Window on new physics via the scaling of SM effective operators

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J.Elias-Mirò, S. Gupta, C. Grojean, D.M.
Scaling and tuning of EW and Higgs observables
JHEP 1405 (2014) 019 *arXiv: 1312.2928*
(also arXiv: 1405.3841)

Higgs Hunting 2014

Orsay,
21/07/2014

SM effective theory

We assume $\Lambda_{NP} \gg m_h$

In this case it is possible to describe experiments at the electroweak scale using an effective field theory framework:

We assume L and B conservation

$$\mathcal{L} = \mathcal{L}^{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{d=6} + (\text{dim} \;\; > 6)$$

Leading deformations of the SM

59 independent dim-6 operators for 1 family of fermions.

Grzadkowski et al. 1008.4884

SM effective theory

EFT framework →

- (fairly) model-independent
- link EW observables (oblique param, TGC) and Higgs observables

SM effective theory

EFT framework →

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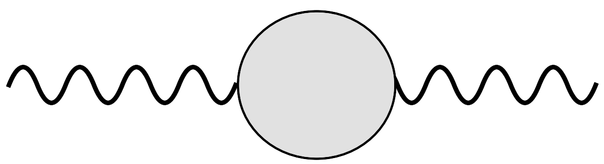
We fix a particular set of observables we are interested in, and then study only the operators which give the most relevant contribution to these observables

Technical detail 1:

In order to have a consistent computation it is however important to specify a complete basis and carefully treat the redundant operators (e.g. those generated at one-loop need to be redefined back into the basis).

EW and Higgs observables

We focus on the following 10 (pseudo-)observables*:*

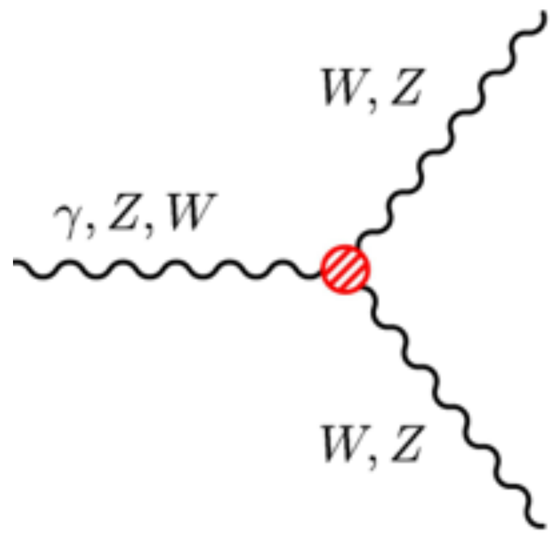


$\hat{S},\ \hat{T},\ W,\ Y$

$\lesssim 10^{-3}$

Barbieri, Pomarol, Rattazzi, Strumia
hep-ph/0405040

Gfitter 1209.2716



$g_1^Z\,,\ k_\gamma\,,\ \lambda_\gamma$

$\lesssim 10^{-2}$

LEP EW Working Group
1302.3415

$$\hat{c}_i \sim \frac{m_W^2}{\Lambda^2} c_i$$

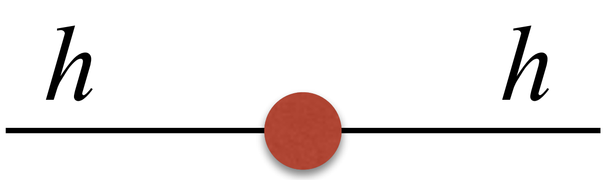
$BR(h \to \gamma\gamma\ /\ \gamma Z)$

$\hat{c}_{\gamma\gamma}$ $\quad$ $\hat{c}_{\gamma Z}$

$\lesssim 10^{-3}$ $\quad$ $\lesssim 10^{-2}$

Pomarol, Riva 1308.2803

(bounds so strong because these are loop-generated in the SM)



$\hat{c}_H$

$\lesssim 0.5$

EW and Higgs observables

After constructing a complete basis, the relevant 10 operators contributing to those observables are:

current-current (CC) operators
(tree-level in renormalizable, minimally-coupled theories)

$$
\begin{aligned}
\mathcal{O}_H &= \frac{1}{2}(\partial^\mu |H|^2)^2 \\
\mathcal{O}_T &= \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2 \\
\mathcal{O}_W &= ig\left(H^\dagger \tau^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu} \\
\mathcal{O}_B &= ig' Y_H \left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu} \\
\mathcal{O}_{2W} &= -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2 \\
\mathcal{O}_{2B} &= -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2
\end{aligned}
$$

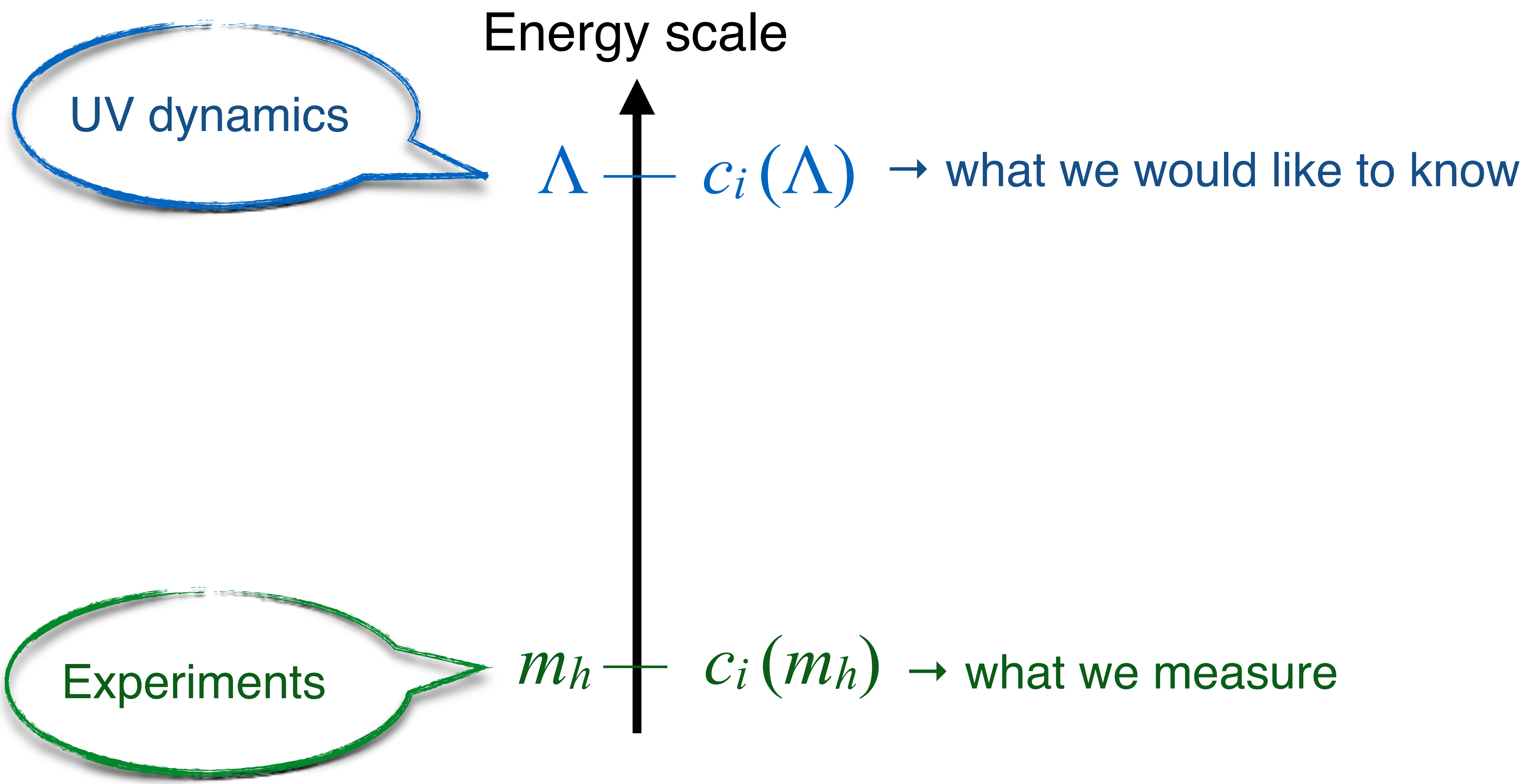
Non-CC operators
(usually generated at loop level)

$$
\begin{aligned}
\mathcal{O}_{BB} &= g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu} \\
\mathcal{O}_{WB} &= g g' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu} \\
\mathcal{O}_{WW} &= g^2 |H|^2 W^a_{\mu\nu} W^{a\mu\nu} \\
\mathcal{O}_{3W} &= \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}
\end{aligned}
$$

