The linear-non-linear frontier for the Goldstone Higgs

Kirill Kanshin

in collaboration with
F. Feruglio, B. Gavela, P. Machado, S. Rigolin, S. Saa

based on

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`hep-ph/1610.xxxxx`

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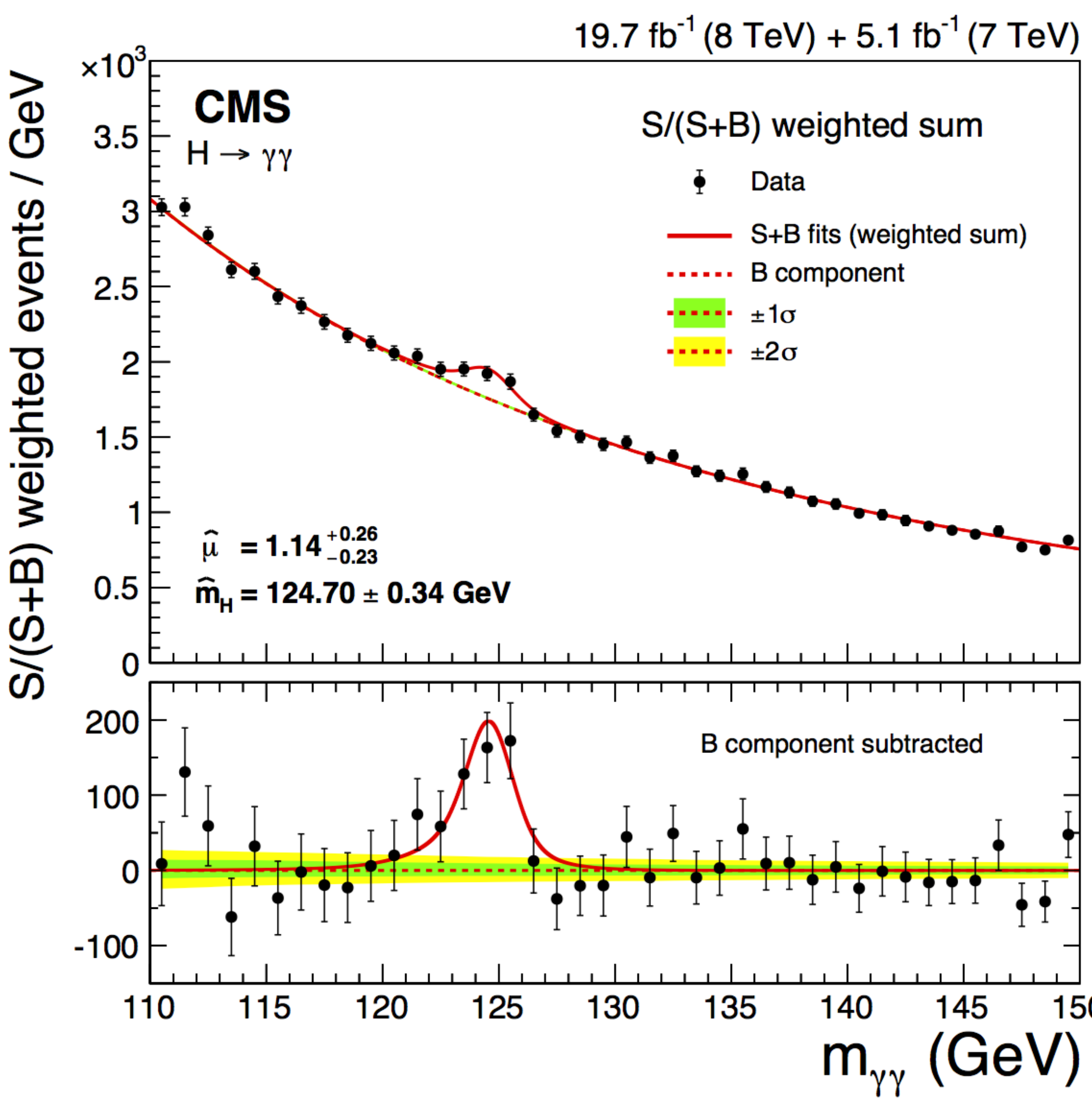
Quo vadis?

lat. Where are you going?

In 2012 the Higgs boson has been discovered

Since then no more gifts of nature has been seen at the LHC (statistical fluctuations are NOT gifts)



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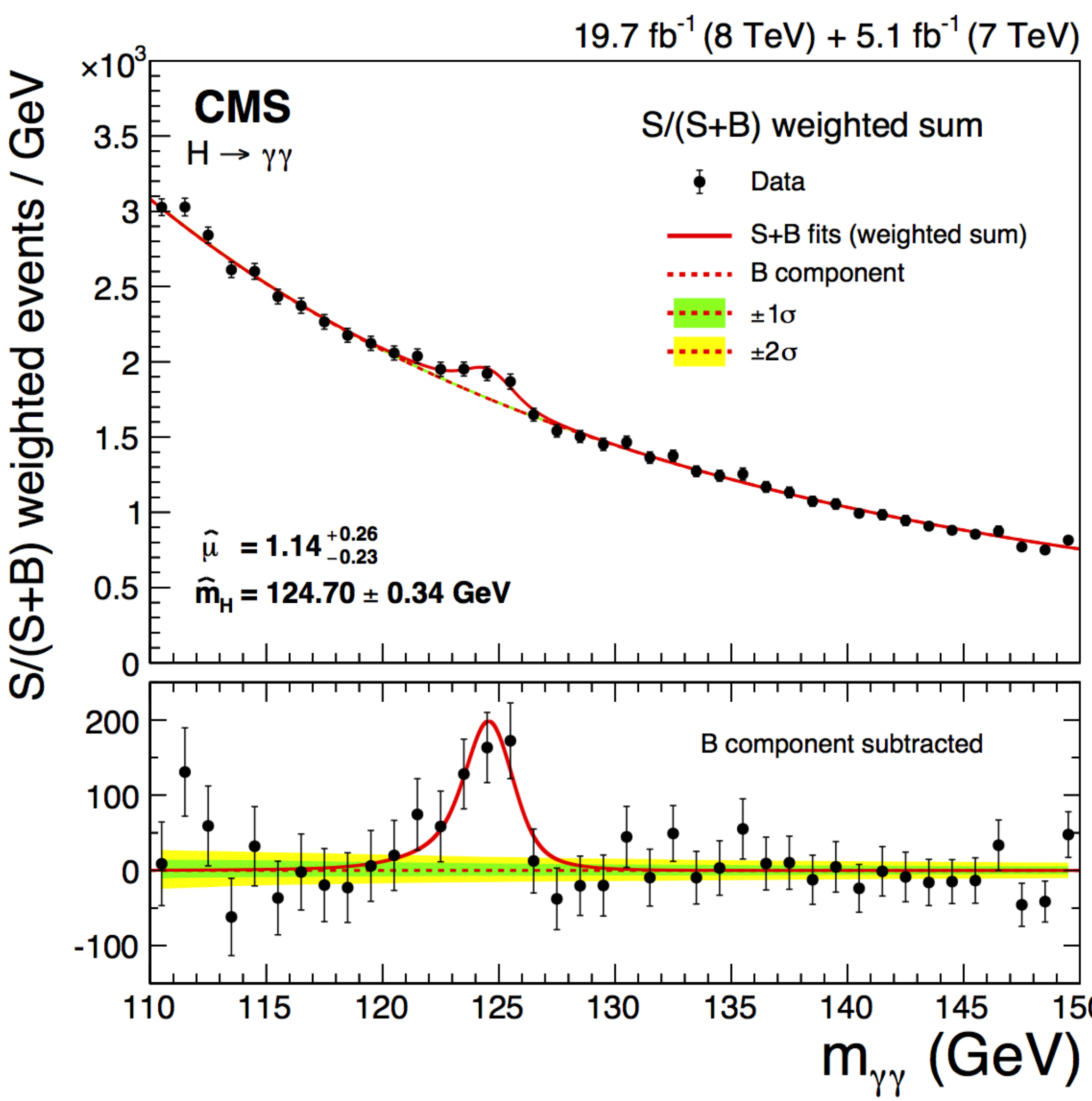


In this situation EFTs are effective

It is a tool to pursue the discovery of BSM physics

Though in general EFT contains huge number of parameters

Benchmark models restrict the number of parameters

BSM folklore

Folklore — *the traditional beliefs, customs, and stories of a community, passed through the generations by word of mouth (or arxiv)*

Common choice of the benchmark models either

involve new symmetries:

- SUSY (weakly coupled theories)
- composite higgs, little higgs (strongly coupled)
- goldstone higgs (strongly or weakly coupled)

based on other mechanisms

- anthropic selection
- relaxion mechanism

Those theories provide with the dynamical explanation for the EWSB and resolve the **hierarchy problem** (instability of higgs mass at quantum level)

Goldstone Higgs models

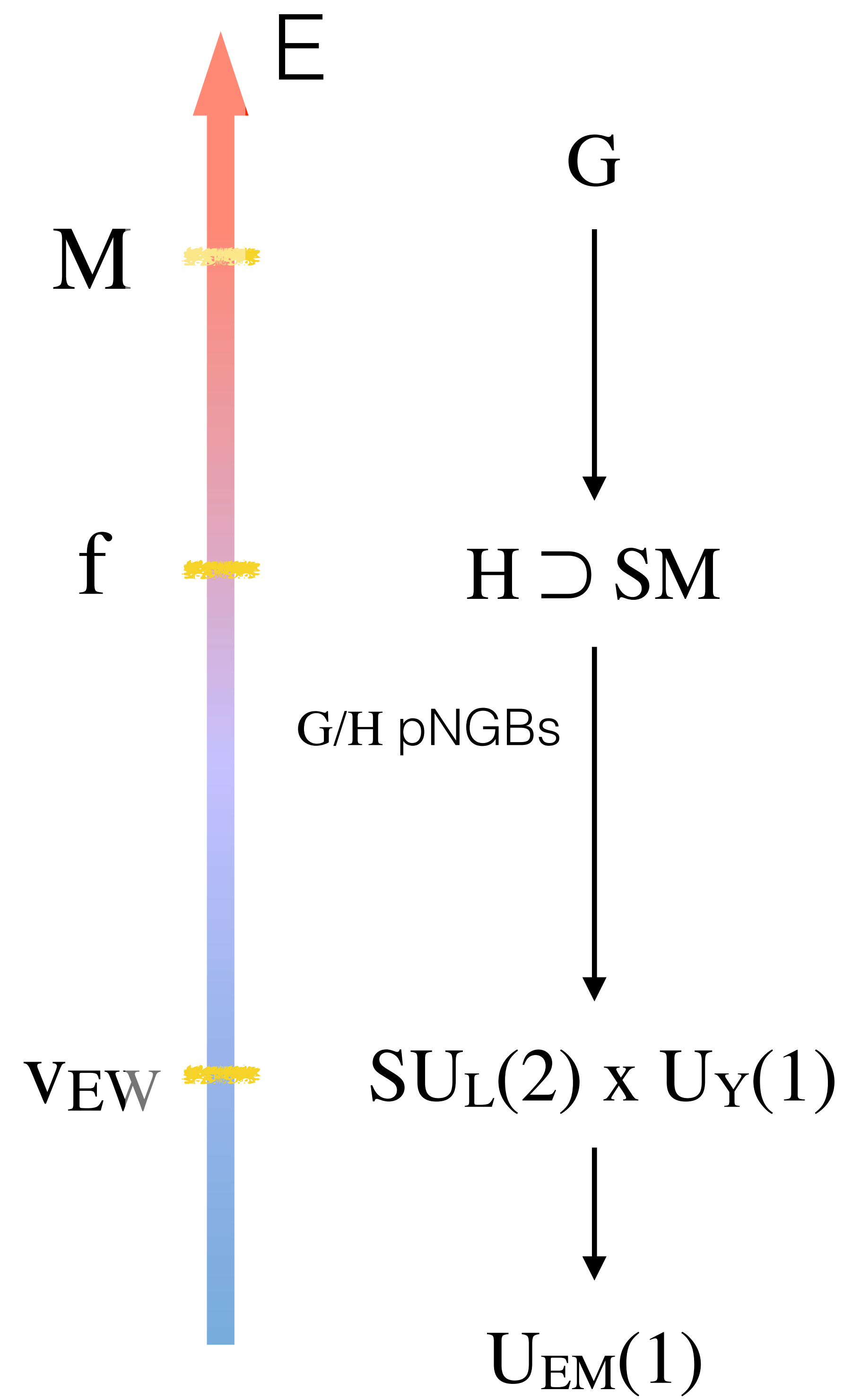
The global symmetry **G** at high scales

broken to smaller symmetry **H**
at energy scale **f**

Higgs boson arises as pNGB of this
breaking, living in **G/H** coset,

the Higgs mass parameter is protected
against the radiative corrections by
global symmetry

