中国物理学会高能物理分会第十一届全国会员代表大会暨学术年会

相对论重离子碰撞中QCD相图实验研究进展

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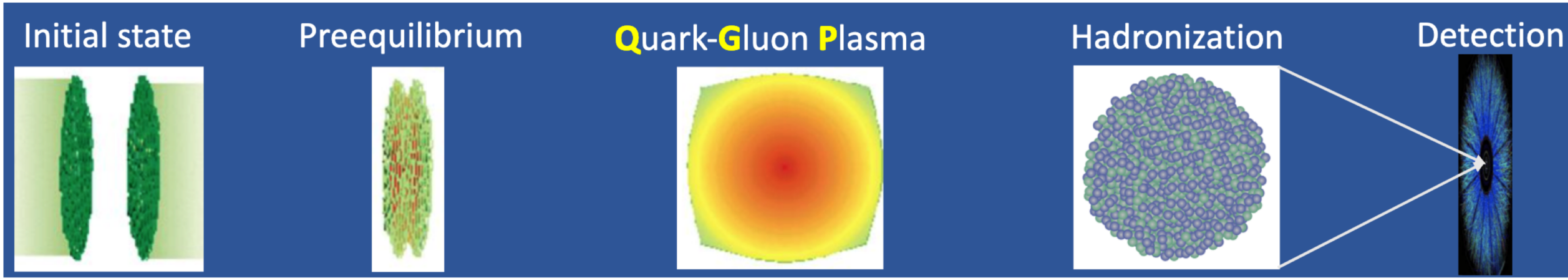
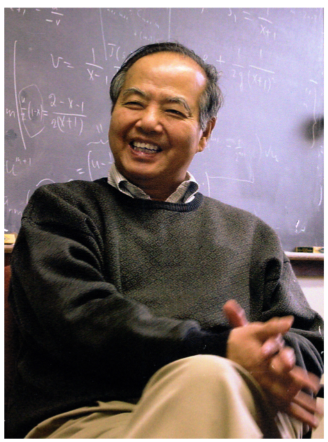
Central China Normal University (华中师范大学)

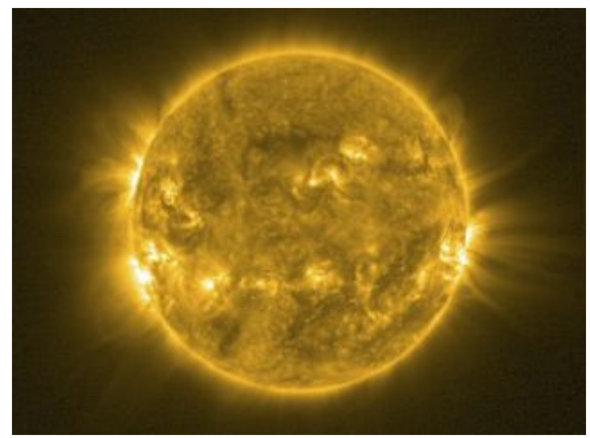
2022年8月8-11日

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。



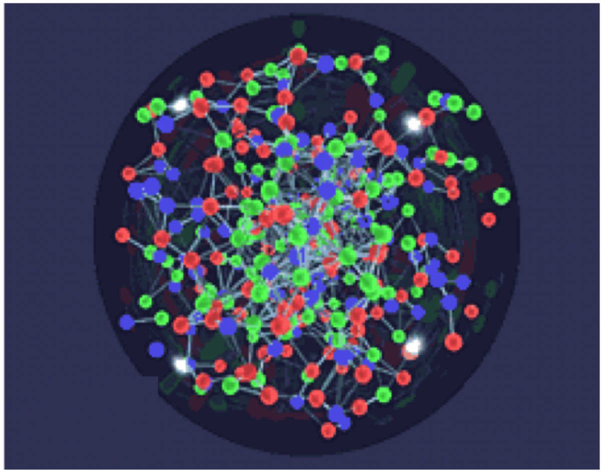


太阳核心温度：20000000 K (夸克仍被禁闭在强子中)

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

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。

两大主要物理目标：QGP性质以及QCD相结构



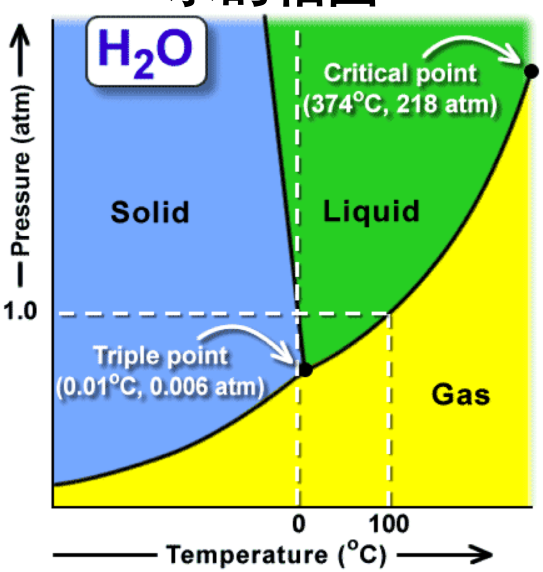
夸克、胶子为自由度的强耦合理想流体 (sQGP)

1. 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
- 涡旋、磁场强度

2. 研究产生QGP的条件，探索QCD相结构(一级相变边界、临界点)？如：水的相变

水的相图



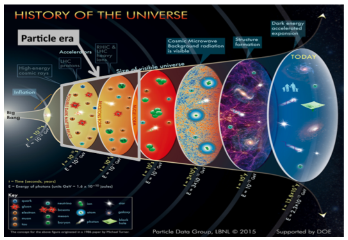
临界现象：

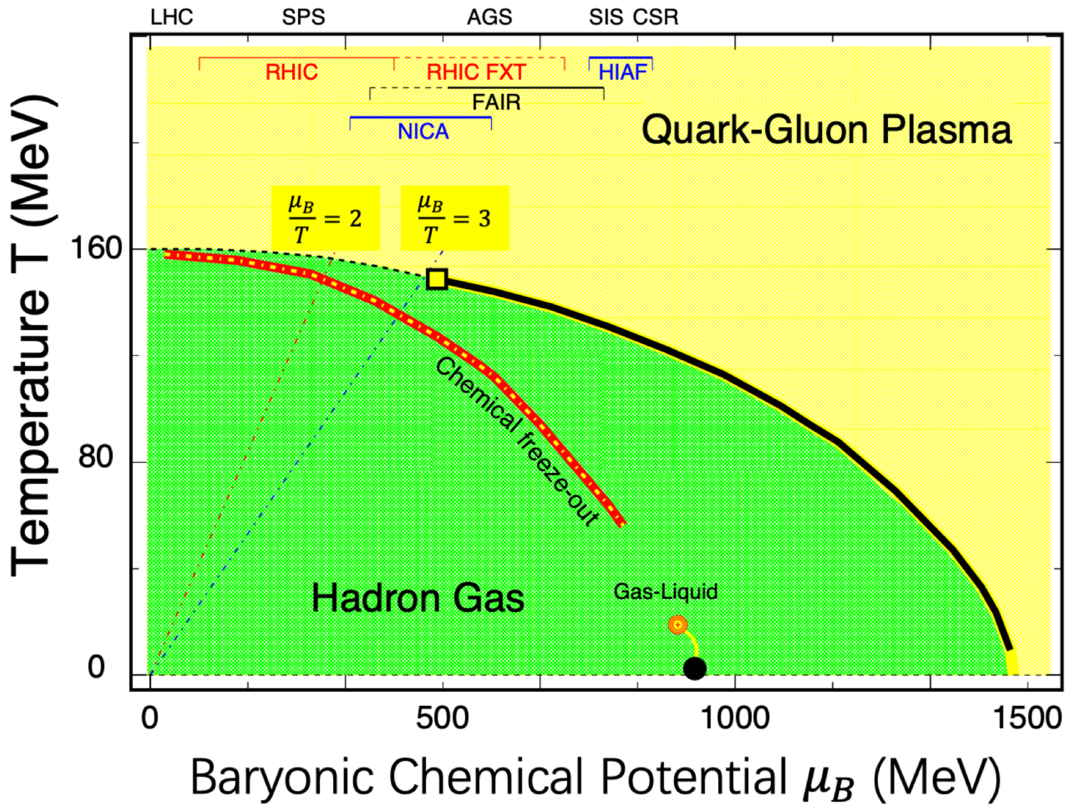
- **密度涨落增强与关联长度增大：**
  临界乳光现象
- **系统的对称性决定临界指数：即热力学量的临界发散行为**

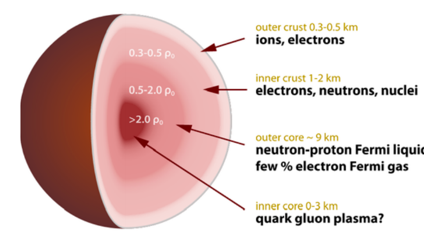
内因：相互作用、系统对称性
外因：外部条件的改变

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.
Temperature : T_c ~ 156 MeV

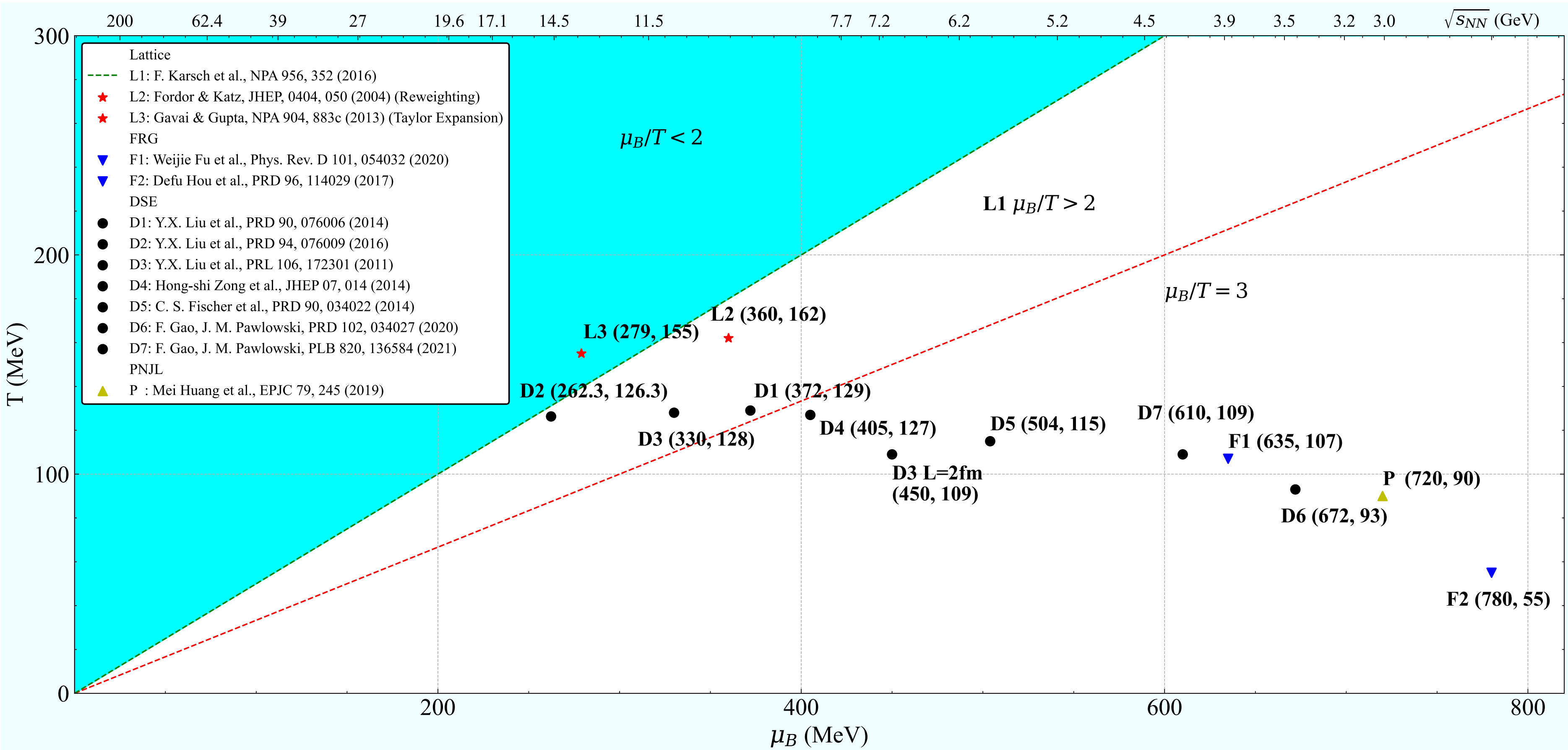
Y. Aoki, et al. Nature 443, 675 (2006).
A. Bazavov, 丁亨通(HotQCD Coll.)等，Phys. Lett. B 795, 15 (2019)

高重子密度区核物质相结构，如QCD临界点、一阶相变边界，是我国核物理学科发展战略待解决的关键科学问题之一，也是我国大科学装置强流离子加速器(HIAF)的一个主要物理目标(广东惠州建设中)。

马余刚、许怒、刘峰，中国科学:物理学 力学 天文学,2020,50(11):124-132.

