SU(2) gauge theory with many flavors of domain-wall fermions

- Introduction
- Setup
- Result of simulation: Nf=2, 4, 6, 8

  Static potential/meson masses/decay consstant
- Summary/outlook

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Introduction

- SU(2) gauge theory
  - Many works on confinement mechanism, finite temperature/density
  - Beyond standard model: technicolor, conformal window, dark matter
    - F. Bursa et al. (2011), H.Ohki et al. (2010), Lewis, Pica, Sannino (2012) T. Karavirta et al. (2012), M. Hayakawa et al. (2013)
- Chiral dynamics depending on gauge group and fermion repr.
  - Different symmetry breaking pattern

Fundamental	Adjoint
SU(2): SU(2Nf) → Sp(2Nf)	SU(N): SU(2Nf) → SO(2Nf)
SU(N) N>2: SU(Nf)xSU(Nf) → SU(Nf)	

  - Dependence on number of flavors
  - Finite temperature/density
  - Eigenvalue distribution – comparison to random matrix theory

Strategy

- Chiral symmetric fermion is better device
  - Overalp: best symmetry, high numerical cost, involved setup (Aoki phase, etc.) H.M., Kikukawa, Yamada, Nagai, Lattice 2010, 2009
  - Domain-wall: good properties, numerically feasible
    - Approaches to overlap with large Ns
    - Residual mass probes explicit chiral symmetry violation

Domain-wall

- Topology changes
- Large lattice is possible

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Improved domain-wall

Mesurement:

- Spectroscopy
- Eigenvalue/vectors, etc.

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Ovelap

- Fixed topology
- p-regime/ε-regime

Present work

- Lattice actions:
  - Iwasaki gauge action
  - Standard domain-wall fermions: Nf=2, 4, 6, 8
- Survey of Nf-dependence with fixed setup
  - Applicability of domain-wall (and overlap) fermions
  - Confining/conformal feature ?
  - Static potential
  - Meson masses and decay consts/residual mass
  - Eigenmodes of domainwall/overlap fermion operators (underway)
- Fundamental setup: making basis for further studies
  - Finite T/μ, adjoint fermions
  - Comparion with improved domain-wall, dynamicsal overlap
  - Condition to access the ε-regime

Setup

- Lattice size: 16^3x32, Ns=16
- Configuration generation: Hybrid Monte Carlo
  - Domain-wall/Pauli-Villars
  - Omelyan integrator + multi-time step (2-level)
  - About 1000 tranjectories at each parameter set

Nf	beta	m
2	0.85	0.20, 0.10, 0.05
	0.90	0.20, 0.10, 0.05
4	0.85	0.20, 0.10, 0.05, 0.03
	0.90	0.20, 0.10, 0.05
6	0.80	0.20, 0.10, 0.05
	0.85	0.20, 0.10, 0.05
	0.90	0.20, 0.10, 0.05
8	0.80	0.20, 0.10, 0.05
	0.85	0.20, 0.10, 0.05

Resources/environment

- Machines
  - Hitachi SR16000, IBM Blue Gene/Q at KEK
  - φ at KMI, Nagoya Univ.



Code:

  - Bridge++ (C++)
    - Cf. S.Ueda's poster
  - Fortran code

- JLDG (Japan Lattice Data Grid)
  - for fast data transfer

Japan Lattice Data Grid

Domain-wall fermion

- Standard domain-wall fermion action

$$\begin{aligned} S_{DW} &= \sum_{x,s} \bar{\psi}(x,s) D_W(x,y;-M_0)\psi(y,s) \\ &-\frac{1}{2}\sum_{x,s} \bar{\psi}(x,s)\left[(1-\gamma_5)\psi(x,s+1) + (1+\gamma_5)\psi(x,s-1) - 2\psi(x,s)\right] \\ &+m\left[\bar{\psi}(x,1)P_R\psi(x,L_s) + \bar{\psi}(x,L_s)P_L\psi(x,1)\right] \end{aligned}$$

$$D_W(x,y;M) = M\delta_{x,y} - \frac{1}{2}\sum_{\mu=1}^{4}\left\{(1-\gamma_\mu)U_\mu(x)\delta_{x+\hat{\mu},y} + (1+\gamma_\mu)U_\mu^\dagger(x-\hat{\mu})\delta_{x-\hat{\mu},y} - 4\delta_{x,y}\right\}$$

  - M_0: domain-wall height, m: fermion mass
  - Ls: extent of 5-th direction
  - Boundary conditions: $P_R\psi(s=0) = P_L\psi(s=L_s+1) = 0$
  - 4D fermion field:

$$\begin{aligned} q(x) &= P_L\,\psi(x,s=1) + P_R\,\psi(x,s=L_s) \\ \bar{q}(x) &= \bar{\psi}(x,s=1)P_R + \bar{\psi}(x,s=L_s)P_L \end{aligned}$$

Residual mass

- Residual mass

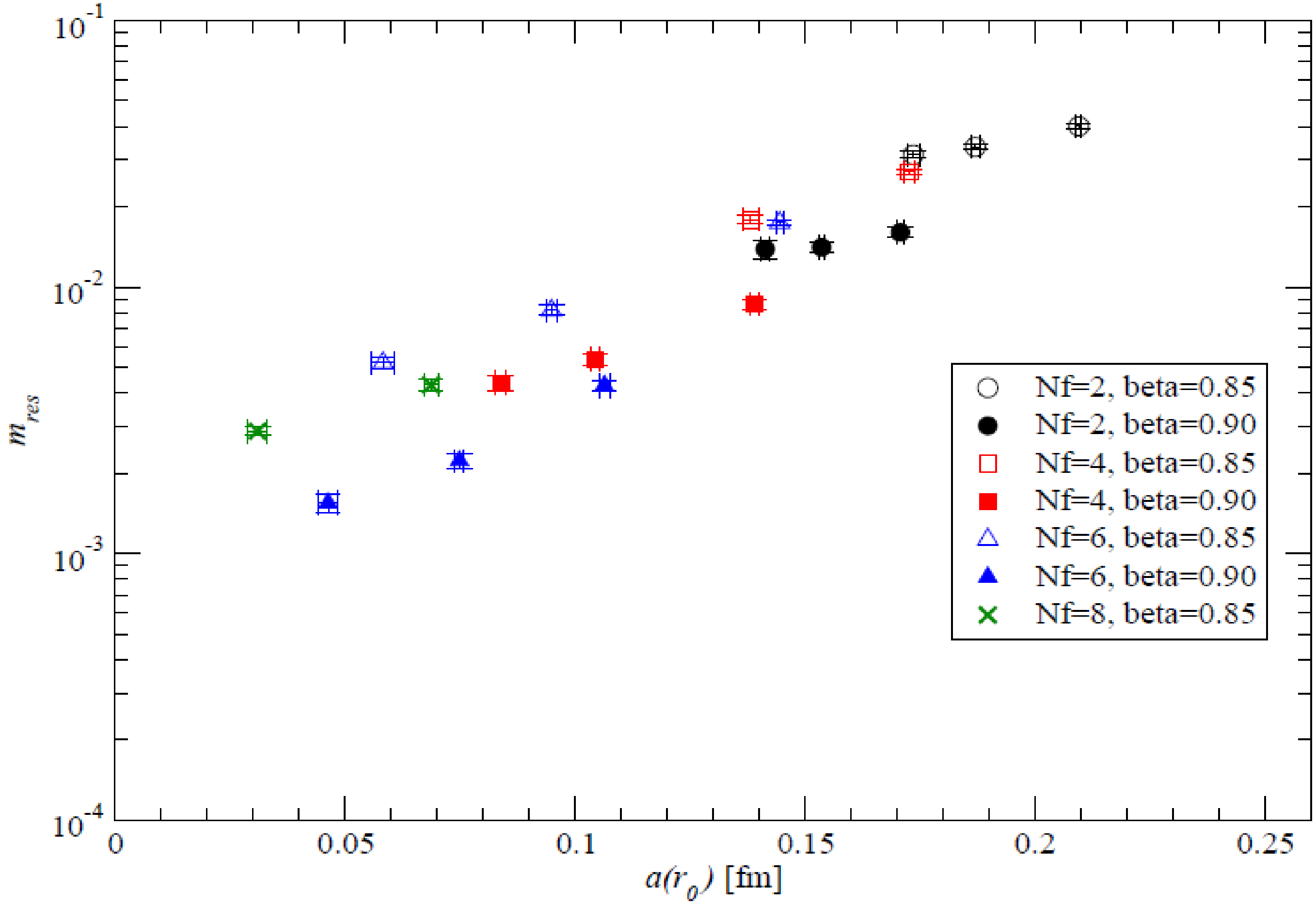
$$R(t) = \frac{\sum_{\vec{x}} \langle J_{5q}(\vec{x},t) P(0) \rangle}{\sum_{\vec{x}} \langle P(\vec{x},t) P(0) \rangle},$$

