The USQCD BSM Project

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U.S. DOE's INCITE Program

- Innovative and Novel Computational Impact on Theory and Experiment
- Current Leadership Class Resources:
  - Jaguar (Cray XT5) at Oak Ridge National Laboratory in Tennessee.
  - Intrepid (IBM BlueGene/P) at Argonne National Laboratory in Illinois.
- New Leadership Class Resources (starting next year):
  - Titan (Cray XT6, 292K AMD cores + ??? GPUs) at Oak Ridge.
  - Mira (IBM BlueGene/Q, 48 racks, 768K cores) at Argonne.
- USQCD receives one of the largest grants of time for lattice gauge theory, which is divided amongst five projects, of which one is BSM physics.

Goals of the USQCD BSM Program

- U.S. DOE's INCITE Program is an opportunity to apply very large resources to lattice gauge theory studies of beyond the standard model (BSM) physics.
- Such large resources are ideal for producing ensembles of gauge configurations in large lattice volumes.
- It is important that the ensembles are useful in producing results relevant for LHC phenomenology.
- For the ensembles to be of broad interest, the choice of model is chosen through a consensus process.
- Each of the members of the BSM group are actively working on BSM calculations on their own or as part of other scientific collaborations.
- Our current project is SU(3) Yang-Mills with $N_f=8$.
- Starting to plan for the next project once $N_f=8$ is completed.

SU(3), N_f=8 HISQ Lattice Generation

- The best approach to connecting lattice gauge theory studies to electroweak phenomenology is using the correspondence between low energy constants (LECs) in the electroweak and hadronic chiral lagrangians.
- They parameterize many interesting possible deviations from the standard model, including the S parameter, WW scattering, triple gauge vertices, ...
- To date, no lattice BSM calculation has been able to perform a standard extraction of the LECs:
  - The finite volume effects seem more severe than QCD.
  - The radius of convergence seem to be smaller than in QCD.
- This project will be the first serious attempt to reach the chiral regime using lattices as large as $64^3 \times 128$.

Why do we need large volumes?

- Anticipated scales: $a^{-1} \sim 4\ M_V \sim 16\ M_P \sim 50\ F_P \sim L^{-1}$.
  - Bare coupling controls $a \cdot M_V$. Bare mass controls $a \cdot M_P$.
  - Dynamics determines $M_V \cdot F_P$.
  - $$$ controls L/a. Realistically, $L/a=64$ is the current upper limit.
- Finite volume effects controlled by $M_P \cdot L$ and $F_P \cdot L$.
  - Empirical rules from QCD: $M_P \cdot L > 4$ and $F_P \cdot L > 1$.
- Chiral expansion parameter: $\chi = M_P^2/(4\pi F_P)^2 \sim 0.06$.
  - Should the expansion parameter be proportional to N_f?
  - $N_f=2$: $\chi \to 0.12$ and $N_f=8$, $\chi \to 0.5$.

Flavor Dependence of ChiPT

$$M_\pi^2 = 2mB \left\{1 + \frac{2mB}{(4\pi F)^2}\left[2\alpha_8 - \alpha_5 + N_f\left(2\alpha_6 - \alpha_4\right) + \frac{1}{N_f}\log\frac{2mB}{(4\pi F)^2}\right]\right\}$$

$$F_\pi = F\left\{1 + \frac{2mB}{(4\pi F)^2}\left[\frac{1}{2}\left(\alpha_5 + N_f\alpha_4\right) - \frac{N_f}{2}\log\frac{2mB}{(4\pi F)^2}\right]\right\}$$

$$\langle\overline{q}q\rangle = F^2 B\left\{1 + \frac{2mB}{(4\pi F)^2}\left[\frac{1}{2}\left(2\alpha_8 + \eta_2\right) + 2N_f\alpha_6 - \frac{N_f^2 - 1}{N_f}\log\frac{2mB}{(4\pi F)^2}\right]\right\}$$