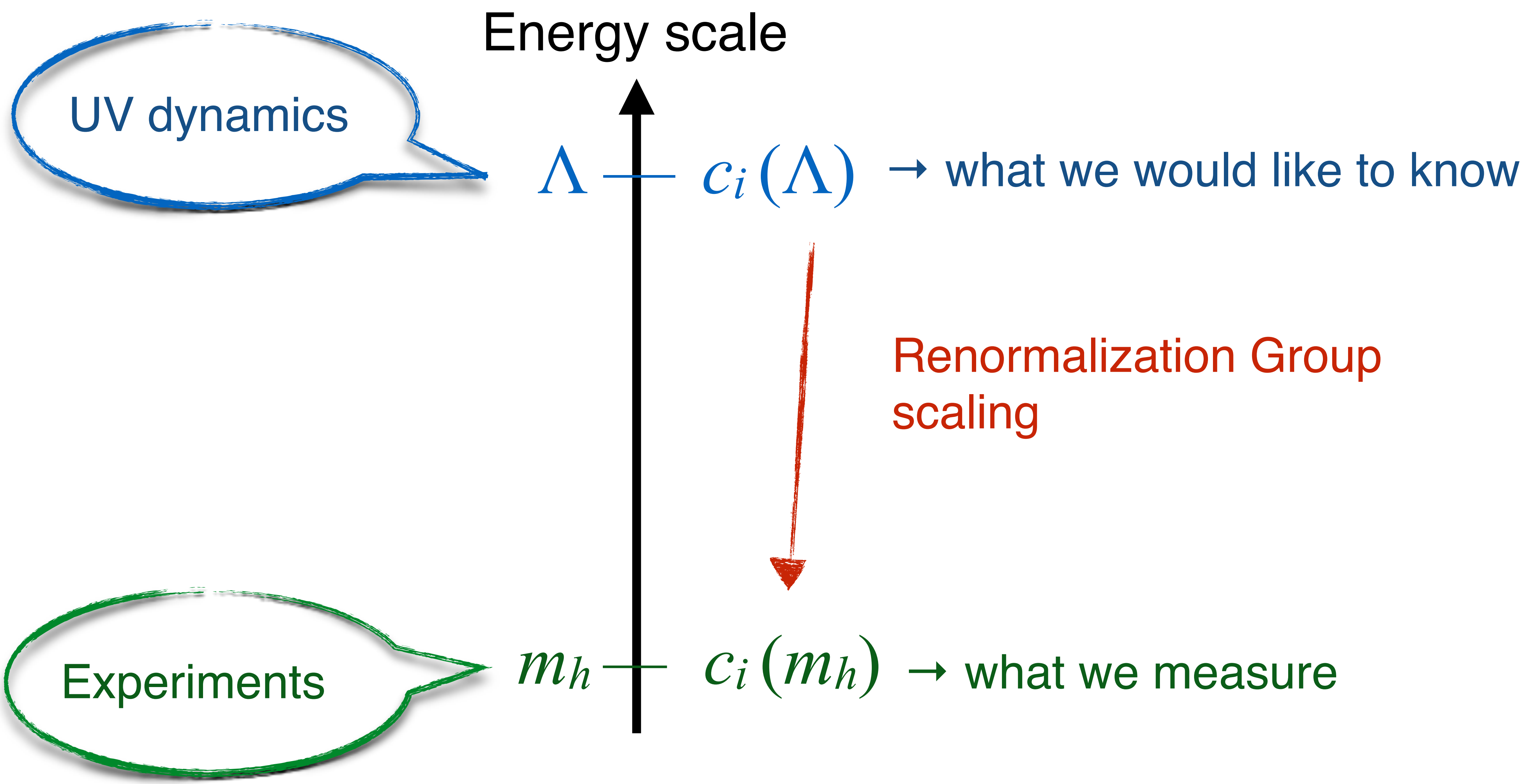
We “rotate" the coefficients to the *"observable basis"* in which

1 coefficient ⟷ 1 observable

RG scaling of the coefficients

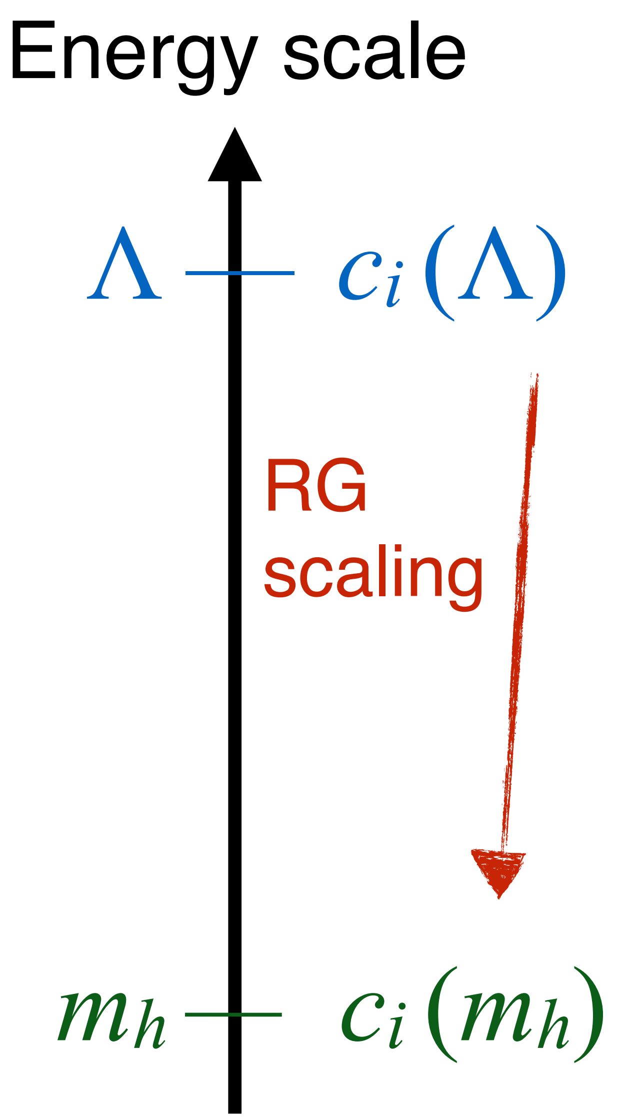


RG scaling of the coefficients



The coefficients mix among themselves along this RG flow.

