Light composite Higgs

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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 can mean many things

In this talk: strong dynamics, new strongly interacting sector with new gauge group and new fermions

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

Think of QCD

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

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

Most problems presented in perturbation theory or model calculations or some other uncontrolled framework

We have tools now to address them, we understand lattice QCD

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

Motivation

Many theories to choose from

$SU(N)$ gauge group, N_f flavors of fermions in representation R

Pick a theory with the most chance to be viable phenomenologically

$R \neq fund$ is already a new game in town

Changes the picture completely for the old problems that were raised

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

- Constraints on strong dynamics based extensions

- N_f and R dependence of infrared dynamics

- Conformal window

- Lattice results for the sextet model

- Light Higgs, potential dark matter candidate, 2 TeV vector particle, another nearby new particle, potentially small S-parameter, no unwanted new massless particles, . . .

Constraints

Asymptotic freedom

Spontaneous chiral symmetry breaking in infrared, $f_\pi = 250\,GeV$

At least 3 Goldstones $\rightarrow$ eaten by W and Z

$S \sim VV - AA$ small

Slowly changing (walking) coupling: FCNC and quark masses

Conformal window

Constraints might be accommodated once we understand infrared dynamics

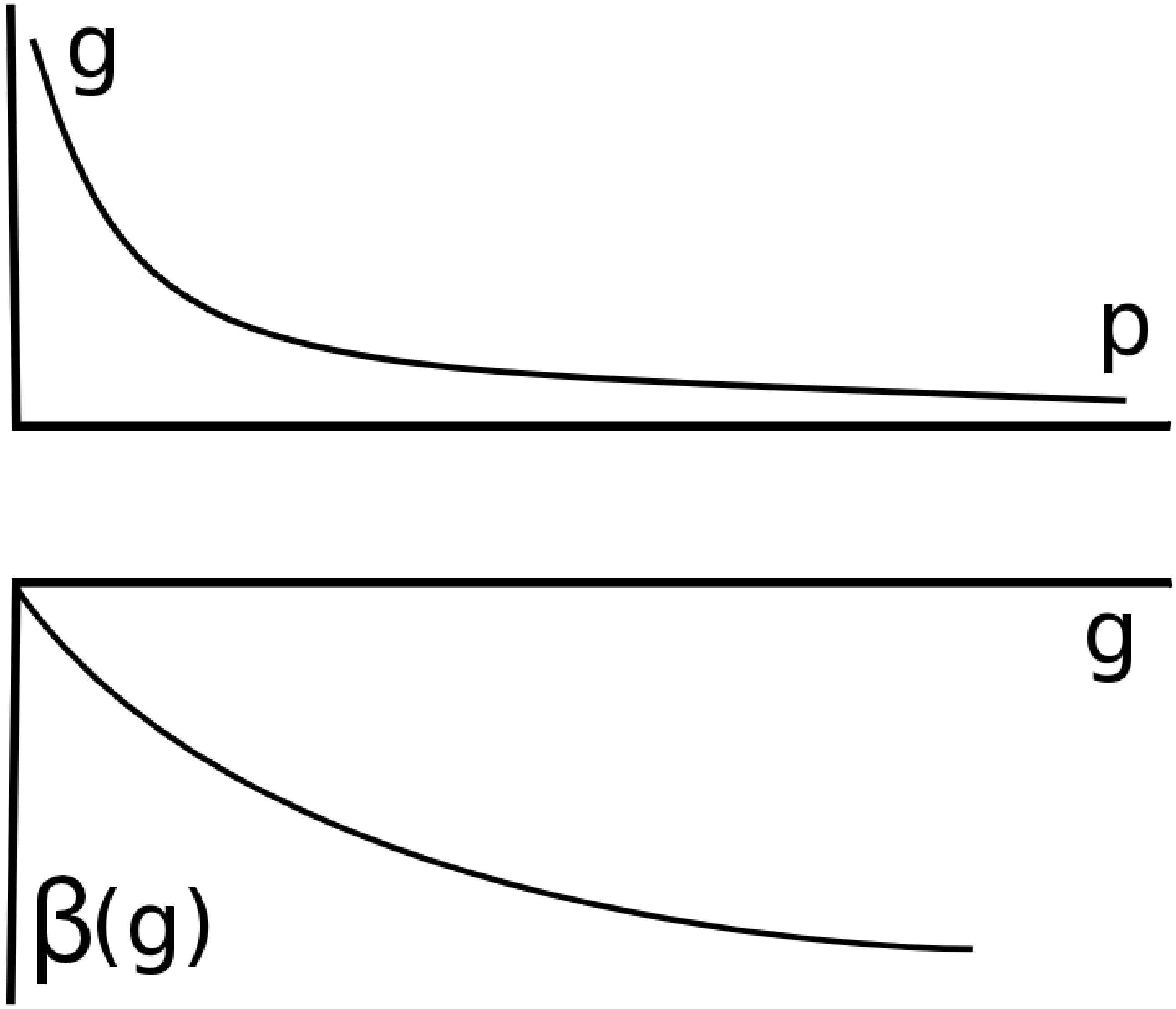
$SU(N)$ gauge theory with N_f fermions in R

$$
\begin{aligned}
\beta(g) &= \mu\frac{dg}{d\mu} = \beta_1\frac{g^3}{16\pi^2} + \beta_2\frac{g^5}{(16\pi^2)^2} \\
\beta_1 &= -\frac{11}{3}N + \frac{4}{3}N_f T(R) \\
\beta_2 &= -\frac{34}{3}N^2 + \left(\frac{5}{3}N + C_2(R)\right) 4T(R)N_f
\end{aligned}
$$

Asymptotic freedom: $\beta_1 < 0$, perturbation theory reliable

$$N_f < \frac{11N}{4T(R)}$$

Asymptotic freedom



Conformal window, N_f-dependence

Non-trivial fixed point $\beta(g_*) = 0$:

Exists if $\beta_1 < 0$ and $\beta_2 > 0$ Banks-Zaks

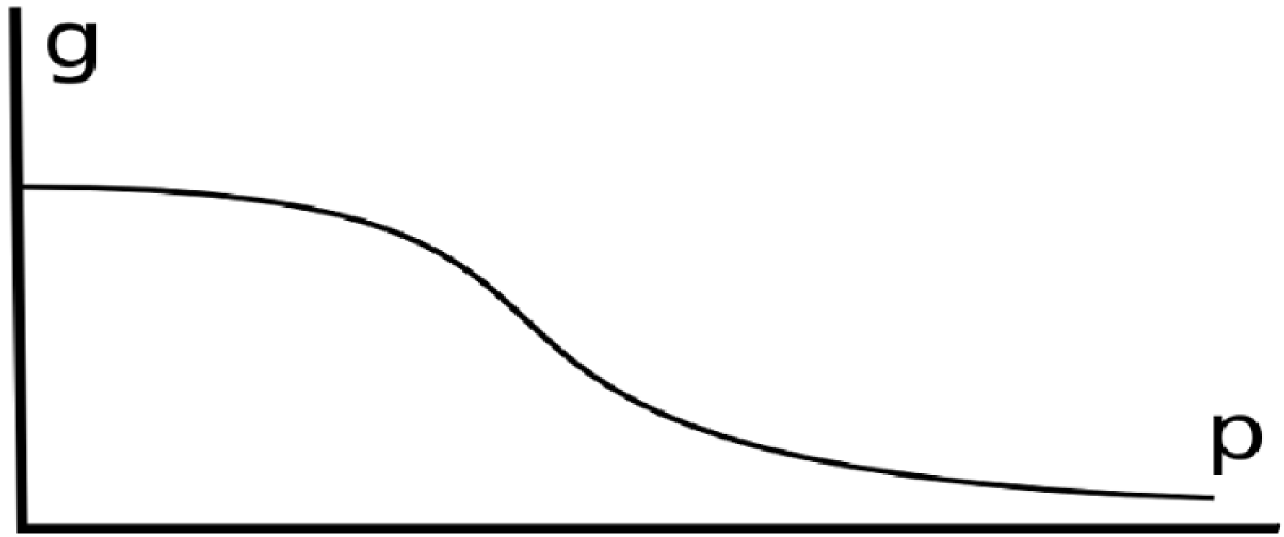
$g_* = 4\pi\sqrt{-\frac{\beta_1}{\beta_2}}$

