Fine lattice simulations with chirally symmetric fermions

J. Noaki (KEK)

S. Aoki, G. Cossu, H. Fukaya, S. Hashimoto and T. Kaneko

for JLQCD Collaboration

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JLQCD's new project

- Target: precise calculation for quark-flavor physics
  - *eg. B-, D- form factors ← SuperKEKB/Belle-II @ KEK*
- N_f = 2+1 simulation with good control of systematic errors
  - chiral symmetry: $m_{res} << m_{ud}$
  - continuum extrapolation: a = 2.4, 3.6, 4.8 GeV and more
  - light quarks: m_π = 500, 400, 300 MeV and lighter
  - large lattice volume satisfying $m_\pi L > 4$
- Domain-Wall (Möbius) fermion
  - m_{res} < 0.5 MeV with L_s = 12 or smaller

Basic studies / presentations

- Choice of the fermion action
  - T. Kaneko, study in HMC, Tue. 17:40--
  - S. Hashimoto, chiral symm. violation, Tue. Poster
- Code developments
  - G. Cossu, our code and its performance, Tue. Poster
- Tests for applications
  - Y. Cho, Brillouin improvement for heavy quark, Thu. 17:50--
  - H. Fukaya, reweighting to the overlap simulation, Fri. 14:20--
- First physics results : this talk

Plan of this talk

- Numerical simulation
  - Lattice action
  - Profile & status
- Measurements of observables
  - scale setting
  - hadron spectrum
- Inspective study of generated configs
  - thermalization / autocorrelation
- Summary & outlook

Numerical Simulation

Domain-Wall (Möbuis) fermions

Kaplan 1992; Shamir 1994; Borici 1997; Chiu 1998; Brower et al. 2001

- 5D representation

$$D^{(5)}_{DW}(m) = 1 + b(4+M)D_W - (1 - c(4+M)D_W) \cdot \begin{bmatrix} 0 & P_- & & & & -mP_+ \\ P_+ & 0 & P_- & & & \\ & \ddots & \ddots & \ddots & & \\ & & \ddots & \ddots & \ddots & \\ & & & P_+ & 0 & P_- \\ -mP_- & & & & P_+ & 0 \end{bmatrix}$$

D_W: Wilson Dirac op with mass $-M$

- 4D effective operator

$$D^{(4)}_{DW}(m) = \left[\mathcal{P}^{-1} D^{(5)}_{DW}(m=1)^{-1} \cdot D^{(5)}_{DW}(m)\mathcal{P}\right]_{11}$$

$$= \frac{1+m}{2} + \frac{1-m}{2}\gamma_5 \tanh\left(L_s \tanh^{-1} H_M\right)$$

$$\mathcal{P} \equiv \begin{bmatrix} P_- & P_+ & & & \\ & P_- & \ddots & & \\ & & \ddots & \ddots & \\ & & & P_- & P_+ \\ P_+ & & & & P_- \end{bmatrix}$$

$L_s \to \infty$

sign function approx.

– scaled Shamir kernel: $H_M = \gamma_5 \frac{b D_W}{2 + c\, D_W}$

we set b = 2, c = 1

See T. Kaneko's talk and S. Hashimoto's poster for more details.

Gauge generation : profile

- N_f = 2+1 QCD
  - action: Symanzik gauge + Domain-Wall (Möbius)
    - tree-level Symanzik action for topology changing
    - 3 levels of stout smearing
    - m_{res} < 0.5 MeV
  - $m_\pi L > 4$, m_π = 500, 400, 300, ~ 220 MeV
  - a^{-1} = 2.4, 3.0, 3.6, 4.8 GeV
  - standard RHMC for the 5D representation with e/o preconditioning
  - Performance: 16 → 30 Gflops/node

IBM BG/Q, 1.2PFlops peak

see G. Cossu's poster for more details

  - Gauge configs are stored in steps of 10 trajs.

Gauge generation: status

see T. Kaneko's talk for more details

- β = 4.17, a^{-1}~2.4 GeV

32^3x64x12

m_{ud}	m_π[MeV]	# traj
m_s=0.030		
0.007	310	3000
0.012	400	3000
0.019	500	3000
m_s=0.040		
0.0035	240	3000
0.007	310	3000
0.012	400	3000
0.019	500	3000
m_s=0.040, 48^3x96		
0.0035	240	1500

- β = 4.35, a^{-1}~3.6 GeV

48^3x96x8

m_{ud}	m_π[MeV]	#traj (τ=1)	#traj (τ=2)
m_s=0.018			
0.0042	290	1850	280
0.0080	410	3280	260
0.0120	500	3360	—
m_s=0.025			
0.0042	290	2470	235
0.0080	410	3580	330
0.0120	500	3540	430

so far, meagurements are done on the τ=1 configs.

Measuremtnts of observables

Calculation of Wilson flow

- Wilson flow   Lüscher 2010
  - defined by $V_{x\mu}(0) = U_{x\mu}, \quad \left.\frac{dV_{x\mu}}{dt}\right|_t = -g_0^2 \partial_{x\mu} S_g[V] \cdot V_{x\mu}(t)$

    (MD-force of Wilson gauge action)

    - Runge-Kutta alg.: t → t + ε ➡ flow of gauge config.
  - energy density $E \equiv \left.\frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu}\right|_t$
    - reference values to determine lattice scale:

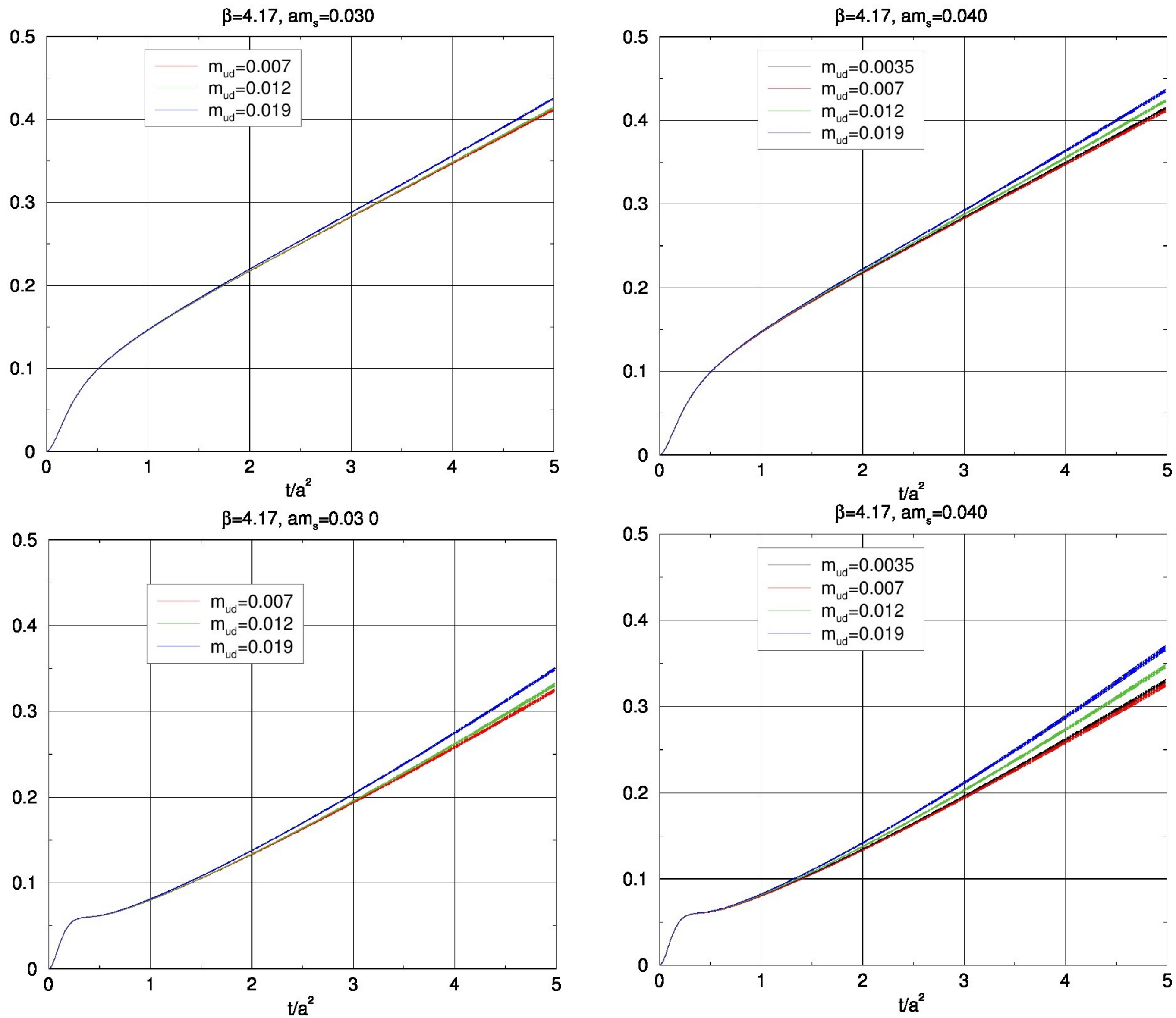
$$\left[t^2 \langle E \rangle\right]_{t=t_0} = 0.3 \qquad \left\{ t \frac{d}{dt} \left[t^2 \langle E \rangle\right] \right\}_{t=w_0^2} = 0.3$$

