The Higgs width in the SMEFT

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based on 1906.06949
in collaboration with T. Corbett and M. Trott

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)

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

More than a parameterization

the complete SMEFT Lagrangian, truncated at a given order,
is always* **a self-consistent QFT** and
a valid description of Nature

* assuming nearly-decoupled BSM matching SM sym + fields and evaluating at $E \ll \Lambda$

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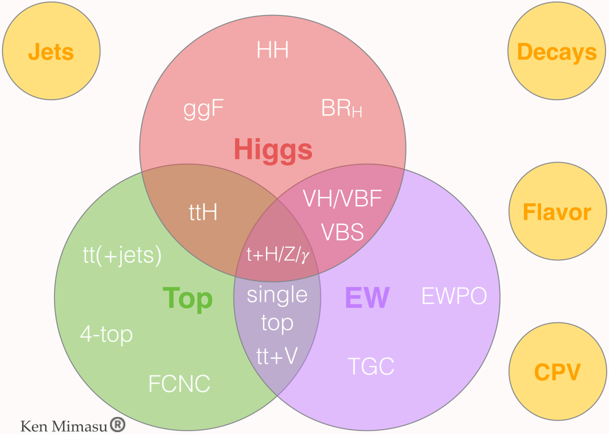
- combination of different processes / sectors required



Global SMEFT analyses

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How many parameters? depends on:
- flavor assumptions
- linear / quadratic terms retained
- LO/NLO QCD (SMEFT)

For reference:

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

Brivio,Jiang,Trott 1709.06492

WZH pole obs. = resonance-dominated processes. Interference only.

Example 1: Higgs and EW processes

- $U(3)^5$ flavor symmetry
- all relevant interactions included **23 relevant operators**
- tree-level, interference only

Brivio,Hays,Smith,Trott,Žemaitytė in preparation

also: Ellis,Murphy,Sanz,You 1803.03252 **20**

Z,W couplings

$$\begin{aligned}
\mathcal{Q}_{Hl}^{(1)} &= (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)\\
\mathcal{Q}_{He} &= (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)\\
\mathcal{Q}_{Hq}^{(1)} &= (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)\\
\mathcal{Q}_{Hq}^{(3)} &= (iH^\dagger \overleftrightarrow{D}^i_\mu H)(\bar{q}\sigma^i\gamma^\mu q)\\
\mathcal{Q}_{Hu} &= (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)\\
\mathcal{Q}_{Hd} &= (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)
\end{aligned}$$

$$\begin{aligned}
\mathcal{Q}_{HD} &= (D_\mu H^\dagger H)(H^\dagger D^\mu H)\\
\mathcal{Q}_{HWB} &= (H^\dagger\sigma^i H)W^i_{\mu\nu}B^{\mu\nu}\\
\mathcal{Q}_{Hl}^{(3)} &= (iH^\dagger \overleftrightarrow{D}^i_\mu H)(\bar{l}\sigma^i\gamma^\mu l)\\
\mathcal{Q}'_{ll} &= (\bar{l}_p\gamma^\mu l_r)(\bar{l}_r\gamma^\mu l_p)
\end{aligned}$$

input quantities

Bhabha scattering

$$\begin{aligned}
\mathcal{Q}_{ee} &= (\bar{e}\gamma^\mu e)(\bar{e}\gamma^\mu e)\\
\mathcal{Q}_{le} &= (\bar{l}\gamma^\mu l)(\bar{e}\gamma^\mu e)\\
\mathcal{Q}_{ll} &= (\bar{l}_p\gamma^\mu l_p)(\bar{l}_r\gamma^\mu l_r)
\end{aligned}$$

$$\begin{aligned}
\mathcal{Q}_{Hbox} &= (H^\dagger H)\square(H^\dagger H)\\
\mathcal{Q}_{HG} &= (H^\dagger H)G^a_{\mu\nu}G^{a\mu\nu}\\
\mathcal{Q}_{HB} &= (H^\dagger H)B_{\mu\nu}B^{\mu\nu}\\
\mathcal{Q}_{HW} &= (H^\dagger H)W^i_{\mu\nu}W^{i\mu\nu}\\
\mathcal{Q}_{uH} &= (H^\dagger H)(\bar{q}\tilde{H}u)\\
\mathcal{Q}_{dH} &= (H^\dagger H)(\bar{q}Hd)\\
\mathcal{Q}_{eH} &= (H^\dagger H)(\bar{l}He)\\
\mathcal{Q}_{G} &= \varepsilon_{abc}G^{a\nu}_\mu G^{b\rho}_\nu G^{c\mu}_\rho\\
\mathcal{Q}_{uG} &= (\bar{q}\sigma^{\mu\nu}T^a\tilde{H}u)G^a_{\mu\nu}
\end{aligned}$$

