

Composite Dark Matter and the Higgs

G.Cacciapaglia (IPNL)

14/9/2017 @ ETC* Trento

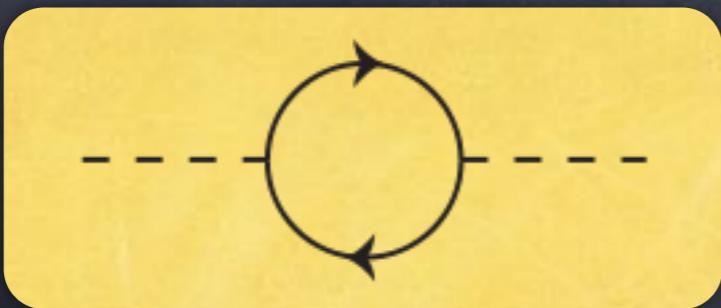


Do we still need BSM?



We have a pretty
good idea of
the mechanism

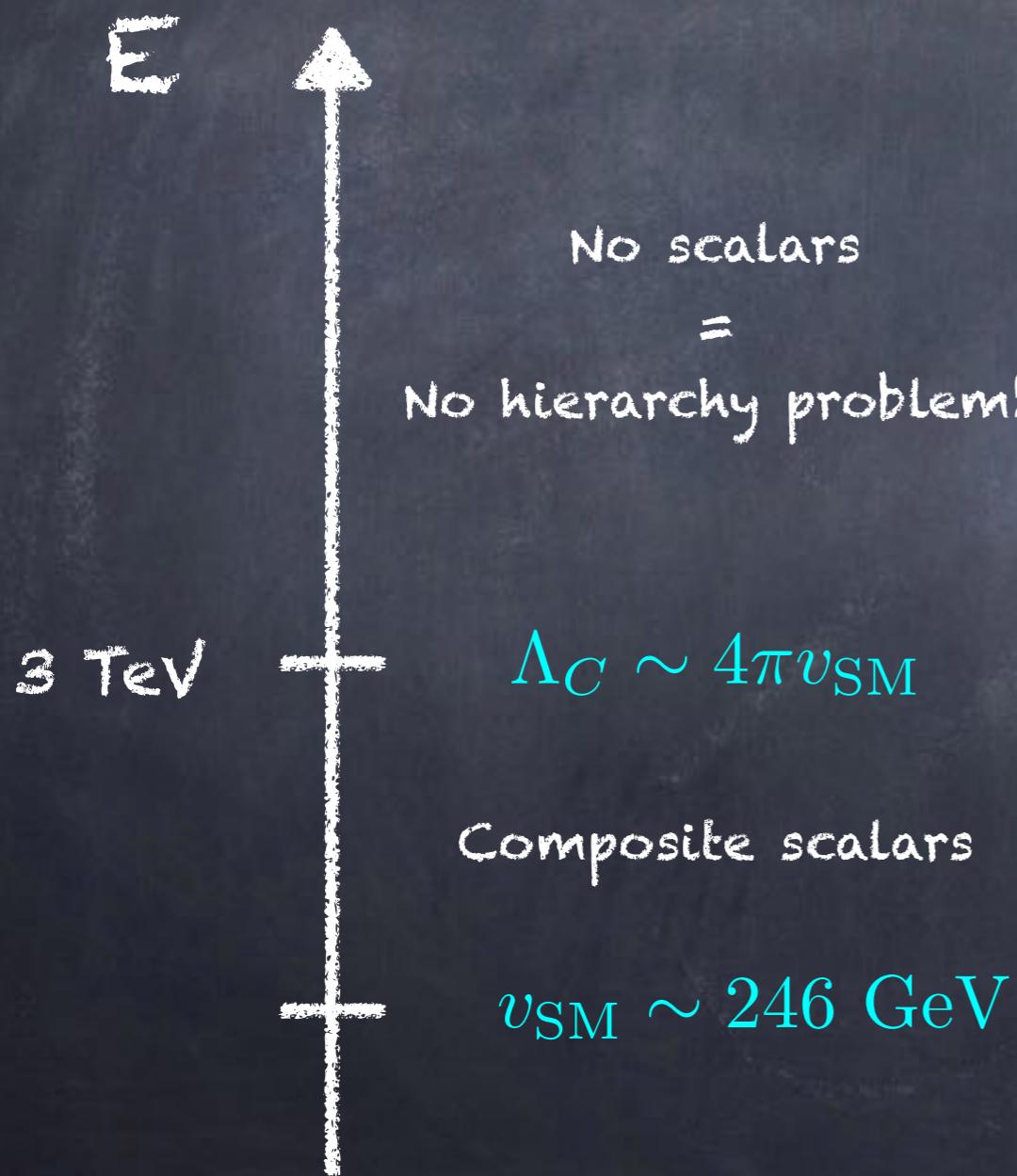
But, we don't know how to protect it:



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

DO we still need BSM?

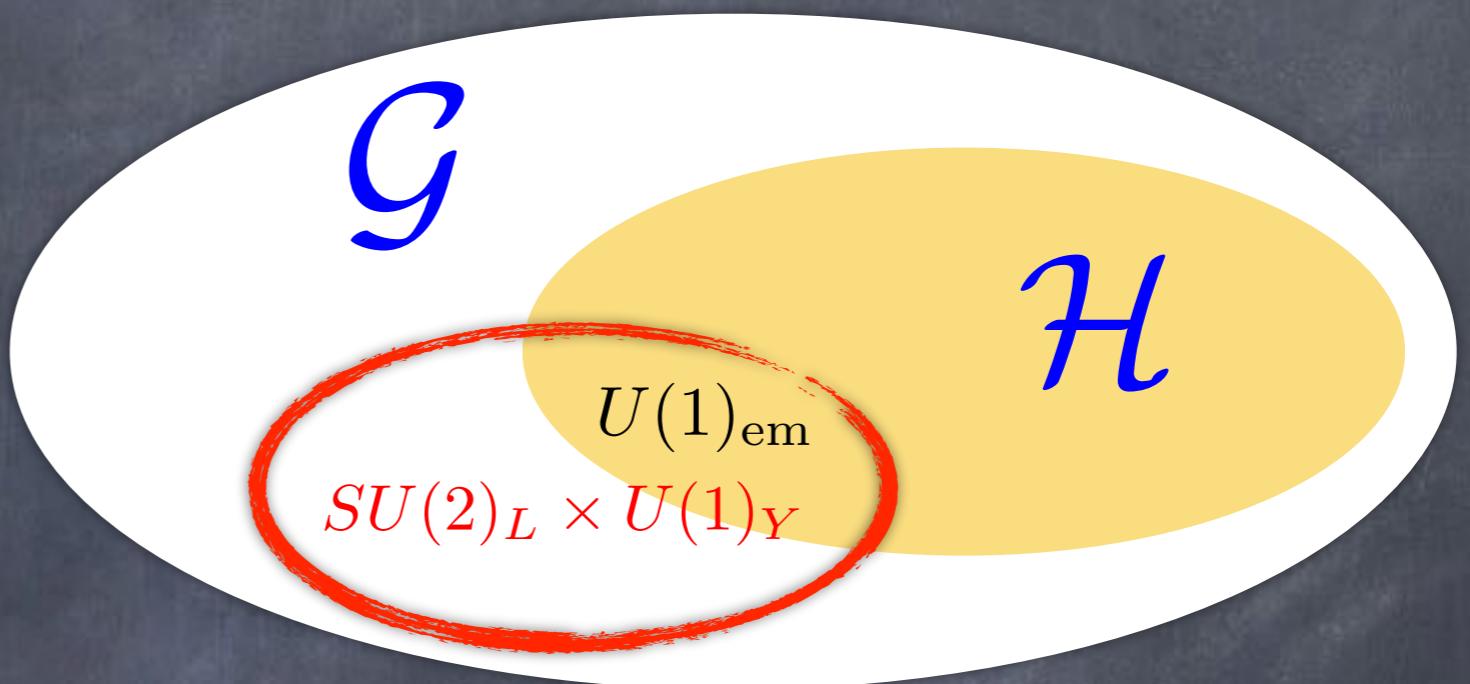
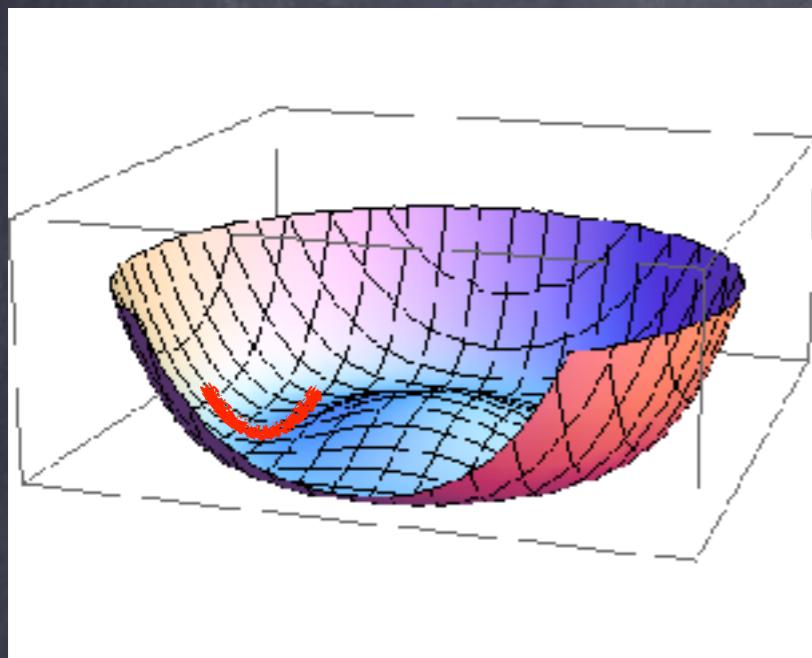
Compositeness is a way to dynamically protect
the Higgs mechanism!



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

Compositeness scale

Compositeness, and the Higgs boson



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

QCD template:

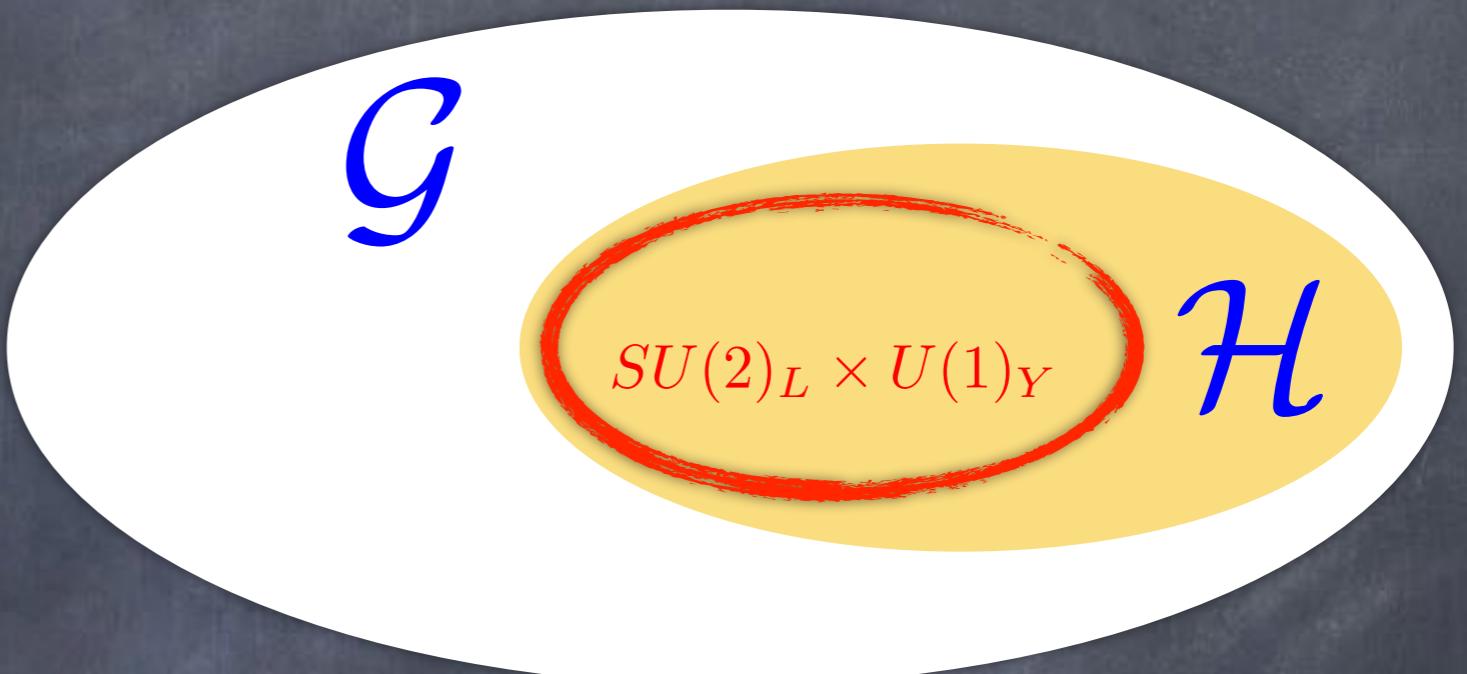
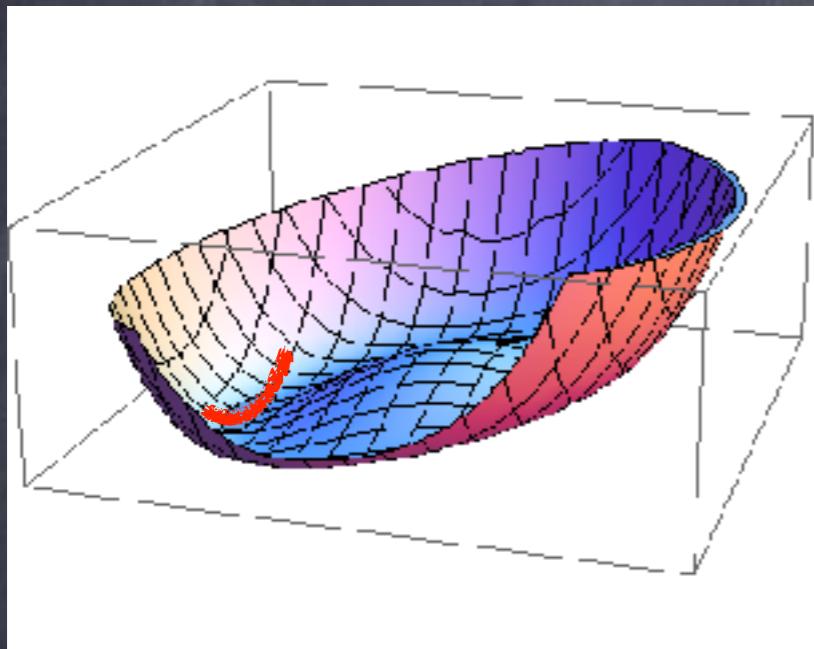
- Goldstones include the longitudinal d.o.f. of W and Z

$\leftarrow \pi$ pions

- the Higgs is a heavy bound state (singlet under H)

$\leftarrow \sigma$ sigma

Compositeness, and the Higgs boson

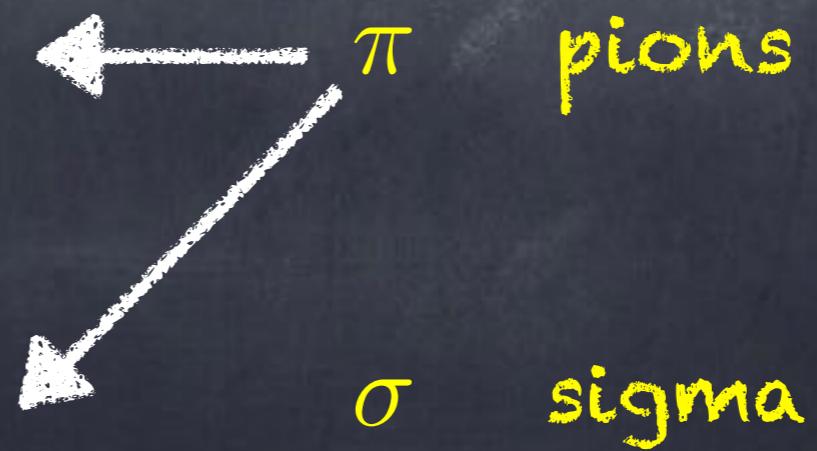


$\mathcal{G} \rightarrow \mathcal{H}$

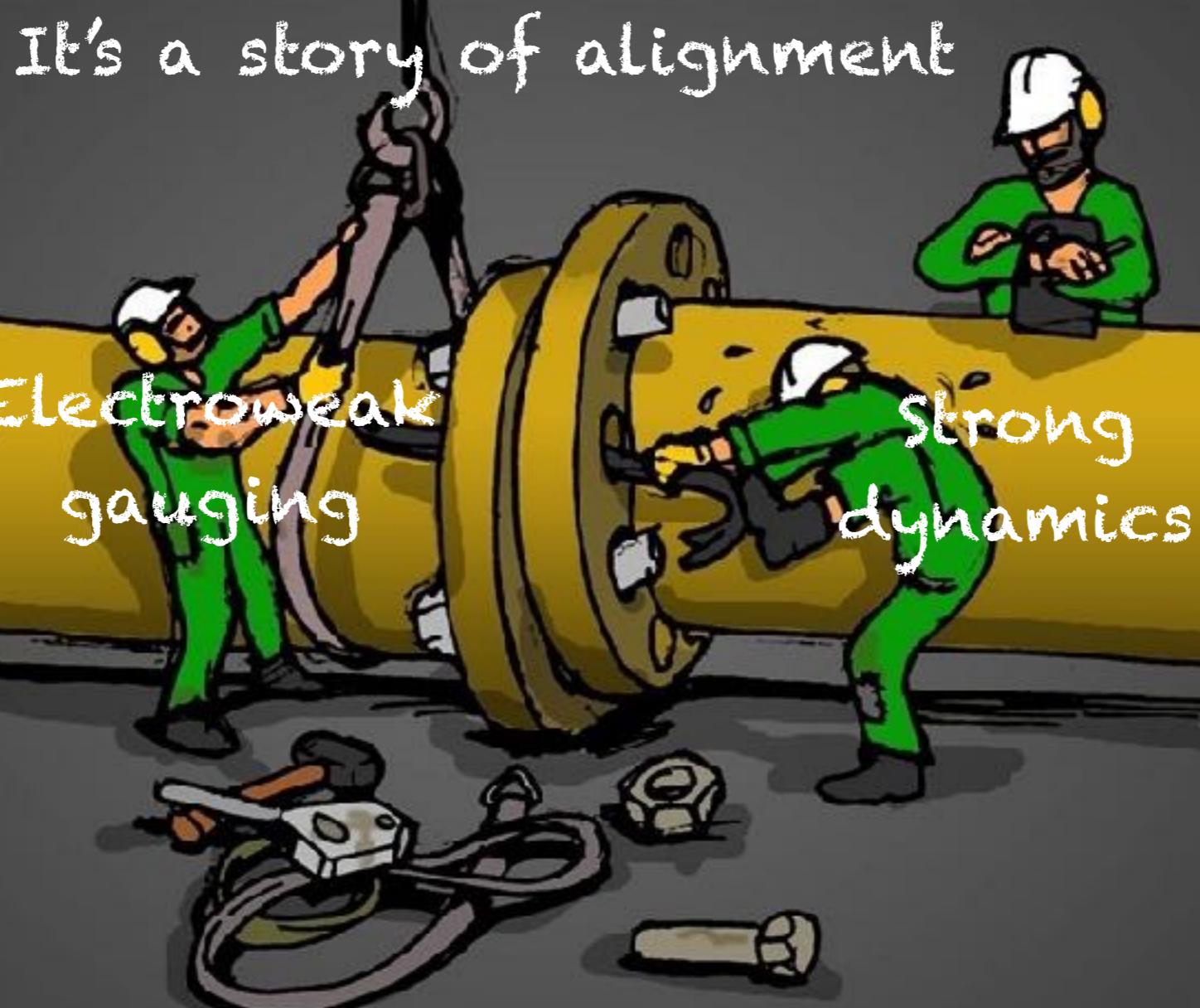
QCD template:

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

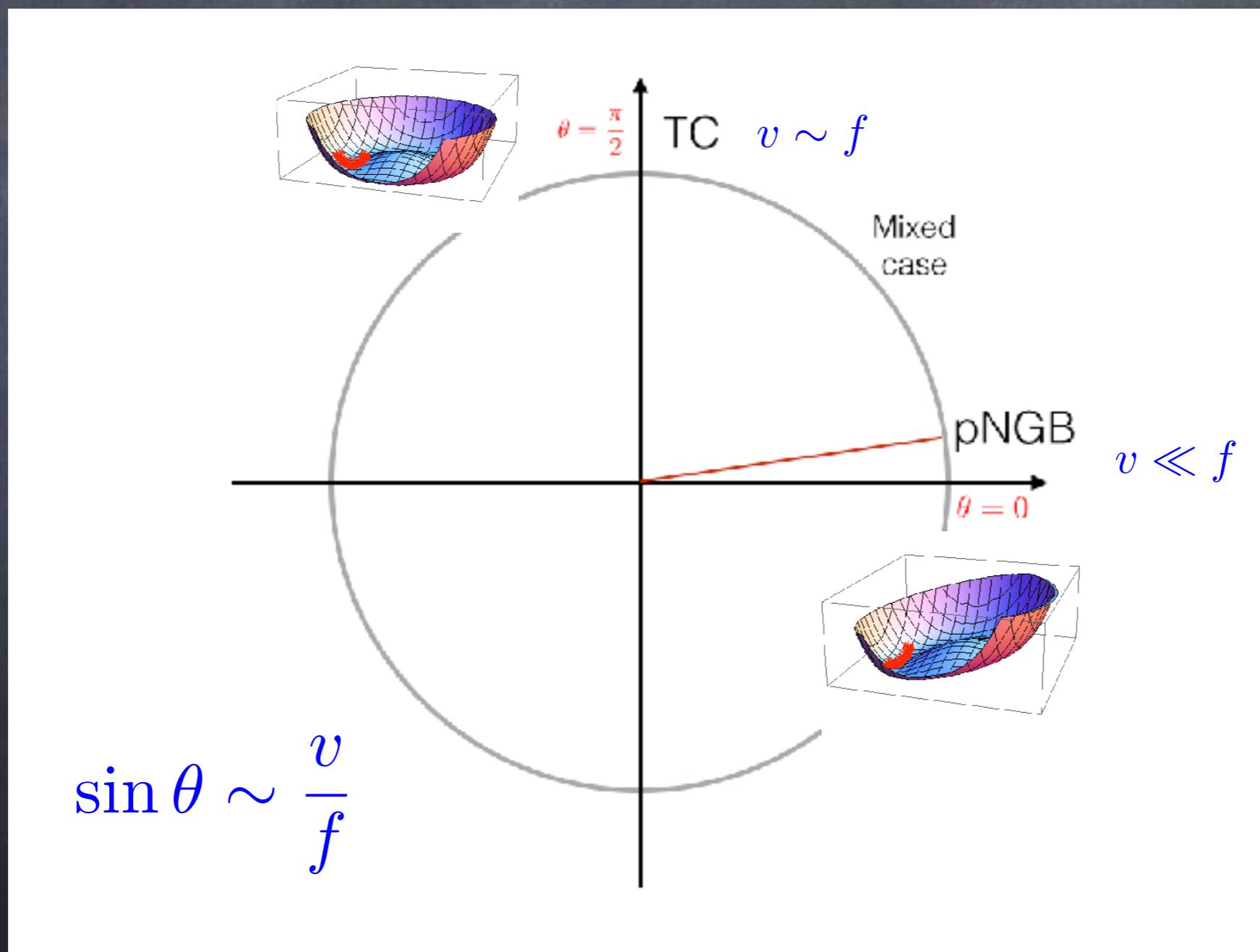
- the Higgs is a pseudo-Goldstone (pNGB)



Compositeness, and the Higgs boson



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
- 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!

