Nuclear Science Computing Center at CCNU

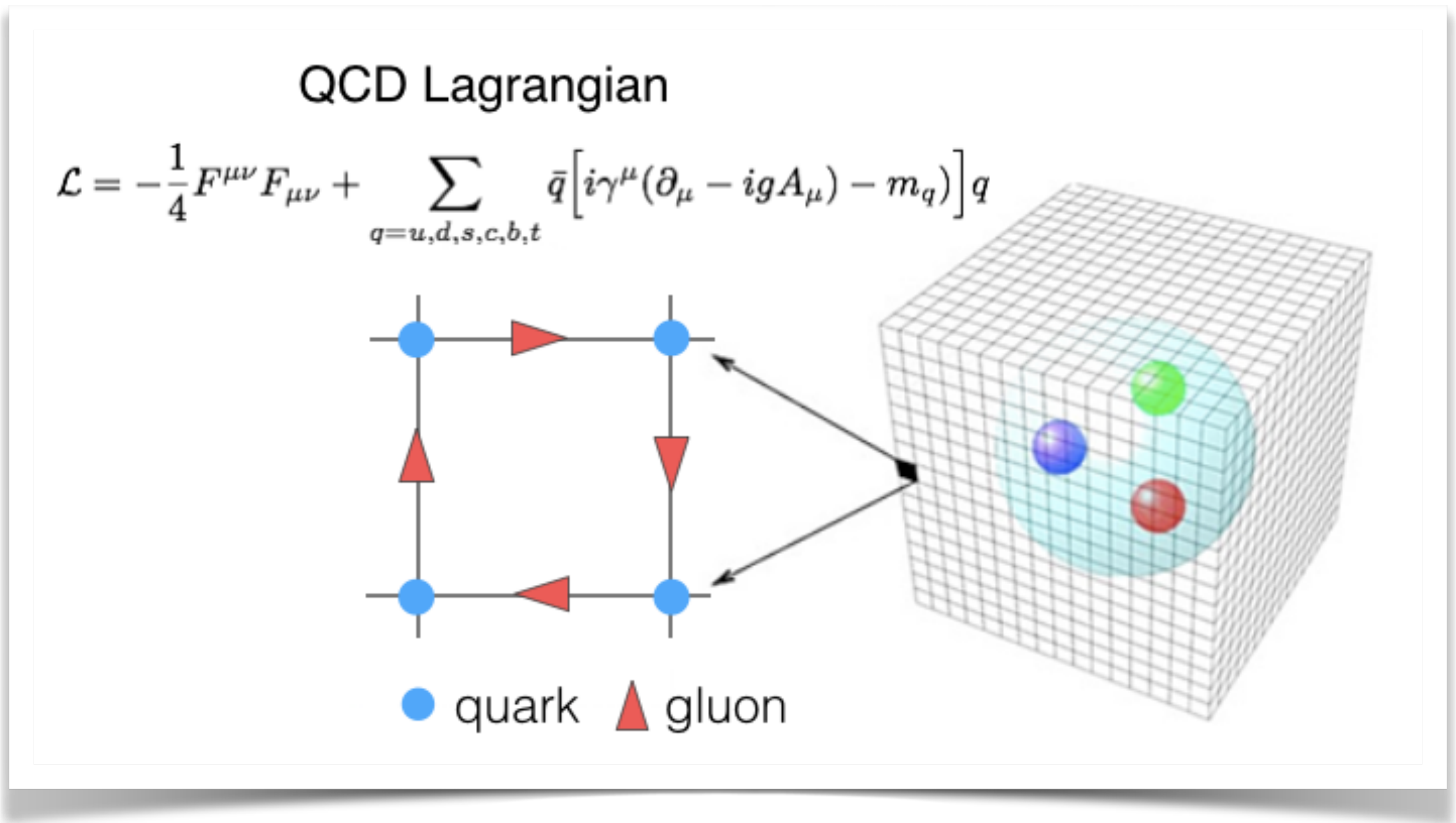
Scientific opportunities & Computing challenges in Hot & Dense Lattice QCD

Heng-Tong Ding (丁亨通)
Central China Normal University (华中师范大学)

中国格点QCD第一届年会@华南师范大学，online
2021.10.30

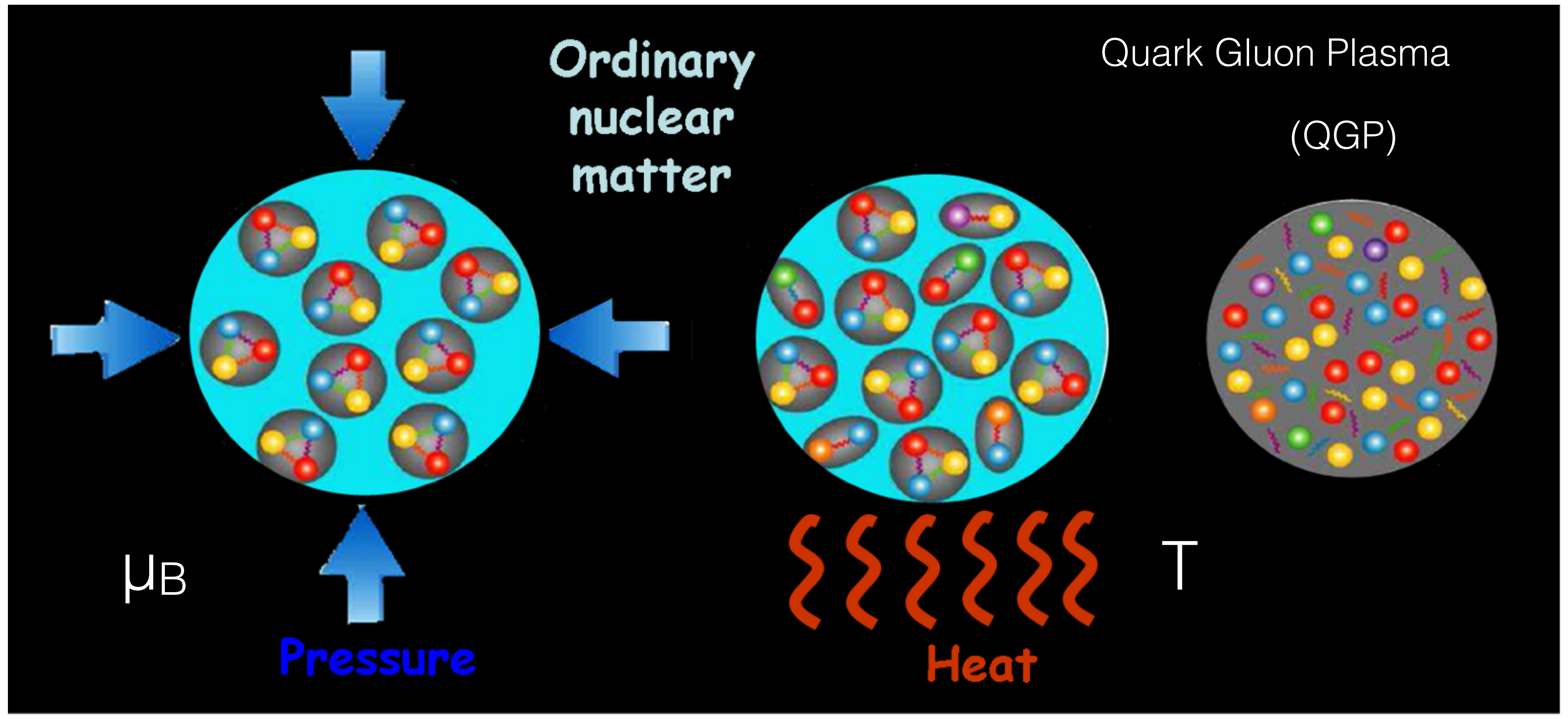
Lattice QCD at nonzero temperature & density

Differences from T=0 lattice QCD



$T = (aN_\tau)^{-1}$ with smaller temporal extent

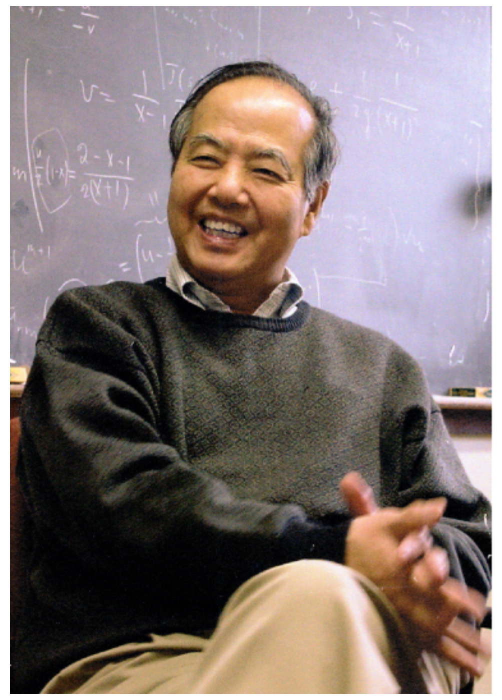
anti-periodic boundary conditions in the temporal direction



Equilibrium & near-equilibrium properties of strong-interaction matter in extreme conditions

high T, large baron density, strong magnetic field…

"The whole is more than sum of its parts."
Aristotle, Metaphysica 10f-1045a



超高温或高密度：激发强相互作用真空、找寻丢失的对称性

“核子重如牛，对撞生新态。”

Ink painting masterpiece 1986:
"Nuclei as Heavy as Bulls, Through Collision Generate New States of Matter"
by Li Keran,
reproduced from open source works of T.D.Lee.

N·H
ELSEVIER

Nuclear Physics A590 (1995) 11c-28c

NUCLEAR PHYSICS A

RHIC and QCD: an overview

T. D. Lee

Columbia University,

Two Puzzles Of Modern Physics

Vacuum As a Condensate

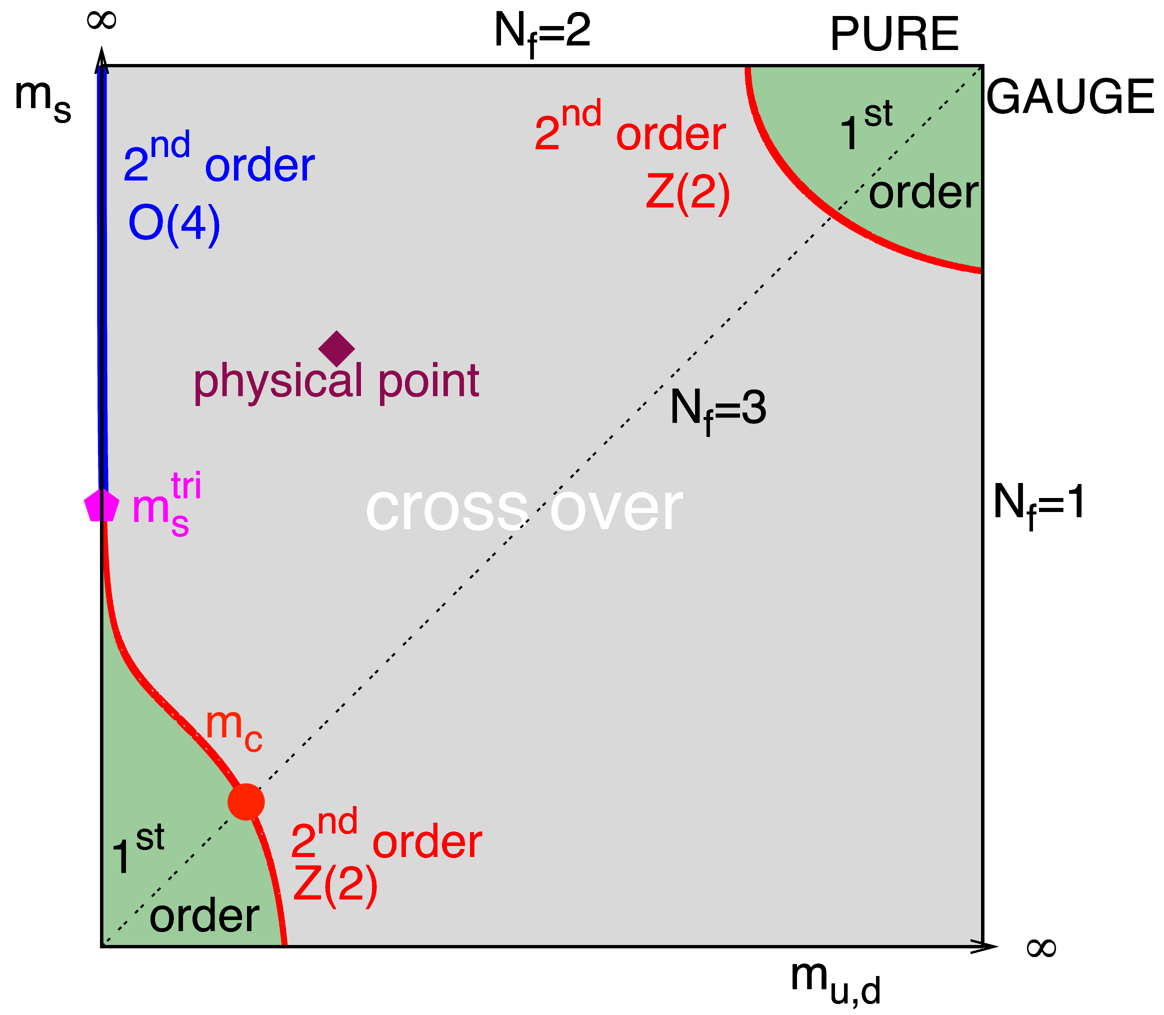
RHIC Physics and QCD

Phase Transitions
Present Theoretical Limitations

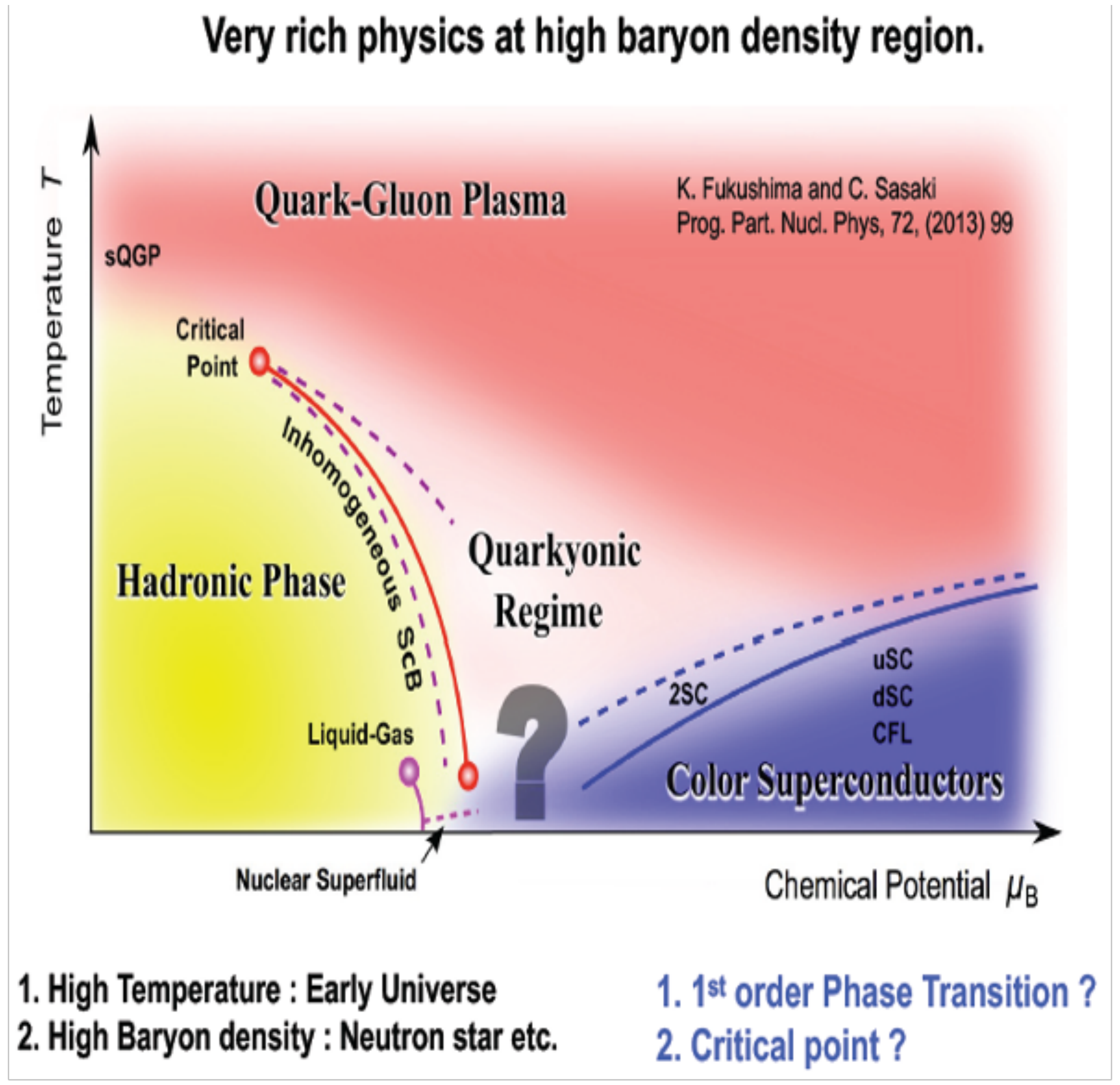
A New Theoretical Approach

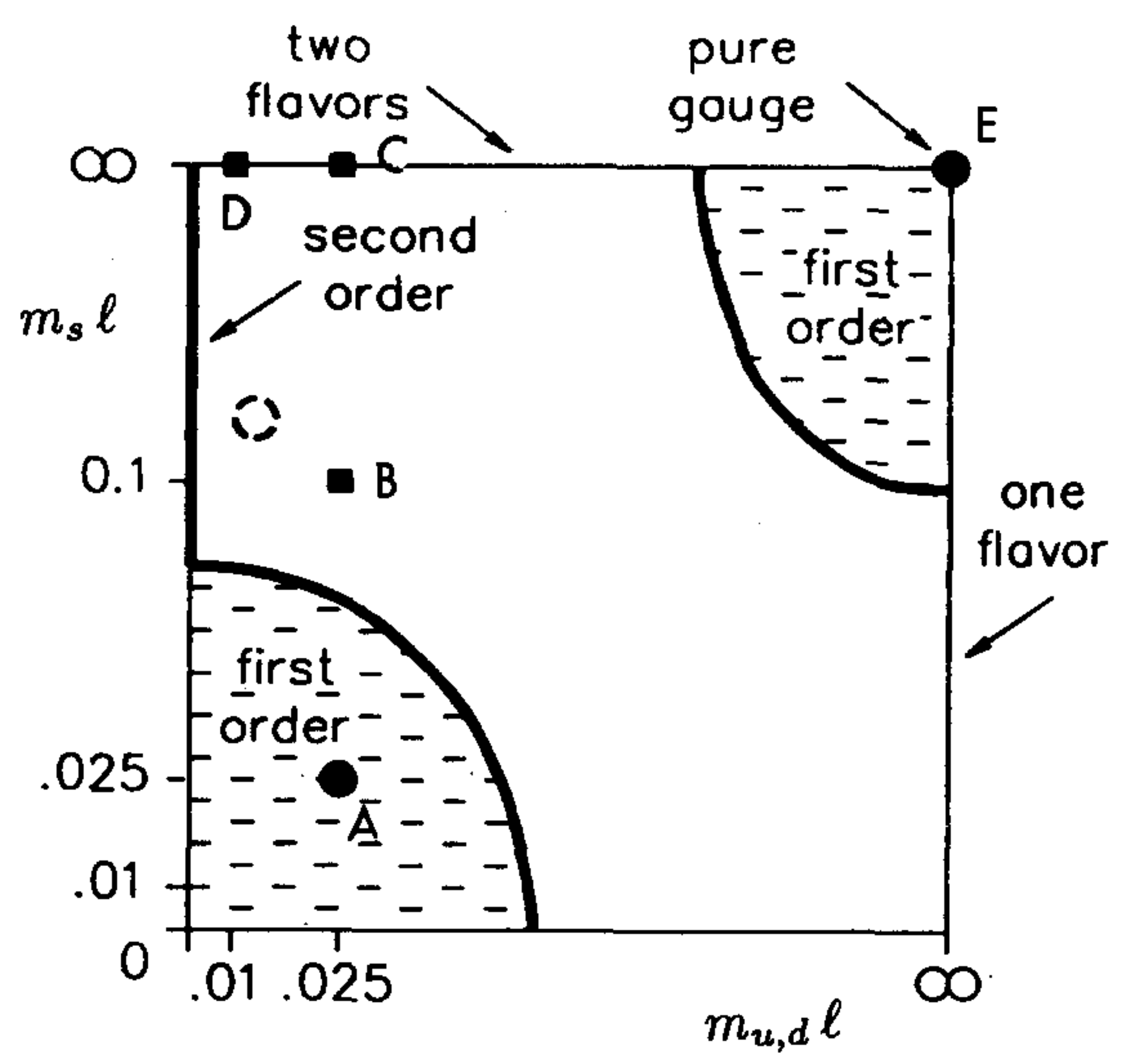
Elimination of Spurious Fermion Solutions
Noncompact Formulation of Lattice QCD

Columbia plot, QCD critical point, In-medium hadron properties...

