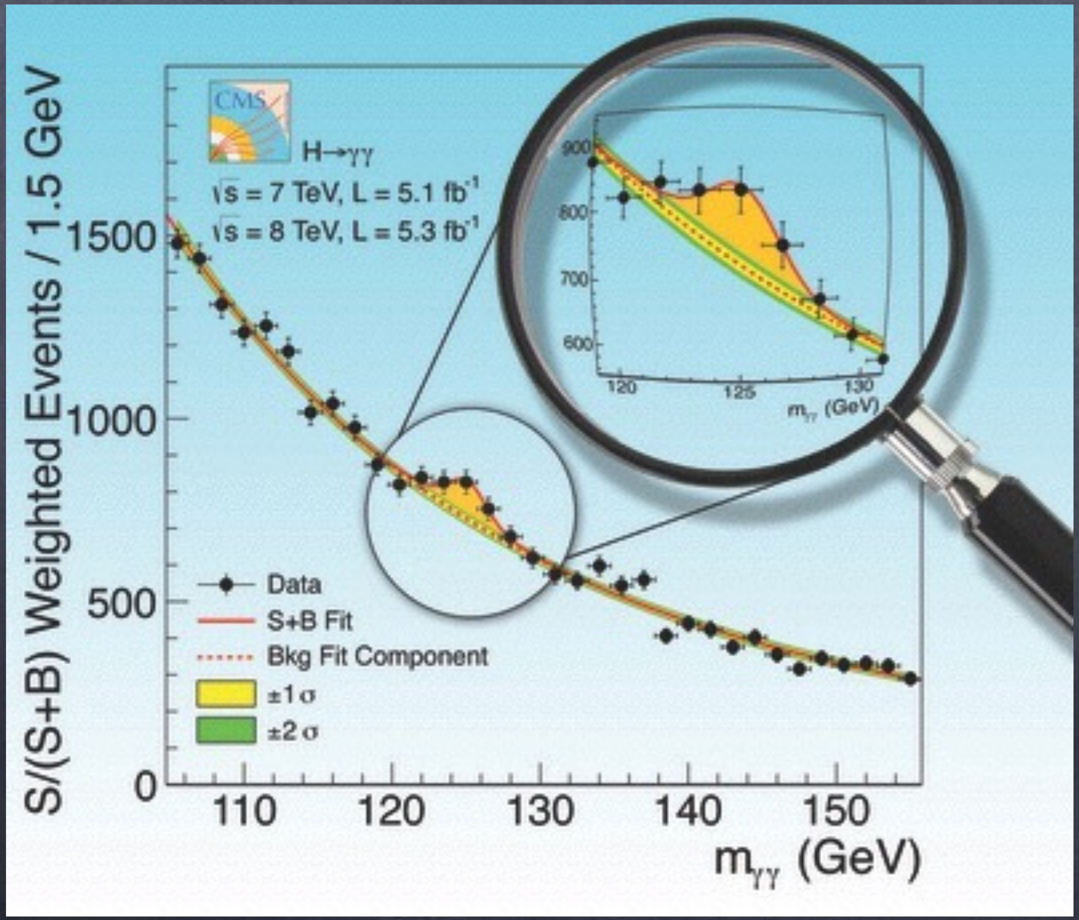
Higgs, Dark Matter, di-photon: a confining dynamics to rule them all!

G.Cacciapaglia (IPNL)
@ Montpellier

Monsieur le Higgs: enfin!

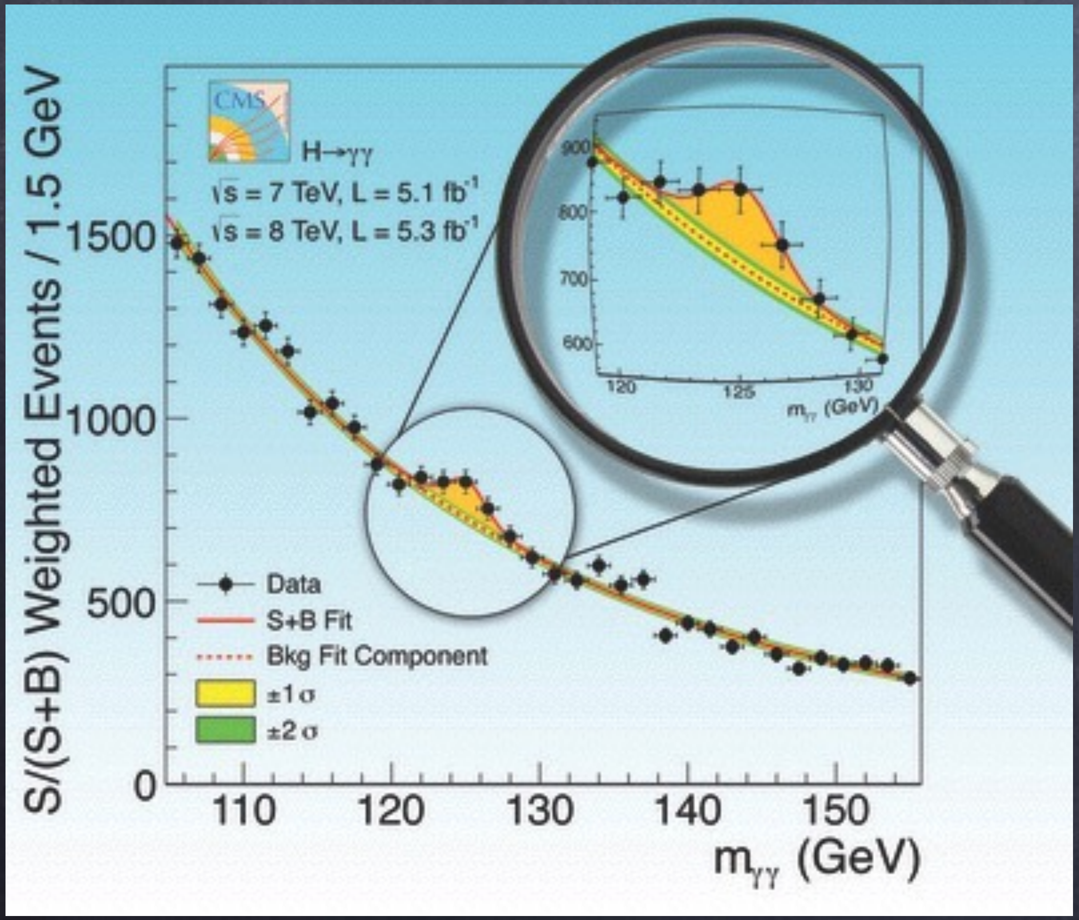


The Standard Model is finally complete!

(is it?)

Monsieur le Higgs: enfin!

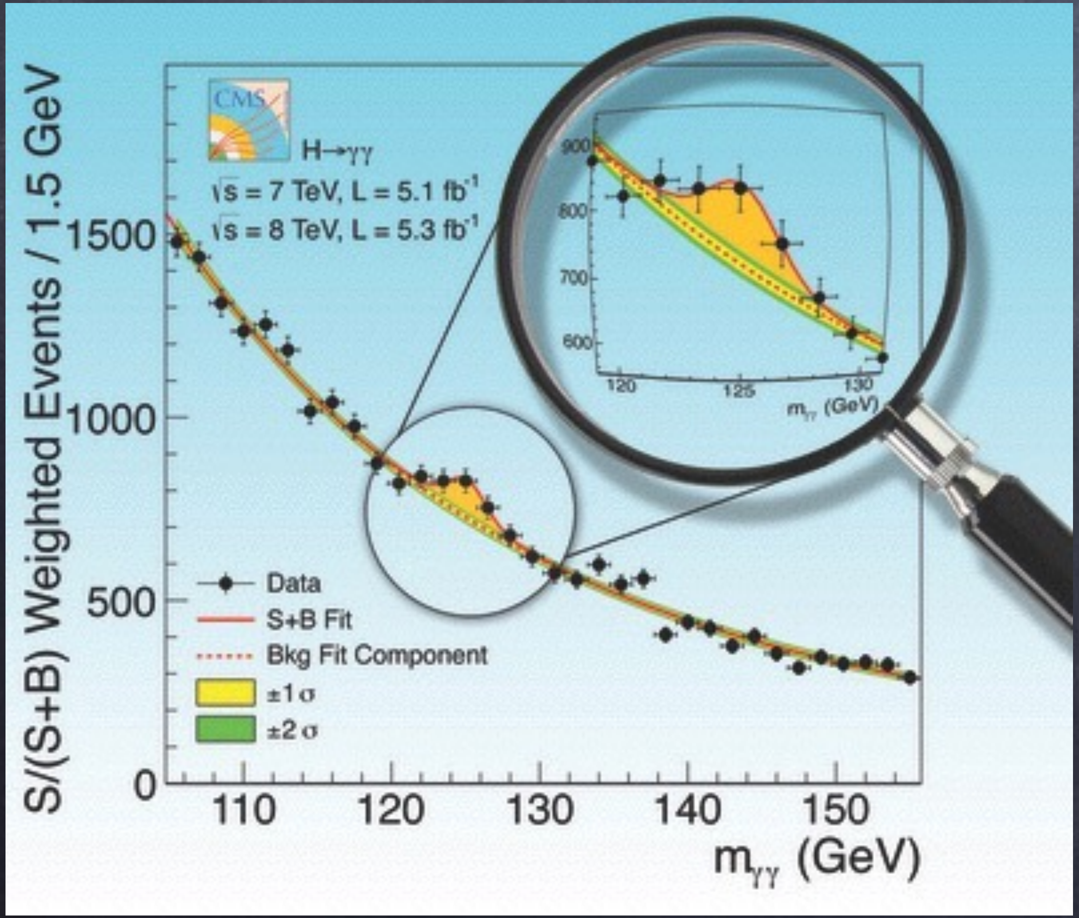
...and the LHC crew is happy!



Monsieur le Higgs: enfin!

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

We have a new toy,

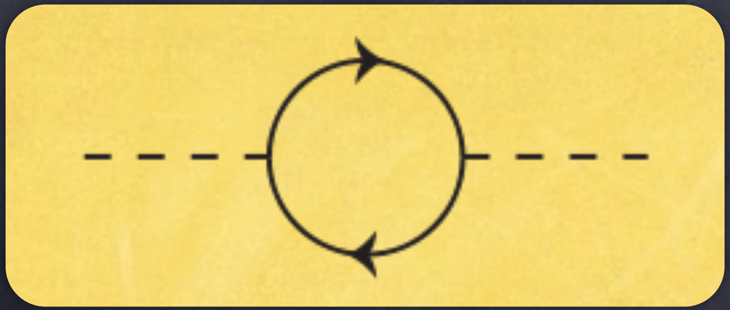


a new probe in the EW sector!

Do we still need BSM?

We have a pretty good idea of the mechanism

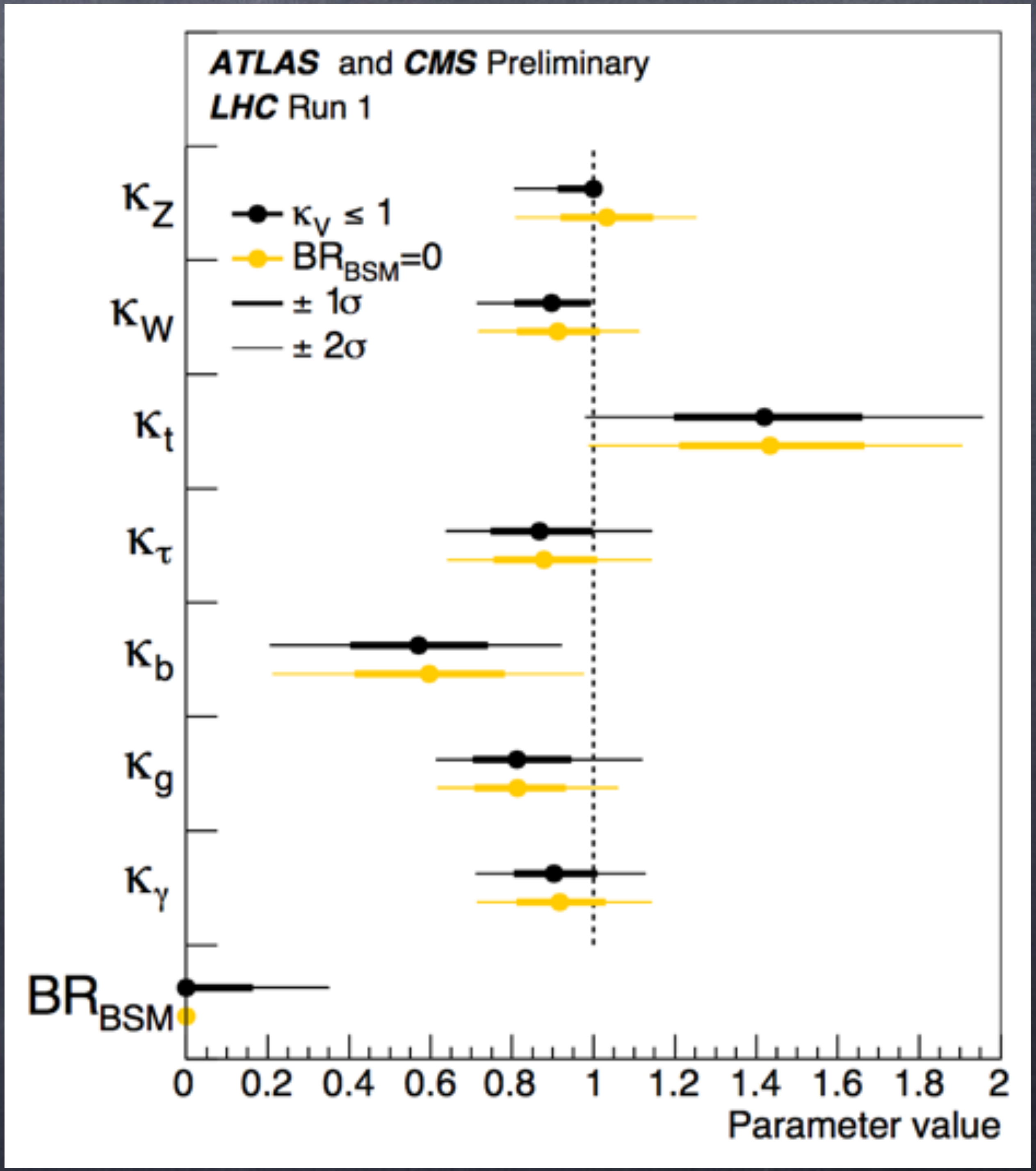
But, we dont know how to protect it:



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

Do we still need BSM?

