On the quantum structure of indirect BSM effects

Alex Pomarol, CERN & UAB (Barcelona)

Purpose of this talk:

Little story about zeros…

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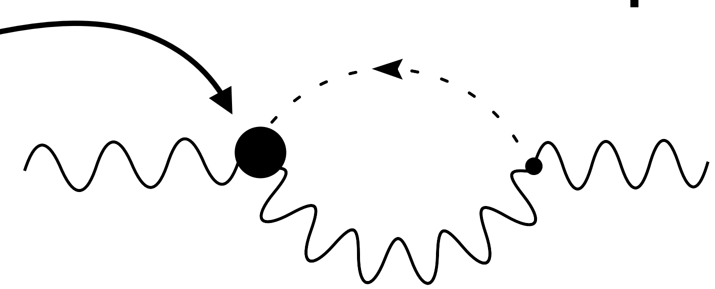
The SM is an EFT with higher-dim operators (what we call BSM!)
At the quantum-level operator mix:

- To understand these mixings is crucial in order to see how restrictions can arise from well-measured quantities: **S, T, hγγ, …**

e.g. HZZ coupling  restricted by **S**

- Effects can be important in the future to unravel the UV model

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Little story about <u>zeros</u>…

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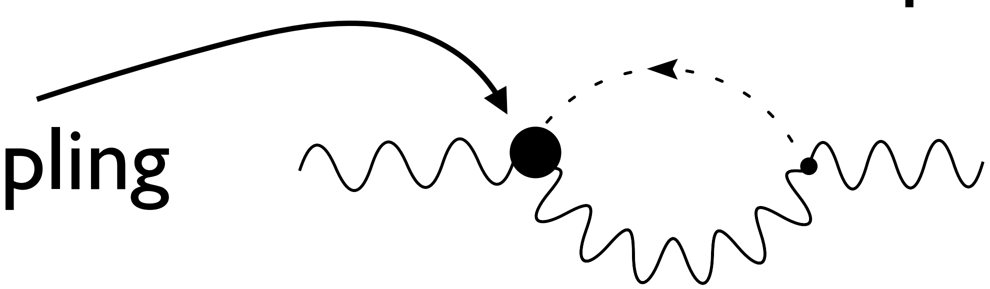
e.g. HZZ coupling  restricted by **S**

- Effects can be important in the future to unravel the UV model

We will see that an interesting set of **<u>one-loop non-renormalization results</u>** can be derived (the choice of the **correct basis** is crucial)

EFT captures the (indirect) impact of BSMs

Under the assumption that the
new-physics scale Λ is heavier than M_W,
we can perform an expansion in derivatives and SM fields

(assuming lepton & baryon number)

$$\mathcal{L}_{\rm eff} = \frac{\Lambda^4}{g_*^2}\mathcal{L}\left(\frac{D_\mu}{\Lambda}\,,\ \frac{g_H H}{\Lambda}\,,\ \frac{g_{f_{L,R}} f_{L,R}}{\Lambda^{3/2}}\,,\ \frac{g F_{\mu\nu}}{\Lambda^2}\right) \simeq \mathcal{L}_4 + \mathcal{L}_6 + \cdots$$

SM

leading deviations from the SM

One-loop mixing of dim-6 operators

Interesting situations could arise from mixing:

Tree-level **One-loop induced**

$\mathcal{O}_{tree}$ $\mathcal{O}_{loop}$ **at Λ**

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RG evolution

$$c_{loop}(m_W) \sim \frac{c_{tree}}{16\pi^2} \log \frac{\Lambda}{m_W}$$ **at m_W**

Due to the log, dominant effect from running!!

$$\log(3\ \mathrm{TeV}/m_W)^2 \sim 7$$

One-loop mixing of dim-6 operators

Example 1: **SM after integrating out W/Z:**

Tree-level **One-loop induced**

$$\mathcal{O}_{tree} = (\bar{c}_L \gamma^\mu b_L)(\bar{s}_L \gamma^\mu c_L) \qquad \mathcal{O}_{loop} = \bar{s}_L \sigma^{\mu\mu} b_R F_{\mu\nu}$$

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RG evolution

No mixing between "tree" and "loop" operators at the one-loop level

B.Grinstein, R..Springer and M.Wise 90

no explanation of the reason of why this happens!

One-loop mixing of dim-6 operators

Example 2: Hγγ from BSMs (SUSY/SILH)

Tree-level

$$\mathcal{O}_{tree} = (\partial_\mu |H|^2)^2$$

↪ affects hVV

One-loop induced

$$\mathcal{O}_{loop} = |H|^2 B^{\mu\nu} B_{\mu\nu}$$

↪ affects hγγ

One-loop mixing of dim-6 operators

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No mixing between "tree" and "loop" operators at the one-loop level

Otherwise the analysis of Higgs couplings from ATLAS/CMS (the (in)famous "**kappas**") would have had a very different interpretation in BSMs!

Pattern of operator mixing I

"Loop" operators

<u>defined</u> as arising from renormalizable BSMs

$$H^\dagger \bar{f}_R \sigma^{\mu\nu} t^a f_L \, F^a_{\mu\nu} \longrightarrow \text{fermion dipoles}$$

$$H^\dagger t^a t^b H F^a_{\mu\nu} \; F^{b\,\mu\nu} \longrightarrow h\gamma\gamma,\, hZ\gamma, hGG$$

$$f^{abc} F^{a\,\nu}_{\mu} F^{b\,\rho}_{\nu} \; F^{c\,\mu}_{\rho} \longrightarrow \text{TGC}$$

+ CP-violating

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"Current-current" operators

$$J_i \cdot J_j$$

$$J^{a\,\mu}_H = H^\dagger t^a D^\mu H$$

$$J^{a\,\mu}_f = \bar{f} t^a \gamma^\mu f$$

$$, \ldots$$

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, ...

J. Elias-Miro, J.R. Espinosa, E. Masso, A.P. 13; Jenkins, Manohar, Trott 13

One exception to this rule:

$$\mathcal{O}_{yy} = \left(\bar{f}_R t^a f_L\right) \left(\bar{f}_R t^a f_L\right) \sim \psi^4$$ in weyl notation

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Pattern of operator mixing II

. R.Alonso, E.Jenkins, A.Manohar 15

Holomorphy:

In the basis: $\mathcal{O}_{3F_\pm} = \mathcal{O}_{3F} \mp i\mathcal{O}_{3\tilde{F}}$

$\mathcal{O}_{FF_\pm} = \mathcal{O}_{FF} \mp i\mathcal{O}_{F\tilde{F}}$

$$\begin{cases} \mathcal{O}_{3F} = f^{abc} F_\mu^{a\,\nu} F_\nu^{b\,\rho} F_\rho^{c\,\mu} \\ \mathcal{O}_{FF} = H^\dagger t^a t^b H F^a_{\mu\nu} F^{b\,\mu\nu} \end{cases}$$

The one-loop anomalous dimensions of the complex Wilson-coefficients do not depend on their complex-conjugates:

J.Elias-Miro, J.R.Espinosa, A.P. 15

$$\boxed{\frac{\partial \gamma_{c_i}}{\partial c_j^*} = 0}$$

$$c_i = \{c_{3F_+}, c_{FF_+}, c_D, c_y, c_{yy}, c_R^{ud}\}$$

Only one exception to this rule was found from explicit calculations

(1 out of 36 !)

Pattern of operator mixing I+II

☛ suggests a possible explanation using <u>supersymmetry</u>:

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Supersymmetry can be an useful tool even for <u>non</u>-supersymmetric theories

➥ for an alternative approach, see Cheung-Shen 15 using Spinor Helicity formalism

e.g. : QCD n-gluon scattering at tree-level:

<u>Same as in Susy-QCD as gauginos appear at the loop-level</u> !

☛ easy to prove: $A_n^{tree}[g^- g^+ g^+ \cdots g^+] = A_n^{tree}[g^+ g^+ \cdots g^+] = 0$

as it was shown by long explicit calculations!

Supersymmetrization

Dim-4 operators:

SM $\longrightarrow$ **MSSM** **(with one Higgs)**

<u>if</u> <u>**both**</u> y_u & y_d are simultaneously present,
a source of susy-breaking is needed

$$\int d^2\theta y_u HQU + \int d^4\theta y_d H^\dagger QD\eta^\dagger \qquad \eta \equiv \theta^2$$

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Dim-6 operators:

Loop operators $\longrightarrow$ **F-term of non-chiral operators**

e.g. $\mathcal{O}_{FF} = |\phi|^2 F_{\mu\nu}F^{\mu\nu} \longrightarrow \Phi^\dagger e^{V_\Phi}\Phi\, \mathcal{W}^\alpha \mathcal{W}_\alpha = -\frac{1}{2}\theta^2 \mathcal{O}_{FF} + \cdots$

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Break susy! $\int d^4\theta\Phi^\dagger e^V_\Phi \Phi\mathcal{W}^\alpha\mathcal{W}_\alpha\eta^\dagger$

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same for fermion dipoles (ffF) & vector dipoles (F^3)

Loop operators $\longrightarrow$ F-term of non-chiral operators

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$$\mathcal{O}_D = \phi(q\sigma^{\mu\nu}u)F_{\mu\nu} \longrightarrow \Phi \, (Q\overleftrightarrow{\mathcal{D}}_\alpha U) \, \mathcal{W}^\alpha = -\theta^2 \mathcal{O}_D + \cdots$$

$$\mathcal{O}_{3F} = f^{abc} F_\mu^{a\,\nu} F_\nu^{b\,\rho} F_\rho^{c\,\mu} \longrightarrow f^{abc} \mathcal{D}^\beta \mathcal{W}^{a\,\alpha} \mathcal{W}_\beta^b \mathcal{W}_\alpha^c = i\theta^2 \mathcal{O}_{3F} + \cdots$$

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Susy protected!