$$J_{5q}(x) = -\bar{\psi}(x, L_s/2) P_L \psi(x, L_s/2+1) + \bar{\psi}(x, L_s/2+1) P_R \psi(x, L_s/2).$$

  - Averaged over large t
  - Quantifies explicit chiral symmetry breaking of domain-wall formulation

Nf-dependence of residual mass

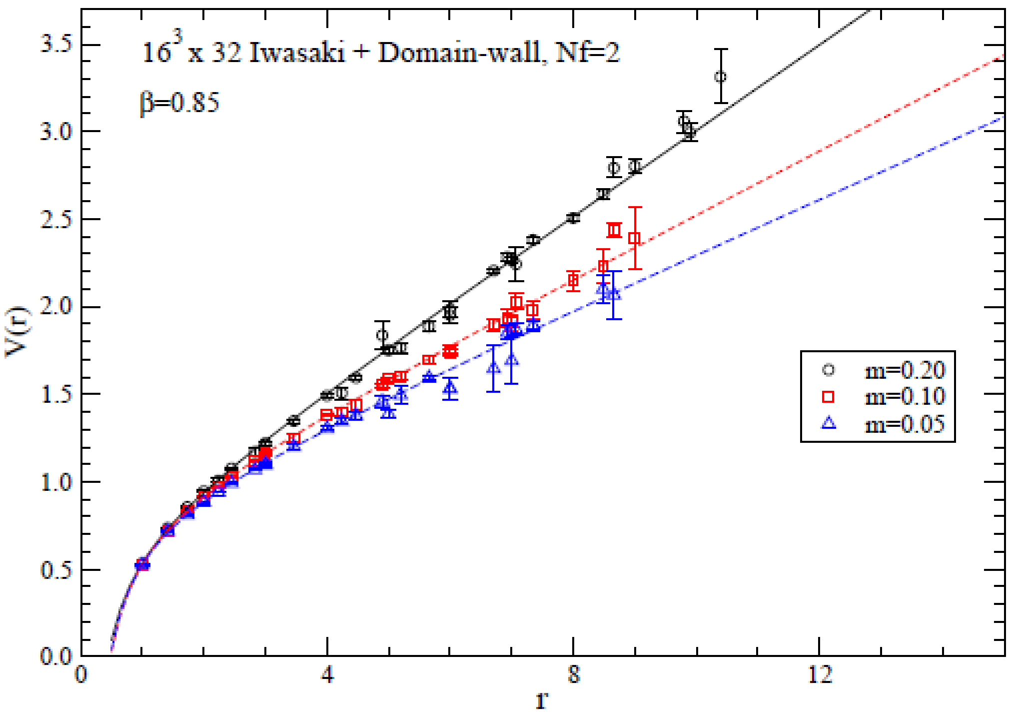
- General tendency: m_{res} decreases as lattice spacing increases
- To go below present residual mass, larger Ns or improved domain-wall are necessary

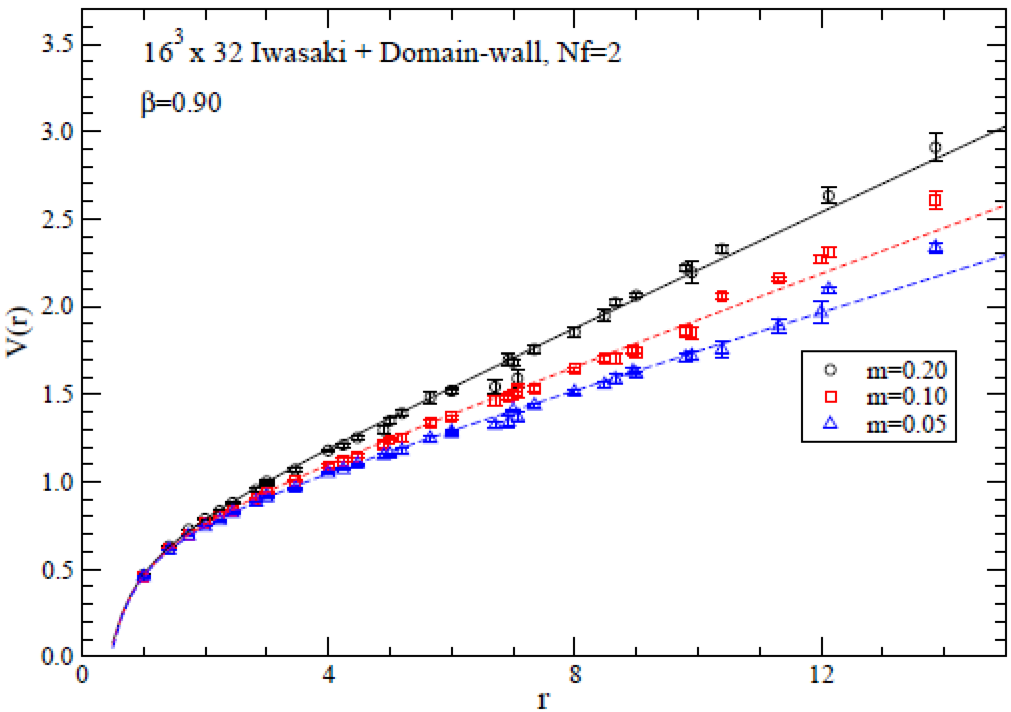


Static potential: Nf=2

Nf	beta	m
2	0.85	0.20, 0.10, 0.05
	0.90	0.20, 0.10, 0.05

- Static potential
  - Fitted to V(r) = const – A/r + σ r
  - Sommer scale r_0 (or string tension) → "lattice spacing"

