Effects of the low lying Dirac modes on the spectrum of QCD

L.Ya. Glozman, C.B. Lang, Mario Schröck

Universität Graz

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- C.B. Lang, M. Schröck: PRD 84 (2011), arXiv:1107.5195
- L.Ya. Glozman, C.B. Lang, M. Schröck: *in preparation*
- M. Schröck: PLB 711 (2012), arXiv:1112.5107

Outline

Why are the lowest Dirac eigenmodes interesting?

The Banks-Casher relation

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

directly relates the density of the Dirac modes near the origin $\rho(0)$ to the chiral condensate.

Reminder: chiral symmetry and its breaking

When neglecting the two lightest quark masses, the QCD Lagrangian becomes invariant under the symmetry group

$$SU(2)_L \times SU(2)_R \times U(1)_A$$

The axial vector part of the $SU(2)_L \times SU(2)_R$ symmetry is broken spontaneously in the vacuum whereas the vector part is (approximately) preserved. The $U(1)$ axial symmetry is not only broken spontaneously but also explicitly (axial anomaly).

"Unbreaking" chiral symmetry

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  - what happens to the pion, the Goldstone boson of dynamical chiral symmetry breaking?

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  - is the broken chiral symmetry responsible for the $\Delta - N$ splitting?

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- Landau gauge quark propagator:
  - what happens to the dynamical mass generation of quarks as shown by the momentum space mass function?

Reducing quark propagators

- Consider the Hermitian Dirac operator $D_5 \equiv \gamma_5 D$ (real eigenvalues)
- Split the quark propagator $S \equiv D^{-1}$ into a low mode (lm) part and a *reduced* (red) part

$$
\begin{aligned}
S &= \sum_{i \le k} \mu_i^{-1} \left| v_i \right\rangle \left\langle v_i \right| \gamma_5 + \sum_{i > k} \mu_i^{-1} \left| v_i \right\rangle \left\langle v_i \right| \gamma_5 \\
&= S_{\mathrm{lm}(k)} + S_{\mathrm{red}(k)}
\end{aligned}
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$$= S_{\mathrm{lm}(k)} + S_{\mathrm{red}(k)}$$

- In this work we investigate the *reduced* (red) part of the propagator

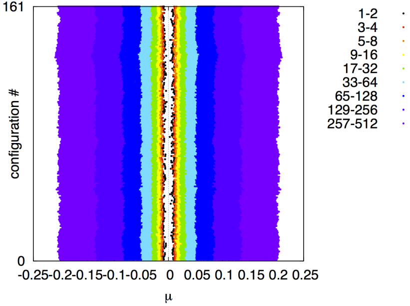
$$S_{\mathrm{red}(k)} = S - S_{\mathrm{lm}(k)}$$

The setup

- 161 configurations Gattringer et al., PRD 79 (2009)
- size $16^3 \times 32$
- two degenerate flavors of light fermions, $m_\pi = 322(5)\,\mathrm{MeV}$
- lattice spacing $a = 0.1440(12)\,\mathrm{fm}$
- Chirally Improved (CI) Dirac operator Gattringer, PRD 63 (2001) (approximate solution of the Ginsparg-Wilson equation)
- three different kinds of quark sources: Jacobi smeared narrow (0.27 fm) and wide (0.55 fm) sources and a P wave like derivative source $\rightarrow$ serves a large operator basis for the variational method.

Eigenvalues

D_5



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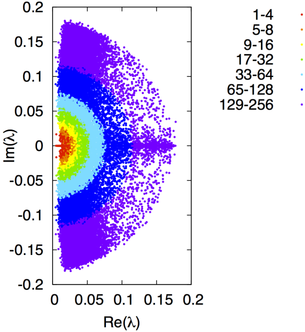

Mesons

We explore the following isovector mesons which would be related via the chiral symmetry L.Ya. Glozman, Physics Reports 444 (2007)

$U(1)_A$	$SU(2)_L \times SU(2)_R$ (axial)
$\pi \longleftrightarrow a_0$	$\rho \longleftrightarrow a_1$
$\rho \longleftrightarrow b_1$	

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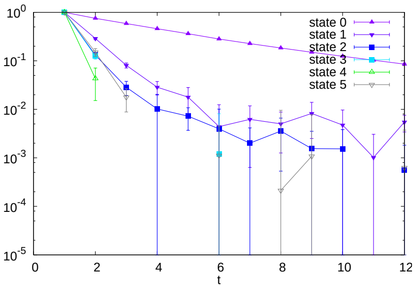
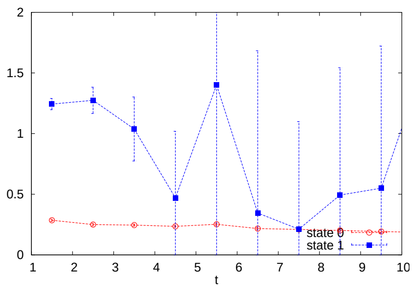
$U(1)_A$	$SU(2)_L \times SU(2)_R$ (axial)
$\pi \longleftrightarrow a_0$	$\rho \longleftrightarrow a_1$
$\rho \longleftrightarrow b_1$	$\pi \longleftrightarrow f_0$
	$a_0 \longleftrightarrow \eta$

π, $J^{PC} = 0^{-+}$, red(0)

all states: correlators

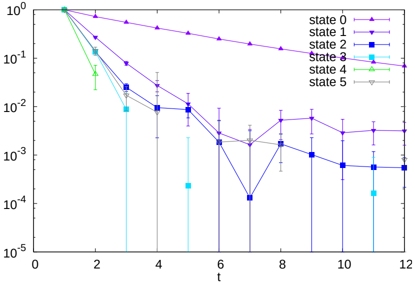


lowest state(s): eff. masses



π, $J^{PC} = 0^{-+}$, red(2)

all states: correlators



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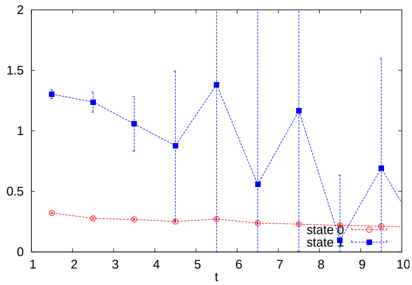
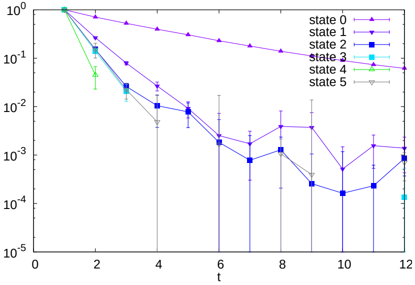
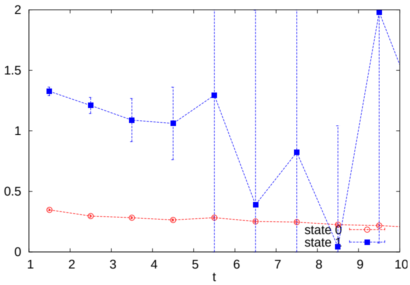


π, $J^{PC} = 0^{-+}$, red(4)

all states: correlators

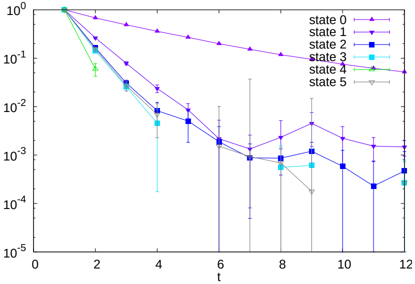


lowest state(s): eff. masses

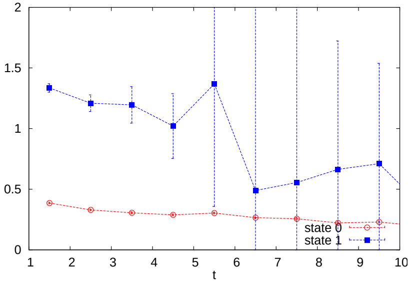


π, $J^{PC} = 0^{-+}$, red(8)

all states: correlators

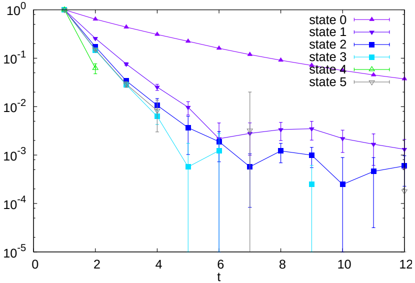


lowest state(s): eff. masses

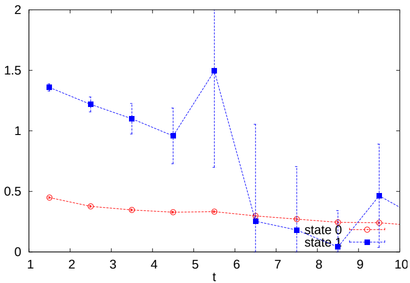


π, $J^{PC} = 0^{-+}$, red(16)

all states: correlators

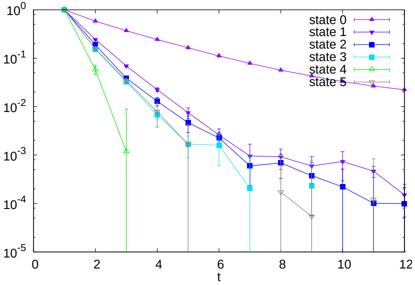


lowest state(s): eff. masses

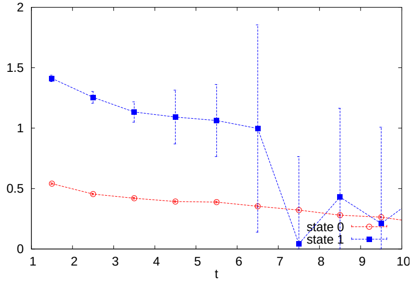


π, $J^{PC} = 0^{-+}$, red(32)

all states: correlators

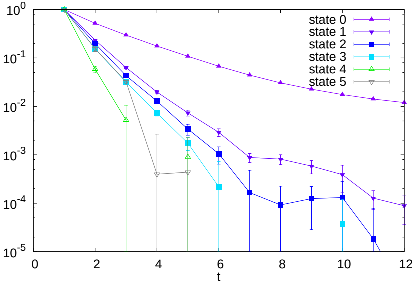


lowest state(s): eff. masses

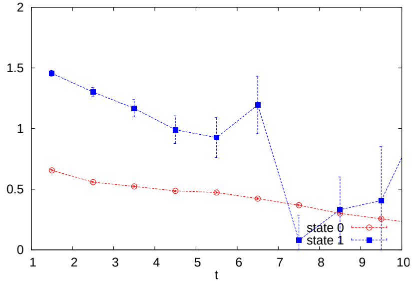


π, $J^{PC} = 0^{-+}$, red(64)

all states: correlators

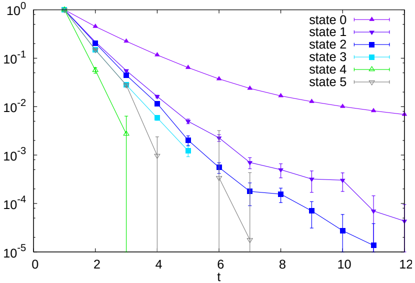


lowest state(s): eff. masses

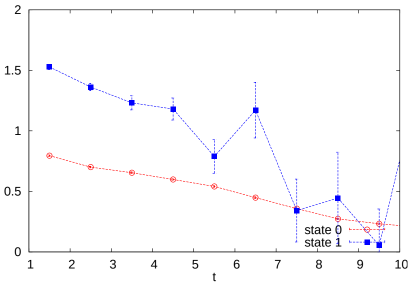


π, $J^{PC} = 0^{-+}$, red(128)

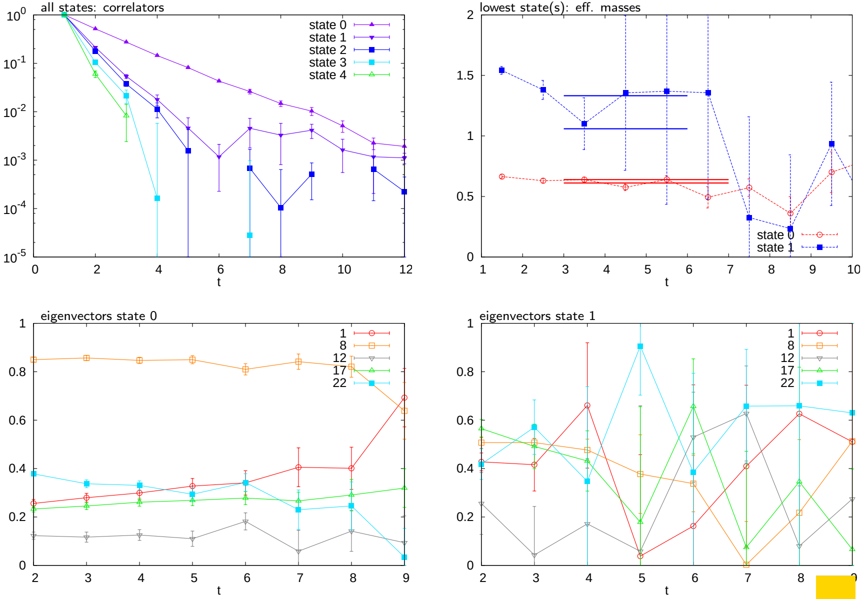
all states: correlators



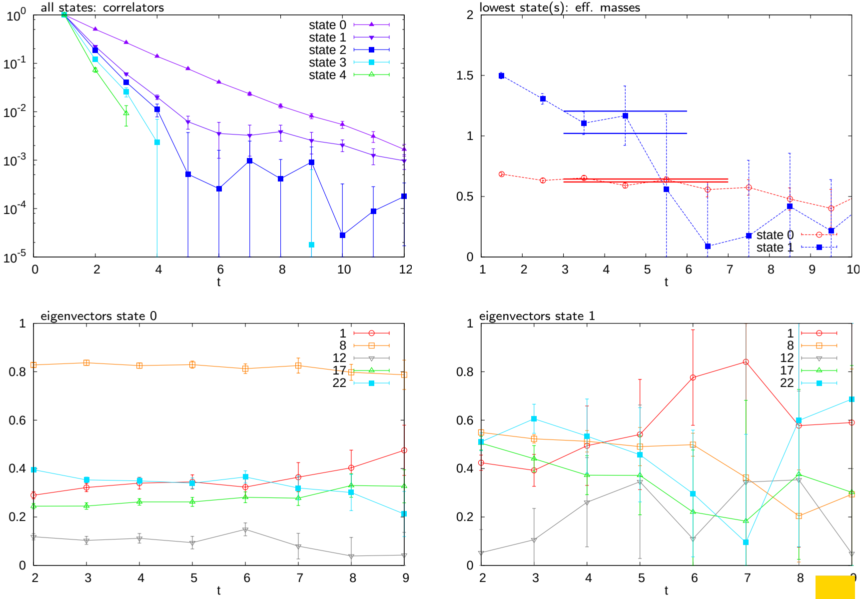
lowest state(s): eff. masses



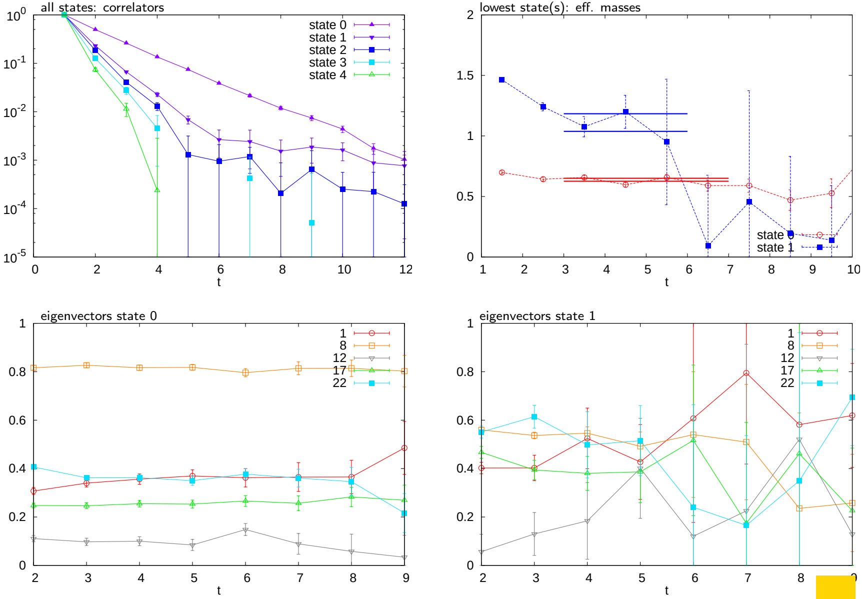
ρ, $J^{PC} = 1^{--}$, red(0)



