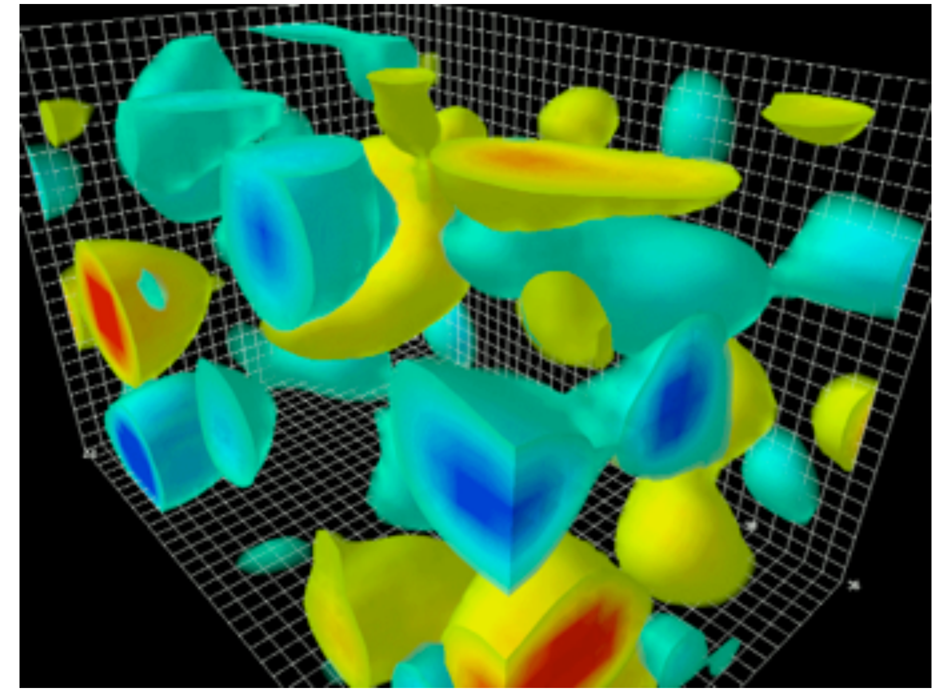
Experimentally yet unobserved hadrons from QCD thermodynamics



Heng-Tong Ding (丁亨通)
Central China Normal University (CCNU)

中国科学技术大学交叉学科理论研究中心
合肥，2014.9.18

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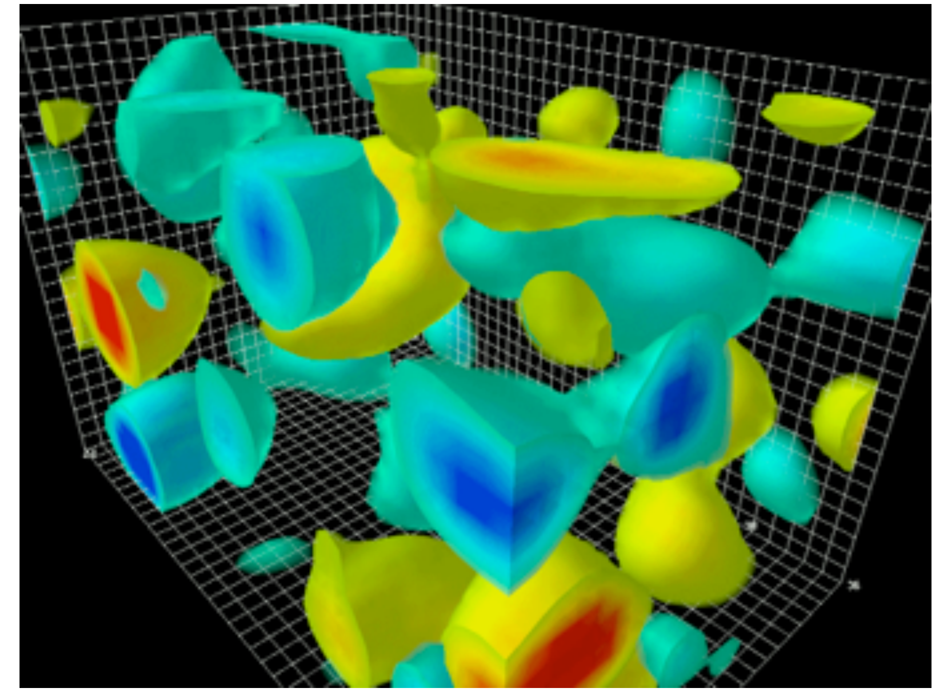

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A newly founded lattice QCD group@CCNU (2013.10-)

Group members:

- 1 Professor: Heng-Tong Ding (丁亨通)
- 1 Postdoc: Prasad Hegde
- 1 PhD student Hai-Tao Shu （舒海涛） & 1 master student Sheng-Tai Li （李圣泰）

Research interests: properties of nuclear matter under extreme conditions

- QCD phase diagram
- QCD Equation of state at nonzero baryon density
- In-medium hadron properties

Outcomes: 3 publications in journals + 5 conference proceedings

- 2 Phys. Rev. Lett. (published by Editors' suggestions) + 1 Phys. Lett. B
- 3 Nucl. Phys. A + 2 Proceedings of Science
- 2 invited plenary talks (Quark Matter 2014 + Hard Probes 2013)
- 3 parallel talks (2 in Lattice 2014 + 1 in Quark Matter 2014) + 1 seminar@YITP

Homepage: http://ioppweb.ccnu.edu.cn/~htding

Experimentally not yet observed hadrons from QCD thermodynamics

Heng-Tong Ding (丁亨通)
Central China Normal University (CCNU)

Phys. Rev. Lett. 113(2014) 072001, Phys. Lett. B 737 (2014) 210

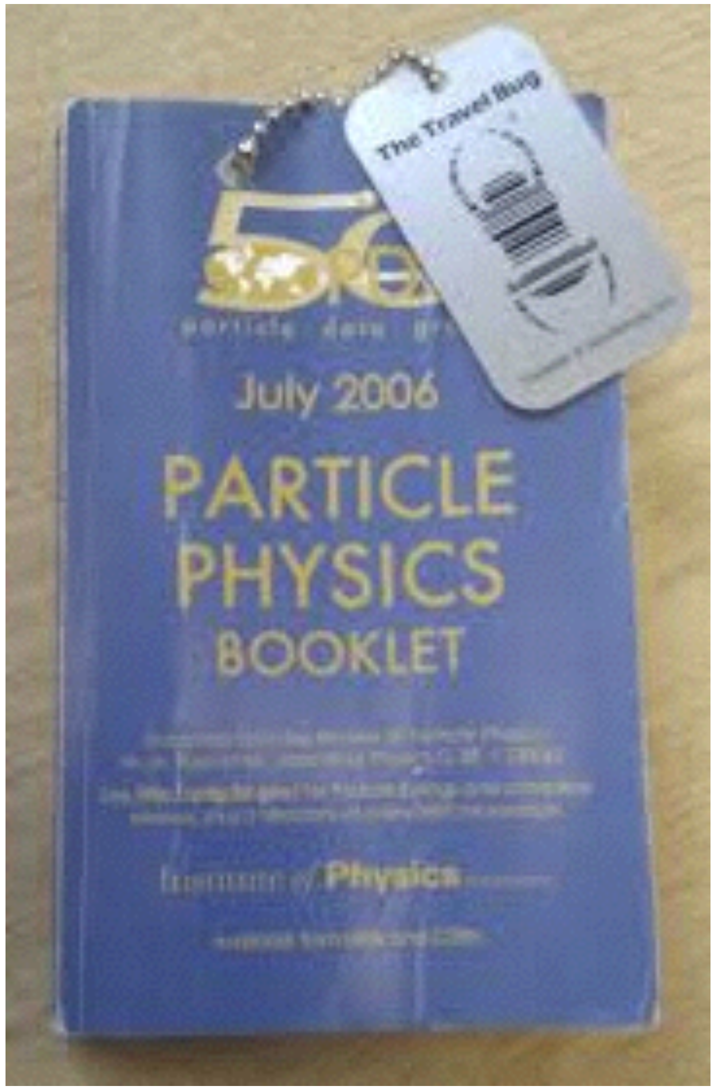
Phys. Rev. Lett. 13(2014)082001, Phys.Rev. Lett. 111(2013)082301

BNL-Bielefeld-CCNU collaboration

A. Bazavov, H.-T. Ding, P. Hegde, O. Kaczmarek, F. Karsch, E. Laermann, Y. Maezawa, S. Mukherjee, H. Ohno, P. Petreczky, C. Schmidt, S. Sharma, W. Söldner, M. Wagner

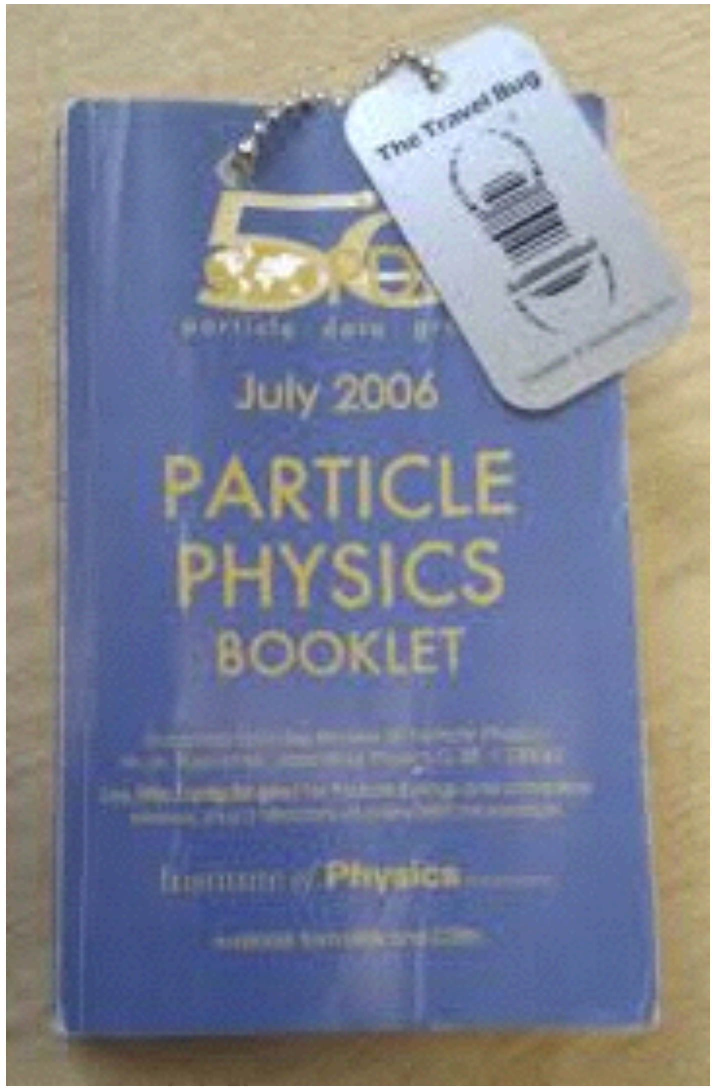
中国科学技术大学交叉学科理论研究中心
合肥，2014.9.18

Particle Data Book(let)

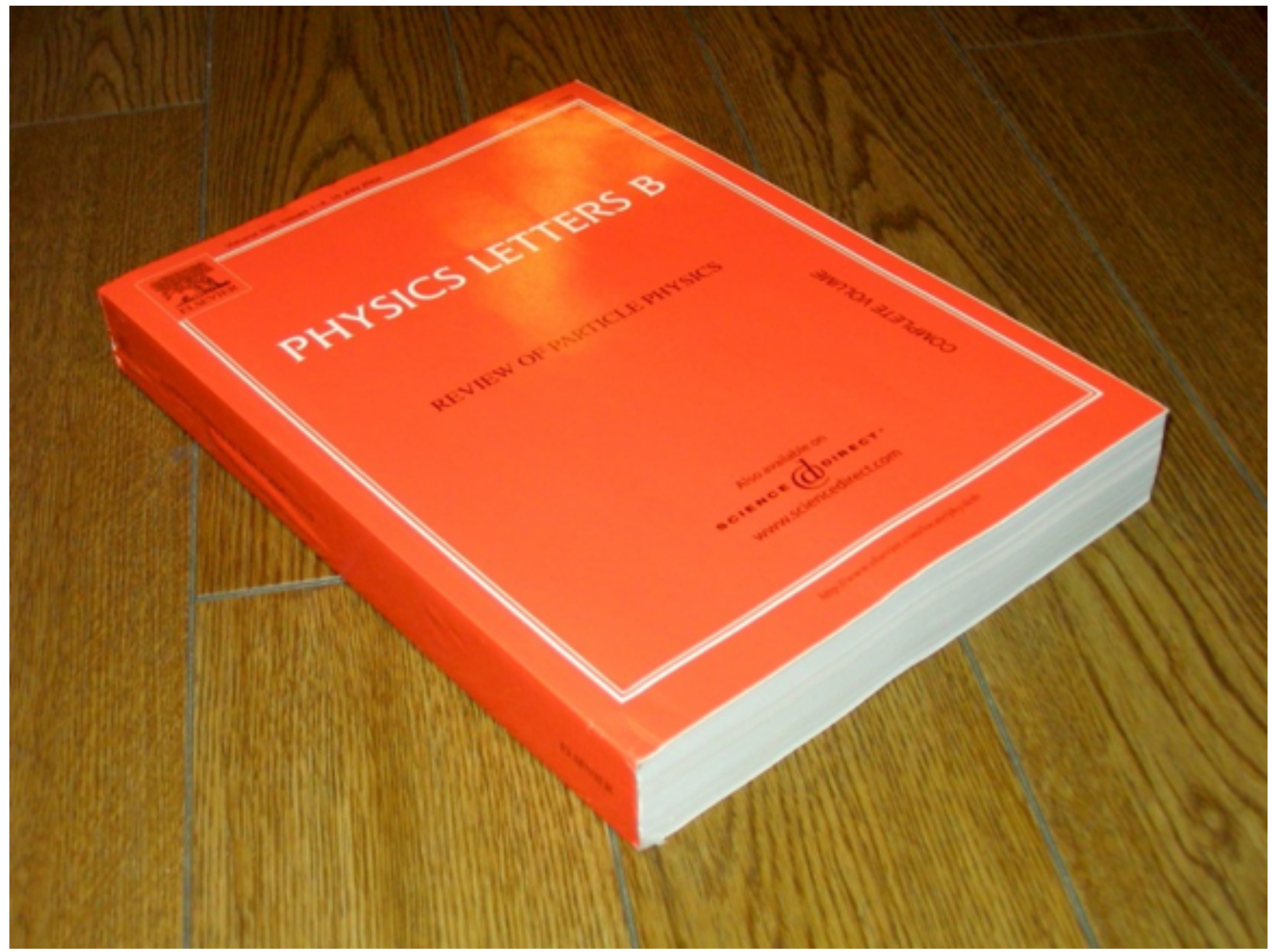


Travel Particle data book

Particle Data Book(let)



Travel Particle data book



BROOKHAVEN NATIONAL LABORATORY Newsroom Media & Communications Office

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Contacts: Karen McNulty Walsh, (631) 344-8350 or Peter Genzer, (631) 344-3174 PRINT

First Indirect Evidence of So-Far Undetected Strange Baryons 第一个关于实验上尚未探测到的奇异强子存在的间接证据

"Invisible" particles containing at least one strange quark lower the temperature at which other particles "freeze out" from quark-gluon plasma

August 19, 2014

The research was carried out by the Brookhaven Lab's Lattice Gauge Theory group, led by Frithjof Karsch, in collaboration with scientists from Bielefeld University, Germany, and Central China Normal University. The

Added Berndt Mueller, Associate Laboratory Director for Nuclear and Particle Physics at Brookhaven, "This finding is particularly remarkable because strange quarks were one of the early signatures of the formation of the primordial quark-gluon plasma. Now we're using this QGP signature as a tool to discover previously unknown baryons that emerge from the QGP and could not be produced otherwise."

http://www.bnl.gov/newsroom/news.php?a=11659

Editors' Suggestion 编辑建议发表文章

额外的奇异强子的热力学贡献和
对实验中的冻结条件的影响

PDF

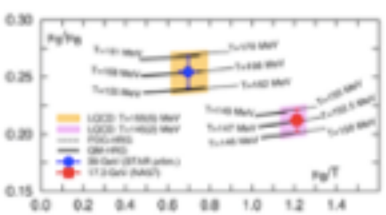
Export Citation

Additional Strange Hadrons from QCD Thermodynamics and Strangeness Freezeout in Heavy Ion Collisions

A. Bazavov, H.-T. Ding, P. Hegde, O. Kaczmarek, F. Karsch, E. Laermann, Y. Maezawa, Swagato Mukherjee, H. Ohno, P. Petreczky, C. Schmidt, S. Sharma, W. Soeldner, and M. Wagner

Phys. Rev. Lett. **113**, 072001 (2014) – Published 11 August 2014

BNL-Bielefeld-CCNU collaboration



Unobserved hadrons - specifically those made of strange quarks - provide insight into lattice QCD calculations near the Quark Gluon Plasma phase transition.

comments from the Editor

abstract

We compare lattice QCD results for appropriate combinations of net strangeness fluctuations and their correlations with net baryon number fluctuations with predictions from two hadron resonance gas (HRG) models having different strange hadron content. The conventionally used HRG model based on experimentally established strange hadrons fails to describe the lattice QCD results in the hadronic phase close to the QCD crossover. Supplementing the conventional HRG with additional, experimentally uncharted strange hadrons predicted by quark model calculations and observed in lattice QCD spectrum calculations leads to good descriptions of strange hadron thermodynamics below the QCD crossover. We show that the thermodynamic presence of these additional states gets imprinted in the yields of the ground-state strange hadrons leading to a systematic 5–8 MeV decrease of the chemical freeze-out temperatures of ground-state strange baryons.

实验上尚未观测到的粒子——特别是那些奇异强子，让我们理解了格点量子色动力学在QGP相变附近的计算结果

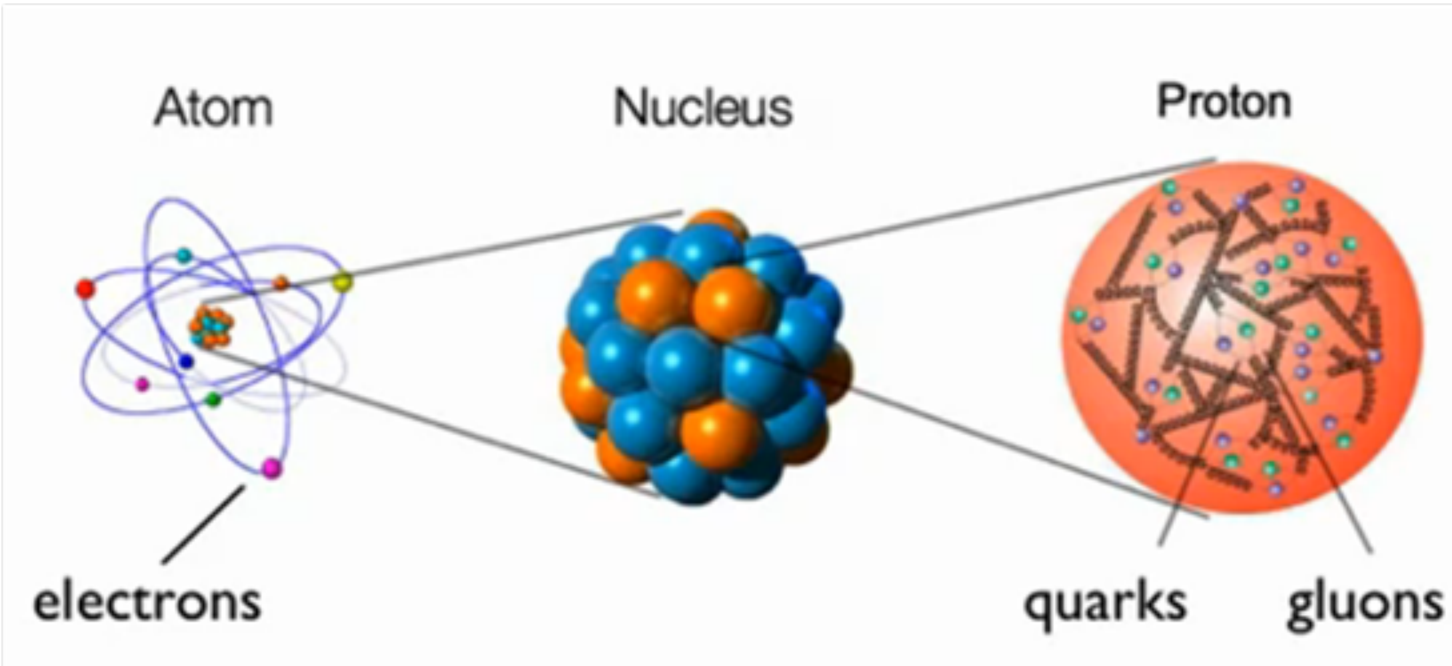
Outline

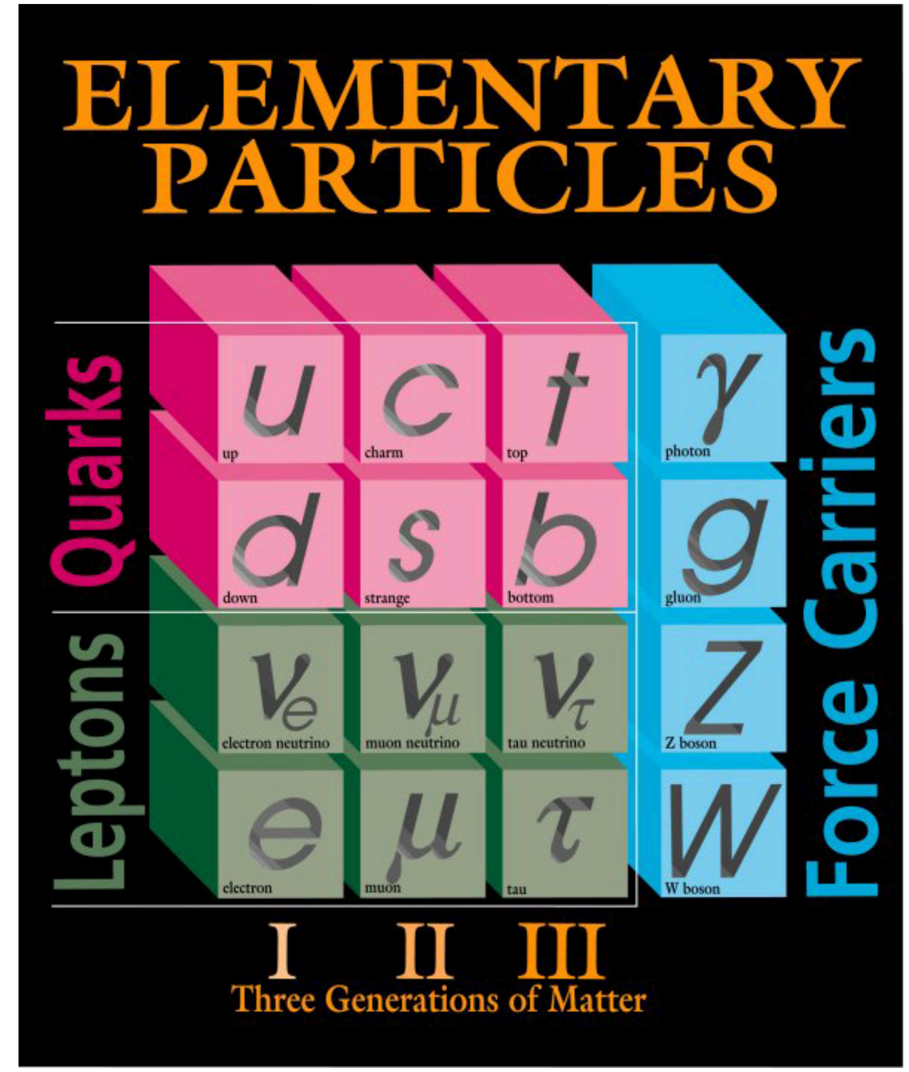
- Lattice QCD and QCD transition

- Evidence for the thermodynamic contribution from experimentally not yet observed hadrons

