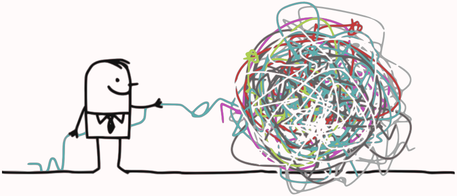
Tools & strategies for EFT analyses @LHC

Ilaria Brivio

Niels Bohr Institute, University of Copenhagen



The Niels Bohr International Academy

VILLUM FONDEN

centre for particle physics Discovery

The SMEFT

SMEFT = Effective Field Theory with SM fields + symmetries

a systematic expansion in canonical dimensions $(v, E/\Lambda)$:

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

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

C_i free parameters (Wilson coefficients)

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

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- any UV compatible with the SM in the low energy limit can be matched onto the SMEFT
- a convenient phenomenological approach: systematically classifies <u>all</u> the possible new physics signals

The SMEFT – where we are

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B cons. $N_f = 1 \rightarrow$ 1 76 22 895

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$N_f = 3 \rightarrow$ 3 2499 948 36971

- # of parameters know for all orders

Lehman 1410.4193
Lehman,Martin 1510.00372
Henning,Lu,Melia,Murayama 1512.03433

The SMEFT – where we are

Weinberg PRL43(1979)1566

Lehman 1410.4193
Henning,Lu,Melia,Murayama 1512.03433

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Leung,Love,Rao Z.Ph.C31(1986)433
Buchmüller,Wyler Nucl.Phys.B268(1986)621
Grzadkowski et al 1008.4884

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- efficient matching techniques developed: CDE/UOLEA

Henning,Lu,Murayama 1412.1837,1604.01019
del Aguila,Kunszt,Santiago 1602.00126
Drozd,Ellis,Quevillon,You 1512.03003
Ellis,Quevillon,You,Zhang 1604.02445,1706.07765
Fuentes-Martin,Portoles,Ruiz-Femenia 1607.02142
Zhang 1610.00710

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- complete RGE available in the Warsaw basis

Alonso,Jenkins,Manohar,Trott 1308.2627,1310.4838,1312.2014
Grojean,Jenkins,Manohar,Trott 1301.2588
Alonso,Chang,Jenkins,Manohar,Shotwell 1405.0486
Ghezzi,Gomez-Ambrosio,Passarino,Uccirati 1505.03706

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Pruna,Signer 1408.3565
Hartmann,(Shepherd),Trott 1505.02646,1507.03568,1611.09879
Ghezzi,Gomez-Ambrosio,Passarino,Uccirati 1505.03706
Gauld,Pecjak,Scott 1512.02508
Deutschmann,Duhr,Maltoni,Vryonidou 1708.00460

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Dedes,Materkowska,Paraskevas,Rosiek,Suxho 1704.03888

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- 1-loop results available for selected processes
- formulation in R_ξ gauge
- various tools available for numerical analysis

Our new tool: the SMEFTsim package

Brivio,Jiang,Trott 1709.06492
feynrules.irmp.ucl.ac.be/wiki/SMEFT

an **UFO & FeynRules model** with*:

1. the complete B-conserving Warsaw basis for 3 generations, including all complex phases and ~~CP~~ terms
2. automatic field redefinitions to have **canonical kinetic terms**

⇝ **backup**

3. automatic **parameter shifts** due to the choice of an input parameters set

Main scope:

estimate **tree-level** $|\mathcal{A}_{SM}\mathcal{A}^*_{d=6}|$ **interference** terms → theo. accuracy ∼ %

* at the moment only LO, unitary gauge implementation

Our new tool: the SMEFTsim package

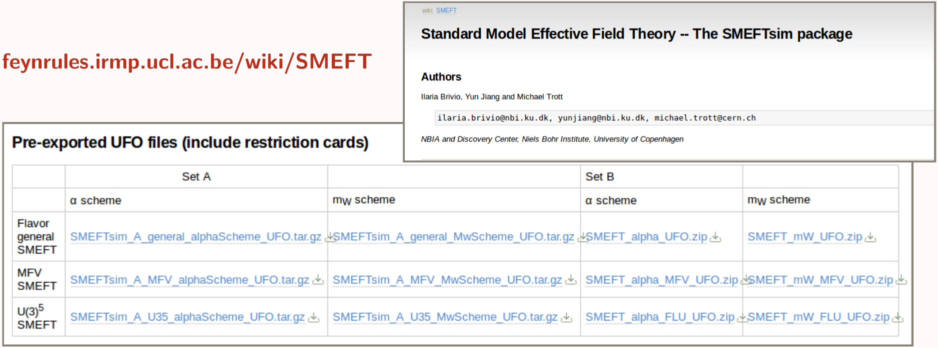
We implemented 6 different frameworks

Brivio, Jiang, Trott 1709.06492

③ flavor structures $\begin{cases} \text{general} \\ U(3)^5 \text{ symmetric} \\ \text{linear MFV} \end{cases}$ × ② input schemes $\begin{cases} \hat{\alpha}_{\rm em},\, \hat{m}_Z,\, \hat{G}_f \\ \hat{m}_W,\, \hat{m}_Z,\, \hat{G}_f \end{cases}$

in 2 independent, equivalent models sets (A, B): best for debugging and validation

feynrules.irmp.ucl.ac.be/wiki/SMEFT



wiki: SMEFT

Standard Model Effective Field Theory -- The SMEFTsim package

Authors

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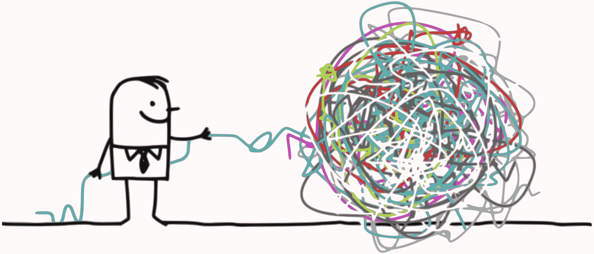
NBIA and Discovery Center, Niels Bohr Institute, University of Copenhagen

