Higgs physics and Effective Field Theories

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Introduction

★ One of the main programs for the LHC Run 2 (and beyond) is pursuing precision measurements in Higgs and electroweak processes:

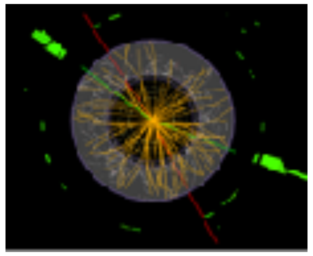
search for small deviations from the SM.

Natural theoretical interpretation:
Effective Field Theory approach

★ We do not know what New Physics will be like.

It is important to present data in the most robust and model-independent way.

From measurement to interpretation



With each step:
- more assumptions on NP
- more power to combine different datasets

Data

↓

Fiducial/diff. XS, ← *Unfolding*

↓

Simplified Template XS ← *Combine different channels*

↓

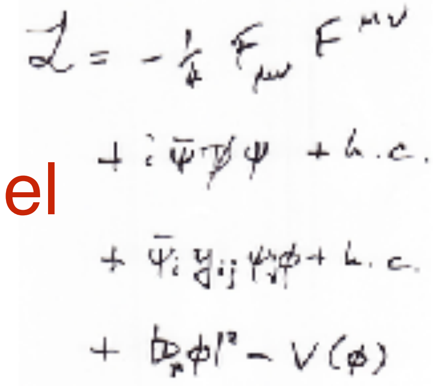
Pseudo-observables ← *Combine production and decay*

↓

EFT ← *Combine Higgs + EW + top physics +..*

↓

Explicit NP model ← *Combine with direct searches*

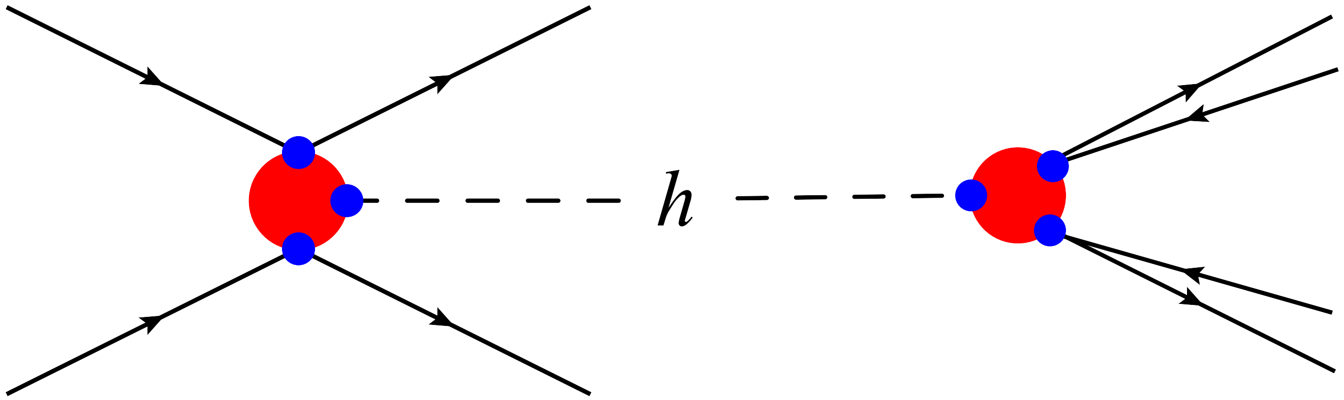


$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \bar{\psi}_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$

Higgs PO

PO are defined from:

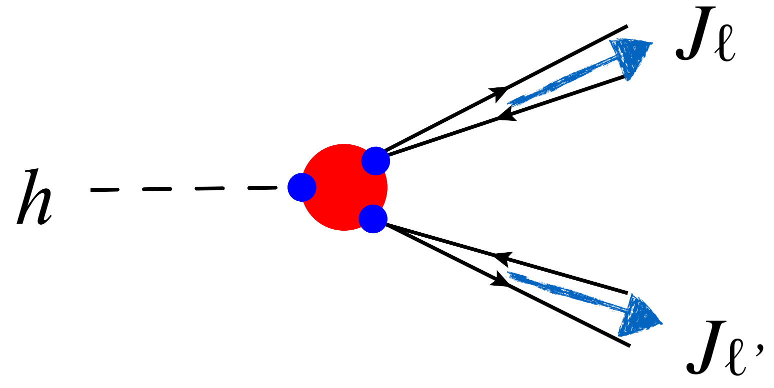
a decomposition of **on-shell amplitudes** (NWA),
based on Lorentz invariance and crossing symmetry,

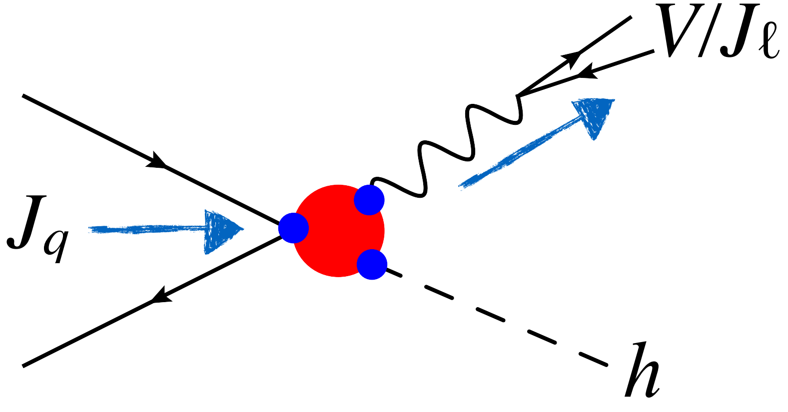


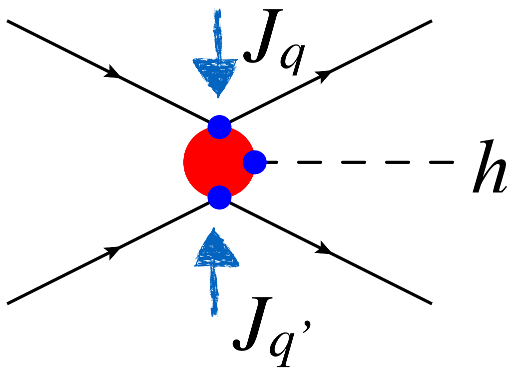
and a momentum expansion around the physical poles in the amplitude,
assuming no new light states in the kinematical regime of interest.