- Influence of missing hadron states in the determination of hadronization T in the strange hadron sector

quarks, gluons & strong force





mass of proton ~ 938 MeV

mass of u(d) quarks ~ 3 MeV

$m=E/c^2$

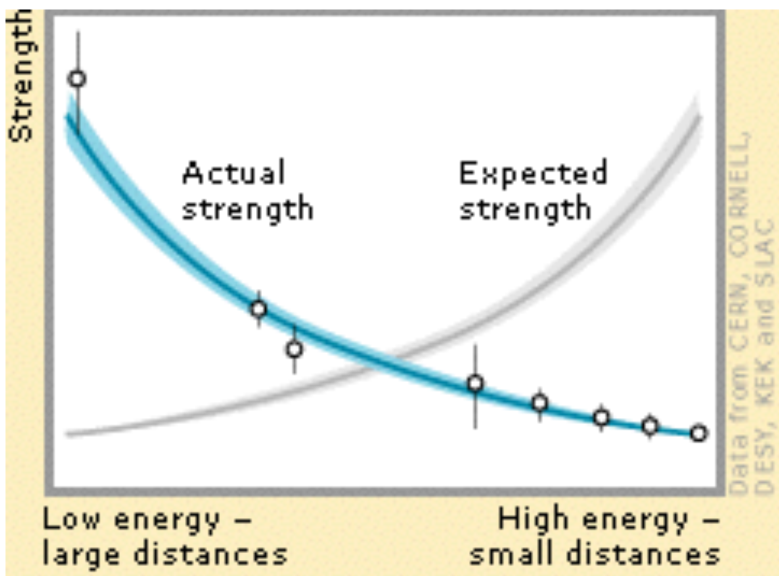
99% of the proton mass comes from the strong force

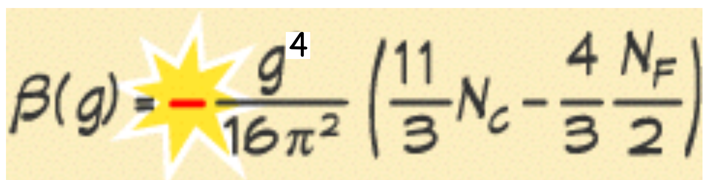
Quantum ChromoDynamics

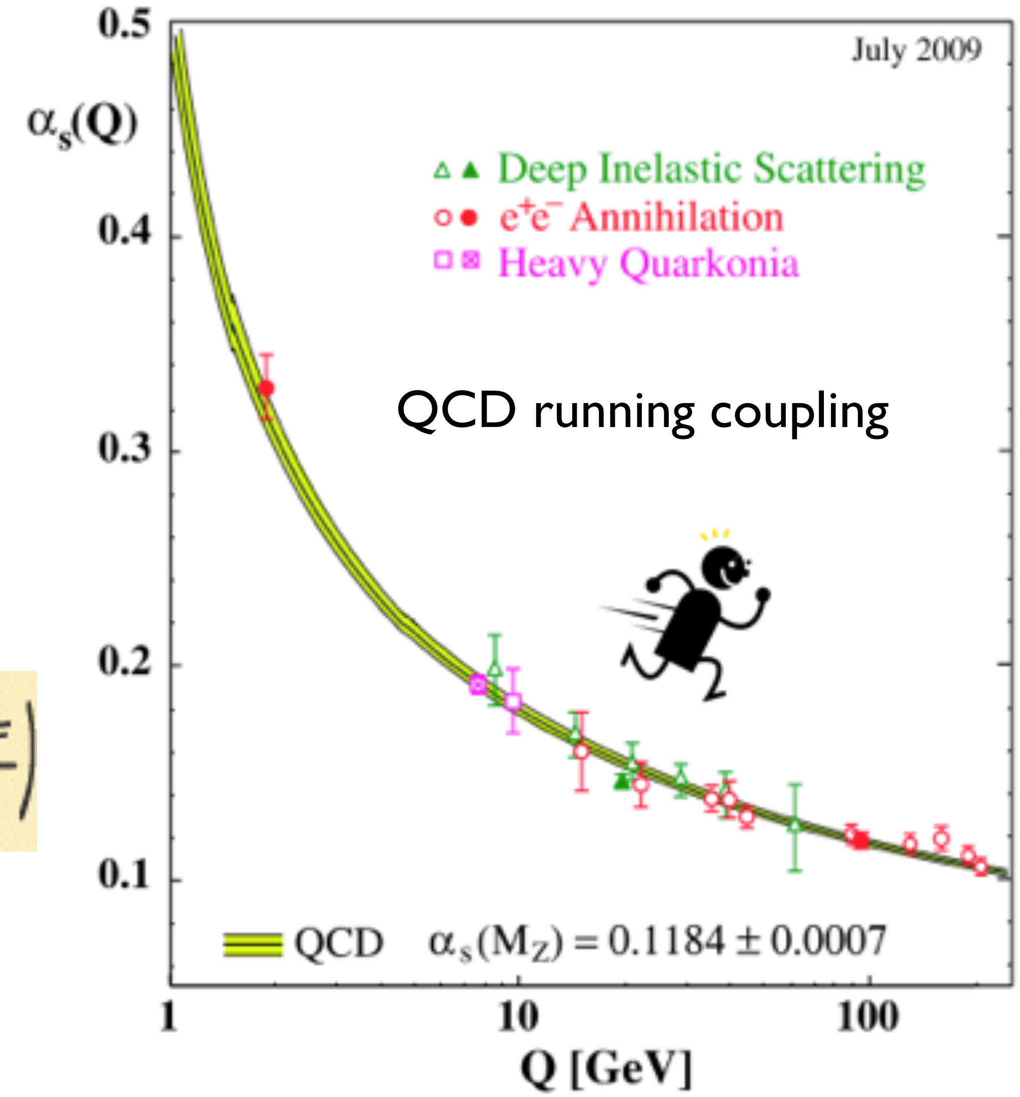
$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + \bar{q}\gamma^\mu (i\partial_\mu - g t^a A^a_\mu) q - m\bar{q}q$$

two peculiar features of QCD:

asymptotic freedom





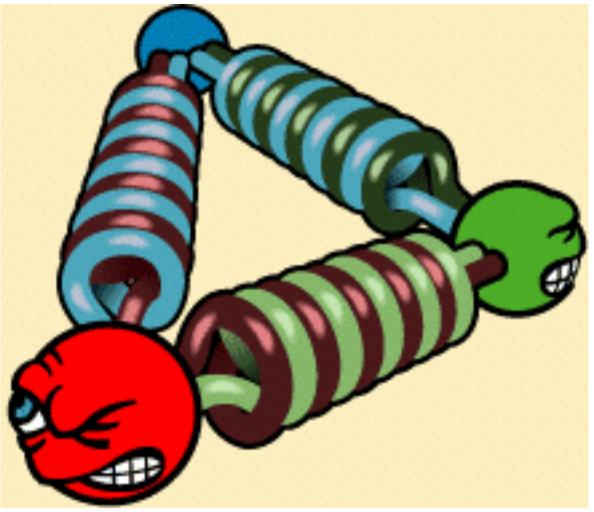


David J. Gross H. David Politzer Frank Wilczek

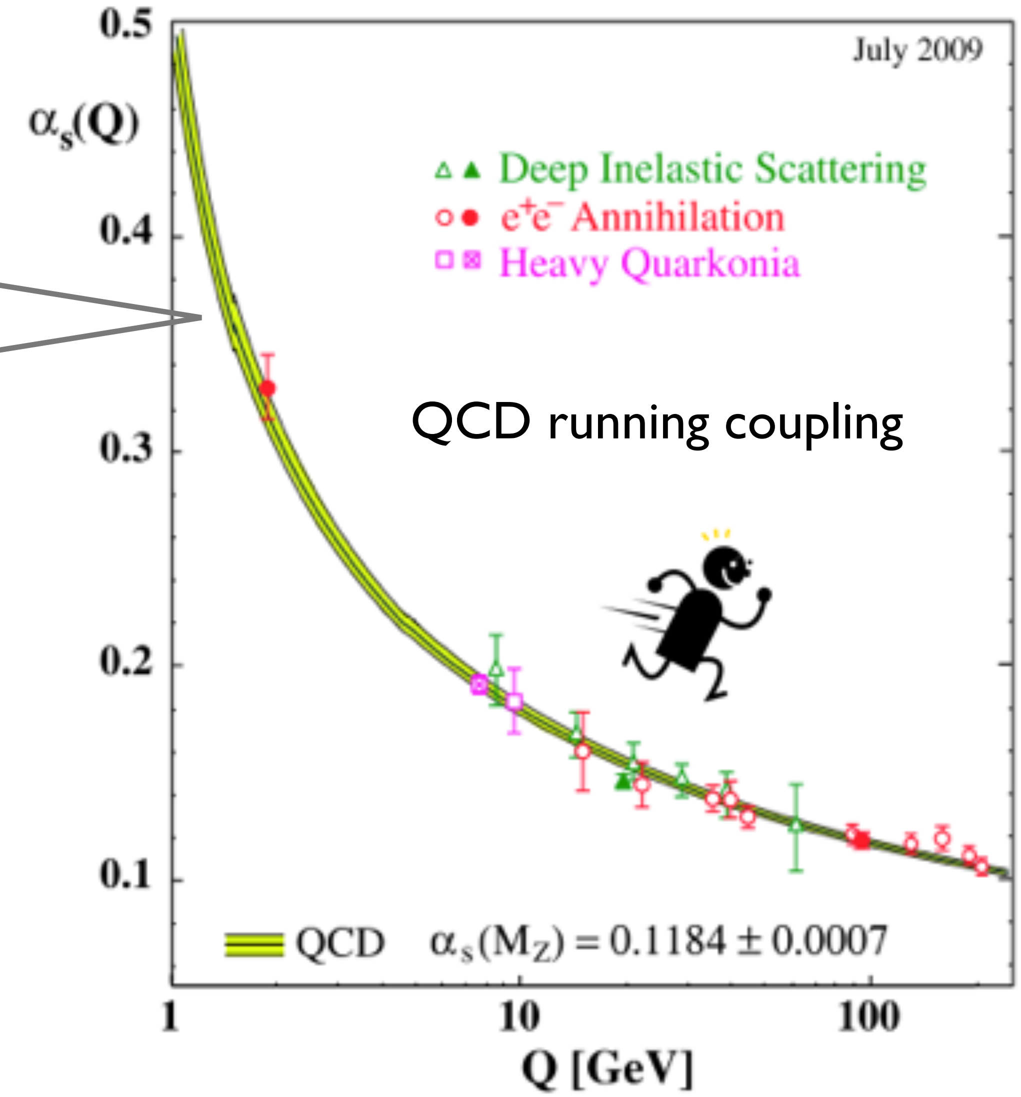
2004

for the discovery of asymptotic freedom in the theory of the strong interaction

confinement



Non-perturbative physics



perturbative methods not able to describe low-energy & long distance physics

first principle calculations?

Lattice gauge theory

PHYSICAL REVIEW D VOLUME 10, NUMBER 8 15 OCTOBER 1974

Confinement of quarks*

Kenneth G. Wilson

Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14850

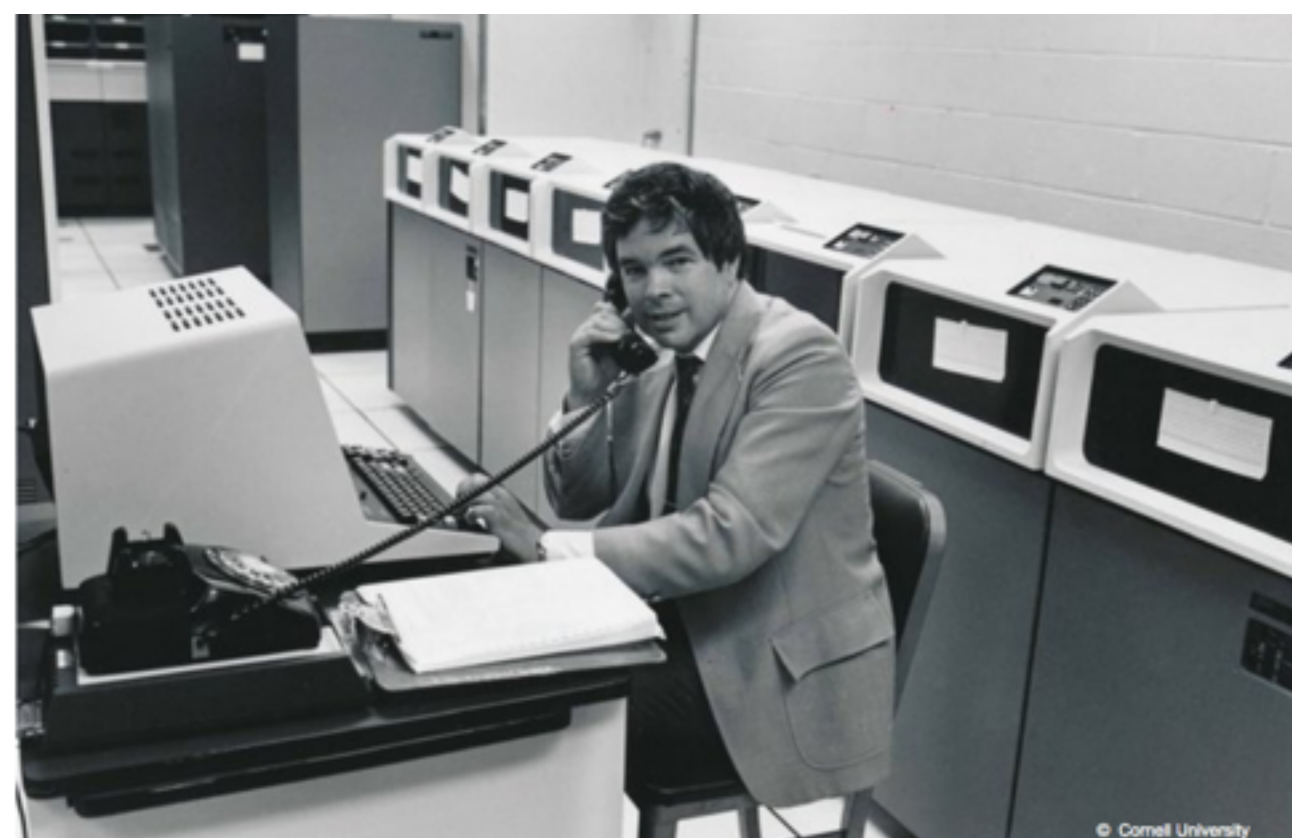
(Received 12 June 1974)

A mechanism for total confinement of quarks, similar to that of Schwinger, is defined which requires the existence of Abelian or non-Abelian gauge fields. It is shown how to quantize a gauge field theory on a discrete lattice in Euclidean space-time, preserving exact gauge invariance and treating the gauge fields as angular variables (which makes a gauge-fixing term unnecessary). The lattice gauge theory has a computable strong-coupling limit; in this limit the binding mechanism applies and there are no free quarks. There is unfortunately no Lorentz (or Euclidean) invariance in the strong-coupling limit. The strong-coupling expansion involves sums over all quark paths and sums over all surfaces (on the lattice) joining quark paths. This structure is reminiscent of relativistic string models of hadrons.

Kenneth G. Wilson
June 8, 1936 - June 15, 2013

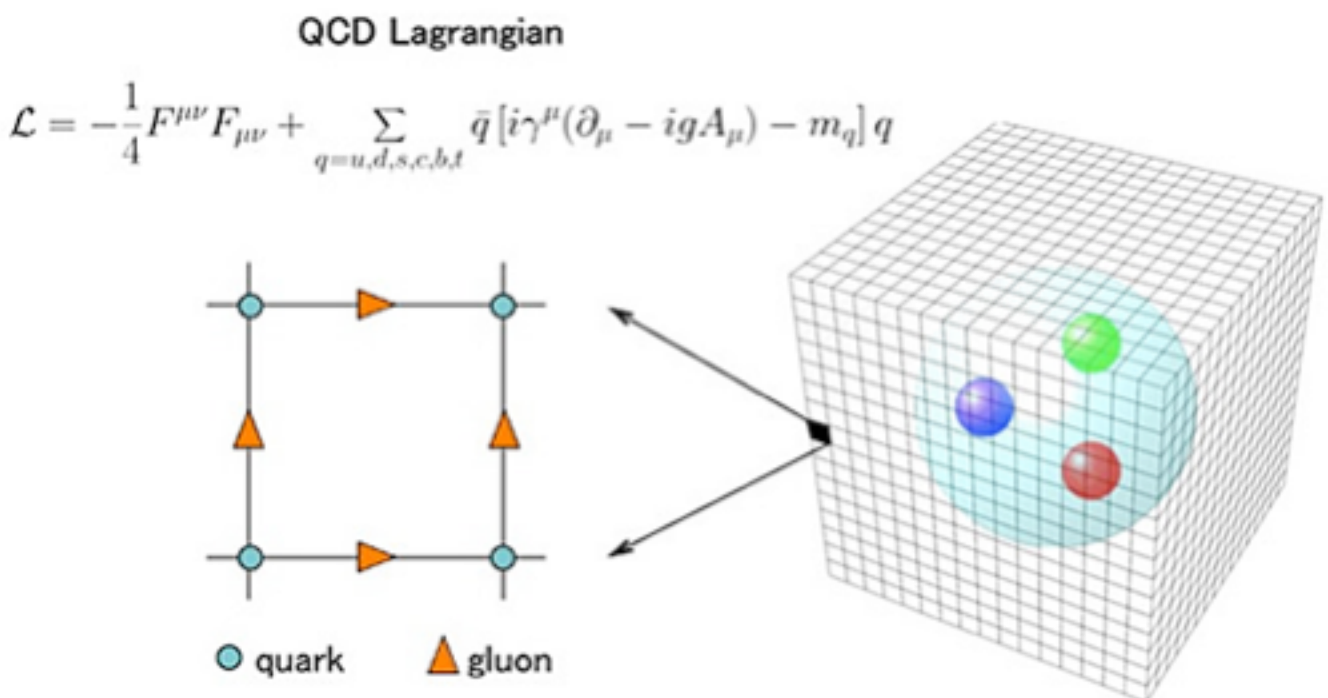
for his theory for
critical phenomena
in connection with
phase transitions

1982



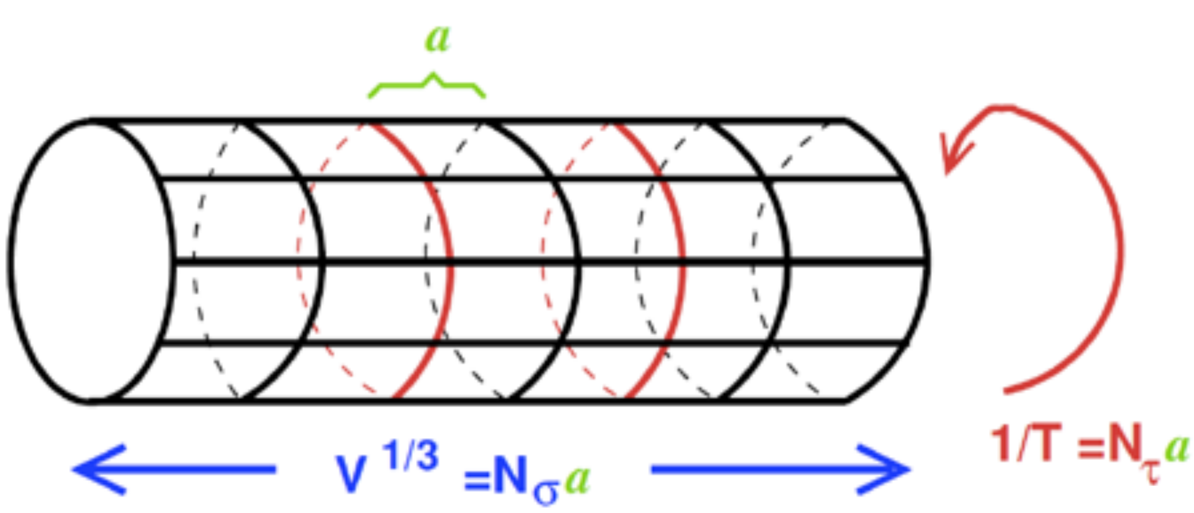
Formulation of lattice gauge theory

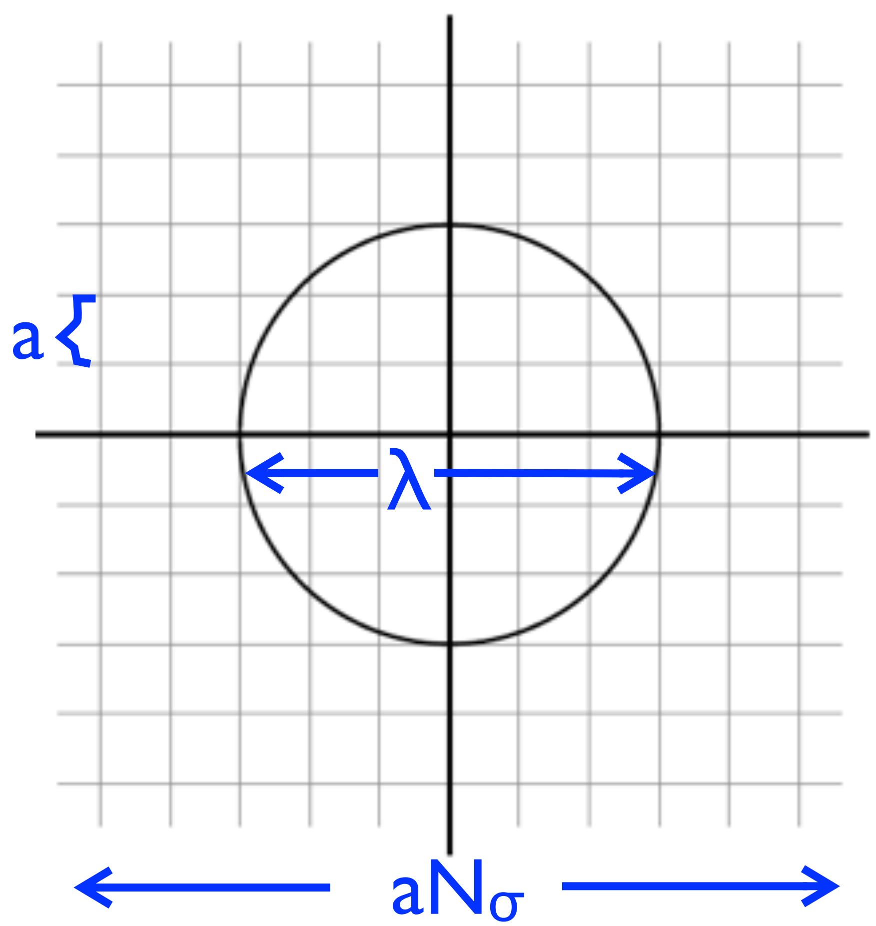
Lattice QCD calculation is a non-perturbative implementation of field theory using the Feynman path integral approach



- discretization of space time
- the transcription of the gauge and fermions degree of freedom
- construction of the action
- definition of the measure of integration in the path integral
- the transcription of the operators used to probe the physics

Basics of Lattice QCD





- Four dim. Euclidean lattice $N_\sigma^3 \times N_\tau$
- Temperature $T = 1/(N_\tau a)$
- $a \ll \lambda \ll N_\sigma a$
- To get continuum physics, make $a \to 0$ at constant V and T

Input parameters

- lattice gauge coupling: $\beta(= 6/g^2)$
- quark masses
- lattice size: $N_\tau, \; N_\sigma$

No free parameters
input bare parameters of QCD Lagrangian
fixed by reproducing physics at T=0

Basics of Lattice QCD (cont.)

