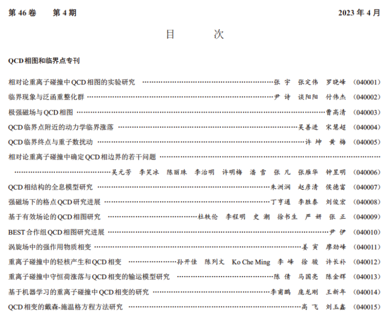




核技术“QCD相图和临界点专刊”(2023)



核技术


第 46 卷 第 4 期 2023 年 4 月

目 次

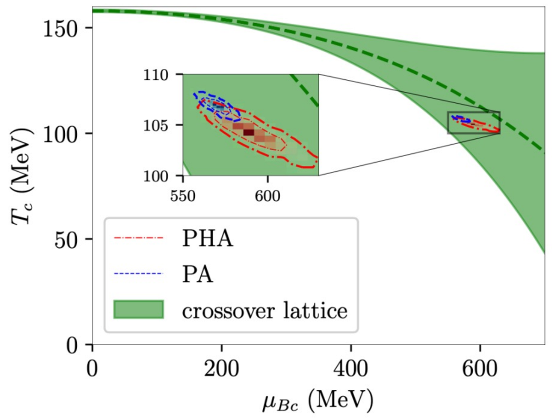
QCD 相图和临界点专刊

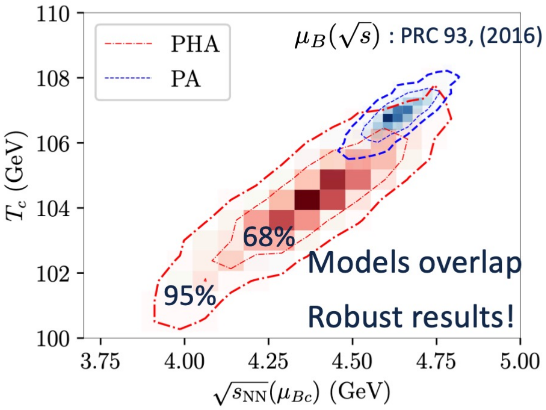
关键科学问题：高重子密度区是否存在一级相变边界和QCD相变临界点

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

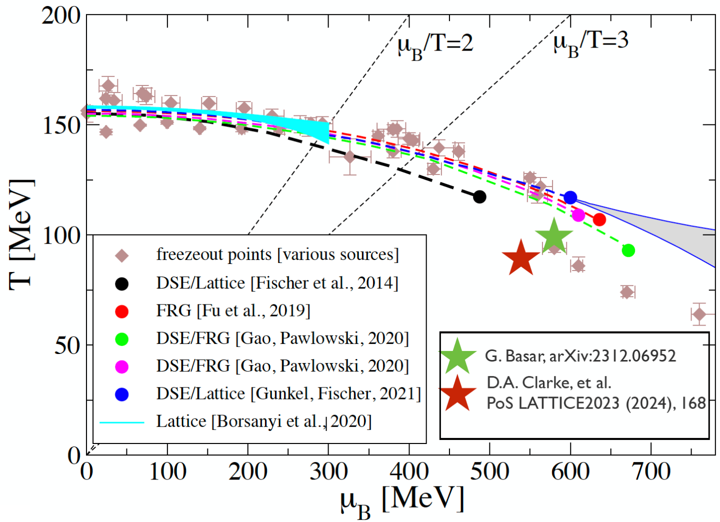
客座编辑：陈列文、黄梅、刘玉鑫、罗晓峰、马余刚

QCD相变临界点的位置：理论和模型计算





Holography+ Bayesian : Hippert et al., arXiv : 2309.00579

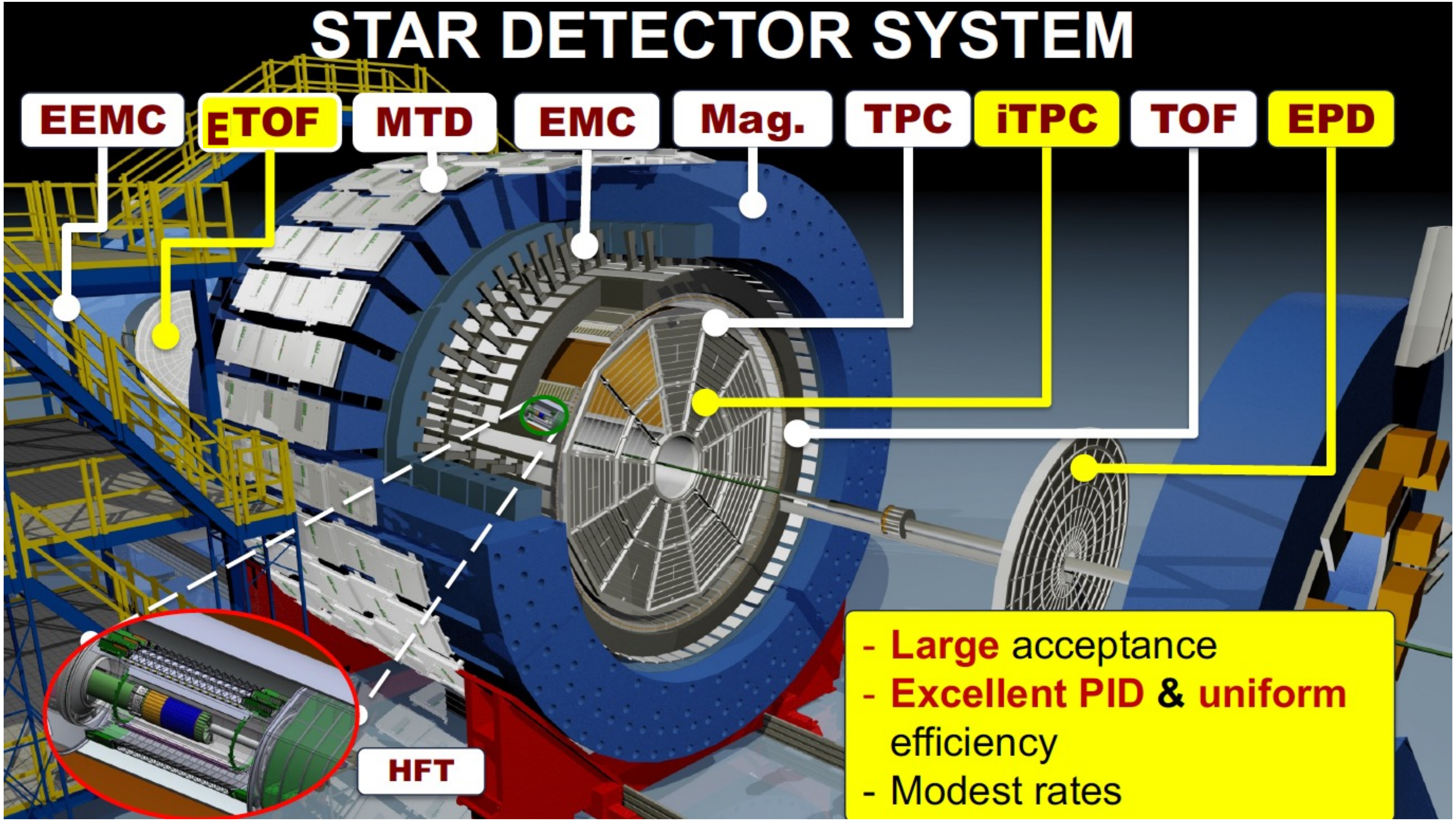


CPOD2024

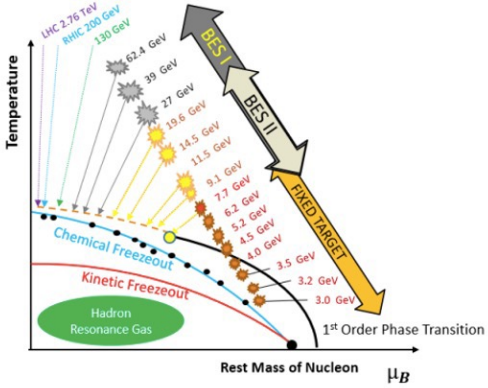
