Lattice QCD beyond the Standard Model

Ethan T. Neil (Colorado)
Mackenzie-fest
11/07/19

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- *"It's fine to be interdisciplinary, but you don't want to sound like you don't know what you want to be when you grow up."*

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- I (and the whole community) owe Paul an enormous debt for everything he did behind the scenes to keep the USQCD project organized and running like clockwork, so postdocs like me could just get on with the business of research.

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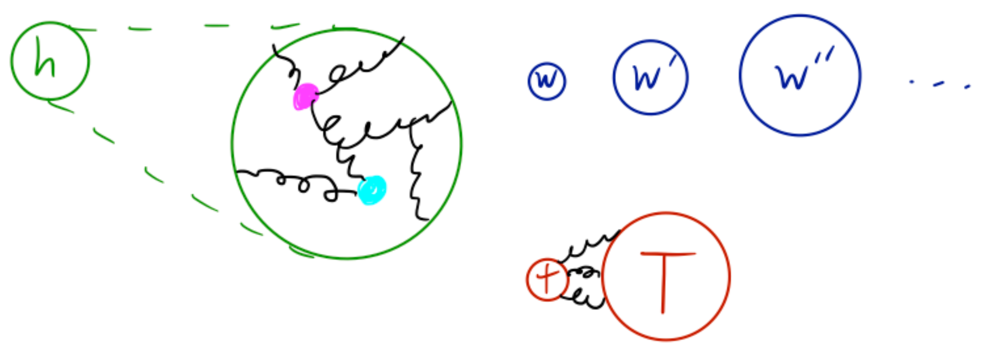
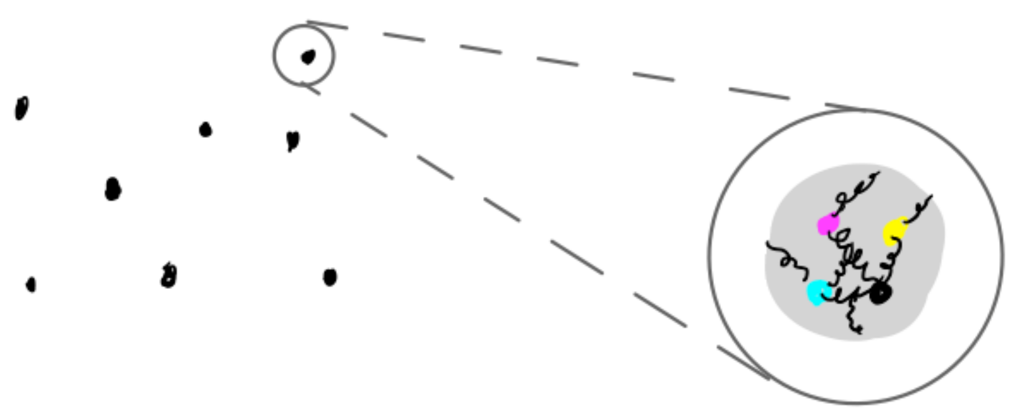
- Plots shown are from our paper, unless noted otherwise. They collect lattice QCD results from a few collaborations: ETMC, LHPC, PACS-CS, and some of our own simulations.

Motivation: composite BSM

Many proposals for models of new physics include *strongly-coupled Yang-Mills* interactions, which leads naturally to composite states.

Composite Higgs: new strongly-coupled sector at the electroweak scale; Higgs is a composite bound state. (W/Z, top often have some composite part too.)



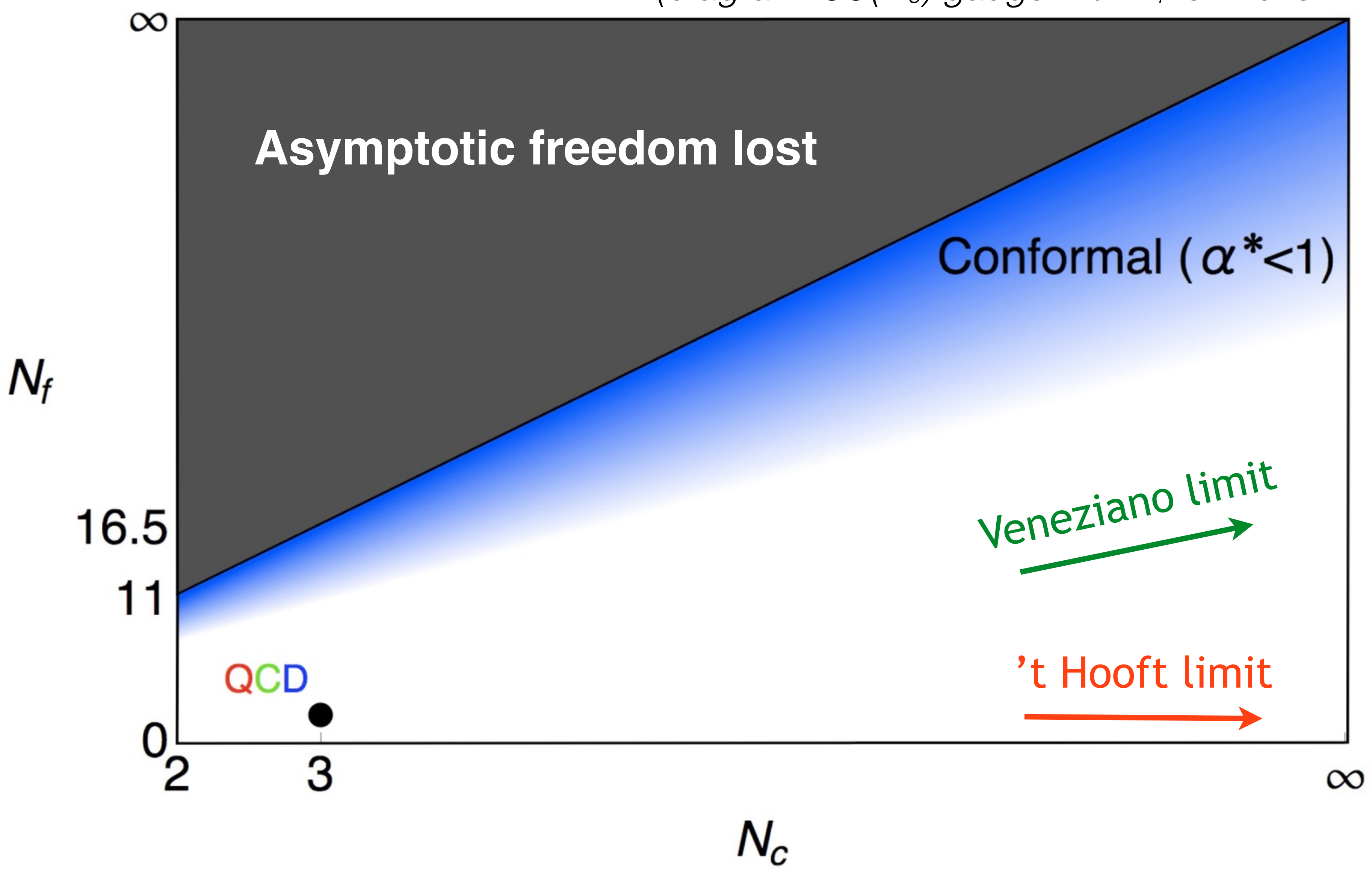


Composite dark matter: dark "hidden sector" which is strongly coupled. Can appear naturally with composite Higgs or GUT theories, or neutral naturalness (mirror/twin sector.)

These are interesting and rich models, but they can be hard to study because strong coupling prevents perturbative calculations. **Lattice calculations** can fill in the blanks!

Exploring the theory space

(diagram: SU(N_c) gauge with N_f fermions in fundamental irrep)



Aside from specific models, lattice can give non-perturbative insight into the broader space of gauge-fermion theories, which exhibits:

- **rich phase structure** (IR-conformal phase transition),
- **emergent dynamics** (4d conformal field theories),
- **well-established trends** (the 't Hooft and Veneziano large-N limits.)

Modeling the theory space

- If we have models like 't Hooft large-N expansion available, why do we need lattice?
- Lattice gives *quantitative* information in a vast space for which we have only one real-world example (QCD). Allows us to:
  - Test and validate models of theory space
  - Search for novel phenomena that might require new models
  - Fill in details that the models don't provide
- Analogous to the *Wigner-Eckart theorem* in quantum mechanics. Symmetry gives us a big part of the story, but we still have to calculate the reduced matrix elements to make concrete predictions!

$$\langle j', m' | \hat{T}_q^{(k)} | j, m \rangle = \langle jk; mq | jk; j'm' \rangle \langle j' || \hat{T}^{(k)} || j \rangle$$

From QCD to “QCD”

- I’ll make some references to the larger space, but the main focus of this talk is on the QCD point: SU(3) with a couple light flavors.

- There are a number of BSM scenarios where a new SU(3) with a couple of light flavors is a reasonable choice. (e.g. “dark baryon” dark matter.)

- There are a smaller number of BSM scenarios in which a new SU(3) sector is *compulsory*; mostly “twin” or “mirror” scenarios. (These are examples of “neutral naturalness”, which is receiving more attention with no obvious LHC discoveries to fix the Higgs hierarchy problem.)

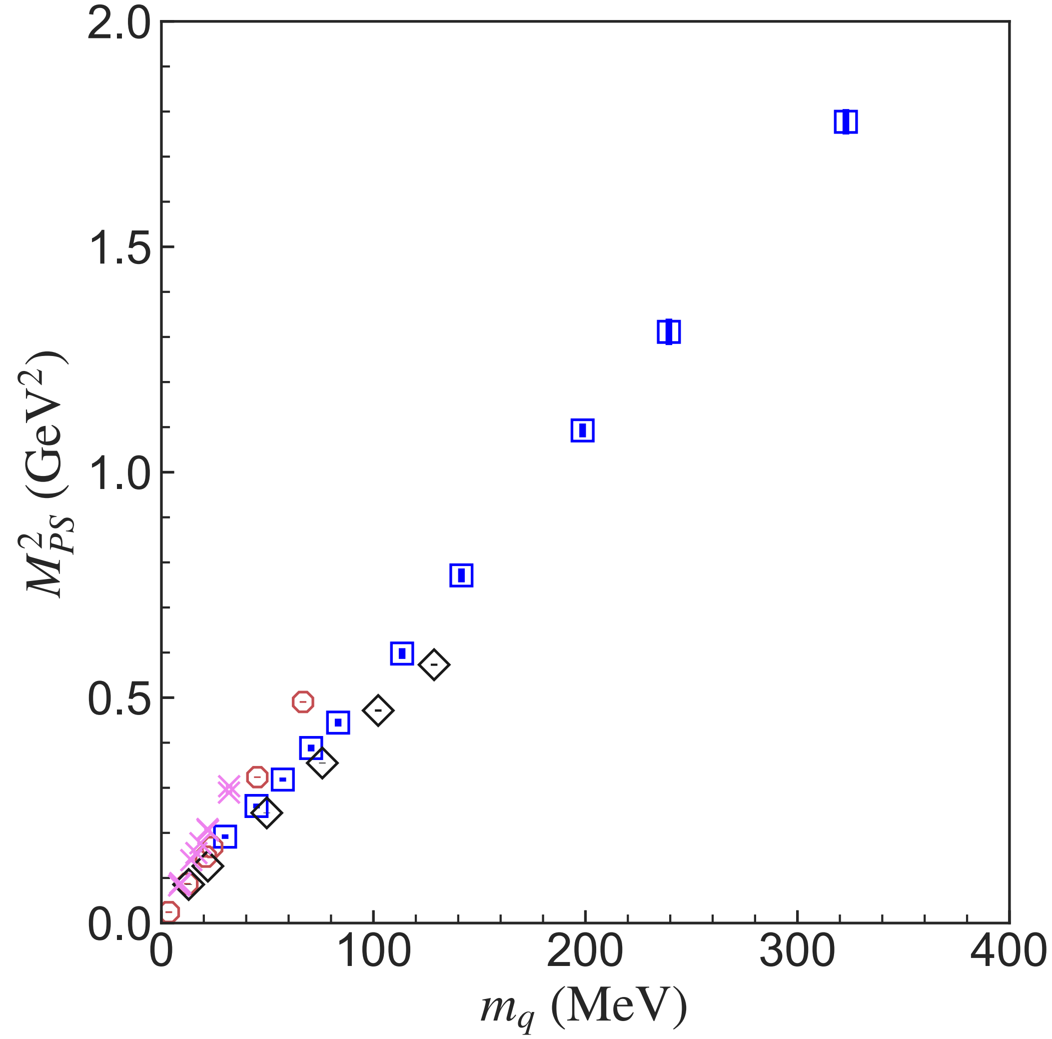
a) Pseudoscalar mesons

Pseudoscalar mesons

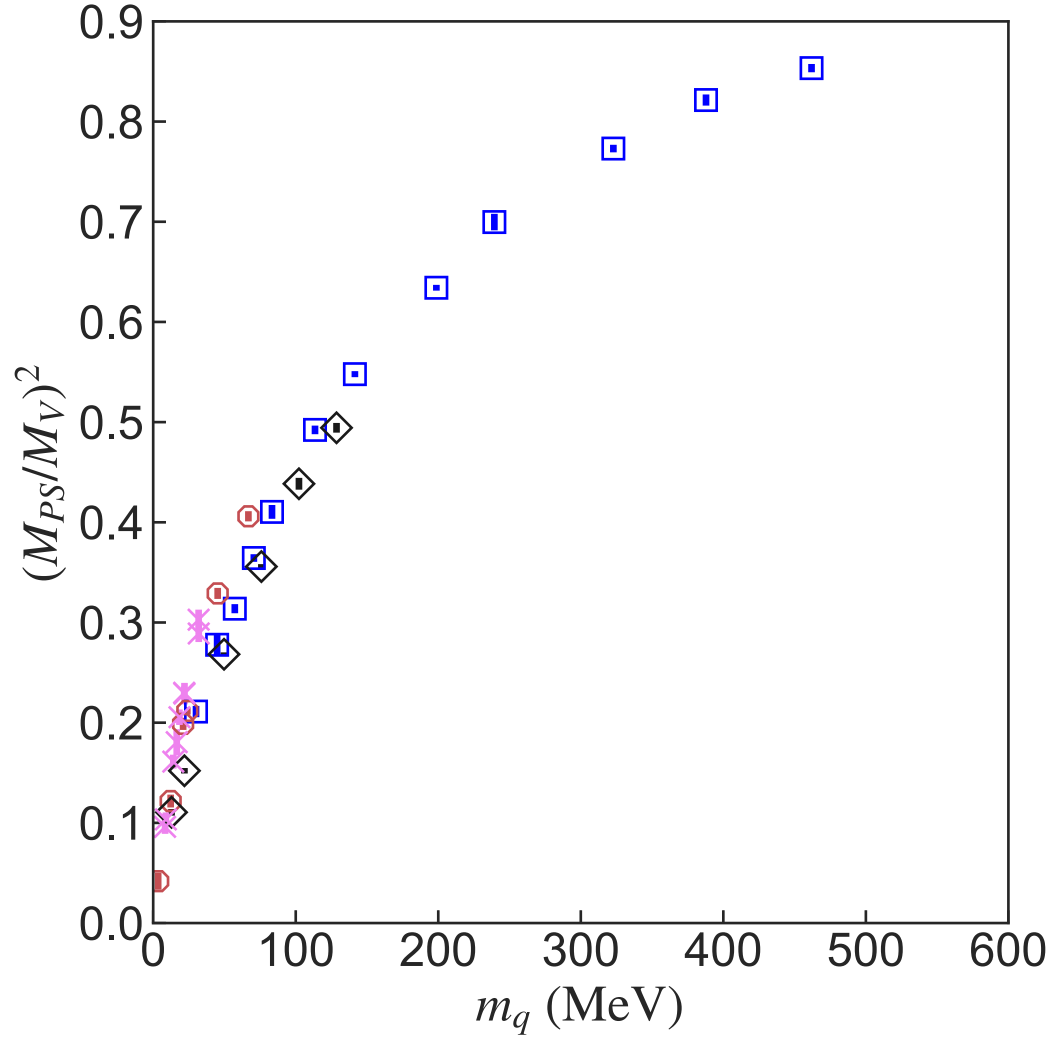
- Pions (kaons, etas) are pseudo-Goldstones, so we don't need lattice to understand many of their properties - chiral perturbation theory.
- Lattice can give the low-energy constants needed to make quantitative predictions, e.g. slope of M_{PS}^2 vs. m_q.
- We can also explore up to much heavier quark masses than we can trust with chiral perturbaion theory.

