Mesons upon low-lying Dirac mode exclusion

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Motivation

Massless QCD Lagrangian with two flavours is invariant under

$$U(2)_L \otimes U(2)_R = U(1)_A \otimes U(1)_V \otimes SU(2)_A \otimes SU(2)_V$$

- $SU(2)_A$ is spontaneously broken ($\langle\overline{\psi}\psi\rangle \neq 0$)
- $U(1)_A$ is broken both spontaneously and anomalously

Chiral symmetry breaking effects are important for the hadron spectrum.

How would the hadron spectrum look like
if we artificially remove the chiral symmetry breaking dynamics?

What is the primary physics for the binding force in hadrons?

Banks-Casher relation and SCSB

Low-lying eigenmodes of the Dirac operator encode the effects of SχSB

Banks-Casher (1980)

$$\langle 0|\overline{q}q|0\rangle = -\pi\rho(0)$$

$$\rho(0) \neq 0 \Longleftrightarrow S\chi SB$$

Goal: isolate the effects of chiral symmetry breaking in hadrons by excluding the low-lying mode dynamics

Overlap Operator

$$D(m) = (\rho + \frac{m}{2}) + (\rho - \frac{m}{2})\gamma_5\, sign(H_w)$$

Satisfies Ginsparg-Wilson(1982) relation

$$\gamma_5 D + D\gamma_5 = \frac{1}{\rho} D\gamma_5 D(0)$$

Quark propagators

We use stochastic all-to-all overlap fermion propagators

provided by JLQCD Collaboration

Define reduced quark propagators

$$S_{RD(k)}(x,y) = \sum_{n=k+1}^{N} \frac{1}{\lambda_n} u_n(x) u_n^\dagger(y) = S_{100-k} + S_{Stoch} \qquad (1)$$

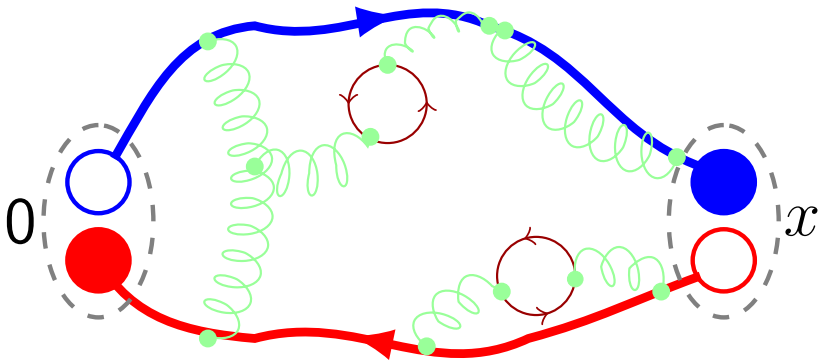
- k is the number of excluded low-lying modes

Lattice setup

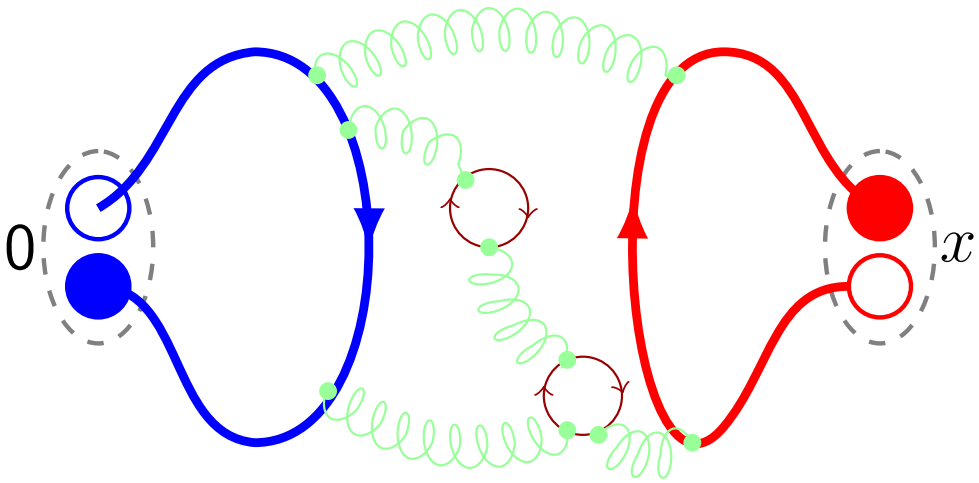
- dynamical $n_f = 2$, $N_S^3 \times N_T = 16^3 \times 32$ lattice size
- 100 conf, $a \sim 0.12$ fm, $L \approx 1.9$ fm
- $m_\pi = 289(2)$ MeV, $Q_{top} = 0$. S.Aoki et al (2008)
- $N_r = 1$, $N_d = N_c \times N_D \times N_T/2$ - noise dilution scheme

Meson propagators

$$G(t,x) = \langle \mathcal{O}(x)\mathcal{O}^\dagger(0)\rangle \tag{2}$$



Connected (C)



Disconnected (D)

$I = 0$:

$$G(t,x) = C + D \tag{3}$$

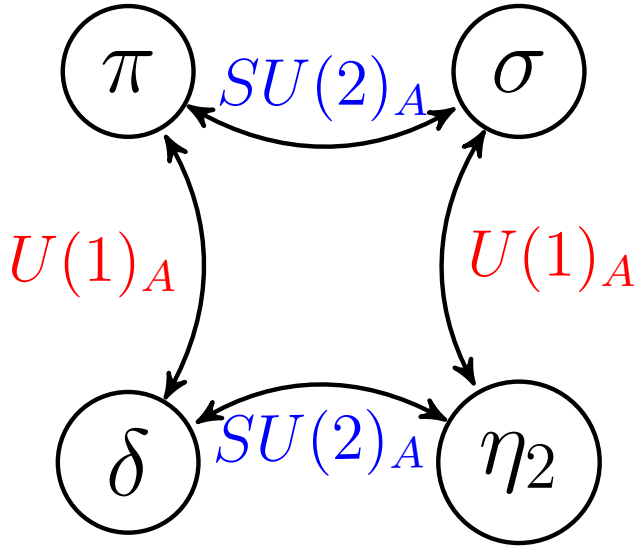
$I = 1$:

