Composite Higgses: non-minimal, Dark Matter and light T

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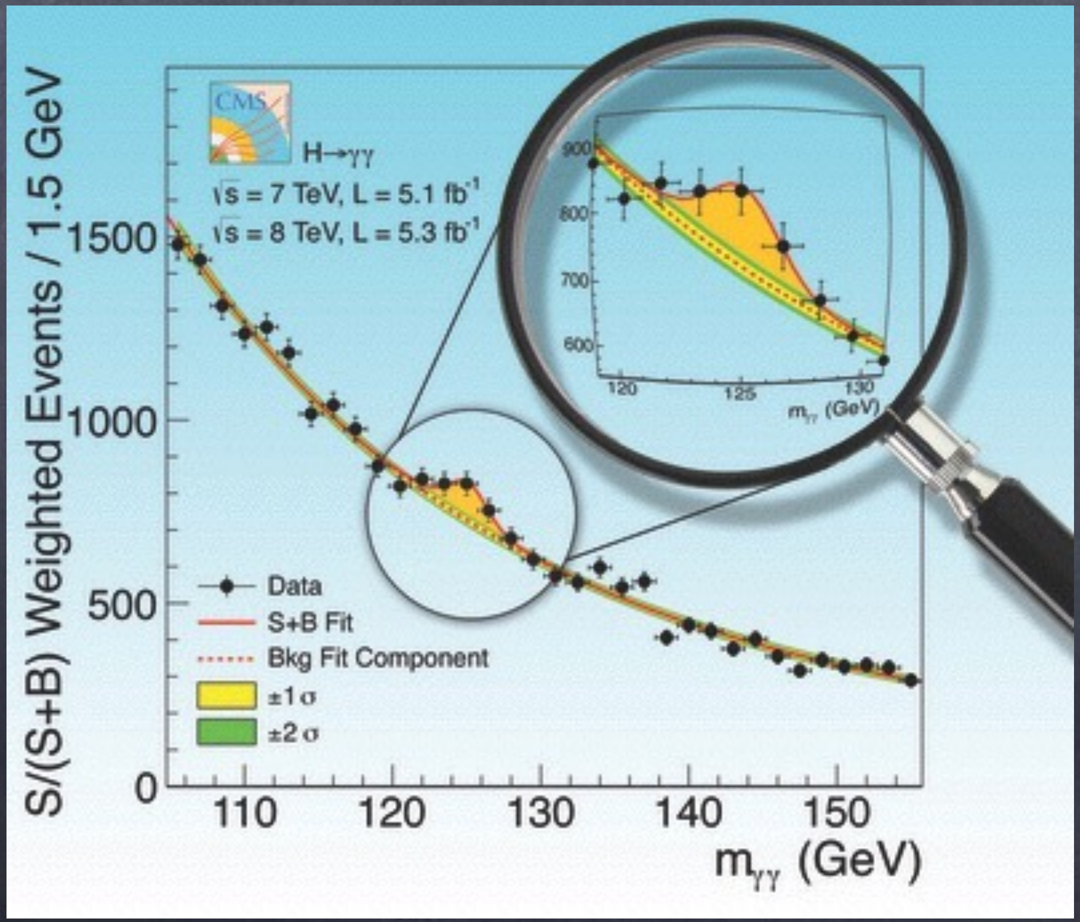
Monsieur le Higgs: enfin!

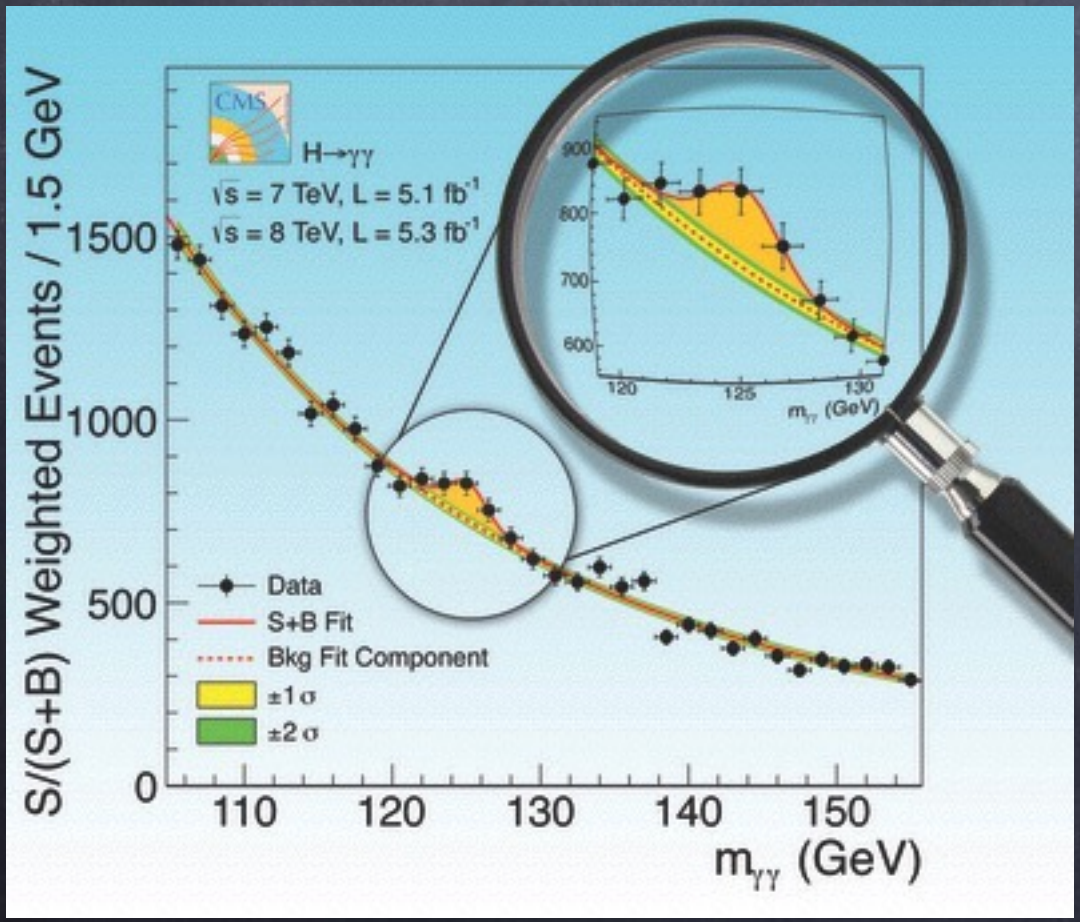


The Standard Model is finally complete!

(is it?)

Monsieur le Higgs: enfin!

...and the LHC crew is happy!

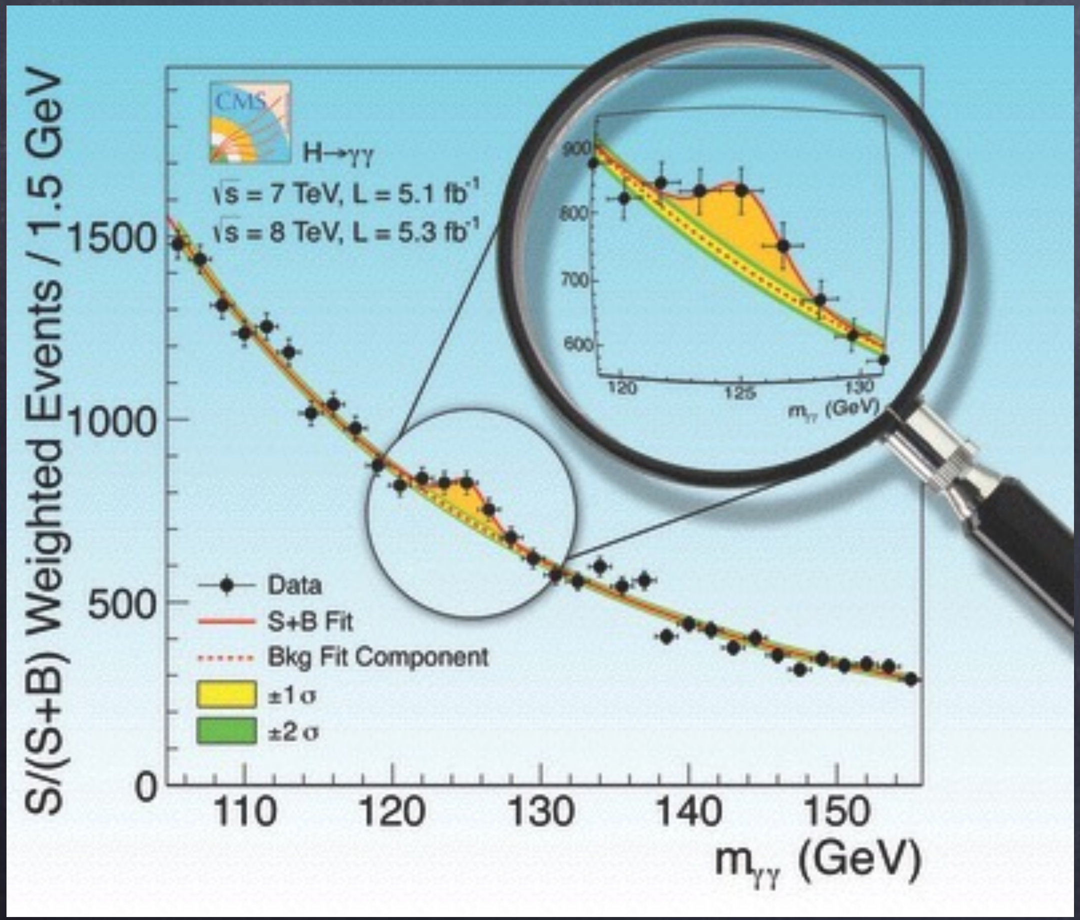


Monsieur le Higgs: enfin!