Expectation value of QCD observables on the lattice

$$< \mathcal{O} >= \frac{1}{Z} \int \mathcal{D}\mathcal{U}\ \mathcal{D}\psi\ \mathcal{D}\bar{\psi}\ \mathcal{O}\ e^{-S_{lat}}$$

$$S_{lat} = S_g + S_f$$

$$Z = \int \mathcal{D}\mathcal{U}\ \mathcal{D}\psi\ \mathcal{D}\bar{\psi}\ e^{-S_{lat}} = \int \mathcal{D}\mathcal{U}\ e^{-S_g}\ \det M_f$$

- S_f: staggered, Wilson, Domain Wall fermions...
- Operator with each configuration is summed up with weight $\exp(-S_{lat})$
- Average over configurations with huge degree of freedoms

$N_{deg.} \otimes N_c \otimes N_f \otimes N_{spin} \otimes N_d \otimes N_\sigma^3 \otimes N_T \gtrsim 10^6$

- Monte Carlo simulations: generate gauge field configurations with weight $\exp(-S_g+\log(\det M_f))$
  - $\det M_f$=constant: quenched approximation
  - $\det M_f \neq$constant: dynamical full QCD simulation
- O: chiral condensates, susceptibilities, correlation functions

Top500 List - June 2014

Rank	Site	System	Cores	Rmax (TFlop/s)	Rpeak (TFlop/s)	Power (kW)	
1	National Super Computer Center in Guangzhou China	**Tianhe-2 (MilkyWay-2)** - TH-IVB-FEP Cluster, Intel Xeon E5-2692 12C 2.200GHz, TH Express-2, Intel Xeon Phi 31S1P NUDT	3,120,000	33,862.7	54,902.4	17,808	MIC
2	DOE/SC/Oak Ridge National Laboratory United States	**Titan** - Cray XK7 , Opteron 6274 16C 2.200GHz, Cray Gemini interconnect, NVIDIA K20x Cray Inc.	560,640	17,590.0	27,112.5	8,209	GPU
3	DOE/NNSA/LLNL United States	**Sequoia** - BlueGene/Q, Power BQC 16C 1.60 GHz, Custom IBM	1,572,864	17,173.2	20,132.7	7,890	BGQ
4	RIKEN Advanced Institute for Computational Science (AICS) Japan	K computer, SPARC64 VIIIfx 2.0GHz, Tofu interconnect Fujitsu	705,024	10,510.0	11,280.4	12,660	CPU
5	DOE/SC/Argonne National Laboratory United States	**Mira** - BlueGene/Q, Power BQC 16C 1.60GHz, Custom IBM	786,432	8,586.6	10,066.3	3,945	BGQ
6	Swiss National Supercomputing Centre (CSCS) Switzerland	**Piz Daint** - Cray XC30, Xeon E5-2670 8C 2.600GHz, Aries interconnect , NVIDIA K20x Cray Inc.	115,984	6,271.0	7,788.9	2,325	GPU
7	Texas Advanced Computing Center/Univ. of Texas United States	**Stampede** - PowerEdge C8220, Xeon E5-2680 8C 2.700GHz, Infiniband FDR, Intel Xeon Phi SE10P Dell	462,462	5,168.1	8,520.1	4,510	MIC
8	Forschungszentrum Juelich (FZJ) Germany	**JUQUEEN** - BlueGene/Q, Power BQC 16C 1.600GHz, Custom Interconnect IBM	458,752	5,008.9	5,872.0	2,301	BGQ
9	DOE/NNSA/LLNL United States	**Vulcan** - BlueGene/Q, Power BQC 16C 1.600GHz, Custom Interconnect IBM	393,216	4,293.3	5,033.2	1,972	BGQ
10	Government United States	Cray XC30, Intel Xeon E5-2697v2 12C 2.7GHz, Aries interconnect Cray Inc.	225,984	3,143.5	4,881.3		CPU
14	National Supercomputing Center in Tianjin China	**Tianhe-1A** - NUDT YH MPP, Xeon X5670 6C 2.93 GHz, NVIDIA 2050 NUDT	186368	2566.0	4701.0	4040	GPU
28	National Supercomputing Centre in Shenzhen (NSCS) China	**Nebulae** - Dawning TC3600 Blade System, Xeon X5650 6C 2.66GHz, Infiniband QDR, NVIDIA 2050 Dawning	120640	1271.0	2984.3	2580	
46	National Supercomputing Center in Jinan China	**Sunway Blue Light** - Sunway BlueLight MPP, ShenWei processor SW1600 975.00 MHz, Infiniband QDR National Research Center of Parallel Computer Engineering & Technology	137200	795.9	1070.2	1074	
48	National Super Computer Center in Hunan China	**Tianhe-1A Hunan Solution** - NUDT YH MPP, Xeon X5670 6C 2.93 GHz, Proprietary, NVIDIA 2050 NUDT	53248	771.7	1342.8	1155	

Architectures for
High Performance Computing:

- Intel, MIC, Co-processors
  Multiple Integrated Cores
- Nvidia, GPU gaming cards
  Graphic Processing Unit
- IBM: Blue Gene/Q

QCDSP:
QCD on a digital Signal Processor

- 0.6 Tflops
- completed 1998
- Gordon Bell Prize

QCDOC:
QCD On a Chip

- 10 Tflops
- completed 2005
- Parent of IBM Bluegene

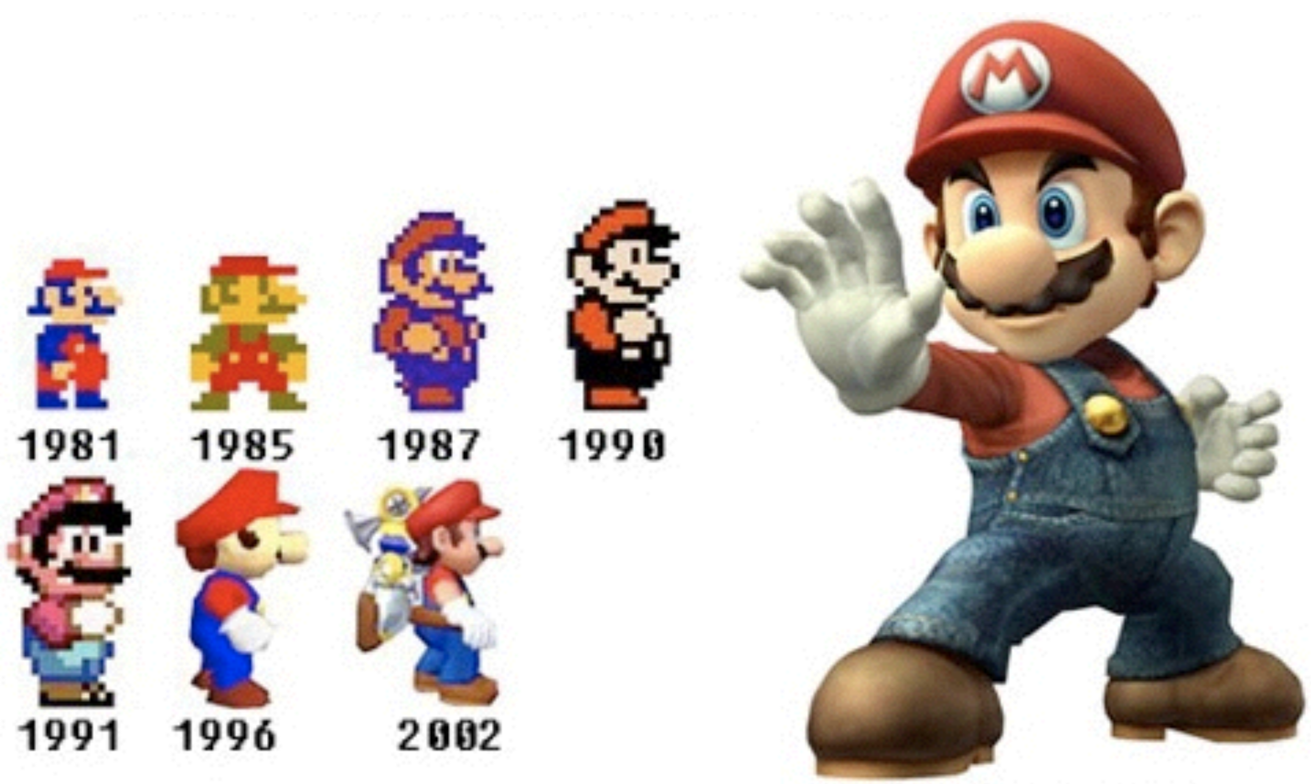
Lattice QCD as a video game

Győző I. Egri [a], Zoltán Fodor [a,b,c,*], Christian Hoelbling [b], Sándor D. Katz [a,b], Dániel Nógrádi [b], Kálmán K. Szabó [b]

[a] *Institute for Theoretical Physics, Eötvös University, Budapest, Hungary*
[b] *Department of Physics, University of Wuppertal, Germany*
[c] *Department of Physics, University of California, San Diego, USA*

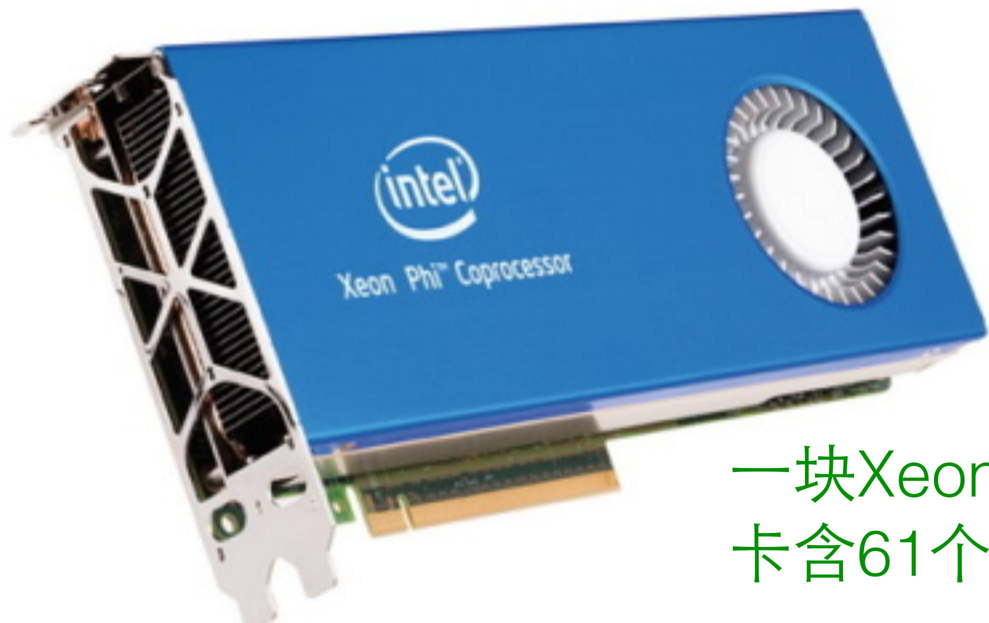
Received 2 February 2007; received in revised form 29 May 2007; accepted 7 June 2007

Available online 15 June 2007



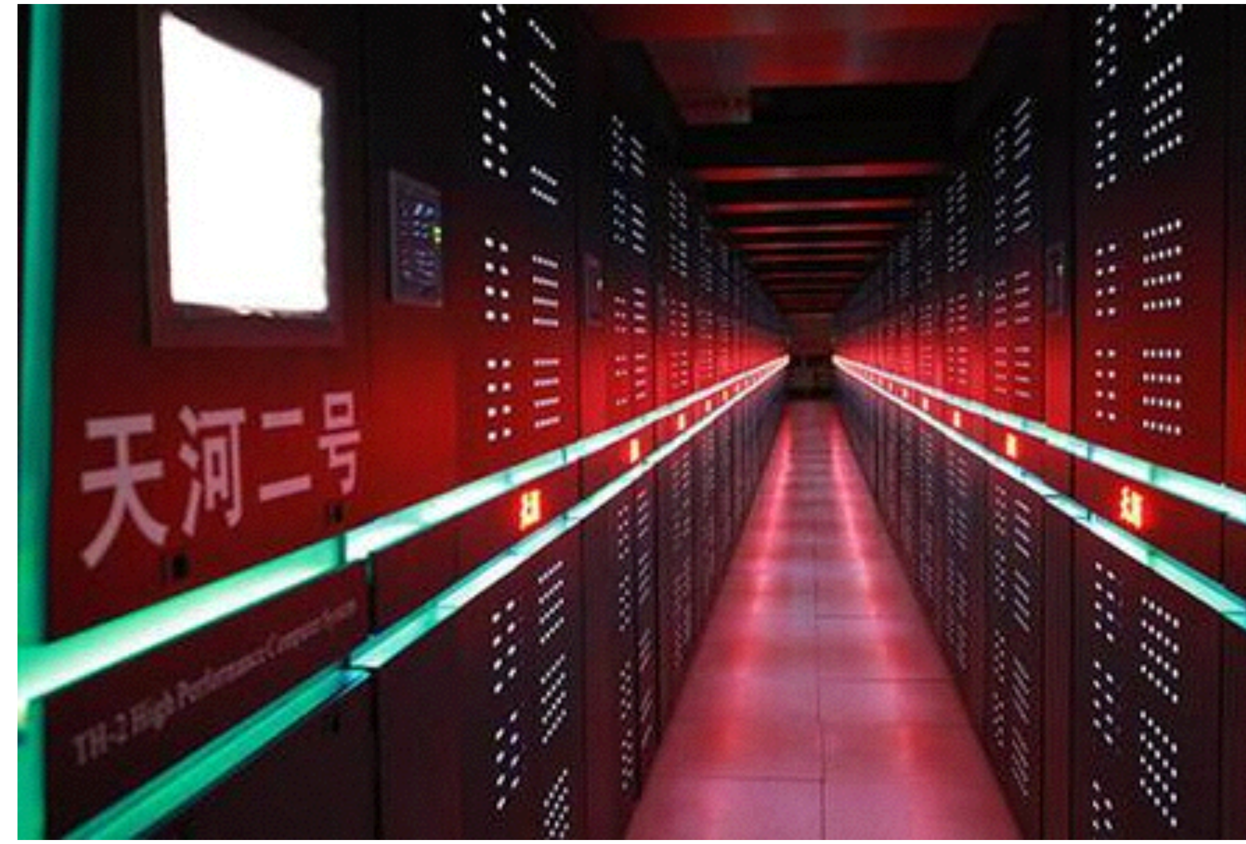
天津超算中心天河二号
GPU架构

至强协处理器(Xeon Phi Co-processor)@天河二号



一块Xeon Phi 7120P
卡含61个协处理器

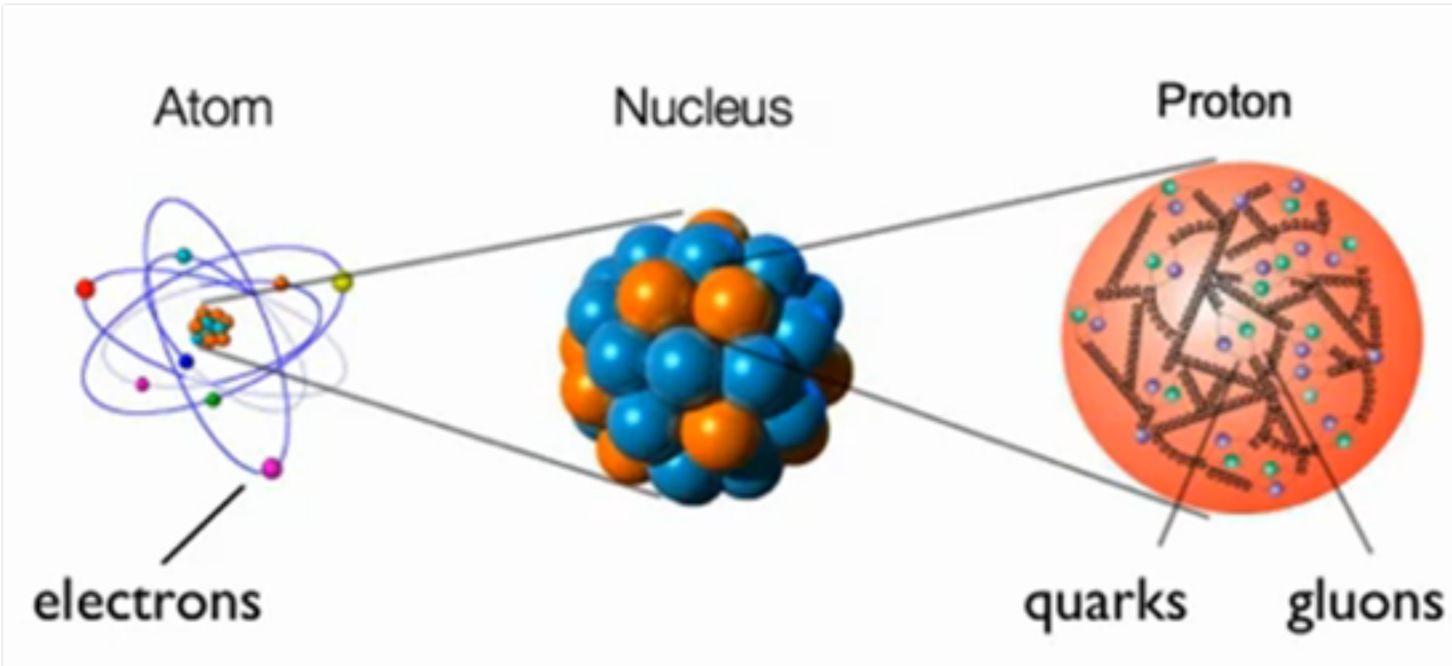
- 研发调试：已购买了2台高性能计算机，共4块Xeon Phi 7120p卡，总计 268(4x61 + 4x6)核
- 编写优化了符合Xeon Phi Coprocessor 架构的、适合于做QCD 相结构工作的计算程序

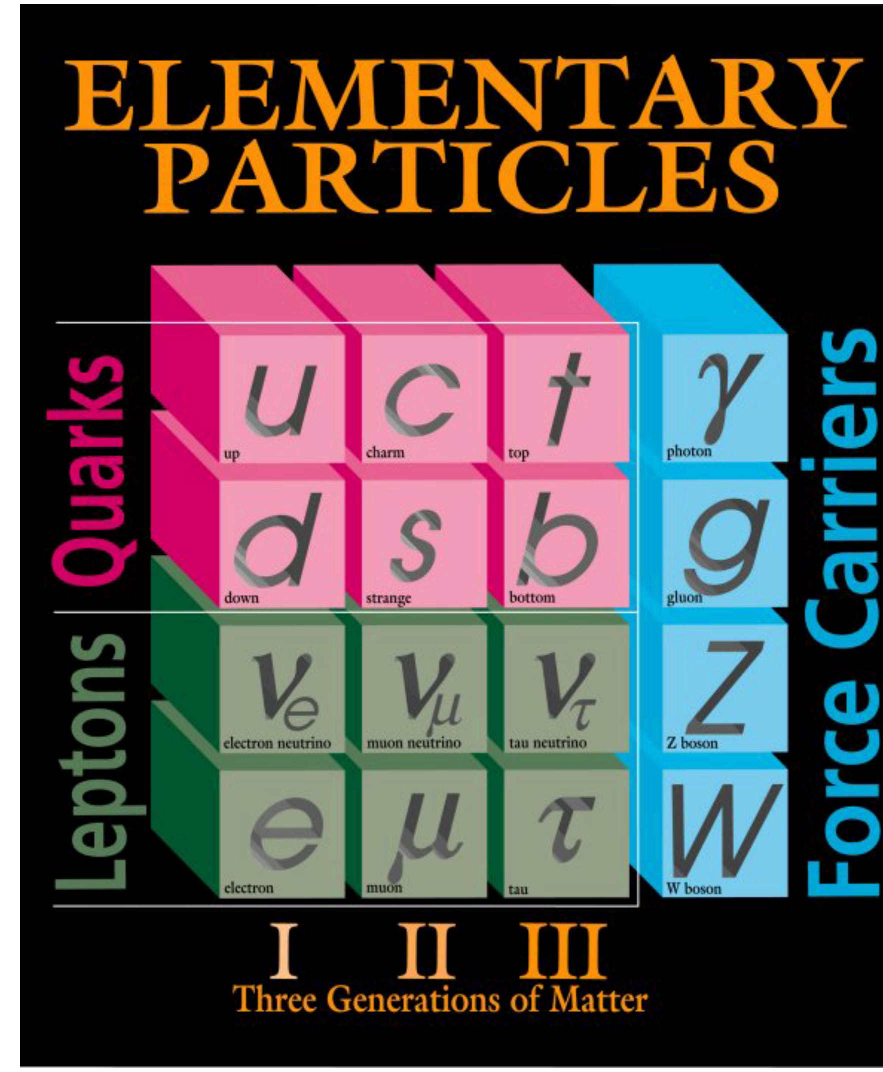


广州超算中心(中山大学)的天河二号
目前世界上最快的超级计算机

- 正在免费试用天河二号上的计算资源

mass of proton calculated from QCD ?





mass of proton ~ 938 MeV

mass of u(d) quarks ~ 3 MeV

Only Lattice QCD is able to calculate the mass of proton

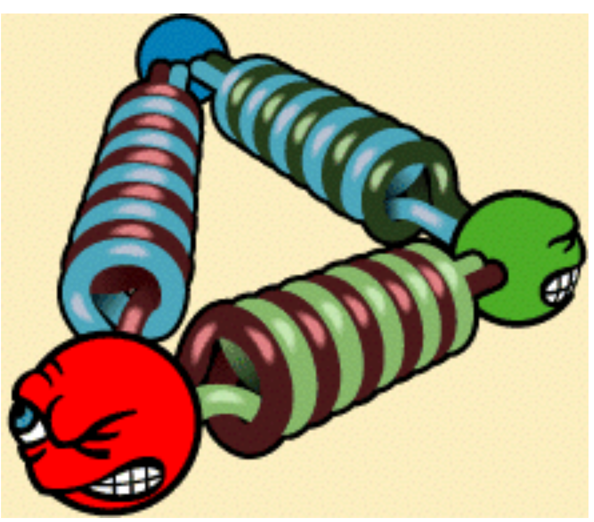
first numerical lattice QCD study

PHYSICAL REVIEW D VOLUME 21, NUMBER 8 15 APRIL 1980

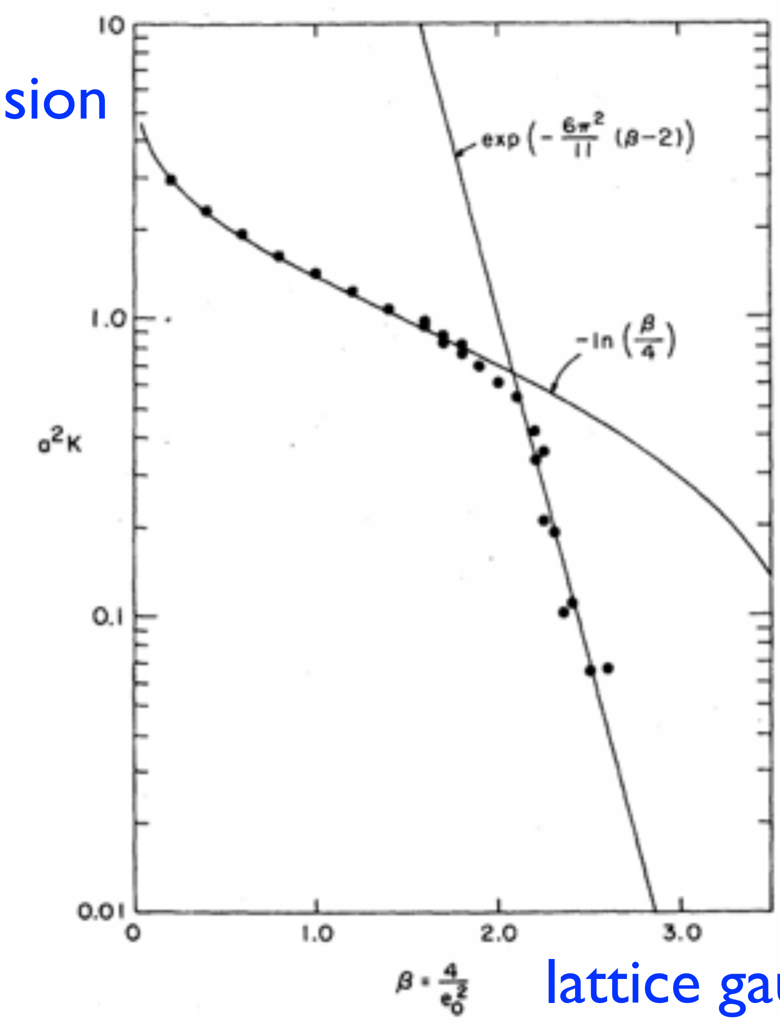
Monte Carlo study of quantized SU(2) gauge theory

Michael Creutz
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973
(Received 24 October 1979)

Using Monte Carlo techniques, we evaluate path integrals for pure SU(2) gauge fields. Wilson's regularization procedure on a lattice of up to 10^4 sites controls ultraviolet divergences. Our renormalization prescription, based on confinement, is to hold fixed the string tension, the coefficient of the asymptotic linear potential between sources in the fundamental representation of the gauge group. Upon reducing the cutoff, we observe a logarithmic decrease of the bare coupling constant in a manner consistent with the perturbative renormalization-group prediction. This supports the coexistence of confinement and asymptotic freedom for quantized non-Abelian gauge fields.