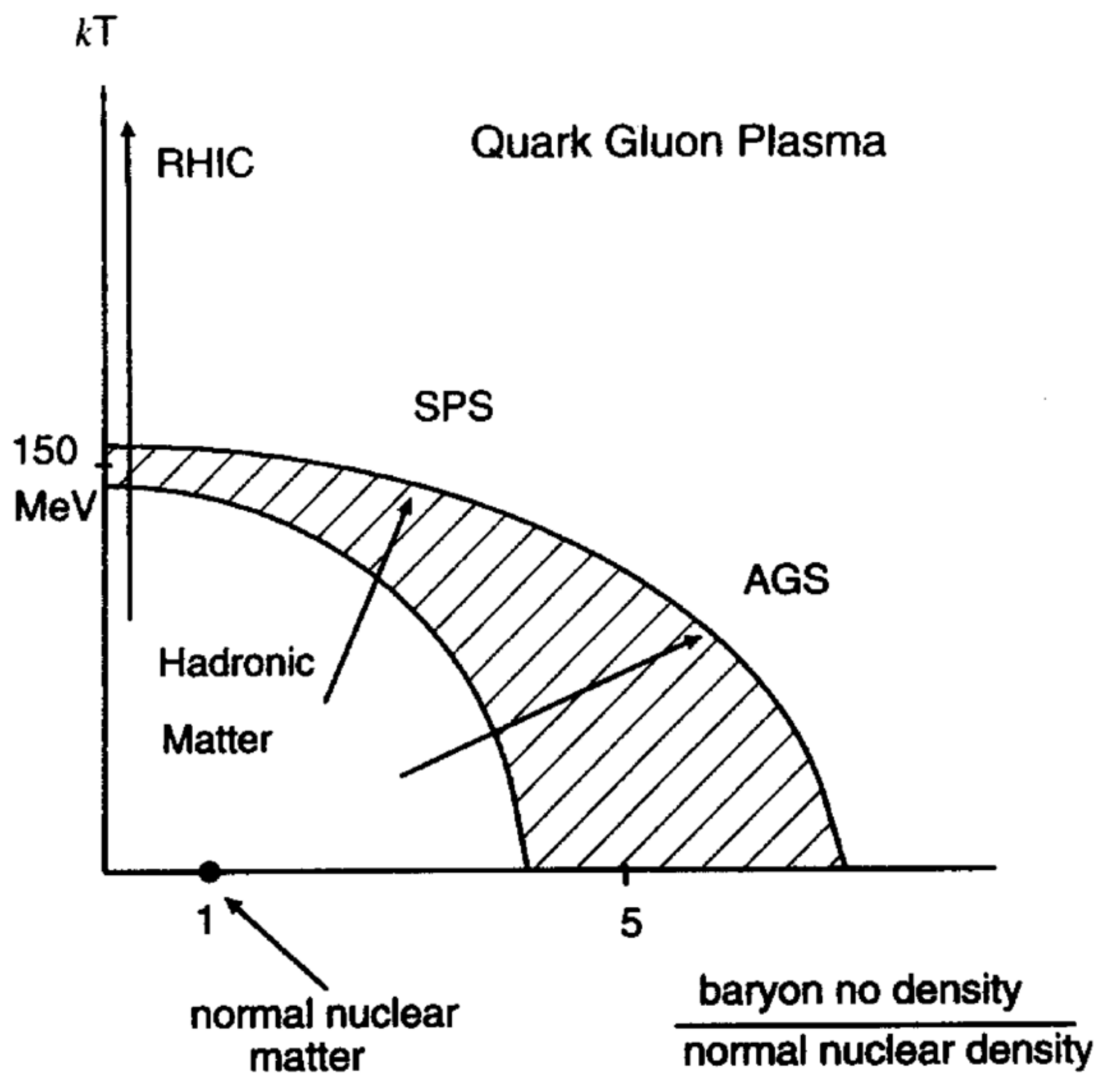


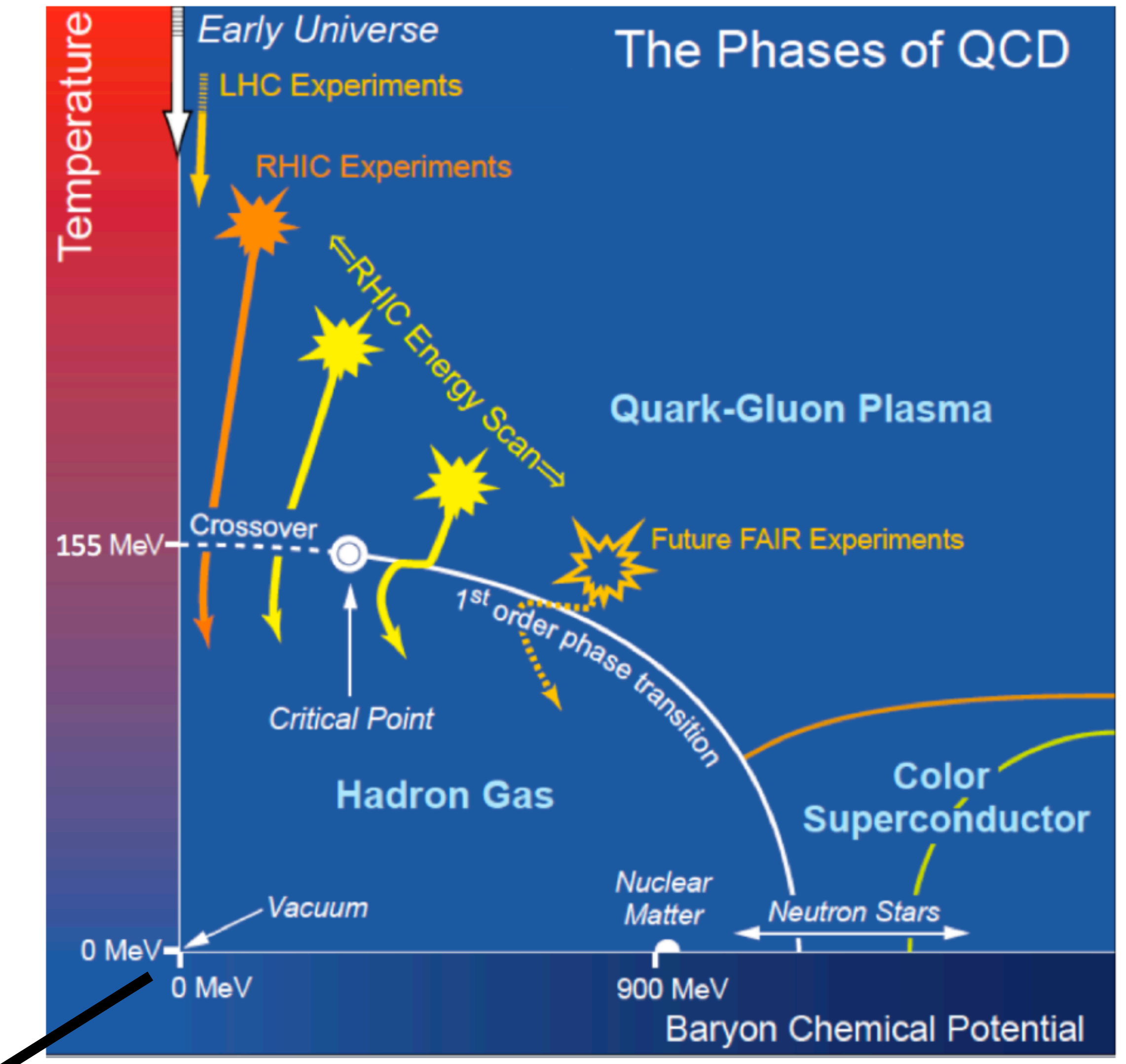
H.-T. Ding, F. Karsch, S. Mukherjee
Int.J.Mod.Phys. E24 (2015) no.10, 1530007



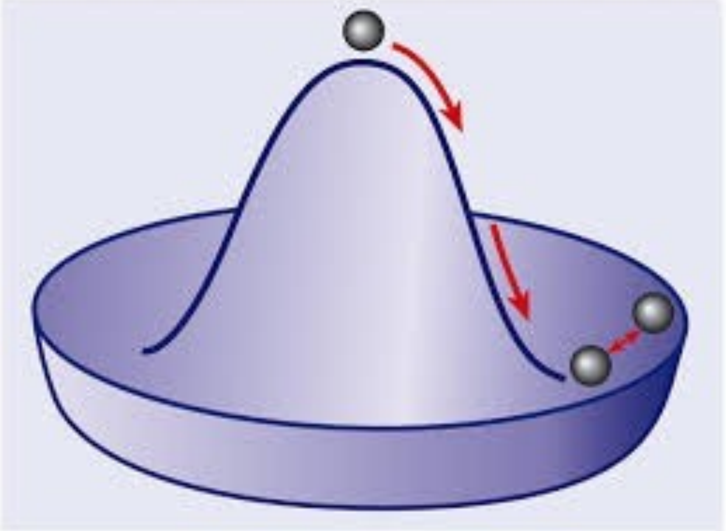


T.-D. Lee, NPA 1995



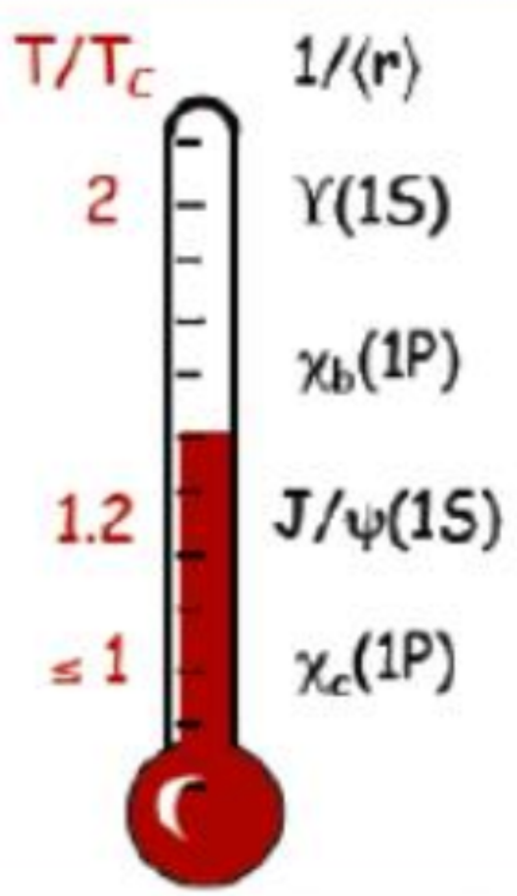


eB, μ_I

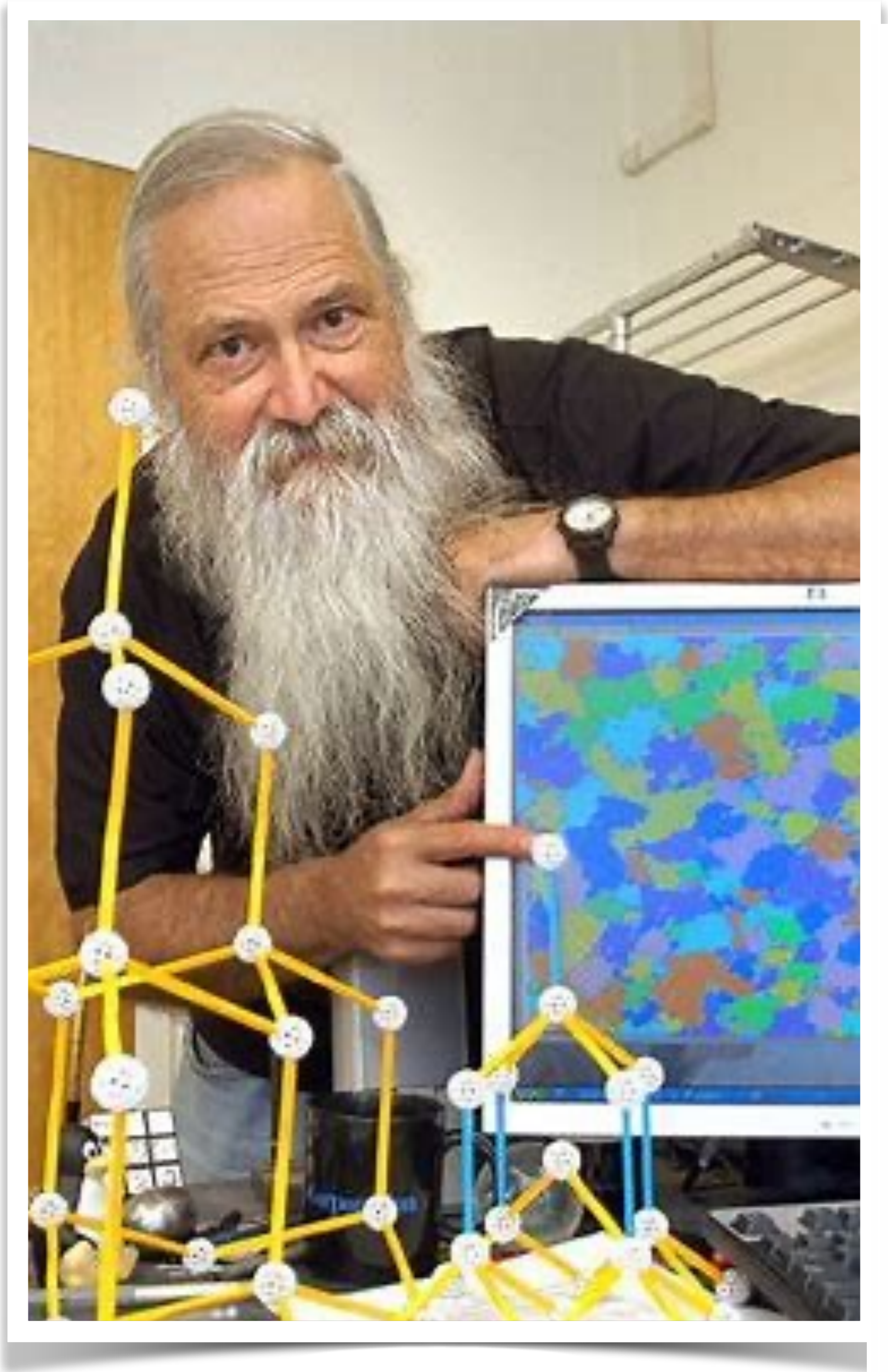


π, σ

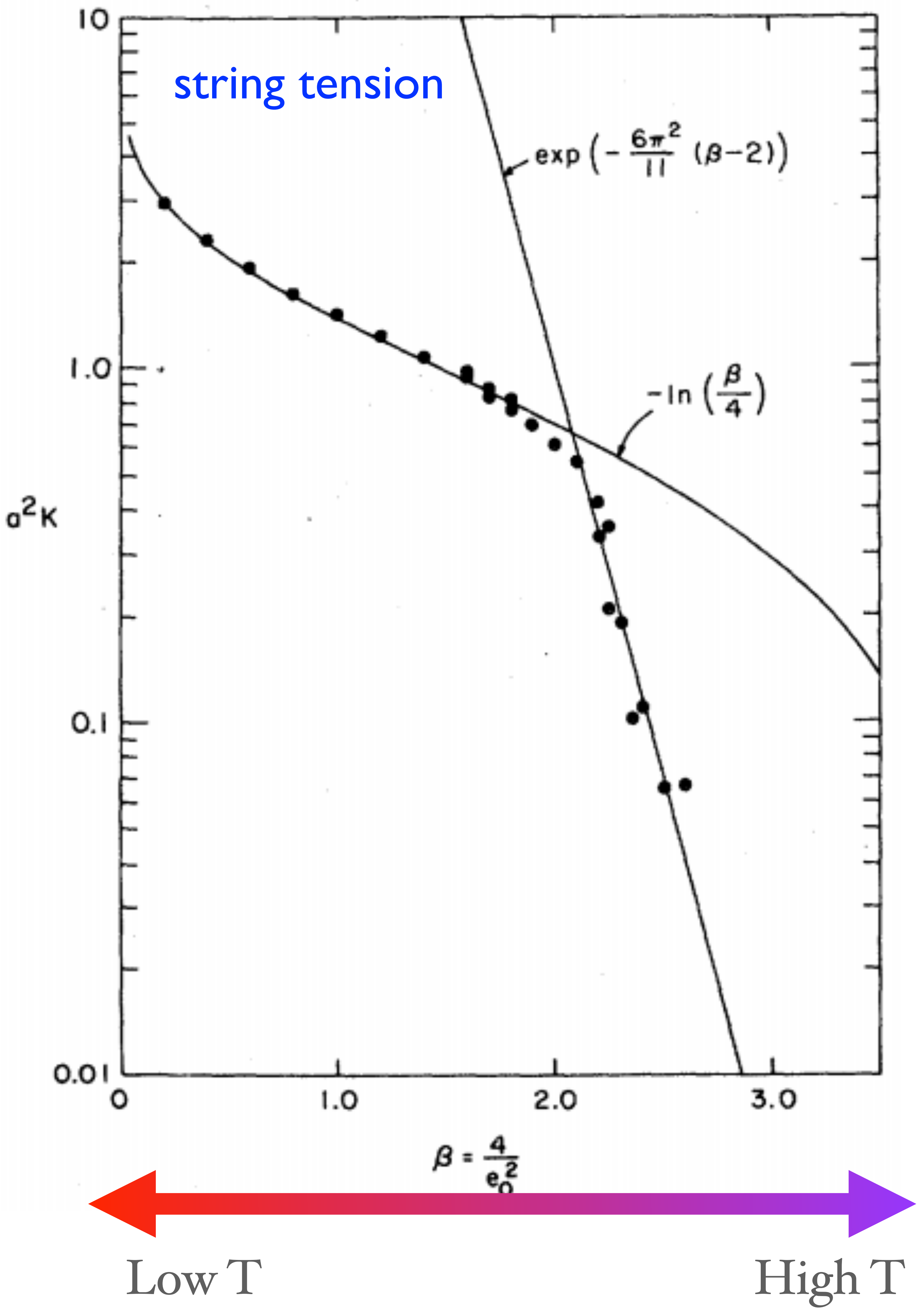
ρ, a_1



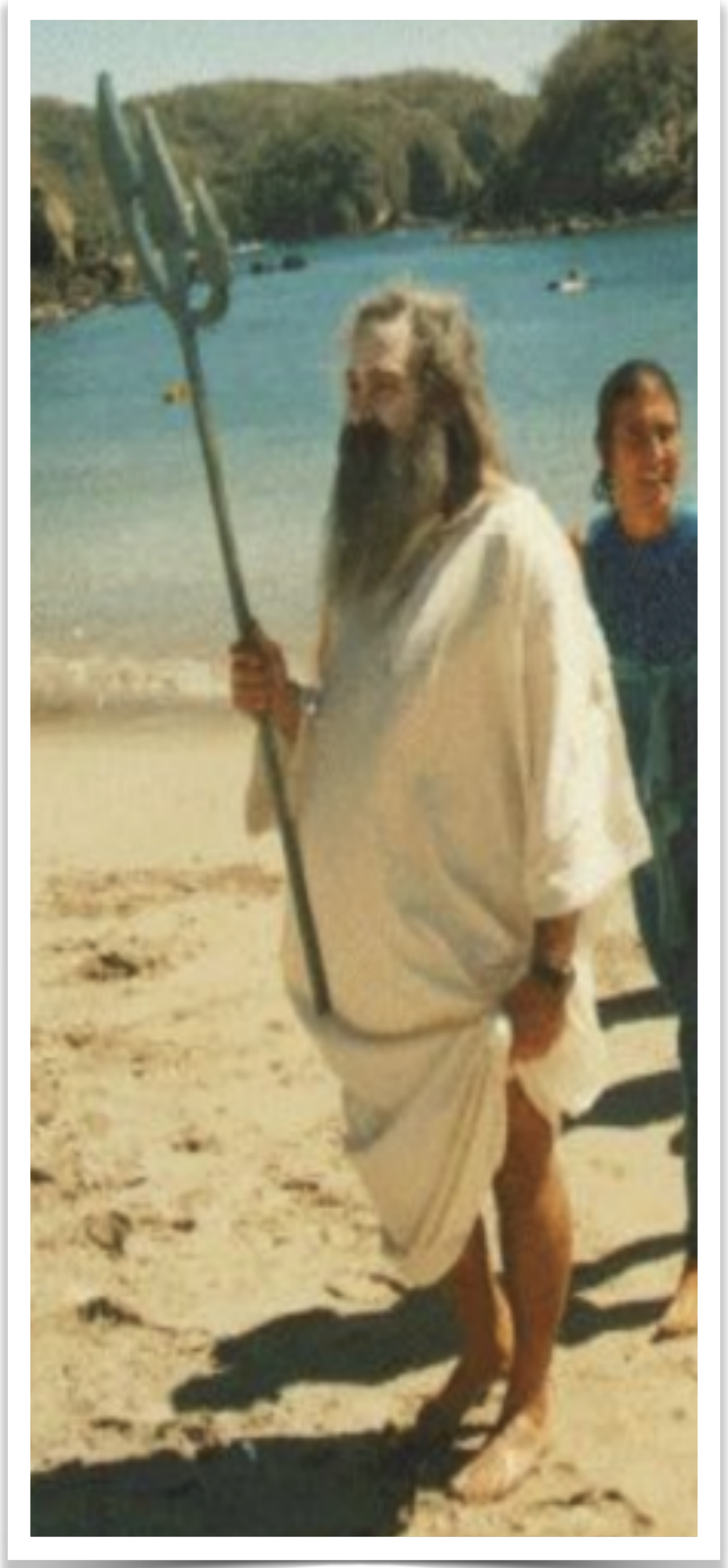
Nonzero T: First numerical lattice simulations



Michale Creutz
@BNL



PRD 1980, cited by 1112 records



Michale Creutz
on the beach

Spawned
golden age
in lattice QCD

(Most likely) the first LQCD simulation at nonzero T in China

第 13 卷 第 6 期　　高 能 物 理 与 核 物 理　　Vol. 13, No. 6
1989 年 6 月　　HIGH ENERGY PHYSICS AND NUCLEAR PHYSICS　　June, 1989

二维和三维空间 $SU(2)$ 规范群的 Wilson 圈平均值*

李志兵　郑维宏　郭硕鸿
（中 山 大 学，广 州）

摘　　要

本文采用改进了的 Monte Carlo 方法在二维和三维空间计算了 $SU(2)$ 格点规范理论的 n×m Wilson 圈平均值，并与分立子群 Y_{120} 以及二维的准确结果作了比较.

THE WILSON LOOP EXPECTATION VALUES IN 2-AND 3-DIMENSIONAL $SU(2)$ LGT

Li Zhibing　Zheng Weihong　Guo Shuohong
(*Zhongshan University, Guangzhou*)

Abstract

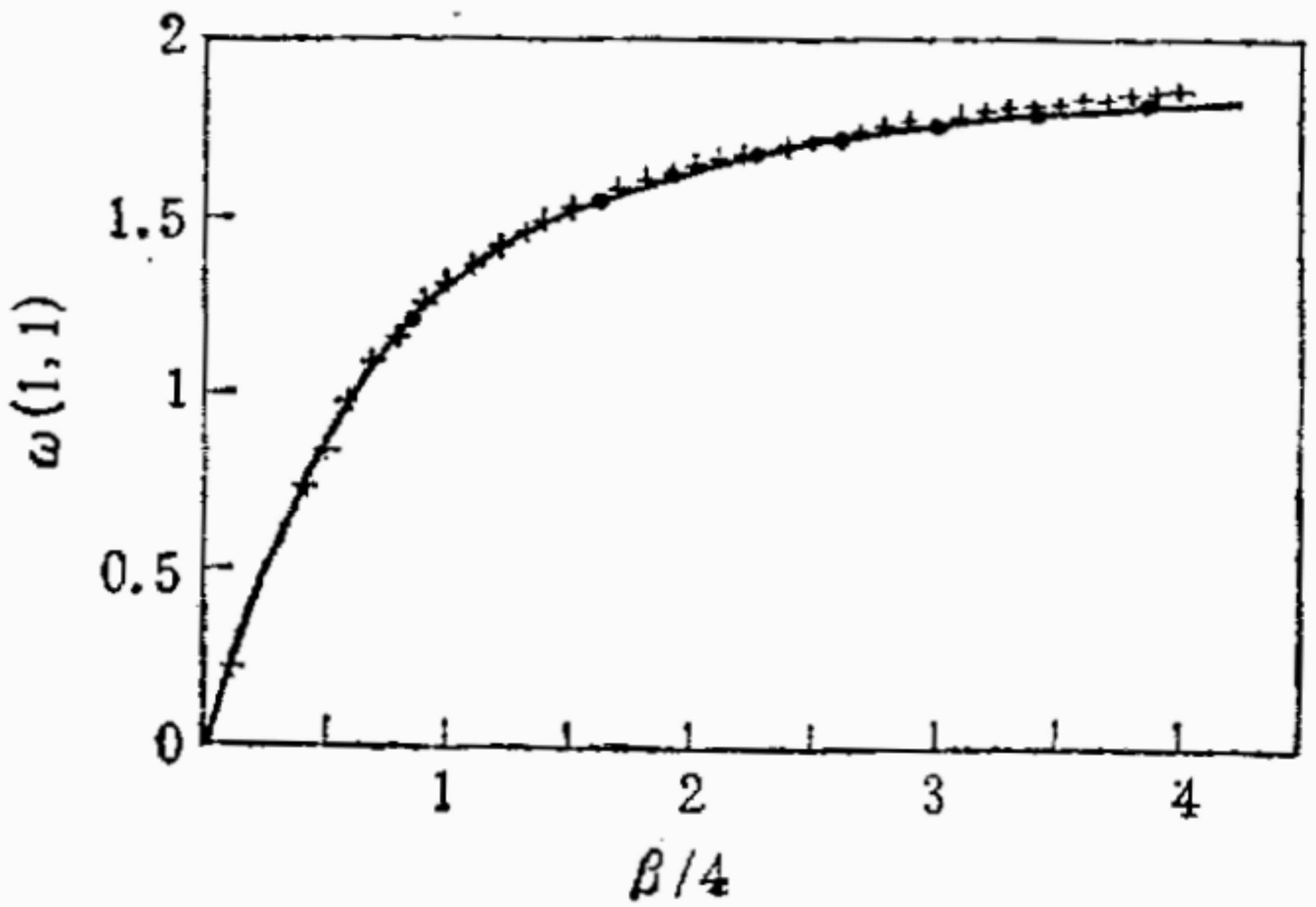
An improved Monte Carlo scheme is applied to the computation of the expectation values of n×m Wilson loops in both 2-and 3-dimensional $SU(2)$ lattice gauge theories. The results are compared with those simulated by the discrete group Y_{120} and the exact results in two dimensions.

* 本工作得到中山大学高等学术中心基金会和国家教委科学基金会的资助.
本文 1988 年 6 月 11 日收到.

在哈密顿形式格点理论中[1]，三维空间的 Wilson 圈与胶球质量、弦张力和玻色凝量等有非常密切的关系[2]. 因为维数比拉氏形式格点理论少一维，所需的 Monte Carlo 模拟时间就大大减少(代价是增加了解析运算量). 这一点给在大中型计算机上获取较好的结果提供了机会.

研究三维纯规范场的另一个很重要的理由涉及到有限温度 QCD 的性质. 三维纯规范场理论作为极高温（或高密度）FQCD 的极限理论，在描述早期宇宙和高能重离子碰撞中可能找到其应用[3].

常用的模拟 $SU(2)$ 群的方法主要有 Metropolis 方法[5]和 Creutz 提出的 heat bath 方法[6]. Cabibbo 和 Marinari 等在模拟 $SU(2)$ 的基础上，把 Creutz 的方法推广到 $SU(N)$ 群的模拟[7]. 最近 Y. F. Deng 改进了他们的方法[8]，进一步提高了 MC 叠代的效率. 本文采用 Deng 的方法对二维和三维的 $SU(2)$ 规范群进行了 Monte Carlo 模拟，并改进了 Wilson 圈的测量方法，使测量时间约缩短三分之一.



