# Composite Dark Matter models

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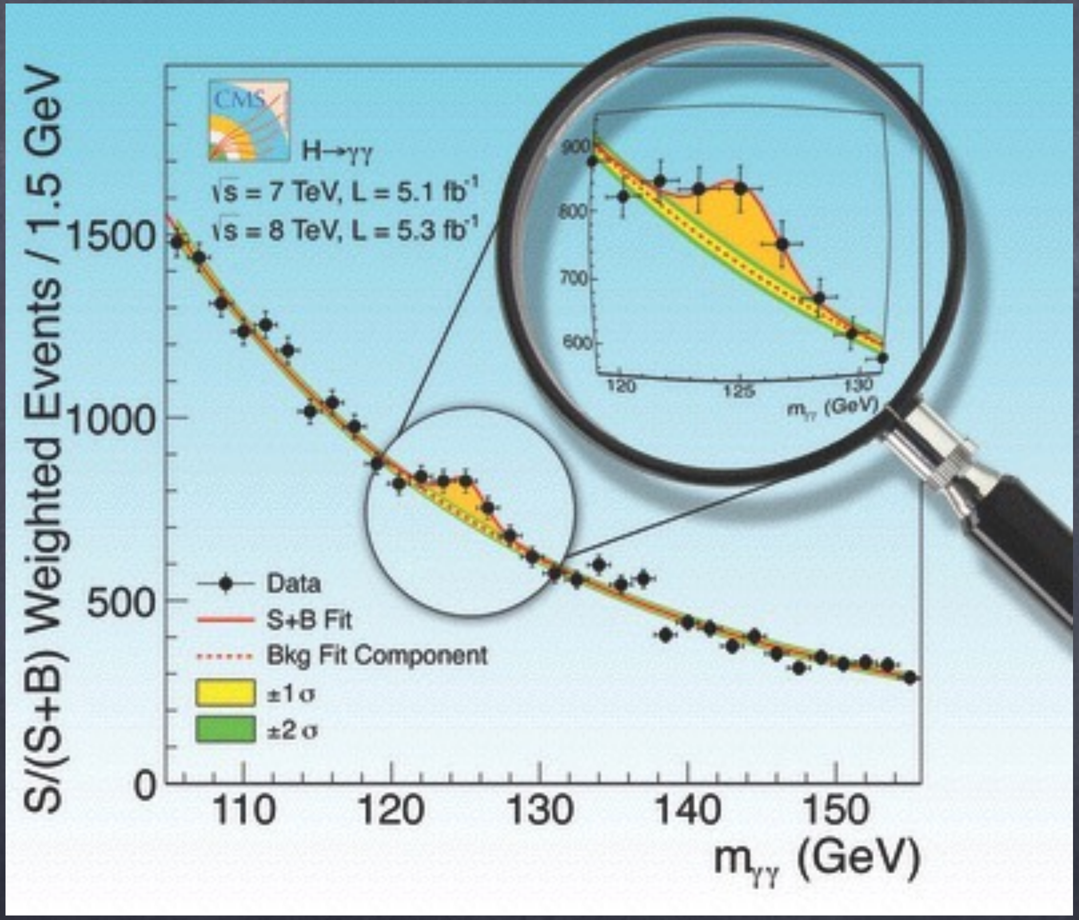
# Monsieur le Higgs: enfin!



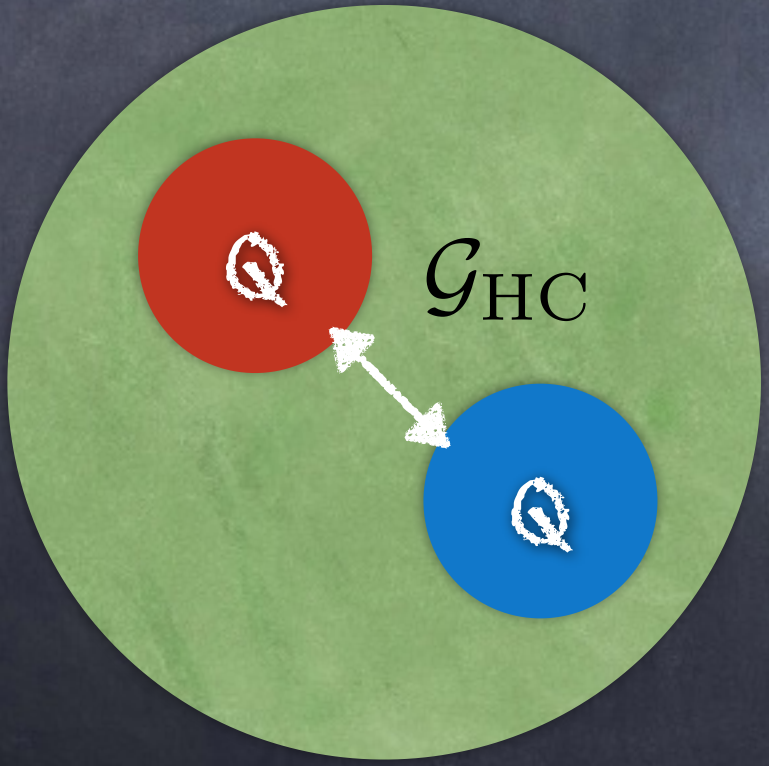
The Standard Model is finally complete!

(is it?)

Can it be the first ever elementary scalar particle?

# Compositeness: who are thou?

Think of QCD as a template:



- spin-0 states are made of more elementary fermions
- a new confining (gauge) force binds them together
- spectrum depends on the global (flavour) symmetries

$$SU(2) \times SU(2) \to SU(2)$$

$$\Rightarrow 3 \quad \text{pions}$$

# Compositeness: who are thou?

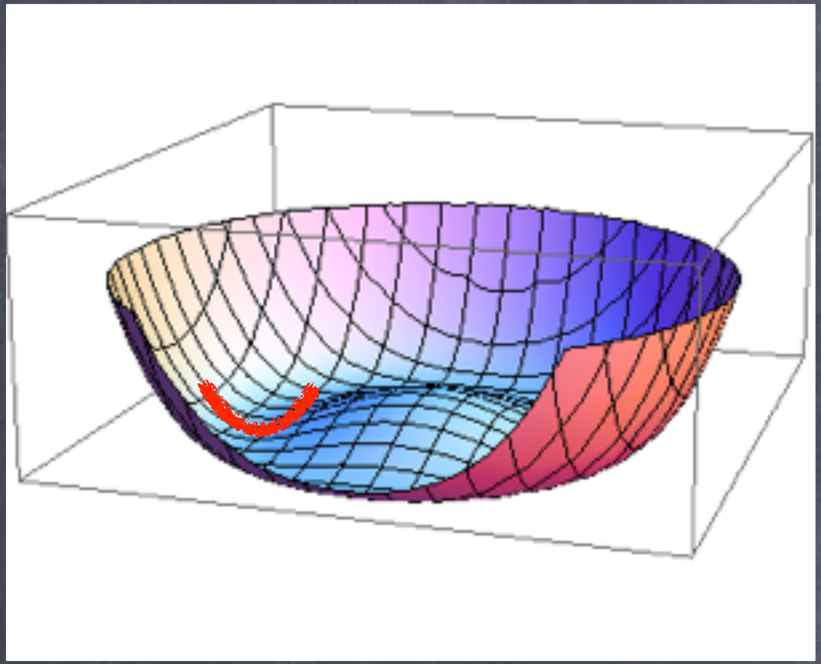
## Dark compositeness:

- Spin-0: the lightest pion may be stable (Dark Pion)
- Spin-1/2: protected by a Techni-Baryon number (asymmetric DM)
- Spin-1 and higher: typically decay into pions/baryons

# Compositeness:
# who are thou?

One dynamics to rule the all!

# Compositeness, and the Higgs boson



Global symmetry of the system:

$$\begin{tikzcd} \mathcal{G} \arrow[r] \arrow[d] & \mathcal{H} \arrow[d] \\ SU(2) \times U(1) \arrow[r] & U(1)_{\rm em} \end{tikzcd}$$

SM gauge symmetry!

