QCD medium

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Outline

QCD medium in colliders

QCD in the early universe is about a medium in thermal equilibrium: expansion rate much smaller than response time of the medium. So adiabatic expansion: ideal fluid dynamics. Easy application of lattice computations of thermodynamics and phase diagram: QGP to hadron phase crossover.

QCD in heavy-ion collisions more interesting: expansion rate not far separated from response times. So fluid dynamics involves dissipation and other out-of-equilibrium physics. Finite size and lifetime requires more detailed understanding of fluctuations around equilibrium: lattice and effective theories.

Other talks

QCD matter	Hydrodynamics+
S. Dutta	J-Y. Ollitrault
R. Sharma	S. Pal
A. Islam	C. Chattopadhyaya
	A. Jaiswal
	V. Roy

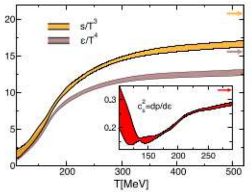
Outline

Introduction

QCD medium

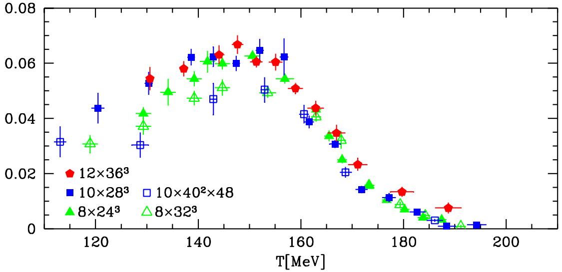
Heavy Ion Collisions

Crossover at finite temperature



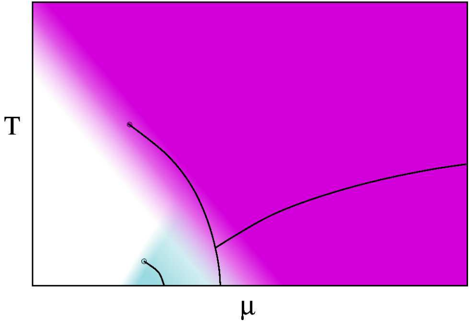
Susceptibilities should diverge or be discontinuous at a phase transition. Instead a gradual change over a range of 20 MeV.

Borsanyi et al, 2014



Aoki et al, 0903.4155

The phase diagram of QCD

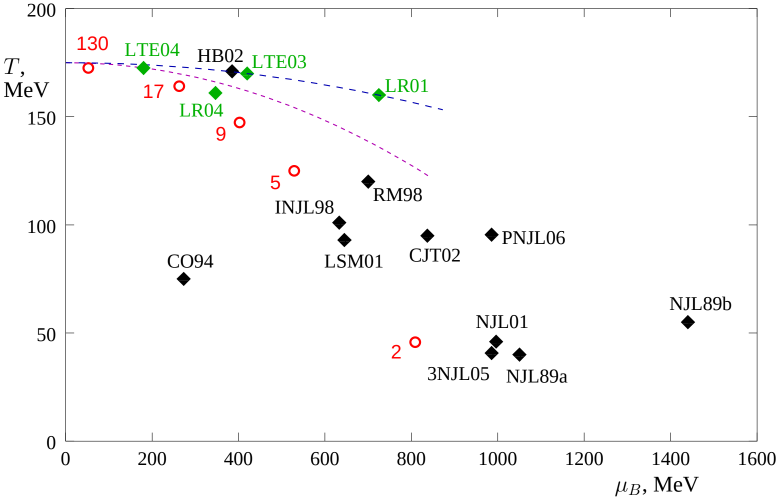


Baryon number is conserved in QCD; so a chemical potential μ: fairly generic phase diagram. Best estimate of the critical point today:

$$\frac{\mu_E}{T_E} = 1.8 \pm 0.2 \qquad \frac{T_E}{T_c} = 0.94 \pm 0.02$$

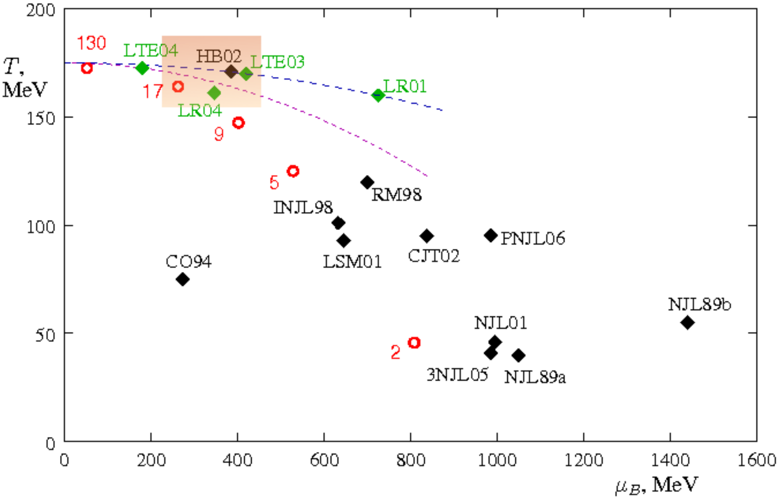
(ILGTI) Datta, Gavai, SG: 2016

Phase diagram: QCD critical point



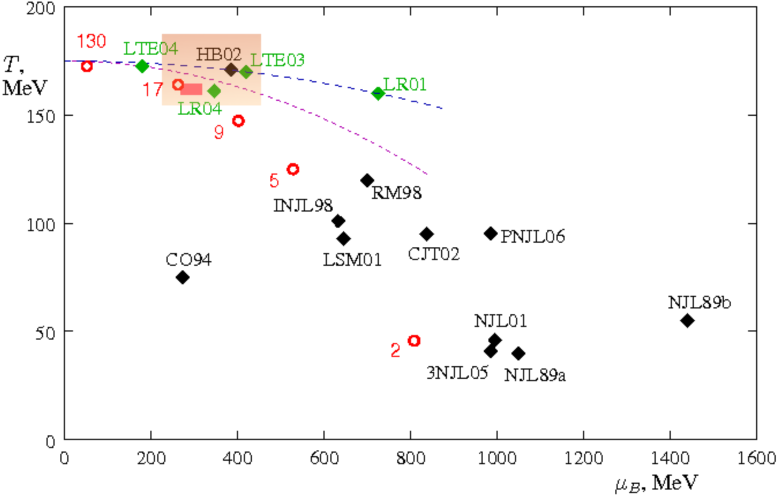
Stephanov: Lattice 2006

Phase diagram: QCD critical point



SG: Quark Matter 2011

Phase diagram: QCD critical point



2017-18

Effective (thermal) field theory

SG and Sharma, arXiv:1710.05345

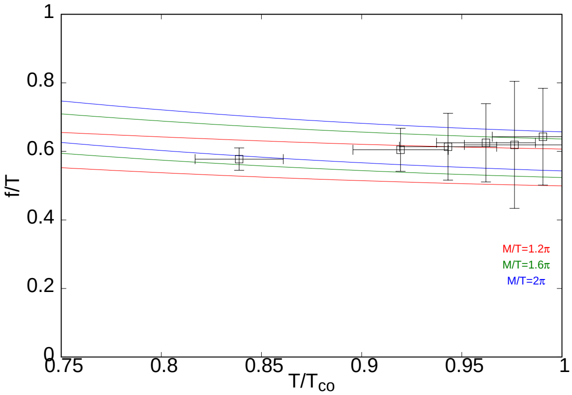
Typical momentum in a thermal medium: T. Low-energy theory implies $p \ll T$. So full equation of state is out of reach, but correlations and transport may be computed.

Particles are relativistic ($E \gg m$ or $m = 0$). But presence of a heat bath means no Lorentz invariance. Immediate consequence

$$\mathcal{L} = m\overline{\psi}\psi + \overline{\psi}\partial\!\!\!/_0\psi + u\overline{\psi}\partial\!\!\!/_i\psi + \cdots$$

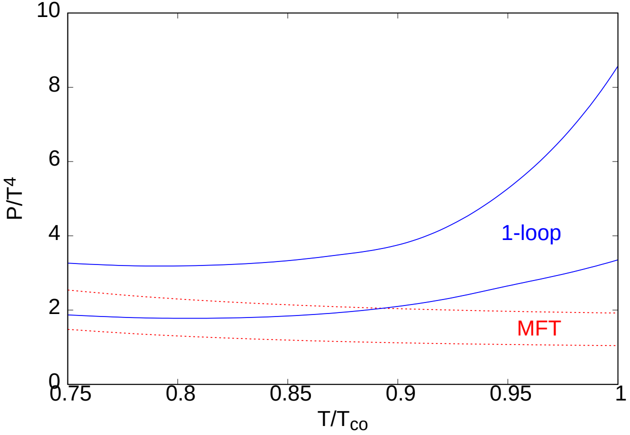
Difference between screening mass (static correlators) and pole mass (causal correlators). Very large number of couplings in the EFT, but can be fixed by matching to lattice results.

