原子核结构与相对论重离子碰撞前沿交叉研讨会, 大连, Aug. 1-5, 2023

强相互作用物质相图实验研究进展

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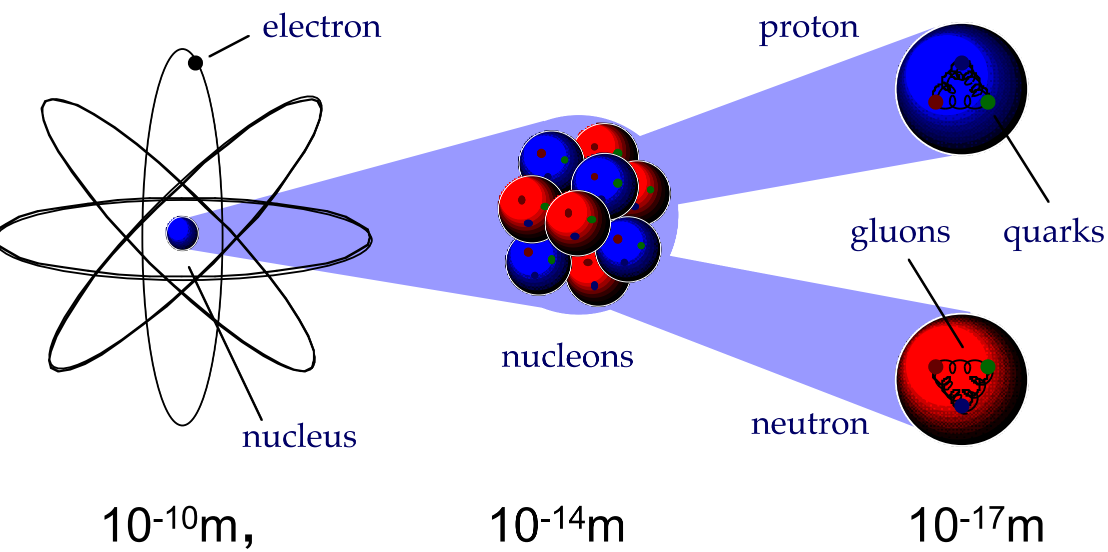
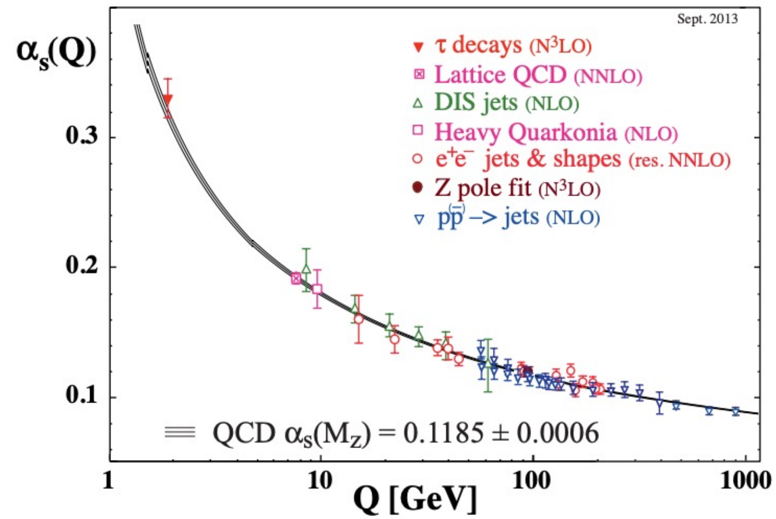
华中师范大学

2023年8月2日

强相互作用力与夸克禁闭

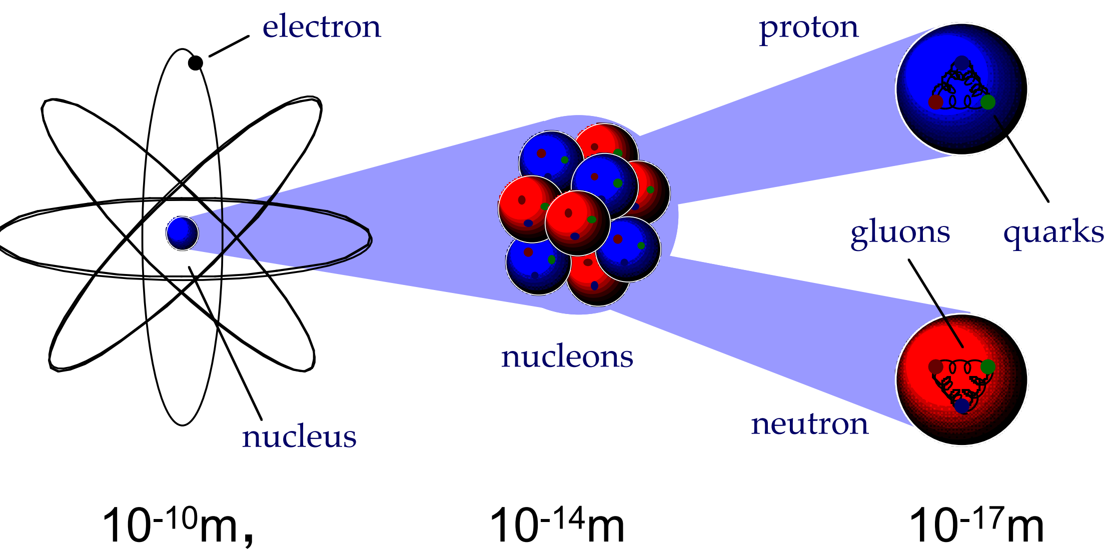


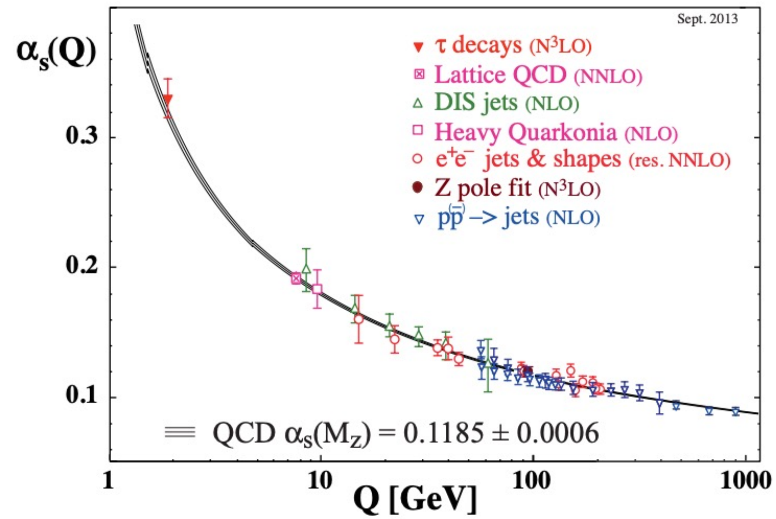


- 夸克禁闭：夸克是组成物质的基本单元，自然界没有发现自由的夸克。
- 量子色动力学是描述强相互作用力的成功理论 ：渐进自由

能否使夸克从核子中解禁闭，形成一种由夸克、胶子自由度组成的新物态， 夸克胶子等离子体（Quark-Gluon Plasma）？

强相互作用力与夸克禁闭





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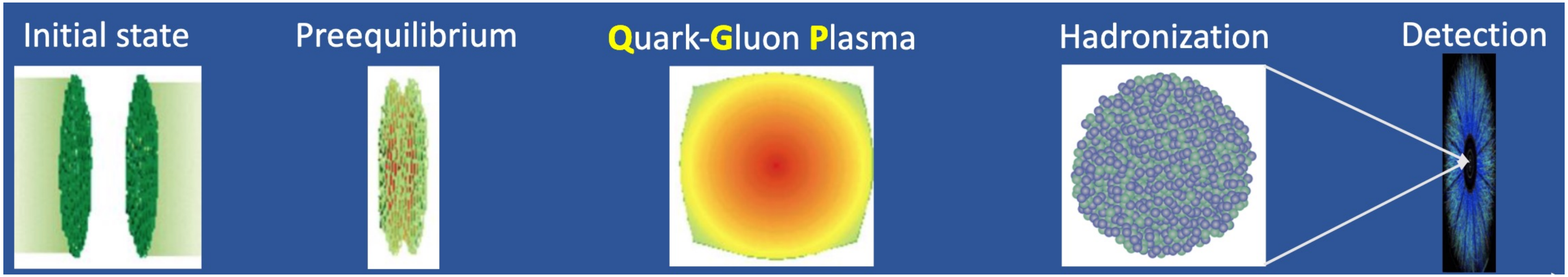
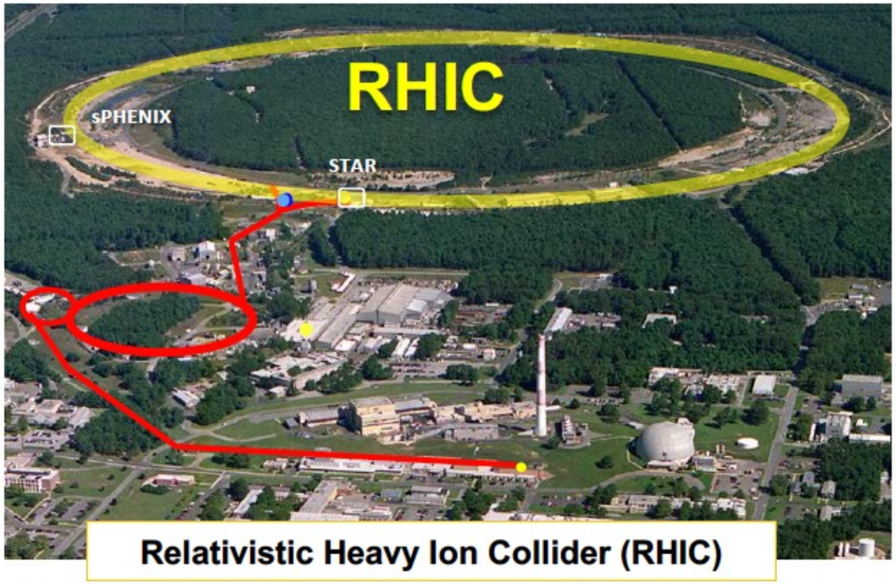
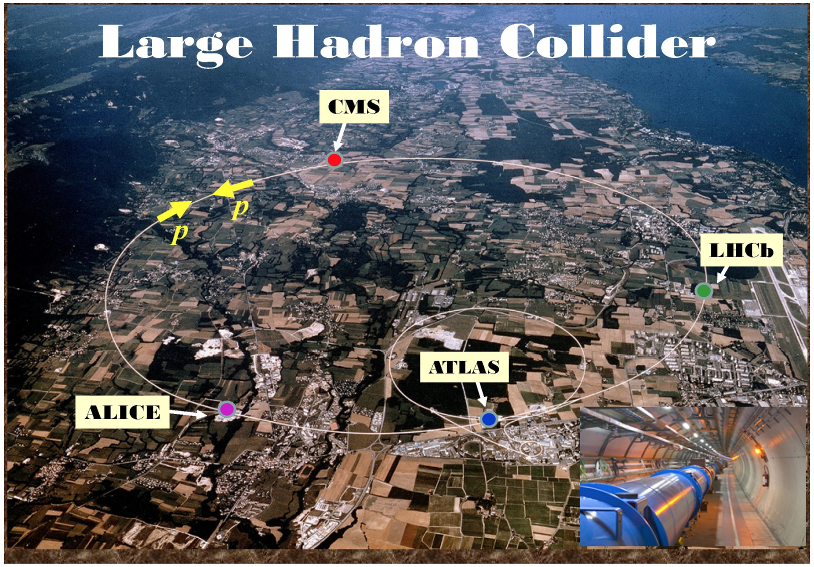
研究夸克层次的凝聚态物理（QCD涌现性质）
1）QGP性质， 2）QCD相结构

相对论重离子碰撞：加热到万亿度(10^{12} ℃)



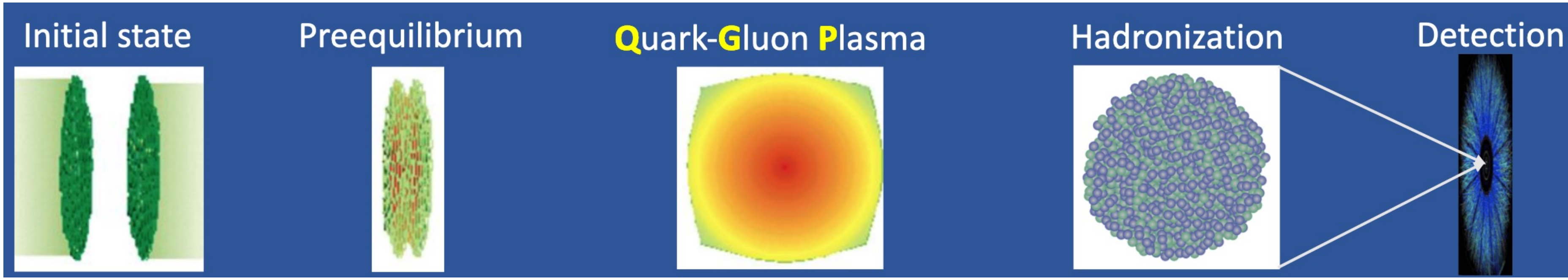
人类目前为止制造的最高温度：约为太阳中心温度的10万倍。





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。

相对论重离子碰撞：加热到万亿度(10^{12} ℃)



