Composite Dark Matter and the Higgs

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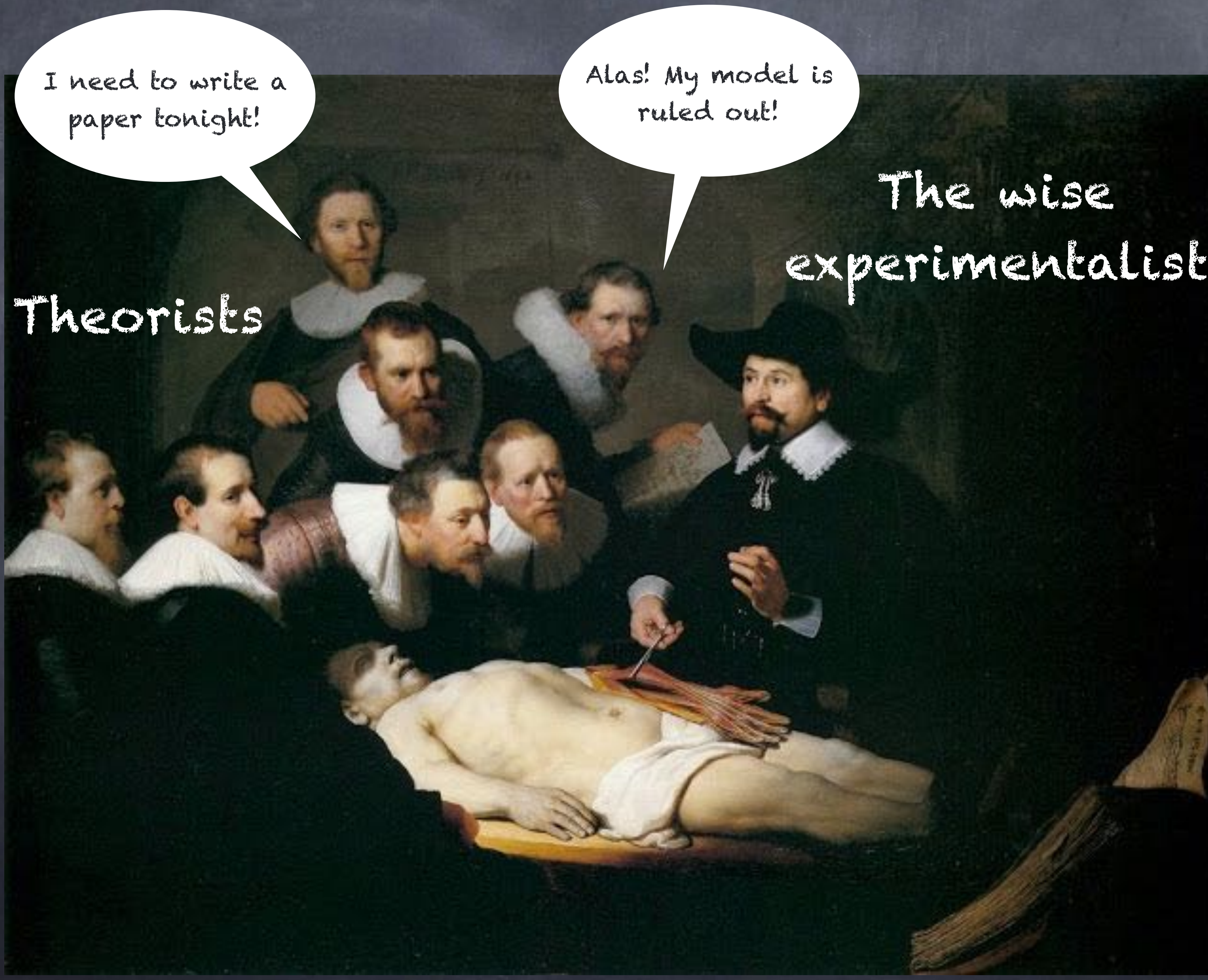
The ideal world:



The real world:

Higgs couplings!

Flavour!

No DM!

EWPTs!

Struggling to put together a model in the midst of "buzzers"!

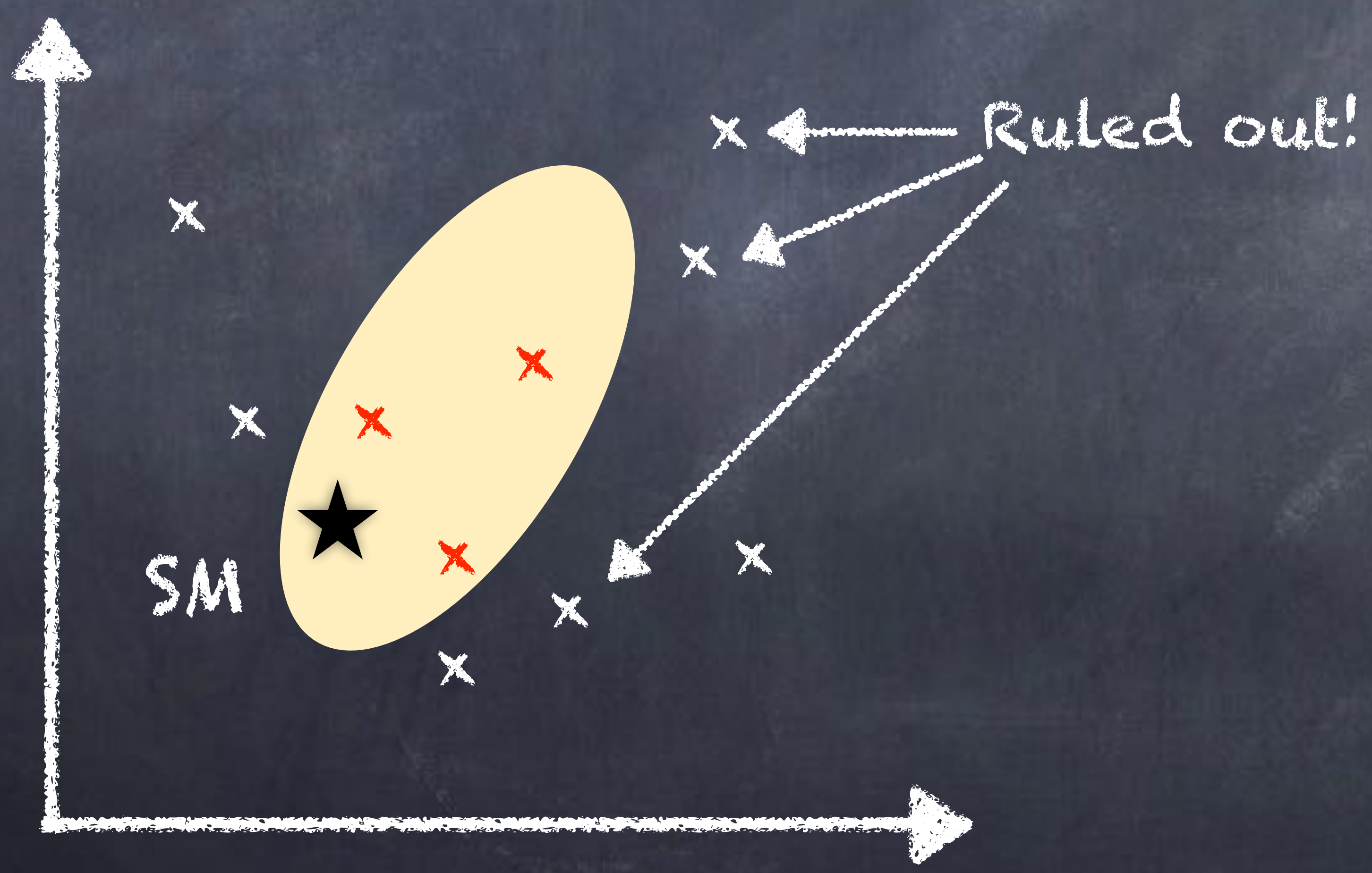
Top couplings!

No bumps!

Higgs mass!

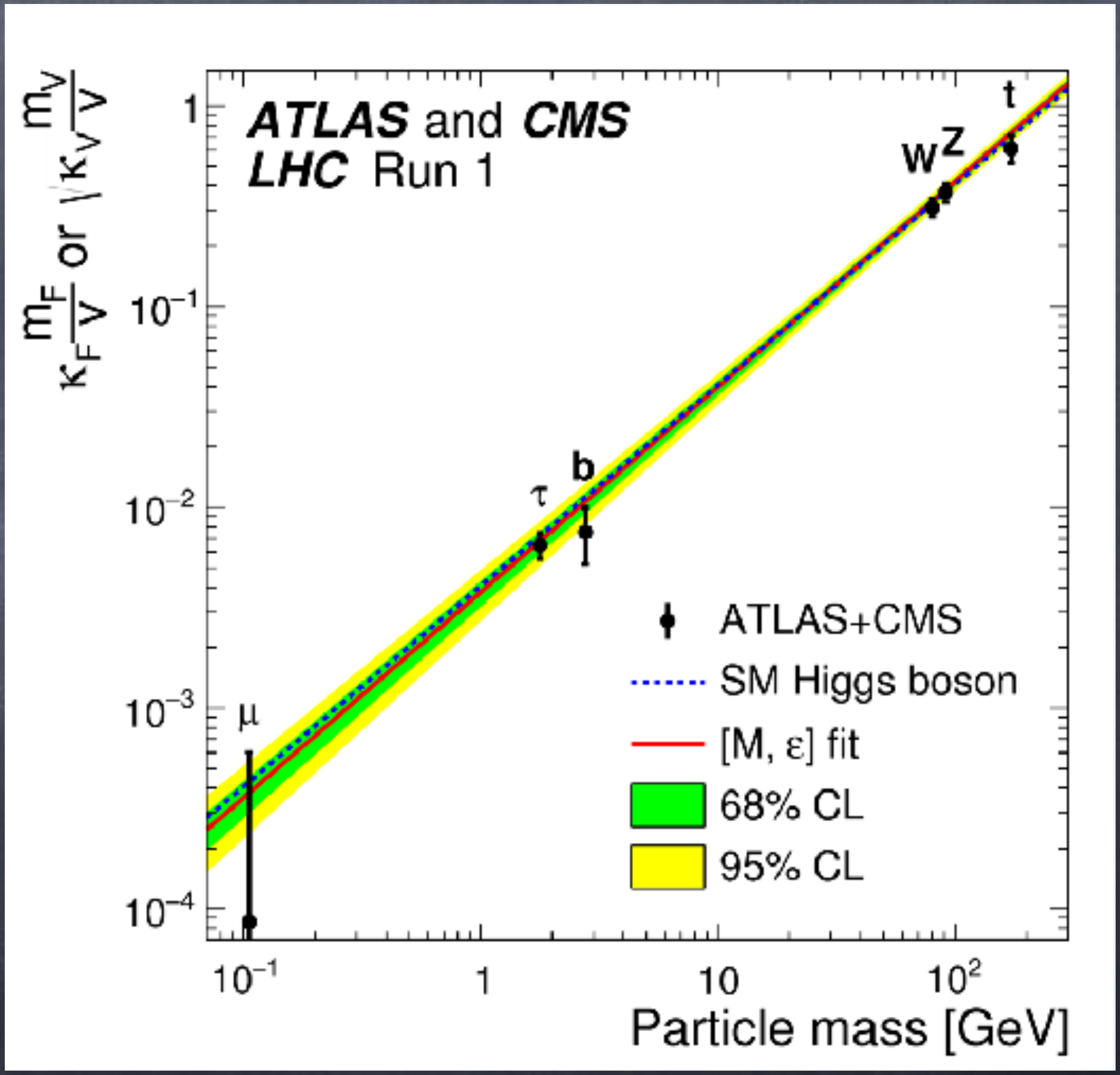
What is our job?

