From Walking Gauge Theory to Higgs Compositeness Using EFT

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Based on:
arXiv:1702.00480 [1]
and in progress work

Lattice Strong Dynamics Collaboration

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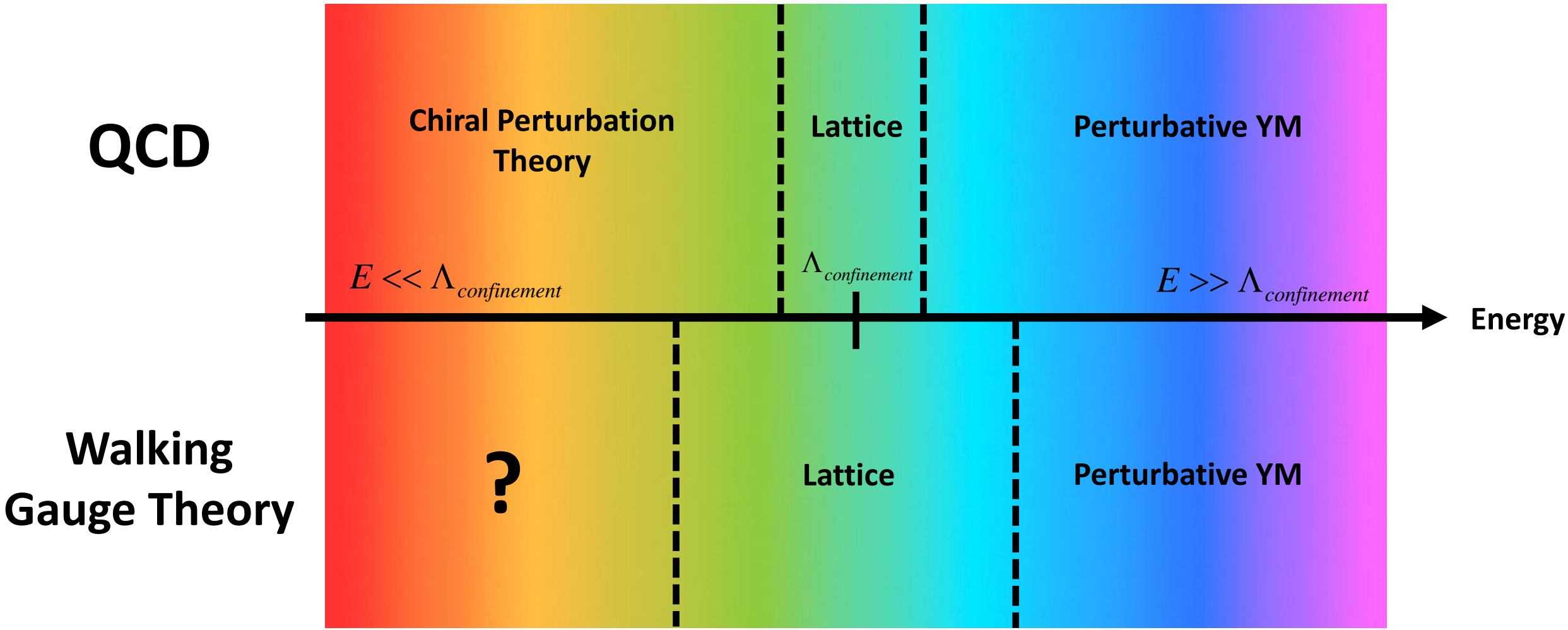
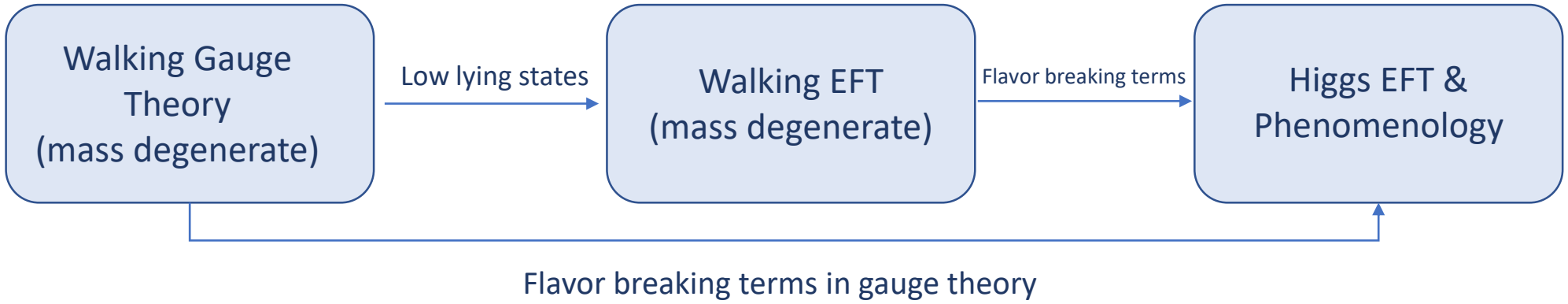
Confining Gauge Theories at High and Low Energies