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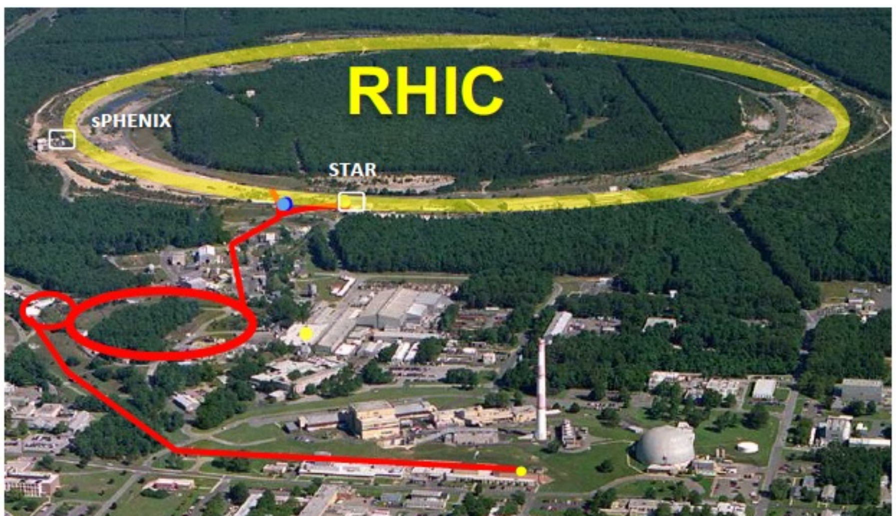

Relativistic Heavy Ion Collider (RHIC)

RHIC top collision energies:
- $\sqrt{s_{NN}}$ = 200 GeV U+U / Au+Au / Zr+Zr / Ru+Ru / O+O
- $\sqrt{s}$ = 510 GeV p+p

RHIC Beam Energy Scan (BES):
- $\sqrt{s_{NN}}$ = 200 – 7.7 GeV (collider mode)
- $\sqrt{s_{NN}}$ = 17.3 – 3 GeV (fixed-target mode)

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。

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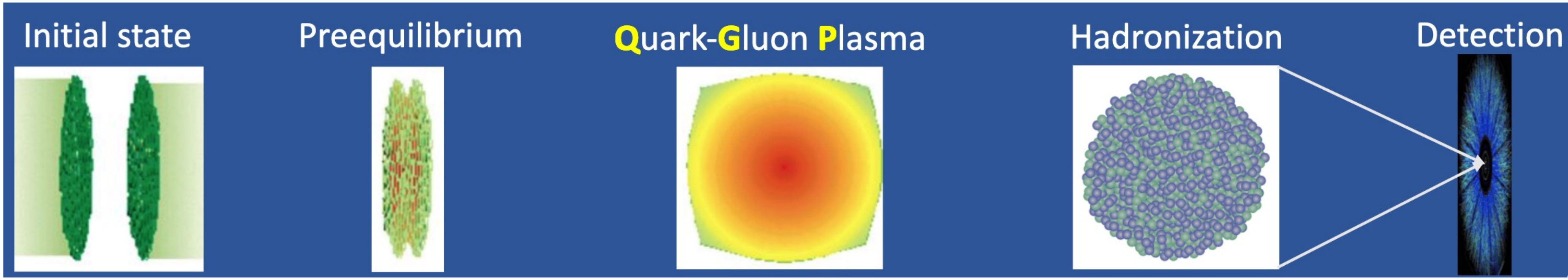
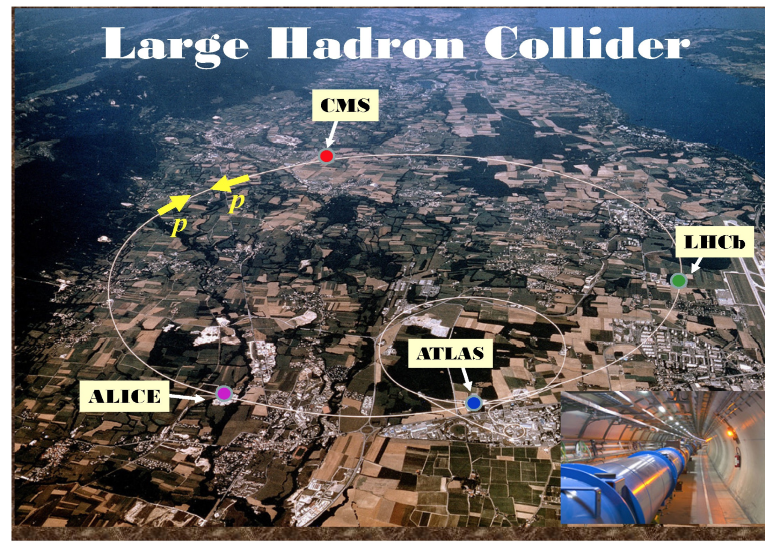


人类目前为止制造的最高温度：约为太阳中心温度的10万倍。

LHC collision energies:

- $\sqrt{s_{NN}}$ = 0.9, 2.76, 5.02, 5.44 TeV
  Xe+Xe, Pb+Pb
- $\sqrt{s}$ = 0.9 – 13 TeV p+p
- $\mu_B \to 0$



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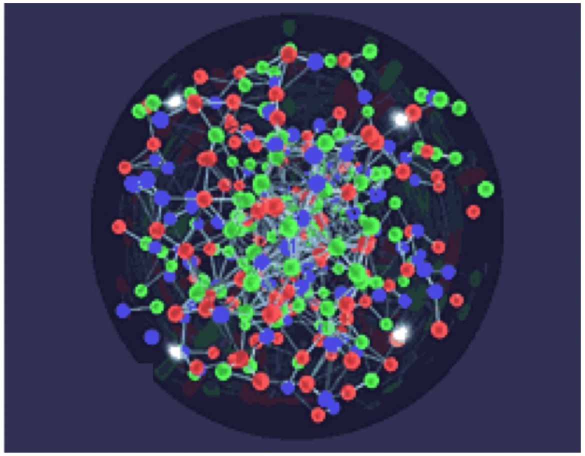
QGP新物态和相变

QGP:强耦合理想流体



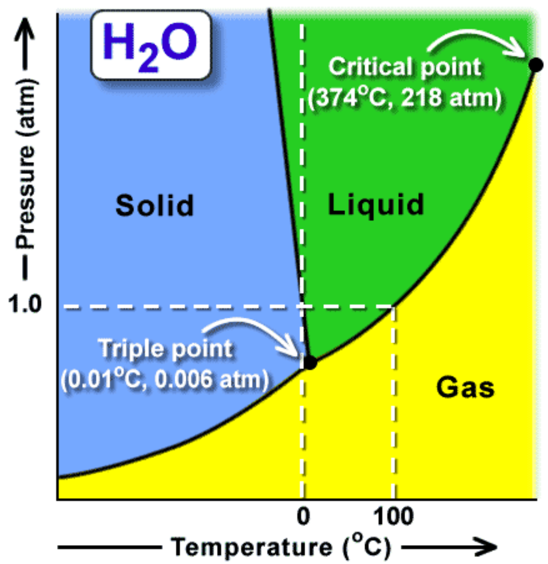
QGP的重要性质，如：

- ➢ 强耦合低粘滞
- ➢ 强涡旋
- ➢ 强电磁场

RHIC White Paper (2005) : nucl-ex/0501009
Hot QCD White Paper：2303.17254
ALICE: 2211.04384 (review)

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？

水的相图



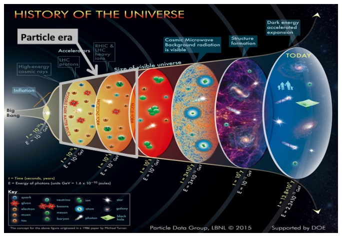
内因：相互作用、系统对称性
外因：外部条件的改变 (如温度、压强)

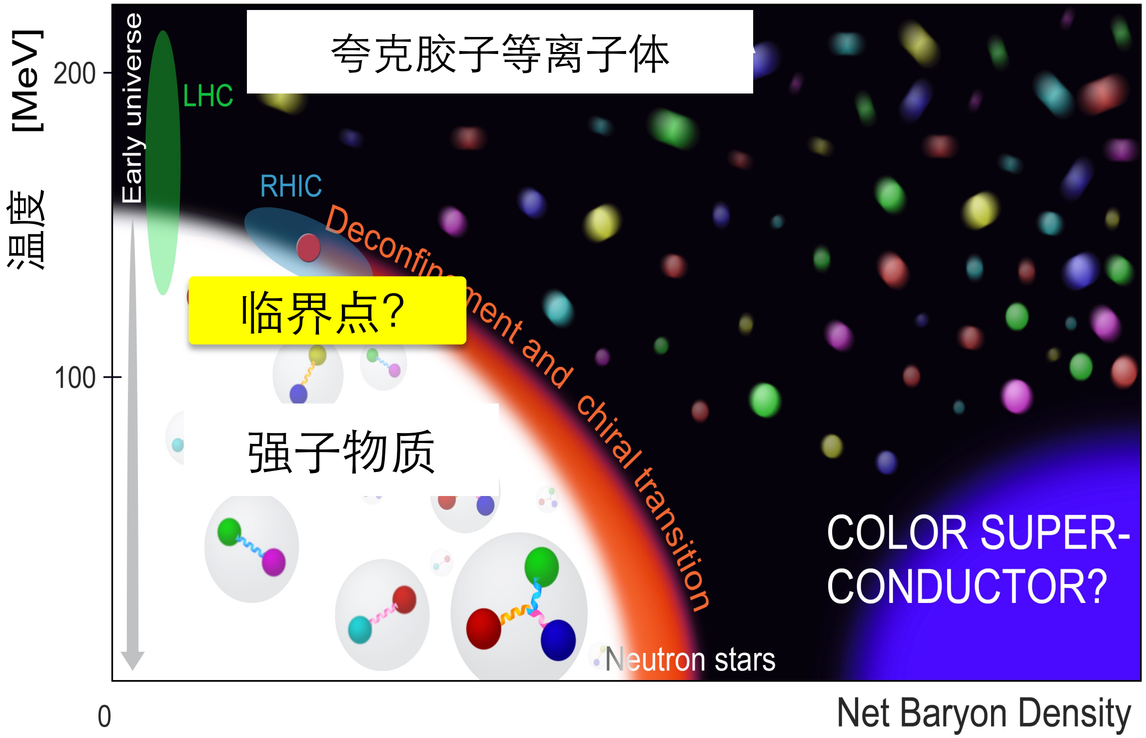
临界现象：

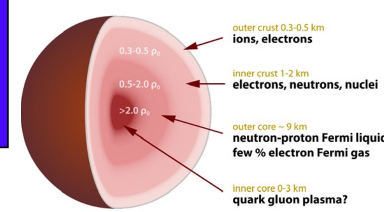
- ➢ **密度涨落增强与关联长度增大：**
  临界乳光现象
- ➢ **系统的对称性决定临界指数：即热力学量的临界发散行为**

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







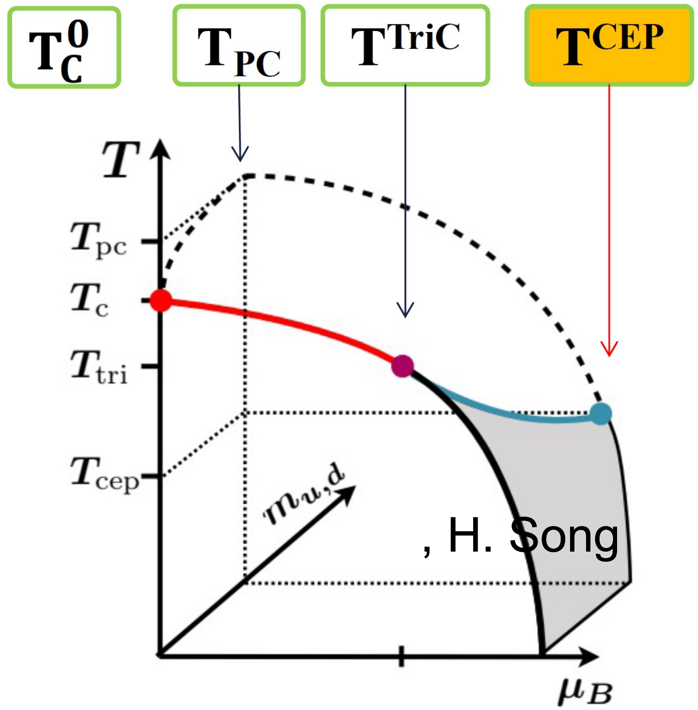
Smooth Crossover at μ_B=0.
Transition Temperature : T_c ~ 156 MeV