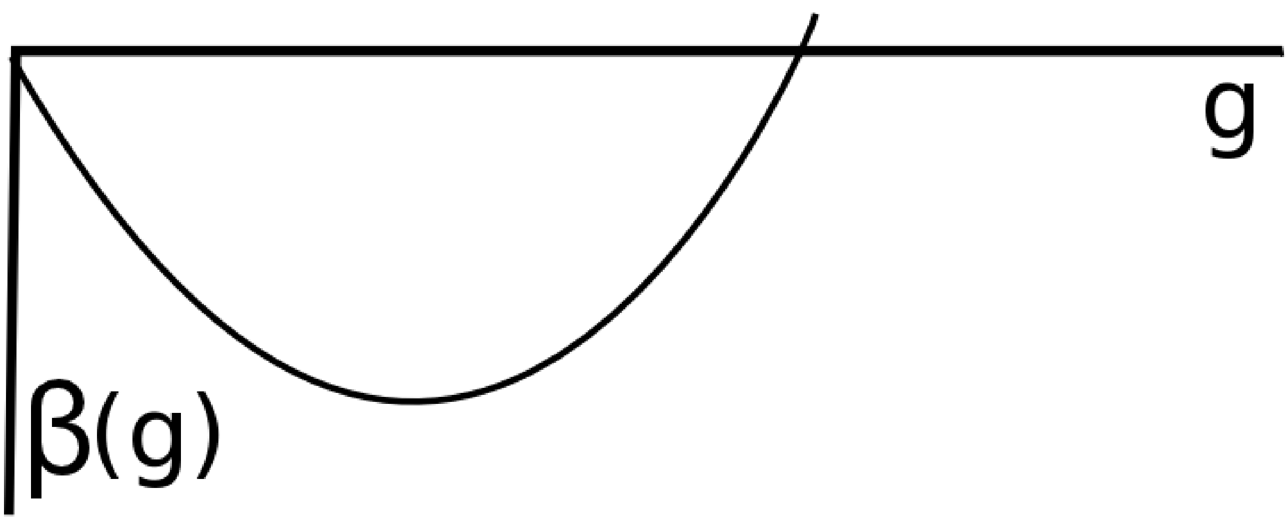
$N_f^{low} = \frac{34N^2}{4T(R)(5N+3C_2(R))} < N_f < \frac{11N}{4T(R)} = N_f^{up}$

This N_f range is the conformal window

Fixed point g_* an IR fixed point.

Infrared fixed point





Conformal window, N_f-dependence

How trustworthy is this?

$$N_f^{low} = \frac{34N^2}{4T(R)(5N+3C_2(R))} < N_f < \frac{11N}{4T(R)} = N_f^{up}$$

Upper end of the conformal window: loss of asymptotic freedom
$\longrightarrow$ perturbation theory is trustworthy, even 1-loop is enough

$g_* = 4\pi\sqrt{-\frac{\beta_1}{\beta_2}}$ is small because β_1 is small

Lower end of the conformal window: 2-loop is suspect

$g_* = 4\pi\sqrt{-\frac{\beta_1}{\beta_2}}$ is large because β_2 is small

Conformal window, N_f-dependence

Where we know what we are doing: close to upper end of the conformal window

E.g. $N = 3$, $R = fund$, $N_f^{up} = 16.5$

For example $N_f = 16$ 2-loop result is probably okay, a non-trivial weakly interacting 4D CFT

Conformal window, N_f-dependence

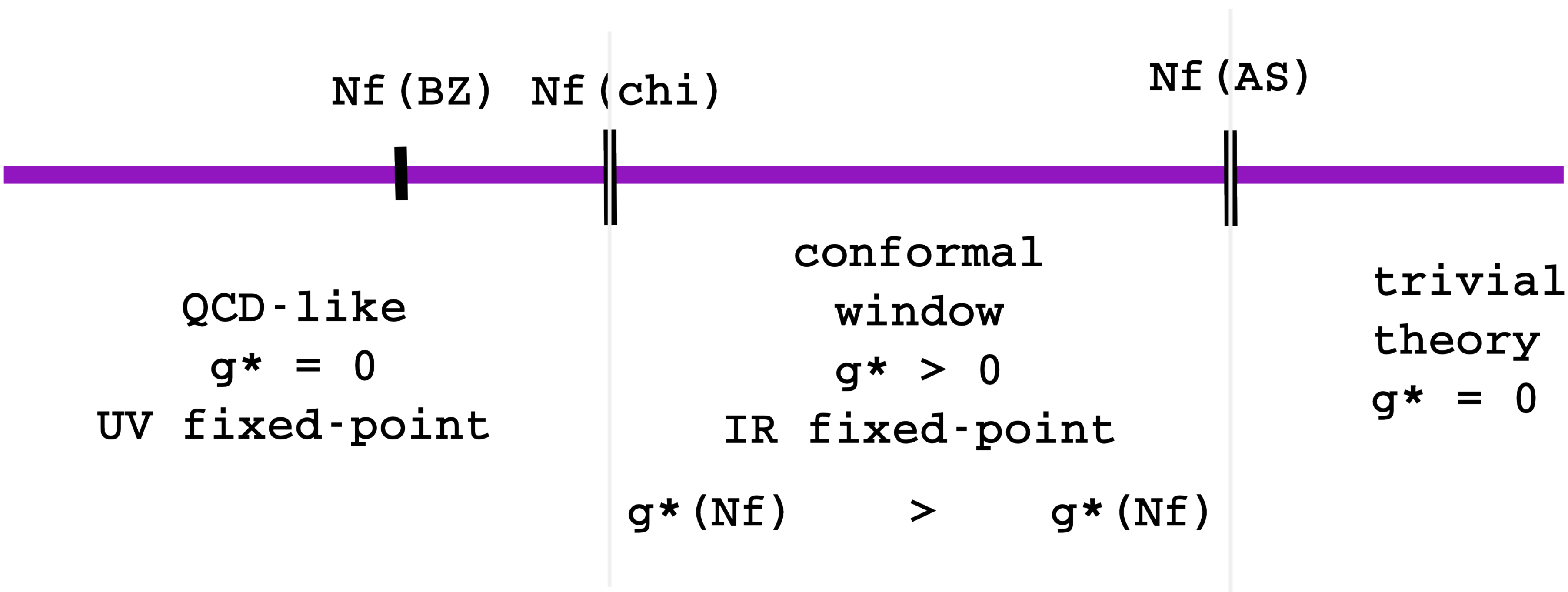
Even though 2-loop result is unreliable for N_f^{low} the lesson is that there exists an N_f^{low} but we can't compute it in perturbation theory

Is real N_f^{low} smaller or larger than 2-loop N_f^{low}?

Probably larger.

As N_f decreases from upper end of conformal window g_* grows $\longrightarrow$ if not too large still CFT $\longrightarrow$ as it gets large chiral symmetry breaks $\longrightarrow$ scale is generated $\longrightarrow$ conformal symmetry lost $\longrightarrow$ no IR fixed point $\longrightarrow$ we are outside the conformal window.

Conformal window, N_f-dependence summary



N_f increases from left to right

Examples

Perturbative 2-loop N_f^{low}

$SU(2)$

- $R : j = 1/2, \quad 5.551... < N_f < 11$
- $R : j = 1, \quad 1.0625 < N_f < 2.75$
- $R : j = 3/2, \quad 0.32 < N_f < 1.1$