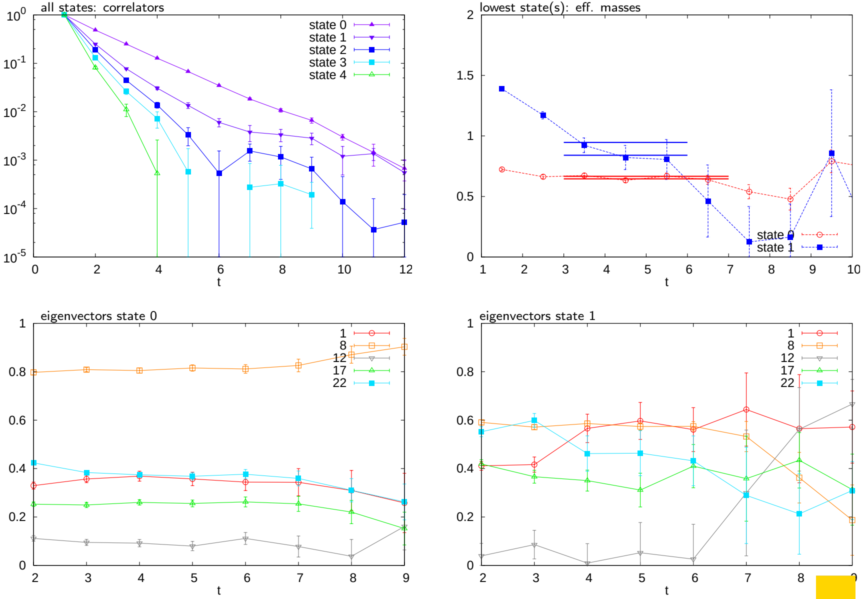
ρ, $J^{PC} = 1^{--}$, red(2)



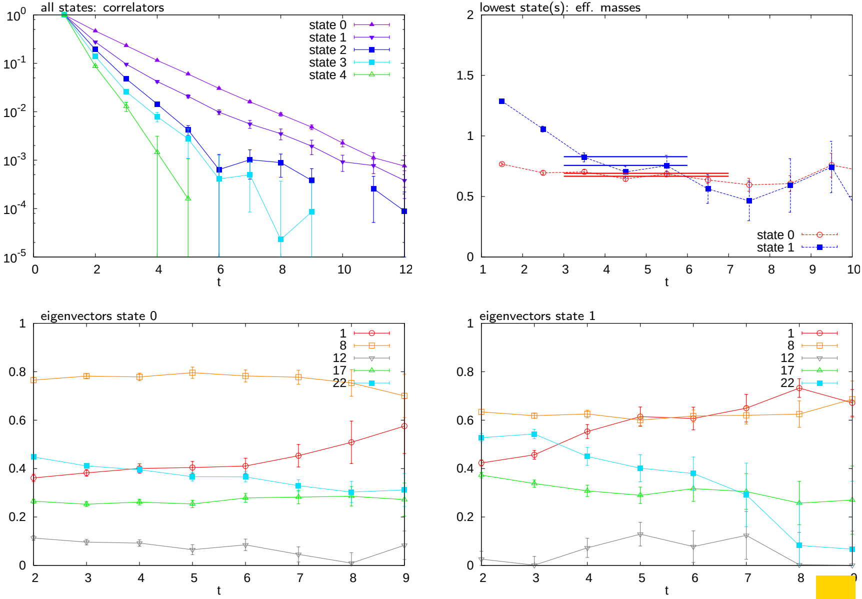
ρ, $J^{PC} = 1^{--}$, red(4)



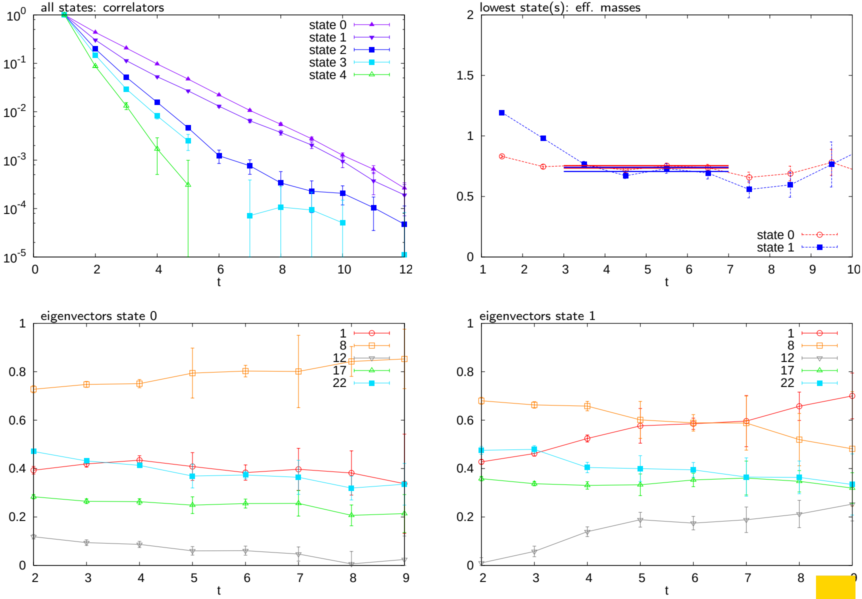
ρ, $J^{PC} = 1^{--}$, red(8)



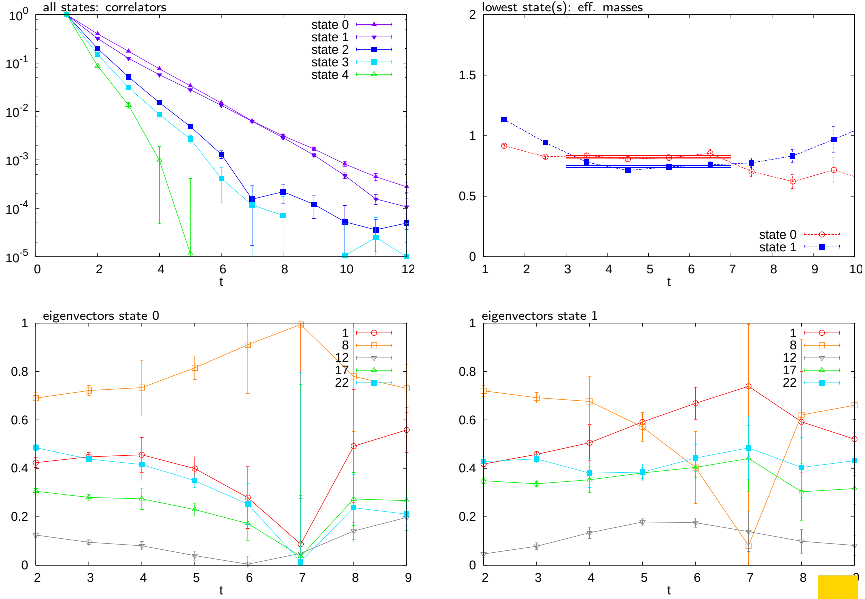
ρ, $J^{PC} = 1^{--}$, red(16)



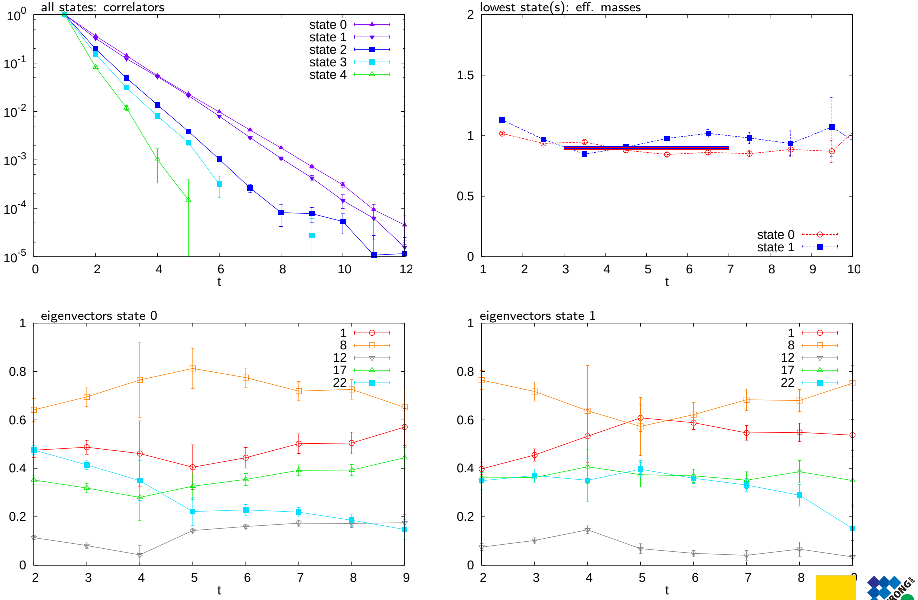
ρ, $J^{PC} = 1^{--}$, red(32)



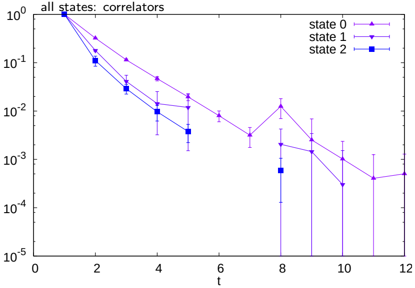
ρ, $J^{PC} = 1^{--}$, red(64)

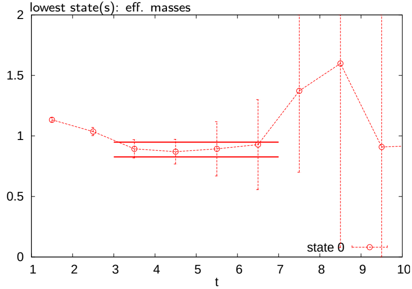


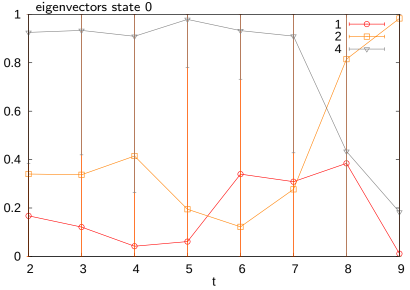
ρ, $J^{PC} = 1^{--}$, red(128)



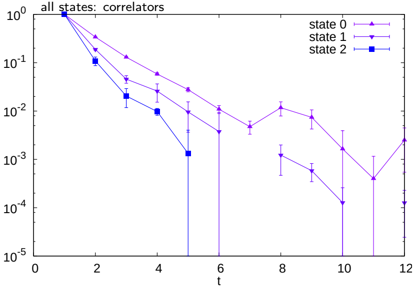
a_1, $J^{PC} = 1^{++}$, red(0)


all states: correlators
state 0
state 1
state 2
t


lowest state(s): eff. masses
state 0
t


eigenvectors state 0
1
2
4
t

a_1, $J^{PC} = 1^{++}$, red(2)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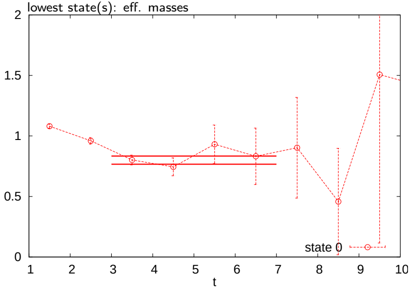
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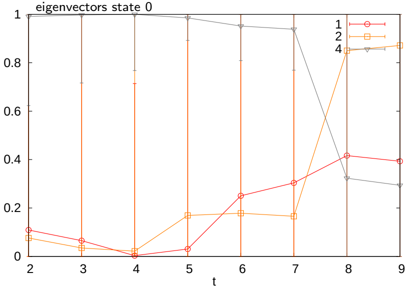
state 0
t


eigenvectors state 0
1
2
4
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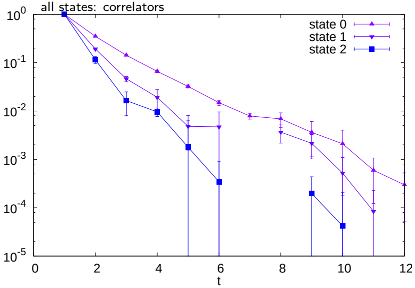
a_1, $J^{PC} = 1^{++}$, red(4)


all states: correlators
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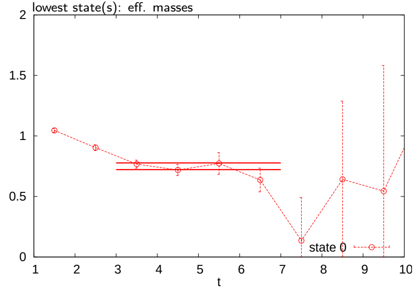
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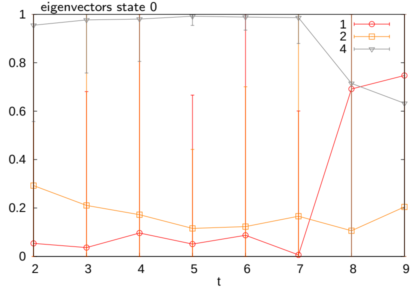
eigenvectors state 0
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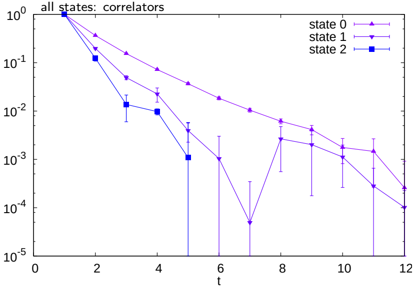
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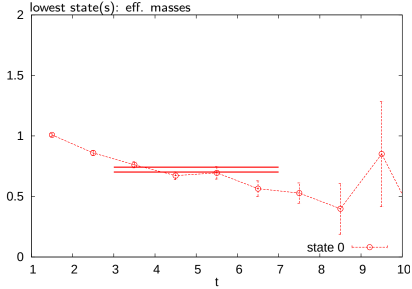
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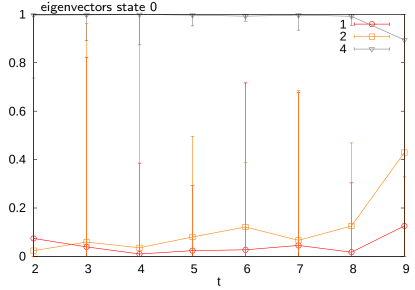
state 0
t


eigenvectors state 0
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4
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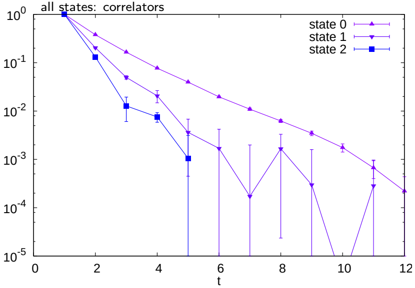
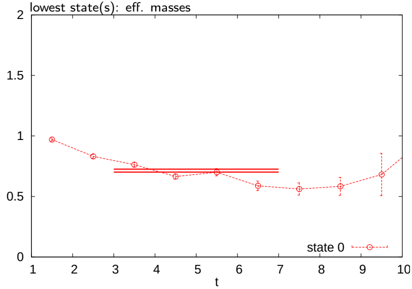
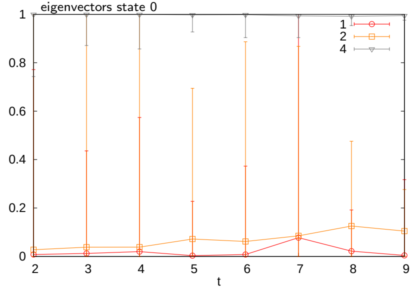
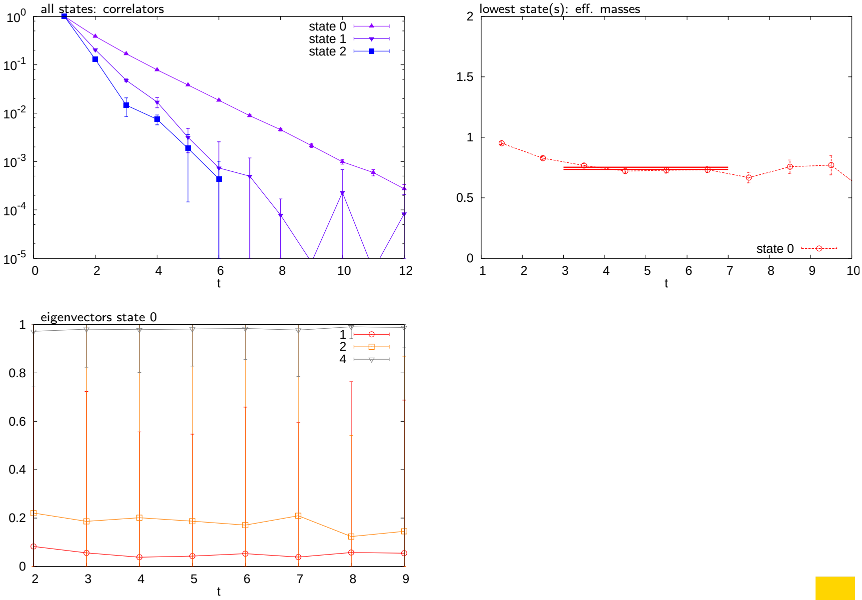
a_1, $J^{PC} = 1^{++}$, red(16)



