Compositeness in Physics Beyond the Standard Model

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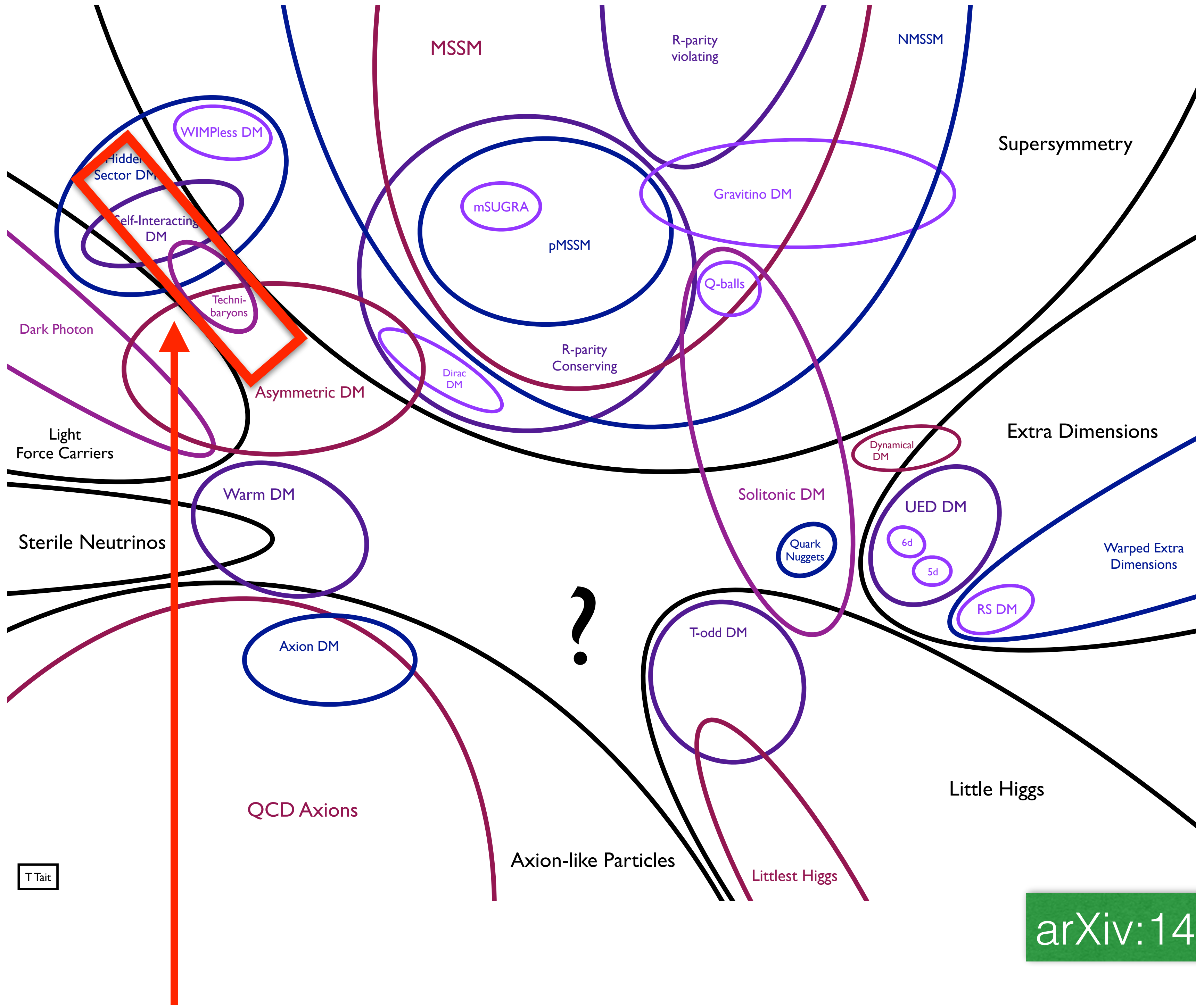
Looking for Compositeness

- Compositeness mechanisms (*i.e.* confinement) can naturally generate mass scales well below the Planck scale.
- Today, there are two mass scales that observations say clearly exist but lack a natural explanation:
  - Dark matter exists and it should be more massive than neutrinos (cold dark matter, not axions).
  - The Higgs boson has a mass of 125 GeV but the Standard Model mechanism is severely fine-tuned.
- Constituents are normally SM-charged, but hadrons can be SM-neutral, leading to suppressed interactions.

Composite Dark Matter @ Snowmass



arXiv:1401.6085

Where is composite dark matter?

Coupling Dark Matter to SM

- The usual WIMP miracle suggests $M_{DM} \sim O(M_{Higgs})$ and symmetric abundance set by thermal freezeout.
- SIDM related to galaxy formation anomalies $M_{DM} \sim O(M_{proton})$ and asymmetric abundance set by matter-antimatter asymmetry.
- Not exhaustive, but either prototype suggests dark matter must be coupled to the Standard Model.
- But, observed limits on potential DM-SM interactions are very constrained:
    - LEP-II constrains any new charged particles $M < 90$ GeV.
    - Z exchange ruled out: $\sigma(DM+N \rightarrow DM+N) \sim 10^{-38}$ cm^2 but XENON/LUX $\sigma(DM+N \rightarrow DM+N) < 10^{-45}$ cm^2.
    - Even generic Higgs exchange now severely constrained by latest direct detection results.

Coupling Dark Baryons to SM

	$\psi\,\sigma^{\mu\nu}\,\psi\,F_{\mu\nu}$ Mag. Moment dim. 5	$(\psi\psi)\,v_\mu\,\partial_\nu\,F^{\mu\nu}$ Charge Radius dim. 6	$(\psi\psi)\,F_{\mu\nu}\,F^{\mu\nu}$ Polarizability dim. 7
Odd N_c No Flavor Sym.	✔	✔	✔
Odd N_c Flavor Sym			✔
Even N_c No Flavor Sym.		✔	✔
Even N_c Flavor Sym.			✔

- Odd N_c gives dark fermions, even N_c gives dark bosons.
- Dark flavor symmetries can be used to suppress dim. 5-6 operators but can stabilize dark mesons (G-parity).
- Generically two dark doublets needed to ensure polarizability is leading operator but dark pions can decay [Stealth Dark Matter: arXiv:1402.6656, arXiv:1503.04203, arXiv:1503.04205].

Lattice Strong Dynamics Collaboration

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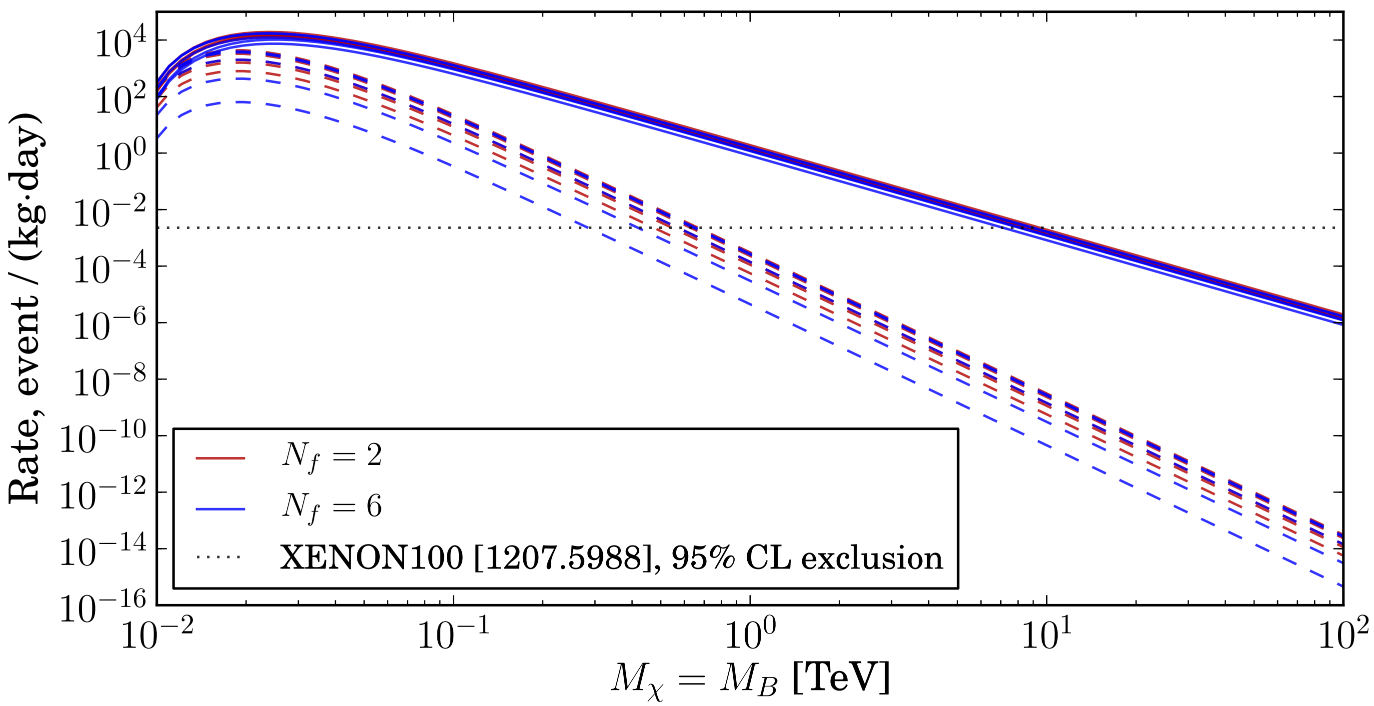
with James Ingoldby (Yale)

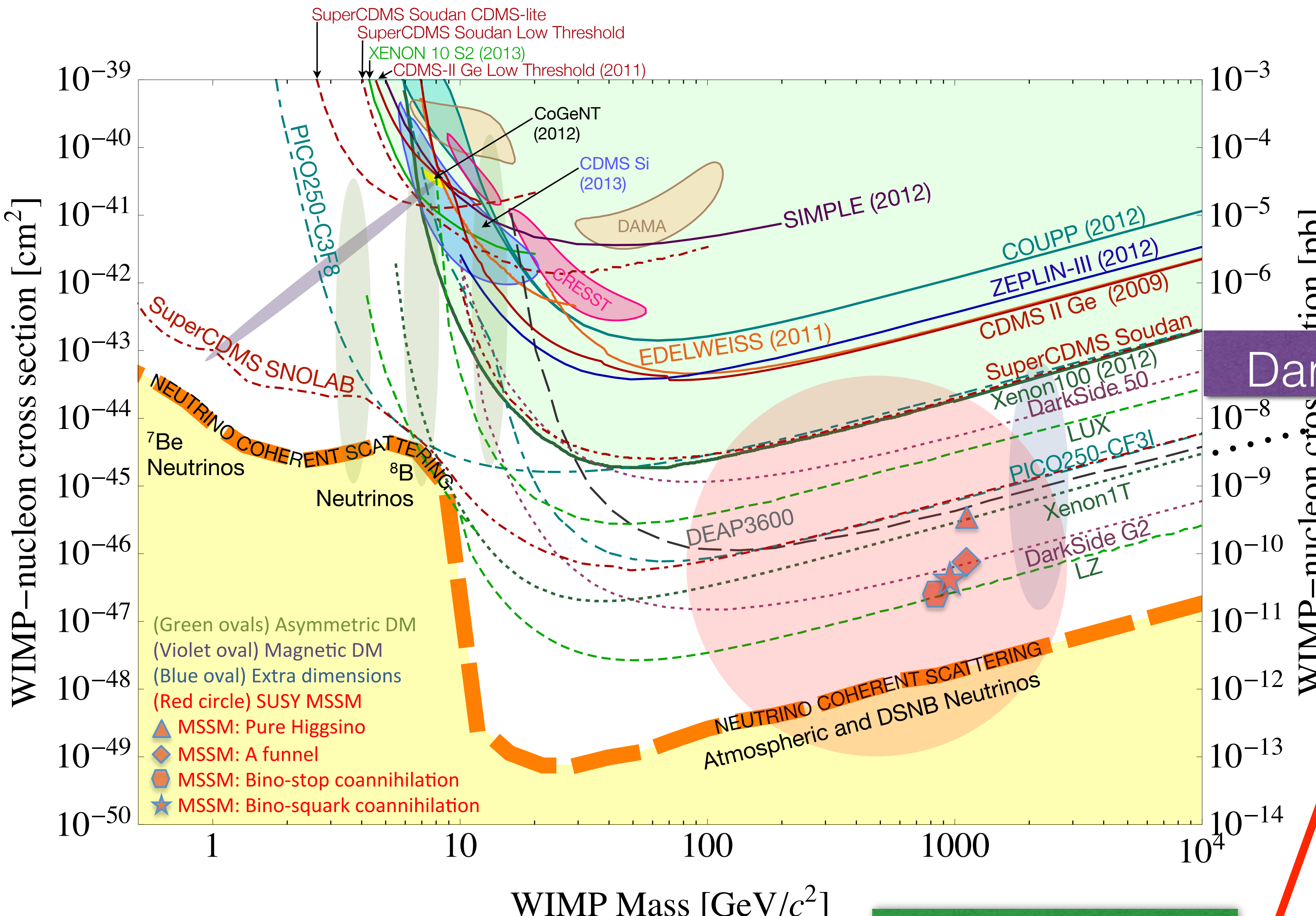
SU(3) Dark Fermion



	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	$SU(3)_D$
Q_1	1	1	2/3	3
Q_2	1	1	-1/3	3
Q_S	1	1	0	3

- [LSD Collab., Phys. Rev. D 88, 014502 (2013)]
- Composite fermion dark matter from new vector-like SU(3) gauge theory with Dirac mass terms. Can be a thermal relic. Free parameters: M_{DM} and $M_{D\pi}$ / M_{DM}.
- Solid lines: magnetic moment. Dashed lines: charge radius.
- Stealth mechanism could be applied to kill these interactions.

View from Snowmass (II)



Dark SU(3) Fermion

arXiv:1401.6085

Partial wave unitarity?
Griest-Kamionkowski

Where is composite dark matter?

