The first MadAnalysis 5 workshop on LHC recasting @ Korea

Composite Models - 1

Model building issues

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24/8/2017

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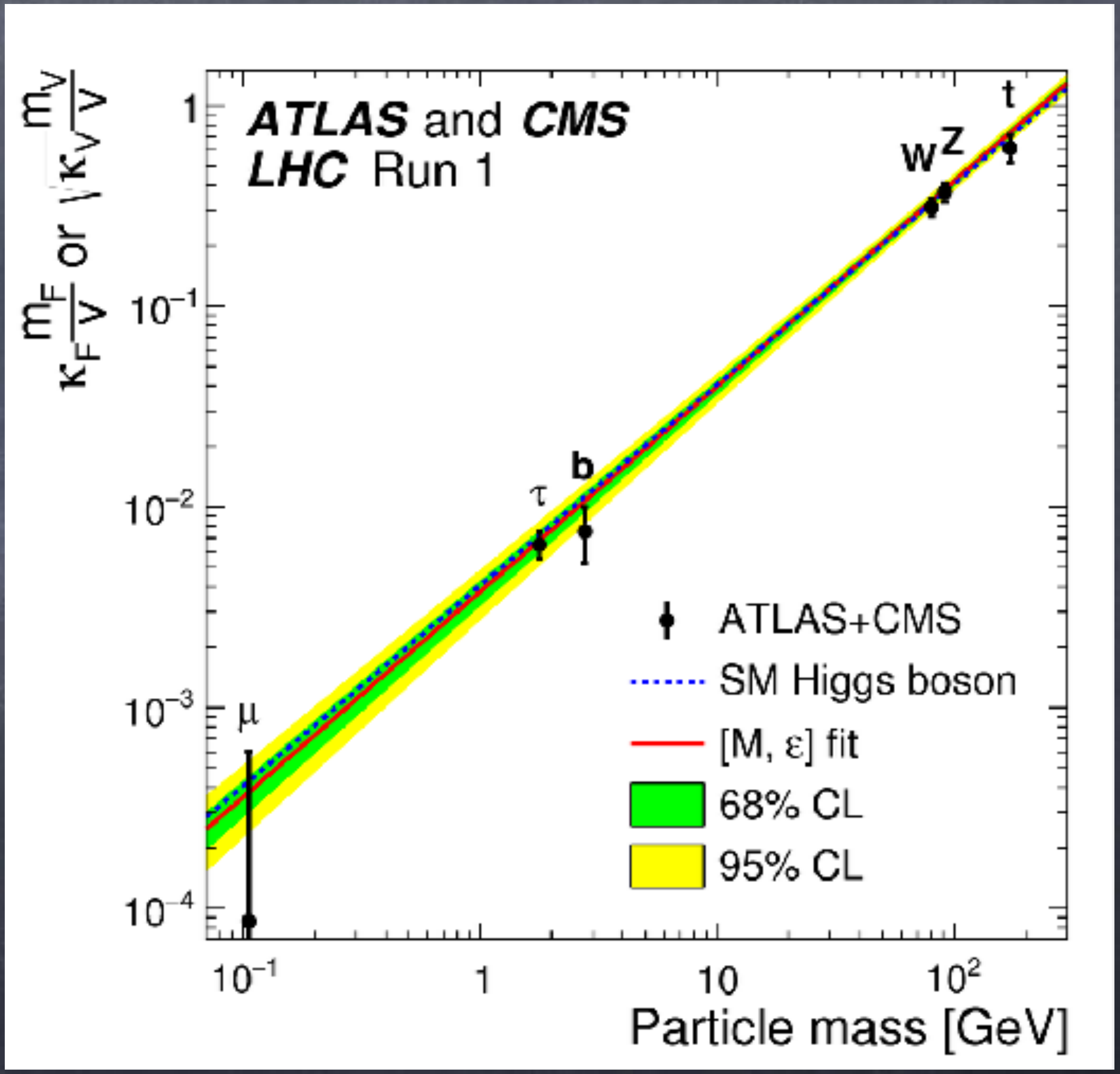
Université de Lyon

What do we know about the Higgs?

- The mass has been precisely measured!
- The couplings follow the SM expectations: being proportional to mass.
- The uncertainties are still large! O(10%)
- Coupling measurements are always subject to model assumptions!!!



What do we know about the Higgs?

- Theoretical modelling, i.e. the Standard Model Higgs

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \phi)^\dagger (D^\mu \phi) + \mu^2 \phi^\dagger \phi - \lambda \, (\phi^\dagger \phi)^2$$

"wrong sign"

It well describes the symmetry breaking, but no dynamical insight!

$$\tau^i = \frac{\sigma^i}{2}$$

Pauli matrices

$$\phi = e^{i\pi^i \tau^i} \cdot \begin{pmatrix} 0 \\ v + \frac{h}{\sqrt{2}} \end{pmatrix}$$

$$v = \frac{\mu}{\sqrt{2\lambda}} \sim 246 \;\; \text{GeV}$$

What do we know about the Higgs?

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \phi)^\dagger (D^\mu \phi) + \mu^2 \, \phi^\dagger \phi - \lambda \, (\phi^\dagger \phi)^2$$

- Custodial symmetry as a lucky accident:

$$\phi = \begin{pmatrix} \varphi_u \\ \varphi_d \end{pmatrix} \qquad \tilde{\phi} = (i\sigma^2) \cdot \phi^* = \begin{pmatrix} \varphi_d^* \\ -\varphi_u^* \end{pmatrix}$$

Both transform as doublets of SU(2) [pseudo-real irrep]

- We can rewrite the Lagrangian as:

$$\Phi = \left(\tilde{\phi} \; \phi \right) = \begin{pmatrix} \varphi_d^* & \varphi_u \\ -\varphi_u^* & \varphi_d \end{pmatrix} \qquad \mathcal{L}_{\text{Higgs}} = \frac{1}{2} \text{Tr} \left[(D_\mu \Phi)^\dagger (D^\mu \Phi) \right] + \frac{\mu^2}{2} \text{Tr} \left[\Phi^\dagger \Phi \right] + \ldots$$

$$\Phi \to U_L \cdot \Phi \cdot U_R^\dagger$$

uncovers a "hidden" invariance under a global SU(2)L x SU(2)R

What do we know about the Higgs?

- Non-linear description:

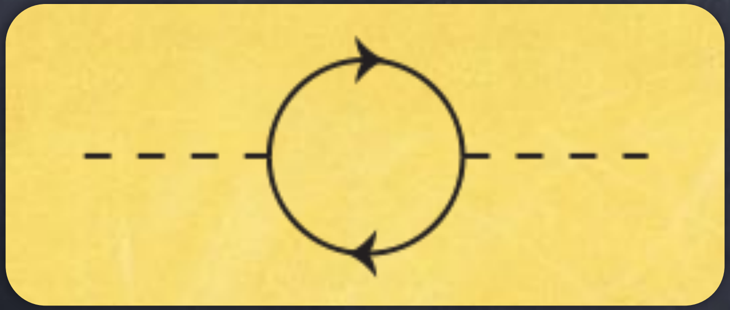
$$\Sigma = e^{i\pi^i \tau^i} \cdot \begin{pmatrix} 0 \\ v \end{pmatrix} \qquad \mathcal{L}_{NL} = f(h)\,(D_\mu \Sigma)^\dagger (D^\mu \Sigma) - V(h)$$

- It correctly describes the symmetry breaking.
- The coupling of h to gauge bosons ARE proportional to the mass (but not determined).
- However: trilinear h coupling is not determined!

Do we still need BSM?

We have a pretty good idea of the mechanism

But, we dont know how to protect it:



$$\delta m_h^2 \sim \frac{g^2}{16\pi^2} M_{\mathrm{NPh}}^2$$

Do we still need BSM?

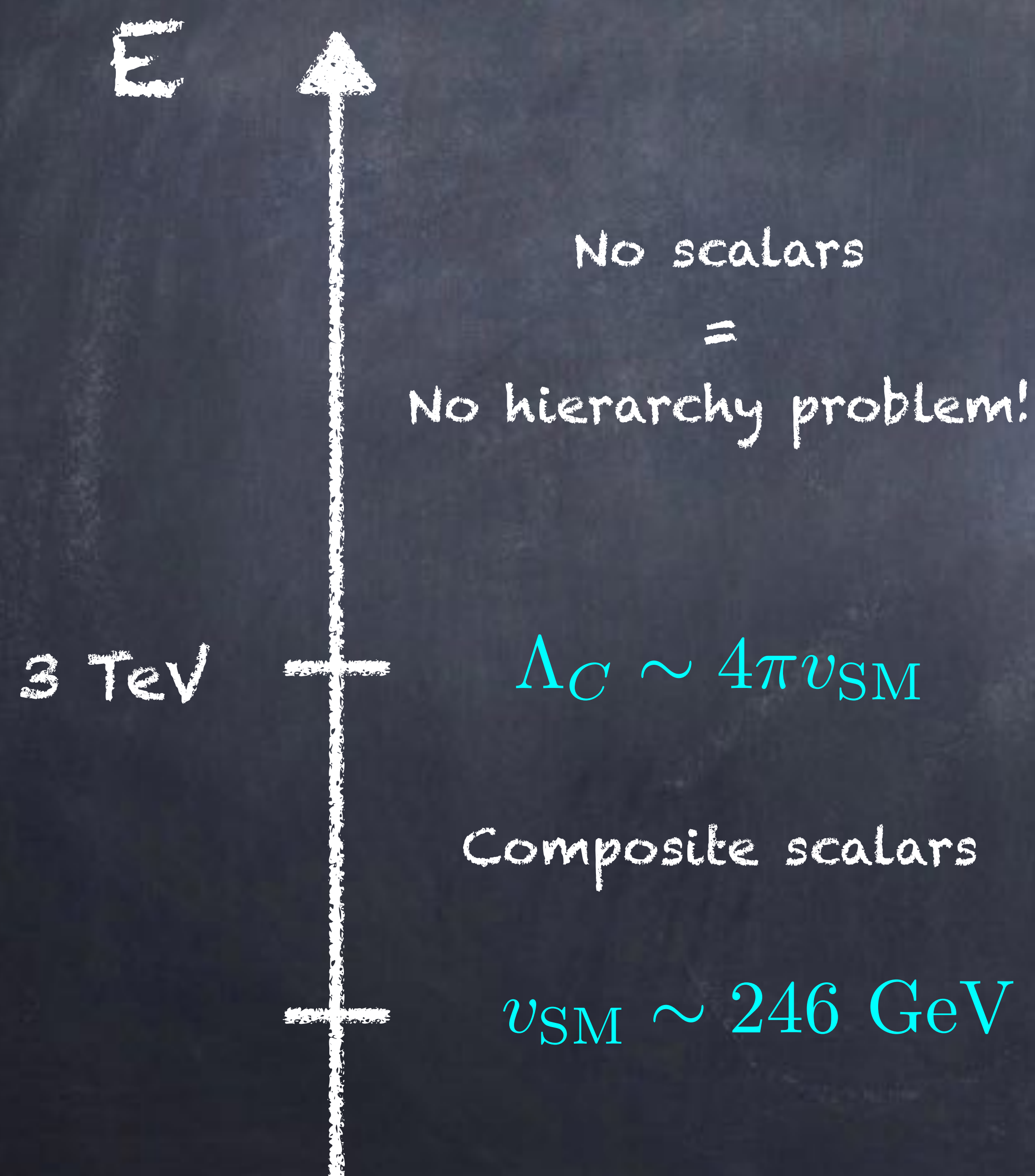
Compositeness is a way to dynamically protect the Higgs mechanism!

$$\delta m_h^2 \sim \frac{g^2}{16\pi^2} M_{\mathrm{NPh}}^2$$

Compositeness scale

Do we still need BSM?

Compositeness is a way to dynamically protect the Higgs mechanism!



$$\delta m_h^2 \sim \frac{g^2}{16\pi^2} M_{\rm NPh}^2$$

Compositeness scale

The QCD template

Symmetry breaking by compositeness
is an experimentally tested mechanism!

$$q = \begin{pmatrix} u \\ d \end{pmatrix}$$

$$\langle \bar{q}q \rangle = \langle \bar{q}_R q_L \rangle = (2,2)_{\mathrm{SU(2)_L \times SU(2)_R}}$$

The quark condensate in QCD
breaks the EW symmetry!