- Models can be ruled out, but cannot be proven right!



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!
- 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?

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

- 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:

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

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

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?

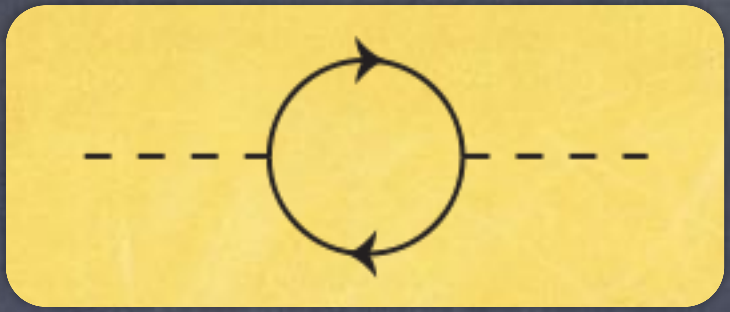
We have a pretty good idea of the mechanism

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!



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

Compositeness scale

Do we still need BSM?

Compositeness is a way to dynamically protect the Higgs mechanism!

E

No scalars

=

No hierarchy problem!

3 TeV $\Lambda_C \sim 4\pi v_{\rm SM}$

Composite scalars

$v_{\rm SM} \sim 246$ GeV

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

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!

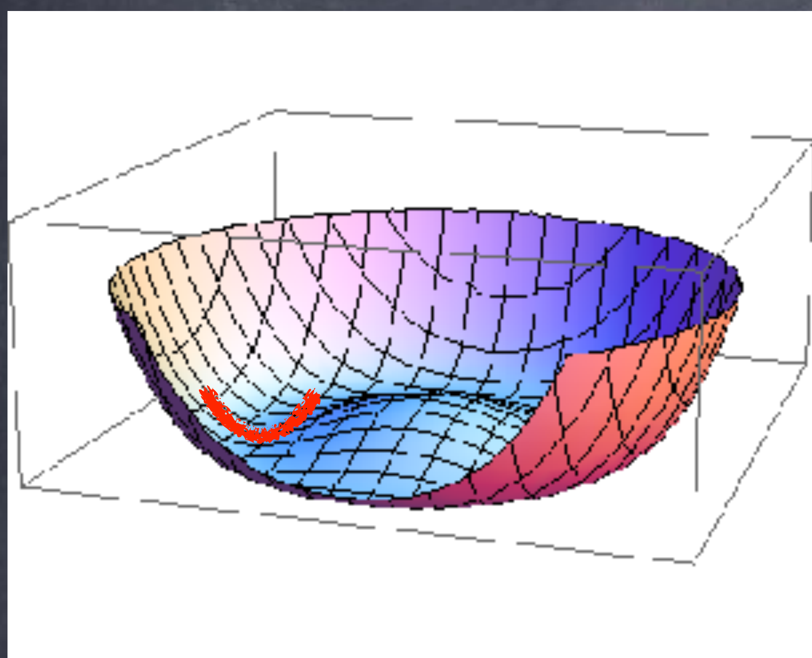
$$m_W = \frac{g f_\pi}{2} \sim 40 \text{ MeV}$$

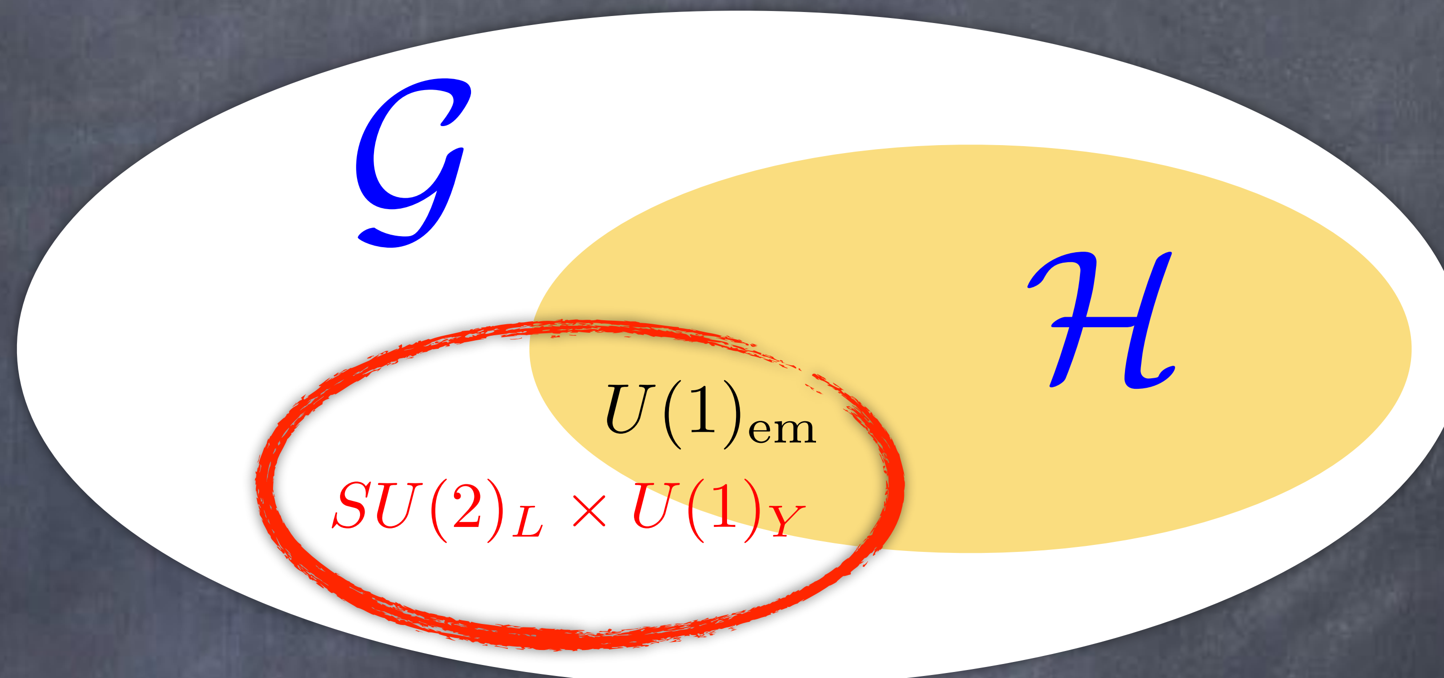
This observation led to the development of
Technicolor in 1979-80.

