Precision EW physics in the SMEFT

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Lectures plan

Lectures 1 & 2 – theory

- SMEFT generalities
- SMEFT at $d = 6$: Warsaw basis
- EWSB, Field and couplings redefinitions
- Flavor structure
- EW input parameter schemes
- SMEFT corrections in propagators

Lectures 3 & 4 – phenomenology & more advanced aspects

- Basics of SMEFT predictions
- How is SMEFT probed in the EW sector? EWPO, diboson, Higgs etc
- Global fits: structure, status, examples
- The geometry of the scalar manifold

Material that will be provided

- List of useful references
- List of useful formulas
- Exercise sheets + solutions
- Slides

Lectures 1& 2

The Warsaw basis

Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

1	X^3
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

2	φ^6 and $\varphi^4 D^2$ 3
Q_φ	$(\varphi^\dagger\varphi)^3$
$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$
$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$

	$\psi^2\varphi^3$ 5
$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$

4	$X^2\varphi^2$
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$

6	$\psi^2 X\varphi$
Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G^A_{\mu\nu}$
Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W^I_{\mu\nu}$
Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$

	$\psi^2\varphi^2 D$ 7
$Q^{(1)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q^{(3)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q^{(1)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q^{(3)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

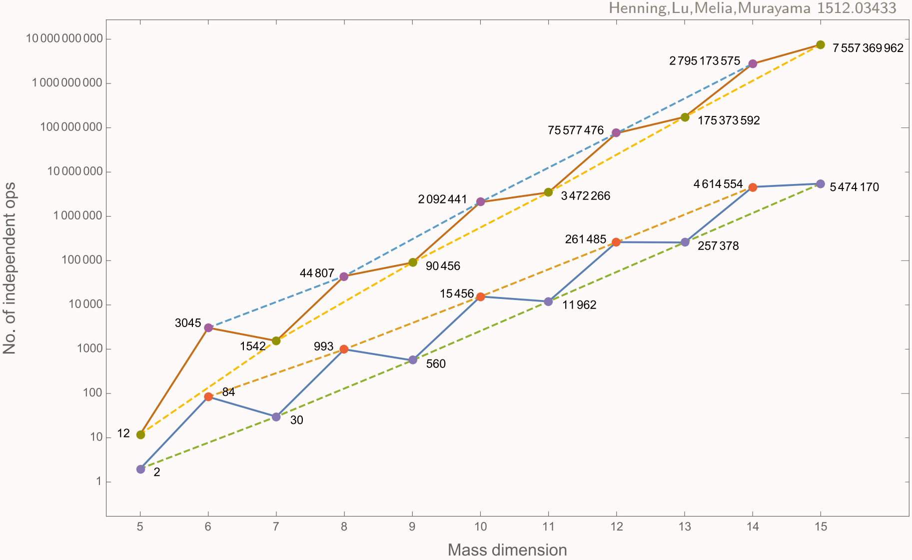
The Warsaw basis

Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

8a $(\bar LL)(\bar LL)$		8b $(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$ 8c	
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}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

8d $(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$		

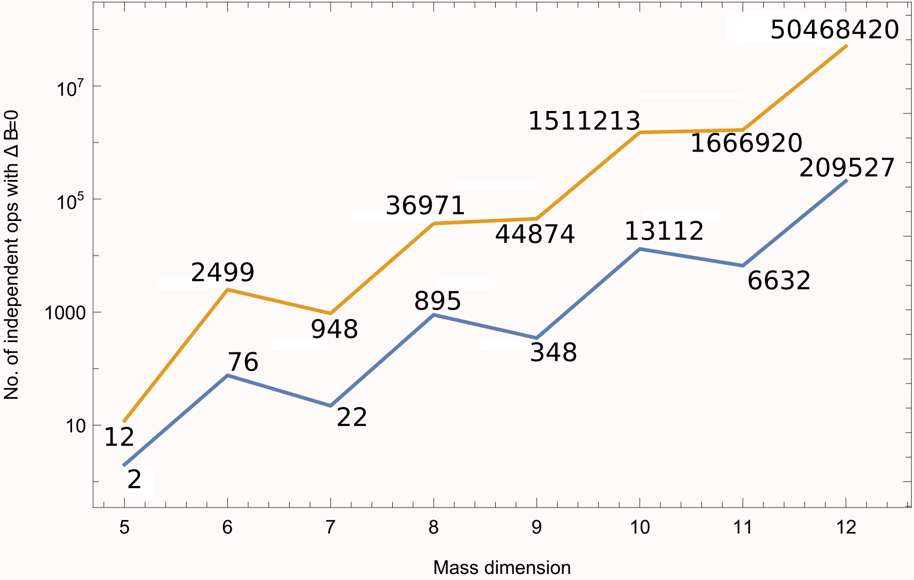
SMEFT: number of independent parameters



SMEFT: number of independent parameters

imposing $\Delta B = 0$

Henning,Lu,Melia,Murayama 1512.03433



A very large flavorful parameter space

Classification within Warsaw basis

Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

Class	CP	~~CP~~	Total
X^3	2	2	4
$\varphi^6 + \varphi^4 D^2$	3	-	3
$\varphi^2 X^2$	4	4	8
$\varphi^2\psi^2$	27	27	54
$\varphi X \psi^2$	72	72	144
$\varphi^2 D\psi^2$	51	30	81
$(\bar{L}L)(\bar{L}L)$	171	126	297
$(\bar{R}R)(\bar{R}R)$	255	195	450
$(\bar{L}L)(\bar{R}R)$	360	288	648
$(\bar{L}R)(\bar{R}L)$	81	81	162
$(\bar{L}R)(\bar{L}R)$	324	324	648

