MATTER

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for the Indian Lattice Gauge Theory Initiative

at IIT-Roorkee

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Can the mass of this system be computed from the standard model of particle physics?

1. Protein folding and other entropic terms ≈ 1 eV
2. Binding energy of electrons ≈ 1 KeV
3. Electron rest mass ≈ 1 MeV
4. Proton mass ≈ 1 GeV

Can the answer be obtained with accuracy of about 1 part in 10^{-3}?

Does particle physics predict the Avogadro number?

$\Lambda_{\overline{\mathrm{MS}}}$, $\langle \phi \rangle$, α, $\cdots$

1. The order of magnitude and the first two to three digits should come from QCD.

2. If we get this much, then we can begin on the remainder. That involves the Higgs mechanism— which gives mass to leptons and quarks.

3. We expect that the digits after the sixth would require astronomically hard work with quantum electrodynamics or its derived theories.

The first three digits

Any method of computing this must also make other predictions which could be independently tested in experiments. Now complications rear their heads!

π, ρ, f_0, Δ, H, θ, f_B, m_s, $\delta_{I=2,L=0}$, $\cdots$

Plan of the talk

1. Brief introduction: lattice field theory as an unified computational scheme for particle physics.

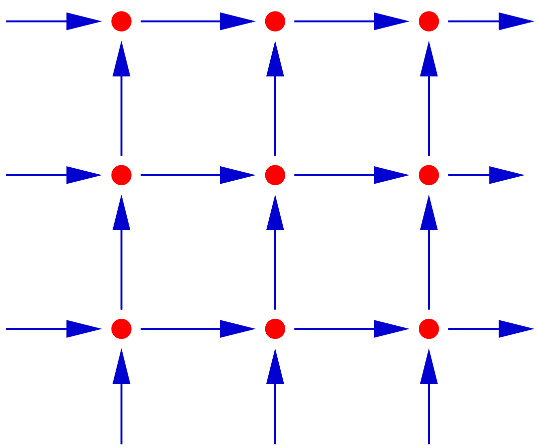
2. Orientation in particle thermodynamics: relativistic matter, its phase transitions and a rough sketch of the phase diagram.

3. New results in QCD thermodynamics: the critical point in QCD and properties of hot matter.

Collaborators: Saumen Dutta, Rajiv Gavai, Robert Lacaze, Pushan Majumdar, Manu Mathur, Swagato Mukherjee, Rajarshi Ray.

Machines: 486, Pentiums, SGI Origin, DEC α, NEC SV5, CRAY X1

Lattice Quantum Field Theory



Gauge action = product of gauge fields around a square (Wilson, Symanzik)
Scalar action = product of fields at neighbouring sites (Higgs, Ising)
Matter action = a discretization of the Dirac equation (Wilson, Kogut and Susskind, Naik, Kaplan, Neuberger and Narayanan, $\cdots$)
Estimate partition functions—

$$Z = \int dU \, d\psi d\overline{\psi} \, \mathrm{e}^{-S}.$$

Doing Lattice Quantum Field Theory

Creutz (1980)

Monte Carlo procedure used for the integration, *i.e.*, the average over all configurations of fields. Works only when the integrand is non-negative. We will eventually be interested in the case of complex integrands.

Requires solving Dirac equation repeatedly. Easiest run: 4×12^3 lattice ($2T_c$), Dirac equation solved once in 160 s on DEC α and 6 s on CRAY X1. Need around 7×10^4 solutions (about 11 α days; 11 CRAY hours) to get one point on a curve. Typical run actually much harder, but speeds up more on the CRAY.

A discretized differential equation is a matrix. Solving the Dirac equation is equivalent to inverting a matrix. Amount of time this requires increases with the density of eigenvalues near zero (condition number). But

$$\langle\overline{\psi}\psi\rangle = \frac{1}{\pi}\rho(0) \qquad \text{(Banks-Casher formula)}$$

Solving the Dirac equation is a genuinely hard process.

Solving Quantum Field Theory

The **I**ndian **L**attice **G**auge **T**heory **I**nitiative

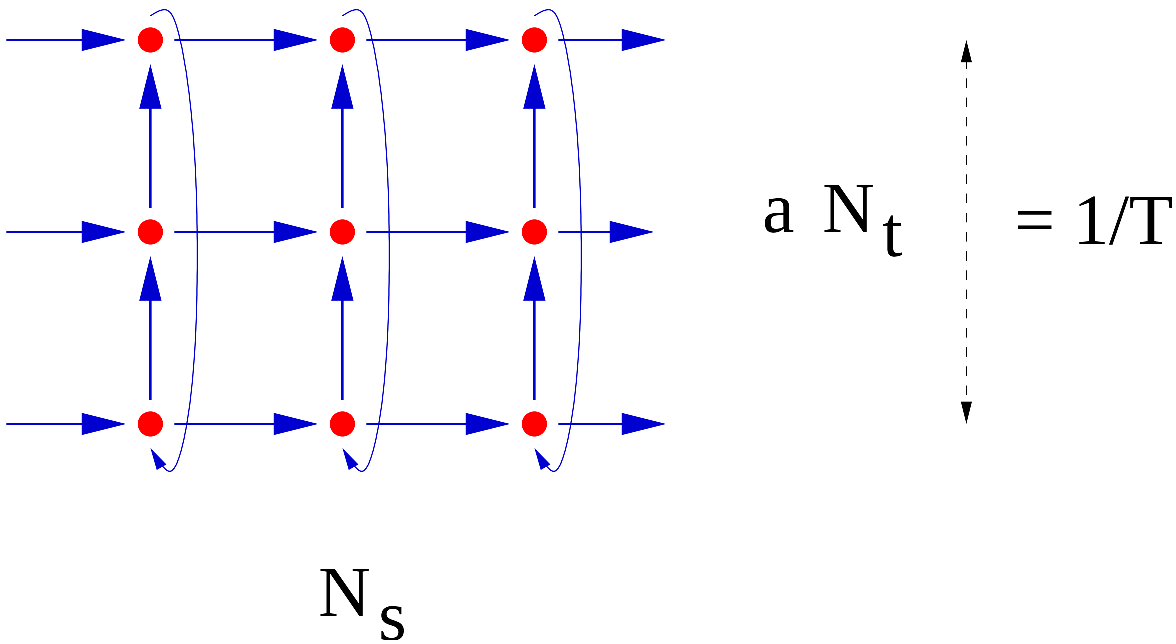
Relativistic Quantum Field Thermodynamics

$P(T, \{\mu\})$

Mass is not conserved $\Rightarrow$ particle number not conserved. (Example: photon gas).