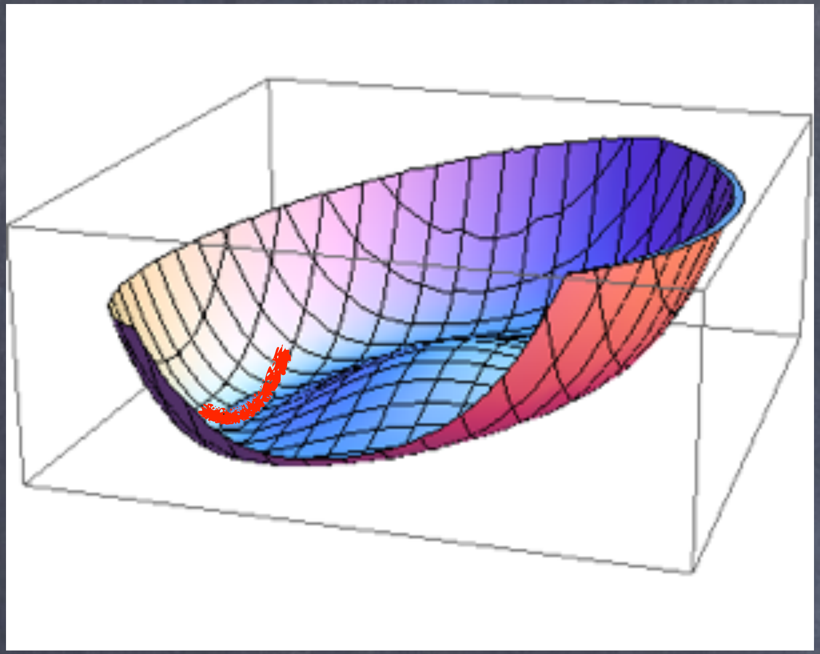
- Goldstones include the longitudinal d.o.f. of W and Z
- the Higgs is a heavy bound state (singlet under H)

QCD template:

$\pi$ pions

$\sigma$ sigma

# Compositeness, and the Higgs boson



Global symmetry of the system:

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

$$SU(2) \times U(1) \rightarrow U(1)_{\text{em}}$$

SM gauge symmetry!

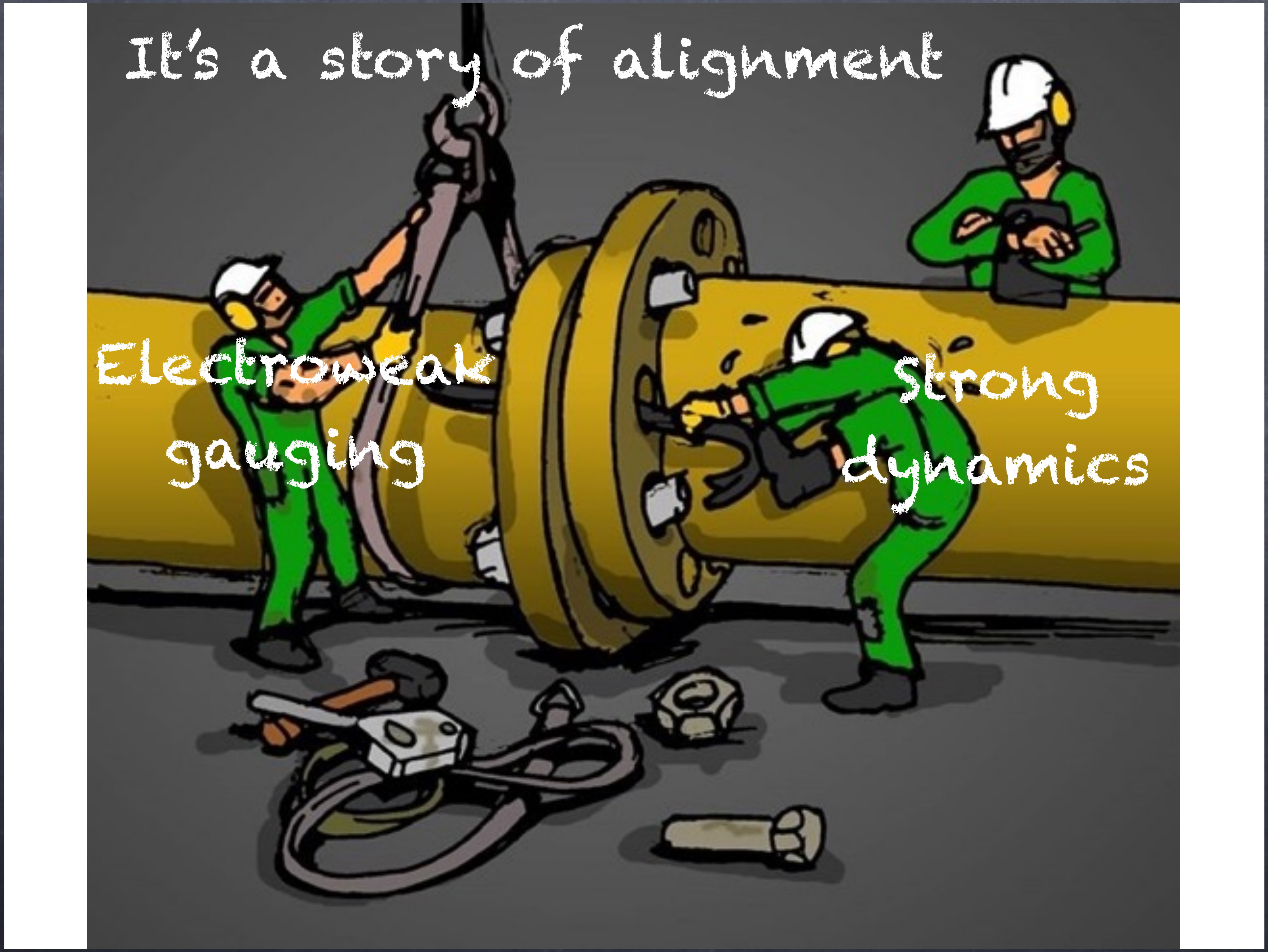
- Goldstones include the longitudinal d.o.f. of W and Z
- the Higgs is a pseudo-Goldstone

QCD template:

$\pi$ pions

$\sigma$ sigma

# Compositeness, and the Higgs boson



# 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

| coset | Q | $N_{min}$ | doublets | pNGBs |
|---|---|---|---|---|
| SU(N)/Sp(N) | pR | 4 | 1 | 5 |
| SU(N)/SO(N) | R | 5 | 1 | 14 |
| SU(N)xSU(N)/ SU(N) | C | 4 | 2 | 15 |

← Minimal!

Dugan, Georgi, Kaplan
1985!!!

G.C., T.Ma
1508.07014

# The minimal case

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

$SU(2)_{\rm HC}$ $\psi = \Box$

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

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

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

Is it there a parity stabilising the (1,1)?

