Two Higgs doublet models emerging from composite Higgs dynamics

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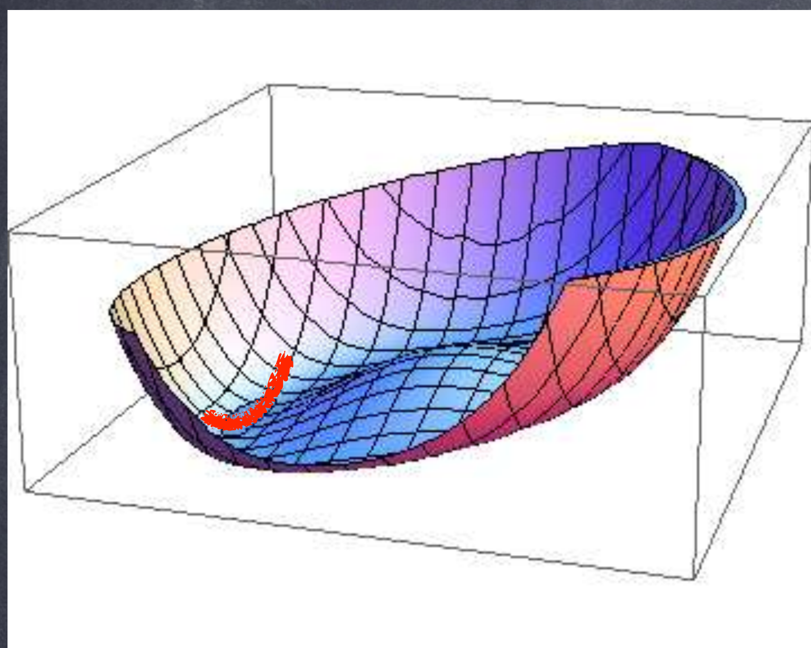
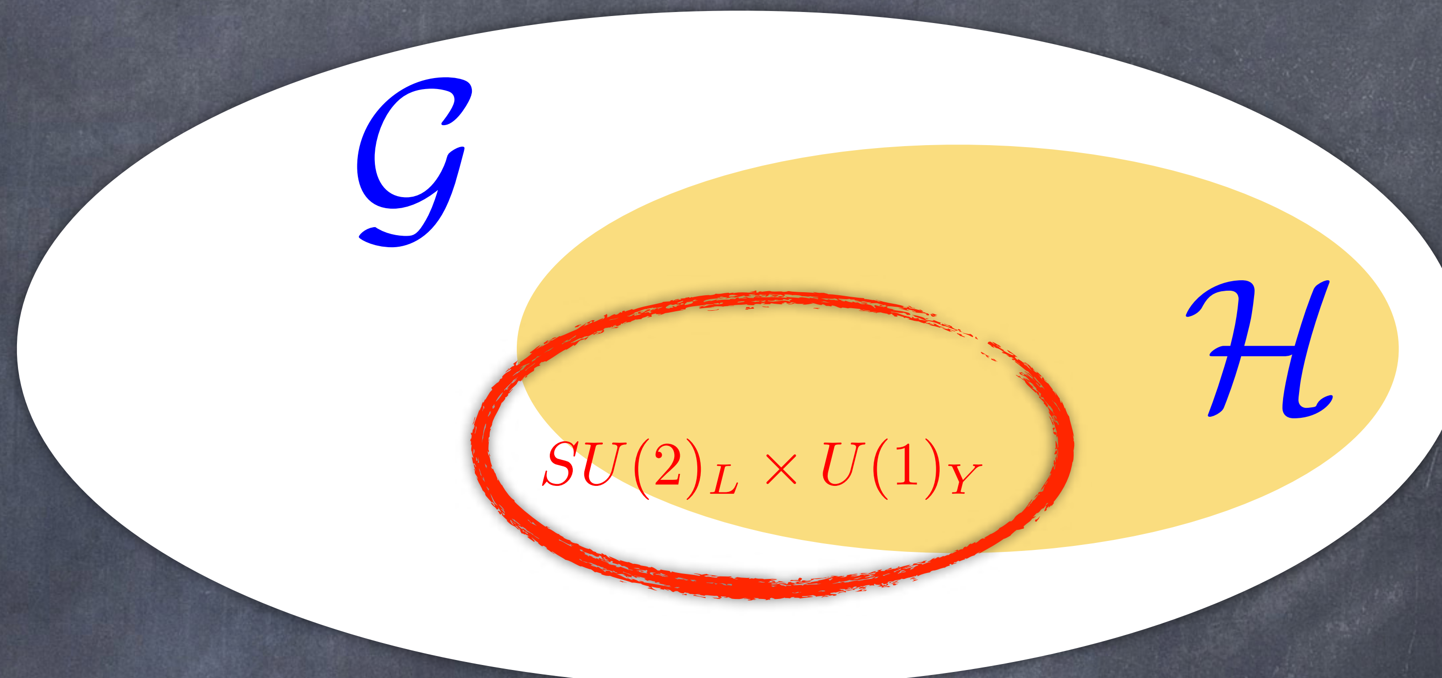
Compositeness, and the Higgs boson





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

QCD template:

- Goldstones include the longitudinal d.o.f. of W and Z

π pions

- the Higgs is a pseudo-Goldstone (pNGB)

σ sigma

Compositeness, and the Higgs boson

ANATOMY OF A COMPOSITE HIGGS MODEL

Michael J. DUGAN, Howard GEORGI and David B. KAPLAN

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

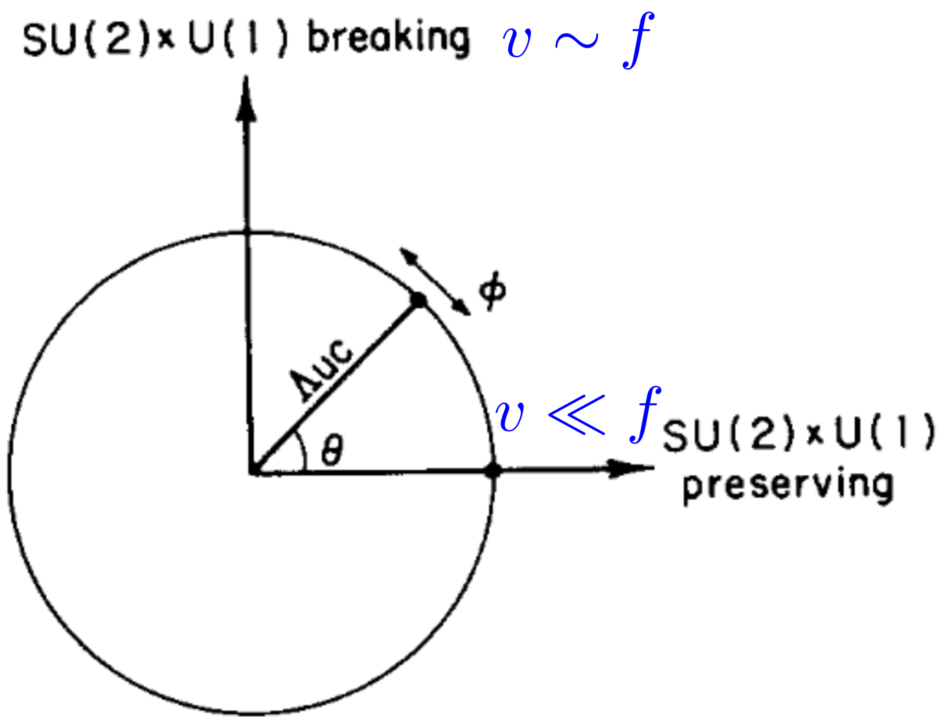
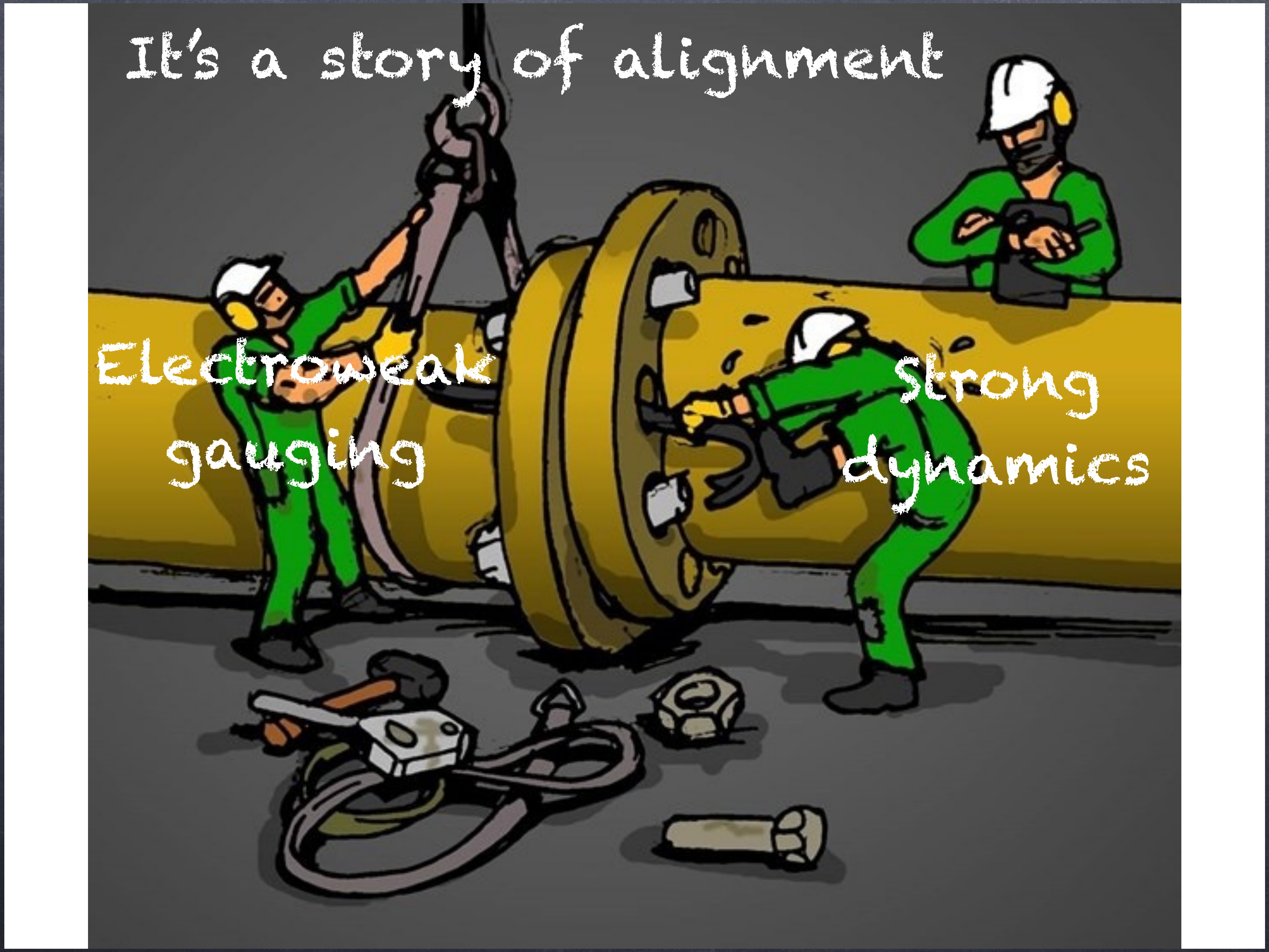