Distinction between Walking EFT and Higgs EFT

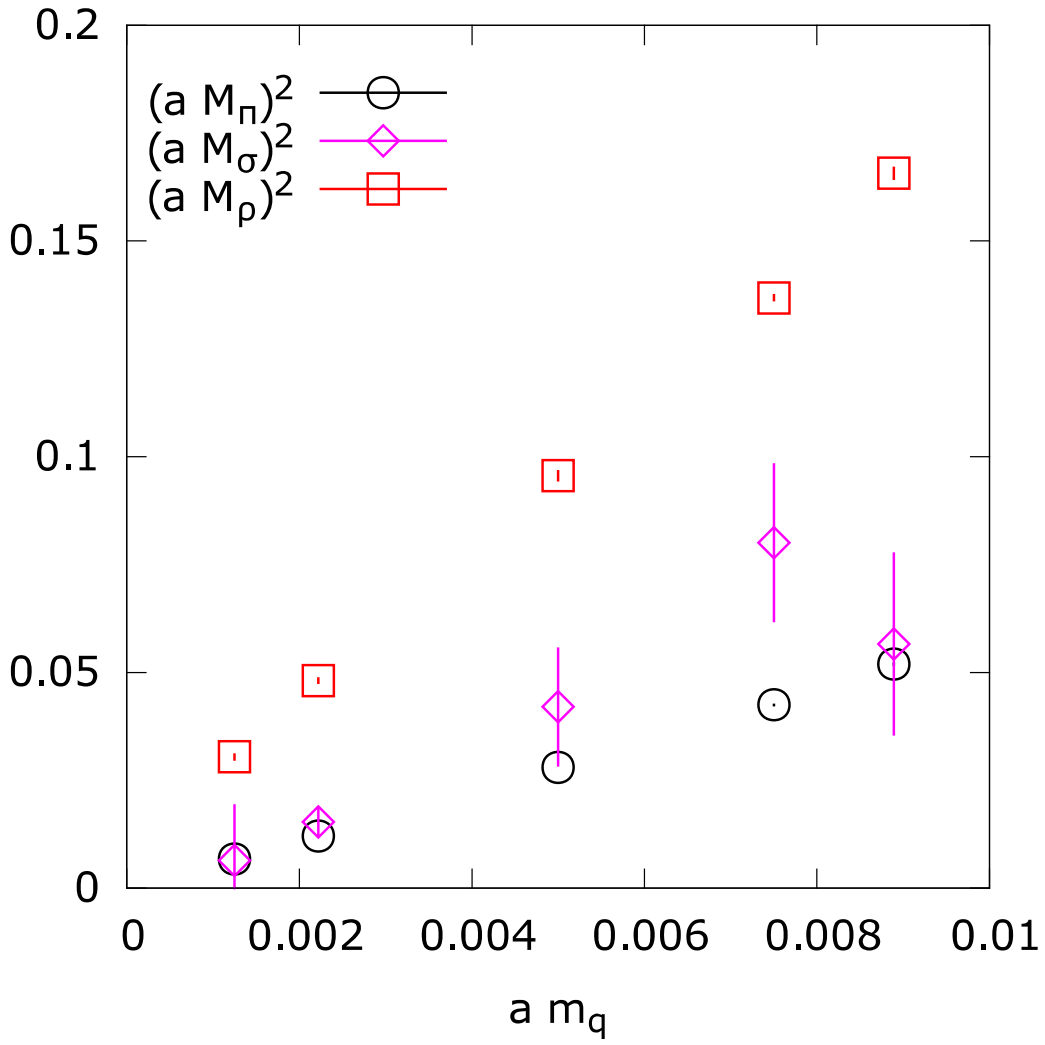
- To make connection to Standard Model, eventually have to break flavor groups down to Standard Model global symmetry
- Many walking theories have a large flavor group with many PNGBs [2]
- Some other walking models do not come with additional PNGBs. For example, “minimal composite Higgs” [3][4]



Spectrum of Nf=8 QCD and implications for EFT

- SU(3) gauge theory with 8 flavors in fundamental rep
  - Recent studies of 8f spectrum by latKMI [5] and LSD [1,2]
- Pions and Sigma nearly degenerate and well separated from the rho (and other heavier states, not shown)
- Sigma cannot be “integrated out” of effective theory at these distances from chiral limit
- Chiral extrapolations cannot be performed without EFT
  - Particularly important: $\frac{M_\sigma}{F_\pi}$
- Seek EFT description that is good up to next resonance, M_ρ
- Improved studies of systematic errors in 8f spectrum have been discussed in talk by George Fleming at 15:20 today
- The most recent progress on studying the sigma mass in 8f QCD has been discussed in talk by Enrico Rinaldi at 15:00 today

Data from [1,2]



Approximate Empirical Laws

- Light states adhere approximately to simple empirical laws:

$$M_\pi^2 = B_\pi m_q \quad F_\pi^2 = f_\pi^2 + B_f m_q \quad M_\sigma^2 = m_\sigma^2 + B_\sigma m_q$$

- In these mass ranges,

$$f_\pi^2 << B_f m_q$$

  - Expect significant qualitative changes when this inequality is saturated

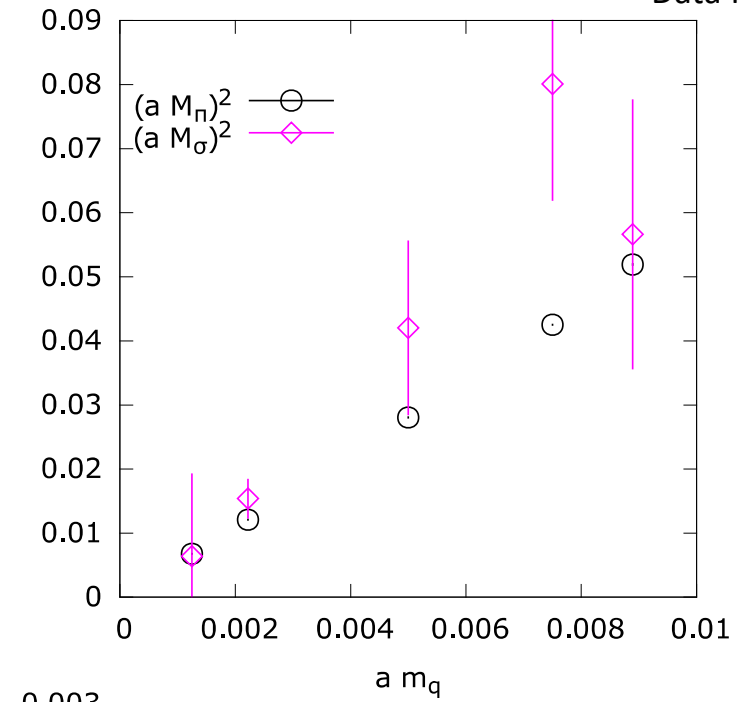
- Empirical “law” for sigma somewhay dubious because of large errors

