Lattice Insights for Composite BSM Models

Ethan T. Neil (Colorado/RIKEN BNL)
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University of Colorado Boulder

RIKEN BNL Research Center

(recent review on composite DM/lattice:
EN and Graham Kribs, arXiv:1604.04627)

Motivation: composite BSM

Composite BSM physics?

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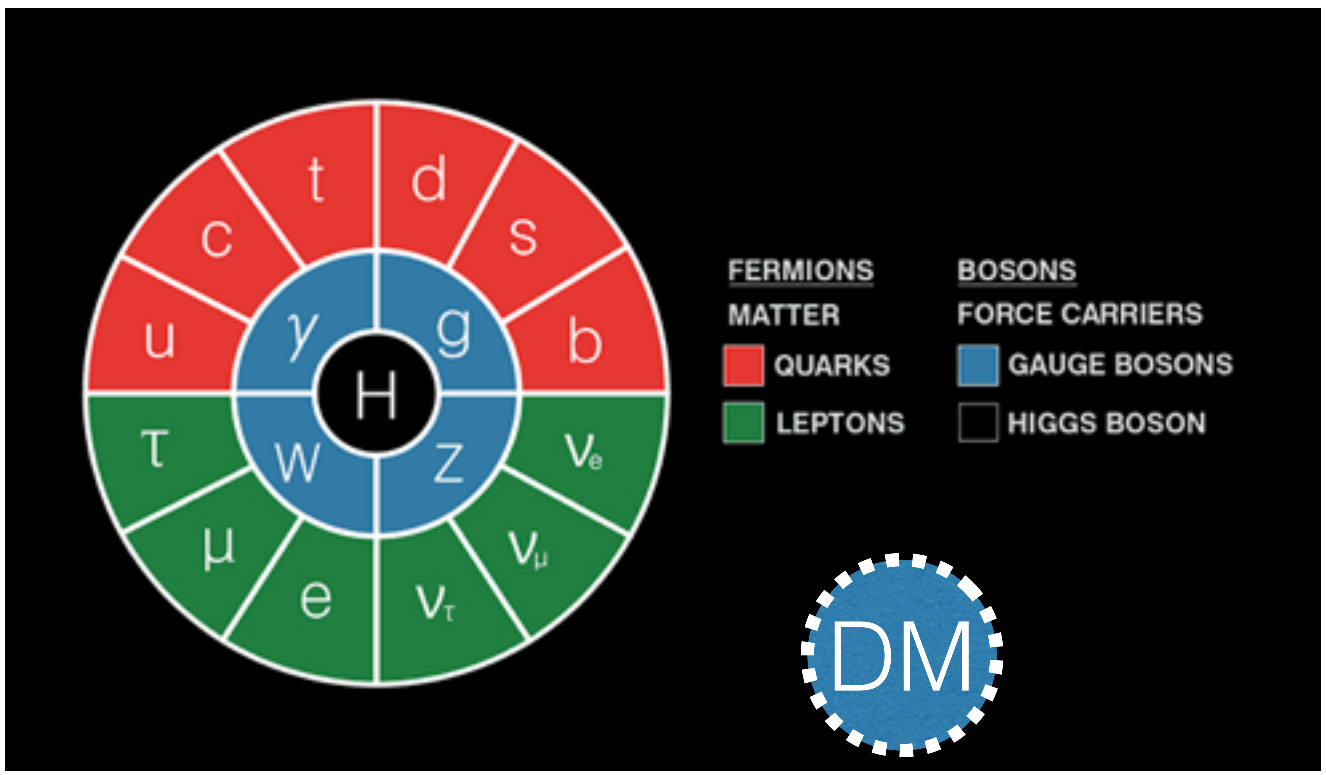
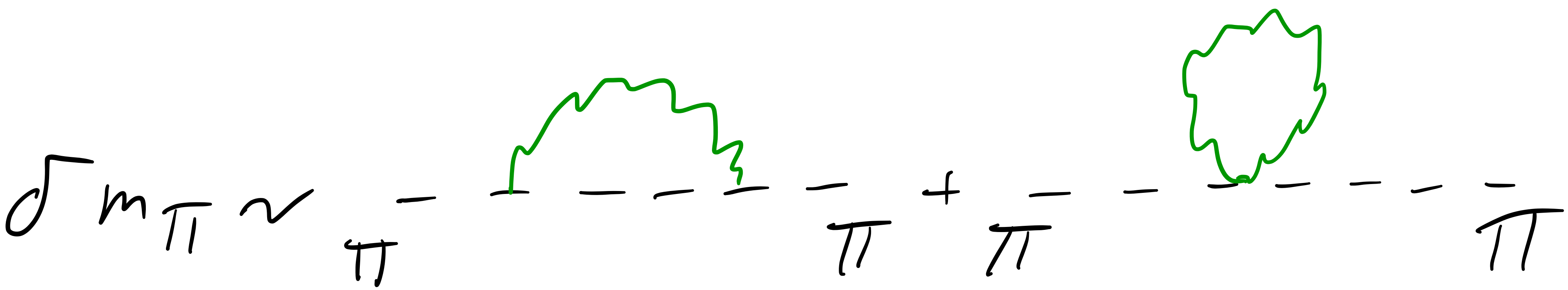


- The Standard Model has many theoretical puzzles, including Higgs naturalness and dark matter.
- Extending the SM: QCD has examples of mechanisms that can be useful (cosmically stable particles, massive scalars w/o naturalness.)
- The idea of composite BSM (from non-Abelian gauge dynamics) is to generalize these ideas from QCD and put them to use.

Lessons from QCD: scalars

- The mass of the pi+ meson in QCD is subject to radiative corrections from the photon:



- Quadratically divergent $(3\alpha/4\pi)\,\Lambda^2$ contribution to the mass! Fine-tuning problem if $\Lambda >> 140$ MeV. But we know this is an EFT: for $\Lambda \sim 800$ MeV, we see other resonances, and eventually quarks and gluons.

- **If Higgs is composite** with new resonances ~ TeV scale, then that naturalness problem is solved in the same way! (Potential little hierarchy between m_h and Λ, but this could be due to symmetry e.g. h is a pseudo-Goldstone boson.)

(credit to C. Pica, Lattice 2016 for this nice approach to describing the "anatomy" of composite Higgs)

Composite Higgs, in detail[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:

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

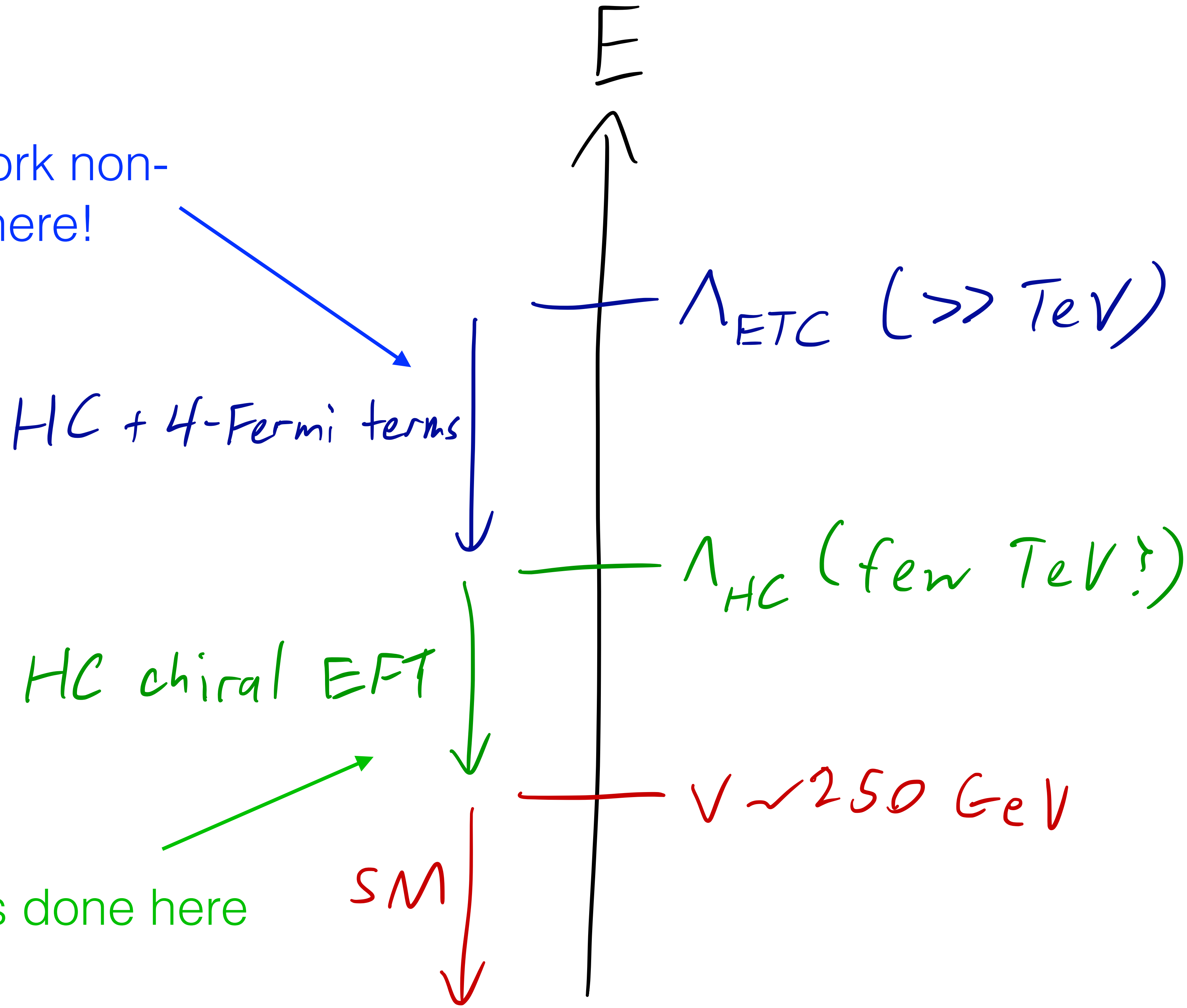
- EW breaking, and SM mass terms. No fundamental scalar —> four-fermion operators:

$$\frac{1}{\Lambda^2_{UV}} \bar{f} f \mathcal{O}_B \quad \text{or} \quad \frac{1}{\Lambda^2_{UV}} \bar{f} \mathcal{O}_F$$

(extended technicolor) (partial compositeness)

[1] more info: TASI lectures by R. Contino, arXiv:**1005.4269**; review by Panico and Wulzer, arXiv:**1506.01961**

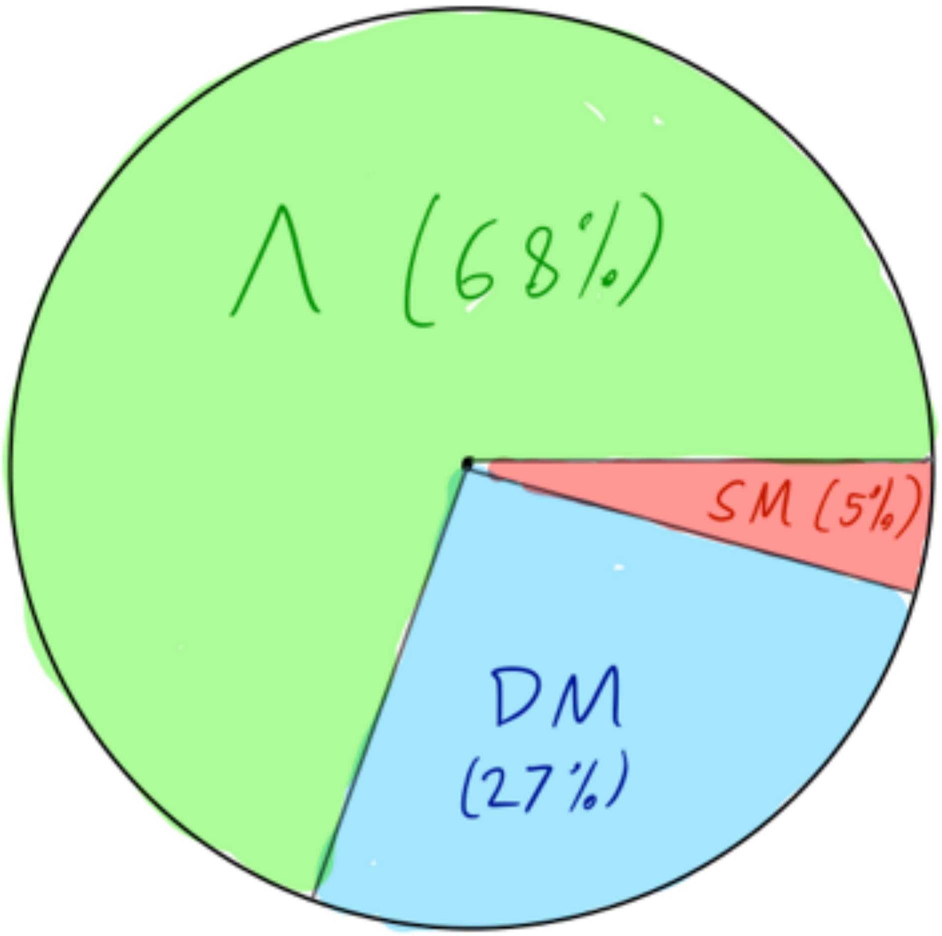
with lattice, can work non-perturbatively here!



most pheno studies done here

Lessons from QCD: baryons (DM)

- Strong evidence for particle dark matter. Must be stable and neutral - but not too neutral (cosmic coincidence problem)
- QCD has two nice examples:
  - proton (stable due to accidental $U(1)_B$)
  - neutron (neutral, but unbound quarks interact in early-universe thermal bath)
- **Composite dark matter** models combine both properties into a single candidate arising from a "hidden" strongly-coupled gauge sector.
- (Note: mesonic models of DM do exist as well, although a bit more work to motivate stability. I'll return to this point.)



