Light scalar from lattice strong dynamics

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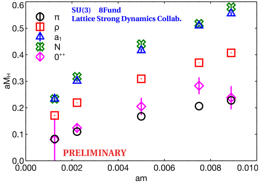
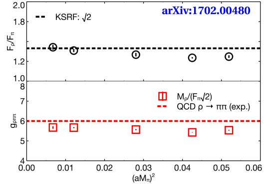
WE-Heraeus-Seminar *Understanding the LHC*
Physikzentrum Bad Honnef, 14 February 2017

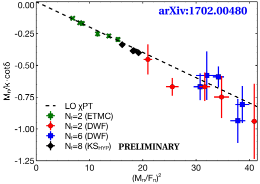
PRD 93:114514 (2016) [arXiv:1601.04027]
ProcSci LATTICE2016:242 (2017) [arXiv:1702.00480]
and work in progress with the Lattice Strong Dynamics Collaboration

Overview

- Several groups are using lattice gauge theory to explore strongly coupled systems with non-QCDlike dynamics
- These studies find remarkably light scalars in many IR-conformal and near-conformal systems
- Using 8-flavor SU(3) gauge theory as a representative example we are studying more quantities to constrain the low-energy EFT

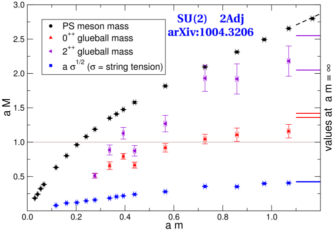


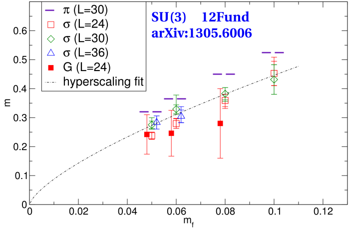




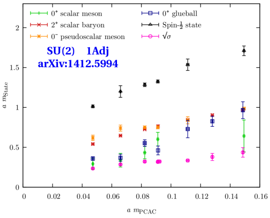
Light scalars from beyond-QCD lattice calculations

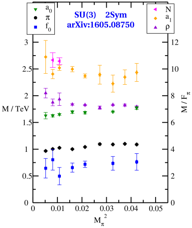
Not so shocking in mass-deformed IR-conformal theories

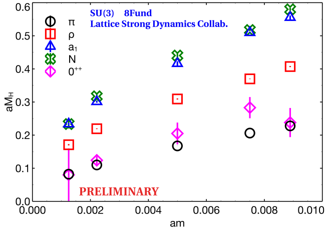




More surprising in systems apparently exhibiting spontaneous chiral symmetry breaking





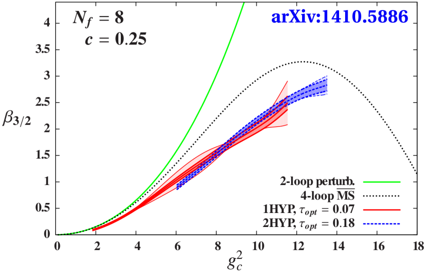


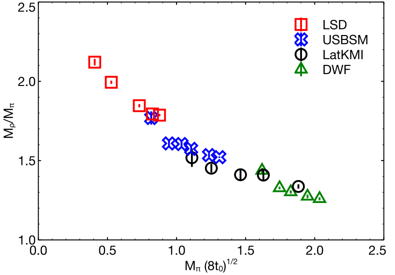
Lattice Strong Dynamics Collaboration

Argonne	Xiao-Yong Jin, James Osborn
Bern	DS
Boston	Rich Brower, Claudio Rebbi, Evan Weinberg
Colorado	Anna Hasenfratz, Ethan Neil
Edinburgh	Oliver Witzel
Livermore	Pavlos Vranas
RBRC	Enrico Rinaldi
UC Davis	Joseph Kiskis
Yale	Thomas Appelquist, George Fleming, Andrew Gasbarro

