RHIC-STAR实验QCD相图研究进展

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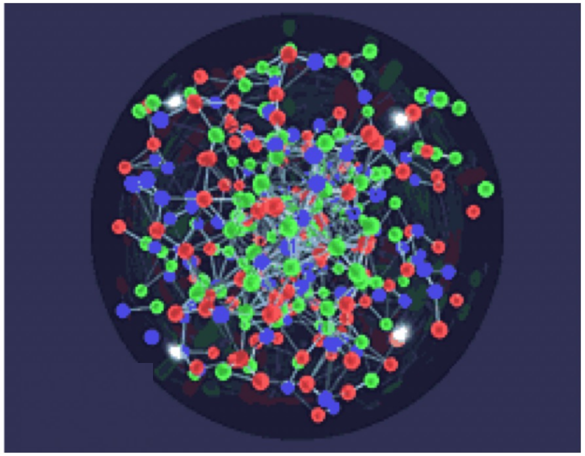
2022年7月29-31日

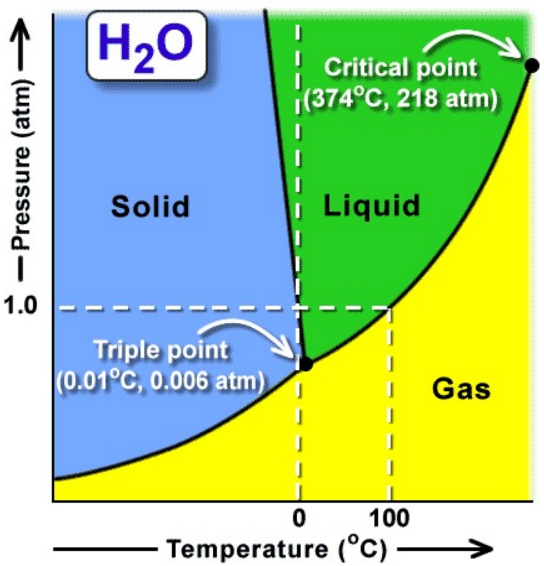
2019年中山大学“中国RHIC物理二十年”会议合影

QCD Thermodynamics

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
- 涡旋、磁场强度

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)?

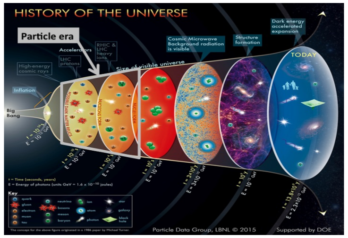
内因：相互作用、系统对称性
外因：外部条件的改变

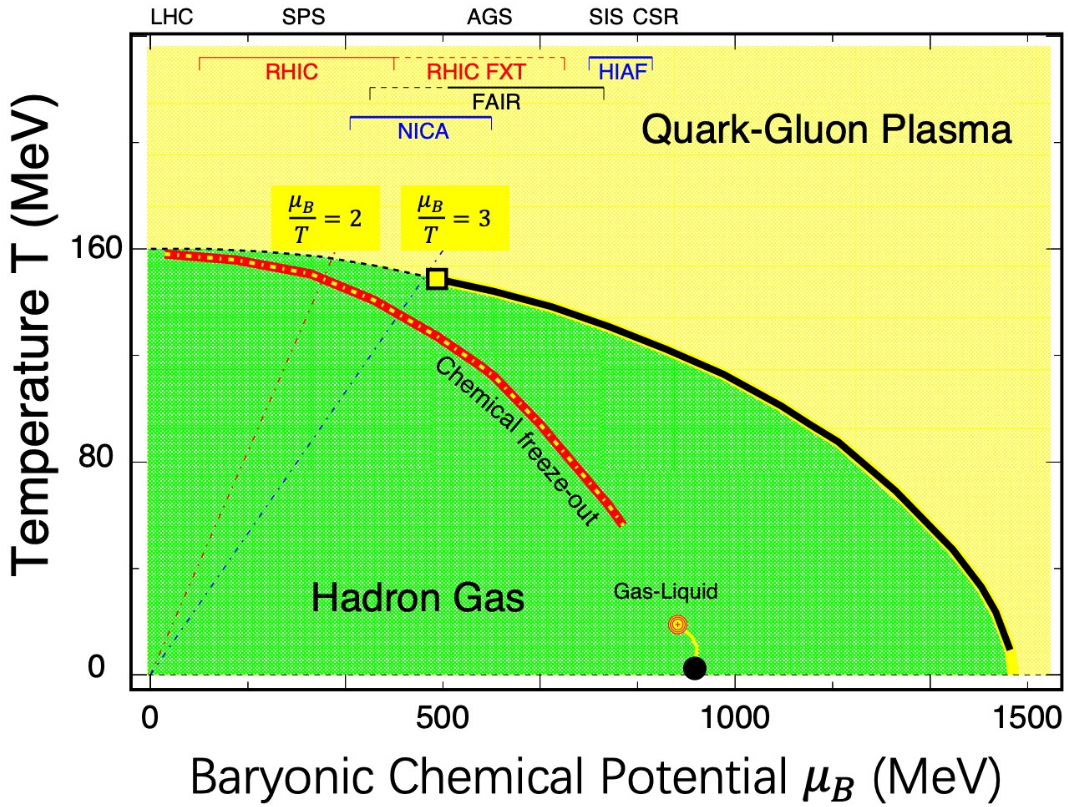
临界现象：

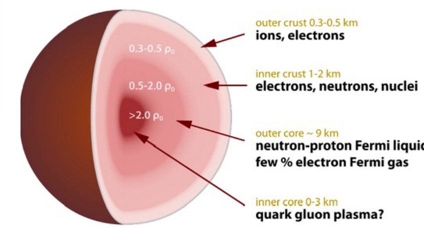
- **密度涨落增强与关联长度增大：**
  临界乳光现象
- **系统的对称性决定临界指数：即热力学量的临界发散行为**

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





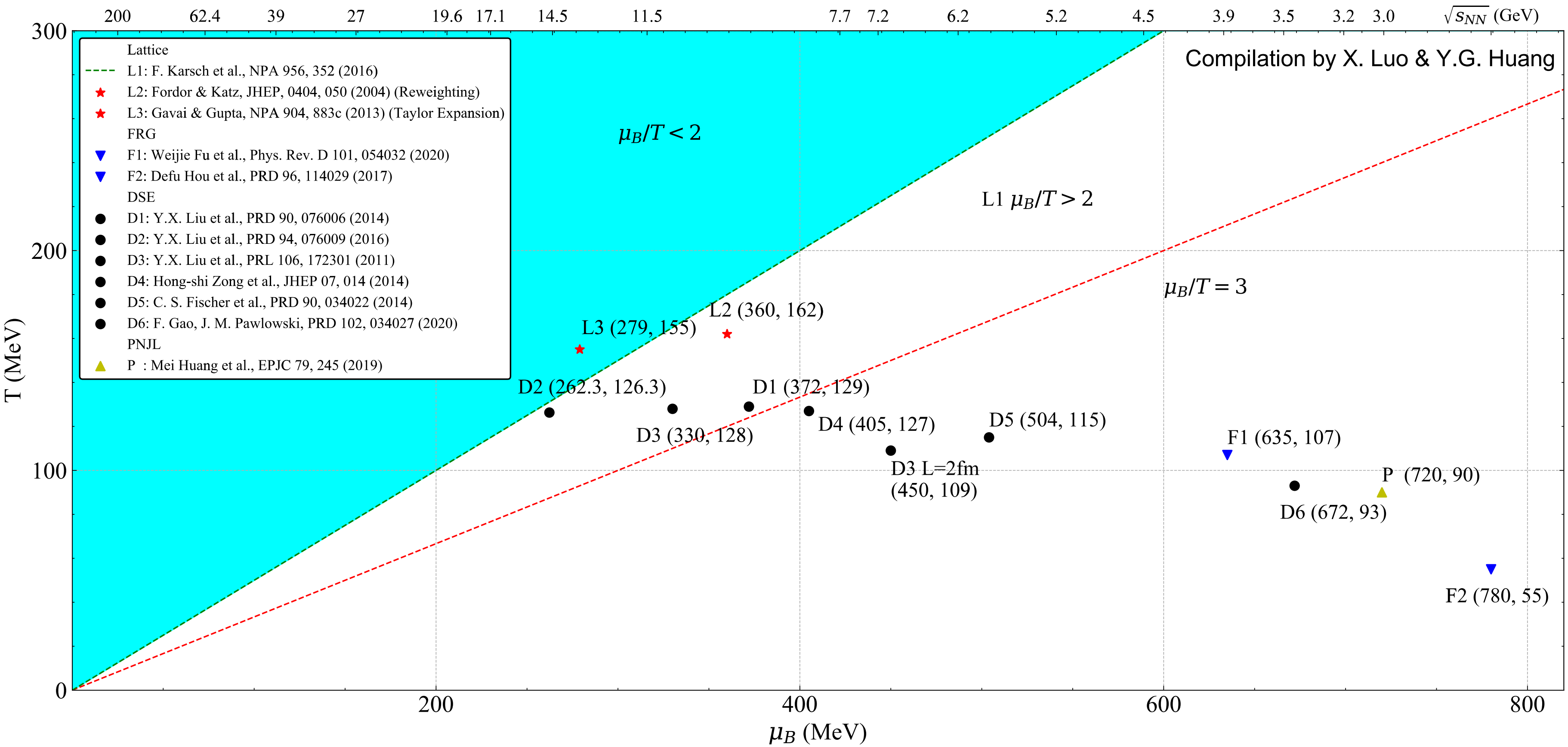


它是我国核物理学科发展战略待解决的关键科学问题之一，也是我国大科学装置强流离子加速器(HIAF)的一个主要物理目标(广东惠州建设中)