...ak susy! $\int d^4\theta\, \Phi^\dagger e^V_\Phi \Phi \mathcal{W}^\alpha \mathcal{W}_\alpha \eta^\dagger$

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ak susy! $\int d^4\theta\, \Phi^\dagger e^V_\Phi \Phi \mathcal{W}^\alpha \mathcal{W}_\alpha \eta^\dagger$

Susy protected!

same for f mion dipole

an spurion (η) for power counting

Are there "tree" operators of the same class

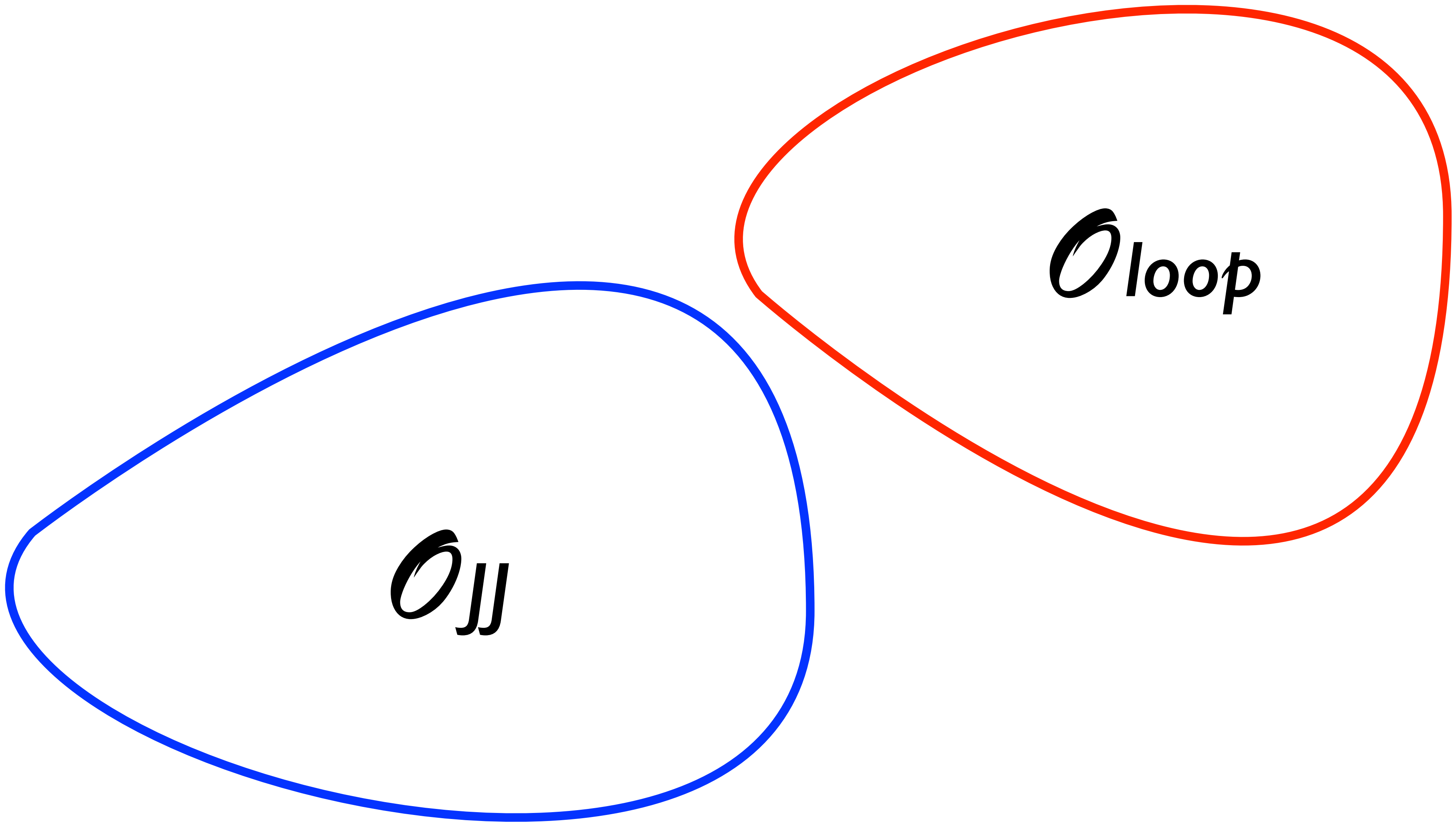
(Susy protected: arising from F-term of non-chiral operators)?

$$\mathcal{O}_{y_u} = |\phi|^2 \phi q u \longrightarrow \left(\Phi^\dagger e^{V_\Phi} \Phi\right) \Phi Q U = \theta^2 \mathcal{O}_{y_u} + \cdots$$

$$\mathcal{O}_{y_u y_d} = q u q d \longrightarrow (QU)\, \mathcal{D}^2 \,(QD) \;=\; -4\theta^2 \mathcal{O}_{y_u y_d} + \cdots$$