# The minimal case

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

$SU(2)_{\rm HC}$ $\qquad \psi = \square$

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

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

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

$P \in Sp(4)$

$$P = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

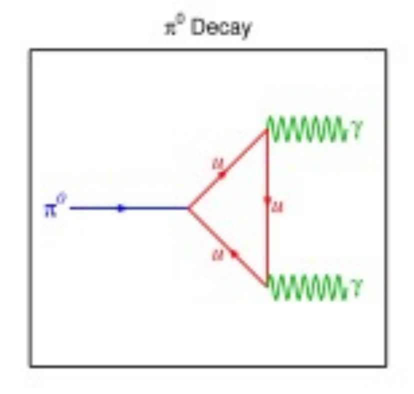
$$(2,2) \to -(2,2)$$

$$(1,1) \to (1,1)$$

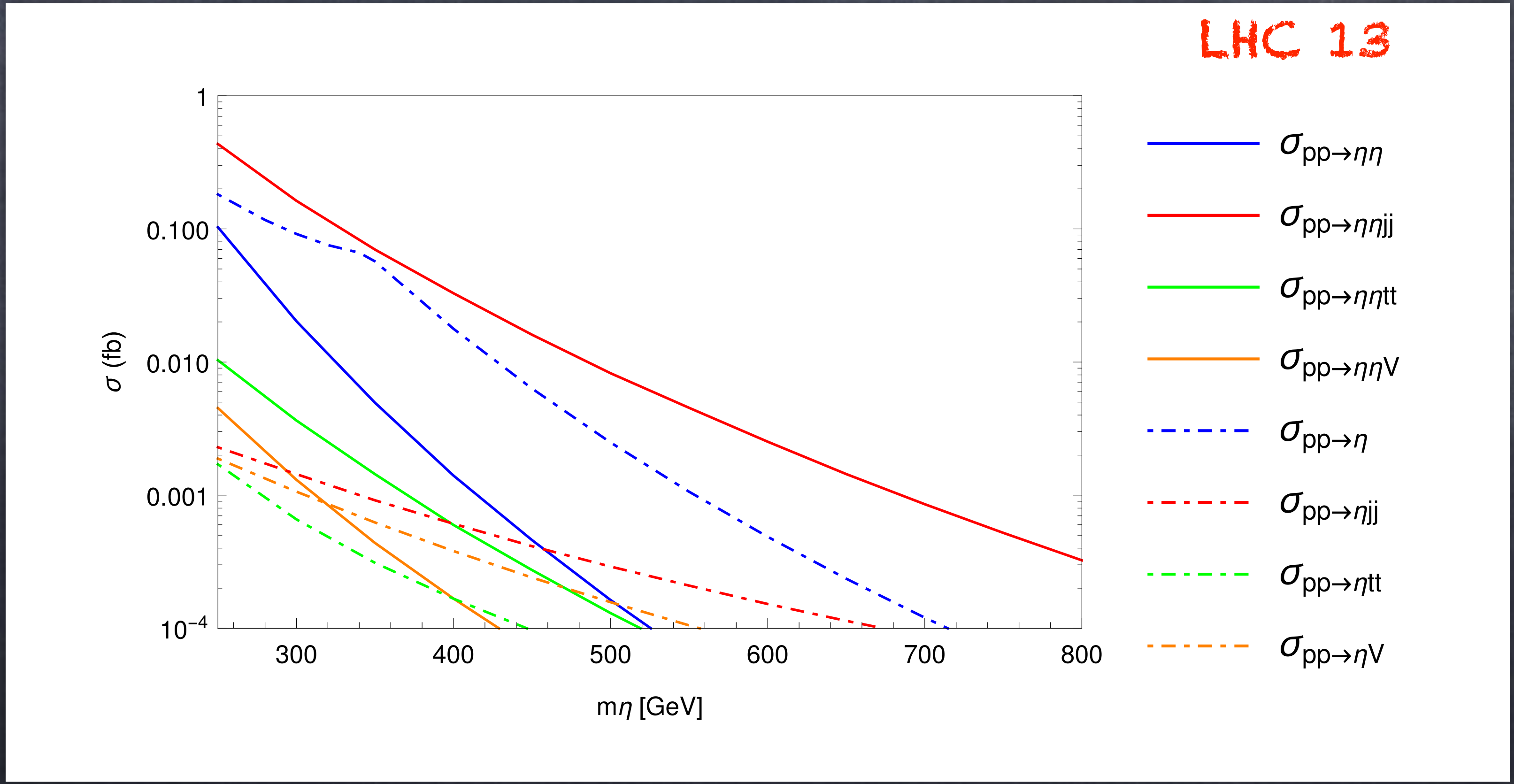
# The minimal case

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

Singlet cannot be
Dark Matter!



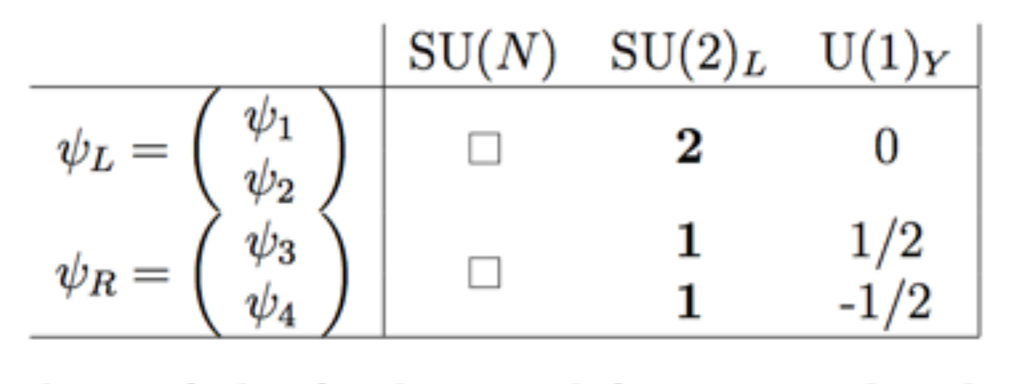
Anomalous coupling to:
WW, ZZ, Z gamma



# A composite 2HDM

G.C., T.Ma
1508.07014

$SU(3)_{\text{HC}}$

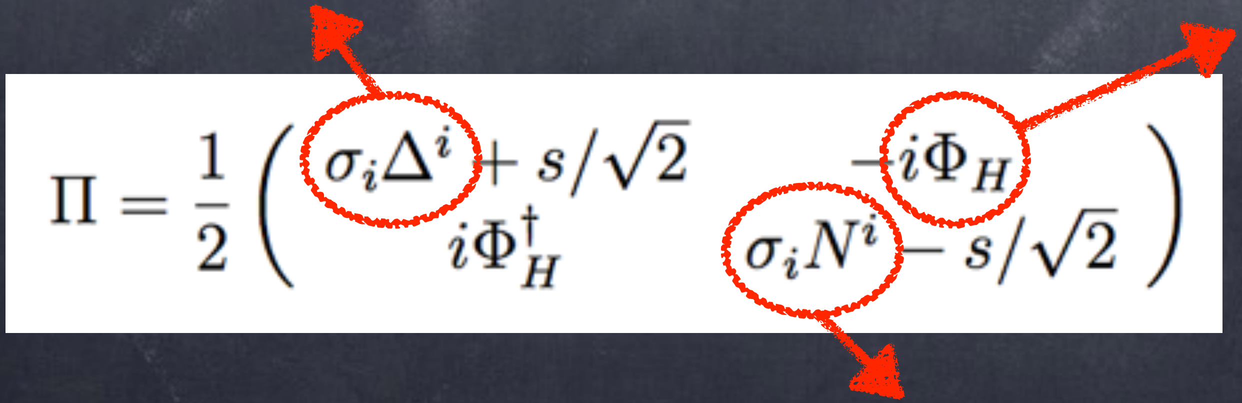


| | SU($N$) | SU(2)$_L$ | U(1)$_Y$ |
|---|---|---|---|
| $\psi_L = \begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix}$ | □ | **2** | 0 |
| $\psi_R = \begin{pmatrix}\psi_3\\ \psi_4\end{pmatrix}$ | □ | **1**<br>**1** | 1/2<br>-1/2 |

$$SU(4) \times SU(4) \to SU(4)$$

Triplet

Complex bi-doublet
(2HDM)



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

SU(2)R Triplet

# A composite 2HDM

$SU(3)_{\mathrm{HC}}$

G.C., T.Ma
1508.07014

Is it there a parity stabilising the pions?

$$\Sigma = e^{\frac{i}{f}\Pi} \qquad \Sigma \to P \cdot \Sigma^T \cdot P \qquad P = \begin{pmatrix} \sigma^2 & 0 \\ 0 & -\sigma^2 \end{pmatrix}$$

$$\left.\begin{aligned} s &\to s \\ H_1 &\to H_1 \end{aligned}\right\} \text{Mimics the minimal case}$$

$$\left.\begin{aligned} H_2 &\to -H_2 \\ \Delta &\to -\Delta \\ N &\to -N \end{aligned}\right\} \text{Dark Sector!}$$

# A composite 2HDM

G.C., T.Ma
1508.07014

$$\Pi = \frac{1}{2}\left(\begin{array}{cc} \sigma_i \Delta^i + s/\sqrt{2} & -i\Phi_H \\ i\Phi_H^\dagger & \sigma_i N^i - s/\sqrt{2} \end{array}\right)$$

$$\langle \Phi_H \rangle = \langle H_1 + iH_2 \rangle = \left(\begin{array}{cc} ve^{i\beta} & 0 \\ 0 & ve^{i\beta} \end{array}\right)$$

$$\Sigma = \left(\begin{array}{cc} \cos\theta\ \mathbf{1} & e^{i\beta}\sin\theta\ \mathbf{1} \\ -e^{i\beta}\sin\theta\ \mathbf{1} & \cos\theta\ \mathbf{1} \end{array}\right)$$

Beta can be removed by
an SU(4) rotation:

$$\Omega_\beta = \mathrm{Exp}\left[-i\frac{\beta}{2}\left(\begin{array}{cc} 1 & 0 \\ 0 & -1 \end{array}\right)\right] = \left(\begin{array}{cc} e^{-i\beta/2} & 0 \\ 0 & e^{i\beta/2} \end{array}\right)$$

Beta = relative phase of the two T-quarks!