The scenario naturally introduces
the mass gap between the observed
scalar excitation and related BSM states



Maybe represent composite or elementary degrees of freedom

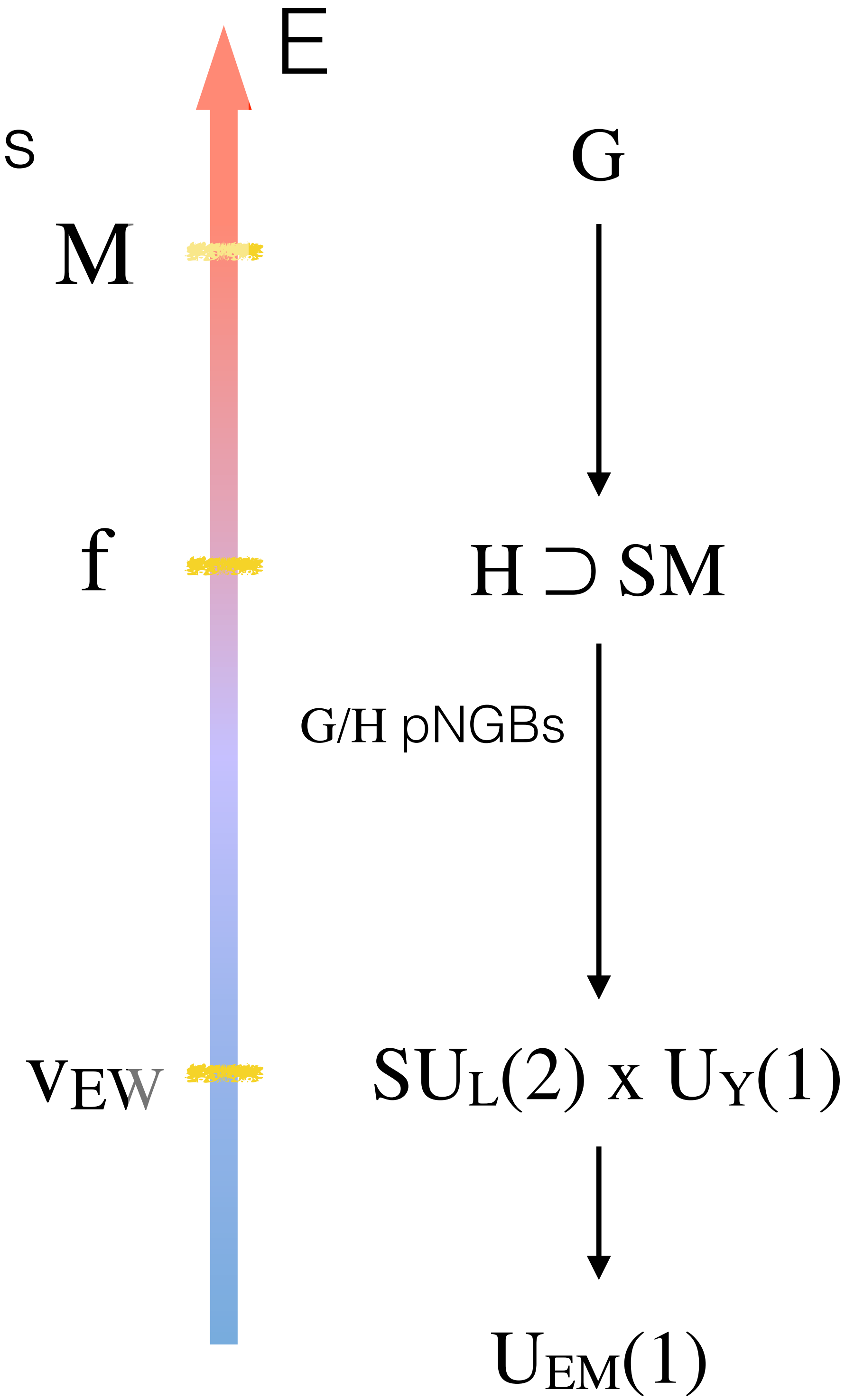
Goldstone Higgs models

The minimal setup, SO(5)/SO(4), produces 4 pNBGs
[Agashe, Contino, Pomarol '05]

Non-minimal are based on bigger cosets
SU(5)/SO(5), SO(6)/SO(5) etc.
[Georgi, Kaplan '84] [Gripaios, Pomarol, Riva, Serra '09]

At low energies typically they are described by *nonlinear sigma model*,

which is nonrenormalisable theory containing untruncated polynomials of pNGB fields.



What is the simplest renormalizable UV completion for the theories of this kind?

The linear σ-model

We know it from QCD! [Gell-Mann, Lévy ’60]

$$\phi = (\pi_1, \pi_2, \pi_3, \sigma)$$

$$\mathcal{L}_L^{QCD} = \frac{1}{2}(D\phi)^2 - \lambda\left(\phi^2 - f_\pi^2\right)^2$$

To minimise the potential $\langle\sigma\rangle = f_\pi$

Sigma particle acquires a mass $m_\sigma^2 = 8\lambda f_\pi^2$

$f_0(500)$ or σ [g]
was $f_0(600)$

$I^G(J^{PC}) = 0^+(0^{++})$

Mass $m = (400\text{–}550)$ MeV
Full width $\Gamma = (400\text{–}700)$ MeV

$f_0(500)$ DECAY MODES	Fraction (Γ_i/Γ)
$\pi\pi$	dominant
$\gamma\gamma$	seen

There IS a sigma-like state in QCD, but it is VERY broad

The linear σ-model

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$$\phi = (\pi_1, \pi_2, \pi_3, \sigma)$$

$$\mathcal{L}_L^{QCD} = \frac{1}{2}(D\phi)^2 - \lambda\left(\phi^2 - f_\pi^2\right)^2$$

Taking the limit $\lambda \to \infty$, while f_π is fixed implies $m_\sigma \to \infty$

The sigma particle decouples as $\sigma^2 = f_\pi^2 - \vec{\pi}^2$

Resulting Lagrangian is a nonlinear sigma model
aka *chiral perturbation theory*

$$\mathcal{L}_{NL}^{QCD} = \frac{1}{4} Tr[(D\Sigma)^2]$$

$$\Sigma = \sigma + i\vec{\tau}\vec{\pi}$$

The linear σ-model

for the Goldstone Higgs

Linearised SO(5)/SO(4) model contains 4 pNGB + additional scalar ***σ***.
All together they form a ***5plet*** under SO(5).

$$\phi = (\pi_1, \pi_2, \pi_3, \sigma) \longrightarrow \phi = (\underbrace{\pi_1, \pi_2, \pi_3}_{W_L^{\pm}, Z_L}, h, \sigma)$$

- Renormalizable theory
- Gauged under $SU_L(2) \times U_Y(1)$

[Barbieri, Bellazzini, Rychkov, Varagnolo '07]
[Contino, Marzocca, Pappadopulo, Rattazzi '11]
[Feruglio, Gavela, KK, Machado, Rigolin, Saa '16]

[Alanne, Gertov, Meroni, Sannino '16]
[Fichet, von Gersdorff, Pontón, Rosenfeld '16]
[Buchalla, Cata, Celis, Krause '16]

- Fermion masses are introduced through partial compositeness and proto-yukawa terms

- Can represent ***composite*** or ***elementary*** degrees of freedom

Scalar sector

In unitary gauge there are two physical fields ***h*** and ***σ***

$$V(h,\sigma) = \lambda\left(h^2+\sigma^2-f^2\right)^2 + \alpha f^3\sigma - \beta f^2 h$$

SO(5) invariant

small explicit SO(5) breaking due to CW mechanism

Fermionic and gauge sectors contain *SO(5) non invariant couplings*
At loop level they generate explicit breaking of SO(5) in the scalar potential

We include only the minimal set of terms, which are divergent at one loop.
They have to be included at tree level to make theory renormalizable.

Both *h* and *σ* obtain VEVs and masses

The physical states are mixed:

unphysical **mixing matrix** **physical**

$$\begin{pmatrix} h \\ \sigma \end{pmatrix} \to \begin{pmatrix} \cos\gamma & \sin\gamma \\ -\sin\gamma & \cos\gamma \end{pmatrix} \begin{pmatrix} h \\ \sigma \end{pmatrix}$$

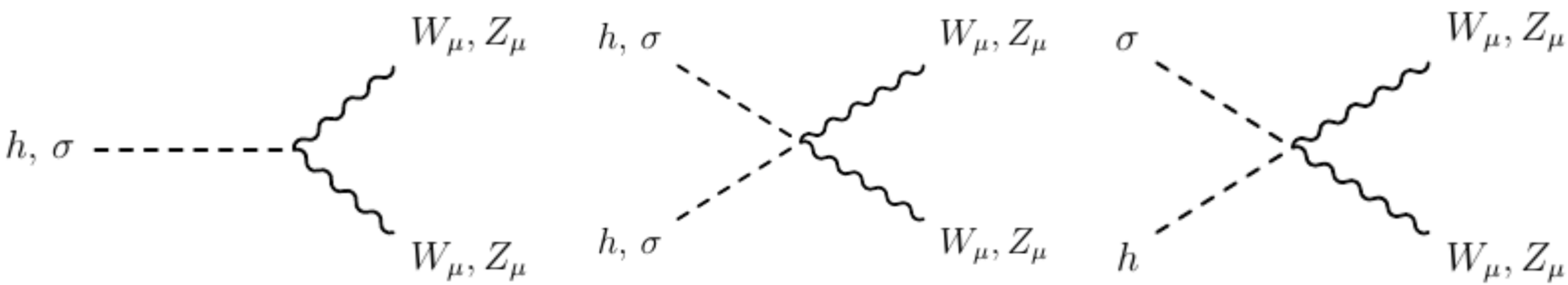
Observables in the scalar sector $\left(G_F = \frac{1}{\sqrt{2}v^2},\ m_h,\ m_\sigma,\ \sin\gamma\right)$