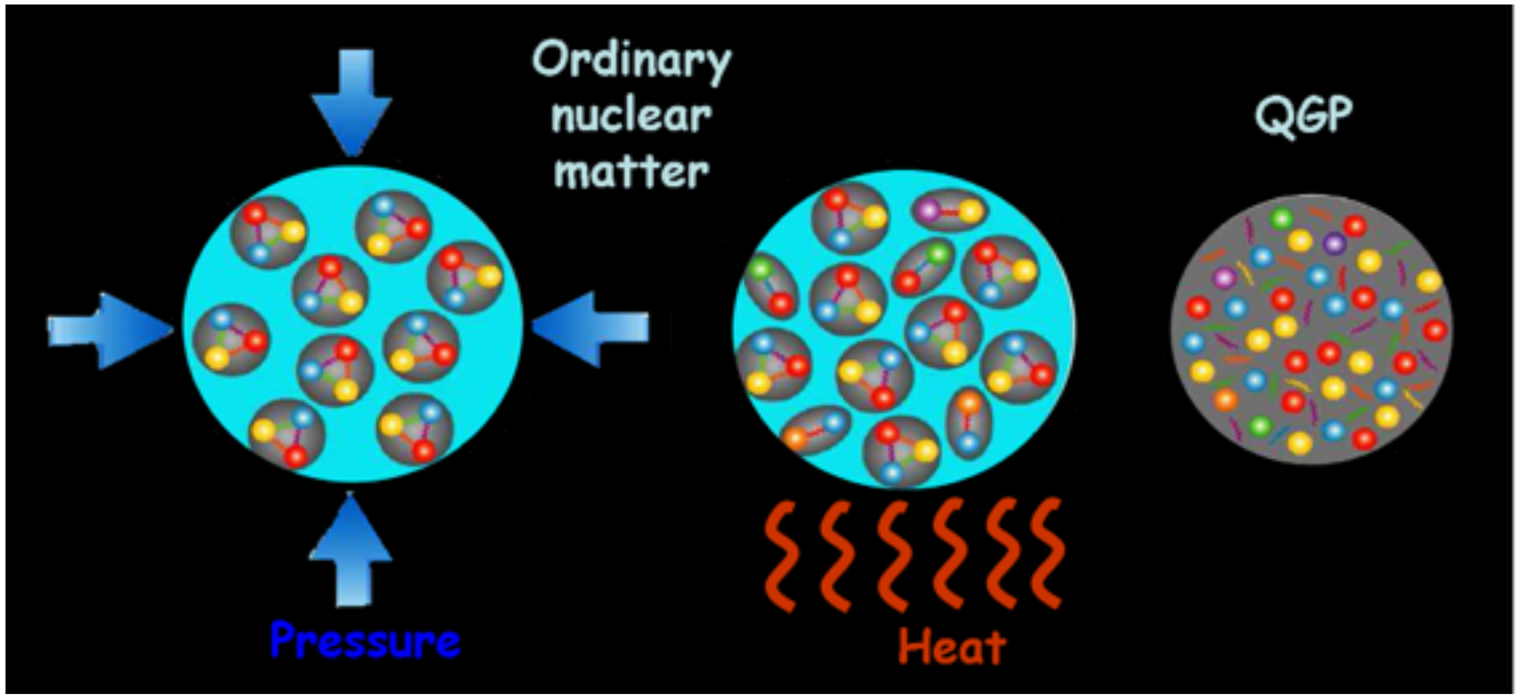


string tension



lattice gauge coupling

QGP: a new state of matter

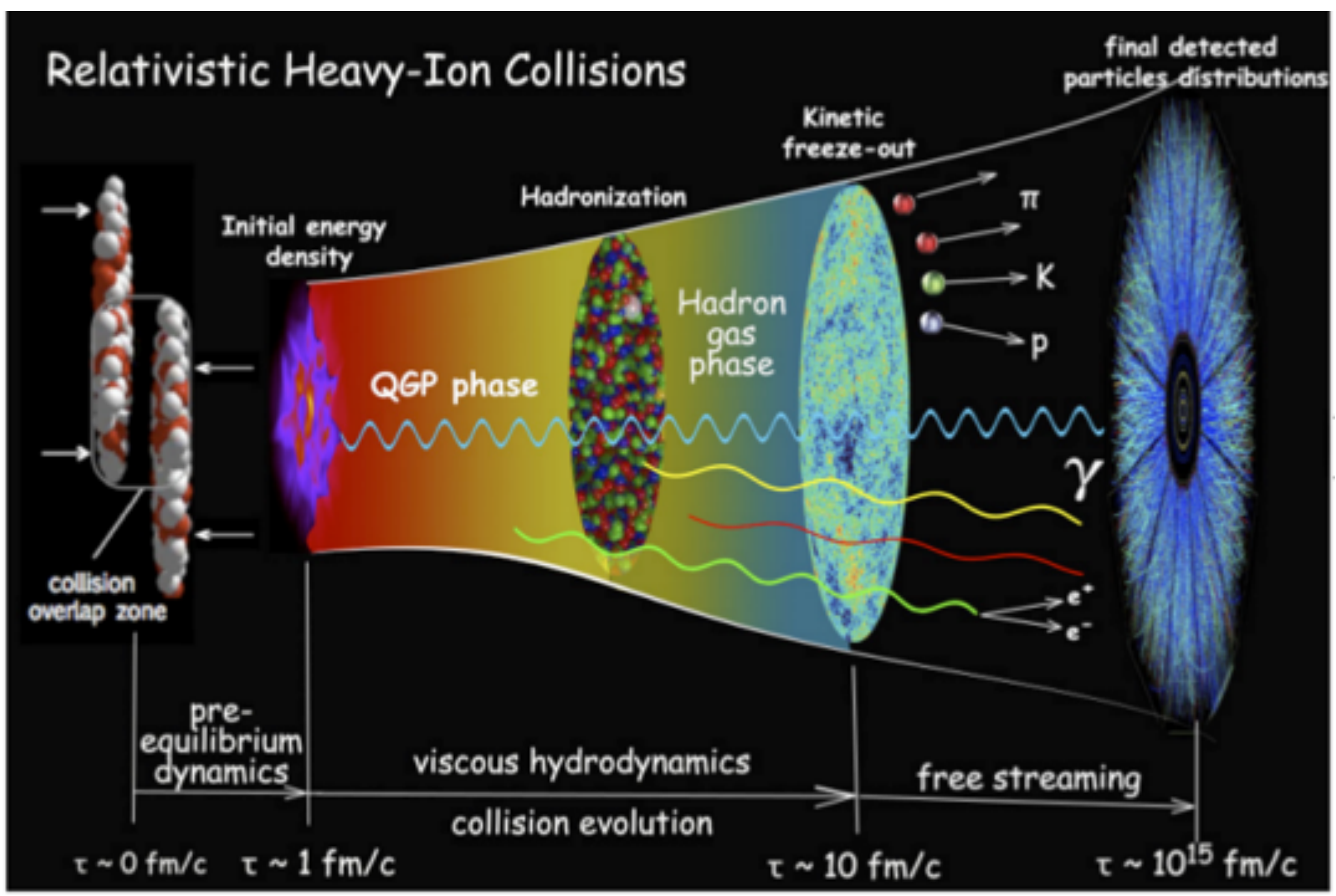


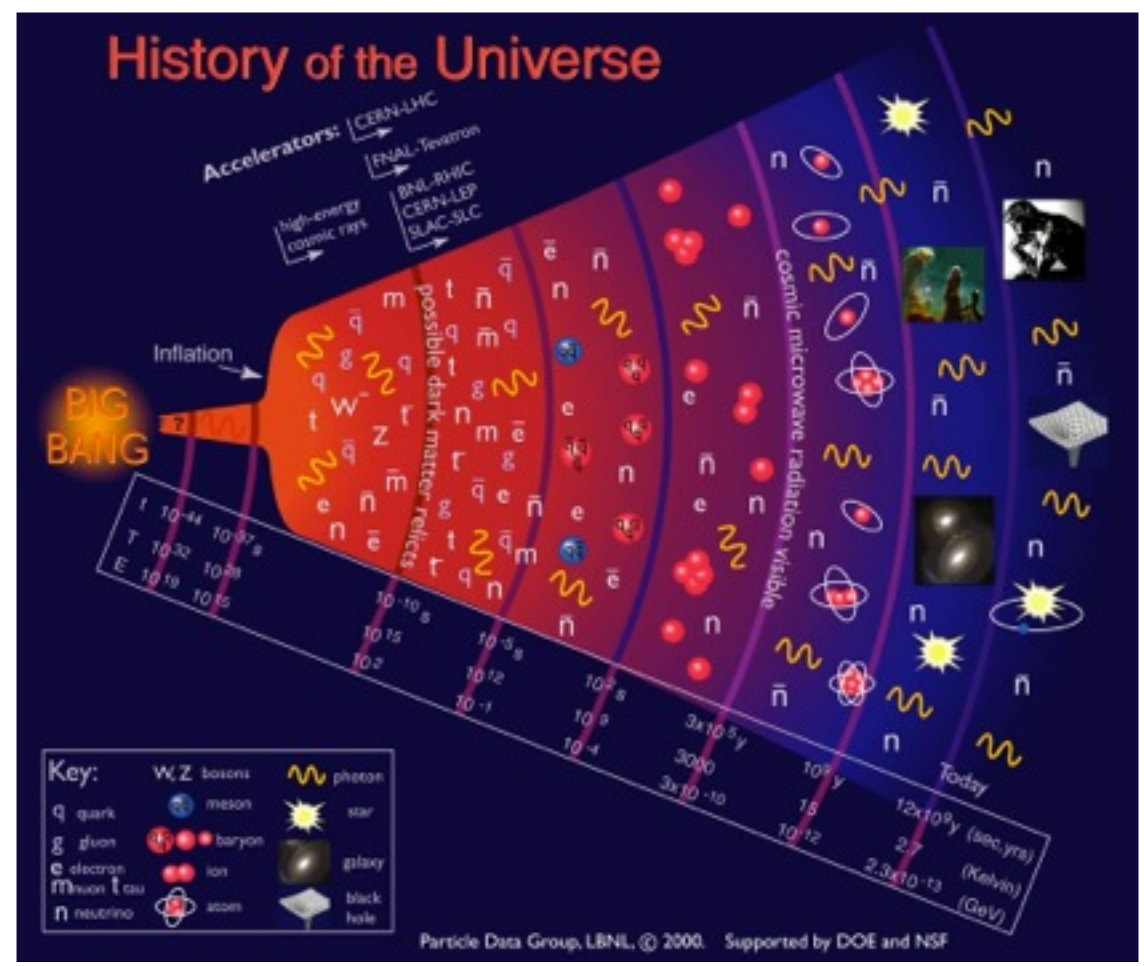
$\mu_B \gg \Lambda_{QCD}$ or $T \gg \Lambda_{QCD}$

Quark Gluon Plasma

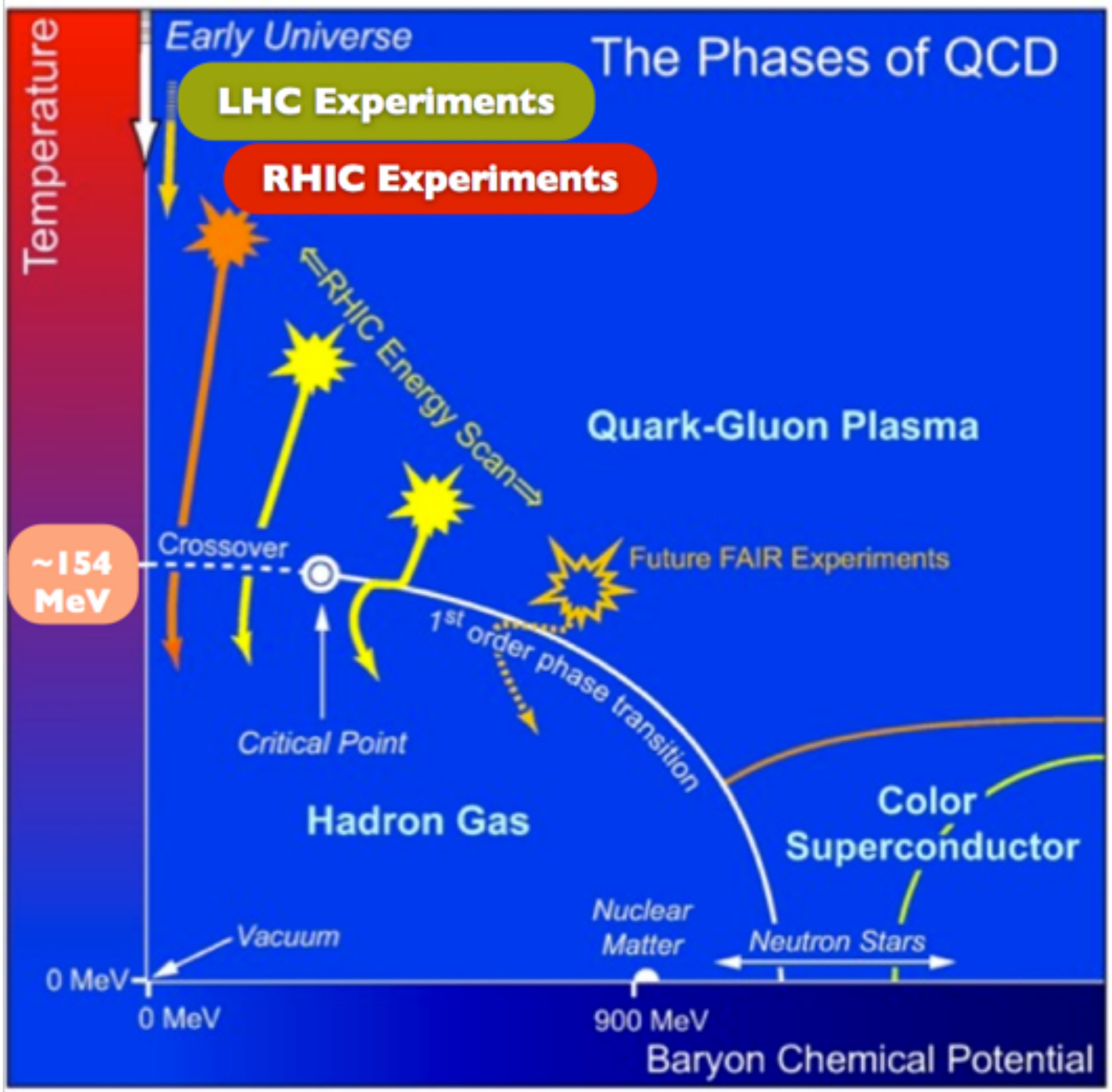
A new state of matter

quarks & gluons get liberated from nucleons





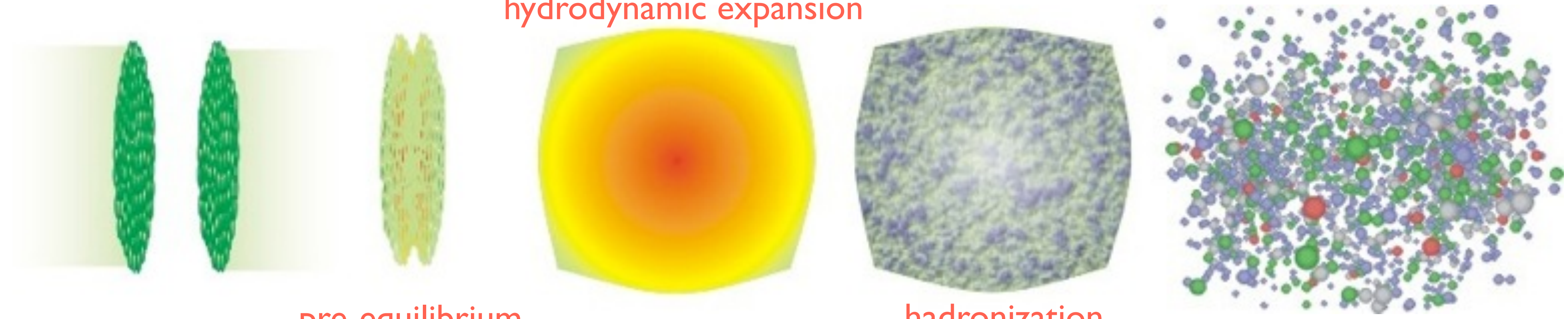
Exploring properties of QCD medium in Heavy Ion Collisions

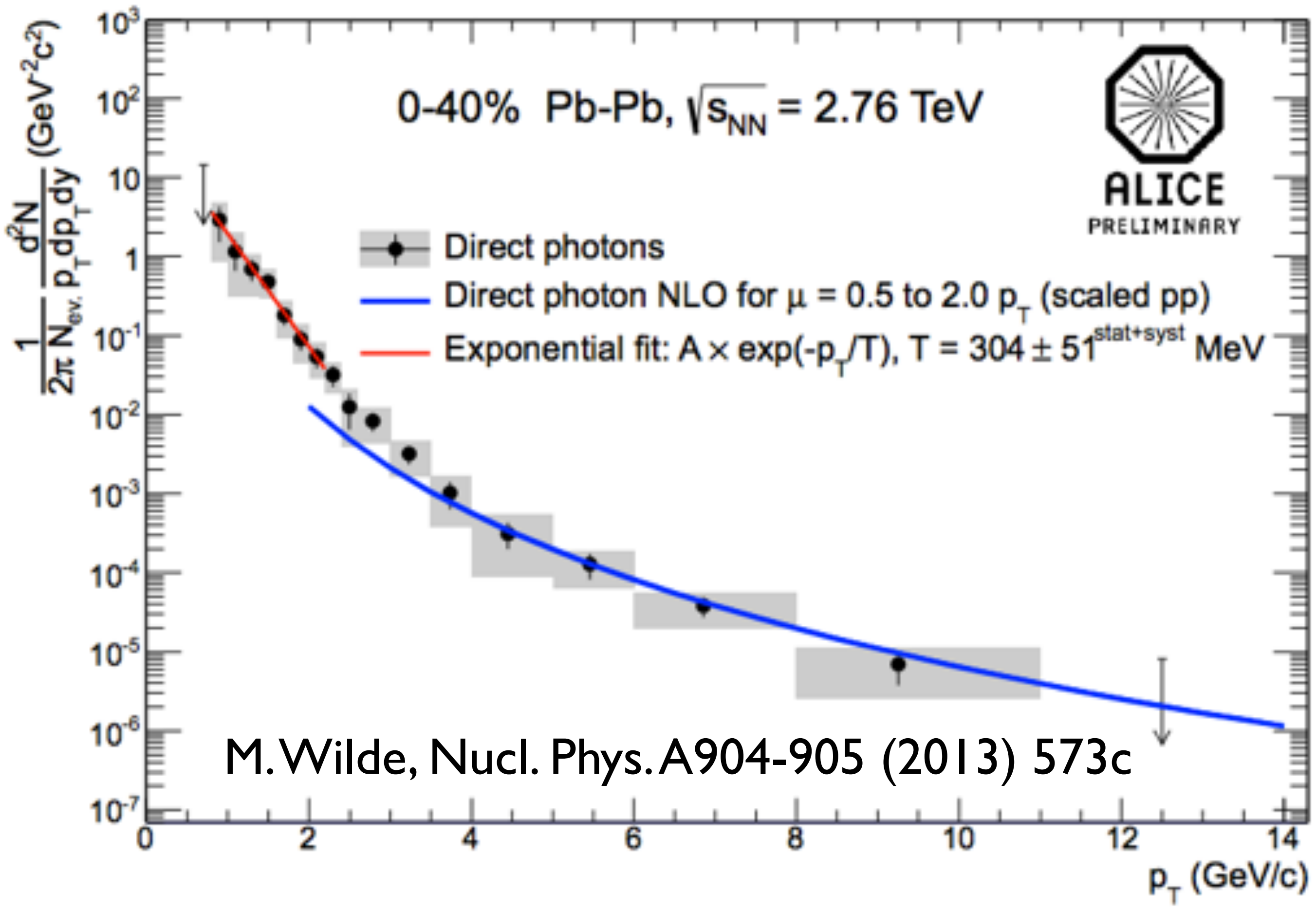


Schematic QCD phase diagram for nuclear matter

- What are the phases of strongly interacting matter and what roles do they play in cosmos?
- What does QCD predict for the properties of strongly interacting matter ?
- Experimentally, LHC@CERN, RHIC@BNL, FAIR@GSI are designed to address the above two fundamental questions
- Theoretically, Lattice QCD gives first-principles calculations of nuclear physics