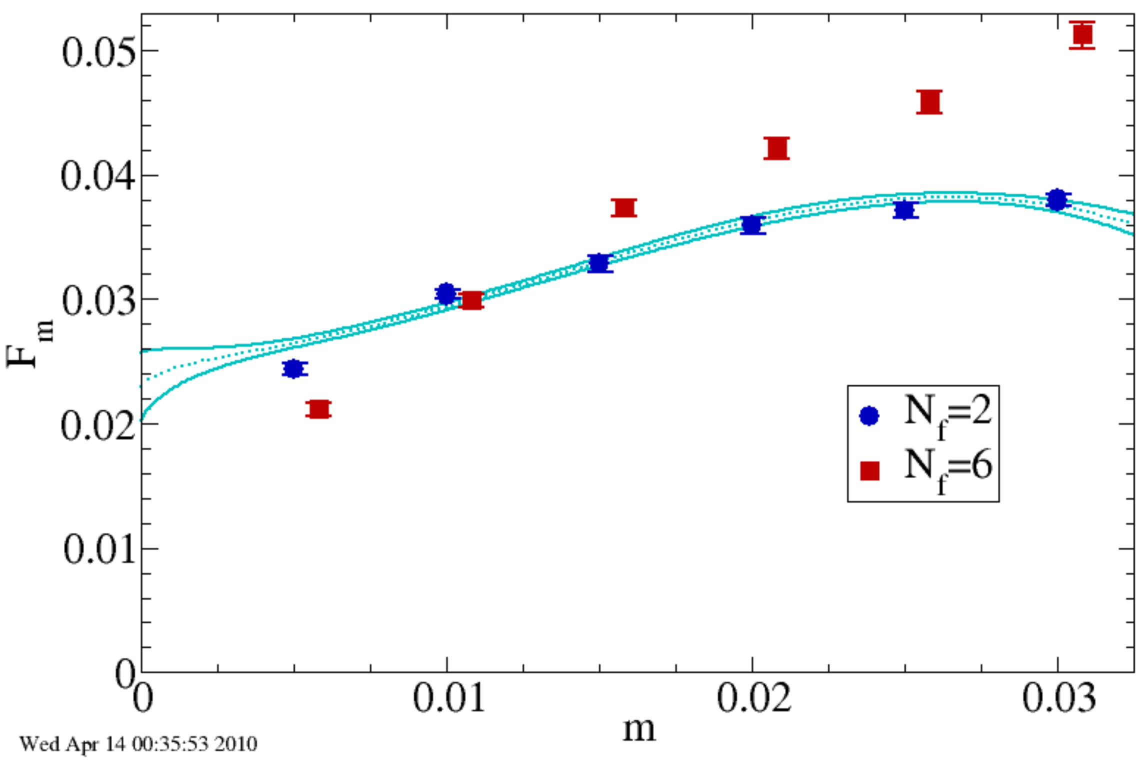
- Generically, NLO terms in ChiPT have explicit linear dependence on N_f. An exception is the chiral log in $(M_\pi)^2$.
- The $\alpha_i \sim O(1)$ low energy constants.
- $\eta_2 \sim O(a^{-2})$ contact term: UV-sensitive slope for condensate.
- Should we think of the expansion parameter proportional to N_f?