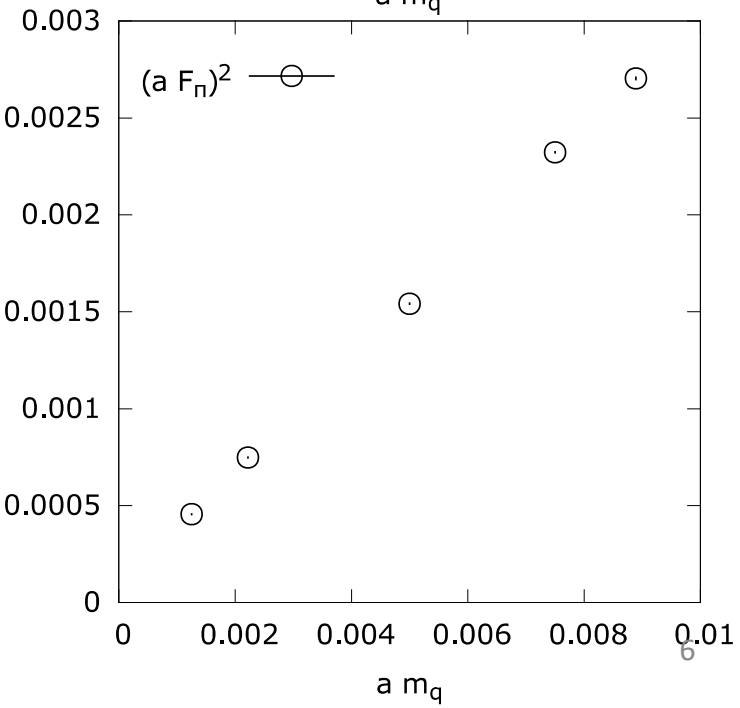
- Compare to LO Chiral Perturbation Theory

$$M_\pi^2 = B_\pi m_q \qquad F_\pi^2 = f_\pi^2$$

- XPT cannot reproduce significant linear behavior in decay constant
  - This was discussed in detail in proceedings [1]

Data from [1,2]

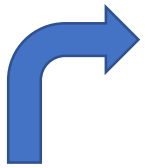




EFT approaches Beyond XPT for Walking Gauge Theories

	No Scale Symmetry	Scale Symmetry
No Special Multiplet	• XPT + Light Isosinglet Scalar [6,7] • Couplings between sigma and pions general • Many LECs, more difficult to constrain with limited lattice data	• "Dilatonic XPT" [8,9,10] • Sigma couples to XPT as a compensating field • Couplings between sigma and pions constrained by scale invariance • Recently tested against lattice data with promising initial results [11]

Linear Multiplet	• Linear Sigma EFT
	  • SU(N) formulation by Schechter and Ueda[12] for QCD
	  • This work: application to walking gauge theory
	• Pions and Sigma transform together under flavor group in linear multiplet
		• "Dilatonic Linear Sigma EFT"
		  • This work
		• Pions and Sigma transform together under flavor group in linear multiplet AND scale invariance is softly broken



THIS TALK

$SU_L(N_f)$x $SU_R(N_f)$ Linear Multiplet: Field Content

- Fields live in bifundamental representation: $M_a^{\bar{b}}$
  - $2N_f^2$ Real degrees of freedom
  - But one Goldstone degree of freedom must be excluded due to anomaly
- Transform Linearly under $SU_L(N_f)$x $SU_R(N_f)$: $M \rightarrow LMR^\dagger$
- Express degrees of freedom via a polar decomposition (CCWZ):

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

$T_a \in su(N_f)$

- Full symmetry is nonlinearly realized in this basis
- 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)

$SU_L(N_f) \times SU_R(N_f)$ Linear Multiplet: Lagrangian

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

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

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

Note:

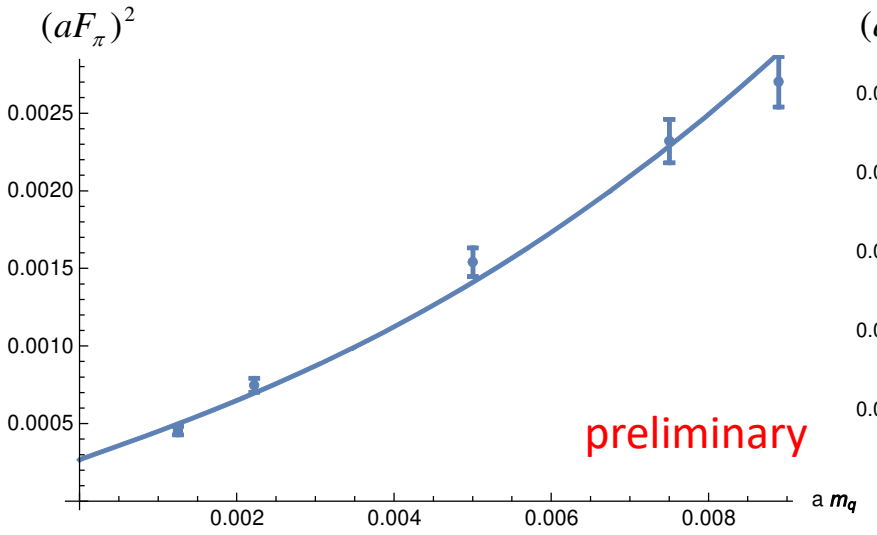
$$F_\pi = \frac{\langle 0|\sigma|0\rangle}{\sqrt{N_f}}$$

