Strongly-Coupled Signatures through WW Scattering

Presented by
Michael I. Buchoff

Lawrence Livermore National Lab

With the
LSD Collaboration

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Lattice Strong Dynamics Collab.

(as of Oct. 4, 2011)

Argonne	Heechang Na, James Osborn
Berkeley	Sergey Syritsyn
Boston	Ron Babich, Richard Brower, Michael Cheng, Claudio Rebbi, Oliver Witzel
Colorado	David Schaich
Fermilab	Ethan Neil
Harvard	Mike Clark
Livermore	MIB, Pavlos Vranas, Joe Wasem
UC Davis	Joe Kiskis
Washington	Saul Cohen
Yale	Tom Appelquist, George Fleming, Meifeng Lin, Gennady Voronov

Primary Questions (as of Today)

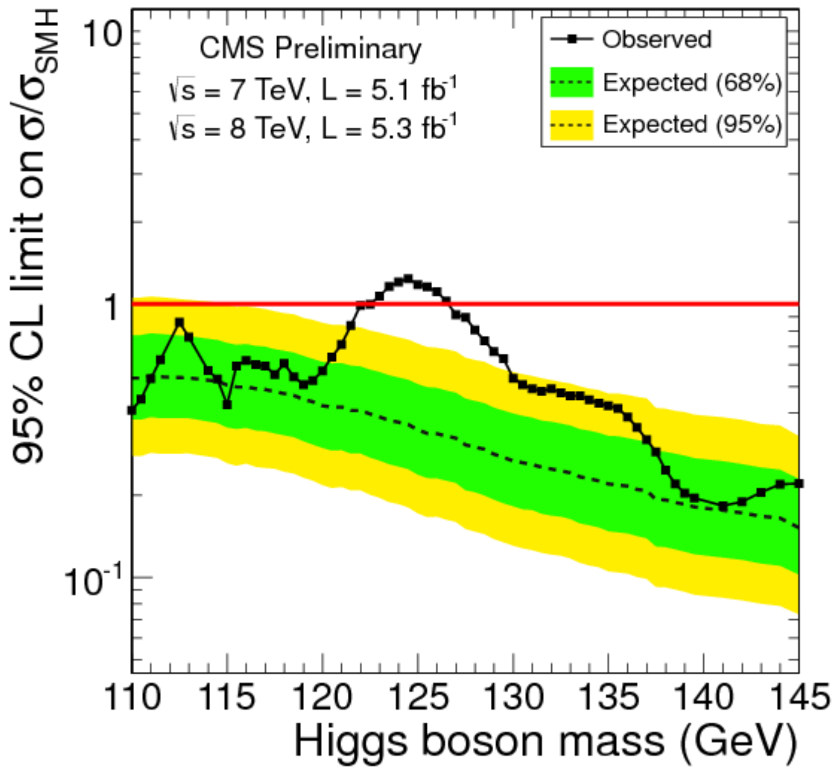
In light of LHC discovery...
how viable is technicolor?

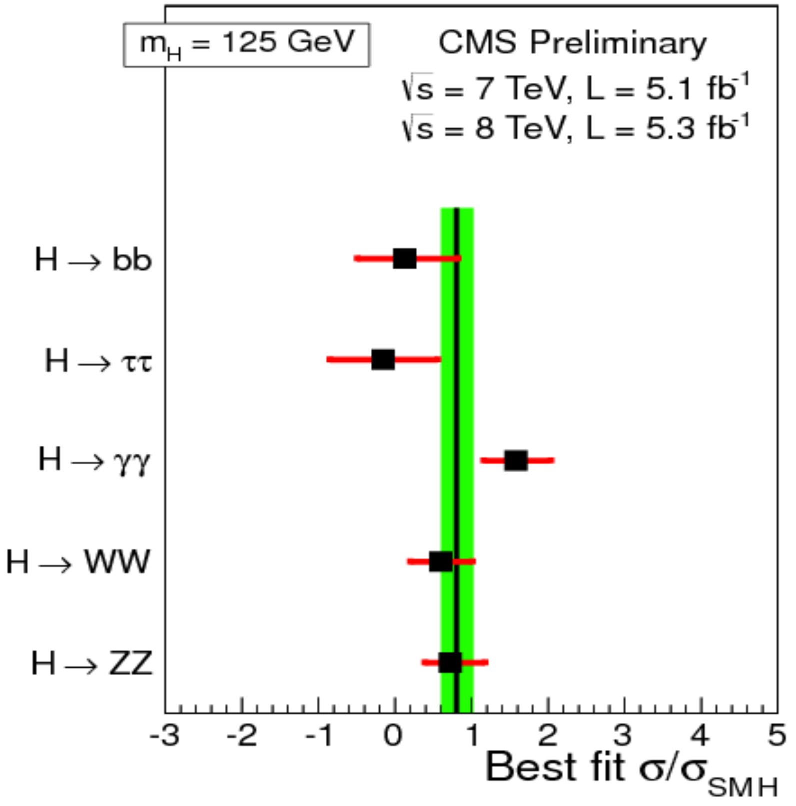
Using the lattice, which channels
can composite EW breaking be tested?

What is the best strategy to address
these questions?

