Composite phenomenology as a target for lattice QCD

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Outline

- Motivation
- Examples of systems
  - "Twin Higgs"
  - Strongly interacting dark matter
- Example of model: the KSRF relation (and related quantities)
- Takeaway thoughts

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Motivation

- Lattice QCD has a very specific goal: QCD at physical quark masses
- Simulation data away from the chiral limit is uninteresting in its own right

However

- Some beyond standard model phenomenology incorporates confining dynamics
  - Composite Higgs
  - Strongly interacting dark matter
- Sometimes, the models do not involve zero mass or small mass fermions
- Sometimes, the gauge group is even $SU(3)$

Uninteresting lattice QCD results can actually be interesting!

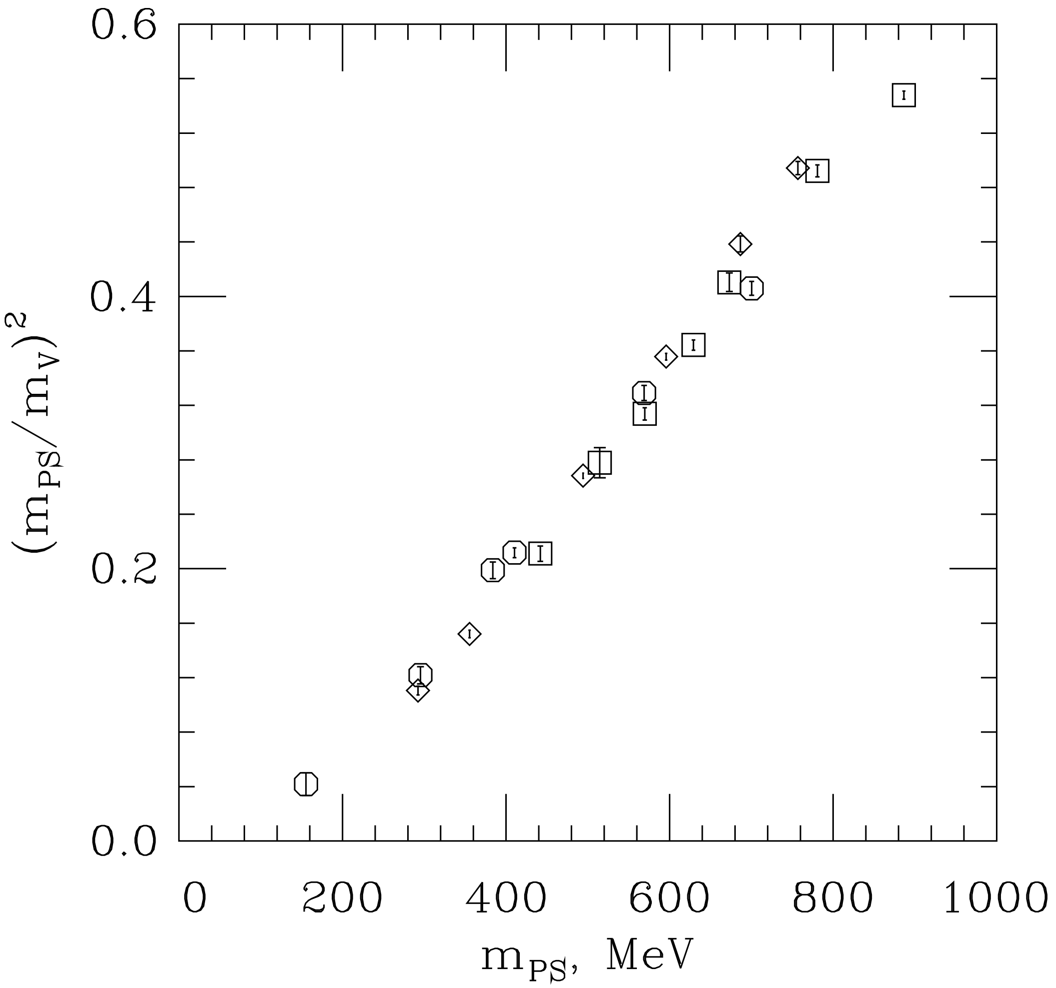