“How heavy are your pions?”

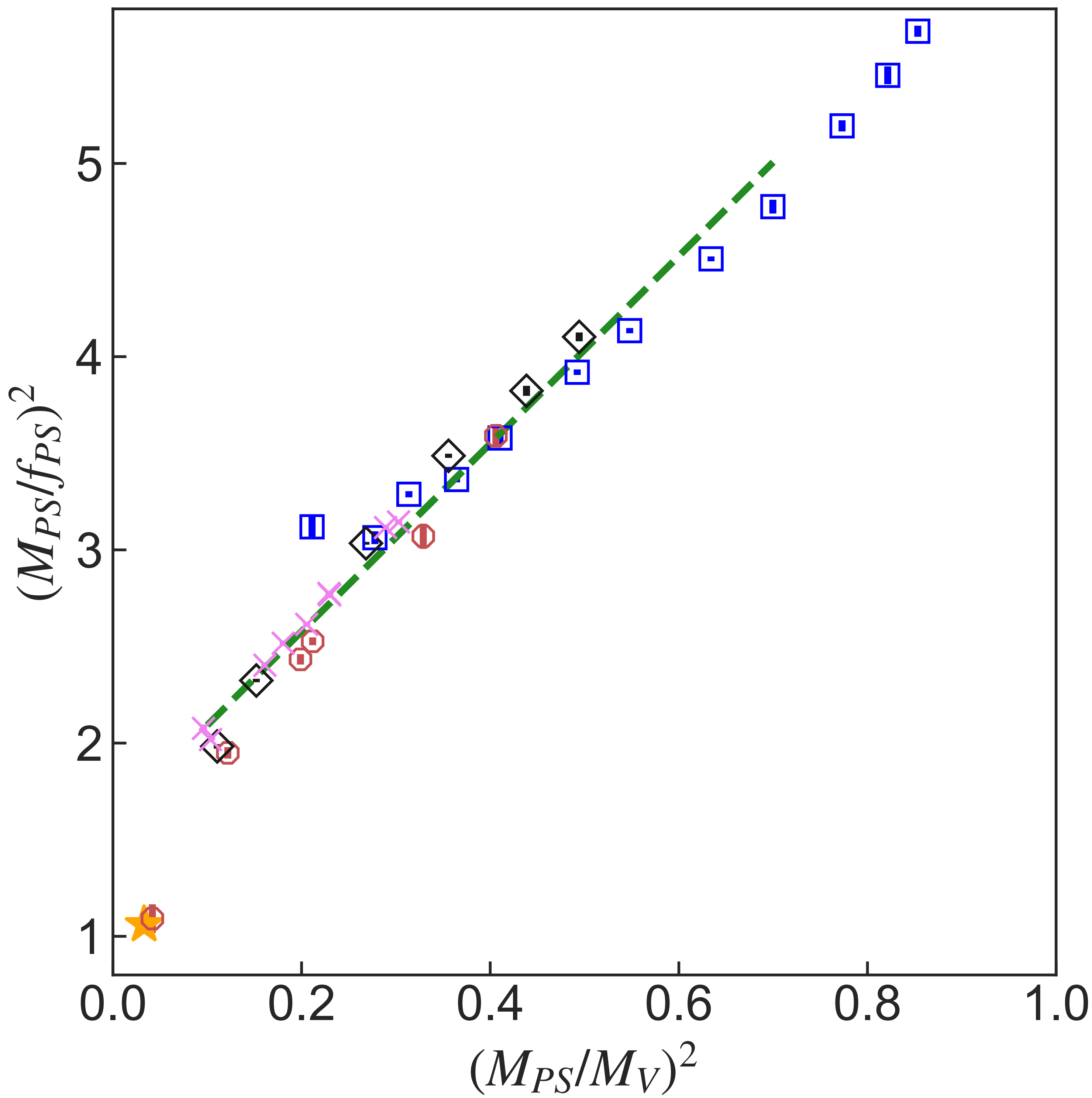
(from EN and T. DeGrand, arXiv:1910.08651)



(lattice results from Walker-Loud et al, PACS-CS, and ETMC; see paper)



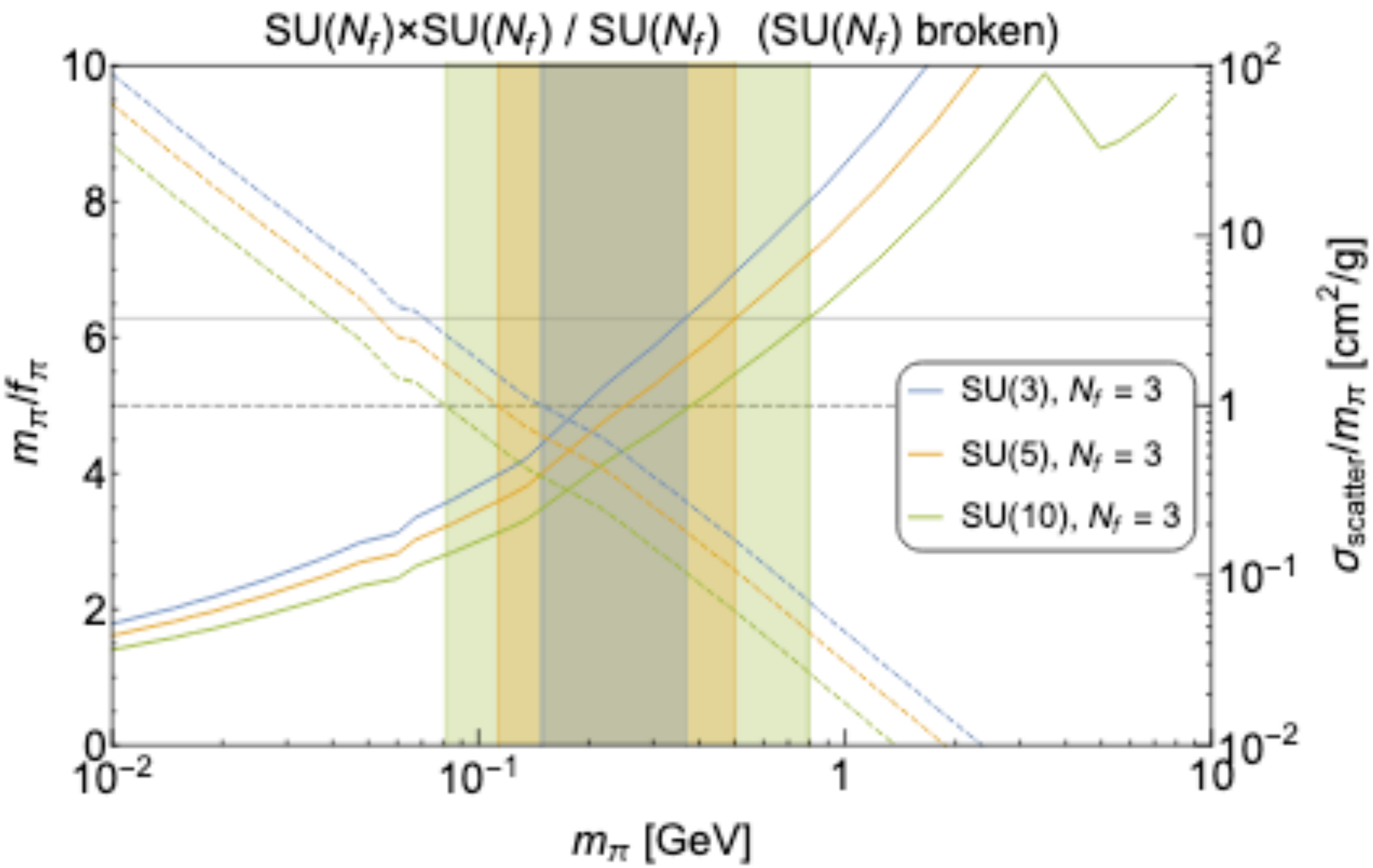
- Gell-Mann-Oakes-Renner (GMOR) relation: $M_{PS}^2 = 2Bm_q$. Pseudoscalar meson (“pion”) mass is a good RG-invariant proxy for quark mass.
- For converting to different models, it’s often easier to work with a dimensionless ratio like M_{PS}/M_V instead.



- Shown left: ratio of pseudoscalar mass to decay constant (note 130 MeV convention)
- Linear trend for intermediate quark masses evident from data; accurate ~10%.
- Note that M/F only varies from 0 in the chiral limit to around 5-6 at the heaviest masses probed.

Example: SIMP dark matter

(from Y. Hochberg, E. Kuflik, H. Murayama, T. Volansky and J. Wacker, arXiv:1411.3727)

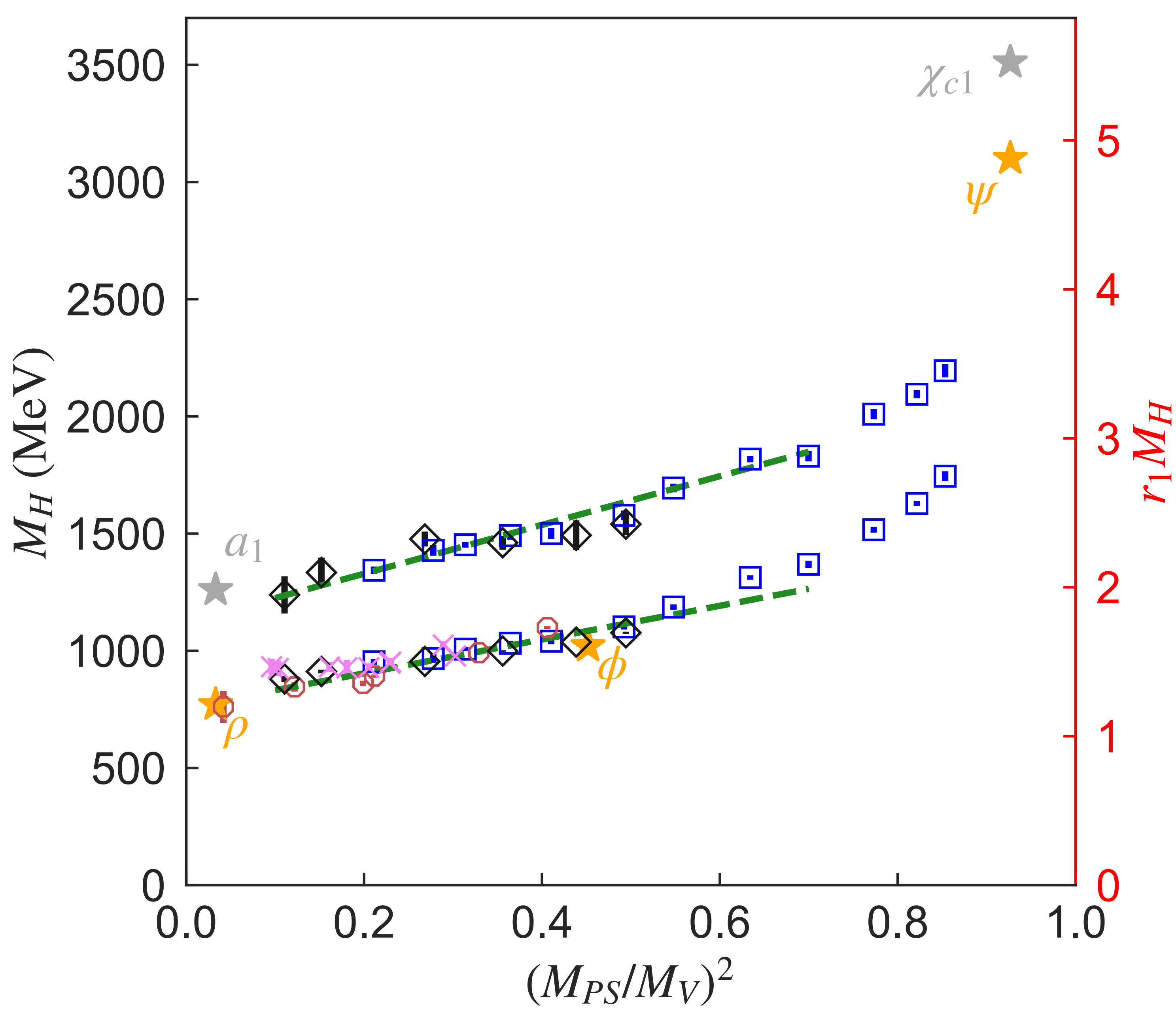


No more non-perturbative free parameters once scale (x-axis) and quark mass (y-axis) are fixed! Other predictions from strong interactions here?