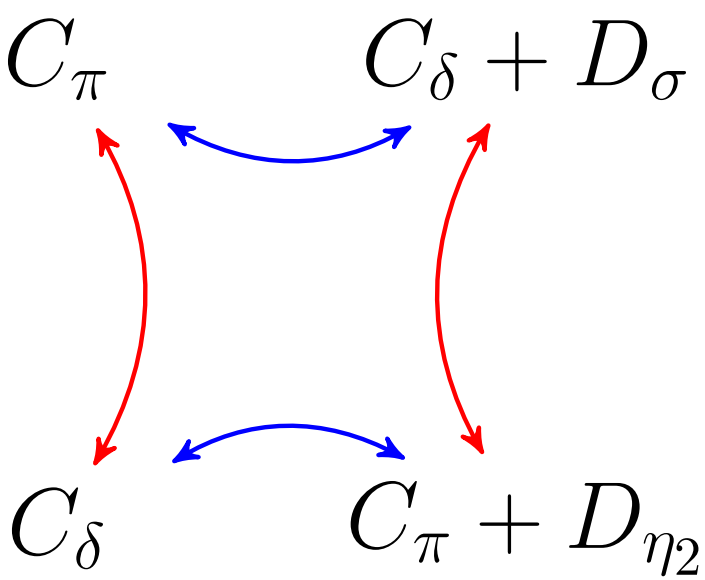
$$G(t,x) = C \tag{4}$$

Here we consider only $J = 0, 1$ non-exotic mesons

J=0 Mesons

J=0 mesons



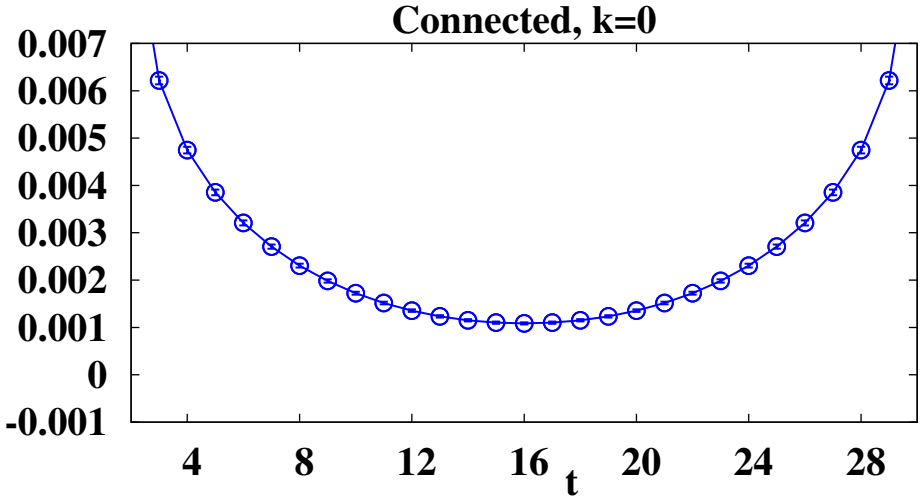


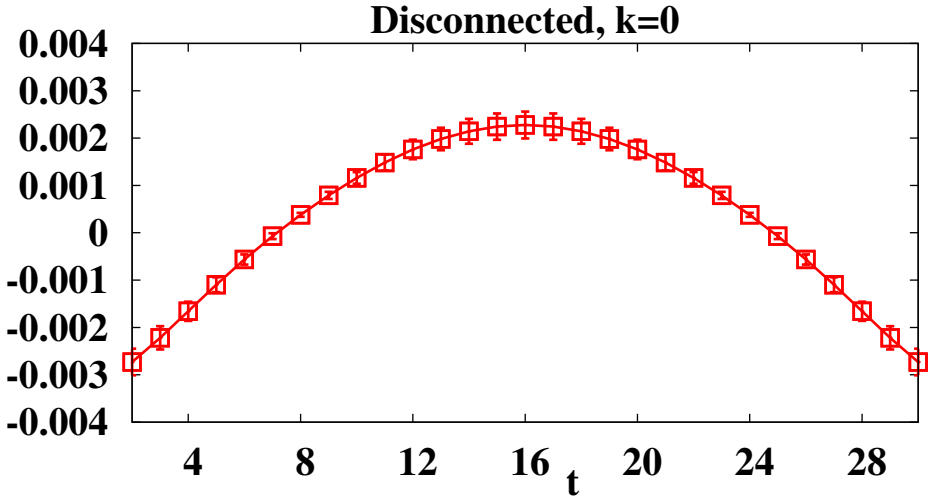
Restoration of both $SU_A(2)$ and $U_A(1)$ symmetries requires

$$C_\pi = C_\delta \ \&\& \ D_\sigma = D_{\eta_2} = 0$$

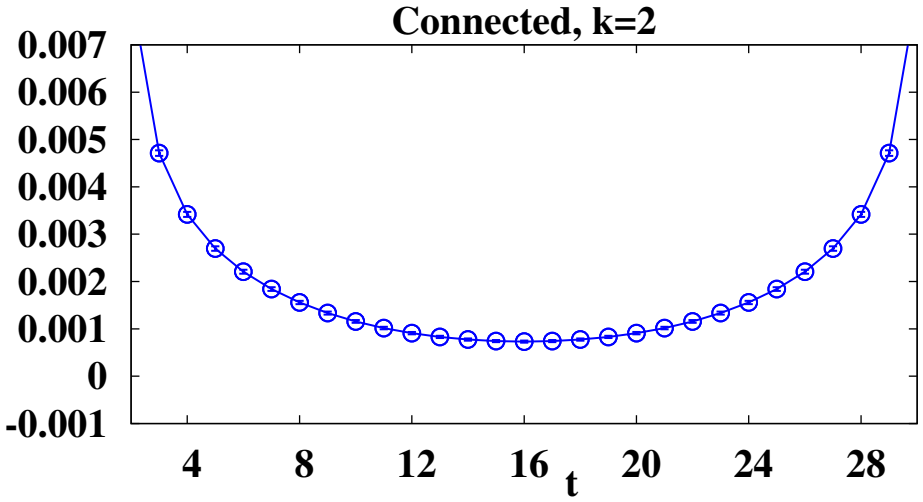
$J = 0$: $\pi(\eta_2)$ - Connected vs. Disconnected

