LSD SU(3) N_f=8 Project

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for the
Lattice Strong Dynamics (LSD) Collaboration

Lattice for Beyond the Standard Model Physics
Boulder, Colorado
April 5, 2018

Can the Higgs Boson be Composite?

- From the LHC we have learned that the Standard Model has a Higgs boson whose mass is half as large as the VEV of the Higgs field.
- A minimal SU(2)xSU(2) ~ O(4) linear sigma model (LSM) for the Higgs sector works quite well for calculational purposes but is confusing as it seems renormalizable to high scales but also fine tuned.
- We can imagine the Higgs sector is composite and the LSM is part of a low-energy EFT but experiment currently gives us little guidance as to the breakdown scale of the EFT or even all the relevant degrees of freedom (dof) of the EFT.
- SU(3) N_f=2 (QCD) is an example composite theory that has just the right low energy dof for composite Higgs, but the mass is four times the VEV.
- So, if the Higgs is composite it is probably embedded in a larger EFT than the O(4) LSM.

Requirements for Composite Higgs

- If a gauge theory with 3 or more NG bosons is to be a candidate for a composite Higgs theory, it should pass a few tests (order of difficulty):

    1. The Higgs boson should have a mass about half the VEV in the chiral limit.

    2. If there are more than three NG bosons, can the rest be given a modest mass while keeping the Higgs mass light?

    3. Below the mass scale of the extra NG bosons (and other hadrons) does a SU(2)xSU(2) LSM emerge?

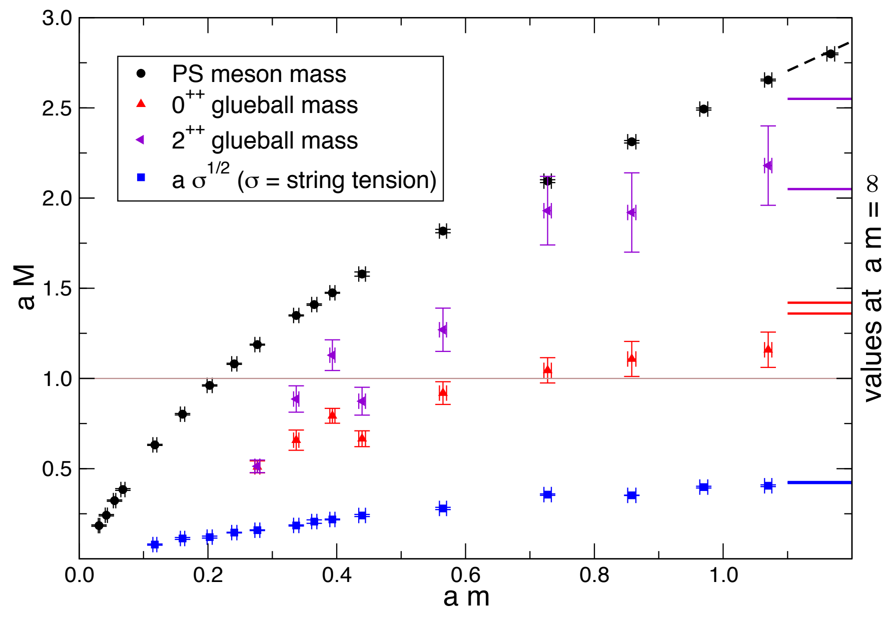
    4. If the Higgs is to be composite, how does the Yukawa mechanism work? How are FCNC suppressed?

- Extra hadrons are not necessarily a problem, *e.g.* if the 750 GeV diphoton or 2 TeV diboson resonances had been confirmed, they could be accommodated in these models as an η or ρ meson.

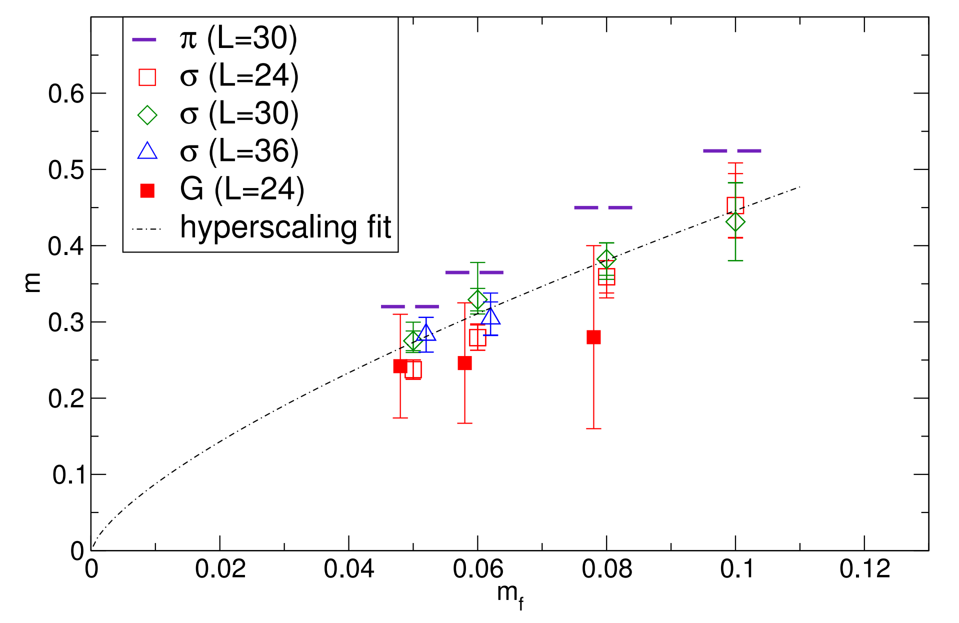
Theories with Light Scalars

- Mass-deformed IRFP theories with very light scalars.

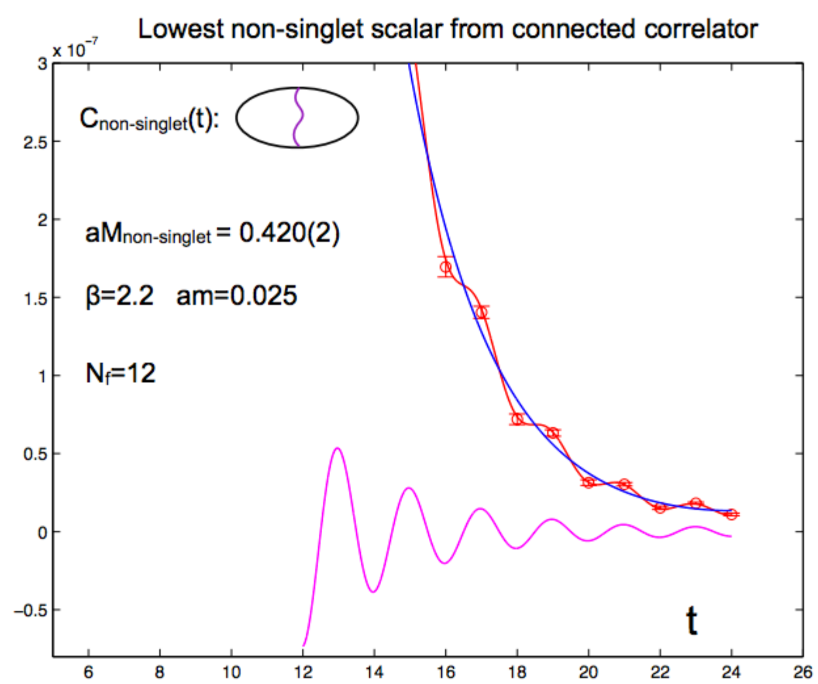
SU(2) N_f=2 adj (Edinburgh)
Phys. Rev. D 82, 014510 (2010)

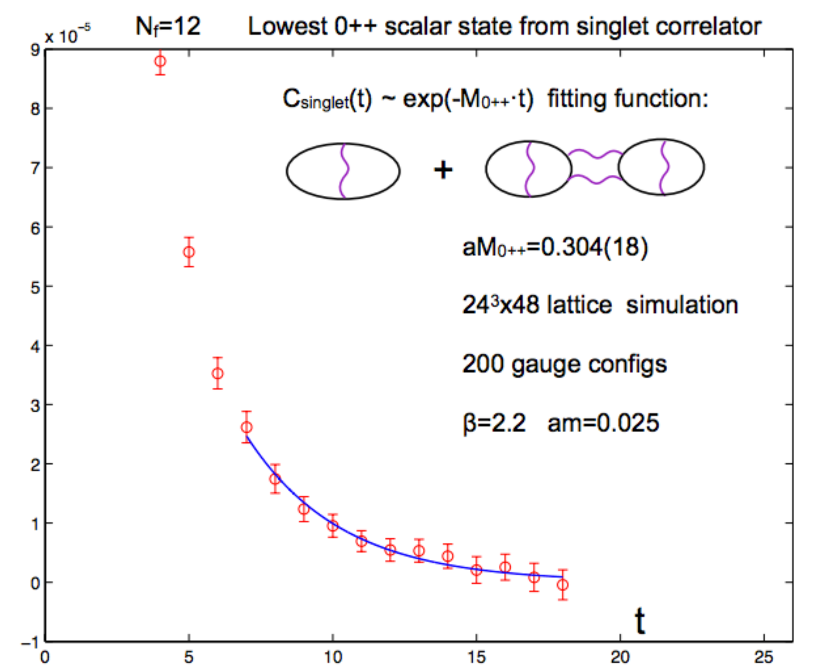


SU(3) N_f=12 fund (LatKMI)
Phys. Rev. Lett. 111, 162001 (2013)



