Lattice explorations of a composite Higgs

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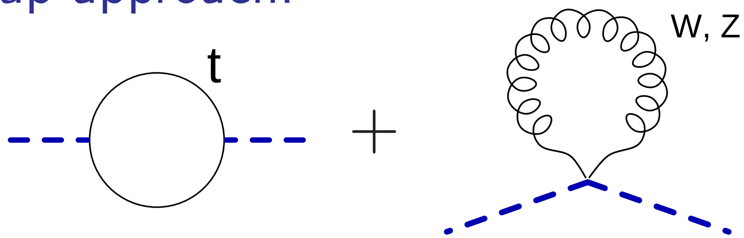
Hierarchy problem: [un]naturalness of the Higgs potential

- Higgs potential: $V(h) = -\mu^2 h^2 + \lambda h^4$

EW scale: $\sqrt{2}\,\langle h \rangle = \mu/\sqrt{\lambda} \simeq 246$ GeV, Higgs mass: $m_H = \sqrt{2}\mu \simeq 125$ GeV

- What symmetry stops μ^2 from becoming as large as $M^2_{\rm Planck}$?

- Bottom-up approach:

$-\mu^2 =$  $+$ new physics $\approx g^2 \Lambda^2_{\rm new}$

⋆ Supersymmetry: (not this talk) each SM field has "super-partner" of opposite statistics; $\Lambda_{\rm new} =$ supersymmetry breaking scale

⋆ New strong dynamics at the few TeV scale

Higgs is pseudo Nambu-Goldstone boson arising from

– approximate flavor symmetry of new sector ("Composite Higgs")

– approximate scale symmetry of new sector ("Walking technicolor")

Composite Higgs

- "Hypercolor": new strong sector with scale $f \gg h$ $\qquad$ ($f \sim 1$ to few TeV)
- Within hypercolor theory, Higgs is exact Nambu-Goldstone boson of (chiral) flavor symmetry breaking
- Higgs potential from coupling to SM fields: EW gauge bosons, top quark, ...

$$V_{\rm eff}(h) \;=\; -\alpha \cos^2(h/f) + \beta \sin^2(2h/f)$$

- EW gauge bosons only: $\alpha = (3g^2 + g'^2) C_{LR} > 0$, $\beta = 0$

  $\Longrightarrow$ vacuum alignment (see next slide)

  $\Longrightarrow$ By itself, would lead to $h = 0$

  Recall pion mass splitting: $M^2_{\pi^\pm} - M^2_{\pi^0} = (e^2/f^2) C_{LR} > 0$ $\qquad$ [DGMLY 1967]

- Will need top quark contribution to $V_{\rm eff}(h)$ to trigger EW symmetry breaking

⋆ How much tuning of α and β is needed for $h/f \ll 1$?

“UV complete” composite Higgs

[Ferretti & Karateev 2013]

- Hypercolor sector has global symmetry G spontaneously broken to H with

$$H \supset SU(3)_{\rm color} \times SU(2)_L \times SU(2)_R \times U(1)_X$$
$$\supset SU(3)_{\rm color} \times SU(2)_L \times U(1)_Y \qquad Y = T_{3R} + X$$

$\Rightarrow$ EW gauge bosons couple to unbroken generators $\Rightarrow$ vacuum alignment

- coset G/H must contain Higgs doublet: $(2,2)$ of $SU(2)_L \times SU(2)_R$
- Unbroken custodial symmetry $\Rightarrow$ ρ parameter $\equiv \frac{M_W^2}{M_Z^2 \cos^2(\theta_W)} \approx 1$
- partially composite top quark:
  need hyperbaryons that can couple linearly to $q_L = (t_L, b_L)$ and to t_R
- SM $\times$ hypercolor is anomaly free
- QCD & hypercolor are asymptotically free

⋆ don't worry about b and other SM fermion masses

Ferretti's model – Higgs field & EW couplings

- $SU(4)$ gauge theory with 5 sextet Majorana fermions $\Upsilon_i, \quad i = 1, 2, \ldots, 5$
- Non-linear sigma model (sextet is real representation):

$$\begin{aligned} \Sigma_{ij} &\sim \langle \Upsilon_i \Upsilon_j \rangle \sim \langle \Upsilon_j \Upsilon_i \rangle \\ \Sigma &= \Sigma^T = \exp(2i\Pi/f) \in SU(5)/SO(5) \\ \Sigma &\to g\Sigma g^T \,, \quad g \in SU(5) \end{aligned}$$

- embedding of Higgs $\qquad SU(2)_L \times SU(2)_R \approx SO(4) \subset SO(5)$

$$\Pi = \text{singlet} + \text{Higgs} + 3\ \text{triplets} = (1,1) + (2,2) + (3,3) \ \Rightarrow \ 14\ \text{NGBs}$$

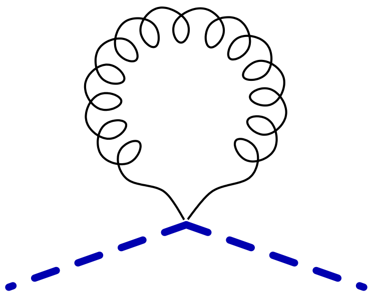
$$\text{Higgs} = \sqrt{2} \begin{pmatrix} 0 & 0 & 0 & 0 & \mathrm{Im}\, H_+ \\ 0 & 0 & 0 & 0 & \mathrm{Re}\, H_+ \\ 0 & 0 & 0 & 0 & -\mathrm{Im}\, H_0 \\ 0 & 0 & 0 & 0 & \mathrm{Re}\, H_0 \\ \mathrm{Im}\, H_+ & \mathrm{Re}\, H_+ & -\mathrm{Im}\, H_0 & \mathrm{Re}\, H_0 & 0 \end{pmatrix}$$

