Theory introduction: Effective Field Theories

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What is an Effective Field Theory?

A pragmatic definition:

it's a field theory that describes the **IR limit** of an underlying UV sector in terms of only the light degrees of freedom

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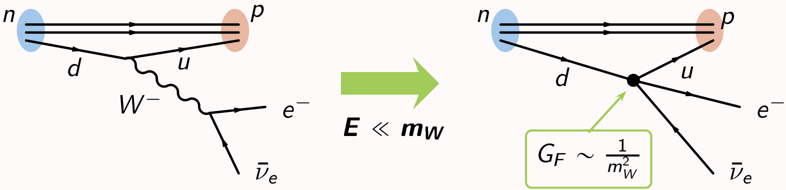
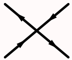
A classical example: **Fermi's interaction** for β-decays

"True" theory: Electroweak interactions | EFT: Fermi's interactions



$$\mathcal{A}\left(\frac{1}{m_W^2}\right)$$

$$\mathcal{A}(0) + \frac{1}{m_W^2}\left(\right.$$  $$\left. + \dots \right) + \mathcal{O}\left(m_W^{-4}\right)$$

EFTs: basic principles

Subject: impact of physics $\mathcal{P}$ with scale Λ on observables measured at $E \ll \Lambda$
Λ can be a mass, confinement scale, etc.

- at $E \ll \Lambda$ $\mathcal{P}$ states cannot be produced on-shell $\Rightarrow$ **internal** lines only
  $\Rightarrow$ S-matrix contribution is analytical:
  non-analyticity only happens at resonance $E \sim \Lambda$
- **Decoupling theorem**: Appelquist,Carrazzone PRD11 (1975) 2856
  Green's functions with internal $\mathcal{P}$ are suppressed by Λ^n
- **Uncertainty principle**:
  virtual particles of mass M are localized within $\Delta x \simeq \frac{1}{\Delta p} = \frac{1}{M}$

$\mathcal{P}$ effects at $E \ll \Lambda$ are described by
local, **analytic** operators with $\mathbf{1/\Lambda^n}$ **suppressions**

↕

Taylor expansion in (E/Λ) at the Lagrangian level (and also S-matrix and obs.)

EFTs: basic principles

for E/Λ sufficiently small the $\mathcal{P}$ sector **decouples**

this means:

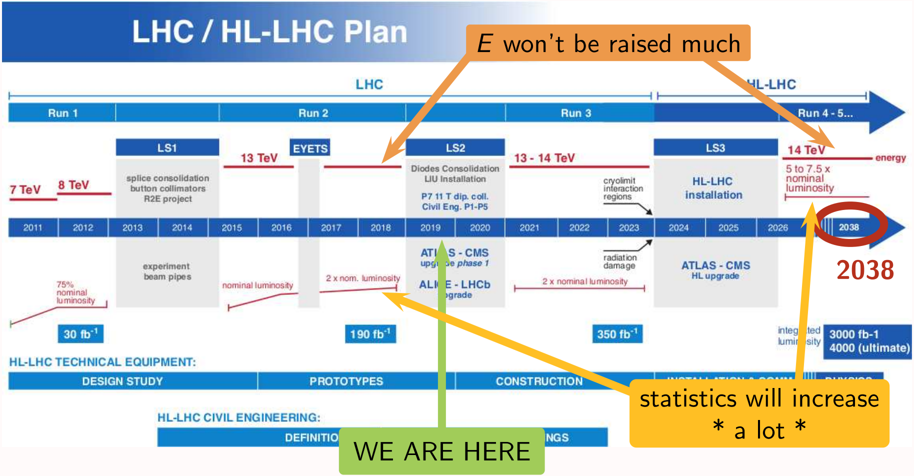
- the $\mathcal{P}$ sector is not resolved completely at $E \ll \Lambda$. only the dominant effects, according to power counting
- the details of $\mathcal{P}$ are irrelevant for physics at $E \ll \Lambda$
- UV divergences in the $\mathcal{P}$ theory are subtracted from low-E physics

same principle as usual **renormalization**: UV modes can be subtracted out of the physical description, that becomes independent of them.

This ensures we can factor UV and IR components:

$$\mathscr{L} \supset \frac{C_i^{UV}(\mu)}{\Lambda^n} \mathcal{O}_i^{IR}(\mu)$$

LHC: plans for the future



there's much room for improvement in precision →

worth having
a systematic program
for **indirect searches**

The power of EFTs

- full QFTs with their own regularization/renormalization schemes
  not just anomalous couplings!