Pre-exported UFO files (include restriction cards)

	Set A		Set B	
	α scheme	m_W scheme	α scheme	m_W scheme
Flavor general SMEFT	SMEFTsim_A_general_alphaScheme_UFO.tar.gz	SMEFTsim_A_general_MwScheme_UFO.tar.gz	SMEFT_alpha_UFO.zip	SMEFT_mW_UFO.zip
MFV SMEFT	SMEFTsim_A_MFV_alphaScheme_UFO.tar.gz	SMEFTsim_A_MFV_MwScheme_UFO.tar.gz	SMEFT_alpha_MFV_UFO.zip	SMEFT_mW_MFV_UFO.zip
$U(3)^5$ SMEFT	SMEFTsim_A_U35_alphaScheme_UFO.tar.gz	SMEFTsim_A_U35_MwScheme_UFO.tar.gz	SMEFT_alpha_FLU_UFO.zip	SMEFT_mW_FLU_UFO.zip

The SMEFT – a big knot to untangle!

many operators around at the same time in any given observables



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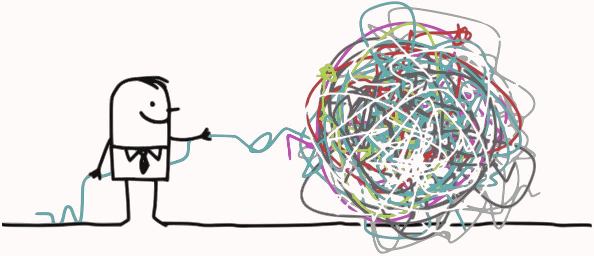

we want to untangle this without breaking any strings

[extract reliable constraints (or measurements!)
possibly without introducing any bias]

*If we want to be agnostic about the UV *,*
what do EFT methods allow us to conclude about BSM physics?

* decoupled and matching the SM in the low E limit

A global ongoing effort

The Wilson coefficients of the SMEFT have been constrained by several groups

Just in the last years:

very incomplete list!

Corbett et al. 1207.1344 1211.4580 1304.1151 1411.5026 1505.05516

Ciuchini,Franco,Mishima,Silvestrini 1306.4644

de Blas et al. 1307.5068, 1410.4204, 1608.01509, 1611.05354, 1710.05402

Pomarol, Riva 1308.2803

Englert,Freitas,Müllheitner,Plehn,Rauch,Spira,Walz 1403.7191

Ellis,Sanz,You 1404.3667 1410.7703

Falkowski,Riva 1411.0669

Falkowski,Gonzalez-Alonso,Greljo,Marzocca 1508.00581

Berthier,(Bjørn),Trott 1508.05060, 1606.06693

Englert,Kogler,Schulz,Spannowsky 1511.05170

Butter,Éboli,Gonzalez-Fraile,Gonzalez-Garcia,Plehn,Rauch 1604.03105

Freitas,López-Val,Plehn 1607.08251

Falkowski,Golzalez-Alonso,Greljo,Marzocca,Son 1609.06312

Krauss,Kuttimalai,Plehn 1611.00767

. . .

Untangling the SMEFT

Ideally: a giant global fit where all the C_i are free parameters

In practice: we can only fit subsets of operators, because of

- limited computational possibilities
- insufficient # of measurements
- insufficient exp. accuracy
- ...

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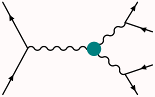
☛ **reducing the parameter space is crucial!**

the selection has to be made carefully to avoid missing signals or obtaining basis-dependent results

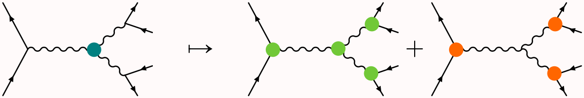
Examples

❶ BSM model $\longrightarrow W^a_{\mu\nu} D^\mu H^\dagger \sigma^a D^\nu H$ affecting



Using the Warsaw basis:

$$W^a_{\mu\nu} D^\mu H^\dagger \sigma^a D^\nu H \quad \mapsto \quad \mathcal{Q}_{HW},\ \mathcal{Q}_{HWB},\ \mathcal{Q}^{(3)}_{Hq},\ \mathcal{Q}^{(3)}_{Hl} + \text{Higgs ops.}$$



removing C_{HWB}, $C^{(3)}_{Hq}$ or $C^{(3)}_{Hl}$ this effect couldn't be reproduced anymore

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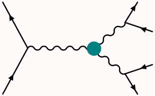

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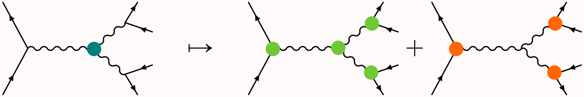

