From Gauge Theory to Higgs Compositeness Using EFT

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In progress

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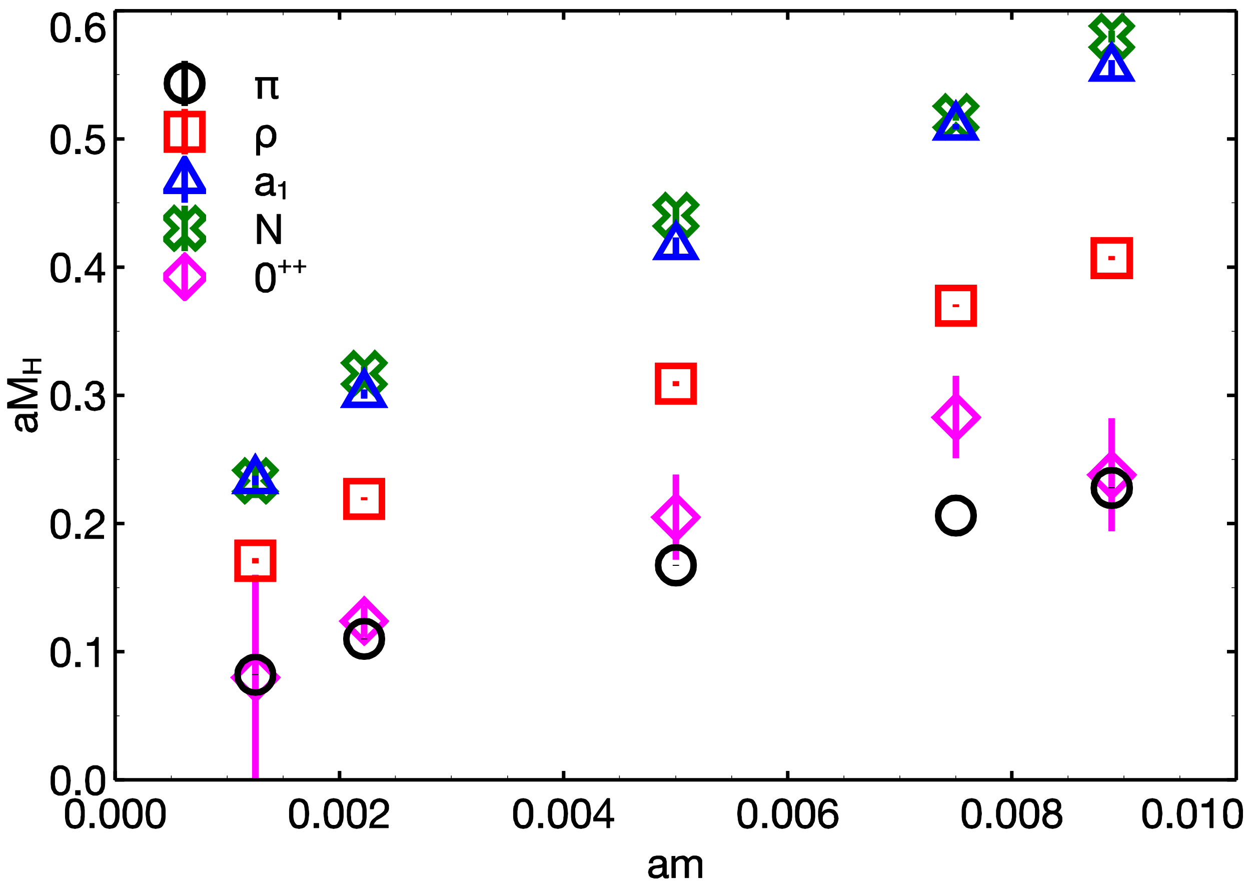
Exploring Yang Mills at Strong Coupling

- Yang Mills Theories admit a variety of novel behaviors in the IR as the numbers of flavors and colors is varied
  - QCD-like confinement, walking confinement, *conformality (fixed points!)*
  - Confirmed by lattice calculations
- Useful to understand the scope of IR behaviors for any phenomenological applications that point towards strong coupling
  - C.f. 750 GeV , 2 TeV excesses
- Can nearly conformal theories provide a composite Higgs sector?
  - **Interesting light scalar state in walking theories.**
  - What is the low energy EFT describing the light states? LECs?

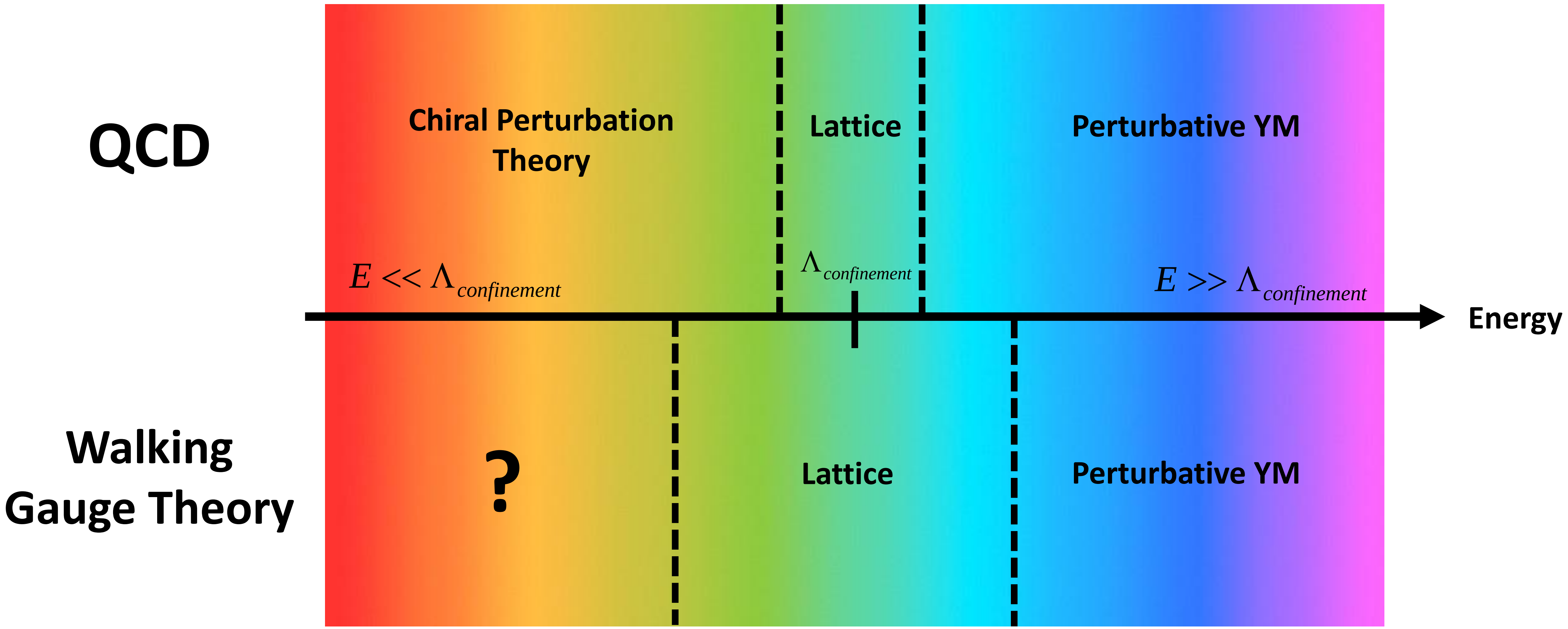
Light Scalar Resonance in a Walking Theory