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



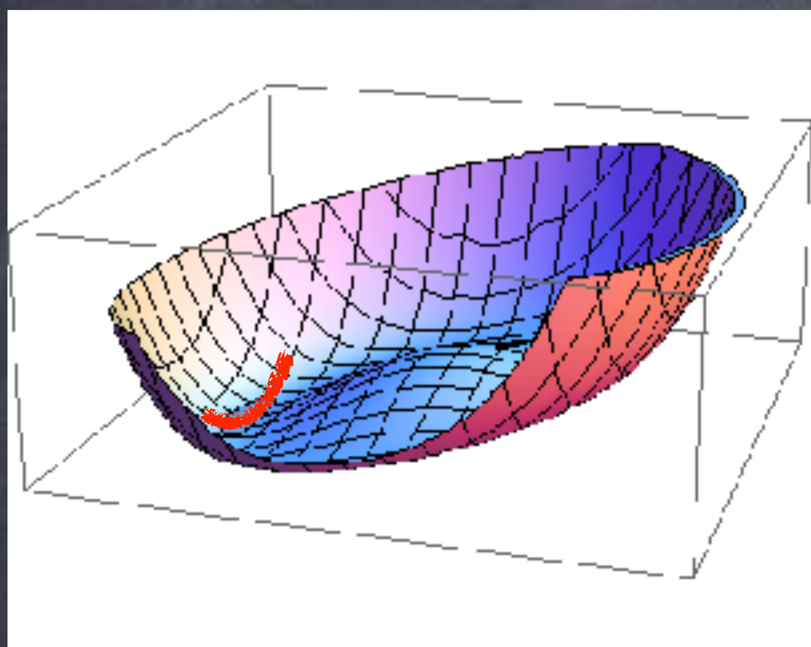


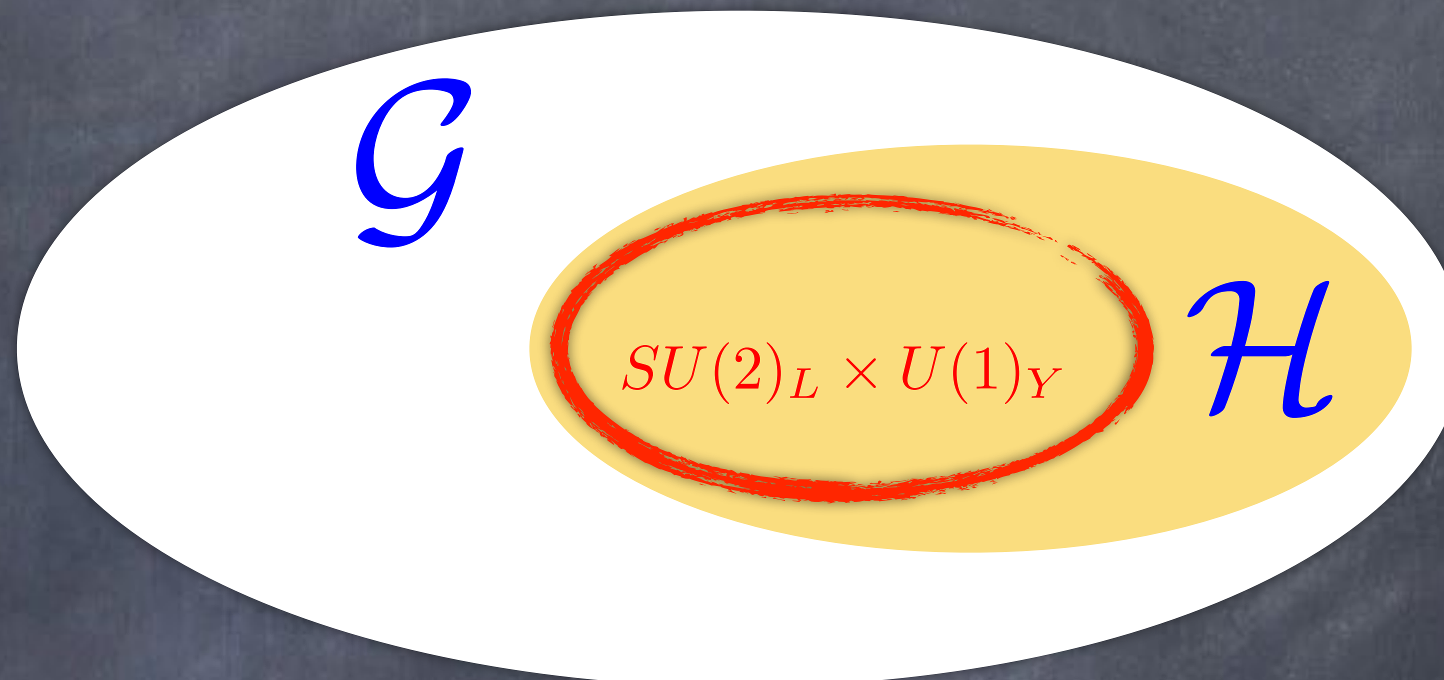
$\mathcal{G} \to \mathcal{H}$

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





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

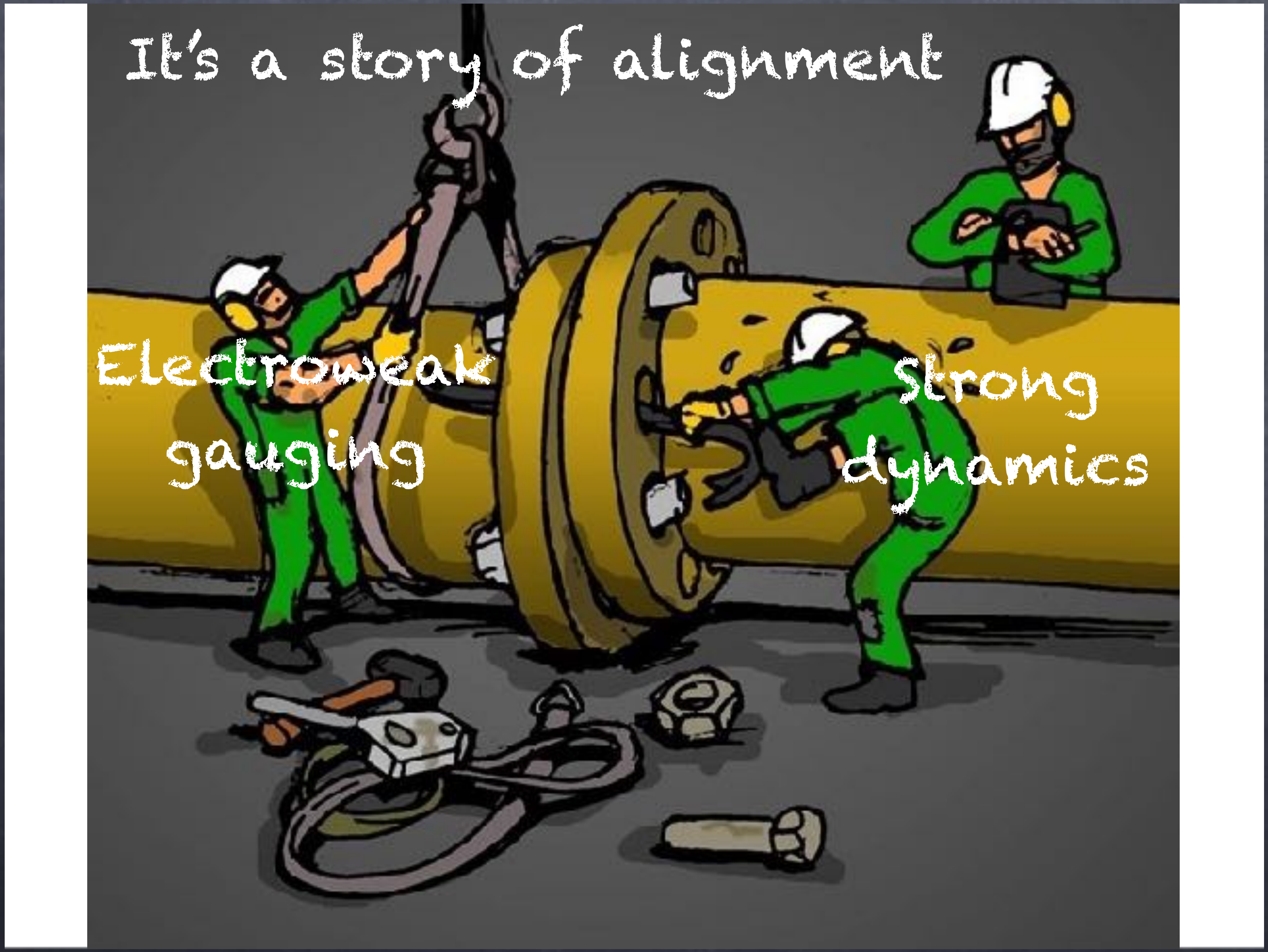
QCD template:

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

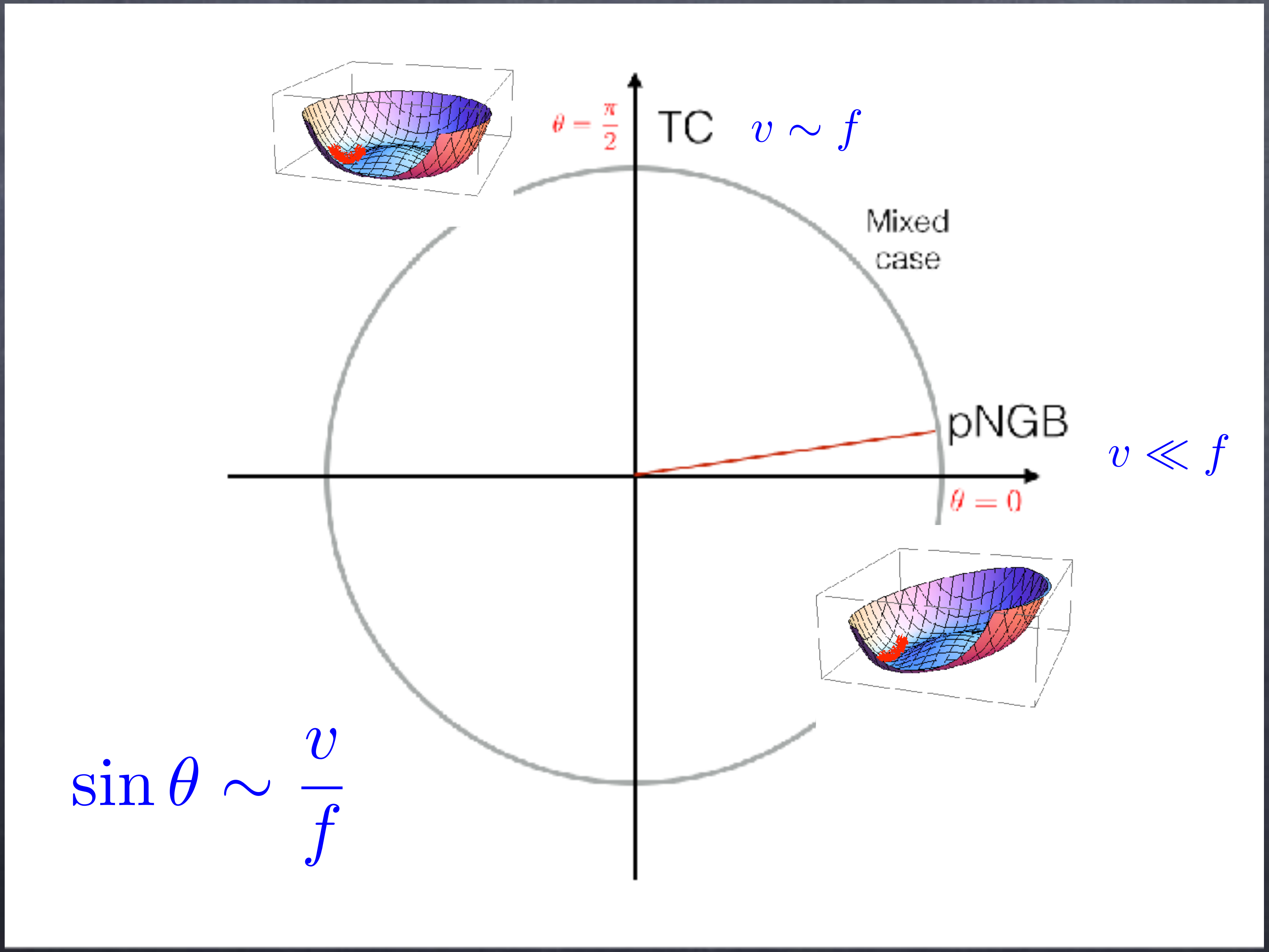
π pions

σ sigma

Compositeness, and the Higgs boson



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

In this paper we explain how to construct models where the weak interactions are broken by the composite Higgs mechanism. Such theories differ markedly from $SU(2)\times U(1)$ breaking scenarios that involve either fundamental scalars or technicolor. The low-energy spectrum of such theories include a composite Higgs boson, as well as exotic composite scalars and a new massive $U(1)$ gauge boson. We analyze in detail the workings of the $SU(5)/SO(5)$ composite Higgs model, previously described by two of the authors, in order to acquaint the reader with the generic traits of such theories.

