Is the Higgs a Composite Scalar?

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LSD Collaboration

L—S
D

Lattice **S**trong **D**ynamics Collaboration

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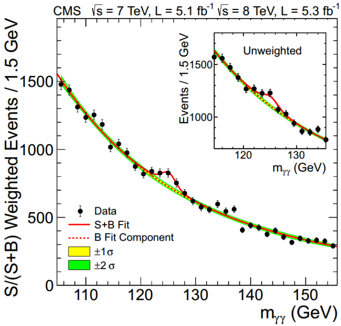


Figure: [Phys. Lett. B 716 (2012)]

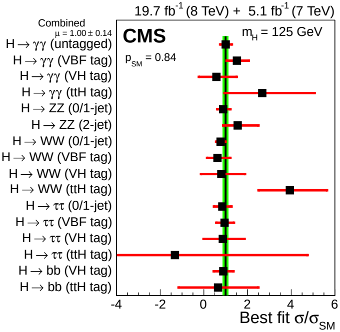
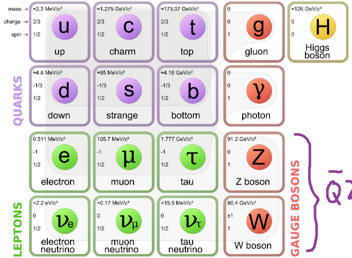


Figure: [Eur.Phys.J. C75 (2015)]

- The Higgs Boson looks very Standard Model.
- There's still the need for a UV completion.

A Composite UV Completion



$\Rightarrow \bar{Q}Q$

$\bar{Q}\gamma_5\sigma^i Q$

Figure: Modified from Wikipedia: "Standard Model"

- Higgs: $\bar{Q}Q$ scalar composite of strong dynamics.

Possibly Composite Teases from the LHC

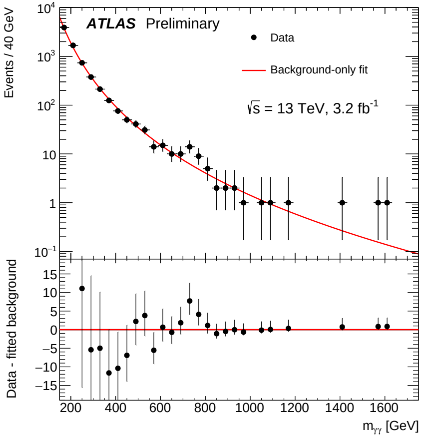


Figure: ATLAS Diphoton @ 13 TeV

[ATLAS-CONF-2015-081]

- 750 GeV diphoton bump: η'-like state from a new composite sector?
- 2 TeV diboson bump: ρ-like state, not fully excluded, especially if state is *broad*.

Not QCD!

The new sector can't just be scaled up QCD.

- QCD has...
  - a broad scalar close to the vector mass,
  - a large S-parameter, and
  - no walking regime.
- More flavors can produce different, interesting behavior.

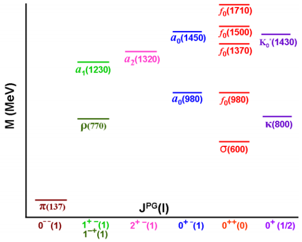


Figure: [Phys.Rev. D76 (2007)]

Composite Models

- It is not easy to build a viable composite model for EWSB.
- Broadly speaking, there are two steps:

1. Pick a general model and study if it has certain features.
2. Worry about connecting it to the Standard Model.

Composite Models

- It is not easy to build a viable composite model for EWSB.
- Broadly speaking, there are two steps:

1. Pick a general model and study if it has certain features. $\leftarrow$ This talk
2. Worry about connecting it to the Standard Model.

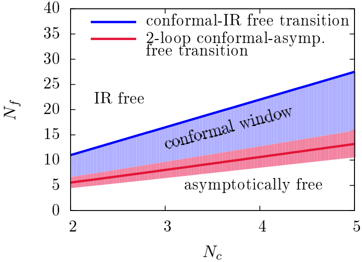
- The interest in multi-flavor QCD is motivated by the beta function.

