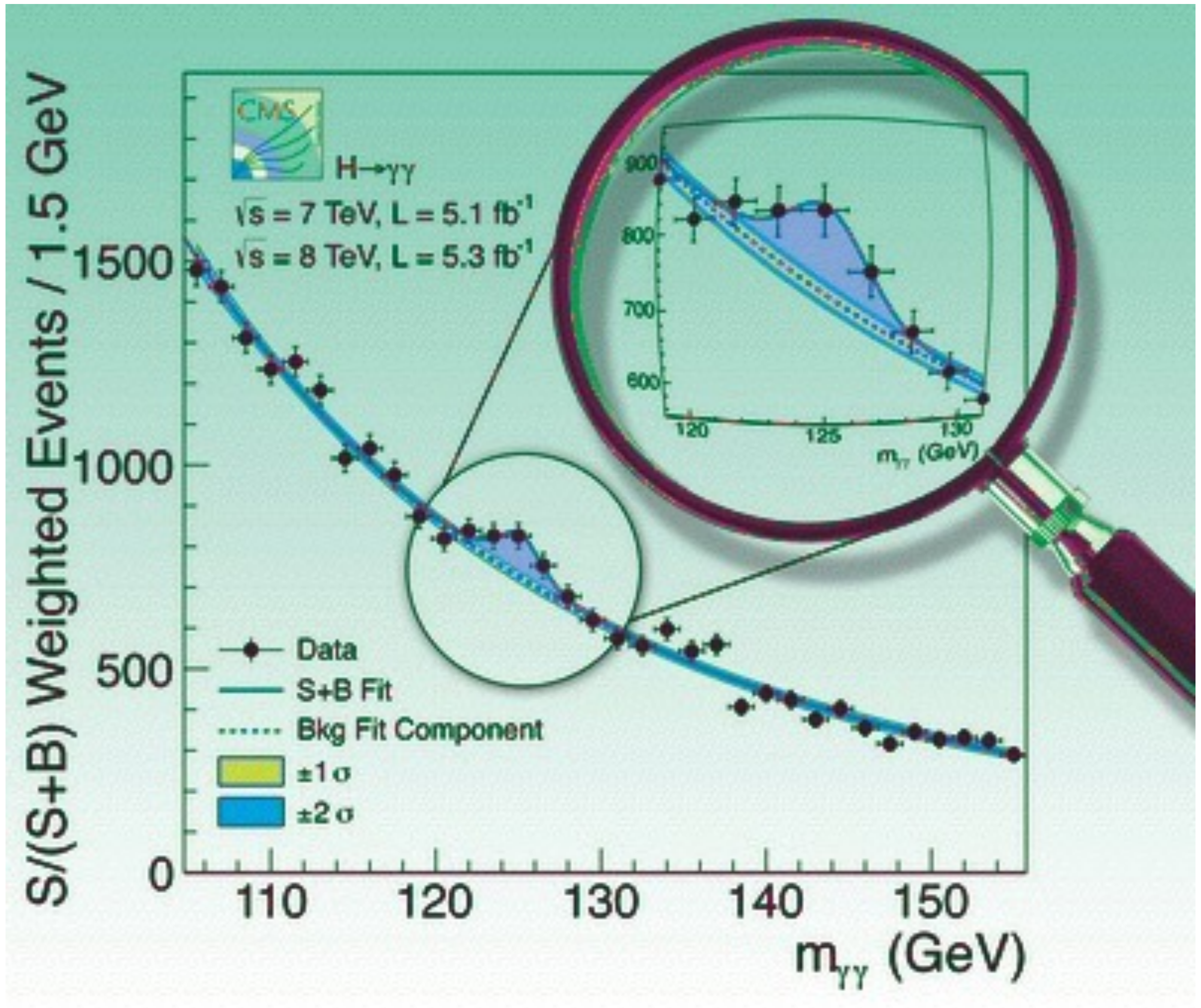
Strongly coupled gauge theories: What can lattice calculations teach us?

Anna Hasenfratz
University of Colorado Boulder
CERN, Nov 25, 2015

Higgs era of particle physics

The 2012 discovery of the Higgs boson "completed" the Standard Model



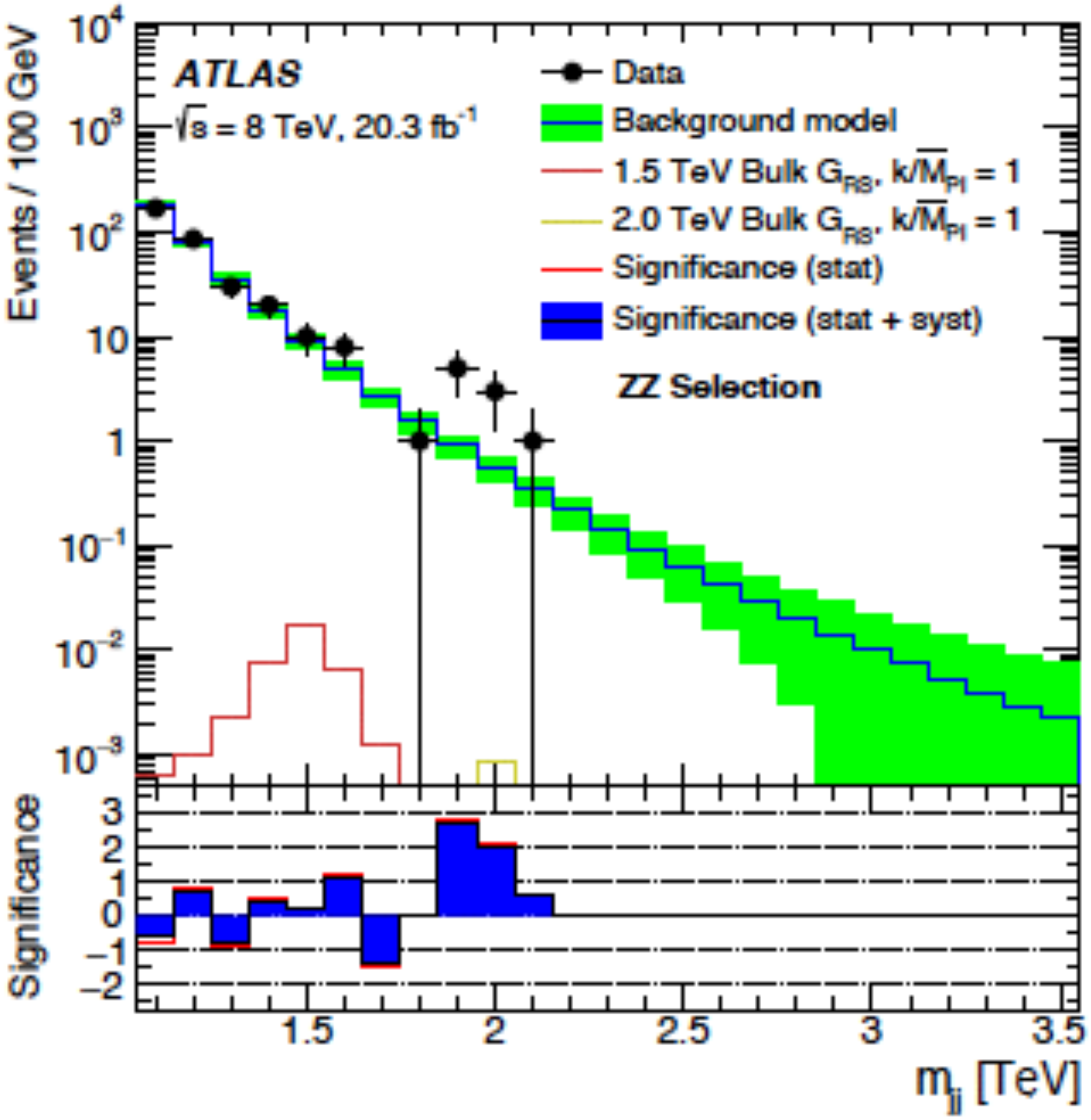
Yet many questions remain open

- The Standard Model is not UV complete
- What is the Higgs boson
- What is the nature of electroweak symmetry breaking?

No answers — yet

Higgs era of particle physics

Tantalizing possibility from ATLAS : 3.5 σ excess at 2TeV suggesting a vector resonance (1506.00962)

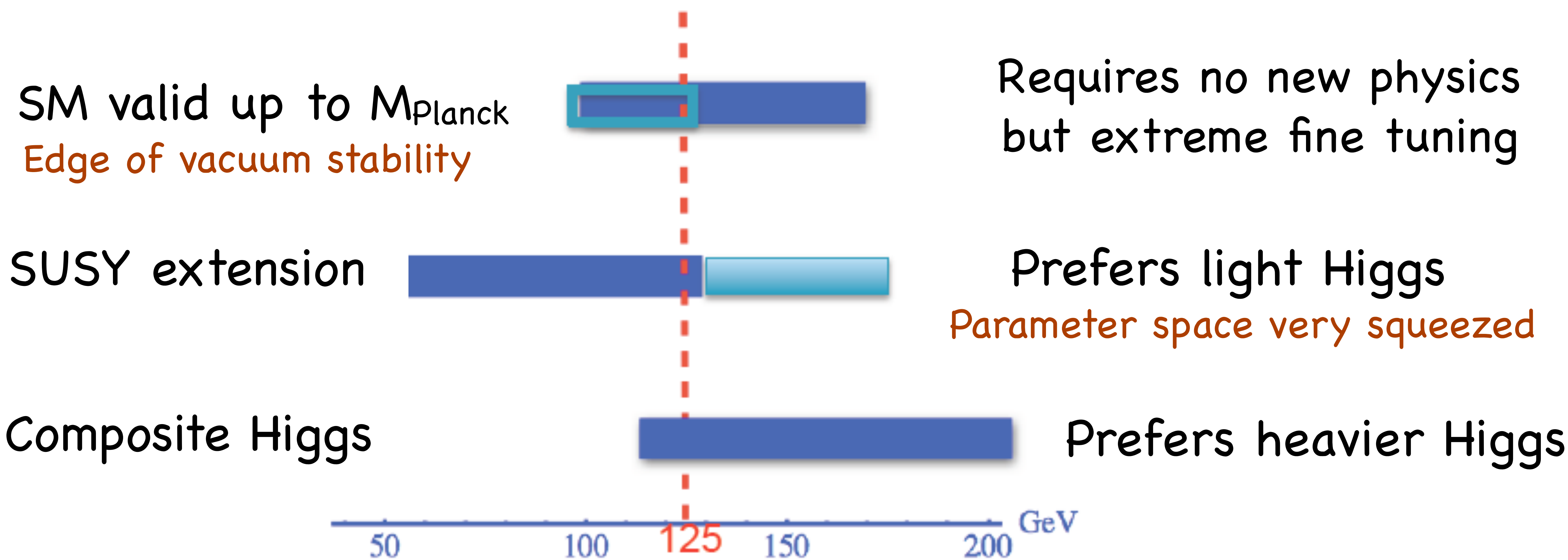


- Does the ATLAS result point to new physics?(if it is indeed there)
- Which BSM models can describe it?
- What other predictions do those models have?

Possible BSM models

a few popular options …

blue bands represent typical ranges for Higgs mass (from M. Carena)



New symmetries are needed to stabilize a scalar against (quadratic) UV divergences (below the Planck mass).

Composite Higgs - strong dynamics

Assume a new interaction:

N_f fermions, $SU(N_c)$ gauge fields, coupled to the Standard Model:

if spontaneously chirally broken

- 3 Goldstone pions become the longitudinal W, Z
  —> break EW symmetry
- The Higgs could be a $\bar{q}q$ (possibly qq) bound state
- Tower of additional hadronic states appear in experiments

What keeps the Higgs light?

Spontaneously broken symmetry —> massless Goldstone bosons

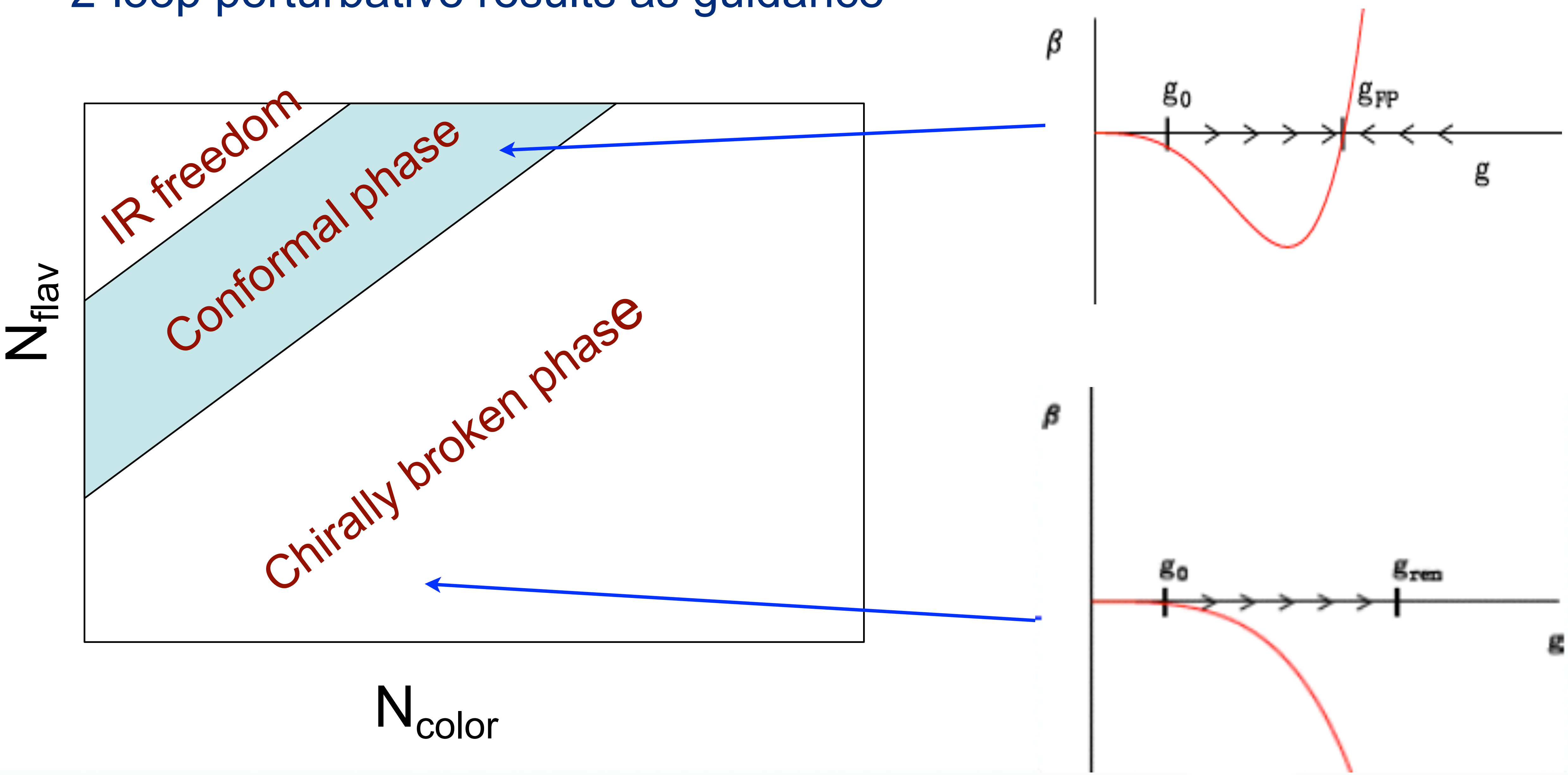
- Flavor symmetry: SSB leads to massless "pions"
- Scale symmetry: SSB leads to dilaton: near-conformal models

This is not the 80's technicolor!

Theory space:

SU(N_{color} ≥2) gauge fields + N_{flavor} fermions in some representation

2-loop perturbative results as guidance



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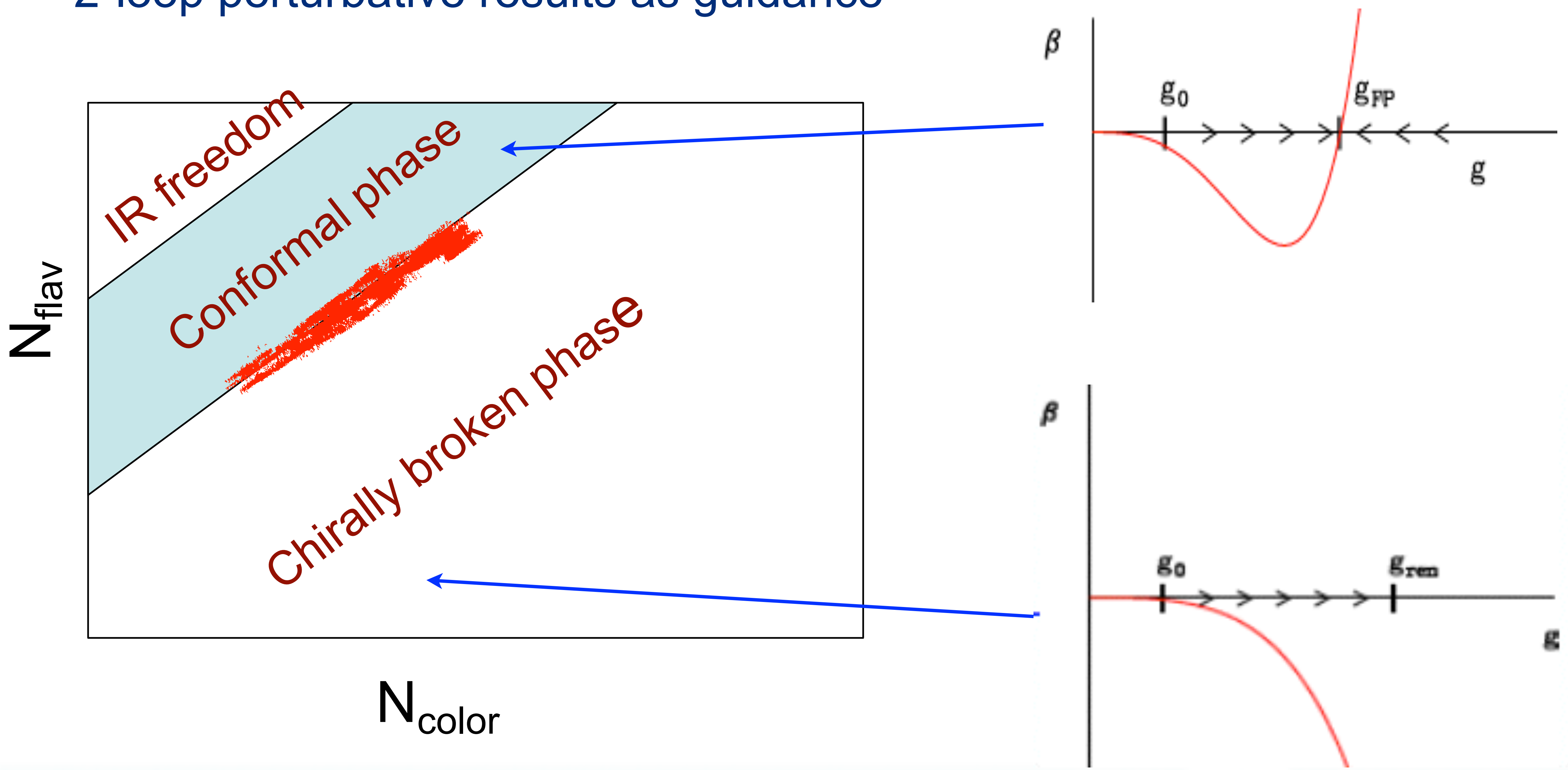

Candidates

Any candidate model must be

- chirally broken - below the conformal window
- has 3 massless Goldstone pions
- most likely strongly coupled
- light scalar, enhanced condensate, etc

SU(2) gauge, adjoint fermions: $N_f = 2$: conformal ;

SU(2) gauge, fundamental fermions:

$N_f = 4$: chirally broken ; $N_f = 8$: conformal ; $N_f = 6$??