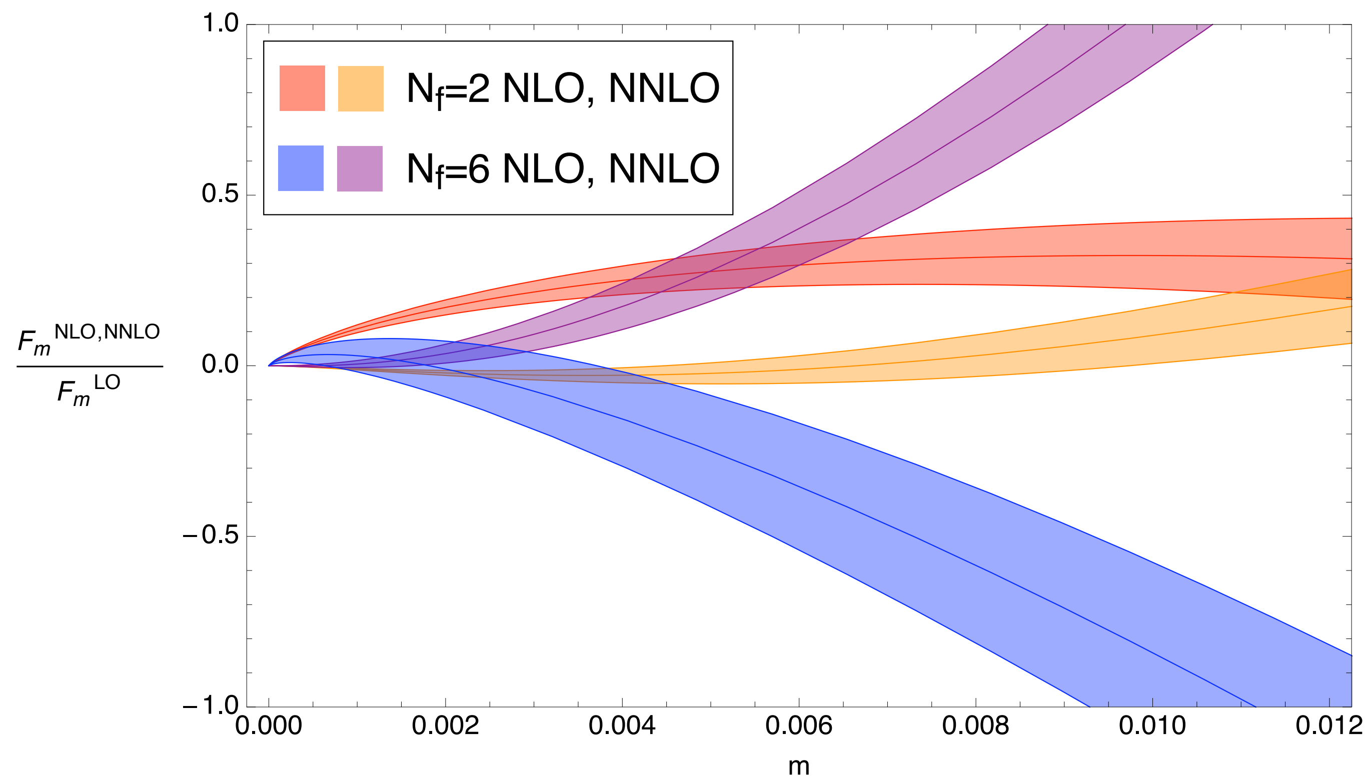
Non-analytic flavor factors in NNLO ChiPT

	$m \log(m)$	$m^2 \log^2(m)$
M_π^2	N_f^{-1}	$-3/8\, N_f^2 + 1/2 - 9/2\, N_f^{-2}$
F_π	$-1/2\, N_f$	$3/16\, N_f^2 + 1/2$
$\langle qq \rangle$	$-N_f + N_f^{-1}$	$3/2 - 3/2\, N_f^{-2}$

- J. Bijnens and J. Lu, JHEP11(2009)116 [arXiv:0910.5424]
- Small NLO coeff for M_π^2 is not generic and doesn't persist to higher orders.
- The chiral expansion parameter seems to grow with N_f so smaller fermion masses and larger volumes are required as N_f increases.

