Composite Higgs models based on a conformal fixed point

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University of Colorado Boulder

Holography, conformal field theory, and lattice
June 26 2016, Edinburgh

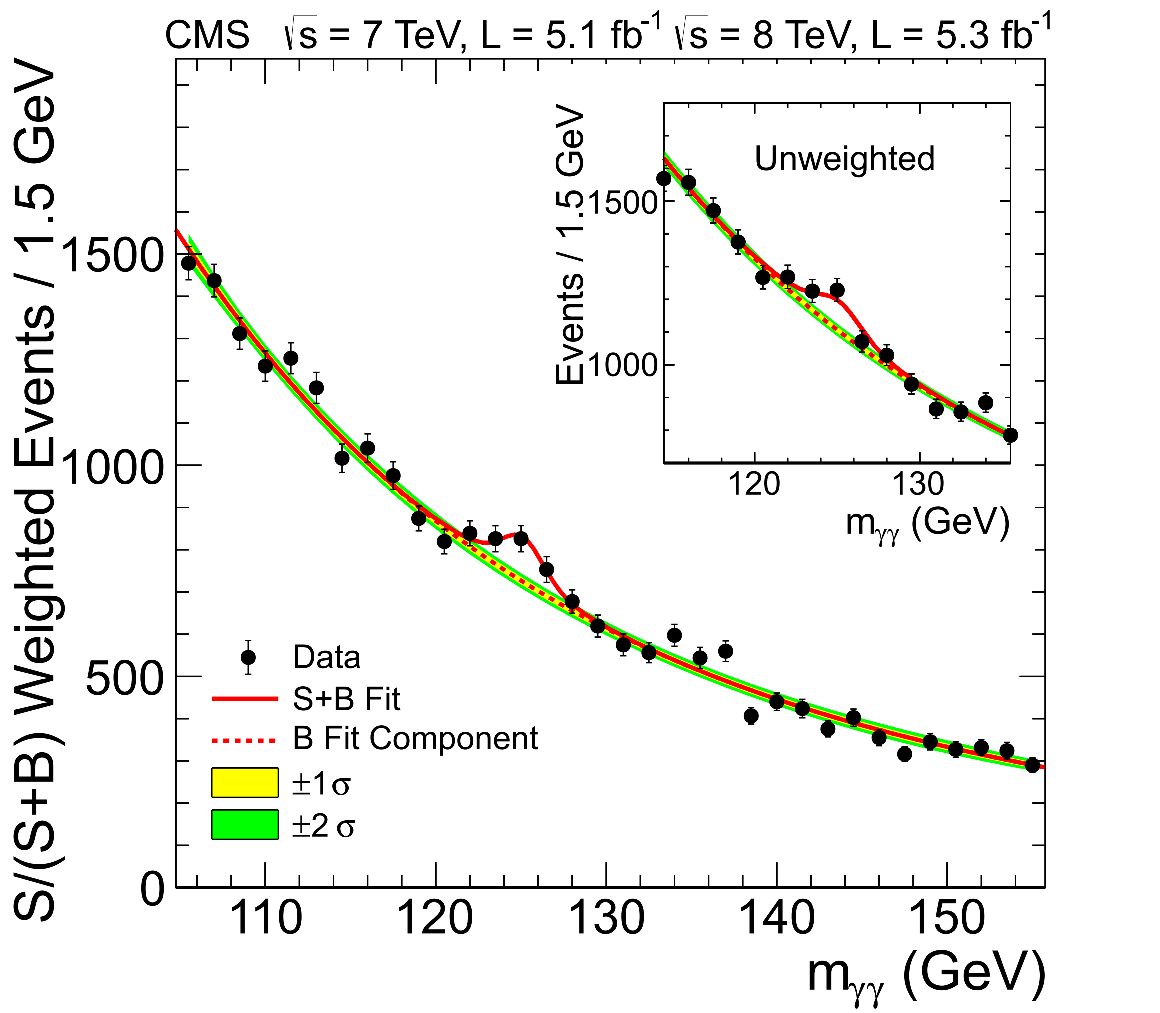
R.Brower, A.H, C.Rebbi,
E.Weinberg, O.Witzel,
PRD93, 114514 (2016)
& in prep

Higgs era of particle physics

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

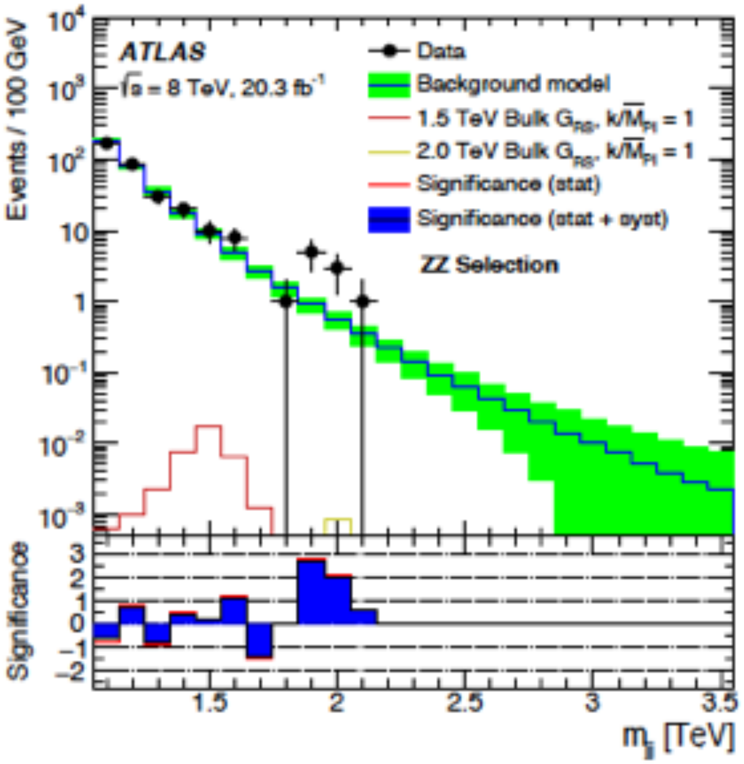
- not UV complete
- naturalness /hierarchy problem
- DM, neutrinos, ……

➡ Implies new physics

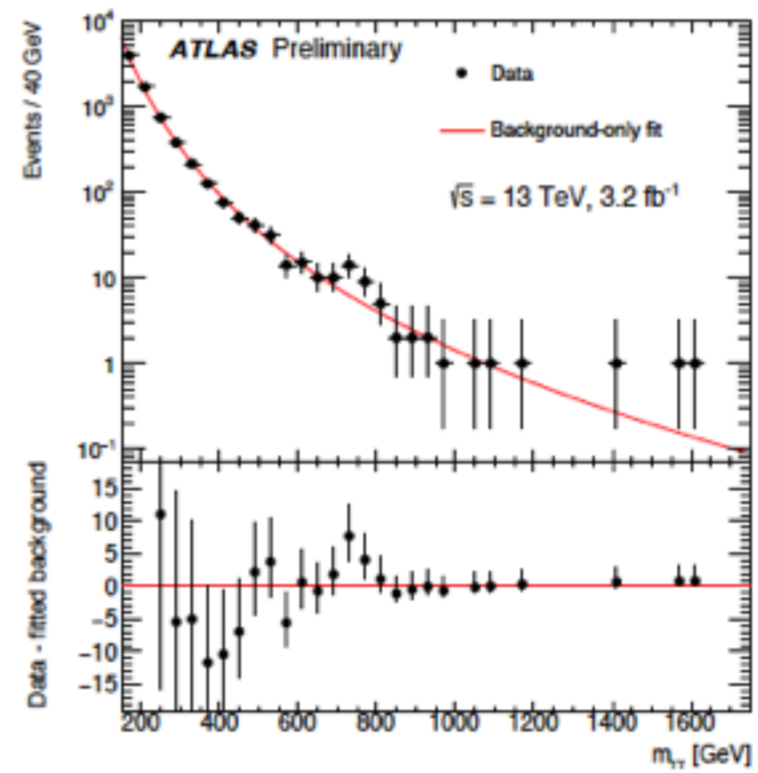


Tantalizing hints at new physics

We might be at the brink of discovering beyond-SM physics:



June 2015: ATLAS reported 3.5 σ excess at 2TeV suggesting a vector resonance (1506.00962)



December 2015: both ATLAS and CMS found excess at 750 GeV suggesting a scalar resonance

- What are the possible (consistent) BSM models?
- What other predictions do those models have?

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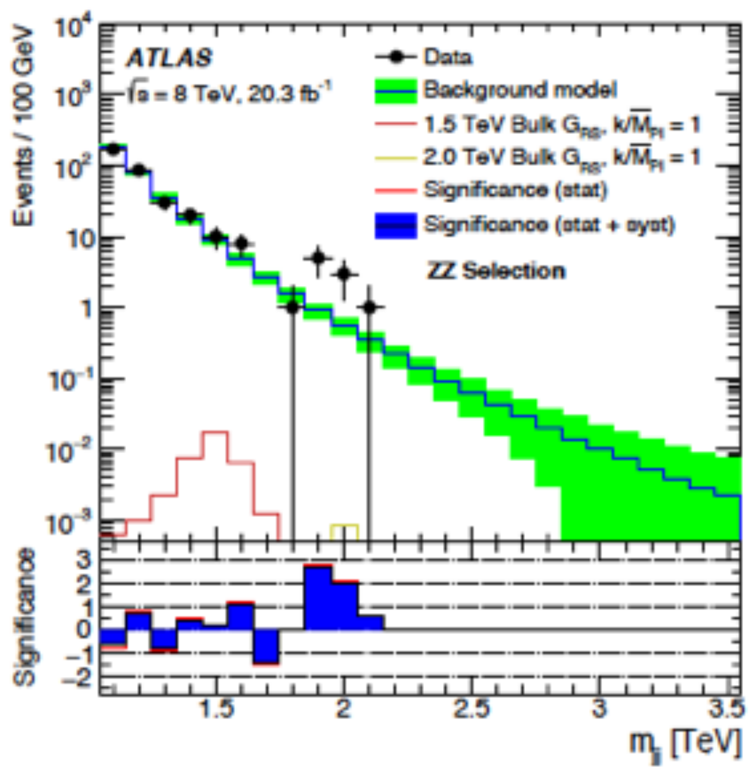

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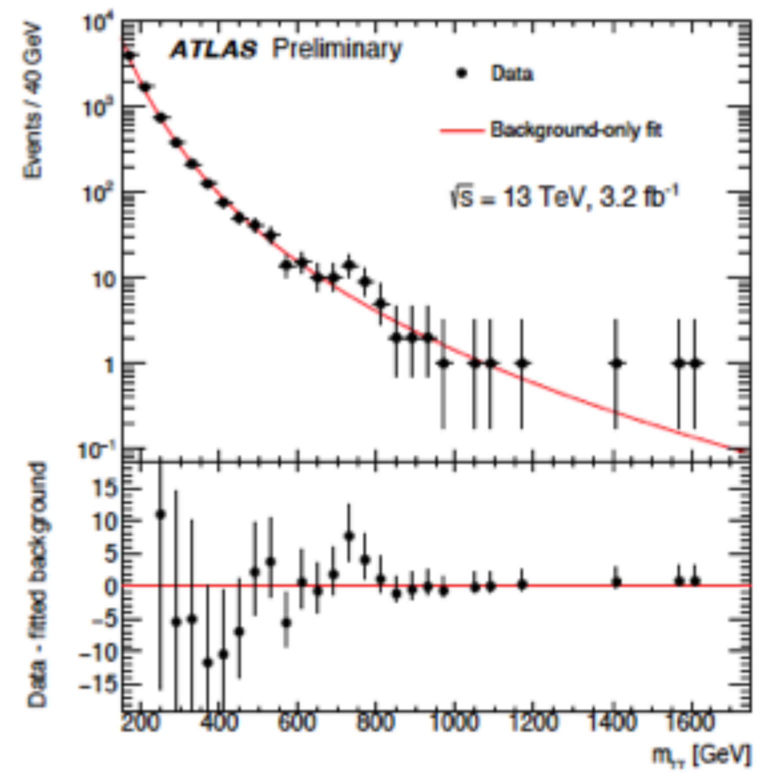

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"Bump hunting", talk by C. Leonidopoulos, 6/30 @ 16:00

Composite Higgs - strong dynamics

The solution could be a set of new, strongly interacting systems:

N_f fermions, $SU(N_c)$ gauge fields, chirally broken, coupled to the SM

- EW symmetry breaking by massless pions ✓
- Higgs sector

What keeps the Higgs light ?

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Dilaton-like Higgs:

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

→ possibly light 0++ scalar

F_π = SM vev ~ 246GeV

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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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  What keeps the Higgs light ?
- Fermion/Yukawa sector

  How to generate SM fermion masses ?