Gauge bosons part of Higgs potential

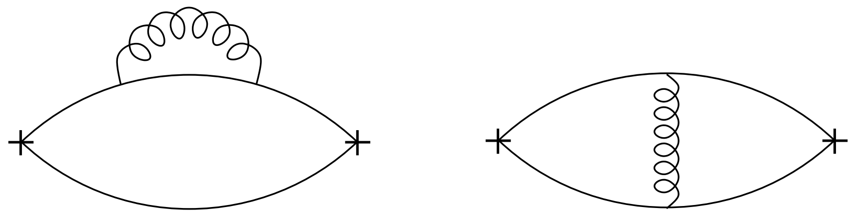
$$C_{LR} \quad = \quad \int_0^\infty dq^2 q^2\, \Pi_{LR}(q^2)$$

$$q^2\,\Pi_{LR}(q^2) \quad = \quad \langle \mathcal{A}_\mu \mathcal{A}_\nu - \mathcal{V}_\mu \mathcal{V}_\nu \rangle^\perp \;\geq\; 0$$

[Witten 1983]

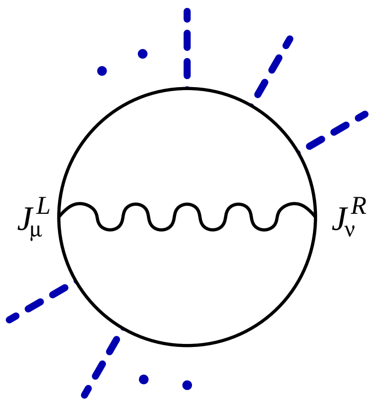


$\Rightarrow$



chiral symmetry relates diagrams
with $0, 1, 2, \ldots$ NGBs

$\Rightarrow$



Lattice calculation of C_{LR}

- Simulating 5 Majoranas is hard; for now, 4 Majoranas = 2 Diracs

$\Longrightarrow$ Can use standard HMC algorithm

- Coset $SU(4)/SO(4)$ not $SU(5)/SO(5)$; hopefully C_{LR} is not too different.
- Dynamical Wilson-clover fermions (no chiral symmetry for $m \to 0$)
- Calculate C_{LR} with valence overlap fermions

$\Longrightarrow$ exact chiral symmetry for $m \to 0$

$\Longrightarrow$ need mixed-action Chiral Perturbation Theory

In this exploratory study:

two $12^3 \times 24$ ensembles with different lattice (gauge) actions

same lattice spacing ($r_1/a \approx 3 \;\Longrightarrow\; a^{-1} \approx 2$ GeV in QCD)

Direct summation

Π_{LR} is transverse part of

$$-\sum_x e^{iqx} \left\langle J_\mu^L(x) J_\nu^R(0) \right\rangle_{\text{conn}}$$

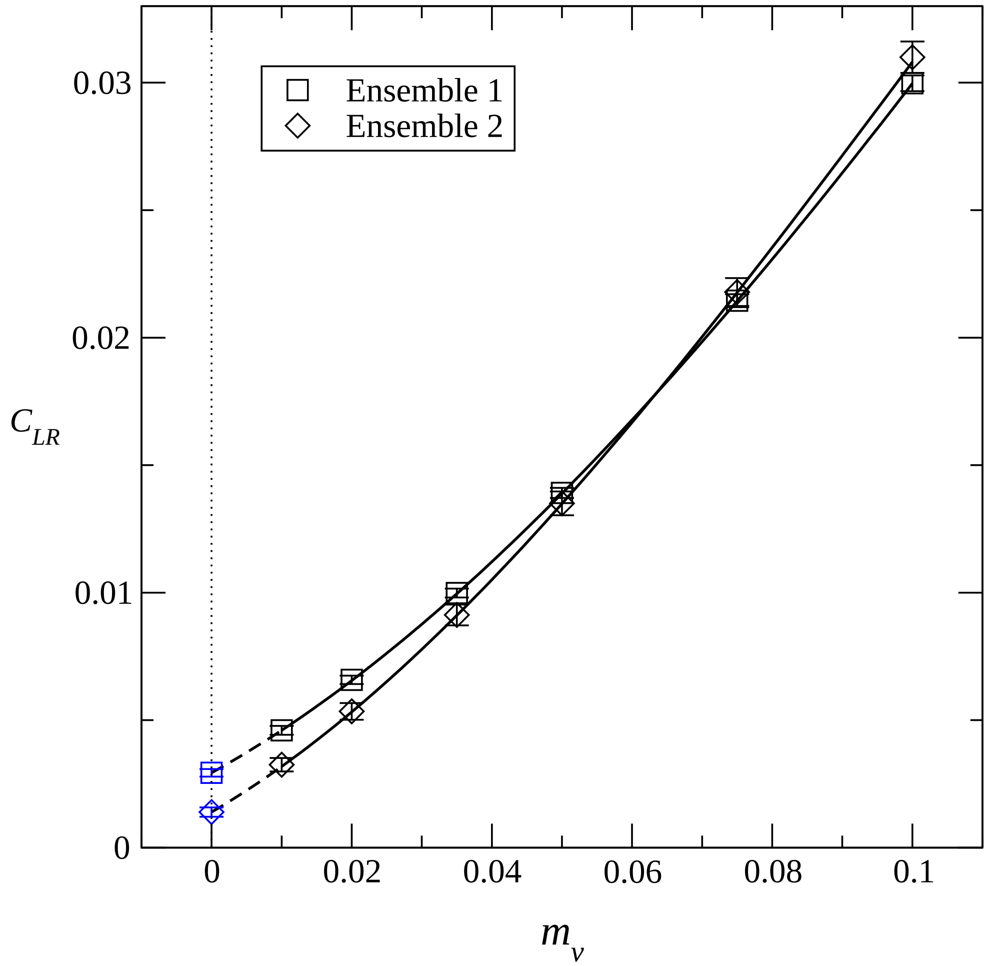
mode sum:

$$C_{LR}(m_v) = \frac{16\pi^2}{V} \sum_{q_\mu} \Pi_{LR}(q_\mu)$$

while modelling pole

at $q_\mu = 0$ via

$$\Pi_{LR}(q_\mu) \simeq c + \frac{f_\pi^2}{q^2}$$



Minimal Hadron Approximation

$$\Pi_{LR}(q^2) \approx \frac{f_\pi^2}{q^2} + \frac{f_{a_1}^2}{q^2 + m_{a_1}^2} - \frac{f_\rho^2}{q^2 + m_\rho^2}$$