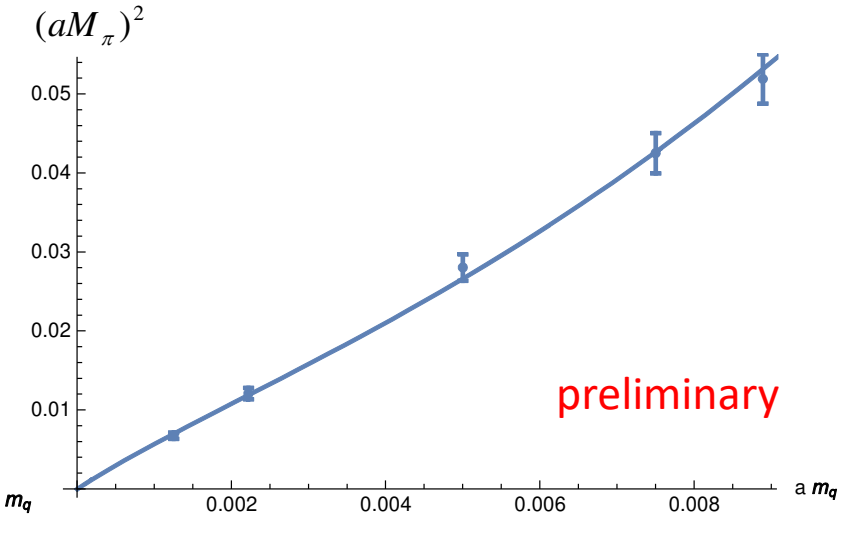
- Breaking potential determined by spurion analysis (similar to XPT)