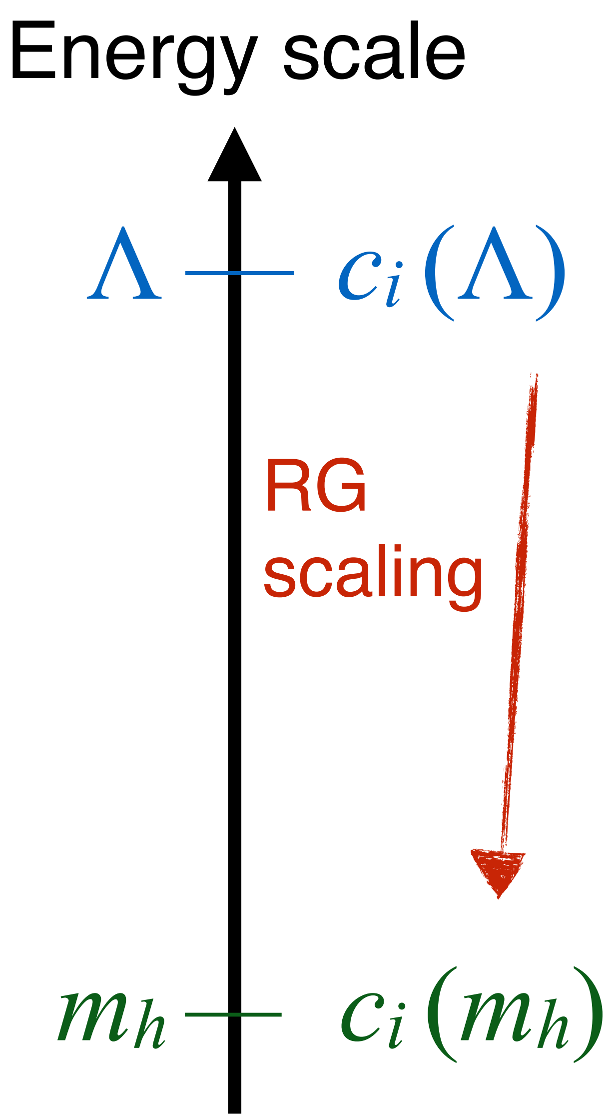
RG scaling of the coefficients



$$\delta(\mathrm{obs})_i|_{m_h} = \hat{c}_i(m_h) = \hat{c}_i(\Lambda) - \frac{1}{16\pi^2}\hat{\gamma}_{ij}\hat{c}_j(\Lambda)\log\left(\frac{\Lambda}{m_h}\right)$$

We computed the relevant anomalous dimension matrix

RG scaling of the coefficients



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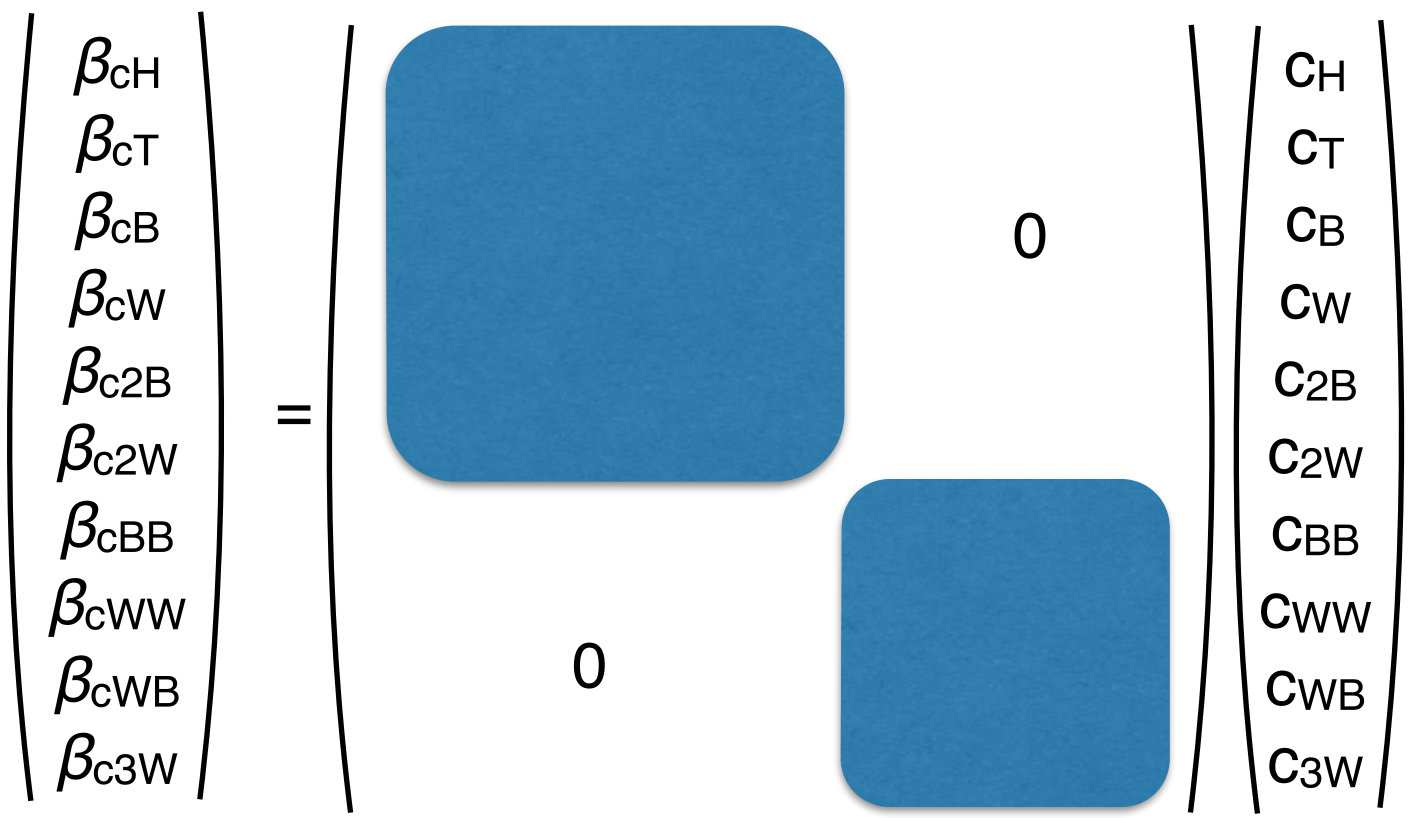
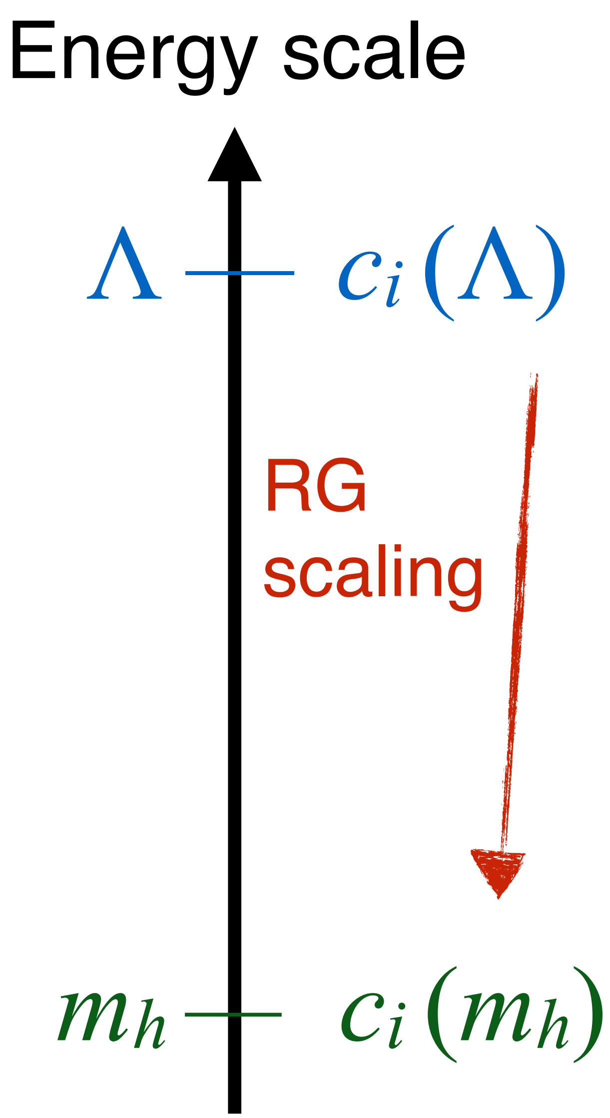
Technical detail 2:

Our basis is well-suited for this purpose because the relevant anomalous dimension matrix is block-diagonal:



RG scaling of the coefficients



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We computed the relevant anomalous dimension matrix

A well known example:

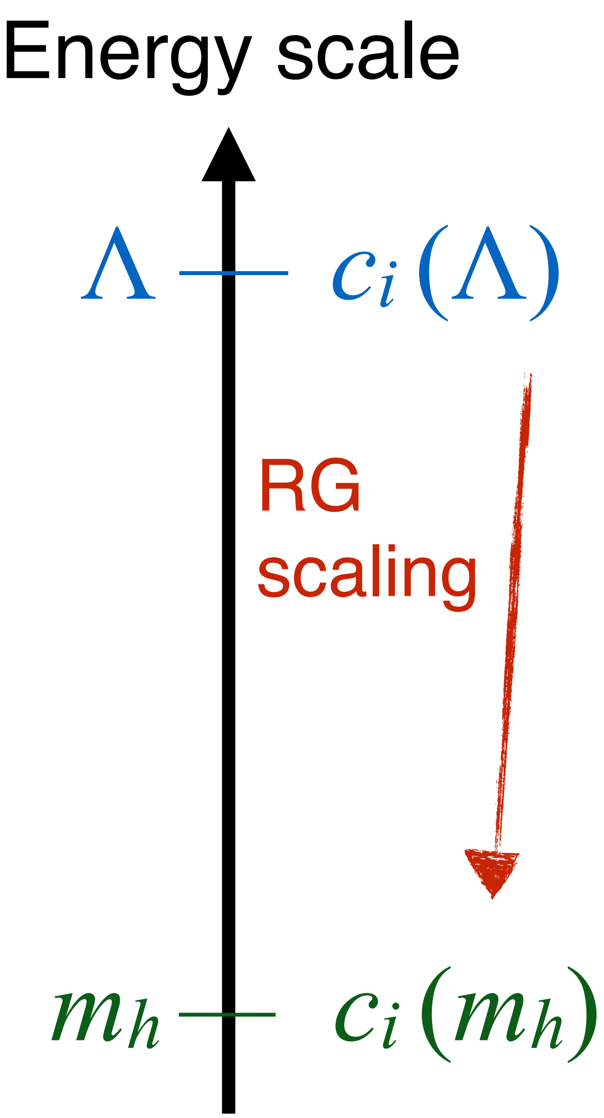
Barbieri et al. 0706.0432

$$\hat{S} = \hat{c}_S(m_Z) = \hat{c}_S(\Lambda) + \frac{g^2}{16\pi^2}\frac{1}{6}\hat{c}_H \log\frac{\Lambda}{m_Z} + \ldots$$

$$\hat{T} = \hat{c}_T(m_Z) = \hat{c}_T(\Lambda) - \frac{g'^2}{16\pi^2}\frac{3}{2}\hat{c}_H \log\frac{\Lambda}{m_Z} + \ldots$$

Direct bound
(from experiment)

RG scaling of the coefficients



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$$\hat{T} = \hat{c}_T(m_Z) = \hat{c}_T(\Lambda) - \frac{g'^2}{16\pi^2}\frac{3}{2}\hat{c}_H \log\frac{\Lambda}{m_Z} + \ldots$$

Direct bound
(from experiment)

In **absence of tuning or correlations** each term should be bounded approximately by the same value.

RG-induced bounds

If a weakly constrained coefficient contributes to the RG of a strongly constrained one, we can put an RG-induced bound on it by assuming absence of tuning/correlations.

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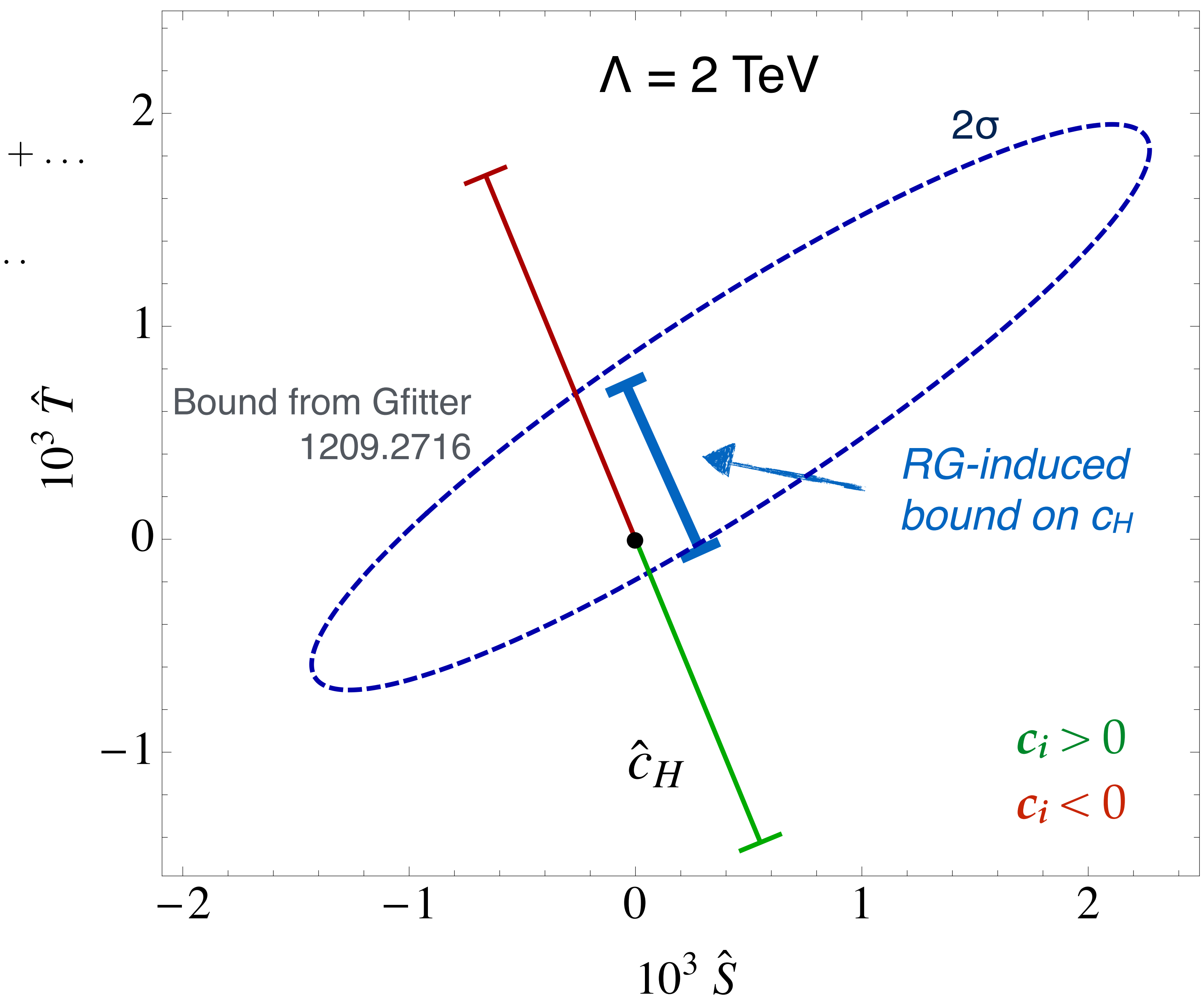
The length of the lines corresponds to the present 2σ direct bound:

$$\hat{c}_H(m_h) \in [-0.6, 0.5]$$

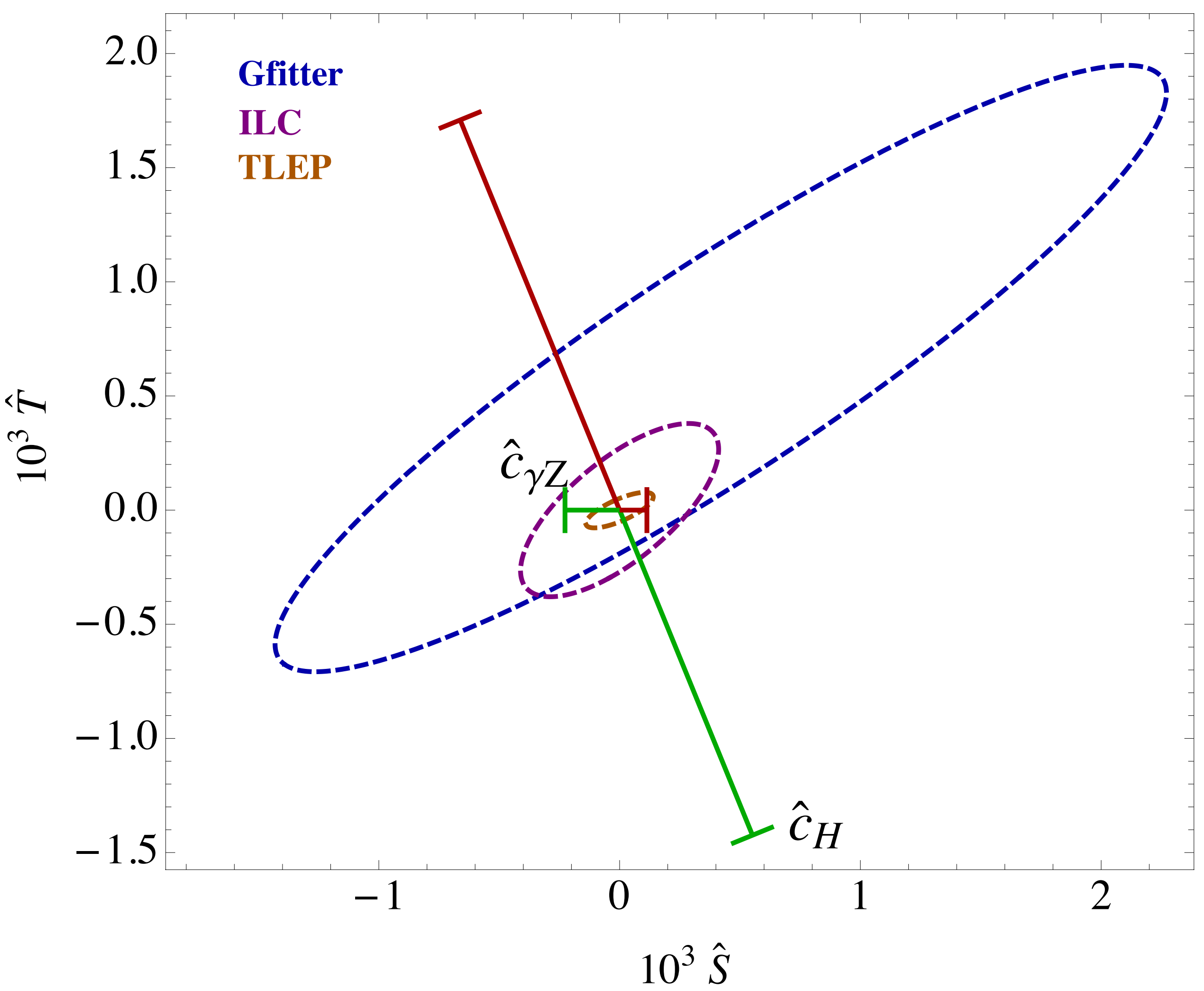
RG-induced bound:

$$\hat{c}_H(m_h) \in [-0.2, 0.05]$$

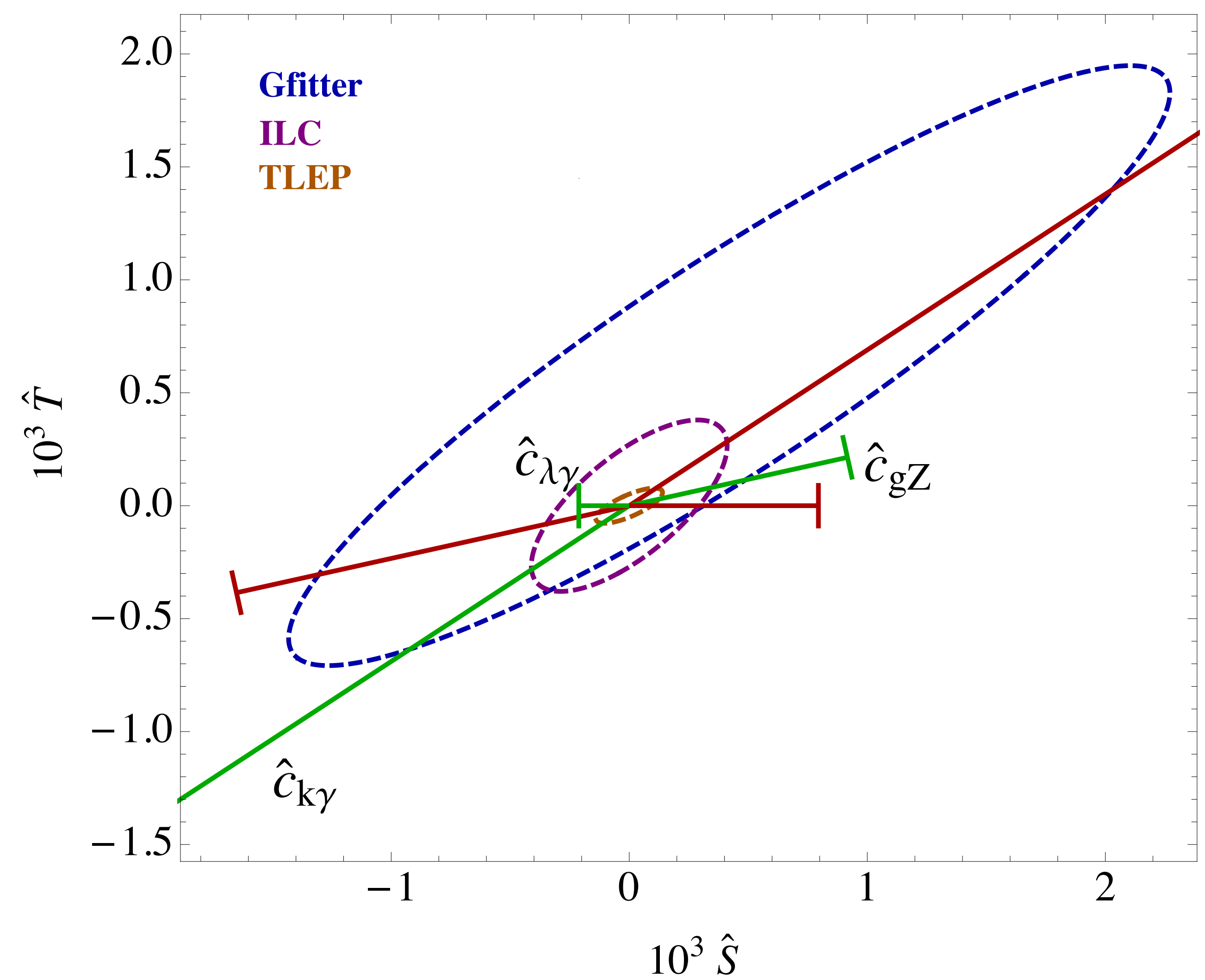


RG-induced bounds

Higgs



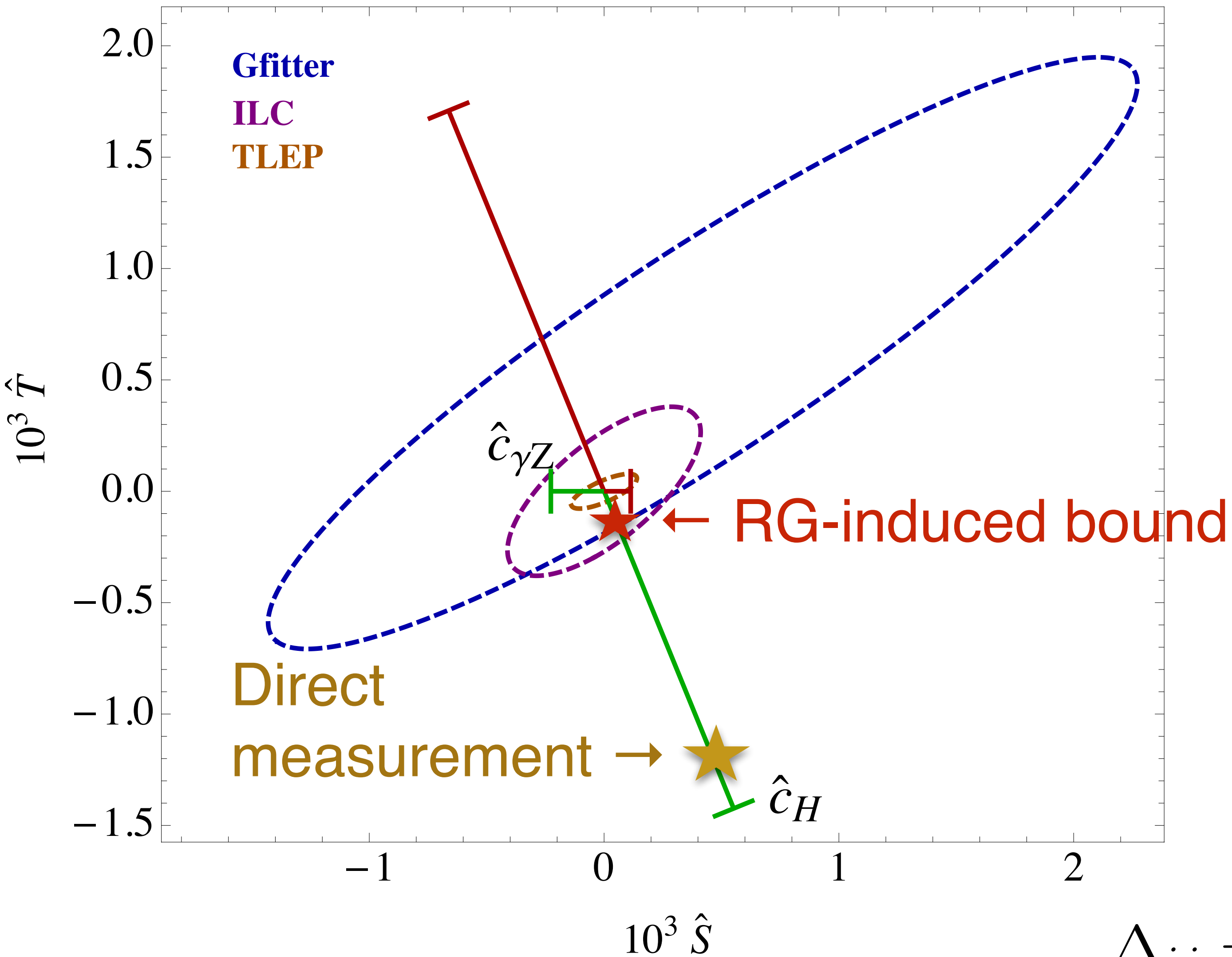
TGC



From the h→γγ constraint:

$$\hat{c}_{\kappa\gamma} \in [-0.2, 0.3]\ ,$$
$$\hat{c}_{\lambda\gamma} \in [-0.05, 0.10]$$

Another window on NP



Say LHC will measure a deviation in the Higgs couplings near the present bound

★ $$|\hat{c}_H| > \epsilon_H^{low} > 0\ ,$$

but no deviation in S and T is observed:

$$\epsilon_H^{low} > \epsilon_{H,(S,T)}^{RG}$$

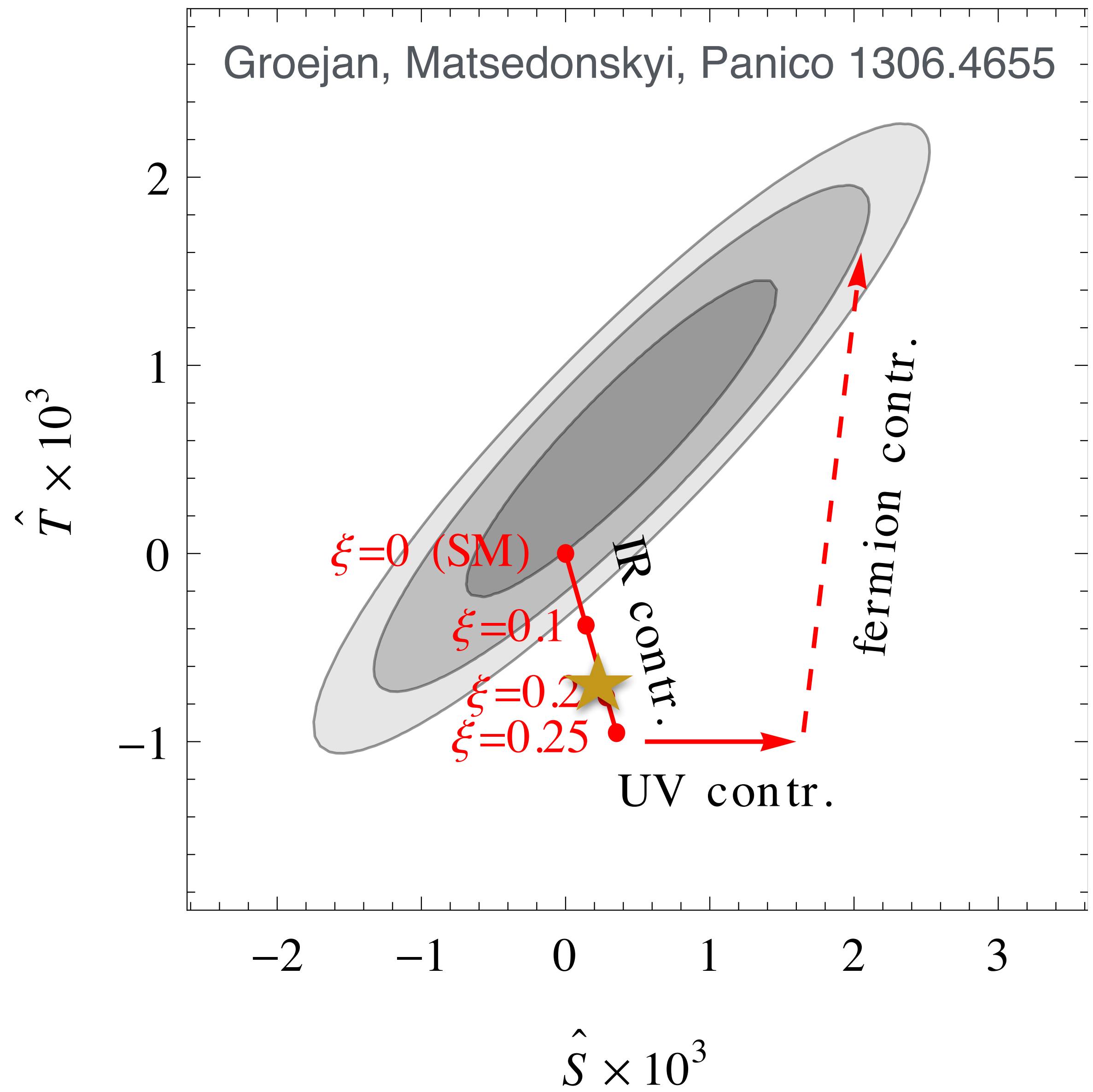
Some amount of tuning in the RG equation is needed:

$$\Delta_{ij} = \left| \frac{\partial \log \delta(\mathrm{obs})_j|_{m_h}}{\partial \log \hat{c}_i(\Lambda)} \right| \qquad \Delta_{ij} > \epsilon_j^{low} / \epsilon_{ji}^{RG}$$

The necessity for such tunings (or correlations) could provide us useful information on the structure of the UV dynamics