SU(3) gauge, fundamental fermions:

$N_f = 6$: chirally broken ; $N_f = 12$: conformal ; $N_f = 8$??

SU(3) gauge, sextet (sym rep) fermions: $N_f = 2$??

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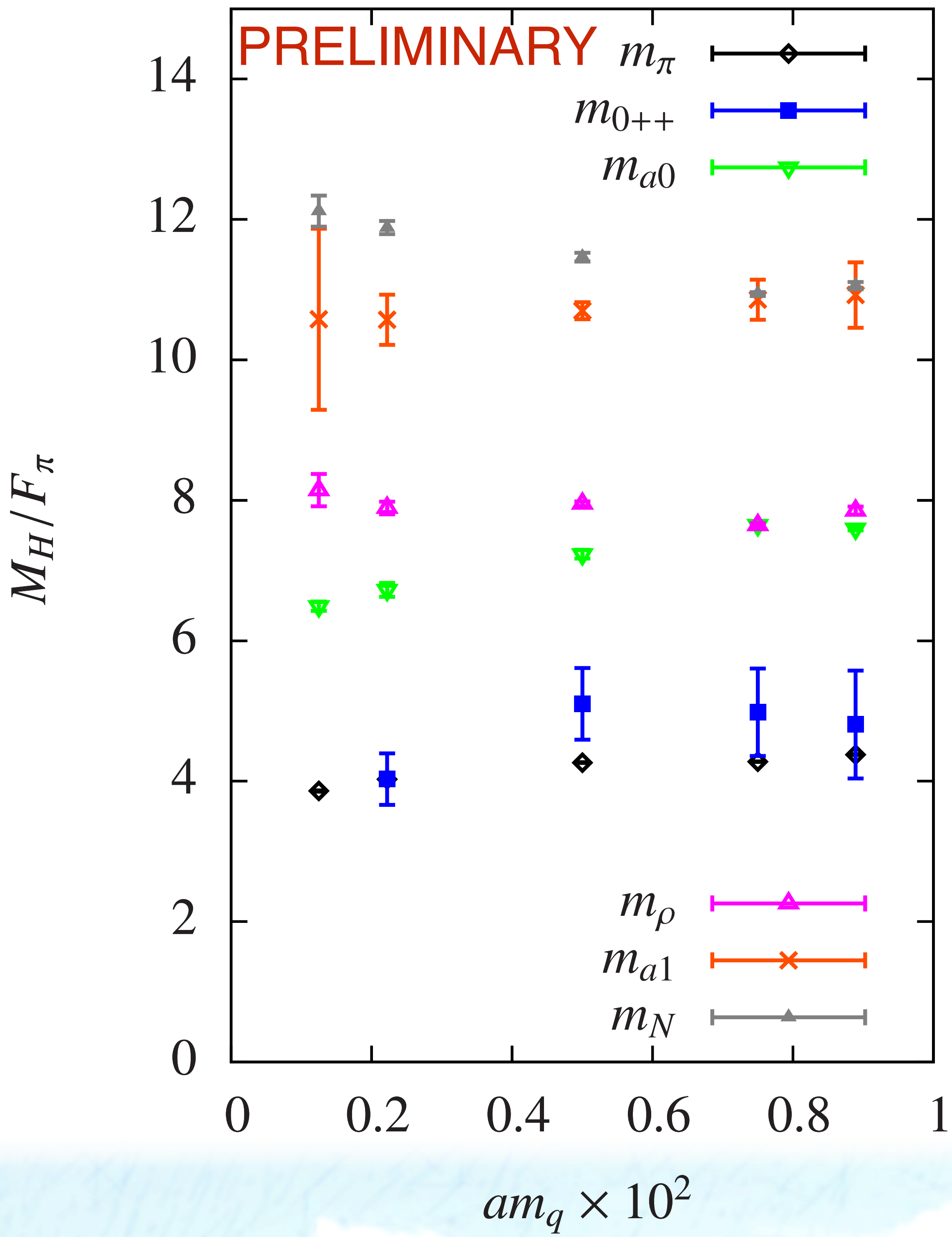
SU(3) gauge, sextet (sym rep) fermions: $N_f = 2$??

SU(3) with 8 fundamental fermions

8-flavor fundamental : old time favorite (?)

- close to the conformal window
  (finite T studies inconclusive, AH, D. Schaich)
- if chirally broken, it has way too many Goldstones
- extensive studies buy LatKMI collaboration and others
- new large scale study by LSD Coll. (1512.xxxx)

SU(3) with 8 fundamental fermions



M_H / F_π vs m_f

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

In BSM scenario

$$F_\pi \sim vev = 250 GeV$$

With $M_\rho / F_\pi \approx 8$ this model predicts a 2TeV vector resonance!

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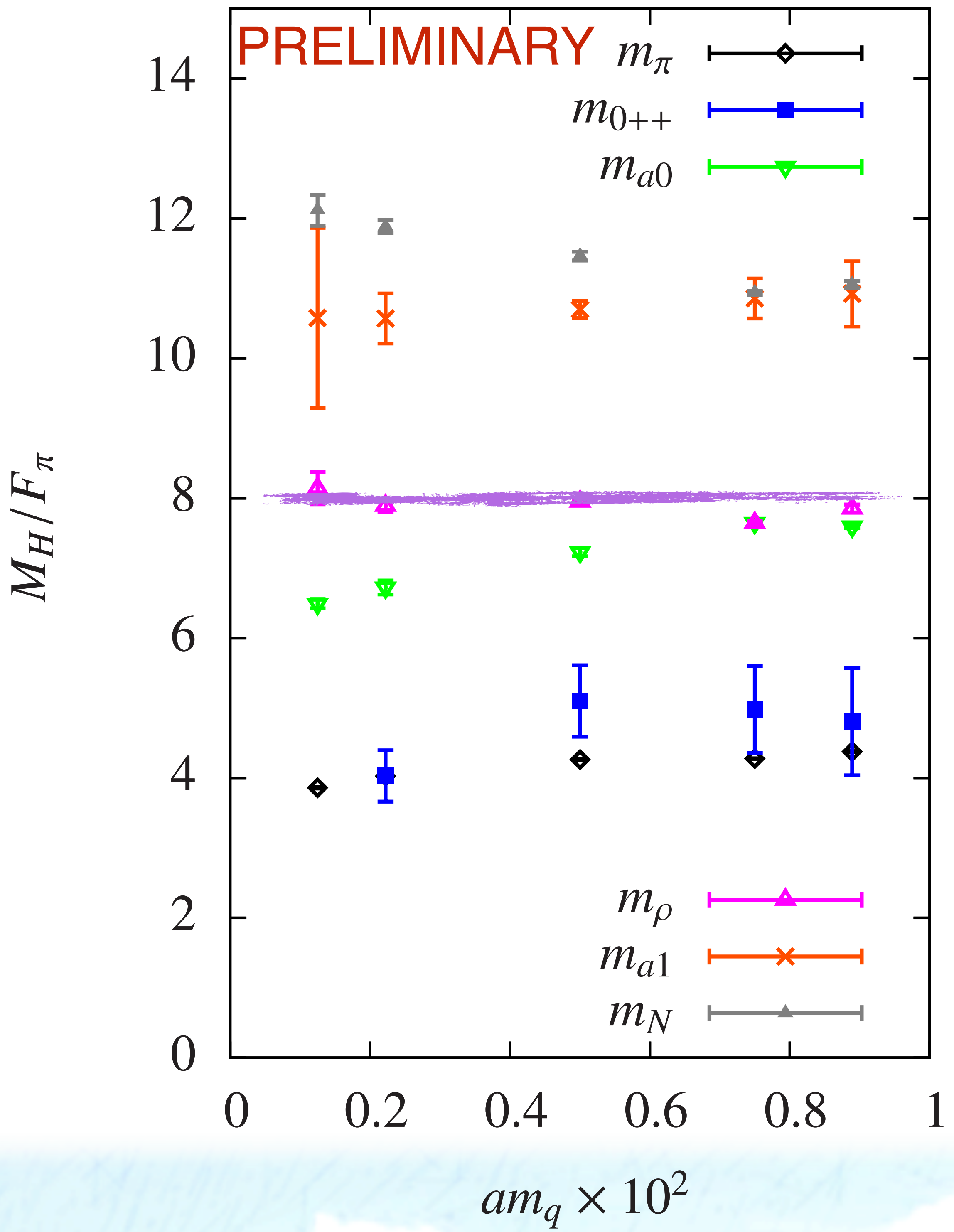

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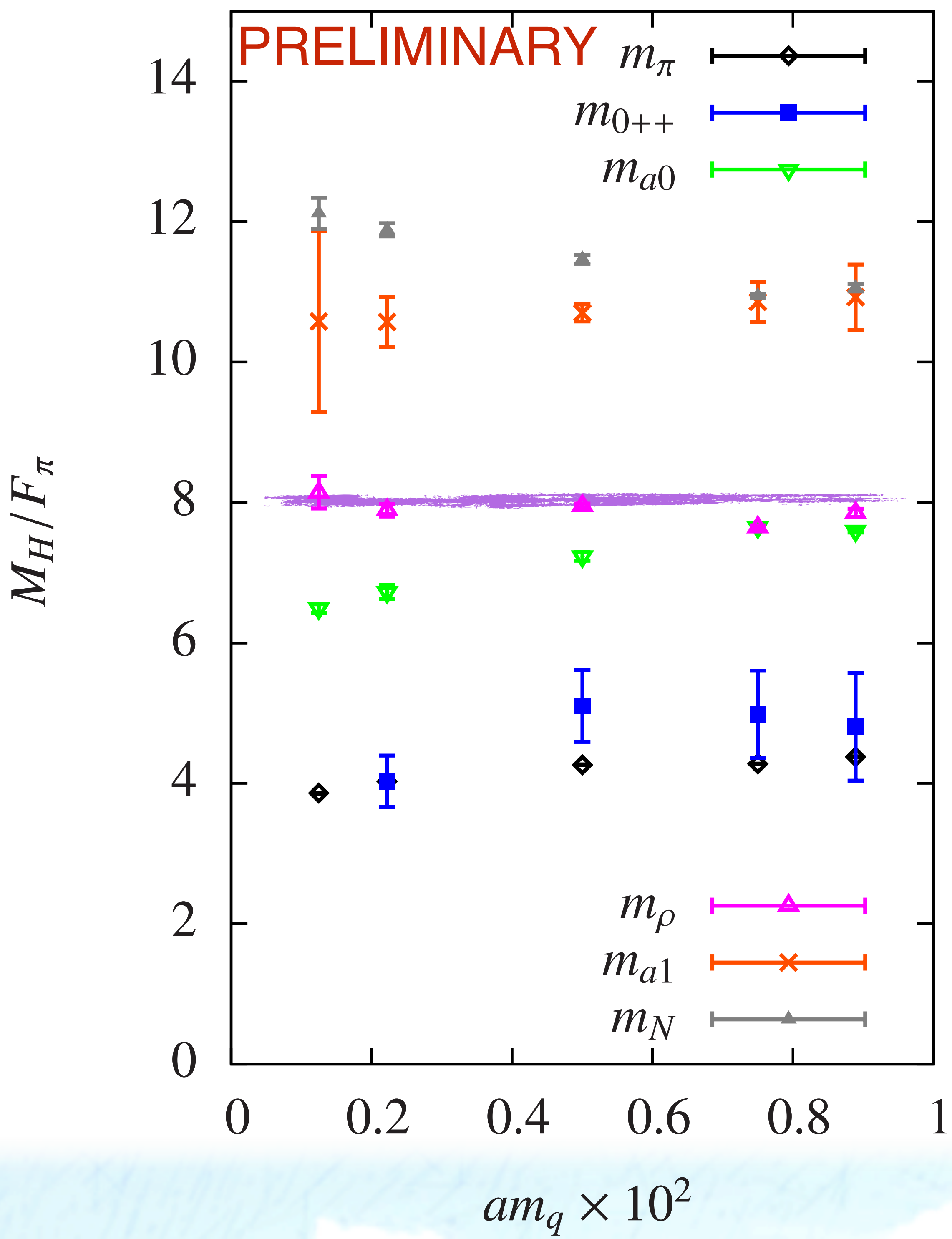


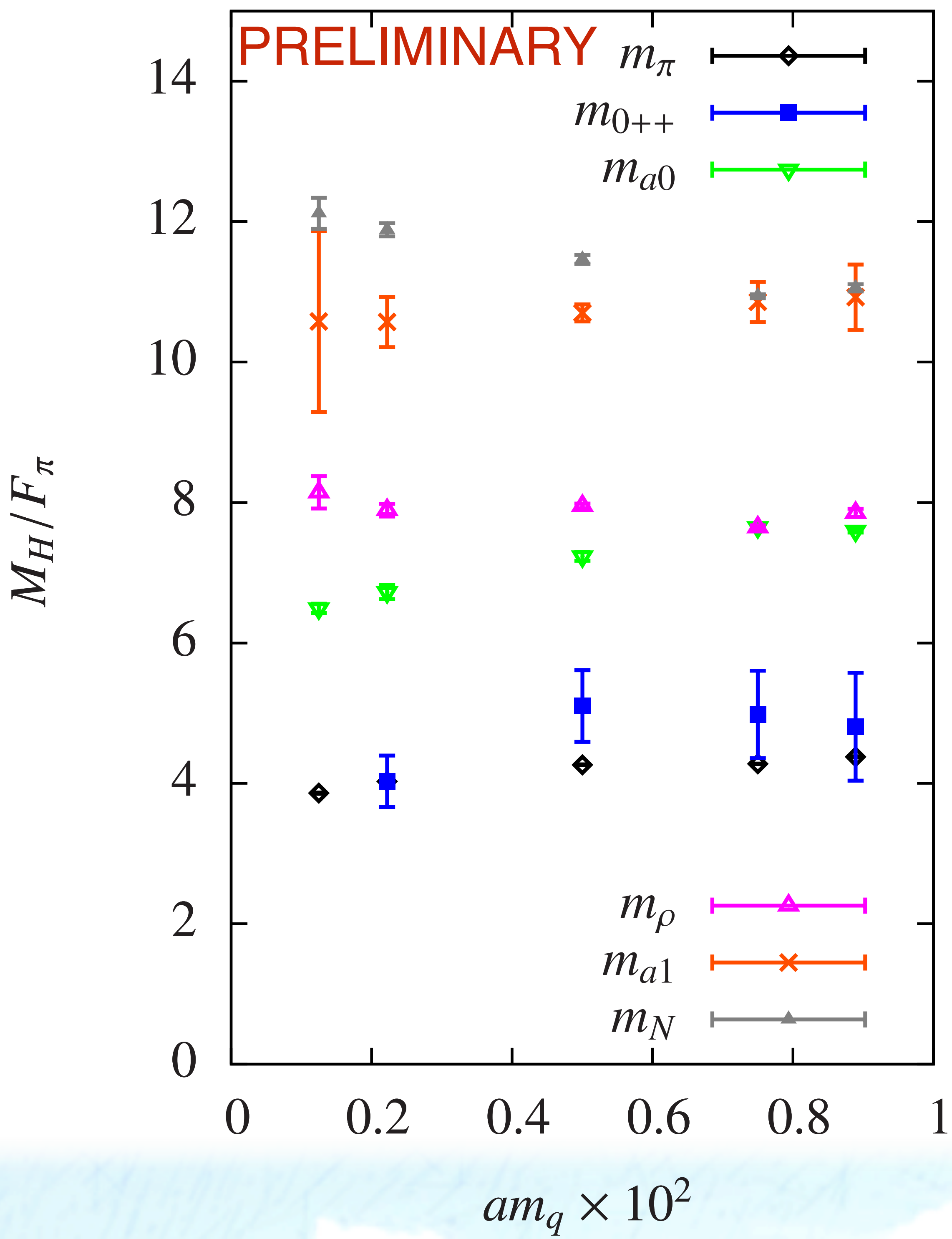
2TeV vector resonance
is very exciting

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

- QCD
- 4-flavor SU(3) fund.
- 8 flavor SU(3) fund.
- 2 flavor sextet
- 12 flavor SU(3) fund.

Why?

SU(3) with 8 fundamental fermions



Several resonances are in the 2-3 TeV range

0^{++} scalar:

- it is degenerate with or lighter than the pion
- in a chirally broken model it must “peel off” from the pion

How to take the chiral limit?

Near-conformal models with degenerate fermions

Issues, Questions:

- Is there a system with N_c color, N_f flavor in given rep that is close enough to the conformal window?

- Will the spontaneously broken conformal symmetry lead to a light dilaton? Or is a light scalar accidental?

- What happens to the extra Goldstone bosons?

- Is there walking? Are the EW constraints satisfied?