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❷ Z-pole data from LEP1 has two **flat directions** in the Warsaw basis:

$$w_B = -\frac{1}{3}C_{Hd} - C_{He} - \frac{1}{2}C_{Hl} + \frac{1}{6}C^{(1)}_{Hq} + \frac{2}{3}C_{Hu} + 2C_{HD} - \frac{1}{2t_\theta}C_{HWB}$$

$$w_W = C^{(3)}_{Hq} + C^{(3)}_{Hl} - t_\theta C_{HWB}$$

removing one of these operators artificially breaks it

Han, Skiba 0412166
Grojean,Skiba,Terning 0602154
Brivio,Trott 1701.06424

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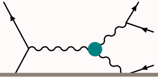


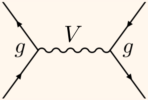
Using the W

$W^a_{\mu\nu} D^\mu$ I … s.

removing C_H … ore

Brivio,Trott 1701.06424

These flat directions reflect
a **reparameterization invariance** of Z-pole observables



$$\begin{cases} V_\mu \to (1+\epsilon) V_\mu \\ g \to g/(1+\epsilon) \simeq (1-\epsilon) g \end{cases}$$

They are a property of $\bar\psi\psi \to \bar\psi\psi$ processes.

⇝ **backup**

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Example – close to a pole

Brivio,Jiang,Trott 1709.06492

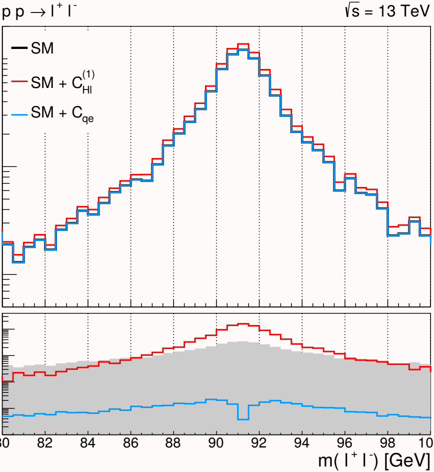
most ψ^4 operators give diagrams with less resonances

expected to be **suppressed** wrt. "pole operators" by

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

$B = \{Z, W, h\}$

$n = \#$ missing resonances



Drell-Yan via Z resonance ➜

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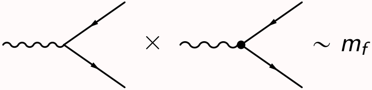
Example: dipole operators can be neglected for $f \neq t, b$



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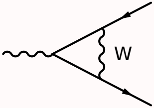
$\mathcal{A}_{SM}$ is very suppressed:



$$\sim \frac{m_j^2 V^*_{jk} V ji}{32\pi^2 m_W^2}$$

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Brivio,Jiang,Trott 1709.06492

The counts reduce significantly!

	total $N_f = 3$	WZH poles
general	2499	~ 46
MFV	~ 108	~ 30
$U(3)^5$	~ 70	~ 24

Road-map and challenges

Towards a general EFT analysis of precision measurements:

1. Complete a “WHZ poles program”

   Brivio,Jiang,Trott 1709.06492

   - design optimized experimental analyses

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Brivio,Jiang,Trott 1709.06492

Experimental precision needed

UV coupling to SM

On poles: $$\text{NP impact} \sim \frac{v^2 g}{M^2} = \frac{v^2}{\Lambda^2}$$ **EFT cutoff**

mass of new resonances

$$g \simeq 1 \quad M \gtrsim 2-3 \text{ TeV} \rightarrow 1\%$$ **at least!**

(LHC reach)

On tails: $$\text{NP impact} \sim \frac{E^2 g}{M^2} = \frac{E^2}{\Lambda^2} \rightarrow \text{few - tens }\%$$

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   - better treatment of theoretical uncertainties due to neglected higher orders + radiative corrections, initial/final state radiation etc
   - new statistical tools to make the most out of the fit information

     Brehmer,Cranmer,Kling,Plehn 1612.05261
     Murphy 1710.02008

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   - inclusion of $d = 8$ operators (construct a basis!)

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   - inclusion of $d = 8$ operators (construct a basis!)

Further goals to keep in mind: SMEFT vs HEFT

The SMEFT is not the only EFT that extends the SM!

Important alternative: **HEFT**

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Important alternative: **HEFT**

a.k.a. electroweak chiral Lagrangian with a light Higgs
nonlinear effective theory
nonlinear Lagrangian for a light Higgs
EChL
ECLh
EWChL
EWχL
HEWχL
...

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Important alternative: **HEFT**

Main idea: the Higgs does not need to be in a doublet

Appelquist,Bernard PRD22 200
Longhitano PRD22 1166
Nucl.Phys.B188 118

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

independent

h

treated as a singlet
with arbitrary couplings

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

Grinstein,Trott 0704.1505
Contino 1005.4269

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

adimensional

↓

derivative expansion $\sim \chi$PT

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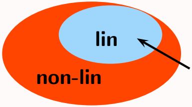
⟶ a **very general** EFT



contains the SMEFT
as a particular limit

⟶ matches composite Higgs models + other UVs with significant **nonlinear** effects in the EWSB sector (dilaton, inflaton. . .)