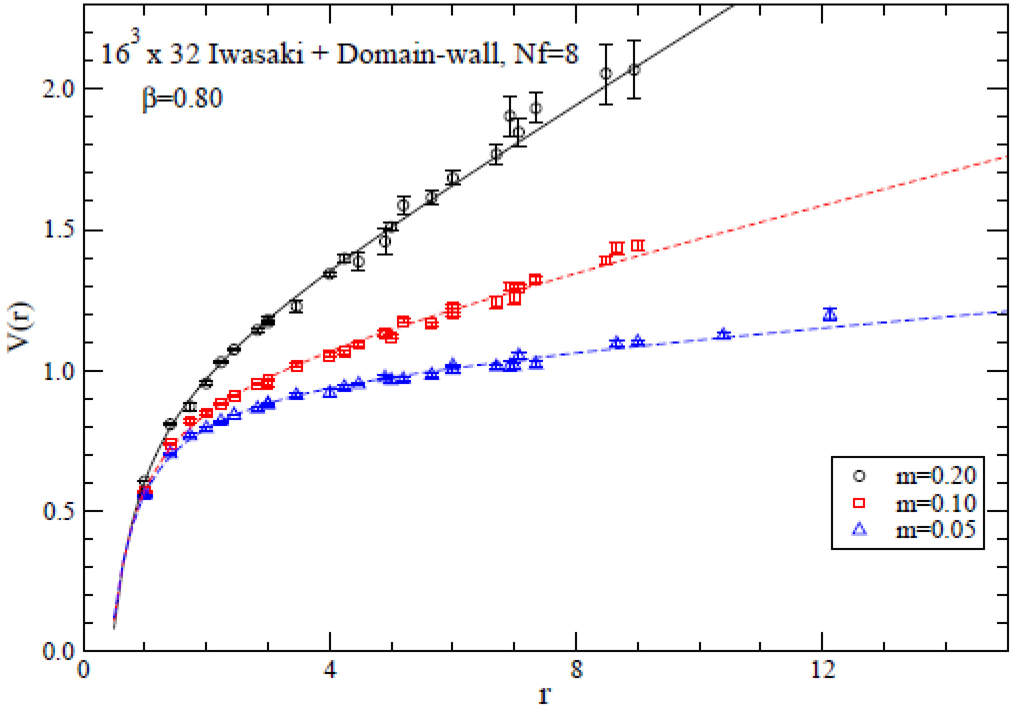


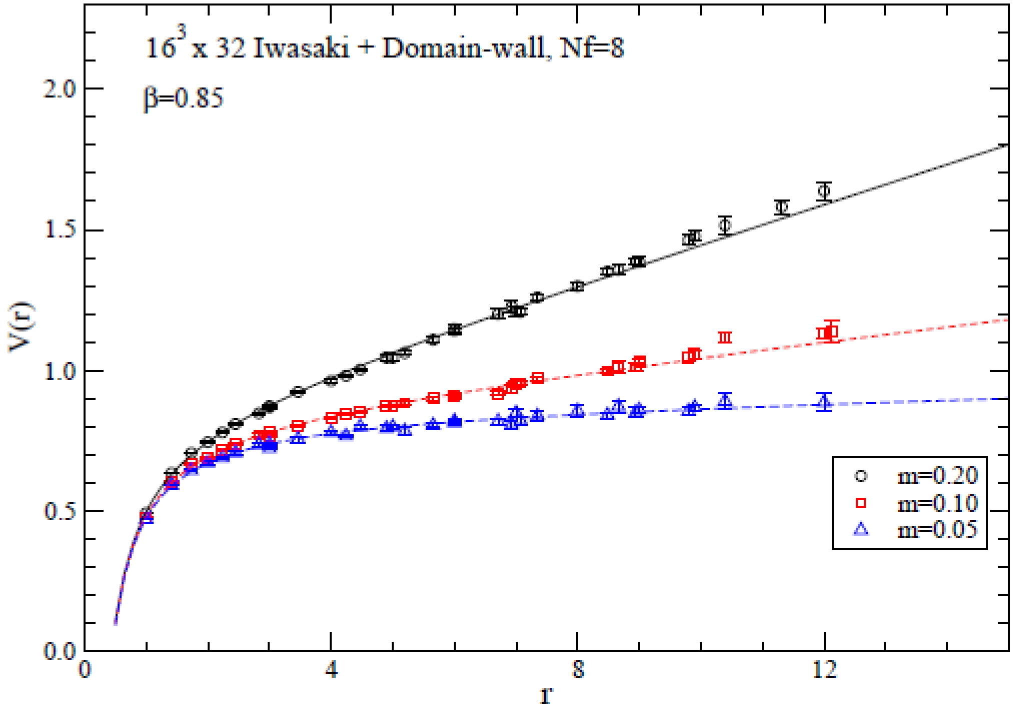


Static potential: Nf=8

Nf	beta	m
8	0.80	0.20, 0.10, 0.05
	0.85	0.20, 0.10, 0.05

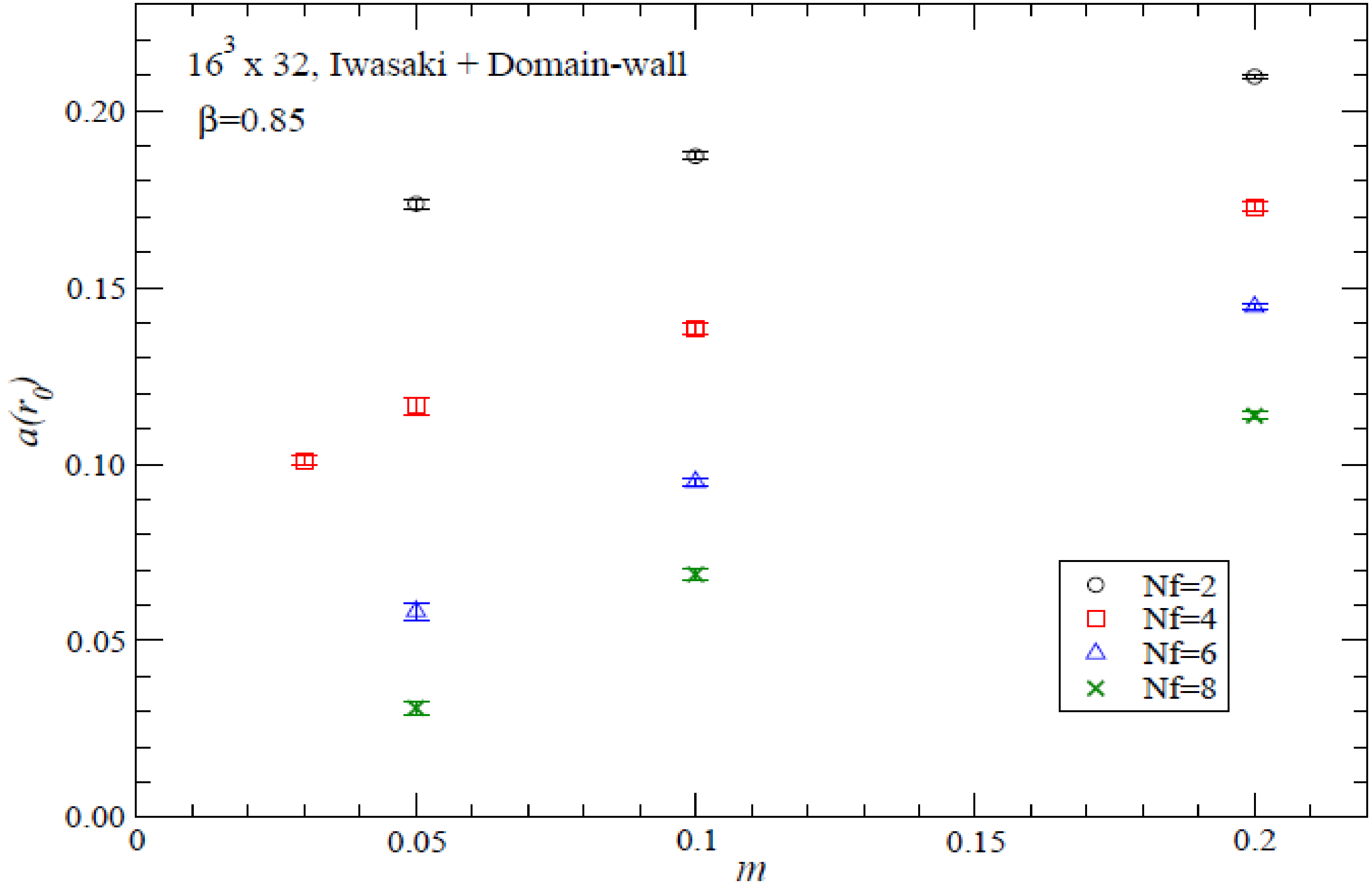
- Static potential
  - Bare mass dependence is large
  - String tension seems to vanish as m goes to zero