Targets

- Spectroscopy – presented as scale-independently as possible
  - Pheno people work with Λ_{QCD} and Yukawas instead of quark masses
  - Perhaps show m_H in MeV vs $(m_{PS}/m_V)^2$ (to easily rescale)?
- f_{PS} and other LEC's (used for extracting Higgs parameters)
- f_V and f_A
  - Used for Z-boson couplings to the dark sector
  - Used for vector dominance, "kinetic mixing" of photon and dark photon
- g_{VPP} (the $V \to PP$ coupling)
- 5-Goldstone couplings (pheno people use the Wess - Zumino - Witten vertex)
- Matrix elements of scalar currents, for Higgs couplings – nucleon sigma terms (and related objects)

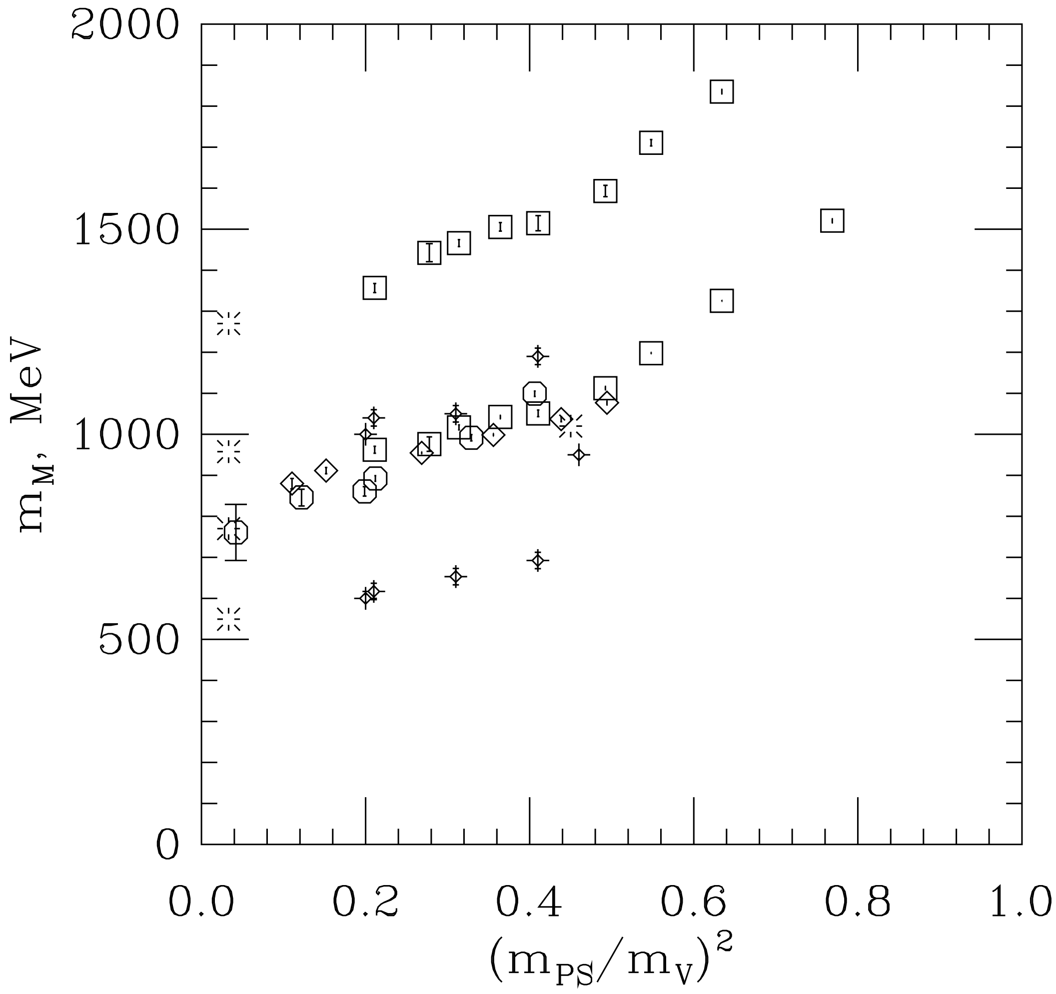
Useful to quote FLAG: "To date, no significant differences between results with different values of N_f have been reported in the quantities listed in Tables"

