2+1 flavor fine lattice simulation at finite temperature with domain wall fermions

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1: YITP, 2: R-CCS, 3: Osaka, 4: KEK

Lattice 2021

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acknowledgements

- Codes used:
  - HMC
    - Grid / Regensburg → poster by N. Meyer
  - Measurements:
    - BQCD
    - Bridge++（Wilson multigrid on Fugaku → talk by I.Kanamori (Wed))

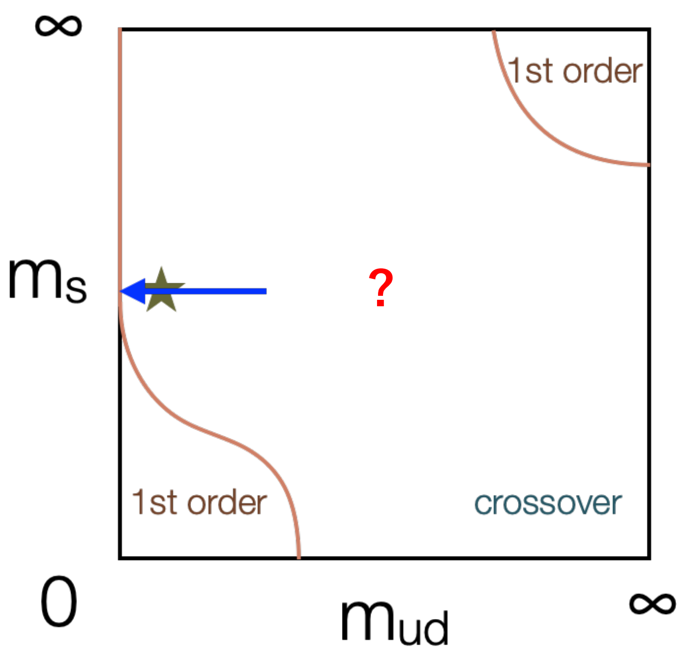
- MEXT program
  成果創出加速プログラム
  Program for Promoting Researches on the Supercomputer Fugaku
  - Simulation for basic science: from fundamental laws of particles to creation of nuclei

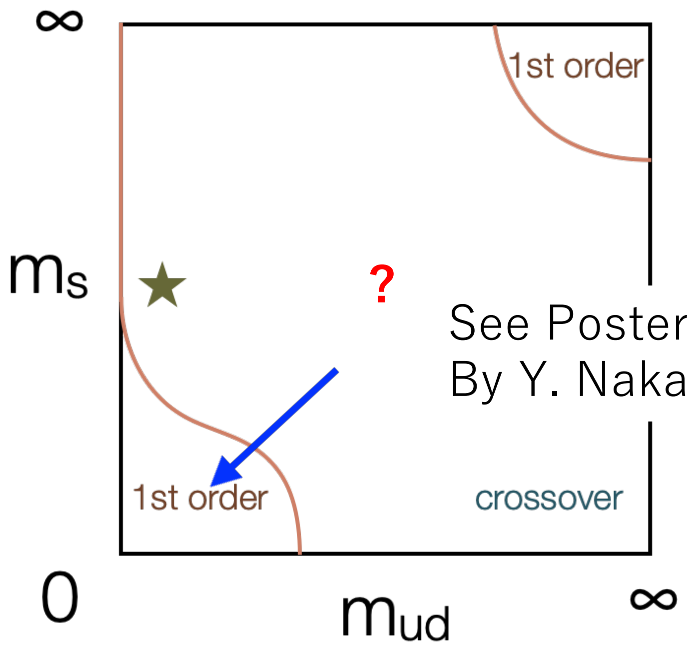
- Computers
  - Oakforest-PACS
  - Polaire and Grand Chariot at Hokkaido University
  - supercomputer Fugaku provided by the RIKEN Center for Computational Science

- Fugaku: software / performance → plenary talk by Y. Nakamura (Fri)

Intro

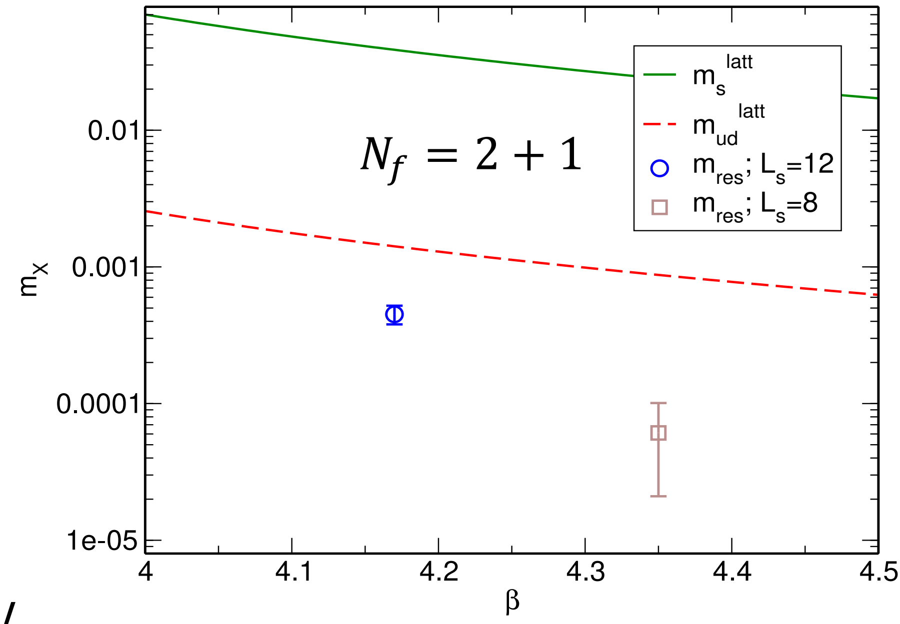
- N_f=2+1 thermodynamic property
  - through chiral symmetric formulation
  - Order of the transition
  - (pseudo) critical temperature
  - Location of the phase boundary
  - Near the physical point
- Chiral symmetric formulation
  - Ideal to treat flavor SU(2) and $U(1)_A$ properly
  - Domain wall fermion (DWF) : practical choice
- DWF and chirality
  - Fine lattice needed
  - Aiming for a < 0.08 fm (eventually)
  - Current search domain: 0.08 < a < 0.12fm





