Composite Higgs Models and Lattice Simulations

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Outline:

1) Quick overview of composite Higgs
2) Highlights of lattice results
3) Outlook and summary

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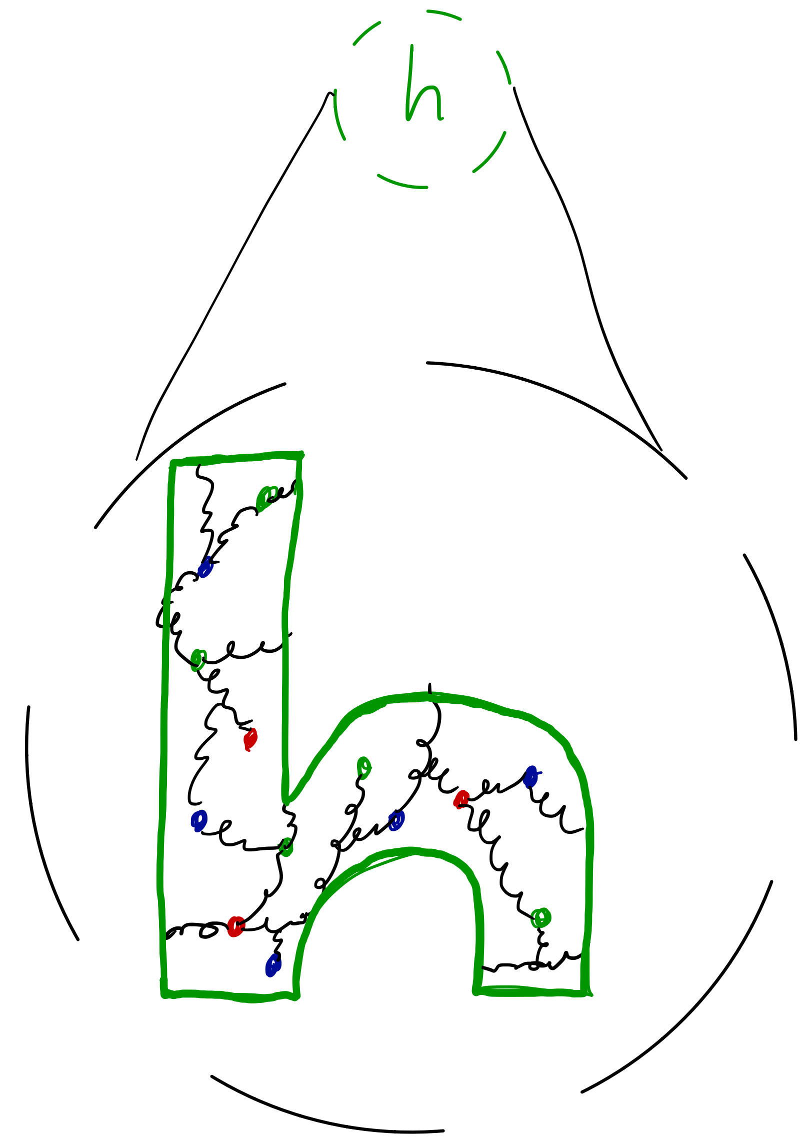
Quick overview: composite Higgs

Composite Higgs, briefly

- Higgs is a composite bound state - no fundamental scalars!
- EW symmetry broken by strong condensate directly[1], or by generated Higgs potential[2]
- Natural **dark matter** candidates (e.g. “dark baryons”), stabilized by accidental symmetry e.g. the proton[3].
- Downside: underlying physics is strongly-coupled, so prediction can be difficult…



1 “technicolor”
2 “composite Higgs”, “little Higgs”, …
3 See || talk by E. Rinaldi, Friday morning.

(credit to C. Pica for this nice approach to describing the "anatomy" of composite Higgs)

Composite Higgs, continued[1]

$$\mathcal{L} = \mathcal{L}_{SM} - \mathcal{L}_h + \mathcal{L}_{HC} + \mathcal{L}_{\text{int}}$$

- Fundamental Higgs terms removed
- New strong "hypercolor" gauge+fermion interactions:

$$\mathcal{L}_{HC} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu,a} + \sum_{i=1}^{N_f} \bar{\psi}_i \gamma^\mu D_\mu \psi_i$$

- EW breaking, and SM mass terms. No fundamental scalar —> four-fermion operators:

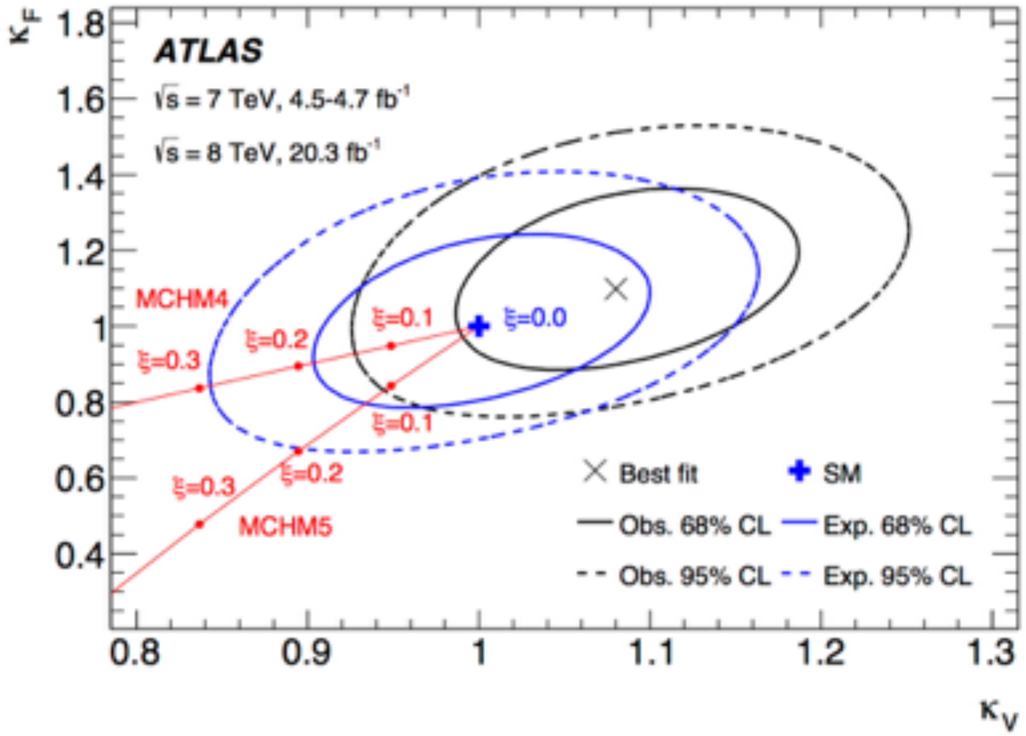
$$\frac{1}{\Lambda_{UV}^2} \bar{f} f \mathcal{O}_B \qquad \text{or} \qquad \frac{1}{\Lambda_{UV}^2} \bar{f} \mathcal{O}_F$$