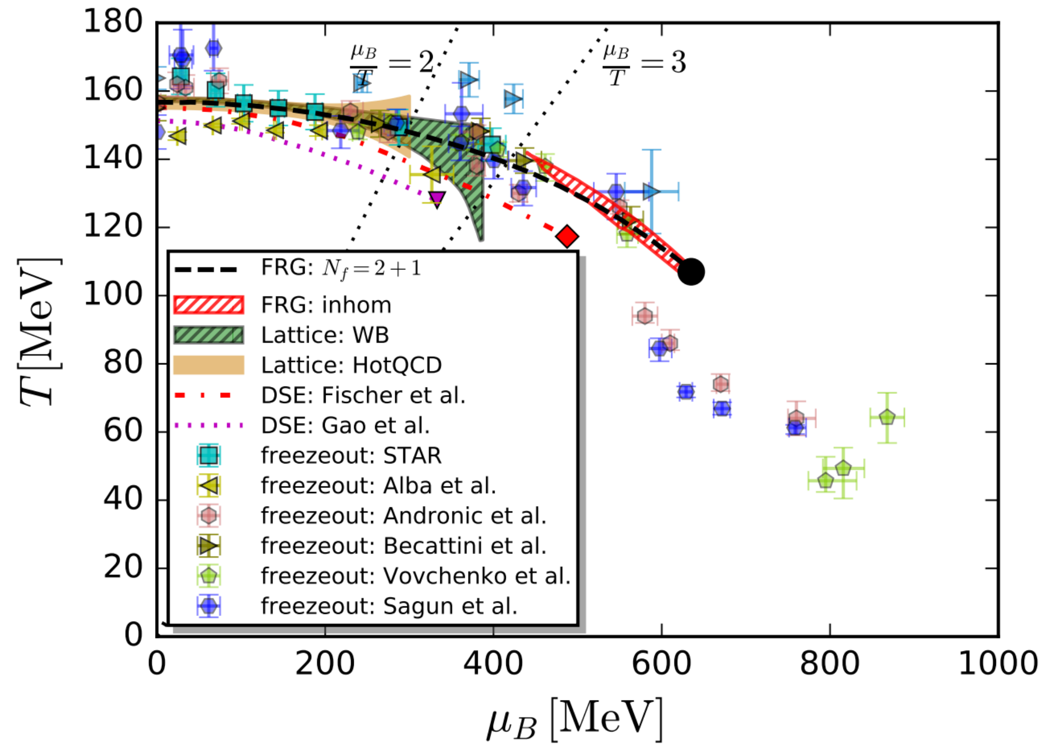
Y. Aoki, et al. Nature 443, 675 (2006).
A. Bazavov et al.(HotQCD)，Phys. Lett. B 795, 15 (2019)

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

QCD Phase Structure from Lattice QCD and DSE/FRG





Lattice QCD:

赝临界温度：T_{PC} = 156.5 +/- 1.5 MeV

手征相变温度：T_C = 132(+3)(-6) MeV

临界点位置：$\mu_B/T_c > 3$

F. Karsch et al. (HotQCD),
Phys. Lett. B 795, 15(2019)
Phys. Rev. Lett. 123, 062002(2019)

FRG：$(T_{\rm CEP}, \mu_{B\,{\rm CEP}}) = (107, 635)$ MeV.

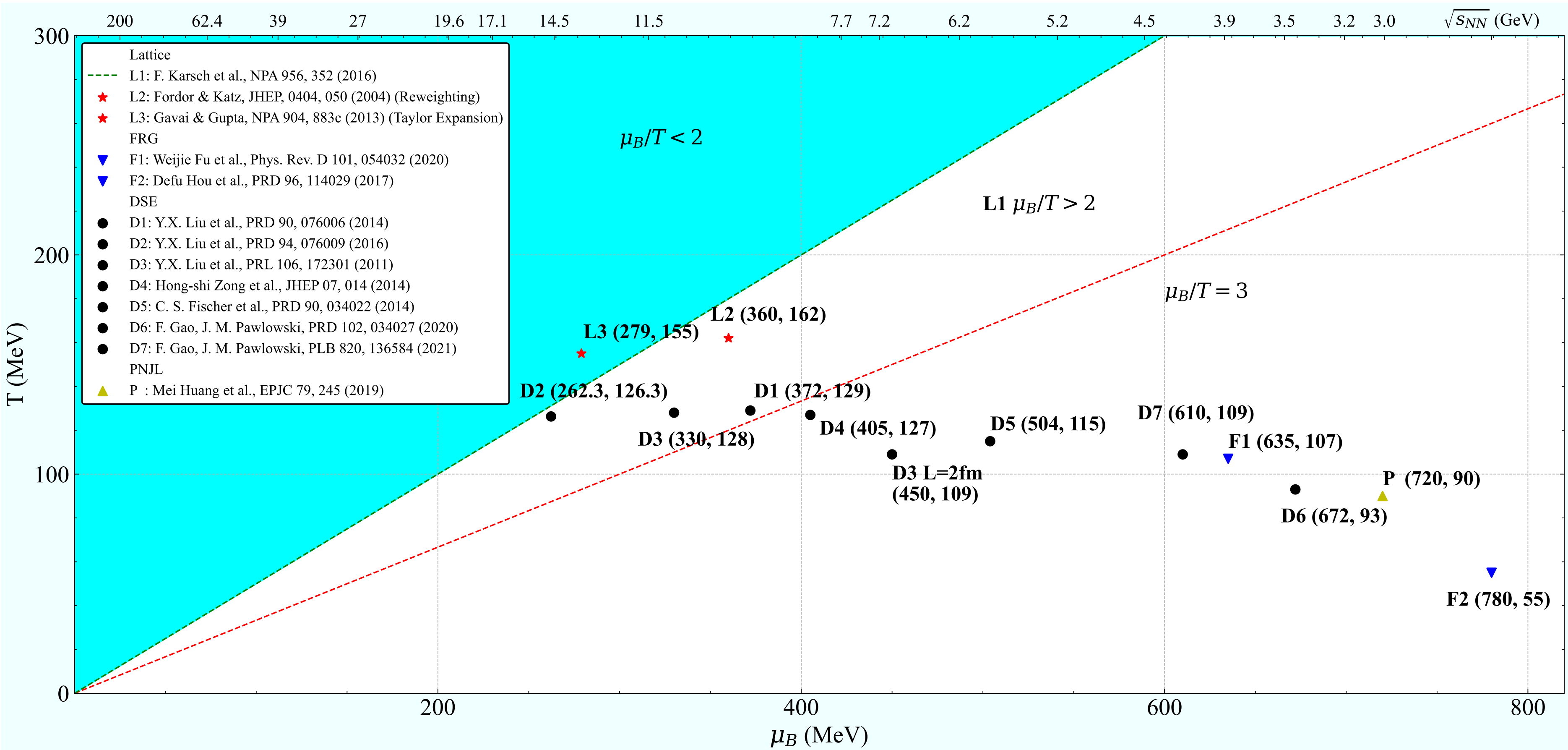
付伟杰, Jan M. Pawlowski, F. Rennecke,
PRD 101, 054032 (2020) [Citation: 191]

DSE：(109, 610) MeV [Citation: 55]

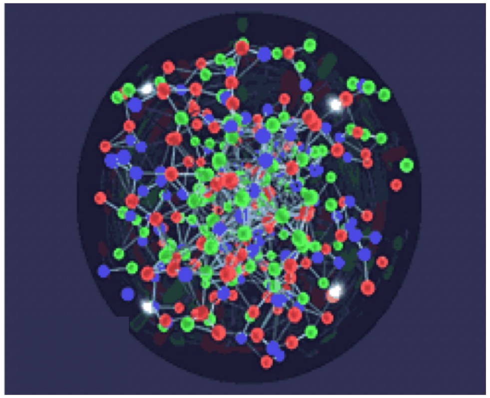
高飞, Jan M. Pawlowski, PLB 820, 136584 (2021)

QCD临界点位置：理论模型计算

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



关于探索QCD物质相图、寻找相变临界点的思考



理想情况：

一个容器中放入静态普通核物质，对其加热到万亿摄氏度，并观测相变现象

现实情况：

能够达到相变条件的可控实验只有相对论重离子碰撞

1. 选择灵敏观测量
2. 进行重离子碰撞能量扫描, 对观测量进行测量

-> 观测到QCD临界点信号？

用重离子碰撞去寻找临界点相变的一些限制和注意事项：

1) 需要确定碰撞过程中发生了QGP相变
2) 有限体积、时间和动力学非平衡演化效应
3) 末态强子散射等背景效应

理论家：怎么合理的引入状态方程并考虑以上效应，模拟真实重离子碰撞并将计算结果与实验结果进行比较？

Fluctuations of Conserved Quantities (B, Q, S)

守恒荷：净重子 (**B**)、净电荷 (**Q**)、净奇异数 (**S**)
矩与累积矩(C)：方差(二阶，σ^2)、偏度 (三阶，**S**)、峰度 (四阶，κ)

Measured multiplicity N, $\langle \delta N \rangle = \mathrm{N} - \langle N \rangle$

mean: $M = \langle N \rangle = C_1$

variance: $\sigma^2 = \langle (\delta N)^2 \rangle = C_2$

skewness: $S = \langle (\delta N)^3 \rangle / \sigma^3 = C_3 / C_2^{3/2}$

kurtosis: $\kappa = \langle (\delta N)^4 \rangle / \sigma^3 - 3 = C_4 / C_2^2$

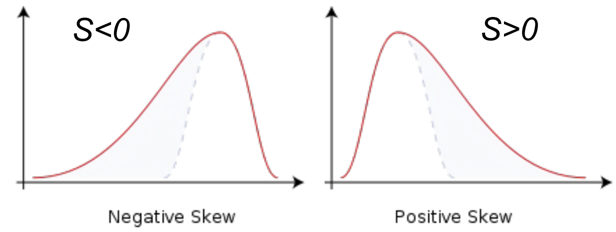
Moments, cumulants and susceptibilities:

2^{nd} order: $\sigma^2/M \equiv C_2/C_1 = \chi_2/\chi_1$

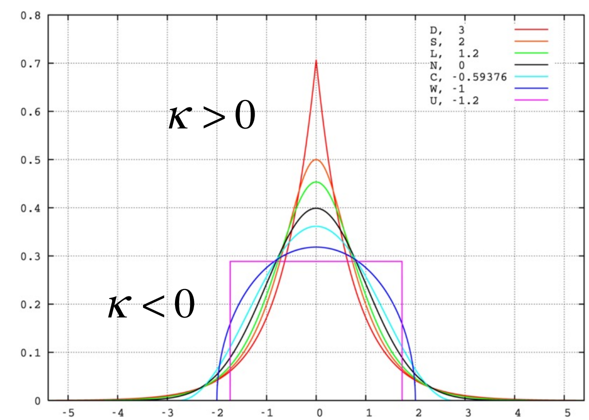
3^{rd} order: $S\sigma \equiv C_3/C_2 = \chi_3/\chi_2$

