Composite Higgs models based on a conformal fixed point

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Based on

R. Brower, A. H, C. Rebbi, E. Weinberg, O. Witzel, PRD93, 114514 (2016)

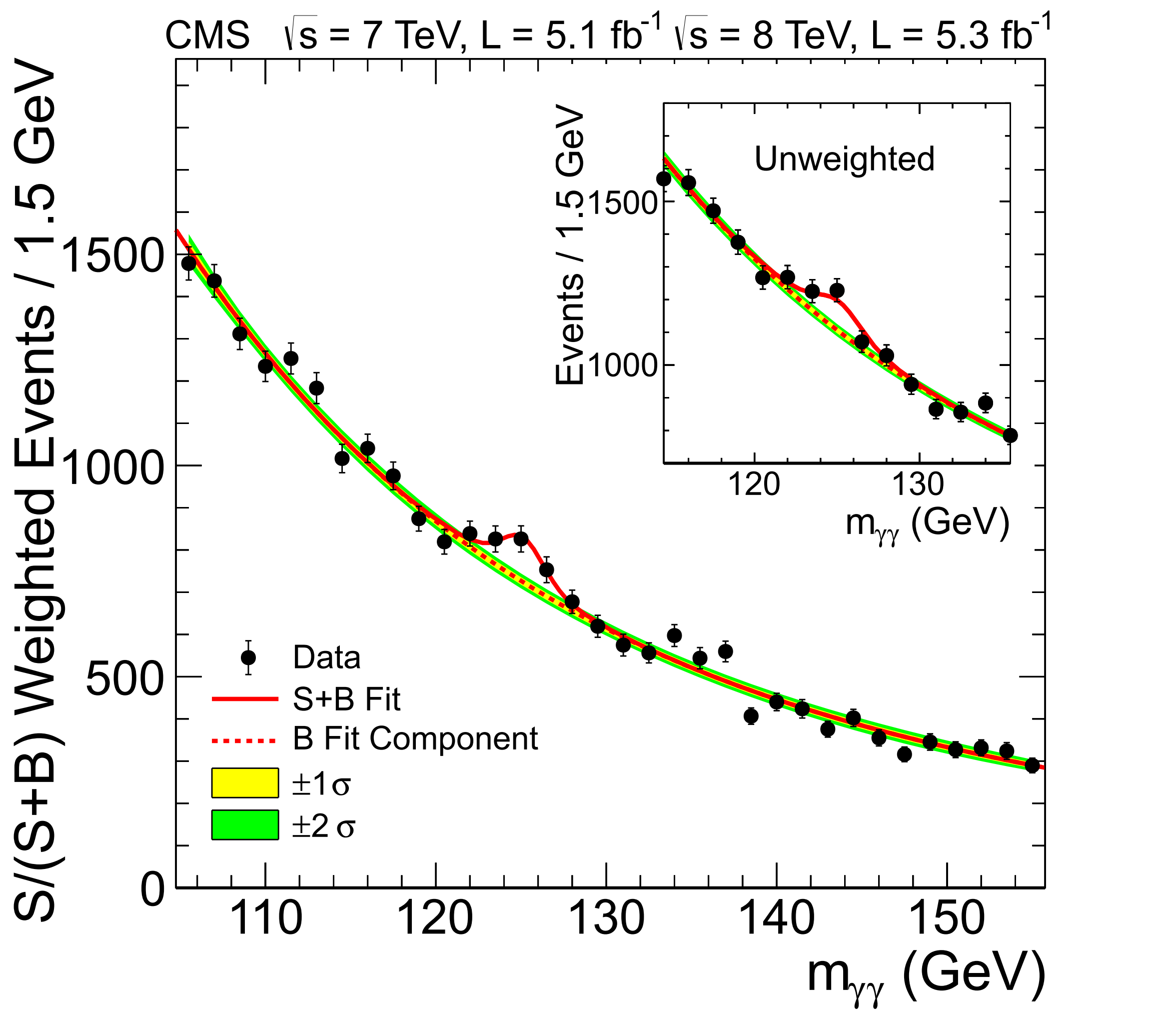
and A. H, C. Rebbi, O. Witzel, (1609.01401)

Higgs era of particle physics

Even with the 125GeV Higgs the Standard Model is not stand-alone:

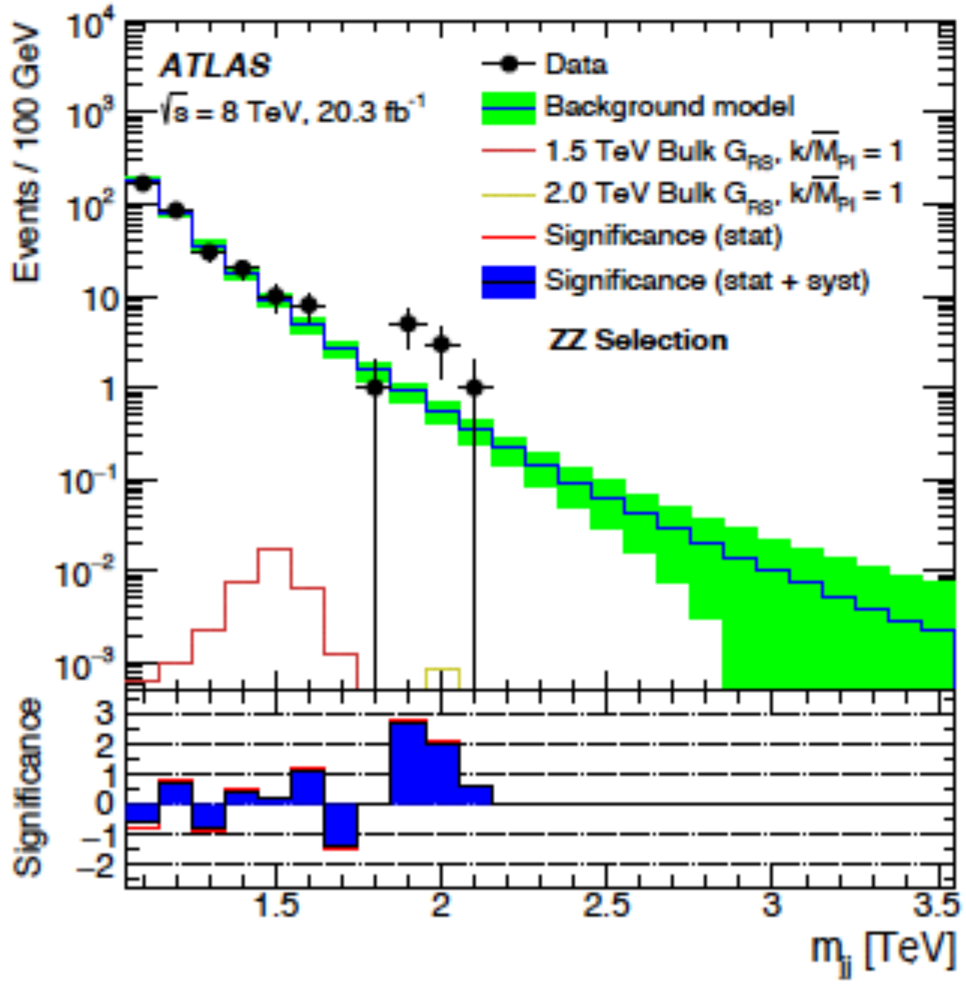
- not UV complete
- naturalness /hierarchy problem
- DM, neutrinos, ……

➡ Implies new physics



New Physics

There were hints in June 2015



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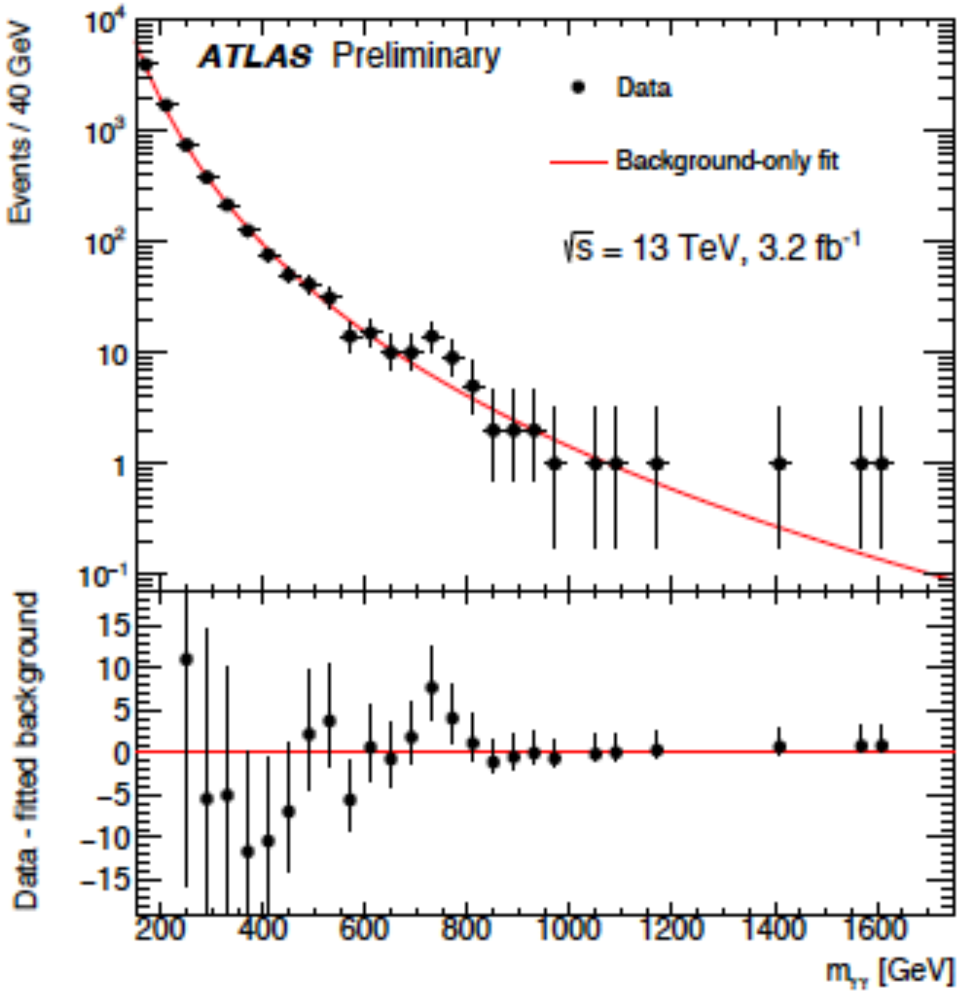

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Hints in September 2016

But
there must be new physics

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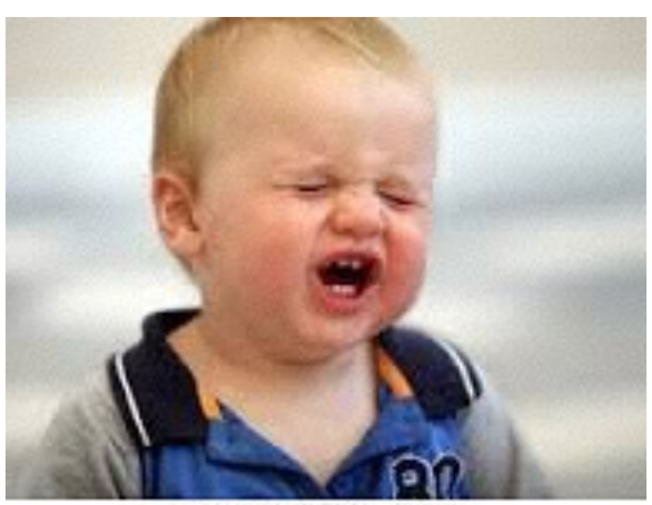

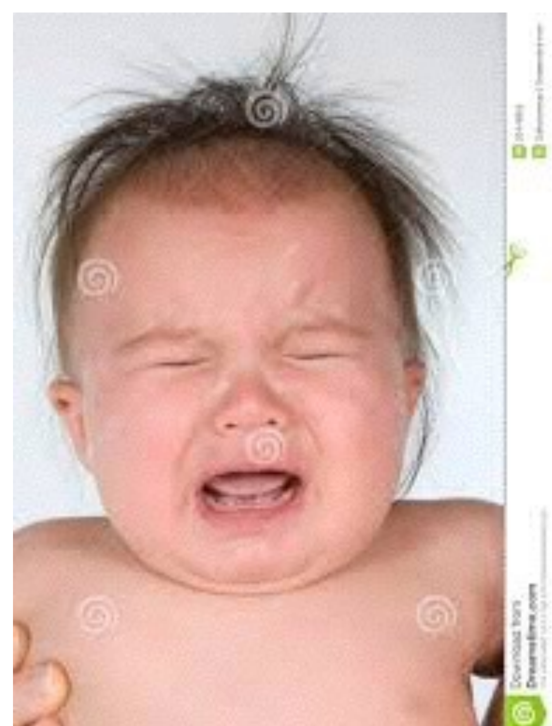

Composite Higgs Models

Most strongly coupled BSM models are effective models, describing part of the dynamics:

Start with Higgsless, massless SM $\longrightarrow$ Full SM

$$\mathcal{L}_{SM\,0} \longrightarrow \mathcal{L}_{SM}$$

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Full SM + additional states from $\mathcal{L}_{SD}$

The construction has to

- predict the 125GeV Higgs
- give mass to the SM gauge fields
- give mass to the SM fermions :
  4-fermion interaction or partial compositness
- give mass to $\mathcal{L}_{SD}$ fermions and generate 4-fermion interactions: $\mathcal{L}_{UV}$ sector

$$\mathcal{L}_{SD} = \mathcal{L}_{SD1} + \mathcal{L}_{SD2} + \ldots$$

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$$\mathcal{L}_{UV} \rightarrow \mathcal{L}_{SD} + \mathcal{L}_{SM\,0} + \mathcal{L}_{int} \rightarrow \mathcal{L}_{SM} + \ldots$$

This could come from a UV complete theory

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Light Higgs

$\mathcal{L}_{SD}$: N_f fermions, $SU(N_c)$ gauge, chirally broken, coupled to the SM

- EW symmetry breaking by massless pions ✓
- Higgs sector

What keeps the Higgs light ?

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Pseudo Nambu-Goldstone Higgs:

Higgs is a pNGB; its mass emerges from interactions

non-trivial vacuum alignment

F_π = (SM vev) / sin(χ) > 246GeV

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The system is below but close to the conformal window: broken conformal symmetry

$\rightarrow$ possibly light 0++ scalar

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  What keeps the Higgs light ?
- Fermion/Yukawa sector

  How to generate SM fermion masses ?