Compositeness, and the Higgs boson

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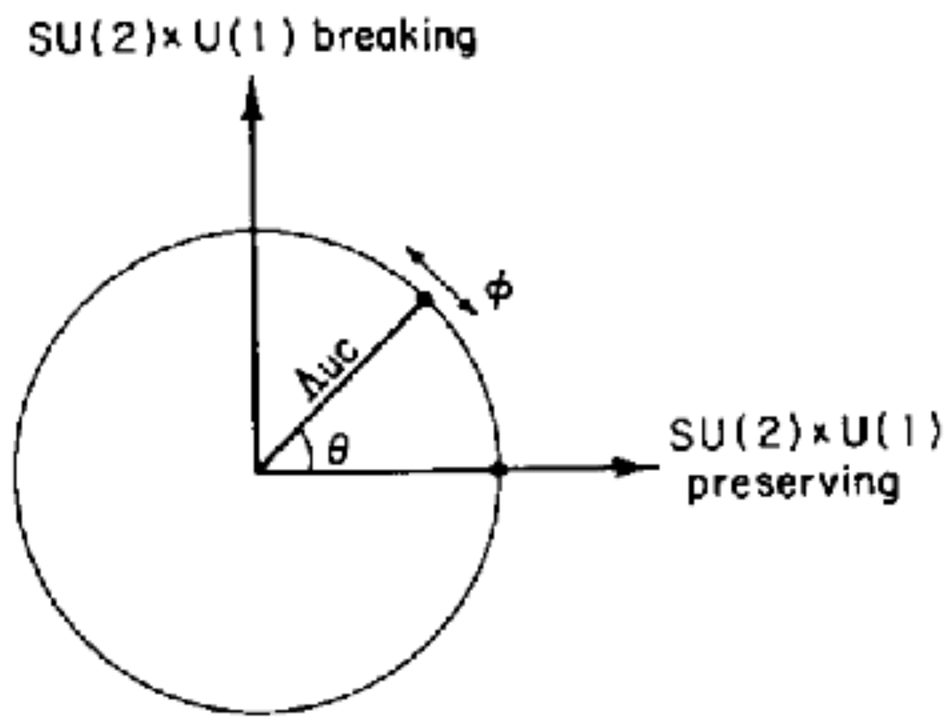


Fig. 1. Shown above is the circle of almost degenerate minima for the ultrafermion condensate, with radius $\Lambda_{\rm UC}$. The true vacuum of a composite Higgs theory misaligns with the SU(2)×U(1) preserving direction by an angle θ. In the SU(2)×U(1) preserving basis, it looks like the PGB field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

Compositeness, and the Higgs boson

ANATOMY OF A COMPOSITE HIGGS MODEL

Conjecture:

- Any good idea in BSM has been studied in the 70's or early 80'
- Corollary: it is still worth our time to study them in view of what we know now!

direction by an angle θ. In the SU(2)$\times$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:

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

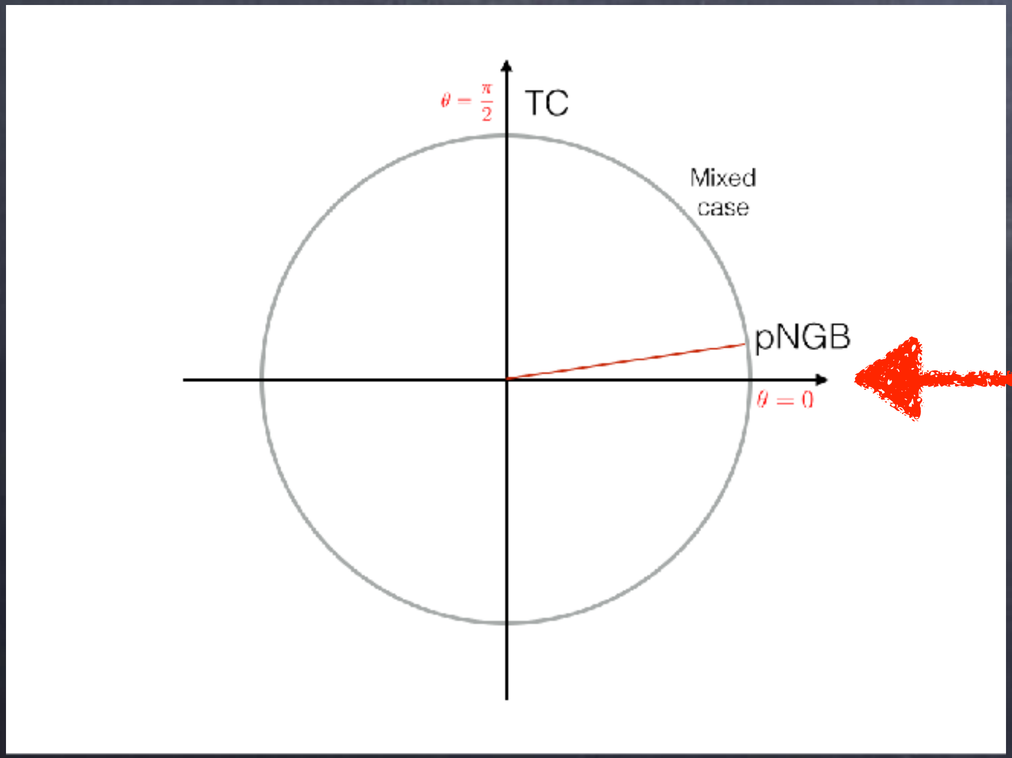
		QCD	TC	pNGB	
	f	130 MeV	246 GeV	1.2 TeV	
pions ->	pNGBs	135 MeV	255 GeV	1.3 TeV	<- the Higgs?
	sigma	500 MeV	950 GeV	4.7 TeV	
	rho	775 MeV	1.5 TeV	7 TeV	
	proton	938 MeV	1.8 TeV	9 TeV	

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

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	$(\mathbf{2}, \mathbf{2})_{\pm \mathbf{2}} = 2 \cdot (\mathbf{2}, \mathbf{2})$	[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	$\mathbf{4}_{-5} + \bar{\mathbf{4}}_{+\mathbf{5}} = 2 \cdot (\mathbf{2}, \mathbf{2})$	[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 (see tomorrow)

The FCD approach

	G_{TC}	G_F	SM
ψ	R_{TC}	R_F	R_{SM}

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

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

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

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:

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

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

$$d \sim 1.$$

The hot potato: flavour!

100.000 TeV — Λ_{flavour} — Light fermions

Conformal region

Λ_{top}

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

Multi-scale model

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

$$\downarrow$$

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

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: $d_H > 1$ $\quad d_{H^2} > 4$

Let's postulate the existence of fermionic operators:

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

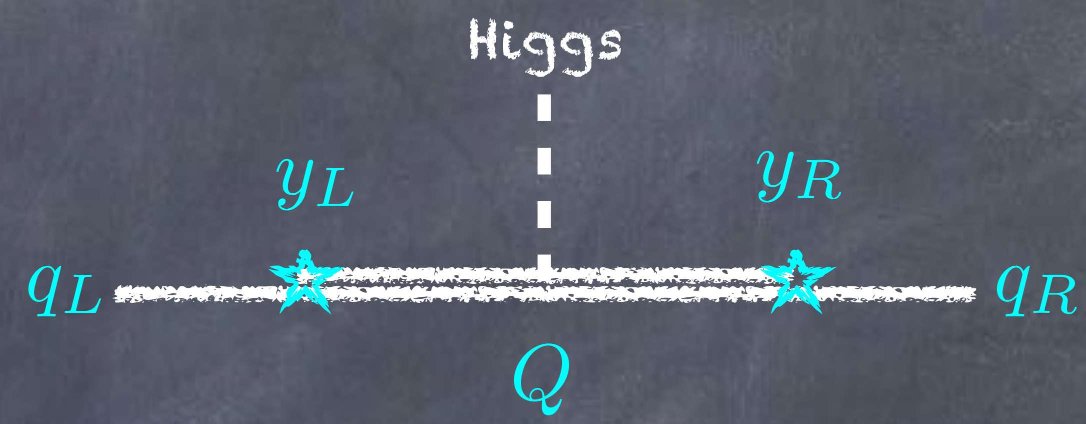
This dimension is not related to the Higgs!

$$\Downarrow$$

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

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

Partial compositeness

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

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

Composite Dark Matter

- Some pNGBs may be stable due to residual unbroken global symmetries
- Stable techni-baryons may give rise to asymmetric DM

S.Nussinov
Phys.Lett. B165, 55 (1985)

SU(4)/Sp(4)?

Frigerio, Pomarol, Riva, Urbano
1204.2808

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

$$
\mathcal{L}_{\mathrm{WZW}} = \frac{d_\psi\cos\theta}{64\pi^2}\frac{\eta}{f}\left(g^2\ W_{\mu\nu}\tilde{W}^{\mu\nu}-g'^2\ B_{\mu\nu}\tilde{B}^{\mu\nu}\right)
$$

No linear couplings in the chiral Lagrangian, however it decays via the WZW interactions.

SU(4)/Sp(4)?

TC limit: $\theta = \dfrac{\pi}{2}$

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

$$
\mathcal{L}_{\mathrm{WZW}} = \cancel{\frac{d_\psi \cos\theta}{64\pi^2}\frac{\eta}{f}}\left(g^2\, W_{\mu\nu}\tilde{W}^{\mu\nu} - g'^2\, B_{\mu\nu}\tilde{B}^{\mu\nu}\right)
$$

Rhyttov, Sannino
0809.0713

In the TC limit, $Sp(4) \subset U(1)_{em} \times U(1)_{DM}$

$\phi = \dfrac{h + i\eta}{\sqrt{2}}$ is charged under the unbroken $U(1)_{DM}$, and thus stable (TIMP).

A composite 2HDM

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

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

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

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?

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

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

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

A composite 2HDM

G.C., T.Ma
1508.07014

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

$$\langle \Phi_H \rangle = \langle H_1 + i H_2 \rangle = \left(\begin{array}{cc} v e^{i\beta} & 0 \\ 0 & v e^{i\beta} \end{array}\right)$$

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

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

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1508.07014

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

4 "Yukawa" couplings!

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

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

Potential for theta

Set to zero by phase-shift

Custodial violating VEVs!!!

A composite 2HDM

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1508.07014

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

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

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

Potential for theta

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

Set to zero by phase-shift

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

DM parity!

Custodial violating VEVs!!!