temperature required to form QGP





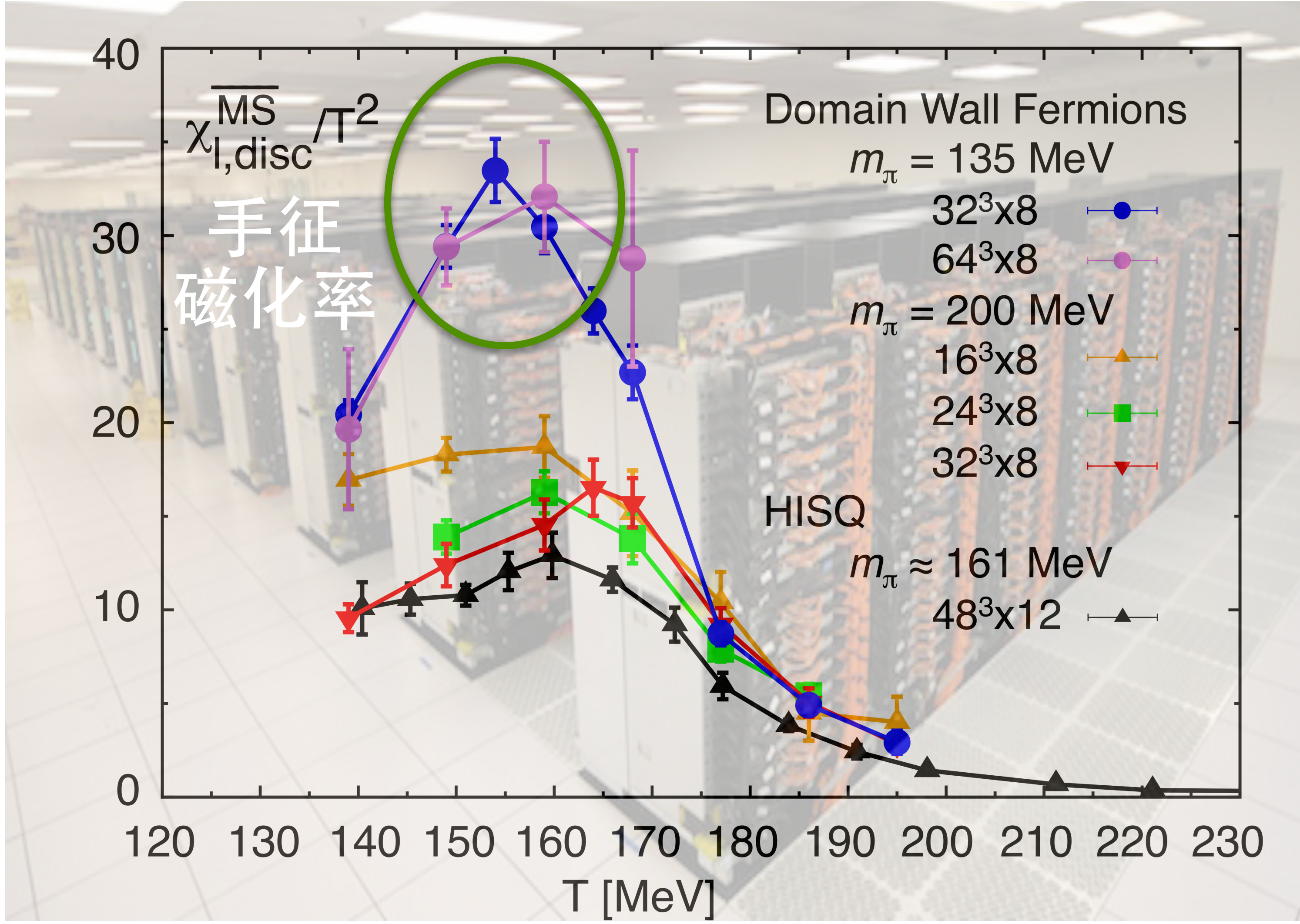
RHIC: T_{avg}=221±19±19 MeV

PHENIX: Phys.Rev.Lett.104:132301,2010

LHC: T_{avg}=304±51 MeV

ALICE: Nucl. Phys. A904-905 (2013) 573c

Are these temperatures high enough to form a Quark Gluon Plasma ?



[HotQCD collaboration], Phys. Rev. Lett.113(2014)082001

HotQCD collaboration:
Bielefeld University, BNL, CCNU, Columbia University, INT, LLNL, LANL

第一次利用了在有限格点间距下保持夸克对称性的格点QCD得到了QCD平滑过渡相变温度为155(1)(8) MeV

called lattice QCD [1]. Their simulations of deconfinement—the first to be performed with a version of lattice QCD that accurately describes the masses and, in particular, the symmetries of the quarks—yield the critical temperature for the transition to occur, and show that it is a smooth crossover, rather than an abrupt change.

工作被美国物理学会《物理·观点》栏目专题报道

Gert Aarts, viewpoint for PRL, Physics 7, 86 (2014)

确定了RHIC & LHC中产生的温度足够高可以使强相互作用核物质发生相变

Deconfinement aspects of QCD transition

Light-quark hadrons get deconfined around T_c,
charmonia and bottomonia may survive at $T>T_c$ Matsui & Satz PLB '86

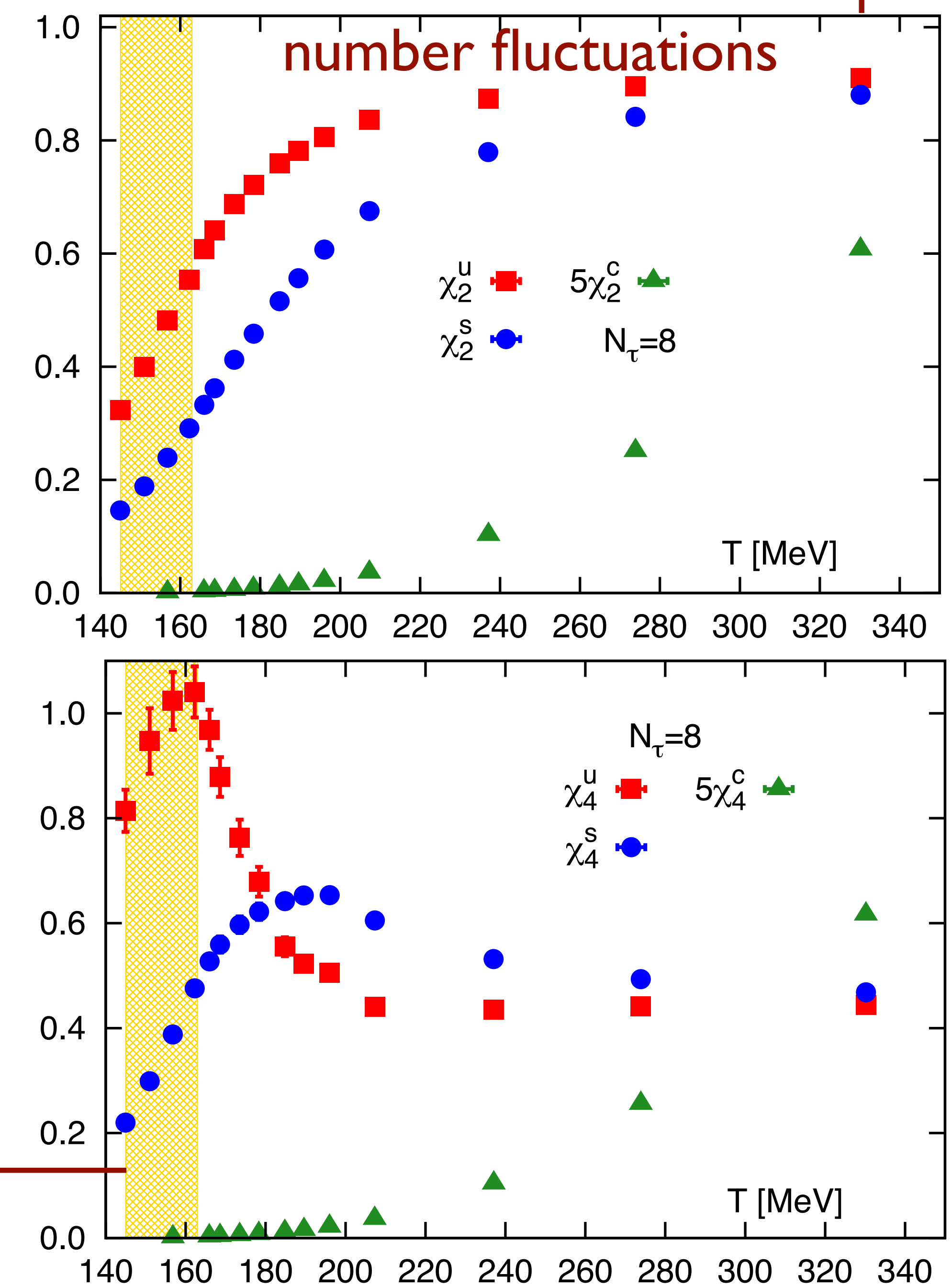
How about open charm & strange hadrons ?

Strange quark, less affected by chiral symmetry, may remain confined at $T > T_c$?

Do strange hadrons survive at higher temperature ?

Freeze-out/hadronization hierarchy between light-quark & strange hadrons ?

2nd & 4th order cumulants of quark number fluctuations



T_c=154(9) MeV

HotQCD, PRD85(2012)054503
Wuppertal-Budapest, JHEP 1009 (2010) 073

fluctuations of conserved quantum numbers

In the confined hadronic phase: electric charge Q, baryon number B of hadrons are integer numbers

In the deconfined QGP phase: Q and B of quarks are fractional numbers

fluctuations of B/Q/S/C and their correlations: probe the deconfined degrees of freedom for strange (S) and charm (C), irrespective of quark mass

$$\chi_{mn}^{XY} = \frac{\partial^{(m+n)}\left(p(\hat{\mu}_X, \hat{\mu}_Y)/T^4\right)}{\partial\hat{\mu}_X^m \partial\hat{\mu}_Y^n}\Big|_{\vec{\mu}=0}, \quad \hat{\mu}=\mu/T,\ X,Y=\{B,Q,S,C\}$$

"order parameters": construct observables that vanish in one phase and are nonzero in the other phase

Bazavov, HTD et al., Phys.Rev. Lett. 111(2013)082301

Partial pressure of heavy-light hadrons from HRG

- In the Hadron Resonance Gas (HRG) model, open heavy (strange or charm) mesons and baryons follow Boltzmann statistics as m/T >>1

$$P_{M/B}(T,\vec{\mu}) = \sum_{i \in \text{open C/S hadrons}} P^i_{M/B} \cosh(B_i\hat{\mu}_B + Q_i\hat{\mu}_Q + S_i\hat{\mu}_S + C_i\hat{\mu}_C)$$

differences of baryon-X correlations (X=Q,S,C):

$$\chi^{BX}_{31} - \chi^{BX}_{11} = \sum_i (B_i^3 - B_i) \times g_i(m^{hadron}) \longrightarrow$$

depends on hadron spectrum

if B=0,1, degrees of freedom are hadrons, $\chi^{BX}_{31} = \chi^{BX}_{11}$

if B=1/3, degrees of freedom are quarks, $\chi^{BX}_{31} \neq \chi^{BX}_{11}$

- the decomposition of partial pressure arising from open charm baryons

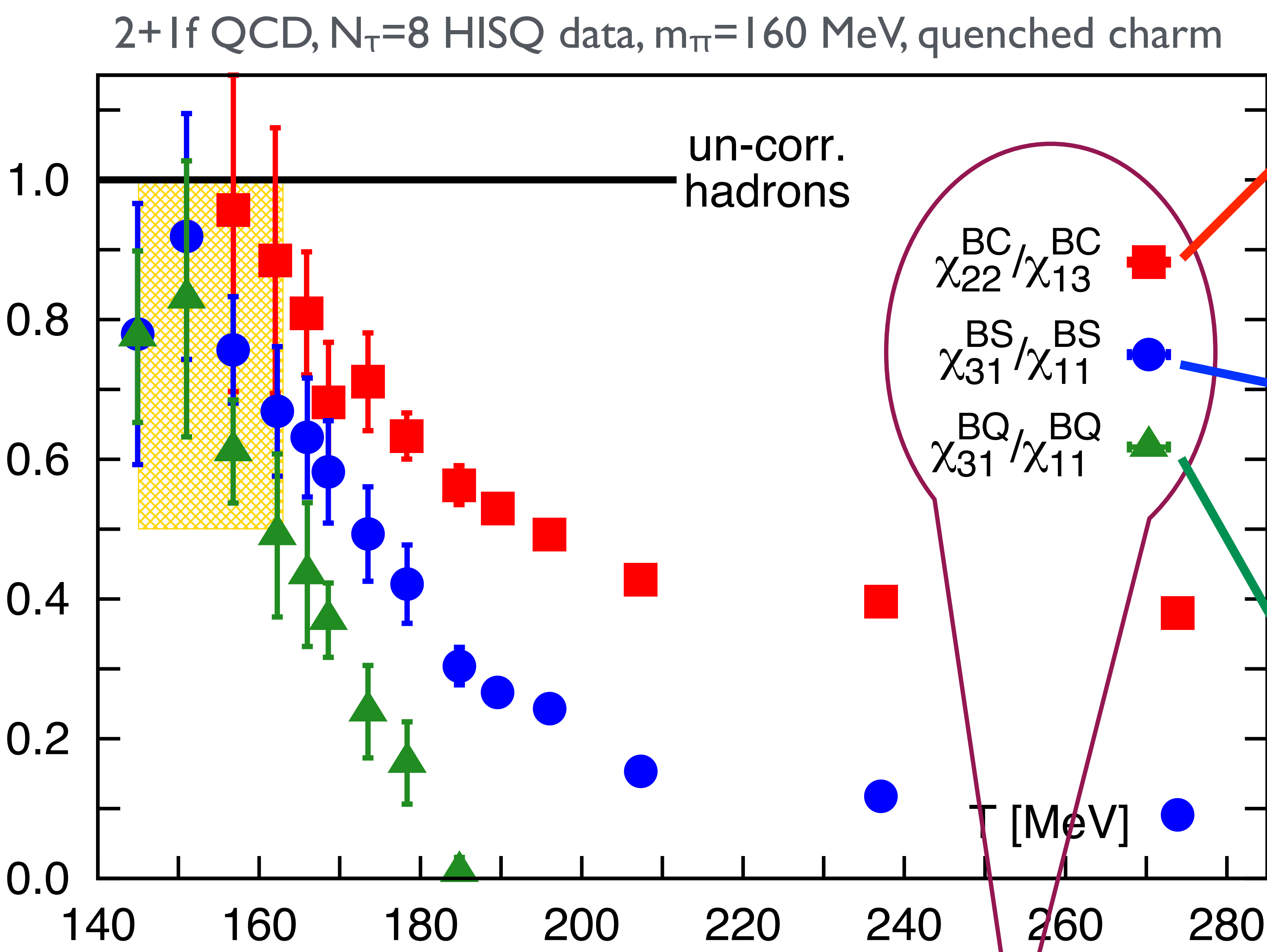
$$P^C_B(T,\vec{\mu}) = B_{C,1} + B_{C,2} + B_{C,3} \Rightarrow \chi^{BC}_{mn} = B_{C,1} + 2^n B_{C,2} + 3^n B_{C,3}$$

P_B is dominated by |C|=1 baryons due to large mass of |C|=2,3 baryons

$\Downarrow$ m+n>2 and even

$\boxed{\text{in the hadronic phase: } \chi^{BC}_{mn} \simeq B_{C,1} \text{, e.g. } \chi^{BC}_{13} \simeq \chi^{BC}_{22}}$

deconfinement of open charm & strange hadrons



ratio of baryon-charm correlation: receives contributions only from charm d.o.f

ratio of baryon-strangeness correlation: receives contributions only from strange d.o.f

ratio of baryon-charge correlation: receives contributions from all quark d.o.f

all equal to unity in an uncorrelated hadron resonance gas

Both open strange and charm hadrons start to get deconfined in the chiral crossover region

A. Bazavov, HTD et al., [BNL-Bielefeld-CCNU], Phys. Lett. B 737(2014)210

Editors' Suggestion 编辑建议发表文章

额外的奇异强子的热力学贡献和对实验中的冻结条件的影响

PDF

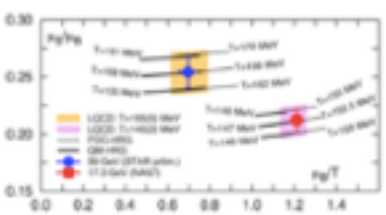
Export Citation

Additional Strange Hadrons from QCD Thermodynamics and Strangeness Freezeout in Heavy Ion Collisions

A. Bazavov, H.-T. Ding, P. Hegde, O. Kaczmarek, F. Karsch, E. Laermann, Y. Maezawa, Swagato Mukherjee, H. Ohno, P. Petreczky, C. Schmidt, S. Sharma, W. Soeldner, and M. Wagner

Phys. Rev. Lett. **113**, 072001 (2014) – Published 11 August 2014

BNL-Bielefeld-CCNU collaboration



Unobserved hadrons - specifically those made of strange quarks - provide insight into lattice QCD calculations near the Quark Gluon Plasma phase transition.

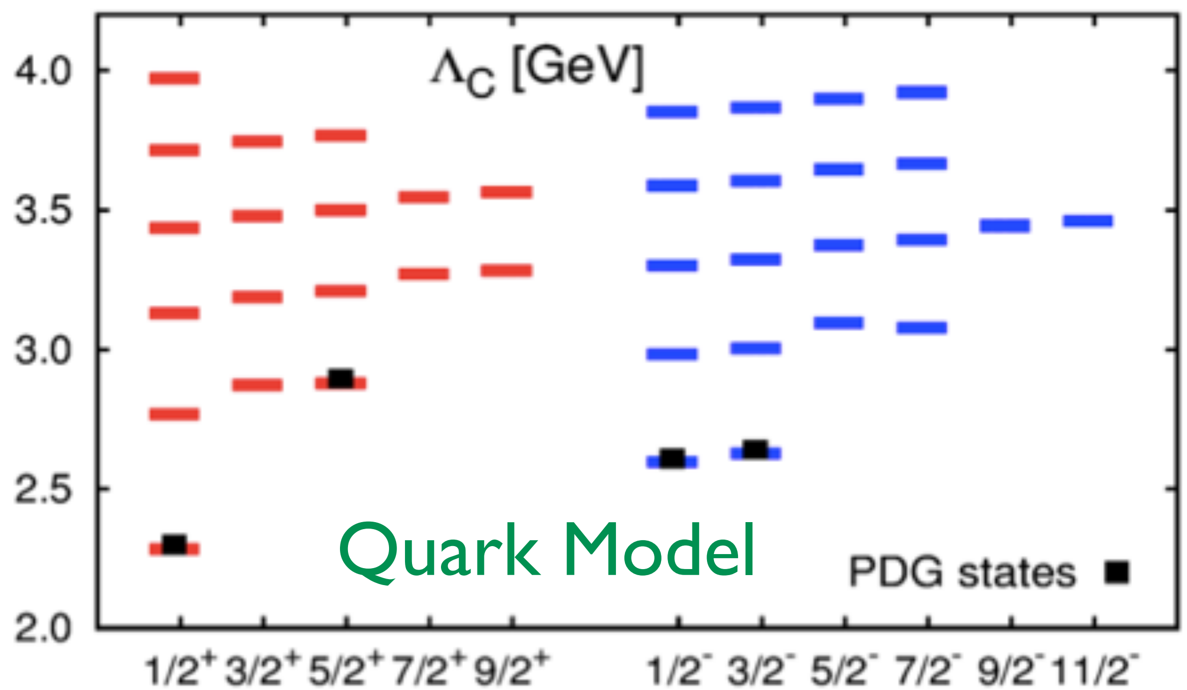
comments from the Editor

abstract

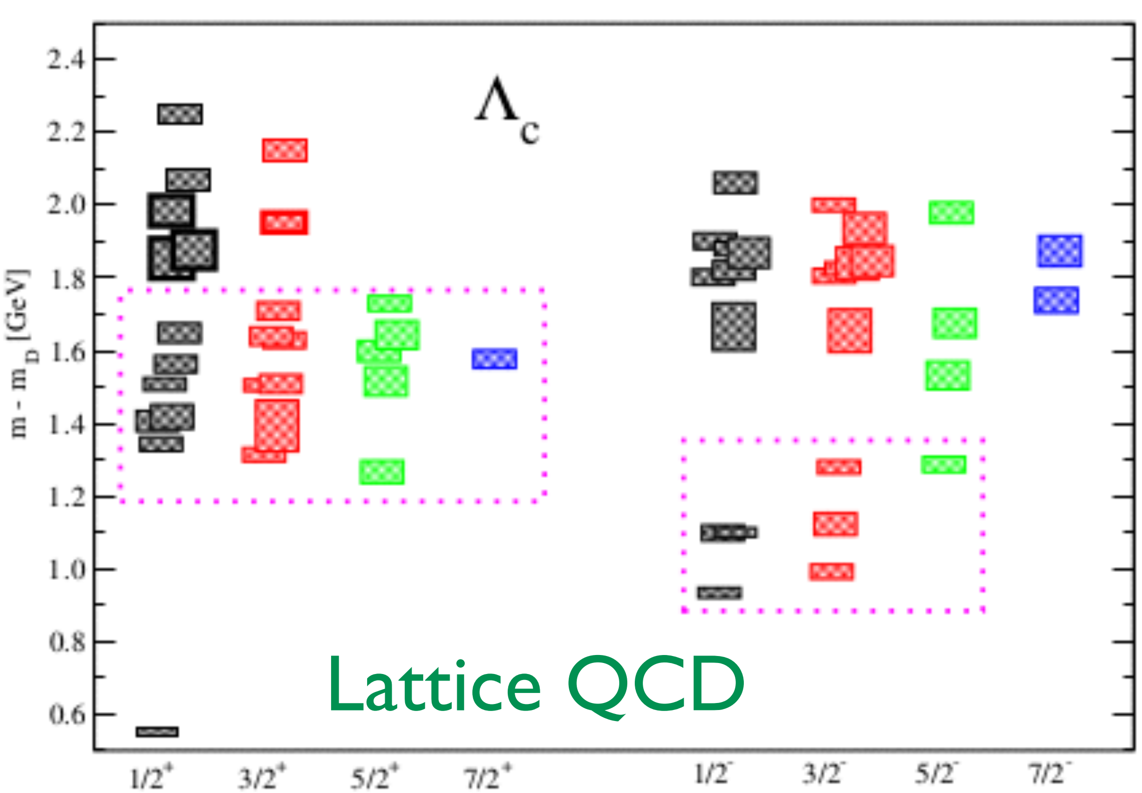
We compare lattice QCD results for appropriate combinations of net strangeness fluctuations and their correlations with net baryon number fluctuations with predictions from two hadron resonance gas (HRG) models having different strange hadron content. The conventionally used HRG model based on experimentally established strange hadrons fails to describe the lattice QCD results in the hadronic phase close to the QCD crossover. Supplementing the conventional HRG with additional, experimentally uncharted strange hadrons predicted by quark model calculations and observed in lattice QCD spectrum calculations leads to good descriptions of strange hadron thermodynamics below the QCD crossover. We show that the thermodynamic presence of these additional states gets imprinted in the yields of the ground-state strange hadrons leading to a systematic 5–8 MeV decrease of the chemical freeze-out temperatures of ground-state strange baryons.