- calculations are done **order by order in** $\delta = (E/\Lambda)$
  → rationale for expected size of contributions: power counting
  → systematically improvable

- allow compute matrix elements **without knowing the UV**
  → only input: low E fields & symmetries
  → works even if the UV is *non-perturbative*
  e.g. chiral perturbation theory: $\pi - \pi$ scattering computed in 1966

- **model independent**, within low-energy assumption

- systematic classification of **all** effects compatible with low-E assumptions

- a universal language for interpretation of measurements

An EFT for BSM searches: the SMEFT

fundamental assumptions:

- new physics nearly decoupled: $\Lambda \gg (v, E)$
- at the accessible scale: **SM** fields + symmetries

☛ a Taylor expansion in canonical dimensions ($\delta = v/\Lambda$ or E/Λ):

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \dots$$

$\mathcal{L}_n = \sum_i C_i \mathcal{O}_i^{d=n}$

C_i free parameters (Wilson coefficients)

$\mathcal{O}_i$ invariant operators that form a complete, non redundant basis

The Warsaw basis

Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r\varphi)$
$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r\widetilde\varphi)$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r\varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\,\widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\,\widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\,\widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\,\widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

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Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu \tau^I q_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu \tau^I l_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

Constructing a basis

SM fields + symmetries

↓

all the allowed invariant structures at dimension d

remove terms that give equivalent physics (redundant at S-matrix level) via

- **integration by parts**

  e.g. $\partial_\mu(H^\dagger H)\partial^\mu(H^\dagger H) = -(H^\dagger H)\,\Box\,(H^\dagger H)$

- **equations of motion (EOM)**

  e.g. $(H^\dagger H)(\bar\psi_L i\not{D}\psi_L) \sim (H^\dagger H)(\bar\psi_L H\psi_R)$

a basis

=

minimal set of independent operators (parameters) for the most general classification of BSM effects

Some remarks

- the basis choice is not unique but the *physics* is basis-independent.
- customary choice with large consensus: **Warsaw basis**

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(a) EOMs move effects between different sectors

$$\begin{aligned}\Box H^\dagger \Box H \equiv \quad & D_\mu H^\dagger D^\mu H \\ & + \bar\psi_L H y \psi_R + (\bar\psi_L H y \psi_R)(H^\dagger H) + \text{h.c.} \\ & + (\bar\psi_R y \psi'_L)(\bar\psi'_L y \psi_R) + \text{h.c.} \\ & + (\bar\psi_L y \psi'_R)(\bar\psi'_L y \psi_R) + \text{h.c.} \\ & + H^\dagger H + (H^\dagger H)^2 + (H^\dagger H)^3\end{aligned}$$

(exact coefficients omitted)

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(a) EOMs move effects between different sectors

$$D_\mu G^{a\mu\nu} D^\rho G^a_{\rho\nu} \equiv (\bar{q} T^a q + \bar{u} T^a u + \bar{d} T^a d)^2$$

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(b) the physical meaning of individual parameters is basis-dependent

example:

$$\mathscr{L} \supset -(C^1_{Hq} - \mathbf{C^3_{Hq}})\bar{t}tZ - (C^1_{Hq} + \mathbf{C^3_{Hq}})\bar{b}bZ - \mathbf{C^3_{Hq}}(\bar{t}bW + \text{h.c.})$$

2 independent parameters: $(C^1_{Hq}, \mathbf{C^3_{Hq}})$

in general changing basis changes the values of the EFT parameters

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example:

$$\mathscr{L} \supset -C_{Hq}^{-}\bar{t}tZ - (C_{Hq}^{-} + \mathbf{2C_{Hq}^{3}})\bar{b}bZ - \mathbf{C_{Hq}^{3}}(\bar{t}bW + \text{h.c.})$$

2 independent parameters:

$$(C_{Hq}^{1}, C_{Hq}^{3})$$

$$(C_{Hq}^{-} \equiv C_{Hq}^{1} - C_{Hq}^{3}, \mathbf{C_{Hq}^{3}})$$

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example:

$$\mathscr{L} \supset -(C^{+}_{Hq} - \mathbf{2C^{3}_{Hq}})\bar{t}tZ - C^{+}_{Hq}\bar{b}bZ - \mathbf{C^{3}_{Hq}}(\bar{t}bW + \text{h.c.})$$

2 independent parameters:

(C^{1}_{Hq}, C^{3}_{Hq})
$(C^{-}_{Hq} \equiv C^{1}_{Hq} - C^{3}_{Hq}, C^{3}_{Hq})$
$(C^{+}_{Hq} \equiv C^{1}_{Hq} + C^{3}_{Hq}, \mathbf{C^{3}_{Hq}})$

in general changing basis changes the values of the EFT parameters

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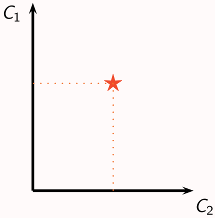

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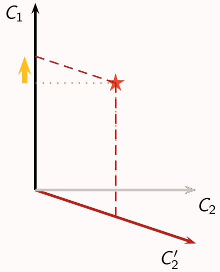
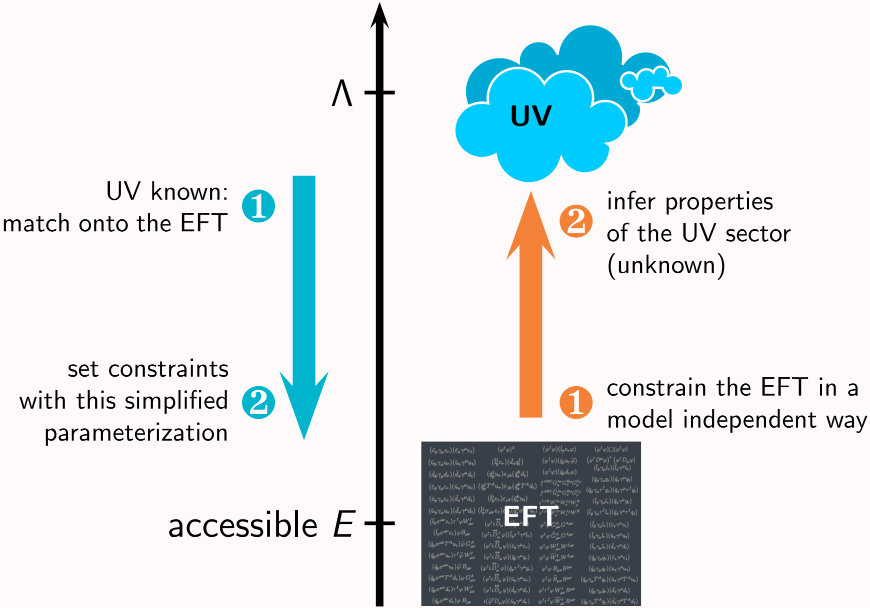