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



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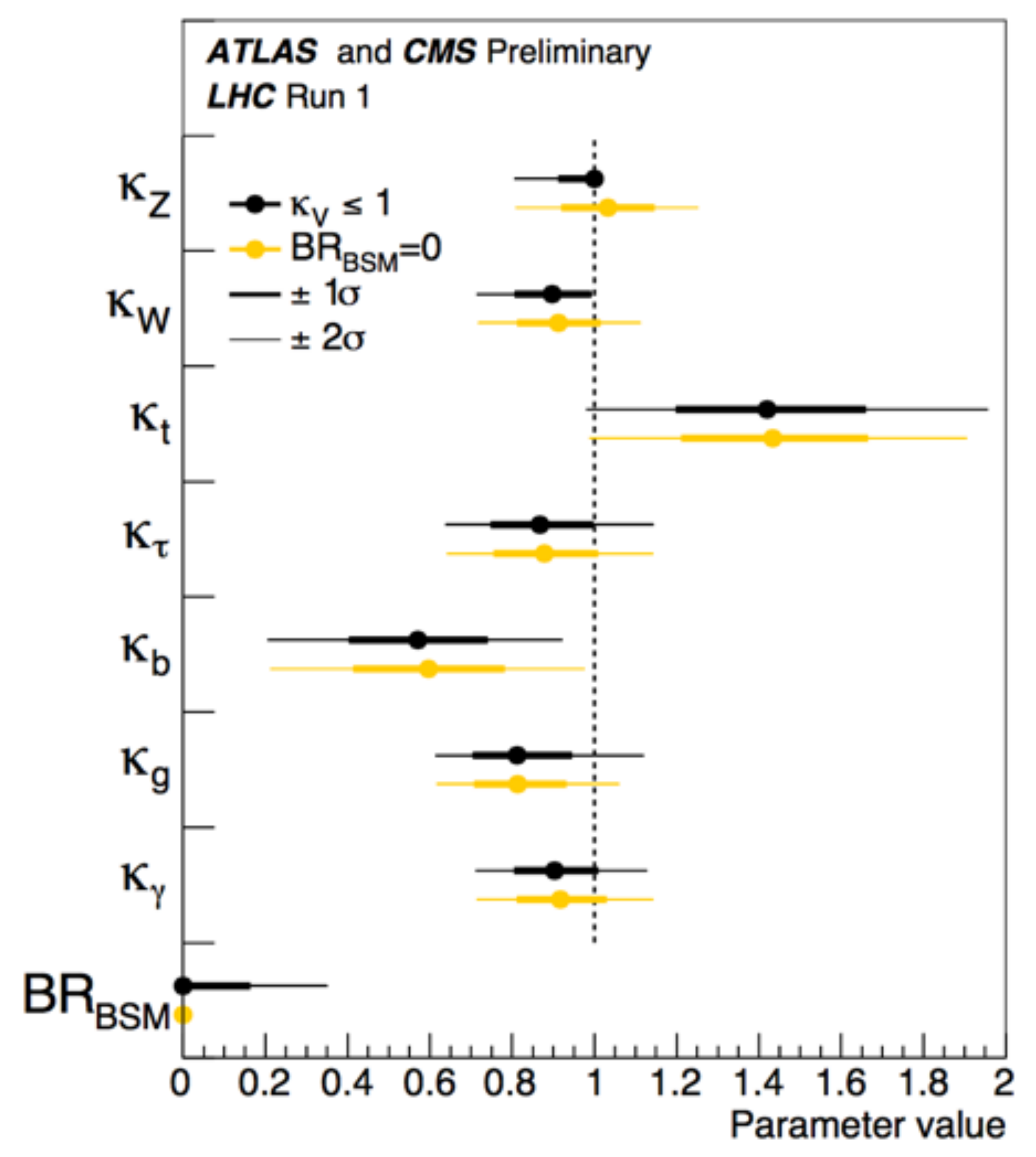
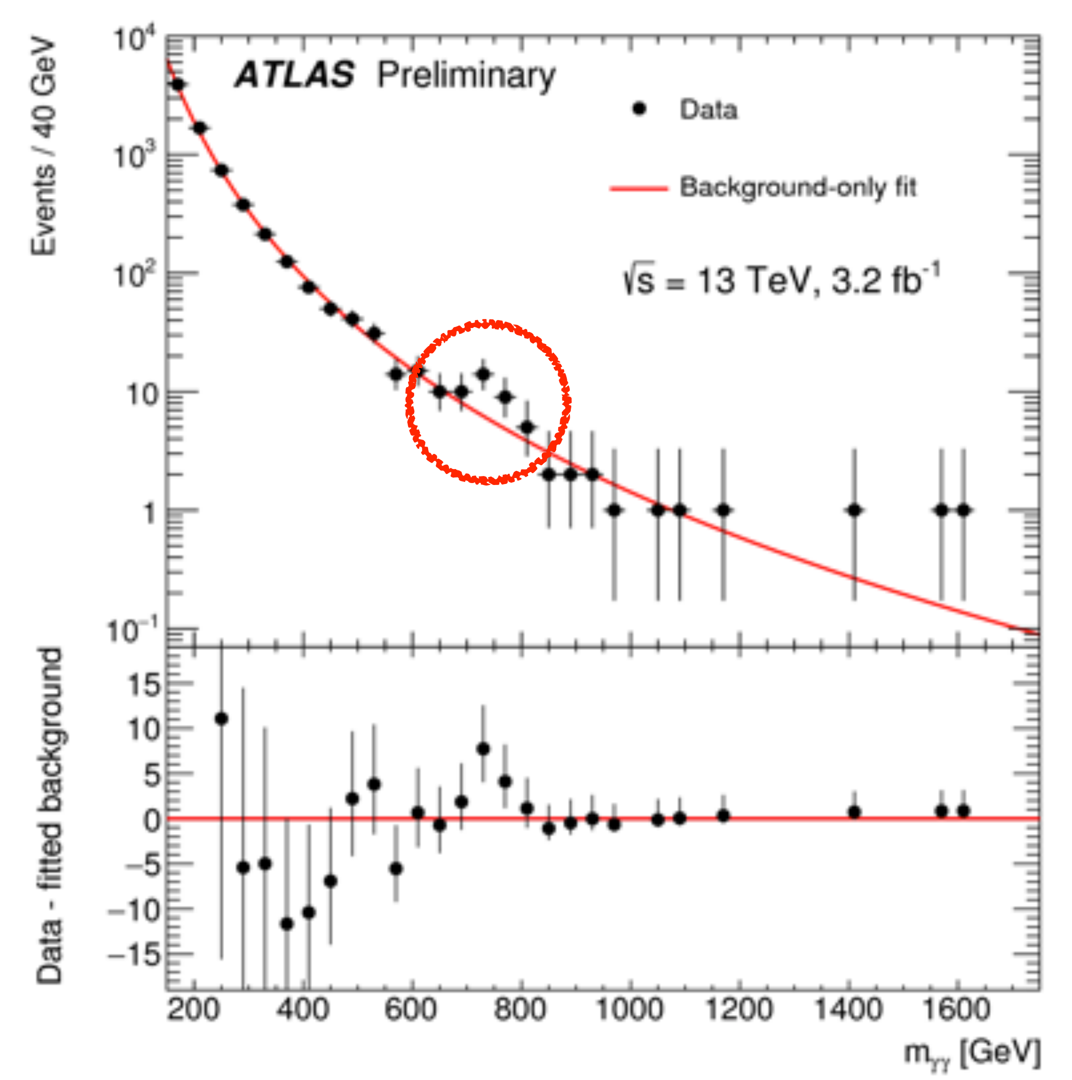
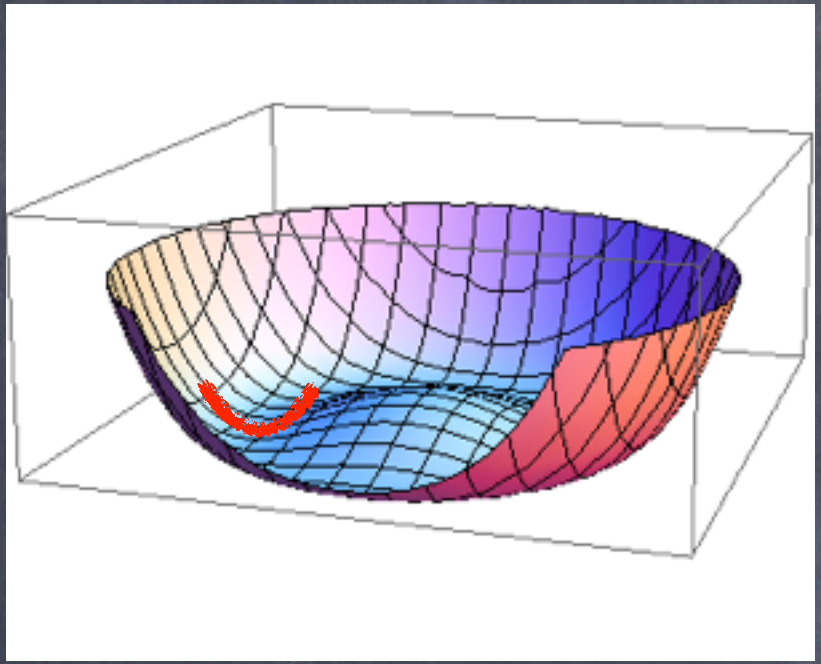




Compositeness, and the Higgs boson



Global symmetry of the system:

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

SM gauge symmetry!

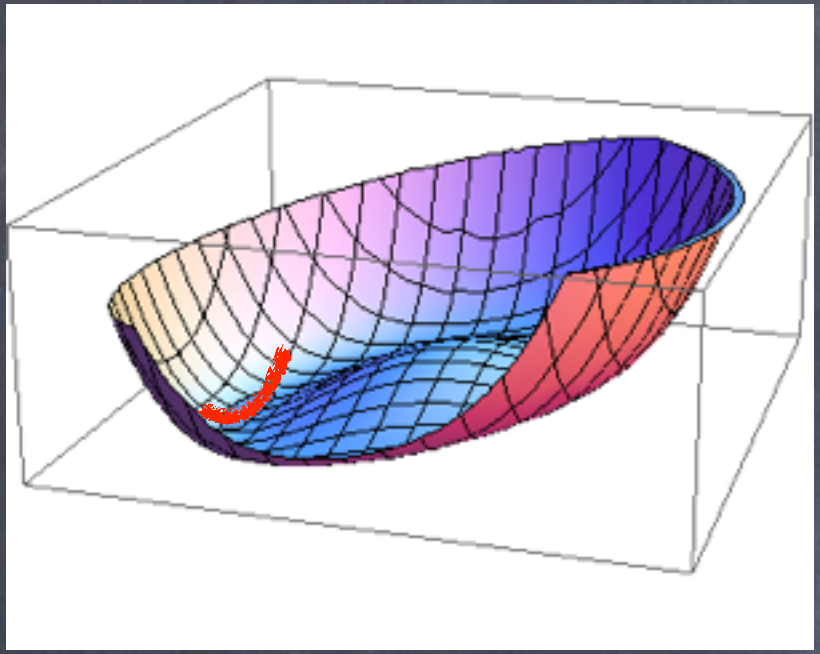
- Goldstones include the longitudinal d.o.f. of W and Z
- the Higgs is a heavy bound state (singlet under H)

QCD template:

π pions

σ sigma

Compositeness, and the Higgs boson



Global symmetry of the system:

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

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

SM gauge symmetry!

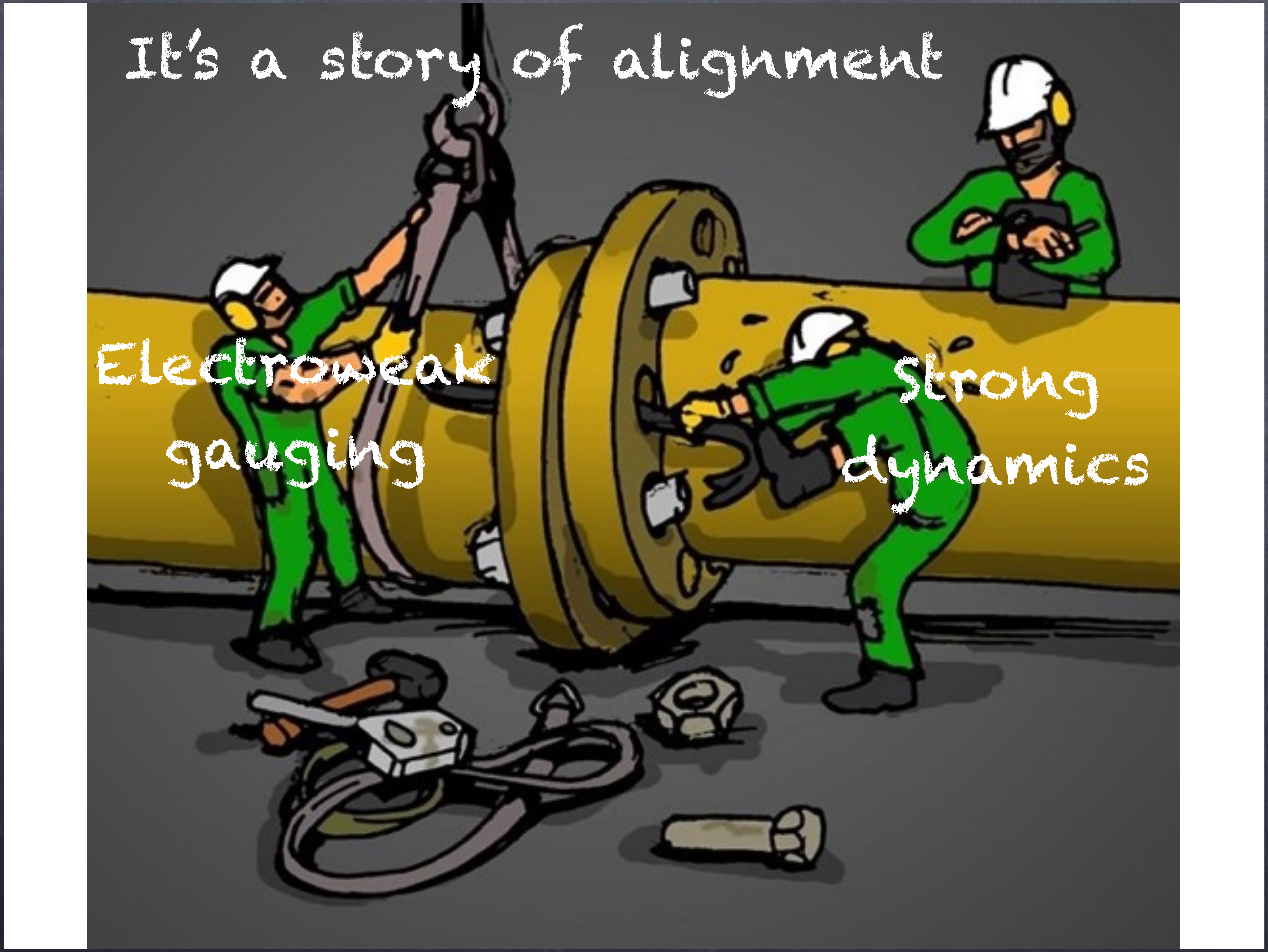
- Goldstones include the longitudinal d.o.f. of W and Z
- the Higgs is a pseudo-Goldstone

