Responses of hadrons to chemical potential at finite temperature

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Introduction and motivation

Difficulty of lattice QCD at finite baryon density

$$D(\mu) = \gamma_5 D(-\mu)^\dagger \gamma_5 \Rightarrow \det D(\mu)^\dagger \neq \det D(\mu) \tag{1}$$

$\Rightarrow$ Oscllating weight

Several challenges

Glasgow method:(See. I.M.Barbour et al.,98)

Simulations at fixed baryon number:

Bielefeld group(O.Kaczemarek etal., 98-99)

Practically still difficult

Another way:

See responses at $\mu = 0$!

Not many works

Quark number susceptibilities : Gottlieb et al., 1987-1997

$\frac{d<n>}{d\mu}$ *Jump at* T_c

$\Leftrightarrow$ *change of nature of fermion number carrier*

This work : See the responses of hadrons!

The first order and the second order responses of mass and coupling.

$$\frac{dM}{d\mu}, \quad \frac{d^2M}{d\mu^2}, \quad \gamma^{-1}\frac{d\gamma}{d\mu}, \quad \gamma^{-1}\frac{d^2\gamma}{d\mu^2} \tag{2}$$

Hadronic correlators and responses of mass and coupling

Suppose that a hadronic correlator is dominated by a hadronic pole,

$$C(x) = \sum_{y,z,t} < H(x,y,z,t)H(0,0,0,0)^\dagger >= A(e^{-\hat{M}\hat{x}} + e^{-\hat{M}(L_x-\hat{x})}) \quad . \quad (3)$$

where $\hat{M} = aM$ and $\hat{x} = x/a$.

The first derivatives with respect to chemical potential μ:

$$C(x)^{-1}\frac{dC(x)}{d\hat{\mu}} = A^{-1}\frac{dA}{d\hat{\mu}} + \frac{d\hat{M}}{d\hat{\mu}}[(\hat{x} - \frac{L_x}{2})\tanh(\hat{M}(\hat{x} - \frac{L_x}{2})) - \frac{L_x}{2})] \quad . \quad (4)$$

The second derivative:

$$\begin{aligned} C(x)^{-1}\tfrac{d^2C(x)}{d\hat{\mu}^2} &= A^{-1}\tfrac{d^2A}{d\hat{\mu}^2} \\ &+(2A^{-1}\tfrac{dA}{d\hat{\mu}}\tfrac{d\hat{M}}{d\hat{\mu}} + \tfrac{d^2\hat{M}}{d\hat{\mu}^2})[(\hat{x} - \tfrac{L_x}{2})\tanh(\hat{M}(\hat{x} - \tfrac{L_x}{2})) - \tfrac{L_x}{2})] \\ &+(\tfrac{d\hat{M}}{d\hat{\mu}})^2[((\hat{x} - \tfrac{L_x}{2})^2 + \tfrac{L_x^2}{4} - L_x(\hat{x} - \tfrac{L_x}{2})\tanh(\hat{M}(\hat{x} - \tfrac{L_x}{2}))]. \end{aligned} \quad (5)$$

Responses expressed by quark propagators

Meson in the flavor non-singlet channel.

$$< H(n)H(0)^\dagger >=< T\Delta >_0 \, / < \Delta >_0 \tag{6}$$

where

$$T = \mathrm{Tr}(g(n:0,\mu_u)\Gamma g(0:n,\mu_d)\Gamma^\dagger) \tag{7}$$

$$\Delta = \det(D(\mu_u))\det(D(\mu_d)) \quad . \tag{8}$$

Here , $< O >_0$ and $<>$ mean

$$< O >_0 = \int [dU] O exp(-S_G) / \int [dU] exp(-S_G) \tag{9}$$

$$< O > = \int [dU] O \Delta exp(-S_G) / \int [dU] \Delta exp(-S_G) \quad . \tag{10}$$