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

$O(X^1,M^1)$ $O(X^1,M^3)$

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

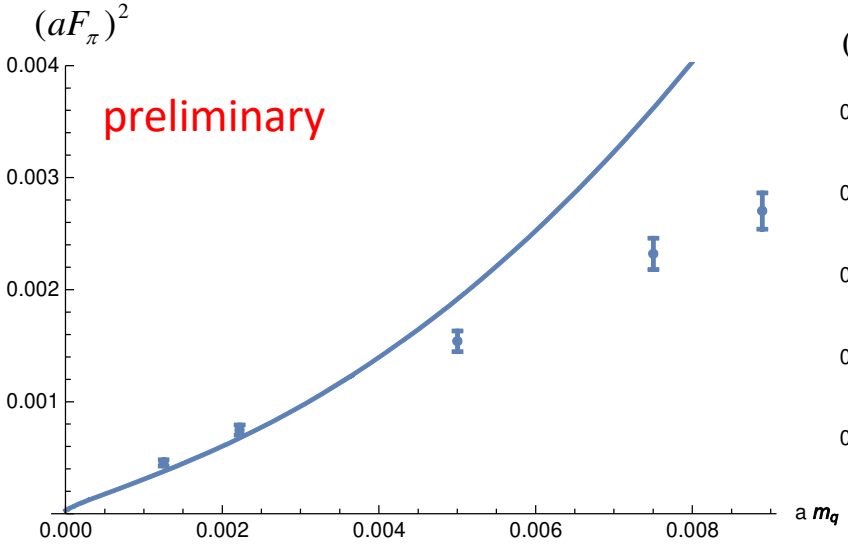


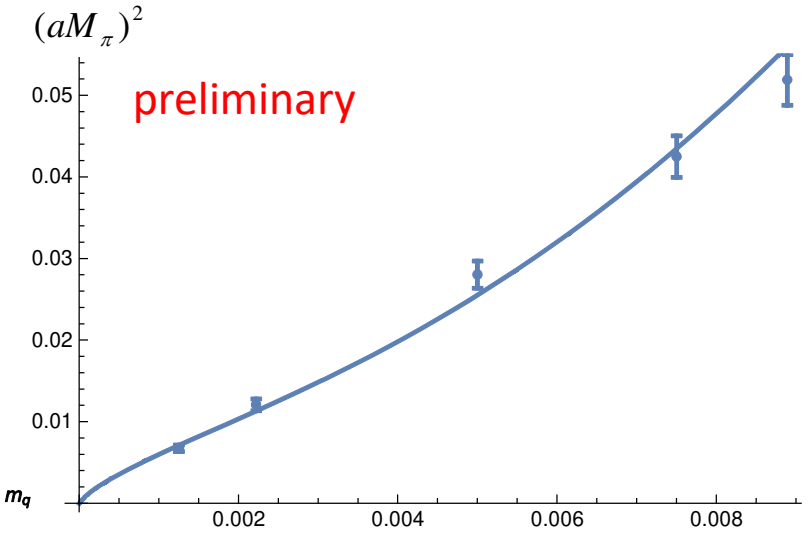


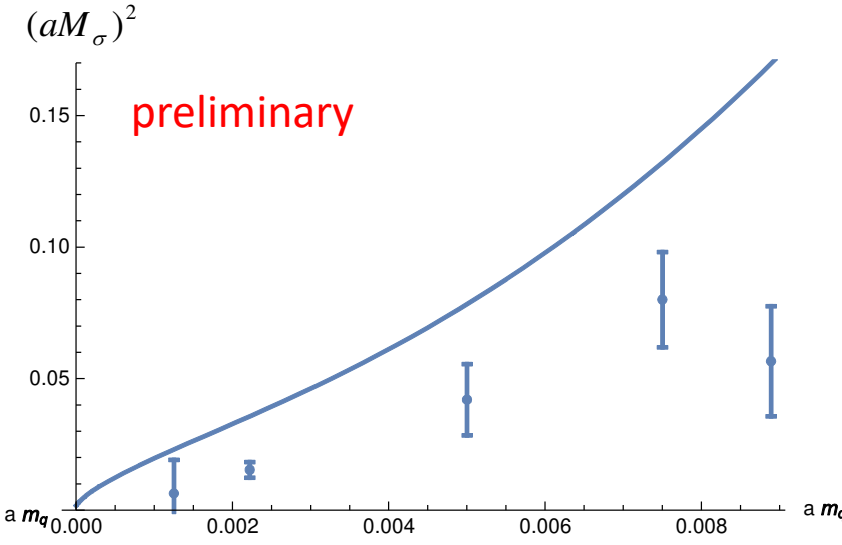
χ^2/dof = 1.2
With 3% Systematic Errors

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







Linear Multiplet + Scale Invariance: Lagrangian

- Write down most general action symmetric under flavor group, parity, and classical scale invariance, including only marginal operators

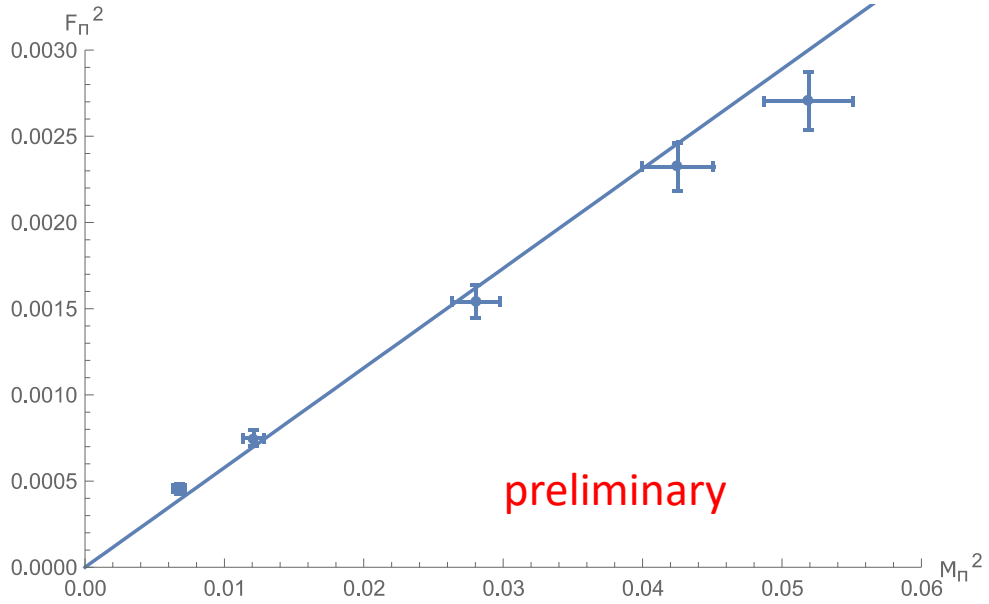
$$\mathcal{L}_{LSM} = \frac{1}{2}\left\langle \partial_\mu M \partial^\mu M^\dagger \right\rangle - V_0\left(M^\dagger M\right) - V_{SB}(M, \mathcal{M})$$

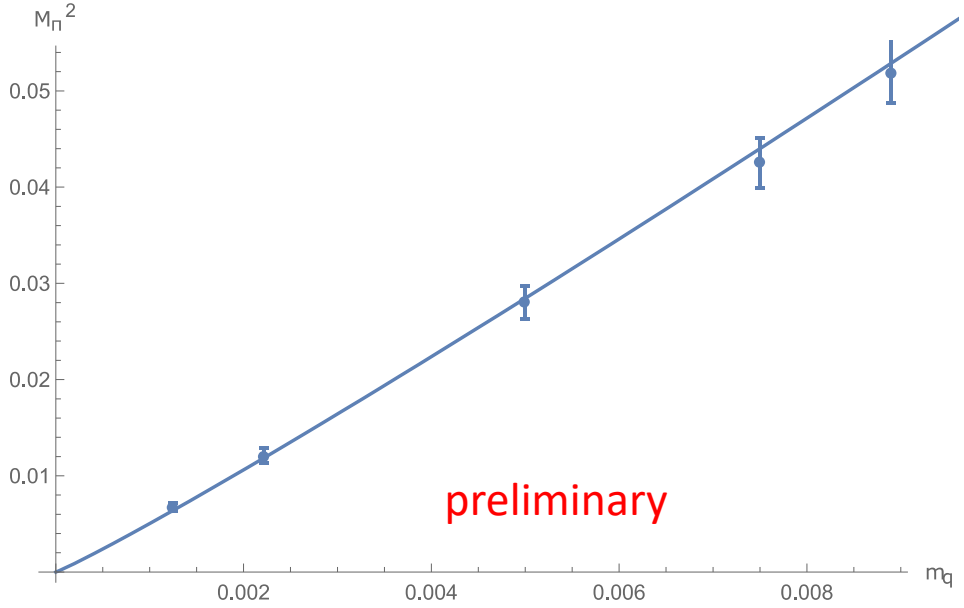
$$V_0 = \frac{m_\sigma^2 - m_a^2}{8f^2}\left\langle M^\dagger M \right\rangle^2 + \frac{N_f m_a^2}{8f^2}\left\langle \left(M^\dagger M\right)^2 \right\rangle$$