we use $t_0^{1/2}$ = 0.1465 fm , w_0 = 0.1755 fm   BMW Collab. 2012

Wilson Flow result, β = 4.17 32^3x64

$t^2\langle E\rangle$

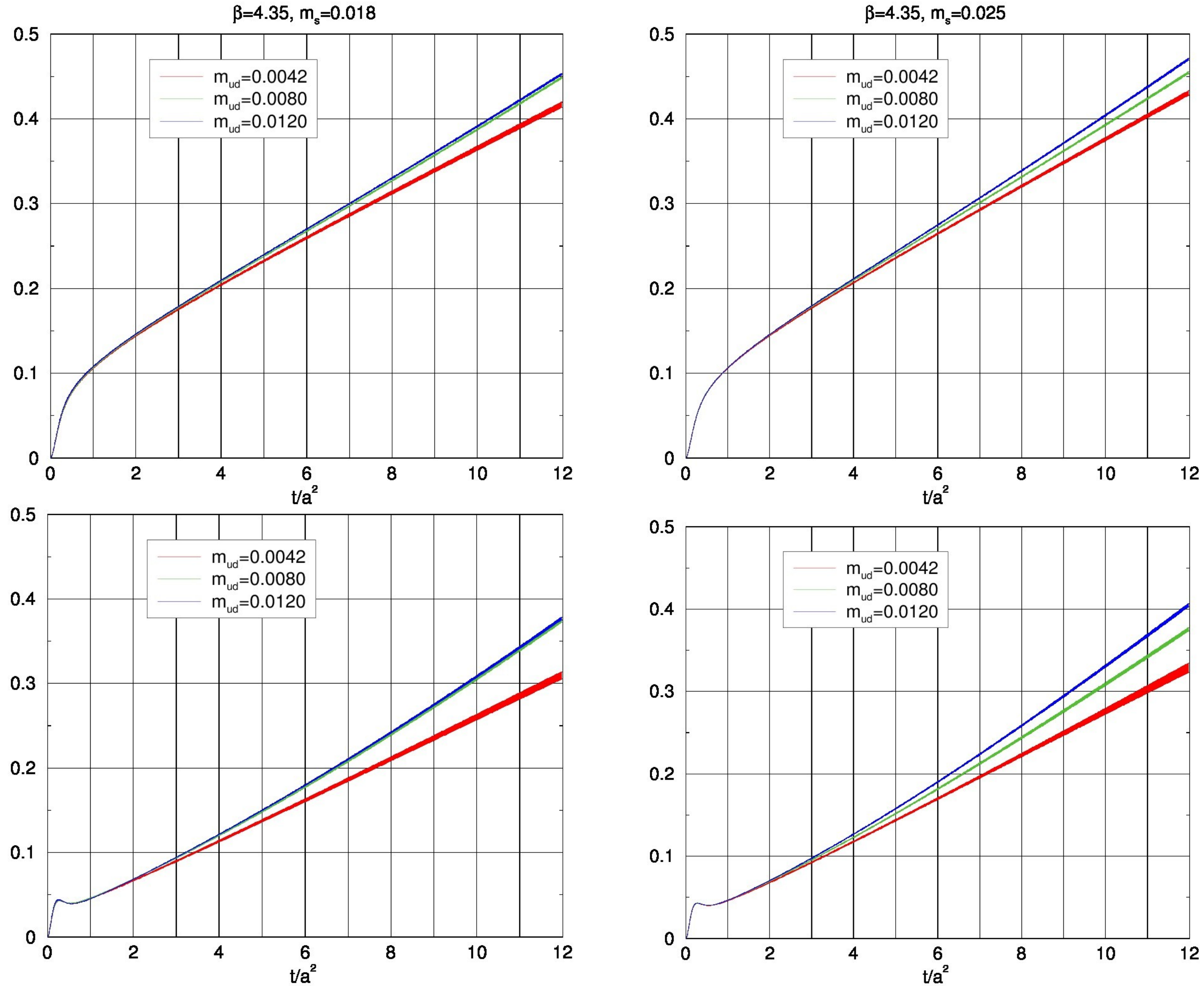
$t\, d\,\{t^2\langle E\rangle\}/dt$



Wilson Flow result, β = 4.35, 48^3x96

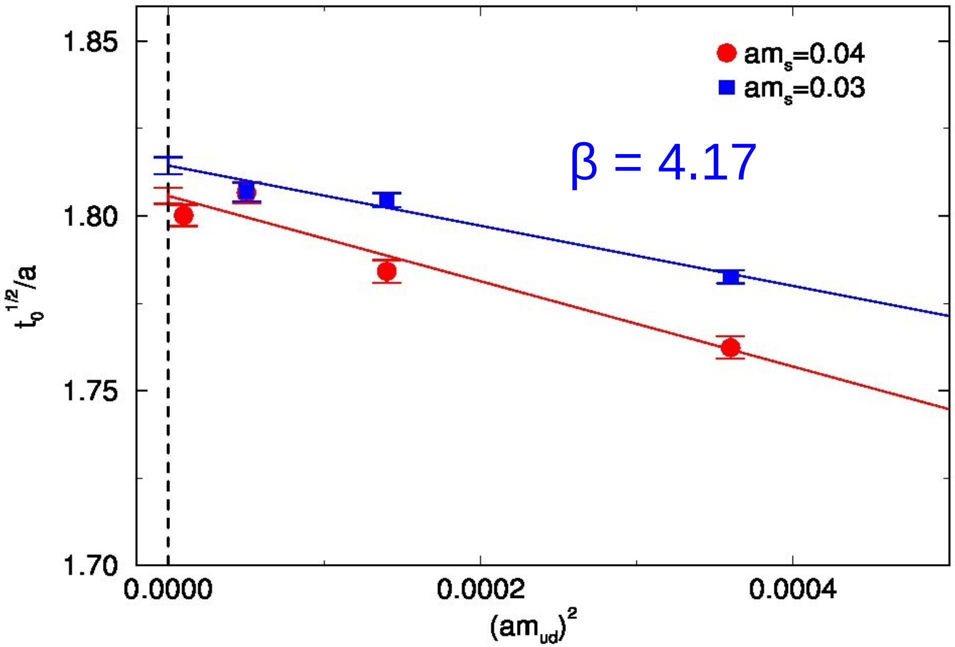
$t^2\langle E\rangle$

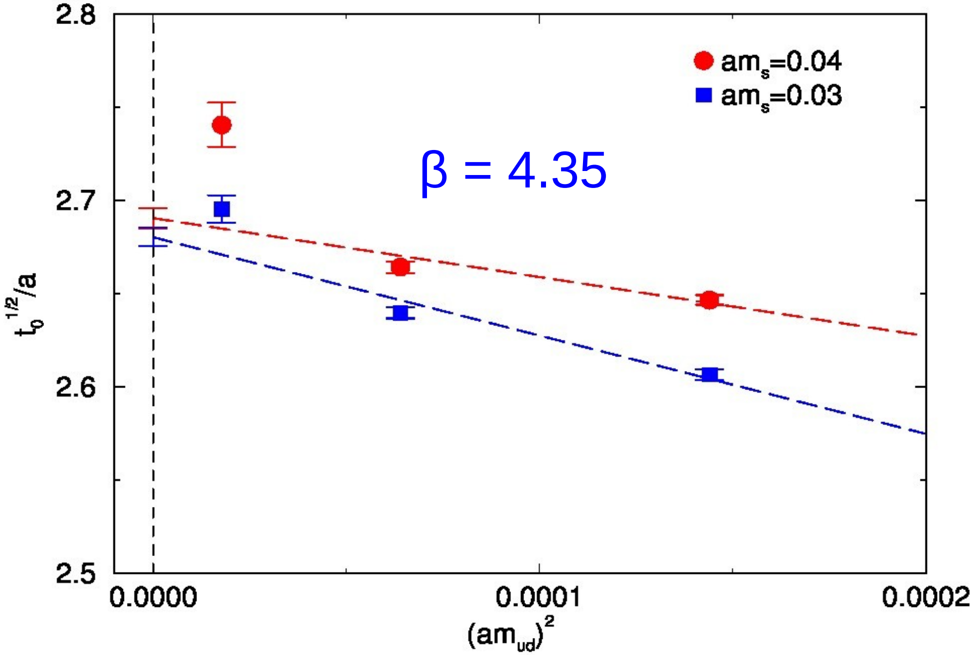
$t\, d\{t^2\langle E\rangle\}/dt$



Lattice scale

- preliminary determination by t_0
  - can be measured at smaller t than w_0





β = 4.17: a^{-1} = 2.472(3) - 2.484(2) GeV ; β = 4.35: a^{-1} ~ 3.68(1) GeV

systematic errors yet to be studied.

too small statistical error ?

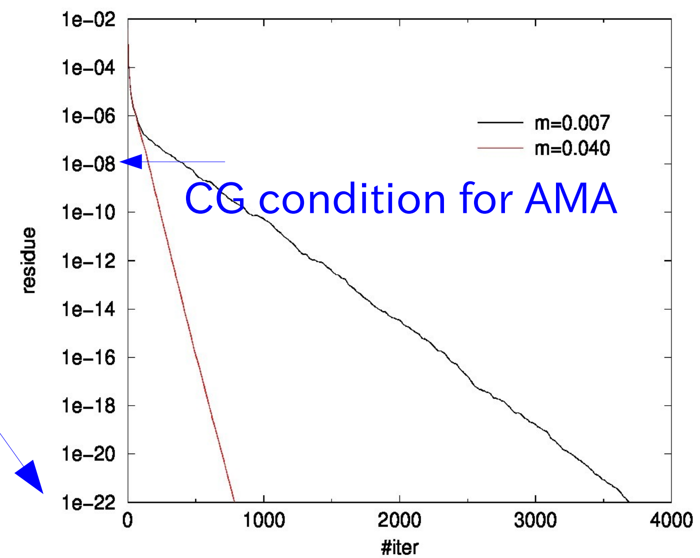
Light hadron mass spectrum

- 2-point correlators from $[D_{\mathrm{DW}}^{(4)}]^{-1}$
  - sourece smearing: $e^{-\alpha r}$ with Coulomb gauge
  - all-mode-averaging (AMA) to improve signal   Blum, Izubuchi and Shintani 2012
    - compute correlators $C^{bulk}(t)$ with relaxed stopping condition as well