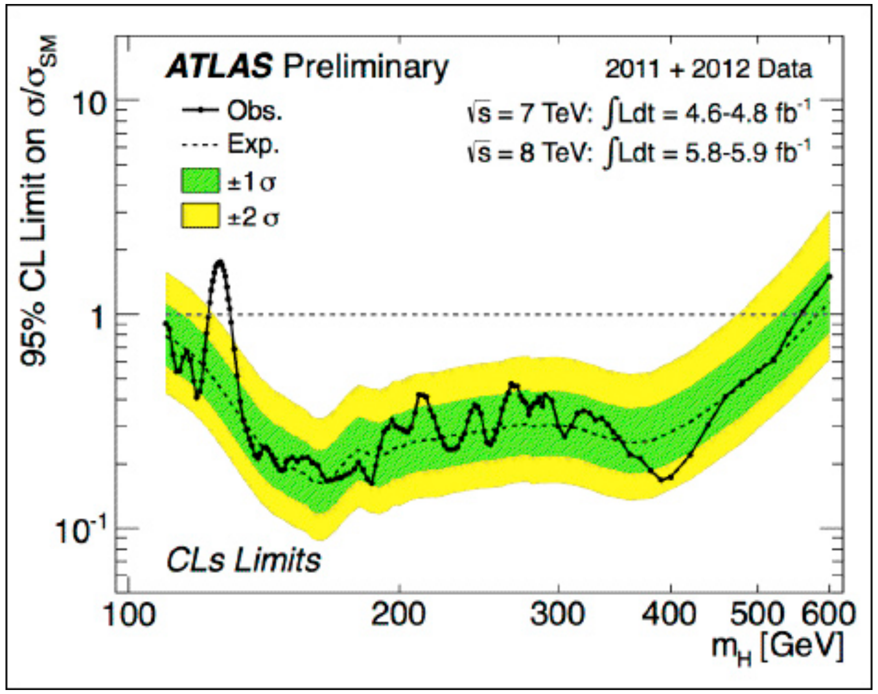
LHC Discovery

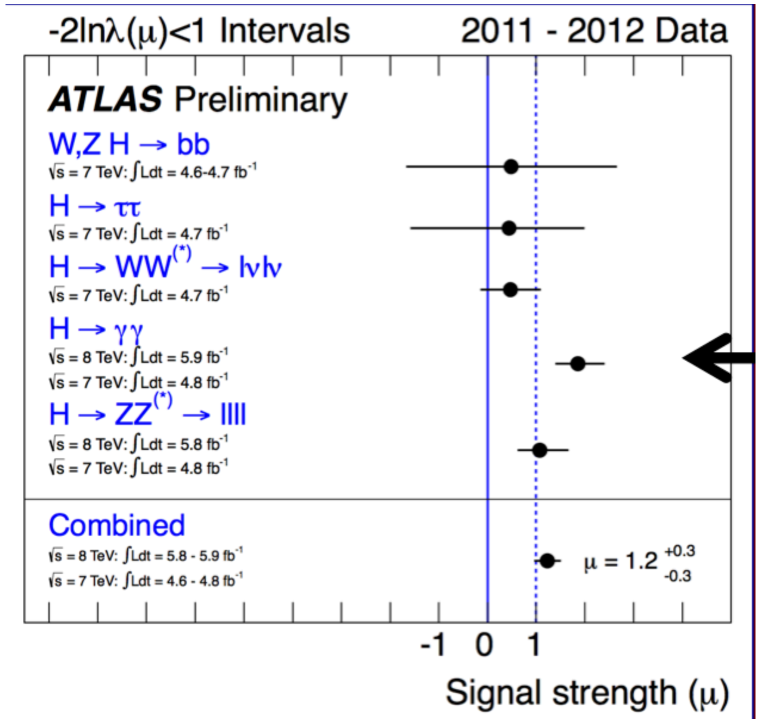
CMS:





ATLAS:





Both experiments consistent with ~125 GeV scalar

Implications for technicolor?

$$\boxed{\frac{m_{0^{++}}}{f_\pi} \sim 0.5}$$

$$\frac{m_{0^{++}}}{f_\pi} \sim 5 \quad \text{for QCD}$$

Very restrictive...two theoretical possibilities:

1. "Pseudo-dilaton" near conformal window

$$m_{0^{++}} \sim \frac{(N_f - N_f^c)}{N_c}$$

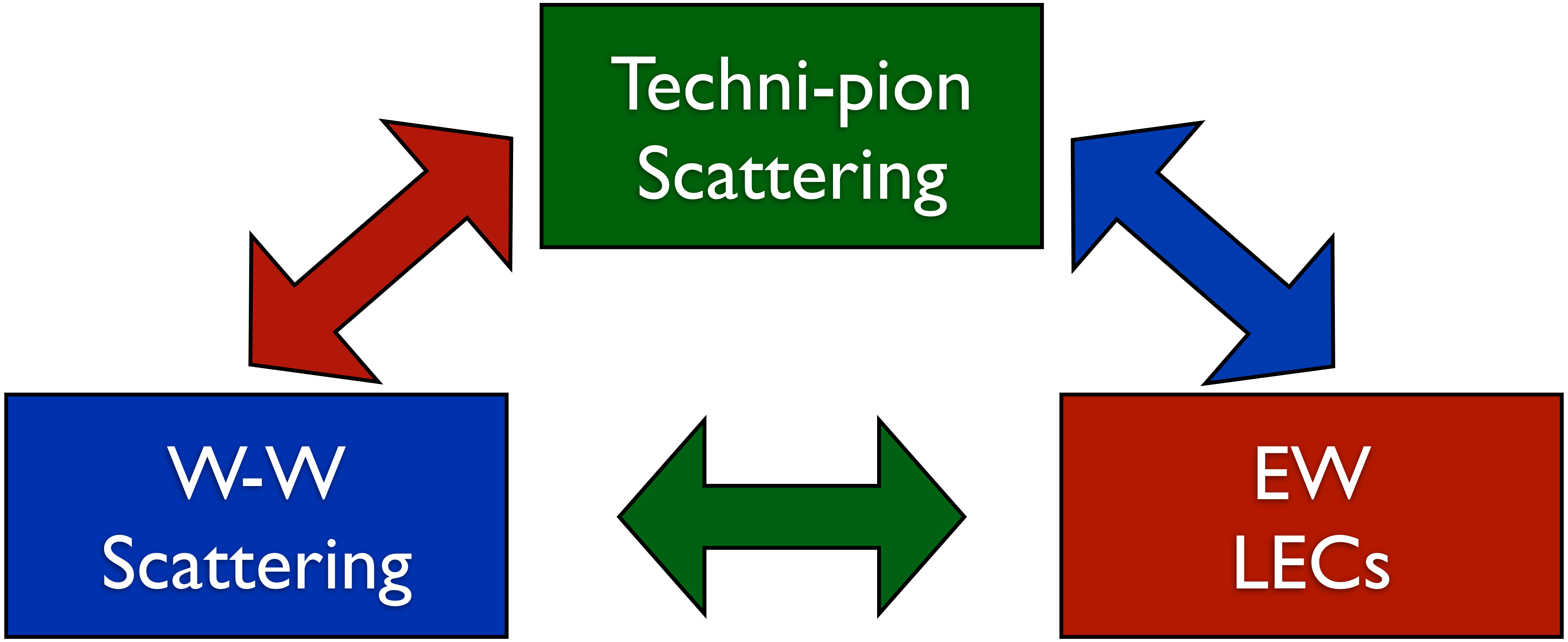
2. Scalar, Goldstone di-quark in real/pseudo-real rep.

- Need ext. sector to violate techni-baryon number?

Classic Question

Using the lattice, which channels can composite EW breaking be tested?

Goal: Address this question using pion scattering as probe



Techni-pion Scattering

W-W Scattering

EW LECs

Why WW Scattering?