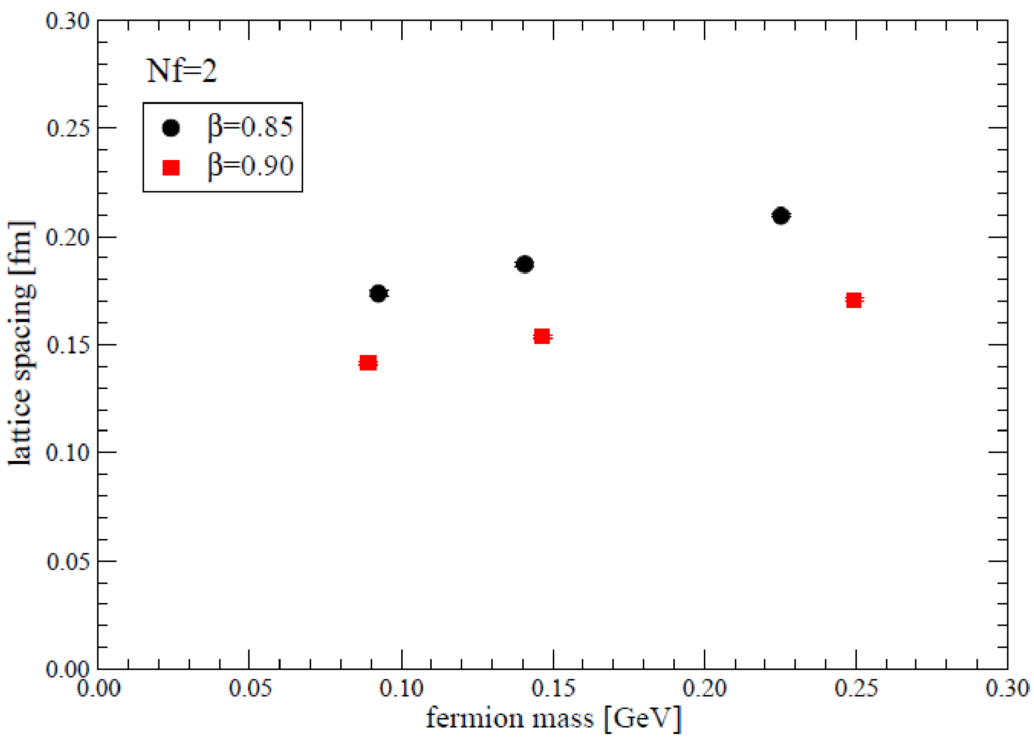
Nf dependence of static potential

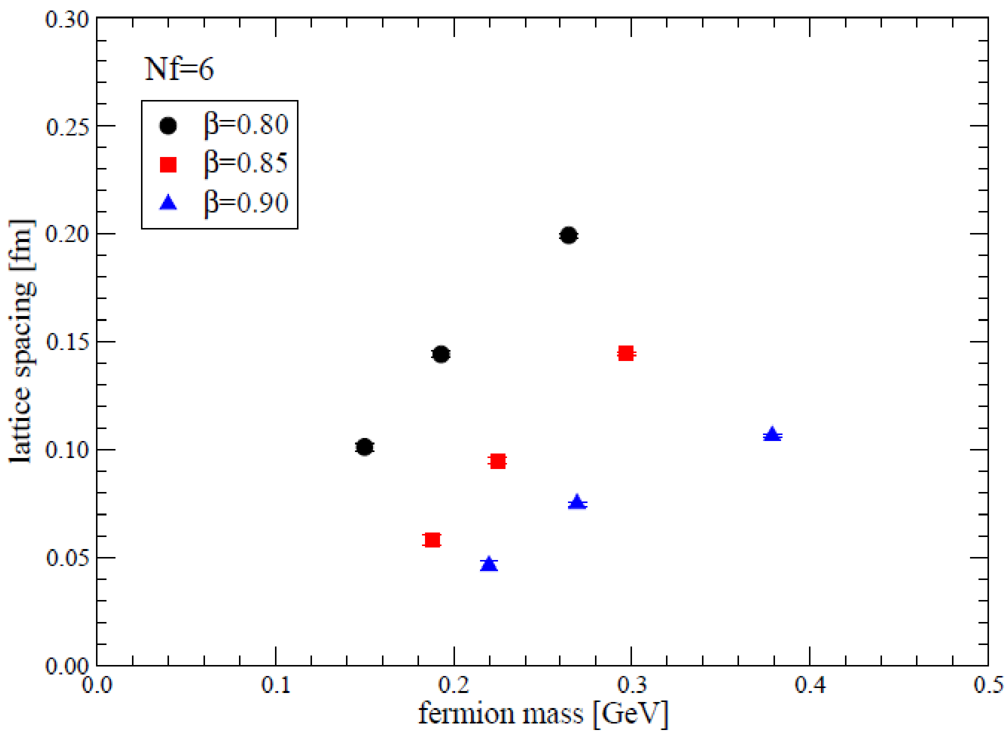
- "lattice spacing" (lattice scale) set by r_0 = 0.49 fm
- Nf-dependence grows as Nf increases.
- For Nf=8 (and 6), confining feature seem to disappear at m=0.