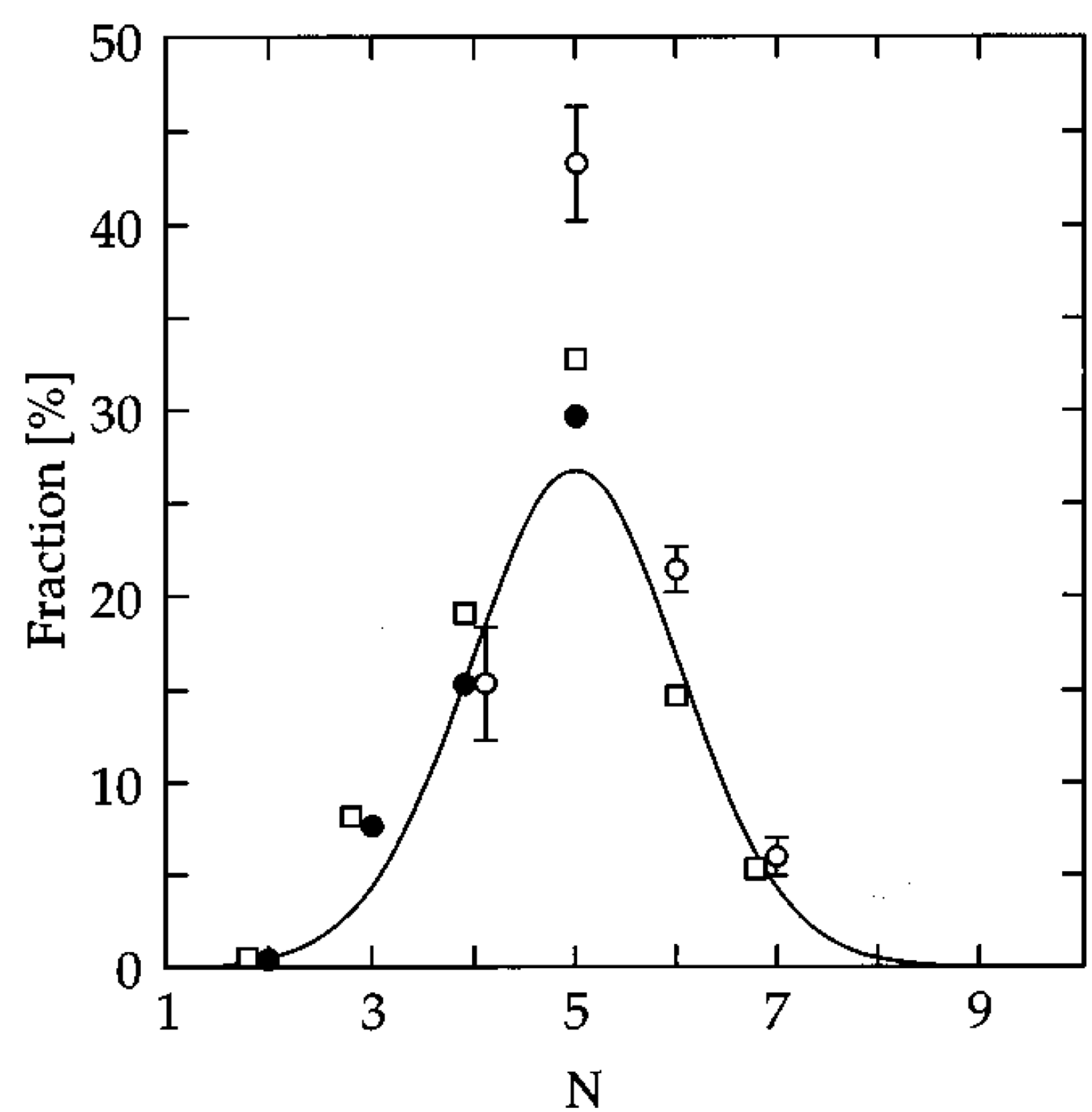
Partial Wave Unitarity

$$(\sigma_J)_{\max} v_{\rm rel} \approx \frac{4\pi(2J+1)}{m_X^2 v_{\rm rel}} \approx \frac{3\times10^{-22}(2J+1)\,{\rm cm}^3/{\rm sec}}{[m_X/(1\ {\rm TeV})]^2}\,.$$

$$\Omega_{\rm dm}h^2 = 0.1199(27) \simeq 3\times10^{-27}{\rm cm}^3{\rm s}^{-1}\langle\sigma_{\rm A}v\rangle^{-1}$$

$$\langle\sigma_{\rm A}v\rangle \sim \frac{\alpha^2}{M_{\rm dm}^2} \sim \alpha^2\left(\frac{100\ {\rm GeV}}{M_{\rm dm}}\right)^2 10^{-21}{\rm cm}^3{\rm s}^{-1}$$

- K. Griest and M. Kamionkowski, PRL 64 (1990) 615
- Assumes only 2→2 scattering.
- Partial wave unitarity sets a limit on the cross section in any partial wave.
- Combining this with the freeze out calculation puts a limit on thermal relics around 300 TeV.
- But, for $N\bar{N}$ annihilation, BR to 2π < 0.01. Naïve GK limit doesn't apply.

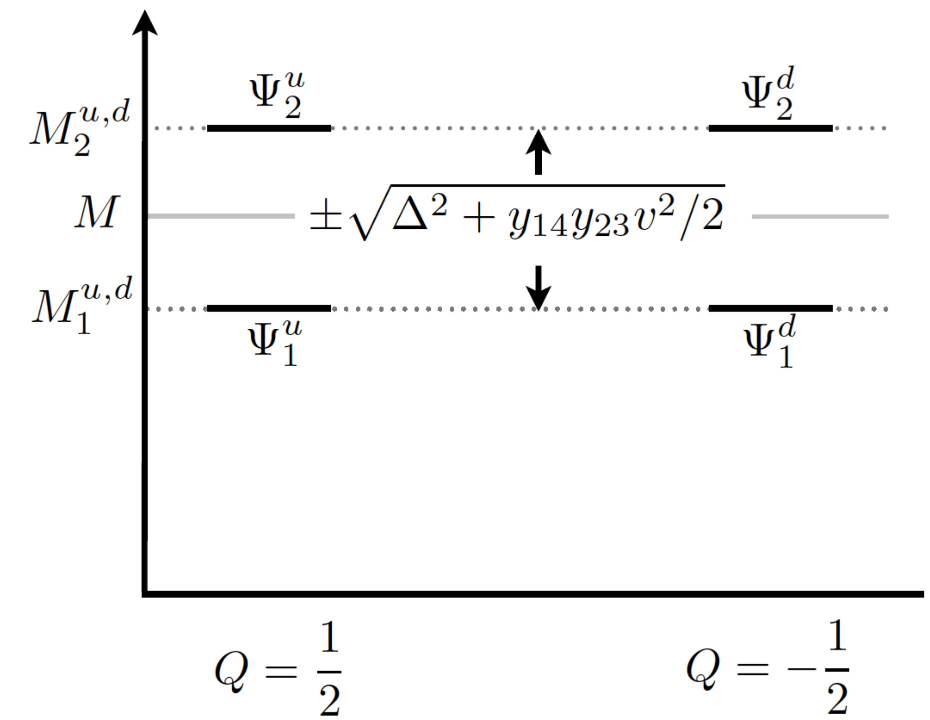


[C. Amsler, RMP 70 (1998) 1293]

Stealth Dark Matter (I)

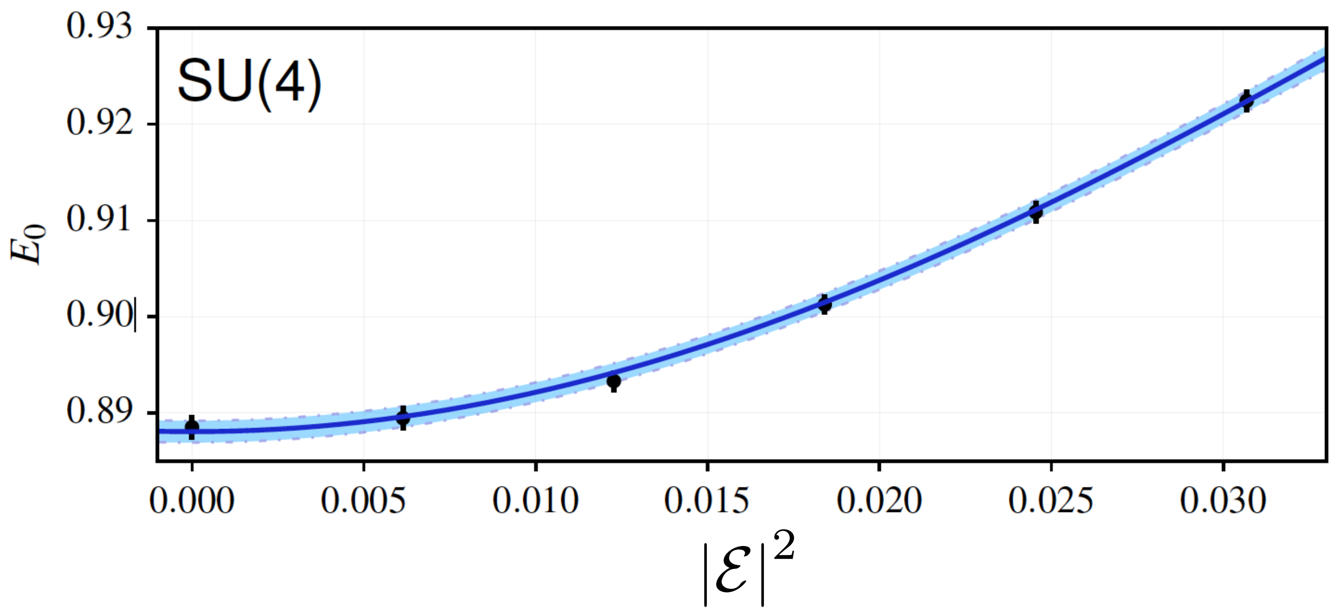
- Composite dark matter can be lighter than 20 TeV if the leading low-energy interaction is dim. 7 polarizability.
- Requires even N_c so that baryons are scalars to eliminate magnetic moment interaction.
- Requires a global SU(2) custodial symmetry to eliminate charge radius interaction.
- Minimal coupling to weak SU(2) to enable dark pion decay. Now some coupling to Higgs boson.
- Also need vector-like masses so that dark sector doesn't impact Higgs vacuum alignment.
- Minimal model: Dark SU(4) color with $N_f = 4$ Dirac flavors.

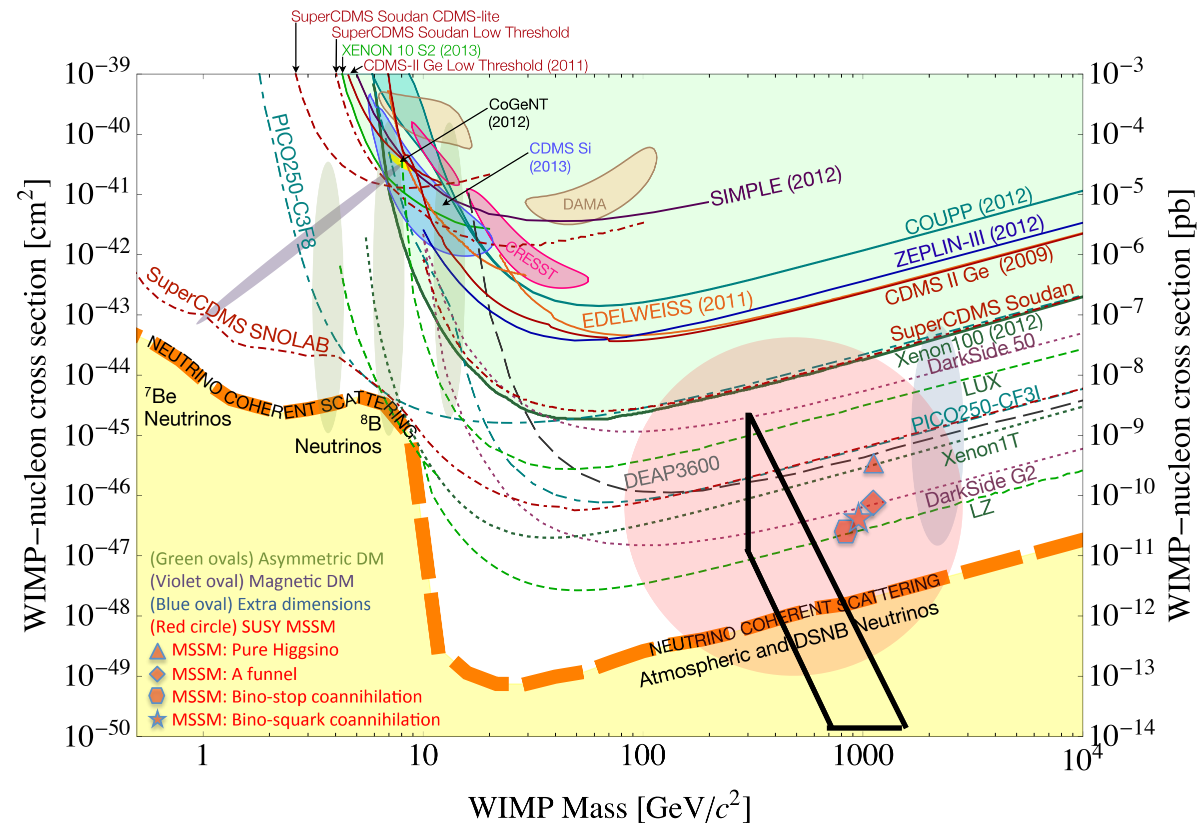
Stealth Dark Matter (II)



- Stable dark baryon is $(\psi_1^u\, \psi_1^u\, \psi_1^d\, \psi_1^d)$.
- Splitting between ψ_1 and ψ_2 Dirac doublets due either to vector mass splitting Δ or Yukawa couplings y.
- Coupling to Higgs can be made as small as needed (not a fine tuning) so that polarizability is dominant DM interaction, yet large enough to ensure no relic density of dark pions.
- Higgs VEV still dominates electroweak vacuum alignment and contributions to S and T parameters are small.
- arXiv:1402.6656, arXiv:1503.04203, arXiv:1503.04205.

SU(4) Polarizability





$$E_0(\mathcal{E}) = M_B + 2C_F\,|\mathcal{E}|^2$$

- Coherent DM-nucleus cross section:

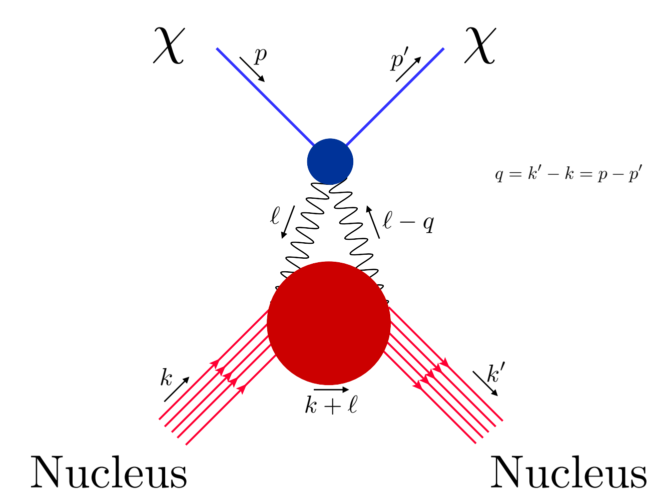
$$\sigma \simeq \frac{\mu_{n\chi}^2}{\pi A}\left\langle \left| C_F f_F^A \right|^2 \right\rangle$$

- Nuclear matrix element [O(3) uncertainty]:

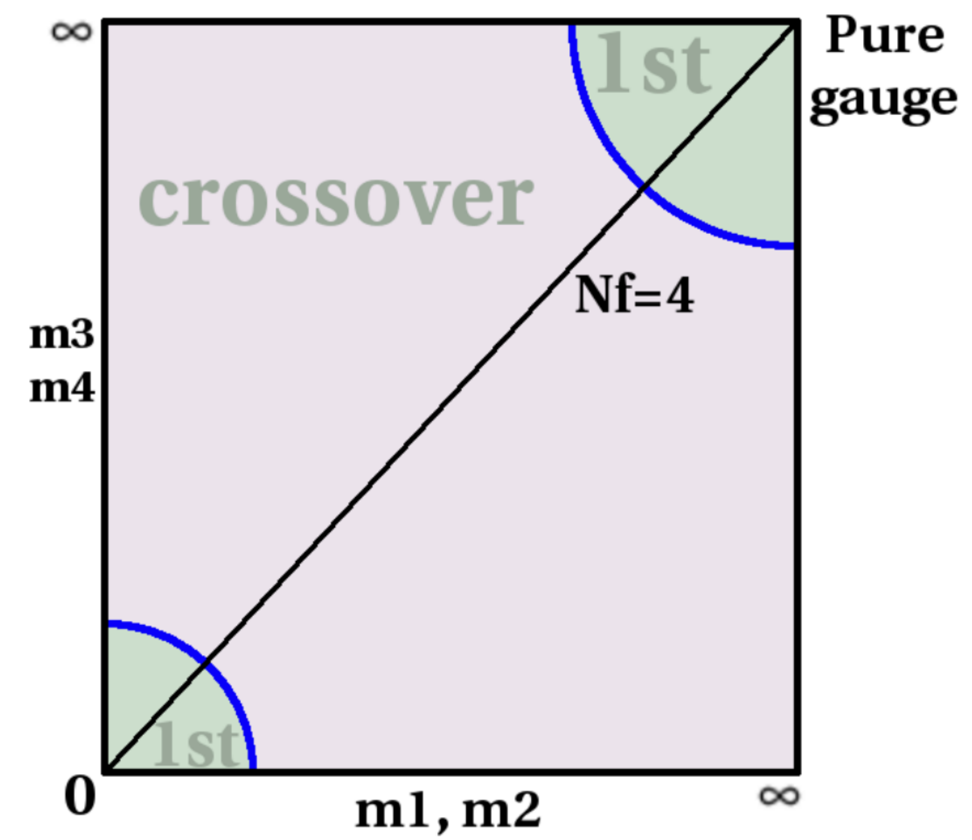
$$f_F^A = \langle A\,|F^{\mu\nu}F_{\mu\nu}|\,A\rangle$$

- Direct detection signal below neutrino background for $M_B > 1$ TeV. Stealth!