Scalar sector

couplings to gauge bosons

$$\mathcal{L}_{gauge} \supset \left(1 + \frac{h}{v}\cos\gamma + \frac{\sigma}{v}\sin\gamma\right)^2 \left(M_W^2 W_\mu^+ W^{\mu -} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu\right)$$

Couplings are simply defined by mixing of scalars,
and suppressed by **cos(γ)** and **sin(γ)** for ***h*** and ***σ*** respectively



$$M_W^2 = \frac{1}{4} g^2 \langle h \rangle^2 \qquad M_Z^2 = \frac{1}{4}(g^2 + g'^2)\langle h \rangle^2$$

Therefore we can identify

$$\langle h \rangle = v = 246\mathrm{GeV}$$

Scalar sector

couplings to gauge bosons

$$\mathcal{L}_{gauge} \supset \left(1 + \frac{h}{v}\cos\gamma + \frac{\sigma}{v}\sin\gamma\right)^2 \left(M_W^2 W_\mu^+ W^{\mu-} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu\right)$$

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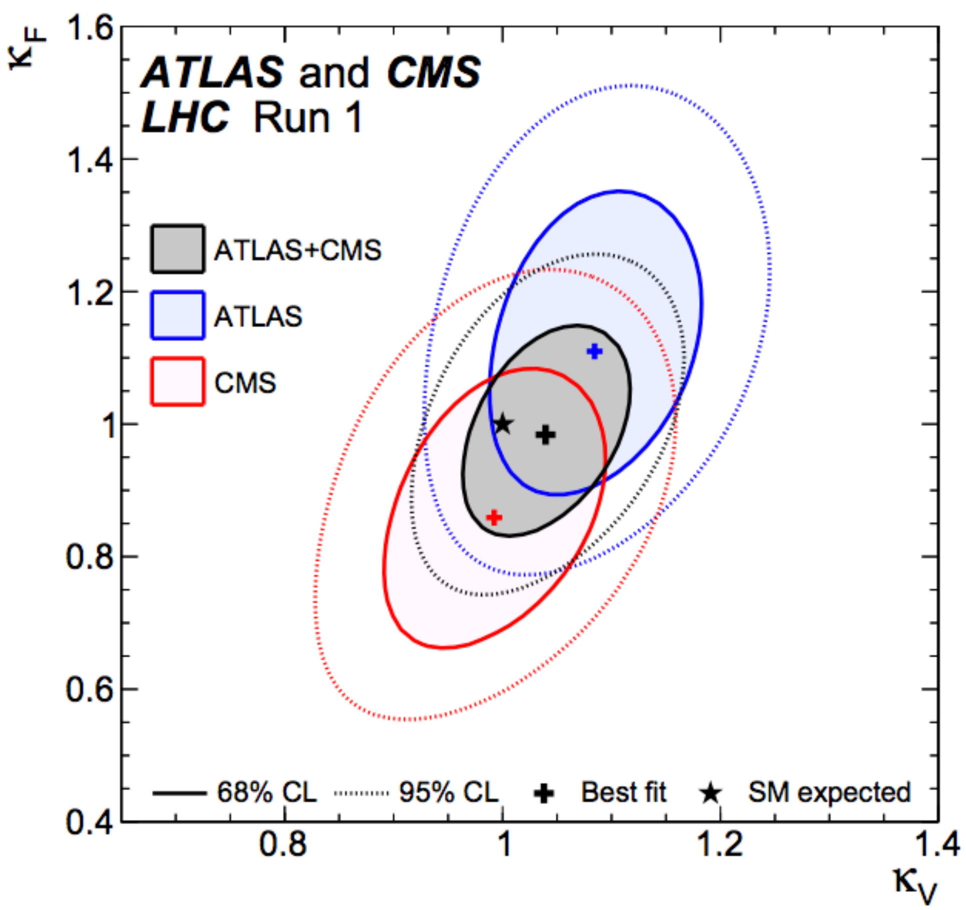
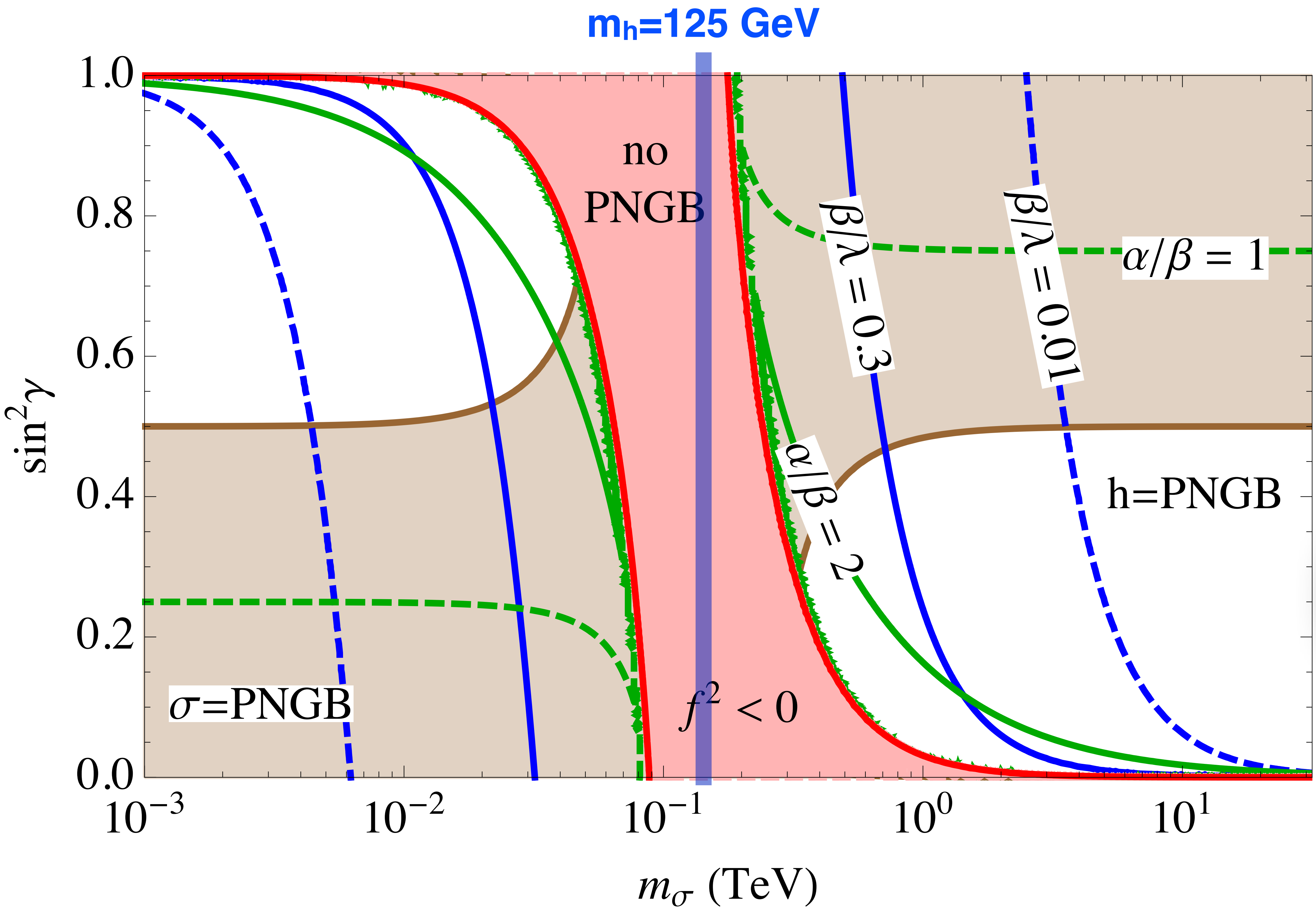


Suppressed coupling of ***h*** to gauge bosons together with coupling to gluons, dominated by top loop but also suppressed by **cos(γ)** leads to

$$\sin^2\gamma < 0.18 \text{ at } 2\sigma$$

Scalar sector

$$V(h,\sigma) = \lambda\left(h^2+\sigma^2-f^2\right)^2+\alpha f^3\sigma-\beta f^2 h$$



$v > \langle\sigma\rangle$

$v < \langle\sigma\rangle$

Scalar sector

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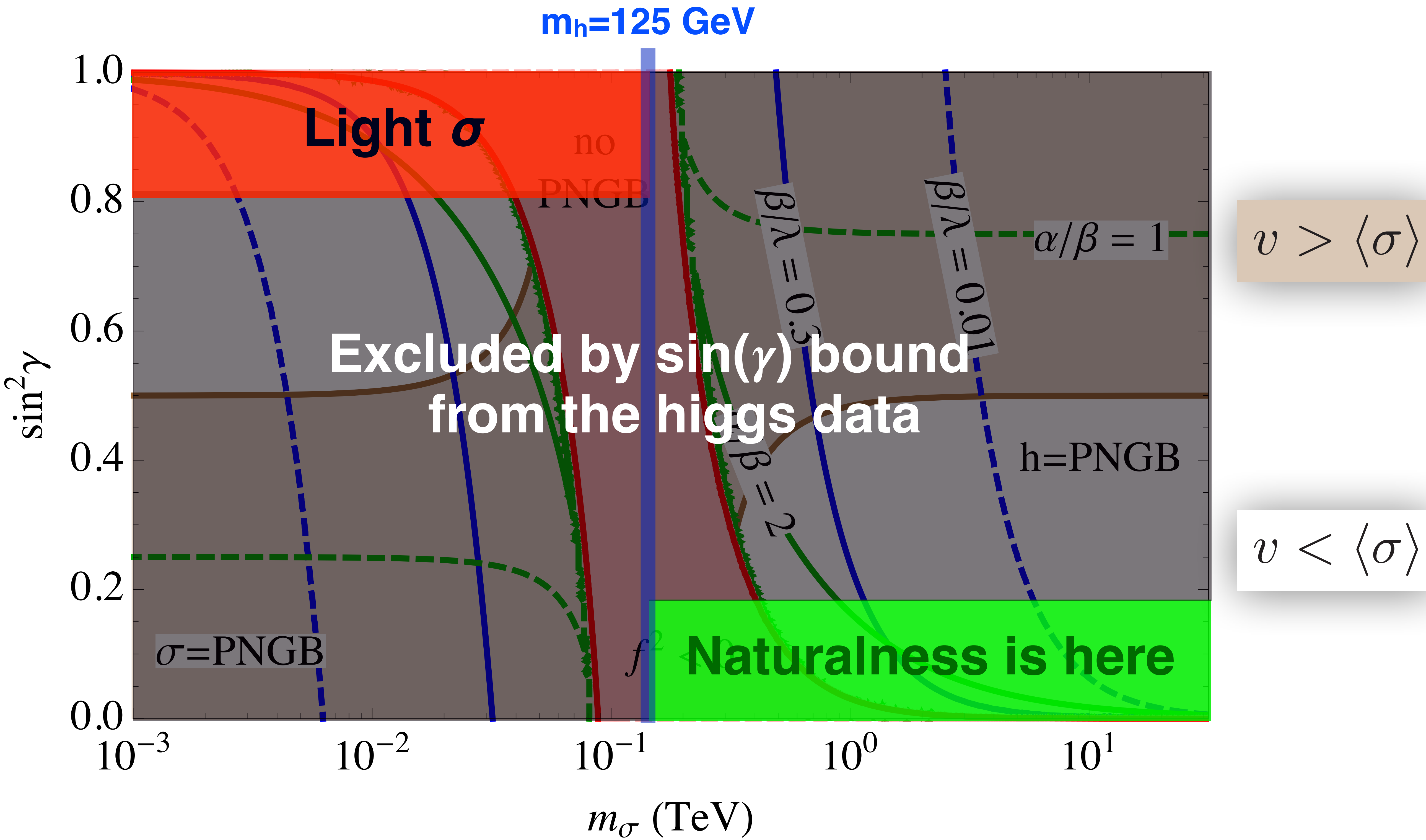