The first and the second derivatives are

$$\begin{aligned} \frac{d}{d\hat{\mu}} < H(n)H(0)^\dagger > \; &= \frac{<\dot{T}\Delta + T\dot{\Delta}>_0}{<\Delta>_0} - \frac{<T\Delta>_0 <\dot{\Delta}>_0}{<\Delta>_0^2} \\ &=< \dot{T} + T\frac{\dot{\Delta}}{\Delta} > - < T >< \frac{\dot{\Delta}}{\Delta} > \end{aligned}$$

and

$$\begin{aligned} \frac{d^2}{d\hat{\mu}^2} < H(n)H(0)^\dagger > \; &= \frac{<\ddot{T}\Delta + 2\dot{T}\dot{\Delta} + T\ddot{\Delta}>_0}{<\Delta>_0} \\ &-2\frac{<\dot{T}\Delta + T\dot{\Delta}>_0 <\dot{\Delta}>_0}{<\Delta>_0^2} - \frac{<T\Delta>_0}{<\Delta>_0}[\frac{<\ddot{\Delta}>_0}{<\Delta>_0} - 2(\frac{<\dot{\Delta}>_0}{<\Delta>_0})^2] \\ &=< \ddot{T} + 2\dot{T}\frac{\dot{\Delta}}{\Delta} + T\frac{\ddot{\Delta}}{\Delta} > -2< \dot{T} + T\frac{\dot{\Delta}}{\Delta} >< \frac{\dot{\Delta}}{\Delta} > \\ &- < T > [< \frac{\ddot{\Delta}}{\Delta} > -2(< \frac{\dot{\Delta}}{\Delta} >)^2] \end{aligned} \tag{11}$$

At zero baryon density

At $\mu = 0$,

$$< \dot{\Delta} >_0 = 0 \quad \text{at} \quad \mu = 0. \tag{12}$$

$\Leftrightarrow < N_q > = 0$ at $\mu = 0$.

Also note:

$d\det(D)/d\mu = \mathrm{Tr}[\dot{D}D^{-1}]\det(D)$: anti-hermitian at $\mu = 0$.

$$\mathrm{Tr}[\dot{D}D^{-1}] = \mathrm{Tr}[\dot{D}\gamma_5\gamma_5 D^{-1}] = -\mathrm{Tr}[\gamma_5 \dot{D}^\dagger (D^\dagger)^{-1}\gamma_5] = -\mathrm{Tr}[\dot{D}D^{-1}]^* \quad . \tag{13}$$

$d\det(D)/d\mu$ changes sign for $U \to U^\dagger$ while the measure and gluonic action is invariant.

$\Rightarrow$ its expectation value is 0.

$$\begin{aligned} \frac{d}{d\hat{\mu}} < H(n)H(0)^\dagger > &=< \dot{T}\Delta + T\frac{\dot{\Delta}}{\Delta} > \\ \frac{d^2}{d\hat{\mu}^2} < H(n)H(0)^\dagger > &=< \ddot{T} + 2\dot{T}\frac{\dot{\Delta}}{\Delta} + T\frac{\ddot{\Delta}}{\Delta} > - < T >< \frac{\ddot{\Delta}}{\Delta} > \quad . \end{aligned} \tag{14}$$

Formulae for isoscalar response

Case of isoscalar chemical potential.

$$\mu_S = \mu_u = \mu_d \tag{15}$$

Note:

$$g(0; n, \mu_d) = \gamma_5 g^\dagger(n; 0, -\mu_d)\gamma_5 \tag{16}$$

$\Rightarrow$

$$T = \mathrm{Tr}[g(n:0, \mu_S)\Gamma\gamma_5 g(n:0, -\mu_S)^\dagger \gamma_5 \Gamma^\dagger] \tag{17}$$

Expanded propagator as

$$\begin{aligned} g(\hat{\mu}) &= g - \hat{\mu} g\dot{D}g + \tfrac{\hat{\mu}^2}{2}(2g\dot{D}g\dot{D}g - g\ddot{D}g) + O(\hat{\mu}^3) \\ g(-\hat{\mu}) &= g + \hat{\mu} g\dot{D}g + \tfrac{\hat{\mu}^2}{2}(2g\dot{D}g\dot{D}g - g\ddot{D}g) + O(\hat{\mu}^3) \end{aligned}$$

g and D are propagator and fermion operator at zero chemical potential

And

$$\dot{g} = -g\dot{D}g \tag{18}$$

The first derivatives at $\hat{\mu}_S = 0$ is

$$\dot{T} = -i2\mathrm{Imtr}[(g\dot{D}g)_{n;0}\Gamma\gamma_5 g^\dagger_{n;0}\gamma_5\Gamma^\dagger] \quad . \tag{19}$$

