Strong dynamics on the lattice

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in collaboration with

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Motivation

2012 July: we have a 125 GeV Higgs boson

Standard Model may be valid up to Planck scale

But the problems (hierarchy problem, naturalness, dark matter) didn't go away suddenly

Light Higgs is a new constraint on Beyond Standard Model extensions

Where do we stand with composite Higgs, strong dynamics?

Motivation

Composite Higgs – Strong Dynamics in this talk:

New strongly interacting sector with new gauge group and new fermions

Electro weak symmetry breaking $\longrightarrow$ spontaneous chiral symmetry breaking

Think of QCD

Higgs is a composite flavor singlet scalar meson (f_0 or σ)

Can it be light?

Different sceniario from PNGB

Motivation

This is an old idea! (Weinberg, Susskind, ..., late 70's)

Many early problems

- scaled up QCD doesn't work ($\Lambda_{QCD} = \Lambda \sim O(100) GeV$)
- S-parameter large?
- Higgs heavy (or Higgsless)
- many new massless particles?
- large FCNC vs. quark masses

Motivation

Problems may be due to QCD intuition and/or perturbation theory

We have lattice tools now to address them

Let's use lattice QCD techniques to do first principle calculations

Close to conformal window $\rightarrow$ very different properties from QCD

Motivation

Many theories to choose from

Hope to convince you that $SU(3)$ with

$N_f = 2$ and $R =$ sextet is a minimal model

and is promising phenomenologically

Outline and summary

- Sextet model – expectations
- Particle spectrum from lattice
- Light scalar
- Running coupling
- Conclusion (caveats, difficulties, questions)

Why $SU(3)$ sextet $N_f = 2$?

Dietrich, Sannino, Tuominen: hep-ph/0405209, hep-ph/0611341

- Asymptotically free
- Perturbatively: just below conformal window (Schwinger-Dyson)
- Slowly changing coupling? (FCNC vs. quark masses)
- Perturbatively: small S-parameter
- Complex representation: exactly 3 Goldstones $\rightarrow$ eaten by W and Z

Why $SU(3)$ sextet $N_f = 2$?

Very similar to $N_f = 2$ QCD

$R = fundamental$ replaced by $R = sextet = 2 - index - symm$

But very different properties

$f_\pi = 250\ GeV$

Non-perturbative (lattice) studies

We only study the model in isolation as $SU(3)$ gauge theory with $N_f = 2$ fermions in sextet

Forget about rest of Standard Model

Questions for this talk

- Chiral symmetry breaking does happen?
- Particles in the spectrum? Light Higgs?
- Running coupling (is it walking?)