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

临界点位置：理论模型计算

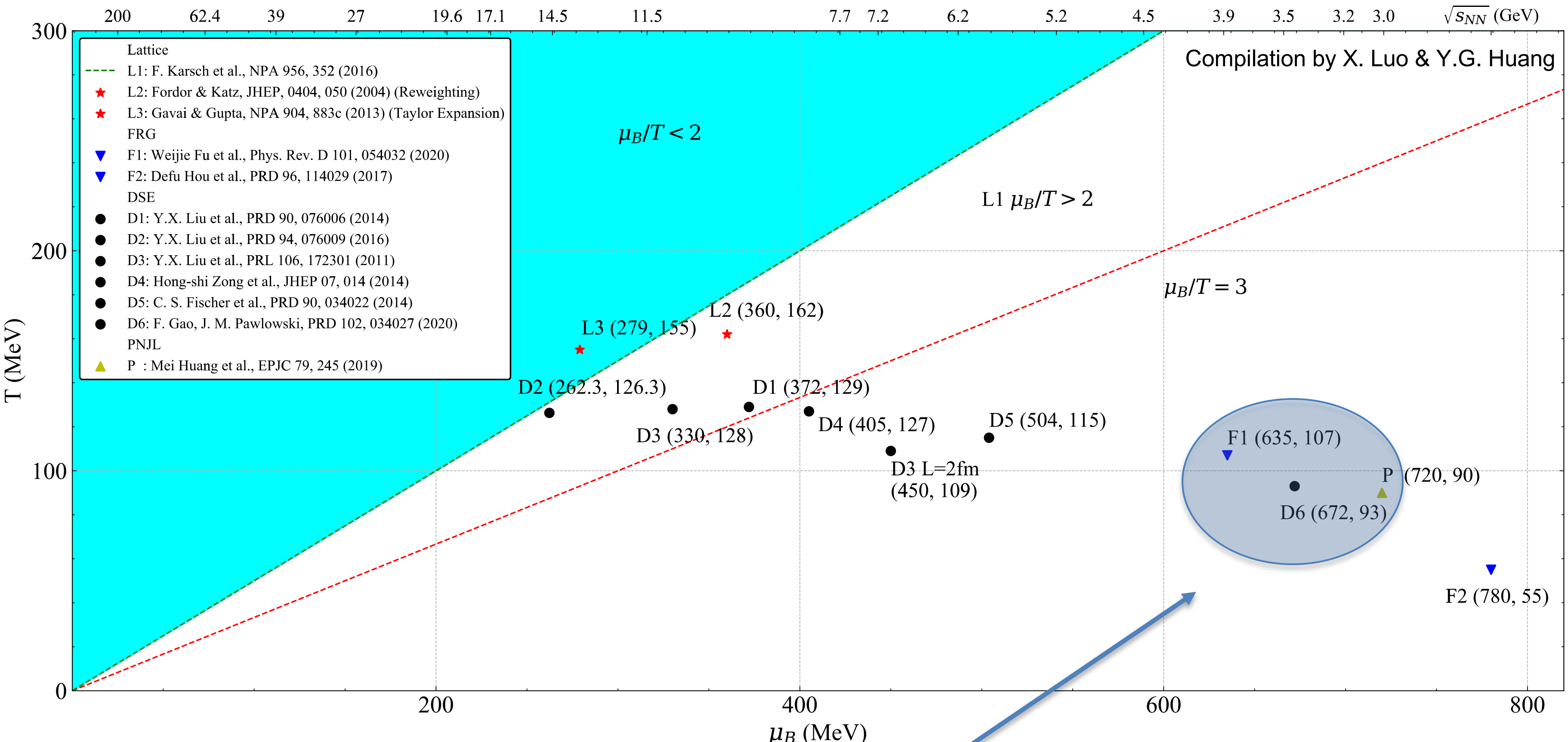
Preliminary collection from Lattice, DSE, FRG and PNJL (2004-2020)



理论上确定QCD相变临界点的位置有较大的不确定性。

临界点位置：理论模型计算

Preliminary collection from Lattice, DSE, FRG and PNJL (2004-2020)



见伟杰报告

理论计算：当前QCD临界点最有可能所在相图区域。

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

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)

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).

2. Fluctuations signals the Quark Deconfinement.

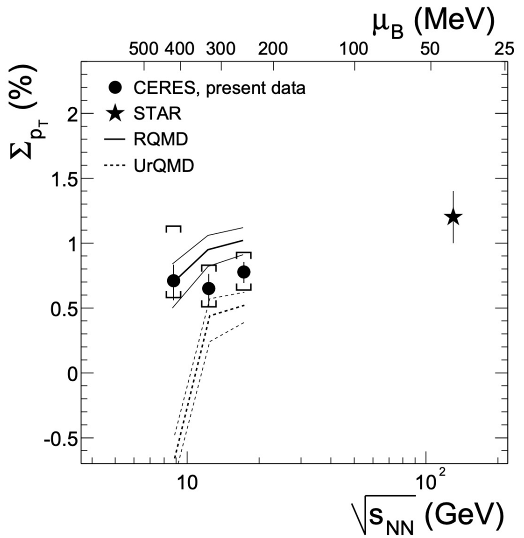
S. Jeon and V. Koch, Phys. Rev. Lett. 85, 2076(2000).
M. Asakawa, U. Heinz and B. Muller, Phys. Rev. Lett. 85, 2072 (2000).

热力学强度量与延展量的涨落相关

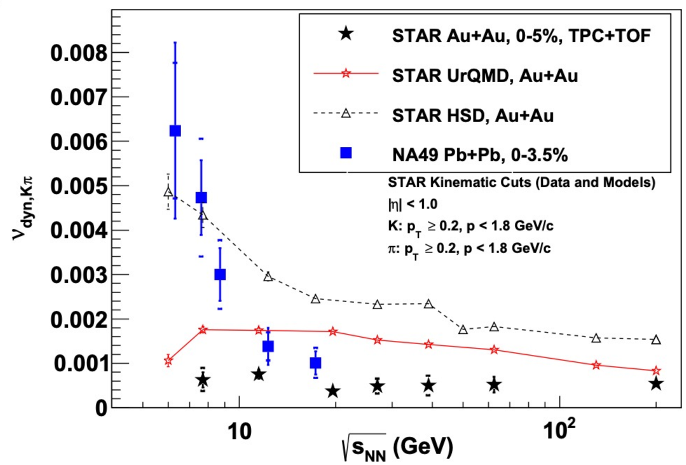
比热 -> 能量涨落
不可压缩系数->粒子数涨落

系统关联长度

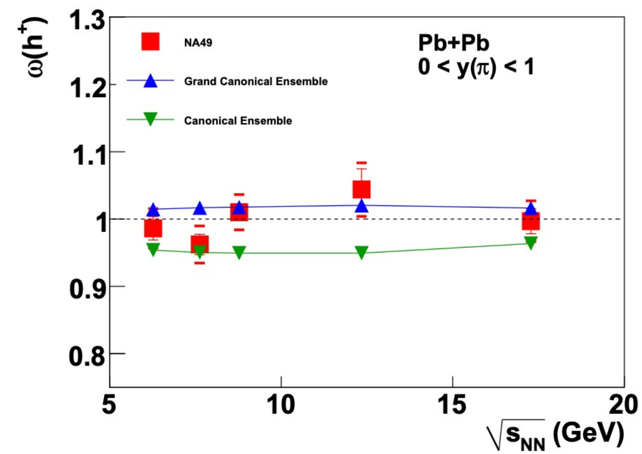
Mean p_T fluctuations



Particle ratio fluctuations



Multiplicity fluctuations



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

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

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

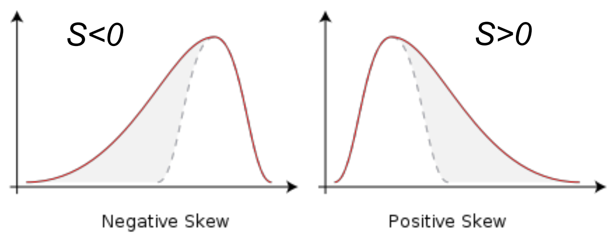
Higher Order Fluctuations of Conserved Quantities (B, Q, S)

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

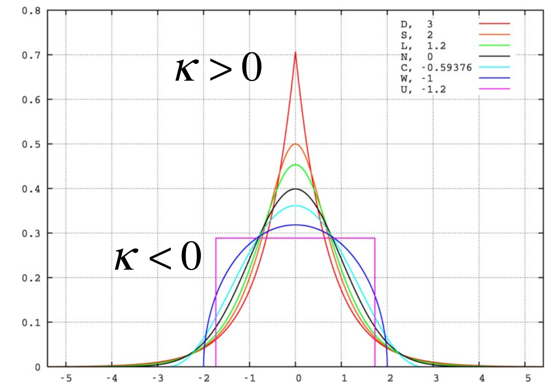
$$<\delta N> = N - <N>$$
$$C_1 = M = <N>$$
$$C_2 = \sigma^2 = <(\delta N)^2>$$
$$C_3 = S\sigma^3 = <(\delta N)^3>$$
$$C_4 = \kappa\sigma^4 = <(\delta N)^4> - 3<(\delta N)^2>^2$$

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

Skewness (S) → asymmetry



Kurtosis (κ) → Sharpness

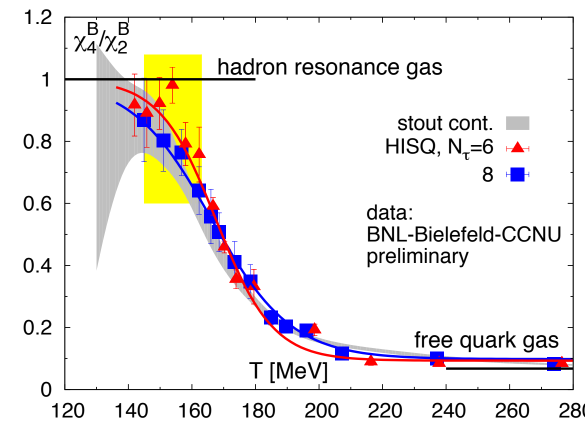


M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009); 107, 052301 (2011).
M.Asakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009).