Examples

Perturbative 2-loop N_f^{low}

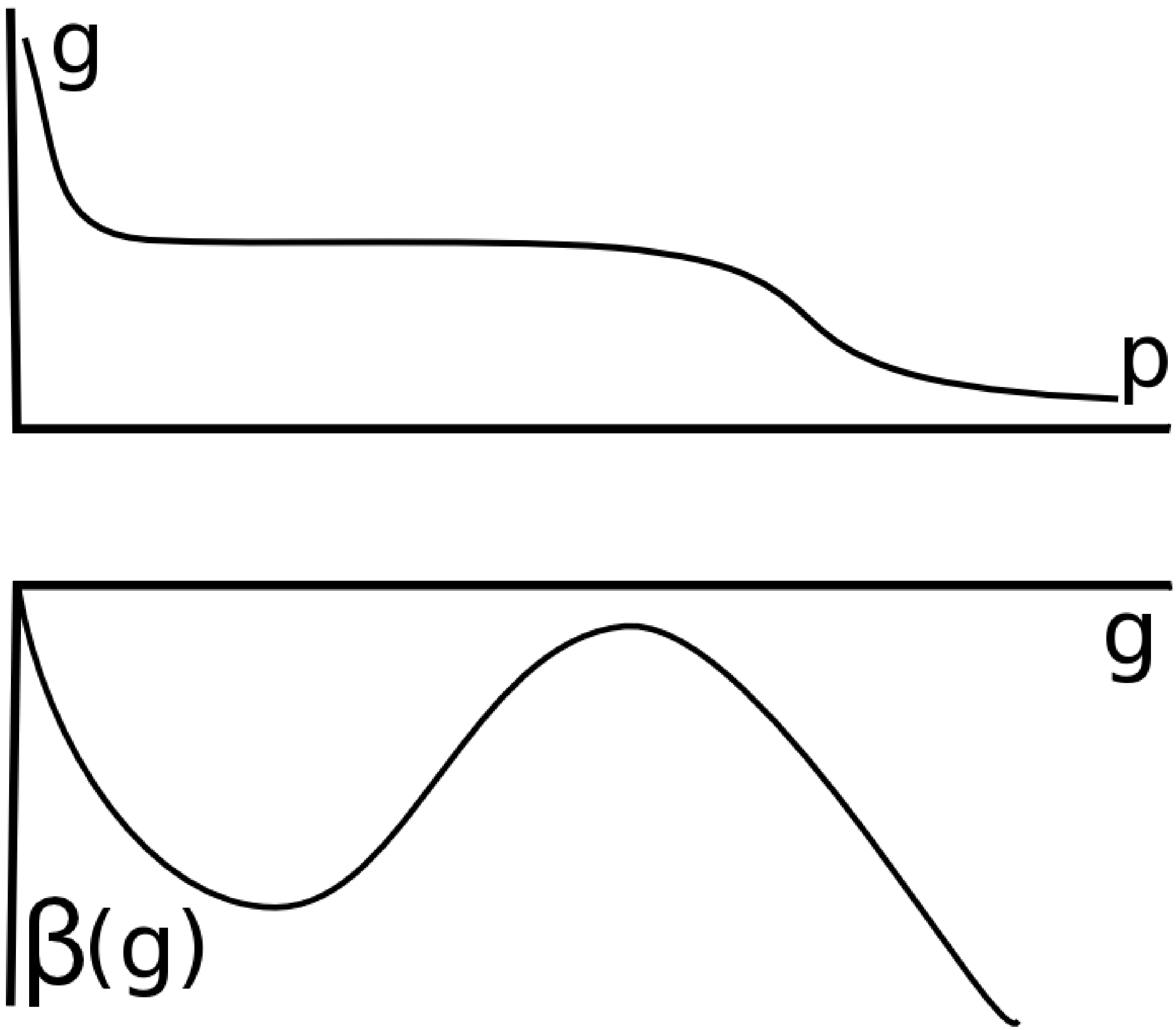
$SU(3)$

- $R = fund, \quad 8.05... < N_f < 16.5$

- $R = sextet, \quad 1.224 < N_f < 3.3$

- $R = adj, \quad 1.0625 < N_f < 2.75$

N_f just below lower end of conformal window



Conformal window, N_f-dependence

Constraints:

- Below conformal window
- Just below: slowly changing coupling
- Chiral symmetry breaking smaller than much below conformal window, $S \sim VV - AA$ might be small (non-perturbative reasoning)
- Small N_f, S smaller (perturbative reasoning)
- Complex representation $\rightarrow$ pattern same as in QCD $SU(N_f) \times SU(N_f) \rightarrow SU(N_f)$ for $N > 2$
- At least $N_f = 2 \rightarrow$ at least 3 Goldstones

The model

- $SU(3)$ gauge theory with $N_f = 2$ flavors in the sextet
- Similar to massless 2 flavor QCD but: fundamental $\rightarrow$ sextet
- Sextet: 2-index symmetric representation $\psi_{ab}, \quad a, b = 1, 2, 3$

Dietrich, Sannino

The model

Some differences and similarities relative to QCD

- Asymptotic freedom (QCD $N_f < 16.5$): sextet $N_f < 3.3$
- Large N for $SU(N)$ (QCD fermions $\sim O(N)$): sextet fermions $\sim O(N^2)$
- Distance from conformal window (QCD large): sextet small (Schwinger-Dyson)
- Topology and index theorem (QCD $I = Q$): sextet $I = 5Q$
- Both: $N_f = 1$ anomaly breaks chiral symmetry group completely
- Both: representations complex, for $SU(3)$

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?
- Running coupling (is it walking?)

Lattice setup

Particle spectrum

- Finite lattice spacing a
- Finite volume L
- Finite fermion mass $m > 0$
- Chiral limit $m \to 0$ in large volumes at finite lattice spacing
- Decrease lattice spacing (2 values at the moment)
- Express things in chiral limit in dimensionless combinations
- $f_\pi = 250 GeV$ scale setting

Lattice setup

Particle spectrum

- Staggered fermions (fast!)

- Need rooting trick for $N_f = 2$
  from QCD: as long as m finite, not too small, it's okay

- Stout-improvement

- Symanzik tree level improved gauge action

- $\beta = 3.20$ and 3.25

Particle spectrum

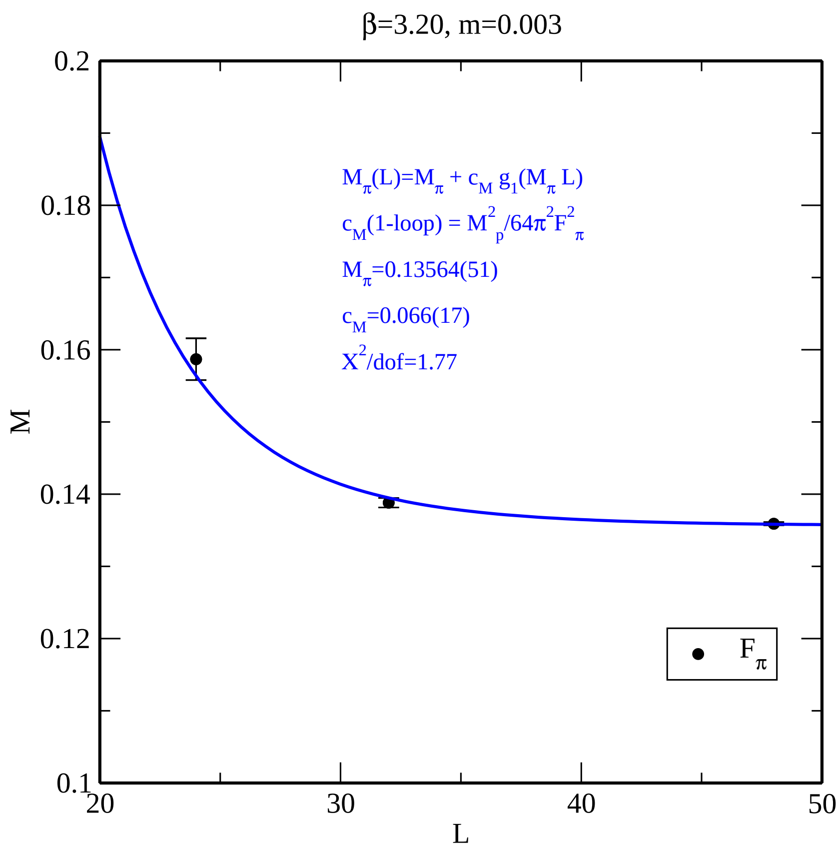
Using QCD terminology consider

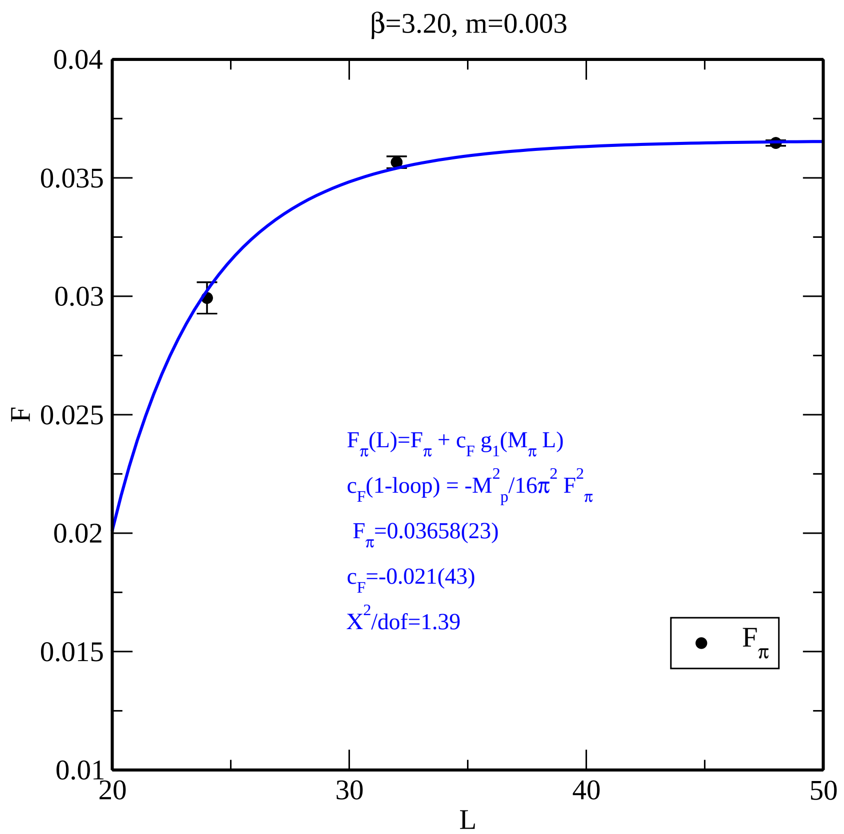
$$m_\pi \quad f_\pi \quad m_{a_0} \quad m_\rho \quad m_{a_1} \quad m_N \quad m_{f_0} = m_{0^{++}} = m_{Higgs}$$