Nf dependence of static potential

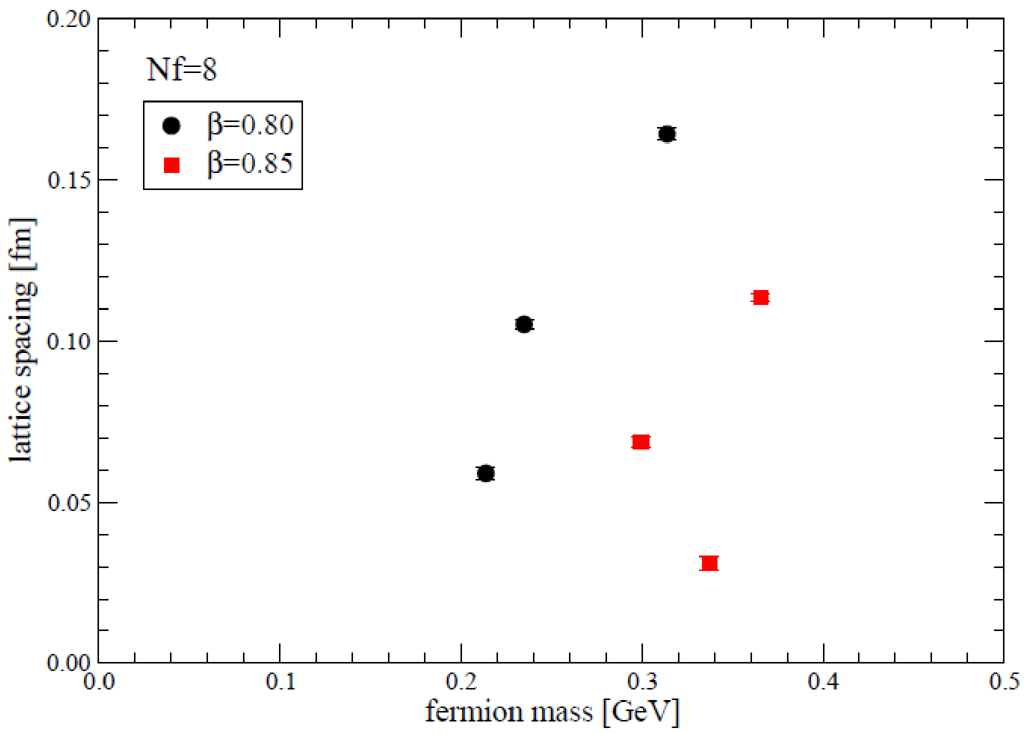
- Lattice spacing vs fermion mass (residual + bare)
  - No renormalization for fermion mass
- Extrapolation to massless limit seems successful for Nf=2 while not for Nf=6, and 8 (next page)





Nf dependence of static potential

- Nf=8: massless limit is hardly taken
- Confining feature seams to disapper at massless limit
- Caution: at beta=0.85 and m=0.05, volume might be too small



Meson spectroscopy

- Partial quenched analysis
  - ← Large sea quark mass dependence for large Nf
  - Valence fermion mass dependence is obsevred on given config.
- Measurement
  - Meson correlators are measured in standard way → mass, decay const.
  - Solving linear equations only for one of color components is needed (thanks to pseudoreality of SU(2))

$$\begin{aligned} D_{DW}(x,s;y,s') &= C^{-1}(-i\sigma_2)^{-1} R D_{DW}(y,s';x,s)^T R C(-i\sigma_2), \\ &= C^{-1}(-i\sigma_2)^{-1}\gamma_5 D_{DW}(x,s;y,s')^* \gamma_5 C(-i\sigma_2) \end{aligned}$$

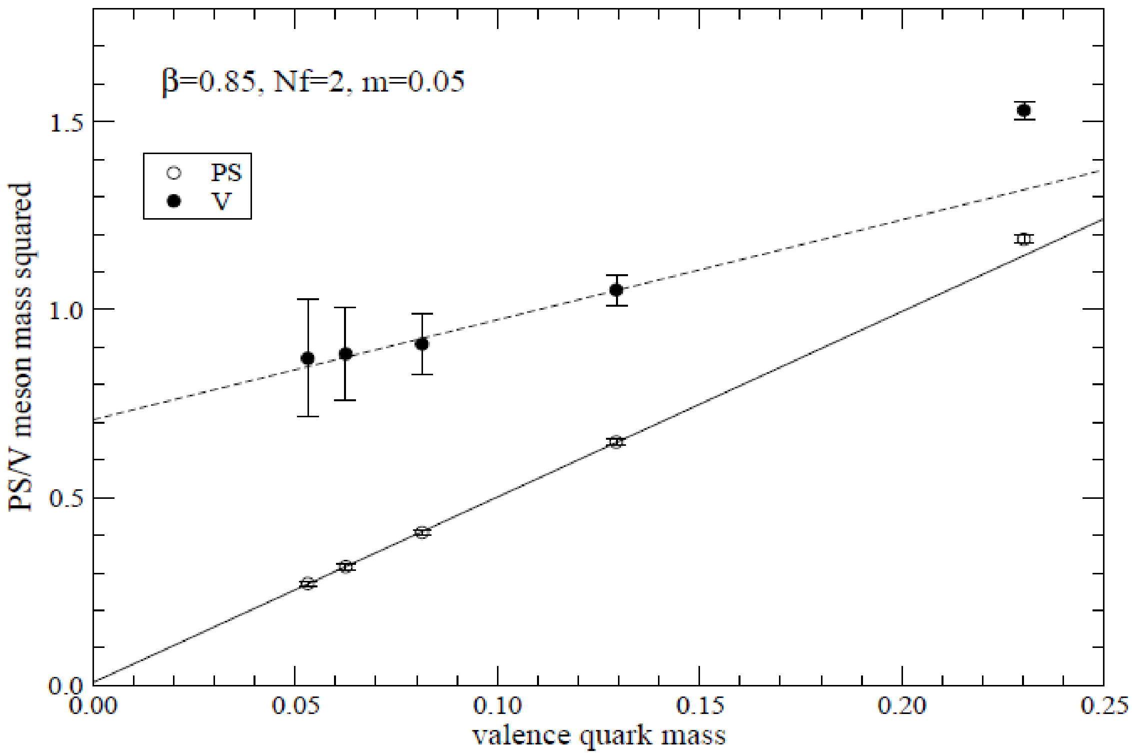
→ baryon and meson correlators are identical

Lewis, Pica and Sannino (2012)