See Enrico's talk

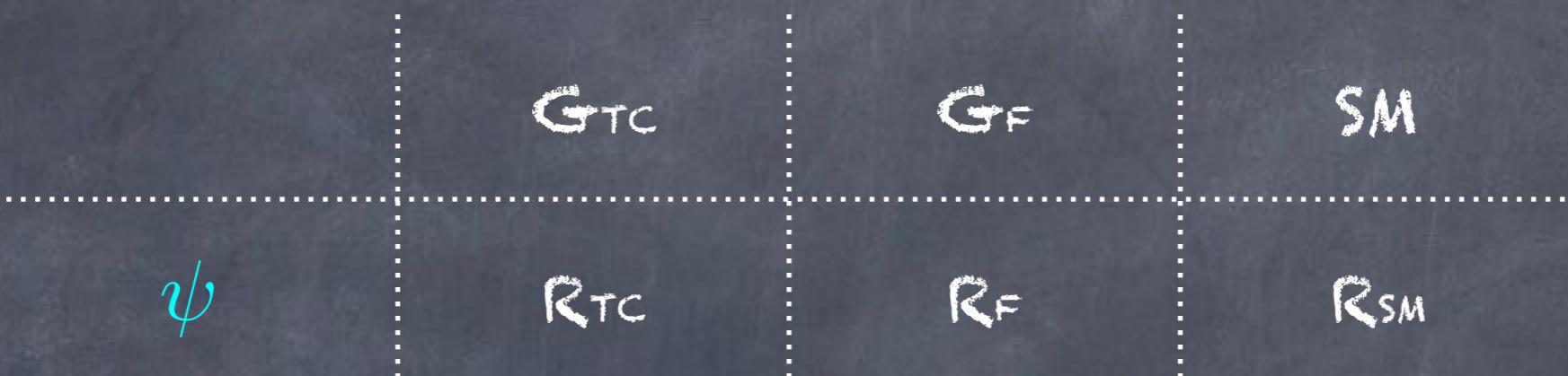
The FCD approach

- Models with a pion-Higgs allow a mass term for the fermions!

$$\text{Gauge-invariant} \quad m \psi\psi \quad \longleftrightarrow \quad \langle\psi\psi\rangle \quad \text{EW preserving} \\ \text{mass term} \qquad \qquad \qquad \qquad \qquad \qquad \text{vacuum}$$

- We will be interested in non-chiral theories ("real" in Roberto's talk)
- Good news for Lattice: chiral limit not needed!

The FCD approach



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

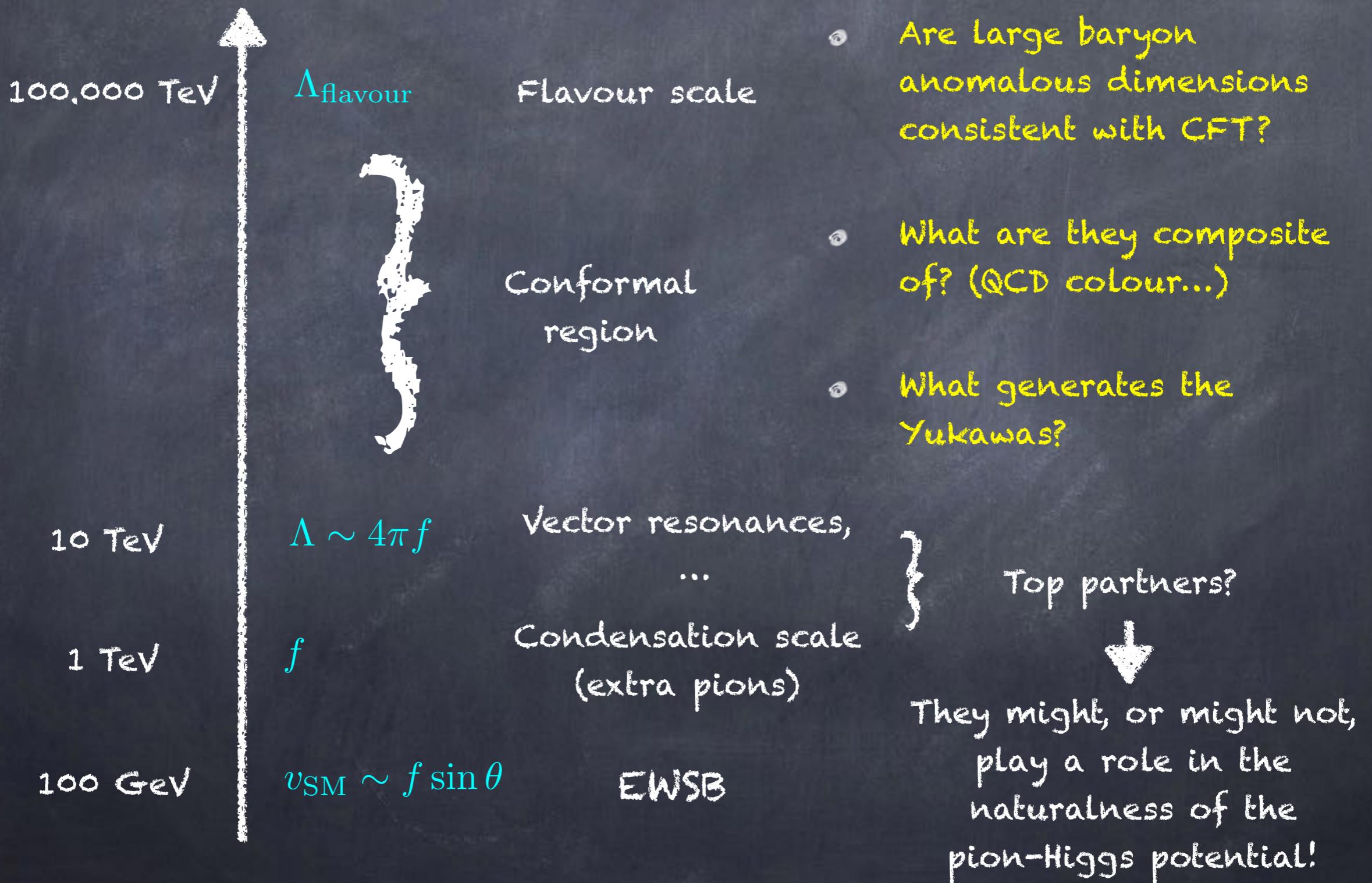
pseudo-real: $G_F = SU(2N_\psi)$ $\langle \psi^i \psi^j \rangle$ $SU(2N_\psi) \rightarrow Sp(2N_\psi)$

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

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!!!
$SU(4) \times SU(4)$ $/SU(4)$	$SU(N)$ 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!



Composite Dark Matter

- Some pions 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)

See Michele's talk

Compositeness: DM and the Higgs!

One dynamics to rule them all!



SU(4)/Sp(4)?

Frigerio, Pomarol, Riva, Urbano
1204.2808

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

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

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

$SU(4)/Sp(4)$?

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

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

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

Ryttov, Sannino
0809.0713

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

$$\phi = \frac{h + i\eta}{\sqrt{2}}$$

is charged under the unbroken $U(1)_{DM}$,
and thus stable (TIMP).

A composite 2HDM

G.C., T.Ma
1508.07014

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

"QCD with
4 flavours"

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

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

Triplet

Complex bi-doublet (2HDM)

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

SU(2)_R Triplet

The diagram illustrates the decomposition of the complex bi-doublet (2HDM) into a triplet and a SU(2)_R triplet. The complex bi-doublet is represented by a 2x2 matrix with elements labeled as $\sigma_i \Delta^i + s/\sqrt{2}$, $-i\Phi_H$, $i\Phi_H^\dagger$, and $\sigma_i N^i - s/\sqrt{2}$. Red arrows point from the first column to a 'Triplet' and from the second column to a 'Complex bi-doublet (2HDM)'. A third red arrow points from the second column to a 'SU(2)_R Triplet'.

A composite 2HDM

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

G.C., T.Ma
1508.07014

Is it there a parity stabilising the pions?

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

$$\left. \begin{array}{l} s \rightarrow s \\ H_1 \rightarrow H_1 \\ H_2 \rightarrow -H_2 \\ \Delta \rightarrow -\Delta \\ N \rightarrow -N \end{array} \right\} \begin{array}{l} \text{Mimics the minimal case} \\ \text{Dark Sector!} \end{array}$$

A composite 2HDM

G.C., T.Ma
1508.07014

$$\Pi = \frac{1}{2} \begin{pmatrix} \sigma_i \Delta^i + s/\sqrt{2} & -i\Phi_H \\ i\Phi_H^\dagger & \sigma_i N^i - s/\sqrt{2} \end{pmatrix} \quad \langle \Phi_H \rangle = \langle H_1 + iH_2 \rangle = \begin{pmatrix} ve^{i\beta} & 0 \\ 0 & ve^{i\beta} \end{pmatrix}$$

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

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

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

Beta = relative phase of the two T-quarks!

A composite 2HDM

G.C., T.Ma
1508.07014

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

4 "Yukawa" couplings!

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

$$V_{\text{top}}(\theta) = -C_t f^4 \left[8|Y_t|^2 \sin^2 \theta + \leftarrow \text{Potential for theta} \right]$$

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

Set to zero by phase-shift $\rightarrow +4\sqrt{2} \text{Im}(Y_D^* Y_t) \sin \theta \frac{h_2}{f}$

Custodial
violating
VEVs!!!

$$\begin{aligned} & \rightarrow +2\sqrt{2} \text{Re}(Y_D^* Y_t) \sin(2\theta) \frac{A_0}{f} \\ & \rightarrow +4 \text{Im}(Y_T^* Y_t) \sin^2 \theta \frac{N_0 + \Delta_0}{f} + \dots \end{aligned}$$

A composite 2HDM

G.C., T.Ma
1508.07014

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

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DM parity!

Custodial violating VEVs!!!

A composite 2HDM: spectrum

The spectrum essentially depends on 2 parameters:

- A Yukawa coupling;
- A mass difference.