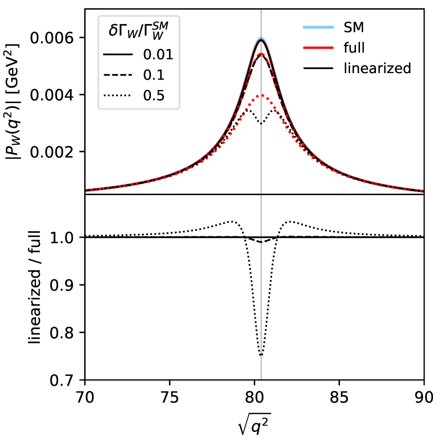
- most parameters from **fermionic** terms
- **flavor** has dramatic impact on counting

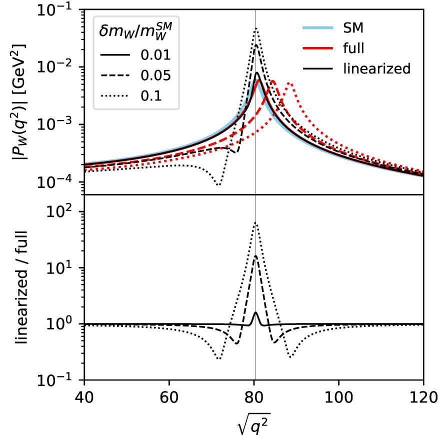
Examples:

$B_{\mu\nu}(\bar{q}_i\sigma^{\mu\nu} d_j)\varphi$	9 + 9
$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_i\gamma^\mu u_j)$	6 + 3
$(\bar{l}_i\gamma_\mu l_j)(\bar{l}_k\gamma^\mu l_l)$	27 + 18
$(\bar{e}_i\gamma_\mu e_j)(\bar{u}_k\gamma^\mu u_l)$	45 + 36
$(\bar{l}_i^l e_j)(\bar{d}_k q_l^l)$	81 + 81

Propagator corrections

$$\frac{i(-\eta^{\mu\nu}+q^\mu q^\nu/m_W^2)}{p^2-m_W^2+i\Gamma_W m_W}\left[1+\frac{im_W\,\Delta\Gamma_W}{p^2-m_W^2+i\Gamma_W m_W}-\frac{(2m_W-i\Gamma_W)\,\Delta m_W}{p^2-m_W^2+i\Gamma_W m_W}\right]+\mathcal{O}(\Lambda^{-4})$$



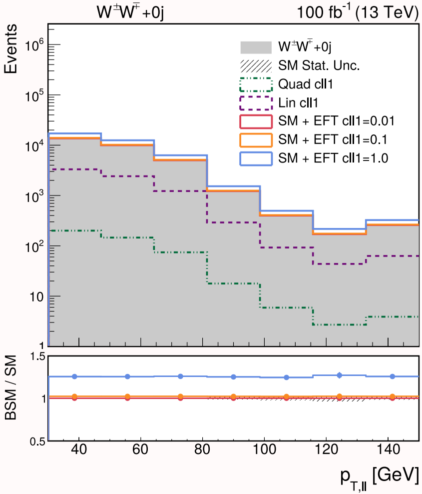


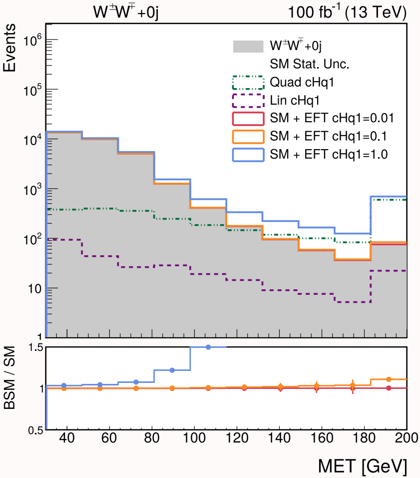
Lectures 3 & 4

SMEFT effects: rescaling vs. shape change

Bellan,Boldrini,Brambilla,IB et al 2108.03199

parton level simulation of $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu$ with $\{m_W, m_Z, G_F\}$ inputs