QCD at large m_{PS}/m_V

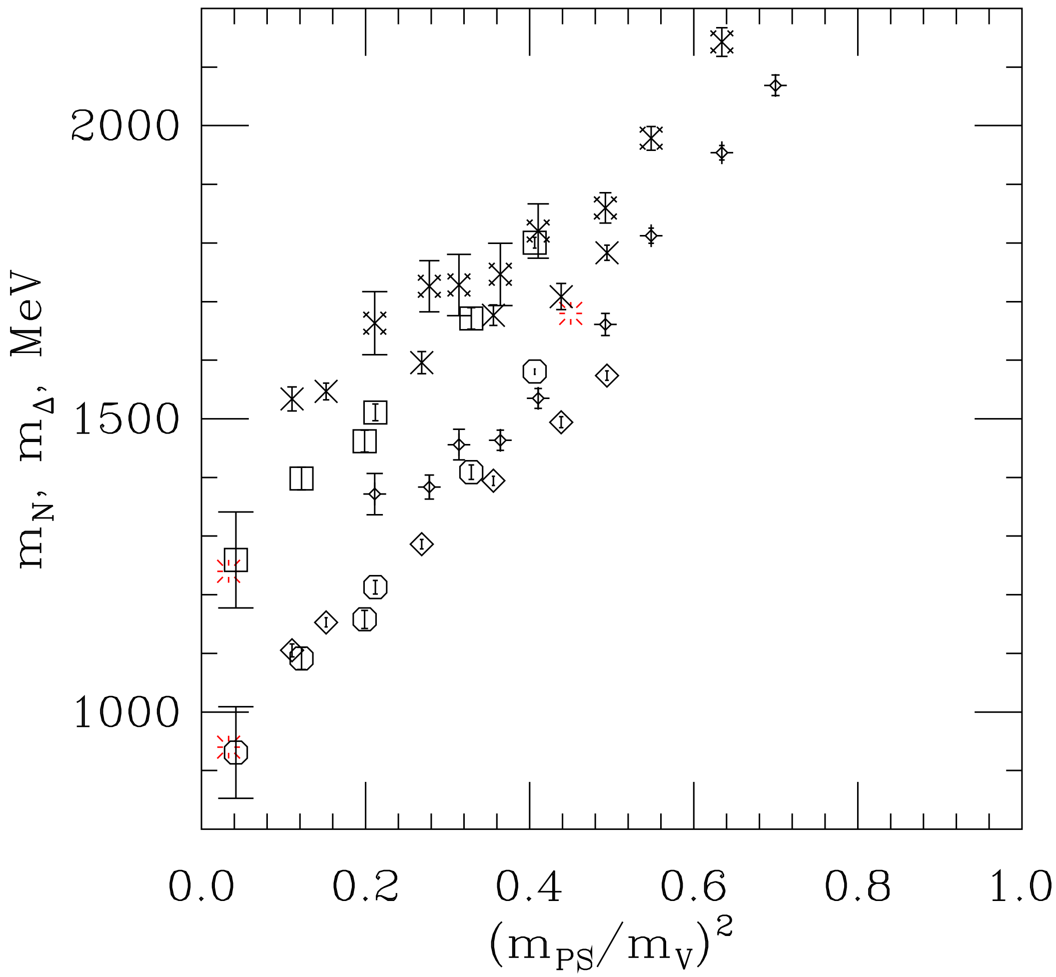
All the spectroscopy is out there!