QCD template:

π pions

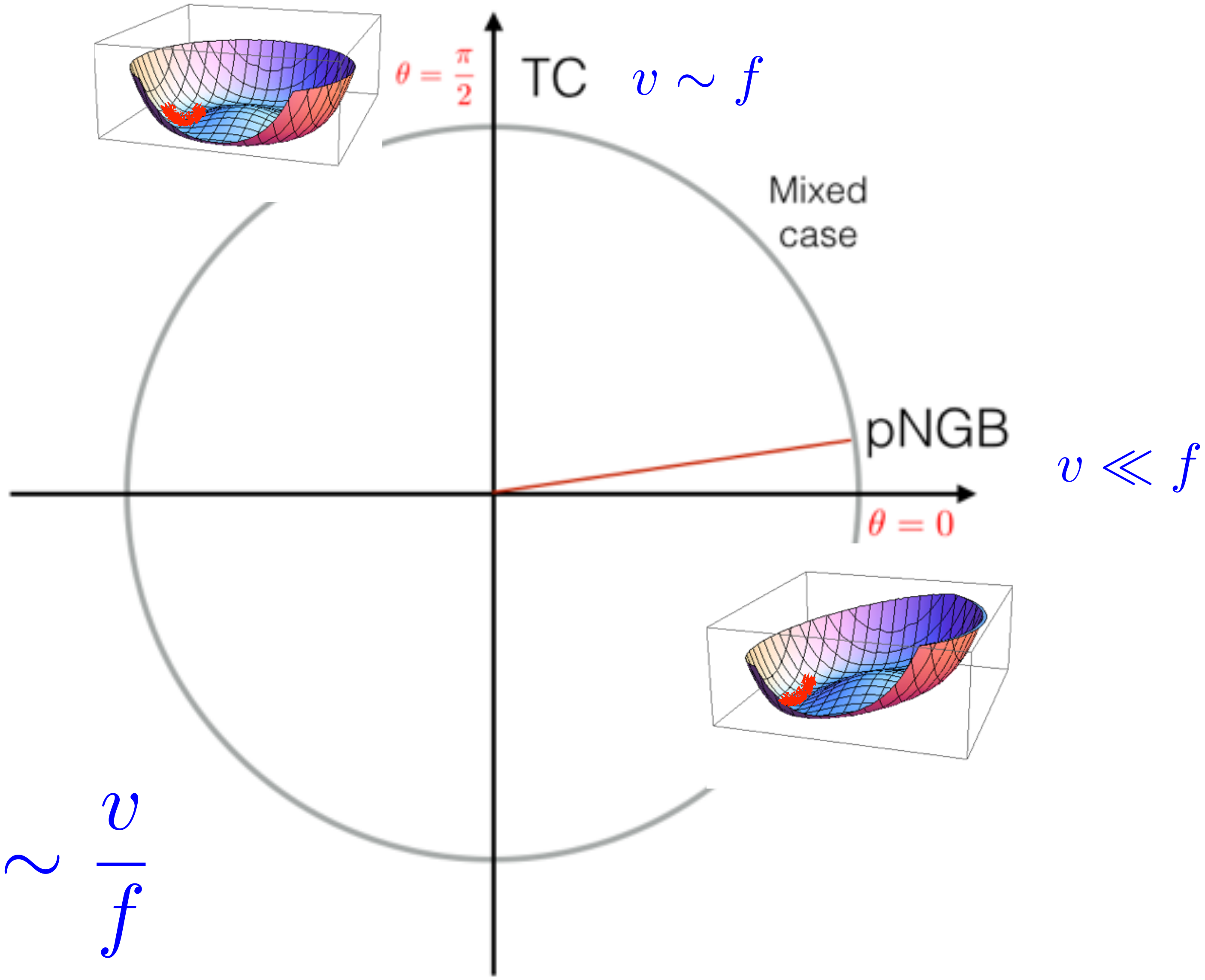
σ sigma

Compositeness, and the Higgs boson



It's a story of alignment

Compositeness, and the Higgs boson



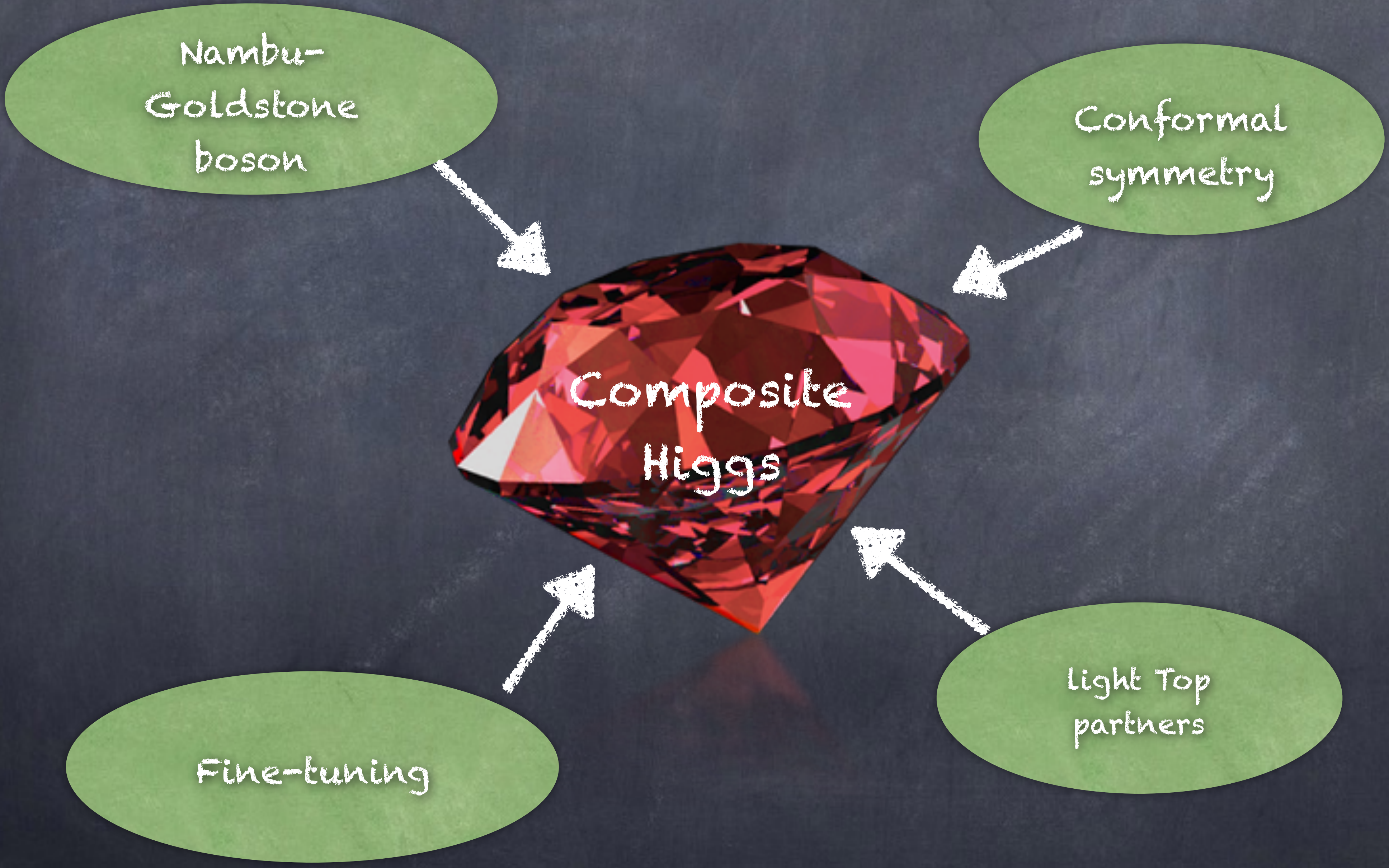
$$\sin\theta \sim \frac{v}{f}$$

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!

Provocative slide
(for the composite alchemists)



Nambu-Goldstone boson

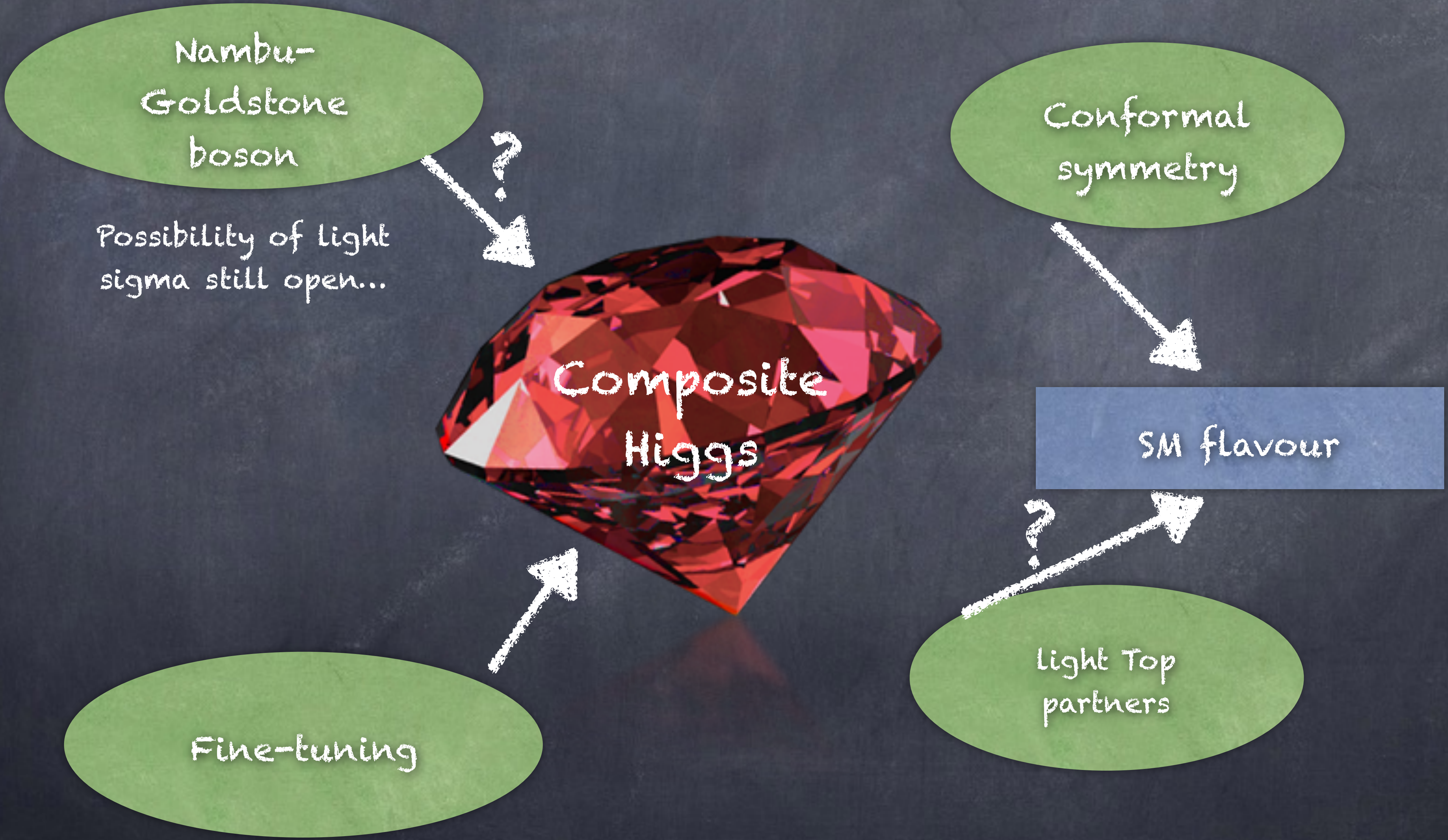
Conformal symmetry

Composite Higgs

Fine-tuning

light Top partners

Provocative slide
(for the composite alchemists)



Nambu-Goldstone boson

?

Possibility of light sigma still open...