H processes

PRELIMINARY

TGC

$$\mathcal{Q}_W = \varepsilon_{ijk}W^{i\nu}_\mu W^{j\rho}_\nu W^{k\mu}_\rho$$

Example 2: top quark processes

- $U(2)_q \times U(2)_u \times U(2)_d$
- top interactions only for now
- up to NLO QCD, quadratic SMEFT

Brivio, Bruggisser, Maltoni, Moutafis, Plehn, Vryonidou, Westhoff, Zhang 1910.03606

22 relevant operators

also: Hartland, Maltoni, Nocera, Rojo, Slade, Vryonidou, Zhang 1901.05965 **34**

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tZ $\quad$ $t\bar{t}Z, t\bar{t}W$ $\quad$ single t $\quad$ $t\bar{t}$

$$\mathcal{Q}_{tB} = (\bar{Q}\tilde{H}\sigma^{\mu\nu} t) B_{\mu\nu}$$
$$\mathcal{Q}_{Ht} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{t}\gamma^\mu t)$$

$$\mathcal{Q}_{bW} = (\bar{Q}H\sigma^{\mu\nu}\sigma^k b) W^k_{\mu\nu}$$
$$\mathcal{Q}_{Htb} = (i\tilde{H}^\dagger D_\mu H)(\bar{t}\gamma^\mu b)$$

$$\mathcal{Q}_{tG} = (\bar{Q}\tilde{H}\sigma^{\mu\nu} T^A t) G^A_{\mu\nu}$$

$$\mathcal{Q}^1_{Qu} = (\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u) \qquad \mathcal{Q}^8_{Qu} = (\bar{Q}\gamma_\mu T^A Q)(\bar{u}\gamma^\mu T^A u)$$
$$\mathcal{Q}^1_{Qd} = (\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d) \qquad \mathcal{Q}^8_{Qd} = (\bar{Q}\gamma_\mu T^A Q)(\bar{d}\gamma^\mu T^A d)$$
$$\mathcal{Q}^1_{tu} = (\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u) \qquad \mathcal{Q}^8_{tu} = (\bar{t}\gamma_\mu T^A t)(\bar{u}\gamma^\mu T^A u)$$
$$\mathcal{Q}^1_{td} = (\bar{t}\gamma_\mu t)(\bar{d}\gamma^\mu d) \qquad \mathcal{Q}^8_{td} = (\bar{t}\gamma_\mu T^A t)(\bar{d}\gamma^\mu T^A d)$$
$$\mathcal{Q}^{1,1}_{Qq} = (\bar{Q}\gamma_\mu Q)(\bar{q}\gamma^\mu q) \qquad \mathcal{Q}^{1,8}_{Qq} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}\gamma^\mu T^A q)$$
$$\mathcal{Q}^1_{tq} = (\bar{t}\gamma_\mu t)(\bar{q}\gamma^\mu q) \qquad \mathcal{Q}^8_{tq} = (\bar{t}\gamma_\mu T^A t)(\bar{q}\gamma^\mu T^A q)$$

$$\mathcal{Q}^3_{HQ} = (iH^\dagger \overleftrightarrow{D}^i_\mu H)(\bar{Q}\sigma^i\gamma^\mu Q)$$
$$\mathcal{Q}^1_{HQ} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$$
$$\mathcal{Q}_{tW} = (\bar{Q}\tilde{H}\sigma^{\mu\nu}\sigma^k t) W^k_{\mu\nu}$$

$$\mathcal{Q}^{3,8}_{Qq} = (\bar{Q}\gamma_\mu\sigma^k T^A Q)(\bar{q}\gamma^\mu\sigma^k T^A q)$$
$$\mathcal{Q}^{3,1}_{Qq} = (\bar{Q}\gamma_\mu\sigma^k T^A Q)(\bar{q}\gamma^\mu\sigma^k T^A q)$$

An important observable: the Higgs width

a crucial observable for the Higgs sector

SM: $$\Gamma_H \simeq 4 \text{ MeV} \quad \to \quad \frac{\Gamma_H}{m_H} \simeq 3 \cdot 10^{-5} \ll 1$$

$\Rightarrow$ Higgs measurements can be factored into

$$\sigma(i \to H) \times Br(H \to f)$$

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SMEFT: probe separately production and decay

$$Br_{\rm SMEFT}(H \rightarrow f) = \left[\frac{\Gamma(H \rightarrow f)}{\Gamma_H^{\rm tot}}\right]_{\rm SM} \left[1 + \frac{\delta\Gamma(H \rightarrow f)}{\Gamma_{\rm SM}(H \rightarrow f)} - \frac{\delta\Gamma_H^{\rm tot}}{\Gamma_{H,\rm SM}^{\rm tot}}\right]$$

- both $\delta\Gamma(H \rightarrow f)$ and $\delta\Gamma_H^{\rm tot}$ need to be determined
- $\delta\Gamma_H^{\rm tot}$ enters all processes $\rightarrow$ **strong impact** on global SMEFT analyses!