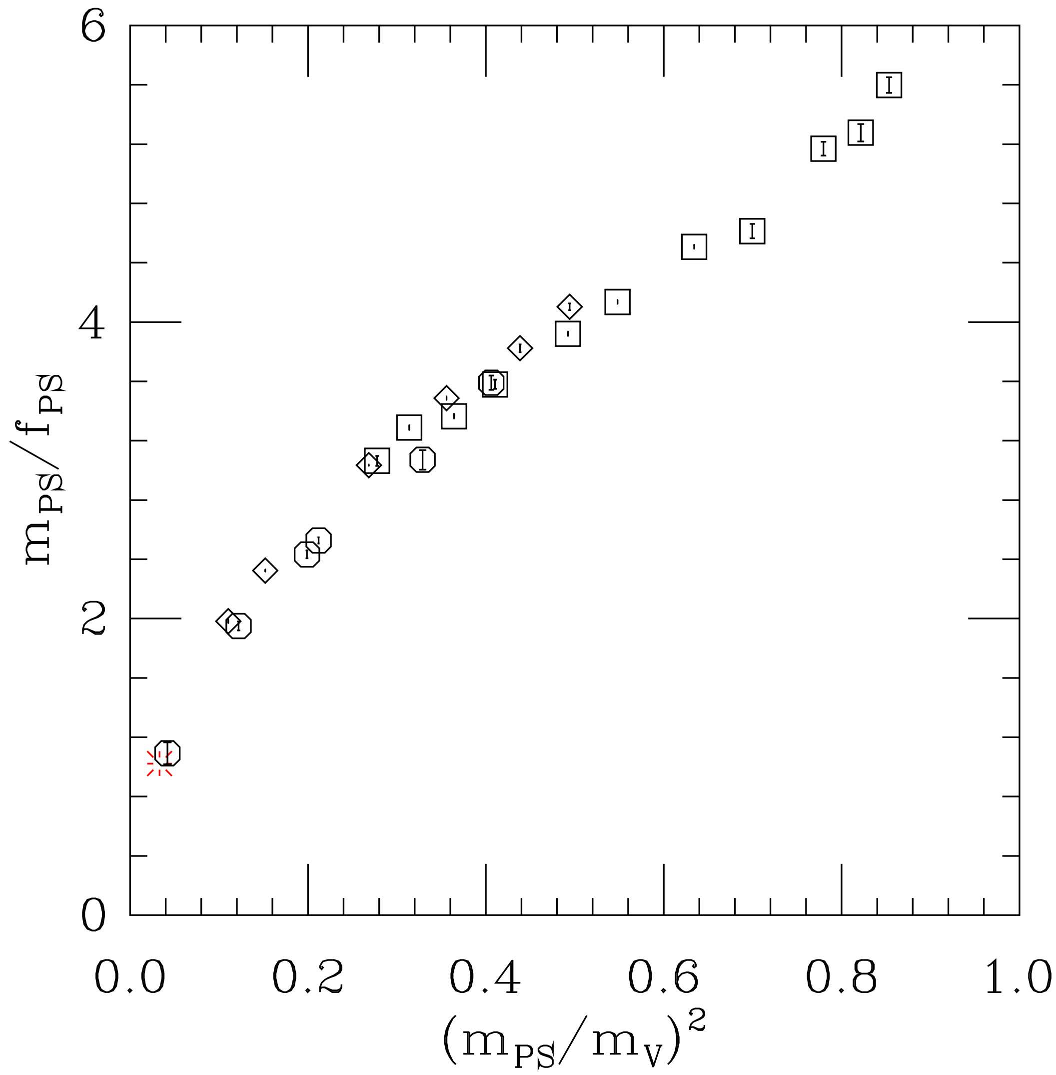
$(m_{PS}/m_V)^2$ versus pion mass in MeV.



Meson spectroscopy (vector and axial vector mesons, η, η') vs $(m_{PS}/m_V)^2$.



Somewhat messy baryon spectroscopy vs $(m_{PS}/m_V)^2$ (bursts N, Δ, Ω)



m_{PS}/f_{PS} vs $(m_{PS}/m_V)^2$. ($f_\pi = 137$ MeV.) Note the limited range. . .