4^{th} order: $\kappa\sigma^2 \equiv C_4/C_2 = \chi_4/\chi_2$

Skewness (S) → asymmetry



Kurtosis (κ) → Sharpness



各阶累积矩(C_n/C_m)比值：

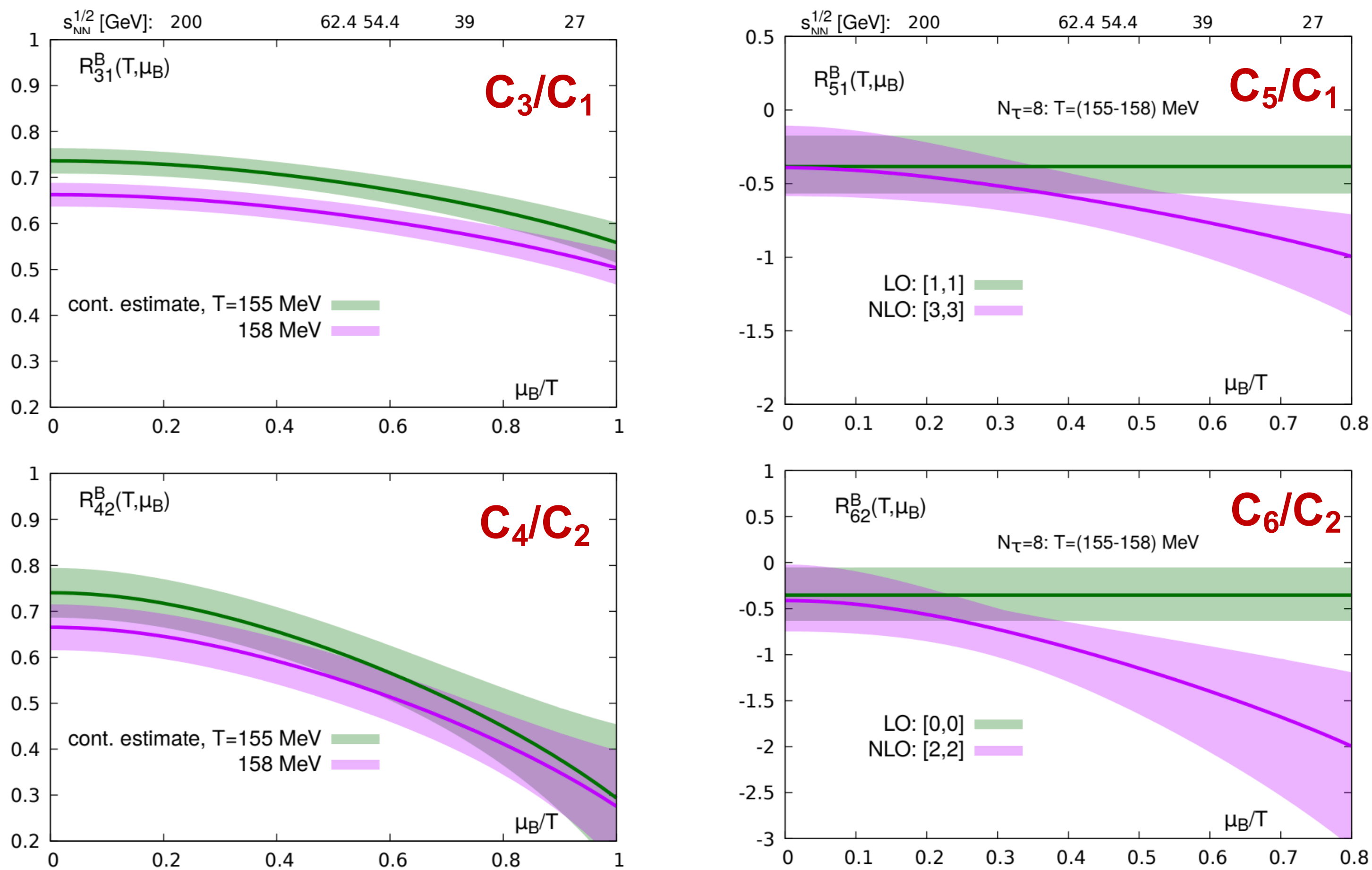
1. 对关联长度 (ξ) 敏感
2. 与系统感应率 (χ) 直接相关

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

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

Cheng et al, PRD (2009) 074505. F. Karsch and K. Redlich , PLB 695, 136 (2011). B. Friman et al., EPJC 71 (2011) 1694.
S. Gupta, X. Luo et al., Science, 332, 1525(2012). A. Bazavov et al., PRL109, 192302(12) // S. Borsanyi et al., PRL111, 062005(13)

格点QCD计算的重子数涨落



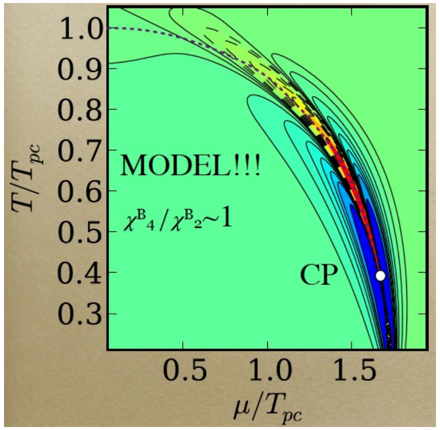
QCD相图平滑穿越区重子数涨落两个特征：1) 低阶到高阶显示出排序, 2) 五、六阶涨落出现负值

$$C_3/C_1 > C_4/C_2 > 0 > C_5/C_1 > C_6/C_2$$

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

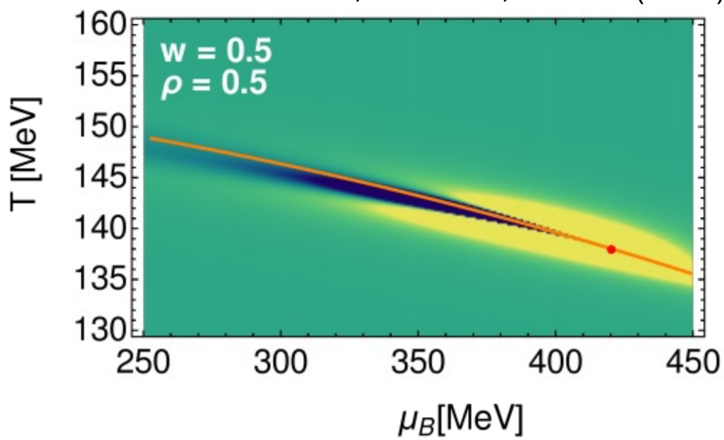
重子数的四阶涨落($\kappa\sigma^2$)：基于QCD的有效模型计算

PQM V. Skokov, QM2012



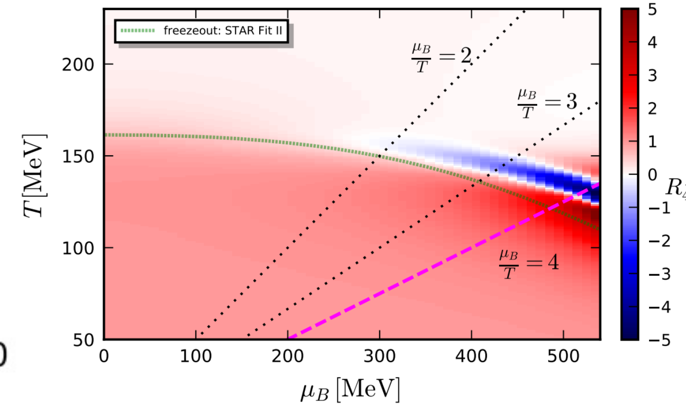
3D Ising Mapping

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

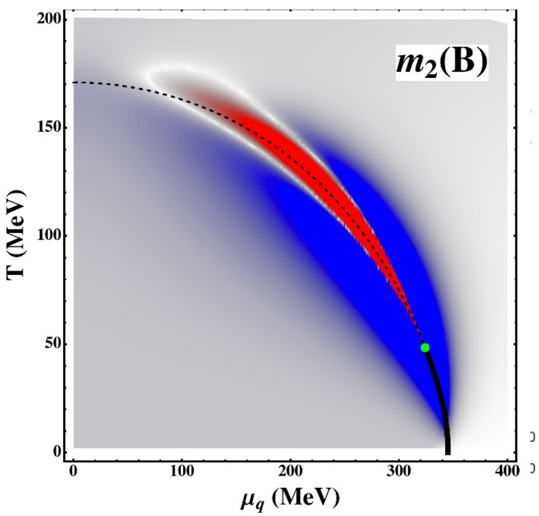


FRG

付伟杰等 PRD 104 (2021) 9, 094047

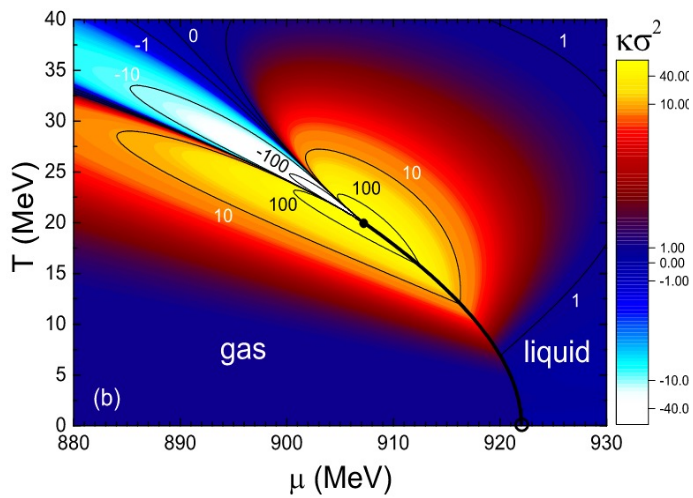


NJL



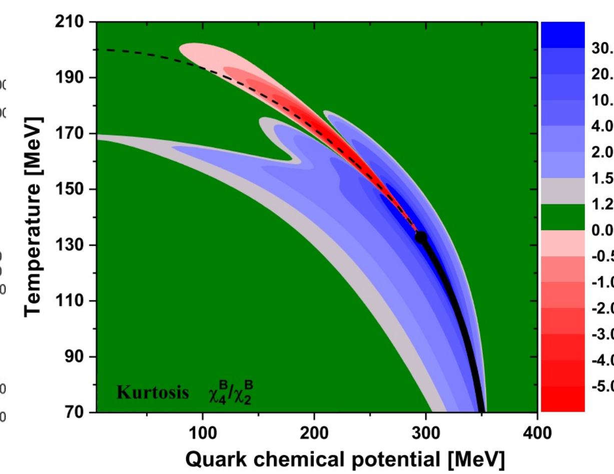
邓建等, PRD93, 034037 (2016)
范文凯等, CPC 43, 054109 (2019)

van der Waals (VDW)



Vovchenko et al., PRC92, 054901 (2015)

PNJL

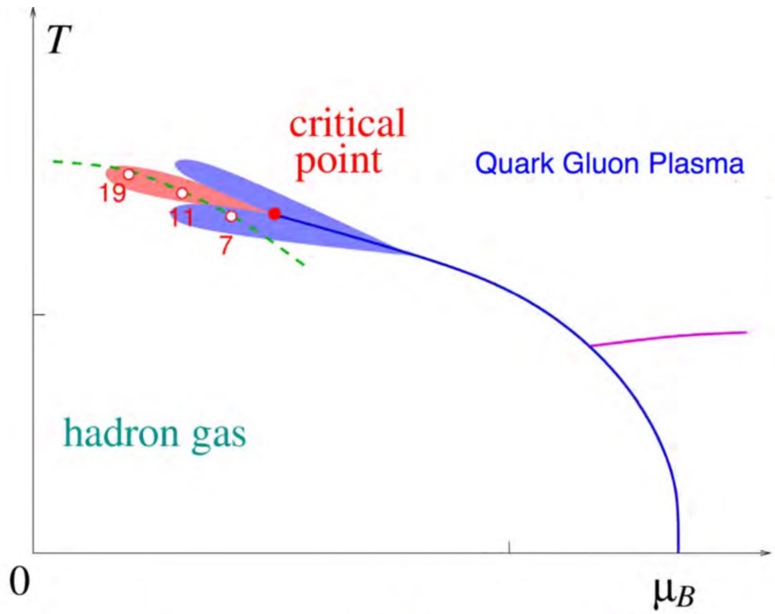


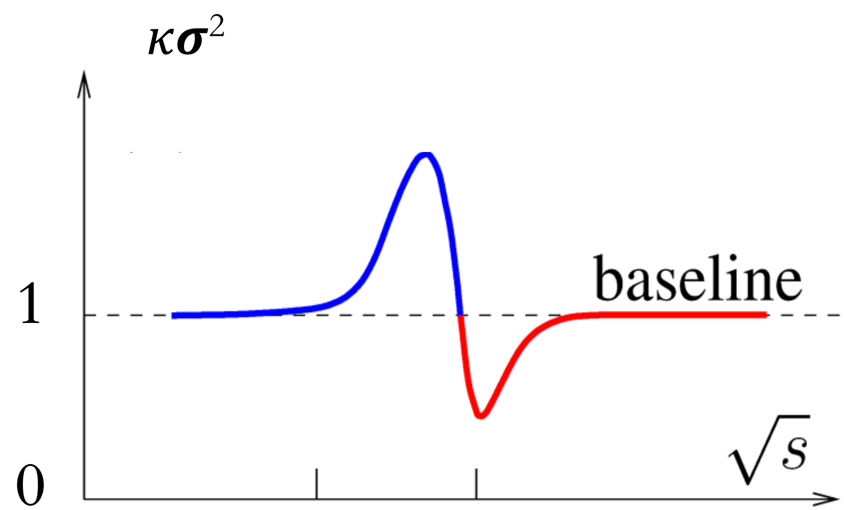
邵国运等, EPJC 78, 138 (2018)
黄梅等, EPJC 79, 245 (2019).