Lattice

β	N_s	N_t	m_q
3.20	48	96	0.002, 0.003, 0.004
	40	80	0.002, 0.003, 0.004
	32	64	0.003, 0.004, 0.005, 0.006, 0.007, 0.008
	28	56	0.003, 0.004, 0.005, 0.006, 0.007, 0.008
	24	48	0.003, 0.004, 0.005, 0.006, 0.007, 0.008, 0.009, 0.010, 0.012, 0.014
3.25	48	96	0.002, 0.003, 0.004
	40	80	0.002, 0.003, 0.004
	32	64	0.004, 0.005, 0.006, 0.007, 0.008
	28	56	0.003, 0.004, 0.005, 0.006, 0.007, 0.008
	24	48	0.003, 0.004, 0.005, 0.006, 0.007, 0.008

Lattice





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

Lattice - mesons

Meson mass measurements very similar to staggered QCD

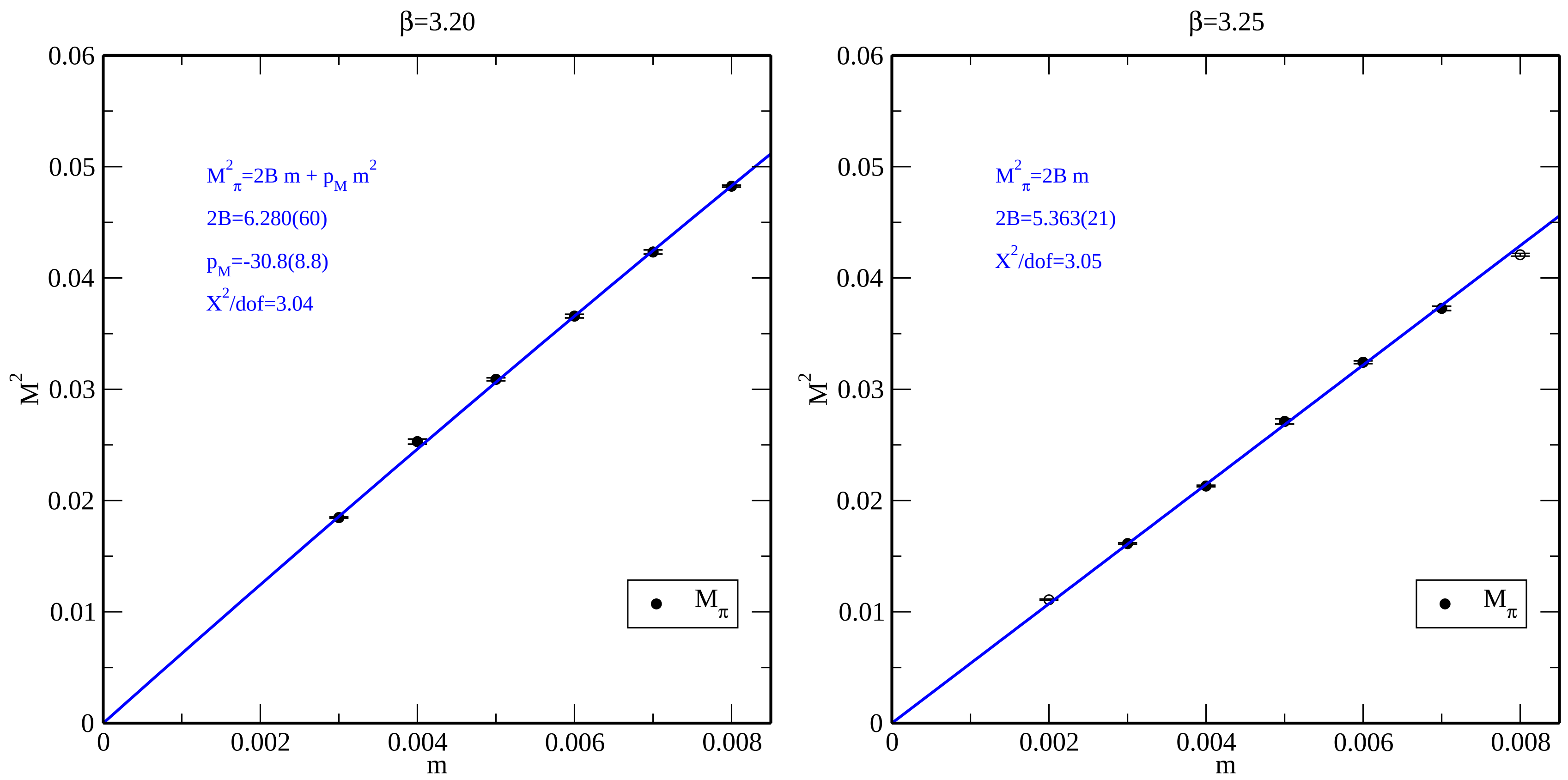
Correlators contain also parity partners

Taste splitting: non-degeneracy between tastes

Tastes degenerate in continuum limit (validity of rooting trick, widely believed to be the case)

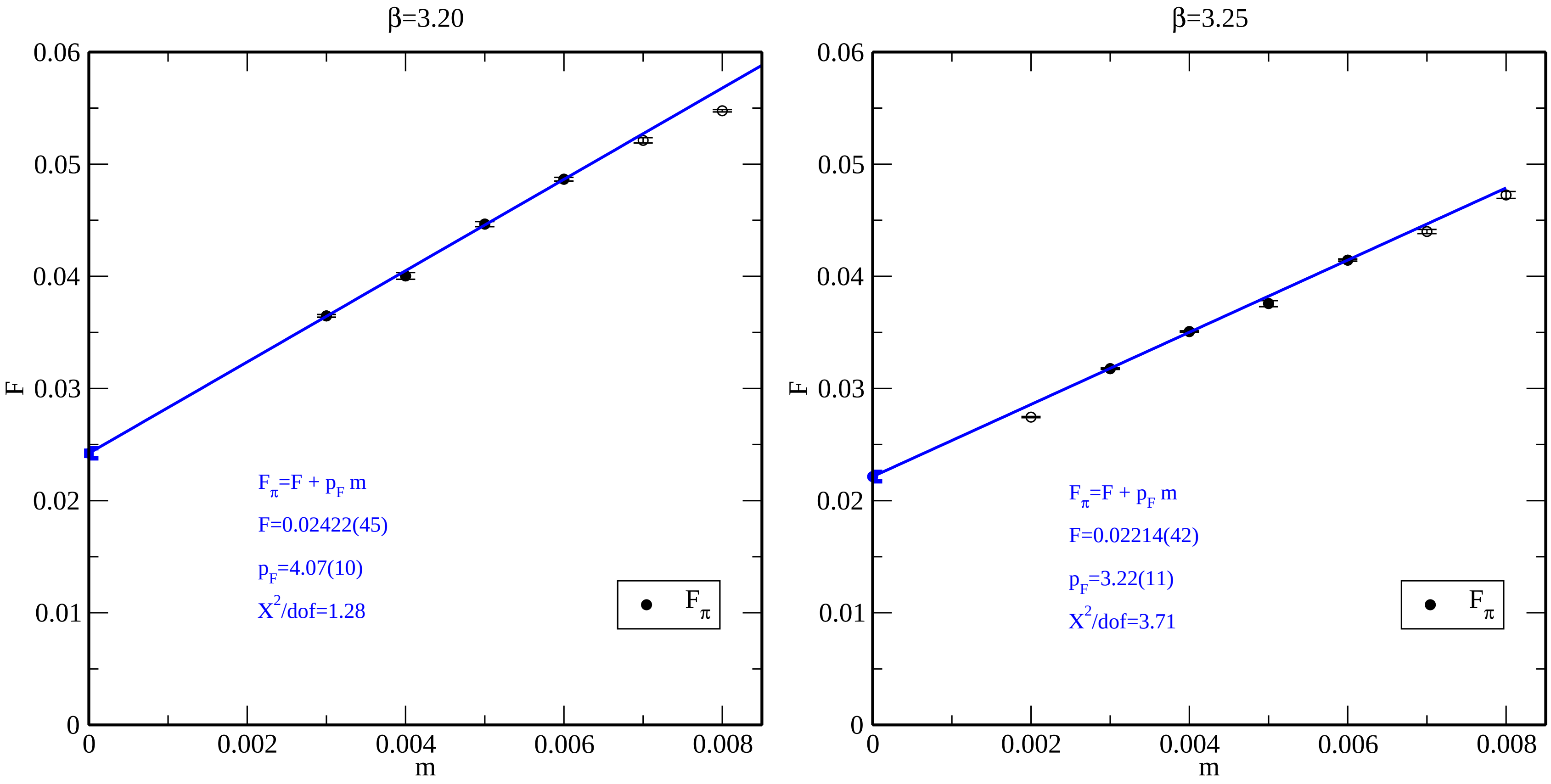
Gives f_π in chiral limit in the pseudo-scalar channel, scale setting, $f_\pi = 250\,GeV$