μ needs conservation law

A chemical potential can be introduced for every conserved quantum number. (Examples: net particle number, electrical charge, hypercharge)



What we know of high T QCD matter

Theory: It is a plasma

Overall charge/colour neutrality— Debye screening, Landau damping.
Probes: all quantitative— need to measure correlations between fluctuations and viscosities or other dissipative response functions.

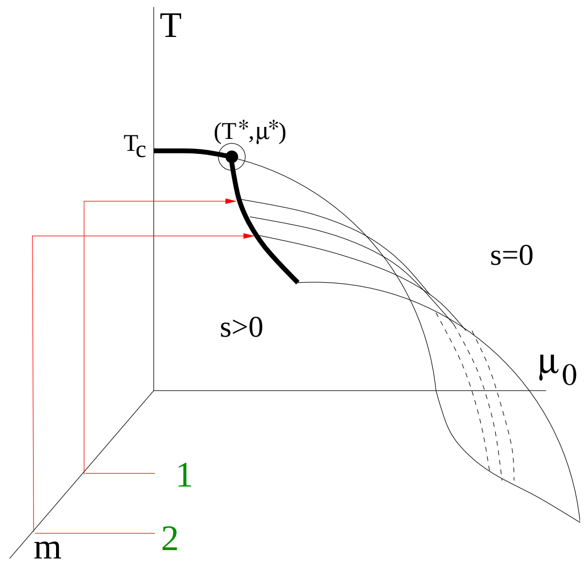
Theory: It is a weakly dissipative fluid

Small viscosity, small correlation lengths.
Consequences: many qualitative— probes lose momentum quickly (jet quenching?), early thermalization, independent fluctuations, speed of sound, etc.

Experiment: It is a weakly dissipative fluid

Heavy-ion collisions observe nearly ideal collective flow and jet quenching

Phase diagrams of QCD: older results

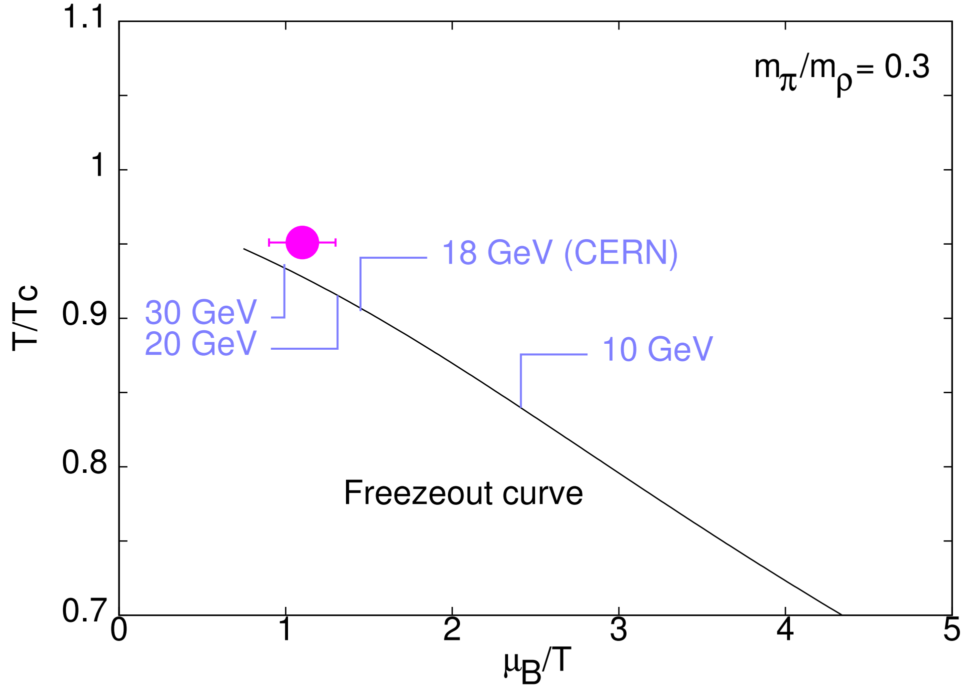


1. **Fodor and Katz (2000)** $m_\pi/m_\rho = 0.185(2)$, $m_\rho/T_c = 5.372(5)$, $Lm_\pi = 3.1$–3.9
2. **Allton et al (2003)** $m_\pi/m_\rho = 0.70(1)$, $m_\rho/T_c = 5.5(1)$, $Lm_\pi = 15.4(5)$

Compensation between m_π dependence and L dependence: accidental?

Berges and Rajagopal, Halasz, Jackson, Shrock, Stephanov and Verbaarschot: (1998)

The phase diagram of QCD



$$T/T_c \approx 0.95,\ \mu_B/T \approx 1.1$$

Small quark mass, large volumes— **Gavai and Gupta, hep-lat/0412035**

Extra dimensions in the phase diagram

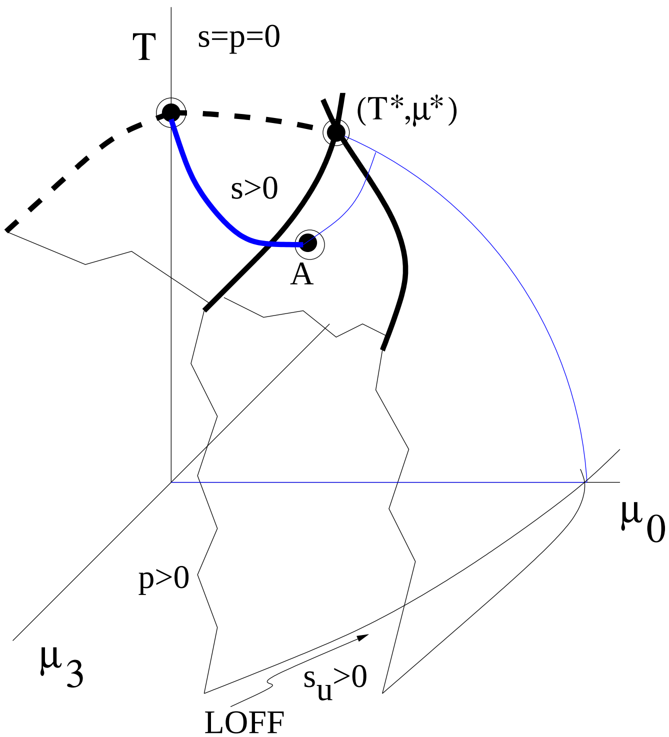
5 parameters for $N_f = 2$:
T, $\mu_0 = (\mu_u + \mu_d)/2 = \mu_B/3$, $\mu_3 = (\mu_u - \mu_d)/2 = \mu_I$, $m = (m_u + m_d)/2$, $\Delta m = m_u - m_d$.