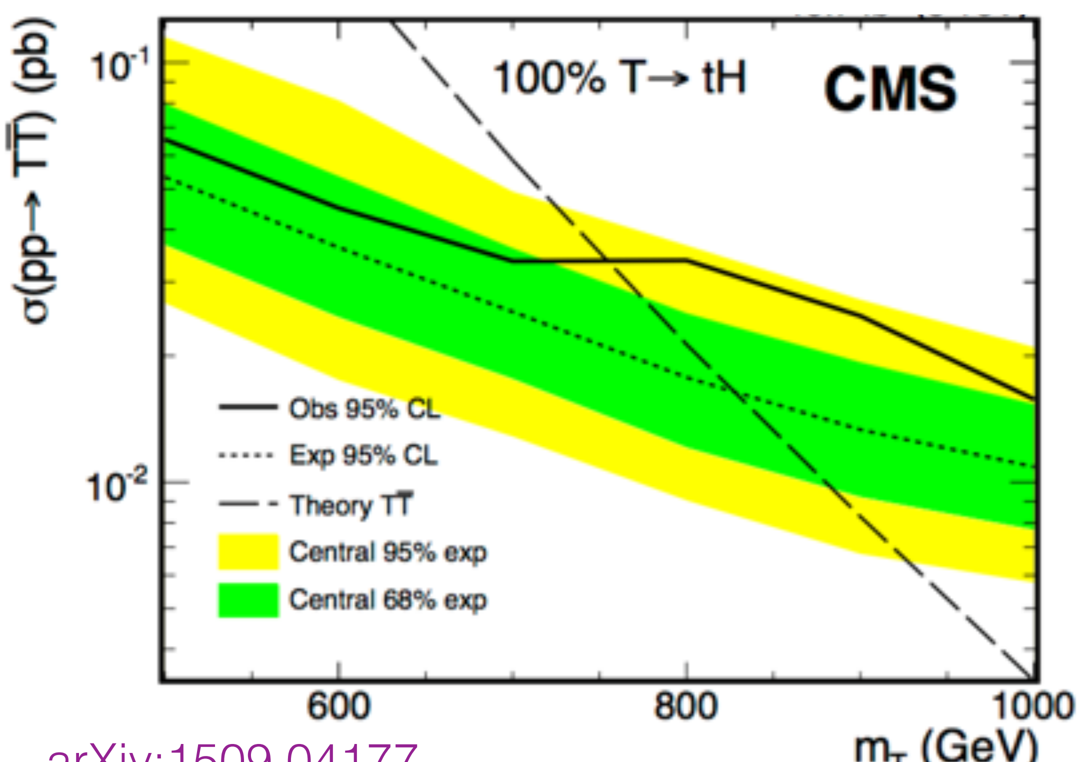
(extended technicolor) (partial compositeness)

[1] more info: TASI lectures by R. Contino, arXiv:1005.4269

Composite Higgs at colliders

arXiv:1509.00672





arXiv:1509.04177

- Signals vary depending on model, but some generic features:
  - Lots and lots of new particles! (But can be many TeV and/or very broad.) EW boson final states are common (since these states are partly composite!)
  - Excited states of EW bosons, W'/Z'/h'. With PC, top-partner T (and related exotics like $X_{5/3}$)
  - Can have QCD colored states (needed with top partners)

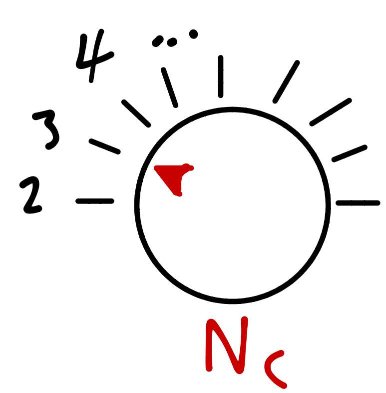
Some examples: limits on modified Higgs couplings (top), top-partner search (bottom)

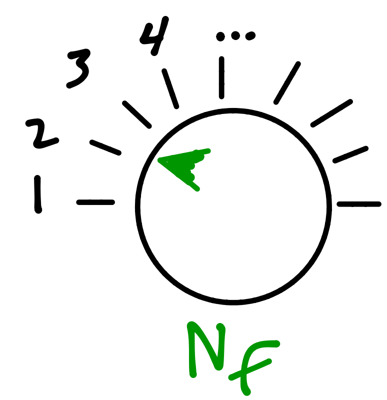
Lattice and Composite Higgs[1,2]

- Lattice gauge theory is **numerical** and **non-perturbative** - can work with $\mathcal{L}_{HC}$ directly! (No details on lattice here, but see Ruth Van de Water's plenary)

- Very successful for QCD, and we can turn the dials to study more general theories:

$$\mathcal{L} = -\frac{1}{4g^2}\sum_{a=1}^{N_c^2-1} F^a_{\mu\nu}F^{\mu\nu,a} + \sum_{j=1}^{N_f} i\bar{\psi}_j\gamma^\mu D_\mu \psi_j$$





(N_c,N_f,**R**): SU(N_c) gauge theory, N_f fermions in irrep **R**

- (Multiple reps are interesting for partial compositeness[3], limited lattice results so far.)

[1] T. DeGrand, arXiv:1510.05018
[2] C. Pica plenary @ Lattice 2016
[3] Ferretti & Karateev, arXiv:1312.5330

Lattice for composite Higgs: highlights

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

Vector Meson Dominance

- Vector meson dominance (VMD): saturation of vector channel by a single resonance (ρ). Phenomenological model of low-energy quantities based on rho mass and width.

- VMD works well in QCD (~10%) for some things, e.g. KSRF[1] relations:

$$F_\rho = \sqrt{2}\, F_\pi \; , \quad g_{\rho\pi\pi} = \frac{M_\rho}{\sqrt{2}\, F_\pi} \; ,$$