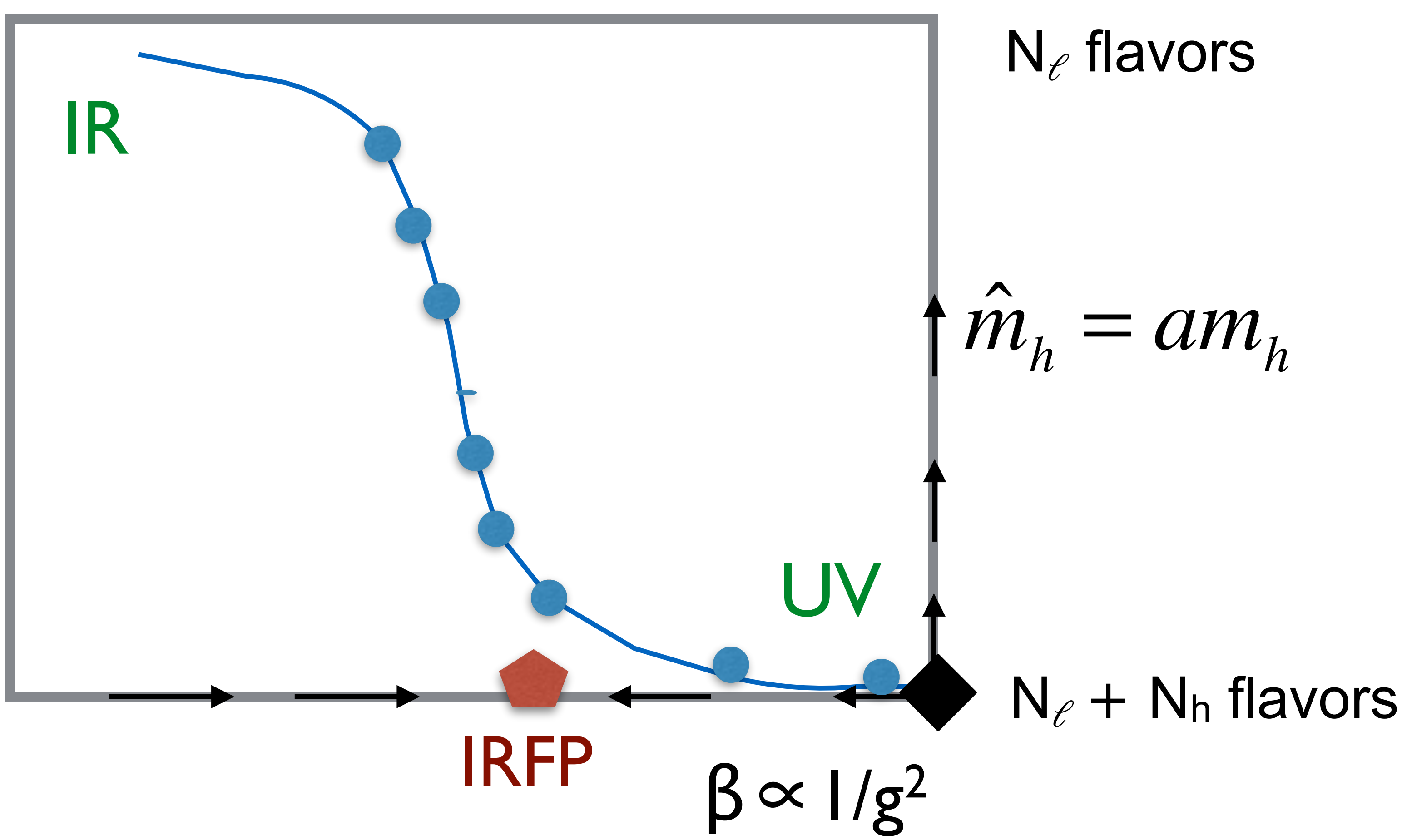
Mass split model : a different approach

Build a model on a conformal IRFP :

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

  N_ℓ flavors are massless, $m_\ell = 0$ —> chirally broken

  N_h flavors are massive, m_h varies —> decouple in the IR



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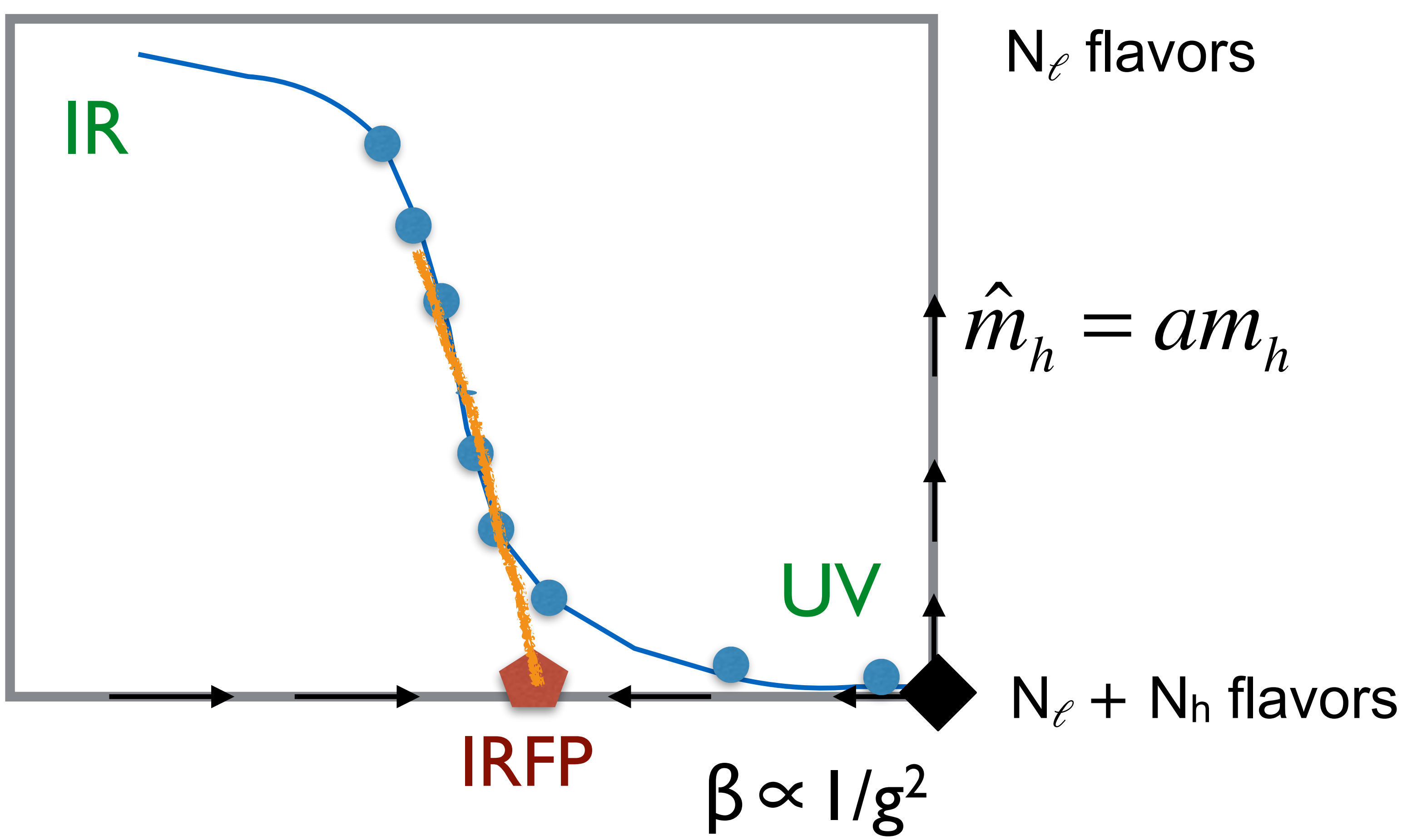
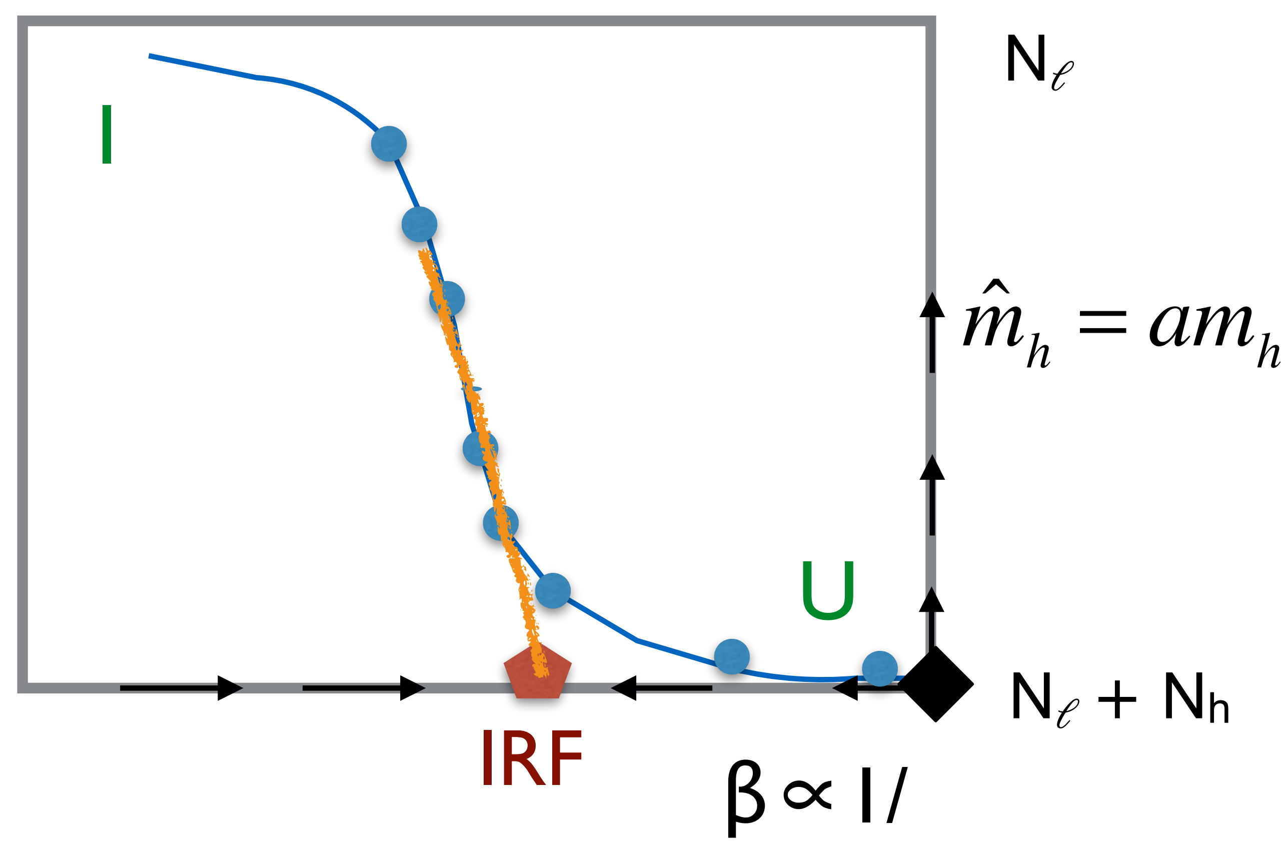


Wilson renormalization group description

When discussing a conformal model it is convenient to use Wilson RG description:

- use bare parameters at the UV scale
- define a continuum (infinite cut-off) system by tuning to criticality

- Critical surface is at $m_h = 0$;
- There is a fixed point (IRFP) somewhere on this infinite dimensional surface —
- The location of the IRFP is scheme dependent



Spectrum: Hyperscaling

In conformal systems Wilson RG considerations predict m_h dependence:

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 correlator at large b behaves

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

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

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

Amplitudes (F_π) also show hyperscaling

Hyper scaling in mass split systems

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

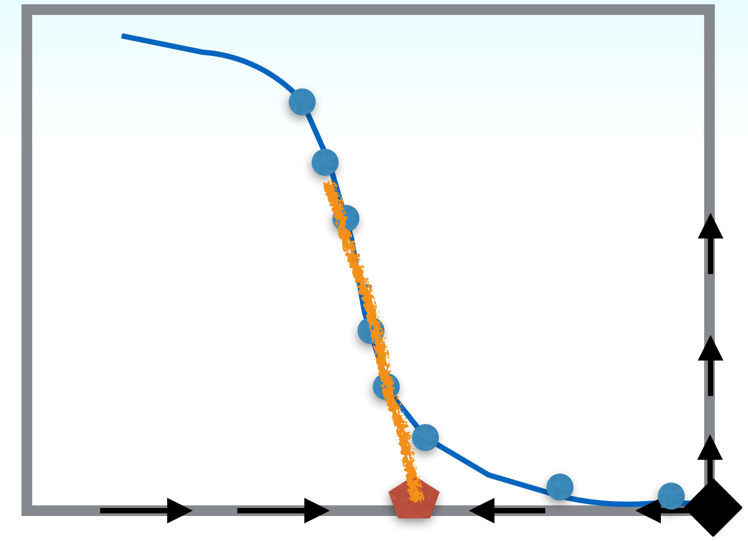
mass split systems show the same hyperscaling in the $m_\ell = 0$ limit

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

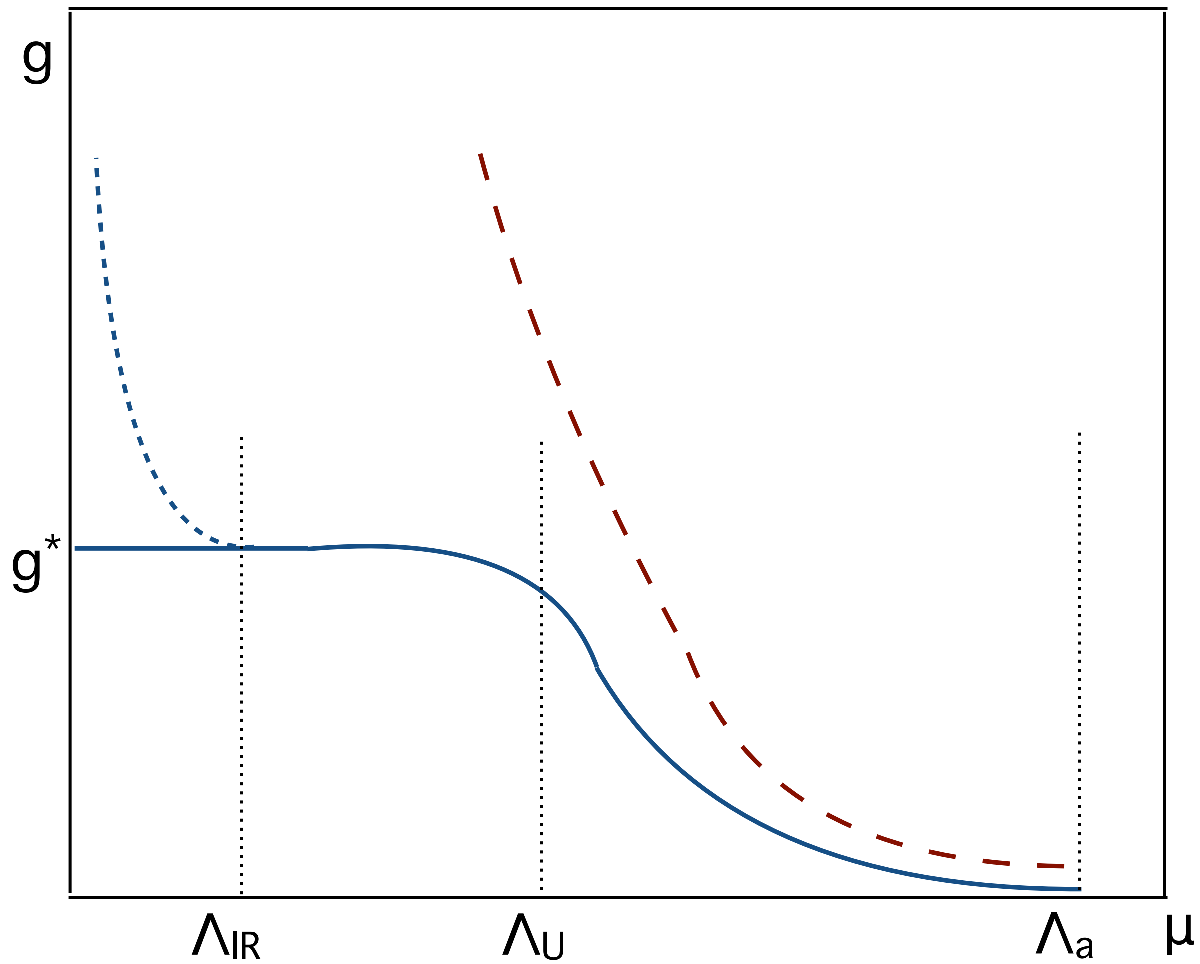
(M_H can be all light, heavy or mixed fermion hadrons)

—> Ratios like M_H / F_π are independent of m_h

Mass split model - 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

$m_h \to 0$

N_ℓ + N_h mass split systems

ideally

$N_\ell + N_h = 2 + 8$: $N_f = 10$ is close to the conformal window

(or

$N_\ell + N_h = 2 + 1 + 1 + 1 + 1$ …… : cascade from $N_f = 16$ to $N_f = 2$)

Pilot study:

$N_\ell + N_h = 4 + 8$: conformal in the UV, $N_l=4$ flavor in the IR

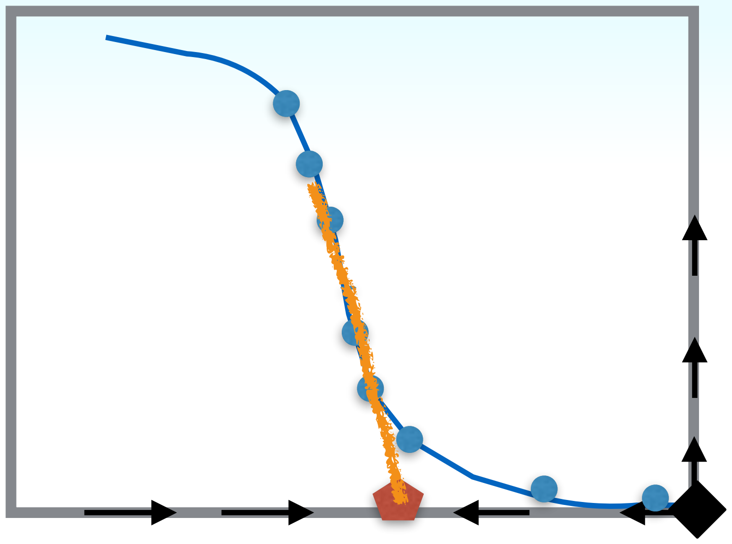
in collaboration with R. Brower, C. Rebbi, E. Weinberg, O. Witzel

arXiv:1411.3243, 1511.xxx

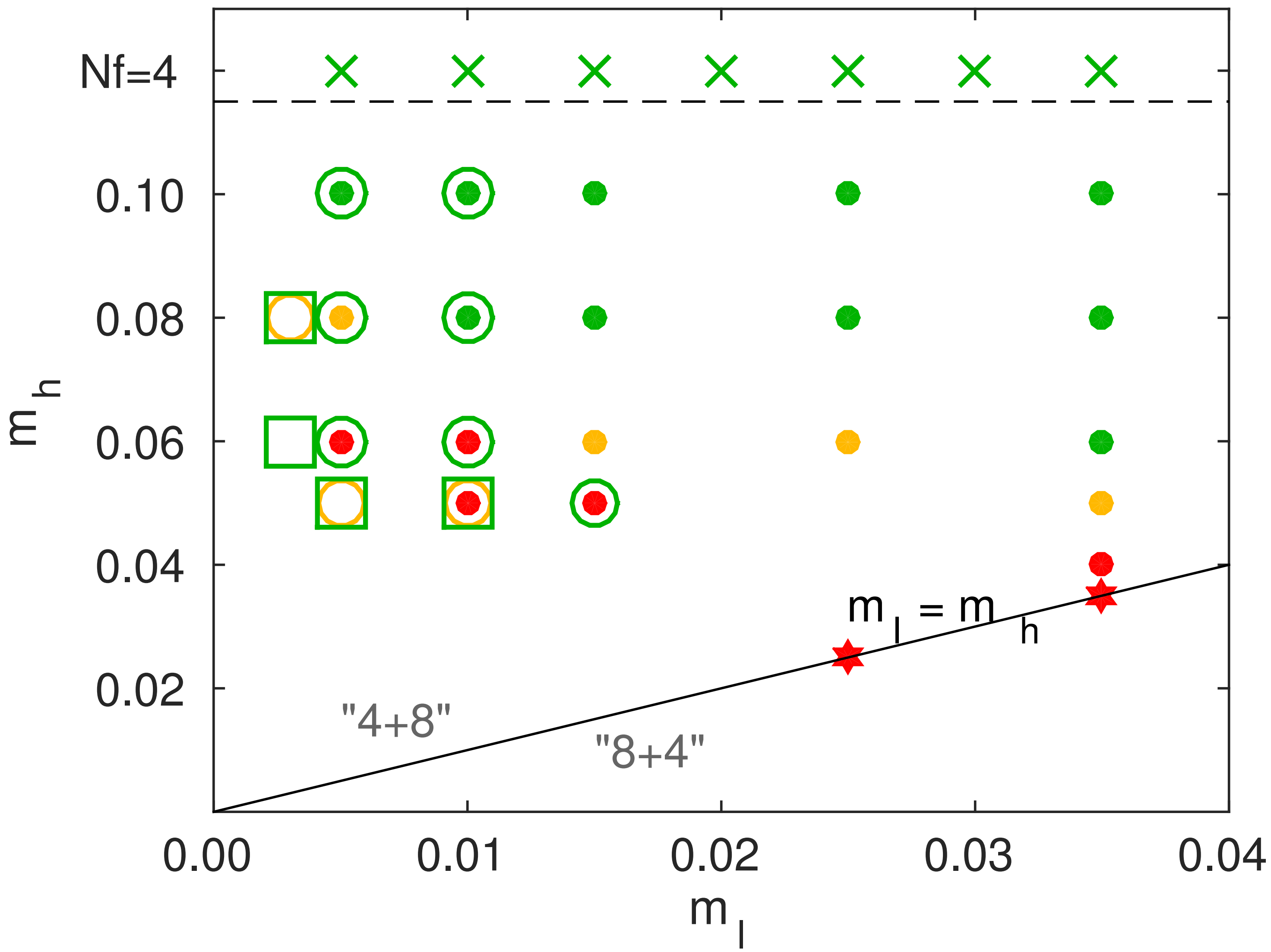
Why 4+8 ? We use staggered fermions:

4 and 8 flavors do not require rooting

$N_\ell + N_h = 4 + 8$: 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

Running coupling

Gradient flow transformation defines a renormalized coupling

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

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

It is appropriate to determine the renormalized running coupling

- on large enough volumes
- at large enough flow time
- in the continuum limit

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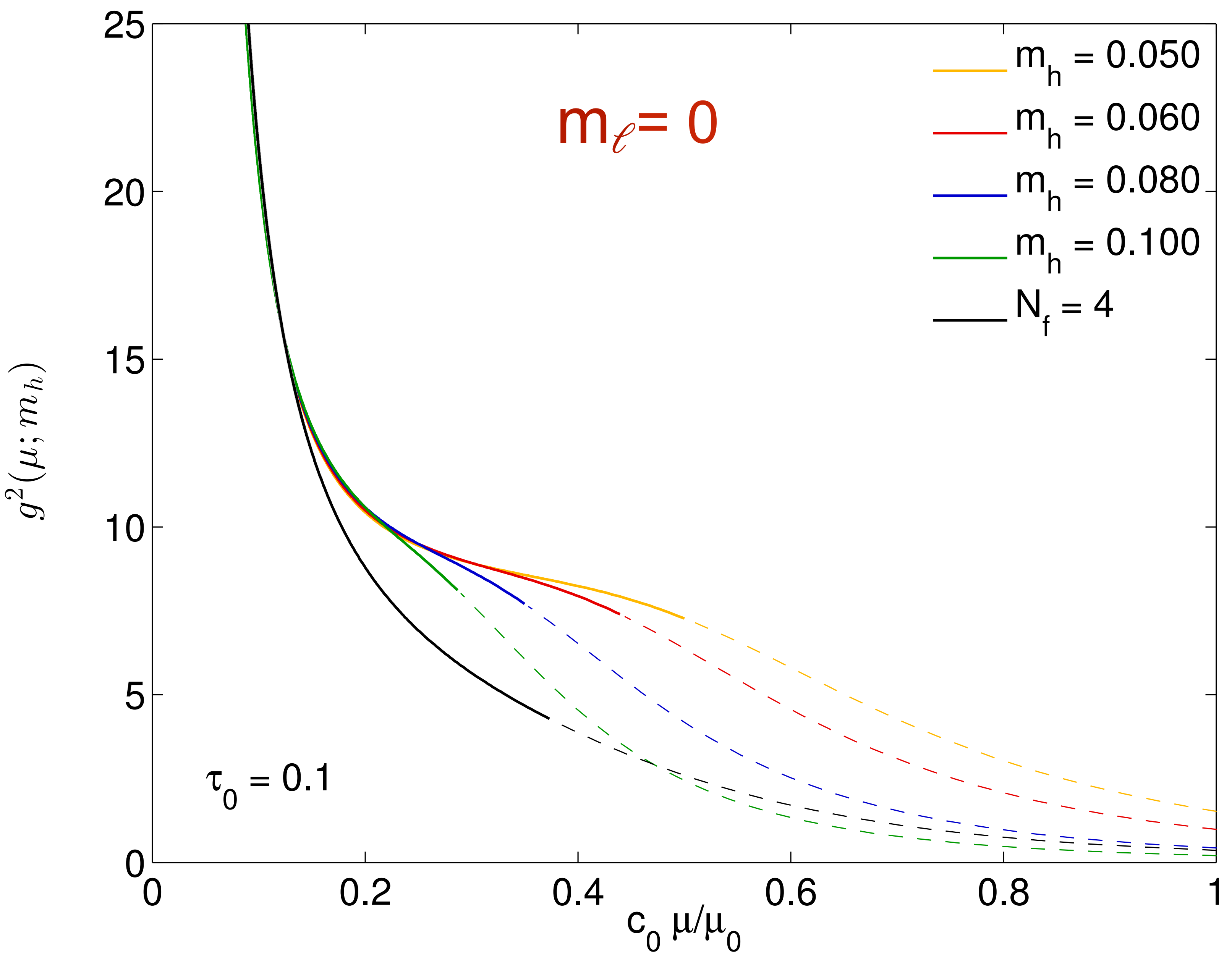
} use t-shift improved coupling

Improved running coupling : 4+8 flavors



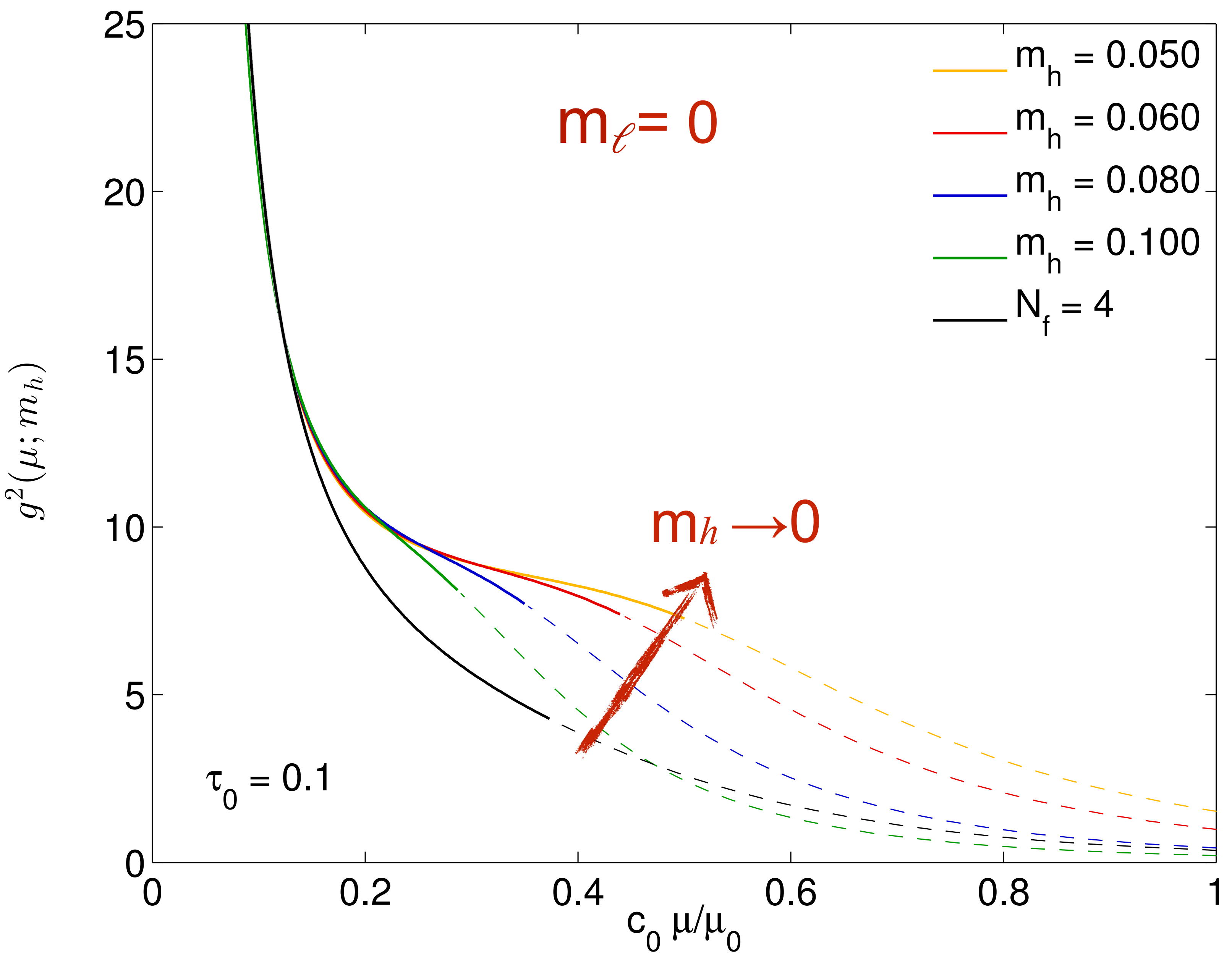
There are error bars on this plot!

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

Improved running coupling : 4+8 flavors



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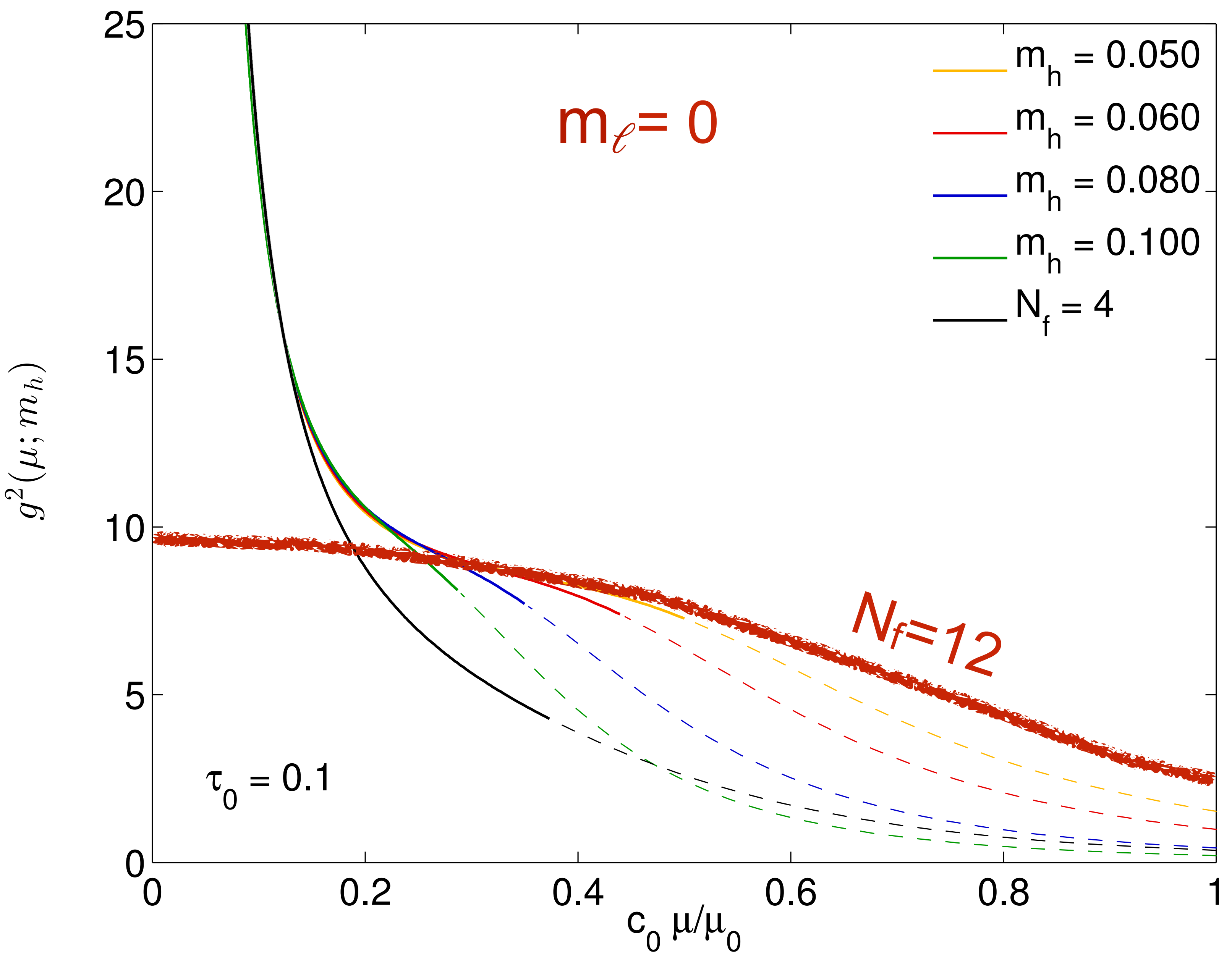

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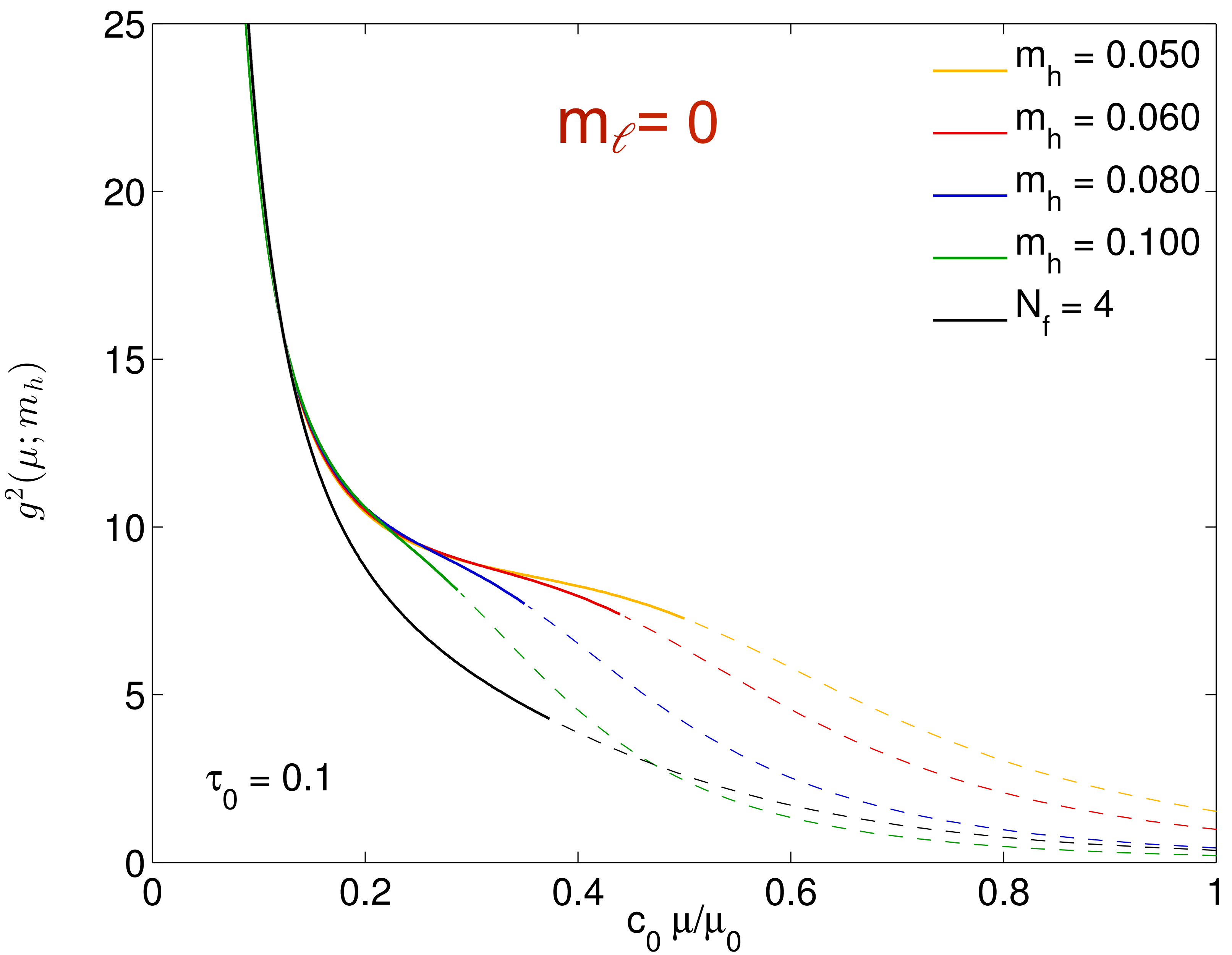