Inputs and outputs



Fit T_c get the chiral critical point. Fit pion screening propagator at one temperature. Get screening mass, pion velocity, pion "decay constant" and pion 4-point coupling and its T-dependence.

A qualitative lesson



A rise in the contribution of the EFT to the pressure near the QCD cross over is a robust prediction.

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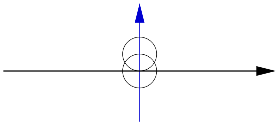
Heavy Ion Collisions

Azimuthal anisotropy = flow

In collisions of elementary particles there is only one vector in the initial state: the direction of motion. Symmetry in the transverse plane, so no azimuthal angle dependence.

$$v_n = \langle \cos n\phi \rangle \,.$$

Azimuthal anisotropy = flow

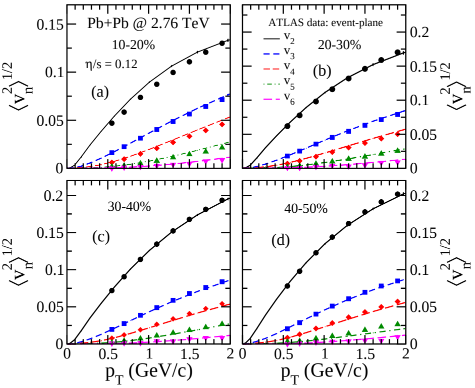


In collisions of extended particles, there are two vectors in the initial state: the direction of motion and the line joining the centers. So the particle yield has ϕ dependence.

$$v_n = \langle \cos n\phi \rangle \, .$$

Fluctuations explain flow

Chattopadhyay, Bhalerao, Ollitrault, Pal, arXiv:1710:03050

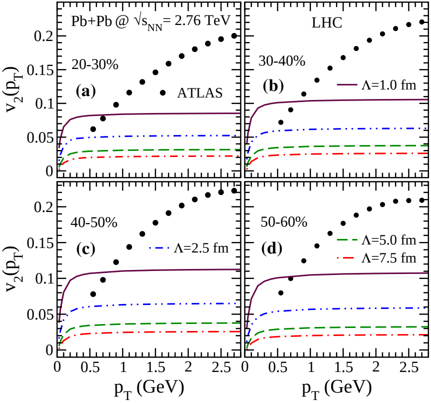


Initial state fluctuations, pre-equilibrium dynamics using AMPT, followed by viscous hydrodynamics.

Effect of freezeout on flow

Jaiswal and Bhaduri, arxiv:1712.02707

Cooper-Frye freeze-out prescription modified to account for anisotropic escape probability: $P_{esc} = \exp(-\int \rho\sigma dl)$.

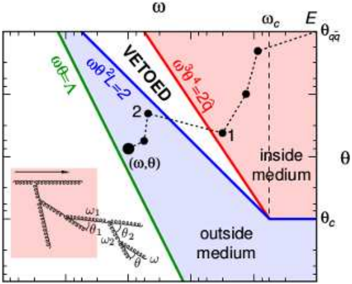


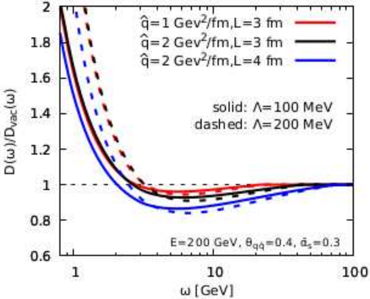
Here $\Lambda = 1/\sigma$.

Jet fragmentation in Pb+Pb collisions

Caucal, Iancu, Mueller, and Soyez, arXiv:1801:09703

- Pb+Pb collisions at the LHC ⇒ hot partonic medium: QGP
- In-medium interactions modify jet fragmentation to partons
- Vacuum-like parton cascades occur very fast and can be factorized (in time) from the medium-induced cascades





As compared to the vacuum case, one sees enhancement at small energies and slight depletion at intermediate energies.

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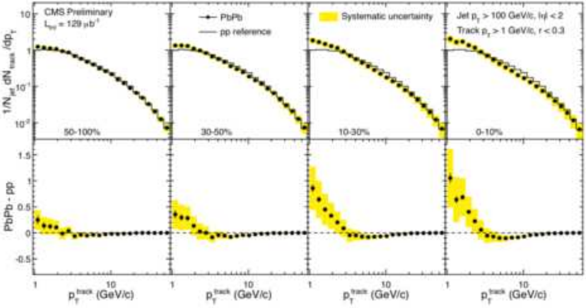

Good agreement with the data ! (first in perturbative QCD)