Fig. 1. Shown above is the circle of almost degenerate minima for the ultrafermion condensate, with radius Λ_{UC}. The true vacuum of a composite Higgs theory misaligns with the SU(2)×U(1) preserving direction by an angle θ. In the SU(2)×U(1) preserving basis, it looks like the PGB field ϕ, corresponding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

Compositeness, and the Higgs boson



The hot potato: flavour!

100.000 TeV	Λ_{flavour}	Light fermions
		IR conformal region
Λ_{top}		
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, Higgs

Multi-scale model

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

Still, for the top, one would need:

$$\Lambda_{\text{top}} \sim 4\pi f$$

UV completion?

100,000 TeV — Λ_{flavour} — Light fermions

IR conformal region

Theory in the conformal window (IR fixed point)

Λ_{top}

Heavy states?

Top interactions?

10 TeV — $\Lambda \sim 4\pi f$ — Vector resonances, top partners?

1 TeV — f — Condensation scale (extra pions)

Theory with a mass gap!

100 GeV — $v_{\text{SM}} \sim f \sin\theta$ — EWSB, Higgs

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 (thus providing embedding in the global symmetry)
- Couple them to SM fermions

↓

- Guides EFT construction!
- Lattice results can be used!

The FCD approach

- The symmetry breaking pattern determined by the irrep of the underlying fermions!
- The minimal case of SU(4)/Sp(4)!

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

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

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

Minimal models *

coset	GTC	TF	pNGBs	doublets	
SU(4)/Sp(4)	Sp(2N)	fund	5	1	T.Ryttov, F.Sannino 0809.0713 Galloway, Evans, Luty, Tacchi 1001.1361 Minimal!
SU(5)/SO(5)	SU(4)	6	14	1	Dugan, Georgi, Kaplan 1985!!!
SU(4)xSU(4)/SU(4)	SU(N)	fund	15	2	G.C., T.Ma 1508.07014
SU(6)/Sp(6)	Sp(2N)	fund	14	2	G.C., C.Cai, H.Zhang 1805.07619
SU(6)/SO(6)	SU(4)	6	20	2	G.C., A.Deandrea, A.Kushwaha to appear

* other models exists, but without underlying description.

A minimal case

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

	$SU(2)_{TC}$	$SU(4)_\psi$	$SU(2)_L$	$U(1)_Y$
$\begin{pmatrix}\psi^1\\ \psi^2\end{pmatrix}$	$\square$	$\square$	**2**	0
ψ^3	$\square$		**1**	-1/2
ψ^4	$\square$		**1**	1/2

The EW symmetry
is embedded in the global
flavour symmetry
SU(4) !

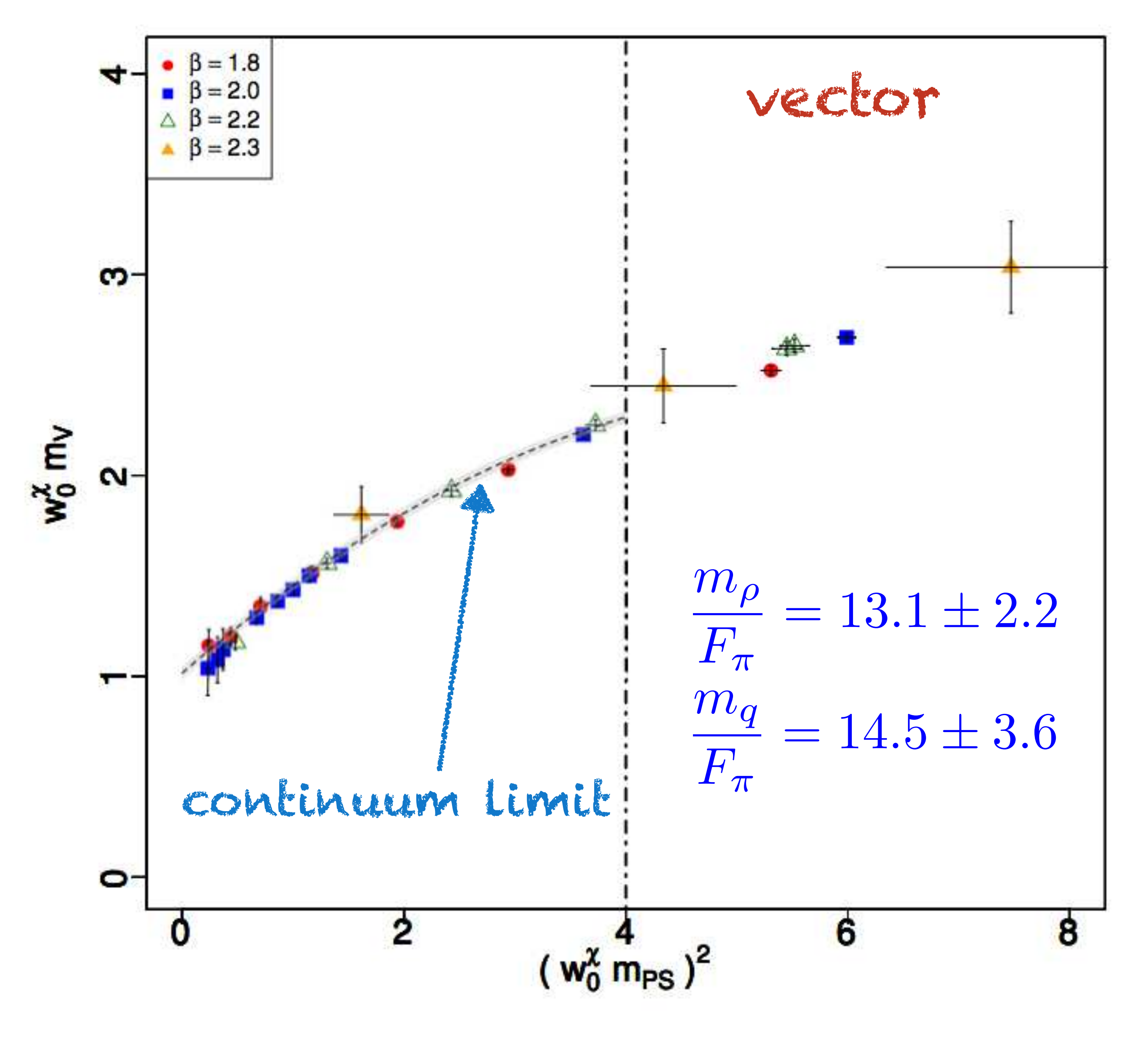
$$H \sim \langle \begin{pmatrix} \psi^1 \\ \psi^2 \end{pmatrix} \psi^4 \rangle$$