- Lower mass limit due to LEP-II bound on new charged particles



Gravity Waves



- SU(4) gauge theory with $N_f=4$ very heavy or very light quark masses expected to have strong first order confinement transition. [Pisarski and Wilczek, PRD 29 (1984) 388]

- Bubble collisions in early universe can lead to stochastic gravitational wave background. [Talk by Admir Greljo]

- LSD is mapping out phase diagram of SU(4) Stealth Dark Matter. So far, first order region in heavy quark regime extends at least as far as $M\pi / M\rho \sim 0.8$. Computation of latent heat and bubble nucleation rate in progress.

- See David Schaich's talk at Lattice 2019 [https://indico.cern.ch/event/764552/contributions/3428284/]

Composite Higgs Boson?

- Typically, UV-complete theories of composite Higgs bosons start with technicolor-like EWSB mechanism.

- In generic technicolor, the Higgs VeV is associated with the techni-pion decay constant: $v \sim f_{\pi T} \sim 250$ GeV.

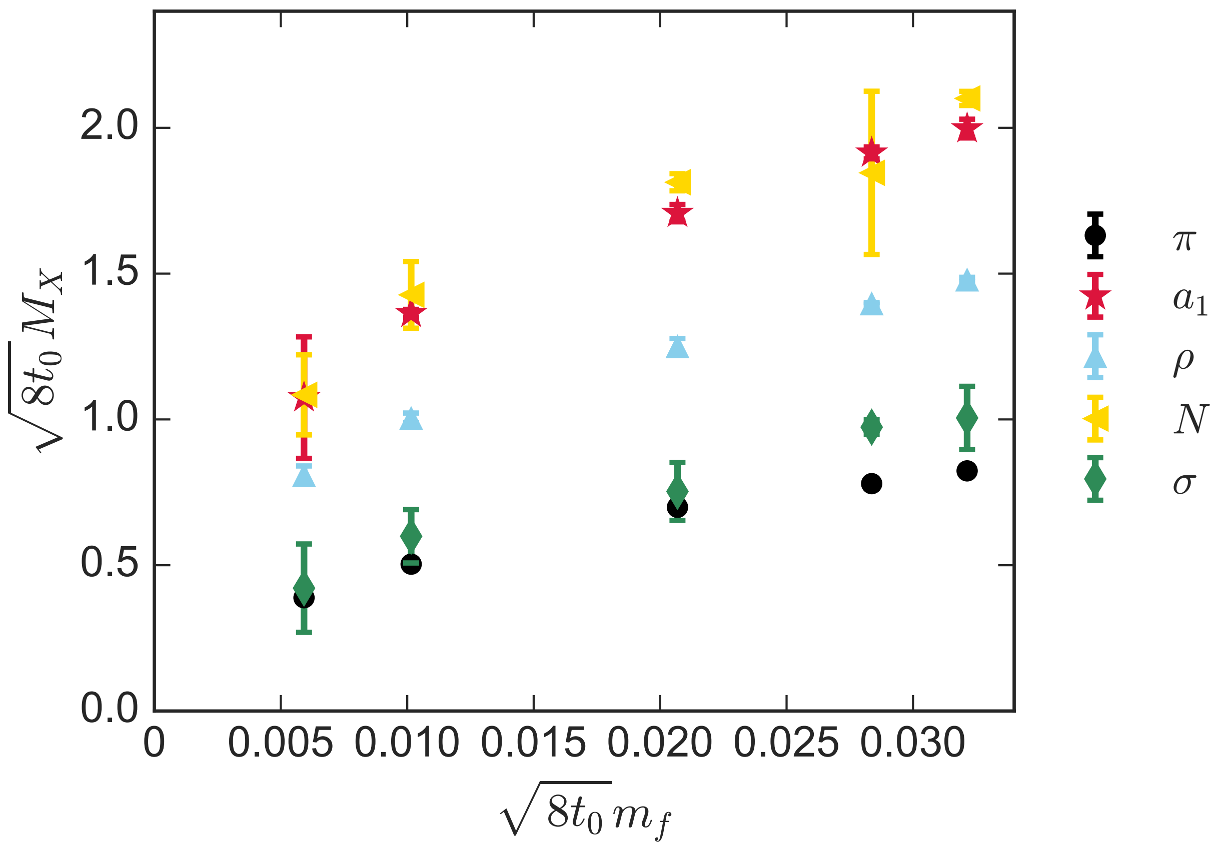
- If the technicolor theory is like QCD, the composite Higgs boson is very heavy (4.3-6.0 $f_{\pi T} \sim$ 1.1-1.5 TeV) broad resonance.

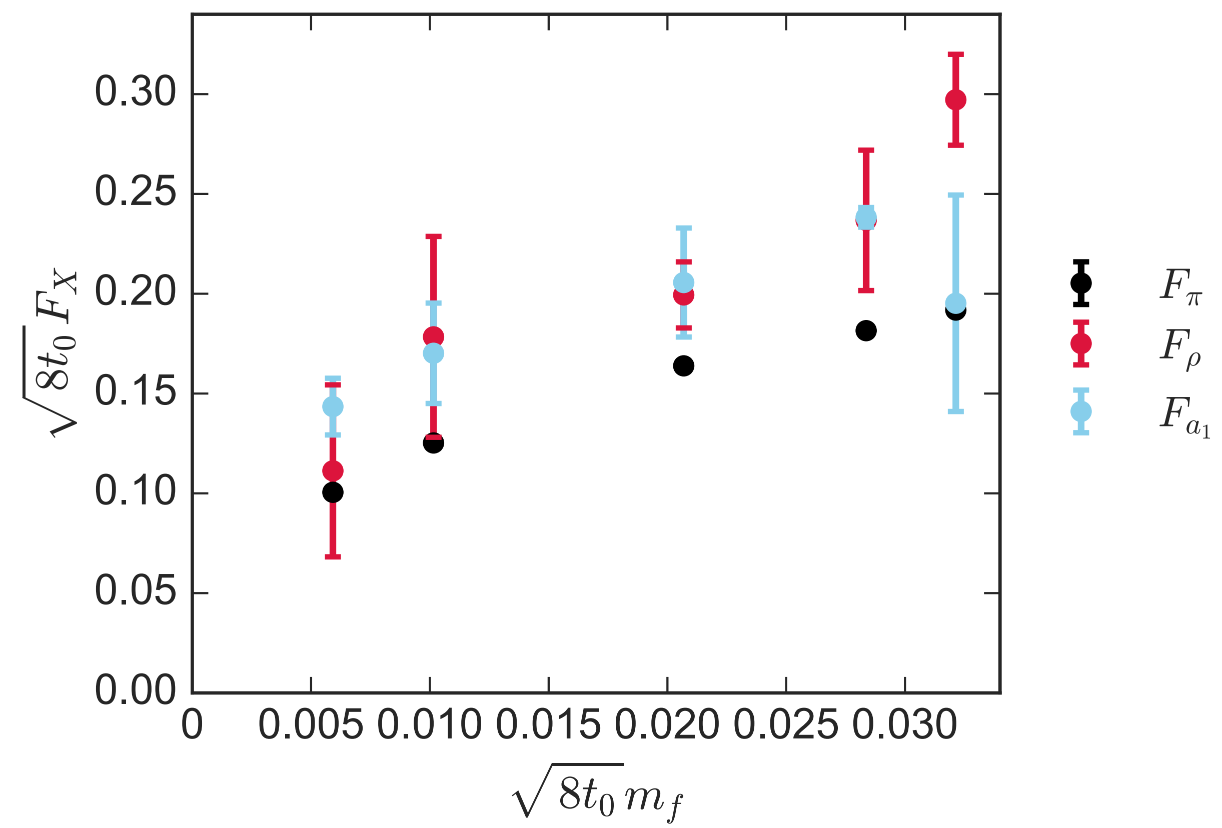
- Viable composite Higgs models must have different dynamics to produce light, narrow Higgs boson.

- Current EFT descriptions based on light Higgs as pseudo-dilaton [GGS, PRL 100 (2008) 111802] or generalized Linear Sigma Model [LSD, PRD 98 (2018) 114510].

Evidence for Light Scalar in SU(3) Nf=8

LSD Collaboration, Phys.Rev. D99 (2019) 014509



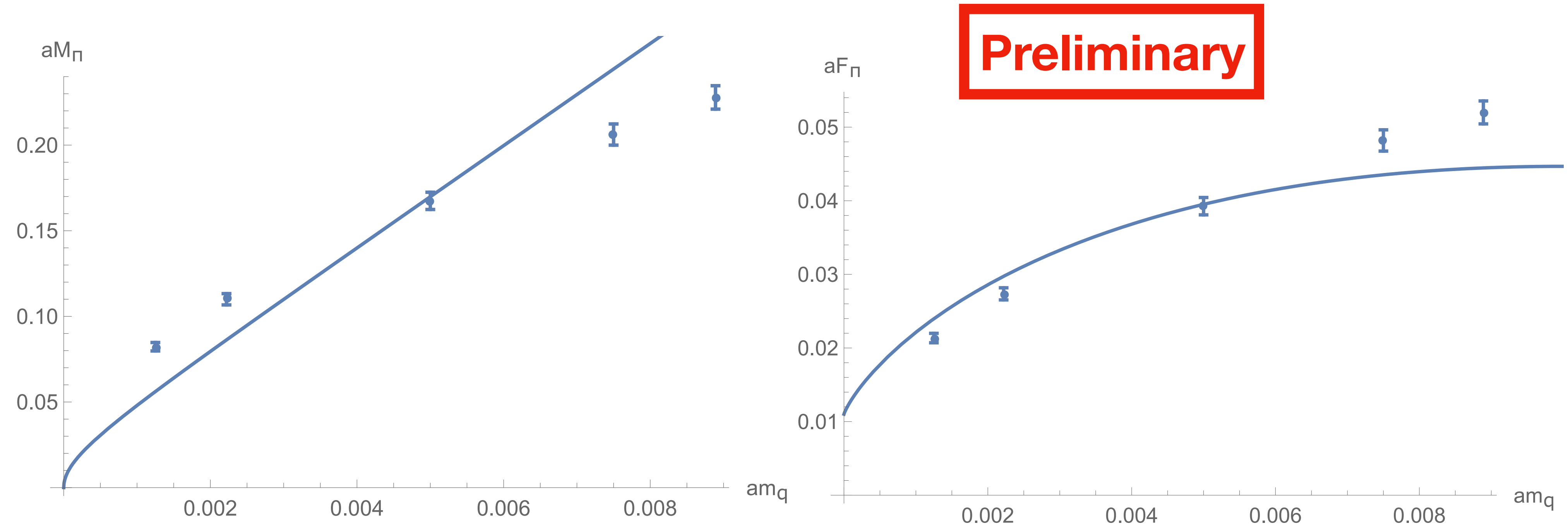


- In LO χPT, $F_\pi(m_q) \sim f_\pi$. The lattice results show NLO >> LO for $F_\pi(m_q)$, but $M_\sigma \sim M_\pi << M_\rho$.

- **Notational convention**: chiral limit m_X , finite quark mass M_X

SU(3) Nf=8 NLO Fits

Lattice units
χ^2/dof=29



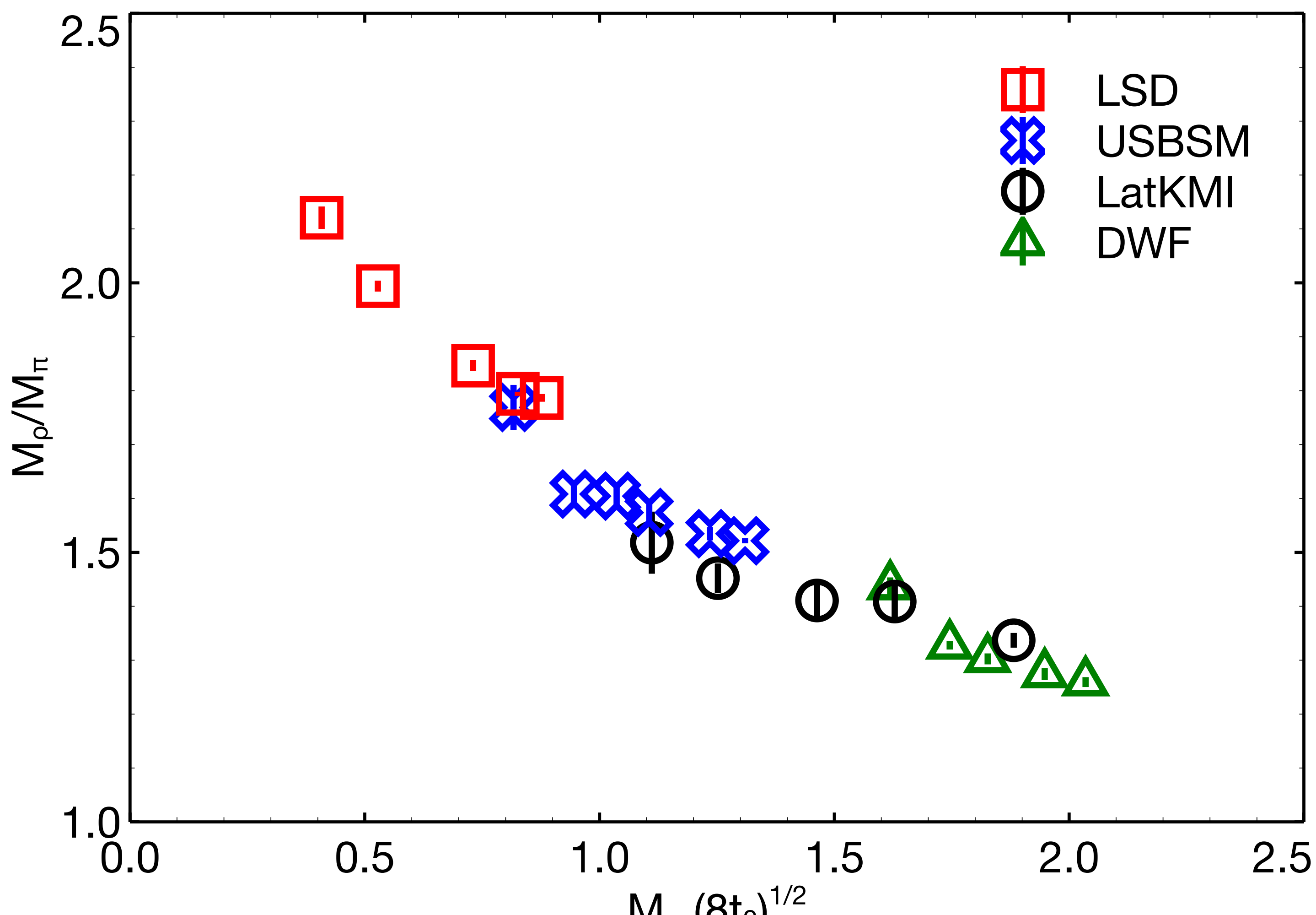
- Large slope on $F\pi$ leads to poor fit for χPT in current mass range.
- Adding a general scalar to chiral Lagrangian will not solve this problem although the fits might have low χ^2/dof due to many fit parameters.