in general changing basis changes the values of the EFT parameters

Top-down and bottom-up



From UV model to EFT: Matching

(1) Integrating out a heavy state

pedestrian procedure: solve the EOM of the heavy particle in the limit $p^2 \ll M^2$.
replace solution in $\mathscr{L}$

e.g. RH seesaw neutrino

Broncano,Gavela,Jenkins hep-ph/0210271, 0307058, 0406019
Abada,Biggio,Bonnet,Gavela,Hambye 0707.4058
Trott,Elgaard-Clausen 1703.04415

$$\mathscr{L}_N = i\bar{N}\partial\!\!\!/ N - \left[\frac{1}{2}\bar{N}MN^c + \bar{N}y(\tilde{H}^\dagger\ell) + \text{h.c.}\right]$$

EOM:

$$(i\partial\!\!\!/ - M)N = y\,\tilde{H}^\dagger\ell + \text{h.c.} \qquad \rightarrow \qquad N \simeq \left[\frac{1}{M} - \frac{i\partial\!\!\!/}{M^2} + \dots\right]\left[y\tilde{H}^\dagger\ell + \text{h.c.}\right]$$

replacing:

$$\mathscr{L}_{N,EFT} = \frac{y^2}{2M}(\bar{\ell}\tilde{H})(\tilde{H}^T\ell^c) + \mathcal{O}(M^{-2})$$

The procedure can be extended to **1-loop** but becomes complex

From UV model to EFT: Matching

(1) Integrating out a heavy state

functional methods allow general matching up to 1-loop:

Covariant Derivative Expansion (CDE)
Universal One-Loop Effective Action (UOLEA)
Expansion by regions

Henning,Lu,Murayama 1412.1837,1604.01019
del Aguila,Kunszt,Santiago 1602.00126
Boggia,Gomez-Ambrosio,Passarino 1603.03660
Drozd,Ellis,Quevillon,You 1512.03003
Ellis,Quevillon,You,Zhang 1604.02445,1706.07765
Fuentes-Martin,Portoles,Ruiz-Femenia 1607.02142
Zhang 1610.00710
(Krämer),Summ,Voigt 1806.05171, 1908.04798

universal structure assumed, e.g. for complex scalar Φ

$$\mathscr{L} = -\Phi^\dagger(D^2 + M^2 + U(x))\Phi + (\Phi^\dagger B(x) + \text{h.c.}) + \dots$$

At tree level:

$$\mathscr{L}_{EFT} \supset \frac{1}{M^2} B^\dagger B + \frac{1}{M^4} B^\dagger(-D^2 - U)B + \dots$$

subtleties:
- non-degenerate states — now mostly solved
- mixed heavy-light loops
- open derivatives

From UV model to EFT: Matching

(2) Map effects to a chosen basis

integrating out particles leads to **arbitrary** Lagrangians

- $d \leqslant 4$ terms reabsorbed in redefinitions
- $d > 4$ terms mapped to a basis.
  Needs an algorithm and the basis to be **complete**

! all coefficients and signs must be kept track of

Useful tools [see 1910.11003]:

`BasisGen`	Criado 1901.03501
`abc_eft`	Aebischer,Stangl in progress
`DEFT`	Gripaios,Sutherland 1807.07546
`DsixTools`	Celis,Fuentes-Martin,Vicente,Virto 1704.04504
`wilson`	Aebischer,Kumar,Straub 1704.04504
`MatchingTools`	Criado 1710.06445
`MatchMaker`	Anastasiou,Carmona,Lazopoulos,Santiago in progress
`CoDEx`	Das Bakshi,Chackrabortty,Patra 1808.04403

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(3) Match S-matrix elements: fix $C_i(UV)$

- equate S-matrix elements in full theory and EFT, evaluated at a common *matching scale*, order by order in perturbation theory
- loop amplitudes usually computed in **dim reg** + $\overline{\mathbf{MS}}$
- UV divergences are canceled independently in the EFT and in the UV.
  The two theories have independent regularization/renormalization schemes.
- IR divergences are the same in the EFT and in the UV

→ The UV - EFT relation generally becomes highly non-trivial

de Blas,Criado,Perez-Victoria,Santiago 1711.10391
Passarino 1901.04177

HEFT = Non-linear EFT = EW chiral Lagrangian

The Higgs does not need to be in a exact SU(2) doublet

$$H = \frac{v+h}{\sqrt{2}}\,\mathbf{U}\begin{pmatrix}0\\1\end{pmatrix}$$

independent

h

treated as a singlet
with arbitrary couplings

$$\mathcal{F}(h) = 1 + 2a\frac{h}{b} + b\frac{h^2}{v^2} + \dots$$

$\mathbf{U} = e^{i\pi^I\sigma^I/v}$

adimensional

derivative expansion $\sim \chi$PT

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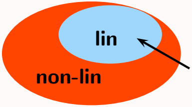
⟶ a **very general** EFT



contains the linear as a particular limit

⟶ matches composite Higgs models
nonlinear effects in the EWSB sector
mixings of the physical Higgs with extra scalars
...