Method	μ_c (MeV)	T_c (MeV)
Holography + Bayesian	560 - 625	101 - 108
FRG/DSE	495 - 654	108 - 119
Lee-Yang edge singularities	500 - 600	100 - 105
Lattice QCD	$\mu_c/T_c > 3$	-
Summary	**495 - 654**	**100 - 119**

(μ_c, T_c) = (495 - 654, 100 - 119) MeV → $3.5 < \sqrt{s_{NN}} < 4.9$ GeV

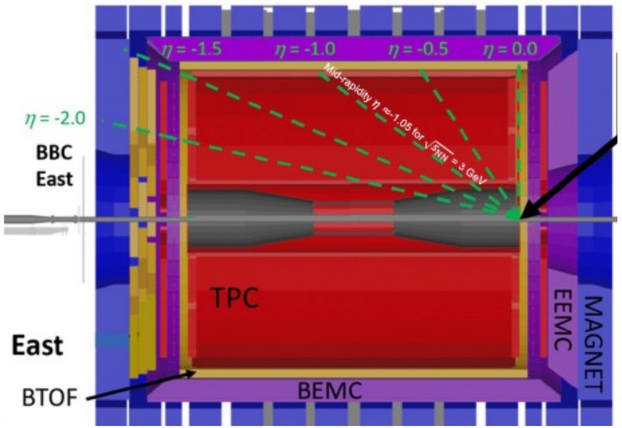
STAR探测器

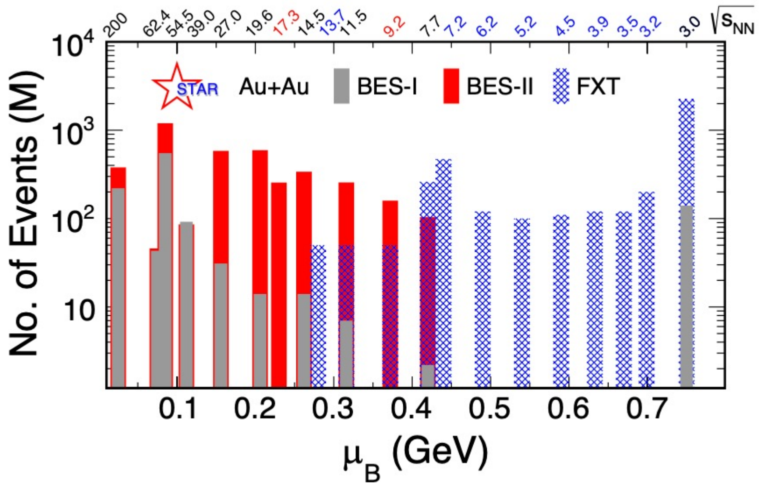

STAR DETECTOR SYSTEM
EEMC
ETOF
MTD
EMC
Mag.
TPC
iTPC
TOF
EPD
HFT
- Large acceptance
- Excellent PID & uniform efficiency
- Modest rates