Conformal symmetry

Composite Higgs

SM flavour

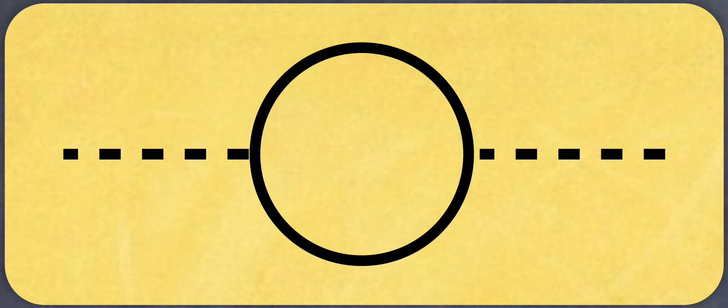
?

light Top partners

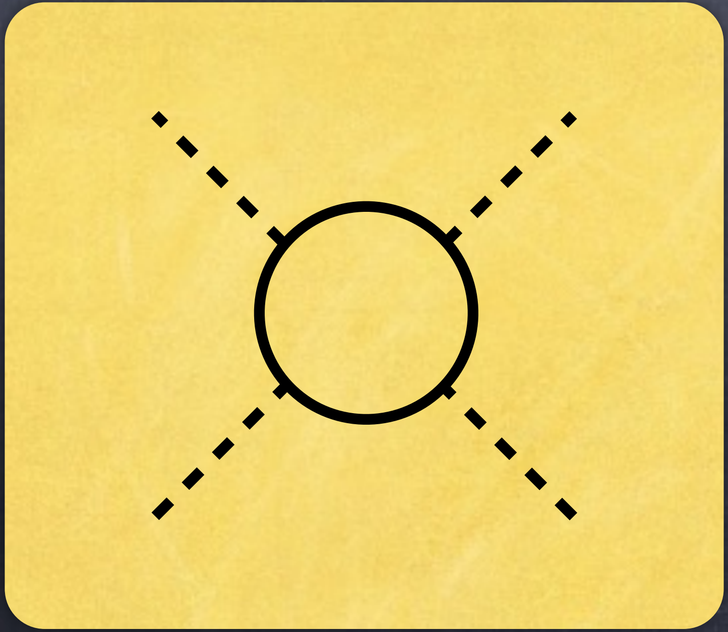
Fine-tuning

Not severe...

Anatomy of the potential

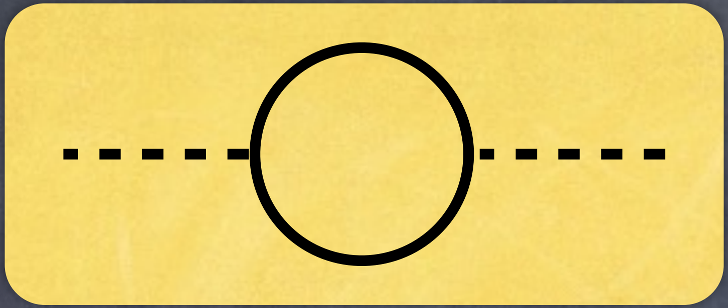


$$\delta m_h^2 \sim \frac{y^2}{16\pi^2}\Lambda^2$$



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

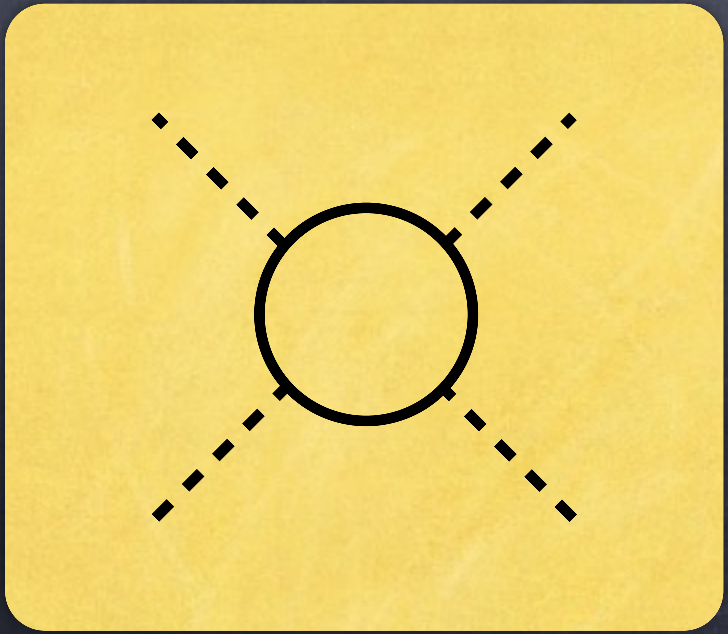
Anatomy of the potential



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

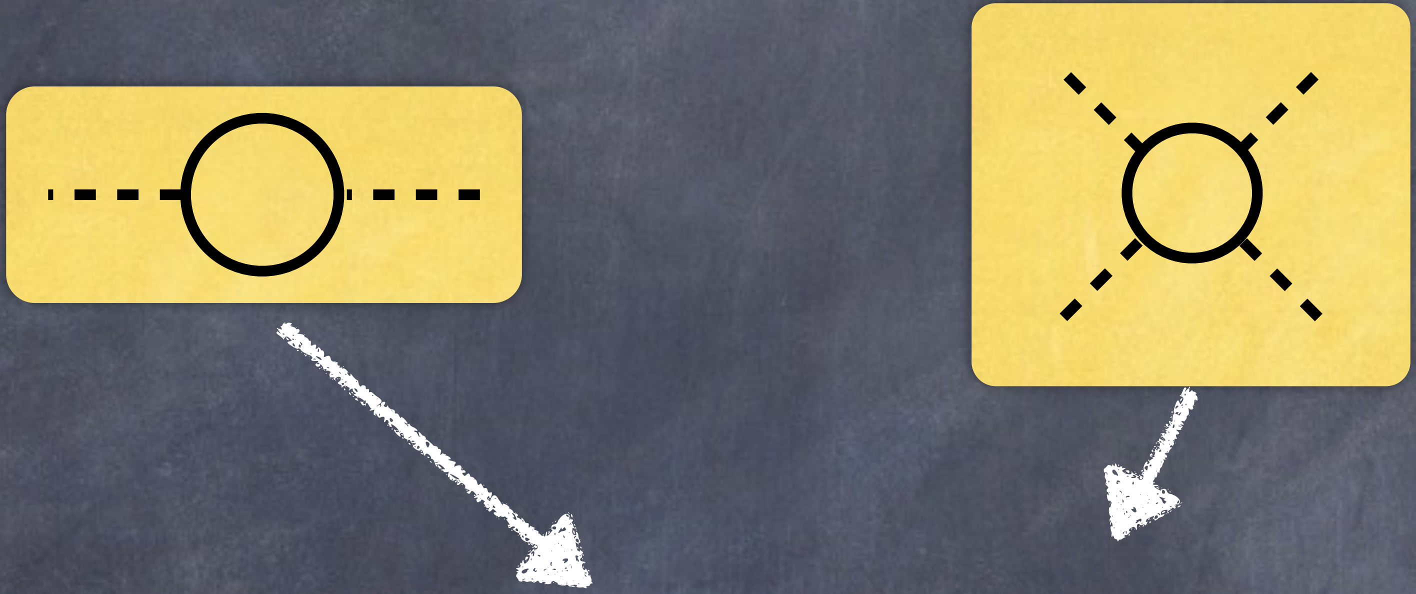
$$\Lambda \sim 4\pi f$$

Strong dynamics estimate



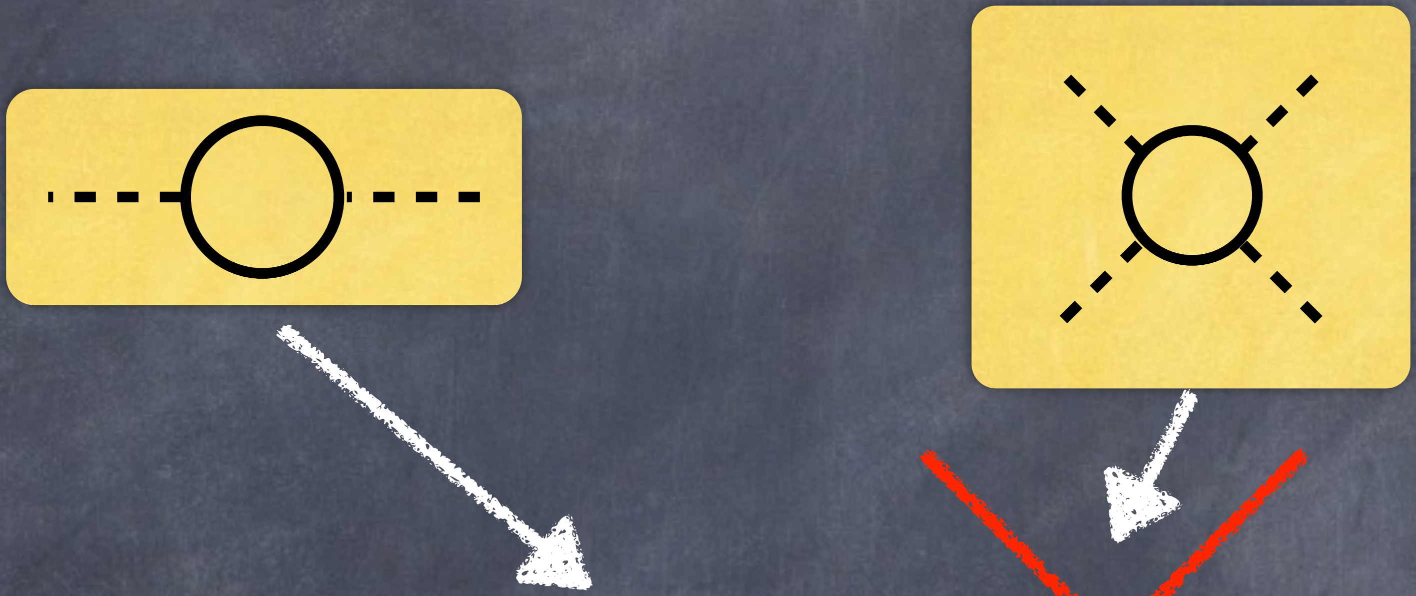
$$\delta\lambda \sim \frac{y^4}{16\pi^2}\log\Lambda$$

Anatomy of the potential



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

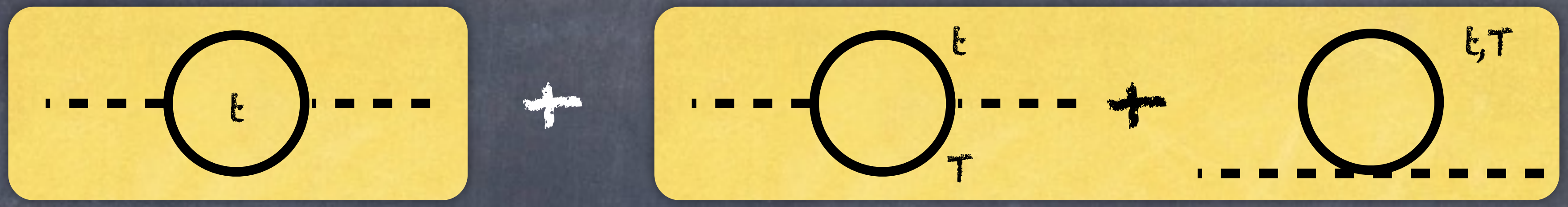
Anatomy of the potential



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

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

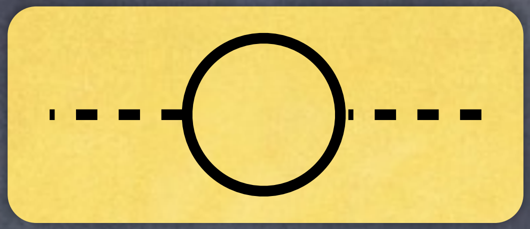
Anatomy of the potential



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

Minimum: $\theta \sim \epsilon$

Anatomy of the potential



Explicit symmetry breaking?

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

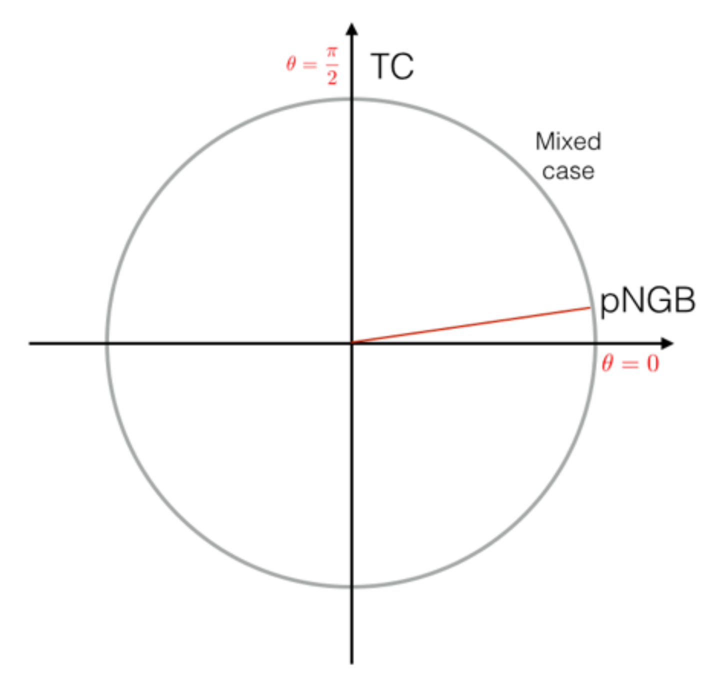
Minimum: $\theta \sim \epsilon$

Possible!