An example – "twin Higgs models"

Goes back to Chacko, Goh, Harnik, hep-ph/0506256 – a "solve the hierarchy problem" model

Make H an $SU(4)$ fundamental scalar, with a potential

$$V(H) = -m^2 H^\dagger H + \lambda (H^\dagger H)^2 \tag{1}$$

H gets a VEV, $f = m/\sqrt{2\lambda}$

Break $SU(4)$ explicitly by gauging an $SU(2)_A \times SU(2)_B$ subgroup. ($SU(2)_A \rightarrow SU(2)_L$)

Gauge loops contribute a quadratically divergent mass to H components,

$$\Delta V = \frac{9 g_A^2 \Lambda^2}{64\pi^2} H_A^\dagger H_A + \frac{9 g_B^2 \Lambda^2}{64\pi^2} H_B^\dagger H_B \tag{2}$$

Impose a symmetry ($H_A \leftrightarrow H_B$ forcing $g_A = g_B$)

$$\Delta V = \frac{9 g^2 \Lambda^2}{64\pi^2} (H_A^\dagger H_A + H_B^\dagger H_B) = \frac{9 g^2 \Lambda^2}{64\pi^2} H^\dagger H \tag{3}$$

to remove quadratically divergent mass for Goldstones from gauge fields

Loops generate a non $SU(4)$ invariant GB mass $\sim g^2 f / 4\pi$

Generalize this stabilization to all of the SM with a "twin" of every SM particle

Gymnastics to prevent disasters...Yukawas can be different in twin sector

But (unlike for most BS models), $N_c = 3$ is mandatory

Several variants in the literature

- A copy of every fermion (issue: light particles at BBN)
- Or just a copy of the t and b (and both are heavy)
  - Quenched glueballs
  - Quarkonia

Phenomenology presented in terms of

- $\Lambda \neq \Lambda_{QCD}$ setting the overall scale
- Yukawas set the quark masses

An example – strongly interacting dark matter

"Strongly - interacting" means $3 \to 2$ couplings are important

Example: A. Berlin et al, 1801.05805 (with predecessors back to 2015)

- Dark matter as PGB's
- Explicit model is $SU(3)$ with $N_f = 3$ fundamentals
  - Other possibilities out there ($SU(2)$ w/ fundamentals)
- Often, predictions in terms of m_{PS}/f_{PS}, spanning an unphysically large range
- 1801.05805 wants $m_{PS}/m_V \sim 1/2$
- Long story about $3 \to 2$ in terms of f_V, g_{VPP}
- Dark photon (AKA rho meson)
- Unusual fermion charge assignments ($Q = \text{diag}(+1, -1, -1)$)

Goals of papers are to compute $3 \to 2$ rate, coupling of dark photon to EM photon

A case study – the KSRF relation

Phenomenologists combine chiral dynamics and vector mesons in an effective Lagrangian

$$\mathcal{L} = \frac{F^2}{4}\mathrm{Tr}(D_\mu U D^\mu U^\dagger) - \frac{1}{8}\mathrm{Tr} G_{\mu\nu} G^{\mu\nu} + \ldots \tag{4}$$

with the usual Goldstone field

$$U = \exp(i\Phi/F) \tag{5}$$

and vector mesons introduced with a covariant derivative

$$D_\mu \Phi = \partial_\mu \Phi + \frac{ig}{2}[\Phi, V_\mu] \tag{6}$$

They have a self coupling from

$$G_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu \tag{7}$$

. . . in $\mathcal{L}$ includes phenomenological V mass terms, couplings

(KSRF is Kawarabayashi, Suzuki, Riadzuddin, Fayazuddin, 1966)

Bottom line is phenomeological expression for

$$\langle 0|\bar{u}\gamma_i d|V\rangle = m_V^2 f_V \epsilon_i \tag{8}$$

$$f_V = \sqrt{2}\frac{f_{PS}}{M_V}. \tag{9}$$

(and other observables)