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



STAR Fixed Target Mode



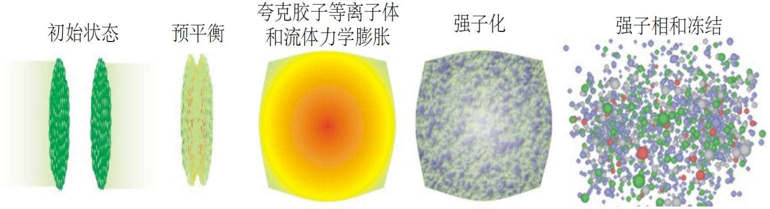


- x10-20 more statistics in BES-II compared to BES-I at collider energies
- BES-II: Collider energies (7.7 – 27 GeV), FXT energies (3.0 - 13.7 GeV)
- μ_B coverage : $25 < \mu_B < 750$ MeV

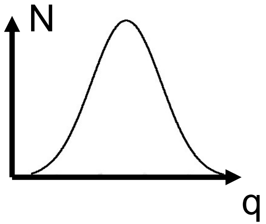
STAR, arXiv:1007.2613
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0493
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

临界点的灵敏观测量：守恒荷分布的高阶矩

临界点:关联长度(ξ)、系统感应率 (χ)发散 ⟷ **守恒荷涨落(系统关联长度的响应)**



逐事件守恒荷分布 ⟶



高阶矩：
方差(二阶，σ^2)、
偏度 (三阶，S)、
峰度 (四阶，κ)

守恒荷：净重子 (B)、净电荷 (Q)、净奇异数 (S)

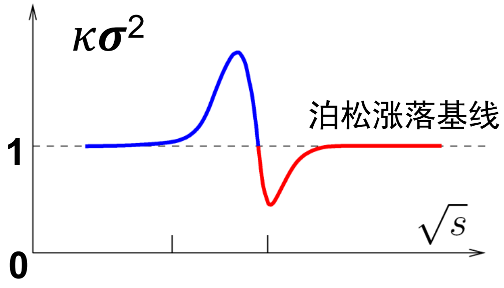
实验观测量

$$\kappa\sigma^2 = \frac{\chi^{(4)}}{\chi^{(2)}} \propto \xi^5$$

1. 与系统感应率 (χ) 相关
2. 与关联长度 (ξ) 敏感

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

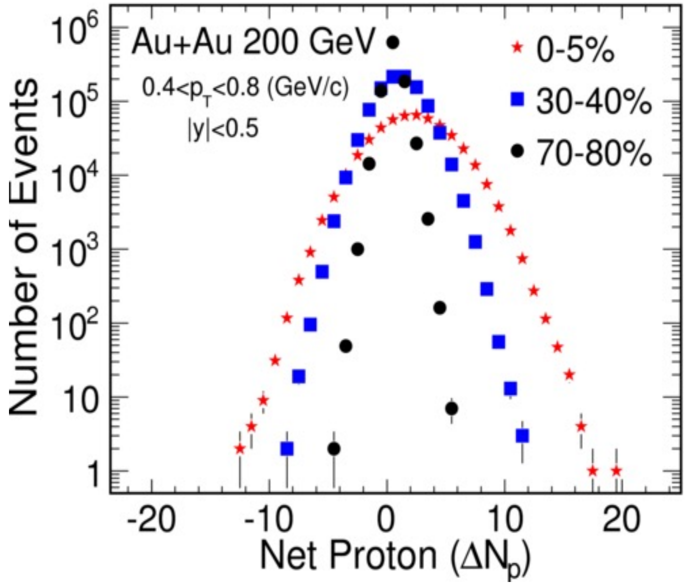
理论预言的QCD临界点信号

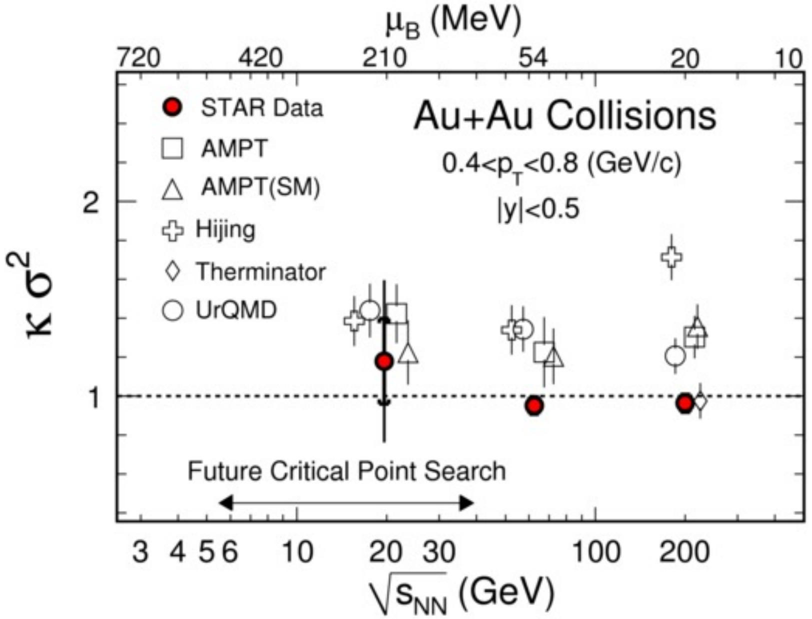


碰撞能量

M.A. Stephanov,
Phys. Rev. Lett. 102, 032301 (2009)
Phys. Rev. Lett. 107, 052301 (2011)

净质子数分布高阶矩的首次测量





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

First measurement

Verified the feasibility of the high moments observable in heavy-ion experiment.

