Theory Aspects of EFT Interpretation

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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 (v/Λ or E/Λ):

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

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

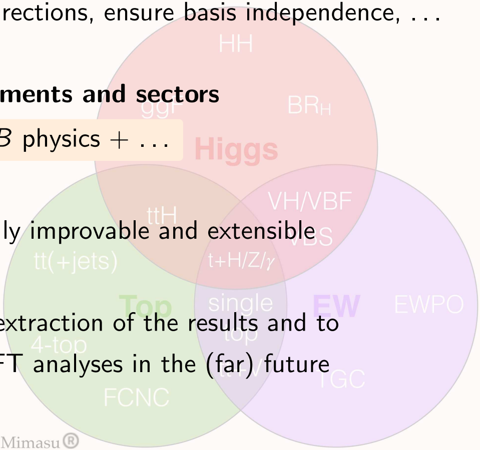
C_i free parameters (Wilson coefficients)
→ embed all UV information

$\mathcal{O}_i$ invariant operators that form
a complete, non redundant **basis**
→ embed the IR information

Target: global EFT analyses @LHC (and beyond)

measure as many SMEFT parameters as possible in order to infer information about BSM physics

- Combining is crucial: remove flat directions, ensure basis independence, ...
- Aim for a combination **across experiments and sectors**
  LEP + Higgs + LHC EW + top + B physics + ...
- Step-by-step approach, systematically improvable and extensible
- Would like to minimize bias in the extraction of the results and to maximize reinterpretability of SMEFT analyses in the (far) future



Ken Mimasu®

The LHC EFT WG

Coordination activities for LHC experiments started this year within the **LHC EFT Working Group**. `https://lpcc.web.cern.ch/lhc-eft-wg`

Targets summarized in a Google doc and organized in 5 Areas:

1. EFT formalism
2. Predictions & tools
3. Experimental measurements & Observables
4. Fits & related systematics
5. Benchmark scenarios from UV models

6 Area meetings have already taken place. `https://indico.cern.ch/category/12374/`
one upcoming on Feb 22 (Area 4)

this talk : not on behalf of the WG, but based on discussions in areas 1, 2

Theory topics in EFT...

...with an eye to reinterpretation issues

To be covered today:

- Bases: converging to Warsaw
- Flavor assumptions
- Global symmetries: CP, custodial,...
- Input parameters
- Truncation, validity, SMEFT uncertainties
- Other points on the list

Flavor assumptions

Bordone,Catá,Feldmann 1910.02641
Faroughy,Isidori,Wilsch,Yamamoto 2005.05366
Brivio,(Jiang,Trott) 1709.06492, 2012.11343

w/o flavor assumptions $\mathcal{L}_6$ has 2499 free parameters

$O_{He,pr} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$ has **9** independent par.

$O_{ledq,prst} = (\bar{l}^i_p e_r)(\bar{d}_s q^i_t)$ has **162**

freedom can be reduced imposing a **symmetry**. Maximal:

$$U(3)^5 \equiv U(3)_q \times U(3)_u \times U(3)_d \times U(3)_l \times U(3)_e$$

→ only invariant contractions allowed
→ Yukawa couplings typically promoted to **spurions**:

$$Y_u \mapsto \Omega_u Y_u \Omega_q^\dagger, \quad Y_d \mapsto \Omega_d Y_d \Omega_q^\dagger, \quad Y_e \mapsto \Omega_e Y_e \Omega_l^\dagger$$

$O_{He,pr}\,\delta_{pr}$ has **1** independent par.

$O_{ledq,prst}\,(Y_e^\dagger)_{pr}(Y_d)_{st}$ has **2**

$\mathcal{L}_6 + U(3)^5$ has **85** free parameters

Flavor assumptions

Several options available:

- free indices (2499) → likely unable to constrain them all
- Higgs/EW: $U(3)^3$ (∼85)
- top: symmetries based on $U(2)$ for quarks ($\sim 150 - 300$)

Top WG note 1802.07237

Points for global analyses:

- flavor sym. useful to encapsulate **blind directions**
- relax as we flavor sensitivity introduced (top/B physics...)
- can only be fully mapped less → more restrictive!
- an idea: **staged** scenarios. e.g. top proposal:

baseline

$U(2)_{q+u+d}$ | $U(2)_q \times U(2)_u \times U(2)_d$ | top-philic

more restrictive →

Global symmetries

- CP

eg. Warsaw basis contains
- 1149/2499 [general] CP odd parameters
- $\sim$ 25/85 $[U(3)^5]$

$\longrightarrow$ generally do not interfere in inclusive measurements: SM CP even at high-E but can give signatures at **differential** level