Also

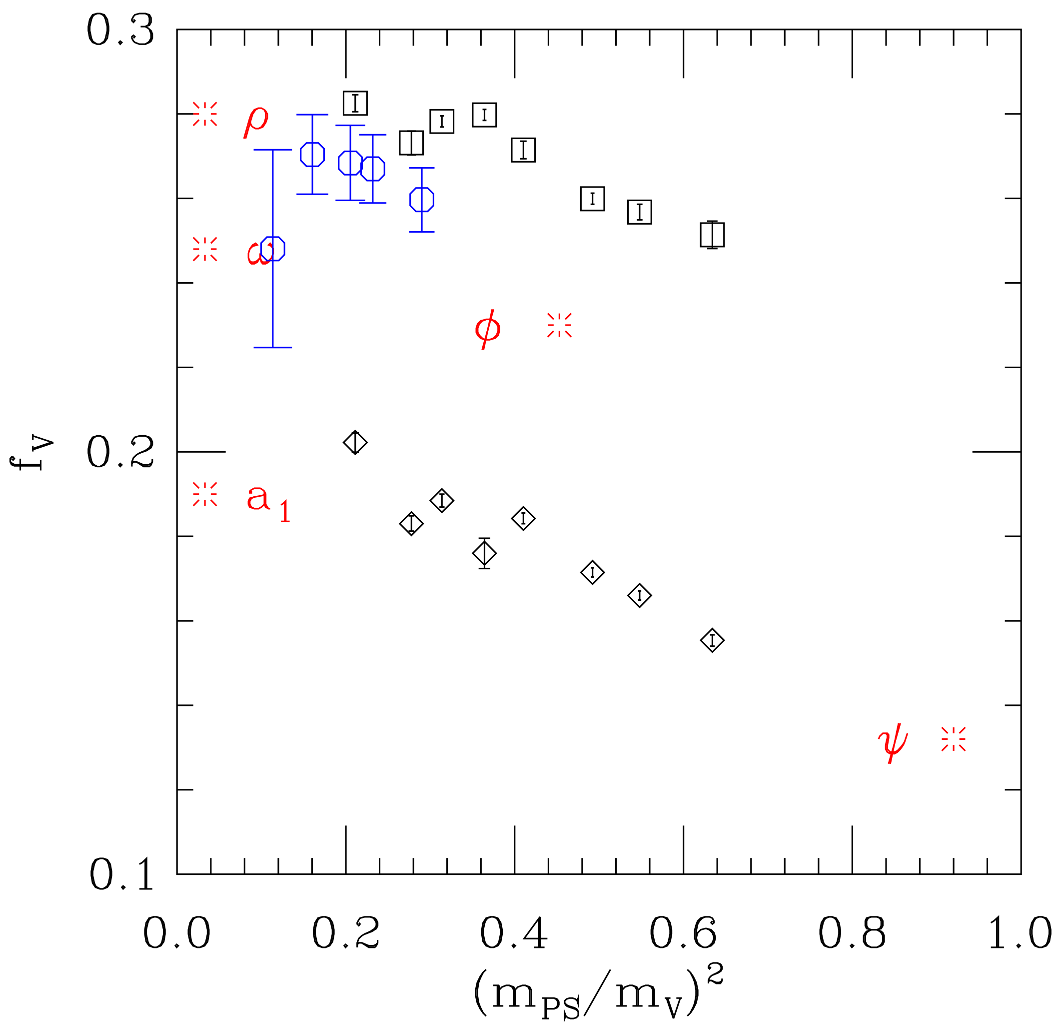
$$g_{VPP} = \frac{M_V}{f_{PS}}. \tag{10}$$