Different mechanism

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What is $\mathcal{L}_{SD}$?

Some of the promising candidates for $\mathcal{L}_{SD}$ are chirally broken in the IR but conformal in the UV: (Luti&Okui(hep-lat/00409274), Dietrich&Sannino(hep-ph/0611341) , Vecchi(1506.00623), Ferretti(1312.5330),…..

conformal chirally broken

UV $\longrightarrow$ IR

Λ_{UV} Fermion masses Λ_{IR} Higgs dynamics

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UV → IR

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Many possibilities:

- SU(3) gauge with 4 flavors
- SU(4) with 2 reps. flavors
- SU(3) gauge with 8 flavors
- SU(3) gauge with 2 sextet
- SU(2) gauge with 2 flavors
- etc

Ma, Cacciapaglia,JHEP1603,211
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conformal | chirally broken

UV $\longrightarrow$ IR

Λ_{UV} Fermion masses Λ_{IR} Higgs dynamics

Add enough fermions to drive the system into the conformal window;
If the fermions are massive*, they will decouple at Λ_{IR}

Many possibilities:
- SU(3) gauge with 4 flavors
- SU(4) with 2 reps. flavors
- SU(3) gauge with 8 flavors
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* What gives mass to the additional fermions?
That is dynamics beyond Λ_{UV} .

Lattice realization: 4+8 mass-split model

"Prototype": SU(3) gauge with 4ℓ+8h fundamental flavors

(N_h=8 "heavy" and N_ℓ=4 light or massless)

conformal | chirally broken

UV Λ_{UV} Fermion masses Λ_{IR} Higgs dynamics → IR

Add 8 "heavy" fundamental flavors: N_f = 4+8 = 12 :
→ conformal dynamics

SU(3) gauge with 4 light fundamental flavors:
prototype pNGB or dilaton-Higgs

The construction

- ensures chiral symmetry breaking in the IR
- "walking" is arbitrarily tunable by m_h
- anomalous dimensions are that of the conformal IRFP

This system is a prototype - many similar models are possible

Why 4 light flavors?

Proposed pNGB scenario : (Ma, Cacciapaglia, JHEP 1603 (2016) 211)

4 massless/ light flavors → 15 Goldstone bosons

Quantum numbers are determined by their SM couplings

Transformation under $SU(2)_L \times SU(2)_R$ custodial symmetry

$$15_{SU(4)} = (2,2)+(2,2)+(3,1)+(1,3)+(1,1)$$

Honestly: that was the simplest lattice model to investigate.

Good enough for a prototype / pilot study

Why 12 total flavors?

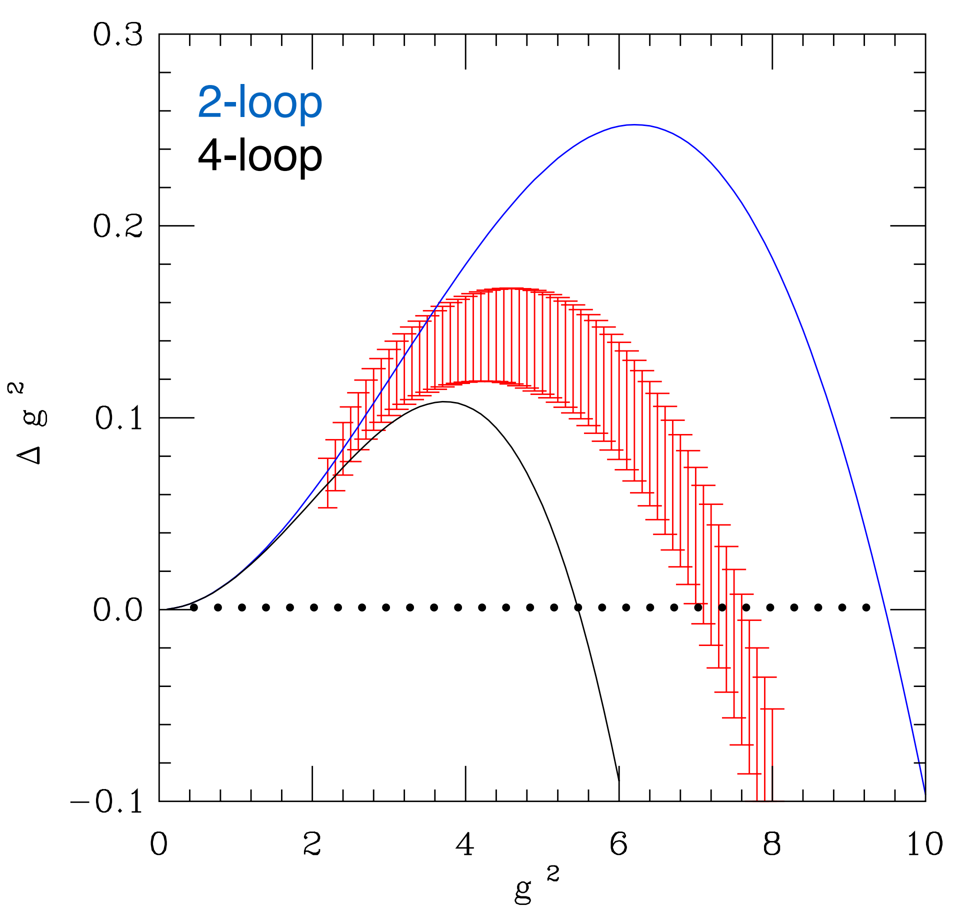
There is strong evidence that N_f=12 is **conformal** (mass degenerate chiral lim.)

UV physics of 4+8 is governed by IRFP

→ g^2 is irrelevant , m_h controls dynamics

→ walking

→ anomalous dimension determined by IRFP



Step scaling function vs g^2

(c=0.3, τ_0=0.1, volumes 16^4 to 36^4)

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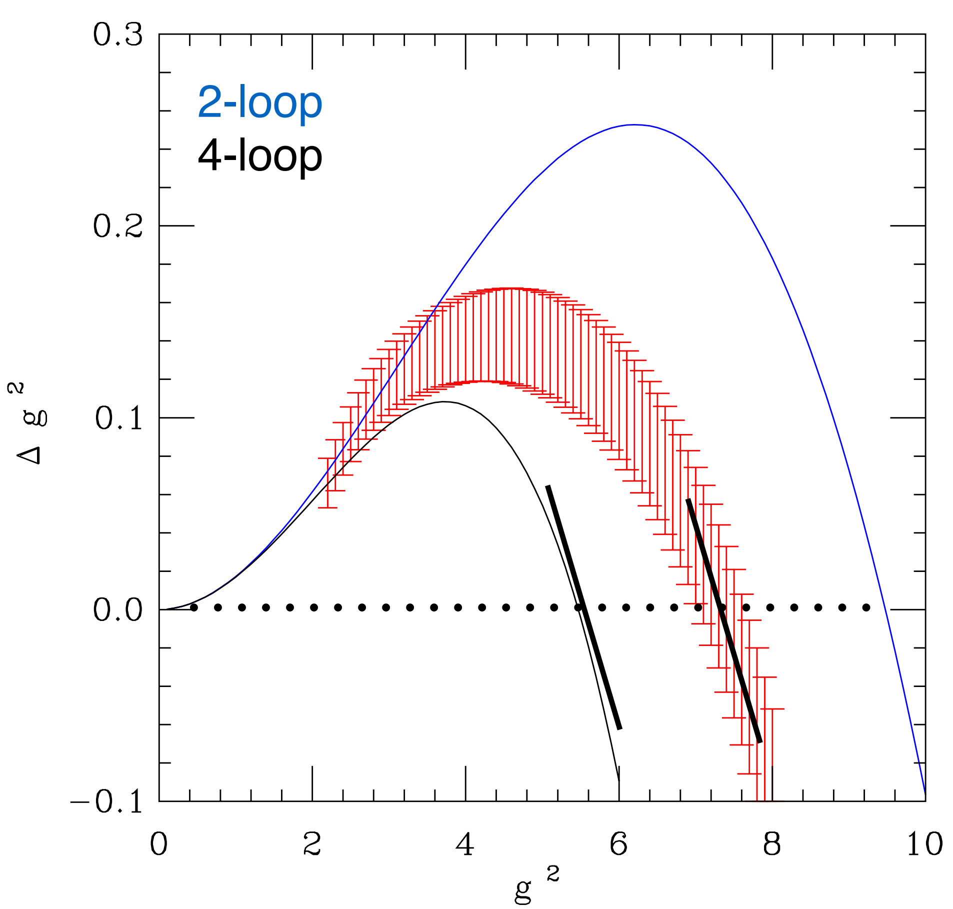

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Even the slope is close to 4-loop PT

Lattice study of 4+8 mass-split model

Questions for lattice study:

- How predictive is this model?
- What is the spectrum: light-light, and heavy-heavy, heavy-light?
- What is the effect of the 8 heavy flavors on the light spectrum?
- Is the heavy spectrum present in the IR dynamics?
- How does the coupling run/walk ?
- What is the anomalous dimension at the IRFP: $\psi\psi\psi$ and $\bar{\psi}\psi$.

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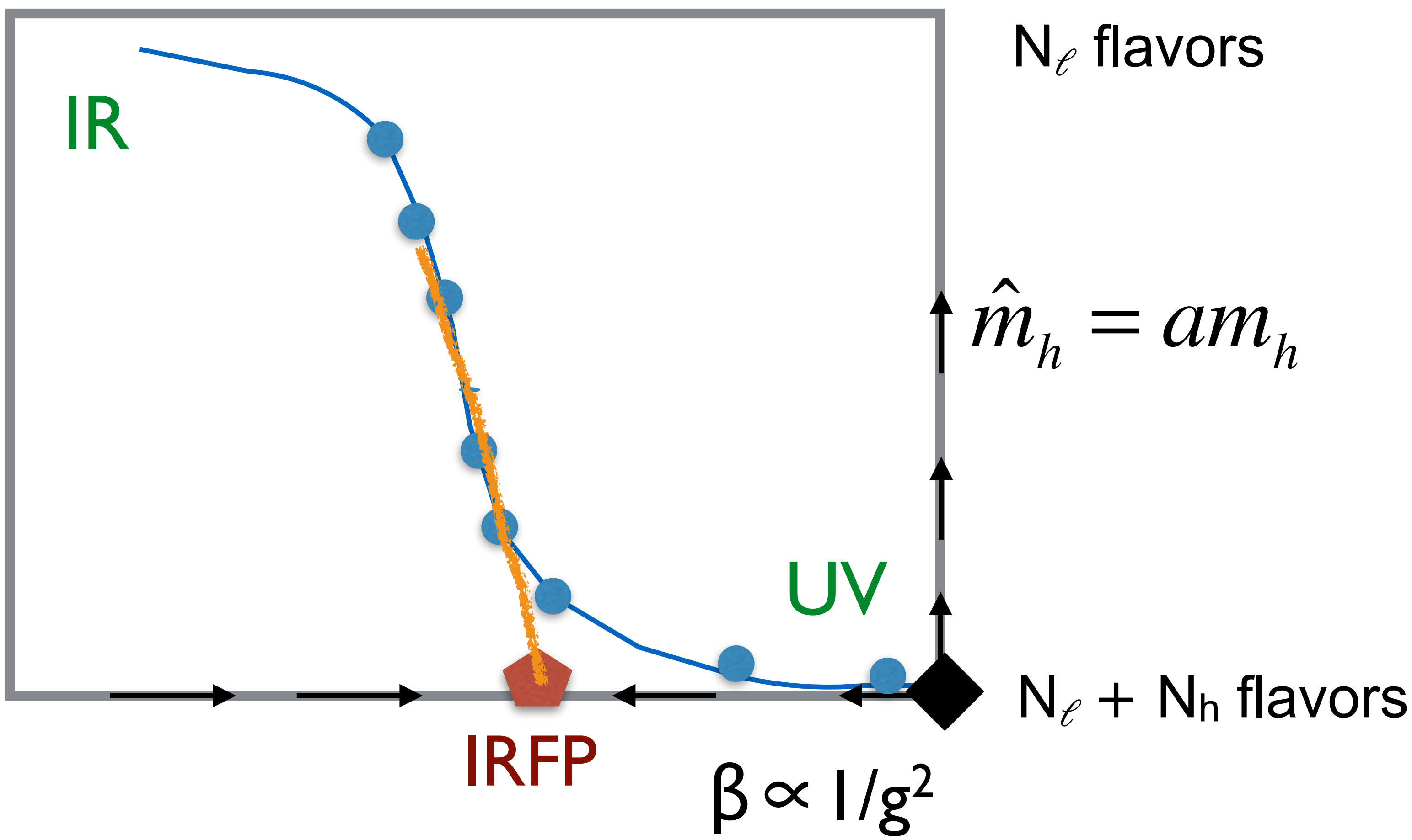
Phase diagram of a mass-split model

Recap:

- Take N_f above the conformal window
- Split the masses: $N_f = N_\ell + N_h$

  N_h flavors are massive, m_h varies → decouple in the IR

  N_ℓ (= 2 - 4) flavors are massless, $m_\ell = 0$ → chirally broken



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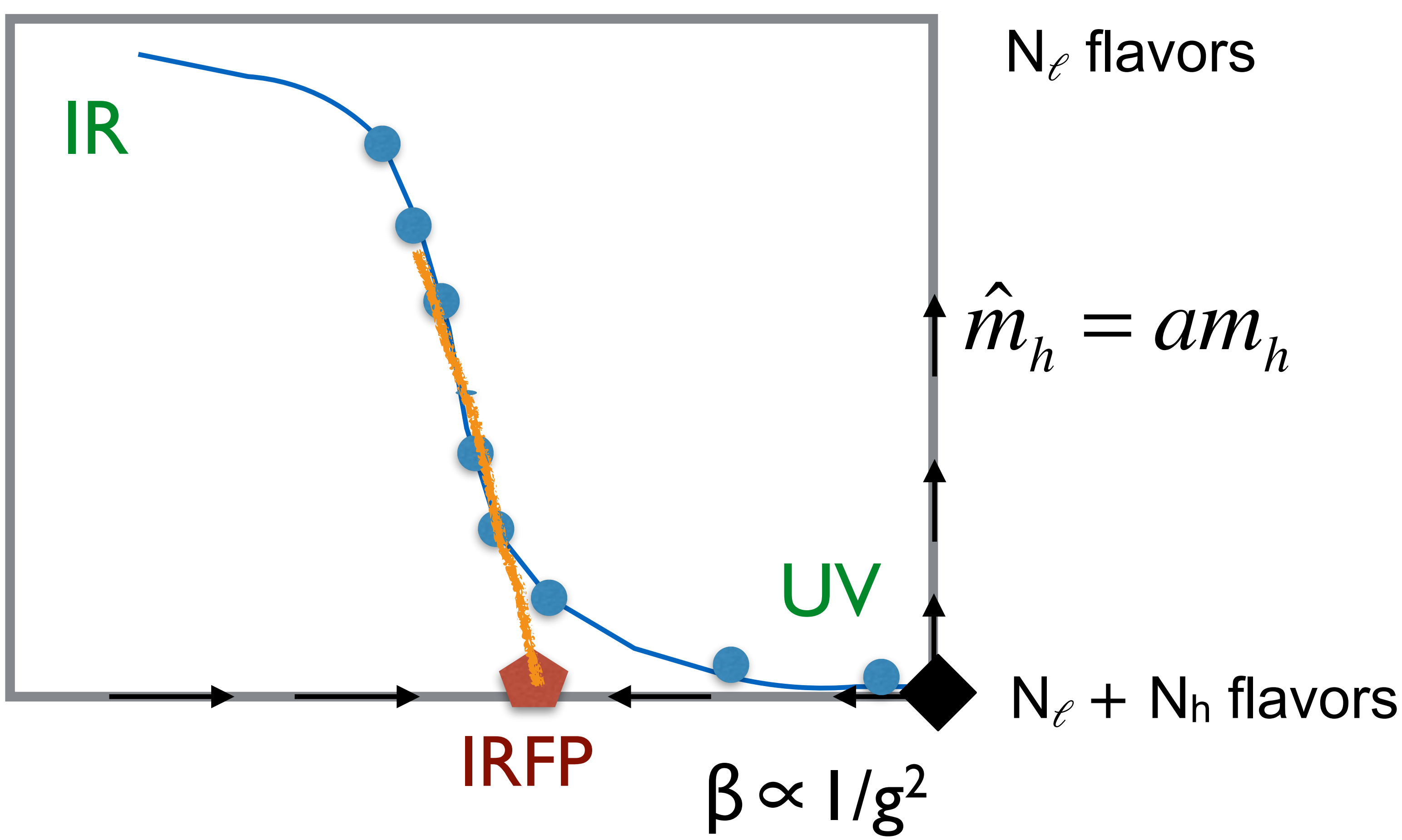

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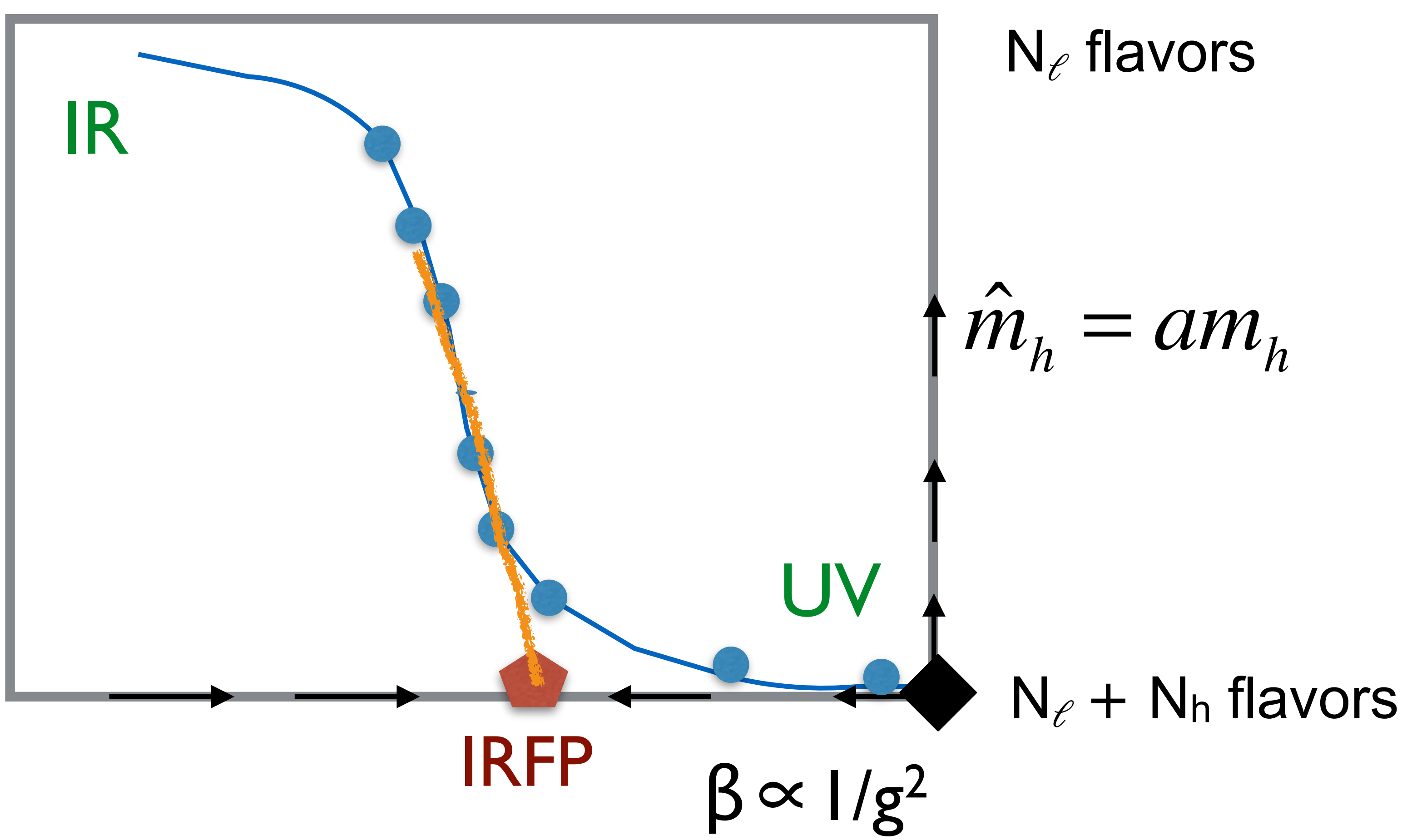

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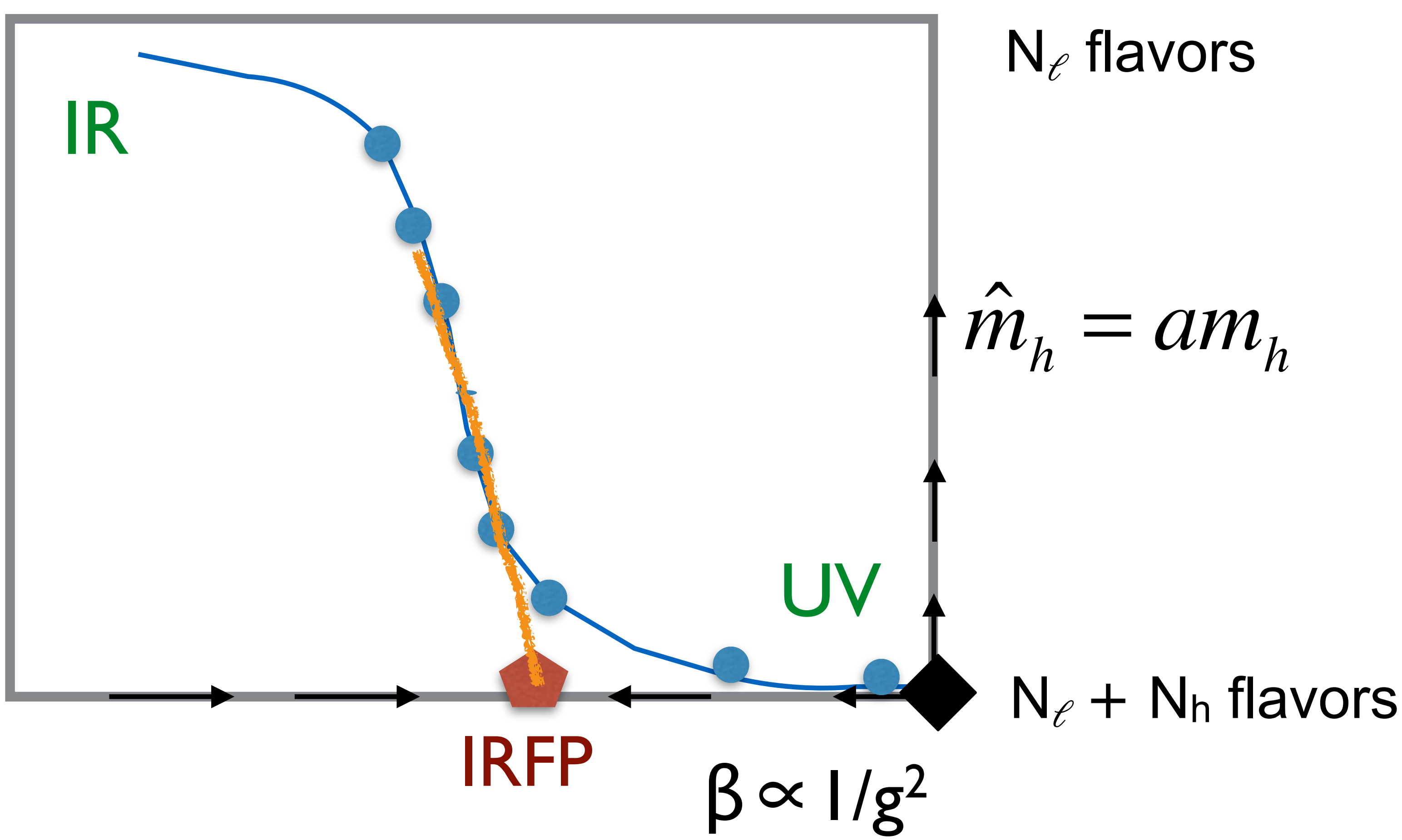

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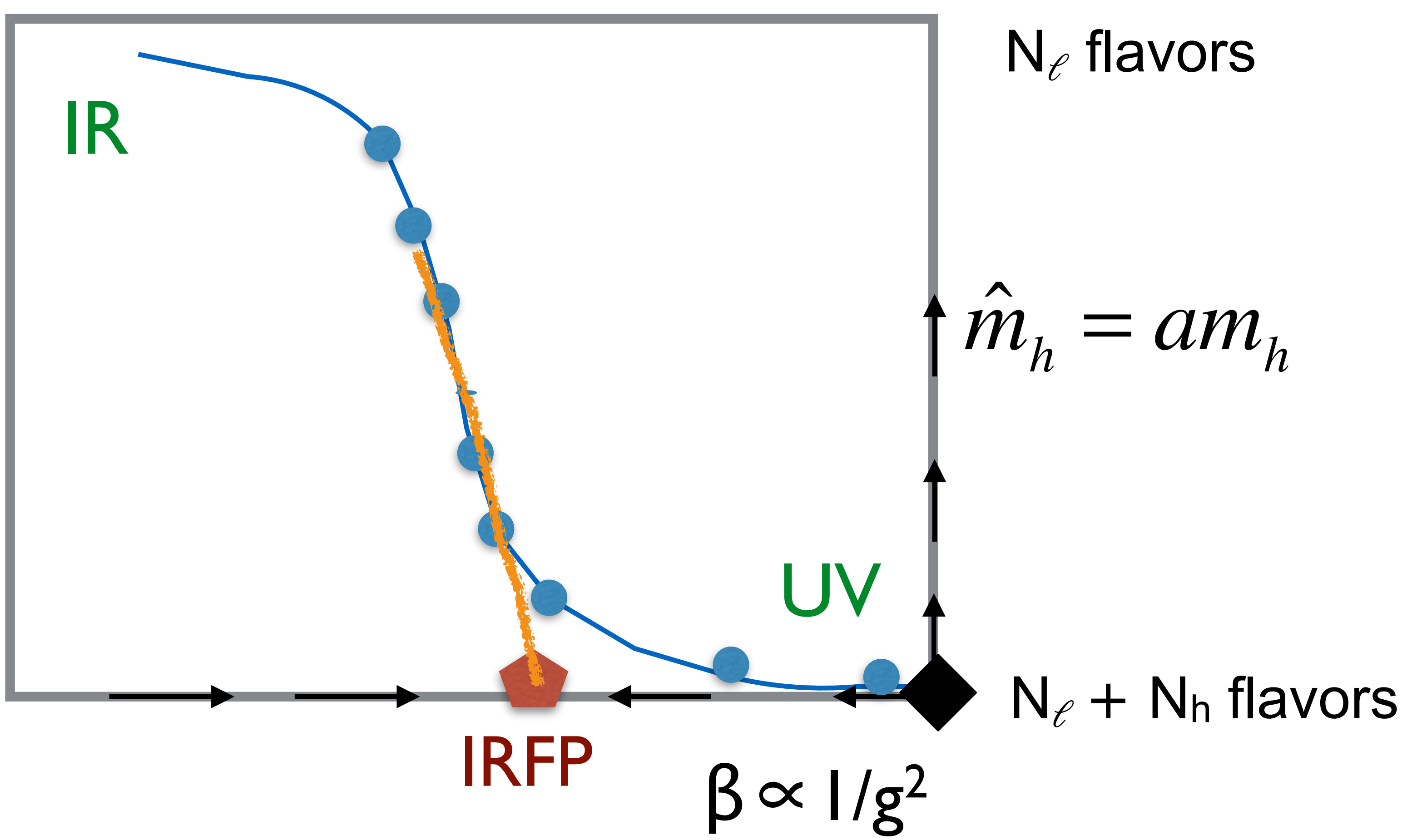