- SU(3) gauge theory with 8 flavors in the fundamental rep
  - Near edge of conformal window (see for example [3])
- Pion and Sigma nearly degenerate at $M_\pi / M_\rho \approx 1/2$
  - Contrast with heavy scalar in QCD [4][5]
- Well separated from other states
  - Seek an EFT to describe Pions and Sigma in these mass ranges
  - XPT does not provide a good fit [1]
  - Here we will examine the conjecture that the EFT is a **linear sigma model**.
    - Other EFT starting points: dilaton [9] or simply agnostic [10,11]

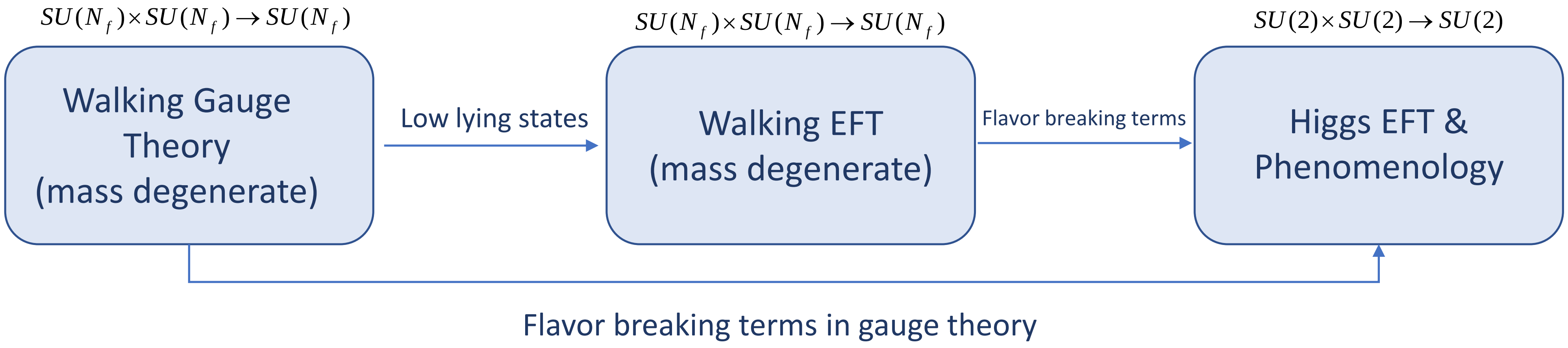


[2]

Confining Gauge Theories at High and Low Energies



Distinction between Walking EFT and Higgs EFT



The Nf=8 theory we consider has a large flavor group with many PNGBs

Some other walking models based on SU(2) flavor and do not come with additional PNGBs. For example [6][7]

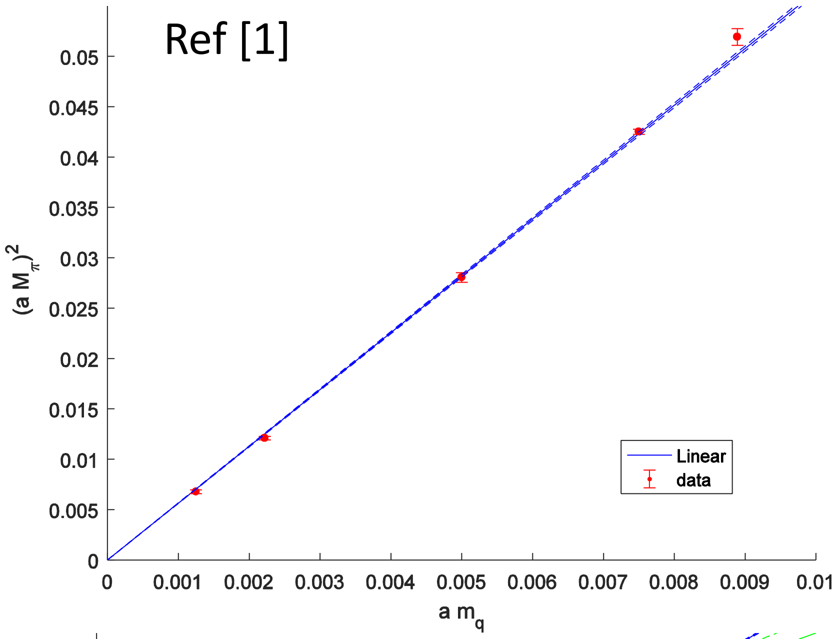
An Initial Analysis: Fitting to XPT

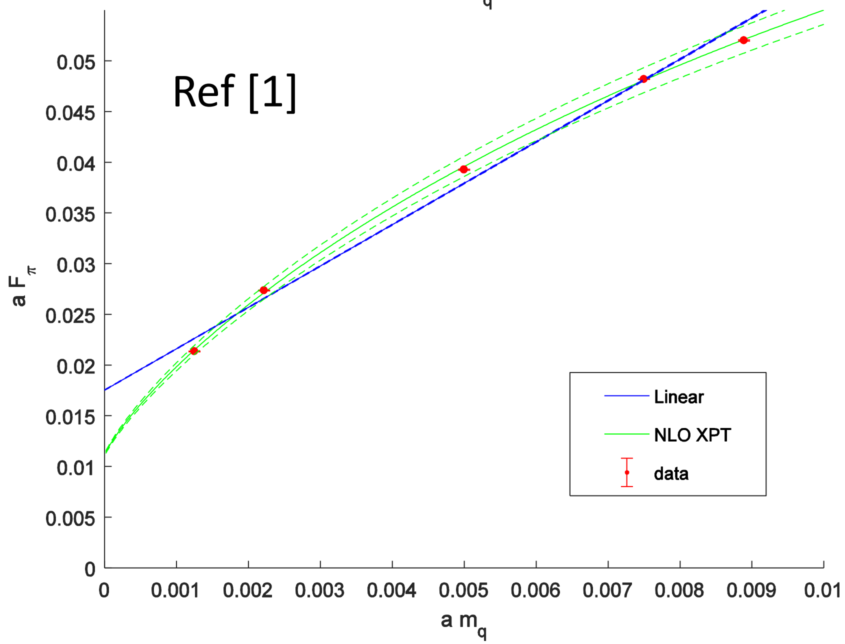
- At leading order in Chiral Perturbation Theory