  - 4-fermion interaction
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  - partial compositeness

There are many phenomenological models. In this workshop:

G. Ferretti	T. Appelquist
L. Vecchi	D. Marzocca
C. Englert	…….

Composite Higgs - role of lattice simulations

A UV complete model might need more than one gauge sector and is strongly coupled. Some might

- have a light 0++ scalar and/or
- be walking and/or
- have large anomalous mass dimension and/or
- have large baryon anomalous dimension, etc

How do the various parts fit together?

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Non-perturbative questions that lattice simulations can investigate:

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Non-perturbative questions that lattice simulations can investigate:

- Where is the conformal window?
- What are the (tunable ?) parameters that control near-conformal behavior?
- What is the spectrum of near-conformal models?
- What are the anomalous dimensions at a conformal FP?

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Non-perturbative questions that lattice simulations can investigate:

While lattice models are UV complete, they are still effective models

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A “prototype” model

Gabriele Ferretti and Luca Vecchi said it all this morning:

Λ_{UV} CONFORMAL Λ CONFINING

UV $\longrightarrow$ IR

Here the theory is conformal, e.g. $Sp(4)$ with large enough N_ψ, N_χ.

The CFT operator $\mathcal{O} \approx \psi\chi\psi$ acquires a (large?) anomalous dimension $\Delta_{\mathcal{O}}$.

At Λ some fermions decouple: $N_\psi \to 4$, $N_\chi \to 6$ and the theory confines and breaks χS.

$\mathcal{O}$ creates a (light?) composite fermion of mass $M_{\mathcal{O}}$.

From G. Ferretti’s talk

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N=4 light/massless fundamental flavors (Luca Vecchi Cacciapaglia, Ma)

From G. Ferretti’s talk

A “prototype” model

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N_f=12 fundamental flavors
→ conformal IRFP

N=4 light/massless fundamental flavors (Luca Vecchi Cacciapaglia, Ma)

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 $SU(2)_L$ x $SU(2)_R$ custodial symmetry

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

2 Higgs doublets, 3 Goldstone pions, DM candidate

Additional fermions are needed to generate SM fermion masses either through 4-fermion terms or partial compositeness

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

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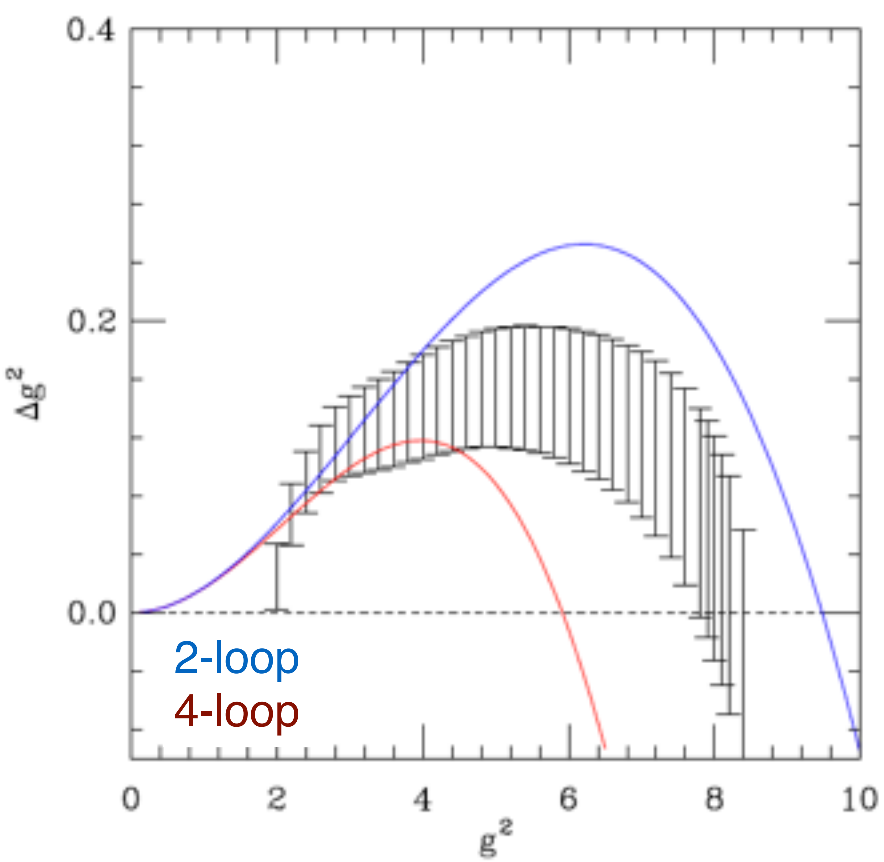

Improved step scaling function

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

A.H, D. Schaich, in preparation

N_f=12 is too deep in conformal phase;

N_f=10 would be a better choice

A “prototype” lattice model

Both dilaton-like and pNGB models require additional fermions

→ Effective model:

4 (or 2) light plus N heavy flavors :

- Does N matter? What should it be to satisfy EWP tests?
- How do the extra fermions influence the light spectum?
- Does the heavy spectrum show up?
- What is the predictive power of this model?

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Lattice study:

N_f = 4+8 flavor system with 4 light/massless and 8 heavy flavors

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

Follow up : N_f=4+6 , 2+8, (4+4, 2+6) (LSD collaboration, in preparation)

Why 4+8 ? We use staggered fermions:
4 and 8 flavors do not require rooting

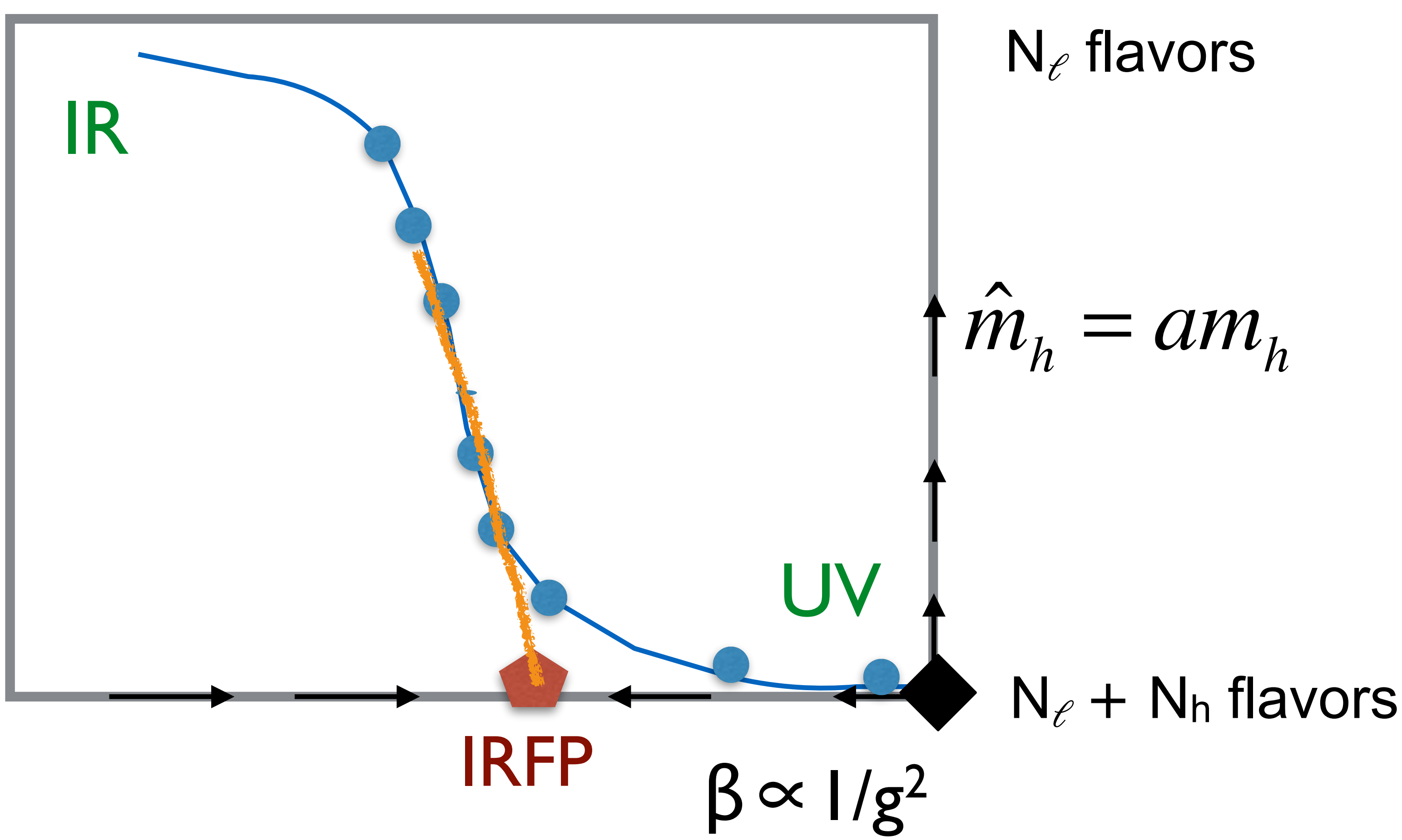
Chiral symmetry breaking at a conformal IRFP

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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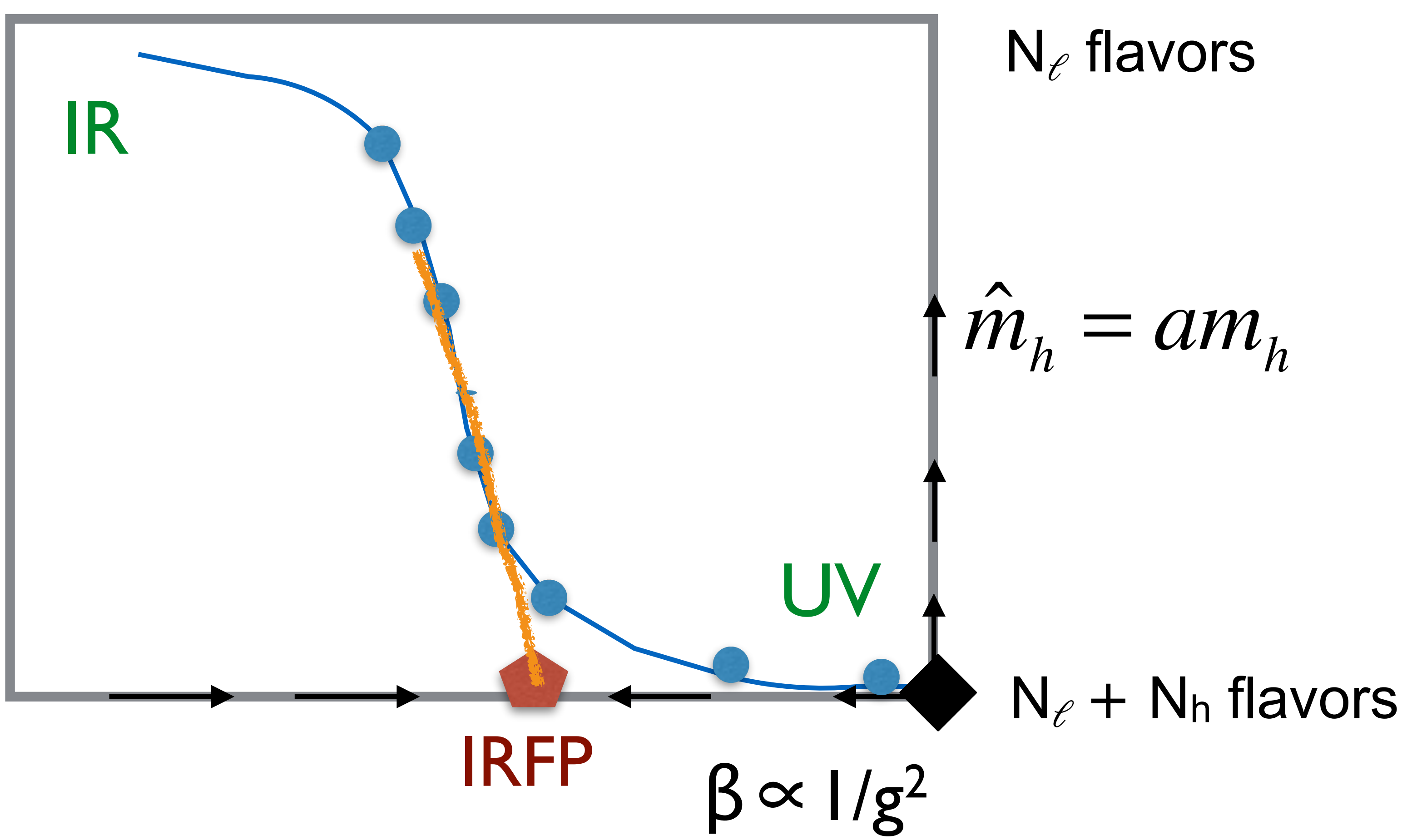