Another window on NP

For example, in Composite Higgs Models



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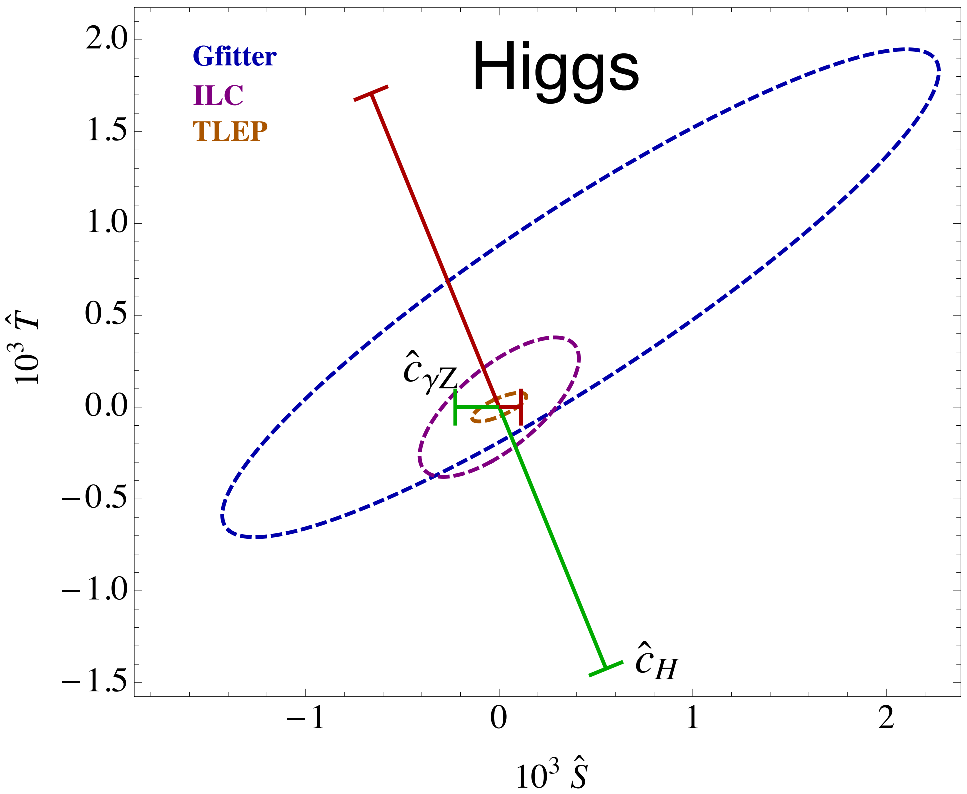
Future Prospects

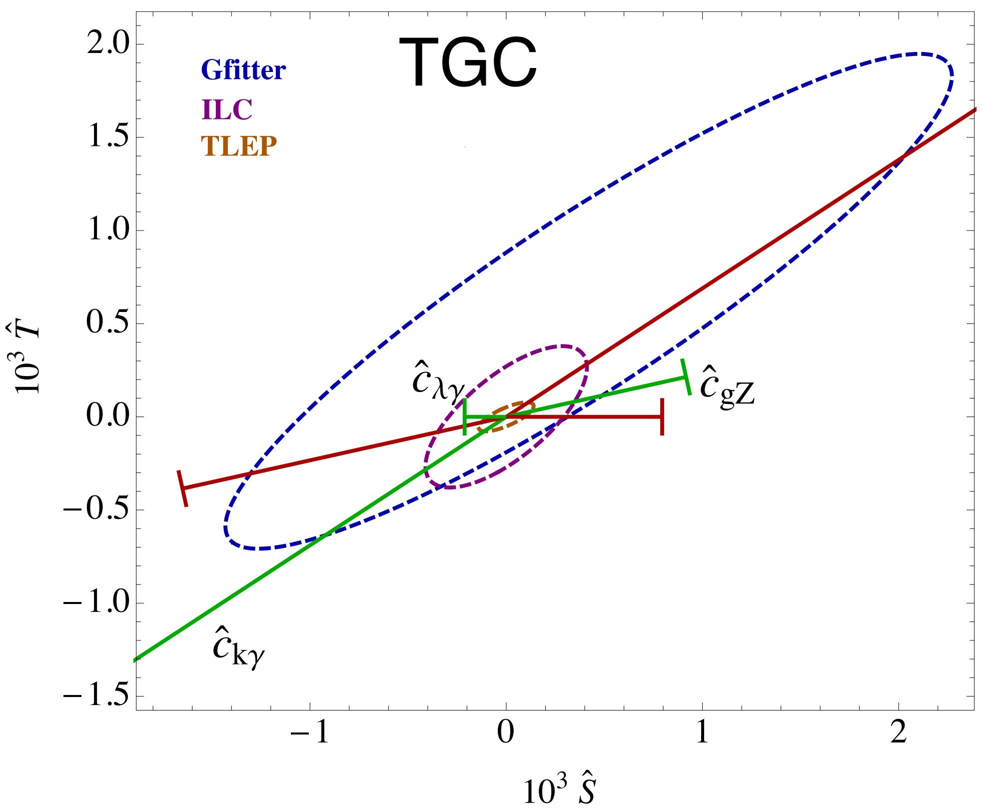
D.M. 1405.3841



Direct bounds, now and future prospects:

Obs.	Now	LHC (300 fb^{-1})	HL-LHC (3 ab^{-1})	ILC	TLEP
$\hat{c}_S$	$[-1,2]\times10^{-3}$ [6]	–	–	1.4×10^{-4} [12]	5×10^{-5} [13]
$\hat{c}_T$	$[-1,2]\times10^{-3}$ [6]	–	–	1.6×10^{-4} [12]	3.1×10^{-5} [13]
$\hat{c}_{gZ}$	$[-4,2]\times10^{-2}$ [7]	3×10^{-3} [9]	2×10^{-3} [9]	1.8×10^{-4} [10]	n.a.
$\hat{c}_{k\gamma}$	$[-10,7]\times10^{-2}$ [7]	3×10^{-2} [9]	1×10^{-2} [9]	1.9×10^{-4} [10]	n.a.
$\hat{c}_{\lambda\gamma}$	$[-6,2]\times10^{-2}$ [7]	9×10^{-4} [9]	4×10^{-4} [9]	2.6×10^{-4} [10]	n.a.
$\hat{c}_{\gamma\gamma}$	$[-1,2]\times10^{-3}$ [8]	1×10^{-4} [14]	4×10^{-5} [14]	7.6×10^{-5} [14]	2.9×10^{-5} [14,11]
$\hat{c}_{\gamma Z}$	$[-6,10]\times10^{-3}$ [8]	9×10^{-4} [14]	2×10^{-4} [14]	n.a.	n.a.
$\hat{c}_H$	$[-6,5]\times10^{-1}$ [8]	1×10^{-1} [14]	5×10^{-2} [14]	5×10^{-2} [14]	1×10^{-2} [14,11]

[6] Gfitter 1209.2716
[7] LEP EW w.g. 1302.3415
[8] Pomarol, Riva 1308.2803
[9] F. Gianotti et. al. hep-ph/0204087
[10] ILC 1306.6352
[11] TLEP 1308.6176
[12] Baak et al. 1310.6708
[13] S. Mishima “talk at 6th TLEP Workshop” 2013
[14] S. Dawson et al. 1310.8361



RG-induced bounds, now and future prospects:

mix. to $(\hat{S},\hat{T})$	Now	ILC	TLEP
$\hat{c}_{\gamma Z}$	$[-2,6]\times10^{-2}$	2×10^{-2}	5×10^{-3}
$\hat{c}_H$	$[-2,0.5]\times10^{-1}$	7×10^{-2}	2×10^{-2}
$\hat{c}_{gZ}$	$[-3,1]\times10^{-2}$	8×10^{-3}	3×10^{-3}
$\hat{c}_{k\gamma}$	$[-5,2]\times10^{-2}$	9×10^{-3}	3×10^{-3}
$\hat{c}_{\lambda\gamma}$	$[-2,8]\times10^{-2}$	2×10^{-2}	7×10^{-3}

mix. to $\hat{c}_{\gamma\gamma}$	Now	LHC	HL-LHC	ILC	TLEP
$\hat{c}_{k\gamma}$	$[-0.2,0.3]$	2×10^{-2}	7×10^{-3}	1×10^{-2}	5×10^{-3}
$\hat{c}_{\lambda\gamma}$	$[-0.05,0.10]$	5×10^{-3}	2×10^{-3}	4×10^{-3}	1×10^{-3}

Summary

- Assuming that the scale of new physics $\Lambda \gg v$, we study the SM effective theory
- We focus on a set of 10 EW and Higgs observables and the most relevant operators and compute the relevant anomalous dimension matrix.
- We construct an "observable" basis, and express the RG equations in this basis.