- Composite dark matter model where 2—>3 interactions set “dark pion” relic density
- <u>Left axis, solid lines:</u> M/F needed to obtain correct dark matter relic density
- <u>Right axis, dashed lines:</u> self-scattering cross section, dashed horizontal line shows upper bound
- *From last slide*: the plot should probably end around M/F < 6, with a somewhat lower bound to trust chiral effective theory.

b) Vector mesons

(lattice results from Walker-Loud et al, PACS-CS, and ETMC; see paper)

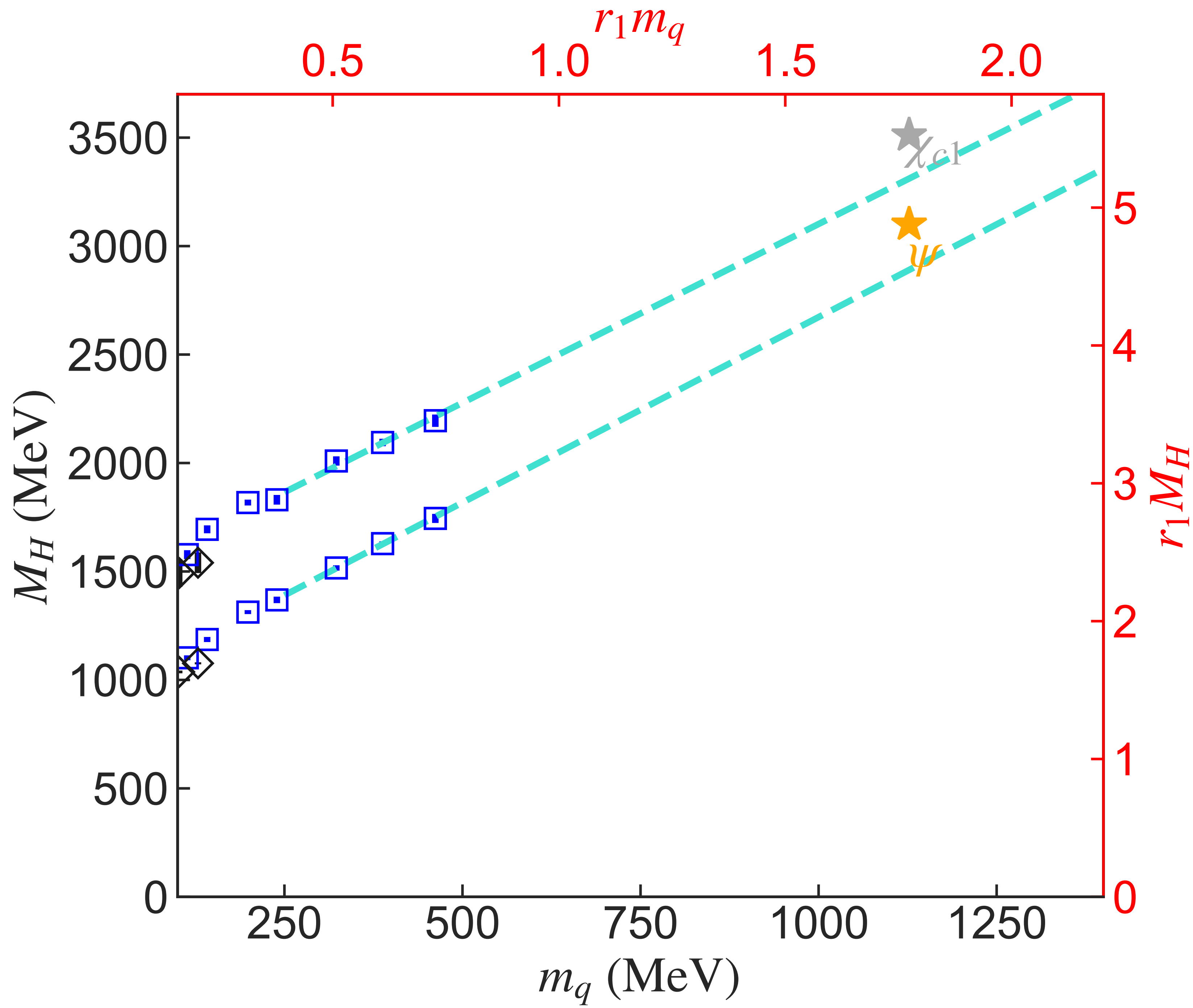


- Vector and axial-vector meson masses, overlaid PDG masses (stars)
- Data from multiple groups; no careful treatment of systematics, or even continuum extrapolation!
- Linear fit good to ~10% accuracy over the range $0.1 < (M_{PS}/M_V)^2 < 0.7$ - roughly 200 MeV to 1 GeV pion masses.
- Deviation at heavy-quark end as the ratio on the x-axis approaches 1 asymptotically.

- For working at very heavy masses, the quark mass itself is dominant; linear fit in m_q works well

- Even extrapolation to charm mass works at 10% accuracy level!

- (If you have bottom-like quarks or heavier, heavy-quark EFT or pure-gauge lattice results are probably more useful.)



[1]K. Kawarabayashi and M. Suzuki, Phys. Rev. Lett.16, 255 (1966); Riazuddin and Fayyazuddin, Phys. Rev. 147,1071 (1966).

Vector Meson Saturation

- Saturation of vector channel by a single resonance (ρ) gives a phenomenological model of low-energy quantities, based on rho mass and width.

- VMS works well in QCD (~10%) for some things, e.g. KSRF relations:

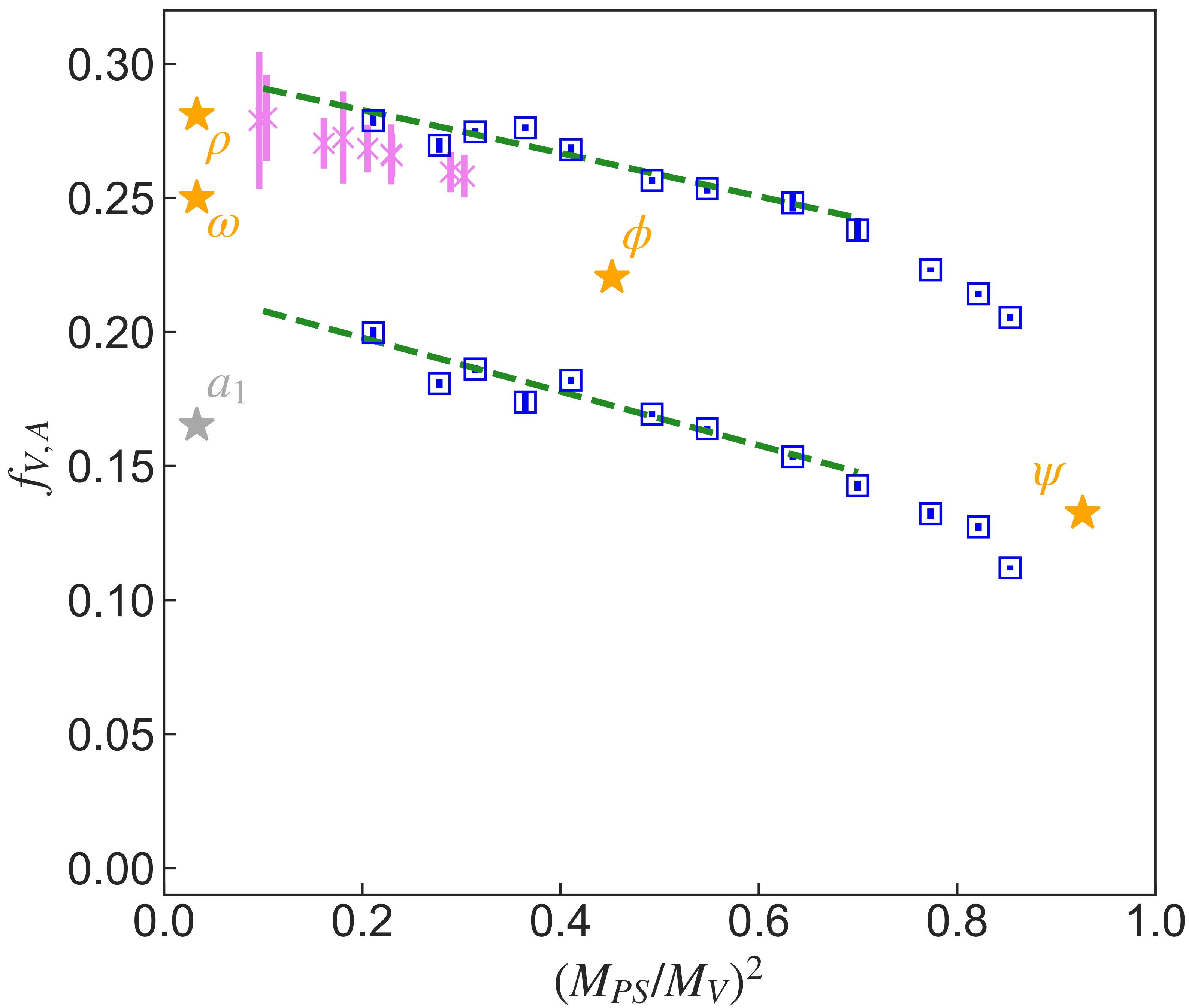
$$\sim \langle 0|J^\mu|\rho\rangle \longrightarrow F_\rho = \sqrt{2}\ F_\pi\ , \quad g_{\rho\pi\pi} = \frac{M_\rho}{\sqrt{2}\ F_\pi}\ ,$$

$$\sim \langle \pi\pi|J^\mu|\rho\rangle \longrightarrow \Gamma_\rho \approx \frac{g^2_{\rho\pi\pi}\ M_\rho}{48\pi} \approx \frac{M_\rho^3}{96\pi F_\pi^2}$$

large-N_c:

$$\frac{M_\rho}{F_\pi} \sim \frac{1}{\sqrt{N_c}}$$

- What happens if we move away from physical QCD?



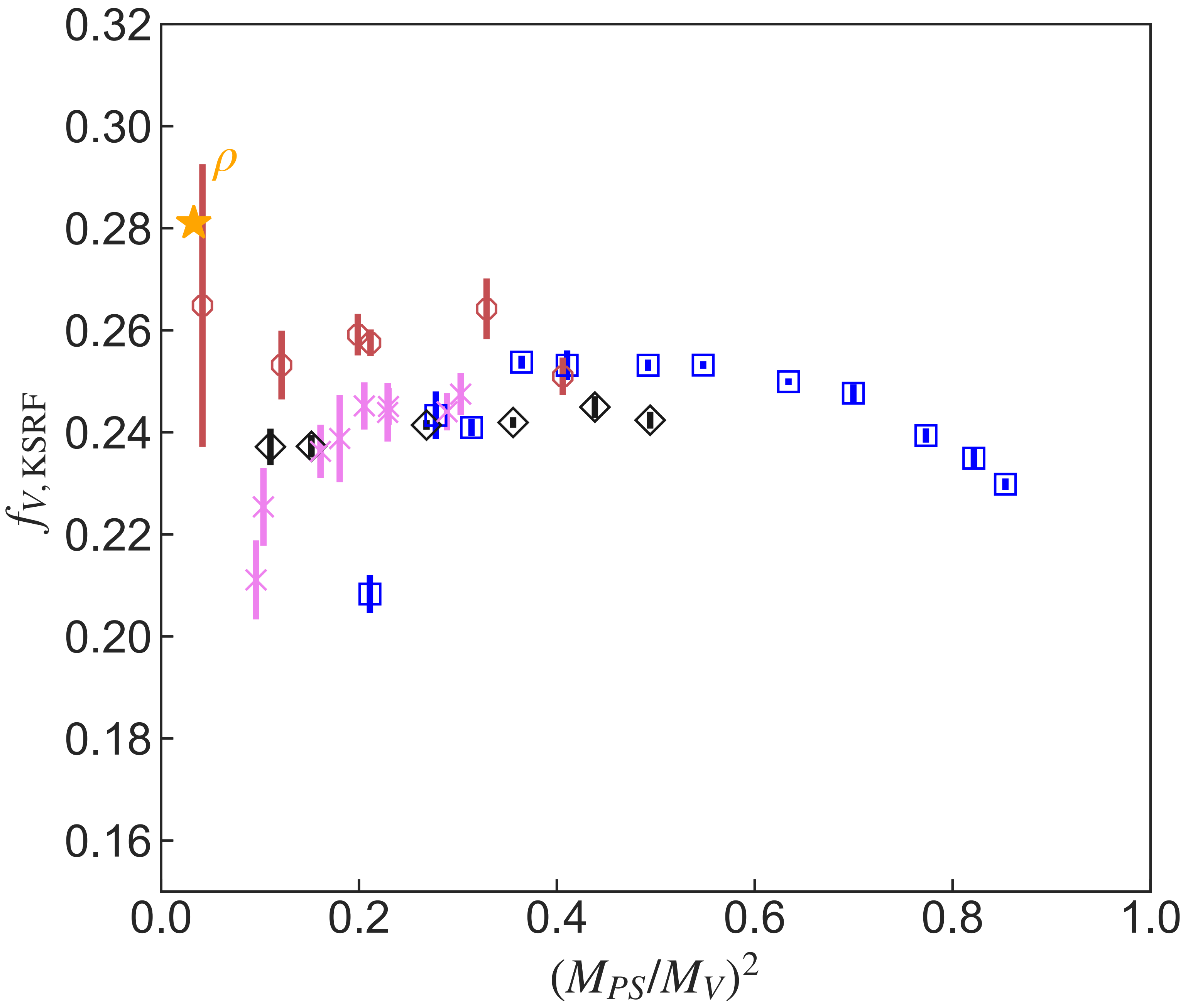
- Direct calculation of vector and axial-vector decay constants, defined as:

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

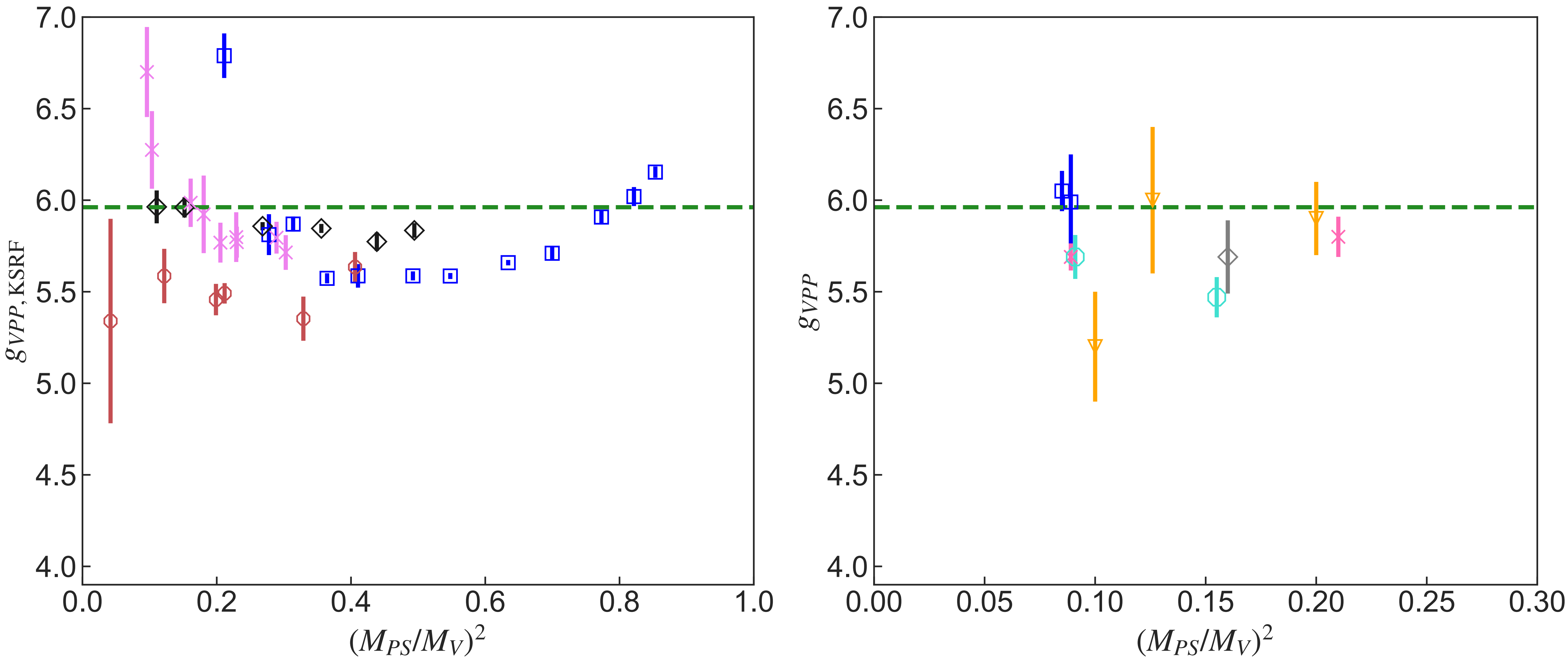
- QCD results again show reasonable qualitative agreement; determined from PDG using

$$\Gamma(V \to e^+e^-) = \frac{4\pi\alpha^2}{3} M_V f_V^2 \langle q \rangle^2$$

- What if we try to predict f_V using KSRF instead?