See Poster
By Y. Nakamura

N_f=2 Möbius DWF



- Lessons learned
  - Chiral symmetry important for discussing
    - chiral, $U(1)_A$ problems
  - Reweighting to overlap essential
  - For reweighting to be successful for DW - OV
    - Fine lattice needed (efficiency of reweighting): $a \lesssim 0.1$ fm
    - Smoothness of configuration & smallness of m_{res}
  - For reweighting to be successful in general
    - Large volume is problematic
    - It may not work for further finer lattices
- Expectation
  - Finer the lattice, smaller m_{res}
  - DWF itself eventually becomes good enough
  - Aiming fine lattice DWF simulation would help in any sense

N_f=2 Möbius DWF

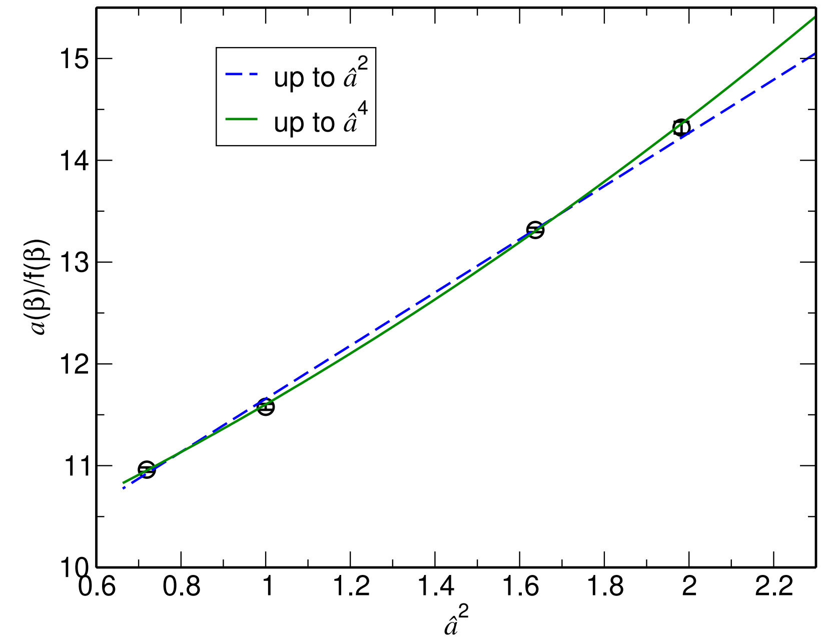
- Action
  - Tree-level improved Symanzik gauge
  - stout-smeared, scale-factor 2 Shamir
- So far studied
  - $U(1)_A$ and chiral symmerty
  - Topological charge
  - Chiral susceptibility → Fukaya (poster)
- Simulation setup
  - Fix β
  - Fix N_t
  - Vary m

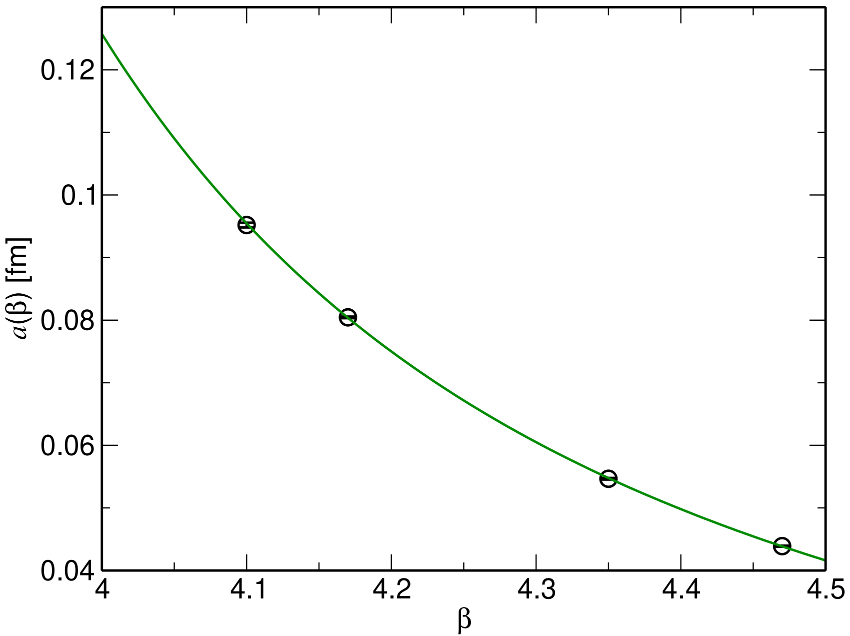
N_f=2+1

- Action: same as N_f=2
- Simulation setup (we follow most of the simulations by now)
  - Fix β
  - Fix N_t
  - Fix m_s^{latt} near physical
  - Vary m_l^{latt}
  - Aiming to understand the role of chiral symmetry, $U(1)_A$, topology
  - See next talk by K. Suzuki
- ↔ fix physics and vary T in this study
  - Line of Constant Physics
  - Aiming to study the (pseudo) criticality w/ fixed physics