Soto, Talavera, Tarrus, Nucl. Phys. B 866 (2013) 270
Hansen, Langeable, Sannino Phys. Rev. D 95 (2017) 036005
Hansen, Langeable, Sannino arXiv:1810.11993 [hep-ph]
Cata, Mueller arXiv:1906.01879 [hep-ph]

Not hyperscaling

- Mass-deformed IRFP theories have hadron masses which scale in constant ratios in approach to conformity: $M_\rho/M_\pi \sim$ const as $M_\pi \to 0$.
  [Del Debbio and Zwicky, PRD 82 (2010) 014502]
  [Appelquist et al, PRD 84 (2011) 054501]

- Pretty clear evidence that $N_f=8$ is outside conformal window since pion is becoming light relative to rho meson. Very different from $N_f=12$.



Dilaton EFT

Goldberger, Grinstein, Skiba, Phys.Rev.Lett. 100 (2008) 111802
Matsuzaki, Yamawaki, Phys.Rev.Lett. 113 (2014) 082002
Golterman, Shamir, Phys.Rev. D94 (2016) 054502
Appelquist, Ingoldby, Piai, JHEP 1707 (2017) 035

- A general feature of Dilaton EFT's is that the dilaton has a separate breaking potential with it's own condensate f_d (not unlike χPT+scalar).
- But, the EFT is predictive because the requirement that the scalar couple to NGBs as conformal compensator fixes most LECs.
- The near-degeneracy of $M_\pi \sim M_\sigma$ over a range of masses (*i.e. same slope*) has flavor-dependent consequence for f_d:
  $M_\pi^2 \sim m_q$, $M_d^2 \sim N_f\,(f_\pi^2\,/\,f_d^2)\,m_q$.
- Implies $f_d \sim \mathrm{sqrt}(N_f)\,f_\pi$. This will lead to deviations in scalar self-couplings from Higgs-like behavior. *n.b.* for sextet model $N_f=2$.

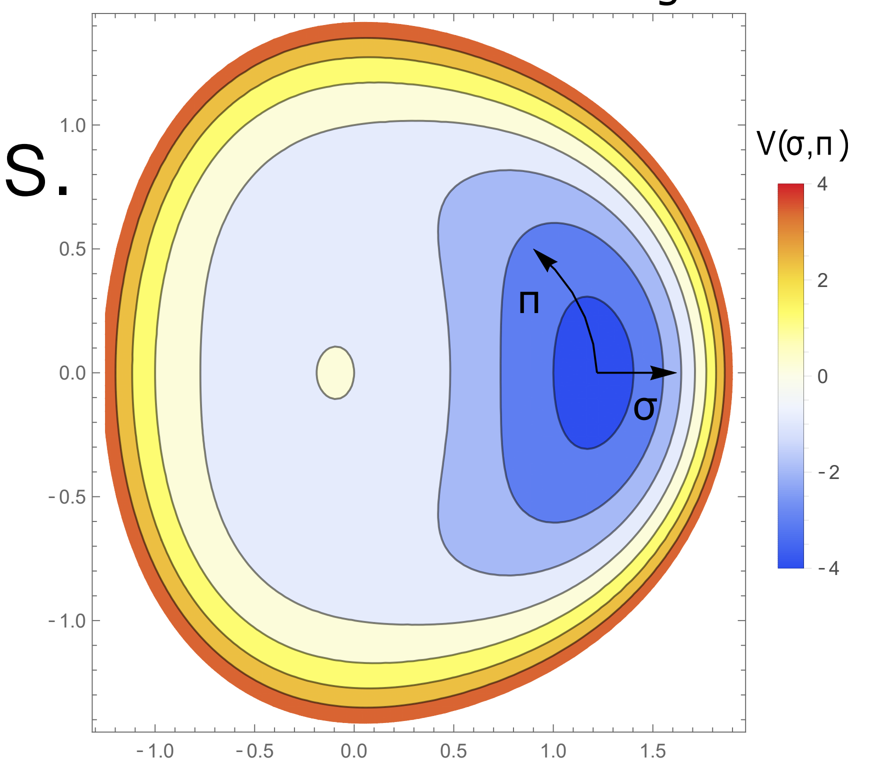
$$M_\pi^2 = BF_\pi^{\,p-2}, \quad M_d^2 = \frac{yN_f f_\pi^2}{2f_d^2}(p-y)BF_\pi^{\,p-2}.$$

Linear Sigma Model EFT

LSD Collaboration, Phys.Rev. D98 (2018) 114510
Floor, Gustafson, Meurice, Phys.Rev. D98 (2018) 094509

- Gell-Mann-Levy linear sigma model was early EFT for QCD. $N_f=2$ version isomorphic to O(4). Only π and σ included. Naively renormalizable as $\Lambda\to\infty$.
- $N_f>2$ requires additional dof: a_0, η'. Removing heavy η' means no longer renormalizable as $\Lambda\to\infty$.
- Can naturally incorporate light a_0 mesons.
- Very predictive as vev of σ tied to χSB.
- Naïve problem with slopes: $M_\pi^2 \sim m_q$, $(M_\sigma^2 - m_\sigma^2) \sim 3\ m_q$.

Scalar Potential in Linear Sigma EFT



Explicit Symmetry Breaking

Spurion $\chi = B\, m_q$, $B \sim \langle qq \rangle / f_\pi^2$

$$V_{SB} = -\sum_{i=1}^{9} \tilde{c}_i O_i(x),$$

Relative size of χSB:

$$\frac{m_q B_\pi}{\Lambda^2} \sim \left(\frac{M_\sigma}{\Lambda}\right)^\alpha \ll 1$$

Estimate: $\Lambda \sim M_\rho$ when $M_\rho = 2\, M_\pi$

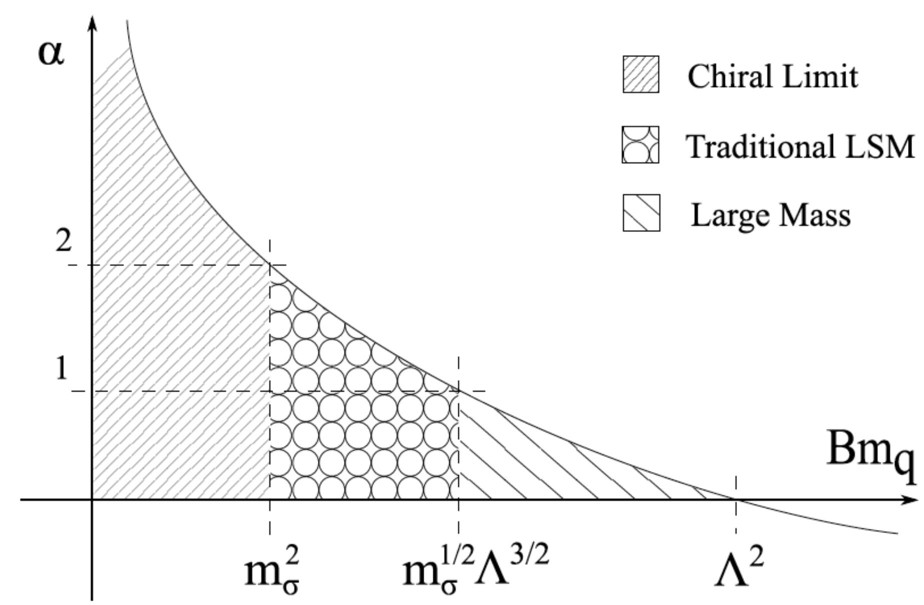
Symbol	Operator	$\alpha \lesssim 1$	$1 < \alpha \leq 2$
O_1	$\langle \chi^\dagger M + M^\dagger \chi \rangle$	✓	✓
O_2	$\langle M^\dagger M \rangle \langle \chi^\dagger M + M^\dagger \chi \rangle$	✓	X
O_3	$\langle (M^\dagger M)(\chi^\dagger M + M^\dagger \chi) \rangle$	✓	X
O_4	$\langle \chi^\dagger M + M^\dagger \chi \rangle^2$	✓	X
O_5	$\langle \chi^\dagger \chi M^\dagger M \rangle$	✓	X
O_6	$\langle \chi^\dagger \chi \rangle \langle M^\dagger M \rangle$	✓	X
O_7	$\langle \chi^\dagger M \chi^\dagger M + M^\dagger \chi M^\dagger \chi \rangle$	✓	X
O_8	$\langle \chi^\dagger \chi \rangle \langle \chi^\dagger M + M^\dagger \chi \rangle$	✓	X
O_9	$\langle (\chi^\dagger \chi)(\chi^\dagger M + M^\dagger \chi) \rangle$	✓	X

$$\frac{F^2}{f^2} = 1 + \frac{2}{m_\sigma^2}\left[2Bm_q\frac{f}{F} + 6Bm_q(c_2+c_3)F + 2B^2m_q^2(4c_4+c_5+c_6+2c_7) + 2B^3m_q^3\frac{c_8+c_9}{F}\right],$$

$$M_\pi^2 = 2Bm_q\frac{f}{F} + 2Bm_q(c_2+c_3)F + 8B^2m_q^2(c_4+c_7) + 2B^3m_q^3\frac{c_8+c_9}{F},$$

$$M_\sigma^2 = m_\sigma^2 + 6Bm_q\frac{f}{F} + 6Bm_q(c_2+c_3)F + 4B^2m_q^2(4c_4+c_5+c_6+2c_7) + 6B^3m_q^3\frac{c_8+c_9}{F},$$

$$M_a^2 = m_a^2\frac{F^2}{f^2} + 4Bm_q\frac{f}{F} + 8Bm_q c_2 F + 2B^2m_q^2(8c_4+c_5+c_6+2c_7) + 4B^3m_q^3\frac{c_8+c_9}{F}.$$



$M_\sigma^2 \geq 3\, M_\pi^2$?

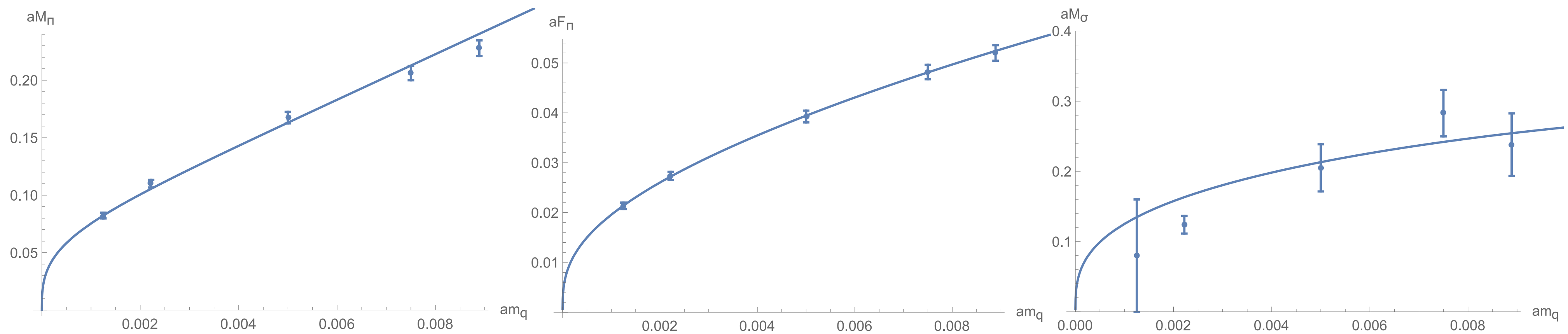
$$3M_\pi^2 - M_\sigma^2 + m_\sigma^2 = 4B^2m_q^2(2c_4 - c_5 - c_6 + 4c_7),$$

- If m_σ is light ($\sim f_\pi$) new kinematic regimes are opened in the linear sigma model. These new regimes match lattice results.

SU(3) Nf=8 LSM9 LO Fits

Preliminary

Lattice units
χ^2/dof=1.30



- LSM with 9 LO breaking terms, required when *Mσ ~ Mπ*, so far is good description of lattice results.

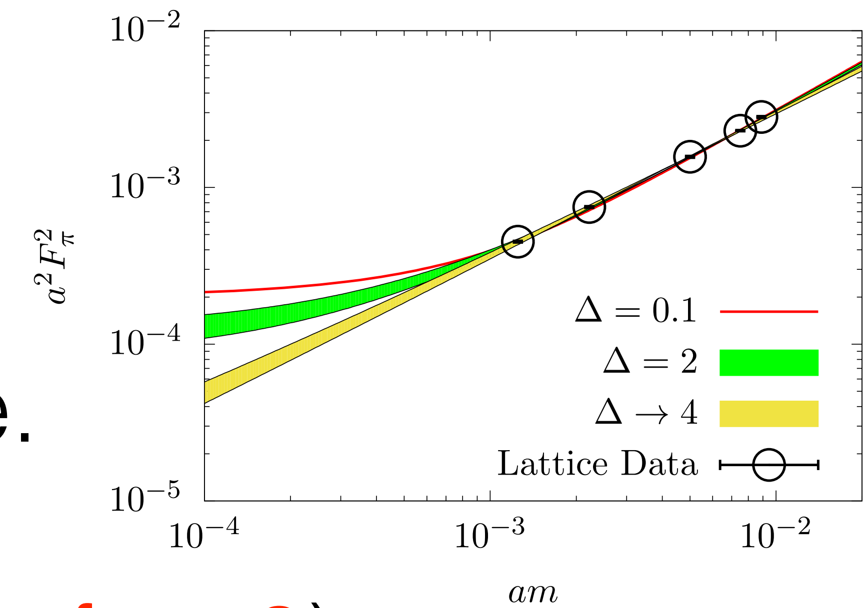
- James Ingoldby has computed dilaton and LSM EFT expressions for *I=0,1,2 ππ* scattering lengths *a* and effective ranges *b*, scalar decay constant *Fσ~⟨σ|ψψ|0⟩*. Lattice calculations underway.

$$a_{PP}M_\pi = -\frac{M_\pi^2}{16\pi F_\pi^2} + \frac{c_4 B^2 m_q^2}{\pi N_f F_\pi^2} + \frac{c_7 B^2 m_q^2}{2\pi F_\pi^2} + \frac{\left[-M_\pi^2 + 4(c_2+c_3)F_\pi\sqrt{\frac{N_f}{2}}Bm_q + 8(c_4+c_7)B^2 m_q^2\right]^2}{8\pi N_f F_\pi^2 M_\sigma^2}.$$

Preliminary

SU(3) Nf=8 Dilaton Fits

[Appelquist, Ingoldby, Piai, arXiv:1908.00895]

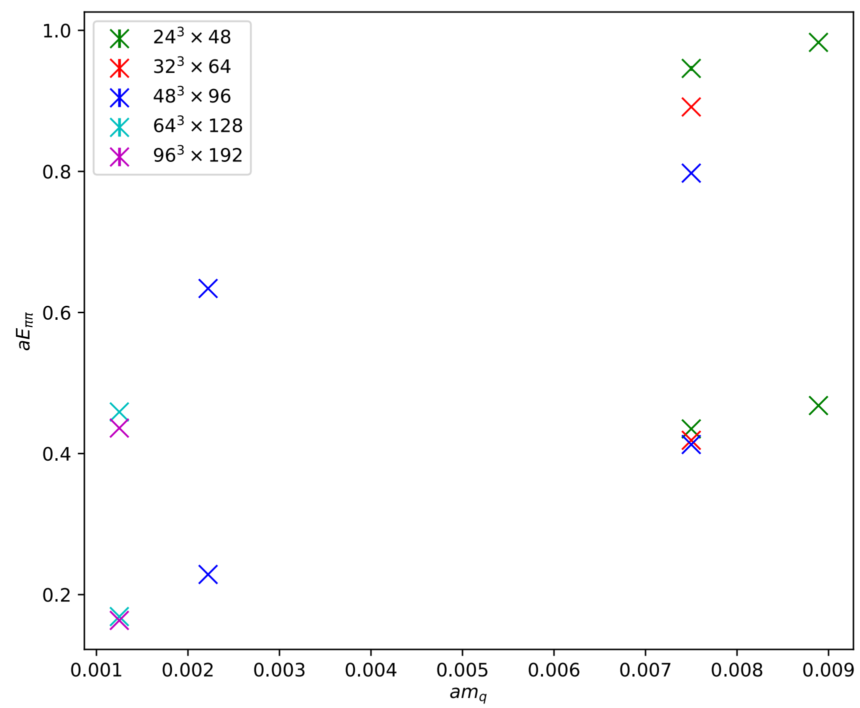


- Dilaton potential should be sensitive to scaling dimension Δ of leading operator breaking conformal invariance.
- $\Delta \to 4$ approaches hyperscaling limit (m_σ, $f_\pi \to 0$)
- Current lattice calculations $M_\sigma \sim M_\pi$ do not constrain Δ but upcoming calculations at smaller quark masses will.