      $$C(t) = (C(t) - C^{bulk}(t)) + C^{bulk}(t)$$

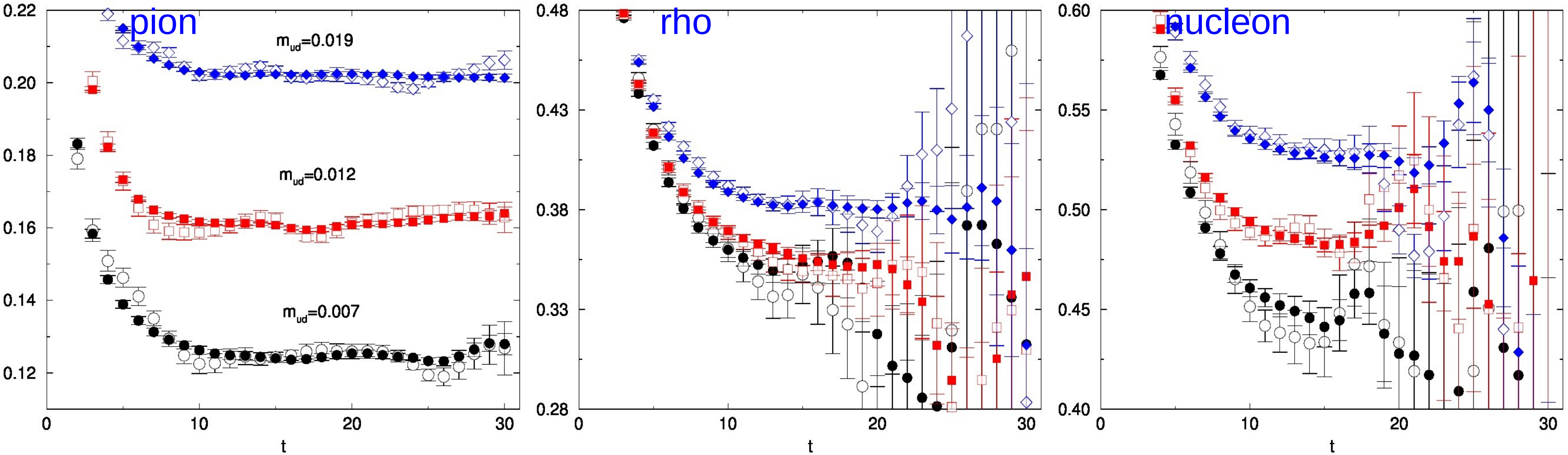
    - improve $C^{bulk}(t)$ by averaging over multiple time-slices
      ← much cheapar than usual case
    - how much gain?

      β=4.17: measurements at t_{src} = 0,2,4,....,62
      with ~10% iterations of the regular precision

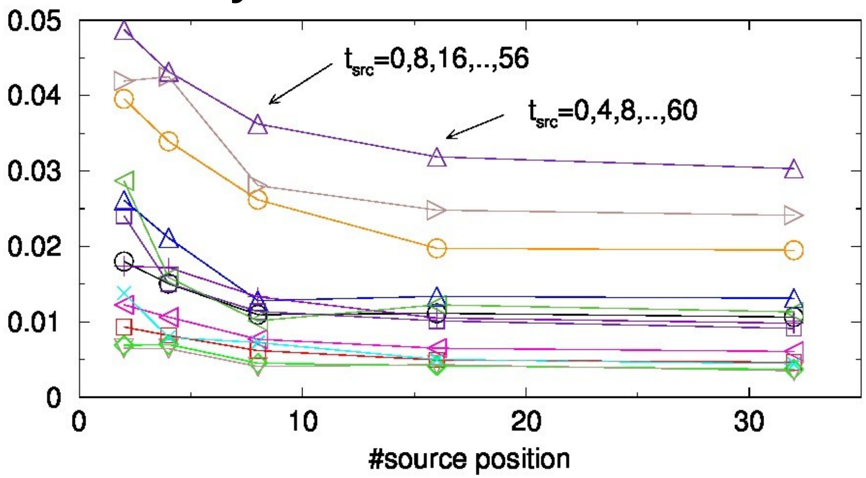


Performance of AMA

– at a glance : β = 4.17, m_s = 0.030   filled: AMA applied; open: conventional



how many sources for relaxed correlators?



error sizes of rho mass

→ start to satulate from t_{step} = 8

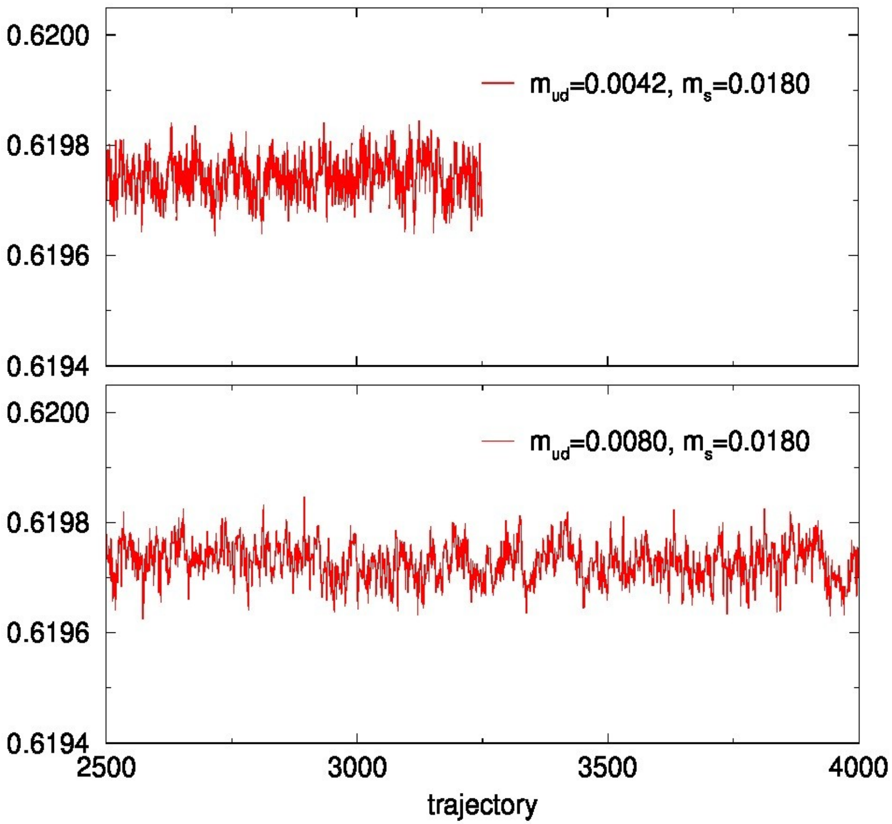
t_{step} = 12 for 48^3x96 lattice

Inspective study of generated configurations
($\beta = 4.35$)