- f_V reconstructed from f_{PS} using KSRF relation; good agreement up to fairly heavy quark mass! Very weak quark mass dependence.



- Left panel: vector-PP strong decay coupling estimated using second KSRF relation. Right panel: direct lattice calculations of the strong decay matrix element.

- Again, both agree well with each other and with PDG decay width of the rho (green dashed line); very little quark mass dependence.

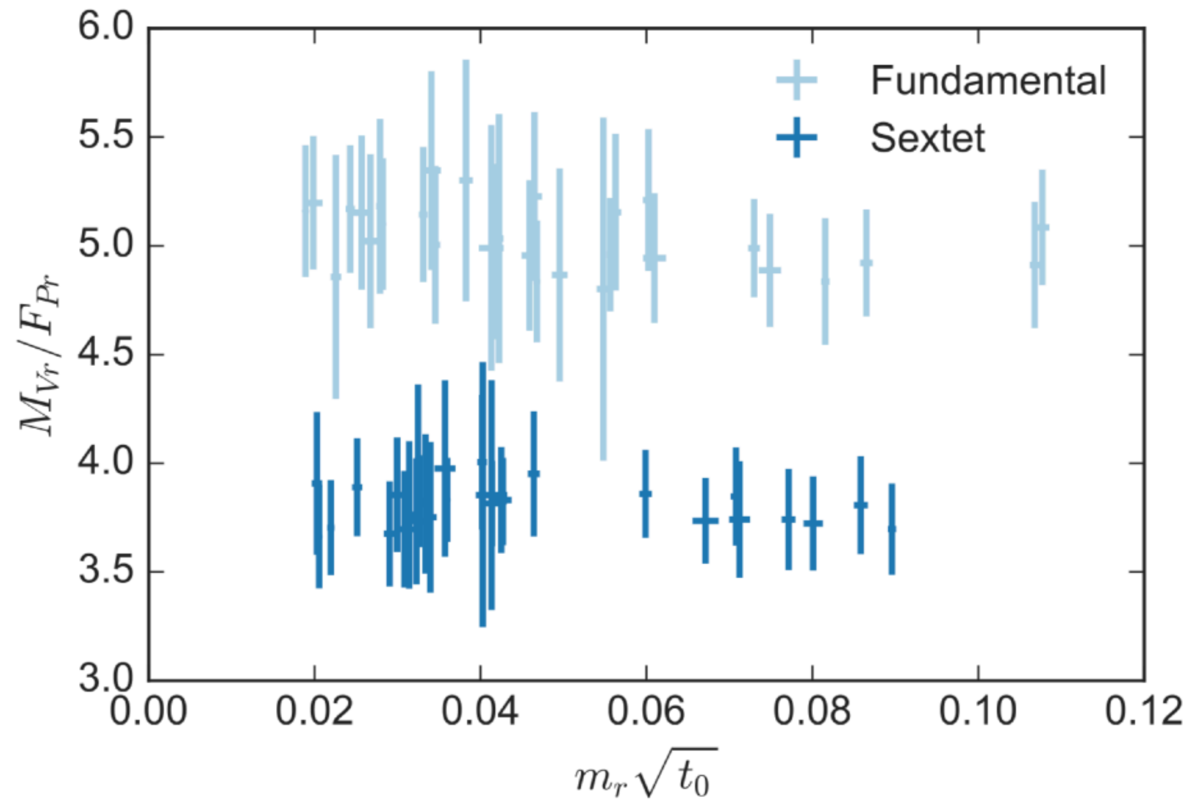
- Beyond QCD, there is growing evidence that KSRF and M_V/F_{PS} is surprisingly consistent across many different theories

- Top: KSRF from SU(4) with fermions in 4 and 6 irreps - composite Higgs model. Expected large-N decrease is seen from QCD.

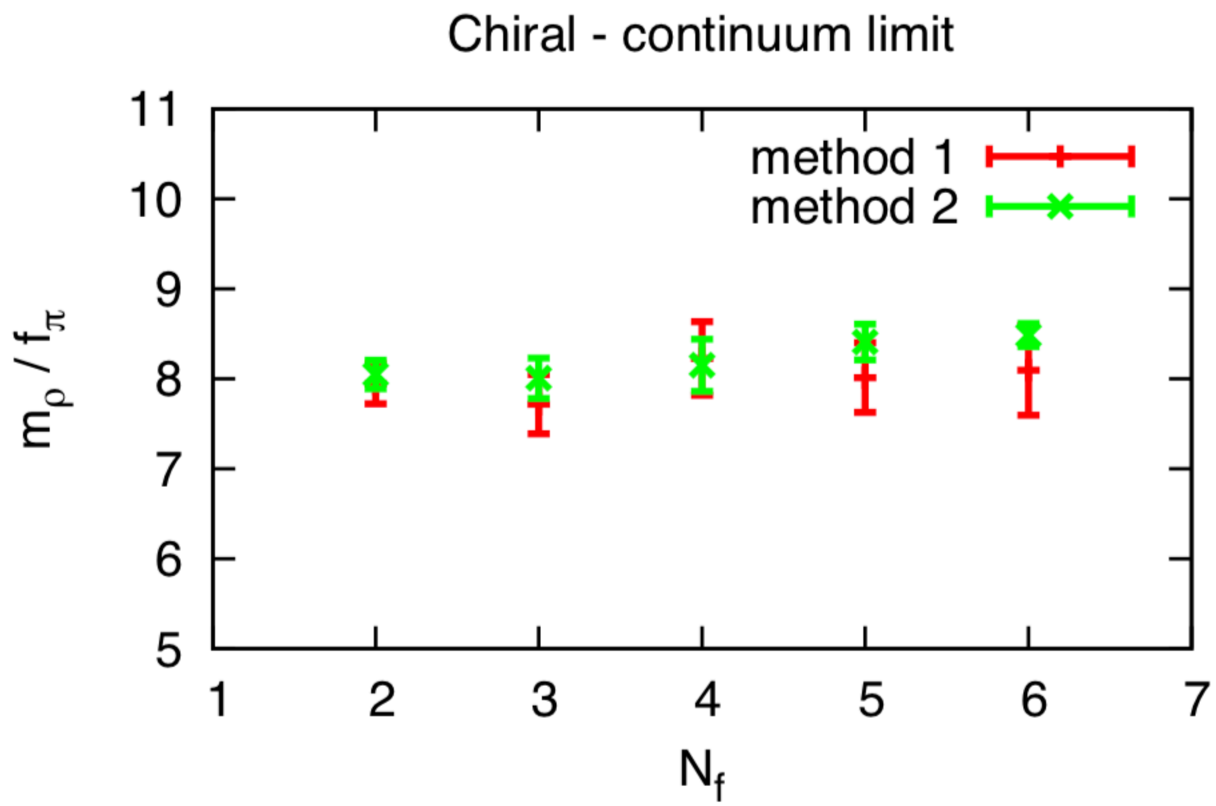
- Bottom: KSRF for SU(3) with more light fermions, in the massless limit; little to no dependence on N_f.

- For composite theories where g_ρ is taken as a parameter, strongly suggests that the range of allowed values is likely rather narrow…

(TACoS collaboration, arXiv:1710.00806)



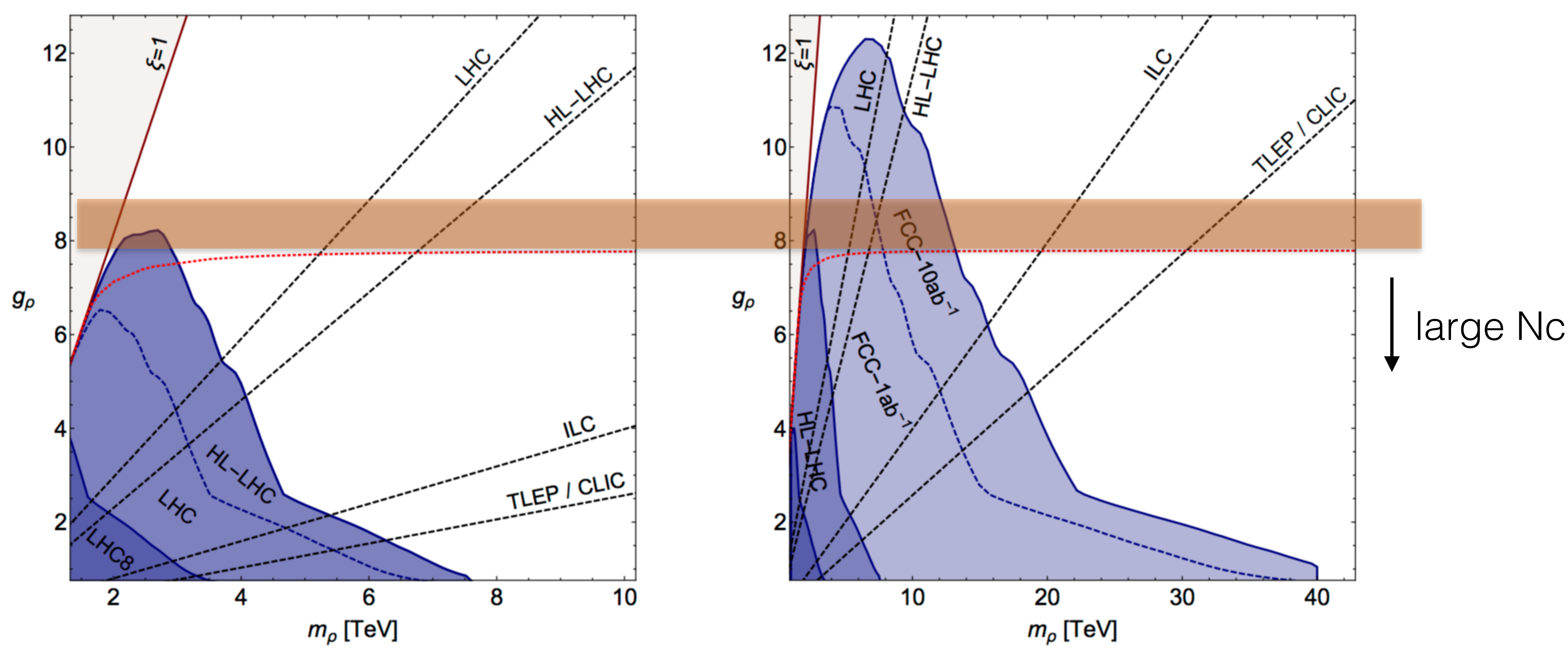
(D. Nogradi + L. Szikszai, arXiv:1905.01909)



Application: vector mesons in composite Higgs

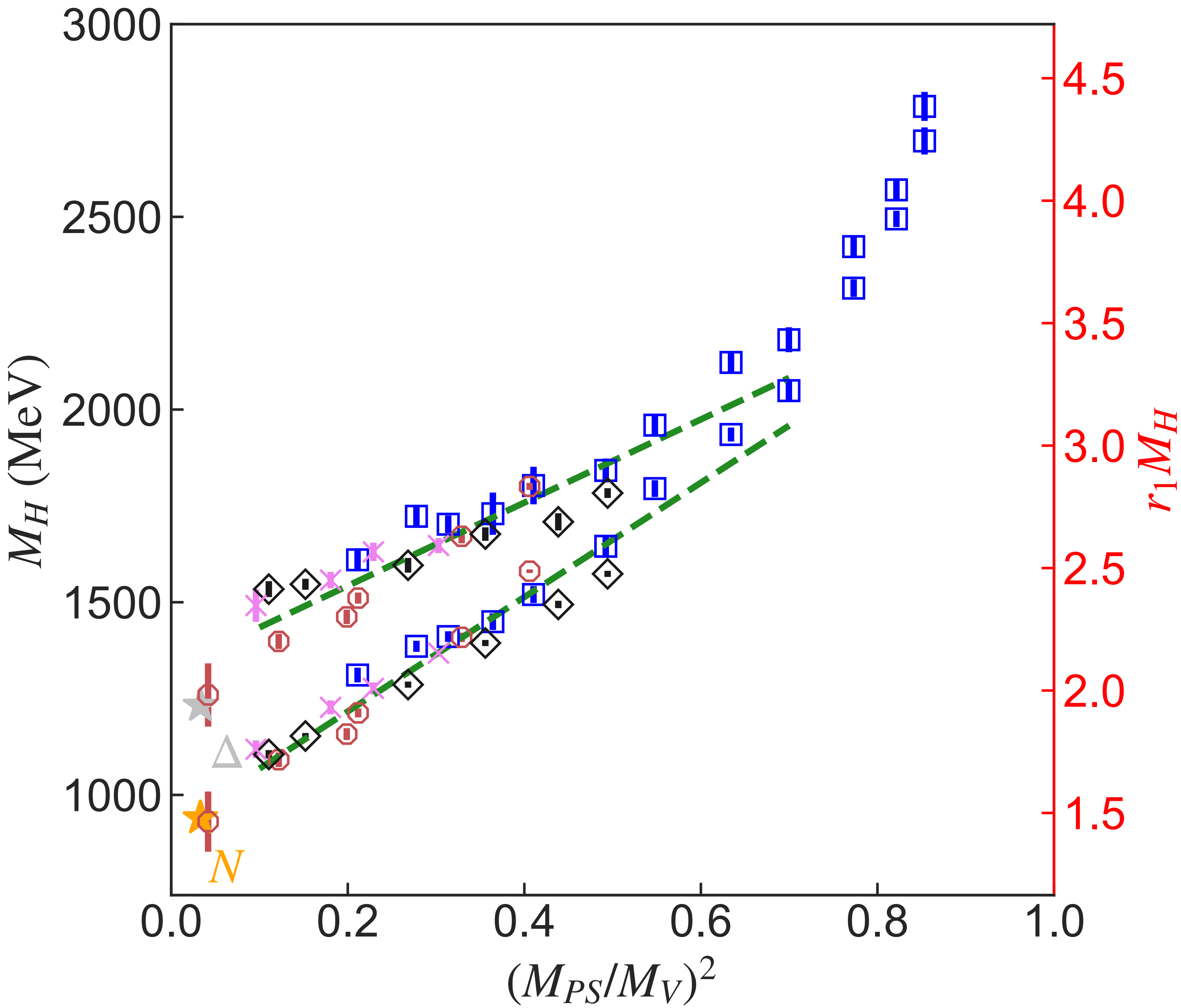
(note different convention:) $M_\rho = g_\rho f$