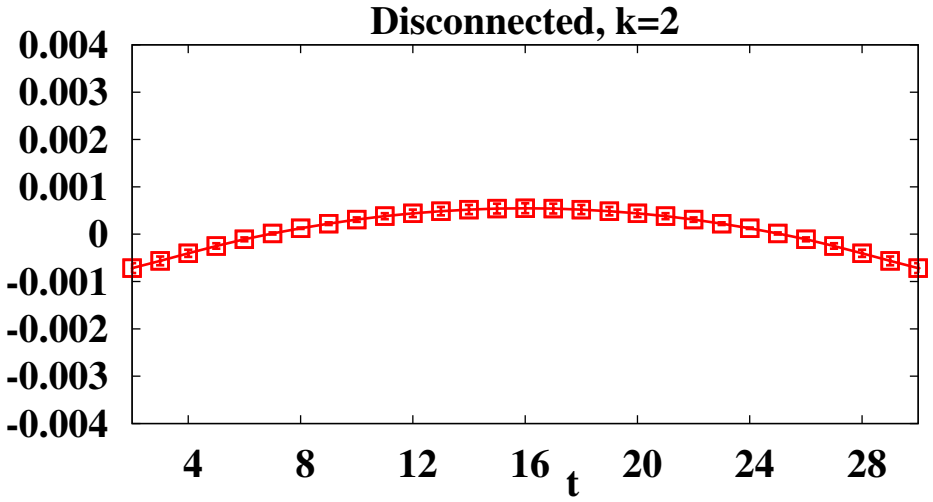
$k = 0$





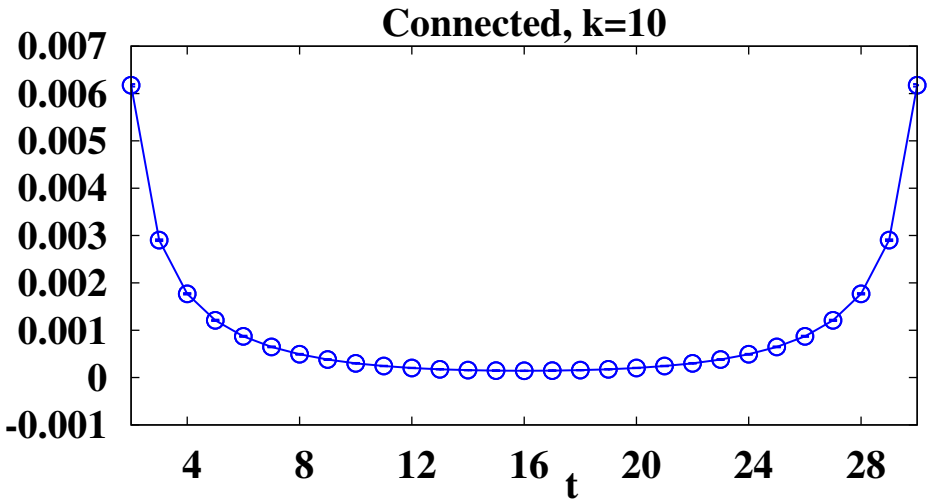
$k = 2$

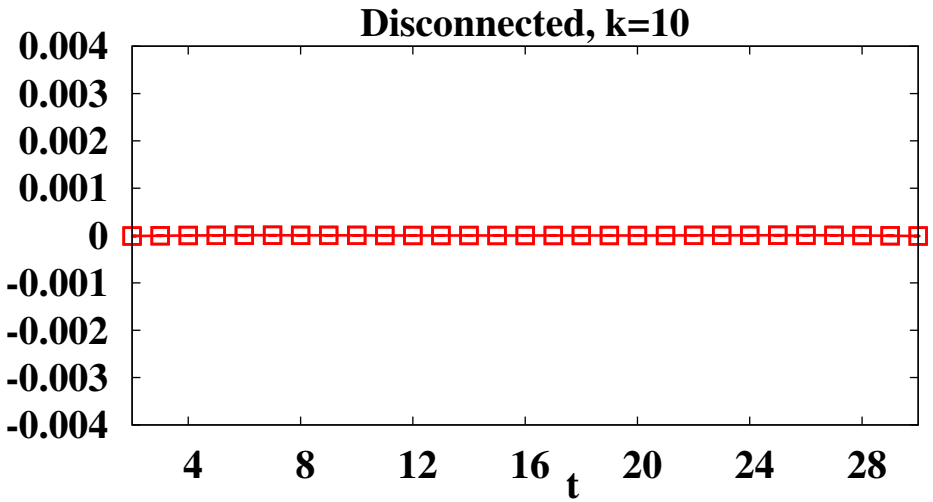




$J = 0$: $\pi(\eta_2)$ - Connected vs. Disconnected

$$k = 10$$



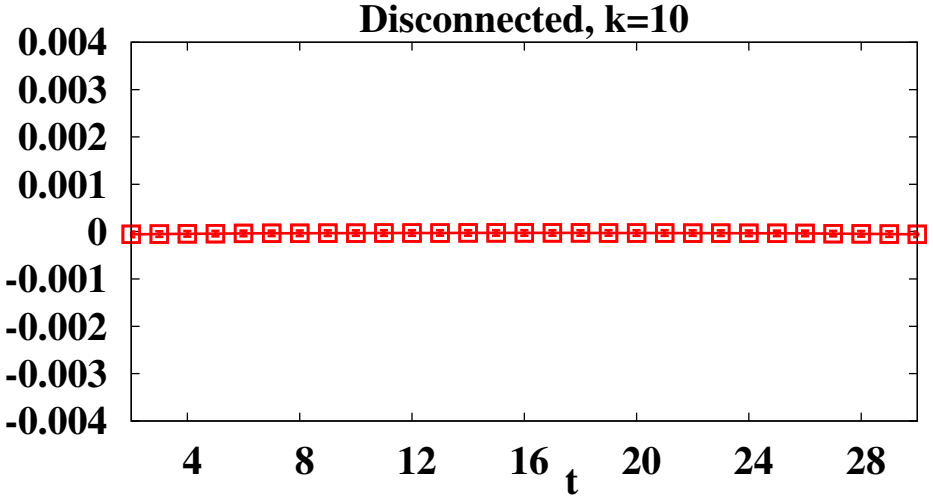