For a theorist, this is the beginning of a new era!

We have a new toy,

a new probe in the EW sector!



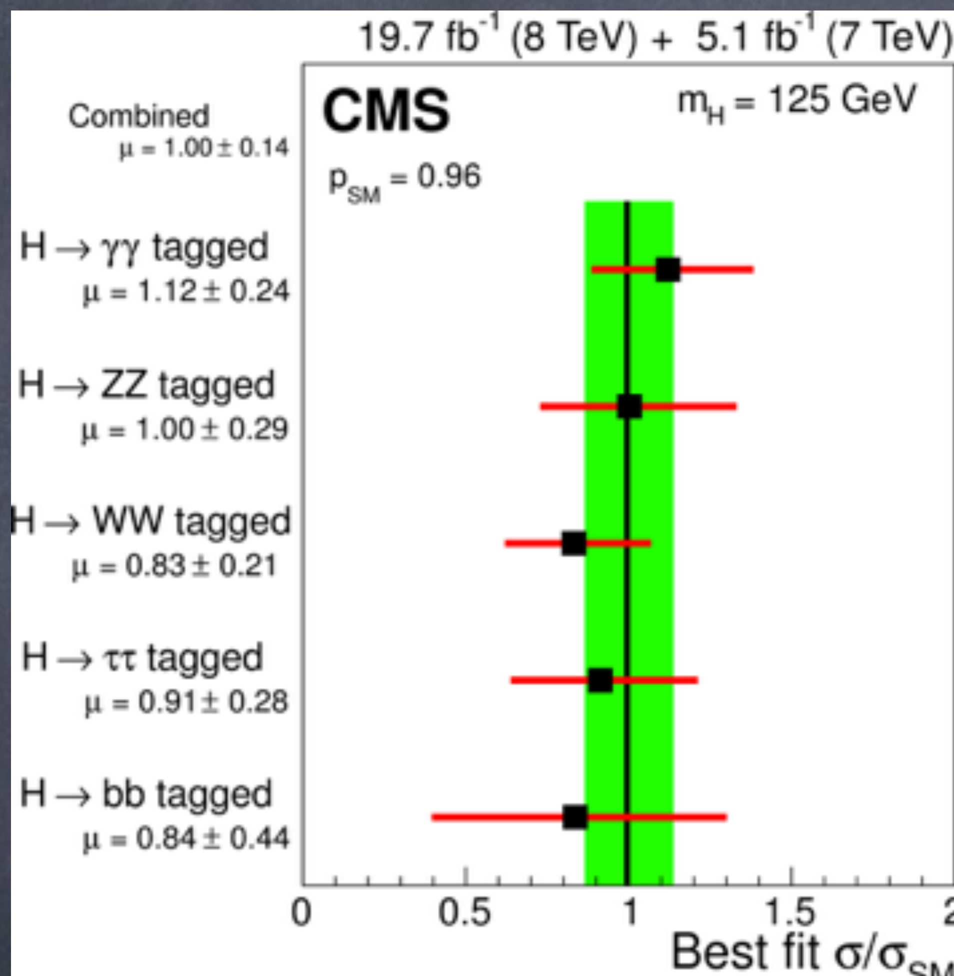
Do we still need BSM?

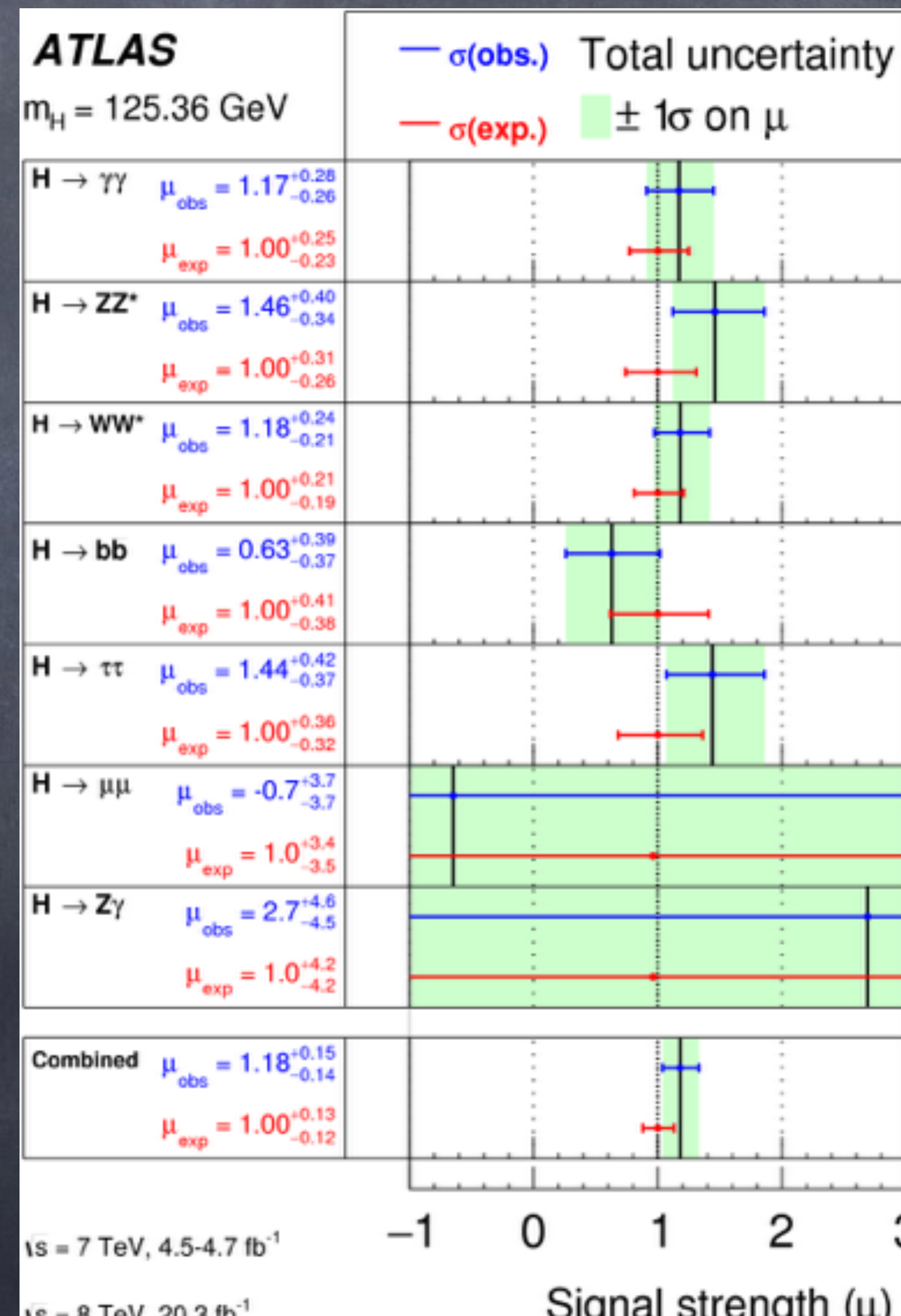
We have a pretty good idea of the mechanism

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?



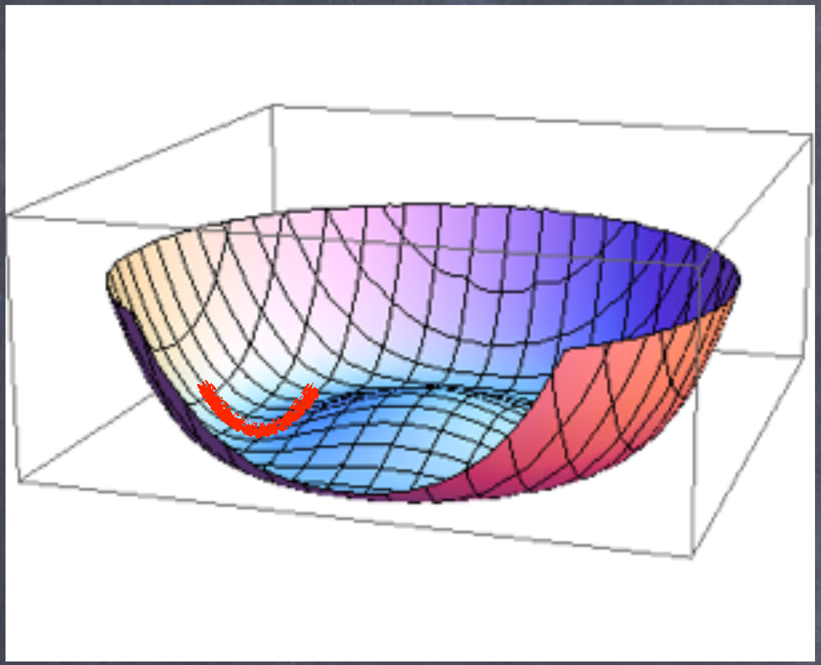


- Still large uncertainties on the Higgs coupling measurements.
- Ample space for BSM!!!!!