建立和完善数据分析方法、研究非临界效应

建立和完善数据分析方法：

统计误差计算、去除自关联、压低体积涨落、探测效率修正等

a) 运用统计中的Delta定理，推导出高阶矩统计误差解析公式并将其应用到实验数据，精确计算出观测量统计误差

J. Phys. G:39, 025008 (2012)

b) 提出中心度宽度修正, 压低体积涨落及消除自关联背景影响

J. Phys. G:40, 105104 (2013)

c) 发展逐粒子探测效率修正方法, 使效率修正更加简化和精确

Phys. Rev. C 91, 034907(2015)

Phys. Rev. C 99, 044917(2019)

Chin. Phys. C45, 104001 (2021)

d) 发展出修正高阶矩测量中的事件堆叠效应方法

Nucl. Instrum. Meth. A1026, 166246 (2022)

研究非临界效应：

为寻找QCD临界点提供非临界参考基线

a) 研究核平均场以及重子数守恒效应对净质子数涨落的影

Phys. Lett. B 762, 296(2016)

Phys. Lett. B 774, 623(2017)

b) 运用输运模型研究净奇异数和净电荷涨落能量依赖

Phys. Rev. C 94, 024901(2016)

Phys. Rev. C 95, 014914(2017)

Phys. Rev. C 96, 014909(2017)

c) 研究共振态衰变、强子散射以及体积涨落对净质子数涨落的影响

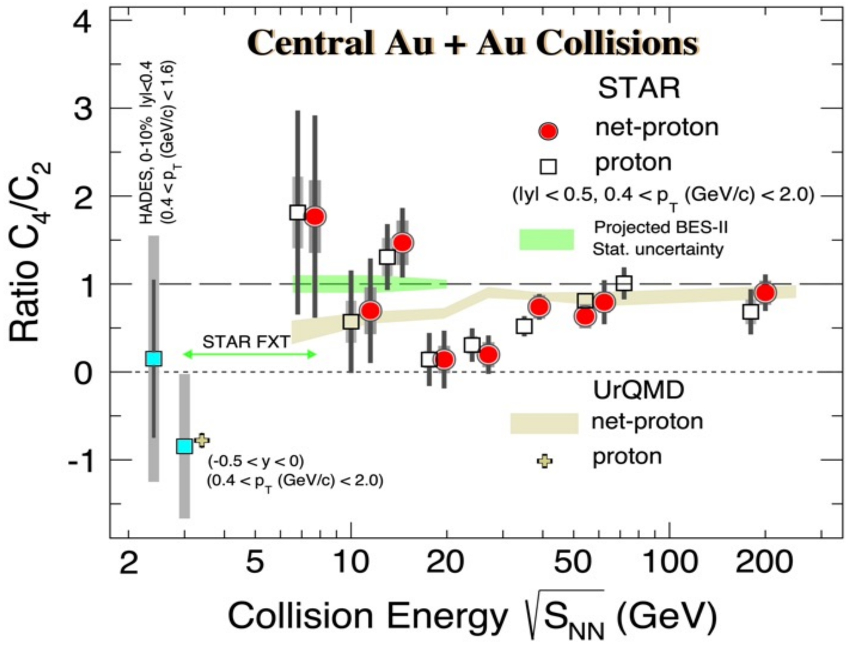
Phys. Rev. C101, 034902 (2020)

Phys. Rev. C101, 034909 (2020)

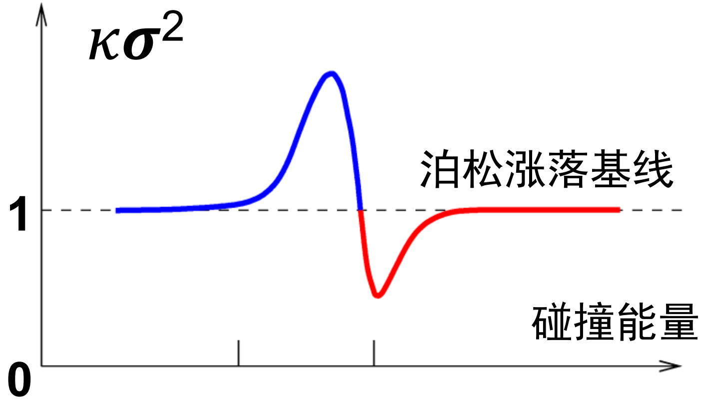
Chin. Phys. C45, 064003 (2021)

综述：XFL, N. Xu, Nucl. Sci. Tech. 28,112 (2017)

净质子数涨落的能量依赖：第一阶段能量扫描实验结果



理论预言: 临界点信号



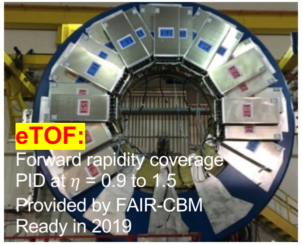
M.A. Stephanov,
Phys. Rev. Lett. 102, 032301 (2009)
Phys. Rev. Lett. 107, 052301 (2011)

1) 净质子数四阶涨落($\kappa\sigma^2$)的非单调能量依赖, 与理论预言临界点信号一致
2) 3 GeV为强子相互作用占主导，给出寻找QCD临界点的能量下限

7.7-200 GeV: STAR, Phys. Rev. Lett. 126, 092301 (2021) ; Phys. Rev. C 104, 024902 (2021)
3 GeV: STAR, Phys. Rev. Lett. 128, 202303 (2022) ; Phys. Rev. C 107, 024908 (2023)