QCD临界点位置：理论模型计算

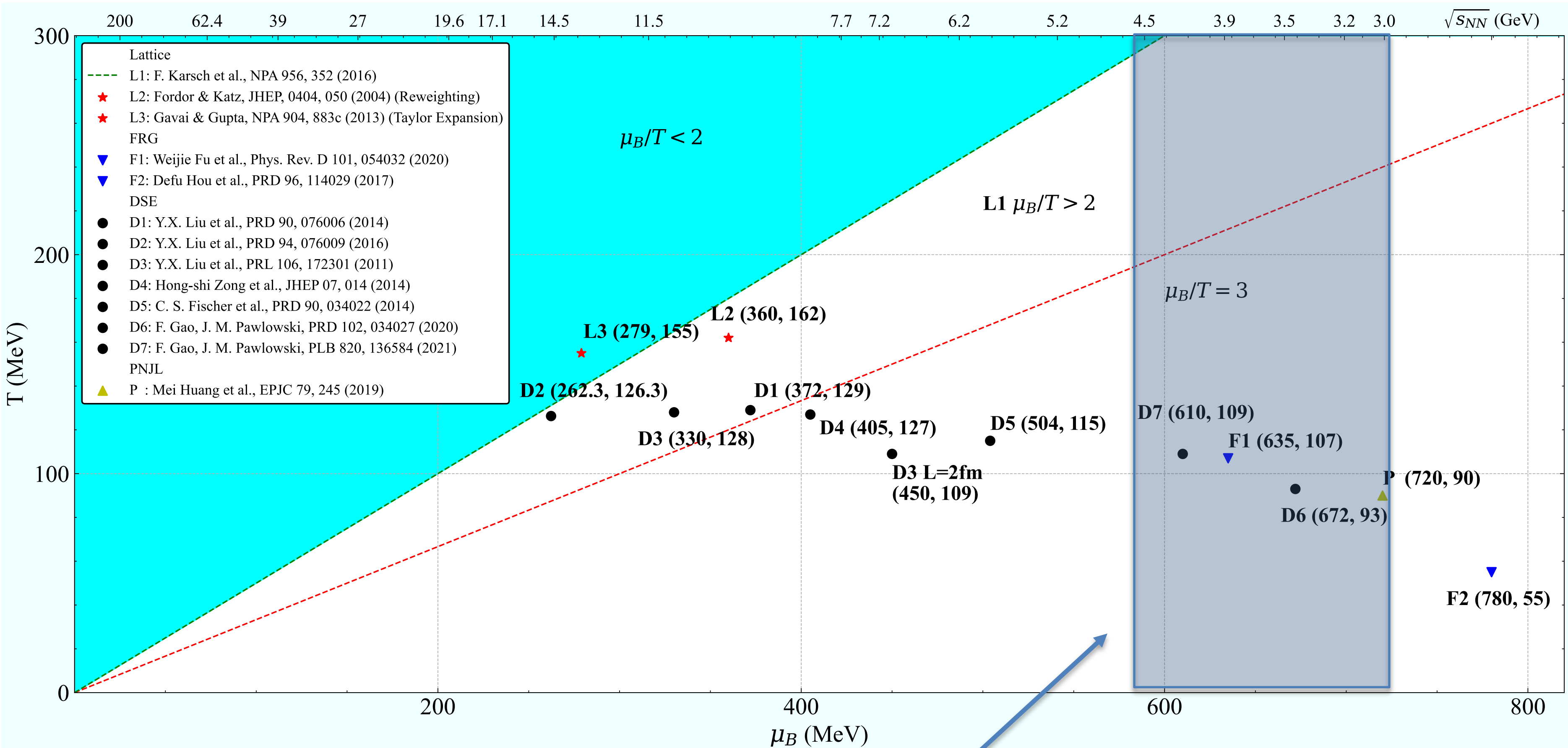
Preliminary collection from Lattice, DSE, FRG and PNJL (2004-2021)



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)



DSE, FRG 计算：当前QCD临界点最有可能所在相图区域。

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

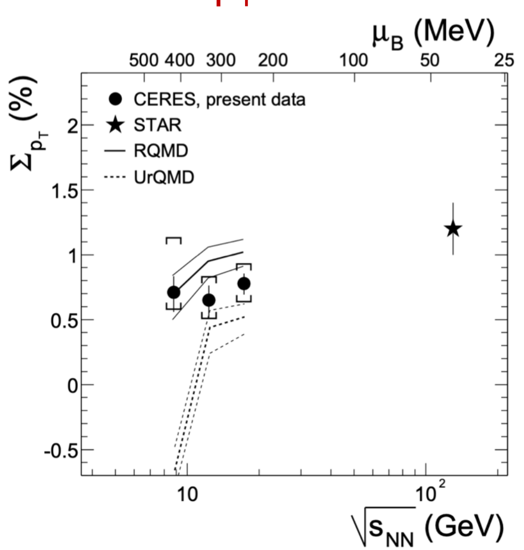
比热 -> 能量涨落
不可压缩系数->粒子数涨落

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).

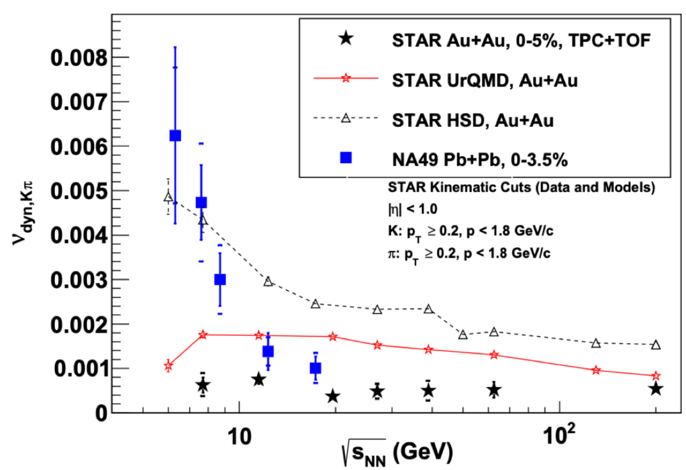
系统关联长度

Mean p_T fluctuations



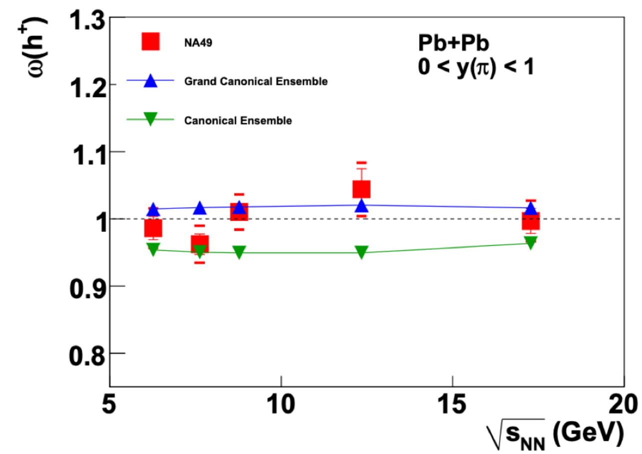
CERES, Nucl. Phys. A 727:97,2003
STAR, Phys. Rev. C 99 (2019) 44918

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

Higher Order Fluctuations of Conserved Quantities (B, Q, S)

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

$$< \delta N >= N- < N >$$

$$C_1 = M =< N >$$

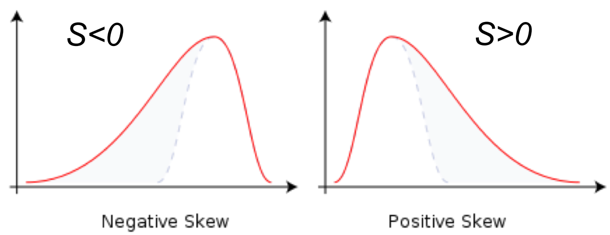
$$C_2 = \sigma^2 =< (\delta N)^2 >$$

$$C_3 = S\sigma^3 =< (\delta N)^3 >$$

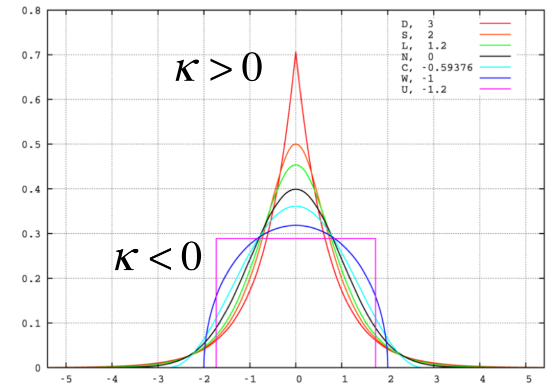
$$C_4 = \kappa\sigma^4 =< (\delta N)^4 > -3 < (\delta N)^2 >^2$$

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

Skewness (S) → asymmetry



Kurtosis (κ) → Sharpness

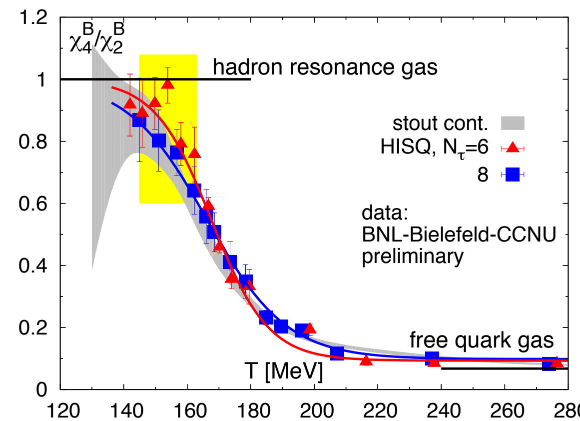


M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009); 107, 052301 (2011).
M.Asakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009).