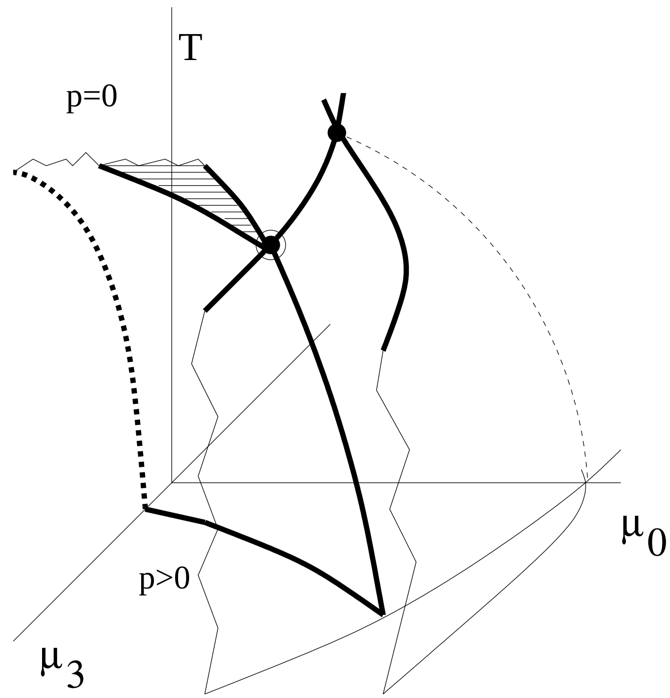
7 parameters for $N_f = 2 + 1$:
T, μ_B, μ_I, μ_Y (μ_s), m, Δm, m_s.

Partial exploration of the phase diagram:
Son and Stephanov (2000), Klein Toublan and Verbaarschot (2003), Nishida (2003), Barducci, Casalbuoni, Pettini and Ravagli (2004)

Gibbs phase rule predicts complex phase diagram.

The phase diagram of QCD (4)

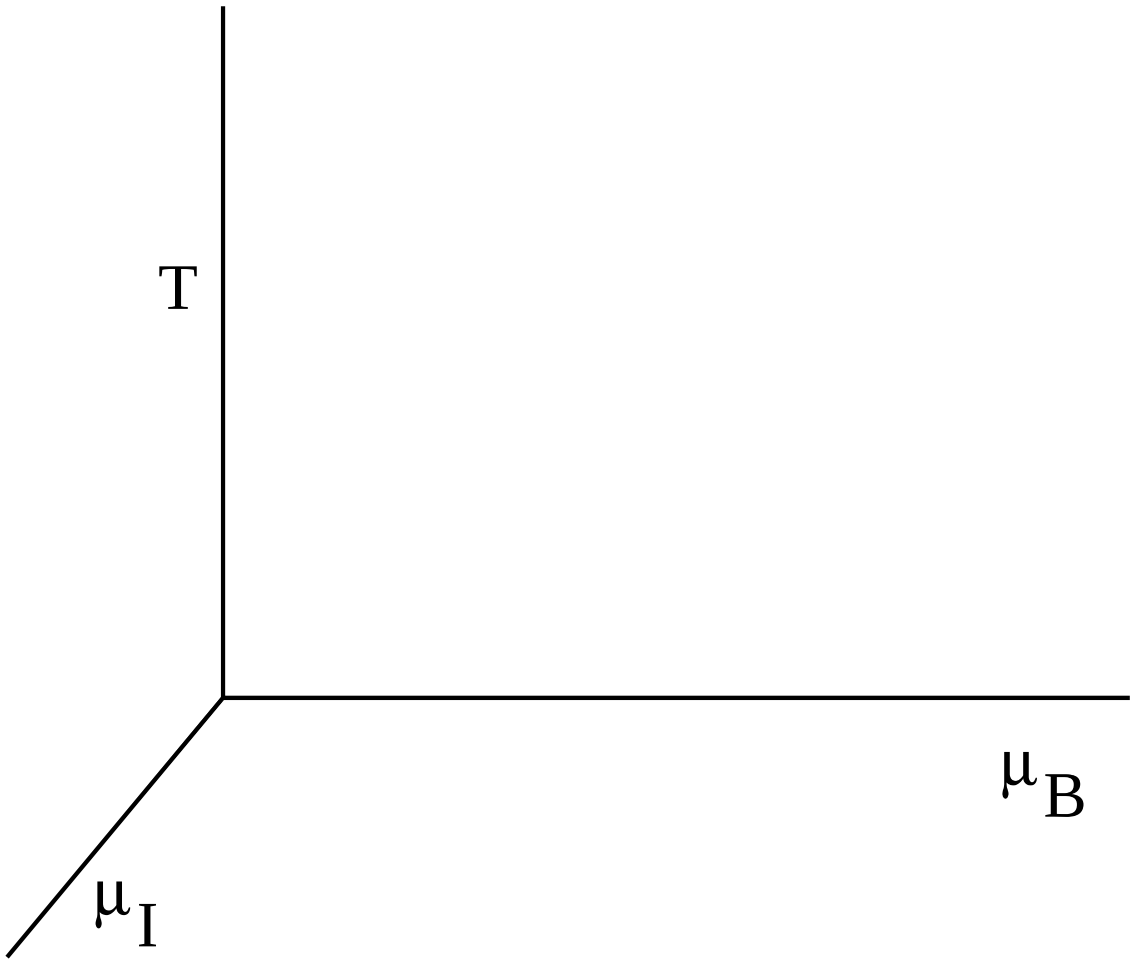




(T^*, μ^*)— penta-critical point (earlier called tri-critical: only for $m_u = m_d =$)
A— tri-critical point (remains for arbitrary m_u and m_d).