(Thamm, Torre and Wulzer, 1502.01701)

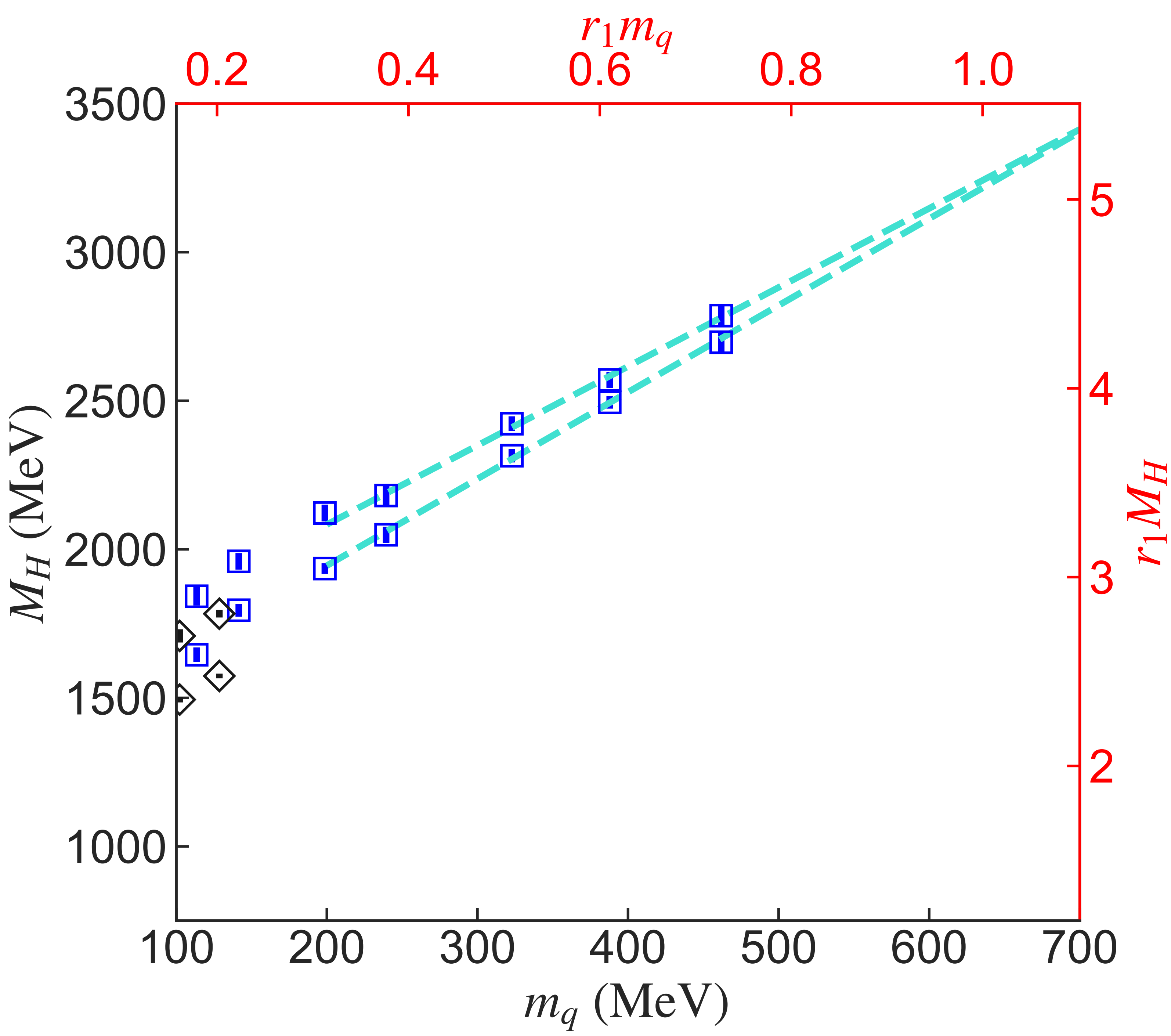


- Bounds from direct searches (blue), indirect bounds on Higgs potential parameter ξ (dashed lines.) With likely g_ρ from lattice, LHC direct searches may not have enough reach, need future colliders.
- Large coupling gives width Γ/M over 10%. Focused searches for large-width objects might help?

c) Baryons



- Baryon masses, spin 1/2 (bottom) and 3/2 (top) , again with overlaid PDG masses (stars)
- Linear fit once again works well over the range $0.1 < (M_{PS}/M_V)^2 < 0.7$; strong deviations seen away from this regime
- Spin splitting becomes negligible on absolute scale when quark mass is heavy enough



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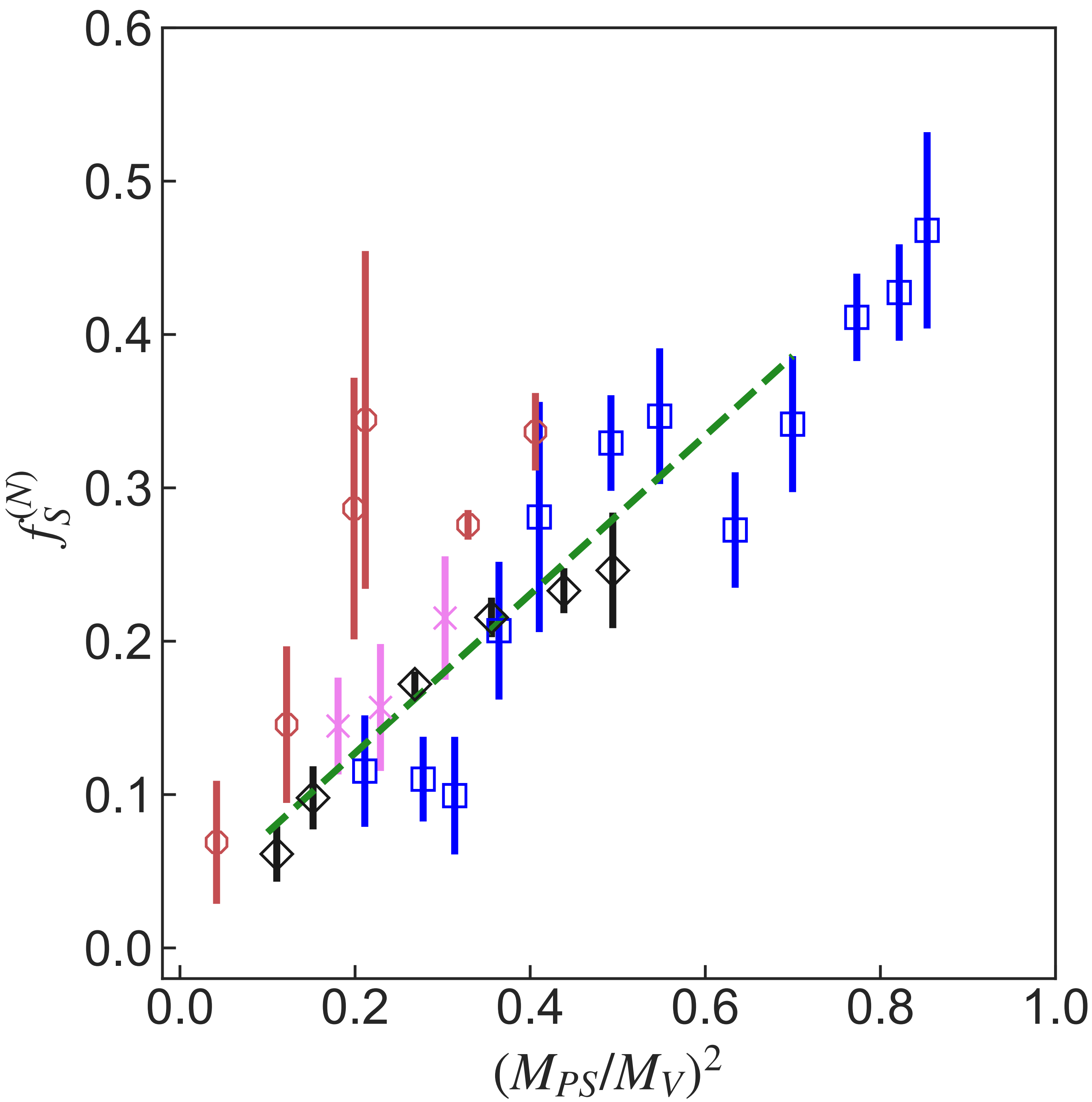
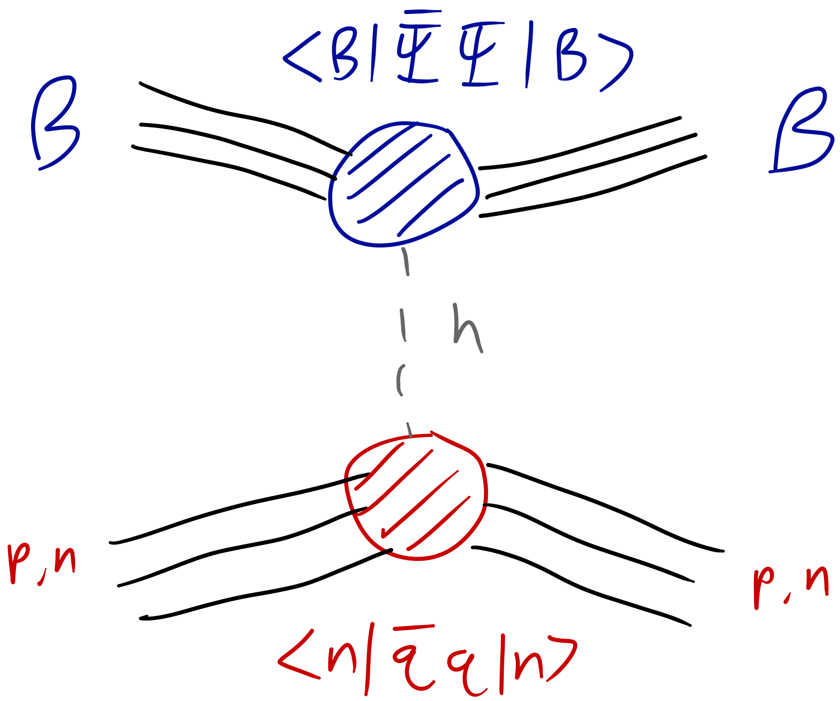


- Spectrum gives the scalar baryon form factor “for free” via Feynman-Hellmann theorem:

$$f_S^{(N)} \equiv \frac{\langle N|\, m_q \bar{q} q\, |N\rangle}{M_N} = \frac{m_q}{M_N}\frac{\partial M_N}{\partial m_q}$$

- Once again, simple linear relation between f_S and $(M_{PS}/M_V)^2$ gives a good qualitative description

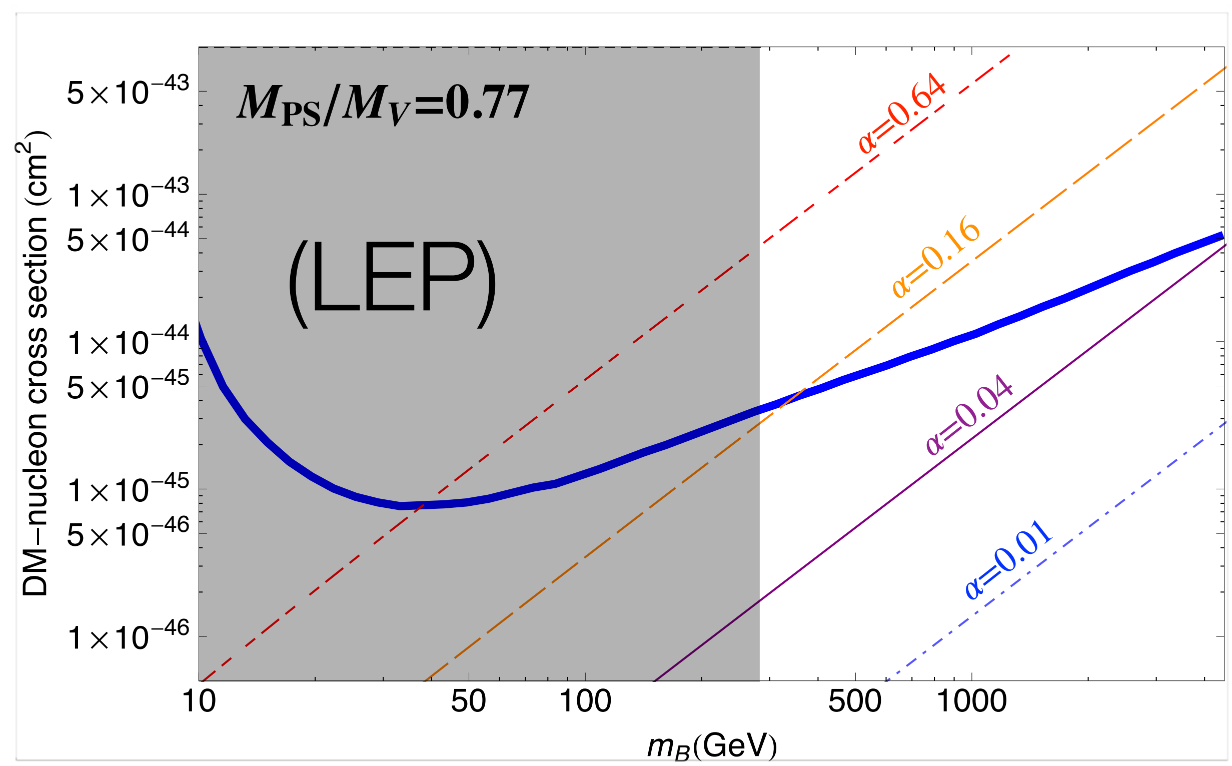
- This form factor determines Higgs-nucleon coupling (“sigma term” in QCD often discussed for general dark matter detection.)