SU(2)

- 8x8
+ 12x12

南开大学： 刘玉斌

江苏大学： 吴良凯

浙江大学： 张剑波

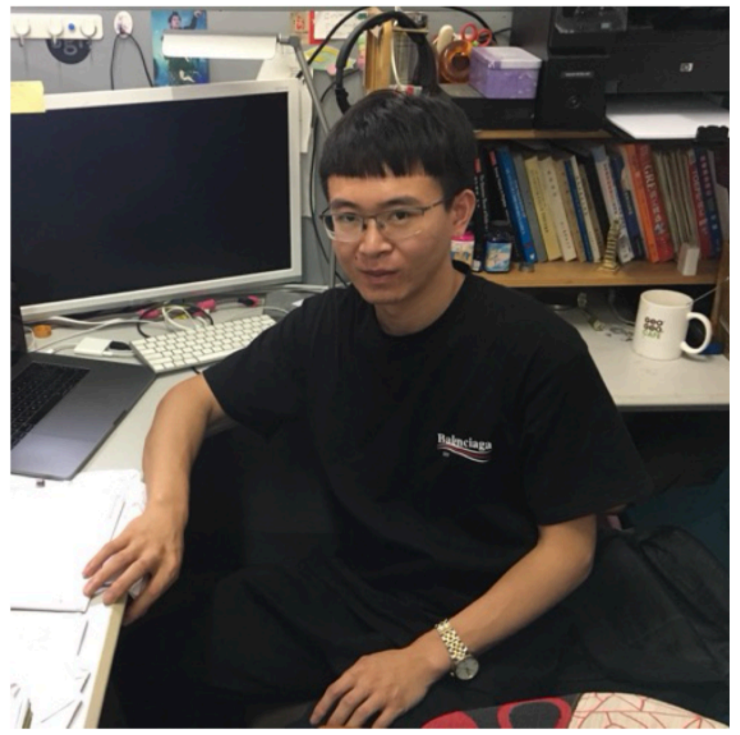
浙江外国语大学： 程贞

华中师大： 丁亨通，李胜泰

Lattice QCD group@CCNU

现课题组成员：1名教授 +1名工程师+ 2名博士后 + 3名博士生 + 5名直博生(硕士阶段) +1名硕士

丁亨通，教授
2013-至今，华中师大

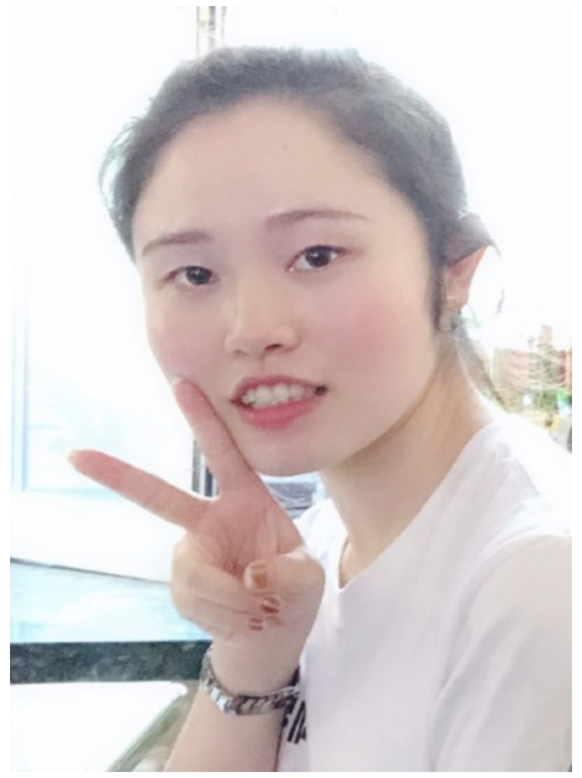


李胜泰, 工程师,
2021-至今，华中师大
核科学计算中心软件负责人

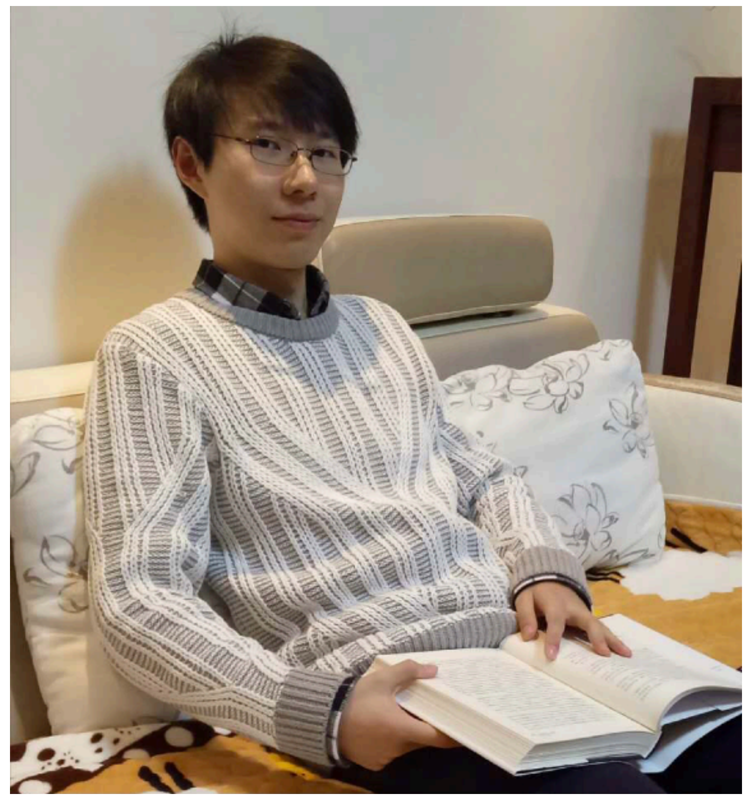
刘俊宏，博士后

高翔，博士后

汪晓丹, 华博计划博士生



施岐, 华博计划博士生



黄玮平, 华博计划博士生

李文汐，直博生

张英杰，直博生

罗冉，直博生

张丹，直博生

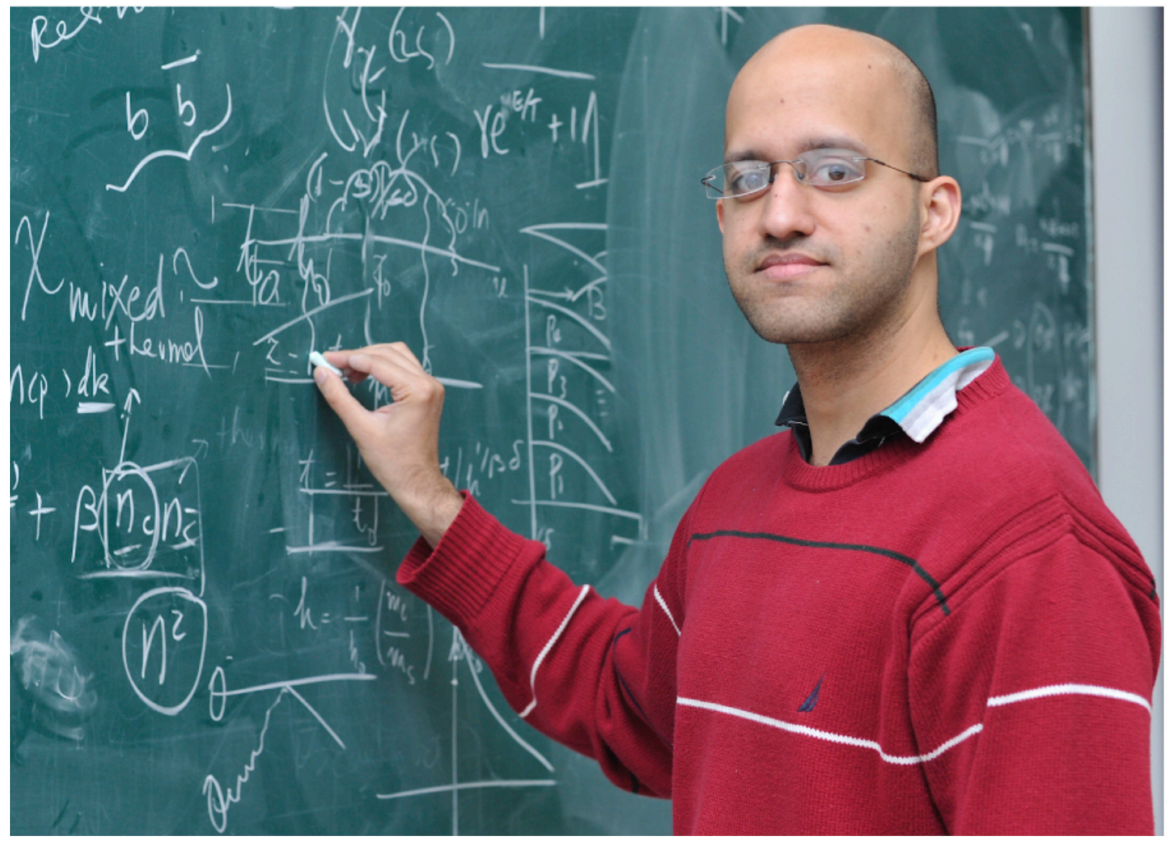
张成，直博生

林敏，硕士生

Previous group members

原课题组成员：

已毕业硕士5名、博士3名，出站博士后2名



Prasad Hegde，博士后
(2013-2016)
美国纽约州州立大学石溪分校博士，出站后被国际著名教育研究单位——印度科学研究院(IISc, Banglore）聘为副教授

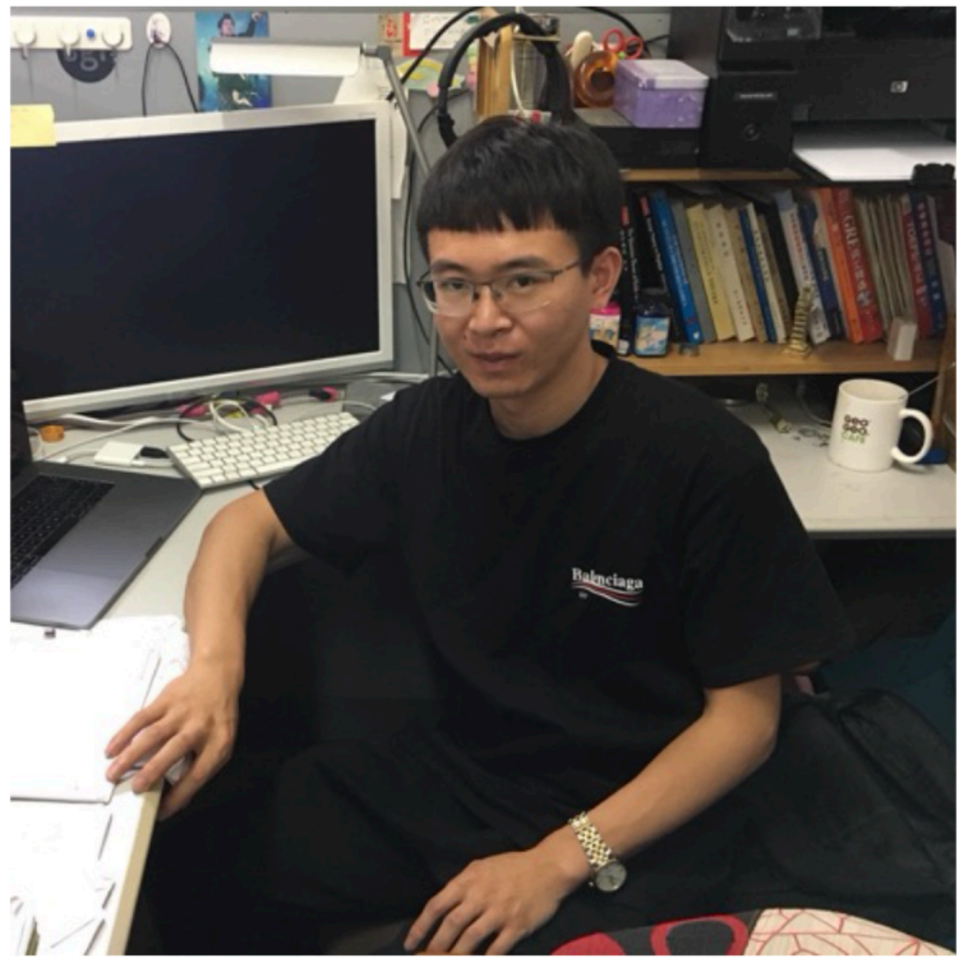
QCD EoS at nonzero μ_B

Akio Tomiya, 博士后
(2015-2018)
日本大阪大学博士
出站后赴RIKEN-BNL美国分部做博士后

Strong magnetic field

舒海涛, 博士生
(2013-2018)
博士毕业后赴德国Bielefeld大学做博后, 现在在德国Regensburg大学做博士后

Quarkonia



李胜泰, 博士生
(2013-2019)
博士毕业后赴中科院近代物理研究所做博士后

Chiral phase transition T

张瑜，博士生
(2016-2021)
博士毕业后赴日本理化研究所RIKEN-Kobe做博后

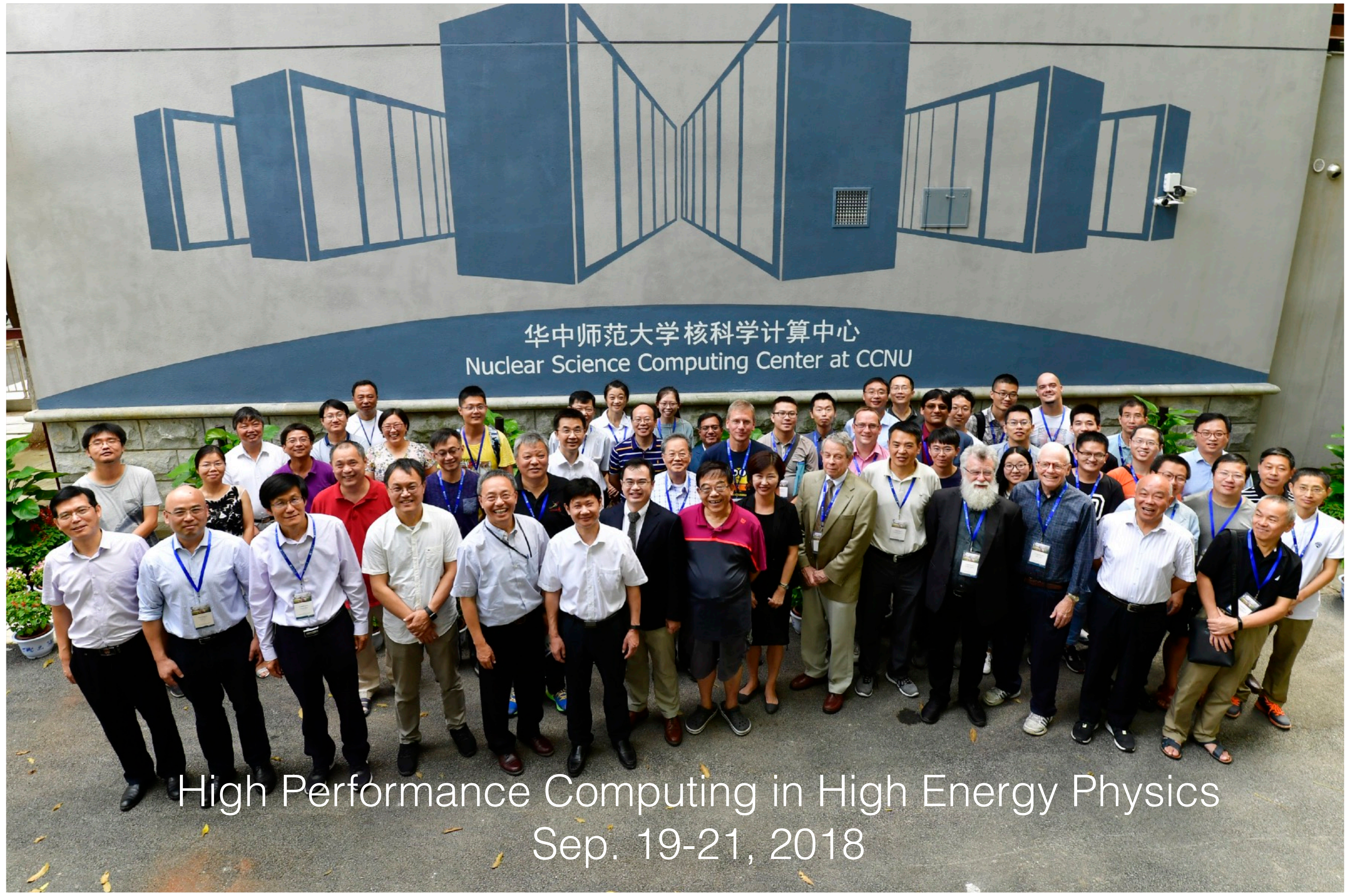
Axial U1 anomaly

华中师范大学核科学计算中心
Nuclear Science Computing Center at CCNU

N: Nuclear **S**: Science **C³**: Color 3 -> QCD

“道生一，一生二，二生三，三生万物。” — 《道德经》老子 600 BC

2018年成立运行，2PFlops/s，5 papers published in PRL (LQCD, 2)



Sun, Oct. 31
16:50-17:20

Axial U1 anomaly

丁亨通, 李胜泰, 复谷昭夫, S. Mukherjee, 汪晓丹, **张瑜**, PRL 126 (2021) 082001

Mon, Nov. 1
15:00-15:30

Quarkonia and heavy quark diffusion in the hot gluonic medium

L. Altenkort, A. M. Eller, O. Kaczmarek, L. Mazur, G. D. Moore , **舒海涛,** PRD103 (2021) 1, 014511

丁亨通, O. Kaczmarek, A.-L. Lorenz, H. Ohno,H. Sandmeyer, **舒海涛**，arXiv: 2108.13693

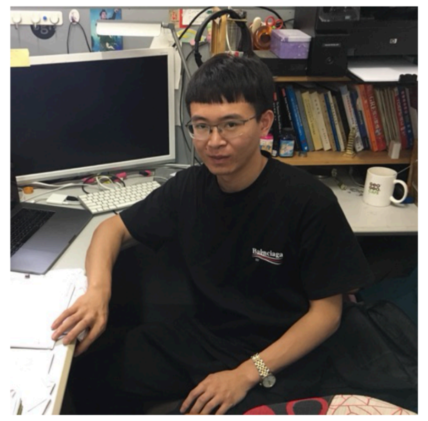
Mon, Nov. 1
15:30-16:00

Fluctuations of conserved charges in strong magnetic fields

丁亨通, 李胜泰, 施岐, 汪晓丹, EPJA 57 (2021) 6, 202,

丁亨通，**刘俊宏**，李胜泰，汪晓丹，in preparation

Mon, Nov. 1
16:00-16:30



Chiral properties of QCD in strong magnetic fields at T=0

丁亨通, **李胜泰**, 复谷昭夫, 汪晓丹, 张瑜, PRD 104 (2021) 1

Tue, Nov. 2
16:30-16:50

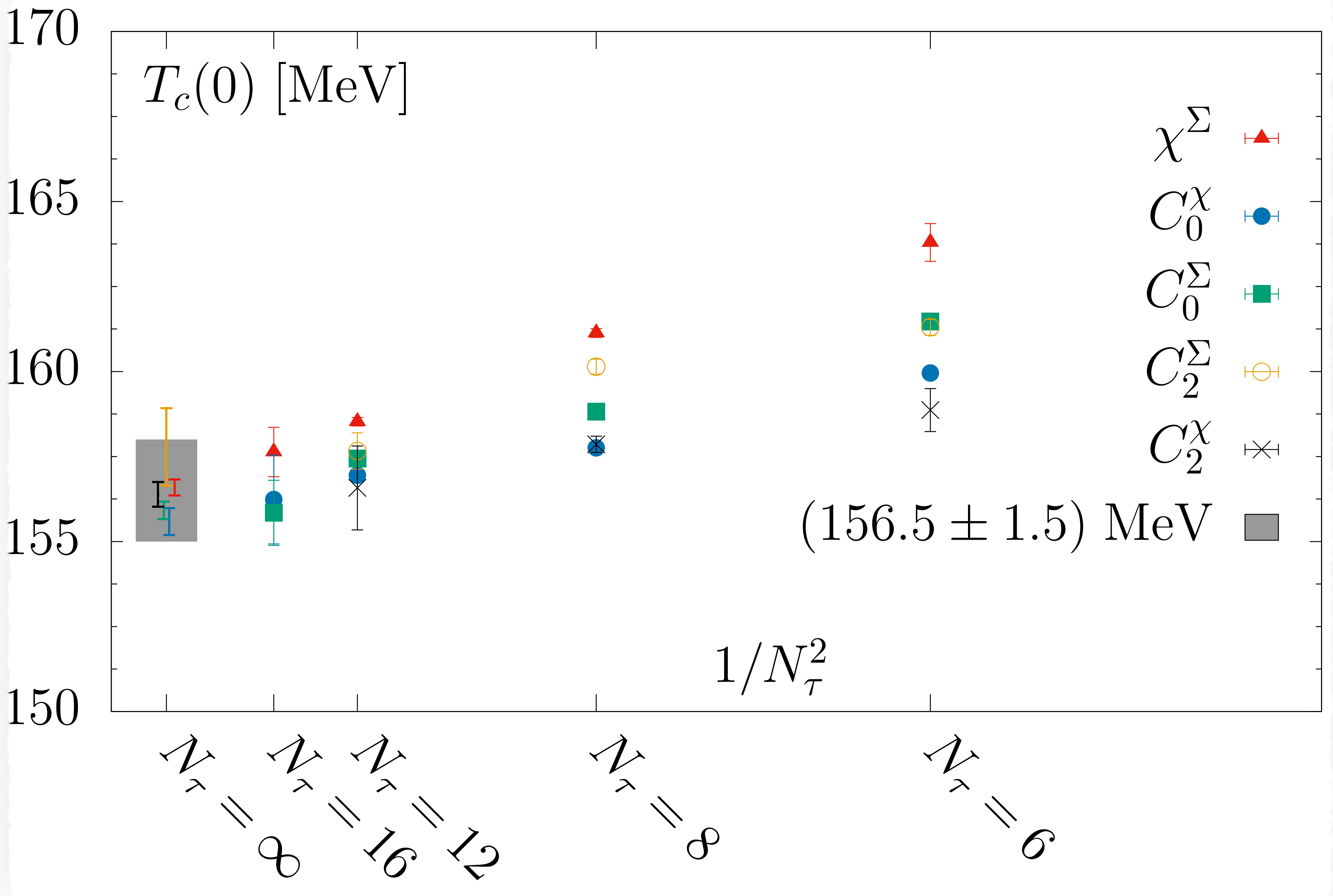
Machine learning spectral functions in lattice QCD

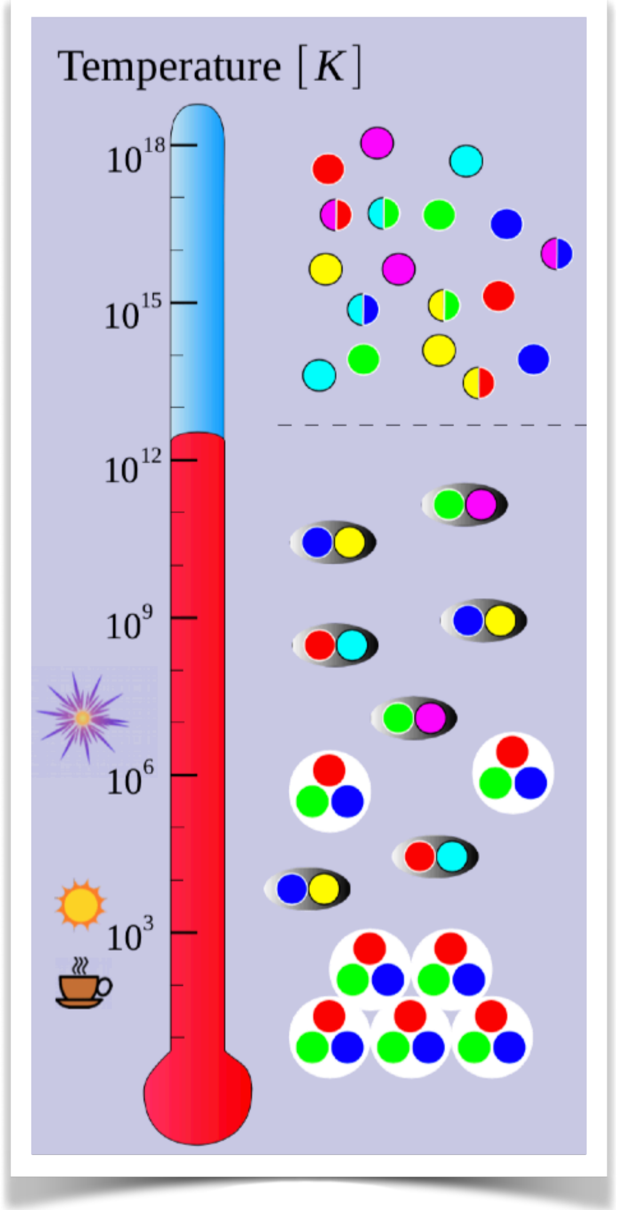
陈世阳, 丁亨通, 刘非易, G. Papp, 杨纯斌, arXiv: 2110.13521