HPO for h→4f and EW production

[Gonzalez-Alonso, Greljo, Isidori, Lindert, D.M. 1504.04018,1512.06135, YR4]







Described by the same on-shell correlation function → same parametrisation (PO), in different kinematical regions and with different currents.

HPO for h→4f and EW production

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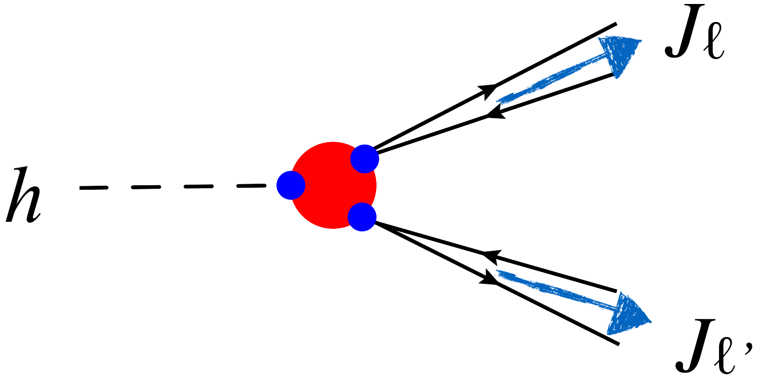
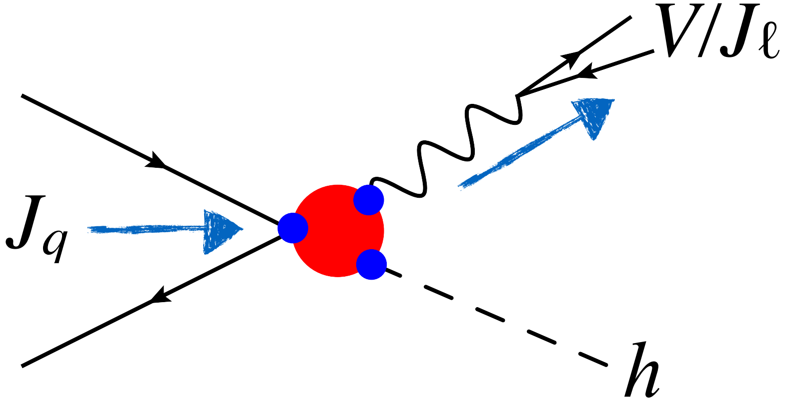
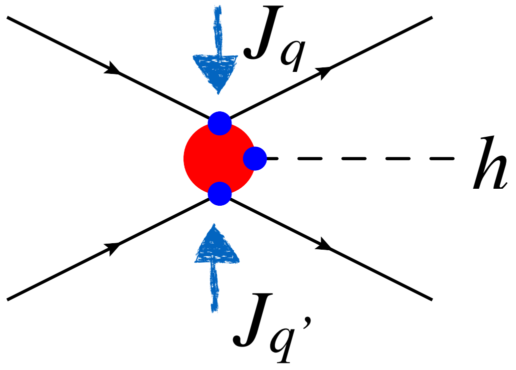






Described by the same on-shell correlation function → same parametrisation (PO), in different kinematical regions and with different currents.

Only 3 tensor structures allowed by Lorentz symmetry. Define a form factor for each one. PO are defined from the residues of the different pole structures (propagators):

e.g. $h \to e^+e^- \mu^+\mu^-$

In the SM $\kappa_X \to 1,\ \epsilon_X \to 0,\ \lambda_X^{\rm CP} \to 0$

$$
\begin{aligned}
\mathcal{A} =& i\frac{2m_Z^2}{v_F}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta \mu)\times \\
&\Bigg[\left(\kappa_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2}\frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}\frac{g_Z^e}{P_Z(q_1^2)}\right) g^{\alpha\beta} + \\
&+\left(\epsilon_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \kappa_{Z\gamma}\epsilon_{Z\gamma}^{\rm SM,eff}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \kappa_{\gamma\gamma}\epsilon_{\gamma\gamma}^{\rm SM,eff}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)\frac{q_1\cdot q_2\ g^{\alpha\beta} - q_2{}^\alpha q_1{}^\beta}{m_Z^2} + \\
&+\left(\epsilon_{ZZ}^{\rm CP}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \lambda_{Z\gamma}^{\rm CP}\epsilon_{Z\gamma}^{\rm SM,eff}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \lambda_{\gamma\gamma}^{\rm CP}\epsilon_{\gamma\gamma}^{\rm SM,eff}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)\frac{\varepsilon^{\alpha\beta\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\Bigg]
\end{aligned}
$$

$$P_Z(q^2) = q^2 - m_Z^2 + i m_Z \Gamma_Z$$

Parameter counting - PO

Higgs (EW) decay amplitudes

Amplitudes	Flavor + CP	Flavor Non Univ.	CPV
$h \to \gamma\gamma, 2e\gamma, 2\mu\gamma$ $4e, 4\mu, 2e2\mu$	6 $\kappa_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}, \varepsilon_{ZZ}$ $\varepsilon_{Ze_L}, \varepsilon_{Ze_R}$	$\varepsilon_{Z\mu_L}, \varepsilon_{Z\mu_R}$	$\varepsilon^{CP}_{ZZ}, \lambda^{CP}_{Z\gamma}, \lambda^{CP}_{\gamma\gamma}$
$h \to 2e2\nu, 2\mu2\nu, e\nu\mu\nu$	4 $\kappa_{WW}, \varepsilon_{WW}$ $\varepsilon_{Z\nu_e}$, Re(ε_{We_L})	$\varepsilon_{Z\nu_\mu}$, Re($\varepsilon_{W\mu_L}$) Im($\varepsilon_{W\mu_L}$)	ε^{CP}_{WW}, Im(ε_{We_L})

Test UV symmetries!