$J = 0$: $\delta(\sigma)$

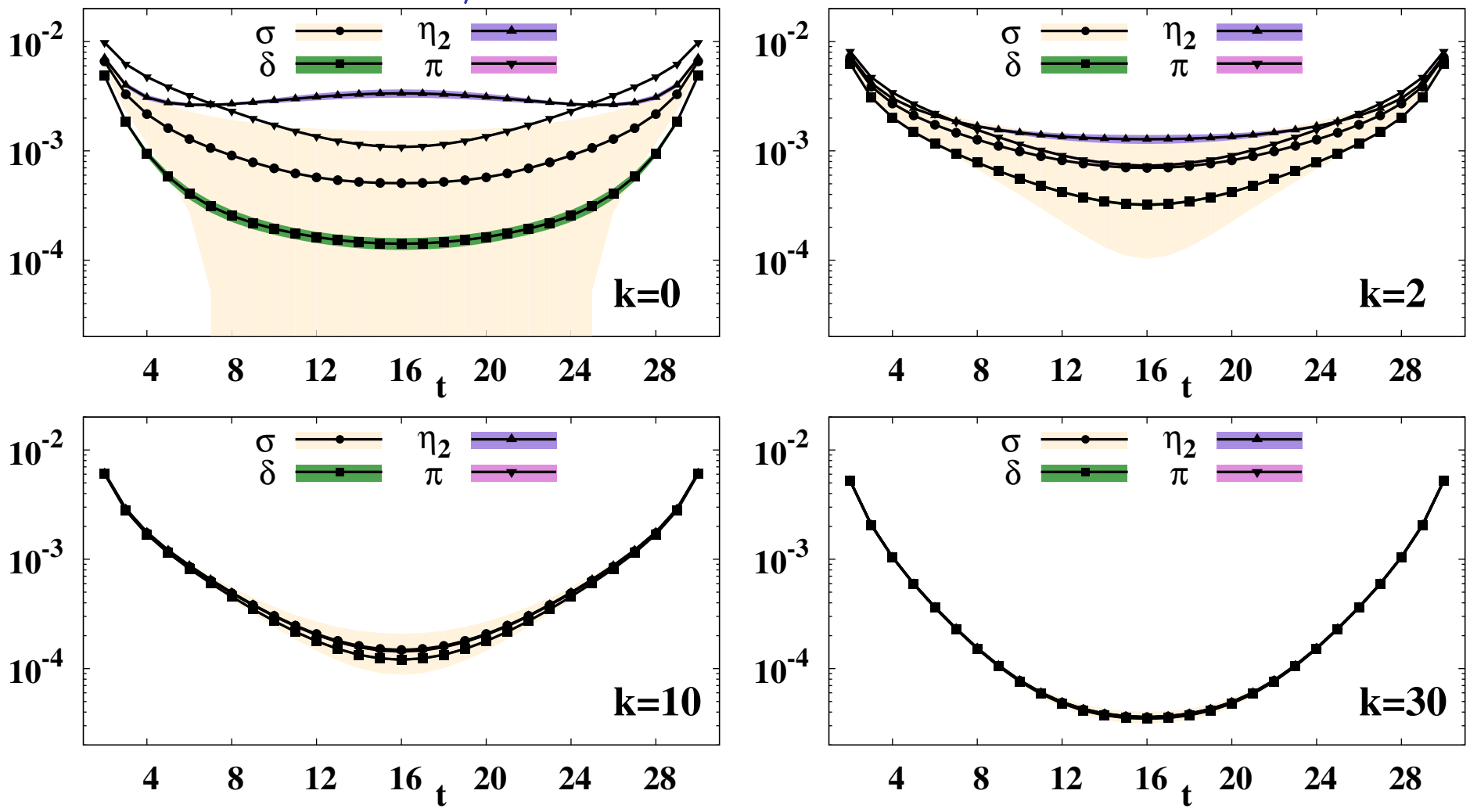
$$C_\sigma = C_\delta + \cancelto{0}{D_\sigma}$$

compare with

$$C_{\eta_2} = C_\pi + \cancelto{0}{D_{\eta_2}}$$



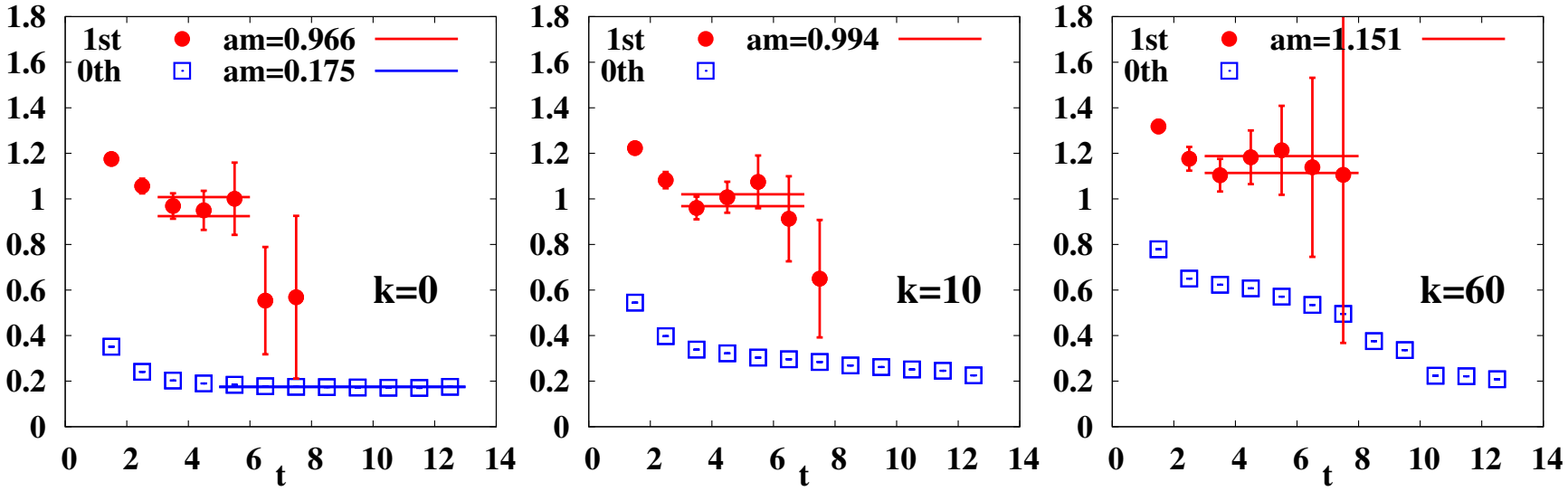
$J = 0$: isoscalar / isovector correlators