实验上尚未观测到的粒子——特别是那些奇异强子，让我们理解了格点量子色动力学在QGP相变附近的计算结果

Hadron Resonance Gas model: revisited



Ebert et. al., EPJC66(2010)197, PRD84(2011)014025



Padmanath et.al., arXiv:1311.4806 [hep-lat]

$$P_{\text{total}} = \sum_{\text{all hadrons}} P_h$$

hadrons listed in PDG + ???

More states are predicted in relativistic Quark Model (QM) than listed in PDG

LQCD calculations give similar results with QM

Any thermodynamic significance from additional hadron states predicted in QM?

Additional open strange hadrons in HRG

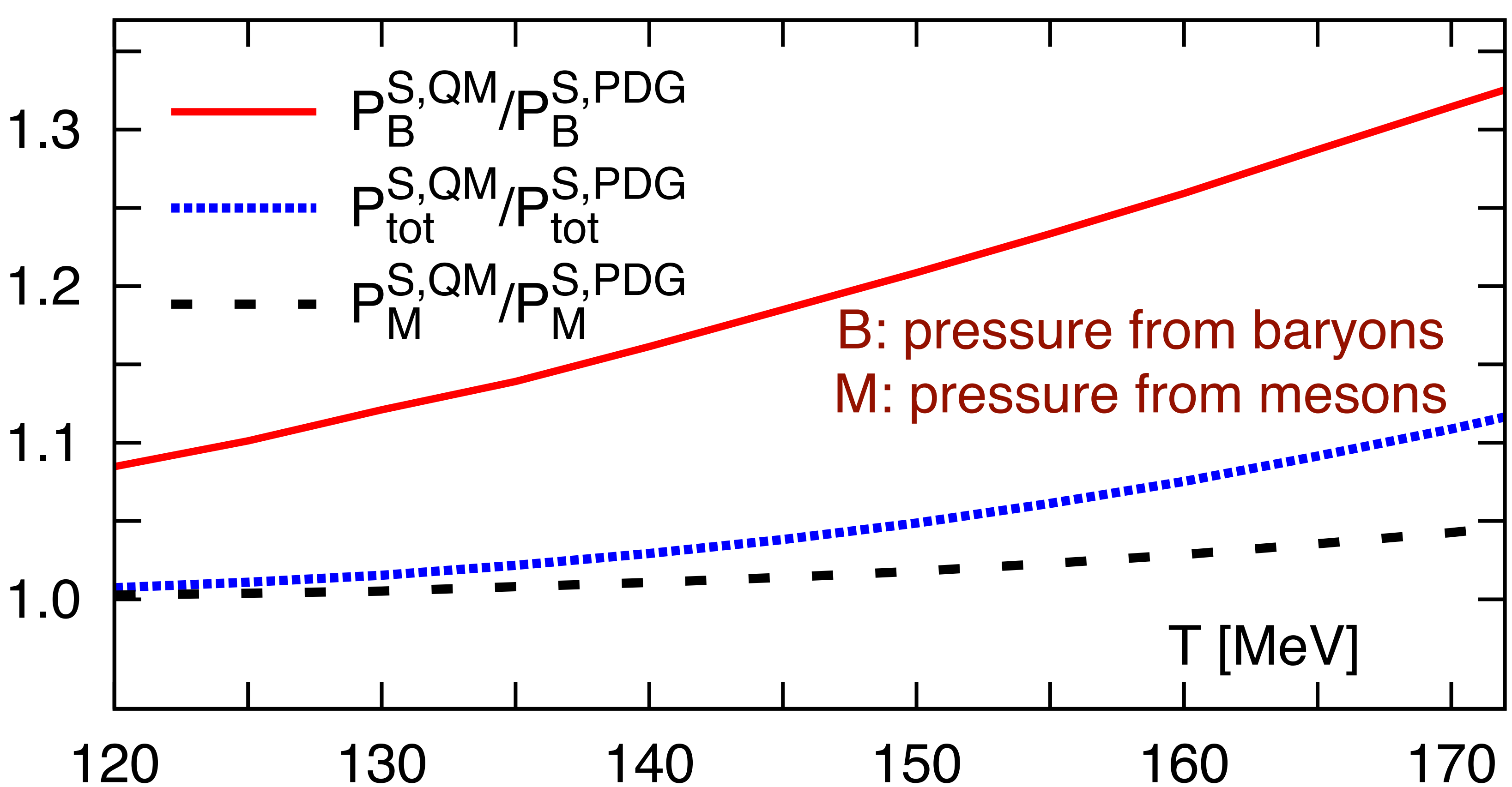
Boltzmann approximation:

$$P^{S,X}_{M/B}(T,\vec{\mu}) = \frac{T}{2\pi^2}\sum_{i\in X} g_i \left(\frac{m_i}{T}\right)^2 K_2(m_i/T)\cosh(B_i\hat{\mu}_B + Q_i\hat{\mu}_Q + S_i\hat{\mu}_S)$$

with X=QM, PDG and $\hat{\mu}=\mu/T$

P^{PDG}: 利用实验上已经观测到的粒子的谱(PDG)计算得到的压强

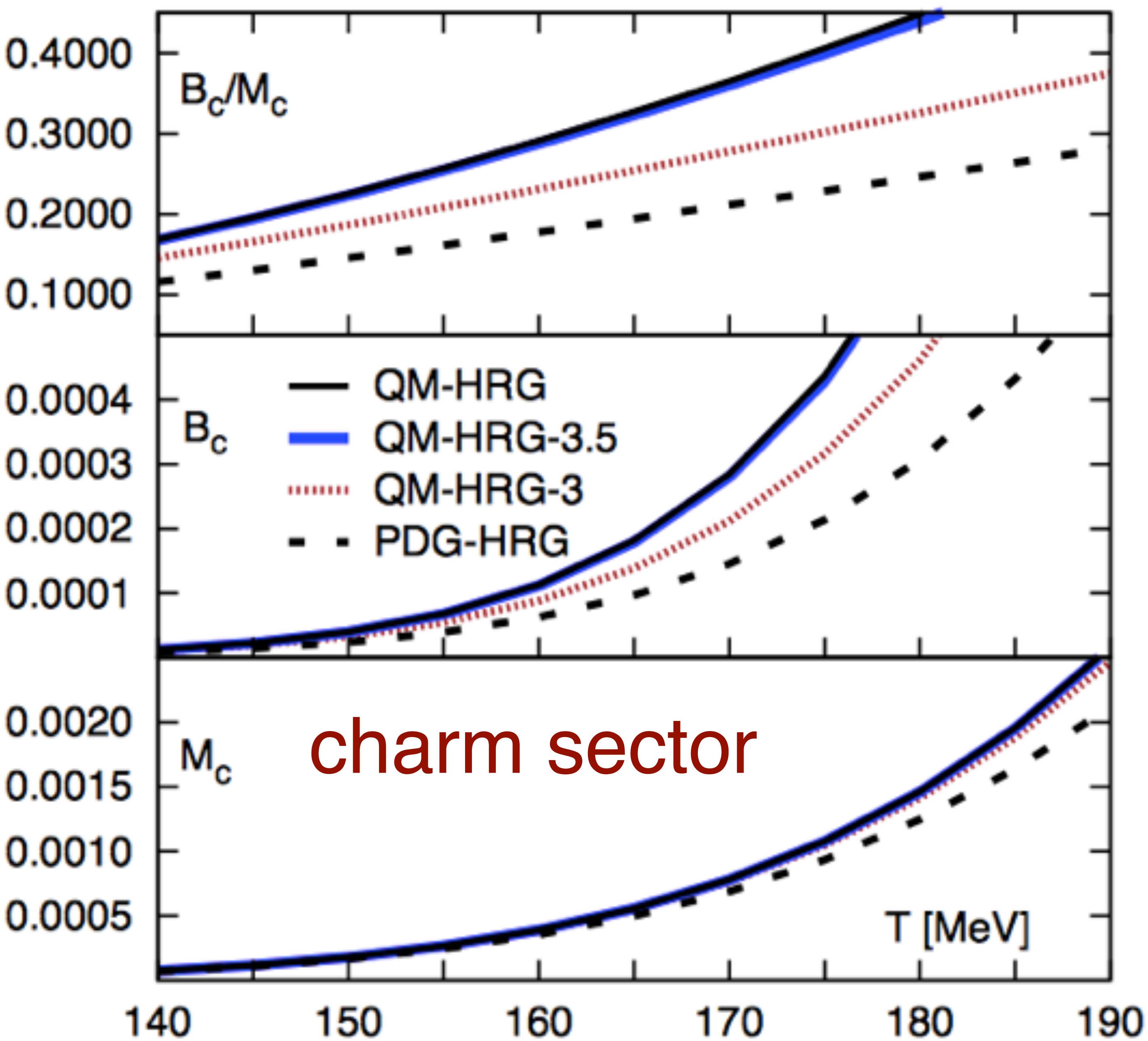
P^{QM}: 利用夸克模型预言的粒子的谱(QM)做计算得到的压强



strange baryons experimentally much less known, additional baryons contribute up to 30%

open strange mesons experimentally well known

Additional open charm hadrons in HRG



B: pressure from baryons
M: pressure from mesons

Less baryons than mesons are listed in PDG

The additional states from the Quark Model (QM) give considerable contributions to partial pressures at T<154 MeV

A. Bazavov, HTD et al., [BNL-Bielefeld-CCNU], PRL'14, PLB '14

Construction of observables to probe the abundance

decomposition of partial pressure (P) arising from heavy-light hadrons in HRG:

$$P_{M/B}(T,\vec{\mu}) = \sum_{i \in \text{open C/S hadrons}} P^{i}_{M/B} \cosh(B_i\hat{\mu}_B + Q_i\hat{\mu}_Q + S_i\hat{\mu}_S + C_i\hat{\mu}_C)$$

charm sector:

$$P^C_M(T,\vec{\mu}) = M_C, \qquad P^C_B(T,\vec{\mu}) = B_{C,1} + B_{C,2} + B_{C,3}$$

$$\chi^{BC}_{mn} = B_{C,1} + 2^n B_{C,2} + 3^n B_{C,3} \simeq B_{C,1} \longleftarrow \text{partial P arising from baryons}$$

$$\chi^{C}_{n} = M_C + B_{C,1} + 2^n B_{C,2} + 3^n B_{C,3} \simeq M_C + B_{C,1} \quad \text{with n even}$$

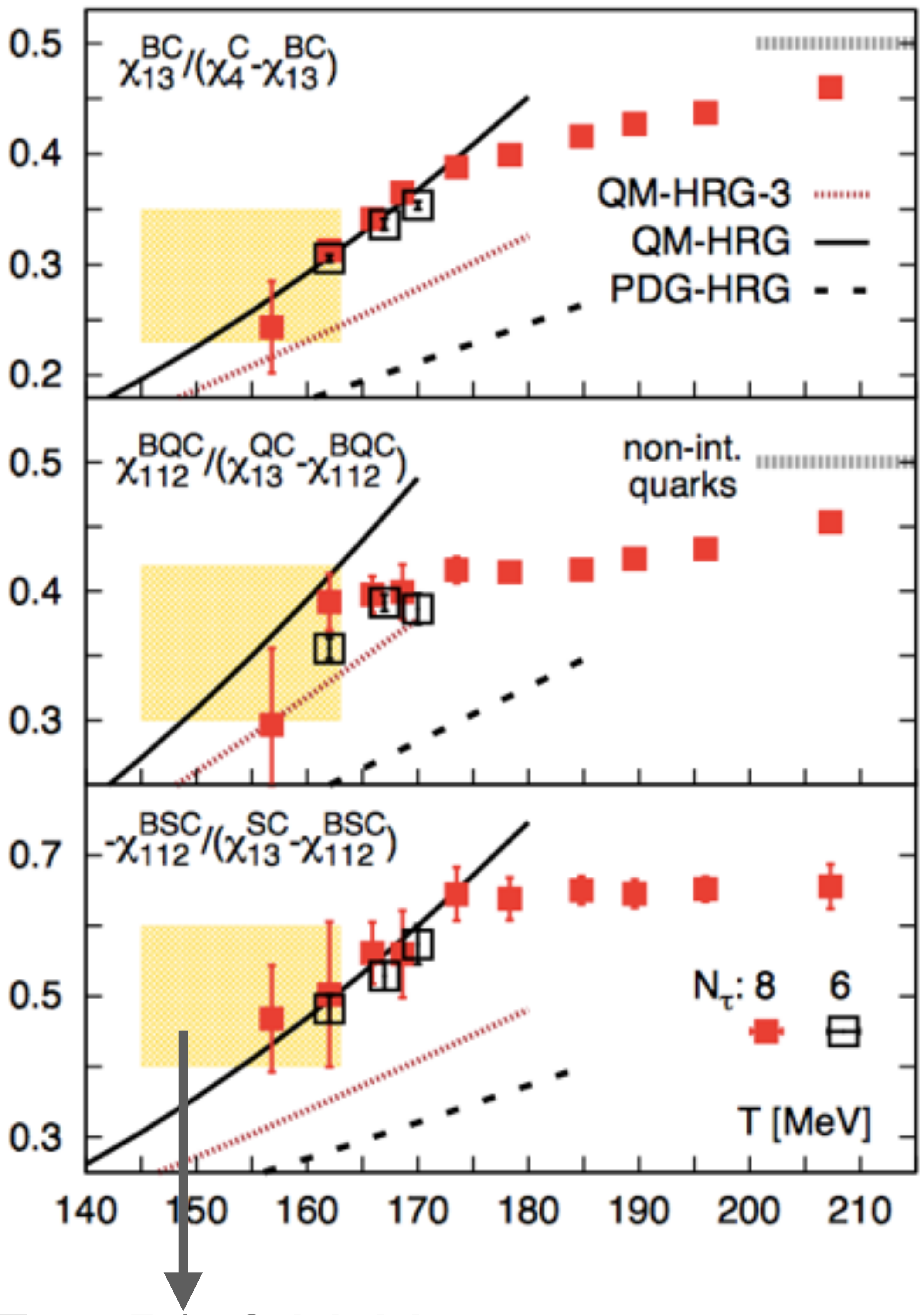
$$\chi^{C}_{n} - \chi^{BC}_{mn} \simeq M_C \longleftarrow \text{partial P arising from mesons}$$

- observables probing the relative contribution of baryons and mesons to the partial pressures

$$\chi^{BC}_{mn}/(\chi^C_n - \chi^{BC}_{mn}) \quad \text{, e.g.} \quad \chi^{BC}_{13}/(\chi^C_4 - \chi^{BC}_{13})$$

Abundance of open charm hadrons

2+1f QCD, N_τ=8 HISQ data, m_π=160 MeV



T_c=154±9 MeV

Use appropriate projections to check the relative contributions of:

charm baryons to open charm mesons

charged charm baryons to open charm mesons

strange-charmed baryons to strange-charmed mesons

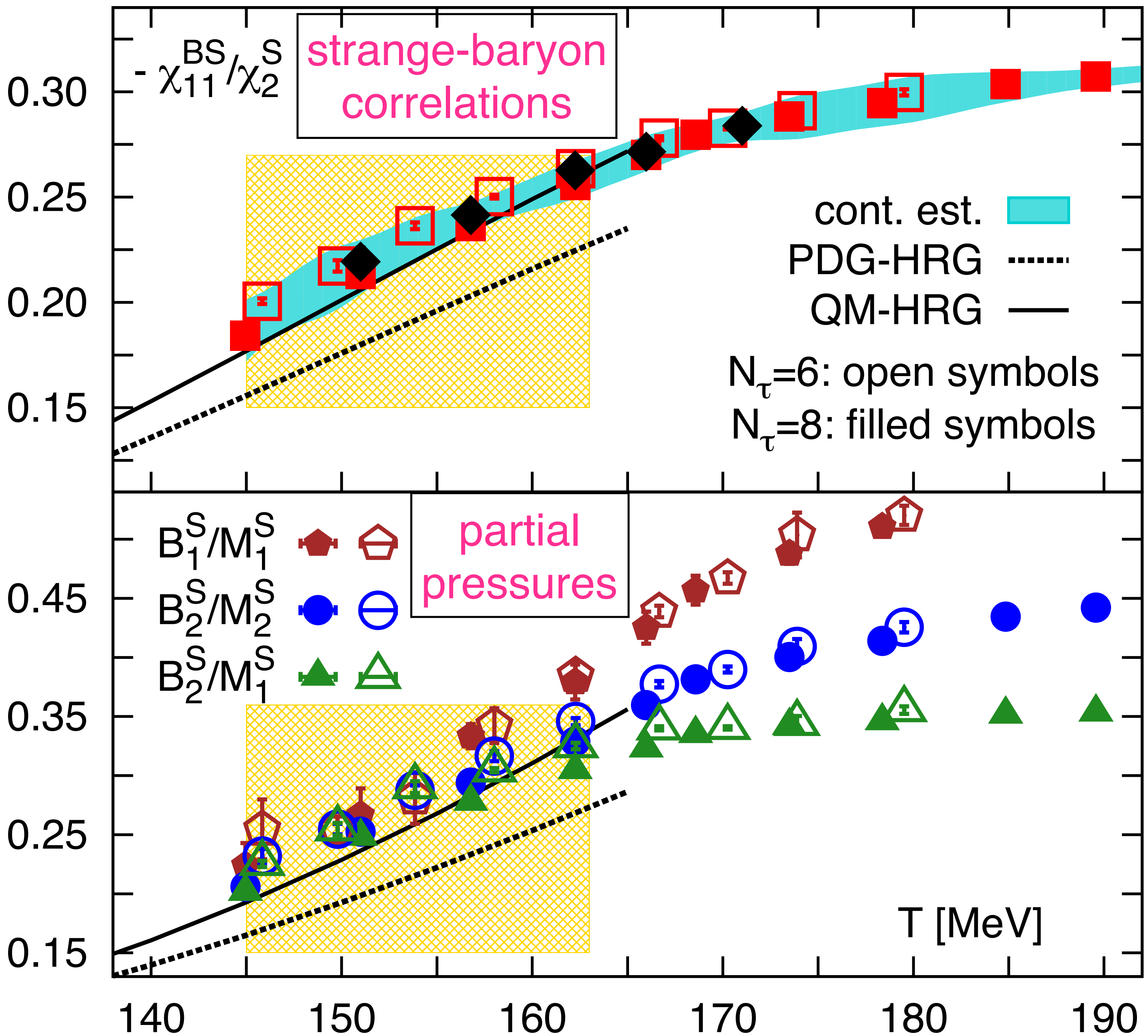
Clear evidence of the additional, non-PDG listed states from QCD thermodynamics is found

A. Bazavov, HTD et al., [BNL-Bielefeld-CCNU], 1404.4043

Importance of additional states has also been pointed out in

Majumder and Mueller, PRL 105(2010)252002 & Beitel, Gallmeister and Greiner, 1402.1458

Relative contributions of strange baryons to open strange mesons



PDG-HRG:
利用实验上已经观测到的粒子的谱做的计算

QM-HRG:
利用夸克模型预言的粒子的谱做的计算

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

找到了实验上未观测到的粒子对QCD相变贡献的证据

A. Bazavov et al.[BNL-Bielefeld-CCNU], Phys. Rev. Lett. 113 (2014)072001

strangeness chemical potential in HIC

strangeness neutrality in HIC: N_S=0 enforces dependence of μ_S on μ_B and T

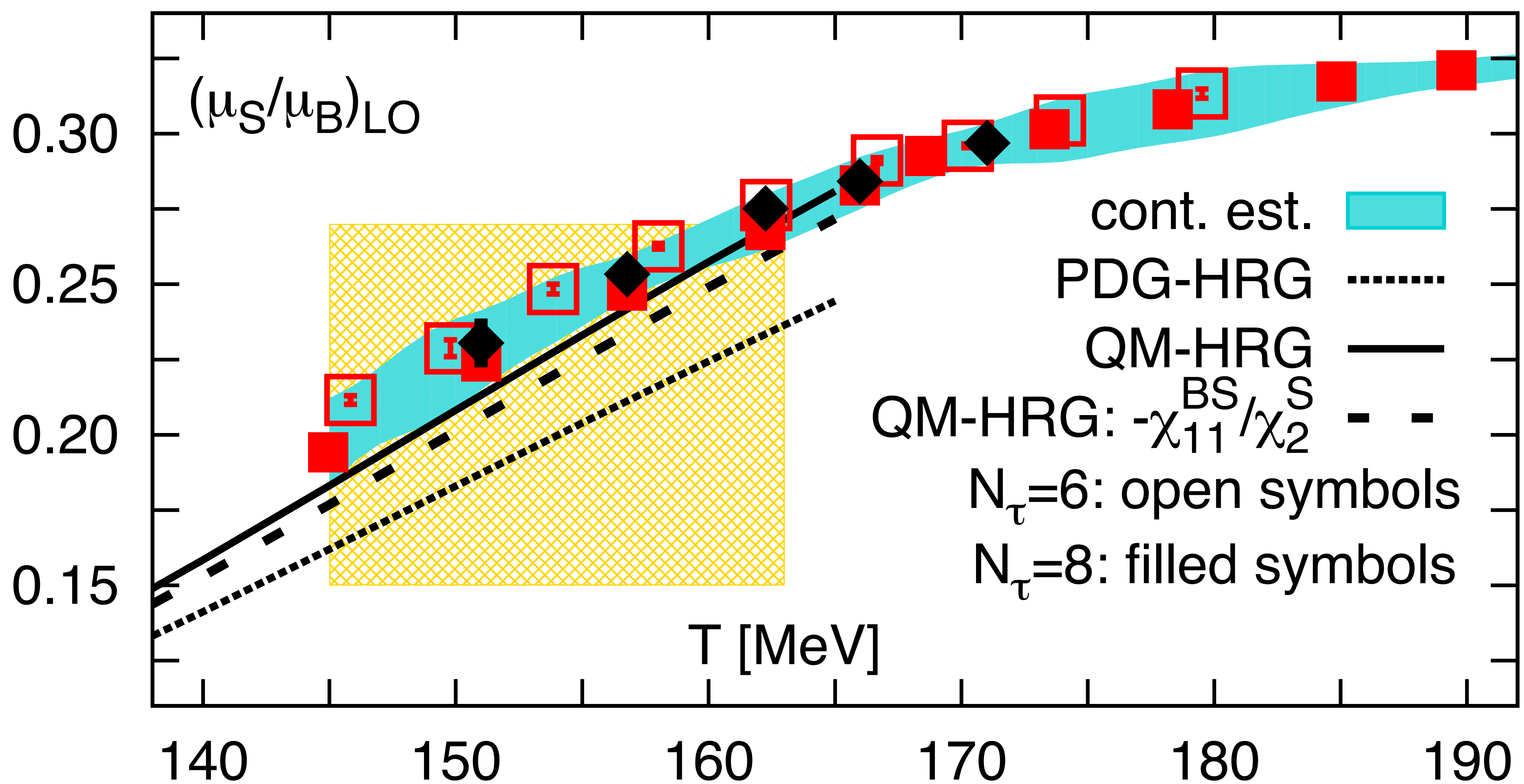
expand μ_S/μ_B in a Taylor series of μ_B:

$$\frac{\mu_S}{\mu_B} \simeq \boxed{-\frac{\chi_{11}^{BS}}{\chi_2^S}} - \frac{\chi_{11}^{QS}}{\chi_2^S}\frac{\mu_Q}{\mu_B} + \mathcal{O}(\mu_B^2)$$