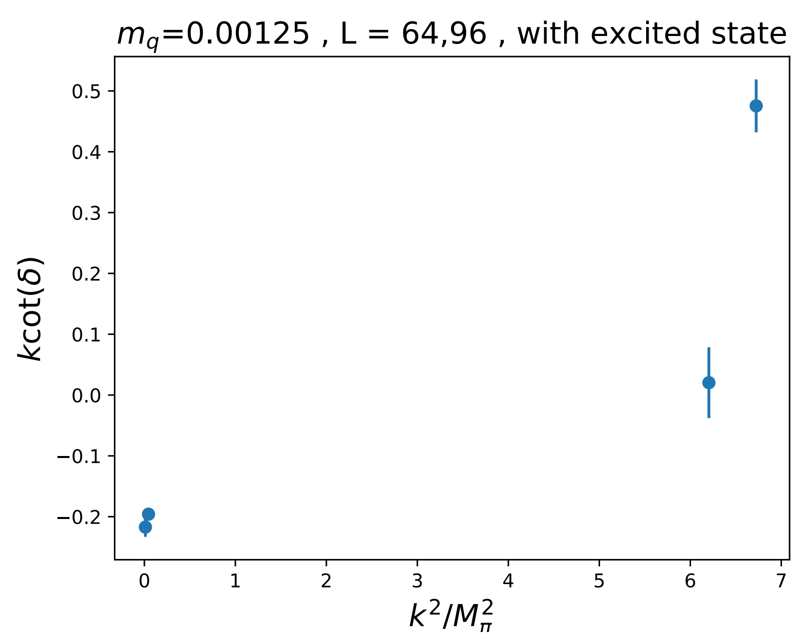
$$\mathcal{L} = \frac{1}{2}\partial_\mu\chi\partial^\mu\chi + \mathcal{L}_\pi + \mathcal{L}_M - V(\chi)\,, \qquad \mathcal{L}_\pi = \frac{f_\pi^2}{4}\left(\frac{\chi}{f_d}\right)^2 \mathrm{Tr}\left[\partial_\mu\Sigma\,(\partial^\mu\Sigma)^\dagger\right] \qquad \mathcal{L}_M = \frac{m_\pi^2 f_\pi^2}{4}\left(\frac{\chi}{f_d}\right)^y \mathrm{Tr}\left[\Sigma + \Sigma^\dagger\right]$$

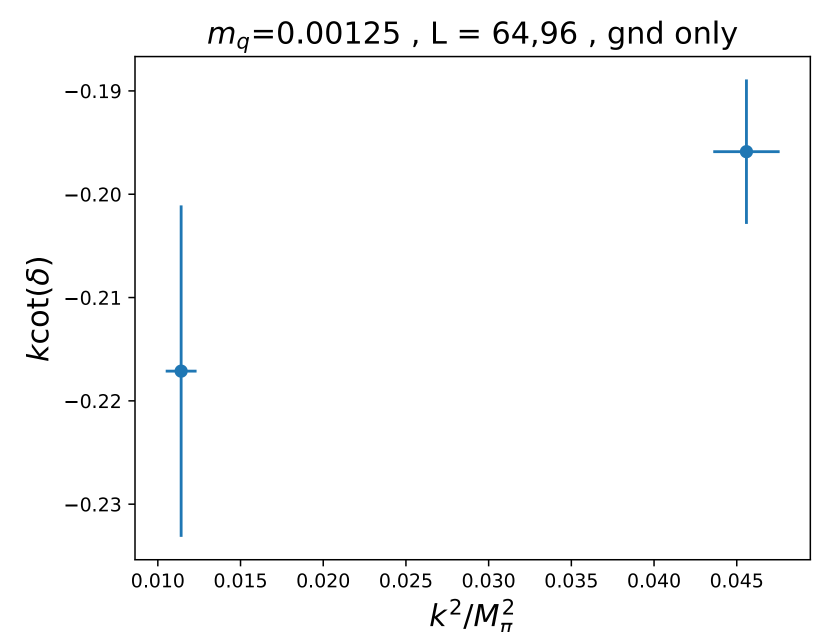
$$V_\Delta(\chi) \equiv \frac{m_d^2\chi^4}{4(4-\Delta)f_d^2}\left[1 - \frac{4}{\Delta}\left(\frac{\chi}{f_d}\right)^{\Delta-4}\right]$$

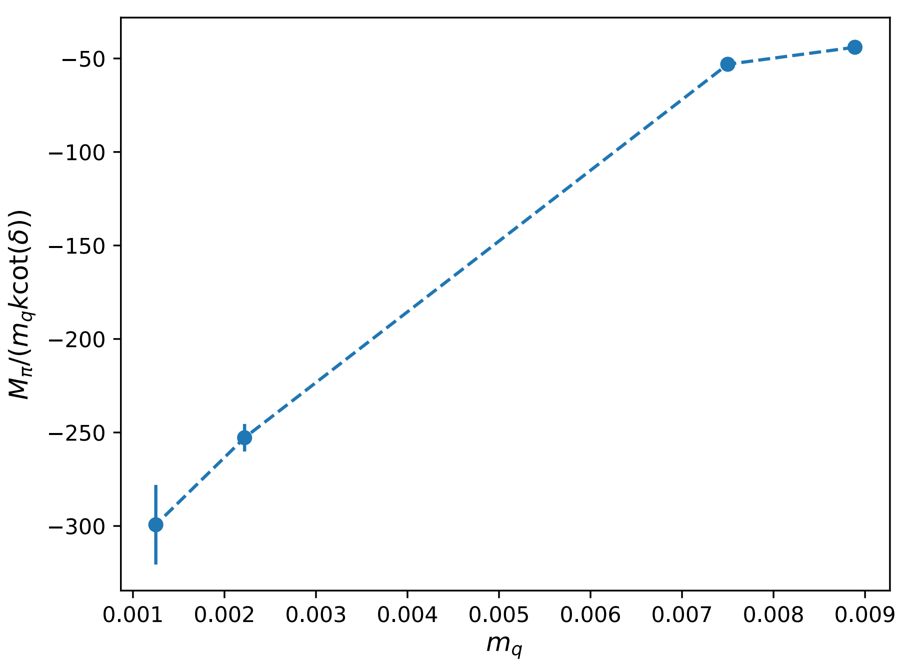
I=2 $\pi\pi$ scattering



Two-pion energy levels in various box sizes.
Big gap in scattering k^2 using excited states.
Working on using moving frames.
Still some sensitivity to effective range.







The ratio on the left should be constant at LO in chiPT.
Fits to other EFT's in progress:

$a_{\pi\pi} M_\pi = - M_\pi^2/(16\pi F_\pi^2) + \ldots$

LSD Collaboration, Phys.Rev.D 85 (2012) 074505
Gasbarro, Fleming, PoS LATTICE2016 (2017) 242

Summary

- Confinement mechanism naturally generates mass scales below the Planck scale.
- Confinement may play a role in Higgs sector and dark matter.
  - Confinement can generate naturally light isosinglet scalars, essential for composite Higgs boson. Dynamics is different than QCD.
  - Confinement can also sequester charged constituents in to neutral composites, a natural mechanism in composite dark matter.
- New confining sectors may generate gravitational waves through confinement transitions in early universe if first order.
- If dark matter is baryonic, do dark nuclei form?

Backup Slides

What is Compositeness?

- My definition of composite BSM physics will be new species of fermions, charged under a new confining gauge interaction.
    - In EWSB context, this new interaction is often called *technicolor*.
    - In the dark matter context, this new gauge interaction is often called *dark color*.
- These new constituent fermions usually carry some SM charges. Otherwise the model would be truly dark.
- New constituent fermions can be massless (if NG bosons needed) or massive (vector-like mass terms are technically natural).

Hints or Coincidences? (I)

- $\Omega_{DM} / \Omega_B \sim 5.3$.

- Baryonic matter-antimatter asymmetry: $n_B \gg n_{\overline{B}}$

- If dark matter is also asymmetric *and* $n_{DM} \sim n_B$:

- $M_{DM} \sim 5.3\ M_B \sim 5$ GeV.

- Is it just a coincidence that the baryonic and dark matter densities are of the same order of magnitude? Or should we be looking for 5 GeV dark matter?

- Counter example: $\Omega_v << \Omega_{DM}$ but it's not clear that they couldn't have been of the same order.

Hints or Coincidences? (II)

- Ω_{DM} could have been set by thermal freeze-out, leading to a symmetric abundance: $n_{DM} = n_{\overline{DM}}$
- Freeze-out occurs when the temperature falls below the mass and the abundance is determined by the annihilation cross section.
- If dark matter were to have a mass around 100 GeV, to get the right symmetric abundance, it should have an annihilation cross section whose magnitude is typical of electroweak processes.
- Is it a coincidence or a "miracle"? Or, should we look for 100 GeV dark matter that is somehow tied to electroweak physics?

Astrophysical Hints?

- Dark matter plays a big role in galaxy formation and there are observations that don't agree with ΛCDM simulations:
  - Bulge-less disk galaxies, Cusp/Core problem, "Too Big to Fail", Missing Satellites.
- One proposed solution to some of these problems is to make self-interacting dark matter.

$\sigma(v_{\rm rms})/M \sim 0.5 - 50\ {\rm cm^2\ g^{-1}}, \quad v_{\rm rms} \simeq 10 - 100\ {\rm km\ s^{-1}}$ arXiv:1412.1477

- Translate these numbers into natural units, it suggests dark matter masses as low as 10 MeV if weakly-coupled, up to 5 GeV if strongly coupled. Another coincidence?
- A more mundane possibility is baryon physics left out of simulations is responsible can explain anomalies. arXiv:1501.00497 [astro-ph]

Dark Matter Summary

- Dark matter constituents can carry electroweak charges and still the stable composites are currently undetectable. Stealth!
- No new forces required beyond SU(N) confining dark color force.
- Abundance can arise either by symmetric thermal freeze-out or by asymmetric dark baryogenesis.
- Future experiments could eventually rule out dark baryons with mag moments, even beyond the Griest-Kamionkowski bound.
- Composite dark matter around 1 GeV is still a challenge due to LEP bounds.
- We need to work harder to inform the broader DM community about our exciting results!

Scalar Sector of QCD (I)

- The linear sigma model is the classic low energy description of χSB in QCD but it is unclear what sets the mass scale for the **σ** meson, *i.e.* the lightest 0^{++} meson.

- QCD has five (or six) light isoscalar scalars below charm threshold: $f_0(500)$, $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$ [and maybe $f_0(1790)$].

- Only two of these states can be predominantly $(\bar{q}q)$, others might be $(\bar{q}\bar{q})(qq)$ or $(\bar{q}q)(\bar{q}q)$ or even glue balls or pseudo-dilatons. Which one is the **σ**?

- One recent model [Janowski, Giacosa, Rischke, PRD 90 114005 (2014)] has all these effective dof's yet can't yet reproduce $f_0(500)$.

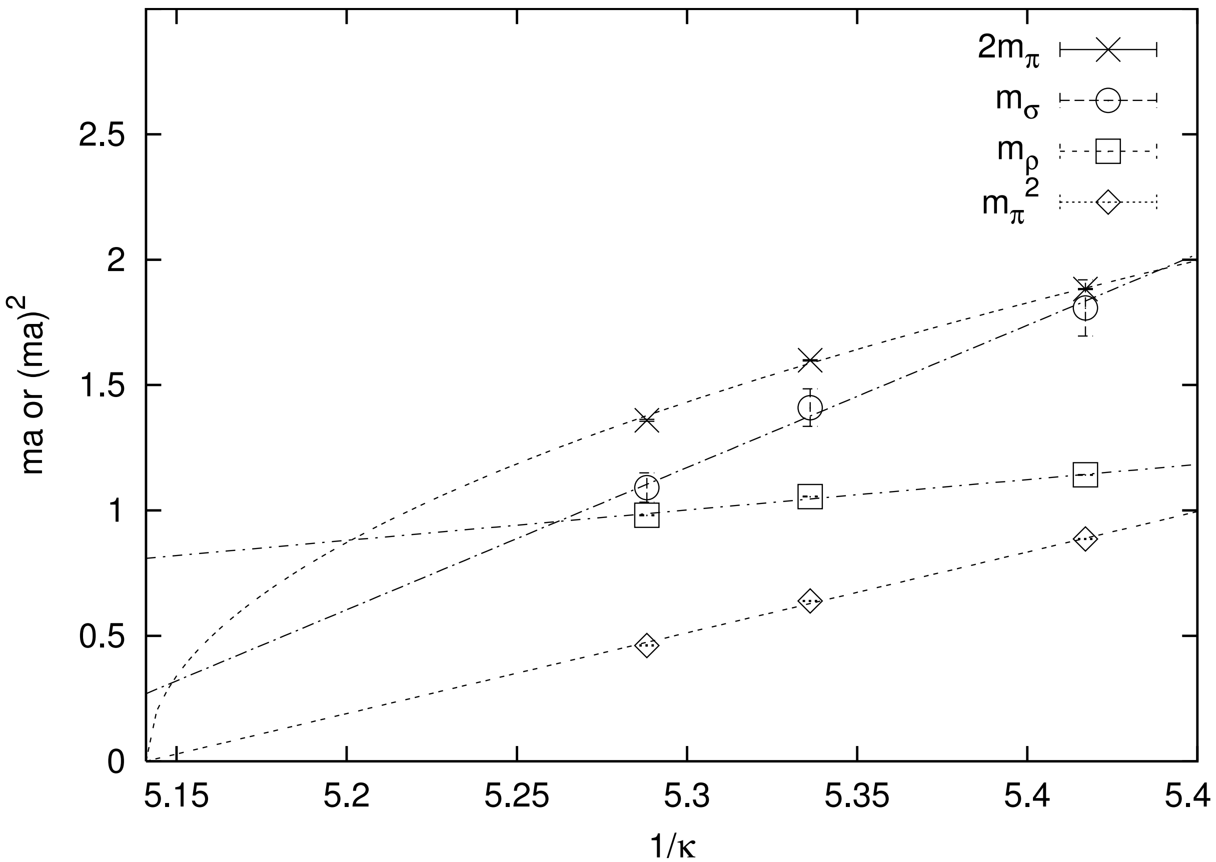
- I've been told that lattice QCD calculations of $I=0$ $\pi\pi$ scattering are underway and that results might be available within a year.