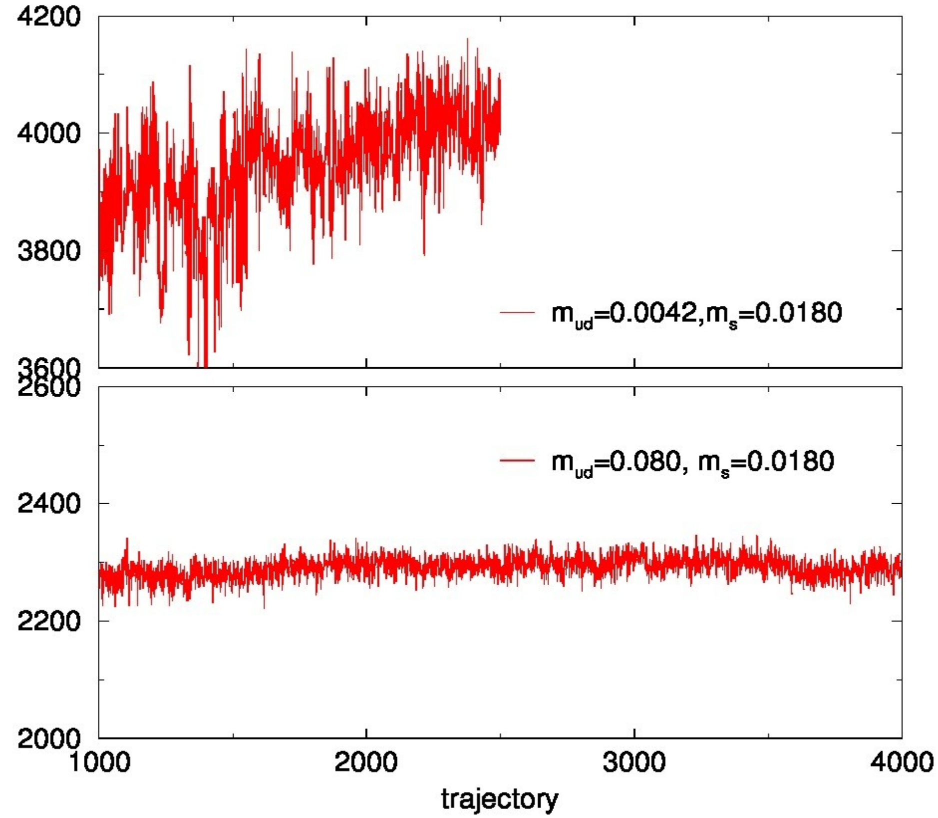
Thermalization: β = 4.35

- monitoring HMC from various angles

plaquette



#iteration of CG

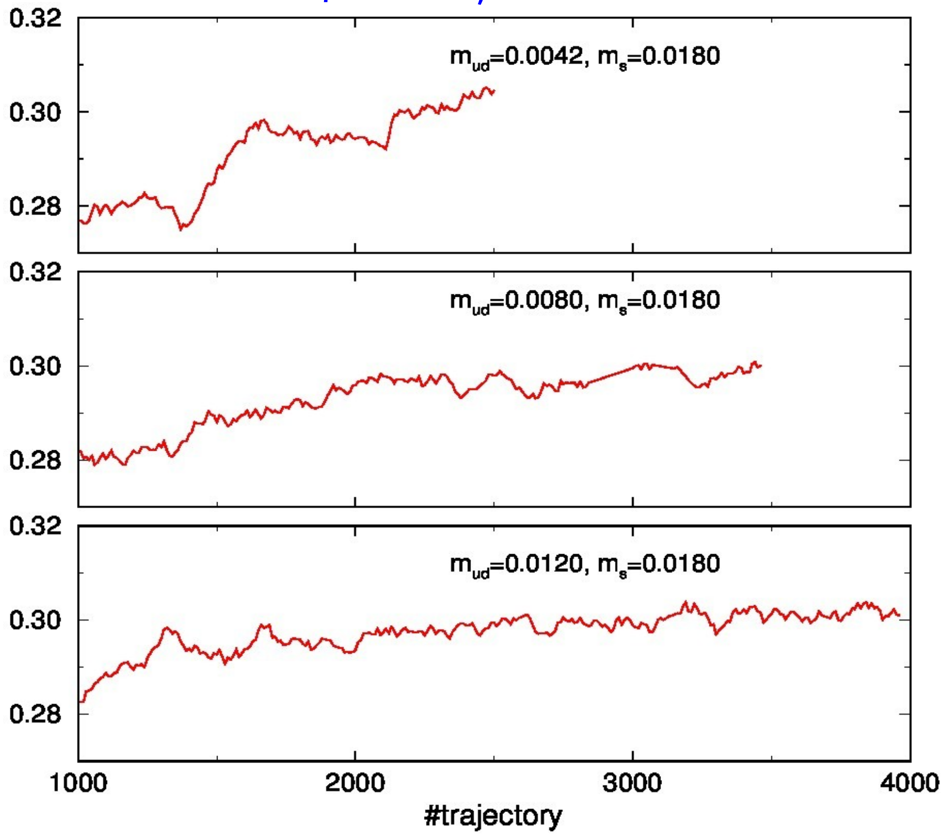


conventional plaquette monitoring ignores unthermalized configs!