Generators of SU(4) corresponding to $SU(2)_L \times SU(2)_R$

$$S^{1,2,3} = \frac{1}{2}\begin{pmatrix} \sigma_i & 0 \\ 0 & 0 \end{pmatrix}, \qquad S^{4,5,6} = \frac{1}{2}\begin{pmatrix} 0 & 0 \\ 0 & -\sigma_i^T \end{pmatrix},$$

The vector resonance

Lattice results:



$\sin\theta \leq 0.2$

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

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

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

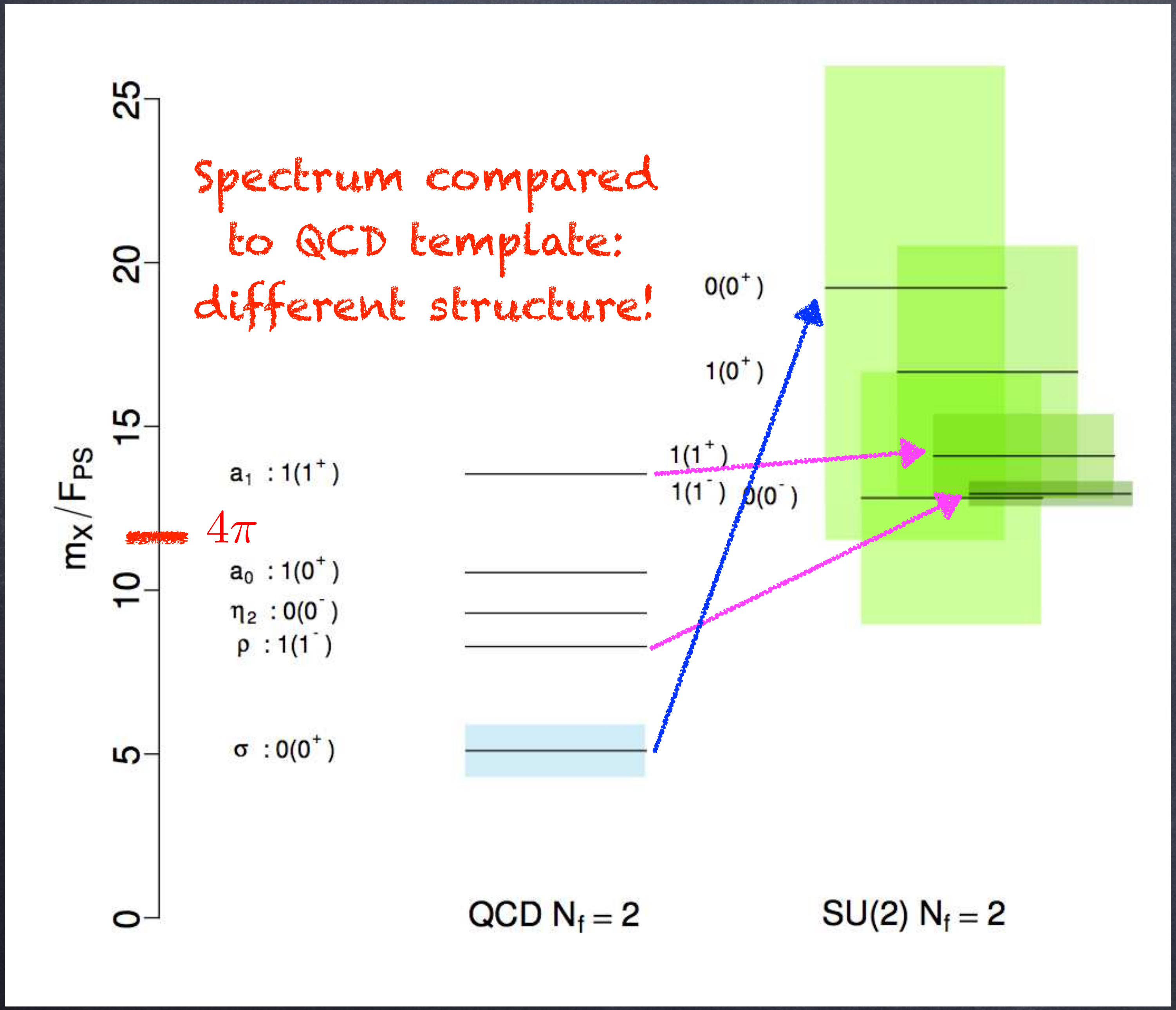
$$m_\eta \sim \frac{m_h}{\sin\theta} \gtrsim 600\ GeV$$

$$m_h = 125\ GeV$$

Arthur, Drach, et al. 1602.06559

The spectrum

Lattice results:



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Composite dynamics

- a tale of 3 friends:

Composite Higgs

- Some pNGBs transform like the Higgs doublet
- The lightest scalar resonance (non pNGB) may play the role of the Higgs boson

A minimal case

Anti-symmetric

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

Sp(4) ~ SO(5) contains a SO(4) subgroup:
identify with custodial symmetry!

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

$$\Sigma_0 = \begin{pmatrix} (i\sigma^2) & 0 \\ 0 & -(i\sigma^2) \end{pmatrix}$$

Preserves the EW generators.

A minimal case

Broken SU(4) generators

$$X^1 = \frac{1}{2\sqrt{2}} \begin{pmatrix} 0 & \sigma_3 \\ \sigma_3 & 0 \end{pmatrix}, \quad X^2 = \frac{1}{2\sqrt{2}} \begin{pmatrix} 0 & i \\ -i & 0 \end{pmatrix}, \quad X^3 = \frac{1}{2\sqrt{2}} \begin{pmatrix} 0 & \sigma_1 \\ \sigma_1 & 0 \end{pmatrix},$$
$$X^4 = \frac{1}{2\sqrt{2}} \begin{pmatrix} 0 & \sigma_2 \\ \sigma_2 & 0 \end{pmatrix}, \quad X^5 = \frac{1}{2\sqrt{2}} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$

$X^1,\ X^2,\ X^3,\ X^4$ Higgs doublet X^5 singlet

$$\Sigma = e^{\frac{i}{2f}\sum_i X^i \pi^i} \cdot \Sigma_0 \cdot e^{\frac{i}{2f}\sum_i X^{i^T} \pi^i} = U \cdot \Sigma_0 \cdot U^T = U^2 \cdot \Sigma_0$$

Let's give a VEV to the Higgs:

$\langle \pi^4 \rangle = v$ $\quad\quad$ $\Sigma_0' = e^{i\frac{v}{f}X^4} \cdot \Sigma_0$ $\quad\quad$ New EW breaking vacuum

A minimal case

$$e^{i\frac{v}{f}X^4} = \left(\cos\frac{v}{2\sqrt{2}f} + i2\sqrt{2}X^4\sin\frac{v}{2\sqrt{2}f}\right)$$

$$= \left(\cos\theta + i2\sqrt{2}X^4\sin\theta\right) \qquad \theta = \frac{v}{2\sqrt{2}f}$$

Defines a rotation in the SU(4) space! To study the theory in the new vacuum, it is enough to apply this rotation to the strong sector!

→

The EW embedding, however, is not rotated.

↓

Mis-alignment!

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

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

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

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) ⊂ $U(1)_{em} \times U(1)_{DM}$

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

A composite 2HDM

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

G.C., T.Ma
1508.07014

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

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

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

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

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

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

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

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

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

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

4 "Yukawa" couplings!

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

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

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!!!

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

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

A composite 2HDM

G.C., T.Ma
1508.07014

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

4 "Yukawa" couplings!

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

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

Potential for theta

Set to zero by phase-shift

Custodial violating VEVs!!!

DM parity!

A composite 2HDM: spectrum

The spectrum essentially depends on 2 parameters:

- A Yukawa coupling; Y_0
- A mass difference. $\delta = \dfrac{m_{\psi_L} - m_{\psi_R}}{m_{\psi_L} + m_{\psi_R}}$