SU(3) N_f=12 fund (LatHC)
USQCD White Paper 2013

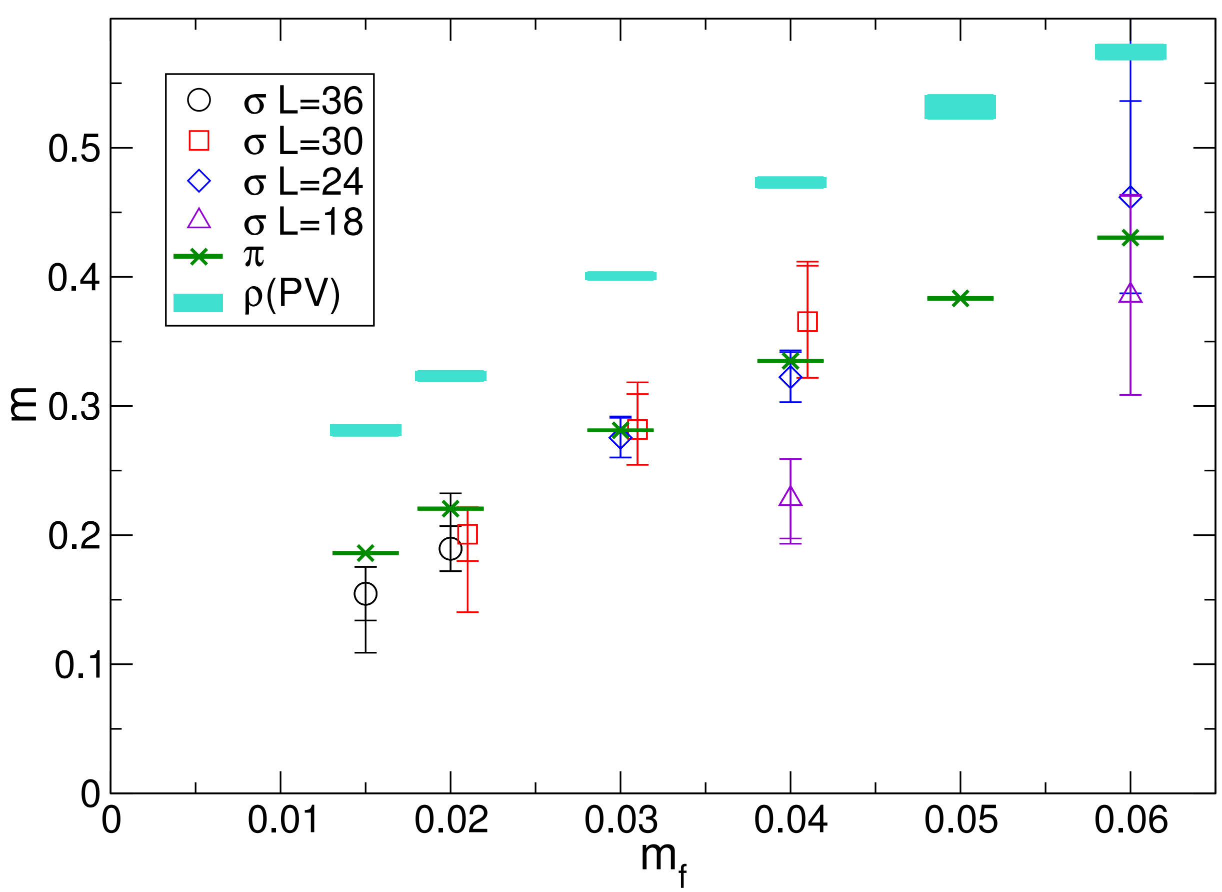




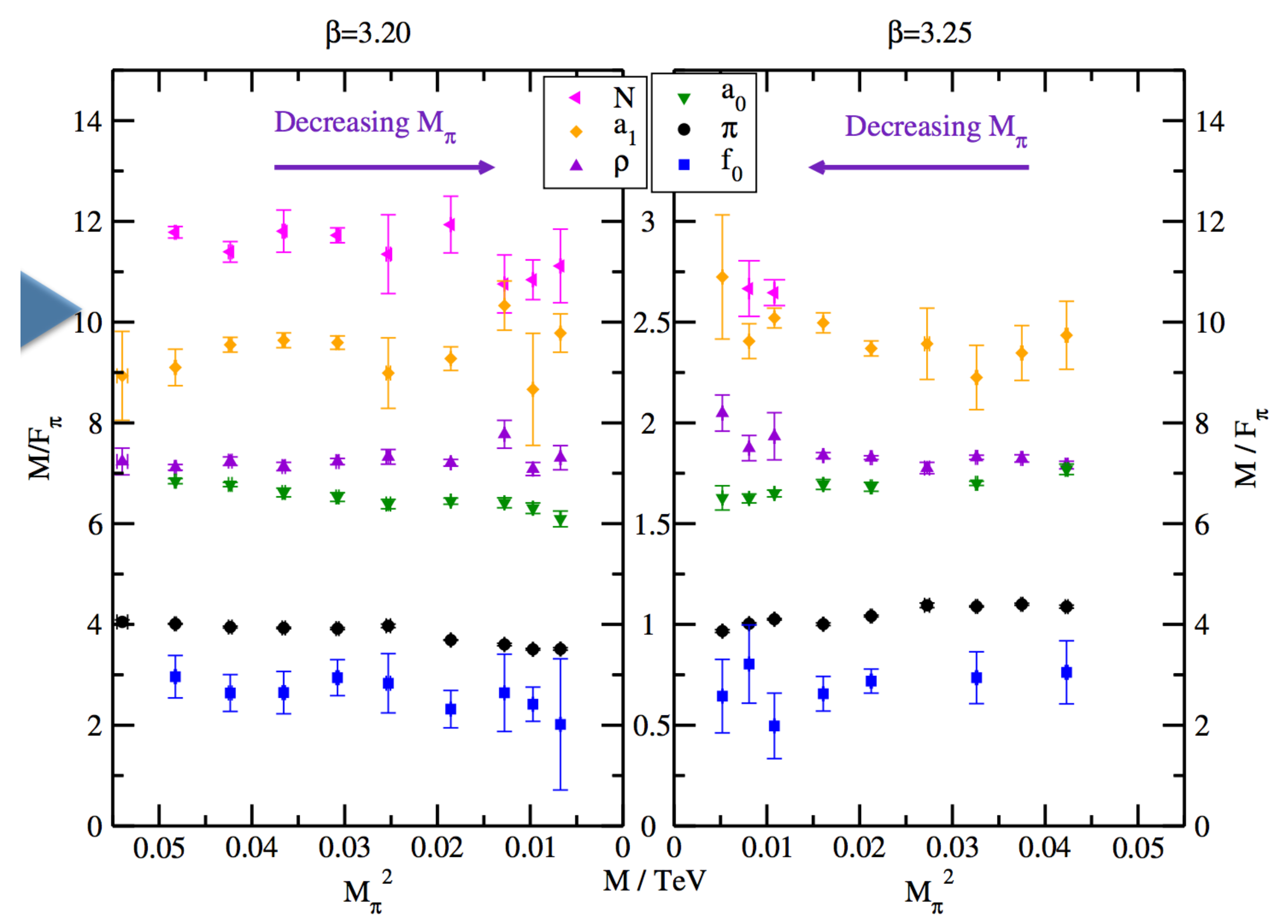
More Light Scalars

- Theories likely just outside conformal window also have light scalars.