the **rest** from susy-preserving term or with other spurion dependence

Groups of dim-6 operators



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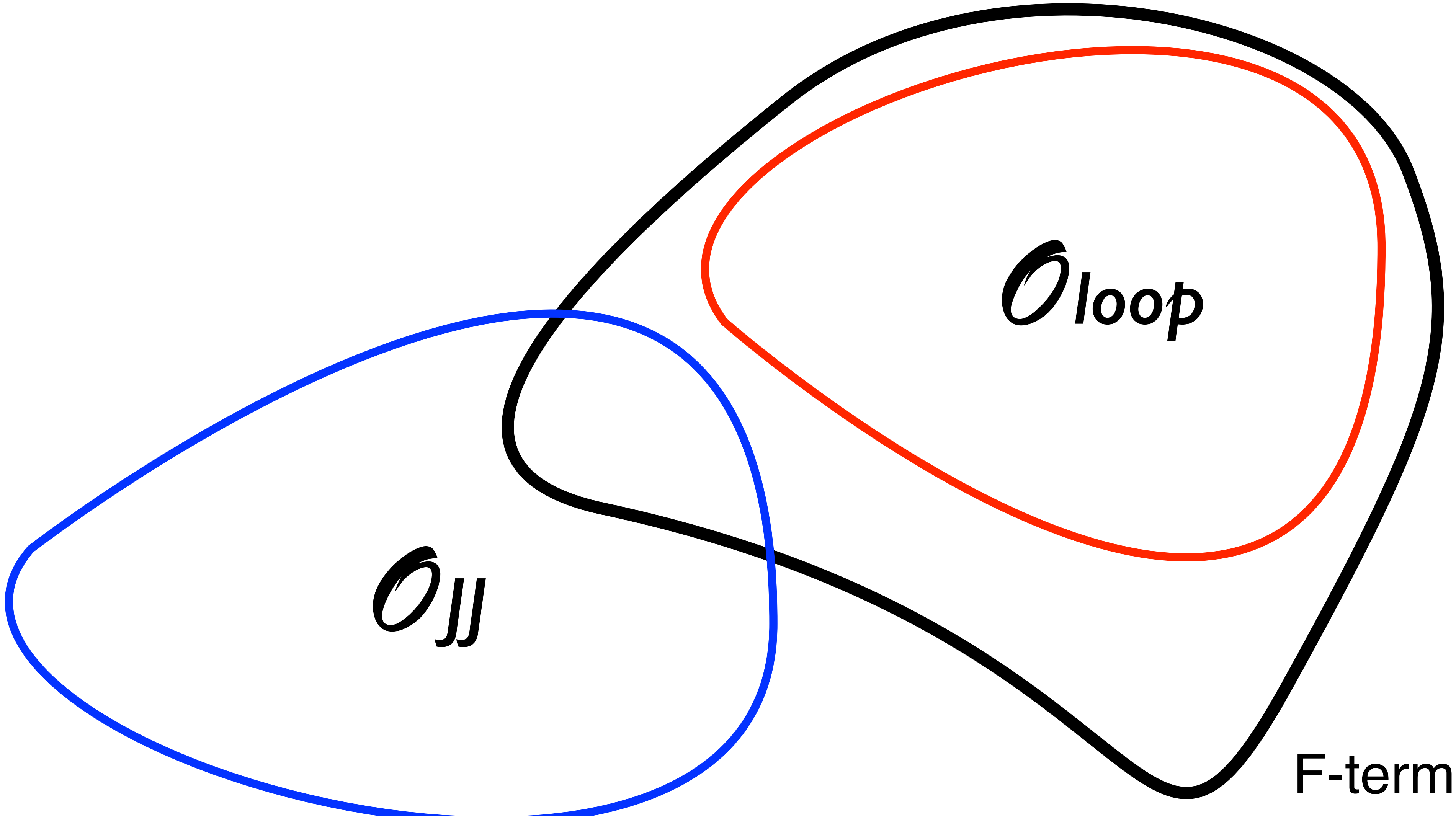
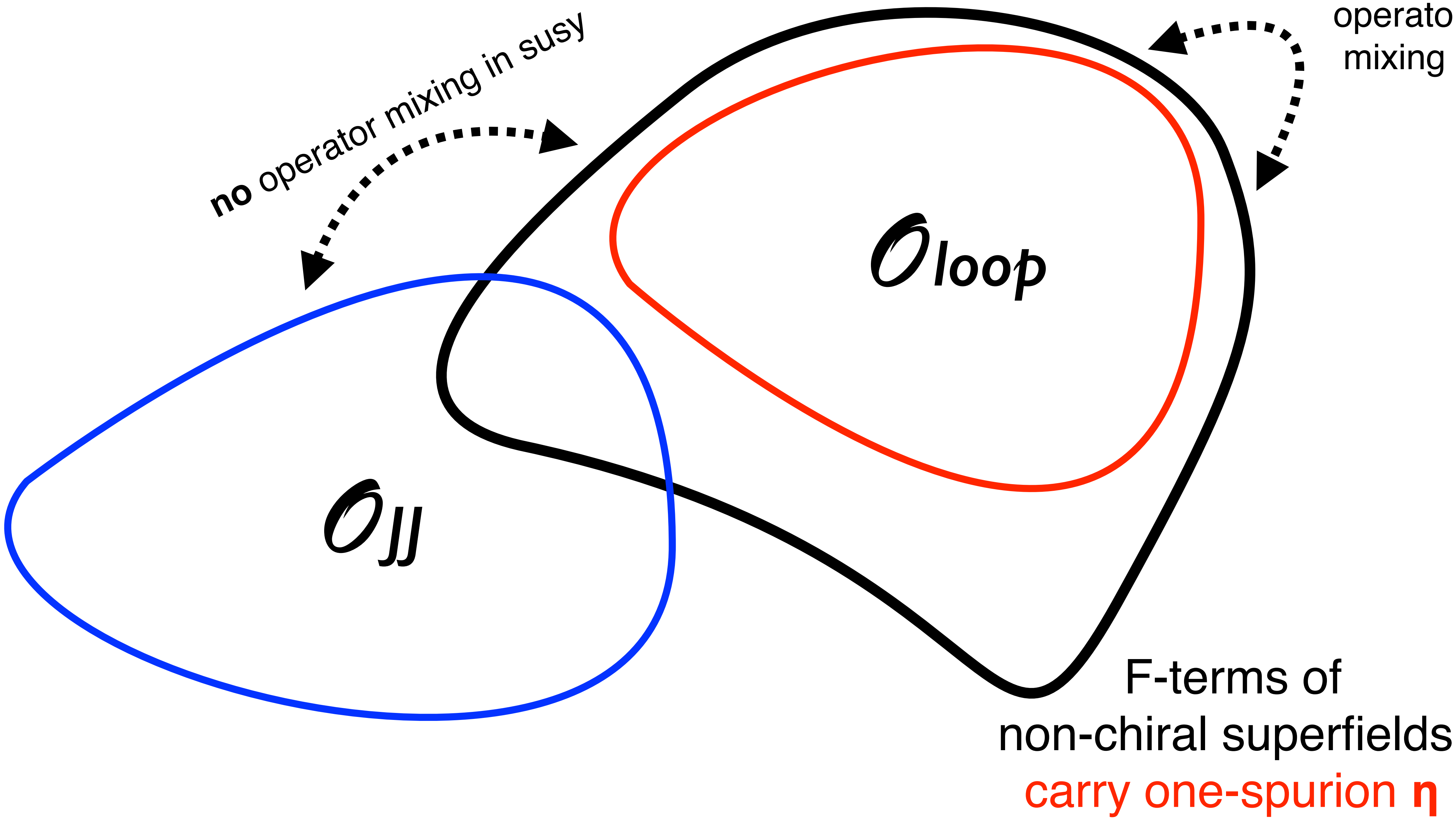


F-terms of
non-chiral superfields:
carry one-spurion η

Groups of dim-6 operators



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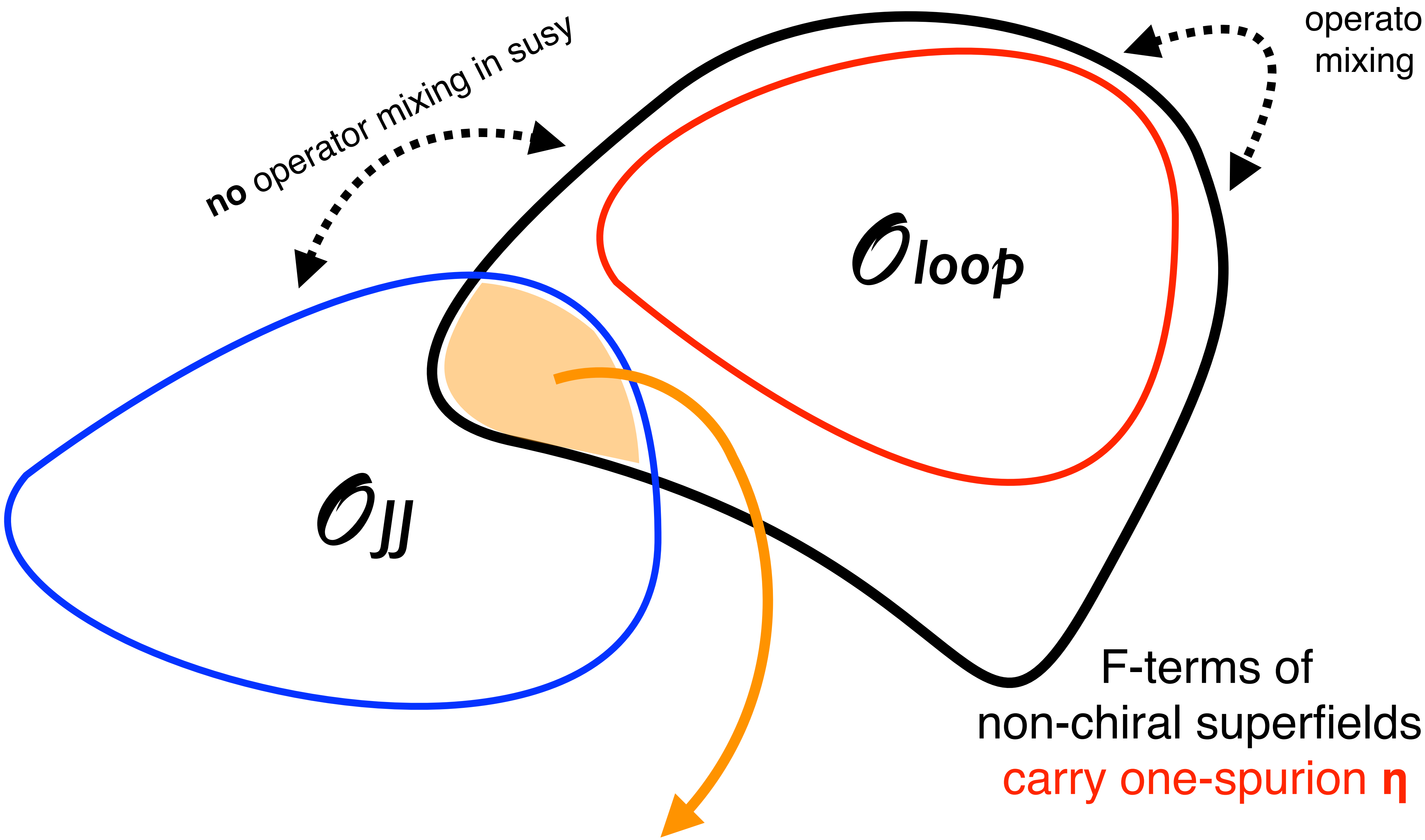

$$\mathcal{O}_y = |H|^2 H \bar{f}_R f_L$$

$$\mathcal{O}_{yy} = \left(\bar{f}_R t^a f_L\right)\left(\bar{f}_R t^a f_L\right)$$