$SU(2)_L \otimes SU(2)_R \otimes U(1)_A$ symmetry is restored

What about the bound states?

$J = 0$: π - states



No pion ground state - no pseudo-Goldstone boson in the system

$k > 20$: σ, η_2, δ are identical to the π states pattern

J=1 Mesons

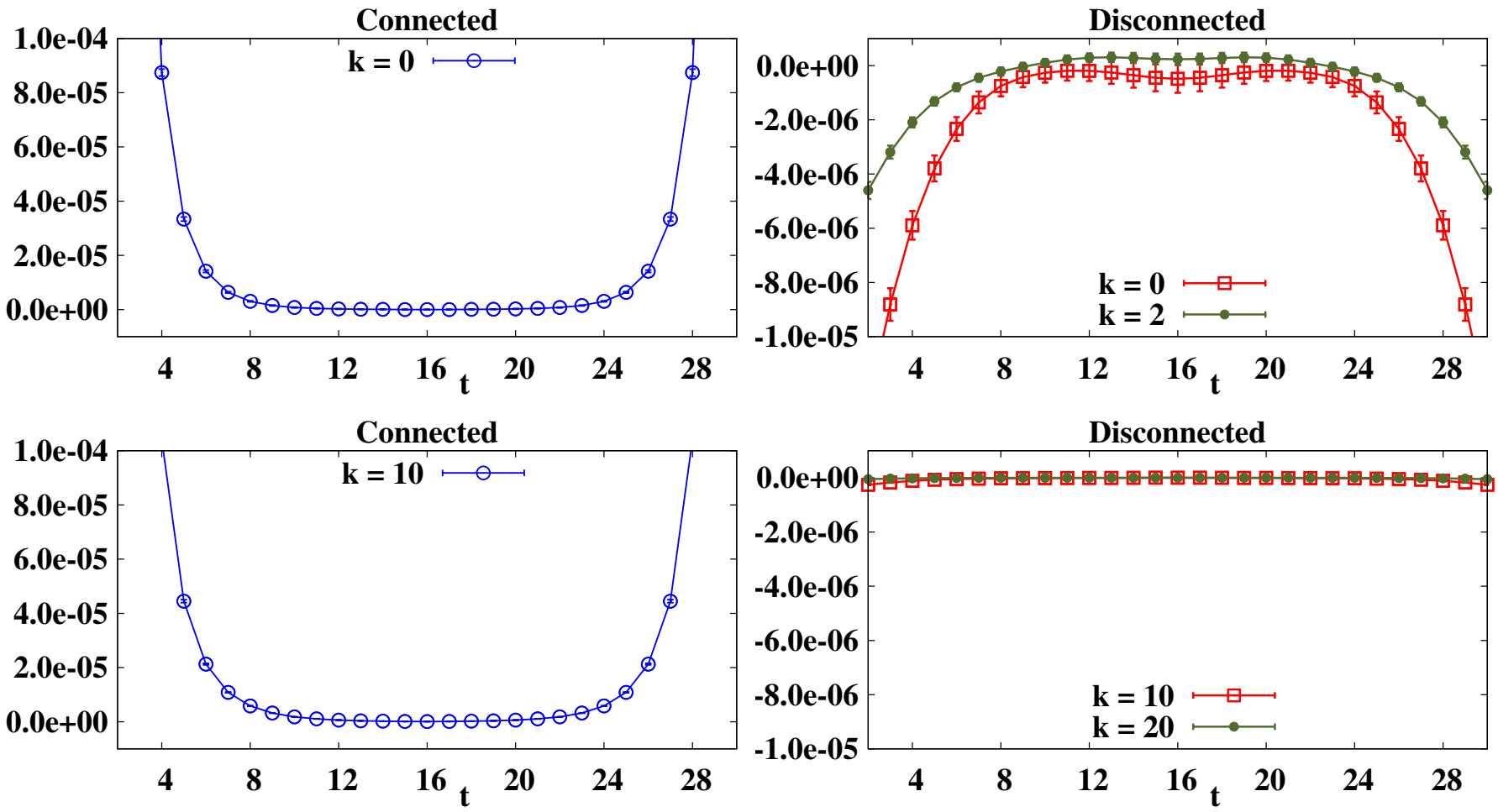
J=1:

Multiplets of the parity-chiral group $SU(2)_L \otimes SU(2)_R \otimes C_i$

R	Mesons (I, J^{PC})		
$(0,0)$	$\omega(0,1^{--})$	$\xleftrightarrow{SU(2)_A}$	$f_1(0,1^{++})$
$(\frac{1}{2},\frac{1}{2})_a$	$\omega'(0,1^{--})$	$\xleftrightarrow{SU(2)_A}$	$b_1(1,1^{+-})$
	$U(1)_A \updownarrow$		$\updownarrow U(1)_A$
$(\frac{1}{2},\frac{1}{2})_b$	$h_1(0,1^{+-})$	$\xleftrightarrow{SU(2)_A}$	$\rho'(1,1^{--})$
$(1,0)\oplus(0,1)$	$a_1(1,1^{++})$	$\xleftrightarrow{SU(2)_A}$	$\rho(1,1^{--})$