2. Direct connect to the susceptibility of the system

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

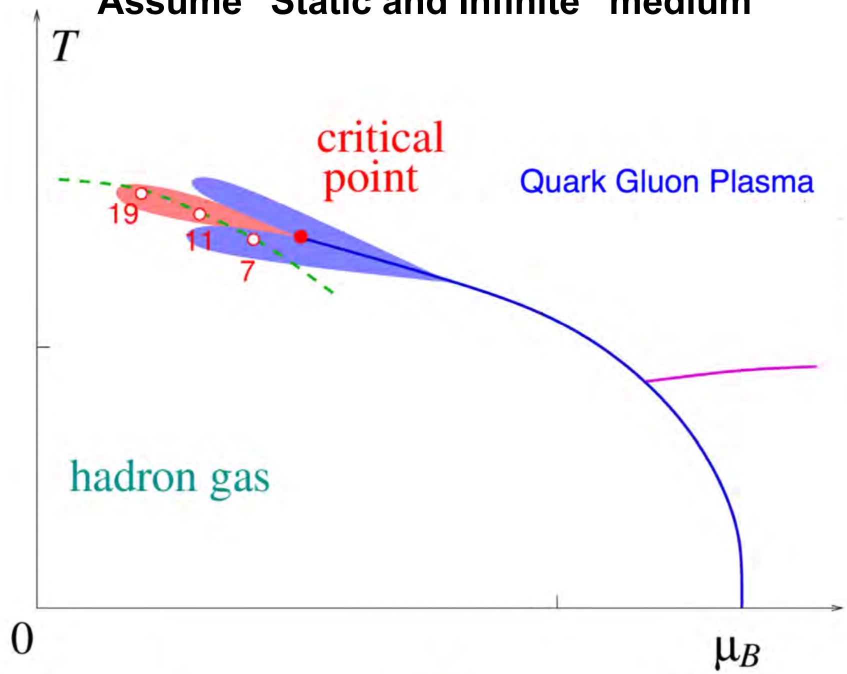
$$\chi_q^{(n)} = \frac{1}{VT^3} \times C_{n,q} = \frac{\partial^n (p/T\wedge 4)}{\partial(\mu_q)^n}, q = B,Q,S$$

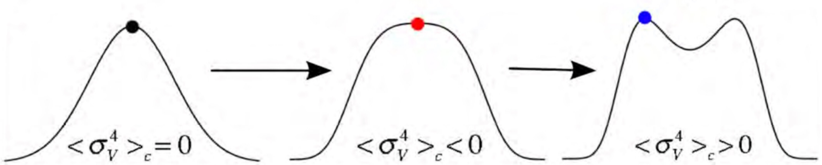


Cheng et al, PRD (2009) 074505. F. Karsch and K. Redlich , PLB 695, 136 (2011).
S. Gupta, et al., Science, 332, 1525(2012). A. Bazavov et al., PRL109, 192302(12) // S. Borsanyi et al., PRL111, 062005(13)

Signals of QCD Critical Point : Theory/Model

Assume "Static and Infinite" medium

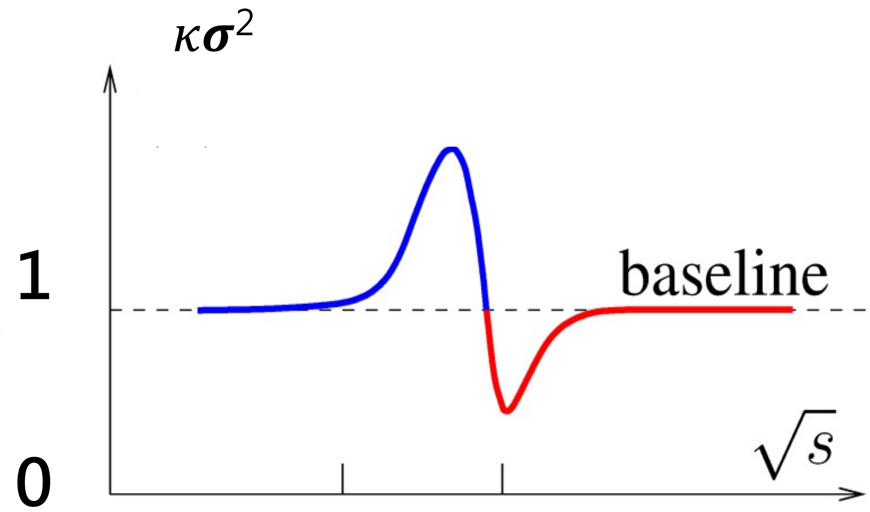




M. Stephanov, PRL107, 052301 (2011); J. Phys. G 38, 124147 (2011).
Schaefer et al., PRD 85, 034027 (2012); W. Fu et al., PRD 94, 116020 (2016).
J.W. Chen, J. Deng, et al., PRD 93, 034037 (2016). PRD 95,014038 (2017).
W. K. Fan, X. Luo, H.S. Zong, IJMPA 32, 1750061 (2017);
G. Shao et al., EPJC 78, 138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

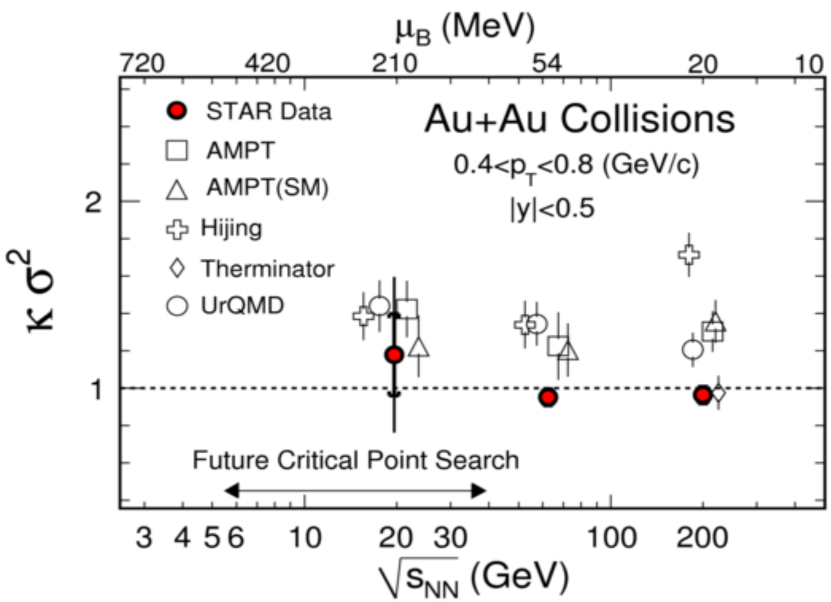


$\kappa\sigma^2 = 1$ (Poisson Fluctuations)

Characteristic signature of CP:
Non-monotonic energy dependence

"Oscillation Pattern"
Especially the Peak at low energies

第一阶段能量扫描高阶矩测量结果



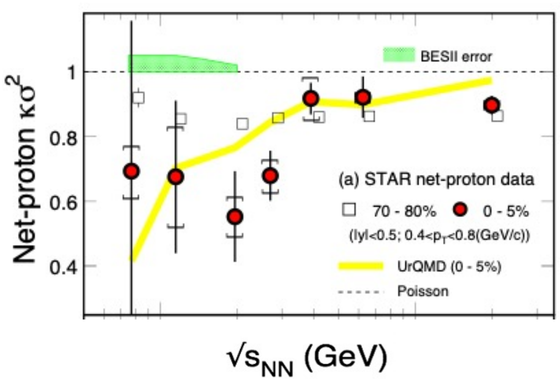
首次测量：验证了该观测量在STAR重离子碰撞实验中的可行性

STAR, PRL105, 022302(2010).