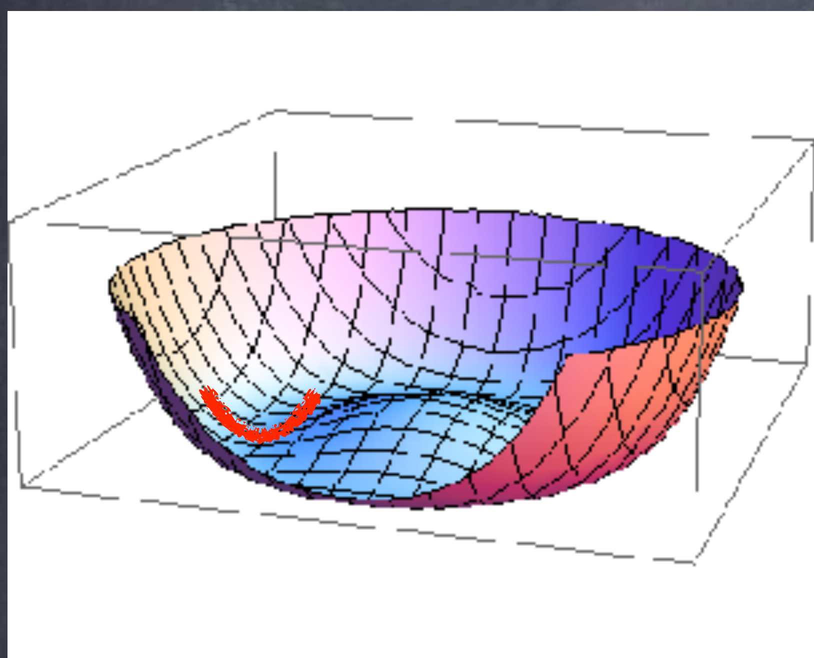
$$m_W = \frac{g f_\pi}{2} \sim 40 \text{ MeV}$$

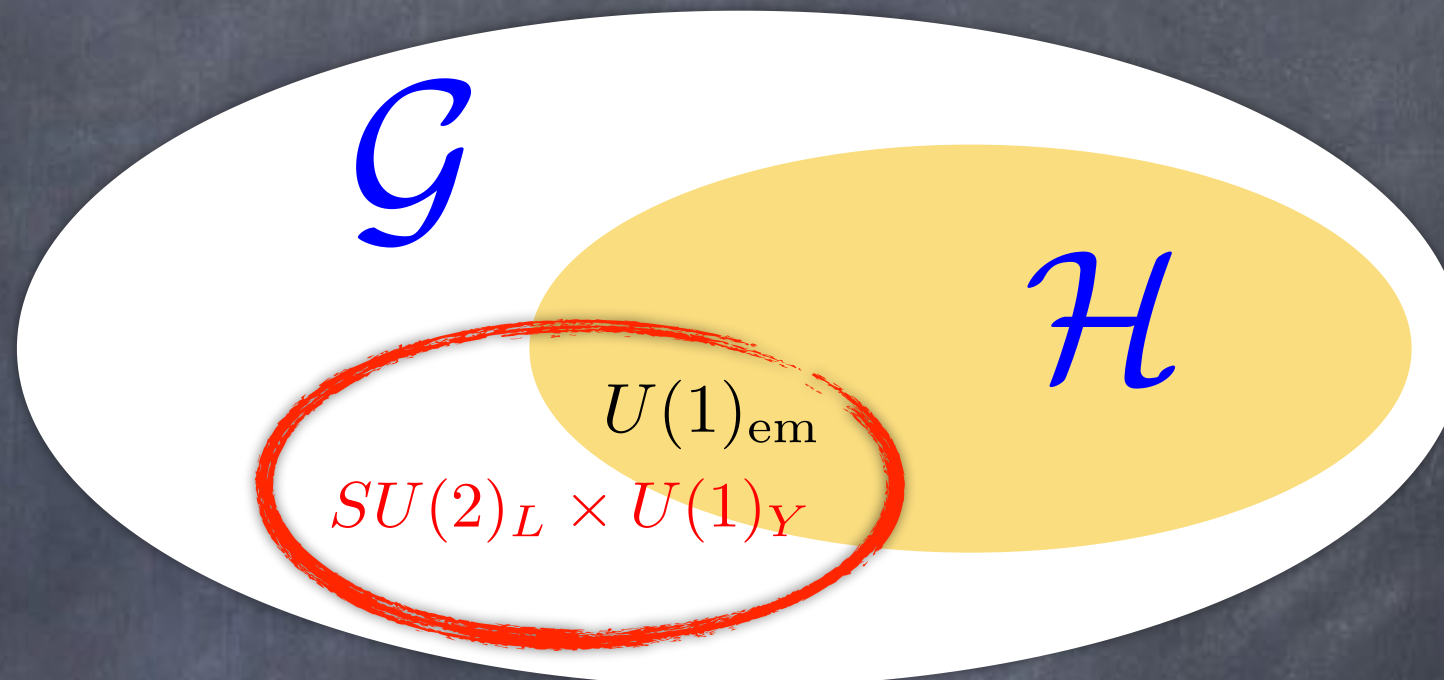
This observation led to the development of
Technicolor in 1979-80.

Note: this ideas is as old as the Standard Model itself!

- "Implication of dynamical symmetry breaking", S.Weinberg, Phys.Rev. D13 (1976) 974
- "Mass without scalars", S.Dimopoulos and L.Susskind, Nucl.Phys. B155 (1979) 237

Compositeness, and the Higgs boson



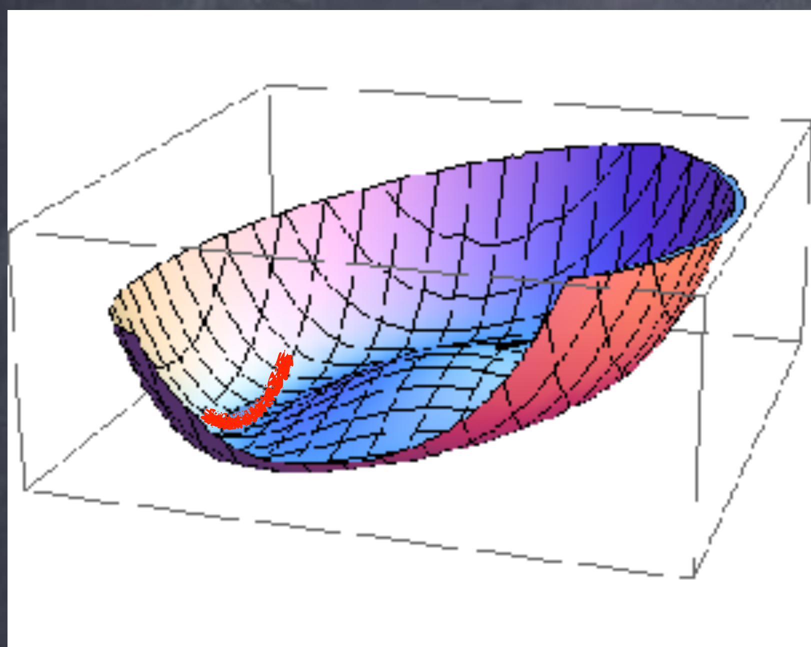


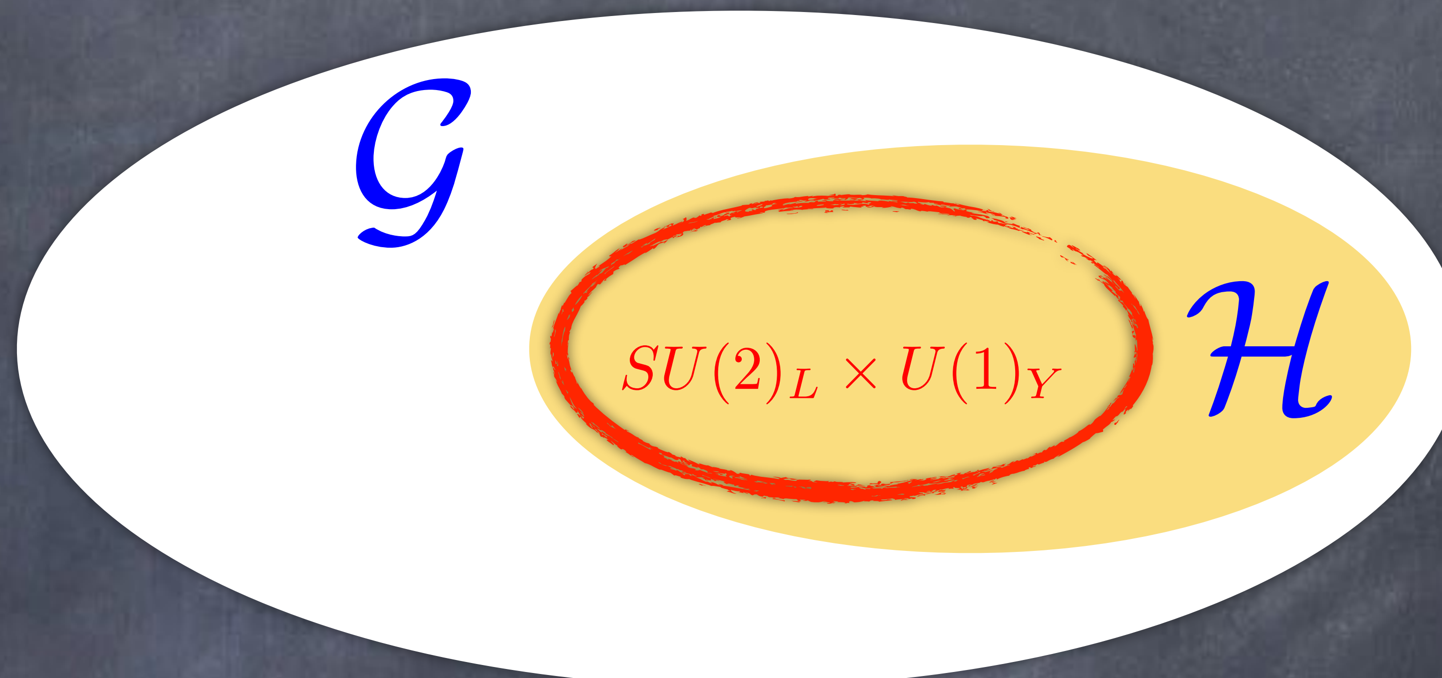
$\mathcal{G} \to \mathcal{H}$

QCD template:

- Goldstones include the longitudinal d.o.f. of W and Z ← π pions
- the Higgs is a heavy bound state (singlet under H) ← σ sigma

Compositeness, and the Higgs boson



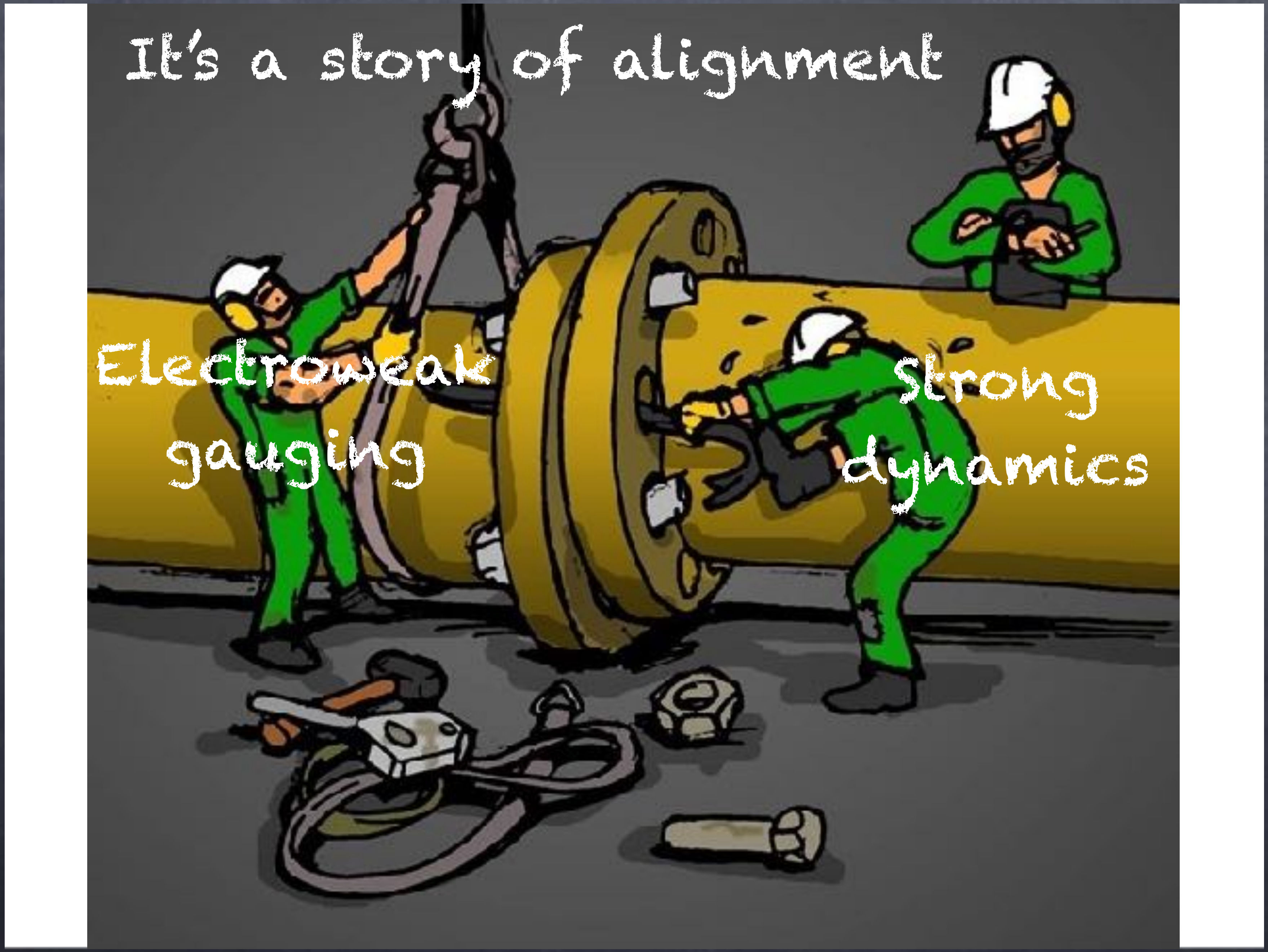


$\mathcal{G} \to \mathcal{H}$

QCD template:

- Goldstones include the longitudinal d.o.f. of W and Z ← π pions
- the Higgs is a pseudo-Goldstone (pNGB) ← σ sigma

Compositeness, and the Higgs boson



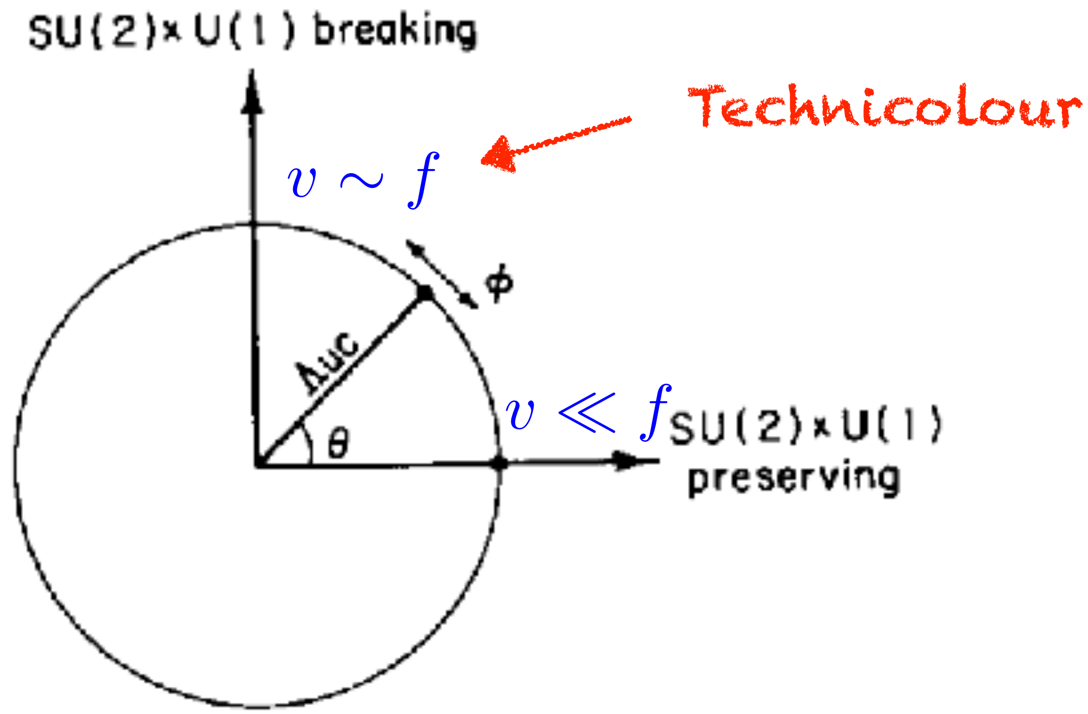
Compositeness, and the Higgs boson

ANATOMY OF A COMPOSITE HIGGS MODEL

Michael J. DUGAN, Howard GEORGI and David B. KAPLAN

Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA

Received 14 November 1984



$$\sin\theta \sim \frac{v}{f}$$

Fig. 1. Shown above is the circle of almost degenerate minima for the ultrafermion condensate, with radius Λ_{UC}. The true vacuum of a composite Higgs theory misaligns with the SU(2)×U(1) preserving direction by an angle θ. In the SU(2)×U(1) preserving basis, it looks like the PGB field ϕ, corresponding to angular excitations, has developed a VEV. The mass of the W is then characterized by the scale $\Lambda_{UC} \sin\theta$, and the shifted ϕ-field (properly normalized) is the Higgs boson.