Fermions

Fermion sector is extended by heavy vectorlike fermions ψ, forming *complete* representations of SO(5)

On the other hand Standard Model fermions transforming under $SU_L(2)$ x $U_Y(1)$ form *incomplete* representations of SO(5)

No direct interaction between SM fermions and scalars, instead heavy fermions have *proto-Yukawa* interactions

Heavy fermion representations are chosen to form singlet operators after contraction with a scalar 5plet, for example

$$\mathcal{L}_{\text{proto-Yukawa}} \supset y(\psi^{(5)}\phi)\psi^{(1)}$$

Where $\psi^{(5)}$ is SO(5) 5plet, while $\psi^{(1)}$ is a singlet

Fermions

Additional global $U_X(1)$ charge for the heavy fermions
eventually allows for the mixing between vectorlike and SM fermions

The heavy fermion multiplets then can be decomposed under $SU_L(2)$ x $U_Y(1)$
for example for the 5plet and singlet representations (we ll refer to it **5-1-1**)

$$\psi^{(5)}_{+2/3} \sim (X, Q, T^{(5)}), \qquad \psi^{(5)}_{-1/3} \sim (Q', X', B^{(5)}),$$

$$\psi^{(1)}_{+2/3} \sim T^{(1)} \qquad \psi^{(1)}_{-1/3} \sim B^{(1)}$$

Singlet fields are coupled to right handed SM fermions

Charge/Field	X	Q	$T_{(1,5)}$	Q'	X'	$B_{(1,5)}$
$\Sigma_R^{(3)}$	$+1/2$	$-1/2$	0	$+1/2$	$-1/2$	0
$SU(2)_L \times U(1)_Y$	$(2,+7/6)$	$(2,+1/6)$	$(1,+2/3)$	$(2,+1/6)$	$(2,-5/6)$	$(1,-1/3)$
x	$+2/3$	$+2/3$	$+2/3$	$-1/3$	$-1/3$	$-1/3$
q_{EM}	$X^u = +5/3$ $X^d = +2/3$	$Q^u = +2/3$ $Q^d = -1/3$	$+2/3$	$Q'^u = +2/3$ $Q'^d = -1/3$	$X'^u = -1/3$ $X'^d = -4/3$	$-1/3$

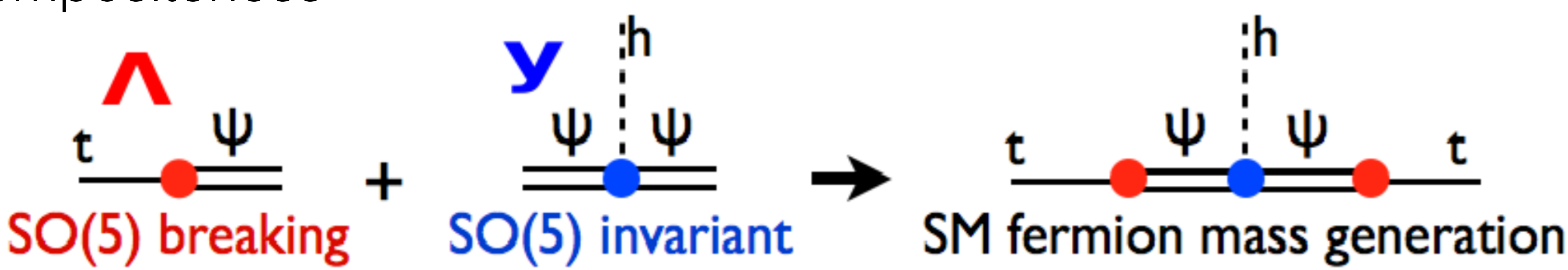
Fermions

Mixing between SM and vectorlike fermions aka partial compositeness,

[Kaplan '91]

Top quark: $\Lambda_1 \; \bar{q}_L Q_R + \Lambda_1' \; \bar{q}_L Q_R' + \Lambda_2 \; \bar{T_L}^{(5)} t_R + \Lambda_3 \; \bar{T_L}^{(1)} t_R$

partial compositeness | proto-Yukawas | massive SM fermions



The result is see-saw like expression for the top Yukawa

$$y_t \sim y \; \Lambda^2 / M_\psi^2$$

SM fermion Yukawa is suppressed by the vectorlike fermion masses!

Fermions
scalar potential generation

Generalised mass matrix of all the fermions in the theory contains SO(5) breaking

$$-\bar{\Psi}_L \mathcal{M}(h,\sigma)\Psi_R$$

Through Coleman—Weinberg mechanism it propagates to the scalar potential at one loop.

Among other terms it contains *divergent* *SO(5) breaking* one

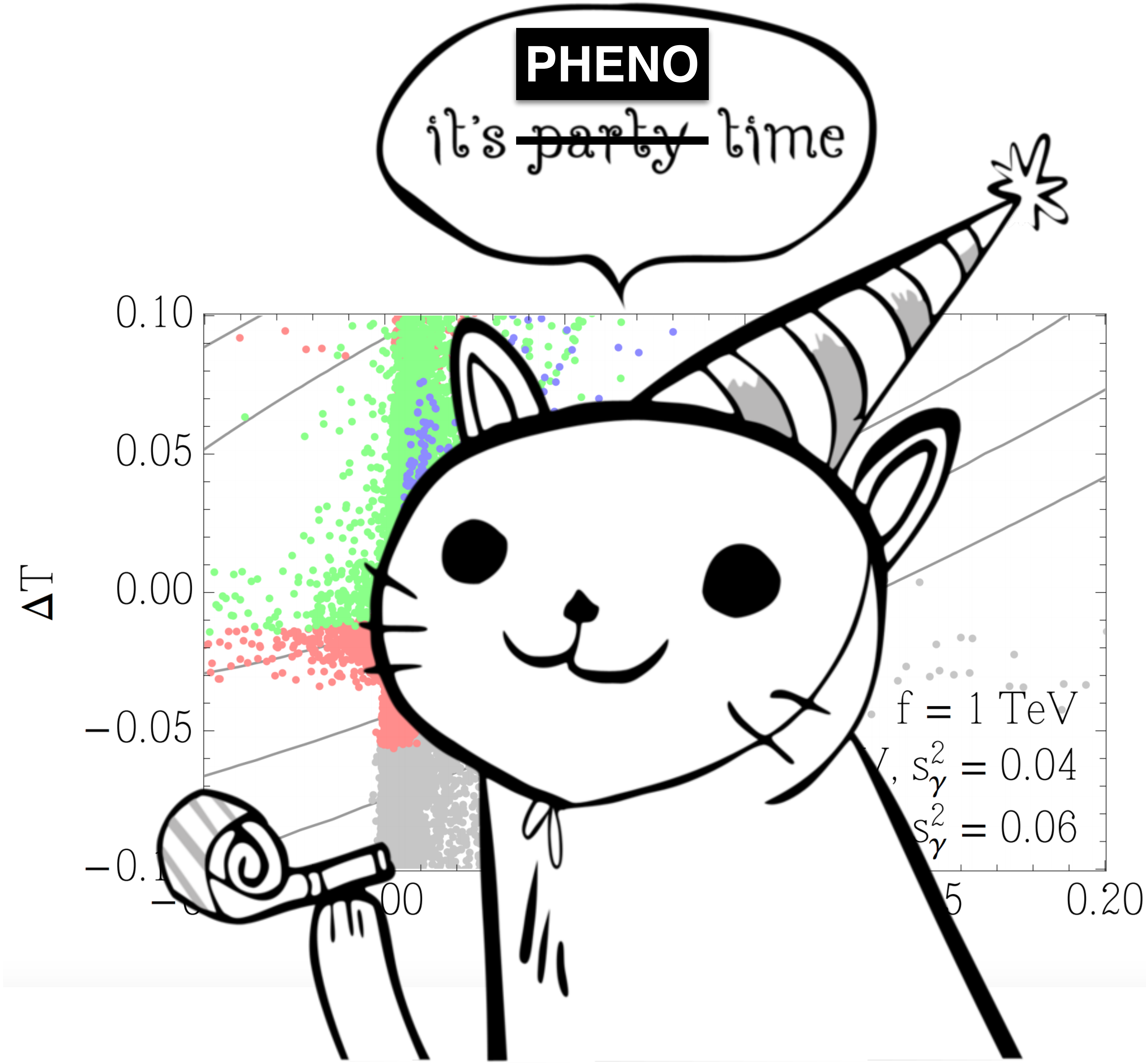
$$V_{\rm CW} \supset \frac{1}{64\pi^2}\,{\rm Tr}\left[(\mathcal{M}\mathcal{M}^\dagger)^2\right]\log\left(\frac{\Lambda^2}{\mu^2}\right)$$

$${\rm Tr}[(\mathcal{M}\mathcal{M}^\dagger)^2] = [{\rm SO}(5)_{\rm inv}] + A\sigma + Bh^2$$

we introduce SO(5) breaking terms in the potential at tree level, they act as a counterterms and cancel the divergencies above