The second derivative at $\hat{\mu}_S = 0$ is obtained as

$$\begin{aligned} \ddot{T} = 4\mathrm{Retr}[(g\dot{D}g\dot{D}g)_{n;0}\Gamma\gamma_5 g^\dagger_{n;0}\gamma_5\Gamma^\dagger] - 2\mathrm{Retr}[(g\ddot{D}g)_{n;0}\Gamma\gamma_5 g^\dagger_{n;0}\gamma_5\Gamma^\dagger] \\ -2\mathrm{tr}[(g\dot{D}g)_{n;0}\Gamma\gamma_5(g\dot{D}g)^\dagger_{n;0}\gamma_5\Gamma^\dagger] \end{aligned} \tag{20}$$

Derivatives of Δ.

$$\begin{aligned} \frac{d}{d\hat{\mu}}\det(D) = & \quad \mathrm{Tr}[\dot{D}g]\det D \\ \frac{d^2}{d\hat{\mu}^2}\det(D) = & \quad \{\mathrm{Tr}[\ddot{D}g] - \mathrm{Tr}[\dot{D}g\dot{D}g] + \mathrm{Tr}[\dot{D}g]^2\}\det(D) \end{aligned} \tag{21}$$

$\Rightarrow$

$$\begin{aligned} \dot{\Delta}/\Delta = & \quad 2\mathrm{Tr}[\dot{D}g] \\ \ddot{\Delta}/\Delta = & \quad 2\mathrm{Tr}[\ddot{D}g] - 2\mathrm{Tr}[\dot{D}g\dot{D}g] + 4\mathrm{Tr}[\dot{D}g]^2 \quad . \end{aligned} \tag{22}$$

Combining eq.s (14),(19),(21) and (22),

$$\frac{d}{d\hat{\mu}} \quad \mathrm{Re} < H(n)H(0)^\dagger >= 0 \tag{23}$$

and

$$\begin{aligned} \frac{d^2}{d\hat{\mu}^2} \quad & \mathrm{Re} < H(n)H(0)^\dagger >= \\ & 4\mathrm{Re} < \mathrm{tr}[(g\dot{D}g\dot{D}g)_{n:0}\Gamma\gamma_5 g^\dagger_{n:0}\gamma_5\Gamma^\dagger)] > \\ & -2\mathrm{Re} < \mathrm{tr}[(g\ddot{D}g)_{n:0}\Gamma\gamma_5 g^\dagger_{n:0}\gamma_5\Gamma^\dagger)] > \\ & -2\mathrm{Re} < \mathrm{tr}[(g\dot{D}g)_{n:0}\Gamma\gamma_5 (g\dot{D}g)^\dagger_{n:0}\gamma_5\Gamma^\dagger] > \\ & +8 < \mathrm{Im}\mathrm{tr}[(g\dot{D}g)_{n:0}\Gamma\gamma_5 g^\dagger_{n:0}\gamma_5\Gamma^\dagger]\mathrm{Im}\mathrm{Tr}[\dot{D}g] > \\ & +2\mathrm{Re}\{< \mathrm{tr}[g_{n:0}\Gamma\gamma_5 g^\dagger_{n:0}\gamma_5\Gamma^\dagger](\mathrm{Tr}[\ddot{D}g] - \mathrm{Tr}[\dot{D}g\dot{D}g] + 2\mathrm{Tr}[\dot{D}g]^2) > \\ & - < \mathrm{tr}[g_{n:0}\Gamma\gamma_5 g^\dagger_{n:0}\gamma_5\Gamma^\dagger] >< (\mathrm{Tr}[\ddot{D}g] - \mathrm{Tr}[\dot{D}g\dot{D}g] + 2\mathrm{Tr}[\dot{D}g]^2) >\}. \end{aligned} \tag{24}$$

Formulae for isovector response

Isovector chemical potential,

$$\mu_V = \mu_u = -\mu_d \quad . \tag{25}$$

The derivatives of Δ:

$$\dot{\Delta} = \frac{d}{d\mu_V}(\det(D(\mu_V))\det(D(-\mu_V))|_{\mu_V=0} = 0 \quad . \tag{26}$$

And

$$\ddot{\Delta} = \ 2\{\mathrm{Tr}[\ddot{D}g] - \mathrm{Tr}[\dot{D}g\dot{D}g]\}\det(D)^2 \quad . \tag{27}$$