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

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

A composite 2HDM: spectrum

The spectrum essentially depends on 2 parameters:

- A Yukawa coupling;
- A mass difference.

$$\delta = \frac{m_{\psi_L} - m_{\psi_R}}{m_{\psi_L} + m_{\psi_R}}$$

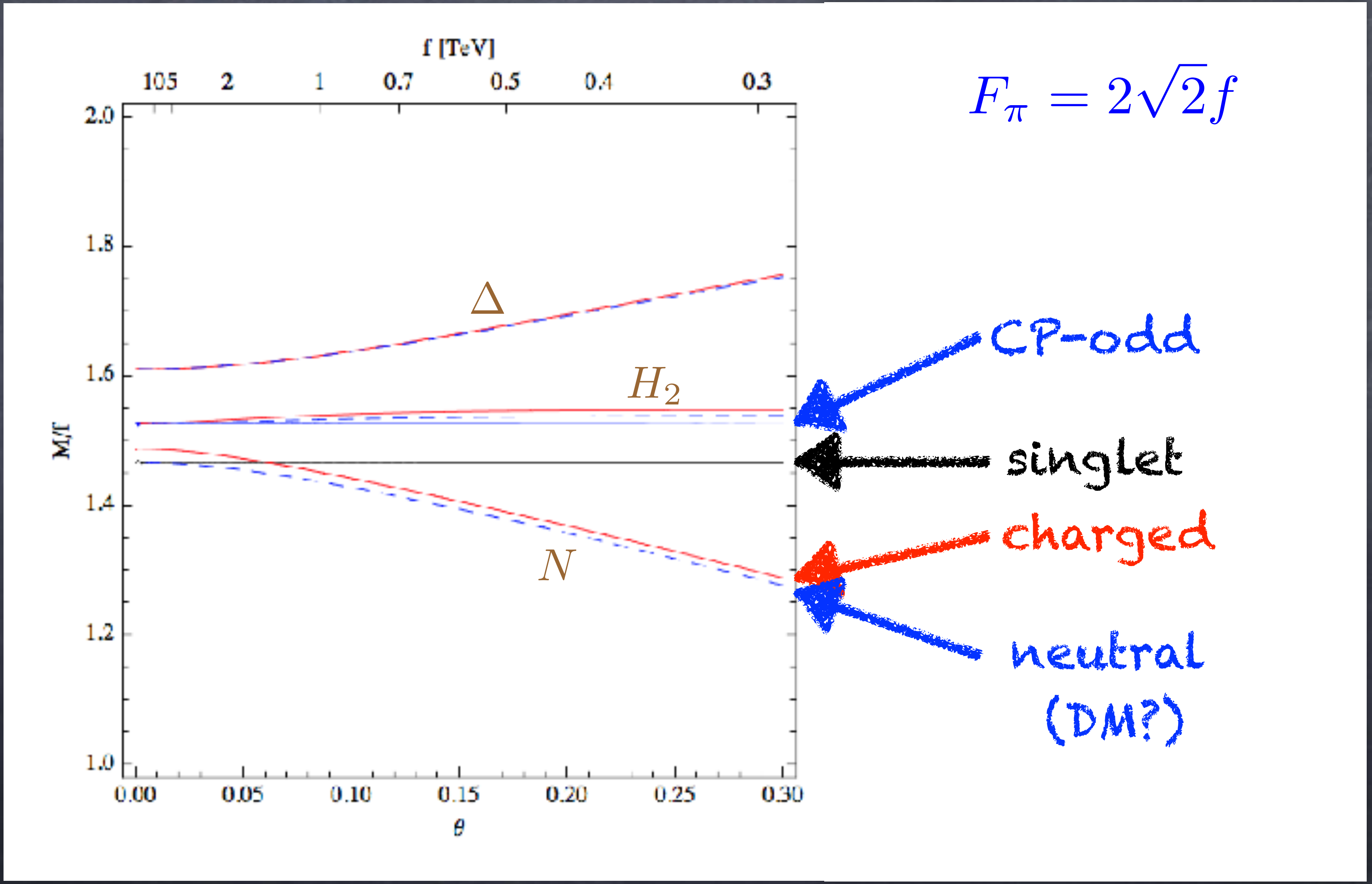
$$m_s = \frac{m_h}{\sin\theta}$$

$$m^2_{\eta_1} \sim m^2_{N_0} \sim m^2_s(1-\delta) + \ldots, \qquad m^2_{\eta_1^\pm} \sim m^2_{N^\pm} \sim m^2_{\eta_1} + C_g \frac{m_Z^2 - m_W^2}{4\sin^2\theta} + \ldots$$

$$m^2_{\eta_2} \sim m^2_{\eta_2^\pm} \sim m^2_{h_2} \sim m^2_{H^\pm} \sim m^2_s + C_g \frac{2m_W^2 + m_Z^2}{16\sin^2\theta} + \ldots$$

$$m^2_{\eta_3} \sim m^2_{\eta_3^\pm} \sim m^2_\Delta \sim m^2_s(1+\delta) + C_g \frac{m_W^2}{2\sin^2\theta} + \ldots$$

A composite 2HDM: spectrum



A composite 2HDM: Dark-Matter

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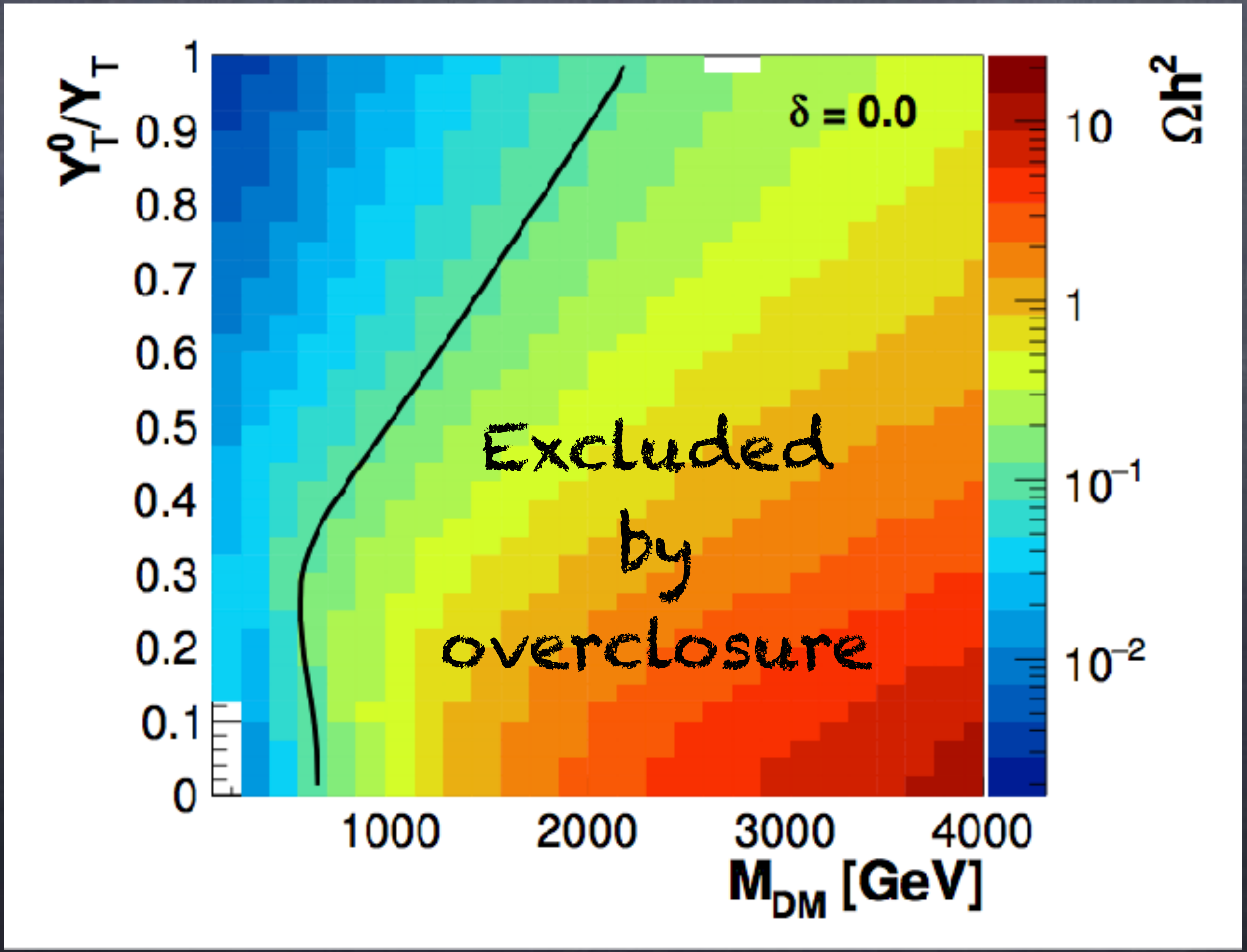
1703.06903

Relic abundance:



A composite 2HDM: Dark-Matter

Direct Detection

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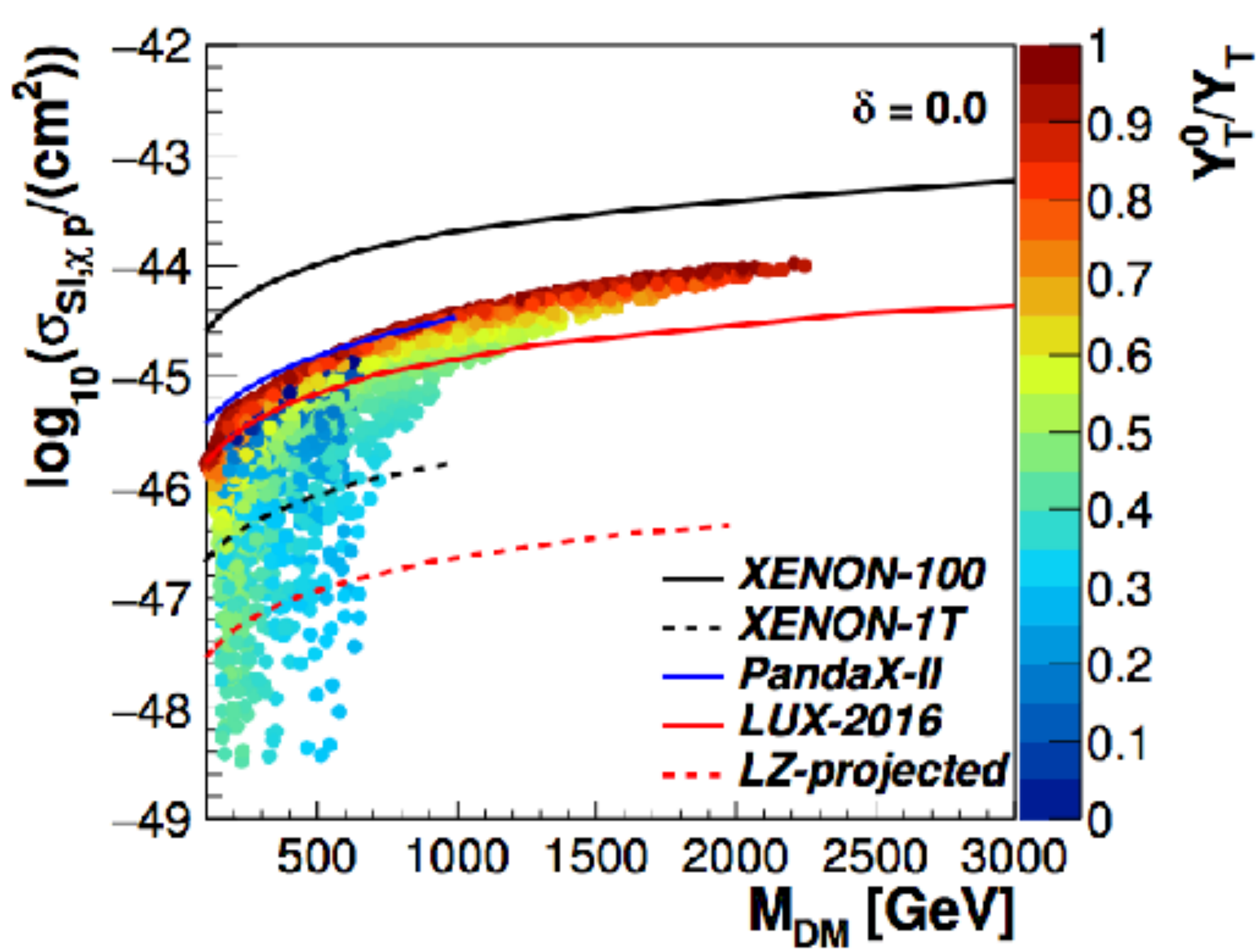
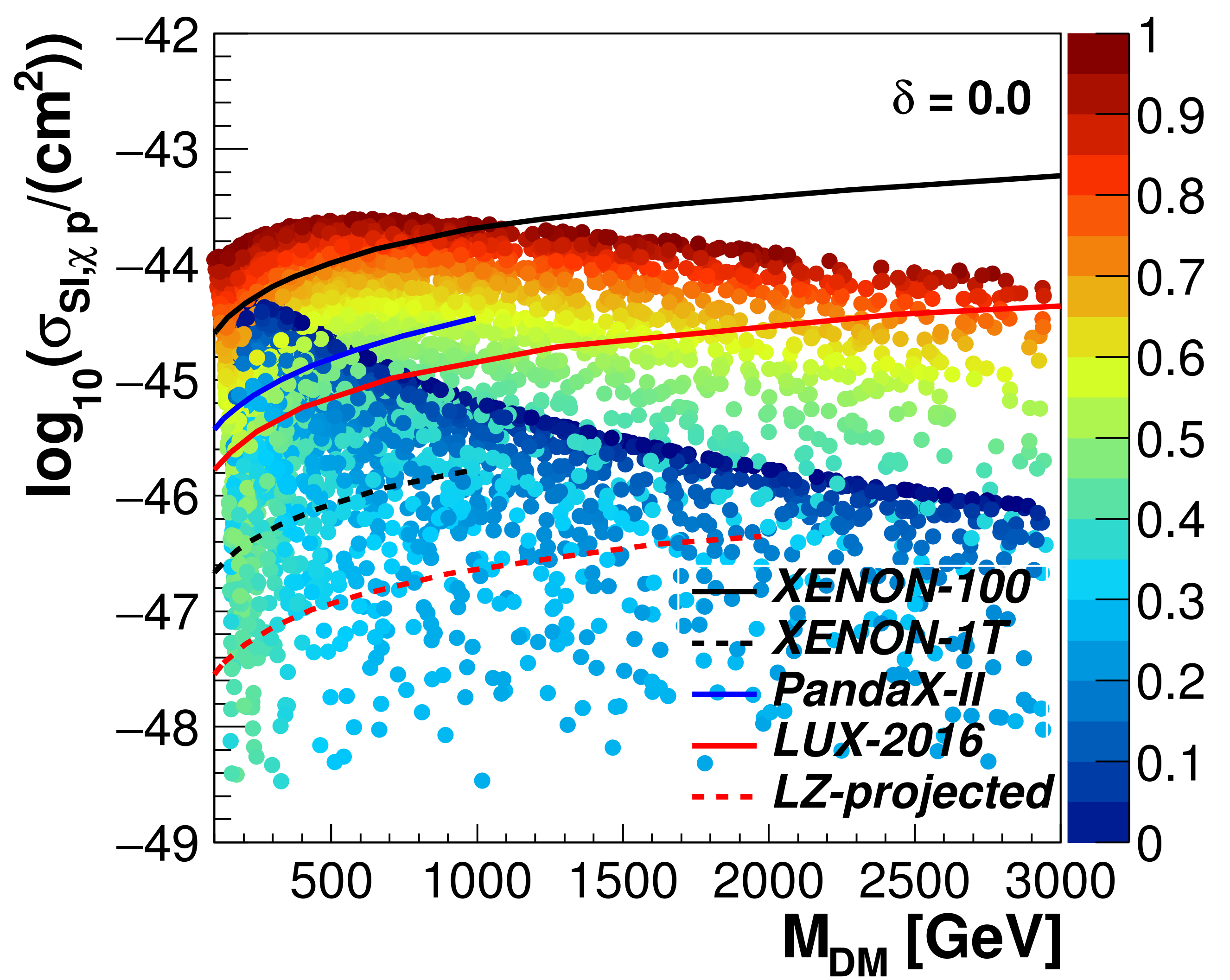
Thermal relic



Fixing DM relic



A composite 2HDM: Dark-Matter

Indirect Detection

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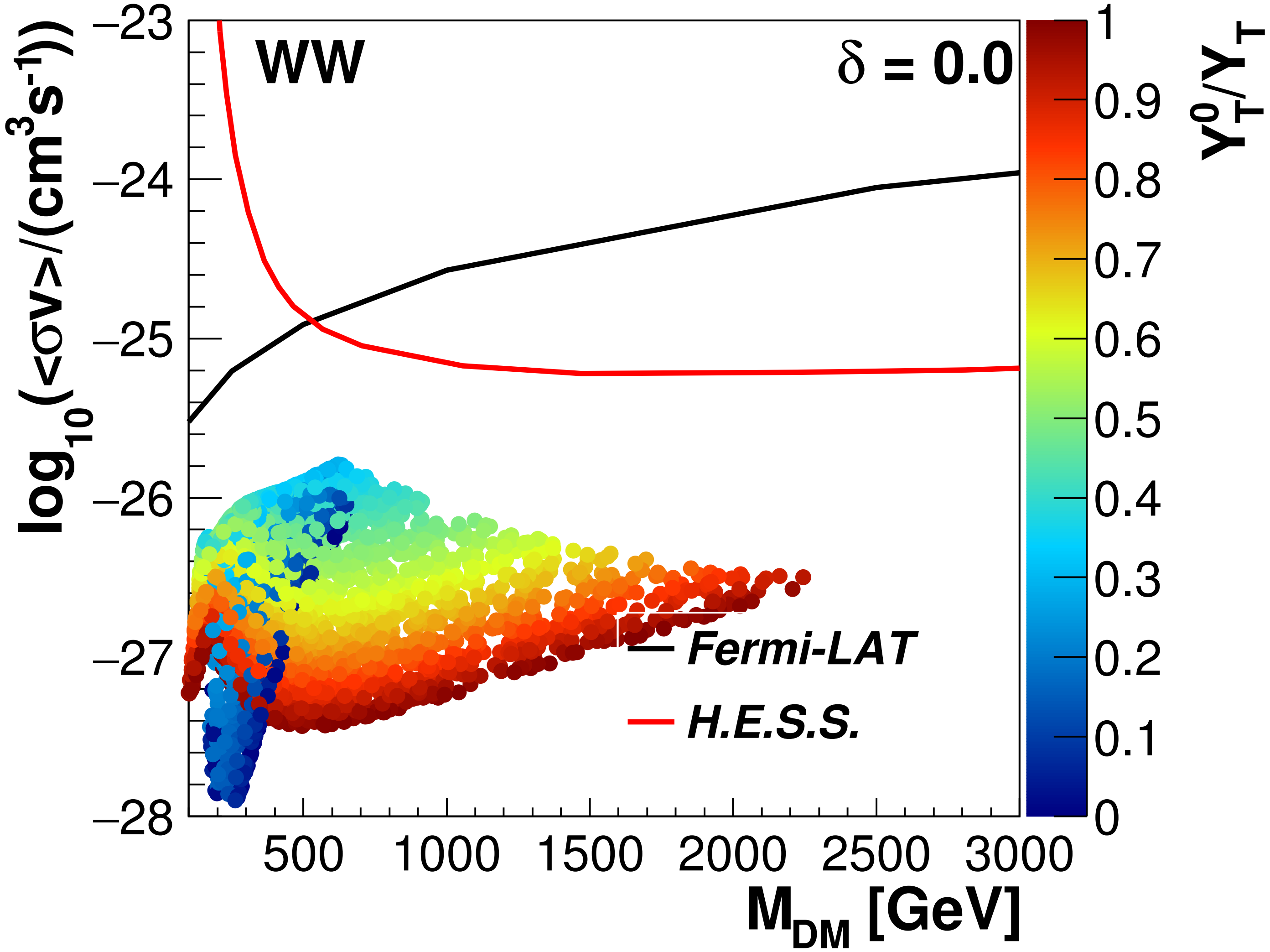
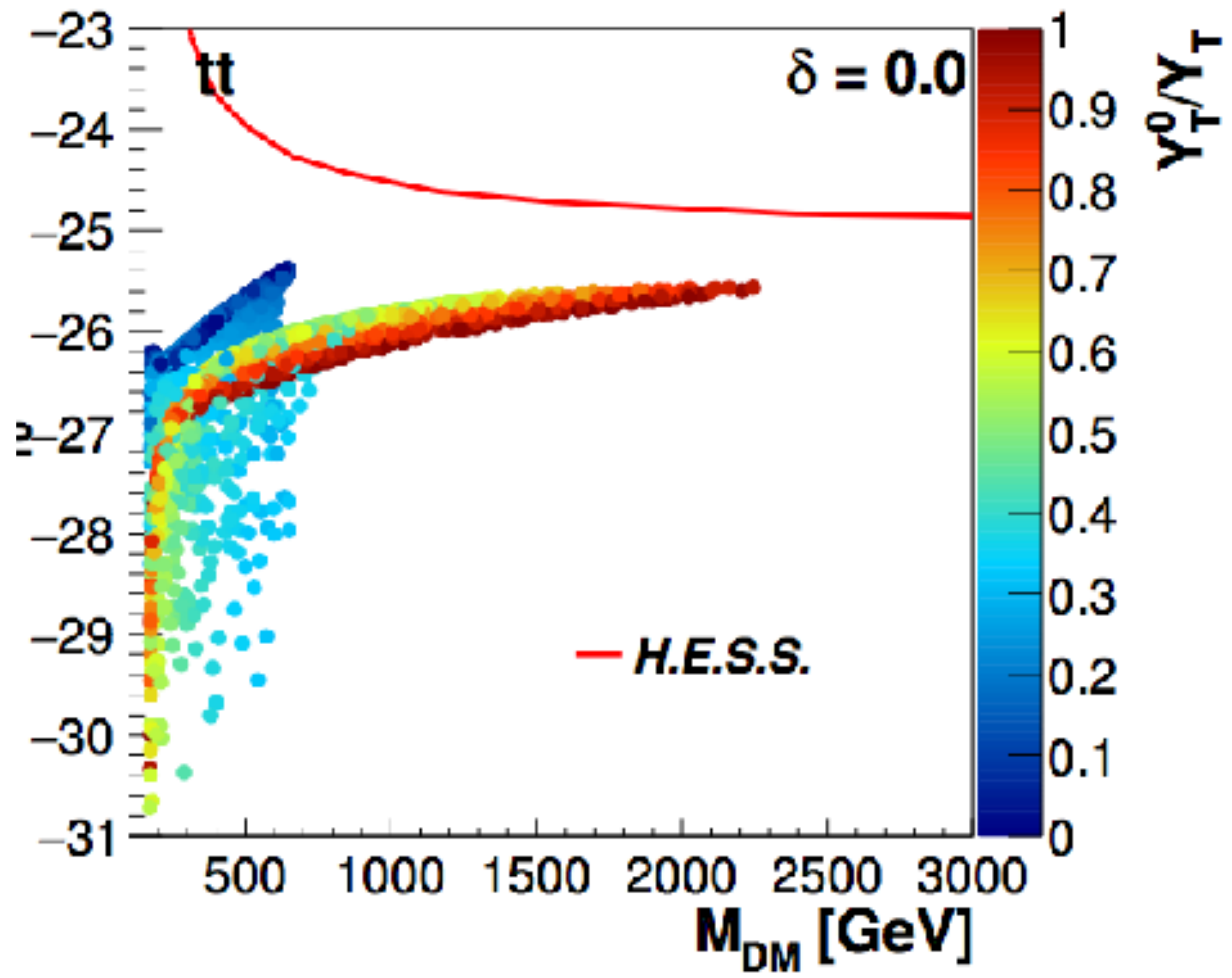
Thermal relic abundance