How predictive is this model?

$$g^2, m_h, m_\ell$$

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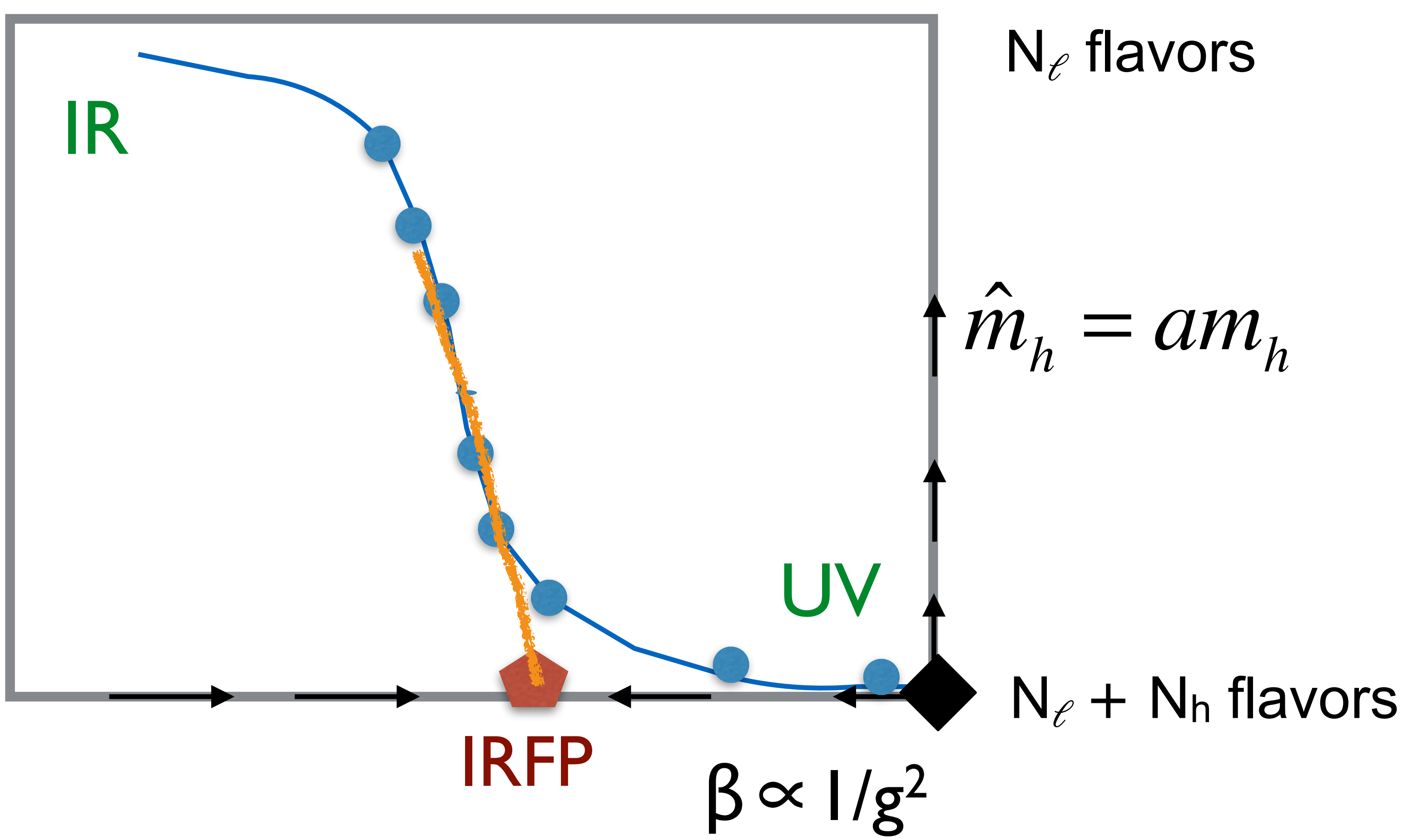

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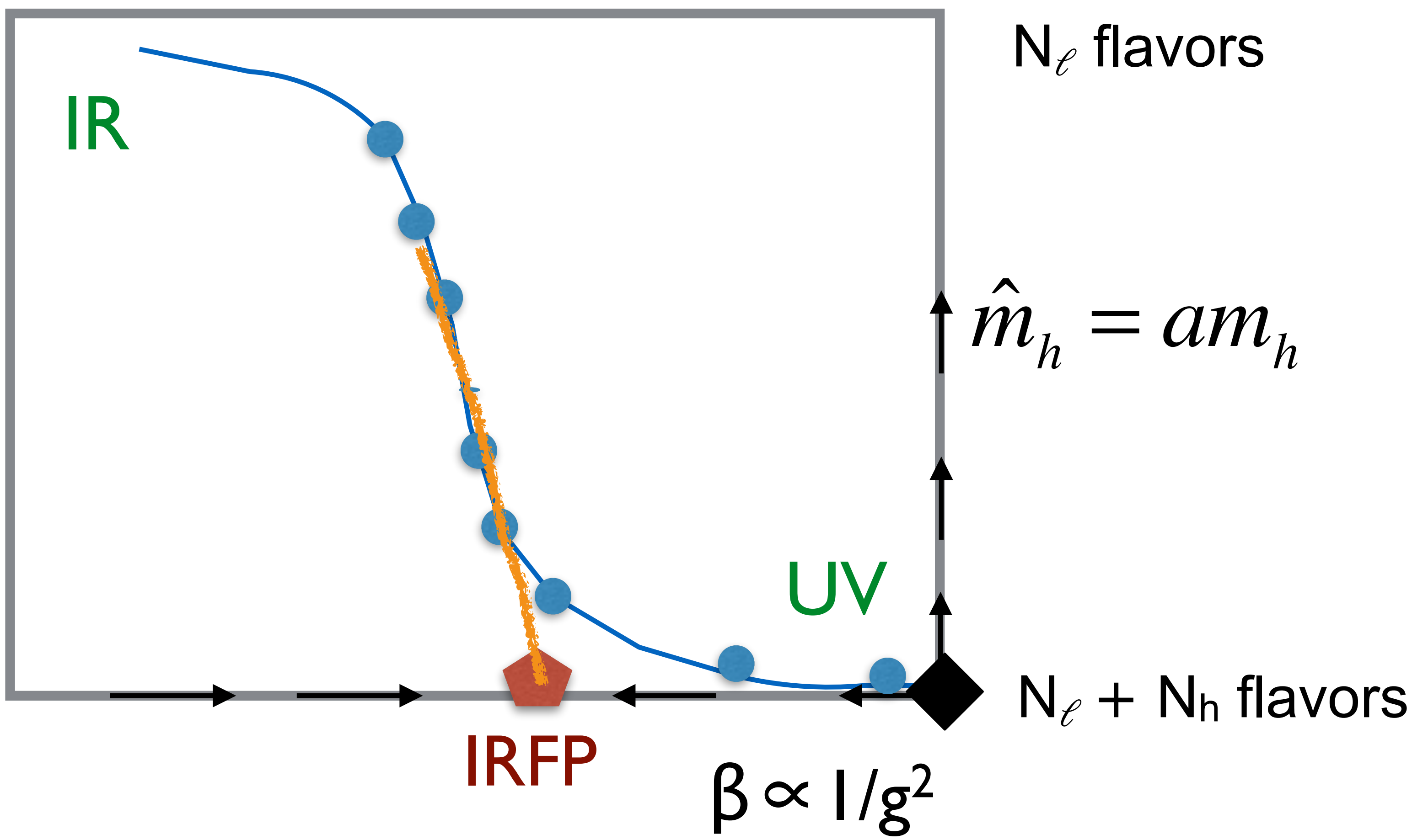

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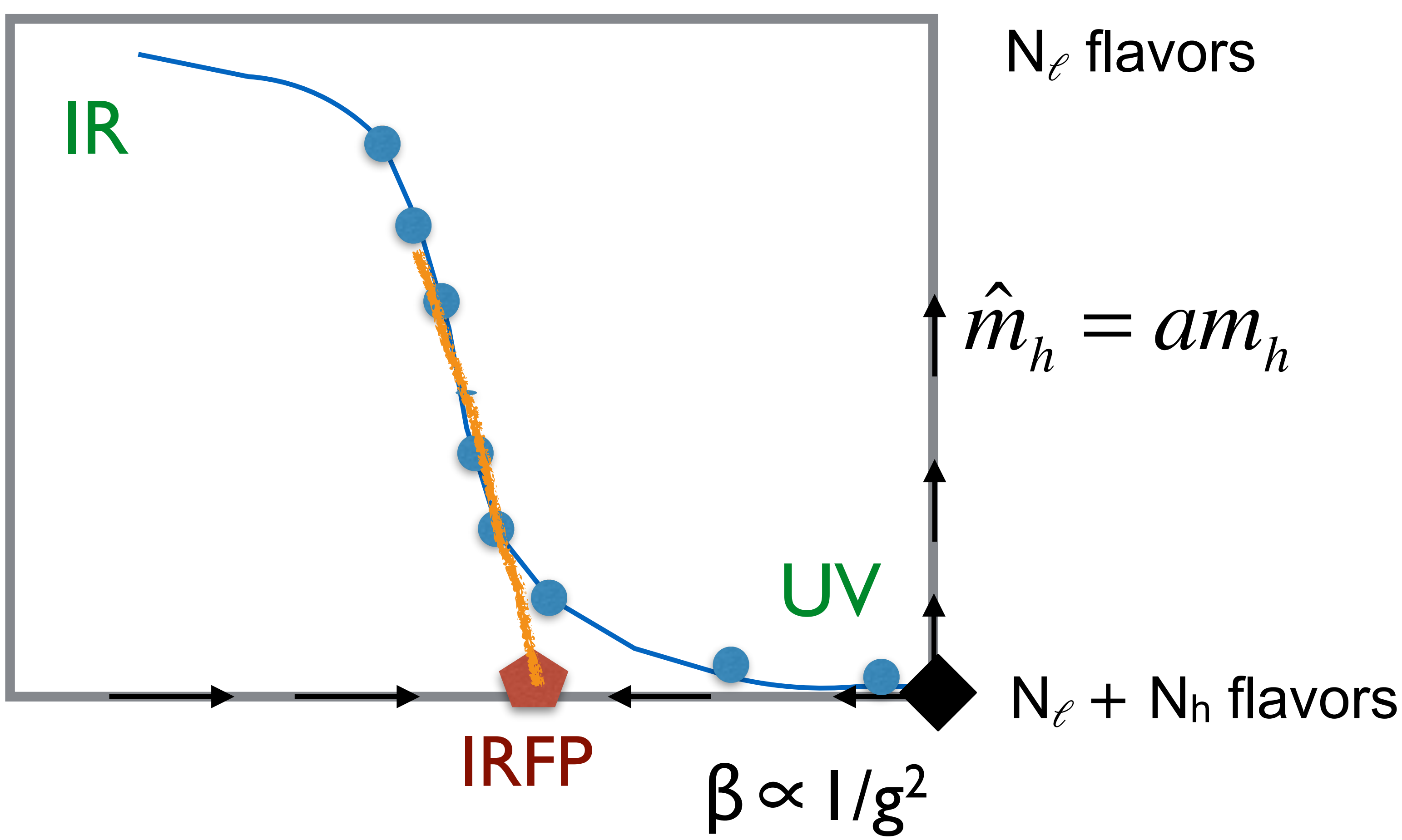
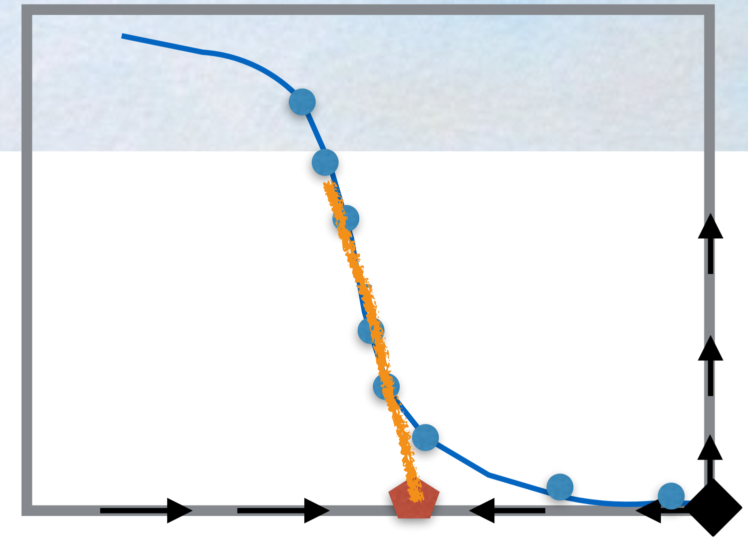


How predictive is this model?