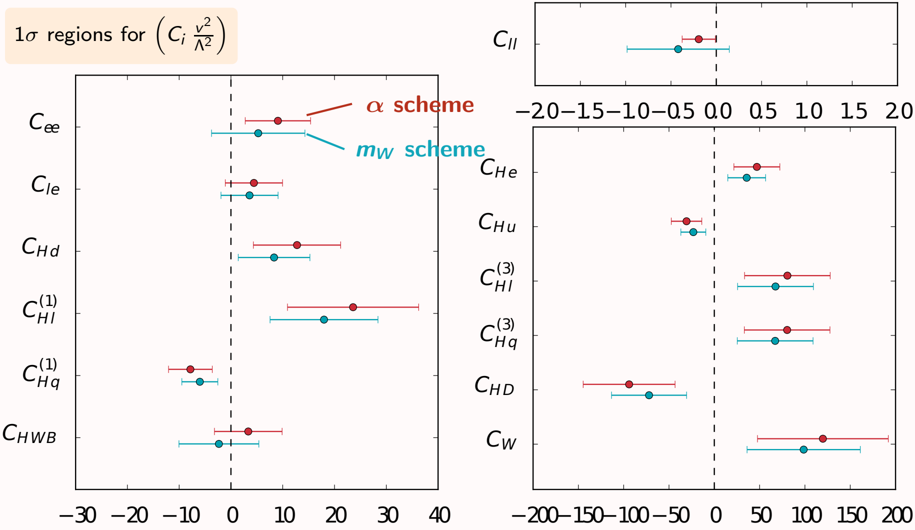


Pure EW fit

Z-pole + m_W + bhabha + WW (LEP2)

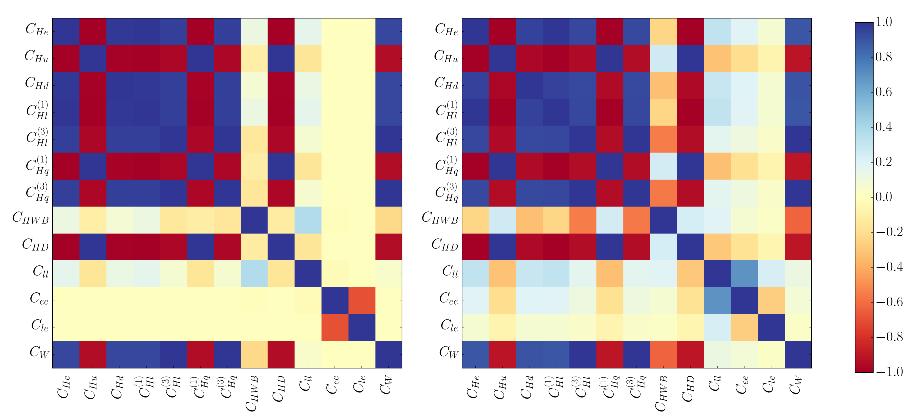
1σ regions for $\left(C_i \frac{v^2}{\Lambda^2}\right)$

Brivio, Trott 1701.06424



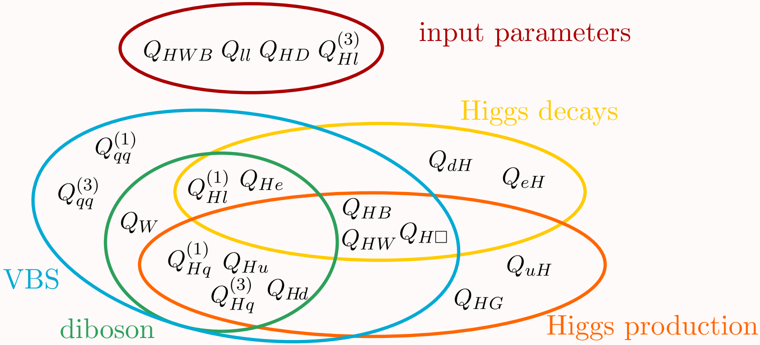
Pure EW fit – correlations

$\{\alpha, m_Z, G_F\}$ $\{m_W, m_Z, G_F\}$



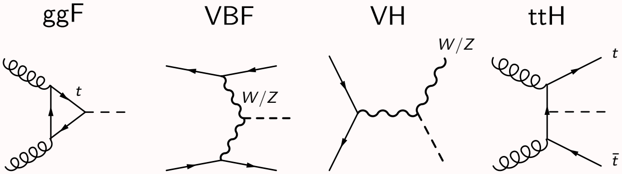
SMEFT for EW and Higgs sectors

leading Warsaw basis operators in Higgs and EW processes: ~ 20

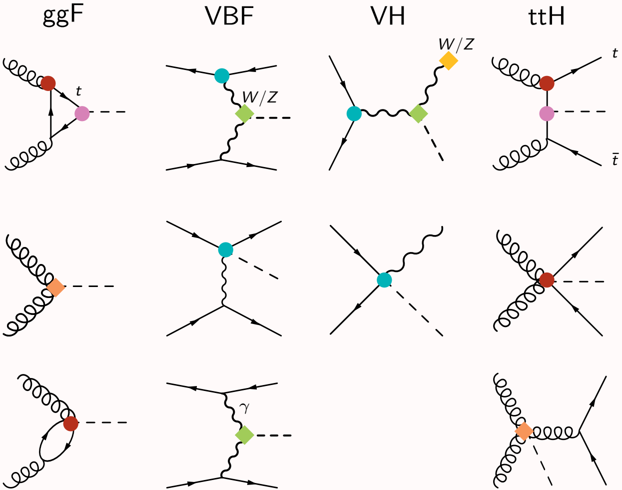


+ CP odd + flavor indices + others entering through loop corrections . . .