Lattice - pseudo-scalar meson



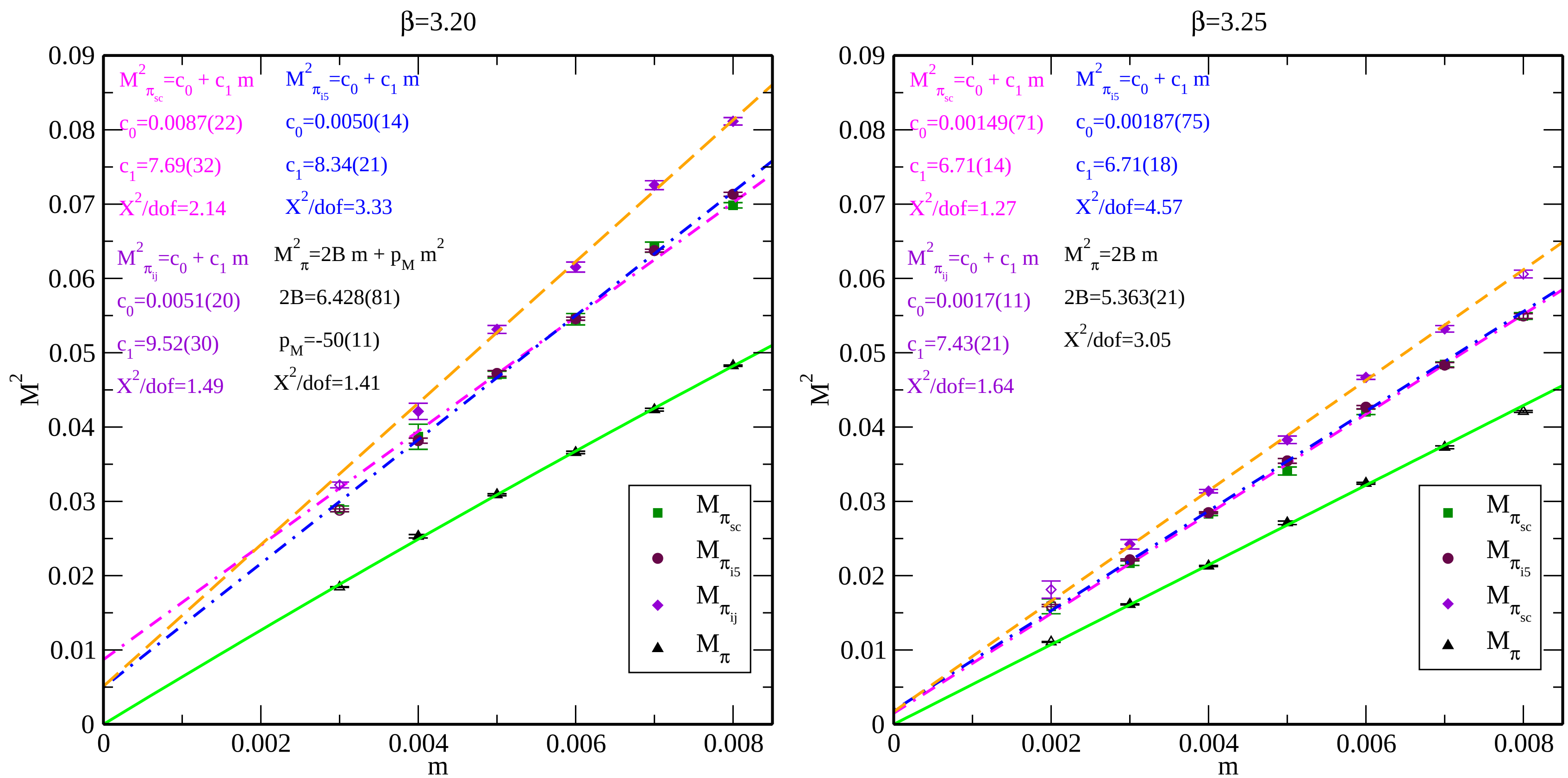
Unable to resolve chiral logs

Lattice - pseudo-scalar meson



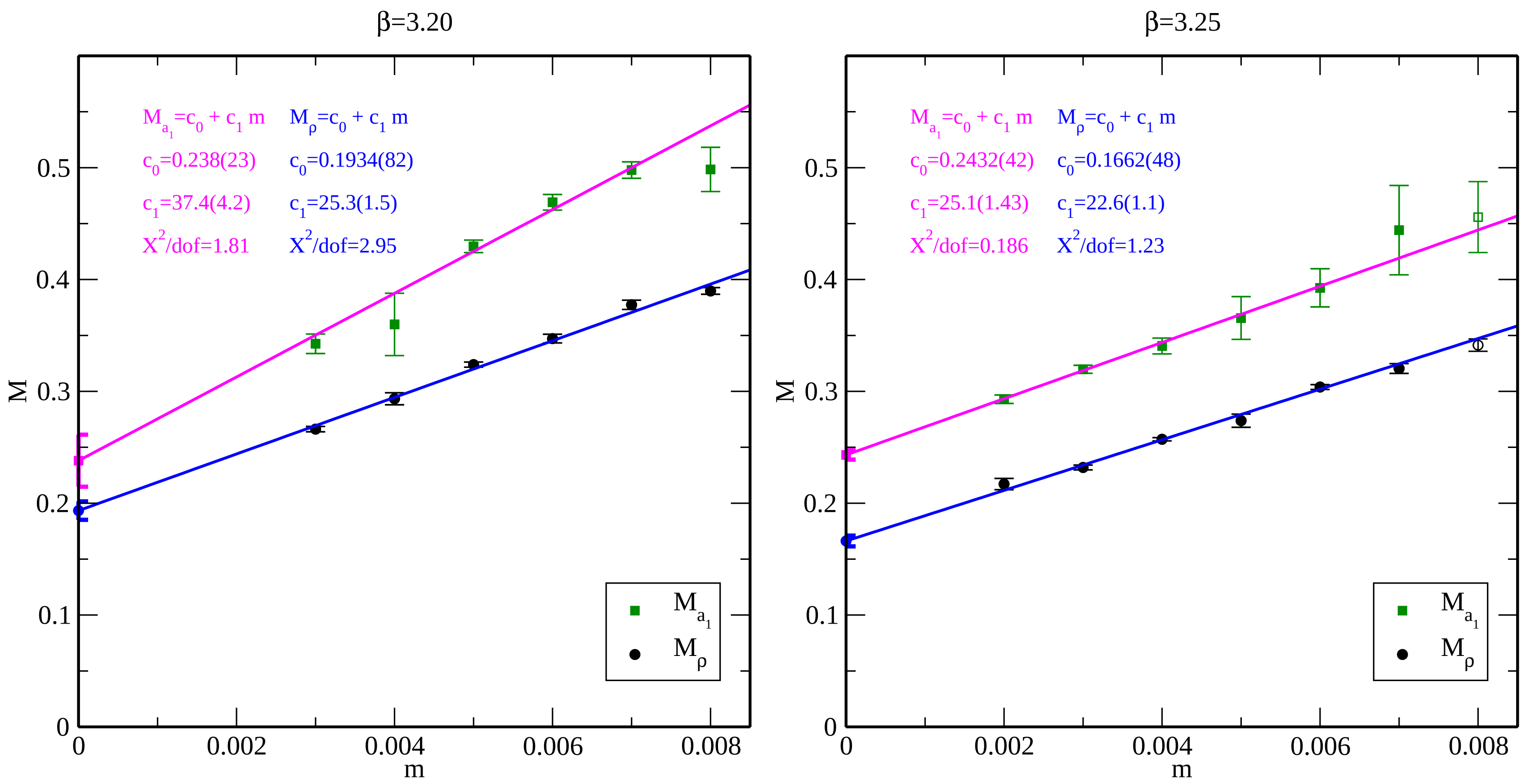
Much stronger m-dependence than in QCD

Lattice - pseudo-scalar meson



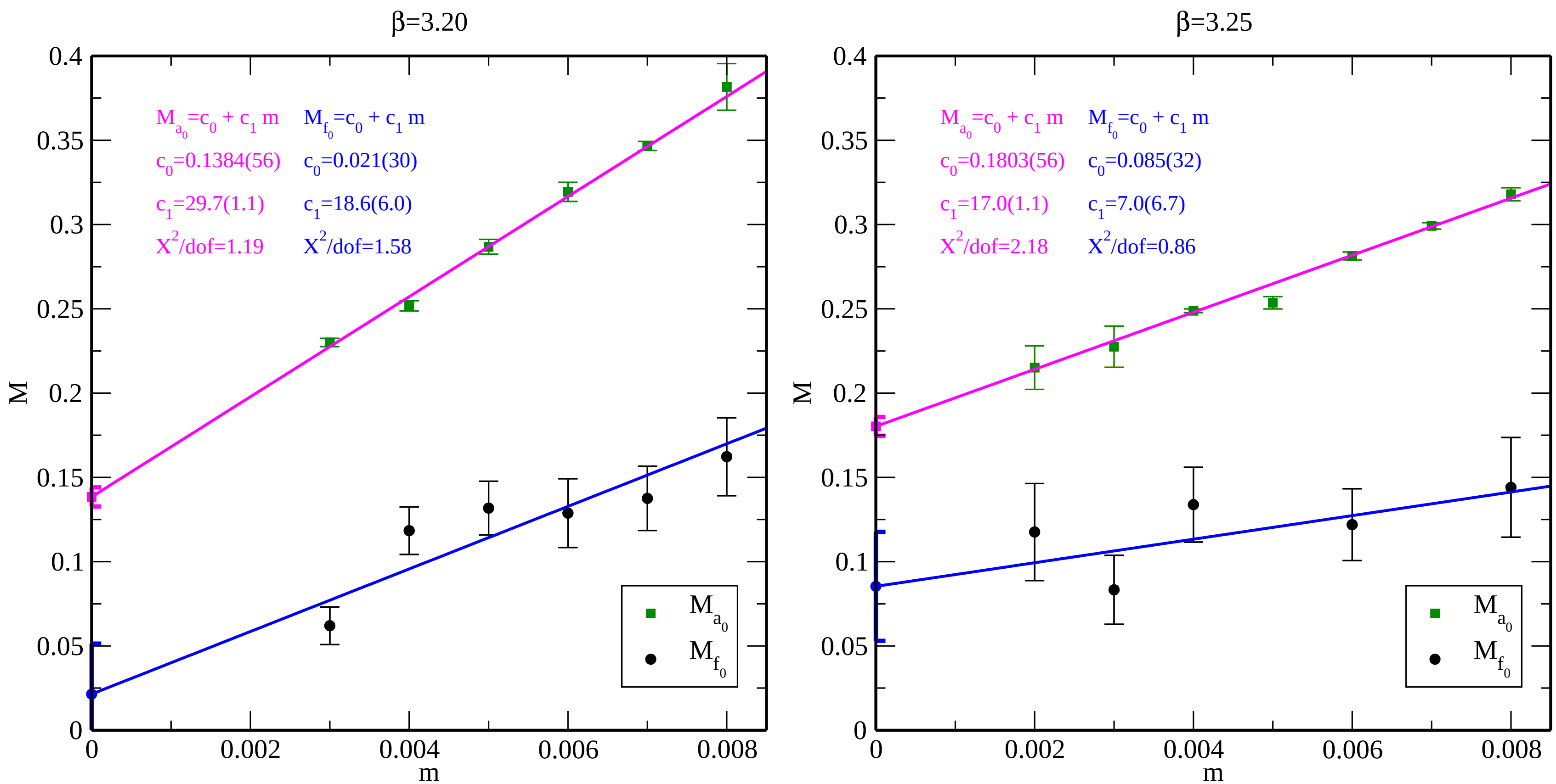
Note the different slopes, in QCD parallel

Lattice - vector mesons ϱ and a_1



Within reach of LHC Run 2

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

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

T_{ABC} symmetric