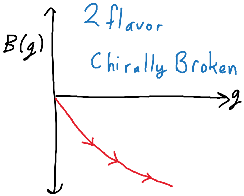
$$\beta(g) = -\beta_0 g^3 - \beta_1 g^5 + \mathcal{O}(g^7)$$

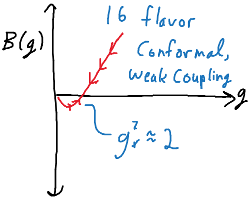
$$\beta_0 = \left[\frac{11}{3}N_c - \frac{2}{3}N_f\right]/(4\pi)^2$$

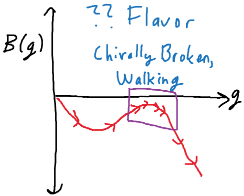
$$\beta_1 = \left[\frac{34}{3}N_c^2 - \left(\frac{13}{3}N_c - \frac{1}{N_c}\right)N_f\right]/(4\pi)^4$$

$\beta_1 = 0 \rightarrow N_f \approx 8.05$





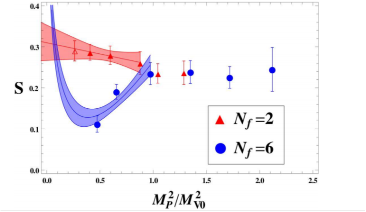




The lattice and many-fermion physics

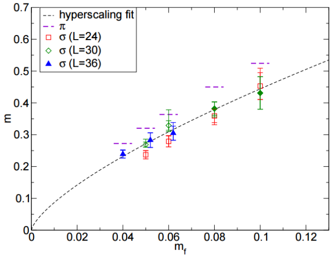
- We can use the lattice as a probe of new non-perturbative physics.

- The lattice has indicated S parameter suppression with more flavors.



[Schaich, LATTICE 2011, arXiv:1111.4993]

- It has also indicated that $SU(3)$ 12 flavor is conformal.



[Aoki et al., LATTICE 2014, arXiv:1501.06660]

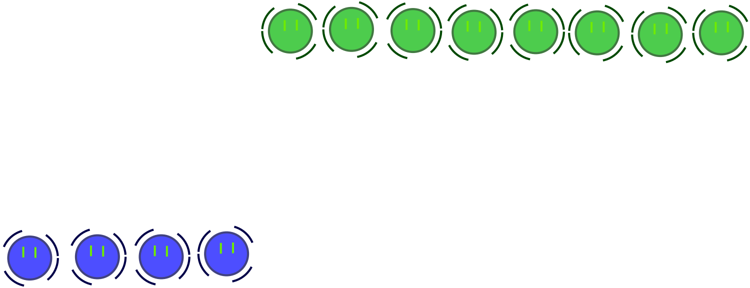
- And, in the mass-deformed theory, has a light scalar.

Our model

1. Pick a general model and study if it has certain features.
   - Lattice study of $SU(3)$ with 8 fundamental flavors
     - Chiral Kogut-Susskind “Staggered” fermions: multiples of 4 flavors.
   - Right near 2-loop (strongly coupled...) opening of conformal window.
   - Likely confining, but possibly conformal. We cannot definitively tell.
     - “Feature, not a bug.”
2. Worry about connecting it to the Standard Model.

Aside: Partner 4+8 Project

- We have a parter project with 4 chiral, 8 massive flavors.
  - Brower et al., "A composite Higgs model at a conformal fixed point"
  - Available at arXiv:1512.02576.
- Begin to address the question: "What happens when we decouple some fermions in a (near-)conformal theory?"
  - Important for non-minimal (>3 pNGB) composite models.



Lattice Details

- $SU(3)$ gauge group, 8 continuum fermions
- Gauge action: fundamental-adjoint with $\beta_a = -\beta/4$ [Cheng et al. 2013][Cheng et al. 2014]
  - Negative adjoint term helps avoid lattice fixed point
- Fermion action: 1-nHYP smeared staggered [Hasenfratz et al. 2007]
  - nHYP smearing helps push to stronger coupling (avoid lattice phase)
- Software: HMC and most measurements in FUEL [J. Osborn]
- Runs:
  - "Fixed" $M_\pi L$:
  - $24^3, m = 0.00889; 32^3, m = 0.005; 48^3, m = 0.00222; 64^3, m = 0.00125$
  - Finite volume:
  - 24^3 and 32^3, $m = 0.0075$
  - Large mass (connect to LatKMI):
  - $24^3, m = 0.035$

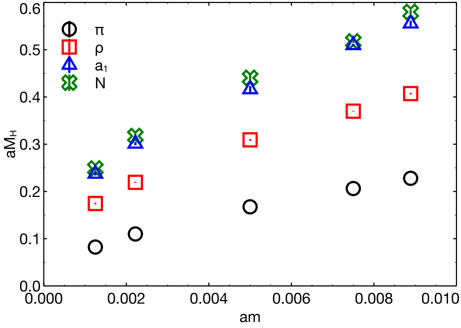
Quark-Line Connected Spectrum

- Interested in ground state in many isomultiplet channels
- Using QCD language:

- π (0^{-+}) — $W^{\pm}, Z$
- ρ (1^{--}) — di-boson resonance?
- N $(\frac{1}{2}^{+})$ — dark matter?
- a_0 (0^{++}) — detector signal?
- a_1 (1^{++}) — detector signal?

