EFFECTIVE FIELD THEORY FOR BSM

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SMEFT Lagrangian

Effective Lagrangian for a Higgs doublet

Buchmuller and Wyler NPB 268 (1986) 621

⋮

Grzadkowski et al. JHEP 1010 (2010) 085

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \bar{c}_i O_i \equiv \mathcal{L}_{SM} + \boxed{\Delta\mathcal{L}_{SILH}} + \Delta\mathcal{L}_{cc} + \Delta\mathcal{L}_{dipole} + \Delta\mathcal{L}_V + + \Delta\mathcal{L}_{4\psi}$$

16 operators

(12 CP even, 4 CP odd)

Best operator basis to test light composite Higgs

Giudice, Grojean, Pomarol, Rattazzi JHEP 0706 (2007) 045

$$\begin{aligned}
\Delta\mathcal{L}_{SILH} = \; & \frac{\bar{c}_H}{2v^2}\,\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\,\lambda}{v^2}\left(H^\dagger H\right)^3 \\
& + \left(\frac{\bar{c}_u}{v^2}\, y_u\, H^\dagger H\, \bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\, y_d\, H^\dagger H\, \bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\, y_l\, H^\dagger H\, \bar{L}_L H l_R + h.c.\right) \\
& + \frac{i\bar{c}_W\, g}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i\bar{c}_B\, g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right) \\
& + \frac{i\bar{c}_{HW}\, g}{m_W^2}\left(D^\mu H\right)^\dagger \sigma^i \left(D^\nu H\right) W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\, g'}{m_W^2}\left(D^\mu H\right)^\dagger \left(D^\nu H\right) B_{\mu\nu} \\
& + \frac{\bar{c}_\gamma\, {g'}^2}{m_W^2}\, H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{\bar{c}_g\, g_S^2}{m_W^2}\, H^\dagger H G^a_{\mu\nu} G^{a\mu\nu} \\
& + \frac{i\tilde{c}_{HW}\, g}{m_W^2}\left(D^\mu H\right)^\dagger \sigma^i \left(D^\nu H\right) \tilde{W}^i_{\mu\nu} + \frac{i\tilde{c}_{HB}\, g'}{m_W^2}\left(D^\mu H\right)^\dagger \left(D^\nu H\right) \tilde{B}_{\mu\nu} \\
& + \frac{\tilde{c}_\gamma\, {g'}^2}{m_W^2}\, H^\dagger H B_{\mu\nu} \tilde{B}^{\mu\nu} + \frac{\tilde{c}_g\, g_S^2}{m_W^2}\, H^\dagger H G^a_{\mu\nu} \tilde{G}^{a\mu\nu}
\end{aligned}$$

Effective Lagrangian for a Higgs doublet

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$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \bar{c}_i O_i \equiv \mathcal{L}_{SM} + \Delta\mathcal{L}_{SILH} + \boxed{\Delta\mathcal{L}_{cc}} + \Delta\mathcal{L}_{dipole} + \Delta\mathcal{L}_V + + \Delta\mathcal{L}_{4\psi}$$

6 current-current operators

$$\begin{aligned}
\Delta\mathcal{L}_{cc} = & \frac{i\bar{c}_{Hq}}{v^2}\left(\bar{q}_L\gamma^\mu q_L\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}'_{Hq}}{v^2}\left(\bar{q}_L\gamma^\mu\sigma^i q_L\right)\left(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H\right) \\
& + \frac{i\bar{c}_{Hu}}{v^2}\left(\bar{u}_R\gamma^\mu u_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}_{Hd}}{v^2}\left(\bar{d}_R\gamma^\mu d_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \\
& + \left(\frac{i\bar{c}_{Hud}}{v^2}\left(\bar{u}_R\gamma^\mu d_R\right)\left(H^{c\,\dagger} \overleftrightarrow{D}_\mu H\right) + h.c.\right) \\
& + \frac{i\bar{c}_{HL}}{v^2}\left(\bar{L}_L\gamma^\mu L_L\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)
\end{aligned}$$

Effective Lagrangian for a Higgs doublet

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8 dipole operators

$$\begin{aligned}\Delta\mathcal{L}_{dipole} = {} & \frac{\bar{c}_{uB}\, g'}{m_W^2}\, y_u\, \bar{q}_L H^c \sigma^{\mu\nu} u_R\, B_{\mu\nu} + \frac{\bar{c}_{uW}\, g}{m_W^2}\, y_u\, \bar{q}_L \sigma^i H^c \sigma^{\mu\nu} u_R\, W^i_{\mu\nu} + \frac{\bar{c}_{uG}\, g_S}{m_W^2}\, y_u\, \bar{q}_L H^c \sigma^{\mu\nu} \lambda^a u_R\, G^a_{\mu\nu} \\ & + \frac{\bar{c}_{dB}\, g'}{m_W^2}\, y_d\, \bar{q}_L H \sigma^{\mu\nu} d_R\, B_{\mu\nu} + \frac{\bar{c}_{dW}\, g}{m_W^2}\, y_d\, \bar{q}_L \sigma^i H \sigma^{\mu\nu} d_R\, W^i_{\mu\nu} + \frac{\bar{c}_{dG}\, g_S}{m_W^2}\, y_d\, \bar{q}_L H \sigma^{\mu\nu} \lambda^a d_R\, G^a_{\mu\nu} \\ & + \frac{\bar{c}_{lB}\, g'}{m_W^2}\, y_l\, \bar{L}_L H \sigma^{\mu\nu} l_R\, B_{\mu\nu} + \frac{\bar{c}_{lW}\, g}{m_W^2}\, y_l\, \bar{L}_L \sigma^i H \sigma^{\mu\nu} l_R\, W^i_{\mu\nu} + h.c.\end{aligned}$$

Effective Lagrangian for a Higgs doublet

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$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \bar{c}_i O_i \equiv \mathcal{L}_{SM} + \Delta\mathcal{L}_{SILH} + \Delta\mathcal{L}_{cc} + \Delta\mathcal{L}_{dipole} + \boxed{\Delta\mathcal{L}_V} + \boxed{\Delta\mathcal{L}_{4\psi}}$$

22 four-fermion operators

7 operators built with gauge fields only
(5 CP even, 2 CP odd)

$$\begin{aligned}\Delta\mathcal{L}_V = &\frac{\bar{c}_{2W}}{m_W^2}\left(D^\mu W_{\mu\nu}\right)^i \left(D_\rho W^{\rho\nu}\right)^i + \frac{\bar{c}_{2B}}{m_W^2}\left(\partial^\mu B_{\mu\nu}\right)\left(\partial_\rho B^{\rho\nu}\right) + \frac{\bar{c}_{2G}}{m_W^2}\left(D^\mu G_{\mu\nu}\right)^a \left(D_\rho G^{\rho\nu}\right)^a \\ &+ \frac{\bar{c}_{3W}\, g^3}{m_W^2}\,\epsilon^{ijk} W_\mu^{i\,\nu} W_\nu^{j\,\rho} W_\rho^{k\,\mu} + \frac{\bar{c}_{3G}\, g_S^3}{m_W^2}\, f^{abc} G_\mu^{a\,\nu} G_\nu^{b\,\rho} G_\rho^{c\,\mu} \\ &+ \frac{\tilde{c}_{3W}\, g^3}{m_W^2}\,\epsilon^{ijk} W_\mu^{i\,\nu} W_\nu^{j\,\rho} \tilde{W}_\rho^{k\,\mu} + \frac{\tilde{c}_{3G}\, g_S^3}{m_W^2}\, f^{abc} G_\mu^{a\,\nu} G_\nu^{b\,\rho} \tilde{G}_\rho^{c\,\mu}\end{aligned}$$

In total: 59 dim-6 operators for 1 SM family

For a review see: RC, Ghezzi, Grojean, Muhlleitner, Spira JHEP 07 (2013) 035

Naive estimate at the matching scale m_* (SILH power counting):

$$\bar{c}_H, \bar{c}_T, \bar{c}_6, \bar{c}_\psi \sim O\left(\frac{v^2}{f^2}\right), \quad \bar{c}_W, \bar{c}_B \sim O\left(\frac{m_W^2}{m_*}\right), \quad \bar{c}_{HW}, \bar{c}_{HB}, \bar{c}_\gamma, \bar{c}_g \sim O\left(\frac{m_W^2}{16\pi^2 f^2}\right)$$

$$\bar{c}_{H\psi}, \bar{c}'_{H\psi} \sim O\left(\frac{\lambda_\psi^2}{g_*^2}\frac{v^2}{f^2}\right), \quad \bar{c}_{Hud} \sim O\left(\frac{\lambda_u \lambda_d}{g_*^2}\frac{v^2}{f^2}\right), \quad \bar{c}_{\psi W}, \bar{c}_{\psi B}, \bar{c}_{\psi G} \sim O\left(\frac{m_W^2}{16\pi^2 f^2}\right)$$

where $f \equiv m_*/g_*$

Processes with 0, 1, 2, ... Higgses *related*

Q: Which operators are already constrained by experiments w/o Higgs ?