The Higgs width in the SMEFT - setup

Focus on the leading contributions:

- LO in the EFT: up to SM - $\mathcal{L}_6$ **interference**.

$$\Gamma_H = \Gamma_{H,\mathrm{SM}}\left[1+\frac{\delta\Gamma_H}{\Gamma_{H,\mathrm{SM}}}\right] \qquad \frac{\delta\Gamma_H}{\Gamma_{H,\mathrm{SM}}} = \sum_i a_i \bar{C}_i = \sum_i a_i \left(C_i \frac{v^2}{\Lambda^2}\right)$$

- **tree level**.

  SM couplings $H\gamma\gamma$, $HZ\gamma$, Hgg included as effective vertices for $H \to f\bar{f}\gamma \,/\, \gamma\gamma \,/\, gg$.

  Neglected in other channels.

- up to **4-body** decays.

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Conventions and assumptions:

- Warsaw basis — Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884
- **U(3)^5 flavor symmetry** $\to g_{Hff} \sim y_f$ also in the SMEFT
- **inclusive** calculation, not differential $\to$ CP odd terms do not contribute
- **2 input schemes**: $\{m_W, m_Z, G_F\}$, $\{\alpha_{\mathrm{em}}, m_Z, G_F\}$

⇝ backup

The Higgs width in the SMEFT

leading channels:

$$H \to \bar{f}f$$

$$H \to gg$$

$$H \to \gamma\gamma$$

$$H \to \bar{f}f\gamma$$

$$H \to 4f$$

- $4f, \gamma\gamma, \bar{b}b$ most relevant ones individually
- **all** need to be calculated for $\delta\Gamma_H^{\rm tot} \to Br$

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$$\frac{\Gamma(H \to \bar{f}f)}{\Gamma_{SM}(H \to \bar{f}f)} \simeq 1 + 2\delta g_{Hff}$$

$$\delta g_{Hff} = \bar{C}_{H\Box} - \frac{\bar{C}_{HD}}{4} - \bar{C}^{(3)}_{Hl} + \frac{\bar{C}'_{ll}}{2} - \frac{5}{2}\bar{C}_{fH}$$

Alonso,Jenkins,Manohar,Trott 1312.2014

- renorm. of the H field
- contrib. to μ decay $\to G_F \to v$
- direct $\mathcal{O}_{fH}$ contribution $\left(-\frac{3}{2}\bar{C}_{fH}\right)$ + contrib. to $m_f \to y_f$ $\left(-\bar{C}_{fH}\right)$

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$$\frac{\Gamma(h \to gg)}{\Gamma^{SM}(h \to gg)} \simeq 1 + \frac{16\pi^2}{g_s^2 I^g}\bar{C}_{HG}\,, \qquad I^g \simeq 0.375$$

Manohar,Wise 0601212

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$$\mathscr{C}_{\gamma\gamma} = s_\theta^2\,\bar{C}_{HW} + c_\theta^2\,\bar{C}_{HB} - s_\theta c_\theta\,\bar{C}_{HWB}$$

Bergström,Hulth Nucl.Phys.B259(1985)137
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Manohar, Wise 0601212

loop-factor enhancement
in the relative correction:

tree-level SMEFT vs loop SM

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available as $H \to ZZ^*$, $H \to WW^* \quad \times Br(Z, W)$
relying on narrow width approx. for Z, W.

good in SM but **not sufficient** in the SMEFT!

main reason: tree $\gamma\gamma, Z\gamma$ mediated diagrams

also missing:

- CC - NC interference
- crossed-current interference in ZZ diagrams
- $\delta\Gamma_V$, δm_V^2 corrections for off-shell boson

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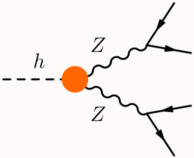
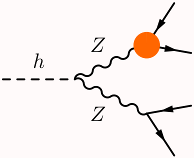
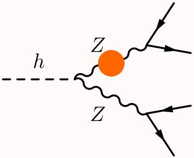
H $\rightarrow$ 4f in the SMEFT

① corrections to SM diagrams







$\propto g_{\mu\nu}$ (SM-like)

