# Charmonium physics
# in
# finite temperature lattice QCD

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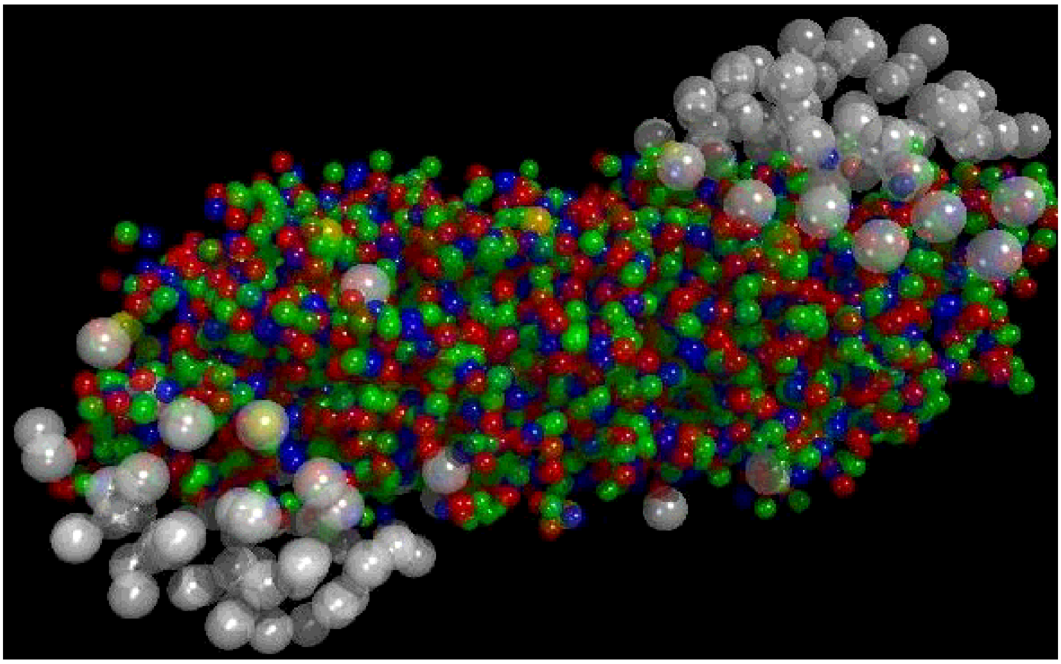
PRESS RELEASE

# New State of Matter created at CERN



At a special seminar on 10 February, spokespersons from the experiments on CERN* 's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

Theory predicts that this state must have existed at about 10 microseconds after the Big Bang, before the formation of matter as we know it today, but until now it had not been confirmed experimentally. Our understanding of how the universe was created, which was previously unverified theory for any point in time before the formation of ordinary atomic nuclei, about three minutes after the Big Bang, has with these results now been experimentally tested back to a point only a few microseconds after the Big Bang.

# Introduction

Signals of Quark-Gluon Plasma formation

$\Downarrow$

- $J/\psi$ suppression above $T_c$

  Matsui and Satz (1986)

- Mass shift near $T_c$

  Hashimoto et al (1986)

We study these signals

from Charmonium physics at $T \geq 0$

$\Downarrow$

Finite temperature lattice QCD

# Contents

# What can the Lattice QCD predicts ?

Quark propagator with interaction ( $T \geq 0$ )

$\Downarrow$

**Hadron correlator**

$\Longrightarrow$ Hadron masses

- Pole mass ( temporal mass )
- Screening mass ( spatial mass )