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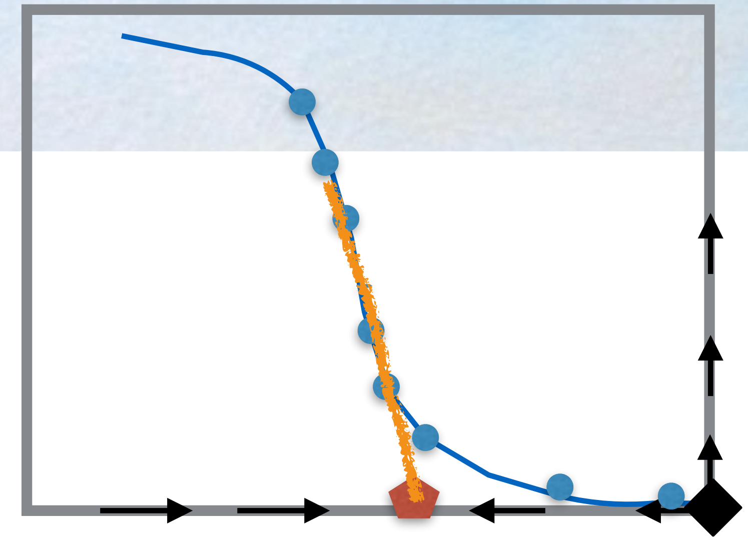
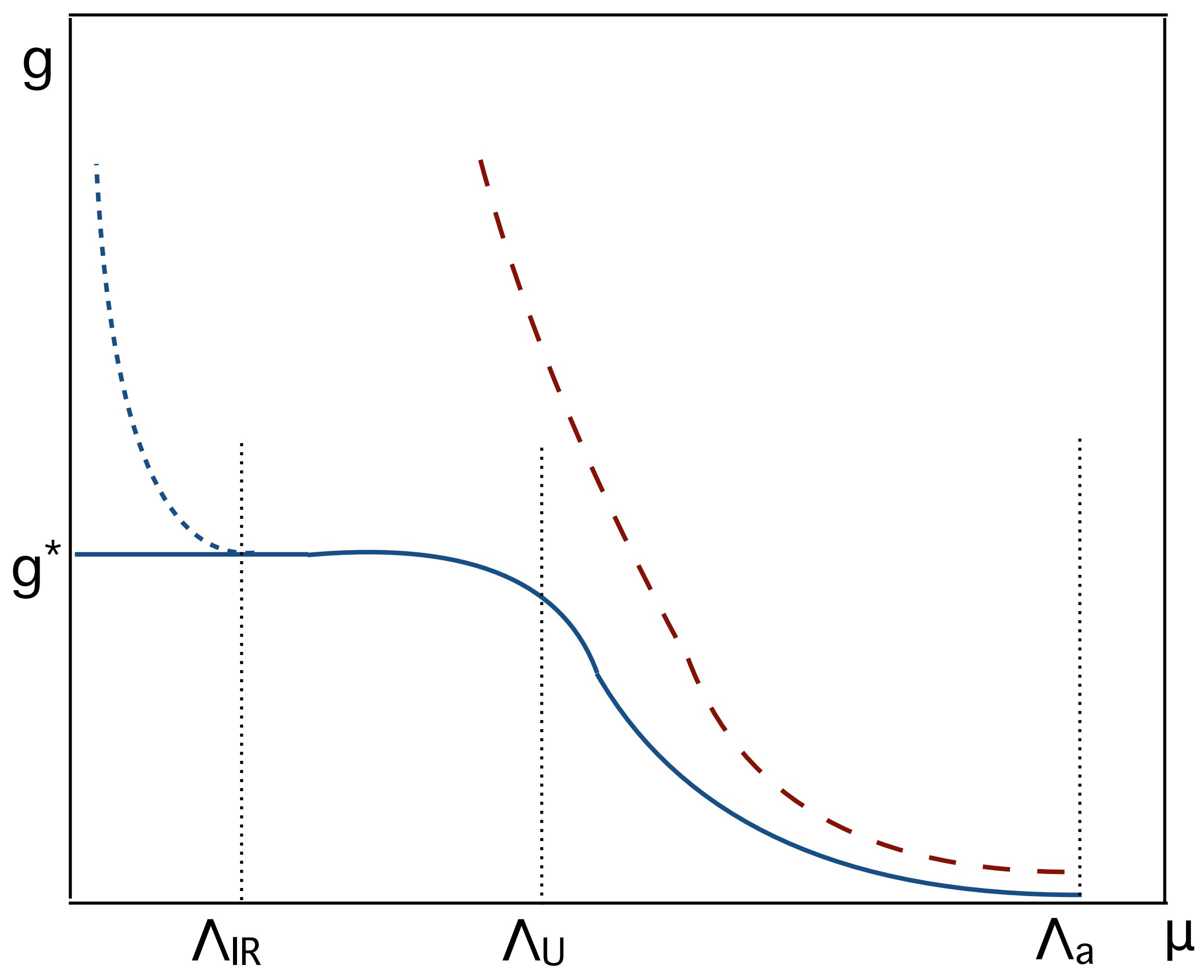
$\downarrow$

sets the scale

Running coupling



RG flows predict the running coupling:



3 regions:

- UV :
  from cut-off to g ~ g*
- walking: m_h small, g~g*
- IR :
  heavy flavors decouple,
  N_ℓ light flavors are
  chirally broken

walking can be tuned by

$m_h \to 0$

Running coupling on the lattice

Gradient flow transformation defines a renormalized coupling

Luescher arXiv:1006.4518

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

t: flow time;

E(t):energy density

g^2_{GF} is used for scale setting as

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- on large enough volumes
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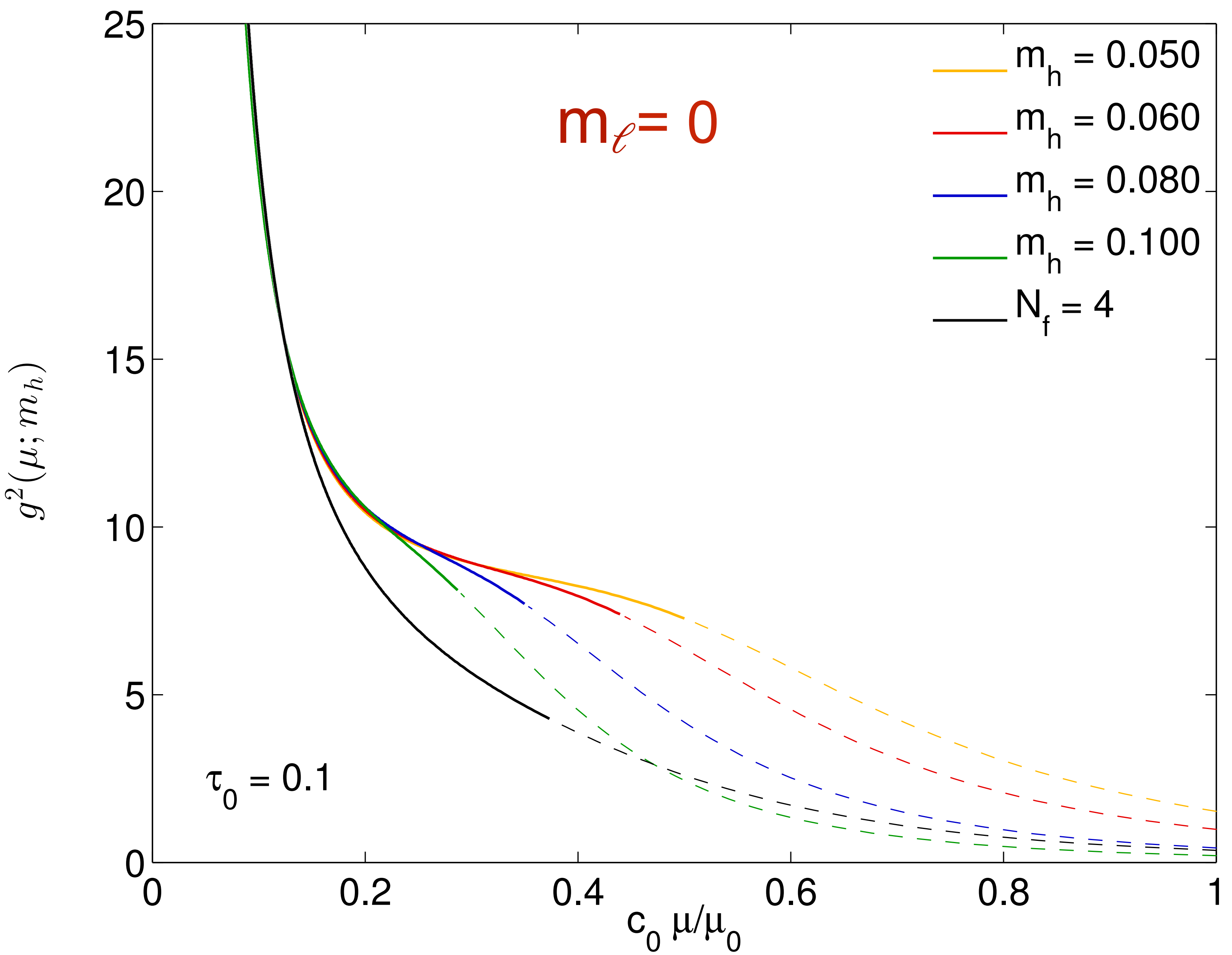
use t-shift improved coupling

Running coupling : 4+8 flavors



There are error bars on this plot!

N_f=4 : running fast

$g^2_{GF}(\mu)$ develops a "shoulder" as $m_h \to 0$: this is walking !

Walking range can be tuned arbitrarily with m_h

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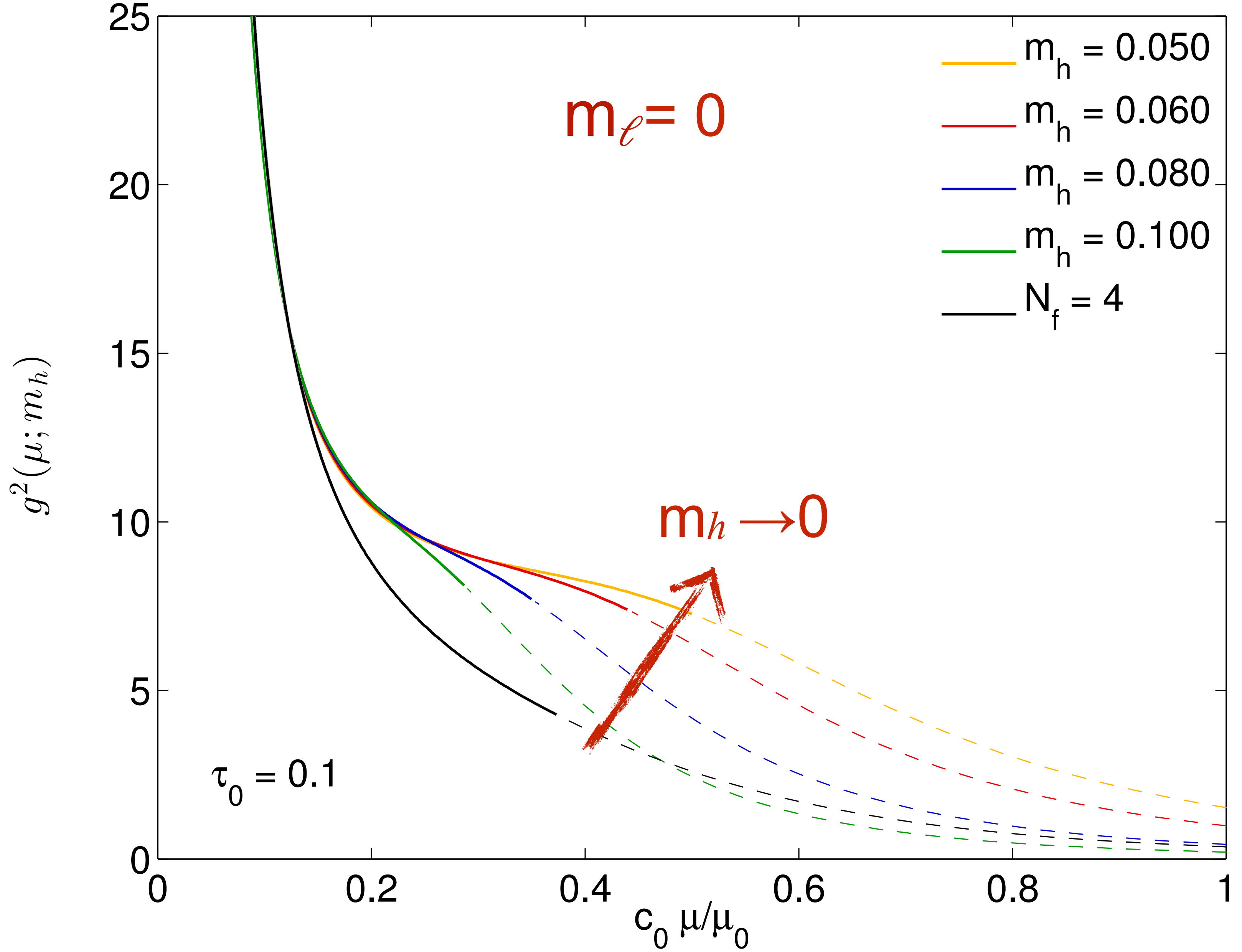

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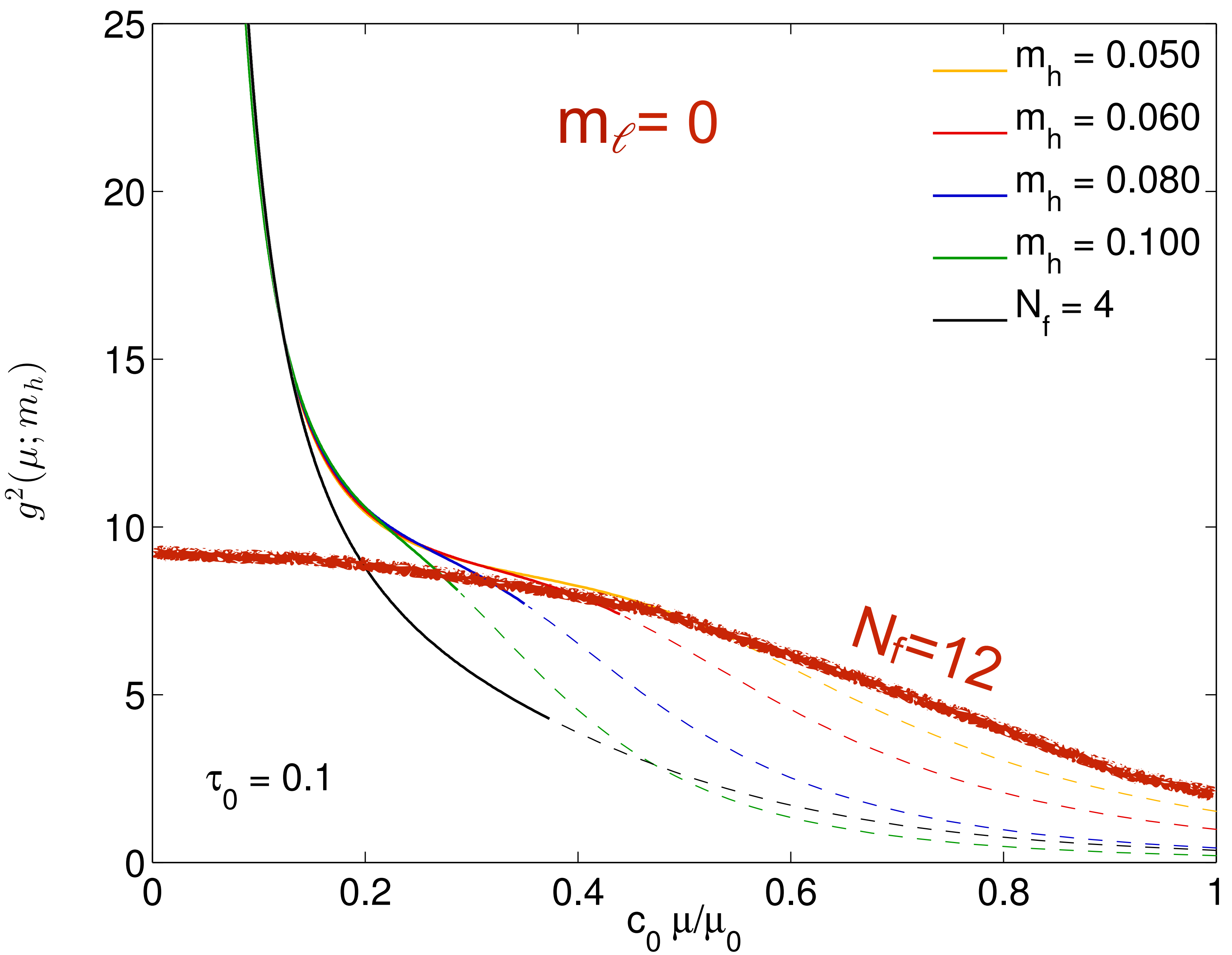