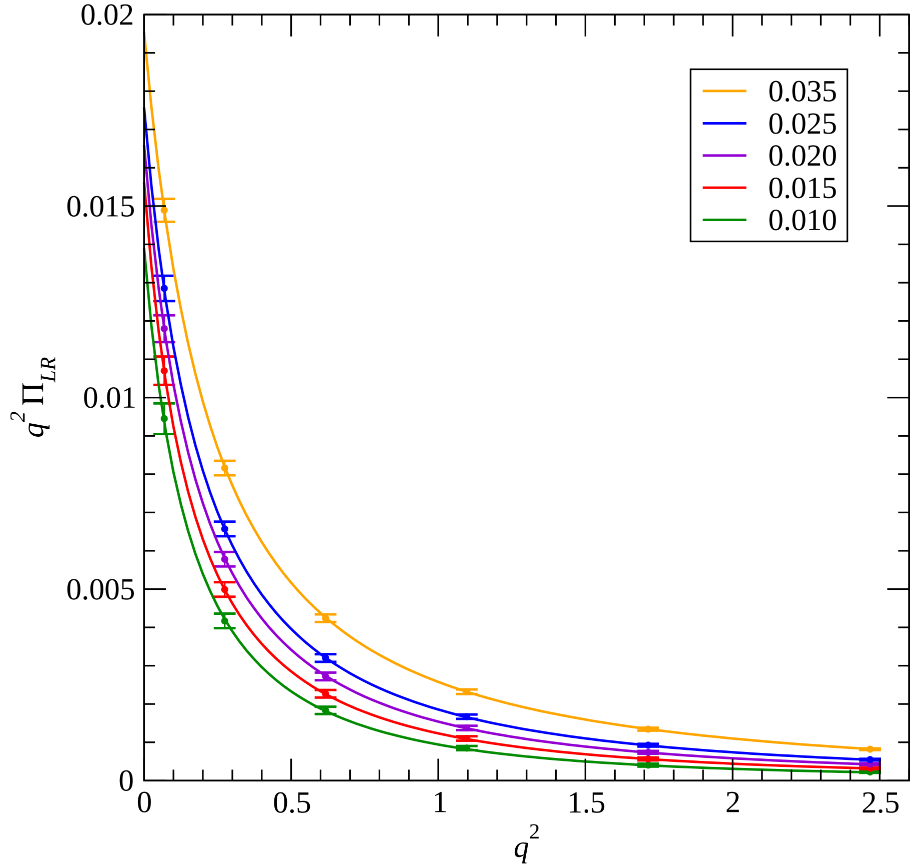
kinematical pole at $q^2 = 0$ (any $m_\pi \geq 0$)

5 parameter fits to different rays

in momentum space

Then integrate

$$C_{LR} \approx f_\pi^2 \frac{m_{a_1}^2 m_\rho^2}{m_{a_1}^2 - m_\rho^2} \log\left(\frac{m_{a_1}^2}{m_\rho^2}\right)$$



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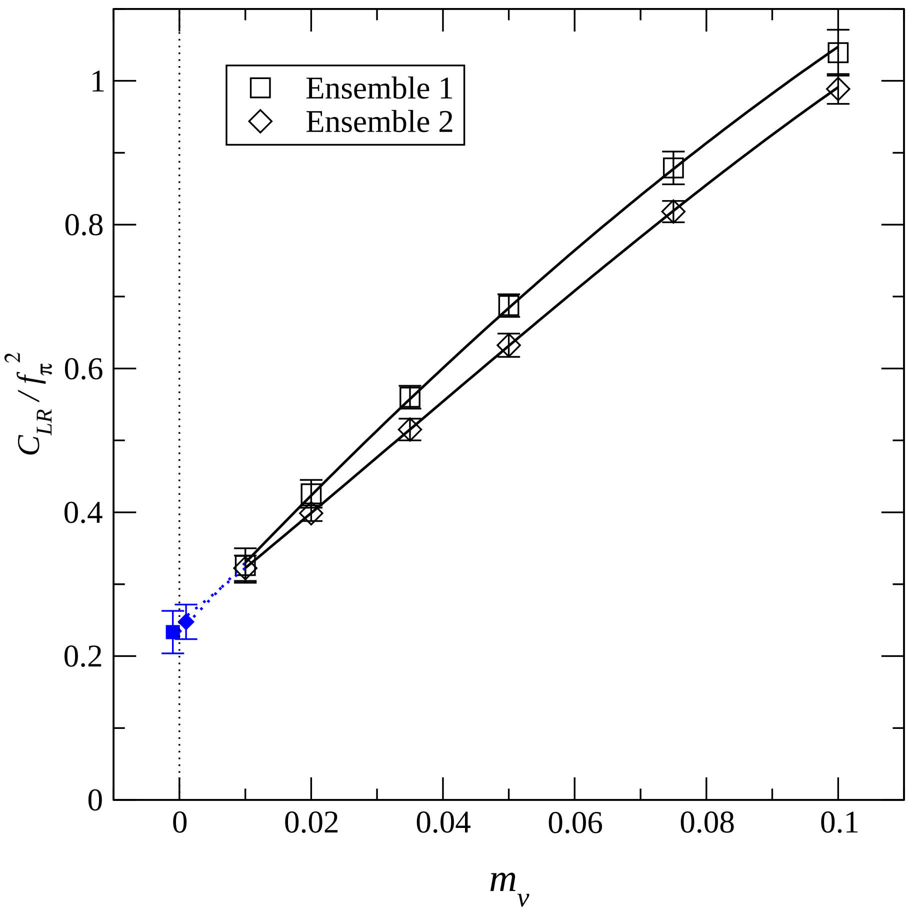
$$C_{LR} \approx f_\pi^2 \frac{m_{a_1}^2 m_\rho^2}{m_{a_1}^2 - m_\rho^2} \log\left(\frac{m_{a_1}^2}{m_\rho^2}\right)$$

Look at ratio C_{LR}/f_π^2

no continuum limit yet



Ferretti's model – top quark sector

- $SU(4)$ gauge theory with 5 sextet Majorana fermions $\Upsilon_{i[AB]}$,
  and now adding 3 fundamental Dirac fermions Ψ^a_A, $\tilde{\Psi}^A_a$.