QCD相变临界点信号：理论模型预言

Caveats : Dynamical 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).
S. Tang, S. Wu, H. Song, arXiv : 2303.15017

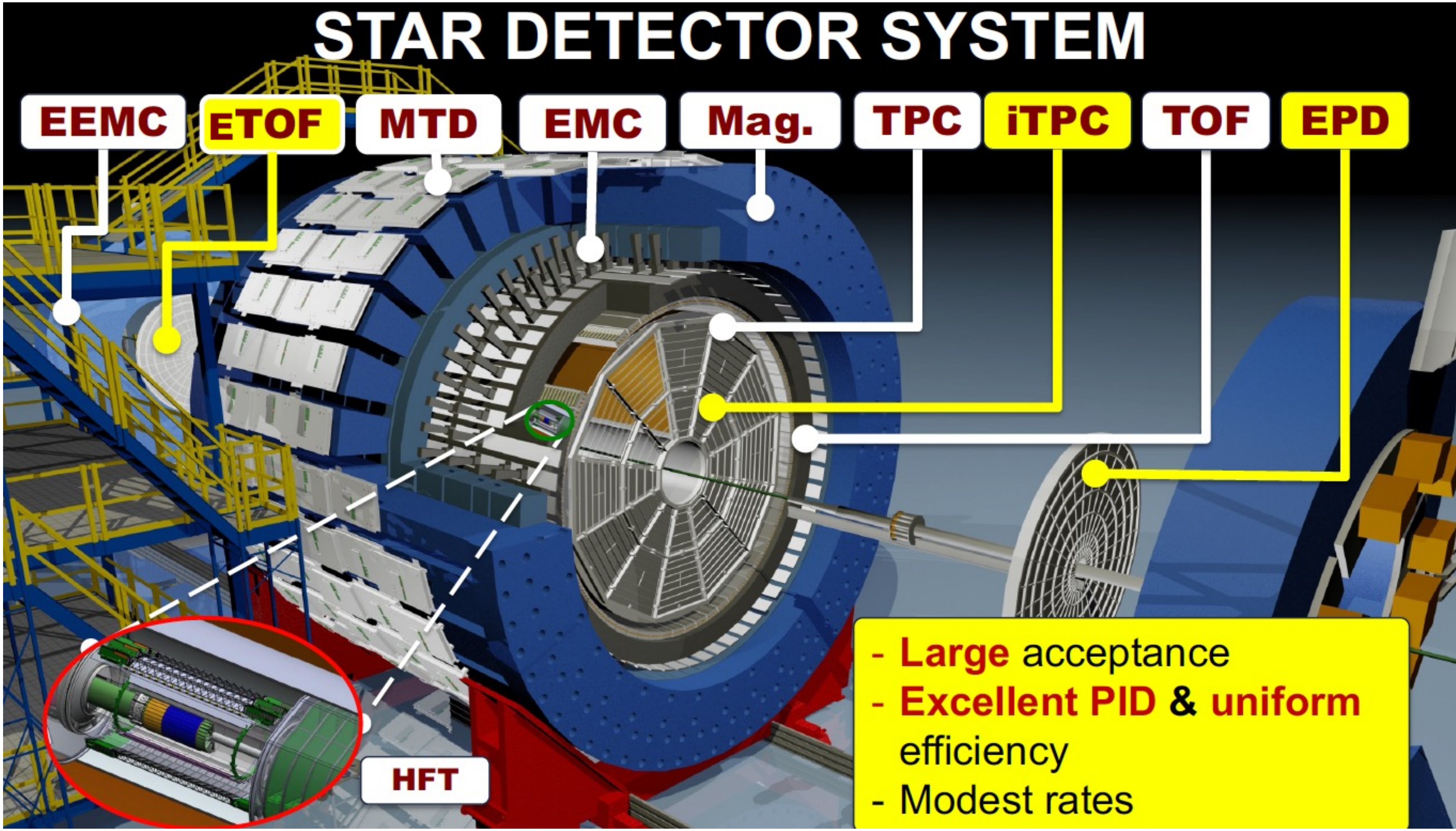




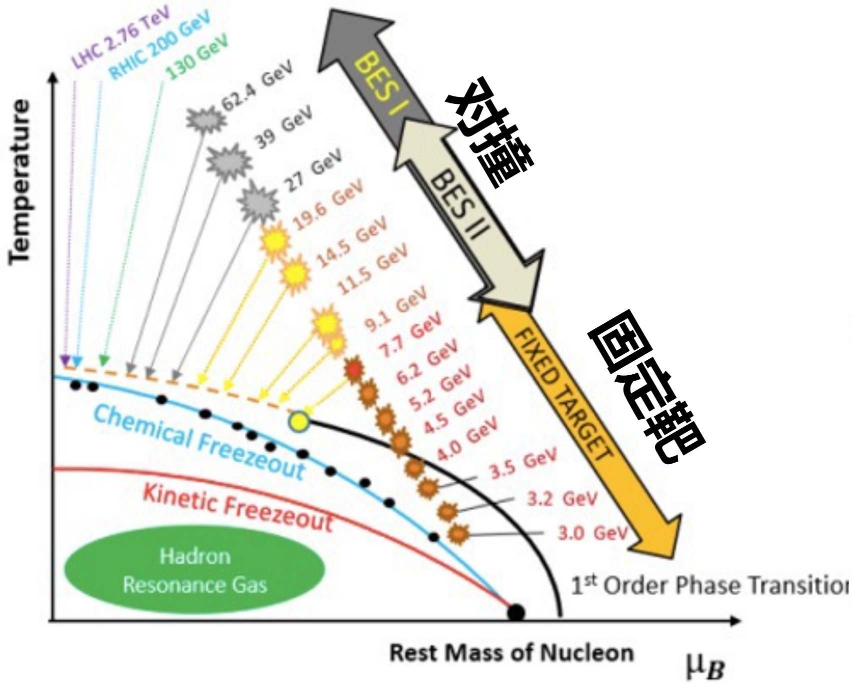
M. Stephanov, PRL107, 052301 (2011); J. Phys. G 38, 124147 (2011).
Schaefer et al., PRD 85, 034027 (2012); W. Fu et al., PRD 94, 116020 (2016).
J.W. Chen, J. Deng, et al., PRD 93, 034037 (2016). PRD 95,014038 (2017).
W. K. Fan, X. Luo, H.S. Zong, IJMPA 32, 1750061 (2017);
G. Shao et al., EPJC 78, 138 (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.

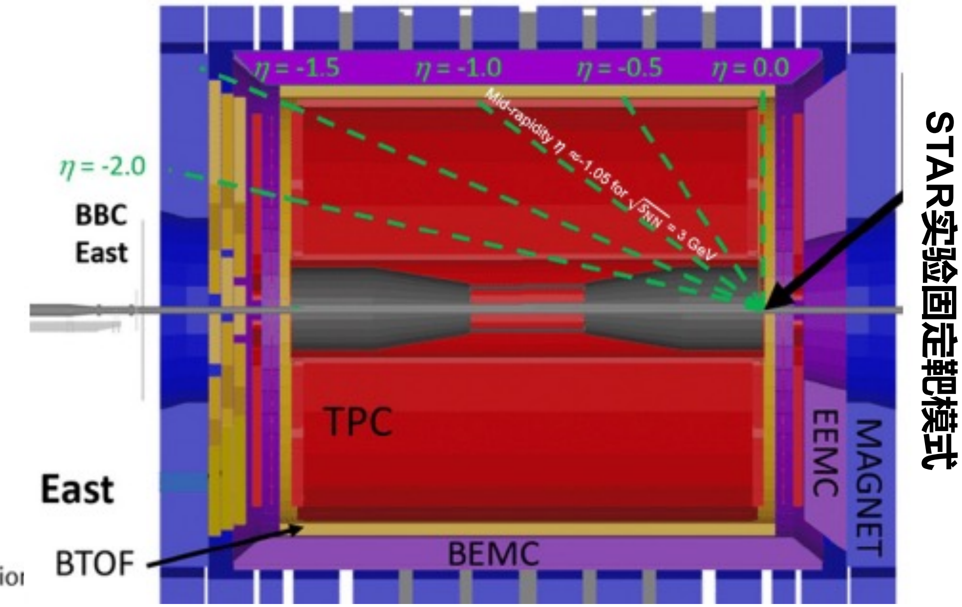
$\kappa\sigma^2 = 1$ (Poisson Fluctuations)

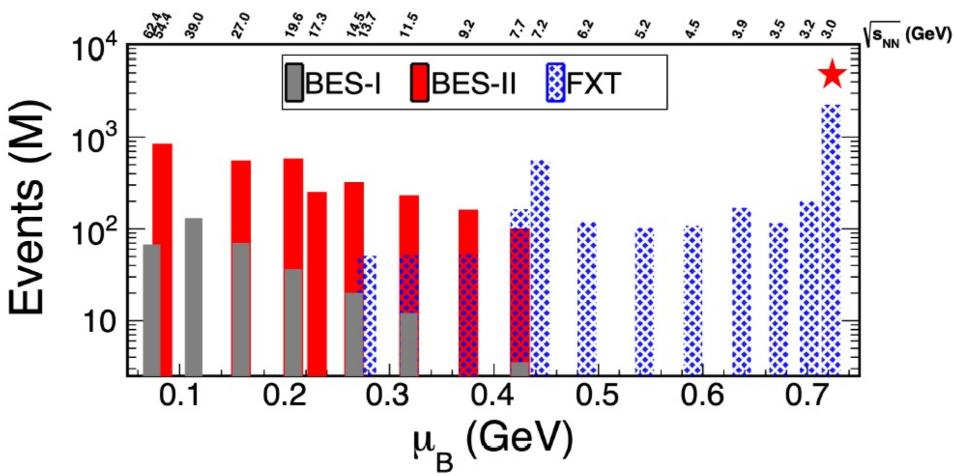
"Oscillation Pattern"
Especially the Peak at low energies


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)







- ➢ 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.