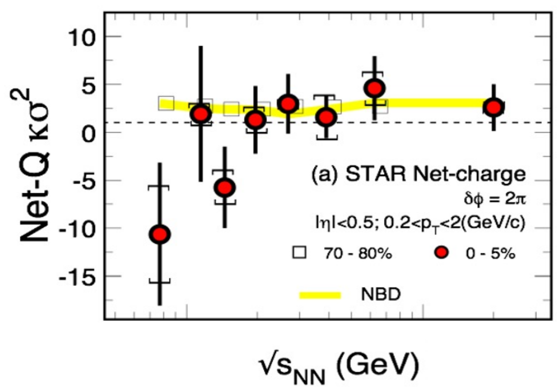
寻找QCD临界点信号：非单调能量依赖

Total citation of the 4 papers : ~ 1500

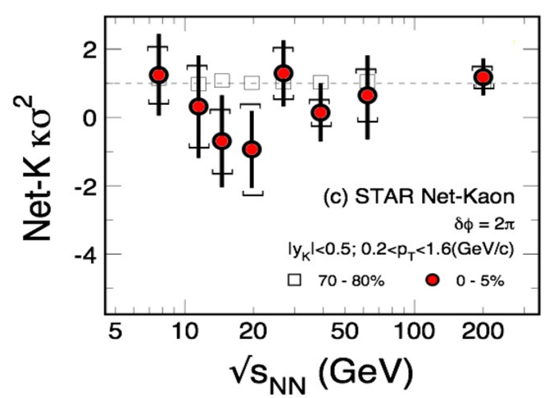
净质子



净电荷



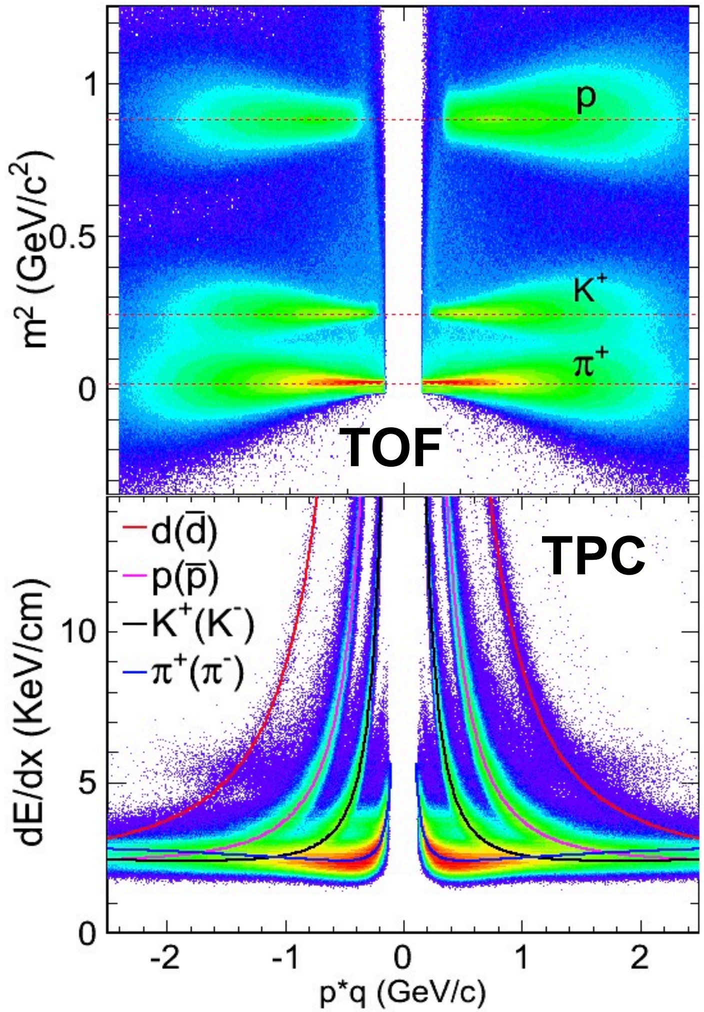
净K介子



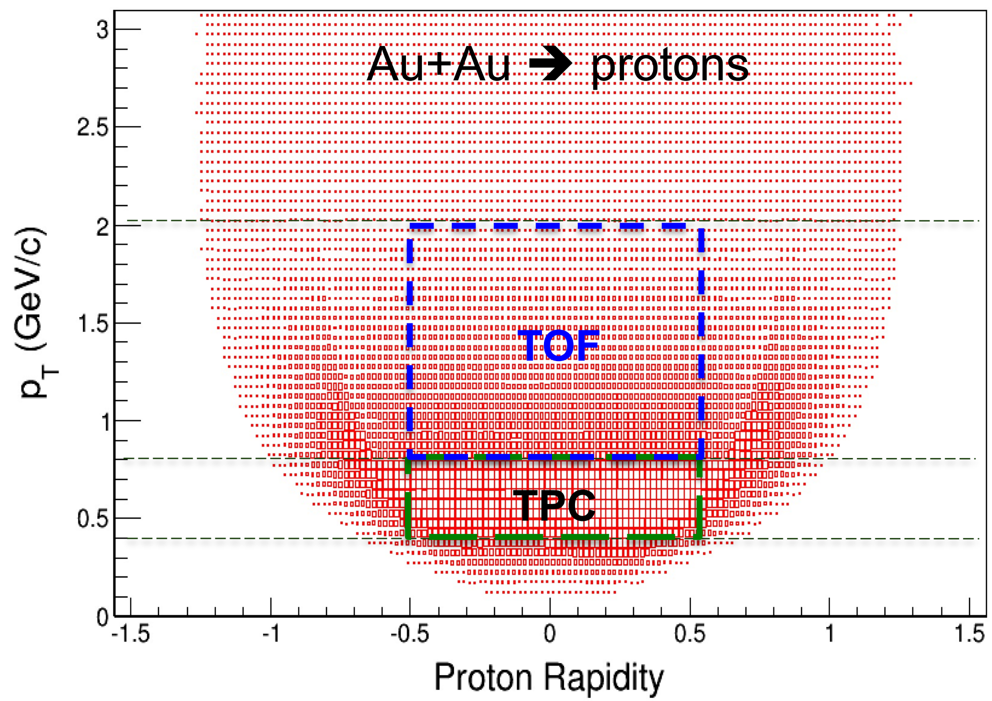
STAR, PRL 112, 032302 (2014).　STAR, PRL113, 092301 (2014).　STAR, PLB 785, 551 (2018).

Enlarge p_T Acceptance

Multi-Particle Correlations : Larger acceptance -> Larger signal



B. Ling, M. Stephanov, Phys. Rev. C 93, 034915 (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): $\varepsilon_{TPC} \sim 0.8$

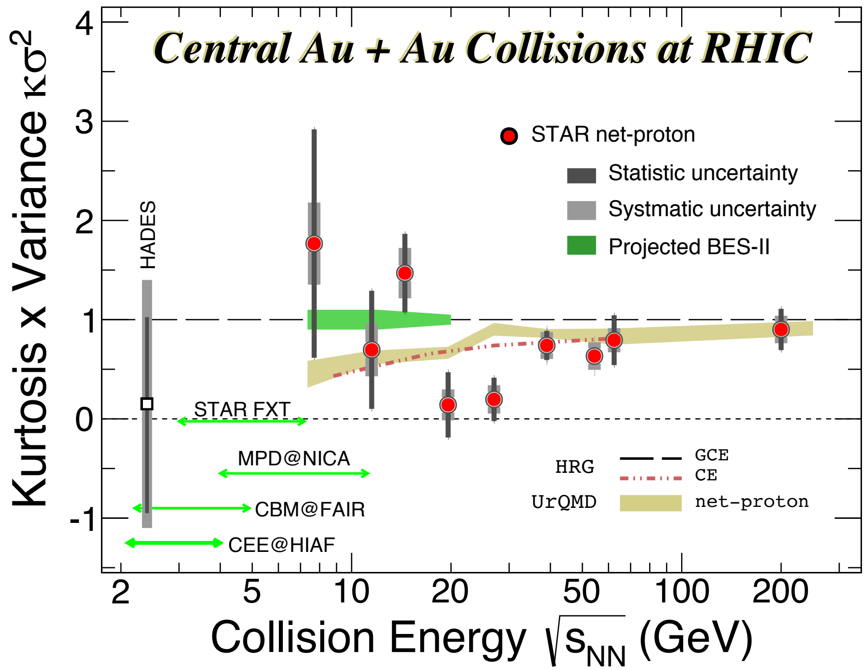
TPC+TOF ($0.8 \leq p_T \leq 2$ GeV/c): $\varepsilon_{TPC} * \varepsilon_{TOF} \sim 0.5$

X. Luo, N. Xu, Nucl. Sci. Tech. 28, 112 (2017) [被引295次]

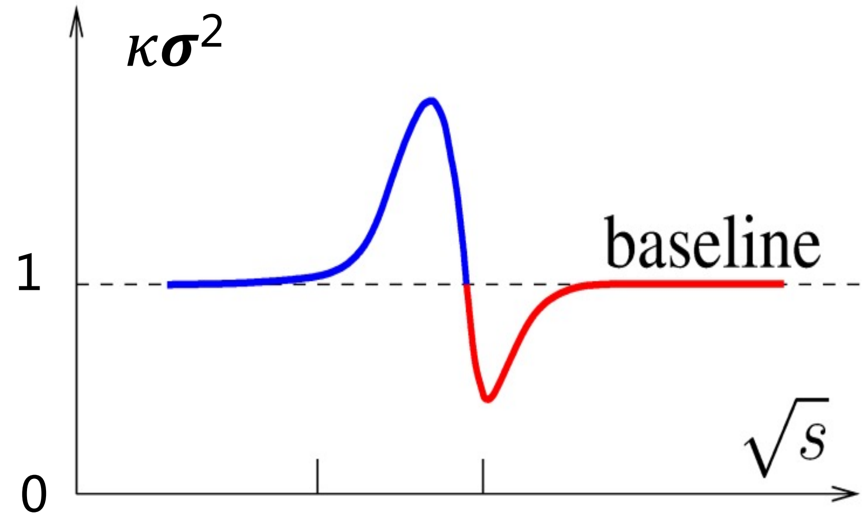
X. Luo, Phys. Rev. C 91, 034907 (2015).

净质子数涨落的高阶矩测量 (宽横动量：0.4~2 GeV/c)