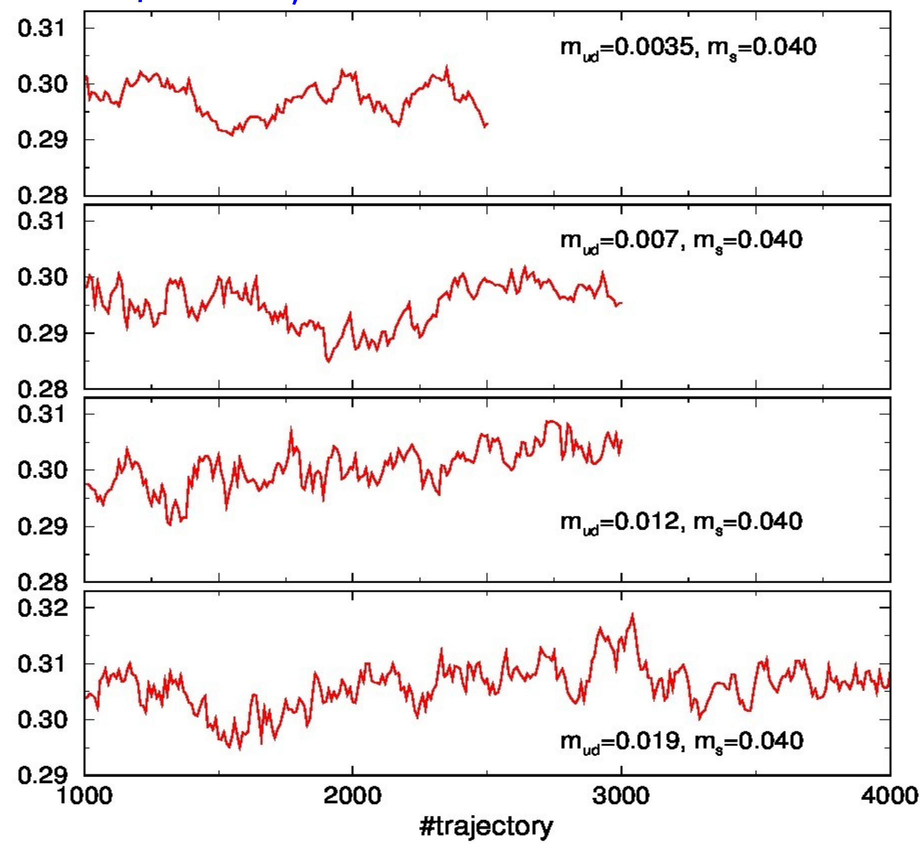
Thermalization in Wilson flow

– history of $t^2\langle E\rangle$ (around t_0)

β =4.35, 48^3x96

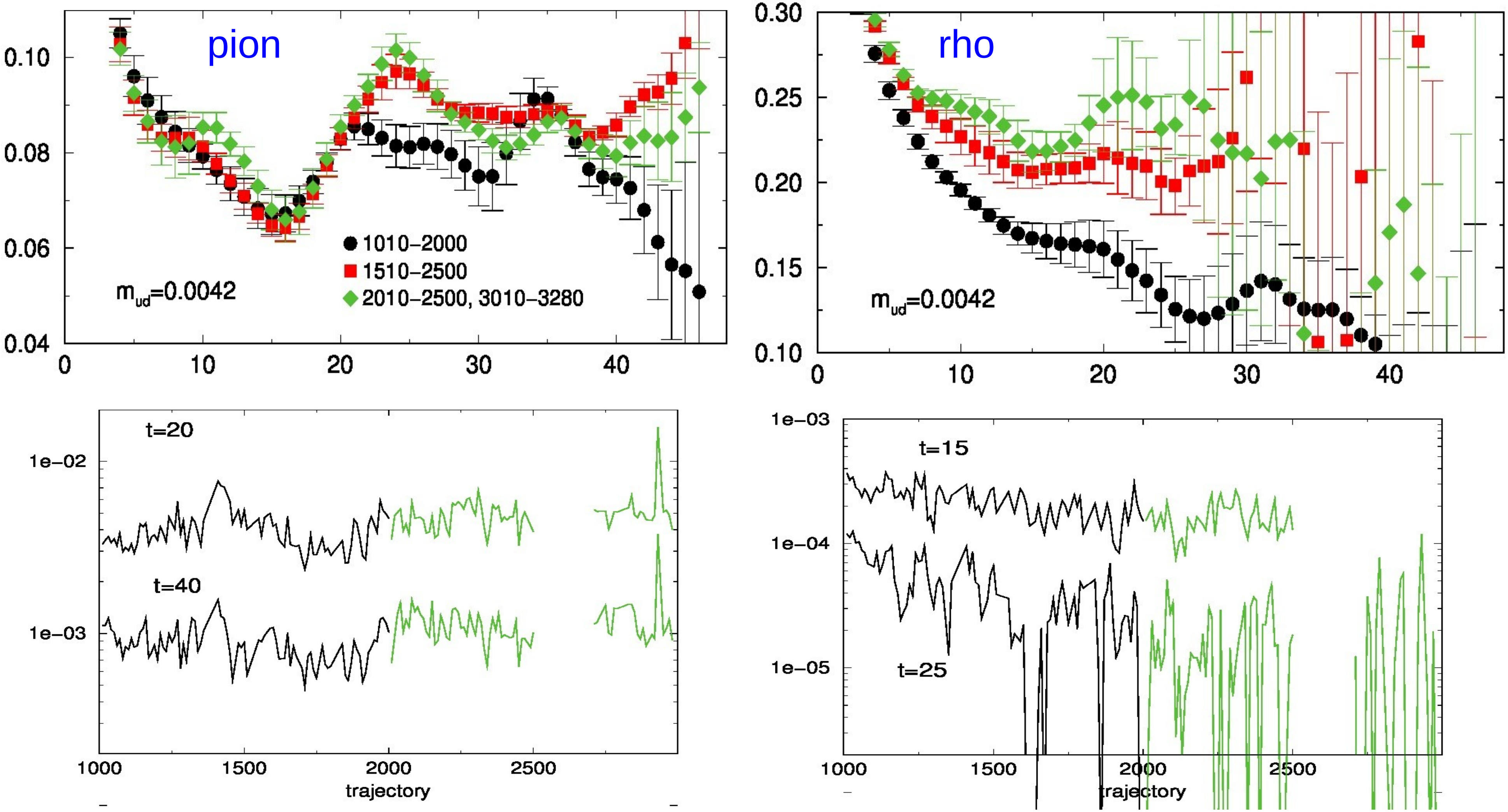


β =4.17, 32^3x64



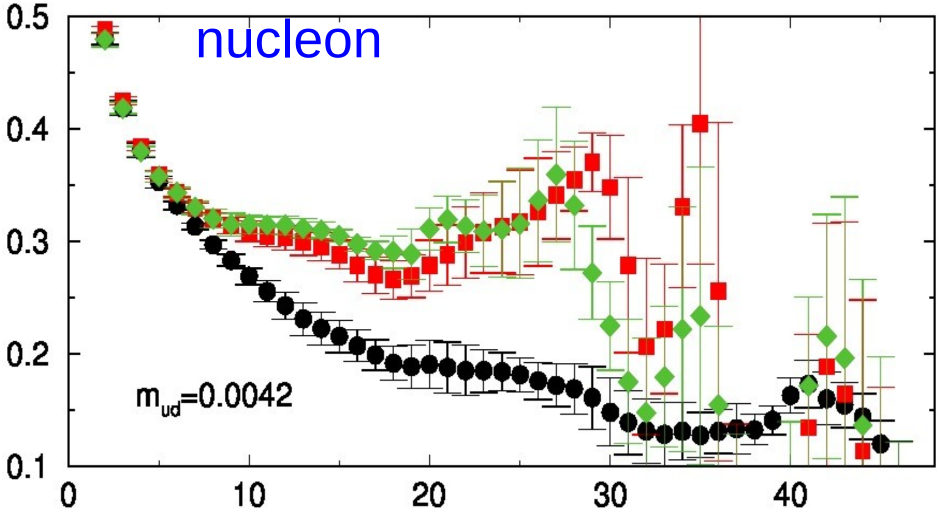
objects on WF is also sensitive to the thermalization