NLO corrections are small at μ_B <200 MeV

additional states contribute to the relative abundance of strange baryons to open strange mesons

In the strange hadron sector, the PDG-HRG based analyses give a larger freeze out temperature than QM-HRG and lattice QCD



A. Bazavov et al.[BNL-Bielefeld-CCNU], Phys. Rev. Lett. 113 (2014)072001

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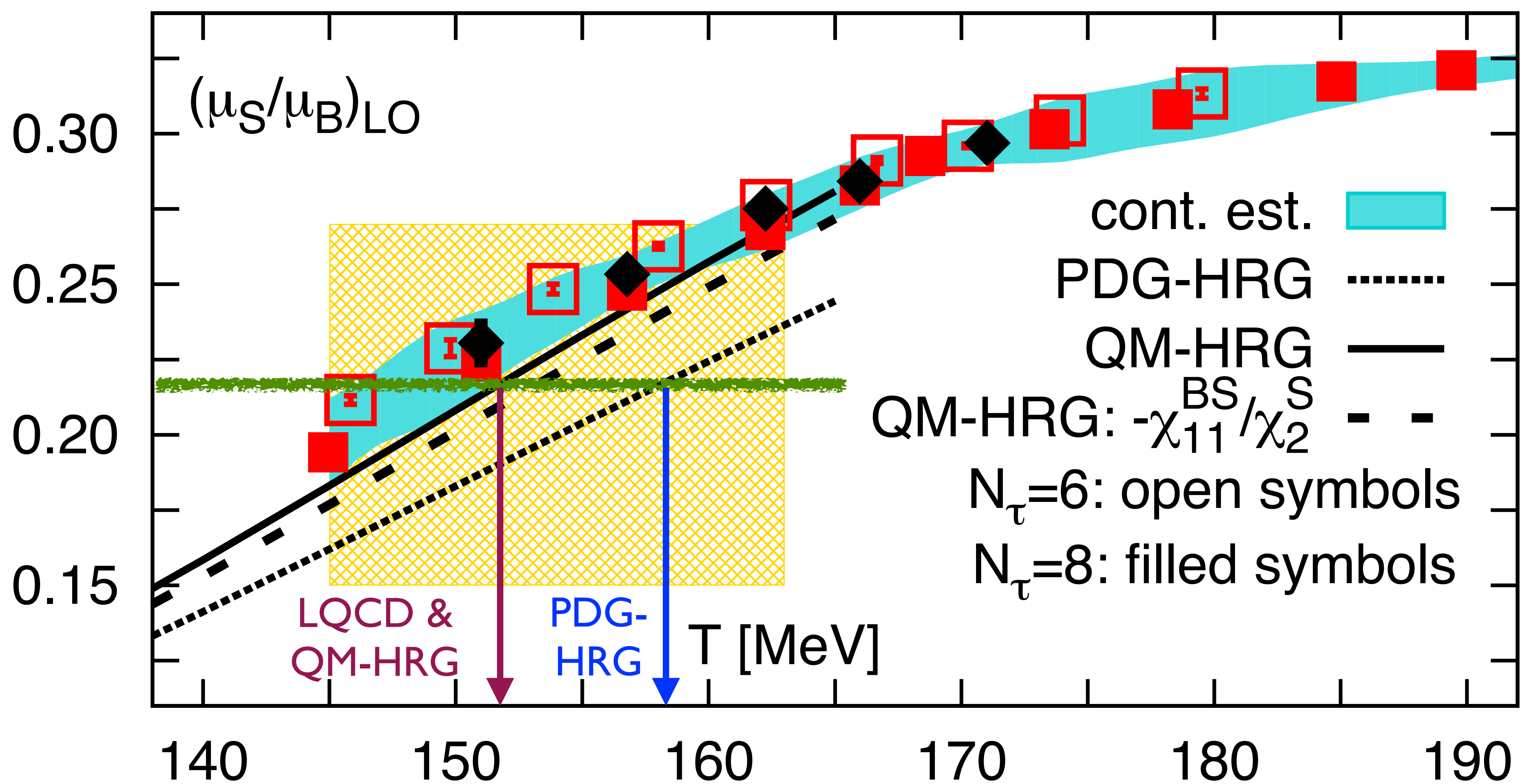
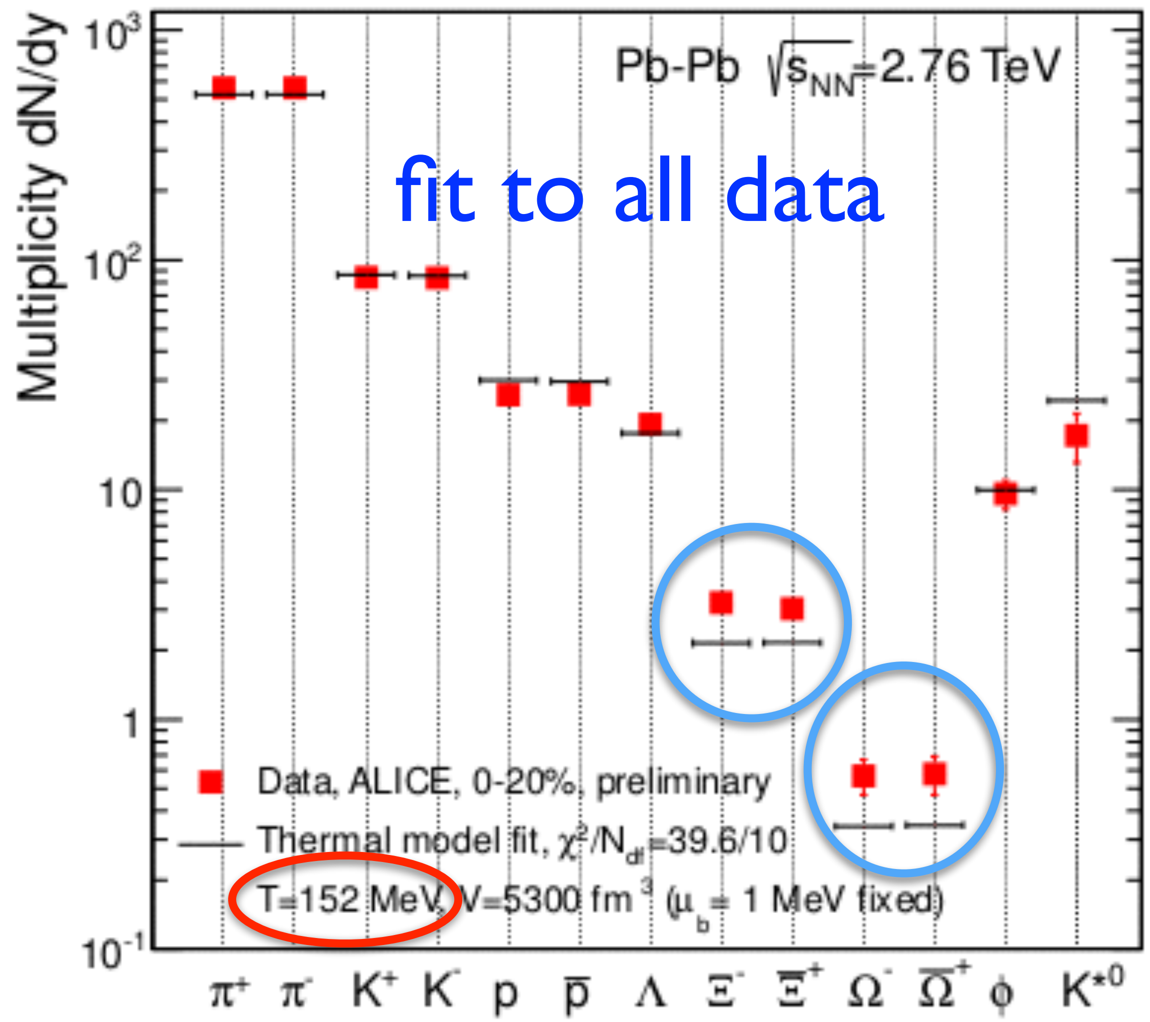
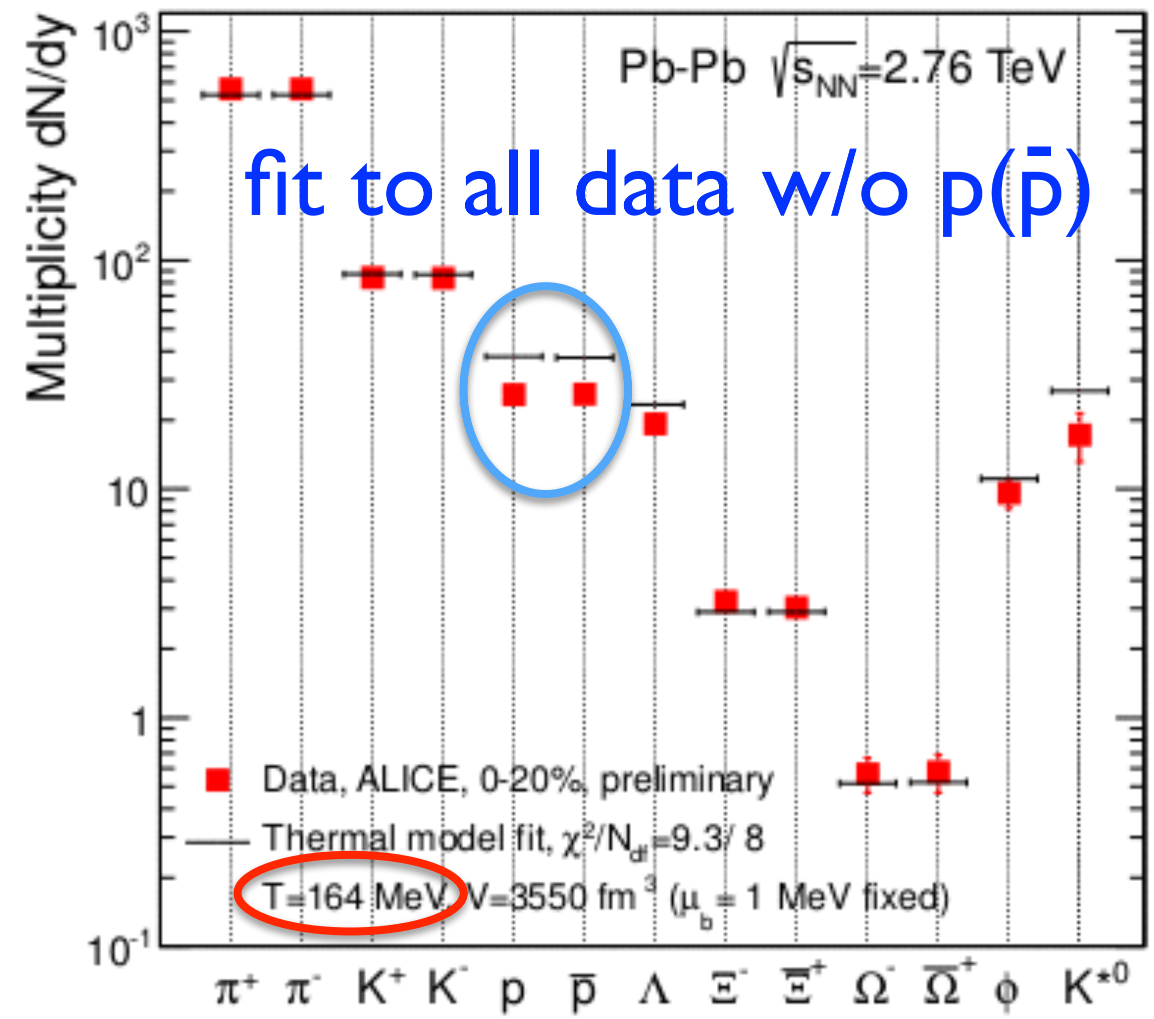


A. Bazavov et al.[BNL-Bielefeld-CCNU], Phys. Rev. Lett. 113 (2014)072001

Hierarchy freeze out for light and strange hadrons ?





Andronic et al., Nucl. Phys. A904 (2013) 535c

~ 10-5 MeV systematic difference in the freeze out T from separate fits to light and strange hadrons using PDG-HRG

two freeze out stages for light and strange hadrons?

Alba et al., arXiv:1403.4903,Bugaev et al., EPL 104(2013)22002, Bellwied et al., [WB Collaboration], Phys.Rev. Lett. 111(2013)202302, Chatterjee, Godbole, Gupta, PLB 727(2013)554

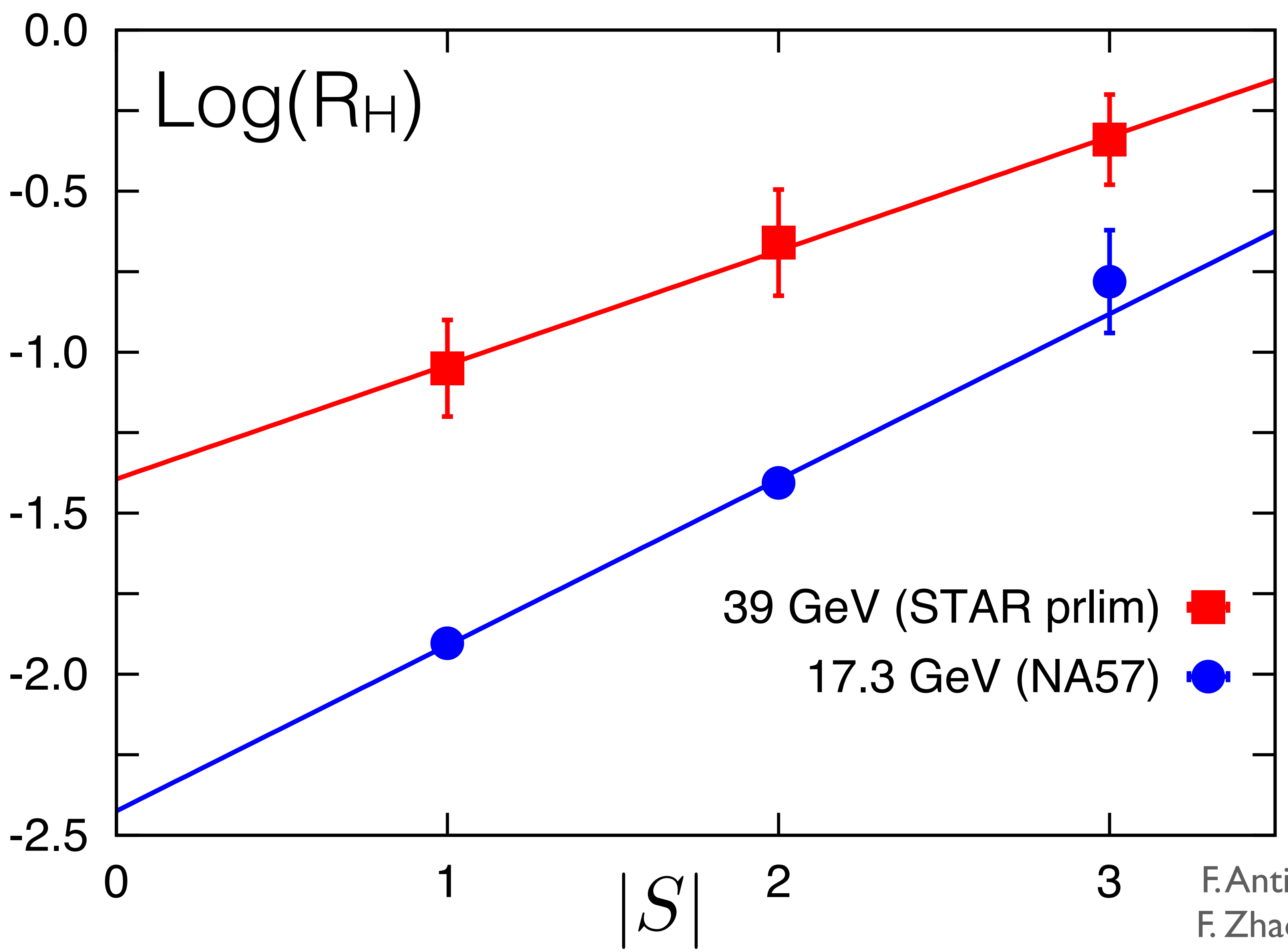
Strange hadron yields in HIC

Two-parameter fit to experiment data using HRG ansatz

irrespective of the details of hadron spectrum

$$R_H \equiv \frac{\bar{H}_S}{H_S} = \exp\left[-2\boxed{(\mu_B^f/T^f)} \times \left(1 - \boxed{(\mu_S^f/\mu_B^f)}|S|\right)\right]$$