SMEFT in Higgs production

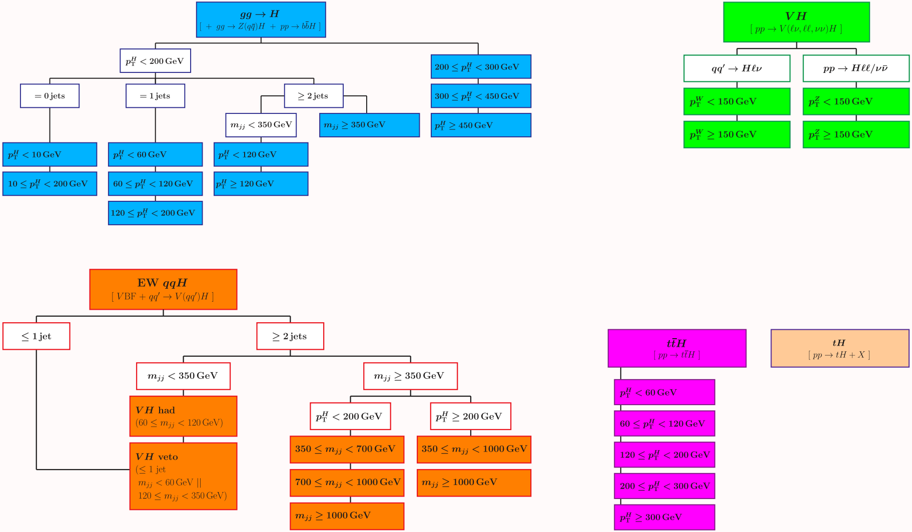


SMEFT in Higgs production



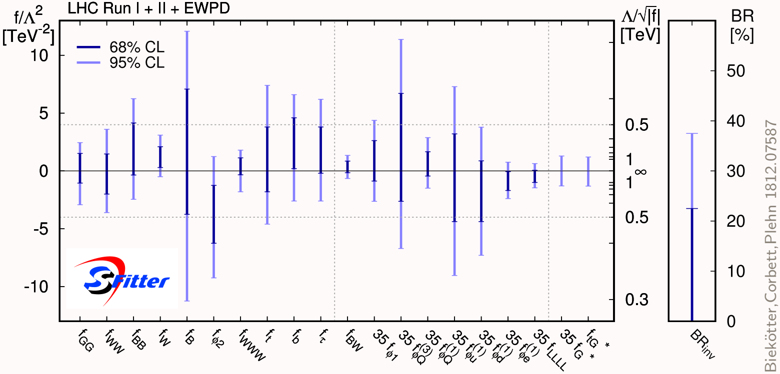
Simplified Template Cross Sections (STXS)

from: ATLAS H10 2207.00348 (stage 1.2)



Higgs + EW fit results

typically: EWPO from LEP
+ diboson measurements (LEP2/LHC)
+ Higgs production/decay rates



HISZ basis

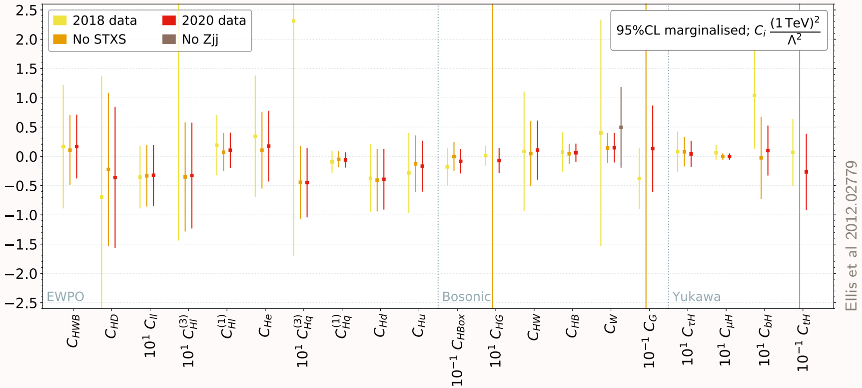
Hagiwara et al PRD48(1993)2182

Higgs + EW fit results

typically: EWPO from LEP

+ diboson measurements (LEP2/LHC)