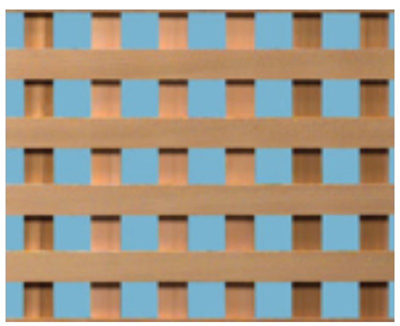
Lattice simulations beyond QCD

Lattice gauge theory

- To study strongly-coupled SU(N) theories, we need *non-perturbative* techniques. Lattice gauge theory! Numerical, but fully non-perturbative.
- Lattice has been used on QCD with enormous success in calculating masses of hadrons and various matrix elements (particularly for nuclear and flavor physics)
- For BSM, can act as a "numerical laboratory" to allow us to explore what happens as we change theories away from QCD.

Start with the path integral:

$$\langle \mathcal{O} \rangle = \frac{1}{\mathcal{Z}} \int \mathcal{D}U \mathcal{D}\overline{\psi} \mathcal{D}\psi \; \mathcal{O}(U, \overline{\psi}, \psi) \exp\left(-S[U, \overline{\psi}, \psi]\right)$$



$$\langle \mathcal{O} \rangle = \frac{1}{N} \sum_{U \in \mathcal{U}} \langle \mathcal{O} \rangle_U$$

- Discretize spacetime to make the path integral finite dimensional
- Monte Carlo evaluation of the integral on high-performance computers (*importance sampling* weighted by exp(-S))
- Obtain weighted gauge ensemble. Can measure many observables with one ensemble!

Lattice and Composite BSM[1,2]

- Lattice gauge theory is **numerical** and **non-perturbative** - can work with L_{HC} directly!

- From QCD, we can "turn the dials" to study more general theories:

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

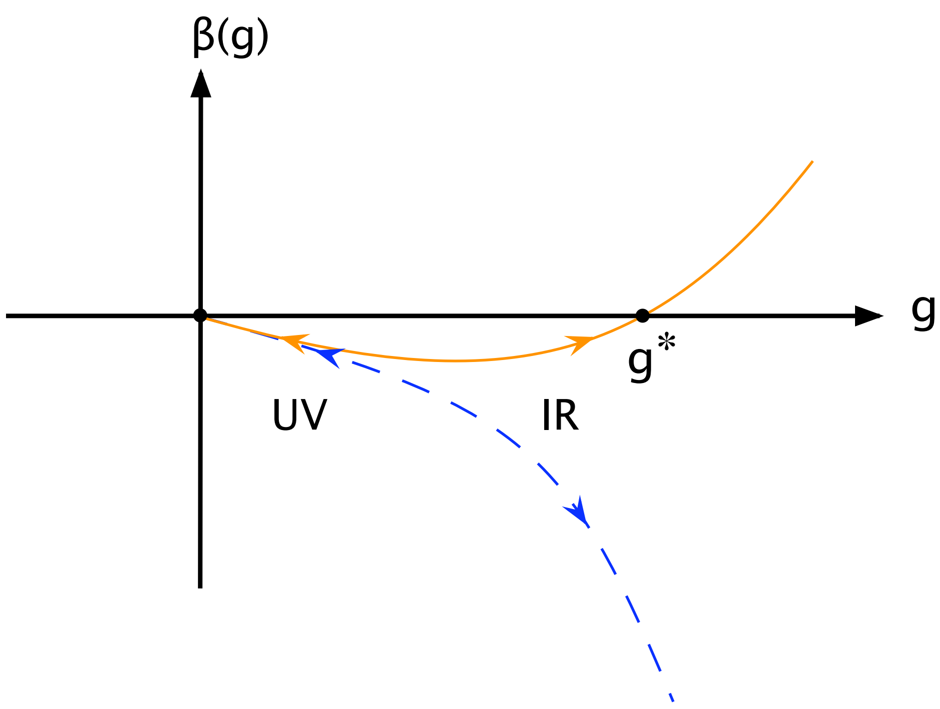
(N_c,N_f,**R**): SU(N_c) gauge theory, N_f fermions in irrep **R**

- (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

Gauge theory and the β-function

- Interesting phase structure as Nc and Nf are varied - easiest to understand in terms of β-function.



$$\beta(\alpha) \equiv \frac{\partial \alpha}{\partial(\log \mu^2)} = -\beta_0 \alpha^2 - \beta_1 \alpha^3 - \ldots$$

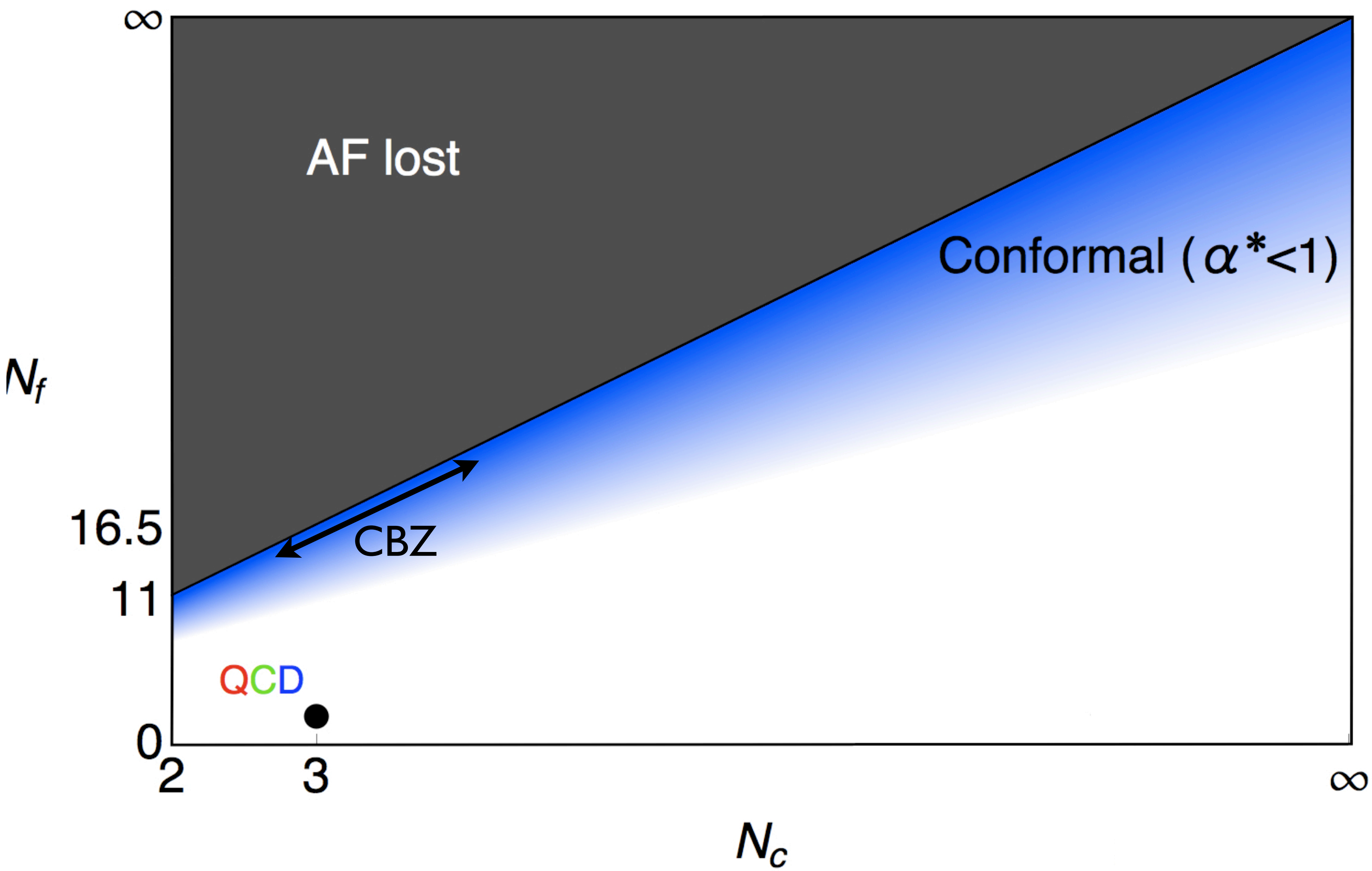
$$\beta_0 = \frac{1}{4\pi}\left(\frac{11}{3}N_c - \frac{2}{3}N_f\right)$$

$$\beta_1 = \frac{1}{16\pi^2}\left(\frac{34}{3}N_c^2 - \left[\frac{13}{3}N_c - \frac{1}{N_c}\right]N_f\right)$$

(R=fundamental)

- With Nf small (QCD), coupling grows in IR and confines
- Large enough Nf creates an infrared fixed point. Scale invariance in IR, no confinement or chiral symmetry breaking.

Theory space

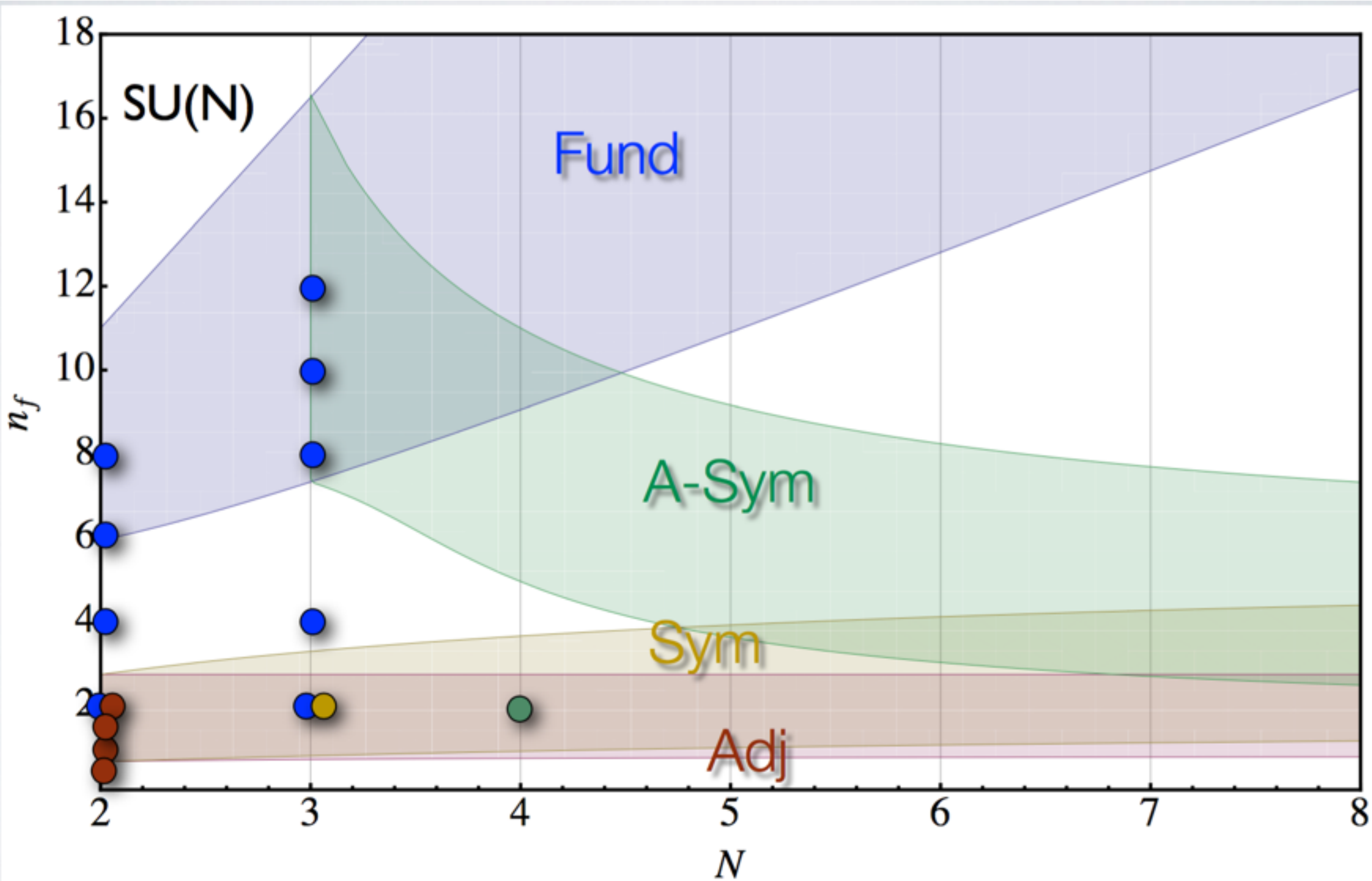


"CBZ" = "Conformal Banks-Zaks": expansion where conformal fixed point coupling is deeply perturbative