$\propto g_{\mu\nu} p{\cdot}q - p_\nu q_\mu$ $(Z_{\mu\nu} Z^{\mu\nu} h)$

$\delta g_L, \delta g_R$

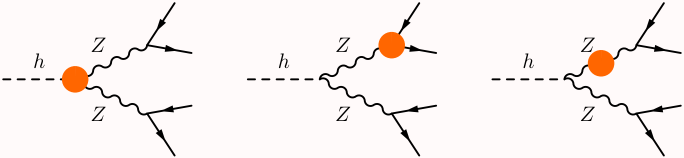
$$\frac{-i m_Z \delta\Gamma_Z + (2 m_Z - i\Gamma_Z)\delta m_Z}{p^2 - m_Z^2 + i\Gamma_Z m_Z}$$

$\uparrow$

hard to extract from MC simulation!
full treatment requires analytic calculation

$H \to 4f$ in the SMEFT

① corrections to SM diagrams



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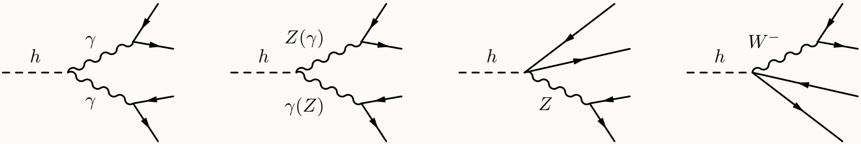
$\delta g_L, \delta g_R$

$$\frac{-im_Z\delta\Gamma_Z + (2m_Z - i\Gamma_Z)\delta m_Z}{p^2 - m_Z^2 + i\Gamma_Z m_Z}$$

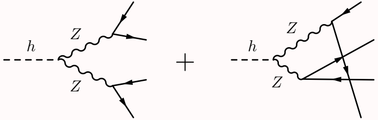
② genuine SMEFT diagrams



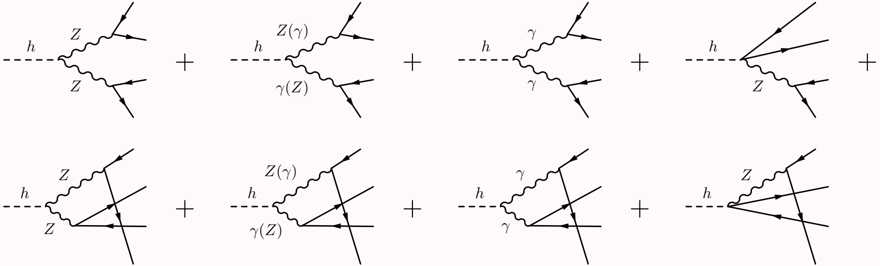
H → 4f in the SMEFT - complexity

$h \to e^+ e^- e^+ e^-$

SM

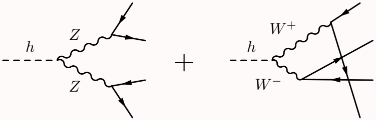


interfering with

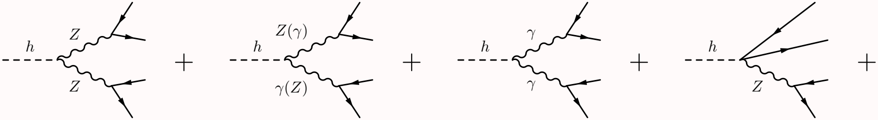


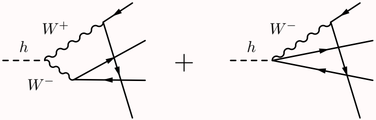
$h \to \bar{u}\, u\, \bar{d}\, d$

SM



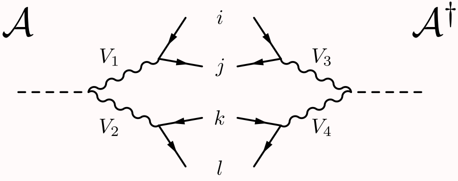
interfering with





H $\to$ 4f - analytic calculation

fully analytical treatment. automated with general decomposition:



$$\mathcal{A}\mathcal{A}^\dagger \sim g_{HV_1V_2}\, g_{HV_3V_4} \sum_n \mathcal{T}^{(n)}$$

$$\mathcal{T}^{(n)} = \mathcal{K}^{(n)}\left(g_{L,R}^{ij,V_1}, g_{L,R}^{ij,V_3}, g_{L,R}^{kl,V_2}, g_{L,R}^{kl,V_4}\right) \mathcal{F}^{(n)}_{V_1V_2V_3V_4}(p_a, m_a), \quad a = \{i,j,k,l\}$$

for $m_a \equiv 0$ there are only **8** independent $\mathcal{F}_{V_1V_2V_3V_4}$. For each $\{V\}$ set:

- numerical integration of phase space: `Vegas` in `Mathematica` T. Hahn 0404043
- cross-check: `RAMBO` + 2 independent parameterizations of phase space