N_f=2+1 Möbius DWF

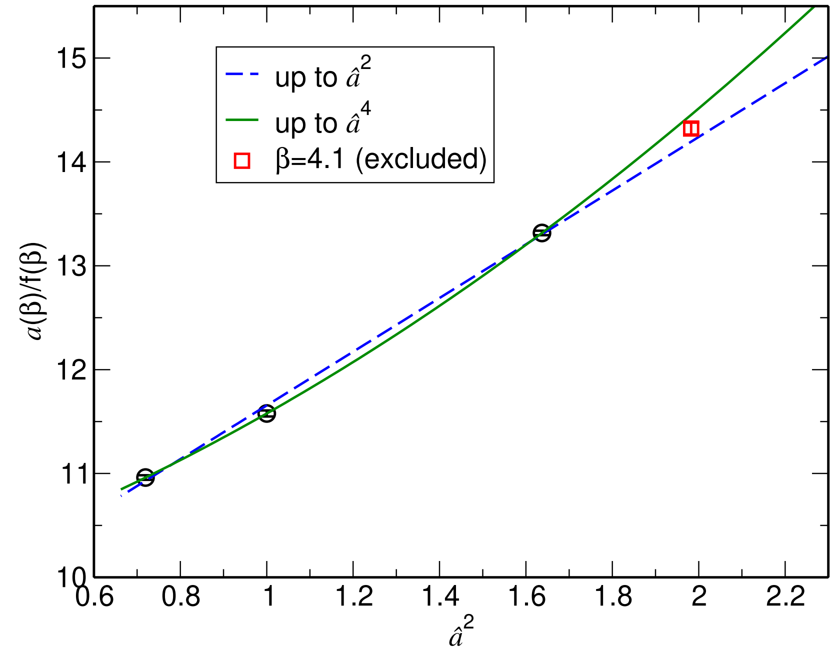
- $a(\beta)$
- Using
  - JLQCD T=0 lattices with t_0 meas.
    - a=0.080, 0.055, 0.044 fm (published)
    - a=0.095 fm (pilot study)
  - Parameterization of Edwards et al (1998)
    - $a = c_0 f(g^2)(1 + c_2\hat{a}(g)^2 + c_4\hat{a}(g)^4)$.
    - $$\hat{a}(g)^2 \equiv [f(g^2)/f(g_0^2)]^2,$$
      $$f(g^2) \equiv (b_0 g^2)^{-b_1/2b_0^2} \exp\left(-\frac{1}{2b_0 g^2}\right),$$
      $$b_0 = \frac{1}{(4\pi)^2}\left(11 - \frac{2}{3}N_f\right), \quad b_1 = \frac{1}{(4\pi)^4}\left(102 - \frac{38N_f}{3}\right),$$
    - Fit to $\hat{a}^4$ works well