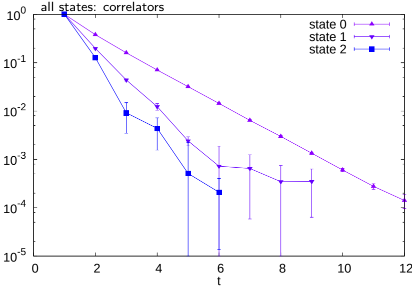


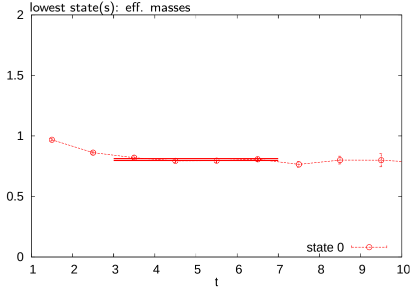


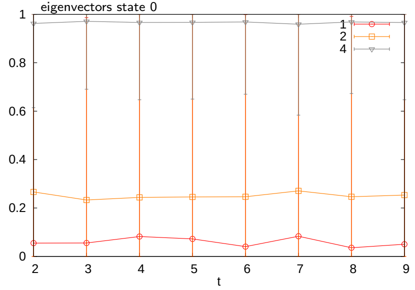
a_1, $J^{PC} = 1^{++}$, red(32)



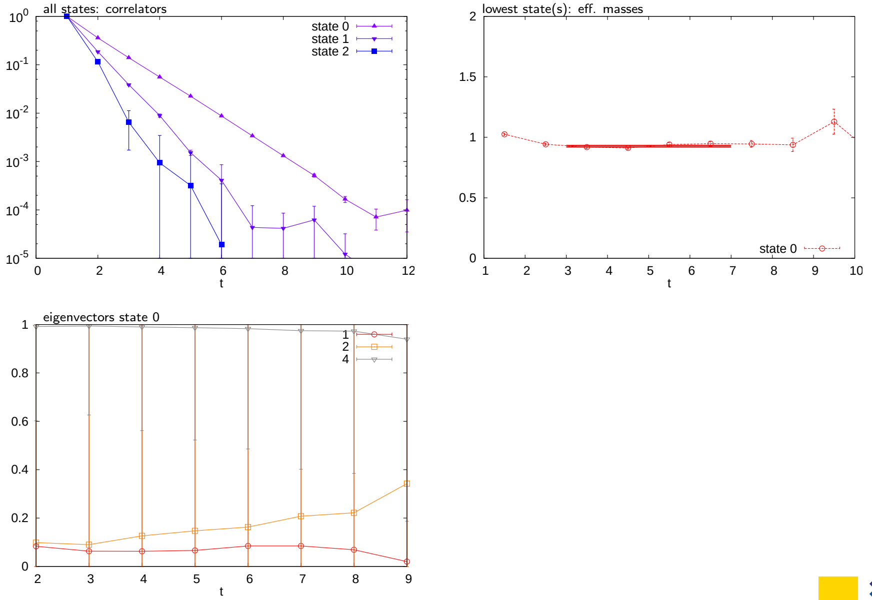
a_1, $J^{PC} = 1^{++}$, red(64)



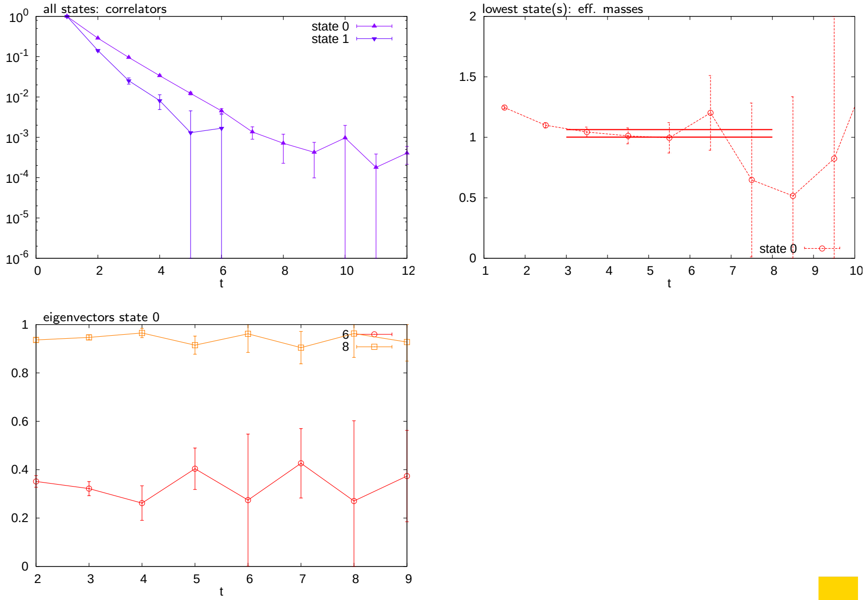




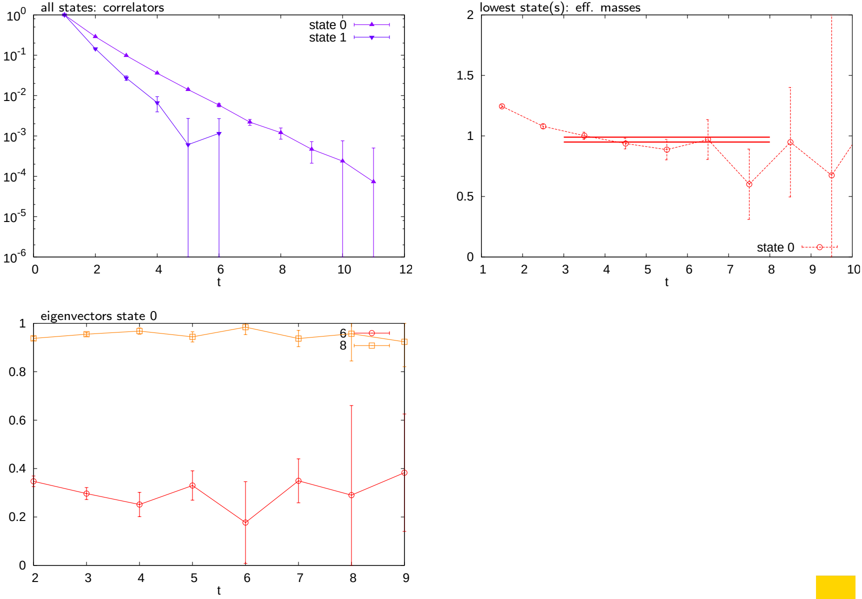
a_1, $J^{PC} = 1^{++}$, red(128)



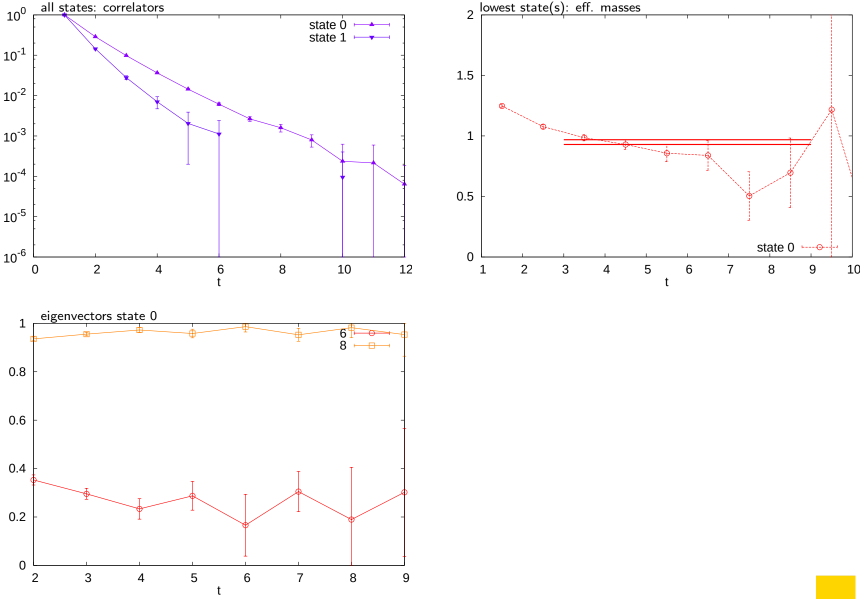
b_1, $J^{PC} = 1^{+-}$, red(0)


all states: correlators
state 0
state 1
t
lowest state(s): eff. masses
state 0
t
eigenvectors state 0
6
8
t

b_1, $J^{PC} = 1^{+-}$, red(2)


all states: correlators
state 0
state 1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
2
4
6
8
10
12
t
lowest state(s): eff. masses
2
1.5
1
0.5
0
state 0
1
2
3
4
5
6
7
8
9
10
t
eigenvectors state 0
6
8
1
0.8
0.6
0.4
0.2
0
2
3
4
5
6
7
8
9
t

b_1, $J^{PC} = 1^{+-}$, red(4)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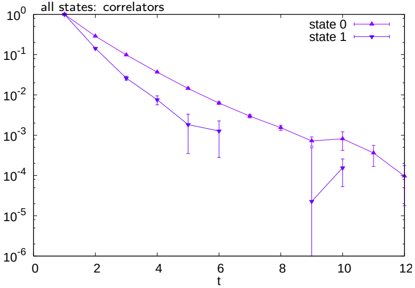
b_1, $J^{PC} = 1^{+-}$, red(8)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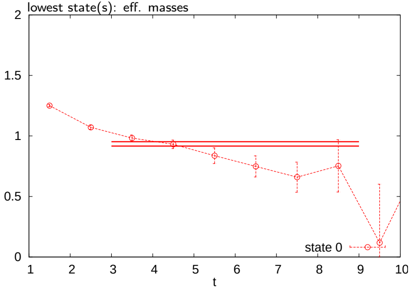
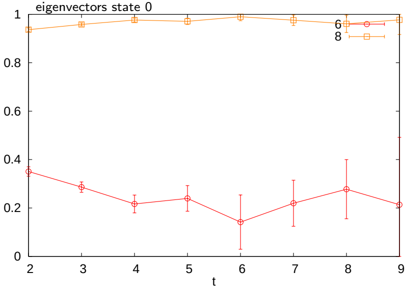
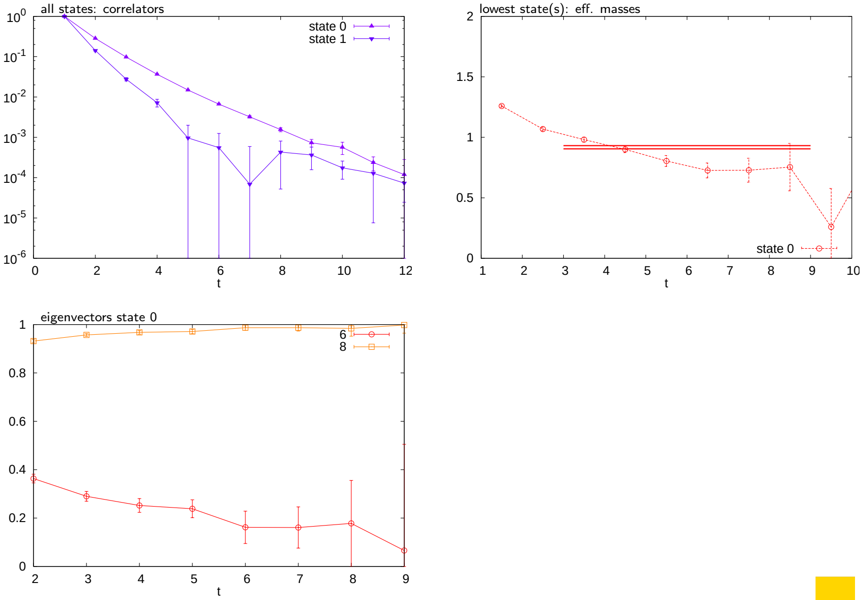
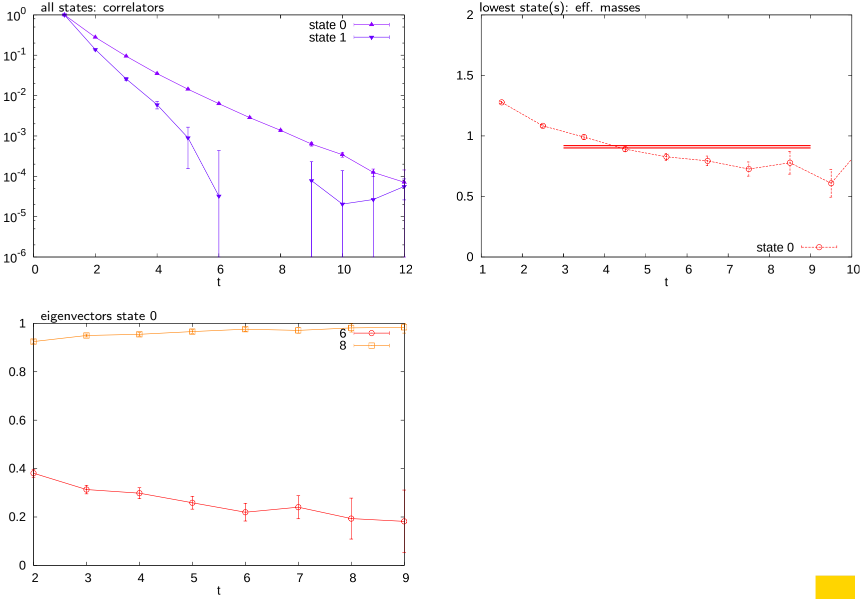

lowest state(s): eff. masses
state 0
t


eigenvectors state 0
6
8
t

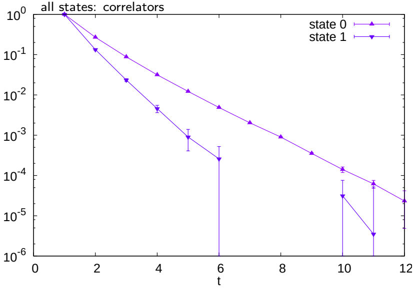
b_1, $J^{PC} = 1^{+-}$, red(16)

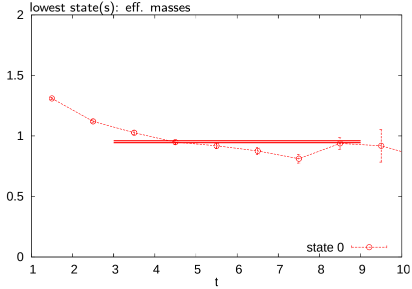


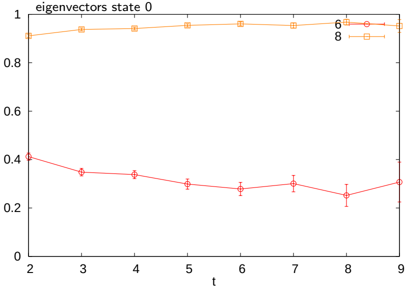
b_1, $J^{PC} = 1^{+-}$, red(32)



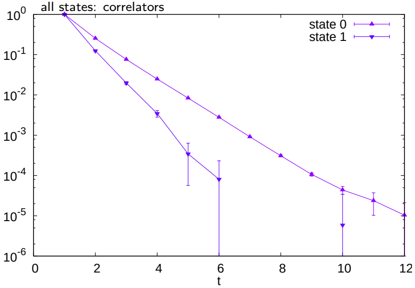
b_1, $J^{PC} = 1^{+-}$, red(64)