$$M_\pi^2 = 2Bm_q \quad F_\pi = F \ \text{(constant)}$$

  - Mass looks strikingly like LO XPT
  - F deviates significantly from LO XPT
  - Combined fit to NLO XPT fails

- Incompatibility with XPT was pointed earlier in Nf=6 study [8]





[1]

$SU_L(N_f)$x $SU_R(N_f)$ Linear Sigma Model: Field Content

- Fields live in bifundamental representation: $M_a^{\bar{b}}$
- Transform Linearly under $SU_L(N_f)$x $SU_R(N_f)$:

$$M \to LMR^\dagger$$

- $2N_f^2$ Real degrees of freedom
- Express degrees of freedom via a polar decomposition: $M = \Sigma S$

$$\Sigma = \exp(i\pi_a T_a / F_\pi) \quad S = \frac{\sigma}{\sqrt{N_f}} + a_a T_a$$

- Without flavored scalars, fields do not form a complete linear representation
    - $N_f = 2$ is special. Admits a real linear representation due to isometry with O(4)
- Symmetry is nonlinearly realized in this basis

Decoupling limit for flavored scalars

$$m_a^2 \xrightarrow{\text{fixed } f, m_\sigma} \infty$$

$SU_L(N_f)$x $SU_R(N_f)$ Linear Sigma Model: Leading Order Lagrangian

- First, write down most general action symmetric under flavor group and parity, including all relevant and marginal operators

$$\mathcal{L}_{LSM} = \frac{1}{2}\left\langle \partial_\mu M \partial^\mu M^\dagger \right\rangle - V_0\left(M^\dagger M\right) - V_{SB}(M, \mathcal{M})$$

$$V_0 = -\frac{1}{4} m_\sigma^2 \left\langle M^\dagger M \right\rangle + \frac{m_\sigma^2 - m_a^2}{8 f^2}\left\langle M^\dagger M \right\rangle^2 + \frac{N_f m_a^2}{8 f^2}\left\langle \left(M^\dagger M\right)^2 \right\rangle$$

- Symmetry breaks spontaneously: $SU_L(N_f) \times SU_R(N_f) \rightarrow SU_V(N_f)$
- Nonlinear sigma model decoupling limit: $m_\sigma^2, m_a^2 \overset{\text{fixed } f}{\rightarrow} \infty$
- Pion decay constant is proportional to vev (depends on mq at tree level): $F_\pi = \frac{\langle 0|\sigma|0\rangle}{\sqrt{N_f}}$

Explicit Breaking Terms and Power Counting

- Two expansions
  - EFT expansion: $\frac{M}{\Lambda} \sim \frac{F_\pi}{M_\rho}$
  - Chiral expansion: $\frac{\mathrm{X}}{\Lambda^2} \sim \frac{m_q B}{M_\rho^2}$

For our data:

$$\frac{F_\pi}{M_\rho} \approx \frac{1}{8} < 1$$

$$0.1 < \frac{m_q B}{M_\rho^2} < 0.2$$

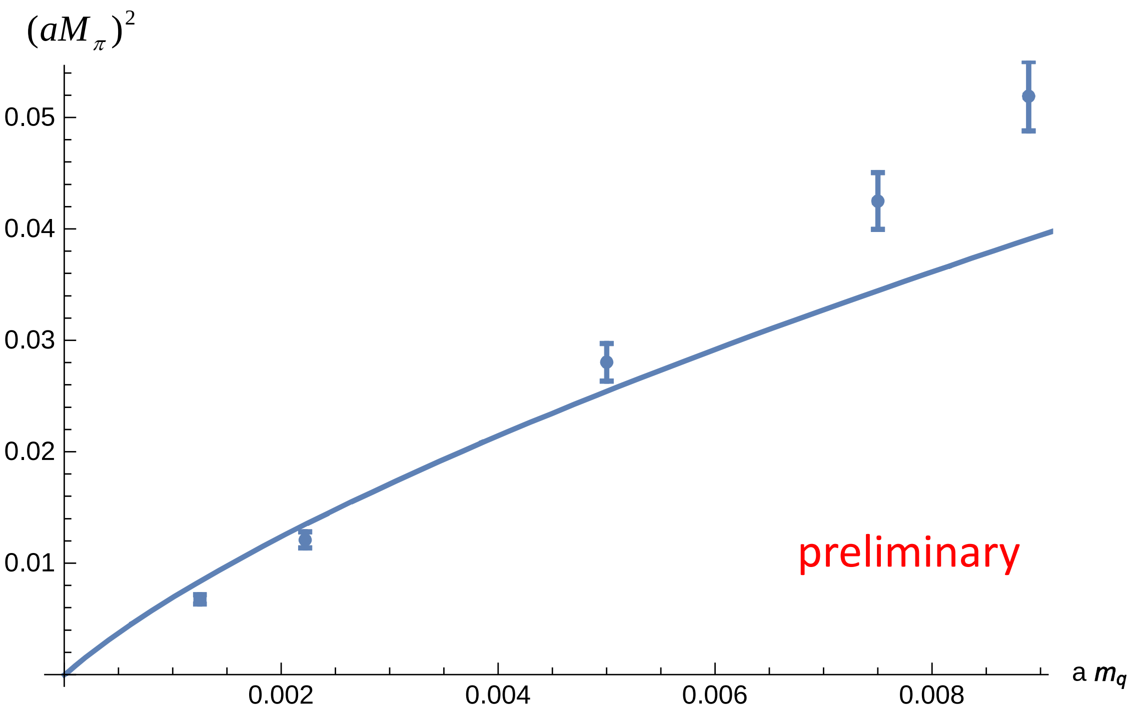
- We will consider the breaking terms:

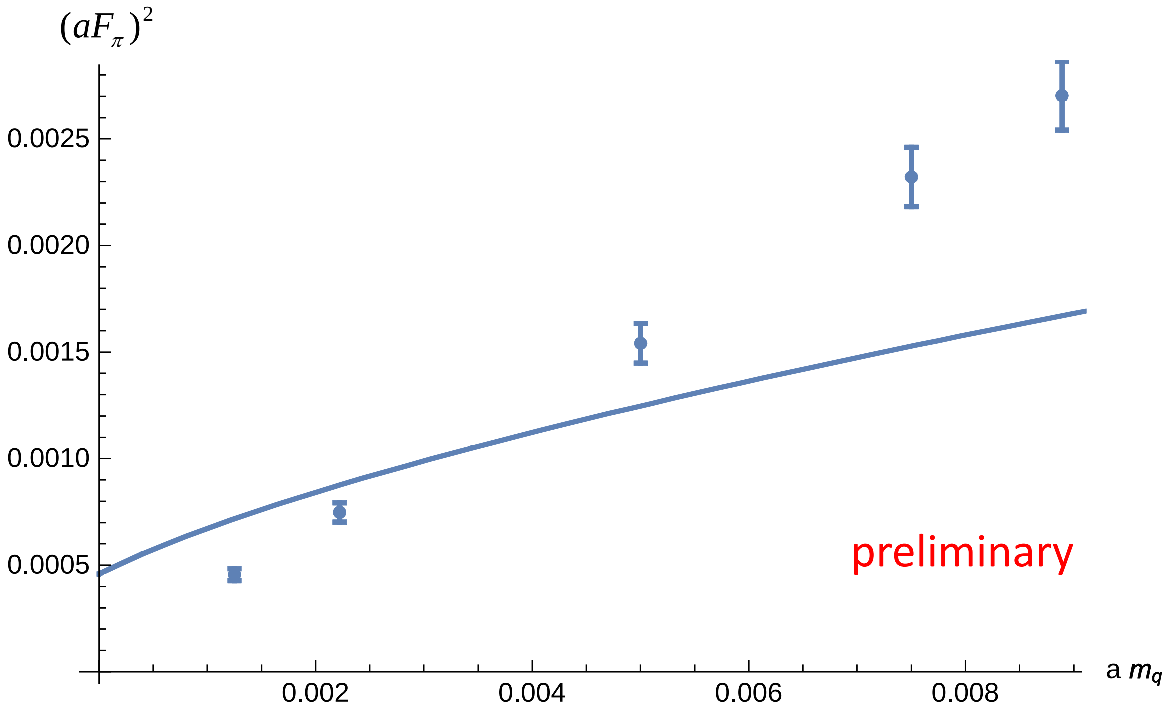
$$V_{SB} = \boxed{\frac{-f}{\sqrt{N_f}}\left\langle \mathrm{X}^\dagger M + \mathrm{X} M^\dagger \right\rangle} \boxed{- \frac{c_1}{f\sqrt{N_f}}\left\langle M^\dagger M\right\rangle\left\langle \mathrm{X}^\dagger M + \mathrm{X} M^\dagger \right\rangle - \frac{c_2\sqrt{N_f}}{f}\left\langle \left(M^\dagger M\right)\mathrm{X}^\dagger M + \left(M M^\dagger\right)\mathrm{X} M^\dagger \right\rangle}$$

O(X¹,M¹) O(X¹,M³)

$$c_{1,2} \sim \frac{f}{\Lambda}$$

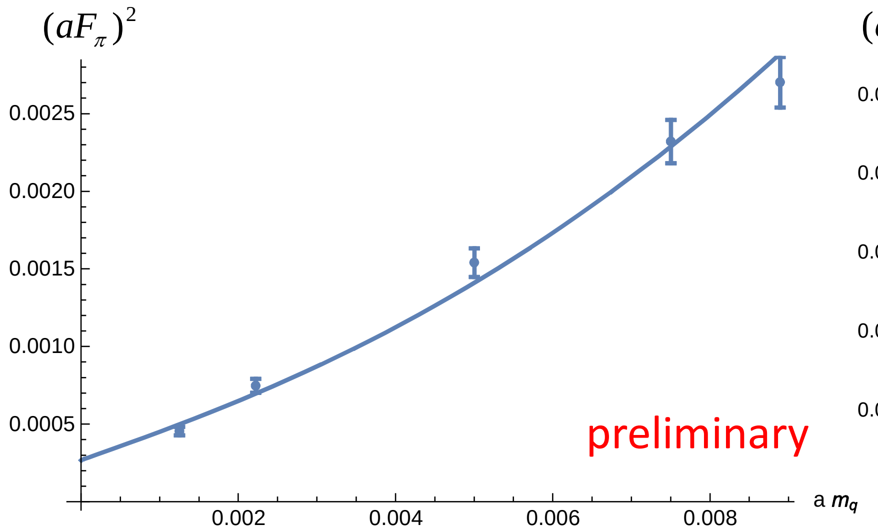
Fits of M_π and F_π to linear sigma up to O(X^1,M^1)

