Chiral perturbation theory at finite isospin

Quark and pion condensation

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Outline

- Introduce our research objective
- Introduce Chiral Perturbation theory
- Present some of my work
- Present some of my recent results
- Outlook
- Questions

Introduction

- QCD with $N_f = 2, \quad (f = u, d)$.
- Chemical potentials μ_u and μ_d, or equivalently $\mu_B = \frac{1}{2}(\mu_u + \mu_d)$ and $\mu_I = \frac{1}{2}(\mu_u - \mu_d)$.
- We consider $\mu_B = 0$ and $\mu_I > 0$.
- This regime does not have a fermion sign problem, and provides a playground for comparing QCD models and effective theories with first principle lattice calculations.

Introduction

- A possible scenario for the phase diagram is shown below.
- We focus on the BEC, and the transition to the BEC.

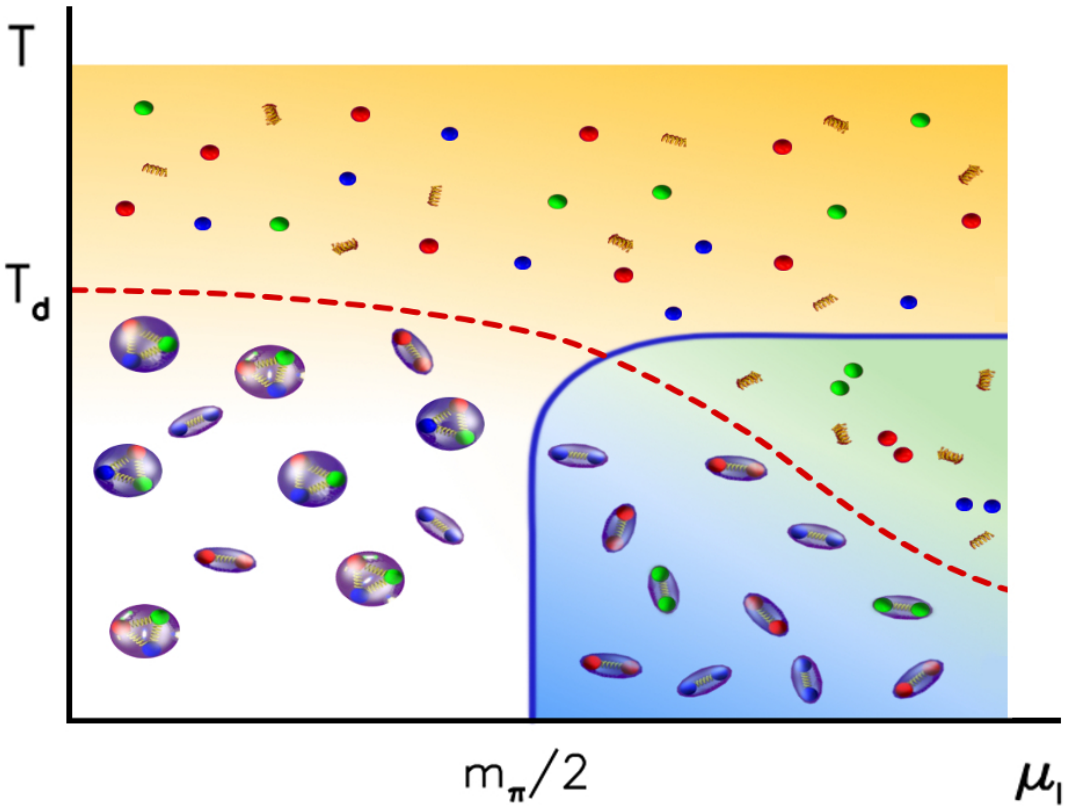


Figure: Figure from Ref.[1], used with author's permission.

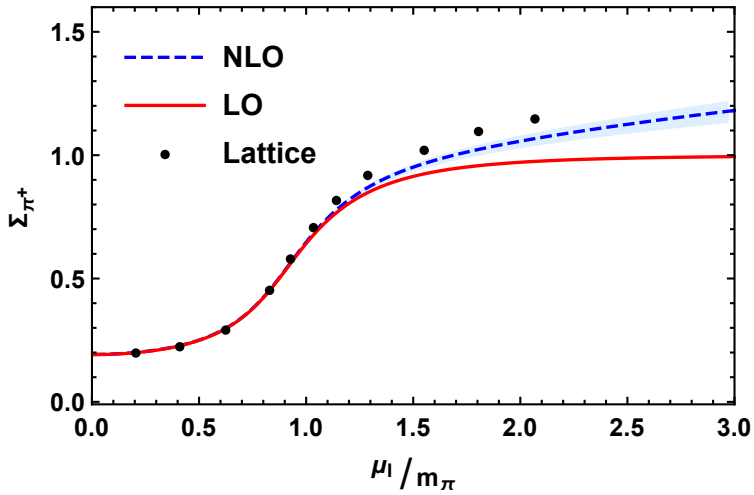
Chiral Perturbation theory (χPT)