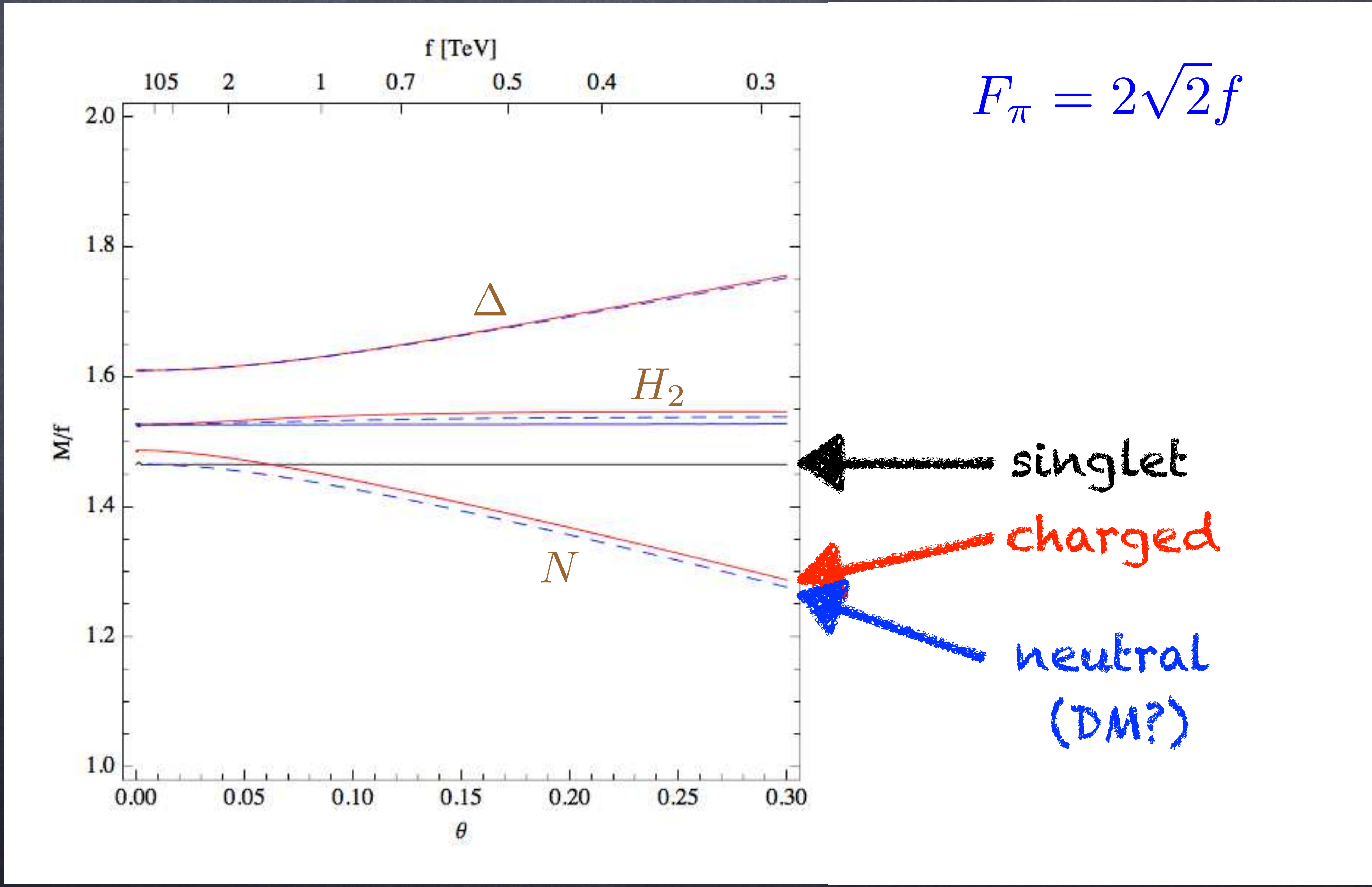
$$m_s = \frac{m_h}{\sin\theta}$$

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

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

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

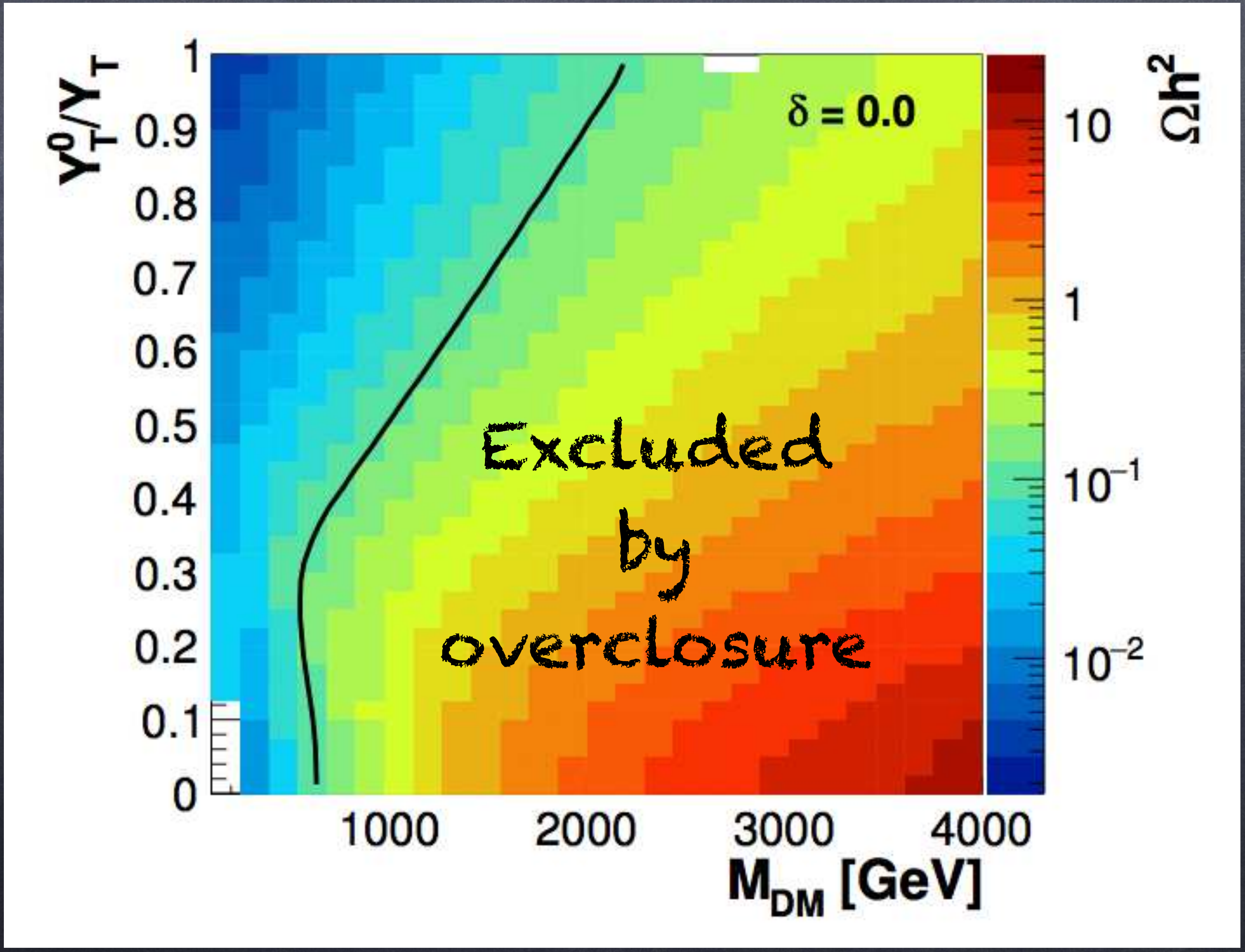
A composite 2HDM: spectrum



A composite 2HDM: Dark-Matter

G.C., T.Ma, Y.Wu, B.Zhang
1703.06903

Relic abundance:



A composite 2HDM: Dark-Matter

Direct Detection

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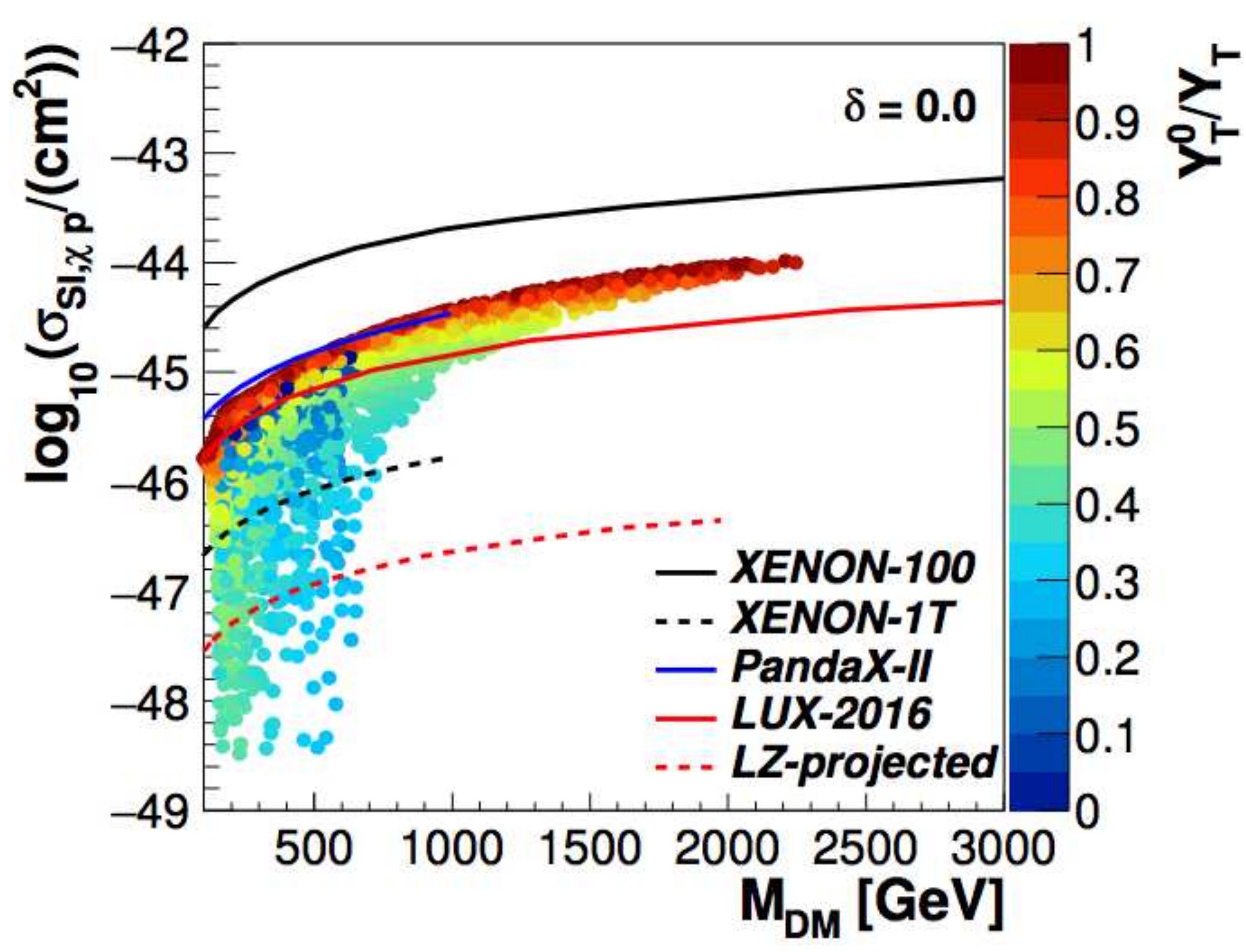
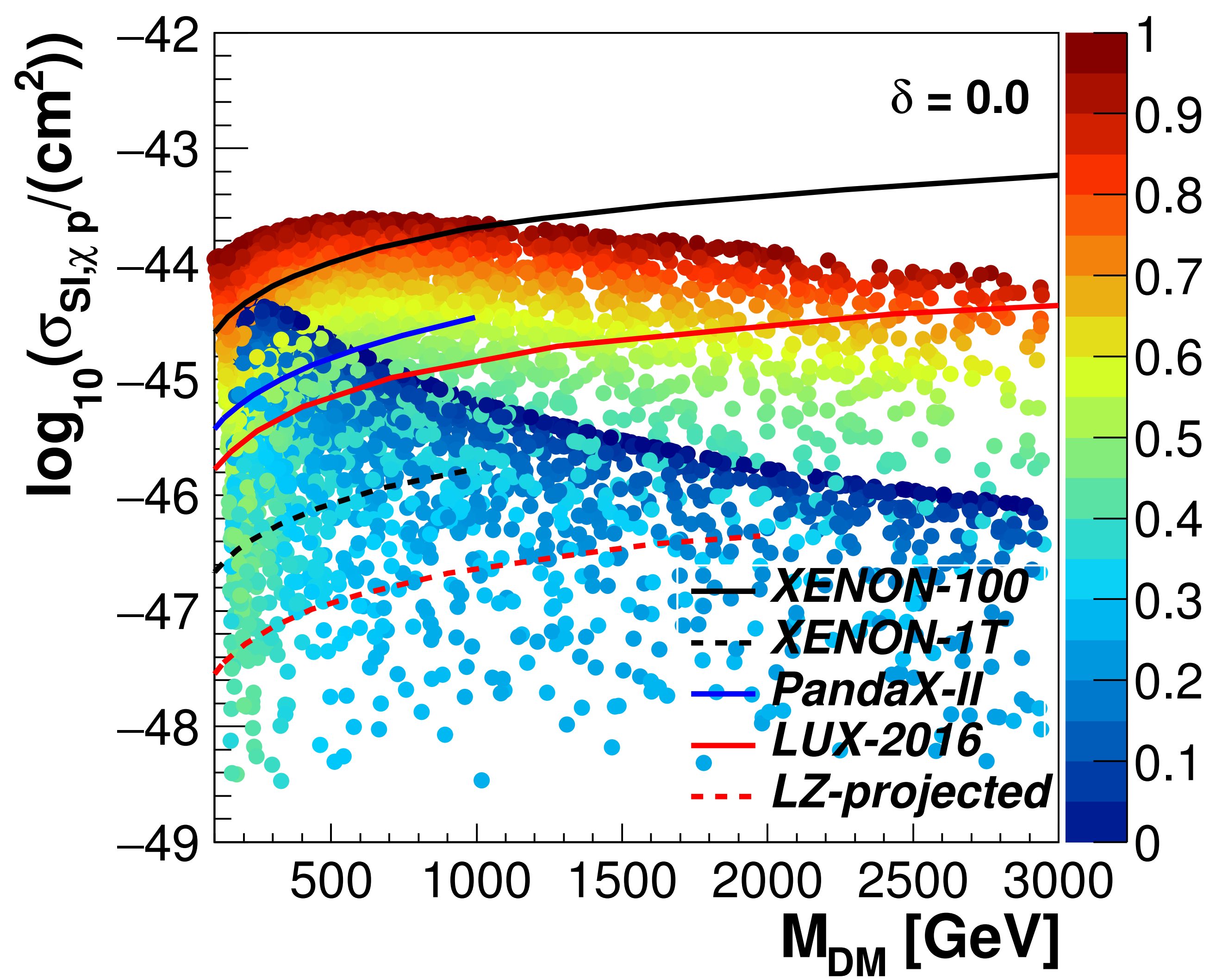
1703.06903

