Study on the newly discovered mesons in the charm region with chiral fermions.

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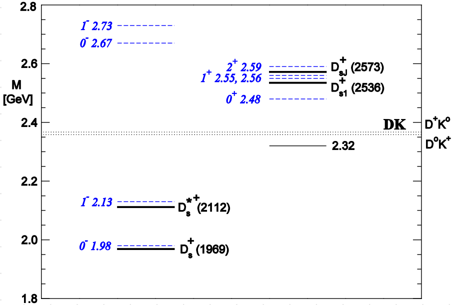
The Newly Discovered Mesons in the Charm Region

- Many candidates of tetraquark states are discovered recently.
- In the charm region: $D_{s0}(2317)$, $X(3872)$, $Z^{+}(4430)$, ...
- Tetraquarks or conventional mesons?
  Lattice QCD will tell ...

$D_{s0}^*(2317)$

- $I(J^P) = 0(0^+)$
- Mass = $2317.8 \pm 0.6 MeV$
- Decay to: $D_s\pi$, $D_s\gamma, \ldots$



Valence overlap fermions on 2+1 flavor domain wall fermion configurations

- Chiral symmetry
- Small $O(a^2)$ and $O(m^2a^2)$ errors
+ Accelerated with Deflation and HYP smearing algorithm
+ Accelerated with Multi-mass algorithm

Table: Speedup comparison of inversion[1]

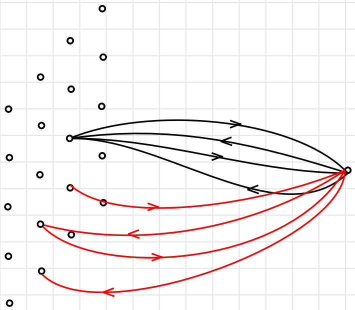
		16^3x32			24^3x64			32^3x64		
	residue	w/o D	D	D+S	w/o D	D	D+S	w/o D	D	D+S
lowmode	10^{-8}	0	200	200	0	200	200	0	400	400
inner iter	10^{-11}	340	321	108	344	341	107	309	281	101
outer iter	10^{-8}	627	72	85	2931	147	184	4028	132	156
overhead				5 pro			5 pro			6 pro
speed up				23			51			79

[1] A. Li et al., arXiv1005.5424v1

Z_4 Grid Source

- Grid: To increase the statistics.
  - The grid spacing is set to 8
- Z_4 noise: To eliminate the contaminations.
  - Use forward propagators for anti-quarks:

$$D^{-1}\eta = \left(D^{\dagger -1}\eta^{*}\right)^{*,T_d,T_c}$$



The volume dependence of spectrum weight

- For point source and summed point sink: [2]
  - One-particle and two-particle states can be distinguished with the volume dependence :

$$C^{1p}(t) = \frac{M^2}{2E} e^{-Et}$$

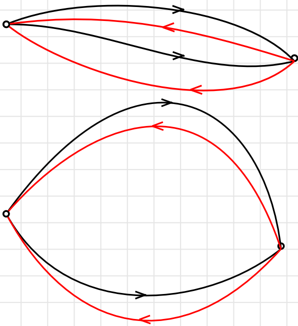
$$C^{2p}(t) = \frac{M_1^2 M_2^2}{4VE_1E_2} e^{-(E_1+E_2)t}$$

  - But for summation of a set of states, The volume dependence depends on the structure of the energy levels.

[2] N. Mathur et al., Phys. Rev. D76 (2007) 114505.

Hybrid spatial boundary condition[3]

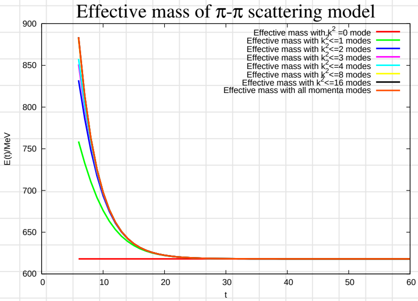
- With point source, the possible "quark momenta" on every dimension are :
  - With periodic spatial boundary condition: $0, \pm\frac{2\pi}{L}, \pm\frac{4\pi}{L}, ...$
  - With anti-periodic spatial boundary condition: $\pm\frac{\pi}{L}, \pm\frac{3\pi}{L}, ...$
- With hybrid spatial boundary condition:
  - The ground state of a tetraquark keeps zero momentum
  - The ground states of two scattering mesons have momenta of $(\pm\frac{\pi}{L}, \pm\frac{\pi}{L}, \pm\frac{\pi}{L})$