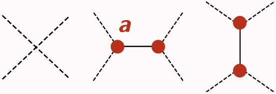
HEFT: relaxing unitarization in SM

Scalar sector of the SM: what do we need?

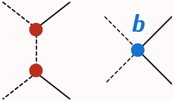
- $m_{W,Z} \neq 0$ $\rightarrow \pi^a$ in a SU(2) fundamental. minimal field: $\mathbf{U} = e^{i\pi^a\sigma^a/v}$
- $+$ exact unitarity at all E $\rightarrow (\mathbf{h}, \pi^a)$ in a SU(2) doublet

Contino, TASI lectures 1005.4269

$$\mathcal{A}(W_L^+ W_L^- \rightarrow W_L^+ W_L^-) \simeq \frac{s+t}{v^2}(1-a^2)$$

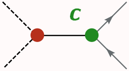


$$\mathcal{A}(W_L^+ W_L^- \rightarrow hh) \simeq \frac{s}{v^2}(b-a^2)$$



$a = b = c = 0$
unitarity violated in VBS
at $s \sim 4\pi v^2 \simeq (500\,\mathrm{GeV})^2$

$$\mathcal{A}(W_L^+ W_L^- \rightarrow \psi\bar{\psi}) \simeq \frac{m_\psi\sqrt{s}}{v^2}(1-ac)$$

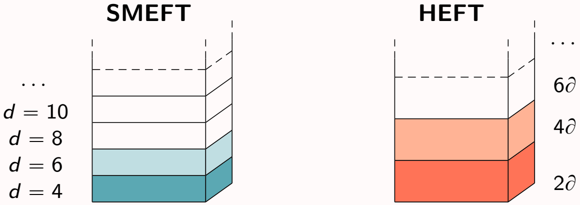


$a = b = c = 1$
unitarity exact.
$\equiv h$ in a doublet

HEFT **free a, b, c** $\rightarrow$ unitarity only partially from Higgs

SMEFT vs. HEFT

The two parameterizations are physically different:



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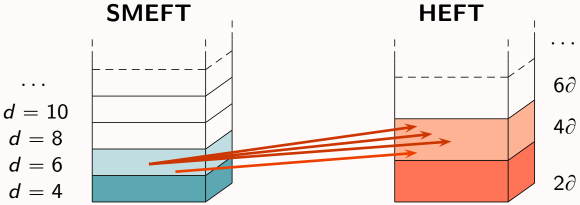

Correspondence: replacing $\Phi \to \frac{v+h}{\sqrt{2}} \mathbf{U} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

Two main categories of effects:

❶ correlations: $D_\mu \Phi \sim (v+h) D_\mu \mathbf{U} + \mathbf{U} \partial_\mu h$ ↔ decorrelations: $D_\mu \mathbf{U}$ and $\partial_\mu h$ independent

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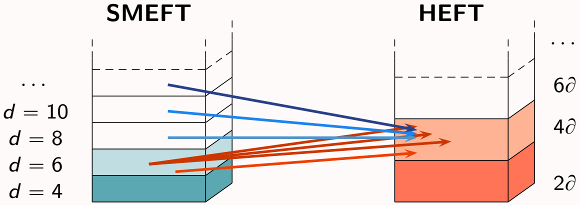

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Two main categories of effects:

❶ correlations: $\leftrightarrow$ decorrelations:

$D_\mu \Phi \sim (v+h) D_\mu \mathbf{U} + \mathbf{U} \partial_\mu h$ — $D_\mu \mathbf{U}$ and $\partial_\mu h$ independent

❷ The chiral NLO contains effects that appear only at $d = 8$ or higher in the linear expansion