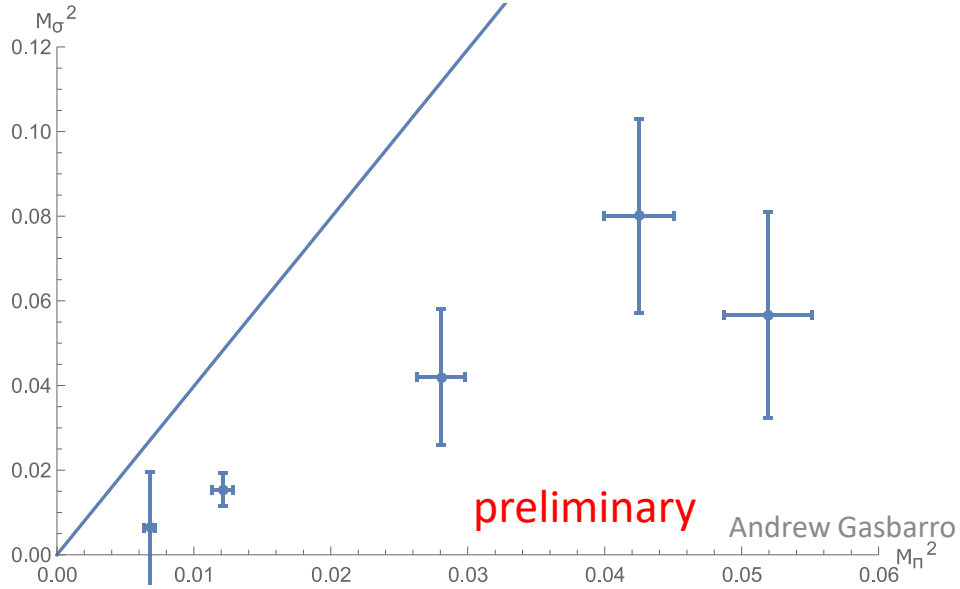
- Breaking potential determined by spurion analysis. Spurions transform under scale symmetry as well!

$$V_{SB} = -\frac{m_\sigma^2}{4}\left\langle M^\dagger M \right\rangle + f\left(\frac{\left\langle M^\dagger M \right\rangle}{f^2}\right)^b \left\langle X^\dagger M + X M^\dagger \right\rangle$$