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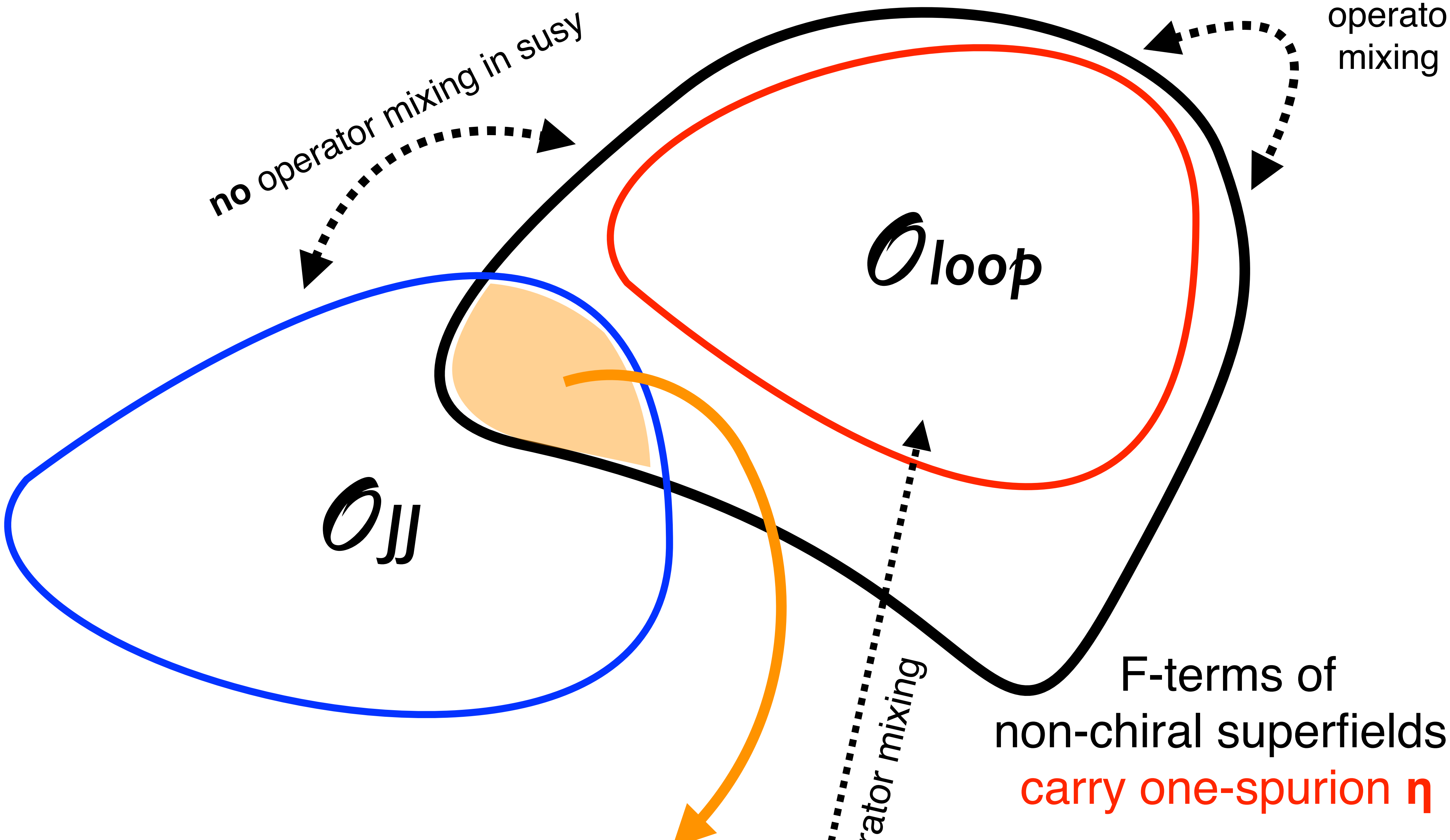

$$\mathcal{O}_y = |H|^2 H \bar{f}_R f_L$$

trivially cannot contribute

$$\boxed{\mathcal{O}_{yy} = \left(\bar{f}_R t^a f_L\right)\left(\bar{f}_R t^a f_L\right)}$$

the only "tree-level" operator affecting "loop" one: <u>Dipole of *f*</u>
<u>(as explicit calculations showed)</u>

The SM EFT $\mathcal{O}_{yy}$ operators:

$$
\begin{aligned}
\mathcal{O}_{y_u y_d} &= (\bar{Q}_L^r u_R)\epsilon_{rs}(\bar{Q}_L^s d_R)\,, \\
\mathcal{O}_{y_u y_d}^{(8)} &= (\bar{Q}_L^r T^A u_R)\epsilon_{rs}(\bar{Q}_L^s T^A d_R)\,, \\
\mathcal{O}_{y_u y_e} &= (\bar{Q}_L^r u_R)\epsilon_{rs}(\bar{L}_L^s e_R)\,, \\
\mathcal{O}'_{y_u y_e} &= (\bar{Q}_L^{r\,\alpha} e_R)\epsilon_{rs}(\bar{L}_L^s u_R^\alpha)\,,
\end{aligned}
$$

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$$\mathcal{O}'_{y_u y_e} = (\bar{Q}_L^{r\,\alpha} e_R)\epsilon_{rs}(\bar{L}_L^s u_R^\alpha)\,,$$

trivially cannot contribute

from integrating out a scalar with quantum numbers:

a) **$(1,2)_{1/2}$**
b) **$(8,2)_{1/2}$**
c) Leptoquark **$(3,2)_{-7/6}$**

Holomorphy:

$$\boxed{\frac{\partial \gamma_{c_i}}{\partial c_j^*} = 0}$$

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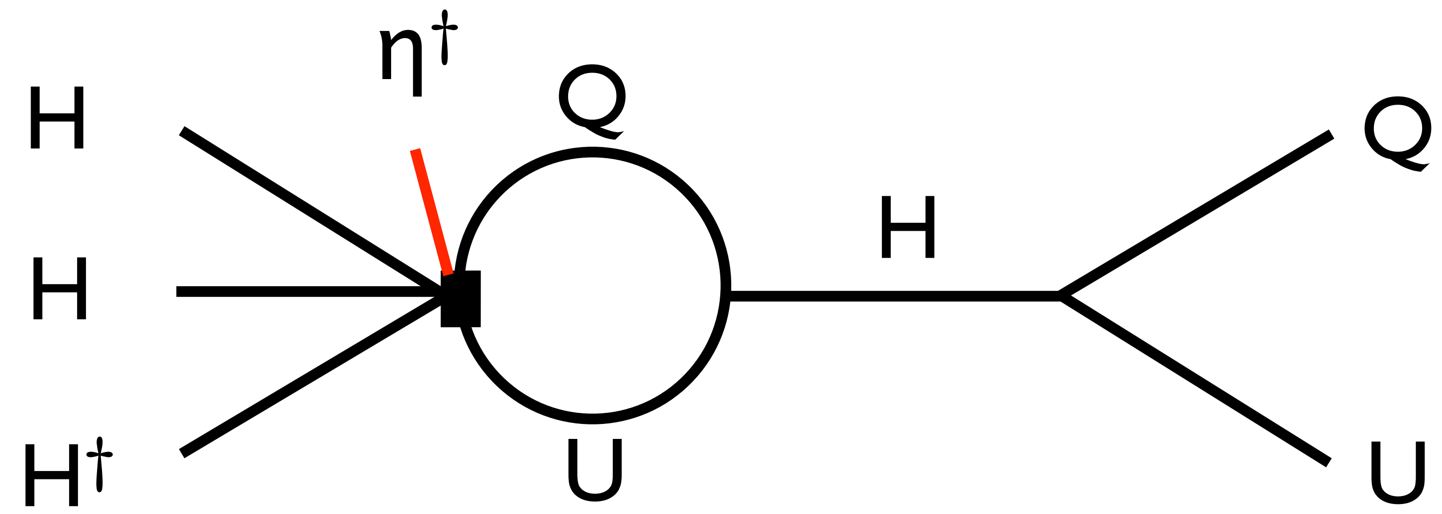
Operators with $\eta^\dagger$
cannot generate those with η