SG and R. Ray, in progress

Experimental probes of the thermodynamics of QCD



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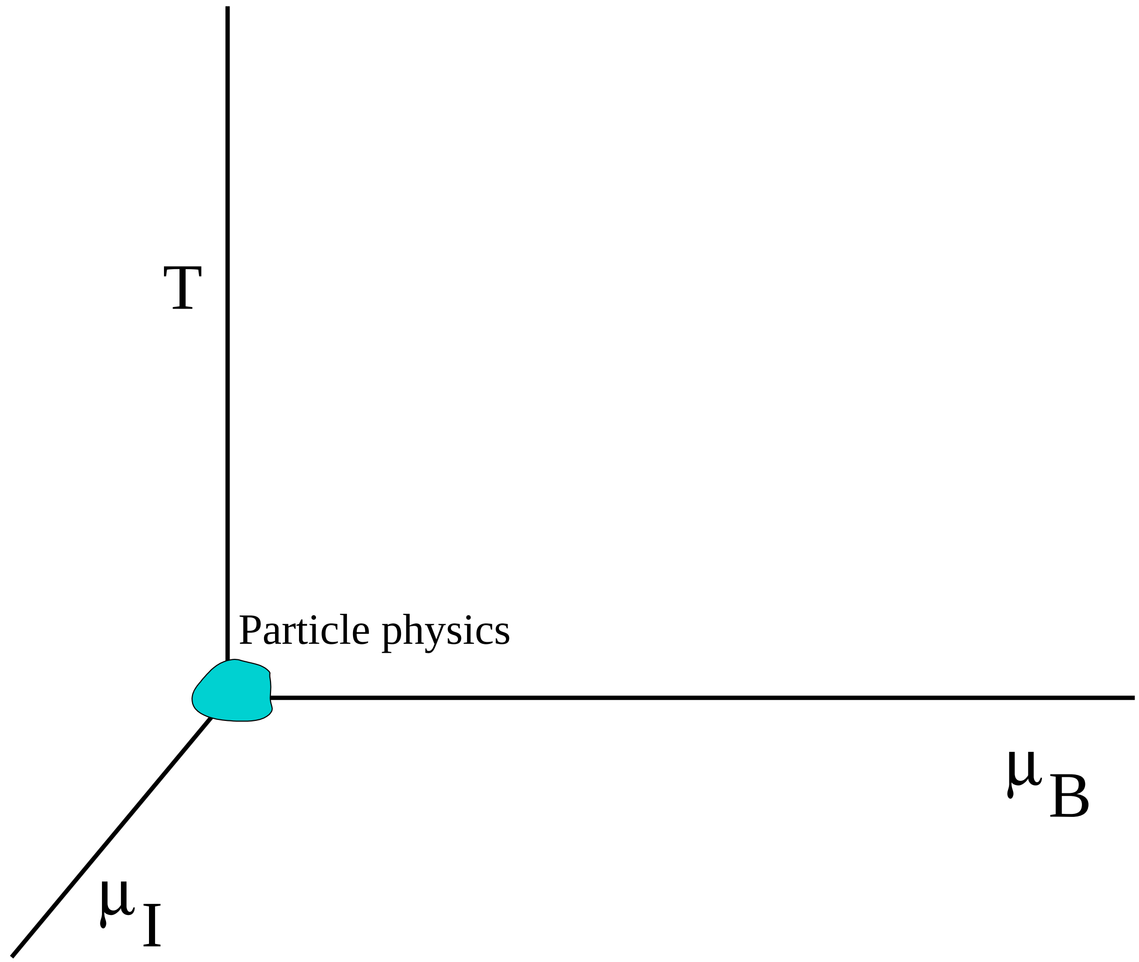

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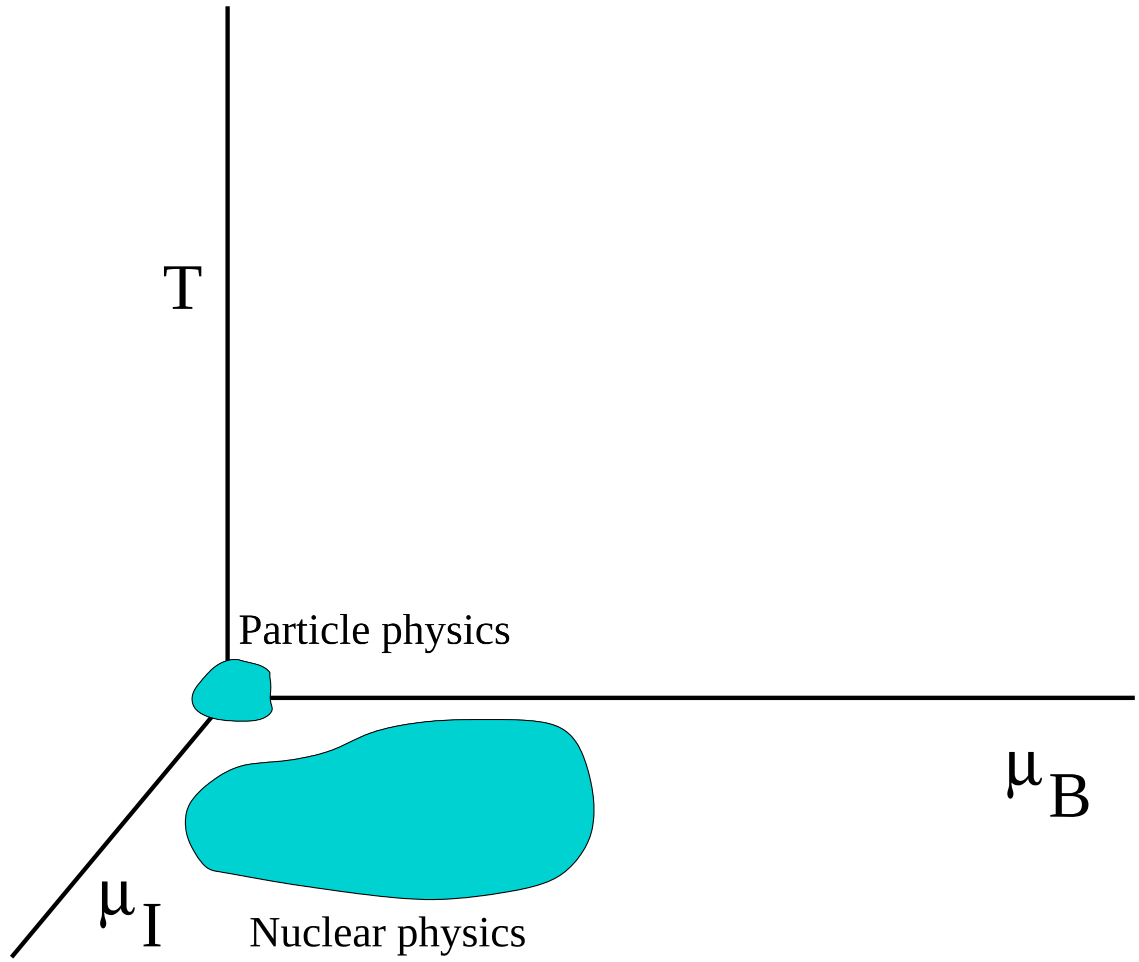