Derivatives of T:

$$\dot{T} = -2\mathrm{ReTr}[(g\dot{D}g)\Gamma\gamma_5 g^\dagger\gamma_5\Gamma^\dagger] \ \ . \tag{28}$$

And

$$\begin{aligned}\ddot{T} = 4\mathrm{ReTr}[(g\dot{D}g\dot{D}g)\Gamma\gamma_5 g^\dagger\gamma_5\Gamma^\dagger] - 2\mathrm{ReTr}[(g\ddot{D}g)\Gamma\gamma_5 g^\dagger\gamma_5\Gamma^\dagger] \\ +2\mathrm{Tr}[g\dot{D}g\Gamma\gamma_5(g\dot{D}g)^\dagger\gamma_5\Gamma^\dagger]\end{aligned} \tag{29}$$

$\Rightarrow$

$$\tfrac{d}{d\hat{\mu}} \ \ \mathrm{Re} < H(n)H(0)^\dagger >= -2\mathrm{Retr}[(g\dot{D}g)_{n:0}\Gamma\gamma_5 g^\dagger_{n:0}\gamma_5\Gamma^\dagger] \tag{30}$$

and

$$\begin{aligned}&\tfrac{d^2}{d\hat{\mu}^2} \ \ \mathrm{Re} < H(n)H(0)^\dagger >= \\ &4\mathrm{Re} < \mathrm{tr}[(g\dot{D}g\dot{D}g)_{n:0}\Gamma\gamma_5 g^\dagger_{n:0}\gamma_5\Gamma^\dagger)] > \\ &-2\mathrm{Re} < \mathrm{tr}[(g\ddot{D}g)_{n:0}\Gamma\gamma_5 g^\dagger_{n:0}\gamma_5\Gamma^\dagger)] > \\ &+2\mathrm{Re} < \mathrm{tr}[(g\dot{D}g)_{n:0}\Gamma\gamma_5(g\dot{D}g)^\dagger_{n:0}\gamma_5\Gamma^\dagger] > \\ &+2\mathrm{Re}\{< \mathrm{tr}[g_{n:0}\Gamma\gamma_5 g^\dagger_{n:0}\gamma_5\Gamma^\dagger](\mathrm{Tr}[\ddot{D}g] - \mathrm{Tr}[\dot{D}g\dot{D}g]) > \\ &- < \mathrm{tr}[g_{n:0}\Gamma\gamma_5 g^\dagger_{n:0}\gamma_5\Gamma^\dagger] >< (\mathrm{Tr}[\ddot{D}g] - \mathrm{Tr}[\dot{D}g\dot{D}g]) >\} \quad .\end{aligned} \tag{31}$$

$ma =$	0.025	$ma =$	0.017	$ma =$	0.0125
β	No. of conf.s	β	No. of conf.s	β	No. of conf.s
5.26	300	5.26	300	5.26	300
5.34	120	5.34	120	5.33	300

Table 1: Status of configurations

Simulations and features of data

a. Lattices are $16 \times 8^2 \times 4$.

b. R-algorithm to simulate $Nf = 2$ QCD.

Time step of molecular dynamics : $\delta\tau = 0.01$.

Taking account of reduction factor of fermion loop.

3. To evaluate the trace, 'Tr', Z_2 noise method is used.

Number of noise vector is two hundred.

4. Hadronic correlators are measured by using corner-type wall source with Coulomb gauge fixing.

Features of the data

$$\begin{aligned}
(A): &\quad 2\sum_{y,z,t} \mathrm{Re} < |(g\dot{D}g)_{n:0}|^2 > \\
(B): &\quad 4\sum_{y,z,t} \mathrm{Re} < \mathrm{tr}[(g\dot{D}g\dot{D}g)_{n:0} g^{\dagger}_{n:0}] > \\
(D): &\quad 2\sum_{y,z,t} \mathrm{Re} < \mathrm{tr}[(g\ddot{D}g)_{n:0}\Gamma\gamma_5 g^{\dagger}_{n:0}\gamma_5\Gamma^{\dagger})] >
\end{aligned} \tag{32}$$