净质子数涨落的能量依赖：STAR实验第二阶段能量扫描实验结果

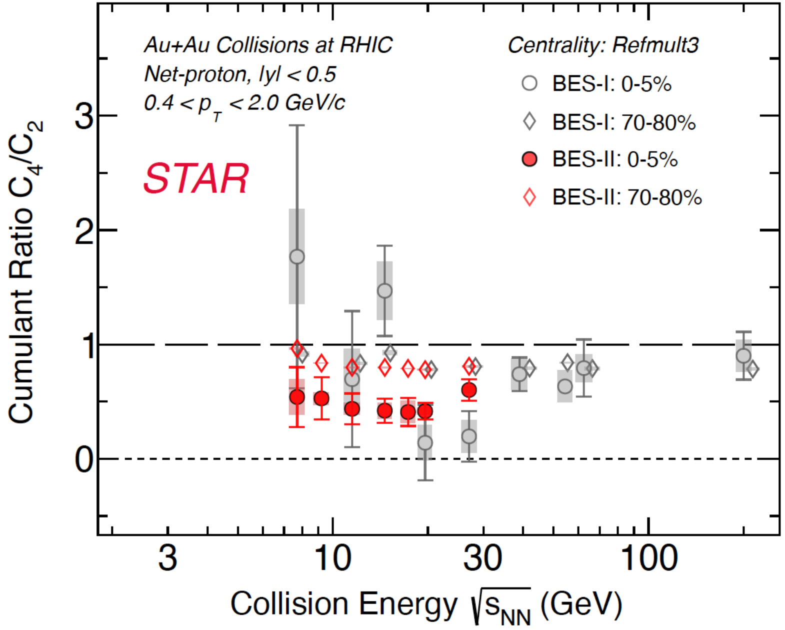
STAR Major Upgrades for BES-II



STAR BES Program:
Au+Au collisions

$\sqrt{s_{NN}}$ (GeV)	Events BES-I (10^6)	Events BES-II (10^6)
7.7	3	**45**
9.2	-	**78**
11.5	7	**110**
14.6	20	**178**
17.3	-	**116**
19.6	15	**270**
27	30	**220**

Precision Measurement on BES-II



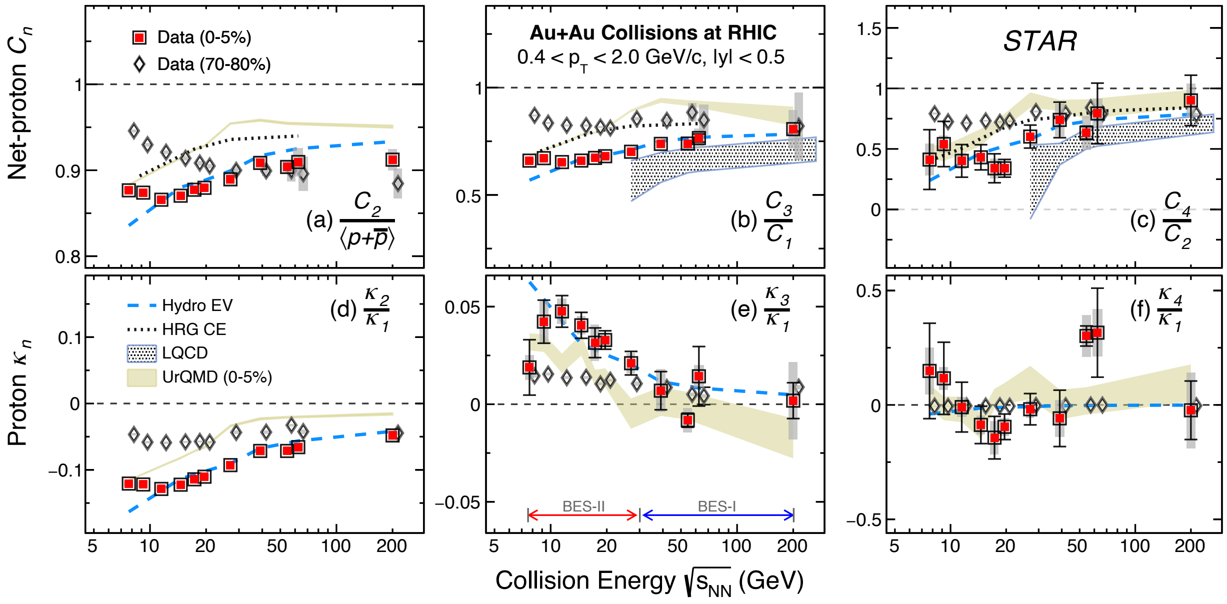
BES-II and BES-I results are consistent !

BES-II : Better statistical precision

Better control on systematics !