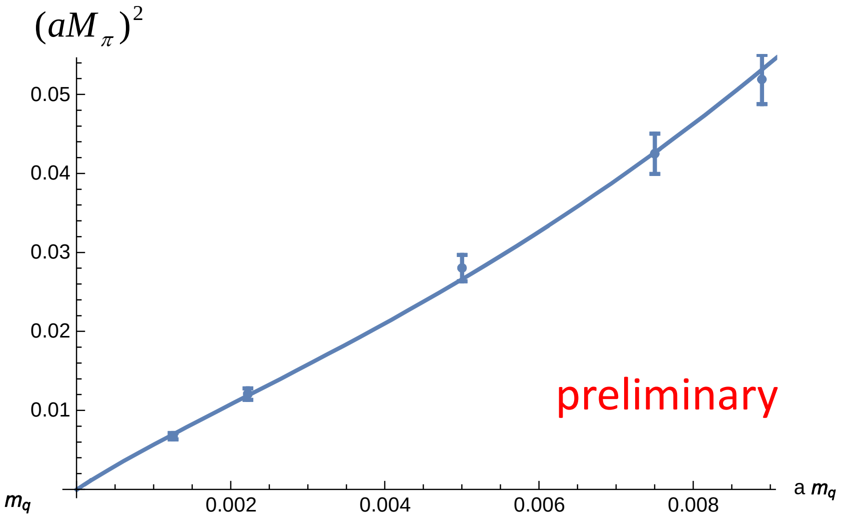




χ^2/dof = 37.6
With 3% systematic errors

Fits of F_π , M_π ,and M_σ to linear sigma up to $O(X^1,M^3)$

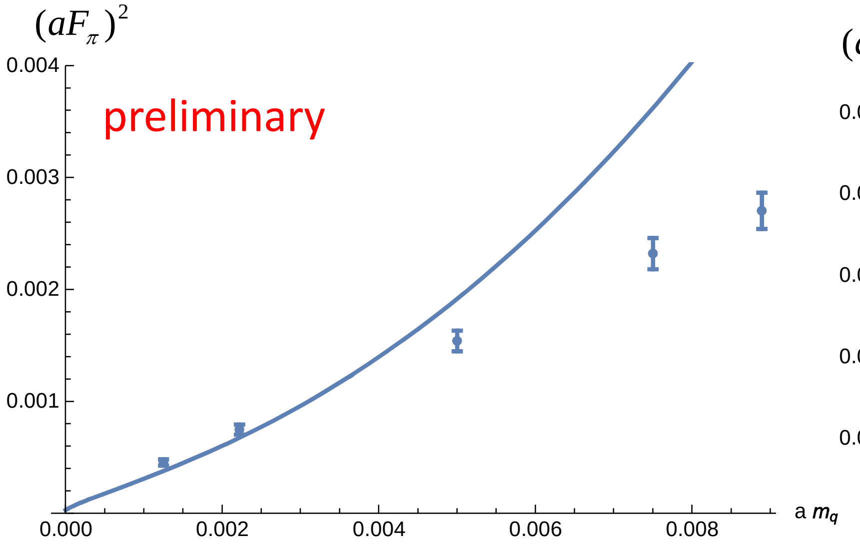


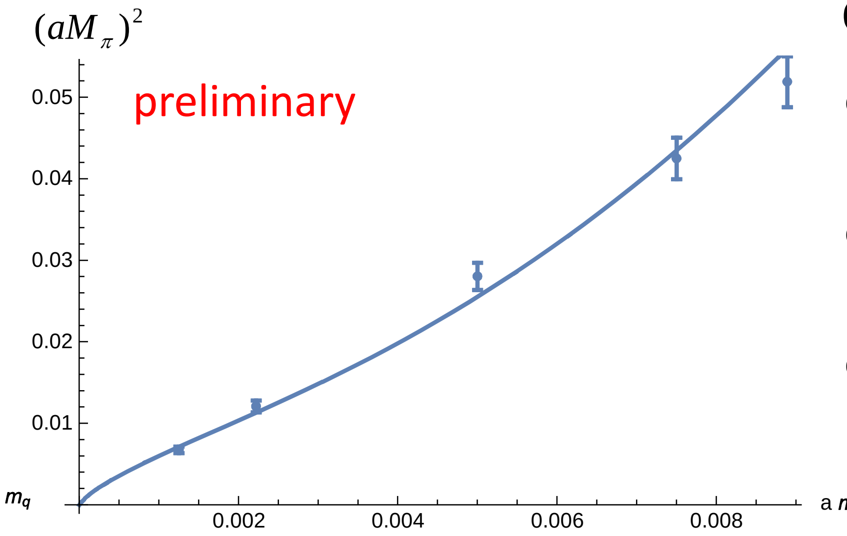


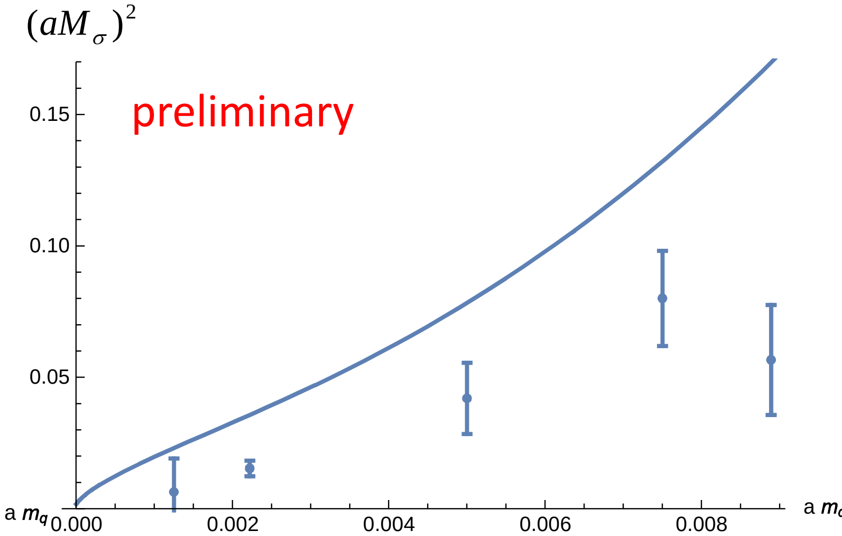
χ^2/dof = 1.2
With 3% Systematic Errors

Fitting all 5 quark masses: χ^2/dof = 12.4
With 3% systematic errors

Fitting first 3 quark masses: χ^2/dof = 10.9
With 3% systematic errors







Take Aways

- Large class of confining gauge theories exist who differ significantly from QCD in the IR
- Lattice results for 8f theory show a light scalar in spectrum nearly degenerate with pions
- Chiral perturbation theory fails to fit to light states of 8f theory
  - Seeking a better EFT description of light states
- Constructed SU(N)xSU(N) linear sigma model as an alternative EFT description
- Leading order Linear sigma with $O(X^1,M^3)$ breaking terms fails to provide a good fit to lattice data for M_π ,F_π , and M_σ simultaneously
  - Fit improves slightly at smaller m_q
  - NLO terms maybe not negligible
  - Breaking potential could be too restrictive
- If LSM continues to fail
  - Motivates dilatonic EFT analysis [9]
  - Could take approach of more “agnostic” EFT analyses that couples sigma to pions more generally [10][11]