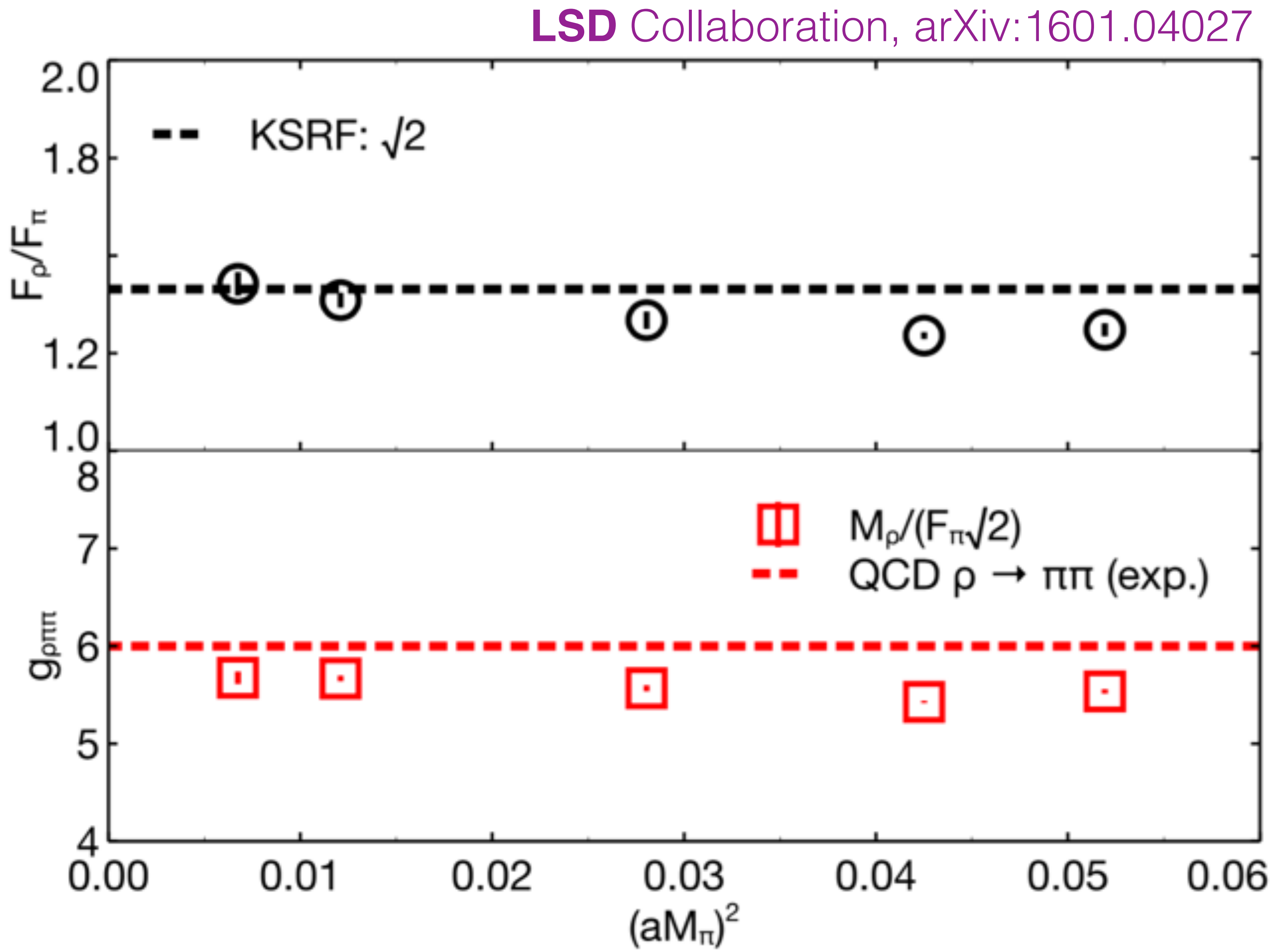
$$\Gamma_\rho \approx \frac{g_{\rho\pi\pi}^2\, M_\rho}{48\pi} \approx \frac{M_\rho^3}{96\pi F_\pi^2}$$

electroweak decay

HC-strong decay

- What happens in other strongly-coupled models?

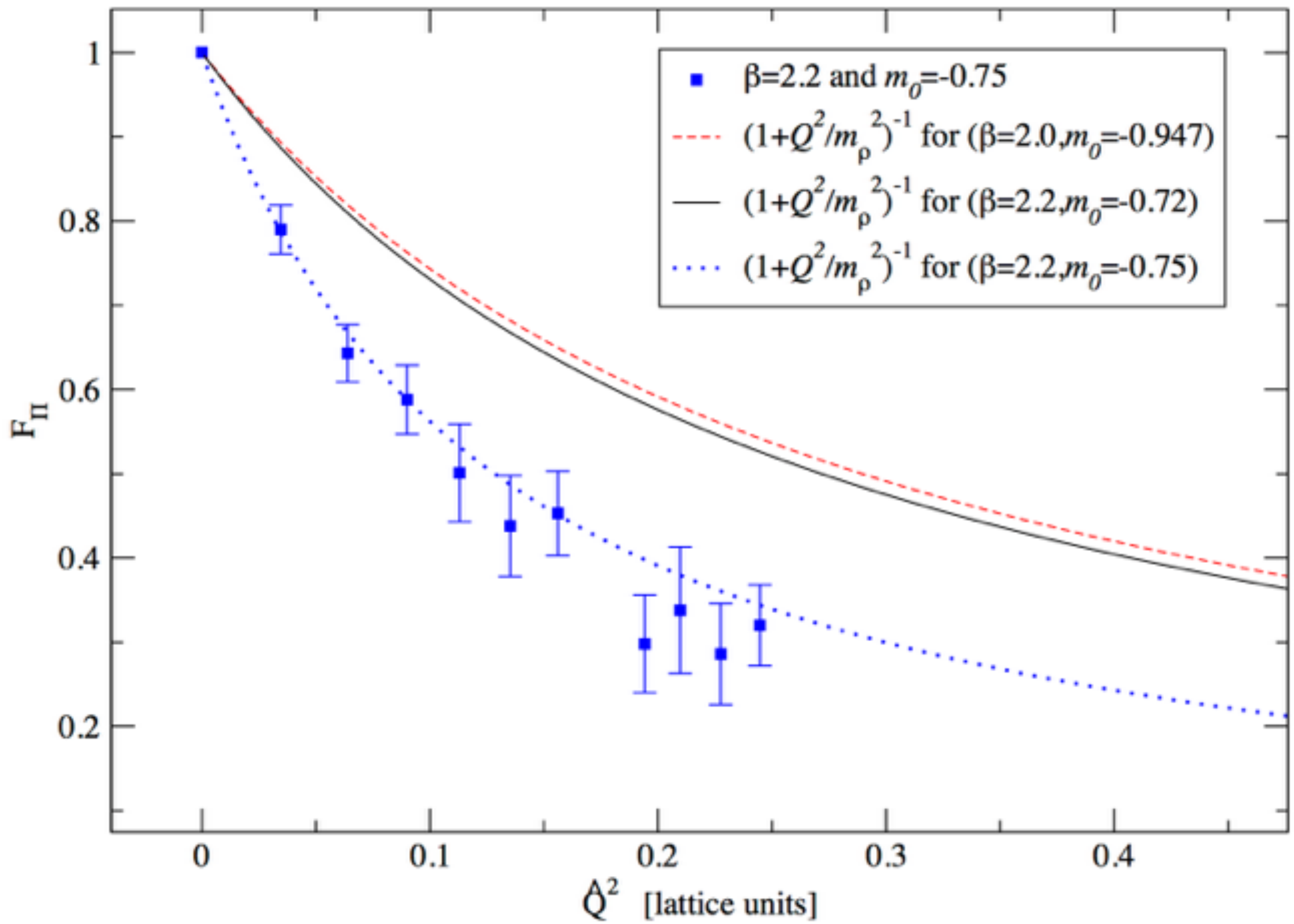
(3,8,F)



- Test of one KSRF relation (F_ρ/F_π), nice agreement, little mass dependence
- Other relation gives $g_{\rho\pi\pi}$ from M_ρ/F_π (convention: F_π~93 MeV in QCD.)

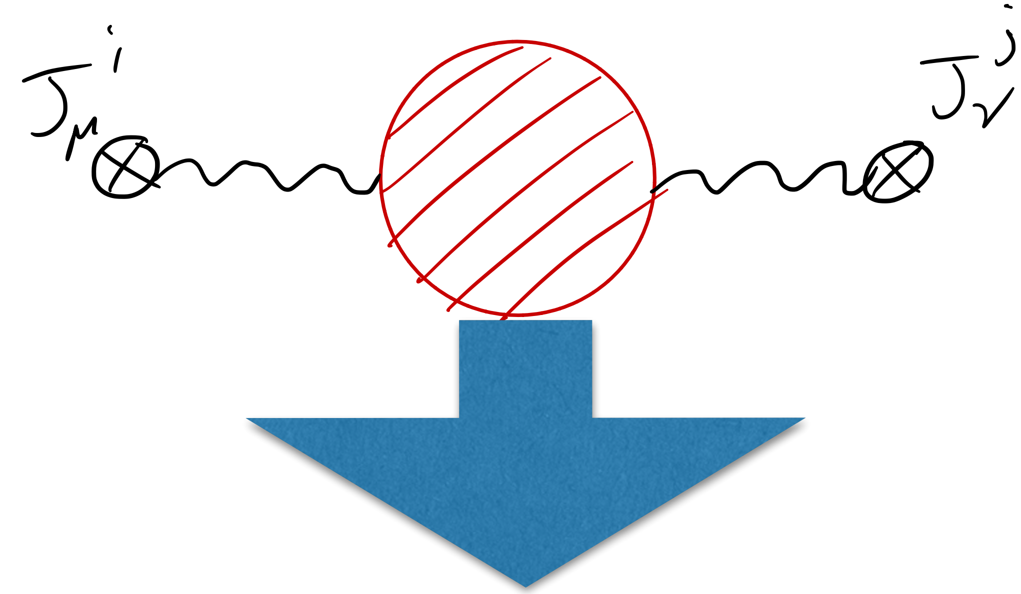
(2,2,**F**)

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



- Another test of VMD: 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.