$$\begin{aligned}
&(\mathrm{e}) && : 2\sum_{y,z,t} < \mathrm{Imtr}[(g\dot{D}g)_{n:0} g^{\dagger}_{n:0}]\mathrm{ImTr}[\dot{D}g] > /C(x) \\
&(\mathrm{c}-\mathrm{f}) && : \tfrac{1}{2}\sum_{y,z,t} \mathrm{Re} < |g_{n:0}|^2(\mathrm{Tr}[\ddot{D}g] - \mathrm{Tr}[\dot{D}g\dot{D}g] + \tfrac{1}{2}\mathrm{Tr}[\dot{D}g]^2) >_{cc} /C(x) \\
&(\mathrm{a}-\mathrm{b}-\mathrm{d}) && : (A - B - D)/C(x) \\
&\mathrm{total} && : (\mathrm{a}-\mathrm{b}-\mathrm{d}) + (\mathrm{e}) + (\mathrm{c}-\mathrm{f})
\end{aligned} \tag{33}$$

Here, $< AB >_{cc}$ means cross correlation,$< AB > - < A >< B >$.

All the quantities are measurable with acceptable errors.

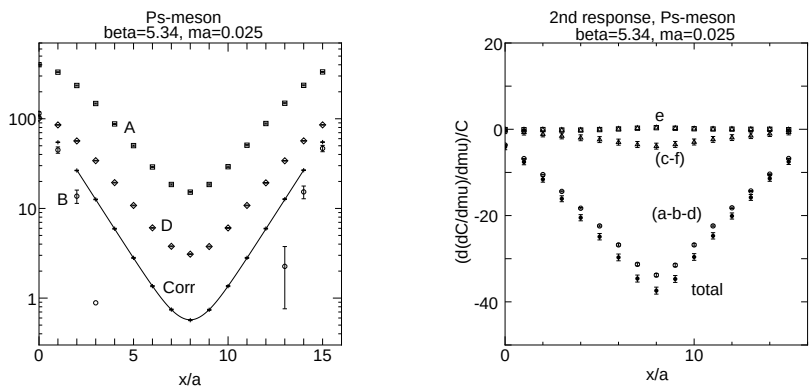

Figure 1: Correlator and some quantities in the second order responses of pseudoscalar meson at $\beta = 5.34$ and $ma = 0.025$. The curve is fitting by single pole formula (**??**)

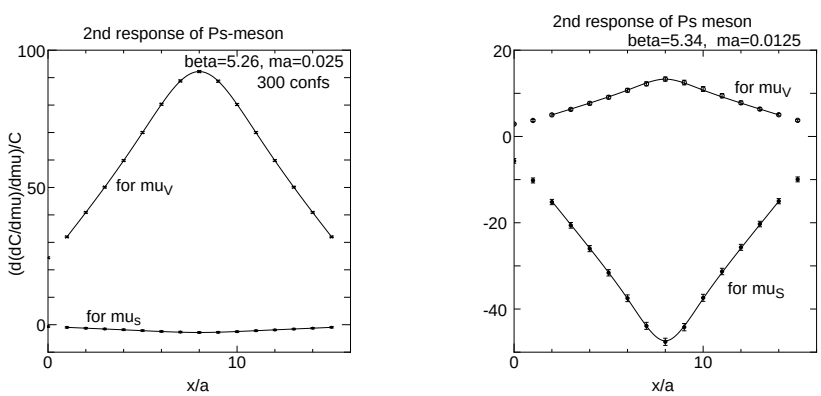

Figure 2: (Left figure) The second response of pseudoscalar meson correlator at $\beta = 5.26$ and $ma = 0.025$. The curves are fittings by formula (5). (Right figure) The same one but $\beta = 5.34$ and $ma = 0.0125$.

Note: The response of genuine coupling of the hadronic pole γ.