Fits of F_π , M_π ,and M_σ to scale invariant linear sigma, tree level







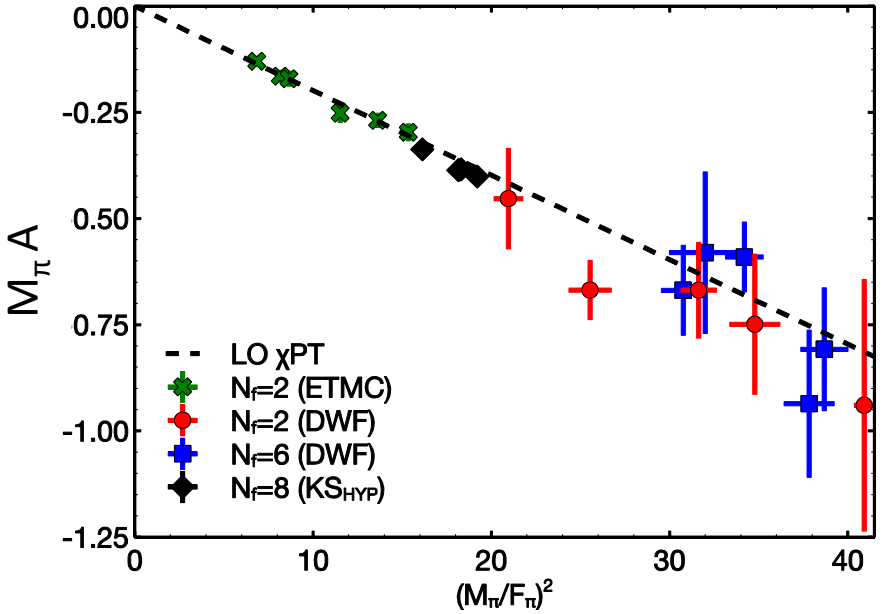
χ^2/dof = 7.5
With 3% Systematic Errors

More Information from Pion Scattering

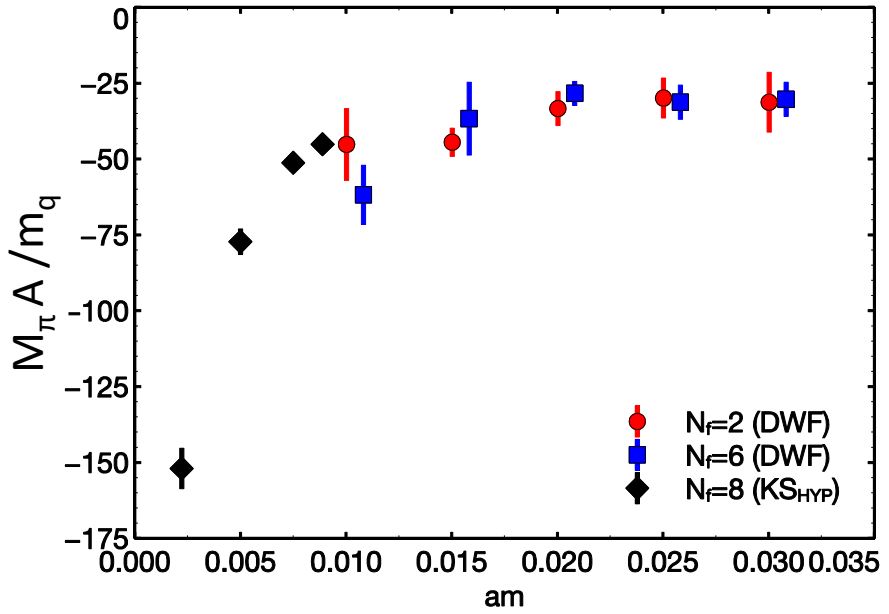
- Scattering length agrees well with LO XPT when plotted against physical (computed) values of M_π/F_π

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

- Plotted against bare quark mass, very poor agreement with LO XPT
- Scattering data in process of being analyzed with various EFT options



Ref [1]



Ref [1]

Conclusions & Outlook

- Linear Sigma EFT provides significant improvement over XPT in fitting PNGB data, F_π and M_π
- Tree level expressions do not provide good combined fit to F_π , M_π and M_σ
  - Loops may not be negligible
- More work being done on the lattice to further constrain EFT
  - Pion scattering
  - Form factors (in progress)

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Backup Slides

An Initial Analysis: Fitting to XPT

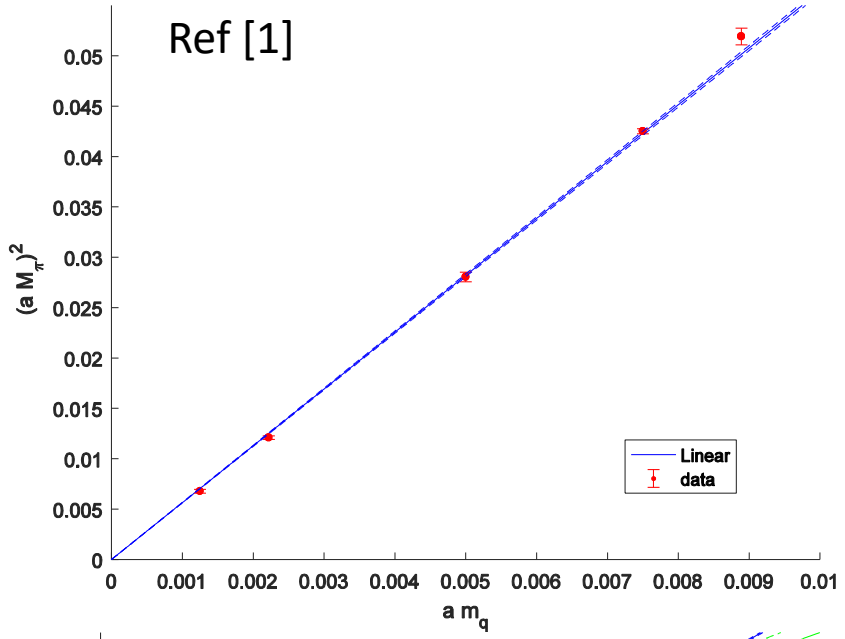
- At leading order in Chiral Perturbation Theory

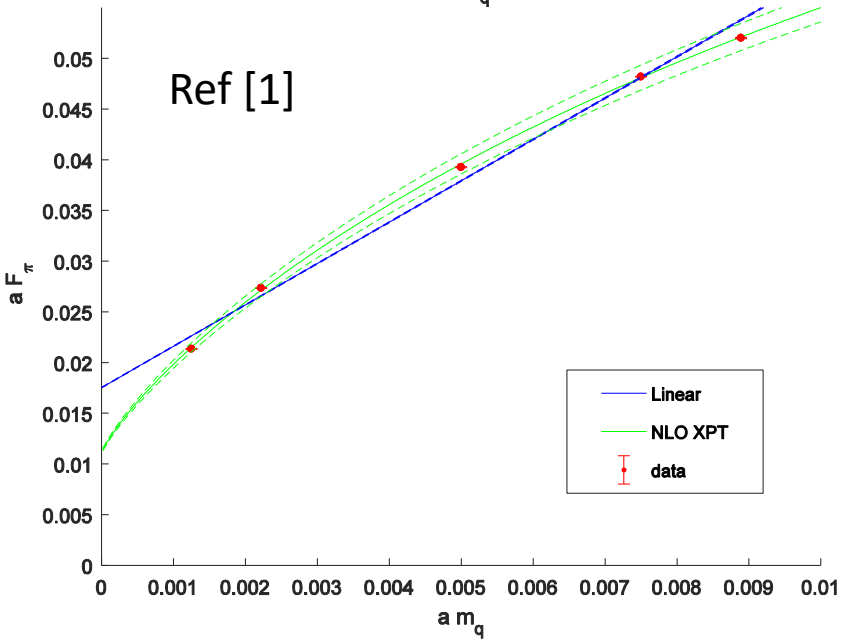
$$M_\pi^2 = 2Bm_q \qquad F_\pi = F \ \text{(constant)}$$