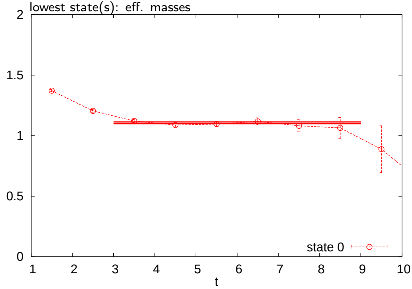


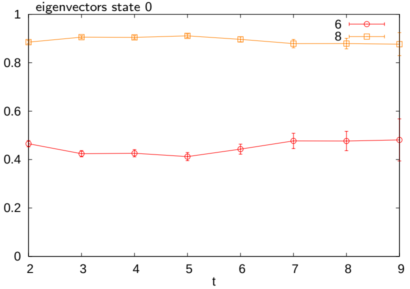




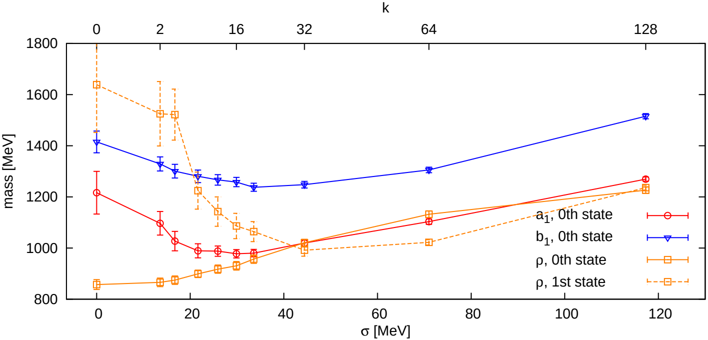
b_1, $J^{PC} = 1^{+-}$, red(128)







Meson masses vs. Dirac eigenmode reduction level

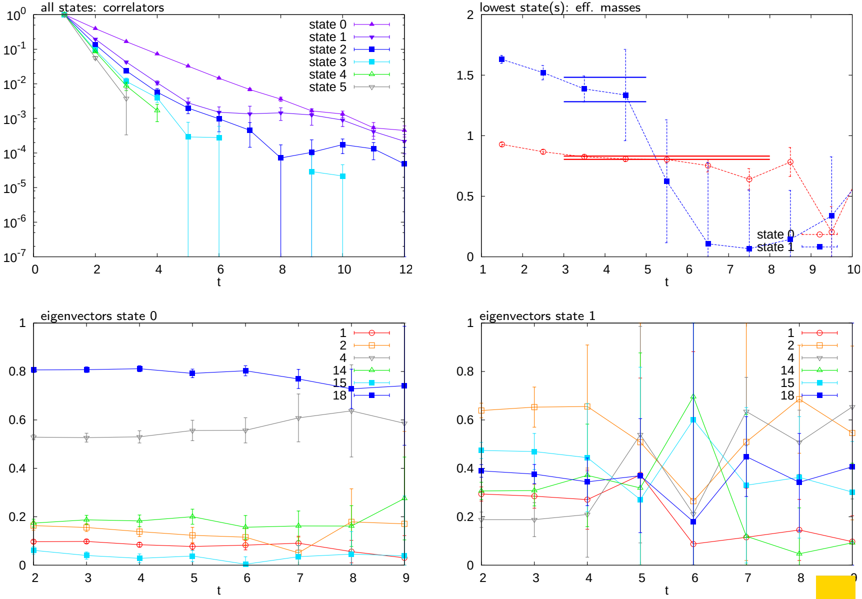


Baryons

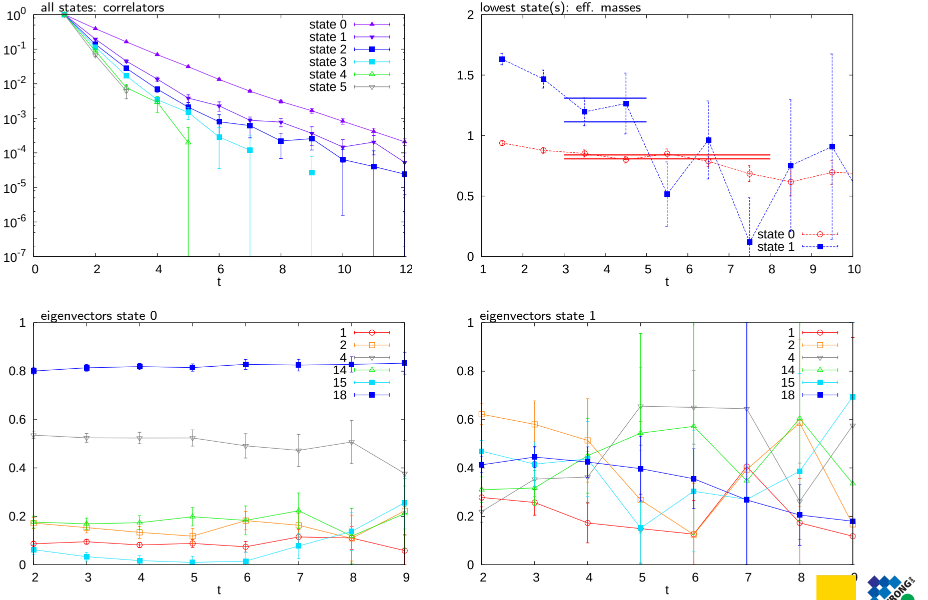
We investigate the nucleon and the Δ both with negative and positive parity

- in the constituent quark model, the splitting between the Δ and the nucleon is thought to be (at least partly) due to a Goldstone boson exchange interaction: what happens to the splitting when we restore the chiral symmetry?
- do the masses of the nucleon and the $N(1535)$ meet?

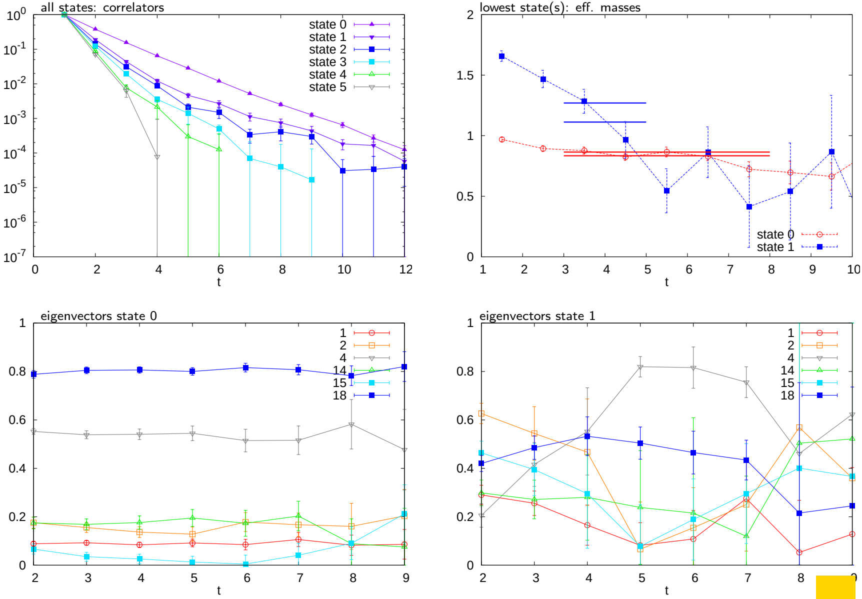
$N(+)$, red(0)


all states: correlators
state 0
state 1
state 2
state 3
state 4
state 5
t
lowest state(s): eff. masses
state 0
state 1
t
eigenvectors state 0
1
2
4
14
15
18
t
eigenvectors state 1
1
2
4
14
15
18
t

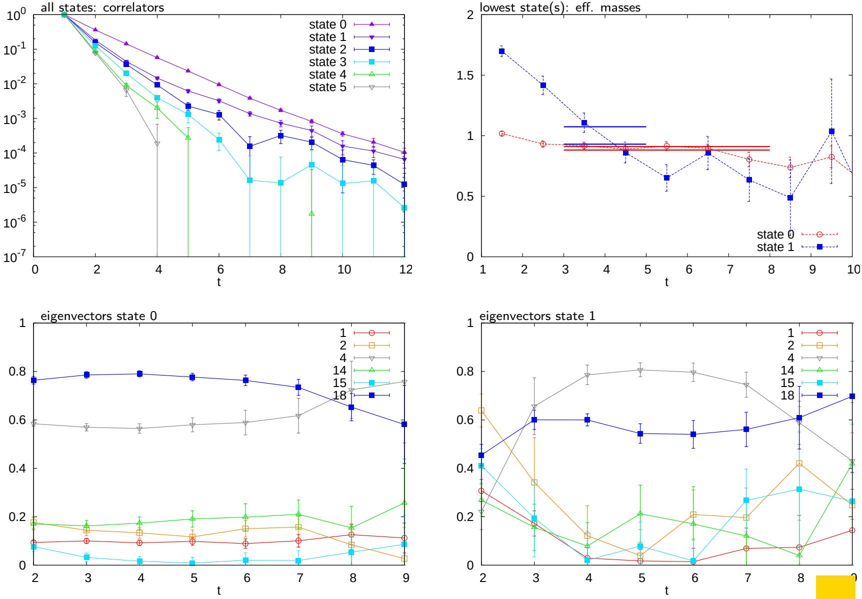
$N(+)$, red(2)


all states: correlators
state 0
state 1
state 2
state 3
state 4
state 5
t
lowest state(s): eff. masses
state 0
state 1
t
eigenvectors state 0
1
2
4
14
15
18
t
eigenvectors state 1
1
2
4
14
15
18
t

$N(+)$, red(4)


all states: correlators
state 0
state 1
state 2
state 3
state 4
state 5
t
lowest state(s): eff. masses
state 0
state 1
t
eigenvectors state 0
1
2
4
14
15
18
t
eigenvectors state 1
1
2
4
14
15
18
t

$N(+)$, red(8)


all states: correlators
state 0
state 1
state 2
state 3
state 4
state 5
t
lowest state(s): eff. masses
state 0
state 1
t
eigenvectors state 0
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18
t
eigenvectors state 1
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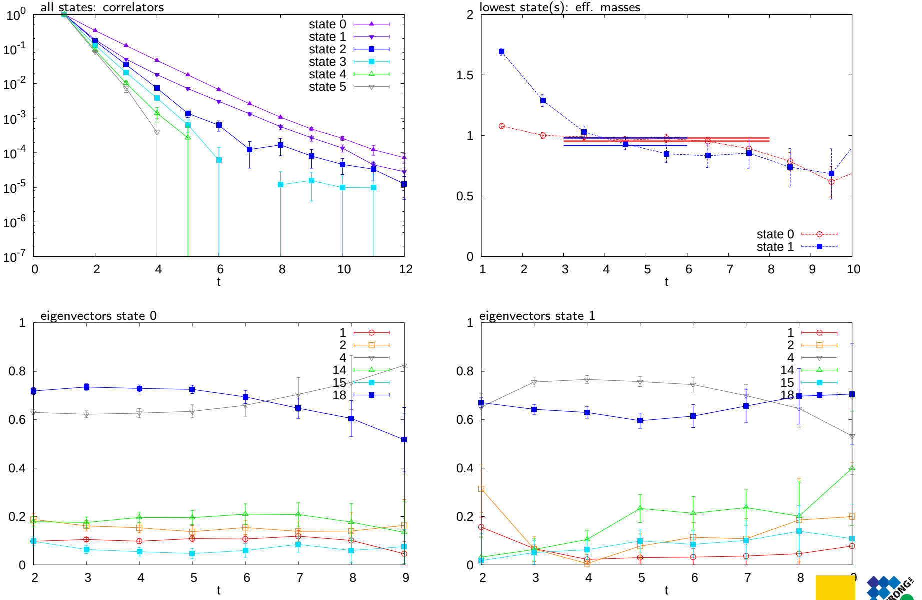
4
14
15
18
t

$N(+)$, red(16)


all states: correlators
state 0
state 1
state 2
state 3
state 4
state 5
t
lowest state(s): eff. masses
state 0
state 1
t
eigenvectors state 0
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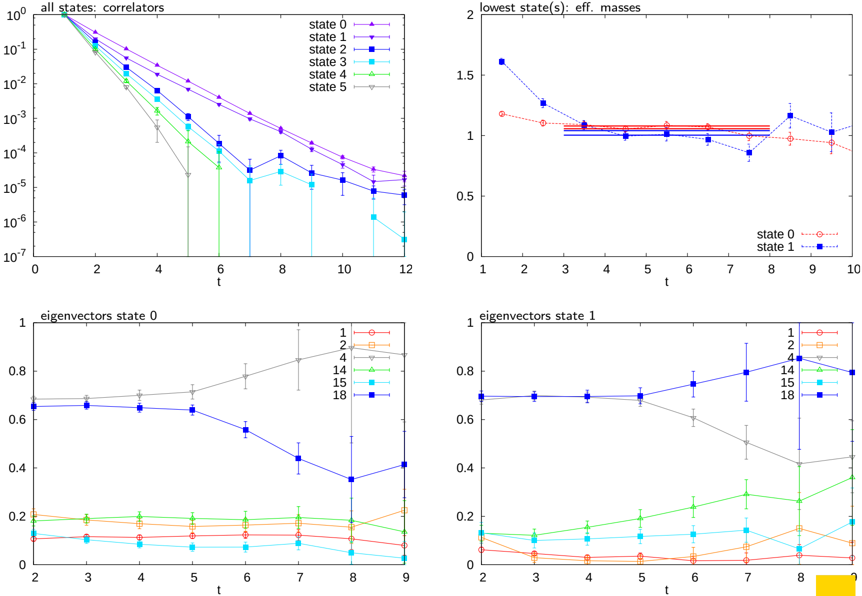
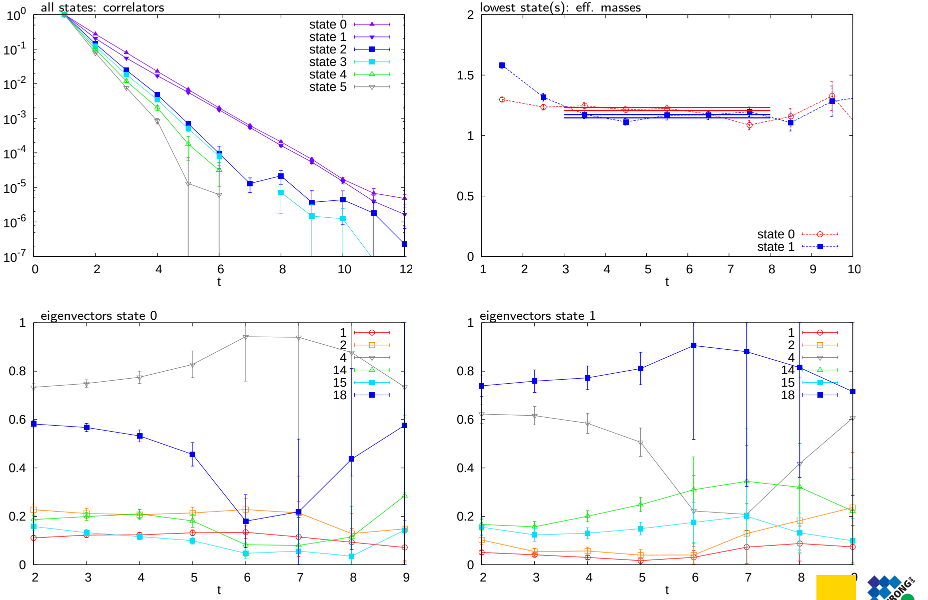
14
15
18
t
eigenvectors state 1
1
2
4
14
15
18
t

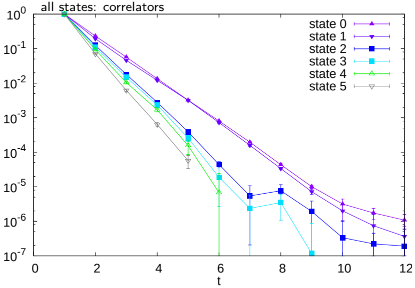
$N(+)$, red(32)

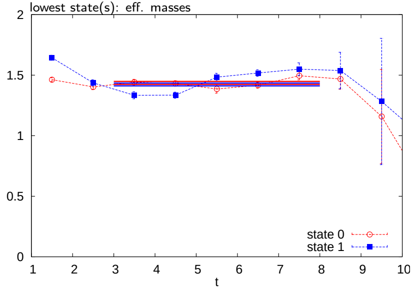

all states: correlators
state 0
state 1
state 2
state 3
state 4
state 5
t
lowest state(s): eff. masses
state 0
state 1
t
eigenvectors state 0
1
2
4
14
15
18
t
eigenvectors state 1
1
2
4
14
15
18
t

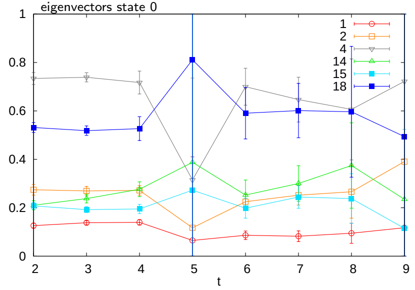
$N(+)$, red(64)