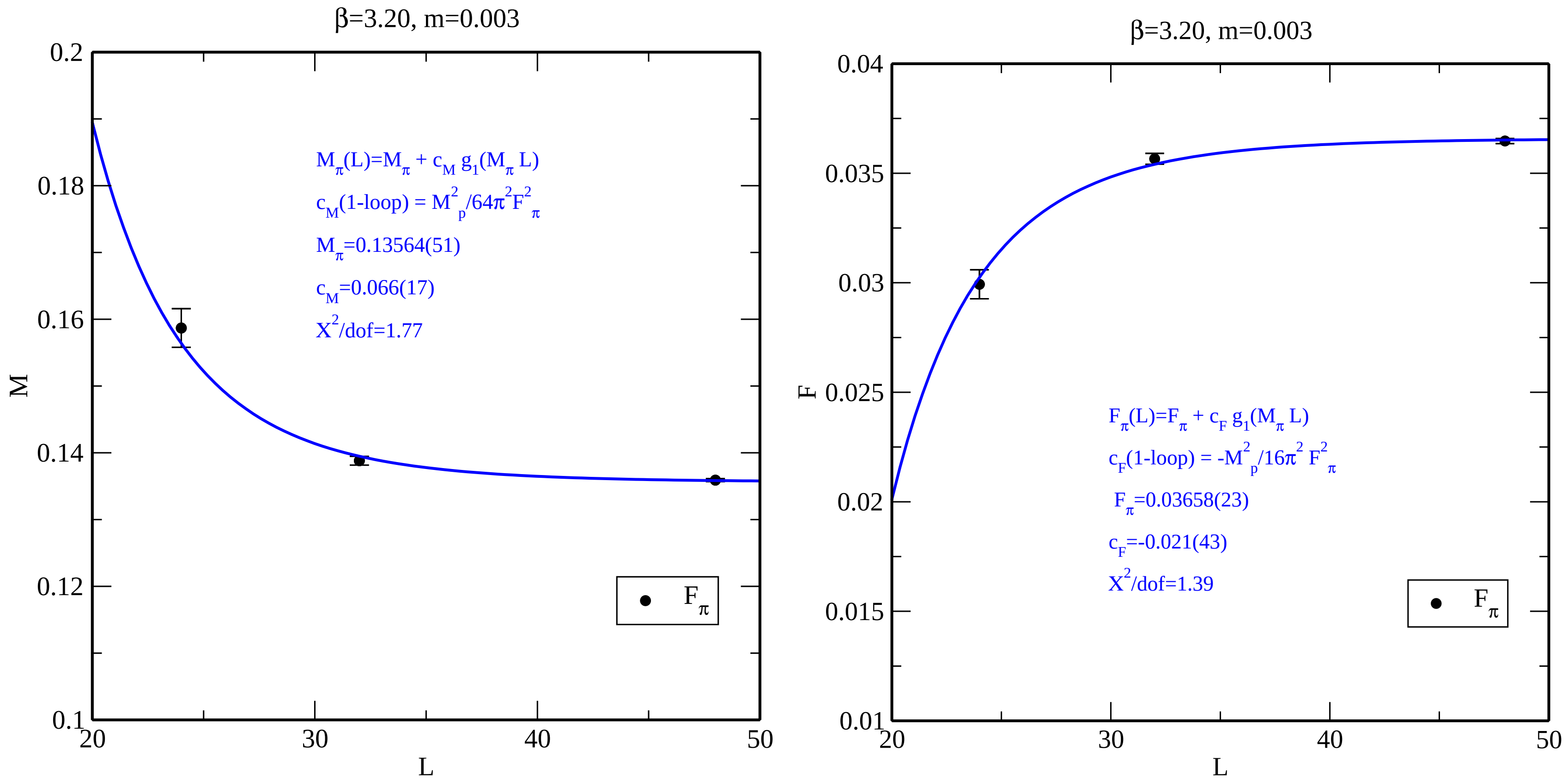
Lattice

Particle spectrum (staggered fermions)

Using QCD terminology consider

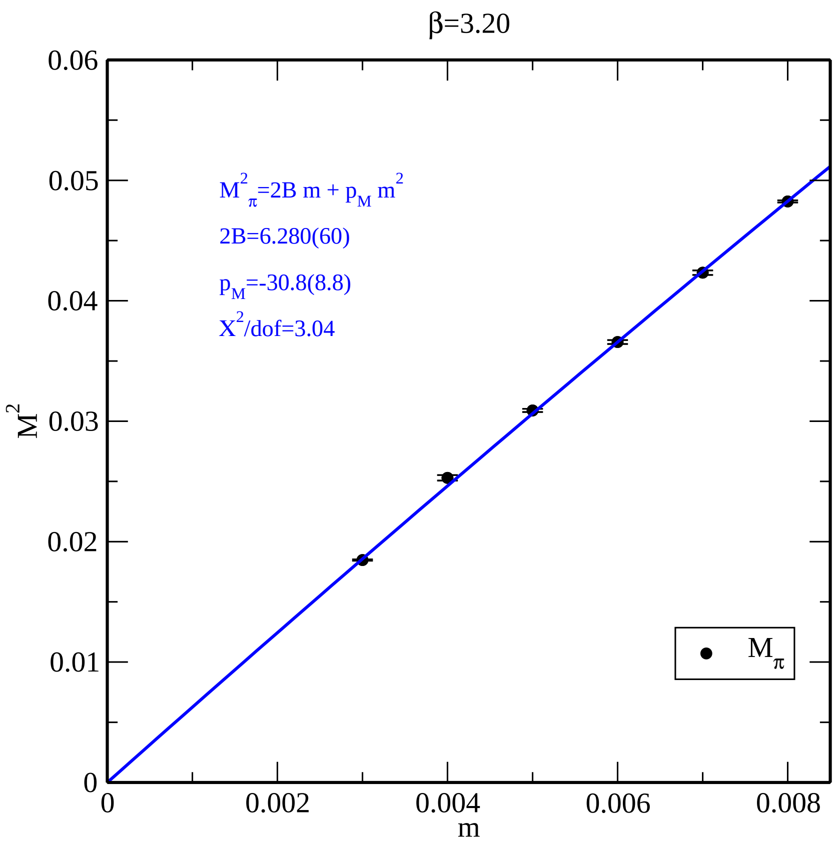
$$m_\pi \quad f_\pi \quad m_{a_0} \quad m_\rho \quad m_{a_1} \quad m_N \quad m_{\eta'} \qquad m_{f_0} = m_{0^{++}} = m_{Higgs}$$

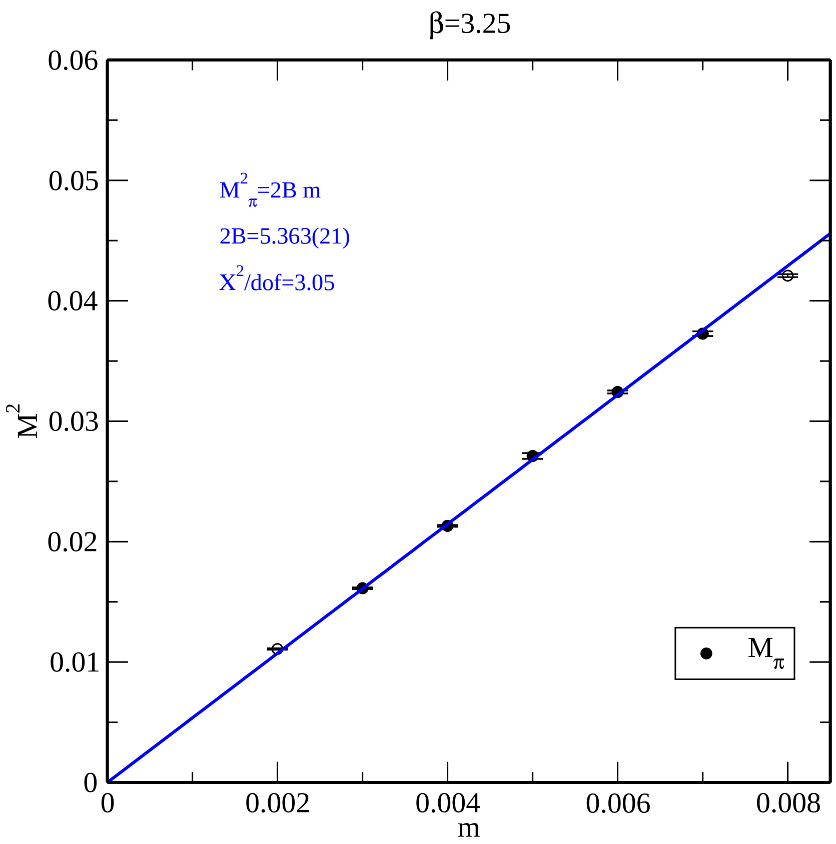
Lattice – finite volume effects



Already at $\beta = 3.20$ and $m = 0.003$, 32^3 is not enough, $m_\pi L > 6{-}7$ needed