# A composite 2HDM

G.C., T.Ma
1508.07014

$$\mathcal{L}_{\rm Yuk} = -f\,(\bar{q}^{\alpha}_{L} t_R)\,\left[{\rm Tr}[P_{1,\alpha}(\underline{y_{t1}}\Sigma + \underline{y_{t2}}\Sigma^\dagger)] + (i\sigma_2)_{\alpha\beta}{\rm Tr}[P_2^\beta(\underline{y_{t3}}\Sigma + \underline{y_{t4}}\Sigma^\dagger)]\right] + h.c.$$

$$Y_t = \frac{y_{t1} - y_{t2} - (y_{t3} - y_{t4})}{2\sqrt{2}}, \qquad Y_D = \frac{y_{t1} - y_{t2} + (y_{t3} - y_{t4})}{2\sqrt{2}},$$
$$Y_T = \frac{y_{t1} + y_{t2} + (y_{t3} + y_{t4})}{2\sqrt{2}}, \qquad Y_0 = \frac{y_{t1} + y_{t2} - (y_{t3} + y_{t4})}{2\sqrt{2}}.$$

4 "Yukawa" couplings!

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

Potential for theta

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

Set to zero by phase-shift

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

Custodial violating VEVs!!!

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

$$\left. + \; 4\,{\rm Im}(Y_T^* Y_t)\sin^2\theta\,\frac{N_0 + \Delta_0}{f} + \ldots \right]$$

# A composite 2HDM

G.C., T.Ma
1508.07014

$$\mathcal{L}_{\rm Yuk} = -f\,(\bar{q}_L^{\alpha} t_R)\ \left[ {\rm Tr}[P_{1,\alpha}(\underline{y_{t1}}\Sigma + \underline{y_{t2}}\Sigma^\dagger)] + (i\sigma_2)_{\alpha\beta}{\rm Tr}[P_2^\beta(\underline{y_{t3}}\Sigma + \underline{y_{t4}}\Sigma^\dagger)] \right] + h.c.$$

4 "Yukawa" couplings!

$$Y_t = \frac{y_{t1} - y_{t2} - (y_{t3} - y_{t4})}{2\sqrt{2}}, \quad Y_D = \frac{y_{t1} - y_{t2} + (y_{t3} - y_{t4})}{2\sqrt{2}},$$
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$$V_{\rm top}(\theta) \quad = -C_t f^4 \quad \left[ 8|Y_t|^2 \sin^2\theta + \right.$$

← Potential for theta

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

DM parity!

Set to zero by phase-shift →

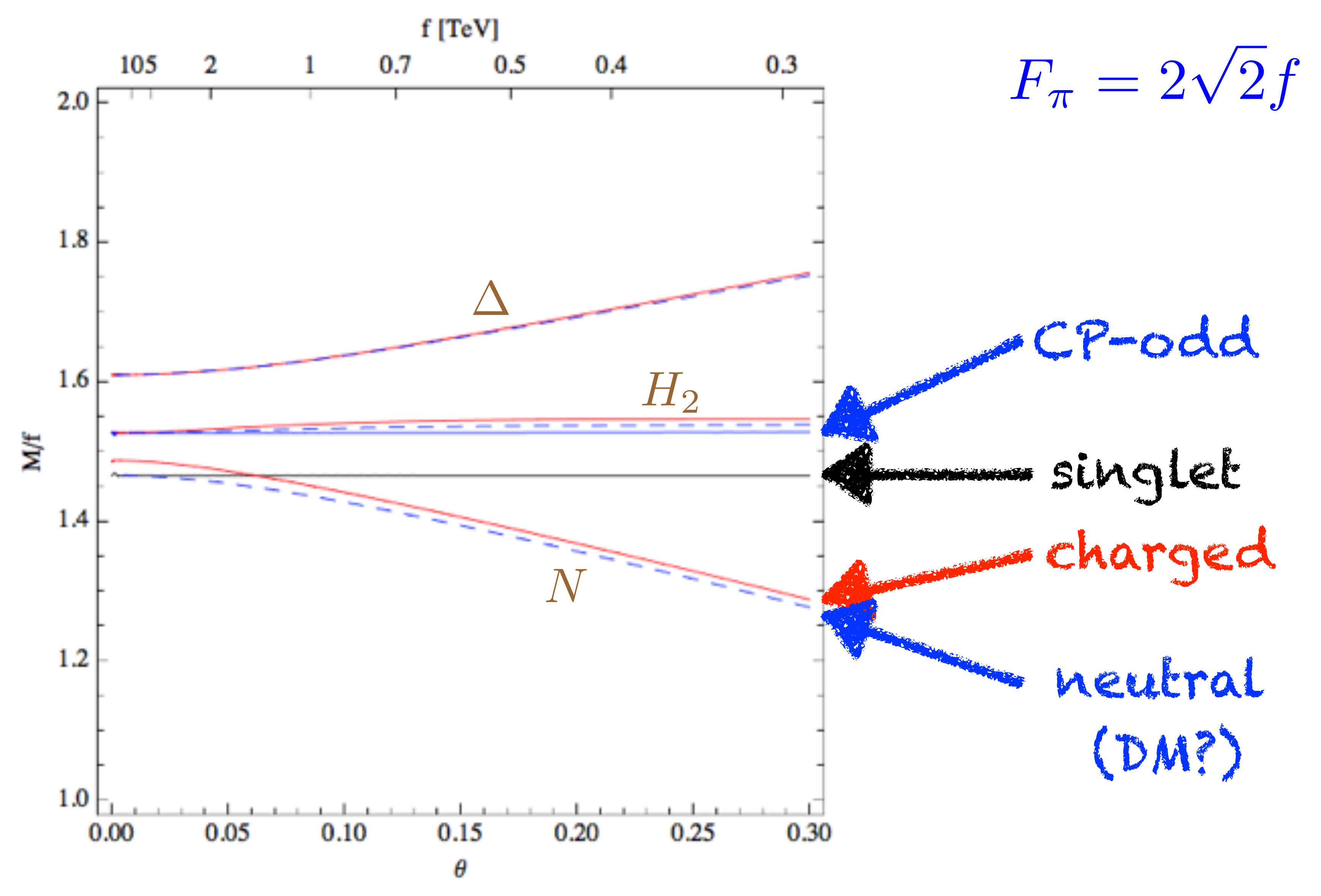
$$+4\sqrt{2}\ {\rm Im}(\cancel{Y_D^*}Y_t)\sin\theta\ \frac{h_2}{f}$$

Custodial violating VEVs!!!

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

$$\left. +\ 4\ {\rm Im}(\cancel{Y_T^*}Y_t)\sin^2\theta\ \frac{N_0 + \Delta_0}{f} + \ldots \right]$$

# A composite 2HDM: spectrum

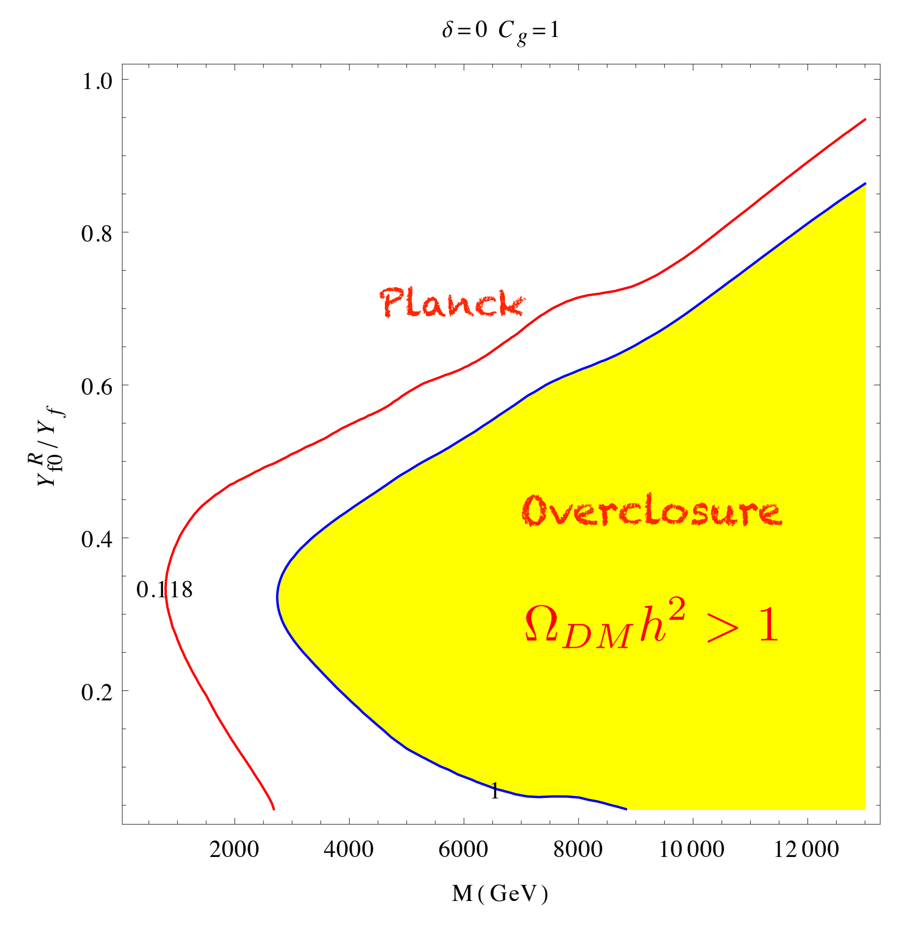


$$F_\pi = 2\sqrt{2}f$$

# A composite 2HDM: Dark-Matter

- Singlet pheno similar to SU(4)/Sp(4) case
- Other pNGBs can be stable:

DM = SU(2)R triplet



Preliminary results

(G.C., T.Ma, S.Zhao, B.Zhang)

Good DM thermal relic densities possible.

$$m_{DM} \sim 1 \div 2 \text{ TeV}$$

$$\sin\theta \sim 0.1$$

SU(6)/Sp(6) and others under investigation!

# The hot potato: flavour!

## Typical top-partner scenario:

G.Ferretti, D.Karateev
1312.5330, 1604.06467

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

$Q$ $\chi$ $T' = QQ\chi$ or $Q\chi\chi$

SM : EW — colour + hypercharge

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

↓

pNGB Higgs
DM?

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

coloured pNGBs
di-boson

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

light top partners

Exception: 1506:00623

# Predicting di-boson resonances

More precisely, the global symmetries are:

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

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

$$\frac{\kappa_i}{f_a} = \frac{q_\psi \kappa_i^\psi + q_\chi \kappa_i^\chi}{\sqrt{q_\psi^2 f_\psi^2 + q_\chi^2 f_\chi^2}}\,,$$

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

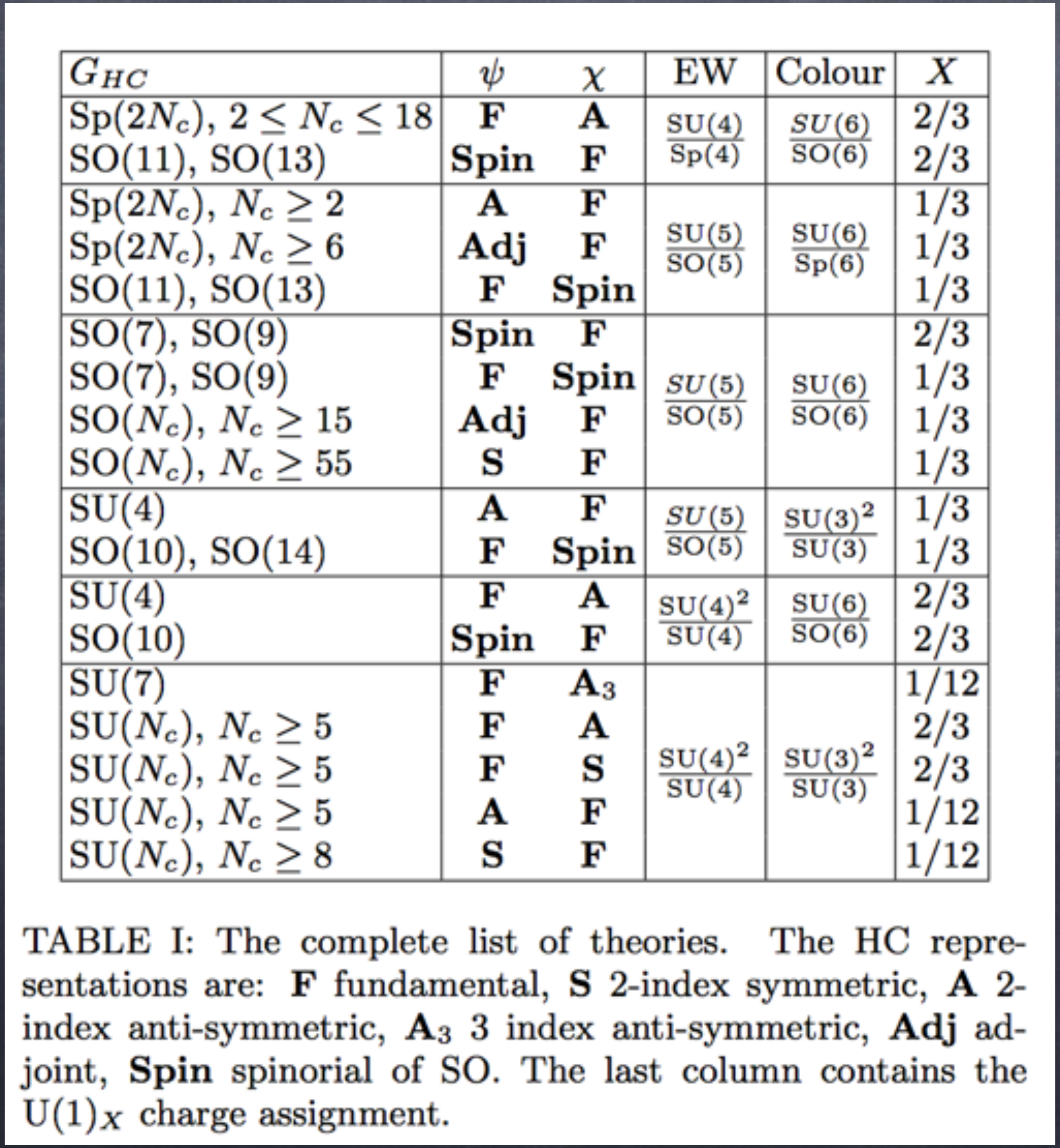
Cai, Flacke, Lespinasse 1512.04508

Anomalous U(1) -> heavy $\eta'$

Orthogonal U(1) -> pNGB $a$

Decays and production only via WZW anomaly.

# Predicting di-boson resonances



| $G_{HC}$ | $\psi$ | $\chi$ | EW | Colour | $X$ |
|---|---|---|---|---|---|
| Sp($2N_c$), $2 \leq N_c \leq 18$ | **F** | **A** | $\frac{SU(4)}{Sp(4)}$ | $\frac{SU(6)}{SO(6)}$ | 2/3 |
| SO(11), SO(13) | **Spin** | **F** | | | 2/3 |
| Sp($2N_c$), $N_c \geq 2$ | **A** | **F** | $\frac{SU(5)}{SO(5)}$ | $\frac{SU(6)}{Sp(6)}$ | 1/3 |
| Sp($2N_c$), $N_c \geq 6$ | **Adj** | **F** | | | 1/3 |
| SO(11), SO(13) | **F** | **Spin** | | | 1/3 |
| SO(7), SO(9) | **Spin** | **F** | $\frac{SU(5)}{SO(5)}$ | $\frac{SU(6)}{SO(6)}$ | 2/3 |
| SO(7), SO(9) | **F** | **Spin** | | | 1/3 |
| SO($N_c$), $N_c \geq 15$ | **Adj** | **F** | | | 1/3 |
| SO($N_c$), $N_c \geq 55$ | **S** | **F** | | | 1/3 |
| SU(4) | **A** | **F** | $\frac{SU(5)}{SO(5)}$ | $\frac{SU(3)^2}{SU(3)}$ | 1/3 |
| SO(10), SO(14) | **F** | **Spin** | | | 1/3 |
| SU(4) | **F** | **A** | $\frac{SU(4)^2}{SU(4)}$ | $\frac{SU(6)}{SO(6)}$ | 2/3 |
| SO(10) | **Spin** | **F** | | | 2/3 |
| SU(7) | **F** | $\mathbf{A}_3$ | $\frac{SU(4)^2}{SU(4)}$ | $\frac{SU(3)^2}{SU(3)}$ | 1/12 |
| SU($N_c$), $N_c \geq 5$ | **F** | **A** | | | 2/3 |
| SU($N_c$), $N_c \geq 5$ | **F** | **S** | | | 2/3 |
| SU($N_c$), $N_c \geq 5$ | **A** | **F** | | | 1/12 |
| SU($N_c$), $N_c \geq 8$ | **S** | **F** | | | 1/12 |

TABLE I: The complete list of theories. The HC representations are: **F** fundamental, **S** 2-index symmetric, **A** 2-index anti-symmetric, $\mathbf{A}_3$ 3 index anti-symmetric, **Adj** adjoint, **Spin** spinorial of SO. The last column contains the U(1)$_X$ charge assignment.