Compositeness, and the Higgs boson

QCD template:

$f = v$ $\qquad\qquad$ $\frac{v}{f} \sim 0.2$

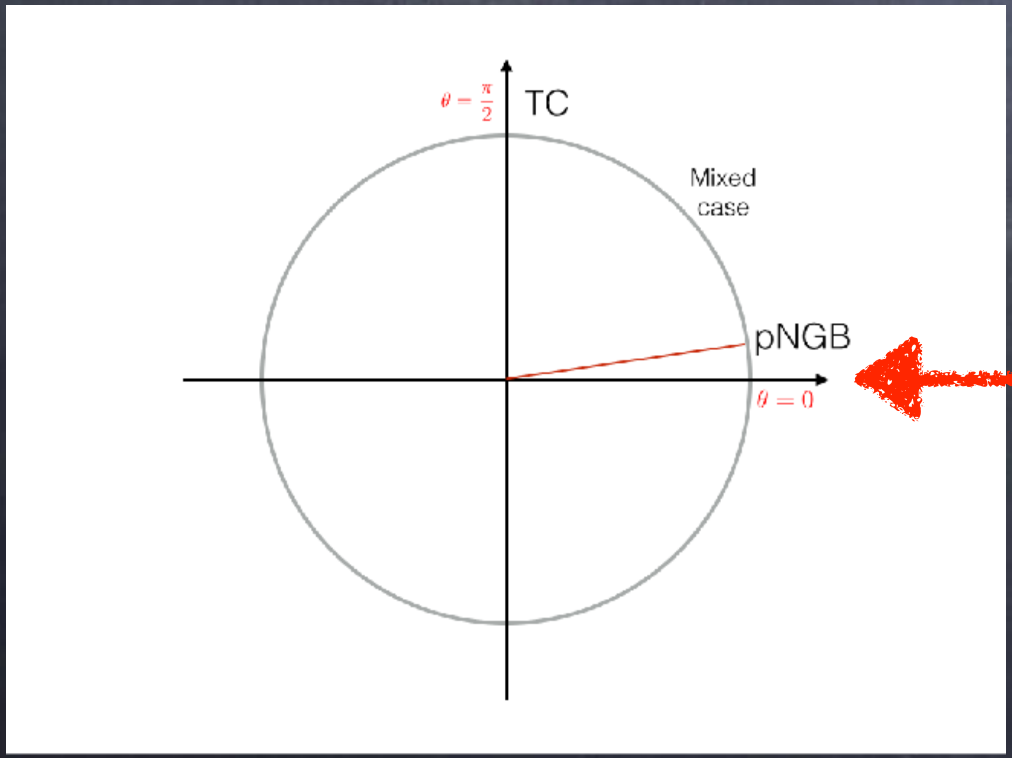
		QCD	TC	pNGB	
	f	130 MeV	246 GeV	1.2 TeV	
pions ->	pNGBs	135 MeV	255 GeV	1.3 TeV	<- the Higgs?
	sigma	500 MeV	950 GeV	4.7 TeV	
	rho	775 MeV	1.5 TeV	7 TeV	
	proton	938 MeV	1.8 TeV	9 TeV	

Anatomy of the potential

Higgs mass in the small theta limit:

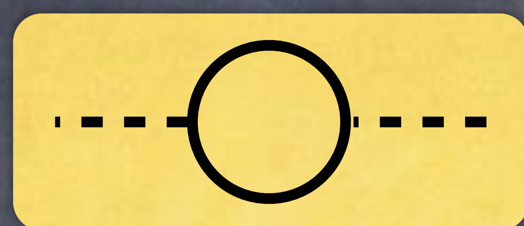
$$m_h \sim y f \sin\theta \sim y v_{SM}$$

Naturally in the right ballpark,
without fine tuning!



The Higgs needs to become a massless Goldstone to join the other 3 in a full multiplet of the unbroken SU(2)xU(1) symmetry

Anatomy of the potential



$$V \sim \alpha \sin^2 \theta + \beta \sin^4 \theta$$

Minima:

$\beta \ll \alpha \longrightarrow \theta \sim \frac{\pi}{2}$

$\beta \sim \alpha \longrightarrow \theta \sim \epsilon$

pNGB Composite Higgses: which model?

$\mathcal{G}$	$\mathcal{H}$	C	N_G	$\mathbf{r}_{\mathcal{H}} = \mathbf{r}_{SU(2)\times SU(2)}\ (\mathbf{r}_{SU(2)\times U(1)})$	Ref.
SO(5)	SO(4)	✓	4	$\mathbf{4} = (\mathbf{2}, \mathbf{2})$	[11]
SU(3) × U(1)	SU(2) × U(1)		5	$\mathbf{2}_{\pm 1/2} + \mathbf{1}_0$	[10, 35]
SU(4)	Sp(4)	✓	5	$\mathbf{5} = (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$	[29, 47, 64]
SU(4)	$[SU(2)]^2 \times U(1)$	✓*	8	$(\mathbf{2}, \mathbf{2})_{\pm 2} = 2 \cdot (\mathbf{2}, \mathbf{2})$	[65]
SO(7)	SO(6)	✓	6	$\mathbf{6} = 2 \cdot (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$	–
SO(7)	G_2	✓*	7	$\mathbf{7} = (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$	[66]
SO(7)	SO(5) × U(1)	✓*	10	$\mathbf{10}_0 = (\mathbf{3}, \mathbf{1}) + (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$	–
SO(7)	$[SU(2)]^3$	✓*	12	$(\mathbf{2}, \mathbf{2}, \mathbf{3}) = 3 \cdot (\mathbf{2}, \mathbf{2})$	–
Sp(6)	Sp(4) × SU(2)	✓	8	$(\mathbf{4}, \mathbf{2}) = 2 \cdot (\mathbf{2}, \mathbf{2})$	[65]
SU(5)	SU(4) × U(1)	✓*	8	$\mathbf{4}_{-5} + \bar{\mathbf{4}}_{+5} = 2 \cdot (\mathbf{2}, \mathbf{2})$	[67]
SU(5)	SO(5)	✓*	14	$\mathbf{14} = (\mathbf{3}, \mathbf{3}) + (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{1})$	[9, 47, 49]
SO(8)	SO(7)	✓	7	$\mathbf{7} = 3 \cdot (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$	–
SO(9)	SO(8)	✓	8	$\mathbf{8} = 2 \cdot (\mathbf{2}, \mathbf{2})$	[67]
SO(9)	SO(5) × SO(4)	✓*	20	$(\mathbf{5}, \mathbf{4}) = (\mathbf{2}, \mathbf{2}) + (\mathbf{1} + \mathbf{3}, \mathbf{1} + \mathbf{3})$	[34]
$[SU(3)]^2$	SU(3)		8	$\mathbf{8} = \mathbf{1}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{3}_0$	[8]
$[SO(5)]^2$	SO(5)	✓*	10	$\mathbf{10} = (\mathbf{1}, \mathbf{3}) + (\mathbf{3}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$	[32]
SU(4) × U(1)	SU(3) × U(1)		7	$\mathbf{3}_{-1/3} + \bar{\mathbf{3}}_{+1/3} + \mathbf{1}_0 = 3 \cdot \mathbf{1}_0 + \mathbf{2}_{\pm 1/2}$	[35, 41]
SU(6)	Sp(6)	✓*	14	$\mathbf{14} = 2 \cdot (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{3}) + 3 \cdot (\mathbf{1}, \mathbf{1})$	[30, 47]
$[SO(6)]^2$	SO(6)	✓*	15	$\mathbf{15} = (\mathbf{1}, \mathbf{1}) + 2 \cdot (\mathbf{2}, \mathbf{2}) + (\mathbf{3}, \mathbf{1}) + (\mathbf{1}, \mathbf{3})$	[36]

Table 1: Symmetry breaking patterns $\mathcal{G} \to \mathcal{H}$ for Lie groups. The third column denotes whether the breaking pattern incorporates custodial symmetry. The fourth column gives the dimension N_G of the coset, while the fifth contains the representations of the GB's under $\mathcal{H}$ and $SO(4) \cong SU(2)_L \times SU(2)_R$ (or simply $SU(2)_L \times U(1)_Y$ if there is no custodial symmetry). In case of more than two SU(2)'s in $\mathcal{H}$ and several different possible decompositions we quote the one with largest number of bi-doublets.

Bellazzini, Csaki, Serra 1401.2457

The FCD approach

G.C., F.Sannino
1402.0233

- Define a confining gauge group (G_{TC})
- Add in N fermions charged under the confining group G_{TC}
- Assign SM quantum numbers to the fermions (thus providing embedding in the global symmetry)
- Couple them to SM fermions

The FCD approach

	G_{TC}	G_F	SM
ψ	R_{TC}	R_F	R_{SM}

R_{TC} is real: G_F = $SU(N_\psi)$ $\langle \psi^i \psi^j \rangle$ $SU(N_\psi) \to SO(N_\psi)$

pseudo-real: G_F = $SU(2N_\psi)$ $\langle \psi^i \psi^j \rangle$ $SU(2N_\psi) \to Sp(2N_\psi)$

complex: G_F = $SU(N_\psi)^2$ $\langle \bar{\psi}^i \psi^j \rangle$ $SU(N_\psi)^2 \to SU(N_\psi)$

The FCD approach

coset	GTC	TF	Higgs doublets	pNGBs	
SU(4)/Sp(4)	Sp(2N)	fund	1	5	← Minimal!
SU(5)/SO(5)	SU(4)	6	1	14	Dugan, Georgi, Kaplan 1985!!!
SU(4)xSU(4) /SU(4)	SU(N)	fund	2	15	G.C., T.Ma 1508.07014
SU(6)/Sp(6)	Sp(2N)	fund	2	14	G.C., M.Lespinasse in prep.

The hot potato: flavour!

100,000 TeV	Λ_{flavour}	Scale of fermion mass generation
		How can this hierarchy be generated?
10 TeV	$\Lambda \sim 4\pi f$	Vector resonances, ...
1 TeV	f	Condensation scale (extra pions)
100 GeV	$v_{\text{SM}} \sim f \sin\theta$	EWSB

Higgs

$$\mathcal{L}_{\text{fermions}} = \frac{1}{\Lambda^2_{\text{fl.}}}(\psi\psi)(q_L^c q_R)$$

$$+\frac{1}{\Lambda^2_{\text{fl.}}}(q_L^c q_R)(q_L^c q_R) + \frac{1}{\Lambda^2_{\text{fl.}}}(\psi\psi)^2$$

FCNCs

Higgs mass

$$m_{\text{top}} \sim \frac{(4\pi f)^3}{\Lambda^2_{\text{fl.}}}\sin\theta$$

Too small!

The hot potato: flavour!

100.000 TeV	Λ_{flavour}	Scale of fermion mass generation
		Intermediate conformal region
10 TeV	$\Lambda \sim 4\pi f$	Vector resonances, ...
1 TeV	f	Condensation scale (extra pions)
100 GeV	$v_{\text{SM}} \sim f \sin\theta$	EWSB

$$(\psi\psi) \to \mathcal{O}_H$$

$$\dim[\mathcal{O}_H] = d_H$$

effective Yukawa:

$$\frac{1}{\Lambda_{\text{fl.}}^{d-1}} \mathcal{O}_H q_L^c q_R$$

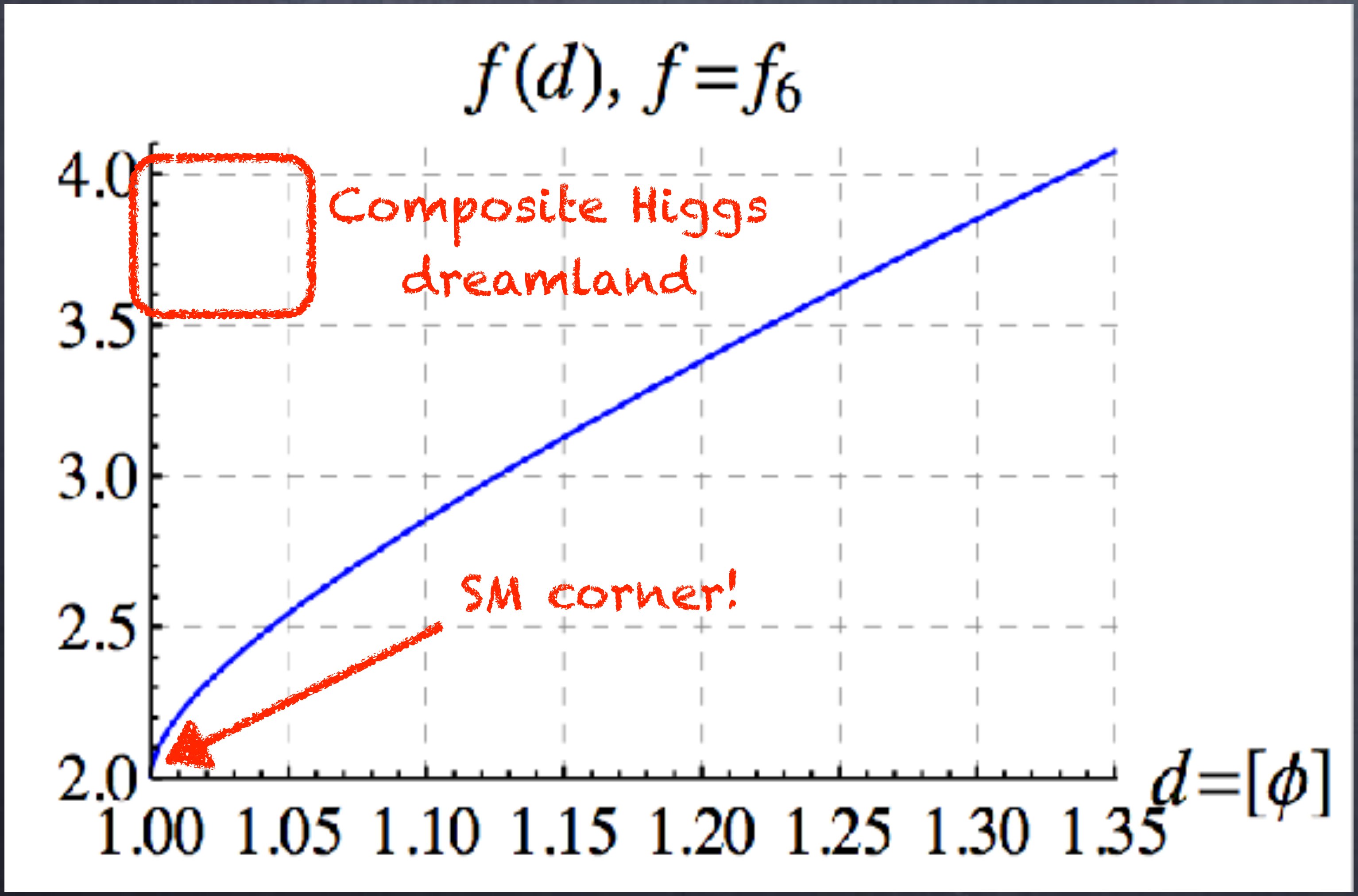
$$m_{\text{top}} \sim \left(\frac{4\pi f}{\Lambda_{\text{fl.}}}\right)^{d-1} 4\pi f \sin\theta$$

$$d \sim 1.$$

A no-go theorem?