2. Direct connect to the susceptibility of the system

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

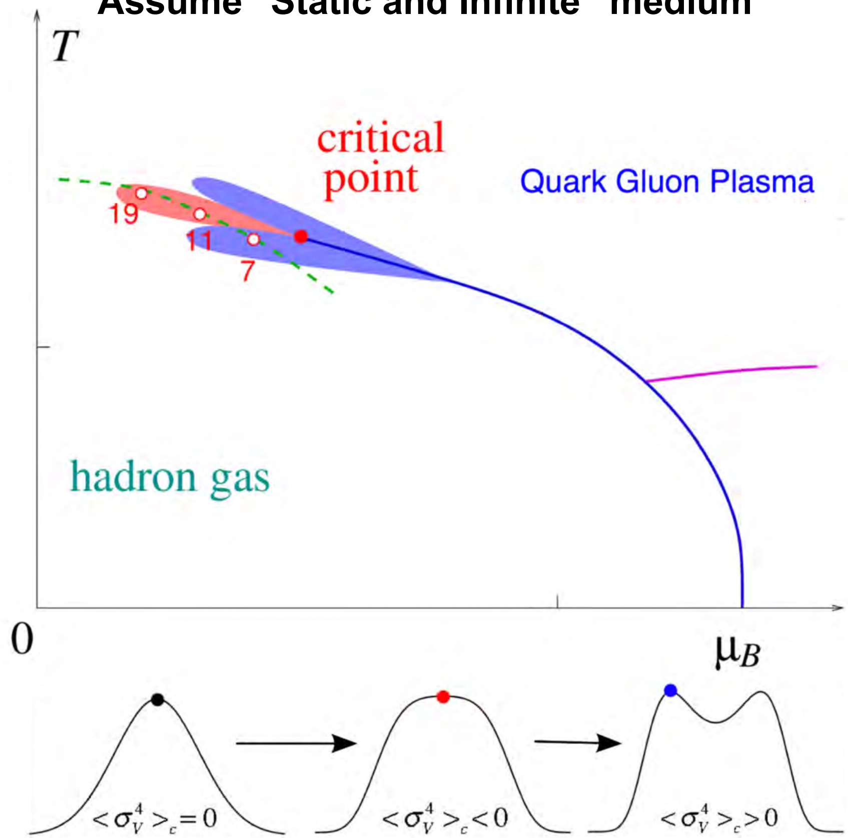
$$\chi_q^{(n)} = \frac{1}{VT^3} \times C_{n,q} = \frac{\partial^n (p/T \wedge 4)}{\partial(\mu_q)^n}, q = B,Q,S$$



Cheng et al, PRD (2009) 074505. 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)

Signals of QCD Critical Point : Theory/Model

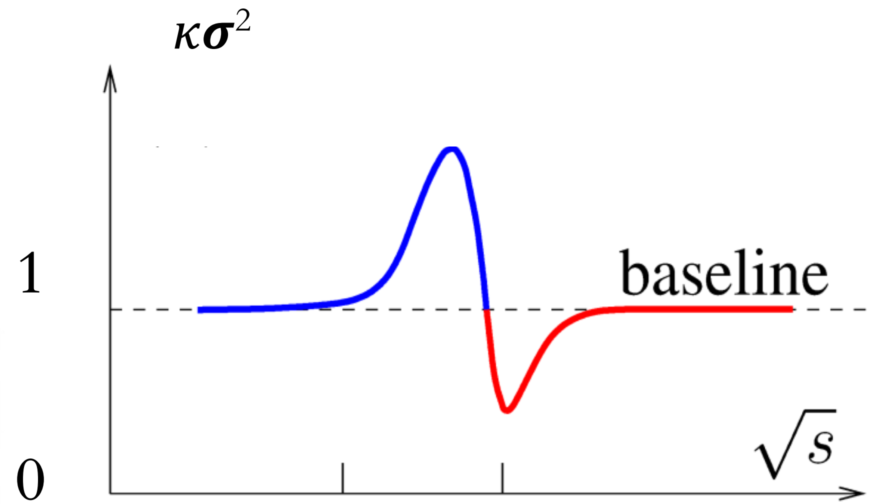
Assume "Static and Infinite" medium



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).

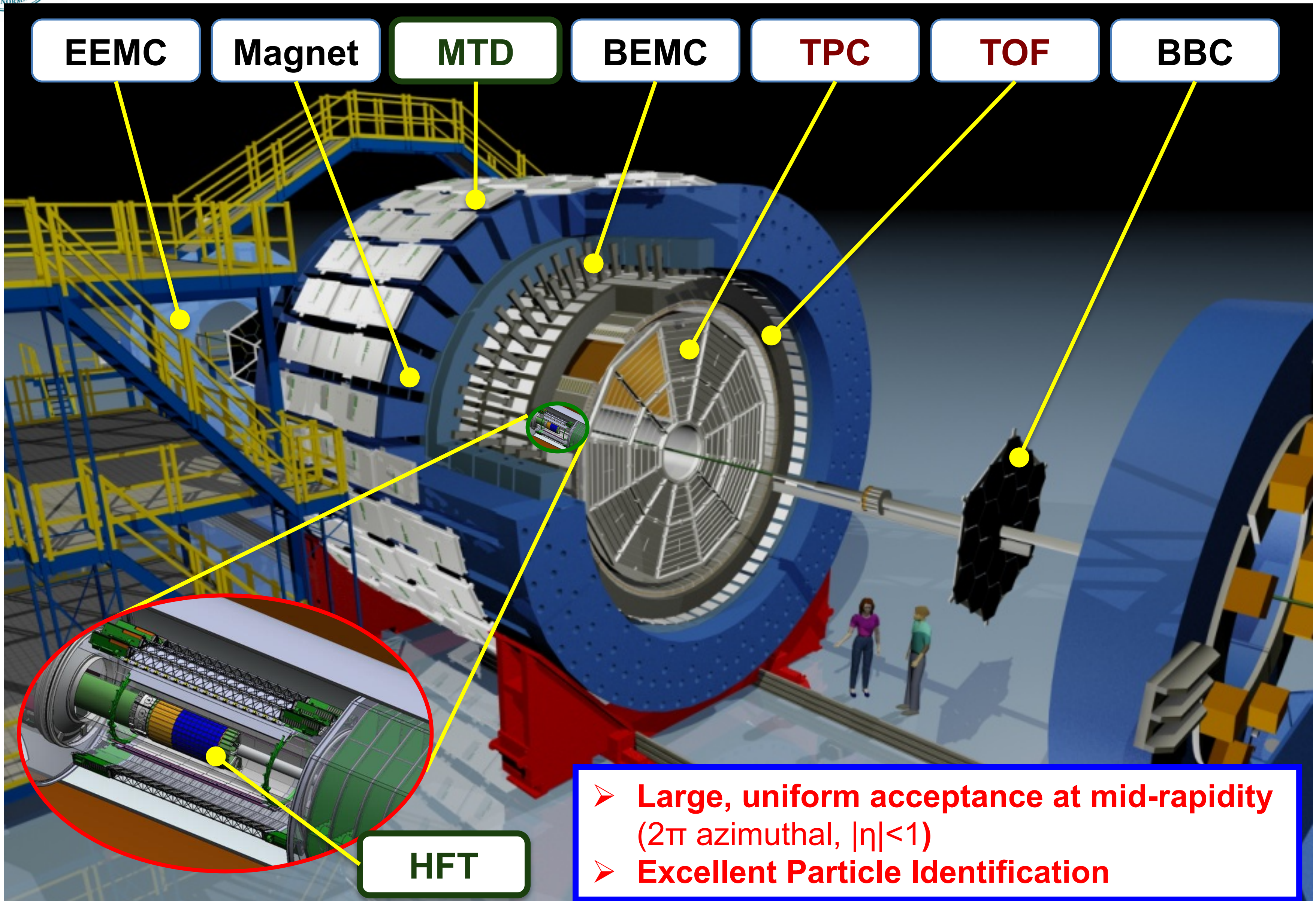


$\kappa\sigma^2 = 1$ (Poisson Fluctuations)

Characteristic signature of CP:
Non-monotonic energy dependence

"Oscillation Pattern"
Especially the Peak at low energies

STAR Detector System



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

BES-I & II at RHIC (2010-2017, 2018-2021)

Collider mode Au+Au Collisions **FXT mode**

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	**BES II / BES I**	μ_B (MeV)	T_{CH} (MeV)
200	238	2010	25	166
62.4	46	2010	73	165
54.4	1200	2017	83	165
39	86	2010	112	164
27	30 (560)	2011/2018	156	162
19.6	**538** / 15	**2019**/2011	206	160
14.5	**325** / 13	**2019**/2014	264	156
11.5	**230** / 7	**2020**/2010	315	152
9.2	**160** / 0.3	**2020**/2008	355	140
7.7	**100** / 3	**2021**/2010	420	140
17.3	**250**	**2021**	230	158

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	**BES II / BES I**	μ_B (MeV)	T_{CH} (MeV)
7.7	50+112	2019+2020	420	140
6.2	118	2020	487	130
5.2	103	2020	541	121
4.5	108	2020	589	112
3.9	117	2020	633	102
3.5	116	2020	666	93
3.2	200	2019	699	86
3.0	259	2018	750	80
3.0	**2000**	**2021**	750	80

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

STAR, arXiv:1007.2613

https://drupal.star.bnl.gov/STAR/starnotes/public/sn0493

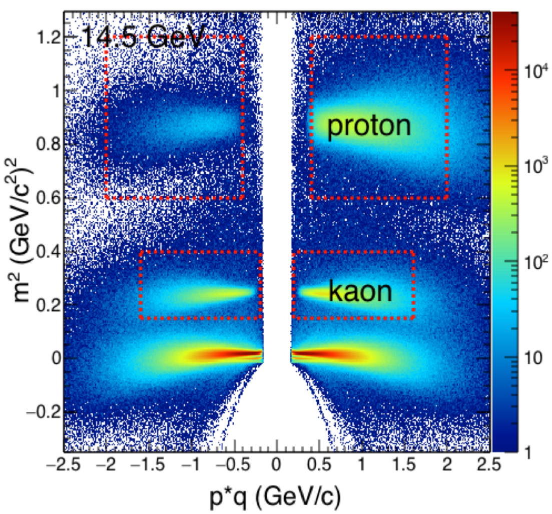
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

- Most precise data to map the QCD phase diagram :
  $3 \leq \sqrt{s_{NN}} \leq 200$ GeV, $25 < \mu_B < 750$ MeV

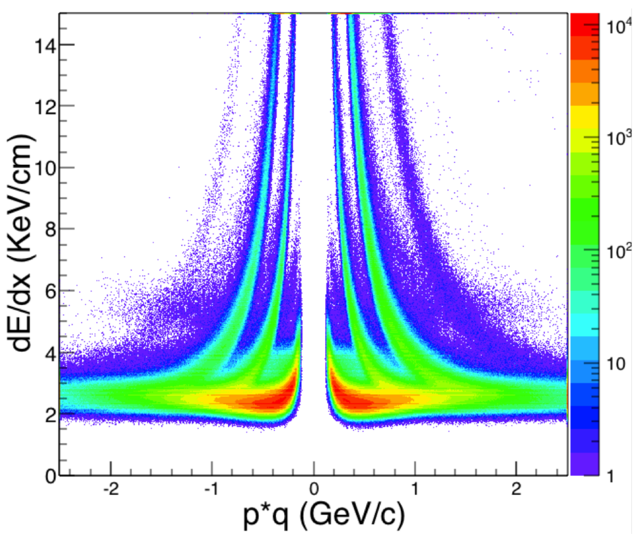
Analysis Details- I

	Net-Charge	Net-Proton	Net-Kaon
Kinematic cuts	$0.2 < p_T$ (GeV/c) < 2.0 $\|\eta\| < 0.5$	$0.4 < p_T$ (GeV/c) < 2.0 $\|y\| < 0.5$	$0.2 < p_T$ (GeV/c) < 1.6 $\|y\| < 0.5$
Particle Identification	Reject protons form spallation for $p_T < 0.4$ GeV/c	$0.4 < p_T$ (GeV/c) < 0.8 → TPC $0.8 < p_T$ (GeV/c) < 2.0 → TPC+TOF	$0.2 < p_T$ (GeV/c) < 0.4 → TPC $0.4 < p_T$ (GeV/c) < 1.6 → TPC+TOF
Centrality definition, → *to avoid auto-correlations*	Uncorrected charged primary particles multiplicity distribution	Uncorrected charged primary particles multiplicity distribution, without (anti-)protons	Uncorrected charged primary particles multiplicity distribution, without (anti-)kaons
	$0.5 < \|\eta\| < 1.0$	$\|\eta\| < 1.0$	$\|\eta\| < 1.0$