in terms of which the vector meson decay width is

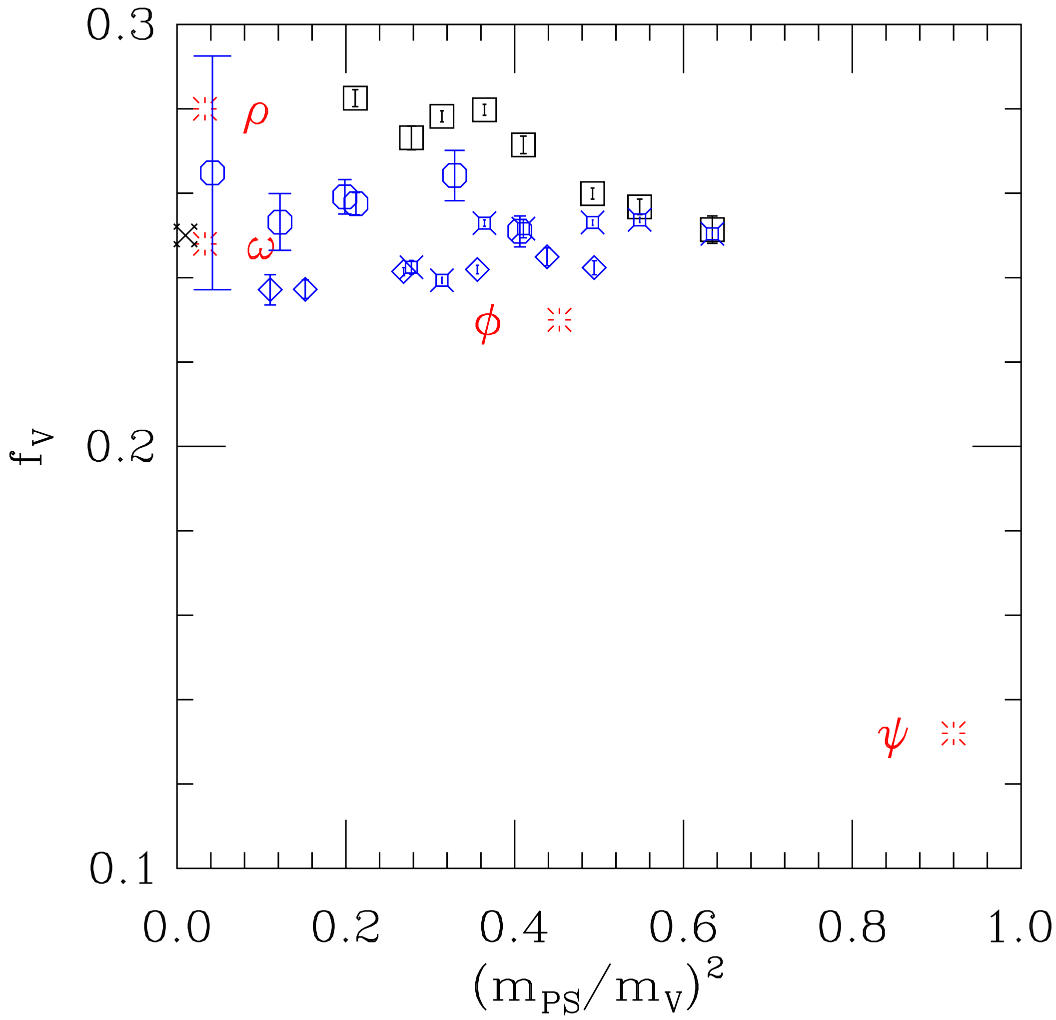
$$\Gamma(V \to PP) \simeq \frac{g_{VPP}^2}{48\pi m_V^2}(m_V^2 - 4m_{PS}^2)^{3/2}. \tag{11}$$