Conformal transition is an active area of lattice research

Theory space, from the lattice

C. Pica, plenary talk at Lattice 2016 - BSM presentations at that year's conference



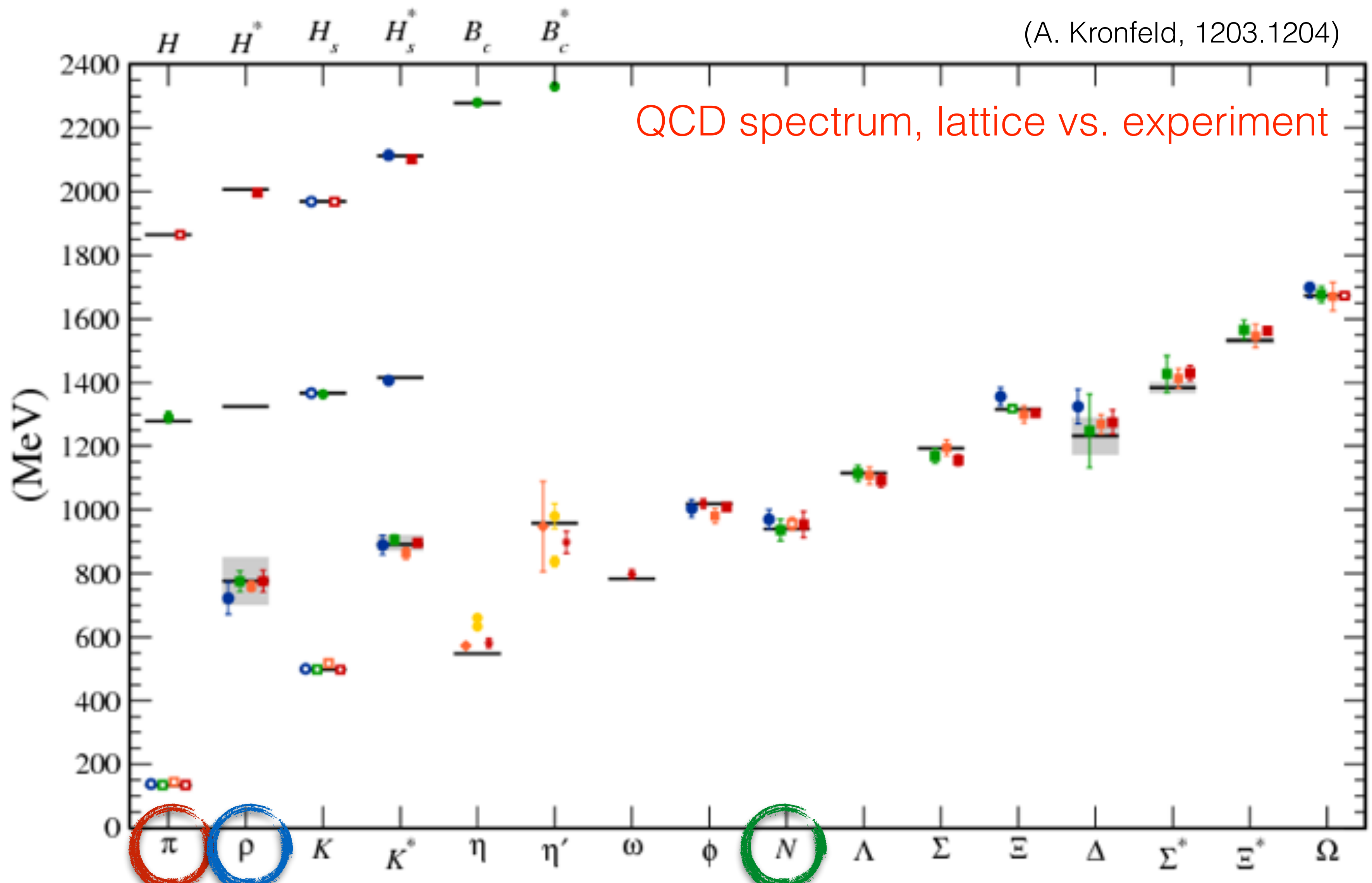
(note: bands are analytic estimates of the edge of the conformal transition, probably not reliable.)

Philosophy of lattice BSM approach

- In the future: lattice can play a similar role as in QCD if a composite theory is discovered (precision), once we understand what the underlying field content is.
- Present: lattice acts more like a “parameter scan” of the large theory space. We can’t study every possible strongly-coupled model, but we can study several and look for regularities (or surprises.)
- Gives the most likely places to look, until we know more. (i.e., lattice studies can find new lampposts to look under.)

A tour of results by particle type

- The rest of the talk will connect lattice results with composite Higgs and dark matter pheno, organized by state.



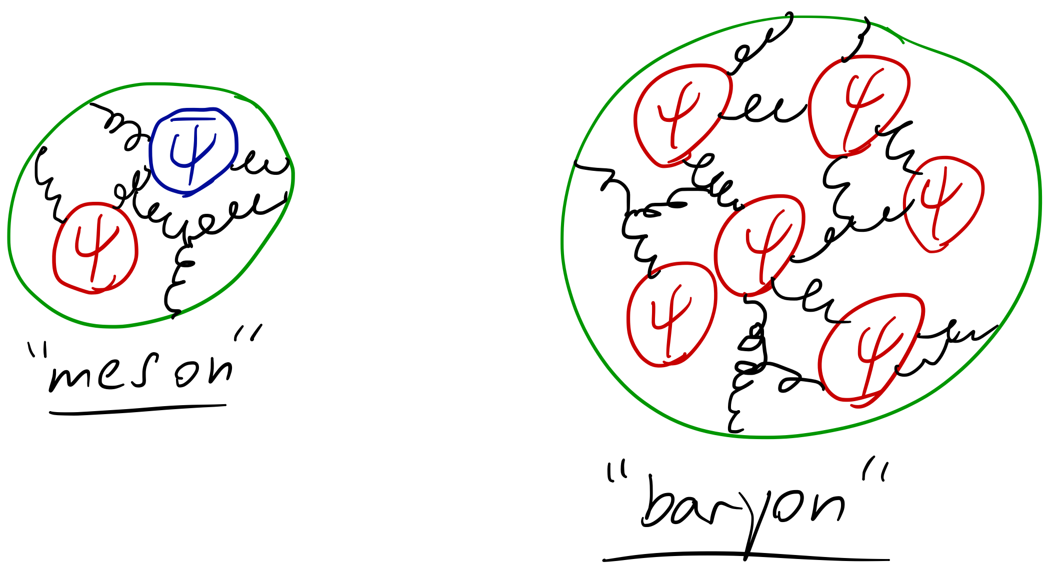
π: (pseudo)-Goldstones (+Higgs)

ρ: lightest vector meson

B: lightest baryon

Composite states: B

Composite states: B



- Baryons are relatively heavy, so may be harder to see than other resonances. But special properties make them interesting.

- Baryons can be fermions —> quark mass by mixing (partial compositeness)

- Baryons can be stable (baryon #) —> dark matter

Stability of composite DM

- Lightest mesons (Π) can be stabilized by flavor symmetries[1] or G-parity[2], but then one has to argue against the presence of dimension-5 operators like:

$$\frac{1}{\Lambda}\bar{\Psi}\Psi H^\dagger H \longrightarrow$$

instability over lifetime of the universe, even with $\Lambda = M_{Planck}$.

- Accidental dark baryon number[3] symmetry provides automatic stability for B on very long timescales (as long as $N_c > 2$!) E.g. for $N_c=4$, decay through dimension-8

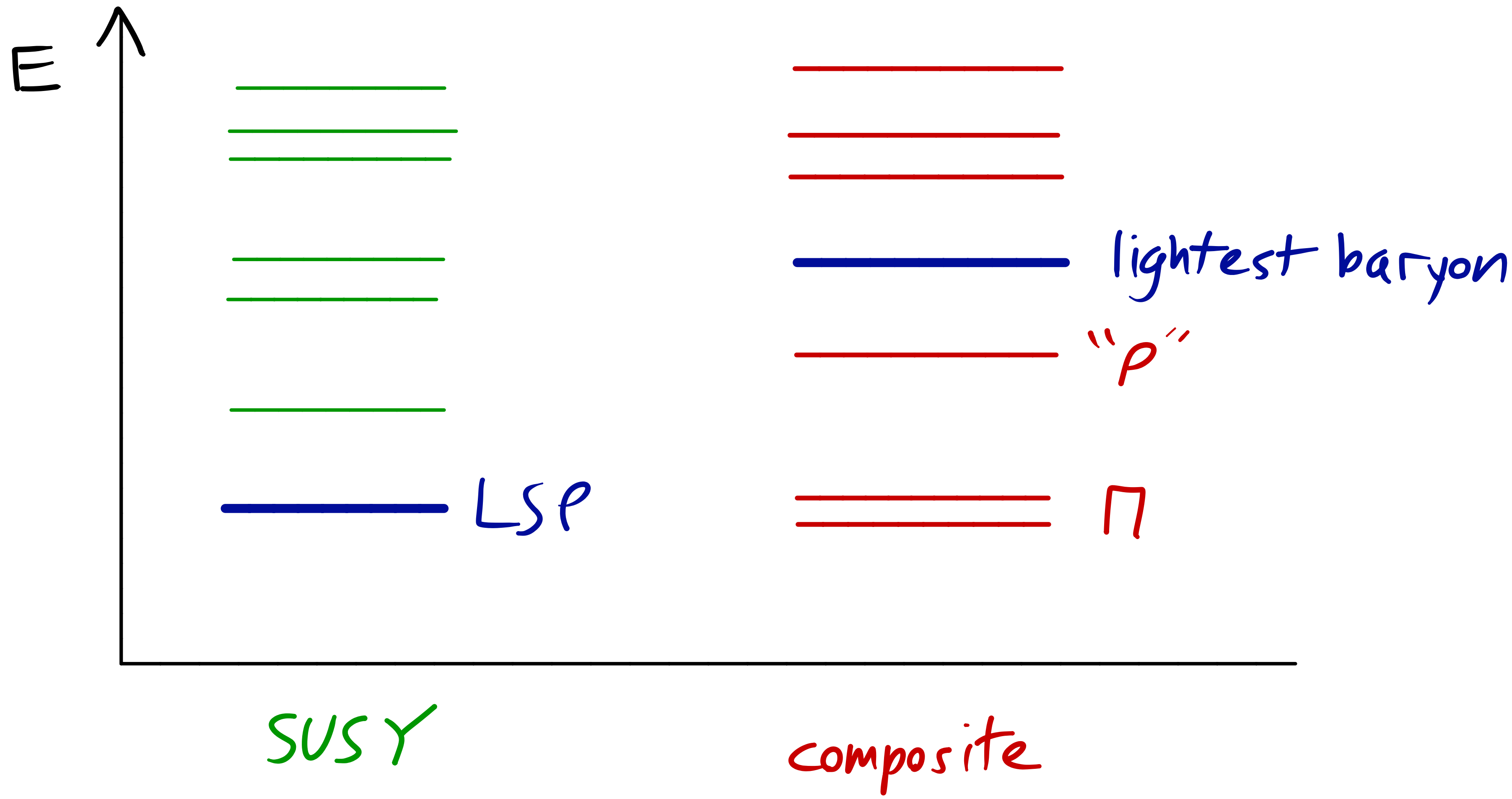
$$\frac{1}{\Lambda^4}\Psi\Psi\Psi\Psi H^\dagger H$$

[1]T. Ryttov and F. Sannino, arXiv:0809.0713; M. Buckley and EN, arXiv:1209.6054; Y. Hochberg, E. Kuflik, H. Murayama, T. Volansky, J. Wacker, arXiv:1411.3727

[2]Y. Bai and R. Hill, arXiv:1005.0008

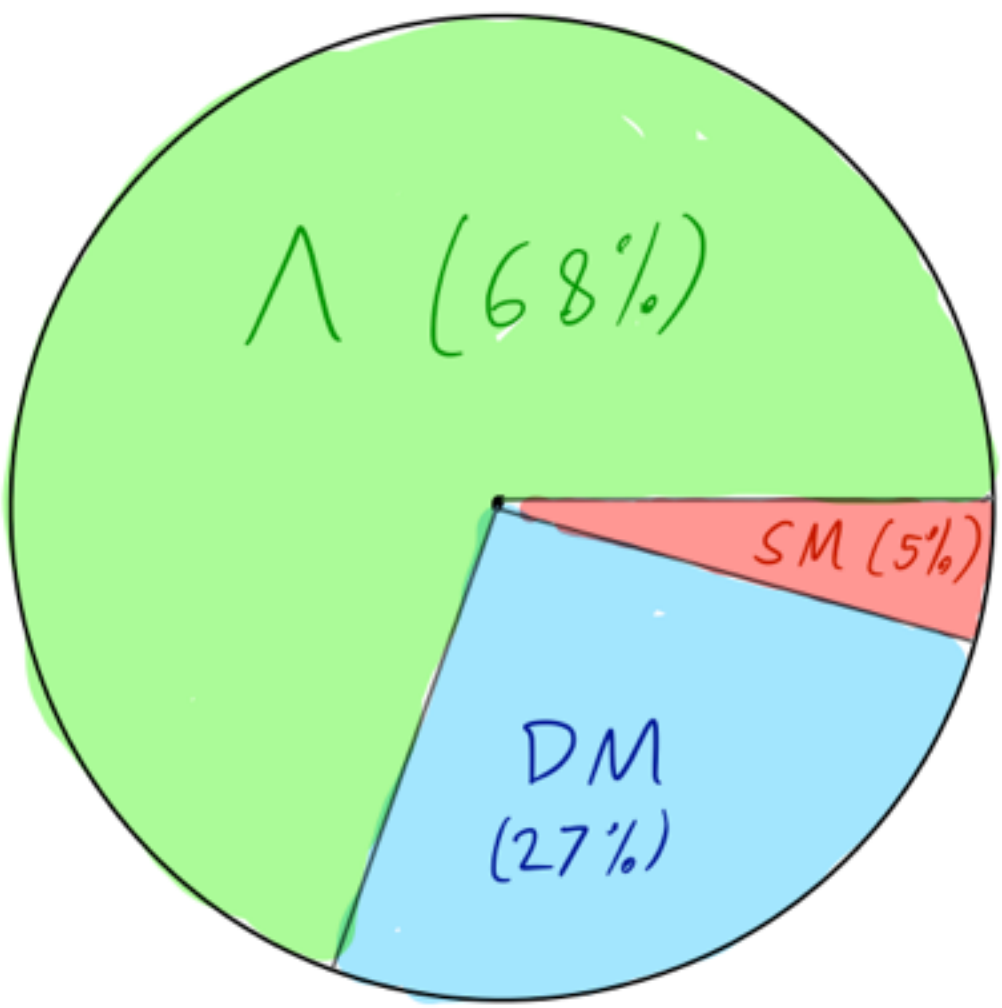
[3]nice discussion and classification in arXiv:1503.08749