Scalar Sector of QCD (II)

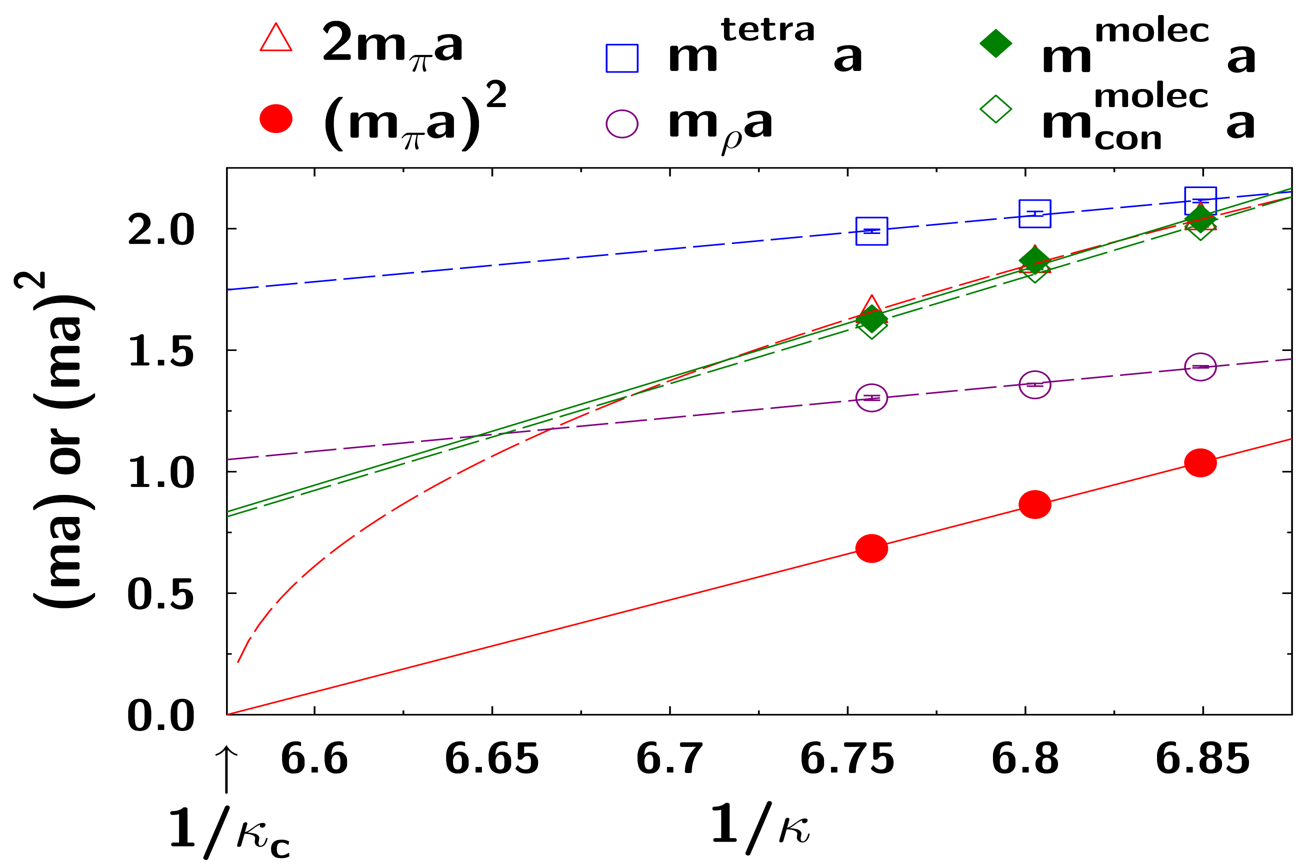
- With first lattice QCD results of the $f_0(500)$ resonance, perhaps something interesting can be said about the heavy quark limit, where isotriplet states become heavier than glueballs:
  - At what quark mass does the σ become stable?
  - At what quark mass does the σ become as light as the π?

Scalar Sector of QCD (III)

- Some heavy quark results from lattice SCALAR collaboration:



T. Kunihiro et al,
PRD **70**, 034504 (2004)



M. Wakayama et al,
PRD **91**, 094508 (2015)

Naive Argument Against Composite Higgs

- In QCD, $M_\sigma \approx 4\ f_\pi$, and it's width is large. Assume this is a generic feature of confining, chirally-broken gauge theories.

- If the Higgs boson was composite, it's mass should be $M_h \approx 4{\times}250$ GeV with a very broad width. That's not what's observed at LHC so Higgs is not composite.

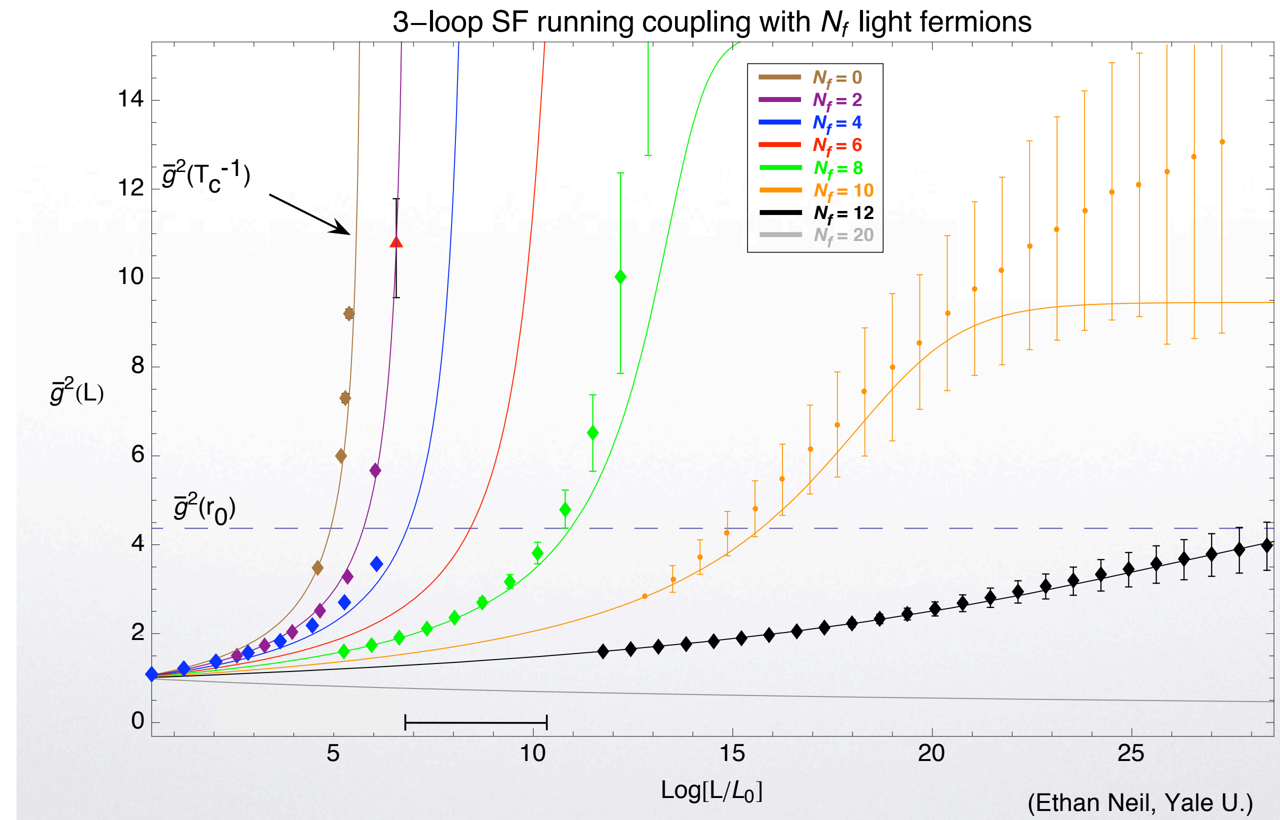
- But In QCD, we've experimentally seen at least five scalar states plus the rest of the meson spectrum and yet we still don't have a clear understanding of the lightest scalar. So, what gives us confidence that we can rule out compositeness for the SM Higgs boson after having observed a single state?

What happens to QCD with increasing N_f?

- In QCD, $\overline{g}(L)$ is asympotically free and runs rapidly until SSB and confinement: $\overline{g}(L_c)=\overline{g}_c$.

- As N_f increases, the running slows down.

- For large N_f, $\overline{g}(L)$ flows to $\overline{g}^*$ at IR fixed point(IRFP). No EWSB, no 126 GeV boson.



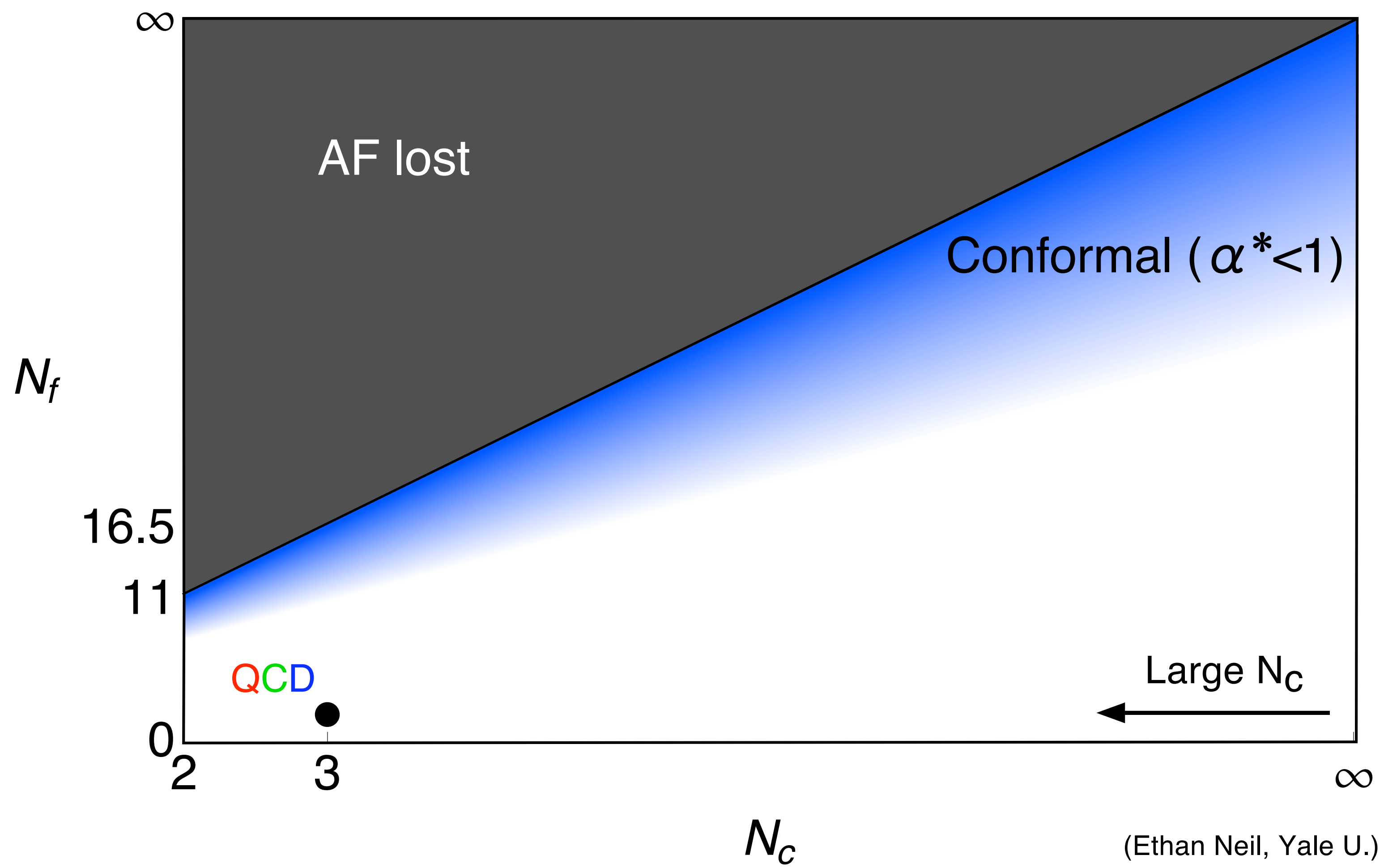
- Walking theories may exist nearby theories with strongly-coupled IRFP: $\overline{g}^* \lesssim \overline{g}_c$.

- Unlike QCD, walking theories have two dynamically generated scales: $\Lambda_{IR} << \Lambda_{UV}$ and the theory is nearly conformal between IR and UV scales.

- In composite Higgs models, usually $\Lambda_{UV} >$ 1000 TeV is preferred and Λ_{IR} is related to scale of EWSB.

Looking for Pseudo-Dilatons

- For $N_f = 0–1$, confinement but no NG bosons.
- For $N_c = 2$, enhanced chiral symmetry $SU(2N_f)/Sp(2N_f)$. pNGB Higgs?
- Pert. theory indicates IRFP for $N_f \lesssim 5.5 \cdot N_c$.

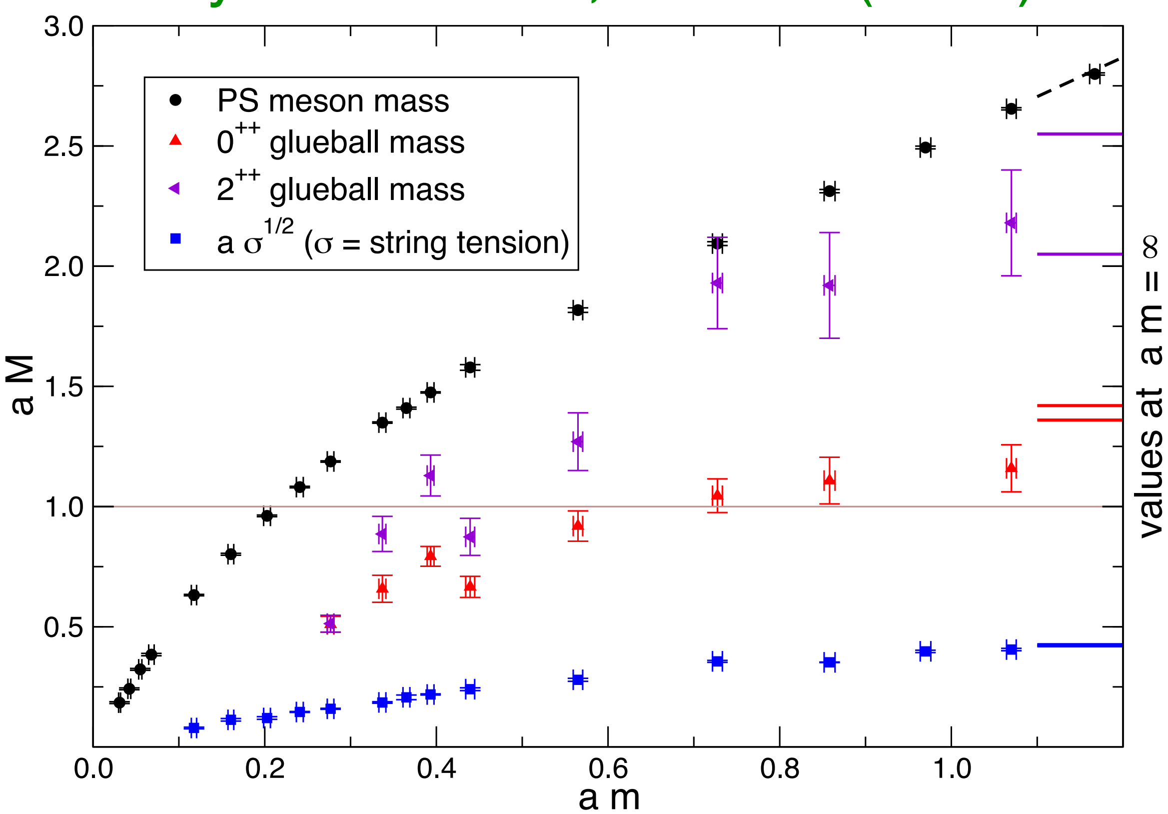


- What is the nature of the quantum phase transition at the bottom of the conformal window? Are pseudo-dilatons an order parameter?
- One simple search strategy: start from QCD and increase N_f.