- Central to perturbative unitarity question

Longitudinal Modes:

$$\mathcal{A}(W_L^+ W_L^- \to W_L^+ W_L^-) \simeq \frac{g^2}{4m_W^2}(s+t) \sim E^2$$

Perturbative unitarity breaks down: $\sqrt{s} \lesssim 2.2 \text{ TeV}$

Two possibilities:

1) New particles emerge that protect perturbative unitarity

2) New strong dynamics emerge (ala QCD)

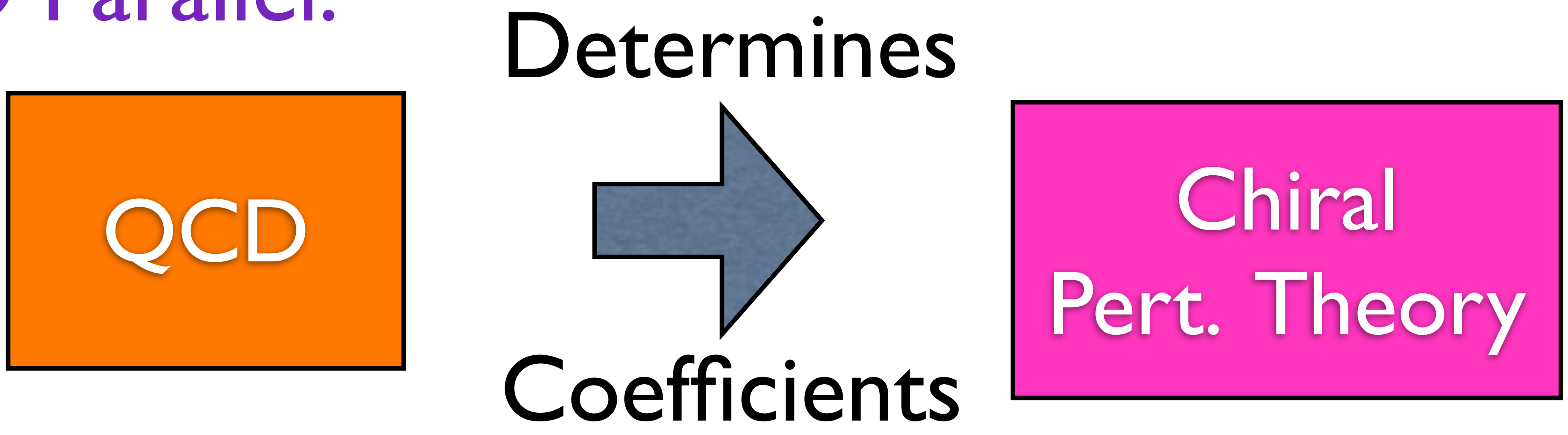
- Pion-pion scattering unitarized by excited states, resonances, etc.

Our approach to WW

Effective Field Theory

(other approaches include Equivalence Theorem, etc.)

QCD Parallel:



QCD

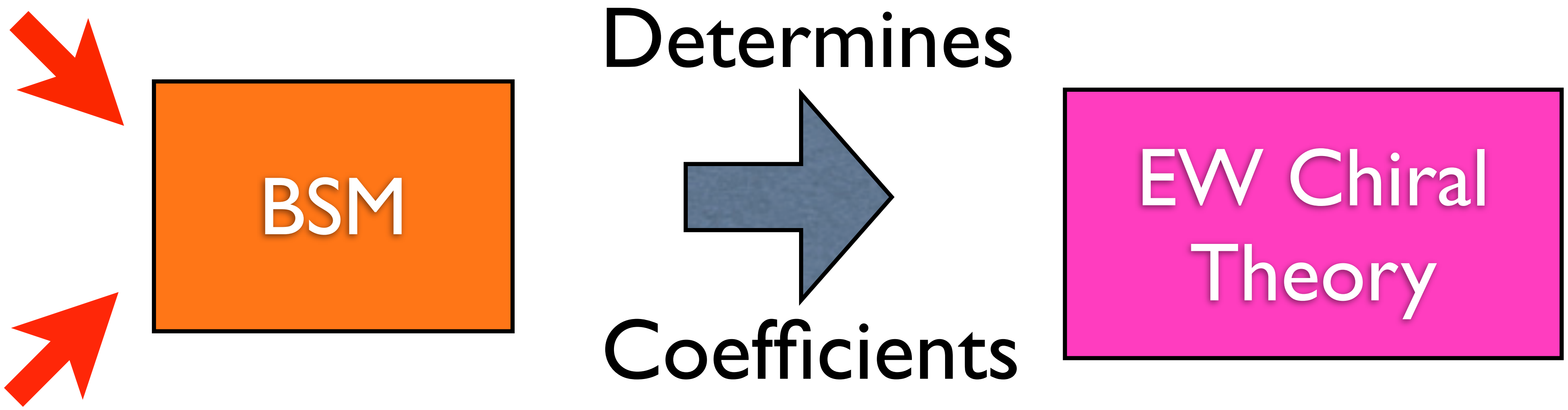
Determines

Coefficients

Chiral Pert. Theory

(known d.o.f.: pions, kaons, etc.)

BSM:



BSM

Determines

Coefficients

EW Chiral Theory

(known d.o.f.: W, Z, etc.)

Hadronic Chiral Lagrangian

EFT of Hadronic scale physics resulting from QCD

Include all terms that respect: $SU(2)_L \otimes SU(2)_R$

$$\mathcal{L}_{LO} = \frac{f^2}{4} \mathrm{tr}\left[(\partial_\mu U)^\dagger (\partial^\mu U) + \chi_+\right]$$

$$\mathcal{L}_{NLO} = \frac{\ell_1}{4}[\mathrm{tr}(V_\mu V^\mu)]^2 + \frac{\ell_2}{4}[\mathrm{tr}(V_\mu V_\nu)]^2 + \frac{\ell_3}{16}\mathrm{tr}(\chi_+)^2 + \frac{\ell_4}{4}\mathrm{tr}(V_\mu V^\mu \chi_+)$$

$$U = \exp\left(\frac{i\vec{\tau}\cdot\vec{\pi}}{f}\right) \qquad V_\mu = (\partial_\mu U)U^\dagger$$

$$\chi_+ = U^\dagger \chi U^\dagger + U\chi^\dagger U \qquad \chi = 2Bm\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix}$$

Electroweak Chiral Lagrangian

EFT of EW scale physics resulting from TeV scale physics

Include all terms that respect: $SU(2)_L \otimes U(1)_Y$

At leading order: (Quite Simple)

$$\mathcal{L}_{LO} = \frac{f^2}{4}\mathrm{tr}\left[(D_\mu U)^\dagger (D^\mu U)\right] - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{2}\mathrm{tr}W_{\mu\nu}W^{\mu\nu} + \frac{1}{4}\beta_1 g^2 f^2 [\mathrm{tr}(TV_\mu)]^2$$

$$D_\mu U = \partial_\mu U + ig\frac{\vec{\tau}}{2}\cdot\vec{W}_\mu U - ig' U\frac{\tau_3}{2}B_\mu$$

$$T = U\tau_3 U^\dagger \qquad V_\mu = (D_\mu U)U^\dagger$$

Electroweak Chiral Lagrangian

EFT of EW scale physics resulting from TeV scale physics

Include all terms that respect: $SU(2)_L \otimes U(1)_Y$

At leading order: (Quite Simple)