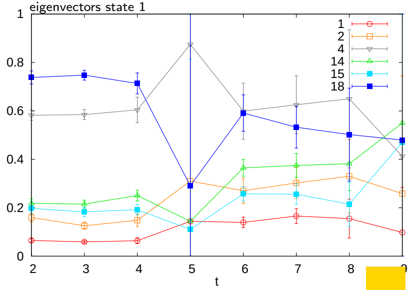

all states: correlators
state 0
state 1
state 2
state 3
state 4
state 5
t
lowest state(s): eff. masses
state 0
state 1
t
eigenvectors state 0
1
2
4
14
15
18
t
eigenvectors state 1
1
2
4
14
15
18
t

$N(+)$, red(128)

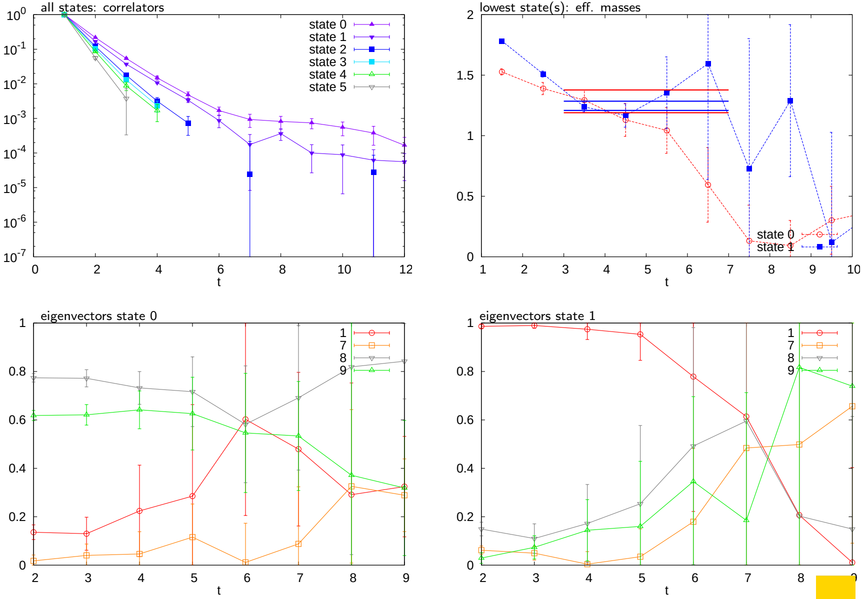

all states: correlators
state 0
state 1
state 2
state 3
state 4
state 5
t


lowest state(s): eff. masses
state 0
state 1
t

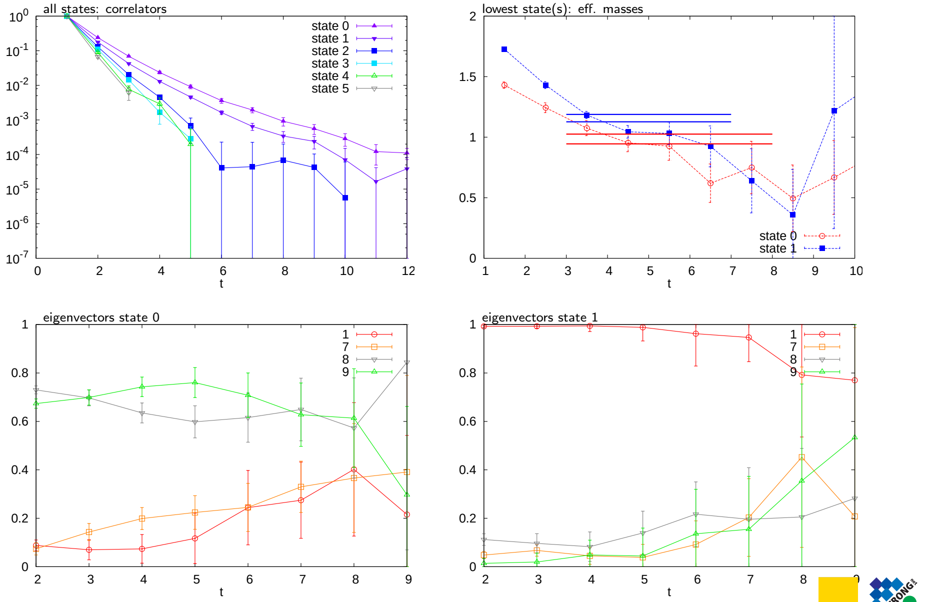

eigenvectors state 0
1
2
4
14
15
18
t


eigenvectors state 1
1
2
4
14
15
18
t

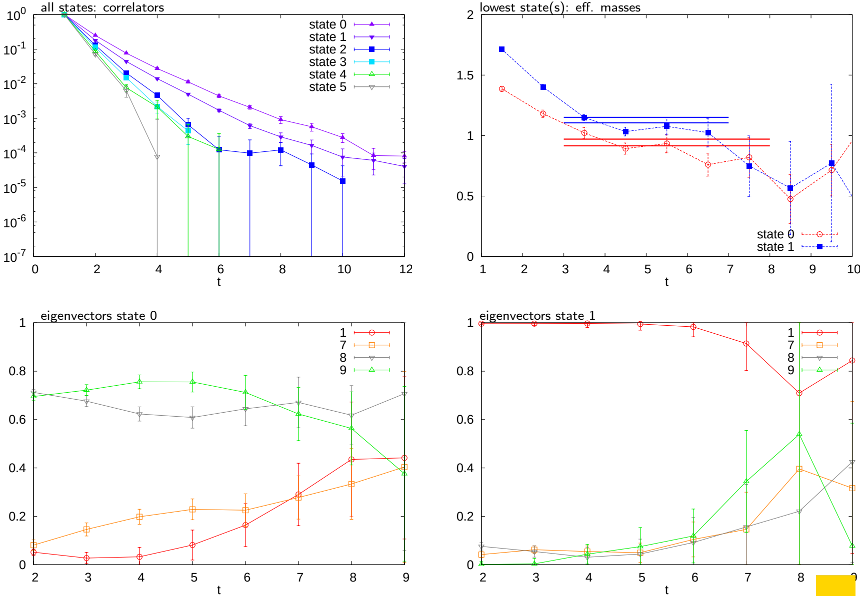
$N(-)$, red(0)


all states: correlators
state 0
state 1
state 2
state 3
state 4
state 5
t
lowest state(s): eff. masses
state 0
state 1
t
eigenvectors state 0
1
7
8
9
t
eigenvectors state 1
1
7
8
9
t

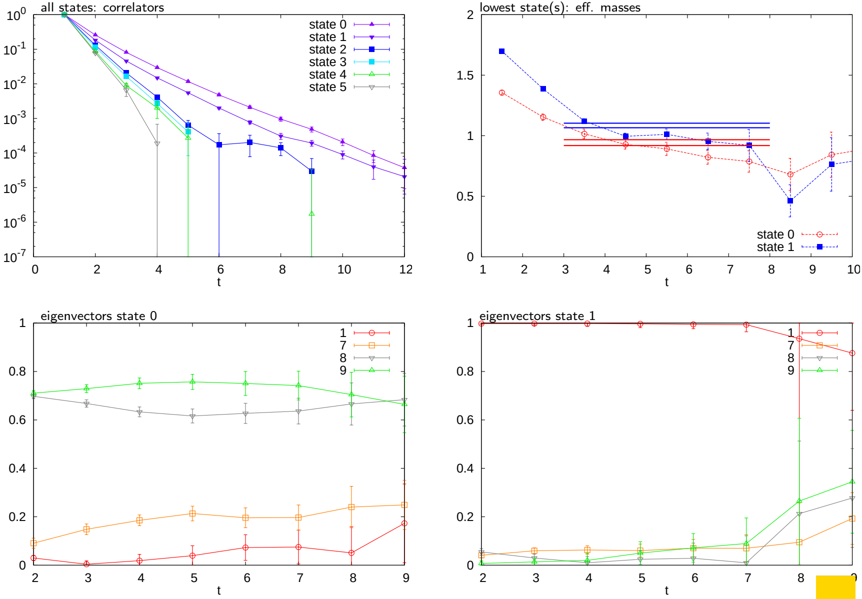
$N(-)$, red(2)


all states: correlators
state 0
state 1
state 2
state 3
state 4
state 5
t
lowest state(s): eff. masses
state 0
state 1
t
eigenvectors state 0
1
7
8
9
t
eigenvectors state 1
1
7
8
9
t

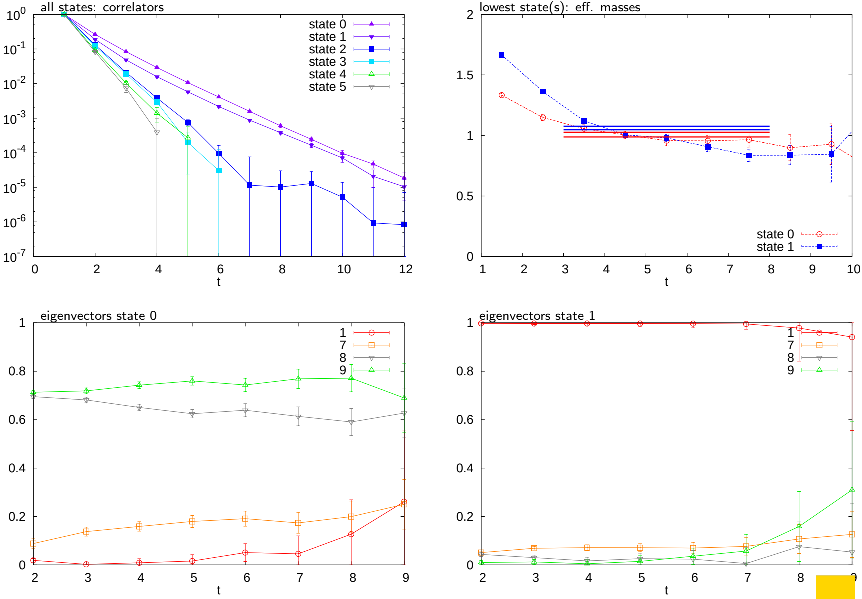
$N(-)$, red(4)


all states: correlators
state 0
state 1
state 2
state 3
state 4
state 5
t
lowest state(s): eff. masses
state 0
state 1
t
eigenvectors state 0
1
7
8
9
t
eigenvectors state 1
1
7
8
9
t

$N(-)$, red(8)

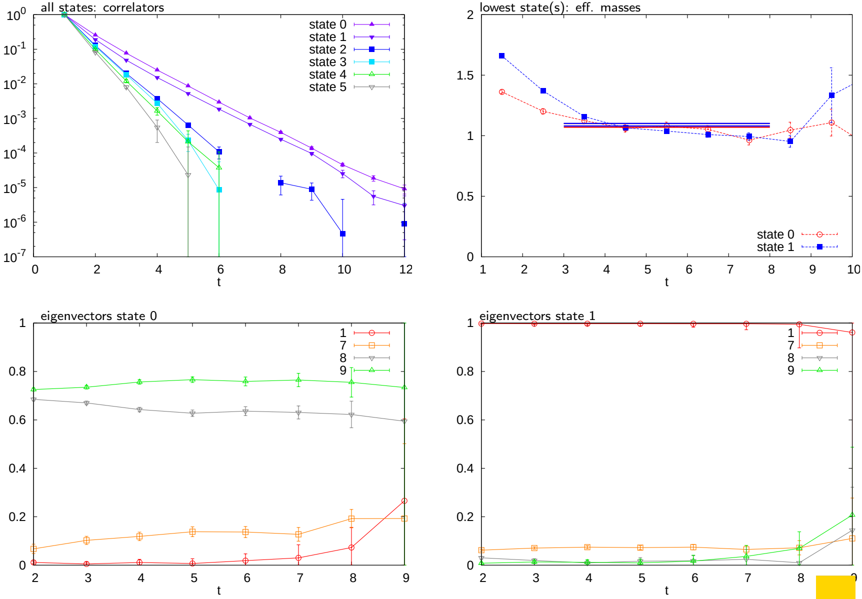

all states: correlators
state 0
state 1
state 2
state 3
state 4
state 5
t
lowest state(s): eff. masses
state 0
state 1
t
eigenvectors state 0
1
7
8
9
t
eigenvectors state 1
1
7
8
9
t

$N(-)$, red(16)



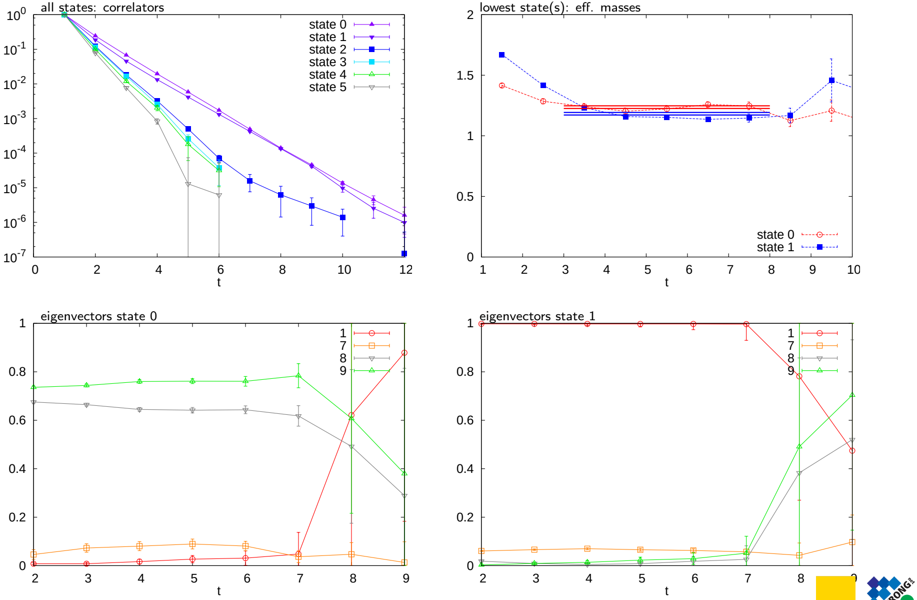
all states: correlators
state 0
state 1
state 2
state 3
state 4
state 5
t
lowest state(s): eff. masses
state 0
state 1
t
eigenvectors state 0
1
7
8
9
t
eigenvectors state 1
1
7
8
9
t

$N(-)$, red(32)

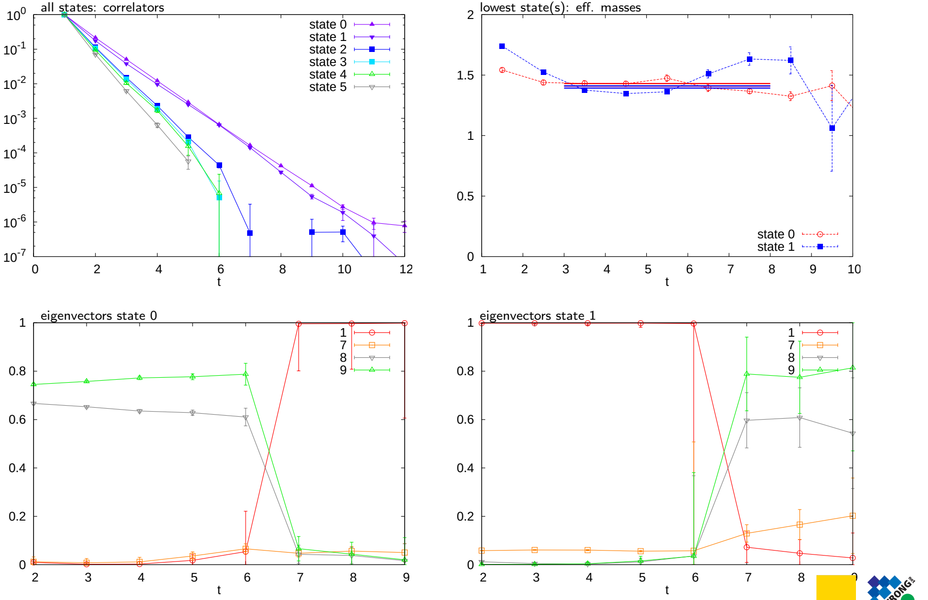


all states: correlators
state 0
state 1
state 2
state 3
state 4
state 5
t
lowest state(s): eff. masses
state 0
state 1
t
eigenvectors state 0
1
7
8
9
t
eigenvectors state 1
1
7
8
9
t

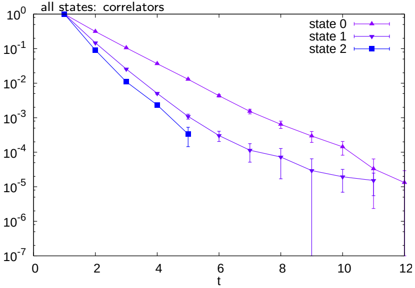
$N(-)$, red(64)