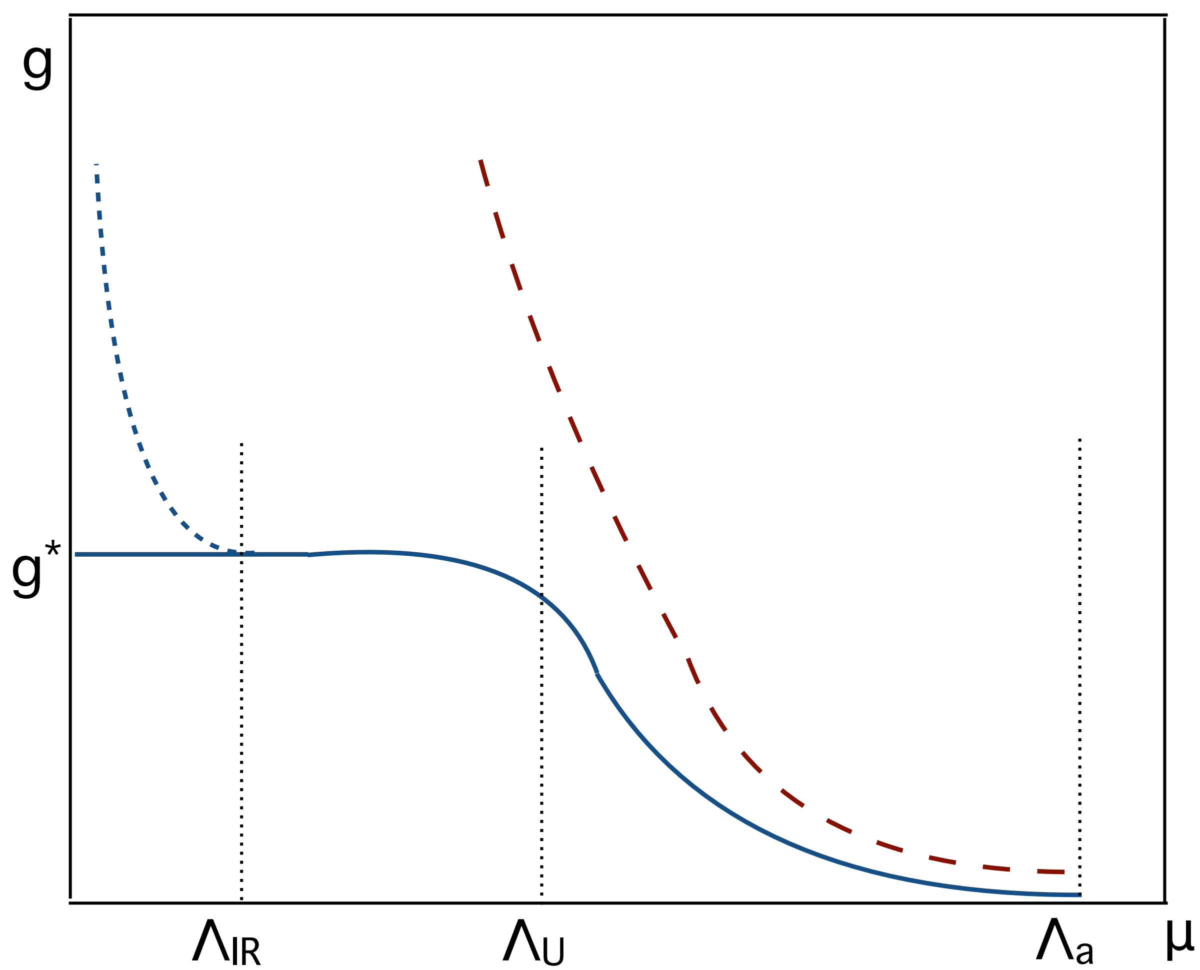
$\cancel{g^2}, m_h, m_\ell \to 0$

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

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

t: flow time;

E(t):energy density

g_{GF}^2 is used for scale setting as

$$g_{GF}^2(t=t_0)=\frac{0.3}{\mathcal{N}}$$

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- on large enough volumes
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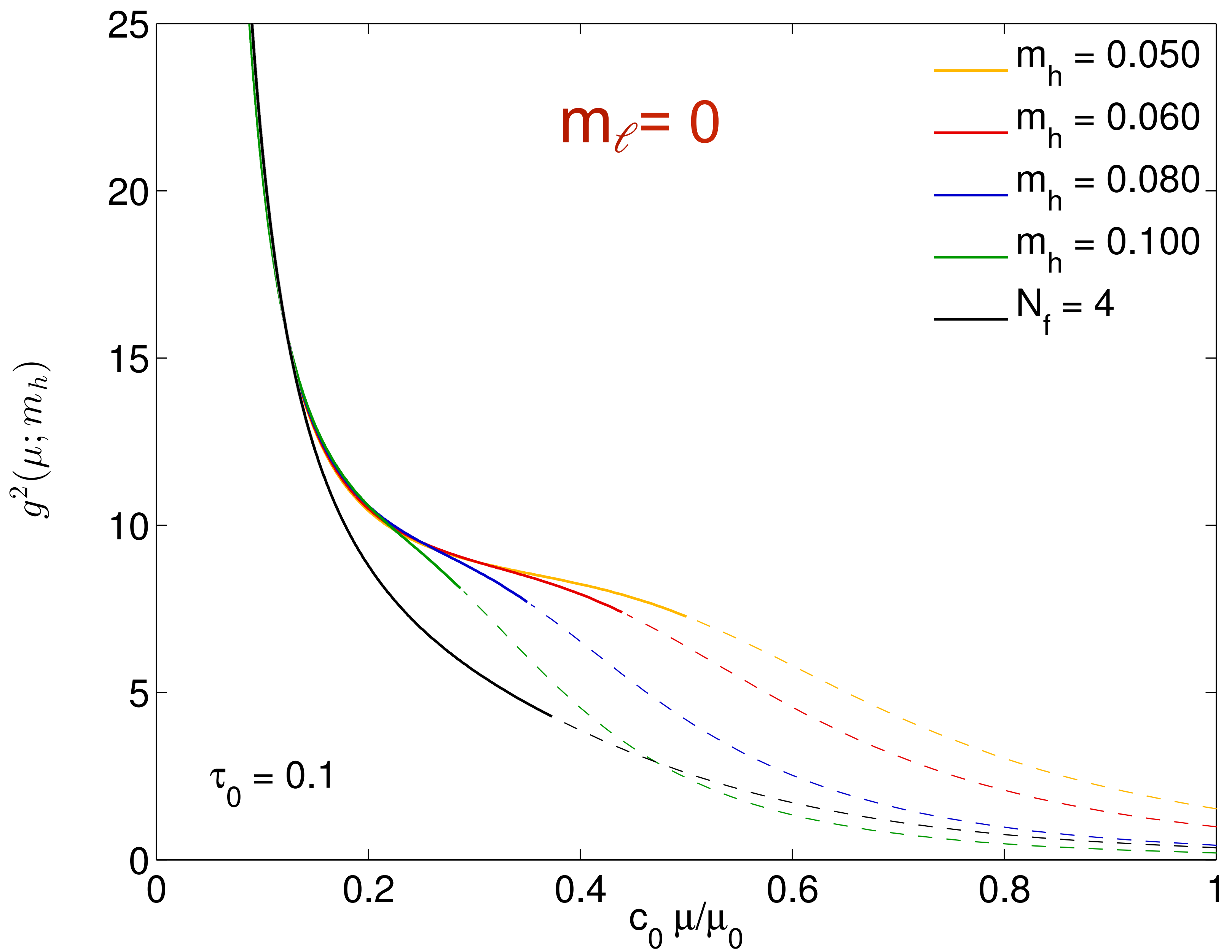
use t-shift improved coupling

Running coupling : 4+8 flavors



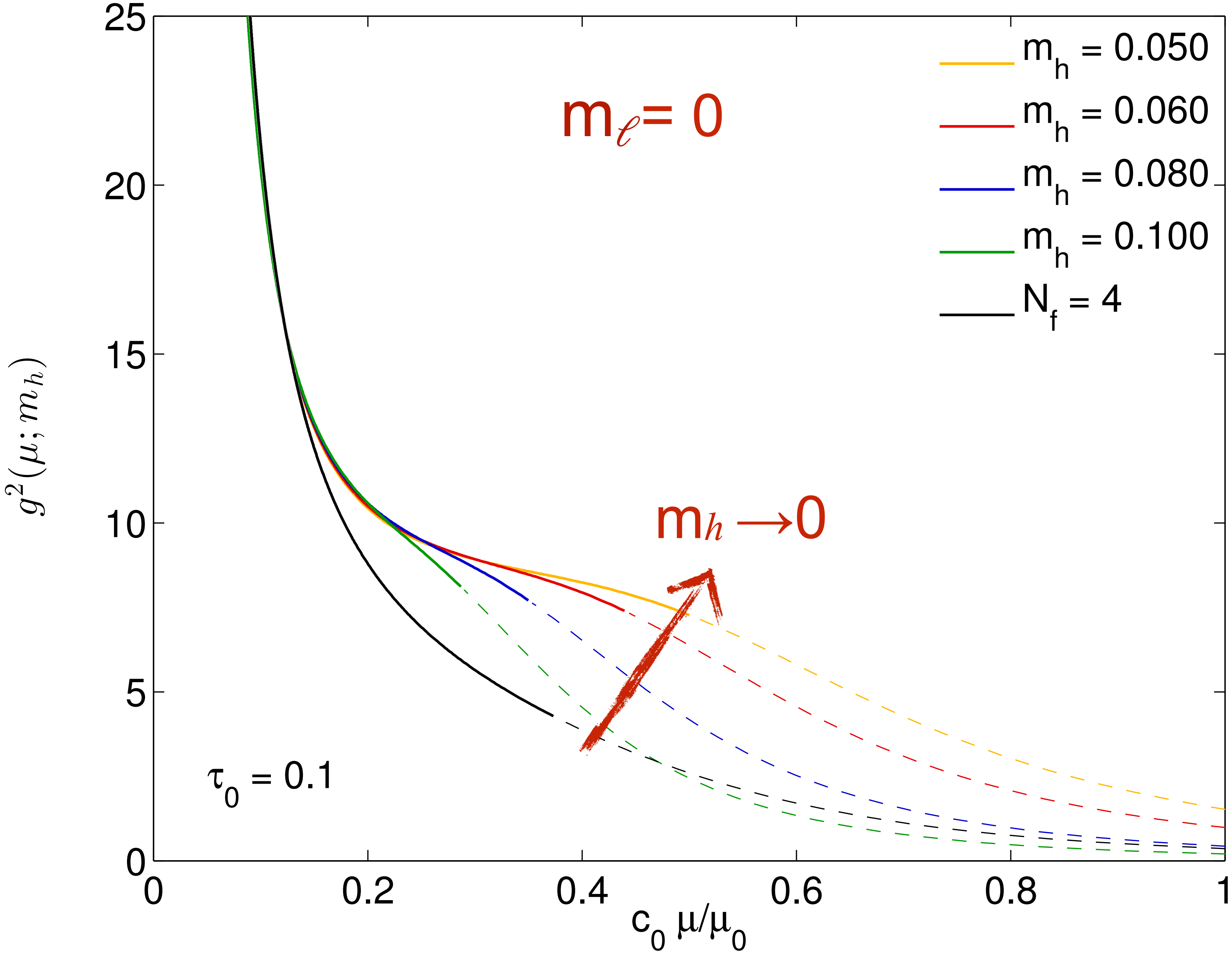
There are error bars on this plot!