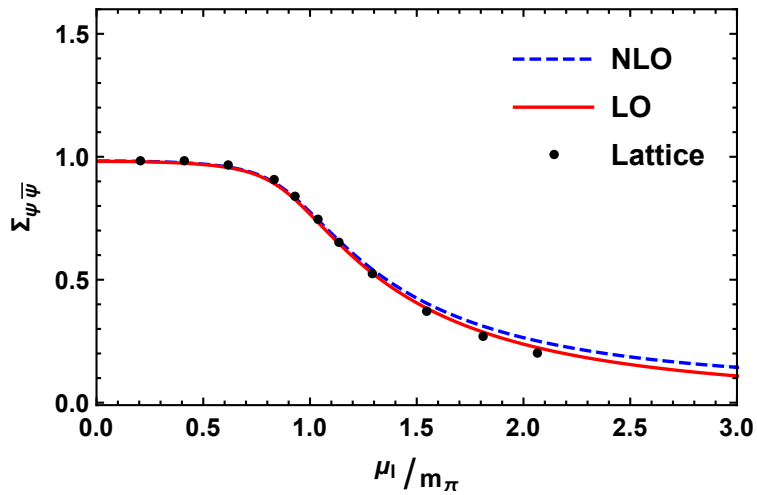
- Low-energy EFT for QCD.
- DoF are (pseudo)Goldstone-bosons.
- Lagrangian is uniquely determined by the global symmetries of QCD and the assumption of chiral symmetry breaking.
- Systematic expansion in powers of momenta.
  $\mathcal{L}_{\text{eff}} = \mathcal{L}_2 + \mathcal{L}_4 + \mathcal{L}_6 + ...$
- Non-renormalizable in the "old sense of the word". Higher order in loops $\implies$ more couplings l_i that are determined from experiments.
- No problem, as long as one is content with finite precision, which is the essence of an EFT.