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Hyperscaling in mass-split models

In conformal systems Wilson RG considerations predict the mass dependence of all dimensional quantities (hyperscaling)

If the scale changes as $\mu \to \mu' = \mu / b, \ b > 1$

the couplings run as

$$\hat{m}(\mu) \to \hat{m}(\mu') = b^{y_m} \hat{m}(\mu) \quad \text{(increases)}$$

$$g \to g^\star$$

Any 2-point correlation function at large b scales as

$$C_H(t; g_i, \hat{m}_i, \mu) \to b^{-2y_H} C_H(t/b; g^\star, b^{y_m}\hat{m}_h, b^{y_m}\hat{m}_\ell, \mu)$$

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Hyperscaling in mass-split models

Masses scale as

$$aM_H \propto (\hat{m}_h)^{1/y_m} F_H(m_\ell / m_h)$$

Ratios are universal functions of m_ℓ/m_h

$$M_{H_1} / M_{H_2} = \Phi_H(m_\ell / m_h),$$
$$M_{H_1} / F_\pi = \tilde{\Phi}_H(m_\ell / m_h)$$

In the $m_\ell=0$ chiral limit dimensionless ratios are independent of m_h

If F_π is known, the rest of the spectrum is predicted - no more free parameters

- True for light-light, heavy-light and heavy-heavy spectrum
- This is very different from QCD!

Corrections to scaling

The gauge coupling in N_f=12 runs slow -

$g \to g^{\star}$ is not a (very) good approximation, corrections are needed

Cheng, A.H.,Y. Liu,Petropoulos,
Schaich,PRD90 (2014) 014509

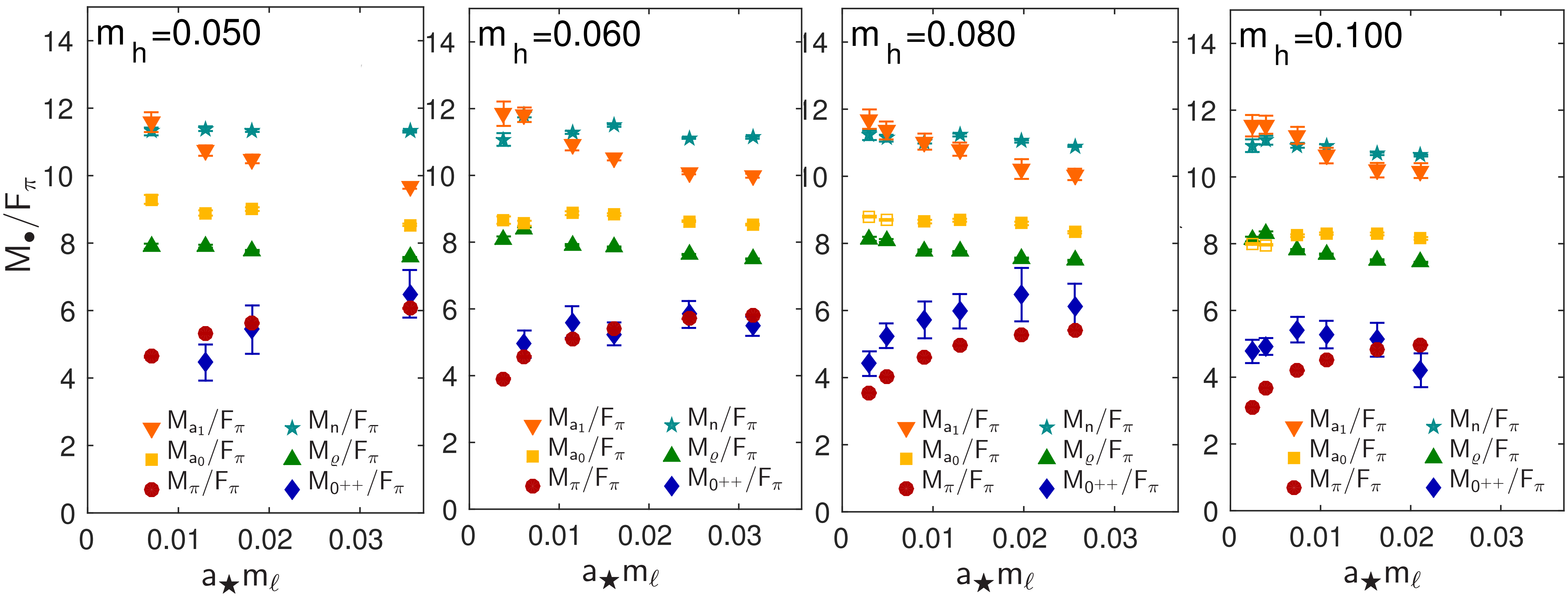
Ratios scale as

$$M_{H_1} / F_\pi = \tilde{\Phi}_H (m_\ell / m_h)(1 + c_0 m_h^{\omega})$$

c_0 depends on g^2 and the observable, ω is universal : both can be determined from N_f=12 studies

Light spectrum

Ratios M_H / F_π are independent of m_h



pion, rho, a0, a1, nucleon and 0^{++} scalar

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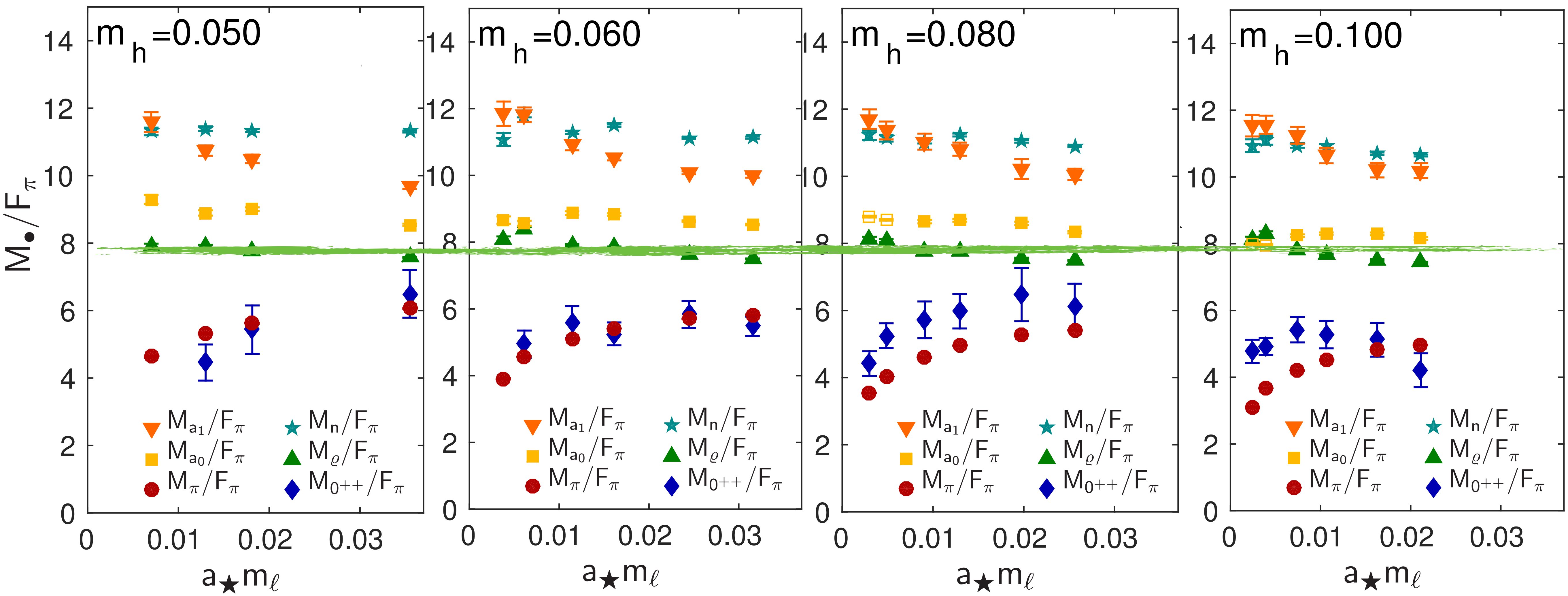

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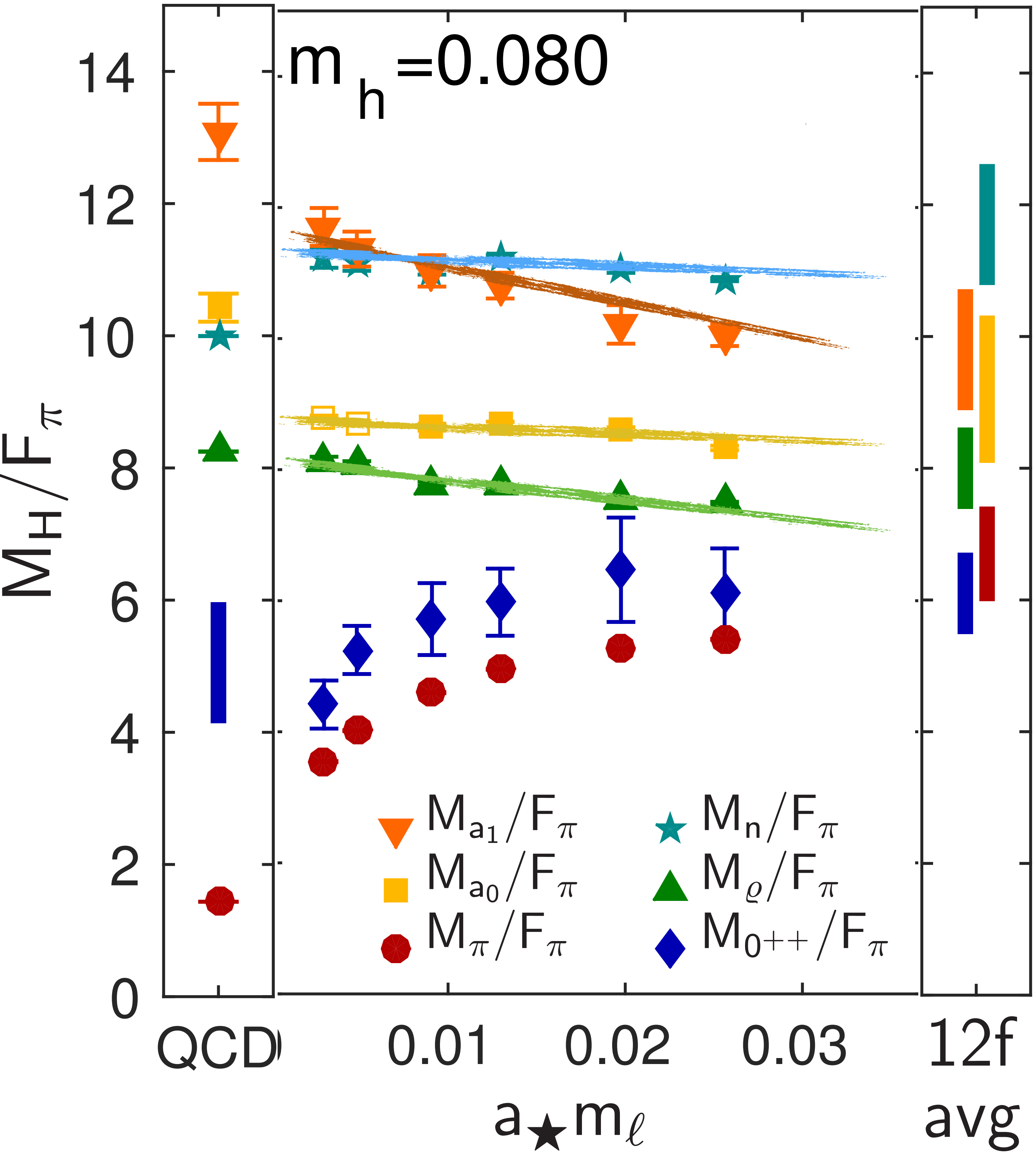
A closer look