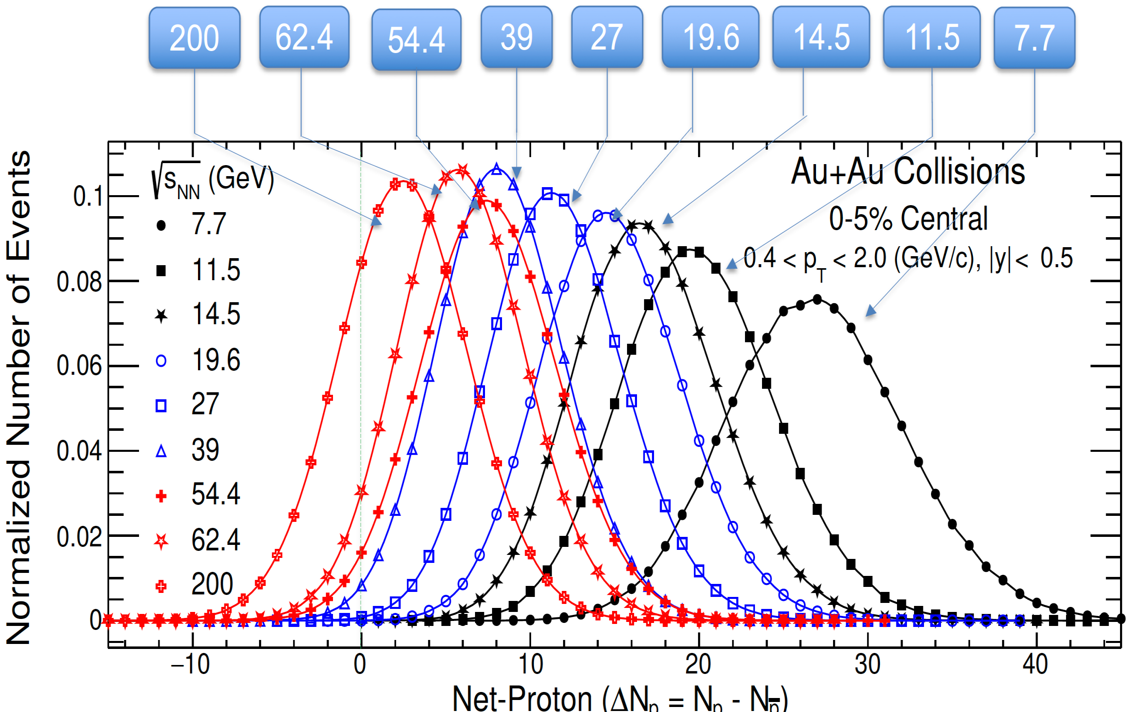
RHIC能量扫描数据统计表

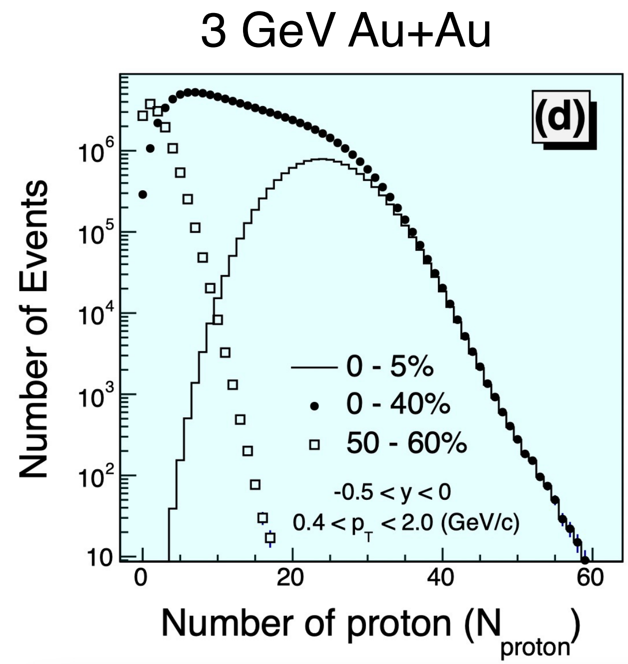
Au+Au Collisions at RHIC （RHIC 金核-金核碰撞）

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

Analysis Details



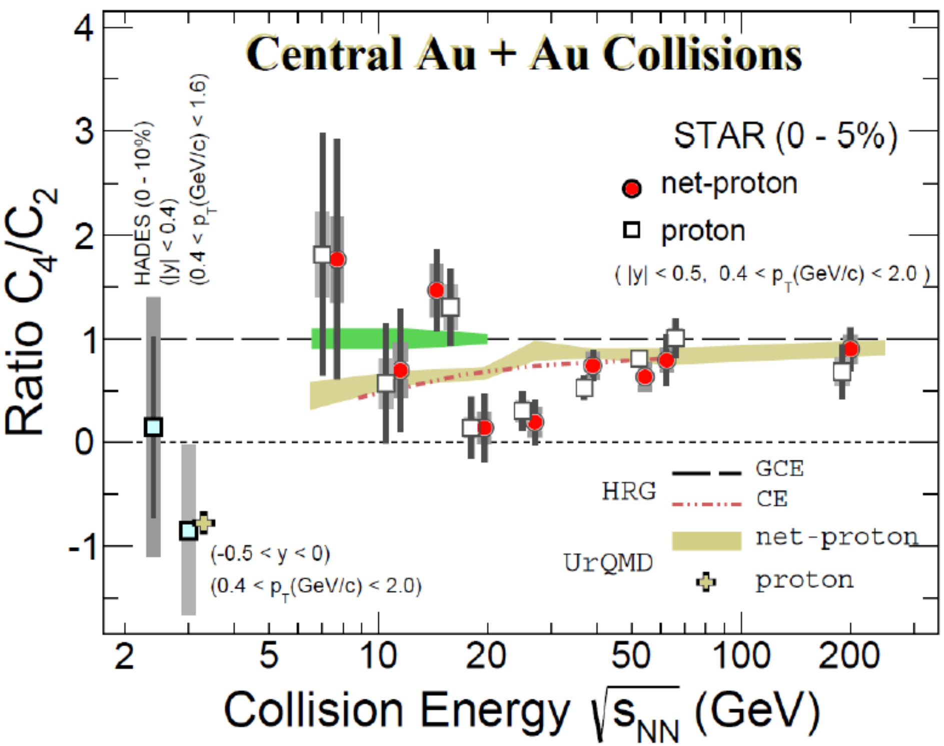


- Centrality bin width correction (CBWC)
- Auto-correlation effect: new centrality definition
- Statistical uncertainty: Delta theorem / bootstrap
- Detector efficiency correction: Binomial model
- Pileup correction
- Initial volume fluctuation correction

- **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）

X.Luo, 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). S. He, X. Luo, Chin. Phys. C43, 104001 (2018), X. Luo and T. Nonaka, PRC99, 044917 (2019); Arghya Chatterjee, PRC 101,034902 (2020) Fan Si, et al. CPC 45, 124001 (2021), X. Luo and N. Xu, Nucl. Sci. Tech. 28, 112 (2017), T. Nonaka et al, Nucl. Inst. Meth. A 984(2020)164632, Y. Zhang et al. Nucl. Inst. Meth. A 1026(2022)166246

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

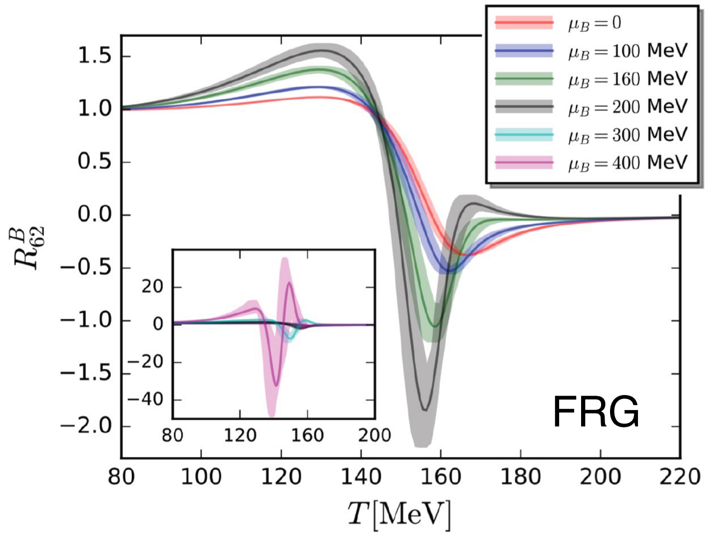


- Non-monotonic energy dependence in central Au+Au collisions (3.1σ)
- The 3 GeV proton C4/C2 is consistent with HADES measurement within uncertainties.
- The consistency of 3 GeV data and hadronic transport model calculation indicates the QCD critical point, if exists in heavy ion collisions, could likely be at energy higher than 3 GeV.
- The analysis of BES-II data (3 - 19.6 GeV) is ongoing !

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

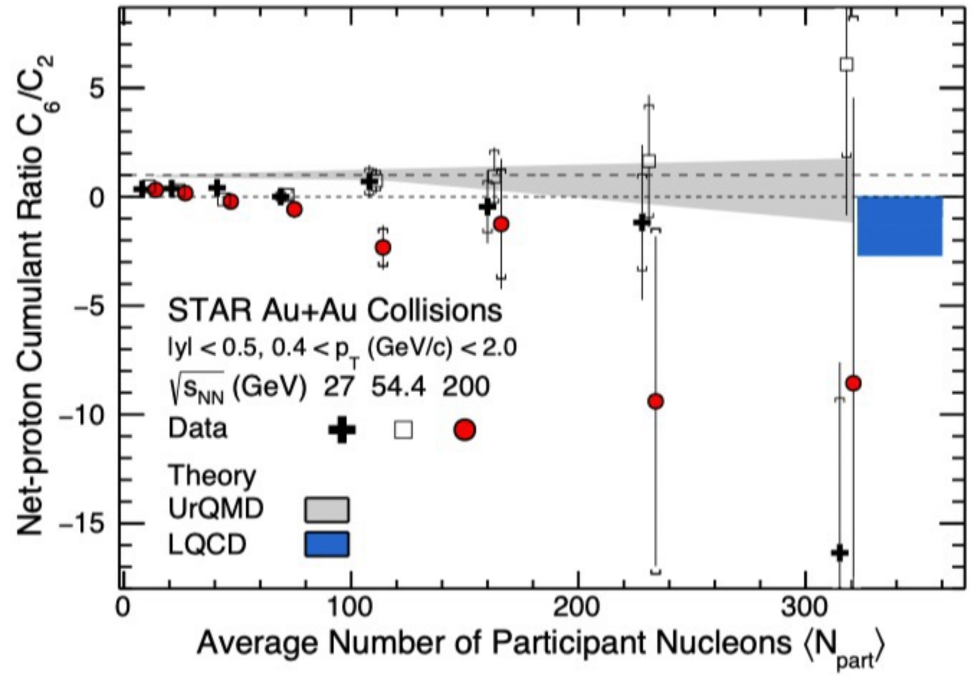
3 GeV: Phys. Rev. Lett. 128, 202303 (2022)
Phys. Rev. C 107, 024908 (2023)

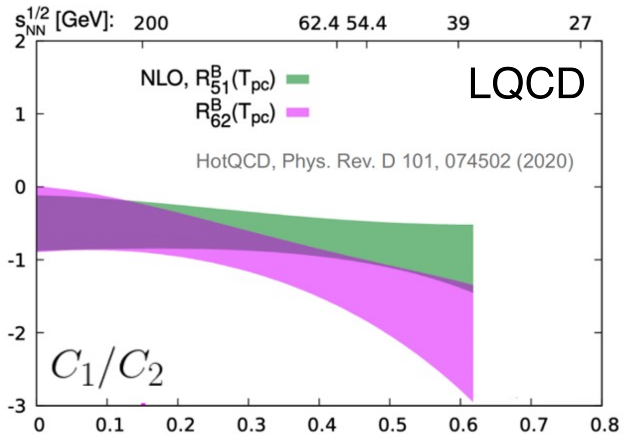
Higher-order baryon number fluctuations



付伟杰等，Phys. Rev. D 104, 094047 (2021)

STAR, Phys. Rev. Lett. 127 (2021) 262301



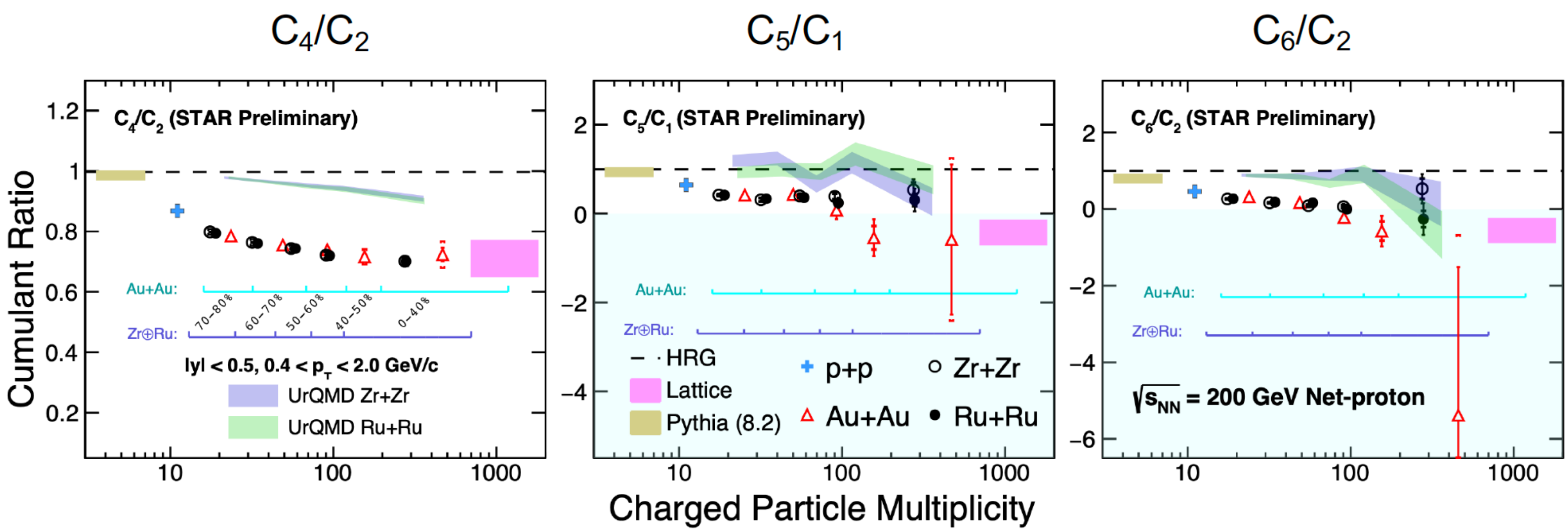


- FRG and Lattice QCD calculation predicts C_5/C_1 and $C_6/C_2 < 0$ due to chiral crossover from hadronic matter to QGP.
- Negative sign of C5 and C6: A signature of chiral crossover.
- 200 GeV data shows a progressively negative trend from peripheral to central collisions. More statistics are needed.

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

C_5/C_1 and C_6/C_2 : System Size Dependence

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



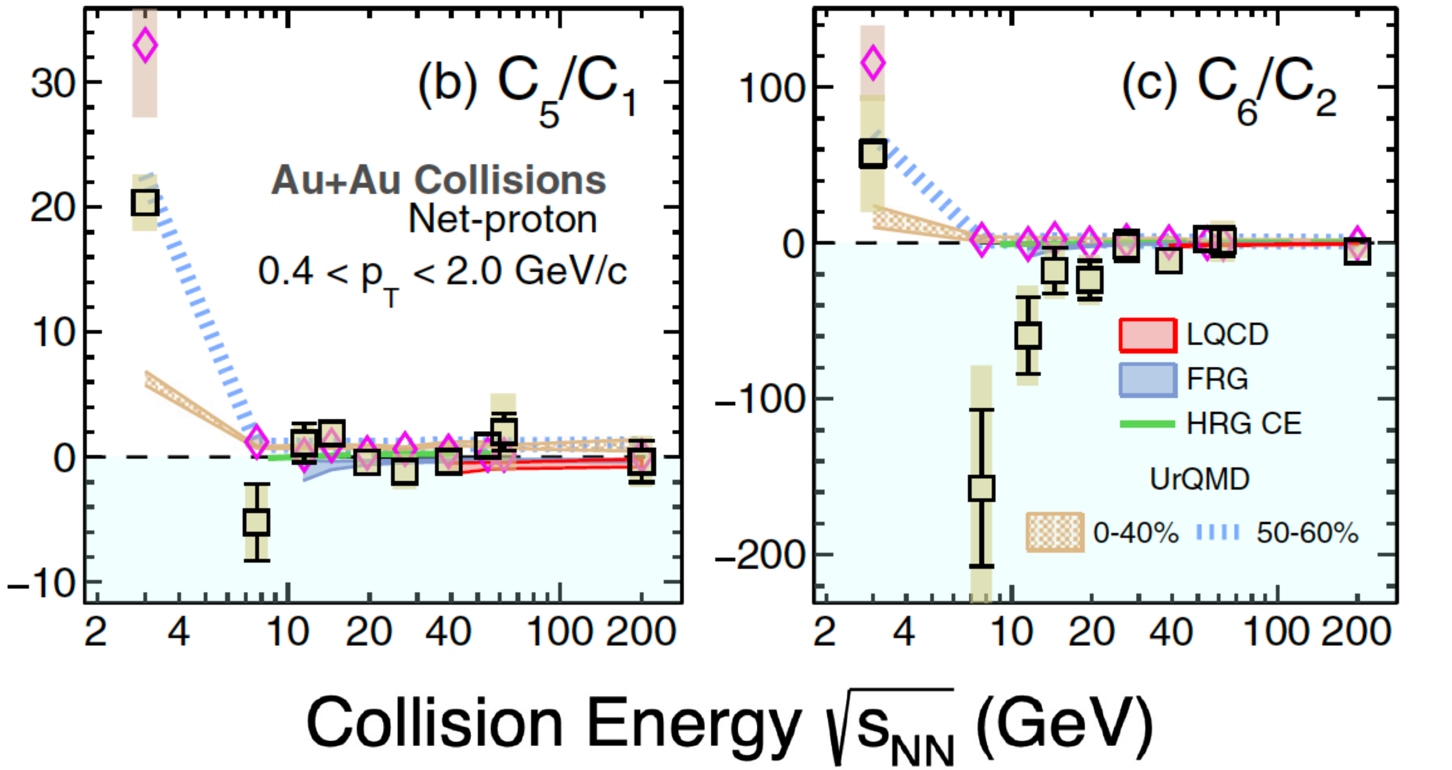
Isobar and *p+p* : under collaboration review

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.