Stable B: composite dark matter



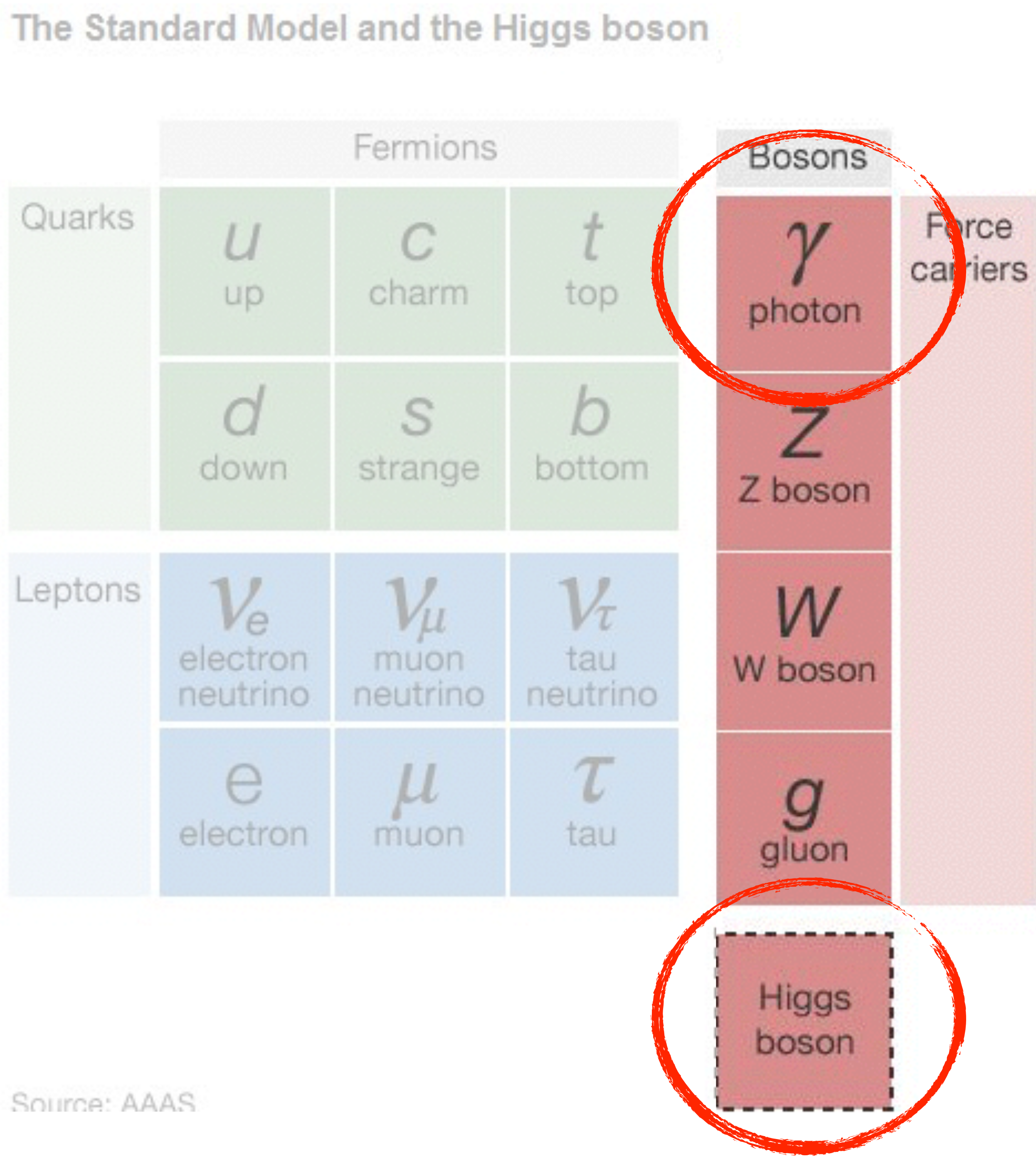
- Somewhat unusual situation in that other dark-sector particles are *much lighter* than the DM.
- Direct-detection searches can be extremely hard for composite baryons, especially if above TeV scale. Colliders may provide the best way to search (but not for the baryon directly.)

Charging the dark sector



- Some DM/SM interaction is crucial for relic density (cosmic coincidence?)
- Other mediator forces are possible, but interesting to assume SM charges in dark sector (suppressed by form factors - neutral at low energy.)
- Charged constituents imply charged bound states, too; neutral DM candidate should be lightest. (Easy to arrange w/positive mass splittings from charge.)

What kind of charge?



skipping for time, but see arXiv:1604.04627 for a review

suppressed relative to γ

useful for meson decay

interesting…*

<u>will discuss this</u>

*Gluonic operators considered before in Bagnasco, Dine, Thomas **PLB 320 (1994) 99-104**. Similar to photon operators in structure, but stronger bounds, particularly from colliders (see Bai and Osborne, arXiv:**1506.07110** and Godbole, Mendiratta, Tait ,arXiv:**1506.01408**)

Lattice Strong Dynamics Collaboration

Xiao-Yong Jin
James Osborn

Rich Brower
Claudio Rebbi
Evan Weinberg

Anna Hasenfratz
Ethan Neil

Ethan Neil
Enrico Rinaldi

Graham Kribs

Joe Kiskis

Oliver Witzel

Pavlos Vranas

David Schaich

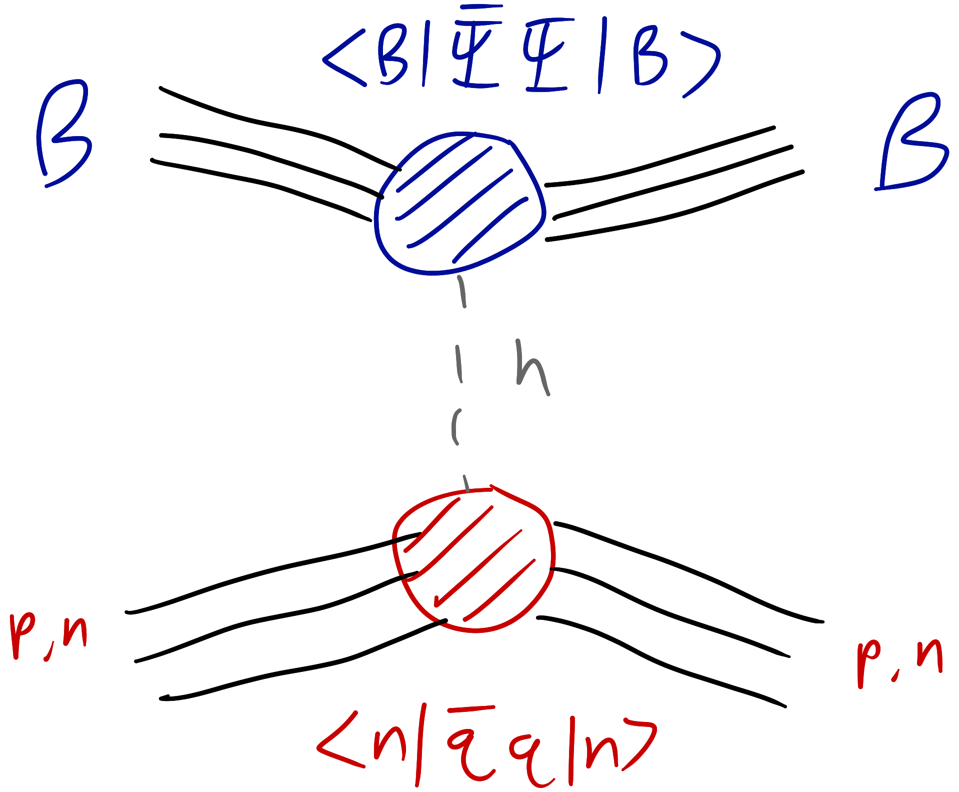
Tom Appelquist
George Fleming
Andy Gasbarro

Direct detection: Higgs exchange

- If the dark-sector fermions couple to Higgs, then they will induce a dark baryon-Higgs coupling ("sigma term")

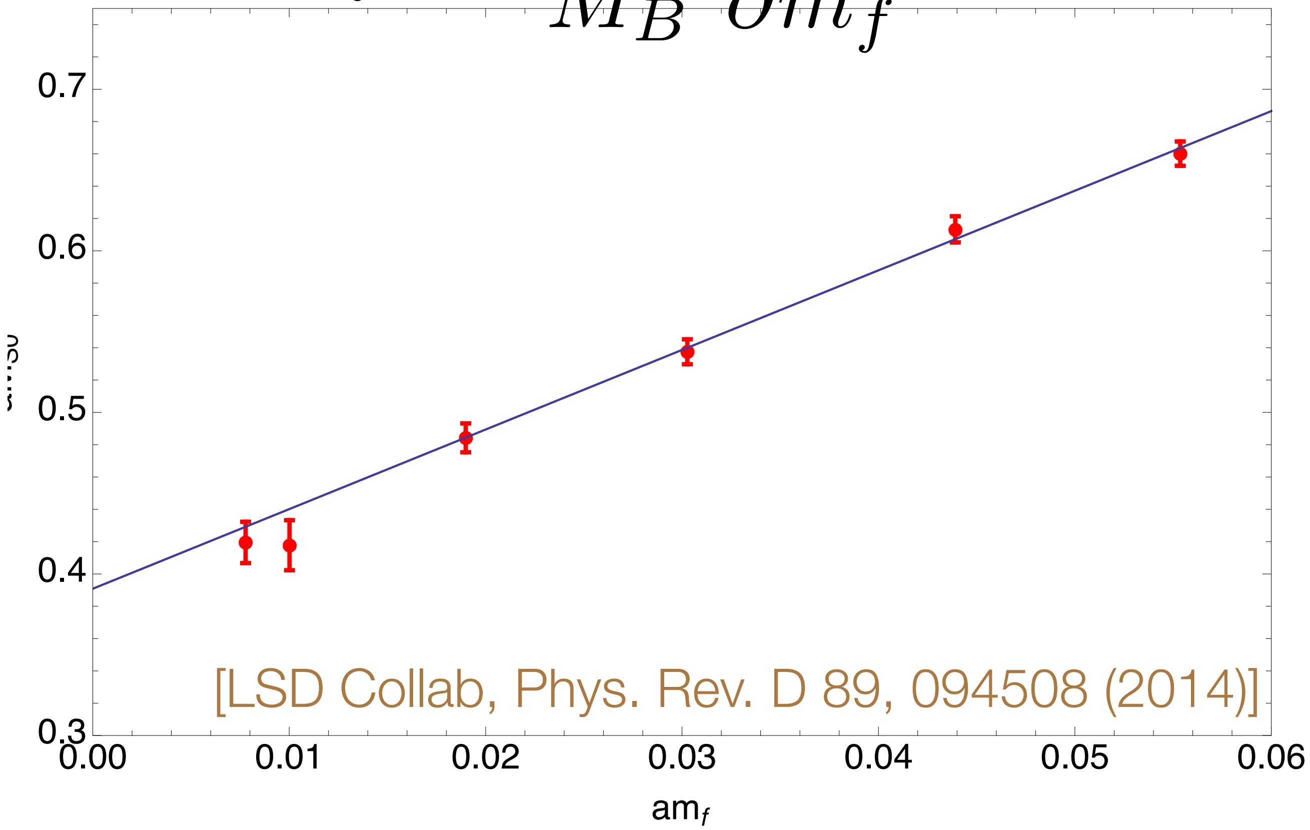
$$\langle p,n|m_q\bar{q}q|p,n\rangle = m_{p,n} f_q^{p_n}$$

$$\langle B|m_f\bar{f}f|B\rangle = m_B f_f^B$$



- Calculate on the lattice with Feynman-Hellman theorem:

$$f_f^B = \frac{m_f}{M_B}\frac{\partial M_B}{\partial m_f}$$



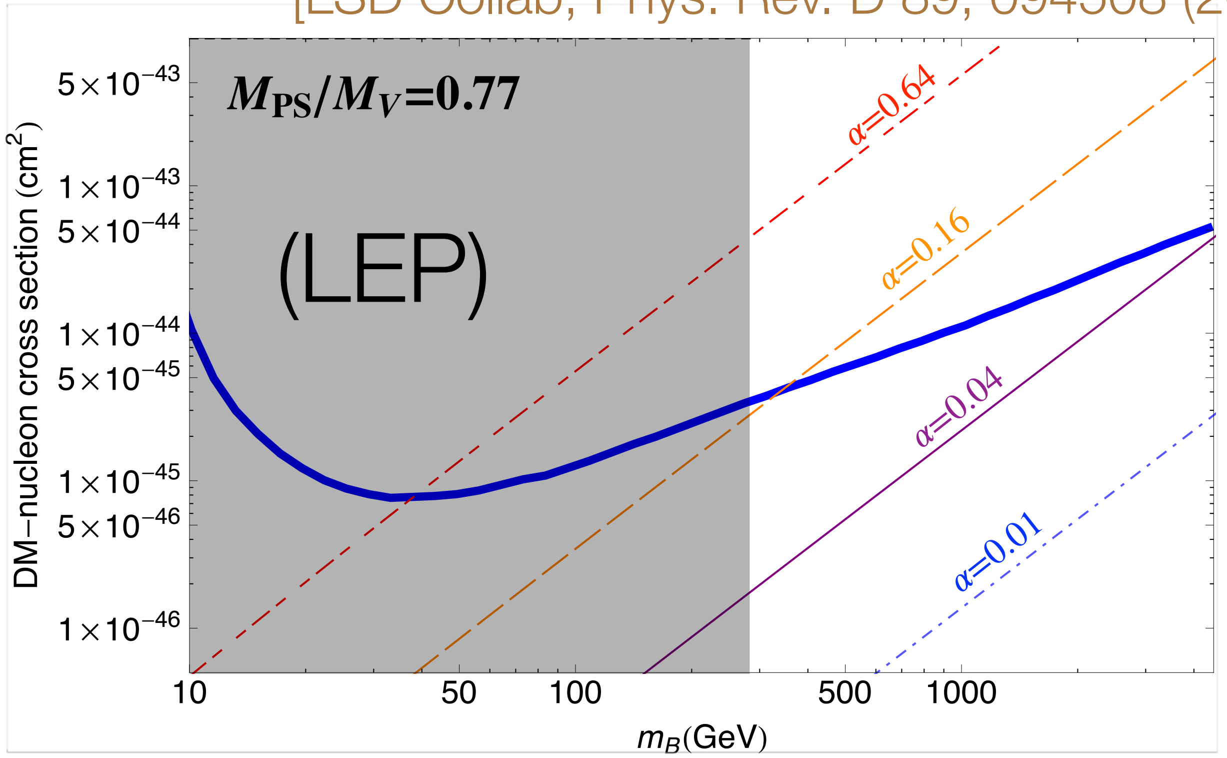
Experimental constraints on Higgs exchange

- Coupling on DM side is model-dependent. How much DM mass can come from Higgs?