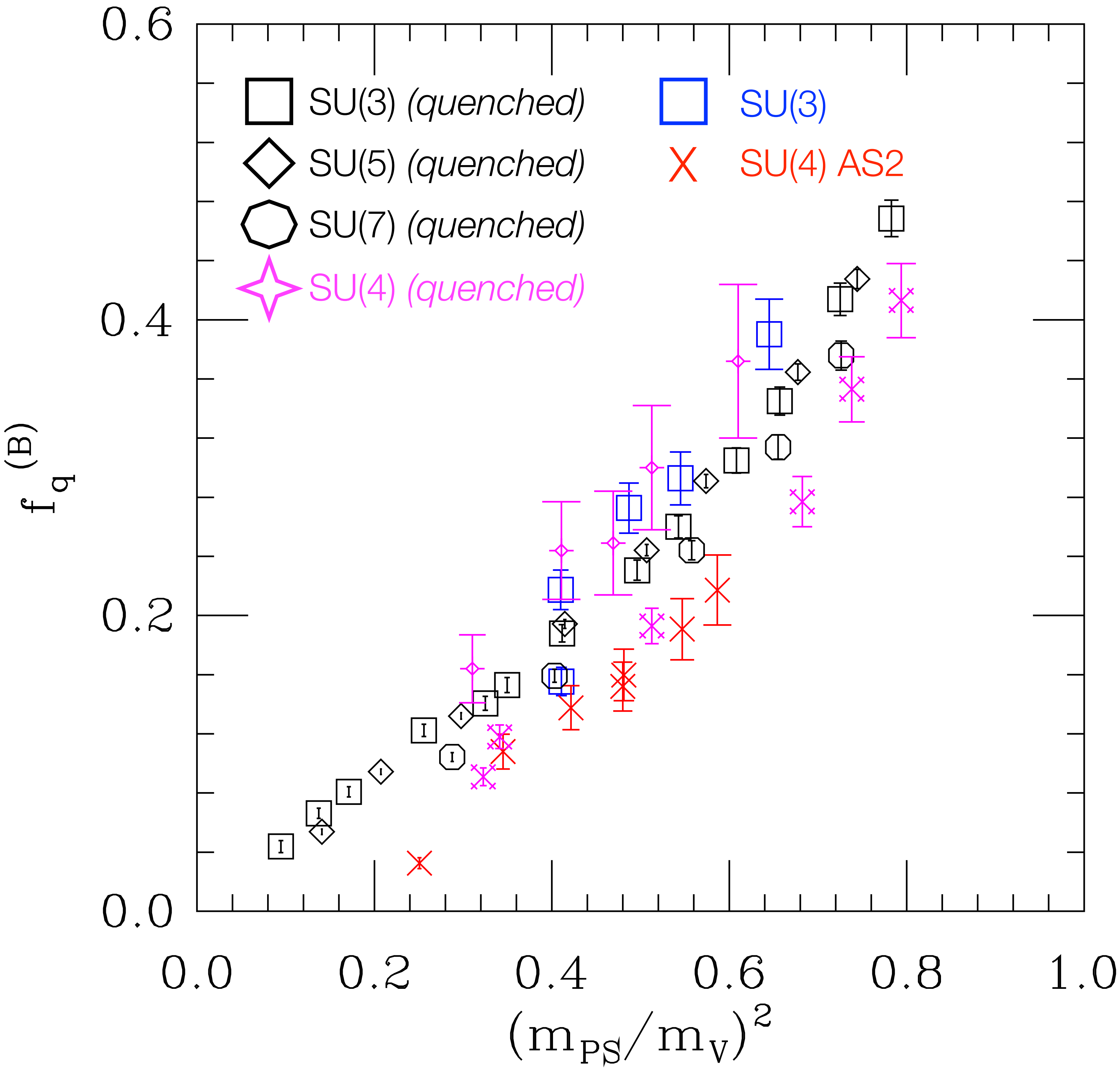


- For detecting baryon-like dark matter through Higgs portal, both the ordinary sigma term and the "dark" sigma term appear
- Strength of Higgs-dark baryon coupling determined by sigma term and by how much "dark quark" mass comes from Higgs:

$$m_f(h) = m + \frac{yh}{\sqrt{2}} \qquad \alpha \equiv \frac{v}{m_f} \frac{\partial m_f(h)}{\partial h}\bigg|_{h=v} = \frac{yv}{\sqrt{2}m + yv} \leq 1$$

- Even using older DM detection results (LUX 2014 on the right, vs. a specific SU(4) model), a~1 is completely ruled out by experiment.
- Strong and generic statement: *fermion masses in composite dark sector can't come from Higgs mechanism alone.*





[T. DeGrand, Y. Liu, EN, B. Svetitsky, Y. Shamir, Phys. Rev. D 91, 114502 (2015)]

- Left: lattice results for the scalar form factor in many different theories, showing near-universal curve vs. $M_{PS}/M_V)^2$
- Statement that composite DM can't have mass generation purely from the Higgs mechanism may be very general!

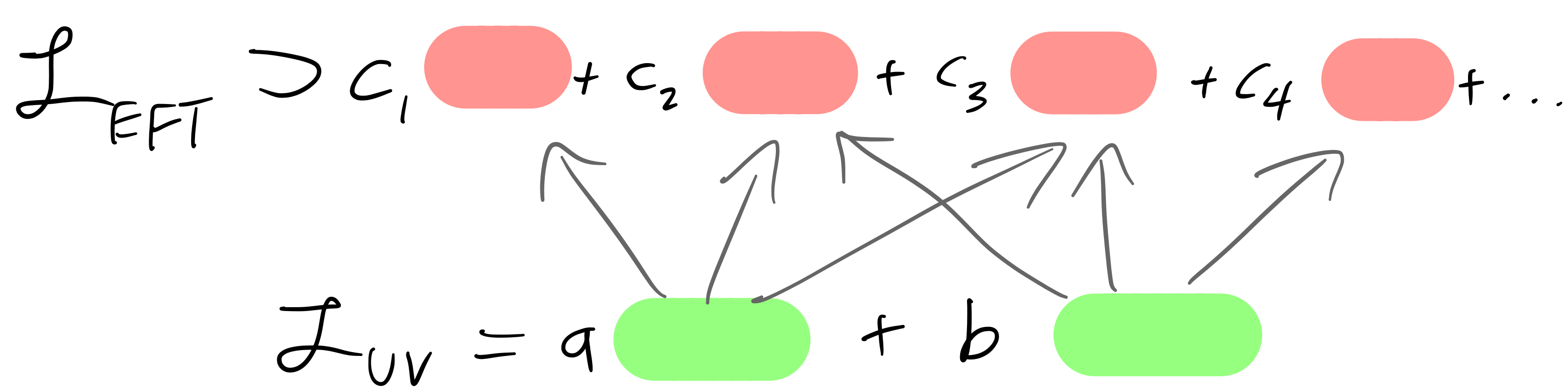
Conclusions

- Lattice can do a lot for composite BSM models; strong constraints on how EFT parameters are related can make models more predictive/narrow parameter space.
- For SU(3) composite sectors, there is a wealth of lattice QCD results **already out there**! Can be used at ~10% level with little to no concern for details of systematic error analysis. For lattice folks, try to present raw data in an easily digestible way, even if it's "unphysical"!
- Didn't cover "exotic states": glueballs, excited/higher spin mesons, gluinos, fermions in higher representations of SU(3), etc. Some scattered results are available - see our paper. Nuclei too!
- **Thank you to Paul for everything!**

Backup slides

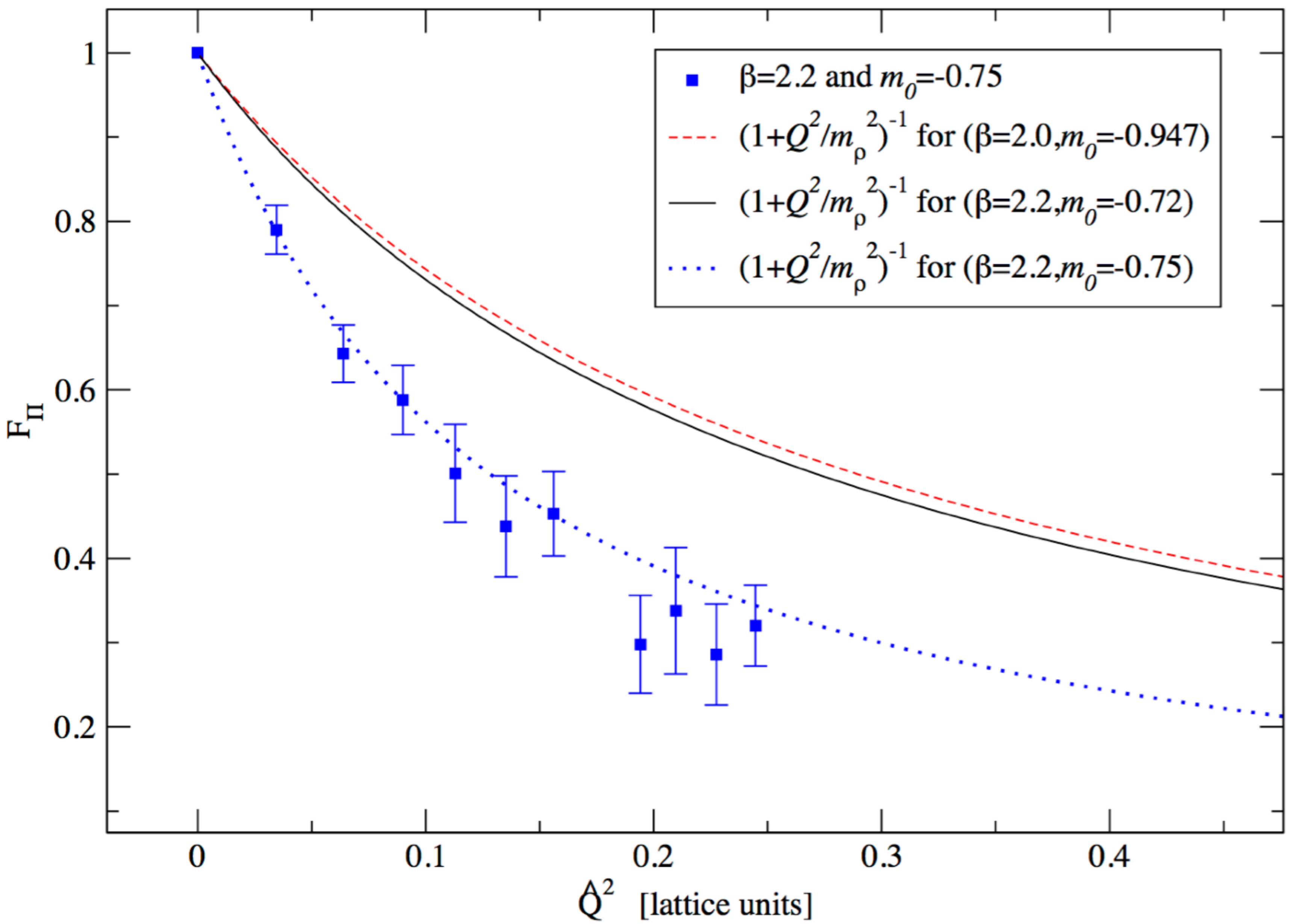
What about effective theories?

- We can take a more bottom-up approach and say: just identify the right effective field theory (EFT) for collider physics, dark matter detection, etc.
- Nothing wrong with this approach, but using *only* the EFT has limited predictive power: need to fix many (infinite!) low-energy constants from experiment.
- Plus, EFT comes with an energy cutoff: fine for working in the low-energy limit at the threshold of discovery, but many details of the full theory are out of reach. (e.g. finite temperature phase transition —> gravity waves)
- **EFT + lattice** allows analytic calculation but many LECs are determined from a handful of underlying UV parameters - best of both worlds!



(2,2,F)

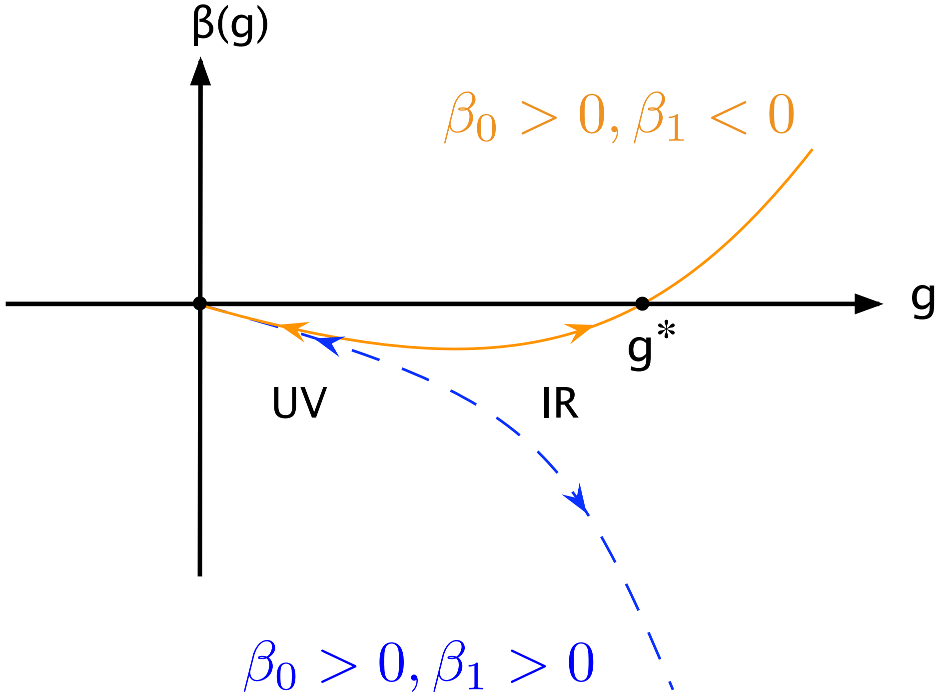
A. Hietanen, R. Lewis, C. Pica and F. Sannino, arXiv:1308.4130



- Another test of VMS: pion vector form factor. Works very well for light "pions" (above).
- More directly, the vector meson should give a resonant contribution to the timelike pion form factor. Harder calculation, but in progress.