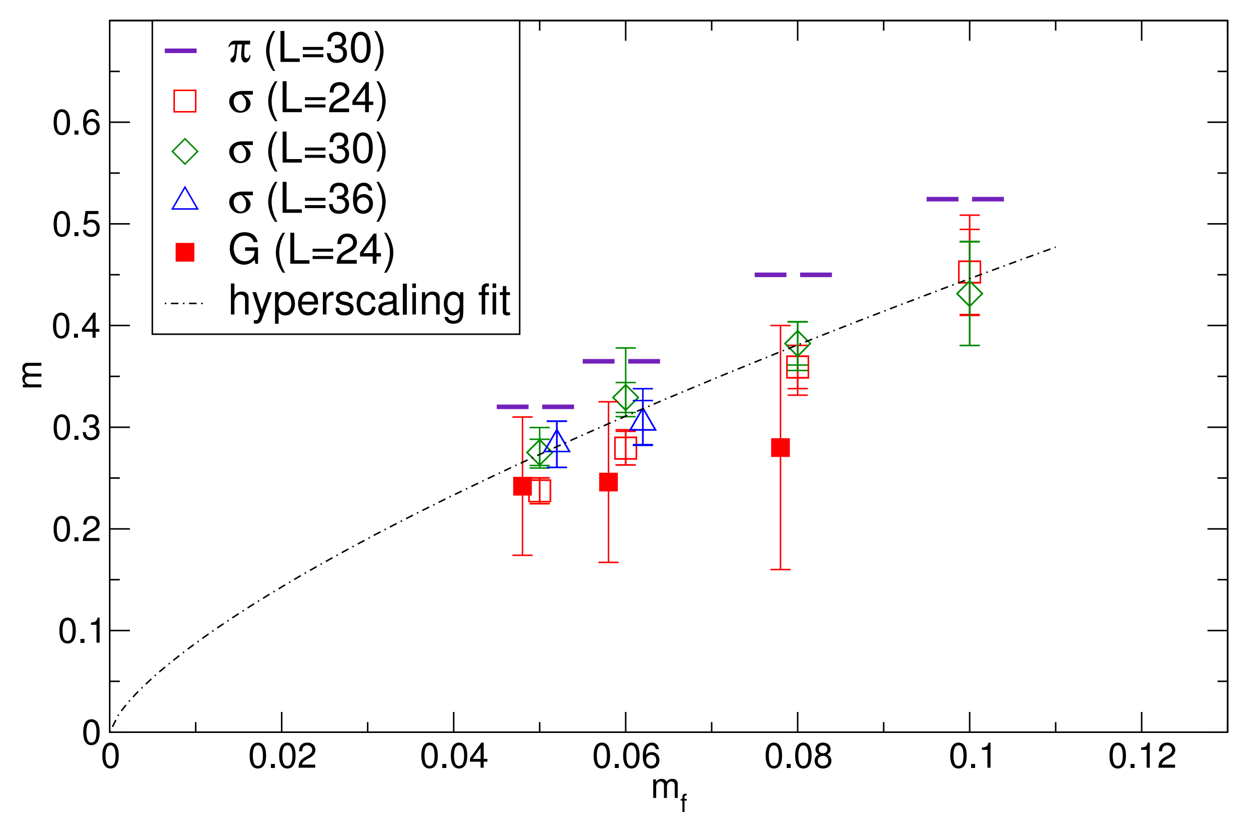
Counterexample (I)

- Mass-deformed IRFP theories seem to have very light scalars.

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



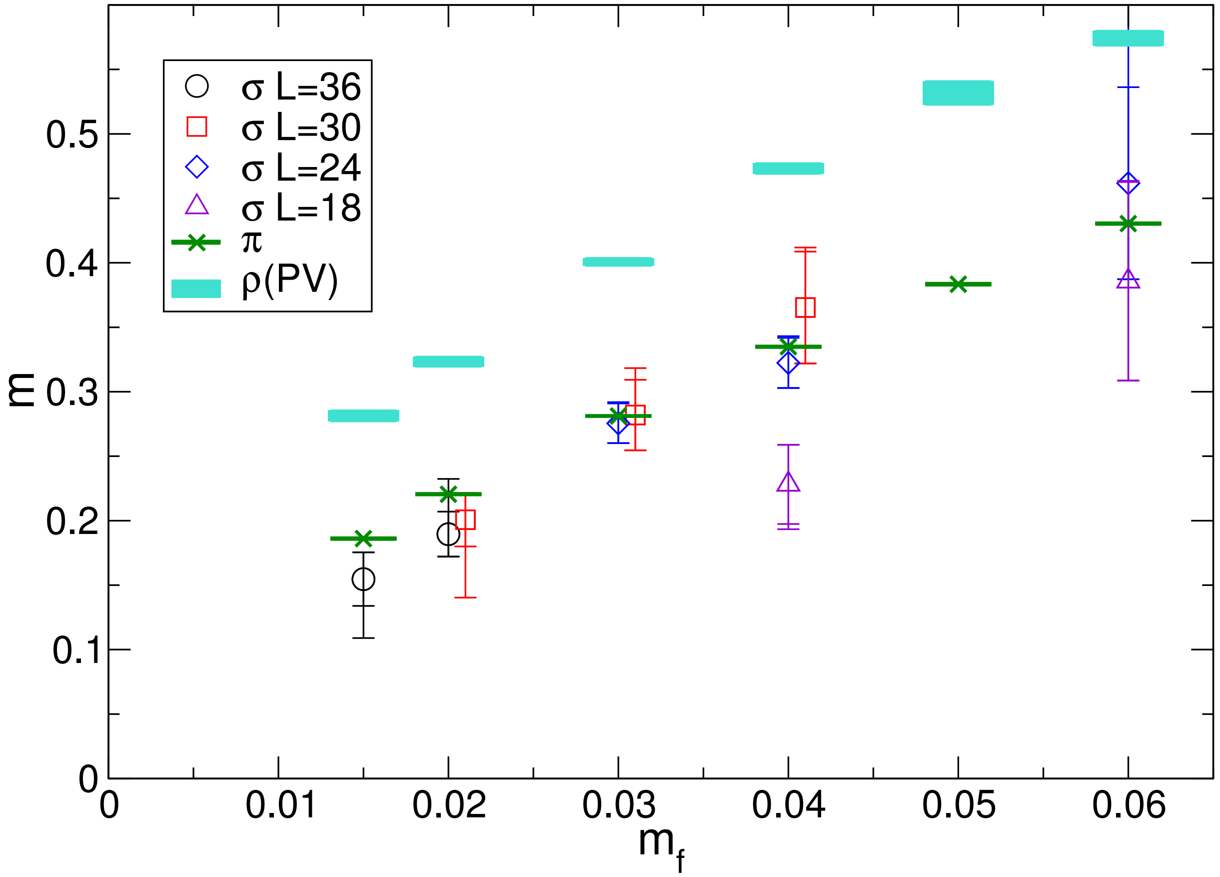
SU(3) N_f=12 fund
LatKMI
Phys. Rev. Lett. 111, 162001 (2013)



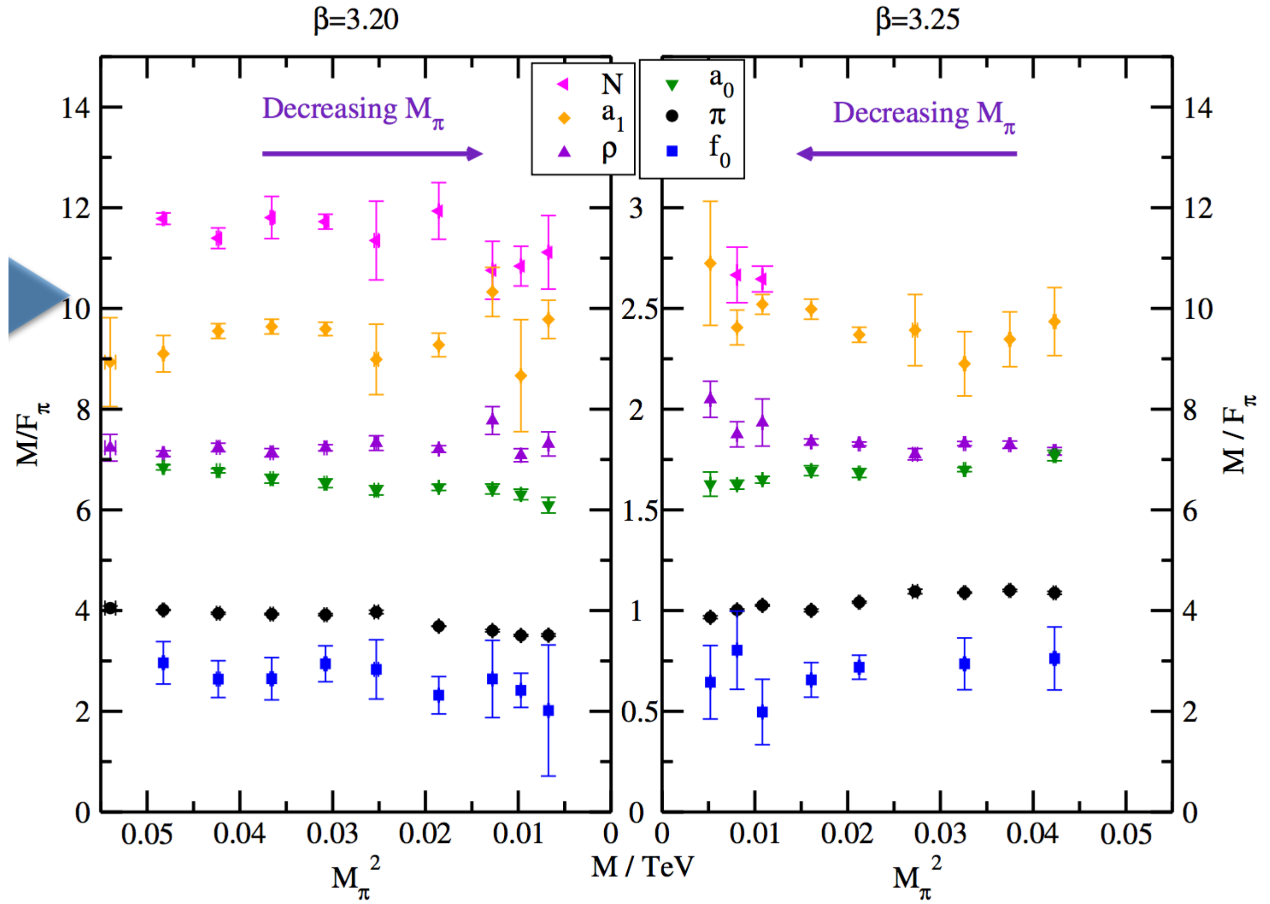
Counterexample (II)

- 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



Naive Argument Failing?

- Broad, heavy scalars do not seem to be a generic feature of confining, chirally-broken gauge theories.

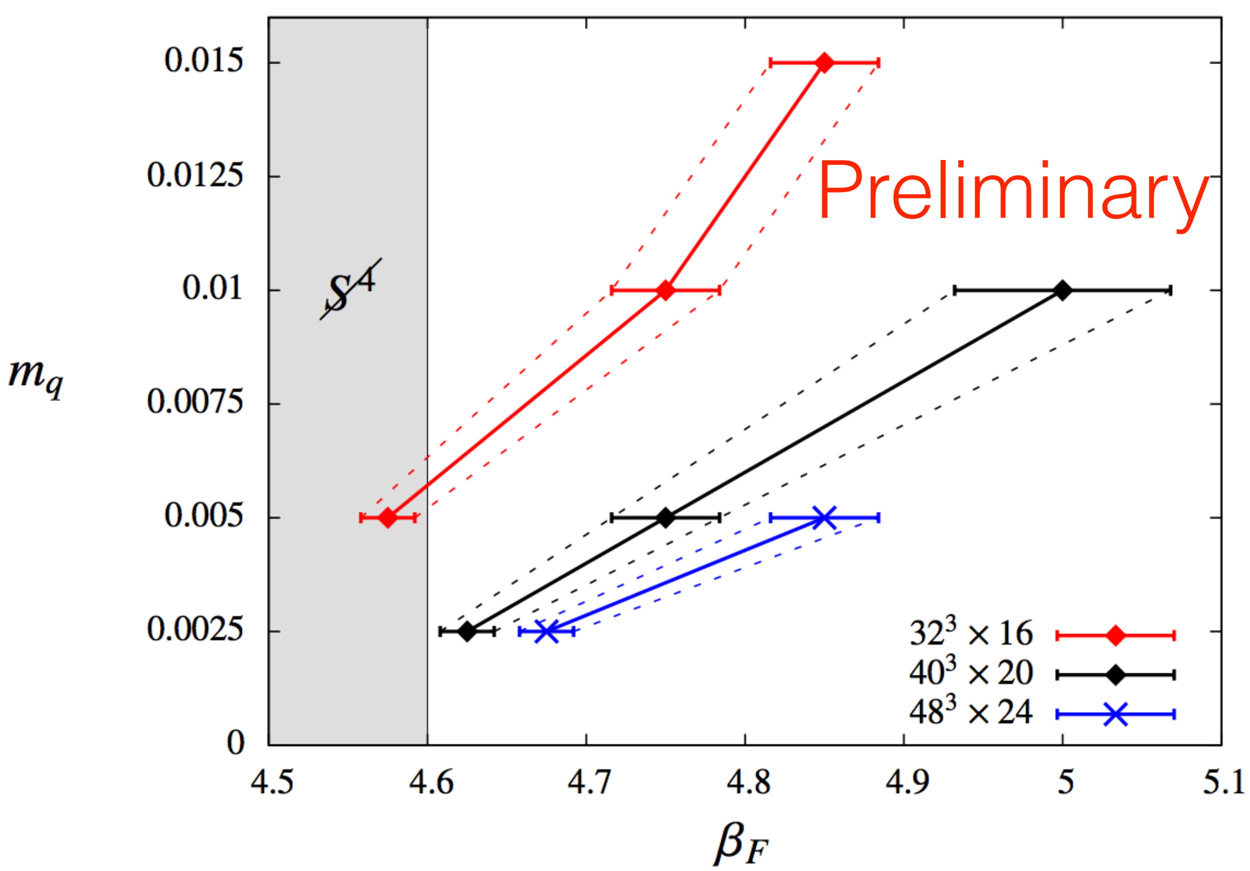
- Instead, near-conformal theories might generically have light scalars (true in every case so far).

- How sure are we that SU(3) N_f=8 is not inside the conformal window?