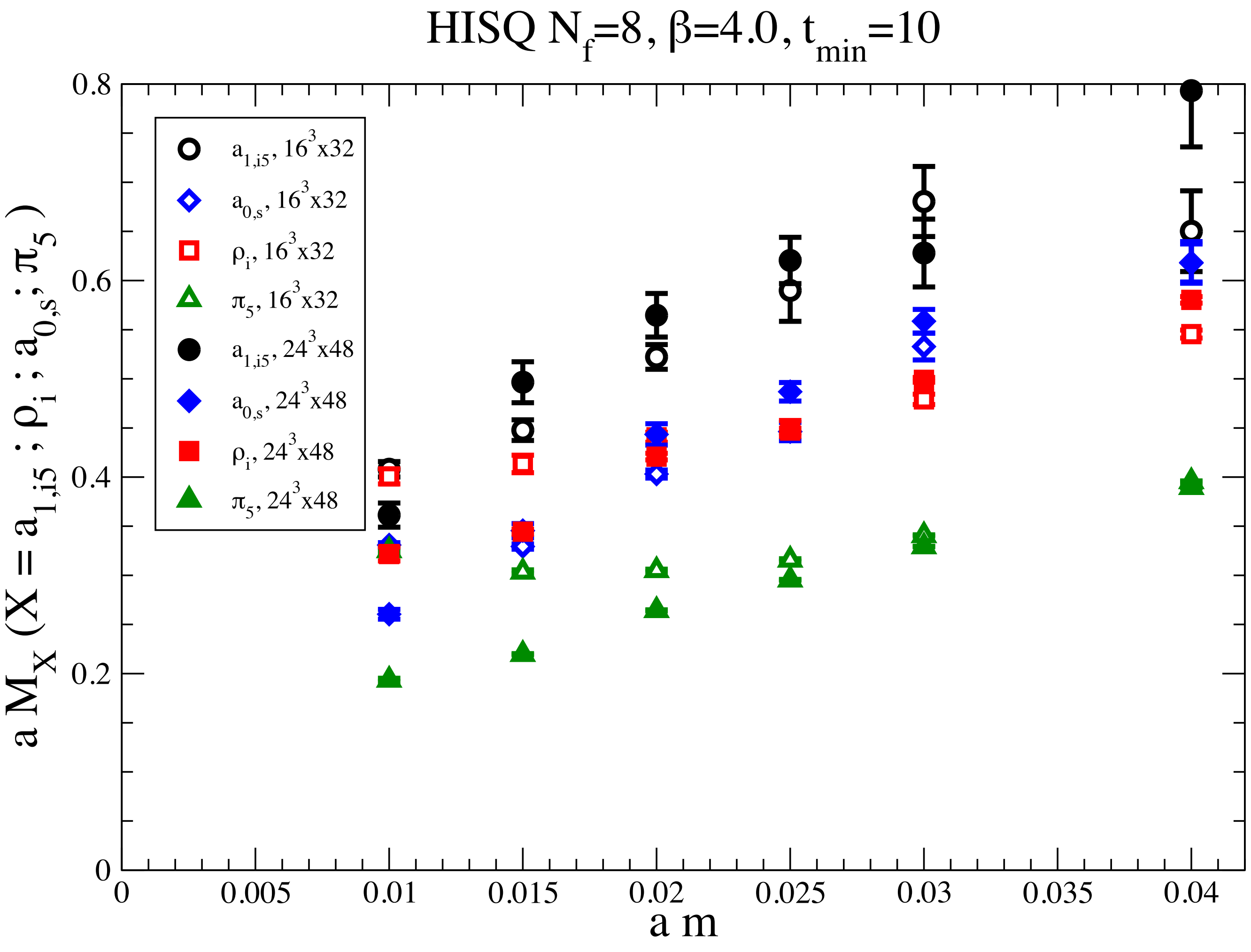
χPT Radius of Convergence





- Evidence of decreasing radius of convergence with increasing N_f on 32^3×64 lattices [E.T. Neil *et al.*, PoS(CD09)088].
- On 32^3×64, m≅0.01: $M_\pi \cdot L$~4 and $F_\pi \cdot L$~1. 48^3×96 or larger lattices needed to reach smaller fermion masses.
- This calculation used domain wall fermions (DWF) which are one of the most computationally expensive fermion formulations. 48^3×96 not feasible before next year (BlueGene/Q, ...)

