Fundamental Composite Higgs Dynamics

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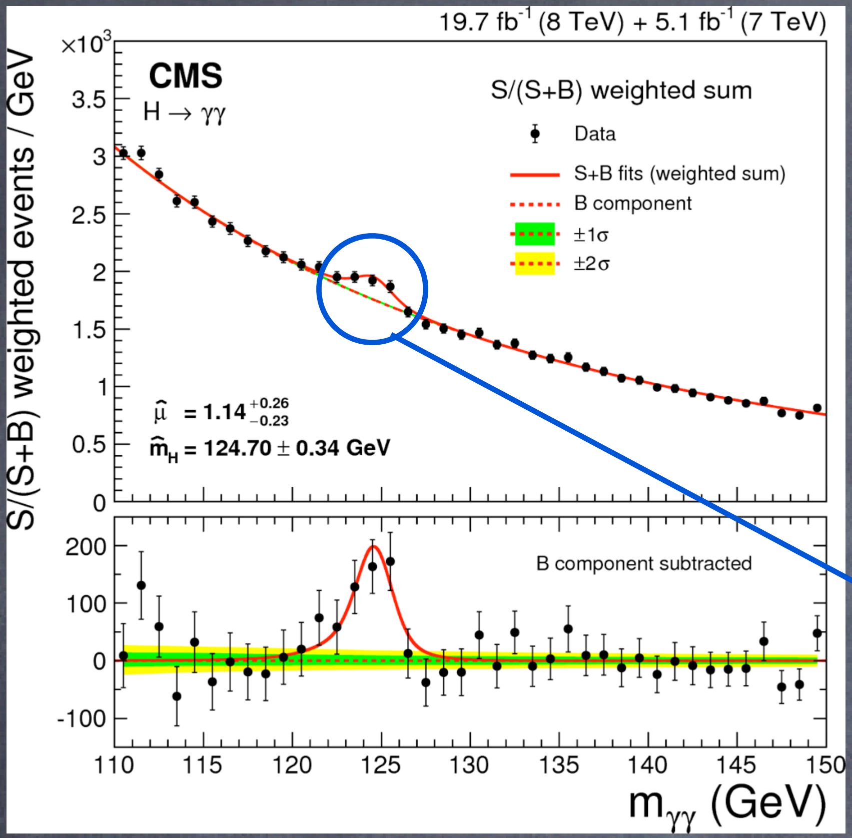
IPNL (Lyon, France)

Kruger 2014, parallel I

Kruger park, 1 Dec. 2014

Based on G.C., F.Sannino 1402.0233
and work in progress with H.Cai, M.Lespinasse, A.Deandrea,
Seung J. Lee, T.Flacke, F.Sannino and the CP3-Origins group

Why do we need BSM?



The Higgs boson has been discovered.

The Standard Model is now complete!

Ian MacNicol / AFP - Getty Images

- The discovery of the Higgs boson has brought the **Naturalness problem** to reality!

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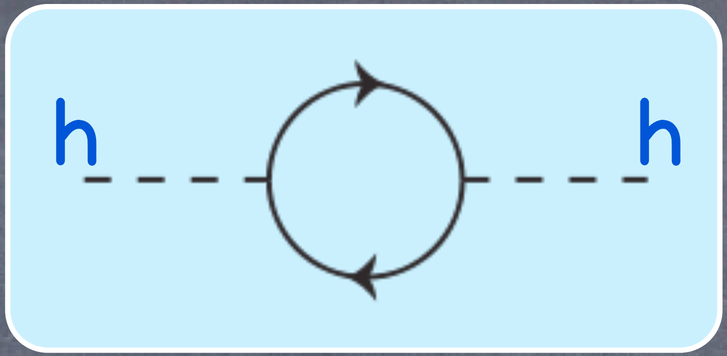

$$\delta m_H^2 \sim \frac{g^2}{16\pi^2} M_{\rm NPh}^2$$

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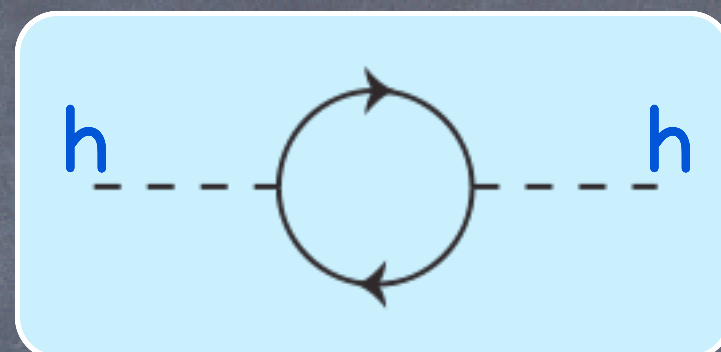


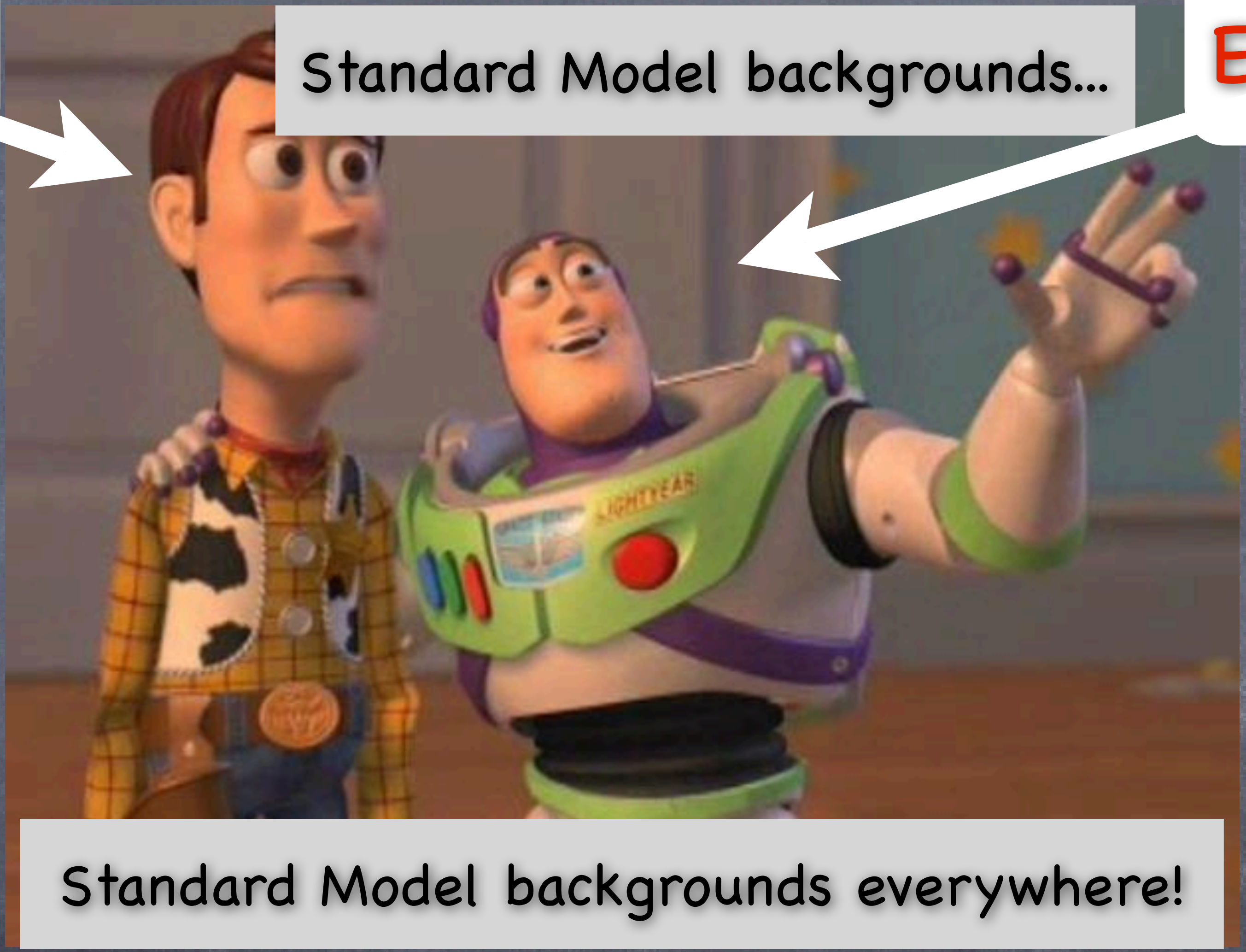
$$\delta m_H^2 \sim \frac{g^2}{16\pi^2} M_{\mathrm{NPh}}^2$$