实验数据



理论预言：临界点信号

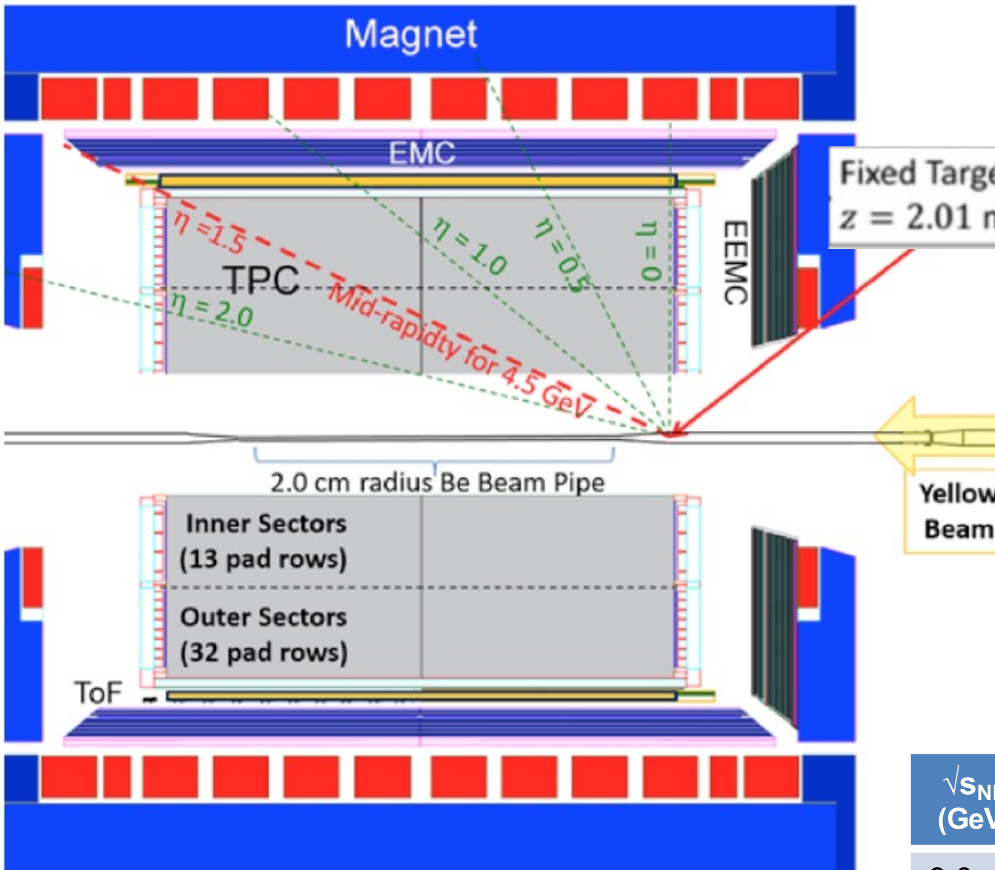


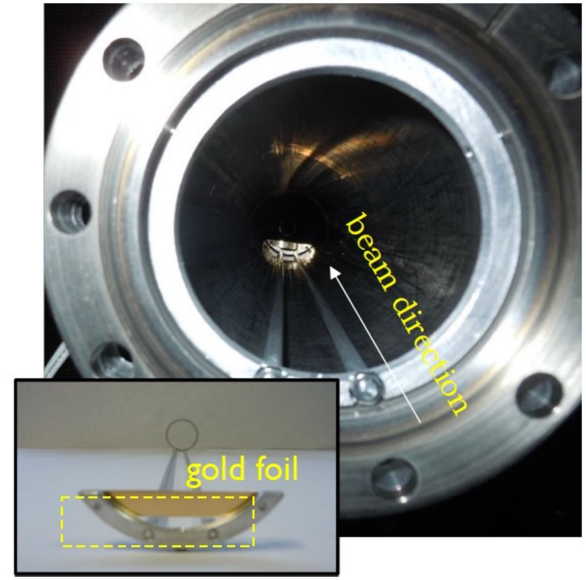
M. Stephanov, PRL107, 052301(2011); JPG 38, 124147 (2011).
JW Chen，J. Deng et al., PRD93, 034037 (2016);

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

1) Non-monotonic energy dependence in central Au+Au collisions, 3.1σ effect
2) Need precise measurement below 20 GeV: BES-II, CBM, NICA etc.
3) Gap between 3-7.7 GeV : important for critical point search.

FXT Experiments at STAR (2018-2021)





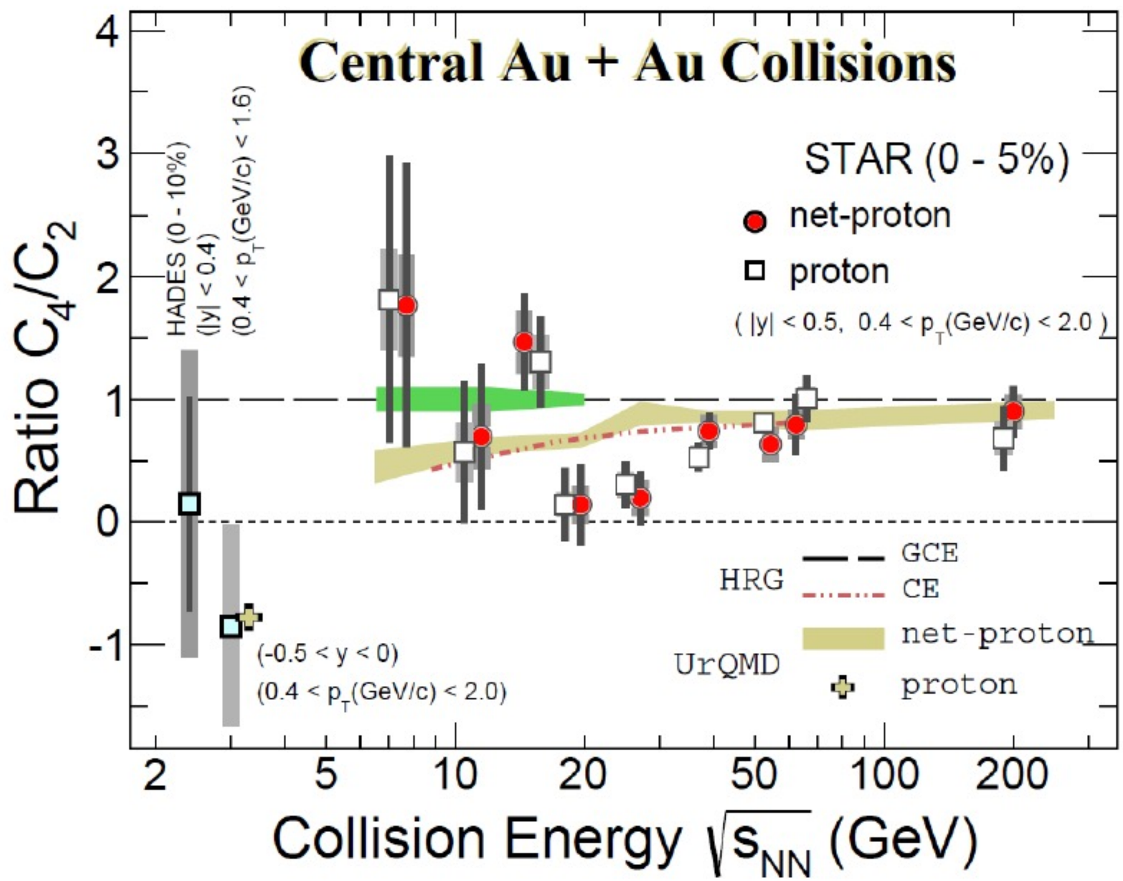
金箔靶： 厚度：250 微米，
安装在距离TPC中心：Z=201 cm

为了扫描更高重子密度的相图区域
STAR进行了固定靶实验

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year	μ_B (MeV)	T_{CH} (MeV)
3.0	259	2018	750	80
3.0	2000	2021	750	80

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

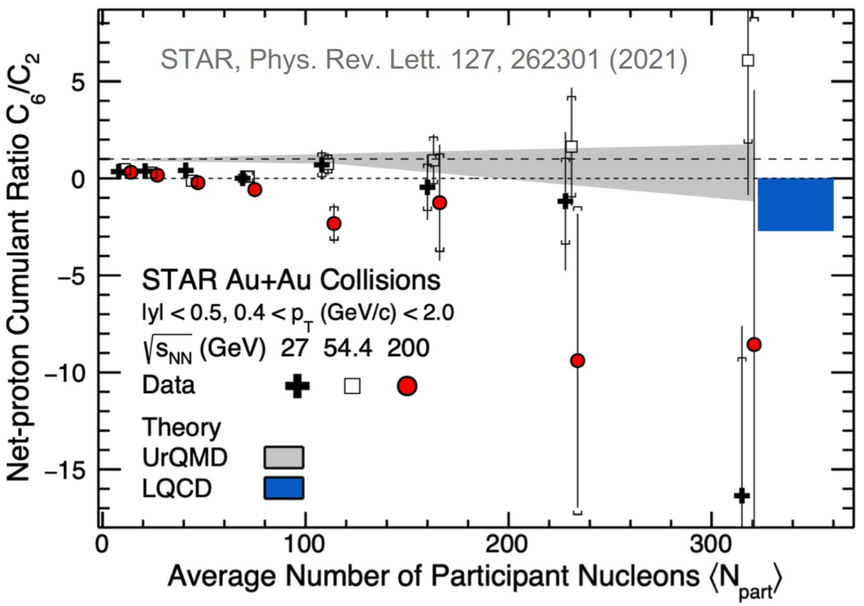
Energy Dependence of Fourth-order Fluctuations



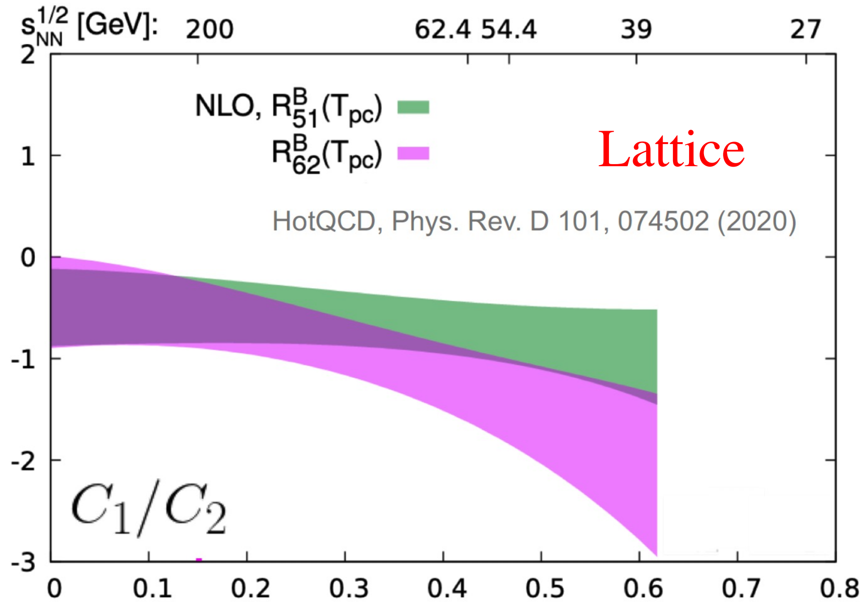
- The suppression of C_4/C_2 is consistent with fluctuations driven by baryon number conservation which indicates a hadronic interaction dominated region in the top 5% central Au+Au collisions at 3 GeV.
- The QCD critical point, if exists in heavy ion collisions, could likely be at energy higher than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

STAR, Phys. Rev. Lett. 128, 202303 (2022)