Anatomy of the potential

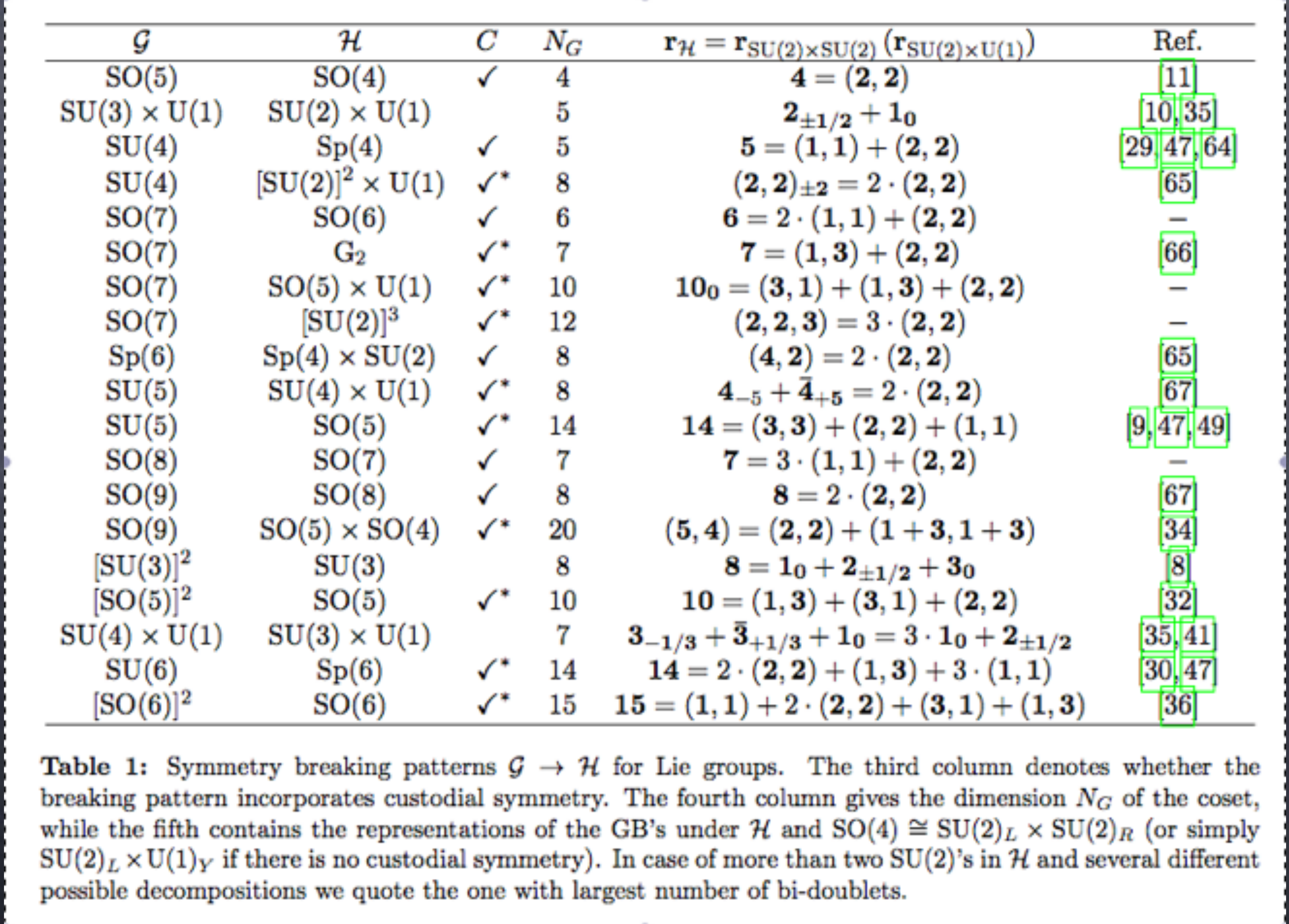
Higgs mass in the small theta limit:

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



Naturally in the right ballpark, without further fine tuning!

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)	$[\mathrm{SU(2)}]^2$ × 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.

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	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 minimal case

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

Anti-symmetric

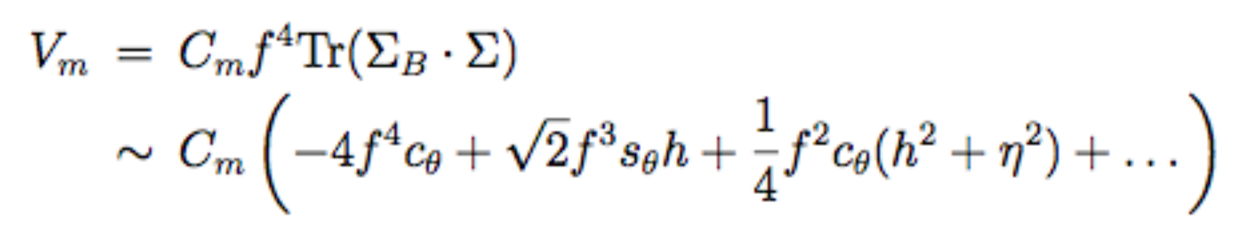
$$\langle \psi^i \psi^j \rangle = 6_{\mathrm{SU}(4)} \to 5_{\mathrm{Sp}(4)} \oplus 1_{\mathrm{Sp}(4)}$$

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

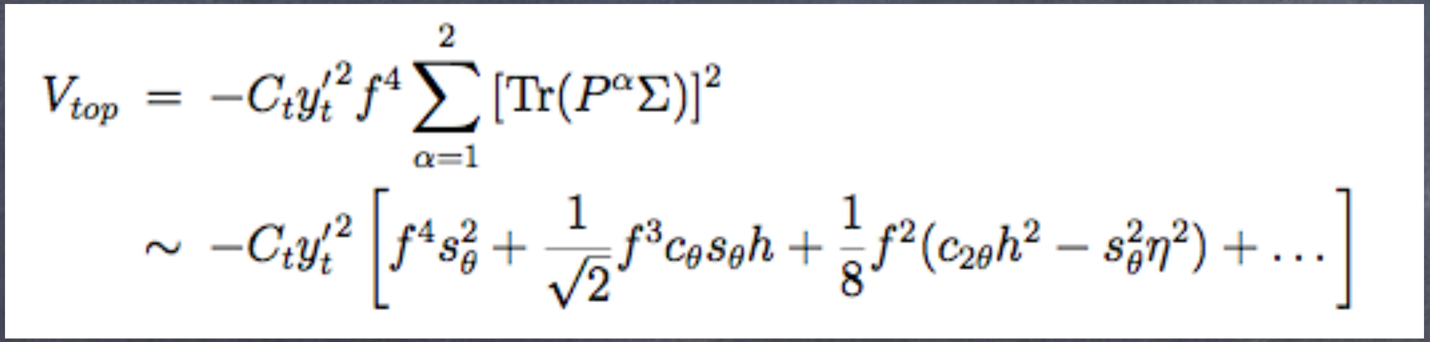
Pions: $5_{\mathrm{Sp}(4)} \to (2,2) \oplus (1,1)$

The minimal case

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



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



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

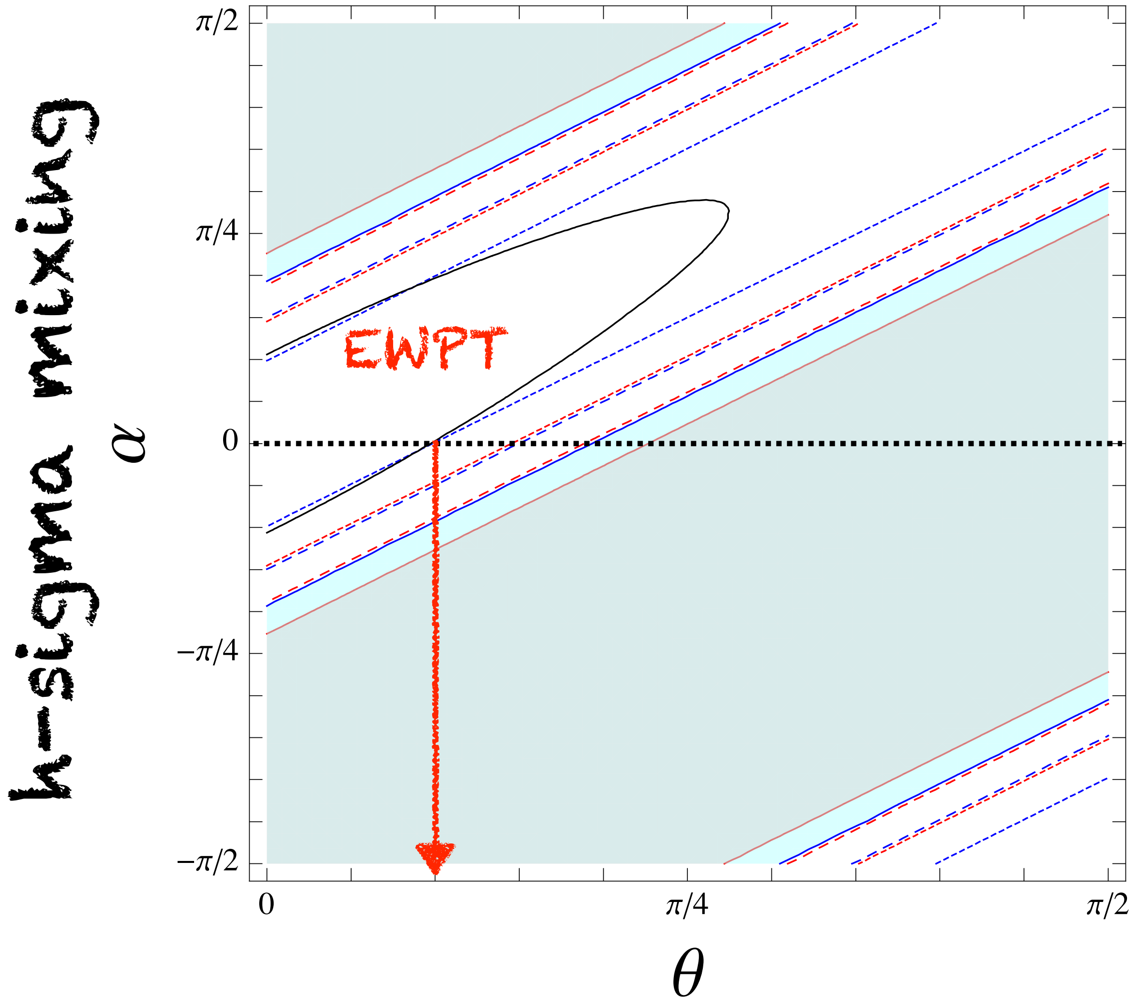
$$m_h \sim \frac{\sqrt{C_t}}{2} y_t f \sin\theta \sim \frac{\sqrt{C_t}}{2} m_t \qquad m_\eta \sim \frac{\sqrt{C_t}}{2} y_t f \sim \frac{m_h}{\sin\theta}$$

$$C_t \sim 2$$

reproduces data!

The minimal case

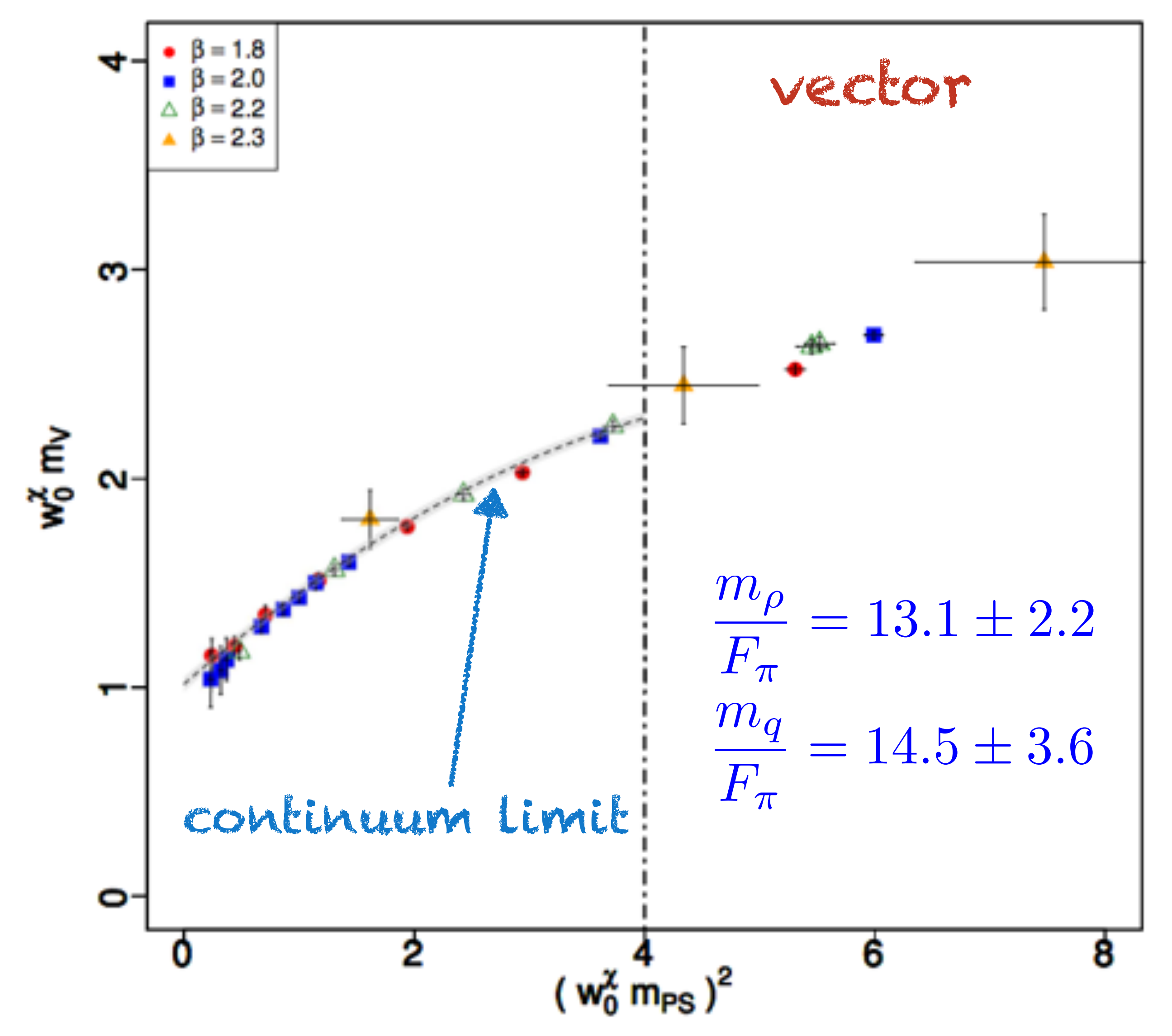
Arbey, G.C., Cai, Deandrea, Le Corre, Sannino
1502.04718