A composite 2HDM: Dark-Matter

Indirect Detection

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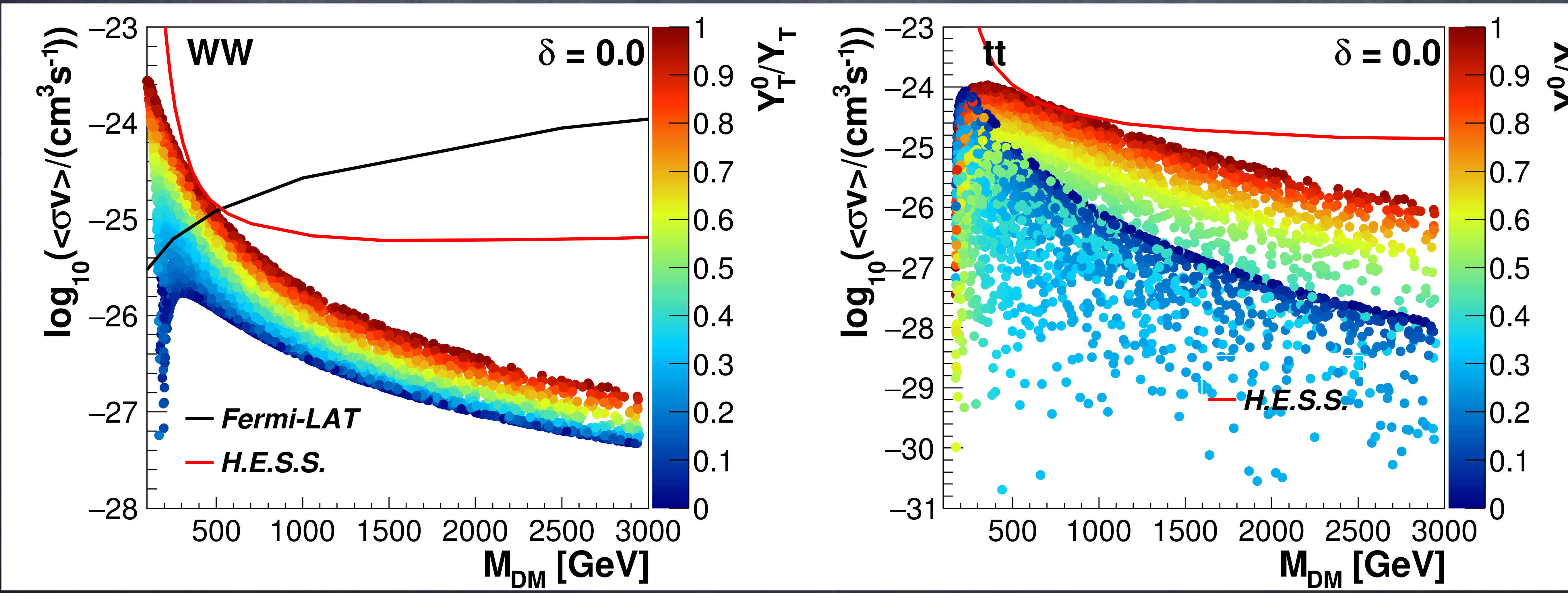
Fixed DM relic abundance



A composite 2HDM: Dark-Matter

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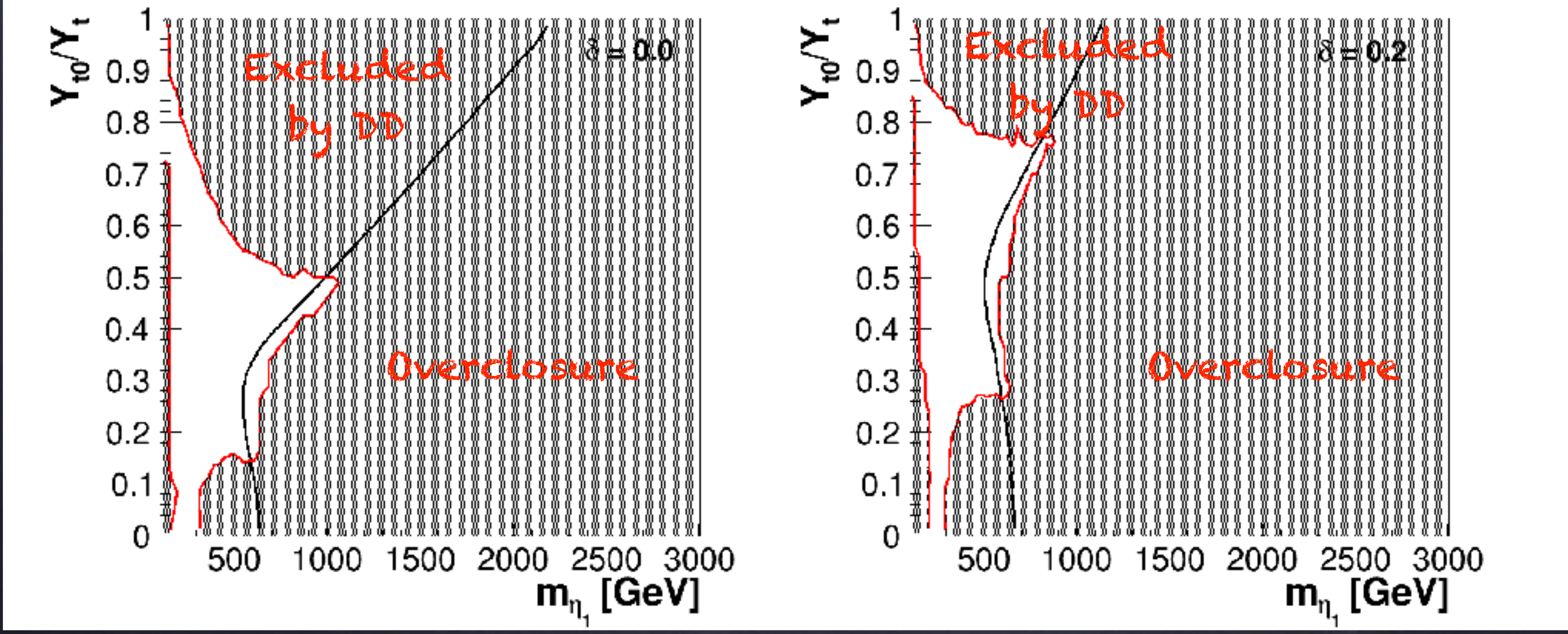
1703.06903

Summary:



Outlook

- Other mass mixing patterns can be explored!