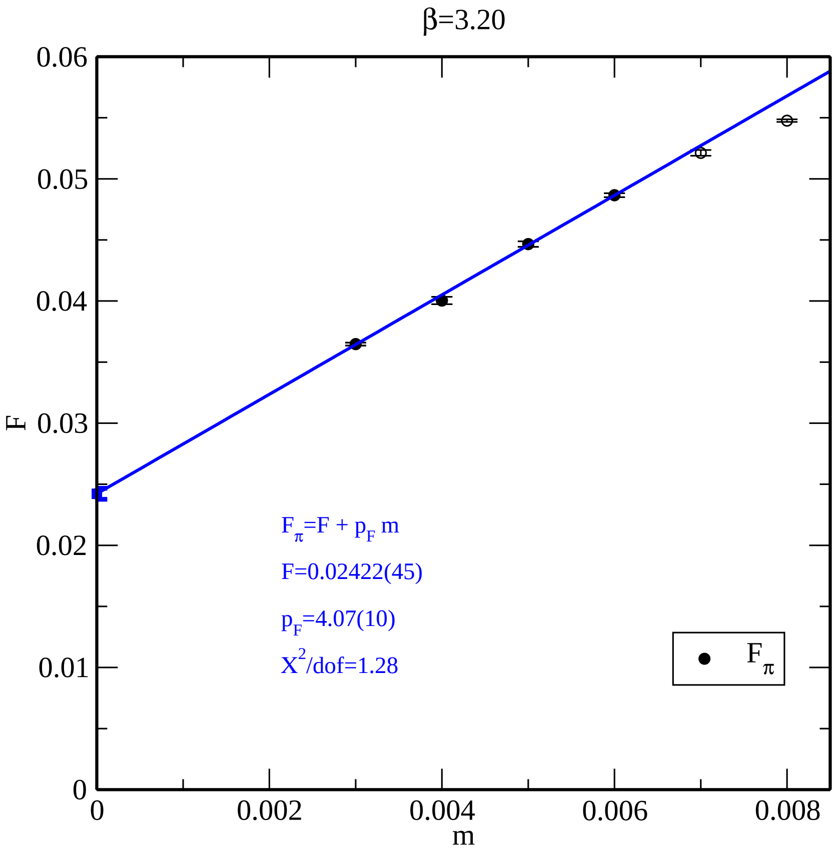
Lattice - pseudo-scalar meson

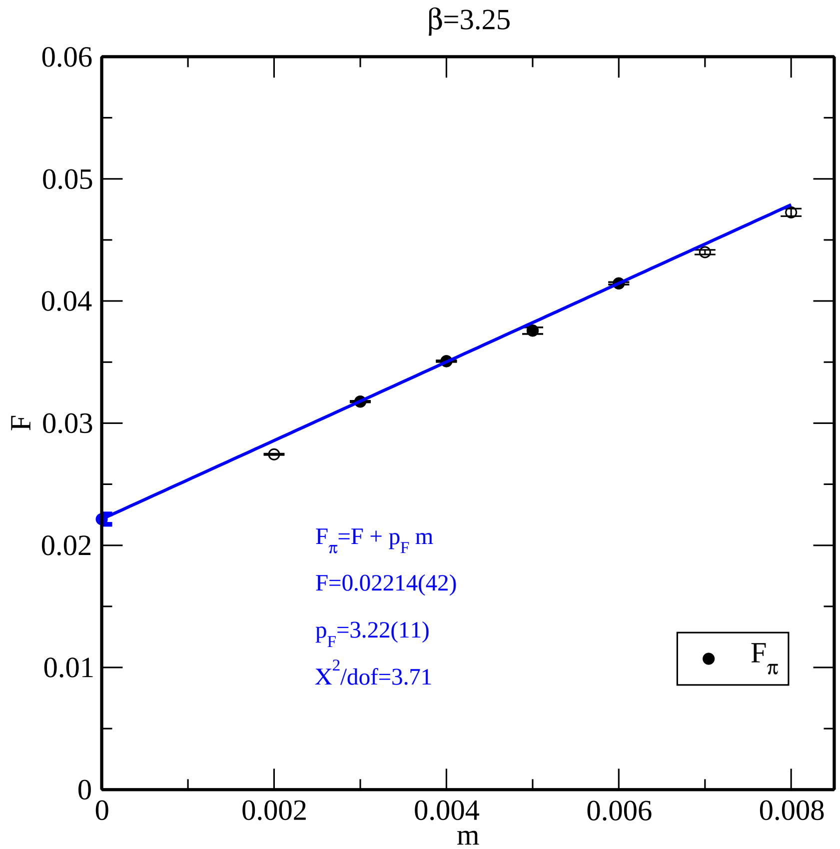




Unable to resolve chiral logs

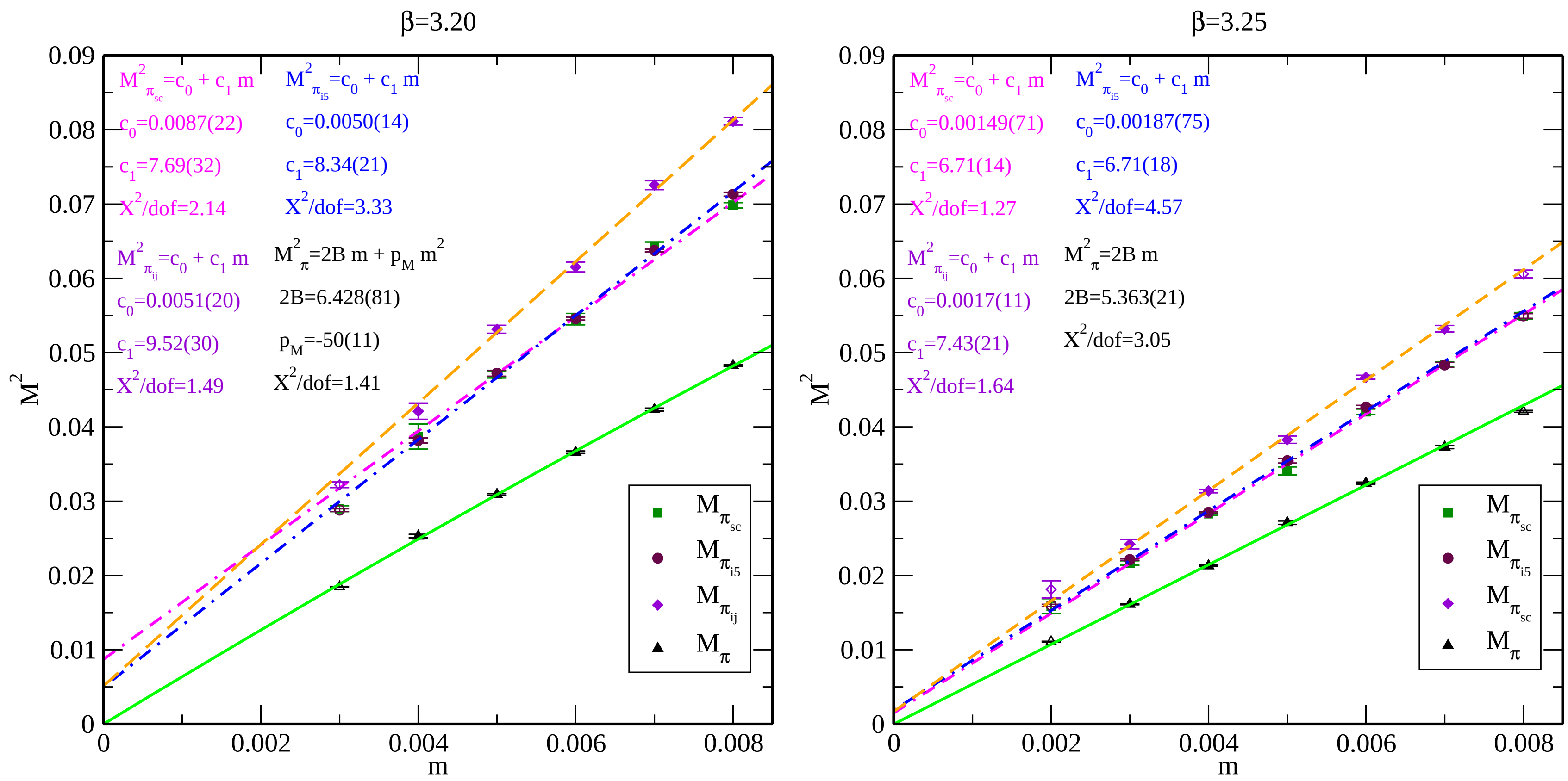