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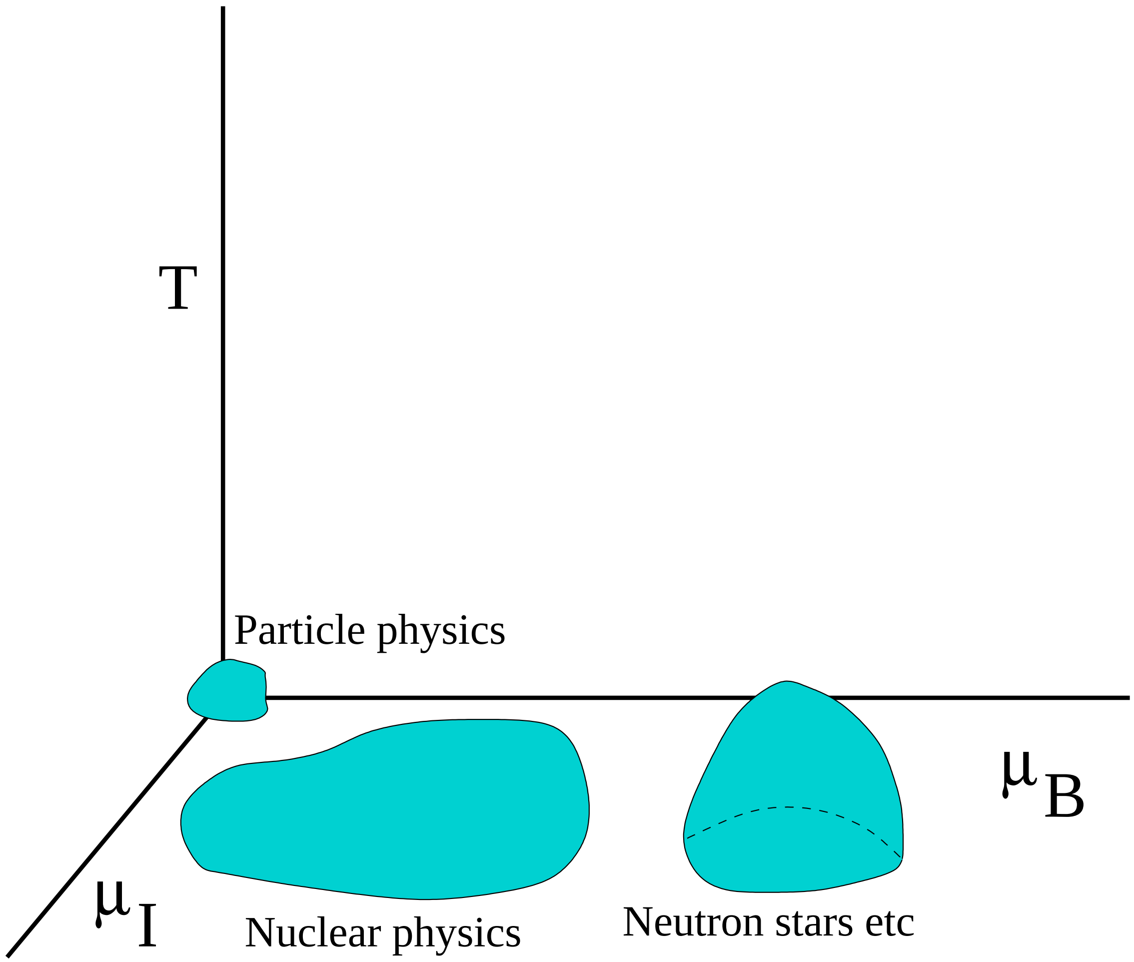

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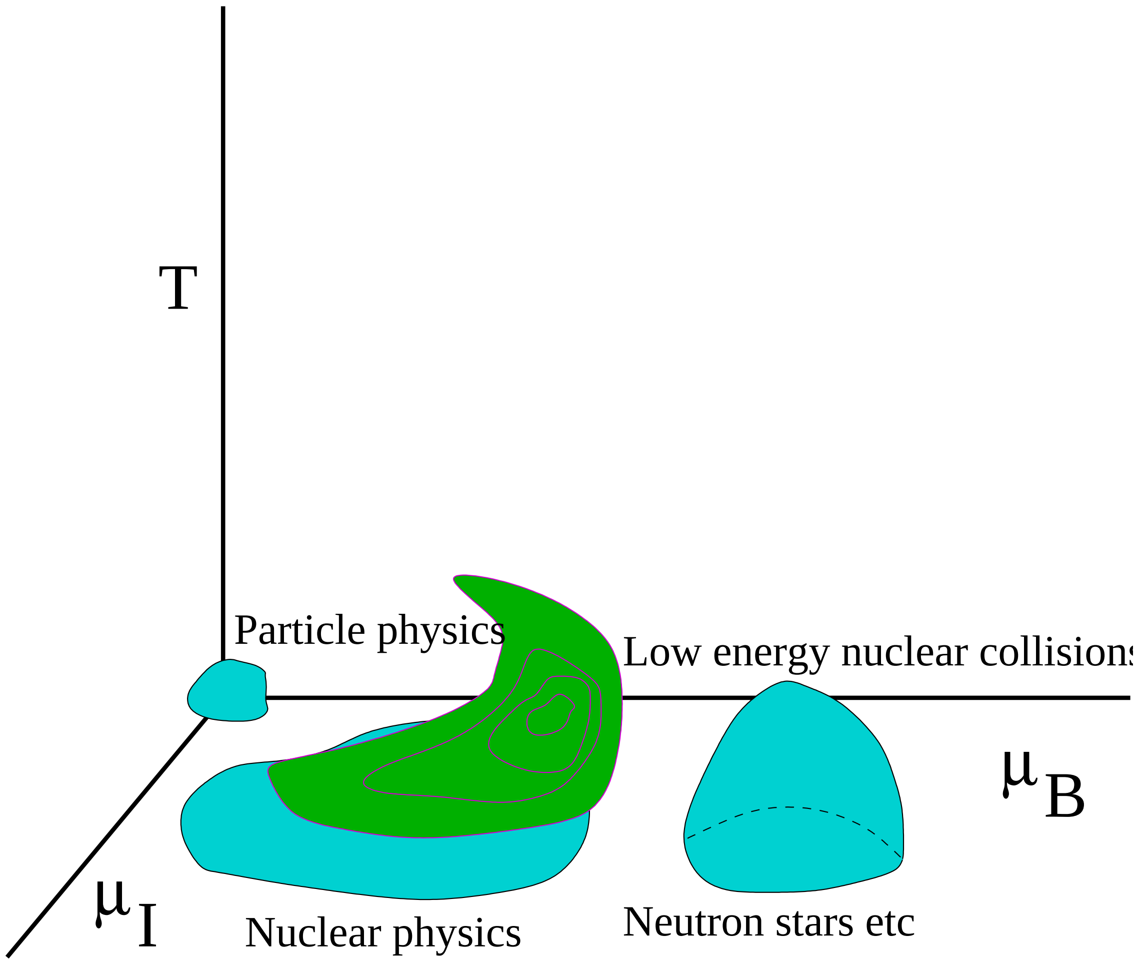