In total: 59 dim-6 operators

17 involve the Higgs

8 affect Higgs physics only

Elias-Miro, Espinosa, Masso, Pomarol JHEP 1311 (2013) 066

Pomarol, Riva JHEP 01 (2014) 151

Operators that affect Higgs physics only

Elias-Miro, Espinosa, Masso, Pomarol
JHEP 1311 (2013) 066

Pomarol, Riva JHEP 01 (2014) 151

$$\boxed{O_H = (\partial_\mu |H|^2)^2}$$

shifts all Higgs couplings

$$O_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$

$$O_{WW} = g^2 |H|^2 W_{\mu\nu} W^{\mu\nu}$$

$$O_{GG} = g_s^2 |H|^2 G_{\mu\nu} G^{\mu\nu}$$

modify inclusive rates (constrained by fit to Higgs couplings)

$$\boxed{\begin{aligned} O_{y_d} &= y_d |H|^2 \bar{q}_L H d_R \\ O_{y_u} &= y_u |H|^2 \bar{q}_L \tilde{H} u_R \\ O_{y_e} &= y_e |H|^2 \bar{L}_L H e_R \end{aligned}}$$

shift $h\psi\psi$

$$O_6 = \lambda |H|^6$$

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$\longleftarrow$ modify inclusive rates (constrained by fit to Higgs couplings)

$h \to \gamma\gamma$

$h \to Z\gamma$

$gg \to h$

$$O_{y_d} = y_d |H|^2 \bar{q}_L H d_R$$

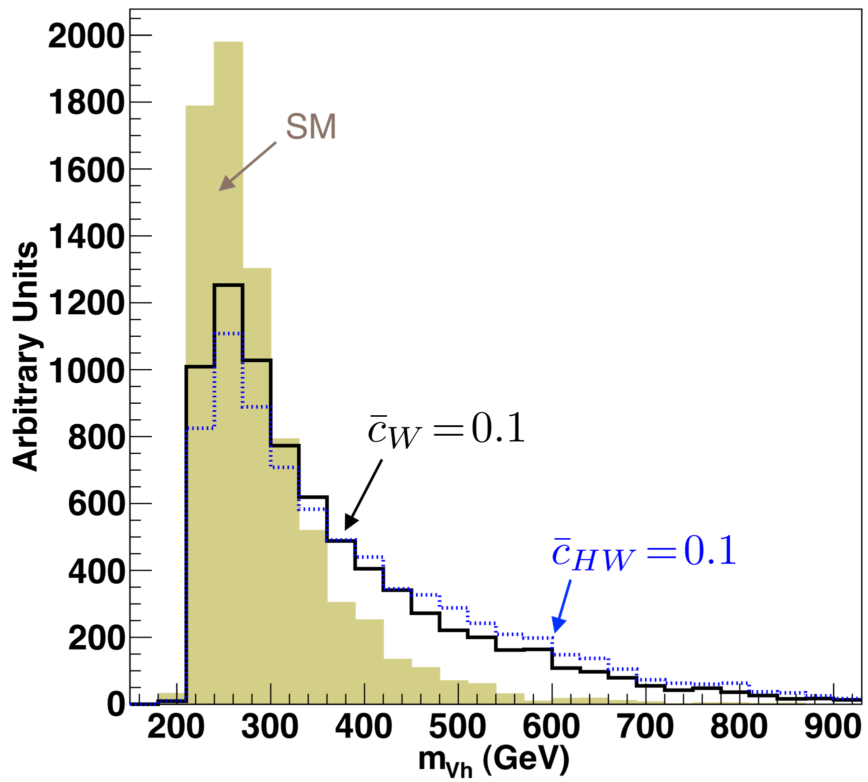
$$O_{y_u} = y_u |H|^2 \bar{q}_L \tilde{H} u_R$$

$$O_{y_e} = y_e |H|^2 \bar{L}_L H e_R$$

$$O_6 = \lambda |H|^6$$

Operators that affect Higgs physics only

Alloul, Fuks, Sanz arXiv:1310.5150



$$O_H = (\partial_\mu |H|^2)^2$$

$$\boxed{\begin{aligned} O_{BB} &= g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu} \\ O_{WW} &= g^2 |H|^2 W_{\mu\nu} W^{\mu\nu} \end{aligned}}$$

modify also differential rates, can be probed by:

— *decays h→WW*, h→ZZ* (angular distributions)*

— *Higgs associated production hV (Higgs p_T, m_{Vh}, and angular distributions)*

— *single-Higgs production via VBF*

$$O_{GG} = g_s^2 |H|^2 G_{\mu\nu} G^{\mu\nu}$$

$$O_{y_d} = y_d |H|^2 \bar{q}_L H d_R$$

$$O_{y_u} = y_u |H|^2 \bar{q}_L \tilde{H} u_R$$

$$O_{y_e} = y_e |H|^2 \bar{L}_L H e_R$$

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$$\boxed{O_{GG} = g_s^2 |H|^2 G_{\mu\nu} G^{\mu\nu}}$$

modifies p_T spectrum of $gg \to h + jet$

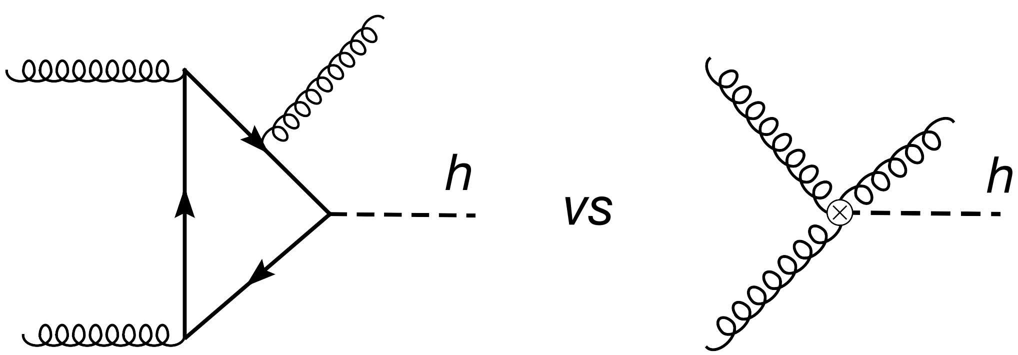
[top loop vs point-like interaction]

$$O_{y_d} = y_d |H|^2 \bar{q}_L H d_R$$

$$O_{y_u} = y_u |H|^2 \bar{q}_L \tilde{H} u_R$$

$$O_{y_e} = y_e |H|^2 \bar{L}_L H e_R$$

$$O_6 = \lambda |H|^6$$



Azatov, Paul JHEP 1401 (2014) 014

Grojean, Salvioni, Schlaffer, Weiler JHEP 1405 (2014) 022

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JHEP 1311 (2013) 066

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$$O_{y_u} = y_u |H|^2 \bar{q}_L \tilde{H} u_R$$

$$O_{y_e} = y_e |H|^2 \bar{L}_L H e_R$$

$$\boxed{O_6 = \lambda |H|^6} \qquad gg \to hh \longleftarrow \text{yet un-probed}$$

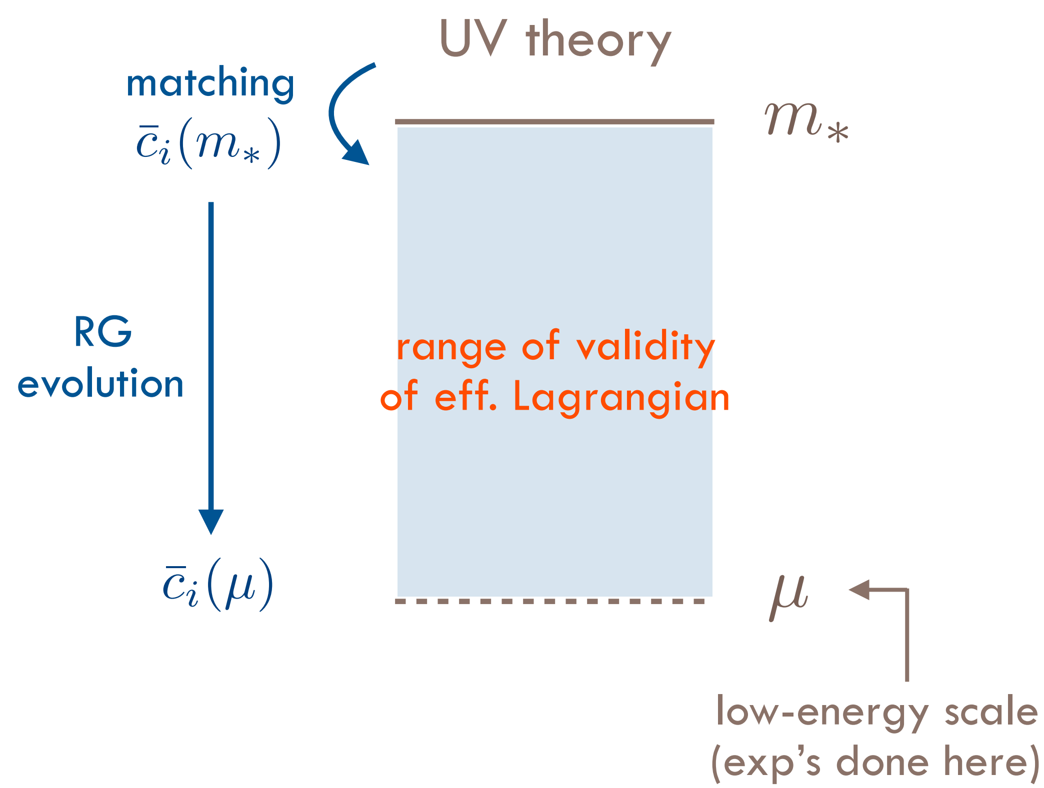
Renormalization of EFT

RG evolution of coefficients

- Loops of *light* (SM) particles induce the RG flow (and mixing) of the coefficients $\bar{c}_i$

$$\bar{c}_i(\mu) = \left(\delta_{ij} + \gamma_{ij}^{(0)} \frac{\alpha_{SM}(\mu)}{4\pi} \log \frac{\mu}{m_*}\right) \bar{c}_j(m_*)$$

Elias-Miró et al. JHEP 1308 (2013) 033; JHEP 1311 (2013) 066
Jenkins et al. JHEP 1310 (2013) 087; JHEP 1401 (2014) 035
Alonso et al. JHEP 1404 (2014) 159



- No big hierarchy between m_* and EW scale, 1-loop corrections to SMEFT are generally *small*

Do we need to go beyond tree level ?