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

Running coupling : 4+8 flavors



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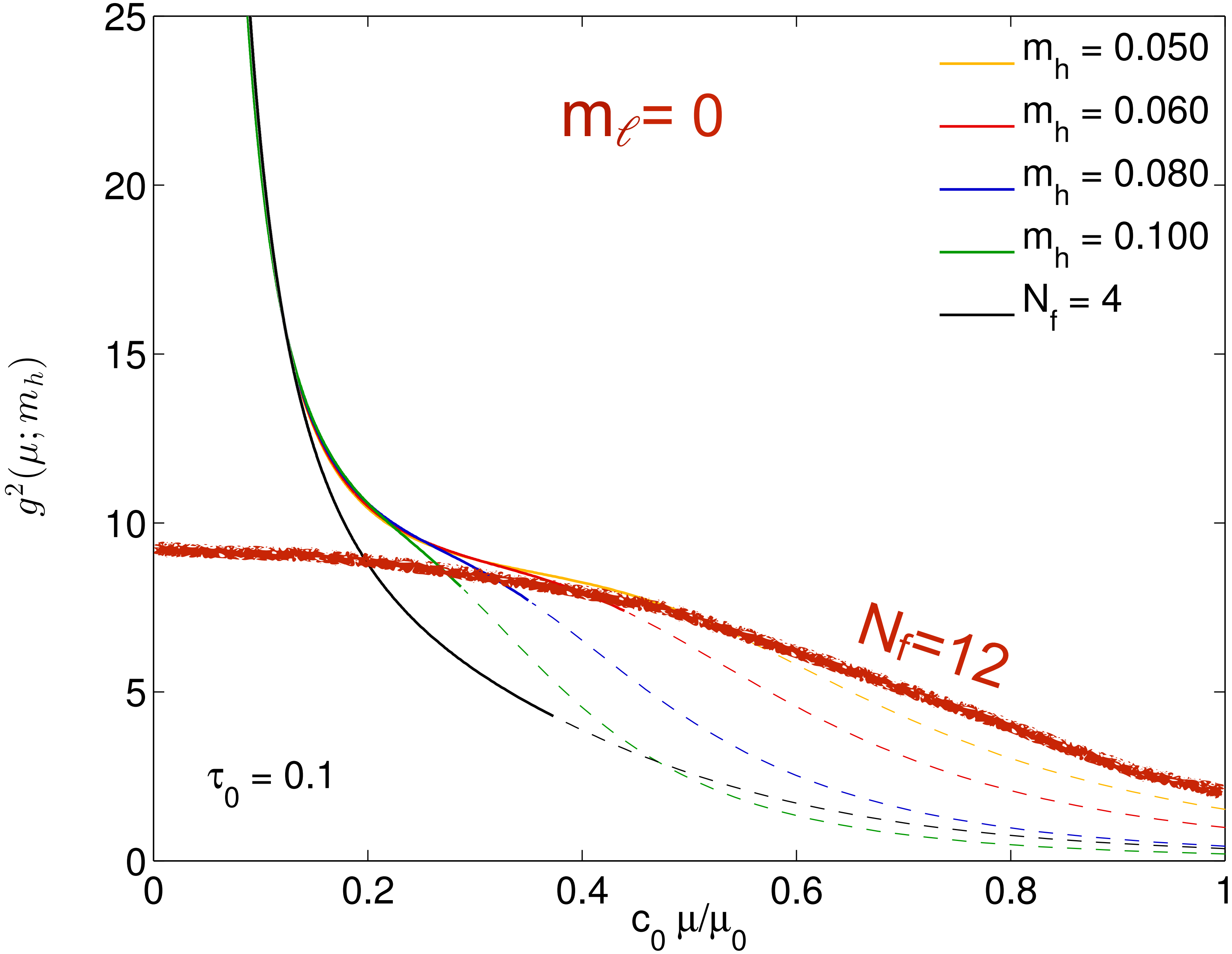

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Hyperscaling

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

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

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

$$g \to g^{\star}$$

Any 2-point correlation function at large b scales as

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

since $\quad C_H(t) \propto e^{-M_H t}$,

$$aM_H \propto (\hat{m})^{1/y_m}$$

Amplitudes (F_π) also show hyperscaling

DeGrand, AH,
PRD80, 034506 (2009)
DelDebbio, Zwicky,
PRD82, 014502 (2010)

Hyperscaling in mass-split systems

Nothing changes in the Wilson RG arguments if some of the masses remain massless:

$$C_H(t;g_i,\hat{m}_i,\mu) = b^{-2y_H} C_H(t/b;g^\star,b^{y_m}\hat{m}_h,\hat{m}_\ell = 0,\mu)$$

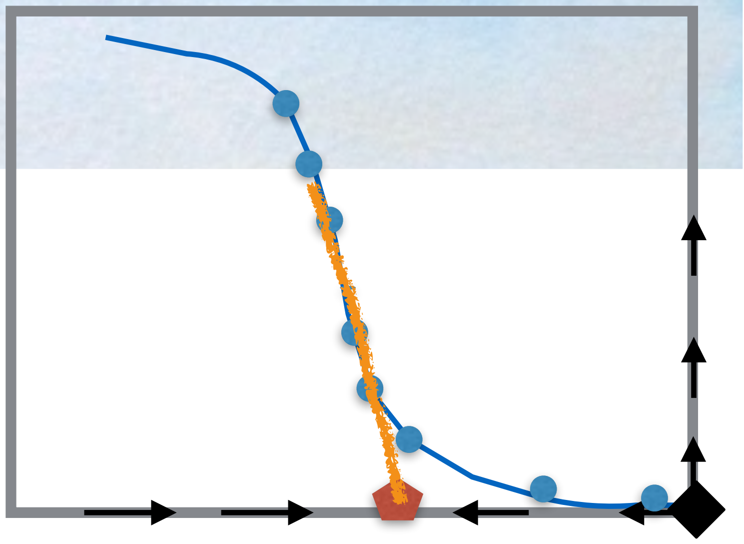
mass split systems show the hyperscaling in the $m_\ell = 0$ limit

$$aM_H \propto (\hat{m}_h)^{1/y_m}$$

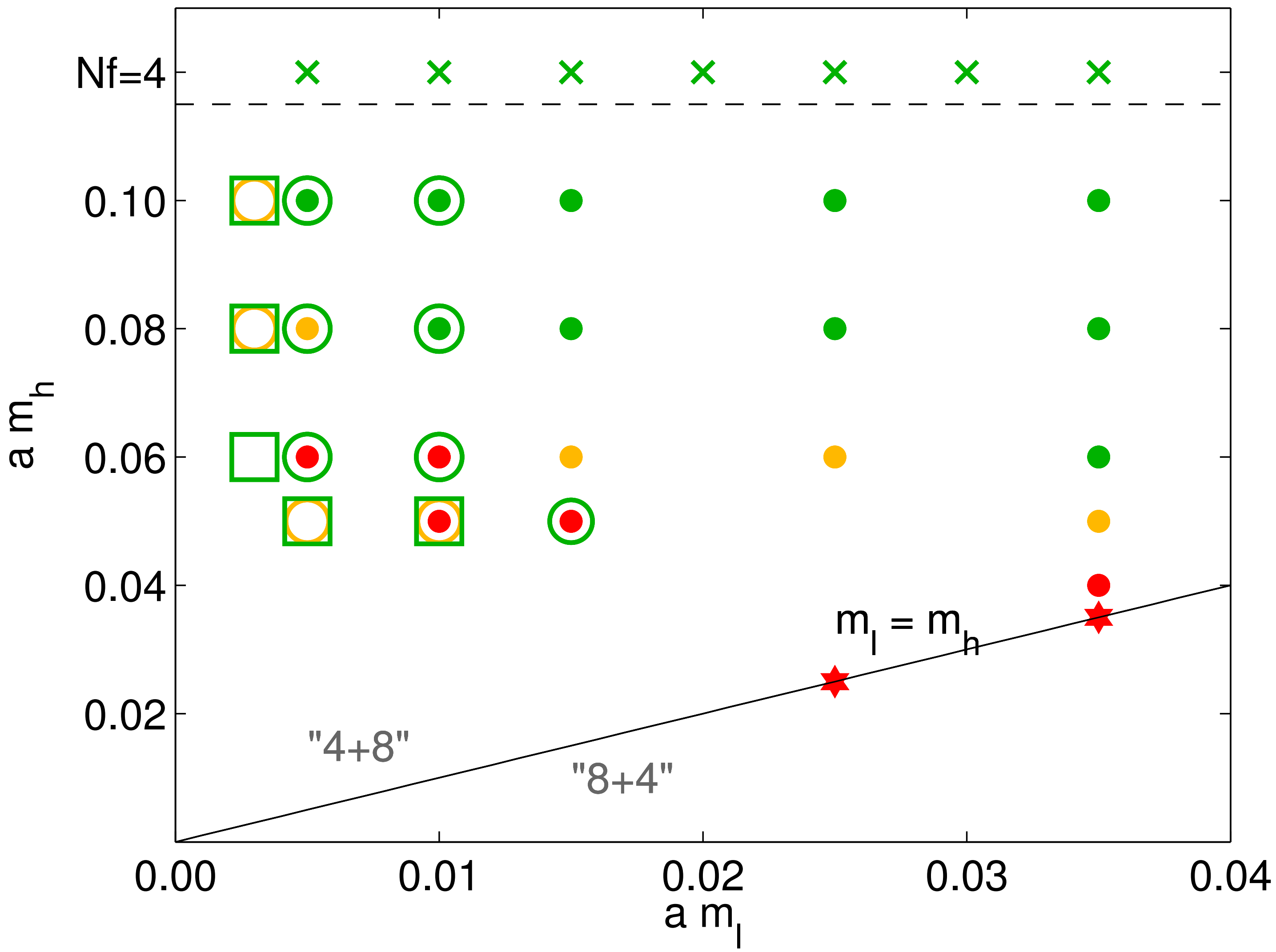
M_H can be all light, all heavy or mixed heavy-light hadron

Ratios like M_H / F_π are independent of m_h even for heavy states!
Models built on a conformal FP are very different from QCD

Parameter space



- β=4.0 (close to the 12-flavor IRFP)
- m_h = 0.100, 0.080, 0.060, 0.050
- m_ℓ = 0.003, 0.005, 0.010, 0.015, 0.025, 0.035



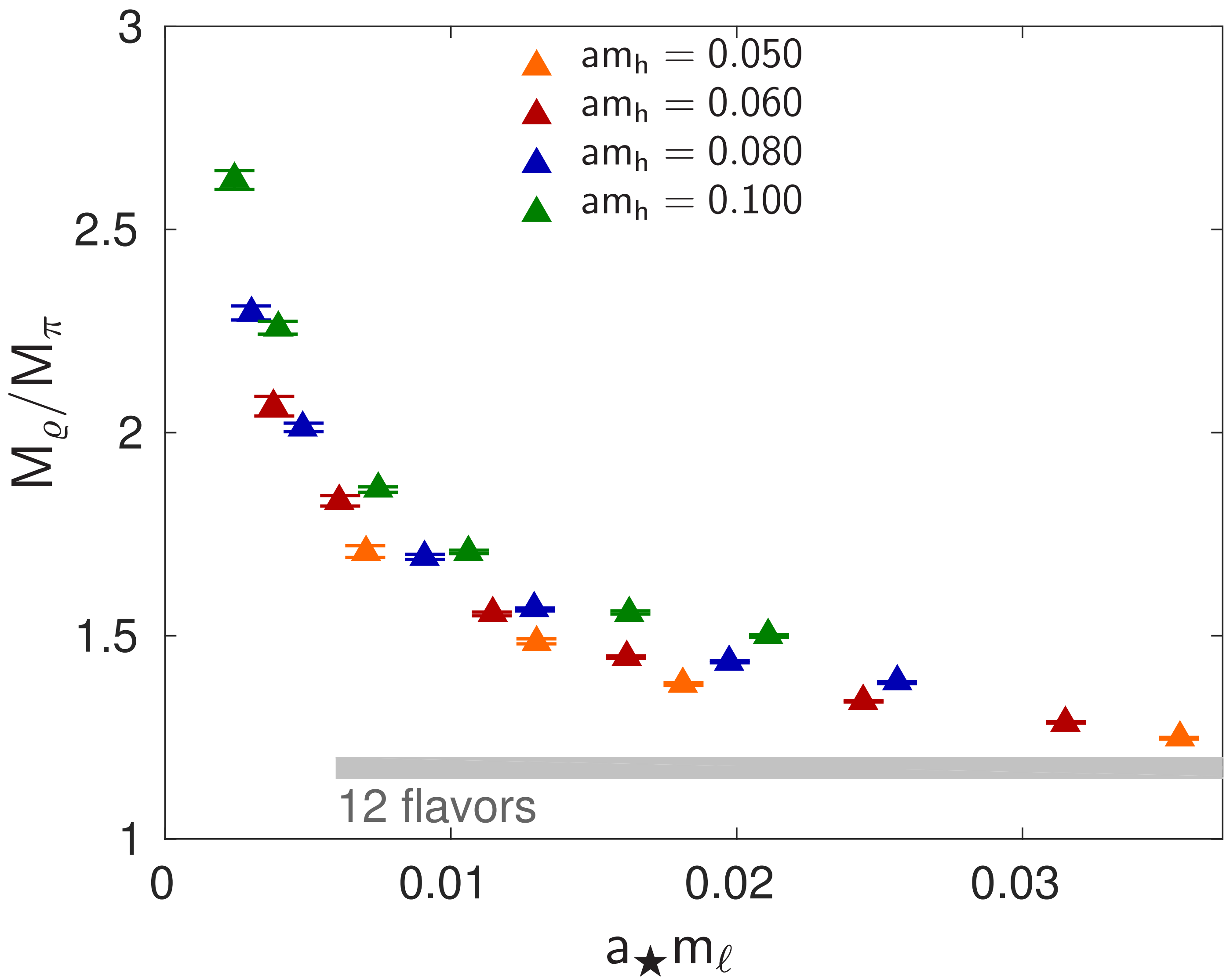
Volumes :
24^3x48, (dots)
32^3x64 (circle), 36^3x64
48^3x96 (square)
Color: volume OK / marginal/ squeezed

20-40,000 MDTU

Is the system chirally broken ?