... or there is New Physics

at/around the TeV scale!

The picture after LHC 8TeV

The hard reality:



Standard Model all the way up?

The TeV scale is a qualitative argument.

And, BSM signals may be not so easy to spot!

Naturalness wiki-how:

how to stabilise the Higgs?

- "Give it" spin:
  - Supersymmetry: associate it to fermions!
  - Part of a gauge field in extra dimensions (Gauge-Higgs U.)
- Set its mass to zero:
  - Link it to a spontaneous symmetry breaking: pNGB Higgs
- Associate it with a stable mass scale:
  - Bound state of a confining dynamic

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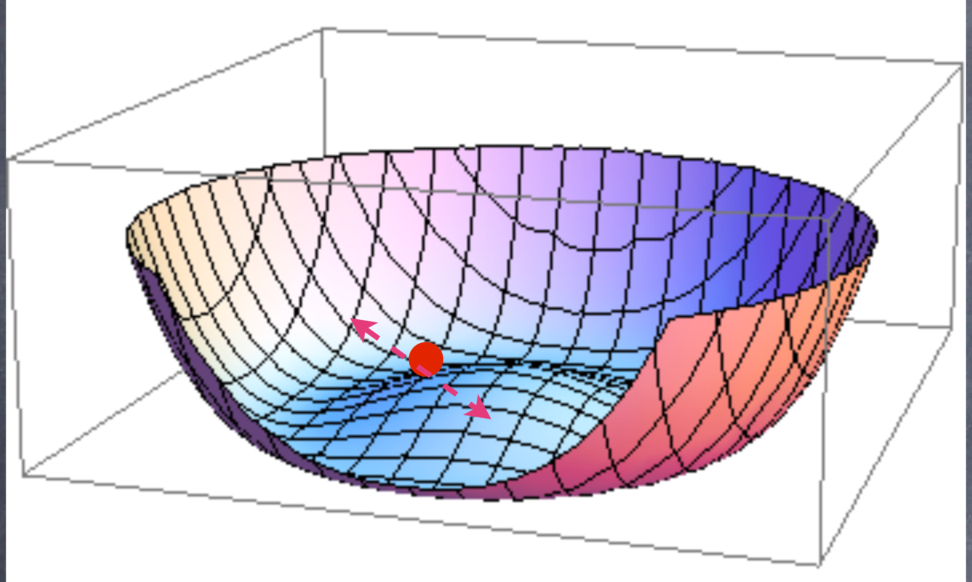
A composite Higgs in pictures



Technicolor Higgs

Large global symmetry
dynamically broken.

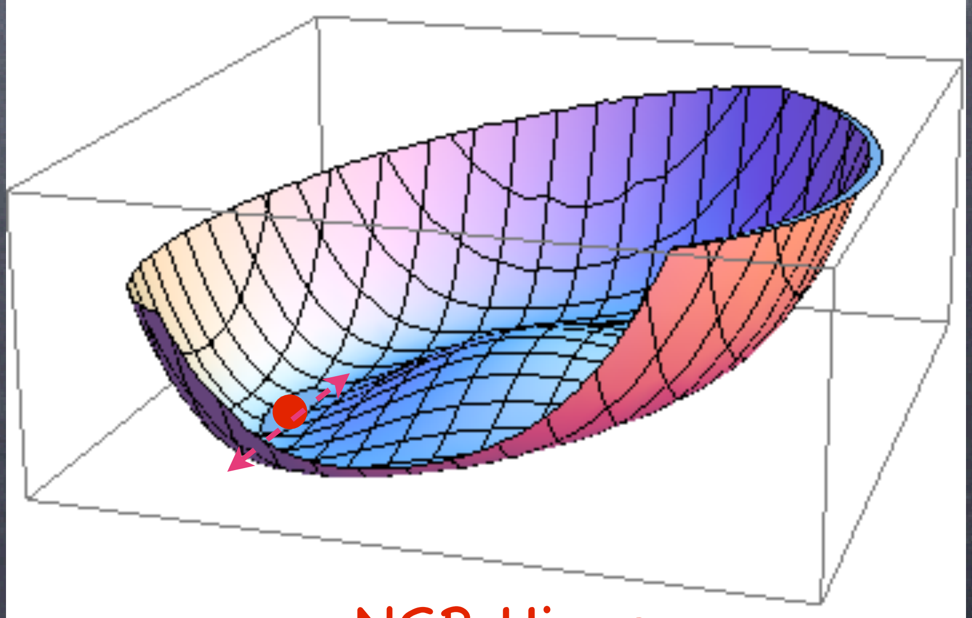
N Goldstone bosons

Mass set by the dynamics!

The global symmetry
broken by quantum effects.

Some Goldstone bosons
acquire mass

Mass smaller that the
scale of dynamics



pNGB Higgs

Can the Higgs be a composite state of a confining dynamics?

1 The Higgs as a (pseudo-)GB of a broken global symmetry:

Global symmetries: $\mathcal{G} \longrightarrow \mathcal{H}$ $\quad h \in \mathcal{G}/\mathcal{H}$

$\cup \qquad \cup$

Gauge symmetries: $\mathcal{G}_{\rm SM} \to U(1)_{\rm em}$

Georgi, Kaplan 1984

2 The Higgs as a heavy spin-0 resonance:

h singlet of $\mathcal{H}$

Dilaton/Radion Higgs

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σ meson in QCD

h singlet of $\mathcal{H}$

Dilaton/Radion Higgs

1 The Higgs as a pseudo-Goldstone Boson

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

What underlying dynamics is up to the job?

1

Principle: a simple model

- Consider a confining gauge group G,
- with N fermions ψ^f in the rep R of G.

If R is real or pseudo-real, the condensate will be:

(The fermions are chiral, and the global flavour symmetry is SU(N))

$$\langle \psi^i \psi^j \rangle \begin{cases} \text{symmetric} & \Rightarrow \quad SU(N) \to SO(N) \\ \text{anti-symmetric} & \Rightarrow \quad SU(N) \to Sp(N) \end{cases}$$

If R is complex, the condensate will be:

(The fermions are not chiral, and the global flavour symmetry is SU(N) x SU(N))

$$\langle \bar{\psi}^i \psi^j \rangle \Rightarrow SU(N) \times SU(N) \to SU(N)$$

1

What underlying dynamics is up to the job?