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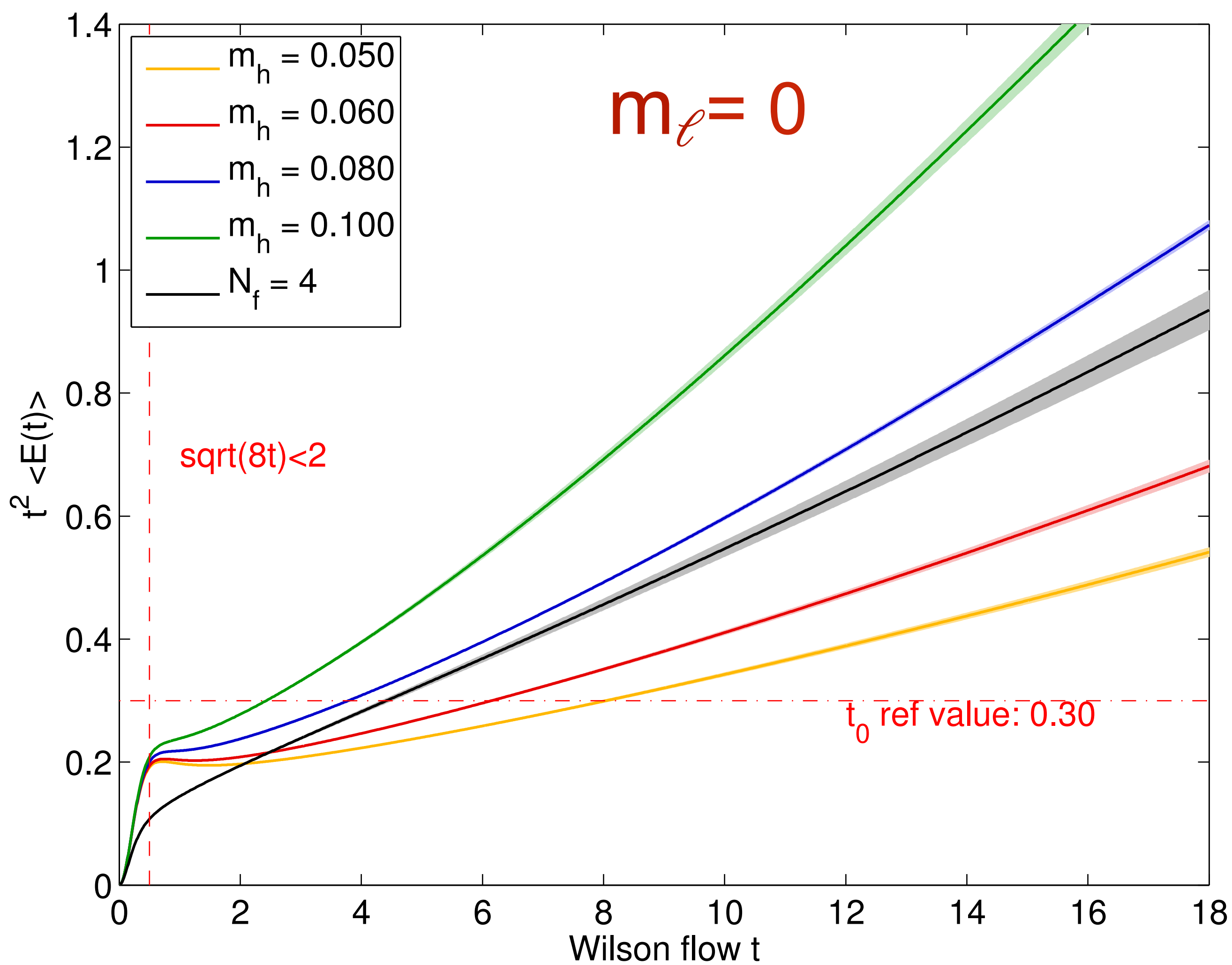
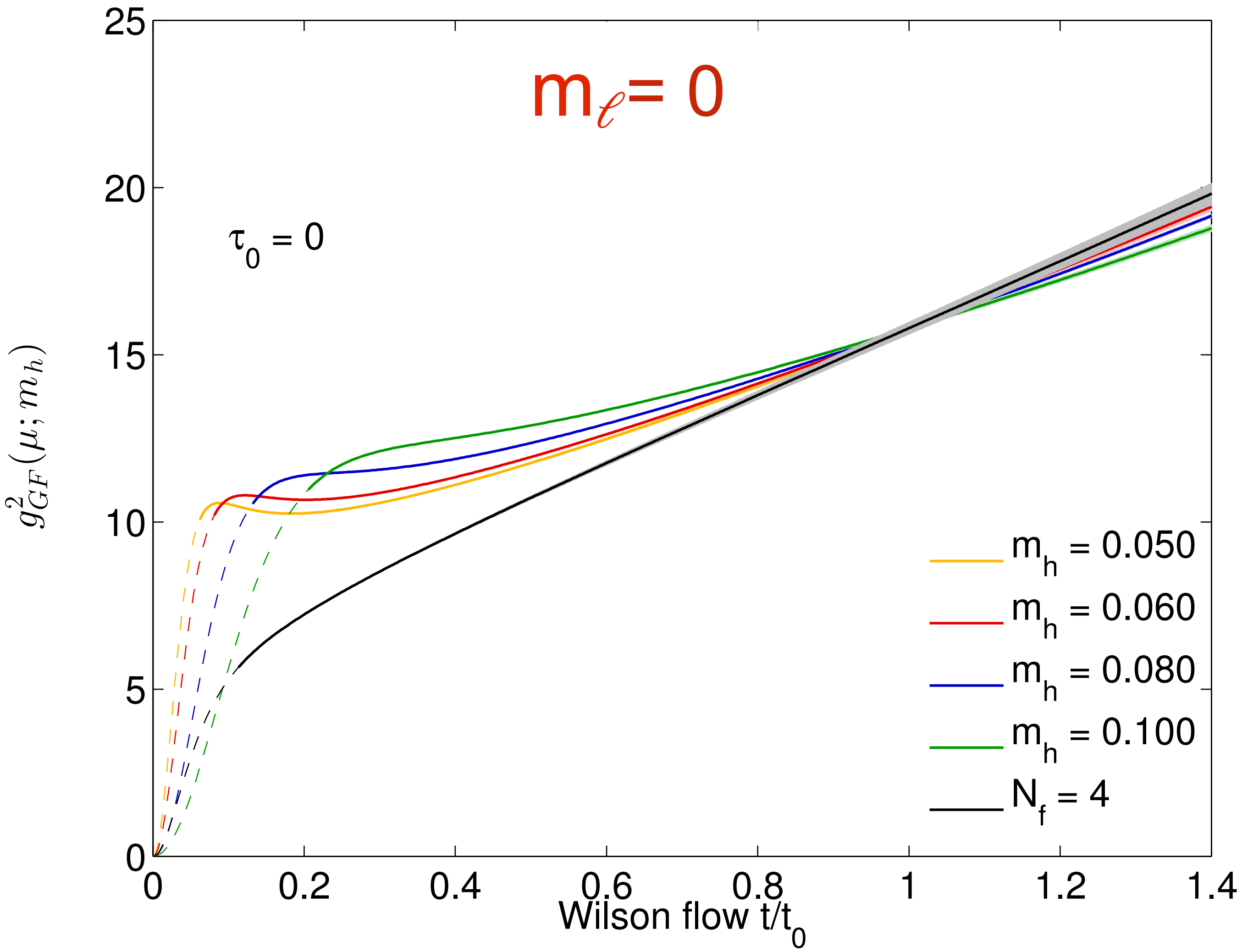
Running coupling

$t^2\langle E(t)\rangle$ in the chiral limit at various m_h values



$g^2_{GF}(t/t_0)$ rescaled by t_0 at various m_h values



Rescaling forces the renormalized couplings to agree at t_0

Fan-out before and after are due to cut-off lattice artifacts

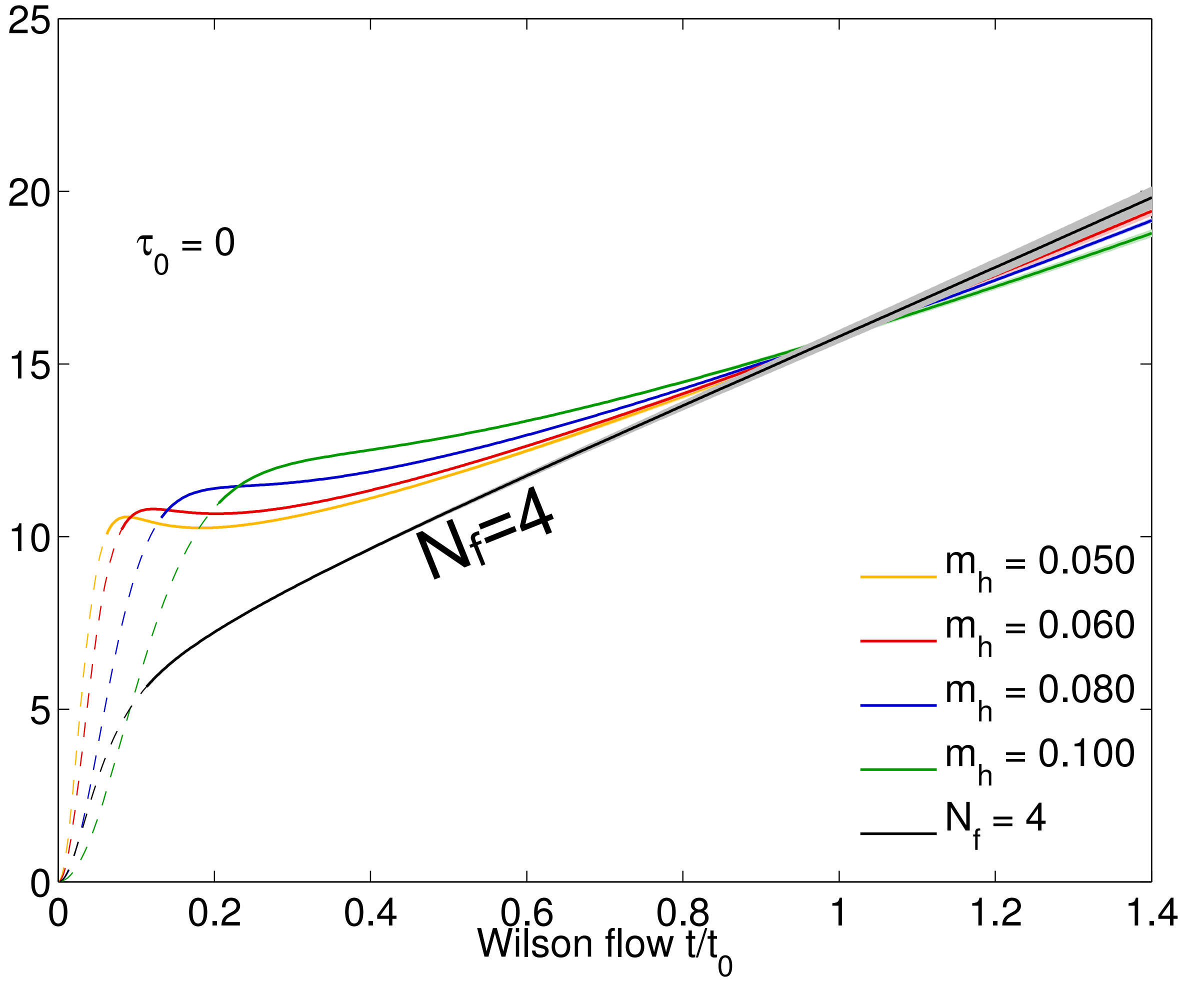
Improved running coupling

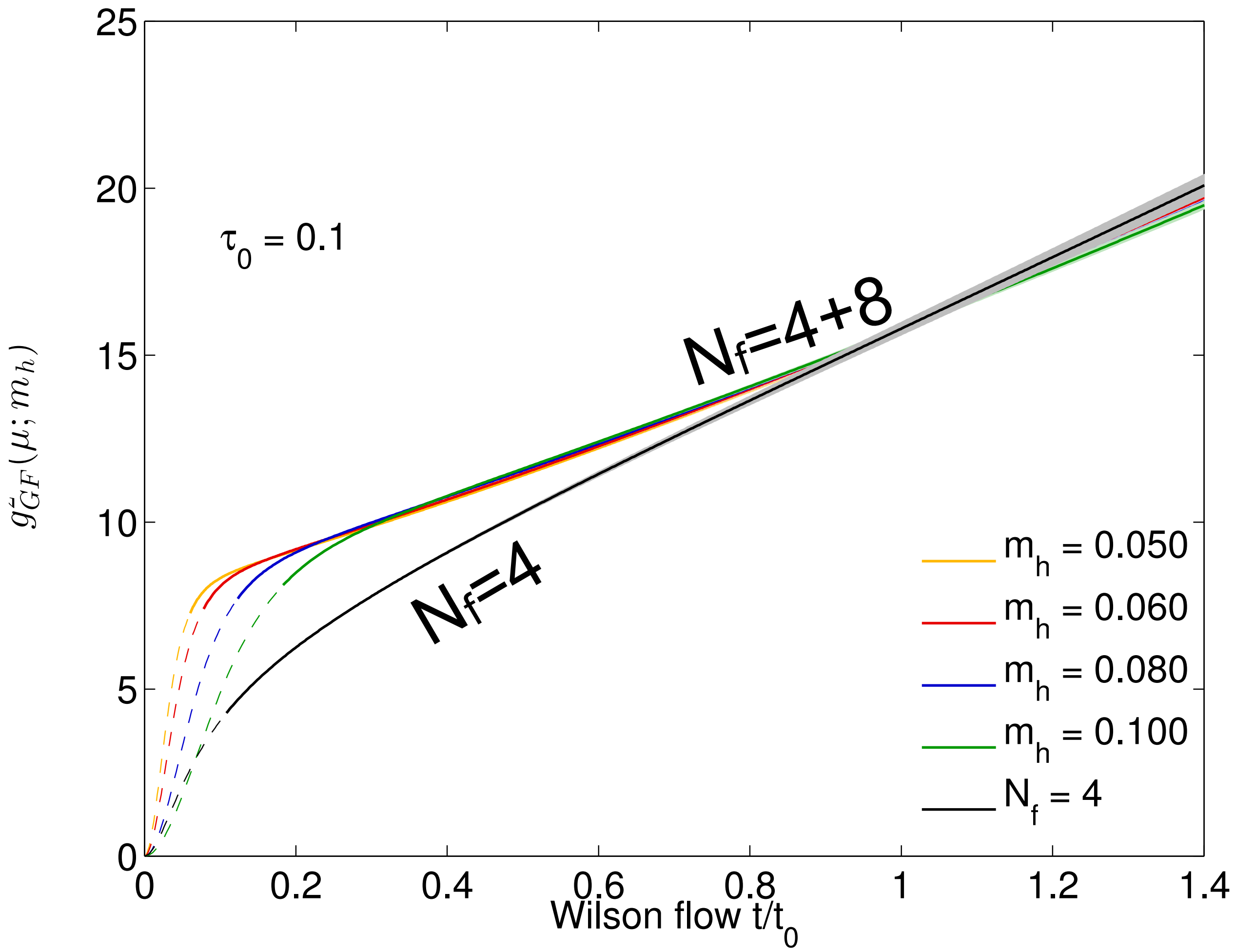
t-shift improved running coupling

$$\tilde{g}^2_{GF}\left(\mu=\frac{1}{\sqrt{8t}}\right)=\frac{1}{\mathcal{N}}t^2\langle E(t+\tau_0)\rangle$$

by adjusting τ_0 most cut-off effects can be removed

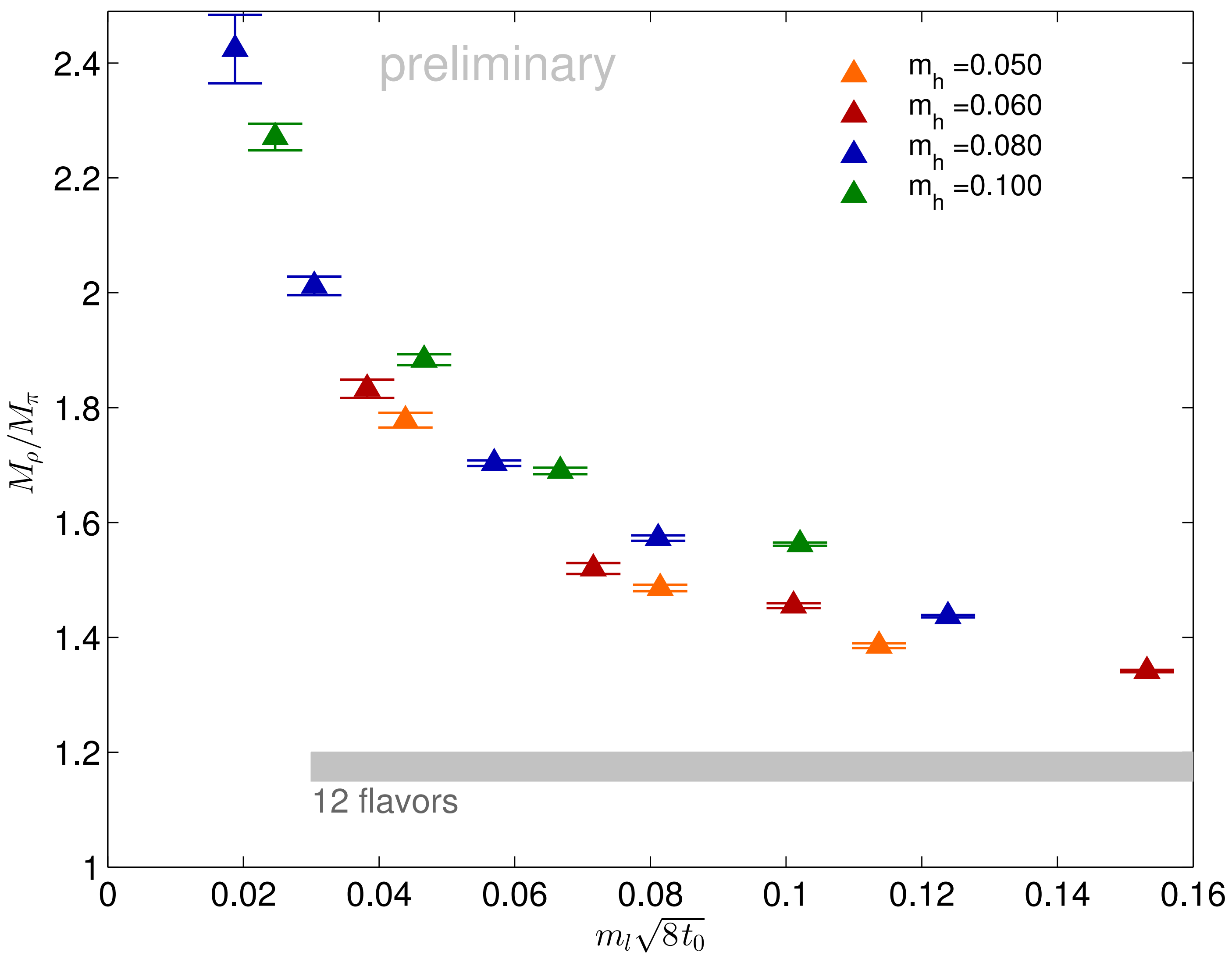
(1404.0984, 1501.07848)





Is the system chirally broken ?

M_ρ/M_π shows that we approach the chiral regime

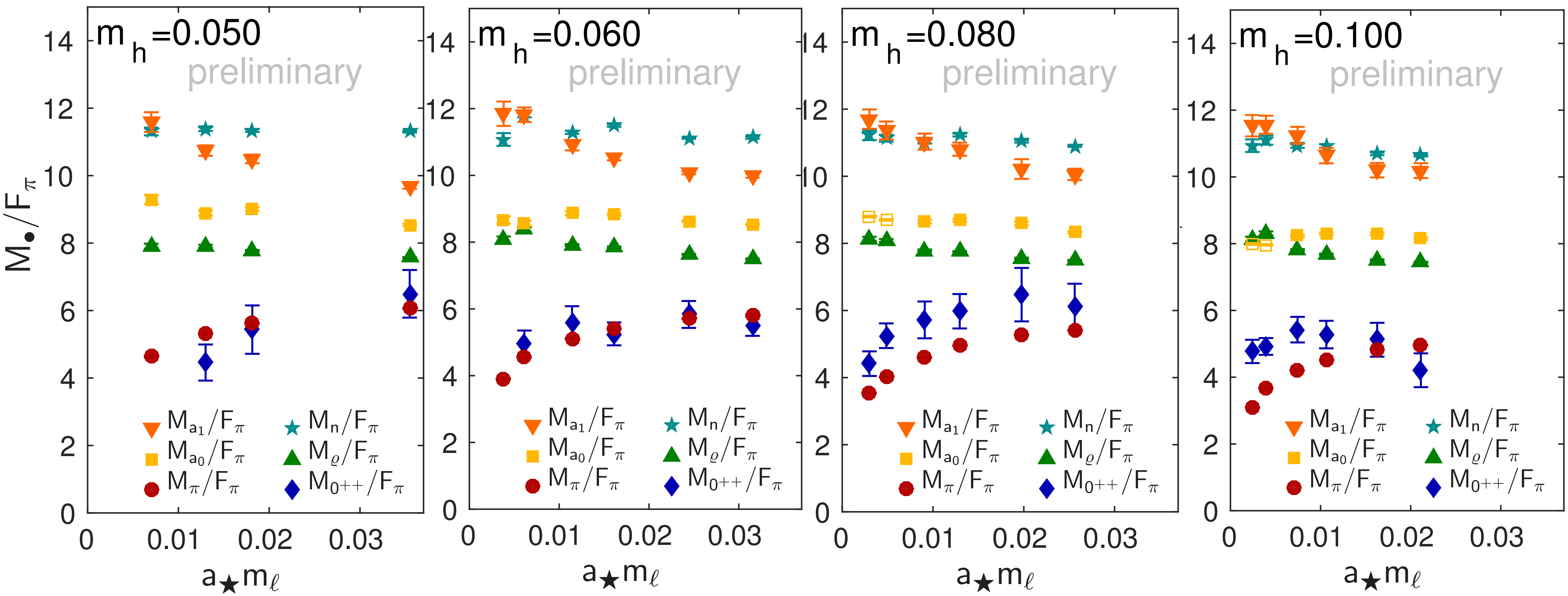


< N_f=12 predicts an almost constant ratio (as should be in a conformal system)

(arXiv:1401.0195)