We know it is …

M_ρ/M_π shows that we approach the chiral regime



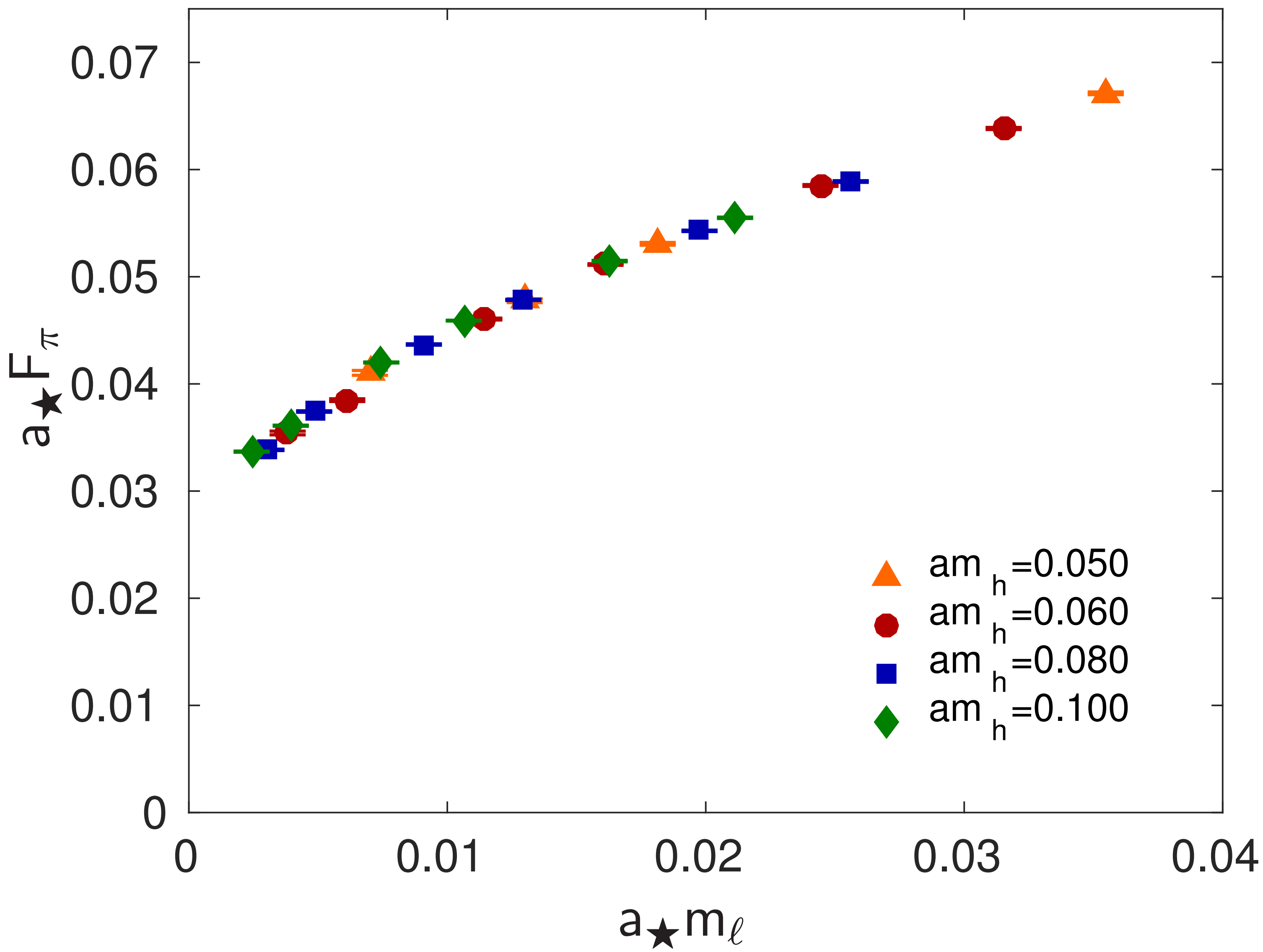
N_f=12 predicts an almost constant ratio

(as should be in a conformal system)

Is the system chirally broken ?

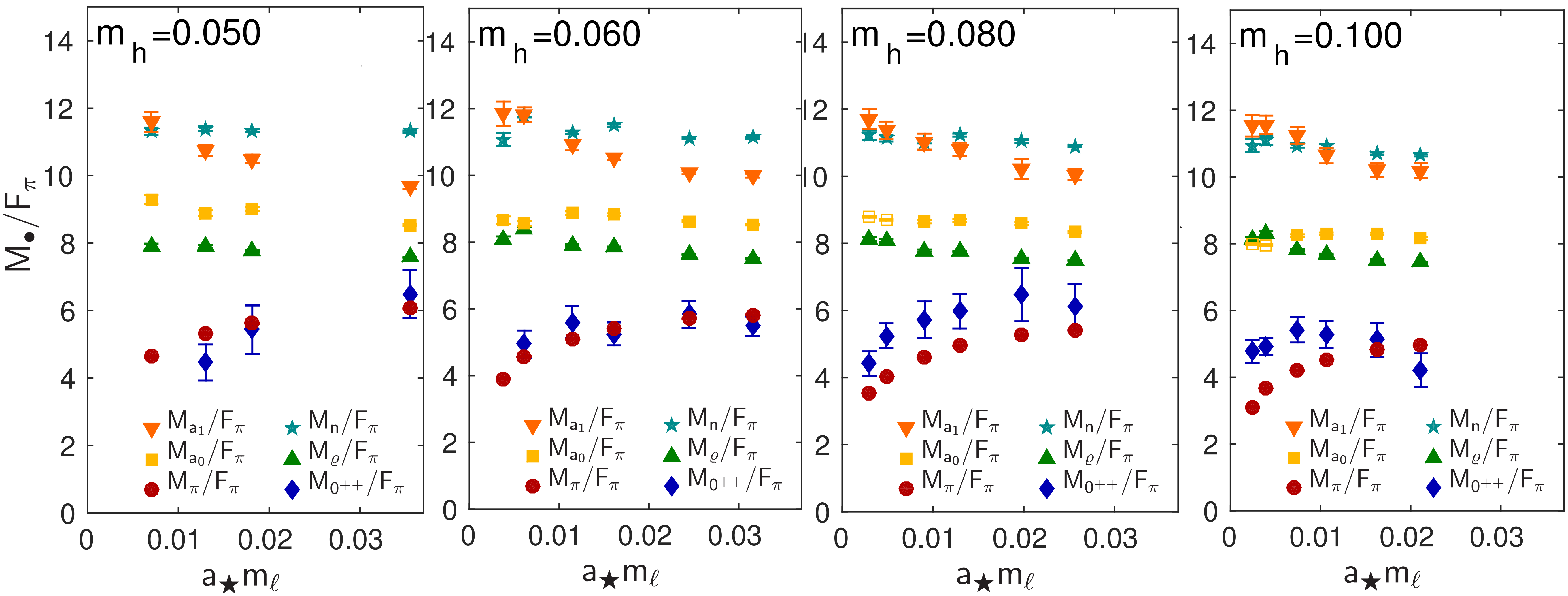
We know it is …

F_π shows hyperscaling even at finite m_ℓ



Light spectrum

Ratios M_H / F_π are independent of m_h



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

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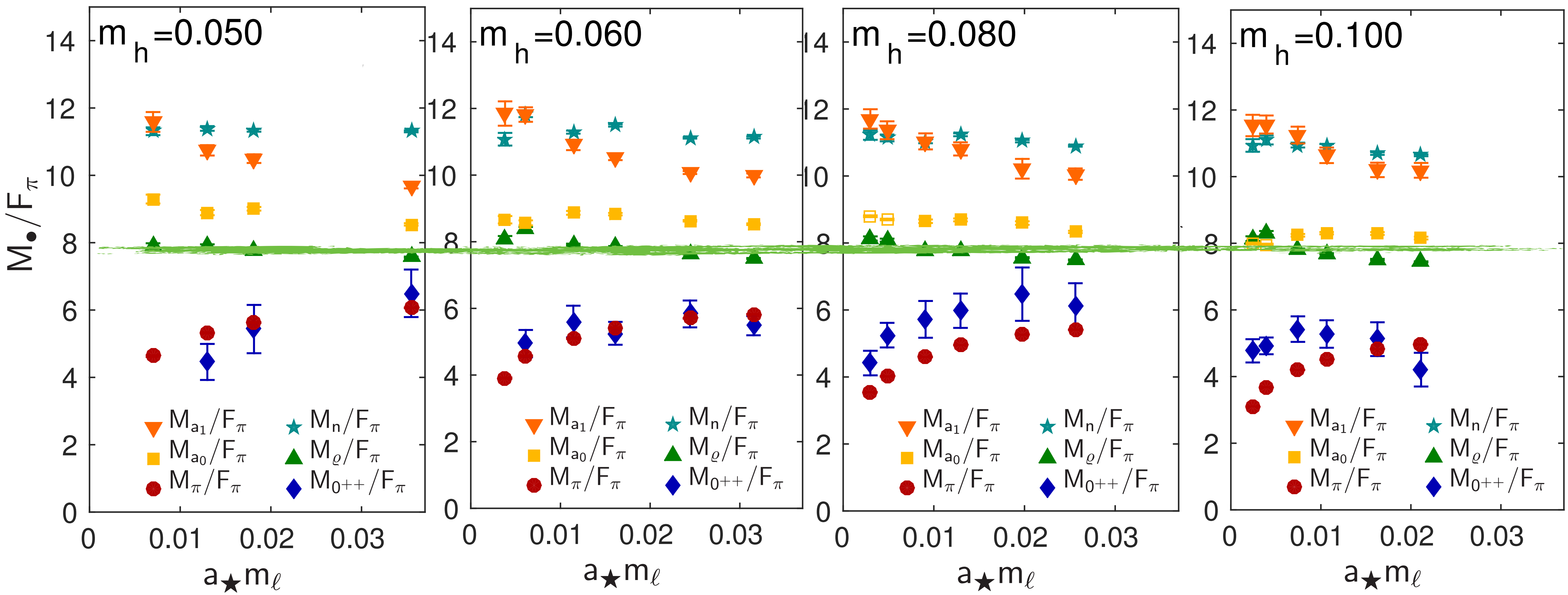

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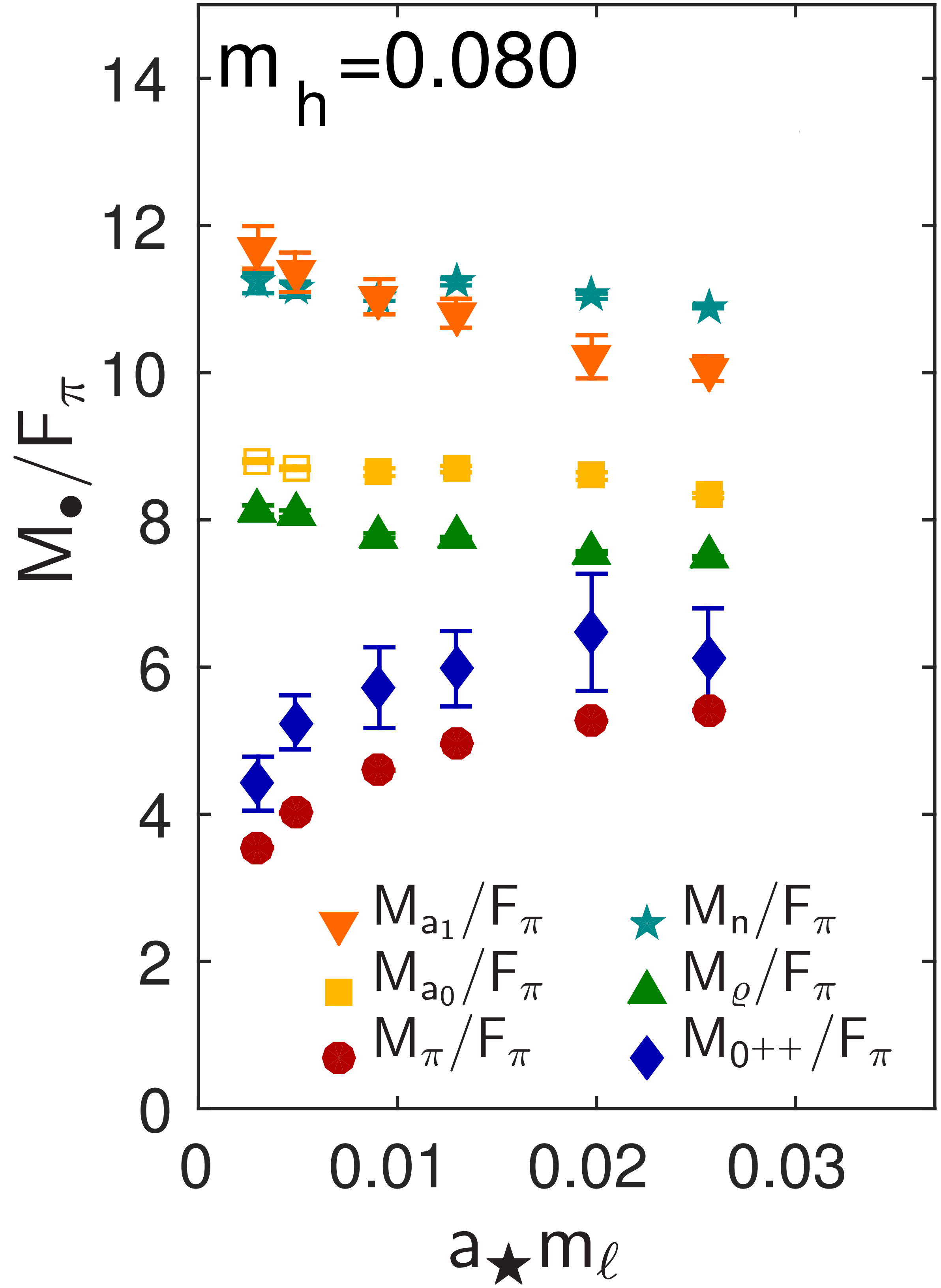