- The bulk of the 1-loop effect (RG running) can be effectively included by setting limits on the value of the coefficients at the *low-energy* scale

- Knowledge of the RG running is however needed when it comes to make assumptions on the coefficients at the scale m_* (ex: to simplify the analysis by neglecting some of the operators)

1-loop effects important if:

[in setting limits]

Some loosely bound coefficients appears in a precisely measured observable at 1-loop level → Ex: $\bar{c}_t$ in $gg \to h$

[in constraining physics at m_*]

A larger coefficient renormalizes a smaller one (for a given power counting). RG effects can be sizeable if UV dynamics is strongly coupled

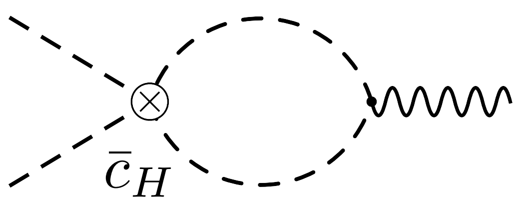
RG evolution of coefficients

- In case of strong dynamics, leading effects come from loops of composite particles (i.e. Higgs, top quarks, ...)

Examples:

1. Running of $\bar{c}_{W+B}$

$$O_{W+B} = \frac{ig}{2m_W^2} D^\nu W^i_{\mu\nu} (H^\dagger \sigma^i \overleftrightarrow{D^\mu} H) + \frac{ig'}{2m_W^2} \partial^\nu B_{\mu\nu} (H^\dagger \overleftrightarrow{D^\mu} H)$$



$$\bar{c}_{W+B}(\mu) = \bar{c}_{W+B}(m_*) - \frac{1}{6} \frac{\alpha_2}{4\pi} \log\left(\frac{\mu}{m_*}\right) \bar{c}_H(m_*)$$

$$\bar{c}_W(m_*), c_B(m_*) \sim \frac{m_W^2}{m_*^2}$$

$$\bar{c}_H(m_*) \sim \frac{v^2 g_*^2}{m_*^2} = \frac{m_W^2}{m_*^2} \frac{g_*^2}{g^2}$$

$$\boxed{\frac{\Delta \bar{c}_{W+B}}{\bar{c}_{W+B}} \sim \frac{g_*^2}{16\pi^2} \log\left(\frac{m_*}{\mu}\right)}$$

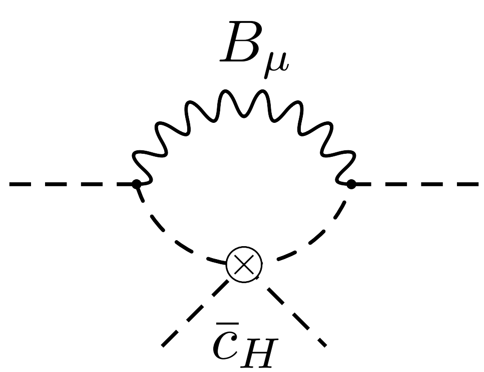
1-loop correction can be large if the UV dynamics is strongly-interacting (g_* large)

RG evolution of coefficients

- In case of strong dynamics, leading effects come from loops of composite particles (i.e. Higgs, top quarks, ...)

Examples:

2. Running of $\bar{c}_T$ $$O_T = \frac{1}{2v^2}\left|H^\dagger \overleftrightarrow{D_\nu} H\right|^2$$



$$\bar{c}_T(\mu) = \bar{c}_T(m_*) + \frac{3}{2}\tan^2\theta_W \frac{\alpha_2}{4\pi}\log\left(\frac{\mu}{M}\right)\bar{c}_H(m_*)$$

$$\bar{c}_T(m_Z) \sim \frac{v^2}{f^2} \times \frac{g'^2}{16\pi^2}\log\left(\frac{m_*}{m_Z}\right)$$

Small but leading effect if $\bar{c}_T(m_*) = 0$ due to custodial invariance

Fit to effective coefficients

EFT fit to experimental data

Two approaches:

- Possible effective strategy:

  Pomarol, Riva JHEP 1401 (2014) 151

Organize data (and group operators) according to how strongly they constrain the effective coefficients

observables	**precision**
input observables (G_F, α_{em}, m_Z), EDMs, (g-2)	better than 10^{-3}
Z-pole observables at LEP1, W mass	10^{-3}
TGC (LEP2)	10^{-2}
Higgs physics (LHC)	10^{-1}

- Global fit:

  Ellis, Murphy, Sanz, You arXiv:1803.0352
  De Blas et at. arXiv:1710.05402

More appropriate as LHC data becomes more and more sensitive

Results:

from: Ellis, Murphy, Sanz, You
arXiv:1803.0352

Coefficient	Central value	1-σ
$\bar{c}_{3G}$	0.005	0.003
$\bar{c}_{3W}$	-0.018	0.023
$\bar{c}_{d}$	0.36	0.15
$\bar{c}_{e}$	0.09	0.11
$\bar{c}_{g}$	0.00002	0.00002
$\bar{c}_{H}$	-1.1	0.6
$\bar{c}_{HB}$	-0.013	0.018
$\bar{c}_{Hd}$	-0.035	0.017
$\bar{c}_{He}$	0.007	0.013
$\bar{c}_{Hq}$	-0.003	0.004
$\bar{c}'_{Hq}$	-0.003	0.003
$\bar{c}_{Hu}$	-0.03	0.013
$\bar{c}_{HW}$	0.002	0.014
$\bar{c}_{\ell\ell}$	-0.009	0.006
$\bar{c}_{T}$	0.005	0.013
$\bar{c}_{u}$	-4.7	2.6
$\bar{c}_{uG}$	0.031	0.016
$\bar{c}_{W} - \bar{c}_{B}$	-0.04	0.04
$\bar{c}_{W} + \bar{c}_{B}$	0.003	0.024
$\bar{c}_{\gamma}$	-0.001	0.0006

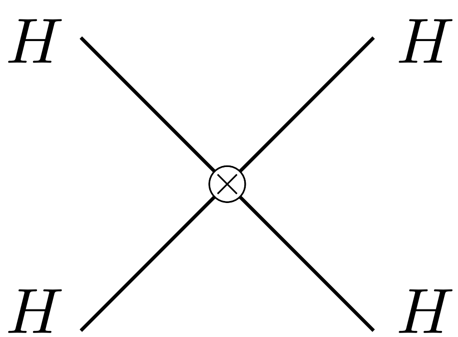
Q: What do the derived limits on $c_i^{(6)}$ imply on the scale Λ of NP ?

☞ *A: estimate of Λ depends on the kind of UV dynamics*

How far can can we extrapolate weakly our theory

Higher-derivative operators
imply strong coupling scale

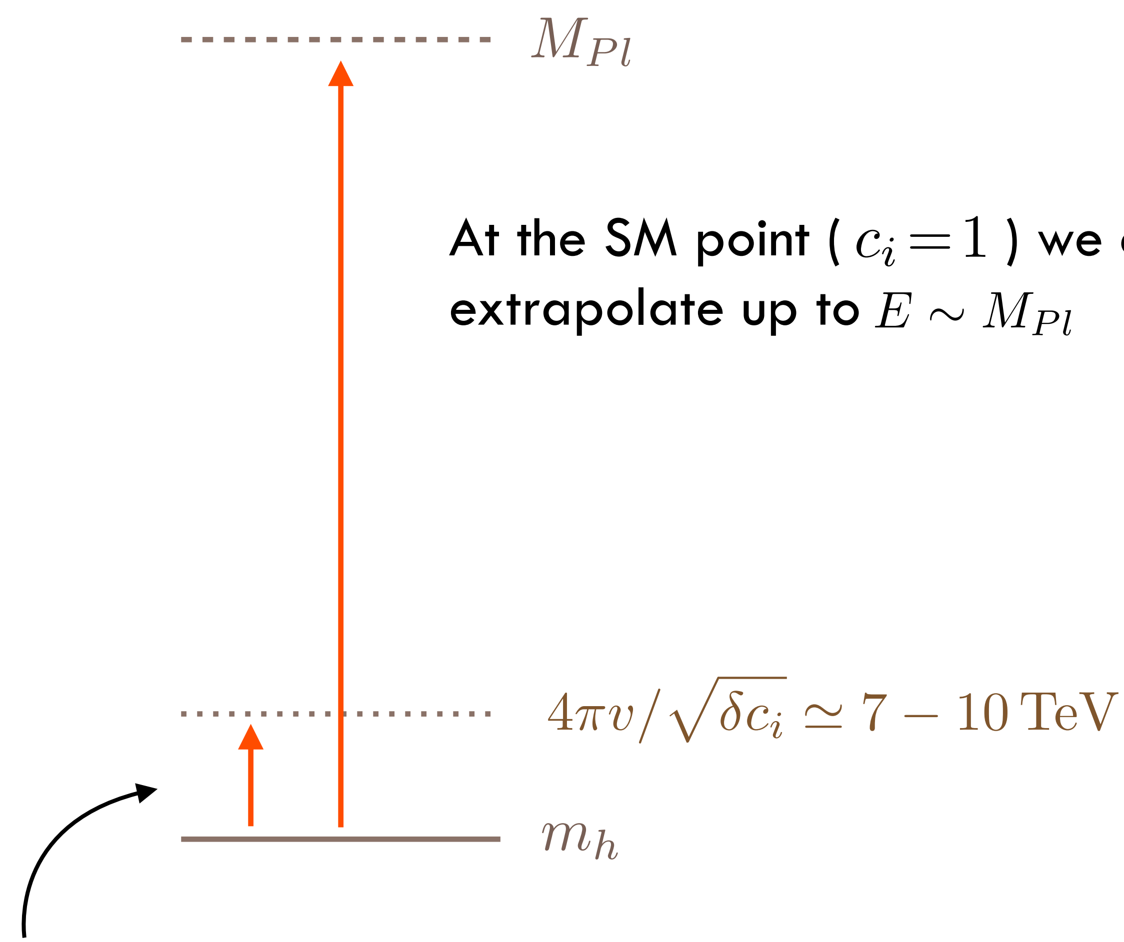
Ex: $$O_H = \left[\partial_\mu (H^\dagger H)\right]^2$$



$$\sim \bar{c}_H \frac{E^2}{v^2}$$

Strong interaction at

$$E \sim \Lambda_S = \frac{4\pi v}{\sqrt{\bar{c}_H}}$$



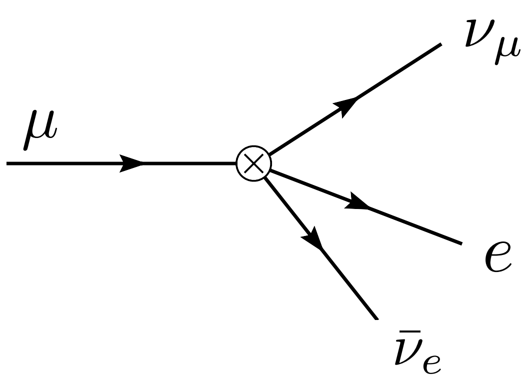
At the SM point ($c_i = 1$) we can extrapolate up to $E \sim M_{Pl}$