Higgs (EW) production amplitudes

Amplitudes	Flavor + CP	Flavor Non Univ.	CPV
VBF neutral curr. and Zh	4 $[\ \kappa_{ZZ}, \kappa_{Z\gamma}, \varepsilon_{ZZ}\ ]$ $\varepsilon_{Zu_L}, \varepsilon_{Zu_R}, \varepsilon_{Zd_L}, \varepsilon_{Zd_R}$	$\varepsilon_{Zc_L}, \varepsilon_{Zc_R}$ $\varepsilon_{Zs_L}, \varepsilon_{Zs_R}$	$[\ \varepsilon^{CP}_{ZZ}, \lambda^{CP}_{Z\gamma}\ ]$
VBF charged curr. and Wh	1 $[\ \kappa_{WW}, \varepsilon_{WW}\ ]$ Re(ε_{Wu_L})	Re(ε_{Wc_L}) Im(ε_{Wc_L})	Im(ε_{Wu_L})

12 independent processes & many differential distributions.

1) ***All that can be measured*** *in these processes (if NP is heavy) are* ***these PO****.*

2) *A robust extraction of PO requires a global analysis.*

The SM Effective Field Theory

$$\Lambda \gg E_{\mathrm{exp}}, m_h$$

particle content + symmetries
as in the SM + L and B conservation

(Higgs is a SU(2)$_L$ doublet)

Leading deformations of the SM

$$\mathcal{L}^{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \boxed{\sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)}} + \sum_j \frac{c_j^{(8)}}{\Lambda^4} \mathcal{O}_j^{(8)} + \ldots$$

59 independent dim-6 operators if flavour universality.
2499 parameters for a generic flavour structure.

[Buchmuller and Wyler '86, Grzadkowski et al. 1008.4884, Alonso et al. 1312.2014]

A step-by-step approach

i.e. how to successfully make sense of 2499 parameters

- Any given on-shell process receives contributions from a limited number of operators $\# \lesssim O(10)$.

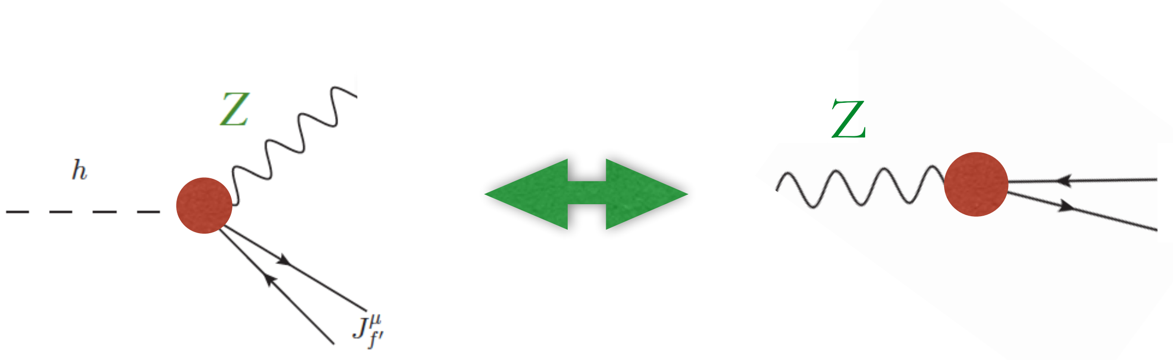
- Hierarchy of precision.
  Some observables are much more precise than others.
  Impose these bounds before going on to less precise ones.
  e.g. Corbett et al. [1211.4580], Pomarol and Riva [1308.2803], ecc..

Note: This process, when correctly done, is basis-independent.

EFT: relating different observables

The same operator can contribute to different processes.

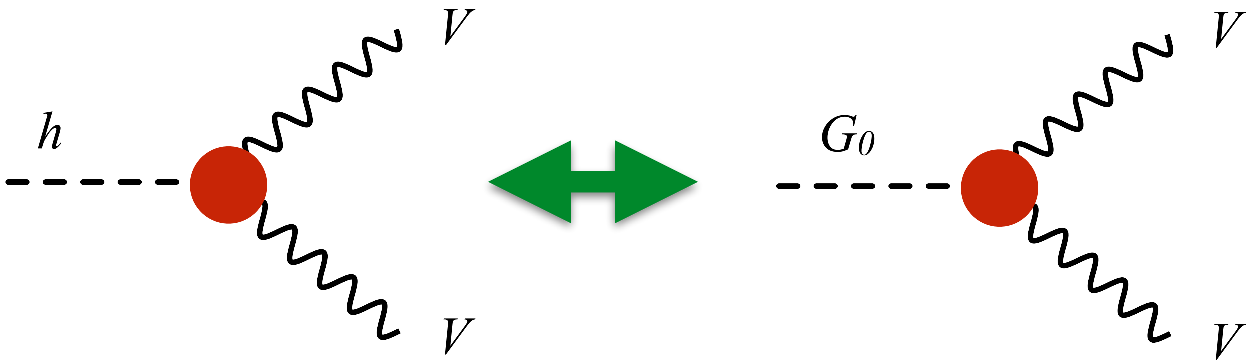
For example: $O_{Hf} = i(H^\dagger \overleftrightarrow{D}_\mu H)\bar{f}\gamma^\mu f = -\frac{1}{2}\sqrt{g^2+g'^2}\,Z_\mu (v+h)^2 \bar{f}\gamma^\mu f$



Z couplings δg_{Zf}

&

$$\mathcal{O}_W = ig\left(H^\dagger \tau^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$$



Triple Gauge Couplings
$\delta\kappa_z$, $\delta g_{1,z}$, λ_Z

Combine Z-pole, WW, and WZ data with Higgs data to derive stronger constraints for the EFT.