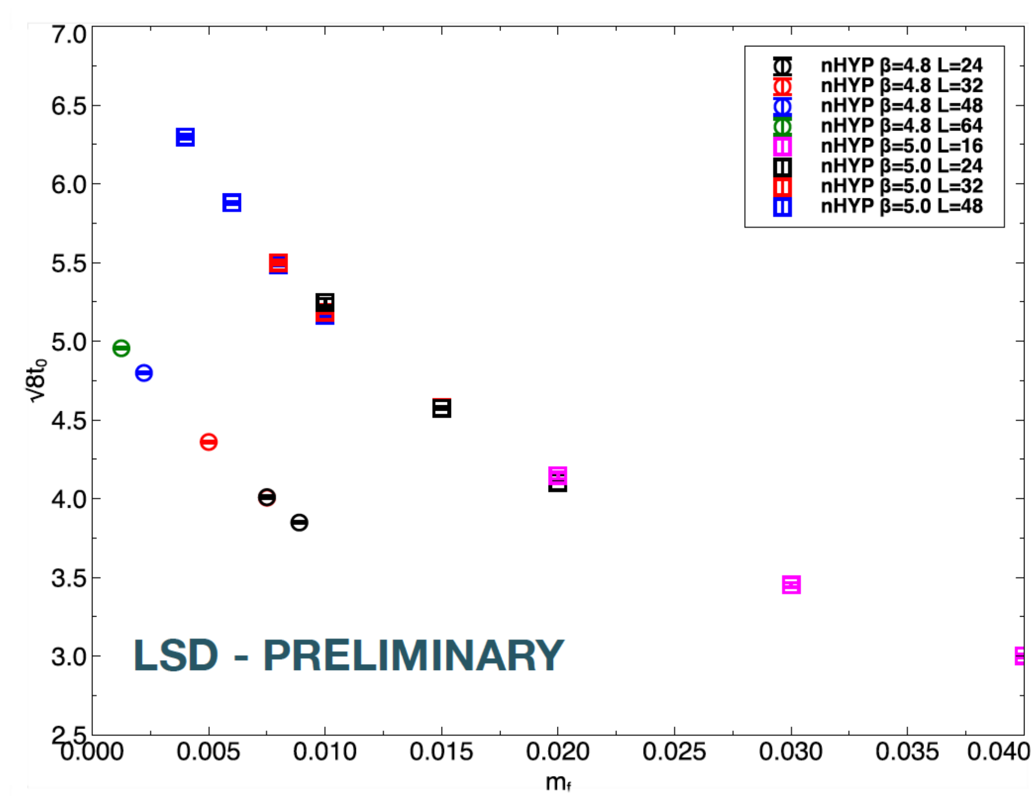
- How sure are we that $M_\sigma \sim f_\pi$ in chiral limit?

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.
- Now using nHYP stag fermions and fund+adj gauge action pioneered by Boulder group to get to somewhat coarser lattices.



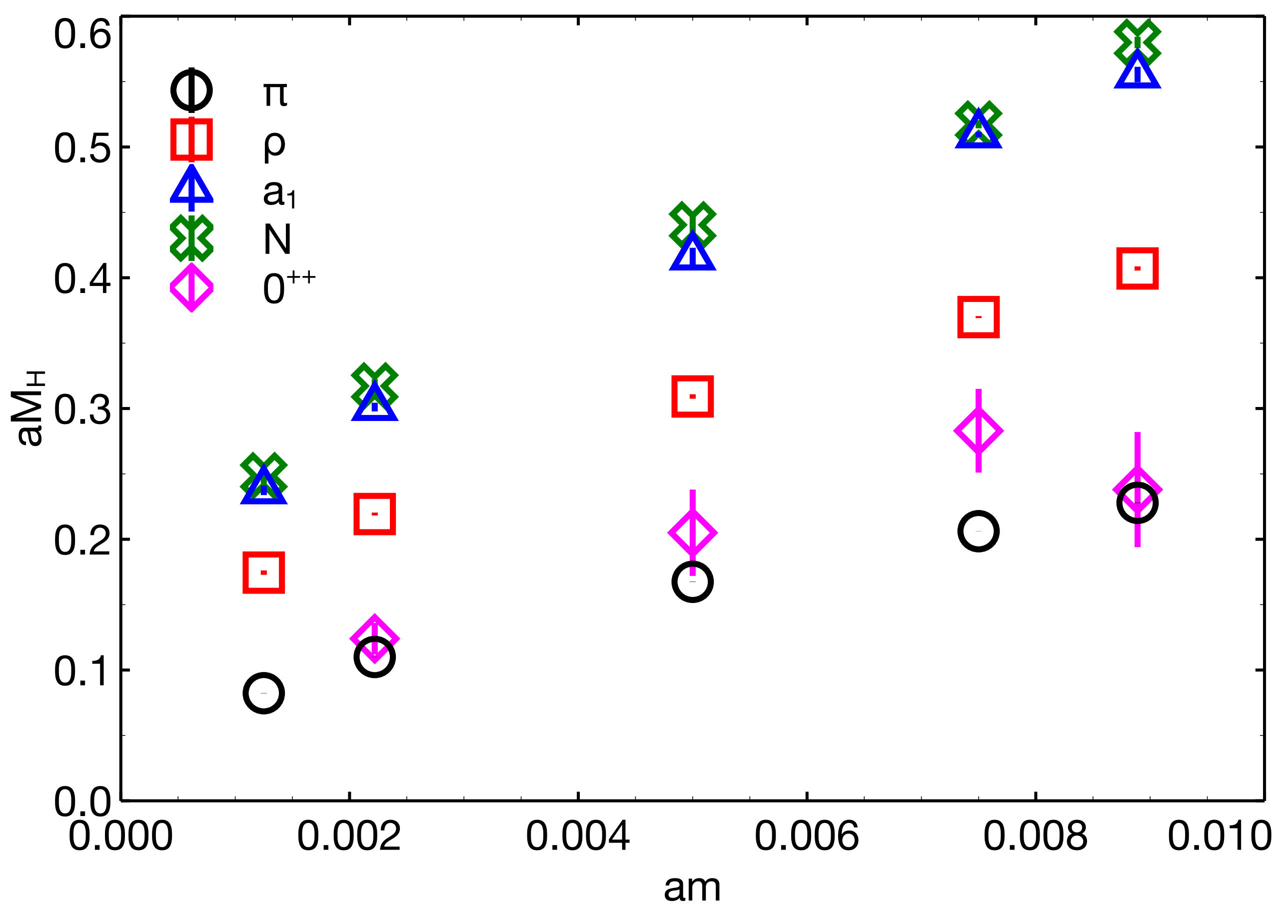
T_c and bulk phase

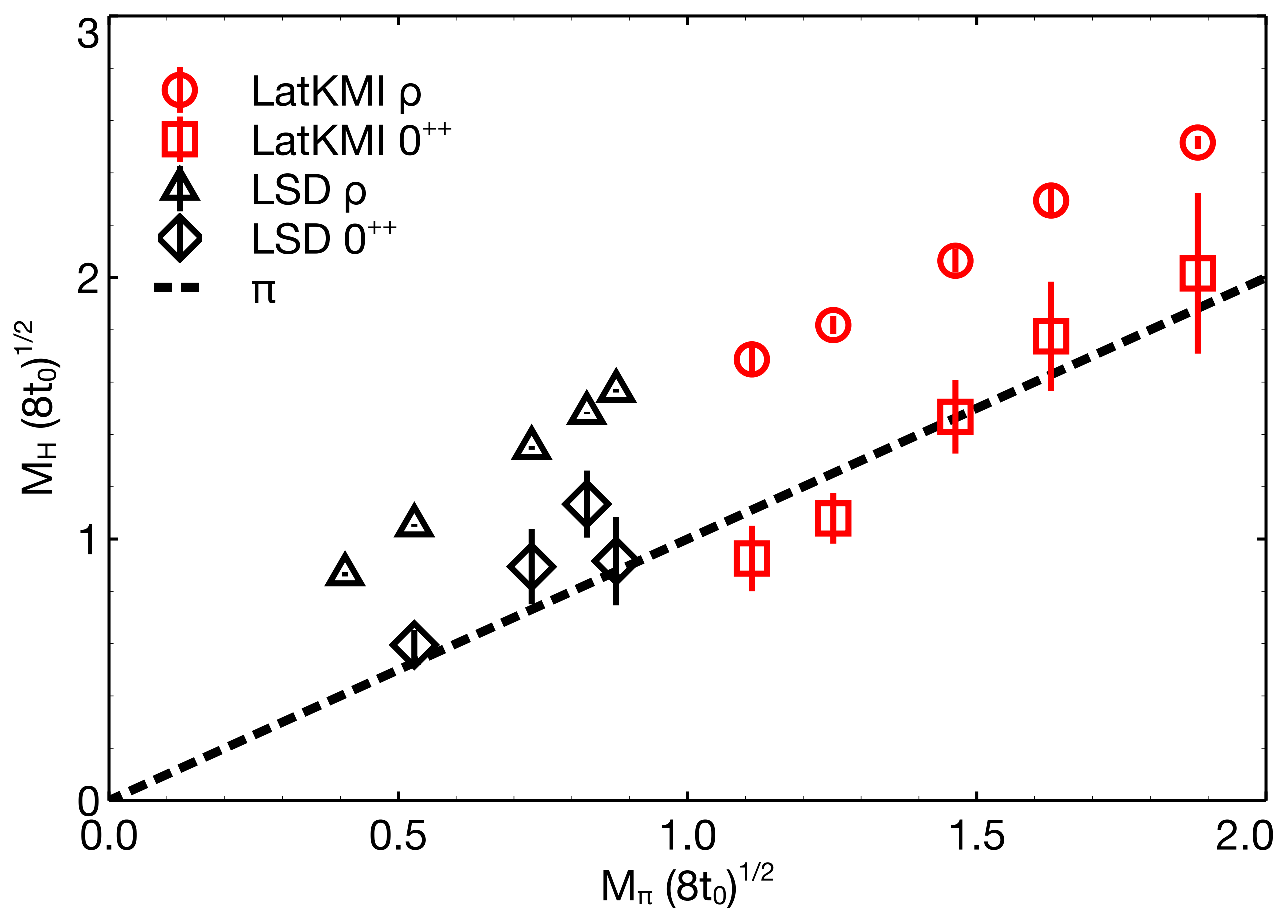


$\langle t^2 E(t) \rangle = 0.3$ @ $t=t_0$

Light hadron spectrum

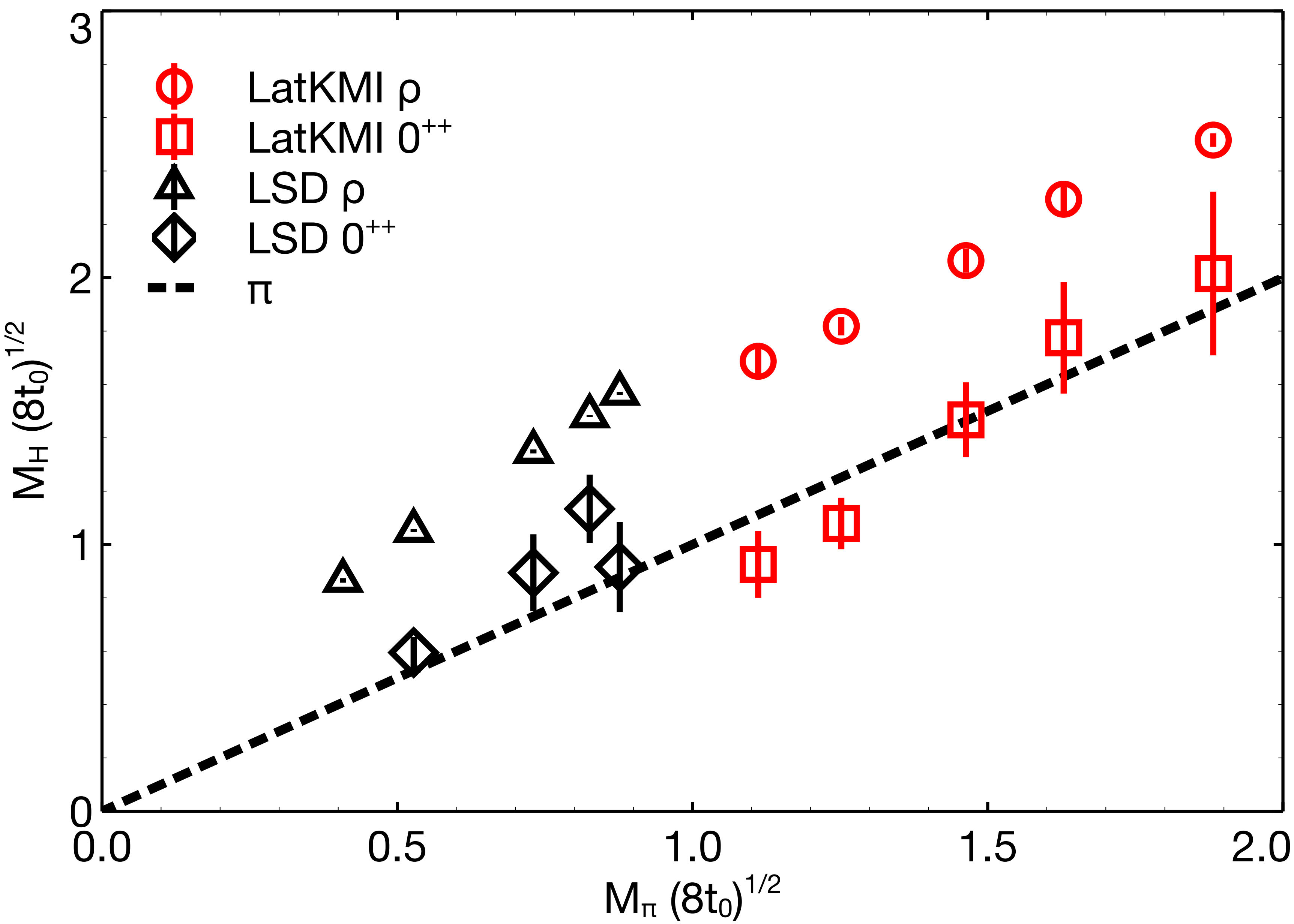
- Spectrum consistent with earlier LSD N_f=8 results but at lighter quark mass.
- Very strong quark mass dependence.
- Submitted to PRL (arXiv:1601.04027)





Isosinglet spectrum

- Stable scalar degenerate with pion even when $M_\pi/M_\rho \lesssim 1/2$.
- Submitted to PRL (arXiv:1601.04027)



Sophisticated Argument Against Composite Higgs

- OK, we found some theories with composite light scalars. Why should the couplings between π's and σ have any relation to h coupling to W,Z?

- i.e. construct χPT$_S$ [Soto, Talavera and Tarrús, NPB **866**, 270 (2013)]

$$\mathcal{L}^{(2)} = \left(\frac{F^2}{4} r_{0d} + F r_{1d} S + r_{2d} S^2 + \cdots\right)\langle D_\mu U D^\mu U^\dagger\rangle + \left(\frac{F^2}{4} r_{0m} + F r_{1m} S + r_{2m} S^2 + \cdots\right)\left(\langle \chi^\dagger U + \chi U^\dagger\rangle - \langle \chi^\dagger + \chi\rangle\right),$$

- Of course, we have to drop by hand scalar self interactions

$$\mathcal{L}^S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}\mathring{m}_S^2 SS - \lambda_1 S - \frac{\lambda_3}{3!}S^3 - \frac{\lambda_4}{4!}S^4 + \cdots$$

- When matched to your theory, why should O(1) LECs look anything like the SM Higgs (i.e. the linear sigma model)?

Future of SU(3) $N_f=8$

- Finishing $I=2$ scattering studies on $96^3\times192$ volumes, $M\pi \times L\sim 7.9$.

- Planning $96^3\times192$ lattice generation this year, $M\pi \times L\sim 5.3$. Should give $M\pi\ /\ M\rho \sim 0.41$.

- Given excellent performance of QUDA on Lassen/Summit, it's possible we can generate $128^3\times256$ lattices with $M\pi\ /\ M\rho \sim 0.35$ year after next.

Reverse-Engineering EFTs

- On the lattice, we have access to the UV-complete theory so let's just compute the relevant quantities:
  - I=0,1,2 pi-pi scattering
  - pi-sigma scattering
  - sigma-sigma scattering
  - scalar form factors
- OK, it's hard, but not as hard as it seems. Remember the sigma is as light as the pion.

Composite Higgs Summary

- We now have clear examples of gauge theories with light scalars.

- Computing at masses $m_\pi \leq f_\pi$, where χPT might work, seems prohibitively expensive. So it's not clear how to extrapolate lattice results to chiral limit.

- I'm skeptical of various proposed EFTs for π-σ system since they don't include all possible interactions allowed by symmetry.

- Do the best we can to compute two particle scattering at accessible quark masses and see if it looks anything like the linear sigma model.

- I really wish I knew how the $f_0(500)$ mass and width in QCD depended on the quark mass. I hope someone will compute it soon.