Higher-order baryon number fluctuations



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



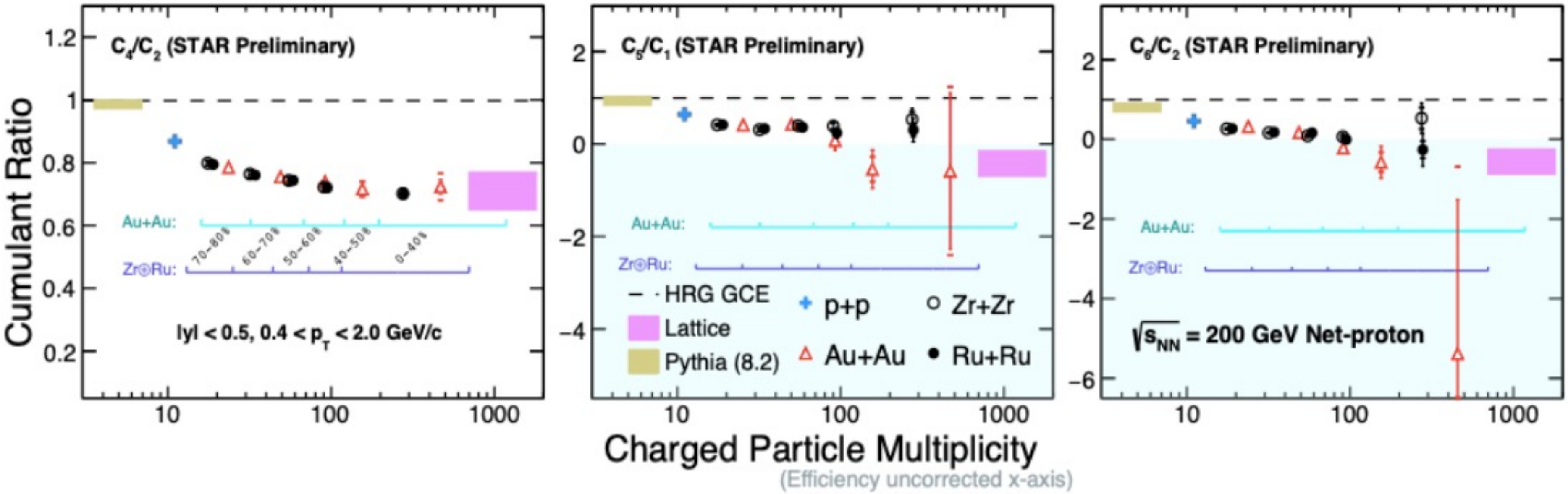
丁亨通(hotQCD)等, Phys. Rev. D 101, 074502 (2020);

- First principle Lattice QCD calculation predicts $C_6/C_2 < 0$.
- C6/C2 progressively negative from peripheral to central collisions

Indicate smooth crossover at 200 GeV.

Different Collision System Size

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

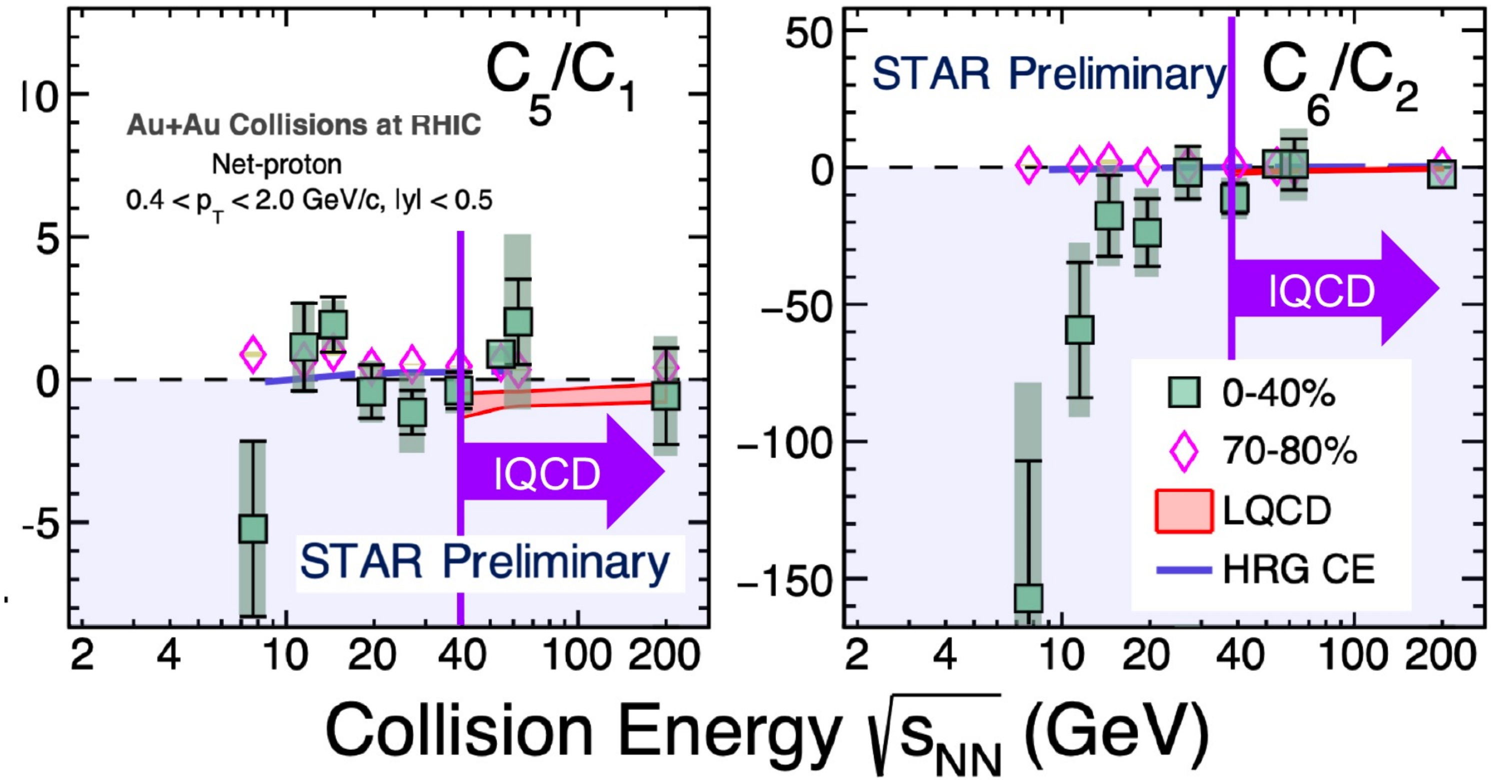


AuAu: PRC 104 (2021) 024902; PRL 126.092301 (2021), PRL 127 (2021) 262301 (2021).
Isobar data and p+p data : QM2022 (文章在合作组内部审核)

- 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.

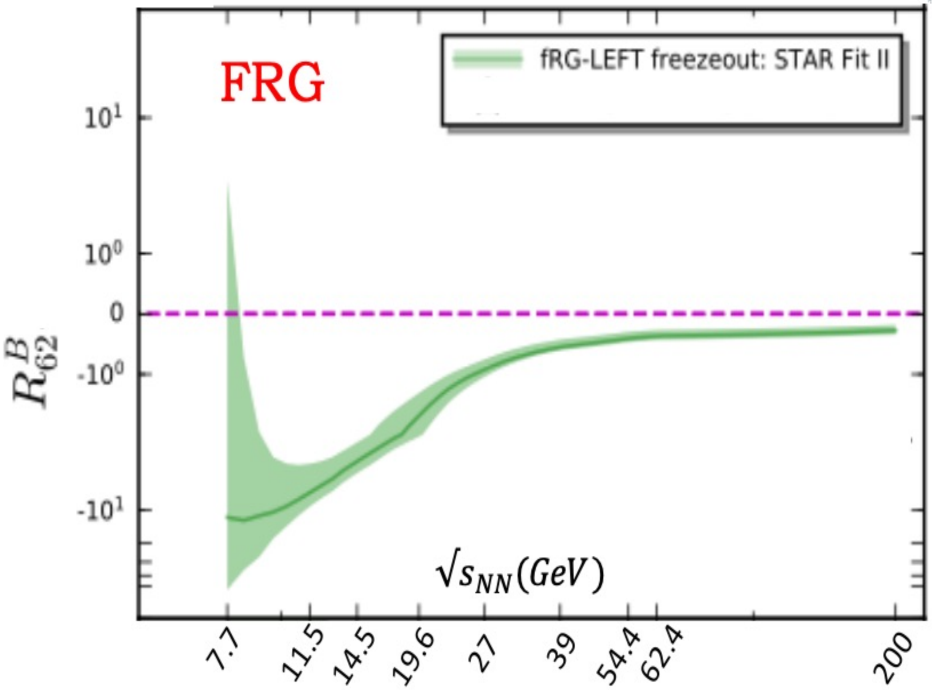
Energy Dependence of Fifth- and Sixth-order cumulants

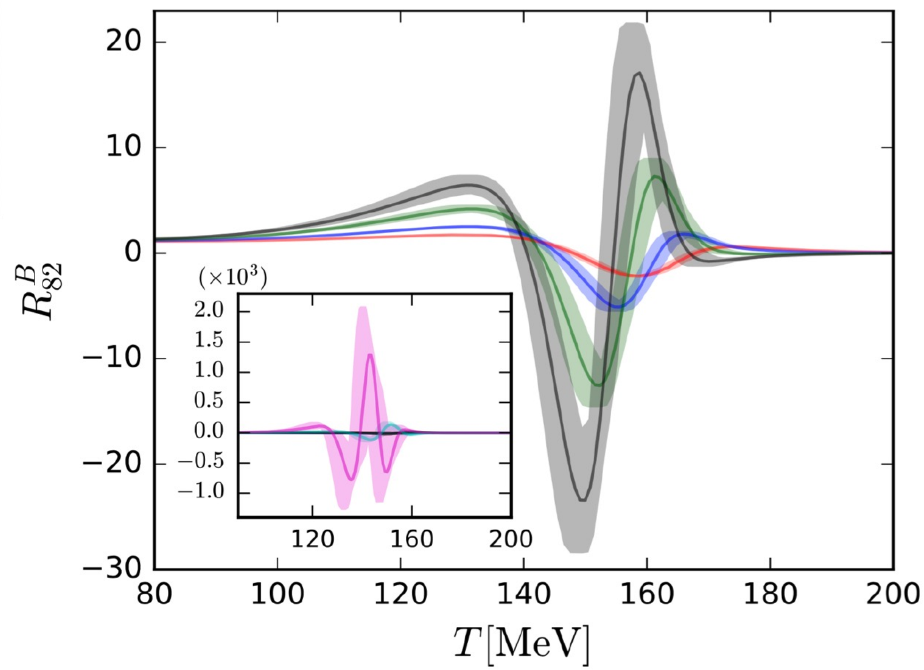


1. C_5/C_1 (0-40%) fluctuates around zero
2. C_6/C_2 progressively negative with decreasing collision energy down to 7.7 GeV
 ~ 1.7 sigma to be negative sign.
3. Consistent with lattice QCD with $\mu_B < 110$ MeV.