$$V(h,\sigma) \supset \alpha f^3\sigma - \beta f^2 h^2$$

This completes the construction of the linear model

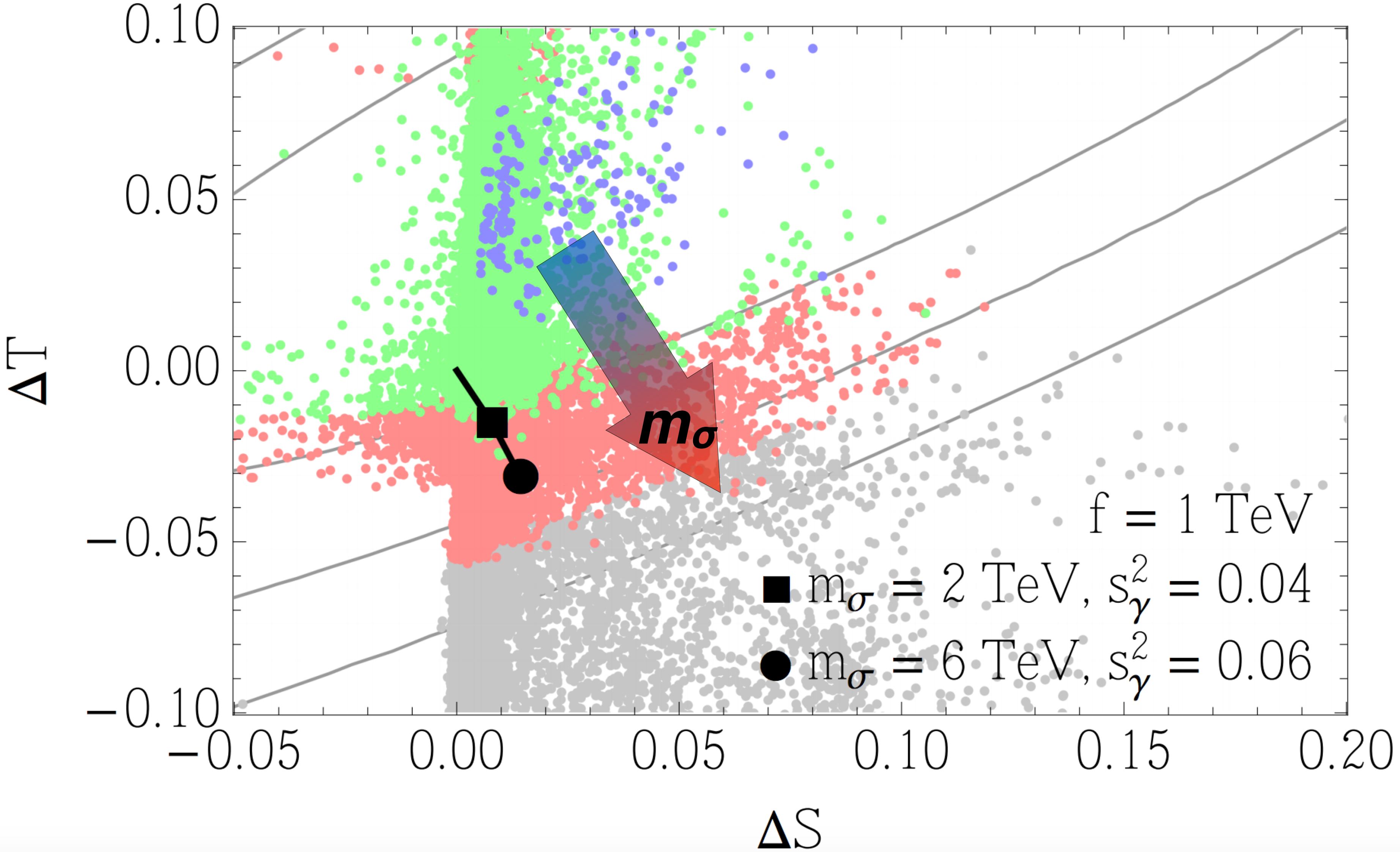

PHENO
it's ~~party~~ time
0.10
0.05
0.00
−0.05
ΔT
f = 1 TeV
s_γ^2 = 0.04
s_γ^2 = 0.06
0.20

EWPT

The fermion phase space is huge and adjustable, so the random scan is performed over the fermion parameters with the masses of heavy fermions within 800 GeV - 10 TeV range

Parameters of the scalar sector are treated independently.

Lower m_σ is better!



Dots represent fermionic contribution

In color: 1σ, 2σ, 3σ regions

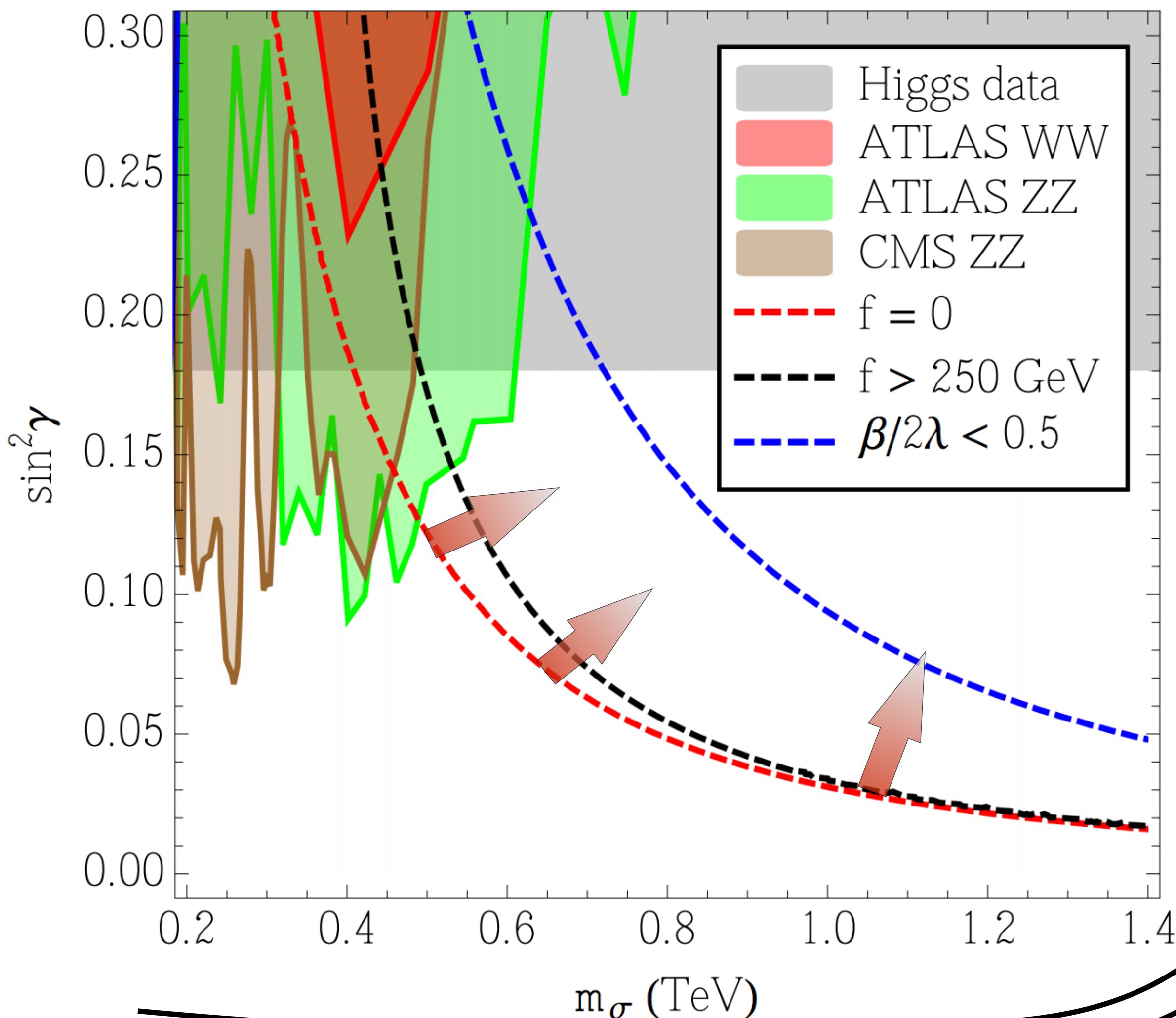
combined for ΔS, ΔT and Δgb

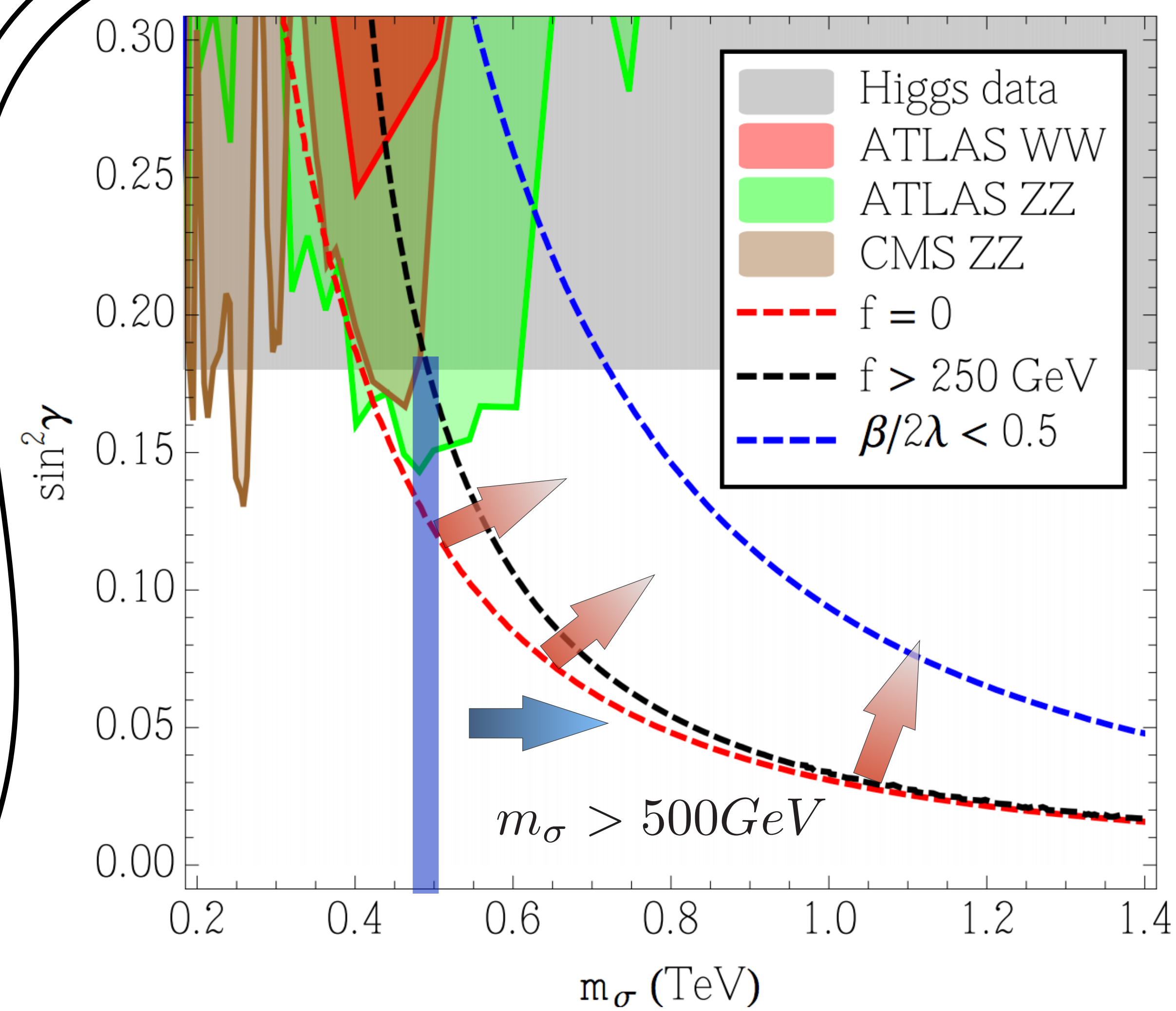
Present bounds for σ scalar @ LHC

Part of the phase space is excluded by sinɣ bound

Region to the right from **red** curve is where the higgs is natural pNGB

Neglecting heavy fermions contributions





Considering sizeable heavy fermion contribution

Future reach is $m_\sigma > 900GeV$

EFT

We consequently integrate out

1) Heavy fermions Ψ
2) Heavy scalar σ

The bosonic effective operators have been derived on general ground for SO(5)/SO(4)

[Alonso, Brivio, Gavela, Merlo, Rigolin ’14]

But we have restriction:
linear model as UV completion!
and fermions!!