Spectrum, **4+8** flavors

Ratios M_H / F_π appear independent of m_h



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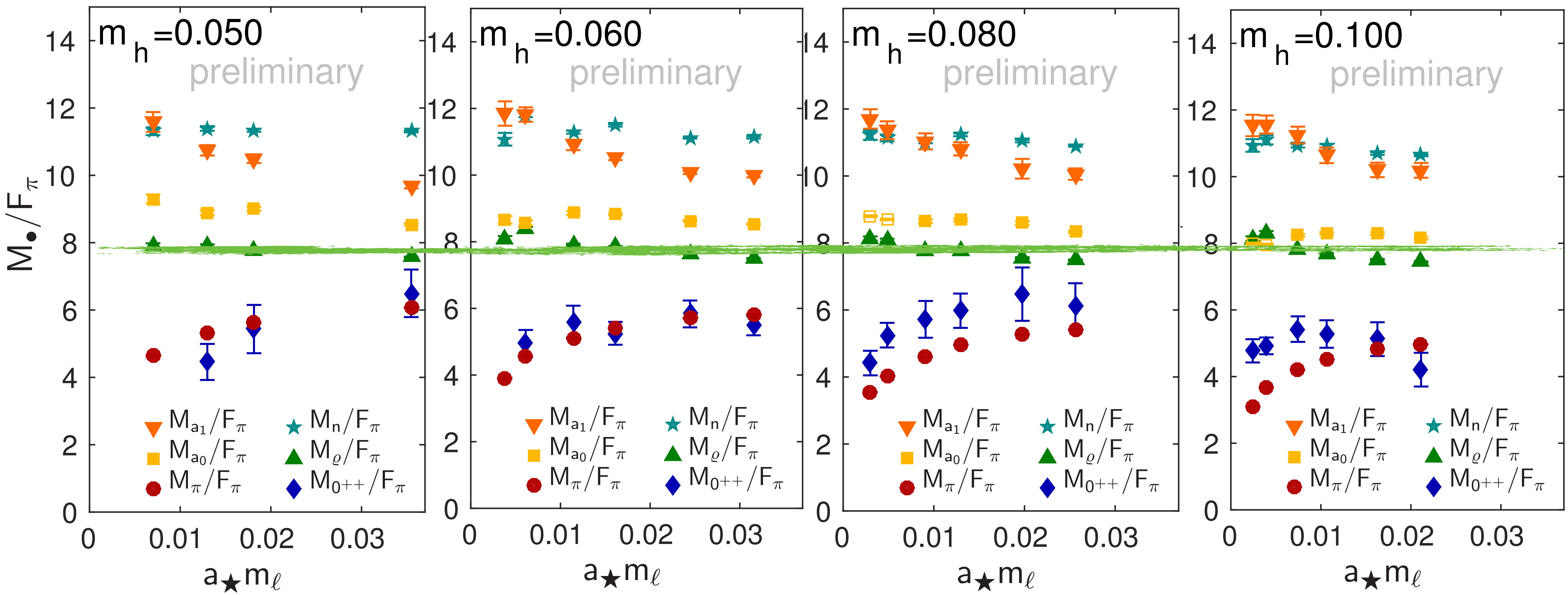

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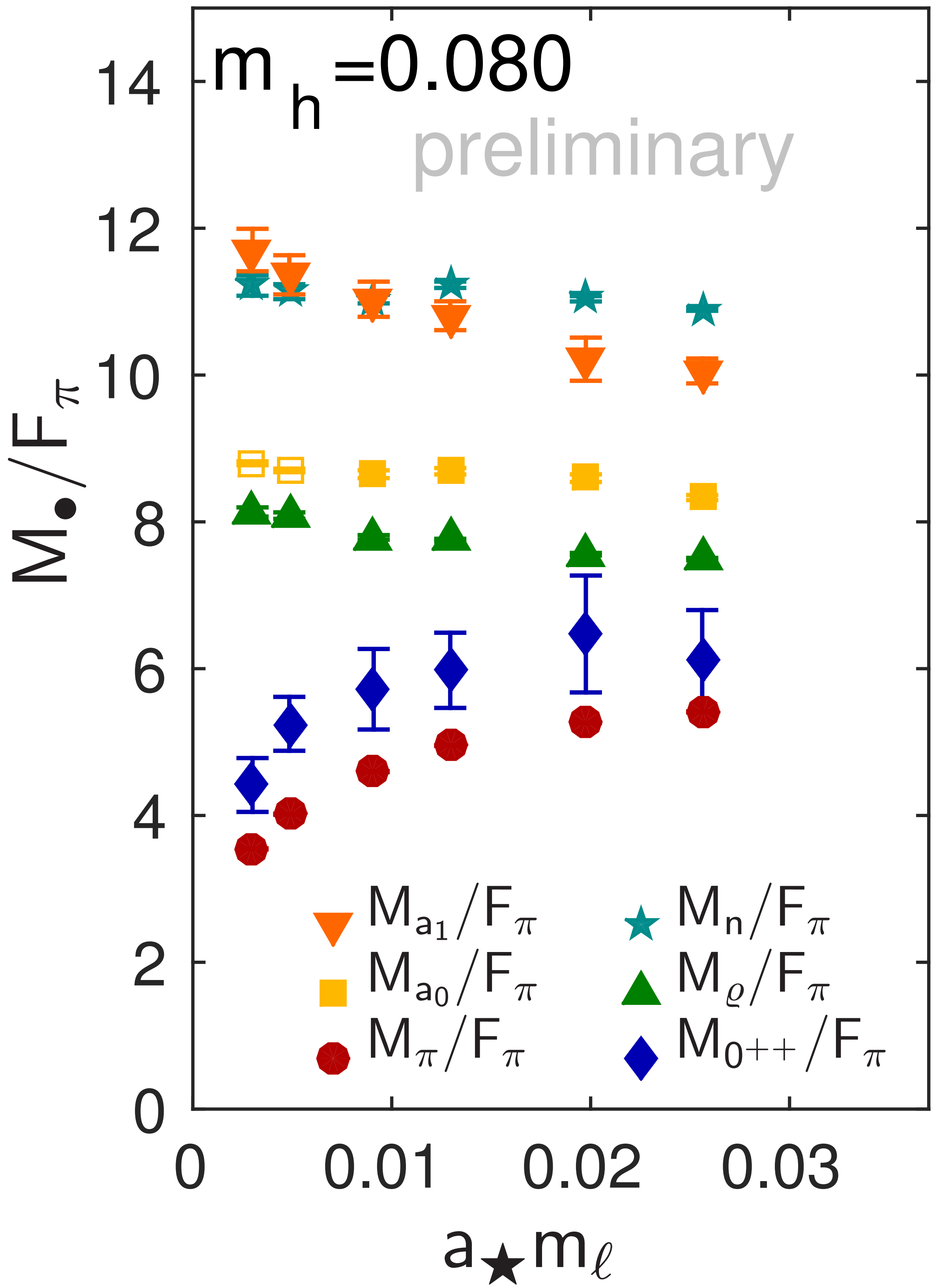

pion, rho, a0, a1, nucleon and 0^{++} scalar

The ratios are very similar to N_f=8 and sextet

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

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

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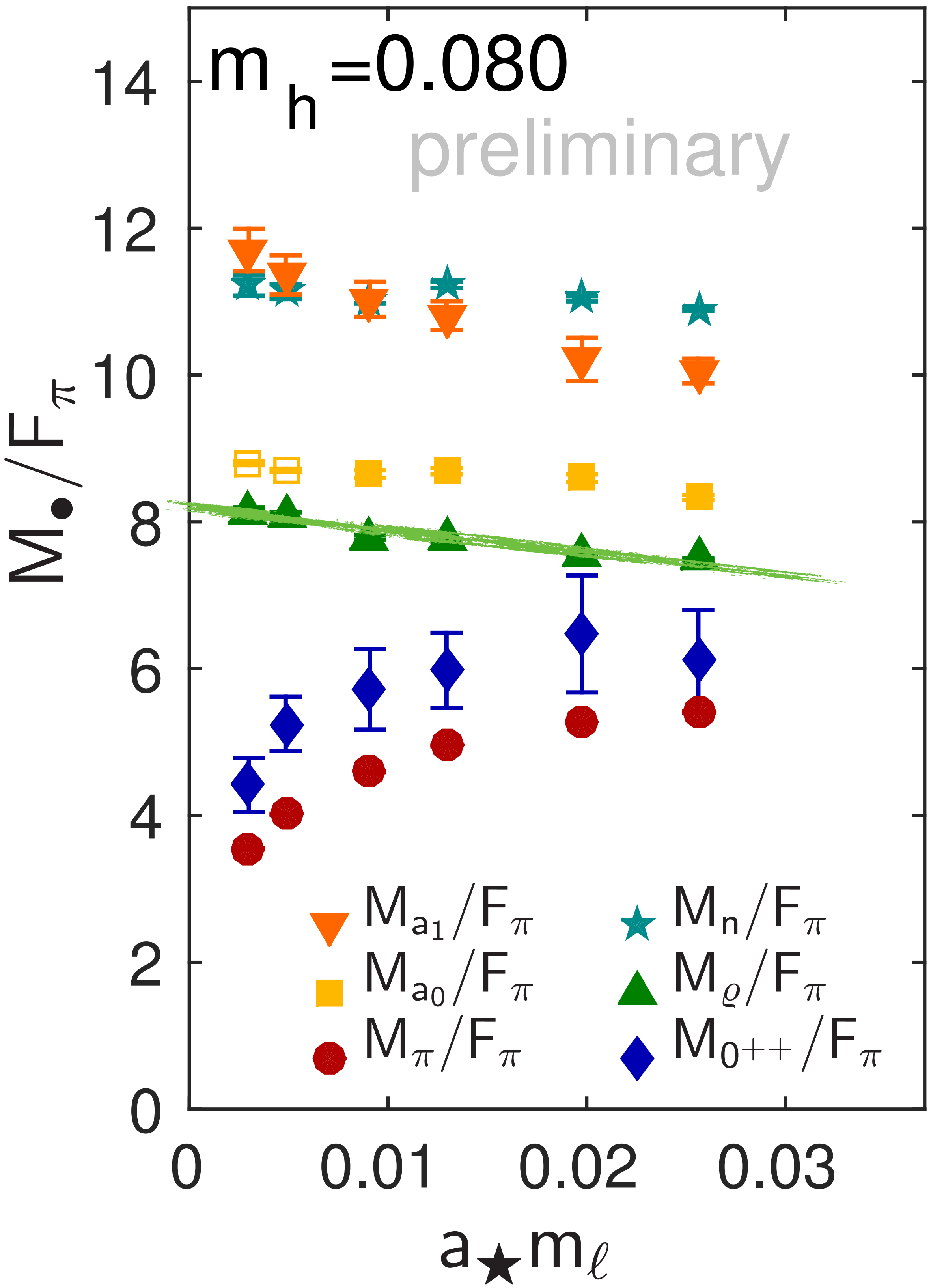

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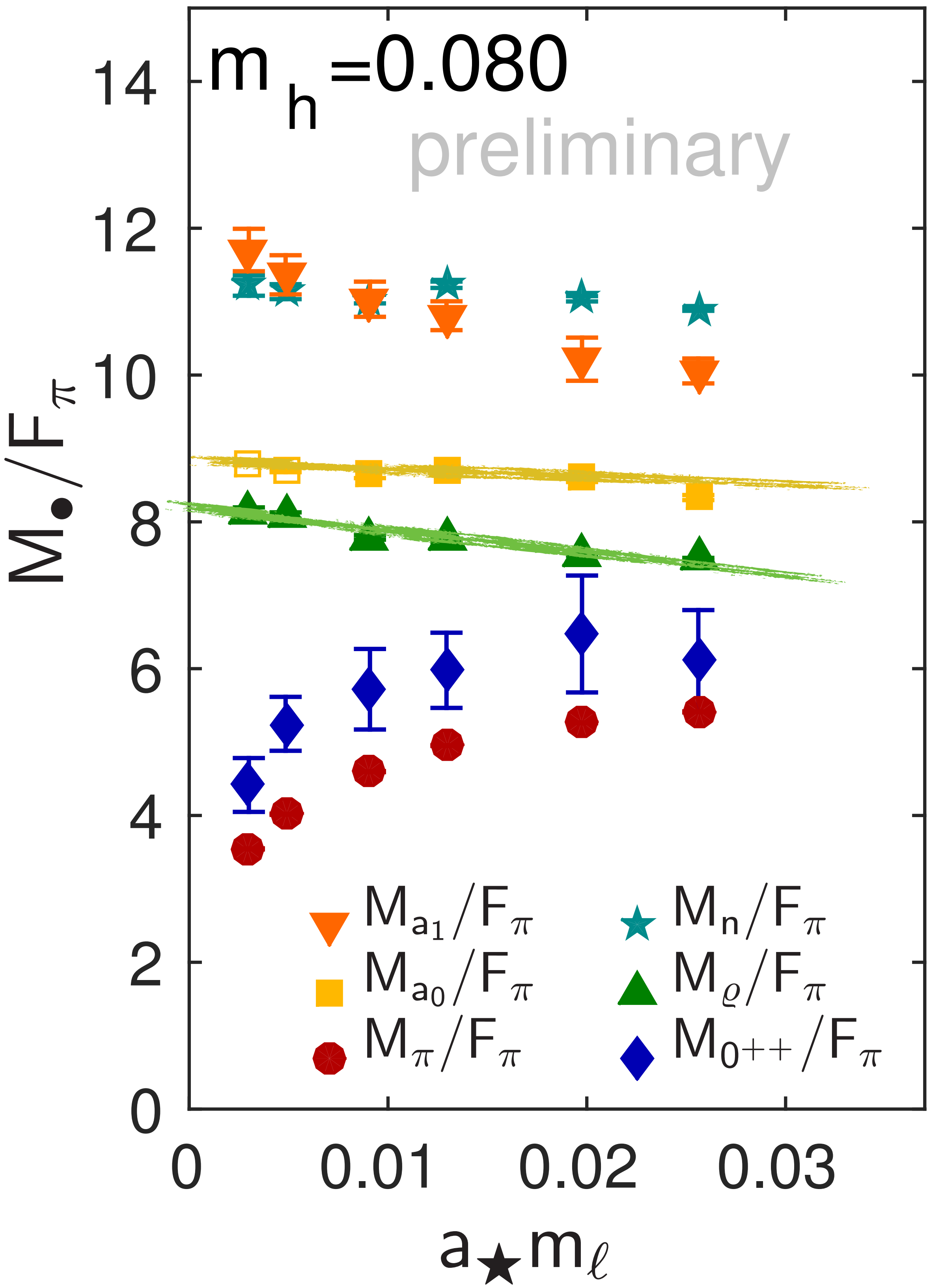

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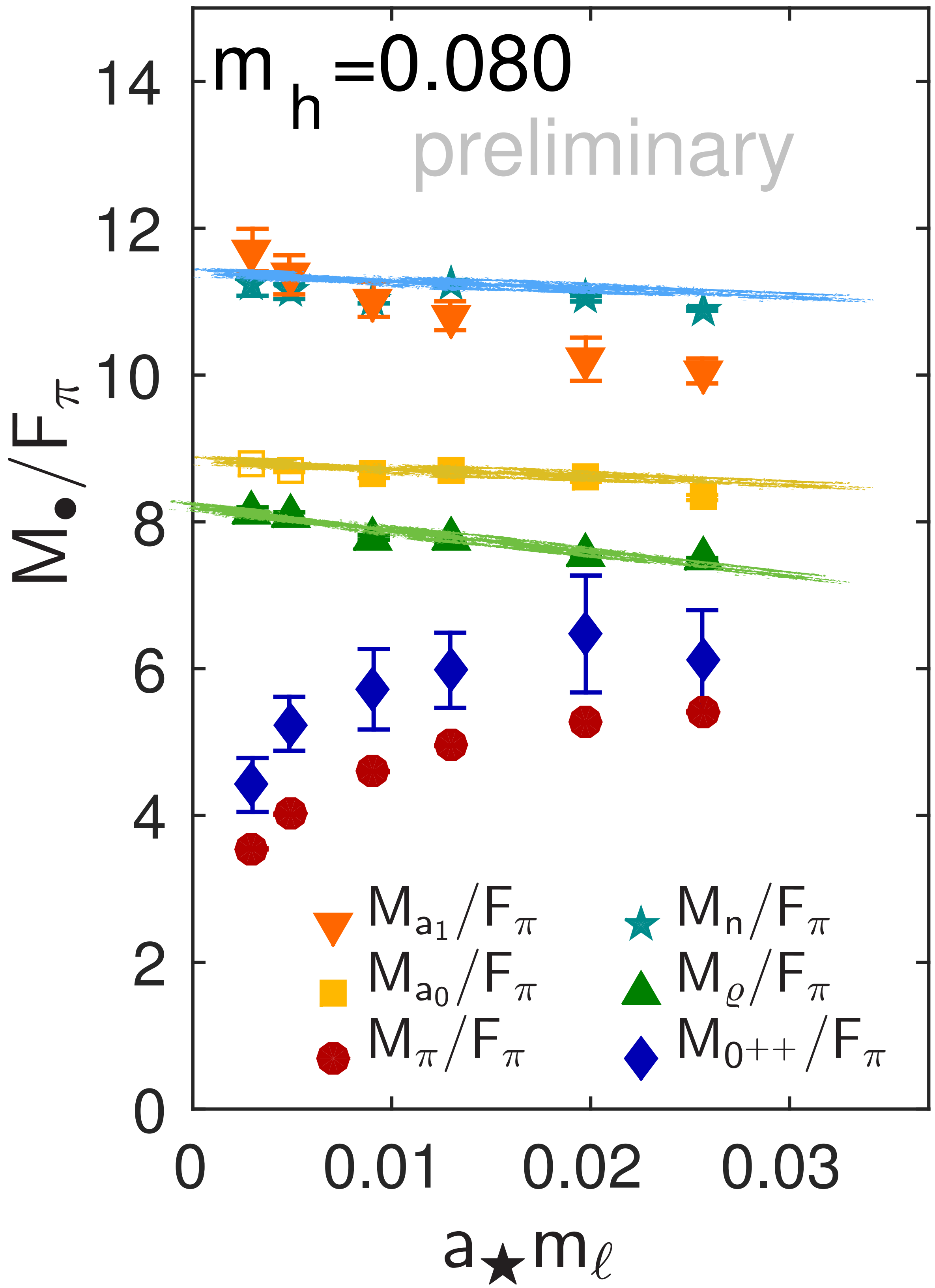