Higgs VEV

$$\mathcal{L}_{LO} = \frac{\boxed{f^2}}{4}\mathrm{tr}\left[(D_\mu U)^\dagger (D^\mu U)\right] - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{2}\mathrm{tr}W_{\mu\nu}W^{\mu\nu} + \frac{1}{4}\beta_1 g^2 f^2 [\mathrm{tr}(TV_\mu)]^2$$

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Electroweak Chiral Lagrangian

EFT of EW scale physics resulting from TeV scale physics

Include all terms that respect: $SU(2)_L \otimes \underset{SU(2)_C}{\cancel{U(1)_Y}}$

Higgs VEV

At leading order: (Quite Simple)

$$\mathcal{L}_{LO} = \frac{\boxed{f^2}}{4}\mathrm{tr}\left[(D_\mu U)^\dagger (D^\mu U)\right] - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{2}\mathrm{tr}W_{\mu\nu}W^{\mu\nu}$$

$$+ \cancel{\frac{1}{4}\beta_1 g^2 f^2 [\mathrm{tr}(TV_\mu)]^2}$$

Custodial-violating term

$$D_\mu U = \partial_\mu U + ig\frac{\vec{\tau}}{2}\cdot\vec{W}_\mu U - ig' U\frac{\tau_3}{2}B_\mu$$

$$T = U\tau_3 U^\dagger \qquad V_\mu = (D_\mu U)U^\dagger$$

Electroweak Chiral Lagrangian

EFT of EW scale physics resulting from TeV scale physics

Include all terms that respect: $SU(2)_L \otimes U(1)_Y$

At leading order: f β_1

At NLO: α_1-α_5 α_6-α_{11}

$\frac{1}{2}\alpha_1 g g' B_{\mu\nu} \mathrm{tr}(T W^{\mu\nu})$ $\frac{1}{4}\beta_1 g^2 f^2 [\mathrm{tr}(T V_\mu))$ $\frac{1}{4}\alpha_8 g^2 [\mathrm{tr}(T W_{\mu\nu})]^2$

$S \sim \alpha_1$ $T \sim \beta_1$ $U \sim \alpha_8$

Dominant terms in WW: (other coefficients experimentally bound/small)

$\alpha_4 [\mathrm{tr}(V_\mu V_\nu)]^2$ $\alpha_5 [\mathrm{tr}(V_\mu V^\mu)]^2$

Electroweak Chiral Lagrangian

EFT of EW scale physics resulting from TeV scale physics

Include all terms that respect: $SU(2)_L \otimes \xcancel{U(1)_Y}$

$SU(2)_C$

At leading order: f $\xcancel{\beta_1}$

At NLO: α_1-α_5 $\xcancel{\alpha_6\text{-}\alpha_{11}}$

$$\frac{1}{2}\alpha_1 g g' B_{\mu\nu}\mathrm{tr}(TW^{\mu\nu}) \qquad \frac{1}{4}\beta_1 g^2 f^2[\mathrm{tr}(TV_\mu)) \qquad \frac{1}{4}\alpha_8 g^2[\mathrm{tr}(TW_{\mu\nu})]^2$$

$$S \sim \alpha_1 \qquad T \sim \beta_1 \qquad U \sim \alpha_8$$

Dominant terms in WW: (other coefficients experimentally bound/small)

$$\alpha_4[\mathrm{tr}(V_\mu V_\nu)]^2 \qquad \alpha_5[\mathrm{tr}(V_\mu V^\mu)]^2$$

Hadron-EW Connection

Hadronic EFT

One Doublet

EW EFT

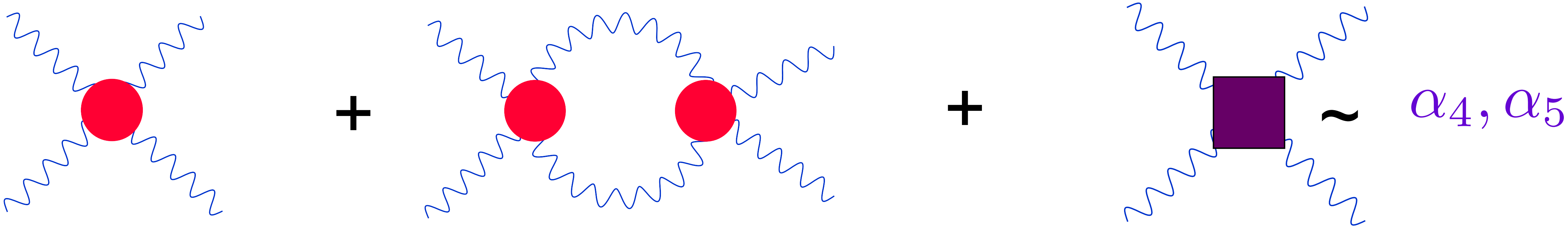
$m_d \to 0$

$$\alpha_5 = \frac{\ell_1}{4} + \mathcal{O}(g)$$

$$\alpha_4 = \frac{\ell_2}{4} + \mathcal{O}(g)$$

$g, g' \to 0$

$$\frac{f^2}{4}\mathrm{tr}(\partial_\mu U^\dagger \partial^\mu U) + \alpha_5\left[\mathrm{tr}(\partial_\mu U^\dagger \partial^\mu U)\right]^2 + \alpha_4\left[\mathrm{tr}(\partial_\mu U^\dagger \partial_\nu U)\right]^2$$



$\mathcal{O}(g^2)$ $\mathcal{O}(g^4)$ $\mathcal{O}(g^4)$

Hadron-EW Connection

Hadronic EFT

Multiple Flavors

EW EFT

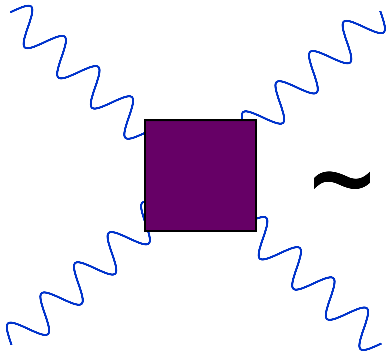
$m_d \to 0$

$p^2 \ll M_{ds}^2, M_{ss}^2$

$g, g' \to 0$

$p^2 \ll M_{ds}^2, M_{ss}^2$

$$\frac{f^2}{4}\mathrm{tr}(\partial_\mu U^\dagger \partial^\mu U) + \alpha_5 \left[\mathrm{tr}(\partial_\mu U^\dagger \partial^\mu U)\right]^2 + \alpha_4 \left[\mathrm{tr}(\partial_\mu U^\dagger \partial_\nu U)\right]^2$$