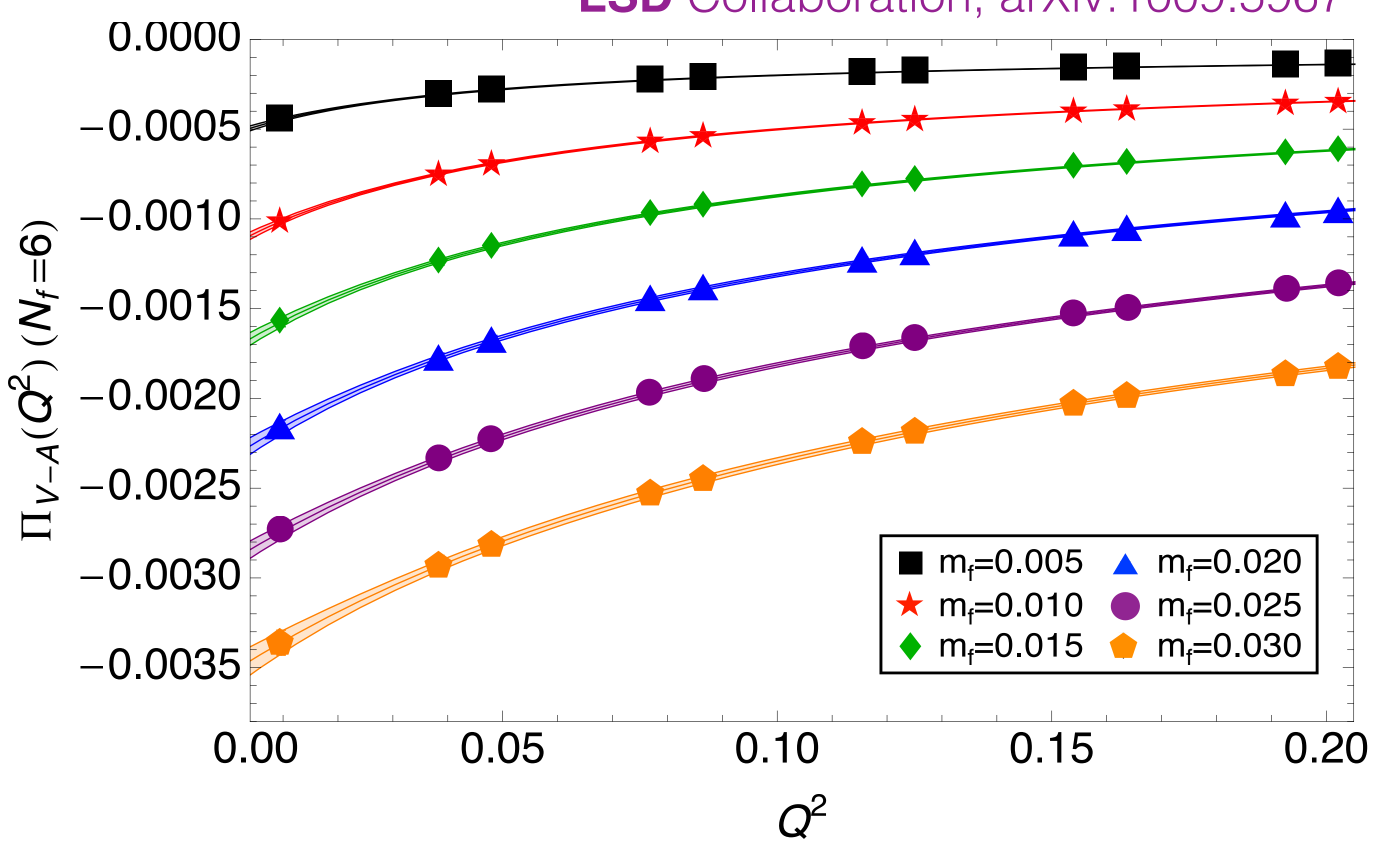
S-parameter and Higgs potential



- Many insights from vacuum polarization - strong correlator of external currents.

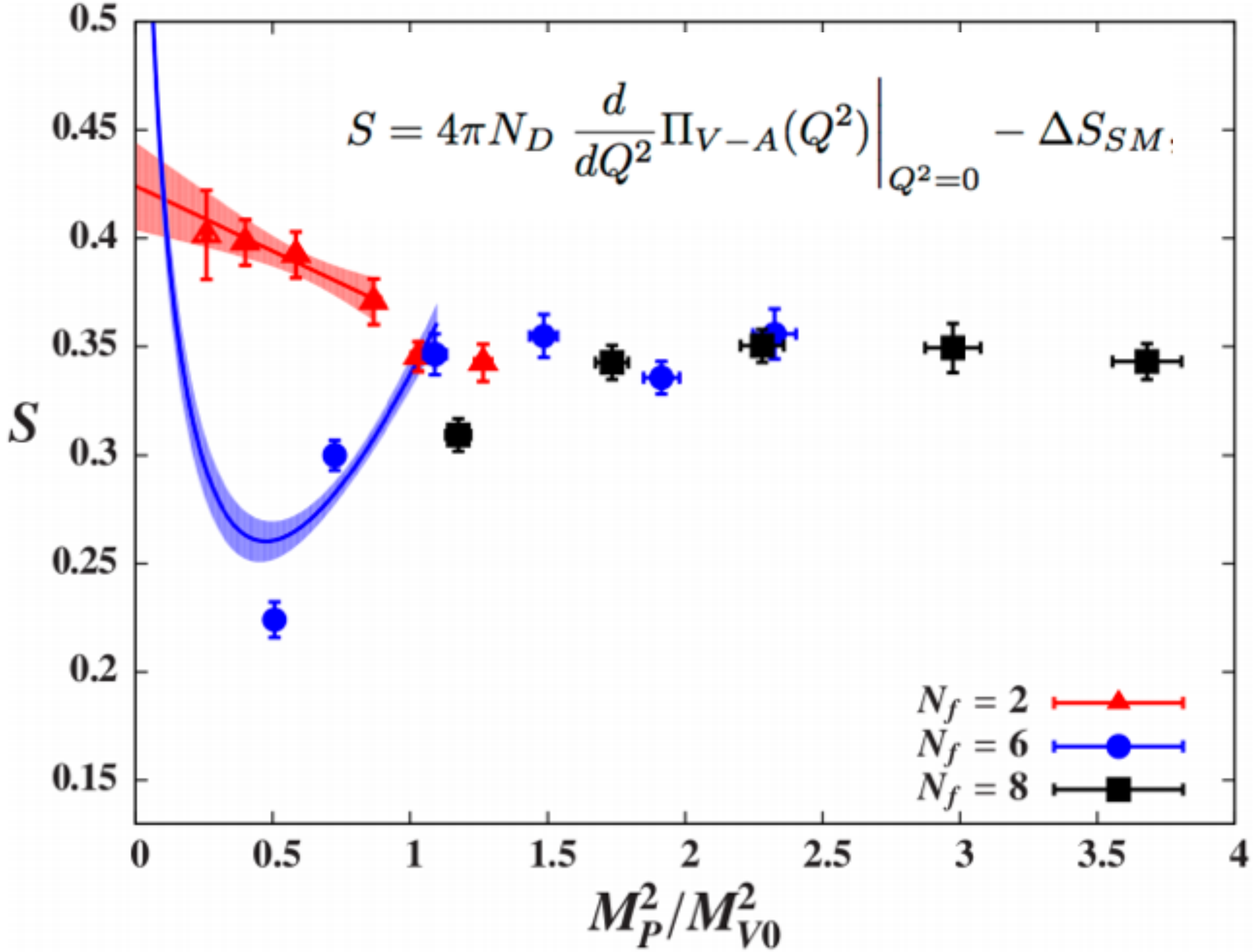
- Calculate on lattice at fixed momentum q^2 and fermion mass m, extrapolate as needed (depends on the quantity and the model…)