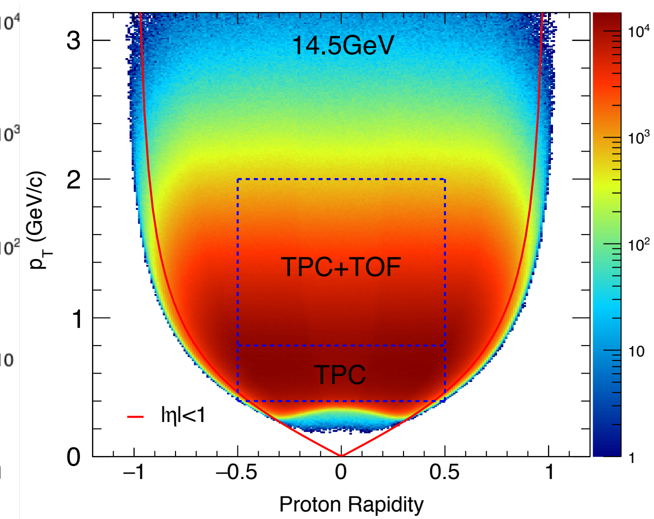
TOF PID



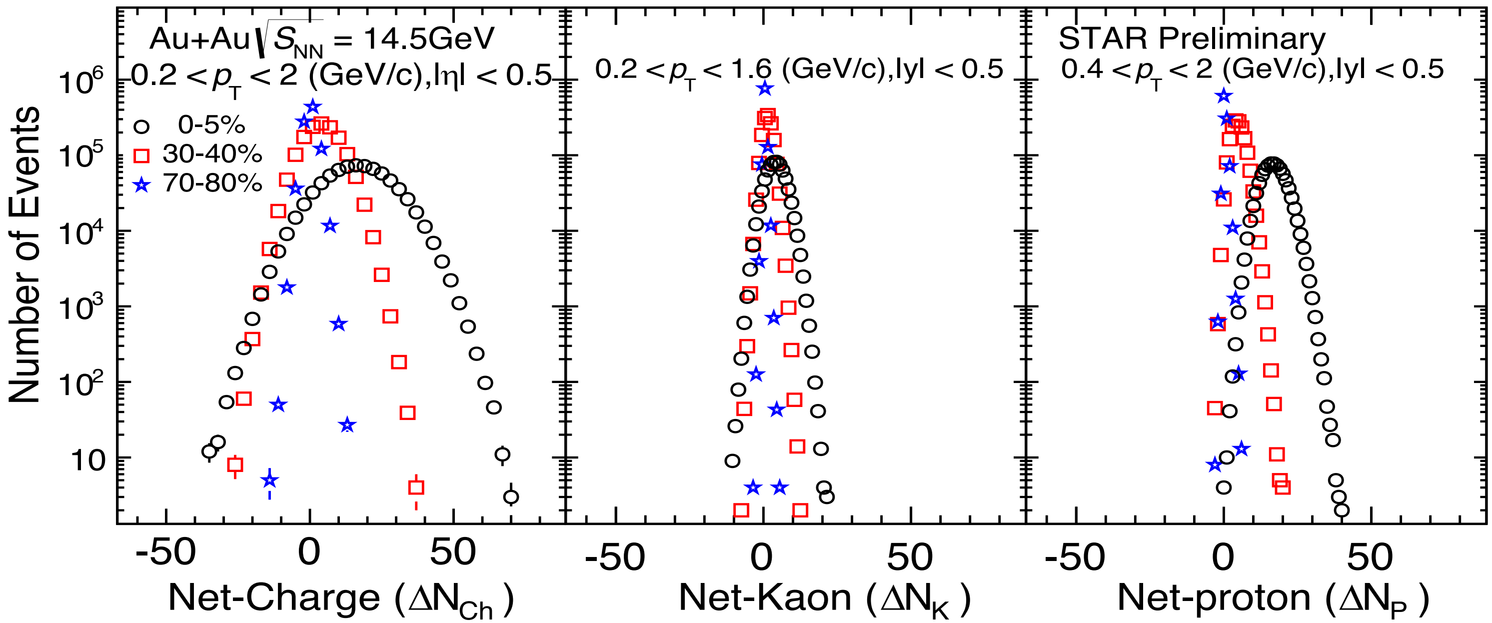
TPC PID



Phase Space



Analysis Details- II

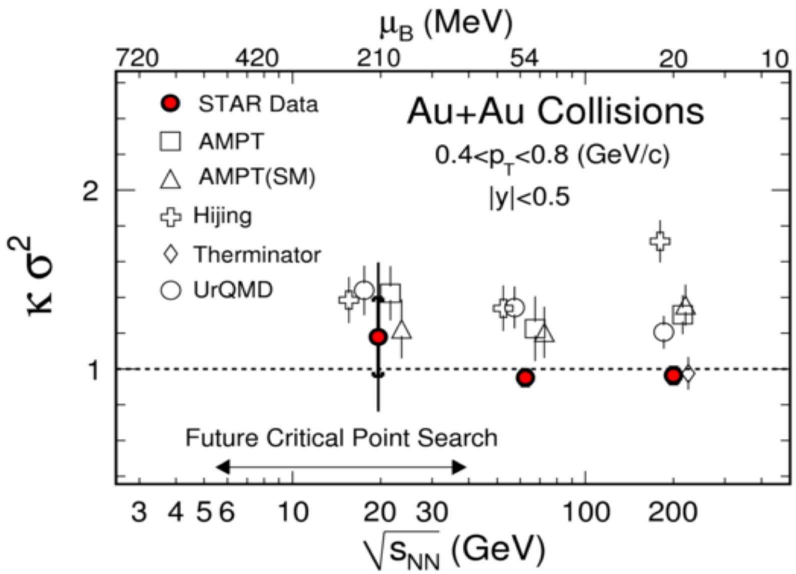


1. Statistical errors estimation : Delta theorem or bootstrap
2. Avoid auto-correlation effects: New centrality definition.
3. Suppress volume fluctuation： Centrality bin width correction (CBWC)
4. Detector efficiency correction : Binomial model

Review Article : X. Luo and N. Xu, Nucl. Sci. Tech. 28, 112 (2017).[被引297次]

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)

第一阶段能量扫描高阶矩测量结果

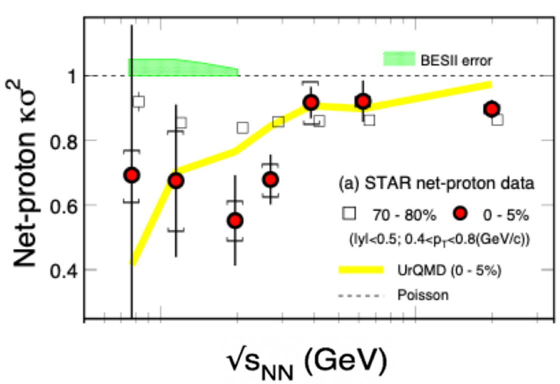


2010年首次测量：验证了该观测量在STAR重离子碰撞实验中的可行性

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

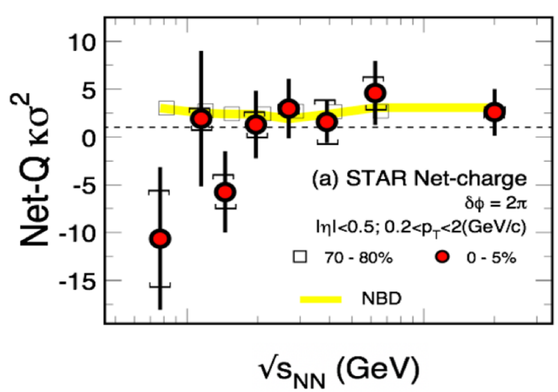
寻找QCD临界点信号：非单调能量依赖

净质子数



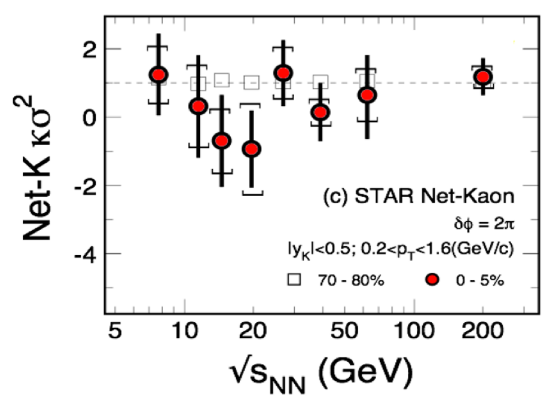
STAR, PRL 112, 032302 (2014).

净电荷数



STAR, PRL113, 092301 (2014).

净K介子数

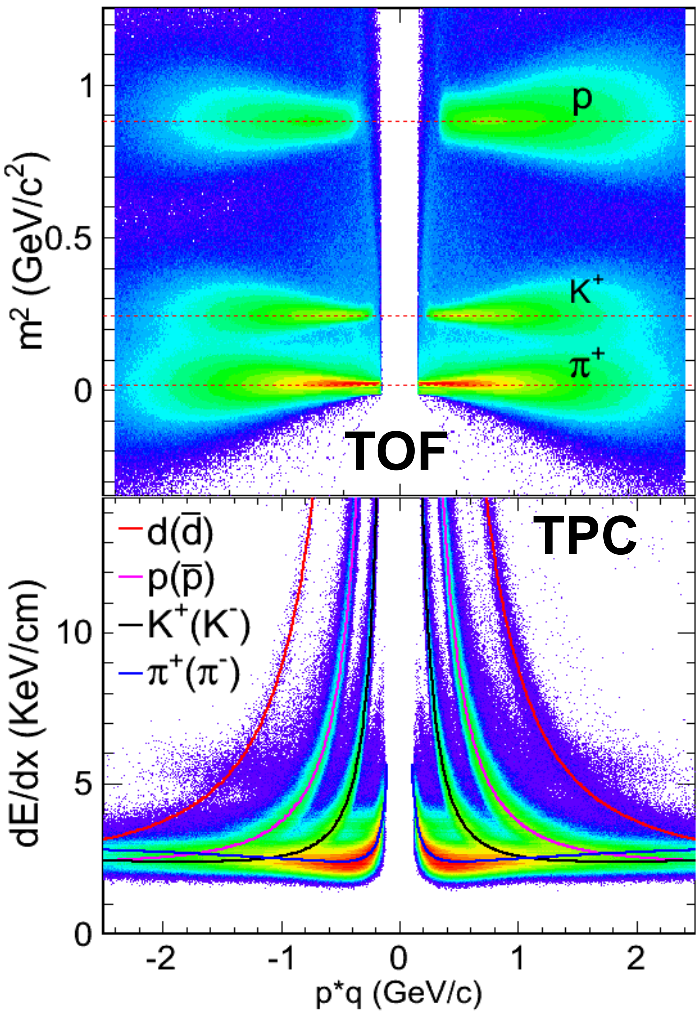


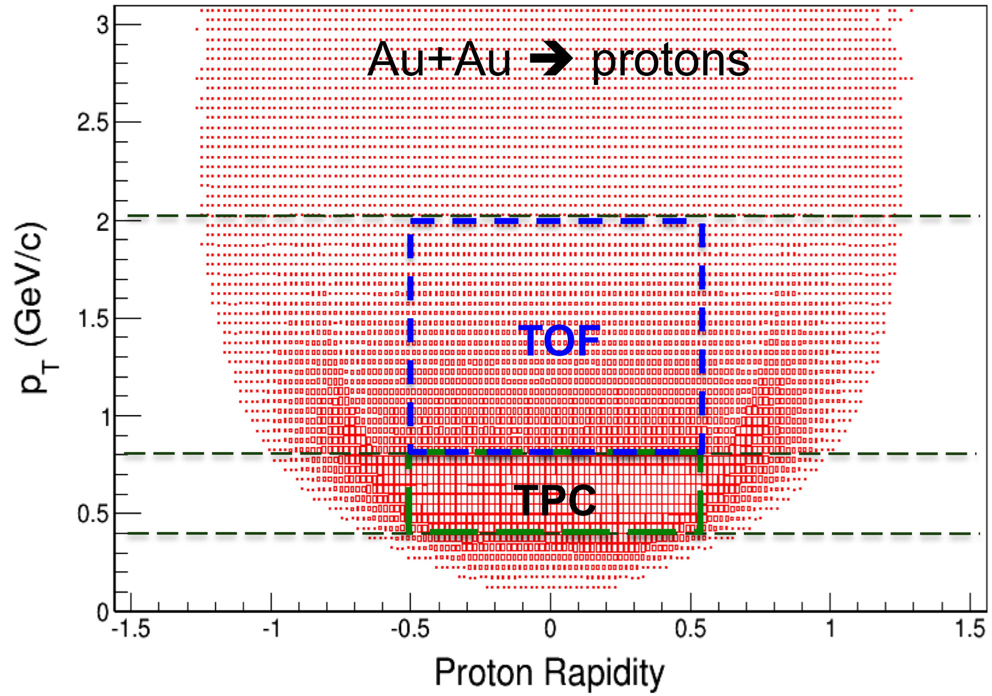
STAR, PLB 785, 551 (2018).