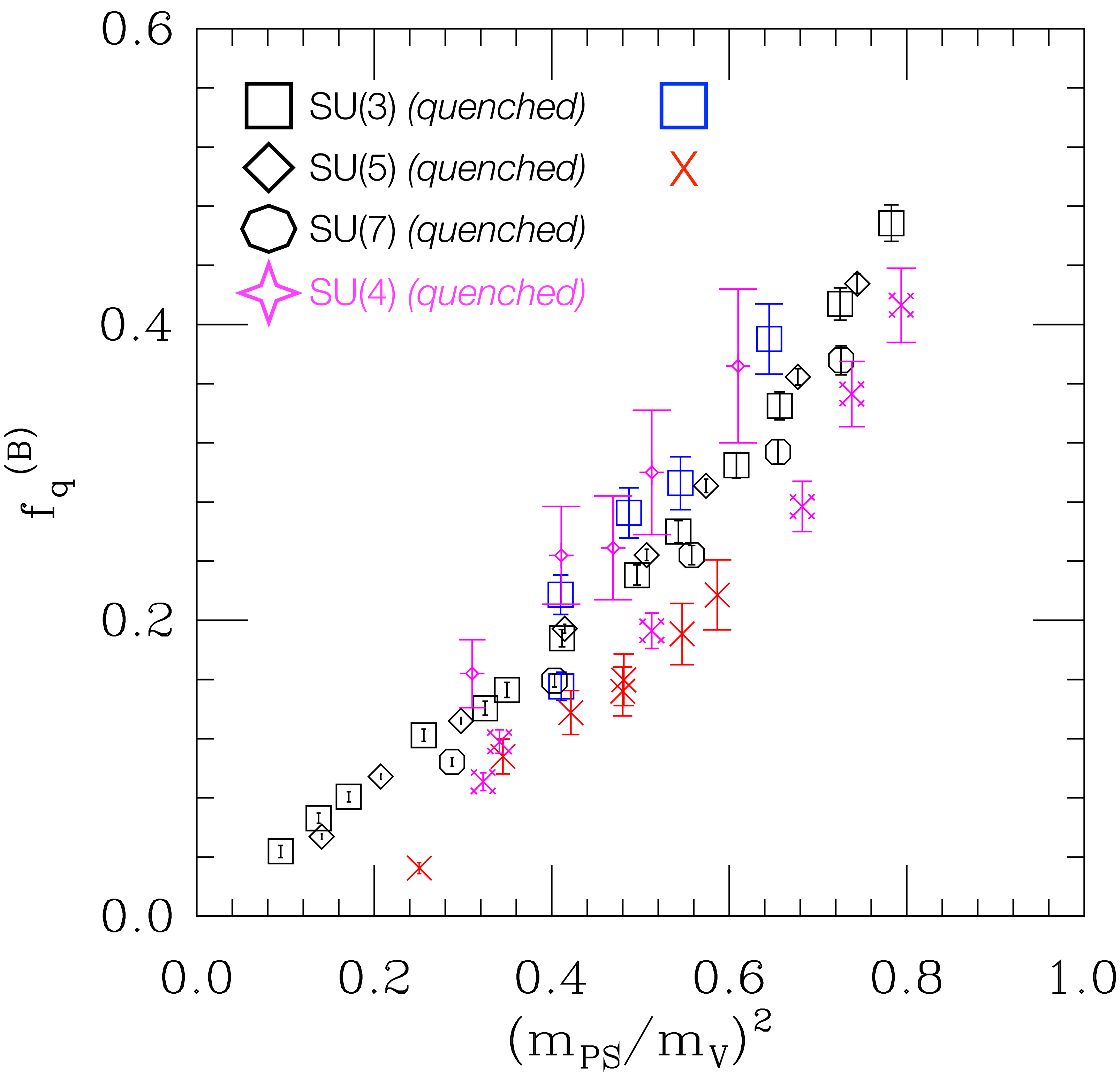
$$m_f(h) = m + \frac{yh}{\sqrt{2}} \quad \Big| \quad \alpha \equiv \frac{v}{m_f} \frac{\partial m_f(h)}{\partial h}\Big|_{h=v} = \frac{yv}{\sqrt{2}m + yv} \leq 1$$

- α=0 for no Higgs coupling, α=1 is pure Higgs mass generation.
- Non-perturbative calculation of scalar matrix element (sigma term) on DM side needed
- α=1 ruled out by experiment in this SU(4) theory!

[LSD Collab, Phys. Rev. D 89, 094508 (2014)]



Generalizing to other models?



- Lattice results hint that this matrix element may be fairly universal for different theories in similar mass regimes (left)
- Statement that composite DM can't have mass generation purely from the Higgs mechanism may be very general!

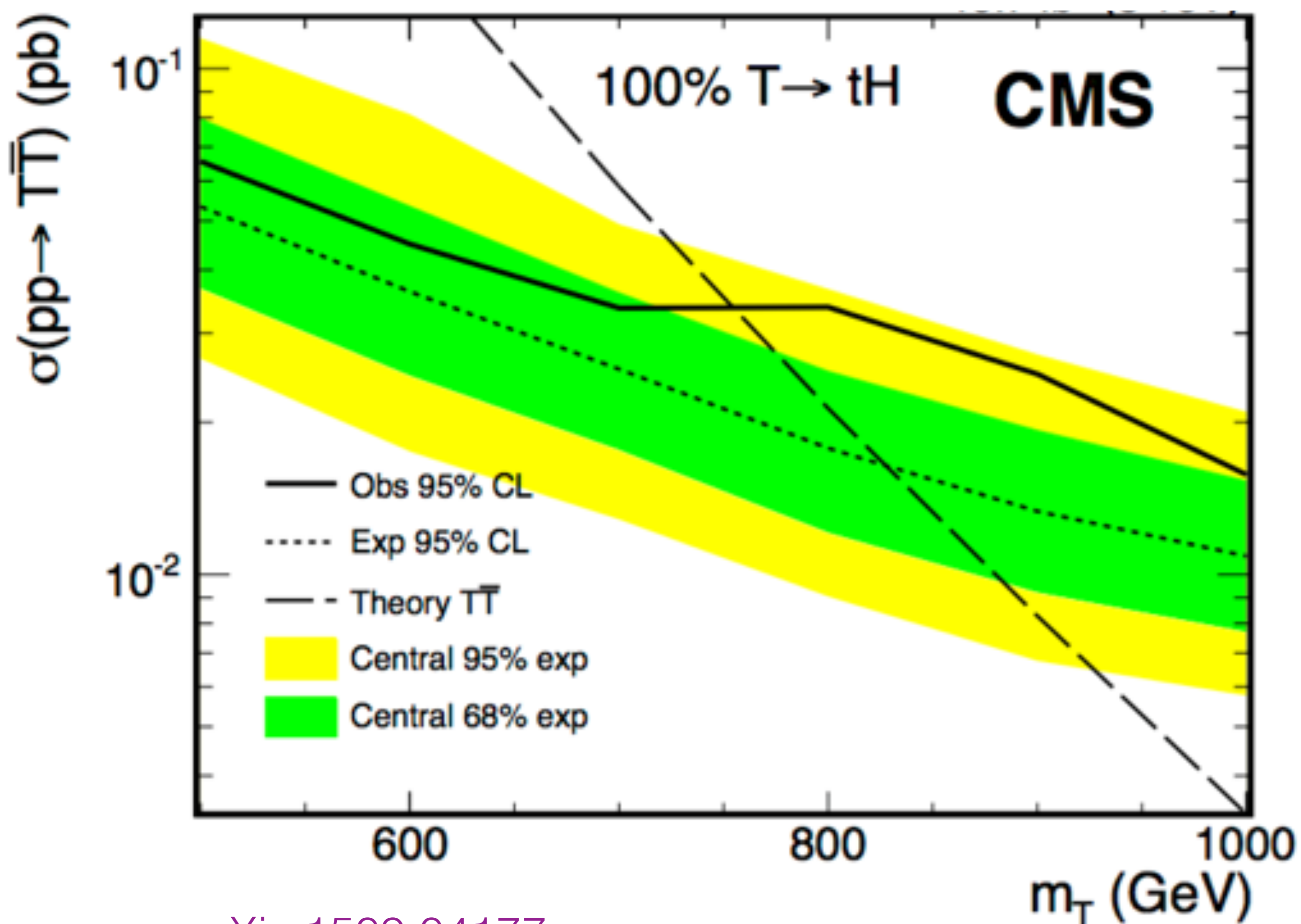
[T. DeGrand, Y. Liu, EN, B. Svetitsky, Y. Shamir, Phys. Rev. D 91, 114502 (2015)]

Fermionic B: partial compositeness

- "Partial compositeness" mass term requires a composite top partner:

$$\frac{1}{\Lambda_{UV}^2} \bar{f} \mathcal{O}_F$$

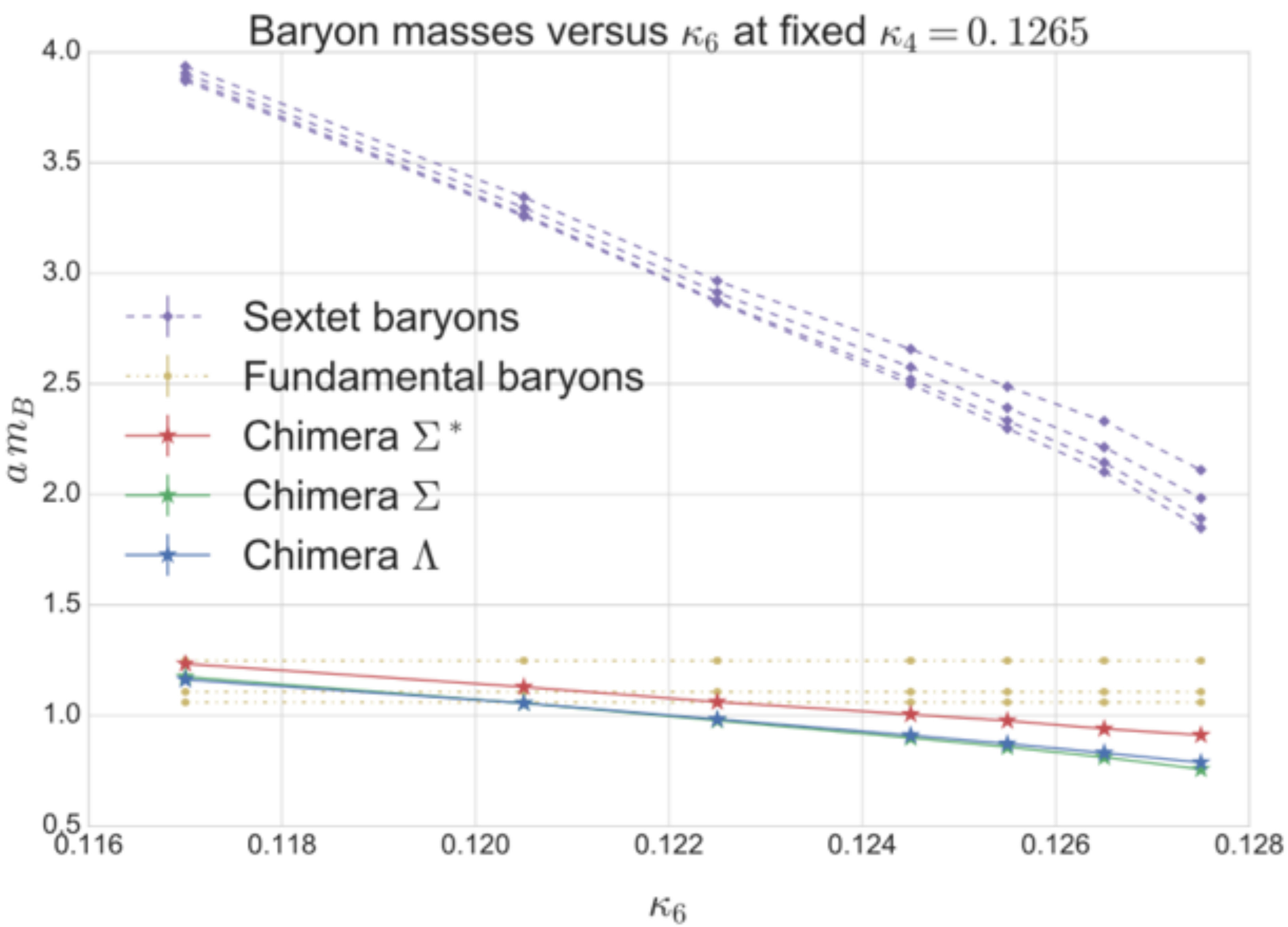
  - Must be a fermion — hypercolor baryon! Color + electroweak charge needed - two fermion species is best.
  - Generally also predict exotic $X_{5/3}$, possibly B partner.
  - Directly constrained by vectorlike quark searches, e.g. plot on the right.



arXiv:1509.04177

Fermionic B: partial compositeness

(4,2,**F+AS2**)



(DeGrand, Svetitsky, Shamir, EN, Jay; 1610.06465)

- With partial compositeness, top partners are *chimeras* - baryons w/mixed fermion reps (EW and color charged)
- Preliminary lattice results (left) for SU(4) show chimera states relatively light - good news, little hierarchy problem if they're too heavy.
- Future work: calculation of decay matrix elements to obtain width.