  - Currently only with local-local correlators

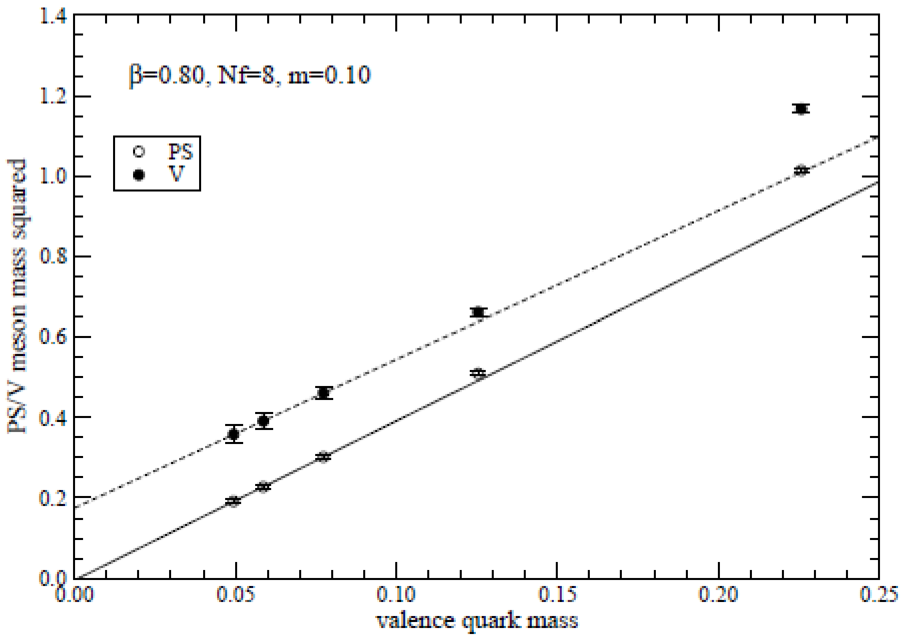
PS and V meson spectra: Nf=2

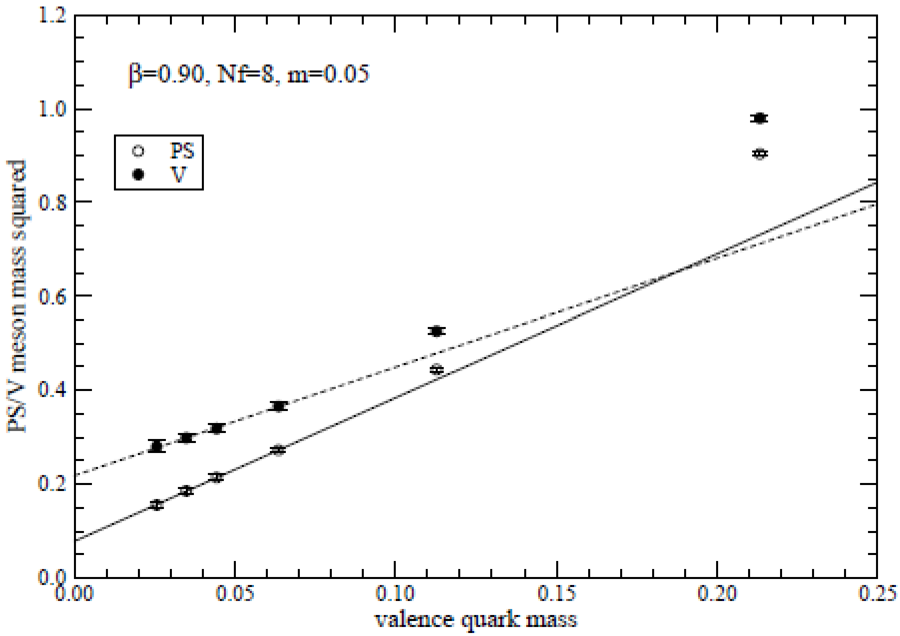
- Valence fermion mass dependence: similar behavior as SU(3) case
- Fermion mass: bare + residual masses



PS and V meson spectra: Nf=8

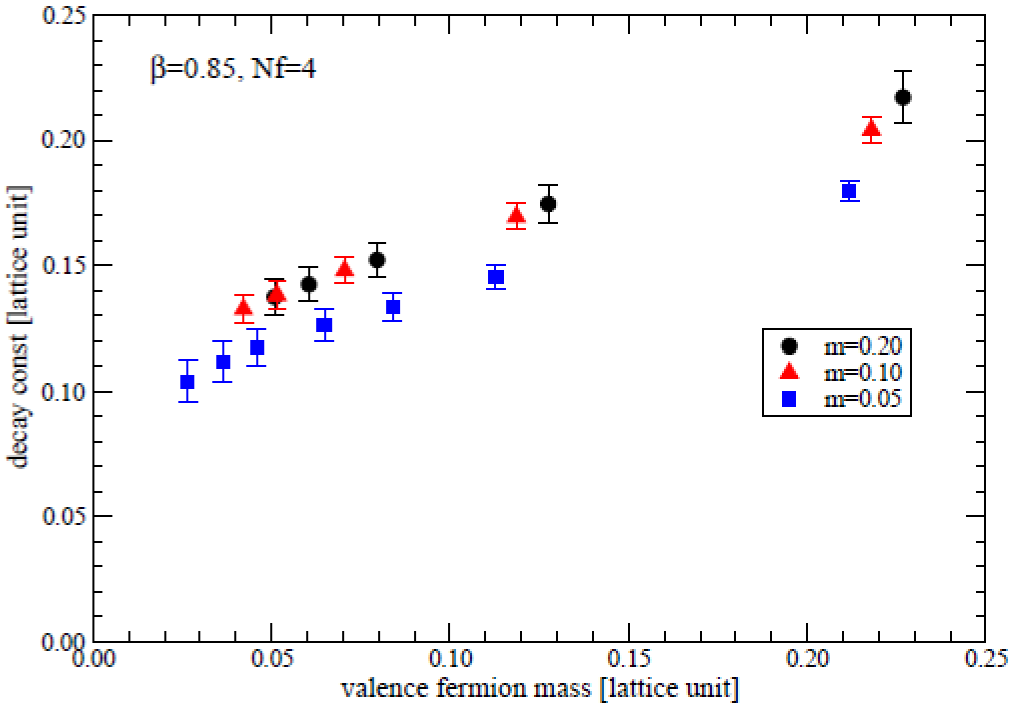
- Nf=8
  - As sea fermion mass decreases, deviation from GMOR relation
  - Finite size effect ?
- Caution:
  - Ground state plateau behavior is transient
    → to be comapred with smeared correlation functions