Chiral crossover/phase transition temperature at physical point and $m_q \to 0$

Made in NSC³

Rigorous definition from O(4) universality class



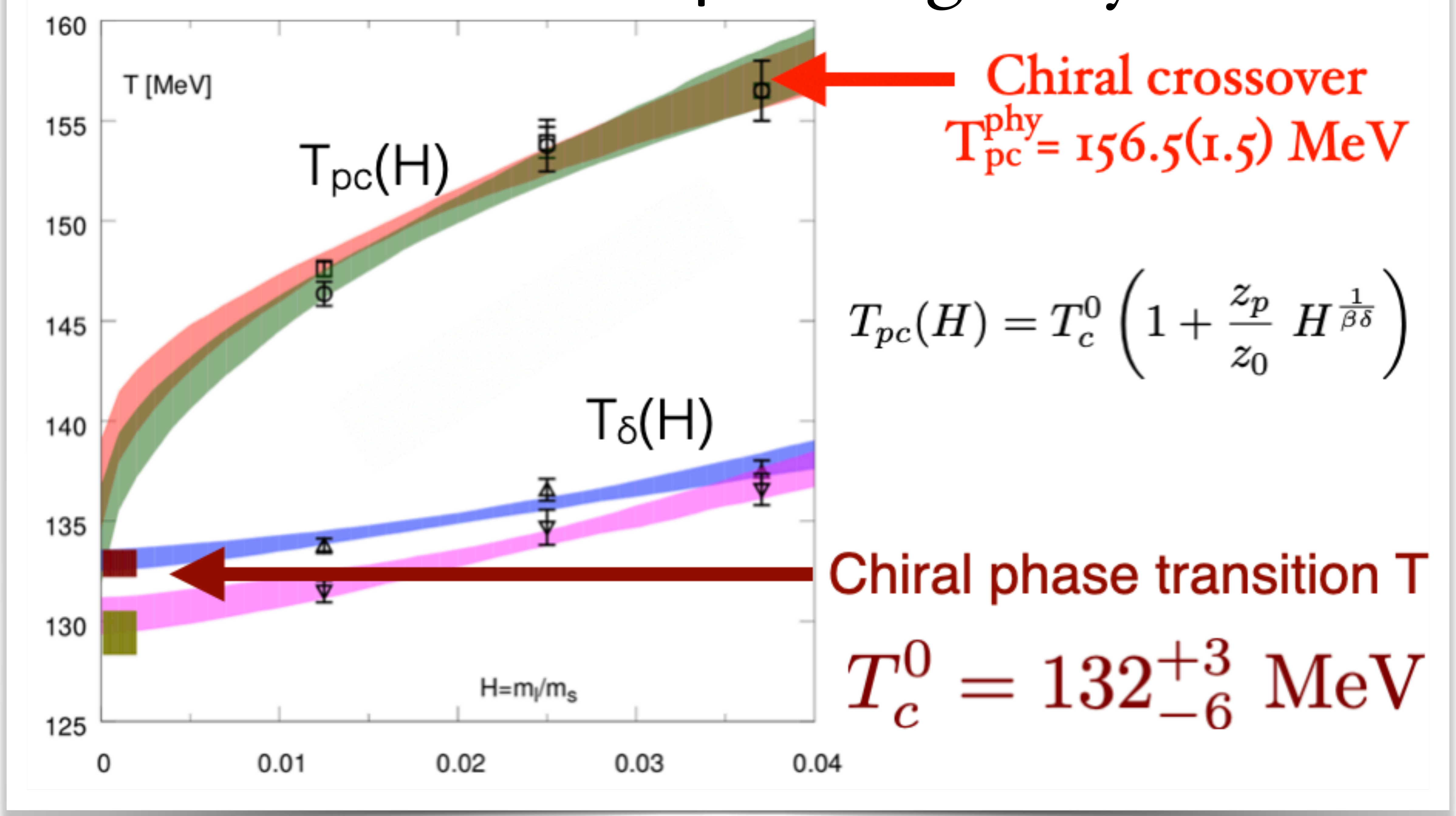


A. Bazavov, HTD, P. Hegde et al. [HotQCD], Phys. Lett. B795 (2019) 15, 被引259次

Chiral crossover transition
T=156.5(1.5) MeV

Consistent results from Wuppertal-Budapest, PRL125 (2020) 052001

Based on O(4) scaling analyses



HTD, P. Hegde, O. Kaczmarek et al.[HotQCD], Phys. Rev. Lett. 123 (2019) 062002，被引93次

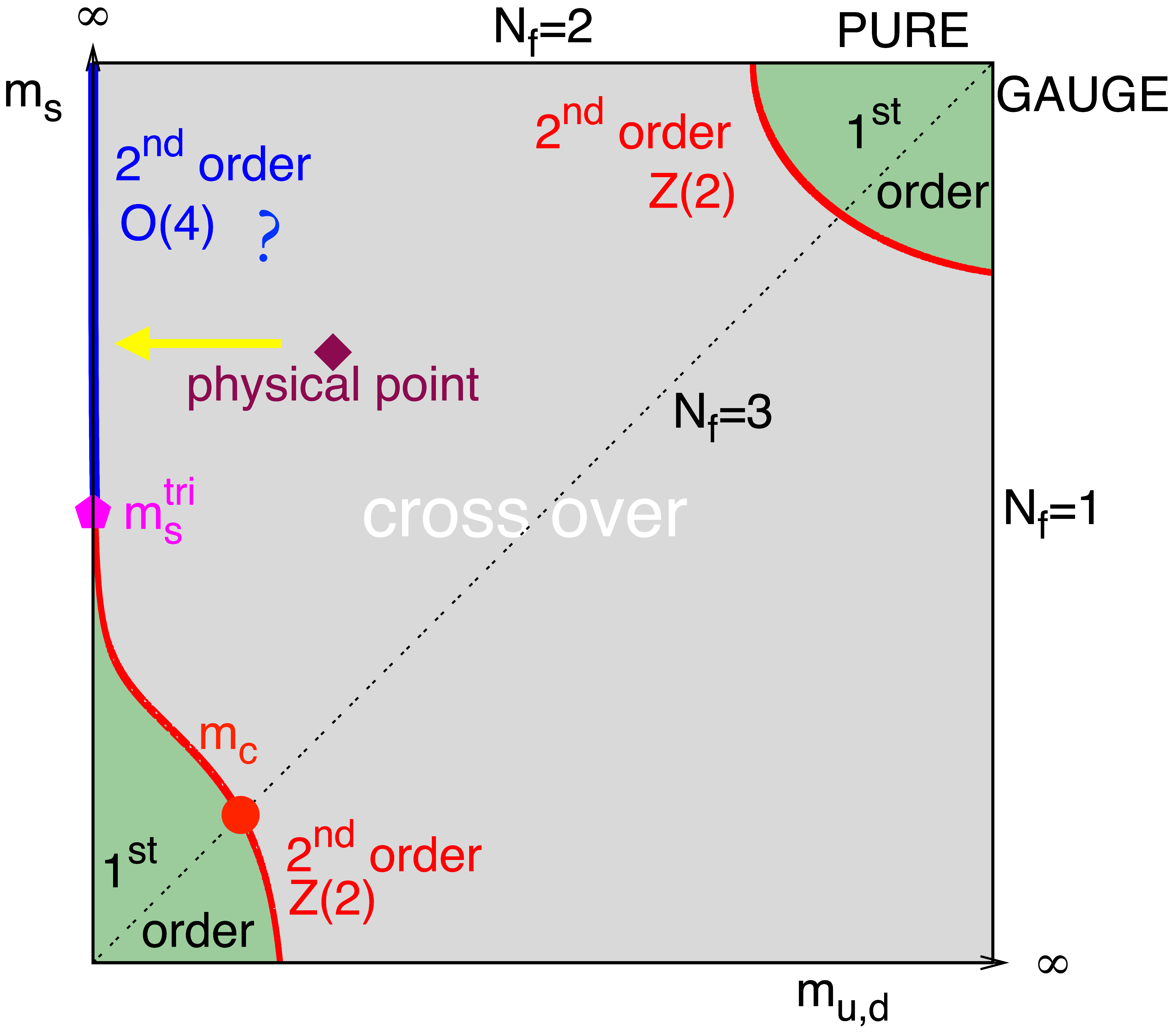
Chiral phase transition T is a possible upper bound of T_{CEP}

李胜泰，晨光杯二等奖

Sun, Oct. 31
16:50-17:20
张瑜

Axial U1 anomaly

Made in NSC3



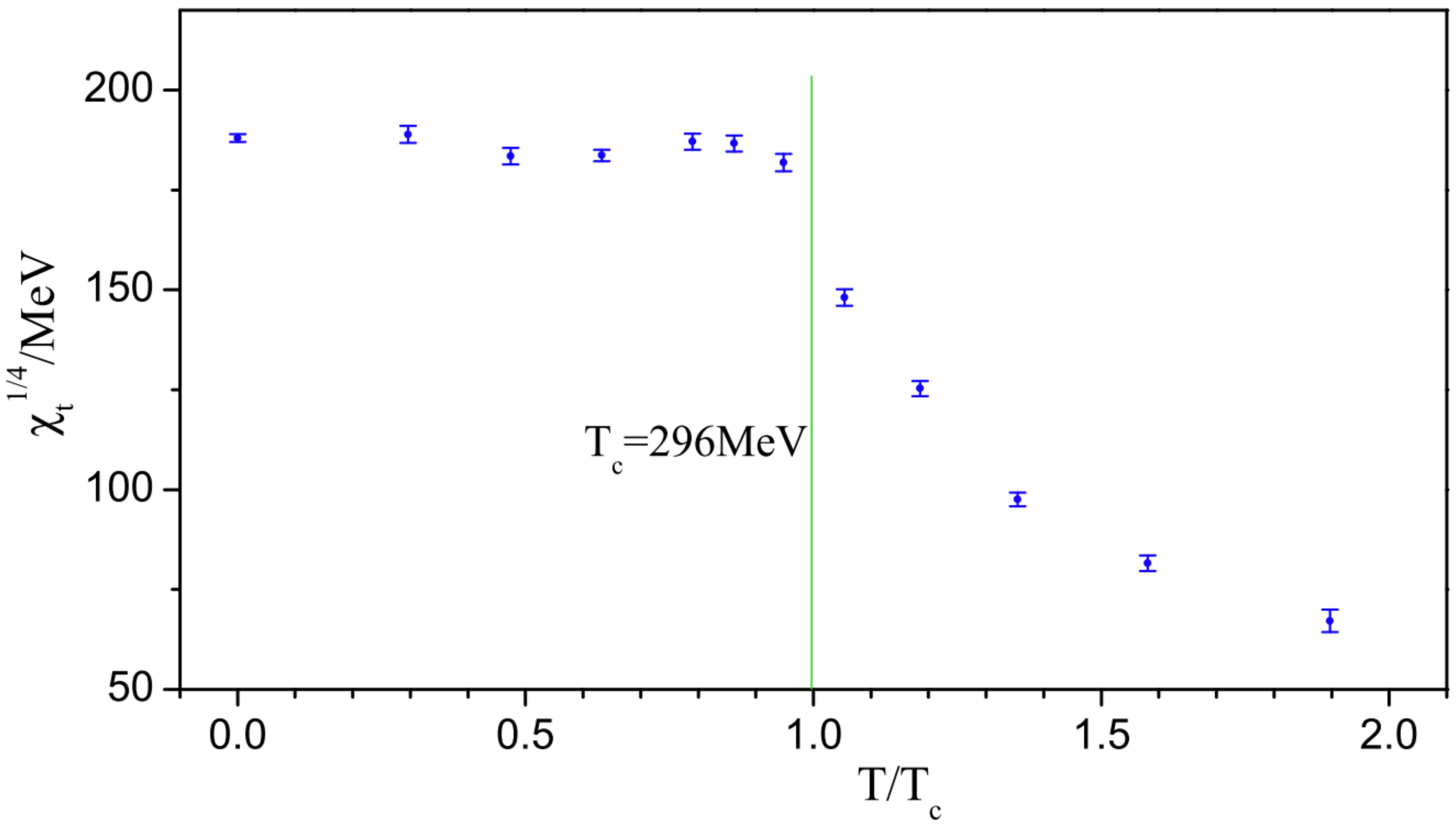
丁亨通, 李胜泰, 复谷昭夫, S. Mukherjee, 汪晓丹, 张瑜,
PRL 126 (2021) 082001

- At a single T~205 MeV
- HISQ/tree action
- N_f=2+1:
  - ☑ Nt=8,12,16 (*a*=0.12,0.08,0.06 fm)
  - ☑ $m_s^{phy}/\mathbf{m_l}$ = 20, 27, 40, 80, 160

    $m_\pi \approx$160,140,110, 80, 55 MeV
  - ☑ 9≥N_s/N_t ≥4
- Novel method to compute the quark mass derivative of Dirac Eigenvalue spectrum

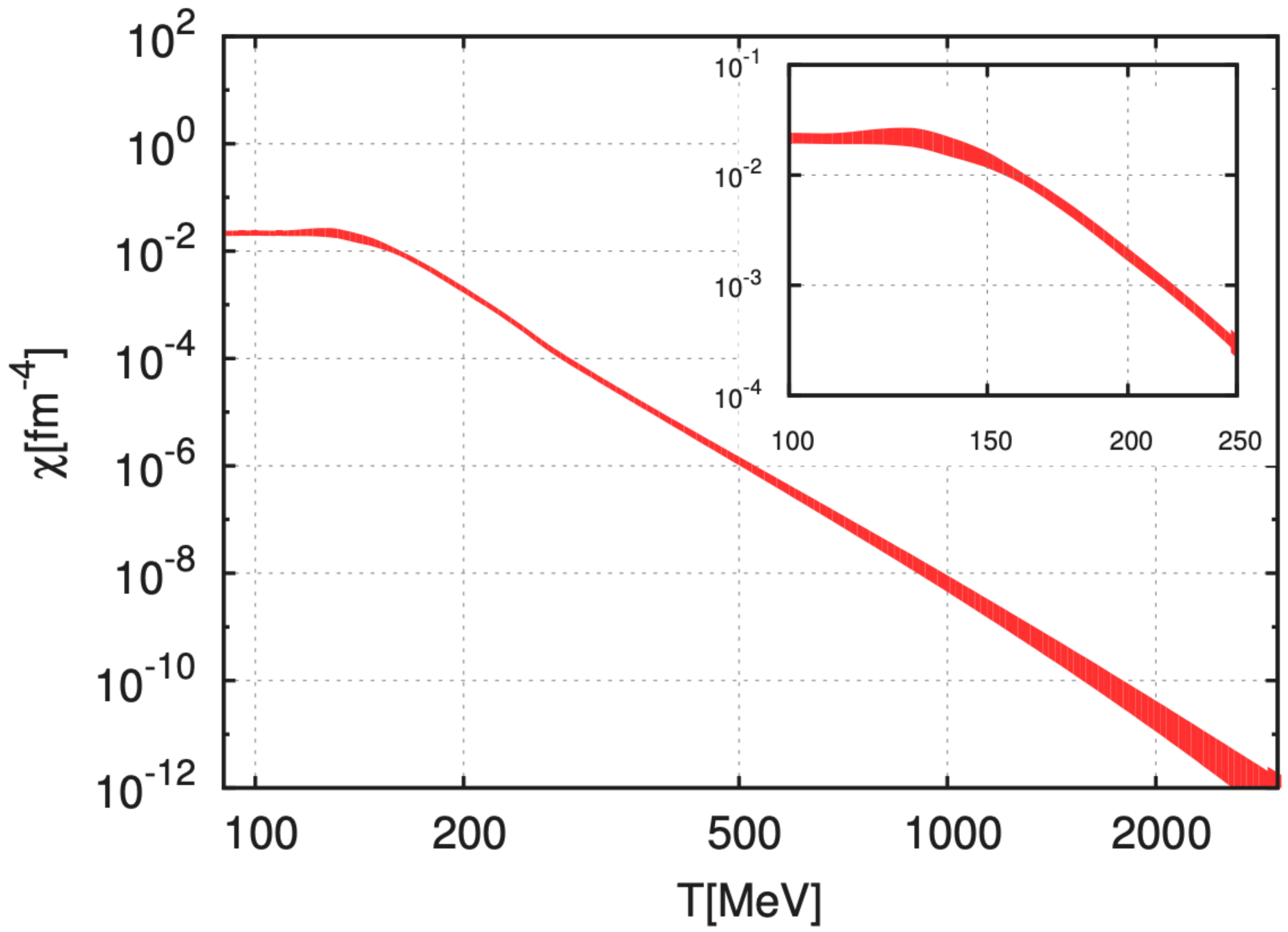
Topological susceptibility at nonzero T

SU(3)



熊光仪，张剑波，陈莹，刘川，刘玉斌，马建平，
Phys.Lett.B 752(2016)34
程贞，张剑波，Chin.Phys.C 45 (2021) 7, 073103

2+1+1 flavor QCD



Borsanyi et al, [WB collaboration],
Nature 539(2016)7627,69-71

Lattice QCD in strong magnetic fields

No sign problem

- B pointing to the z direction & Gauge link multiplied by a U(1) factor

$$u_x(n_x,n_y,n_z,n_\tau)=\begin{cases}\exp[-iqa^2BN_xn_y] & (n_x=N_x-1)\\ 1 & (\text{otherwise})\end{cases}$$

$$u_y(n_x,n_y,n_z,n_\tau)=\exp[iqa^2Bn_x],$$

$$u_z(n_x,n_y,n_z,n_\tau)=u_t(n_x,n_y,n_z,n_\tau)=1.$$

- Quantization of the magnetic field

$$qB=\frac{2\pi N_b}{N_xN_y}a^{-2} \xrightarrow{q_u=2/3e,\ q_d=-1/3e,\ q_s=-1/3e} eB=\frac{6\pi N_b}{N_xN_y}a^{-2}$$

CCNU LQCD group has developed GPU/C++ codes for LQCD simulations at eB=/=0

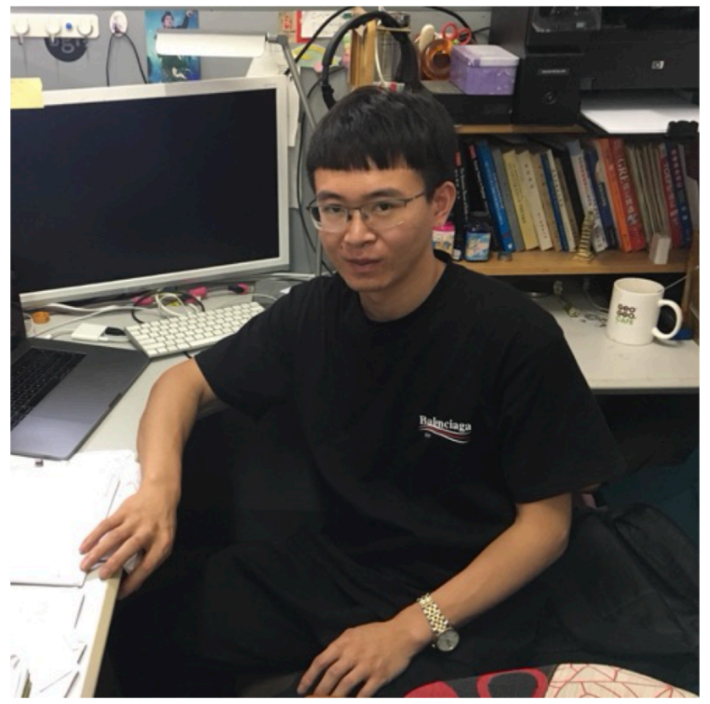
contributors: Akio Tomiya, 李胜泰, 汪晓丹, 李韶荣, 张瑜

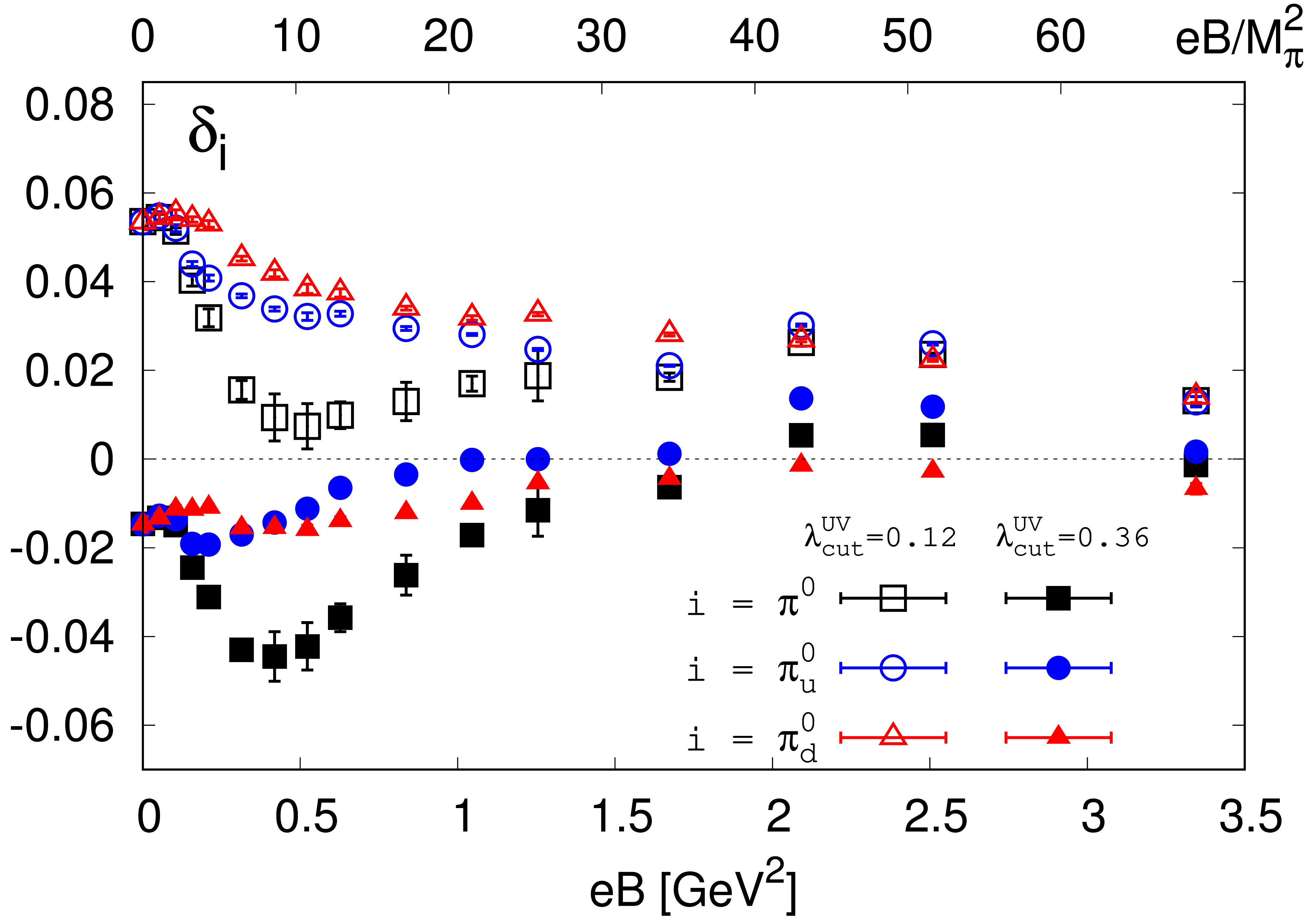
Made in NSC3

EPJ Web Conf. 175 (2018) 07041, *PoS* LATTICE2018 (2019) 163 ,
PoS LATTICE2019 (2020) 250, *Phys.Rev.D* 102 (2020) 5
Eur.Phys.J.A 57 (2021) 6, 202, *Phys.Rev.D* 104 (2021) 1, Acta Phys.Polon.Supp. 14 (2021) 403

First LQCD study on GMOR relation at $eB \neq 0$ and T=0

Mon, Nov. 1
16:00-16:30
李胜泰





$$4m_u\,\langle\bar\psi\psi\rangle_u = 2f^2_{\pi^0_u}M^2_{\pi^0_u}\,(1-\delta_{\pi^0_u})$$
$$4m_d\,\langle\bar\psi\psi\rangle_d = 2f^2_{\pi^0_d}M^2_{\pi^0_d}\,(1-\delta_{\pi^0_d})\,.$$

$$(m_u+m_d)\,\left(\langle\bar\psi\psi\rangle_u+\langle\bar\psi\psi\rangle_d\right) = 2f^2_\pi M^2_\pi\,(1-\delta_\pi)$$