Kleiss,Stirling,Ellis
Comput.Phys.Commun.40(1986)359

Cross-check: MadGraph with SMEFTsim

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

Brivio, Jiang, Trott 1709.06492

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** and **parameter shifts** due to the choice of an input parameters set
3. 6 implementations: 3 flavor assumptions × 2 input schemes

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

wiki: SMEFT

Standard Model Effective Field Theory -- The SMEFTsim package

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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

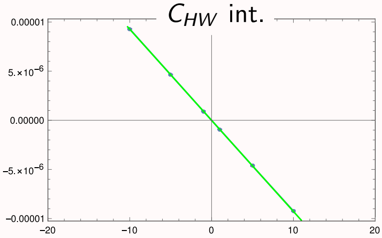
* LO, unitary gauge implementation

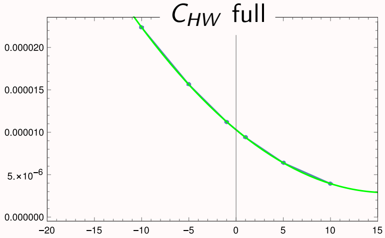
Cross-check: MadGraph with SMEFTsim

e.g $\delta\Gamma_{h\to e^+\mu^-\bar\nu_\mu\nu_e}/\Gamma_{h\to e^+\mu^-\bar\nu_\mu\nu_e,SM}$

extracting dependence on Wilson coefficients:

- estimate full $\Gamma(h\to W^+\mu^-\bar\nu_\mu)$ in SM limit
- estimate pure interference contribution with one C_i turned on ($\times 5$ values)
  $\to$ linear interpolation $x_i + y_i\, C_i$ $\to$ extract y_i
- estimate full $\Gamma(h\to W^+\mu^-\bar\nu_\mu)$ with one C_i turned on ($\times 5$ values)
  $\to$ quadratic interpolation $x_i + y_i\, C_i + z_i\, C_i^2$ $\to$ extract y_i





Cross-check: MadGraph with SMEFTsim

e.g. $\delta\Gamma_{h\to e^+\mu^-\bar{\nu}_\mu\nu_e}/\Gamma_{h\to e^+\mu^-\bar{\nu}_\mu\nu_e,SM}$

normalization:

$\bar{C}_i = C_i\left(\frac{v^2}{\Lambda^2}\right)$

	theory	MG interf	MG full xs
cHW	-1.48788	-1.48776	-1.48849
cHbox	2.	1.99887	1.9991
cHD	-0.5	-0.499949	-0.501474
cHl3	-1.99753	-3.69688	-3.69483
cll1	1.99815	2.00286	2.0001

analytic calculation (→ theory)

Brivio,Corbett,Trott 1906.06949

$y_i/\Gamma_{h\to e^+\nu_e\mu^-\bar{\nu}_\mu,SM}$ from pure interference (→ MG interf)

$y_i/\Gamma_{h\to e^+\nu_e\mu^-\bar{\nu}_\mu,SM}$ from linearized full width (→ MG full xs)

$\delta\Gamma_W$ omitted here: requires hacking propagator corrections in MC

Cross-check: MadGraph with SMEFTsim

e.g. $\delta\Gamma_{h\to e^+\mu^-\bar{\nu}_\mu\nu_e}/\Gamma_{h\to e^+\mu^-\bar{\nu}_\mu\nu_e,SM}$

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two SMEFTsim columns are consistent

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e.g. $\delta\Gamma_{h\to e^+\mu^-\bar{\nu}_\mu\nu_e}/\Gamma_{h\to e^+\mu^-\bar{\nu}_\mu\nu_e,SM}$

normalization:

$\bar{C}_i = C_i\left(\frac{v^2}{\Lambda^2}\right)$

✓ validated with theory

✓ two SMEFTsim columns are consistent

	theory	MG interf	MG full xs
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$\delta\Gamma_W$ omitted here: requires hacking propagator corrections in MC

$H \to 4f$ analytic - results

Example: $H \to e^+e^-\mu^+\mu^-$ $m_f \equiv 0$, m_W scheme

$$\frac{\delta\Gamma(H \to e^+e^-\mu^+\mu^-)}{\Gamma_{\rm SM}(H \to e^+e^-\mu^+\mu^-)} = \sum_i a_i \bar{C}_i = \sum_i a_i \left(C_i \frac{v^2}{\Lambda^2} \right)$$