Bounds on the dimensions of scalar operators can be extracted using bootstrap techniques!

Rattazzi, Rychkov, Tonni, Vichi 0807.0004



$$\phi \equiv \mathcal{O}_H$$

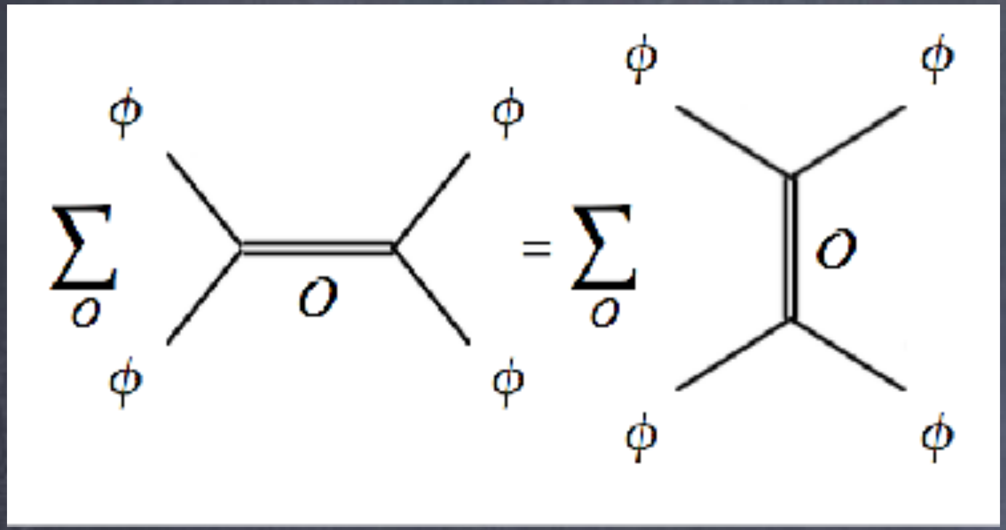
$$d[\phi^2]_{\min} < f(d)$$

Higgs mass operator!

$$\Delta m_H^2 \sim \left(\frac{4\pi f}{\Lambda_{\text{fl.}}}\right)^{d-4} f^2$$

A no-go theorem?

Q: does the bound apply to the Higgs?



$$(\psi^i \psi^j) = \phi^{ij}$$

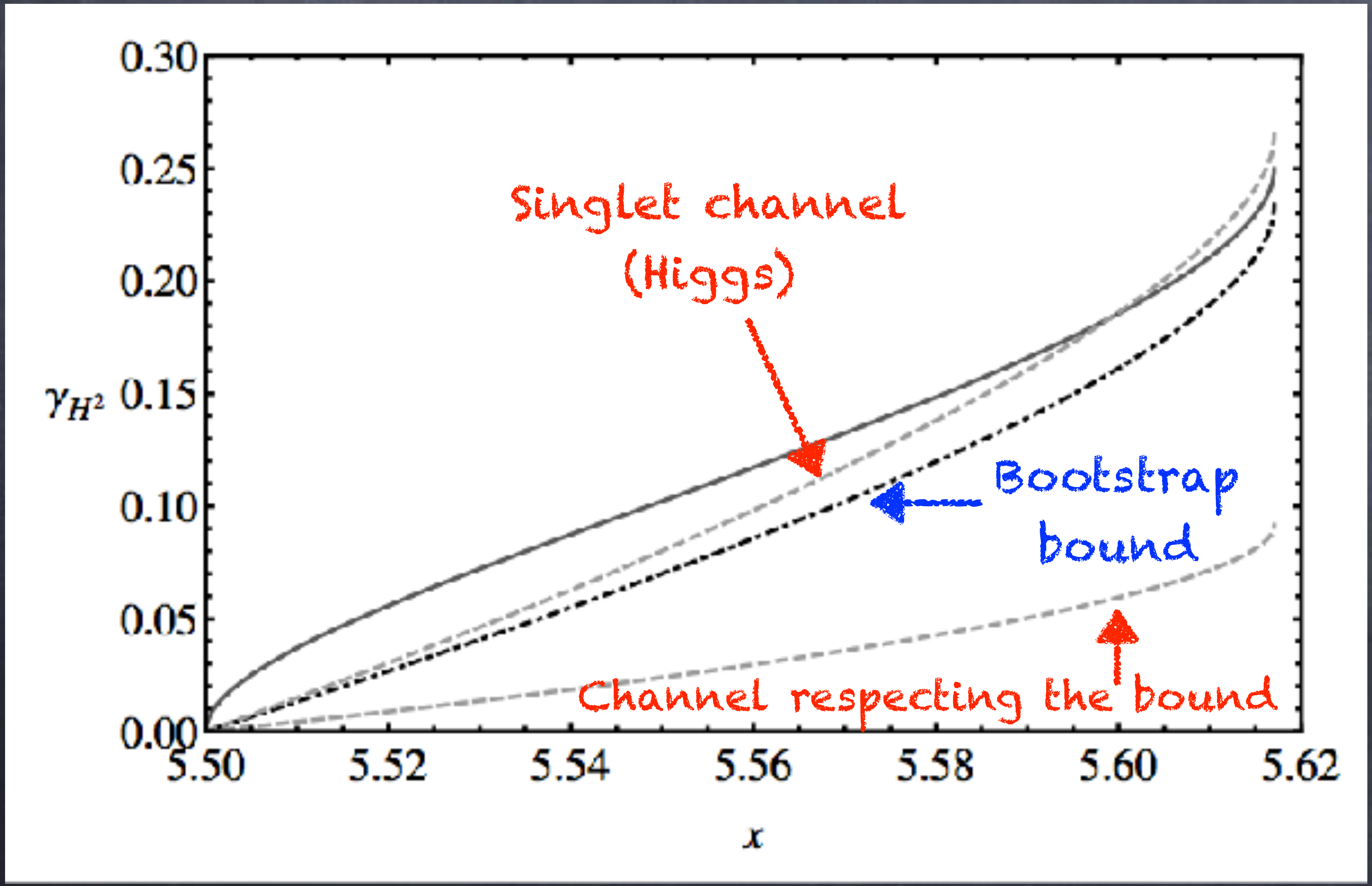
The scalar operator has flavour indices: many by-linear ops appear!

The bound applies to the one with lowest dimension!

A no-go theorem? No...

Q: does the bound apply to the Higgs?

Antipin, Mølgaard, Sannino 1406.6166



Gauge-Yukawa theory with weakly-coupled fixed point.

Dimensions are calculable (but small...)

The hot potato: flavour!

100.000 TeV	Λ_{flavour}	Light fermions
		Conformal region
10 TeV	$\Lambda \sim 4\pi f$	Vector resonances, ...
1 TeV	f	Condensation scale (extra pions)
100 GeV	$v_{\text{SM}} \sim f \sin\theta$	EWSB

Λ_{top}

Multi-scale model

$$m_c \sim \left(\frac{4\pi f}{\Lambda_{\text{fl.}}}\right)^{d-1} 4\pi f \sin\theta$$

$$\sim 0.01 \Rightarrow d \sim 1.5$$

Still, for the top, one would need:

$$\Lambda_{\text{top}} \sim 4\pi f$$

The partial compositeness paradigm

Kaplan Nucl.Phys. B365 (1991) 259

$$\frac{1}{\Lambda_{\text{fl.}}^{d-1}} \mathcal{O}_H q_L^c q_R \qquad \Delta m_H^2 \sim \left(\frac{4\pi f}{\Lambda_{\text{fl.}}}\right)^{d-4} f^2$$

Both irrelevant if

we assume: $d_H > 1$ $\qquad d_{H^2} > 4$

Let's postulate the existence of fermionic operators:

$$\frac{1}{\Lambda_{\text{fl.}}^{d_F-5/2}} (\tilde{y}_L \, q_L \mathcal{F}_L + \tilde{y}_R \, q_R \mathcal{F}_R)$$

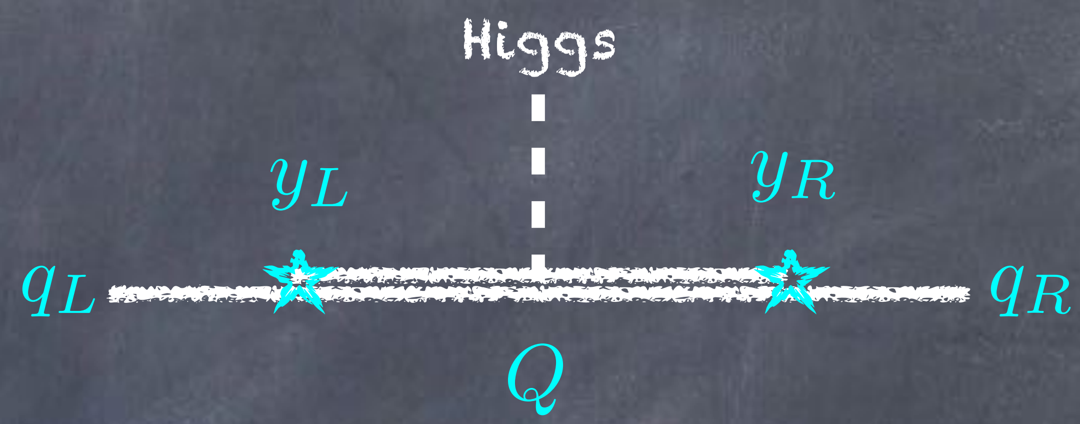
This dimension is not related to the Higgs!

↓

$f(y_L \, q_L Q_L + y_R \, q_R Q_R)$ with $y_{L/R} f \sim \left(\frac{4\pi f}{\Lambda_{\text{fl.}}}\right)^{d_F-5/2} 4\pi f$

The partial compositeness paradigm

$$f(y_L\, q_L Q_L + y_R\, q_R Q_R)$$



$$m_q \sim \frac{y_L y_R f^2}{M_Q^2} f \sin\theta$$

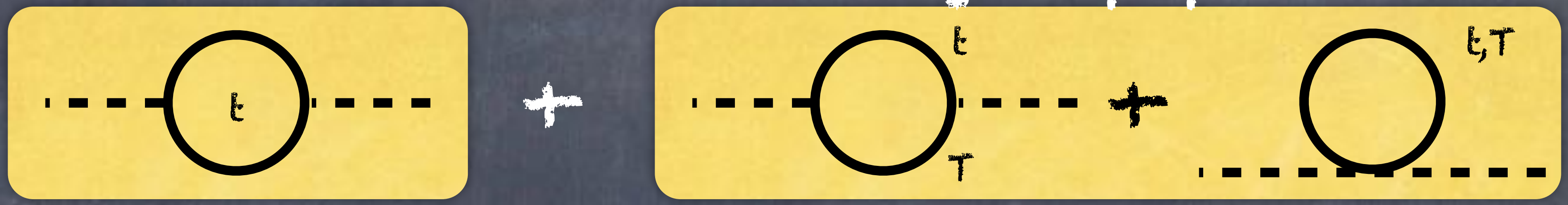
$$M_Q \sim f \Rightarrow y_L, y_R \sim 1$$

Top can cancel top loop, PUVC

$$M_Q \sim 4\pi f \Rightarrow y_L, y_R \sim 4\pi$$

Potential with top partners

Cancellation by top partner loops:



$$V \sim \alpha \sin^2\theta + \beta \sin^4\theta \qquad \beta \sim \alpha$$

Minimum: $\theta \sim \epsilon$

$M_T \sim f$ needed to effectively cut-off the top loops.

$M_T \sim 4\pi f$ Use technifermion mass!

Partial compositeness

100,000 TeV	Λ_{flavour}	Flavour scale
		Conformal region
10 TeV	$\Lambda \sim 4\pi f$	Vector resonances, ...
1 TeV	f	Condensation scale (extra pions)
100 GeV	$v_{\text{SM}} \sim f \sin\theta$	EWSB

Top partners

- Are large baryon anomalous dimensions consistent with QFT?
- What are they composite of? (QCD colour...)
- What generates the Yukawas?