Mass shift

$\Longrightarrow$ Wave function

Hadronic bound state

$J/\psi$ suppression

$\Longrightarrow$ Spectral function

Mass shift & width

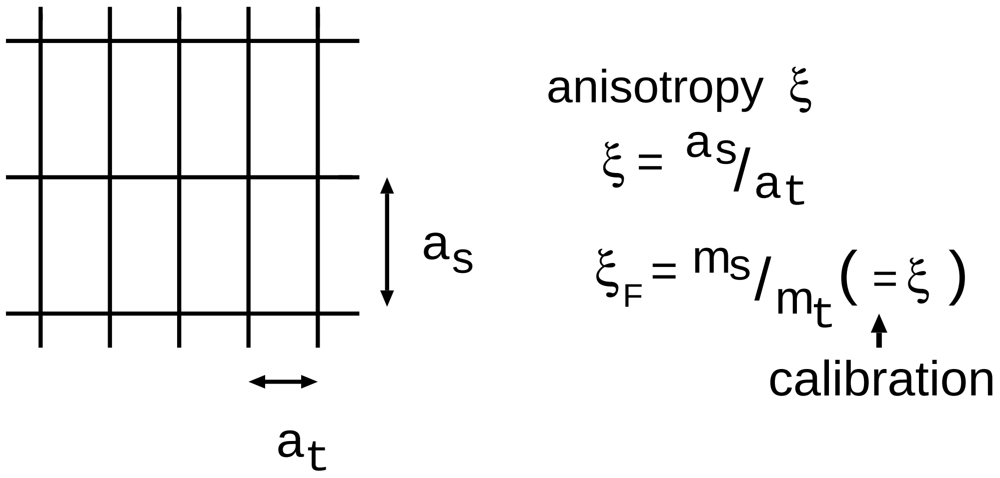
# Anisotropic lattice

We want to calculate pole (temporal) mass.
But $N_t \longrightarrow$ small at high T.

$\Longrightarrow$ Anisotropic Lattice

Karsch (1982)

Burgers, Karsch, Nakamura and Stamatescu (1988)




O Many degree of freedom in temporal direction for small computing power

X Spatial lattice spacing is coarse. $\Longrightarrow$ P.8

X Complicated analysis from a new parameter "anisotropy $\xi$"

# Heavy quark action

- Standard quark action has $O(a)$ error

  Spatial lattice spacing $a_s$ is coarse.

- We study $c\bar{c}$ system on the lattice.

  $c$ quark mass $>$ lattice cut off

**Fermilab (Clover) action on Anisotropic lattice**

$$
\begin{aligned}
S_F(\kappa_s, \gamma_F) &= \sum_x \bar{q}(y) K[U](x,y) q(x) \\
K[U](x,y) &= 1 - \kappa_s \sum_i \left[ \left( \frac{1}{\xi} - \gamma_i \right) T_{+i} + \left( \frac{1}{\xi} + \gamma_i \right) T_{-i} \right] \\
&- \kappa_t \left[ (1-\gamma_4) T_{+4} + (1+\gamma_4) T_{-4} \right] \\
&- \kappa_s \frac{1}{2\xi} c_B \vec{\Sigma} \cdot \vec{B} + \kappa_t \frac{1}{2\xi} c_E \vec{\alpha} \cdot \vec{E}
\end{aligned}
$$

$$
\begin{aligned}
\kappa_t &= \gamma_F \kappa_s \\
c_B, c_E &: \text{Clover coefficients} \\
&\quad (\text{ Mean-field improved }) \\
T_{+\mu}(x,y) &= U_\mu(x) \delta_{x+\hat{\mu},y} \\
T_{-\mu}(x,y) &= U_\mu(x-\hat{\mu}) \delta_{x-\hat{\mu},y}
\end{aligned}
$$

Clover action:Sheikholeslami, Wohlert (1985)

Fermilab action : El-Khadra, Kronfeld, Mackenzie (1997)

c.f. Klassen hep-lat/9809174

# Meson Correlator

$$G_M(\vec{x},t) = \sum_{x,y_1,y_2} \omega_1(\vec{y}_1)\omega_2(\vec{y}_2)$$
$$\times\langle Tr[S(\vec{y}_1,0;\vec{z},t)\gamma_M\gamma_5 S^\dagger(\vec{y}_2,0;\vec{z}+\vec{x},t)\gamma_5\gamma_M^\dagger]\rangle$$

$S(\vec{x}_1,t_1;\vec{x}_2,t_2)$ : quark propagator

$\gamma_M \;=\; \gamma_5\;,\;\gamma_1\;,\;1\;,\;\gamma_1\gamma_5$

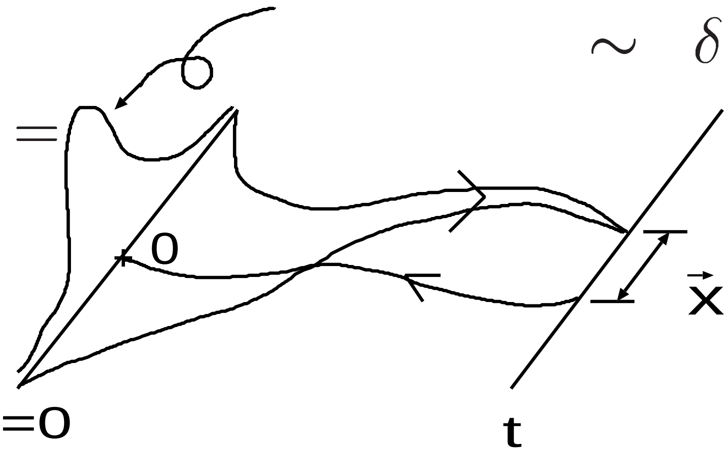
$(\quad M \;=\; P_S\;,\;V\;,\;S\;,\;A\quad)$