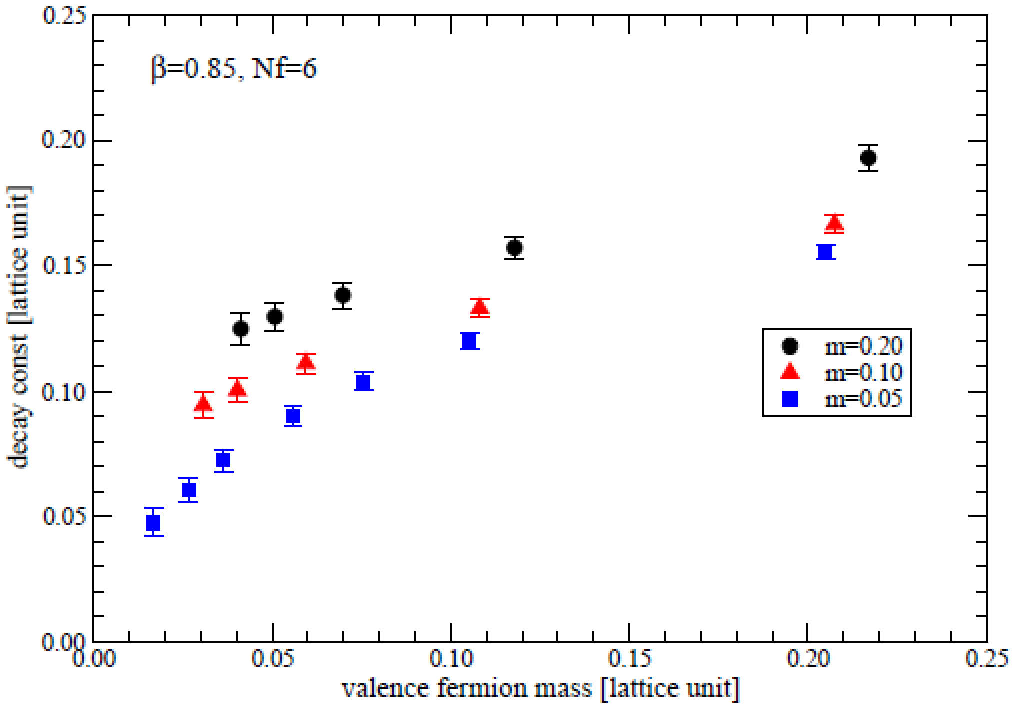




Decay constant

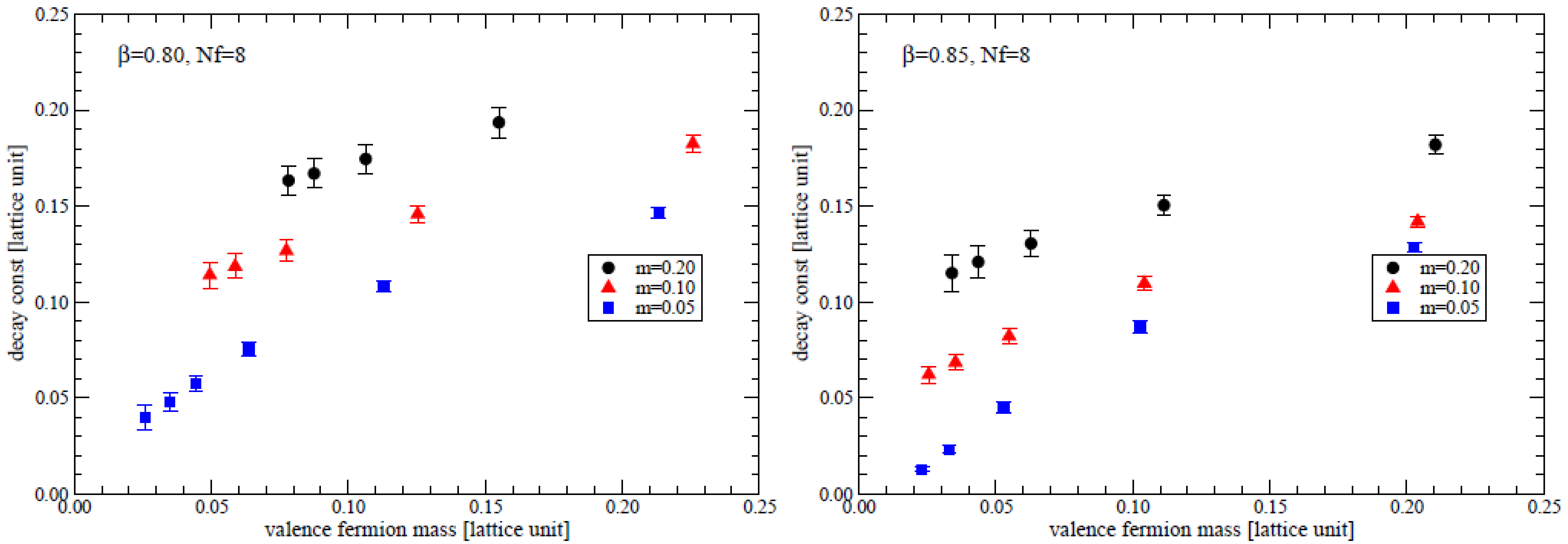
- Nf=4
  - Approaches to finite value as valence mass goes to zero
- Nf=6
  - Sea fermion mass dependence becomes larger