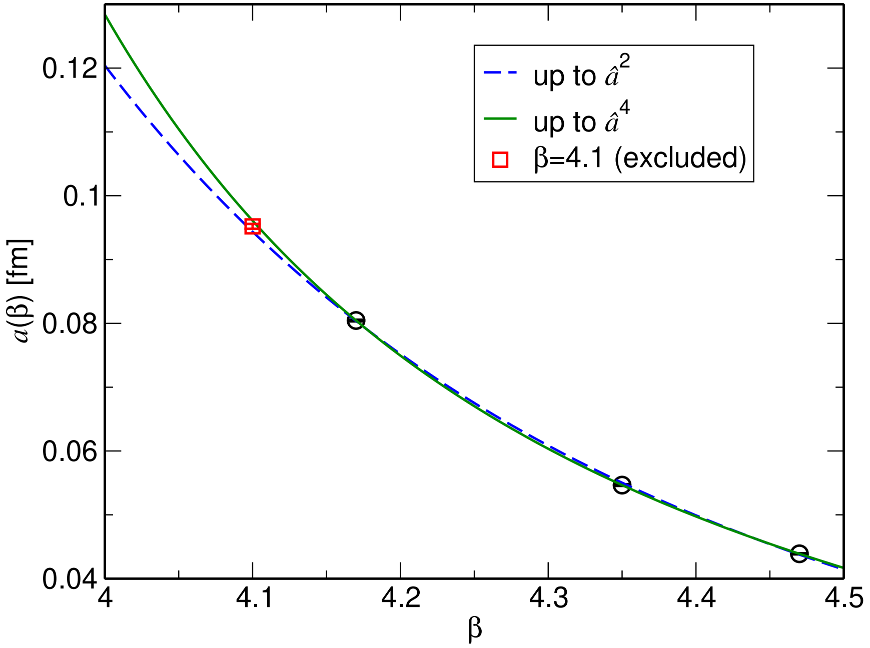




N_f=2+1 Möbius DWF

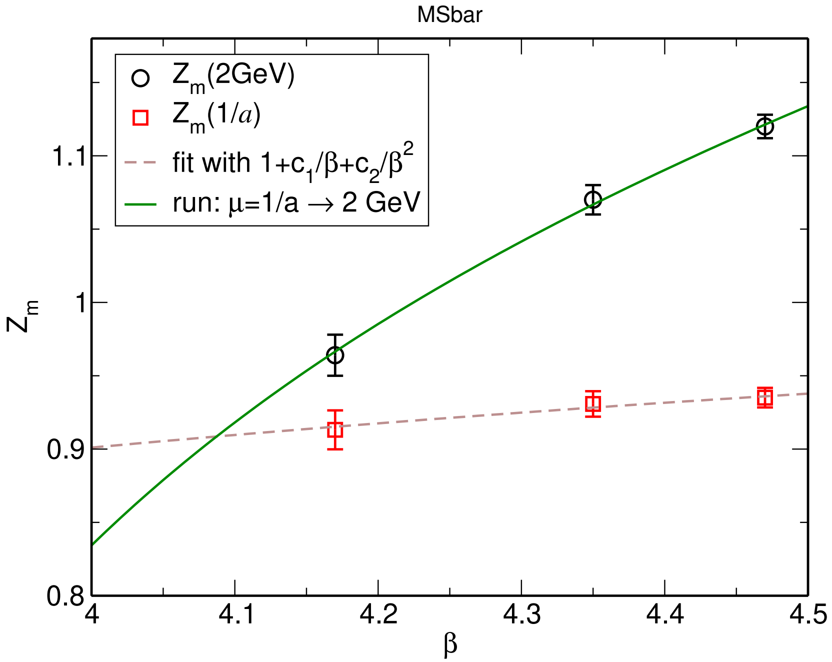
- $a(\beta)$ precision over the range
- Test excluding coarsest one
  - 1 % diff : fit <-> measurement @β=4.1
  - Difference $O(\hat{a}^4) - O(\hat{a}^2)$ fits: good measure of error (maybe overestimating)
- Full range fit
  - @ $\beta = 4.0$ error is ~ few %
  - The fit may be regarded as renormalized trajectory
    - Continuum limit will absorb the error

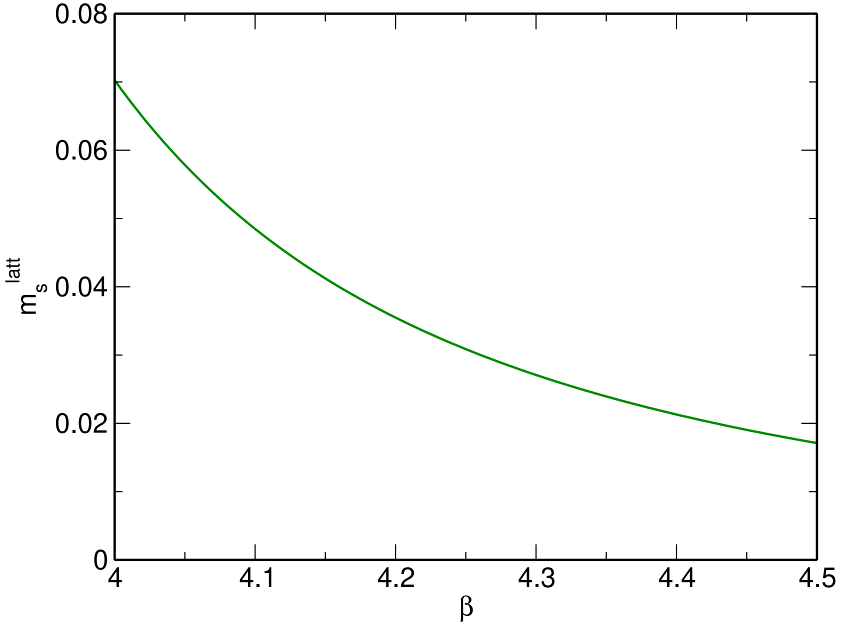




N_f=2+1 Möbius DWF LCP

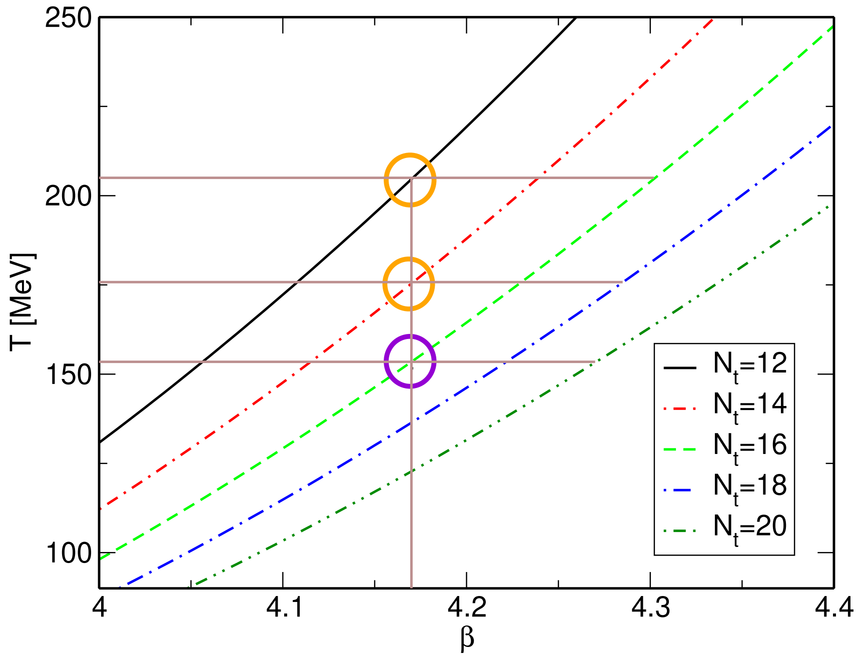
- Quark mass as function of β [fixed physics]
- We use quark mass input
  - $m_s = 92\ MeV$ (MSb 2GeV)
  - $\frac{m_s}{m_{ud}} = 27.4$ (See for example FLAG 2019)
  - $m_q^R = Z_m \cdot (am_q^{latt}) \cdot a^{-1}(\beta)$
- Parameterizing $Z_m(\beta)$
  - Take $Z_m(2GeV)$ w/ NPR Tomii et al 2016
  - $Z_m(2GeV) \to Z_m(a^{-1})$ NNNLO pert.
    - No (large) $\log(a\mu)$
    - Should behave like $1 + d_1 g^2 + d_2 g^4 + \cdots$
  - Fit $Z_m(a^{-1})$ with $1 + c_1\beta^{-1} + c_2\beta^{-2}$
  - $Z_m(a^{-1}) \to Z_m(2GeV)$ NNNLO pert.