EFT

with heavy fermions out

hep-ph/1603.05668

In terms of σ, H **doublet** and **SM fermions** for heavy fermions embeddings considered before (5-1-1)

All coefficients are identified as functions of parameters of fermionic UV completion

Operator	c_i	Leading Order in f/M	D
$\bar{q}_L \widetilde{H} t_R$	$-y_t$	$-\left(\frac{y_1\Lambda_1\Lambda_3}{M_1M_5}\right)\mathcal{Z}_{q_L}^{-1/2}\mathcal{Z}_{t_R}^{-1/2}$	4
$\sigma\,(\bar{q}_L\widetilde{H}t_R)$	$c^t_{\sigma 1}$	$\frac{y_t}{M_5}\left(y_2\frac{\Lambda_2}{\Lambda_3}-\left(y_1\frac{\Lambda_2\Lambda_3}{M_1M_5}+y_2\frac{\Lambda_2\Lambda_3}{M_1^2}\right)\mathcal{Z}_{t_R}^{-1}\right)$	5
$\sigma^2\,(\bar{q}_L\widetilde{H}t_R)$	$c^t_{\sigma 2}$	$-\frac{y_t}{M_1M_5}\Big(y_1y_2-\left(y_1y_2\left(2\frac{\Lambda_2^2}{M_5^2}+\frac{\Lambda_3^2}{M_1^2}\right)+\frac{3y_2^2\Lambda_2^2+y_1^2\Lambda_3^2}{2M_1M_5}\right)\mathcal{Z}_{t_R}^{-1}$ $+2\frac{\Lambda_2^2\Lambda_3^2}{M_1M_5}\left(\frac{y_1^2}{M_5^2}+\frac{2y_1y_2}{M_5M_1}+\frac{y_2^2}{M_1^2}\right)\mathcal{Z}_{t_R}^{-2}\Big)$	6
$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_L\gamma^\mu q_L)$	$c_L^{(1)}$	$\frac{1}{4}\left(\frac{y_1^2\Lambda_1^2}{M_1^2M_5^2}-\frac{y_1'^2\Lambda_1'^2}{M_1'^2M_5'^2}\right)\mathcal{Z}_{q_L}^{-1}$	6
$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{q}_L\tau^i\gamma^\mu q_L)$	$c_L^{(3)}$	$-\frac{1}{4}\left(\frac{y_1^2\Lambda_1^2}{M_1^2M_5^2}+\frac{y_1'^2\Lambda_1'^2}{M_1'^2M_5'^2}\right)\mathcal{Z}_{q_L}^{-1}$	6

+ same ones with $\mathbf{b_R}$ and $\Lambda \rightarrow \Lambda'$

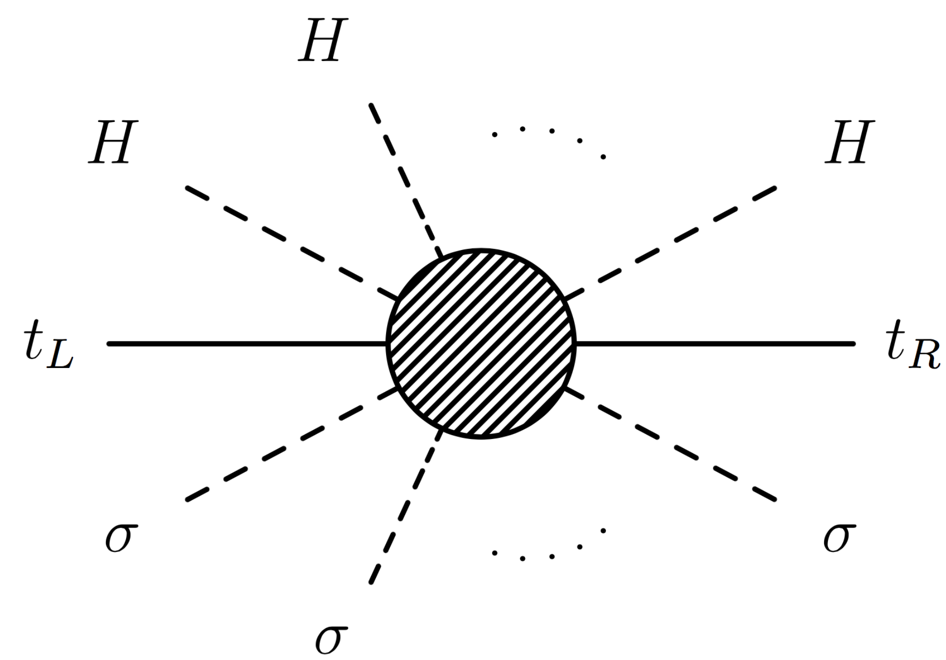
Next step was simply to integrate out the heavy scalar

But can we be more general rather than sticking to one particular embedding?

Heavy fermions integrated out

Various embeddings of heavy fermions into SO(5) multiplets are allowed: **1, 4, 5, 10, 14** you name it.
They may be different for Q_L, T_R and B_R as well as leptons

For any embedding the general consequence of the partial compositeness is the *mass generation* for the SM fermions



$$\mathcal{O}_{\text{Yuk,f}}^{(n,m)} \equiv \bar{q}_L \widetilde{H}\, \text{f}_R \left(\frac{\sigma}{f}\right)^n \left(\frac{2H^\dagger H}{f^2}\right)^m$$

or in polar coordinates

$$\mathcal{O}_{\text{Yuk},f}^{(n,m)} = \frac{1}{\sqrt{2}} \bar{q}_L U f_R \rho \left(\frac{\rho}{f}\right)^{n+2m} c_\varphi^n s_\varphi^{2m+1}$$

For every given set of embeddings (n,m) can be defined.
Some embeddings produce several operators with different (n,m)

Heavy fermions integrated out

$$\mathcal{O}^{(n,m)}_{\text{Yuk},t} = -y_t \bar{q}_L \widetilde{H} t_R \left(\frac{\sigma}{f}\right)^n \left(\frac{H^\dagger H}{f^2}\right)^m$$

Fermion representation (q_L-q_R)	Yukawa interactions $y_f \mathcal{O}^{(n,m)}_{\text{Yuk}}$
5-1, 5-10, 10-5	$y\mathcal{O}^{(0,0)}_{\text{Yuk}}$
5-5, 10-10, 14-10, 10-14, 14-1	$y\mathcal{O}^{(1,0)}_{\text{Yuk}}$
14-14	$3y\mathcal{O}^{(1,0)}_{\text{Yuk}} + 2y'\mathcal{O}^{(1,1)}_{\text{Yuk}} - 8y'\mathcal{O}^{(3,0)}_{\text{Yuk}}$
14-5	$y\mathcal{O}^{(0,0)}_{\text{Yuk}} + y'\mathcal{O}^{(2,0)}_{\text{Yuk}}$
5-14	$y\mathcal{O}^{(0,0)}_{\text{Yuk}} + y'\mathcal{O}^{(0,1)}_{\text{Yuk}} - 4y'\mathcal{O}^{(2,0)}_{\text{Yuk}}$

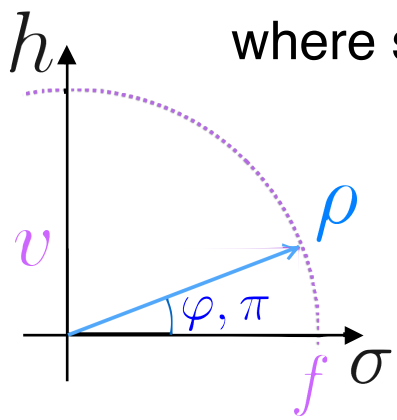
$$y\ (\bar{\psi}^{(5)}\phi)\psi^{(1)} \to y_t(y, M_\psi, \Lambda)\ \bar{q}_L \tilde{H} t_R$$ {n=m=0}

Systematic study of fermion embeddings can be found in [Carena, Da Rold, Pontón '14]

In addition to Yukawa term(s) there are effective operators with σ and ***H doublet***

Heavy scalar integrated out

the calculations are easier in polar coordinates,
where scalar sector is represented by **radial variable ρ** and **four angular ones φ,π**



$$\sigma \equiv \rho\, c_\varphi\,, \qquad H \equiv \frac{1}{\sqrt{2}}\rho\, U\, s_\varphi$$

with $U(\boldsymbol{\pi}) = e^{i\boldsymbol{\tau\pi}}$ being matrix of GBs

Scalar potential generates VEVs and masses for both scalars

$$\rho = \langle\rho\rangle + \sigma, \quad \varphi = \langle\varphi\rangle + h$$

$$\sin^2(\langle\varphi\rangle/f) \sim \frac{v^2}{f^2} = \xi, \quad \langle\rho\rangle \sim f$$

$$m_\sigma{}^2 = 8\lambda f^2 + O\left(\lambda^0\right)$$

$$m_h{}^2 = 2\beta v^2 + O\left(\lambda^{-1}\right)$$ = 125 GeV

β ≅ 0.13

The mass of the heavy scalar is controlled by **large** self coupling **λ**.

Ratio of the scalar masses is doubly suppressed $\frac{m_h^2}{m_\sigma^2} \simeq \frac{\beta\xi}{4\lambda}$

For $\boldsymbol{m_\sigma(\lambda)\to\infty}$ the bosonic sector of the theory is a nonlinear sigma model

$$\mathcal{L}_0 = \frac{1}{2}(\partial\varphi)^2 + \frac{1}{2}(DU)^\dagger DU - V(\varphi)$$

Finite **λ** results in corrections to the leading order Lagrangian

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_1/\lambda + \mathcal{L}_2/\lambda^2 + \ldots$$

All BSM states integrated out. Bosonic operators

Out of all possible operators in the full **bosonic custodial invariant** basis
only **8 are generated** at tree level
they appear at different orders in **1/λ** expansion

hep-ph/1610.xxxxx
tomorrow on arxiv

	Operator	$\mathcal{F}_k(\varphi)$	$1/\lambda^n$
$\mathcal{L}_{2\partial}$	$\mathcal{P}_H = \frac{1}{2}(\partial_\mu h)^2 \mathcal{F}_H(\varphi)$	$1 - \frac{1}{4\lambda}(\alpha c_\varphi - 2\beta s_\varphi^2)$	0
	$\mathcal{P}_C = -\frac{v^2}{4}\langle V_\mu V^\mu \rangle \mathcal{F}_C(\varphi)$	$\frac{1}{\xi}\left[1 - \frac{1}{4\lambda}\left(\alpha c_\varphi - 2\beta s_\varphi^2\right)\right] s_\varphi^2$	0
$\mathcal{L}_{4\partial}$	$\mathcal{P}_{DH} = \frac{1}{v^4}(\partial_\mu h)^4 \mathcal{F}_{DH}(\varphi)$	$\frac{\xi^2}{16\lambda}$	1
	$\mathcal{P}_6 = \langle V_\mu V^\mu \rangle^2 \mathcal{F}_6(\varphi)$	$\frac{s_\varphi^4}{64\lambda}$	1
	$\mathcal{P}_{20} = \frac{1}{v^2}\langle V_\mu V^\mu \rangle (\partial_\nu h)^2 \mathcal{F}_{20}(\varphi)$	$-\frac{\xi}{16\lambda} s_\varphi^2$	1
	$\mathcal{P}_7 = \frac{1}{v}\langle V_\mu V^\mu \rangle (\Box h) \mathcal{F}_7(\varphi)$	$\sqrt{\xi}\left[\frac{1}{128\lambda^2}\left(\alpha + 4\beta c_\varphi\right) s_\varphi^3\right]$	2
	$\mathcal{P}_{\Delta H} = \frac{1}{v^3}(\partial_\mu h)^2 \Box h \mathcal{F}_{\Delta H}(\varphi)$	$-\xi^{3/2}\left[\frac{1}{64 f^3 \lambda^2}\left(\alpha + 4\beta c_\varphi\right) s_\varphi\right]$	2
	$\mathcal{P}_{\Box H} = \frac{1}{v^2}\left(\Box h\right)^2 \mathcal{F}_{\Box H}(\varphi)$	$\mathcal{O}\left(\frac{1}{\lambda^3}\right)$	3