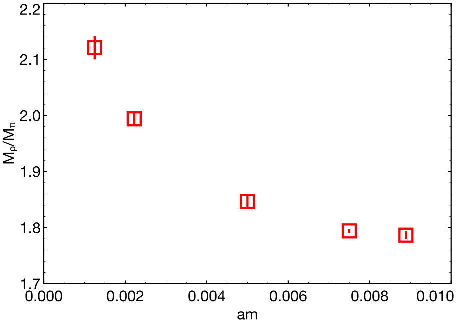
- Use wall sources to project onto ground states [Gupta et al. 1991]
- Also interested in decay constants (93 MeV convention)
  - F_π — electroweak symmetry vev $\approx$ 250 GeV
  - F_ρ, F_{a_1} — production cross-sections, chiral restoration?
  - Use current-current correlators to avoid renormalization

Non-singlet spectrum

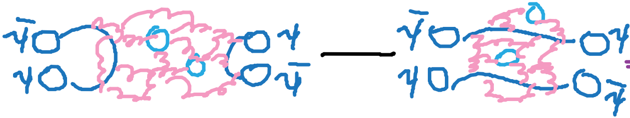


- Unlike QCD: shouldn't trust ChiPT here.
- Spectrum depends heavily on the fermion mass.
  - Curvature at small m_q

Chirally broken?



- Looks chirally broken, or conformal with scaling corrections?
  - Boulder 12 flavor results on conformal scaling corrections: [Cheng et al. 2014]
- Interesting dynamics: $M_\rho > 2M_\pi$



$$\Rightarrow f_\sigma^2 e^{-m_\sigma t} + \cdots$$

Isosinglet Scalar (0^{++})

$$S(t) = \langle \bar\psi_a \psi_a(0)\ \bar\psi_a \psi_a(t) \rangle$$

$$= \frac{1}{\mathcal{Z}} \int [dU d\bar\psi d\psi] \left\{ 2\, \bar\psi(0)\psi(0)\ \bar\psi(t)\psi(t) - \bar\psi(0)\ \psi(0)\ \bar\psi(t)\psi(t) \right\}\ e^{-\frac{1}{g^2}F^2 - \bar\psi_i \not{D}\psi_i - m_q \bar\psi_i \psi_i}$$
$$= \frac{1}{\mathcal{Z}} \int [dU]\ \left\{ 2 G_F(0,0) G_F(t,t) - (G_F(0,t)\gamma_5)^2 \right\}\ \det(D^\dagger D + m_q^2)^{N/2}\ e^{-\frac{1}{g^2}F^2}$$
$$\equiv 2D(t) - C(t)$$

- Factor $G_F(t,t)$ means we need *every* point to itself.

Strategy for disconnected diagrams

- Fitting the isosinglet, 0^{++} meson requires disconnected diagrams.
- 6 $U(1)$ sources with dilution in time, color, and even/odd spatially
- Improved estimator for $\langle\bar{\psi}\psi\rangle$
- Still need large statistics to suppress gauge noise

What this gets us:

$$C(t) = -A_{a_0} e^{-M_{a_0} t} - (-1)^t \left(A_{\pi_{sc}} e^{-M_{\pi_{sc}} t} \right) + \cdots$$

$$S(t) \equiv 2D(t) - C(t) = A_\sigma e^{-M_\sigma t} + (-1)^t \left(A_\eta e^{-M_\eta t} \right) + \cdots$$

$\downarrow$ [Aoki et al., LATTICE 2014, arXiv:1501.06660]

$$2D(t) = A_\sigma e^{-M_\sigma t} - A_{a_0} e^{-M_{a_0} t} + (-1)^t \left(A_\eta e^{-M_\eta t} - A_{\pi_{sc}} e^{-M_{\pi_{sc}} t} \right) + \cdots$$