pion, rho, a0, a1, nucleon and 0^{++} scalar

Chiral limit is quite straightforward

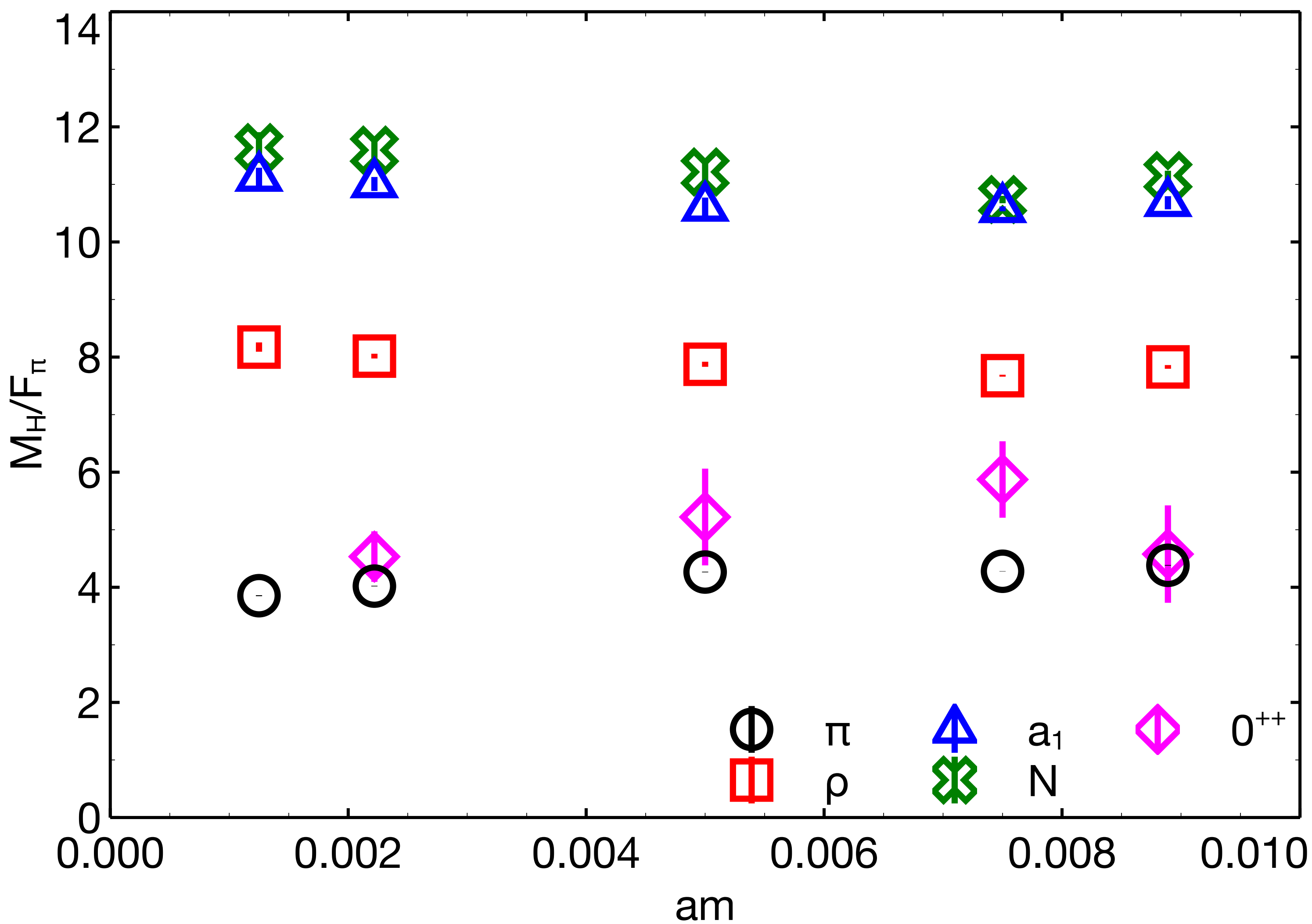
The ratios are very similar to QCD and N_f=12, interpolating in between

0^{++} is just above, closely following the pion - where is the chiral limit ?

Other systems look similar ….

Digression

SU(3) with 8 fundamental fermions   LSD Collaboration



M_H / F_π vs m_f

pion, rho, a1, nucleon
and 0^{++} scalar
Compare to 4+8!

$$M_\rho / F_\pi \approx 8$$

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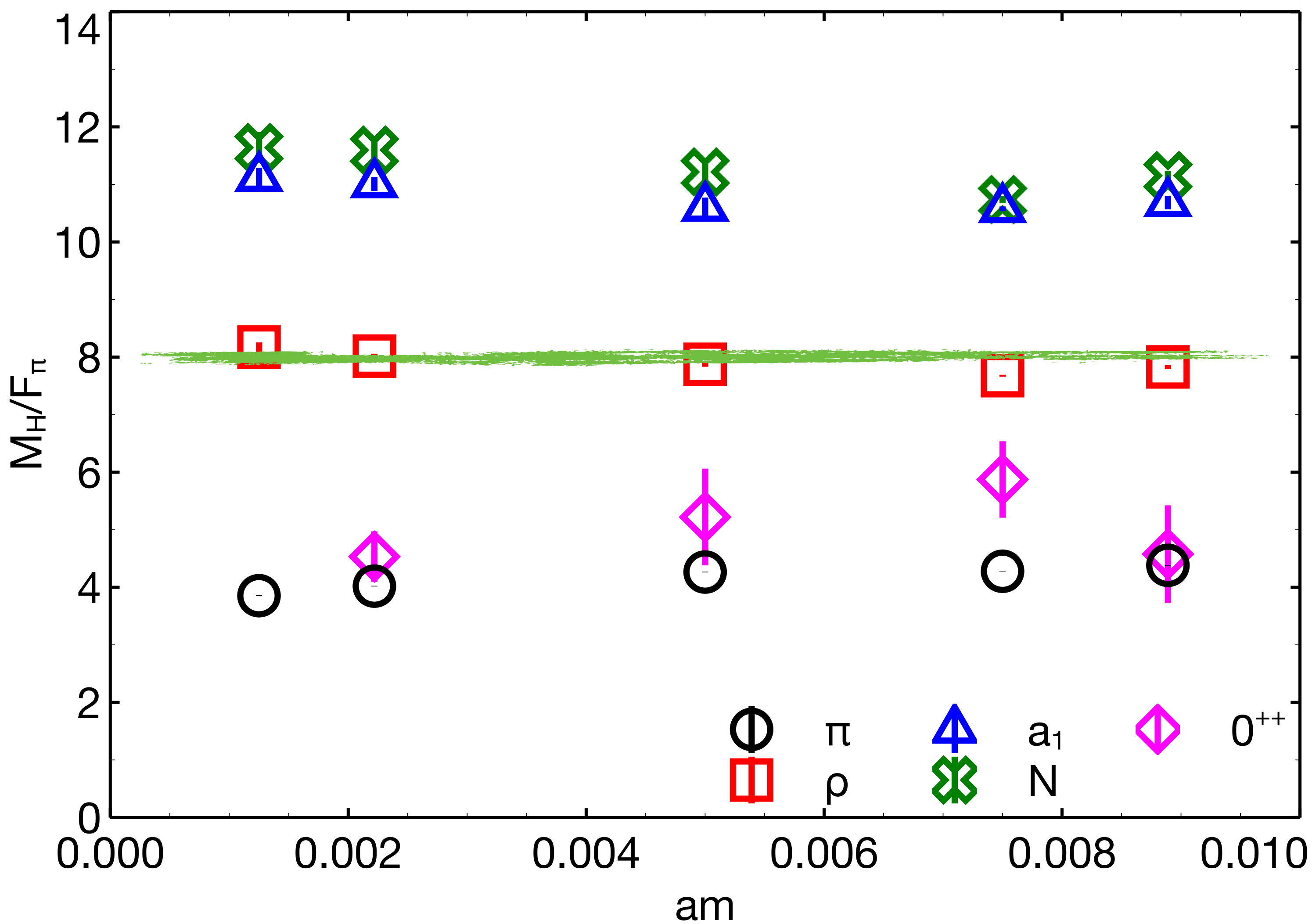

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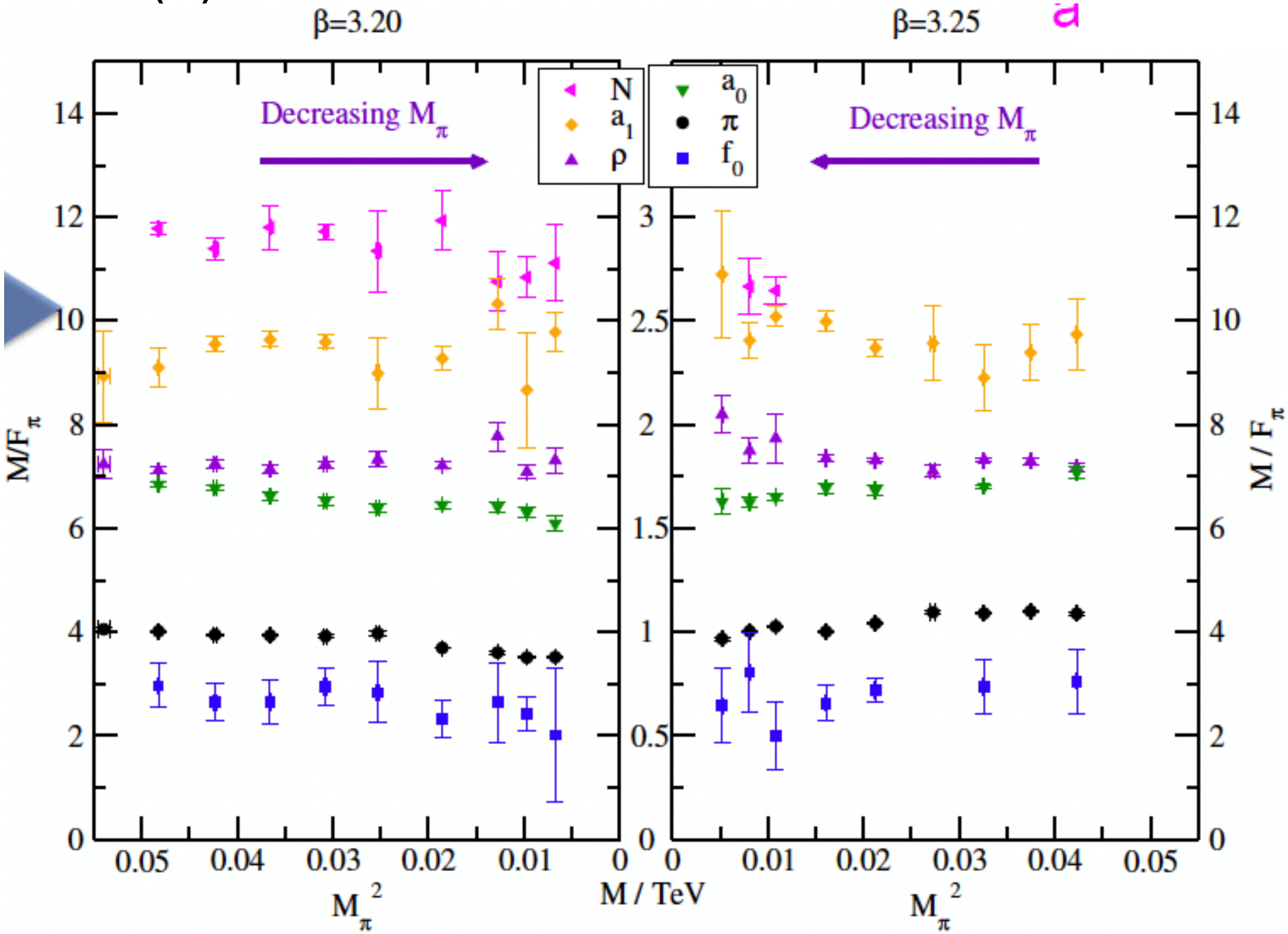


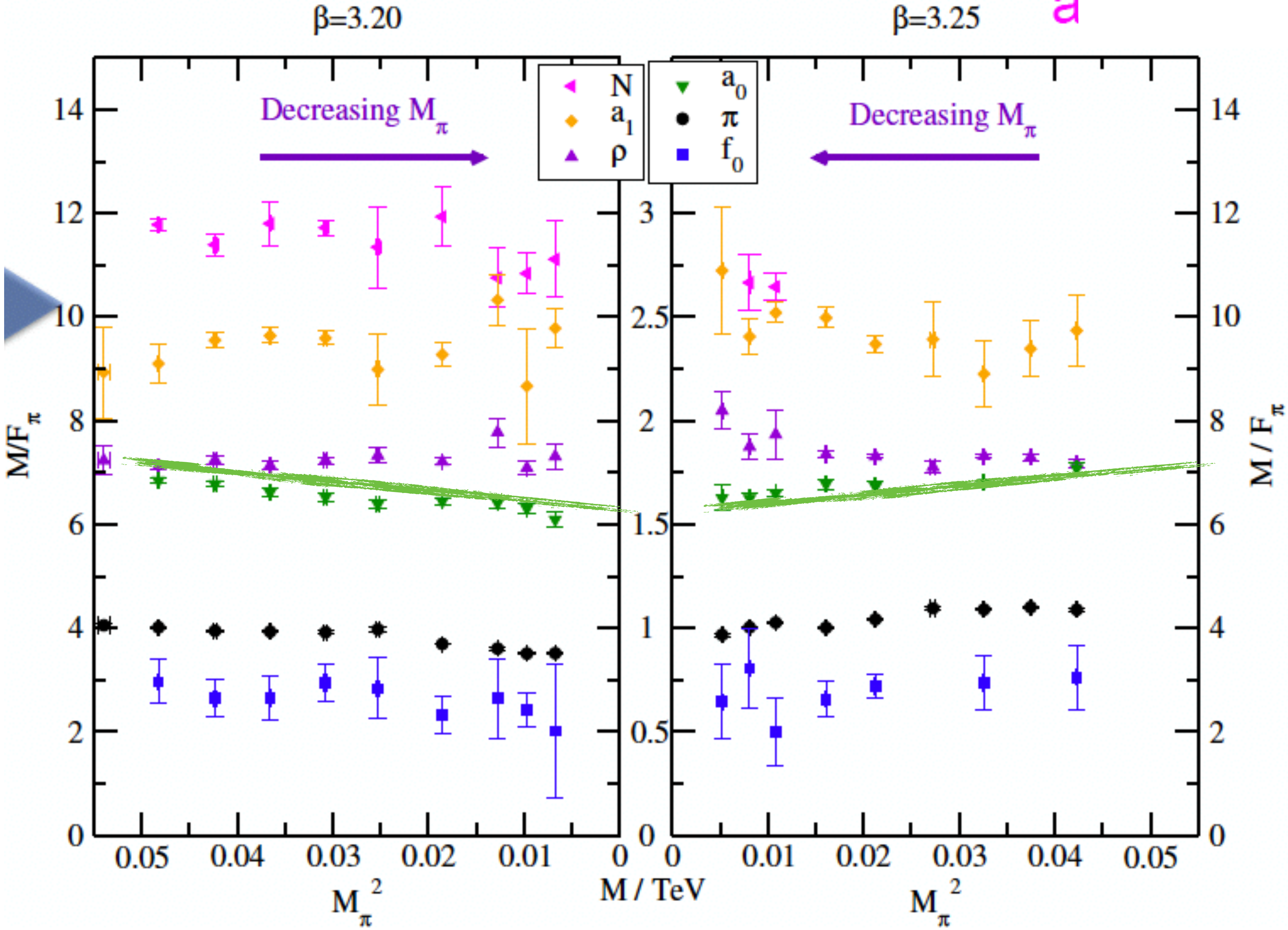
SU(3) with
- 4,4+8,8,12 fundamental
- 2 sextet flavors

all look the same!

Other systems look similar ….