SU(3) N_f=8 fund
LatKMI (Nagoya)
Phys. Rev. D 89, 111502 (2014)



SU(3) N_f=2 sym
LatHC Collaboration
LATTICE 2015



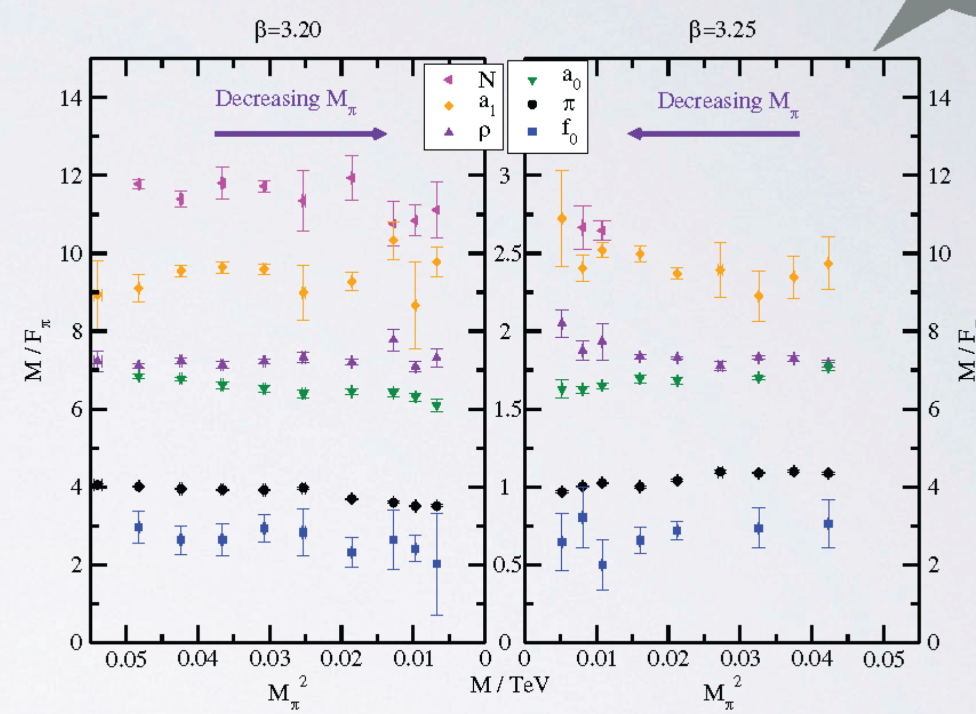
[latest results in Pica arxiv:1701.07782 and Svetitsky arxiv:1708.04840]

★ light
■ heavy

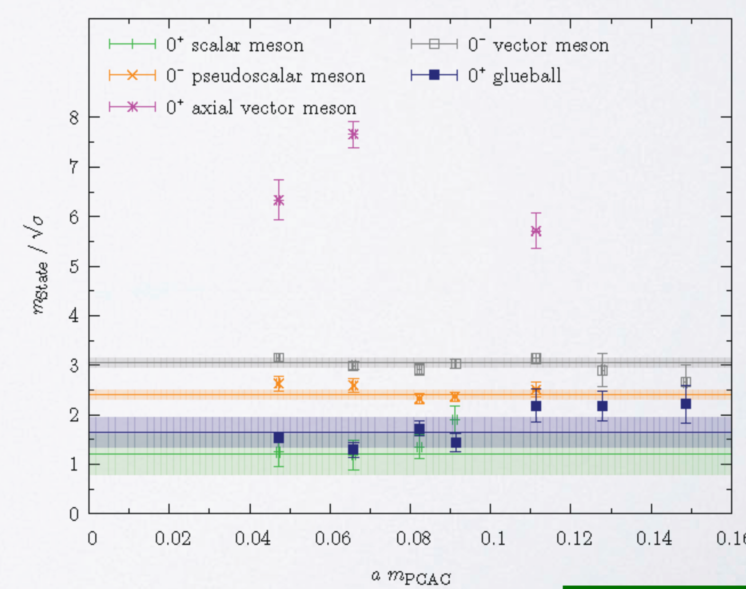
SUMMARY RESULTS

Template Models	Scalar
SU(2) Nf=2 (F)	■
SU(2) Nf=2 (A)	★
SU(2) Nf=1 (A)	★
SU(3) Nf=12 (F)	★
LSD → SU(3) Nf=8 (F)	★
SU(3) Nf=4 (F)	■
SU(3) Nf=2 (S)	★

SU(3) Nf=2 (S)



SU(2) Nf=1 (A)



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Confinement vs. Mass-Deformed IRFP

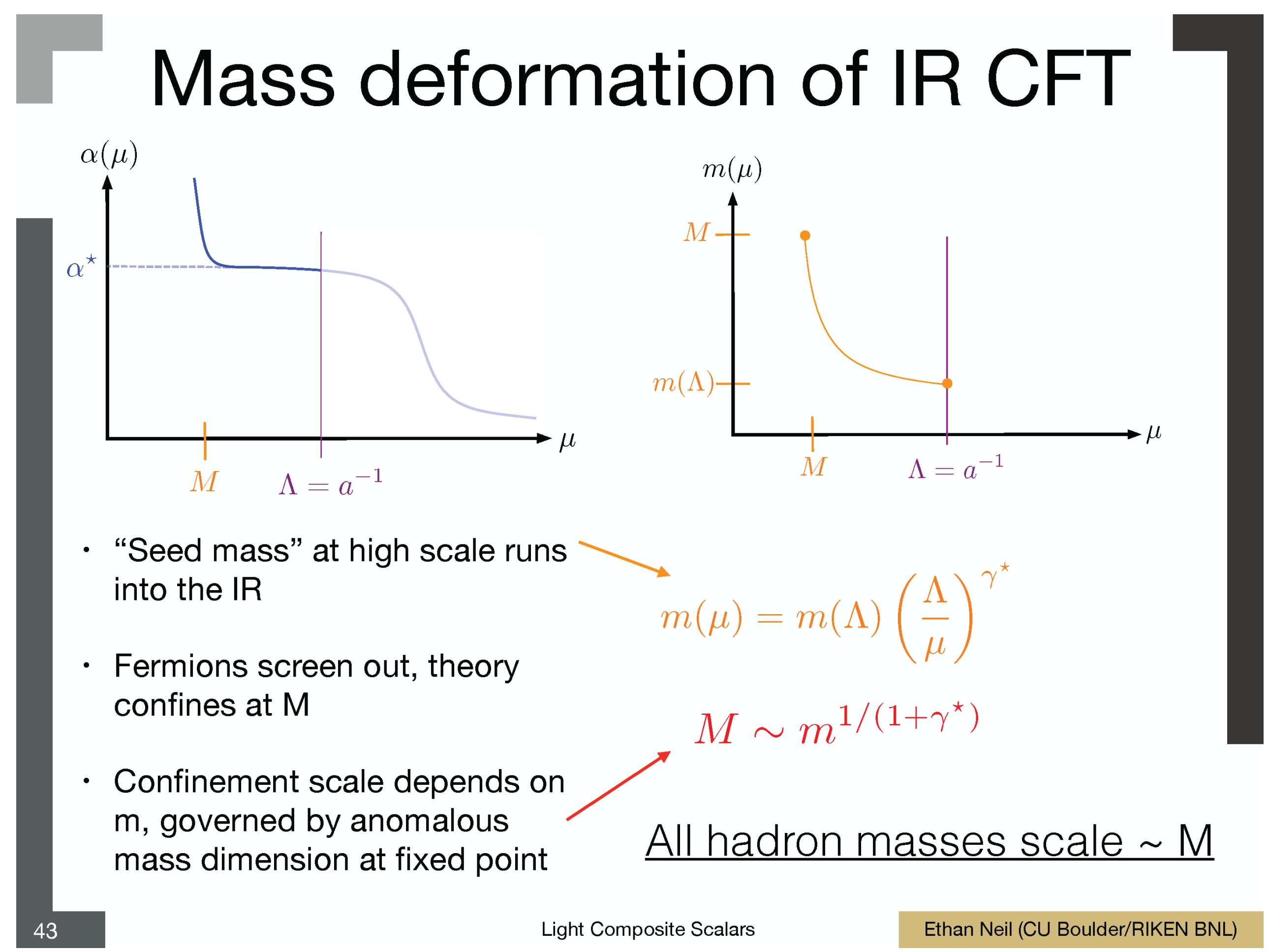
- Confinement is induced in mass-deformed IRFP at scale where fermions decouple

- Theory is IR Conformal if M → 0 as m → 0.

- In walking theory, another scale Λc should emerge.

- Technical challenge in walking theory on lattice is to have physically big enough volume that M << Λc.

- Typically M ~ Λc so it's difficult to conclude whether Λc exists.



Analytic Musings (I)
Why the Higgs boson might be a pseudo-dilaton

- Since 1980's, theorists have wondered whether Nambu-Goldstone theorem applies to quasi-scale invariant theories producing light pseudo-dilatons. [Bardeen, Leung, Love ('86); Yamawaki, Bando, Matumoto ('86); Holdom, Terning ('88); Gusynin, Miransky ('88); Dietrich, Sannino, Tuominen ('05); Appelquist, Bai ('10); Vecchi ('10)]

- There exists a perturbative model of a parametrically-light pseudo-dilaton as a proof of principle [B. Grinstein, P. Uttayarat ('10)]. Importantly, they matched the IR of this theory to a dilaton EFT [Goldberger, Grinstein, Skiba ('08)].

- The dilaton EFT is strikingly similar to the Higgs sector of the Standard Model, so the Higgs boson could be a pseudo-dilaton.