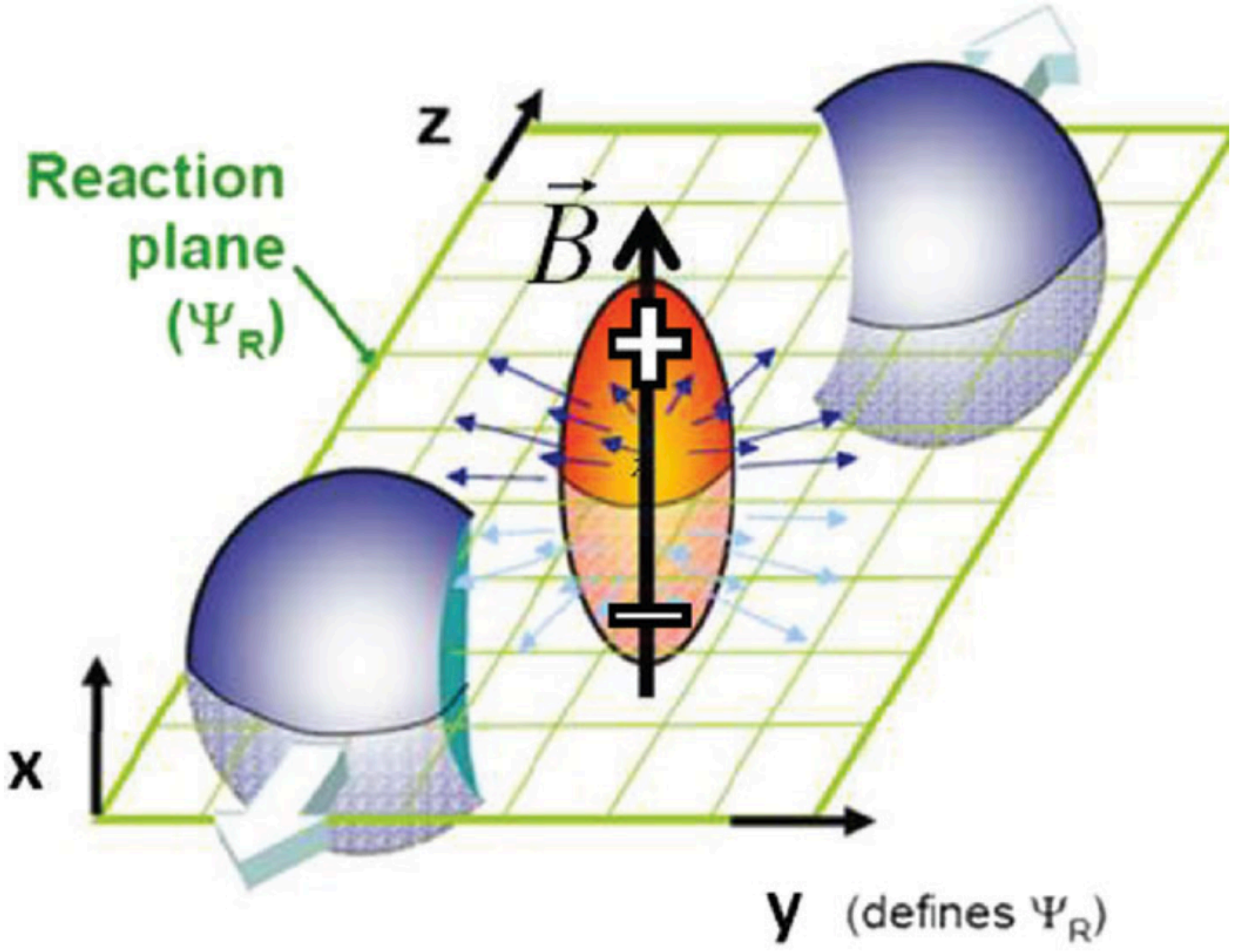
neutral pion remains as a Goldstone boson with eB up to ~3.5 GeV^2

丁亨通, 李胜泰, 复谷昭夫, 汪晓丹, 张瑜, PRD 104 (2021) 1

Probe to detect the existence of magnetic field in Heavy Ion collision

Mon, Nov. 1
15:30-16:00
刘俊宏

Heavy-Ion collision

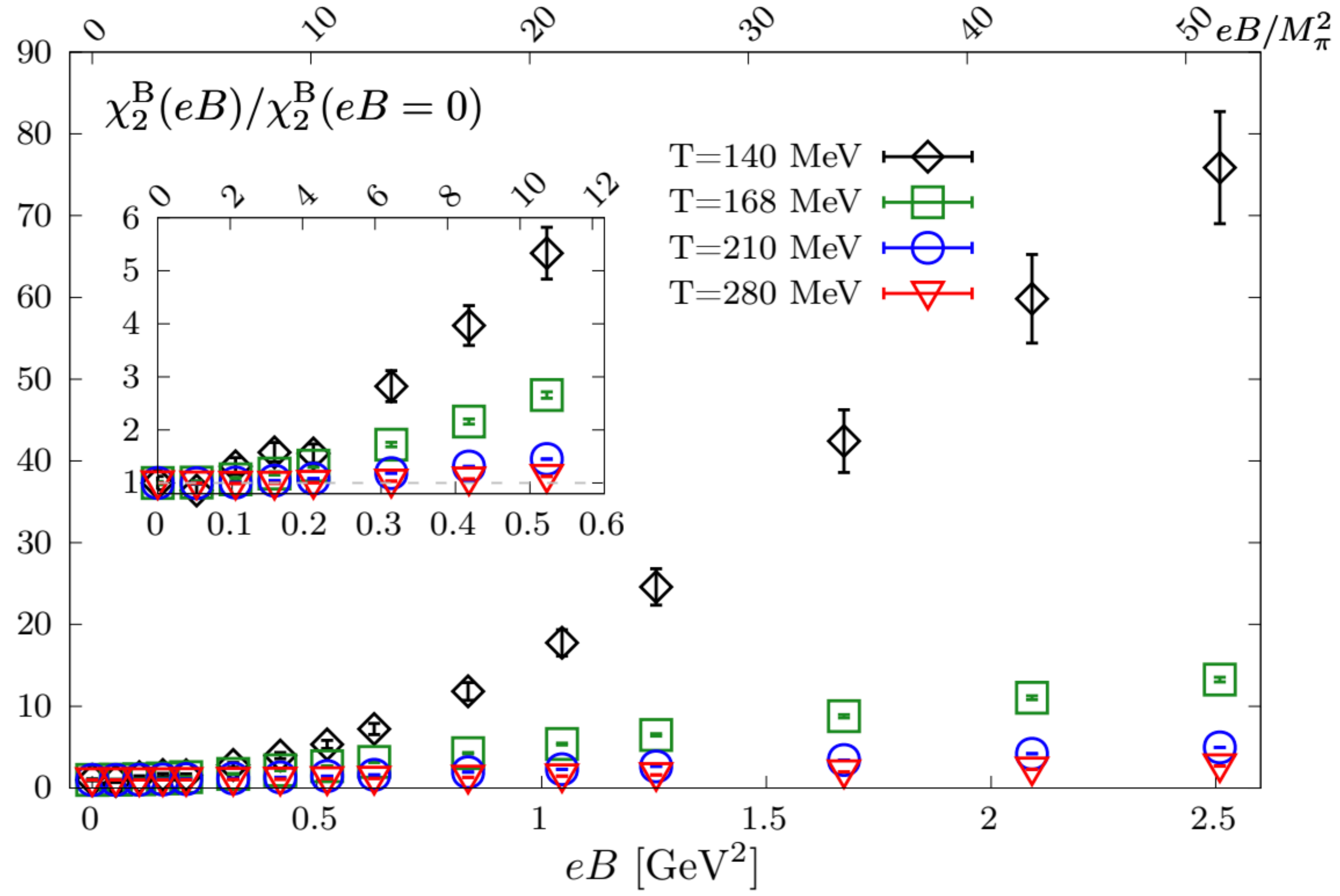


$10^{17\text{-}18}$ Gauss

$$\Lambda_{QCD}^2 \sim 10^4 \text{ MeV}^2 \sim 10^{17} \text{ Gauss}$$

$$1 \text{ Gauss} = 1.95 \times 10^{-14} \text{ MeV}^2$$

Fluctuations of conserved charges

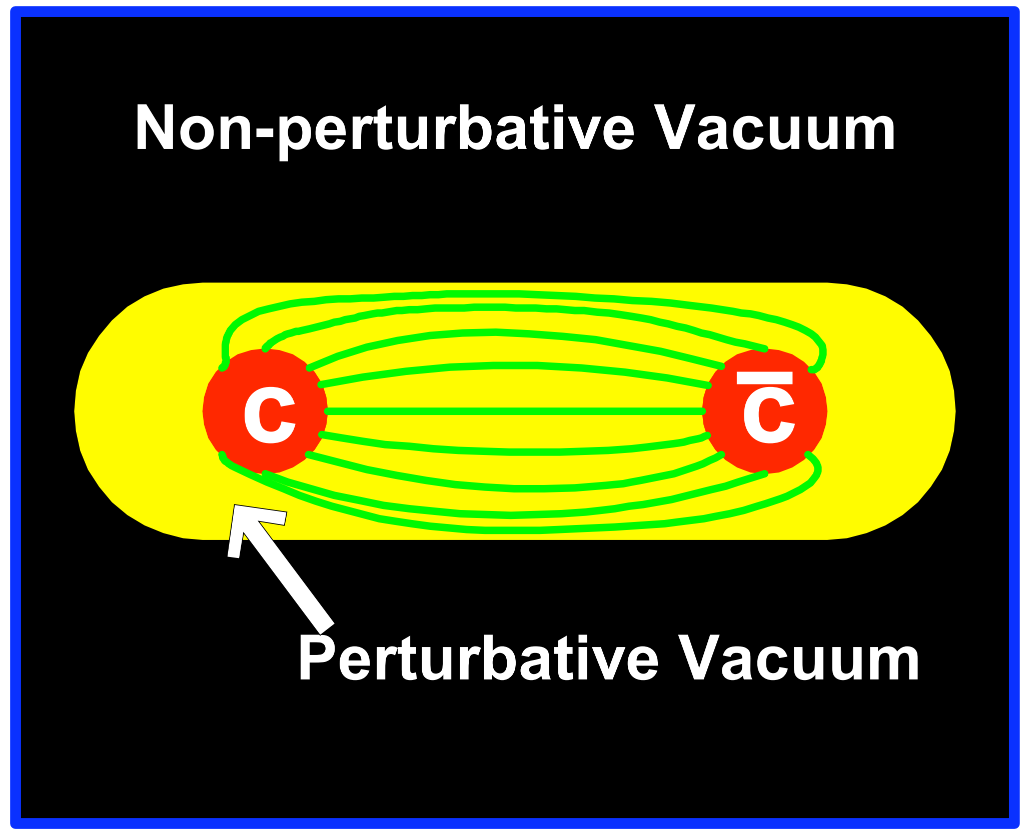


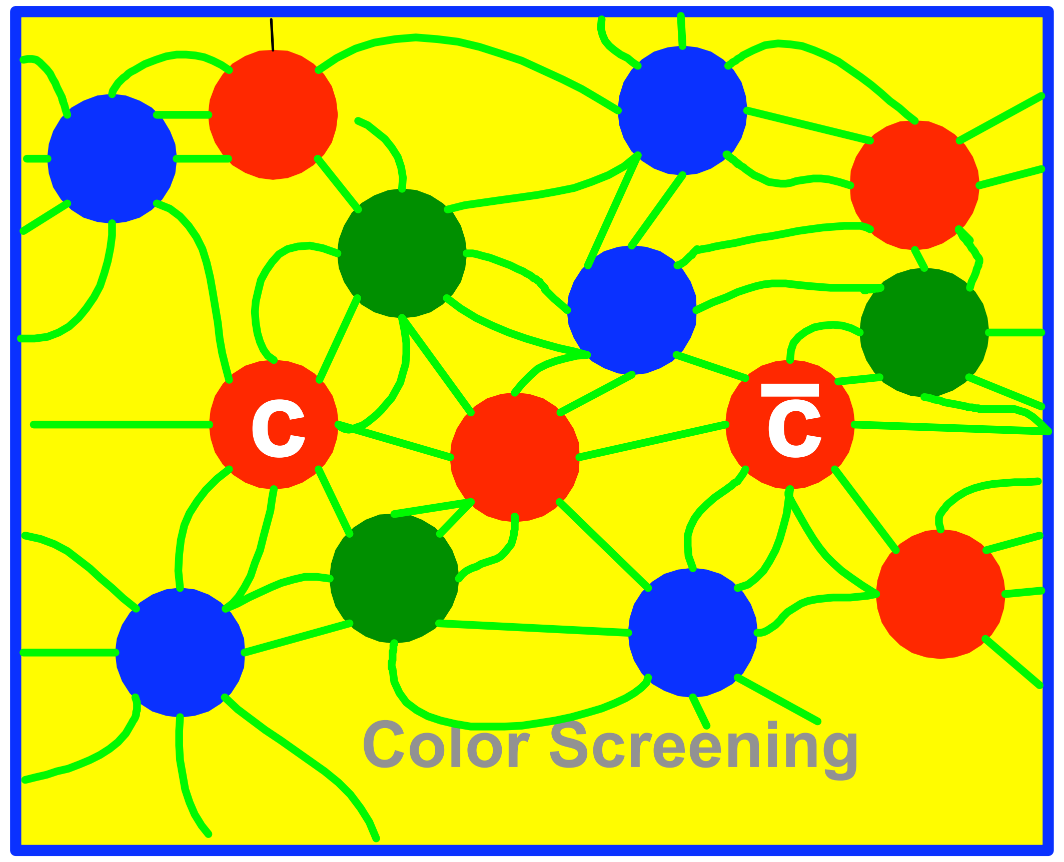
Central Collisions　　Peripheral Collisions

丁亨通, 李胜泰, 施岐, 汪晓丹, EPJA 57 (2021) 6, 202,
丁亨通，刘俊宏，李胜泰，汪晓丹，in preparation

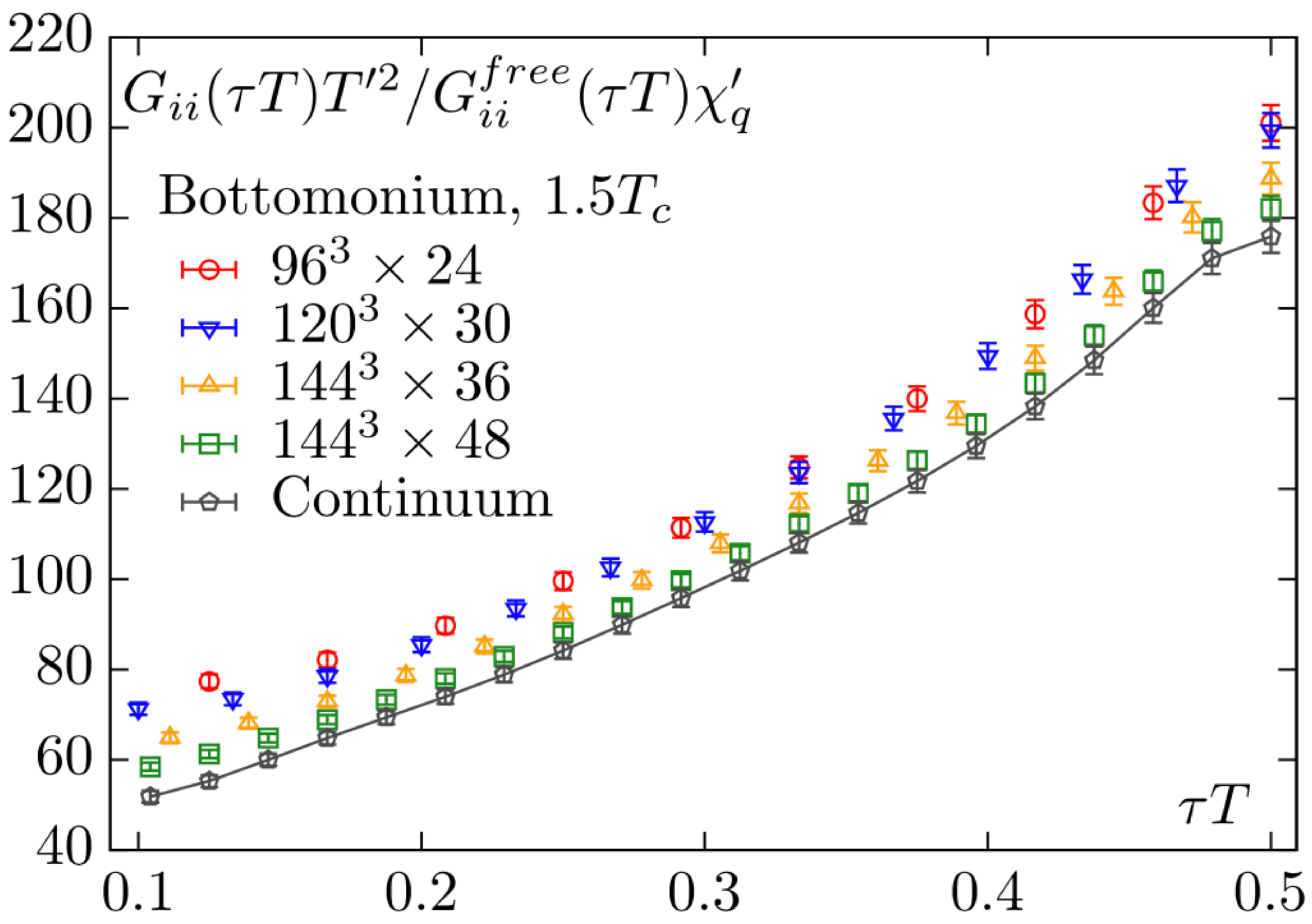
Charm and beauty in hot medium

Mon, Nov. 1
15:00-15:30
舒海涛

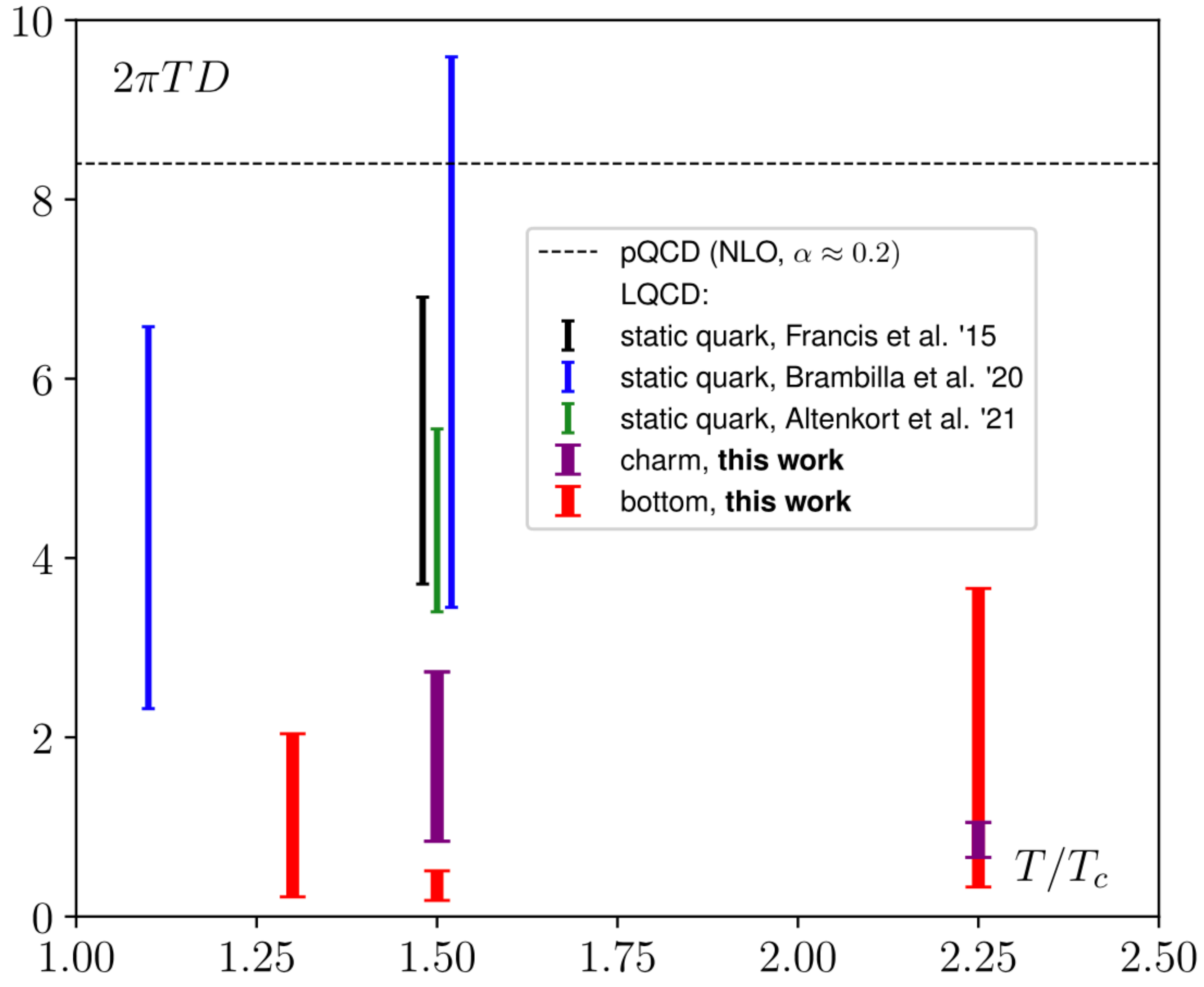




Meson correlation functions



HQ diffusion coefficients



L. Altenkort, A. M. Eller, O. Kaczmarek, L. Mazur, G. D. Moore , 舒海涛, PRD103 (2021) 1, 014511

丁亨通, O. Kaczmarek, A.-L. Lorenz, H. Ohno,H. Sandmeyer, 舒海涛， arXiv: 2108.13693

Explorative study on the inverse problem using machine learning

Tue, Nov. 2
16:30-16:50
陈世阳

$$G(\tau,T)=\sum_{x,y,z}\left\langle J_H(0,\vec{0})J_H^{+}(\tau,\vec{x})\right\rangle_T=\int_0^\infty \frac{\mathrm{d}\omega}{2\pi}\,K(\tau,\omega,T)\rho(\omega,T),$$

Discretized $\mathcal{O}(10)$

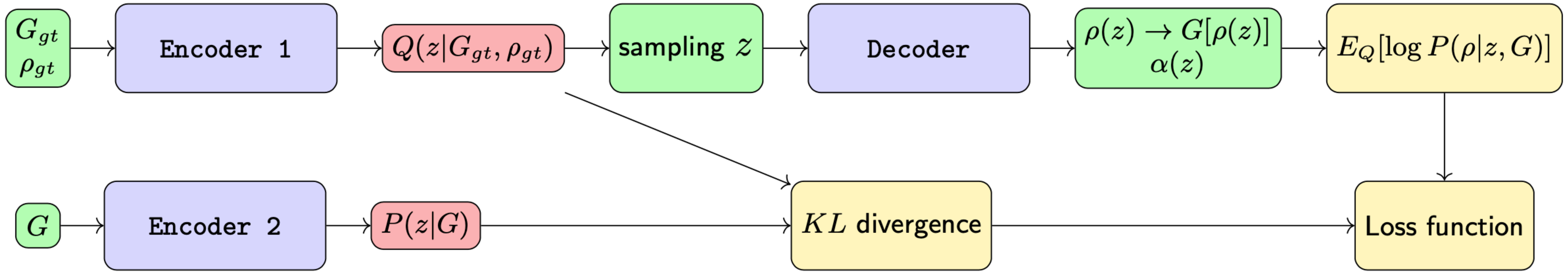
Continuous $\mathcal{O}(10^3)$

χ^2 fitting inconclusive

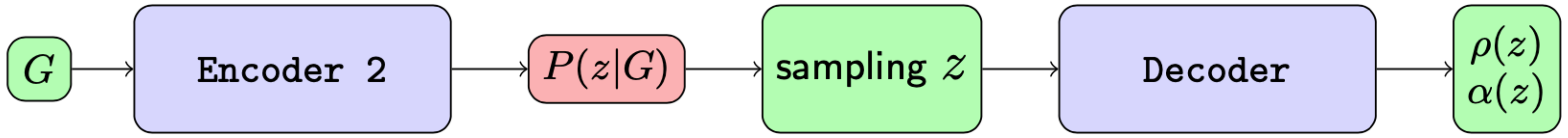
sVAE: Variational autoencoder including an information entropy

$$S=\int_0^\infty \mathrm{d}\omega\left(\rho(z)-\rho_{gt}-\rho(z)\log\left(\frac{\rho(z)}{\rho_{gt}}\right)\right)$$