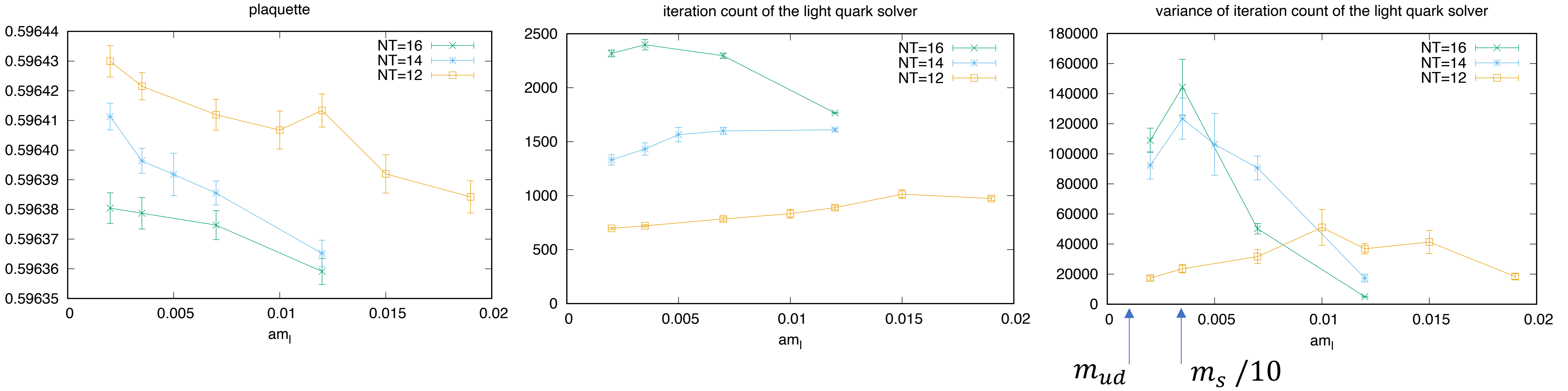




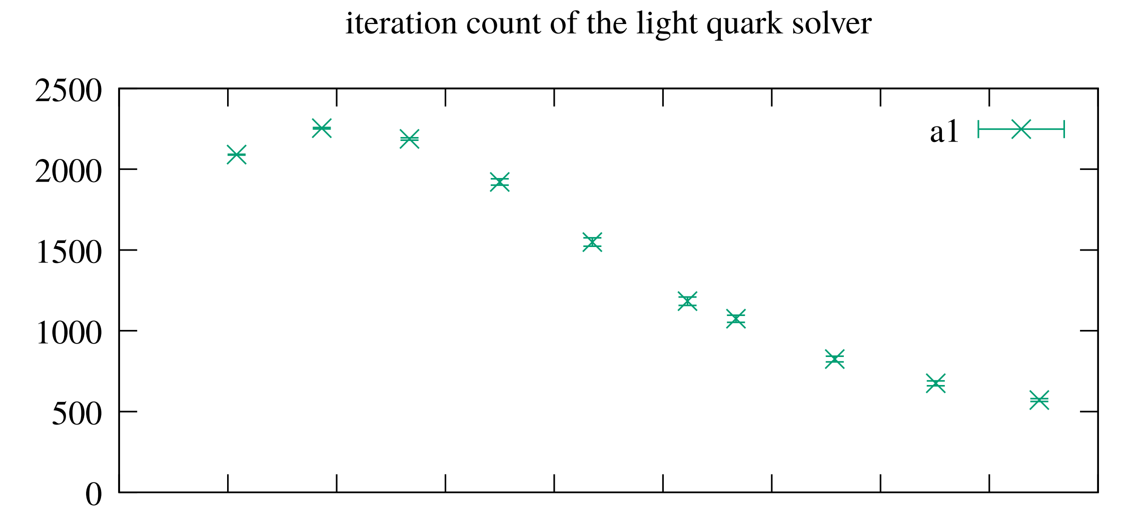
Simulation range

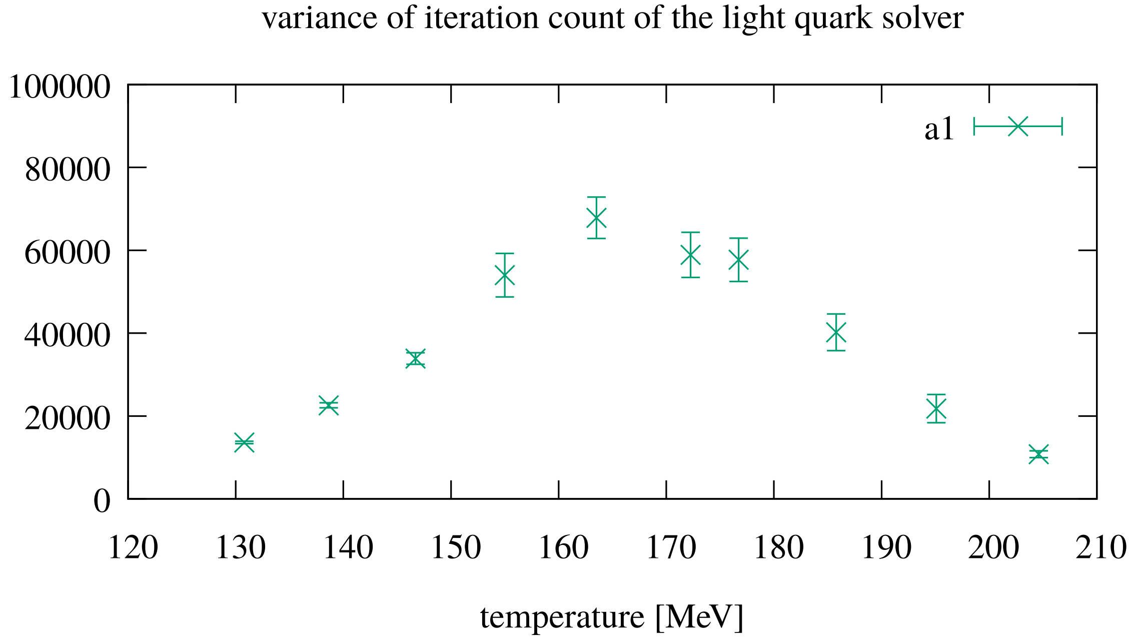
- $T - \beta$ relation $T = 1/(aN_t)$
- Information from fixed β simulation
  - $N_t = 12, 14$
    - $m \to 0$ study (next talk by K. Suzuki)
  - $N_t = 16$: $T \sim 150\ MeV$
  - $N_s = 32,\ L_s = 12$
  - $m_{ud}^{latt} = 0.0014,\ m_s^{latt} = 0.0388$