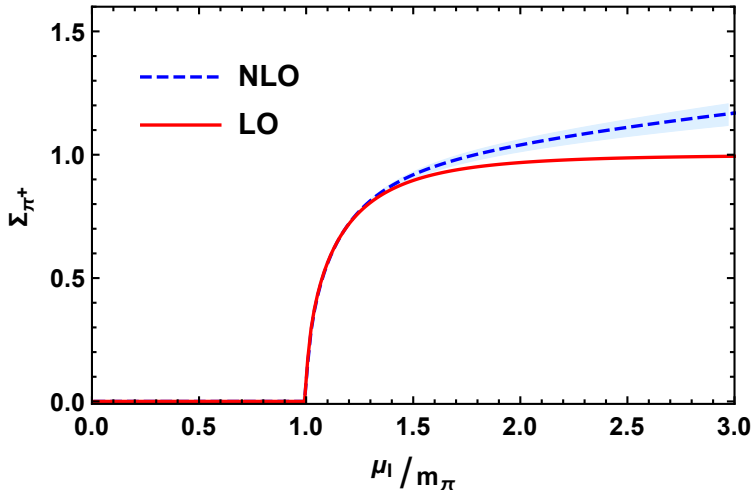
My very recent work

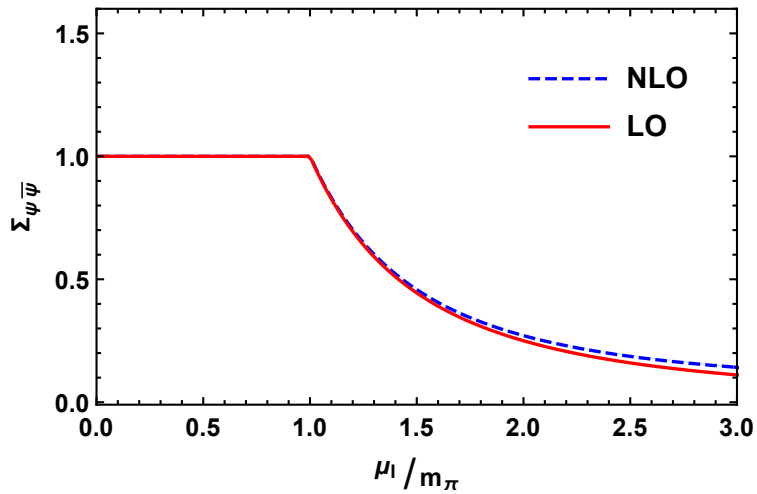
- Derive the free energy to one loop at finite μ_I, T and a nonvanishing pionic source j in the isospin limit $m_u = m_d$.
- Use the free energy to study the quark condensate $\langle \bar{\psi}\psi \rangle$ and pion condensate $\langle \pi^+ \rangle$ at finite μ_I and zero T at next-to-leading order.
- We calculate $\Sigma_{\bar{\psi}\psi} = -\frac{2m_u}{m_\pi^2 f_\pi^2}\left[\langle \bar{\psi}\psi \rangle_{\mu_I,T} - \langle \bar{\psi}\psi \rangle_{0,0}^{j=0}\right] + 1$ and $\Sigma_\pi = -\frac{2m_u}{m_\pi^2 f_\pi^2}\langle \pi^+ \rangle_{\mu_I,T}$.
- The tree-level relation $\Sigma_{\bar{\psi}\psi}^2 + \Sigma_\pi^2 = 1$ is lost.

Quark and pion condensates at zero temperature





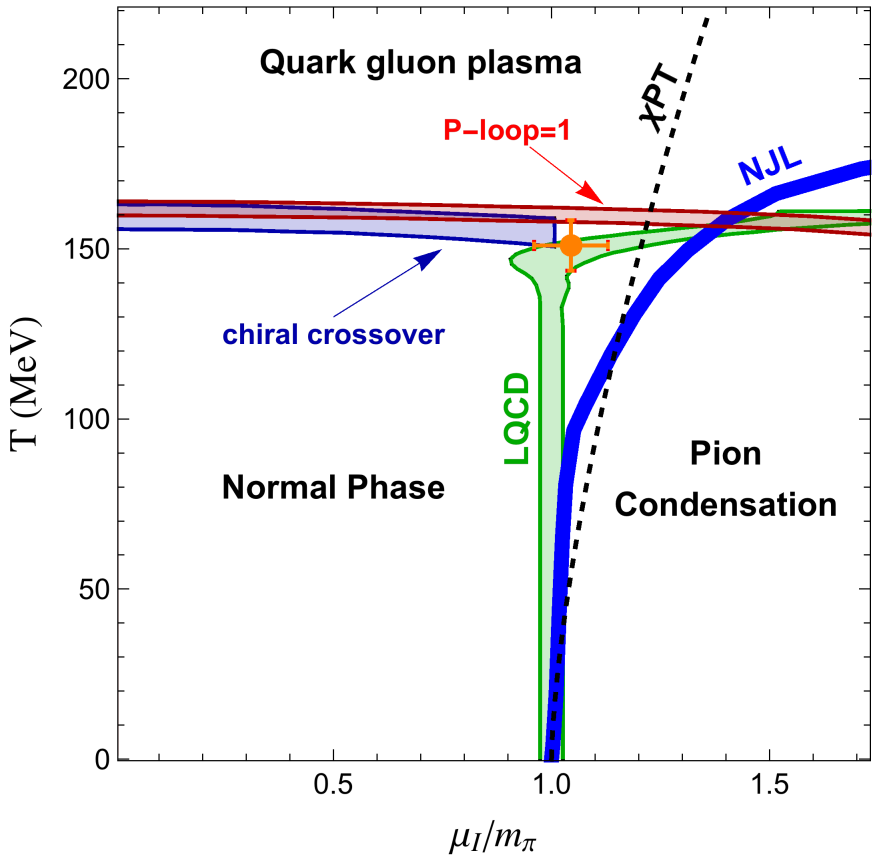




The lattice results are from Ref.[1]. Continuum quark masses have not been calculated in the study.

The next step: Quark and pion condensates and nonzero temperature

Figure from Ref.[2], used with author's permission.



Questions

B. B. Brandt, G. Endrődi, and S. Schmalzbauer, "QCD phase diagram for nonzero isospin-asymmetry", Physical Review D **97** (2018).

M. Mannarelli, "Meson Condensation", Particles **2**, 411–443 (2019).