Lattice - baryons

As a result, very different wave functions

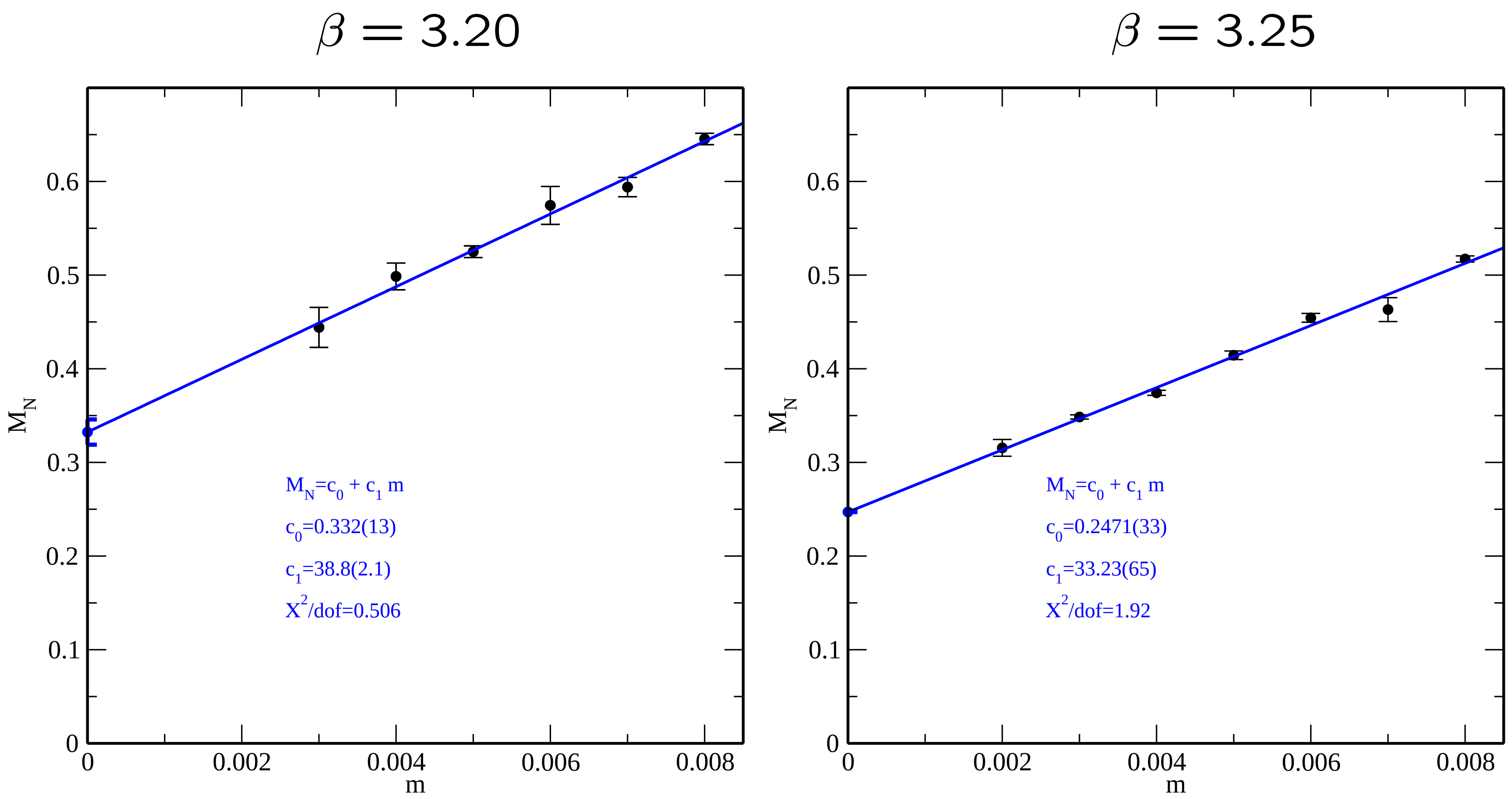
"color" : symmetric, spin-flavor: anti-symmetric

Non-relativistic notation (suppress "color" index):

$$|\psi\rangle = |\uparrow u, \uparrow d, \downarrow u\rangle + |\downarrow u, \uparrow u, \uparrow d\rangle + |\uparrow d, \downarrow u, \uparrow u\rangle -$$

$$|\downarrow u, \uparrow d, \uparrow u\rangle - |\uparrow d, \uparrow u, \downarrow u\rangle - |\uparrow u, \downarrow u, \uparrow d\rangle$$

Lattice - baryons



Dark matter?