Trained to obtain the most probable spectral function:

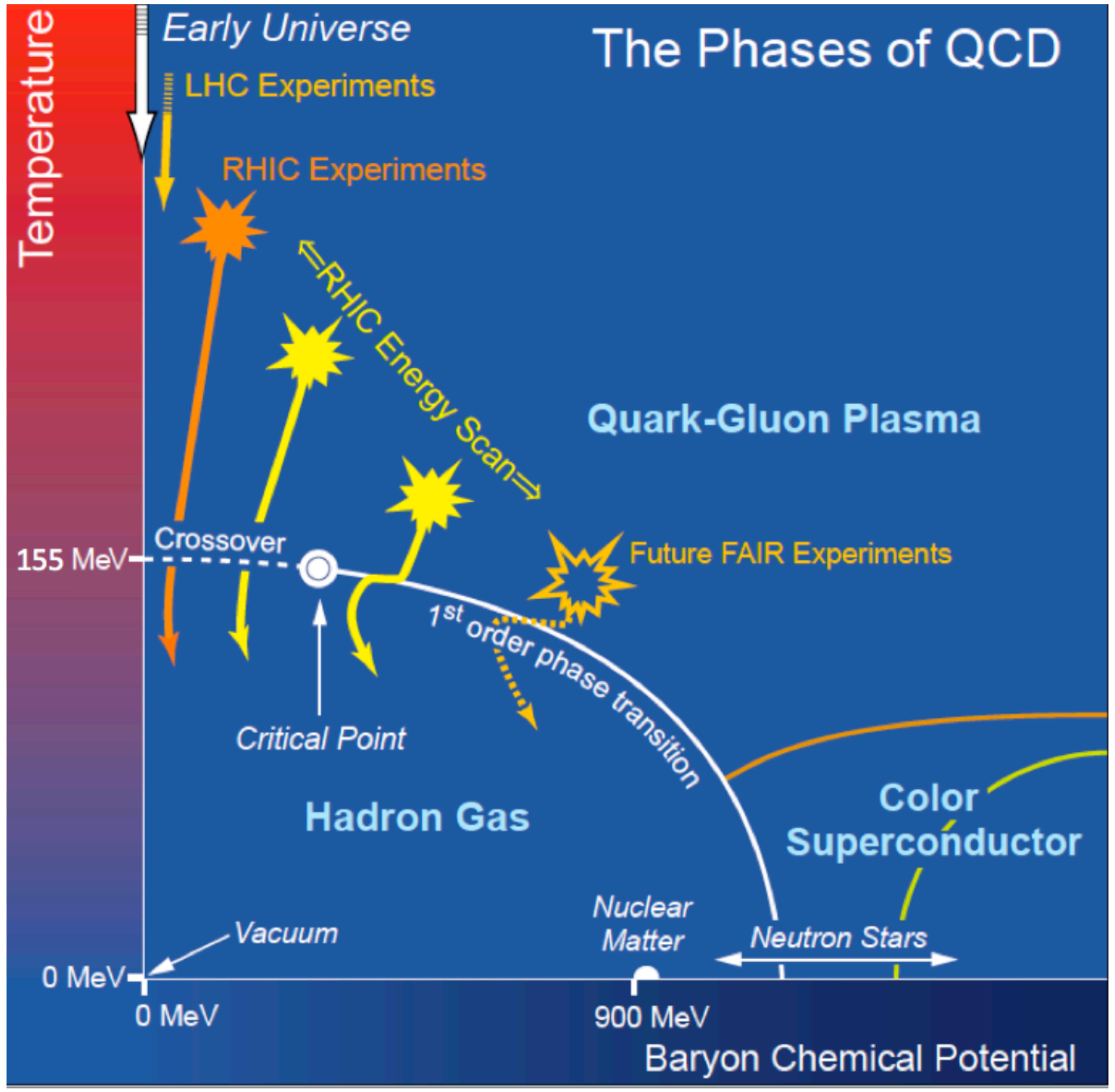


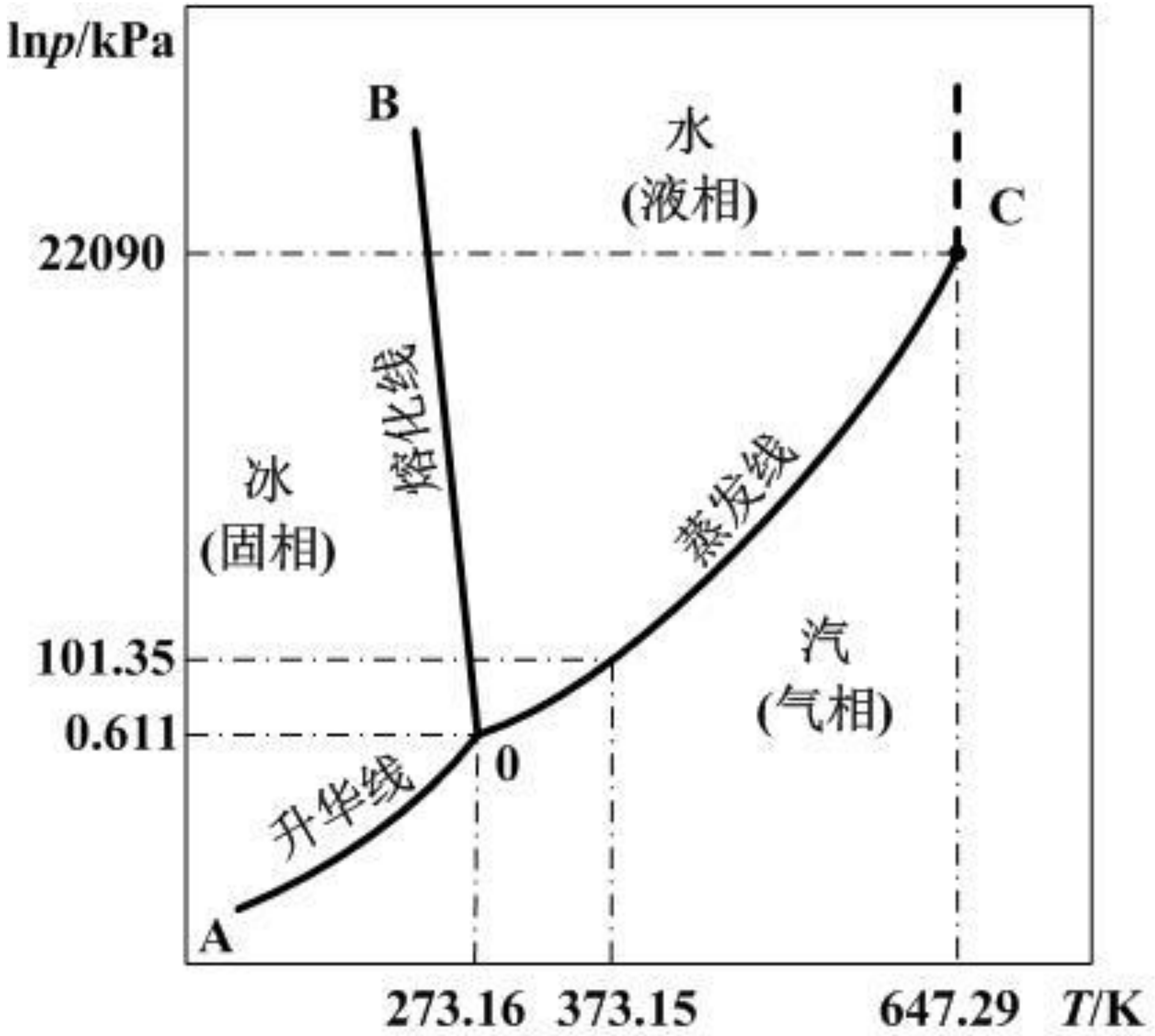
Production process:



陈世阳, 丁亨通, 刘非易, G. Papp, 杨纯斌, arXiv: 2110.13521

Challenges in mapping out the QCD phase diagram



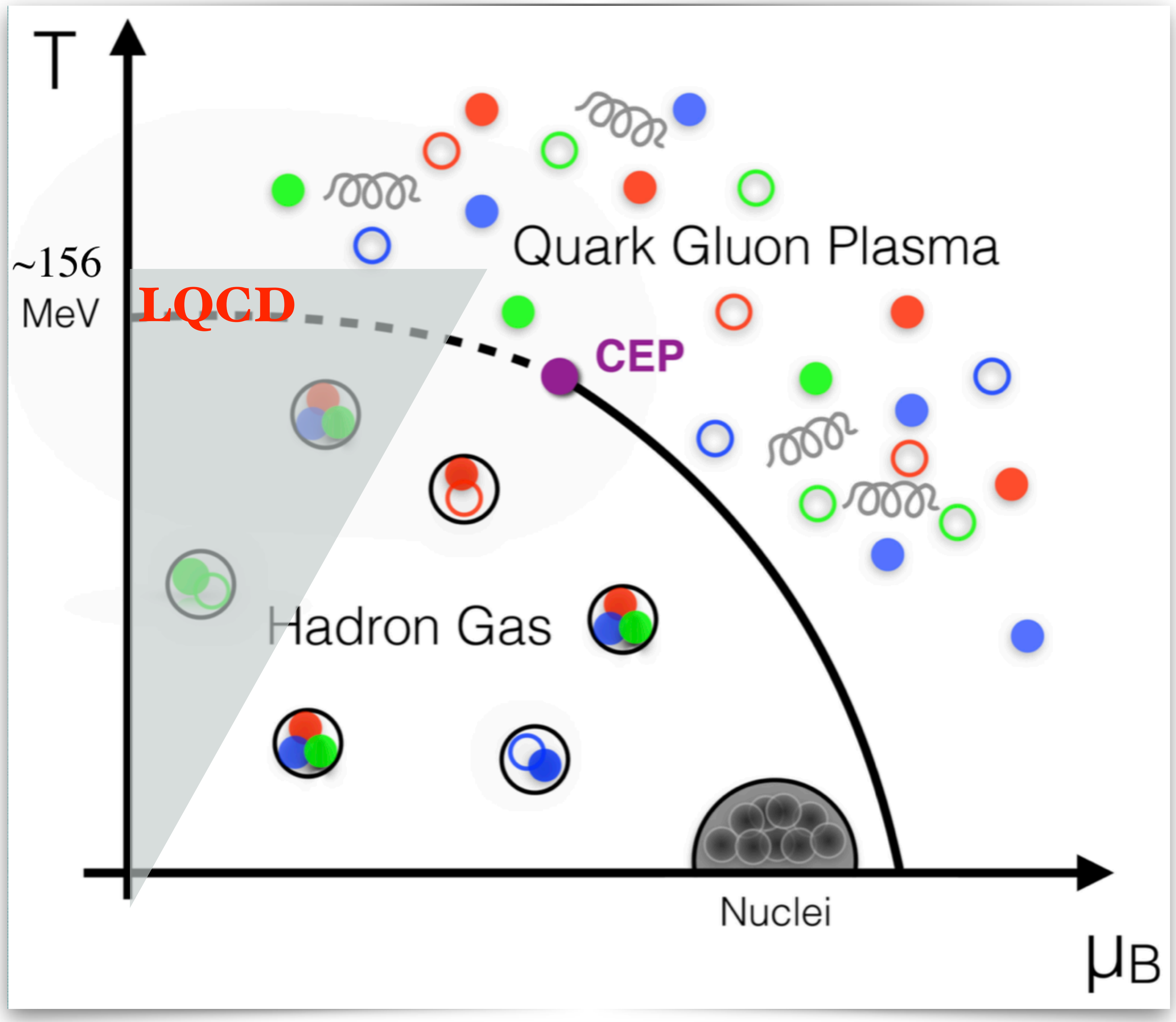


Mon, Nov. 1,
14:00-14:30
付伟杰

Mon, Nov. 1,
14:30-15:00
罗晓峰

- What is the structure of the QCD phase diagram at nonzero baryon density?
- Does it, like that of water, feature a critical end point at large baryon density?

Lattice QCD at nonzero baryon density



HTD, F. Karsch, S. Mukherjee, arXiv:1504.05274

Sign Problem at μ_B=/=0

Taylor Expansion

Imaginary μ_B

Taylor expansion of the QCD pressure:

Allton et al., Phys.Rev. D66 (2002) 074507
Gavai & Gupta et al., Phys.Rev. D68 (2003) 034506

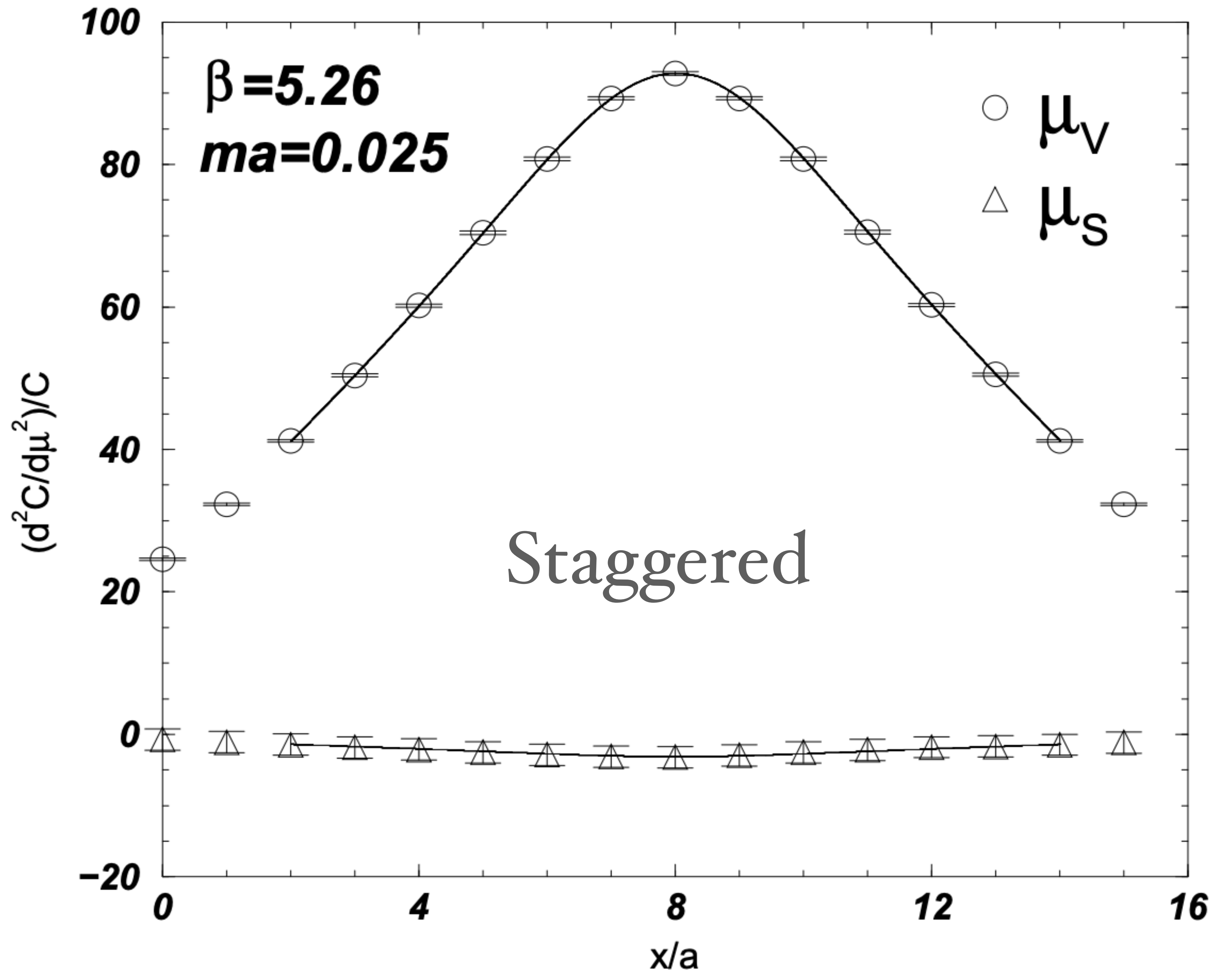
$$\frac{p}{T^4} = \frac{1}{VT^3} \ln \mathcal{Z}(T, V, \hat{\mu}_u, \hat{\mu}_d, \hat{\mu}_s) = \sum_{i,j,k=0}^{\infty} \boxed{\frac{\chi_{ijk}^{BQS}}{i!j!k!}} \left(\frac{\mu_B}{T}\right)^i \left(\frac{\mu_Q}{T}\right)^j \left(\frac{\mu_S}{T}\right)^k$$

- Taylor expansion coefficients at μ=0 are computable in LQCD

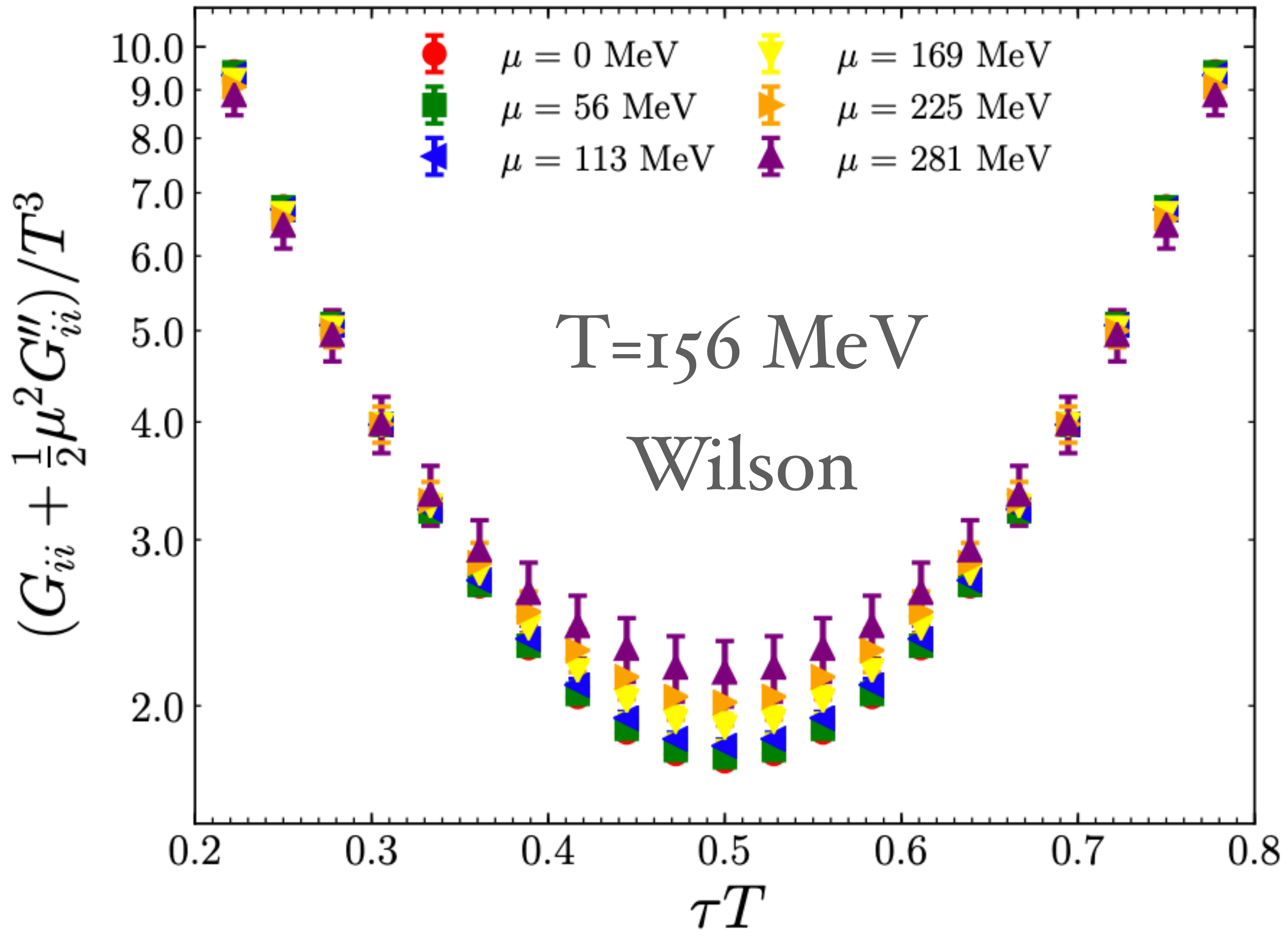
fluctuations of conserved charges:

$$\chi_{ijk}^{BQS} \equiv \chi_{ijk}^{BQS}(T) = \frac{1}{VT^3} \frac{\partial^{i+j+k} P(T,\mu)/T^4}{\partial \hat{\mu}_B^i \partial \hat{\mu}_Q^j \partial \hat{\mu}_S^k} \Big|_{\hat{\mu}_{B,Q,S}=0}$$