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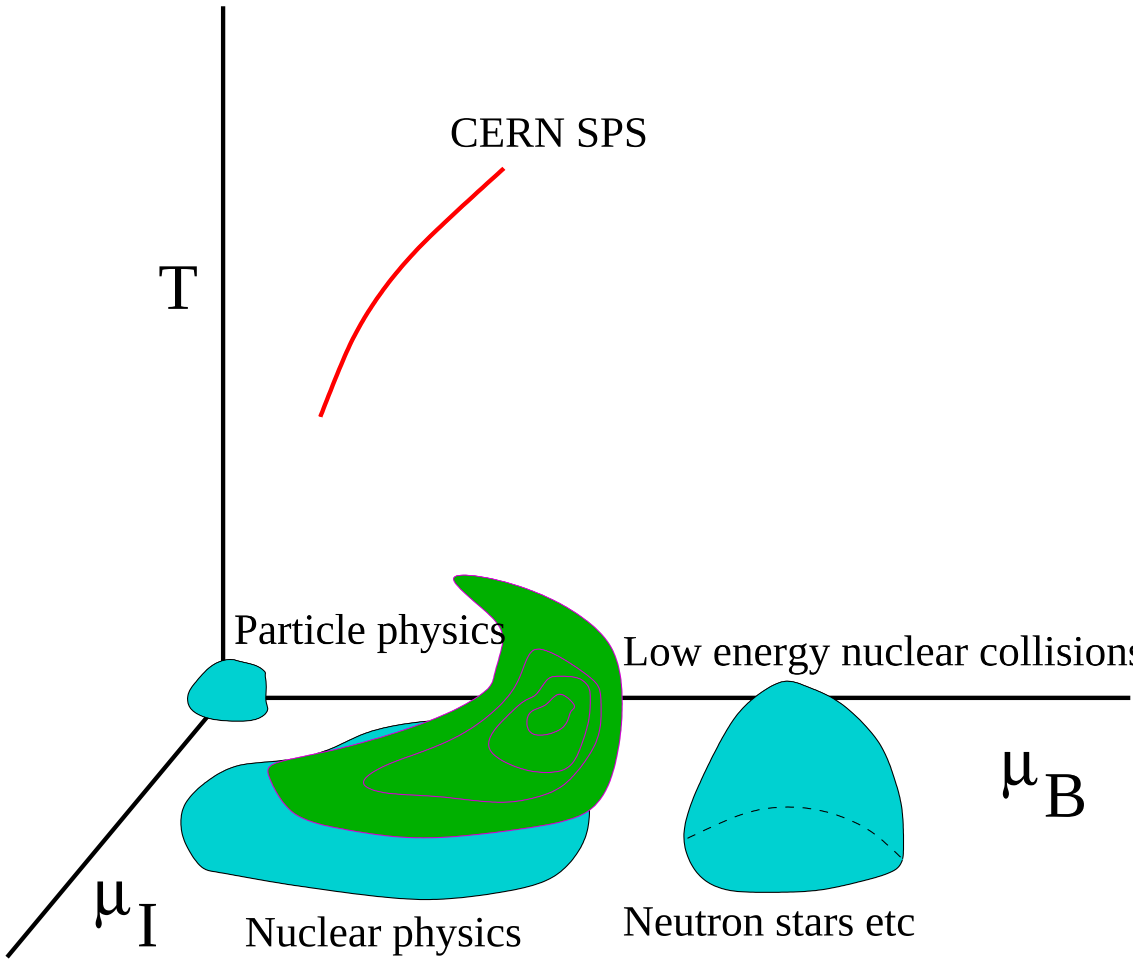