Example: SMEFT contributions to VBS

Operators giving significant contributions to VBS

Gomez-Ambrosio 1809.04189

$\mathcal{Q}_{HD} = (H^\dagger D_\mu H)^*(H^\dagger D^\mu H)$	Vff, TGC/QGC, hVV, m_W
$\mathcal{Q}_{H\Box} = (H^\dagger H)(H^\dagger \Box H)$	hVV
$\mathcal{Q}_{W} = \varepsilon_{ijk} W^i_{\mu\nu} W^{j\nu\rho} W^{k\mu}_\rho$	TGC/QGC
$\mathcal{Q}_{\tilde W} = \varepsilon_{ijk} \tilde W^i_{\mu\nu} W^{j\nu\rho} W^{k\mu}_\rho$	TGC/QGC
$\mathcal{Q}_{HB} = (H^\dagger H) B_{\mu\nu} B^{\mu\nu}$	hVV
$\mathcal{Q}_{HW} = (H^\dagger H) W^i_{\mu\nu} W^{i\mu\nu}$	hVV
$\mathcal{Q}_{HWB} = (H^\dagger \sigma^i H) W^i_{\mu\nu} B^{\mu\nu}$	Vff, TGC/QGC, hVV, m_W
$\mathcal{Q}_{H\tilde W B} = (H^\dagger \sigma^i H) \tilde{W}_{\mu\nu}{}^i B^{\mu\nu}$	TGC/QGC, hVV
$\mathcal{Q}_{ll} = (\bar l \gamma_\mu l)(\bar l \gamma^\mu l)$	Vff, TGC/QGC, m_W
$\mathcal{Q}^{(3)}_{Hl} = (H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar l \sigma^i \gamma^\mu l)$	Vff, TGC/QGC, hVV, m_W
$\mathcal{Q}^{(1)}_{Hl} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar l \gamma^\mu l)$	Vff
$\mathcal{Q}^{(1)}_{Hq} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar q \gamma^\mu q)$	Vff
$\mathcal{Q}^{(3)}_{Hq} = (H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar q \sigma^i \gamma^\mu q)$	Vff
$\mathcal{Q}_{Hu} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar u \gamma^\mu u)$	Vff
$\mathcal{Q}_{Hd} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar d \gamma^\mu d)$	Vff
$\mathcal{Q}_{He} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar e \gamma^\mu e)$	Vff
$\mathcal{Q}^{1}_{qq} = (\bar q_\alpha \gamma_\mu q_\alpha)(\bar q_\beta \gamma^\mu q_\beta)$	$(qq)^2$
$\mathcal{Q}^{1\prime}_{qq} = (\bar q_\alpha \gamma_\mu q_\beta)(\bar q_\beta \gamma^\mu q_\alpha)$	$(qq)^2$
$\mathcal{Q}^{3}_{qq} = (\bar q_\alpha \gamma_\mu \sigma^k q_\alpha)(\bar q_\beta \gamma^\mu \sigma^k q_\beta)$	$(qq)^2$
$\mathcal{Q}^{3\prime}_{qq} = (\bar q_\alpha \gamma_\mu \sigma^k q_\beta)(\bar q_\beta \gamma^\mu \sigma^k q_\alpha)$	$(qq)^2$

= Vff ($\Gamma_{W,Z}$) = TGC/QGC = hVV (Γ_h) = m_W = $(qq)^2$

20 parameters

HEFT operators for VBS - minimal set

31 operators (+ 8 four-quarks) but **many more parameters!**

$\mathcal{P}_C = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu)\mathcal{F}_C$

$\mathcal{P}_T = \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\,\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathcal{F}_T$

$\mathcal{P}_B = B_{\mu\nu} B^{\mu\nu}\mathcal{F}_B$

$\mathcal{P}_W = W^a_{\mu\nu} W^{a\mu\nu}\mathcal{F}_W$

$\mathcal{P}_1 = B_{\mu\nu}\,\mathrm{Tr}(\mathbf{T} W^{\mu\nu})\mathcal{F}_1$

$\mathcal{P}_2 = B_{\mu\nu}\,\mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu,\mathbf{V}^\nu])\mathcal{F}_2$

$\mathcal{P}_3 = \mathrm{Tr}(W_{\mu\nu}[\mathbf{V}^\mu,\mathbf{V}^\nu])\mathcal{F}_3$

$\mathcal{P}_4 = B_{\mu\nu}\,\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_4$

$\mathcal{P}_5 = \mathrm{Tr}(W_{\mu\nu}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_5$

$\mathcal{P}_6 = (\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu))^2\mathcal{F}_6$

$\mathcal{P}_{11} = (\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}_\nu))^2\mathcal{F}_{11}$

$\mathcal{P}_{12} = (\mathrm{Tr}(\mathbf{T} W_{\mu\nu}))^2\mathcal{F}_{12}$

$\mathcal{P}_{13} = i\,\mathrm{Tr}(\mathbf{T} W_{\mu\nu})\,\mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu,\mathbf{V}^\nu])\mathcal{F}_{13}$

$\mathcal{P}_{14} = \varepsilon^{\mu\nu\rho\lambda}\,\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\,\mathrm{Tr}(\mathbf{V}_\nu W_{\rho\lambda})\mathcal{F}_{14}$

$\mathcal{P}_{17} = \mathrm{Tr}(\mathbf{T} W_{\mu\nu})\,\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_{17}$

$\mathcal{P}_{18} = \mathrm{Tr}(\mathbf{T}[\mathbf{V}_\mu,\mathbf{V}_\nu])\,\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_{18}$

$\mathcal{P}_{23} = \mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu)(\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu))^2\mathcal{F}_{23}$

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$\mathcal{P}_{26} = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\,\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu))^2\mathcal{F}_{26}$

$\mathcal{P}_{WWW} = \frac{\varepsilon_{abc}}{\Lambda^2} W^{a\nu}_\mu W^{b\rho}_\nu W^{c\mu}_\rho \mathcal{F}_{WWW}$

$\mathcal{S}_1 = \tilde{B}_{\mu\nu}\,\mathrm{Tr}(\mathbf{T} W^{\mu\nu})\mathcal{F}$

$\mathcal{S}_{WWW} = \frac{\varepsilon_{abc}}{\Lambda^2} \tilde{W}^{a\nu}_\mu W^{b\rho}_\nu W^{c\mu}_\rho \mathcal{F}$