$\varphi = \langle \varphi \rangle + h$ $\quad c_\varphi = \cos(\varphi/f)$ $\quad s_\varphi = \sin(\varphi/f)$ $\quad V_\mu = (D_\mu U)U^\dagger$ $\quad U(\boldsymbol{\pi}) = e^{i\boldsymbol{\tau}\boldsymbol{\pi}}$ is the GB matrix

All BSM states integrated out. Bosonic operators

Out of all possible operators in the full **bosonic custodial invariant** basis
only **8 are generated** at tree level
they appear at different orders in **1/λ** expansion

3 operators are generated even if no explicit breaking of SO(5), i.e. α and β are zero

	Operator	$\mathcal{F}_k(\varphi)$	$1/\lambda^n$
$\mathcal{L}_{4\partial}$	$\mathcal{P}_{DH} = \frac{1}{v^4}(\partial_\mu h)^4 \mathcal{F}_{DH}(\varphi)$	$\frac{\xi^2}{16\lambda}$	1
multi h	$\mathcal{P}_6 = \langle V_\mu V^\mu \rangle^2 \mathcal{F}_6(\varphi)$ ← QGC modification	$\frac{s_\varphi^4}{64\lambda}$	1
	$\mathcal{P}_{20} = \frac{1}{v^2}\langle V_\mu V^\mu \rangle (\partial_\nu h)^2 \mathcal{F}_{20}(\varphi)$	$-\frac{\xi}{16\lambda} s_\varphi^2$	1

Their coefficients are correlated according to "sigma decomposition"

[Alonso, Brivio, Gavela, Merlo, Rigolin '14]

Example of structure which is not generated at tree level: $\langle V_\mu V_\nu \rangle$

$\varphi = \langle \varphi \rangle + h$ $c_\varphi = \cos(\varphi/f)$ $s_\varphi = \sin(\varphi/f)$ $V_\mu = (D_\mu U)U^\dagger$ $U(\boldsymbol{\pi}) = e^{i\boldsymbol{\tau}\boldsymbol{\pi}}$ is the GB matrix

All BSM states integrated out. Fermionic operators

Leading in **1/Mψ** Yukawa coefficient coming from "see-saw" $y^0 \sim y\ \Lambda^2/M_\psi^2$

$P_\pm$ selects t_R or b_R component of the "right doublet"

correction to original effective Yukawa

	Operator	$\mathcal{F}_k(\varphi)$	$1/\lambda^n$
$\mathcal{P}_{\rm Yuk}$	$v\,\bar{q}_{iL} U P_\pm \mathbf{q}_{iR} + \text{h.c.}$	$-\frac{y_i^0}{\sqrt{2\xi}} c_\varphi^n s_\varphi^{2m+1}\left(1 - \frac{n+2m+1}{8\lambda}(\alpha c_\varphi - 2\beta s_\varphi^2)\right)$	0
$\mathcal{P}_{qH}$	$\frac{1}{v^3}(\partial_\mu h)^2 \bar{q}_{iL} U P_\pm \mathbf{q}_{iR} + \text{h.c.}$	$-\frac{y_i^0}{\sqrt{2}}\xi^{3/2}\left(\frac{n+2m+1}{8\lambda}\right) c_\varphi^n s_\varphi^{2m+1}$	1
$\mathcal{P}_{qV}$	$\frac{1}{v}\langle V_\mu V^\mu\rangle \bar{q}_{iL} U P_\pm \mathbf{q}_{iR} + \text{h.c.}$	$\frac{y_i^0}{\sqrt{2}}\sqrt{\xi}\left(\frac{n+2m+1}{16\lambda}\right) c_\varphi^n s_\varphi^{2m+3}$	1
$\mathcal{P}_{4q}$	$\frac{1}{v^2}(\bar{q}_{iL} U P_\pm \mathbf{q}_{iR})(\bar{q}_{jL} U P_\pm \mathbf{q}_{jR}) + \text{h.c.}$	$(2-\delta_{ij}) y_i^0 y_j^0 \xi \frac{(n+2m+1)^2}{32\lambda} c_\varphi^{2n} s_\varphi^{4m+2}$	1
$\mathcal{P}_{4q'}$	$\frac{1}{v^2}(\bar{q}_{iL} U P_\pm \mathbf{q}_{iR})(\bar{\mathbf{q}}_{jR} P_\pm U^\dagger q_{jL}) + \text{h.c.}$	$(2-\delta_{ij}) y_i^0 y_j^0 \xi \frac{(n+2m+1)^2}{32\lambda} c_\varphi^{2n} s_\varphi^{4m+2}$	1

{n,m} dependence differentiate the relative impact of different fermion embeddings in UV complete model

Couplings modification

The expressions for the observables receive corrections **~ 1/λ** or equivalently **~ 1/m_σ**

$$M_W^2 = \frac{g^2 f^2}{4}\left(1 - \frac{\alpha^2}{4\beta^2} + \frac{\beta}{2\lambda}\right)$$

modification of higgs — gauge coupling, assuming **ξ,1/λ <<1**

$$\kappa_V \equiv g_{hVV}/g_{hVV}^{SM} = \sqrt{1-\xi} + 2\frac{m_h^2}{m_\sigma^2}$$

Higgs to fermion coupling modification $\kappa_f = g_{hff}/g_{hff}^{SM}$

$$\kappa_f \simeq \frac{(1+2m)(1-\xi) - n\xi}{\sqrt{1-\xi}} + (2+4m+3n)\frac{m_h^2}{m_\sigma^2}$$

NLO correction is proportional to the ratio of scalar masses

In case of $MCHM_4$ and $MCHM_5$ the modification reads

$$\kappa_f^4 \simeq \sqrt{1-\xi} + 2\frac{m_h^2}{m_\sigma^2}, \quad \kappa_f^5 \simeq \frac{1-2\xi}{\sqrt{1-\xi}} + 5\frac{m_h^2}{m_\sigma^2}.$$

Same as before,
but with NLO corrections for explicit the 5-1-1 {n=m=0} embedding

$\mathcal{M}$ is a mass scale of heavy fermions

$f/\mathcal{M}$ corrections might be important if $f \simeq \mathcal{M}$

	Operator	$\mathcal{F}_i(\varphi)$	$1/\lambda^n$
$\mathcal{P}_{\rm Yuk}$	$v(\bar{q}_{iL} U P_{\pm} \mathbf{q}_{iR})$	$-\frac{y_t^0}{\sqrt{2\xi}} s_\varphi \left[1 - \frac{1}{8\lambda}(\alpha c_\varphi - 2\beta s_\varphi^2) - 2\frac{f}{\mathcal{M}_i} a^i_{\sigma 1} c_\varphi\right]$	0
$\mathcal{P}_{qh}$	$(\partial_\mu h)^2 (\bar{q}_{iL} U P_{\pm} \mathbf{q}_{iR})$	$-\frac{y_i^0}{8\sqrt{2}\lambda f^3} s_\varphi \left(1 - 2\frac{f}{\mathcal{M}_i} a^i_{\sigma 1} c_\varphi\right)$	1
$\mathcal{P}_{qV}$	$\langle V_\mu V^\mu \rangle (\bar{q}_{iL} U P_{\pm} \mathbf{q}_{iR})$	$\frac{y_i^0}{16\sqrt{2}\lambda f} s_\varphi \left(1 - 2\frac{f}{\mathcal{M}_i} a^i_{\sigma 1} c_\varphi\right)$	1
$\mathcal{P}_{4q}$	$(\bar{q}_{iL} U P_{\pm} \mathbf{q}_{iR})(\bar{q}_{jL} U P_{\pm} \mathbf{q}_{jR})$	$(2 - \delta_{ij}) \frac{y_i^0 y_j^0}{32\lambda f^2} s_\varphi^2 \left[1 - 2\left(a^i_{\sigma 1}\frac{f}{\mathcal{M}_i} + a^j_{\sigma 1}\frac{f}{\mathcal{M}_j}\right) c_\varphi\right]$	1
$\mathcal{P}_{4q'}$	$(\bar{q}_{iL} U P_{\pm} \mathbf{q}_{iR})(\bar{\mathbf{q}}_{jR} P_{\pm} U^\dagger q_{jL})$	$(2 - \delta_{ij}) \frac{y_i^0 y_j^0}{32\lambda f^2} s_\varphi^2 \left[1 - 2\left(a^i_{\sigma 1}\frac{f}{\mathcal{M}_i} + a^j_{\sigma 1}\frac{f}{\mathcal{M}_j}\right) c_\varphi\right]$	1

$$a_x = a_x(y, \Lambda, M_\psi)$$

Conclusions

- We have constructed a UV complete renormalisable model for the Goldstone Higgs
- The scalar sector extended by a new scalar σ forms a **linear** representation of global SO(5), broken spontaneously to SO(4)
- Lower mass of the new scalar has less tension with EWPT
- A current bound on scalar mass is m_σ>500GeV, to be risen up to 900 GeV in future
- Effective Yukawa term encompasses various choices of heavy fermion embeddings
- For the energies below the masses of new BSM states effective operators have been identified in the model with effective Yukawa (LO) as well as heavy fermions 5-1-1 repres(NLO)
- First linear corrections to higgs couplings κ_V and κ_f are determined