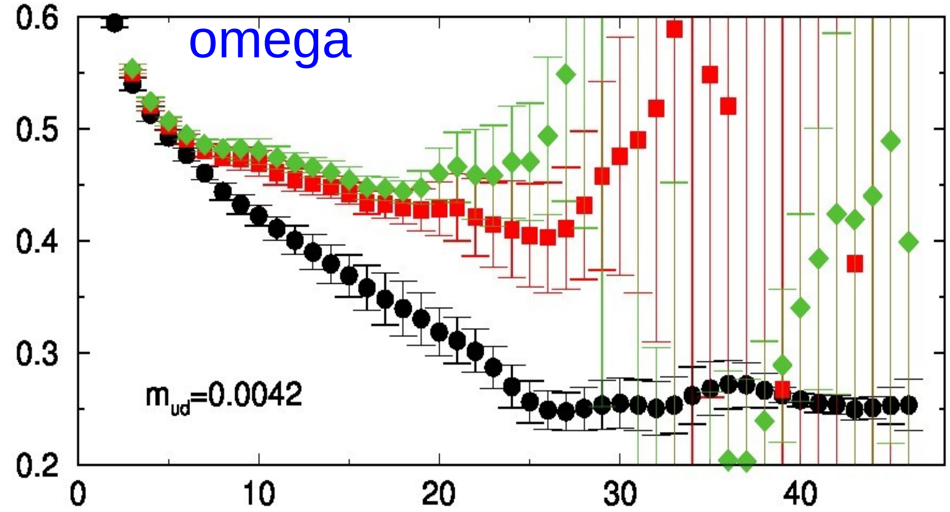
Thermalization in meson correlators

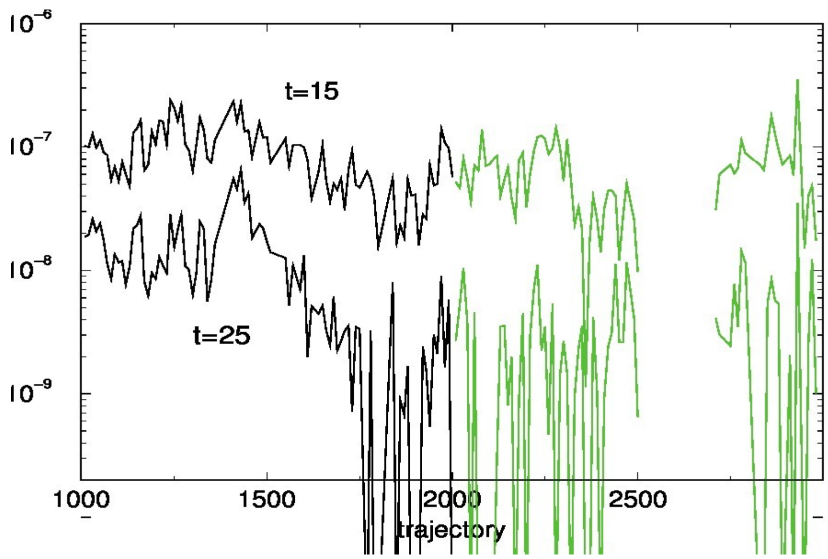


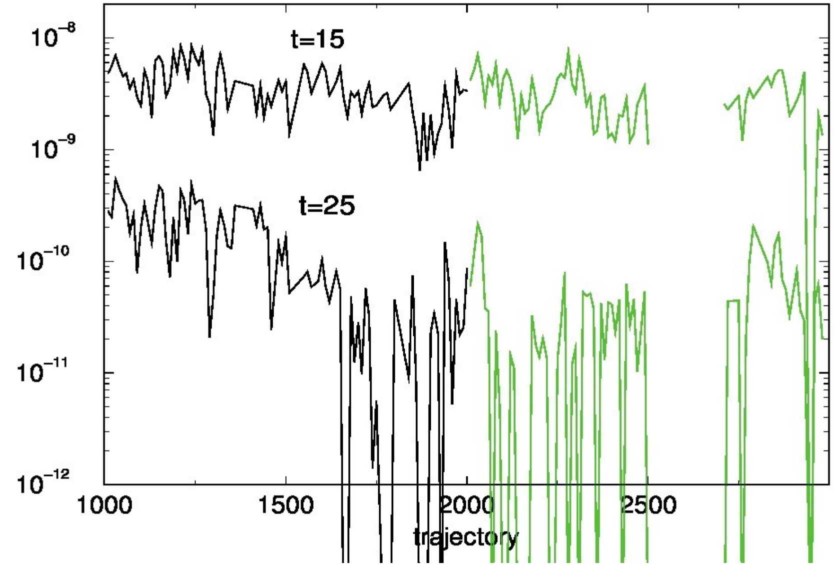
rho is more senistive to the thermalization

