Rho-meson resonance study from Lattice QCD

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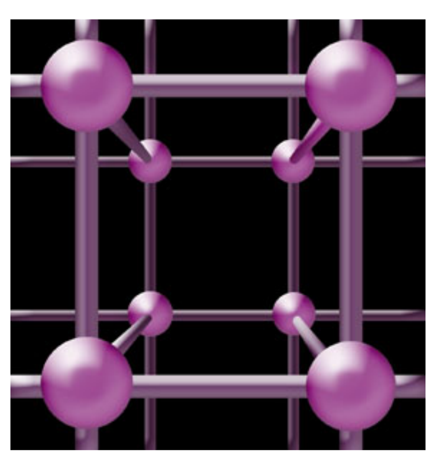
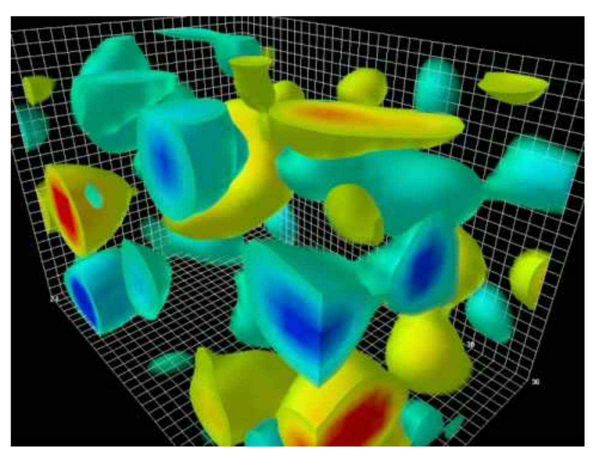
Introduction

Understanding the structure and interactions of subnuclear particles represents the main challenge for today's nuclear physics. These subnuclear particles are made of quarks and anti-quarks. Their behaviors are described in principle by Quantum Chromodynamics(QCD) which can not be solved analytically. Lattice QCD is a 4-D discretized version of QCD that can be solved numerically. However, Lattice QCD is an intensively computational resources demanding approach for QCD. Together with the fast development of the computing resources, LQCD starts to solve practical nuclear problems and becomes a heated approach to study QCD in recent years.





To improve the efficiency, we utilize high performance computing techniques to obtain better performance of our numerical simulations. Particularly, we implemented our LQCD algorithms and parallel computing routines on the GWU Colonial One cluster and GWU IMPACT collaboration cluster.

Rho-meson Resonance

Mesons are made up of quark and antiquark and usually unstable which we called resonance. The resonance can be viewed as a scattering process of several stable mesons. Our goal is to understand these scattering process governed by QCD and compare the simulation results to the natural data which are measured from nuclear experiments. In particular, we focus on the rho-meson resonance in the isospin-1 and spin-1 two pions scattering channel. The reason is that rho-meson is experimentally well measured and a better signal to noise ratio for mesons. For rho resonance case, two pions with back to back momentum will interact with each other and form the rho resonance state and quickly decay back to two pions. Therefore, studying the resonance parameters is equivalent to understanding the interaction process.

Methods

Our starting point is to study the two points correlation function which represents the overlap between two particles which is created at one space and time and the other one is annihilated at other space and time. From the Quantum mechanics point of view, the two points function can be evaluated as overlap coefficients and exponential decay with respect to the energy of the system.

$$\left\langle \hat{O}_2(t)\hat{O}_1^\dagger(0)\right\rangle = \sum_n \left\langle 0|\hat{O}_2|n\right\rangle \left\langle n|\hat{O}_1|0\right\rangle e^{-tE_n}$$