Digression

SU(3) with 2 sextet fermions   LH Collaboration



SU(3) with
- 4,4+8,8,12 fundamental
- 2 sextet flavors

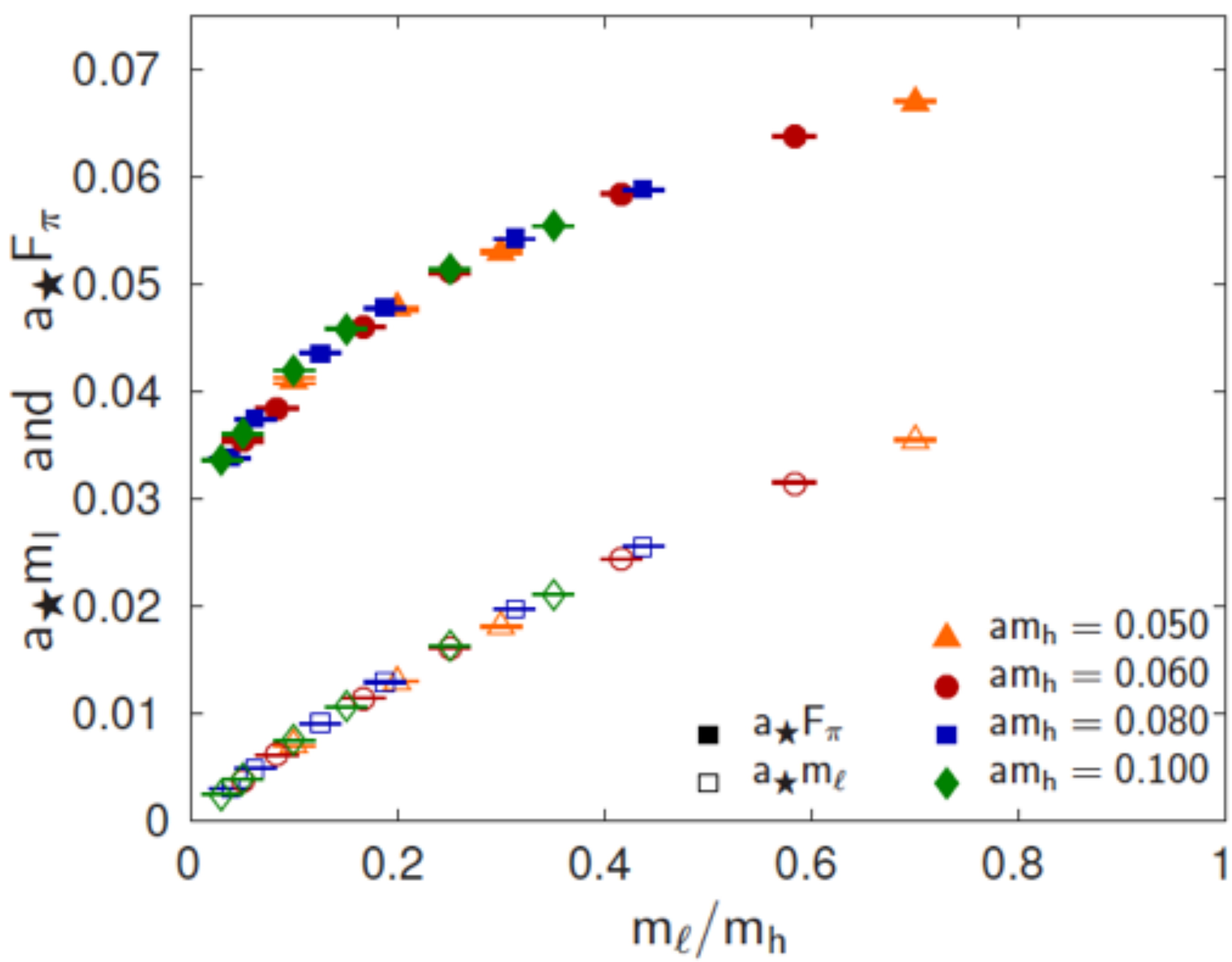
all look the same!

First hyperscaling tests in 4+8:

Ratios are universal functions of m_ℓ/m_h

$$M_{H_1}/F_\pi = \tilde{\Phi}_H(m_\ell/m_h)$$
$$M_{H_1}/M_{H_2} = \Phi_H(m_\ell/m_h),$$

$a_\star F_\pi$ and $a_\star m_\ell$ vs m_ℓ/m_h

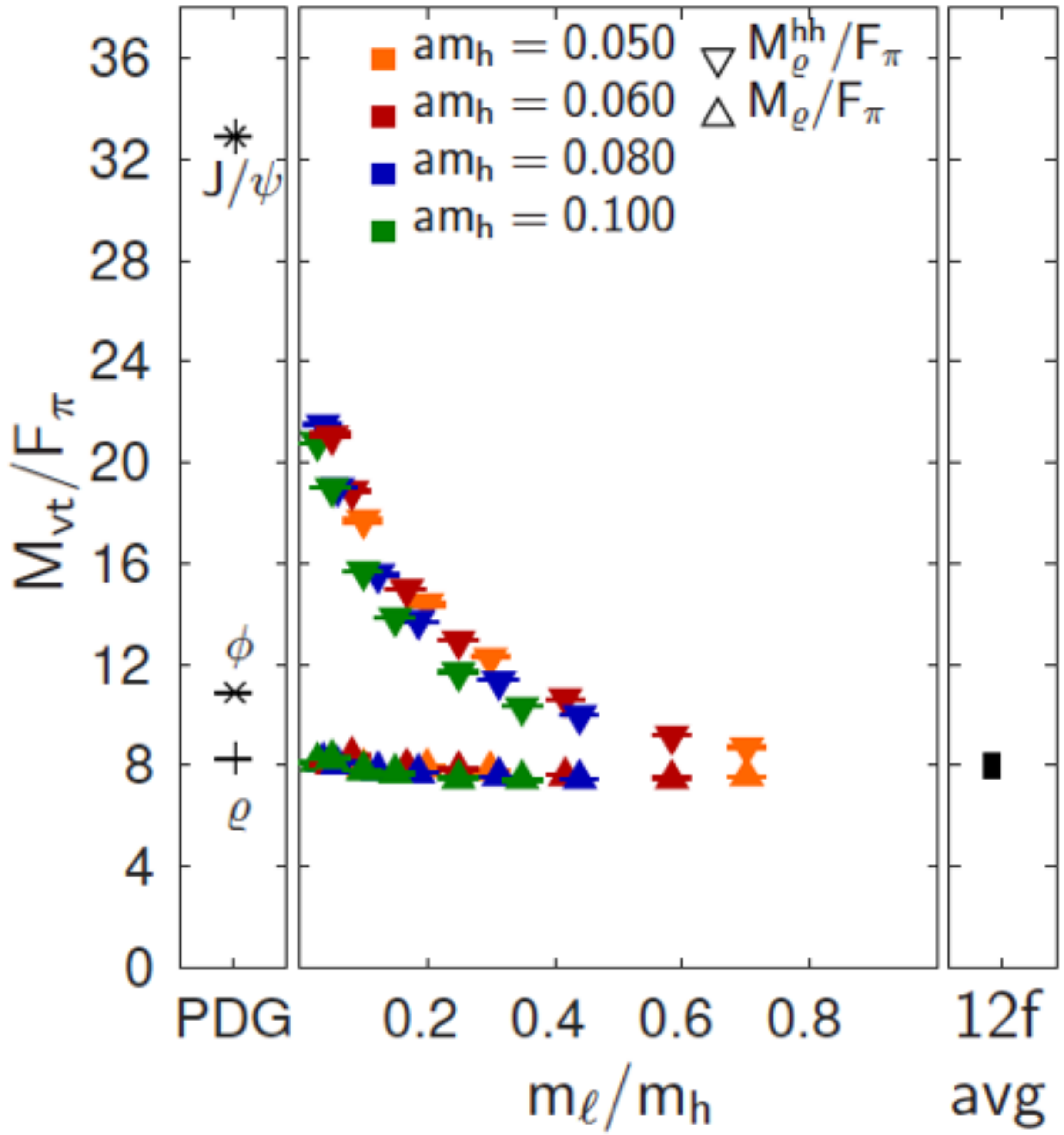


$a_\star F_\pi$ is finite in the chiral limit — of course!

Hyperscaling in m

Light-light and heavy-heavy **vector** in terms of $\mathbf{F_\pi}$

Compare to 12 flavors ($m_\ell = m_h$) and PDG ($m_\ell \ll m_h$)

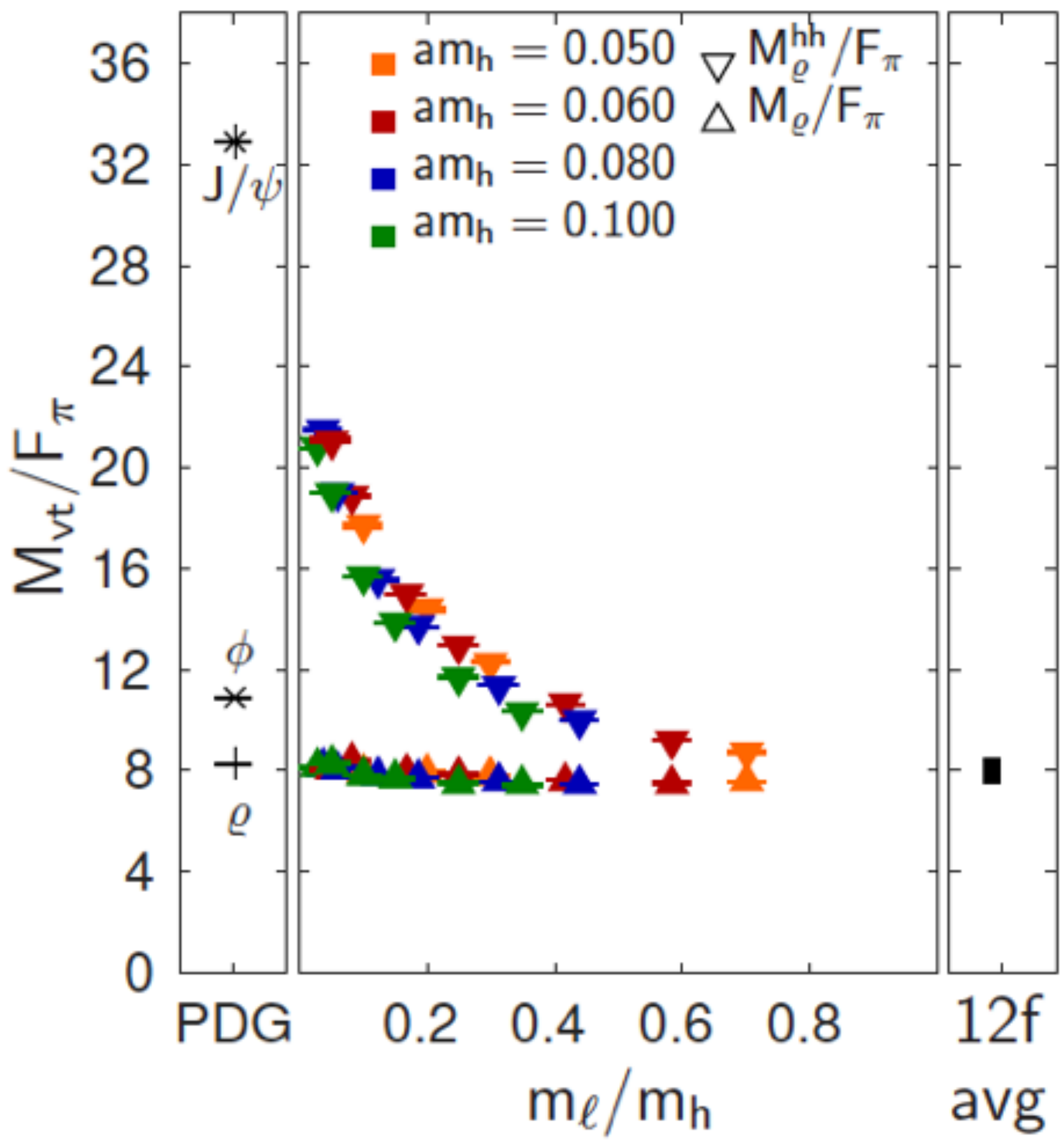


- The 4ℓ+8h heavy spectrum is not QCD-like
- QCD is not hyperscaling

Hyperscaling in m

Light-light and heavy-heavy **vector** in terms of $\mathbf{F_\pi}$

Compare to 12 flavors (m_ℓ=m_h) and PDG (m_ℓ << m_h)



- Heavy M_{vt} / F_π increases but F_π is finite in the chiral limit
- Heavy M_{vt} is only 3 times heavier than light M_{vt}
- It could be accessible in experiments