Quasi-conformality, fermion mass generation and FCNC

- Walking gauge theories were originally proposed to solve a problem with fermion mass generation and FCNC in Extended Technicolor (ETC) [Holdom ('81); Holdom ('85); Akiba, Yanagida ('86)].

- It was quickly conjectured that a light dilaton might also appear in walking technicolor [Yamawaki, Bando, Matumoto ('86)].

- Related discussion by Sannino earlier today.

- In extended technicolor (ETC)[1], masses and FCNC's from

$$\text{Masses}: \quad \frac{(\overline{Q}Q)(\overline{q}q)}{\Lambda^2_{\mathrm{ETC}}} \qquad \text{FCNC's}: \quad \frac{(\overline{q}q)(\overline{q}q)}{\Lambda^2_{\mathrm{ETC}}}$$

- For current limits on FCNC's involving strange quarks

$$\Lambda_{\mathrm{ETC}} \gtrsim 1000 \text{ TeV}$$

- So, the natural scale for strange quark mass in ETC

$$m_s \sim \langle \overline{Q}Q \rangle / \Lambda^2_{\mathrm{ETC}}$$

- In QCD $\langle \overline{\psi}\psi \rangle \sim (3f_\pi)^3$, so in QCD-like TC ($v \sim 246$ GeV)

$$\langle \overline{Q}Q \rangle \sim (3v)^3 \sim (750 \text{ GeV})^3 \quad \Longrightarrow \quad m_s \sim 0.4 \text{ MeV}$$

- Conjectured walking mechanism may provide enhancement

$$\langle \overline{Q}Q \rangle \sim (3v)^2 \Lambda_{\mathrm{ETC}} \quad \Longrightarrow \quad m_s \sim 63 \text{ MeV}$$

- Generating top quark masses a serious challenge for ETC.

[1] T. Appelquist, M. Piai, R. Shrock, Phys. Rev. D **69**, 105002 (2004)

Lattice Strong Dynamics Collaboration

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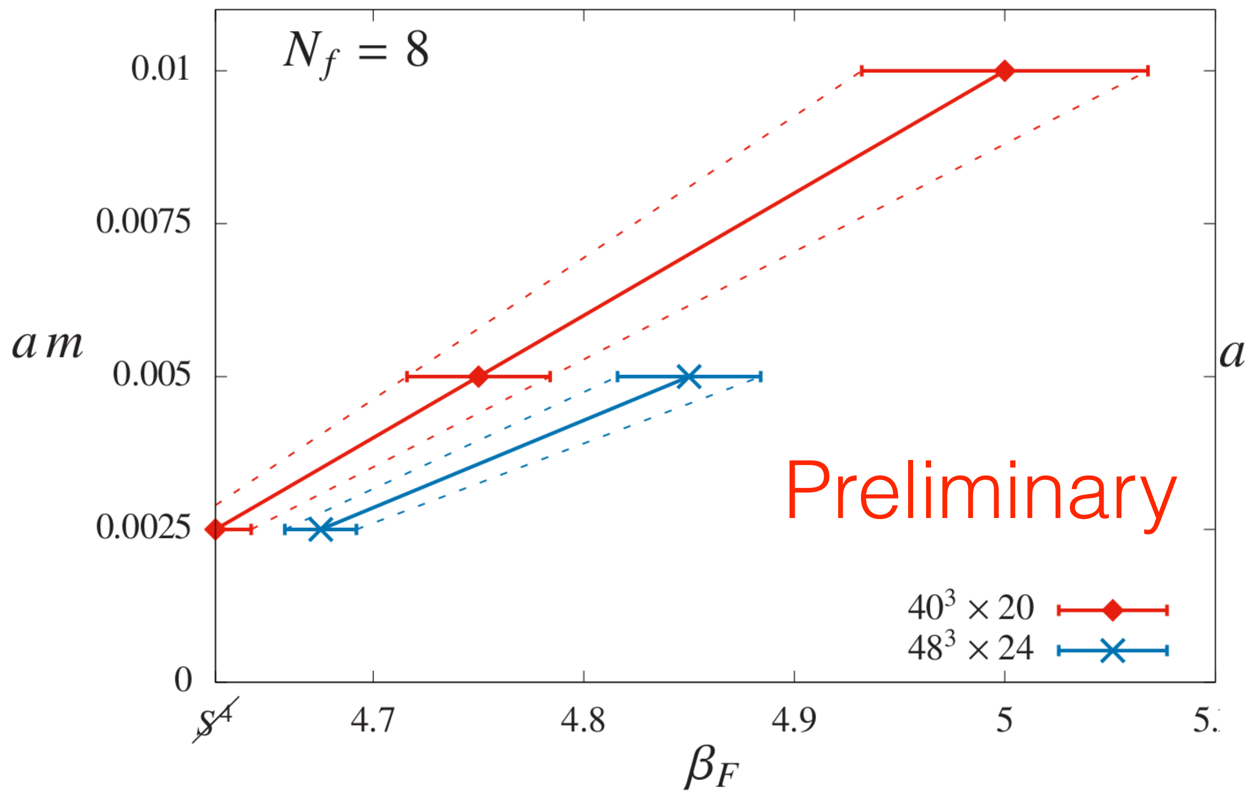
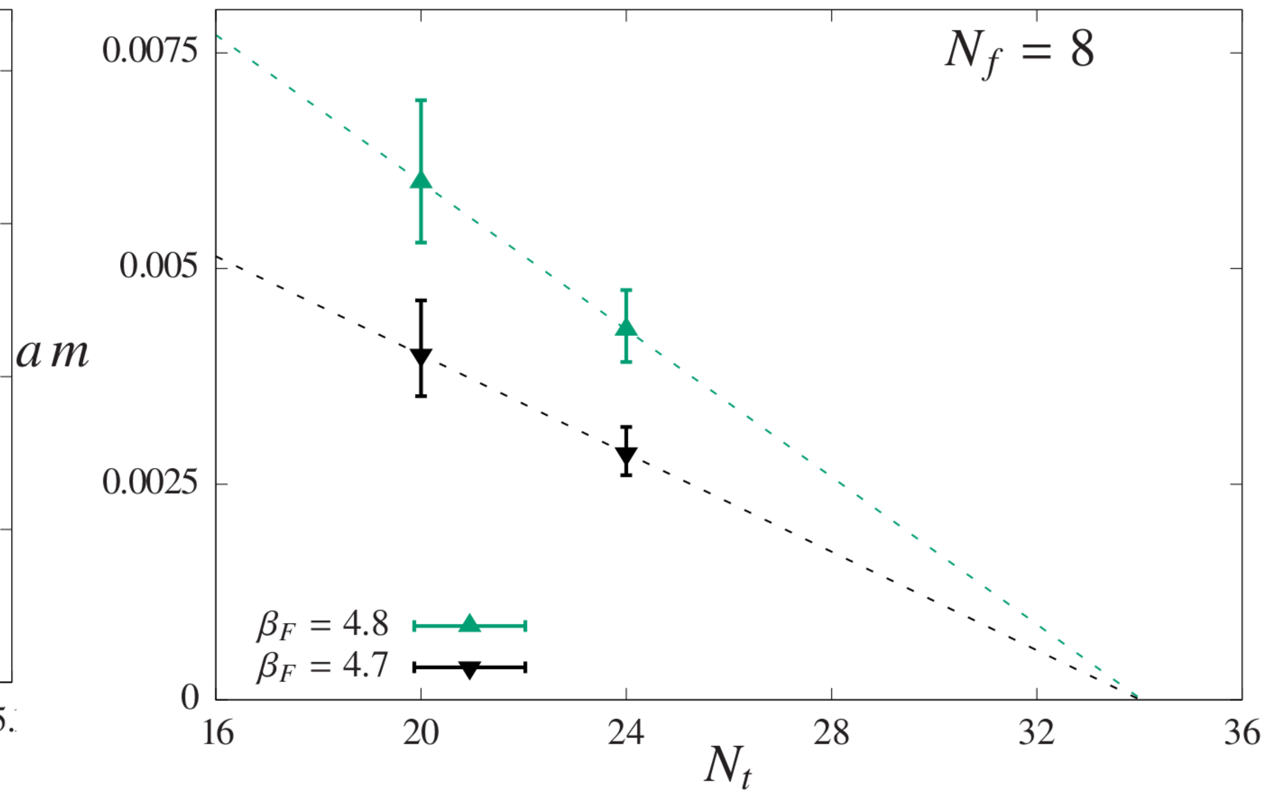
LSD SU(3) N_f=8 Stag

- Earlier USBSM studies (and LatKMI) used HISQ fermions which become prohibitively expensive for N_f=8 on coarse lattices.
- Using nHYP stag fermions and fund+adj gauge action pioneered by Boulder group to get to somewhat coarser (but still very fine) lattices.