Tuning the SU(3), N_f=8 HISQ Action



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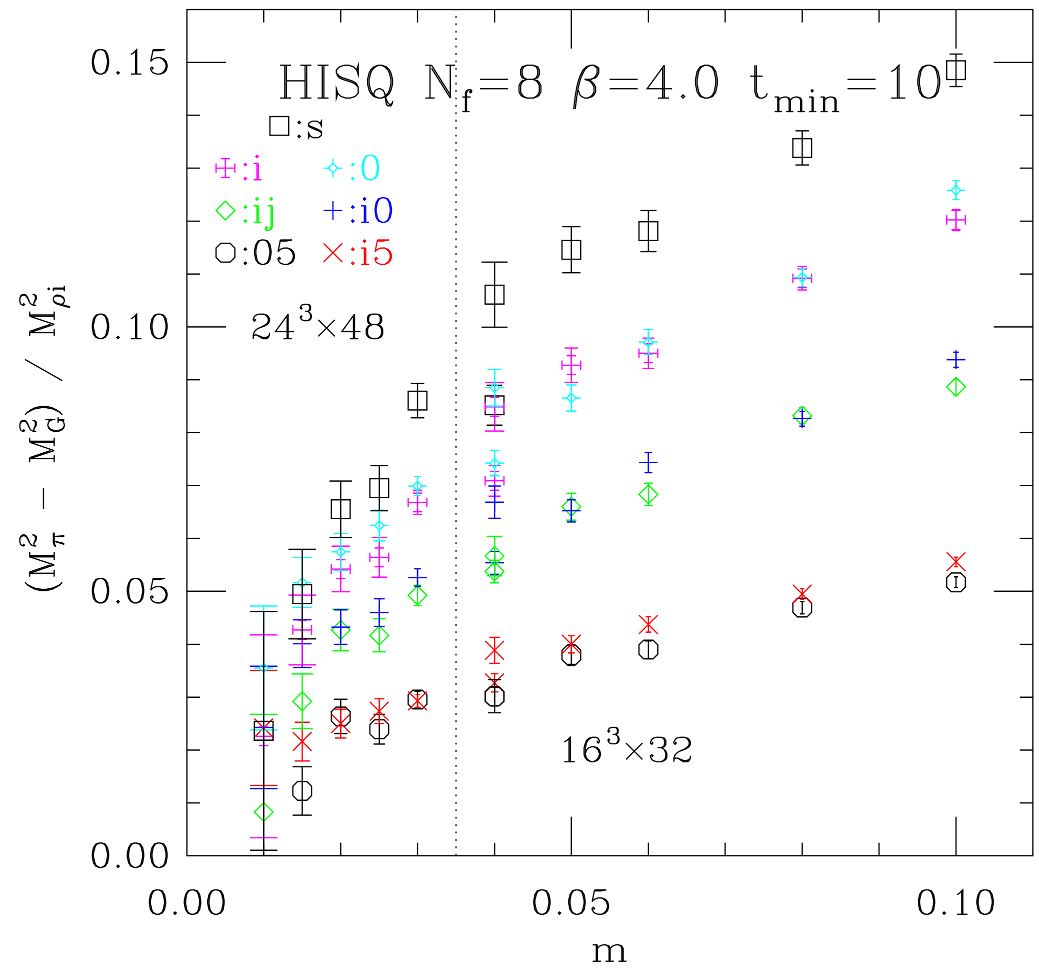


- We have tuned the bare coupling $\beta=10/g_0^2$ to $\beta=4.0$ where we find that $a\cdot M_V \approx 0.25$ in the chiral limit.
- Finite volume effects for $16^3\times32$ become significant for $a\cdot m<0.03$ suggesting $M_P\cdot L \lesssim 5$ to avoid large finite volume effects.
- Taste-breaking appears to be remain quite small even at this relatively strong bare coupling.