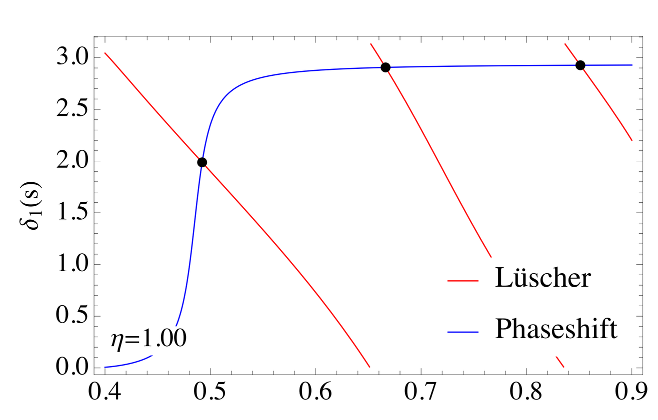
We can extract the energy value information by computing this two point correlation functions. According to Quantum Chromodynamics, the two point function is calculated using path integral formulism. For the lattice method, we can discretize the natural continuous space and time into discrete space and time. Therefore, searching the energy values of the system is tied to calculating the two point function with the path integral. The two point correlation function based on the path integral can be written as the following,

$$\left\langle O_2(t)O_1^\dagger(0)\right\rangle = \frac{1}{Z}\int D[\psi,\bar{\psi},A]e^{-S_{QCD}[\psi,\bar{\psi},A]}O_2[\psi_t,\bar{\psi}_t,A_t]O_1^\dagger[\psi_0,\bar{\psi}_0,A_0]$$

The important sampling method is used to turn this 4-dimensional integral into a mean value of large number of sample values. Each sample value is computed from a Monte Carlo simulation process.

To improve the precision of the energy values of the system, we utilized variational method and LapH smearing method in this study. With the energy spectrum of system, we apply Luscher's formula to these energy spectrum which offers a way to map the energy determined in the finite volume to the physical observable phaseshift :

$$\cot\delta_1(k) = \mathcal{W}_{00}(k,\eta) + \frac{2}{\sqrt{5}}\mathcal{W}_{20}(k,\eta)$$



Luscher's formula gives a relationship between energy values of a finite volume system and its related phaseshift values shown as the red curve.

To parameterize the phaseshift pattern, we use Breit Wigner forms which describes the phaseshift pattern with two parameters the mass of the resonance and the coupling constant:

$$\delta_1(E) = \mathrm{arccot}\,\frac{6\pi(M_R^2 - E^2)E}{g^2p^3}$$

RESULTS

In LQCD, people usually use heavier quark mass than the natural quark mass because of the limited computing resources. The lower value of quark mass the more computing resources are required. We implement the calculation in two different quark mass ensembles (which are related to pion mass about 310MeV and 227 MeV).

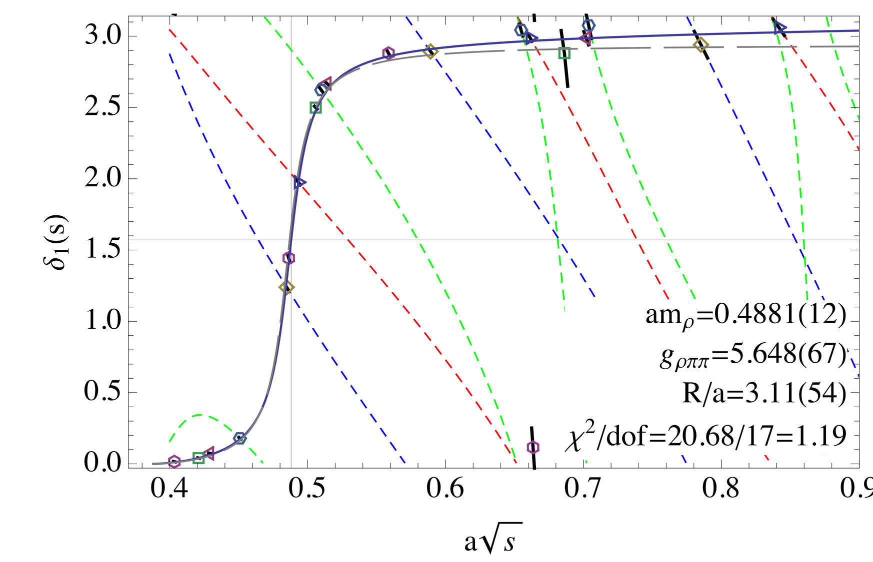


Figure above shows the phaseshift pattern fitted from the LQCD result at pion mass=310MeV ensembles. The resonance parameters mp and g are well determined with less than a 0.2% statistical errors.