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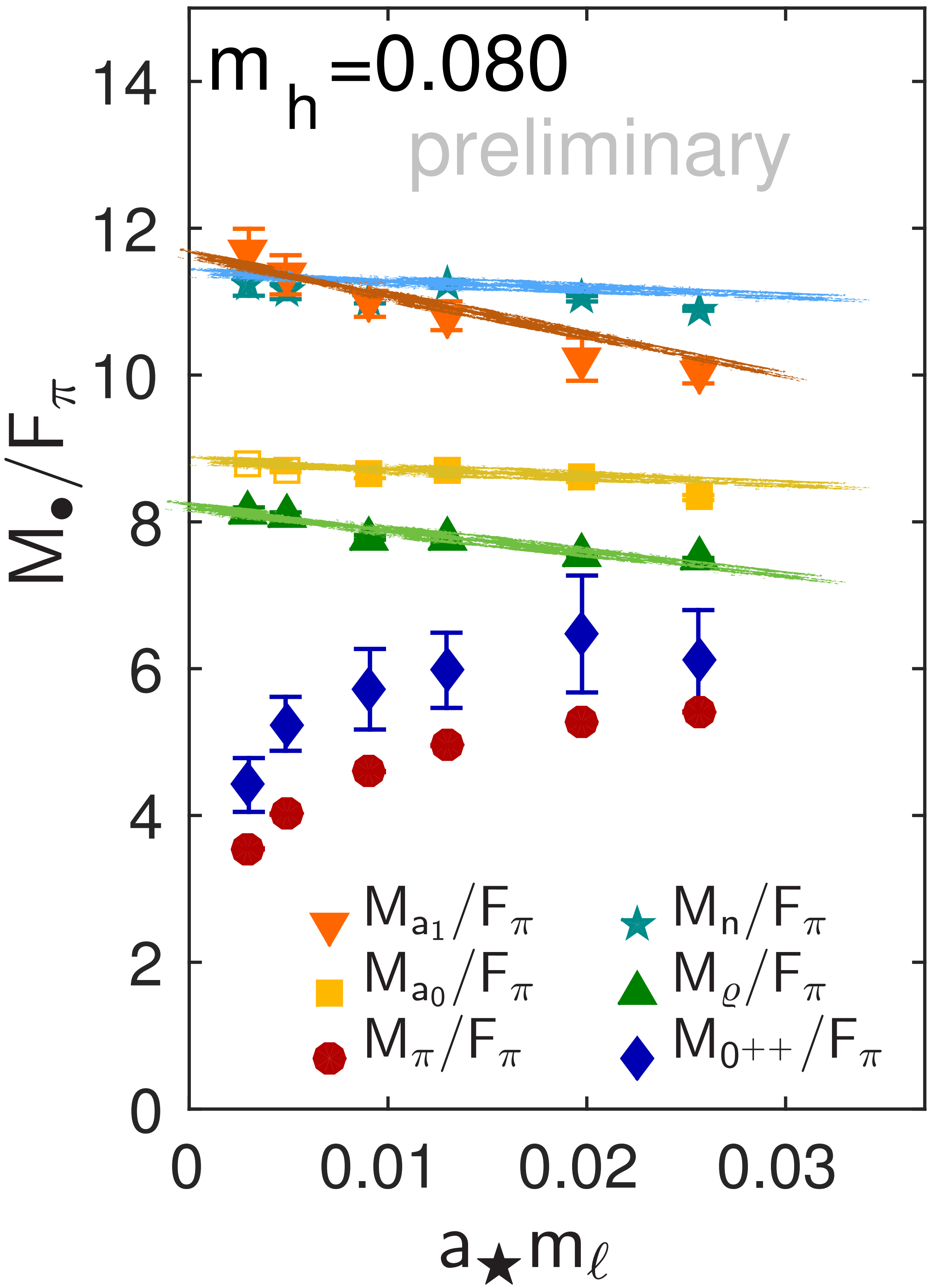

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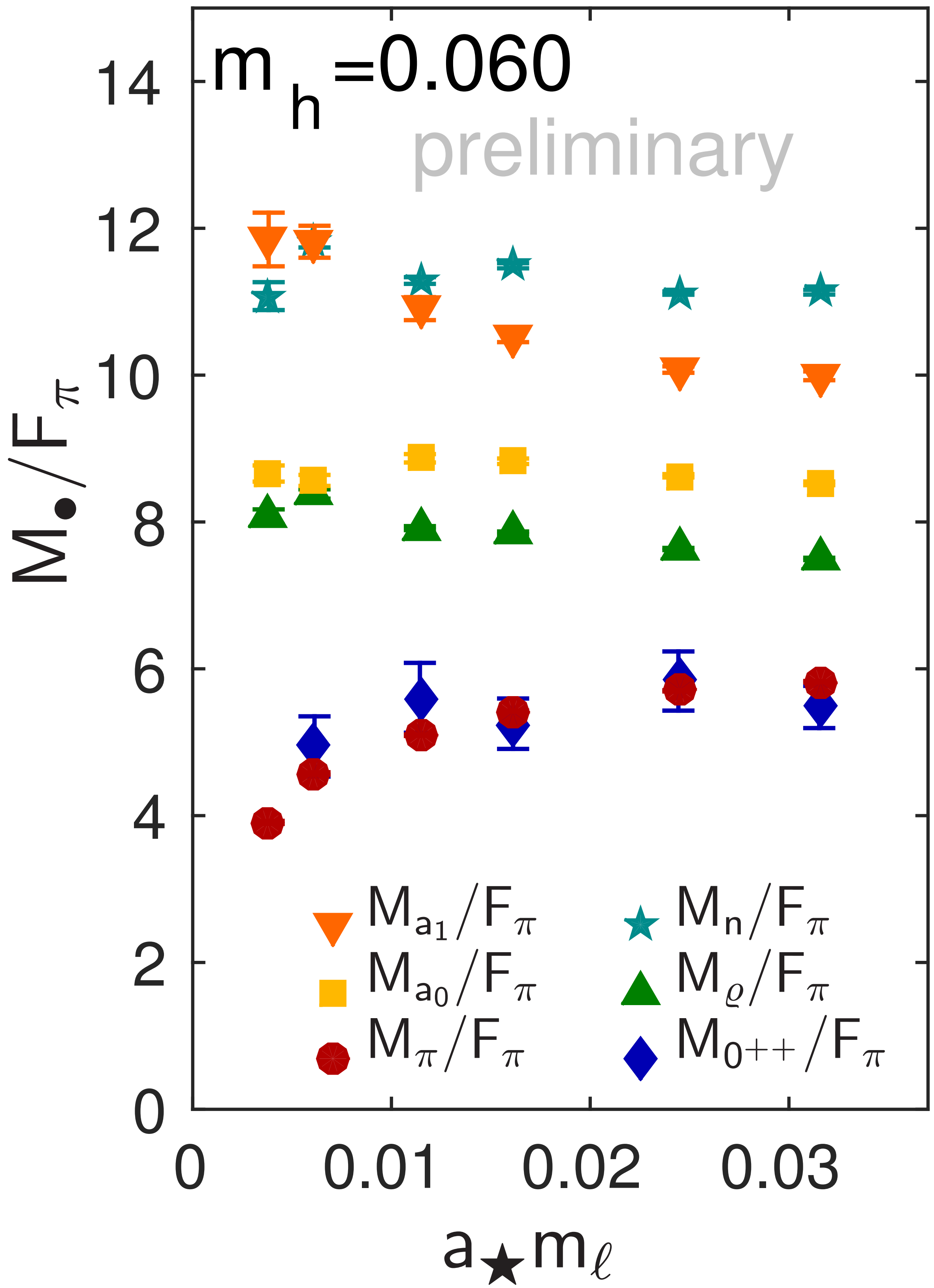

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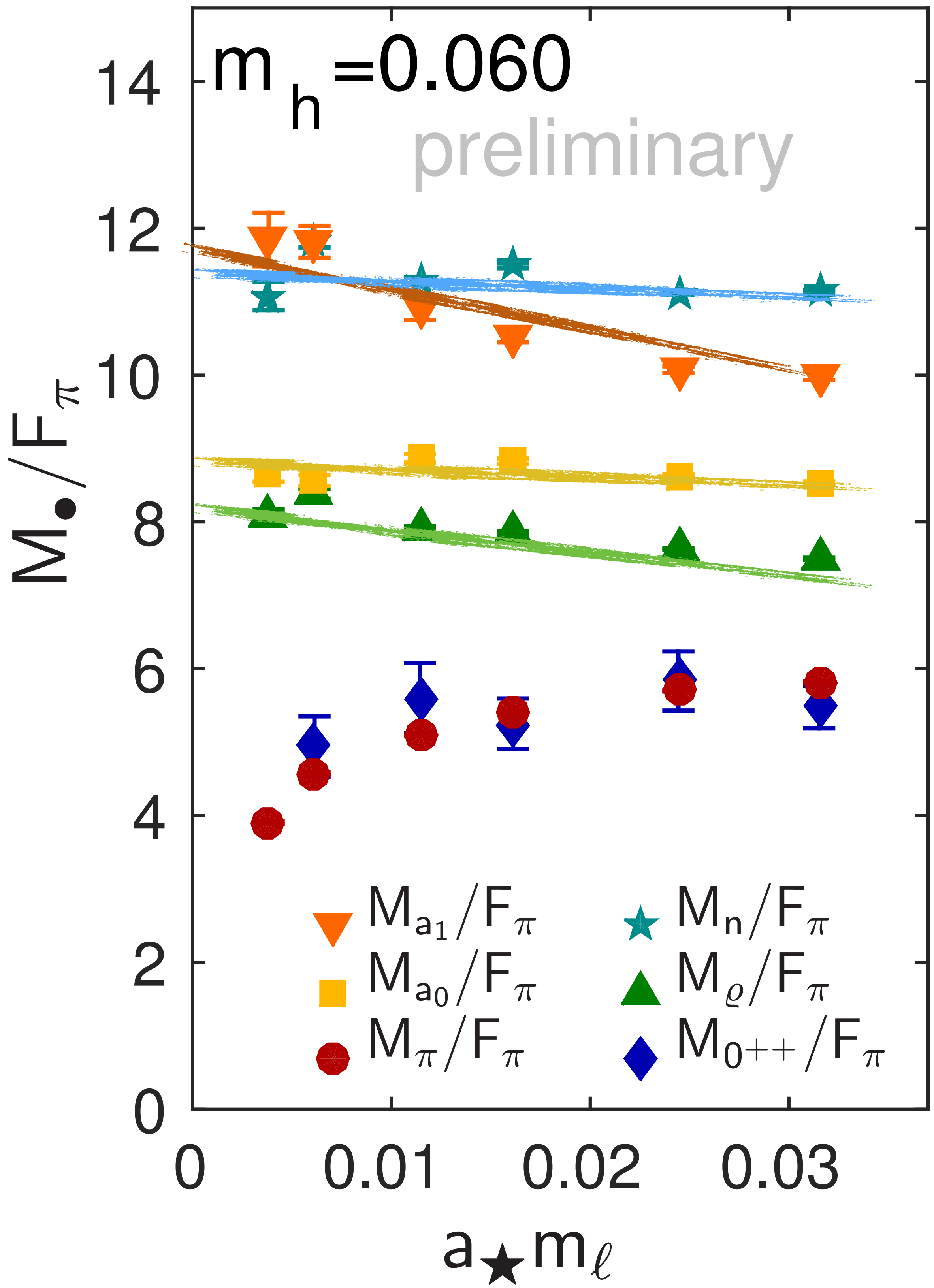

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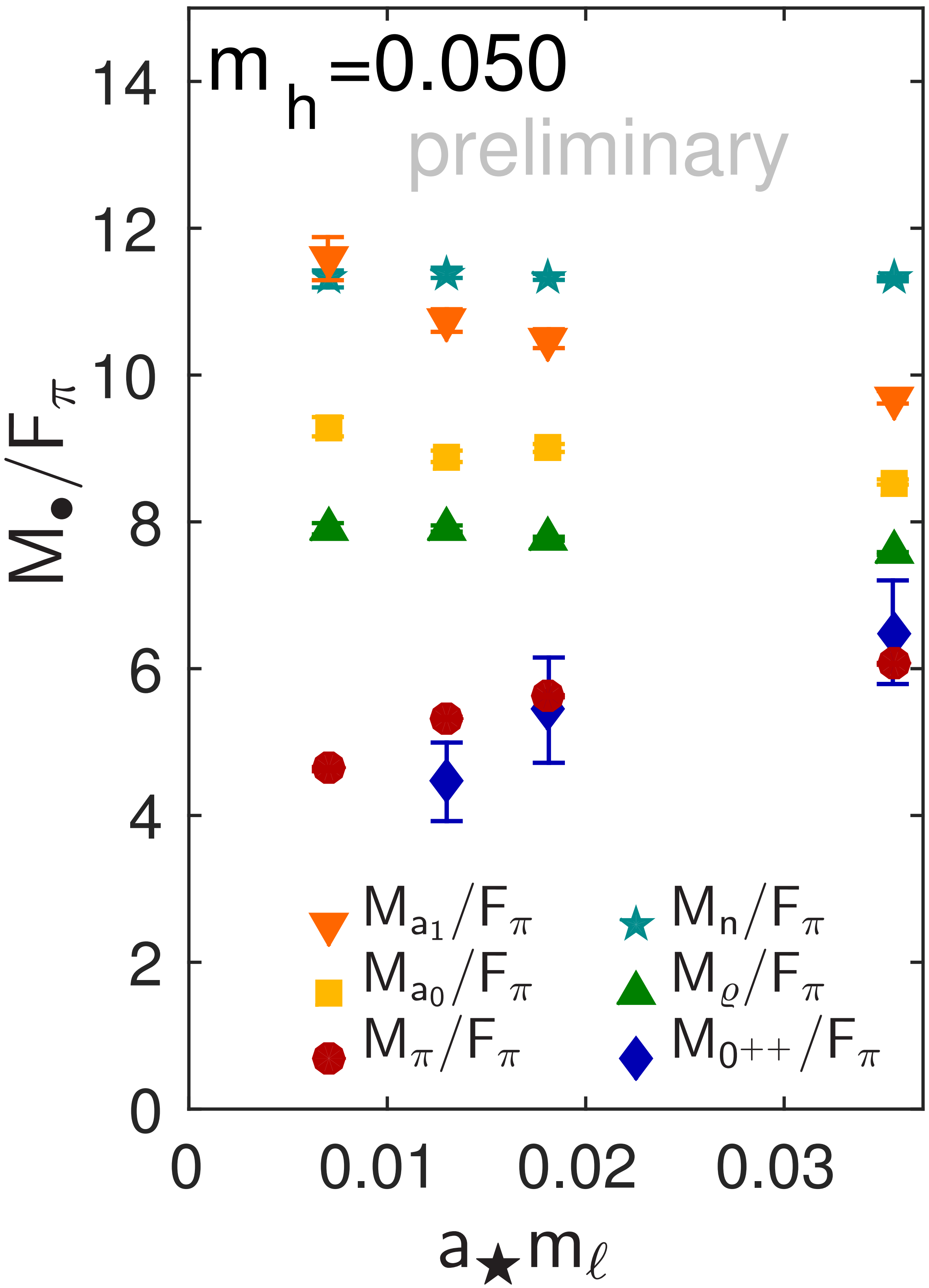

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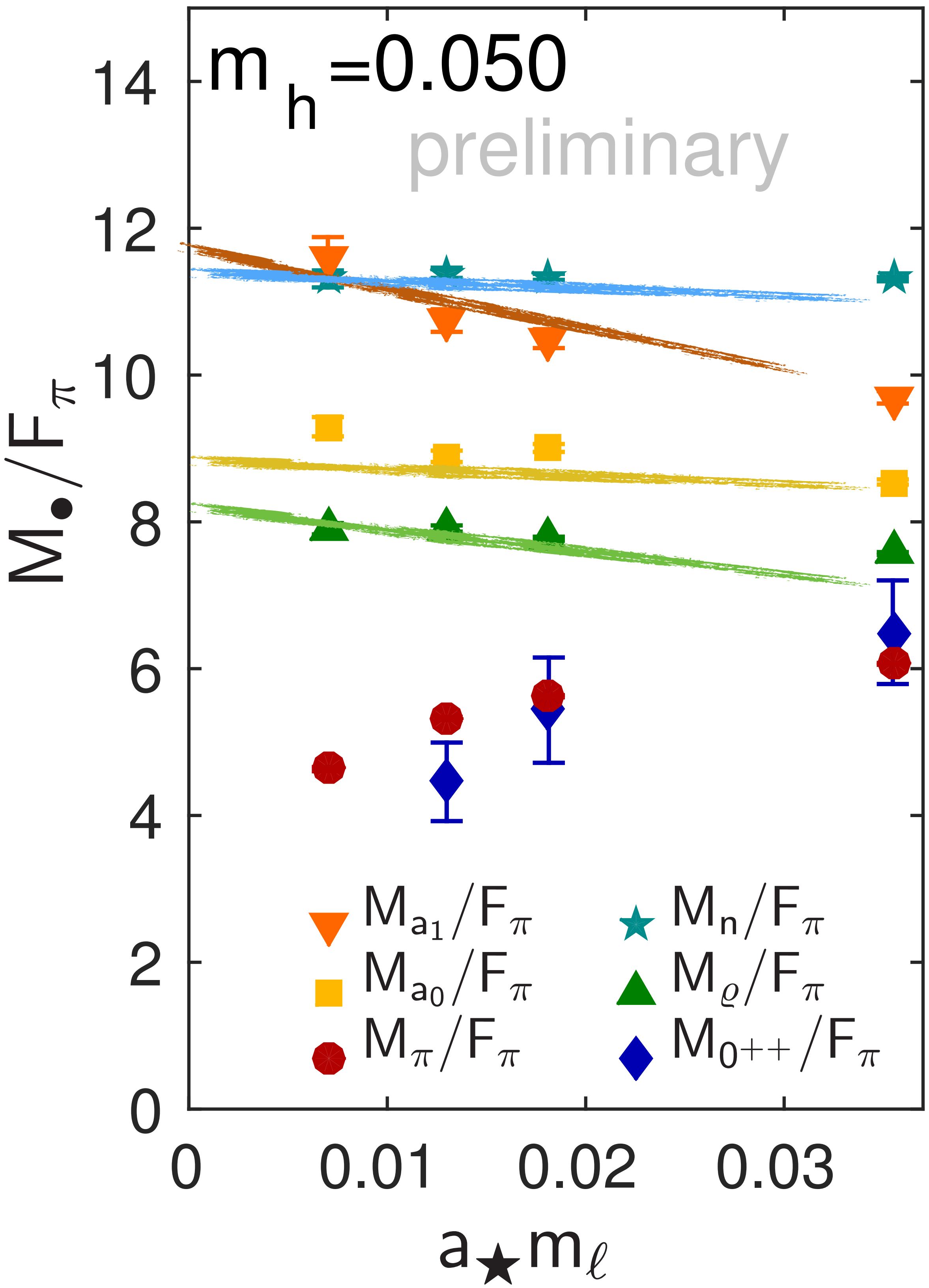

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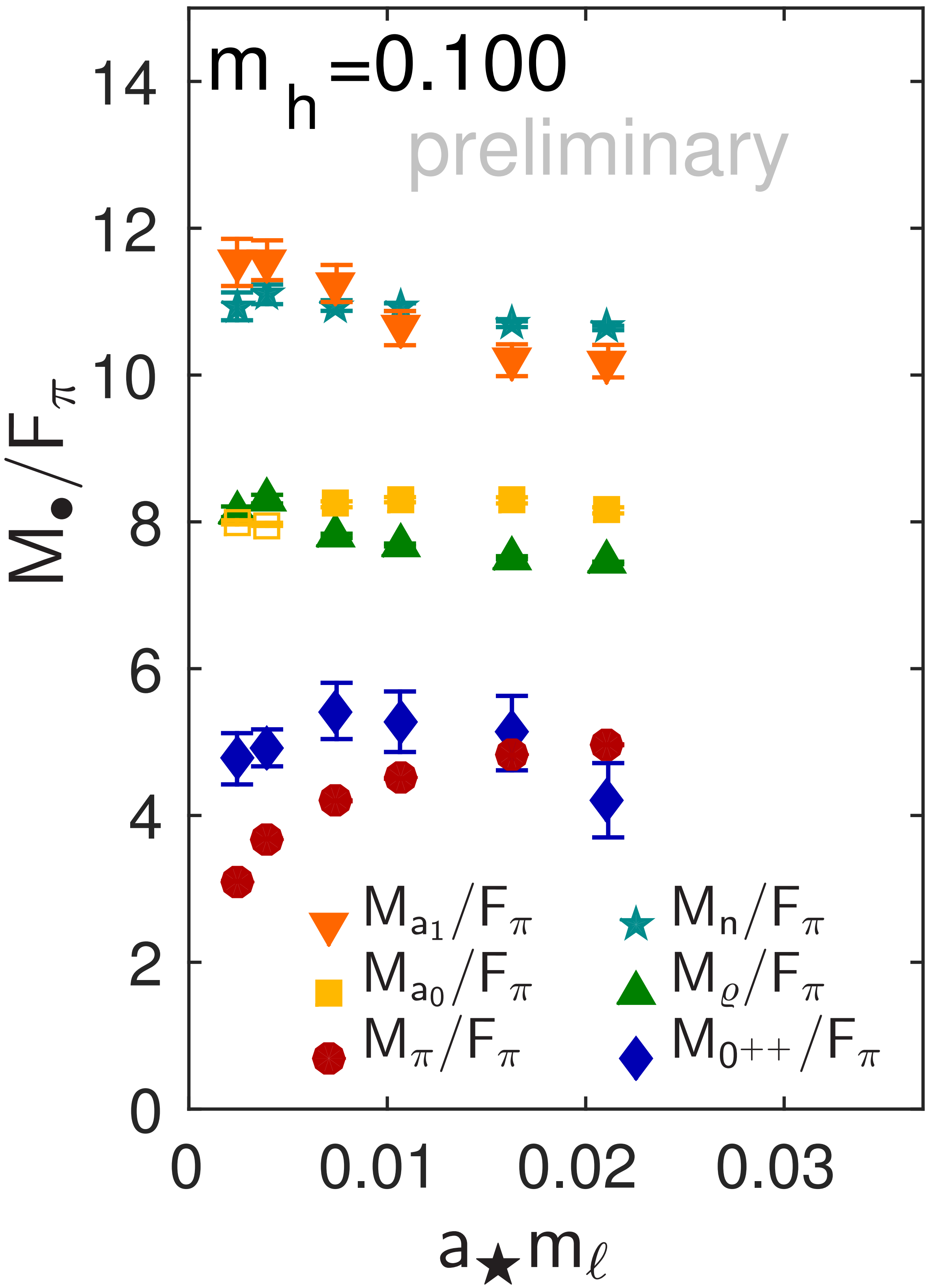