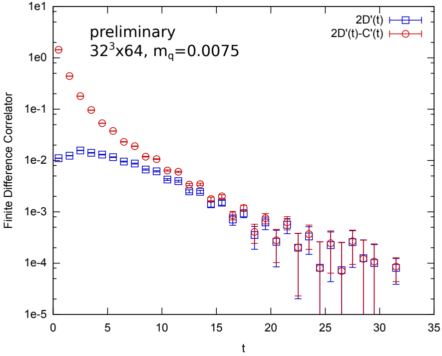
Strategy for disconnected diagrams, continued

$$S(t) \equiv 2D(t) - C(t) = A_\sigma e^{-M_\sigma t} + (-1)^t \left(A_\eta e^{-M_\eta t} \right) + \cdots$$

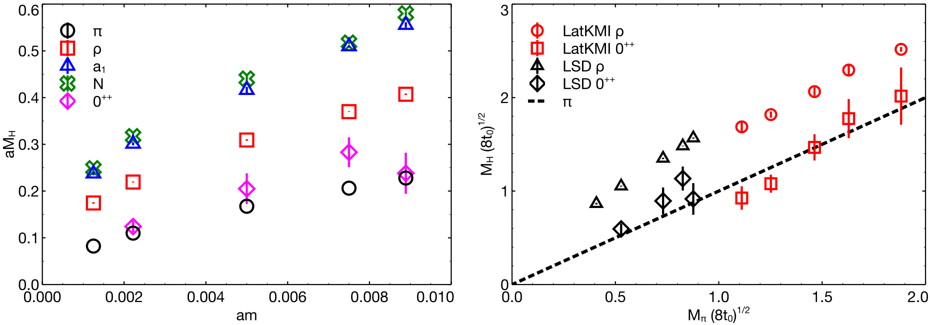
$$2D(t) = A_\sigma e^{-M_\sigma t} - A_{a_0} e^{-M_{a_0} t} + (-1)^t \left(A_\eta e^{-M_\eta t} - A_{\pi_{sc}} e^{-M_{\pi_{sc}} t} \right) + \cdots$$

If $M_{0^{++}} < M_{a_0}$, we can extract from both $D(t)$, $S(t)$ at large t.

- Correlated fit to both parity states
- Vacuum subtraction introduces large uncertainties
- Fit the finite difference:
  - $D(t+1) - D(t)$
  - $S(t+1) - S(t)$
- Average resulting $M_{0^{++}}$, errors in quadrature

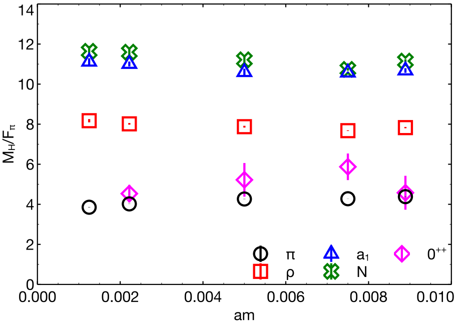


Singlet spectrum



- Generally, the 0^{++} tracks the Goldstone boson in this regime.
  - LatKMI results: [Y. Aoki et al. 2013] [Y. Aoki et al. SCGT15] (Thank you!)
- Very different from QCD!

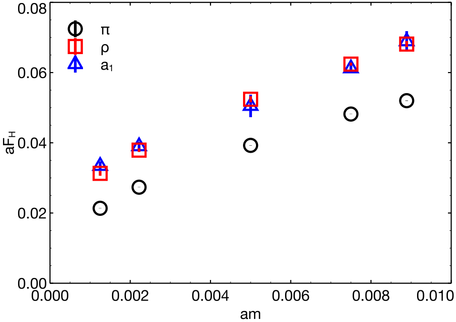
Spectrum Overview

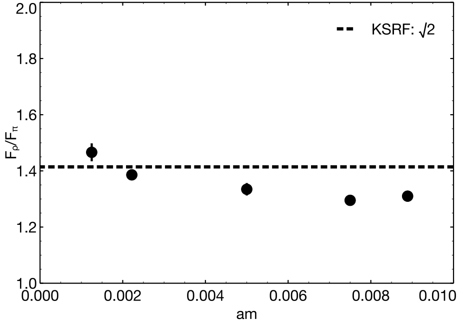


- Look at ratios with $F_\pi \approx v \approx 250 GeV$
- Light $0^{++} \approx \pi < \rho, 2\pi$
- $M_{0^{++}}/F_\pi \approx 4$: What would a top loop do?
- Rich spectrum of other states.

- $M_\rho/F_\pi \approx 8$: 2TeV di-boson resonance?
  - Ratio seen in QCD
  - Also seen in $SU(3)$ 2 flavor sextet [LatHC 2015 (LATTICE2015)]
  - Perhaps a general feature?