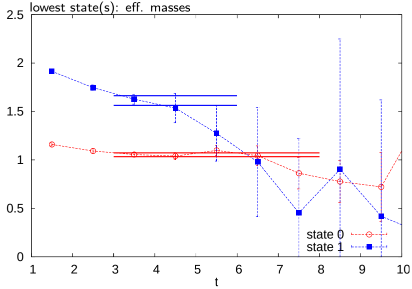

all states: correlators
state 0
state 1
state 2
state 3
state 4
state 5
t
lowest state(s): eff. masses
state 0
state 1
t
eigenvectors state 0
1
7
8
9
t
eigenvectors state 1
1
7
8
9
t

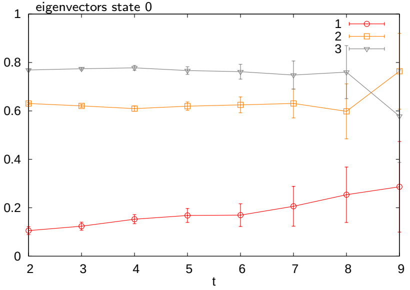
$N(-)$, red(128)

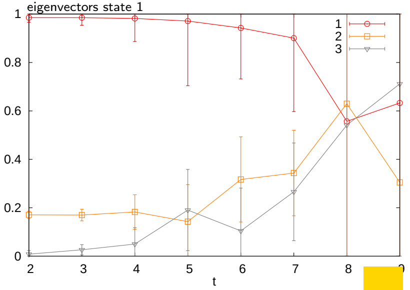

all states: correlators
state 0
state 1
state 2
state 3
state 4
state 5
t
lowest state(s): eff. masses
state 0
state 1
t
eigenvectors state 0
1
7
8
9
t
eigenvectors state 1
1
7
8
9
t

$\Delta(+)$, red(0)

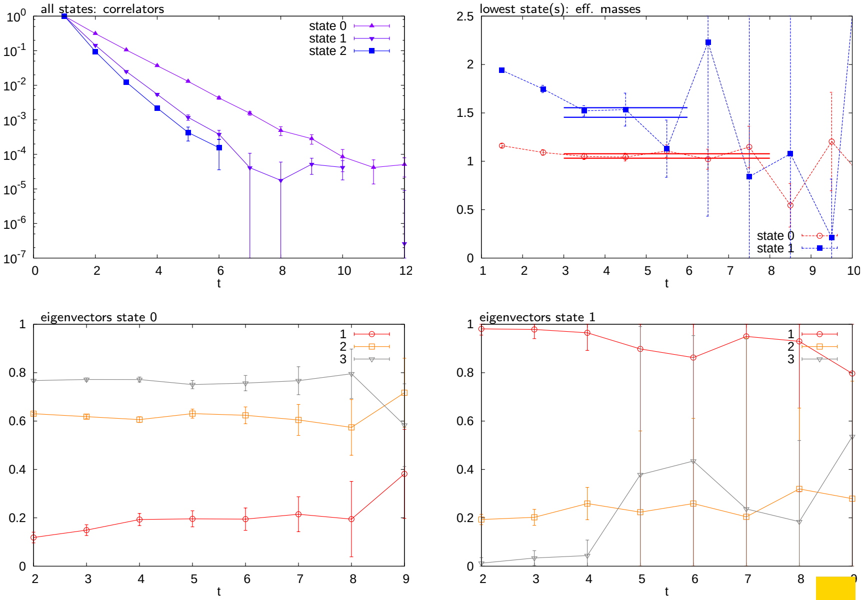

all states: correlators
state 0
state 1
state 2
t


lowest state(s): eff. masses
state 0
state 1
t

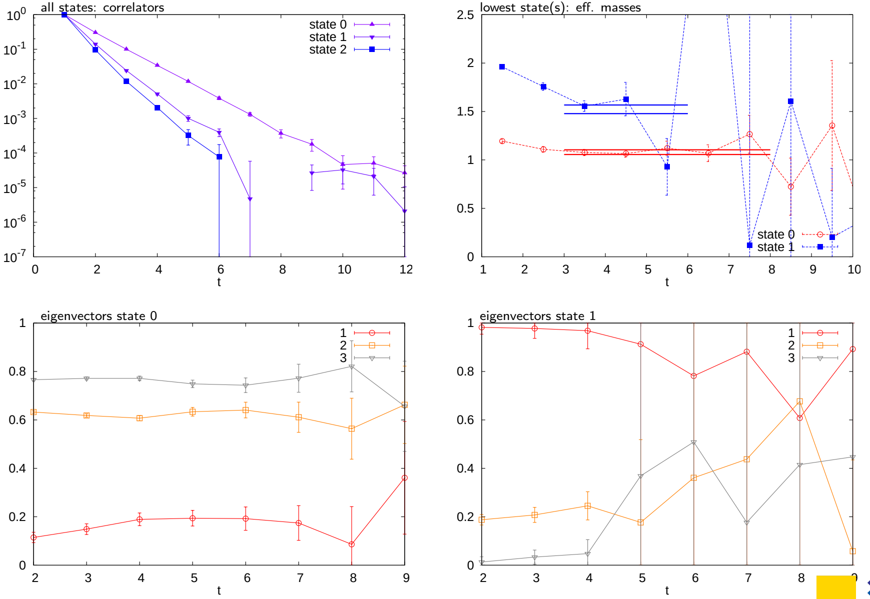

eigenvectors state 0
1
2
3
t


eigenvectors state 1
1
2
3
t

$\Delta(+)$, red(2)


all states: correlators
state 0
state 1
state 2
t
lowest state(s): eff. masses
state 0
state 1
t
eigenvectors state 0
1
2
3
t
eigenvectors state 1
1
2
3
t

$\Delta(+)$, red(4)


all states: correlators
state 0
state 1
state 2
t
lowest state(s): eff. masses
state 0
state 1
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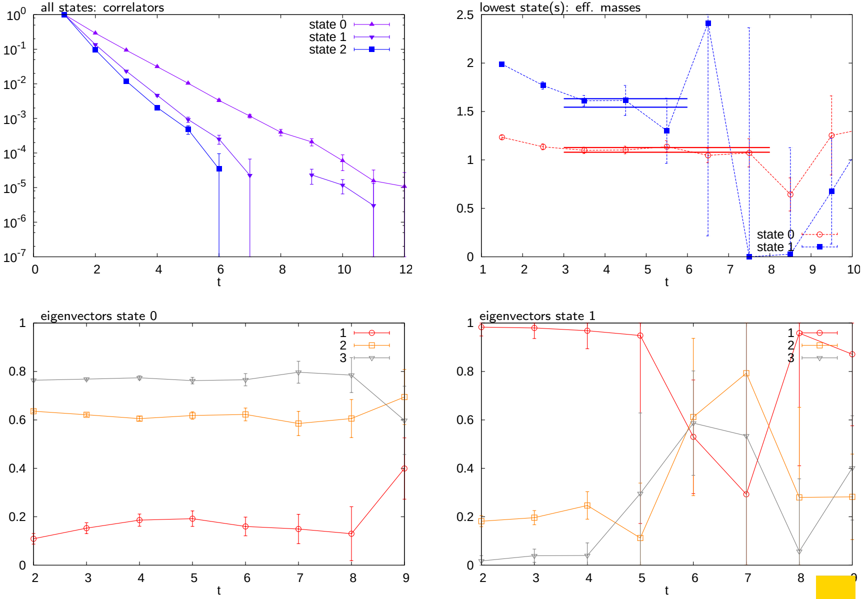
eigenvectors state 0
1
2
3
t
eigenvectors state 1
1
2
3
t

$\Delta(+)$, red(8)


all states: correlators
state 0
state 1
state 2
t
lowest state(s): eff. masses
state 0
state 1
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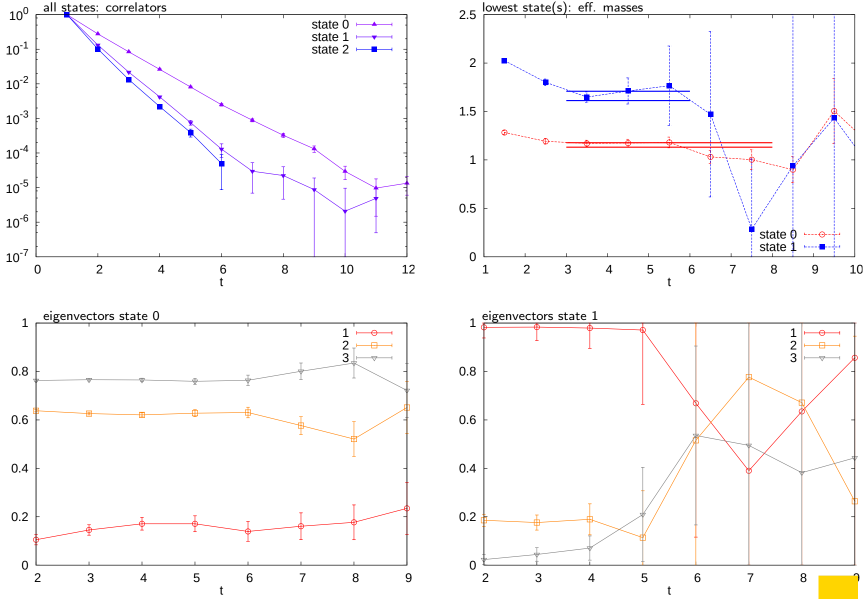
eigenvectors state 0
1
2
3
t
eigenvectors state 1
1
2
3
t

$\Delta(+)$, red(16)


all states: correlators
state 0
state 1
state 2
t
lowest state(s): eff. masses
state 0
state 1
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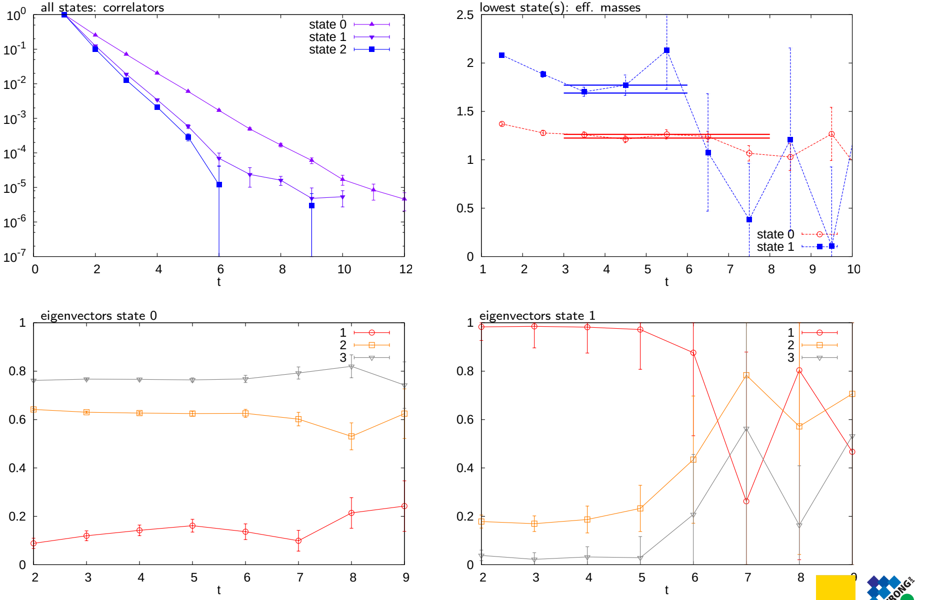
eigenvectors state 0
1
2
3
t
eigenvectors state 1
1
2
3
t

$\Delta(+)$, red(32)


all states: correlators
state 0
state 1
state 2
t
lowest state(s): eff. masses
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eigenvectors state 0
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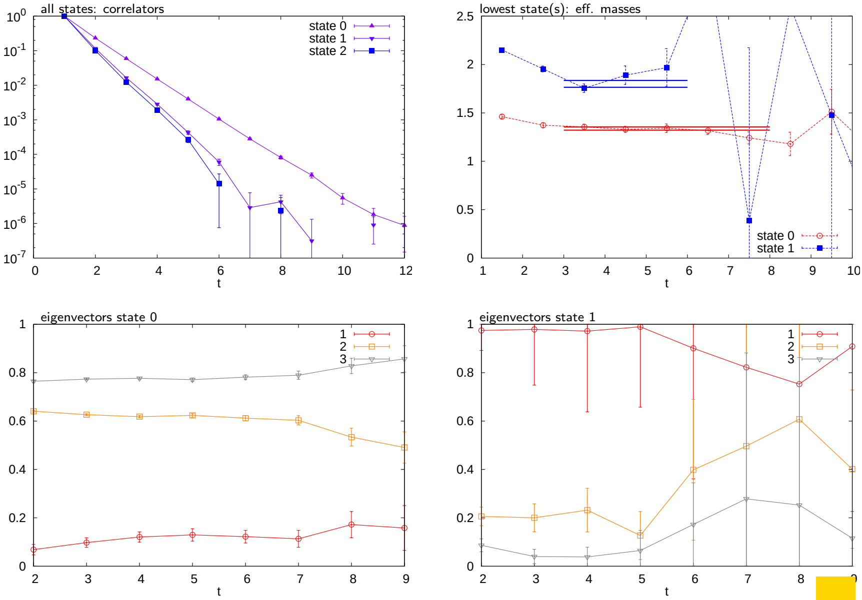
t
eigenvectors state 1
1
2
3
t

$\Delta(+)$, red(64)


all states: correlators
state 0
state 1
state 2
t
lowest state(s): eff. masses
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eigenvectors state 0
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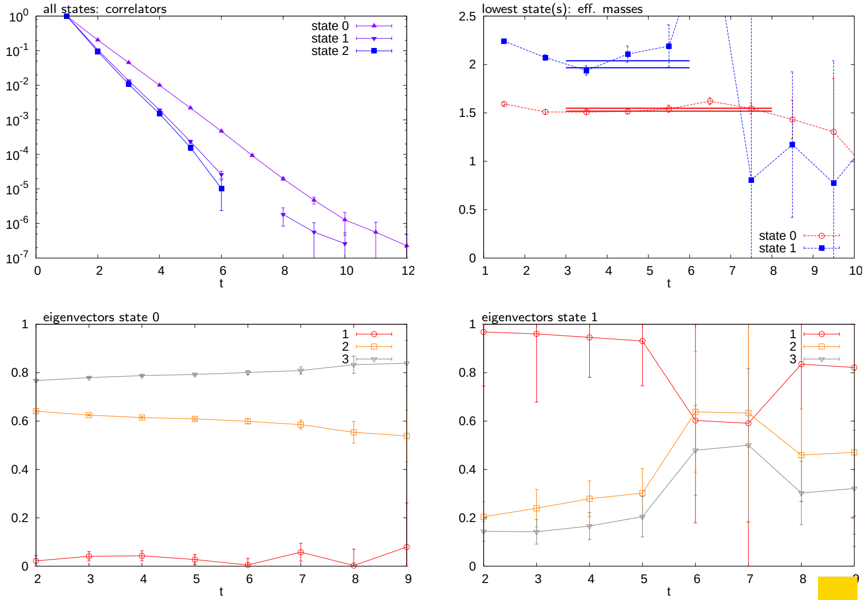
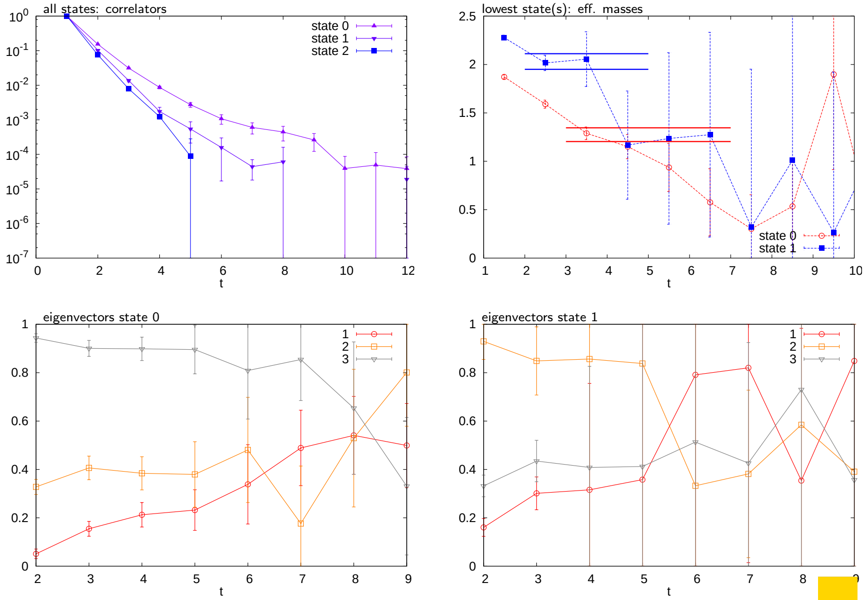
eigenvectors state 1
1
2
3
t