LSD Collaboration, arXiv:1009.5967



$(3, N_f, \mathbf{F})$

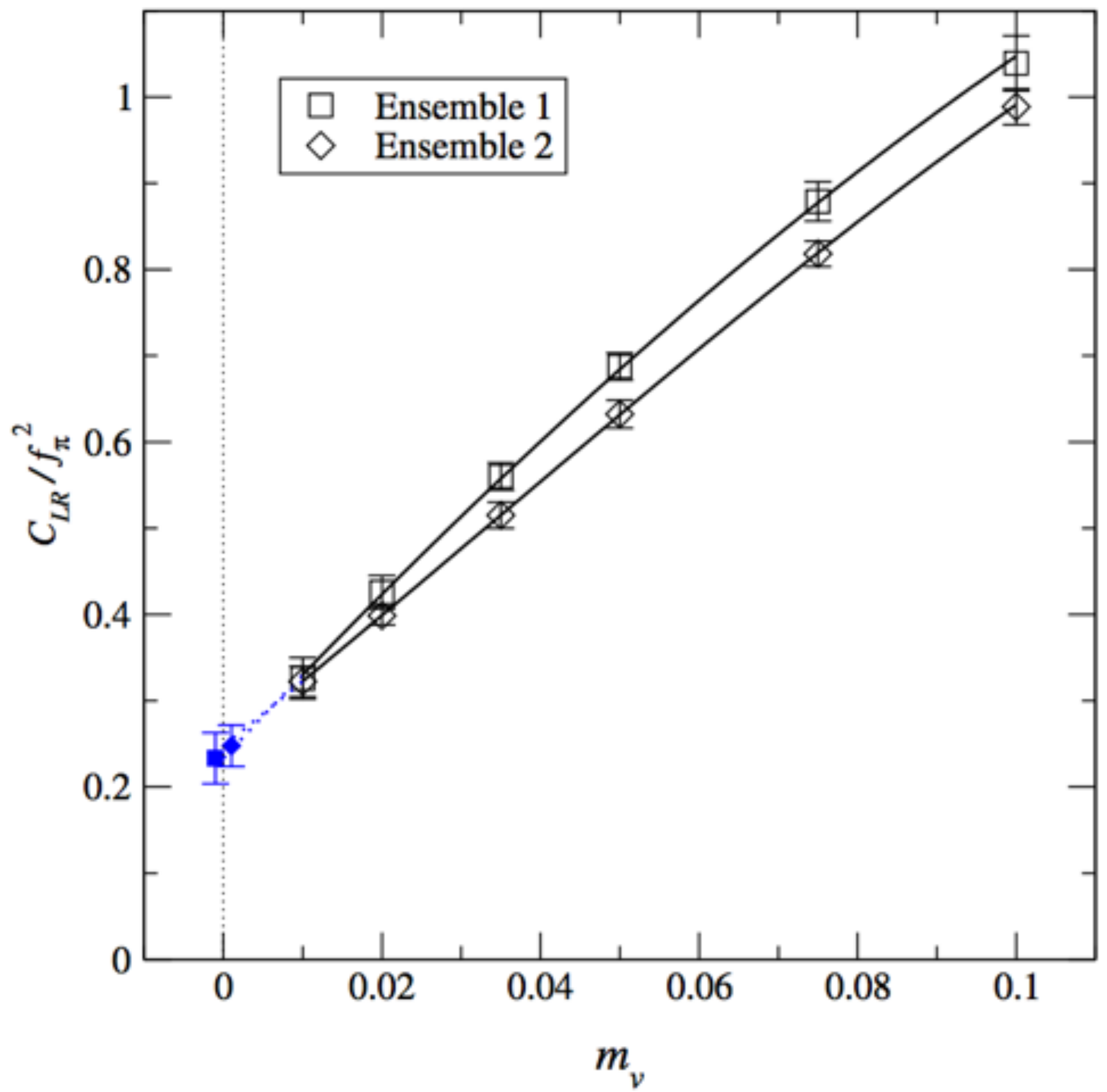
LSD Collaboration, arXiv:1405.4752



- Tantalizing reduction from 2 to 6 fermions, but doesn't seem to unambiguously continue at 8; S remains a challenge for technicolor-like theories

$(\mathbf{4},\mathbf{2},\mathbf{AS_2})$

DeGrand, Golterman, Jay, EN, Shamir, Svetitsky, arXiv:1606.02695



EW contribution to effective Higgs potential:

$$V_{\text{eff}} = C_{LR} \sum_Q \text{tr}\,(Q\Sigma Q^* \Sigma^*)$$

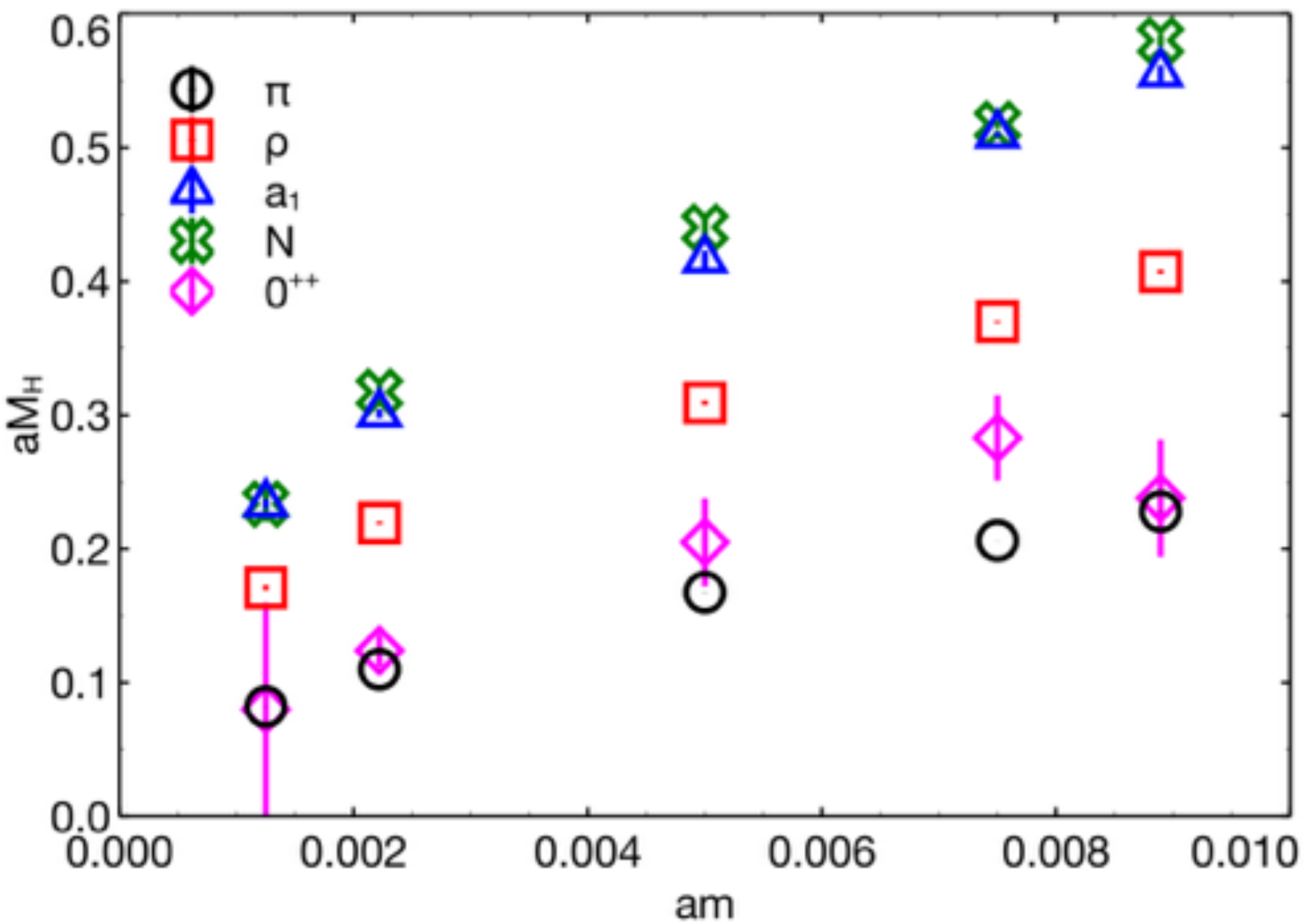
$$C_{LR} = \int_0^\infty dq^2 q^2\, \Pi_{LR}(q^2)$$

coefficient from integrated vac. pol.

Light scalar ($J^{PC}=0^{++}$)?

(3,8,**F**)

LSD Collaboration, arXiv:1601.04027



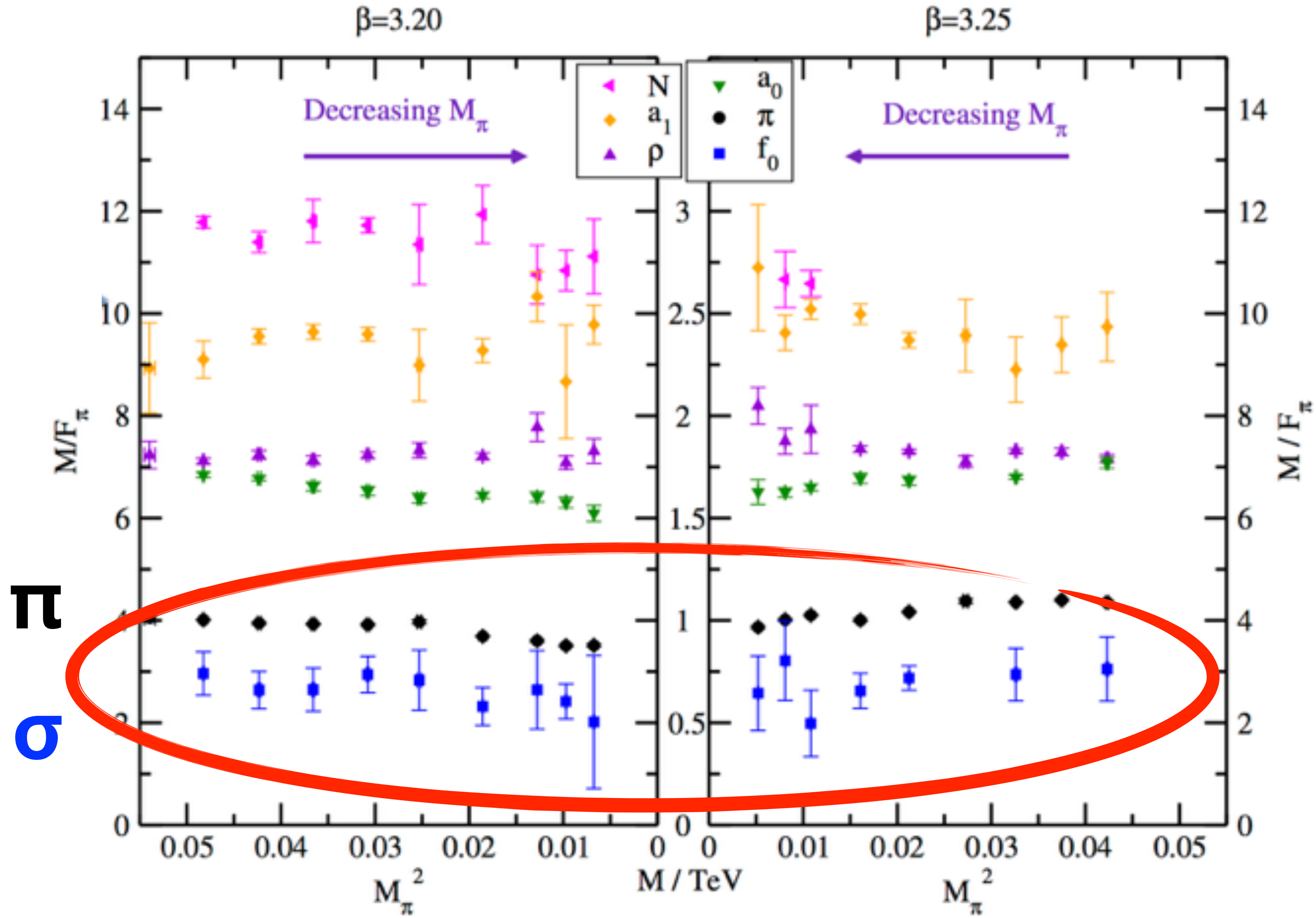
(see poster on Monday by E. Rinaldi)

- A composite Higgs should generally be light compared to other strong resonances. Can occur by construction: Higgs as pseudo-NGB, like pions.
- Emerging hints from lattice that a light scalar can appear regardless: new results (left) confirm initial LatKMI study, showing 0++ near-degenerate with pions![1]
- Another light state…what is the low-energy EFT?