$\mathcal{N}^{\mathcal{Q}}_1 = i\bar{Q}_L\,\gamma_\mu\mathbf{V}^\mu\,Q_L\,\mathcal{F}$

$\mathcal{N}^{\mathcal{Q}}_2 = i\bar{Q}_R\,\gamma_\mu\mathbf{U}^\dagger\mathbf{V}^\mu\mathbf{U}\,Q_R\,\mathcal{F}$

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$\mathcal{N}^{\mathcal{Q}}_8 = i\bar{Q}_R\,\gamma_\mu\mathbf{U}^\dagger\mathbf{T}\mathbf{V}^\mu\mathbf{T}\mathbf{U}\,Q_R\,\mathcal{F}$

$\mathcal{N}^{\ell}_2 = i\bar{L}_R\,\gamma_\mu\mathbf{U}^\dagger\{\mathbf{V}^\mu,\mathbf{T}\}\mathbf{U}\,L_R\,\mathcal{F}\,.$

$R^\ell_2 = (\bar{L}_L\,\gamma_\mu\,L_L)(\bar{L}_L\,\gamma^\mu\,L_L)\mathcal{F}$

$R^\ell_5 = (\bar{L}_L\,\gamma_\mu\mathbf{T}\,L_L)(\bar{L}_L\,\gamma^\mu\mathbf{T}\,L_L)\mathcal{F}$

$$\mathbf{T} = U\sigma^3\mathbf{U}^\dagger$$
$$\mathbf{V}_\mu = D_\mu\mathbf{U}\mathbf{U}^\dagger$$

Quick dictionary:

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$$\mathcal{F}_i \to 1 + h/v + \ldots$$

basis of 1604.06801

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correspond to $d \geqslant 8$ in the SMEFT

basis of 1604.06801

The SMEFT - phenomenology

(A) Predictions for a generic observable:

$$\mathcal{O}_{SMEFT} = \mathcal{O}_{SM}\left[1 + \frac{\Delta\mathcal{O}^{int}}{\mathcal{O}_{SM}} + \frac{\Delta\mathcal{O}^{quad}}{\mathcal{O}_{SM}}\right]$$

$\mathcal{O}_{SM}$: the most accurate available

to be computed: tree level / NLO QCD (NLO SMEFT)

→ **Analytic**

→ **Monte Carlo**

dedicated models [more at this link]

`SMEFTsim`	Brivio,Jiang,Trott 1709.06492
`dim6top`	Durieux,Zhang 1802.07237
`SMEFT@NLO`	Degrande,Durieux,Maltoni, Mimasu,Vryonidou,Zhang

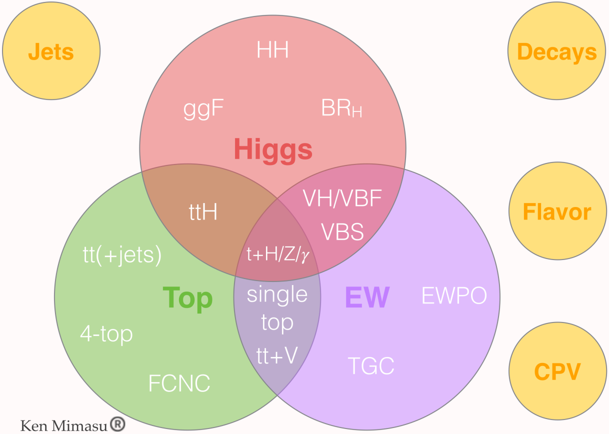
(B) Extract experimental constraints on [ideally measure!] the Wilson coefficients

(C) Compare to UV models matched onto SMEFT /
Infer properties of new physics from deviation pattern

Global SMEFT analyses

ultimate goal: measure as many SMEFT parameters as possible
fitting predictions that include all relevant terms

- individual processes necessarily have blind directions
- combination of different processes / sectors required



Recap & take-home

- EFTs main idea: physics at two very separated scales decouple
  $\rightarrow$ a heavy sector $\mathcal{P}$ is not completely resolved at $E \ll \Lambda$:
  its signatures can be organized in a series in (E/Λ)
- EFTs (the **SMEFT** in particular) are ideal tools for systematic Indirect searches of BSM physics @LHC
- **HEFT** is another EFT candidate for BSM extension. More general than the SMEFT, covers scenarios with non-linearities and scalar mixings
- EFTs are related to specific UV models via a matching procedure.
  The correspondence is often non-trivial.
- To use the full EFT power global analysis of LHC data are required: not just SM stress-test but a means to understand the global picture through precision measurements

Backup slides

Shifts from input parameters

when testing a theory:

set of input measurements

SM:

$\Gamma(\mu \to e\nu\nu) \to \hat{G}_F(\bar{g}_1, \bar{g}_2, \bar{v})$
$\hat{m}_Z(\bar{g}_1, \bar{g}_2, \bar{v})$
Coulomb potential$\to \hat{\alpha_{\rm em}}(\bar{g}_1, \bar{g}_2)$
$\hat{m}_h(\bar{\lambda}, \bar{v})$
$\hat{m}_f(\bar{y}_f, \bar{v})$
$\vdots$

$\bar{X}$ = parameter in canonical $\mathcal{L}$. $\hat{X}$ = parameter inferred from SM relations.