With current knowledge of the Higgs couplings ($\delta c_i \lesssim 0.1 - 0.2$) we can extrapolate so much

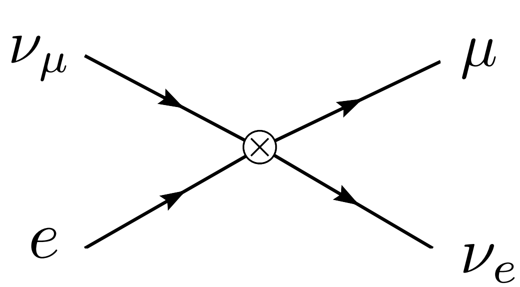
Validity of SMEFT at colliders

<u>Example</u>: Fermi theory

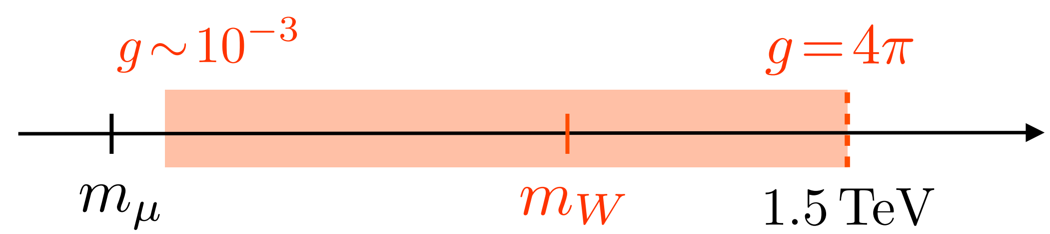
$$\mathcal{L}_{\rm eff} \supset c^{(6)}\,(\bar{e}\gamma_\rho P_L \nu_e)(\bar{\nu}_\mu \gamma_\rho P_L \mu) + \text{h.c.} \qquad c^{(6)} = -\frac{g^2}{2m_W^2}$$



Muon decay measures $c^{(6)} \sim g^2/m_W^2$ → "new physics" scale m_W not directly accessible



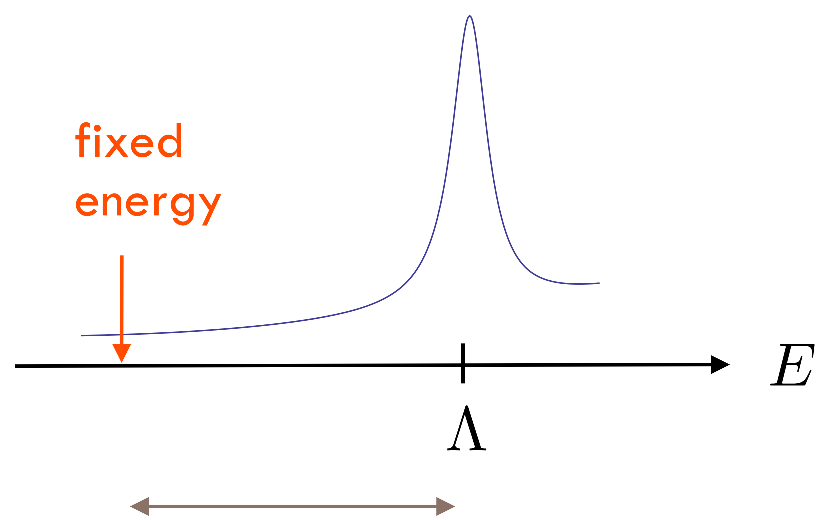
Estimating the scale at which NP shows up (e.g. in neutrino scattering) requires making an assumption on the coupling



☞ *Assessing the validity of the EFT analysis also requires making assumptions of the UV dynamics*

LHC not ideal for an EFT approach

- EFT best suited to fixed-energy, high-precision experiments (ex: LEP, flavor)



large gap of scales requires RG to re-sum large logs

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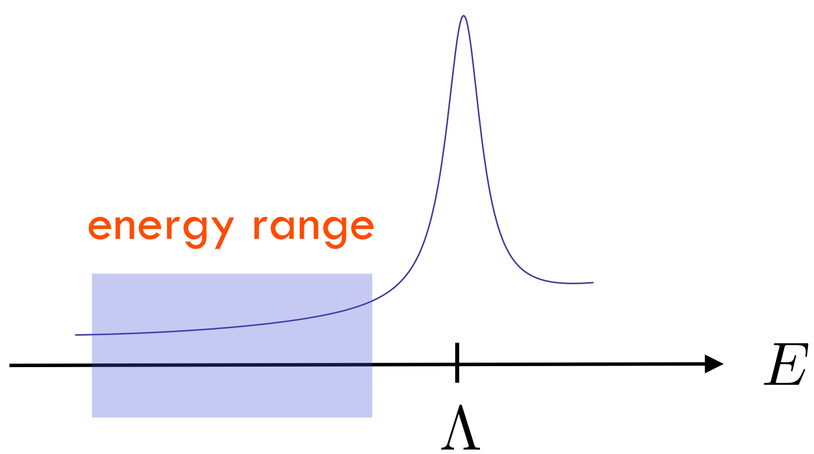


- less suited to low-precision experiments probing an energy range (ex: LHC, hadron machines in general)

EFT fails when max probed energy E_{max} is equal or bigger than physical scale Λ

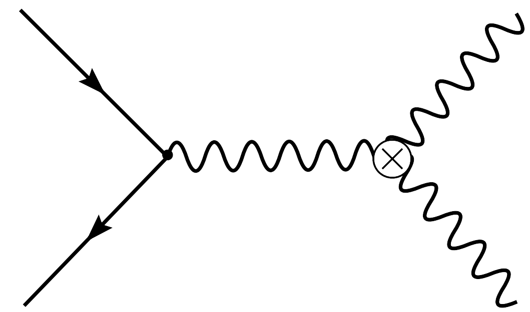
☞ One can check a posteriori, but *needs to know* E_{max}

TGC measurements: LEP vs LHC

Three dim-6 operators affect TGC

$$\left.\begin{aligned} O_{HW} &= D_\mu H^\dagger W^{\mu\nu} D_\nu H \\ O_{HB} &= D_\mu H^\dagger B^{\mu\nu} D_\nu H \end{aligned}\right] \rightarrow V_L V_L$$

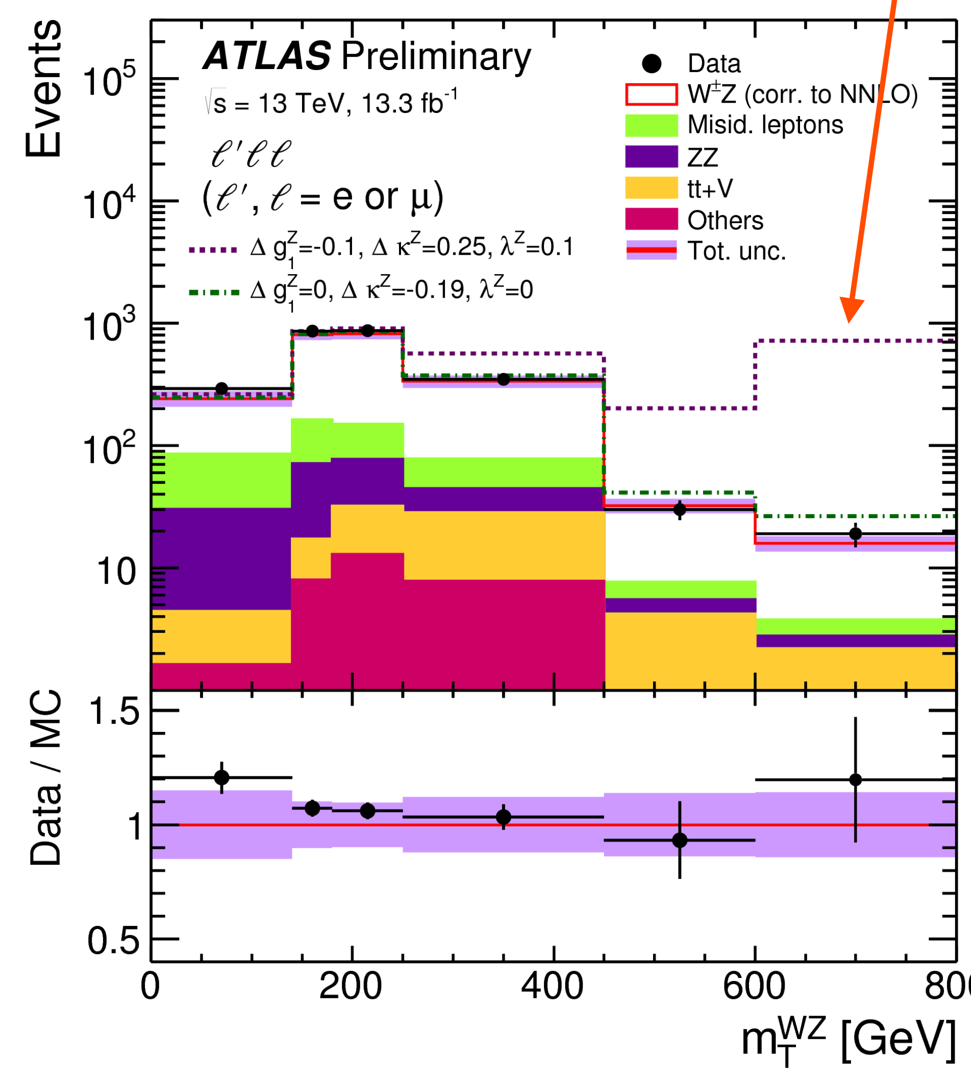
$$O_{3W} = \mathrm{Tr}(W_{\mu\nu} W^{\nu\rho} W_\rho^\mu) \rightarrow V_T V_T$$