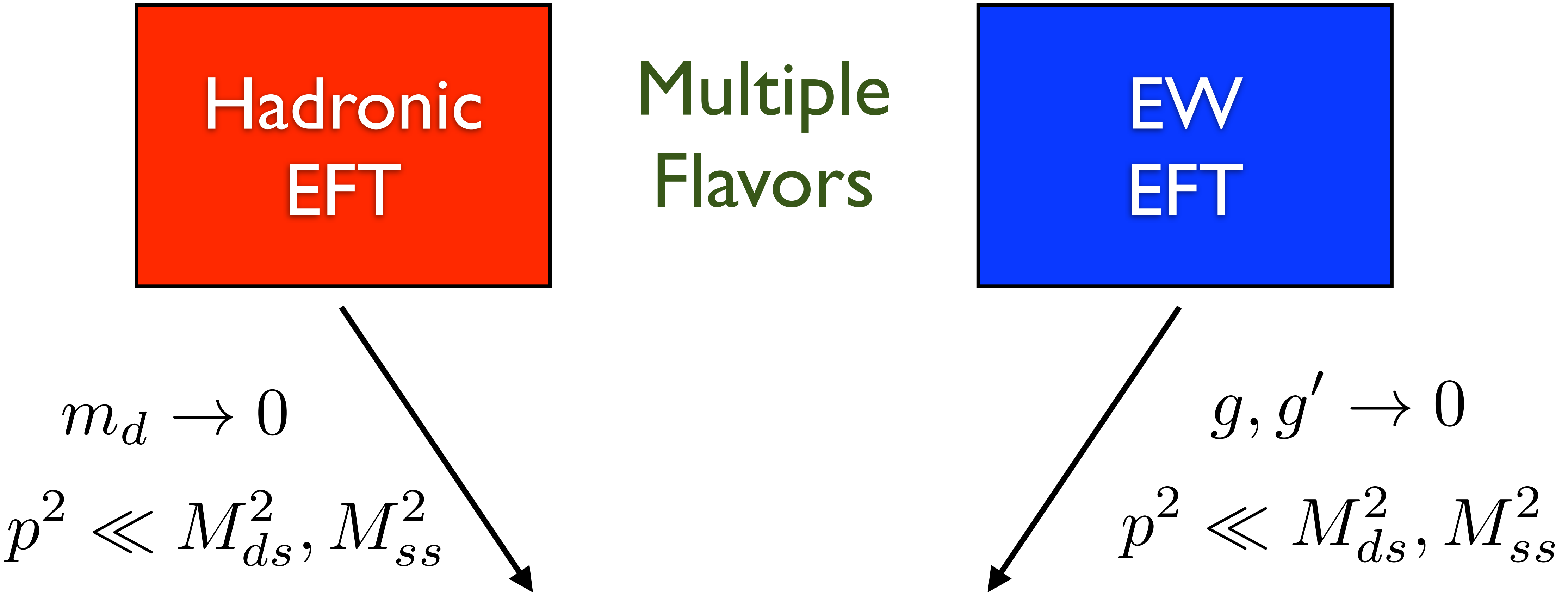
$\sim$ α_4, α_5

$\mathcal{O}(g^4)$

$$\alpha_5 = \frac{\ell_1}{4} + \mathcal{O}(g)$$

$$\alpha_4 = \frac{\ell_2}{4} + \mathcal{O}(g)$$

Hadron-EW Connection



Hadronic EFT

Multiple Flavors

EW EFT

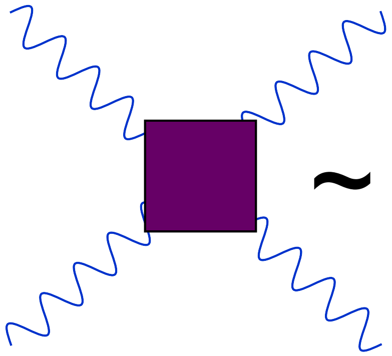
$m_d \to 0$

$p^2 \ll M_{ds}^2, M_{ss}^2$

$g, g' \to 0$

$p^2 \ll M_{ds}^2, M_{ss}^2$

$$\frac{f^2}{4}\mathrm{tr}(\partial_\mu U^\dagger \partial^\mu U) + \alpha_5 \left[\mathrm{tr}(\partial_\mu U^\dagger \partial^\mu U)\right]^2 + \alpha_4 \left[\mathrm{tr}(\partial_\mu U^\dagger \partial_\nu U)\right]^2$$



$\sim \alpha_4, \alpha_5$

$\mathcal{O}(g^4)$

$$\alpha_5 = \frac{\ell_1}{4} + \boxed{\mathcal{O}(g)}$$

$$\alpha_4 = \frac{\ell_2}{4} + \boxed{\mathcal{O}(g)}$$

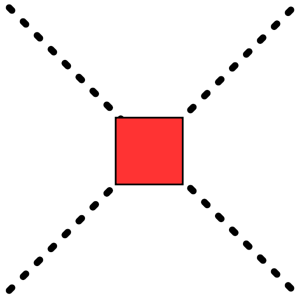
Interesting implication:

Direct probe of strong dynamics!!!

LEC Scale Scorecard

$\widetilde{\alpha}_{4,5}(M_H, M_{ds}):$

1) $\frac{\ell_{1,2}(\mu, M_{ds})}{4}$



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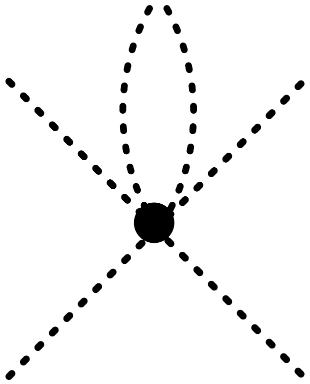
Integrated-out flavors