Exploring the range of possible phenomena
in strongly coupled field theories

Infrared dynamics of 8-flavor SU(3) gauge theory



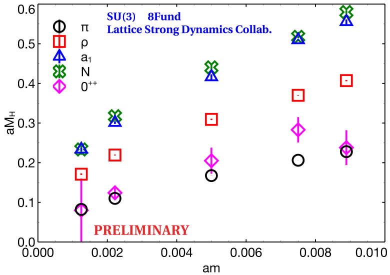


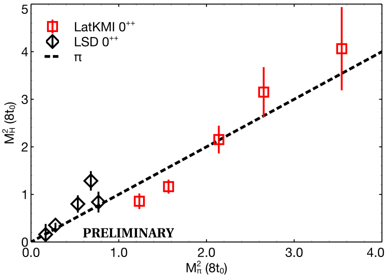
- β function is monotonic up to fairly strong couplings
  No sign of approach towards conformal IR fixed point $[\beta(g_\star^2) = 0]$

- Ratio M_V/M_P increases monotonically as masses decrease
  as expected for spontaneous chiral symmetry breaking (SχSB)
  Mass-deformed conformal hyperscaling predicts constant ratio

Want to strengthen conclusion by matching to low-energy EFT,
but must go beyond QCD-like χPT to include light scalar…

Light scalar in 8-flavor spectrum





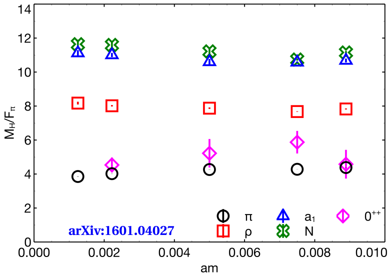
Flavor-singlet scalar degenerate with pseudo-Goldstones
down to lightest fermion masses we can reach on $64^3 \times 128$ lattices

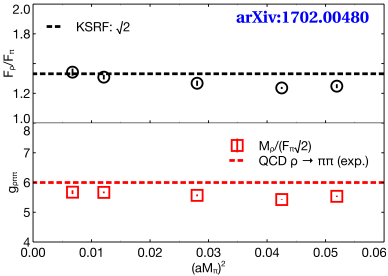
Both M_S and M_P are less than half the vector mass M_V,
and the hierarchy is growing as we approach the chiral limit

This is very different from QCD

Controlled chiral extrapolations need EFT that includes scalar. . .

2TeV vector resonance with width $\Gamma_V \simeq 450$ GeV





$M_V/F_P \simeq 8 \Longrightarrow M_V \simeq 2$ TeV if we assume roughly constant ratio

[NB: SχSB implies $M_P/F_P \to 0$ in chiral limit!]

We measure $F_V \approx F_P\sqrt{2}$ (KSRF relation, suggesting vector domin.)

Applying second KSRF relation $g_{VPP} \approx M_V/(F_P\sqrt{2})$

gives vector width $\Gamma_V = \dfrac{g_{VPP}^2 M_V}{48\pi} \simeq 450$ GeV — hard to see at LHC

Work in progress: Constraining EFT

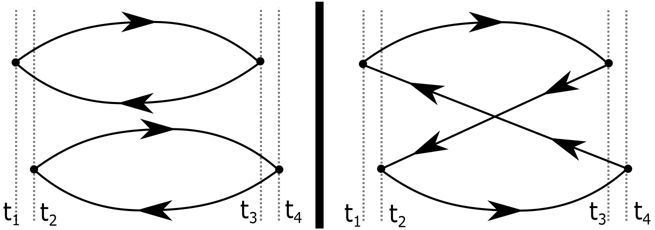
There are many candidate EFTs that include PNGBs + light scalar

(linear σ model; Goldberger–Gristein–Skiba; Soto–Talavera–Tarrus; Matsuzaki–Yamawaki; Golterman–Shamir; Hansen–Langaeble–Sannino; Appelquist–Ingoldby–Piai)

Need lattice computations of more observables to test EFTs

We are now computing $2 \to 2$ elastic scattering of PNGBs & scalar, as well as scalar form factor of PNGB

Example: Scalar exchange in $\pi\pi$ scattering vs. π scalar form factor



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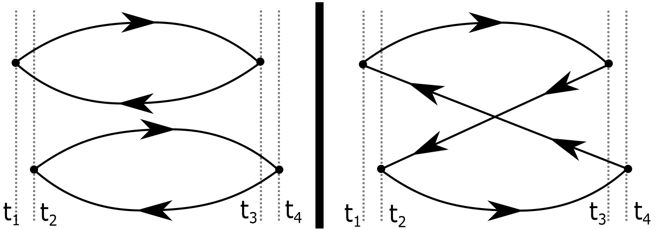
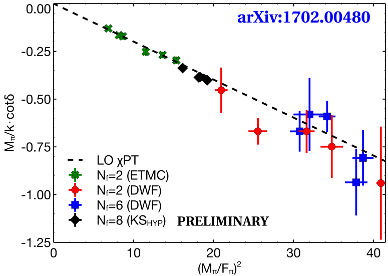
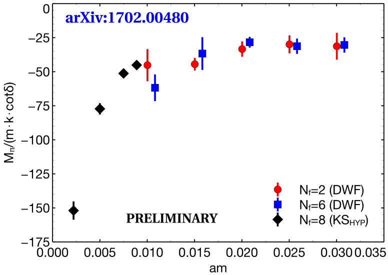
Subsequent step: Analog of πK scattering in mass-split system