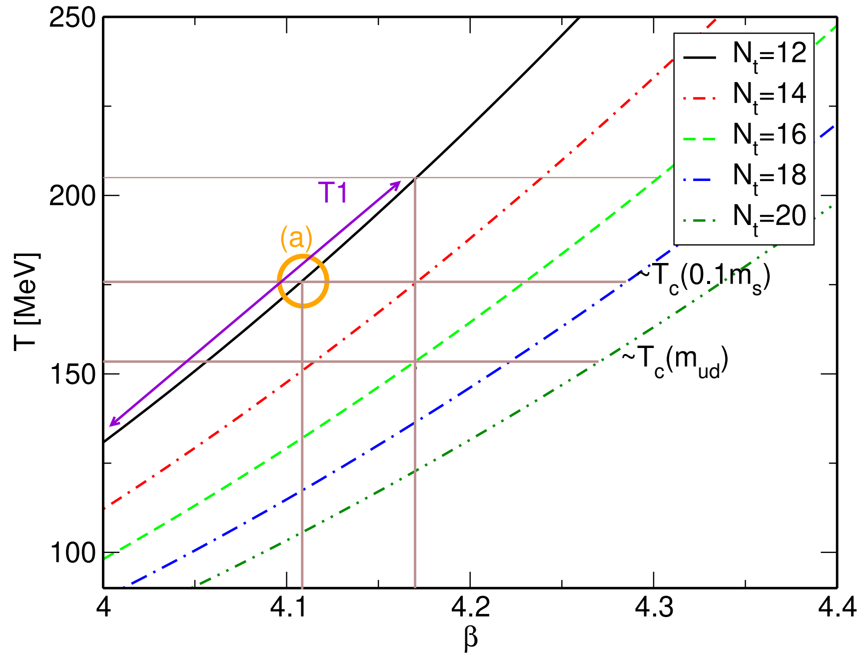




Initial simulations on LCP







- $N_t = 12$ (T1)
- $m = 0.1 m_s$ (a)
- $N_s = 24, L_s = 12$

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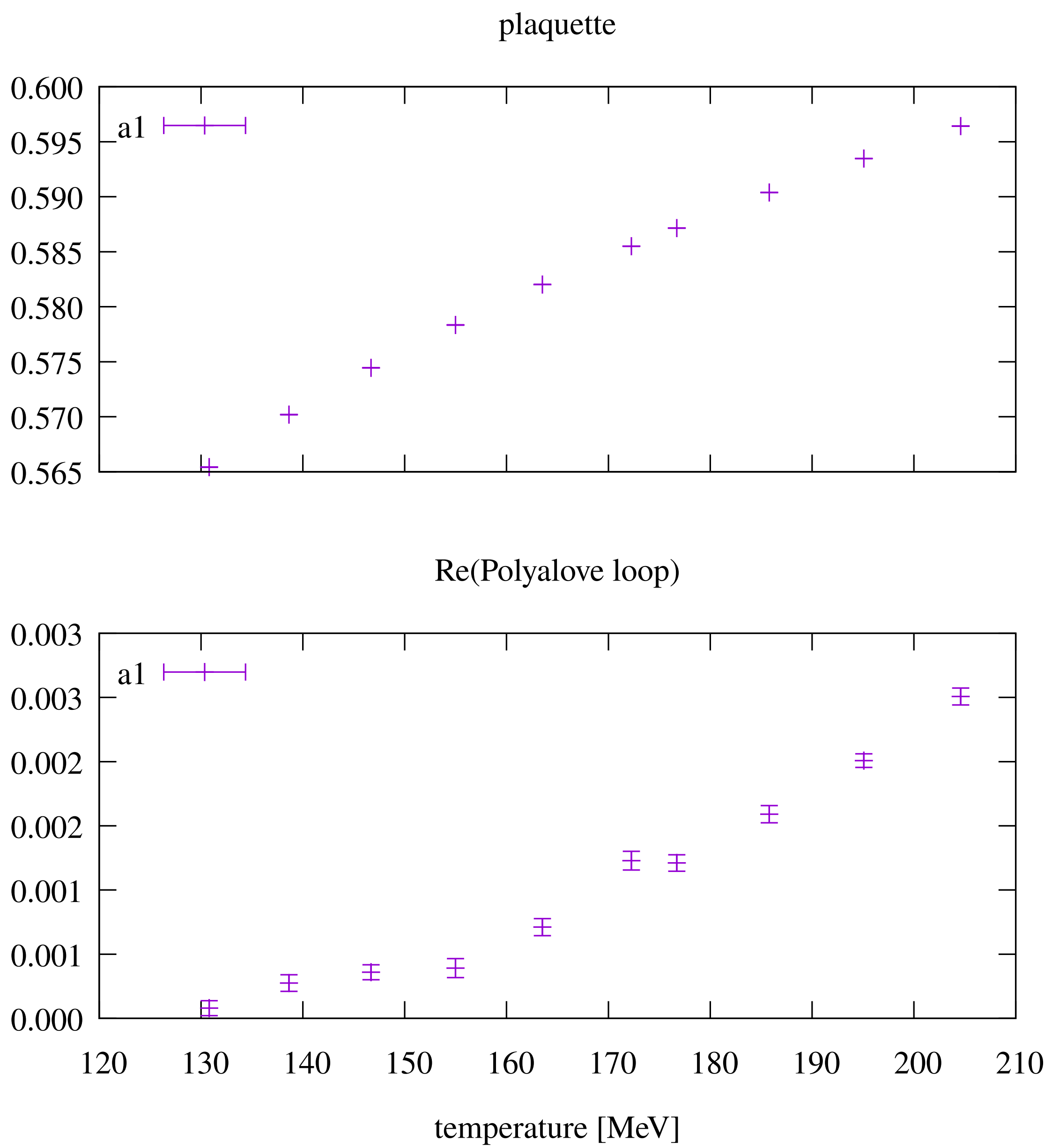