Outline:

- An old idea: compositeness
- Rediscovery of composite Higgses
- Back to the origins: fundamental composite dynamics (FCD) approach
- Non-minimal models, and Dark Matter

Compositeness, and the Higgs boson



Global symmetry of the system:

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

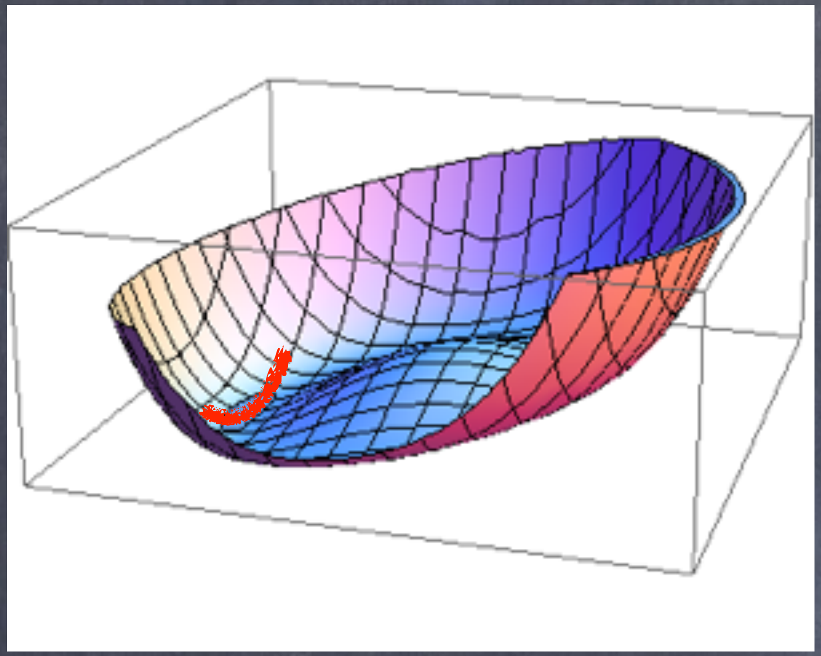
$$SU(2) \times U(1) \to U(1)_{\mathrm{em}}$$

SM gauge symmetry!

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



Global symmetry of the system:

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

$$SU(2) \times U(1) \to U(1)_{\rm em}$$

SM gauge symmetry!

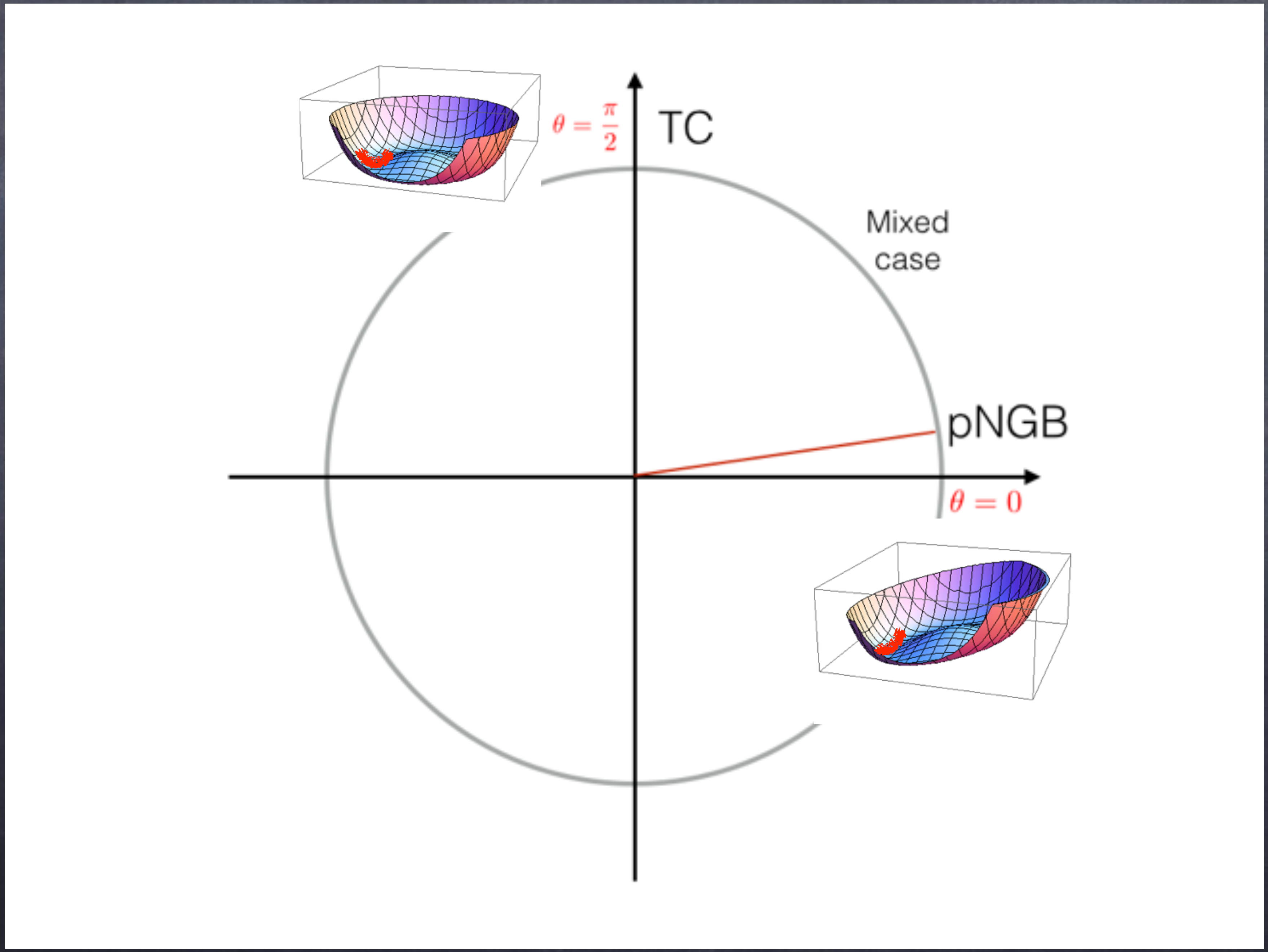
- Goldstones include the longitudinal d.o.f. of W and Z
- the Higgs is a pseudo-Goldstone

QCD template:

π pions

σ sigma

Compositeness, and the Higgs boson



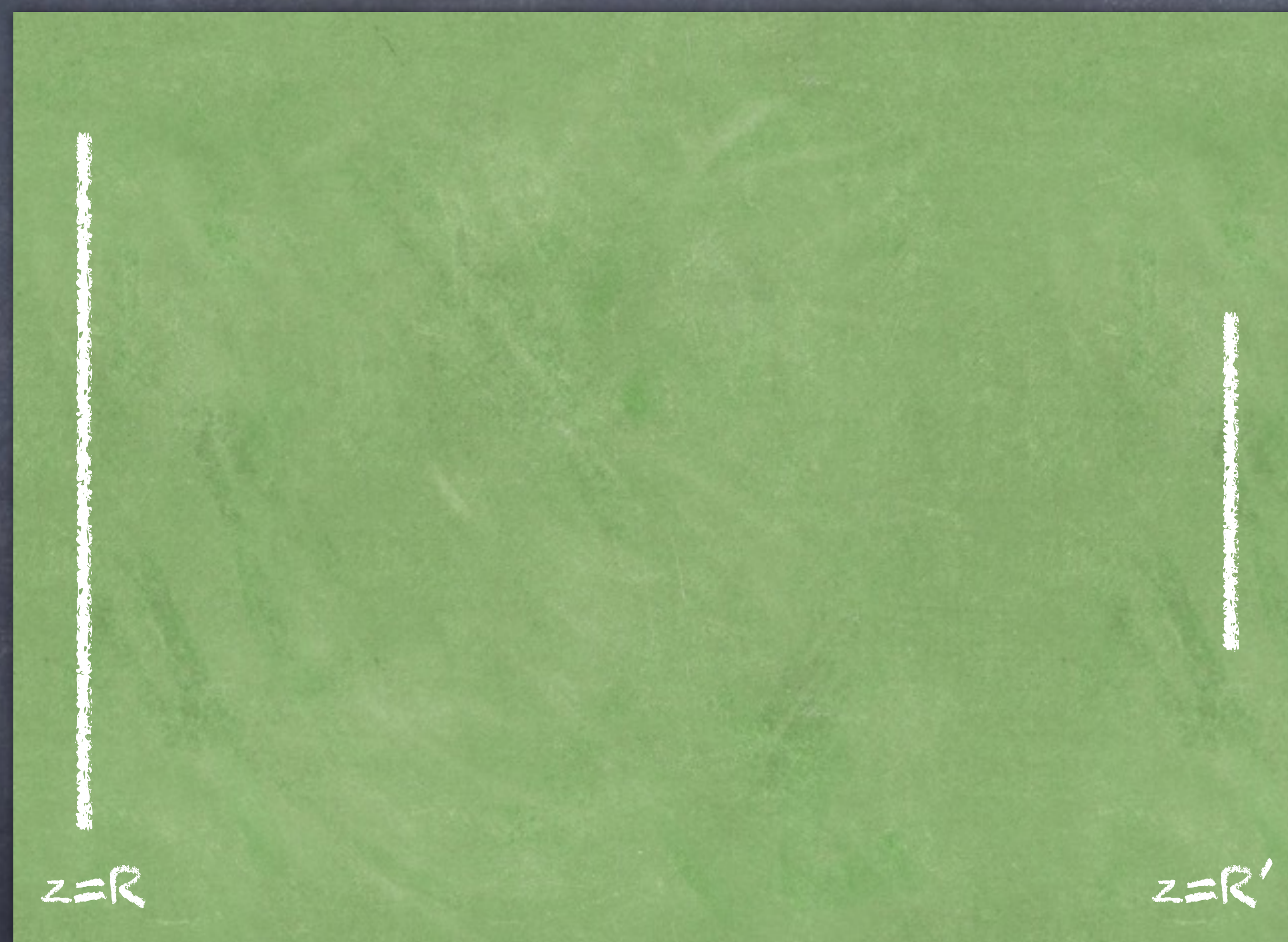
Higgs: p-Goldstone vs. sigma

- 👍 Mass is param. lighter that the compositeness scale
- 👍 The couplings to SM states are naturally close to SM
- 👎 Tuning the tilt in the potential!

- 👎 Mass is expected to be heavy (close to the rho)
- 👐 The couplings to SM states are Unknown!
- 👍 No tuning is necessary!