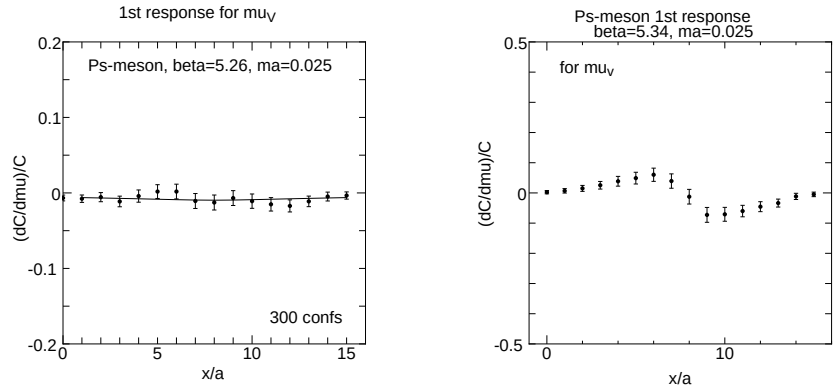

Figure 3: The first response of pseudoscalar meson correlator at $\beta = 5.26$ and $\beta = 5.34$. Quark mass parameter is $ma = 0.025$.

Since

$$\int dydzdt \int \gamma \frac{e^{i(\vec{p}\vec{r}+p_0 t)}}{p^2+M^2} dp = \frac{\gamma}{2M} e^{-Mx} = Ae^{-Mx} \tag{34}$$

Response of γ :

$$\frac{\ddot{\gamma}}{\gamma} = \frac{\ddot{A}}{A} + \frac{\ddot{M}}{M} + 2\frac{\dot{A}}{A}\frac{\dot{M}}{M} \quad . \tag{35}$$

	$\beta = 5.26$		
	$ma = 0.0125$	$ma = 0.017$	$ma = 0.025$
$\hat{M}$	0.295(0.001)	0.352(0.001)	0.427(0.001)
$A^{-1}d^2A/d\hat{\mu_S}$	-1.2(3.0)	-1.3(1.9)	-0.7(1.6)
$d^2\hat{M}/d\hat{\mu_S}^2$	0.18(0.52)	0.27(0.35)	0.35(0.29)
$\gamma^{-1}d^2\gamma/d\hat{\mu_S}^2$	-0.5(3.5)	-0.5(2.2)	-0.2(1.5)

Table 2: Responses of pseudoscalar meson for μ_S at $\beta = 5.26$.

Results for pseudoscalar meson

Responses to the isoscalar chemical potential

a. Response of mass of is small in low temperature phase.

   Persistency of nature of Nambu-Goldstone boson.

   Chiral extrapolation leads that the limiting value of the isoscalar response is consistent with 0

b. The response of the coupling is also small below T_c.

c. The correlator and its response are still well fitted by single pole formulae.

d. Screening mass grows up and the second responses of mass and coupling become sizable.

   Liberation from nature of Nambu-Goldstone boson.

	$\beta = 5.34$		
	$ma = 0.0125$	$ma = 0.017$	$ma = 0.025$
$\hat{M}$	0.751(0.001)	0.747(0.001)	0.756(0.002)
$A^{-1}d^2A/d\hat{\mu_S}$	-4.23(0.49)	-3.68(0.75)	-2.93(0.52)
$d^2\hat{M}/d\hat{\mu_S}^2$	5.39(0.10)	5.82(0.16)	4.31(0.10)
$\gamma^{-1}d^2\gamma/d\hat{\mu_S}^2$	2.95(0.51)	4.12(0.78)	2.77(0.53)

Table 3: Responses of pseudoscalar meson for μ_S at $\beta = 5.34$.

Responses to the isovector chemical potential

a. Large second response of mass in low temperature phase.

   The response of the coupling is also sizable.

   Even manifest for small quark mass parameter.

   No restriction by Nambu-Goldstone boson nature. Light pion couples strongly to isovector chemical potential.

b. The mass tends to decrease in the influence of isovector chemical potential. [**?**]. This is more clearly shown by an expansion:

$$\frac{M(\hat{\mu})}{T}|_{\hat{\mu}} = \frac{M}{T}|_{\hat{\mu}=0} + (\frac{\mu}{T})(\frac{d\hat{M}}{d\hat{\mu}})_{\hat{\mu}=0} + (\frac{\mu}{T})^2\frac{1}{2N_t}(\frac{d^2\hat{M}}{d\hat{\mu}^2})_{\hat{\mu}=0} + O((\hat{\mu})^3)$$

   for fixed β and ma. At $\beta = 5.26$ and $ma = 0.017$, the data suggests

$$\frac{M(\hat{\mu_V})}{T}|_{\hat{\mu_V}} \approx \frac{M}{T}|_{\hat{\mu_V}=0} + (0.023 \pm 0.036)(\frac{\mu_V}{T}) - (1.29 \pm 0.06)(\frac{\mu_V}{T})^2$$

c. In the high temperature phase, the second responses decrease.

d. The first order response to the isovector chemical potential is small and consistent with zero.