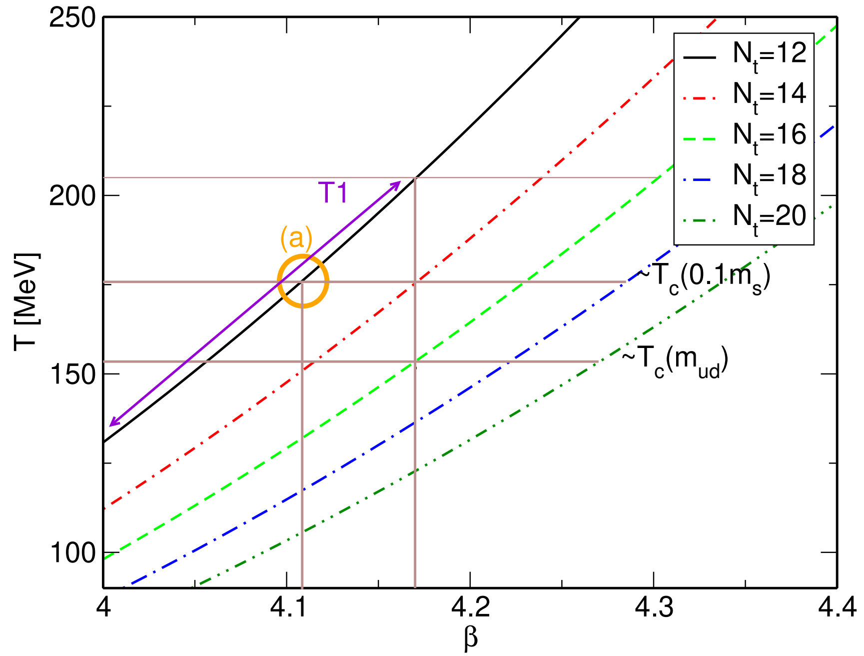

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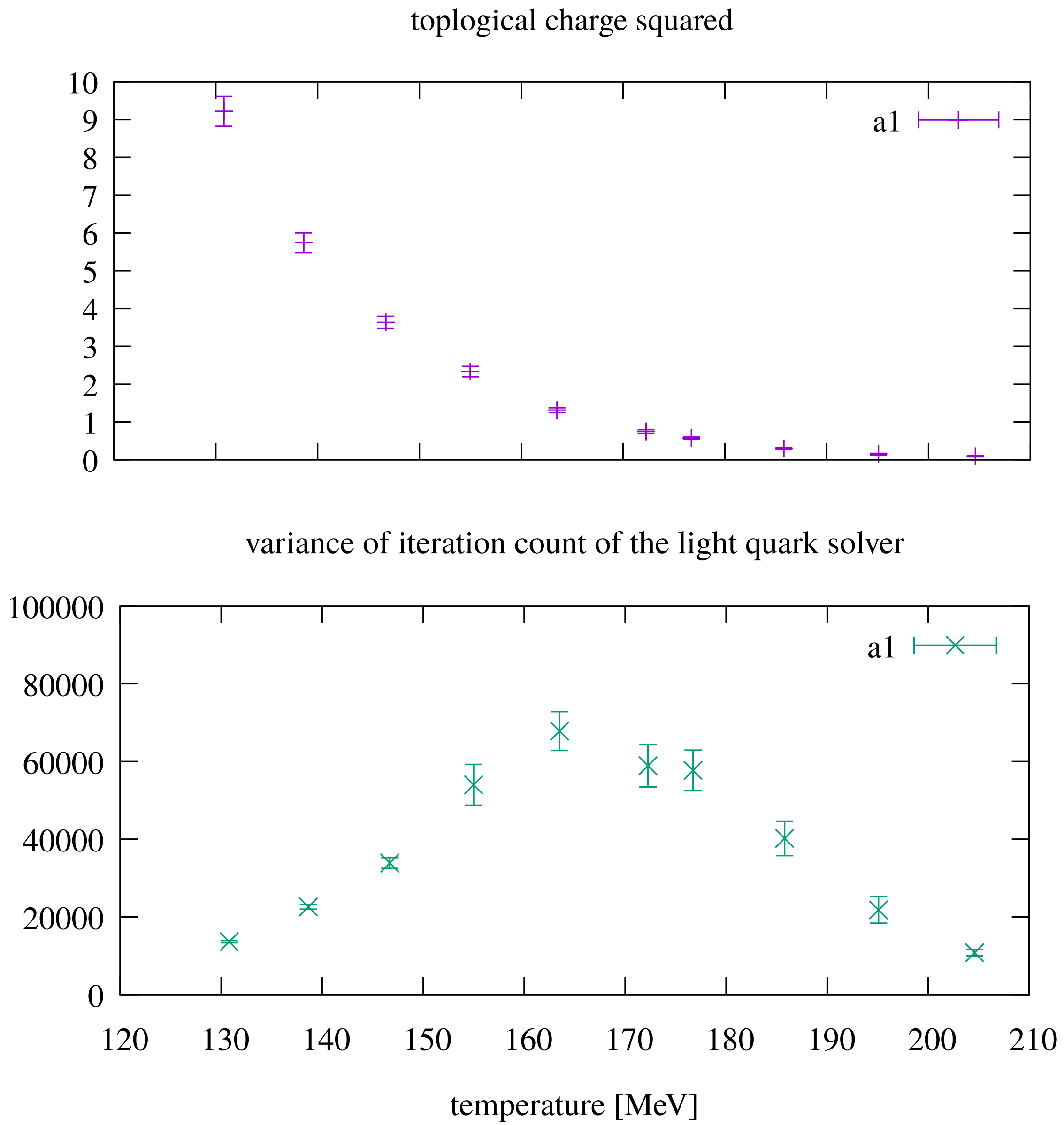

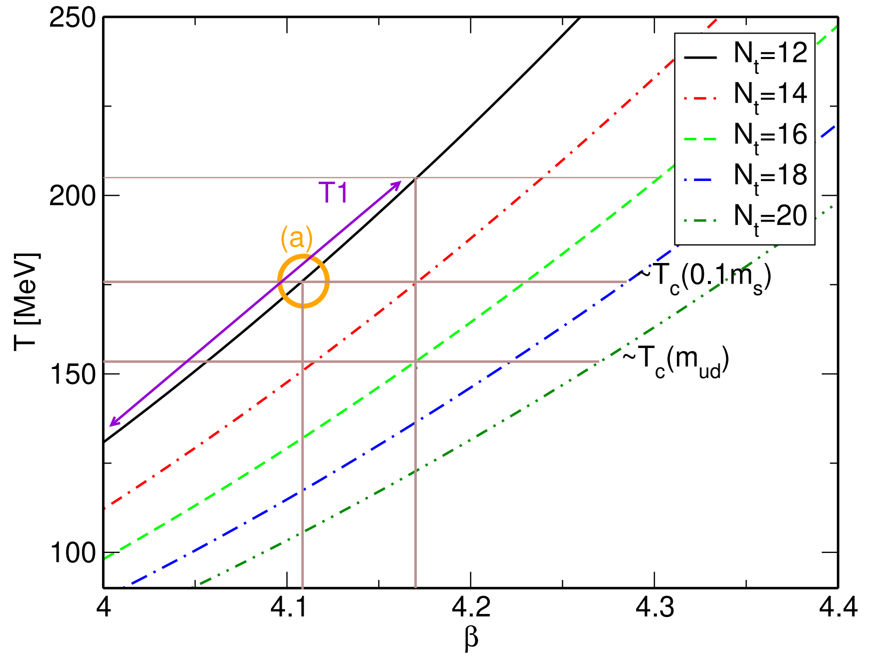

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- $m = 0.1m_s$ (a)
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Summary and outlook

- Summary
  - Möbius DWF simulation for T>0 with $N_t \geq 12$
    - ↔ $N_t=8$ by HotQCD (2012)
  - Along the Line of Constant Physics
  - First simulations with $m = 0.1\, m_s$, $N_s/N_t=2$
    - Underway using Fugaku
- Outlook
  - Statistics is increasing
  - Measurements esp, fermionic
  - Closer to physical mud
  - Another lattice spacing
  - Larger volume

Simulation plan

- T1-(a)
  - $N_t = 12$
  - $m = 0.1m_s$
  - $N_s = 24, L_s = 12$
  - Now underway
- T2-(c)
  - $N_t = 16$
  - $m = 0.1m_s$
  - $N_s = 32, L_s = 12$
  - This is straight forward
- T1-(b)
  - $N_t = 12$
  - $m \simeq m_{ud}$
  - $N_s = 24, L_s = 12$
  - Mass tuning is necessary
    - $m_{res} \simeq m_{ud}$