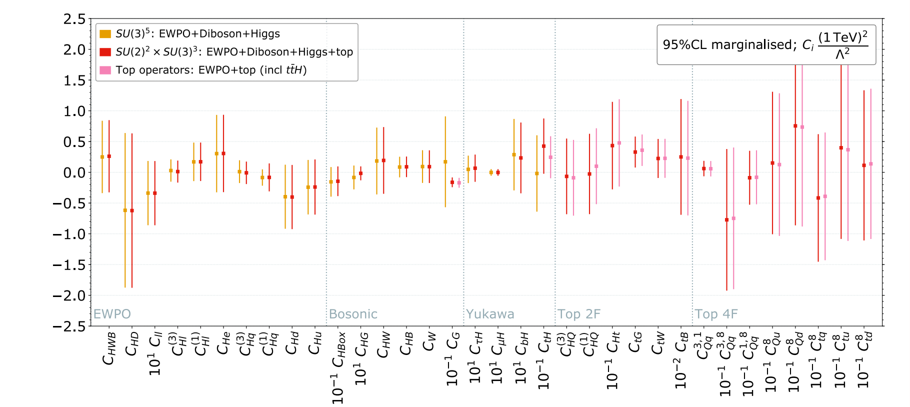
+ Higgs production/decay rates



Warsaw basis Grzadkowski et al 1008.4884

Top + EW + Higgs: global results

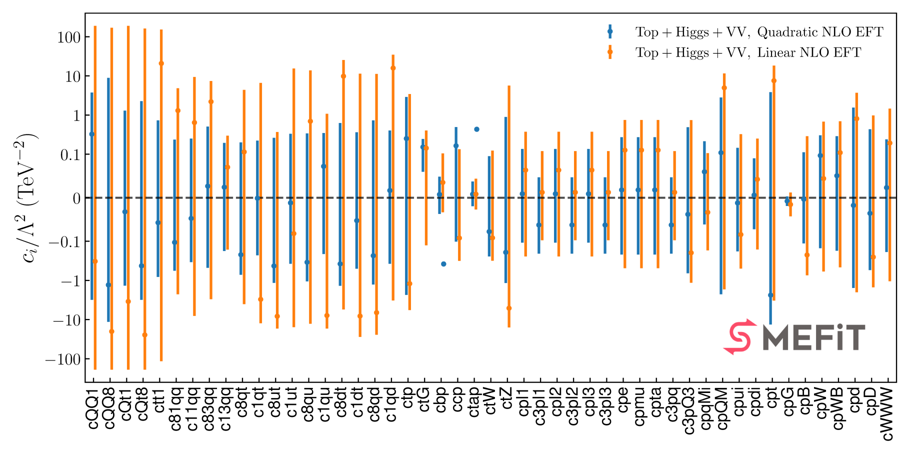
Ellis, Madigan, Mimasu, Sanz, You 2012.02779