[1] LatKMI Collaboration, arXiv:1403.5000

(3,2,S_2)

LatHC Collaboration, talk at "Lattice for BSM Physics 2016"



- Similar outcome, different theory! Other observations of light scalar by other lattice groups: see talk by G. Fleming, Lattice 2016

Outlook and summary

Looking ahead for lattice

- Certain things are easy and straightforward on lattice: spectroscopy, vacuum polarization, “weak” (not-hypercolored) decay matrix elements

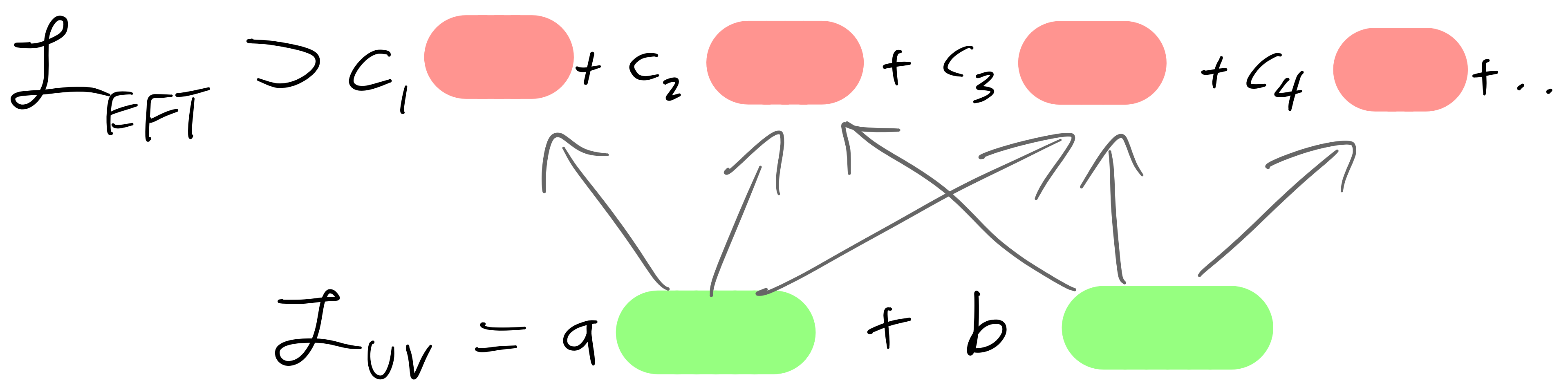
- Anomalous dimensions of operators for mass terms: harder, but work ongoing. Single strong decays (e.g. T —> t Z_L) can be studied, similar to semileptonic hadron decay in QCD.

- Anything with multiple “strong” states (doubly-strong decays, e.g.) are very challenging. So are theories which are nearly scale-invariant.

- Investigation of 0++ state: scattering of “pions” and scalar-channel form factors. Can we identify the low-energy EFT? Is it chiral PT, or something else…?

An appeal to model-builders

- We need ultraviolet-complete theories which yield your favorite composite Higgs EFT!
- Working with UV completions can greatly enhance predictive power: many LECs from a handful of fundamental parameters.

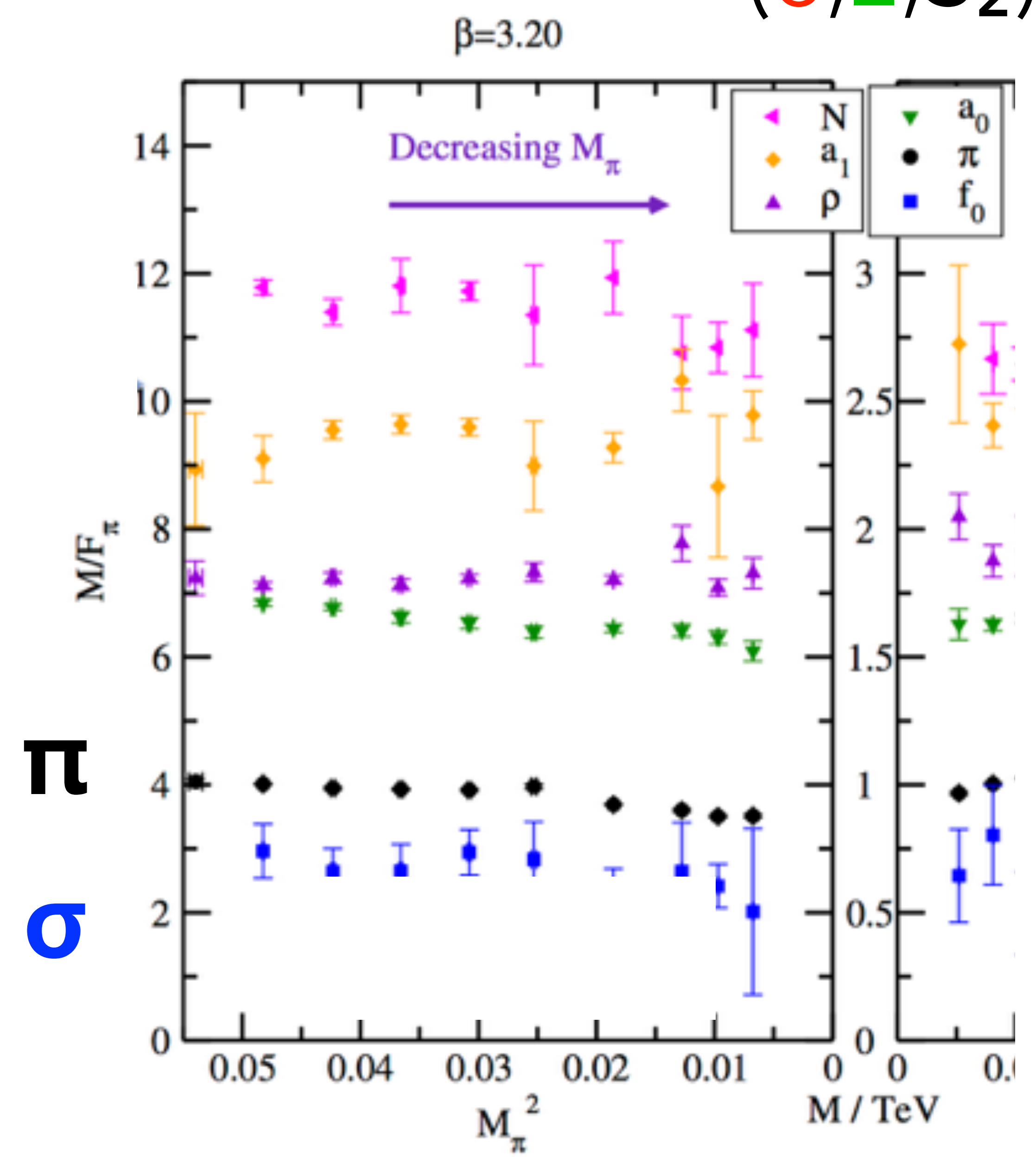


- Lattice/UV completion can also describe things beyond the EFT: heavier resonances, matrix elements, etc.
- Matching calculations to take results from the isolated strongly-coupled sector —> pheno predictions are needed too!

Summary

- Composite Higgs is interesting, but strong coupling is hard.
- Lattice can deal with strong coupling, but needs UV completion to study!
- Vector-meson dominance seems to work well beyond QCD, and $g_{\rho\pi\pi}$~6 is fairly insensitive to fermion mass/ number
- Hints of a light 0++ scalar - what is the EFT for this + “pions”? Work in progress.