+

2) $-\frac{1}{384\pi^2}\log\frac{M_H^2}{\mu^2}$



+

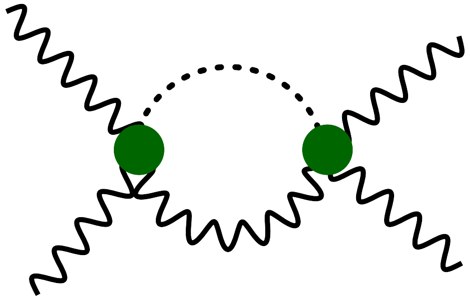
Eaten W and Z

$\sim \log\frac{M_{dd}^2}{\mu^2}$

$\sim \log\frac{M_H^2}{M_{dd}^2}$

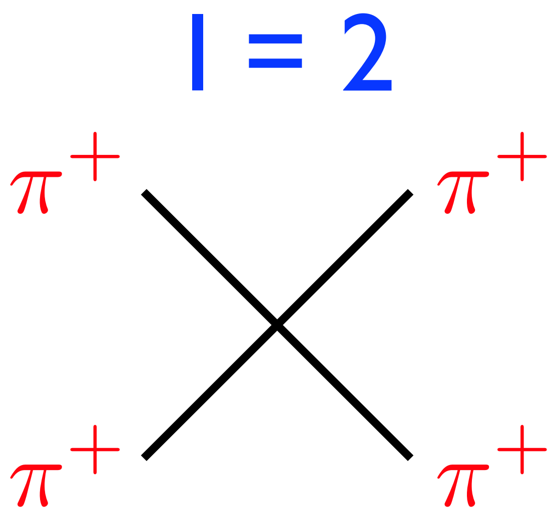
-

3) $\mathcal{O}(10^{-3})$



Pi-Pi Scattering

- Cleanest and most understood hadronic scattering process: theoretically, experimentally, and numerically



Weinberg 1966: **LO Prediction**

$$m_\pi a_{\pi\pi}^{I=2} = -\frac{m_\pi^2}{8\pi f_\pi^2}$$

Gasser and Leutwyler 1985: **NLO Prediction**

$$m_\pi a_{\pi\pi}^{I=2} = -\frac{m_\pi^2}{8\pi f_\pi^2}\left\{1 + \frac{m_\pi^2}{16\pi^2 f_\pi^2}\left[3\log\left(\frac{m_\pi^2}{\mu^2}\right) - 1 - \ell_{\pi\pi}^{I=2}(\mu)\right]\right\}$$

Many Flavor Scattering

Bijnens, Lu 2011: *"Maximal Isospin"*

$$M_P a_{PP} = -\frac{M_P^2}{8\pi F_P^2}\left\{1 + \frac{M_P^2}{16\pi F_P^2}\left[\frac{4(1 - N_F + N_F^2)}{N_F^2}\ln\frac{M_P^2}{\mu^2} - \frac{4(N_F - 1)}{N_F^2} - L_{PP}(\mu)\right]\right\}$$

$$L_{PP} = 512\pi^2(L_0 + 2L_1 + 2L_2 + L_3 - 2L_4 - L_5 + 2L_6 + L_8)$$

Key Points:

1) No explicit flavor dependence in L_{PP}

2) Reduces to two flavor result via matching conditions

$$\ell_1^r(\mu, M_{ds}) = -2L_0^r(\mu) + 4L_1^r(\mu) + 2L_3^r(\mu) + \frac{2 - N_f}{24(32\pi^2)}\log\frac{M_{ds}^2}{\mu^2}$$

$$\ell_2^r(\mu, M_{ds}) = 4L_0^r(\mu) + 4L_2^r(\mu) + \frac{2 - N_f}{12(32\pi^2)}\log\frac{M_{ds}^2}{\mu^2}$$

Many Flavor Scattering

Bijnens, Lu 2011: *"Maximal Isospin"*

$$M_P a_{PP} = -\frac{M_P^2}{8\pi F_P^2}\left\{1 + \frac{M_P^2}{16\pi F_P^2}\left[\frac{4(1-N_F+N_F^2)}{N_F^2}\ln\frac{M_P^2}{\mu^2} - \frac{4(N_F-1)}{N_F^2} - L_{PP}(\mu)\right]\right\}$$

$$L_{PP} = 512\pi^2(L_0 + 2L_1 + 2L_2 + L_3 - 2L_4 - L_5 + 2L_6 + L_8)$$

Key Points:

1) No explicit flavor dependence in L_{PP}

- Can compare different flavor theories directly!!

2) Reduces to two flavor result via matching conditions

$$\ell_1^r(\mu, M_{ds}) = -2L_0^r(\mu) + 4L_1^r(\mu) + 2L_3^r(\mu) + \frac{2-N_f}{24(32\pi^2)}\log\frac{M_{ds}^2}{\mu^2}$$

$$\ell_2^r(\mu, M_{ds}) = 4L_0^r(\mu) + 4L_2^r(\mu) + \frac{2-N_f}{12(32\pi^2)}\log\frac{M_{ds}^2}{\mu^2}$$