- LEP2 operated in a narrow range of com energies $\sqrt{s} \sim 200\,\mathrm{GeV}$
- LHC spans a wide energy interval

sensitivity on NP mainly comes from bins at large energy

ATLAS-CONF-2016-043

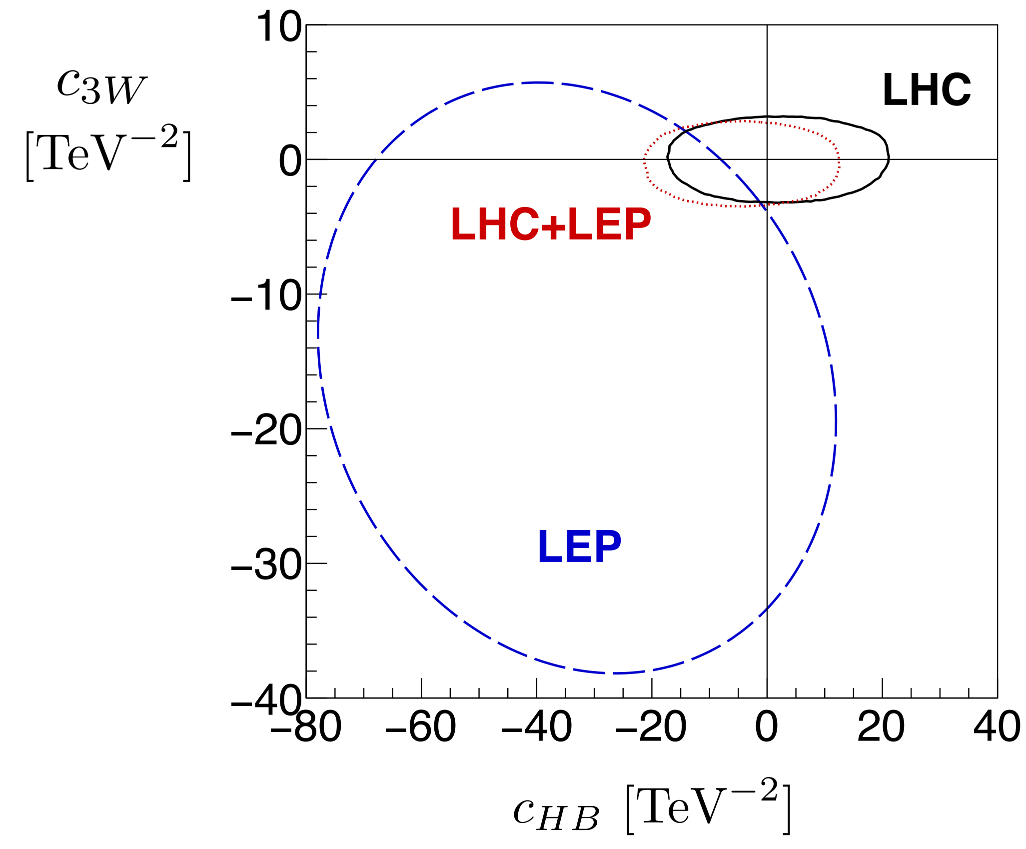


Fit to TGCs

Butter et al. JHEP 1607 (2016) 152

see also:
Falkowski et al. JHEP 1702 (2017) 115
Franceschini et al. JHEP 1802 (2018) 111
Liu and L.T. Wang arXiv:1804.08688

$$\sigma = \sigma_{SM}\left(1 + c_i A_i + c_i c_j B_{ij}\right)$$



1-dimensional 95% CL constraints

LEP	$c_{HW} \in [-7.6, 19]\ \mathrm{TeV}^{-2}$ $c_{HB} \in [-67, 1.8]\ \mathrm{TeV}^{-2}$ $c_{3W} \in [-32, 3.3]\ \mathrm{TeV}^{-2}$	fit dominated by (D=6) linear terms
LHC	$c_{HW} \in [-1.5, 6.3]\ \mathrm{TeV}^{-2}$ $c_{HB} \in [-14.3, 15.9]\ \mathrm{TeV}^{-2}$ $c_{3W} \in [-2.4, 3.2]\ \mathrm{TeV}^{-2}$	fit dominated by $(D=6)^2$ terms

Fit to TGCs

Butter et al. JHEP 1607 (2016) 152

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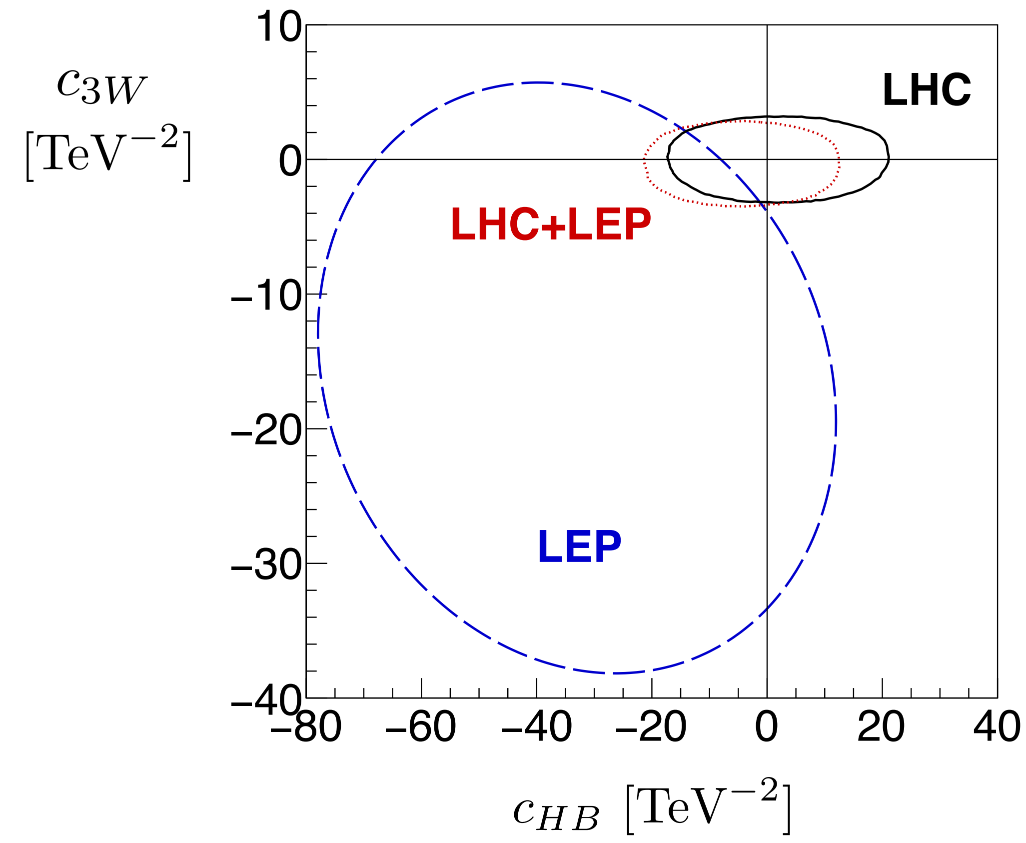

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$$c_{3W} \in [-2.4, 3.2]\ \mathrm{TeV}^{-2}$$

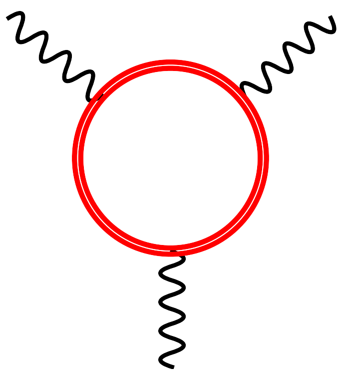
Naively:

- *LHC constraints stronger than LEP ones*
- *c_{3W} slightly more constrained*

Estimating the cutoff scale through SILH power counting (1 coupling, 1 scale):

[Giudice et al. JHEP 0706 (2007) 045]

$$c_{3W} \sim \frac{g}{\Lambda^2}\left(\frac{g^2}{16\pi^2}\right) \qquad\qquad c_{HW,HB} \sim \frac{g}{\Lambda^2}\left(\frac{g_*^2}{16\pi^2}\right)$$



1-dimensional 95% CL constraints

LEP

$$c_{HW} \in [-7.6, 19]\,\mathrm{TeV}^{-2}$$
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$$\rightarrow \Lambda \gtrsim 200\,\mathrm{GeV}\left(\frac{g_*}{4\pi}\right)$$

$$c_{3W} \in [-32, 3.3]\,\mathrm{TeV}^{-2} \rightarrow \Lambda \gtrsim 10\,\mathrm{GeV}$$

LHC

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EFT does <u>not</u> quite work, unless the power counting is different

for example

Strong dipolar interactions

[Liu, Pomarol, Rattazzi, Riva JHEP 1611 (2016) 141]

$$c_{3W} \sim \frac{g_*}{\Lambda^2} \rightarrow \Lambda \gtrsim 2\,\mathrm{TeV}\left(\frac{g_*}{4\pi}\right)^{1/2}$$

95% CL at the LHC

1-dimensional 95% CL constraints

LEP

$$c_{HW} \in [-7.6, 19]\,\mathrm{TeV}^{-2}$$
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Linear vs Quadratic

Notice: Dominance of linear terms (over quadratic ones) is per se neither sufficient nor necessary a condition for the EFT to be valid