  - 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

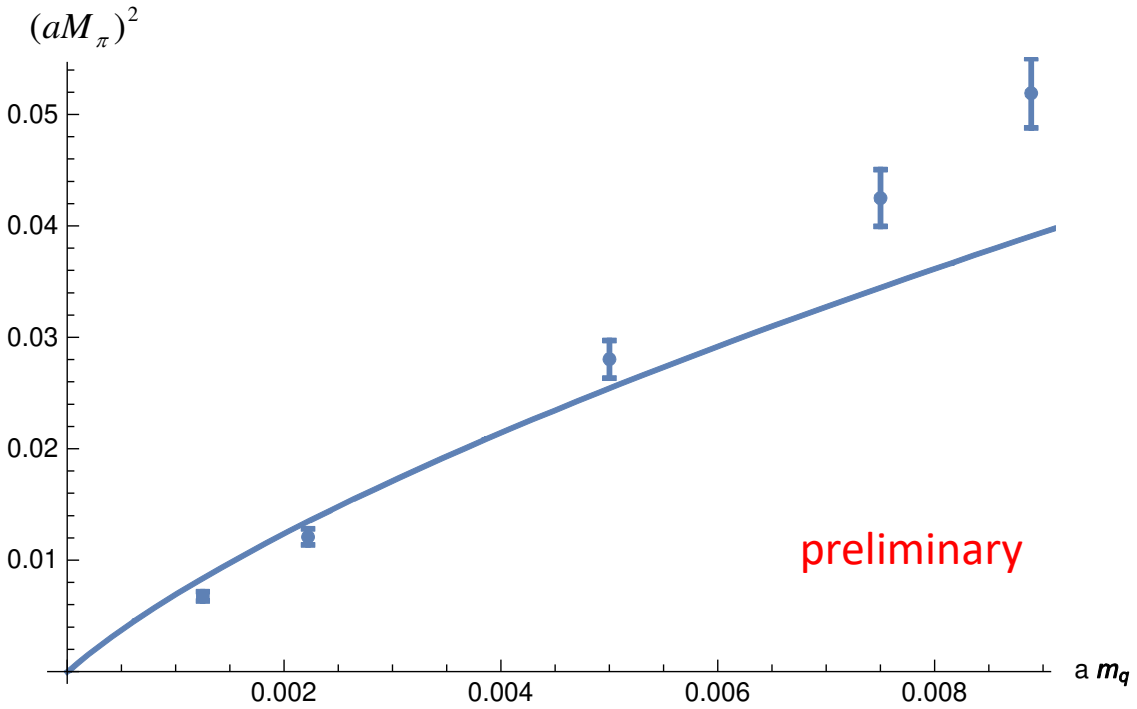
$$\frac{2N_f Bm_q}{(4\pi F)^2} \approx 5.8$$

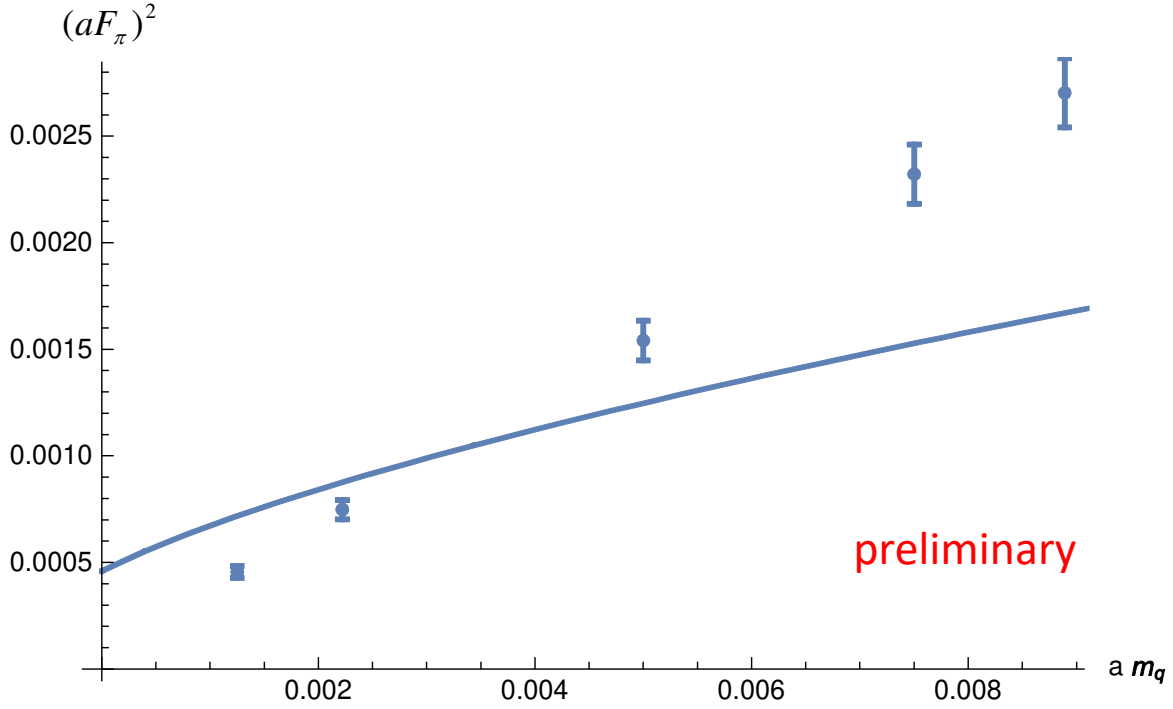
- Incompatibility with XPT was pointed earlier in Nf=6 study [14]





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

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.

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

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

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