STAR, arXiv : 2207.09837, submitted to PRL.

Even higher-order baryon number fluctuations

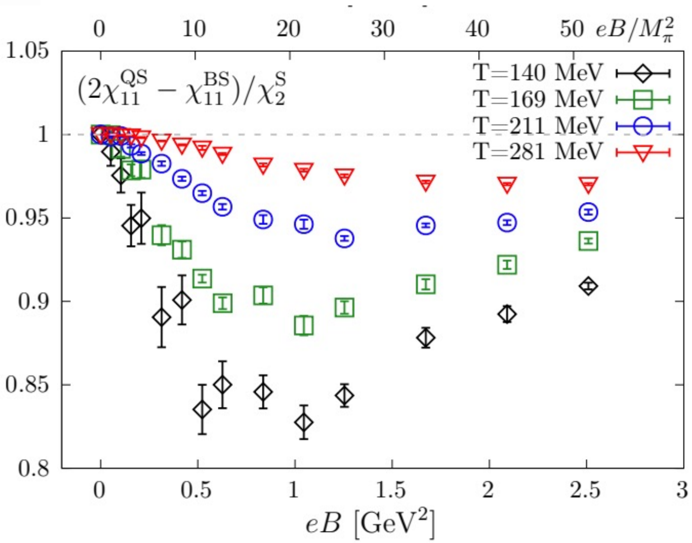


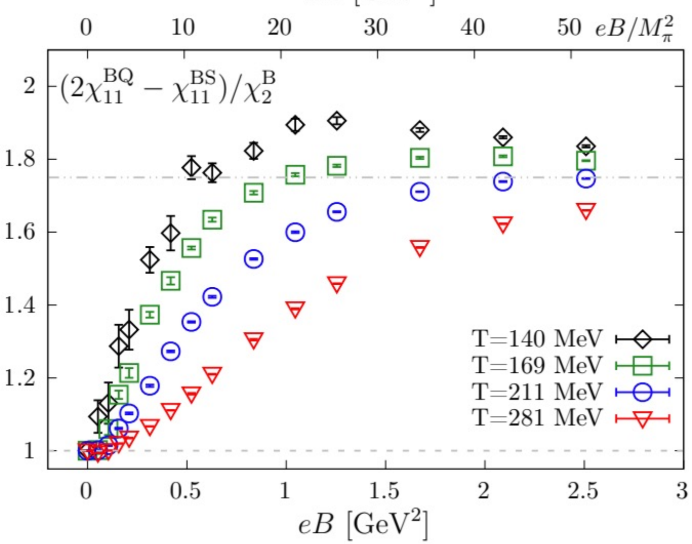


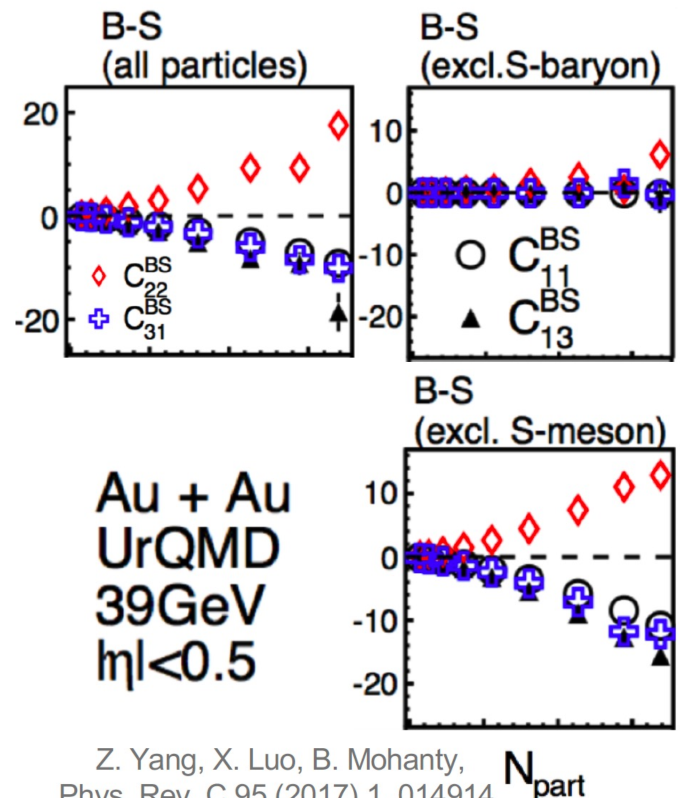
付伟杰, XL等，Phys. Rev. D 104, (2021) 094047 (**Editor Suggestion**)

- Higher-order fluctuations are more sensiive to QCD phase transition.
- Negative C5, C6 and C8 − crossover.
- Exp. : Statistical hungry and background effects maybe complicated.

Probe magnetic field in HIC with conserved charge fluctuations







Z. Yang, X. Luo, B. Mohanty,
Phys. Rev. C 95 (2017) 1, 014914

1. Off-diagonal cumulant sensitive to mag. field
2. Strange baryon, such as Lambda, are important for off-diagonal cumulant analysis
3. Look for mag. field effect in Isobar data

H.-T. Ding, S.-T. Li, Q. Shi,X.-D. Wang, Eur. Phys. J. A 57 (2021) 6, 202

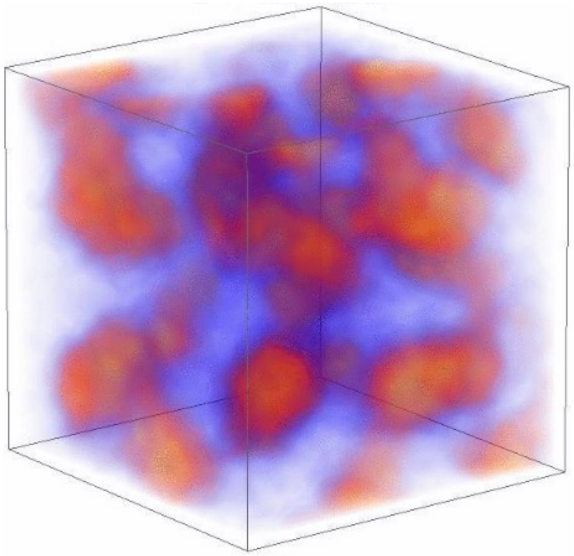
Light nuclei production as probes of QCD phase structure

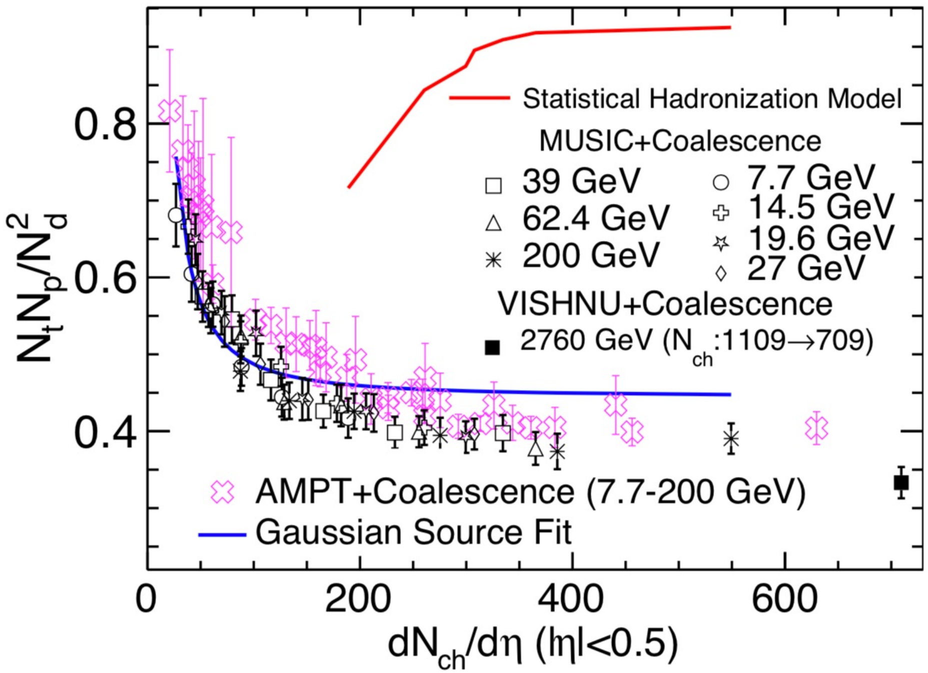
Near first order P.T. or critical point ：
large density fluctuations and baryon clustering

Based on coalescence model:

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

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



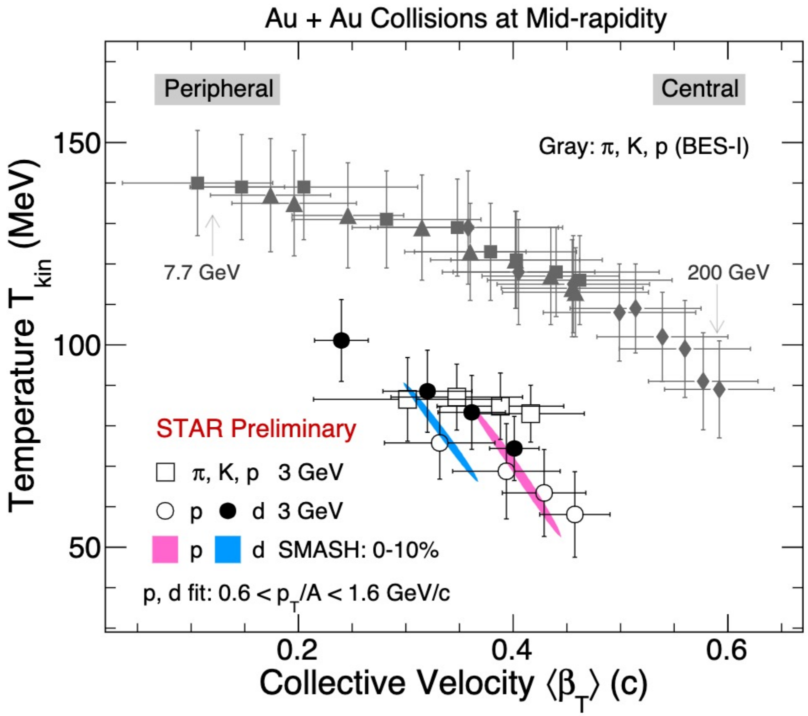


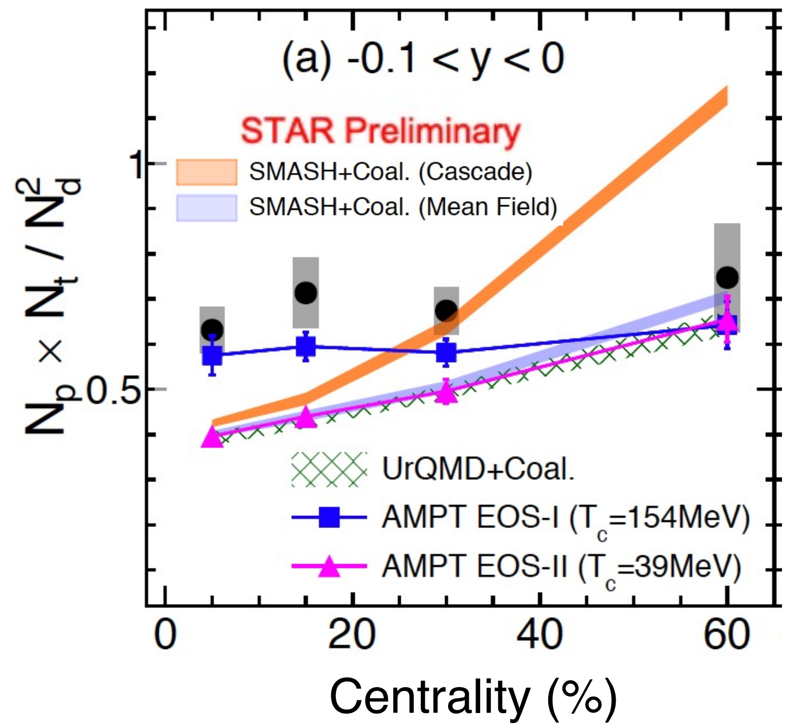
W. Zhao, K.J. Sun, C.M. Ko, X. Luo, Phys. Lett. B 820, 136571 (2021)

- 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.

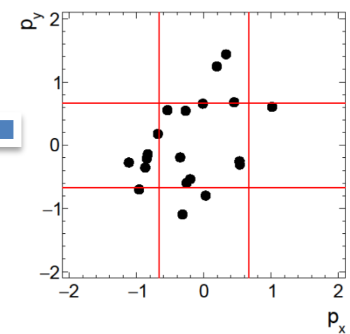
K. J. Sun et al. arXiv: 2205.11010

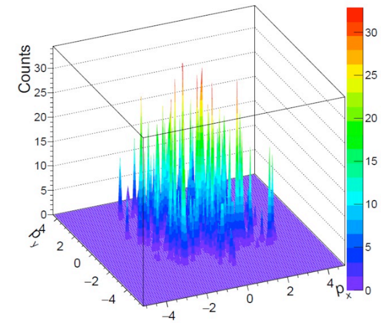
Intermittency (间歇) for Charged Particle at BES-I

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

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



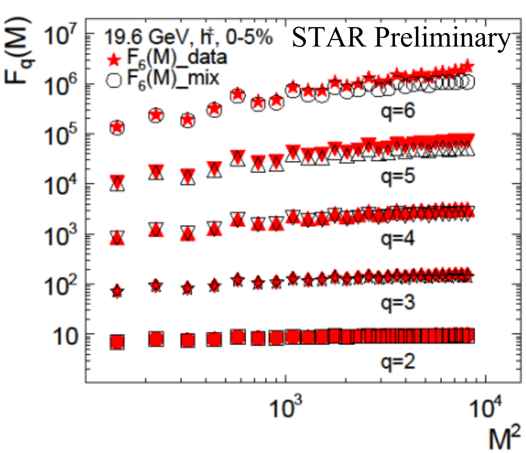


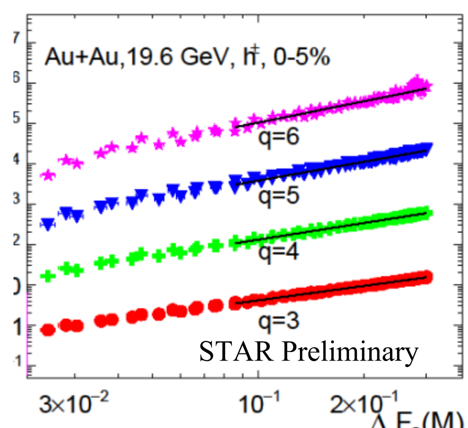
$$\Delta F_q(M) = F_q^{data}(M) - F_q^{mix}(M)$$

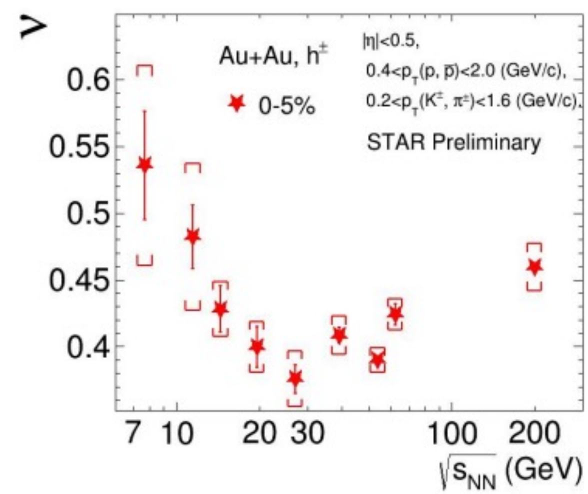
$$\Delta F_q(M) \propto \Delta F_2(M)^{\beta_q}$$

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

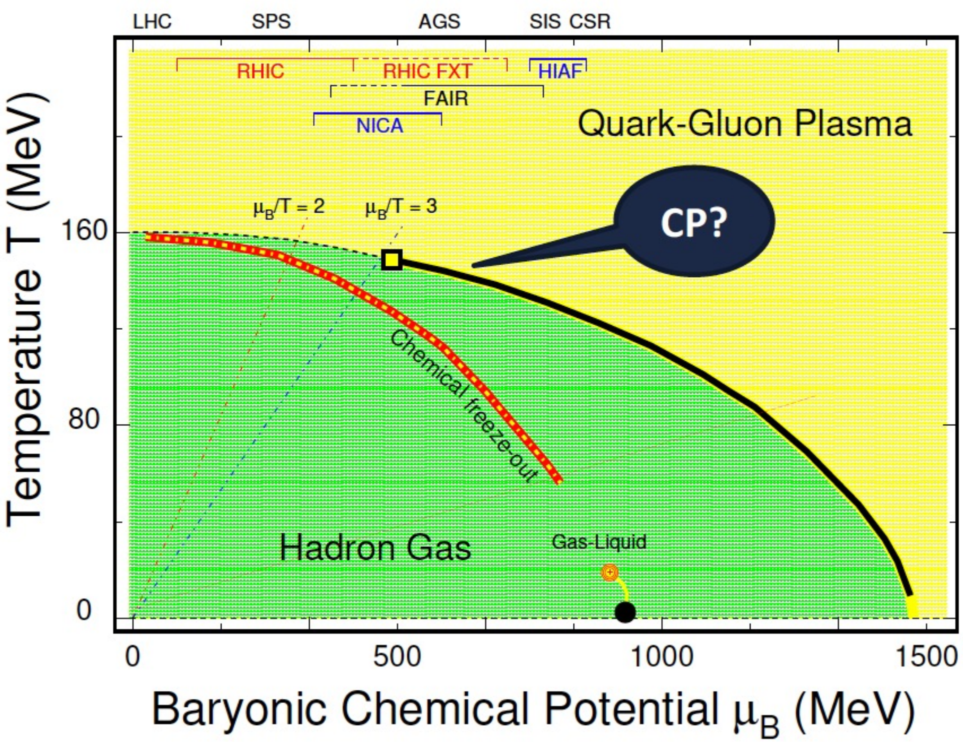
Scaling exponent exhibits a non-monotonic energy dependence in central Au+Au collisions with a minimum around $\sqrt{s_{NN}}$ = 20-30 GeV. Paper is under collaboration review.







Summary and Outlook



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 compare to high energy hadronic dominated

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

4) other sensitive observable !!

Explore the QCD phase structure at high baryon density with high precision:
Future Facilities ($\sqrt{s_{NN}}$ =2 - 11 GeV) : FAIR/CBM, NICA/MPD, HIAF/CEE, JPARC-HI.

Stay tune for exciting physics at high baryon density !!

Thank you ！