34 param, linear, LO + ggH

Top + EW + Higgs: global results

Ethier,Maltoni,Mantani,Nocera,Rojo 2105.00006

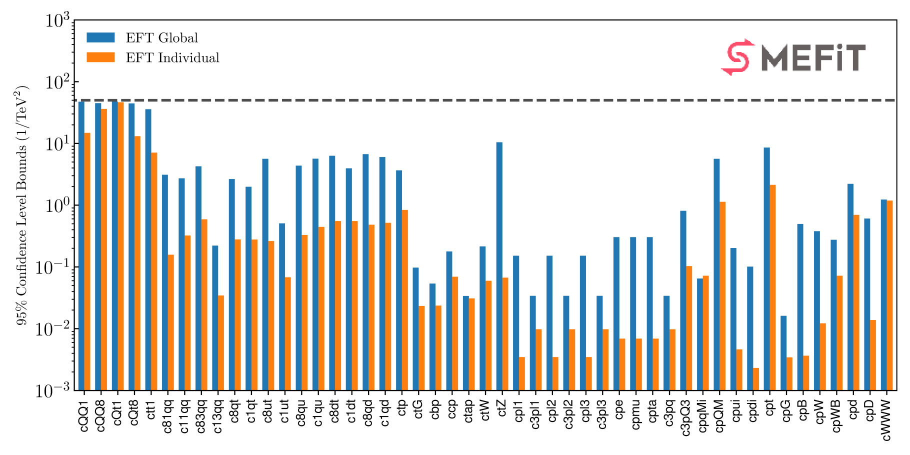


49 param, linear+quadratic, NLO QCD

Top + EW + Higgs: global results

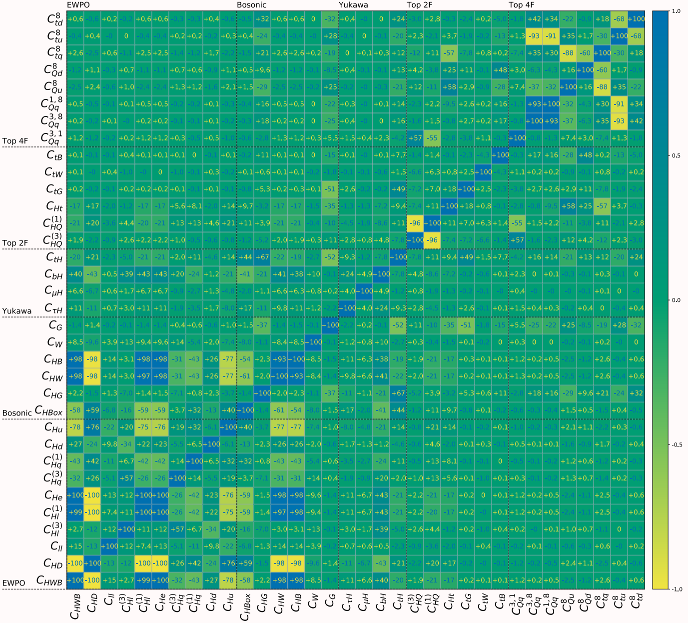
Linear bounds

Ethier,Maltoni,Mantani,Nocera,Rojo 2105.00006

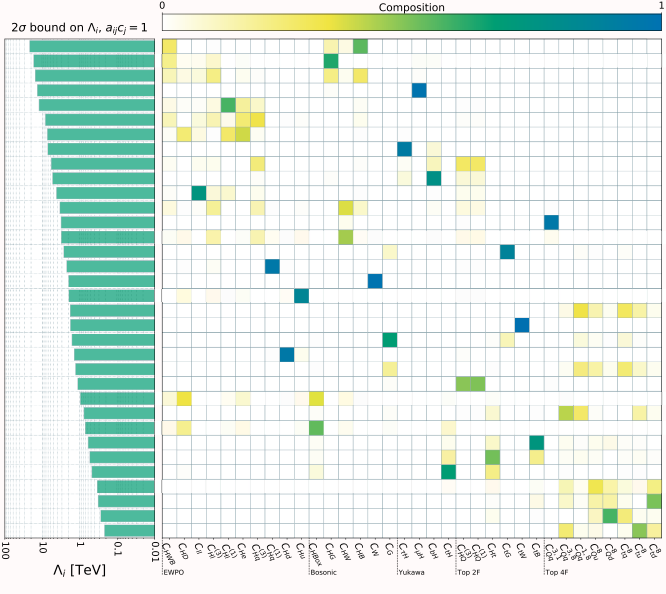


49 param, linear+quadratic, NLO QCD

Top + EW + Higgs: correlation map



Principal Component Analysis



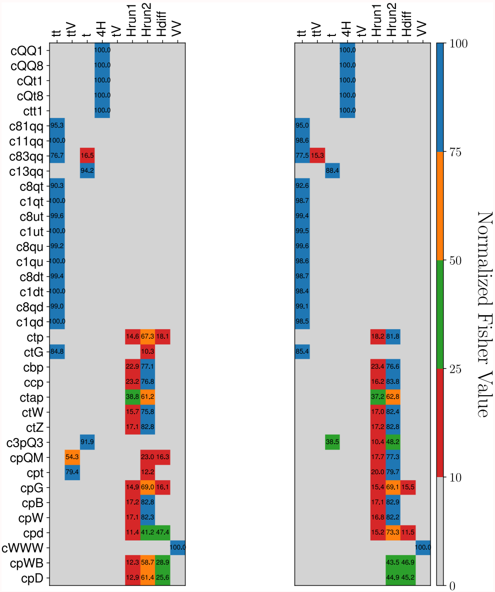
Relative constraining power (%)

EWPO	LEP WW	Run 1, μH	Run 2, μH	STXS	LHC WW&	LHC Zjj	$t\bar{t}$	single top	$t\bar{t}V$
6	–	15	29	50	–	–	–	–	–
35	–	13	28	23	–	–	–	–	–
59	–	7	16	18	–	–	–	–	–
–	–	5	94	1	–	–	–	–	–
99	–	–	–	–	–	–	–	–	–
95	–	–	–	–	3	–	–	–	–
99	–	–	–	–	–	–	–	–	–
–	–	21	45	33	–	–	–	–	–
74	–	2	4	14	6	–	–	–	–
18	–	8	19	55	–	–	–	–	–
73	22	–	–	–	3	–	–	–	–
7	2	5	53	4	29	–	–	–	–
–	–	–	3	–	–	–	–	96	–
7	–	2	39	2	46	–	–	3	–
–	–	–	10	4	–	–	57	–	28
94	2	–	–	–	2	–	–	–	–
–	2	–	–	–	11	86	–	–	–
65	14	2	4	10	4	1	–	–	–
–	–	–	–	–	–	–	99	–	–
–	–	–	–	–	–	–	84	15	–
–	–	–	13	6	–	–	48	–	32
90	5	–	–	1	2	–	–	–	–
–	–	–	5	2	–	–	79	–	13
–	–	–	–	–	–	–	3	78	18
2	3	27	40	12	6	–	4	–	4
–	–	1	2	–	–	–	15	4	77
4	4	14	33	23	7	1	12	–	2
–	–	1	3	1	–	–	4	–	89
–	–	3	10	4	–	–	28	2	53
1	–	8	27	16	2	–	32	–	12
–	–	–	–	–	–	–	58	–	41
–	–	–	–	–	–	–	90	–	10
–	–	–	–	–	–	–	61	–	38
–	–	–	–	–	–	–	95	–	5