$\ni$Gauge fixing : Coulomb gauge

source $\omega(\vec{\mathsf{y}}) \sim \exp\left(-\mathsf{a}\mathsf{y}^{\mathsf{p}}\right)$ (exp)

$\sim \quad \delta(\vec{\mathsf{y}})$ (point)

$G_M(\vec{x},t) =$




$a,p$ are determined from $\vec{x}$-dependence in point-point $P_S$ correlator at $T \simeq 0$

# Results

- Simulation parameter ⇒ P.10
- $c\bar{c}$ bound state
  - t-dependence of "Wave function" ⇒ P.11
  - Numerical results ⇒ P.12
- Mass shift
  - Effective mass ⇒ P.13
  - Effective mass at $T > 0$ ⇒ P.14

    ⇓

  - Effective mass
    from "Variational analysis" ⇒ P.15,16
- Summary & Conclusion ⇒ P.17

## Simulation parameters

Lattice:

Quench ( without dynamical quark effect)

$12^3 \times N_t$ ,$\beta = 5.68$, $\gamma = 4.0$

$N_t = 72$ $(T \simeq 0)$, 20 $(T \langle T_c)$, 16, 12 $(T \rangle T_c)$ :

$T = 1/N_t a_t$

- \#conf. $= 60$
- Anisotropy: $\xi \equiv a_s/a_t = 5.3(1)$

  from the ratio of Wilson loops

  Engels, Karsch and Scheideler (1997), Klassen (1998)
- Cutoff: $a_s^{-1} = 0.85(3)$ GeV,$a_t^{-1} = 4.5(2)$ GeV

  from heavy quark potential

Quark: Anisotropic Fermilab (Clover) action

- Hopping parameter and bare anisotropy:

| $\kappa$ | $\gamma_F$ | $m_{PS}$ | $m_V$ [GeV] |
|---|---|---|---|
| 0.0985 | 3.580 | 3.51(16) | 3.56(16) |
| 0.1032 | 3.670 | 3.04(13) | 3.10(14) |
| 0.1075 | 3.750 | 2.63(12) | 2.70(12) |
| 0.1159 | 3.867 | 1.91(09) | 2.00(08) |

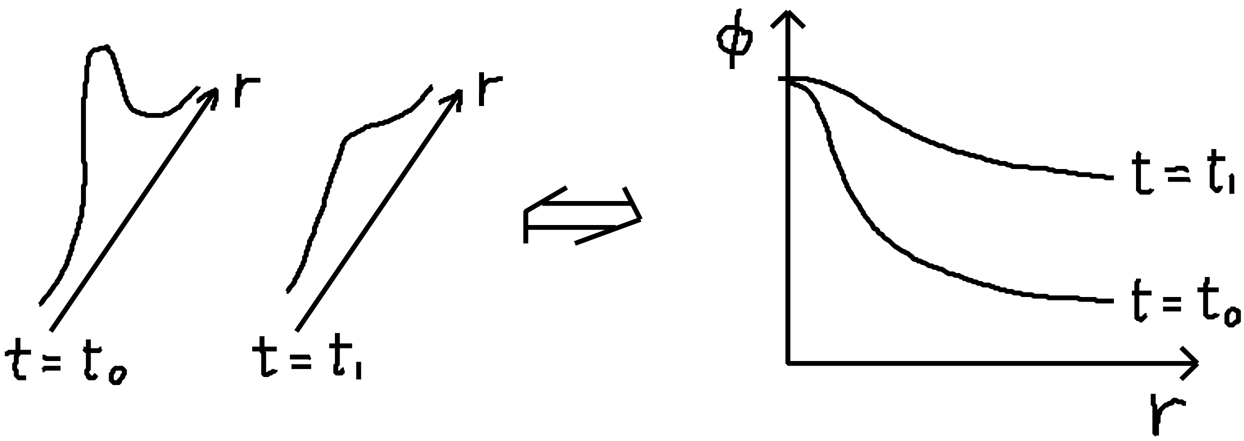
# $c\bar{c}$ bound state

"Wave function"