pion, rho, a0, a1, nucleon and 0^{++} scalar

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

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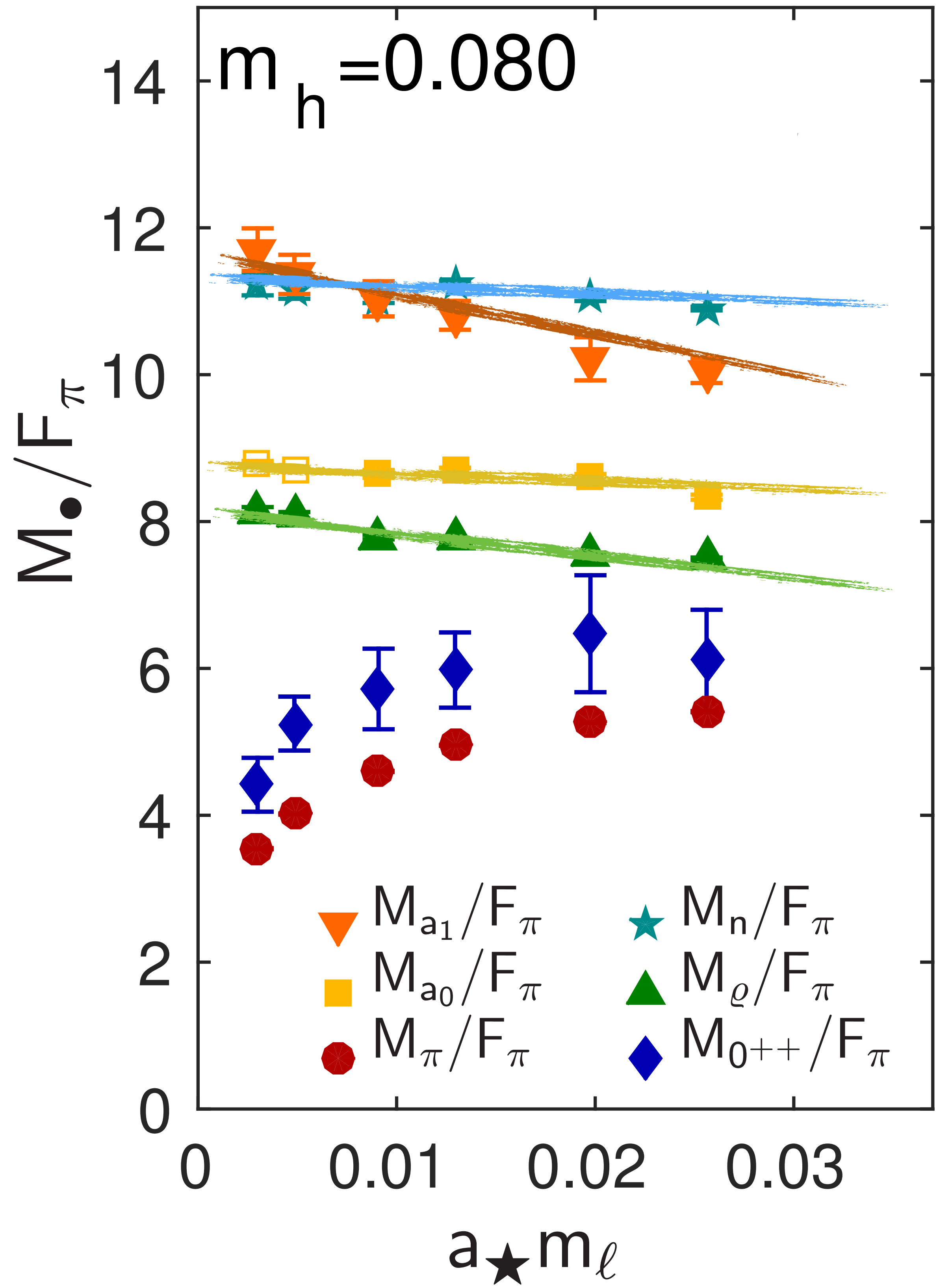

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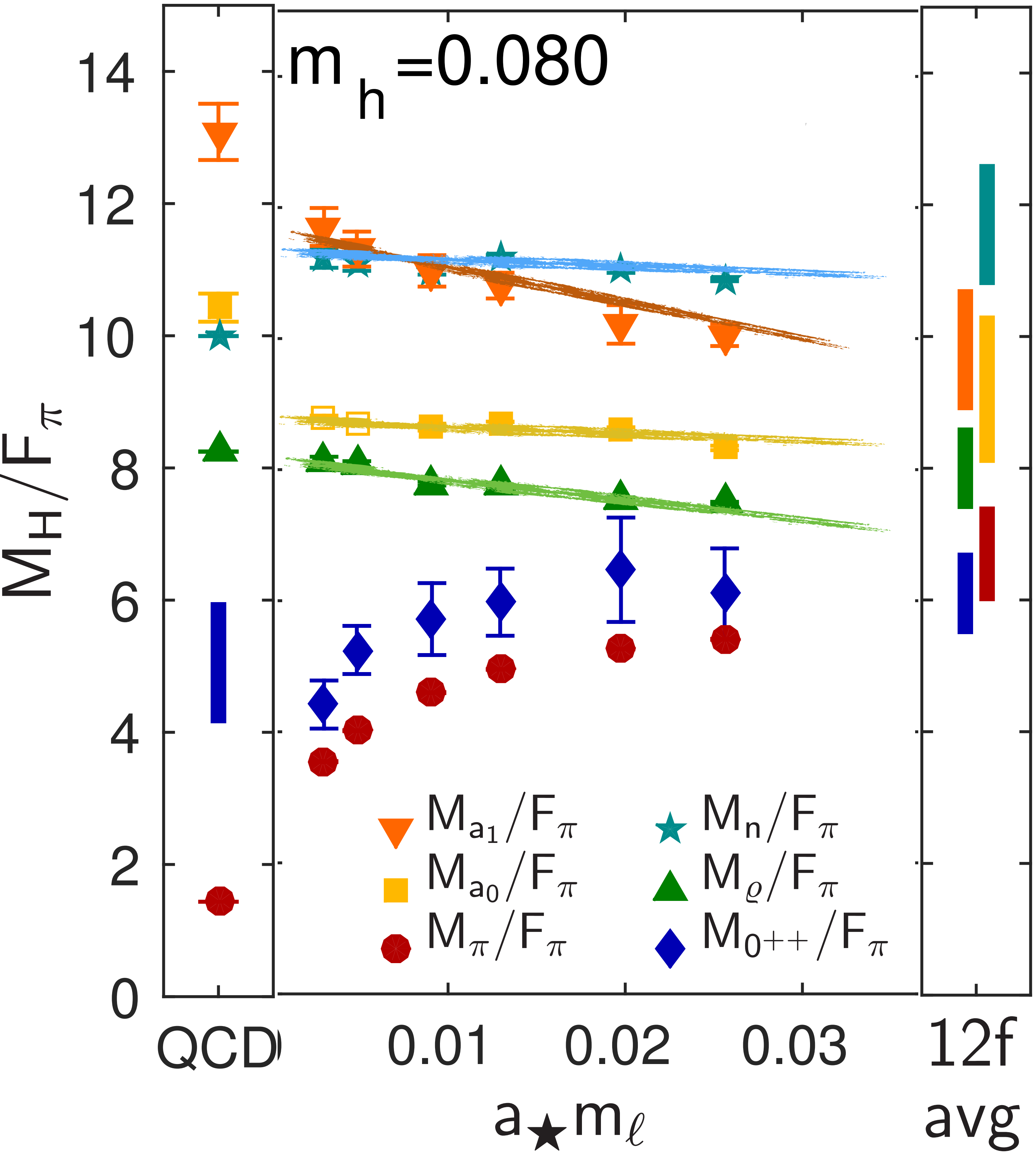


pion, rho, a0, a1, nucleon and 0^{++} scalar

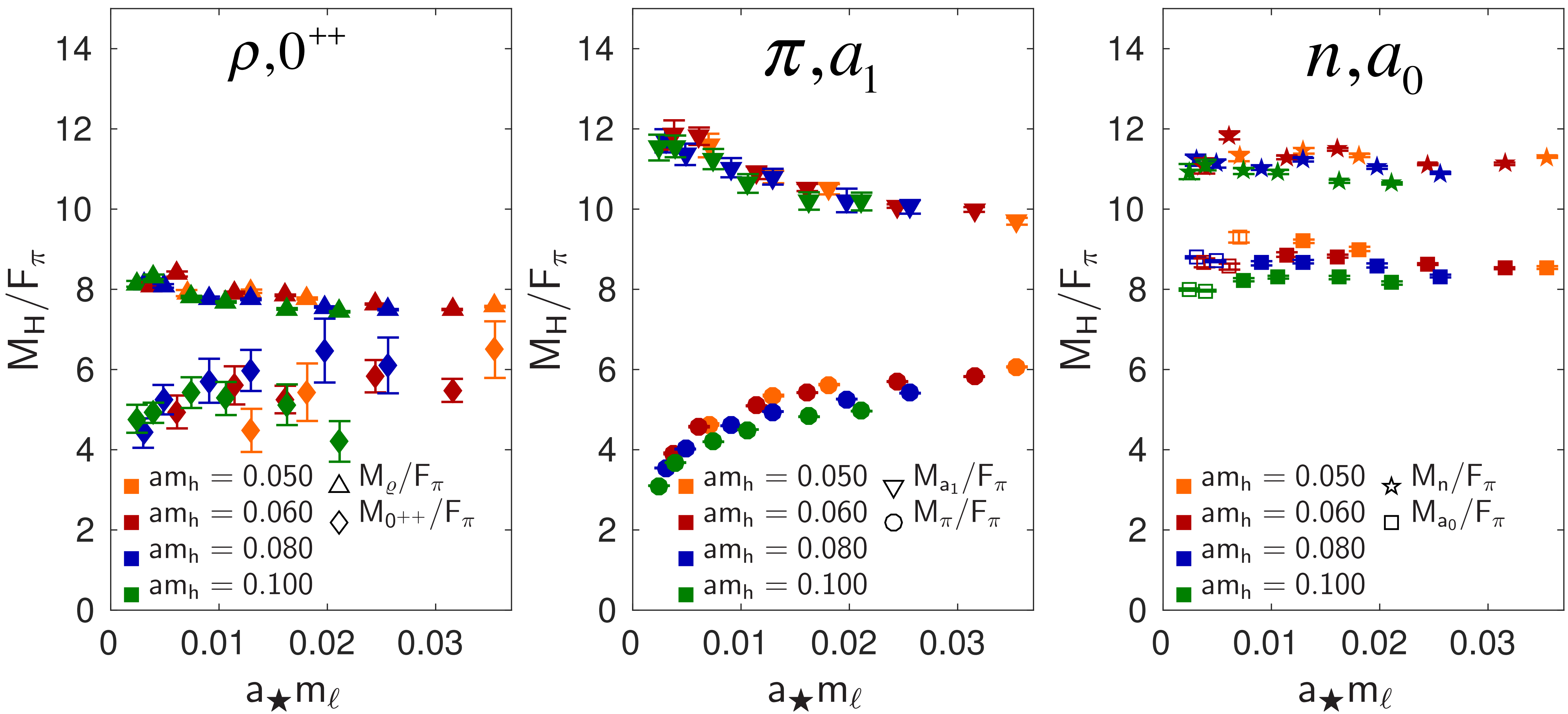
0^{++} is just above, closely following the pion - chiral limit ?