Further goals to keep in mind: SMEFT vs HEFT

The HEFT has seen a very intense development recently:

Operator basis & pheno	Buchalla et al. 1203.6510 1307.5017 1310.2574 1511.00988
	Alonso et.al. 1212.3305
	Brivio et al. 1311.1823 1405.5412 1604.06801
	Gavela et.al. 1406.6367 1409.1571
	Hierro et al. 1510.07899
	Merlo et al. 1612.04832
	Delgado et al. 1308.1629 1311.5993 1404.2866 1609.06206
	Dobado et al. 1507.06386
	Corbett et al 1511.08188
Power counting	Buchalla et al. 1312.5624 1603.03062
	Gavela et al. 1601.07551
Renormalization and RGE	Gavela et al. 1409.1571
	Buchalla et al. 1710.06412
	Alonso,Kanshin,Saa 1710.06848
Relation to specific scenarios	Alonso et al. 1409.1589
	Feruglio et al. 1603.05668
	Gavela et al. 1610.08083
	Hernández-Leon,Merlo 1703.02064

Further goals to keep in mind: SMEFT vs HEFT

SMEFT and HEFT are intrinsically different

identifying which of the two describes Nature
would give fundamental insights in the origin of EWSB

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look for HEFT signatures

- decorrelated Higgs vs. gauge couplings
  from breaking $D_\mu H \sim (v+h) D_\mu \mathbf{U} + \mathbf{U}\partial_\mu h$
  into independent terms
- effects corresponding to $d = 8$ emerging
  at the same order as $d = 6$
  from unsuppressed Goldstone insertions

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Key measurements

- Higgs+gauge couplings and their (de)correlations
- high-E region of processes with external V_L

Complications

- large # of parameters in the HEFT
- most signatures emerge in tails and/or require comparing $n \geqslant 2$ measurements

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see if the SMEFT breaks down

a general and accurate
SMEFT analysis is needed!

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HEFT 2018

Mainz, 16 - 19 April 2018

`indico.mitp.uni-mainz.de/e/heft2018`

Backup slides

The Warsaw basis

Gzadkowski,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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

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

The Warsaw basis

Gzadkowski,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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

Field redefinitions

Gauge bosons

$$\begin{aligned}\mathcal{L}_{\rm SMEFT} \supset & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + \\ & + C_{HB}(H^\dagger H)B_{\mu\nu}B^{\mu\nu} + C_{HW}(H^\dagger H)W^I_{\mu\nu}W^{I\mu\nu} + C_{HWB}(H^\dagger\sigma^I H)W^I_{\mu\nu}B^{\mu\nu} \\ & + C_{HG}(H^\dagger H)G^a_{\mu\nu}G^{a\mu\nu}\end{aligned}$$

to have **canonically normalized kinetic terms** we need to

1. redefine fields and couplings keeping (gV_μ) unchanged:

$$\begin{aligned}\mathcal{B}_\mu &\to B_\mu(1 + C_{HB}v^2) \qquad & g_1 &\to g_1(1 - C_{HB}v^2)\\ \mathcal{W}^I_\mu &\to W^I_\mu(1 + C_{HW}v^2) & g_2 &\to g_2(1 - C_{HW}v^2)\\ \mathcal{G}^a_\mu &\to G^a_\mu(1 + C_{HG}v^2) & g_s &\to g_s(1 - C_{HG}v^2)\end{aligned}$$

2. correct the rotation to mass eigenstates:

$$\begin{pmatrix}\mathcal{W}^3_\mu\\ \mathcal{B}_\mu\end{pmatrix} = \begin{pmatrix}1 & -v^2 C_{HWB}/2\\ -v^2 C_{HWB}/2 & 1\end{pmatrix}\begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}Z_\mu\\ A_\mu\end{pmatrix}$$

(equivalent to a shift of the Weinberg angle)

Alonso Jenkins Manohar Trott 1312.2014

Field redefinitions

Higgs

$$\mathcal{L}_{\rm SMEFT} \supset \frac{1}{2} D_\mu H^\dagger D^\mu H + C_{H\Box}(H^\dagger H)(H^\dagger \Box H) + C_{HD}(H^\dagger D_\mu H)^*(H^\dagger D^\mu H)$$

to have a canonically normalized kinetic term, in unitary gauge, we need to replace

$$h \to h\left(1 + v^2 C_{H\Box} - \frac{v^2}{4} C_{HD}\right)$$

Alonso,Jenkins,Manohar,Trott 1312.2014

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These redefinitions are embedded by default in the SMEFTsim models

Alonso,Jenkins,Manohar,Trott 1312.2014

Shifts from input parameters

SM case.

Parameters in the canonically normalized Lagrangian : $\bar{v}, \bar{g}_1, \bar{g}_2, s_{\bar{\theta}}$

The values can be inferred from the measurements e.g. of $\{\alpha_{\rm em}, m_Z, G_f\}$:

$$\begin{aligned}
\alpha_{\rm em} &= \frac{\bar{g}_1\bar{g}_2}{\bar{g}_1^2+\bar{g}_2^2}\\
m_Z &= \frac{\bar{g}_2\bar{v}}{2c_{\bar{\theta}}}\\
G_f &= \frac{1}{\sqrt{2}\bar{v}^2}
\end{aligned}
\quad\rightarrow\quad
\begin{aligned}
\hat{v}^2 &= \frac{1}{\sqrt{2}G_f}\\
\sin\hat{\theta}^2 &= \frac{1}{2}\left(1-\sqrt{1-\frac{4\pi\alpha_{\rm em}}{\sqrt{2}G_f m_Z^2}}\right)\\
\hat{g}_1 &= \frac{\sqrt{4\pi\alpha_{\rm em}}}{\cos\hat{\theta}}\\
\hat{g}_2 &= \frac{\sqrt{4\pi\alpha_{\rm em}}}{\sin\hat{\theta}}
\end{aligned}$$

in the SM at tree-level $\bar{\kappa} = \hat{\kappa}$

Shifts from input parameters

SMEFT case.