$\Delta(+)$, red(128)



$\Delta(-)$, red(0)


all states: correlators
state 0
state 1
state 2
t
lowest state(s): eff. masses
state 0
state 1
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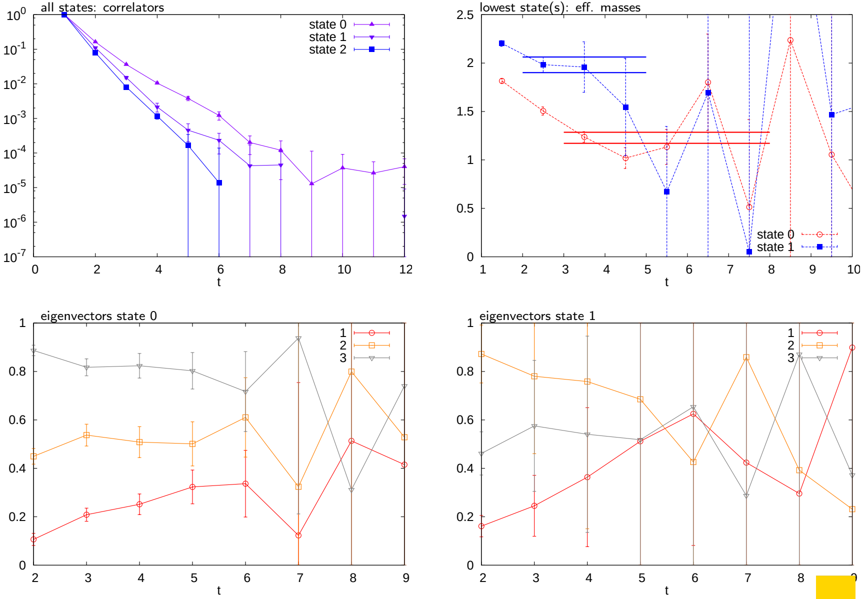
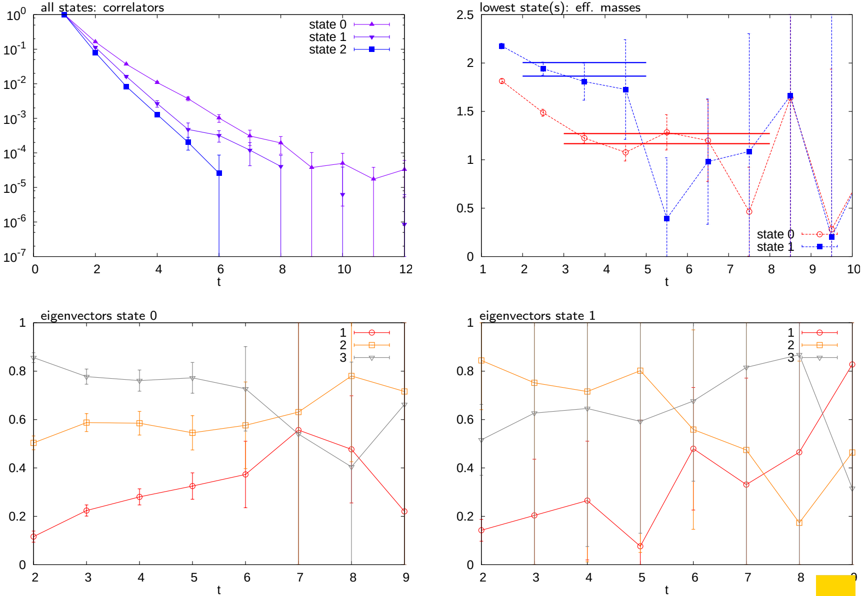
eigenvectors state 0
1
2
3
t
eigenvectors state 1
1
2
3
t

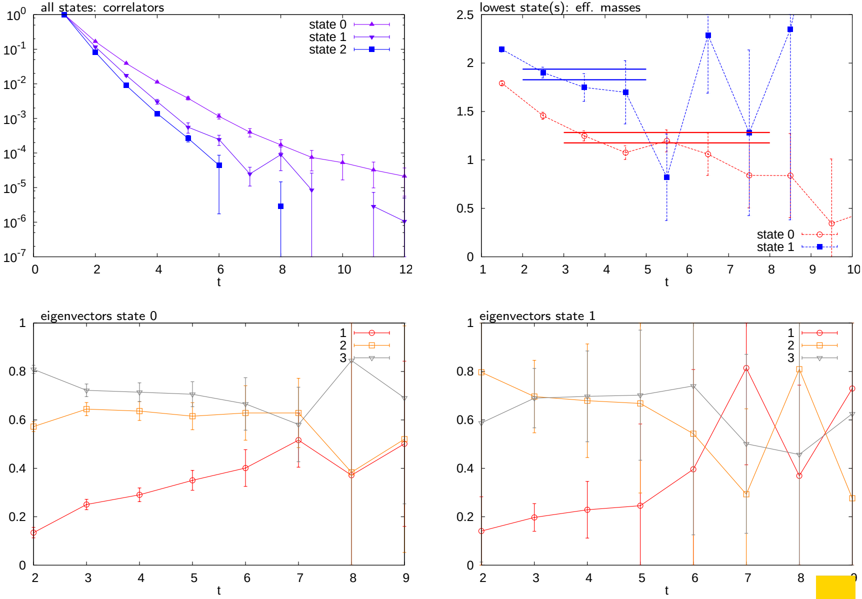
Δ(−), red(2)


all states: correlators
state 0
state 1
state 2
t
lowest state(s): eff. masses
state 0
state 1
t
eigenvectors state 0
1
2
3
t
eigenvectors state 1
1
2
3
t

$\Delta(-)$, red(4)


all states: correlators
state 0
state 1
state 2
t
lowest state(s): eff. masses
state 0
state 1
t
eigenvectors state 0
1
2
3
t
eigenvectors state 1
1
2
3
t

$\Delta(-)$, red(8)


all states: correlators
state 0
state 1
state 2
t
lowest state(s): eff. masses
state 0
state 1
t
eigenvectors state 0
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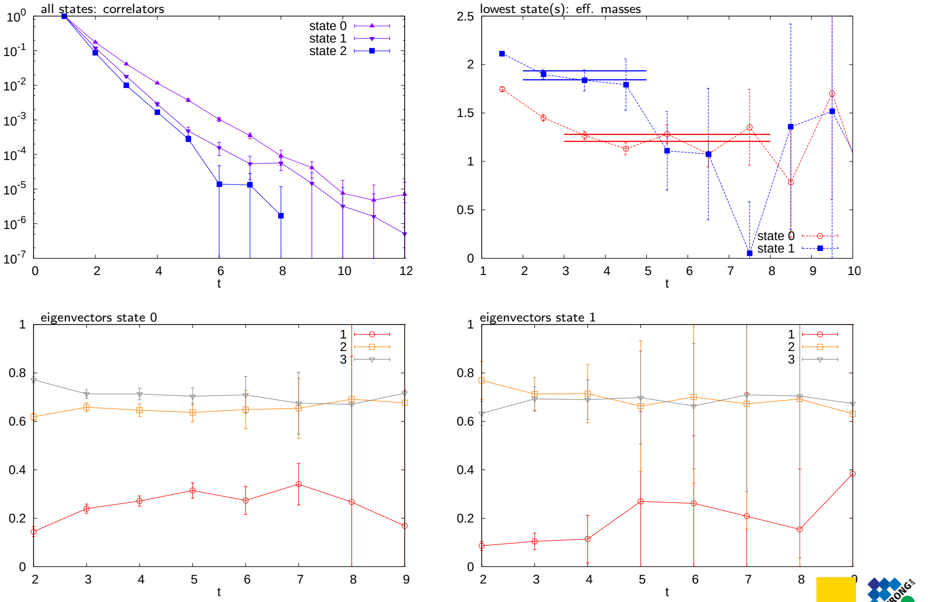
2
3
t
eigenvectors state 1
1
2
3
t

$\Delta(-)$, red(16)



all states: correlators
state 0
state 1
state 2
t
lowest state(s): eff. masses
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state 1
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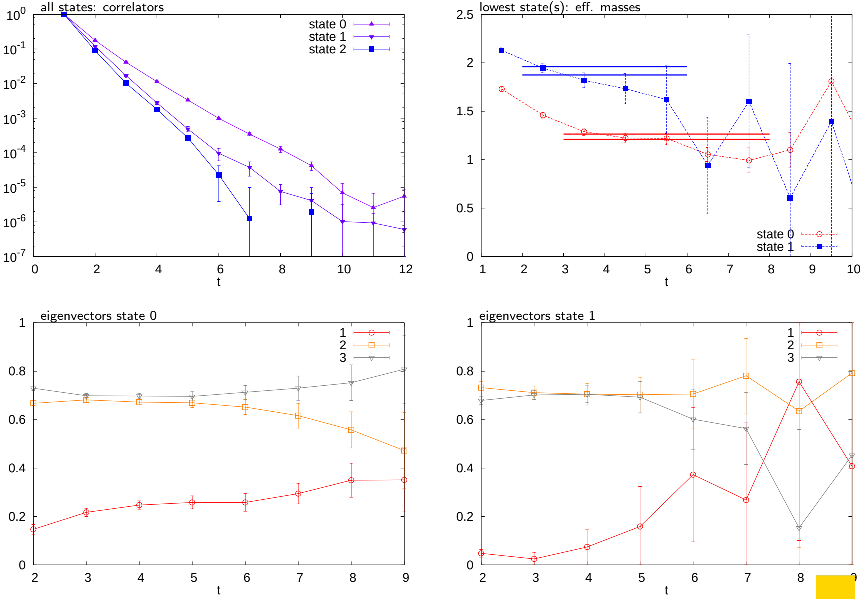
eigenvectors state 0
1
2
3
t
eigenvectors state 1
1
2
3
t

$\Delta(-)$, red(32)


all states: correlators
state 0
state 1
state 2
t
lowest state(s): eff. masses
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state 1
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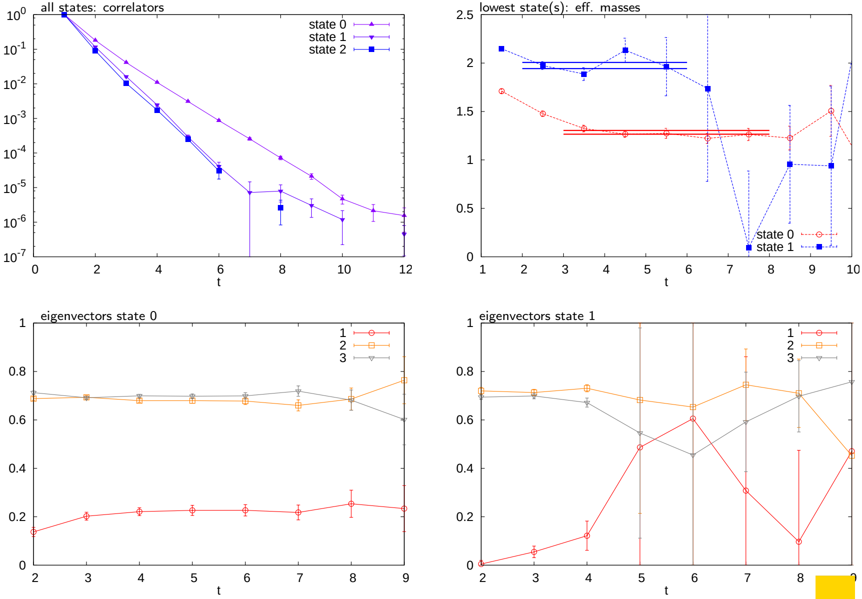
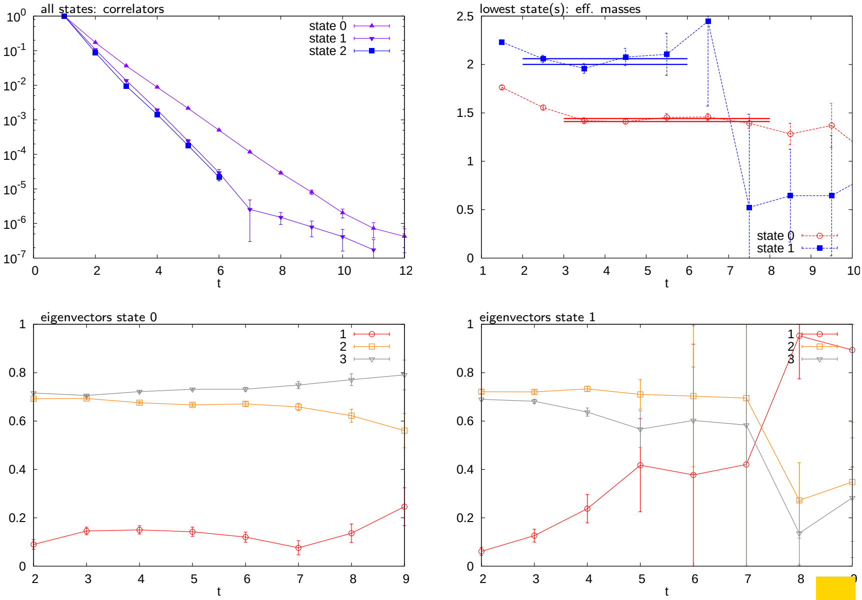
eigenvectors state 0
1
2
3
t
eigenvectors state 1
1
2
3
t

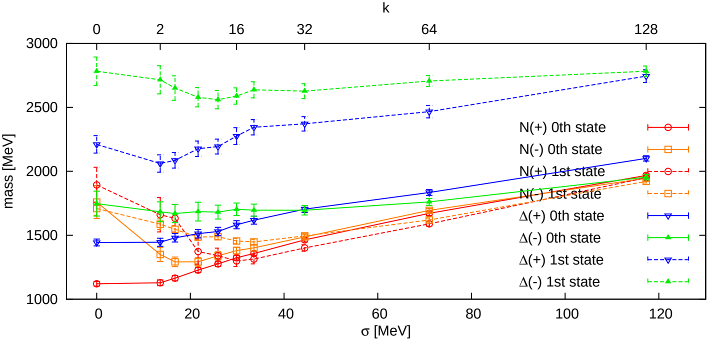
$\Delta(-)$, red(64)


all states: correlators
state 0
state 1
state 2
t
lowest state(s): eff. masses
state 0
state 1
t
eigenvectors state 0
1
2
3
t
eigenvectors state 1
1
2
3
t

$\Delta(-)$, red(128)



Baryon masses vs. Dirac eigenmode reduction level



The lattice quark propagator

The tree-level quark propagator is

$$S_0(p) = \frac{1}{i\not{p} + m_0}$$

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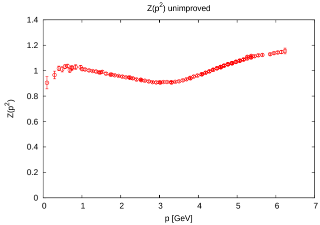
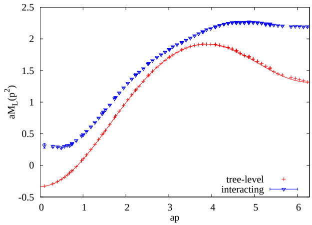
We calculate $S_{\mathrm{bare}}(a;p)$ in Landau gauge on the lattice and therefrom extract

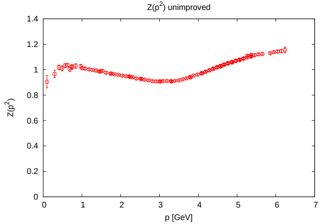
- the renormalization function $Z(\mu;p^2)$
- the renormalization point independent mass function $M(p^2)$

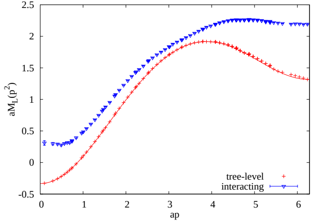
Improving the lattice quark propagator





Improving the lattice quark propagator





To improve the functions we perform

- tree-level improvement to reduce $\mathcal{O}(a)$ errors of off-shell quantities
  Skullerud, Williams (2001) hep-lat/0007028, Heatlie et al. (1991)

$$S_I(x,y) = \langle S_I(x,y;U)\rangle \equiv \langle (1+b_q am)S(x,y;U) - a\lambda\delta(x-y)\rangle$$