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)

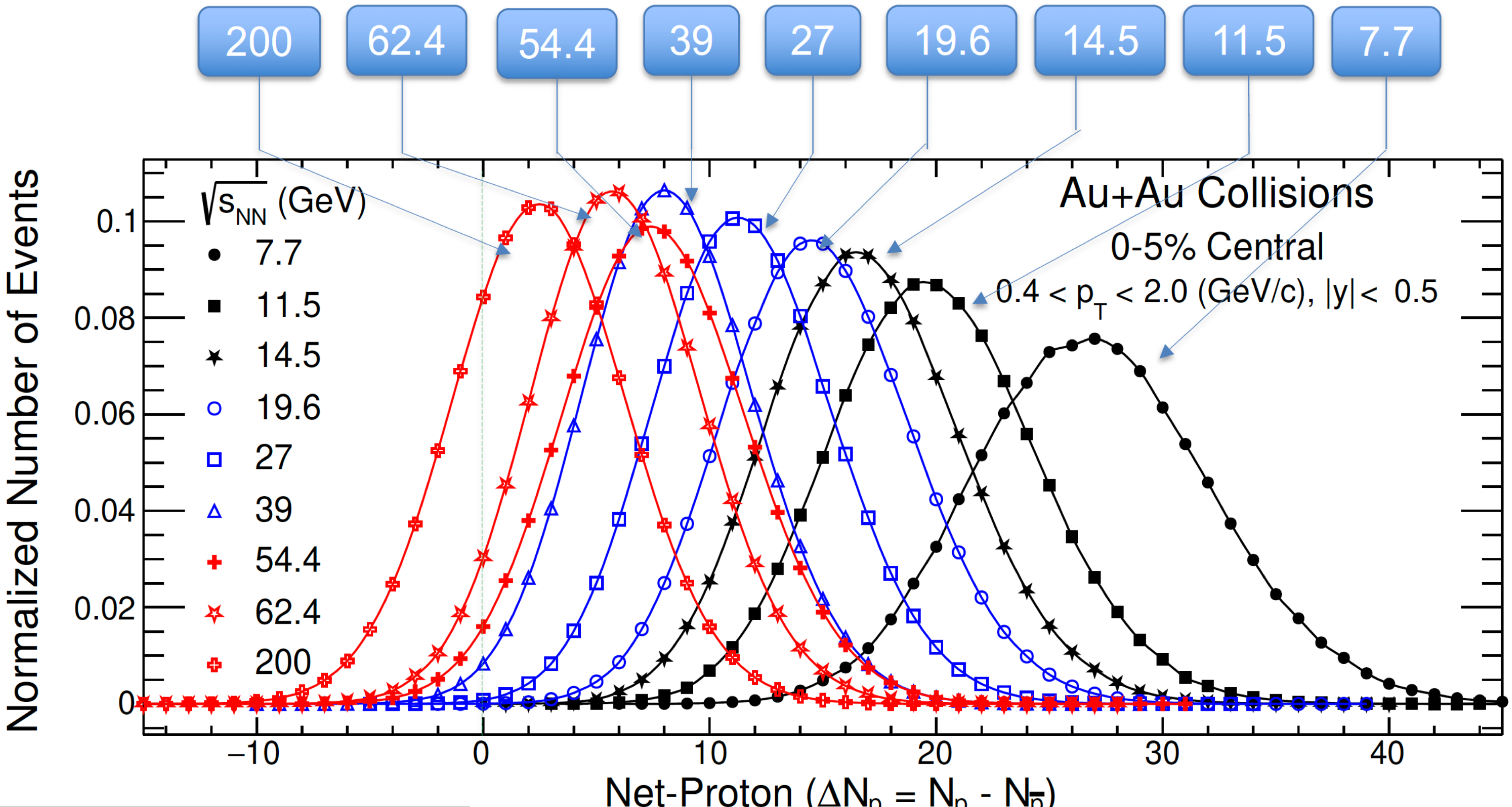




Acceptance: $|y| \leq 0.5$, $0.4 \leq p_T \leq 2$ GeV/c
Efficiency corrections:
TPC ($0.4 \leq p_T \leq 0.8$ GeV/c): $\varepsilon_{TPC} \sim 0.8$
TPC+TOF ($0.8 \leq p_T \leq 2$ GeV/c): $\varepsilon_{TPC} * \varepsilon_{TOF} \sim 0.5$

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

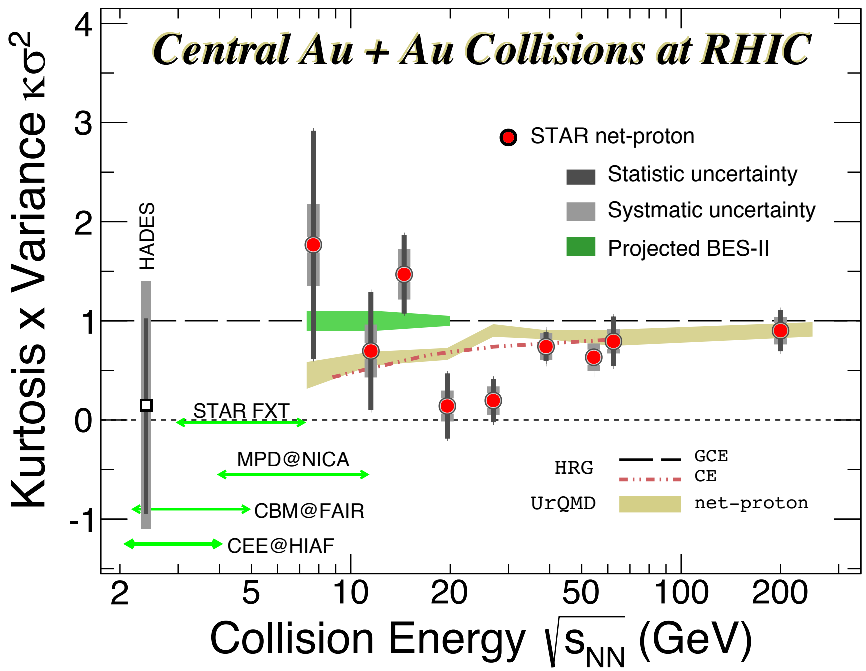
Raw Event-by-Event Net-Proton Distributions



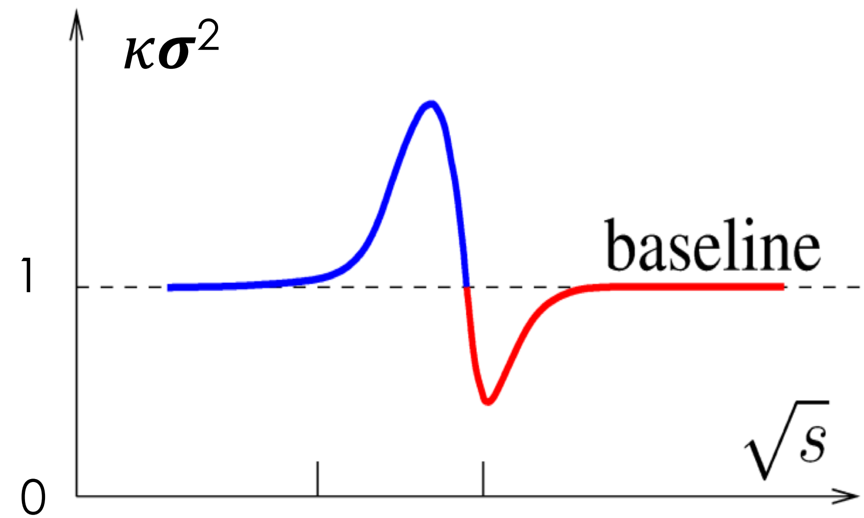
Mean values increase when decreasing energy:
Interplay between baryon stopping and pair production.

第一阶段能量扫描中净质子数涨落的高阶矩测量（横动量范围：0.4~2 GeV/c）

2011-2021：以STAR实验中国组为主导的合作团队经过10年测量、分析得到的实验结果



理论预言：临界点信号



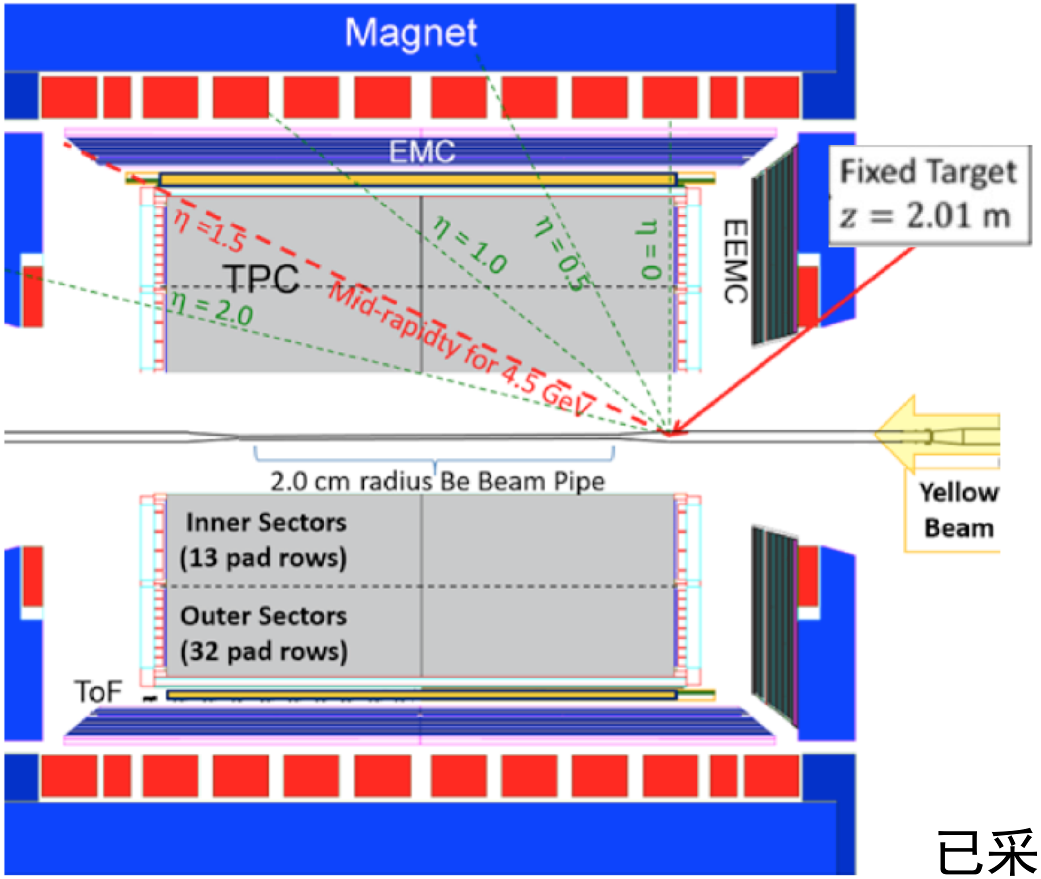
M. Stephanov, PRL107, 052301(2011); JPG 38, 124147 (2011).
JW Chen，J. Deng et al., PRD93, 034037 (2016);

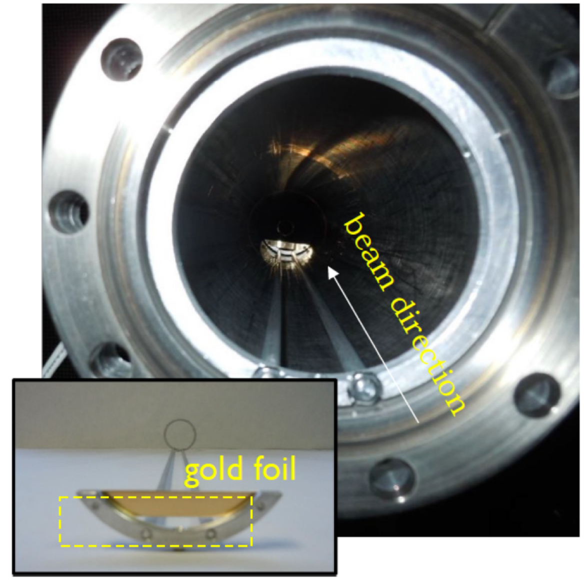
STAR，Phys. Rev. Lett. 126, 092301 (2021)
STAR，Phys. Rev. C 104, 024902 (2021)

关键能区：3 – 19.6 GeV。
第二阶段能量扫描(2019-2021), 实验数据已采集，正在加紧刻度、分析中。

首次在金金中心碰撞中观测到净质子数涨落的非单调能量依赖（3.1σ），与理论预言的QCD临界点信号一致，暗示进入临界区。该测量为在第二阶段能量扫描中3-19.6 GeV能量区间进行高精度测量、进一步明确QCD临界点信号和位置提供重要实验参照。

Fixed-target mode at STAR (2018-2021)