Composite states: ρ

Composite states: ρ

- Lightest vector resonance, typically the lightest resonance which isn't a Goldstone.
- As the lightest resonance, its properties can dictate interactions of the lighter PNGB states - "vector meson saturation".
- Smoking gun for composite Higgs scenarios; appears as W' or Z' but strongly coupled, can be very wide.

[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[1] relations:

electroweak decay →

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

HC-strong decay →

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

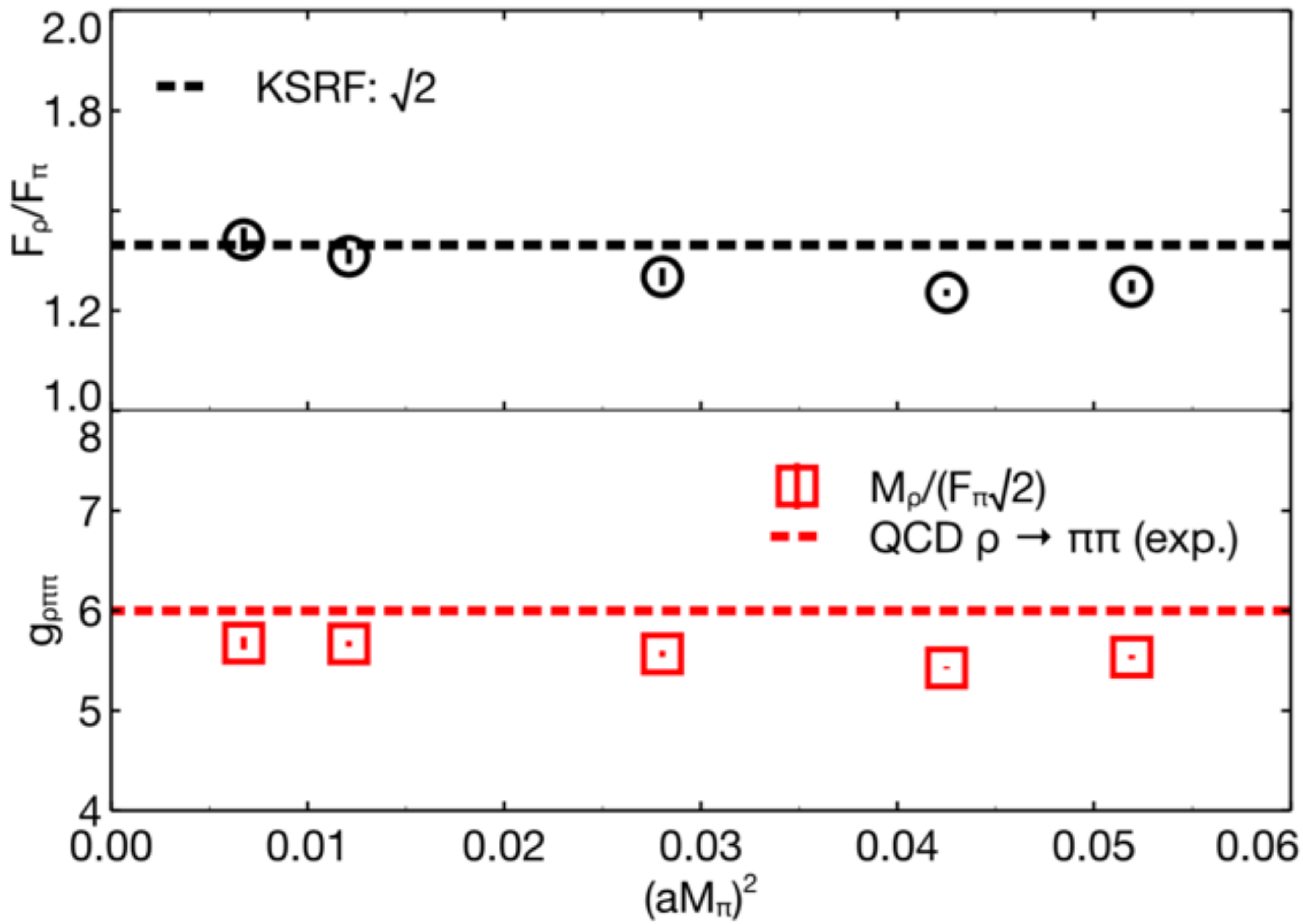
large-N_c:

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

- What happens in other strongly-coupled models?

(3,8,F)

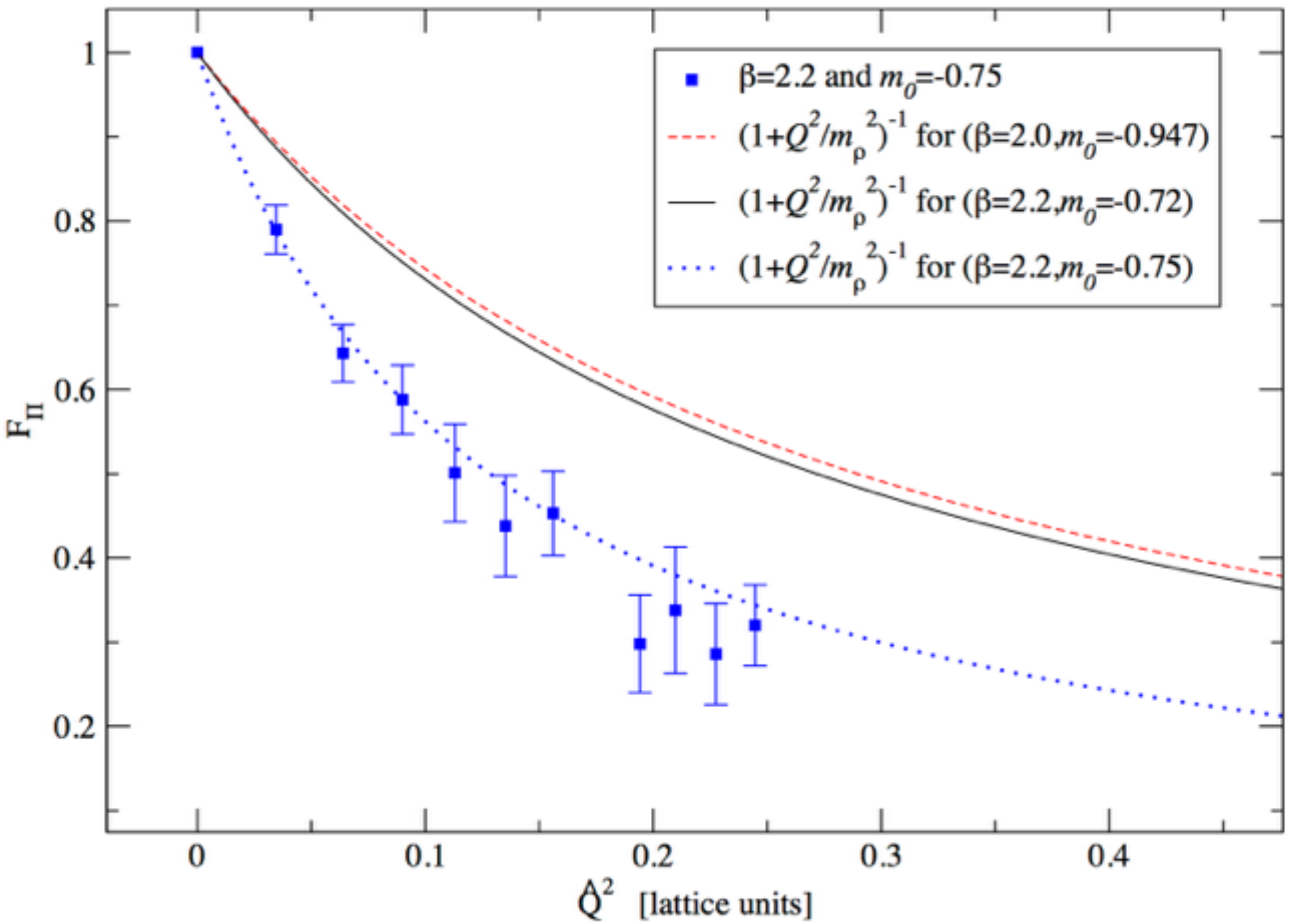
LSD Collaboration, arXiv:1601.04027



- 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.)

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

(2,2,F)

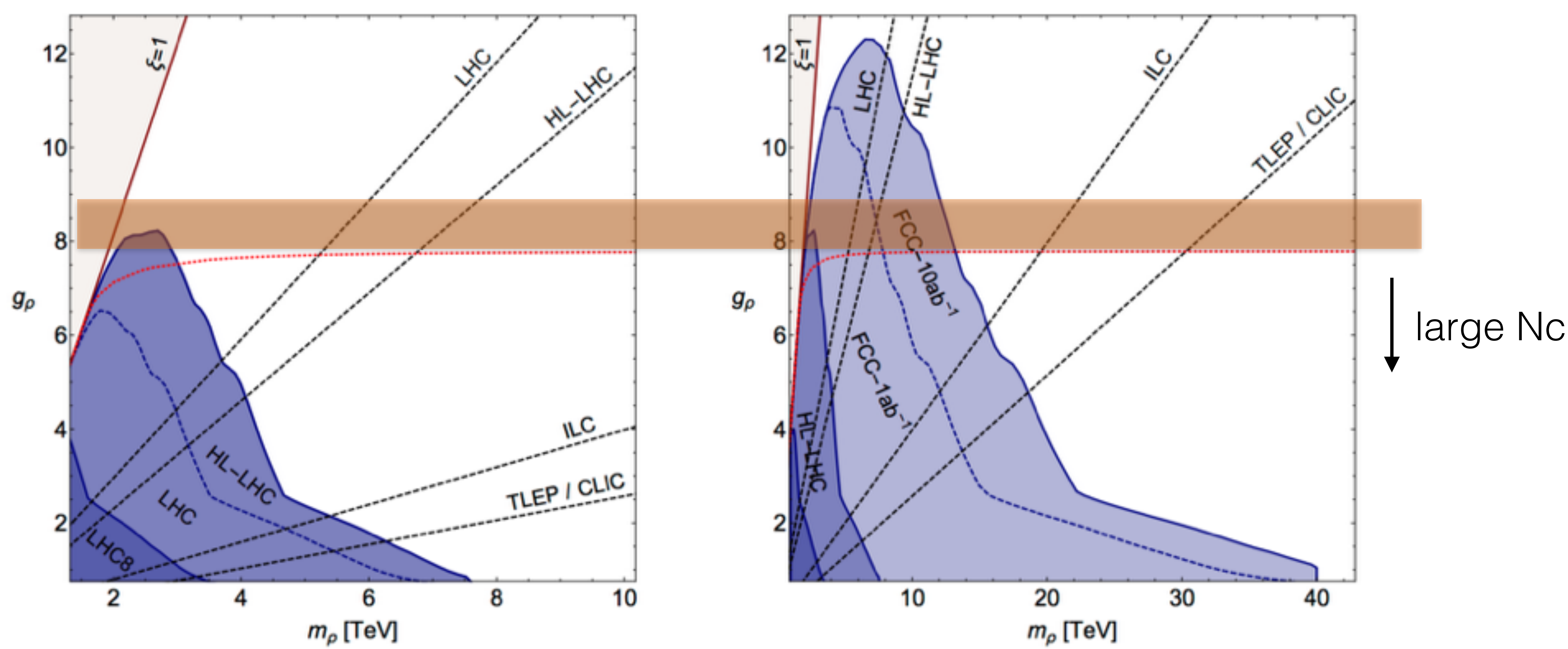


- Another test of VMS: pion vector form factor. Works very well for light “pions” (above).
- More directly, the vector meson should give a resonant contribution to the timelike pion form factor. Harder calculation, but in progress.