Lattice - pseudo-scalar meson





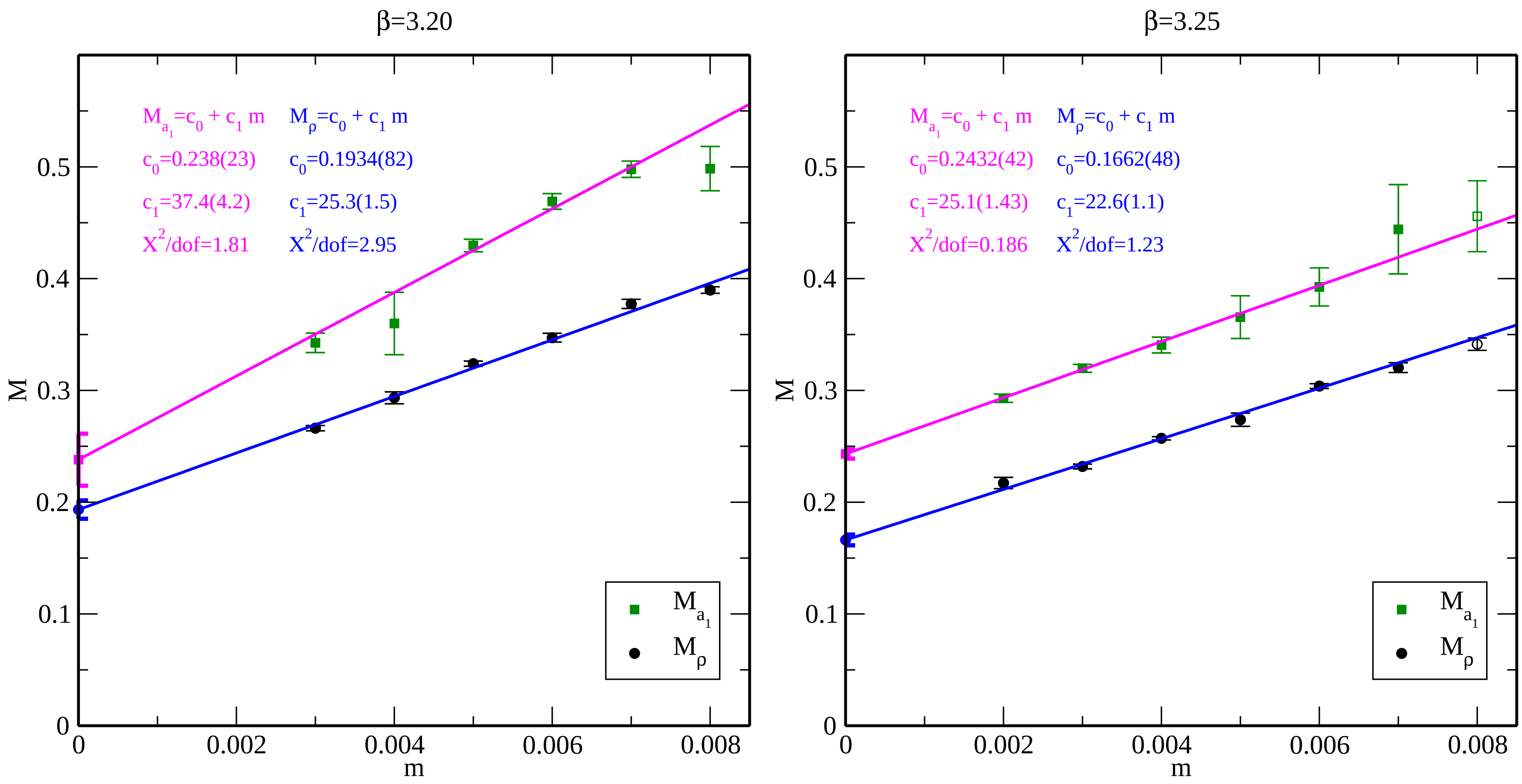
Much stronger m-dependence than in QCD

Lattice - pseudo-scalar meson



Note the different slopes, in QCD parallel