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$$\alpha_{\rm em} = \frac{\bar{g}_1\bar{g}_2}{\bar{g}_1^2+\bar{g}_2^2}\left[1+\bar{v}^2 C_{HWB}\frac{\bar{g}_2^3/\bar{g}_1}{\bar{g}_1^2+\bar{g}_2^2}\right]$$

$$m_Z = \frac{\bar{g}_2\bar{v}}{2c_{\bar{\theta}}} + \delta m_Z(C_i) \qquad \to$$

$$G_f = \frac{1}{\sqrt{2}\bar{v}^2} + \delta G_f(C_i)$$

$$\hat{v}^2 = \frac{1}{\sqrt{2}G_f}$$

$$\sin\hat{\theta}^2 = \frac{1}{2}\left(1-\sqrt{1-\frac{4\pi\alpha_{\rm em}}{\sqrt{2}G_f m_Z^2}}\right)$$

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$$\hat{g}_2 = \frac{\sqrt{4\pi\alpha_{\rm em}}}{\sin\hat{\theta}}$$

in the SM at tree-level $\bar{\kappa} = \hat{\kappa}$

in the SMEFT $\bar{\kappa} = \hat{\kappa} + \delta\kappa(C_i)$

Shifts from input parameters

To have numerical predictions it is necessary to replace $\bar{\kappa} \to \hat{\kappa} + \delta\kappa(C_i)$ for all the parameters in the Lagrangian.

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

$$\delta m_Z^2 = m_Z^2 \hat{v}^2 \left(\frac{c_{HD}}{2} + 2c_{\hat{\theta}} s_{\hat{\theta}} c_{HWB}\right)$$

$$\delta G_f = \frac{\hat{v}^2}{\sqrt{2}} \left((c_{Hl}^{(3)})_{11} + (c_{Hl}^{(3)})_{22} - (c_{ll})_{1221}\right)$$

$$\delta g_1 = \frac{s_{\hat{\theta}}^2}{2(1-2s_{\hat{\theta}}^2)} \left(\sqrt{2}\delta G_f + \delta m_Z^2/m_Z^2 + 2\frac{c_{\hat{\theta}}^3}{s_{\hat{\theta}}} c_{HWB} \hat{v}^2\right)$$

$$\delta g_2 = -\frac{c_{\hat{\theta}}^2}{2(1-2s_{\hat{\theta}}^2)} \left(\sqrt{2}\delta G_f + \delta m_Z^2/m_Z^2 + 2\frac{s_{\hat{\theta}}^3}{c_{\hat{\theta}}} c_{HWB} \hat{v}^2\right)$$

$$\delta s_\theta^2 = 2c_{\hat{\theta}}^2 s_{\hat{\theta}}^2 (\delta g_1 - \delta g_2) + c_{\hat{\theta}} s_{\hat{\theta}} (1-2s_{\hat{\theta}}^2) c_{HWB} \hat{v}^2$$

$$\delta m_h^2 = m_h^2 \hat{v}^2 \left(2c_{H\Box} - \frac{c_{HD}}{2} - \frac{3c_H}{2lam}\right)$$

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\delta g_1 &= -\frac{1}{2} \left(\sqrt{2}\delta G_f + \frac{1}{s_{\hat{\theta}}^2} \frac{\delta m_Z^2}{m_Z^2}\right) \\
\delta g_2 &= -\frac{1}{\sqrt{2}} \delta G_f \\
\delta s_\theta^2 &= 2 c_{\hat{\theta}}^2 s_{\hat{\theta}}^2 (\delta g_1 - \delta g_2) + c_{\hat{\theta}} s_{\hat{\theta}} (1 - 2 s_{\hat{\theta}}^2) c_{HWB} \hat{v}^2 \\
\delta m_h^2 &= m_h^2 \hat{v}^2 \left(2 c_{H\Box} - \frac{c_{HD}}{2} - \frac{3 c_H}{2 lam}\right)
\end{aligned}$$

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$$\delta G_f = \frac{\hat{v}^2}{\sqrt{2}} \left((c_{Hl}^{(3)})_{11} + (c_{Hl}^{(3)})_{22} - (c_{ll})_{1221}\right)$$

$$\delta g_1 = -\frac{1}{2} \left(\sqrt{2}\delta G_f + \frac{1}{s_{\hat{\theta}}^2} \frac{\delta m_Z^2}{m_Z^2}\right)$$

$$\delta g_2 = -\frac{1}{\sqrt{2}} \delta G_f$$

$$\delta s_\theta^2 = 2 c_{\hat{\theta}}^2 s_{\hat{\theta}}^2 (\delta g_1 - \delta g_2) + c_{\hat{\theta}} s_{\hat{\theta}} (1 - 2 s_{\hat{\theta}}^2) c_{HWB} \hat{v}^2$$

$$\delta m_h^2 = m_h^2 \hat{v}^2 \left(2 c_{H\Box} - \frac{c_{HD}}{2} - \frac{3 c_H}{2 lam}\right)$$

the redefinitions $\bar{\kappa} \to \hat{\kappa} + \delta\kappa$
are performed automatically
in the Lagrangian
(both schemes)