Lattice Details

10 DWF Ensembles:

- 32^3 x 64 x 16 lattices

$$am_\rho \sim \frac{1}{5}$$

2 flavor: m_q = 0.010 - 0.030

6 flavor: m_q = 0.010 - 0.030

Note: Neither theory expected to yield light enough scalar

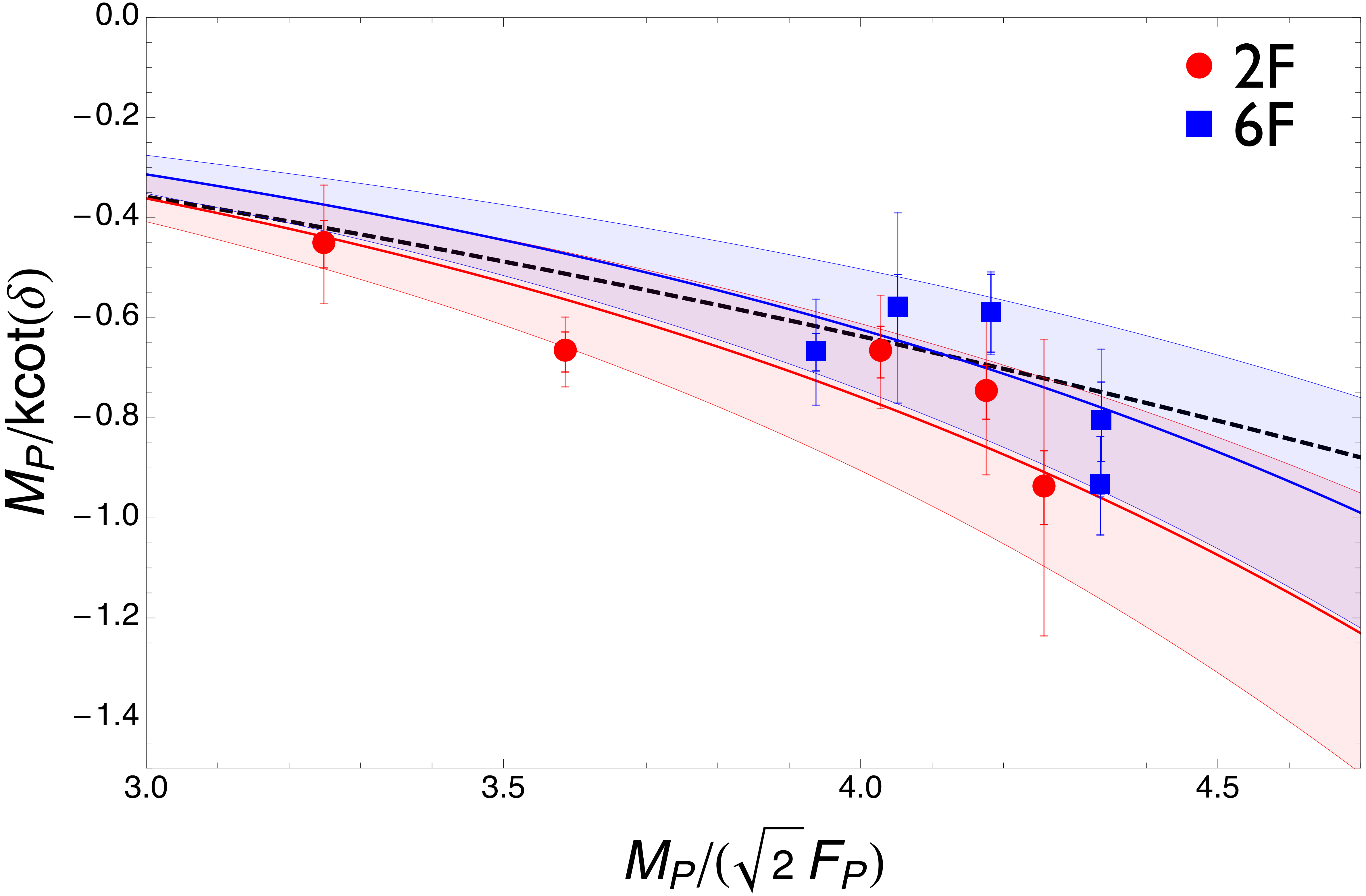
Table 1: 2 Flavor

m_q	# Configs	# Meas
0.010	564	564
0.015	148	444
0.020	131	131
0.025	67	268
0.030	39	154

Table 1: 6 Flavor

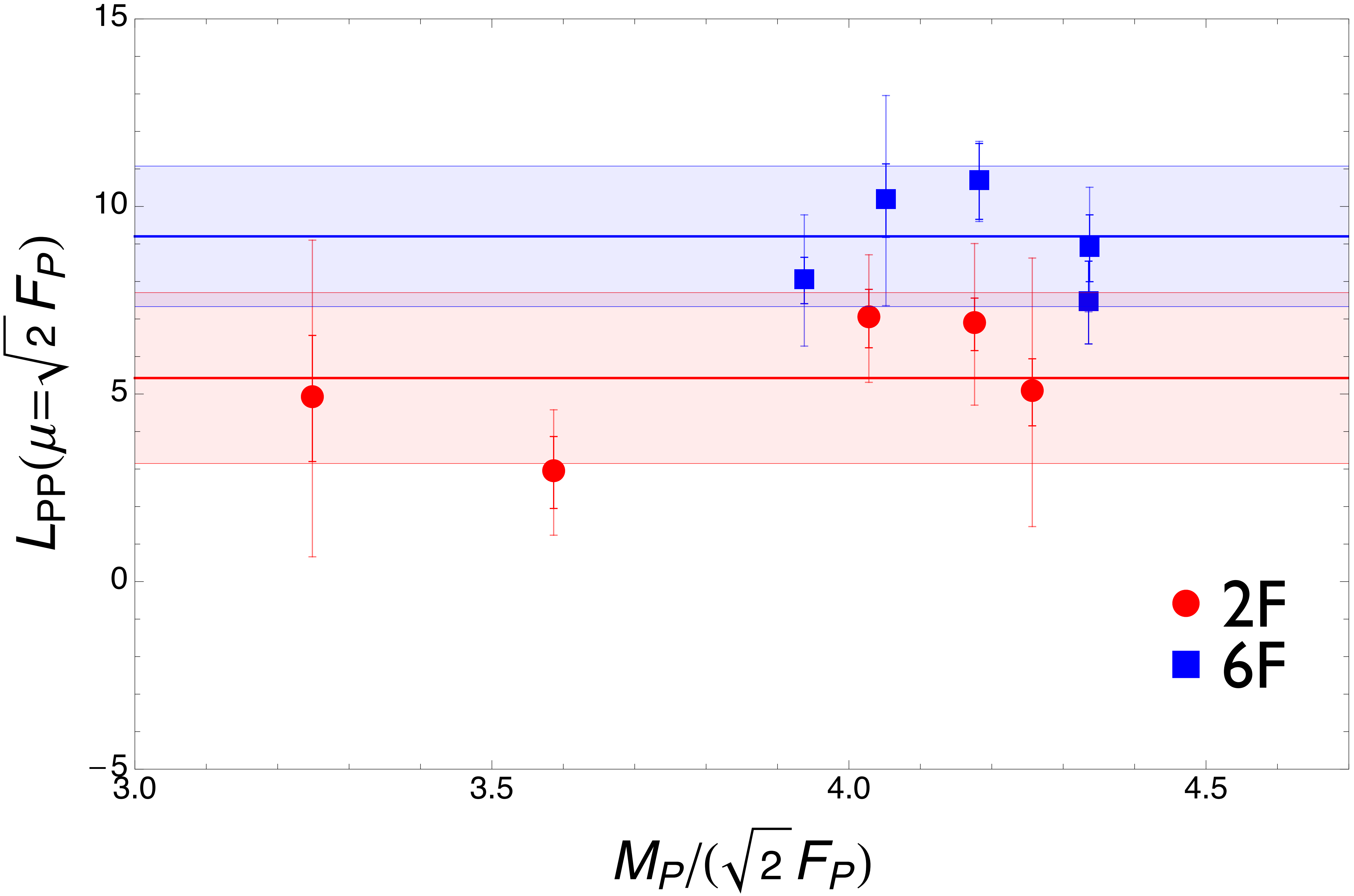
m_q	# Configs	# Meas
0.010	221	882
0.015	112	414
0.020	81	324
0.025	89	267
0.030	72	259

Results



LO Weinberg dominance persists!!!!