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

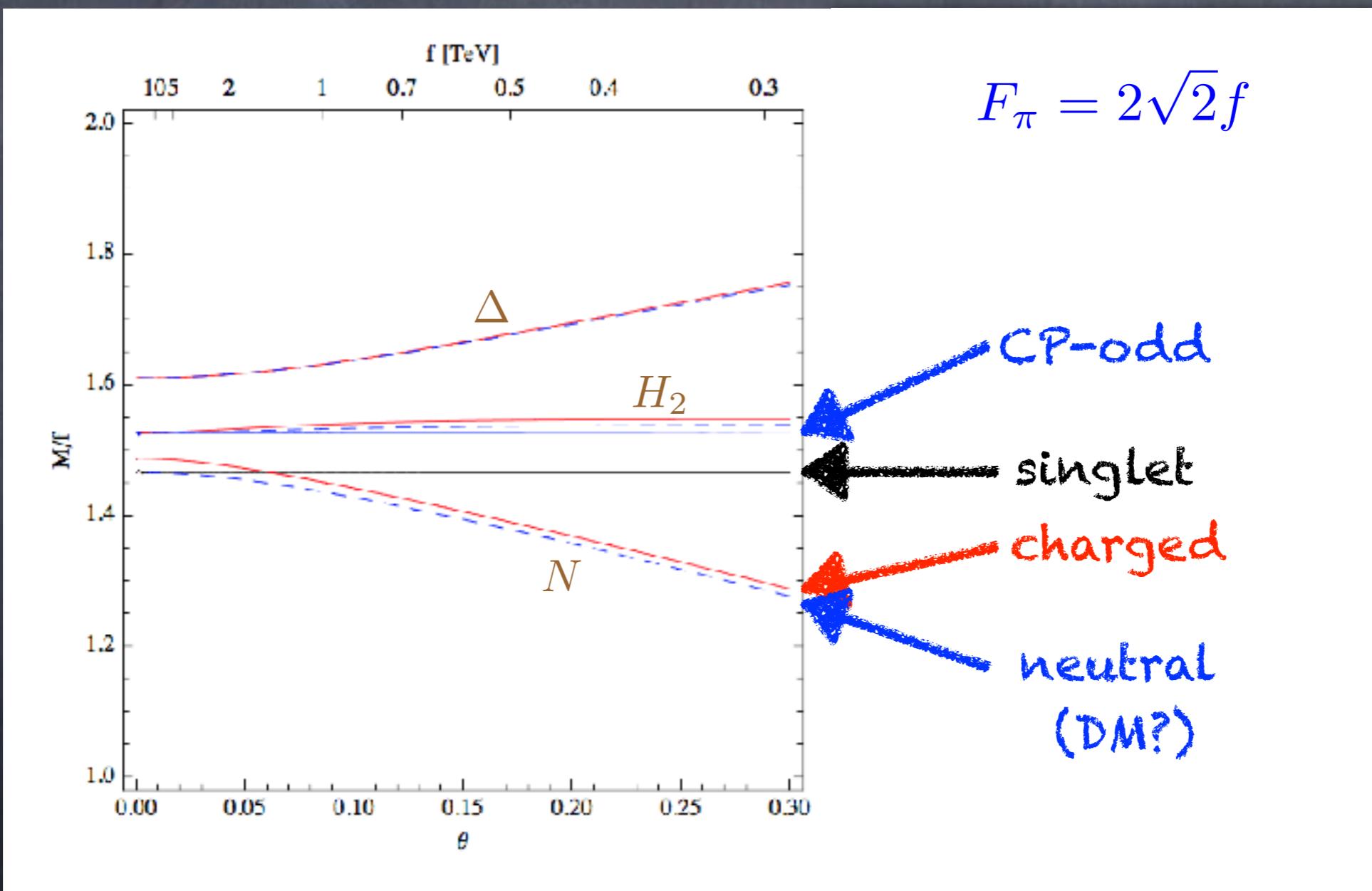
$$m_s = \frac{m_h}{\sin \theta}$$

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

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

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

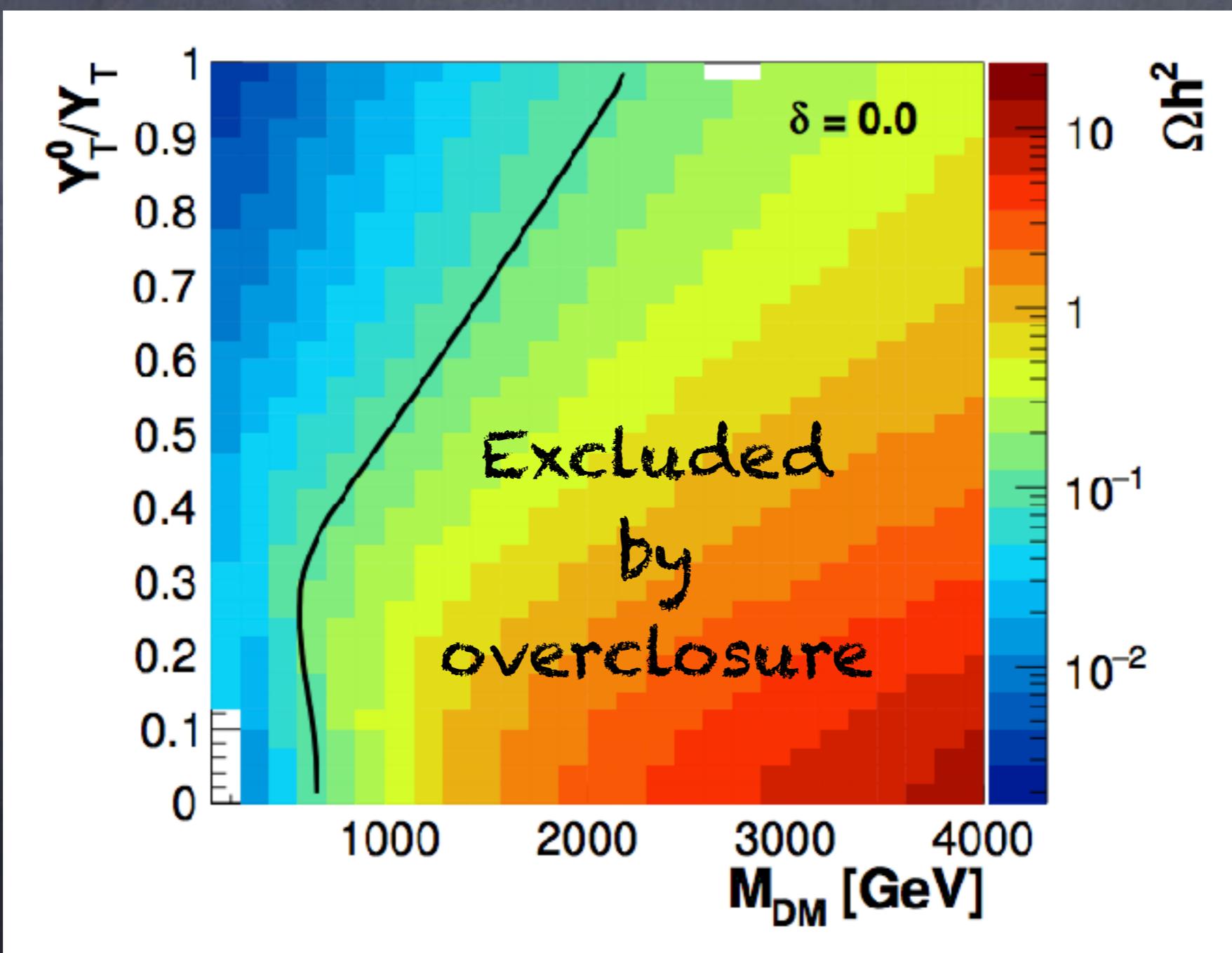
A composite 2HDM: spectrum



A composite 2HDM: Dark-Matter

Relic abundance:

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



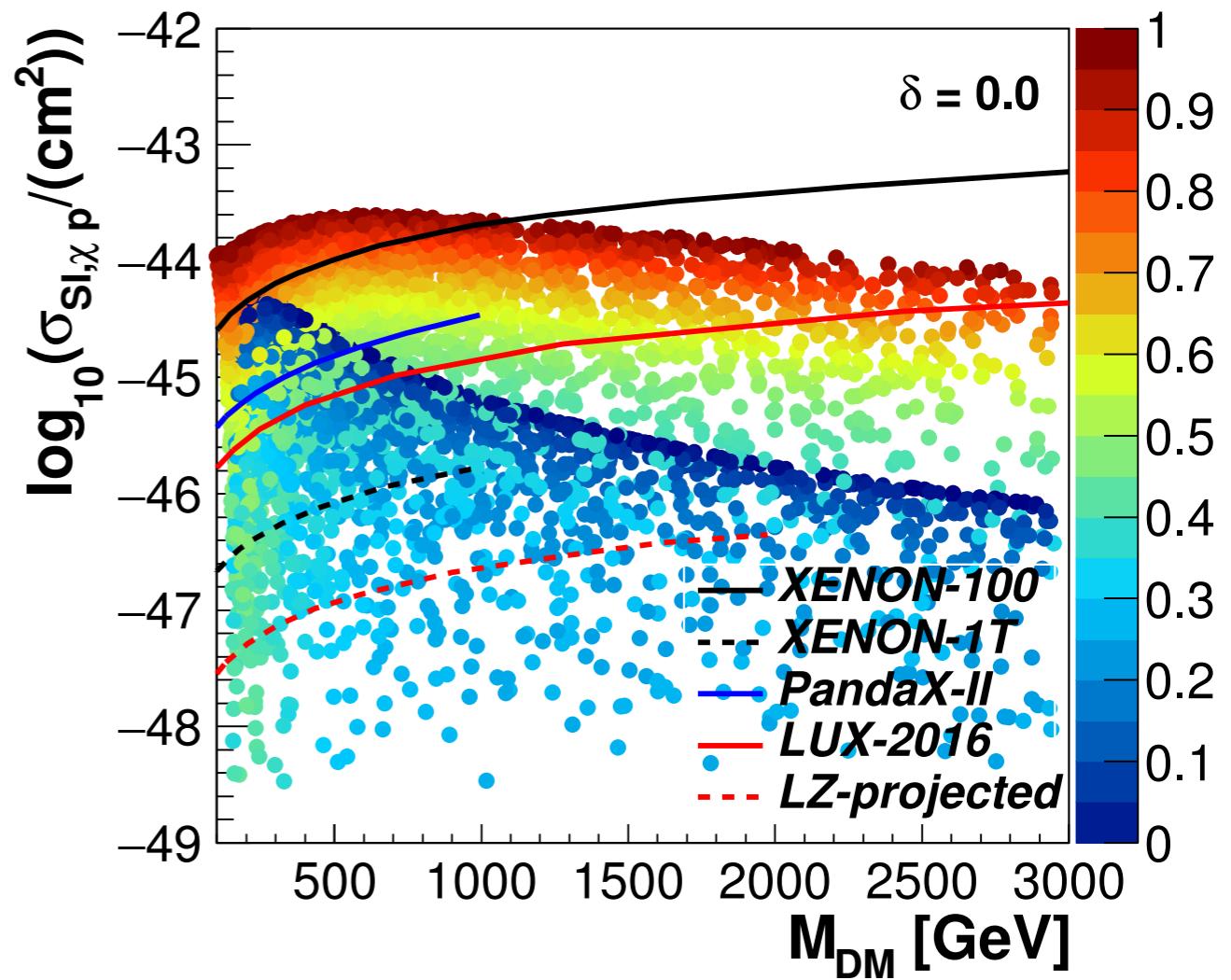
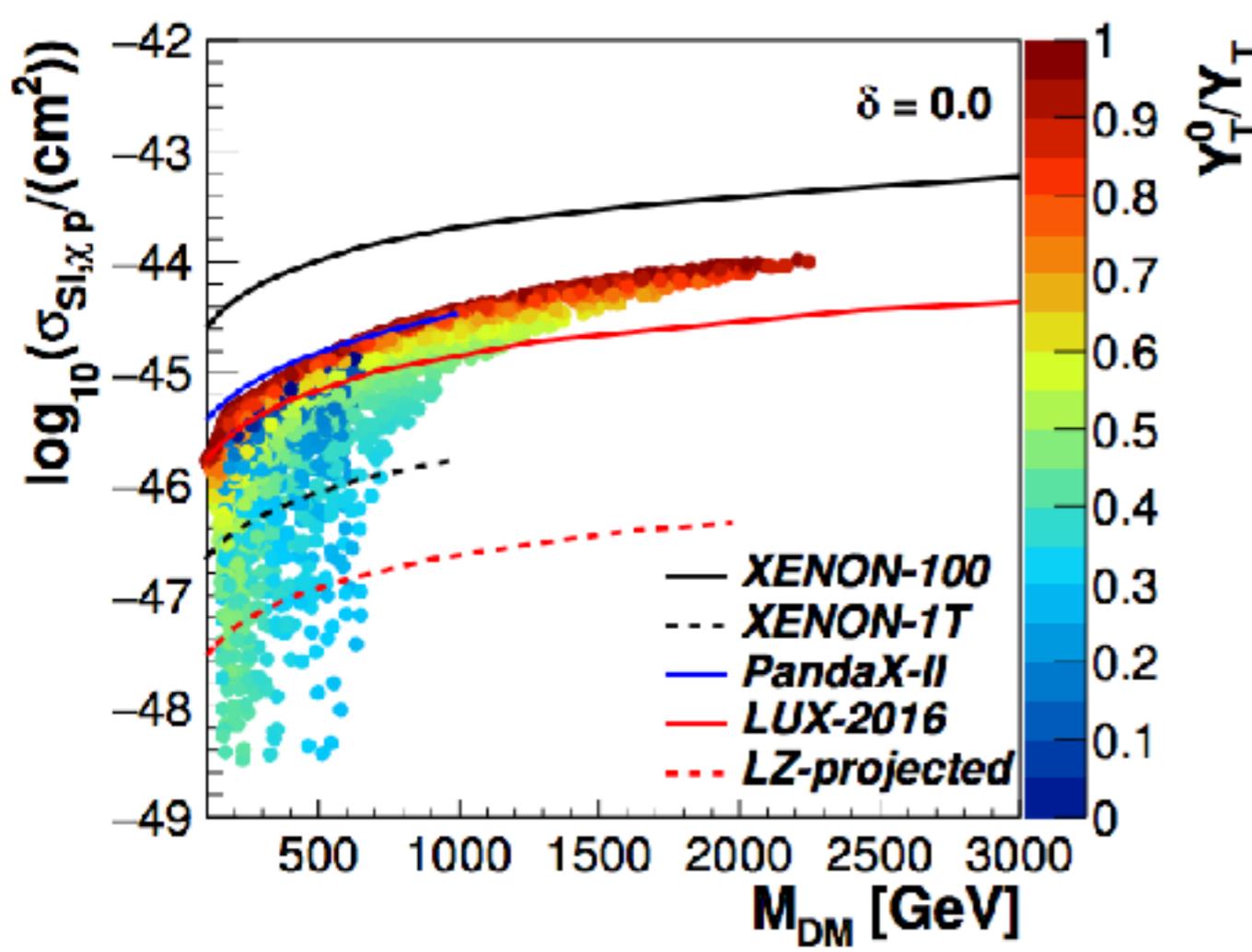
A composite 2HDM: Dark-Matter