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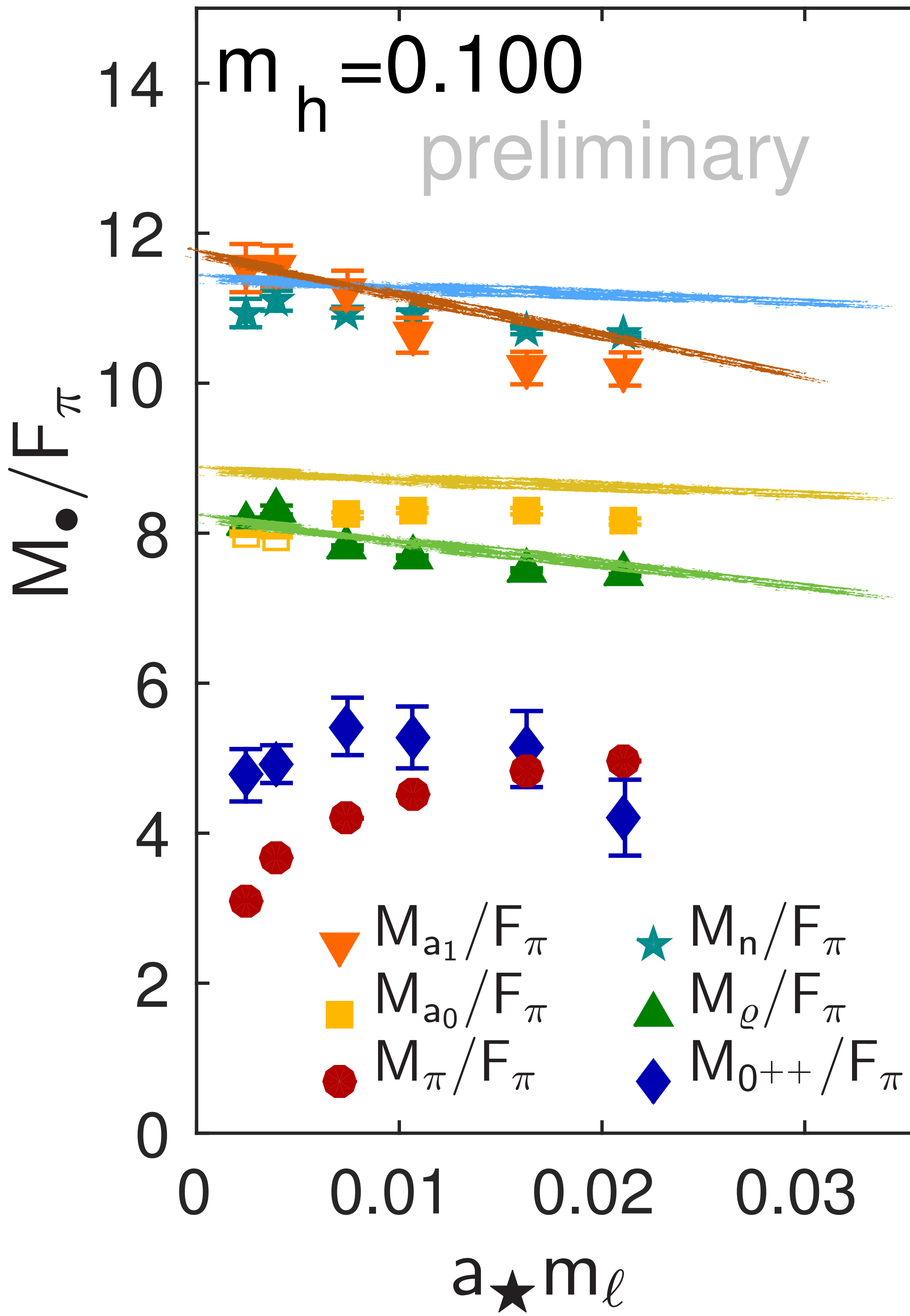

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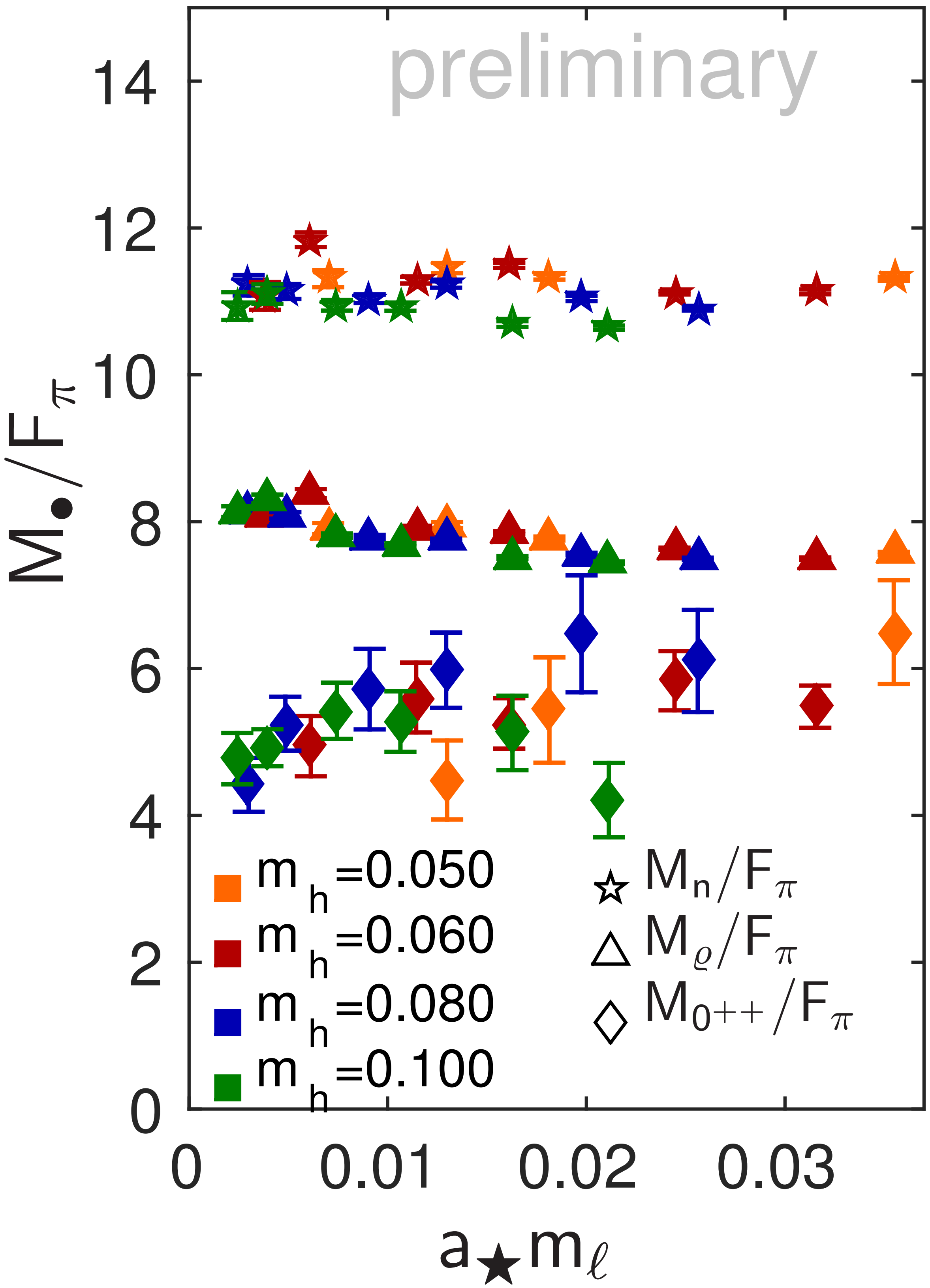
Spectrum, **4+8** flavors: Put it all together



rho, nucleon
and 0^{++} scalar

The ratios are very similar to
N_f=8 and sextet

$$M_\rho / F_\pi \approx 8$$
$$M_N / F_\pi \approx 11$$

0^{++} : chiral limit is difficult but
well separated from the rho

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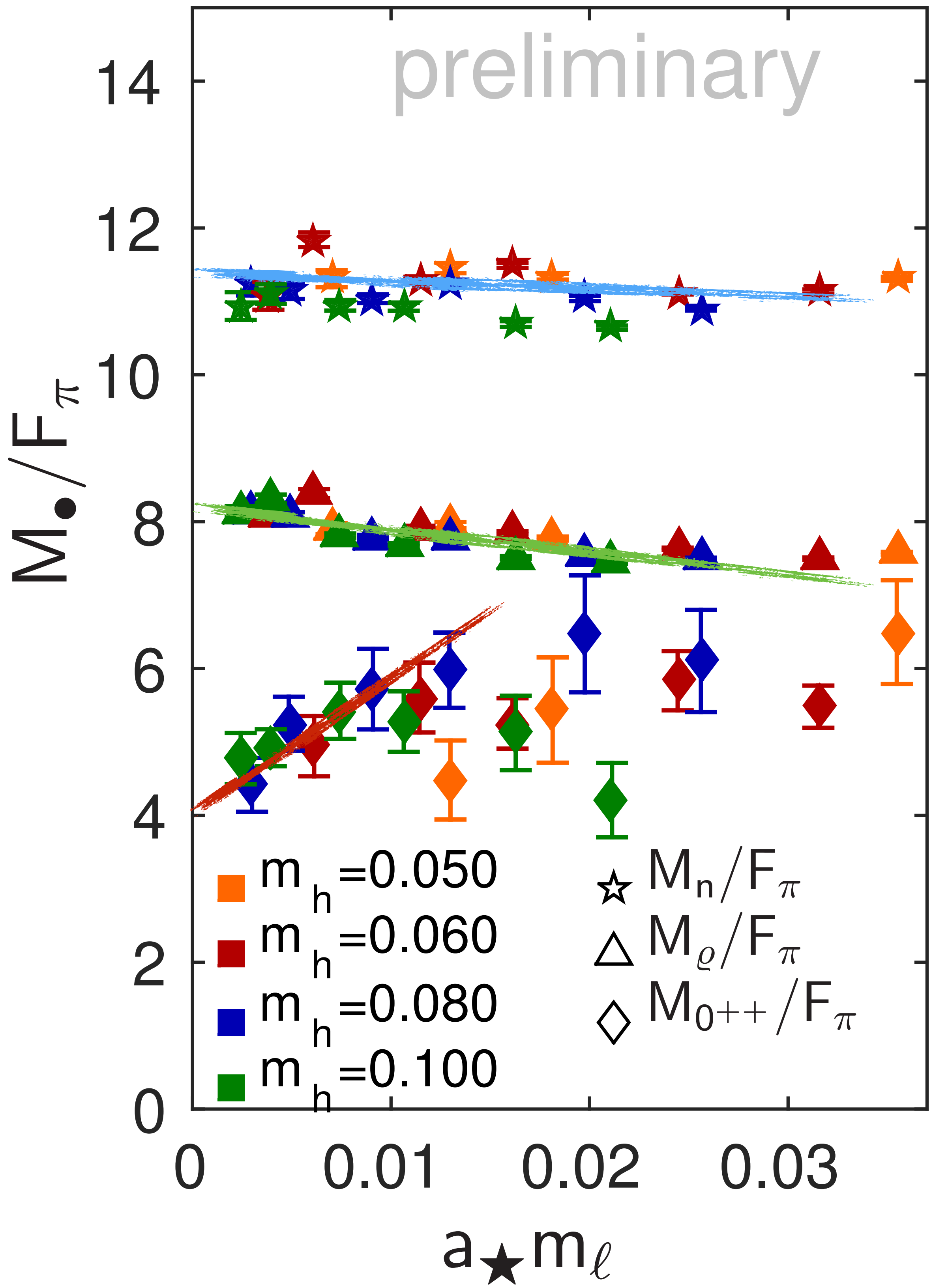

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Mass split models

The 4+8 system is not ideal:

- we need 2 light flavors
- N_f =12 is far above the conformal window with small anomalous dimension $\gamma_m \approx 0.25$

Yet it shows:

- hyperscaling,
- similar general properties as N_f=8
- 0^{++} well separated from heavier excitations

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

Conclusion & Summary

Lots of interesting possibilities ….
Lattice studies are needed to investigate strongly coupled systems
 - individual and generic properties

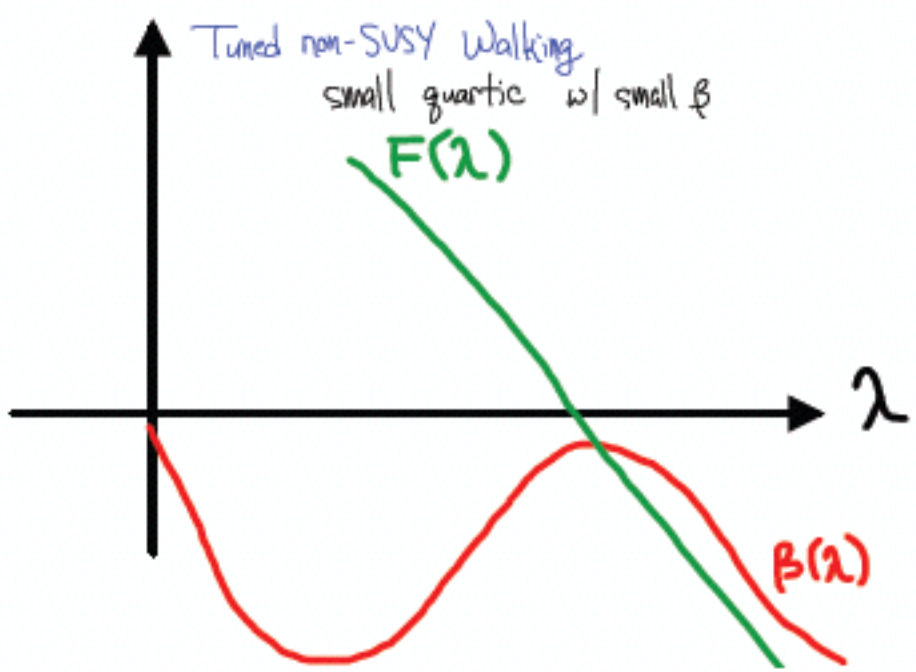
There appear to be some very general features between different models: $M_\rho / F_\pi \approx 8$
with other nearby resonances

Models with split fermion masses, built on a conformal IRFP, offer new approach - yet still show similar general features

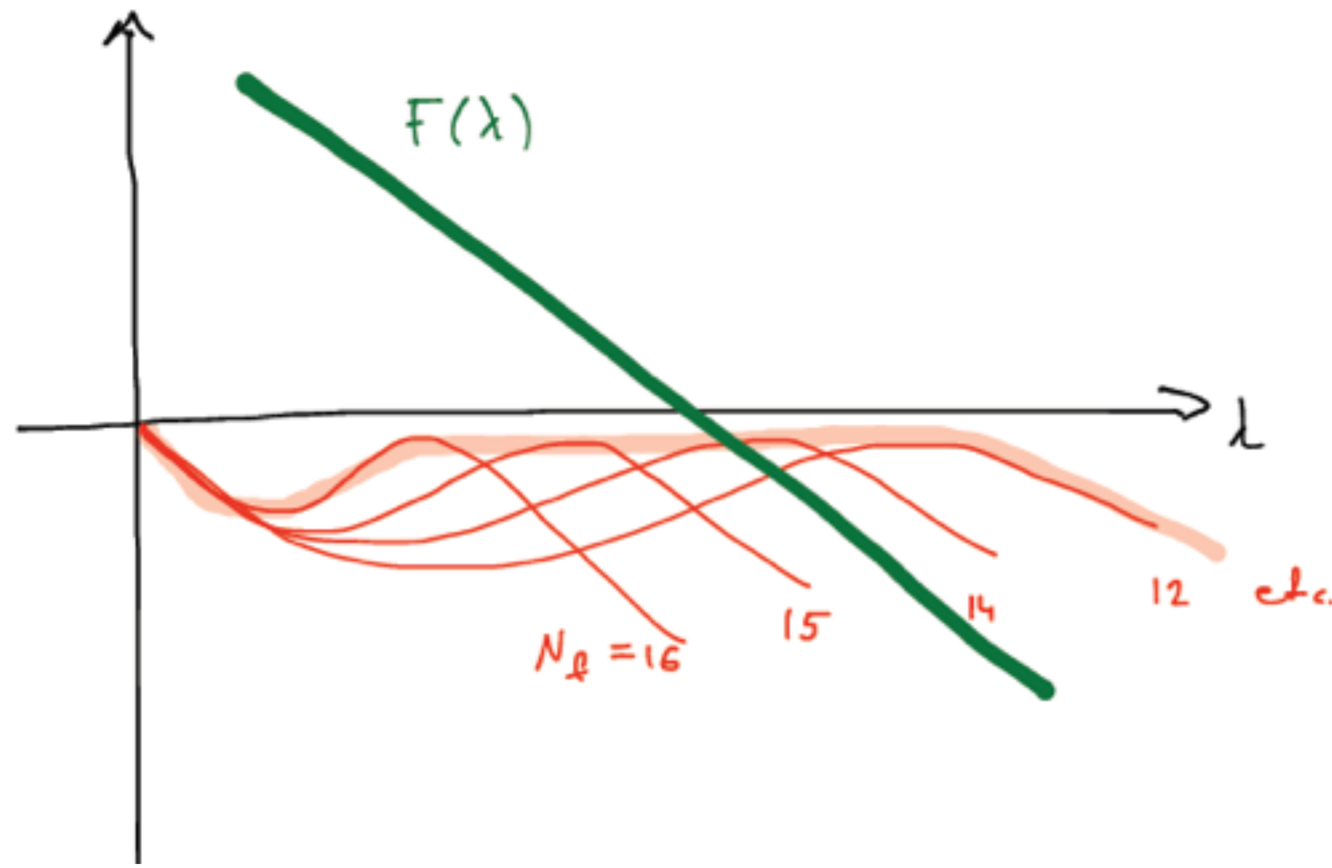
LHC Run-2 could verify / falsify many of the BSM models

EXTRA SLIDES

If the dilaton is not naturally light:



The heavy flavors
can be decoupled sequentially,
making the beta function walk
across a wide coupling range



(J. Hubisz)