Initial 2 $\rightarrow$ 2 elastic scattering results





First looking at analog of QCD $I = 2$ $\pi\pi$ scattering
(simplest case with no fermion-line-disconnected diagrams)

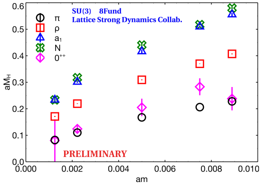
Simplest observable is scattering length $a_{PP} \approx 1/(k \cot \delta)$

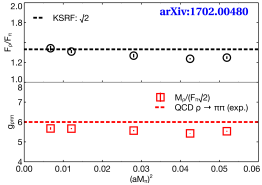
$M_P a_{PP}$ vs. M_P^2 / F_P^2 curiously close to leading-order χPT prediction

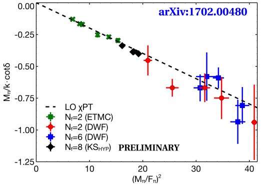
Dividing by fermion mass m reveals expected tension with χPT which predicts $M_P a_{PP}/m =$ const. at LO and involves 8 LECs at NLO

Recapitulation and outlook

- 8-flavor SU(3) gauge theory is a representative system with a light scalar likely related to near-conformal dynamics
- Growing hierarchy between scalar and broad $\sim$2TeV vector
- Chiral extrapolations need an EFT beyond QCD-like χPT
- We are now studying elastic scattering to test potential EFTs







Thank you!

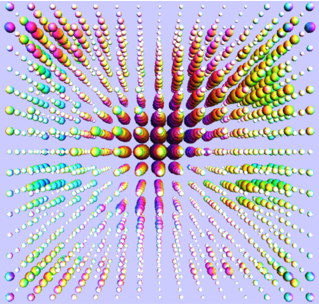
Thank you!

Lattice Strong Dynamics Collaboration

In particular: George Fleming, Andrew Gasbarro, Xiao-Yong Jin,
Enrico Rinaldi, Evan Weinberg

Funding and computing resources

Backup: Essence of numerical lattice calculations



(Image credit: Claudio Rebbi)

Evaluate observables from functional integral via importance sampling Monte Carlo

$$\langle \mathcal{O} \rangle = \frac{1}{\mathcal{Z}} \int \mathcal{D}\Phi \;\; \mathcal{O}(\Phi) \;\; e^{-S[\Phi]}$$

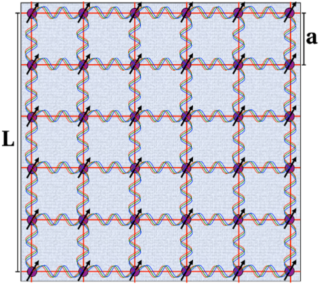
$$\longrightarrow \frac{1}{N} \sum_{i=1}^{N} \mathcal{O}(\Phi_i) \;\; \text{with uncert.} \;\; \propto \sqrt{\frac{1}{N}}$$

Φ are field configurations in discretized euclidean spacetime

$S[\Phi]$ is the lattice action, which should be real and non-negative so that $\frac{1}{\mathcal{Z}} e^{-S}$ can be treated as a probability distribution

The hybrid Monte Carlo algorithm samples Φ with probability $\propto e^{-S}$

Backup: More features of lattice calculations



P. Vranas LLNL

Spacing between lattice sites ("a")
introduces UV cutoff scale $1/a$

Lattice cutoff preserves hypercubic subgroup
of full Poincaré symmetry

Remove cutoff by taking continuum limit:
$a \to 0$ with $L/a \to \infty$

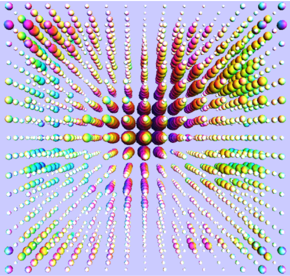
The lattice action S is defined by the bare lagrangian
at the UV cutoff set by the lattice spacing