$\bar{\Lambda}/\Lambda$ $\bar{\Xi}/\Xi$ $\bar{\Omega}/\Omega$

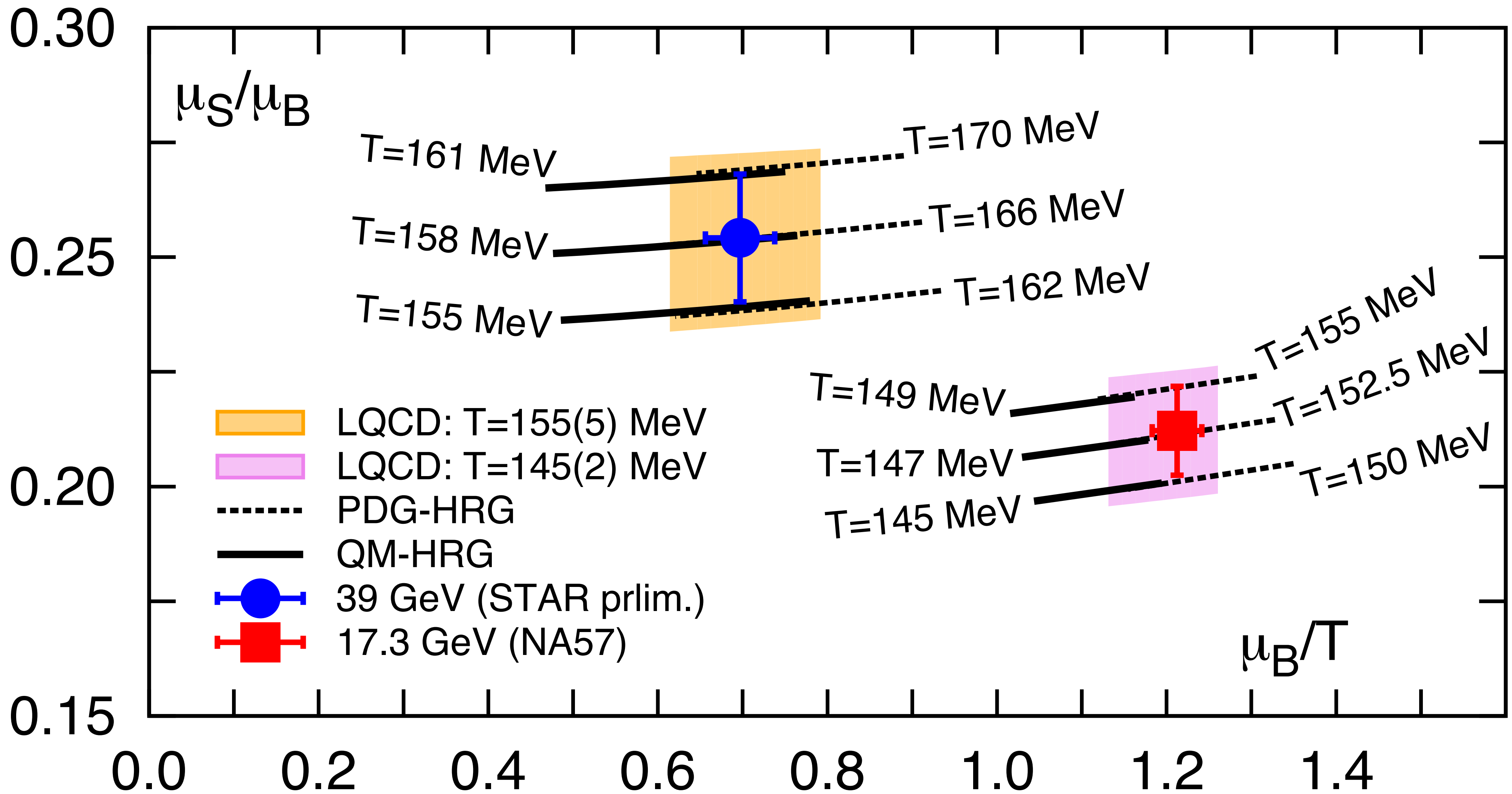


imprinted by the presence of experimentally yet unobserved strange hadrons

Compare the extracted μ_S/μ_B and μ_B/T with those from HRG & Lattice QCD

F. Antinori et al.,PLB 595(2004)68,
F. Zhao, PoS CPOD2013(2013)036

Imprints of unobserved states in strangeness freeze out in HIC

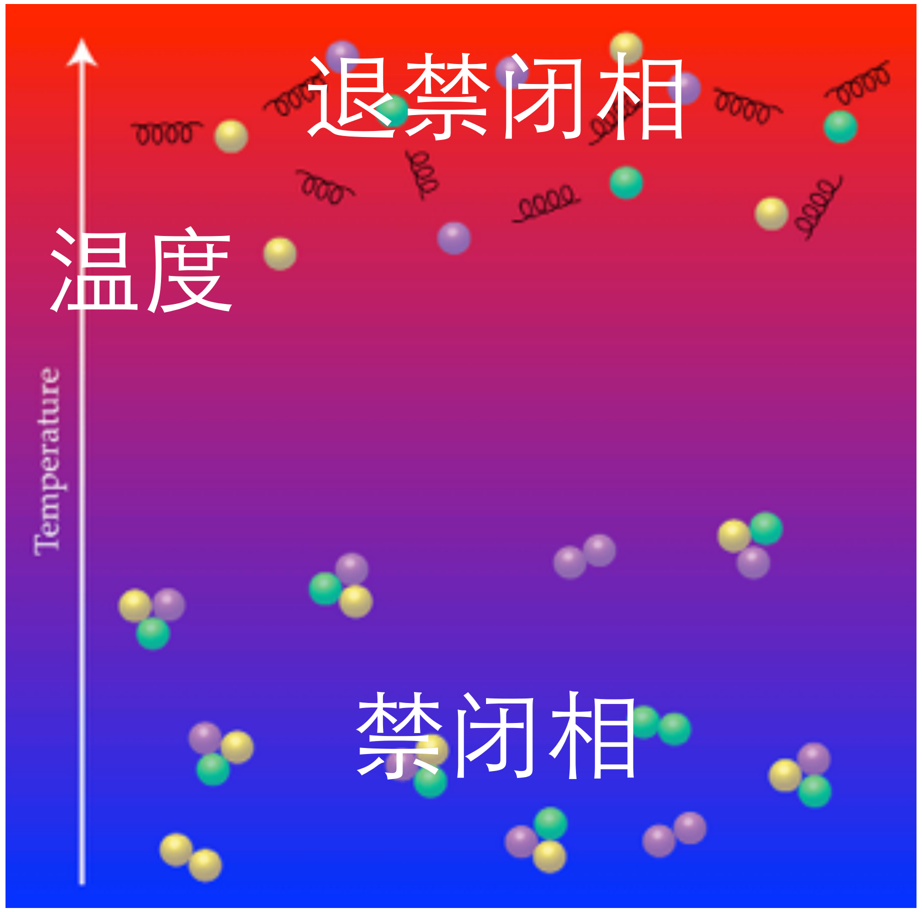


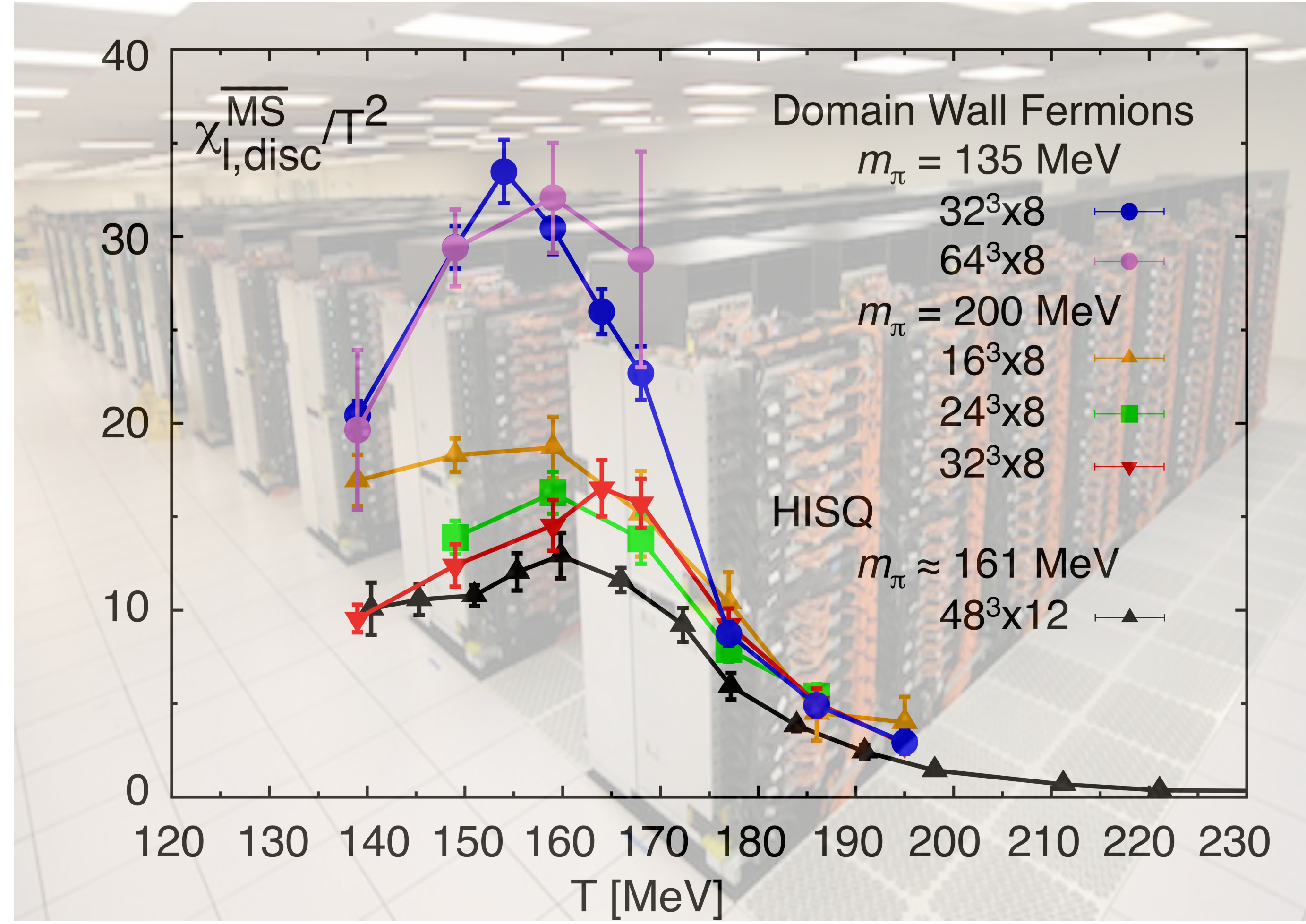
In the strange sector, the PDG-HRG based analysis give larger freeze out temperature than QM-HRG & LQCD by about 5-8 MeV

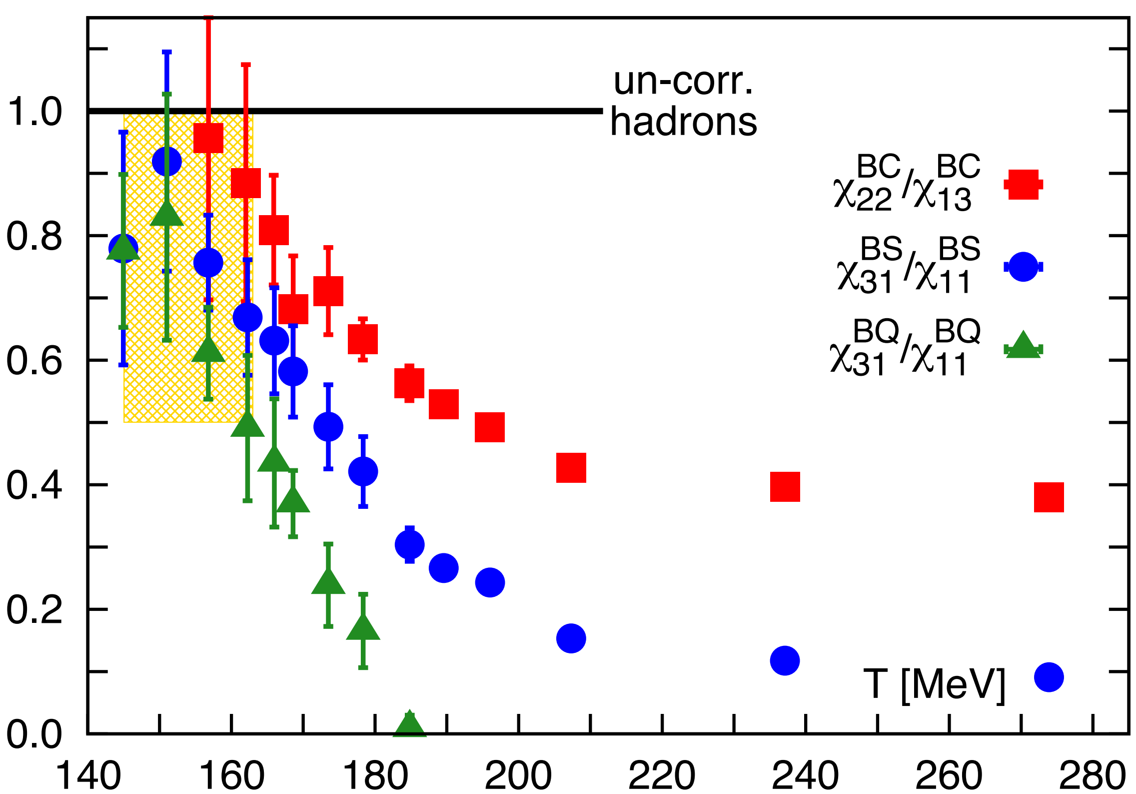
QM-HRG should be the preferable choice to determine freeze out temperature at large μ_B where LQCD is not applicable

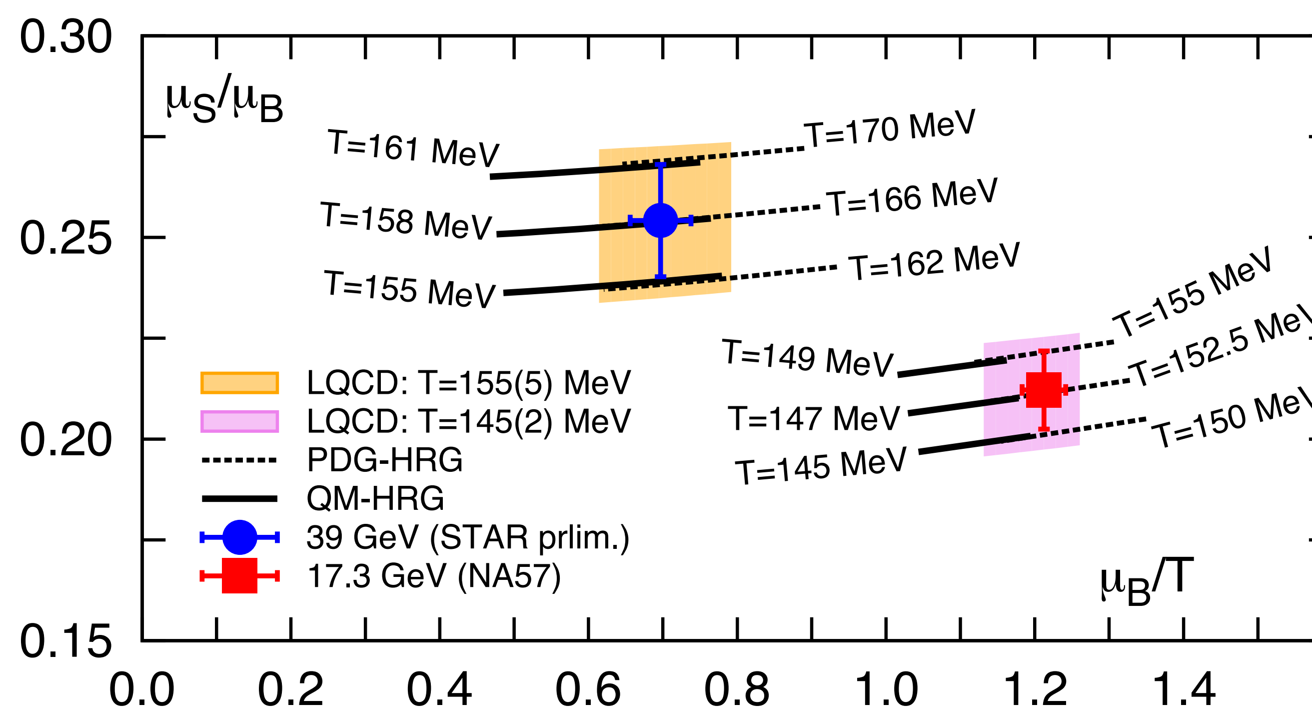
A. Bazavov et al.[BNL-Bielefeld-CCNU], Phys. Rev. Lett. 113 (2014)072001

Summary & Outlook









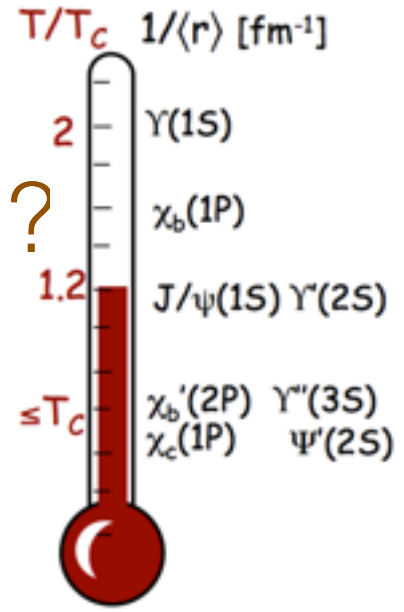
Thoughts on opportunities from high-energy nuclear collisions

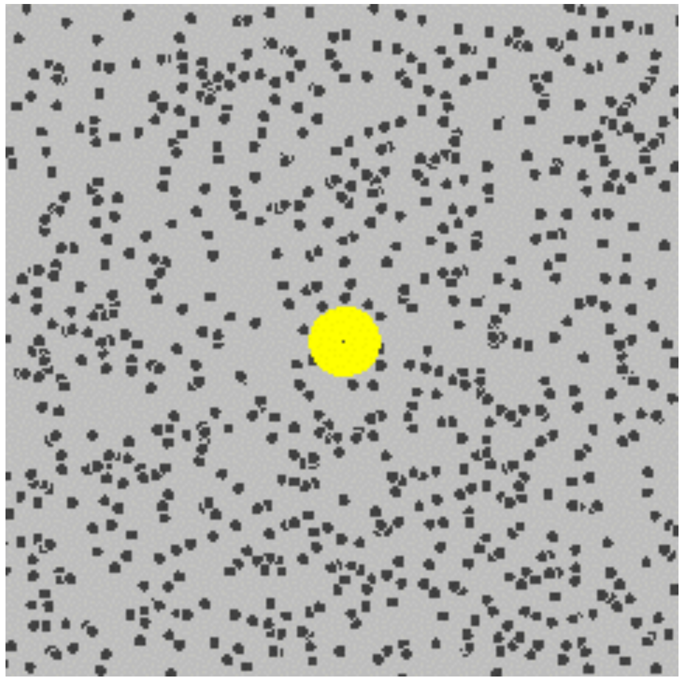
arXiv:1409.2981

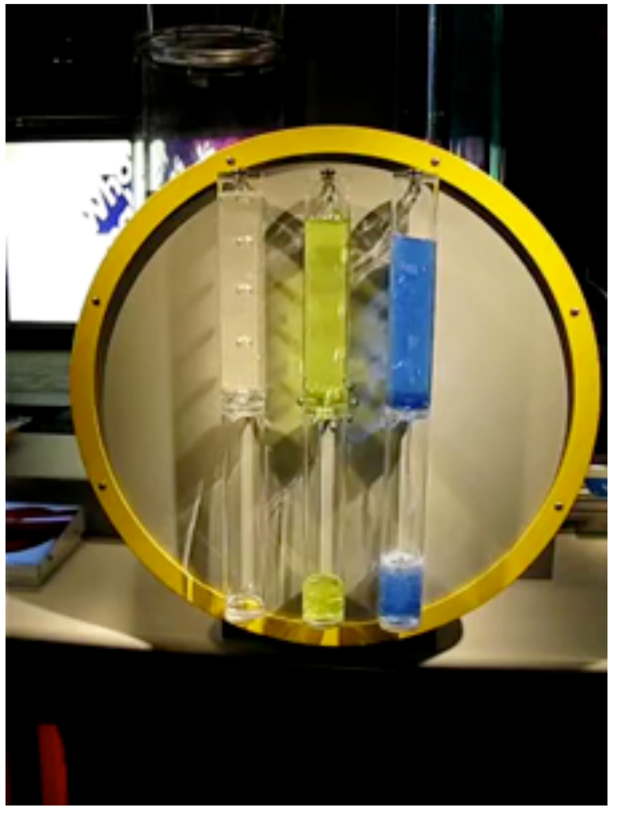
Federico Antinori, Nestor Armesto, Paolo Bartalini, René Bellwied, Peter Braun-Munzinger, Brian Cole, Andrea Dainese, Marek Gazdzicki, Paolo Giubellino, John Harris, Ulrich Heinz, Barbara Jacak, Peter Jacobs, Dmitri Kharzeev, Constantin Loizides, Silvia Masciocchi, Andreas Morsch, Berndt Mueller, Jamie Nagle, Guy Paic, Krishna Rajagopal, Gunther Roland, Karel Safarik, Jurgen Schukraft, Yves Schutz, Johanna Stachel, Peter Steinberg, Thomas Ullrich, Xin-Nian Wang, Johannes Wessels, Urs Achim Wiedemann.

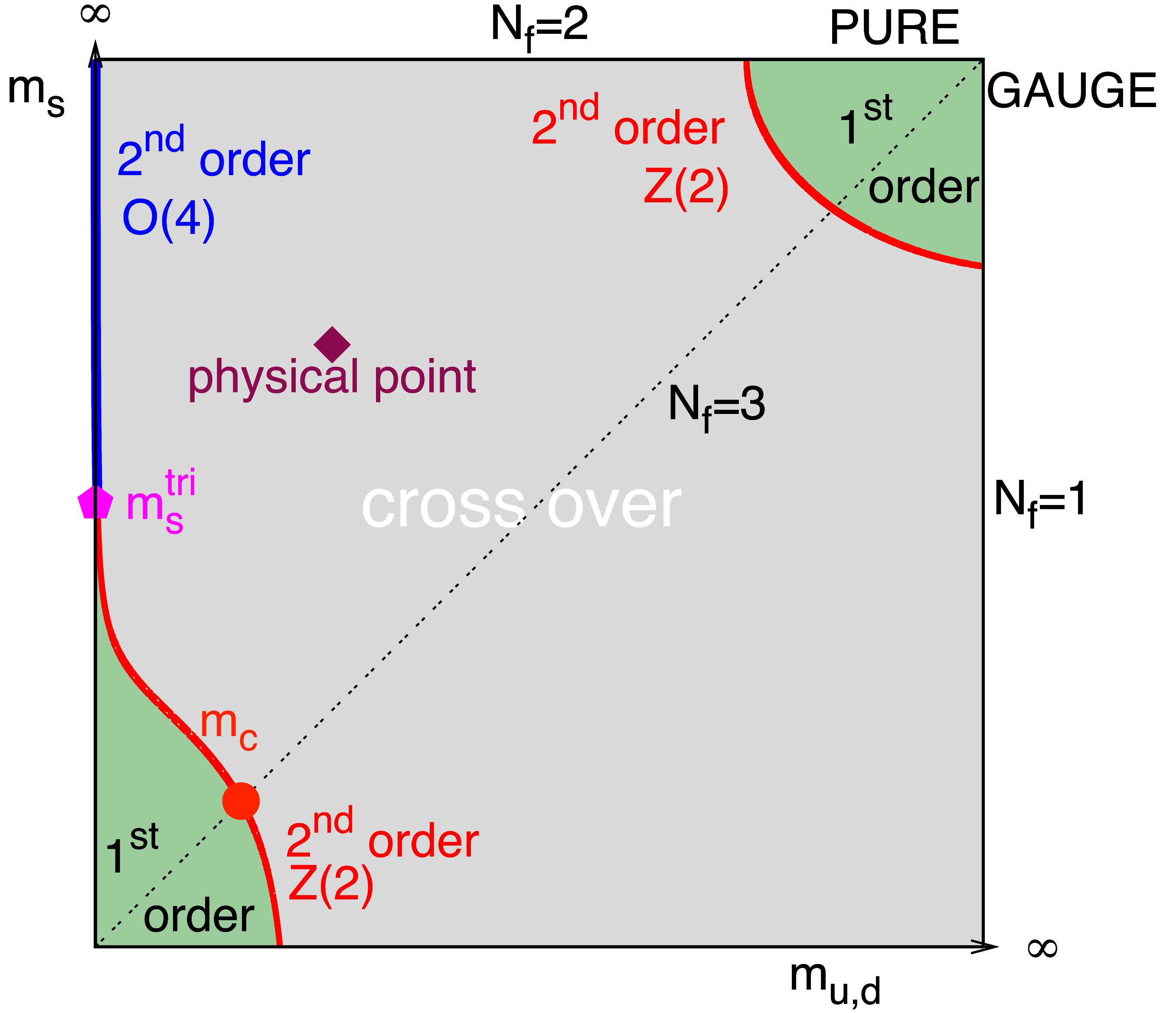
- Initial state
- Initial conditions
- Jets and heavy flavor
- Deconfinement, quarkonia and hadronization
- Phase diagram
- Collectivity and system size

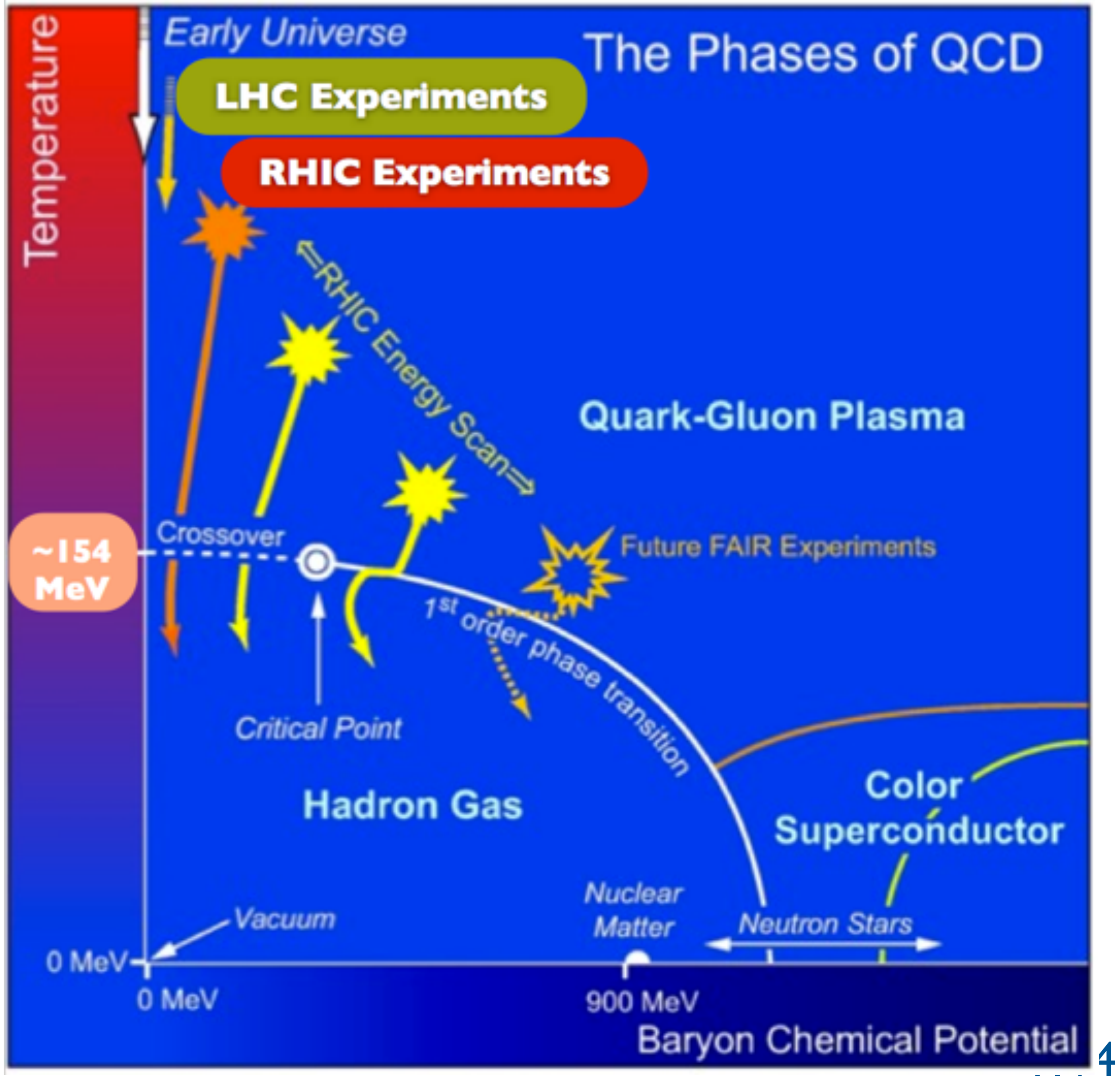
Summary & Outlook











Summary & Outlook