Direct Detection

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

Thermal relic

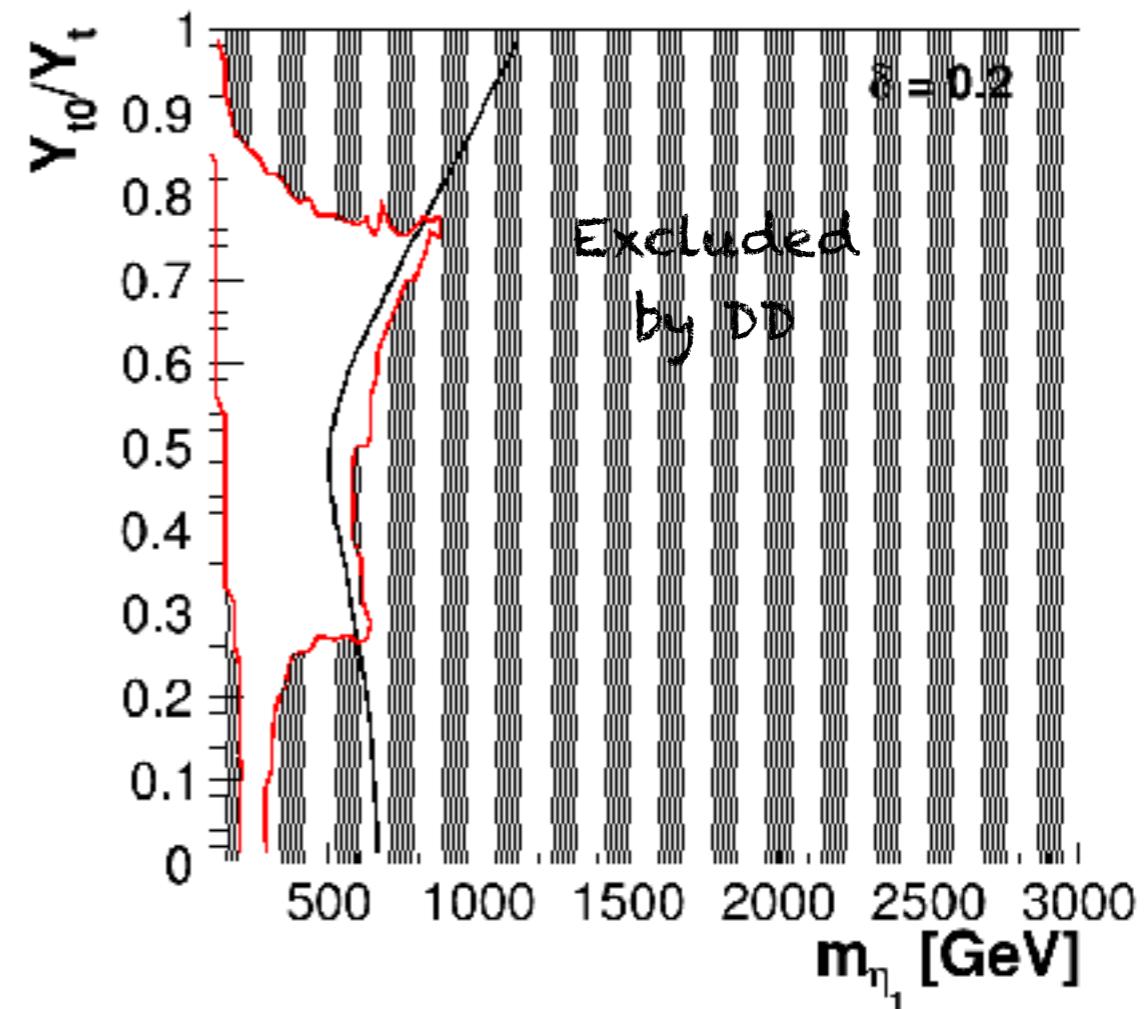
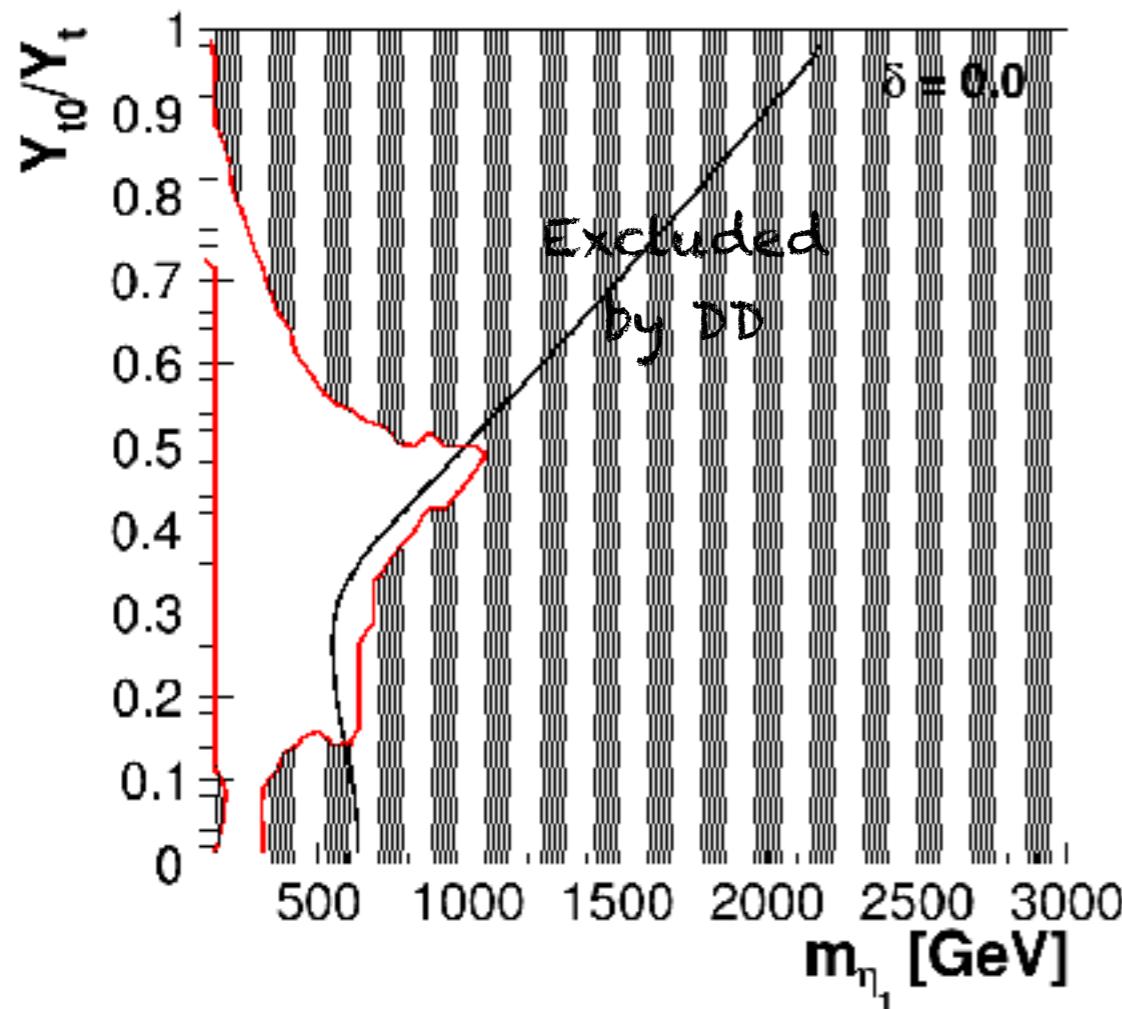
Fixing DM relic



A composite 2HDM: Dark-Matter

Combined bounds:

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



Lattice results

A.Hasenfratz, C.Rebbi, O.Witzel
1609.01401, 1611.07427

Study QCD (i.e. SU(3) gauge theory) with 12 flavours.