# Model scan for the diphoton excess

Belyaev, G.C. Cai, Flacke, Parolini, Serodio 1512.07242

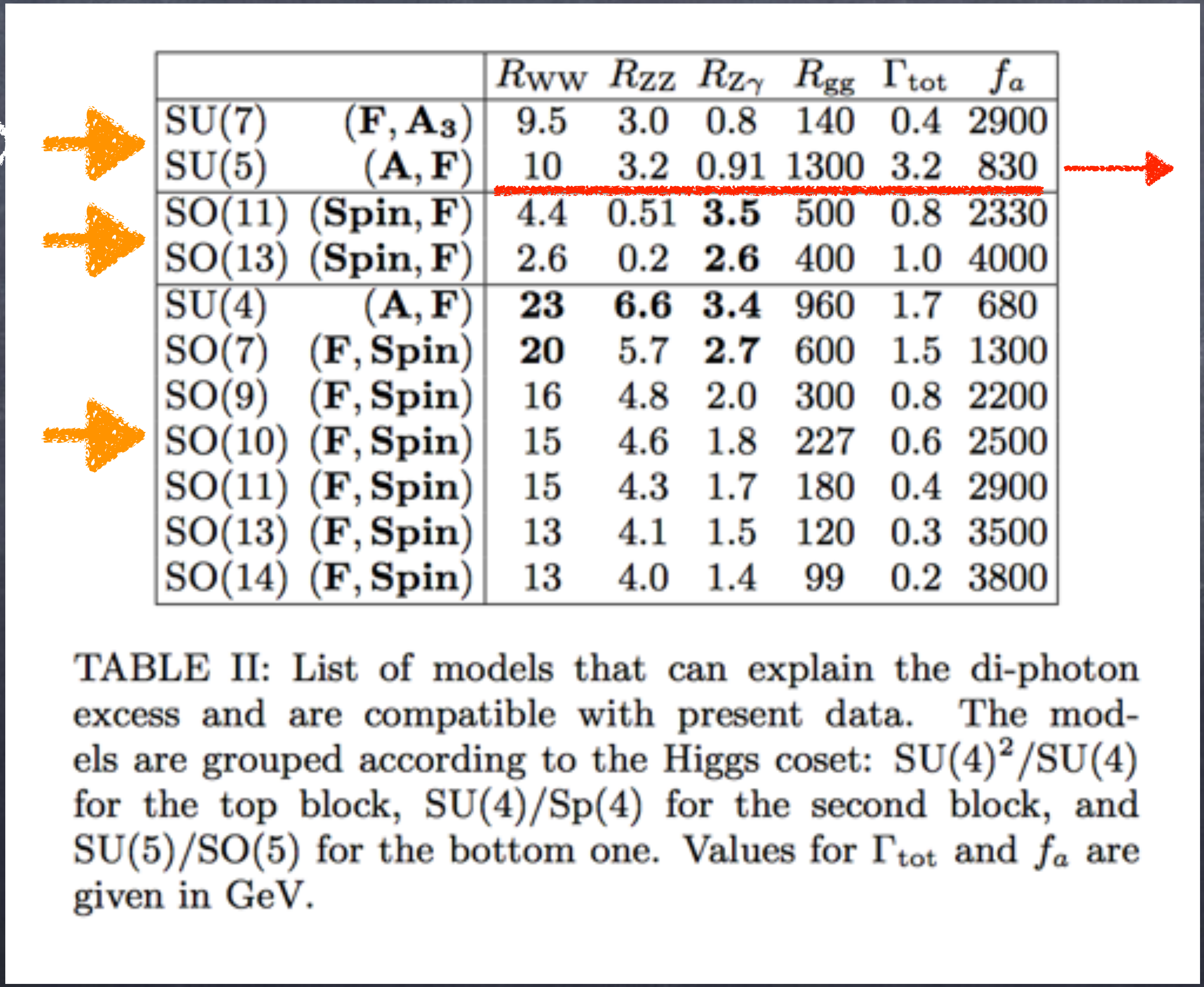
$$R_{XY} = \frac{\mathrm{BR}(\sigma \to XY)}{\mathrm{BR}(\sigma \to \gamma\gamma)}$$

$R_{gg} \lesssim 1400,\ R_{WW} \lesssim 19,\ R_{ZZ} \lesssim 6,\ R_{Z\gamma} \lesssim 2\,,$

SU(4)²/SU(4)

SU(4)/Sp(4)

SU(5)/SO(5)



| | | $R_{WW}$ | $R_{ZZ}$ | $R_{Z\gamma}$ | $R_{gg}$ | $\Gamma_{\rm tot}$ | $f_a$ |
|---|---|---|---|---|---|---|---|
| SU(7) | $(\mathbf{F}, \mathbf{A_3})$ | 9.5 | 3.0 | 0.8 | 140 | 0.4 | 2900 |
| SU(5) | $(\mathbf{A}, \mathbf{F})$ | 10 | 3.2 | 0.91 | 1300 | 3.2 | 830 |
| SO(11) | $(\mathbf{Spin}, \mathbf{F})$ | 4.4 | 0.51 | **3.5** | 500 | 0.8 | 2330 |
| SO(13) | $(\mathbf{Spin}, \mathbf{F})$ | 2.6 | 0.2 | **2.6** | 400 | 1.0 | 4000 |
| SU(4) | $(\mathbf{A}, \mathbf{F})$ | **23** | **6.6** | **3.4** | 960 | 1.7 | 680 |
| SO(7) | $(\mathbf{F}, \mathbf{Spin})$ | **20** | 5.7 | **2.7** | 600 | 1.5 | 1300 |
| SO(9) | $(\mathbf{F}, \mathbf{Spin})$ | 16 | 4.8 | 2.0 | 300 | 0.8 | 2200 |
| SO(10) | $(\mathbf{F}, \mathbf{Spin})$ | 15 | 4.6 | 1.8 | 227 | 0.6 | 2500 |
| SO(11) | $(\mathbf{F}, \mathbf{Spin})$ | 15 | 4.3 | 1.7 | 180 | 0.4 | 2900 |
| SO(13) | $(\mathbf{F}, \mathbf{Spin})$ | 13 | 4.1 | 1.5 | 120 | 0.3 | 3500 |
| SO(14) | $(\mathbf{F}, \mathbf{Spin})$ | 13 | 4.0 | 1.4 | 99 | 0.2 | 3800 |

TABLE II: List of models that can explain the di-photon excess and are compatible with present data. The models are grouped according to the Higgs coset: SU(4)$^2$/SU(4) for the top block, SU(4)/Sp(4) for the second block, and SU(5)/SO(5) for the bottom one. Values for $\Gamma_{\rm tot}$ and $f_a$ are given in GeV.

if $f_a \sim f$

$\sin\theta \sim 0.1$

# 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?
- Di-boson (di-photon) @ the LHC is a "standard candle" for compositeness (via the WZW anomaly)