Thermal relic



Fixing DM relic

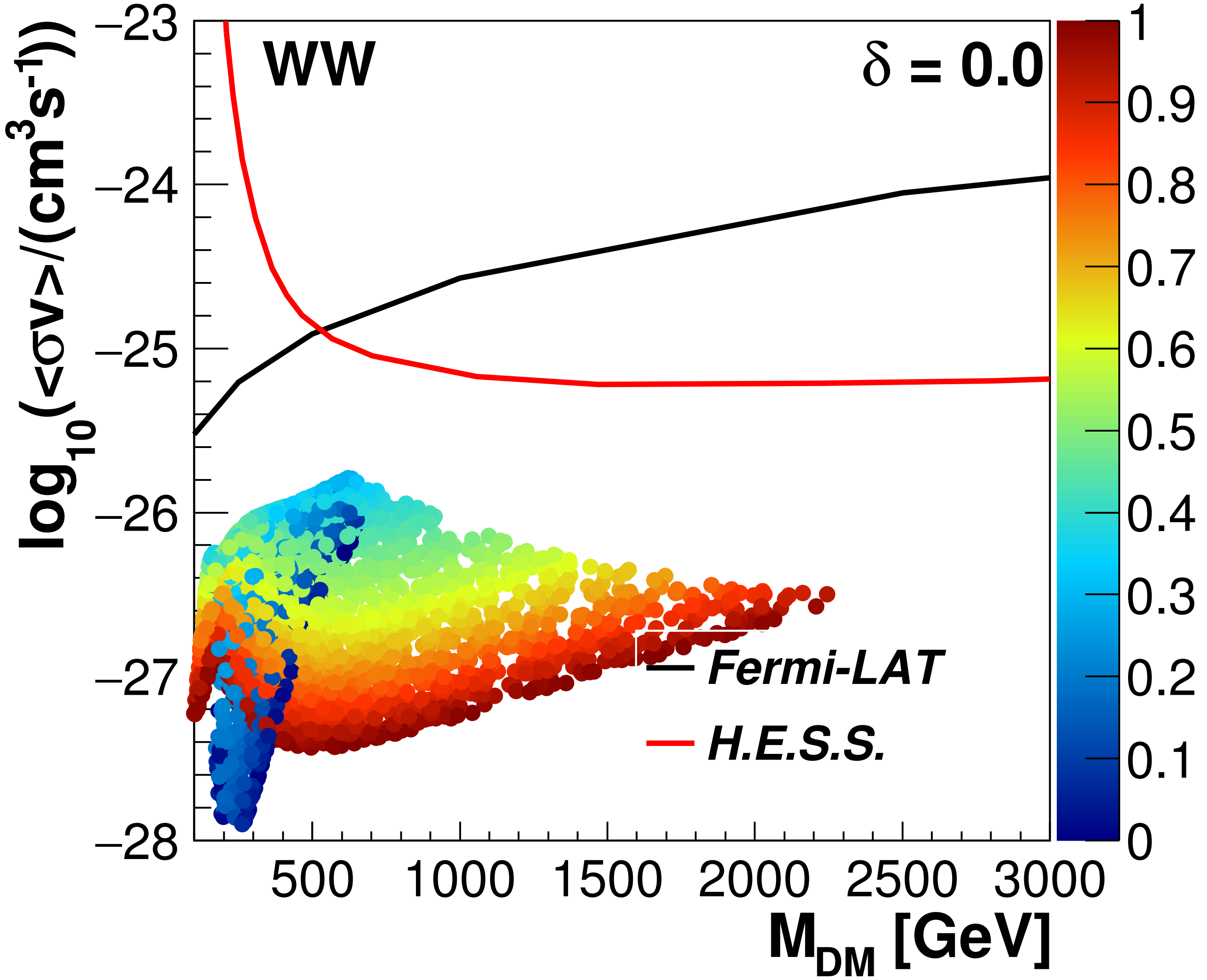


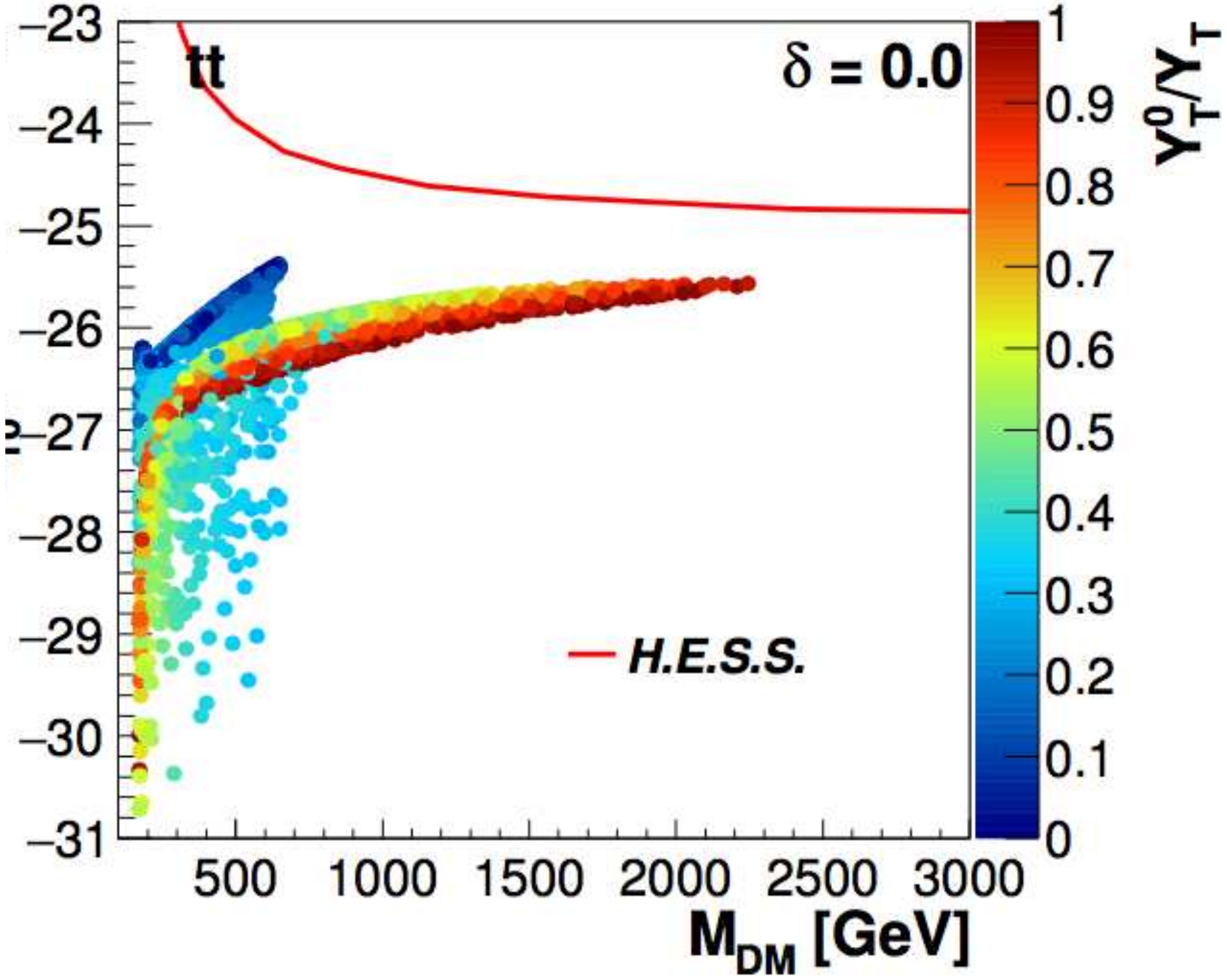
A composite 2HDM: Dark-Matter

Indirect Detection

G.C., T.Ma, Y.Wu, B.Zhang
1703.06903

Thermal relic abundance





A composite 2HDM: Dark-Matter

Indirect Detection

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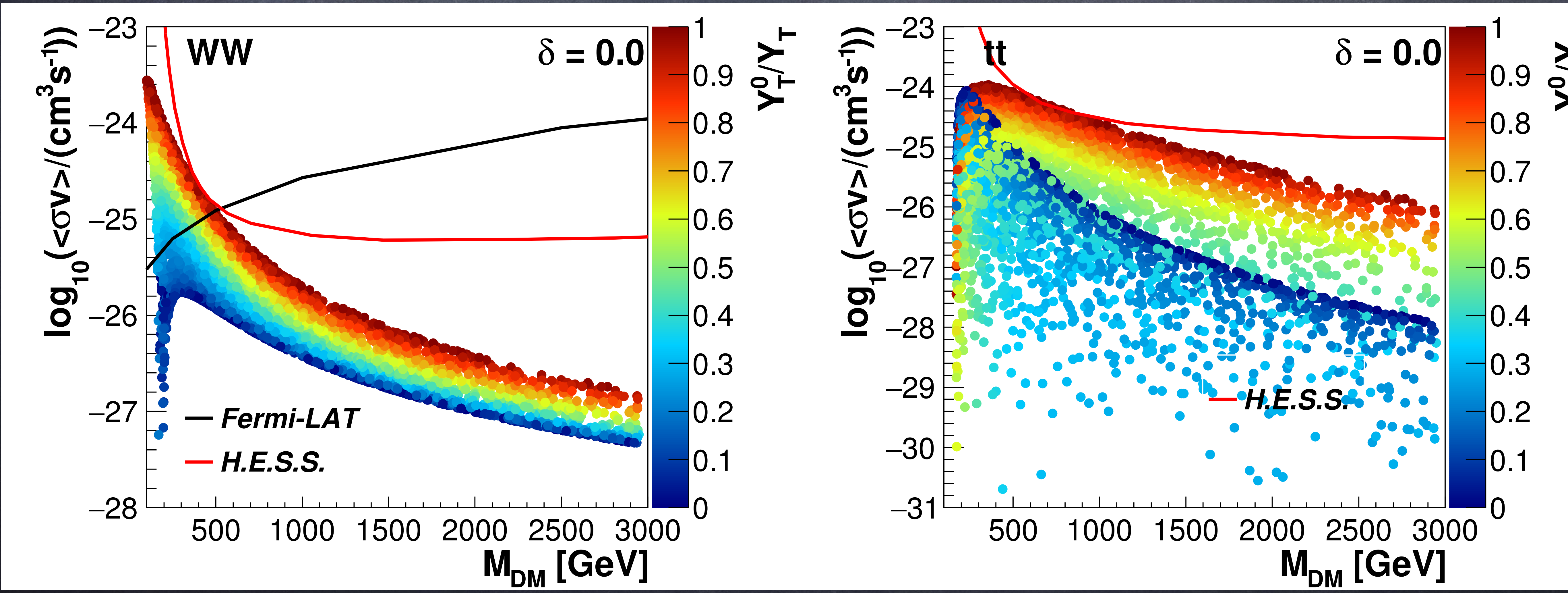
1703.06903

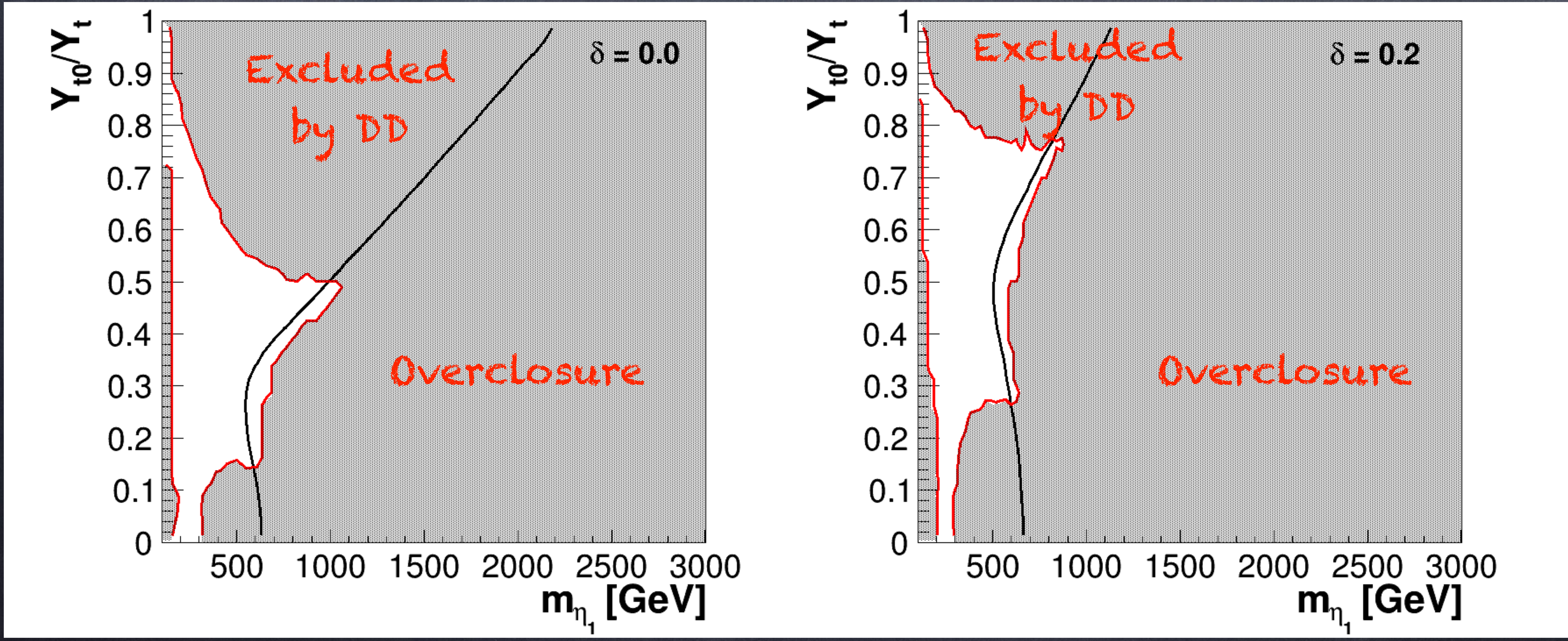
Fixed DM relic abundance



A composite 2HDM: Dark-Matter

G.C., T.Ma, Y.Wu, B.Zhang
1703.06903

Summary:



Another composite 2HDM

Let's add two more flavours to the SU(4)/Sp(4) model:

		$SU(2)_L$	$U(1)_Y$	$SU(2)_L$	Y	Higgs
Case A	ψ_1	$\mathbf{2}$	0	$SU(2)_1$	$T_2^3 + \xi T_3^3$	$(2,2,1)$ $[(2,1,2)$ if $\xi = 1]$
	ψ_2	$\mathbf{1}$	$\pm 1/2$			
	ψ_3	$\mathbf{1}$	$\pm \xi/2$			
Case B	ψ_1	$\mathbf{2}$	0	$SU(2)_1 + SU(2)_2$	T_3^3	$(2,1,2)+(1,2,2)$
	ψ_2	$\mathbf{2}$	0			
	ψ_3	$\mathbf{1}$	$\pm 1/2$			

$$SU(6) > SU(2)_1 \times SU(2)_2 \times SU(2)_3$$

$$\mathbf{14}_{\mathrm{Sp}(6)} \to (2,2,1) \oplus (2,1,2) \oplus (1,2,2) \oplus (1,1,1) \oplus (1,1,1)$$

Composite 2HDM: SU(6)/Sp(6)

G.C., C.Cai, H.H.Zhang
1805.07619

Higgs doublets

$$\frac{1}{2}\begin{pmatrix} -\left(\frac{1}{\sqrt{2}}\eta_1 + \frac{1}{\sqrt{6}}\eta_2\right)\sigma^2 & H_1 & H_2 \\ -H_1^T & -\left(\frac{1}{\sqrt{2}}\eta_1 - \frac{1}{\sqrt{6}}\eta_2\right)\sigma^2 & G \\ -H_2^T & -G^T & -\sqrt{\frac{2}{3}}\eta_2\sigma^2 \end{pmatrix}$$

bunch of singlets

14 pseudo-Goldstones!

The diagonal ones couple to the WZW anomaly.

Composite 2HDM: SU(6)/Sp(6)

G.C., C.Cai, H.H.Zhang
1805.07619

Higgs doublets

$$\frac{1}{2}\begin{pmatrix} -\left(\frac{1}{\sqrt{2}}\eta_1+\frac{1}{\sqrt{6}}\eta_2\right)\sigma^2 & H_1 & H_2 \\ -H_1^T & -\left(\frac{1}{\sqrt{2}}\eta_1-\frac{1}{\sqrt{6}}\eta_2\right)\sigma^2 & G \\ -H_2^T & -G^T & -\sqrt{\frac{2}{3}}\eta_2\sigma^2 \end{pmatrix}$$

bunch of singlets

Two possible vacuum misalignments:

3 directions,
the 2 Higgses
plus a singlet

Composite 2HDM: SU(6)/Sp(6)

G.C., C.Cai, H.H.Zhang
1805.07619

$$\frac{1}{2}\begin{pmatrix} -\left(\frac{1}{\sqrt{2}}\eta_1+\frac{1}{\sqrt{6}}\eta_2\right)\sigma^2 & H_1 & H_2 \\ -H_1^T & -\left(\frac{1}{\sqrt{2}}\eta_1-\frac{1}{\sqrt{6}}\eta_2\right)\sigma^2 & G \\ -H_2^T & -G^T & -\sqrt{\frac{2}{3}}\eta_2\sigma^2 \end{pmatrix}$$

Higgs doublets

Stable!

bunch of singlets

Two possible vacuum misalignments:

3 directions, the 2 Higgses plus a singlet

or

Only one Higgs!

DM-U(1) preserved!

Composite 2HDM: SU(6)/Sp(6)

G.C., C.Cai, H.H.Zhang
1805.07619

2 Yukawa operators for top and 2 for bottom:

$$
\begin{aligned}
V_{\text{Yuk}} = -C_t f^4 \Big\{ & \left(|Y_{t1}|^2 + |Y_{b1}|^2\right) s_\theta^2 + \frac{h_1}{2\sqrt{2}f}\left(|Y_{t1}|^2 + |Y_{b1}|^2\right) s_{2\theta} + \\
& \frac{h_2}{\sqrt{2}f}\left(\Re\, Y_{t1}Y_{t2}^* + \Re\, Y_{b1}Y_{b2}^*\right) c_{\frac{\theta}{2}} s_\theta + \frac{\varphi_0}{\sqrt{2}f}\left(\Re\, Y_{t1}Y_{t2}^* - \Re\, Y_{b1}Y_{b2}^*\right) s_{\frac{\theta}{2}} s_\theta + \\
& \frac{A_0}{\sqrt{2}f}\left(\Im\, Y_{t1}Y_{t2}^* - \Im\, Y_{b1}Y_{b2}^*\right) c_{\frac{\theta}{2}} s_\theta + \frac{\eta_3}{\sqrt{2}f}\left(\Im\, Y_{t1}Y_{t2}^* + \Im\, Y_{b1}Y_{b2}^*\right) s_{\frac{\theta}{2}} s_\theta \Big\}
\end{aligned}
$$

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& \boxed{\frac{A_0}{\sqrt{2}f}\left(\Im\, Y_{t1}Y_{t2}^* \cancel{-} \Im\, Y_{b1}Y_{b2}^*\right) c_{\frac{\theta}{2}} s_\theta + \frac{\eta_3}{\sqrt{2}f}\left(\Im\, Y_{t1}Y_{t2}^* \cancel{-} \Im\, Y_{b1}Y_{b2}^*\right) s_{\frac{\theta}{2}} s_\theta \Big\}}
\end{aligned}
$$

Vanish for real Yukawas!
(no CP violation)

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$$
\begin{aligned}
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& \frac{A_0}{\sqrt{2}f}\left(\Im\, Y_{t1}Y_{t2}^* \;\; \Im\, Y_{b1}Y_{b2}^*\right) c_{\frac{\theta}{2}} s_\theta + \frac{\eta_3}{\sqrt{2}f}\left(\Im\, Y_{t1}Y_{t2}^* \;\; \Im\, Y_{b1}Y_{b2}^*\right) s_{\frac{\theta}{2}} s_\theta \Big\}
\end{aligned}
$$

Cannot vanish simultaneously, unless:

top-bottom cancellation, or $Y_{t2} = Y_{b2} = 0$

Composite 2HDM: SU(6)/Sp(6)

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$$\frac{1}{2}\begin{pmatrix} -\left(\frac{1}{\sqrt{2}}\eta_1+\frac{1}{\sqrt{6}}\eta_2\right)\sigma^2 & H_1 & H_2 \\ -H_1^T & -\left(\frac{1}{\sqrt{2}}\eta_1-\frac{1}{\sqrt{6}}\eta_2\right)\sigma^2 & G \\ -H_2^T & -G^T & -\sqrt{\frac{2}{3}}\eta_2\sigma^2 \end{pmatrix}$$