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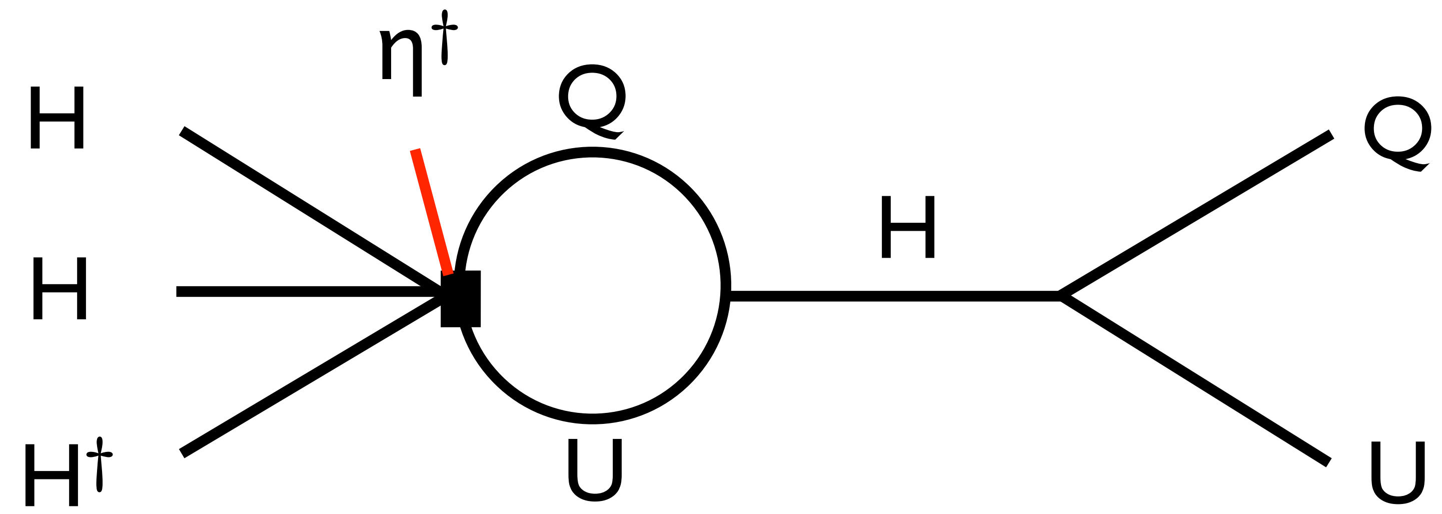
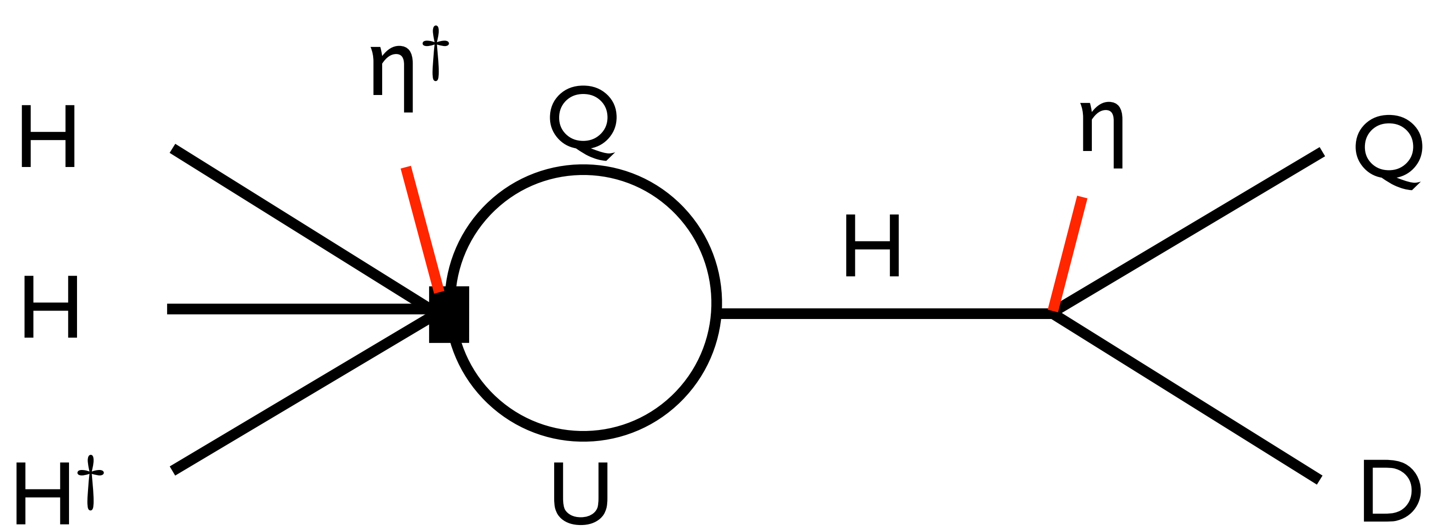


Exception: Extra spurions from (susy-breaking) dim-4 operators
(must be $\propto y_u y_d$):



$$\mathcal{O}_{y_u} \leftrightarrow \mathcal{O}_{y_d}$$

as explicit calculations show

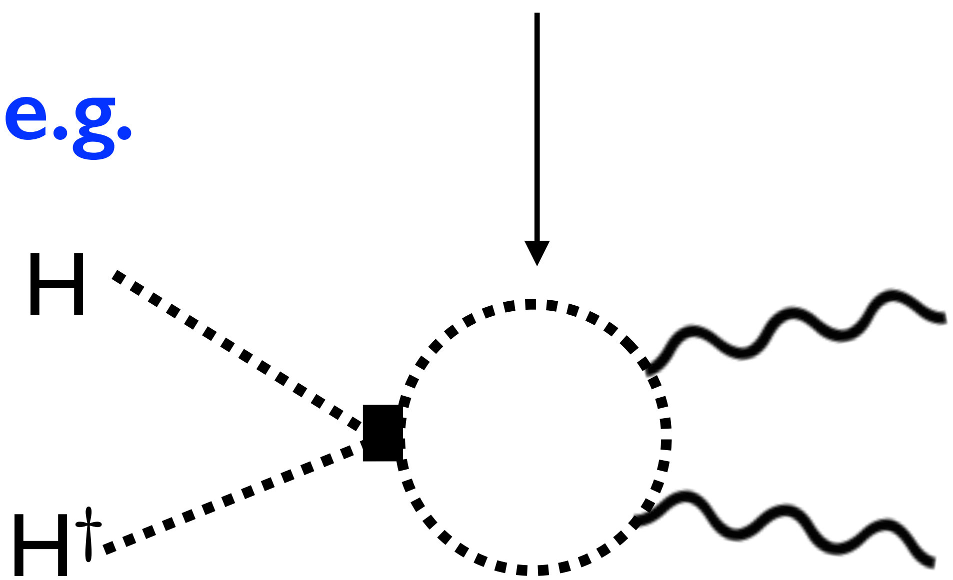
☛ Simple spurion analysis with supersymmetry explains the **one-loop mixing** pattern observed in the SM EFT

But the SM is not supersymmetric…

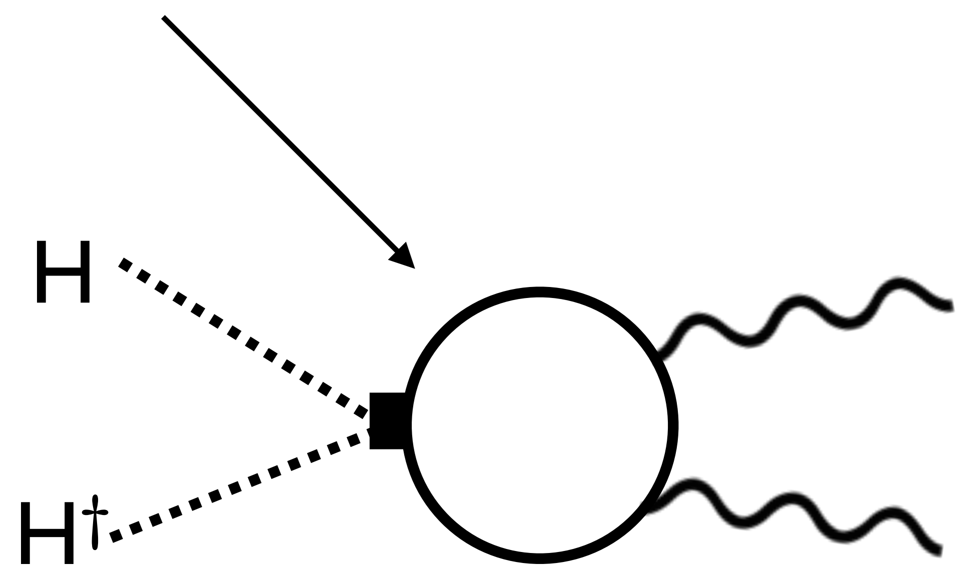
Are superpartners playing a crucial role in the zeros?

When in the susy limit we have zero mixing,
one can just look at loops with
either **SM fields** or **super-partners**: **take the easiest!**

e.g.