# Summary and outlook

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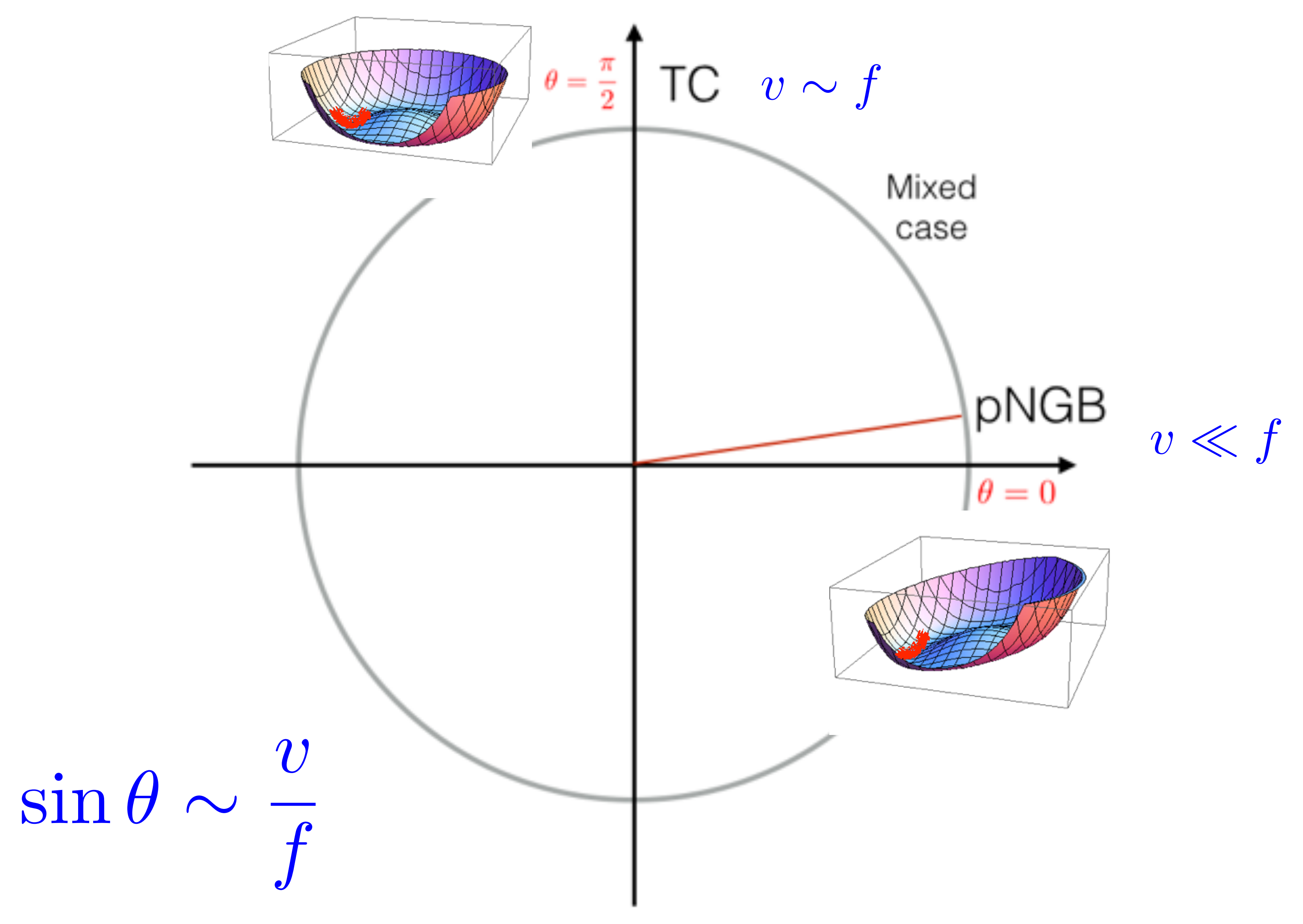
A very cumbersome theory, with simple inner workings!

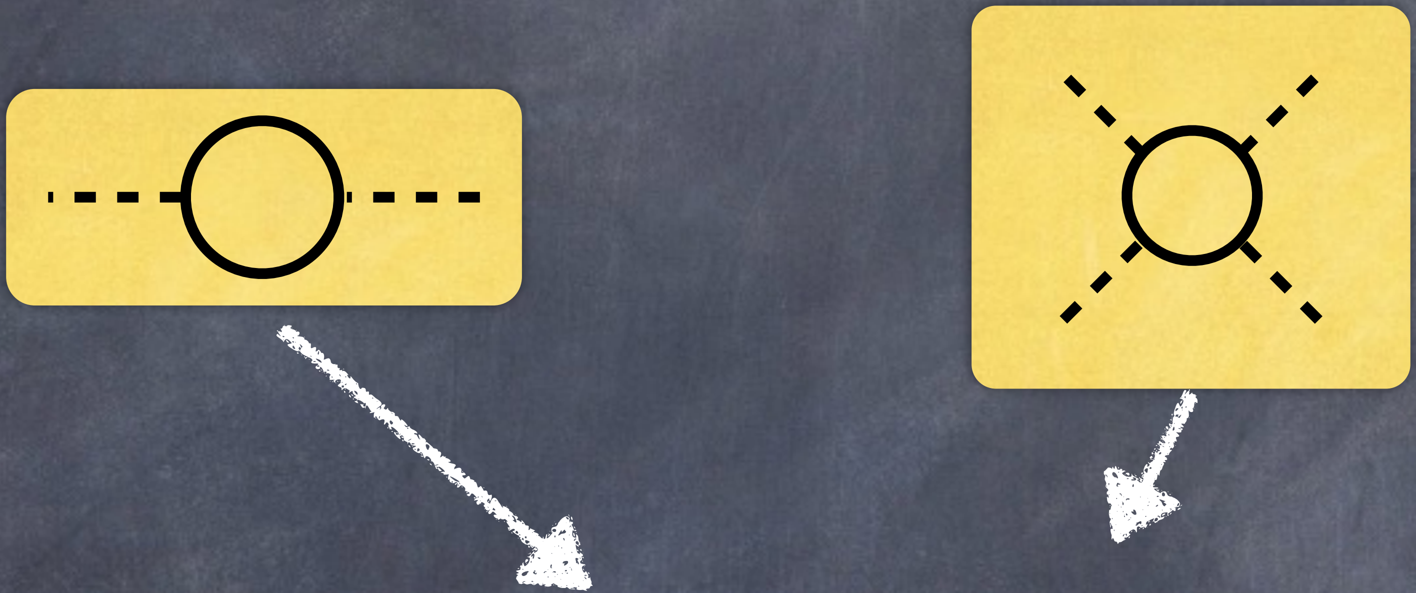
# Backup

# Compositeness, and the Higgs boson



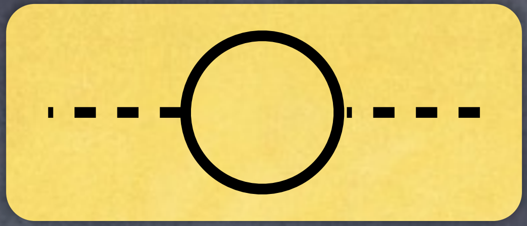
$$\sin\theta \sim \frac{v}{f}$$

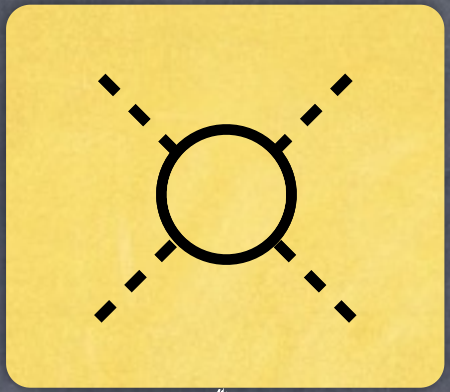
# Anatomy of the potential



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

# Anatomy of the potential

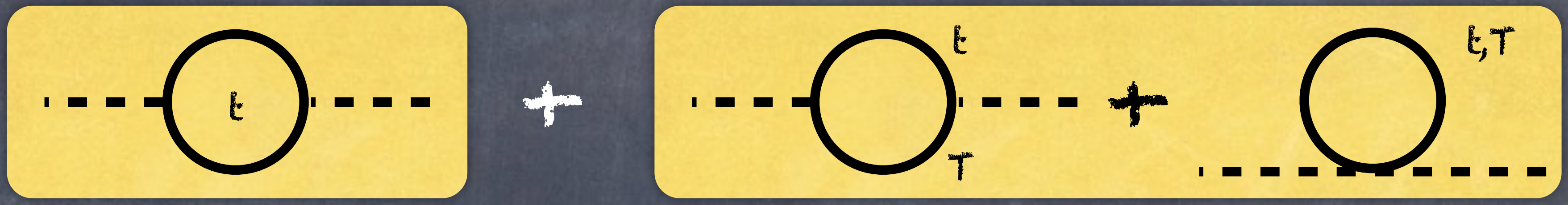




$$V \sim \alpha \sin^2\theta + \xcancel{\beta \sin^4\theta}$$

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

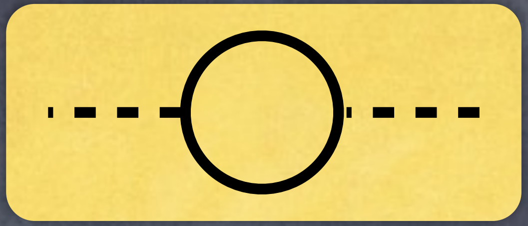
# Anatomy of the potential



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

**Minimum:** $\theta \sim \epsilon$

# Anatomy of the potential



Explicit symmetry breaking?