	$\bar{C}_{HW}$	$\bar{C}_{HB}$	$\bar{C}_{HWB}$	$\bar{C}_{H\Box}$	$\bar{C}_{HD}$	$\bar{C}^{(1)}_{Hl}$	$\bar{C}^{(3)}_{Hl}$	$\bar{C}_{He}$	$\bar{C}^{(1)}_{Hq}$	$\bar{C}^{(3)}_{Hq}$	$\bar{C}_{Hu}$	$\bar{C}_{Hd}$	$\bar{C}'_{ll}$
Z	-0.78	-0.22	0.30	2	0.17	4.38	-1.62	-3.52					3.
A	1.04	-1.08	-0.68										
E						-2.23	-2.23	1.80					
G			-0.38		0.06	0.15	1.14	0.15	-0.39	-1.34	-0.20	0.15	-0.83
tot	0.26	-1.30	-0.76	2.	0.23	2.30	-2.71	-1.58	-0.39	-1.34	-0.20	0.15	2.17

Z	corrections to SM diagram
A	γ diagrams
E	contact diagrams ($HZee$)
G	$\delta\Gamma_Z^{\rm tot}/\Gamma_{Z,SM}$ on + off-shell Z

$H \to 4f$ analytic - results

Example: $H \to e^+ e^- \mu^+ \mu^-$ $\quad m_f \equiv 0$, m_W scheme

$$\frac{\delta\Gamma(H \to e^+ e^- \mu^+ \mu^-)}{\Gamma_{\rm SM}(H \to e^+ e^- \mu^+ \mu^-)} = \sum_i a_i \bar{C}_i = \sum_i a_i \left(C_i \frac{v^2}{\Lambda^2} \right)$$

	$\bar{C}_{HW}$	$\bar{C}_{HB}$	$\bar{C}_{HWB}$	$\bar{C}_{H\Box}$	$\bar{C}_{HD}$	$\bar{C}_{Hl}^{(1)}$	$\bar{C}_{Hl}^{(3)}$	$\bar{C}_{He}$	$\bar{C}_{Hq}^{(1)}$	$\bar{C}_{Hq}^{(3)}$	$\bar{C}_{Hu}$	$\bar{C}_{Hd}$	$\bar{C}'_{ll}$
Z	-0.78	-0.22	0.30	2	0.17	4.38	-1.62	-3.52					3.
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Z	corrections to SM diagram
A	γ diagrams
E	contact diagrams ($HZee$)
G	$\delta\Gamma_Z^{\rm tot}/\Gamma_{Z,SM}$ on + off-shell Z

Impact of previously neglected contributions

(1) photon-mediated diagrams

$\mathcal{O}(1 - 250)\%$ effect

	with γ			without γ		
	$\bar{C}_{HW}$	$\bar{C}_{HB}$	$\bar{C}_{HWB}$	$\bar{C}_{HW}$	$\bar{C}_{HB}$	$\bar{C}_{HWB}$
$h \to e^+e^-\mu^+\mu^-$	0.26	-1.30	-0.38	-0.77	-0.22	0.30
$h \to \bar{u}u\bar{c}c$	1.45	-2.63	-0.29	-0.77	-0.22	1.33
$h \to e^+e^-\bar{d}d$	0.50	-1.55	-0.37	-0.77	-0.22	0.47
$h \to e^+e^-e^+e^-$	0.02	-2.28	0.27	-0.76	-0.21	0.44
$h \to \bar{u}u\bar{u}u$	1.39	-2.72	-0.14	-0.76	-0.21	1.19
$h \to e^+e^-\bar{\nu}_e\nu_e$	-1.49	0.01	-0.06	-1.48	-0.007	-0.07

Impact of previously neglected contributions

(2) $Z - W$ interference terms

$\mathcal{O}(1-200)\%$ effect

$\delta\Gamma(H\to e^+e^-\bar\nu_e\nu_e)/\Gamma_{\rm SM}$ omitting γ and $\delta\Gamma_Z, \delta\Gamma_W$ contrib.

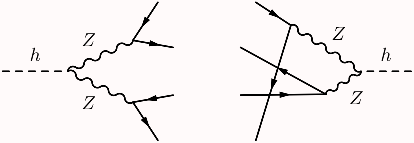
	$\bar C_{HW}$	$\bar C_{HB}$	$\bar C_{HWB}$	$\bar C_{H\Box}$	$\bar C_{HD}$	$\bar C_{Hl}^{(1)}$	$\bar C_{Hl}^{(3)}$	$\bar C_{He}$	$\bar C_{Hq}^{(1)}$	$\bar C_{Hq}^{(3)}$	$\bar C_{Hu}$	$\bar C_{Hd}$	$\bar C'_{ll}$
ZZ	-0.04	-0.01	-0.003	0.09	-0.008	0.004	-0.19	-0.04	0	0	0	0	0.14
WW	-1.49	0	0	2.0	-0.50	0	-3.77	0	0	0	0	0	3.00
WZ	0.04	0.004	**-0.06**	-0.10	-0.04	**-0.01**	0.21	0	0	0	0	0	-0.14
full	-1.49	-0.007	-0.07	2.	-0.55	-0.008	-3.74	-0.04	0	0	0	0	3.
NW	-1.46	-0.01	-0.003	2.	-0.49	0.004	-3.77	-0.04	0.	0.	0.	0.	3.