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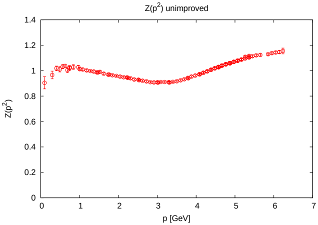

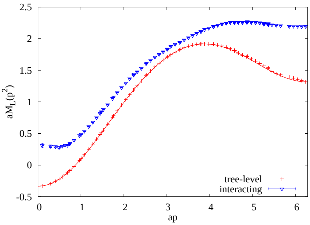

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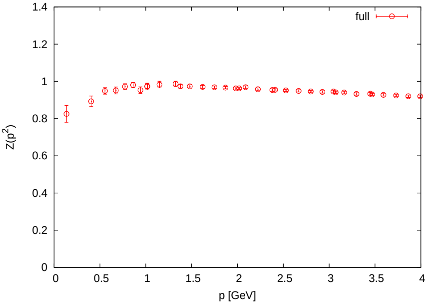
- tree-level correction: $Z \rightarrow Z/Z_0$ and $M \rightarrow M/(M_0 + m_{\mathrm{ren}})$
- a data cut at $4\,\mathrm{GeV}$ since for larger momenta lattice artifacts dominate

The quark propagator under eigenmode reduction



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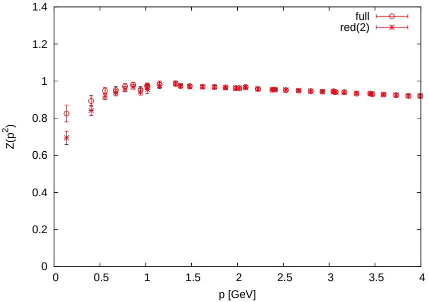

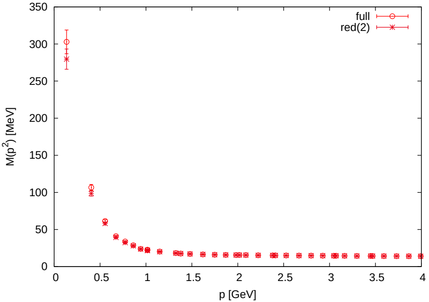

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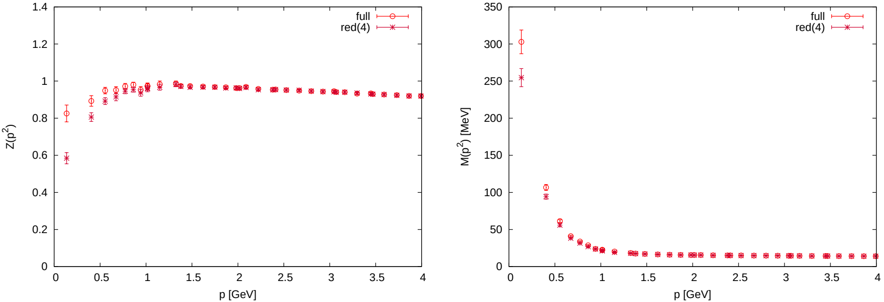

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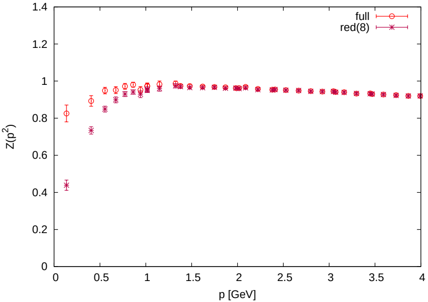

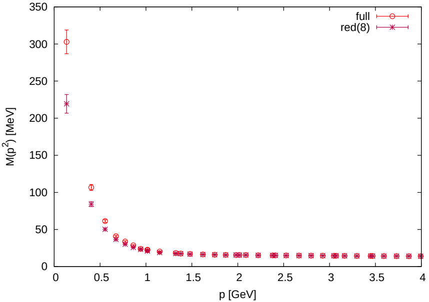

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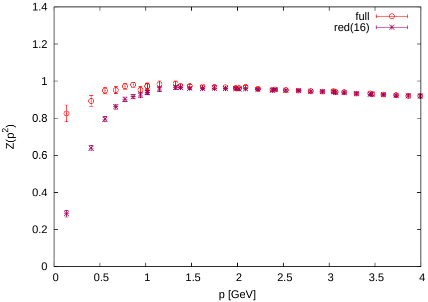

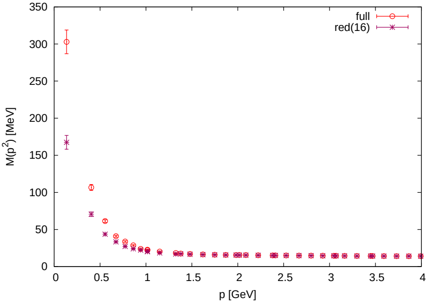

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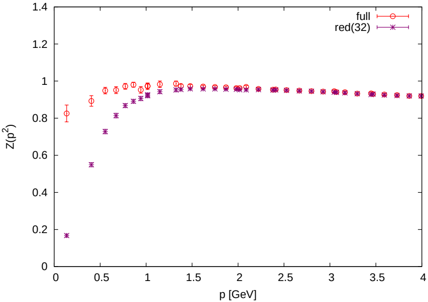

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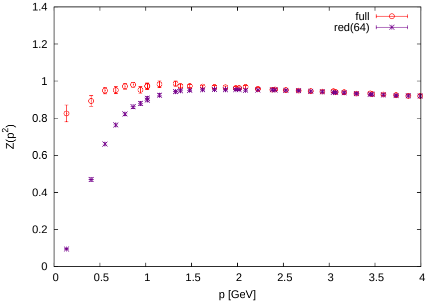

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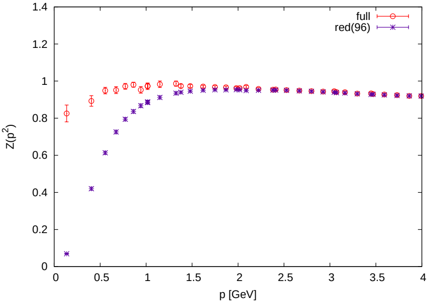

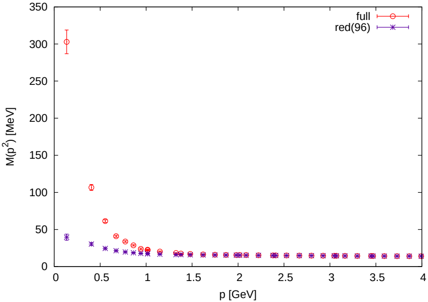

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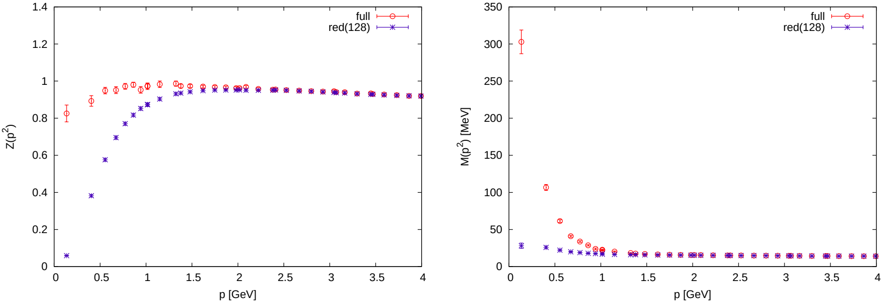

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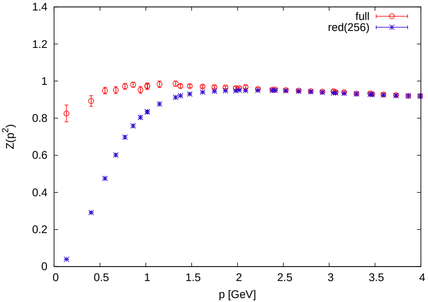

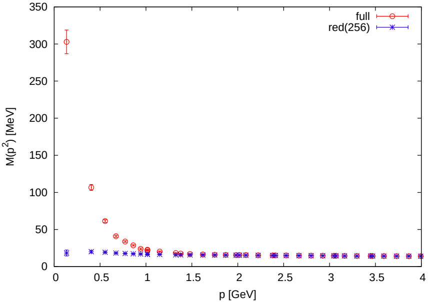

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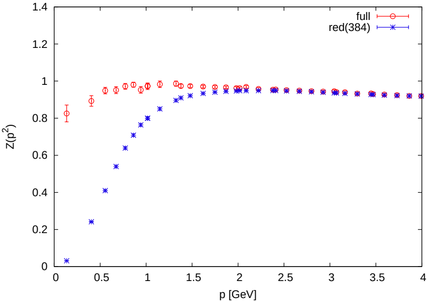

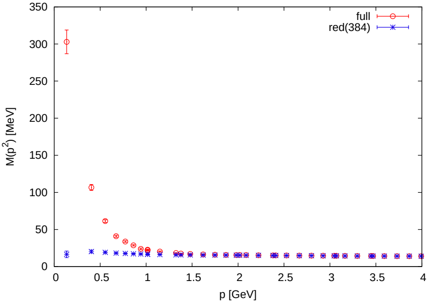

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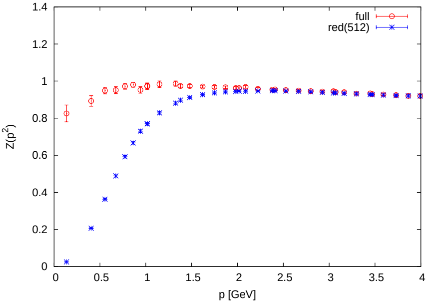
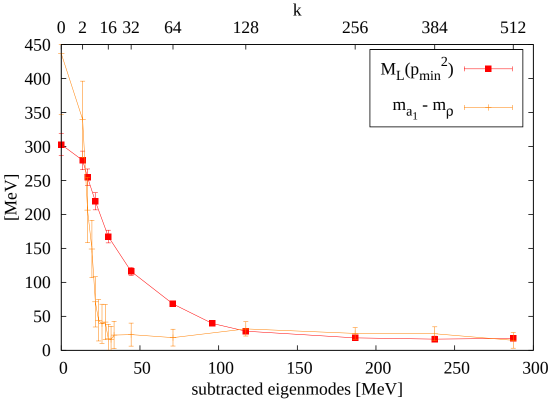


"Constituent quark mass" vs. eigenmode reduction level

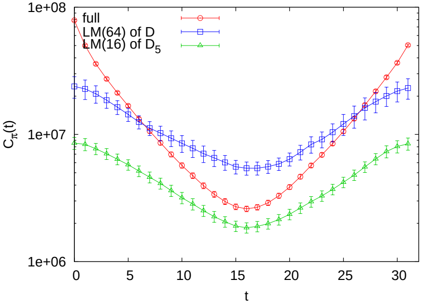


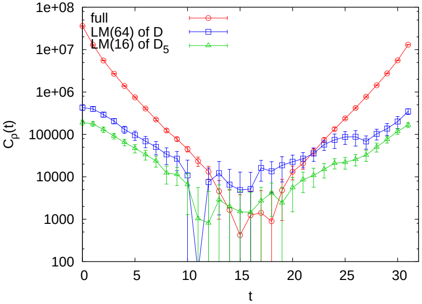
We find a reduction level window where chiral symmetry is restored (as seen by the $a_1 - \rho$ splitting) but dynamical mass is still generated, see also O'Malley, Kamleh, Leinweber, Moran: arXiv:1112.2490

Conclusions

- low lying eigenvalues of the Dirac operator are associated with chiral symmetry breaking
- we have computed hadron propagators while removing increasingly more of the low lying eigenmodes of the Dirac operator
- the confinement properties remain intact, i.e., we still observe clear bound states for most of the studied hadrons
- an exception is the pion, where no clear exponential decay of the correlation function is seen
- the mass values of the vector meson chiral partners a_1 and ρ approach each other
- the nucleon and the $N(1535)$ become degenerate
- the splitting between N and Δ decreases
- the dynamical mass generation of quarks as seem from the IR behavior of $M(p^2)$ decreases towards zero, although it is still at roughly 55% when removing 16 eigenmodes of D_5 which is where we found chiral symmetry to be restored

Low-mode contribution of D and D_5 to the π and ρ correlators





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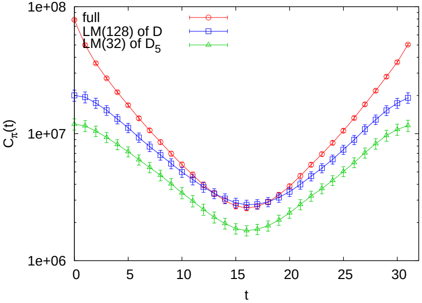

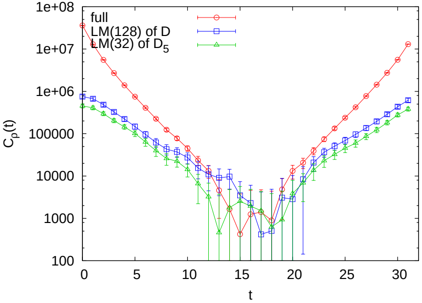

ρ interpolators

$\#_\rho$	interpolator(s)
1	$\overline{a}_n \gamma_k b_n$
8	$\overline{a}_w \gamma_k \gamma_t b_w$
12	$\overline{a}_{\partial_k} b_w - \overline{a}_w b_{\partial_k}$
17	$\overline{a}_{\partial_i} \gamma_k b_{\partial_i}$
22	$\overline{a}_{\partial_k} \epsilon_{ijk} \gamma_j \gamma_5 b_w - \overline{a}_w \epsilon_{ijk} \gamma_j \gamma_5 b_{\partial_k}$

Interpolators for the ρ-meson, $J^{PC} = 1^{--}$. The first column shows the number, the second shows the explicit form of the interpolator. cf. Engel et al., PRD 82 (2010), arXiv:1005.1748

a_1 interpolators

$\#_{a_1}$	interpolator(s)
1	$\overline{a}_n \gamma_k \gamma_5 b_n$
2	$\overline{a}_n \gamma_k \gamma_5 b_w + \overline{a}_w \gamma_k \gamma_5 b_n$
4	$\overline{a}_w \gamma_k \gamma_5 b_w$

a_1-meson, $J^{PC} = 1^{++}$, cf. Engel et al., PRD 82 (2010), arXiv:1005.1748

b_1 interpolators

$\#_{b_1}$	interpolator(s)
6	$\overline{a}_{\partial_k}\gamma_5 b_n - \overline{a}_n\gamma_5 b_{\partial_k}$
8	$\overline{a}_{\partial_k}\gamma_5 b_w - \overline{a}_w\gamma_5 b_{\partial_k}$

b_1-meson, $J^{PC} = 1^{+-}$, cf. Engel et al., PRD 82 (2010), arXiv:1005.1748

N interpolators

- $N^{(i)} = \epsilon_{abc}\, \Gamma_1^{(i)}\, u_a \left(u_b^T\, \Gamma_2^{(i)}\, d_c - d_b^T\, \Gamma_2^{(i)}\, u_c \right)$
- $N(+)$: 1, 2, 4, 14, 15, 18
- $N(-)$: 1, 7, 8, 9

$\chi^{(i)}$	$\Gamma_1^{(i)}$	$\Gamma_2^{(i)}$	smearing	$\#_N$
$\chi^{(1)}$	$\mathbb{1}$	$C\,\gamma_5$	$(nn)n$	1
			$(nn)w$	2
			$(nw)n$	3
			$(nw)w$	4
			$(ww)n$	5
			$(ww)w$	6
$\chi^{(2)}$	γ_5	C	$(nn)n$	7
			$(nn)w$	8
			$(nw)n$	9
			$(nw)w$	10
			$(ww)n$	11
			$(ww)w$	12
$\chi^{(3)}$	$i\,\mathbb{1}$	$C\,\gamma_t\,\gamma_5$	$(nn)n$	13
			$(nn)w$	14
			$(nw)n$	15
			$(nw)w$	16
			$(ww)n$	17
			$(ww)w$	18

cf. Engel et al., PRD 82 (2010), arXiv:1005.1748

Δ interpolators

- $\epsilon_{abc}\, u_a \left(u_b^T\, C\, \gamma_k\, u_c \right)$
- $\Delta(+)$: 1, 2, 3
- $\Delta(-)$: 1, 2, 3

smearing	$\#_\Delta$
$(nn)n$	1
$(nn)w$	2
$(nw)n$	3
$(nw)w$	4
$(ww)n$	5
$(ww)w$	6

cf. Engel et al., PRD 82 (2010), arXiv:1005.1748