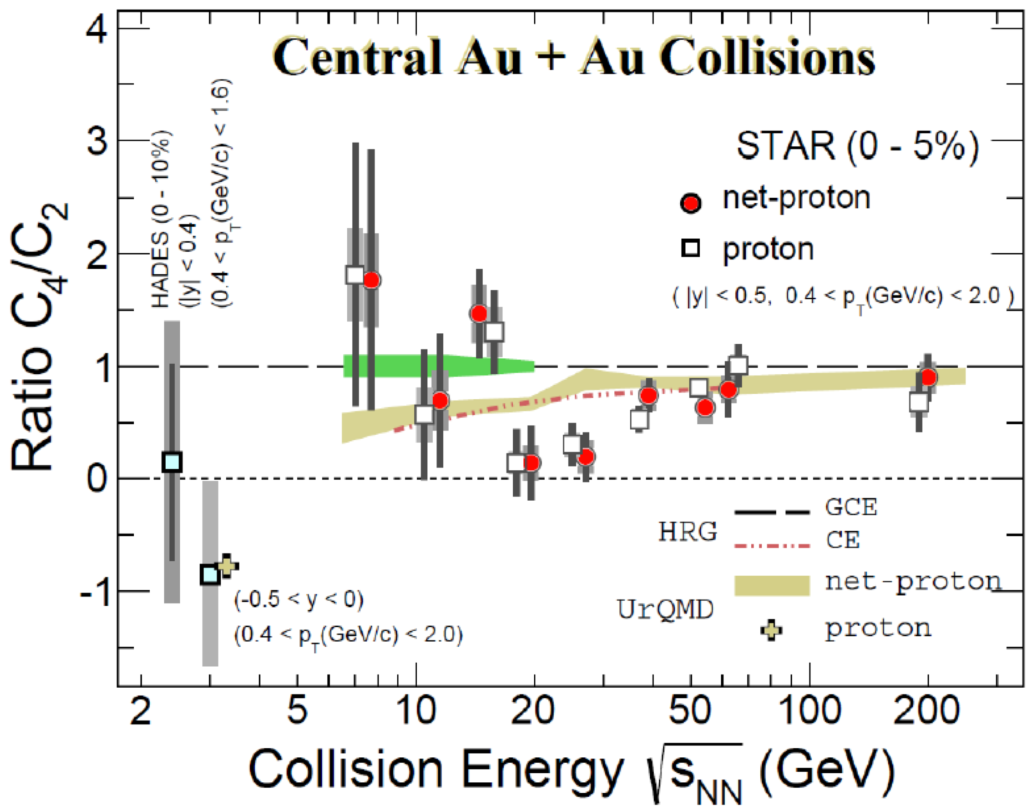
金箔靶：厚度：250 微米，
安装在距离TPC中心：Z=201 cm

为了扫描更高重子密度的相图区域STAR进行了固定靶实验，降低碰撞质心能量。

已采集7个能量点：3，3.2，3.5，3.9，4.5，5.2, 6.2, 7.7 GeV

3 GeV is the lowest energy of STAR fixed target experiment which extends the coverage of μ_B up to 750 MeV !

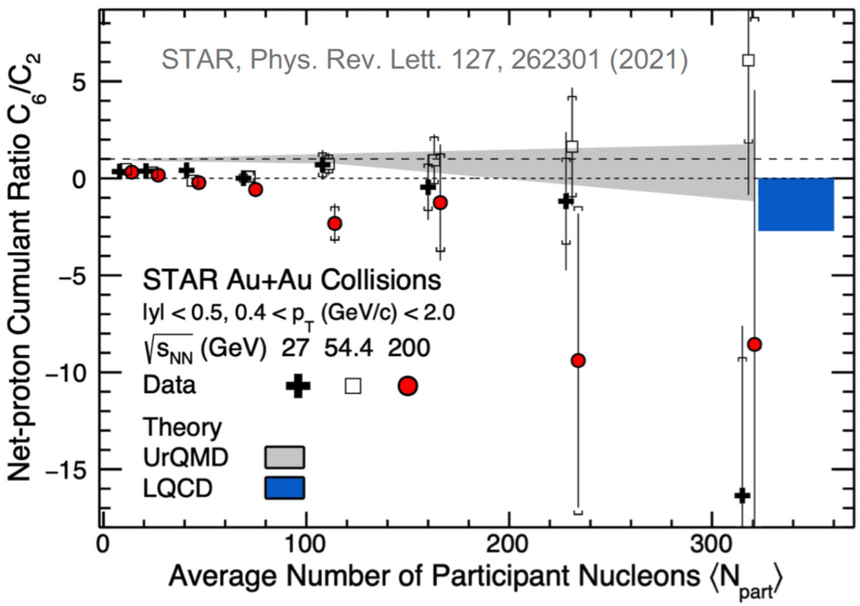
Energy Dependence of Fourth-order Fluctuations

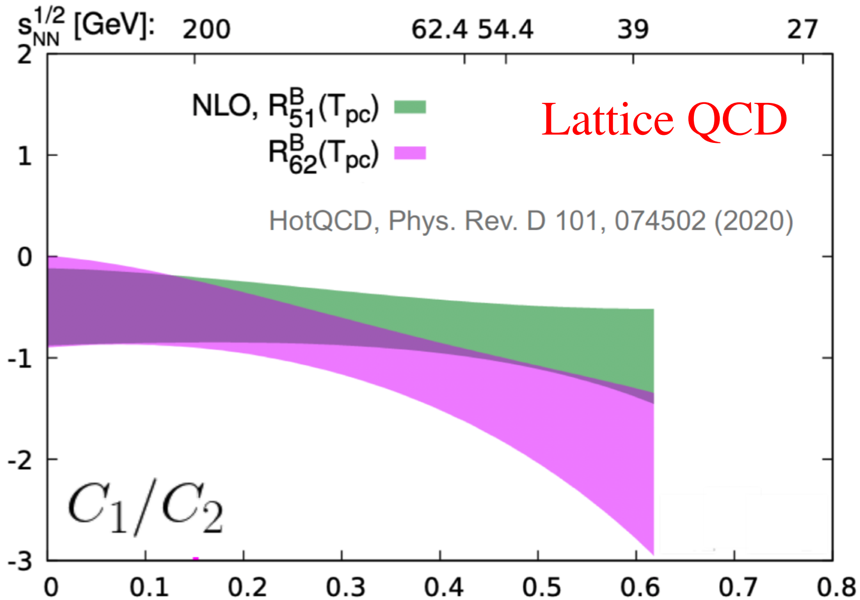


- The suppression of C_4/C_2 is consistent with fluctuations driven by baryon number conservation which indicates a hadronic interaction dominated region in the top 5% central Au+Au collisions at 3 GeV.
- The QCD critical point, if exists in heavy ion collisions, could likely be at energy higher than 3 GeV.

STAR, Phys. Rev. Lett. 128, 202303 (2022)
3 GeV : Yu Zhang (张宇), Ph.D thesis

Higher-order baryon number fluctuations





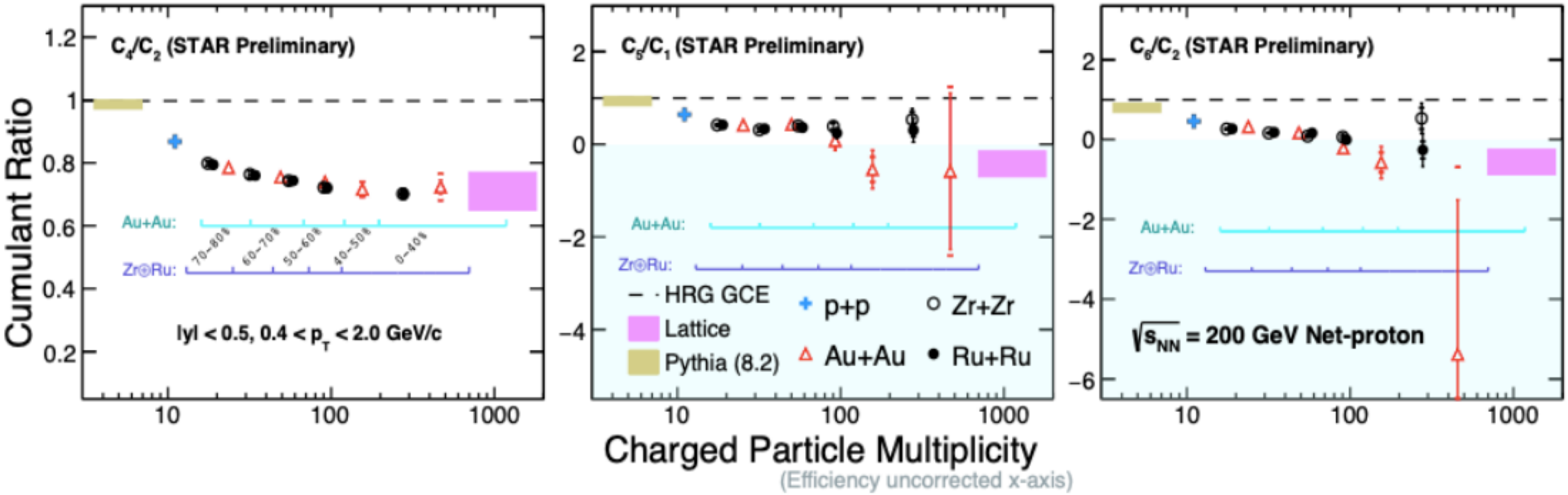
STAR, Phys. Rev. Lett. 127, 262301 (2021)

A. Bazavov, 丁亨通(HotQCD)等, Phys. Rev. D 101, 074502 (2020);

- First principle Lattice QCD calculation predicts $C_6/C_2 < 0$.
- C_6/C_2 progressively negative from peripheral to central collisions Indicate smooth crossover at 200 GeV.

C_6/C_2 : System Size Dependence

Lattice QCD and FRG Model : Negative C_6 when T ~ Tc could serve as experimental evidence of chiral crossover.

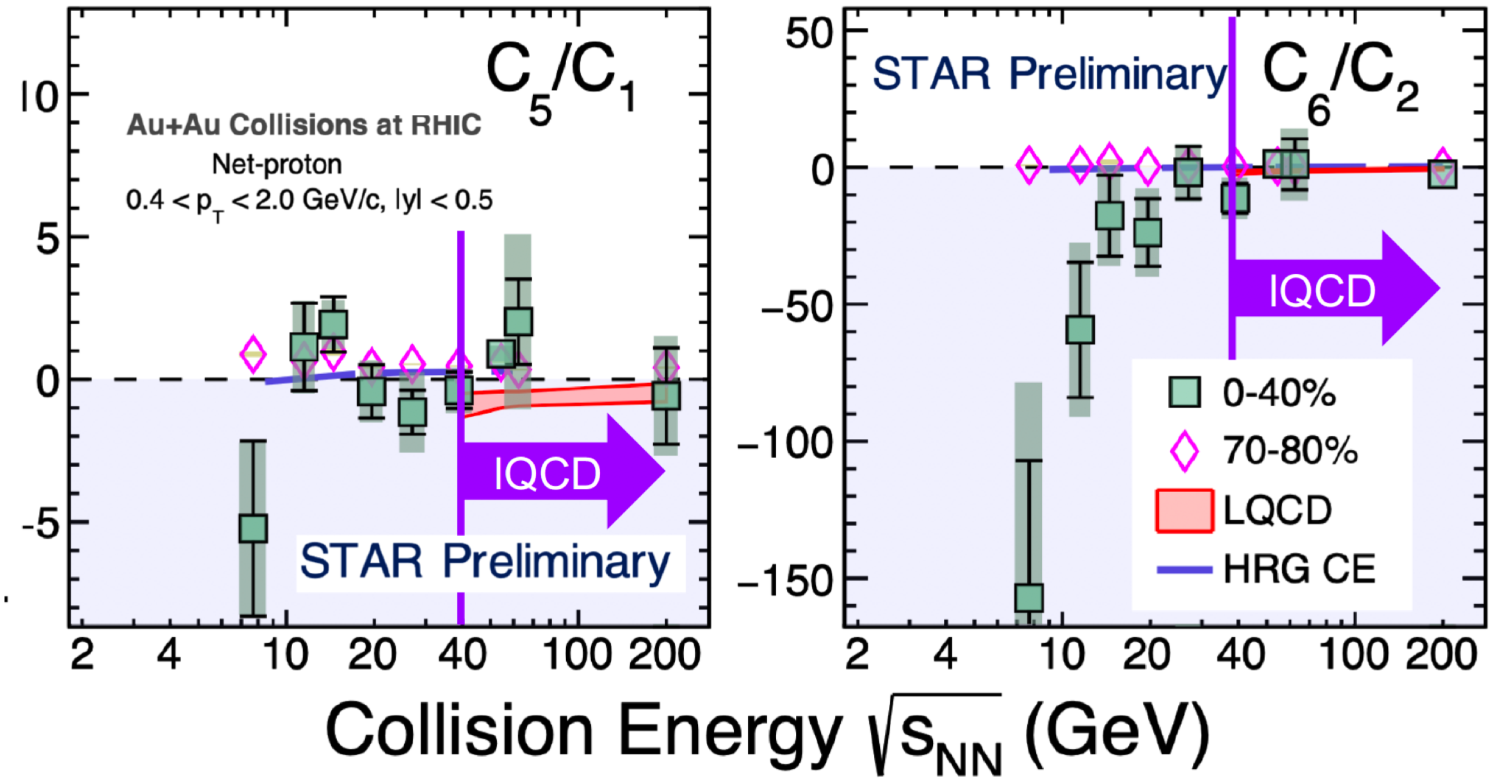


AuAu: PRC 104 (2021) 024902; PRL 126.092301 (2021), PRL 127 (2021) 262301 (2021).
Isobar data and p+p data : QM2022 (文章在合作组内部审核)

- 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.