STAR : **CPOD2024, SQM2024**

Energy Dependence and Model Comparison



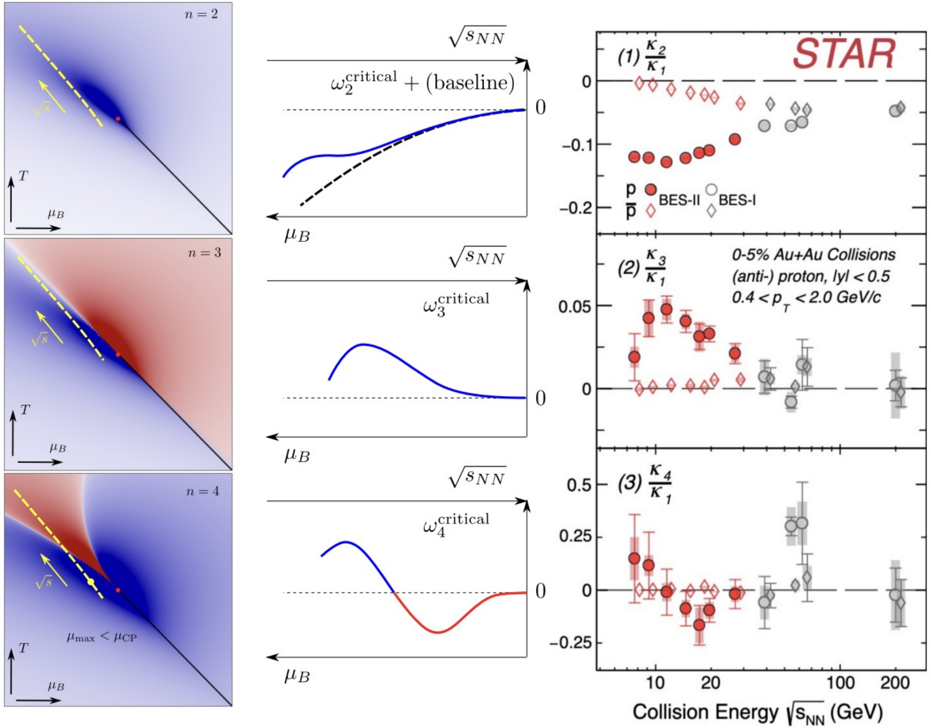
1) UrQMD: hadronic transport and the results are analyzed in the same way as data. S. Bass *et al.*, Prog. Part. Nucl. Phys., **41**, 255 (1998);

2) HRG CE: P.B. Munzinger *et al.* Nucl. Phys. **A1008**, 122141(2021);

3) Hydro: HRG CE + EV, V. Vovchenko *et al.*, Phys. Rev. **C105**, 014904 (2022).

4) LQCD: done for net-baryon A. Bazavov *et al.*, Phys. Rev. D101, 074502 (2020). arXiv : 2407.09335

1. Baryon conservation in all model calculations
2. All proton factorial cumulant ratios show clear non-monotonic dependence
3. Lattice QCD describe the data up to 27 GeV.
4. Precise dynamical modelling is needed to fully understand the data.



QCD critical point: recent developments

Mikhail Stephanov[1,2,*]

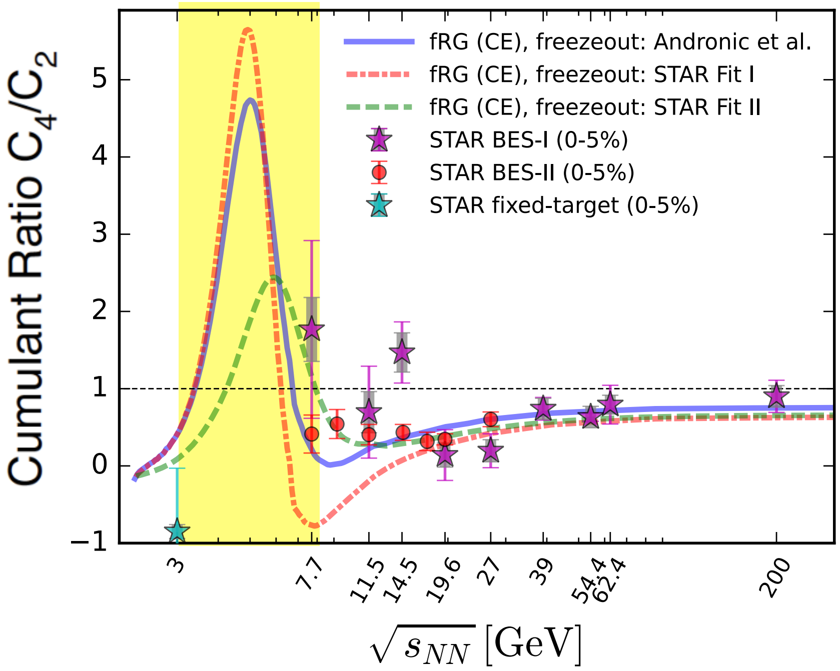
[1]Department of Physics, University of Illinois, Chicago, Illinois 60607, USA
[2]Kadanoff Center for Theoretical Physics, University of Chicago, Chicago, Illinois 60637, USA

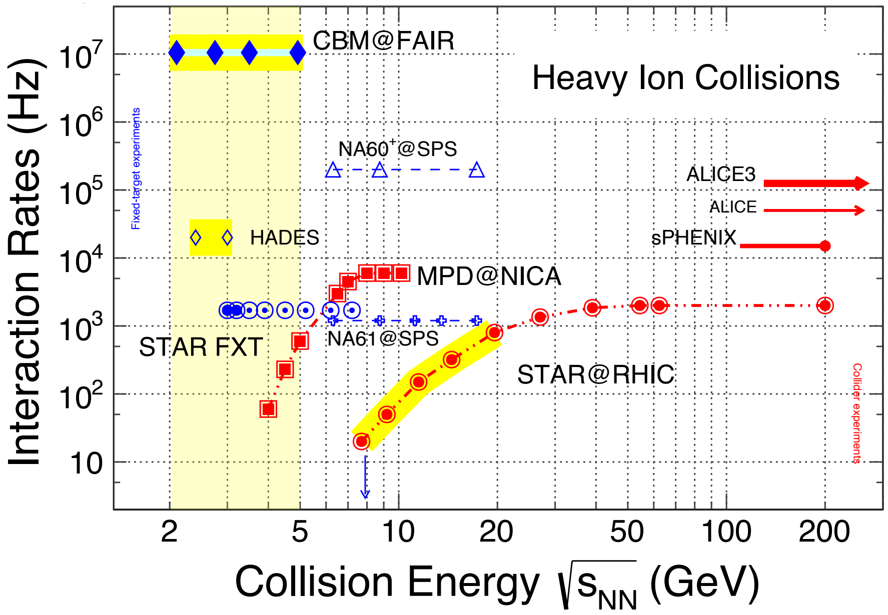
"The release of the BES-II data by STAR represents a major step towards uncovering the structure of the QCD phase diagram. It is remarkable that the non-monotonic features of the data are in qualitative agreement with the expectations from equilibrium thermodynamics near the QCD critical point, if one assumes such a point is located at μB ≳ 420 MeV. Such a location of the critical point would be consistent with recent estimates from various theoretical approaches…. "