- Partial compositeness:
  Top quark couples linearly to hypercolor baryons ("top partners")
  hyperbaryons with same SM quantum numbers as top quark:
  $\Upsilon\Psi\Psi = \epsilon^{ABCD}\epsilon_{abc}\Upsilon_{i[AB]}\Psi^b_C\Psi^c_D$, $\overline{\Upsilon}\Psi\Psi$, $\Upsilon\tilde{\Psi}\tilde{\Psi}$, $\overline{\Upsilon}\tilde{\Psi}\tilde{\Psi}$, $\Upsilon\Psi\bar{\tilde{\Psi}}$, $\overline{\Upsilon}\Psi\bar{\tilde{\Psi}}$

- Symmetry breaking G/H with

$$
\begin{aligned}
G &= SU(5) \times SU(3) \times SU(3)' \times U(1)_B \times U(1)' \\
H &= SO(5) \times SU(3)_{\rm color} \times U(1)_B
\end{aligned}
$$

$\Rightarrow$ First 2-irreps lattice simulations!
(Majorana sextets, Dirac fund.): (4, 2) instead of (5, 3)

Scale separation? [Raby, Dimopoulos, Susskind 1980]

("Tumbling gauge theories," "Maximally attractive channel")

gap-equation critical coupling:
$$\frac{1}{g^2(\Lambda_{\chi\mathrm{SB}})} = \frac{3C_2}{4\pi^2}$$

one-loop running:
$$\frac{1}{g^2(\mu)} = b_1 \log\left(\frac{\mu}{\Lambda_{\mathrm{IR}}}\right)$$

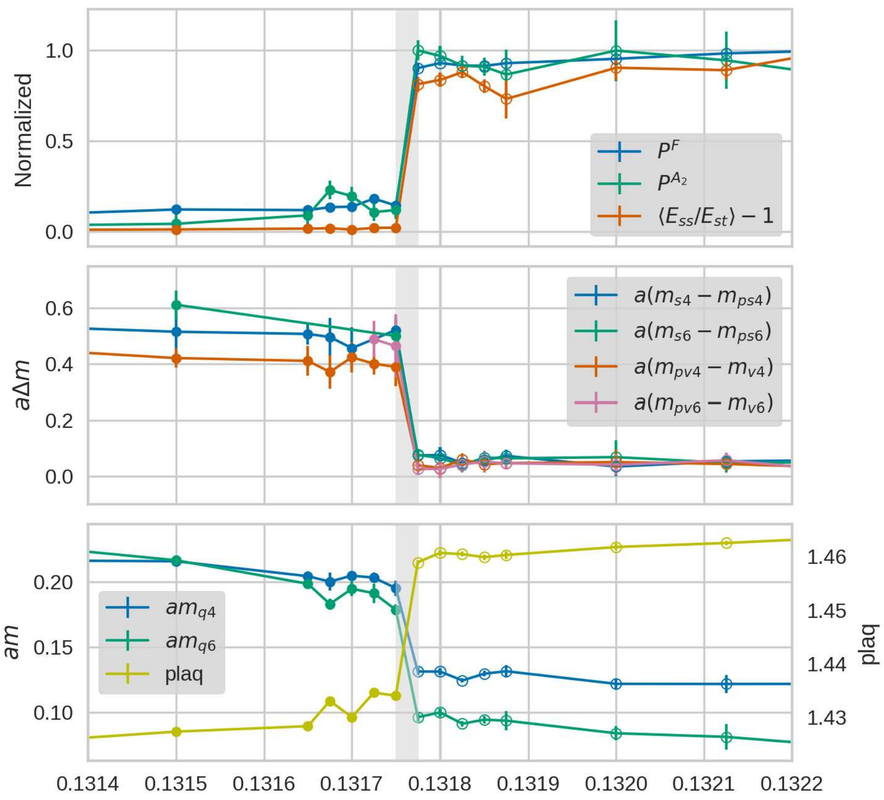
chiral symmetry breaking scale:
$$\frac{\Lambda_{\chi\mathrm{SB}}}{\Lambda_{\mathrm{IR}}} = \exp\left(\frac{3C_2}{4\pi^2 b_1}\right)$$

- For irrep r, $\Lambda_{\chi\mathrm{SB}}(r)$ depends exponentially on $C_2(r)$
- Identify IR scale Λ_{IR} with confinement scale Λ_{conf}
- Exponential behavior of $\Lambda_{\chi\mathrm{SB}}/\Lambda_{\mathrm{conf}}$ found in old-days quenched simulations
- What about dynamical fermions?

Finite-temperature phase transition

bare coupling: β, hopping parameters: κ_4 (fund.), κ_6 (sextet)

slice varying κ_6 at fixed β, κ_4 on $12^3 \times 6$ lattices



Polyakov loops, flow unisotropy

Parity-partners mass splitting

quark masses, plaquette (lattice units)

$\Rightarrow$ single (1st-order) transition!

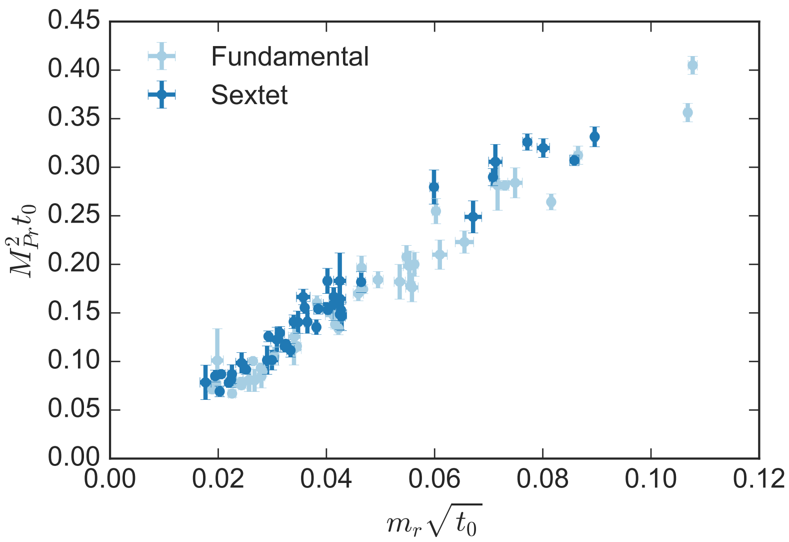
2-reps results: M_π and F_π vs. same-rep fermion mass