EW + Higgs global fits

Once the strong LEP I constraints (≲1%) are imposed,

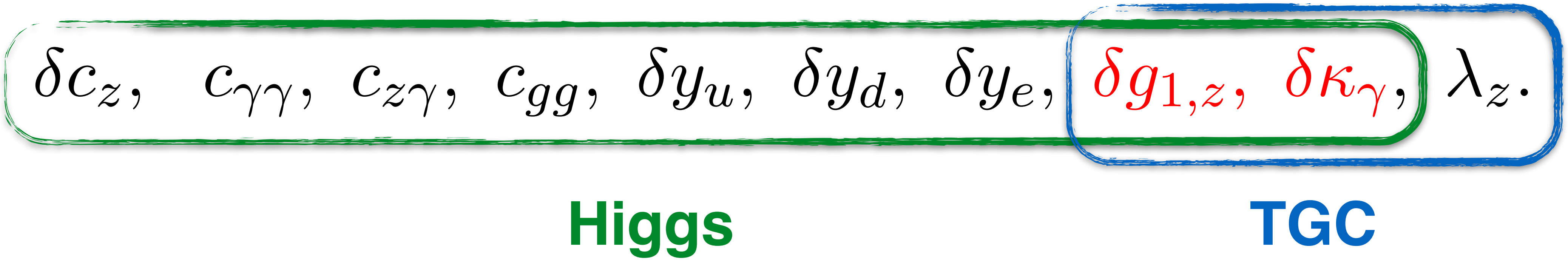
[Pomarol Riva 2013; Efrati et al. 2015; Berthier, Trott 2015]

Assuming MFV, only 10 independent combinations of coefficients contribute at tree-level to Higgs (Run-1) and LEP II (WW) observables.

[Corbett et al. 2013; J. Elias-Miro et al. 2013;
Pomarol Riva 2013; Gupta et al 2014; Falkowski 2015]

Global fit in the 'Higgs basis' [LHCHXSWG 2015]

[Falkowski, Gonzalez-Alonso, Greljo, D.M. PRL 116, 011801 (2016)]



$$\delta c_z, \quad c_{\gamma\gamma}, \ c_{z\gamma}, \ c_{gg}, \ \delta y_u, \ \delta y_d, \ \delta y_e, \ \delta g_{1,z}, \ \delta\kappa_\gamma, \ \lambda_z.$$

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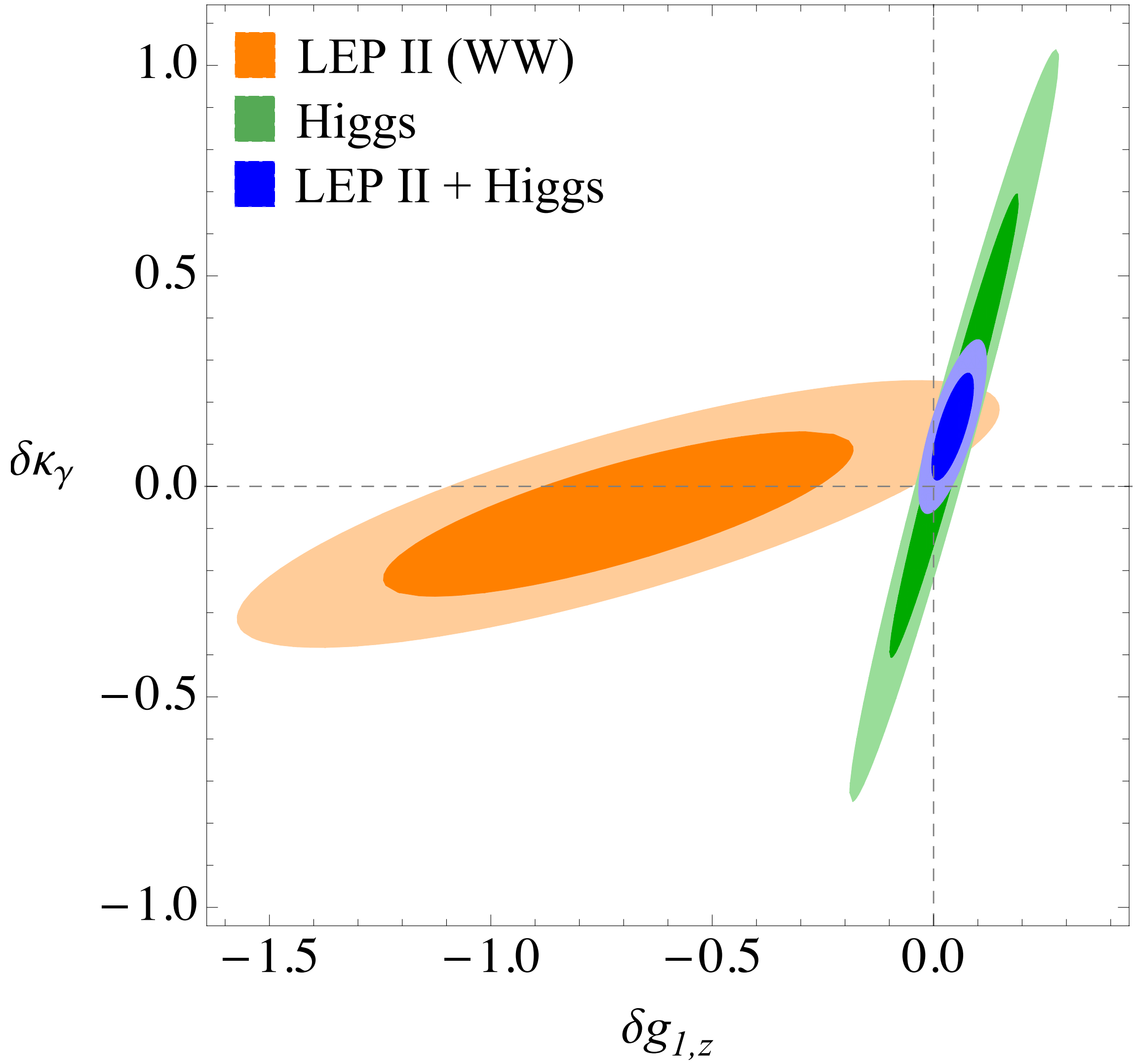
Constraints on TGCs