Rediscovery of composite Higgses

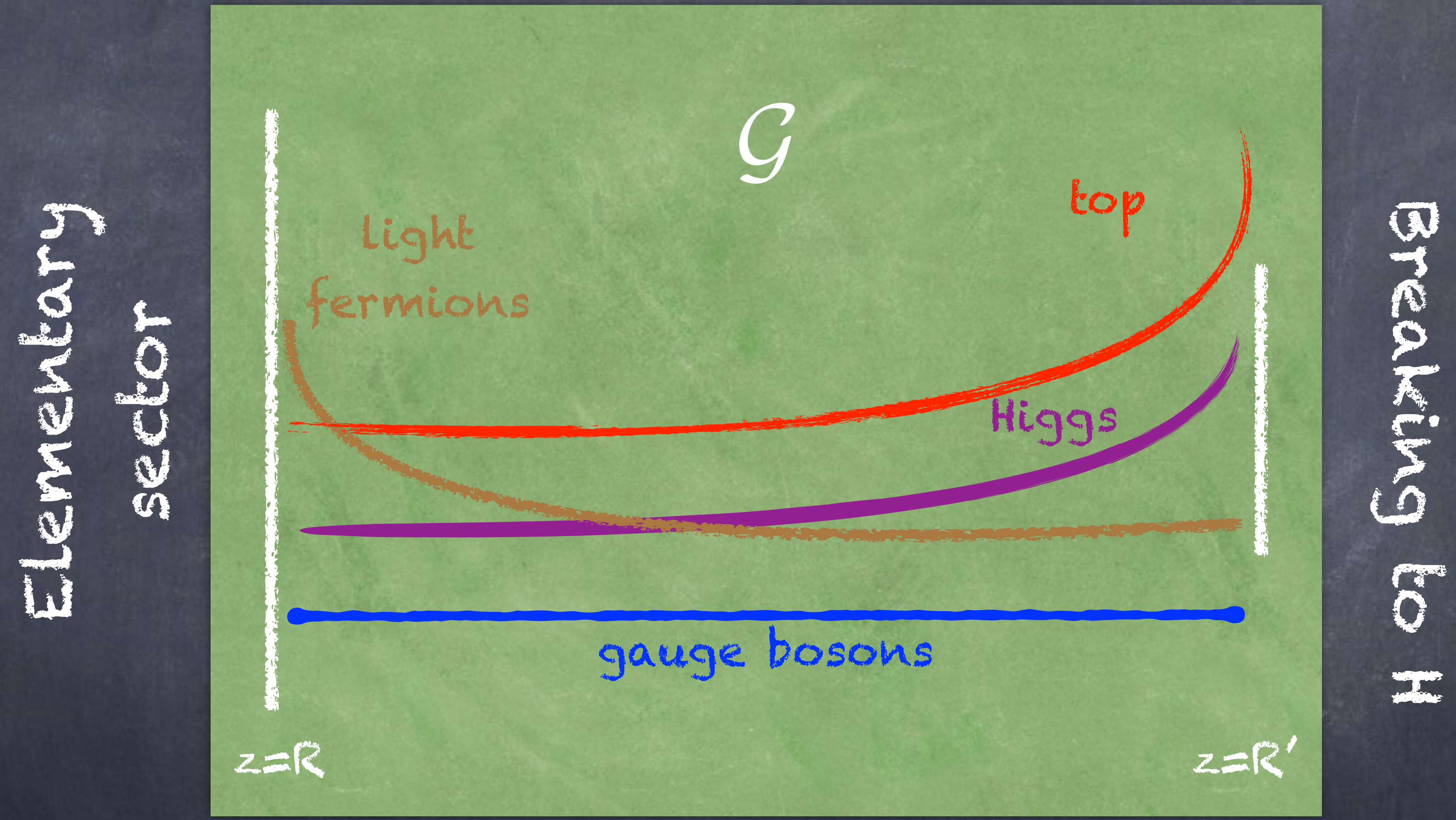
Randall Sundrum



$$ds^2 = \left(\frac{R}{z}\right)^2 \left(dx^2 - dz^2\right)$$

Rediscovery of composite Higgses

Randall Sundrum



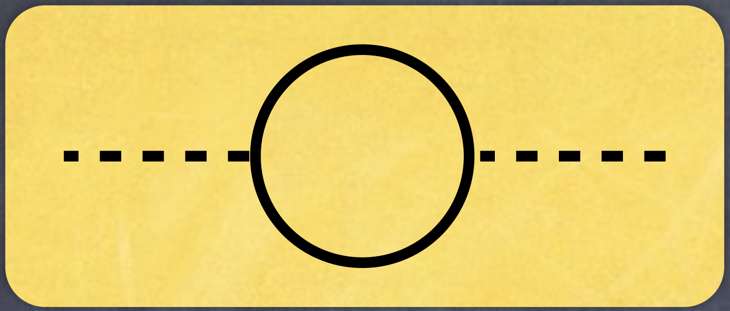
- Conformal dynamics
- UV-insensitive potential
- Fermion partial compositeness
- Flavour under control

Composite Higgses: which model?

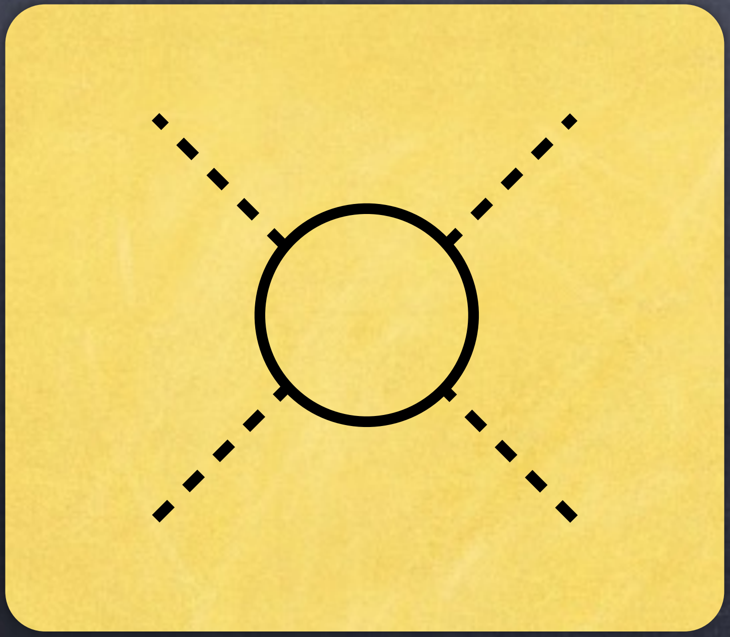
$\mathcal{G}$	$\mathcal{H}$	C	N_G	$\mathbf{r}_{\mathcal{H}} = \mathbf{r}_{\mathrm{SU(2)\times SU(2)}}\ (\mathbf{r}_{\mathrm{SU(2)\times U(1)}})$	Ref.
SO(5)	SO(4)	✓	4	$\mathbf{4} = (\mathbf{2},\mathbf{2})$	[11]
SU(3) × U(1)	SU(2) × U(1)		5	$\mathbf{2}_{\pm 1/2} + \mathbf{1}_0$	[10, 35]
SU(4)	Sp(4)	✓	5	$\mathbf{5} = (\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$	[29, 47, 64]
SU(4)	$[\mathrm{SU}(2)]^2 \times \mathrm{U}(1)$	✓*	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)	$[\mathrm{SU}(2)]^3$	✓*	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]
$[\mathrm{SU}(3)]^2$	SU(3)		8	$\mathbf{8} = \mathbf{1}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{3}_0$	[8]
$[\mathrm{SO}(5)]^2$	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]
$[\mathrm{SO}(6)]^2$	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 $\mathrm{SO}(4) \cong \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ (or simply $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ 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.