After generating and saving an ensemble $\{\Phi_n\}$ distributed $\propto e^{-S}$
it is usually quick and easy to measure many observables $\langle \mathcal{O} \rangle$

Changing the action (generally) requires generating a new ensemble

Backup: Hybrid Monte Carlo (HMC) algorithm

Goal: Sample field configurations Φ_i with probability $\frac{1}{\mathcal{Z}} e^{-S[\Phi_i]}$



(Image credit: Claudio Rebbi)

HMC is a Markov process, based on Metropolis–Rosenbluth–Teller (MRT)

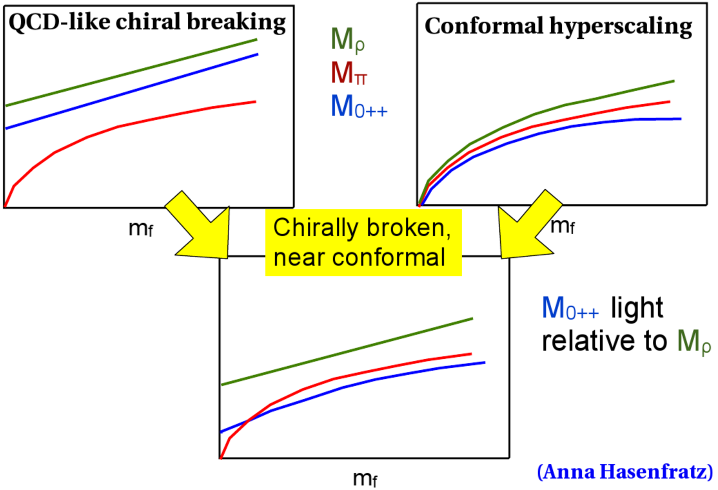
Fermions $\longrightarrow$ extensive action computation, so best to update entire system at once

Use fictitious molecular dynamics evolution

1. Introduce a fictitious fifth dimension ("MD time" τ) and stochastic canonical momenta for field variables
2. Run inexact MD evolution along a trajectory in τ to generate a new four-dimensional field configuration
3. Apply MRT accept/reject test to MD discretization error

Backup: Qualitative picture of lattice results

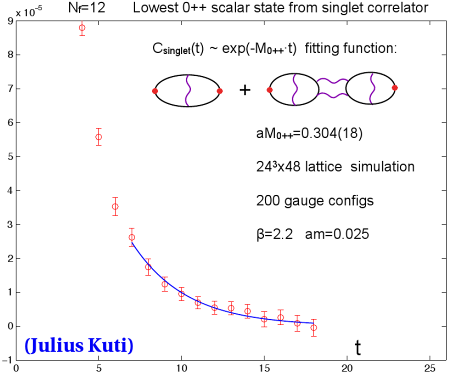
Light scalar likely related to near-conformal dynamics
(unconfirmed interpretation as PNGB of approx. scale symmetry)



Backup: Technical challenge for scalar on lattice

Only the new strong sector is included in the lattice calculation
$\Longrightarrow$ The flavor-singlet scalar mixes with the vacuum

Leads to noisy data and relatively large uncertainties

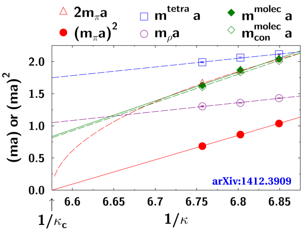


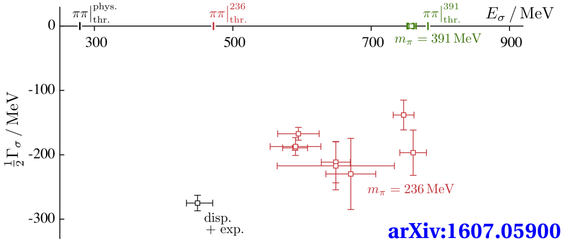
Fermion propagator computation
is relatively expensive