[Falkowski, Gonzalez-Alonso, Greljo, D.M. PRL 116, 011801 (2016)]



All other coefficients have been marginalised.

LEP II data alone suffers from a flat direction in the TGC fit. [Falkowski, Riva 1411.0669]

\+

Higgs data (mainly via VH and VBF production) is sensitive to a different direction.

[Falkowski 1505.00046]

=

Together they provide **strong and robust constraints on the TGC**.

Top-Higgs sector

$t\bar{t}$ tth

$gg \to h\ (+j)$ th

All these processes are affected (in different ways) by the same operators. The most relevant are:

[Degrande et al. 1205.1065, Maltoni et al. 1607.05330, …]

$$\mathcal{L}^{\rm EFT} \supset -\delta k_t \frac{y_t}{v^2} \bar{Q}_L^3 t_R \tilde{H} \left(H^\dagger H - \frac{v^2}{2} \right) + h.c.$$

$$-c_{tg} \frac{g_s y_t}{4v^2} \bar{Q}_L \sigma^{\mu\nu} T^A t_R G^A_{\mu\nu} \tilde{H} + h.c.$$

$$+\frac{c_{4f}}{v^2} \sum_{i=1,2} \left[(\bar{Q}_L^3 u_R^i)(\bar{u}_R^i Q_L^3) + (\bar{Q}_L^i u_R^3)(\bar{u}_R^3 Q_L^i) \right]$$

$$+\frac{y_t^2 c_{gg}}{v^2} (H^\dagger H) G^A_{\mu\nu} G^{A\mu\nu}$$

anomalous top Yukawa

chromo-dipole of top quark

four-fermion operators

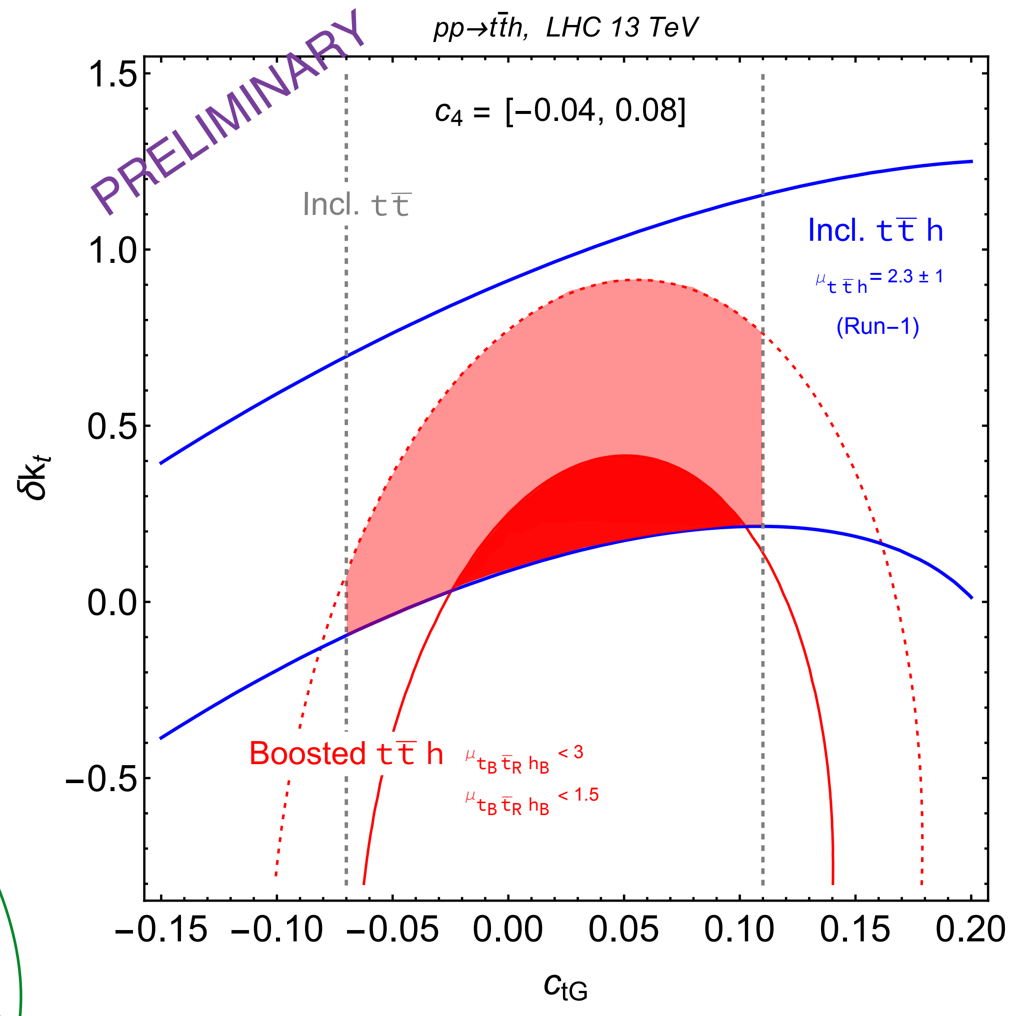
ggH coupling

A global analysis is necessary to disentangle the various contributions.