$$w_\Gamma(r,t) = \sum_{\vec{x}} \langle \bar{q}(\vec{x}+\vec{r},t)\Gamma q(\vec{x},t) O^\dagger(0) \rangle$$

$$\boxed{\phi(r,t) = w_\Gamma(r,t)/w_\Gamma(0,t)}$$

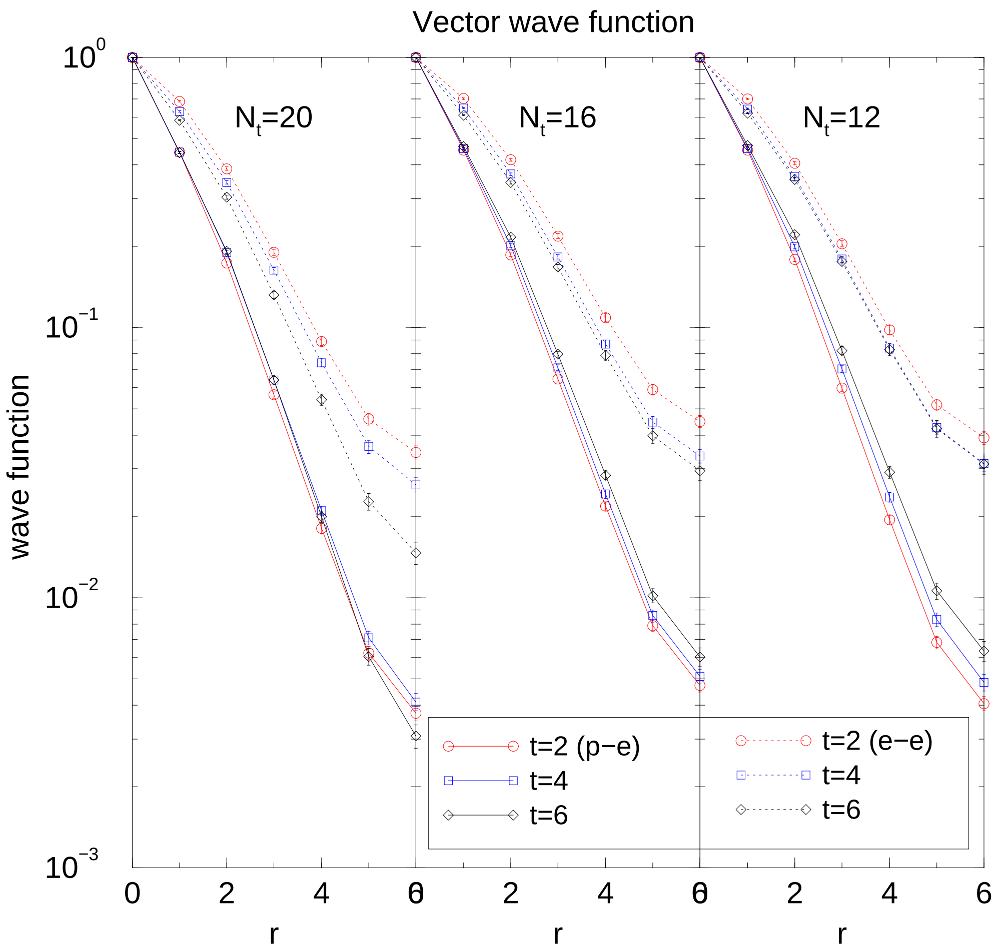
$\phi(r,t)$ : normalized at spatial origin




Spread $\Longleftrightarrow$ Gentle slope

We can discuss the $c\bar{c}$ bound state
by t-dependence of "Wave function".

# Results of "Wave function"




∗ "Wave function" spread at high $T$.

∗ But spatial correlation survive even $T \simeq 1.5T_c$.