Focusing in with lattice results

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

(Thamm, Torre and Wulzer, 1502.01701)



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

ρ in composite dark matter

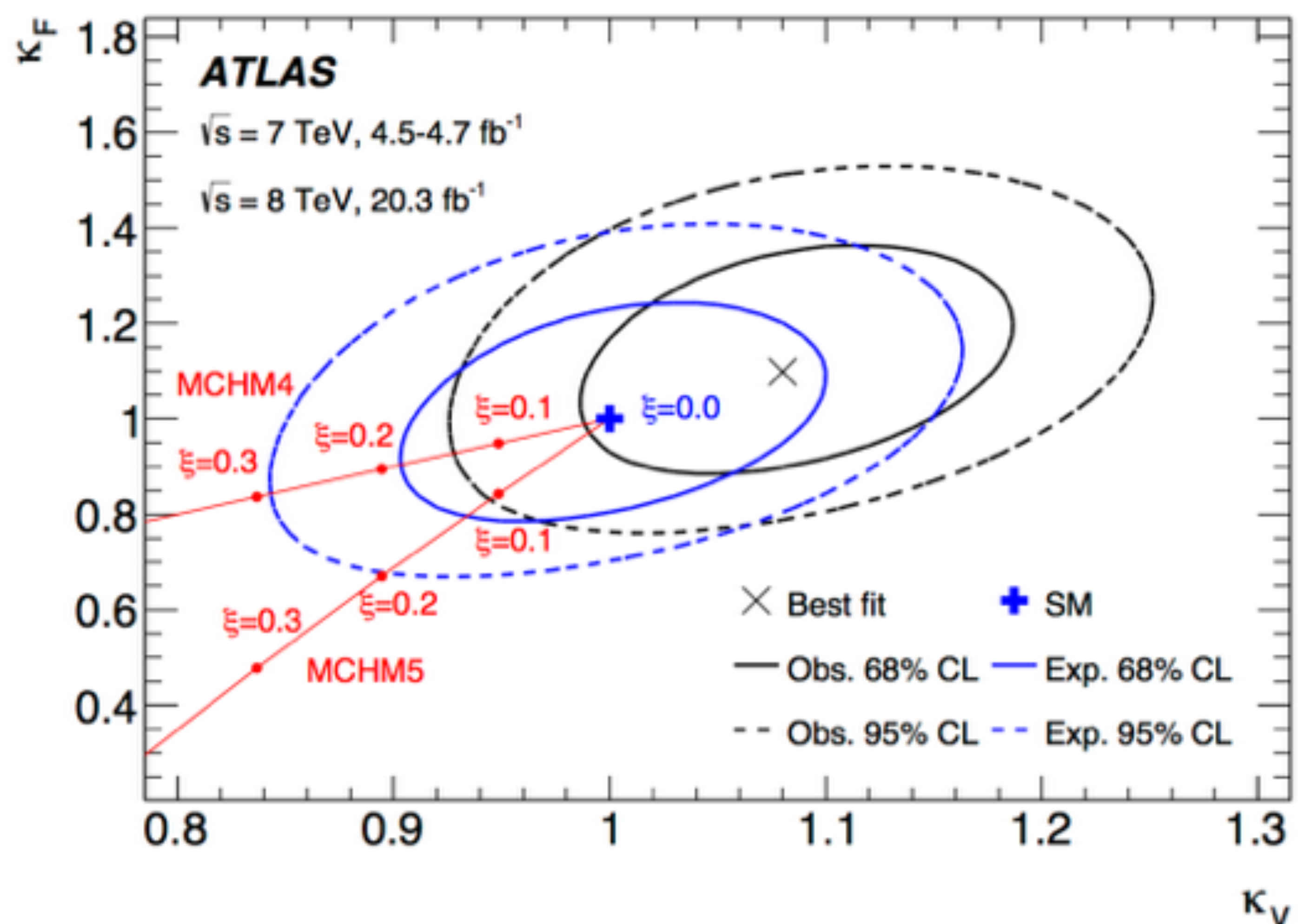
- Note that because cDM doesn't explain EWSB, large width into (W/Z) (W/Z) isn't required; ρ can be narrow.
- If ρ —> ππ is closed kinematically (certainly possible for cDM!) then it can be *very* narrow; dilepton searches apply directly, likely tightest constraint. possibly ρ —> π gamma, work in progress.)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

Composite states: h

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)

Composite Higgs potential

- Vacuum misalignment: electroweak symmetry is not broken directly by the strong force, but by interactions with SM (mainly EW gauge, top.)

- Effective Higgs potential, for example[1]:

$$V_{\text{eff}}(h) = (\alpha - 4\beta)(h/f)^2 + \mathcal{O}(h^4)$$
$$\alpha = (3g^2 + g'^2)C_{LR}$$
$$\beta = (y_t^2/2)C_t$$

- Need $4\beta > \alpha$ for symmetry breaking. Moreover, we know the EW and top Yukawa; given C_{LR} and C_t, there are no free parameters left!

([1]for discussion w/strongly-coupled UV perspective, see Golterman and Shamir, arXiv:1502.00390)

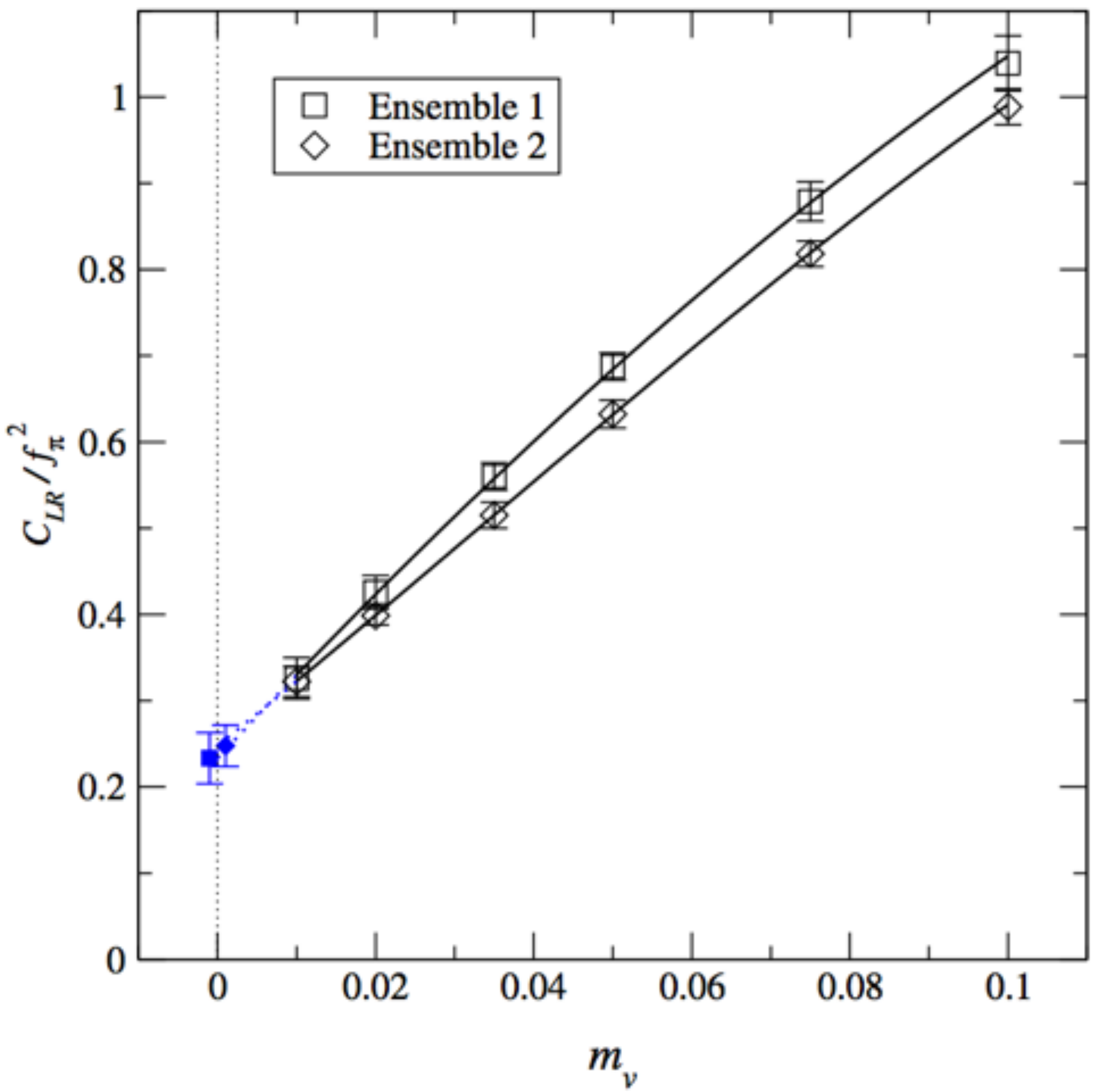
(4,2,AS_2)

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

- Many insights from vacuum polarization - strong correlator of external currents. (Related to e.g. S-parameter.)
- Preliminary “quenched” calculation yields results similar to QCD:

$$C_{LR}/f_\pi^2 \sim 0.2$$

(C_t is much harder, but see 1502.00390 for some thoughts on how to compute on lattice.)



EW contribution to effective Higgs potential:

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

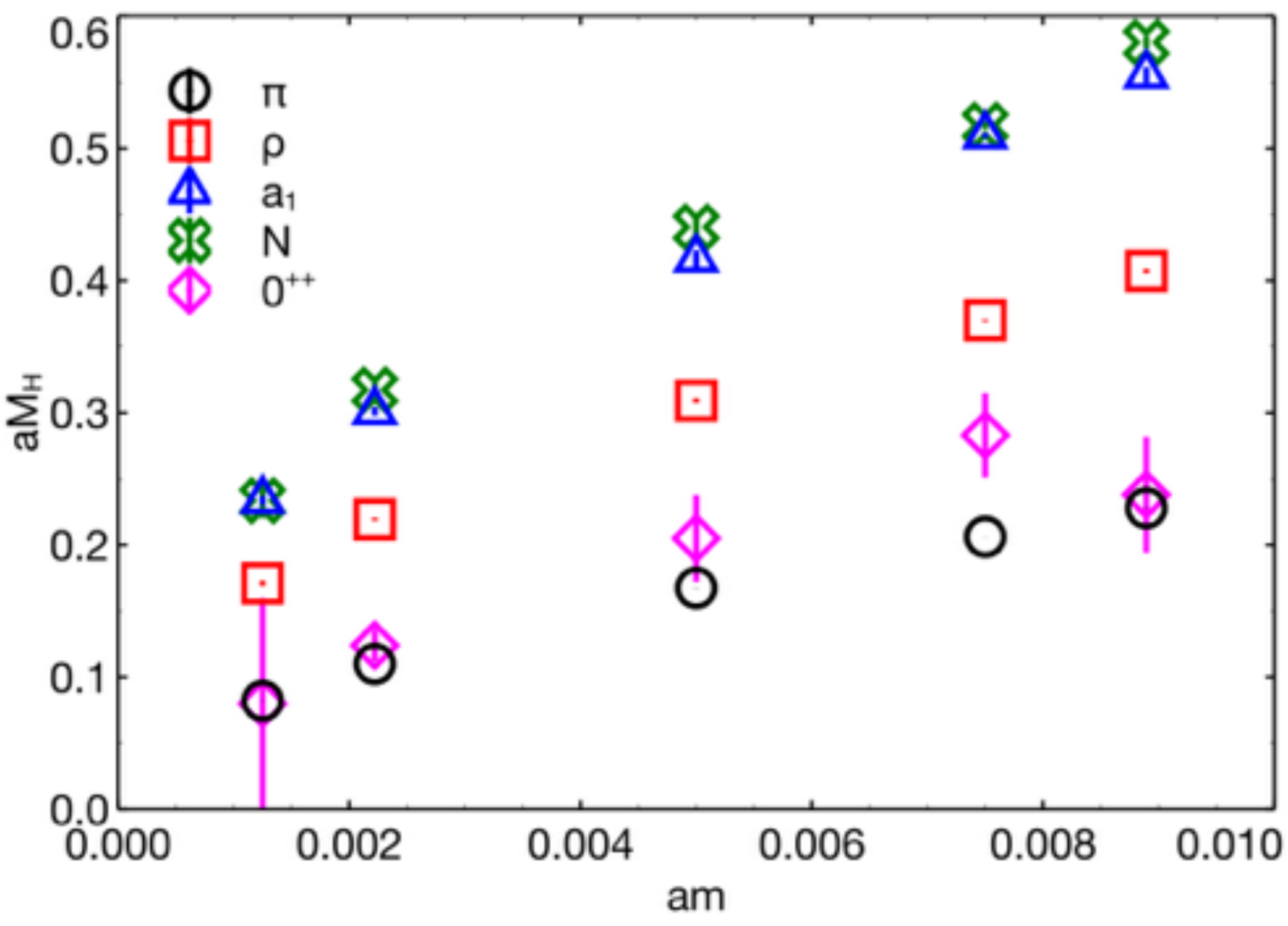
$$C_{LR} = \int_0^\infty dq^2 q^2\, \Pi_{LR}(q^2)$$

coefficient from integrated vac. pol.