There are several recent precision studies for the rho resonance in Lattice QCD community. We make a comparison in the following two figures.

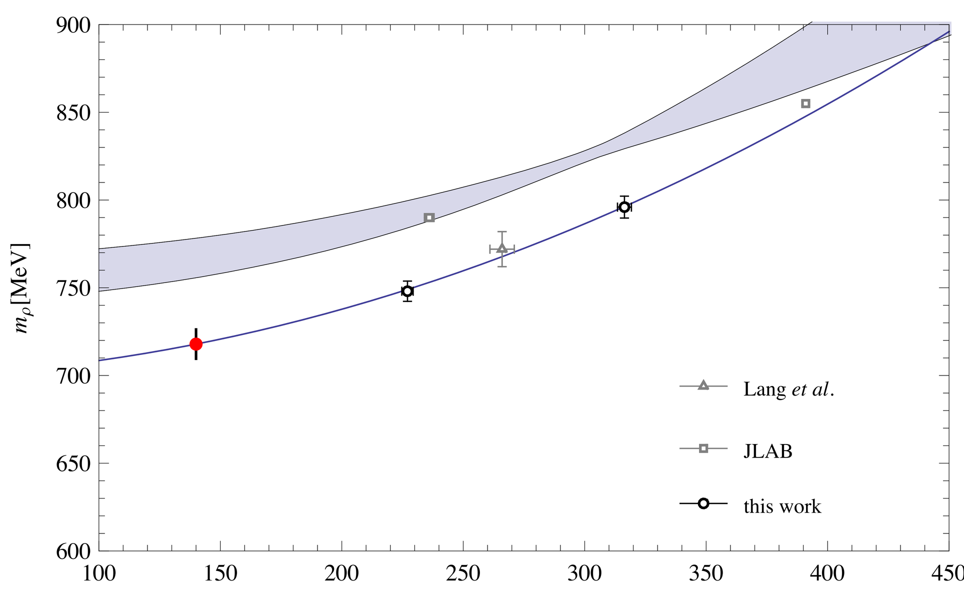


Figure above shows the rho resonance mass results among different group. Our results have small error and lower pion mass compare to other study. The extrapolation value to physical pion mass 140 MeV is about 715MeV which is 60 MeV below the experimental value. There is a discrepancy gap between the results from u and d quark and u, d and s quark study.