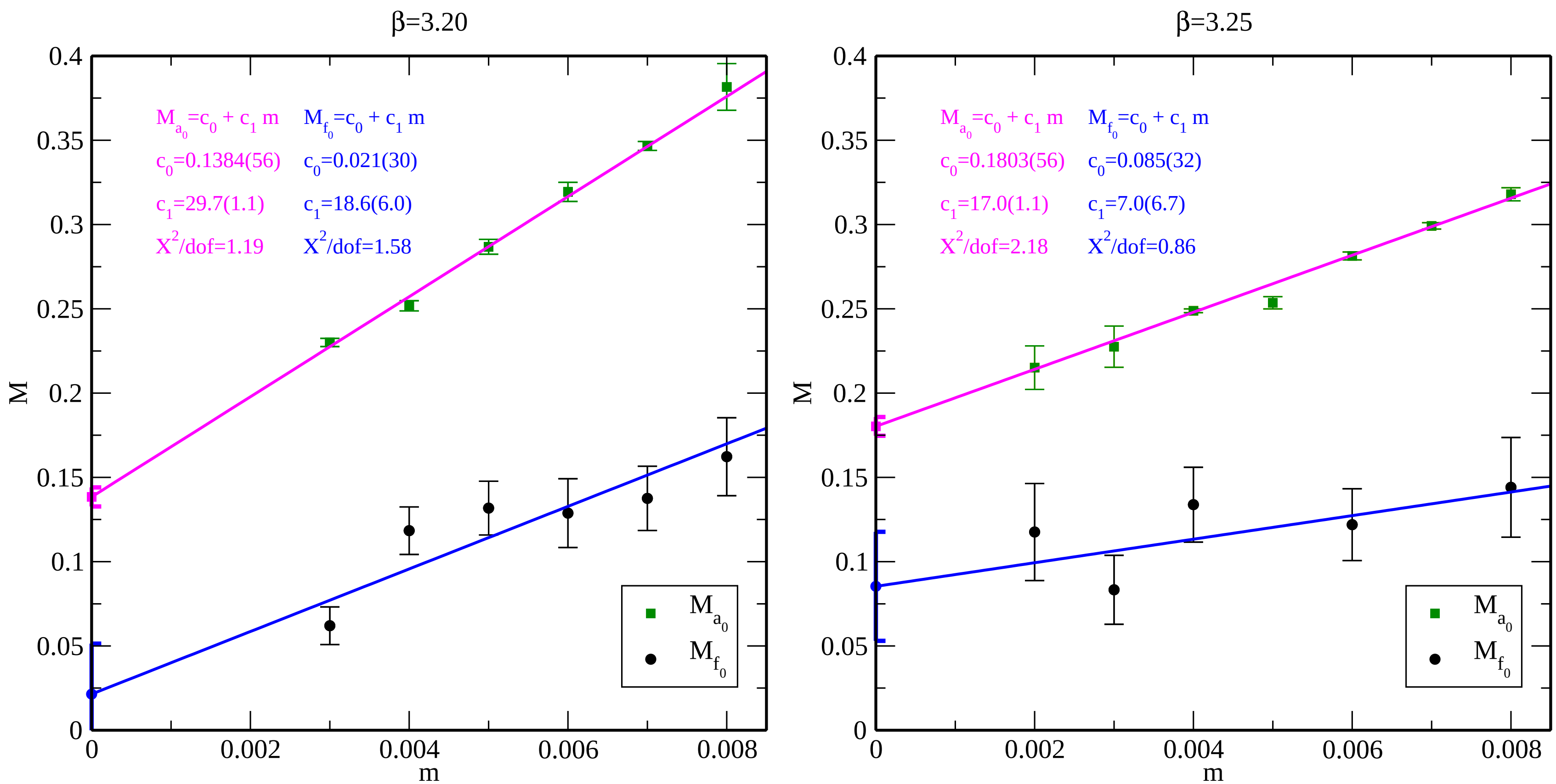
Lattice - vector mesons ϱ and a_1



Within reach of LHC Run 2

Small splitting: $S \sim VV - AA$, small?

Lattice - scalar mesons f_0 and a_0



Remember f_0 is the Higgs!