$\mathcal{G}$	$\mathcal{H}$	C	N_G
SO(5)	SO(4)	✓	4
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SU(4) × U(1)	SU(3) × U(1)		7
SU(6)	Sp(6)	✓*	14
$[SO(6)]^2$	SO(6)	✓*	15

Minimal case

1 bi-doublet + 1 singlet

Batra, Csako 0710.0333
Ryttov, Sannino 0809.0713
Galloway, Evans, Luty, Tacchi 1001.1361
Barnard, Gherghetta, Ray 1311.6562
G.C., Sannino 1402.0233

Contains EW triplets

Ferretti 1404.7137

Non-custodial

This is like QCD

Minimal 2HDM

2 bi-doublets + 6 singlets

G.C., Lespinasse, work in progress

The minimal case:

$$SU(4) \to Sp(4) \sim SO(5)$$

Katz, Nelson, Walker hep-ph/0504252
Gripaios, Pomarol, Riva, Serra, 0902.1483
Galloway, Evans, Luty, Tacchi 1001.1361

- Sp(4) has rank = 2, and it contains an SU(2)xSU(2) subgroup
- The condensate transforms as:

$$\langle \psi^i \psi^j \rangle = \mathbf{6}_{\mathrm{SU}(4)} \to \mathbf{5}_{\mathrm{Sp}(4)} \oplus \mathbf{1}_{\mathrm{Sp}(4)}$$

Goldstone bosons

$$5_{\mathrm{Sp}(4)} \to (2,2) \oplus (1,1)$$

of SU(2)xSU(2): Higgs doublet + singlet

Massive scalar

$$1_{\mathrm{Sp}(4)} \to (1,1)$$

like the σ meson in QCD

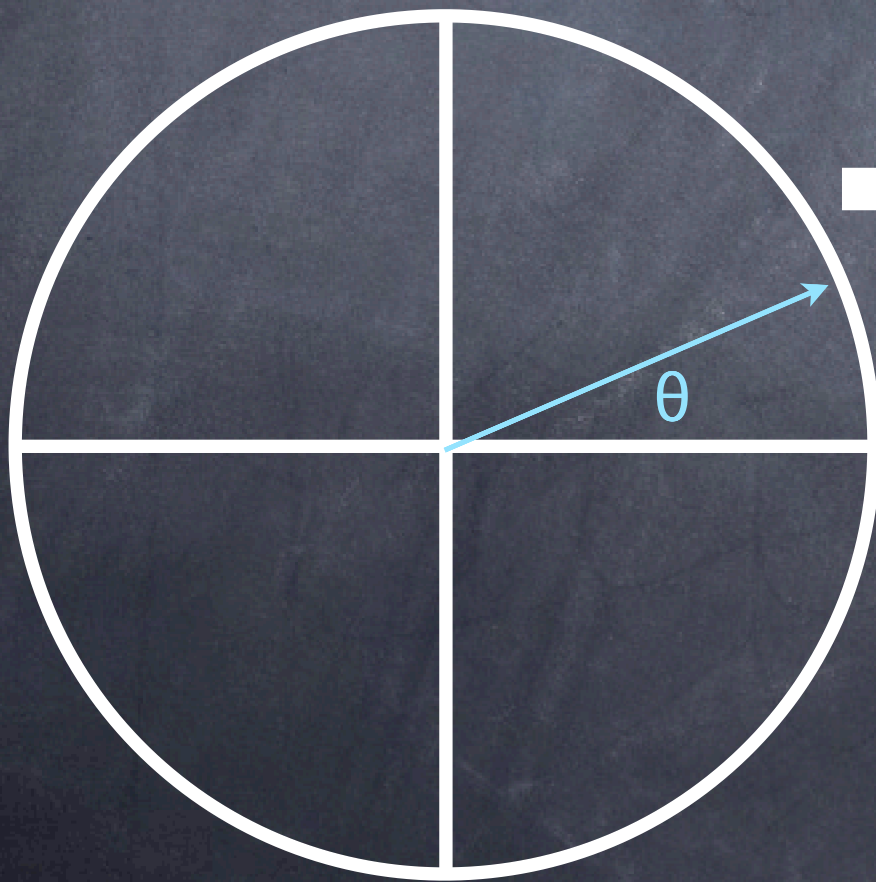
Question 1: does this breaking pattern really take place?

Question 2: how is EW symmetry broken?
(This is an issue of alignment!)

$$
\begin{array}{ccc}
SU(4) & \to & Sp(4) \sim SO(5) \\
\cup & & \cup \\
SU(2)_{\rm L} \times U(1)_{\rm Y} & \to & U(1)_{\rm em}
\end{array}
$$

$\theta = \pi/2$

Technicolour → 2 light scalars, no Higgs
Higgs must be a TC excitation



→ A pseudo-Goldstone (composite) Higgs exists in between!

$\theta = 0$

No EWSB → 4 massless Goldstone Bosons

Cacciapaglia, Sannino
1402.0233

Do we have a dynamical model for this?

$G = SU(2)$ with 4 Weyl doublets Q_i

Batra, Csako 0710.0333
Ryttov, Sannino 0809.0713

$< Q_i Q_j >$ condensate forms and breaks

$SU(4) \to Sp(4) \sim SO(5)$ (proven on the lattice)

Lewis, Pica, Sannino 1109.3513
+ Hietanen 1404.2794

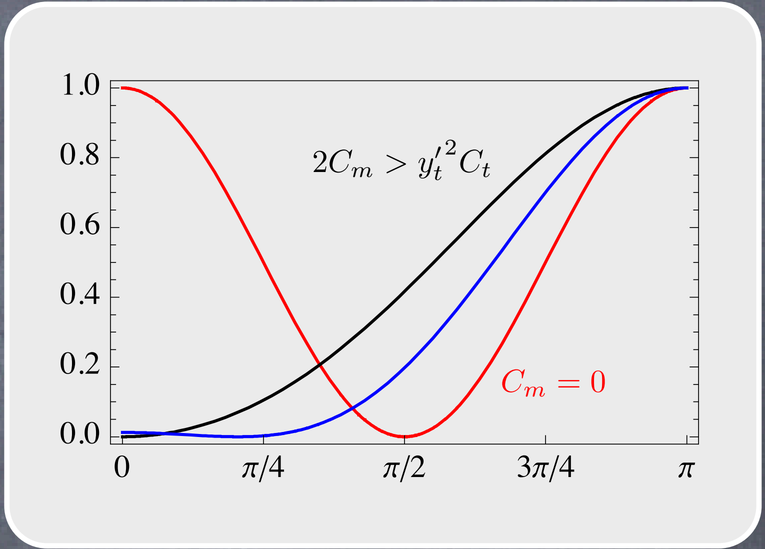
The EW symmetry can be embedded in SU(4) by assigning the following $SU(2)_L \times SU(2)_R$ properties:

$$\begin{pmatrix} Q^1 \\ Q^2 \end{pmatrix} = (2,1)\,, \qquad \begin{pmatrix} Q^3 \\ Q^4 \end{pmatrix} = (1,2)$$

Introducing a potential for θ

$$V(\theta) = {y'_t}^2 C_t \cos^2\theta - 4C_m \cos\theta + \text{const.}$$

$$|\cos\theta|_{\min} = \frac{2C_m}{{y'_t}^2 C_t} \quad \text{if } {y'_t}^2 C_t > 2|C_m|$$



Note: to obtain θ~0, we need to tune ${y'_t}^2 C_t \sim 2C_m$

$$m_\eta^2 = \frac{{y'_t}^2 C_t}{4} f^2$$

$m_h = 125$ GeV for $C_t \sim 2$

$$m_h^2 = \frac{{y'_t}^2 C_t}{4} f^2 \sin^2\theta = m_\eta^2 \sin^2\theta = \frac{C_t m_t^2}{4}$$

$f^2 \sin^2\theta \sim v^2$

The Higgs mass fine-tuning

$$\delta m_h^2\big|_{\text{top}} = \frac{C_t {y_t'}^2 f^2}{8}(2\sin^2\theta - 1)$$

$$\delta m_h^2\big|_{\text{m}} = \frac{2C_m f^2}{8}\cos\theta$$

Both Order f!