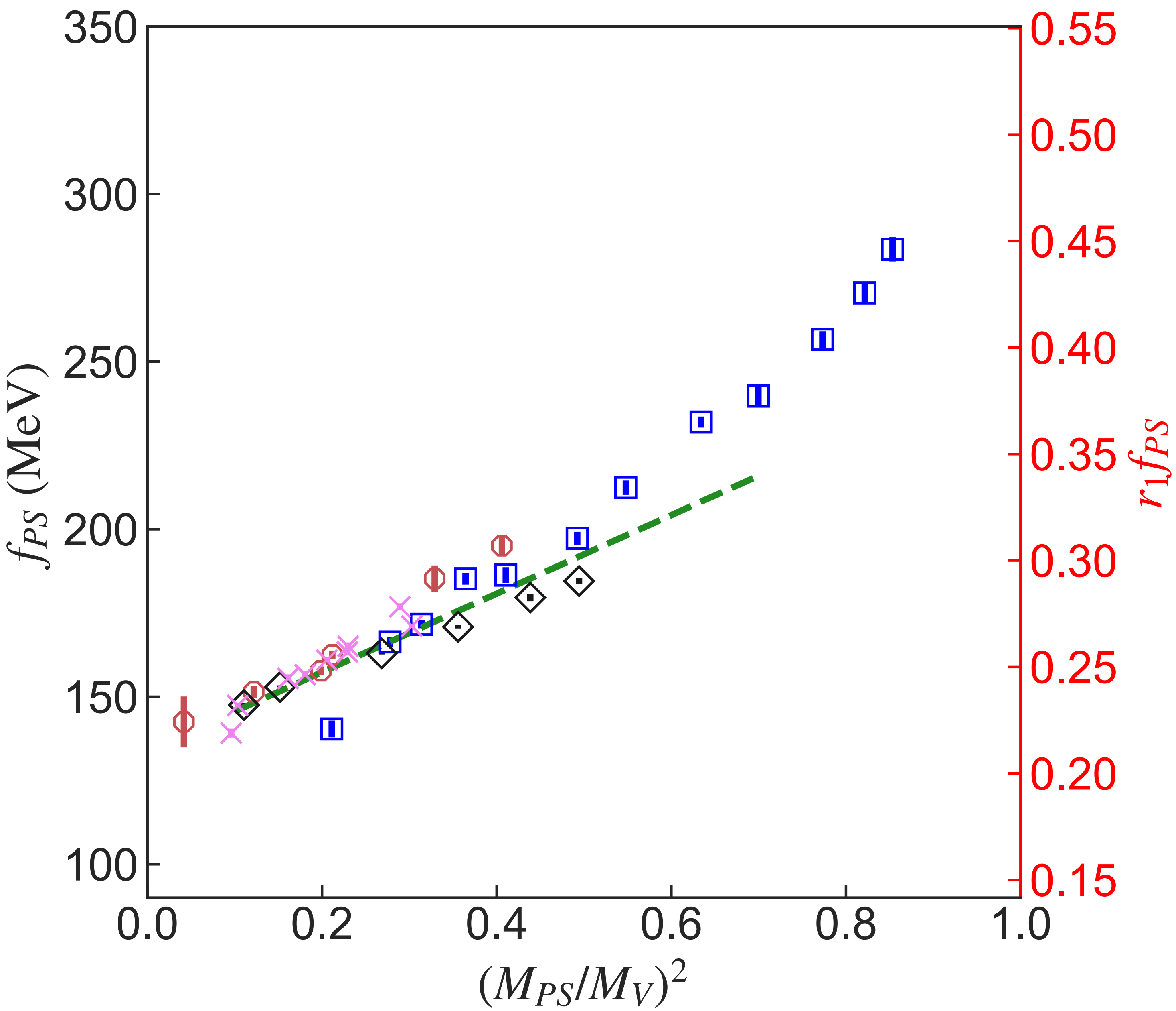
Aside: the infrared-conformal phase

$$\beta(g) \equiv \frac{\partial g}{\partial(\log \mu)} = -\beta_0 g^3 - \beta_1 g^5 - \ldots$$



- Many theories in the space are "cousins" of QCD: color charges *confine* into a spectrum of "hadron" bound states.
- In the infrared-conformal phase, gauge coupling *g* will approach an "infrared fixed point", freezing at some *g*=*g**>0.
- This freezing *restores scale invariance* - we recover a conformal field theory (CFT). CFTs have a unique "spectrum" of operator anomalous dimensions; no confined bound states.

- These CFTs can appear in many models of new physics, but only with *broken scale invariance*, since our world isn't conformal! Still, learning about the symmetric limit is useful and important. (Analogous to supersymmetric BSM models: SUSY must be broken, but it's still useful to describe the physics.)



$$\langle 0|\bar{u}\gamma_0\gamma_5 d|\pi\rangle = M_{PS} f_{PS}.$$

(F~130 MeV in QCD convention.)

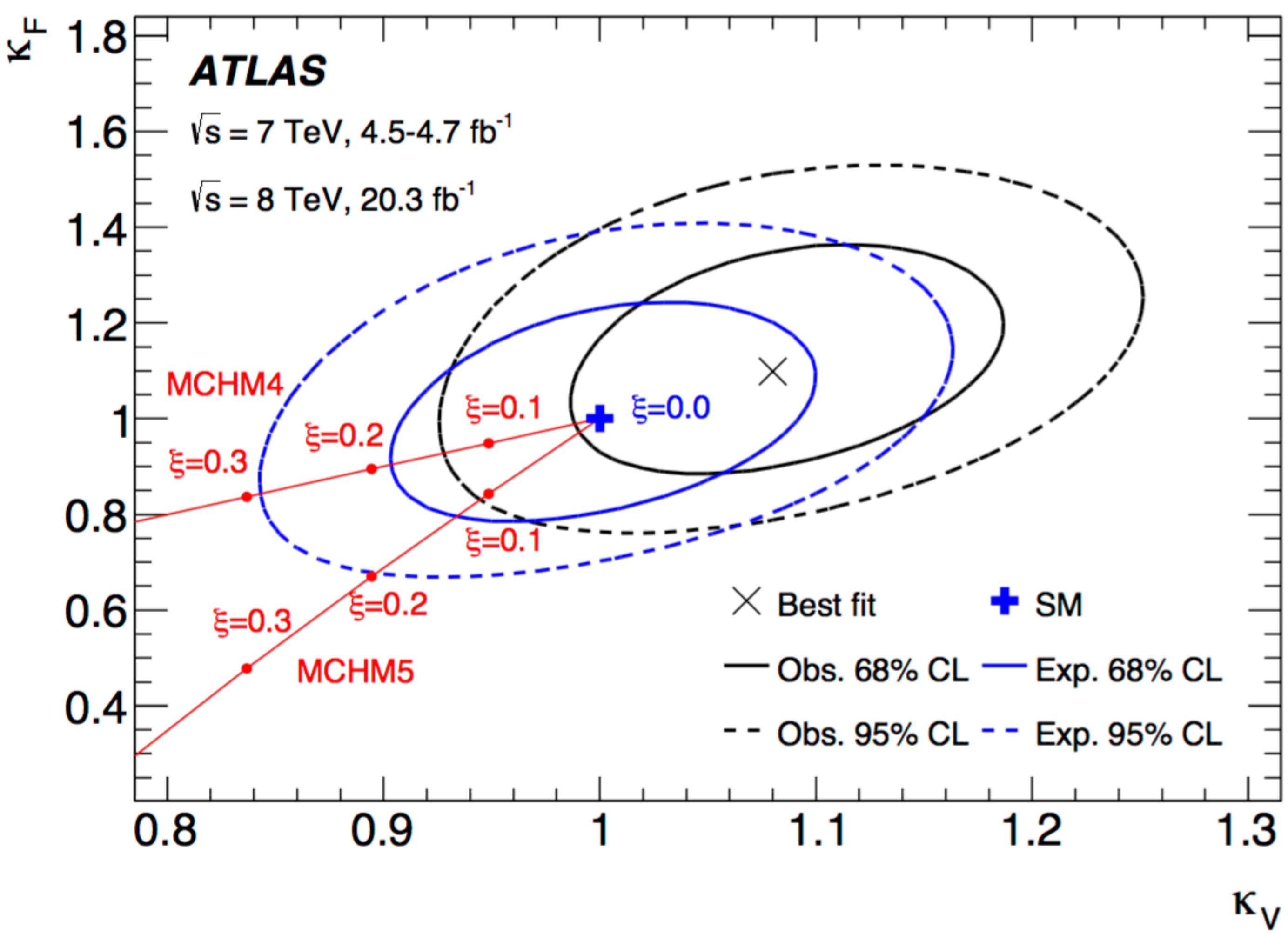
ρ in composite dark matter

- Note that because cDM doesn't explain EWSB, large width into (W/Z) (W/Z) isn't required; ρ can be narrow.
- If ρ —> ππ is closed kinematically (certainly possible for cDM!) then it can be *very* narrow; dilepton searches apply directly, likely tightest constraint. possibly ρ —> π gamma, work in progress.)
- On the other hand, if ρ —> ππ allowed then we should look for pairs of "π" resonances, distinct from W/Z. See e.g. arXiv:1809.10184 (Kribs, Martin, Ostdiek, Tong.)

Composite states: h

- In composite Higgs models, deviations in Higgs couplings appear as $\xi = v^2/f^2$ - identifying $v = f \sin\theta$ through "vacuum misalignment"
- Higgs is fairly "SM Higgs-like", from experiment. Implies $\xi << 1$ - little hierarchy.
- Higgs must also be light compared to other resonances we haven't seen, but this can be due to symmetry (Higgs as pseudo-NG boson)

arXiv:1509.00672

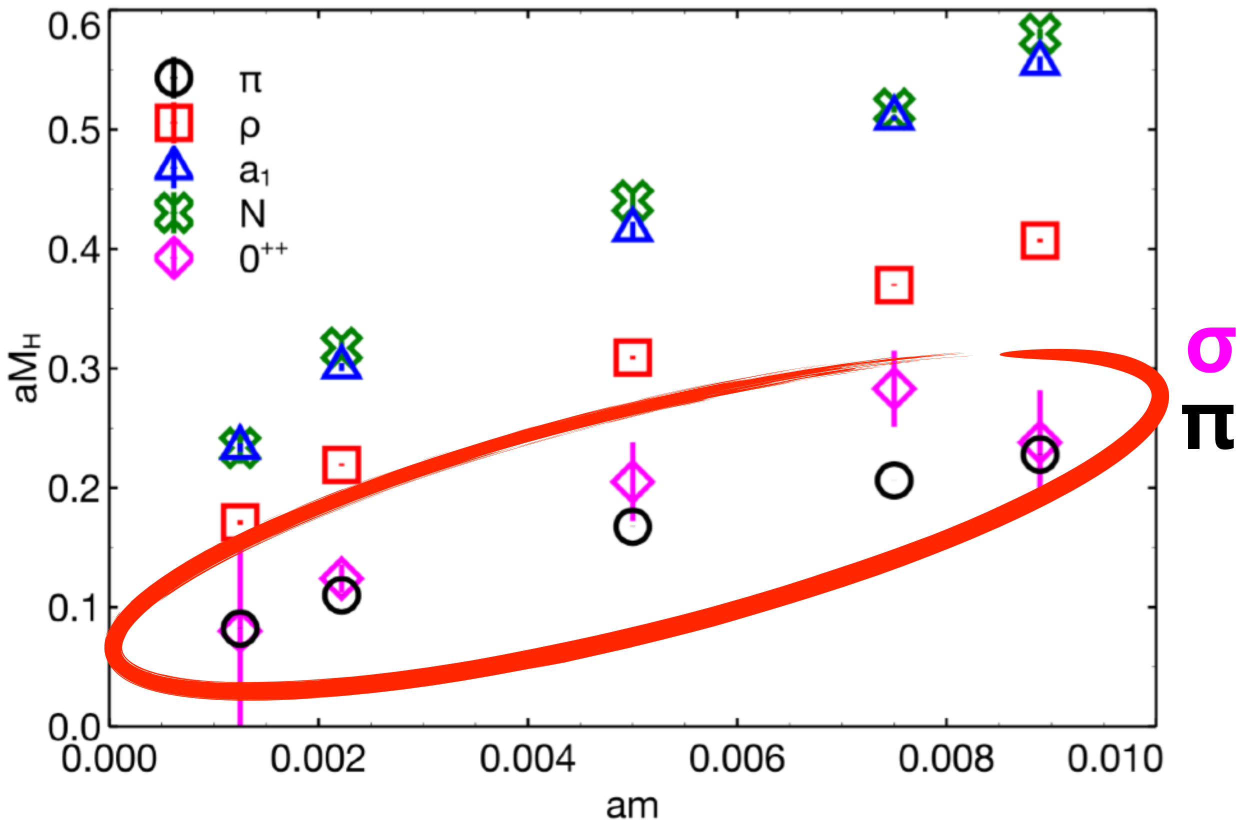


(v: electroweak vev)
(f: scale of compositeness / 2π)