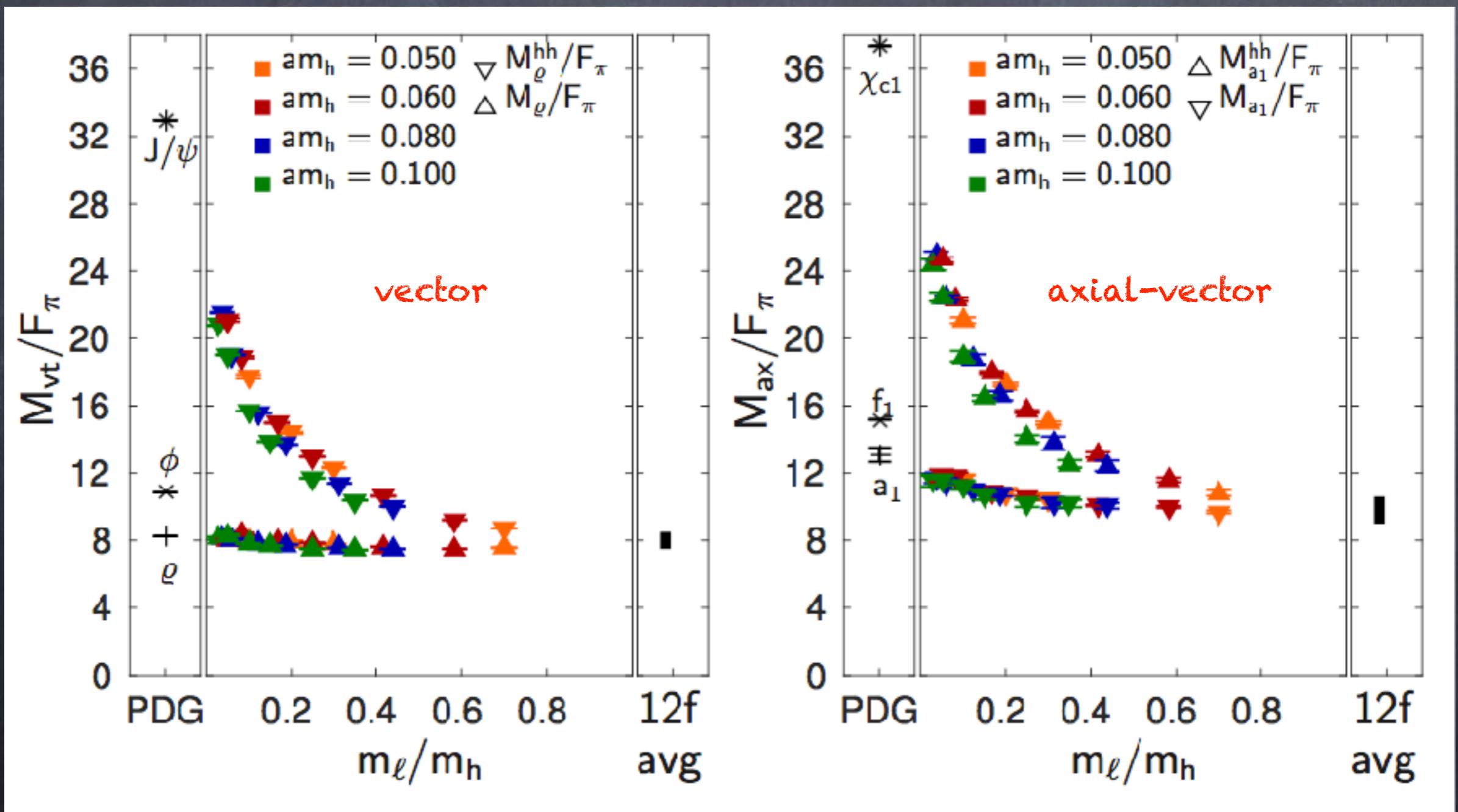
4 flavours are light, with mass m_l

8 flavours are heavy, with mass m_H



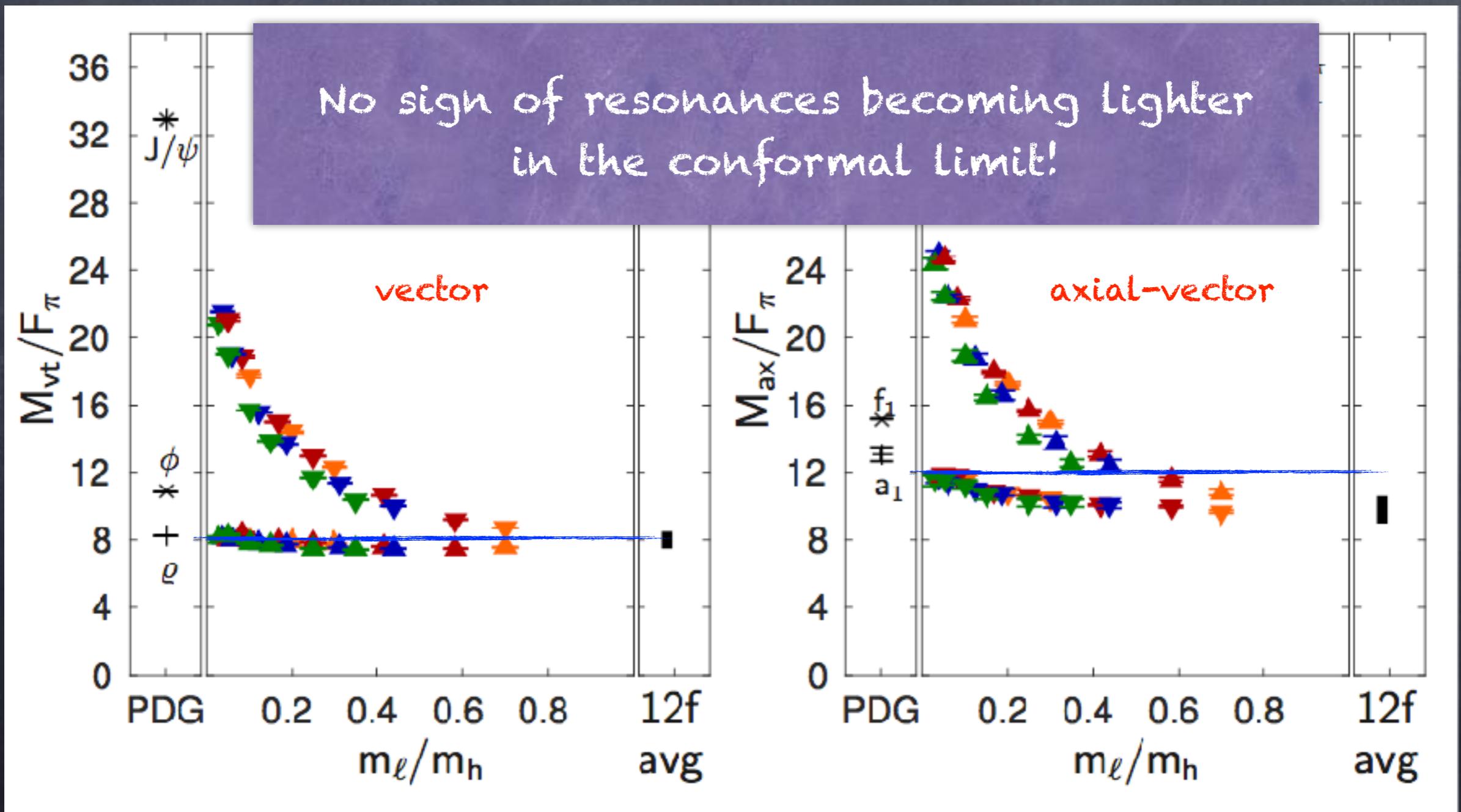
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1609.01401, 1611.07427



Summary

- Simple composite models can contain a Dark pion (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 + welcome Lattice results!

Bonus tracks

A composite 2HDM: EWPTs

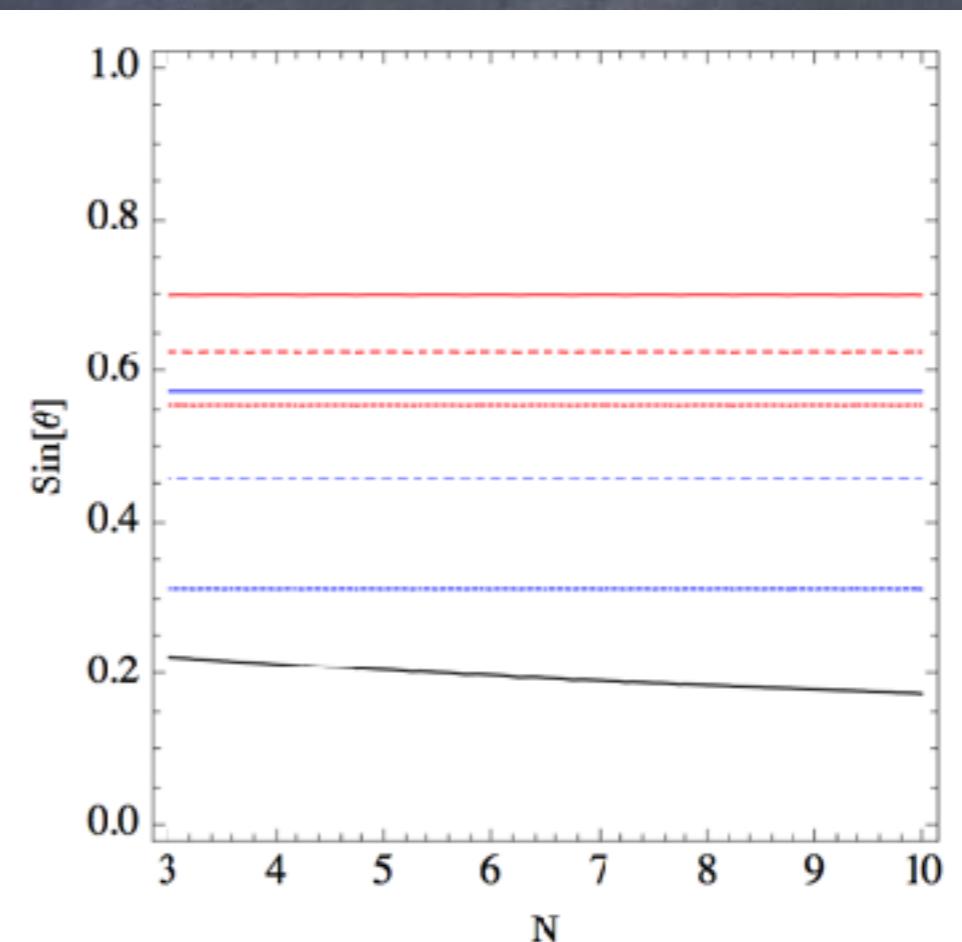
G.C., T.Ma
1508.07014

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

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

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

Bounds similar
to minimal cases.

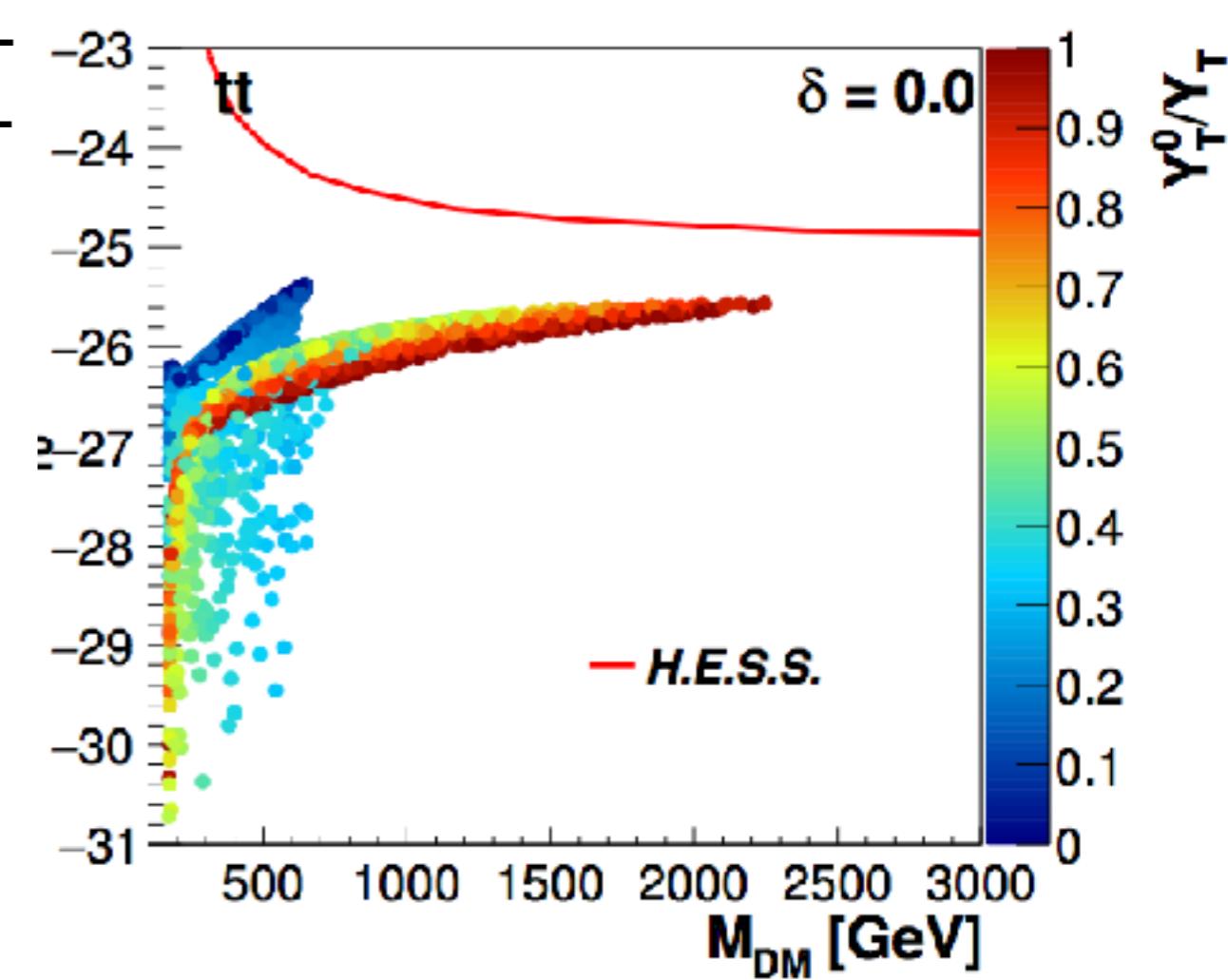
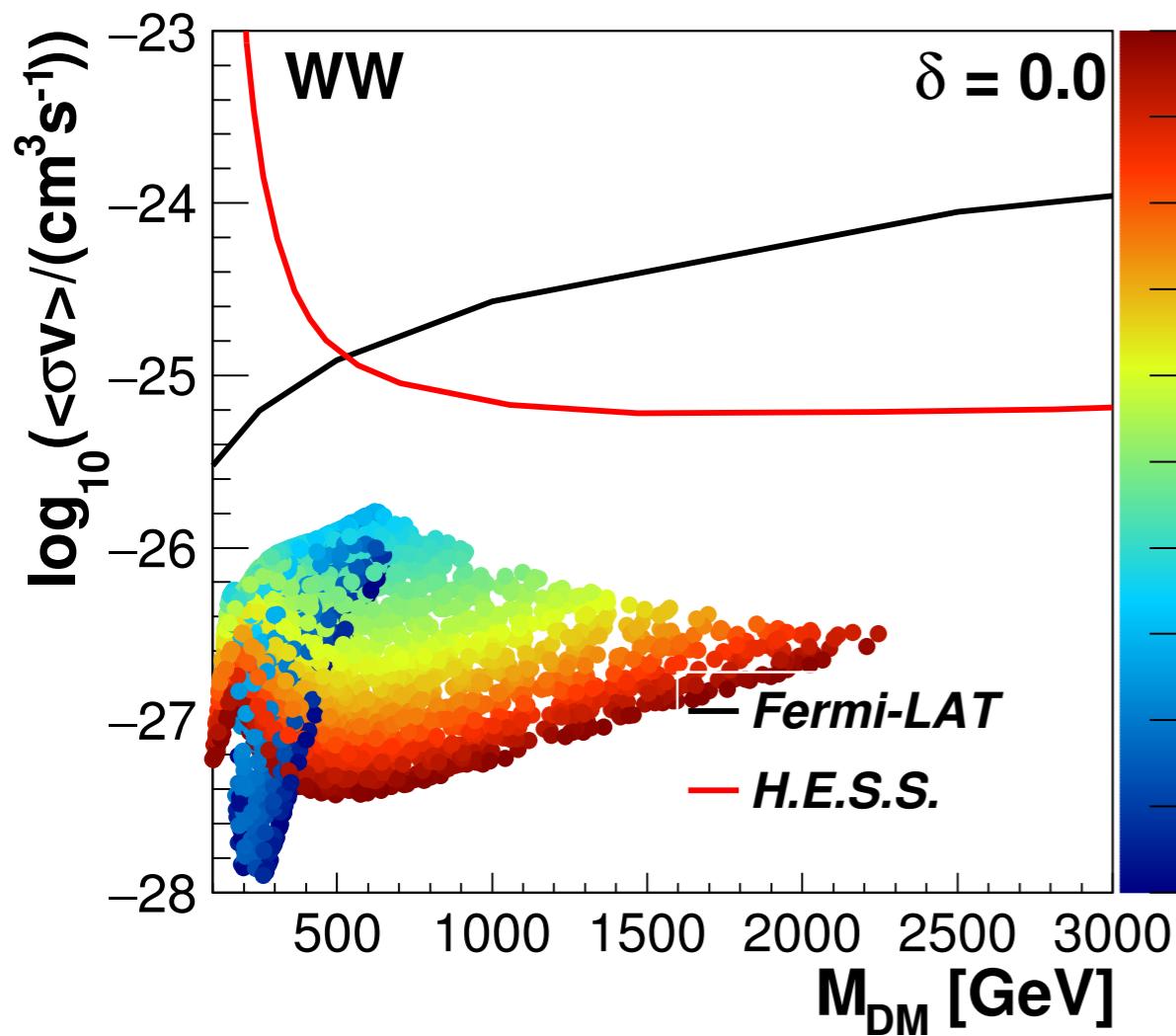