The Higgs mass fine-tuning

$$\delta m_h^2\big|_{\rm top} = \frac{C_t {y_t'}^2 f^2}{8}(2\sin^2\theta - 1)$$

Sum is Order
v = f sin θ

$$\delta m_h^2\big|_{\rm m} = \frac{2C_m f^2}{8}\cos\theta = \frac{C_t {y_t'}^2 f^2}{8}(1 - \sin^2\theta)$$

The tuning that keeps θ small
protects the Higgs mass:

$$m_h \to 0 \quad \text{for} \quad \theta \to 0$$

Predictions from the Lattice:

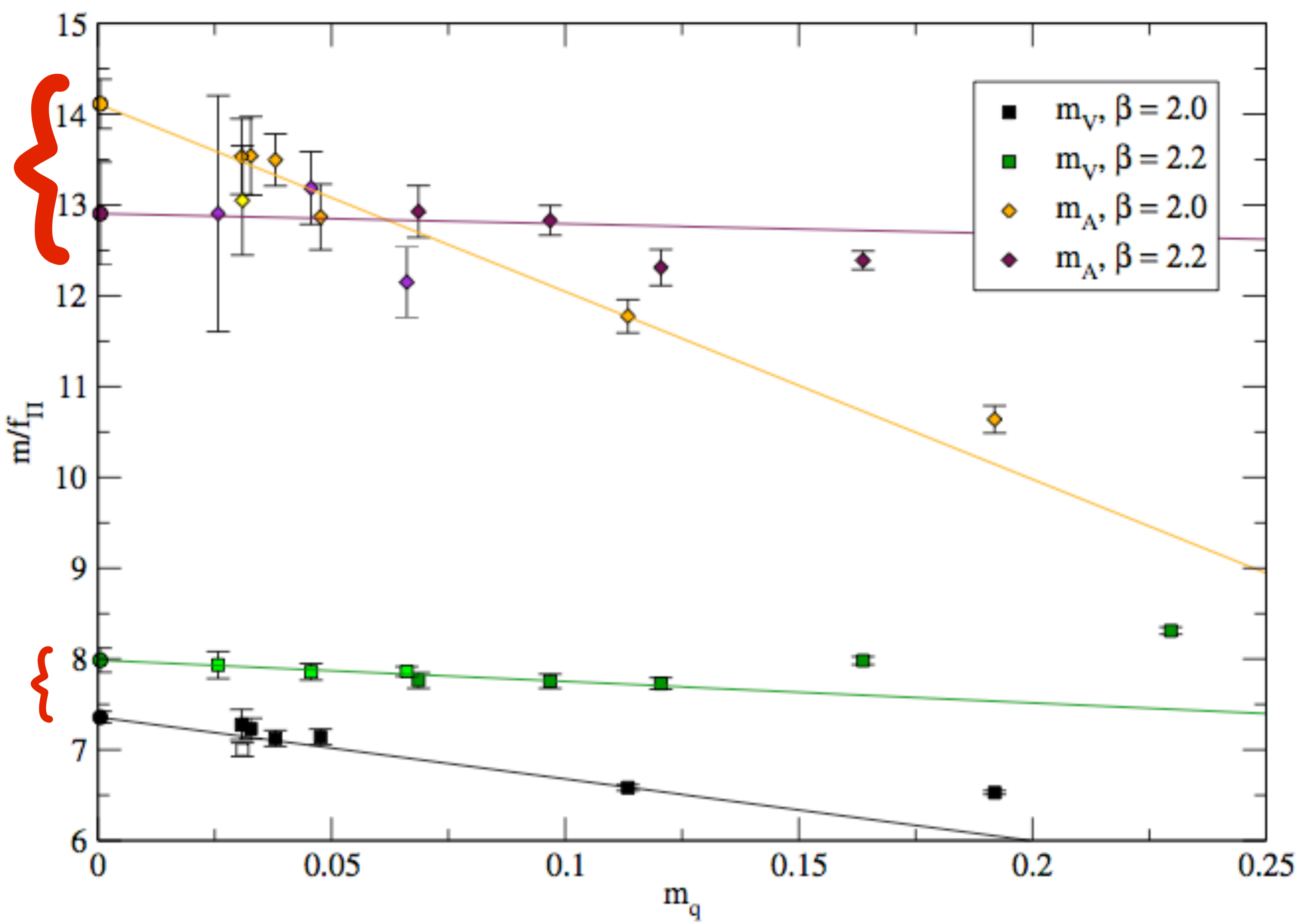


FIG. 6: The vector meson and axial vector meson masses in physical units. The chiral extrapolations have been performed using a linear fit to the points where $m_q < 0.12$.

Lewis, Pica, Sannino 1109.3513
+ Hietanen 1404.2794

Predictions from the Lattice:

Spectrum:

vector resonances

ρ and a

$$m_a = \frac{3.3 \pm 0.7}{\sin\theta}\ \text{TeV}$$

$$m_\rho = \frac{2.5 \pm 0.5}{\sin\theta}\ \text{TeV}$$

Lattice results!

scalar singlet

$$m_\eta = \frac{m_H}{\sin\theta}$$

Higgs

$$m_H = 125\ \text{GeV}$$

Not a prediction!

Predictions from the Lattice:

No light top partners are needed to cancel the top loop!

For sin θ = 0.2 (typical value):

vector resonances ρ and a

$$m_a = 16.5 \pm 3.5 \text{ TeV}$$

$$m_\rho = 12.5 \pm 2.5 \text{ TeV}$$

Lattice results!

scalar singlet $m_\eta = 625 \text{ GeV}$

Higgs $m_H = 125 \text{ GeV}$ Not a prediction!