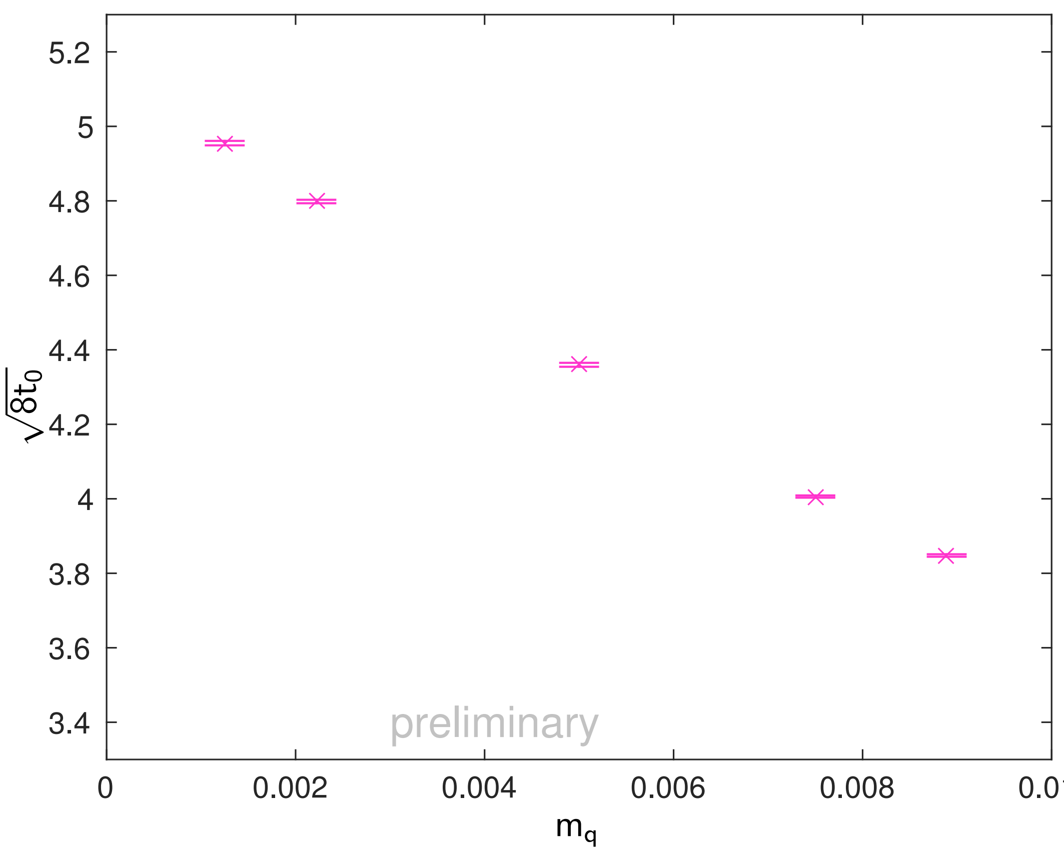




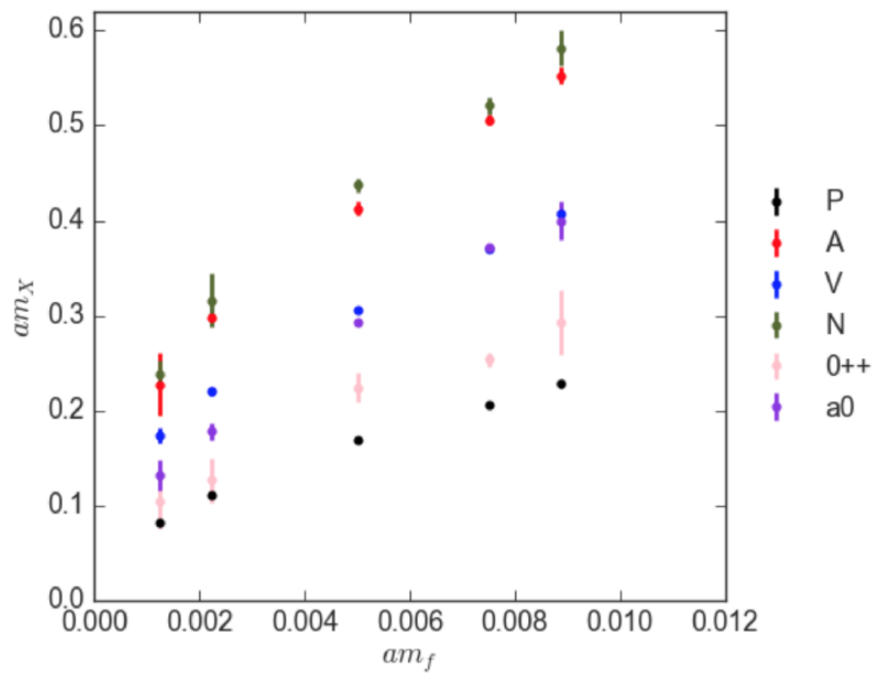
T_c and bulk phase

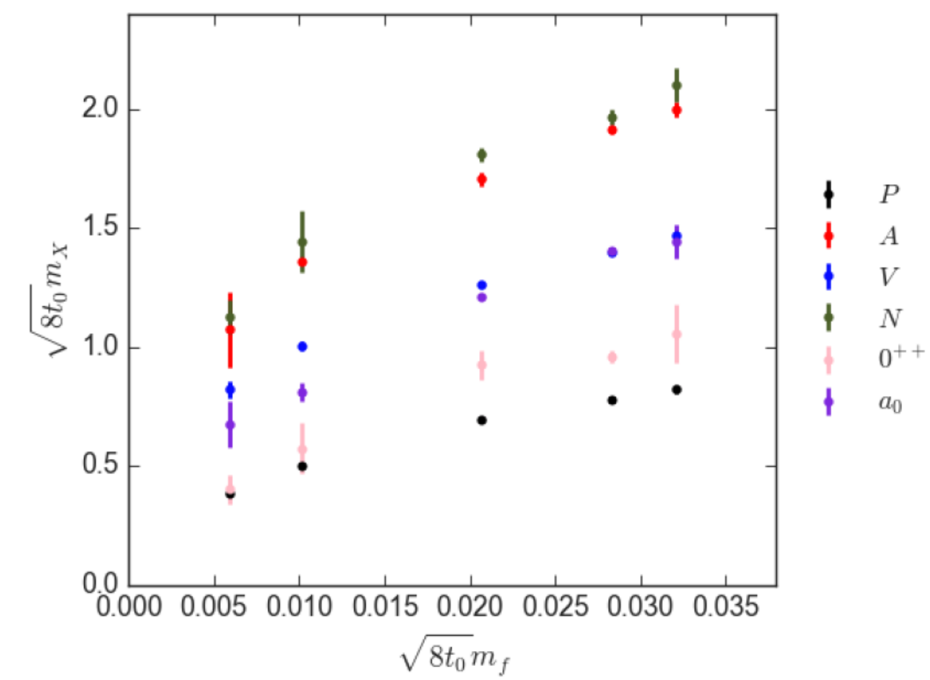
Near Conformal Scale Setting

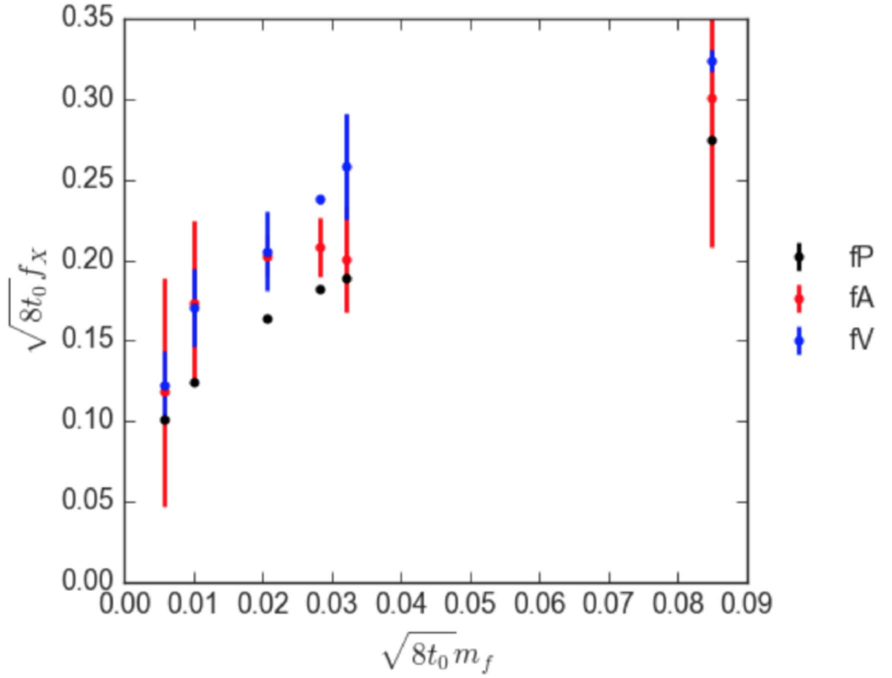
- In QCD, the dynamical scale a^{-1} is strongly affected by gauge coupling and weakly affected by quark mass.
- This reflects strong gluonic anti-screening and weak fermionic screening in vacuum.
- Near conformal dynamics has balanced anti-screening and screening, leading to strong mass dependence in setting the scale