$\rho(1,1^{--})$ and $\rho'(1,1^{--})$ are two independent ρ mesons

J=1: $b_1(h_1)$ - Connected vs. Disconnected

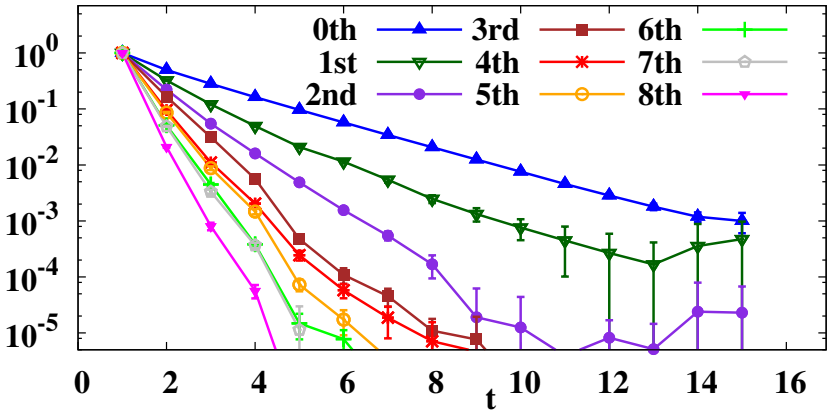


$$C_{h_1} = C_{b_1} + \cancel{D_{h_1}}^{\,0}$$ - similar to $\omega(\rho)$ and $f_1(a_1)$

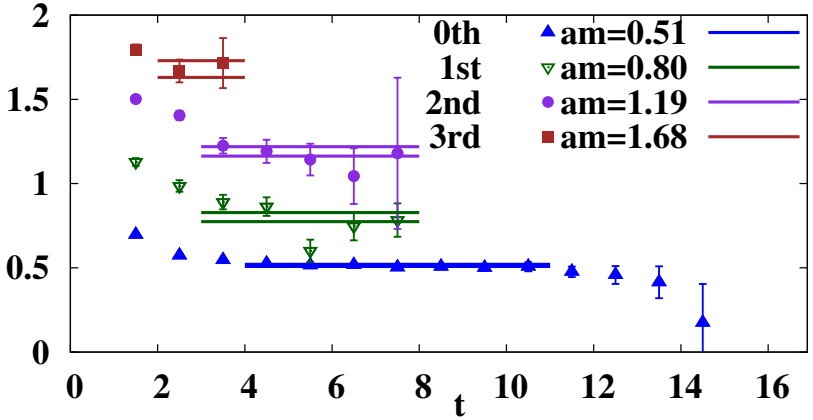
Disconnected pieces vanish as more low-lying eigenmodes are excluded