A slide on the θ = π/2 vacuum:

$$
\begin{aligned}
f^2\,\mathrm{Tr}(D_\mu\Sigma)^\dagger D^\mu\Sigma \;=\;& \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}(\partial_\mu \eta)^2 \\
&+\frac{1}{48 f^2}\left[-(h\partial_\mu\eta - \eta\partial_\mu h)^2\right] + \mathcal{O}(f^{-3}) \\
&+\left(2g^2 W_\mu^+ W^{-\mu} + (g^2+g'^2)Z_\mu Z^\mu\right)\left[f^2 s_\theta^2 + \frac{s_{2\theta} f}{2\sqrt{2}} h\left(1 - \frac{1}{12 f^2}(h^2+\eta^2)\right)\right. \\
&\left. - \frac{1}{8}(c_{2\theta} h^2 + s_\theta^2 \eta^2)\left(1 - \frac{1}{24 f^2}(h^2+\eta^2)\right) + \mathcal{O}(f^{-3})\right] . \qquad (25)
\end{aligned}
$$

h + i η charged under a global unbroken U(1)

Candidate for asymmetric Dark Matter

$$m_{DM}^2 = C_t \frac{{y'_t}^2 f^2}{4} = C_t \frac{m_t^2}{4}$$

Generic θ:

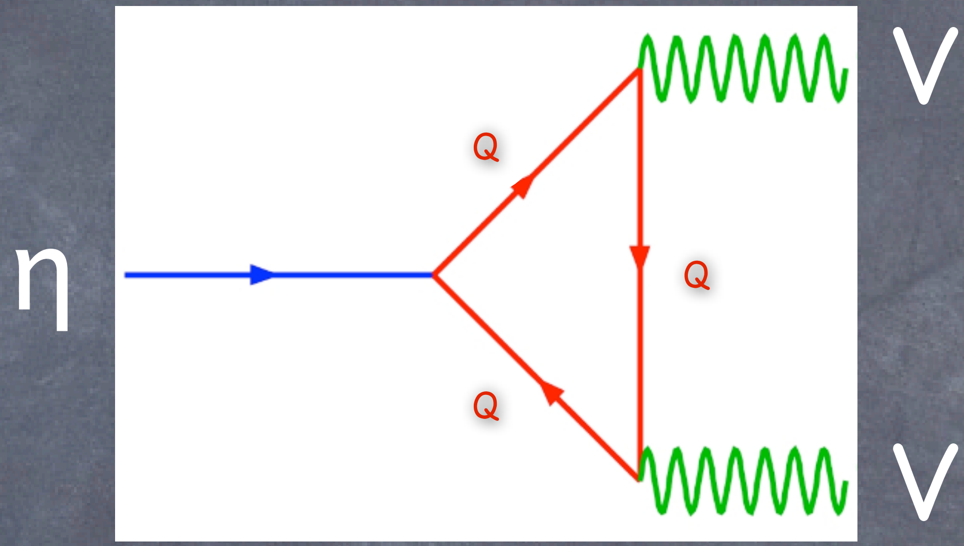
$$
\begin{aligned}
f^2\,\mathrm{Tr}(D_\mu\Sigma)^\dagger D^\mu\Sigma = & \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}(\partial_\mu \eta)^2 \\
& + \frac{1}{48 f^2}\left[-(h\partial_\mu\eta - \eta\partial_\mu h)^2\right] + \mathcal{O}(f^{-3}) \\
& + \left(2g^2 W_\mu^+ W^{-\mu} + (g^2 + g'^2) Z_\mu Z^\mu\right)\left[f^2 s_\theta^2 + \frac{s_{2\theta} f}{2\sqrt{2}} h \left(1 - \frac{1}{12 f^2}(h^2+\eta^2)\right)\right. \\
& \left. + \frac{1}{8}(c_{2\theta} h^2 - s_\theta^2 \eta^2)\left(1 - \frac{1}{24 f^2}(h^2+\eta^2)\right) + \mathcal{O}(f^{-3})\right] . \qquad (25)
\end{aligned}
$$

η has no linear couplings:
Candidate for Dark Matter?

Frigerio, Pomarol, Riva, Urbano
1204.2808

NO!

Once a dynamical theory is defined,
η can decay via the "chiral" anomaly:

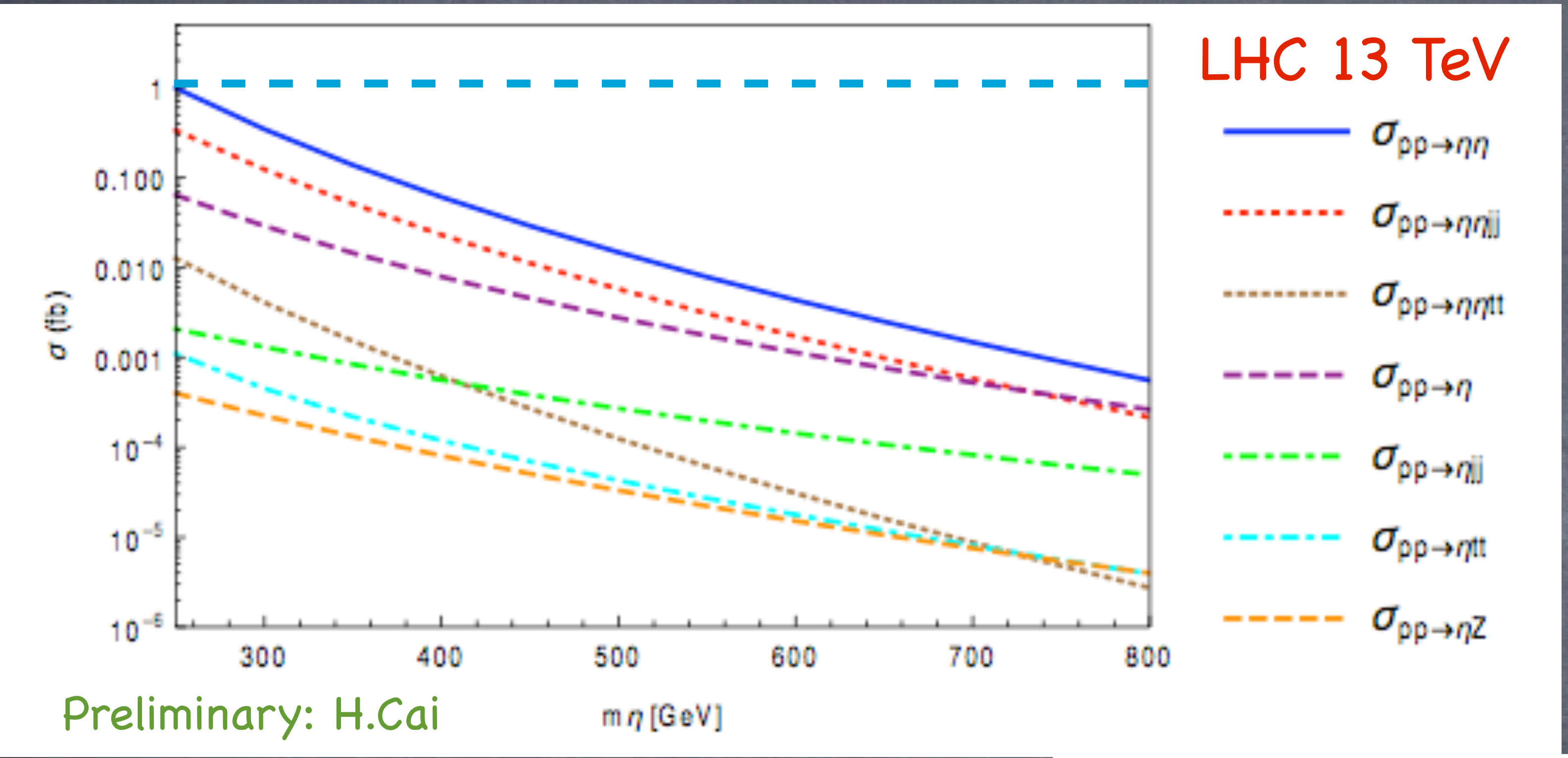


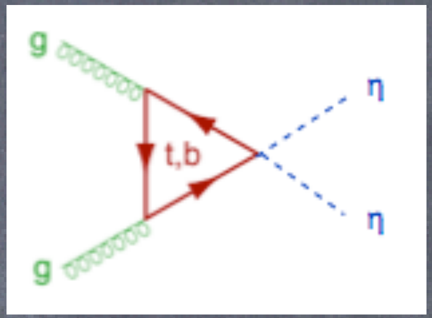
dimension of Q under confining group

$$\mathcal{L}_{WZW} = \frac{d_R}{48\pi^2} \frac{\cos\theta}{2\sqrt{2}f}\, \eta \left(g^2 W^{\mu\nu}\tilde{W}_{\mu\nu} - g'^2 B^{\mu\nu}\tilde{B}_{\mu\nu} \right) + \ldots$$