SMEFTsim: implemented frameworks

We implemented 6 different frameworks:

$$3\ \text{flavor structures}\begin{cases}\text{general}\\ U(3)^5\ \text{symmetric}\\ \text{linear MFV}\end{cases}\quad\times\quad 2\ \text{input schemes}\begin{cases}\hat{\alpha}_{\rm em}, \hat{m}_Z, \hat{G}_f\\ \hat{m}_W, \hat{m}_Z, \hat{G}_f\end{cases}$$

SMEFTsim: implemented frameworks

We implemented 6 different frameworks:

3 flavor structures
- general
- $U(3)^5$ symmetric
- linear MFV

×

2 input schemes
- $\hat{\alpha}_{\rm em}, \hat{m}_Z, \hat{G}_f$
- $\hat{m}_W, \hat{m}_Z, \hat{G}_f$

---

completely general flavor indices:

2499 parameters including all complex phases

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---

assume an **exact flavor symmetry**

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

under which: $\psi \mapsto U_\psi \psi$ for $\psi = \{u, d, q, l, e\}$

- The Yukawas are the only **spurions** breaking the symmetry:

$$Y_u \mapsto U_u Y_u U_q^\dagger \qquad Y_d \mapsto U_d Y_d U_q^\dagger \qquad Y_l \mapsto U_e Y_l U_l^\dagger\ .$$

- flavor indices contractions are fixed by the symmetry → less parameters

Examples:

$$\mathcal{Q}_{Hu} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_r \gamma^\mu u_s)\, \delta_{\mathbf{rs}}$$

$$\mathcal{Q}_{eB} = B_{\mu\nu}(\bar{l}_r H \sigma^{\mu\nu} e_s)\, (\mathbf{Y_l})_{\mathbf{rs}}$$

SMEFTsim: implemented frameworks

We implemented 6 different frameworks:

$$3\ \text{flavor structures}\begin{cases}\text{general}\\ U(3)^5\ \text{symmetric}\\ \text{linear MFV}\end{cases}\times\quad 2\ \text{input schemes}\begin{cases}\hat{\alpha}_{\rm em},\,\hat{m}_Z,\,\hat{G}_f\\ \hat{m}_W,\,\hat{m}_Z,\,\hat{G}_f\end{cases}$$

---

assume $U(3)^5$ symmetry + CKM only source of $\cancel{CP}$

- all Wilson coefficients $\in\mathbb{R}$
- CP odd bosonic operators are absent ($\propto J_{CP}\simeq 10^{-5}$)
- includes the first order in flavor violation expansion. E.g.:

$$\mathcal{Q}_{Hu}=(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_r\gamma^\mu u_s)\left[\mathbb{1}+(\mathbf{Y_u}\mathbf{Y_u^\dagger})\right]_{rs}$$

$$\mathcal{Q}^{(1)}_{Hq}=(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_r\gamma^\mu q_s)\left[\mathbb{1}+(\mathbf{Y_u^\dagger}\mathbf{Y_u})+(\mathbf{Y_d^\dagger}\mathbf{Y_d})\right]_{rs}$$

$$\hookrightarrow\ \bar{u}_L\gamma^\mu\left[\mathbb{1}+Y_u^\dagger Y_u+V_{\rm CKM}Y_d^\dagger Y_d V_{\rm CKM}^\dagger\right]u_L$$

$$+\,\bar{d}_L\gamma^\mu\left[\mathbb{1}+V_{\rm CKM}^\dagger Y_u^\dagger Y_u V_{\rm CKM}+Y_d^\dagger Y_d\right]d_L$$

Global fit to EW precision data - observables

Results from Berthier,Trott. 1502.02570, 1508.05060
Berthier,Bjørn,Trott 1606.06693

103 observables included

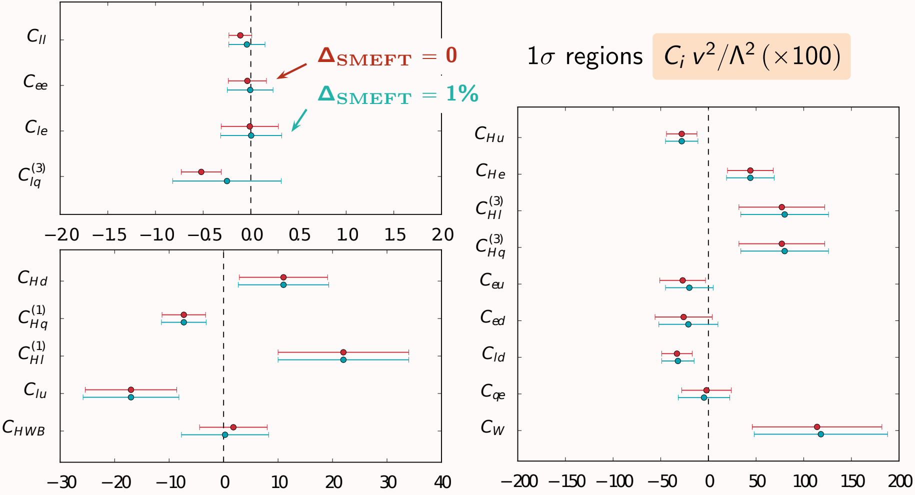
- EWPD near the Z pole: Γ_Z, $R^0_{\ell,c,b}$, $A^{\ell,c,b,\mu,\tau}_{FB}$, σ^0_h
- W mass
- $e^+e^- \to f\bar{f}$ at TRISTAN,PEP,PETRA,SpS,Tevatron,LEP,LEPII
- bhabha scattering at LEPII
- Low energy precision measurements
  - ν-lepton scattering
  - ν-nucleon scattering
  - ν trident production
  - atomic parity violation
  - parity violation in eDIS
  - Møller scattering
  - universality in β decays (CKM unitarity)