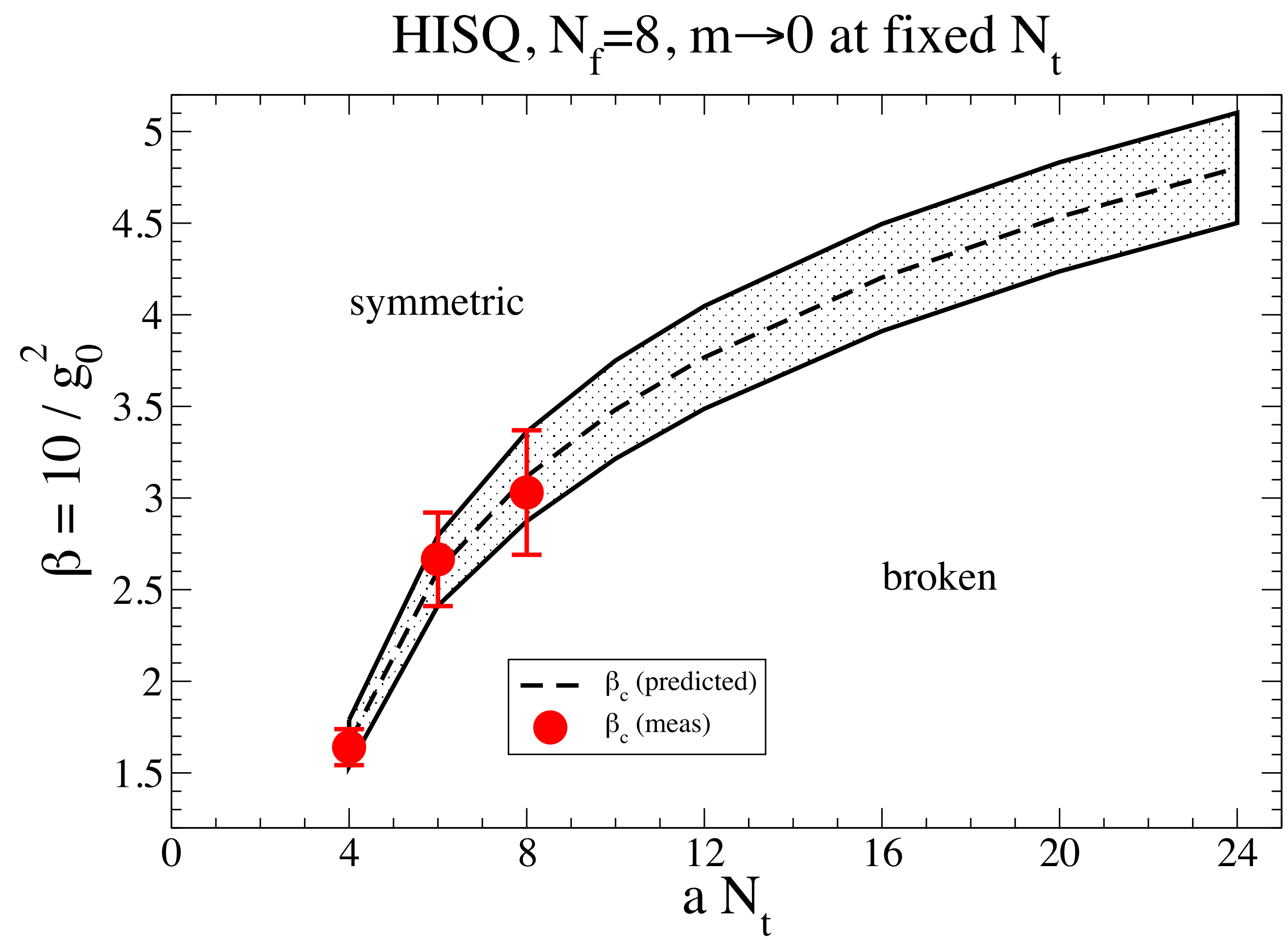
T_c as a cross-check on scale setting

- In QCD, $T_c / M_V \sim 1/5$. Perhaps for $N_f=8$, $T_c / M_V \leq 1/5$.
- Our goal is $a^{-1} \sim 4\, M_V$. At that lattice spacing, $T_c < 0.05\, a^{-1}$.
- So, if we can guess β_c on an $N_t=20$ lattice, then our desired $\beta > \beta_c$ at $N_t=20$.
- Start by finding β_c on $8^3 \times 4$, $12^3 \times 6$, $16^3 \times 8$, $20^3 \times 10$, ...
- Extrapolate β_c vs. N_t to $N_t > 20$ using beta function plus lattice artifacts