$\longrightarrow$ not all analyses can be sensitive to them

$\longrightarrow$ at quadratic level, they are **degenerate** with CP even counterparts. both bounded simultaneously:

$$\sigma \sim ([CP]^2 + [\not{CP}]^2) < \# \;\Rightarrow\; [CP]^2 < \# \text{ and } [\not{CP}]^2 < \#$$

Global symmetries

- custodial

Kribs,Lu,Martin,Tong 2009.10725

the SM Higgs potential has a $O(4) \sim SU(2)_L \times SU(2)_R$ global symmetry:

$$\Sigma = \left(\tilde{H}\ H\right), \qquad \Sigma \mapsto L\,\Sigma\,R^\dagger$$

EWSB breaks it down to the diagonal $SU(2)_{L+R} \equiv$ custodial symmetry

- in the SM, custodial is broken by $g' \neq 0$ and $Y_u \neq Y_d,\ Y_e \neq 0 (Y_\nu)$.

  $\updownarrow$

  $$m_Z \neq m_W,\ \theta_W \neq 0,\ \ldots$$

- SMEFT contains BSM sources of custodial violation.

  e.g. in Warsaw basis $O_{HD},\ O^{(1)}_{Hq},\ O^{(1)}_{Hl},\ O_{Hu},\ O_{Hd},\ O_{He}, \ldots$

  $\rightarrow$ tested eg. by ρ parameter $\sim C_{HD}$

- other symmetries?

Input parameter schemes

SM

(pseudo)-observables $\mathcal{O}$

α_s, d_N
m_Z, $\alpha_{\rm em}$
$\mu \to e\nu\nu$, m_h
m_f
meson decay/osc

→

$\mathcal{L}$ parameters p

QCD	g_s, θ_{QCD}
EW	g, g'
Higgs	v, λ
Yukawa	y_f
CKM	$\theta_{1,2,3}, \delta$

→

analytical / MC **predictions** for any SM process

Numerical value of renormalized p determined from chosen input measurements $\mathcal{O}$:

$$p_{SM}(\mathcal{O})$$

Input parameter schemes

SMEFT

(pseudo)-observables
$\mathcal{O}$

α_s, d_N
m_Z, $\alpha_{\rm em}$
$\mu \to e\nu\nu$, m_h
m_f
meson decay/osc

→

$\mathcal{L}$ parameters p

QCD	g_s, θ_{QCD}
EW	g, g'
Higgs	v, λ
Yukawa	y_f
CKM	$\theta_{1,2,3}, \delta$
EFT	$\mathbf{C_i}$

→

analytical / MC
predictions
for any SM process

One cannot find enough obs. to solve for all C_i.

→ Wilson coefficients dependence expanded around SM solutions:

$$p_{SMEFT}(\mathcal{O}, C) = p_{SM}(\mathcal{O}) + \delta p(C_i) + \dots$$

→ different sets of $\mathcal{O}$ ⇒ different net SMEFT corrections

Input parameter schemes

- inputs choice for QCD, Higgs, Yukawa sector is ∼fixed.
- freedom for **EW sector**: $\{g, g', v\} \longleftrightarrow$ 3 among $\{\alpha_{\rm em}, m_Z, m_W, G_F\}$

Candidate sets:

- $\{\alpha, m_Z, G_F\}$ ✖ not ideal to have masses (m_W) as predicted quantities: pole position depends on C_i.
- $\{m_W, m_Z, G_F\}$
  - ✔ no SMEFT correction to masses
  - ⊖ better convergence at 1-loop, although few % effect
  - ✖ dependence on $(C^3_{Hl})_{11,22}, C_{ll,1221}$ from G_F.
- $\{\alpha, m_W, m_Z\}$
  - ✔ no SMEFT correction to masses
  - ⊖ worse convergence at 1-loop
  - ✔ less parameters
- ...

Input parameter schemes

- inputs choice for QCD, Higgs, Yukawa sector is $\sim$fixed.
- freedom for **EW sector**: $\{g, g', v\} \longleftrightarrow$ 3 among $\{\alpha_{\rm em}, m_Z, m_W, G_F\}$

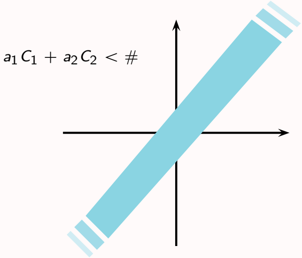
Questions to be addressed:

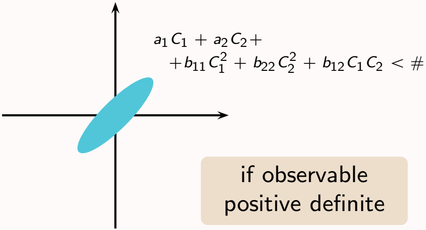
- Which inputs for the EW sector at LHC?
  $\rightarrow$ considerations on theory properties, # SMEFT parameters introduced, convenience for NLO calculations. . .
- Is this choice equally good for other observables (eg. flavor)?
- How to combine **measurements with different inputs**?
  e.g. LEP constraints were all derived with $\{\alpha, m_Z, G_F\}$.
- SMEFT corrections in the determination of α_s / running of α through QCD resonance region?