Summary so far:

- Flavour seems to require the presence of a conformal phase above Lambda
- Needs to explain why large anomalous dimensions, or how couplings to quarks generated at low scale
- Partial compositeness may imply light fermionic bound states.
- Linear couplings of SM quarks need to be generated

Top partners as baryons

Gauge-fermion underlying theory

$$\frac{1}{\Lambda_{\text{fl.}}} \underbrace{q\sigma^{\mu\nu}\psi G_{\mu\nu}}_{\text{T}}$$

$$d_T^{\text{naive}} = 7/2$$

- typically loop-suppressed
- psi need to carry colour and flavour quantum numbers

$$\frac{1}{\Lambda_{\text{fl.}}^2} \underbrace{q\psi\psi\psi}_{\text{T}}$$

$$d_T^{\text{naive}} = 9/2$$

- higher dimension, but easier to generate
- Note: issue with other 4-Fermion interactions non avoided!!! Anomalous dimensions are crucial!

Simplest case: QCD-Like!

L.Vecchi
1506.00623

	$SU(3)$	$SU(3)_c$	$SU(2)_w$	$U(1)_Y$
T	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	a
D	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{3} - \frac{1}{2}a$
S	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$-\frac{1}{6} - \frac{1}{2}a$
S'	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\frac{5}{6} - \frac{1}{2}a$

$$SU(7) \times SU(7) \rightarrow SU(7)$$

- DS (and DS') are Higgs candidates!
- coloured mesons are also present: TS, TT, ...
- 3-fermion baryons: TDS, TSS', ...

Simplest case: QCD-like!

L.Vecchi
1506.00623

	$SU(3)$	$SU(3)_c$	$SU(2)_w$	$U(1)_Y$
T	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	a
D	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{3}-\frac{1}{2}a$
S	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$-\frac{1}{6}-\frac{1}{2}a$
S'	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\frac{5}{6}-\frac{1}{2}a$

$$\mathcal{L}_{\rm PC} = \frac{C_q}{\Lambda_{\rm F}^2} q\overline{TDS} + \frac{C_u}{\Lambda_{\rm F}^2} uTDD + \frac{C_u'}{\Lambda_{\rm F}^2} uTSS' + \frac{C_d}{\Lambda_{\rm F}^2} dTSS + {\rm hc.}$$

Large mass given to T, to remove coloured mesons:
T is like a heavy flavour in QCD.

Simplest case: QCD-Like!

L.Vecchi
1506.00623

	$SU(3)$	$SU(3)_c$	$SU(2)_w$	$U(1)_Y$
T	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	a
D	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{3}-\frac{1}{2}a$
S	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$-\frac{1}{6}-\frac{1}{2}a$
S'	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\frac{5}{6}-\frac{1}{2}a$

$$\mathcal{L}_{\rm PC} = \frac{C_q}{\Lambda_{\rm F}^2} q\overline{TDS} + \frac{C_u}{\Lambda_{\rm F}^2} uTDD + \frac{C'_u}{\Lambda_{\rm F}^2} uTSS' + \frac{C_d}{\Lambda_{\rm F}^2} dTSS + {\rm hc.}$$

Can baryons have large anomalous dimensions?

Simplest case: QCD-like!

Anomalous dimensions can be estimated perturbatively in large Nf QCD

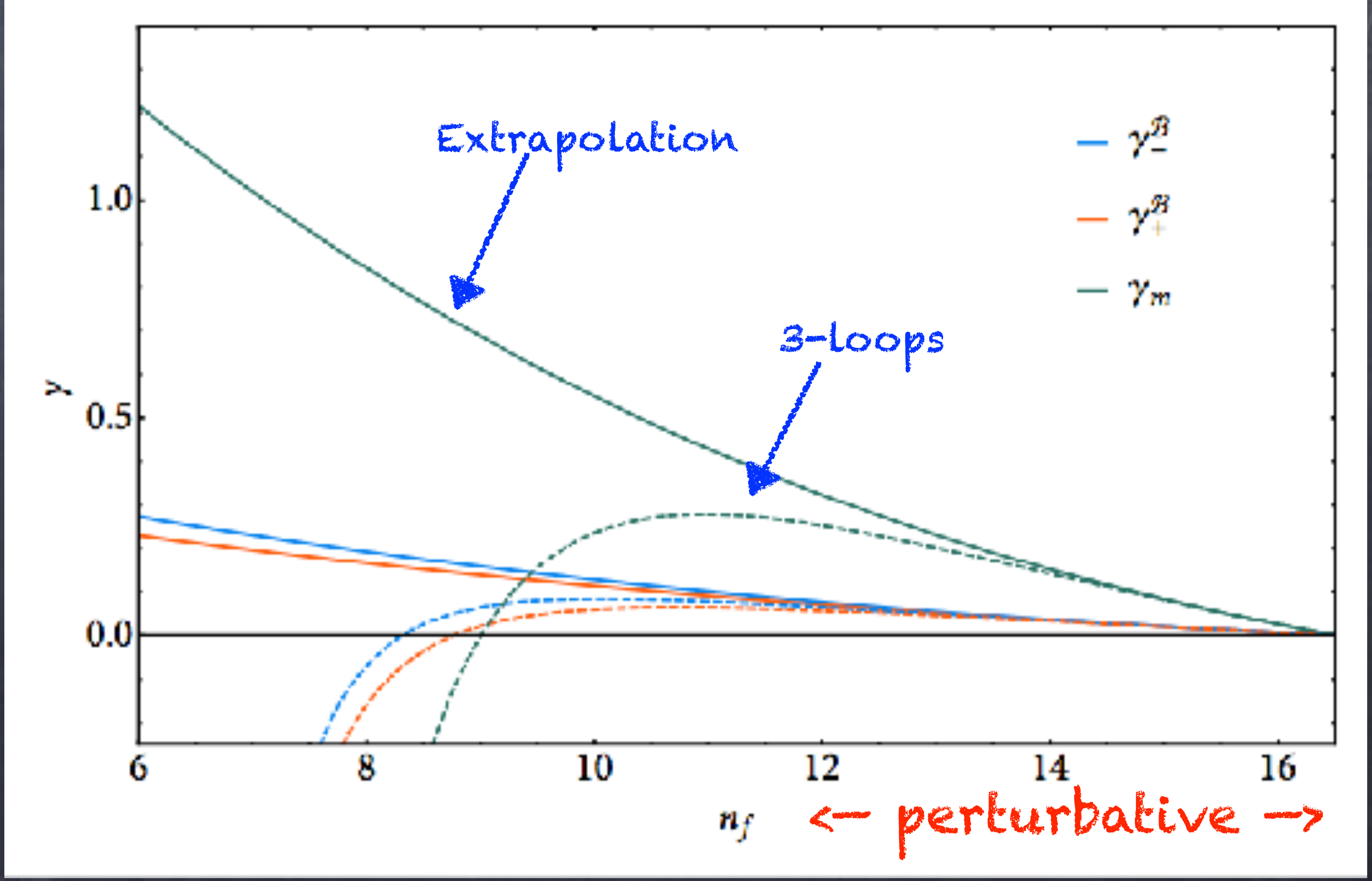
Pica, Sannino 1604.02572
L.Vecchi 1607.02740

$$d_{\psi^3} = 9/2 - \gamma^B$$

$(\gamma^B \sim 2)$

$$d_{\psi^4} = 6 - 2\gamma_m$$

$(\gamma_m \sim 1)$



Simplest case: QCD-like!

Note: anomalous dimensions are physical only at the conformal fixed point!

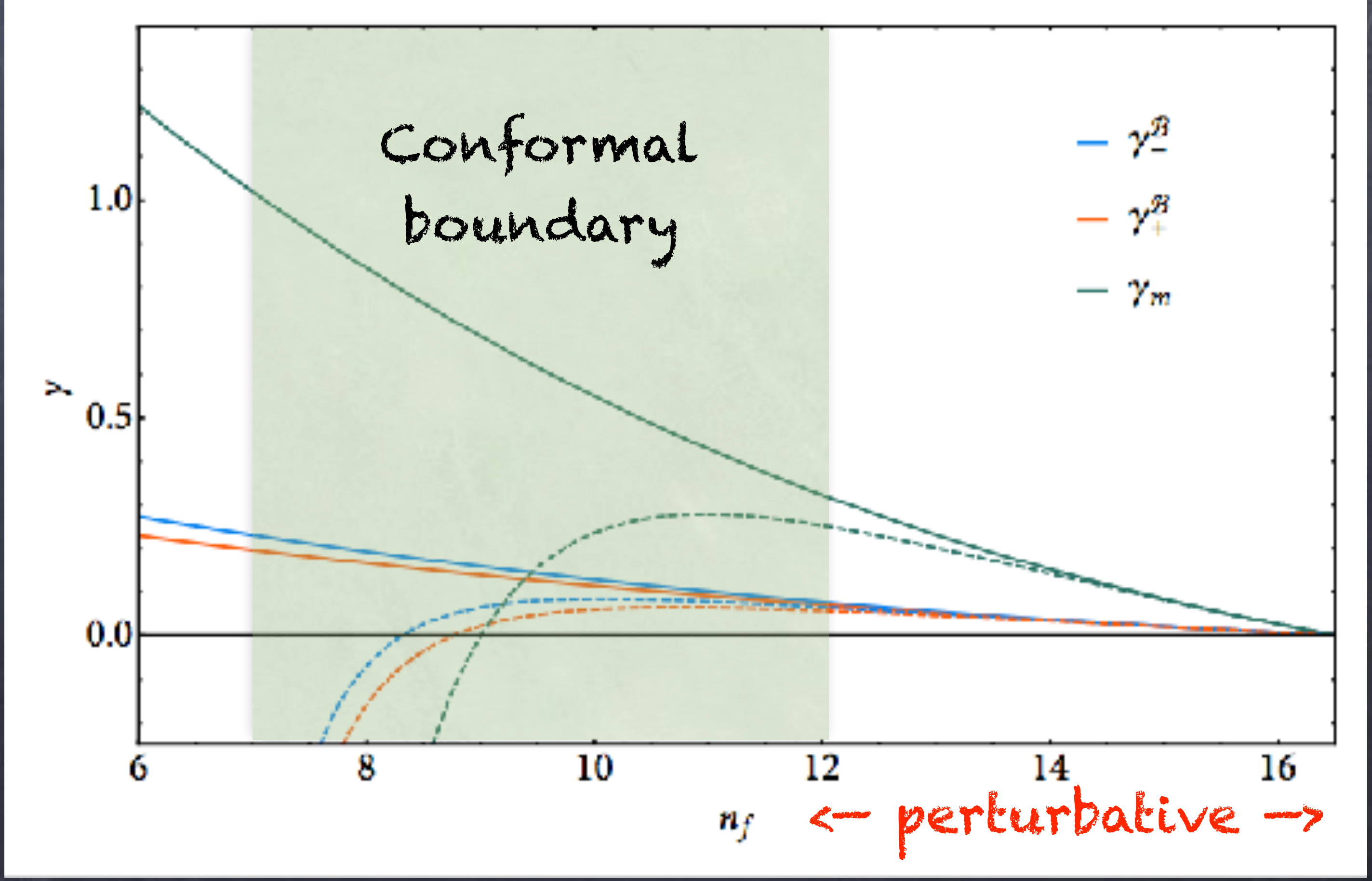
Pica, Sannino 1604.02572
L.Vecchi 1607.02740

$$d_{\psi^3} = 9/2 - \gamma^B$$

$(\gamma^B \sim 2)$

$$d_{\psi^4} = 6 - 2\gamma_m$$

$(\gamma_m \sim 1)$



Sequestering QCD

$\mathcal{G}_{\rm TC}$: rep R — rep R'

G.Ferretti, D.Karateev
1312.5330, 1604.06467

ψ — χ — $T' = \psi\psi\chi \quad \text{or} \quad \psi\chi\chi$

SM : EW — colour + hypercharge

global : $\langle\psi\psi\rangle \neq 0$

↓

pNGB Higgs
DM?

a) $\langle\chi\chi\rangle \neq 0$

coloured pNGBs
di-boson

b) $\langle\chi\chi\rangle = 0$

light top partners
from t Hooft anomaly
conditions?

An example

Baryons: $\psi\psi\chi$

Barnard, Gherghetta, Ray 1311.6562

G_{TC} — Global symmetries

ψ: Q_1–Q_4

	$\mathrm{Sp}(2N_c)$	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{SU}(4)$	$\mathrm{SU}(6)$	$\mathrm{U}(1)$
Q_1 Q_2	$\square$	$\mathbf{1}$	$\mathbf{2}$	0	$\mathbf{4}$	$\mathbf{1}$	$-\frac{6N_c}{2N_c+1}q_\chi$
Q_3	$\square$	$\mathbf{1}$	$\mathbf{1}$	$1/2$			
Q_4	$\square$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$			
χ_1 χ_2 χ_3	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\mathbf{3}$	$\mathbf{1}$	x	$\mathbf{1}$	$\mathbf{6}$	q_χ
χ_4 χ_5 χ_6	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-x$			

Global symmetries

More precisely, the global symmetries are:

$$SU(N_\psi) \times SU(N_\chi) \times U(1)_\psi \times U(1)_\chi$$

WZW term:

$$\mathcal{L} \supset \frac{g_i^2}{32\pi^2} \frac{\kappa_i}{f_a} \, a \, \epsilon^{\mu\nu\alpha\beta} G^i_{\mu\nu} G^i_{\alpha\beta} \, ,$$

Coefficients depend
on the underlying dynamics!

G = A, W, Z, g !!!

Cai, Flacke, Lespinasse 1512.04508

Anomalous U(1) -> heavy η'

Orthogonal U(1) -> pNGB a

Decays and production
only via WZW anomaly.