Shifts from input parameters

when testing a theory:

set of input measurements → infer numerical values to theory parameters

SM:

invert the input obs. definitions to get:

$$\bar{v} = \hat{v}(\hat{G}_F)$$
$$\bar{\lambda} = \hat{\lambda}(\hat{m}_h, \hat{G}_F)$$
$$\bar{y}_f = \hat{y}_f(\hat{m}_f, \hat{G}_F)$$
$$\bar{g}_1 = \hat{g}_1(\hat{\alpha_{\rm em}}, \hat{G}_F, \hat{m}_Z)$$
$$\bar{g}_2 = \hat{g}_2(\hat{\alpha_{\rm em}}, \hat{G}_F, \hat{m}_Z)$$

$\bar{X}$ = parameter in canonical $\mathcal{L}$. $\hat{X}$ = parameter inferred from SM relations.

Shifts from input parameters

when testing a theory:

set of input measurements → infer numerical values to theory parameters → numerical prediction of other observables

SM:

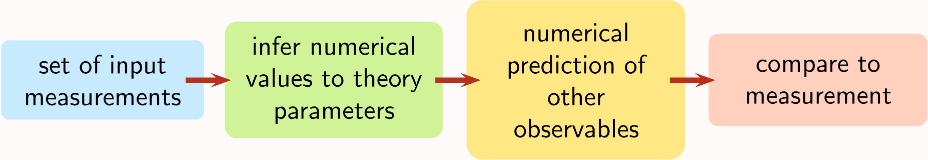
analytic calculations
Monte Carlo generation
...

e.g. at LO
$\bar{m}_W = \bar{m}_Z \cos\bar{\theta}$

$\bar{X}$ = parameter in canonical $\mathcal{L}$. $\hat{X}$ = parameter inferred from SM relations.

Shifts from input parameters

when testing a theory:



SM:

$$\hat{m}_W \stackrel{?}{=} \bar{m}_W$$

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Shifts from input parameters

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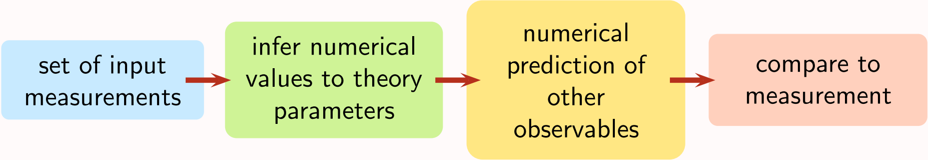

SMEFT:

$\Gamma(\mu \to e\nu\nu) \to \hat{G}_F(\bar{g}_1, \bar{g}_2, \bar{v}, \mathbf{C_i})$
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$\vdots$

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Shifts from input parameters

when testing a theory:

set of input measurements → infer numerical values to theory parameters → numerical prediction of other observables → compare to measurement

SMEFT:

invert the relations linearizing the C_i dependence

$$\begin{aligned}
\bar{v} &= \hat{v}(\hat{G}_F) + \delta v \\
\bar{\lambda} &= \hat{\lambda}(\hat{m}_h, \hat{G}_F) + \delta\lambda \\
\bar{y}_f &= \hat{y}_f(\hat{m}_f, \hat{G}_F) + \delta y_f \\
\bar{g}_1 &= \hat{g}_1(\hat{\alpha_{\rm em}}, \hat{G}_F, \hat{m}_Z) + \delta g_1 \\
\bar{g}_2 &= \hat{g}_2(\hat{\alpha_{\rm em}}, \hat{G}_F, \hat{m}_Z) + \delta g_2
\end{aligned}$$

in a numeric code: convenient to replace

$\bar{X} \to \hat{X} + \delta X$ everywhere in $\mathcal{L}$

$\bar{X}$ = parameter in canonical $\mathcal{L}$. $\hat{X}$ = parameter inferred from SM relations.

Input schemes for the EW sector

$\{\alpha_{\rm em}, m_Z, G_f\}$ scheme

$$\bar{v}^2 = \frac{1}{\sqrt{2}G_F} + \frac{\Delta G_F}{G_F}$$

$$\bar{s_\theta}^2 = \frac{1}{2}\left[1-\sqrt{1-\frac{4\pi\alpha}{\sqrt{2}G_F m_Z^2}}\right]\left[1+\frac{c_{2\theta}}{2\sqrt{2}}\Delta G_F + \frac{c_{2\theta}}{4}\frac{\Delta m_Z^2}{m_Z^2} + \frac{3s_{4\theta}}{8}\frac{v^2}{\Lambda^2}C_{HWB}\right]$$

$$\bar{e}^2 = 4\pi\alpha \; +0$$

$$\bar{g}_1 = \frac{e}{c_\theta}\left[1+\frac{s_\theta^2}{2c_{2\theta}}\left(\sqrt{2}\Delta G_f + \frac{\Delta m_Z^2}{m_Z^2} + 2\frac{c_\theta^3}{s_\theta}\frac{\hat{v}^2}{\Lambda^2}C_{HWB}\right)\right]$$

$$\bar{g}_w = \frac{e}{s_\theta}\left[1-\frac{c_\theta^2}{2c_{2\theta}}\left(\sqrt{2}\Delta G_f + \frac{\Delta m_Z^2}{m_Z^2} + 2\frac{s_\theta^3}{c_\theta}\frac{\hat{v}^2}{\Lambda^2}C_{HWB}\right)\right]$$