Boosted tth signatures

The **total tth rate** provides only information on a single combination

Faroughy, Greljo, Isidori, Kamenik, D.M. - in progress



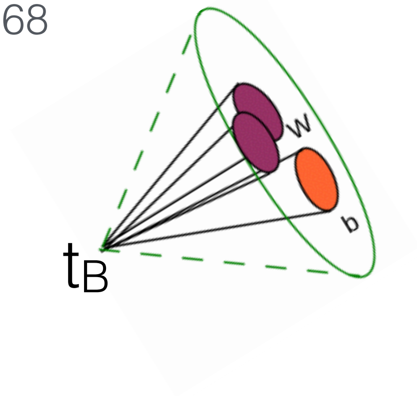
More discriminating power can be obtained:

from **differential distributions**,

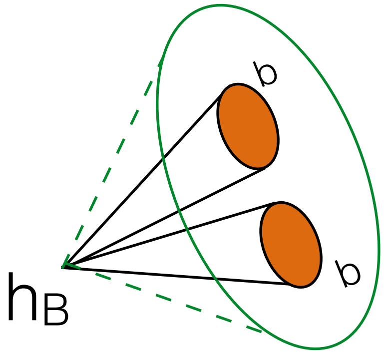
Maltoni et al. 1607.05330

from **boosted tth** signatures.

Plehn et al., 0910.5472, Buckley et al., 1310.6034, Moretti et al., 1510.08468



fat jets



The boosted regime (fat top and Higgs jets) is very sensitive to dim-6 operators. Even a very limited precision could provide strong limits on the EFT.

Summary

Higgs PO

Characterise all the measurable properties of on-shell Higgs boson processes *(h→ 4f, VH and VBF)* in a robust and model-independent way.

SMEFT

- Allows to combine Higgs and non-Higgs measurement.
- Global fits are necessary to get the most from data.

Higgs-EW

Z-pole, WW, WZ,
$h\to 4f$, $\gamma\gamma$, $Z\gamma$, VH, VBF

Higgs-Top-Gluons

$t\bar{t}$, $gg\to h\ (+j)$,
tth, th

Thank you

Prospects for PO in EW production

Flavor-independent PO probed in $h \to 4\ell$ decay. → Focus on quark contact terms.

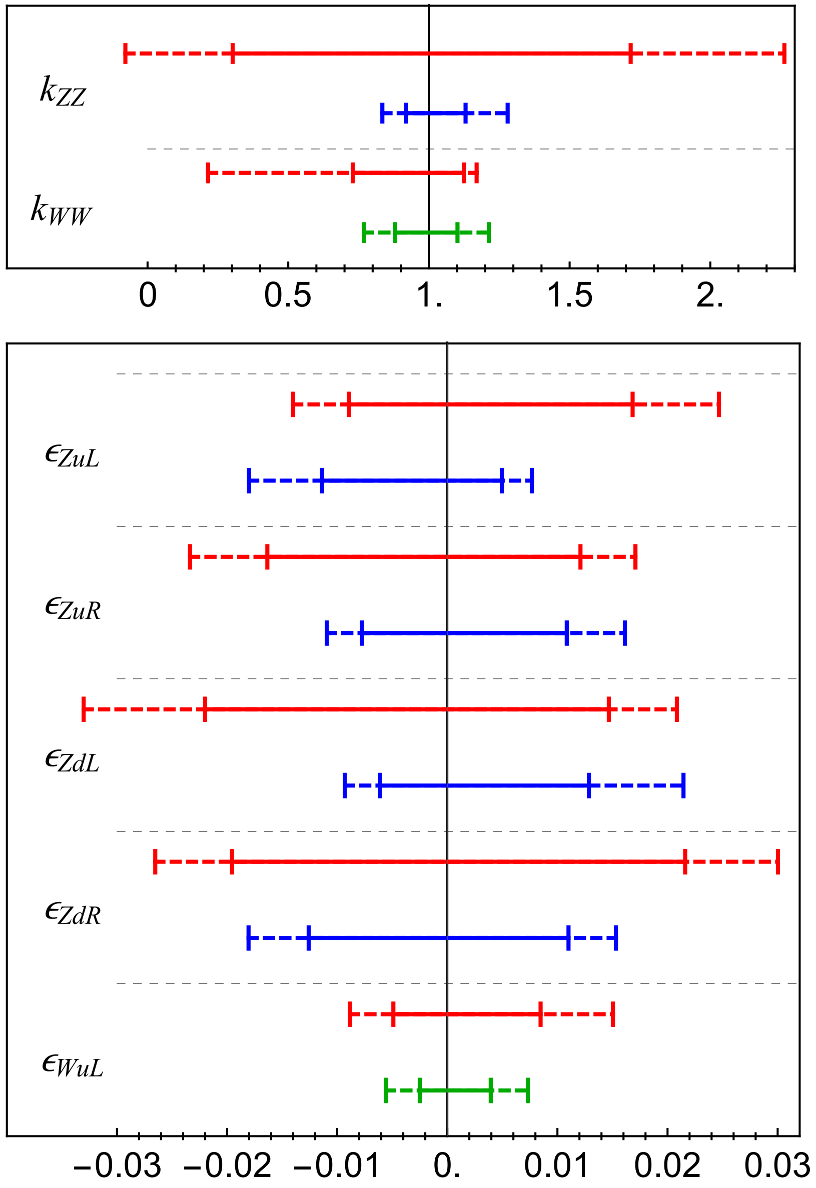
For simplicity let's assume Minimal Flavor Violation.
Consider 7 PO:

κ_{ZZ} , κ_{WW} , ϵ_{Zu_L} , ϵ_{Zu_R} , ϵ_{Zd_L} , ϵ_{Zd_R} , ϵ_{Wu_L}

VBF: fit of the 2D p_T distribution.