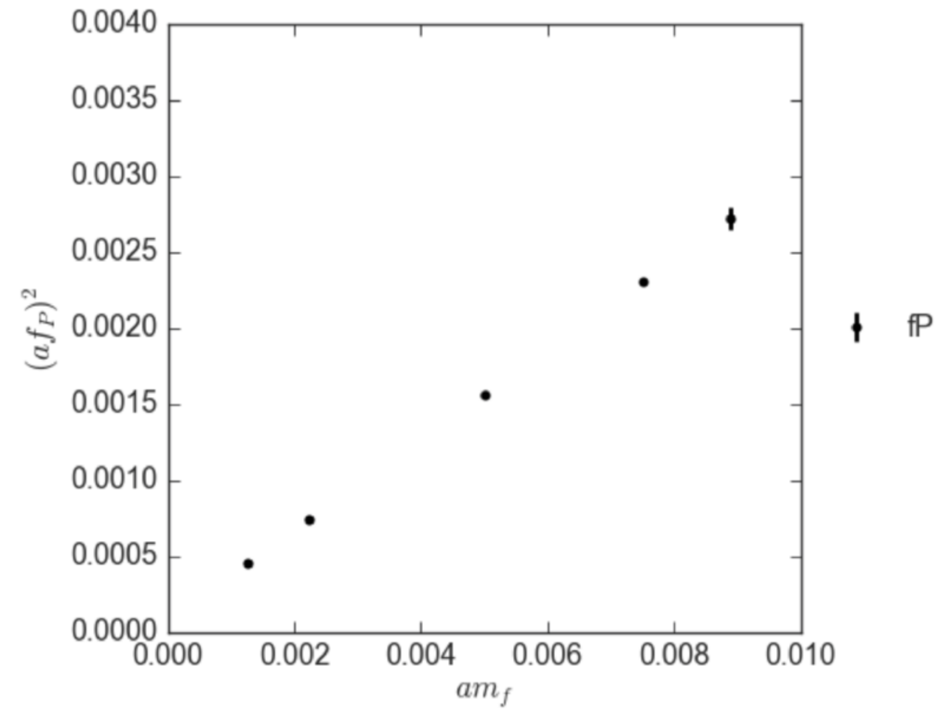


Hadron Spectrum

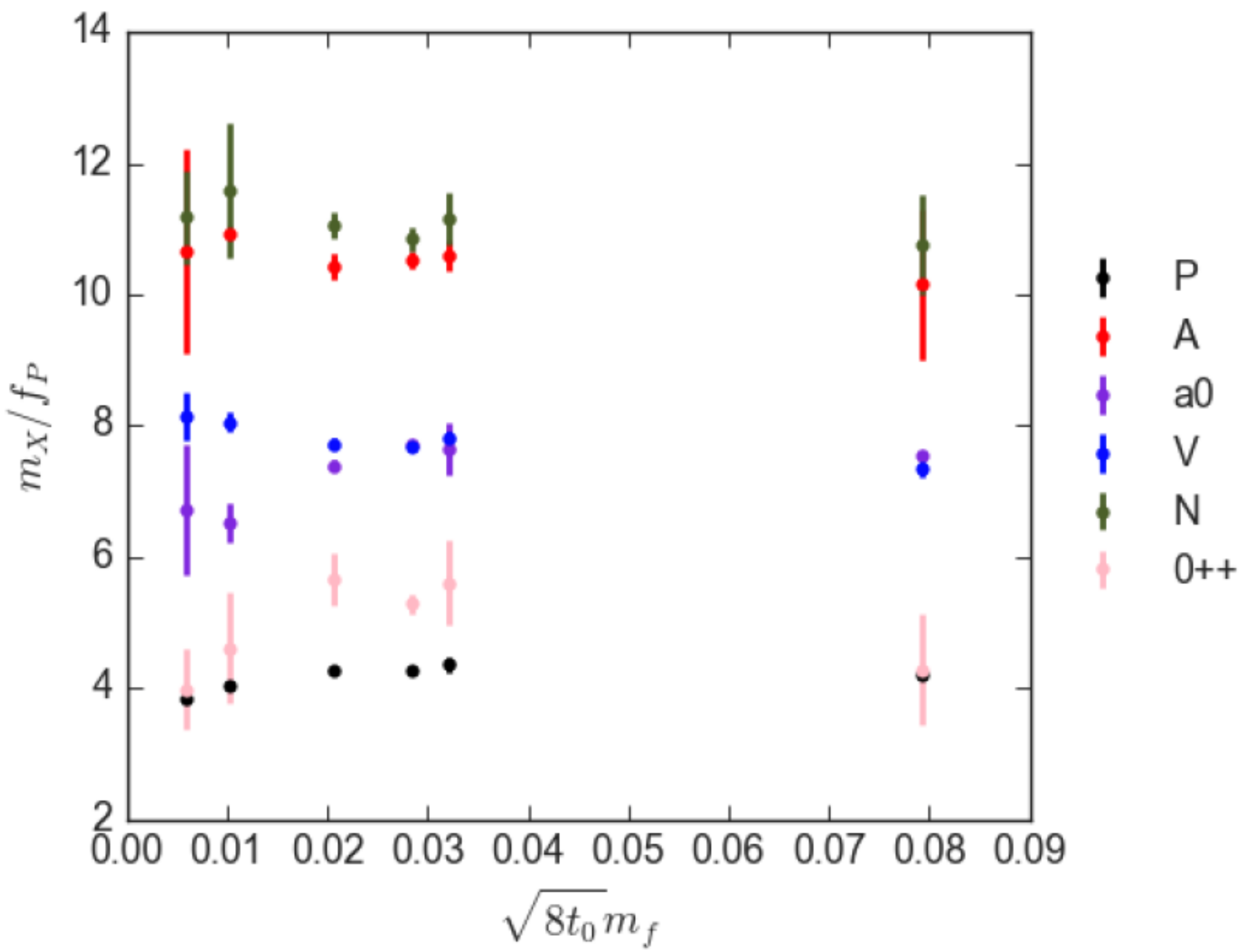


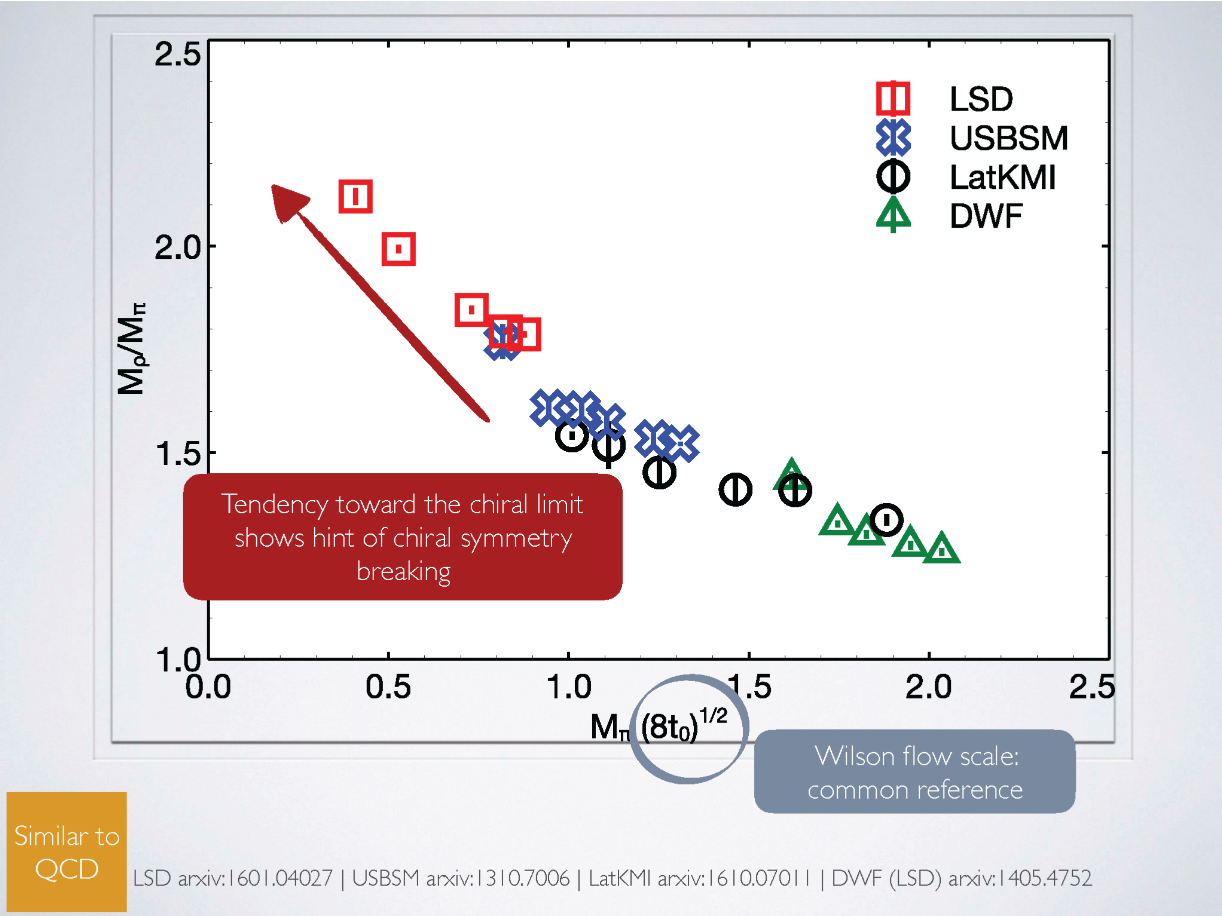






Hyperscaling of Mass-Deformed IRFP?