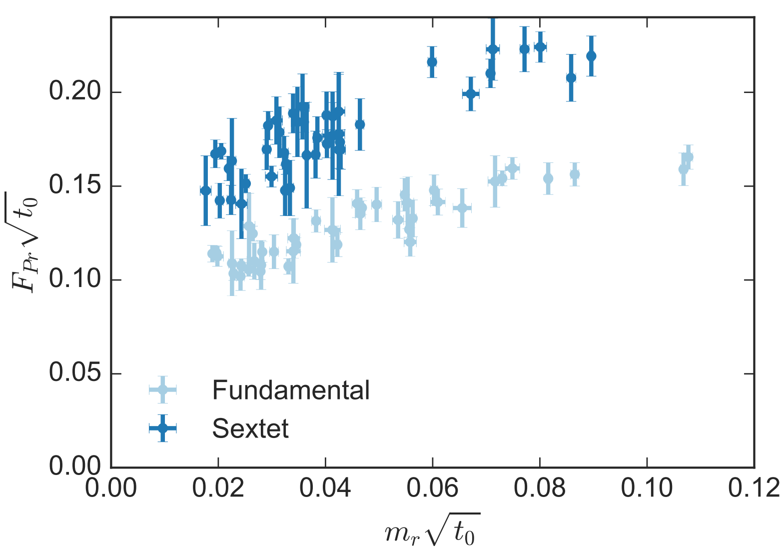
Wilson-clover fermions, nHYP smeared links, Dislocation-Suppressing term

Ensembles: $16^3 \times 18$, $16^3 \times 32$ ($\sim$ twenty each), $24^3 \times 48$ (four)

physical units: flow scale t_0 on the same ensemble

cutoff: 1.5 – 2.2 GeV pion masses: 400 – 800 MeV (“QCD equivalent”)

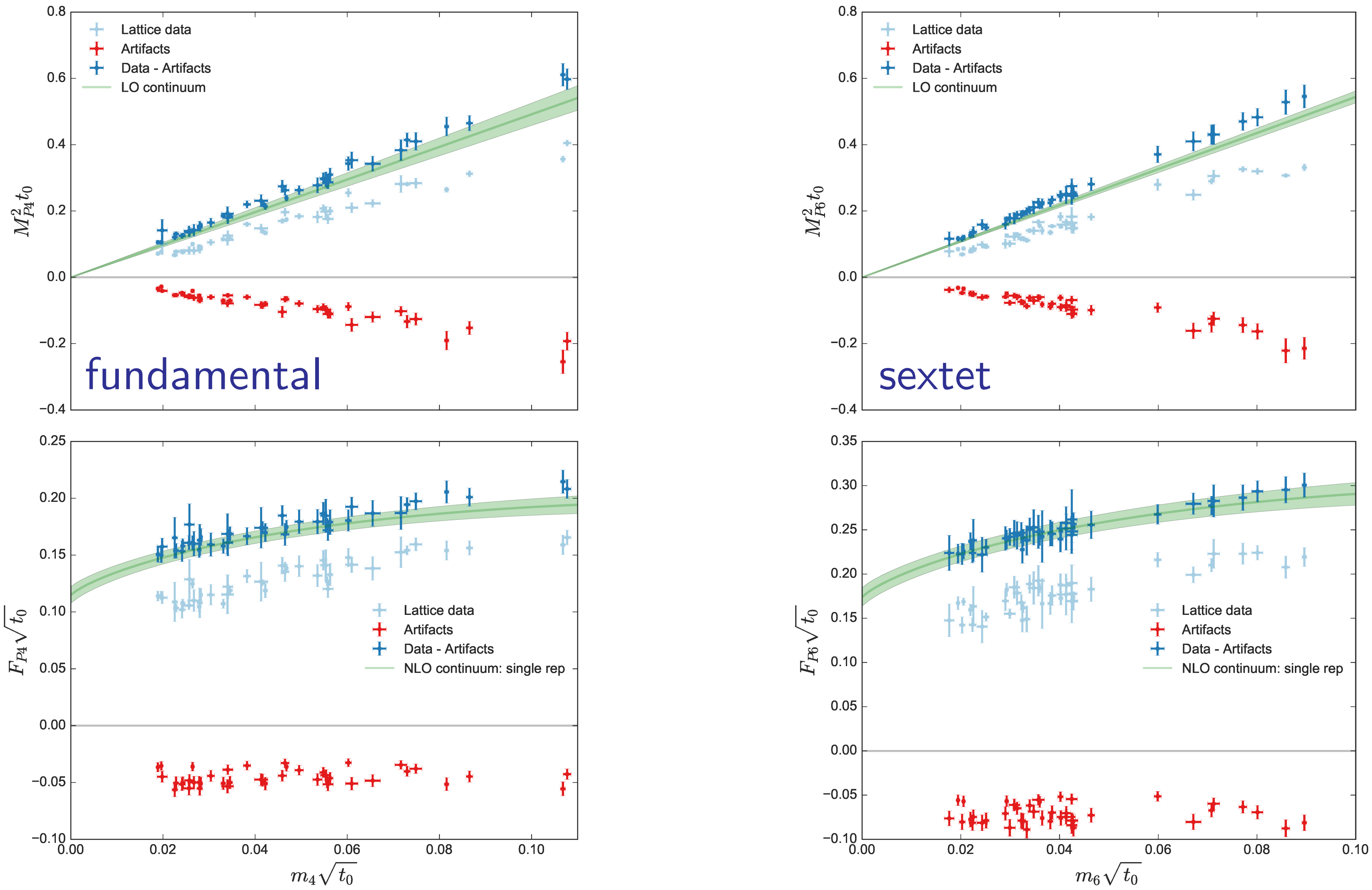




(results depend also on other-rep fermion mass and lattice spacing)