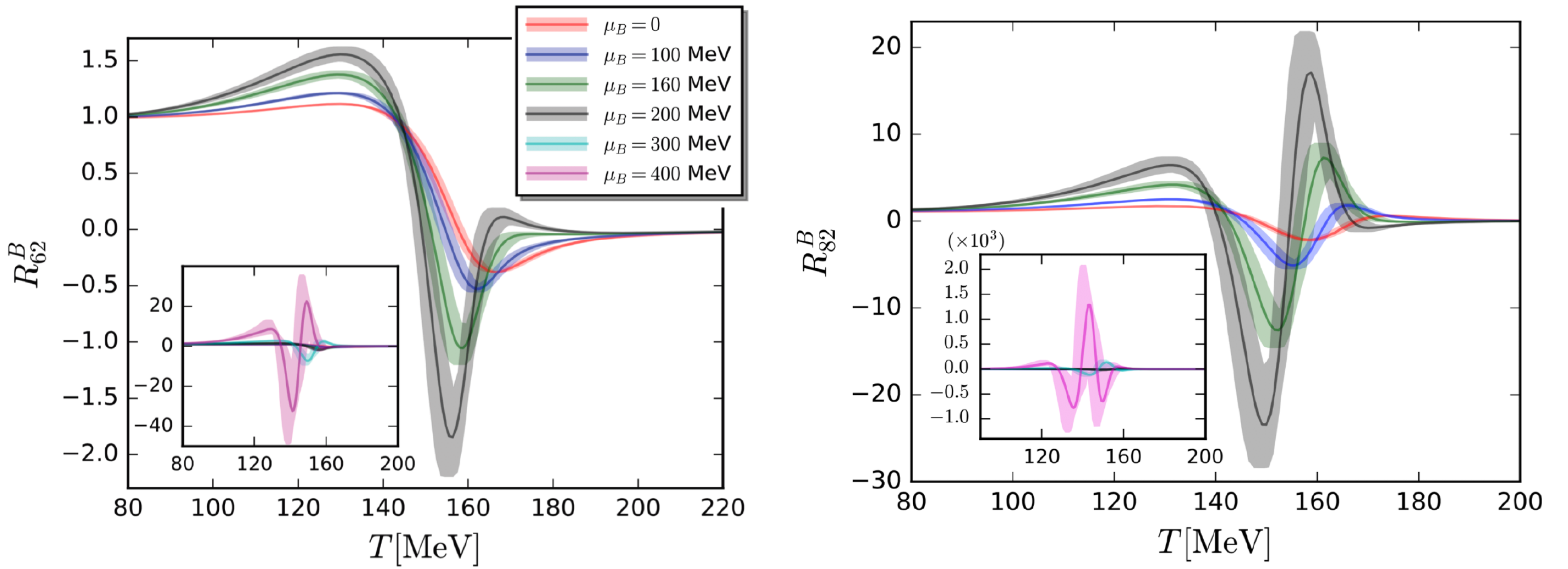
Energy Dependence of Fifth- and Sixth-order cumulants



1. C_5/C_1 (0-40%) fluctuates around zero.
2. C_6/C_2 progressively negative with decreasing collision energy down to 7.7 GeV. ~ 1.7 sigma to be negative sign.
3. Consistent with lattice QCD with $\mu_B < 110$ MeV.

STAR, arXiv : 2207.09837, submitted to PRL.

Even higher-order baryon number fluctuations



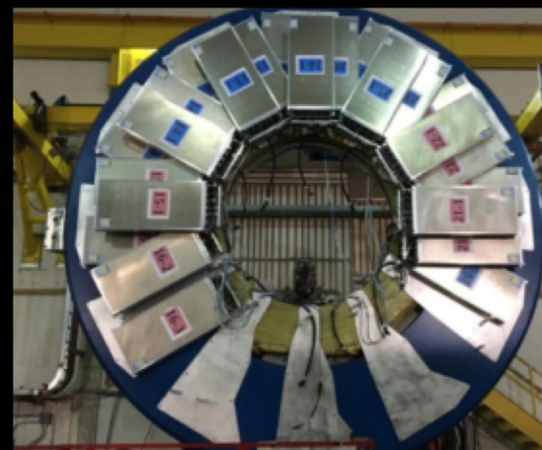
付伟杰, XFL等，Phys. Rev. D 104, (2021) 094047 (Editor Suggestion)

- Higher-order fluctuations are more sensitive to QCD phase transition.
- Negative C6 and C8 − crossover transition.
- Exp. : Statistical hungry and background effects maybe complicated.

STAR：2023-2025年将采集金金200 GeV，20亿个事列，有望精确测量5-8阶涨落。

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

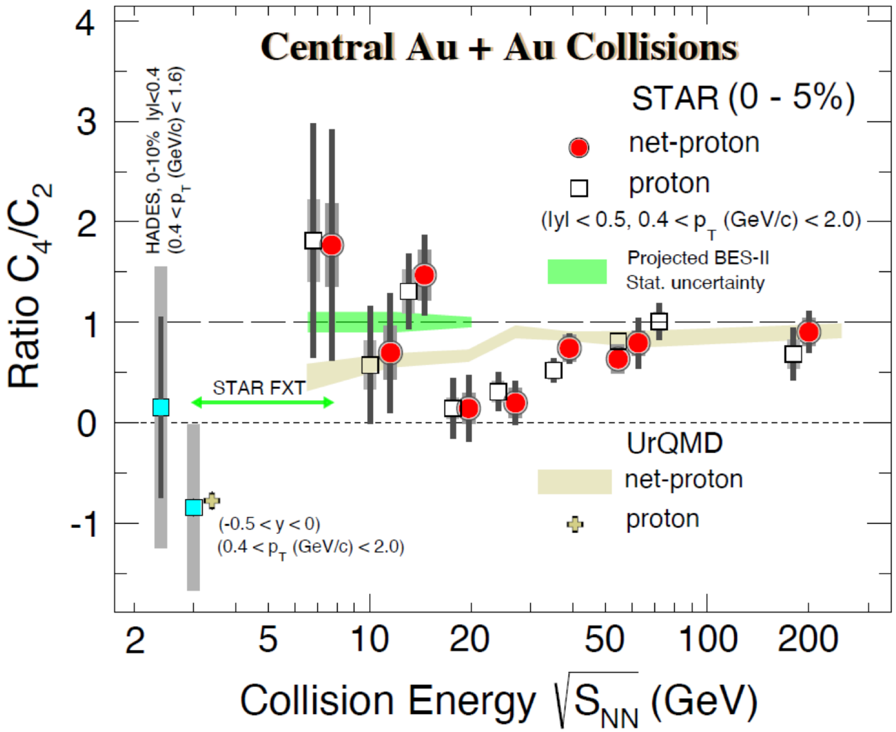
eTOF:
- Forward rapidity coverage
- PID at $\eta = 0.9$ to 1.5
- **Borrowed from CBM-FAIR**
- Ready in 2019

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)

Summary



1) BES-I : Indicate QCD critical point between 3– 40 GeV.

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

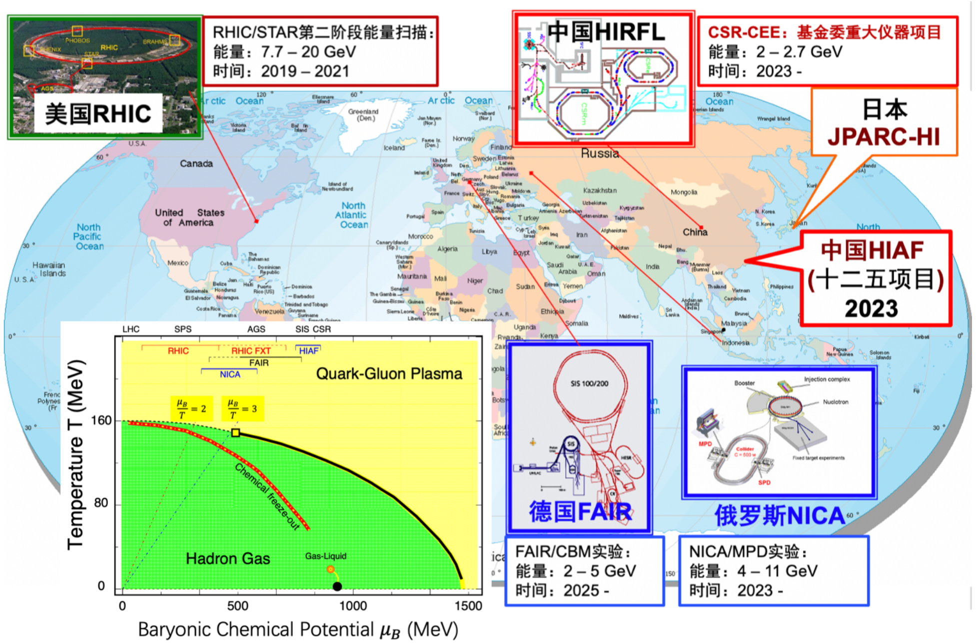
3) At 3 GeV collisions, μ_B ~ 750 MeV, different EOS comparing to high energy. hadronic dominated !

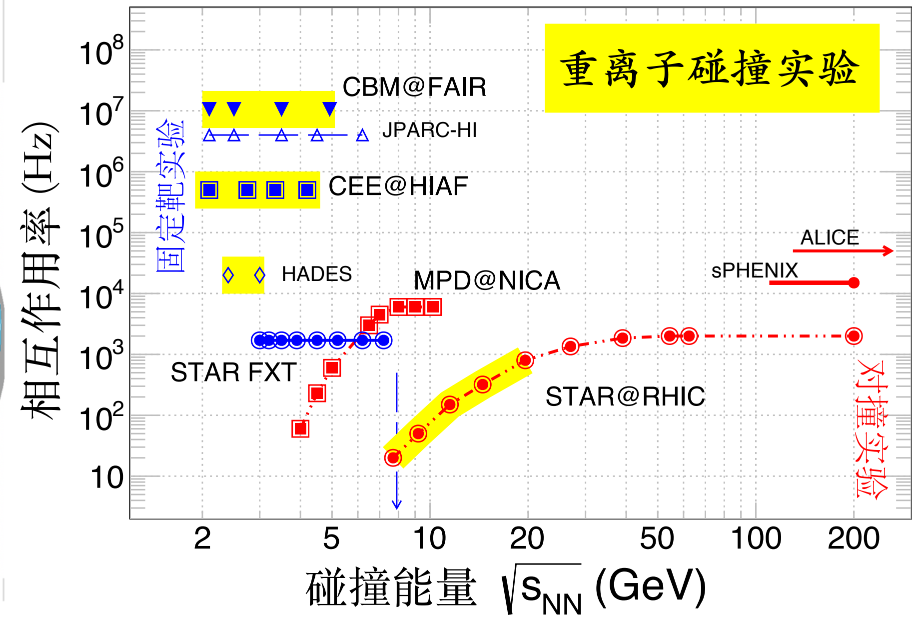
4) BES-II (completed !), analysis ongoing.
7.7 ~ 19.6 GeV (collider)
3 ~ 7.7 GeV (FXT)

5) Other sensitive observable : light nuclei production, intermittency.