Difficult channel, disconnected fermion graphs

$\beta = 3.25$ preliminary, topology?

Lattice - baryons

Baryon states very diferent from QCD

$3 \otimes 3 \otimes 3 = 1 \oplus 2 \times 8 \oplus 10$

$6 \otimes 6 \otimes 6 = 1 \oplus 2 \times 8 \oplus 10 \oplus \overline{10} \oplus 3 \times 27 \oplus 28 \oplus 2 \times 35$

But!

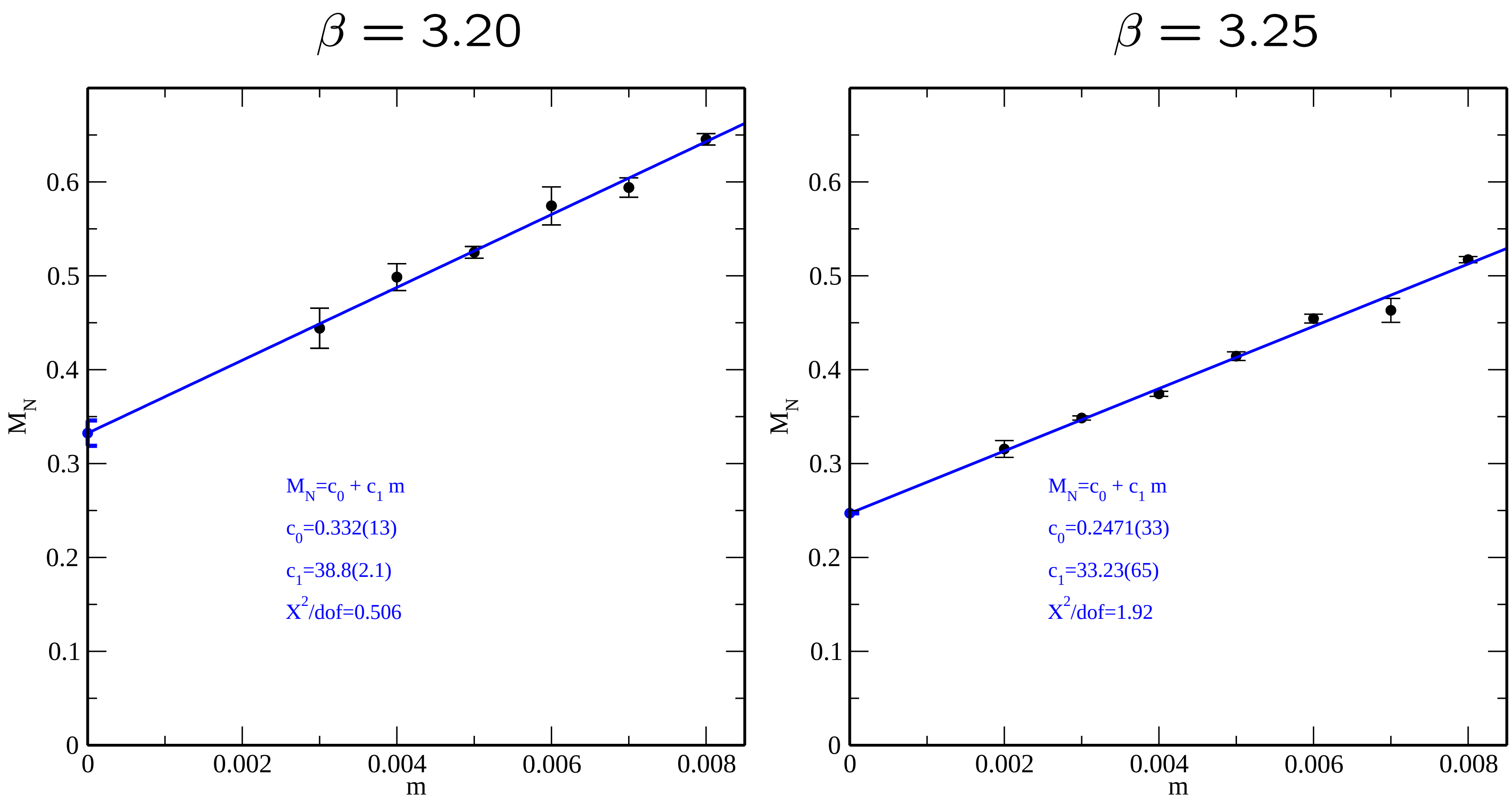
singlet in QCD: $\varepsilon_{abc}\,\psi_a\,\psi_b\,\psi_c$, ϵ_{abc} anti-symmetric

singlet in sextet: $\varepsilon_{abc}\,\varepsilon_{def}\,\psi_{ad}\,\psi_{be}\,\psi_{cf} = T_{ABC}\,\psi_A\,\psi_B\,\psi_C$

$a, b, \ldots = 1, 2, 3$ $A, B, C = 1, 2, 3, 4, 5, 6$

T_{ABC} symmetric

Lattice - baryons



Dark matter?