Quadratic and other Λ^{-4} contributions

$$|A_{SMEFT}|^2 = |A_{SM} + A_6|^2 = |A_{SM}|^2 + Re\left[A_{SM} A_6^\dagger\right] + |A_6|^2$$

- restore sensitivity to non-interfering operators (CP odd, dipoles, ...)
- usually increase fit convergence





if observable positive definite

Quadratic and other Λ^{-4} contributions

$$|A_{SMEFT}|^2 = |A_{SM} + A_6|^2 = |A_{SM}|^2 + Re\left[A_{SM} A_6^\dagger\right] + |A_6|^2$$

- restore sensitivity to non-interfering operators (CP odd, dipoles, ...)
- usually increase fit convergence

Formally are of the same order as

- $\mathscr{L}_8$ - SM interference
- **double** $\mathscr{L}_6$ insertions → not renormalizable with $\mathscr{L}_6$ alone
- quadratic terms in the **expansion** of field/parameter redefinitions in $\mathscr{L}_6$ (from kinetic term normalization, inputs)

SMEFT uncertainties

SMEFT predictions come with theory uncertainties that account for

- missing higher orders in the EFT
  - for dim-6 predictions, uncertainties are dominated by $\mathscr{L}_8$ terms, etc.
  - expected to grow with energy, and → 100% for $E \to \Lambda$

  ↔ EFT validity
- missing perturbative orders
- neglected **subdominant** EFT contributions
- unknown SMEFT corrections to extraction of α_s, PDFs, hadronization, etc
- ...

! don't just represent potential variations of prediction's central value, but also potential **extra parameters / fit d.o.f.s**

EFT validity

SMEFT <u>assumes</u> – no BSM light states ⟷ the expansion holds
– cutoff $M(\propto\Lambda) \gg E$

if conditions fail → parameterization can **fail to reproduce data**
→ the **interpretation** can be impaired

How do we check?

Related to, but conceptually distinct from:

Are our measurements probing the physical EFT region?

<u>insufficient exp. precision</u> → sensitivity only to **too large values of** $(\boldsymbol{C/\Lambda^2})$
→ assuming $C \leqslant 4\pi$, EFT analysis **cannot exclude** $\boldsymbol{M \gtrsim E}$

⟷ **unitarity** constraints

Other theory aspects of EFT (re)interpretation

- Treatment of unstable particles
- Implementation of unitarity constraints, positivity bounds
- Treatment of scale uncertainties in NLO SMEFT calculations
- Strategies for interpretation in terms of UV models
- Interplay with direct searches
- SMEFT or HEFT?
- ...

Backup slides

Beyond SMEFT

. . . should alternative EFTs be considered?

main example: **Higgs EFT (HEFT)**

$$H \mapsto \frac{v + h}{\sqrt{2}}\,\mathbf{U}, \qquad \mathbf{U} = \exp\left(\frac{i\vec{\sigma}\cdot\vec{\pi}}{v}\right)$$

- less restrictive symmetry assumptions
- order-by-order: more parameters
- in principle can capture a **larger range** of BSM models
- generally more convergent than SMEFT for $\Lambda \lesssim 4\pi v$
  $\rightarrow$ can be convenient compared to full dim=8

EFT consistency constraints

- **Unitarity constraints**

  SMEFT operators can induce corrections that grow with energy.

  → partial wave unitarity violated for sufficiently large $C(E/\Lambda)^2$

  → signals EFT breakdown point ↔ **EFT validity** limits

- **Positivity bounds**

  scattering amplitudes need to respect: analyticity
  causality
  partial wave unitarity
  crossing symmetry
  ...

  at all orders in the EFT, within the validity region

  → not all regions of EFT parameter space are physical.

  in practice, model-independent limitations mostly apply to $\mathscr{L}_8$

- ...

Connection with BSM models

UV model (parameters $\{\kappa\}$)

↓

EFT (parameters $\{C\}$)

matching procedure

heavy d.o.f.s are "integrated out"

↓

operators are **mapped** onto the chosen basis and **run** down to EW scale

↓

$C(\kappa)$

can be done efficiently with functional methods, up to 1-loop in the UV model

Connection with BSM models

UV model (parameters $\{\kappa\}$)

EFT (parameters $\{C\}$)

interpretation of EFT measurements

<u>task</u>:
reconstructing UV properties from observed patterns in $\{C\}$

disentangling $\sim$degenerate models

interplay with direct searches
can exploit the complementarity between the two?

d=6: 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}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

d=6: the Warsaw basis

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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		