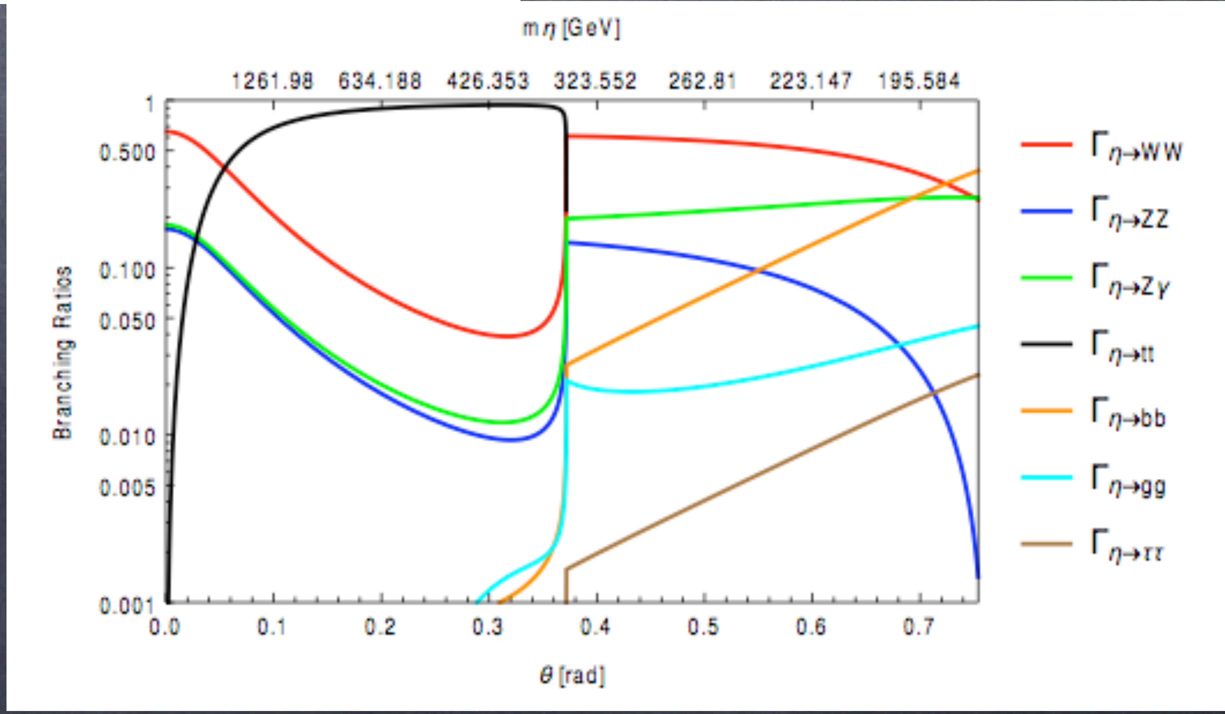
$\eta \rightarrow W\,W,\ ZZ,\ Z\gamma$

The singlet at the LHC:





- The cross sections are too feeble to be observable at the LHC!



Dynamics of partial compositeness

- If the top mass is generated by a 4-Fermi operator (à la ETC), one will also have FCNC operators in the SM:

$$\frac{QQ\, q_L q_R^c}{\Lambda_{ECT}^2} \Rightarrow \frac{q_L q_R^c\, q_L q_R^c}{\Lambda_{ECT}^2}$$

- Way-out: assuming coupling to composite fermions

$$\epsilon_L\, q_L \Psi_L + \epsilon_R\, q_R \Psi_R + \langle QQ \rangle \Psi_L \Psi_R$$

How to define a dynamical model with composite fermions?

Dynamics of partial compositeness

	SU(4) x SU(6)	Sp(4) x SO(6)	SU(3)c x SU(2) x SU(2)
QQ	(6,1)	(1,1) (5,1)	(1,1,1) (1,2,2) + (1,1,1)
FF	(1,21)	(1,1) (1,20)	(1,1,1) (8,1,1) + (6,1,1) + ($\bar{6}$,1,1)
FQQ	(6,6)	(1,6) (5,6)	(3,1,1) + ($\bar{3}$,1,1) (3,2,2) + (3,1,1) + ($\bar{3}$,2,2) + ($\bar{3}$,1,1)
F$\bar{Q}\bar{Q}$	(6,6)	(1,6) (5,6)	(3,1,1) + ($\bar{3}$,1,1) (3,2,2) + (3,1,1) + ($\bar{3}$,2,2) + ($\bar{3}$,1,1)
$\bar{F}\bar{Q}$Q	(1,$\bar{6}$)	(1,6)	(3,1,1) + ($\bar{3}$,1,1)
$\bar{F}\bar{Q}$Q	(15,$\bar{6}$)	(5,6) (10,6)	(3,2,2) + (3,1,1) + ($\bar{3}$,2,2) + ($\bar{3}$,1,1) (3,2,2) + (3,3,1) + (3,1,3) + + ($\bar{3}$,2,2) + ($\bar{3}$,3,1) + ($\bar{3}$,1,3)

Conclusions

Credit: darkroom.baltimoresun.com

We still do not know what is hiding behind the Higgs boson!

- I presented a very simple model of composite Higgs (pNGB)
- which is still viable experimentally
- and we have Lattice calculations of the spectrum.
- <u>No light top partners are needed!</u>
- <u>The smoking guns are additional light scalars (pNGB) - maybe one DM candidate</u>

Bonus track

“Pion” matrix:

$$\Sigma = e^{\frac{i}{f}(hY^4+\eta Y^5)} \cdot \langle QQ \rangle$$

$$= \left[\cos\frac{\sqrt{h^2+\eta^2}}{2\sqrt{2}f}\,1 + \frac{2\sqrt{2}i}{\sqrt{h^2+\eta^2}}\sin\frac{\sqrt{h^2+\eta^2}}{2\sqrt{2}f}\,(hY^4+\eta Y^5)\right]\cdot\langle QQ\rangle$$

Chiral lagrangian:

$$\begin{aligned} f^2\,\mathrm{Tr}(D_\mu\Sigma)^\dagger D^\mu\Sigma \;=\; & \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}(\partial_\mu \eta)^2 \\ & + \frac{1}{48 f^2}\left[-(h\partial_\mu\eta - \eta\partial_\mu h)^2\right] + \mathcal{O}(f^{-3}) \\ & + \left(2g^2 W^+_\mu W^{-\mu} + (g^2+g'^2)Z_\mu Z^\mu\right)\left[f^2 s_\theta^2 + \frac{s_{2\theta} f}{2\sqrt{2}} h\left(1 - \frac{1}{12 f^2}(h^2+\eta^2)\right)\right. \\ & \left. + \frac{1}{8}(c_{2\theta}h^2 - s_\theta^2\eta^2)\left(1 - \frac{1}{24 f^2}(h^2+\eta^2)\right) + \mathcal{O}(f^{-3})\right]\,. \qquad (25) \end{aligned}$$

$$m_W = \sqrt{2} g f \sin\theta = \frac{gv}{2} \Rightarrow v = 2\sqrt{2} f \sin\theta$$

Lagrangian invariant under η → -η : possible DM candidate?