Lattice - η'

Extract from gluonic operator

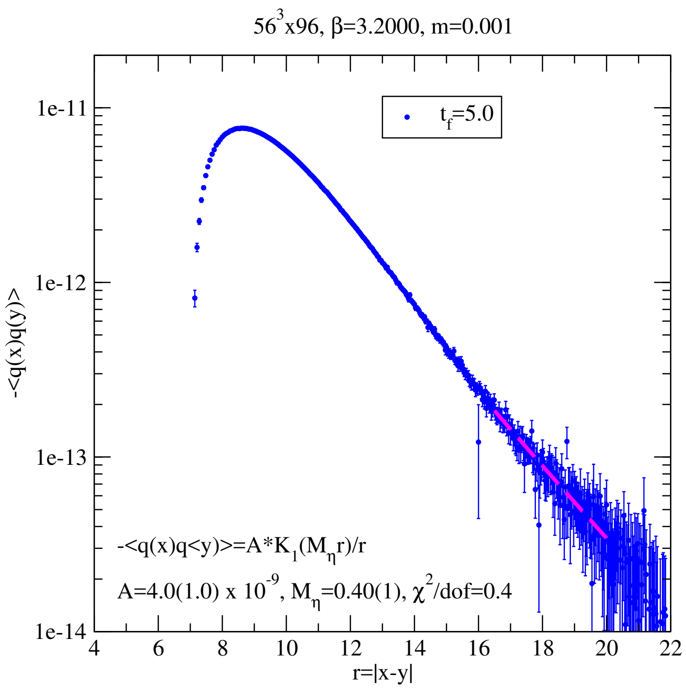
$$q(x) = \frac{1}{32\pi^2}\varepsilon_{\mu\nu\rho\sigma}F_{\mu\nu}(x)F_{\rho\sigma}(x)$$

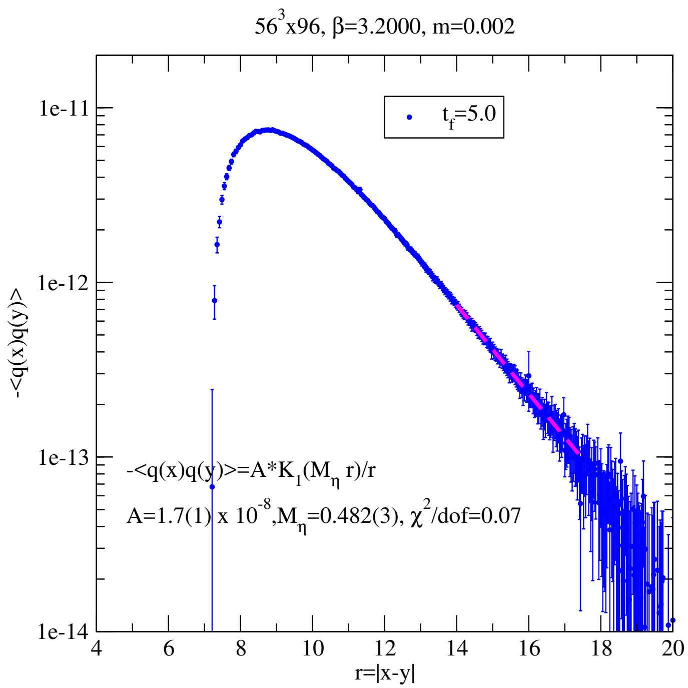
$$-\langle q(x)q(y)\rangle \sim \frac{K_1(m_{\eta'}r)}{r} \qquad r = |x-y|$$

Measure on gradient flow $\longrightarrow$ less noisy

Lattice - η'

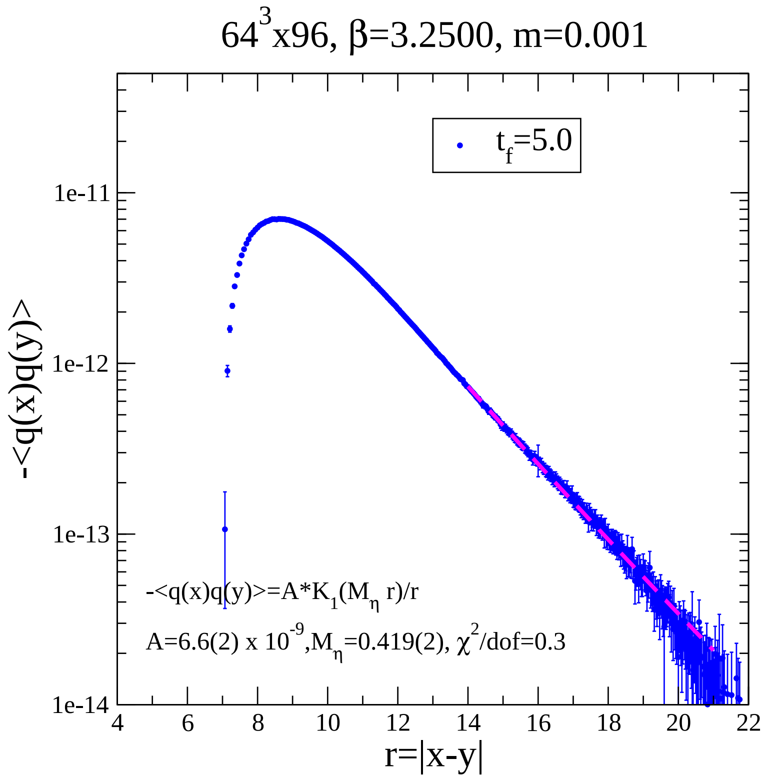
$\beta = 3.20$, preliminary





Lattice - η'

$\beta = 3.25$, preliminary



Spectrum summary 1

$$m_{f_0}/f_\pi \sim 1-2 \qquad m_{f_0} \sim 250-500\,GeV$$

$$m_{a_0}/f_\pi \sim 6-8 \qquad m_{a_0} \sim 1.5-2\,TeV$$

$$m_\varrho/f_\pi \sim 7-8 \qquad m_\varrho \sim 1.8-2\,TeV$$

$$m_{a_1}/f_\pi \sim 10-11 \qquad m_\varrho \sim 2.5-2.7\,TeV$$

$$m_N/f_\pi \sim 11-14 \qquad m_N \sim 2.7-3.5\,TeV$$

$$m_{\eta'}/f_\pi \sim 13-18 \qquad m_{\eta'} \sim 3.2-4.5\,TeV$$

Light scalar separated from the 2-3 TeV region

Higgs at $250 - 500\,GeV$??