$|\phi|^2|D_\mu\phi|^2$



$(i\phi^* \overleftrightarrow{D}_\mu \phi)\psi^\dagger\bar{\sigma}^\mu\psi$

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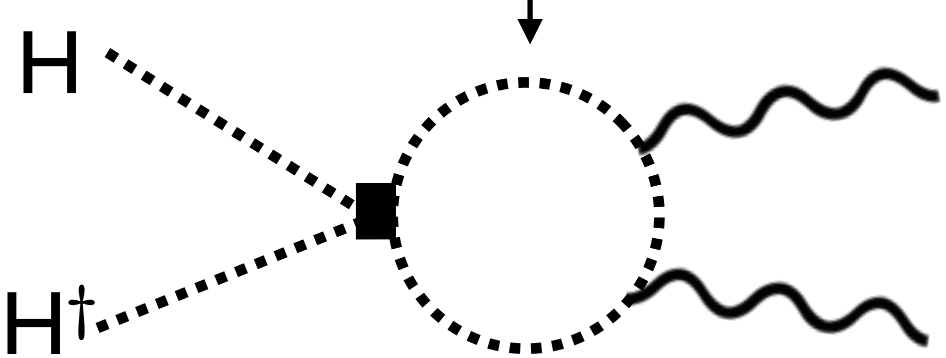

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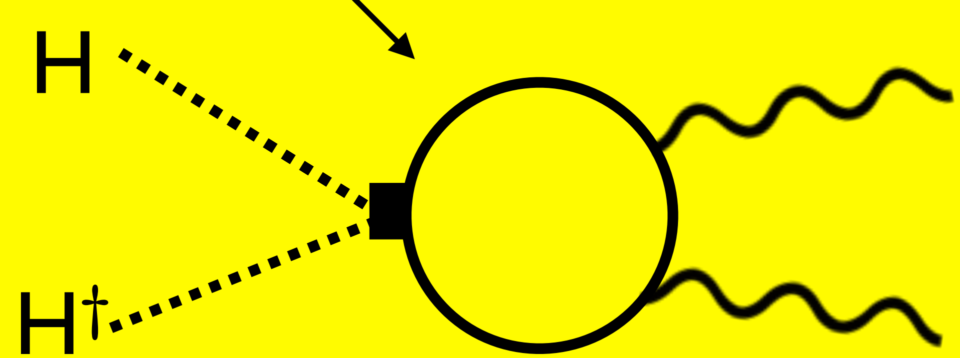


$(i\phi^* \overleftrightarrow{D}_\mu \phi)\psi^\dagger\bar{\sigma}^\mu\psi$

Not possible to give $|\phi|^2 F_{\mu\nu}^2$

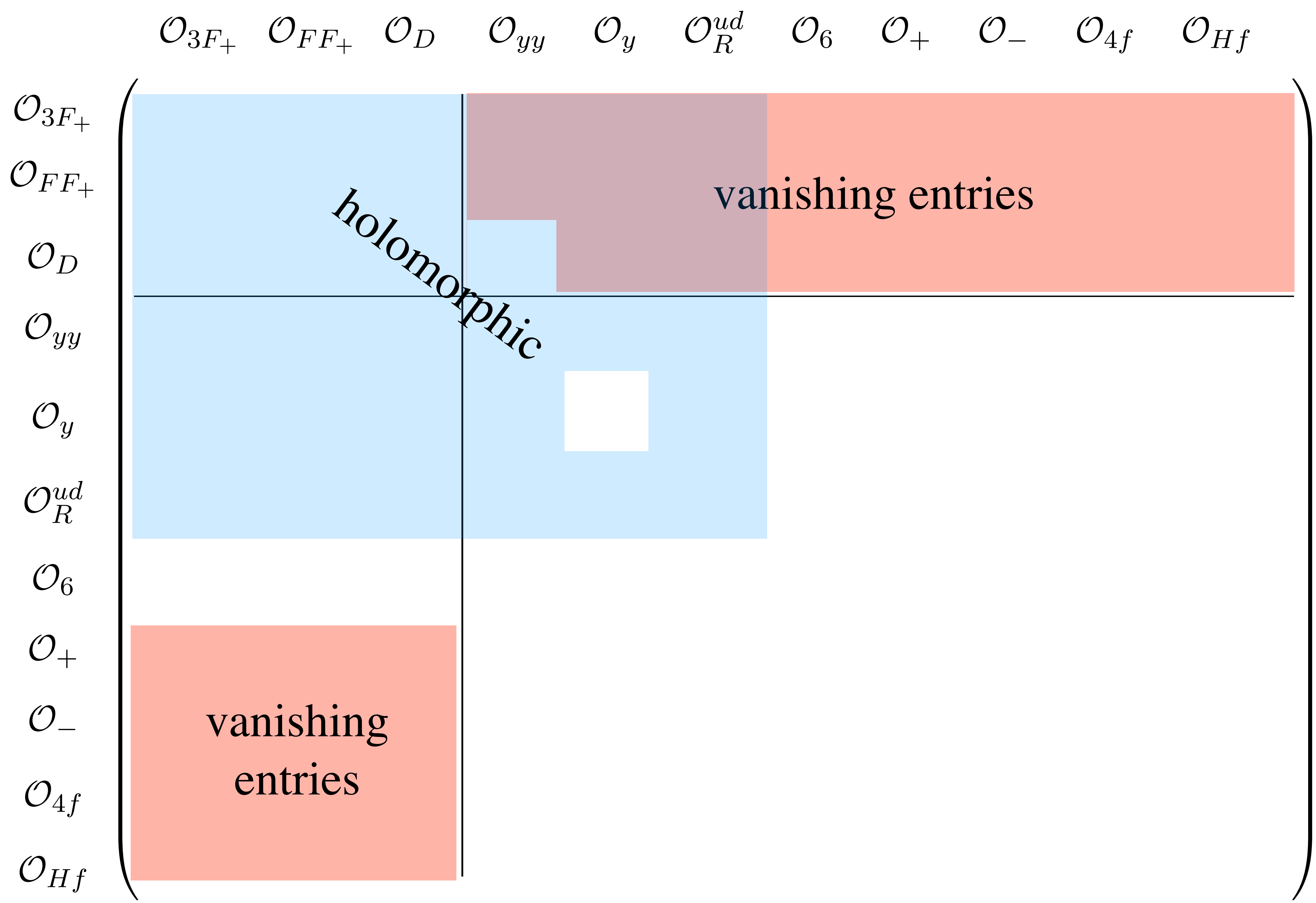
Similarly for the other cases

Holomorphy:

Again, we can either look at **SM field** loop or **super-partner** loop:
The simplest: the diagrams with fermions, as you can follow
the fermion-line to see if it changes direction.
No contribution is found!

☛ Holomorphy is preserved beyond SUSY

This analysis can lead to prove:



$$\mathcal{O}_+ = [2\mathcal{O}_r + \mathcal{O}_H - \mathcal{O}_T] = D_\mu(H_i^\dagger H_j^\dagger)D^\mu(H^i H^j)$$

$$\mathcal{O}_- = \frac{1}{2}[\mathcal{O}_H - \mathcal{O}_T] = |H^\dagger D_\mu H|^2$$

$$\mathcal{O}_{4f} = \left(\bar{f}\gamma^\mu t^a f\right)\left(\bar{f}\gamma_\mu t^a f\right)$$

$$\mathcal{O}_{Hf} = i(H^\dagger t^a)_i(\bar{f}t^a)_j\gamma^\mu D_\mu (H^i f^j)$$

SUSY embedding defines the EFT basis where the mixing of operators is the most minimal

From less to more "diagonal" basis at the one-loop:

Hawigara's basis ➠ SILH basis ➠ Warsaw's basis ➠ "Susy" basis

K.Hagiwara, S.Ishihara, R.Szalapski, D.Zeppenfeld 92

G.Giudice, C.Grojean, A.Pomarol, R.Rattazzi 07

B.Grzadkowski, M.Iskrzynski, M.Misiak, J.Rosiek 10

Best basis for the QCD Chiral lagrangian

Ordinary basis:

$$\mathcal{L}_\chi = \frac{f^2}{4}\langle D^\mu U D_\mu U\rangle + \cdots$$
$$- \; iL_9 \, \langle F_R^{\mu\nu} D_\mu U D_\nu U^\dagger + F_L^{\mu\nu} D_\mu U^\dagger D_\nu U\rangle \; + \; L_{10} \, \langle U^\dagger F_R^{\mu\nu} U F_{L\mu\nu}\rangle$$

Better basis:

"JJ" operator: $\langle (U^\dagger \overleftrightarrow{D}_\nu U) D_\mu F_L^{\mu\nu} + (U \overleftrightarrow{D}_\nu U^\dagger) D_\mu F_R^{\mu\nu}\rangle$

"loop" operator: $\langle U^\dagger F_R^{\mu\nu} U F_{L\mu\nu}\rangle$

$\hookrightarrow$ embedded in $\langle \mathcal{U}^\dagger \mathcal{W}_R^\alpha \mathcal{U} \mathcal{W}_{\alpha L}\rangle$ $\quad \mathcal{U} \equiv e^{i\Phi}$

Φ being a chiral superfield

<u>Not renormalized by loop of pions:</u>

$$\gamma_{\rm loop} \propto \gamma_9 + \gamma_{10} = \frac{1}{64\pi^2} - \frac{1}{64\pi^2} = 0$$