Mesonic correlators at non-zero baryon chemical potential

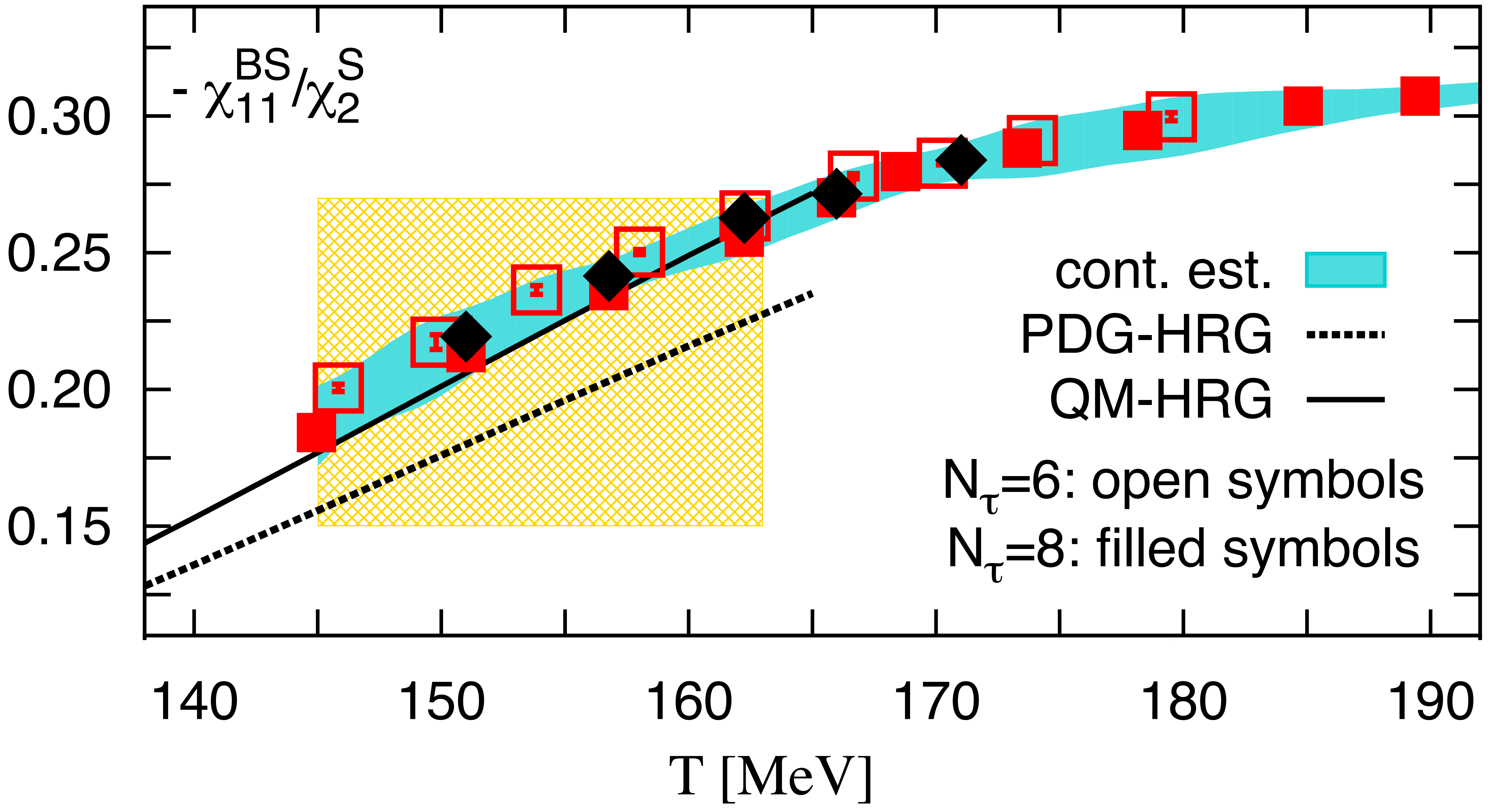


S. Choe,...,刘玉斌 et al., [QCD-TARO Collaboration], *Phys.Rev.D*65(2002)054501



G. Aarts,..,吴良凯 et al., [FASTSUM collaboration], arXiv: 2001.04415, *PoS* LATTICE2019(2020)077

Indirect evidence on experimentally-not-yet-observed strange hadrons



Bielefeld-BNL-CCNU, PRL 113 (2014) 072001

V. Koch, A. Majumder, and J. Randrup , PRL95 (2005) 182301

PDG-HRG:
利用实验上已经观测到的粒子的谱做的强子气体模型计算

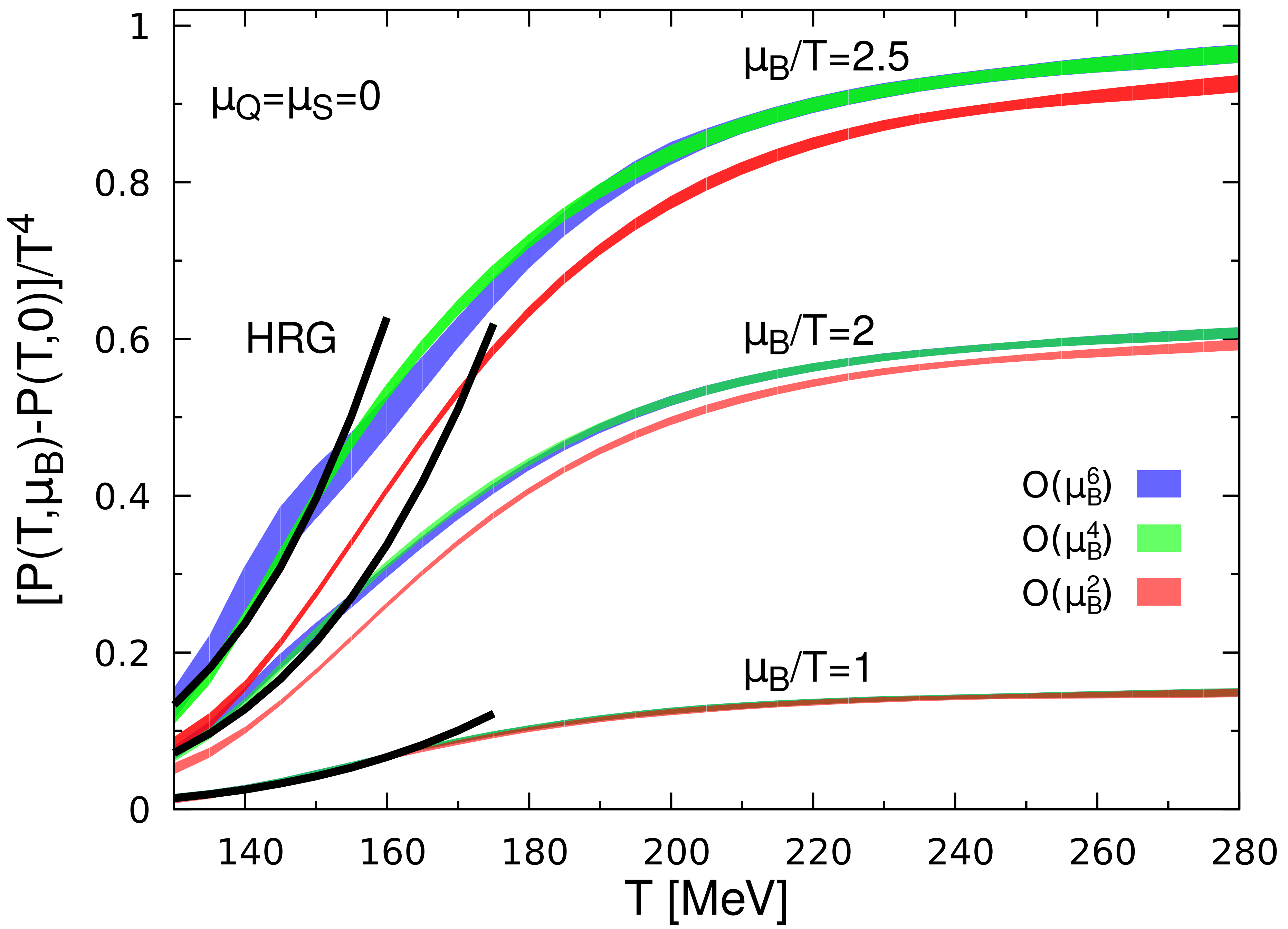
QM-HRG:
利用夸克模型预言的粒子的谱做的强子气体计算

$$\left\{\text{实验上已经观测到的粒子}\right\} \in \left\{\text{夸克模型预言的粒子}\right\}$$

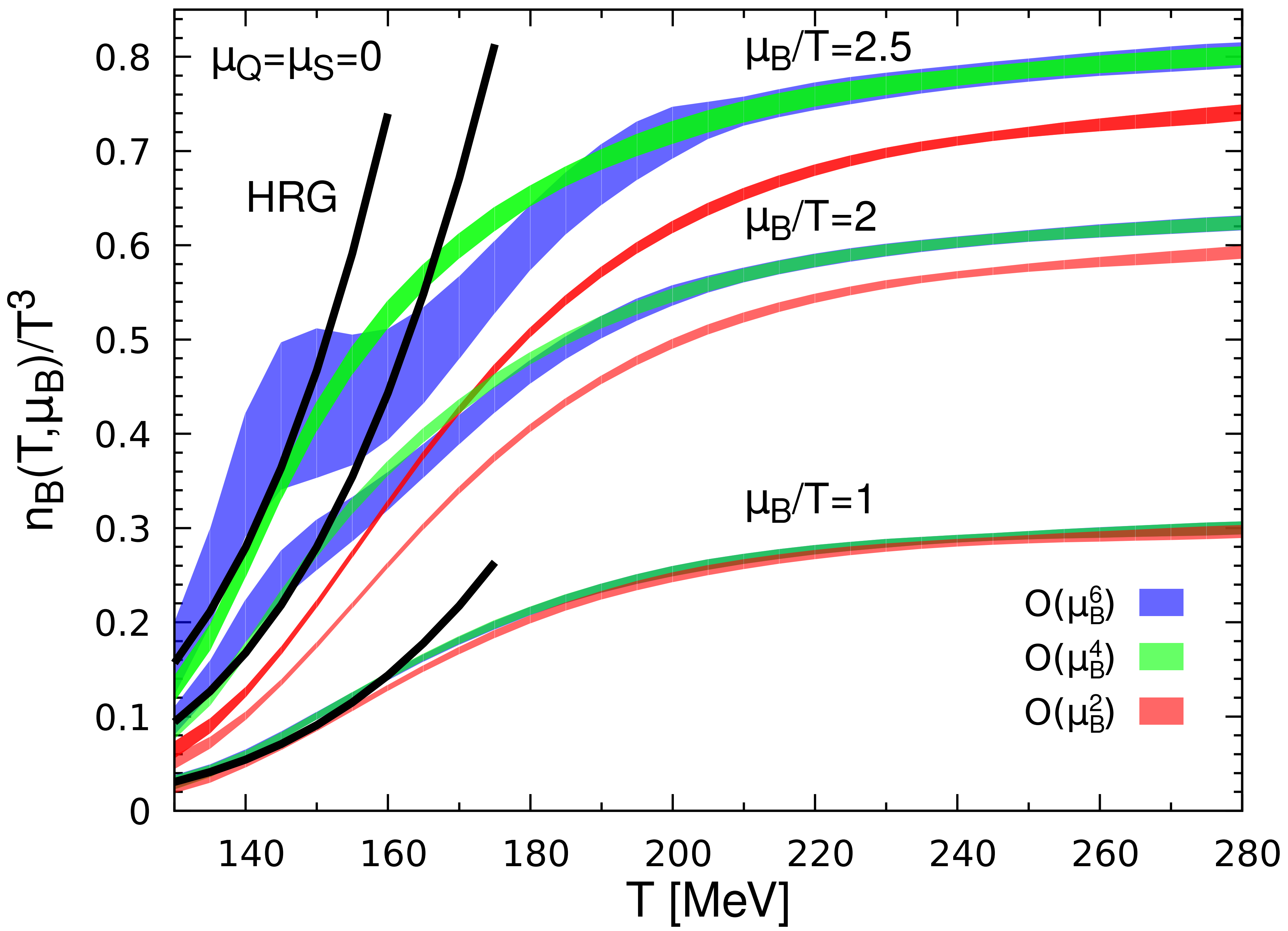
HRG: Hadron Resonance Gas
PDG: Particle Data Group
QM: Quark Model

QCD Equation of State at small baryon density

Pressure difference



Baryon number density

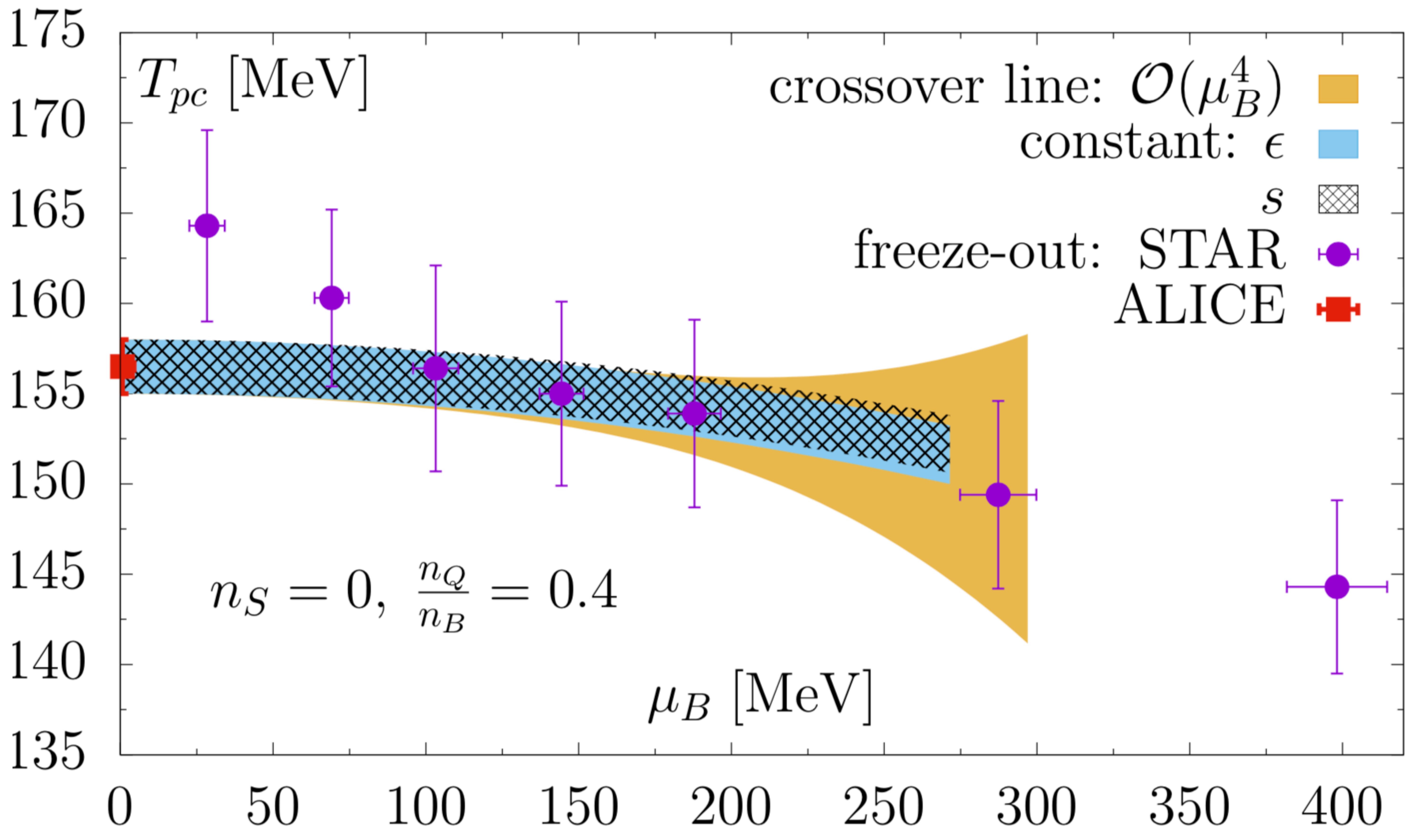


A. Bazavov, HTD. P. Hegde et al.,[HotQCD], Phys.Rev.D 95 (2017) 5, 054504, cited by 303 records

$$\frac{P(T,\mu_B)-P(T,0)}{T^4}=\sum_{n=1}^{\infty}\frac{\chi_{2n}^B(T)}{(2n)!}\left(\frac{\mu_B}{T}\right)^{2n}=\frac{1}{2}\chi_2^B(T)\hat{\mu}_B^2\left(1+\frac{1}{12}\frac{\chi_4^B(T)}{\chi_2^B(T)}\hat{\mu}_B^2+\frac{1}{360}\frac{\chi_6^B(T)}{\chi_2^B(T)}\hat{\mu}_B^4+\cdots\right)$$

The EoS is well under control at $\mu_B/T \lesssim 2$ or $\sqrt{s_{NN}} \gtrsim 12$ GeV

Chiral crossover transition temperature at small baryon density



ALICE data point:

$T_f = 156.5(1.5)$ MeV

Andronic et al, Nature 561 (7723) (2018) 321

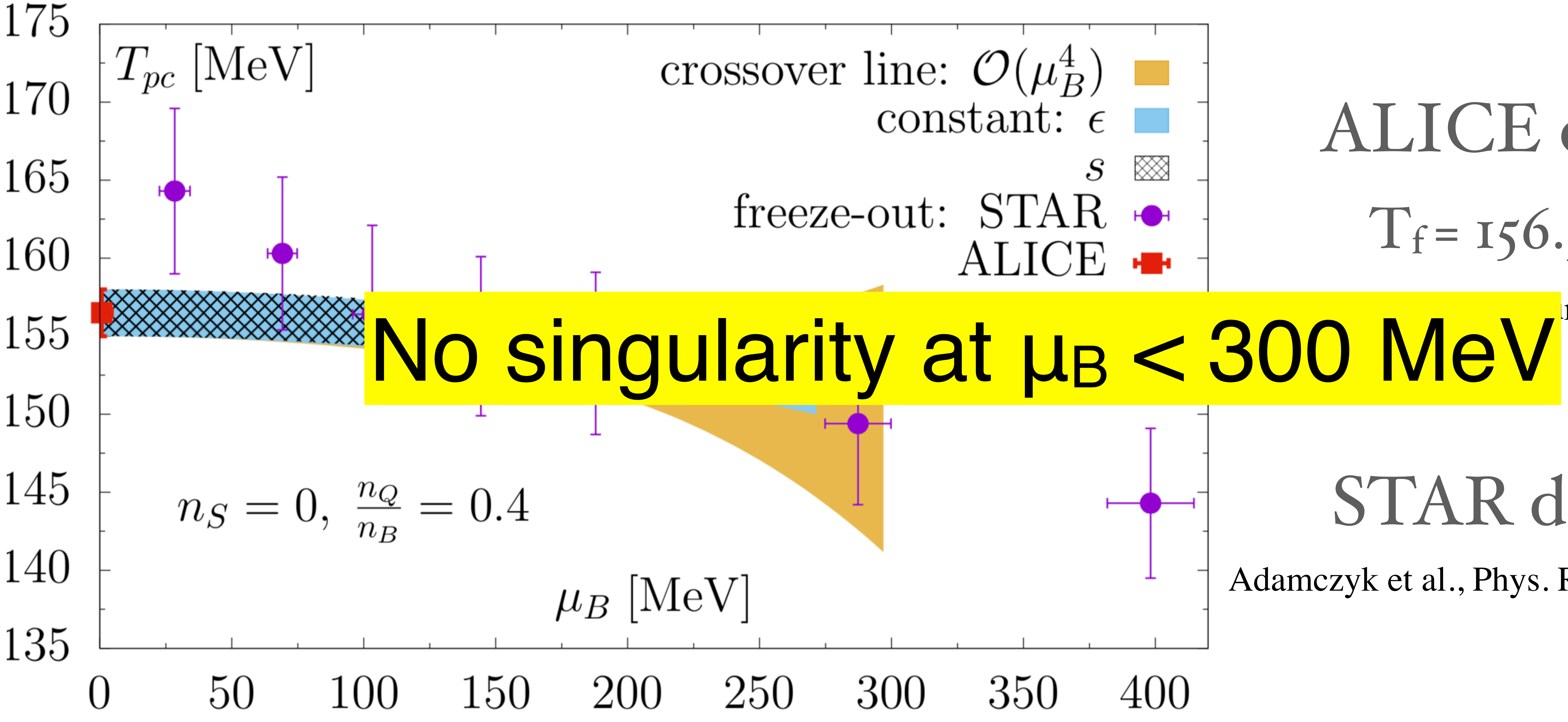
STAR data points:

Adamczyk et al., Phys. Rev. C 96 (4) (2017) 044904

Bazavov, HTD, P. Hegde et al. [HotQCD], Phys. Lett. B795 (2019) 15, cited by 259 records

Consistent results from Wuppertal-Budapest, PRL125 (2020) 052001

Chiral crossover transition temperature at small baryon density



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...re 561 (7723) (2018) 321

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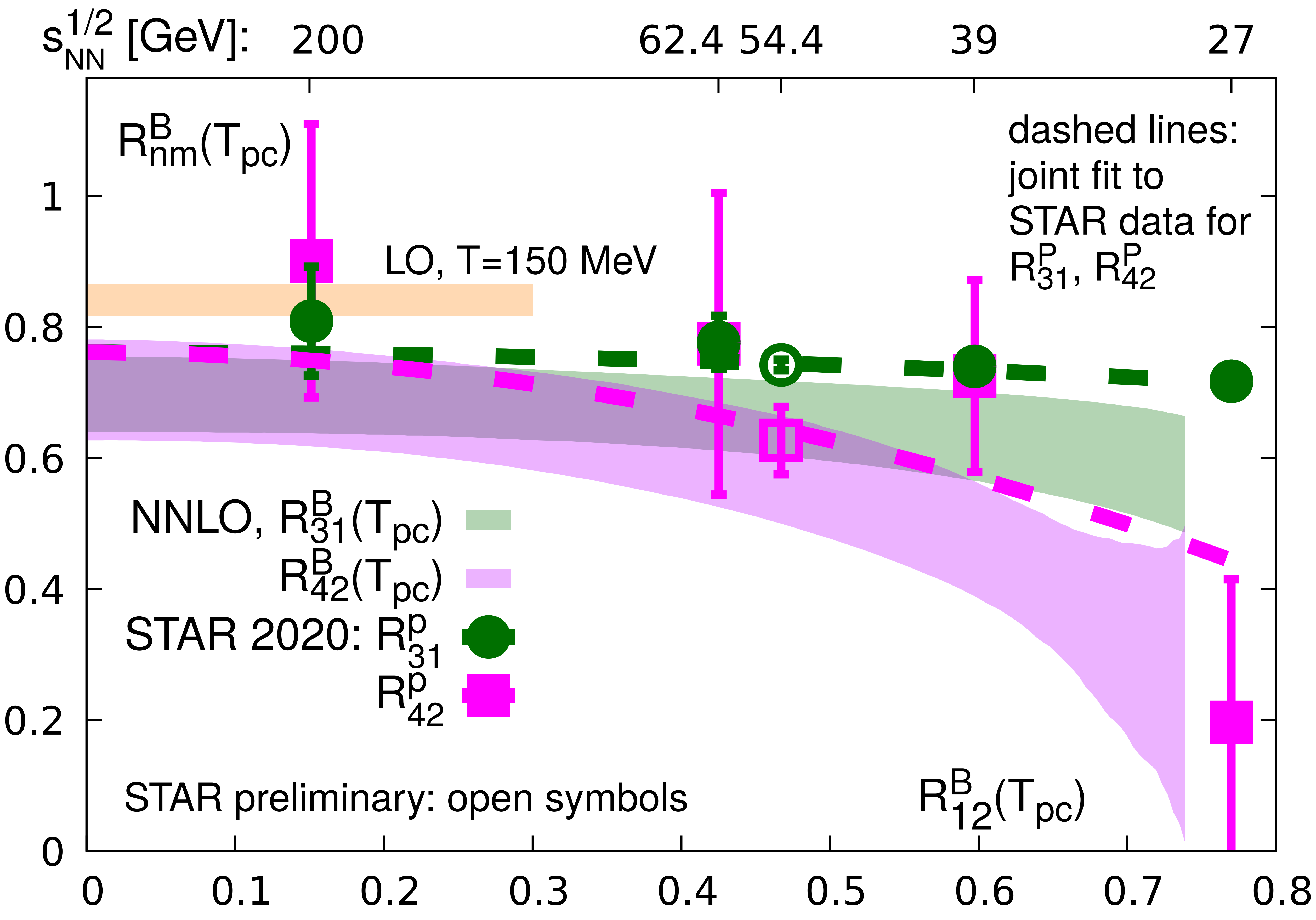
Adamczyk et al., Phys. Rev. C 96 (4) (2017) 044904

Bazavov, HTD, P. Hegde et al. [HotQCD], Phys. Lett. B795 (2019) 15, cited by 259 records

Consistent results from Wuppertal-Budapest, PRL125 (2020) 052001

LQCD meets experiment

LQCD data are obtained at $T_{pc}(\mu_B)$ in NNLO

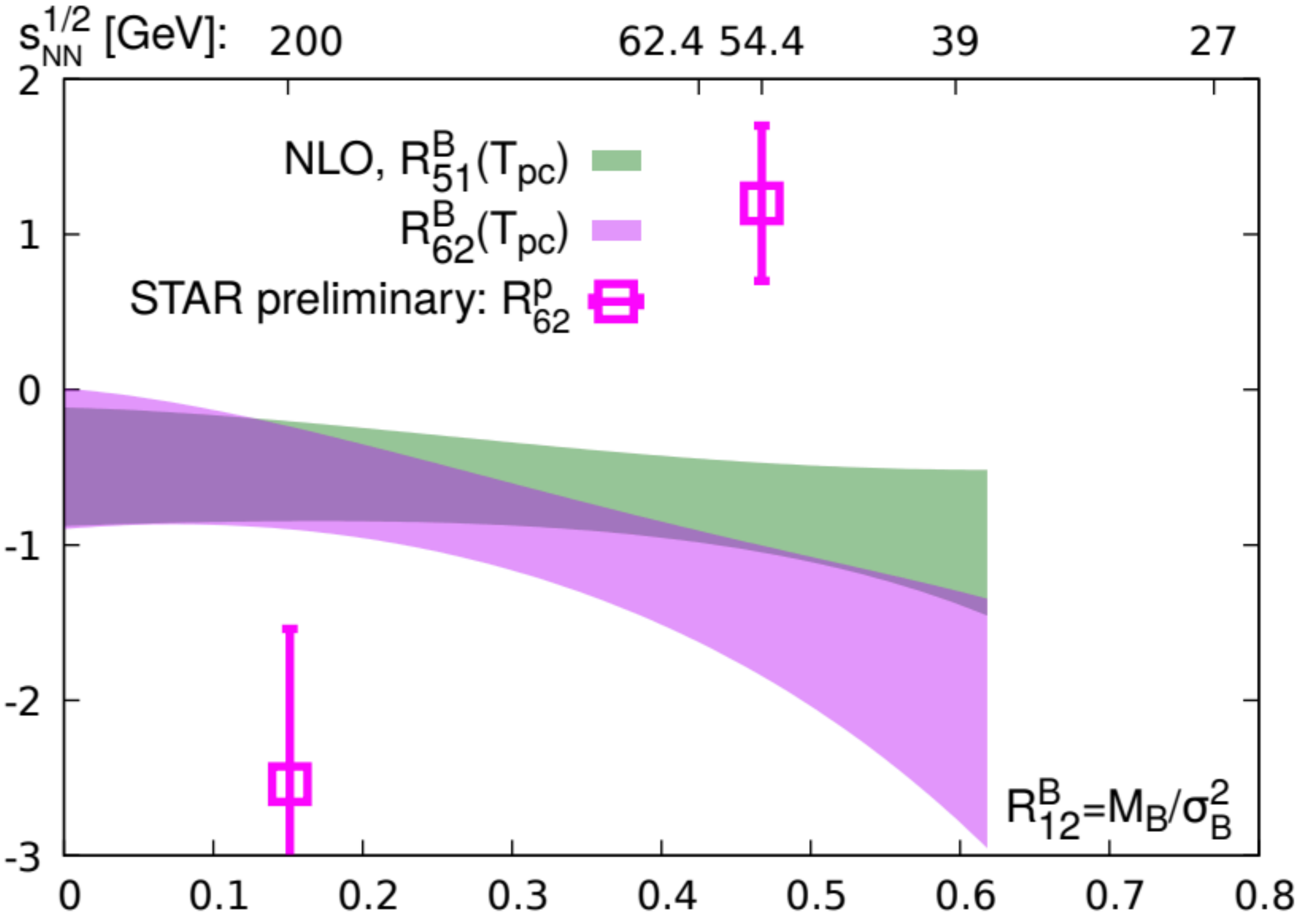


General trend of kurtosis R_{42} & skewness R_{31} ratios are consistent

High statistics data at 54.4 GeV are in good agreement

Bazavov, Bollweg, HTD et al., [HotQCD], *Phys.Rev.D* 101 (2020) 7, 074502, cited by 53 records