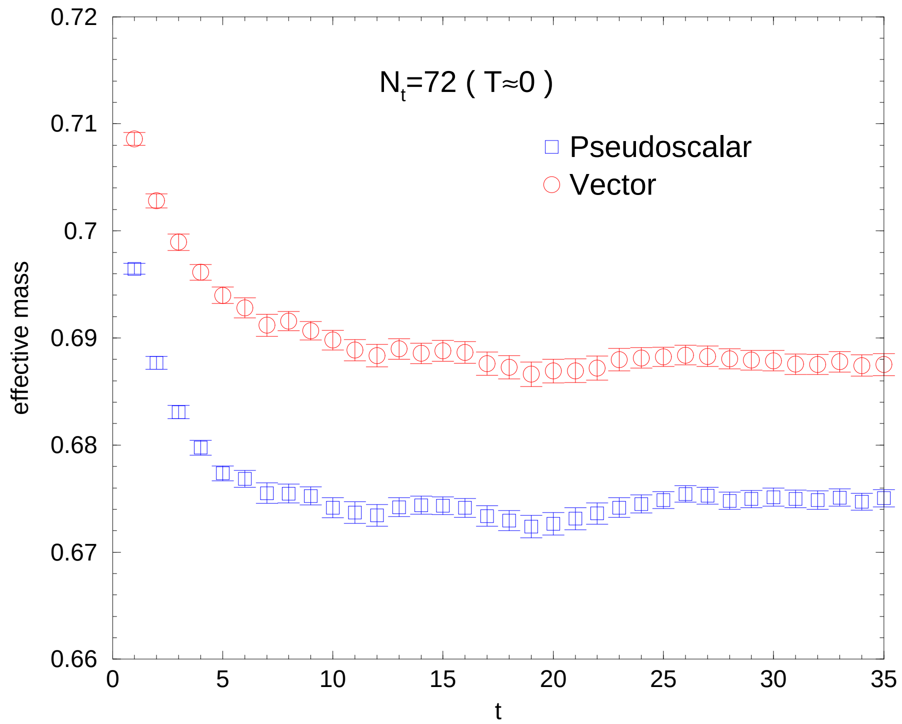
# Mass shift at $T > 0$

Effective mass : $m_{\text{eff}}(t)$

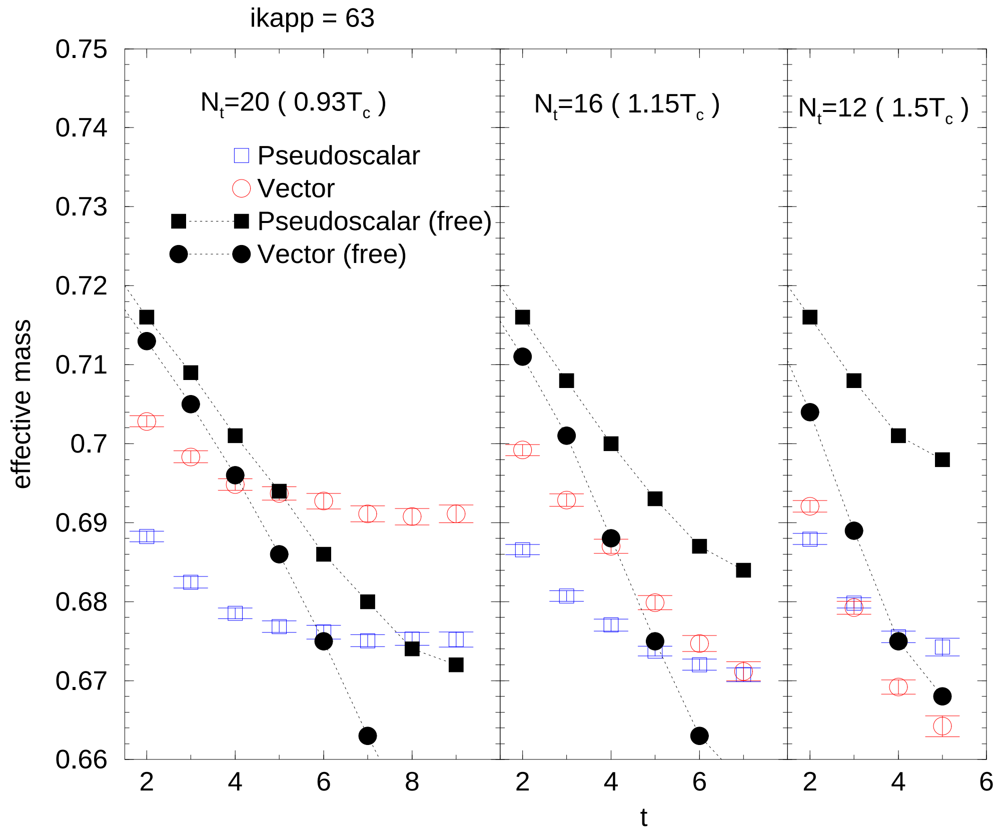
$$\frac{G_M(\vec{x}=0,t)}{G_M(\vec{x}=0,t+1)} = \frac{\cosh\left[m_{\text{eff}}(N_t/2-t)\right]}{\cosh\left[m_{\text{eff}}(N_t/2-t-1)\right]}$$