References

1. Gasbarro, Andrew D., and George T. Fleming. "Examining the Low Energy Dynamics of Walking Gauge Theory." *arXiv preprint arXiv:1702.00480* (2017).
2. Appelquist, Thomas, et al. "Strongly interacting dynamics and the search for new physics at the LHC." *Physical Review D* 93.11 (2016): 114514.
3. Hasenfratz,Anna, David Schaich, and Aarti Veernala. “nonperturbative beta function of eight-flavor SU(3) gauge theory. Arxiv:1410.5886
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5. Bernard, Claude, et al. "Scalar meson spectroscopy with lattice staggered fermions." *Physical Review D* 76.9 (2007): 094504.
6. Fodor, Zoltan, et al. "Toward the minimal realization of a light composite Higgs." *arXiv preprint arXiv:1502.00028* (2015).
7. Fodor, Zoltan, et al. "Status of a minimal composite Higgs theory." *arXiv preprint arXiv:1605.08750* (2016).
8. Appelquist, Thomas, et al. "Toward TeV Conformality." *Physical review letters* 104.7 (2010): 071601.
9. Appelquist, Thomas, James Ingoldby, and Maurizio Piai. "Dilaton EFT Framework For Lattice Data." *arXiv preprint arXiv:1702.04410* (2017).
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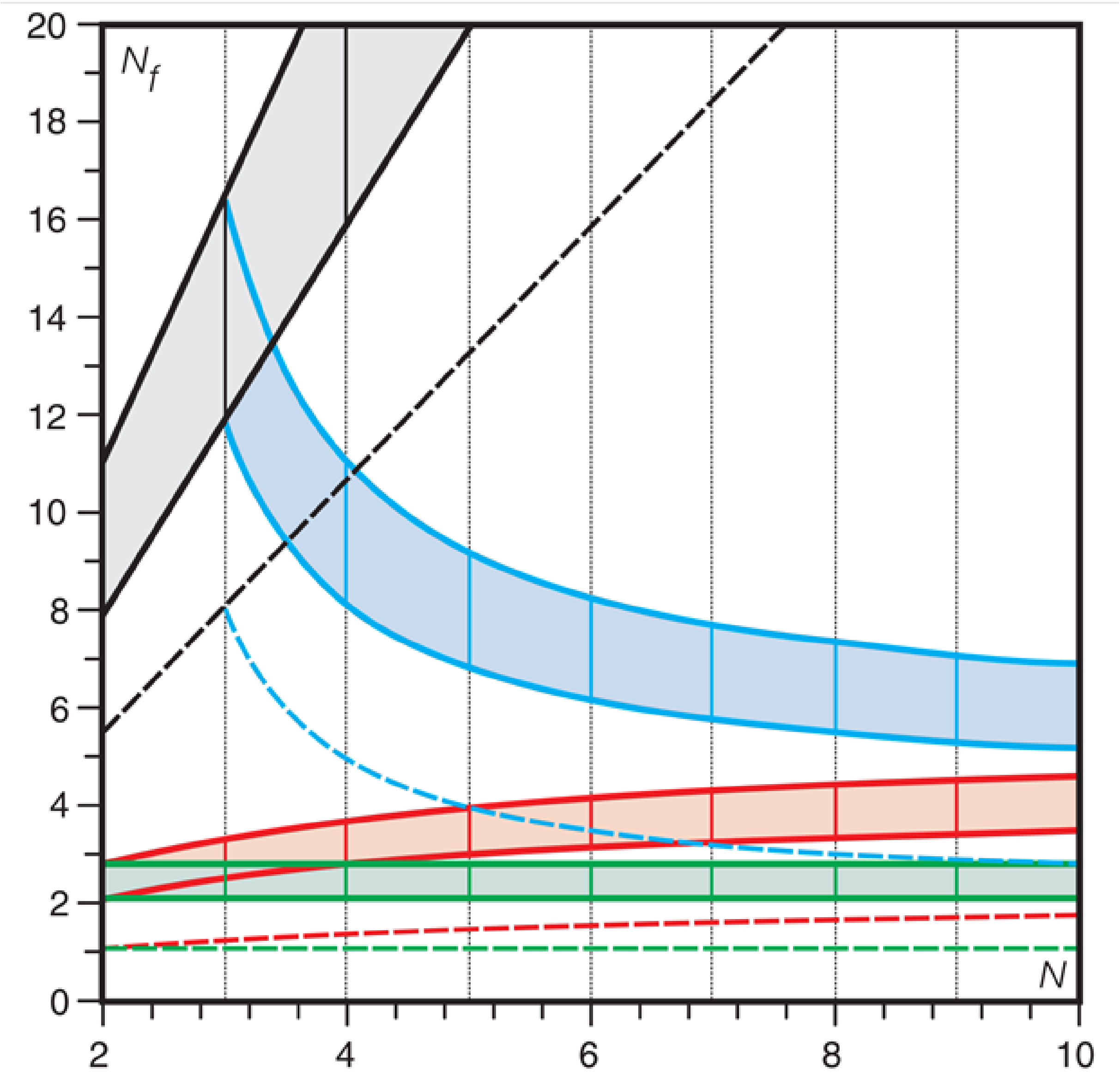
11. Soto, J., P. Talavera, and J. Tarrus. "Chiral effective theory with a light scalar and lattice QCD." *Nuclear Physics B* 866.3 (2013): 270-292.
12. Appelquist, Thomas, et al. "W W scattering parameters via pseudoscalar phase shifts." *Physical Review D* 85.7 (2012): 074505.

Backup Slides

Walking around experimental constraints

- S-Parameter
  - https://arxiv.org/pdf/1009.5967
  - https://arxiv.org/abs/1602.00796
- FCNC and Condensate Enhancement
  - https://arxiv.org/pdf/0910.2224.pdf
- Light Higgs
  - Aoki, Yasumichi, et al. "Light composite scalar in eight-flavor QCD on the lattice." *Physical Review D* 89.11 (2014): 111502.
  - Appelquist, Thomas, et al. "Strongly interacting dynamics and the search for new physics at the LHC." *Physical Review D* 93.11 (2016): 114514.