Ellis, Madigan, Mimasu, Sanz, You 2012.02779

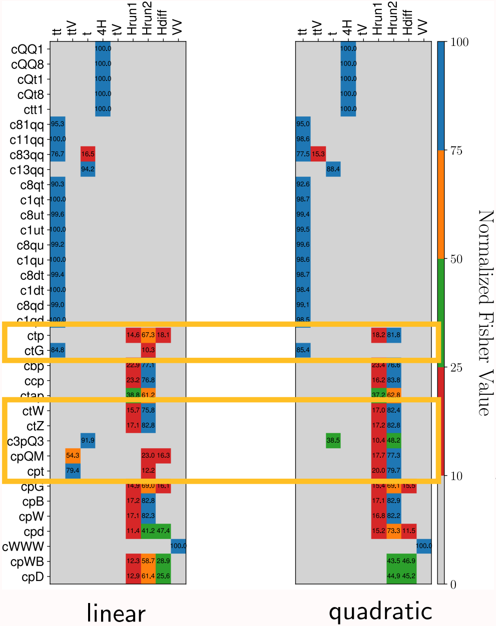
Fisher information

Ethier,Maltoni,Mantani,Nocera,Rojo,Slade,Vryonidou,Zhang 2105.00006



linear quadratic

Fisher information



C_{tG} mostly constrained by $t\bar{t}$

ttV op. constrained by $h \to \gamma\gamma$, single-t, $t\bar{t}V$

SMEFTsim tutorial

Usage in Mathematica: Feynman rules

A Mathematica notebook with examples in the GitHub repository:

```
SMEFTsim_Mathematica_notebooks/SMEFTsim_usage_examples.nb
```

Instructions

- load Feynrules

```
$FeynRulesPath = SetDirectory[‘‘FEYNRULESPATH’’];
<< FeynRules‘;
```

- load SMEFTsim. Flavor and Scheme must be defined first!

```
SetDirectory[‘‘SMEFTSIM_FR_PATH’’];
Flavor = U35;
Scheme = MwScheme;
LoadModel[‘‘SMEFTsim_main.fr’’]
```

accepted flavors: `general, U35, MFV, top, topU3l`

accepted schemes: `alphaScheme, MwScheme`

only the selected combination is loaded.
information about other options cannot be accessed.

Obtaining Feynman rules

- *hVV* vertices

```
frHVV = FeynmanRules[LHiggs + LSMloop + L6cl4, MaxParticles -> 3,
    Contains -> H];
```

- *Zff* vertices

```
frZfer = FeynmanRules[LFermions + L6cl7, MaxParticles -> 3,
    Contains -> Z];
```

- all vertices from **bosonic op.** eg. $\mathcal{O}_{HB}$

```
OHB // FeynmanRules
```

- all vertices from **fermionic op.** eg. $\mathcal{O}_{Hl}^{(1)}$

```
Select[L6cl7, !FreeQ[#, cHl1] &] // FeynmanRules
```

or

```
OHl1[1,1] // FeynmanRules
```

specifying flavor indices

- all FR are given in **input scheme-independent** form, containing `dg1, dgw, dGf...`.
  go to scheme-specific notation applying replacements:

  `.//MwShifts` or `.//alphaShifts`

Available variables and functions

- `LGauge`. Gauge boson kin. terms.
- `LHiggs`. Higgs boson kin. term (incl hVV, $hhVV$)
- `LFermions`. Fermions kin. terms
- `LSMloop`. SM Higgs couplings to $hgg(ggg), h\gamma\gamma, hZ\gamma$
- `L6cl1, ...L6cl7`. Operators of class 1…7
- `L6cl8a, ...L6cl8d`. Operators of class 8a …8d

- `WCsimplify`. Collects the Wilson coefficients in an expression one by one.
- `SMlimit`. Returns the SM limit of an expression.
- `relativeVariation`. Returns an expression normalized to its SM part

- `MwShifts`. Input shifts replacements for $\{m_W, m_Z, G_F\}$ scheme.
- `alphaShifts`. Input shifts replacements for $\{\alpha_{\rm em}, m_Z, G_F\}$ scheme.

Interactive tool

Download notebook + Working material from **NotebookArchive**

- initialize evaluating
```
SetDirectory[NotebookDirectory[]];
<< SMEFTsimFR`
```
- Evaluate (ctrl + Enter) the commands `FRbyOperator` and `FRbyVertex`
  This activates the two interactive tools
- in the `FRbyOperator` type a Wilson coefficient in SMEFTsim notation and hit Enter.
  e.g. cHB, cHu, cuHRe...
  use the options panel to refine the output. You can type more than one coefficient, separated by commas, and also use wildcards e.g. cHu*
- in the `FRbyVertex` type one vertex.
  The fields you can use are in a table that is called via `fieldsTable`
  Separate them by a comma.

SMEFTsim in MadGraph

- download the `Material.tar` with

```
wget https://www.dropbox.com/s/nr1pm0ijxu1es5f/Material.tar
```

  and extract: `tar -xvf Material.tar`

- download `SMEFTsim_U35_MwScheme_UFO` from GitHub, or, in MG5, type

```
import model SMEFTsim_U35_MwScheme_UFO
```

  and it will be automatically downloaded and stored in the `MG5/models/` directory.