What we measure is not “the” Higgs

Coupling to SM: top loop

$$m^2_{Higgs} = m^2_{sextet\, f_0} - const\; m^2_{top}$$

Foadi, et al.

Other particles expected to be effected less

Spectrum summary 2

Model seems consistent with χPT

Model gives rise to a light scalar

New particles with definite properties in 2-3 TeV region

Potential dark matter candidate as well

Important caveats

- Slow topology change
- Unestimated systematics
- Only $20-30\%$ change in lattice spacing
- Coupled scalar-pion dynamics ignored in χPT
- etc.

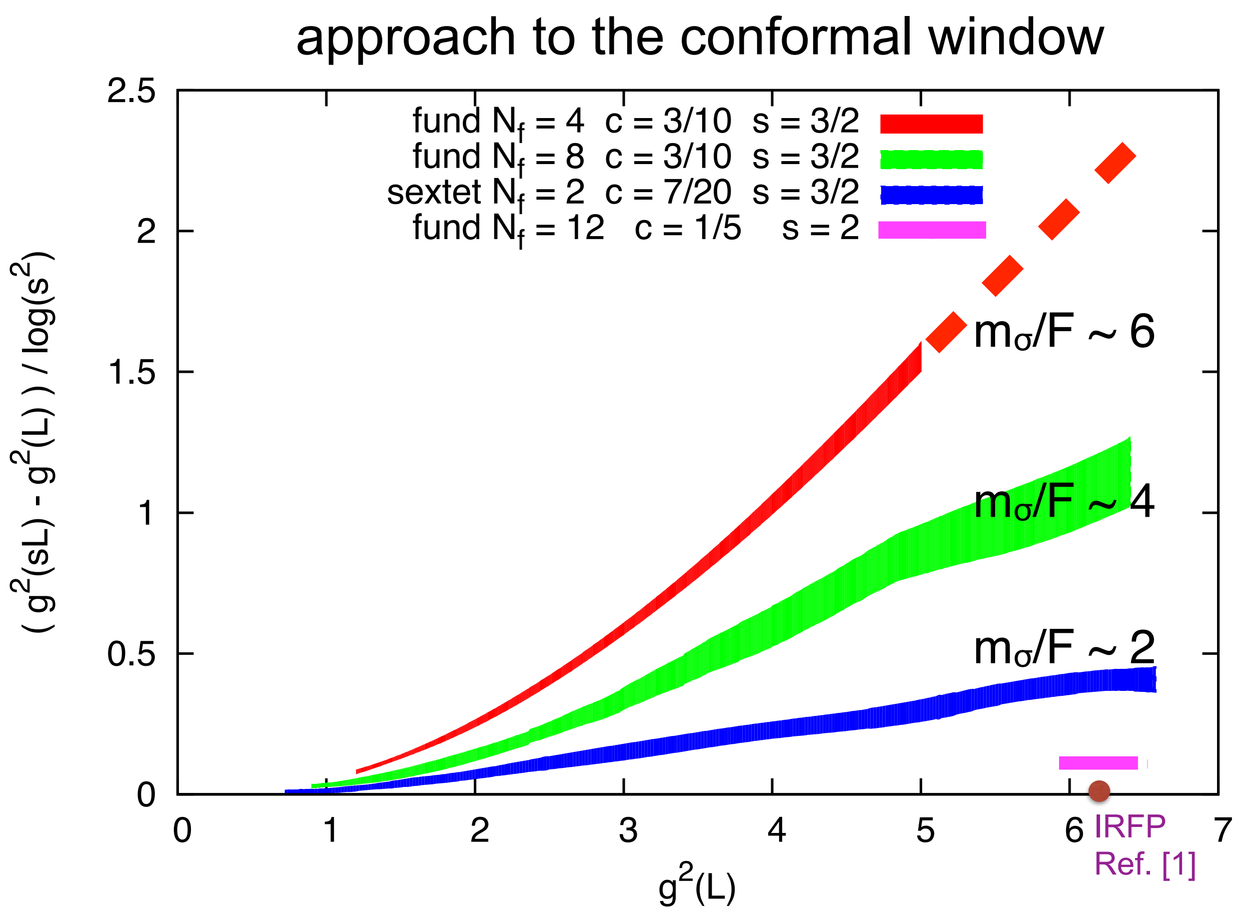
Running coupling

Running scale: $\mu = 1/L$, using gradient flow

$$g^2(L) \sim \langle t^2 E(t) \rangle \qquad c = \frac{\sqrt{8t}}{L} = const$$

Discrete β-function: $\frac{g^2(sL) - g^2(L)}{\log(s^2)}$ $\quad s = 3/2, 2$

Running coupling, extrapolated to continuum



Running coupling summary (for sextet)

No sign of fixed point in the $0 < g^2 < 6.5$ range

3-loop fixed point in $\overline{\mathrm{MS}}$: $g^2 = 6.28$

4-loop fixed point in $\overline{\mathrm{MS}}$: $g^2 = 5.73$

Schwinger-Dyson: no fixed point

Summary and questions

- Sextet model is a minimal composite Higgs model
- Particle spectrum shows chiral symmetry breaking
- Light scalar emerges
- Running coupling consistent with it

Summary and questions

- Lower end of conformal window $\longrightarrow$ light scalar?
- Slow running $\longrightarrow$ light scalar?
- Why light? Dilatation symmetry?
- $m_\rho/f_\pi \sim 8$?

Work in progress and future outlook

Haven't talked about lots of things

- Chiral condensate from Dirac eigenvalues (GMOR)
- Mass anomalous dimension
- Thermodynamics
- etc.

Thank you for your attention!