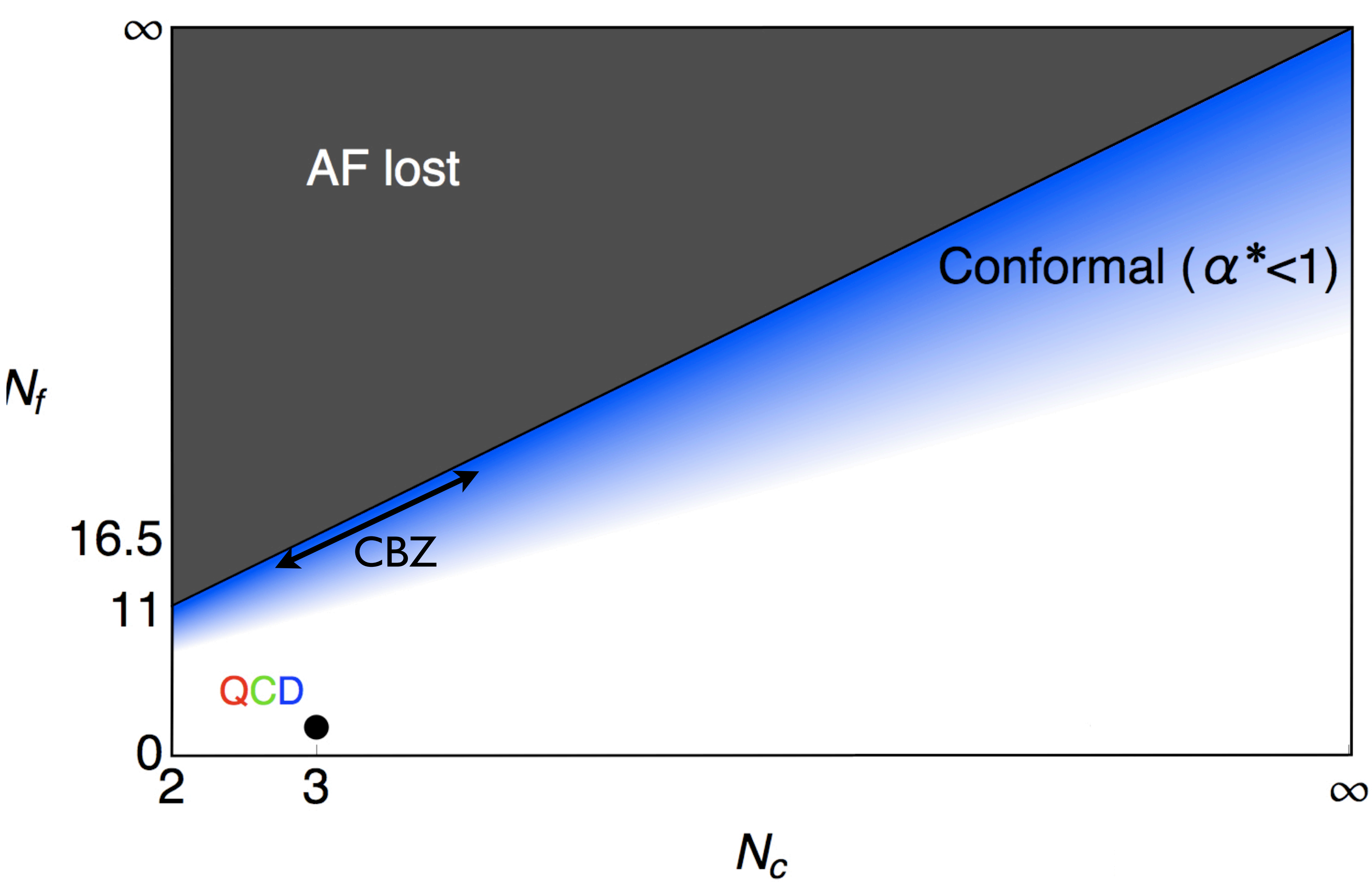
(3,2,S2)



LatHC Collaboration

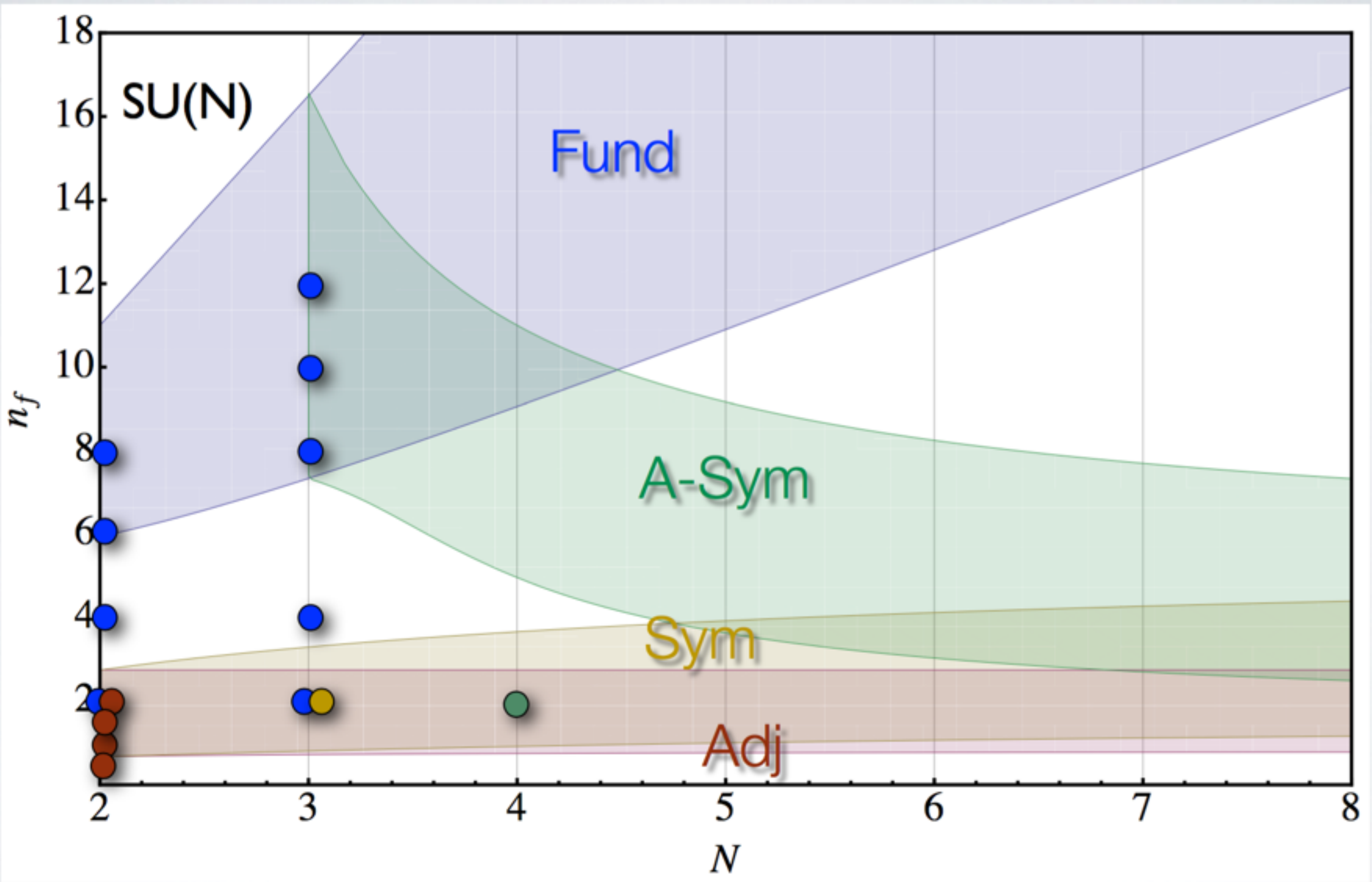
Backup

Theory space



Theory space

C. Pica, plenary talk at Lattice 2016



Mass dependence of 0^{++} in (3,8,F)