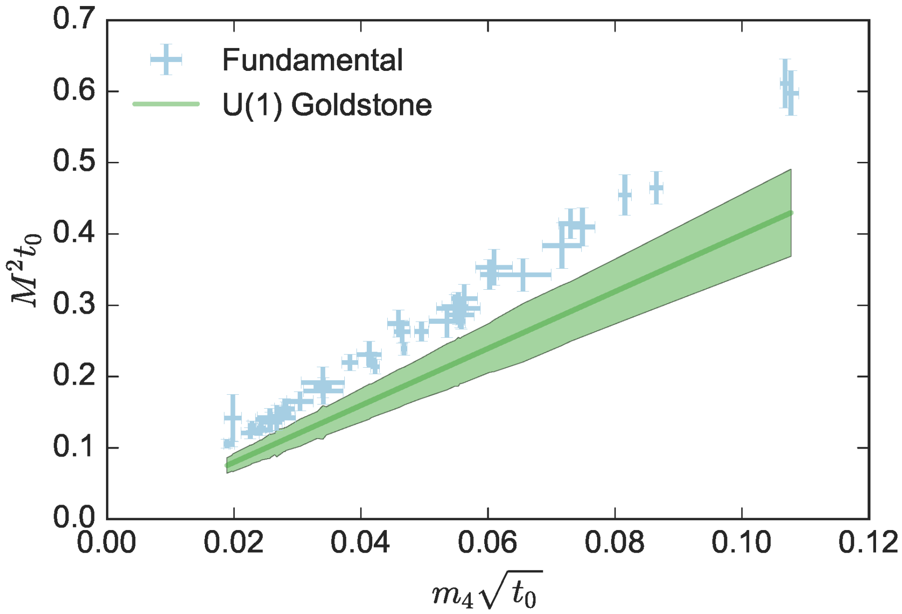
“Remnant scale separation”: $F_\pi(\text{sextet}) > F_\pi(\text{fund.})$

2-reps results: Wilson ChPT



2-reps results: singlet Nambu-Goldstone boson

Singlet mass in sextet chiral limit (extracted from fit)



Singlet somewhat lighter than fund sector pions in this limit

might be interesting for cosmology

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4-fermi couplings and top-induced Higgs potential

- As in technicolor, need extended hypercolor that breaks at high scale $\Lambda_{\rm EHC}$ to generate 4-fermi couplings at $\Lambda_{\rm HC}$ scale

$$\mathcal{L}_{\rm EHC} = \lambda_1 \overline{T}_L^{(\mathbf{5},\mathbf{3},\mathbf{1})} B_R^{(\mathbf{5},\mathbf{3},\mathbf{1})} + \lambda_2 \overline{T}_R^{(\overline{\mathbf{5}},\mathbf{3},\mathbf{1})} B_L^{(\overline{\mathbf{5}},\mathbf{3},\mathbf{1})} + \lambda_3 \overline{T}_L^{(\mathbf{5},\mathbf{1},\mathbf{3})} B_R^{(\mathbf{5},\mathbf{1},\mathbf{3})}$$
$$+ \lambda_4 \overline{T}_R^{(\overline{\mathbf{5}},\mathbf{1},\mathbf{3})} B_L^{(\overline{\mathbf{5}},\mathbf{1},\mathbf{3})} + \lambda_5 \overline{T}_L^{(\overline{\mathbf{5}},\overline{\mathbf{3}},\overline{\mathbf{3}})} B_R^{(\overline{\mathbf{5}},\overline{\mathbf{3}},\overline{\mathbf{3}})} + \lambda_6 \overline{T}_R^{(\mathbf{5},\overline{\mathbf{3}},\overline{\mathbf{3}})} B_L^{(\mathbf{5},\overline{\mathbf{3}},\overline{\mathbf{3}})} + \text{h.c.} \ .$$

spurions

$$T_L = \frac{1}{\sqrt{2}} \begin{pmatrix} i b_L \\ b_L \\ i t_L \\ -t_L \\ 0 \end{pmatrix} , \qquad T_R = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ t_R \end{pmatrix}$$

- Work out: effective top-Yukawa couplings
  top-induced effective potential for Higgs (and other pNGBs)
- Depend on low-energy constants (calculable on lattice), and on λ's

Things to worry about

- top-Yukawa $y_t \sim \lambda\lambda \sim (\Lambda_{\rm HC}/\Lambda_{\rm EHC})^4$ by naive counting
- need small $\Lambda_{\rm HC}/\Lambda_{\rm EHC}$ to keep flavor violations under control
- Way too small y_t unless (a) theory is near-conformal and (b) 4-fermi's have large anomalous dimensions $\Rightarrow$ $y_t \sim (\Lambda_{\rm HC}/\Lambda_{\rm EHC})^{4-2\gamma}$ (..examples??)
- Instead, other fermion masses might come from yet another sector

- Calculate full effective potential; structure varies substantially for different Ferretti-Karateev models
- Study minima as function of $\lambda' s$ (a multi-dimensional problem!)
- Role of other pNGBs: finding singlet VEV is fine; but triplet VEV must not break the custodial symmetry (ρ parameter)
- Difficult to make progress without some understanding of EHC theory

~~Classic technicolor~~

[Susskind 1979]
[Raby, Dimopoulos, Susskind 1980]

- New strong sector
- Elegant mechanism to generate W and Z masses:

  techni-fermions condense, 3 techni-pions eaten by W and Z
- Higgs VEV $v \equiv$ technipion decay constant f
- Fermion masses?

LHC era:

⋆ Higgs-less

⋆ Where are the techni-rho's?

$\Longrightarrow$ Successful technicolor can't be upscaled version of QCD

Walking (extended) technicolor

- Small-but-still-negative beta function
- Fermion condensation break spontaneously both chiral symmetry and approximate scale symmetry
- "Dilatonic Higgs" arising as pseudo Nambu-Goldstone boson for approx. scale symmetry

- Helps with fermion masses, too (original motivation!)

4-fermi operators: $$\frac{\bar{q}q\bar{q}q}{\Lambda_{ETC}^2}, \quad \frac{\bar{q}q\bar{Q}Q}{\Lambda_{ETC}^2}, \quad \frac{\bar{Q}Q\bar{Q}Q}{\Lambda_{ETC}^2}$$

fermion masses: $$\frac{\langle\bar{Q}Q\rangle\,\bar{q}q}{\Lambda_{ETC}^2} \approx \Lambda_{TC}\left(\frac{\Lambda_{TC}}{\Lambda_{ETC}}\right)^{2-\gamma_m}\bar{q}q$$