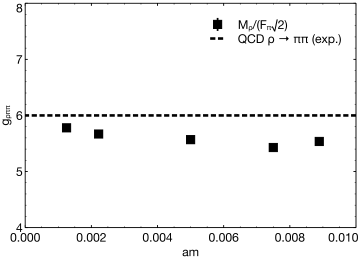
Other Results: Decay Constants





- Decay constants extracted from current correlators: no “Z” factor.
- F_π is smallest; F_ρ, F_{a_1} degenerate w/in errors.
- Interesting: Check Kawarabayashi-Suzuki-Riazuddin-Fayyazuddin (KSRF) relations: $F_\rho M_\rho = 2F_\pi^2 g_{\rho\pi\pi}$; $\quad M_\rho^2 = 2F_\pi^2 g_{\rho\pi\pi}^2$.
  - Predicts $F_\rho = \sqrt{2}F_\pi$—we (roughly) see that!

Vector Meson Phenomenology



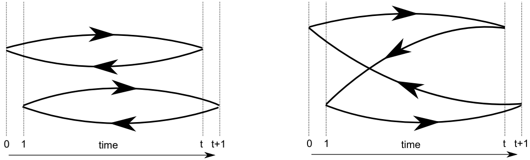
- Production rate related to F_ρ.
- Decay via longitudinal coupling to Goldstones $(W^\pm, Z)$: $g_{\rho\pi\pi}$
- Estimate $g_{\rho\pi\pi}$ via KSRF: $g_{\rho\pi\pi} = \frac{M_\rho}{\sqrt{2}F_\pi}$.
- Estimate $\Gamma_\rho \approx \frac{g^2_{\rho\pi\pi} M_\rho}{48\pi} \approx \frac{M^3_\rho}{96\pi F^2_\pi}$ (Assuming $M_\rho \gg M_\pi$)
  - Using $M_\rho \approx 2\,TeV, F_\pi \approx 250\,GeV \to \Gamma_\rho \approx 450\,GeV$.

8 flavors going forward

1. Pick a general model and study if it has certain features.
   - 8 flavors is a great model to learn about light scalar dynamics.
   - What is the low energy theory when there's a light scalar?
     - We're on the UV complete lattice.
     - We can compute pi-pi scattering, pi-sigma scattering, sigma-sigma scattering.
     - From a field theory standpoint, we can learn a lot.
2. Worry about connecting it to the Standard Model.

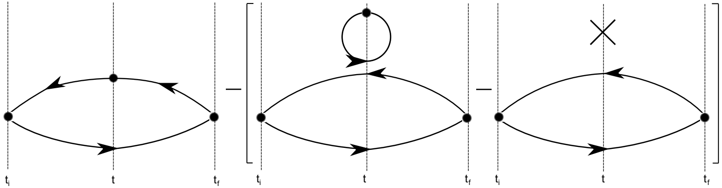
Upcoming work

$I = 2\ \pi^+\pi^+$ scattering



$\rightarrow W^+W^+$ scattering

Scalar form factor of the Pion



$\rightarrow$ Higgs absorption/emission by $W^{\pm}, Z$

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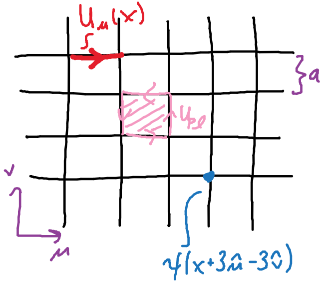
Thank you!

Backup

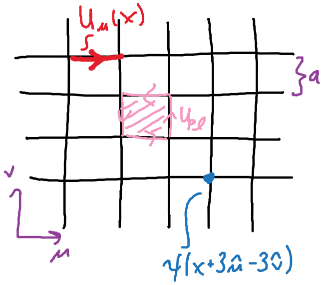
Backup: The Lattice



- Studies are done on 4-dimensional $L \times L \times L \times (2L)$ lattices.
- Common values are $L = 24, 32 \rightarrow \mathcal{O}(1 \text{ million})$ sites.

$$\mathcal{Z} = \int [dUd\bar{\psi}d\psi] e^{-\frac{1}{g^2}F^2 - \bar{\psi}_i \not{D} \psi_i - m_\ell \bar{\psi}_\ell \psi_\ell - m_h \bar{\psi}_h \psi_h}$$

Backup: The Lattice



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- Common values are $L = 24, 32 \to \mathcal{O}(1 \text{ million})$ sites.

$$\mathcal{Z} = \int [dU] \det(D^\dagger D + m_h^2)^{N_h/2} \det(D^\dagger D + m_\ell^2)^{N_\ell/2} e^{-\frac{1}{g^2}F^2}$$

- Having multiple flavors is just adding more fermion determinants.