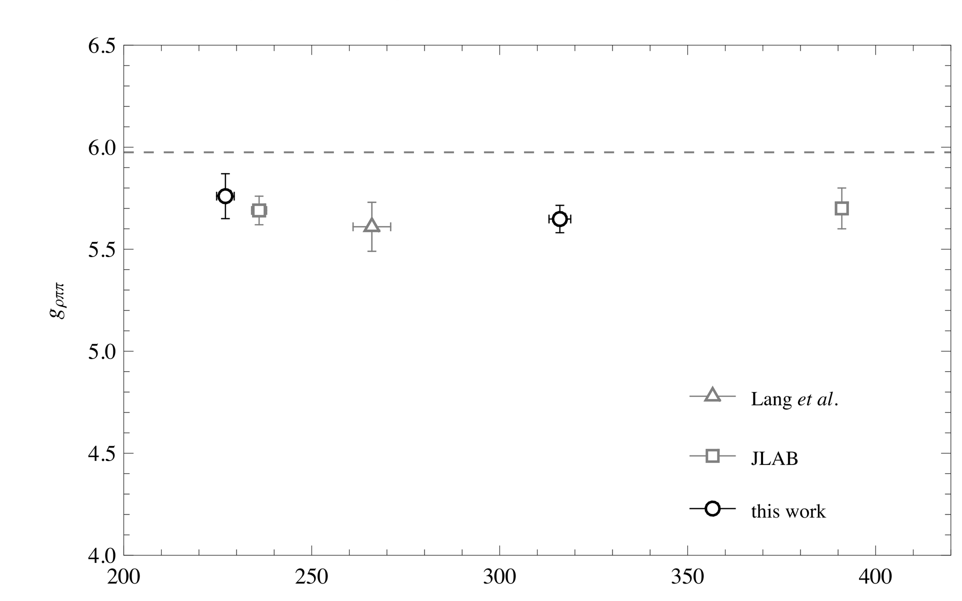
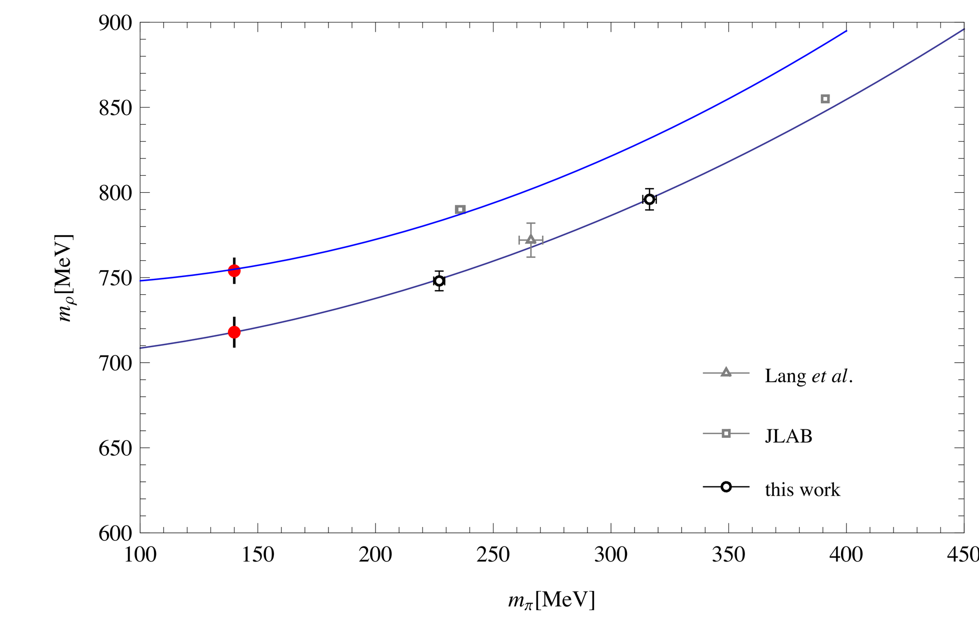


Figure shows the coupling constant with different studies. All studies show a consistent values with different pion mass.

To understand the discrepancy shown between different rho resonance mass studies, we evaluate the contribution of s quark and the KK scattering effects to the rho resonance mass.



This figure shows the consideration of the s quark and KK scattering based on unitary chiral perturbation theory. The rho resonance mass shift 40 MeV up with the correction and the new extrapolated curve go through the JLAB group result which includes the s quark and KK scattering channel.

CONCLUSIONS

- We succeed in determining the rho resonance parameters in two different pion masses using the Lattice QCD method.
- Our study has high precision in recent studies of rho resonance studies in LQCD community.
- We study the effect of s quark and KK scattering channel using unitary chiral perturbation theory.
- This study pave a path for further meson and baryon studies in the future.

ACKKNOWLEGEMENT

This study requires huge amount of computing resources which is about 3 millions CPU-hours and 1.5 million GPU-hours.

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