Anatomy of the potential

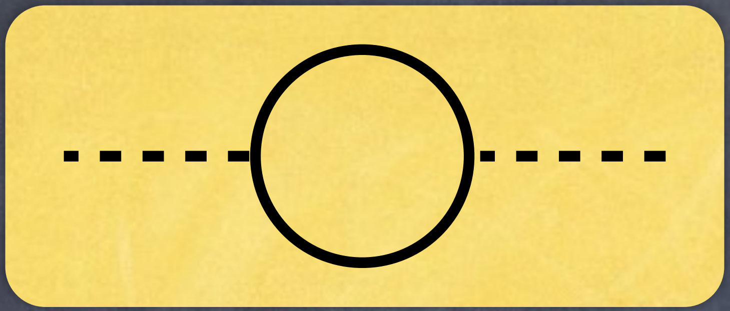


$$\delta m_h^2 \sim \frac{y^2}{16\pi^2}\Lambda^2$$



$$\delta\lambda \sim \frac{y^4}{16\pi^2}\log\Lambda$$

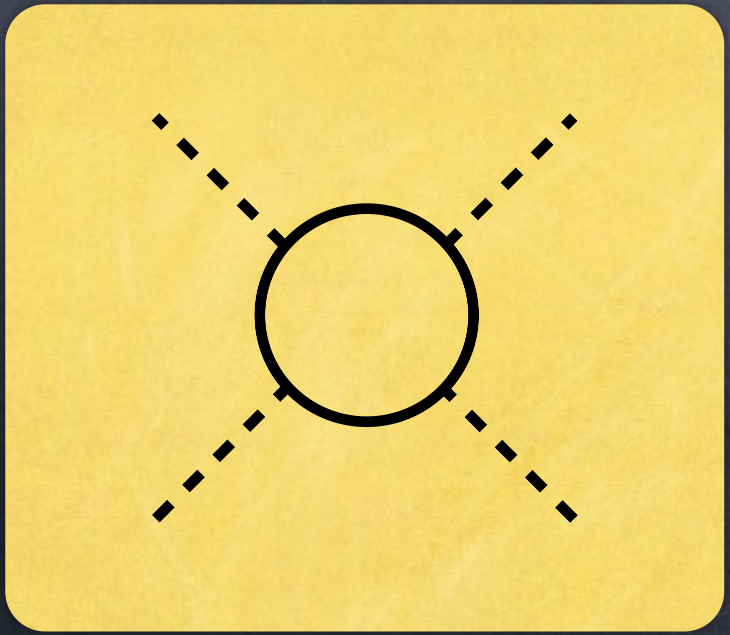
Anatomy of the potential



$$\delta m_h^2 \sim \frac{y^2}{16\pi^2}(4\pi f)^2 \sim y^2 f^2$$

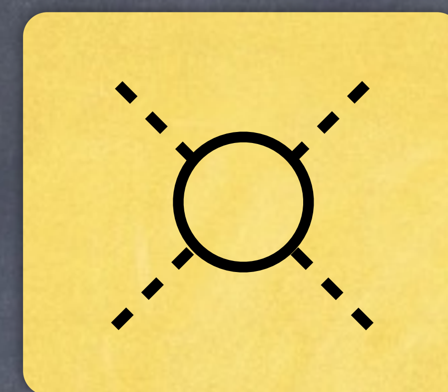
$$\Lambda \sim 4\pi f$$

Strong dynamics estimate



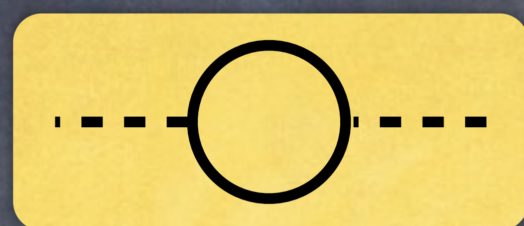
$$\delta\lambda \sim \frac{y^4}{16\pi^2}\log\Lambda$$

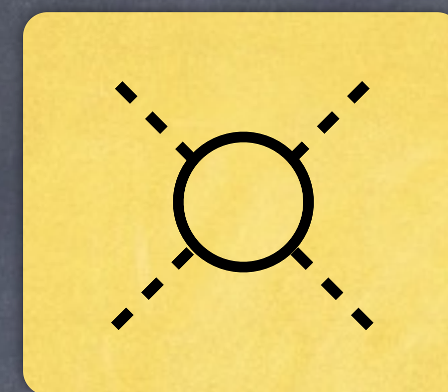
Anatomy of the potential



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

Anatomy of the potential

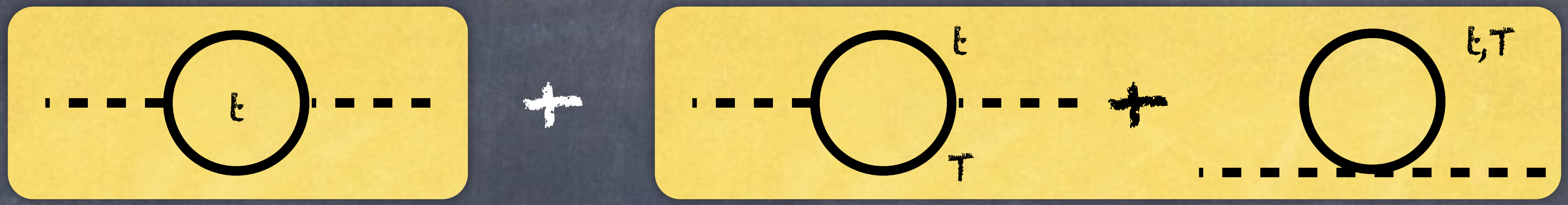




$$V \sim \alpha \sin^2\theta + \beta \sin^4\theta$$

Minimum: $$\theta \sim \frac{\pi}{2}$$

Anatomy of the potential



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

Minimum: $\theta \sim \epsilon$

Anatomy of the potential

Explicit symmetry breaking?

$$V \sim \alpha \sin^2\theta + \gamma \sin\theta$$

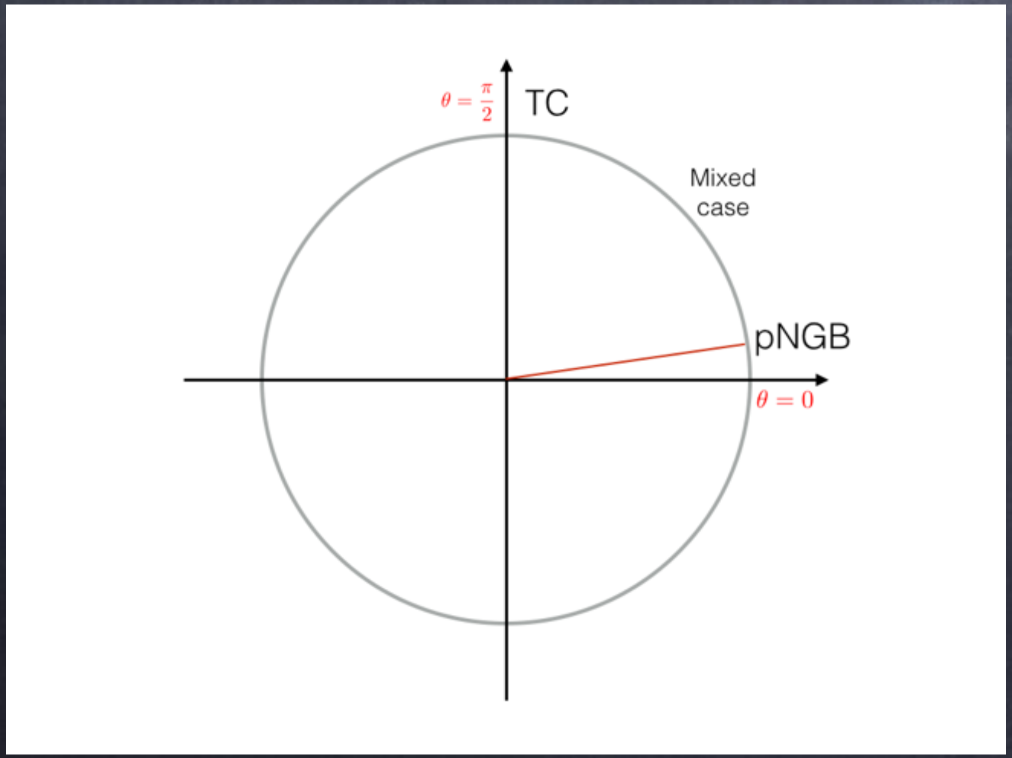
Minimum: $\theta \sim \epsilon$

Possible!

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 further fine tuning!

The FCD approach

G.C., F.Sannino
1402.0233

- Define a confining gauge group (GTC)
- Add in N fermions charged under the confining group GTC
- Assign SM quantum numbers to the fermions
- Couple them to SM fermions

The FCD approach

coset	GTC	TF	doublets	pNGBs	
SU(4)/Sp(4)	Sp(2N)	fund	1	5	← Minimal!
SU(5)/SO(5)	SU(4)	6	1	14	
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 minimal case

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

Anti-symmetric

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

Sp(4) contains a SO(4) subgroup:
identify with custodial symmetry!

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

The minimal case

Galloway, Evans, Luty, Tacchi 1001.1361
G.C., F.Sannino 1402.0233

$$V_m = C_m f^4 \mathrm{Tr}(\Sigma_B \cdot \Sigma)$$
$$\sim C_m \left(-4 f^4 c_\theta + \sqrt{2} f^3 s_\theta h + \frac{1}{4} f^2 c_\theta (h^2 + \eta^2) + \dots \right)$$

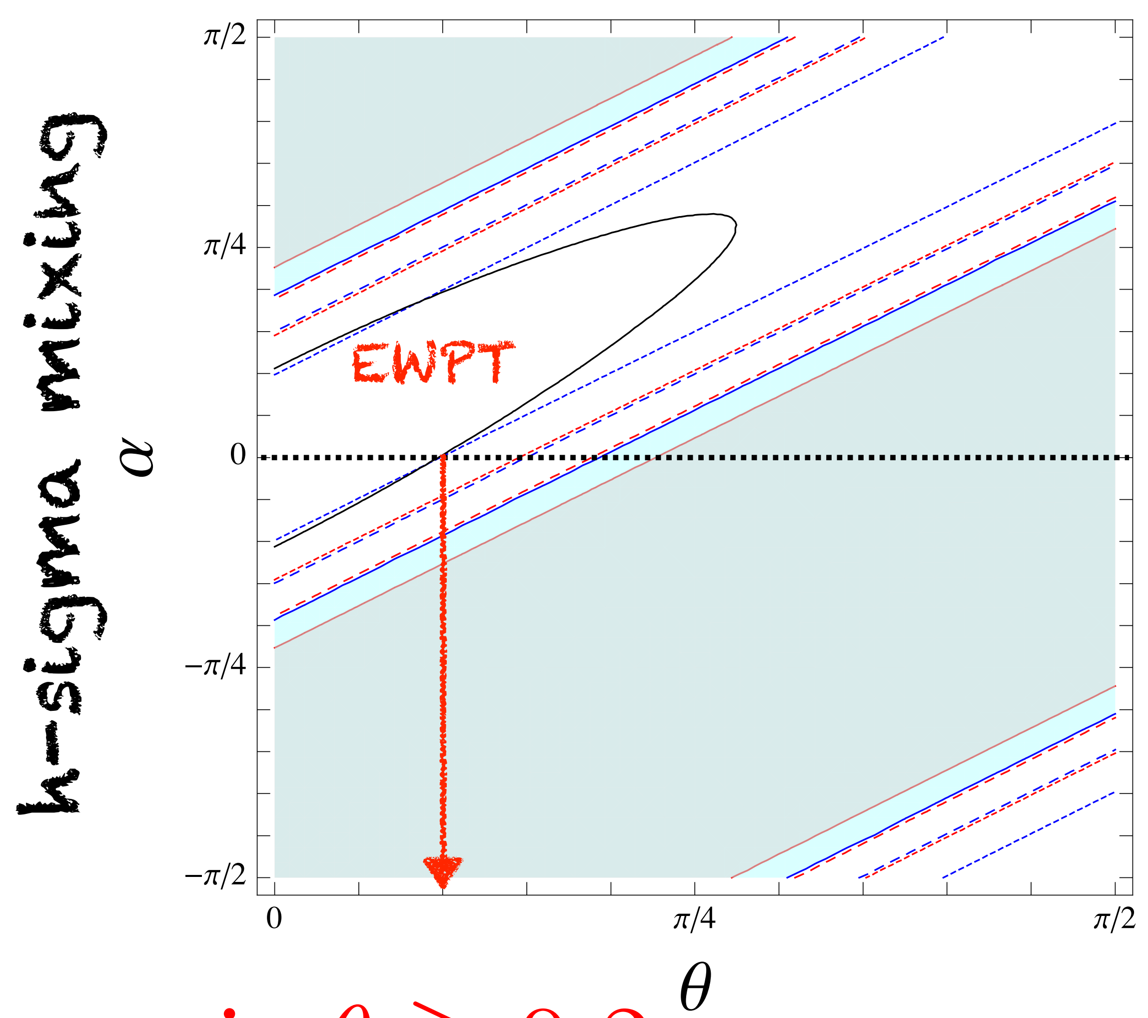
$$V_{top} = -C_t y_t'^2 f^4 \sum_{\alpha=1}^{2} [\mathrm{Tr}(P^\alpha \Sigma)]^2$$
$$\sim -C_t y_t'^2 \left[f^4 s_\theta^2 + \frac{1}{\sqrt{2}} f^3 c_\theta s_\theta h + \frac{1}{8} f^2 (c_{2\theta} h^2 - s_\theta^2 \eta^2) + \dots \right]$$