✗ Not sufficient — Ex: TGC at LEP2

$$\frac{\delta\sigma}{\sigma} \sim \frac{c_{3W}}{g} E^2 \sim \frac{g^2}{16\pi^2} \frac{E^2}{\Lambda^2}$$

small large

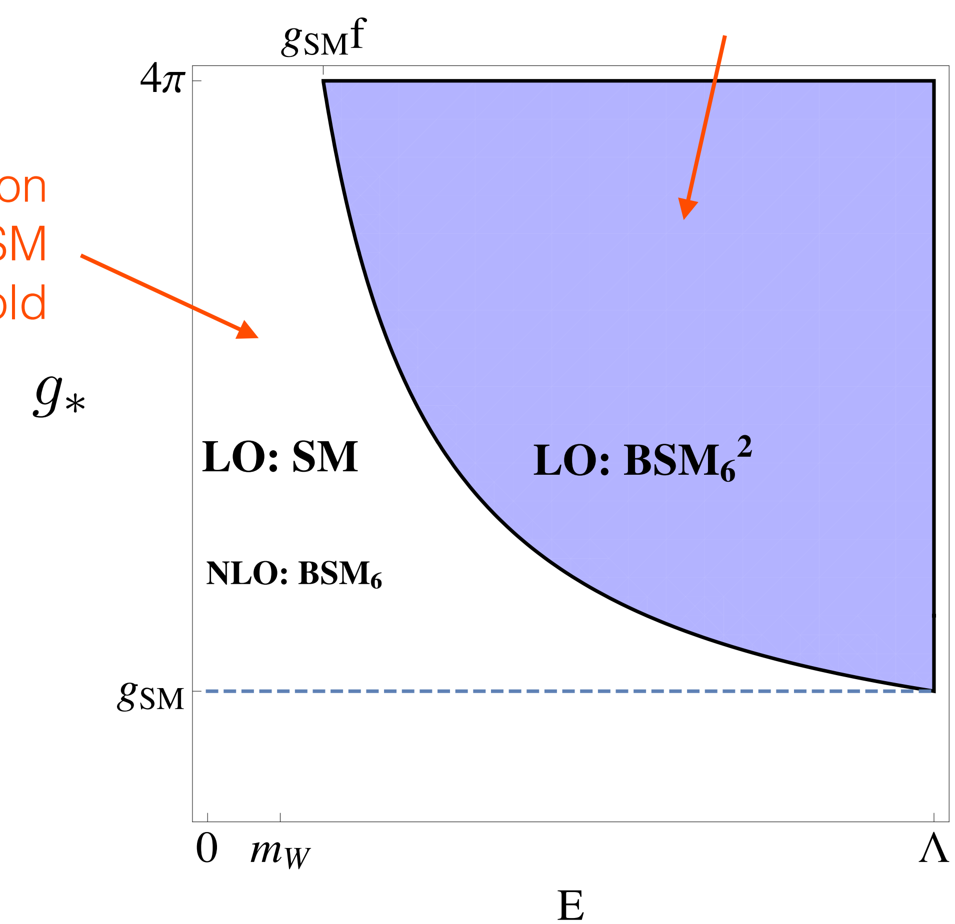
✗ Not necessary — Ex: $V_L V_L \to V_L V_L$ scattering

$$O_6 = (H\partial H)^2 \qquad c^{(6)} \sim \frac{g_*^2}{\Lambda^2}$$

$$\sigma(LL \to LL) \sim \frac{g_{\rm SM}^4}{E^2}\left[1 + \underbrace{\frac{g_*^2}{g_{\rm SM}^2}\frac{E^2}{\Lambda^2}}_{\rm BSM_6 \times\ SM} + \underbrace{\frac{g_*^4}{g_{\rm SM}^4}\frac{E^4}{\Lambda^4}}_{\rm BSM_6{}^2} + \dots\right]$$

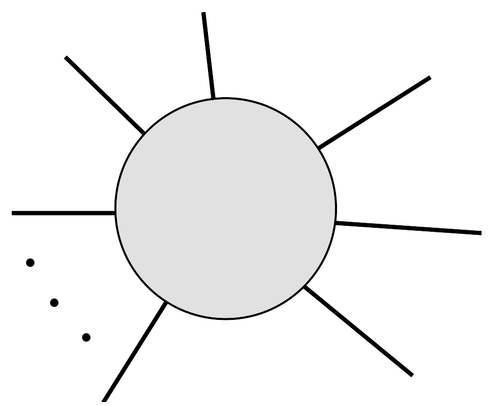
BSM dominates over SM for $\Lambda\, g/g_* < E < \Lambda$

NLO correction from dim6-SM close to threshold



Further challenge to EFT: Non-interference from helicity selection rules

[Azatov, RC, Machado, Riva PRD 92 (2015) 035001]



$$h(A) = \sum_i h_i$$

dim-6 and SM interfere only if they contribute to the same helicity amplitude (*the total helicity* $h(A)$ *must be the same*)

A_4	$\lvert h(A_4^{\rm SM})\rvert$	$\lvert h(A_4^{\rm BSM})\rvert$
$VVVV$	0	4,2
$VV\phi\phi$	0	2
$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

No interference for 4-point amplitudes with at least one transverse boson

Validity:

- at tree-level in the massless (high-energy) limit $E \gg m_W$
- only dim-6 operators
- only 4-point amplitudes

Beyond the leading approximation

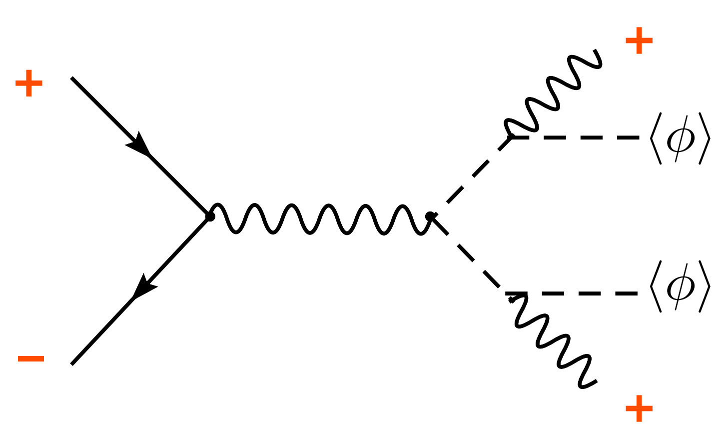
- Non-interference in general fails for higher-point amplitudes and at the 1-loop level

  Leading effect arises at $O(\alpha_S/\pi)$ from real emissions (for inclusive processes) and 1-loop virtual corrections (pure EW corrections similar but smaller)

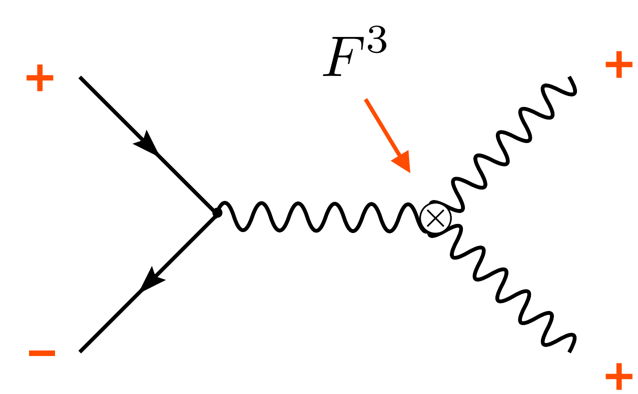
  No log enhancement in the interference due to soft and collinear singularities in real emissions or IR divergences in 1-loop diagrams [see: Dixon and Shadmi NPB 423 (1994) 3]

- Finite-mass effects arise at $O(m_{W,t}^2/E^2)$ and can be determined by considering higher-point amplitudes with Higgs vevs

Ex:



SM: $A_6(\psi^+\psi^-V^+V^+\phi\phi)$



BSM$_6$: $A_6(\psi^+\psi^-V^+V^+)$

- radiative corrections subdominant compared to mass effects except at very high energies $E \gtrsim m_W \sqrt{4\pi/\alpha_S} \sim 1\,\mathrm{TeV}$

Fermion mass insertions usually subdominant except for top quarks (e.g. F^3 interferes at $O(\varepsilon_F^2)$ in $gg \to t\bar{t}$)

- Accessing the $O(1/\Lambda^2)$ corrections from D=6 operators *without relative suppression* is possible by considering $2 \to 3$ processes (i.e. $2 \to 2$ plus extra jet)

ex: constraining F^3 through 3-jet events [Dixon and Shadmi NPB 423 (1994) 3]

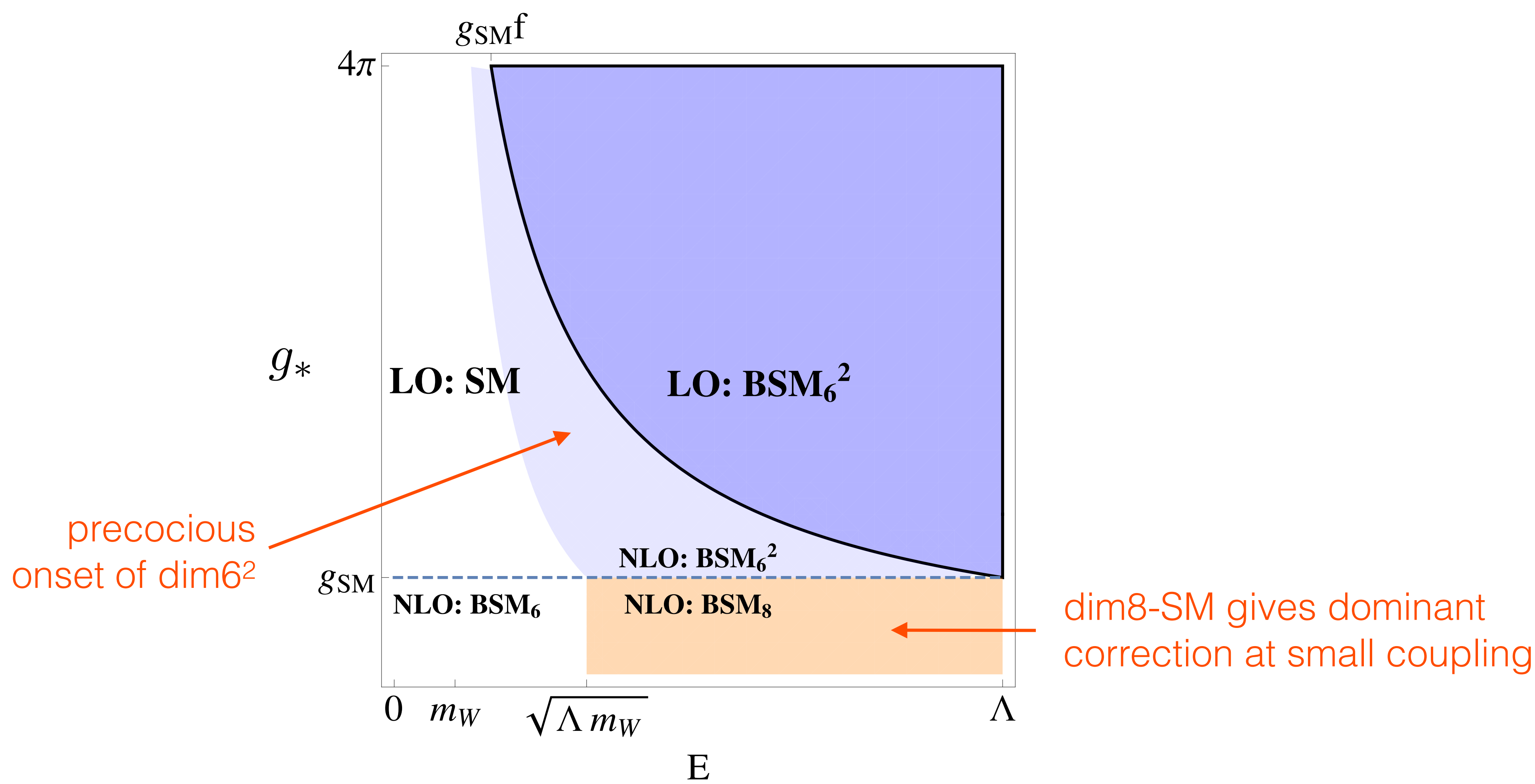
Max gain in sensitivity $\sim \sqrt{4\pi/\alpha_S}$ (at the cost of a reduced S/B)