Stay tuned for the exciting physics from RHIC BES-II (2019-2021) !

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

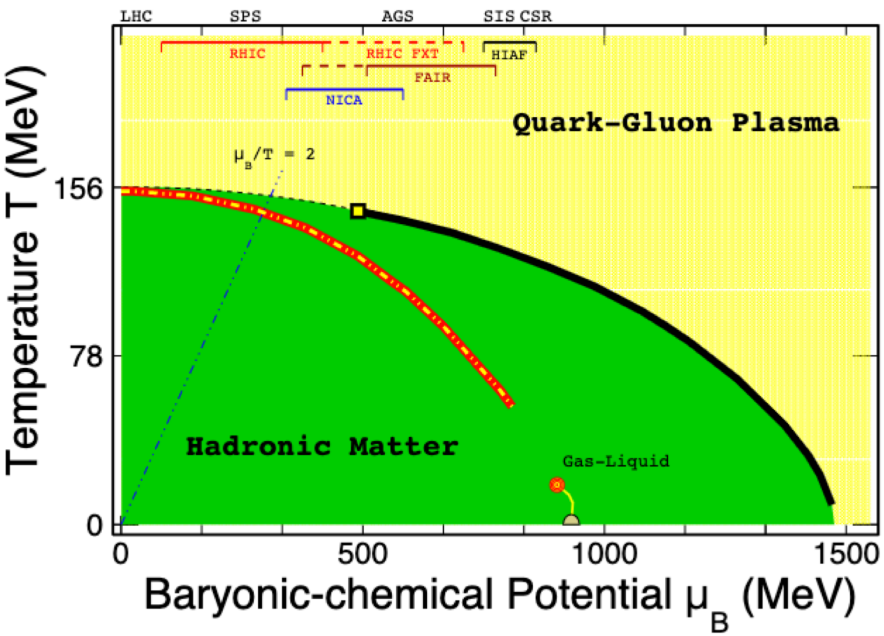
科普(前沿进展)：
XFL、刘峰、许怒,《物理》50(2), (2021)

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.

Book “Properties of QCD Matter at High Baryon Density”



Chapter 6

Concluding Remarks

This review is a collective effort of many experts from several subfields. It comprises of 14 months of work, started in the fall of 2020. A wide range of topics is covered, from the strong interaction properties of the deconfined quark-gluon plasma to the equation of state of compact stars and their connection to high-energy nuclear collisions. Future directions are articulated exploiting high baryon density regime afforded by several accelerator complexes under construction, with natural connection to astro-nuclear physics. The physics of high baryon density is a new beginning for the field of high-energy nuclear collisions.

At the end of "A Brief History of Time", S. Hawking wrote: "We want to make sense of what we see around us and to ask: What is the nature of the universe? What is our place in it and where did it and we come from? Why is it the way it is?"

These, in a sense, are the same questions we are asking. How is the visible world made under the law of Quantum Chromodynamics? What is its phase structure? What are its properties? Our curiosity persists and the quest for a deeper understanding of our universe continues on.

Xiaofeng Luo, Qun Wang, Nu Xu, and Pengfeng Zhuang
January, 2022, Beijing

A collective effort of many experts from several subfields.
Editors : XFL, Qun Wang, Nu Xu, and Pengfeng Zhuang
Springer 2022 in production.

谢谢大家！

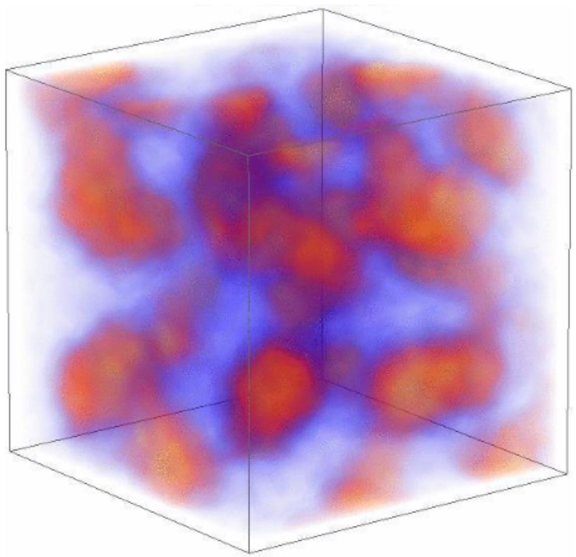
Light nuclei production as probes of QCD phase structure

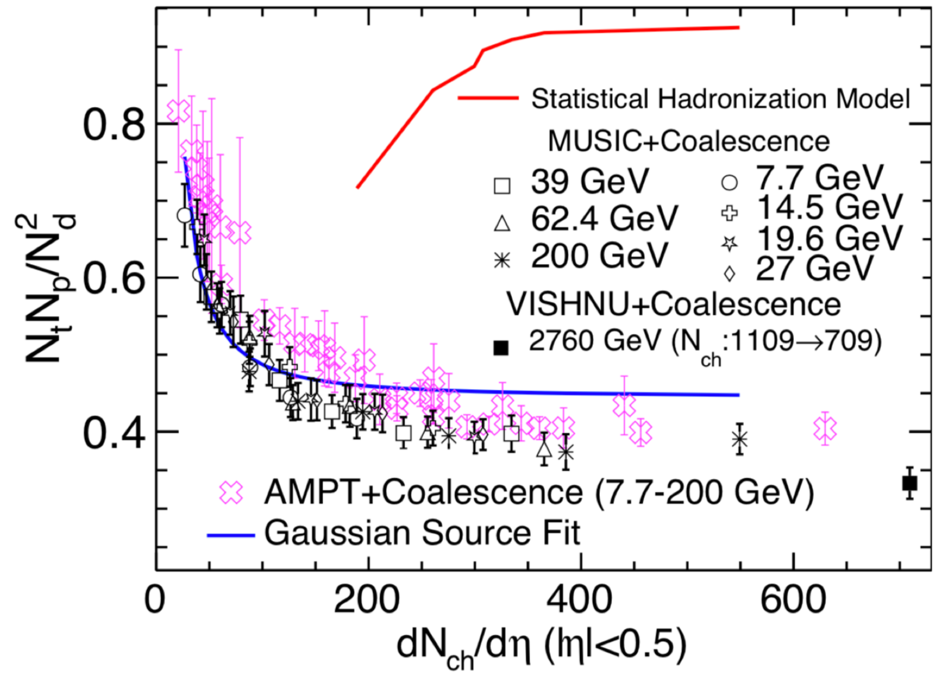
Near first order P.T. or critical point ：
large density fluctuations and baryon clustering

Based on coalescence model:

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

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



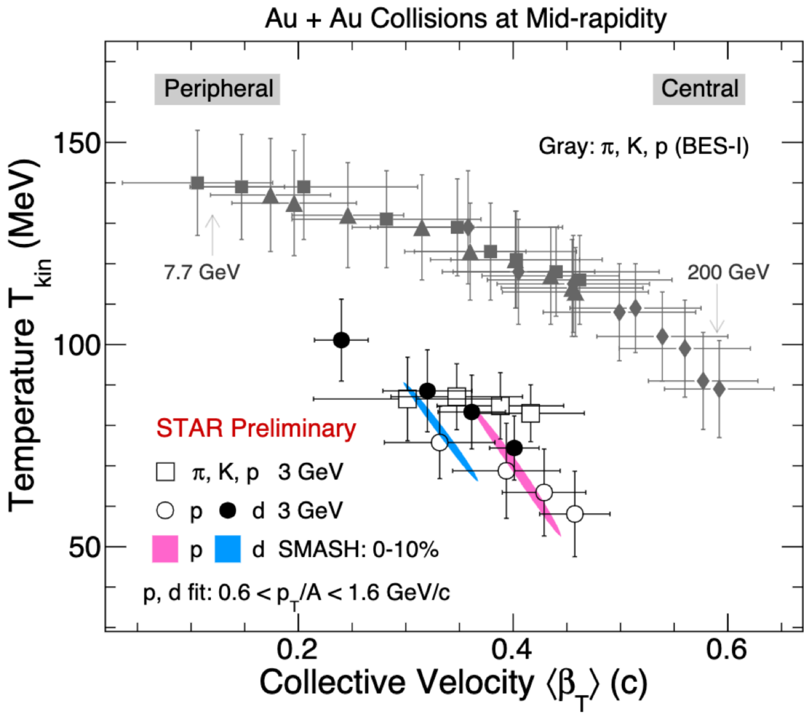


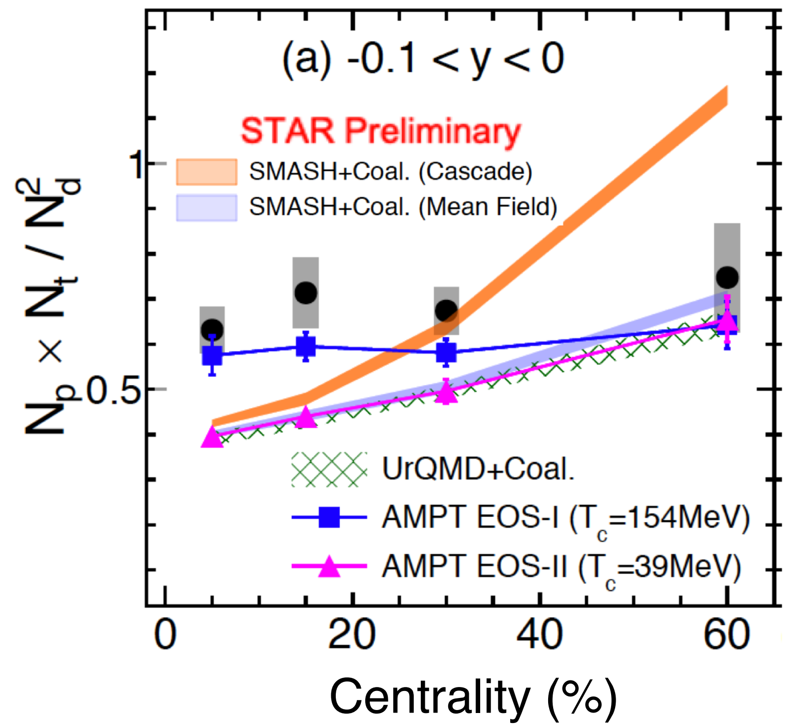
W. Zhao, K.J. Sun, C.M. Ko, X. Luo, Phys. Lett. B 820, 136571 (2021)

➢ The compound yield ratio is a powerful tool to probe the signature of critical point and distinguish the different production mechanism of light nuclei 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). H. Liu et al, Phys. Lett. B 805, 135452 (2020). K. Sun, C. M. Ko, Phys. Rev. C 103,064909 (2021)；W. Zhao et al., Phys. Rev. C102, 044912 (2020); X. G. Deng, Y. G. Ma, Phys. Lett. B 808, 135668 (2020);

Light Nuclei Production in Au + Au Collisions





3 GeV STAR data : 刘慧, QM2022 talk

- FXT 3 GeV shows different trend compared to BES-I Au+Au collisions, indicating a different medium equation of state (EoS) at 3 GeV
- The AMPT model with 1st order P.T. EoS with a critical temperature (~154MeV) shows the same centrality dependence as that observed by STAR experiment
- BES-I triton paper is under collaboration review.

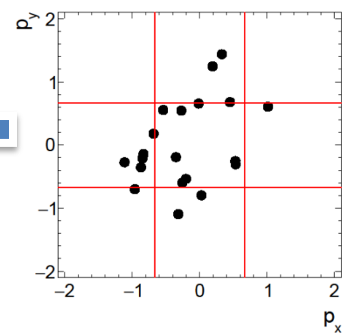
K. J. Sun et al. arXiv: 2205.11010

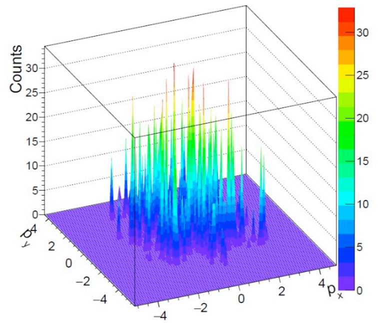
Intermittency (间歇) for Charged Particle at BES-I

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

吴锦(for STAR)，ISMD2021

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





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

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

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

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