$$\bar{m}_W^2 = m_Z^2 c_\theta^2 + \left[1 - \frac{\sqrt{2}s_\theta^2}{c_{2\theta}}\Delta G_F + -\frac{c_\theta^2}{c_{2\theta}}\frac{\Delta m_Z^2}{m_Z^2} - s_\theta^2 t_{2\theta}\frac{\hat{v}^2}{\Lambda^2}C_{HWB}\right]$$

with

$$\Delta m_Z^2 = m_Z^2\frac{v^2}{\Lambda^2}\left[\frac{C_{HD}}{2} + s_{2\theta}C_{HWB}\right] \qquad \Delta G_F = \frac{v^2}{\Lambda^2}\left[(C_{Hl}^3)_{11} + (C_{Hl}^3)_{22} - (C_{ll})_{1221}\right]$$

Input schemes for the EW sector

$\{m_W, m_Z, G_f\}$ scheme

$$\bar{v}^2 = \frac{1}{\sqrt{2}G_F} + \frac{\Delta G_F}{G_F}$$

$$\bar{s_\theta}^2 = \left(1 - \frac{m_W^2}{m_Z^2}\right)\left[1 - c_\theta^2 \frac{\Delta m_Z^2}{m_Z^2} + \frac{s_{4\theta}}{4}\frac{v^2}{\Lambda^2} C_{HWB}\right]$$

$$\bar{e}^2 = 4\sqrt{2} G_F m_W \left(1 - \frac{m_W^2}{m_Z^2}\right)\left[1 - \frac{\Delta G_F}{\sqrt{2}} - \frac{c_\theta^2}{2 s_\theta^2}\frac{\Delta m_Z^2}{m_Z^2} - \frac{s_{2\theta}}{2}\frac{v^2}{\Lambda^2} C_{HWB}\right]$$

$$\bar{g}_1 = \frac{e}{c_\theta}\left[1 - \frac{\Delta G_F}{\sqrt{2}} - \frac{1}{2 s_\theta^2}\frac{\Delta m_Z^2}{m_Z^2}\right]$$

$$\bar{g}_W = \frac{e}{s_\theta}\left[1 - \frac{\Delta G_F}{\sqrt{2}}\right]$$

$$\bar{m}_W^2 = m_W^2 + 0$$

with

$$\Delta m_Z^2 = m_Z^2 \frac{v^2}{\Lambda^2}\left[\frac{C_{HD}}{2} + s_{2\theta} C_{HWB}\right] \qquad \Delta G_F = \frac{v^2}{\Lambda^2}\left[(C_{Hl}^3)_{11} + (C_{Hl}^3)_{22} - (C_{ll})_{1221}\right]$$

SMEFT @ LHC: how many parameters?

Depends on choices of low energy symmetries. e.g. flavor

SMEFT @ LHC: how many parameters?

Depends on choices of low energy symmetries. e.g. flavor

observables, including/excluding quadratic terms

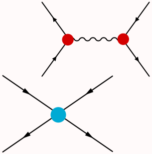
Focusing on interference $\mathcal{A}_{SM}\mathcal{A}_6^*$ only

Selection **due to SM kinematics / symmetries** in the presence of:

- resonances in SM
- FCNCs op.
- dipole op. (interf. $\sim m_f$)
- ...

ψ^4 operators generally **suppressed** wrt. "pole operators" by

$$\left(\frac{\Gamma_B m_B}{v^2}\right)^n \sim \begin{array}{ll} 1/300 & (Z,W) \\ 1/10^6 & (h) \end{array}$$

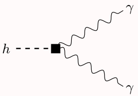


If quadratic terms $|\mathcal{A}_6|^2$ are included, more operators contribute

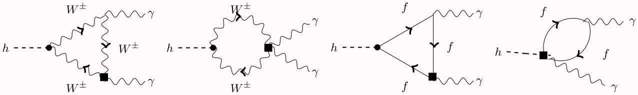
SMEFT @ LHC: how many parameters?

Depends on choices of
- low energy symmetries. e.g. flavor
- observables, including/excluding quadratic terms
- EFT calculation accuracy

loop order



$C_{HW}\,,\ C_{HB}\,,\ C_{HWB}$



$+\ C_W\,,\ C_{HD}\,,\ C_{eW}\,,$
$C_{eB}\,,\ C_{uW}\,,\ C_{uB}\,,\ C_{dW}\,,$
$C_{dB}\,,\ C_{eH}\,,\ C_{uH}\,,\ C_{dH}$

Hartmann,Trott 1505.02646,1507.03568
Ghezzi,Gomez-Ambrosio,Passarino,Uccirati 1505.03706
Dedes,Paraskevas,Rosiek,Suxho,Trifyllis 1805.00302

EFT order

$+$ dimension 8 $+\ \ldots$

SMEFT @ LHC: how many parameters?

Depends on choices of
- low energy symmetries. e.g. flavor
- observables, including/excluding quadratic terms
- EFT calculation accuracy

For reference:

	total $N_f = 3$	unsuppressed interf.*
general	2499	~ 46
MFV	~ 108	~ 30
$U(3)^5$	~ 70	~ 24

Brivio,Jiang,Trott 1709.06492

* parameters entering $H/Z/W$ resonance-dominated processes, interference only.