Implications of non-interference

Example: $V_L V_L \to V_T V_T \quad (\, T = \pm \,)$

$$O_6 = F_{\mu\nu}^2 H^\dagger H \qquad c^{(6)} \sim \frac{g_*^2}{\Lambda^2}$$

$$O_8 = F_{\mu\nu}^2 H^\dagger H\, D^2 \qquad c^{(8)} \sim \frac{g_*^2}{\Lambda^4}$$



$$\sigma(LL \to TT) \sim \frac{g_{SM}^4}{E^2}\left[1 + \underbrace{\frac{g_*^2}{g_{SM}^2}\frac{m_W^2}{\Lambda^2}}_{\mathrm{BSM}_6\,\times\,\mathrm{SM}} + \underbrace{\frac{g_*^4}{g_{SM}^4}\frac{E^4}{\Lambda^4}}_{\mathrm{BSM}_6{}^2} + \underbrace{\frac{g_*^2}{g_{SM}^2}\frac{E^4}{\Lambda^4}}_{\mathrm{BSM}_8\,\times\,\mathrm{SM}} + \dots\right]$$

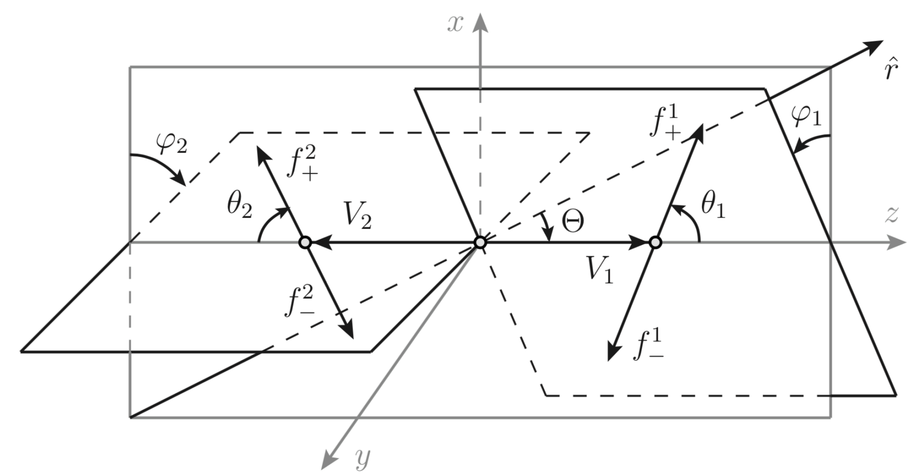
Avoiding non-interference by exclusive processes

Panico, Riva and Wulzer, PLB 776 (2018) 473
Azatov, Elias-Miro, Reyimuaji, Venturini JHEP 1710 (2017) 027

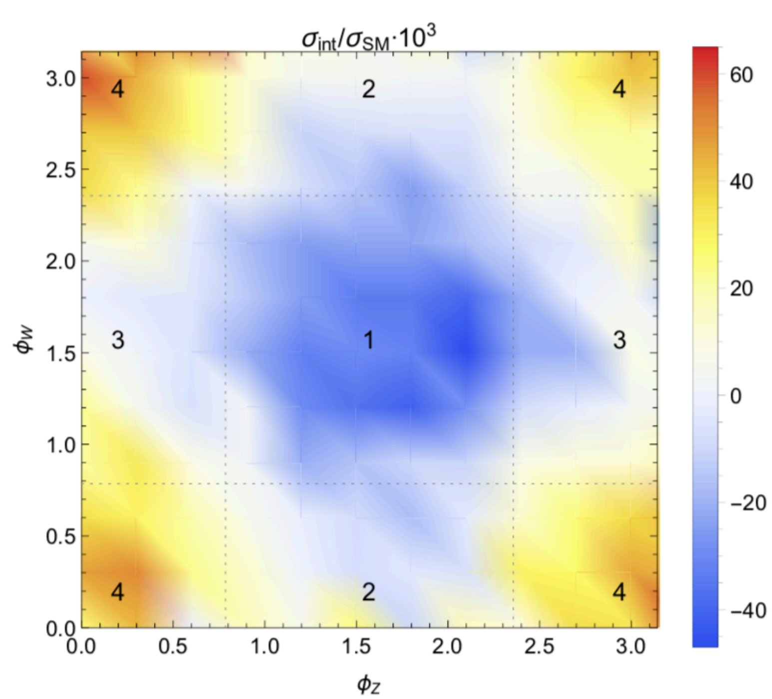
- Vector bosons not asymptotic states, decay to fermions

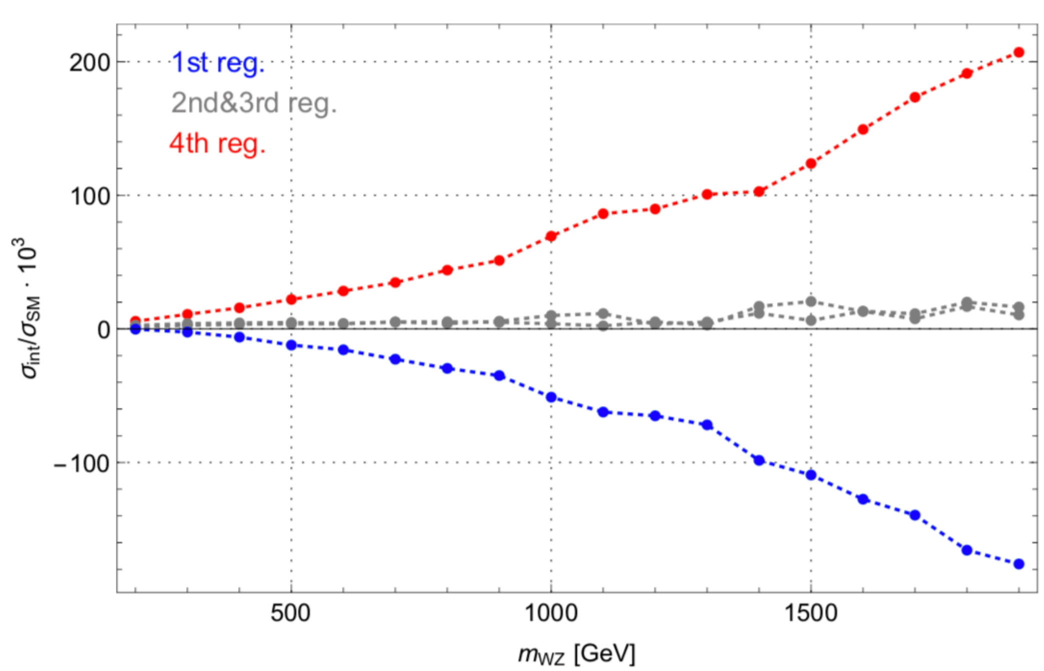
- Interference arises in scattering amplitudes at fixed azimuthal angles

  Averaging over azimuthal angles washes out the interference



$$\frac{d\sigma_{\rm int}(q\bar{q} \to WZ \to 4\psi)}{d\phi_Z\, d\phi_W} \propto \cos(2\phi_Z) + \cos(2\phi_W)$$





Strategy for a consistent EFT analysis of data

[RC, Falkowski, Goertz, Grojean, Riva JHEP 1607 (2016) 144]

1. Fit of coefficients $c_i^{(6)}$ can be done model independently

   Results should be reported as functions of $M_{\rm cut}$ = max characteristic energy scale

$$c_i^{(6)} < \delta_i^{\rm exp}(M_{\rm cut})$$

2. Interpretation of results require assumptions on UV dynamics

   power counting $\longrightarrow$ $c_i^{(6)} = \dfrac{\tilde{c}_i^{(6)}(g_*)}{\Lambda^2}$

3. Consistent (though conservative) limits through *restriction* of dataset: set $M_{cut} = \kappa\,\Lambda$

$$\boxed{c_i^{(6)} = \frac{\tilde{c}_i^{(6)}(g_*)}{\Lambda^2} < \delta_i^{\rm exp}(\kappa\Lambda)}$$

$0 < \kappa < 1$ controls the size of the tolerated error due to higher-derivative operators