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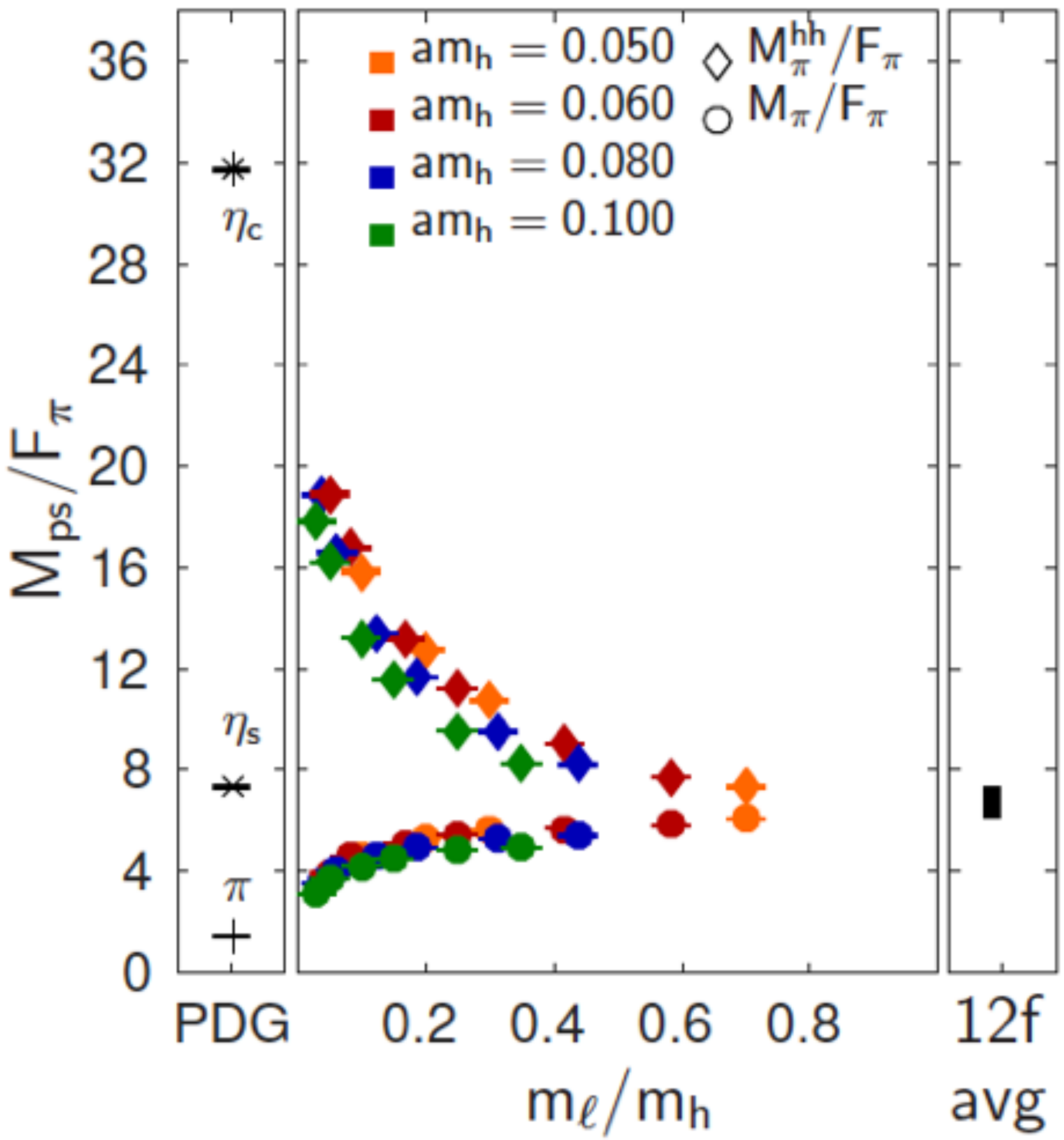
Hyperscaling in m

Light-light and heavy-heavy **pseudo scalar** in terms of $\mathbf{F_\pi}$

Compare to 12 flavors (m_ℓ=m_h) and PDG (m_ℓ << m_h)

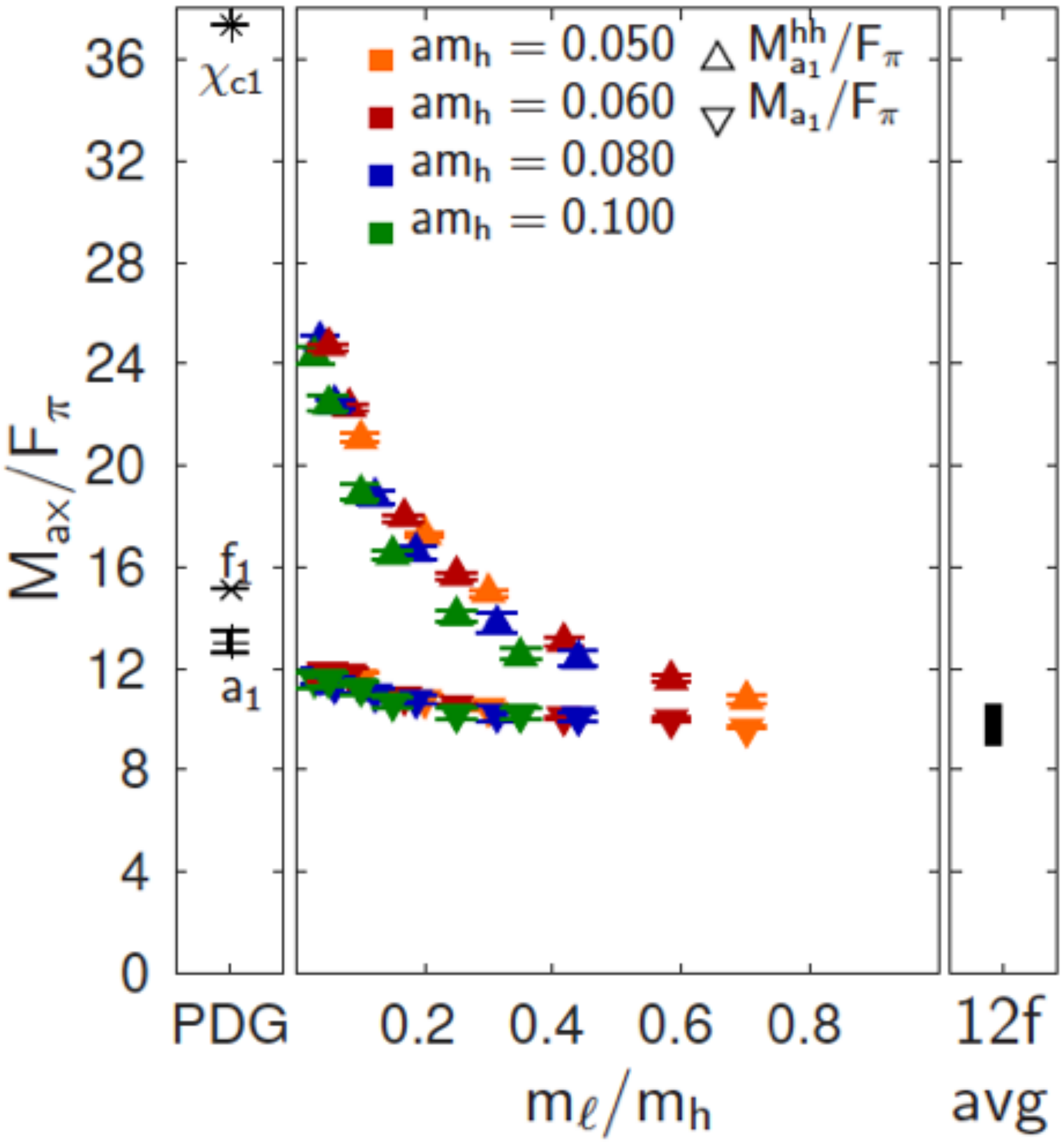


- The 4ℓ+8h heavy spectrum is not QCD-like
- QCD is not hyperscaling

Hyperscaling in m

Light-light and heavy-heavy **a₁** in terms of **F_π**

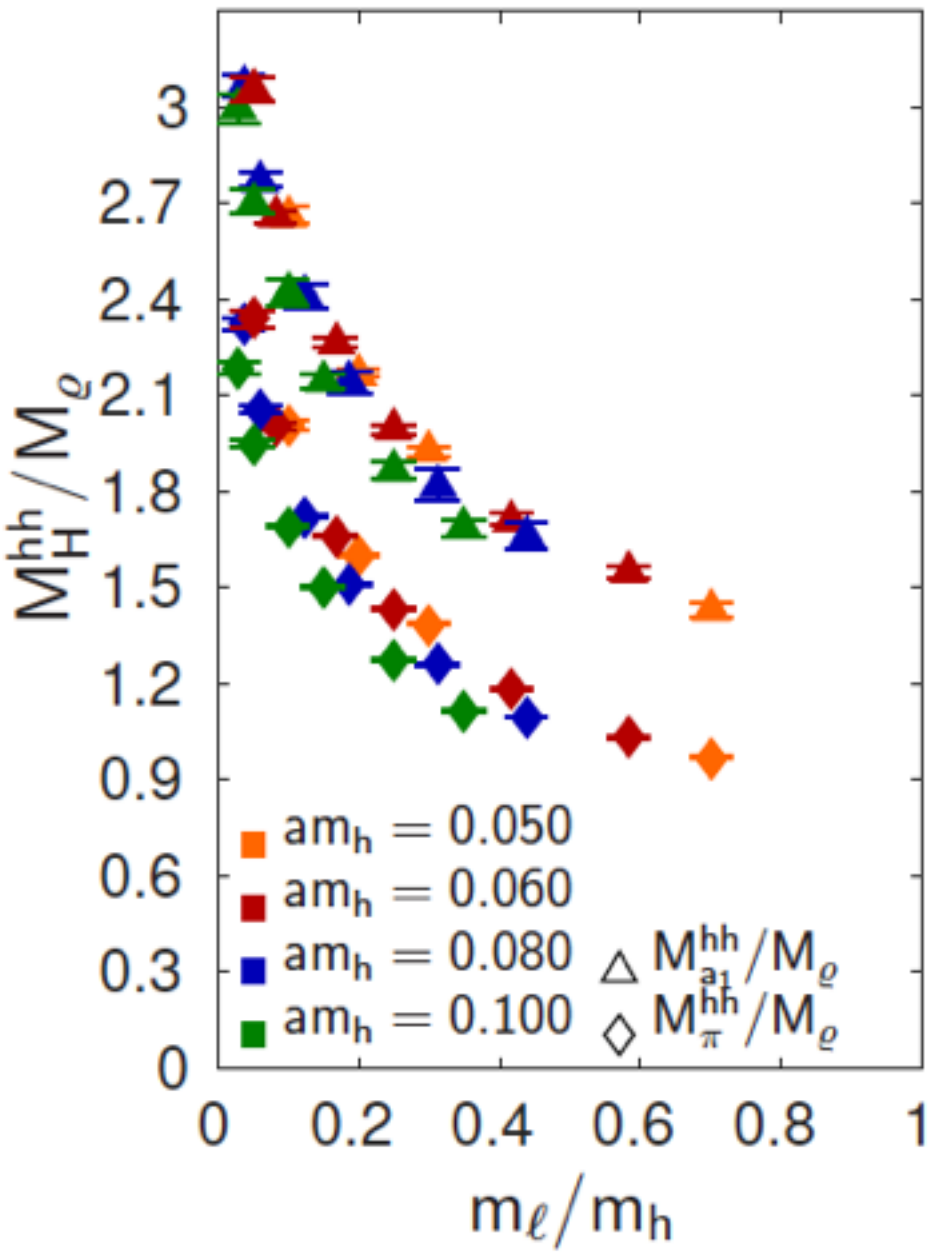
Compare to 12 flavors ($m_\ell = m_h$) and PDG ($m_\ell \ll m_h$)

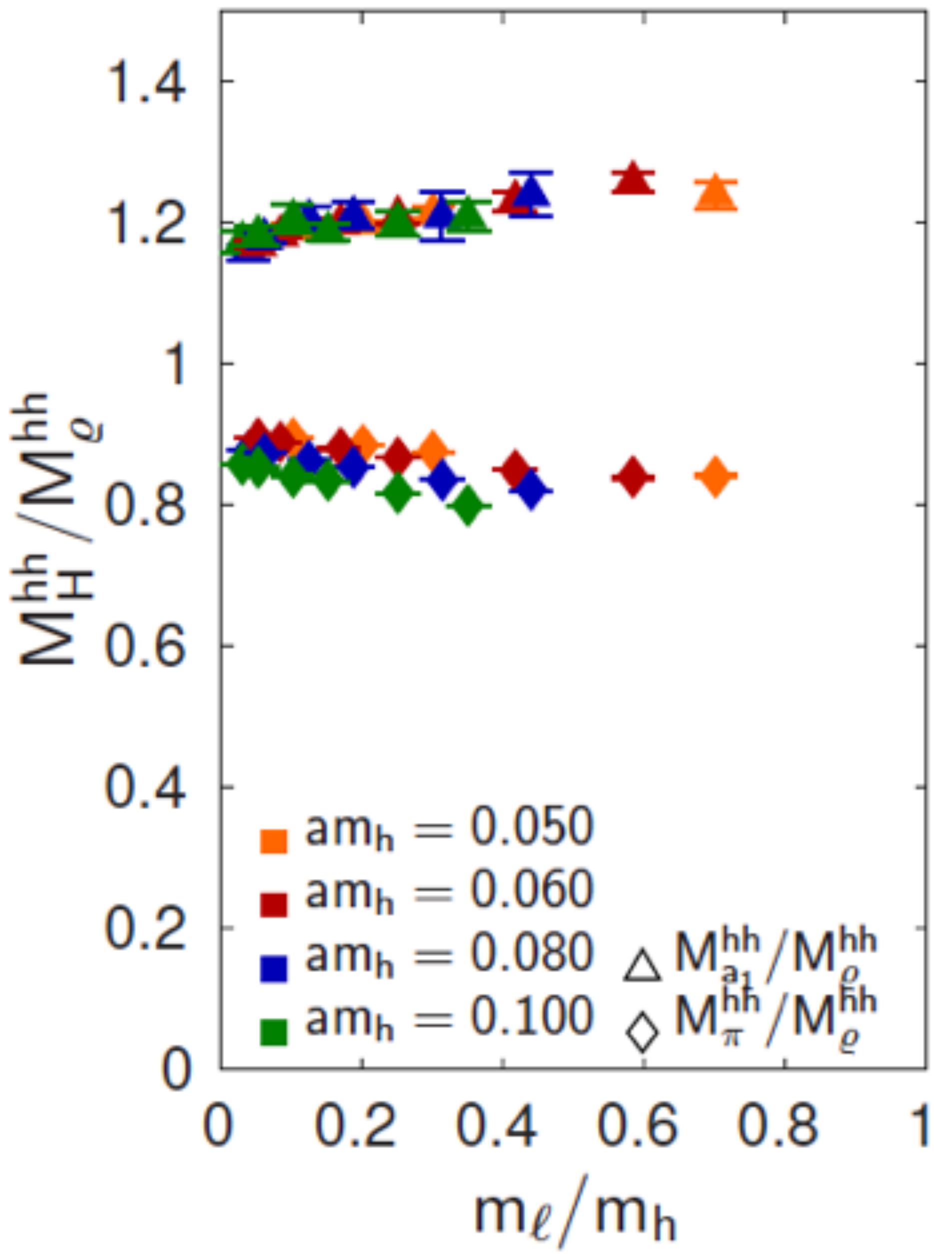


- The 4ℓ+8h heavy spectrum is not QCD-like
- QCD is not hyperscaling

The heavy-heavy spectrum

Light-light and heavy-heavy pseudo **scalar** and **a₁** in terms of **vector mass**





The increase in the heavy-heavy is mostly due to the light normalization

Summary & Outlook

Mass-split models that are conformal in the UV, chirally broken in the IR are best of both worlds:

- controlled walking
- anomalous dimension
- hyperscaling for all masses: predictive power!
- Higgs sector is based on the light/massless fermions
- tower of states few times heavier than F_π
- the heavy-light and heavy-heavy hadrons are also accessible
  h-h, h-l spectrum are very different from QCD

Many interesting possibilities …. lattice studies can investigate no-perturbative properties both specific and generic systems

Synergy between lattice and phenomenology
could benefit both areas

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