$$m_h \sim \frac{\sqrt{C_t}}{2} y_t f \sin\theta \sim \frac{\sqrt{C_t}}{2} m_t \qquad m_\eta \sim \frac{\sqrt{C_t}}{2} y_t f \sim \frac{m_h}{\sin\theta}$$

$C_t \sim 2$ reproduces data!

The minimal case

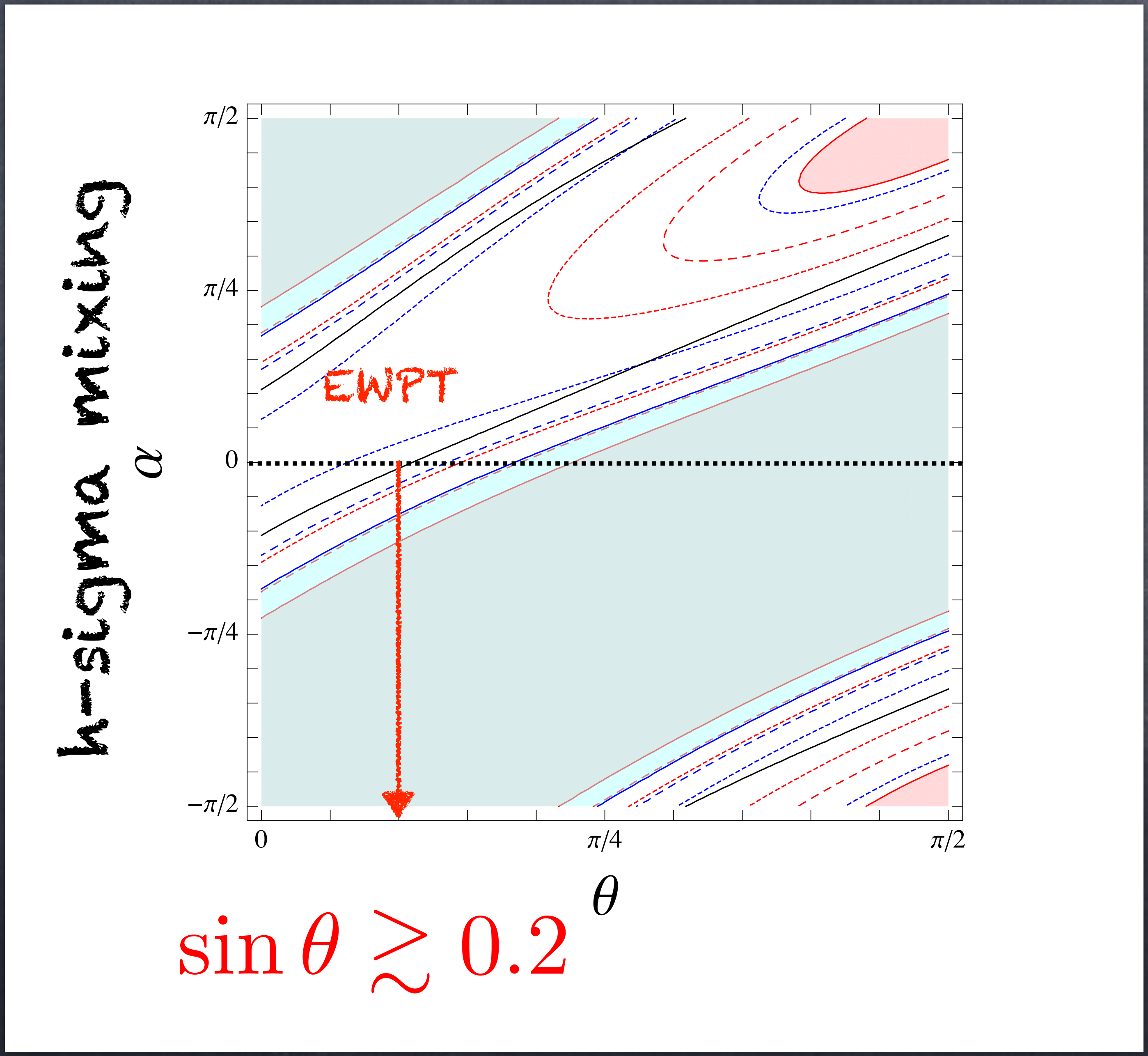
Arbey, G.C., Cai, Deandrea, Le Corre, Sannino
1502.04718



$\sin\theta \gtrsim 0.2$

The minimal case

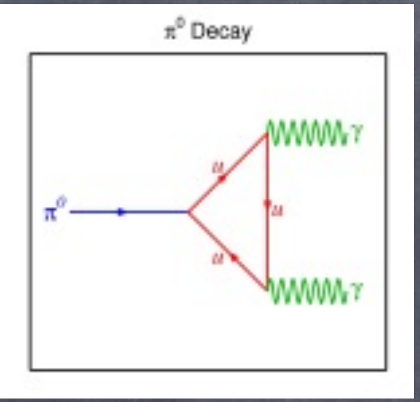
Arbey, G.C., Cai, Deandrea, Le Corre, Sannino
1502.04718



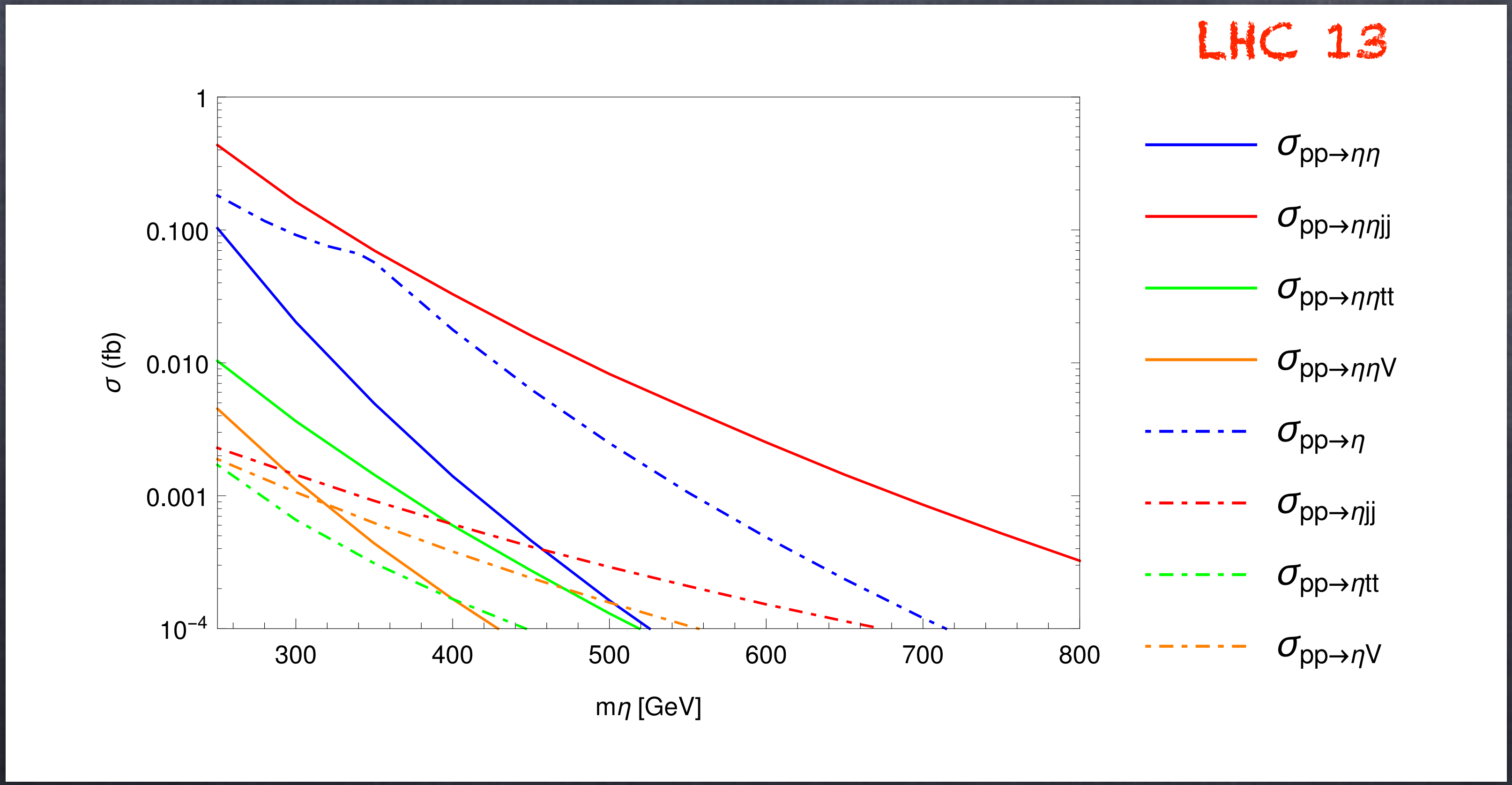
The minimal case

Arbey, G.C., Cai, Deandrea, Le Corre, Sannino
1502.04718

Singlet cannot be Dark Matter!