$$m_{\text{eff}}(t) \quad \underset{t\to\infty}{\longrightarrow} \quad m$$

∘ effective mass at $T = 0$



## ○ Effective mass at $T > 0$




* $*$ No significant change at $T \simeq 0.95T_c$.
* $*$ Significant change at $T \simeq 1.15, 1.5T_c$
* $*$ Effective mass has No plateau at $T > T_c$

  $\Longrightarrow$ Variational analysis

# Variational analysis

$$\mathcal{O}_i^\dagger|0\rangle = z_i|i'\rangle$$

$|i'\rangle$ : Linear combinations of $|i\rangle$ (assumption)

$|i\rangle$ : Eigen states of Hamiltonian.

In the practical calculation,
we get the correlator matrix ( case of $i, j = 3$ )

$$\begin{aligned} C_{ij}(t) &= \langle 0|\mathcal{O}_i(t)\mathcal{O}_j^\dagger(0)|0\rangle \\ &= \begin{pmatrix} C_{11}(t) & C_{12}(t) & C_{13}(t) \\ C_{21}(t) & C_{22}(t) & C_{23}(t) \\ C_{31}(t) & C_{32}(t) & C_{33}(t) \end{pmatrix} \end{aligned}$$

$\Downarrow$

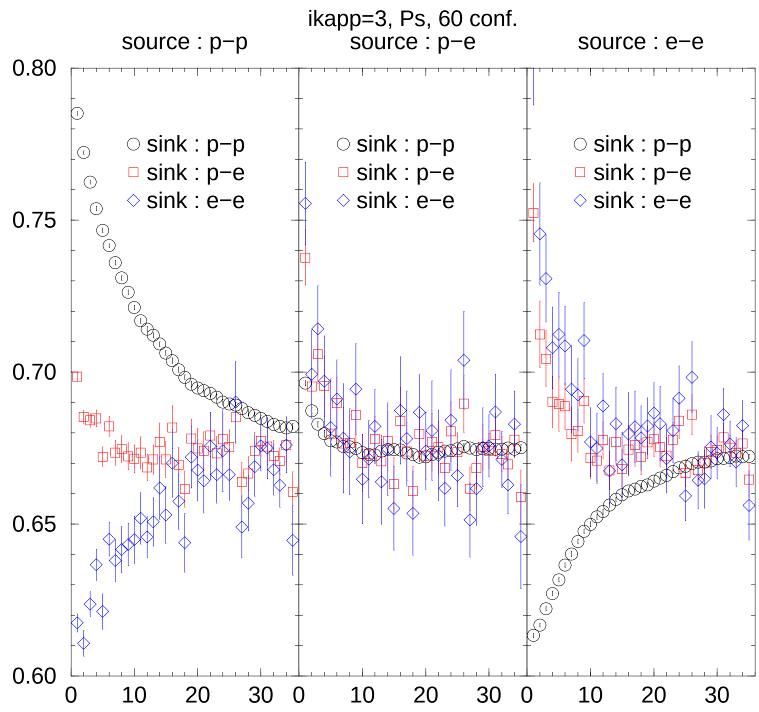
Diagonalize

$|i'\rangle$ basis $\Longrightarrow$ $|i\rangle$ basis