arXiv : 2410.02861

Continue the Critical Point Search

FRG计算：付伟杰, et al., arXiv : 2308.15508





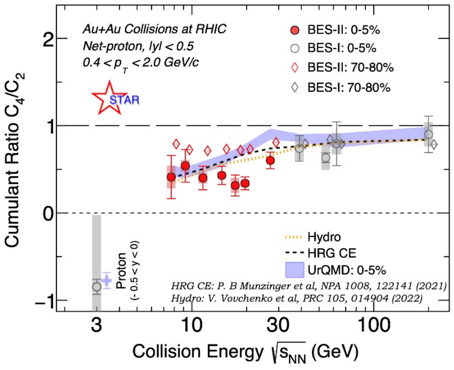
- Experimental Results between 3 – 4.5 GeV (STAR FXT)
- Precise dynamical modeling and non-CP baselines

Future High Baryon Density Experiment :

- FAIR/CBM (2.4 - 4.9 GeV)
- HIAF/CEE (2.1– 4.5 GeV)
- NICA/MPD (4 - 11 GeV)

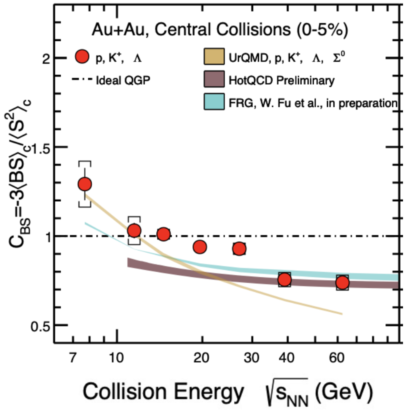
Summary and Outlook

Net-Proton Fluctuations



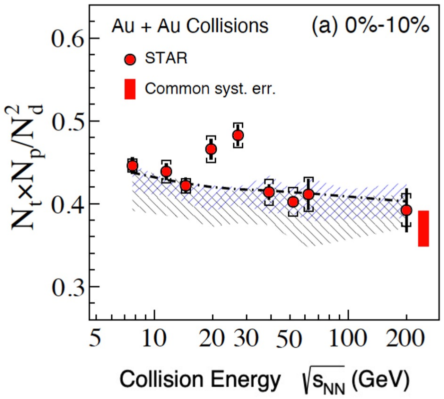
STAR, CPOD2024, SQM2024

BS correlations



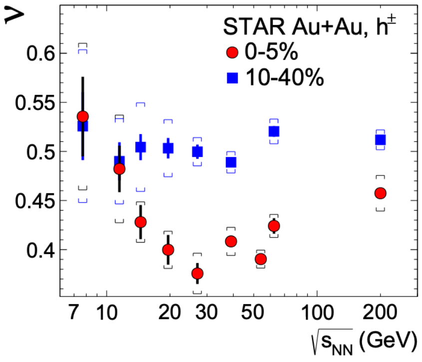
STAR, CPOD2024

Yield Ratio of Light Nuclei

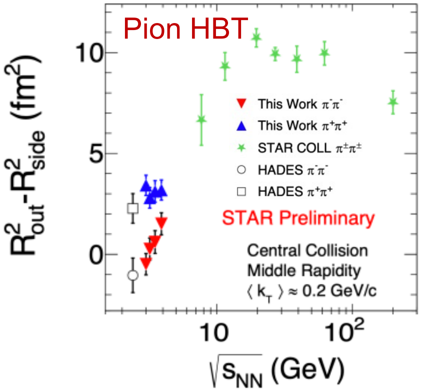


STAR: PRL130, 202301 (2023)

Intermittency



STAR, PLB 845, 138165 (2023)