Model zoology

Ferretti
1604.06467

G_{HC}	ψ	χ	Restrictions	$-q_\chi/q_\psi$	Y_χ	Non Conformal	Model Name
	Real	Real	$SU(5)/SO(5) \times SU(6)/SO(6)$				
$SO(N_{HC})$	$5 \times \mathbf{S}_2$	$6 \times \mathbf{F}$	$N_{HC} \geq 55$	$\frac{5(N_{HC}+2)}{6}$	1/3	/	
$SO(N_{HC})$	$5 \times \mathbf{Ad}$	$6 \times \mathbf{F}$	$N_{HC} \geq 15$	$\frac{5(N_{HC}-2)}{6}$	1/3	/	
$SO(N_{HC})$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	$N_{HC} = 7, 9$	$\frac{5}{6}, \frac{5}{12}$	1/3	$N_{HC} = 7, 9$	M1, M2
$SO(N_{HC})$	$5 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$N_{HC} = 7, 9$	$\frac{5}{6}, \frac{5}{3}$	2/3	$N_{HC} = 7, 9$	M3, M4
	Real	Pseudo-Real	$SU(5)/SO(5) \times SU(6)/Sp(6)$				
$Sp(2N_{HC})$	$5 \times \mathbf{Ad}$	$6 \times \mathbf{F}$	$2N_{HC} \geq 12$	$\frac{5(N_{HC}+1)}{3}$	1/3	/	
$Sp(2N_{HC})$	$5 \times \mathbf{A}_2$	$6 \times \mathbf{F}$	$2N_{HC} \geq 4$	$\frac{5(N_{HC}-1)}{3}$	1/3	$2N_{HC} = 4$	M5
$SO(N_{HC})$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	$N_{HC} = 11, 13$	$\frac{5}{24}, \frac{5}{48}$	1/3	/	
	Real	Complex	$SU(5)/SO(5) \times SU(3)^2/SU(3)$				
$SU(N_{HC})$	$5 \times \mathbf{A}_2$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$	$N_{HC} = 4$	$\frac{5}{3}$	1/3	$N_{HC} = 4$	M6
$SO(N_{HC})$	$5 \times \mathbf{F}$	$3 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$	$N_{HC} = 10, 14$	$\frac{5}{12}, \frac{5}{48}$	1/3	$N_{HC} = 10$	M7
	Pseudo-Real	Real	$SU(4)/Sp(4) \times SU(6)/SO(6)$				
$Sp(2N_{HC})$	$4 \times \mathbf{F}$	$6 \times \mathbf{A}_2$	$2N_{HC} \leq 36$	$\frac{1}{3(N_{HC}-1)}$	2/3	$2N_{HC} = 4$	M8
$SO(N_{HC})$	$4 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$N_{HC} = 11, 13$	$\frac{8}{3}, \frac{16}{3}$	2/3	$N_{HC} = 11$	M9
	Complex	Real	$SU(4)^2/SU(4) \times SU(6)/SO(6)$				
$SO(N_{HC})$	$4 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$	$6 \times \mathbf{F}$	$N_{HC} = 10$	$\frac{8}{3}$	2/3	$N_{HC} = 10$	M10
$SU(N_{HC})$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$6 \times \mathbf{A}_2$	$N_{HC} = 4$	$\frac{2}{3}$	2/3	$N_{HC} = 4$	M11
	Complex	Complex	$SU(4)^2/SU(4) \times SU(3)^2/SU(3)$				
$SU(N_{HC})$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$3 \times (\mathbf{A}_2, \overline{\mathbf{A}}_2)$	$N_{HC} \geq 5$	$\frac{4}{3(N_{HC}-2)}$	2/3	$N_{HC} = 5$	M12
$SU(N_{HC})$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$3 \times (\mathbf{S}_2, \overline{\mathbf{S}}_2)$	$N_{HC} \geq 5$	$\frac{4}{3(N_{HC}+2)}$	2/3	/	
$SU(N_{HC})$	$4 \times (\mathbf{A}_2, \overline{\mathbf{A}}_2)$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$	$N_{HC} = 5$	4	2/3	/	

Model zoology

$G_{\rm HC}$	ψ	χ	Restrictions	$-q_\chi/q_\psi$	Y_χ	Non Conformal	Model Name
	Pseudo-Real	Real	SU(4)/Sp(4) × SU(6)/SO(6)				
$Sp(2N_{\rm HC})$	$4\times\mathbf{F}$	$6\times\mathbf{A}_2$	$2N_{\rm HC}\leq 36$	$\frac{1}{3(N_{\rm HC}-1)}$	$2/3$	$2N_{\rm HC}=4$	M8
$SO(N_{\rm HC})$	$4\times\mathbf{Spin}$	$6\times\mathbf{F}$	$N_{\rm HC}=11,13$	$\frac{8}{3},\ \frac{16}{3}$	$2/3$	$N_{\rm HC}=11$	M9

Defines $\tan\zeta$

Theory confines!

$T' = \psi\psi\chi$

Note: there is enough baryons to give mass to the top (and bottom) only!

Example of predictions: di-boson resonances

Belyaev, Cacciapaglia et al 1610.06591

	Pseudo-Real	Real	SU(4)/Sp(4) × SU(6)/SO(6)				
$Sp(2N_{\rm HC})$	$4\times\mathbf{F}$	$6\times\mathbf{A}_2$	$2N_{\rm HC}\le 36$	$\frac{1}{3(N_{\rm HC}-1)}$	2/3	$2N_{\rm HC}=4$	M8
$SO(N_{\rm HC})$	$4\times\mathbf{Spin}$	$6\times\mathbf{F}$	$N_{\rm HC}=11,13$	$\frac{8}{3}$, $\frac{16}{3}$	2/3	$N_{\rm HC}=11$	M9

The EFT is the same!

Numerical value of couplings:

Model		κ_g	$\frac{\kappa_W}{\kappa_g}$	$\frac{\kappa_B}{\kappa_g}$	$\frac{C_t}{\kappa_g}$ (2,0)	$\frac{C_t}{\kappa_g}$ (0,2)	$\tan\zeta$
M8	a	$-0.77(-0.39)$	$-1.2(-2.5)$	$1.5(0.17)$	$-1.2(-2.5)$	$0.40(0.40)$	
	η'	$1.9(2.0)$	$0.20(0.096)$	$2.9(2.8)$	$0.20(0.0.96)$	$0.40(0.40)$	-0.41
	π_8	7.1	0	1.3	0	0.40	
M9	a	$-4.3(-2.7)$	$-0.55(-2.4)$	$2.1(0.26)$	$-0.068(-0.30)$	$0.18(0.18)$	
	η'	$1.3(3.6)$	$5.8(1.3)$	$8.5(4.0)$	$0.73(0.16)$	$0.18(0.18)$	-3.26
	π_8	$16.$	0	1.3	0	0.18	

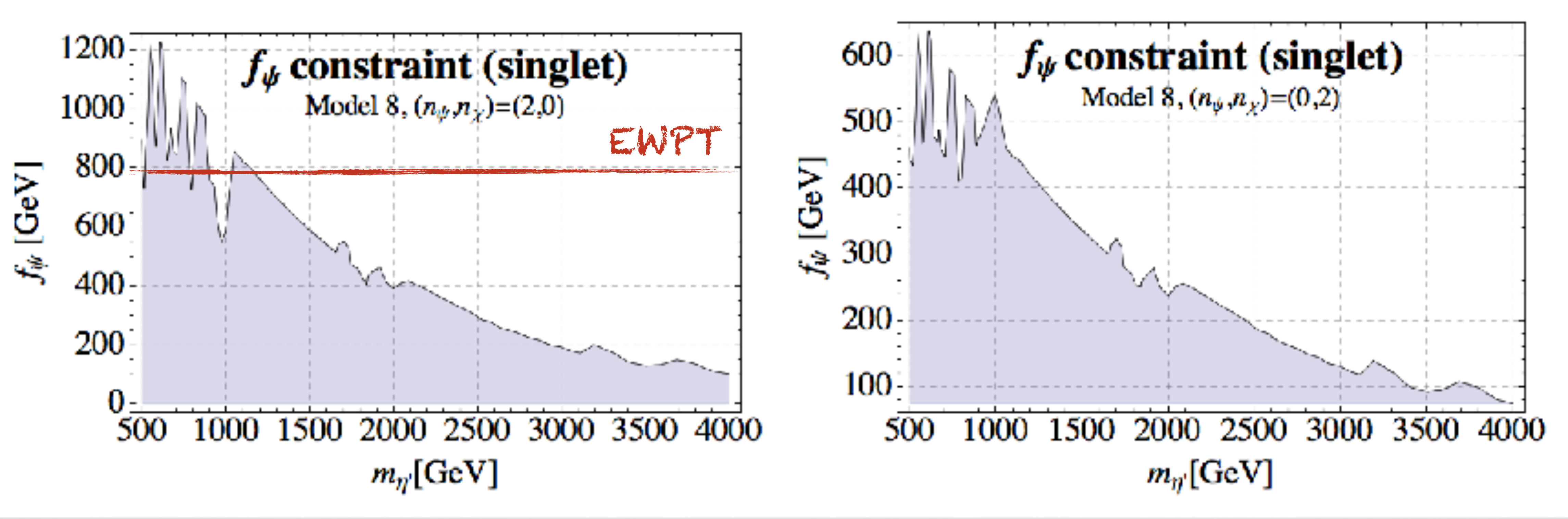
Assuming $f_a = f_\psi = f_\chi$

Model M8

Belyaev, Cacciapaglia et al 1610.06591

"a" too light for the LHC!

$$\left.\frac{m_a}{m_{\eta'}}\right|_{\max} = 0.20$$



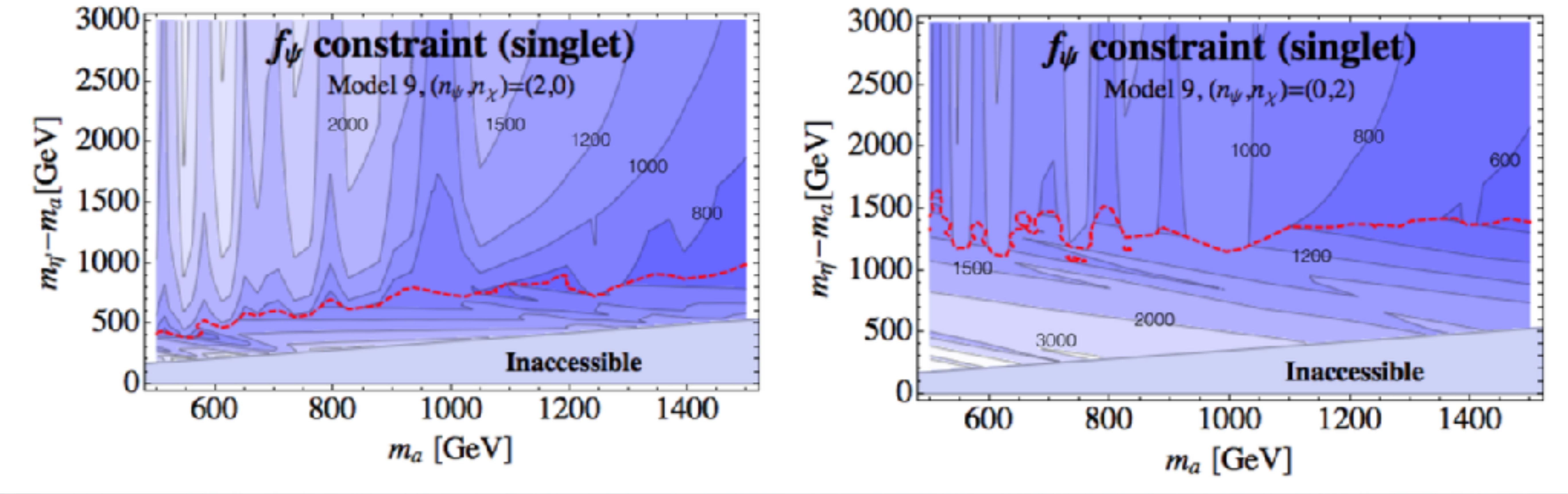
For light masses: bounds competitive with EW precision!

Larger top couplings: reduced diboson rates due to tt BR.

Model M9

$$\left.\frac{m_a}{m_{\eta'}}\right|_{\max} = 0.74$$

Belyaev, Cacciapaglia et al 1610.06591



Above red line, bound driven by "a"!

Bounds stronger than EW precision
in most of the parameter space!

PC with scalars

Sannino, Strumia, Tesi, Vigiani 1607.01659

$$y\, q\, \underbrace{\psi S}_{T}$$

Top partner as a bound state of fermion + scalar!

- No need for anomalous dimensions: the coupling is already marginal
- Many scalars can be added: complete mass and flavour structures
- Naturalness in question (maybe asymptotic safety?)

Litim, Sannino 1406.2337
Pelaggi, Sannino, Strumia, Vigiani 1701.01453

PC with scalars

Sannino, Strumia, Tesi, Vigiani 1607.01659

$y\, q\, \underbrace{\psi S}_{T}$

Top partner as a bound state of fermion + scalar!

	$SU_c(3)$	$SU_L(2)$	$U_Y(1)$	$SU_{\mathcal{F}}(4)$	$U_B(1)$	$Sp_{\mathcal{S}}(6)$
$\mathcal{F}_Q$	1	$\square$	0			
$\mathcal{F}_u$	1	1	$-\frac{1}{2}$	$\square$	0	1
$\mathcal{F}_d$	1	1	$\frac{1}{2}$			
$\mathcal{S}_t$	$\bar{\square}$	1	$-\frac{1}{6}$	1	$-\frac{1}{3}$	$\square$
Q_3	$\square$	$\square$	$\frac{1}{6}$			
t	$\bar{\square}$	1	$-\frac{2}{3}$			
b	$\bar{\square}$	1	$\frac{1}{3}$			

} Doublets of $SU(2)_{TC}$

$$\mathcal{L}_{\text{top-bottom}} = y_{tL} Q_3 \mathcal{S}_t \epsilon_{TC} \mathcal{F}_Q + y_{tR} t \mathcal{S}_t^* \mathcal{F}_d + y_{bR} b \mathcal{S}_t^* \mathcal{F}_u + \text{h.c.}$$

Minimal model on the Lattice

T.Ryttov, F.Sannino 0809.0713
Galloway, Evans, Luty, Tacchi 1001.1361

$$G_{\rm TC} = SU(2) \qquad \begin{pmatrix} U \\ D \end{pmatrix}$$

2 Dirac doublets

$$\psi^1 = U_L \quad \psi^2 = D_L \quad \psi^3 = (i\sigma^2)_{\rm TC} U_R^C \quad \psi^4 = (i\sigma^2)_{\rm TC} D_R^C$$

	$SU(2)_{TC}$	$SU(4)_\psi$	$SU(2)_L$	$U(1)_Y$
$\begin{pmatrix}\psi^1 \\ \psi^2\end{pmatrix}$	$\square$	$\square$	**2**	0
ψ^3	$\square$		**1**	-1/2
ψ^4	$\square$		**1**	1/2