Global fit to EW precision data - results

Berthier, Bjørn, Trott 1606.06693

177 observables

20 Wilson coefficients, assuming CP + $U(3)^5$



$\Delta_{\mathrm{SMEFT}} = 0$

$\Delta_{\mathrm{SMEFT}} = 1\%$

1σ regions $C_i\, v^2/\Lambda^2\, (\times 100)$

Global fit to EW precision data - results

Berthier,Bjørn,Trott 1606.06693

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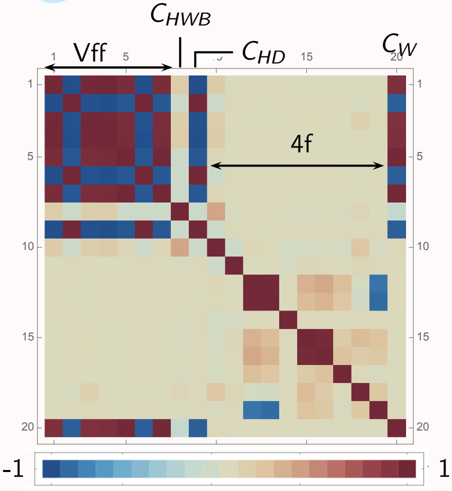
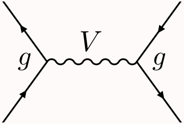


the fit space is highly correlated

The reparameterization invariance

the first fit considered only $\bar\psi\psi \to \bar\psi\psi$ processes

Brivio,Trott 1701.06424



$$V_{\mu\nu}V^{\mu\nu} + g\bar\psi\gamma^\mu\psi V_\mu \longrightarrow (1+2\varepsilon)V_{\mu\nu}V^{\mu\nu} + g\bar\psi\gamma^\mu\psi V_\mu + \mathcal{O}(\varepsilon^2)$$

(*) $V_\mu \to V_\mu(1+\varepsilon)$
$g \to g/(1+\varepsilon)$

non canonical kinetic term.
→ OK adjusting LSZ

at tree level +
$m_f/m_V \ll \varepsilon$

the S-matrix has a reparameterization invariance

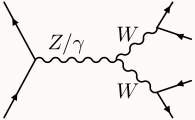
operators modifying the kinetic term normalization have <u>no</u> impact here

$\updownarrow$

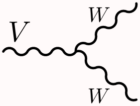
these C_i can be removed from the amplitude via (*)

Breaking the invariance

…needs a process with a TGC! $\bar{\psi}\psi \to \bar{\psi}\psi\bar{\psi}\psi$



In the SMEFT:



rescaling of kinetic term

$gW^i_{\mu\nu}W^{j\mu}W^{k\nu}$

still invariant

not physical.
can be removed via
$(g, V) \to ((1 - C)g, (1 + C)V)$

extra contributions @ $d = 6$

$B_{\mu\nu}W^{i\mu\nu}H^\dagger\sigma^i H$

$W^i_{\mu\nu}D^\mu H^\dagger\sigma^i D^\nu H$

$B_{\mu\nu}D^\mu H^\dagger\sigma^i D^\nu H$

NOT invariant!

induce shifts that
cannot be removed
via (g, V) rescaling

Formulation at the operator level

$\bar\psi\psi \to \bar\psi\psi$ *at tree level and in the limit* $m_\psi/m_Z \ll 1$ are insensitive to

$$\mathcal{Q}_{HW} = W^i_{\mu\nu} W^{i\mu\nu} H^\dagger H$$

$$\mathcal{Q}_{HB} = B_{\mu\nu} B^{\mu\nu} H^\dagger H$$

! not only these though
but any combination equivalent to them via EOM:

$$\frac{\mathcal{Q}_{HW}}{2} = \frac{2i}{g} W^i_{\mu\nu} D^\mu H^\dagger \sigma^i D^\nu H + 2H^\dagger H (D_\mu H^\dagger D^\mu H) + \frac{\mathcal{Q}_{H\Box}}{2} - \frac{t_\theta}{2}\mathcal{Q}_{HWB} + \frac{\mathcal{Q}^{(3)}_{Hq} + \mathcal{Q}^{(3)}_{Hl}}{2}$$

$$\frac{\mathcal{Q}_{HB}}{2} = \frac{2i}{g'} B_{\mu\nu} D^\mu H^\dagger D^\nu H + \frac{\mathcal{Q}_{H\Box}}{2} - \frac{\mathcal{Q}_{HWB}}{2t_\theta} + 2\mathcal{Q}_{HD} + \frac{\mathcal{Q}^{(1)}_{Hq}}{6} + \frac{2}{3}\mathcal{Q}_{Hu} - \frac{\mathcal{Q}_{Hd}}{3} - \frac{\mathcal{Q}^{(1)}_{Hl}}{2} - \mathcal{Q}_{He}$$

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Grojean,Skiba,Terning 0602154

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not constrained in 2 → 2 + **not affecting 2 → 2** ⇒ flat direction

not constrained in 2 → 4 + **probed in 2 → 4** ⇒ constrained!

independently of which operators are retained in the basis!