$$\frac{N_\tau^{-1}}{\exp\left(-\frac{1}{2\beta_0 g_S^2}\right)\left(\frac{\beta_1}{\beta_0^2}+\frac{1}{\beta_0 g_S^2}\right)^{\frac{\beta_1}{2\beta_0^2}}} = \frac{T_c(0)}{\Lambda_S}\left[1+\frac{c^s_{T_c}}{N_\tau^2}+O(a^4)\right]$$

Running of β_c from chiral susc.

N_t	β_c (input)	β_c (fit)
4	1.64(10)	1.66(13)
6	2.67(26)	2.60(19)
8	3.03(34)	3.12(24)
10		3.48(27)
12		3.77(28)
16		4.20(29)
20		4.53(30)
24		4.80(30)



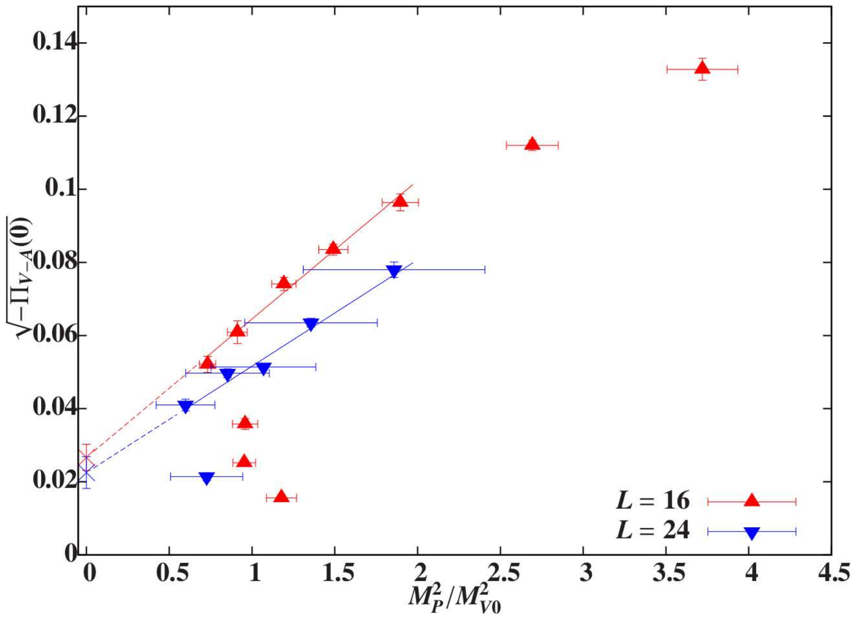
E. Neil (FNAL)

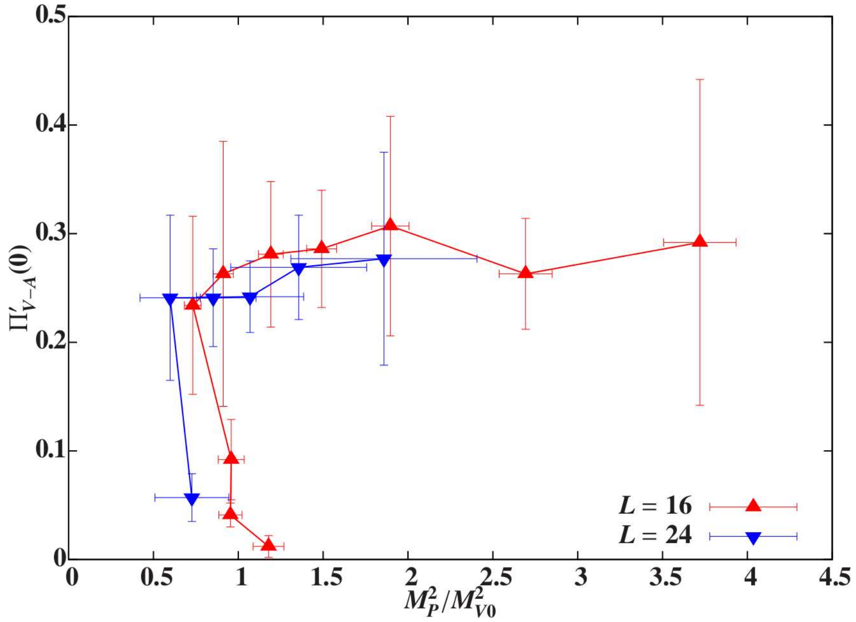
- Note that β=4.0 is around β_c for N_t = 12–17, not N_t > 20.
- Does this mean for N_f=8, $T_c / M_\rho \approx 1/4$? Not as expected!