Spectrum summary 1

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

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

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

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

Note on m_{f_0} next slide

We do see a light scalar separated from the 2-3 TeV region

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

What we measure is not "the" Higgs

Coupling to SM: top loop

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

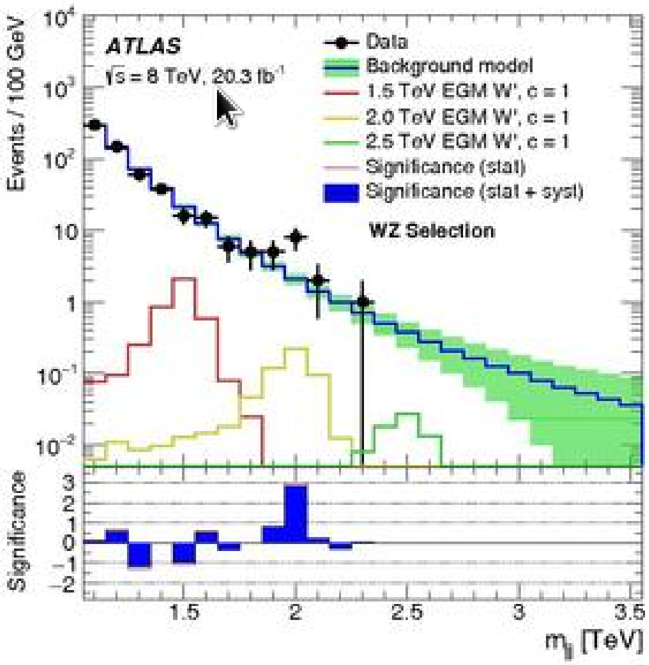
Foadi, et al.

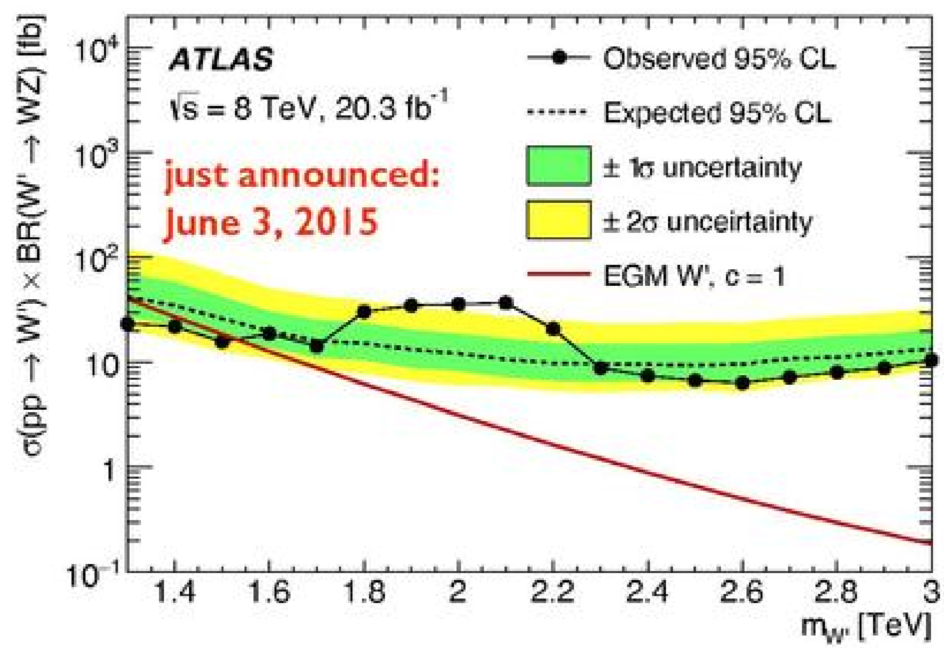
Things don't look so bad anymore :)

Other particles expected to be effected less

New particle at around 2 TeV

$$m_\varrho \sim 1.8 - 2\,TeV$$





both CMS & ATLAS 2014-2015 (significance low ...)!

Prediction for LHC Run 2

$$m_{a_1} \sim 2.5 - 2.7\,TeV$$

Small splitting between a_1 and ϱ: hopefully small S-parameter

Spectrum summary 2

Model gives rise to a light scalar

New particles with definite properties in 2-3 TeV region

Potential dark matter candidate as well

Buyer beware! Slow topology change, unestimated systematics, only $20-30\%$ change in lattice spacing, etc

More lattice results: running coupling

Running scale: μ

Need: $1/L < \mu < 1/a$

Separating 3 scales difficult, instead

$$1/L = \mu < 1/a$$

Running scale is finite volume

Running coupling

β-function: $\mu dg/d\mu$

Can't change L/a infinitesimally on the lattice

$L \longrightarrow sL$ finite change, $s = 3/2, 2$, etc.

Discrete β-function: $(g^2(sL) - g^2(L))/\log(s^2)$

If has a zero $\longleftrightarrow$ infinitesimal version too

g^2 defined from Yang-Mills gradient flow

$t^2 E(t) \sim g^2(t, L)$, $\sqrt{8t}/L = fix$

Running coupling - lattice setup

Simulate in finite 4-volume

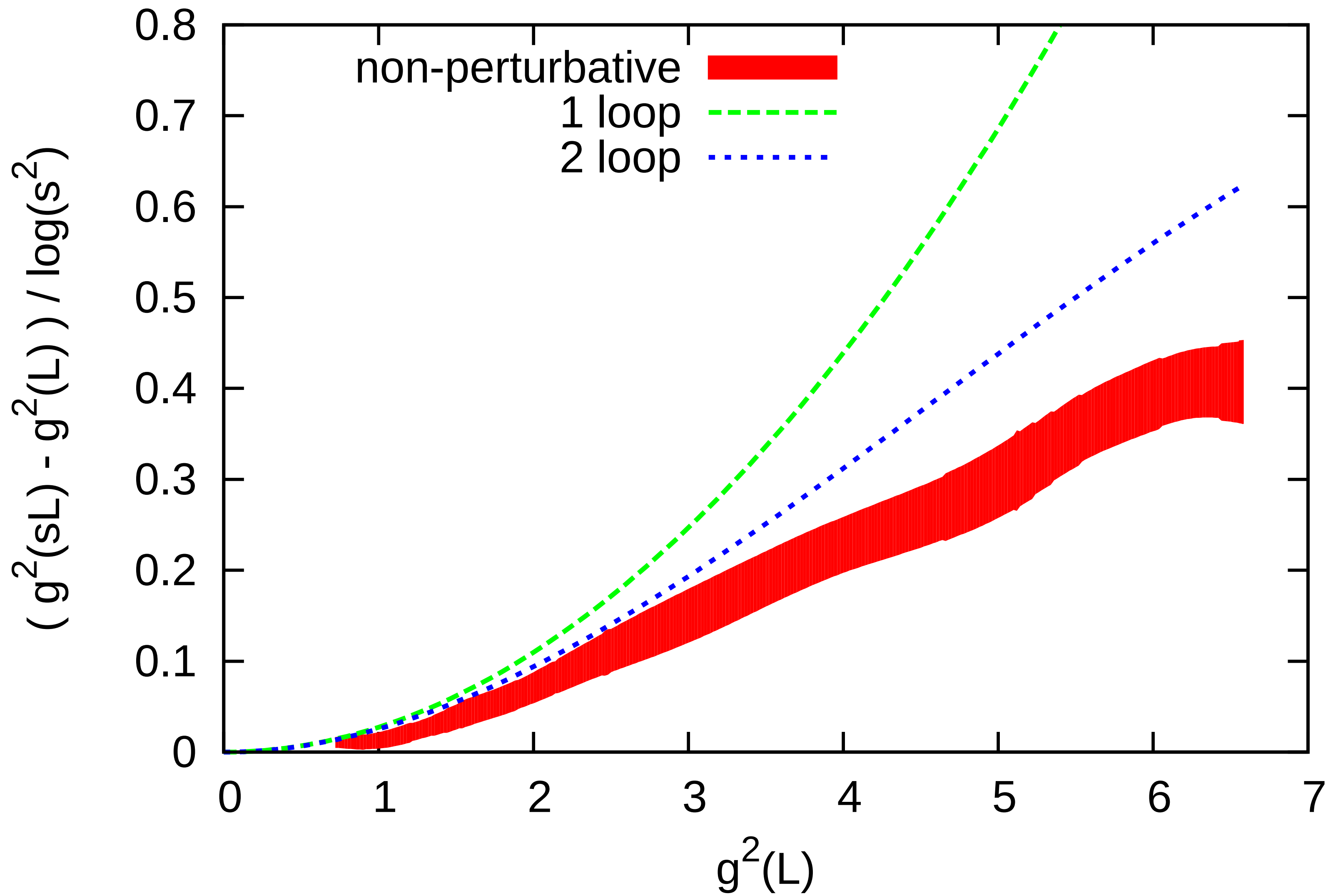
Take several bare couplings β, $L/a \to sL/a$