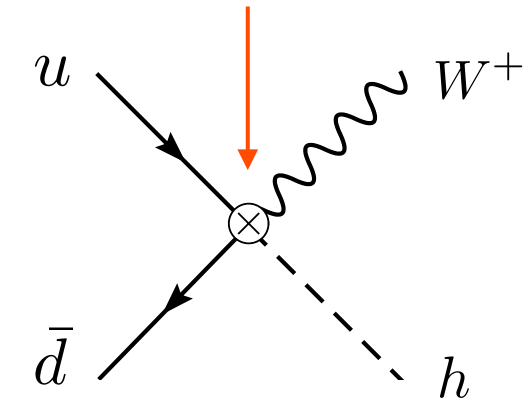
limits on scale Λ set by using data up to $M_{\rm cut} = \kappa\Lambda$

Example of idealized measurement: $u\bar{d} \to W^+ h$

M_{Wh}[TeV]	0.5	1	1.5	2	2.5	3
$\sigma/\sigma_{\rm SM}$	1 ± 1.2	1 ± 1.0	1 ± 0.8	1 ± 1.2	1 ± 1.6	1 ± 3.0

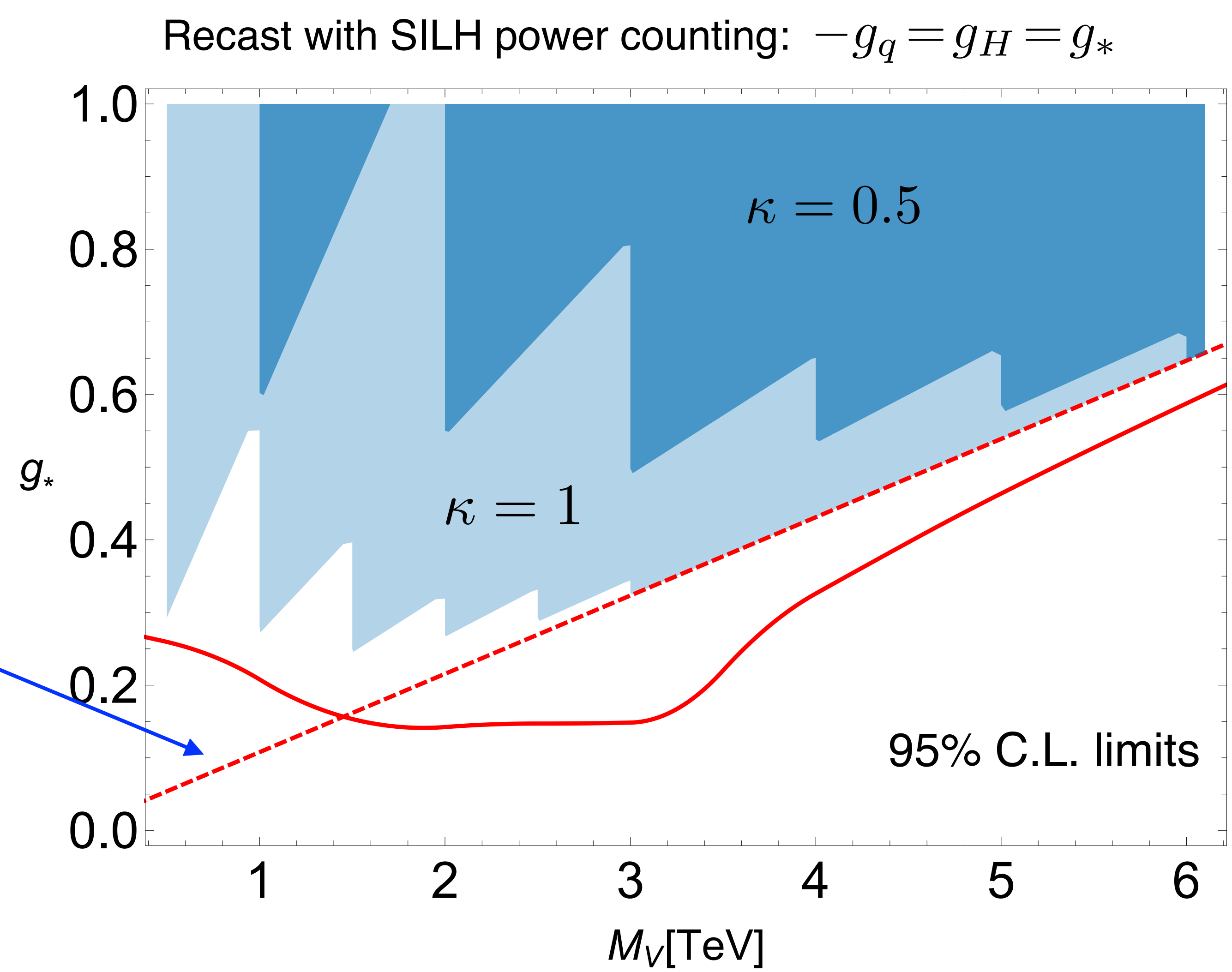
$$O_{H\psi} = i\,\bar{q}_L \gamma_\mu \sigma^a q_L (H^\dagger \sigma^a \overleftrightarrow{D}_\mu H)$$

$$c_{H\psi} = -\frac{g_H g_q}{M_V^2}$$



Model of heavy spin-1:

$$\mathcal{L} \supset i g_H V^i_\mu H^\dagger \sigma^i \overleftrightarrow{D}_\mu H + g_q V^i_\mu \bar{q}_L \gamma_\mu \sigma^i q_L$$



simplified model of spin-1 resonance

inclusive EFT analysis

Beyond dim-6 operators

- D=8 operators can become important in special cases if D=6 ones are suppressed by *symmetries* or *selection rules*

Example: Double Higgs production via gluon fusion (assuming Higgs is a pNGB)

[Azatov, RC, Panico, Son PRD 92 (2015) 035001]

violates the shift (Goldstone) symmetry

$$O_g = H^\dagger H\, G^a_{\mu\nu} G^{a\,\mu\nu}$$

$$c^{(6)} \sim \frac{g_s^2}{16\pi^2}\,\frac{\lambda^2}{\Lambda^2}$$

(λ = weak spurion breaking the shift symmetry)

$$O_{gD0} = (D_\rho H^\dagger D^\rho H) G^a_{\mu\nu} G^{a\,\mu\nu}$$

$$O_{gD2} = (\eta^{\mu\nu} D_\rho H^\dagger D^\rho H - 4 D^\mu H^\dagger D^\nu H) G^a_{\mu\alpha} G^{a\,\alpha}_{\nu}$$

$$c^{(8)} \sim \frac{g_s^2}{16\pi^2}\,\frac{g_*^2}{\Lambda^4}$$

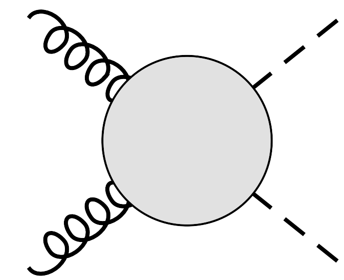
$$A(gg \to hh) \sim \frac{g_s^2}{16\pi^2}\Bigg(\underbrace{y_t^2}_{\text{SM}} + \underbrace{\lambda^2 \frac{E^2}{\Lambda^2}}_{\text{dim-6}} + \underbrace{g_*^2 \frac{E^4}{\Lambda^4}}_{\text{dim-8}} + \dots\Bigg)$$

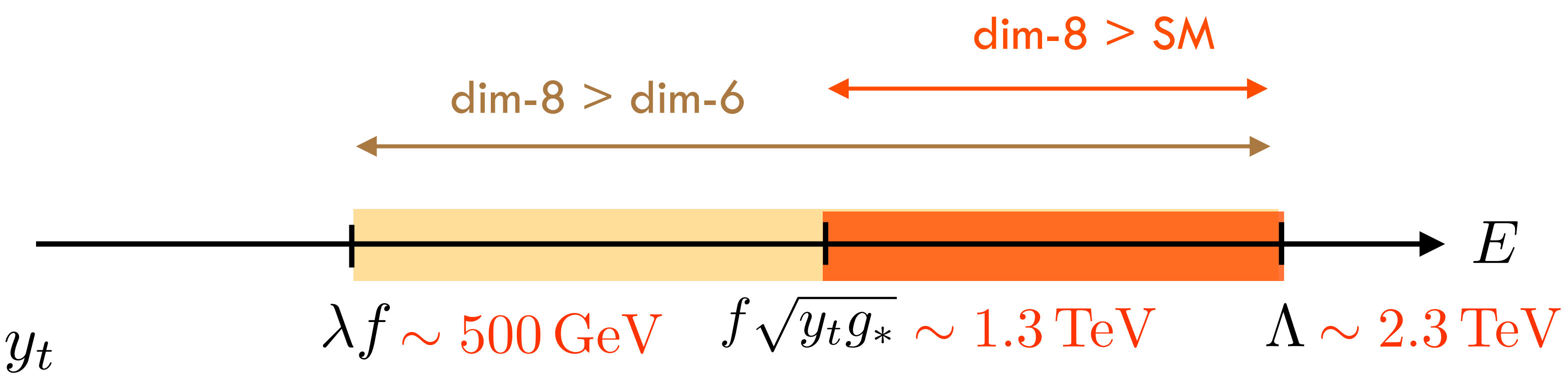
Notice: strong coupling g_* appears only at the dim-8 level

dim-8 dominate over dim-6 for:

$$\boxed{\lambda f < E < \Lambda}$$

In practice: double Higgs production has a very low rate, dim-8 are unobservable at the LHC unless bigger than SM





Example: $\lambda = y_t$

$(v^2/f^2) = 0.1$

$g_* = 3$

For a luminosity: $L = 3\,\mathrm{ab}^{-1}$

- requiring at least 5 events
- including 10% efficiency due to kinematic cuts

Largest value of $m(hh)$[GeV]	$b\bar{b}\gamma\gamma$	$4b$
$\sqrt{s} = 14\,\mathrm{TeV}$	550	1550
$\sqrt{s} = 100\,\mathrm{TeV}$	1350	4300

Probing dim-8 operators is very difficult (perhaps impossible) at the LHC