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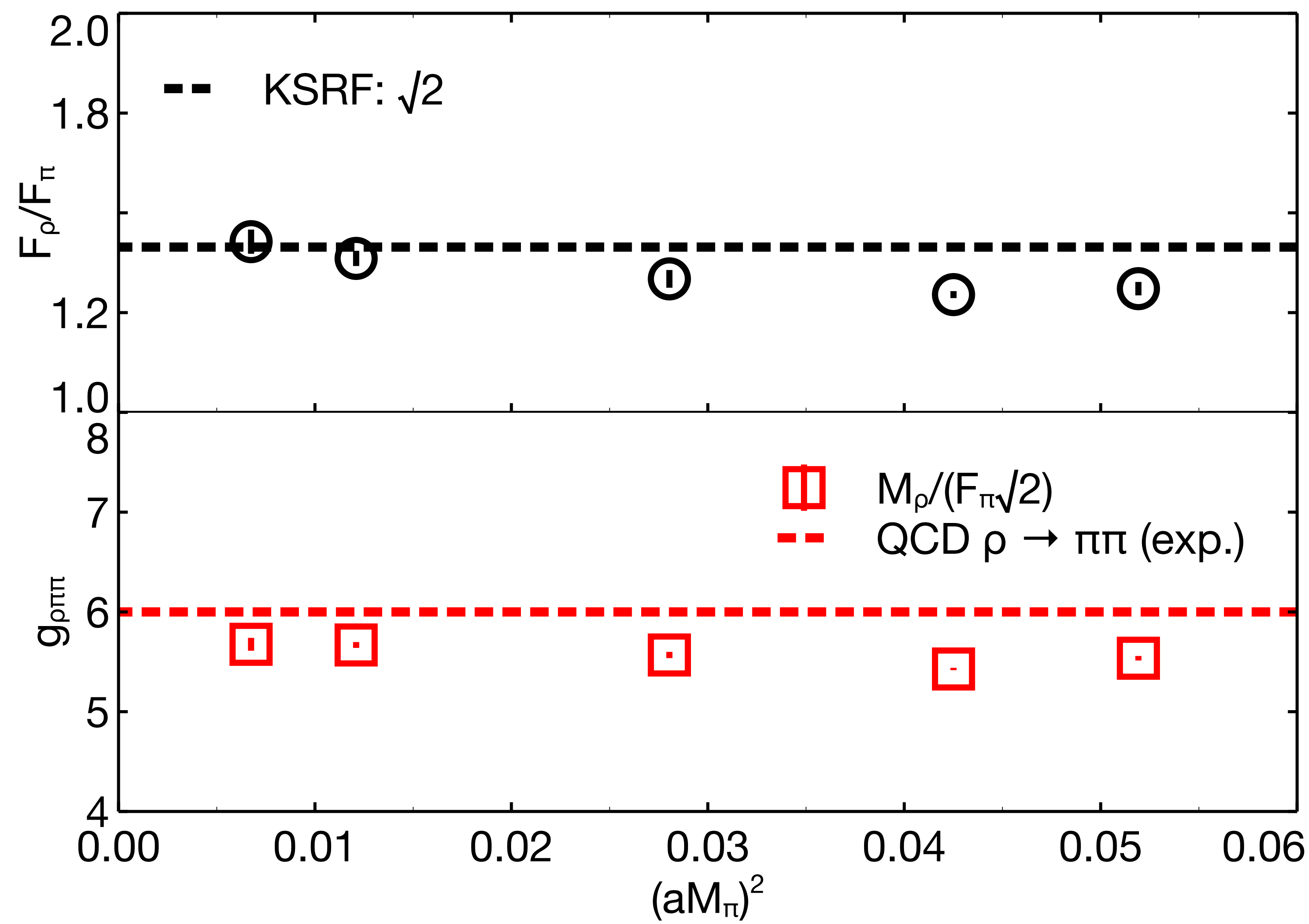
KSRF Relation

- Dynamical origin of vector meson dominance (VMD) not well understood in QCD. Is it also true in N_f=8?
- Seems to be true, so in LHC might expect 2 TeV vector resonances with ~25% width.

$$F_\rho = \sqrt{2}\ F_\pi\ , \quad g_{\rho\pi\pi} = \frac{M_\rho}{\sqrt{2}\ F_\pi}\ ,$$

$$\Gamma_\rho \approx \frac{g_{\rho\pi\pi}^2\ M_\rho}{48\pi} \approx \frac{M_\rho^3}{96\pi F_\pi^2}$$



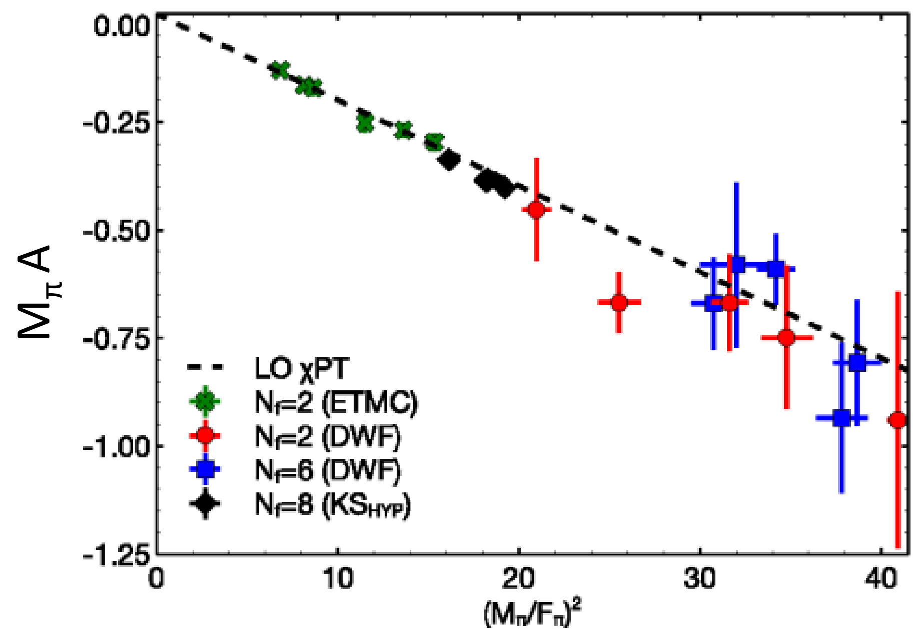
I=2 $\pi\pi$ scattering

A Clue from Pion Scattering

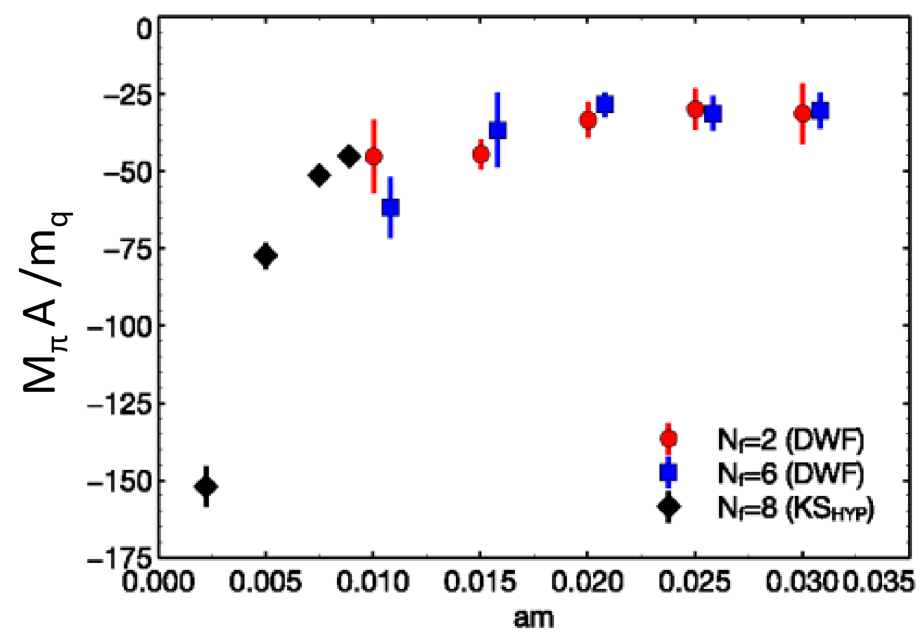
- Scattering length agrees well with LO XPT when plotted against physical (computed) values of M_π/ F_π .