See Klingl, Kaiser, Weise, hep-ph/0607431

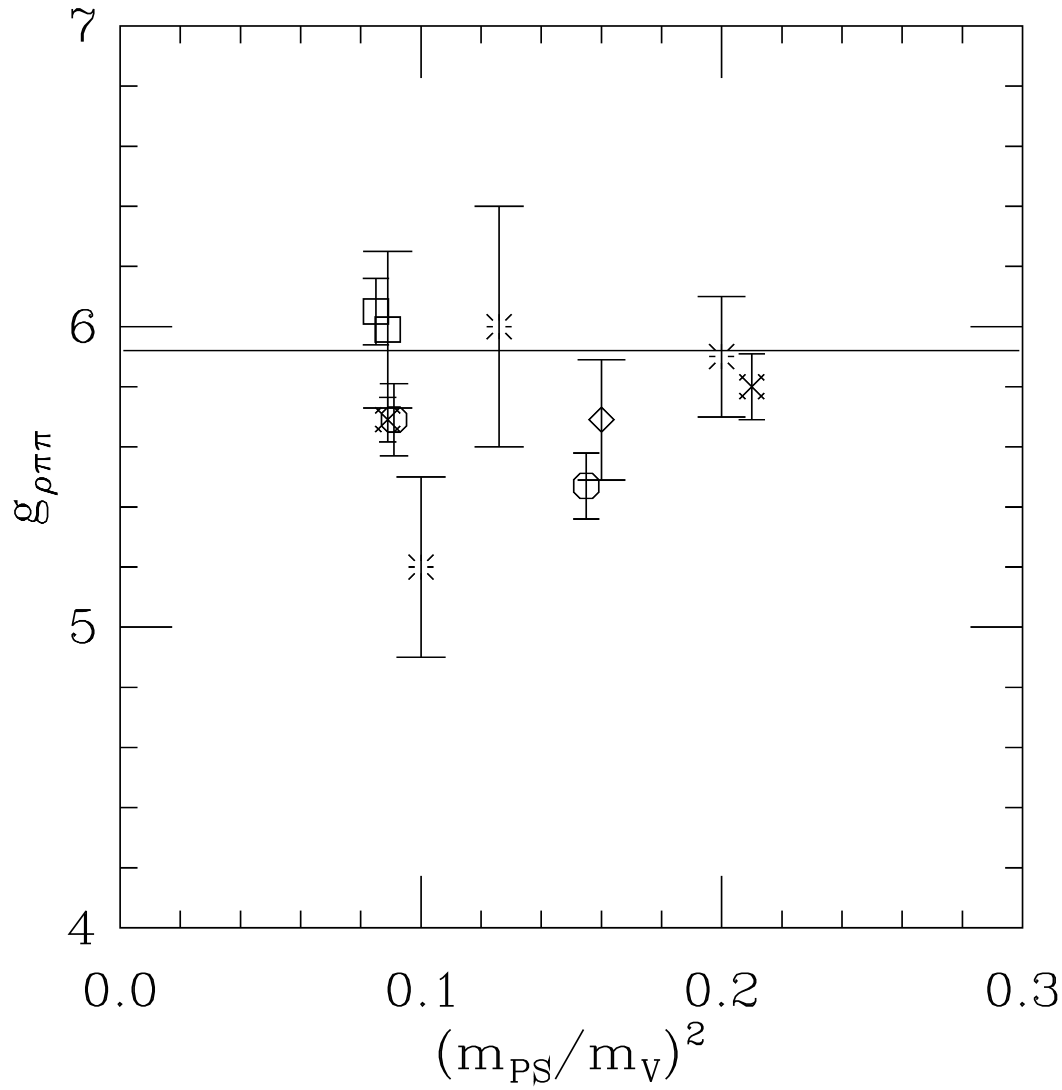
The phenomenologists we know don't know about lattice f_V or g_{VPP}!



f_V and f_A versus $(m_{PS}/m_V)^2$.



f_V versus $(m_{PS}/m_V)^2$. Squares: direct lattice calculations of f_V; blue symbols f_V from KSRF f_{PS} and m_V. The fancy cross is the KSFR result for massless quarks from the physical rho mass and pion decay constant.



The vector meson decay constant g_{VPP} from lattice calculations, as a function of $(m_{PS}/m_V)^2$. The line is the KSFR relation with physical values for the rho mass and f_π.

Takeaway thoughts

- There is a market for $SU(3)$ lattice results away from the chiral limit
- It would be useful to present lattice results in non-lattice-specific formats
- Comparing lattice data to model calculations can be profitable