Zh, Wh: fit of the 1D p_{TV} distribution.

HL-LHC with 3 ab^{-1}



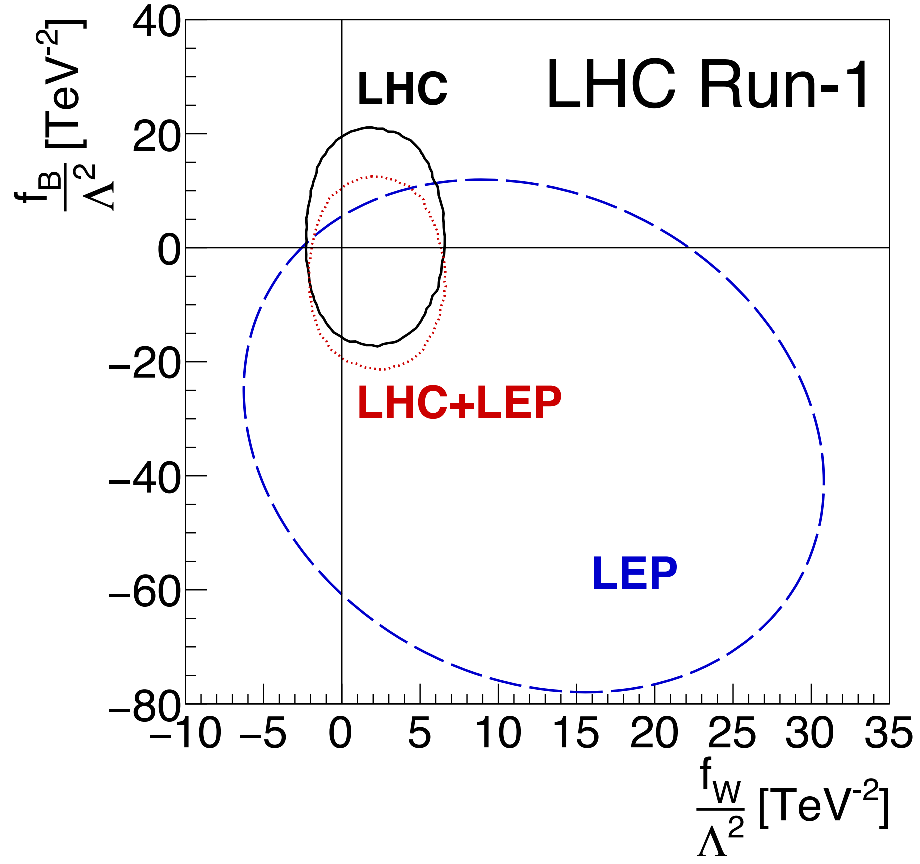
LHC will be able to measure all the contact terms with percent accuracy!

Same conclusion also if no information on the total rate is retained.

WW/WZ production at LHC

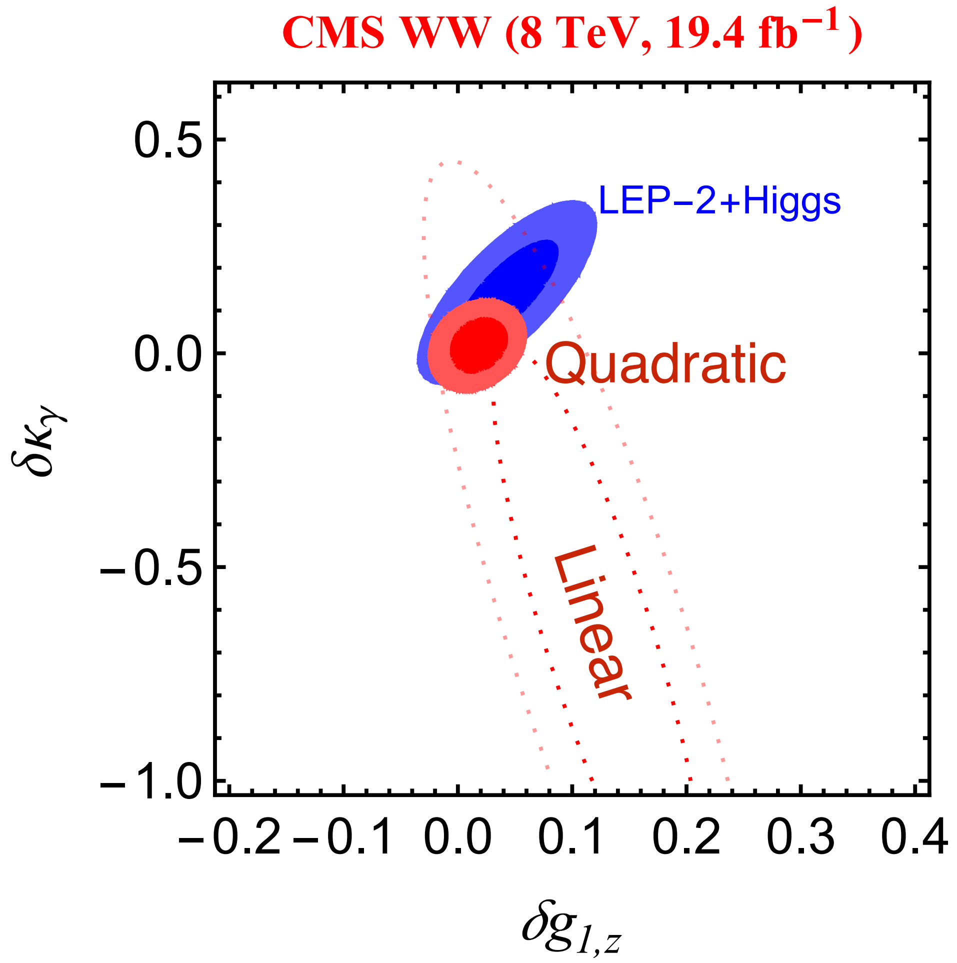
Taken at face value, LHC already provides much stronger constraints than LEP.