full	$ZZ + WW + WZ$
NW	$ZZ + WW$

Impact of previously neglected contributions

(3) NC crossed - interference terms

$\mathcal{O}(\text{few} - 40)\%$ effect



$\delta\Gamma(H \to e^+e^-e^+e^-)/\Gamma_{\rm SM}$ incl. only ZZ and $HZee$ diagrams

	$\bar{C}_{HW}$	$\bar{C}_{HB}$	$\bar{C}_{HWB}$	$\bar{C}_{H\Box}$	$\bar{C}_{HD}$	$\bar{C}^{(1)}_{Hl}$	$\bar{C}^{(3)}_{Hl}$	$\bar{C}_{He}$	$\bar{C}^{(1)}_{Hq}$	$\bar{C}^{(3)}_{Hq}$	$\bar{C}_{Hu}$	$\bar{C}_{Hd}$	$\bar{C}'_{ll}$
full	-0.75	-0.22	0.43	2.	0.28	2.09	-3.91	-1.64	0	0	0	0	3.
NW	-0.78	-0.221	0.30	2.	0.17	2.15	-3.85	-1.73	0.	0.	0.	0.	3.

full	$\lvert\mathcal{A}_{ijkl}\rvert^2 + \lvert\mathcal{A}_{ilkj}\rvert^2 + 2\mathrm{Re}\mathcal{A}_{ijkl}\mathcal{A}^\dagger_{ilkj}$
NW	$\lvert\mathcal{A}_{ijkl}\rvert^2 + \lvert\mathcal{A}_{ilkj}\rvert^2$

Impact of previously neglected contributions

(4) $\delta\Gamma_V$, δm_V from off-shell boson

$\mathcal{O}$(few)% effect

narrow width approx.:

$$\frac{\delta\Gamma(H \to VV^* \to 4f)}{\Gamma_{SM}(H \to VV^* \to 4f)} = (-1)\,\frac{\delta\Gamma_V}{\Gamma_{V,SM}} + \dots$$

full calculation:

$h \to e^+e^-\mu^+\mu^-$	$-0.820 \quad \delta\Gamma_Z/\Gamma_{Z,SM}$
$h \to e^+e^-e^+e^-$	$-0.748 \quad \delta\Gamma_Z/\Gamma_{Z,SM}$
$h \to e^+\nu_e\bar{\nu}_\mu\mu^-$	$-0.915 \quad \delta\Gamma_W/\Gamma_{W,SM}$
$h \to e^+\nu_e\bar{\nu}_e e^-$	$-0.914 \quad \delta\Gamma_W/\Gamma_{W,SM} - 0.038 \quad \delta\Gamma_Z/\Gamma_{Z,SM}$

H → 4f summary

- we did a **fully analytic** calculation, with numerical integration of phase space
- also generated all channels with MG5_aMC@NLO using SMEFTsim
  → where MC well-behaved: agreement to 1% or better ✓
- analytic treatment has a few advantages:
  - allows to separate contributions
  - easier to linearize in $\delta\Gamma_V, \delta m_V$
  - more stable for the massless fermions case with γ diagrams
  - cancellations are reproduced exactly
  - calculation can be **automated** in a dedicated package

    ⇝ a new reweighting tool coming soon
- some previously neglected contributions turn out to be relevant:
  γ diagrams and $Z - W$ interference

The total Higgs width in the SMEFT

putting together all the main contributions* we obtain

$$\Gamma_H^{\rm tot} = \Gamma_{H,SM}^{\rm tot}\left[1+\frac{\delta\Gamma_H^{\rm tot}}{\Gamma_{H,SM}^{\rm tot}}\right]$$

$$\Gamma_{H,SM}^{\rm tot} = 4.100 \text{ MeV}$$

$$\begin{aligned}\frac{\delta\Gamma_H^{\rm tot}}{\Gamma_{H,SM}^{\rm tot}} = & -1.50\,\tilde C_{HB} - 1.21\,\tilde C_{HW} + 1.21\,\tilde C_{HWB} + 50.6\,\tilde C_{HG} \\ & + 1.83\,\tilde C_{H\Box} - 0.43\,\tilde C_{HD} + 1.17\,\tilde C'_{ll} \\ & - 7.85\,Y_c\,\Re\tilde C_{uH} - 48.5\,Y_b\,\Re\tilde C_{dH} - 12.3\,Y_\tau\,\Re\tilde C_{eH} \\ & + 0.002\,\tilde C^{(1)}_{Hq} + 0.06\,\tilde C^{(3)}_{Hq} + 0.001\,\tilde C_{Hu} - 0.0007\,\tilde C_{Hd} \\ & - 0.0009\,\tilde C^{(1)}_{Hl} - 2.32\,\tilde C^{(3)}_{Hl} - 0.0006\,\tilde C_{He},\end{aligned}$$

in the $\{m_W, m_Z, G_F\}$ scheme.