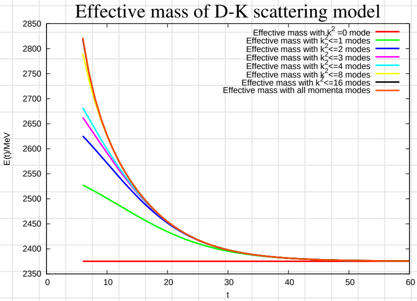


[3] H. Suganuma et al., Prog. Theor. Phys. Suppl. 168 (2007) 168.

Scattering states with all momenta

+ The scattering states: $E(p) = \sqrt{m^2 + p^2}$
- In charm region, the energy levels are dense.
+ The effective masses of different scattering models.





- We have to consider more scattering states with non-zero relative momenta in charm region.

Simulation parameters

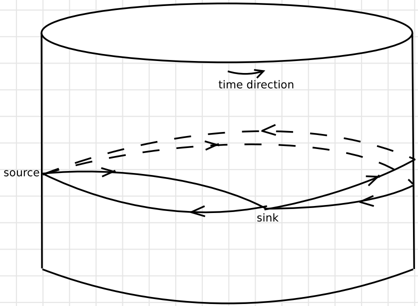
- Configurations: RBC 2+1 flavor domain wall fermion configurations
- Lattice: $16^3 \times 32$ and $24^3 \times 64$, $1/a = 1.73(3) GeV$
- ≈ 40 configurations
- Quark mass: from 0.00140 to 0.90
  - In this case, we use $m_{u/d} = 0.0135(m_\pi = 310 MeV)$, $m_s = 0.067$, $m_c = 0.68$

The interpolation field and states

- We use $\bar{c}\gamma_5 u\bar{u}\gamma_5 s$ for $D_{s0}(2317)$
- The correlation function may contain:
  - DK scattering states
  - $D_s\pi$ scattering states
  - a possible tetraquark state
  - other higher states ...
- Both the scattering states dominate the correlation function
  - The effective mass with the hybrid spatial boundary condition is evidently larger than the one with the ordinary boundary condition
  - Fitting with only DK scattering states is not successful
  - Fitting result with both DK and $D_s\pi$ scattering states is reasonable

Wrap-around States

- Wrap-around states have to be considered in $16^3 \times 32$ lattice



- The correlation function of the state is :

$$C(t) = W\left(e^{-E_1 t - E_2(T-t)} + e^{-E_2 t - E_1(T-t)}\right)$$

The assumption

- The assumption in this model:
  - The matrix elements in the spectrum weight and the energy shifts are not very sensitive to momenta
    - Several low-lying states dominate the correlation function
    - It will be checked and improved with open-jaw diagram calculations
  - The spectrum weight of $D_s\pi$ and DK states are nearly same
    - The fit results are not sensitive to the ratio of $D_s\pi$ and DK states
    - The ratio can be calculated with open-jaw diagram
  - The spectrum weight of the normal states and the wrap-around states are the same
    - The interaction of the two scattering meson is assumed weak

The fitting model

- The fitting model is :

$$C(t) = C_{D_s\pi}(t) + C_{DK}(t) + C^{wrap}_{D_s\pi}(t) + C^{wrap}_{DK}(t) + C_T(t)$$