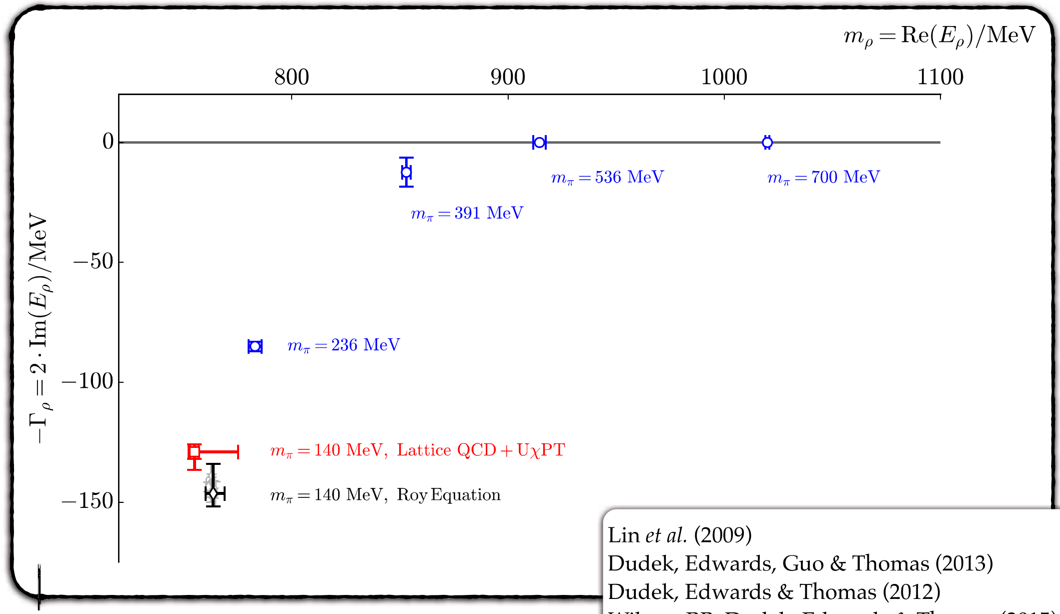


Conformal Window (ladder approximation)

Dietrich, Dennis D., and Francesco Sannino. "Conformal window of SU (N) gauge theories with fermions in higher dimensional representations." *Physical Review D* 75.8 (2007): 085018.

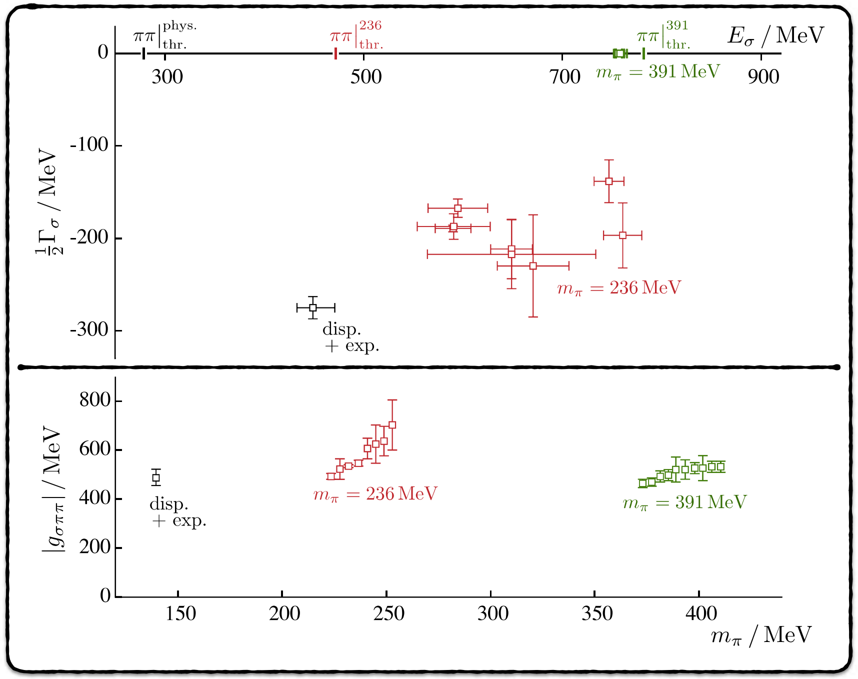
The Sigma f0(500) Resonance in QCD

The ρ vs m_π



Lin *et al.* (2009)
Dudek, Edwards, Guo & Thomas (2013)
Dudek, Edwards & Thomas (2012)
Wilson, RB, Dudek, Edwards & Thomas (2015)
Bolton, RB & Wilson (2015)

The σ / f_0(500) vs m_π



Briceño, Raul A., et al. "Isoscalar π π Scattering and the σ Meson Resonance from QCD." *Physical Review Letters* 118.2 (2017): 022002.

http://www.usqcd.org/meetings/allHands2017/slides/Briceno.pdf

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- At leading order in Chiral Perturbation Theory

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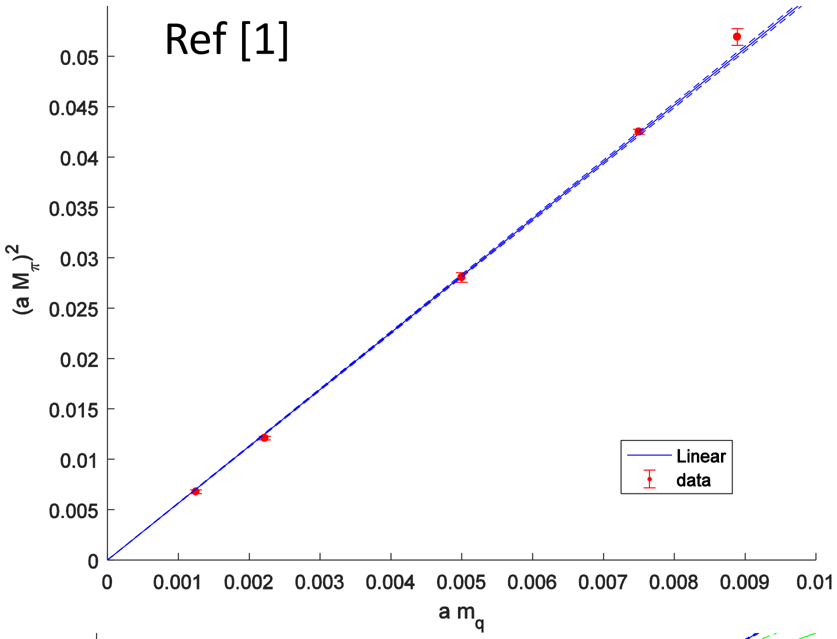
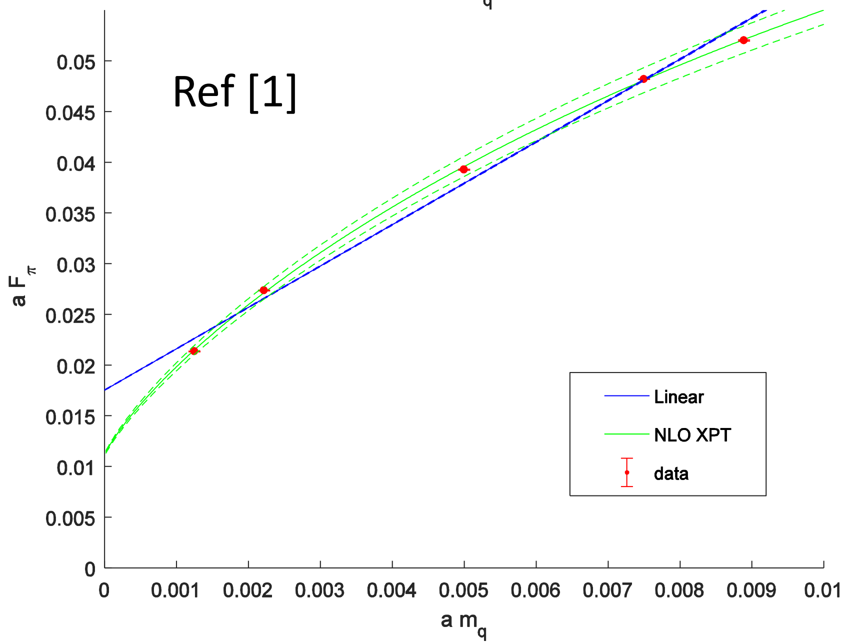
  - Mass looks strikingly like LO XPT
  - F deviates significantly from LO XPT
  - Combined fit to NLO XPT fails