"Disconnected diagrams" formally
need propagators at all L^4 sites

In practice estimate stochastically
to control computational costs

Backup: Isosinglet scalar in QCD spectrum





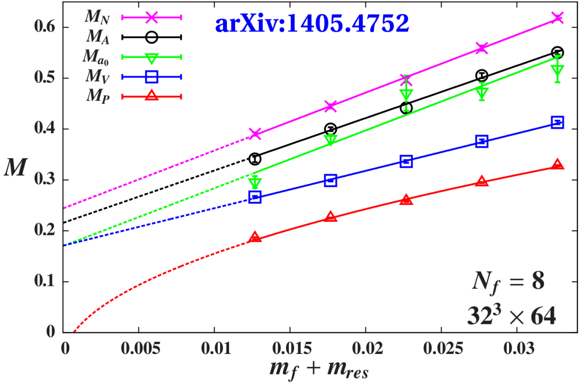
In lattice QCD, the isosinglet scalar is much heavier than the pion

Generally $M_S \gtrsim 2M_P$, and for heavy quarks $M_S > M_V$

For a large range of quark masses m

it mixes significantly with two-pion scattering states

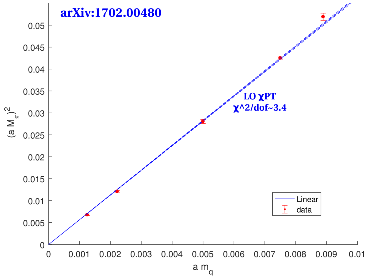
Backup: Non-singlet scalar for $N_F = 8$

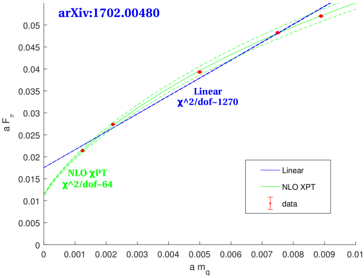


In earlier work with domain wall fermions at heavier fermion masses the non-singlet scalar is heavier than the vector, $M_{a_0} > M_V$

Staggered analyses in progress, but more complicated

Backup: Chiral perturbation theory (χPT) fits





In addition to omitting the light scalar

χPT also suffers from large expansion parameter

$$5.8 \le \frac{2N_F Bm}{16\pi^2 F^2} \le 41.3 \quad \text{for} \quad 0.00125 \le m \le 0.00889$$

Big ($\sim$50σ) shift in F from linear extrapolation vs. NLO χPT

Fit quality is not good, especially for NLO joint fit with χ^2/d.o.f. $> 10^4$

Backup: NLO chiral perturbation theory formulas

$$M_P^2 = 2Bm\left[1 + \frac{2N_F Bm}{16\pi^2 F^2}\left\{128\pi^2\left(2L_6^r - L_4^r + \frac{2L_8^r - L_5^r}{N_F}\right) + \frac{\log\left(2Bm/\mu^2\right)}{N_F^2}\right\}\right]$$

$$F_P = F\left[1 + \frac{2N_F Bm}{16\pi^2 F^2}\left\{64\pi^2\left(L_4^r + \frac{L_5^r}{N_F}\right) - \frac{1}{2}\log(2Bm/\mu^2)\right\}\right]$$

$$\begin{aligned} M_P a_{PP} = \frac{-2Bm}{16\pi F^2}\left[1 + \frac{2N_F Bm}{16\pi^2 F^2}\left\{-256\pi^2\left(\left[1 - \frac{2}{N_F}\right](L_4^r - L_6^r)\right.\right.\right. \\ \left. + \frac{L_0^r + 2L_1^r + 2L_2^r + L_3^r}{N_F}\right) - 2\frac{N_F - 1}{N_F^3} \\ \left.\left. + \frac{2 - N_F + 2N_F^2 + N_F^3}{N_F^3}\log\left(2Bm/\mu^2\right)\right\}\right] \end{aligned}$$

Backup: 2 $\rightarrow$ 2 elastic scattering on the lattice

Measure both E_{PP} and $M_P \longrightarrow k = \sqrt{(E_{PP}/2)^2 - M_P^2}$

s-wave scattering phase shift: $\cot \delta_0(k) = \frac{1}{\pi k L}\, S\left(\frac{k^2 L^2}{4\pi}\right)$

with regularized ζ function $S(\eta) = \sum_{j \neq 0}^{\Lambda} \frac{1}{j^2 - \eta} - 4\pi\Lambda$

Effective range expansion:

$$k \cot \delta_0(k) = \frac{1}{a_{PP}} + \frac{1}{2} M_P^2 r_{PP} \left(\frac{k^2}{M_P^2}\right) + \mathcal{O}\left(\frac{k^4}{M_P^4}\right)$$