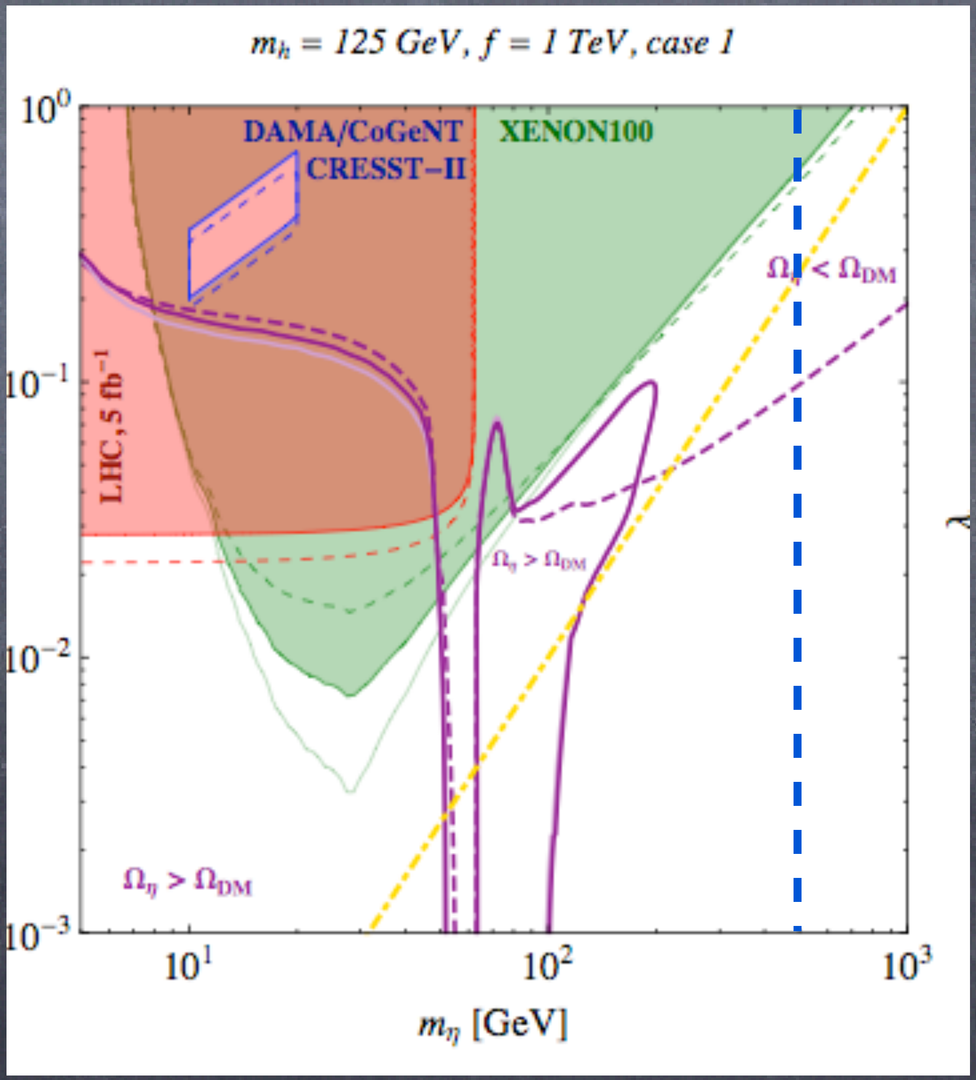
Can η be Dark Matter?

In principle yes:

Frigerio, Pomarol, Riva, Urbano
1204.2808

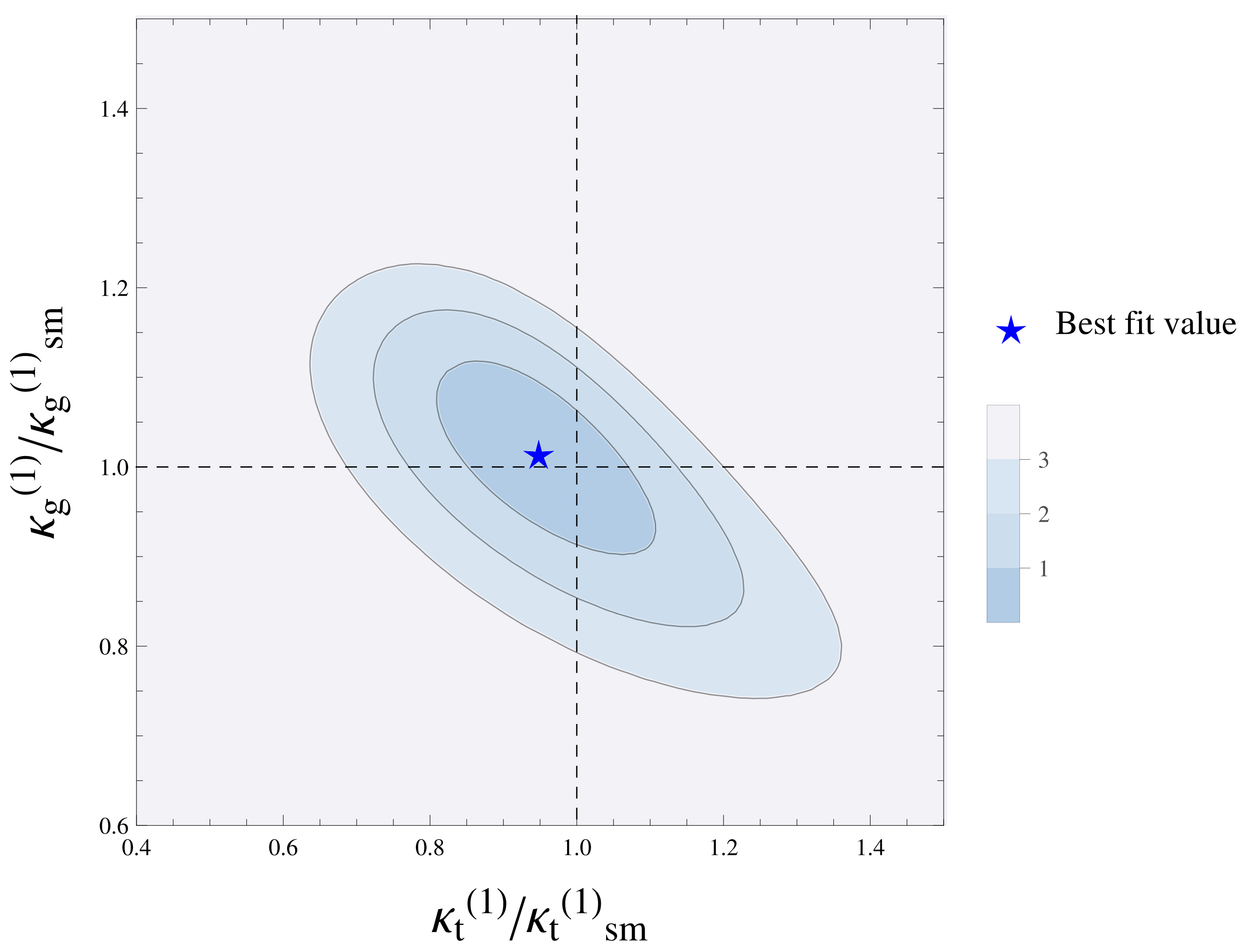
f = 350 GeV

$$\frac{g_{h\eta\eta}}{v}$$



Bounds from Higgs couplings

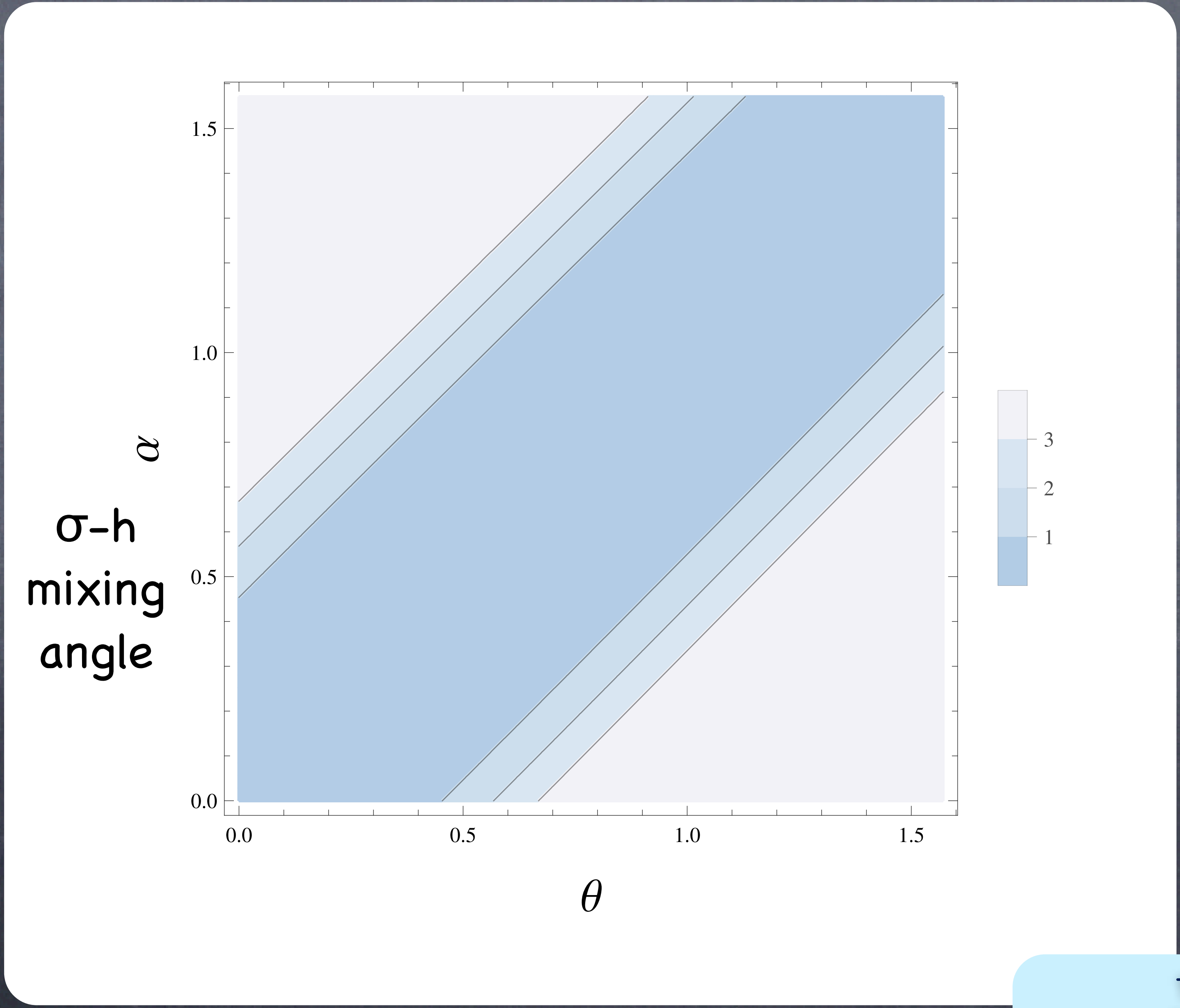
TC limit
$\theta = \pi/2$



Thanks to
S. Le Corre

Bounds from Higgs couplings

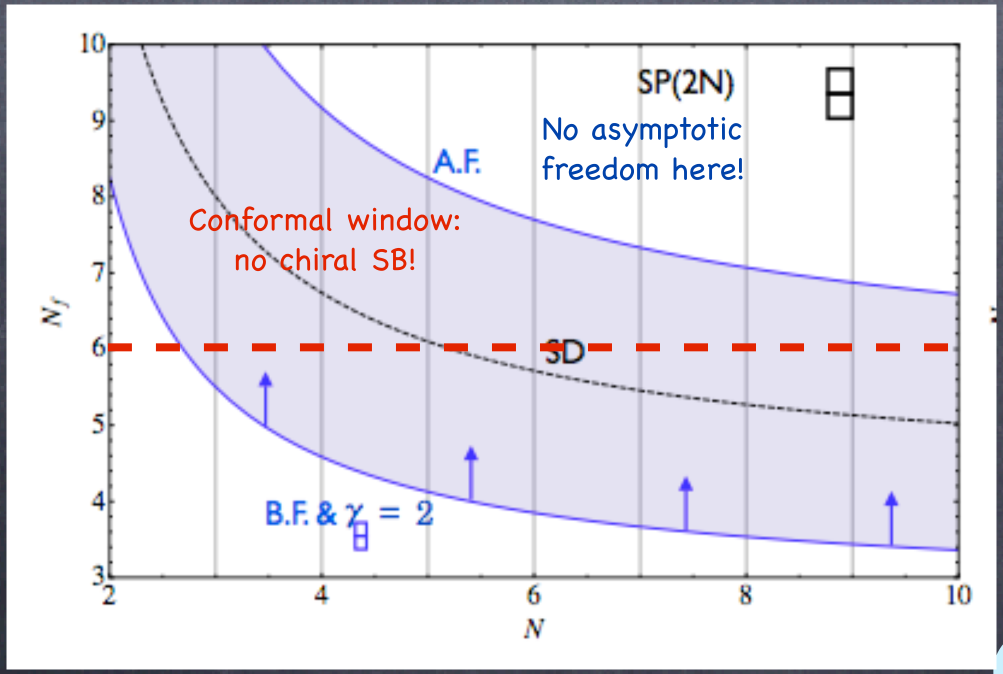
σ couplings at best fit values



Thanks to
S. Le Corre

Open questions:

- From the point of view of the dynamics, all spin-1/2 states have the same bound interactions: their masses should be very similar.
- How to decouple unwanted resonances (have large anomalous dimensions)?
- Coloured pNGB from FF may also be light: how do they affect the LHC phenomenology of top partners?
- Does the theory really form condensates?



Only G = Sp(4) seem to work!

Sannino 0902.3494

Dynamics of partial compositeness

$G = Sp(2N_c)$ with 4 Weyl fund. Q_i

General cases listed in Ferretti, Karateev 1312.5330

+ 6 two-index asymmetric F_k

Barnard, Gherghetta, Ray 1311.6562

Global "flavour" symmetries:

Q -> SU(4) containing $SU(2)_L \times U(1)_Y$

F -> SU(6) containing $SU(3)_c \times U(1)_Y$