$\sin\theta \lesssim 0.2$

The minimal case

Lattice results:



$$\frac{m_\rho}{F_\pi} = 13.1 \pm 2.2$$

$$\frac{m_q}{F_\pi} = 14.5 \pm 3.6$$

Arthur, Drach, et al. 1602.06559

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

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

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

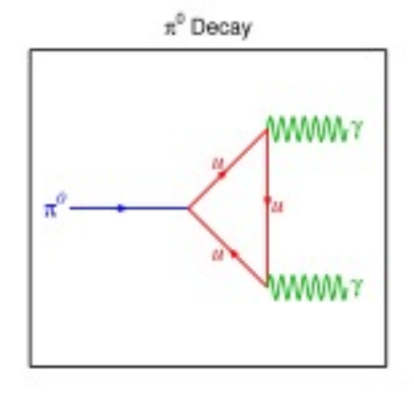
$$m_\eta \sim \frac{m_h}{\sin\theta} \gtrsim 600\ GeV$$

$$m_h = 125\ GeV$$

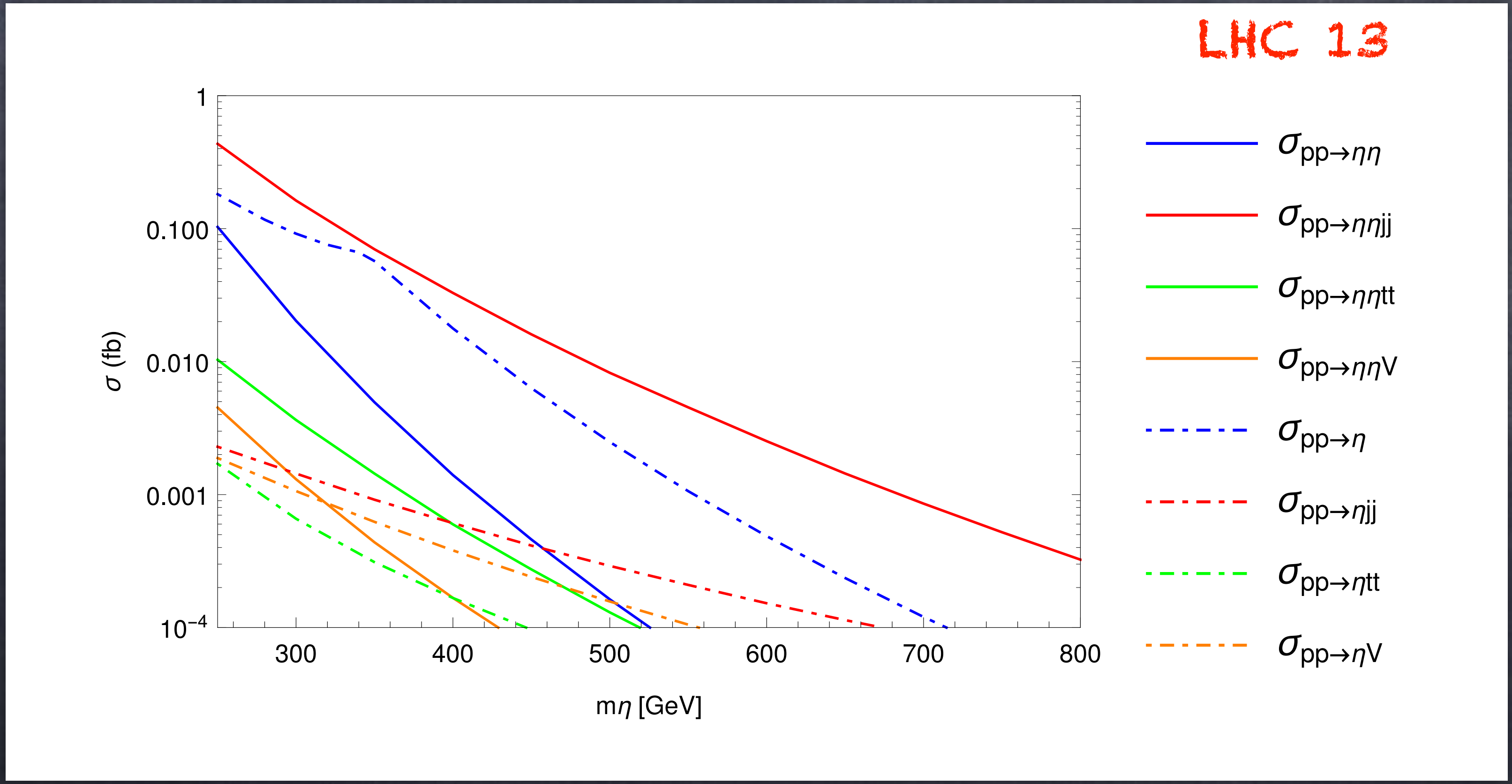
The minimal case

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

Singlet cannot be
Dark Matter!

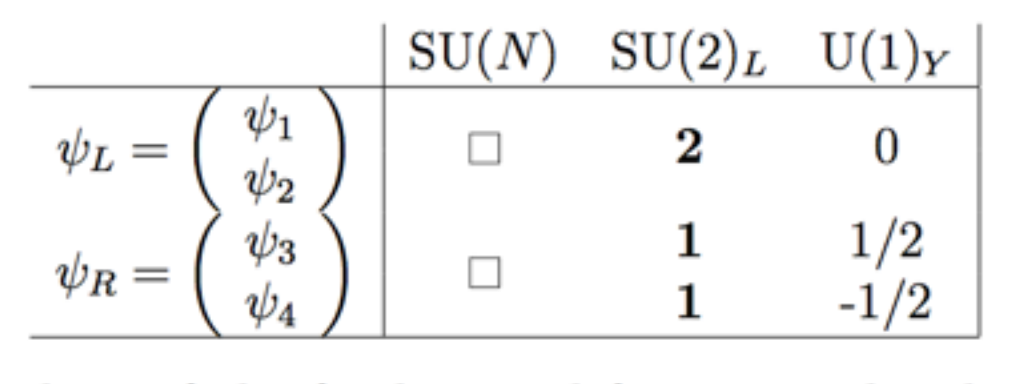


Anomalous coupling to:
WW, ZZ, Z gamma



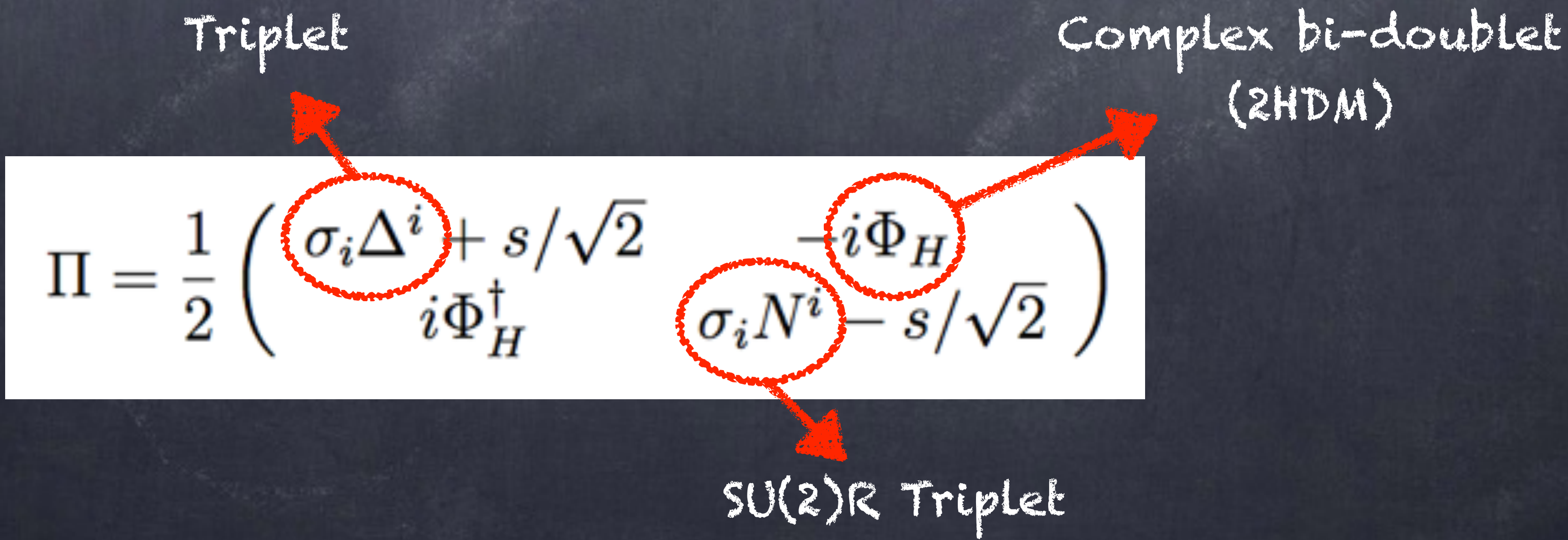
A composite 2HDM

G.C., T.Ma
1508.07014



		SU(N)	SU$(2)_L$	U$(1)_Y$
$\psi_L =$	ψ_1	□	**2**	0
	ψ_2			
$\psi_R =$	ψ_3	□	**1**	1/2
	ψ_4		**1**	-1/2

$$SU(4) \times SU(4) \rightarrow SU(4)$$

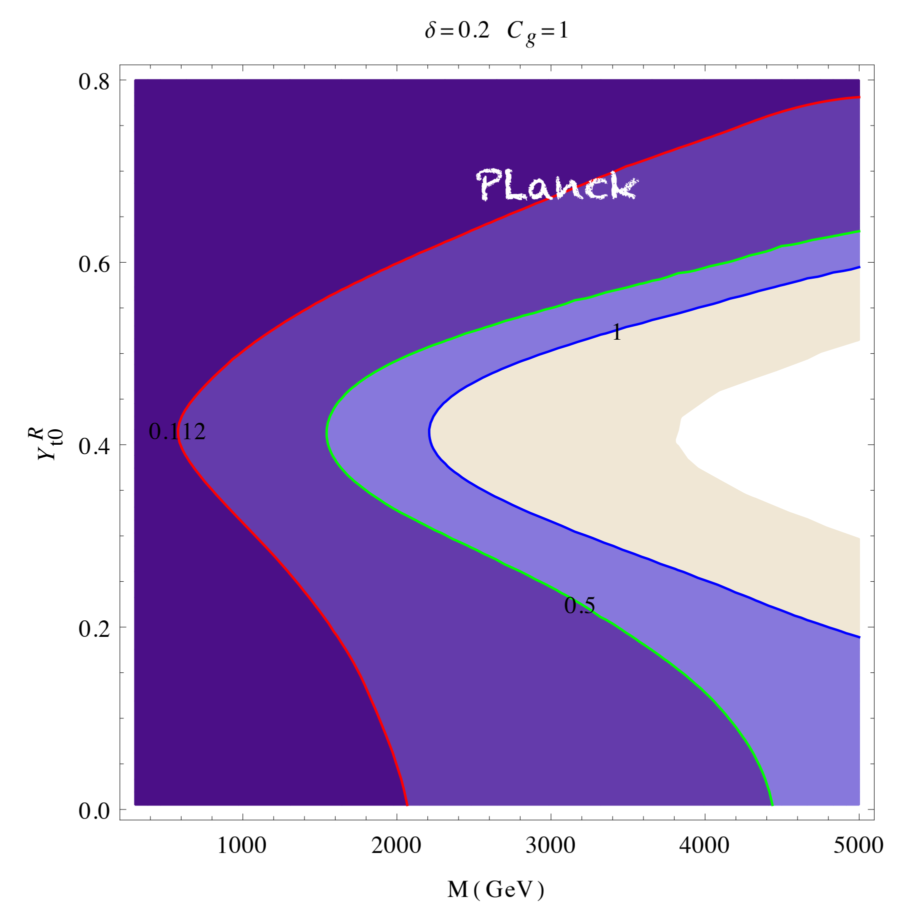


$$\Pi = \frac{1}{2}\begin{pmatrix} \sigma_i\Delta^i + s/\sqrt{2} & -i\Phi_H \\ i\Phi_H^\dagger & \sigma_i N^i - s/\sqrt{2} \end{pmatrix}$$

A composite 2HDM: 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!

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

100.000 TeV	$\Lambda_{\mathrm{flavour}}$	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	$v_{\mathrm{SM}} \sim f \sin\theta$	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? Conformal dynamics, or symmetry reason?
- "Theory of flavour" can be addressed!

The hot potato: flavour!

Typical scenario:

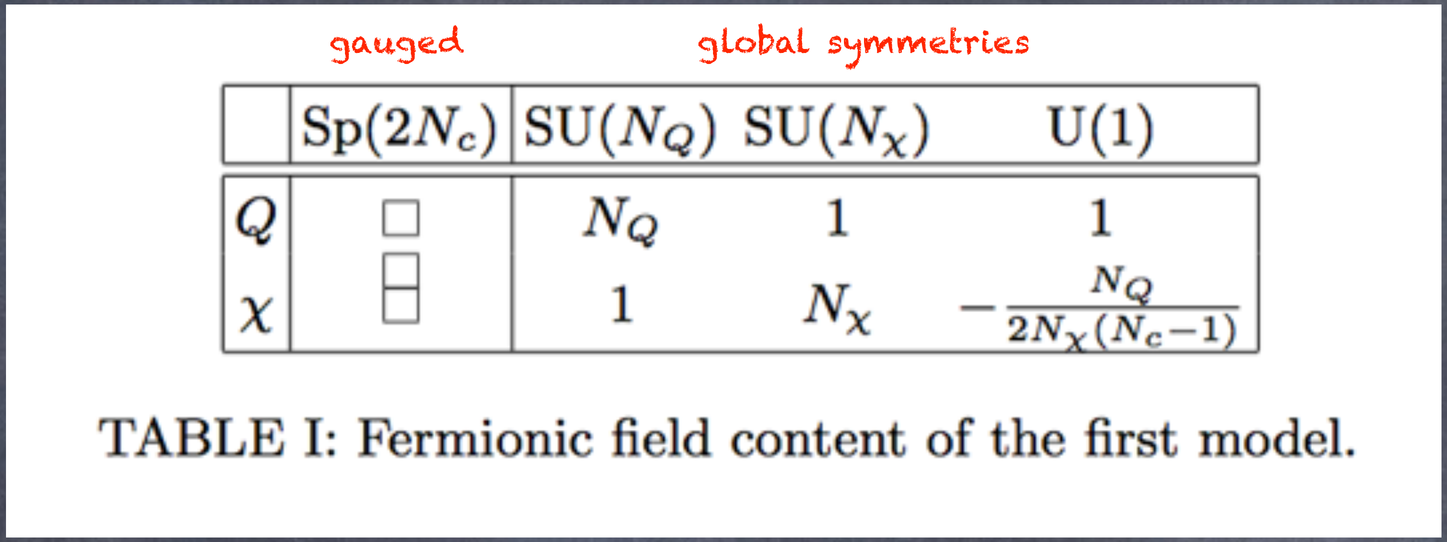
G.Ferretti, D.Karateev
1312.5330, 1604.06467

$\mathcal{G}_{\rm TC}$:	rep R	rep R′
	Q	χ
SM :	EW	colour + hypercharge
global :	$\langle QQ\rangle \neq 0$	a) $\langle\chi\chi\rangle \neq 0$
	$\downarrow$	coloured pNGBs di-boson
	pNGB Higgs DM?	b) $\langle\chi\chi\rangle = 0$
		light top partners

Exception: 1506:00623

Light 't Hooft Top Partners

G.C., A.Parolini
1511.05163



gauged — global symmetries

	Sp($2N_c$)	SU(N_Q)	SU(N_χ)	U(1)
Q	$\square$	N_Q	1	1
χ	$\begin{array}{c}\square\\\square\end{array}$	1	N_χ	$-\frac{N_Q}{2N_\chi(N_c-1)}$

TABLE I: Fermionic field content of the first model.