⋆ In case $\gamma_m \lesssim 1$, not good enough for top mass

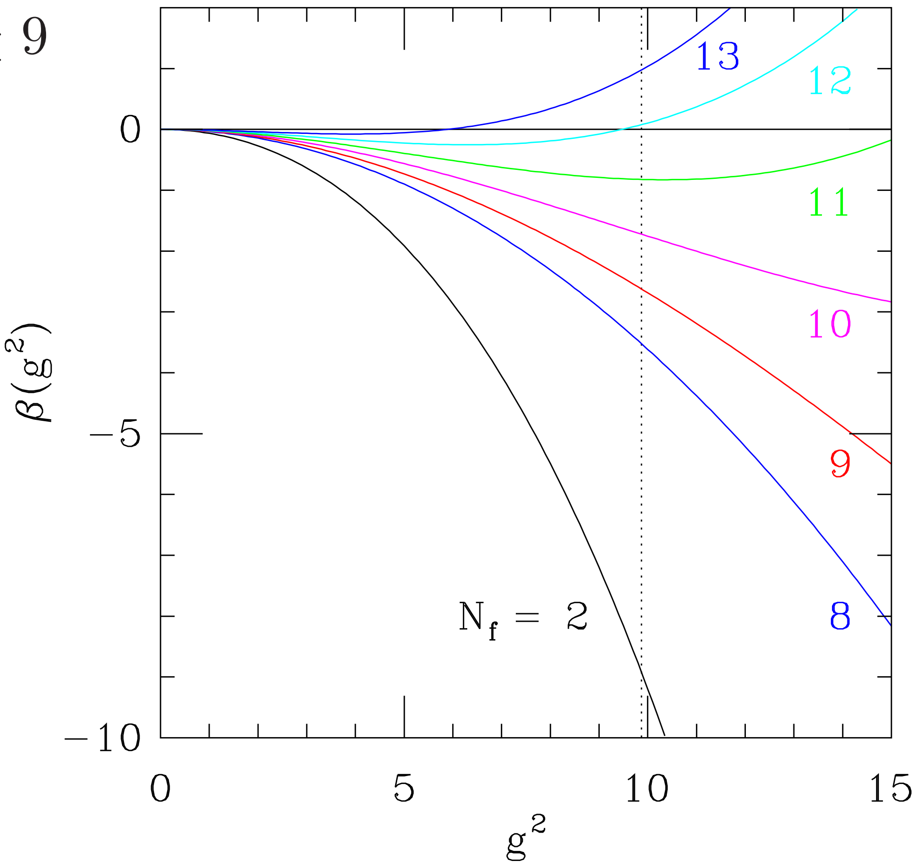
Phases of $SU(3)$ with N_f fundamental-rep Dirac fermions

- running slows with increased N_f
- two-loop IRFP $g_* = g_*(N_f)$ for $N_f \geq 9$
- ChSB when $g^2(\mu)$ reaches g_c^2
- Here $g_c^2 = \pi^2 \simeq 9.87$

$\Rightarrow$ chirally broken if $g_c < g_*$

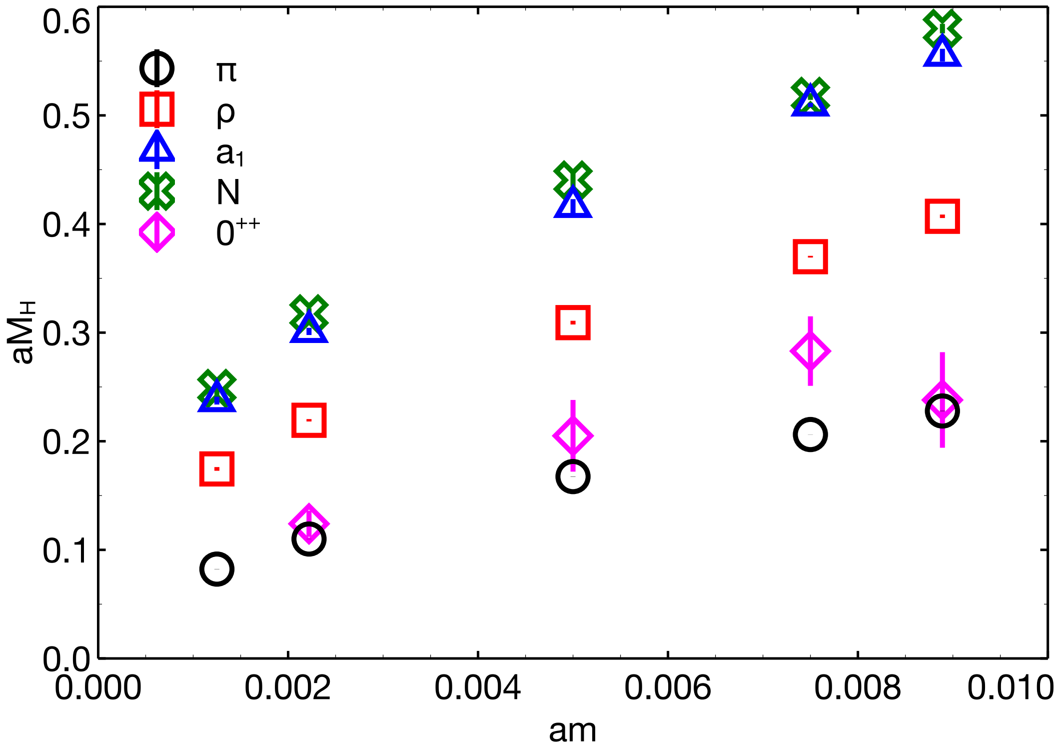
$\Rightarrow$ IR conformal if $g_c > g_*$

- sill of conformal window: $g_* = g_c$
- For $SU(3)$ sill is $N_f^* \simeq 12$



A light flavor-singlet scalar: dilatonic Higgs?

- $SU(3), N_f = 8$ fund. [LatKMI, LSD,..]