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U(1)$_{DM}$ vacuum

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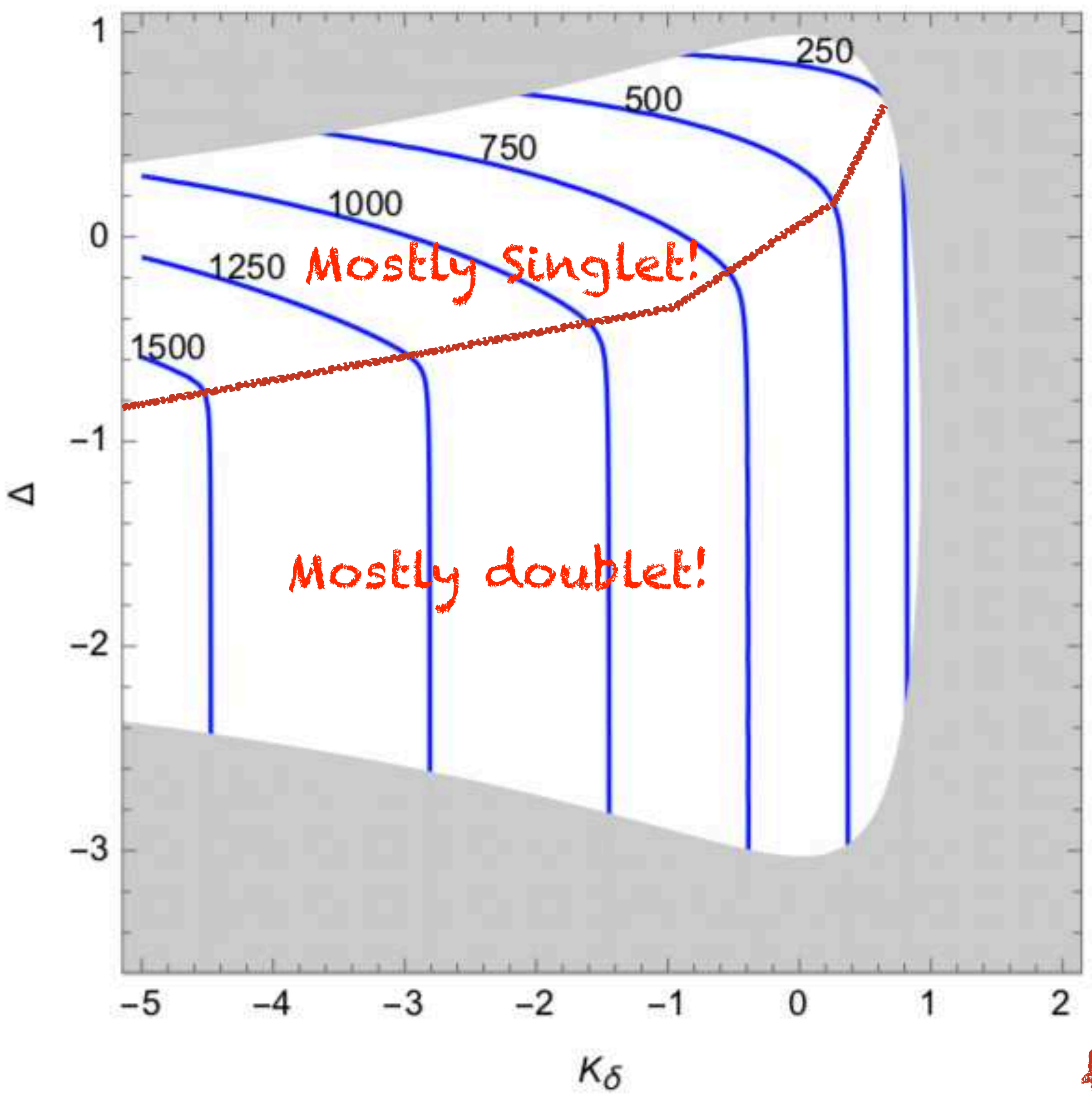
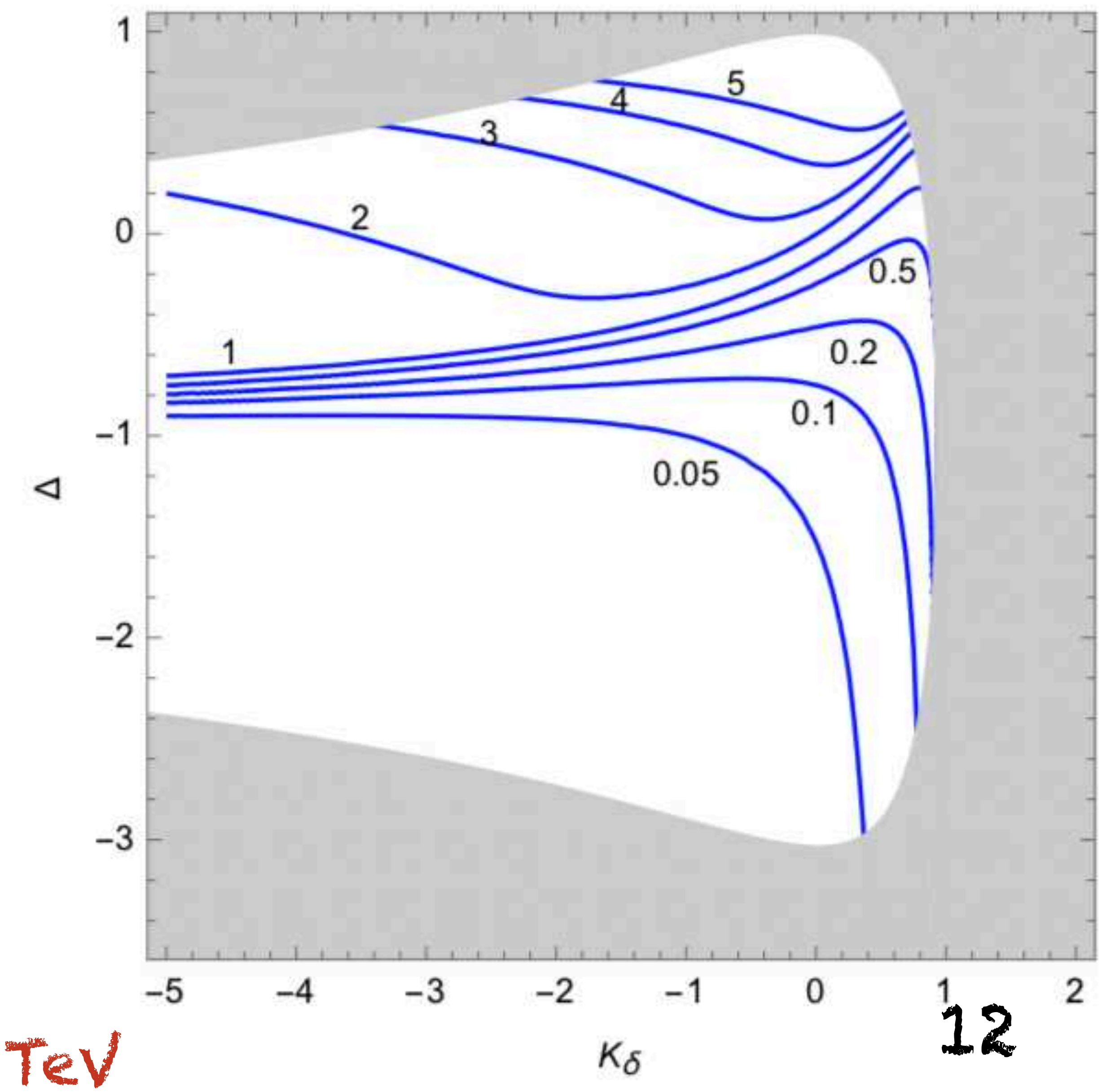
DM mass (GeV)



Splitting from charged



f=1.2 TeV

$U(1)_{DM}$ vacuum

G.C., C.Cai, H.H.Zhang
1805.07619

Problem: both doublet and singlet have a coupling to the Z boson!

$$+\frac{g}{4c_W}Z_\mu\left[\left(1+c_\theta-4s_W^2\right)H^- i\overleftrightarrow{\partial^\mu}H^+ + \left(1-c_\theta-4s_W^2\right)\eta^- i\overleftrightarrow{\partial^\mu}\eta^+ \right.$$
$$\left. +(1+c_\theta)\,H^0 i\overleftrightarrow{\partial^\mu}(H^0)^* + (1-c_\theta)\,\eta^0 i\overleftrightarrow{\partial^\mu}(\eta^0)^*\right]$$

Excluded by Direct Detection, unless

$$\sin\theta \lesssim 10^{-2} \qquad\qquad \sigma_{XENON1T} < 10^{-47\div45}$$

$$\sigma_{V,\eta^0 N} = \frac{(1-c_\theta)^2 g^4 m_N^2}{16\pi c_W^4 m_Z^4}\times\begin{cases}\left(\frac{1}{4}-s_W^2\right)^2, & \text{for protons,}\quad N=p;\\ \left(\frac{1}{4}\right)^2, & \text{for neutrons,}\quad N=n\,.\end{cases}$$

Numerically, this leads to

$$\sigma_{V,\eta^0 p}\sim 2.7\cdot 10^{-41}\,(1-c_\theta)^2\ \mathrm{cm}^2\,,\qquad \sigma_{V,\eta^0 n}\sim 2.3\cdot 10^{-39}\,(1-c_\theta)^2\ \mathrm{cm}^2\,,$$

Further developments:

- Case SU(6)/SO(6) under study

G.C., A.Deandrea, A.Kushwaha

- Generalisation to SU(8)/Sp(8) can lead to models without Z coupling

G.C., C.Cai, H.H.Zhang, M.T.Frandsen, M.Rosenlyst

Interestingly, they are all 2HDMs!!!

Conclusions

- Composite 2HDMs emerge naturally!

張飛 (张飞)
aka Dark Matter

劉備 (刘备)
aka the Higgs

關羽 (关羽)
aka Mr. diboson