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

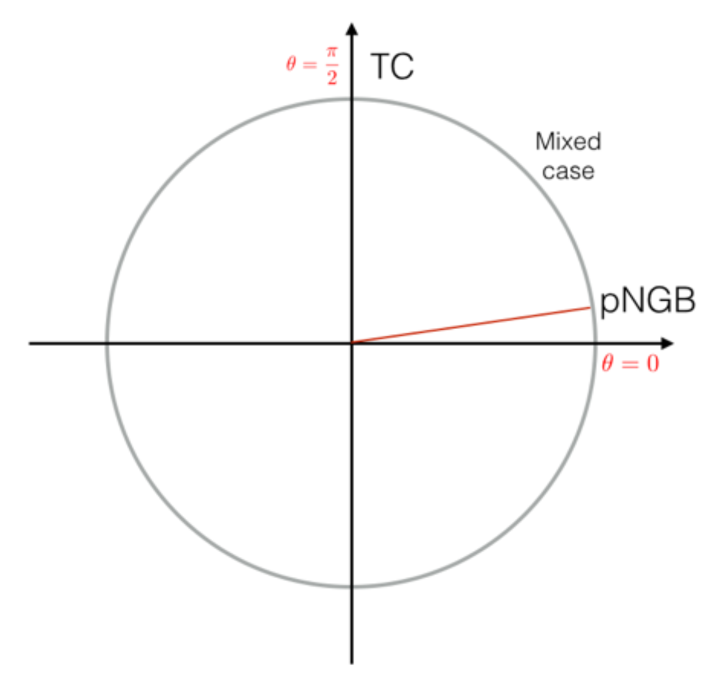
**Minimum:** $\theta \sim \epsilon$

Possible!

# Anatomy of the potential

Higgs mass in the small theta limit:

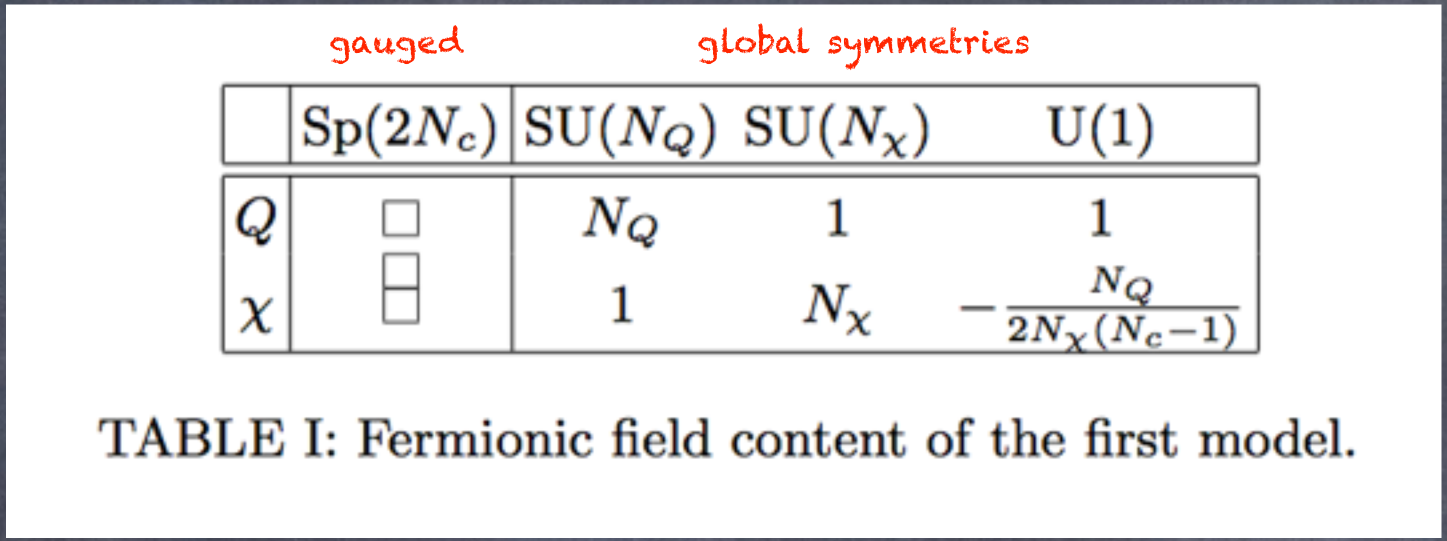
$$m_h \sim y f \sin\theta \sim y v_{SM}$$



Naturally in the right ballpark, without further fine tuning!

# Light 't Hooft Top Partners

G.C., A.Parolini
1511.05163



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

TABLE I: Fermionic field content of the first model.

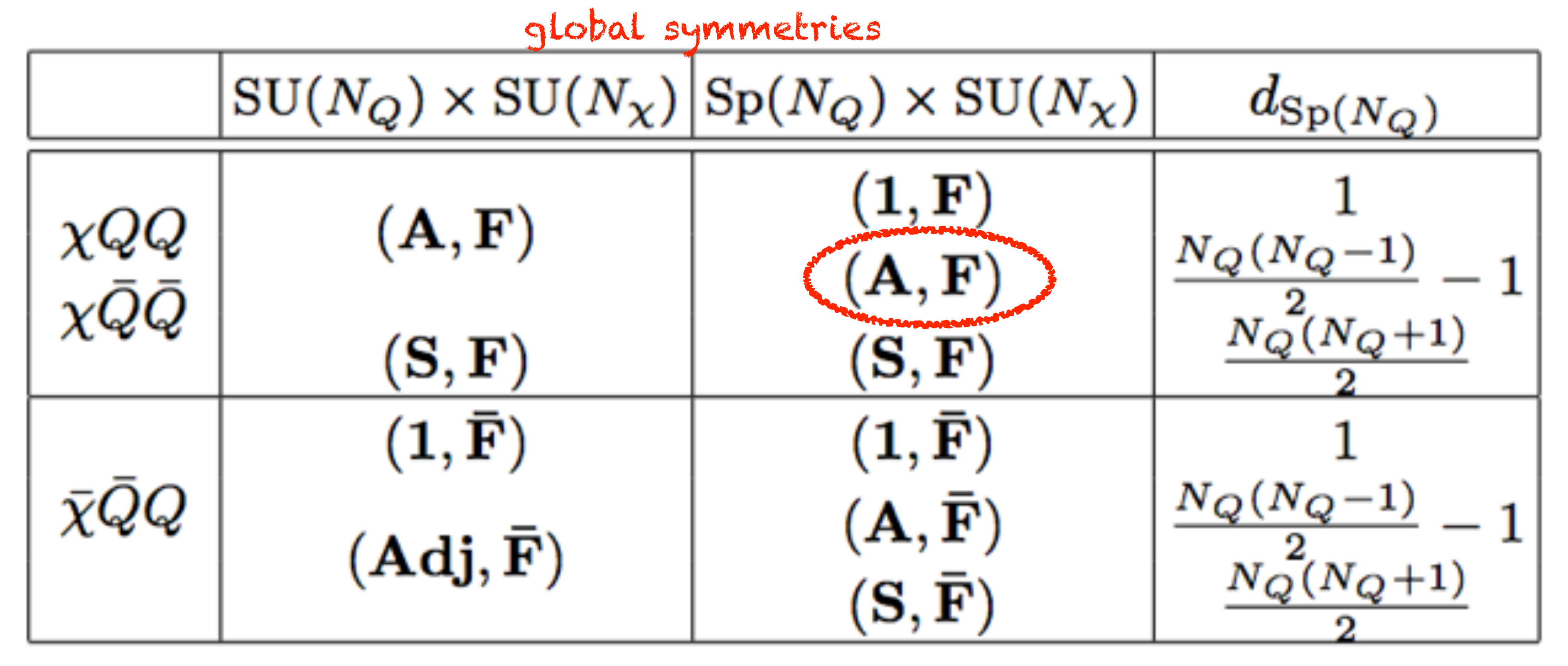
Barnard, Gherghetta, Ray 1311.6562
Ferretti, Karateev 1312.5330

- $\langle QQ \rangle \neq 0$ 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

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

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

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

# A composite 2HDM: EWPTs

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

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

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

Bounds similar to minimal cases.