Anomalous coupling to: WW, ZZ, Z gamma



The minimal case

Lattice results:

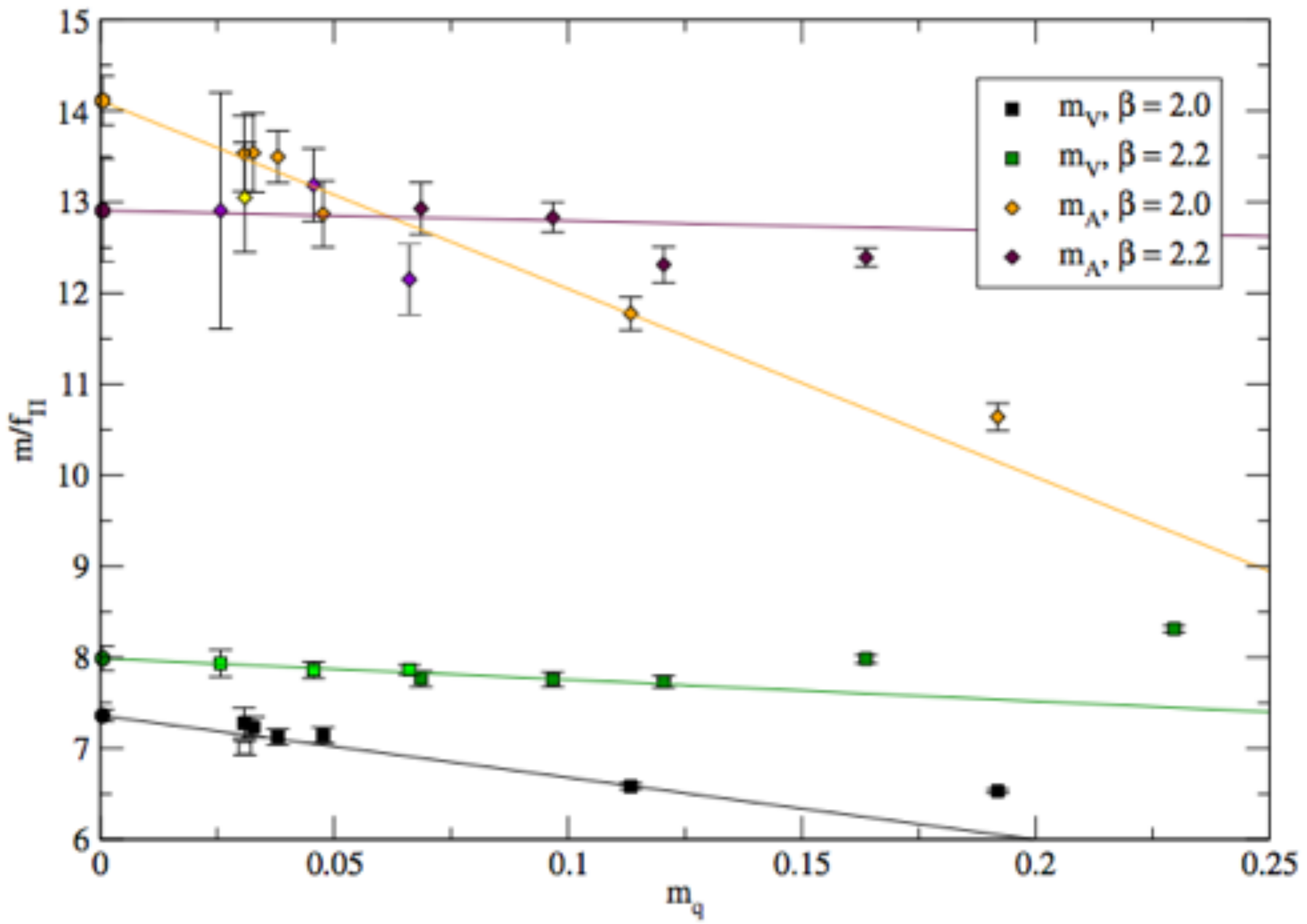


FIG. 6: The vector meson and axial vector meson masses in physical units. The chiral extrapolations have been performed using a linear fit to the points where $m_q < 0.12$.

$$m_a \sim \frac{3\ TeV}{\sin\theta} \gtrsim 15\ TeV$$

$$m_\rho \sim \frac{2.5\ TeV}{\sin\theta} \gtrsim 12\ TeV$$

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

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

$$m_h = 125\ GeV$$

A composite 2HDM

G.C., T.Ma
1508.07014

	SU(N)	SU(2)$_L$	U(1)$_Y$
$\psi_L = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$	$\square$	**2**	0
$\psi_R = \begin{pmatrix} \psi_3 \\ \psi_4 \end{pmatrix}$	$\square$	**1** **1**	1/2 -1/2

$$\mathcal{L}_{FCD} = i\bar{\psi} D_\mu \gamma^\mu \psi - \bar{\psi} M_Q \psi$$

$$\Pi = \frac{1}{2}\begin{pmatrix} \sigma_i \Delta^i + s/\sqrt{2} & -i\Phi_H \\ i\Phi_H^\dagger & \sigma_i N^i - s/\sqrt{2} \end{pmatrix}$$

A composite 2HDM

G.C., T.Ma
1508.07014

$$V_{\rm top}(\theta) = -C_t f^4 \Big[8|Y_t|^2 \sin^2\theta +$$

← Potential for theta

$$2\sqrt{2}|Y_t|^2 \sin(2\theta)\, \frac{h_1}{f} +$$

$$+4\sqrt{2}\, \mathrm{Im}(Y_D^* Y_t) \sin\theta\, \frac{h_2}{f}$$

$$+2\sqrt{2}\, \mathrm{Re}(Y_D^* Y_t) \sin(2\theta)\, \frac{A_0}{f}$$

$$+ 4\, \mathrm{Im}(Y_T^* Y_t) \sin^2\theta\, \frac{N_0 + \Delta_0}{f} + \ldots \Big]$$

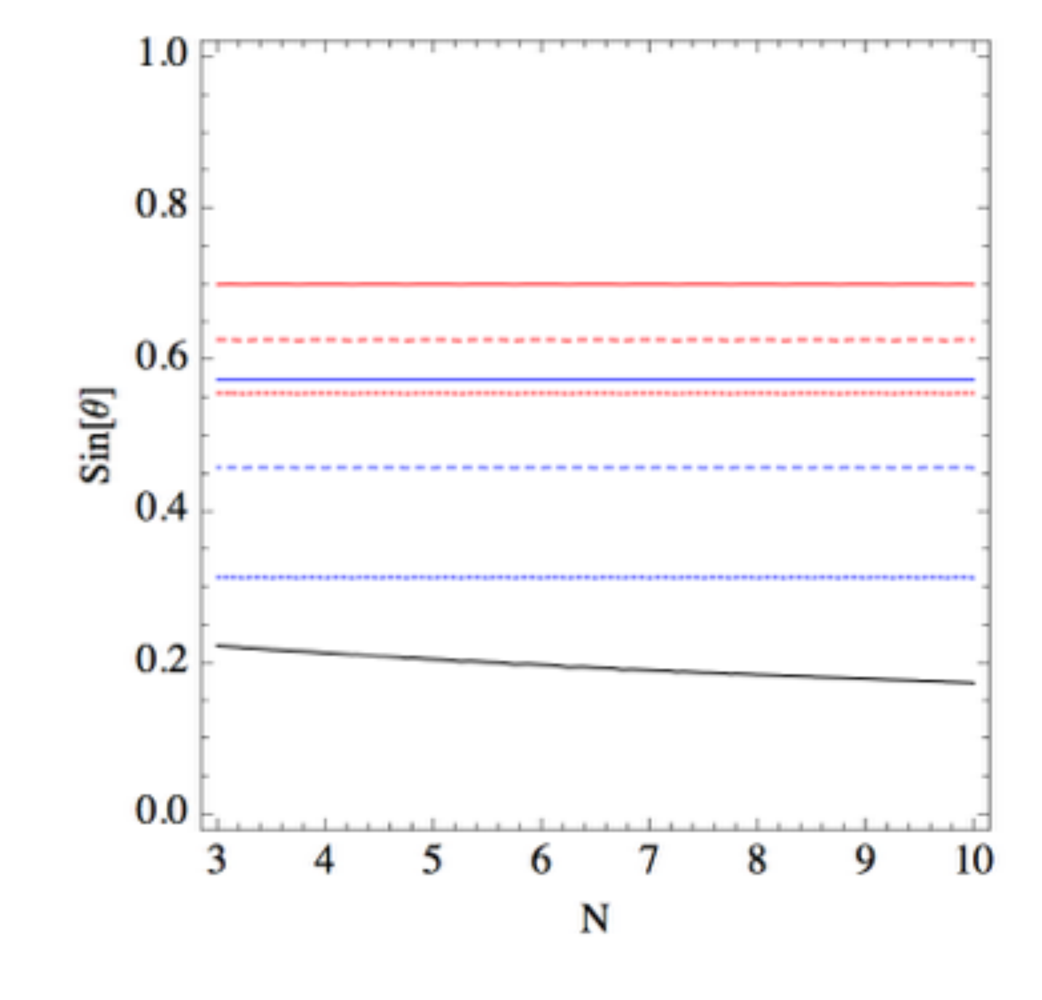
A composite 2HDM: EWPTs

$$\Delta S_{\text{Higgs}} = \frac{1-\kappa_V^2}{6\pi}\ln\frac{\Lambda_{FCD}}{m_h}\,, \quad \Delta T_{\text{Higgs}} = -\frac{3(1-\kappa_V^2)}{8\pi\cos^2\theta_W}\ln\frac{\Lambda_{FCD}}{m_h}\,,$$