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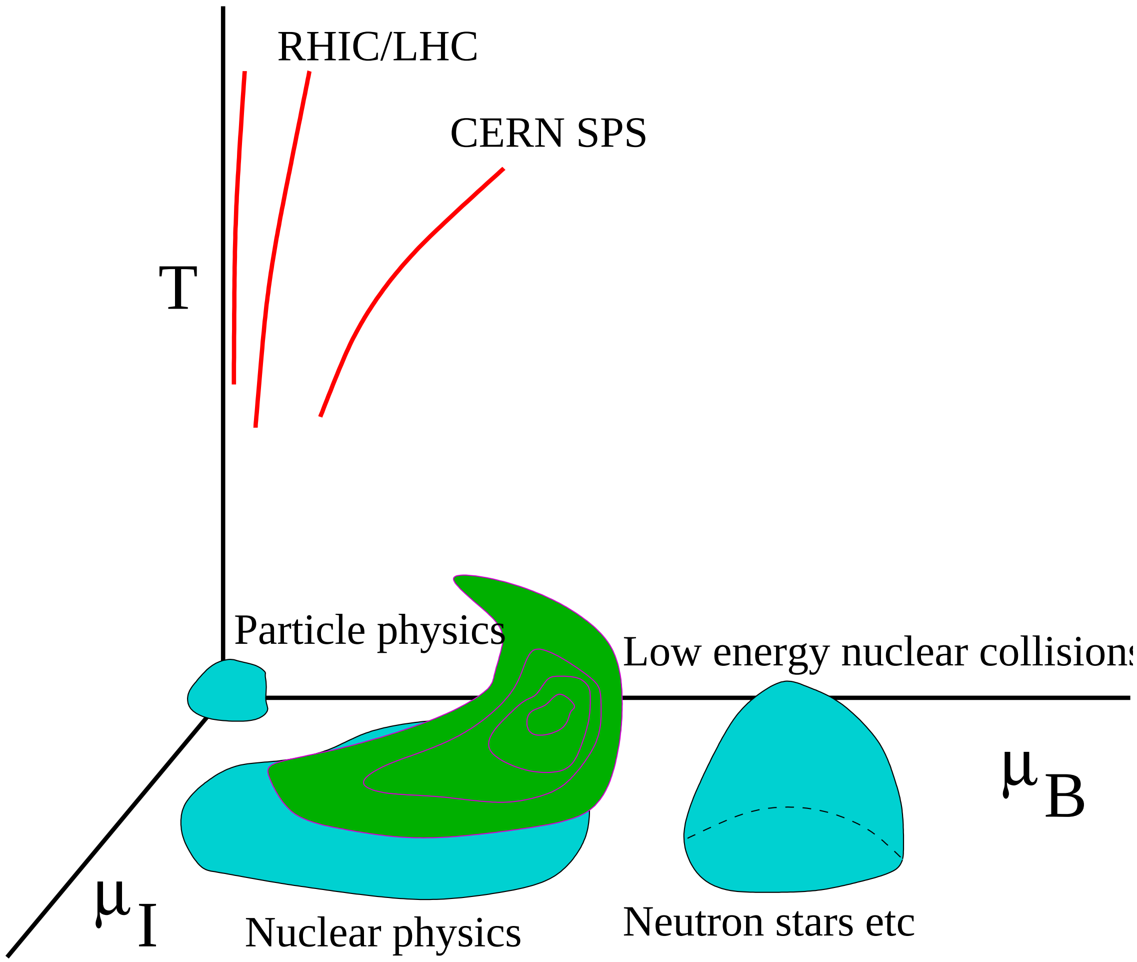

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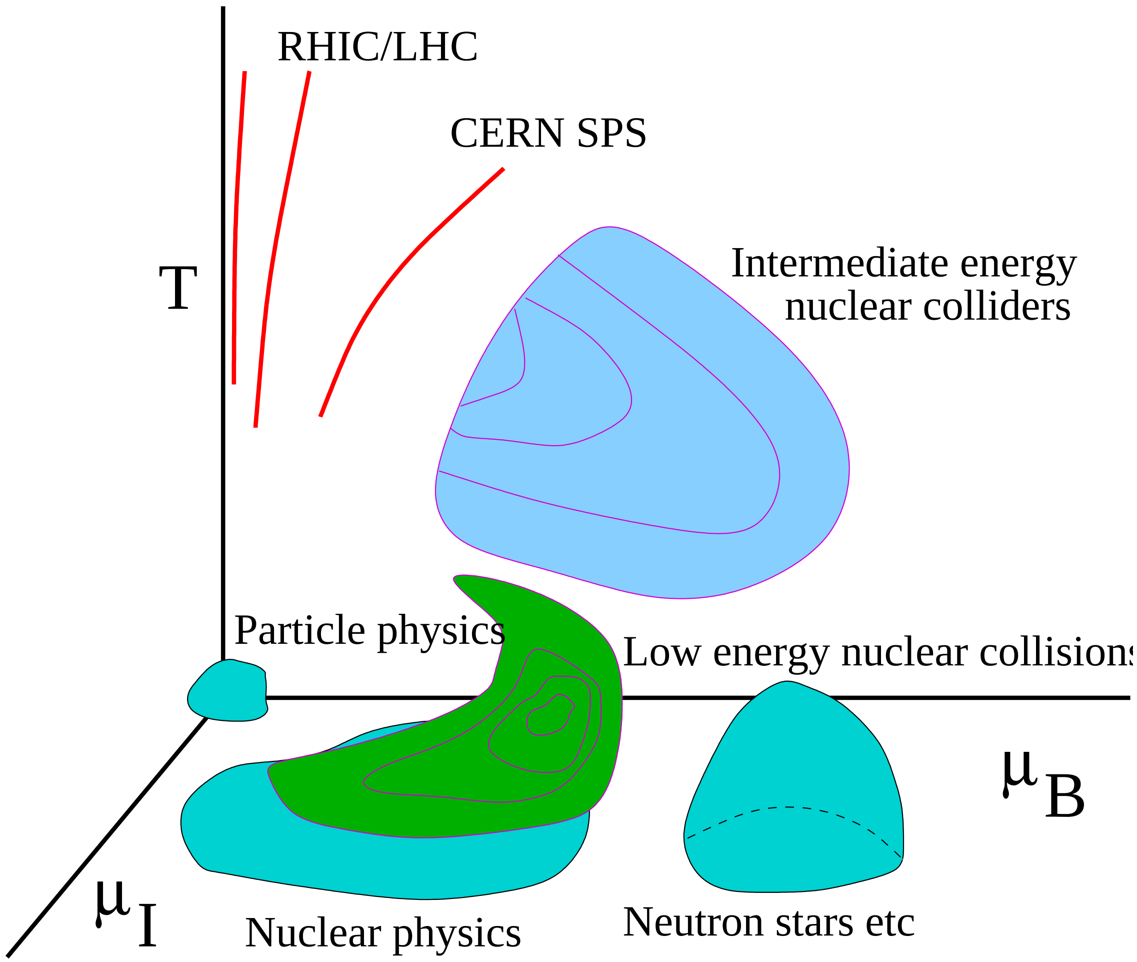


Other recent results

1. Improving the approach to the continuum limit: Datta, Gavai, Mathur

2. The continuum limit and precise determinations of the $\mu = 0$ transition ($T_c/\Lambda_{\overline{\rm MS}} = 1.05 \pm 0.05$ in quenched QCD) or crossover ($T_c/\Lambda_{\overline{\rm MS}} = 0.45 \pm 0.05$ in $N_f = 2$ QCD). SG; Bielefeld, QCDPAX