- in `SMEFTsim_U35_MwScheme_UFO/coupling_orders.py`

  change

```
NPprop = CouplingOrder(name = 'NPprop',
expansion_order = 0,
```

  into

```
NPprop = CouplingOrder(name = 'NPprop',
expansion_order = 99,
```

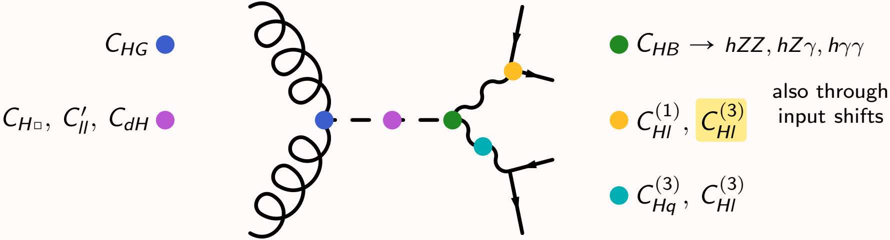
  this enables propagator corrections.

- put the restriction card `restrict_ggF41.dat` into the UFO directory

  the restriction has `linearPropCorrections` = 1. Also needed for propagators.

Exercise: $gg \to h \to e^+e^-\mu^+\mu^-$

1. generate in the SM
2. compute SMEFT corrections for some operators via reweighting:
   pure interference , quadratics , linear corr. from h, Z propagators
3. plot m_{12}, m_{34} to understand the impact of the different operators



1. SM $gg \to h \to e^+e^-\mu^+\mu^-$

- start Madgraph: `MADGRAPHDIR/bin/mg5_aMC`
- in MG: import model with restriction and generate process:

```
import model SMEFTsim_U35_MwScheme_UFO-ggF4l
generate g g > h SMHLOOP==1, h > e+ e- mu+ mu- SMHLOOP=0 @0 NP=0 NPprop=0
output gg_h_eemm
launch
```

- modify `param_card`: set to 0 all SMEFT parameters
- modify `run_card`: set `False = use_syst`

- `g g > h, h > ...` only generates on-shell Higgs signal
- `SMHLOOP` counts SM hgg, $hggg$, $hgggg$, $h\gamma\gamma$, $hZ\gamma$ vertices
- `NP` counts vertices with SMEFT insertions
- `NPprop` counts vertices of dummy particles carrying propagator corr.
- orders specified after `@0` apply to the entire production+decay chain. orders to the left apply only to the corresponding subprocesses.

2. SMEFT corrections to $gg \to h \to e^+e^-\mu^+\mu^-$

- The reweighting commands are already provided in the reweight cards
- They are all launched at once by the shell script. Adjust the `PROCNAME` and `RUNNAME` variables inside the script to match yours.
- Launch and approve all questions:

```
./launch_reweighting.sh
```

order specifications

any interference	`NP<=1 NP^2==1`
specific interf.	`NP<=1 NP^2==1 NPcHl1^2==1`
any square	`NP==1`
specific mixed square	`NP==1 NPcHl1^2==1 NPcHB^2==1`
propagators interf.	`NP=0 NPprop<=2 NPprop^2==2`

`NP` counts vertices in amplitude, `NP^2` counts vertices in **squared** amp.

`g g > h, h > ...` syntax does not allow amp^2 specifications.
we use `g g > h >...` instead, that generally does not restrict to on-shell.

`<=`, `=` are the same

3. Event analysis

- ```
  gunzip gg_h_eemm/Events/run_01/unweighted_events.lhe.gz
  ```
- analyze lhe file and create a .root with histograms
  ```
  python lhe_analyzer.py gg_h_eemm/Events/run_01/unweighted_events.lhe
  lhe_events.root
  ```
  you can visualize this in ROOT with
  ```
  root
  new TBrowser()
  ```
- create plots
  ```
  python plot_histos.py lhe_events.root
  ```
- modify `plot_histos.py` to plot different sets of lines / ranges
  ```

Some physics to notice

- C_{HG} and operators in the Higgs propagators only give overall rescalings
- C_{HG} correction is huge: formally **tree/loop** $\to \mathcal{O}(100)$
- difference between $C_{Hl}^{(1)}$, $C_{Hl}^{(3)}$ purely due to $C_{Hl}^{(3)}$ entering input shifts
- operators in the Z propagator only relevant for $m_{ll} \simeq m_Z$
- propagator corr. bring in new operators, that contribute to other h/Z decays, eg. C_{dH} from $h \to b\bar{b}$, $C_{Hq}^{(3)}$ from $Z \to q\bar{q}$
- $\mathcal{O}_{HB}$ modifies hZZ and introduces $hZ\gamma$ and $h\gamma\gamma$ vertices
  $\to$ spectrum significantly distorted towards low m_{ll}.
  the effect is even stronger at quadratic level.
- the square of $C_{Hl}^{(1)}$ is suppressed