The ratios are very similar to QCD and N_f=12 but not identical

Light spectrum - hyperscaling in m

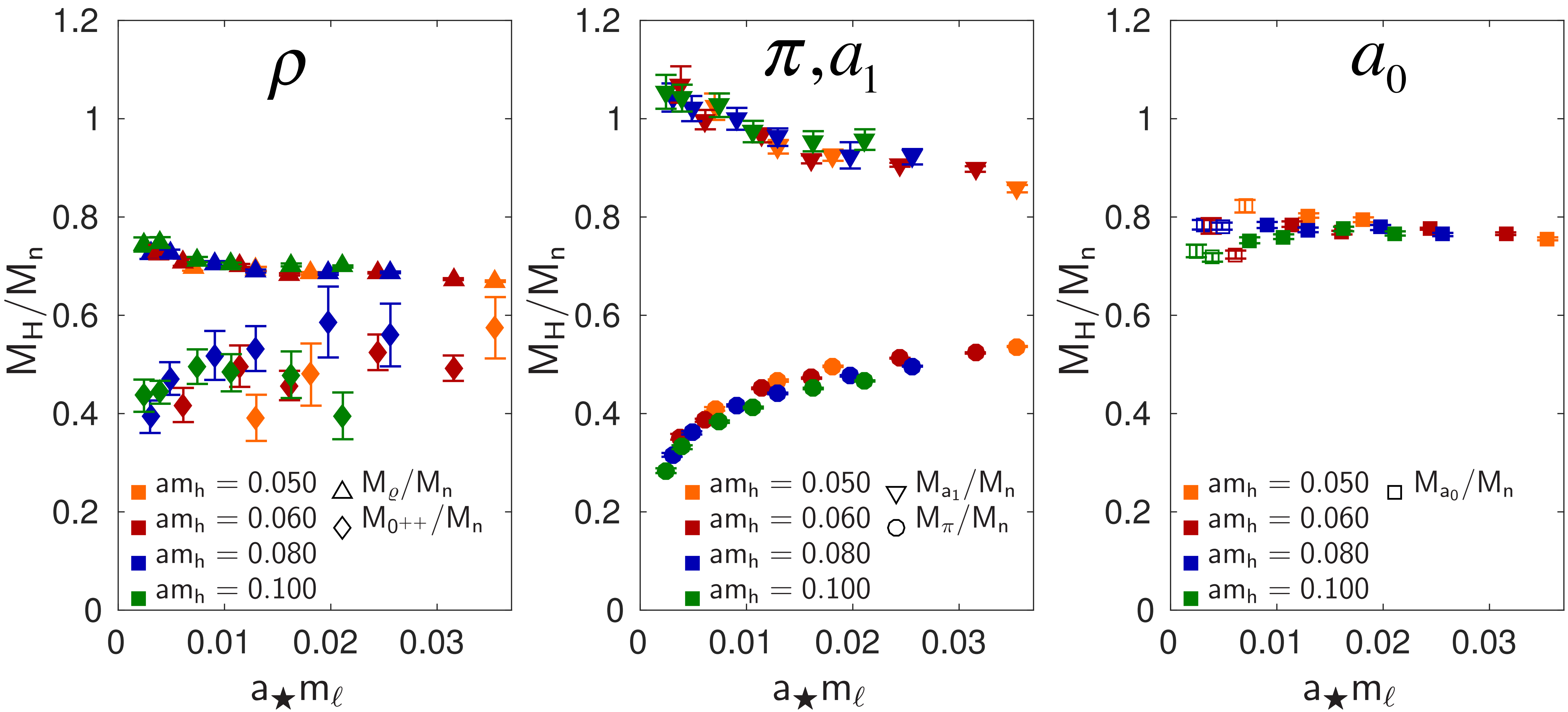
We expect hyperscaling of M_H / F_π in m_h only in the $m_\ell \to 0$ limit

0^{++} is the lightest non-Goldstone state, $M_{0++} / M_\rho \lesssim 0.5$



Light spectrum - hyperscaling in m

M_h / M_n shows even less dependence on m_h even at finite m_ℓ

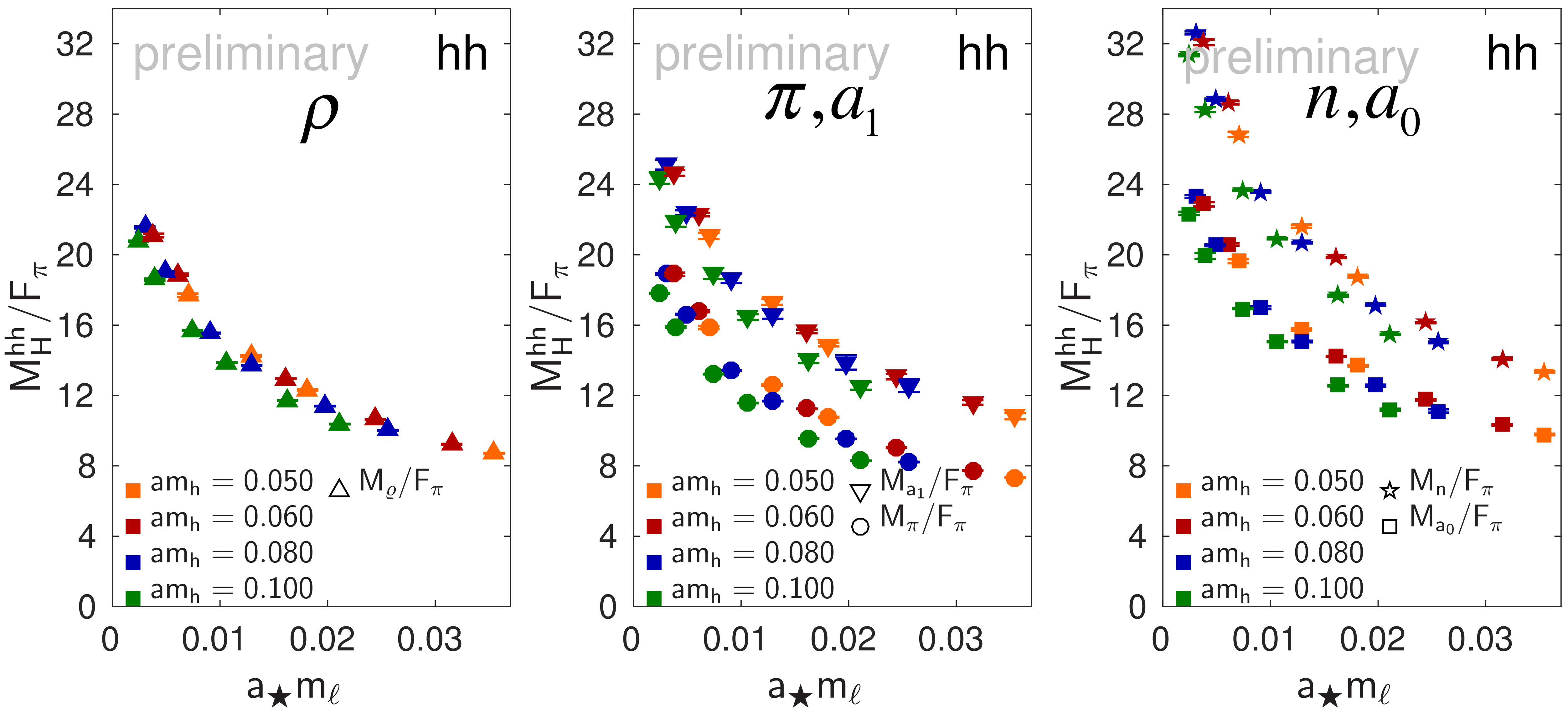


Heavy spectrum - hyperscaling in m

We expect hyperscaling of $M_H^{hh} / F_\pi^{\ell\ell}$ only in the $m_\ell \to 0$ limit

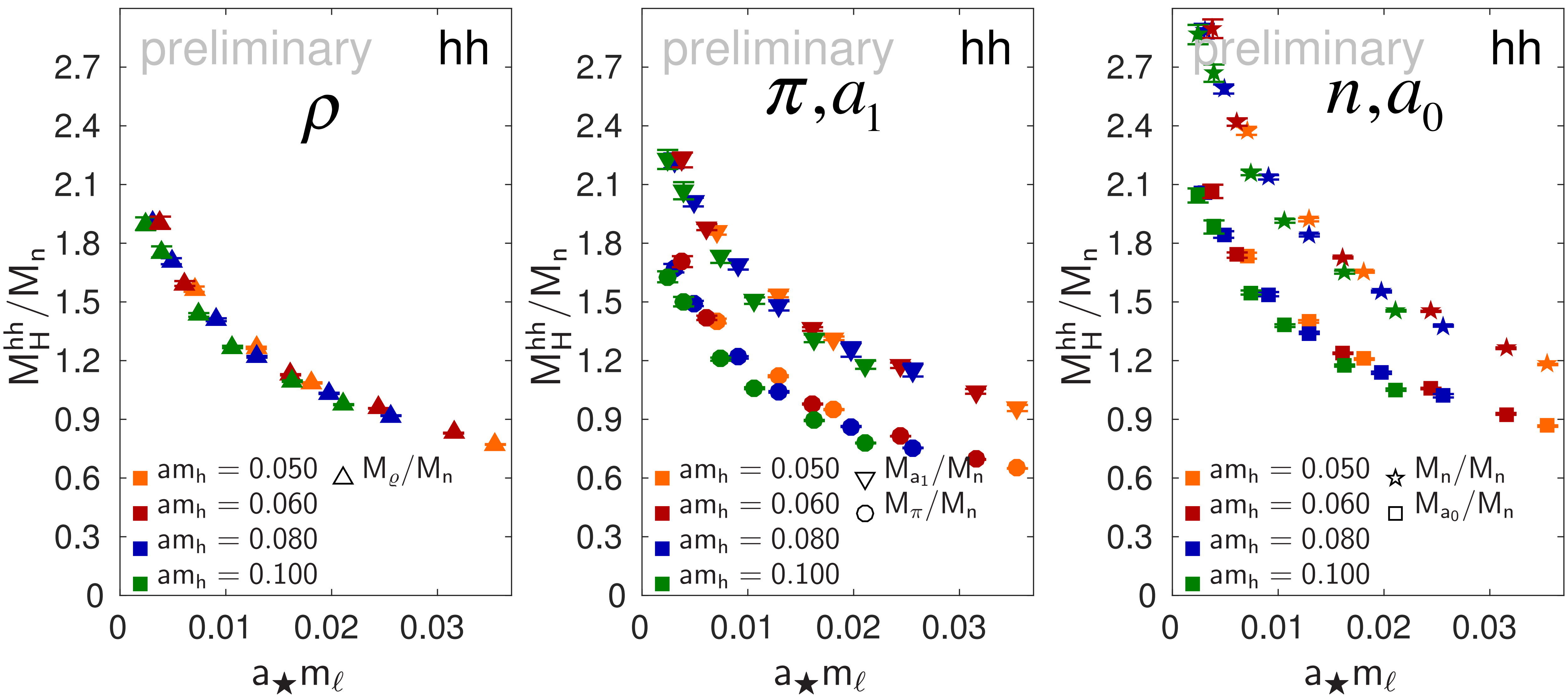
M_H^{hh} is ~3 times heavier than $M_H^{\ell\ell}$ but independent of m_h

Heavy-light spectrum should be in between light-light and heavy-heavy



Heavy spectrum - hyperscaling in m

$M_H^{hh} / M_n^{\ell\ell}$ shows even less dependence on m_h even at finite m_ℓ
but these ratios could be strongly dependent on the conformal IRFP



Chiral symmetry breaking on a conformal FP

Mass-split models that are conformal in the UV, chirally broken in the IR

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

How does the spectrum change if we change N_f or cascade the mass?

Chiral symmetry breaking on a conformal FP

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$\Big\}$ UV

- 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

How does the spectrum change if we change N_f or cascade the mass?

Chiral symmetry breaking on a conformal FP

Mass-split models that are conformal in the UV, chirally broken in the IR

Best of both worlds:

- controlled walking
- anomalous dimension
- hyperscaling for all masses: predictive power!

UV

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IR

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Conclusion & Summary

Many interesting possibilities ….

Lattice studies can investigate strongly coupled systems
- both individual and generic properties

Models with split fermion masses, built on a conformal IRFP, has new and unusual properties

The 4+8 system is not ideal:

- N_f =12 is far above the conformal window with small anomalous dimension $\gamma_m \approx 0.25$
- N_f =10, perhaps even 8 might be better

Questions for the future:
How does the spectrum change if we change N_f or cascade the mass?
What is general, what is model specific?