   A comparative study in Nambu-Jona-Lasnio model (See Choe's poster)

	$\beta = 5.26$		
	$ma = 0.0125$	$ma = 0.017$	$ma = 0.025$
$A^{-1}dA/d\hat{\mu_V}$	0.015(0.067)	0.046(0.043)	0.018(0.027)
$d\hat{M}/d\hat{\mu_V}$	0.006(0.057)	0.023(0.036)	0.005(0.021)
$(d\hat{M}/d\hat{\mu_V})^2$ (*)	-0.033(0.062)	0.035(0.047)	0.010(0.032)
$A^{-1}d^2A/d\hat{\mu}^2$	47.0(1.0)	33.78(0.86)	23.07(0.64)
$d^2\hat{M}/d\hat{\mu_V}^2$	-13.1(0.60)	-10.28(0.47)	-8.56(0.32)
$\gamma^{-1}d^2\gamma/d\hat{\mu_V}^2$	2.6(2.3)	4.6(1.6)	2.8(1.0)

Table 4: Responses of pseudoscalar meson for μ_V at $\beta = 5.26$. (*)Extracted from the second response by eq.(5)

	$\beta = 5.34$		
	$ma = 0.0125$	$ma = 0.017$	$ma = 0.025$
$A^{-1}dA/d\hat{\mu_V}$	-0.0007(0.0094)	0.0026(0.0086)	0.0063(0.0098)
$d\hat{M}/d\hat{\mu_V}$	0.0007(0.0071)	-0.0008(0.0065)	0.0022(0.0023)
$(d\hat{M}/d\hat{\mu_V})^2$ (*)	0.006(0.033)	0.013(0.033)	0.019(0.043)
$A^{-1}d^2A/d\hat{\mu}^2$	2.32(0.64)	2.74(0.64)	3.07(0.85)
$d^2\hat{M}/d\hat{\mu_V}^2$	-1.32(0.32)	-1.48(0.32)	-1.54(0.41)
$\gamma^{-1}d^2\gamma/d\hat{\mu_V}^2$	0.56(0.77)	0.76(0.77)	1.0(1.0)

Table 5: Responses of pseudoscalar meson for μ_V at $\beta = 5.34$. (*)Extracted from the second response by eq.(5)

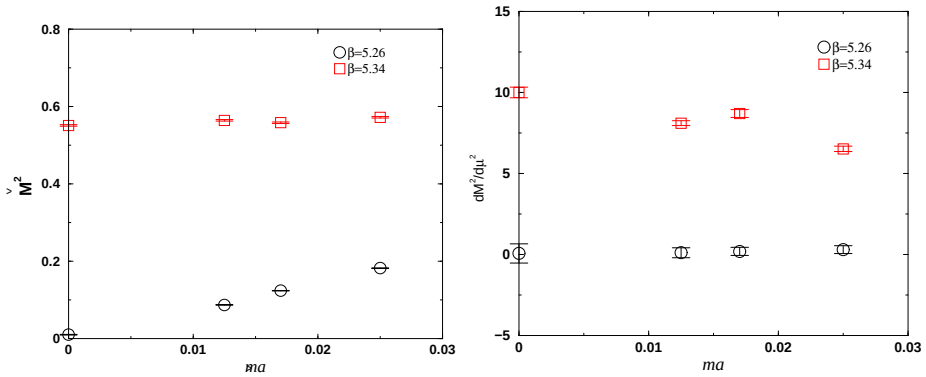

Figure 4: $\hat{M}^2$ (Left) and $d^2\hat{M}^2/d\hat{\mu_S}^2$ (Right) of psedoscalar meson versus ma. β is 5.26.

Results for vector meson

Need more statistics

Features of preliminary data

a. The first order esponse to the isovector chemical potential is small.

b. As for the second order, positive response to the isoscalar chemical potential.

   Negative response of mass to the isovector potential.

c. In comparison with the responses of pseudoscalar meson, for example $d^2\hat{M}/d\hat{\mu_V}^2$, the responses are weak.

d. Deconfining feature in correlator and responses.