Thermalization in baryon correlators







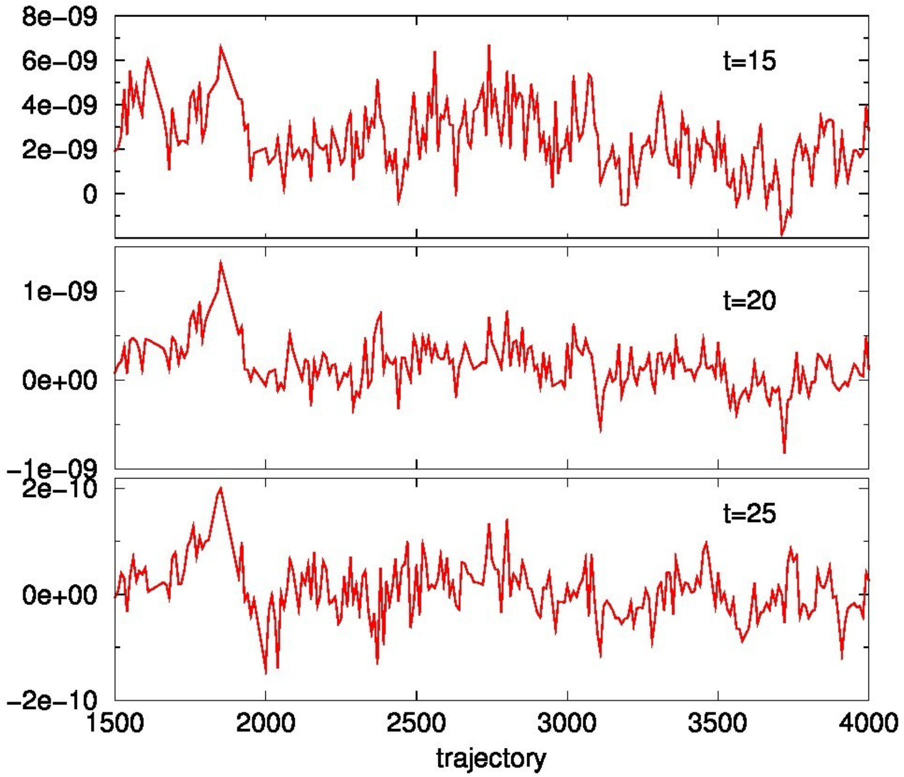


Autocorrelations

- history of omega-correlator is very sensitive to thermalization

→ useful to check auto correlation

β =4.35, mud=0.008, ms=0.018:



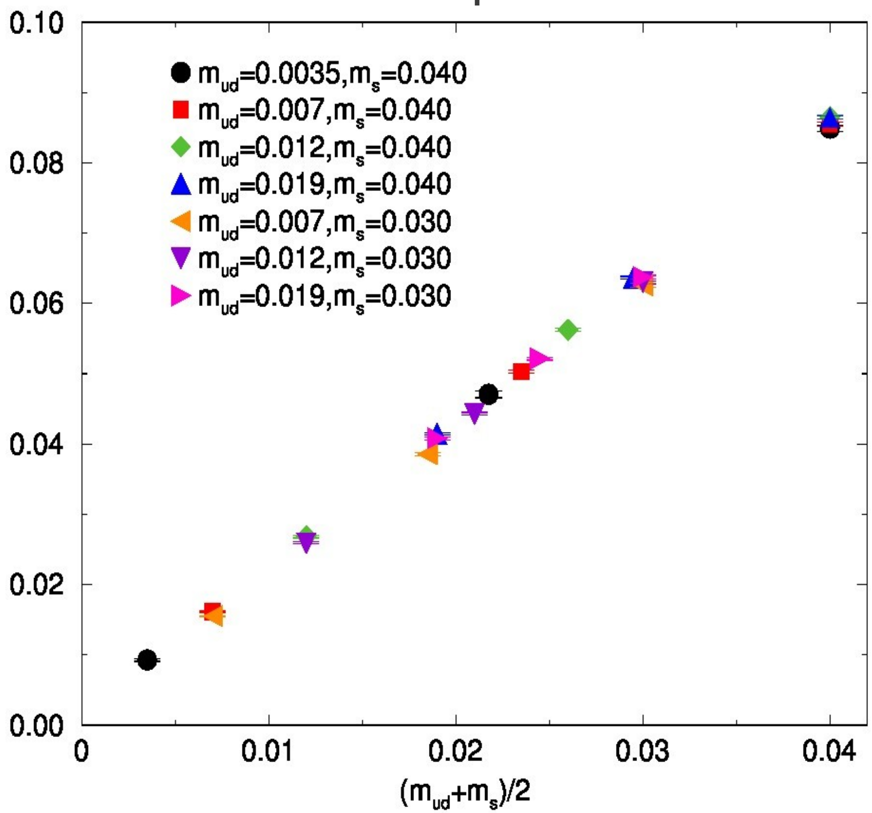
no clear clustering observed 2000- 4000 traj.

Summary & outlook

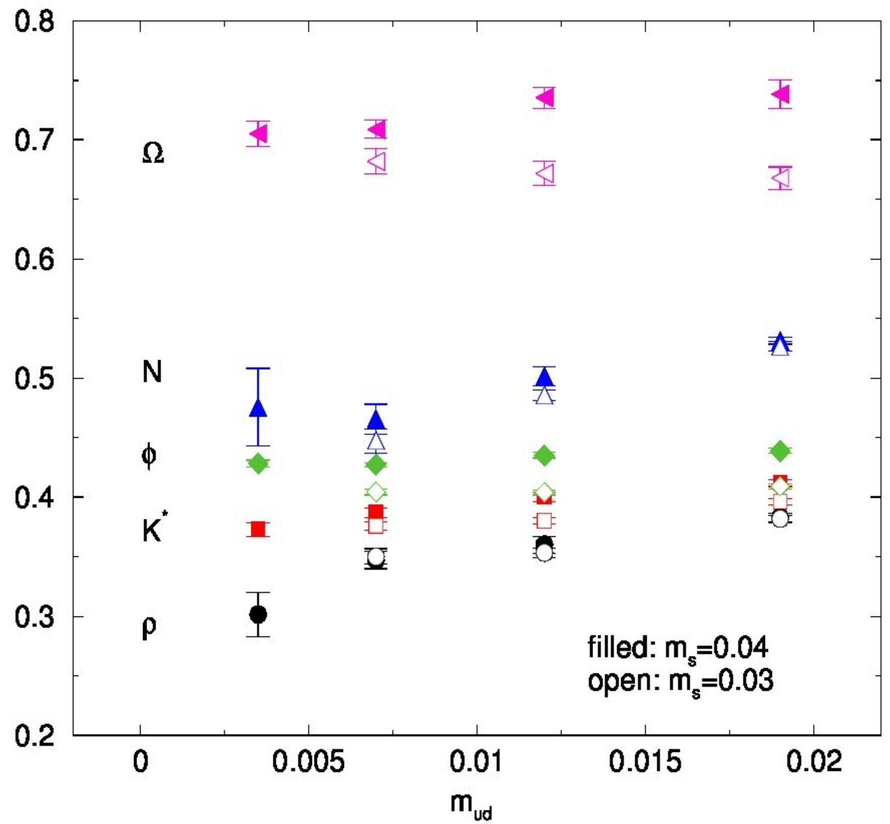
First look at the mass spectrum

$\beta = 4.17$

- PCAC relation in pseudo-scalar



- other hadrons



further improve the signal: inclease the trajectories
and/or low-eigenmodes-averaging

General summary & outlook

- $N_f = 2{+}1$ simulation with Domain-Wall (Möbius) fermions
  - presice control of systematics with chral symm. / discretization / finite volume
- Measurements of basic observables
  - Wilson flow & hadron mass spectrum
- Inspective study of the generated configurations
  - thermalization / autocorrelation strongly depends on objects to monitor
    - new run with $\tau = 2$ is ongoing
- Outlook, or future plan
  - further improvements of statistics
  - application to chiral symmetry dynamics, charm quark physics , etc.
    see H. Fukaya's talk and Y. Cho's talk