[Butter et al. 1604.03105]



(these operators generate two aTGC)

Falkowski, Gonzalez-Alonso, Greljo, D.M., Son [1609.06312]



The bound is driven by quadratic terms.
A detailed study of the EFT validity is in order.

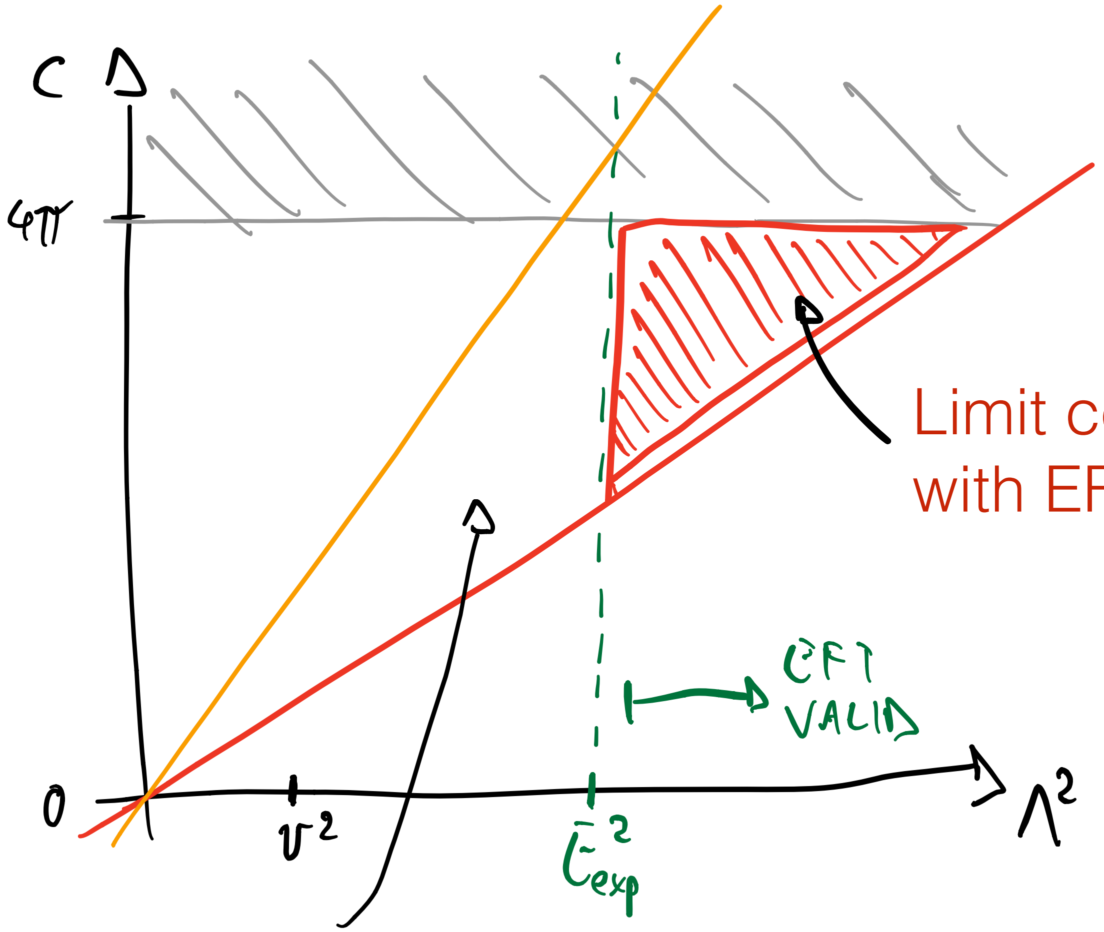
$$\sigma = \sigma^{\rm SM} + \sum_i \left(\frac{c_i^{(6)}}{\Lambda^2} \sigma_i^{(6\times {\rm SM})} + {\rm h.c.} \right) + \sum_{ij} \frac{c_i^{(6)} c_j^{(6)*}}{\Lambda^4} \sigma_{ij}^{(6\times 6)} + \sum_j \left(\frac{c_j^{(8)}}{\Lambda^4} \sigma_j^{(8\times {\rm SM})} + {\rm h.c.} \right) + \dots$$

EFT validity

Ellis, Sanz 1410.7703;
Greljo et al. 1512.06135;
Plehn et al. 1510.03443,1602.05202;
Contino et al. 1604.06444;
Falkowski et al. 1609.06312;
…

Any experimental limit in the EFT approach will be on the combination

$$\boxed{v^2 \frac{C}{\Lambda^2} < \delta_{prec.}} \longrightarrow \begin{cases} C < \frac{\Lambda^2}{v} \delta_{prec.} \\ C \lesssim 4\pi \\ \Lambda \gg E_{exp} \end{cases}$$



Limit consistent with EFT

This region is possibly excluded by same search, but using a 'direct search' approach.

Bad precision at high energy could mean that no scenario is being probed consistently with the EFT.

Increasing the precision enlarges the size of the triangle, accessing more weakly coupled models.