Conclusions

- Dim-6 operator mixing is crucial to understand the impact of BSM on the SM
- Supersymmetry helps to group the operators that mainly mix among themselves
- **Exercise:** From the measurement **$B \to \mu\mu$, $B \to X\gamma$,** which deviations on **TGC** constrains each experiment? Can **top** anomalous-couplings affect **S**?
- Open questions: Beyond one-loop, relation with Spinor Helicity formalism (Cheung-Shen 15), …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	Operators	SSB spurion	Super-operators
JJ-operators	$\mathcal{O}_+ = D_\mu(H_i^\dagger H_j^\dagger)D^\mu(H^i H^j)$	η^0	$(H^\dagger e^{V_H} H)^2$
	$\mathcal{O}_{4f} = \left(\bar{f}\gamma^\mu t^a f\right)\left(\bar{f}\gamma_\mu t^a f\right)$		$(F^\dagger t^a e^{V_F} F)(F^\dagger t^a e^{V_F} F)$
	$\mathcal{O}_{Hf} = i(H^\dagger t^a)_i(\bar{f}t^a)_j\gamma^\mu D_\mu\,(H^i f^j)$		$(H^\dagger t^a e^{V_H} H)(F^\dagger t^a e^{V_F} F)$
	$\mathcal{O}_R^{ud} = (iH^\dagger \overleftrightarrow{D}_\mu \tilde{H})(\bar{d}_R\gamma^\mu u_R)$	$\bar{\mathcal{D}}_{\dot\alpha}\eta^\dagger$	$H^\dagger\bar{\mathcal{D}}^{\dot\alpha}\tilde{H}U^\dagger e^{V_D} D$
	$\mathcal{O}_- = \lvert H^\dagger D_\mu H\rvert^2$	$\lvert\bar{\mathcal{D}}_{\dot\alpha}\eta^\dagger\rvert^2$	$\lvert H^\dagger e^{V_H}\mathcal{D}_\alpha H\rvert^2$
	$\mathcal{O}_6 = \lvert H\rvert^6$	$\lvert\eta\rvert^2$	$(H^\dagger e^{V_H} H)^3$
	$\mathcal{O}_y = \lvert H\rvert^2 H\bar{f}_R f_L$	$\eta^\dagger$	$(H^\dagger e^{V_H} H)HFF$
	$\mathcal{O}_{yy} = \left(\bar{f}_R t^a f_L\right)\left(\bar{f}_R t^a f_L\right)$		$(Ft^a F)\mathcal{D}^2(Ft^a F)$
Loop-operators	$\mathcal{O}_D = H^\dagger\bar{f}_R\sigma^{\mu\nu}t^a f_L\,F^a_{\mu\nu}$		$H(Ft^a\overleftrightarrow{\mathcal{D}}_\alpha F)\,\mathcal{W}^{a\,\alpha}$
	$\mathcal{O}_{FF_+} = H^\dagger t^a t^b H F^a_{\mu\nu}(F^{b\,\mu\nu} - i\tilde{F}^{b\,\mu\nu})$		$(H^\dagger t^a t^b e^{V_H} H)\mathcal{W}^{a\,\alpha}\mathcal{W}^b_\alpha$
	$\mathcal{O}_{3F_+} = f^{abc}F_\mu^{a\,\nu}F_\nu^{b\,\rho}(F_\rho^{c\,\mu} - i\tilde{F}_\rho^{c\,\mu})$		$f^{abc}\mathcal{D}^\beta\mathcal{W}^{a\,\alpha}\mathcal{W}^b_\beta\mathcal{W}^c_\alpha$

Table 1: *Left: Basis of dimension-six SM operators classified as JJ-operators and loop-operators. We also distinguish those that can arise from a supersymmetric D-term (η^0) from those that break supersymmetry either by an spurion $\bar{\mathcal{D}}_{\dot\alpha}\eta^\dagger$, $\eta^\dagger$, $|\bar{\mathcal{D}}_{\dot\alpha}\eta^\dagger|^2$ or $|\eta|^2$. We denote by $F^a_{\mu\nu}$ ($\tilde{F}^a_{\mu\nu}$) any SM gauge (dual) field-strength. The t^a matrices include the $U(1)_Y$, $SU(2)_L$ and $SU(3)_c$ generators, depending on the quantum numbers of the fields involved. Fermion operators are written schematically with $f = \{Q_L, u_R, d_R, L_L, e_R\}$. Right: For each operator in the left column, we provide the super-operator at which it is embedded.*

Different Basis

From SILH by using:

$$\mathcal{O}_B = \mathcal{O}_{HB} + \frac{1}{4}\mathcal{O}_{WB} + \frac{1}{4}\mathcal{O}_{BB} \ ,$$
$$\mathcal{O}_W = \mathcal{O}_{HW} + \frac{1}{4}\mathcal{O}_{WW} + \frac{1}{4}\mathcal{O}_{WB}$$

Hawigara etal. basis: $\mathcal{O}_W,\ \mathcal{O}_B \ \rightarrow \mathcal{O}_{WW},\ \mathcal{O}_{WB}$

Grzadkowski etal. basis: $\mathcal{O}_W,\ \mathcal{O}_B,\ \mathcal{O}_{HW},\ \mathcal{O}_{HB} \ \rightarrow \mathcal{O}_{WW},\ \mathcal{O}_{WB},\ \mathcal{O}_L^{(3)},\ \mathcal{O}_L$

Using also EoM:

$$c_W \mathcal{O}_W \ \leftrightarrow \ c_W \frac{g^2}{g_*^2}\left[-\frac{3}{2}\mathcal{O}_H + 2\mathcal{O}_6 + \frac{1}{2}\mathcal{O}_y + \frac{1}{4}\sum_f \mathcal{O}_L^{(3)\,f}\right] \ ,$$
$$c_B \mathcal{O}_B \ \leftrightarrow \ c_B \frac{g'^2}{g_*^2}\left[-\frac{1}{2}\mathcal{O}_T + \frac{1}{2}\sum_f \left(Y_L^f \mathcal{O}_L^f + Y_R^f \mathcal{O}_R^f\right)\right] \ ,$$

Affecting well-measured quantities by operator mixing under the RG flow:

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$$16\pi^2\gamma_{c_T} = (4N_c y_t^2 - 9g^2 - 3g'^2)c_T + \frac{3}{2}g'^2 c_H + 4N_c y_t^2(c_R - c_L)\ , \quad (65)$$

$$\begin{aligned} 16\pi^2\gamma_{c_R} &= \left[2(4+N_c)y_t^2 - 9g^2 - \frac{8}{3}g'^2\right]c_R + \frac{8}{9}g'^2\left[(N_c+1)c_{RR} + N_c c_{LR}\right] \\ &\quad + 2y_t^2\left[\frac{1}{4}c_H - c_L + N_c c_{LR} - 2(N_c+1)c_{RR}\right]\ , \quad (66) \end{aligned}$$

$$\begin{aligned} 16\pi^2\gamma_{c_L} &= \left[2(2+N_c)y_t^2 - 9g^2 - \frac{8}{3}g'^2\right]c_L + \frac{2}{9}g'^2\left[(2N_c+1)c_{LL} + C_F c_{LL}^{(8)} + \frac{N_c}{2}c_{LR}\right] \\ &\quad + y_t^2\left\{-\frac{1}{4}c_H - c_R - 9c_L^{(3)} - 2N_c c_{LR} + 4N_c c_{LL} + 2\left[c_{LL} + C_F\, c_{LL}^{(8)}\right]\right\}\ , \quad (67) \end{aligned}$$

$$\begin{aligned} 16\pi^2\gamma_{c_L^{(3)}} &= \left[2(1+N_c)y_t^2 - \frac{17}{3}g^2 - 3g'^2\right]c_L^{(3)} + \frac{2}{3}g^2\left[c_{LL} + C_F\, c_{LL}^{(8)}\right] \\ &\quad + y_t^2\left\{\frac{1}{4}c_H - 3c_L - 2\left[c_{LL} + C_F\, c_{LL}^{(8)}\right]\right\}, \quad (68) \end{aligned}$$

$$16\pi^2\gamma_{c_W} = \frac{1}{3}g_H^2\left[-(c_H + c_T) + 16N_c c_L^{(3)}\right], \quad (69)$$

$$16\pi^2\gamma_{c_B} = \frac{1}{3}g_H^2\left[-(c_H + 5c_T) + \frac{8}{3}N_c\,(2c_R + c_L)\right]\ . \quad (70)$$

T: $$\Delta c_T = -0.0030\, c_H + 0.16\,(c_L - c_R) \lesssim 0.002/\xi\ ,$$

S: $$\Delta(c_B + c_W) = 0.010\, c_H - 0.083\, c_R - 0.041\, c_L - 0.25\, c_L^{(3)} \lesssim 0.003\Lambda^2/M_w^2\ ,$$