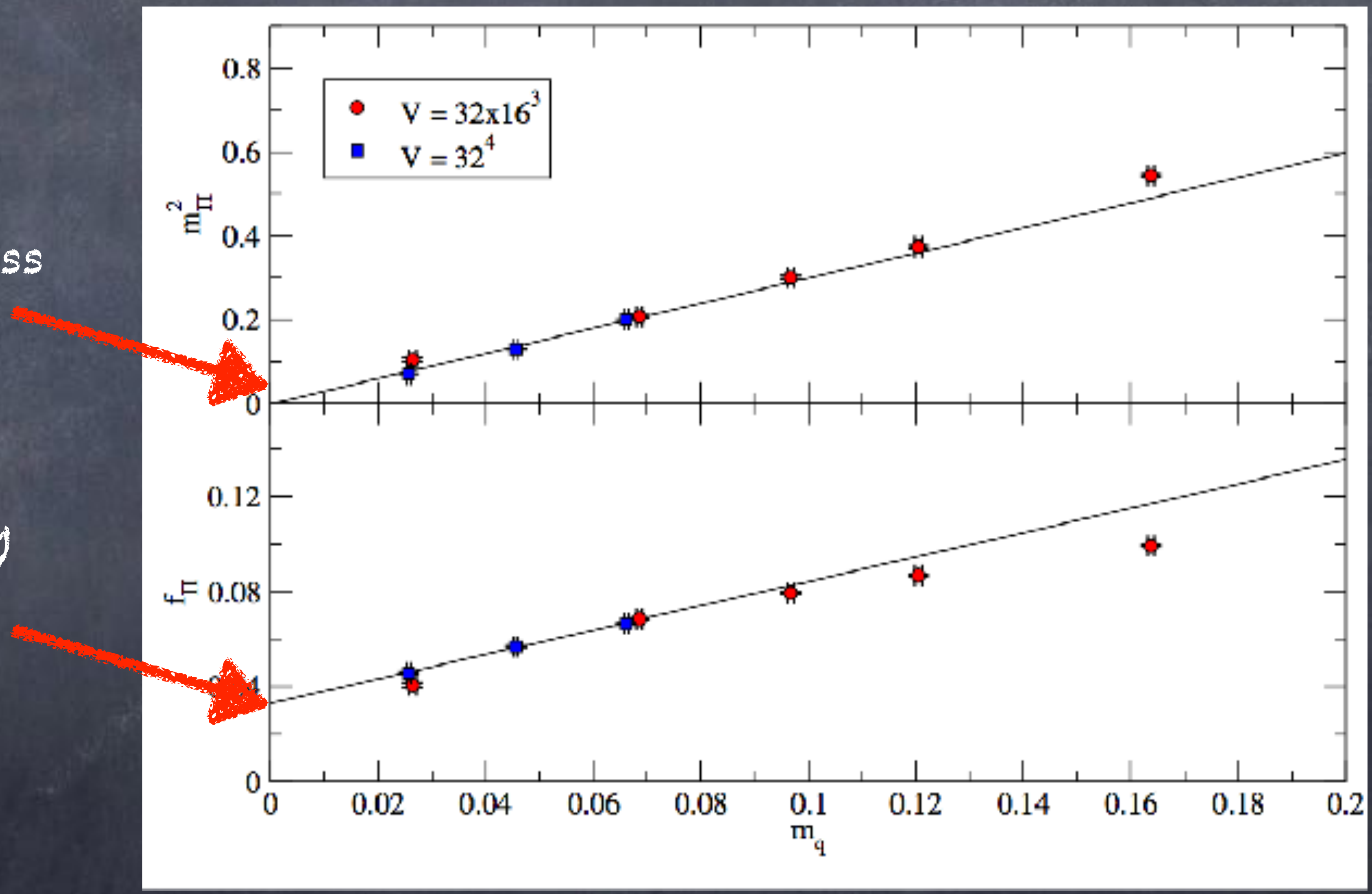
} $SU(2)_R$ doublet

Minimal model on the Lattice

C.Pica, F.Sanninoet al 1412.7302
1607.06654, 1612.09336, ...

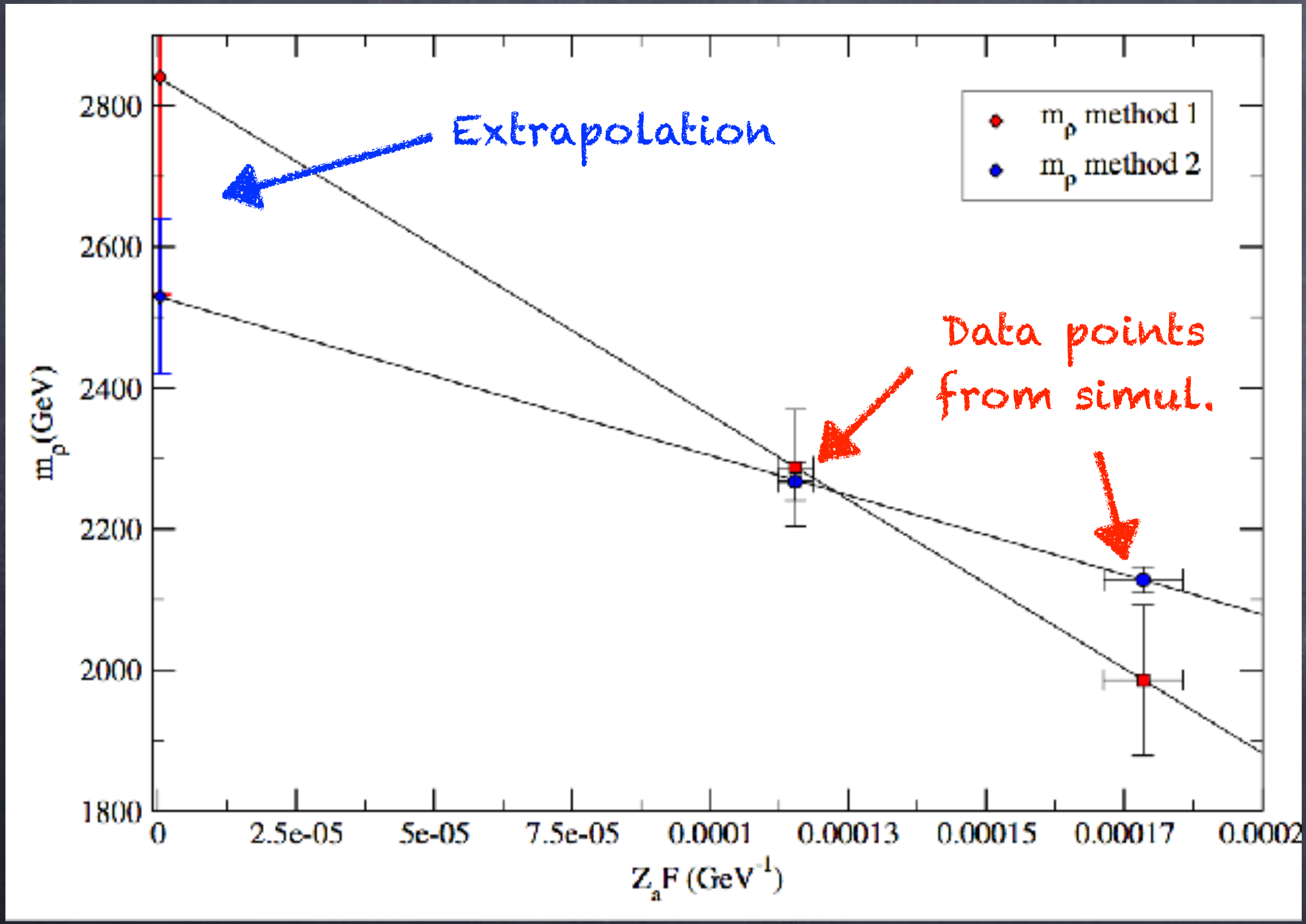
Chiral limit:
for zero mass,
the pions are massless

The global symmetry
is broken as f
is non zero!



- Massless fermions cannot be simulated on the lattice.
- Each point in the plot is extrapolated to the continuum (see next slide)

Continuum limit extrapolation

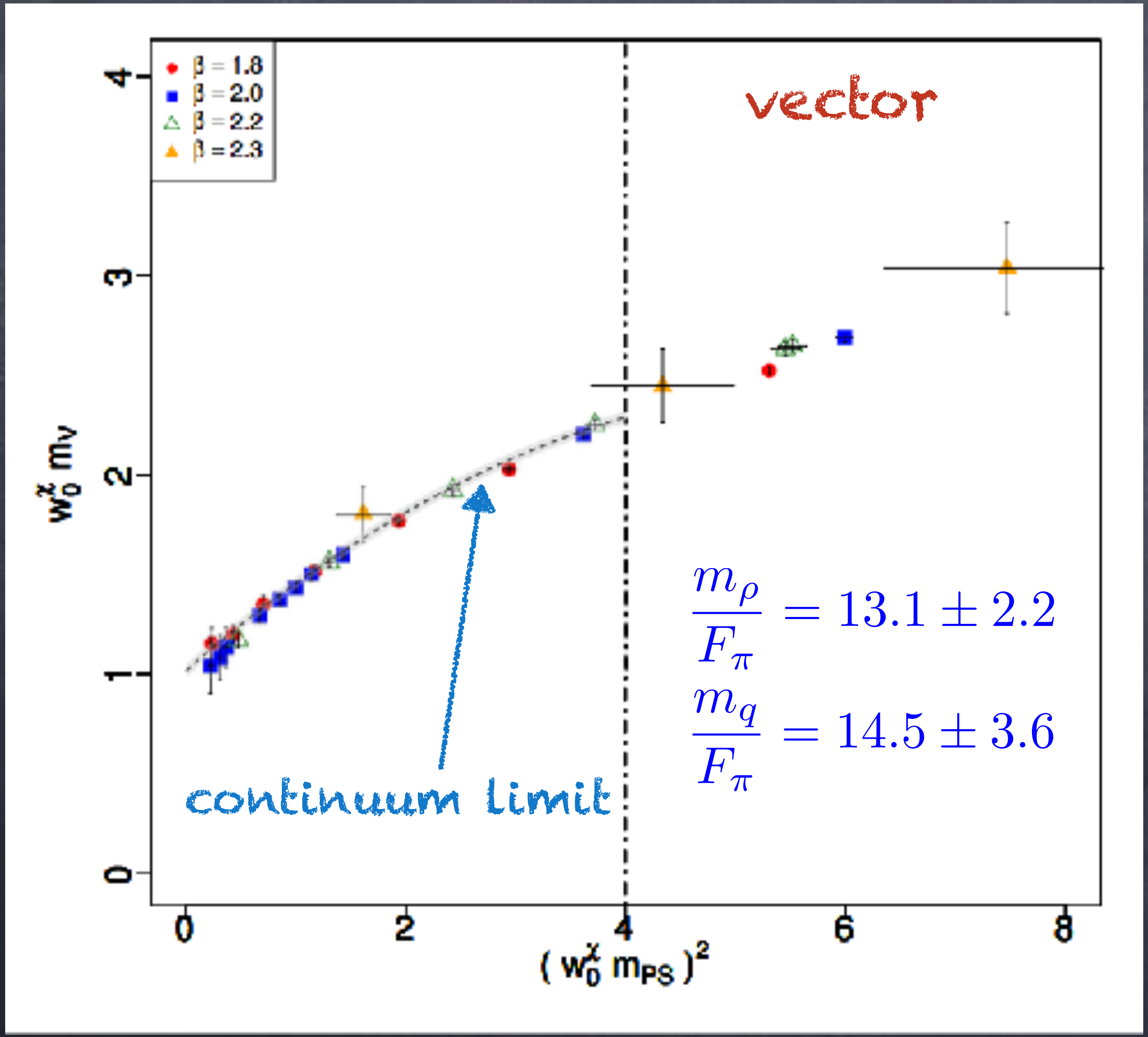


Large errors due to the extrapolation to the continuum

Effects of Lattice spacing and finite volume should be under control.

The vector resonance

Lattice results:



$\sin\theta \leq 0.2$

$$m_a = \frac{3.6 \pm 0.9 \text{ TeV}}{\sin\theta} \gtrsim 18 \text{ TeV}$$

$$m_\rho = \frac{3.2 \pm 0.5 \text{ TeV}}{\sin\theta} \gtrsim 16 \text{ TeV}$$

$$m_\sigma \sim ???$$

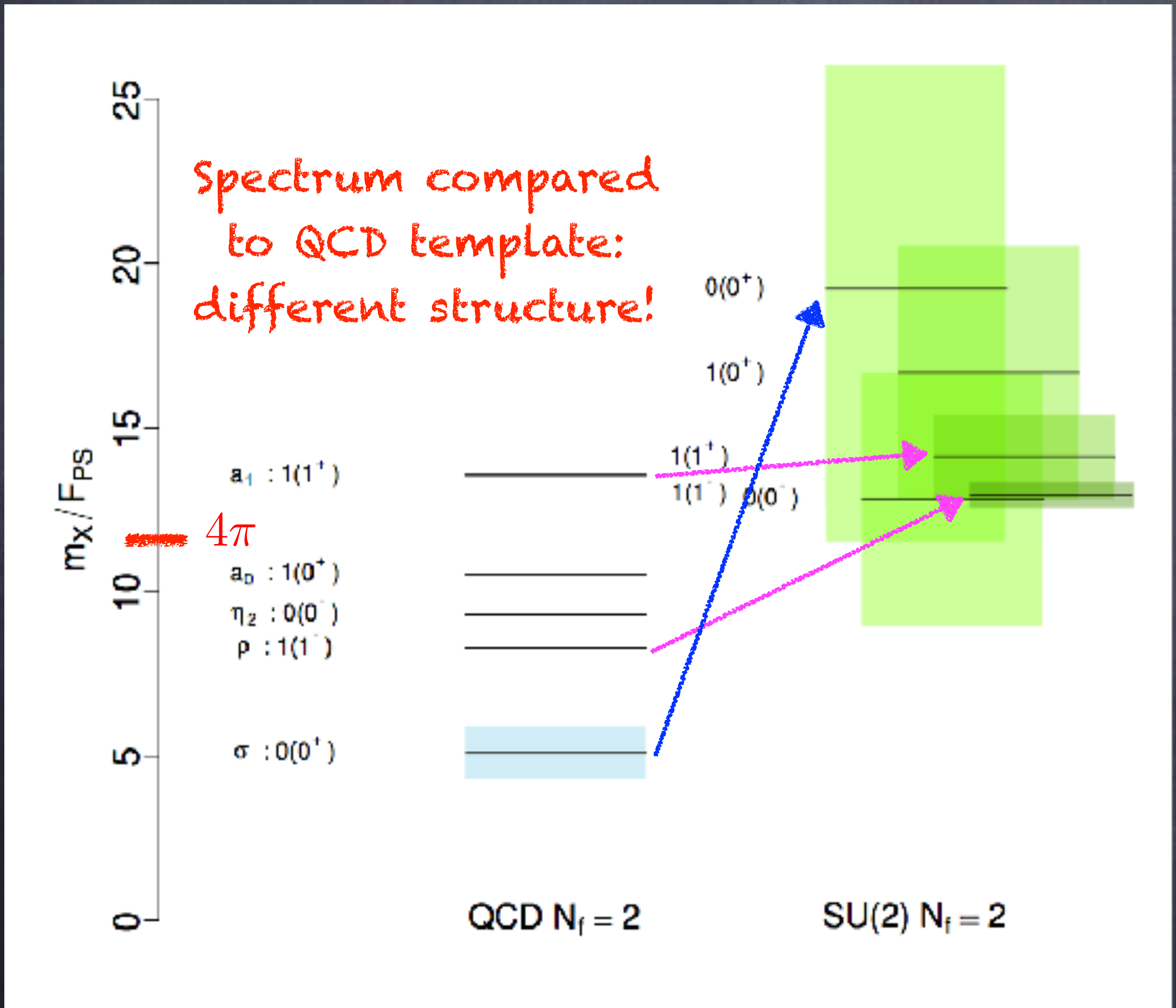
$$m_\eta \sim \frac{m_h}{\sin\theta} \gtrsim 600\ GeV$$

$$m_h = 125\ GeV$$

Arthur, Drach, et al. 1602.06559

The spectrum

Lattice results:



$\sin\theta \leq 0.2$

$$m_a = \frac{3.6 \pm 0.9 \text{ TeV}}{\sin\theta} \gtrsim 18 \text{ TeV}$$

$$m_\rho = \frac{3.2 \pm 0.5 \text{ TeV}}{\sin\theta} \gtrsim 16 \text{ TeV}$$

$$m_\sigma \sim ???$$

$$m_\eta \sim \frac{m_h}{\sin\theta} \gtrsim 600\ GeV$$

$$m_h = 125\ GeV$$

Example 2:
entering the conformal window

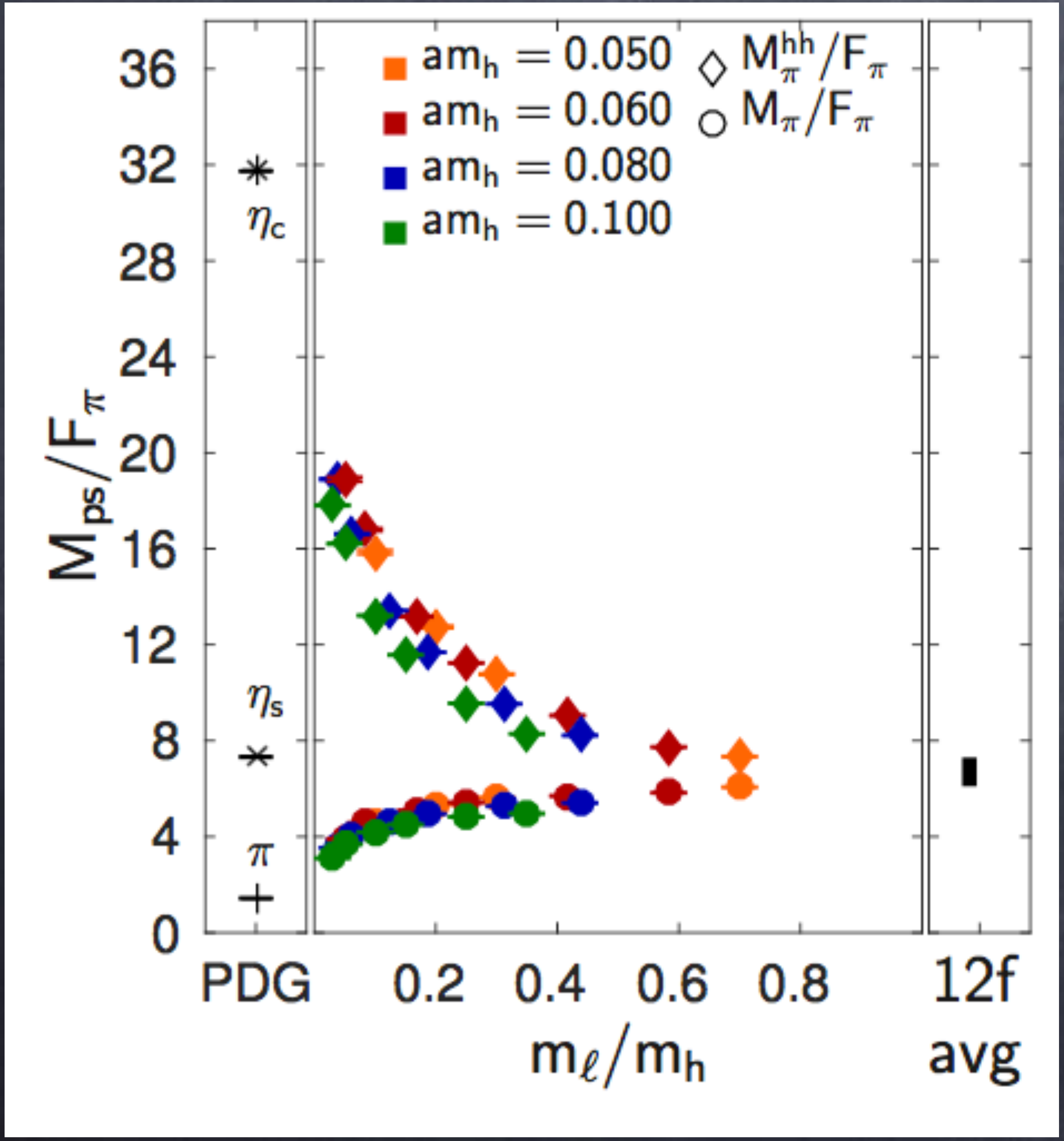
A.Hasenfratz, C.Rebbi, O.Witzel
1609.01401, 1611.07427

Study QCD (i.e. SU(3) gauge theory) with 12 flavours.

4 flavours are light, with mass m_l
8 flavours are heavy, with mass m_H

Example 2:
entering the conformal window

A.Hasenfratz, C.Rebbi, O.Witzel
1609.01401, 1611.07427



- Ratios do not depend on the heavy mass! (f fixed by it)
- For $m_l \ll m_H$, light pions become massless, while heavy one decouple.
- For $m_l \sim m_H$, the 12-flavour model is recovered:

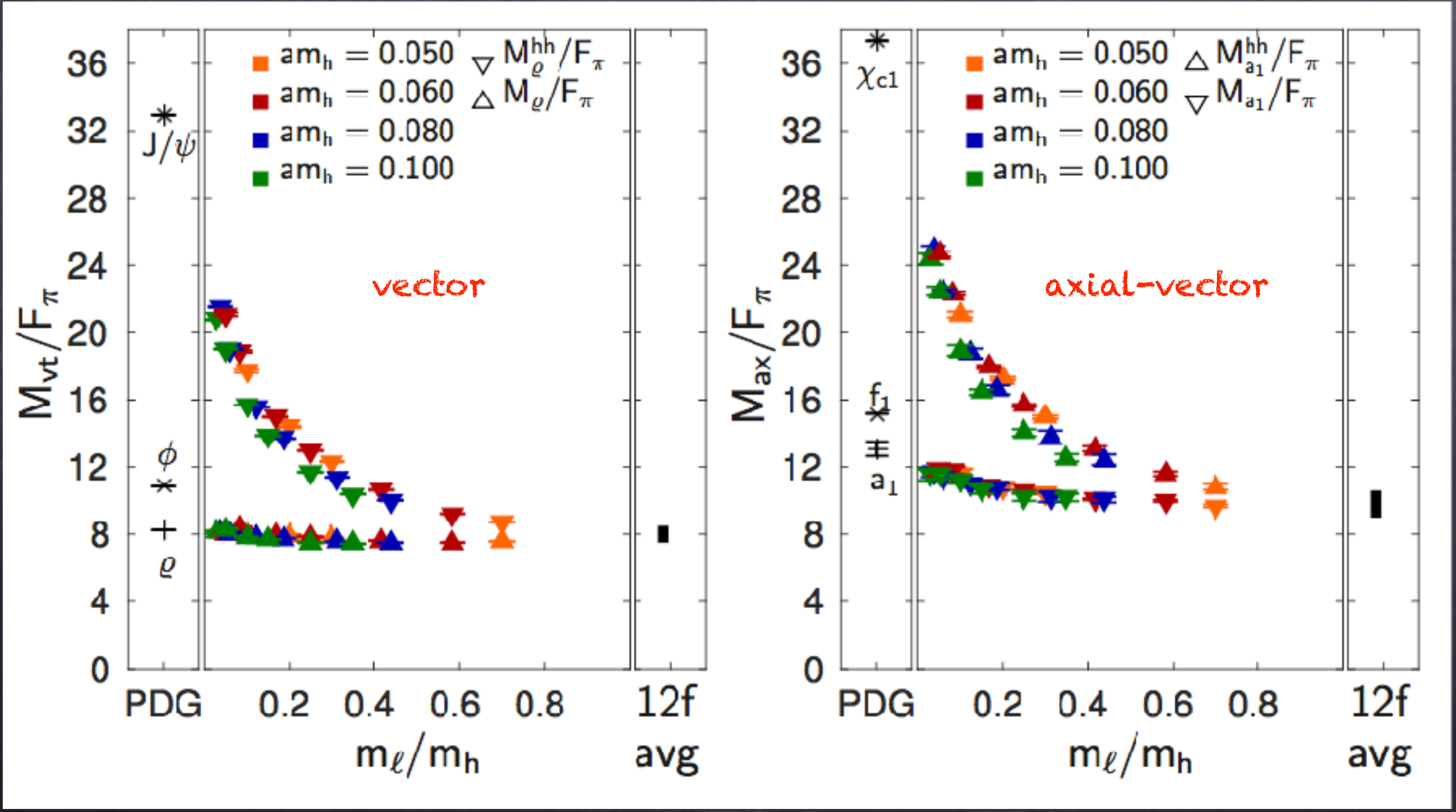
ratios become equal, while both vanish due to conformal behaviour

$$m_\pi \to 0, \quad f_\pi \to 0$$

$$m_\pi/f_\pi \to\sim 7$$

Example 2:
entering the conformal window

A.Hasenfratz, C.Rebbi, O.Witzel
1609.01401, 1611.07427



Example 2:
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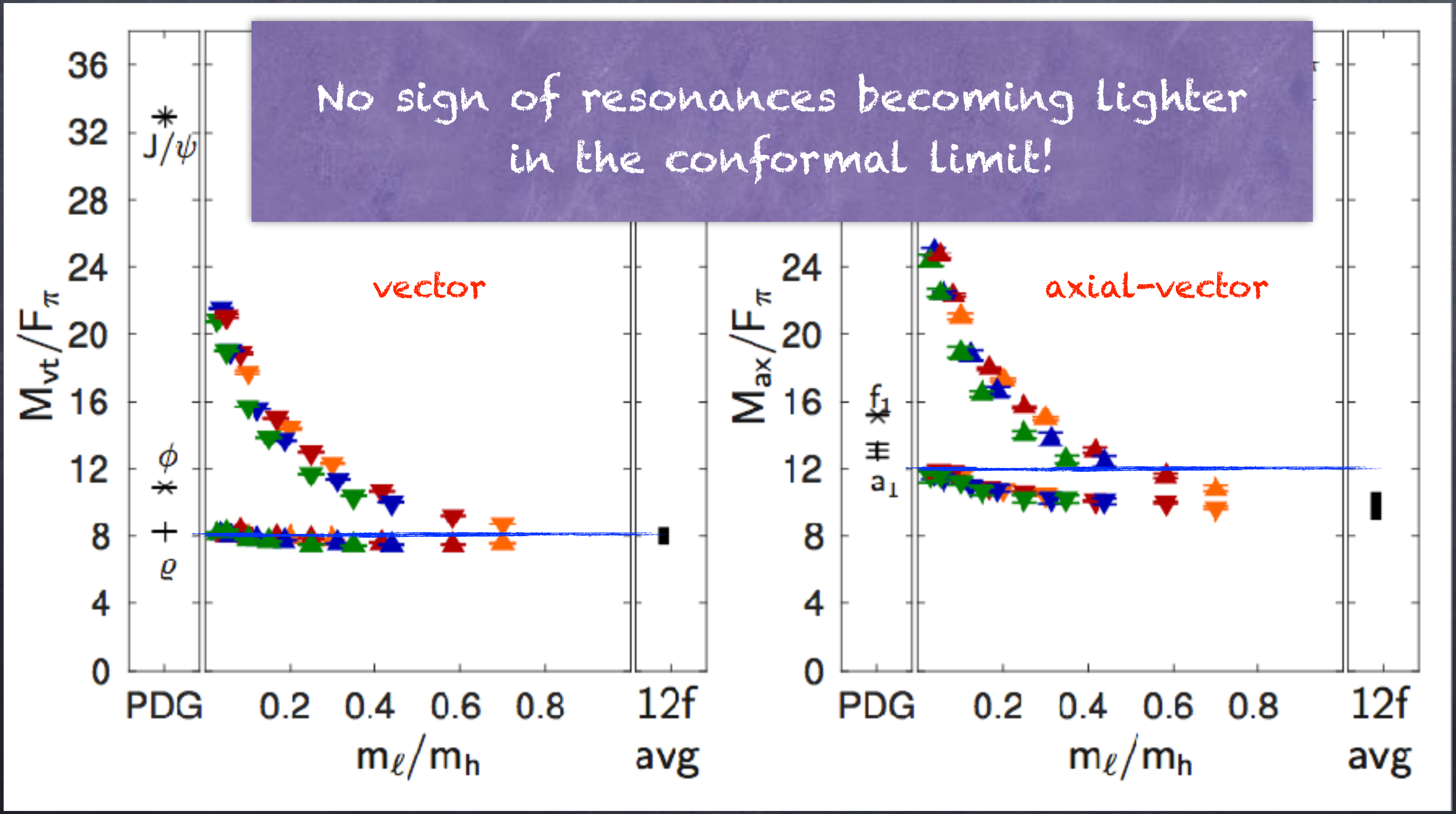

Summary

- Simple composite models can contain a Dark pNGB (and the Higgs)
- Thermal relic natural for moderate tuning
- Testable @ Direct Detection, but no chance @ the LHC!
- More work needed to explore models/theories -> FCD a precious guide!