Thank you for your attention

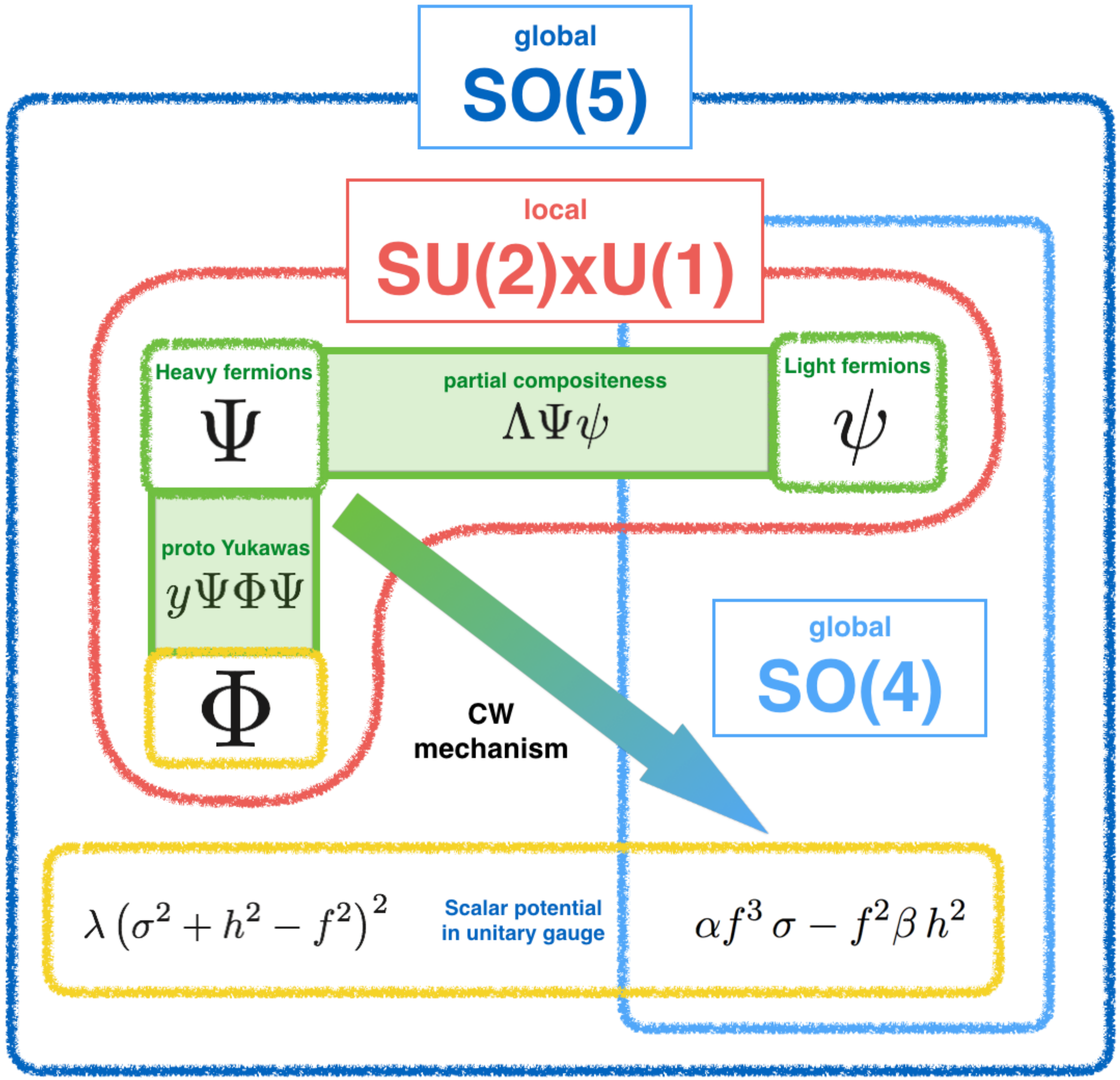
Back up

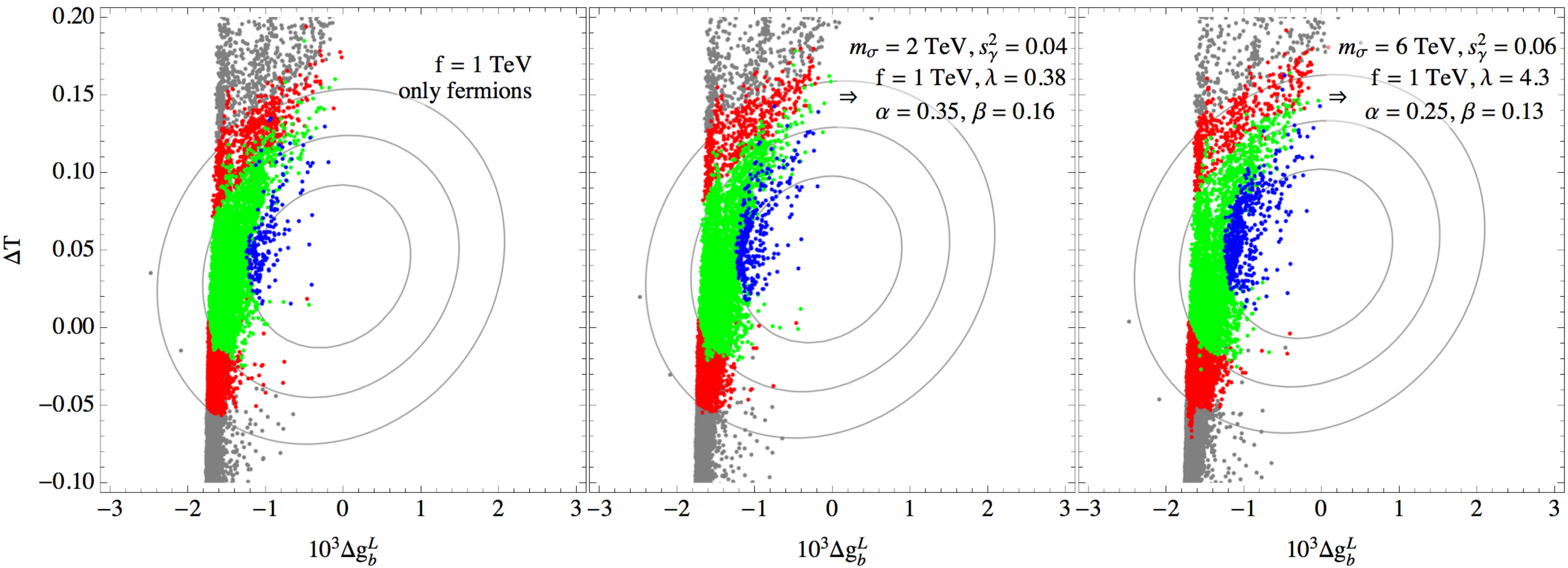
$$\lambda = \frac{\sin^2\gamma m_\sigma^2}{8v^2}\left(1+\cot^2\gamma\frac{m_h^2}{m_\sigma^2}\right) ,$$

$$\frac{\beta}{4\lambda} = \frac{m_h^2 m_\sigma^2}{\sin^2\gamma m_\sigma^4 + \cos^2\gamma m_h^4 - 2m_h^2 m_\sigma^2} ,$$

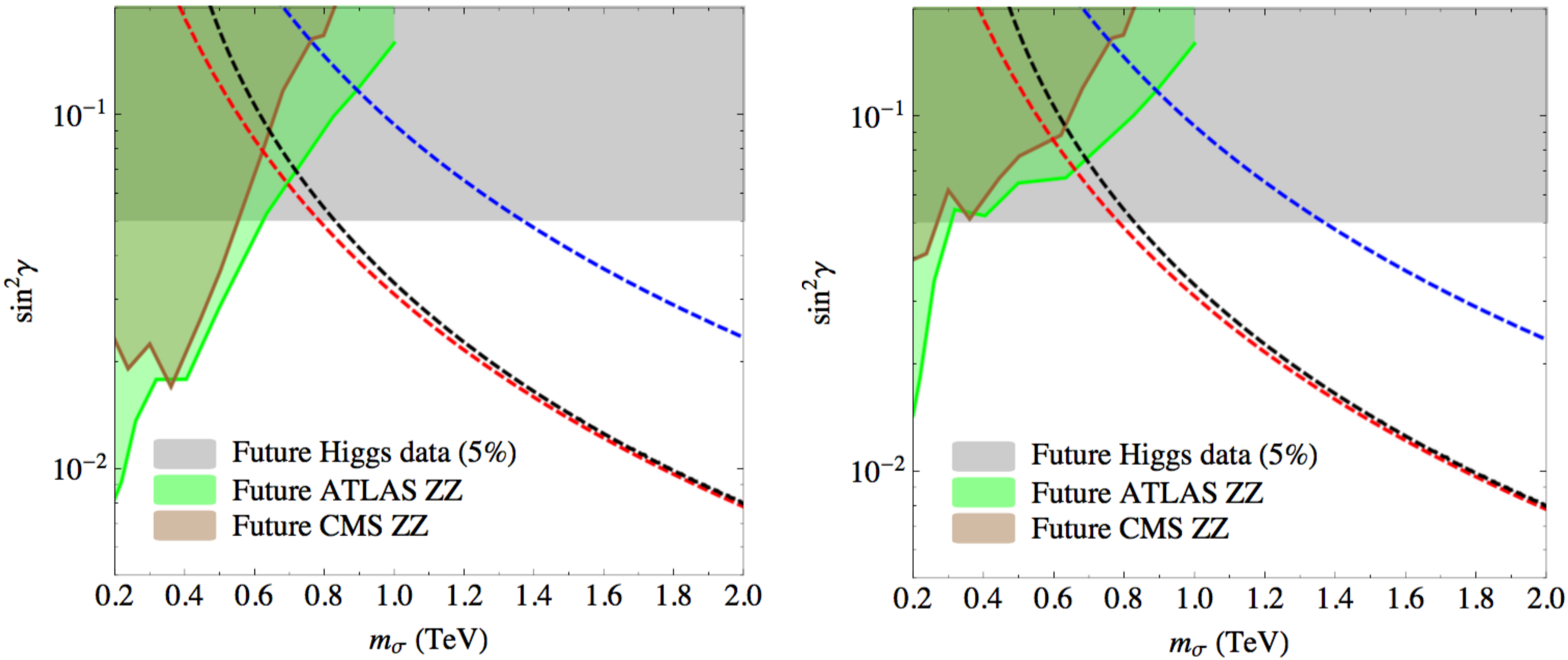
$$\frac{\alpha^2}{4\beta^2} = \frac{\sin^2(2\gamma)(m_\sigma^2 - m_h^2)^2}{4(\sin^2\gamma m_\sigma^4 + \cos^2\gamma m_h^4 - 2m_h^2 m_\sigma^2)} ,$$

$$f^2 = \frac{v^2(\sin^2\gamma m_\sigma^4 + \cos^2\gamma m_h^4 - 2m_h^2 m_\sigma^2)}{(\sin^2\gamma m_\sigma^2 + \cos^2\gamma m_h^2)^2} .$$


global
SO(5)
local
SU(2)xU(1)
Heavy fermions
Ψ
partial compositeness
$\Lambda \Psi \psi$
Light fermions
ψ
proto Yukawas
$y \Psi \Phi \Psi$
Φ
CW
mechanism
global
SO(4)
$\lambda \left(\sigma^2 + h^2 - f^2\right)^2$
Scalar potential
in unitary gauge
$\alpha f^3 \sigma - f^2 \beta h^2$



f = 1 TeV
only fermions
$m_\sigma = 2$ TeV, $s_\gamma^2 = 0.04$
f = 1 TeV, $\lambda = 0.38$
⇒
$\alpha = 0.35$, $\beta = 0.16$
$m_\sigma = 6$ TeV, $s_\gamma^2 = 0.06$
f = 1 TeV, $\lambda = 4.3$
⇒
$\alpha = 0.25$, $\beta = 0.13$
ΔT
$10^3 \Delta g_b^L$


10^{-1}
10^{-2}
$\sin^2\gamma$
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
m_σ (TeV)
Future Higgs data (5%)
Future ATLAS ZZ
Future CMS ZZ
10^{-1}
10^{-2}
$\sin^2\gamma$
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
m_σ (TeV)
Future Higgs data (5%)
Future ATLAS ZZ
Future CMS ZZ