- We base our 8 flavor runs on existing results.

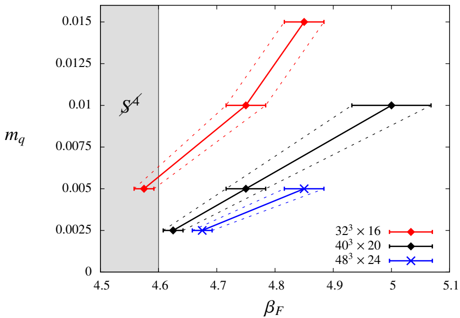

Figure: Finite T studies by Boulder / LSD, in preparation

- Run at strong couplings safe from deconfinement and lattice phases.

Backup: Lattice simulation details

- Lattice study of $SU(3)$ with 8 fundamental flavors
  - Gauge action: fundamental-adjoint with $\beta_a = -\beta/4$ [Cheng et al. 2013][Cheng et al. 2014]
  - Fermion action: nHYP smeared staggered [Hasenfratz et al. 2007]
  - Software: HMC and most measurements in FUEL [J. Osborn]

Backup: Setting and varying a scale

- Along the gradient flow... `[arXiv:1006.4518]`

$$t = \text{gradient flow time}$$

- ...look at a quantity...

$$g^2_{WF}\left(\mu = \frac{1}{\sqrt{8t}}\right) = \frac{1}{\mathcal{N}}\left\langle t^2 E(t)\right\rangle$$

- ...relative to a consistent IR scale.

$$g^2_{WF}(\mu_0 = \frac{1}{\sqrt{8t_0}}) = \frac{0.3}{\mathcal{N}}$$

- μ_0 is an energy scale.
- $\sqrt{8t_0}$ is a length scale.

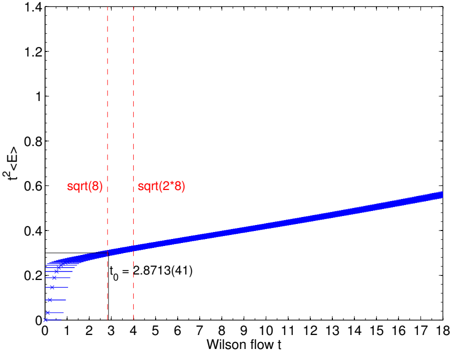

Figure: $48^3 \times 96$, $m_q = 0.00222$

Backup: Scalars in QCD

- There are five (maybe 6) isosinglet scalars below the charm threshold.
- $f_0(500), f_0(980), f_0(1370), f_0(1500), f_0(1710)$ (and maybe $f_0(1790)$).
- Quark model: only two can be predominantly $\bar{Q}Q$.
- Others: meson molecule, diquark pair, glueballs?

Backup: KSRF Relations

$$F_\rho M_\rho = 2F_\pi^2 g_{\rho\pi\pi} \qquad\qquad M_\rho^2 = 2F_\pi^2 g_{\rho\pi\pi}^2$$

These imply:

$$F_V = \sqrt{2}F_\pi \qquad\qquad g_{\rho\pi\pi} = M_\rho / F_\rho$$

These are good at $\approx 20\%$ in QCD, even at heavier pion masses.
Need to add links to citations: use in QCD, how it comes from simple models of massive vectors.

Backup: Strategy for disconnected diagrams

- 8 flavors uses the following setup!
  - 6 $U(1)$ sources with dilution in time, color, and even/odd spatially
  - Improved estimator for $\langle\bar{\psi}\psi\rangle$
  - Dilution in time, color, even/odd space
  - Improved estimator for disconnected piece
  - Still need large statistics to suppress gauge noise
- Analysis strategy.
  - Correlated fit to both parity states
  - Vacuum subtraction introduces large uncertainties
  - Fit an additional constant
  - Equivalent to fitting the finite difference $C(t+1) - C(t)$

$$C(t) = c_{0^{++}} \cosh\left(M_{0^{++}}\left(T/2 - t\right)\right) + c_{\tilde{\pi}_{sc}} \left(-1\right)^{t} \cosh\left(M_{\tilde{\pi}_{sc}}\left(T/2 - t\right)\right) + v$$