A composite 2HDM: Dark-Matter

Indirect Detection

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

Thermal relic abundance

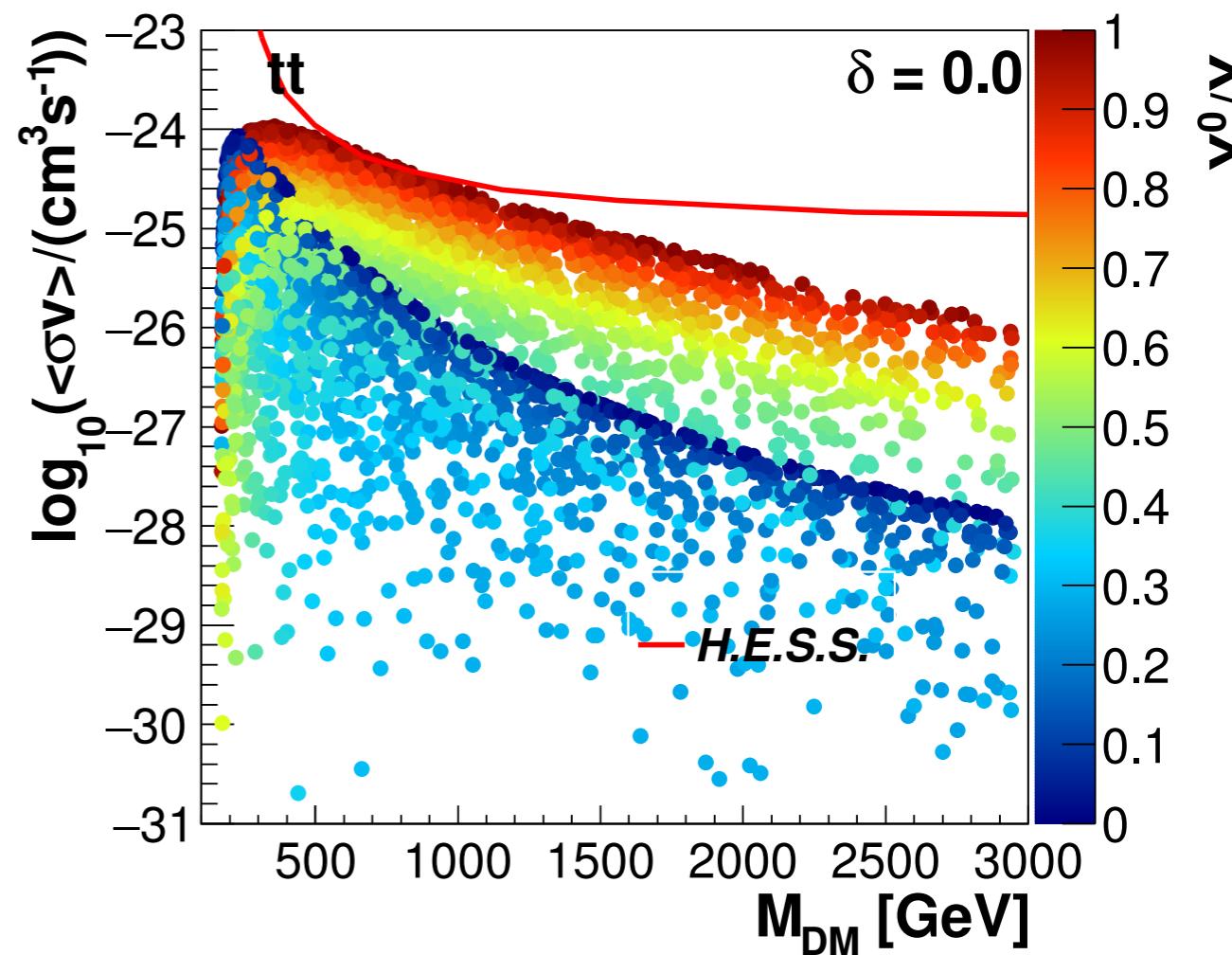
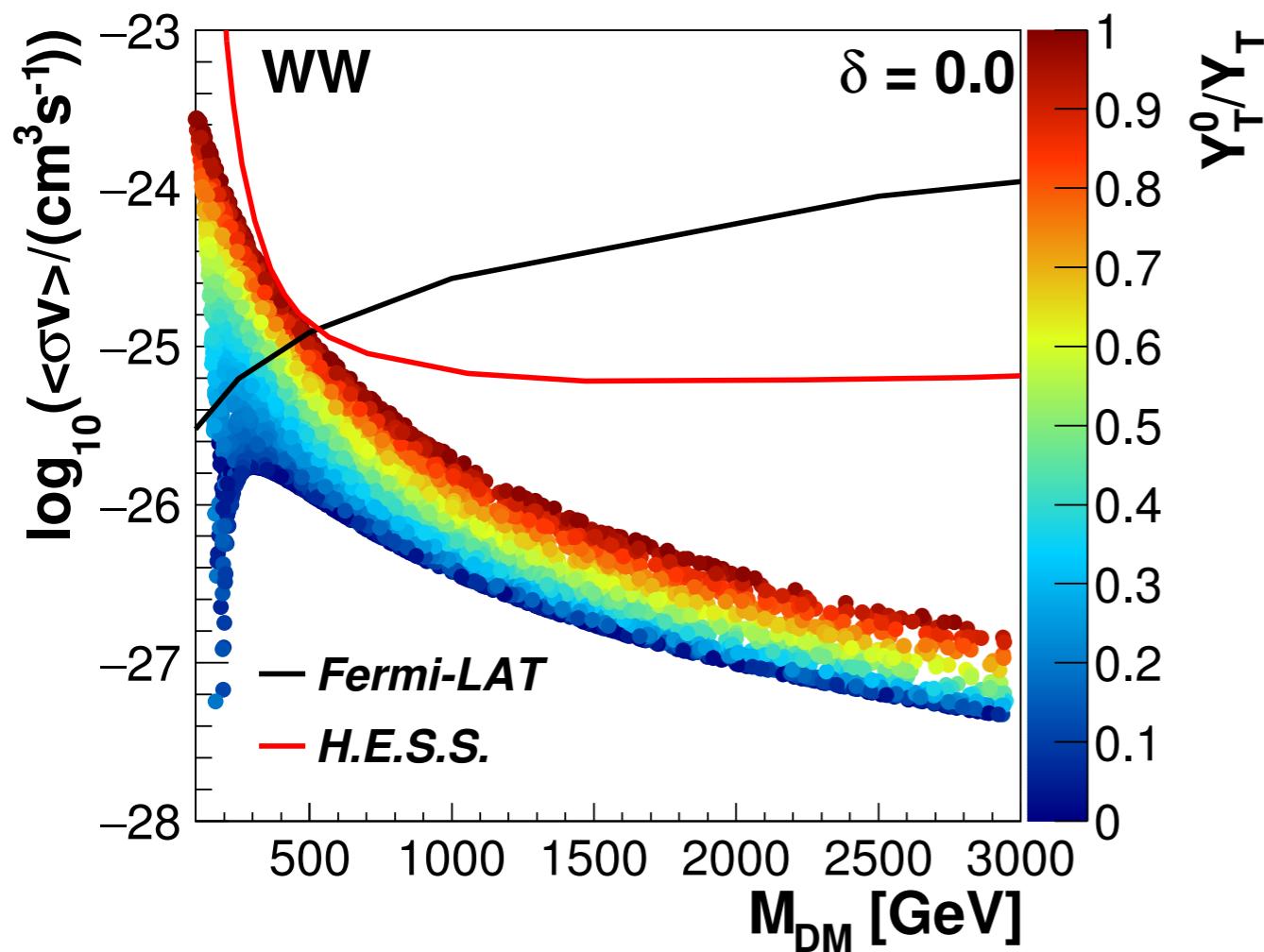