Zbb: $$\Delta[c_L + c_L^{(3)}] = 0.014\, c_R - 0.031\, c_L + 0.057\, c_L^{(3)} - 0.17\, c_{LL} - 0.0064\, c_{LL}^{(8)} + 0.081\, c_{LR} \lesssim 0.002/\xi\ .$$

operators highly constrained

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hγγ: $$\kappa_{\gamma\gamma}(m_h) = \kappa_{\gamma\gamma}(\Lambda) - \gamma_{\gamma\gamma} \log \frac{\Lambda}{m_h}$$

$$16\pi^2 \gamma_{\gamma\gamma} = \left[6y_t^2 - \frac{3}{2}(3g^2 + g'^2) + 12\lambda\right] \kappa_{BB} + \left[\frac{3}{2}g^2 - 2\lambda\right] (\kappa_{HW} + \kappa_{HB}) \ .$$

hγZ:

$$16\pi^2 \gamma_{\gamma Z} = \kappa_{\gamma Z} \left[6y_t^2 + 12\lambda - \frac{7}{2}g^2 - \frac{1}{2}g'^2\right] + (\kappa_{HW} + \kappa_{HB}) \left[2g^2 - 3e^2 - 2\lambda \cos(2\theta_w)\right]$$

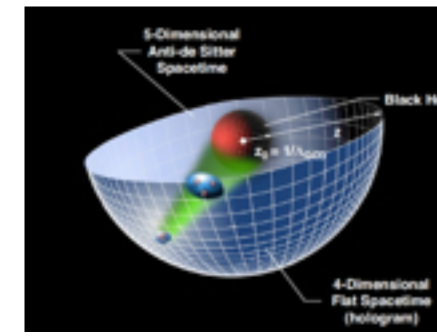
dominant in certain scenarios $\kappa_{BB} \approx 0$ & $\kappa_{HW} - \kappa_{HB} \approx 0$ at Λ

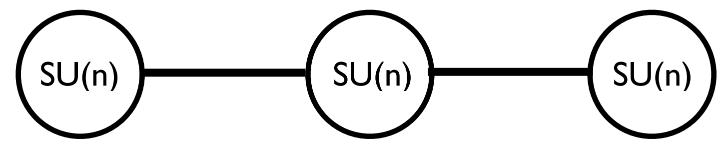
e.g. **H as PGB:**
- H→H+c implies $\kappa_{BB} = 0$
- Left-right symmetry implies $\kappa_{HW} = \kappa_{HB}$

Prediction: $$\frac{\delta\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)} \simeq 1.5 \frac{\delta\Gamma(h \to \gamma Z)}{\Gamma(h \to \gamma Z)}$$

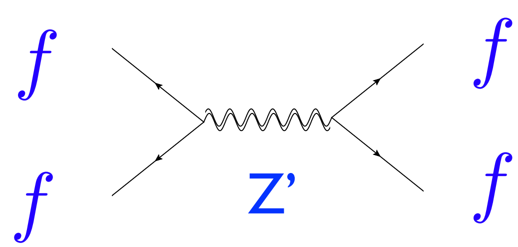
- Separation of operators depending on *Tree-level* vs *Loop* origin

in {
- Renormalizable (weakly-coupled) theories = SUSY, ...
- Holographic models = Strongly-coupled in the large N, large g^2N limit

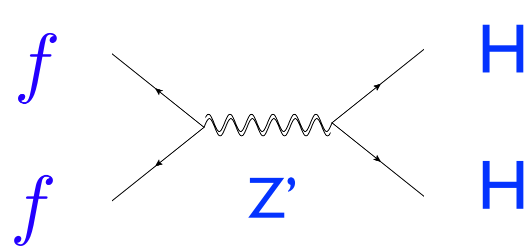


- Little Higgs = 

"tree-level" operators (or "current-current"):



$$\frac{1}{\Lambda^2} J^\mu_f J_{f\,\mu}$$



$$\frac{1}{\Lambda^2} J^\mu_f J_{H\,\mu}$$

can arise from integrating out massive states spin=0,1/2,1

Other interesting one-loop effects:

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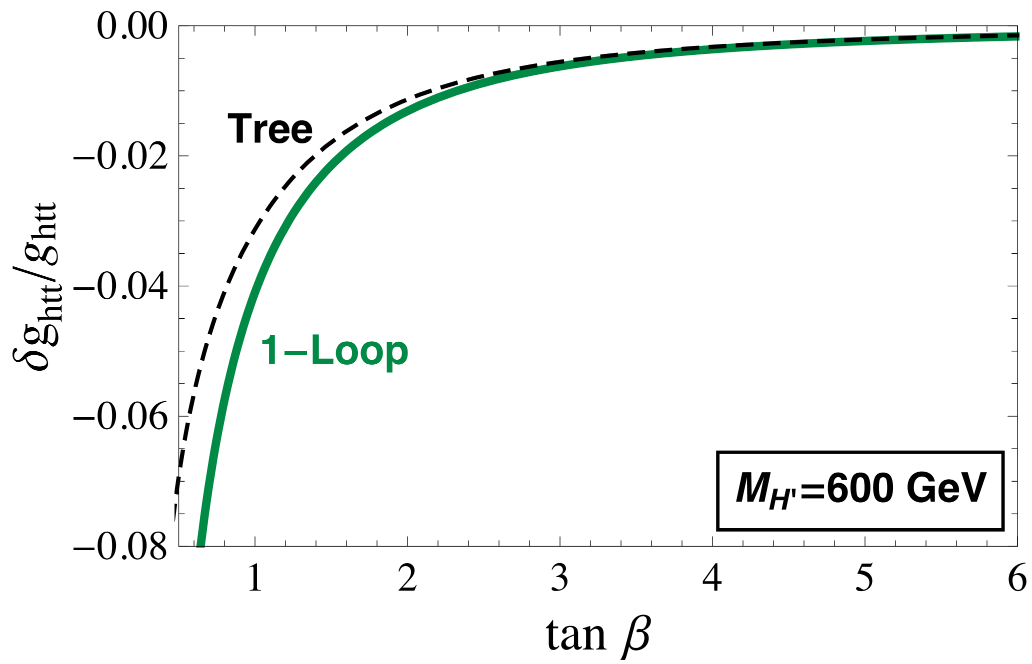
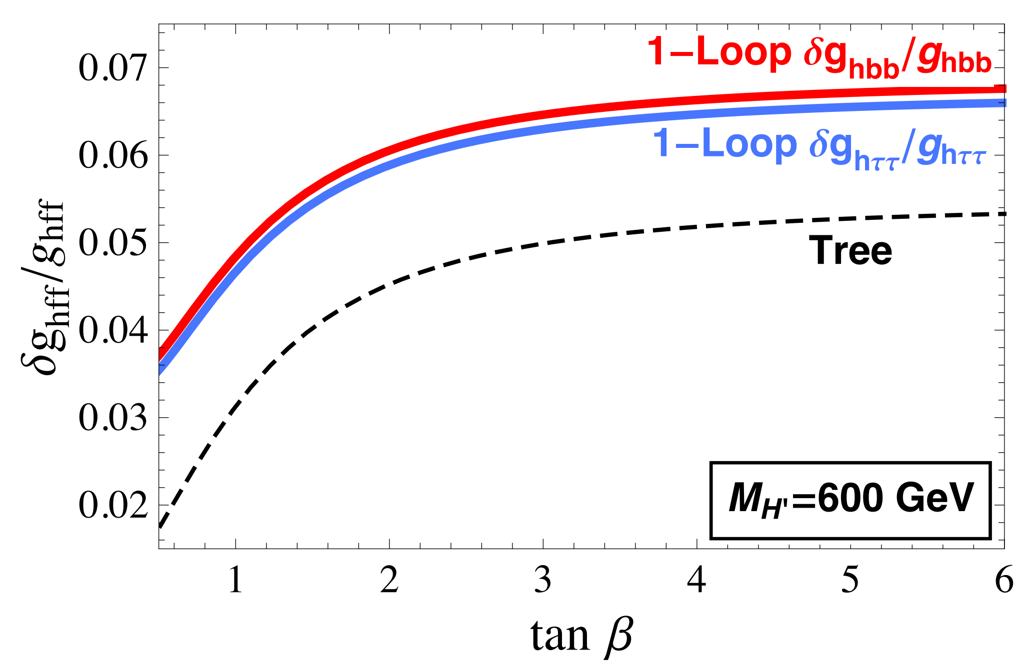
Breaking of universality:

$$c_{y_t}(m_h) = c_{y_b}(m_h)\left(1 - \frac{8y_t^2}{16\pi^2}\log\frac{\Lambda}{m_h}\right) - \frac{3y_t^2 c_H}{16\pi^2}\log\frac{\Lambda}{m_h} \simeq 0.88 c_{y_b}(m_h) - 0.05 c_H\ ,$$

$$c_{y_b}(m_h) = c_{y_\tau}(m_h)\left(1 - \frac{y_t^2}{16\pi^2}\log\frac{\Lambda}{m_h}\right) \simeq 0.98 c_{y_\tau}(m_h)\ , \qquad \Lambda = 2\ \text{TeV},$$

MSSM:





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