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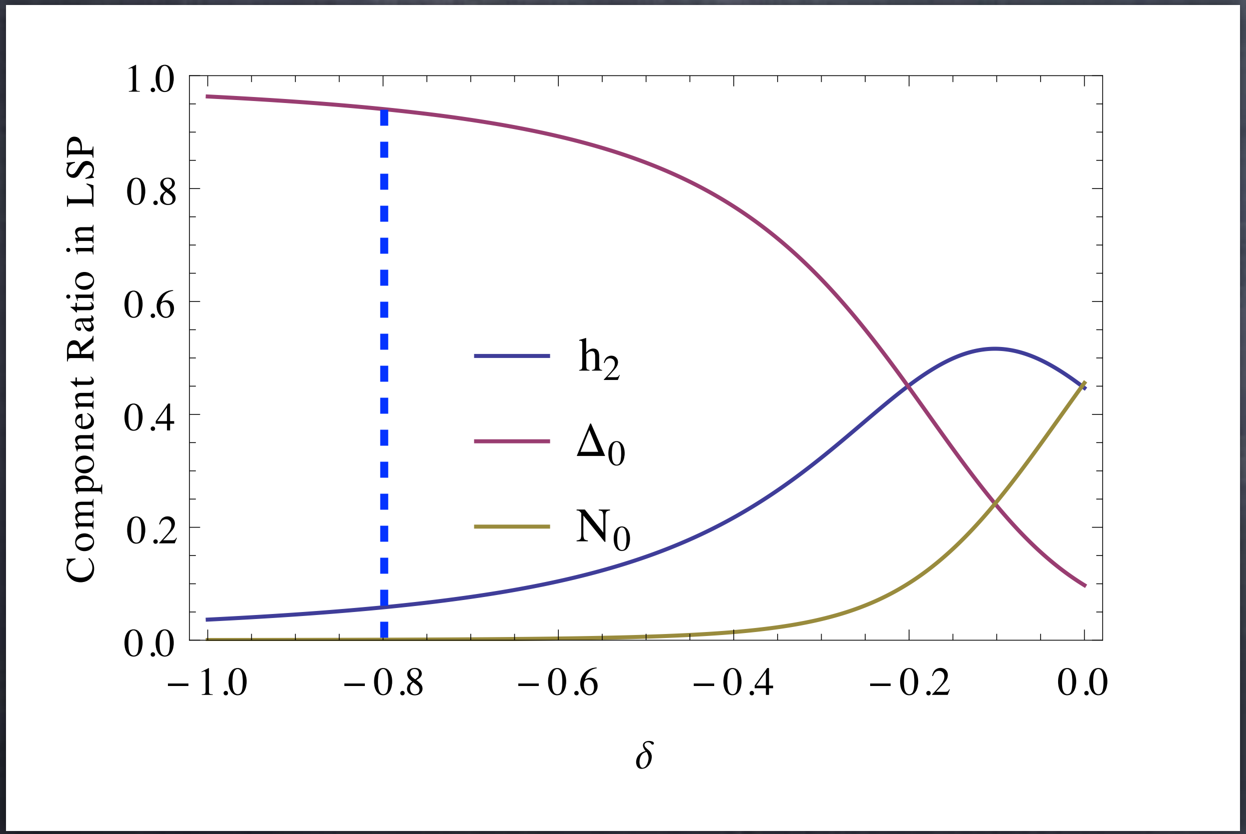
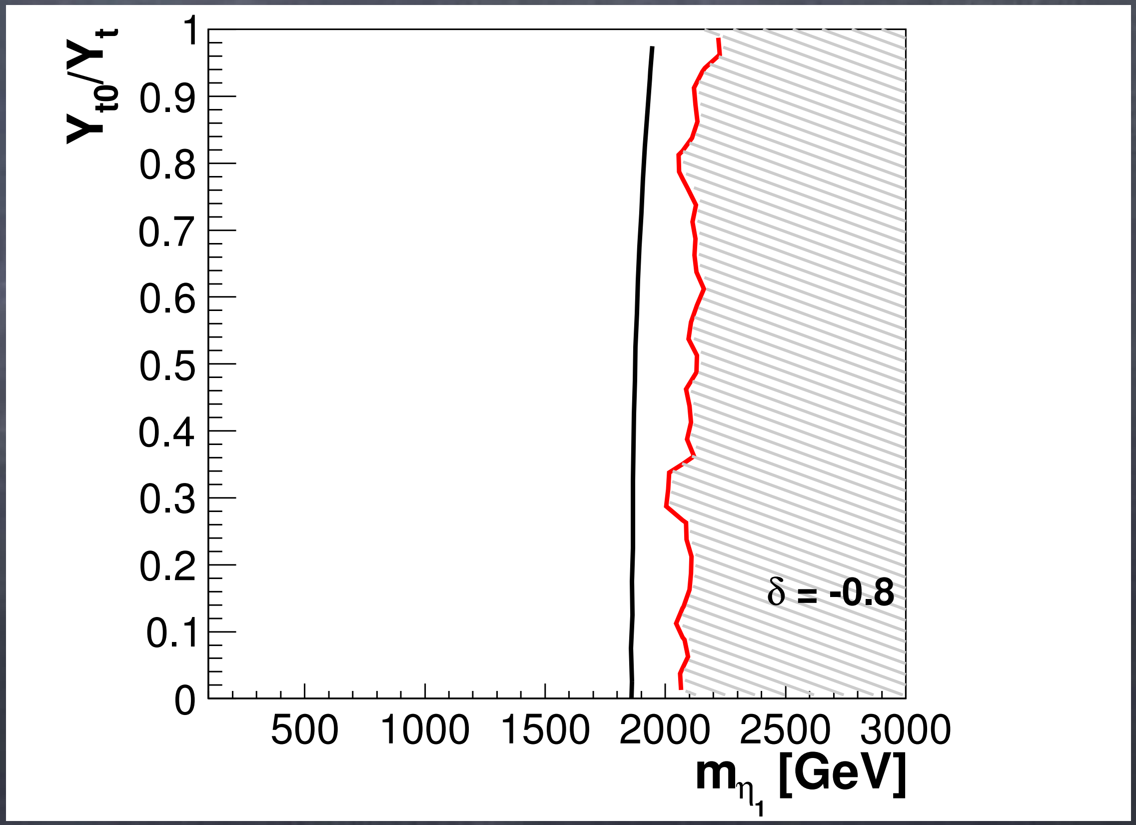


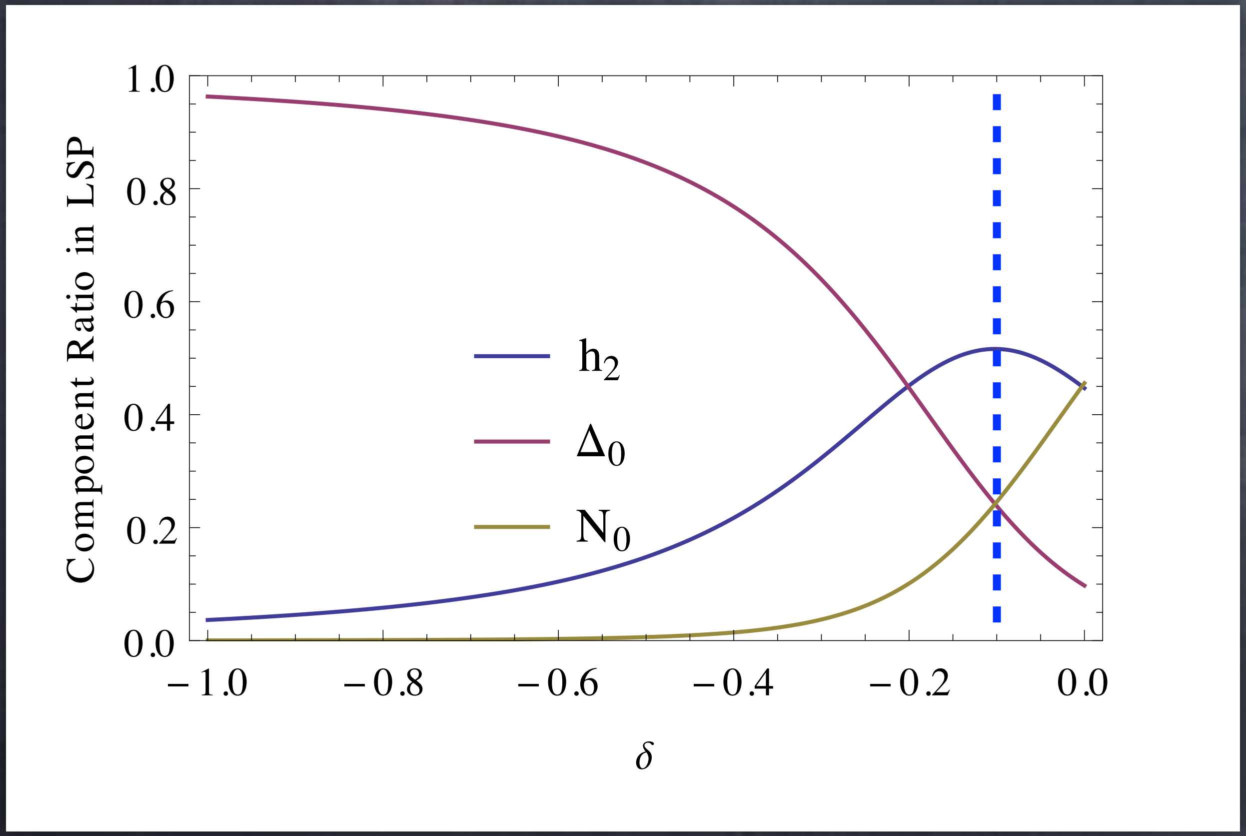


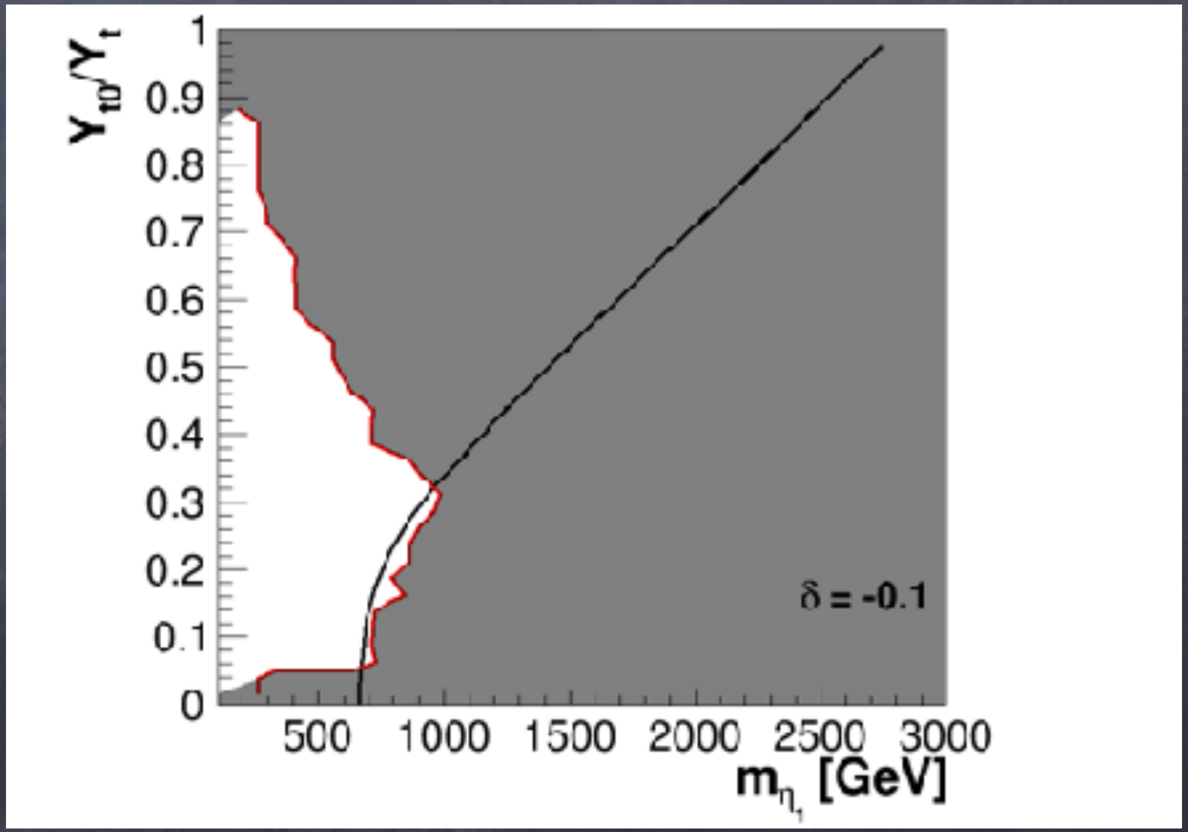
Dominantly SU(2) triplet!

Outlook

- Other mass mixing patterns can be explored!

G.C., T.Ma, Y.Wu, to appear





50% doublet

Outlook

- Other mass mixing patterns can be explored!
- Models with top partner (partial compositeness) can also preserve the DM parity!

G.C., T.Ma, Y.Wu, to appear

Outlook

- Other mass mixing patterns can be explored!
- Models with top partner (partial compositeness) can also preserve the DM parity!
- Other cosets can give rise to Dark Matter:

$SU(6)/Sp(6)$	14 pNGBs -> unbroken U(1) charge	G.C., T.Ma, Y.Wu, to appear
$SU(6)/SO(6)$	20 pNGBs	G.C., A.Deandrea, A.Kushwaha, work in progress

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!

A composite 2HDM: EWPTs

G.C., T.Ma
1508.07014

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

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

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

Bounds similar to minimal cases.