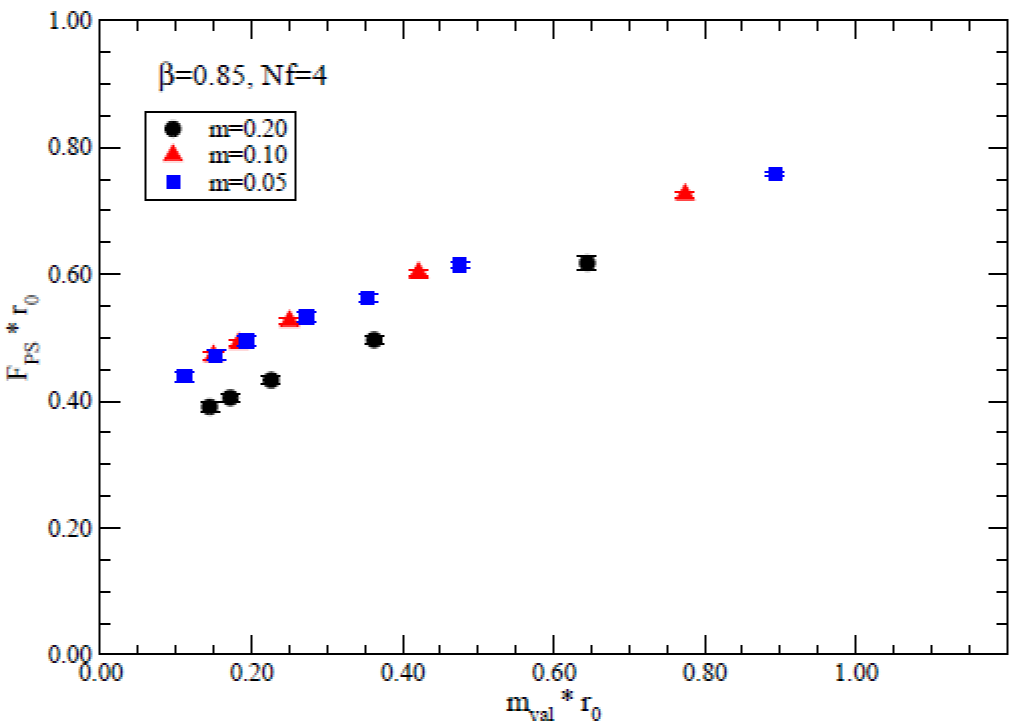
Decay constant

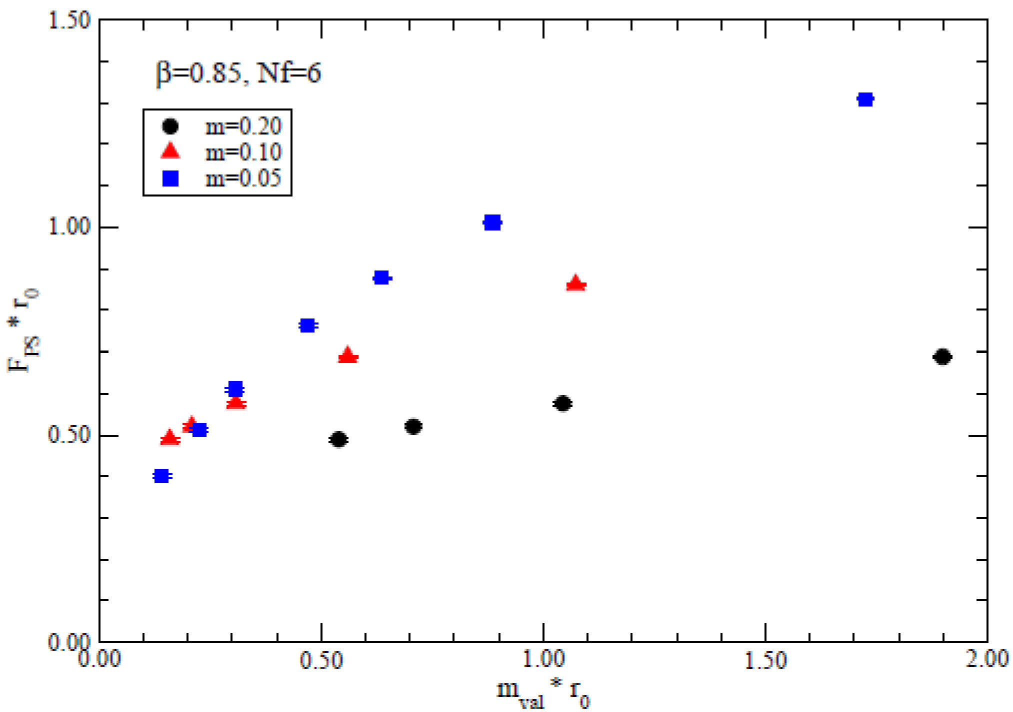
- Nf=8
  - Sea fermion mass dependence is amplified
  - At beta=0.85, no finite massless limit



Decay constant

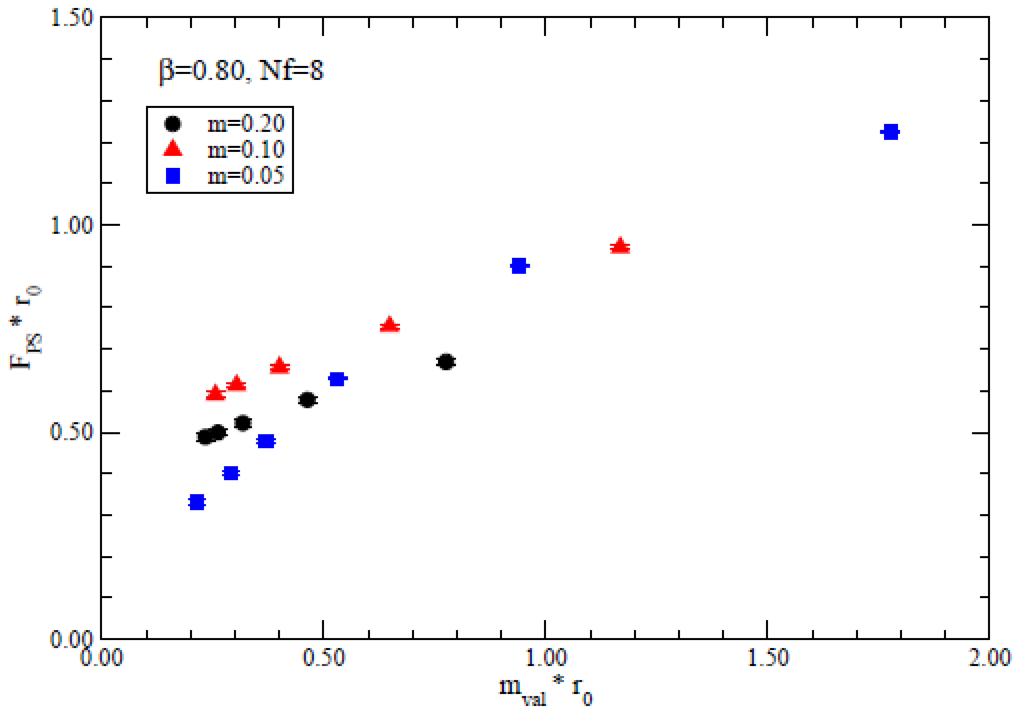
- Scaled by Sommer's scale r_0 form static potential
  - Both F_{PS} and r_0 give lattice scales in QCD
  - Dimensionless combination
  - Nf=4, 6: Similar tendency as results in lattice units

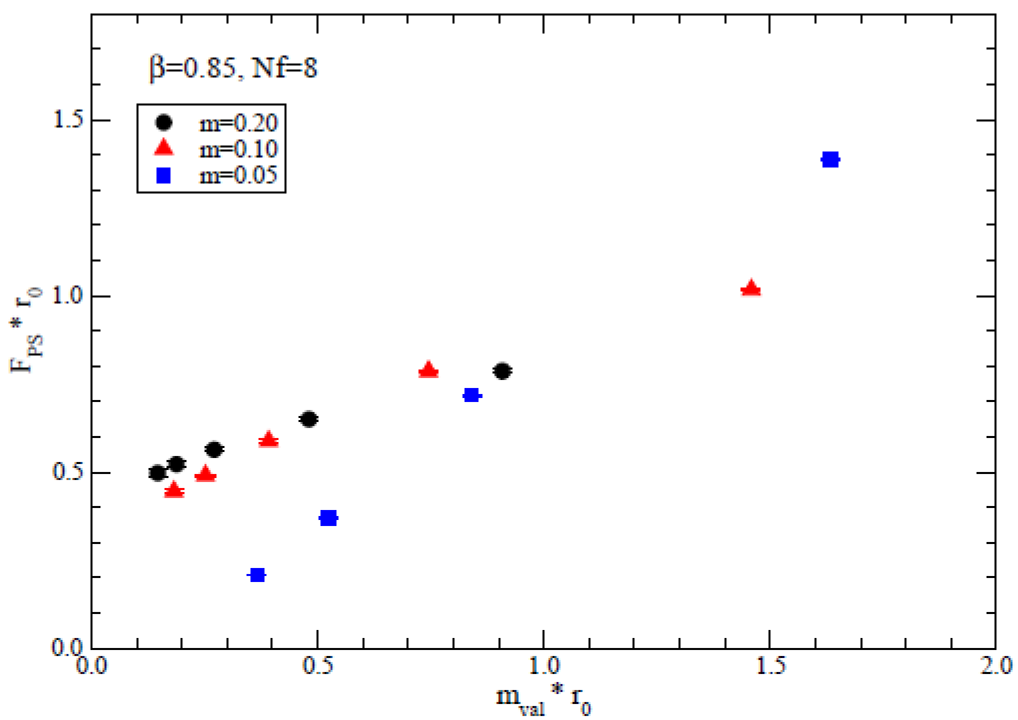




Decay constant

- Nf=8 (scaled)
  - Consistent with no finite massless limit





Summary/outlook

- Summary
  - SU(2) gauge theory with domainwall fermions of Nf=2,4,6,8
  - Nf=8: confining feature tends to disappear at small m
  - Nf=6 is similar, but no unusual behavior in PS and V meson spectra
  - More detailed analyses are underway

- To do
  - So far analysis based on confining/chral symmetry broken phase were applied
  - Analysis to test conformality such as hyperscaling is planned
  - Locality of domainwall/overlap fermion to be confirmed
  - Method to improve signals needed for other channels
  - Eigenmodes of domainwall/overlap fermion operators

Summary/outlook

- Outlook
  - Improvement of domain-wall fermion (to reduce residual mass)
  - finite temperature/density
  - Other gauge group, fermion repr. : adjoint fermions
  - Dynamical overlap (fixed topology) in epsilon-regime