- Assuming absence of tuning and/or correlations in the RG equations, we obtain RG-induced bounds for weakly constrained coefficients which mix to strongly constrained coefficients.
- These RG-induced bounds are already stronger or at the same order as the direct ones.
- Once a deviation from the SM is observed, a violation of the RG-induced bounds could offer a new window on the UV dynamics.

Thank you!

Scaling and tuning of EW and Higgs observables

1312.2928

J.Elias-Mirò, S. Gupta, C. Grojean, D. M.

1405.3841

Backup

“Observable” coefficients

$$\hat{c}_i \sim \frac{m_W^2}{\Lambda^2} c_i$$

EW oblique parameters:

$$\hat{T} = \hat{c}_T(m_W) = \frac{v^2}{\Lambda^2} c_T(m_W) \ , \quad \hat{S} = \hat{c}_S(m_W) = \frac{m_W^2}{\Lambda^2} \left[c_W(m_W) + c_B(m_W) + 4 c_{WB}(m_W) \right]$$

$$Y = \hat{c}_Y(m_W) = \frac{m_W^2}{\Lambda^2} c_{2B}(m_W) \ , \qquad W = \hat{c}_W(m_W) = \frac{m_W^2}{\Lambda^2} c_{2W}(m_W)$$

Anomalous triple gauge couplings:

$$\delta g_1^Z \equiv \hat{c}_{gZ}(m_W) = -\frac{m_W^2}{\Lambda^2} \frac{1}{c_{\theta_W}^2} c_W(m_W) \ , \qquad \delta\kappa_\gamma \equiv \hat{c}_{\kappa\gamma}(m_W) = \frac{m_W^2}{\Lambda^2} 4 c_{WB}(m_W)$$

$$\lambda_Z \equiv \hat{c}_{\lambda\gamma}(m_W) = -\frac{m_W^2}{\Lambda^2} c_{3W}(m_W) \ ,$$

Higgs couplings:

$$\Delta\mathcal{L}_H \supset \frac{\hat{c}_H}{2} \frac{(\partial_\mu h)^2}{2} + \frac{\hat{c}_{\gamma\gamma} e^2}{m_W^2} \frac{h^2}{2} \hat{A}_{\mu\nu} \hat{A}^{\mu\nu} + \frac{\hat{c}_{\gamma Z} \ e g}{m_W^2 c_{\theta_W}} \frac{h^2}{2} \hat{A}_{\mu\nu} \hat{Z}^{\mu\nu}$$

$$\hat{c}_H(m_h) = \frac{v^2}{\Lambda^2} c_H(m_h),$$

$$\hat{c}_{\gamma\gamma}(m_h) = \frac{m_W^2}{\Lambda^2} \left(c_{BB}(m_h) + c_{WW}(m_h) - c_{WB}(m_h) \right),$$

$$\hat{c}_{\gamma Z}(m_h) = \frac{m_W^2}{\Lambda^2} \left(2 c_{\theta_W}^2 c_{WW}(m_h) - 2 s_{\theta_W}^2 c_{BB}(m_h) - (c_{\theta_W}^2 - s_{\theta_W}^2) c_{WB}(m_h) \right)$$

Beyond S, T, W, Y

To be completely general on the possible NP scenarios in electroweak precision observables from LEP1 and LEP2, in our basis one should consider two more operators:

$$\mathcal{O}_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu L_L) \ , \quad \mathcal{O}_{LL}^{1,2} = (\bar{L^1}_L \sigma^a \gamma^\mu L_L^1)(\bar{L}_L^2 \sigma^a \gamma^\mu L_L^2)$$

The first one contributes to lepton couplings to the Z boson, the second one to the measurement of the Fermi constant.

Using observables from LEP1 (Z pole) and LEP2 it is possible to constrain the relevant 6 Wilson coefficients at the per mil level.
This would require a complete fit of LEP observables, which was beyond the purpose of our work.

The order of magnitude of our RG-induced bound will not change.

RG-induced bounds

Coupling	Direct Constraint	RG-induced Constraint
$\hat{c}_S(m_t)$	$[-1, 2] \times 10^{-3}$	-
$\hat{c}_T(m_t)$	$[-1, 2] \times 10^{-3}$	-
$\hat{c}_Y(m_t)$	$[-3, 3] \times 10^{-3}$	-
$\hat{c}_W(m_t)$	$[-2, 2] \times 10^{-3}$	-
$\hat{c}_{\gamma\gamma}(m_t)$	$[-1, 2] \times 10^{-3}$	-
$\hat{c}_{\gamma Z}(m_t)$	$[-0.6, 1] \times 10^{-2}$	$[-2, 6] \times 10^{-2}$
$\hat{c}_{\kappa\gamma}(m_t)$	$[-10, 7] \times 10^{-2}$	$[-5, 2] \times 10^{-2}$
$\hat{c}_{gZ}(m_t)$	$[-4, 2] \times 10^{-2}$	$[-3, 1] \times 10^{-2}$
$\hat{c}_{\lambda\gamma}(m_t)$	$[-6, 2] \times 10^{-2}$	$[-2, 8] \times 10^{-2}$
$\hat{c}_H(m_t)$	$[-6, 5] \times 10^{-1}$	$[-2, 0.5] \times 10^{-1}$

—> from S,T

Barbieri, Pomarol, Rattazzi, Strumia hep-ph/0405040

Gfitter 1209.2716

Pomarol, Riva 1308.2803

LEP EW Working Group 1302.3415

RG mixing

In the observable basis:

Λ = 2 TeV

$$
(\hat{c}_S, \hat{c}_T, \hat{c}_Y, \hat{c}_W, \hat{c}_{\gamma\gamma}, \hat{c}_{\gamma Z}, \hat{c}_{\kappa\gamma}, \hat{c}_{gz}, \hat{c}_{\lambda\gamma}, \hat{c}_H)^t\,(m_t) \simeq
$$

$$
\begin{pmatrix}
0.9 & 0.003 & -0.03 & -0.08 & -0.02 & -0.02 & -0.04 & 0.05 & -0.01 & 0.001 \\
0.03 & 0.8 & -0.02 & -0.009 & 0 & 0 & -0.03 & 0.01 & 0 & -0.003 \\
0.001 & 0 & 0.9 & 0 & 0 & 0 & -0.001 & 0.001 & 0 & 0 \\
0 & 0 & -0.001 & 0.8 & 0 & 0 & 0 & -0.003 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.9 & 0 & 0.006 & 0 & 0.02 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.9 & 0.007 & 0 & 0.03 & 0 \\
0 & 0 & 0 & 0 & -0.02 & -0.02 & 0.9 & 0 & -0.01 & 0 \\
0.0004 & -0.0007 & -0.0004 & 0.1 & 0 & 0 & -0.0004 & 0.9 & 0 & -0.0007 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.9 & 0 \\
-0.02 & 0.03 & 0.01 & -0.4 & 0 & 0 & 0.02 & -0.3 & 0 & 0.8
\end{pmatrix}
\begin{pmatrix}
\hat{c}_S(\Lambda) \\ \hat{c}_T(\Lambda) \\ \hat{c}_Y(\Lambda) \\ \hat{c}_W(\Lambda) \\ \hat{c}_{\gamma\gamma}(\Lambda) \\ \hat{c}_{\gamma Z}(\Lambda) \\ \hat{c}_{\kappa\gamma}(\Lambda) \\ \hat{c}_{gz}(\Lambda) \\ \hat{c}_{\lambda\gamma}(\Lambda) \\ \hat{c}_H(\Lambda)
\end{pmatrix}
$$