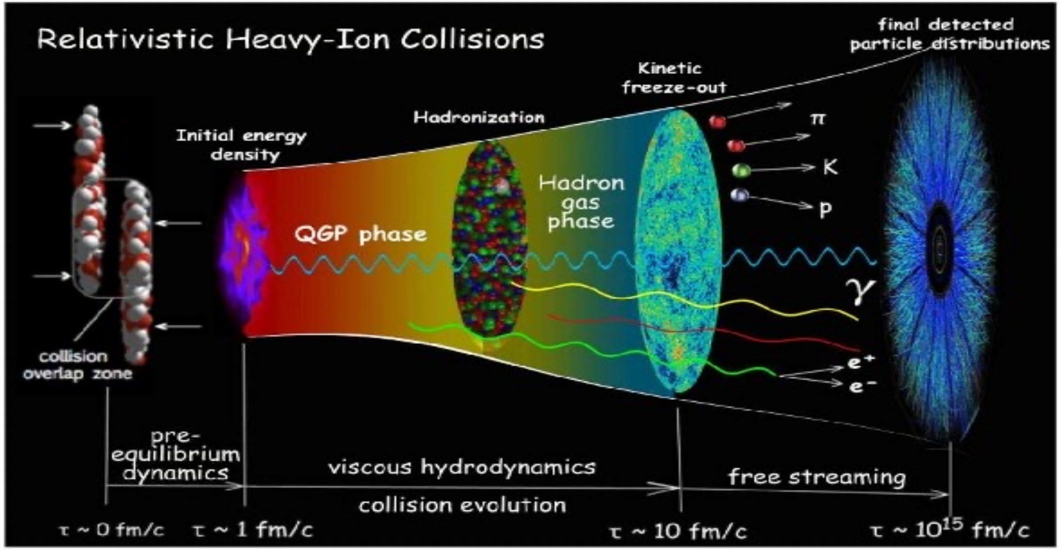


BES-II : high statistics, better acceptance and systematics

1. *Understand the reason lead to the peaks or dips around 20 GeV*
2. *Continue to search for QCD critical point between 3 – 20 GeV*
3. *Need reliable dynamical modeling and non-CP baselines*

Summary and Outlook

Rich physics at high baryon density : QCD phase structure, EoS etc.



Future High Baryon Density Experiment :

- FAIR/CBM (2.4 - 4.9 GeV)
- HIAF/CEE (2.1– 4.5 GeV)
- NICA/MPD (4 - 11 GeV)

1) 研究夸克胶子等离子体性质及其相结构

2) 强子物理：*Baryon-Baryon Interactions -> Understand YN, YY interaction and EoS at high baryon Density*

International Workshop on Physics at High Baryon Density (PHD2024)

https://indico.ihep.ac.cn/event/22462/ Nov. 1-4, 2024@CCNU

International Workshop on Physics at High Baryon Density (PHD2024, 第一届高重子密度物理国际研讨会)

Nov 1 – 4, 2024
Asia/Shanghai timezone

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- Confirmed Speaker
- Local Organizing Committee

袁强、马亚
yuanqiang@mail.ccnu.e…
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第一届高重子密度物理国际研讨会

高能核核碰撞中产生的高重子密度物质蕴含着丰富的物理，对研究强相互作用相结构、宇宙和致密星体演化以及理解极端条件下核物质性质具有重要意义。随着未来国内外重离子大科学装置（德国FAIR/CBM、中国HIAF/CEE、俄罗斯NICA/MPD）的相继建成，高重子密度物理领域正成为国际物理研究的前沿热点。在这一背景下，系统分析和总结已有研究进展并规划未来发展路线，培养和储备高重子密度物理研究的人才队伍, 集聚国内外顶尖科学家的智慧显得尤为必要和重要。因此，我们决定发起"高重子密度物理研讨会"系列会议 (计划每年举办一次，以研讨会搭配更聚焦的小型专题讨论会形式)，旨在为国内外科研人员搭建起高水平的学术交流平台，共同探讨高重子密度区物理的挑战和机遇。同时我们将与国内外核物理理论中心紧密合作，为推动我国高重子密度物理相关研究走向国际前沿打下坚实基础。

第一届高重子密度物理研讨会于2024年11月1日-4日在华中师范大学召开，1号报到，2-4号会议。会议不收取注册费，会议报告为邀请报告。

The high baryon density matter produced in high-energy nuclear-nuclear collisions harbors rich physics, which is of great importance for exploring the phase structure of strong interactions, the evolution of the universe and compact stars, and understanding the properties of nuclear matter under extreme conditions. With the upcoming completion of major heavy-ion facilities around the world (FAIR/CBM in Germany, HIAF/CEE in China, NICA/MPD in Russia), the field of high baryon density physics is becoming a frontier hotspot in international physics research. Against this background, it is particularly necessary and important to systematically analyze and summarize existing research progress, plan future development paths, cultivate and reserve talent teams for high baryon density physics research, and gather the wisdom of top scientists. Therefore, we have decided to launch a series of "Workshop on Physics at High Baryon Density" (planned to be held annually, in the form of seminars combined with more focused small-scale topical discussions), aiming to build a high-level academic exchange platform for researchers worldwide to jointly explore the challenges and opportunities of high baryon density physics. At the same time, we will work closely with domestic and international nuclear physics theory centers to lay a solid foundation for high baryon density physics research.

The first workshop on physics at high baryon density will be held at Central China Normal University from Nov. 1 to 4, 2024, with registration on the Nov. 1st and the meeting time from the Nov. 2nd to the 4th. No registration fee will be charged. The talks are by invitation only.

Physics Topics :

1) QCD Phase Structure at High Baryon Density
2) Nuclear Matter at High Density and Equation of State
3) Dynamical Evolution of Heavy-ion Collisions
4) Nuclear Matter Under Extreme External Fields
5) Hadron Properties in Nuclear Medium
6) Nuclear Physics in Compact Stars

Local Organizing Committee:

Hengtong Ding (Central China Normal University)
Weijie Fu (Dalian University of Technology)
Sophia Han (T.D. Lee Institute, Shanghai Jiao Tong University)
Xiaofeng Luo (Central China Normal University, co-Chair)
Guoliang Ma (Fudan University)
Zebo Tang (University of Science and Technology of China)
Chi Yang (Shandong University)
Pengfei Zhuang (Tsinghua University, co-Chair)
Yapeng Zhang (Institute of Modern Physics, CAS)

谢谢大家！