3. Screening phenomena Datta, Gavai, Lacaze, SG; almost every lattice group in the world since 1988 What are the quasiparticles in the high temperature phase? Datta, SG

4. Transport properties— electrical conductivity and estimate of shear viscosity. SG

5. Bulk properties— EOS: Bielefeld, QCDPAX. Specific heats, bulk compressibility, speed of sound (quantifying departure from conformal theories): Gavai, Mukherjee, SG

Future plans

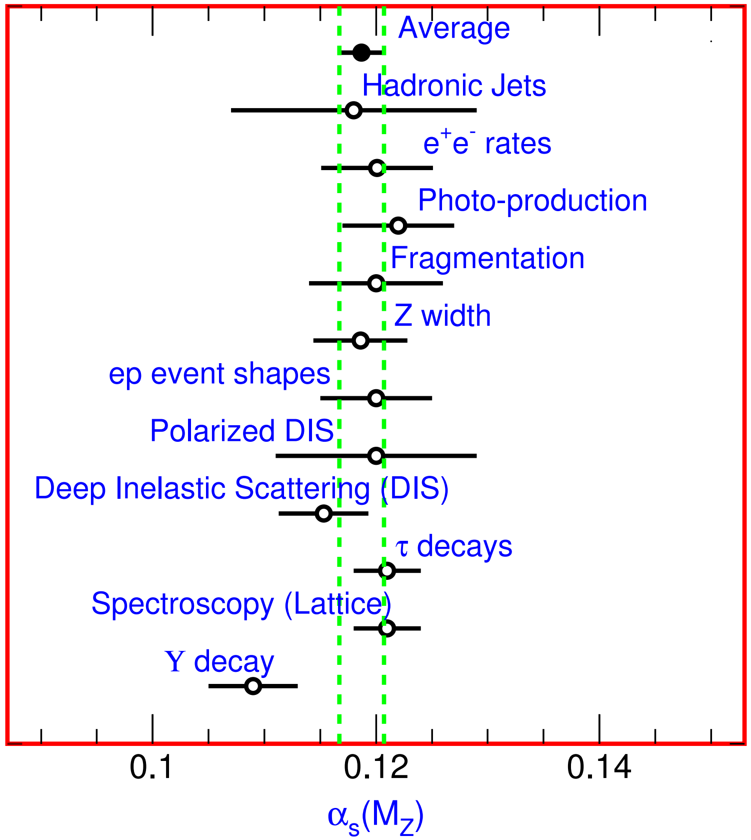
1. Continuum limit of the phase diagram: computational load increases by factor of $(1.5^5 + 2^5) \approx 40$. Other physics comes simultaneously: fluctuation probes in heavy-ion collisions, chemical equilibration, *etc*. Library of configurations open to full collaboration.

2. Chiral limit using chiral fermions: computational load is immense but high payoff likely. Scattered preliminary studies taking place. Much scope for work.

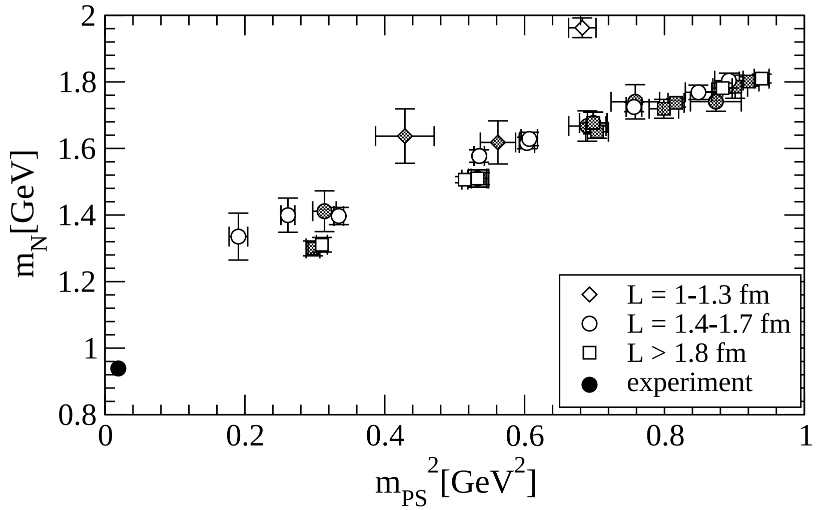
3. EOS, quasiparticles at finite μ, viscosity, $\cdots$ Enormous number of (relatively) low cost projects can be run very fast even as the colliders collect data. Realize the TIFR group's long term project of using the lattice as a tool for phenomenology of heavy-ion physics.

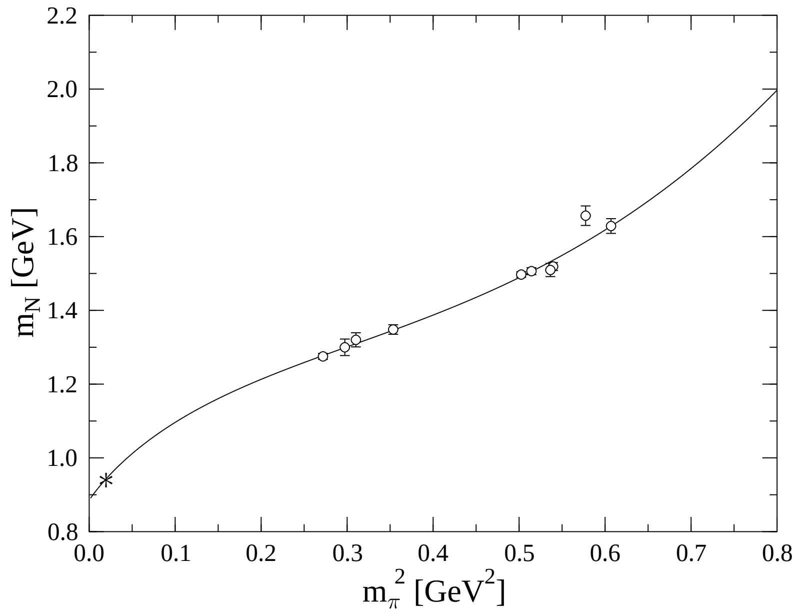
`http://theory.tifr.res.in/~sgupta/ilgti/`

The origin of mass: $\Lambda_{\overline{\rm MS}}$



The proton mass





UKQCD-QCDSF hep-lat/0312030, hep-lat/0312029