J=1: ρ - states

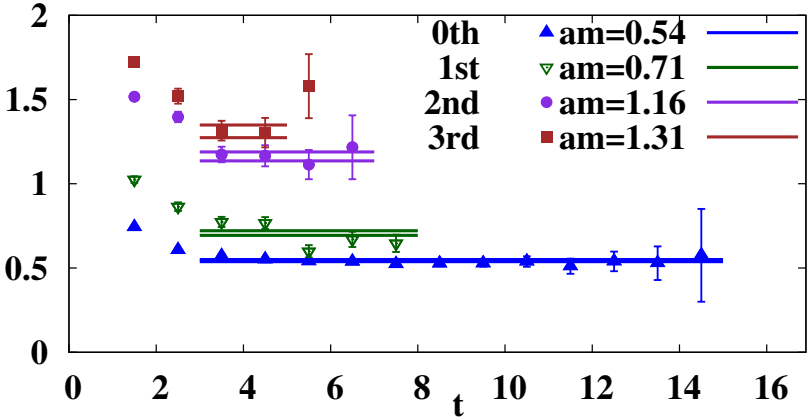
eigenvalues, $k = 0$



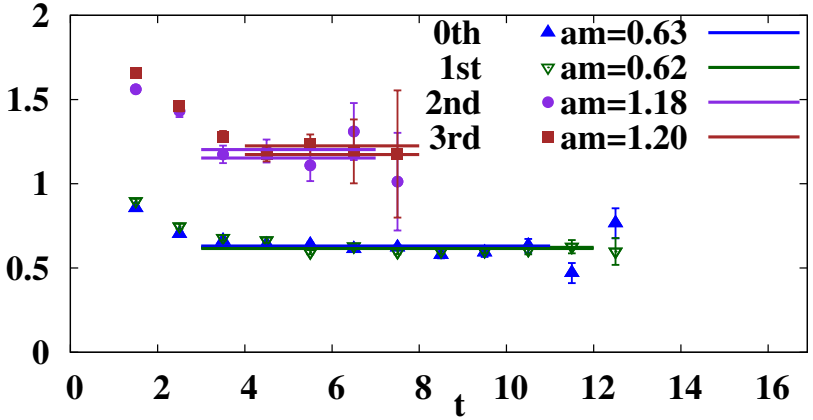
effective masses, $k = 0$



$k = 2$



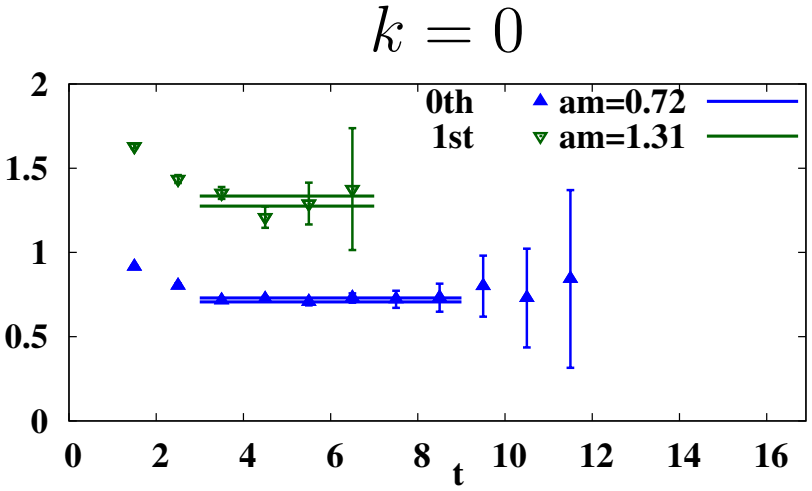
$k = 20$

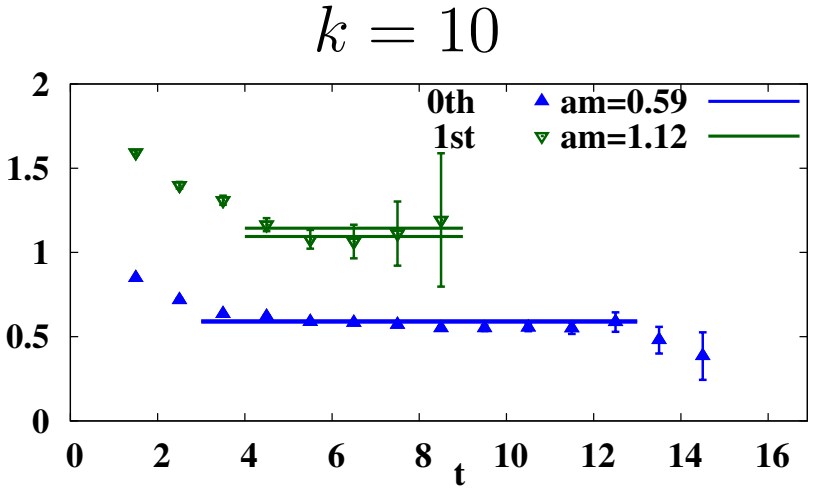


- basis with 10 interpolators
- sufficient number of interpolators with two chiral structures

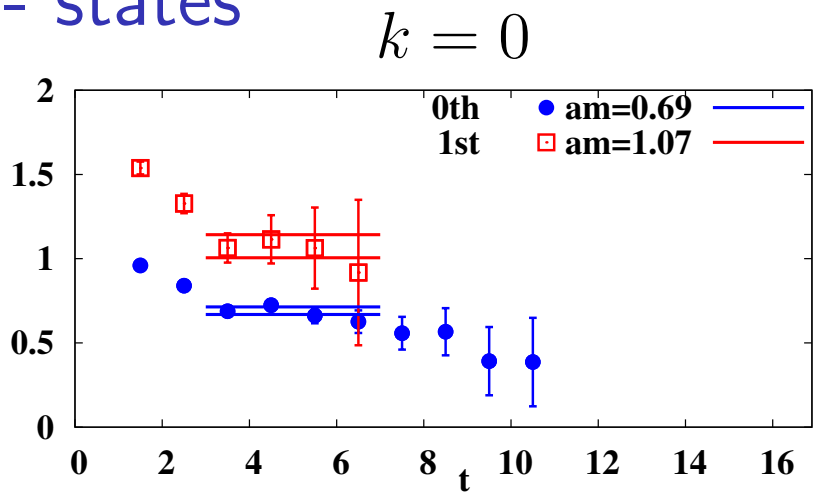
k - number of excluded low-lying eigenmodes