- Loop expansion parameter:
  - Determine "B" from slope of pion mass
  - Determine "F" from intercept of decay constant

$$\frac{2N_f Bm_q}{(4\pi F)^2} \approx 5.8$$

- Incompatibility with XPT was pointed earlier in Nf=6 study [8]





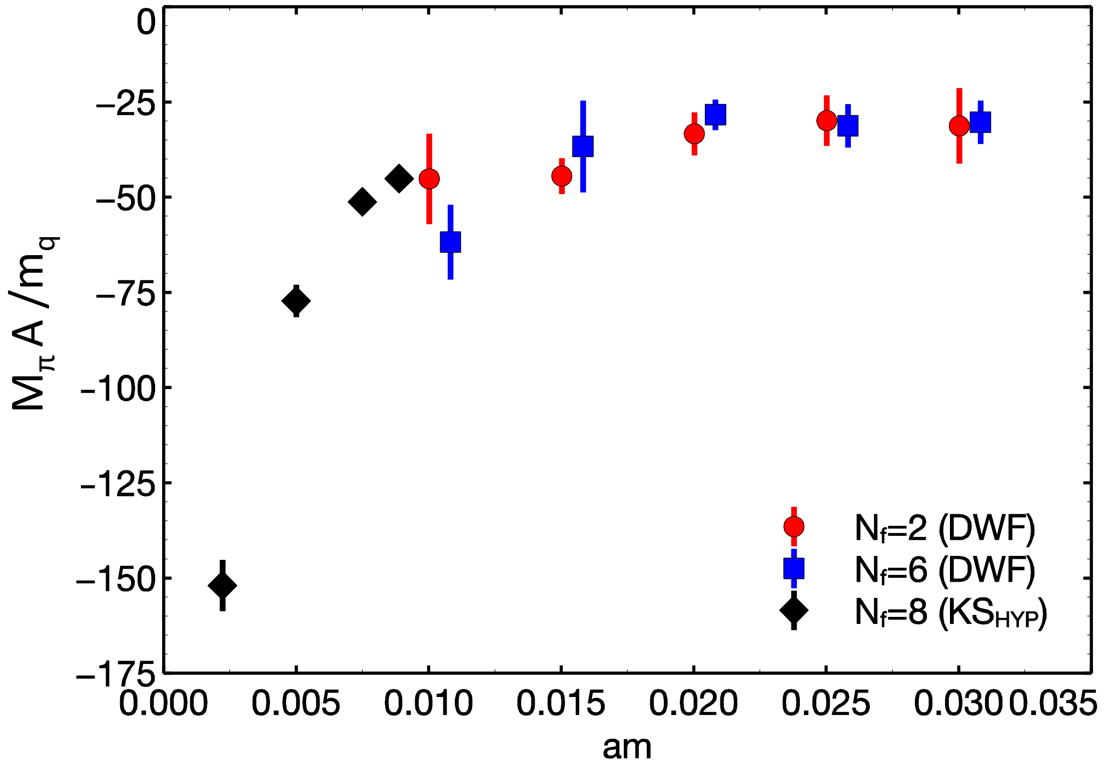
[1]

Another Clue from Pion Scattering

- Nf=2,6 data agrees with LO XPT within error bars
- Nf=8 data deviates significantly from LO XPT behavior

$$\frac{(M_\pi A)_{LO}}{m_q} = \frac{-1}{(16\pi)^2}\frac{2B}{F^2}$$

- Again, suggests F has significant dependence on m_q at tree level



Refs [1][12]

Why Consider the Linear sigma model?

- Most general EFT analysis of pions+sigma has large number of LECs at leading order [10][11]
  - Likely difficult to constrain with existing lattice data.
  - Easier to start by assuming more constrained model and seeing if you can invalidate your assumptions
- Natural interpolation between EFT for Walking and EFT for QCD as $M_\sigma \to \infty$
  - In QCD, sigma too heavy and broad to be useful in low energy EFT, so usually integrated out
  - Here, sigma is light and stable, so don't integrate out
    - Not unique to linear sigma [9]. Connection to Composite Higgs Scenario
  - Standard model Higgs is a Linear Sigma model (though, LHC Higgs might not be)

Explicit Breaking in Underlying Gauge Theory

- Introduce operators to explicitly break symmetry to $SU_V(N_f)$

$$V_{SB} = c_1\left\langle M + M^\dagger \right\rangle + c_2\left\langle M^2 + \left(M^\dagger\right)^2 \right\rangle + c_3\left(\left\langle M\right\rangle^2 + \left\langle M^\dagger\right\rangle^2\right) + c_4\left\langle M\right\rangle\left\langle M^\dagger\right\rangle + c_5\left\langle M^3 + \left(M^\dagger\right)^3\right\rangle + c_6\left\langle M^2 M^\dagger + \left(M^\dagger\right)^2 M\right\rangle + \ldots$$

- Can reduce number of breaking terms by looking to underlying gauge theory for guidance.

- Only source of explicit breaking in Yang Mills model is quark mass.

$$\mathcal{L}_{YM} \supset \psi_{\mathrm{L}}^\dagger \boldsymbol{\mathcal{M}} \psi_R + \psi_{\mathrm{R}}^\dagger \boldsymbol{\mathcal{M}}^\dagger \psi_L$$

- Spurion analysis: treat chiral breaking as an external source which transforms

$$\mathrm{X} \to L X R^\dagger$$