$$(M_\pi A)_{LO} = \frac{-1}{(16\pi)^2}\left(\frac{M_\pi}{F_\pi}\right)^2 = \frac{-1}{(16\pi)^2}\frac{2Bm_q}{F^2}$$

- Plotted against bare quark mass, very poor agreement with LO XPT
- Again, suggests F has significant dependence on chiral breaking at tree level



Ref [1]



Ref [1]

Finite Volume Effects

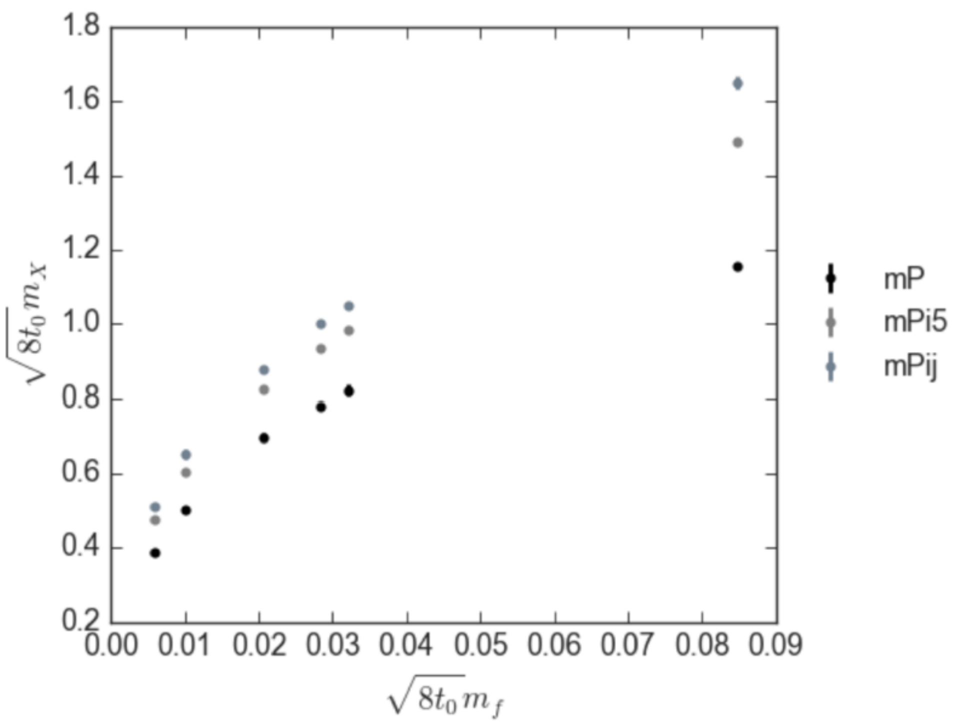
- Finite volume effects are small, order 1% in sensitive quantities and order 2% in ratios at $M_\pi L \sim 5.3$.

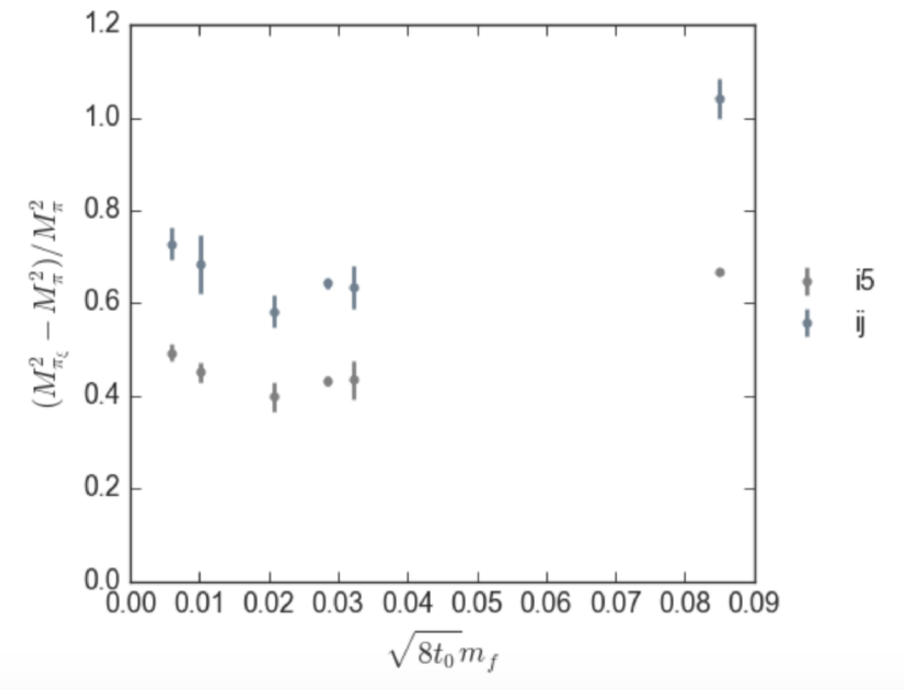
- Note how rapidly quantities change in lattice units with quark mass while ratios change slowly.

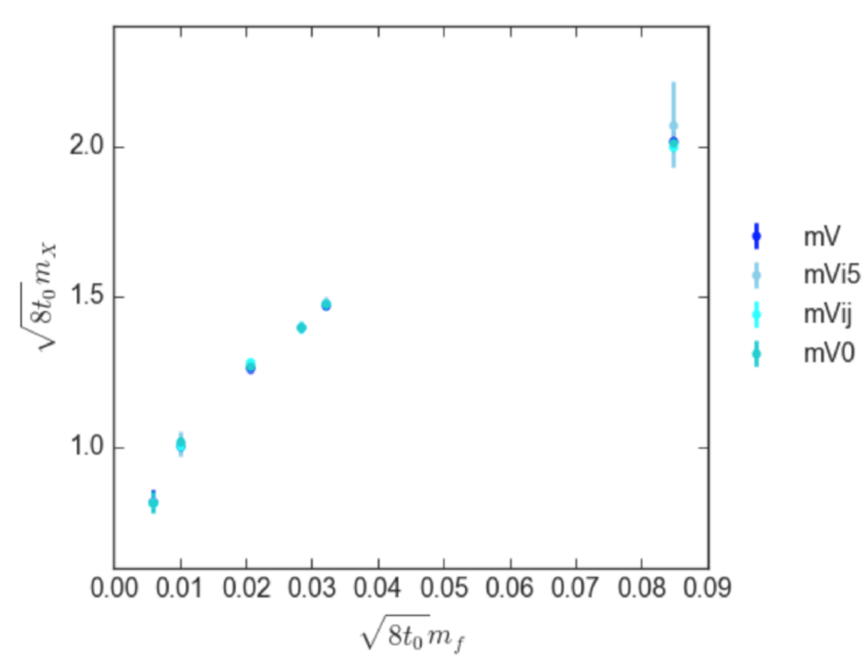
m_f	volume	M_π	F_π	M_π / F_π	$M_\pi L$
0.0075	$24^3 \times 48$	0.21067(19)	0.04746(8)	4.439(9)	5.1
	$32^3 \times 64$	0.20630(6)	0.04823(3)	4.228(3)	6.6
	$48^3 \times 96$	0.20575(3)	0.04827(1)	4.262(1)	9.9
0.005	$32^3 \times 64$	0.16795(10)	0.03939(4)	4.264(6)	5.4
	$48^3 \times 96$	0.16619(7)	0.03996(3)	4.159(4)	8.0
0.00222	$48^3 \times 96$	0.11017(6)	0.02742(3)	4.017(6)	5.3
0.00125	$64^3 \times 128$	0.08273(13)	0.02111(11)	3.918(24)	5.3

Staggered flavor breaking

- Even though $a^{-1} \sim 50\ F_\pi$ the taste breaking is still rather large. Another consequence of near conformal physics.







Conclusions

- LSD SU(3) Nf=8 shows evidence of light scalar [pass test 1].
- Lots of evidence for near-conformal dynamics. Is this related to lightness of scalar?
- These data are all preliminary but very close to publication. All lattice ensembles fixed, just analysis.
- We hope these data can be used to shed light on the nature of the EFT for the low energy spectrum.
- Something you didn't see? Ask, and we can show it in discussion.