A composite 2HDM: Dark-Matter

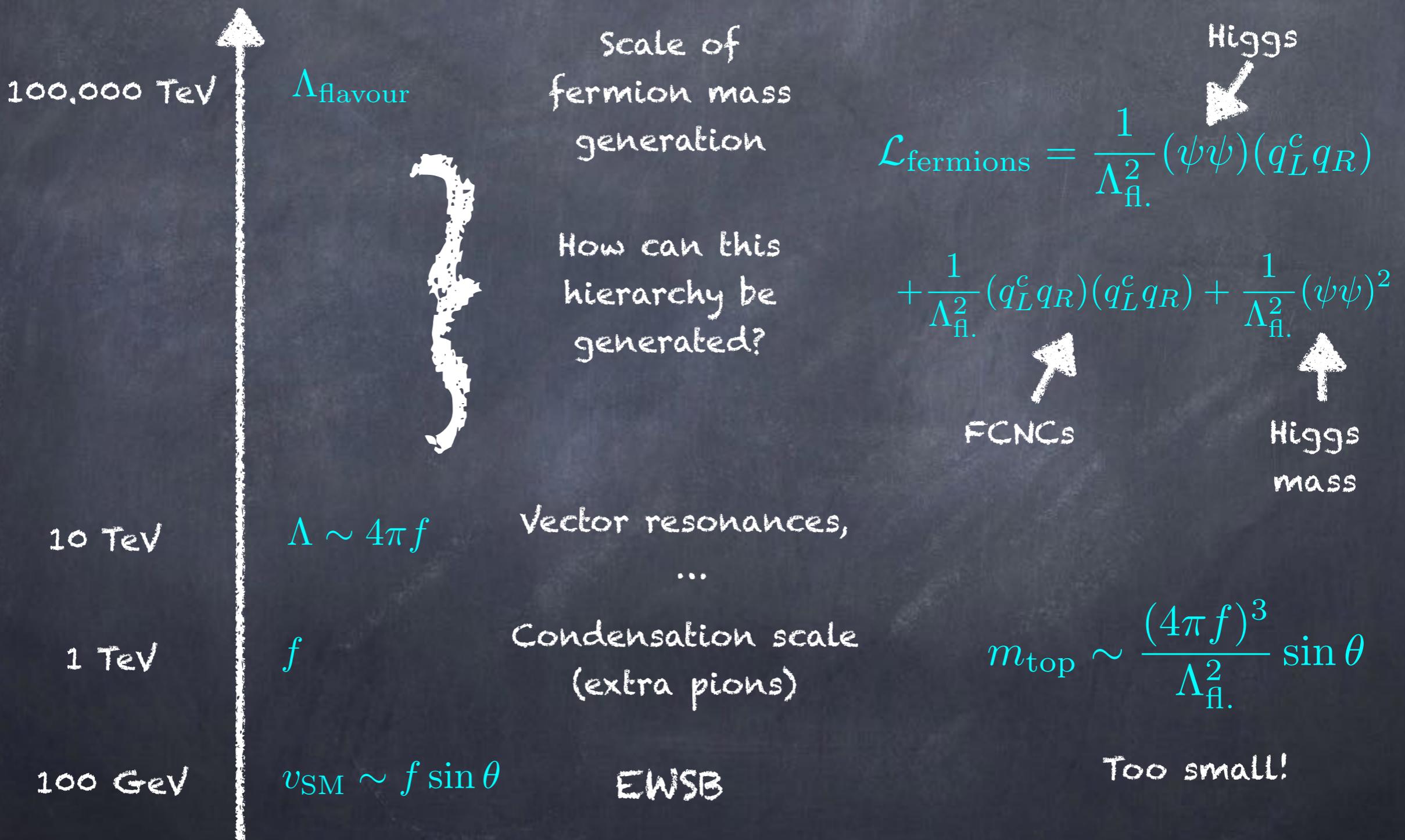
Indirect Detection

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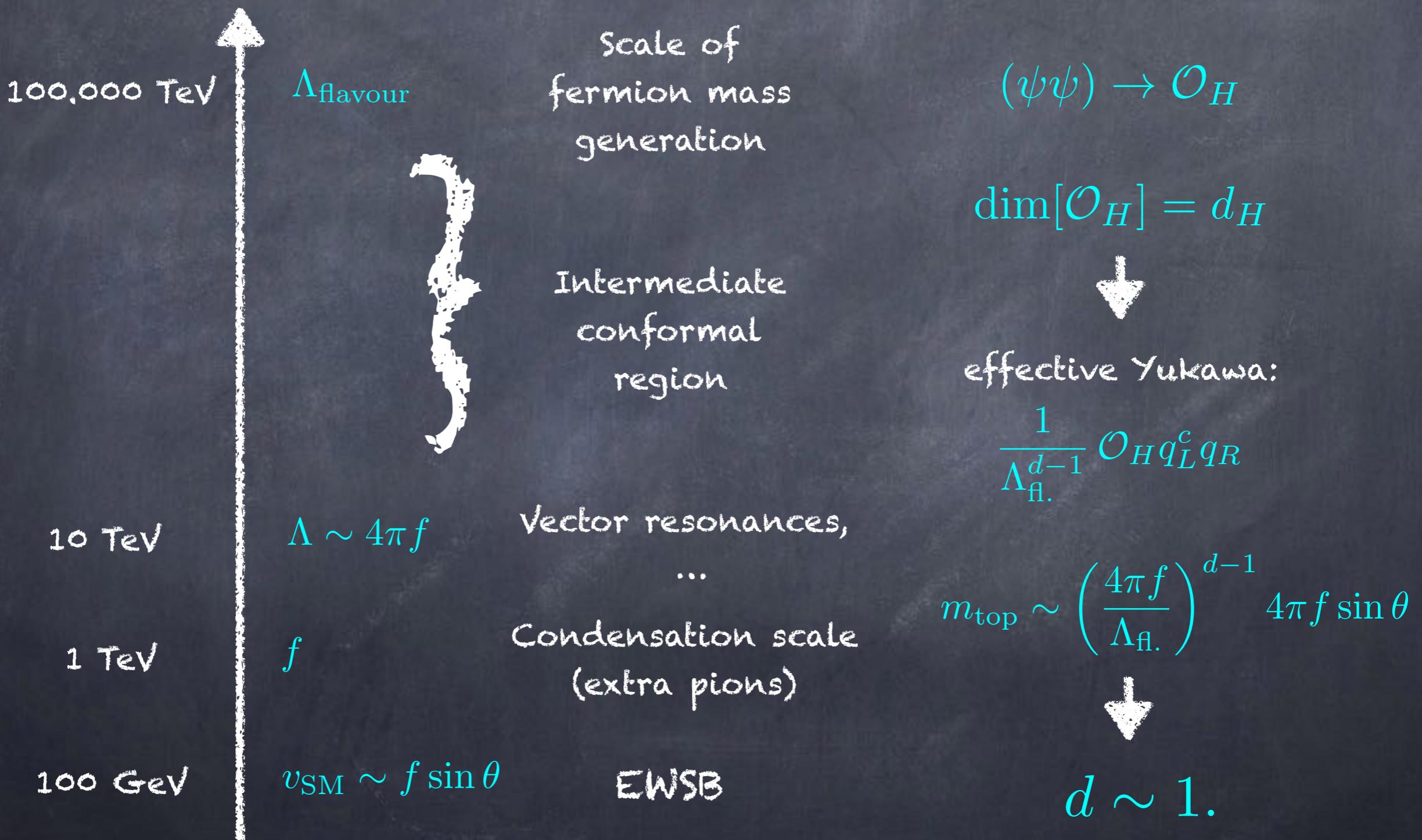
Fixed DM relic abundance



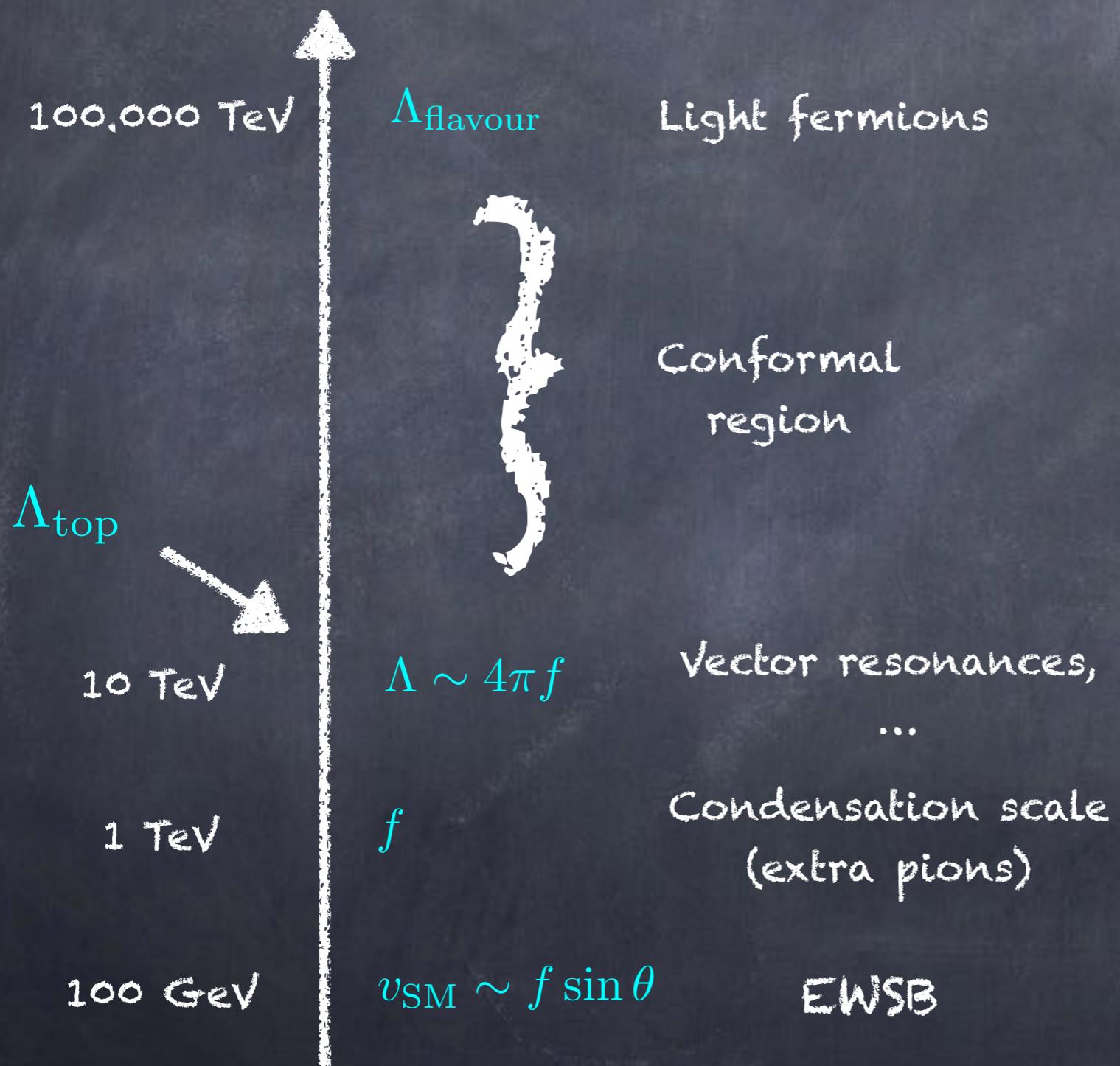
The hot potato: flavour!



The hot potato: flavour!



The hot potato: flavour!



Multi-scale
model

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



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

Still, for the top, one
would need:

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

The partial compositeness paradigm

Kaplan Nucl.Phys. B365 (1991) 259

$$\frac{1}{\Lambda_{\text{fl.}}^{d-1}} \mathcal{O}_H q_L^c q_R \quad \Delta m_H^2 \sim \left(\frac{4\pi f}{\Lambda_{\text{fl.}}} \right)^{d-4} f^2 \quad \text{Both irrelevant if}$$

we assume: $d_H > 1$ $d_{H^2} > 4$

Let's postulate the existence of fermionic operators:

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

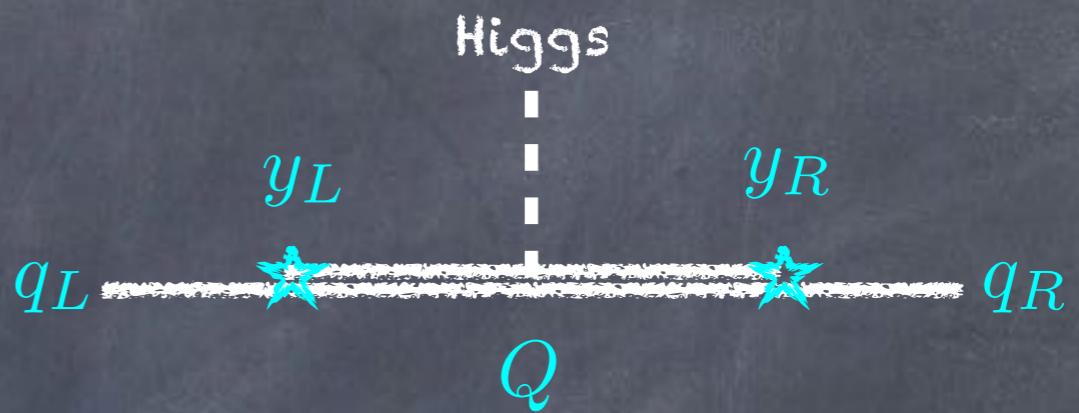
↓

$f(y_L q_L Q_L + y_R q_R Q_R)$ with $y_{L/R} f \sim \left(\frac{4\pi f}{\Lambda_{\text{fl.}}} \right)^{d_F-5/2} 4\pi f$

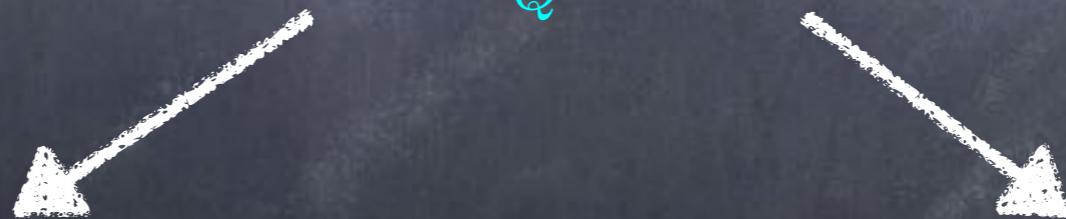
This dimension
is not related
to the Higgs!

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

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