  - with

$$C_{AB} = W\sum_p \frac{e^{-(E_A(p)+E_B(-p)+\Delta E)t}}{E_A(p)E_B(-p)} + (t \leftrightarrow T-t)$$

$$C^{wrap}_{AB} = W\sum_p \frac{e^{-E_A(p)t-E_B(-p)(T-t)}}{E_A(p)E_B(-p)} + (t \leftrightarrow T-t)$$

$$C_T(t) = W'e^{-E't}$$

$$E(p) = \sqrt{m^2+p^2}$$

with ordinary bondary condition: $p = \frac{2k\pi}{L}(k = 0, 1, 2, ...)$

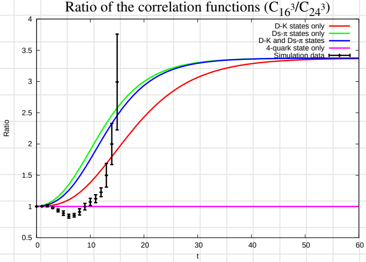
with hybrid bondary condition: $p = \frac{(2k-1)\pi}{L}(k = 0, 1, 2, ...)$

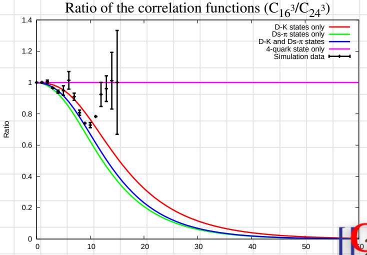
The fit results

	χ^2/DOF	ΔE	W	E'	W'
16 P	0.463	0.39934×10^{-2} $\pm 0.63615 \times 10^{-2}$	0.10712×10^{-6} $\pm 0.63315 \times 10^{-8}$	$0.22639 \times 10^{+1}$ $\pm 0.27234 \times 10^{-1}$	0.18320^{-3} $\pm 0.23682 \times 10^{-4}$
16 H	1.074	0.36784×10^{-2} $\pm 0.64329 \times 10^{-2}$	0.20188×10^{-6} $\pm 0.13729 \times 10^{-8}$	$0.22328 \times 10^{+1}$ $\pm 0.88999 \times 10^{-1}$	0.17110^{-3} $\pm 0.82404 \times 10^{-4}$
24 P	1.264	-0.18854×10^{-2} $\pm 0.39254 \times 10^{-2}$	0.17442×10^{-6} $\pm 0.67182 \times 10^{-8}$	$0.21837 \times 10^{+1}$ $\pm 0.26734 \times 10^{-1}$	0.28339^{-3} $\pm 0.32372 \times 10^{-4}$
24 H	0.946	-0.71741×10^{-2} $\pm 0.40762 \times 10^{-2}$	0.18695×10^{-6} $\pm 0.85325 \times 10^{-8}$	$0.22663 \times 10^{+1}$ $\pm 0.85423 \times 10^{-1}$	0.36241^{-3} $\pm 0.16591 \times 10^{-3}$

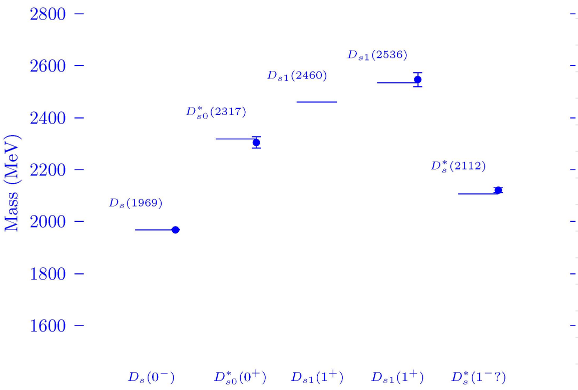
Volume Dependence of Correlation function

- The volume dependence is very complex in the case.
  - We have many states with different spectrum weights and energies.
  - The volume dependence also depends on the interaction of scattering mesons.





The result from conventional meson spectrum Calculation [4]



[4] S.J. Dong et al., arXiv:0911.0868v2

Conclusion

- We did not find a tetraquark state for $D_{s0}(2317)$.
- The result agree with a previous study on the nature of $D_{s0}(2317)$
- Volume dependence method is not fit for this case
- For further study:
  - The open-jaw diagram can be studied and the ratios of the spectrum weights and ΔEs can be extracted.
  - With ΔE available, scattering length and phase shift can be calculated.
  - The charmonium-like states (X(3872), $Z^{+}(4430)$, ...) can be studied with similar method.

Thank you !