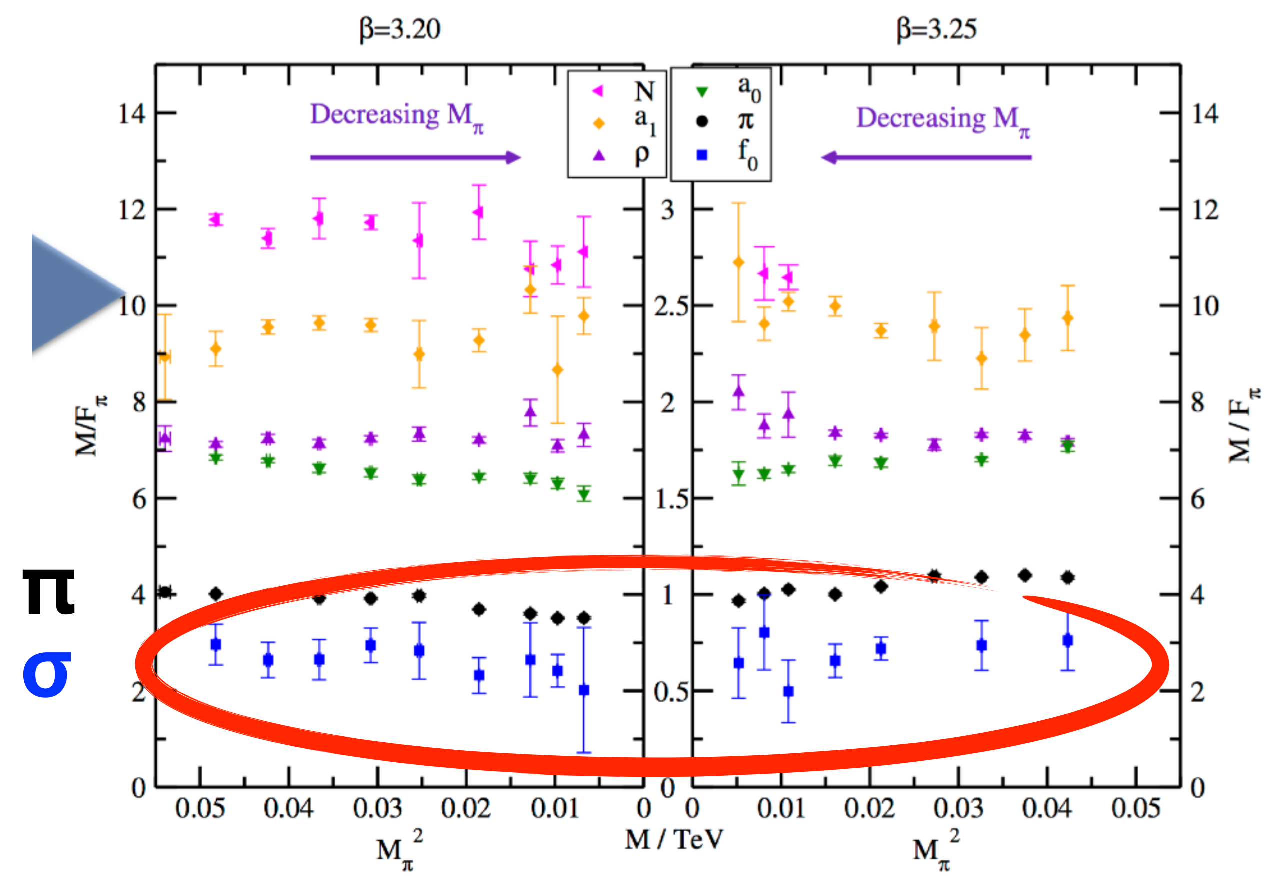
(*see also*: LatKMI Collaboration, arXiv:1305.6006 and 1403.5000)

Emergence of a light scalar particle?

LSD Collaboration, arXiv:1601.04027



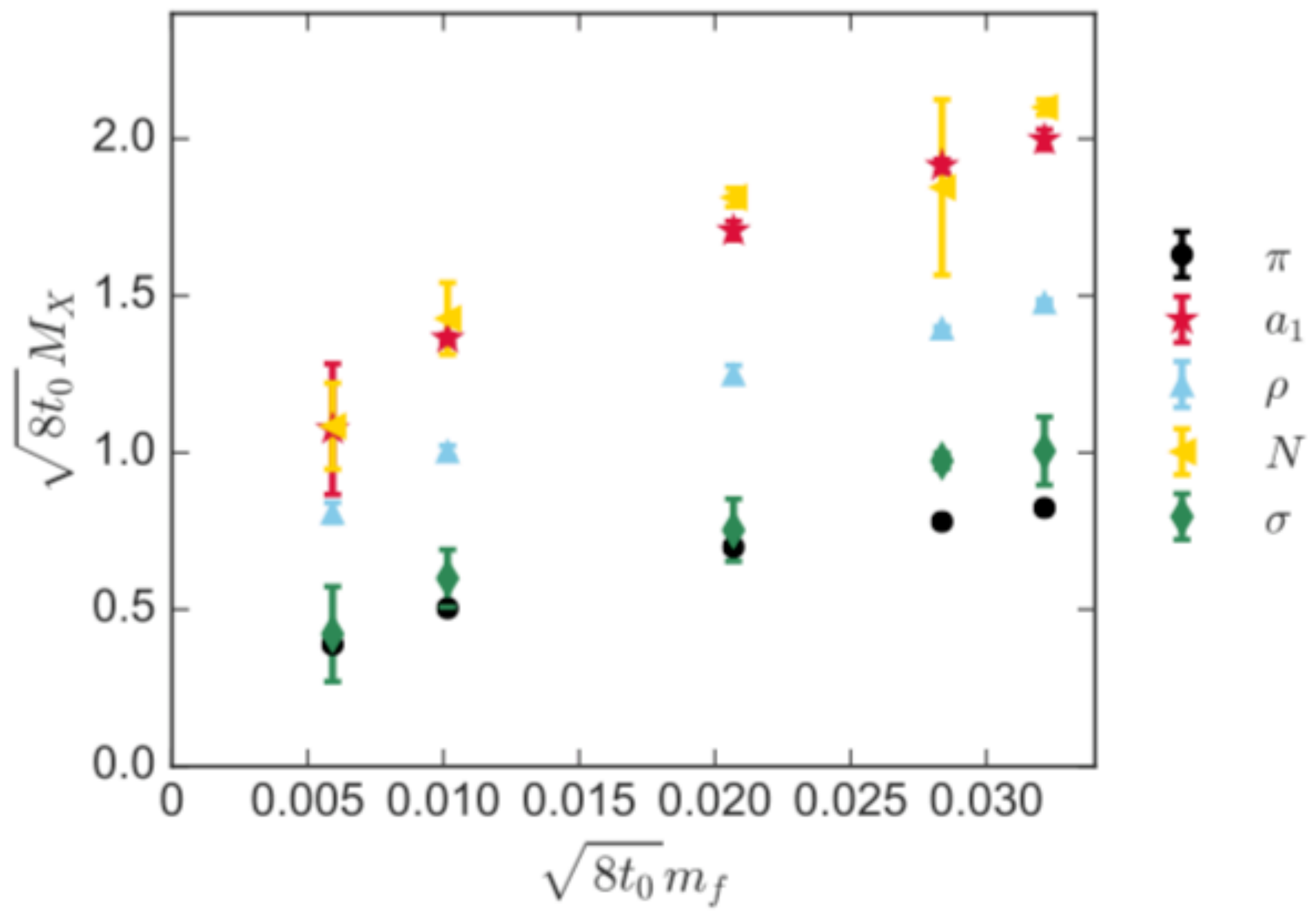
LatHC Collaboration, arXiv:1605.08750



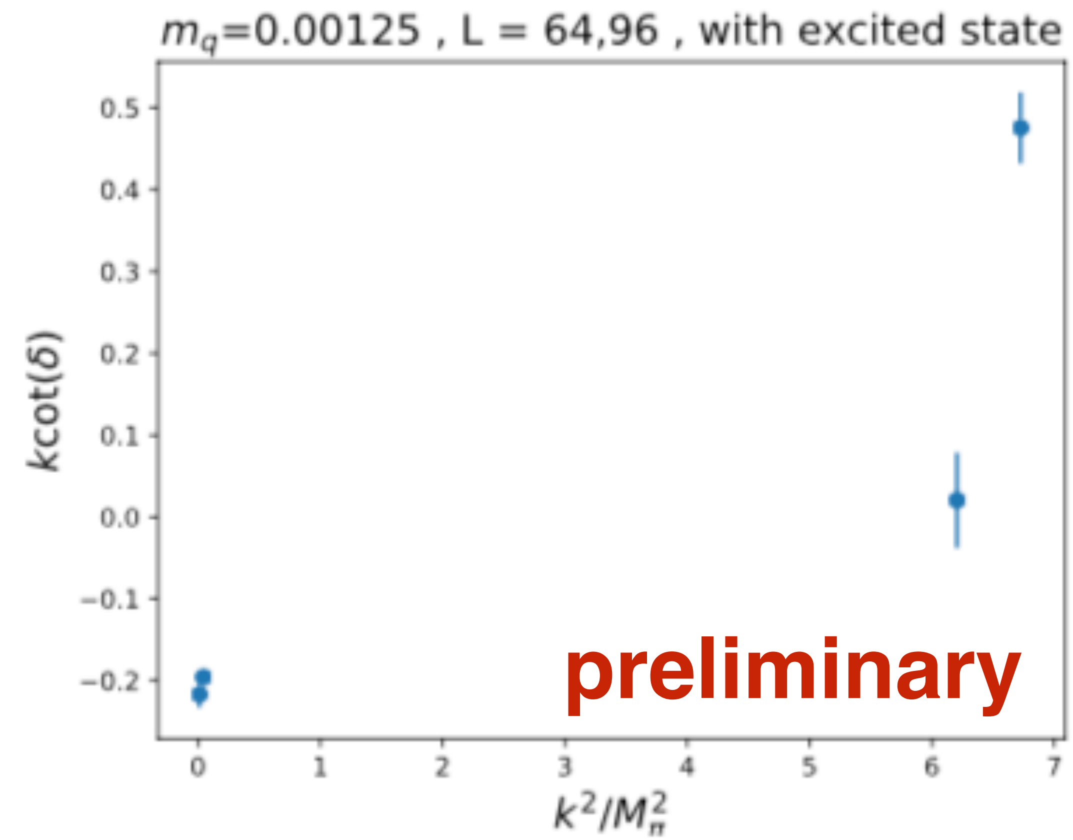
- In QCD (and similar theories), pions are the lightest hadronic states by far, due to their pseudo-Goldstone boson nature.
- But lattice studies in multiple theories (left: SU(3) Nf=8, right: SU(3) Nf=2 “sextet” irrep) revealed a surprising **light 0++ scalar state** as light as the pions!
- This state has the same quantum numbers as the Higgs boson, and has been speculated to be a <u>pseudo-dilaton</u> associated with closeness to the IR-conformal transition.

Light scalar resonance

T. Appelquist et al (**LSD collab**), arXiv:1807.08411



George Fleming (**LSD collab**), Lattice 2019

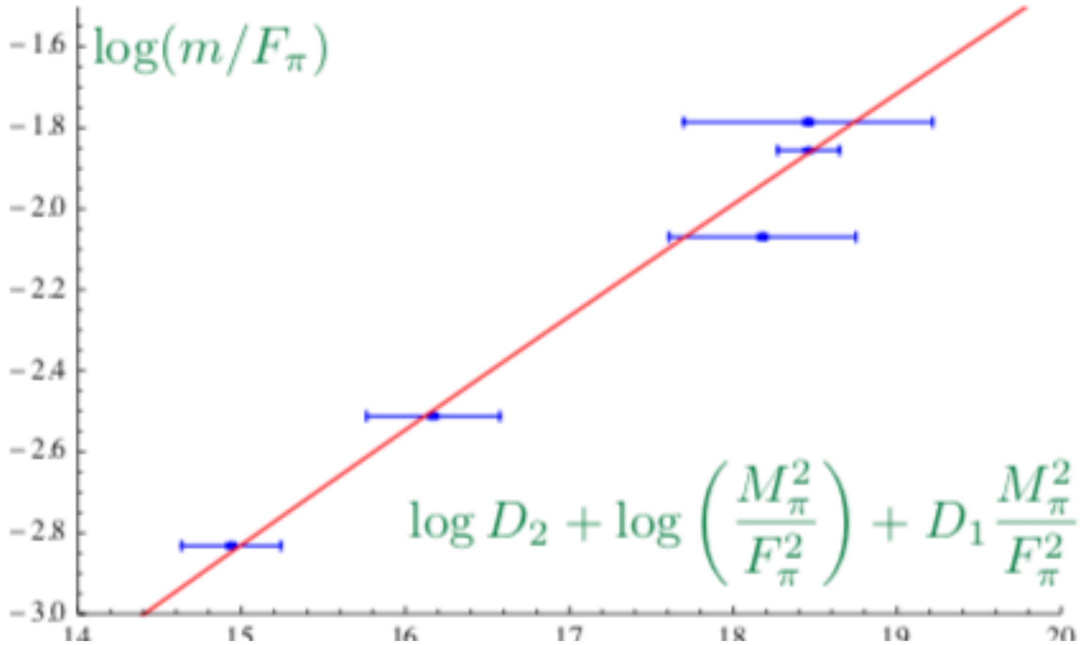


(above: **I=2 π-π scattering** phase shift)

- Updated lattice results confirm the presence of a light 0++ scalar in certain theories, improve precision of spectrum (left)
- Progress is beginning on calculation of other quantities, such as scattering phase shifts (right), in order to probe low-energy EFT

Light scalar EFT?

Maarten Golterman, Lattice 2019

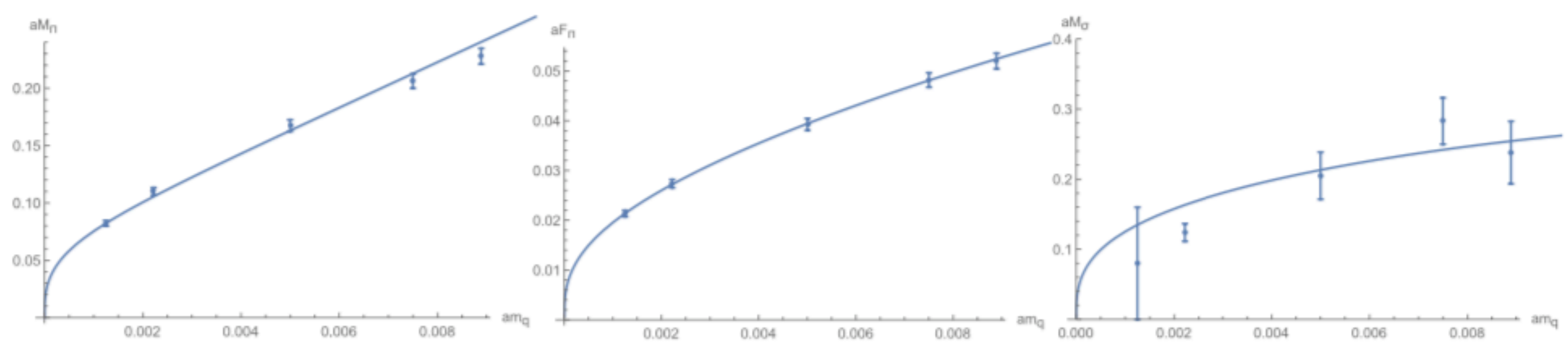


Left: "**dilaton EFT**" (Golterman and Shamir, arXiv:1603.04575) light scalar is associated with breaking of approx. scale invariance near the infrared-conformal phase transition.

Below: "**generalized linear sigma model**", (LSD collaboration, arXiv:1809.02624) scalars are added to chiral effective theory, but no association with scale symmetry

Preliminary

Lattice units
χ^2/dof=1.30



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- Substantial ongoing work on developing EFT descriptions that accommodate a light 0++, and fitting them to lattice data. More work on both ends will be needed to reach firm conclusions.