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The flat directions are a linear superposition of these 2 vectors!

Reducing the parameter space

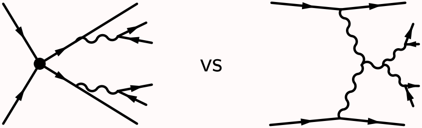
Example – close to a pole

Brivio,Jiang,Trott 1709.06492

most ψ^4 operators give diagrams with less resonances

! Not *always* the case.

E.g. VBS



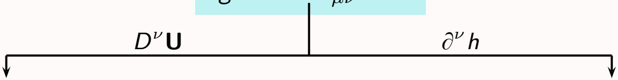
vs

the 4-fermion diagram is not removed by poles selection.

other kinematic variables may help? ▸ can be checked

An example of (de)correlation

$ig' D^\mu H^\dagger B_{\mu\nu} D^\nu H$

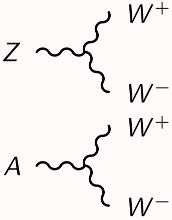


$D^\nu \mathbf{U}$

$\partial^\nu h$

$\mathcal{P}_2 = ig' B_{\mu\nu} \, \mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu])\mathcal{F}_2(h)$

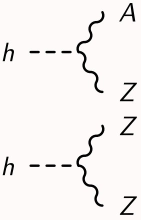
$\mathcal{P}_4 = ig' B_{\mu\nu} \, \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu \mathcal{F}_4(h)$



$Z_{\mu\nu} W^{+\mu} W^{-\nu}$

$A_{\mu\nu} W^{+\mu} W^{-\nu}$

$\leftrightarrow$



$A_{\mu\nu} Z^\mu \partial^\nu h$

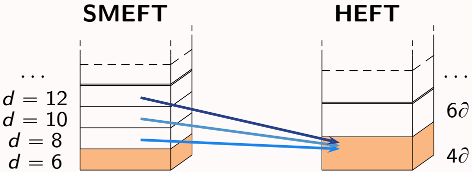
$Z_{\mu\nu} Z^\mu \partial^\nu h$

TGV

HVV

Brivio,Corbett,Éboli,Gavela,Gonzalez-Graile,Gonzalez-Garcia,Merlo,Rigolin 1311.1823

Example of $d = 8$ effect emerging



$$\varepsilon^{\mu\nu\rho\lambda}\left(\Phi^\dagger \overleftrightarrow{D}_\rho \Phi\right)\left(\Phi^\dagger\sigma_i \overleftrightarrow{D}_\lambda \Phi\right) W^i_{\mu\nu}$$

$d = 8$ NNLO in linear

↓

$$\mathcal{P}_{14} = \frac{g}{4\pi}\varepsilon^{\mu\nu\rho\lambda}\,\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\,\mathrm{Tr}(\mathbf{V}_\nu W_{\rho\lambda})\mathcal{F}_{14}(h)$$

4∂ NLO in chiral

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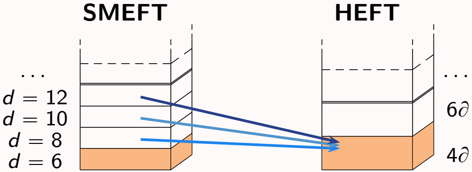
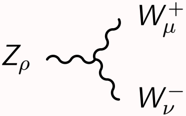
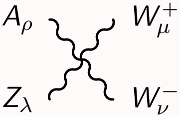
Example of $d = 8$ effect emerging



$\mathcal{P}_{14}$ ➔



$$-\frac{g^3 c_{14}}{2c_\theta}\varepsilon^{\mu\nu\rho\lambda}\partial_\mu W^+_\nu W^-_\rho Z_\lambda + \text{ h.c.}$$



$$-\frac{2eg^3 c_{14}}{c_\theta}\varepsilon^{\mu\nu\rho\lambda} W^+_\mu W^-_\nu Z_\lambda A_\rho + \text{ h.c.}$$

expected comparable in size to other NLO effects

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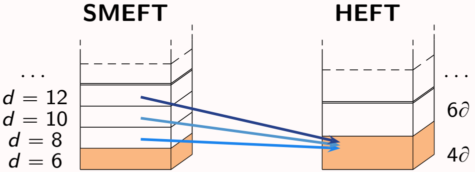
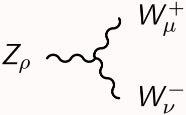
Example of $d = 8$ effect emerging



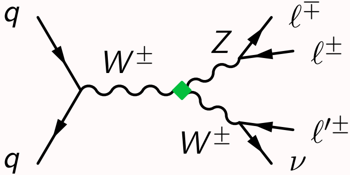
$\mathcal{P}_{14}$ ➔



$$-g c_\theta\, \boxed{g_5^Z}\, \varepsilon^{\mu\nu\rho\lambda}\partial_\mu W^+_\nu W^-_\rho Z_\lambda + \text{h.c.}$$

$$\mathbf{g_5^Z} = \begin{cases} L \quad \dfrac{g}{8c_\theta^2}\dfrac{v^4}{\Lambda^4}c_\varepsilon & \simeq 3\cdot 10^{-4} \\ NL \quad \dfrac{g}{8\pi c_\theta^2}c_{14} & \simeq 3\cdot 10^{-2} \end{cases}$$

with $\Lambda = 1$ TeV and $c_\varepsilon = c_{14} = 1$



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