F_P and S parameter using valence DWF

$$S = 4\pi \frac{N_f}{2}\left[\Pi'_{\mathrm{VV}}(0) - \Pi'_{\mathrm{AA}}(0)\right] + \Delta S_{\mathrm{SM}}$$
$$= \frac{1}{3\pi}\int_0^\infty \frac{ds}{s}\left\{\frac{N_f}{2}\left[R_V(s) - R_A(s)\right] - \frac{1}{4}\left[1 - \left(1 - \frac{m_h^2}{s}\right)^3 \Theta(s - m_h^2)\right]\right\}$$

- We know how to compute S parameter reliably using domain wall fermions (DWF).
- Using DWF valence fermions and HISQ sea fermions, we can also compute S on our HISQ lattices.
- Important for validating computation of S parameter using only HISQ fermions for valence and sea.
- Another indication of where finite volume effects become significant.
- Also get rough estimate of F_P from the intercept.
- Work by D. Schaich.





Outlook for USQCD BSM Project in 2012

Lattice Dimensions	Pion Mass M_{π_5}/M_{ρ_i}	Configs (MD time)	MILC BG/P Core-Hr per unit MD time
$48^3 \times 96$	0.47	162	32K
	0.54	162	32K
	0.58	174	32K
	0.61	204	32K
$32^3 \times 64$	0.58	228	3K
	0.61	258	3K

Table 1: Current performance of BSM lattice generation at $\beta = 4.0$ using the MILC code and our original integration scheme, where $aM_{\rho_i} \approx 0.25$ in the chiral limit. The goal is to generate 1000 MD time units per ensemble. Empirically, the cost scales roughly as $V^{3/2}$ and there is relatively weak quark mass dependence.

Lattice Dimensions	Pion Mass M_{π_5}/M_{ρ_i}	Configs (MD time)	BG/P Core-Hr new FUEL scheme	FNAL J/Psi Core-Hr new FUEL scheme
$48^3 \times 96$	0.47	750	3.07M	1.66M
	0.54	750	3.07M	1.66M
	0.58	750	3.07M	1.66M
	0.61	750	3.07M	1.66M
$64^3 \times 128$	0.36	750	17.26M	9.32M
	0.42	750	17.26M	9.32M
	0.47	750	17.26M	9.32M

Table 2: Proposed lattice generation for BSM studies of the SU(3) N_f=8 technicolor model. The techni-rho mass M_{ρ_i} is assumed to be 0.25 a^{-1} in the chiral limit. This request assumes a factor of eight improvement using the new integration scheme implemented in the FUEL framework, cost scales as $V^{3/2}$ and relatively weak quark mass dependence.

Concluding remarks

- The USQCD BSM Project has access to some of the world's largest supercomputing resources.
- The project generates large lattices for the immediate benefit of the USQCD collaboration. All lattices will be made available worldwide after first publication.
- Our first publication should include details of zero-temperature spectrum, finite temperature phase transition, determination of χPT LECs, condensate enhancement, etc.