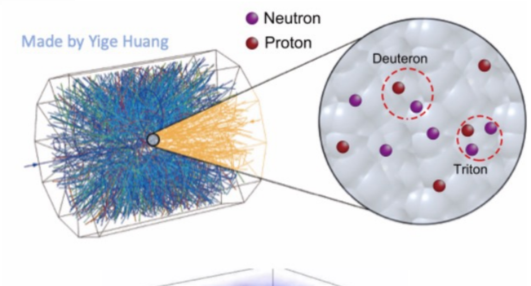
C_5/C_1 and C_6/C_2 : Energy Dependence

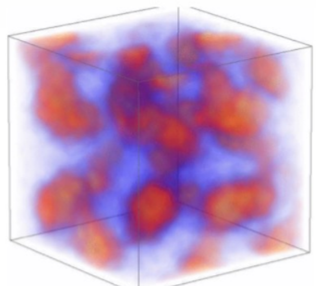


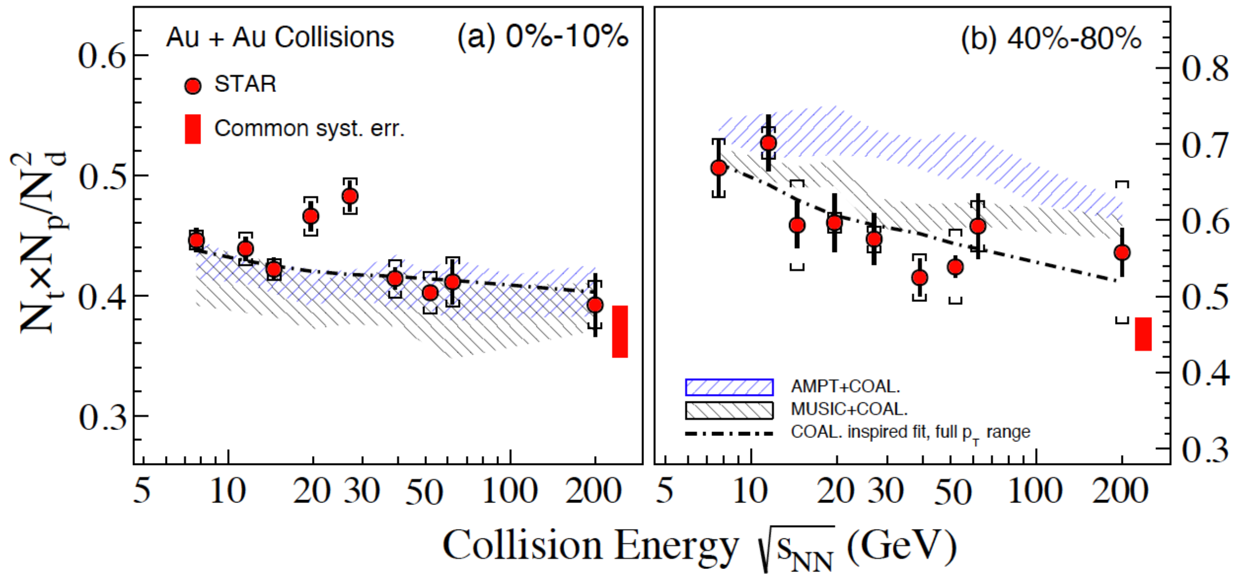
1. C_5/C_1 and C_6/C_2 (0-40%): Consistent with Lattice QCD with $\mu_B < 110$ MeV. (> 39 GeV)
2. C_6/C_2 progressively negative with decreasing collision energy down to 7.7 GeV. ~ 1.7 sigma to be negative sign.
3. 3 GeV 0-40% results : large initial volume fluctuations and consistent with UrQMD.

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

QCD相变灵敏观测量I ： 轻核产额比







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

Coalescence picture：

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

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

The compound light nuclei yield ratio is predicted to be sensitive to the CP and 1st order phase transition.

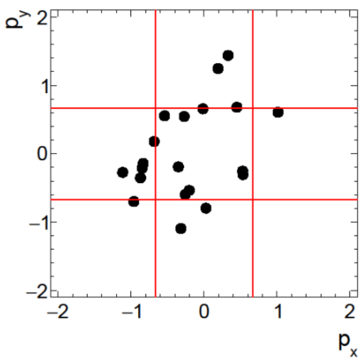
$$N_t \times N_p / N_d^2 = g(1 + \Delta n)$$

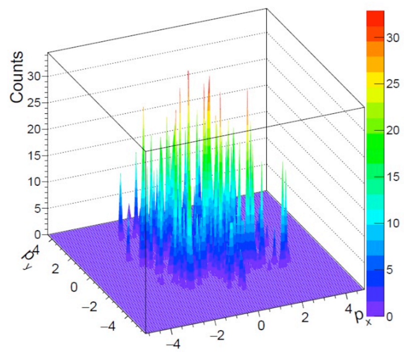
K.-J. Sun, L.-W. Chen, C. M. Ko, J. Pu, and Z. Xu, Phys. Lett. B 781, 499 (2018)

- Non-monotonic behavior observed in 0-10% central Au+Au collisions around 19.6 and 27 GeV with 4.1σ significance deviated from coalescence baseline.
- The yield ratio in peripheral (40%-80%) collisions exhibits a monotonic trend, which can be well described by coalescence models within uncertainties.

QCD相变灵敏观测量II：带电强子的间歇分析

Probing the density fluctuations and long range correlations near the QCD critical point via intermittency analysis in transverse momentum plane.





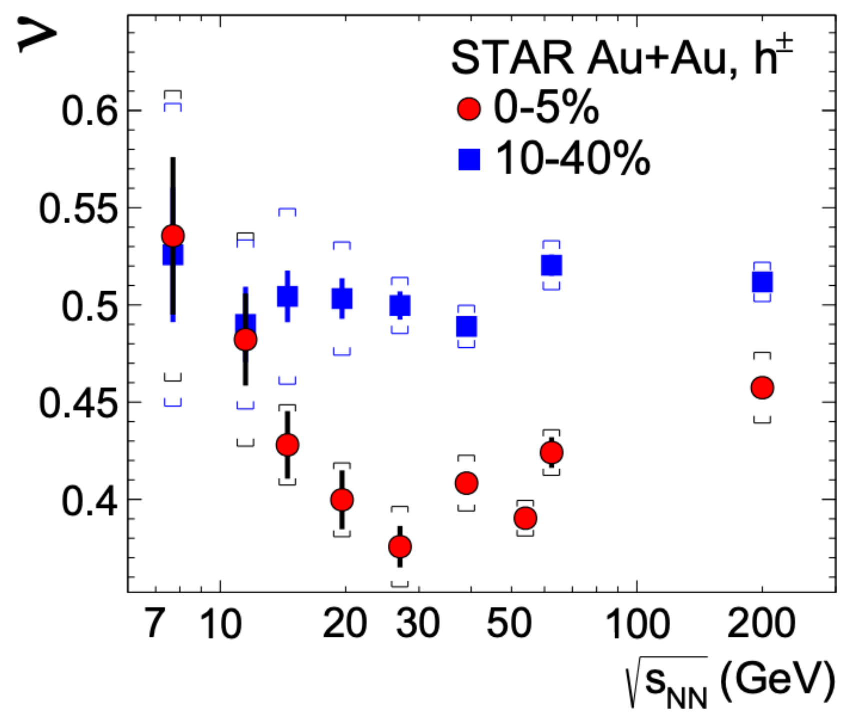
$$F_q(M) = \frac{< \frac{1}{M^D} \sum_{i=1}^{M^D} n_i(n_i-1)\ldots(n_i-q+1) >}{< \frac{1}{M^D} \sum_{i=1}^{M^D} n_i >^q}$$

$$\Delta F_q(M) = F_q^{data}(M) - F_q^{mix}(M)$$

$$\Delta F_q(M) \propto \Delta F_2(M)^{\beta_q}$$

$$\beta_q \propto (q-1)^{\nu}$$

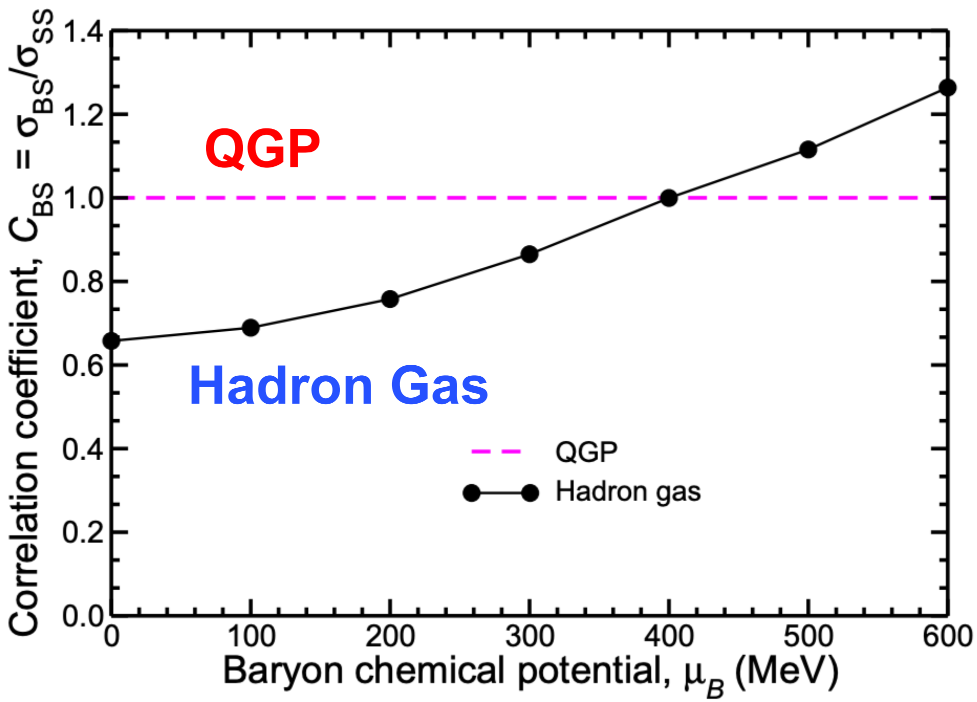
STAR, arXiv: 2301.11062



Scaling exponent exhibits a non-monotonic energy dependence in central Au+Au collisions with a minimum around $\sqrt{s_{NN}}$ = 20-30 GeV.