Results



$$L_{\pi\pi}^{2F}(\mu = \sqrt{2}F_P) = 5.42 \pm 2.28 \qquad \chi^2/\mathrm{d.o.f} = 0.71$$

$$L_{\pi\pi}^{6F}(\mu = \sqrt{2}f_P) = 9.20 \pm 1.87 \qquad \chi^2/\mathrm{d.o.f} = 0.54$$

Two Flavor WW LECs

NLO calculations of M_P F_P $M_P a_{PP}$

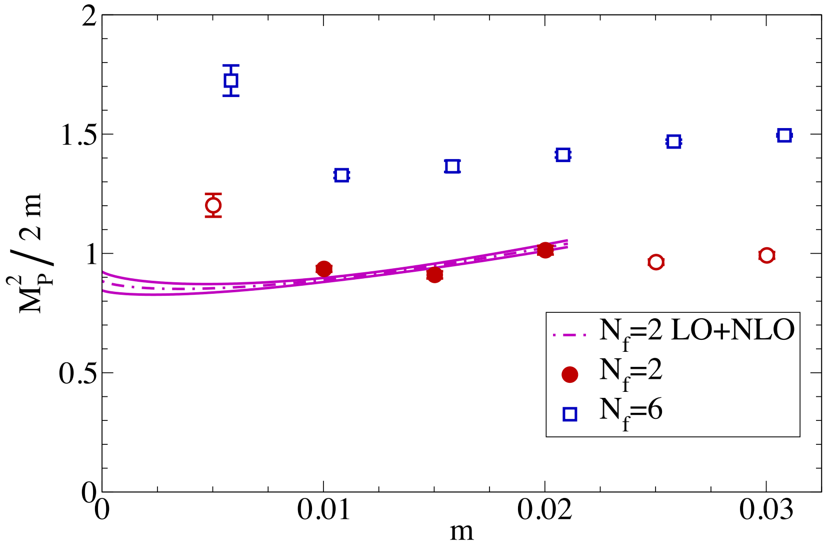
Three EQs, four unknowns

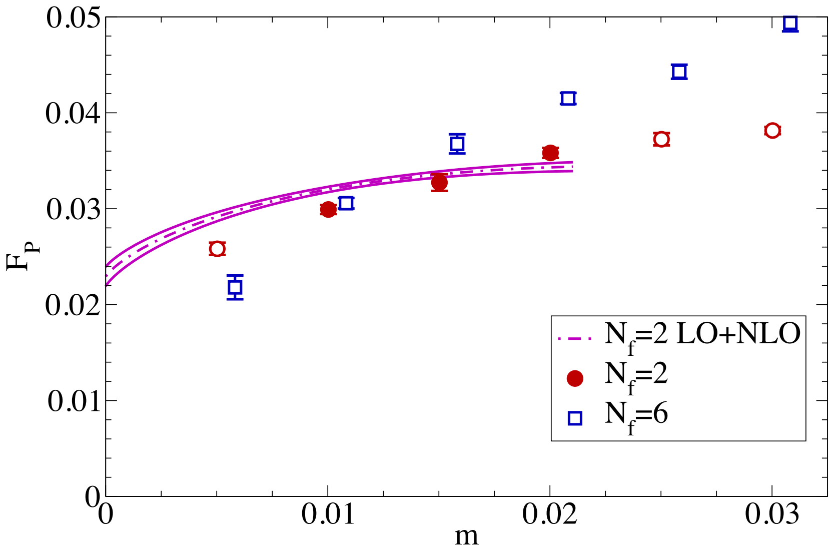
$$\alpha_4^r + \alpha_5^r = (3.43 \pm 0.31) \times 10^{-3} \quad \mu \sim 246 \text{ GeV}$$

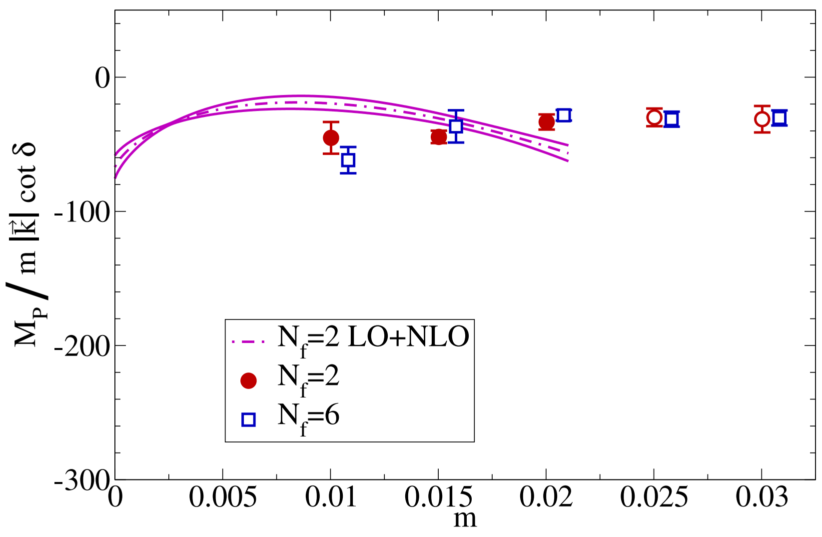
How robust is this result?

How Robust?

- Different Chiral expansion







Subpar Fit Implies:

Need smaller masses

Need larger volume

Need bigger computer

Even Still:

$$\alpha_4^r + \alpha_5^r = (3.34 \pm 0.71) \times 10^{-3}$$

(this fit)

vs.

$$\alpha_4^r + \alpha_5^r = (3.43 \pm 0.31) \times 10^{-3}$$

(previous fit)

Where we Stand

Estimates for 99% CL bounds for 100 inverse fb:

$$-7.7 \times 10^{-3} < \tilde{\alpha_4} < 15 \times 10^{-3}$$
$$-12 \times 10^{-3} < \tilde{\alpha_5} < 10 \times 10^{-3}$$

Eboli et. al.
2006

Two Flavor results:

$$\tilde{\alpha}_4(M_H) + \tilde{\alpha}_5(M_H) = (3.34 \pm 0.17^{+0.08}_{-0.71}) \times 10^{-3} - \frac{\left[\log \frac{M_H^2}{F^2} + \mathcal{O}(1)\right]}{128\pi^2}$$

Six flavor shows early signs for enhanced values, but is currently inconclusive

Future Directions...

1) Ultimately need:

- Different volume(s)
- More statistics & 0.0075 mass point

2) Get W-W parameters in other ways!

- I=2 pi-pi D-wave scattering (more stats, operators)
- Pion form factors (more stats, mass points)
- Eff. Range & Shape Param. (more stats, volumes)
- NNLO analysis (more stats, mass points)
- PQ analysis (more inversions, volumes)

...More relevant directions

1) Lattice calculations of real or pseudo-real rep.

   - Lattice simulations of SU(2) underway

2) Theoretical work

   - Settle on viable SU(2) model
   - Include 125 GeV scalar in EW Chiral EFT
   - Connect SU(2) LECs to WW LECs

Bottom line:
Lattice + WW scattering can say final word on technicolor

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