$^*gg + \gamma\gamma + \bar b b + \bar c c + \tau^+\tau^- + 4f + \bar f f \gamma$

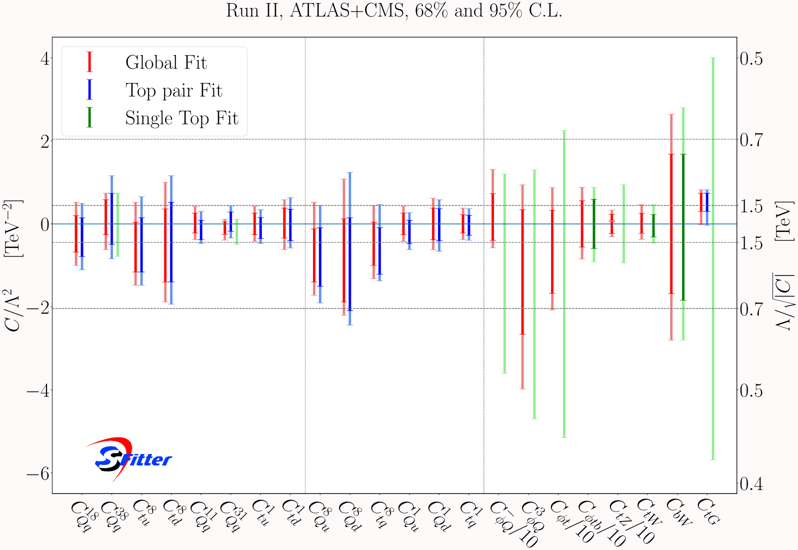
Recap & take-home

- The **SMEFT** is a well-defined, general framework for BSM searches
- It is worth using its full power with a truly global analysis:
  not just SM stress-test but a means to understand the global picture through precision measurements
- Expect 20-30 parameters for the basic scenario in a Higgs/EW/top analysis
- improved calculation of $H \to 4f$ → $\delta\Gamma_H^{\mathrm{tot}}$
  without relying on the narrow width approx. for Z, W
  → crucial for fits of the Higgs sector
- an automated package for `lhe` reweighting to appear soon!
- possible refinements:
  full massive fermions treatment
  phase space integration with cuts → acceptance corrections
  . . .

Backup slides

Top fit results

Brivio,Bruggisser,Maltoni,Moutafis,Plehn, Vryonidou,Westhoff,Zhang 1910.03606



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}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\,\varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\,\varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

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

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:

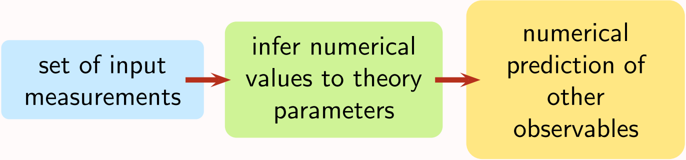
invert the input obs. definitions to get:

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

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

Shifts from input parameters

when testing a theory:



SM:

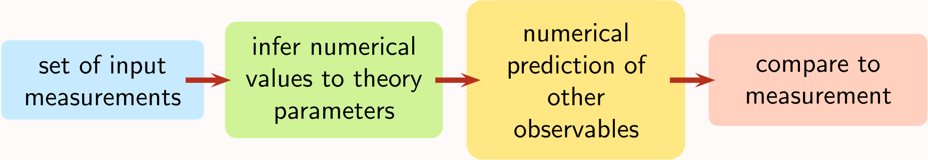
analytic calculations
Monte Carlo generation
...

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:



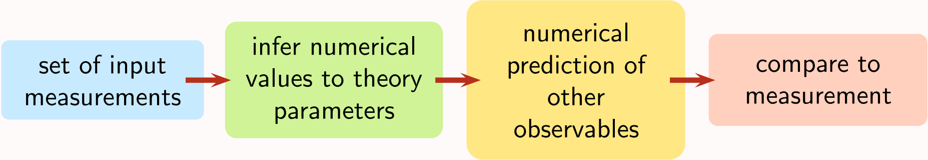
SM:

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

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

Shifts from input parameters

when testing a theory:



SMEFT:

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

$\bar{X}$ = 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 → 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**

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

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

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

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

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

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

with

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