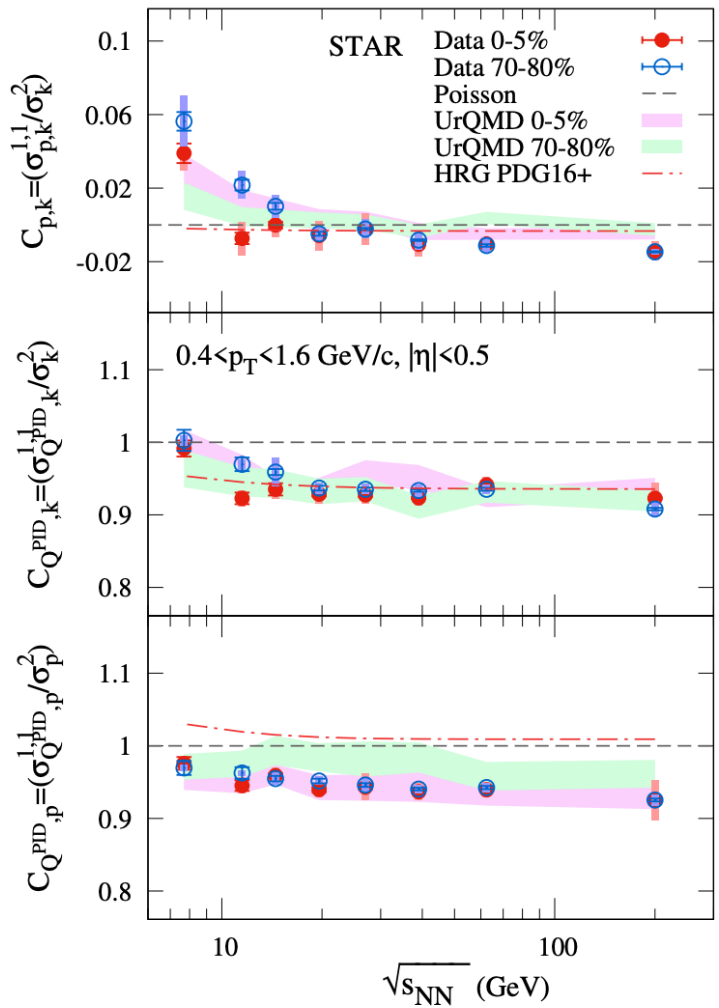
QCD相变灵敏观测量III：重子(B)-奇异(S)数关联

$$C_{BS} = -3\chi^{11}_{BS}/\chi^2_S = -3\frac{<BS> - <B><S>}{<S>^2}$$



V. Koch, et al., Phys. Rev. Lett. 95, 182301 (2005).

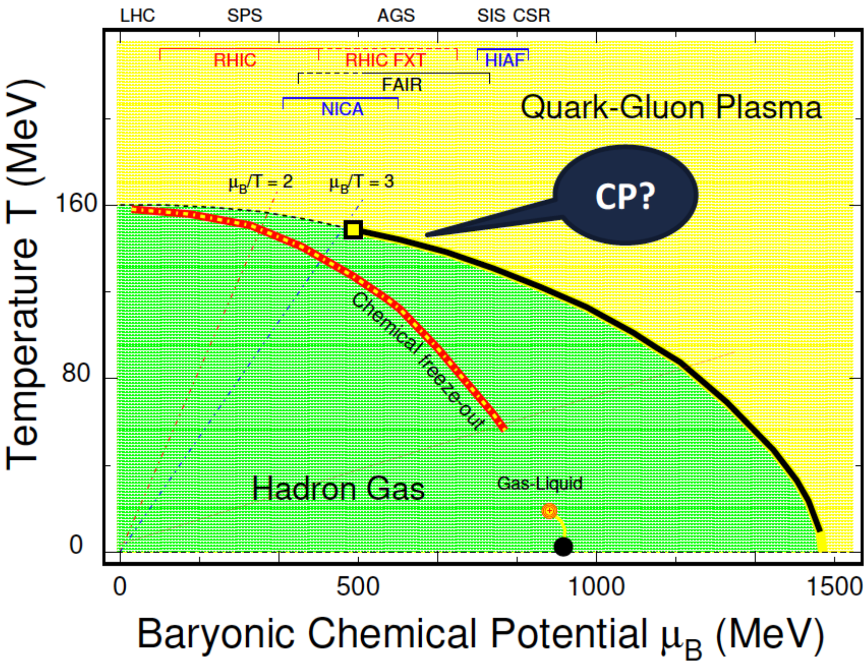
净质子-净K介子关联



STAR, Phys. Rev. C 100, 014902 (2019)

奇异重子如 Λ, Ξ 对重子-奇异数关联非常重要，需要被考虑。数据分析进行中…

总结



1) Au+Au collisions at 200 GeV, μ_B ~ 25 MeV, QGP EOS dominant, smooth crossover transition.

2) At 3 GeV collisions, μ_B ~ 750 MeV, different EOS comparing to high energy. hadronic dominated !

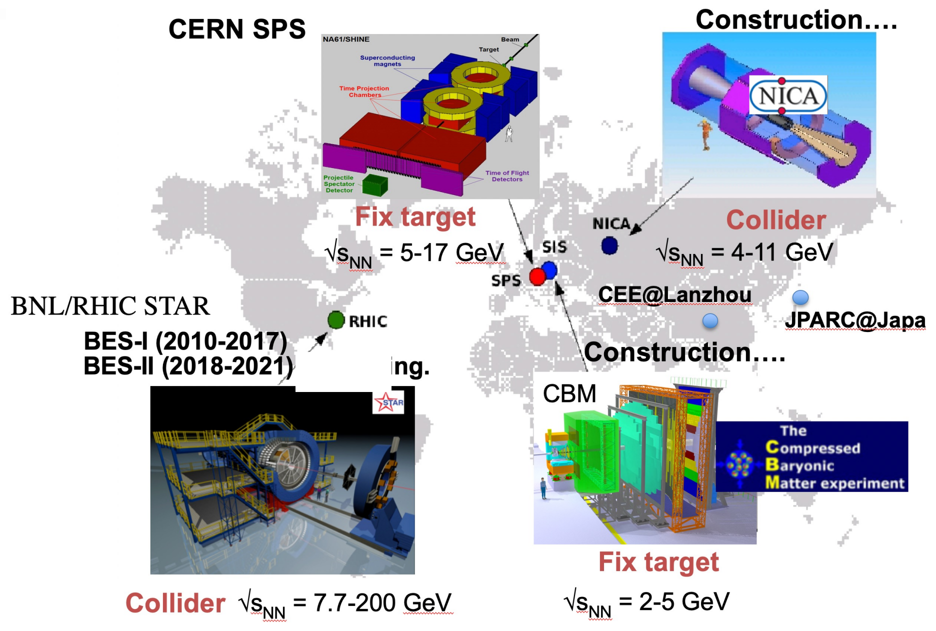
3) BES-I : QCD critical point between 3 – 40 GeV ?

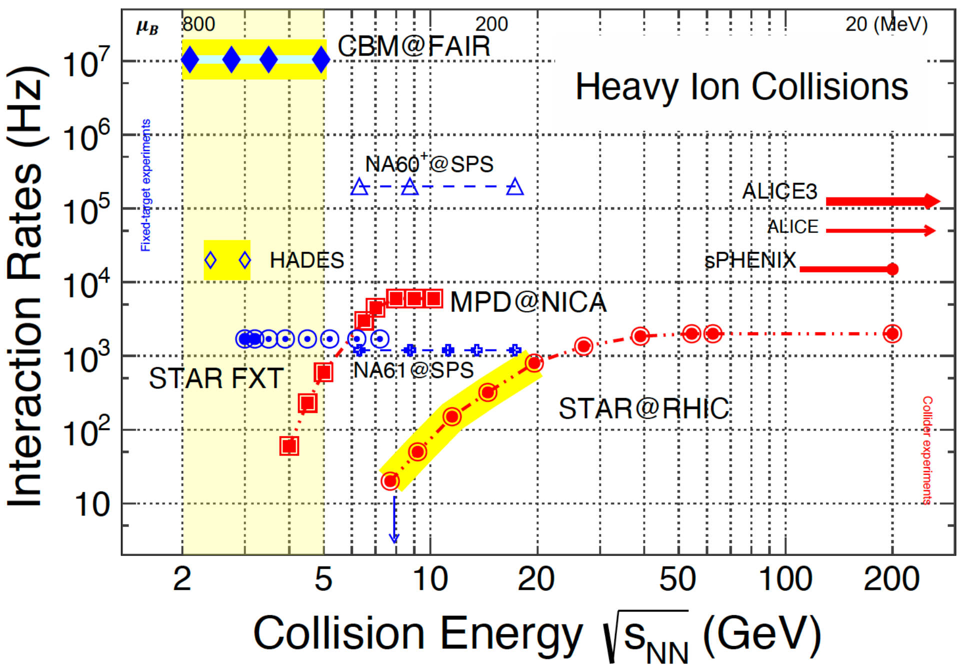
4) BES-II (completed !), analysis ongoing.
   7.7 ~ 19.6 GeV (collider)
   3 ~ 7.7 GeV (FXT)

Net-proton analysis status at BES-II energies

Energy (GeV)	3.2 (FXT)	3.5 (FXT)	7.7	9.2	11.5	14.5	17.3	19.6
Data Production	Done	Done	Done	Done	Done	Done	No	Done
QA	Done	Done	Done	Done	Done	Done	No	Done
Centrality	No	No	Done	Done	Done	Done	No	Done
Purity	Done	Done	Done	No	No	Done	No	Done
Embedding	Done	No	Done	No	No	Done	No	Done
Final Results	No	No	Near final	No	No	Near final	No	Near final

展望





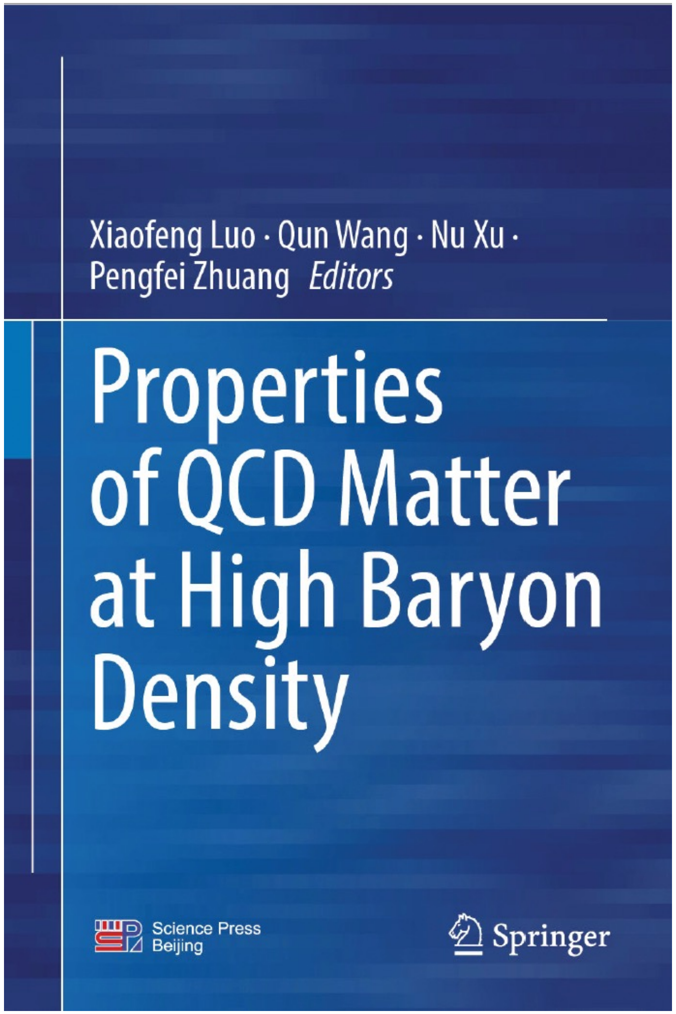
万亿摄氏度下烹煮夸克汤：核物质相结构和量子色动力学相变临界点的实验研究

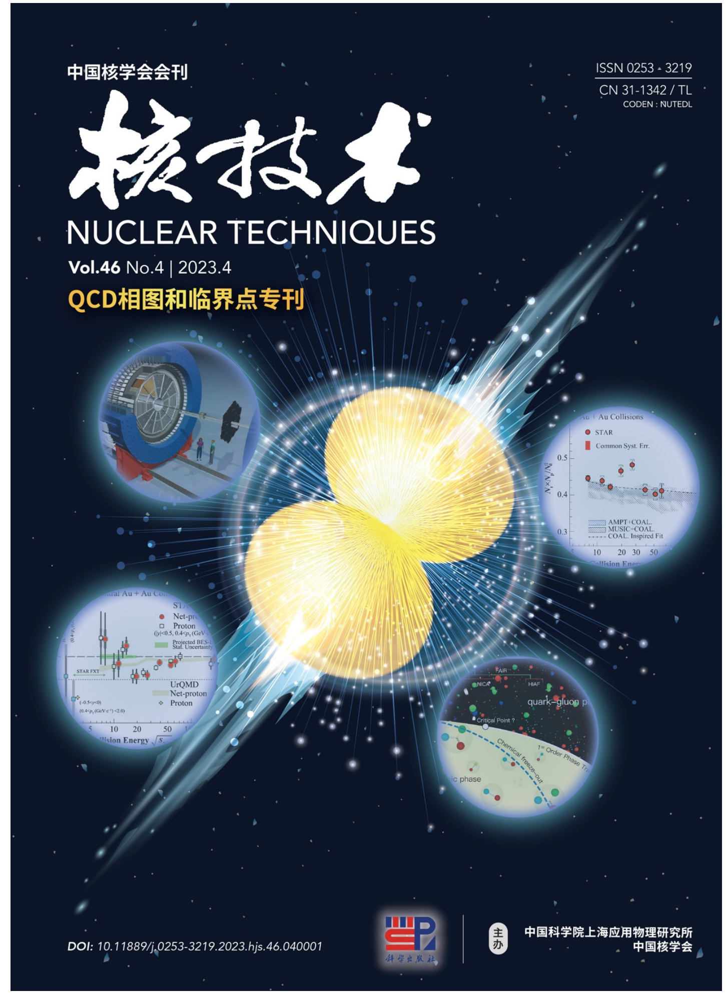
科普(前沿进展)：
XFL、刘峰、许怒，《物理》50(2), (2021)

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.





“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)

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主编：马余刚

谢谢！