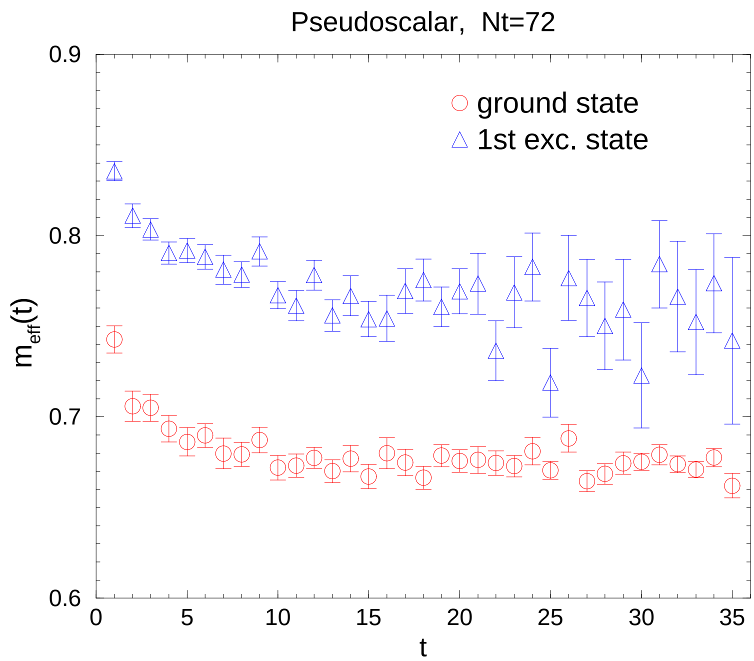
In this study, We used

- $\mathcal{O}_1$ : point-point
- $\mathcal{O}_2$ : point-exp
- $\mathcal{O}_3$ : exp-exp

# Results of variational analysis

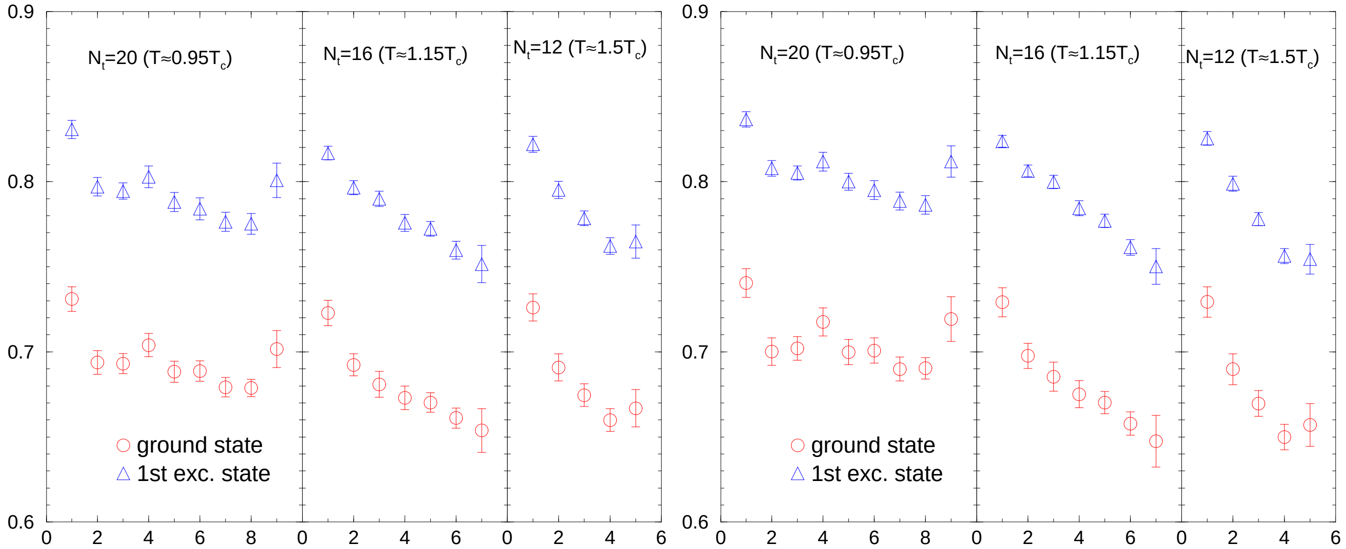



⇓ Diagonalization



- Results of variational analysis at $T > 0$

Pseudoscalar  Vector




$*$ $T < T_c$ : Almost same behavior as $T = 0$

$*$ $T > T_c$ : No plateau. Small mass (?)

## Summary

∘ We use the anisotropic Fermilab action for heavy quark system.

**$c\bar{c}$ bound state**

t-dependence of "Wave function"

$T \longrightarrow$ large, "Wave function" $\longrightarrow$ spread.

But there is spatial correlation above $T_c$

**Mass shift**

Effective mass & Variational analysis

$T < T_c$ : Not large change (slightly up)

$T > T_c$ : Effective mass $\longrightarrow$ Small (?)

## Outlook

- Improvement of hadronic operator
- Fine lattice
- Other channels : baryons etc.
- With dynamical quarks