LQCD meets experiment



R_{62}:
$\sqrt{s_{NN}}$=200 & 54.4 GeV:
deviation from QCD

???: New Physics:
Proton v.s. Baryon,
Non-equilibrium…

Bazavov, Bollweg, HTD et al., [HotQCD], *Phys.Rev.D* 101 (2020) 7, 074502, cited by 53 records

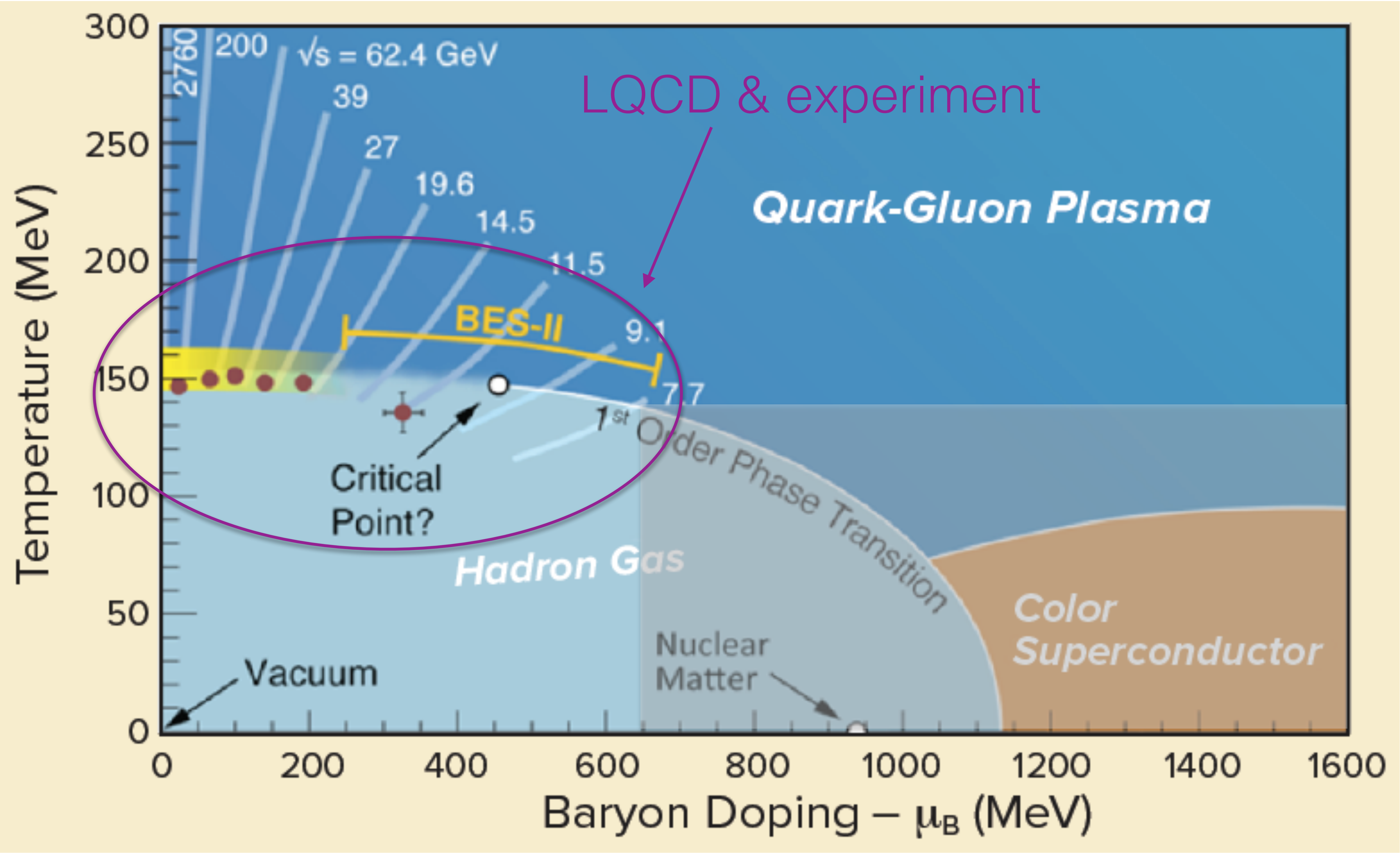
Outlook: Mapping out the QCD phase diagram

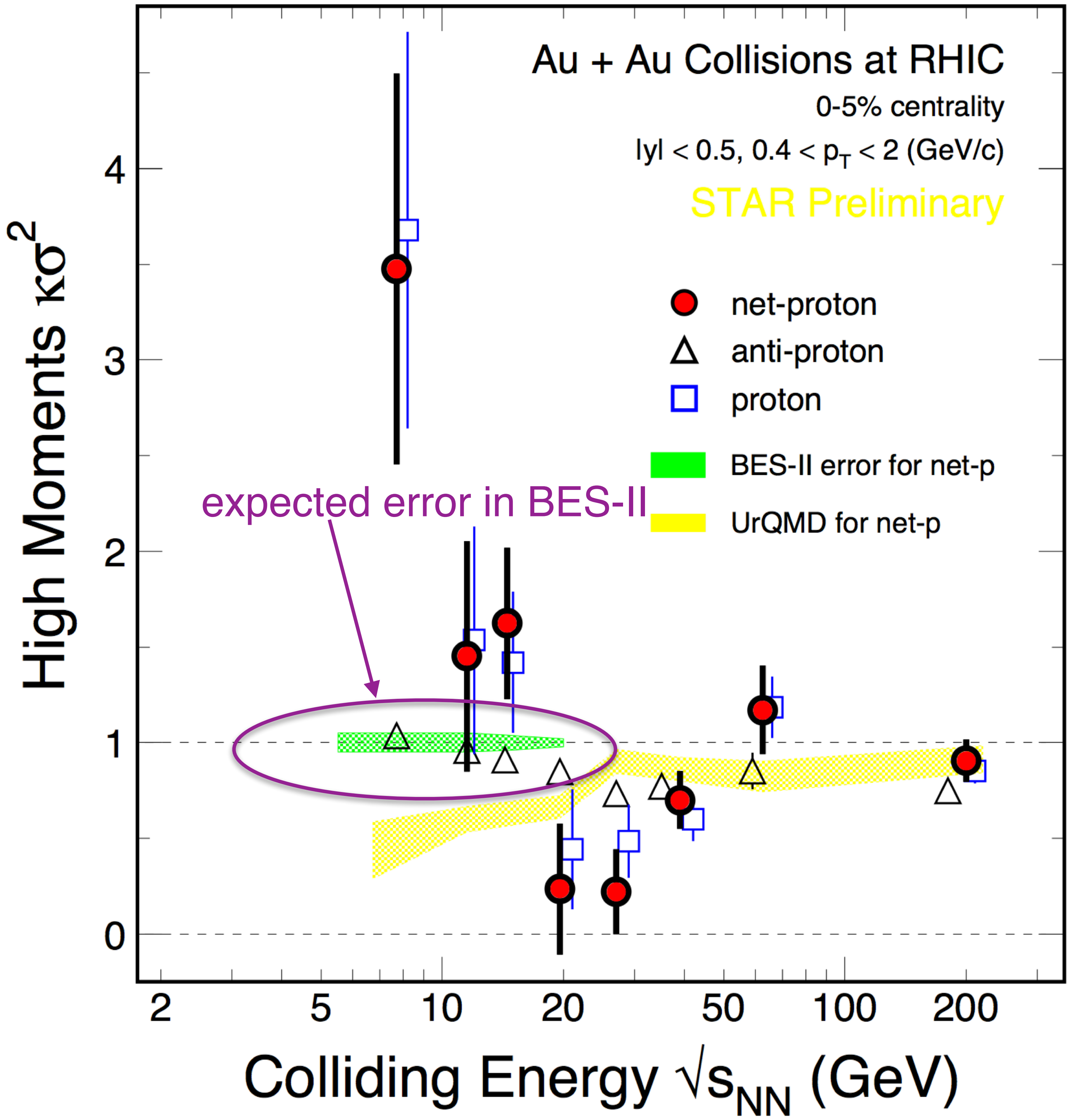
RHIC Beam Energy Scan, Phase II (BES-II)

2019-2021: at least 10 times more statistics for each $\sqrt{s_{NN}}$

Lattice QCD: higher accuracy for the 8th & 10th or even higher order Taylor expansion coefficients

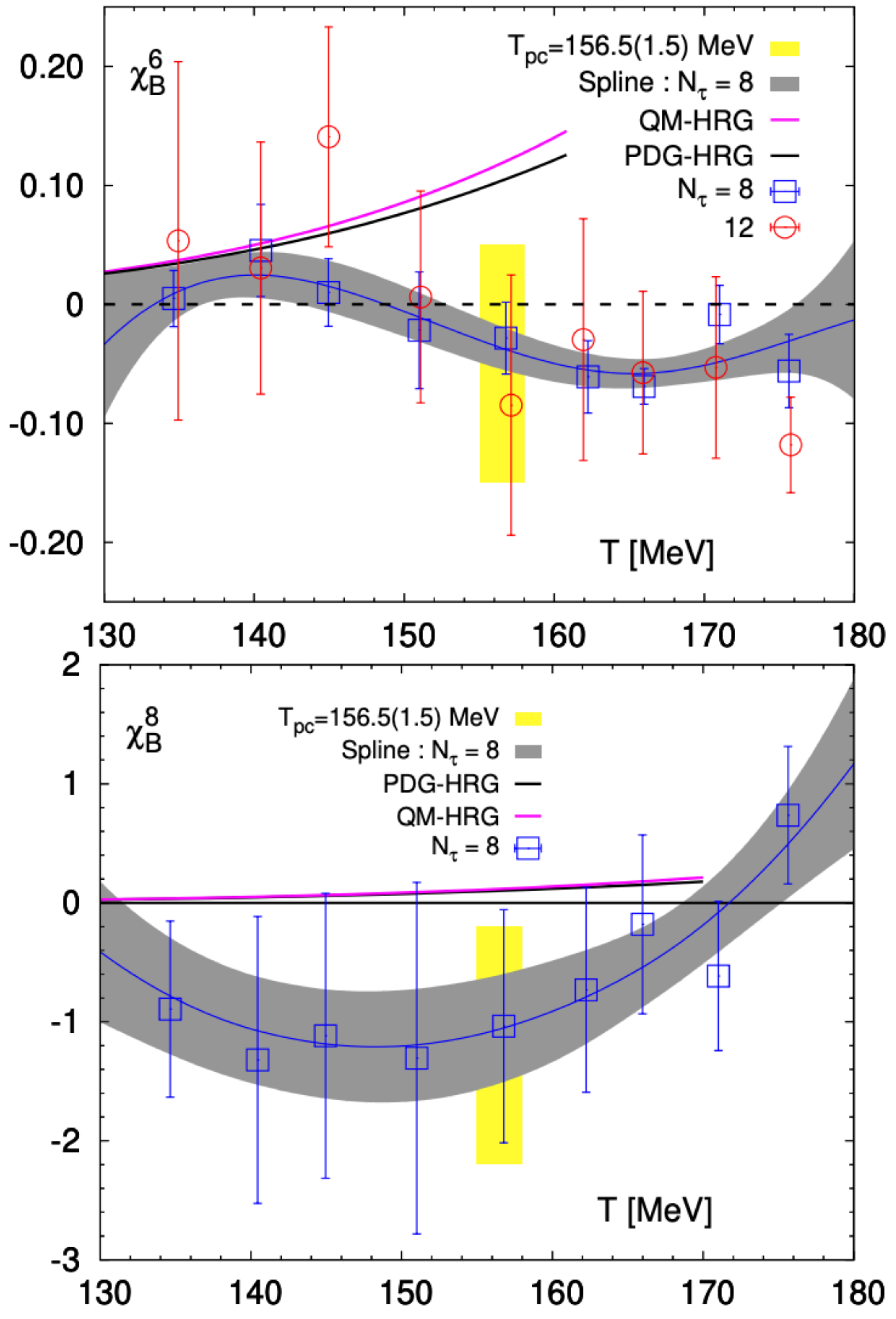
in particular for **T< 135 MeV**



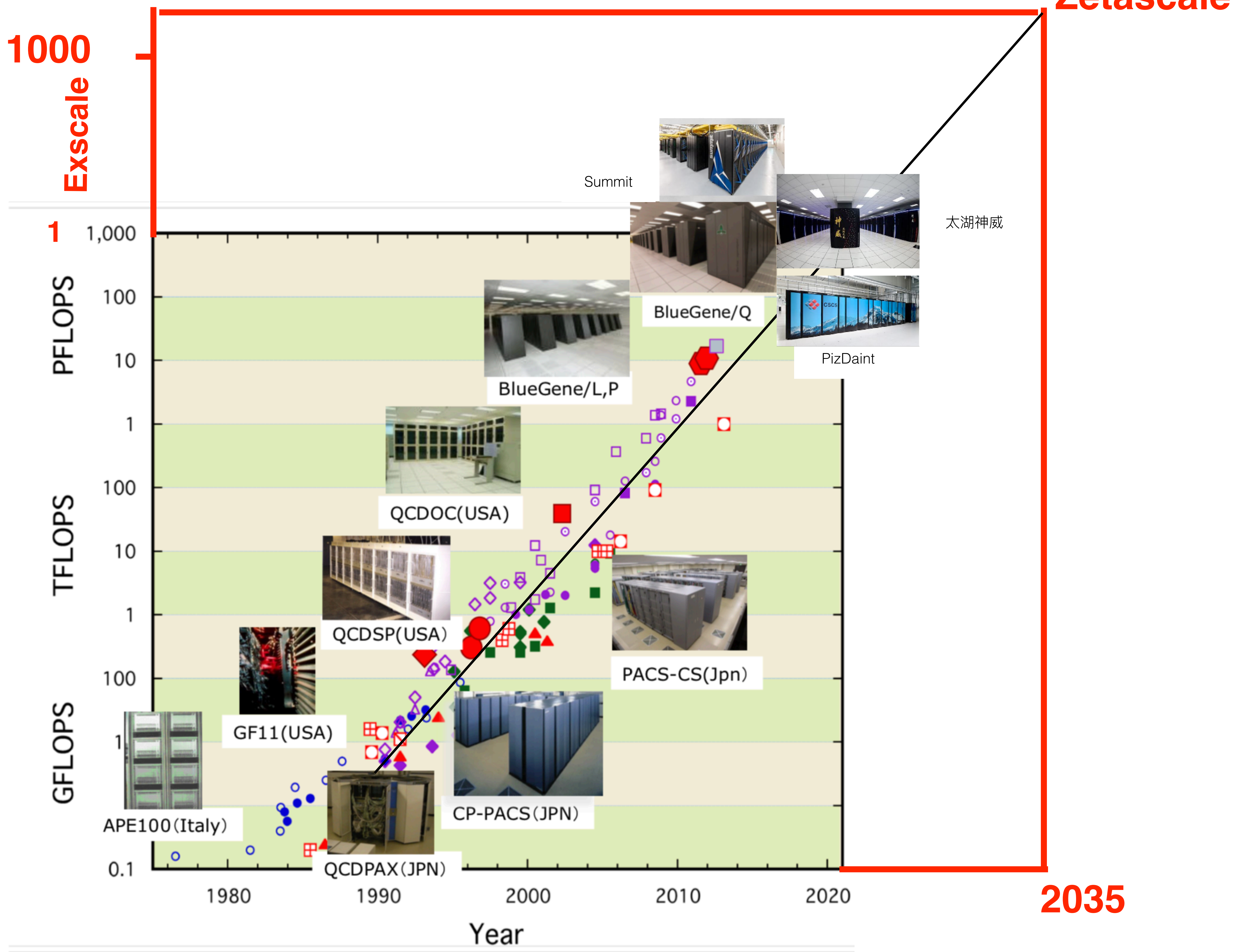


CEP search

(for Nt=8 and T=125 MeV, 2PFlops*year)

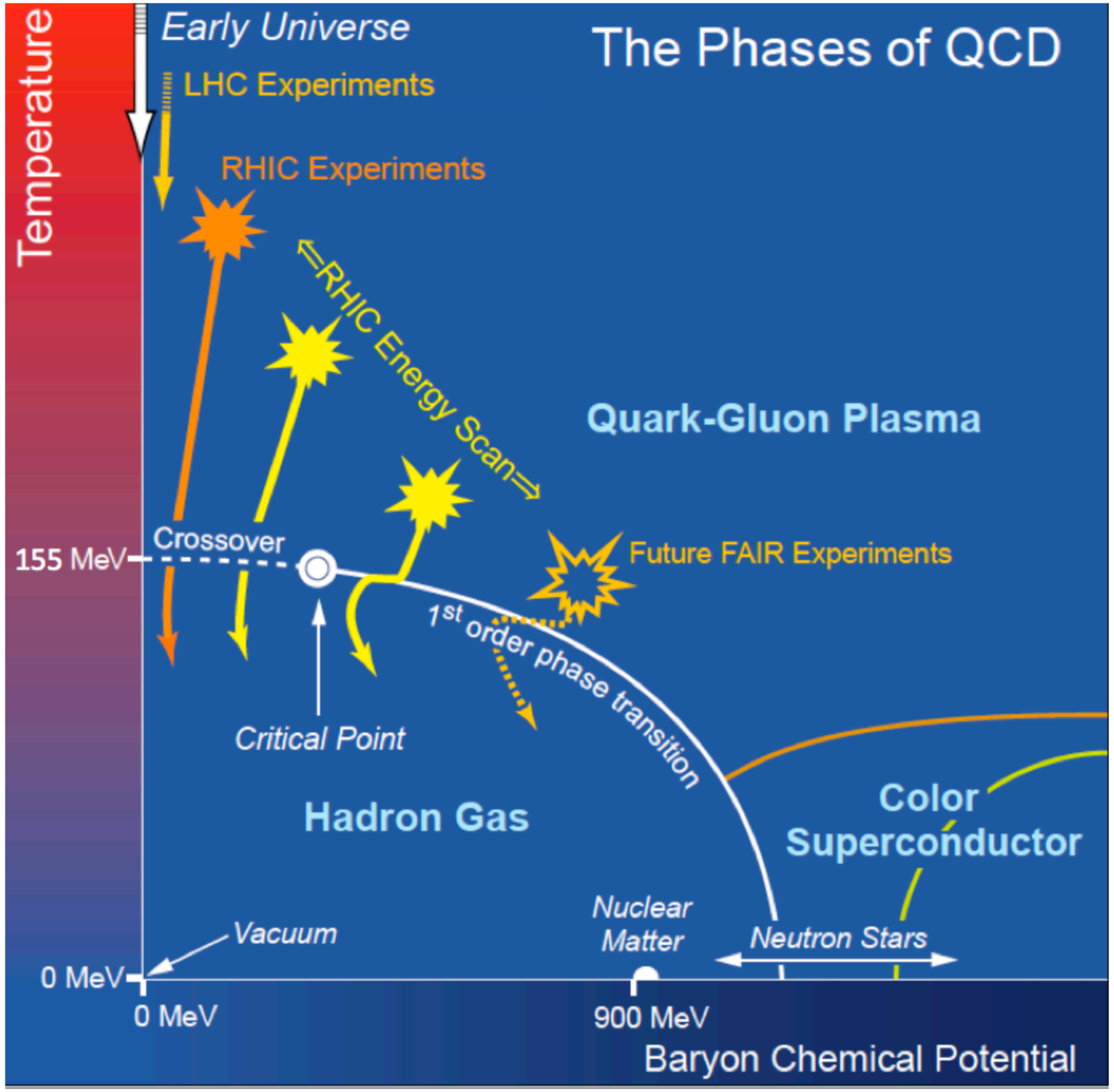


LQCD: Upto 10th order coefficients known soon!
Next step in 5 years



based on A. Ukawa, 2013 HPC summer school

Ongoing/Future heavy ion collision experiments



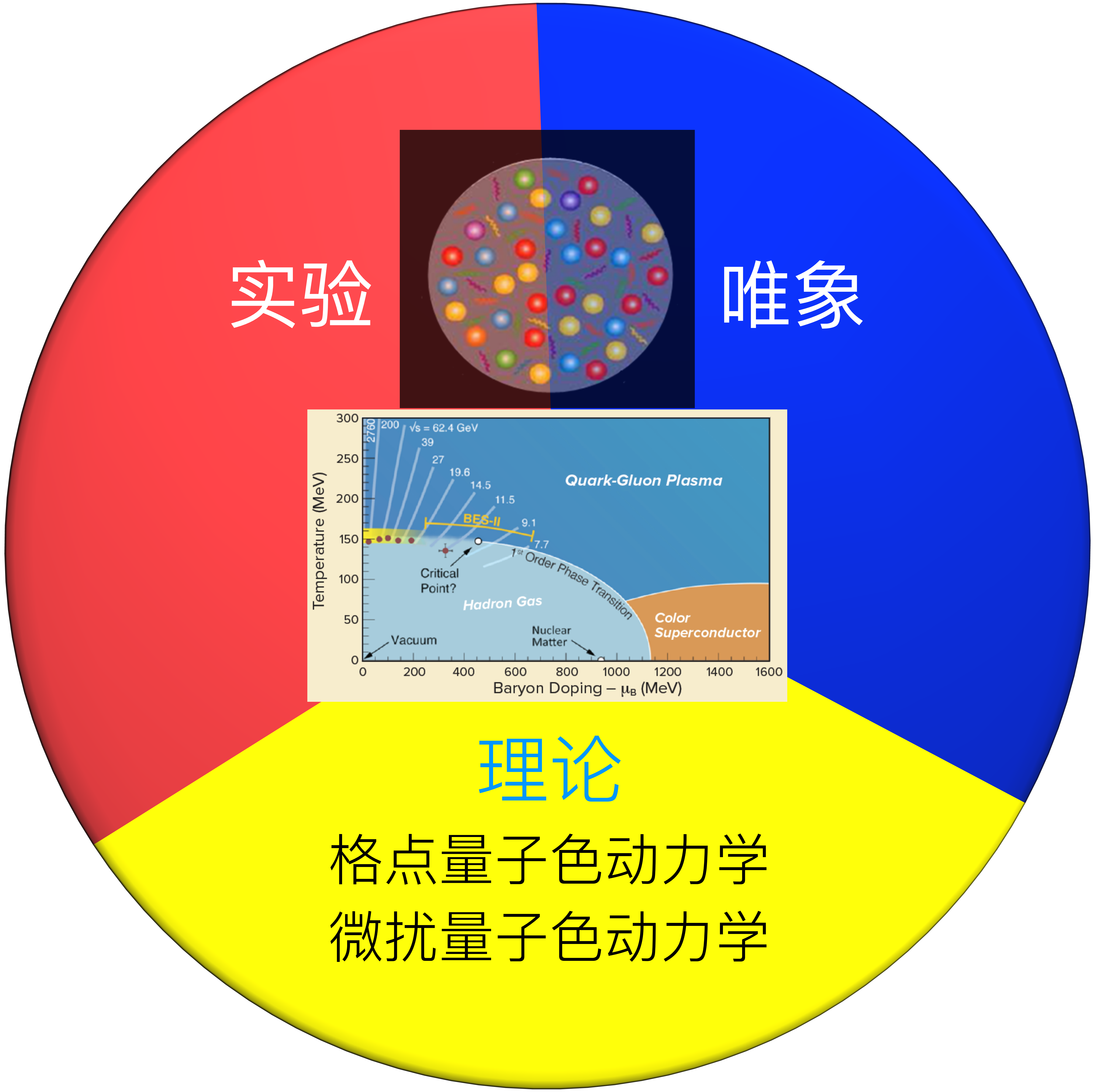
- RHIC@BNL:

  BES II: 2019-2021, FXT: 2021-

  sPHENIX

- ALICE/LHCb/CMS/ATLAS@LHC

- CEE@Lanzhou, FAIR@GSI, NICA@JINR, J-PARC...


实验
唯象
理论
格点量子色动力学
微扰量子色动力学
Quark-Gluon Plasma
BES-II
Critical Point?
1st Order Phase Transition
Hadron Gas
Nuclear Matter
Vacuum
Color Superconductor
Temperature (MeV)
Baryon Doping – μB (MeV)


计算决定未来

谢谢！