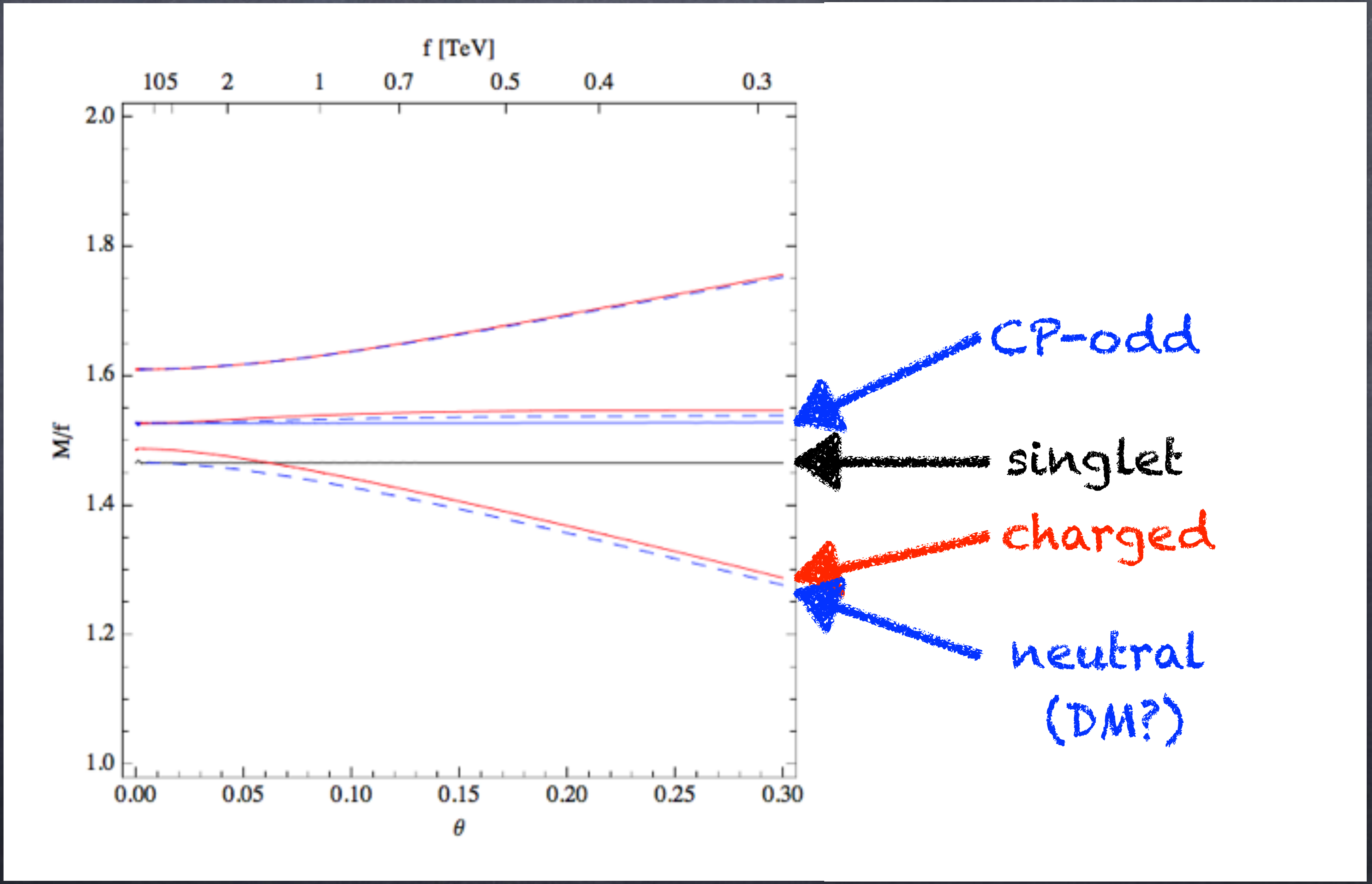
$$\Delta S_{pNGB} = -\frac{\sin^2\theta}{4\pi}\,, \quad \Delta T_{pNGB} = \frac{\sin^2\theta}{8\pi\sin^2\theta_W}\frac{m_{H\pm}^2 - m_{A_0}^2}{m_W^2}\ln\frac{\Lambda_{FCD}}{m_{pNGB}} \sim 0\,,$$

$$\Delta S_{FCD} = \frac{\sin^2\theta}{3\pi}N\,, \qquad \Delta T_{FCD} \sim 0\,,$$

Bounds similar to minimal cases.



A composite 2HDM: spectrum



The hot potato: flavour!

1501.03818
G.C., H.Cai, T.Flacke, S.J.Lee, A.Parolini, H.Serodio

100.000 TeV	Λ_{flavour}	Light flavours	
		near-conformal dynamics	
10 TeV	$\Lambda \sim 4\pi f$	Vectors	+ top mixing
1 TeV	f	Condensation scale (extra pions)	+ top partners
100 GeV	$v_{\text{SM}} \sim f \sin\theta$	EWSB	

The hot potato: flavour!

- In FCD, the origin of the top partial compositeness can be probed!

$$\frac{c}{\Lambda_{\rm top}^2}\, t\psi\psi\psi \to y_t\, tT$$

- Why are the top partners lighter than other resonances?

Light 't Hooft Top Partners

G.C., A.Parolini
1511.05163

	gauged	global symmetries		
	$Sp(2N_c)$	$SU(N_Q)$	$SU(N_\chi)$	$U(1)$
Q	$\square$	N_Q	1	1
χ	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	1	N_χ	$-\frac{N_Q}{2N_\chi(N_c-1)}$

TABLE I: Fermionic field content of the first model.

Barnard, Gherghetta, Ray 1311.6562
Ferretti, Karateev 1312.5330

- $\langle QQ \rangle \neq 0$ breaks $SU(N_Q) \to Sp(N_Q)$, giving a pNGB Higgs.
- In the vacuum $\langle \chi\chi \rangle = 0$, $SU(N_\chi)$ is unbroken.

$$A_{SU(N_\chi)^2} \propto dim(\chi) = (2N_c + 1)(N_c - 1)$$

Light 't Hooft Top Partners

G.C., A.Parolini
1511.05163

global symmetries

	$SU(N_Q)\times SU(N_\chi)$	$Sp(N_Q)\times SU(N_\chi)$	$d_{Sp(N_Q)}$
χQQ $\chi\bar{Q}\bar{Q}$	$(\mathbf{A},\mathbf{F})$ $(\mathbf{S},\mathbf{F})$	$(\mathbf{1},\mathbf{F})$ $(\mathbf{A},\mathbf{F})$ $(\mathbf{S},\mathbf{F})$	1 $\frac{N_Q(N_Q-1)}{2}-1$ $\frac{N_Q(N_Q+1)}{2}$
$\bar{\chi}\bar{Q}Q$	$(\mathbf{1},\bar{\mathbf{F}})$ $(\mathbf{Adj},\bar{\mathbf{F}})$	$(\mathbf{1},\bar{\mathbf{F}})$ $(\mathbf{A},\bar{\mathbf{F}})$ $(\mathbf{S},\bar{\mathbf{F}})$	1 $\frac{N_Q(N_Q-1)}{2}-1$ $\frac{N_Q(N_Q+1)}{2}$

$$A_{SU(N_\chi)^2} \propto dim(\chi) = (2N_c+1)(N_c-1)$$

- Matched if $N_Q = 2N_c$. For $N_Q = 4$, A = 5 of Sp(4) ~ SO(5)!!

...a few words on the diphoton excess

More precisely, the global symmetries are:

$$SU(N_Q) \times SU(N_\chi) \times U(1)_Q \times U(1)_\chi$$

$$\frac{\Gamma_{\sigma\to gg}}{\Gamma_{\sigma\to WW}} = 5.1 \ \ldots \ 3.3,$$
$$\frac{\Gamma_{\sigma\to ZZ}}{\Gamma_{\sigma\to WW}} = 0.29 \ \ldots \ 0.31,$$
$$\frac{\Gamma_{\sigma\to Z\gamma}}{\Gamma_{\sigma\to WW}} = 0.19 \ \ldots \ 0.17,$$
$$\frac{\Gamma_{\sigma\to \gamma\gamma}}{\Gamma_{\sigma\to WW}} = 0.021 \ \ldots \ 0.033,$$

Cai, Flacke, Lespinasse 1512.04508

Anomalous U(1) -> heavy σ'

Orthogonal U(1) -> pNGB σ

Decays and production only via WZW anomaly.

Summary and outlook

- FCD is a guide to build composite Higgs models!
- A very simple Higgs sector is possible (SU(4)/Sp(4))
- Less minimal models feasible: DM? LHC signatures?
- FCD allows to probe fermion mass generations (UV completion, conformal windows...)
- FCD models can be tested on the Lattice!