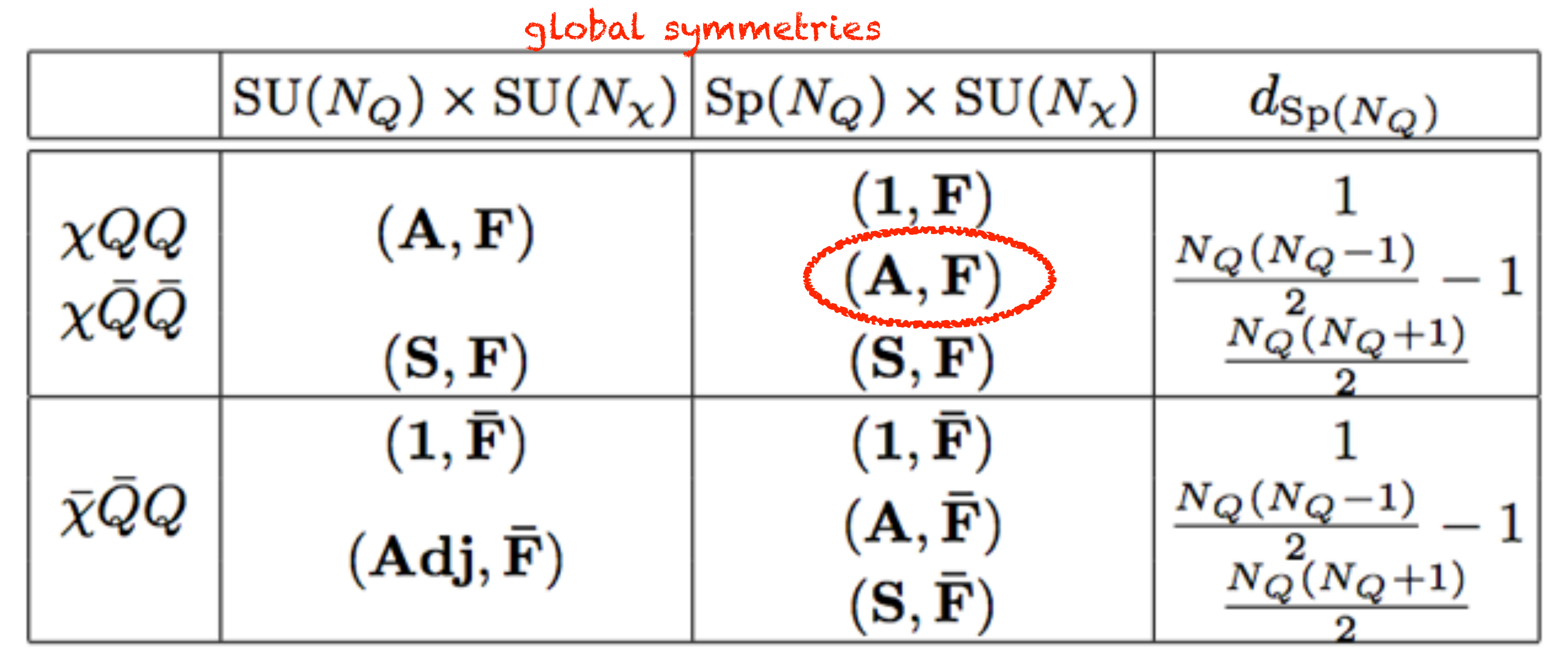
Barnard, Gherghetta, Ray 1311.6562
Ferretti, Karateev 1312.5330

- $\langle QQ\rangle \neq 0$ 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 $\frac{N_Q(N_Q-1)}{2}-1$ $\frac{N_Q(N_Q+1)}{2}$

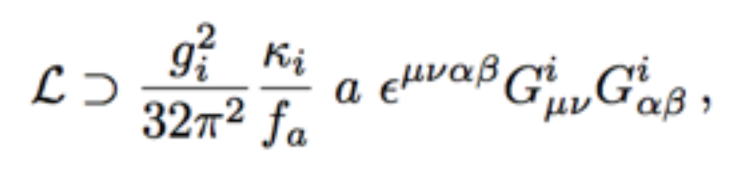
$$A_{SU(N_\chi)^2} \propto dim(\chi) = (2N_c+1)(N_c-1)$$

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

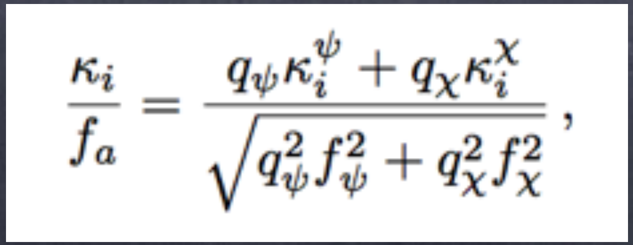
Predicting di-boson resonances

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 !!!

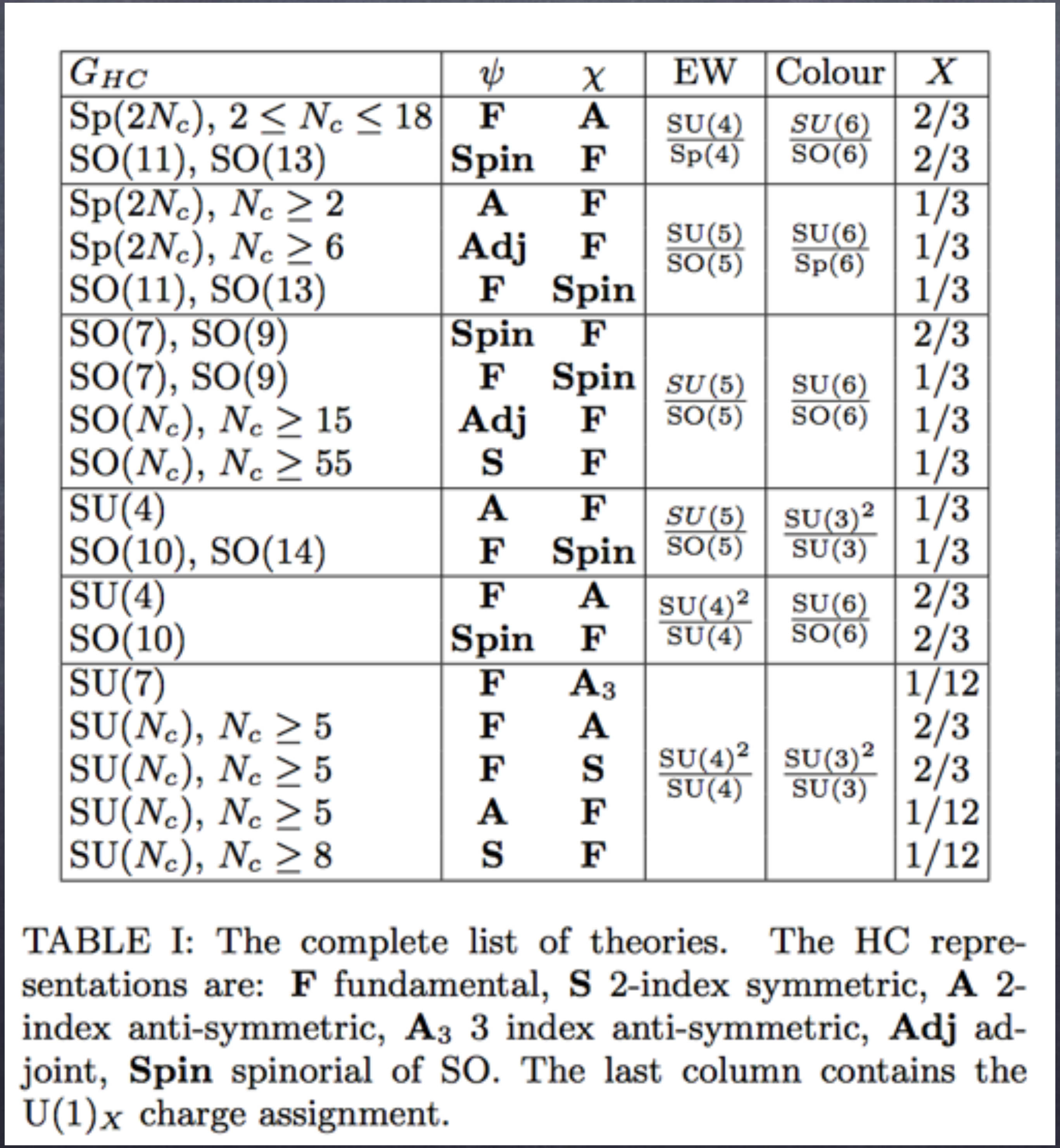
Cai, Flacke, Lespinasse 1512.04508

Anomalous U(1) -> heavy η'

Orthogonal U(1) -> pNGB a

Decays and production only via WZW anomaly.

Predicting di-boson resonances



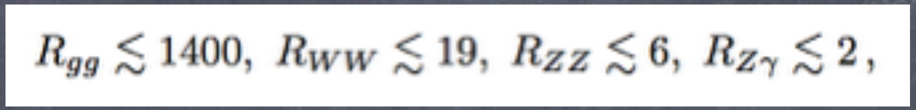
G_{HC}	ψ	χ	EW	Colour	X
$\mathrm{Sp}(2N_c)$, $2 \leq N_c \leq 18$	**F**	**A**	$\frac{\mathrm{SU}(4)}{\mathrm{Sp}(4)}$	$\frac{SU(6)}{\mathrm{SO}(6)}$	2/3
SO(11), SO(13)	**Spin**	**F**			2/3
$\mathrm{Sp}(2N_c)$, $N_c \geq 2$	**A**	**F**	$\frac{\mathrm{SU}(5)}{\mathrm{SO}(5)}$	$\frac{\mathrm{SU}(6)}{\mathrm{Sp}(6)}$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

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

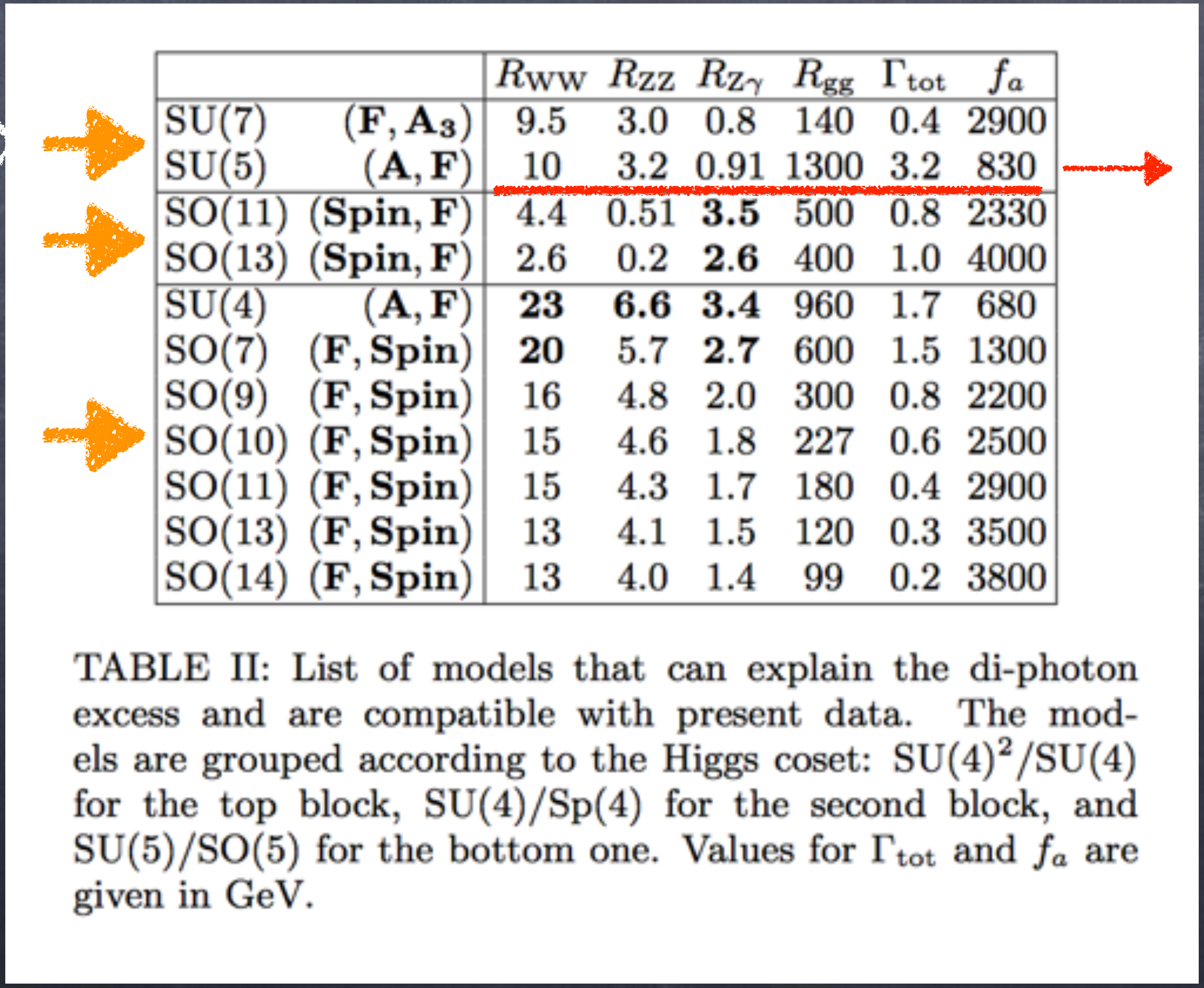


$R_{gg} \lesssim 1400,\ R_{WW} \lesssim 19,\ R_{ZZ} \lesssim 6,\ R_{Z\gamma} \lesssim 2,$