Measure discrete β-function for $8 \to 12$, $12 \to 18$, $16 \to 24$, $20 \to 30$, $24 \to 36$

All together 5 lattice spacings

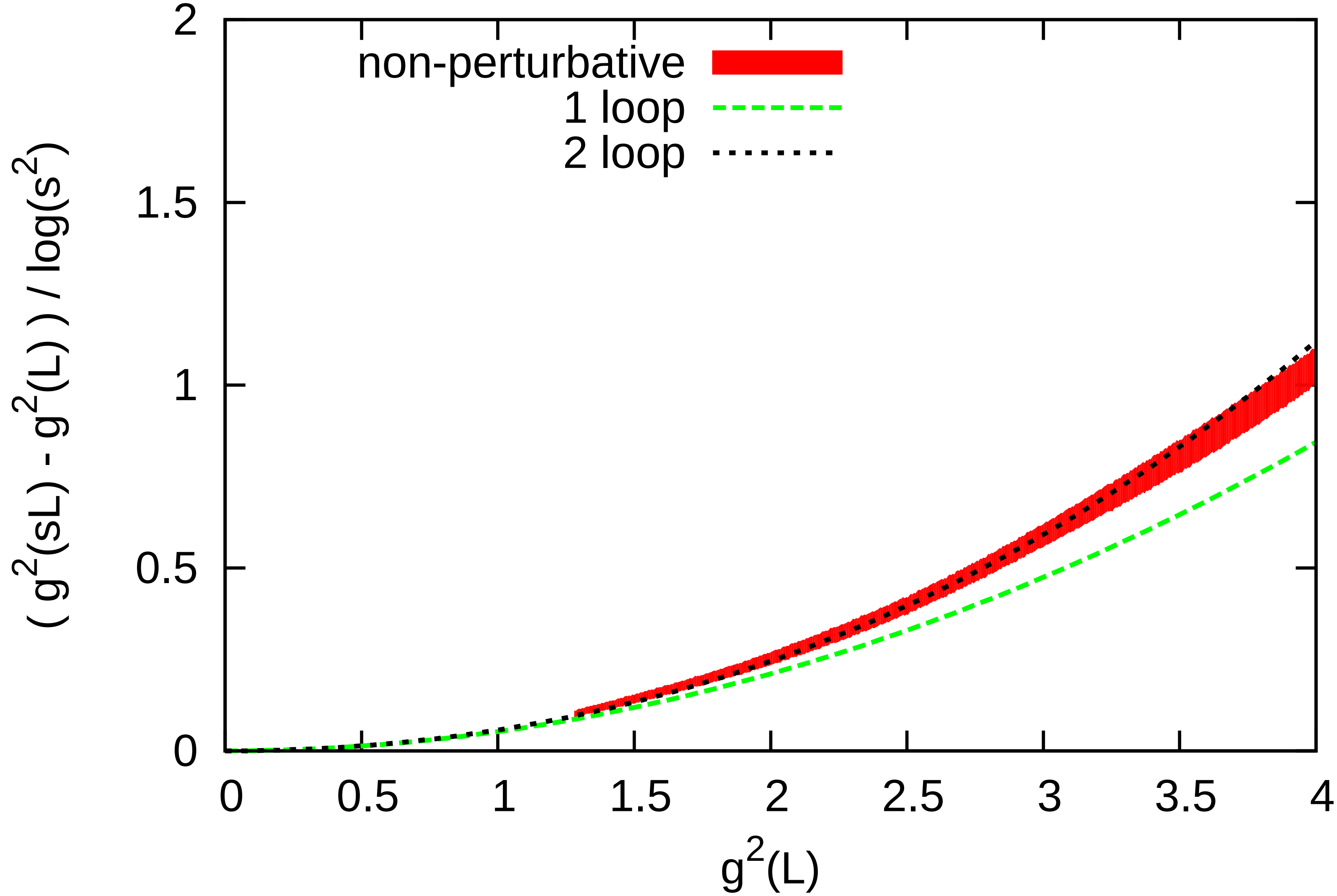
Continuum limit, linear in a^2/L^2

Running coupling - results

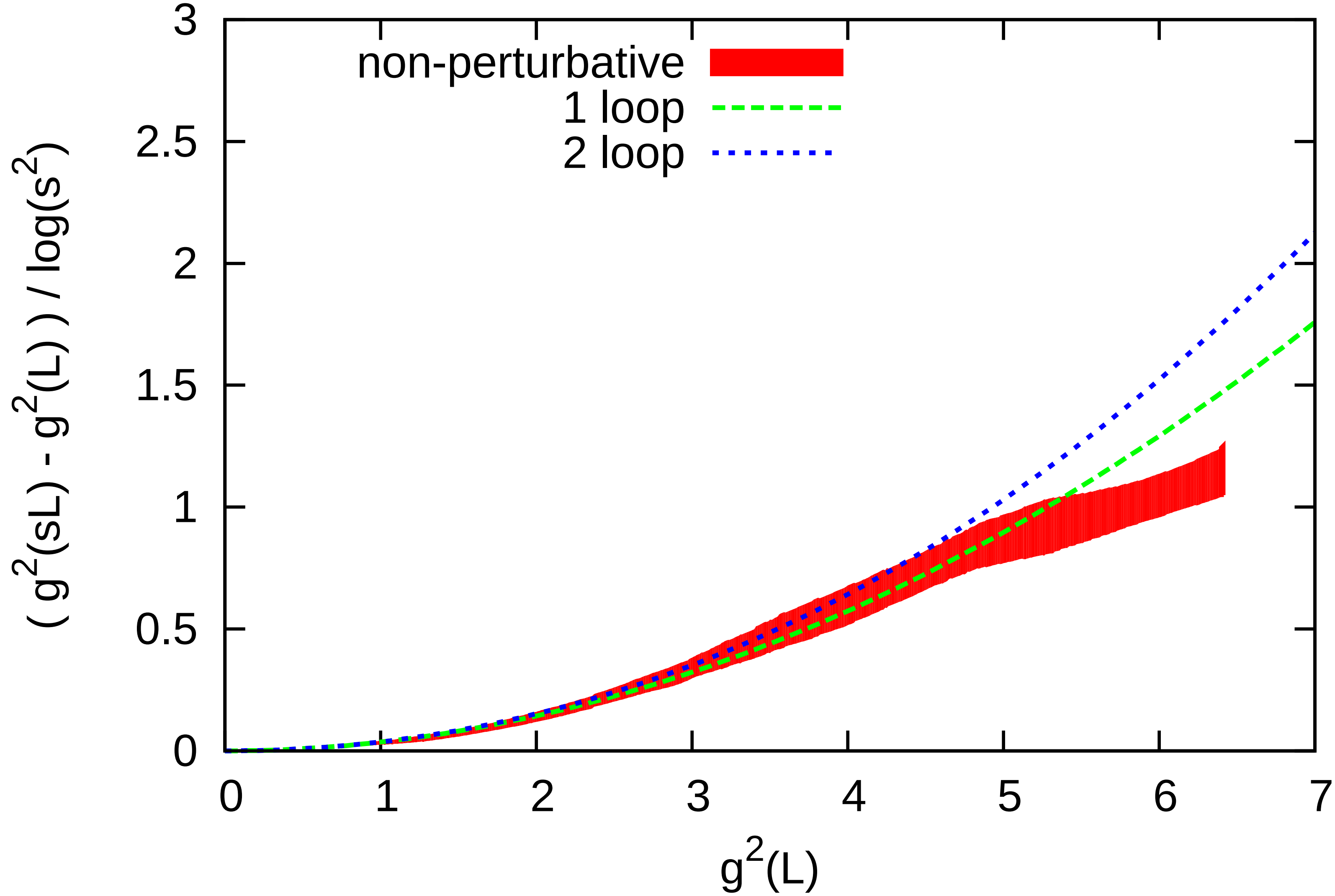


Note scale on y-axis: very small β-function

Comparison with fundamental $N_f = 4$



Comparison with fundamental $N_f = 8$



Running coupling summary

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

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

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

Schwinger-Dyson: no fixed point

Summary

- Sextet model is a minimal composite Higgs model
- Particle spectrum shows chiral symmetry breaking
- Running coupling consistent with it
- Light Higgs
- May explain diboson excess at CMS & ATLAS
- More new particles $\sim$ 2-3 TeV, within reach of LHC Run 2
- If nothing seen: model is dead

Work in progress and future outlook

Haven't talked about lots of things

- Chiral condensate from Dirac eigenvalues (GMOR)
- Mass anomalous dimension
- Started work on thermodynamics
- etc.

Thank you for your attention!