LSD collaboration, PRD 93 (2016) 114514

Consistent low-energy theory must contain both pions and the flavor-singlet scalar

- $SU(3), N_f = 2$ two-index symmetric rep (sextet)

Constructing an Effective Field Theory

- symmetries
- spurions: external fields transforming under the symmetries

– fixing "VEVs" of spurions $\Rightarrow$ explicit breaking of symmetries

– Low-energy constants determined by matching correlation functions defined by differentiation w.r.t. spurions

- Chiral symmetry: spurion $\langle \chi \rangle = m$, effective field $\Sigma \sim \psi_L \overline{\psi}_R$

microscopic theory: $\overline{\psi}_R \chi^\dagger \psi_L + \overline{\psi}_L \chi \psi_R \;\Rightarrow$ effective theory: $\mathrm{tr}\,(\chi^\dagger \Sigma + \Sigma^\dagger \chi)$

- Dilatations: $\Phi_i(x) \to \lambda^{\Delta_i}\,\Phi_i(\lambda x)$, Δ_i scaling dimension of field $\Phi_i(x)$

$$S^{\mathrm{MIC}}(\sigma) \;=\; \int d^d x\, \frac{e^{\sigma(d-4)}}{g_0^2}\left(\frac{1}{4}F^2 + \cdots\right) \;=\; \int \left(\mathcal{L}^{\mathrm{MIC}}(0) + \sigma T_{an} + \cdots\right)$$

$S^{\mathrm{MIC}}(\sigma, \chi)$ invariant in d dimensions if $\chi(x), e^{\sigma(x)}$ transform as scalar fields

Trace anomaly:

$$\partial_\mu S_\mu \;=\; T_{\mu\mu} \;=\; -T_{cl} - T_{an} \;=\; -(\beta(g^2)/4g^2)\,F^2 - (1+\gamma_m) m\,\overline{\psi}\psi$$

Effective Field Theory with pions and dilatonic meson $\tau(x)$

- scale transformation:

source fields: $\sigma(x) \to \sigma(\lambda x) + \log\lambda$, $\chi(x) \to \lambda^{4-y}\chi(\lambda x)$

effective fields: $\tau(x) \to \tau(\lambda x) + \log\lambda$, $\Sigma(x) \to \Sigma(\lambda x)$

- invariant low-energy theory: $\tilde{\mathcal{L}}^{\rm EFT} = \tilde{\mathcal{L}}_\pi + \tilde{\mathcal{L}}_\tau + \tilde{\mathcal{L}}_m + \tilde{\mathcal{L}}_d$ where

$$
\begin{aligned}
\tilde{\mathcal{L}}_\pi &= V_\pi(\tau-\sigma)\,(f_\pi^2/4)\,e^{2\tau}{\rm tr}\,(\partial_\mu\Sigma^\dagger\partial_\mu\Sigma) \\
\tilde{\mathcal{L}}_\tau &= V_\tau(\tau-\sigma)\,(f_\tau^2/2)\,e^{2\tau}(\partial_\mu\tau)^2 \\
\tilde{\mathcal{L}}_m &= -V_M(\tau-\sigma)\,(f_\pi^2 B_\pi/2)\,e^{y\tau}{\rm tr}\left(\chi^\dagger\Sigma+\Sigma^\dagger\chi\right) \\
\tilde{\mathcal{L}}_d &= V_d(\tau-\sigma)\,f_\tau^2 B_\tau\,e^{4\tau}
\end{aligned}
$$

with invariant potentials: $V(\tau(x)-\sigma(x)) \;\to\; V(\tau(\lambda x)-\sigma(\lambda x))$

(Similar to large-N chiral lagrangian with $U(1)_A$ symmetry and η')

$\Rightarrow$ No predictability without <u>power counting</u>

Power counting

- Veneziano limit: $N_f, N_c \to \infty$ with $n_f = N_f/N_c$ fixed
- Assume: $\beta(g^2) \sim n_f - n_f^*$ at the ChSB scale
- Prove: $V(\tau - \sigma) = \sum_{n=0}^{\infty} \sum_{k \geq n} \tilde{c}_{nk} (n_f - n_f^*)^k (\tau - \sigma)^n$

$\Rightarrow$ Systematic expansion in $p^2 \sim m \sim n_f - n_f^* \sim 1/N$

- Set $\sigma = 0$, $\chi = m$, shift τ field, obtain leading order EFT

$$
\begin{aligned}
\mathcal{L}_\pi &= (f_\pi^2/4)\, e^{2\tau} \mathrm{tr}\,(\partial_\mu \Sigma^\dagger \partial_\mu \Sigma) \\
\mathcal{L}_\tau &= (f_\tau^2/2)\, e^{2\tau} (\partial_\mu \tau)^2 \\
\mathcal{L}_m &= -(m f_\pi^2 B_\pi/2)\, e^{y\tau} \mathrm{tr}\left(\Sigma + \Sigma^\dagger\right) \\
\mathcal{L}_d &= \tilde{c}_{11} (n_f - n_f^*)(\tau - 1/4) f_\tau^2 B_\tau\, e^{4\tau}
\end{aligned}
$$

here $y = 3 - \gamma_m^*$, where γ_m^* is mass anomalous dimension at sill

Some tree-level results

- $V_{\rm cl}(\tau)$ bounded below provided $\tilde{c}_{11} < 0$ (recall $n_f < n_f^*$)
- consistent with matching of the trace anomaly

$$\begin{aligned} \partial_\mu S_\mu &= \tilde{c}_{11}(n_f - n_f^*) f_\tau^2 B_\tau e^{4\tau} + (1+\gamma_m^*)\,\frac{f_\pi^2 B_\pi m}{2}\, e^{y\tau} {\rm tr}\,(\Sigma + \Sigma^\dagger) \\ &= -\frac{\beta(g^2)}{4g^2}\, F^2({\rm EFT}) - (1+\gamma_m^*) m\, \overline{\psi}\psi({\rm EFT}) \end{aligned}$$

- $v = \langle\tau\rangle = 0$, for $m = 0$ (τ shift). $v(m)$ monotonically increasing with m
- pion mass: $m_\pi^2 = 2B_\pi m \times e^{(y-2)v(m)}$
- dilatonic meson mass: $m_\tau^2 = 4\tilde{c}_{11}(n_f - n_f^*)B_\tau \times e^{2v(m)}\big(1 + (4-y)v(m)\big)$
- LSD results: $y \approx 2$ [Appelquist *et al.* arXiv:1711.00067]
- Tree level scaling: e.g., $F_\pi(m) = e^{v(m)} f_\pi(0)$

... in Conclusion

Phenomenology

- Fate of Composite Higgs, Dilatonic Technicolor, remains to be seen
- Lattice provides crucial input for UV-complete composite Higgs: spectrum, low-energy constants

Field theory

- Non-perturbative physics of 2-irreps gauge theories
- Near conformal gauge theories

  In particular, are $N_f = 8$ results fully described by dilaton EFT?