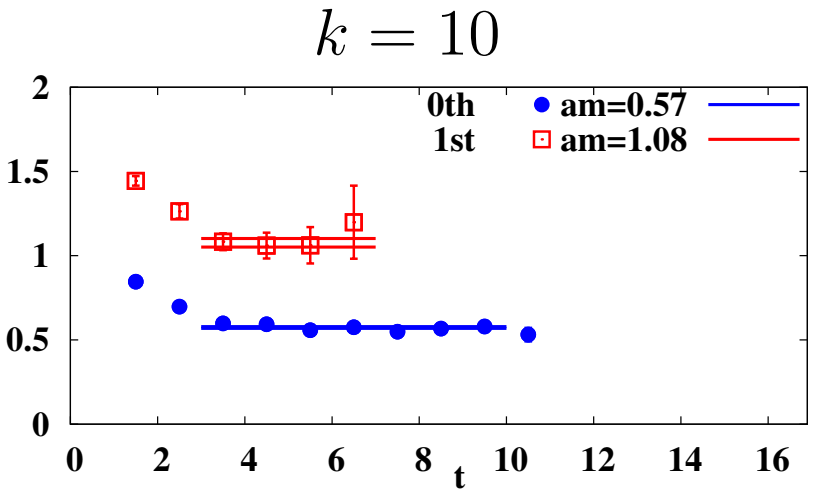
a_1 - states





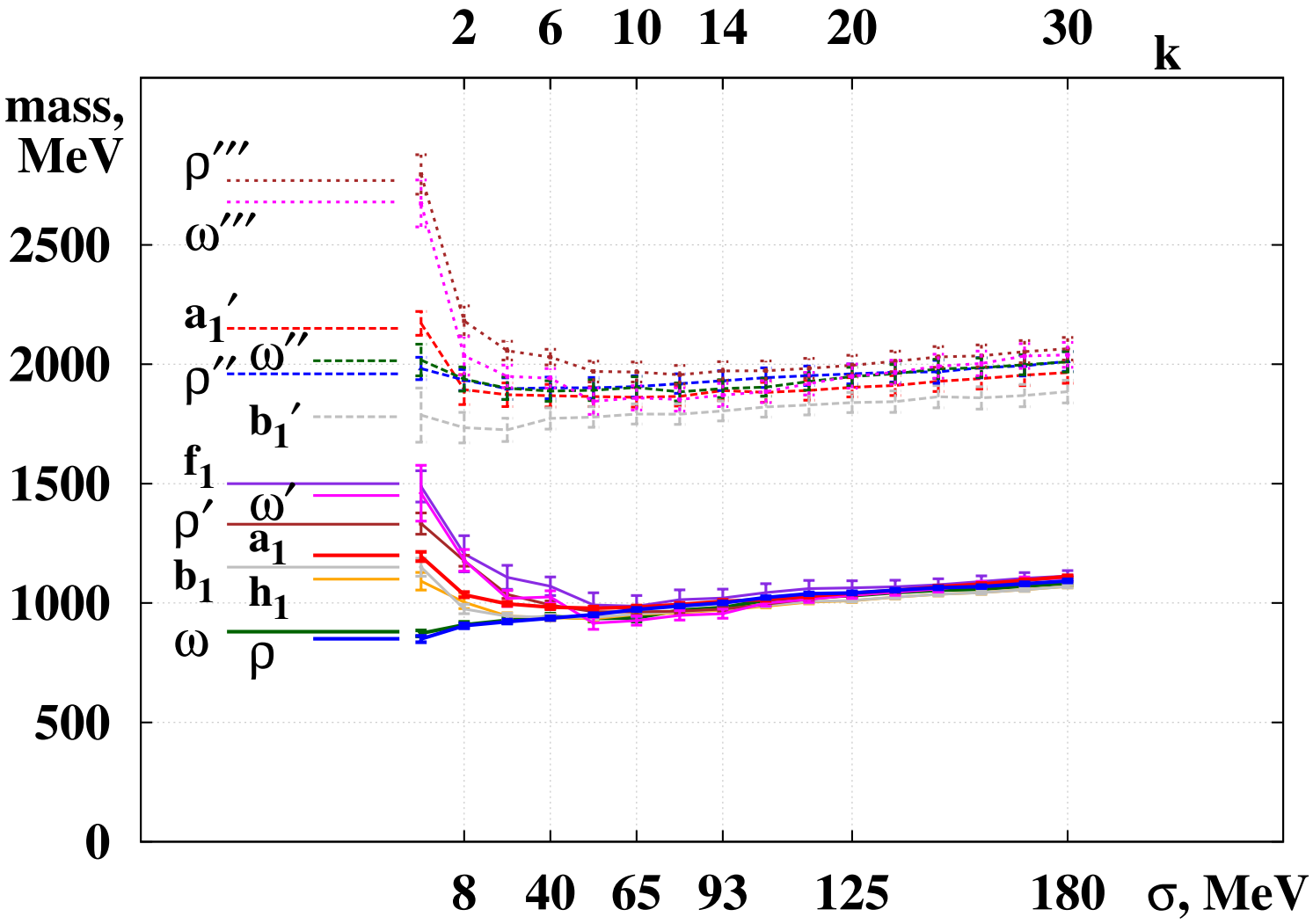
b_1 - states





k - number of excluded low-lying eigenmodes

J=1: Mass evolution of mesons



k - number of excluded low-lying eigenmodes,

σ - energy gap

Summary

- Disconnected contributions become negligibly small upon exclusion of a tiny amount of the low-lying modes from the valence quark propagators
- Both $SU(2)_L \otimes SU(2)_R$ and $U_A(1)$ symmetries are restored in $J = 0$ and $J = 1$ meson sectors

In the chirally restored regime

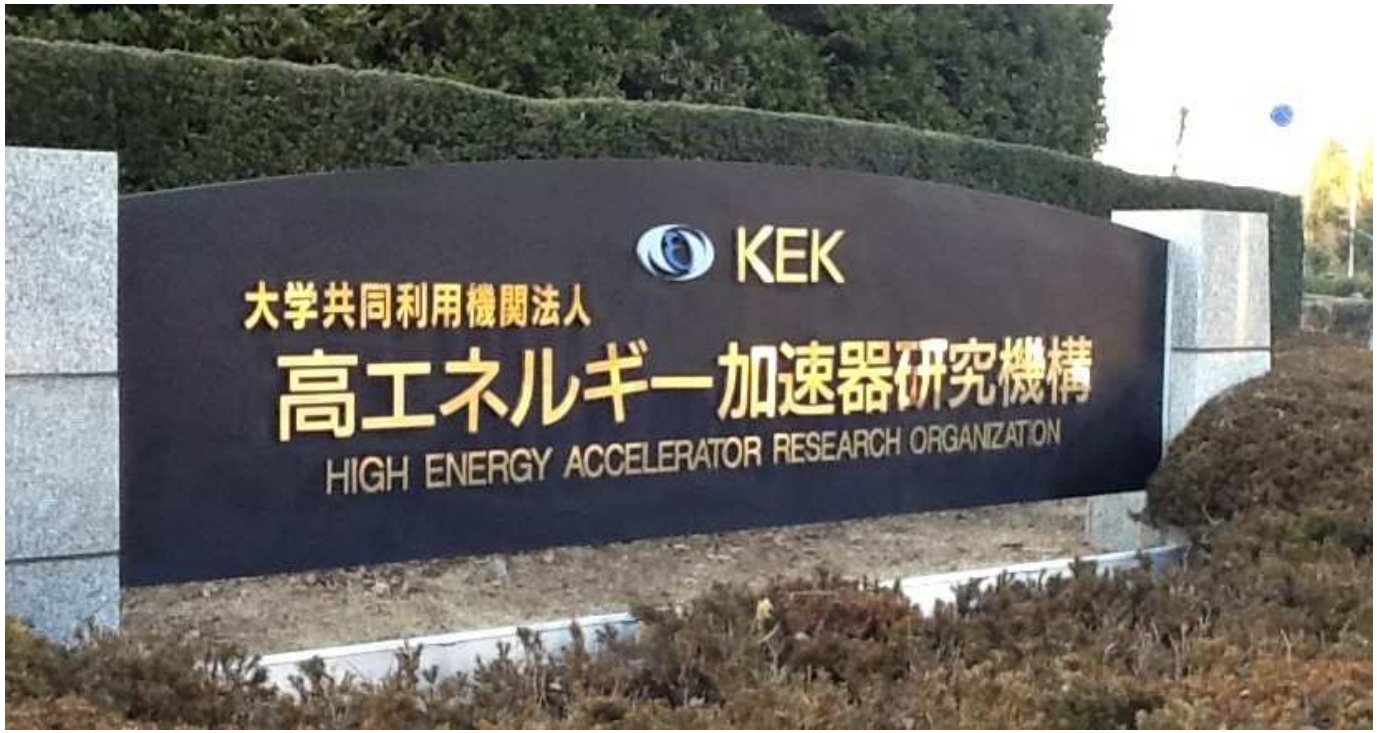
- Ground states of $J = 0$ mesons disappear
- All non-exotic $J = 1$ mesons are degenerate with $M_0 \sim 1$ GeV (hint: higher symmetry)

Please, check Glozman L.Ya. talk for more physics (Parralel 7F @ 14:15)

Special Thanks to

S.Aoki, S. Hashimoto, T.Kaneko

and



for the collaboration

Thank You for Your Attention!