$SU(4)^2/SU(4)$

$SU(4)/Sp(4)$

$SU(5)/SO(5)$



		R_{WW}	R_{ZZ}	$R_{Z\gamma}$	R_{gg}	Γ_{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 Γ_{tot} and f_a are given in GeV.

if $f_a \sim f$

$\sin\theta \sim 0.1$

Summary and outlook

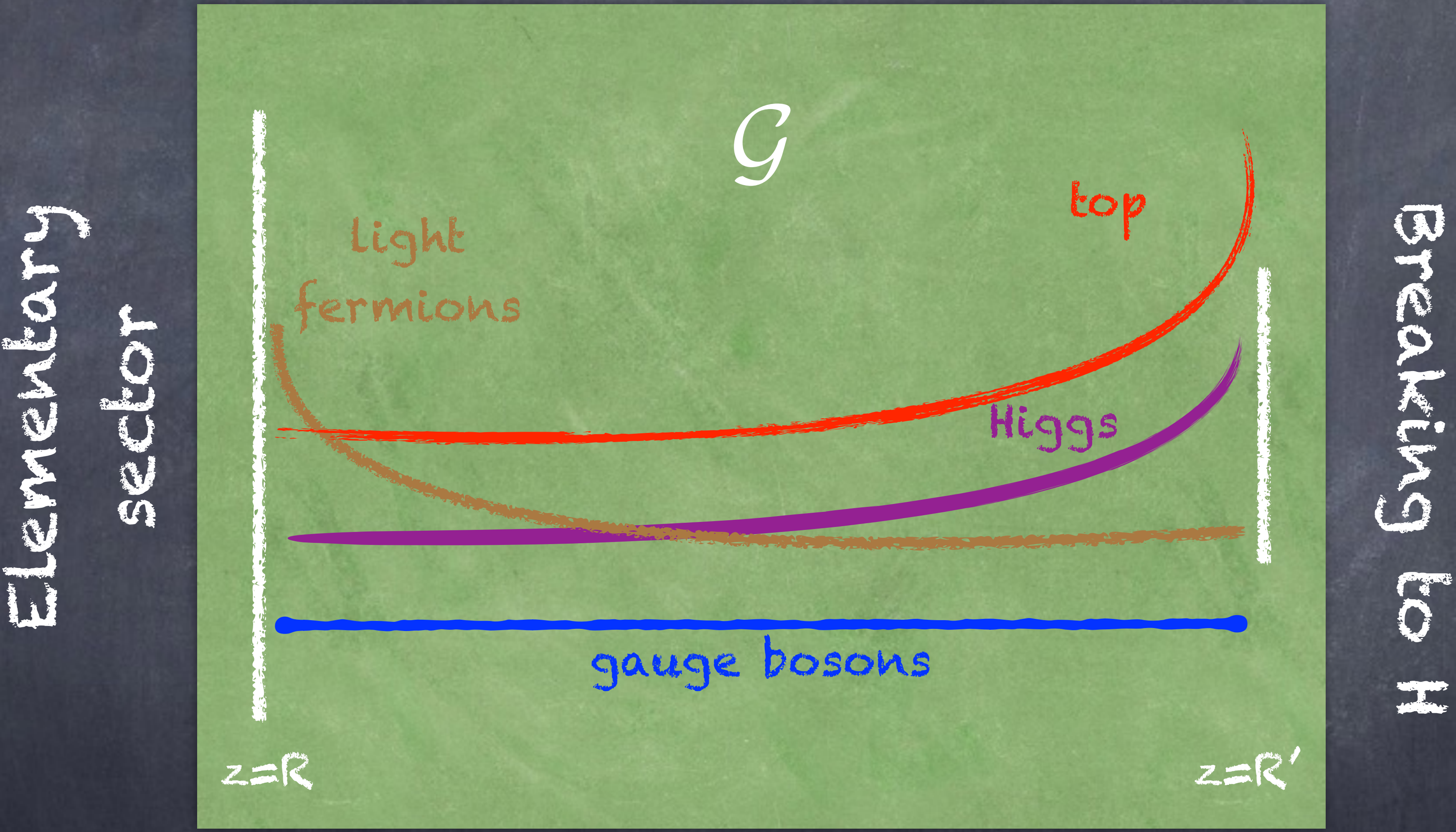
- FCD is a guide to build composite Higgs models!
- A very simple Higgs sector is possible (SU(4)/Sp(4))
- Less minimal models feasible: DM? LHC signatures?
- FCD allows to probe fermion mass generations (UV completion, conformal windows...)
- FCD models can be tested on the Lattice!
- Di-boson (photon) @ the LHC is a "standard candle" for compositeness (via the WZW anomaly)

Backup

Rediscovery of composite Higgses

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

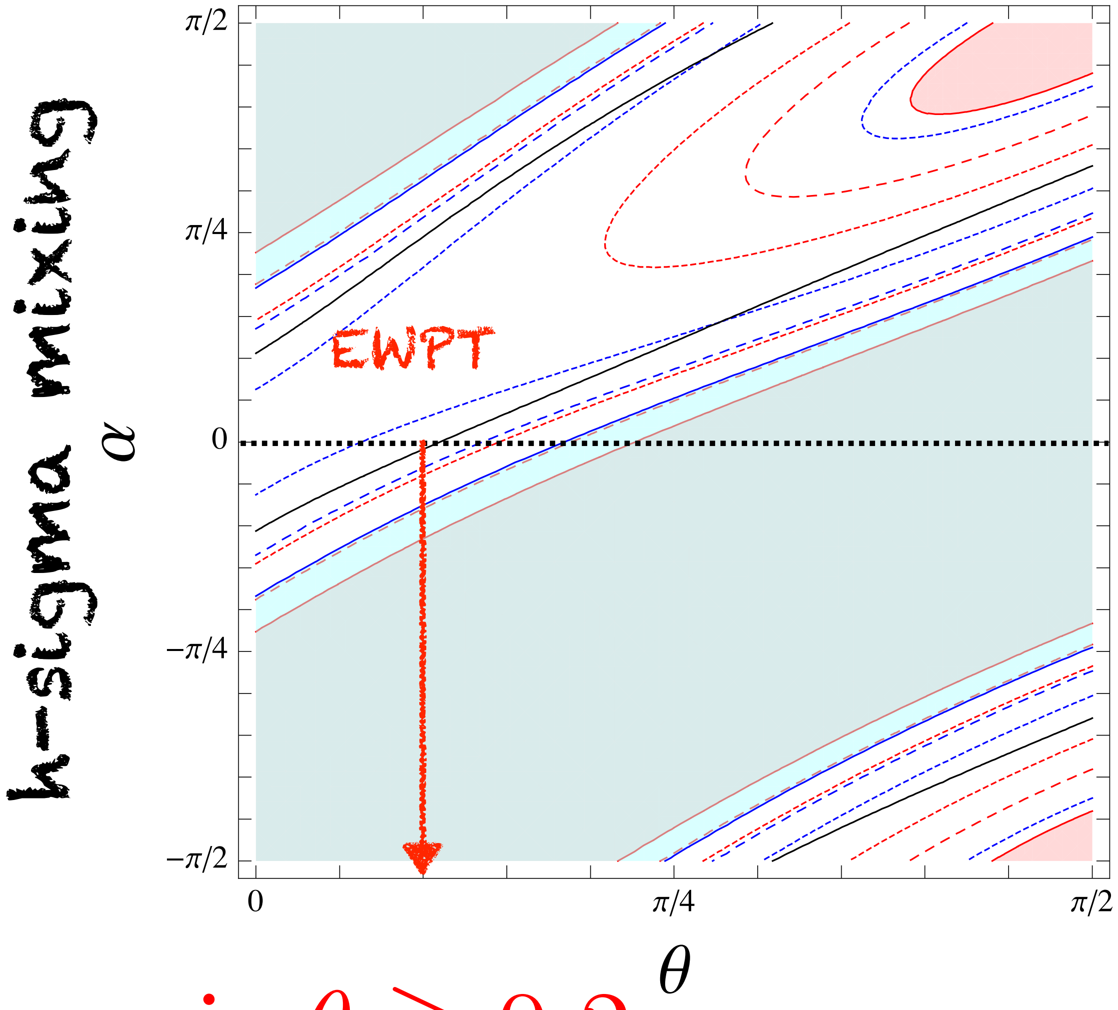
Randall Sundrum



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

The minimal case

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



$\sin\theta \gtrsim 0.2$

A composite 2HDM

G.C., T.Ma
1508.07014

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

$$\langle\Phi_H\rangle = \langle H_1 + iH_2\rangle = \begin{pmatrix} ve^{i\beta} & 0 \\ 0 & ve^{i\beta} \end{pmatrix}$$

$$\Sigma = \begin{pmatrix} \cos\theta\ \mathbf{1} & e^{i\beta}\sin\theta\ \mathbf{1} \\ -e^{i\beta}\sin\theta\ \mathbf{1} & \cos\theta\ \mathbf{1} \end{pmatrix}$$

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

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

Beta = relative phase of the two T-quarks!

A composite 2HDM

G.C., T.Ma
1508.07014

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

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

4 "Yukawa" couplings!

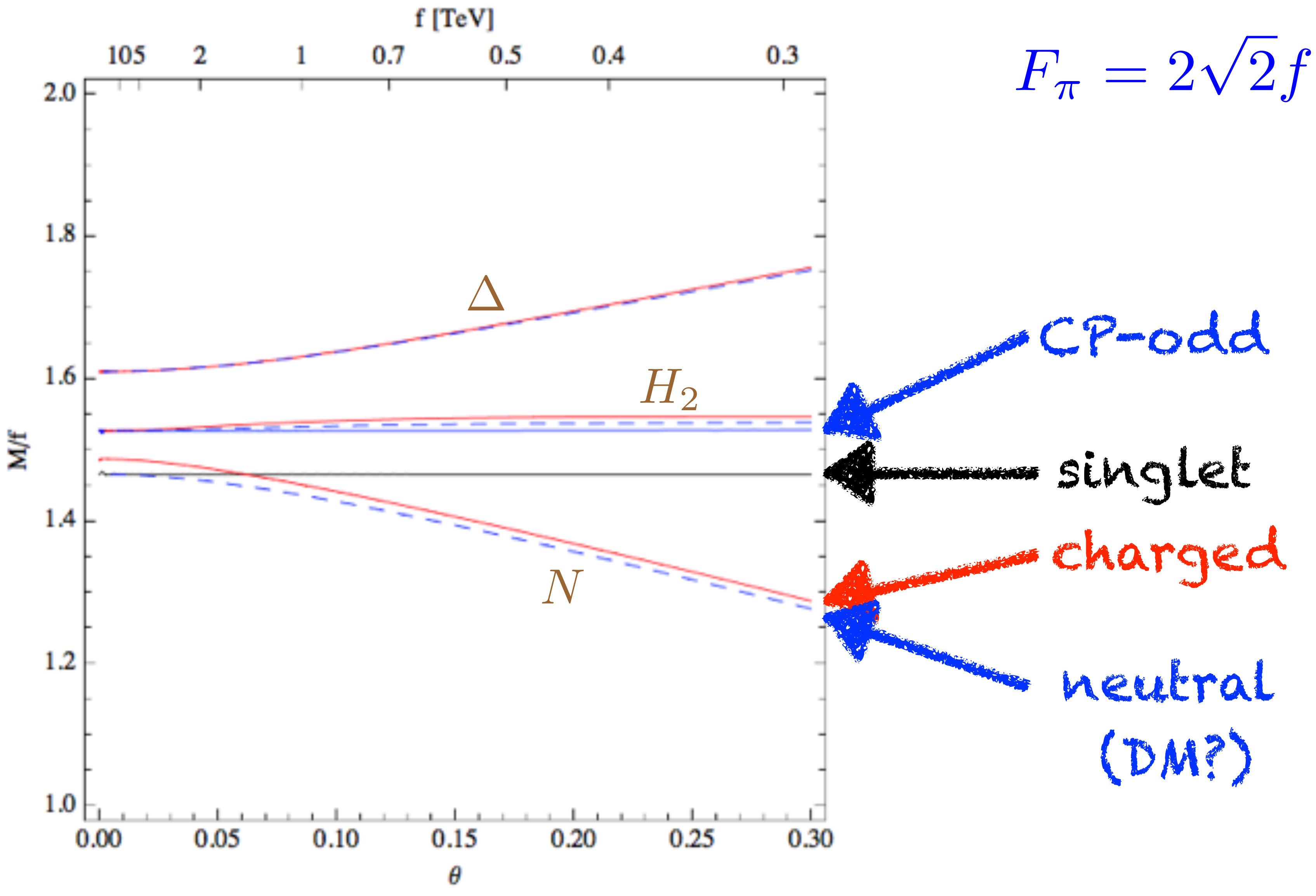
$$\begin{aligned}V_{\rm top}(\theta) \quad = -C_t f^4 \quad \Big[& 8|Y_t|^2 \sin^2\theta + \\ & 2\sqrt{2}|Y_t|^2 \sin(2\theta)\,\frac{h_1}{f} + \\ & +4\sqrt{2}\ {\rm Im}(Y_D^* Y_t)\sin\theta\,\frac{h_2}{f} \\ & +2\sqrt{2}\ {\rm Re}(Y_D^* Y_t)\sin(2\theta)\,\frac{A_0}{f} \\ & +\ 4\ {\rm Im}(Y_T^* Y_t)\sin^2\theta\,\frac{N_0 + \Delta_0}{f} + \ldots \Big]\end{aligned}$$

Potential for theta

Set to zero by phase-shift

Custodial violating VEVs!!!

A composite 2HDM: spectrum



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

A composite 2HDM: EWPTs

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

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

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

Bounds similar
to minimal cases.