   The formulae based on single meson pole dominance, **??**-5 give very poor description to the data. Rather, mesonic correlator composed of free quark gives similar shape

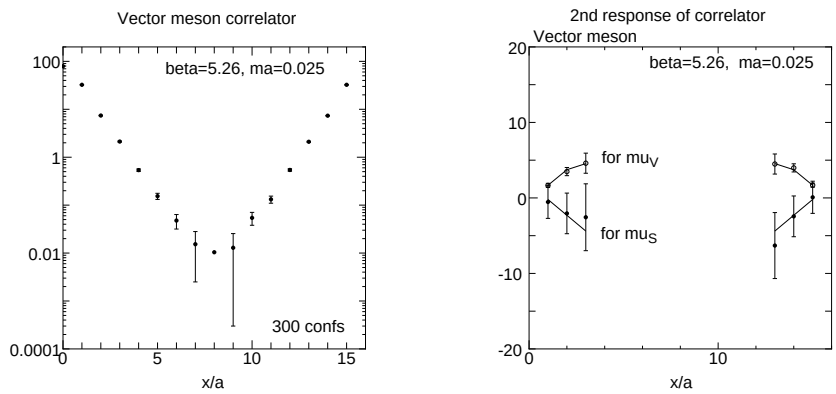

Figure 5: (Left figure) Vector meson correlator at $\beta = 5.26$ and $ma = 0.025$. (Right figure) The second responses of screening mass of vector meson to the isoscalar chemical potential.

	$\beta = 5.26$		$\beta = 5.34$	
	$ma = 0.017$	$ma = 0.025$	$ma = 0.017$	$ma = 0.025$
$\hat{M}$	not yet	1.280(0.013)	deconfined	deconfined
$A^{-1}d^2A/d\hat{\mu_S}$	not yet	1.9(2.7)	/	/
$d^2\hat{M}/d\hat{\mu_S}^2$	not yet	2.1(1.6)	/	/
$\gamma^{-1}d^2\gamma/d\hat{\mu_S}^2$	not yet	3.5(3.0)	/	/

Table 6: Responses of vector meson for μ_S.

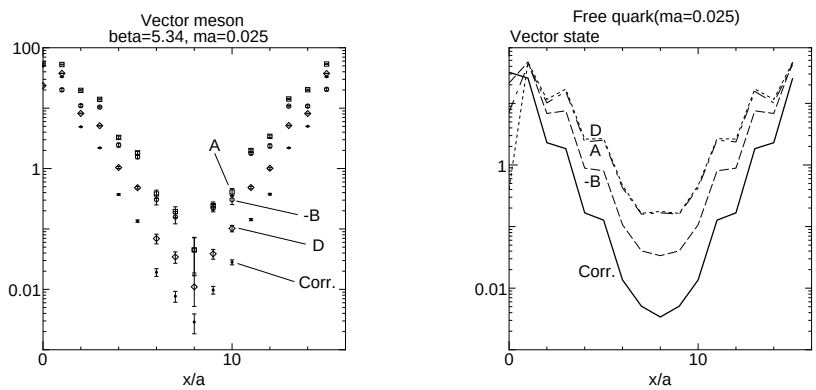

Figure 6: (Left figure) Correlator and other contributions of vector meson at $\beta = 5.34$ and $ma = 0.025$. Notations are the same with eq.(**??**). (Right figure) Correlator and other contributions of vector meson composed of free quark ($ma = 0.025$).

Summary and discussions

Summary

a. Development of a framework for the second order response of hadrons to the chemical potential

b. The first results of responses of screening mass of pseudoscalar and vector mesons

c. Characteristic change of responses of pseudoscalar meson below and above chiral transition.

d. Large response of pseudoscalar meson to the isovector chemical potential in low temperature phase.

e. A hadronic pole gives good description for the response as well as correlator at $\beta = 5.34$ (above $T/T_c \approx 1.1$) in the pseudoscalar channel. On the other hand, vector meson seems to be deconfined there.

Outlook

i Need test on larger lattices.

Present lattice is too coarse ($a \sim 0.3fm$) Differences $N_t = 4$ and $N_t = 6$ lattices have been recognized.

ii Study of chemical potential responses of nucleon.

iii Similarly, those of quark condensate are even more important.

Pilot studies are going.