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

(3,8,F)

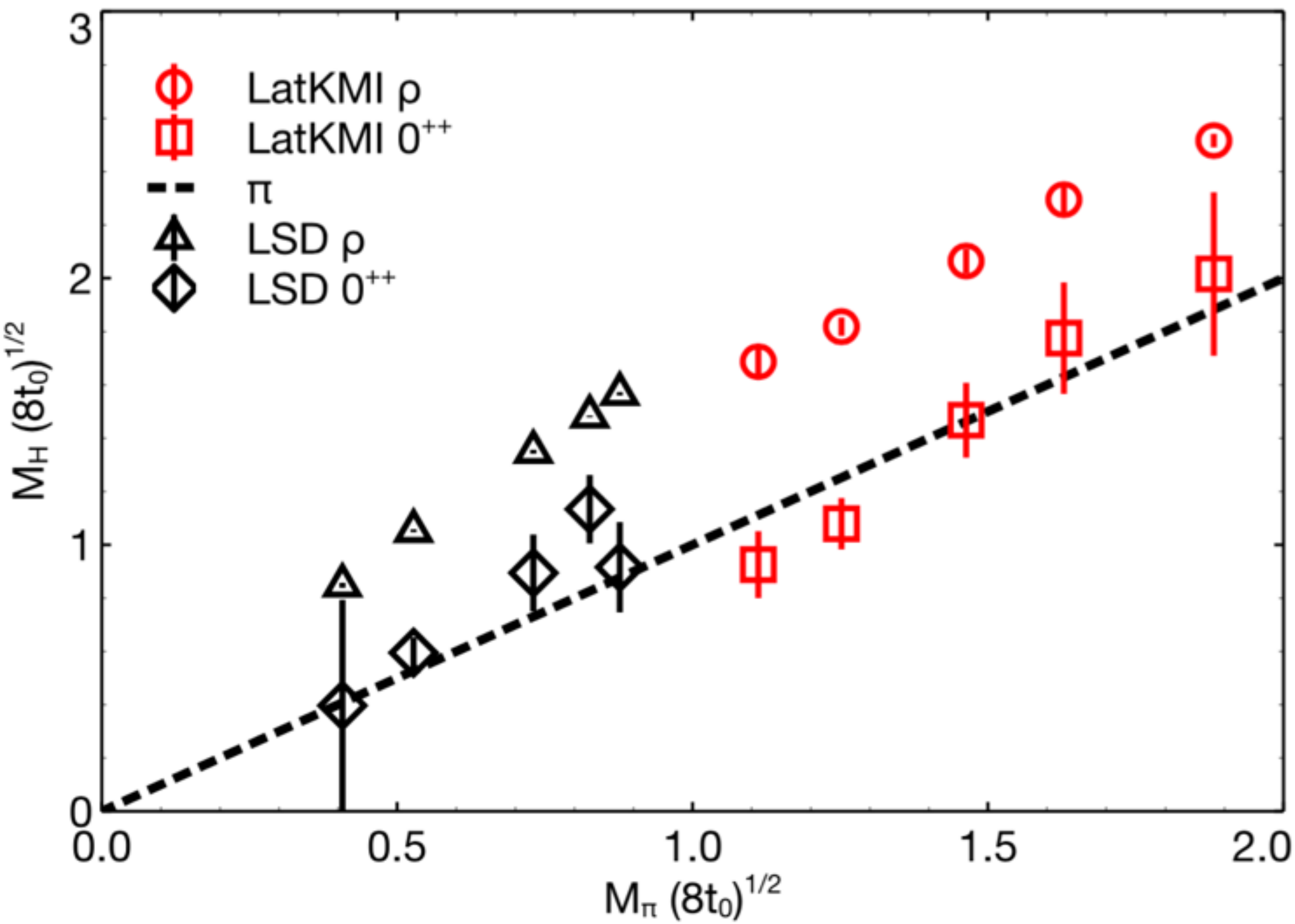
LSD Collaboration, arXiv:1601.04027



- 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? Maybe unmodified chiral perturbation theory isn't always the right description?

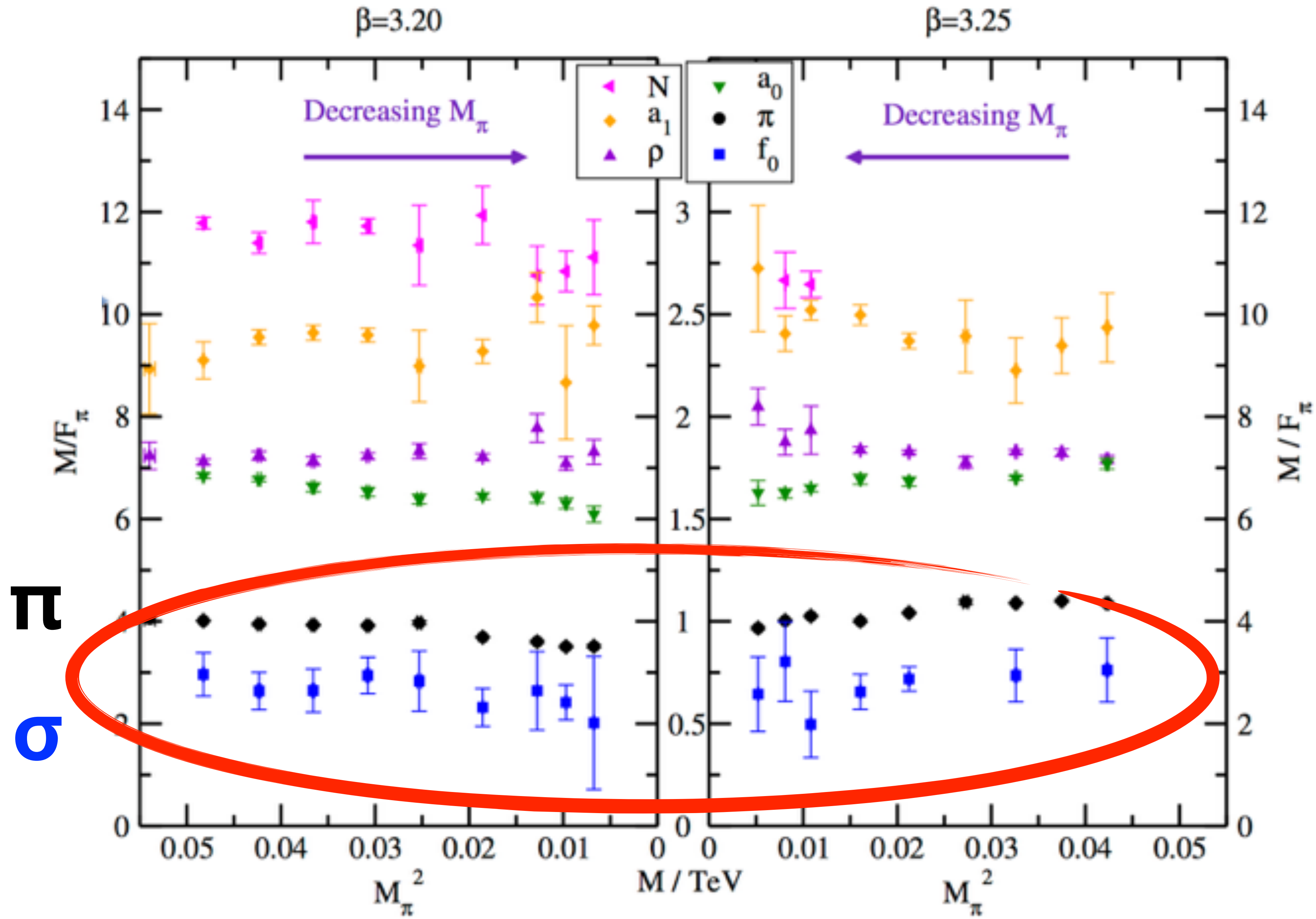
[1] LatKMI Collaboration, arXiv:1403.5000

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



(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 conference
- Ongoing research into this system to learn more, e.g. through calculation of pi-pi scattering. If this sighting holds up, does it have interesting applications in composite Higgs model-building?

Outlook and summary

Composite BSM and colliders

2016 Review of Particle Physics.
Please use this CITATION: C. Patrignani *et al.*(Particl

LIGHT UNFLAVORED MESONS ($S = C = B = 0$)

Particles

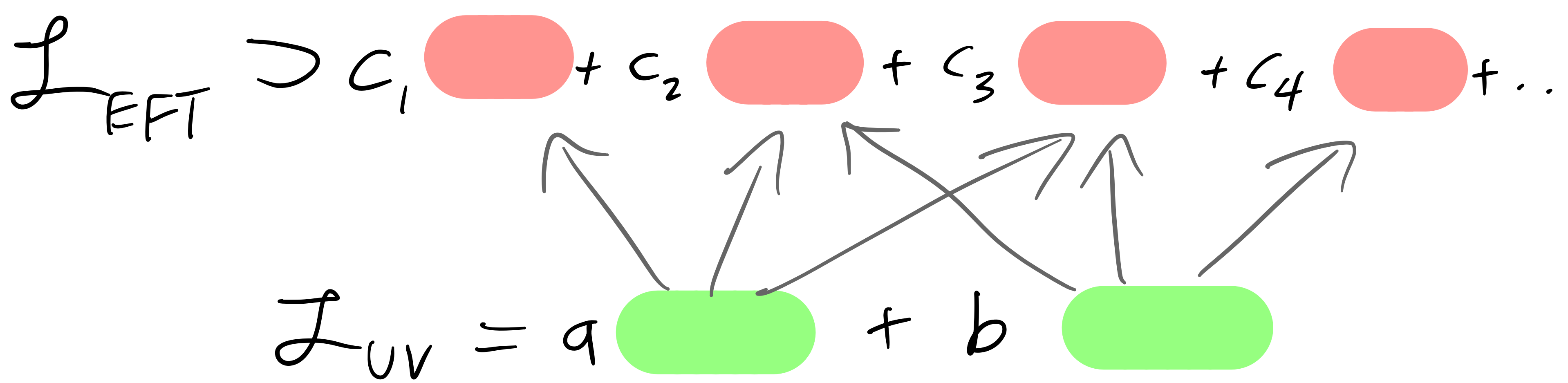
$\pi^{\pm}$
π^{0}
η
$f_0(500)$ or σ was $f_0(600)$
$\rho(770)$
$\omega(782)$
$\eta'(958)$
$f_0(980)$
$a_0(980)$
$\phi(1020)$
$h_1(1170)$
$b_1(1235)$
$a_1(1260)$
$f_2(1270)$
$f_1(1285)$
$\eta(1295)$
$\pi(1300)$
$a_2(1320)$
$f_0(1370)$
$h_1(1380)$
$\pi_1(1400)$
$\eta(1405)$
$f_1(1420)$
$\omega(1420)$
$f_2(1430)$
$a_0(1450)$
$\rho(1450)$
$\eta(1475)$
$f_0(1500)$
$f_1(1510)$
$f_2'(1525)$

- Composite BSM pheno should be very rich, expect to find a huge number of resonances as in QCD
- If the compositeness scale is at the high end of LHC reach (or beyond), enormous physics potential for Higgs factories and higher-energy colliders
- Composite DM can actually have the strongest limits from colliders, as we will see. Partial-wave unitarity requires thermal relic to be < 100 TeV.

An appeal to model-builders

- We need ultraviolet-complete theories which yield your favorite composite Higgs EFT! (Some classification has been done, e.g. Ferretti and Karateev, arXiv:1312.5330)

- 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 BSM is interesting, but strong coupling is hard. Lattice can help (with UV completion.)
- Vector-meson saturation seems to work well beyond QCD, and $g_{\rho\pi\pi}$~6 (in my convention) is fairly insensitive to fermion mass/number
- Hints of a light 0++ scalar - what is the EFT for this + “pions”? Work in progress.
- Composite scenarios in general have very rich pheno, great physics potential at Higgs factory and future energy frontier colliders

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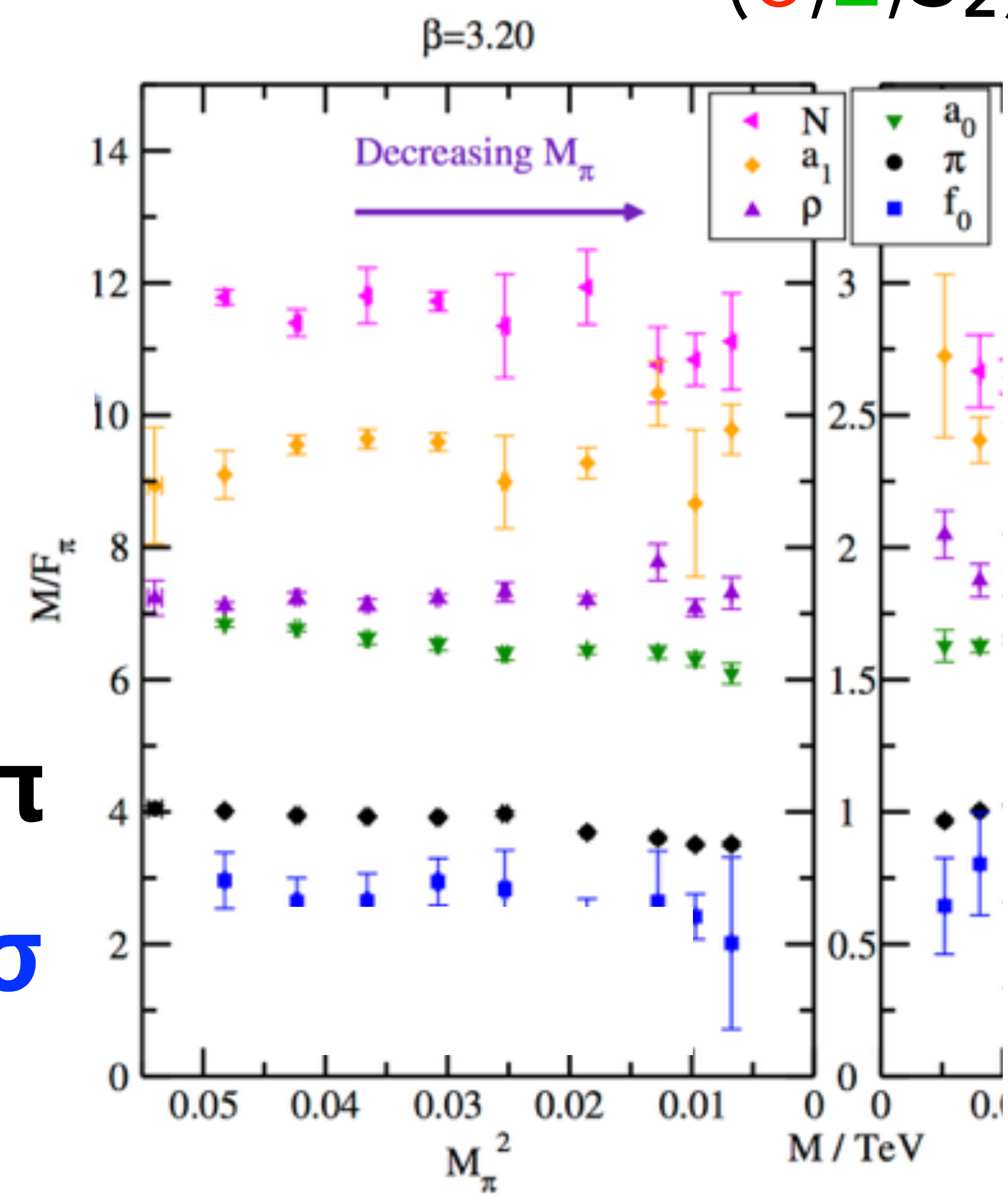

LatHC Collaboration