Automated counter-term computation :

a focus on EW corrections in the SMEFT

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UCLouvain

IRMP

New Physics hidden at high energy ?

Parametrize your ignorance with the effective theory

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\sum_{i_1} c_{i_1} O_{i_1} + \frac{1}{\Lambda^2}\sum_{i_2} c_{i_2} O_{i_2} + \dots$$

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Assuming HEP can be modeled by :

- a Poincaré-invariant local quantum theory,
- UV scale $\Lambda >>$ electroweak scale M_W,
- invariance under SM gauge group.

$\rightarrow$ 59 operators at dimension 6 (ignoring flavor).

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Electroweak corrections in SMEFT : State of the art

e e to Z h

Asteriadis et al.
2406.03557, 2409.11466

EWPO

Biekötter, Pecjak et al.
2503.07724,
Bellafronte, Dawson, Giardino
2304.00029, 2201.09887

Drell-Yan

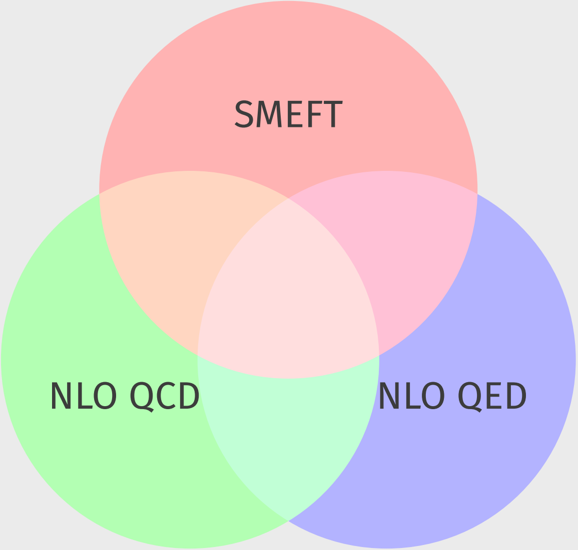
Dawson, Giardino 2105.05852

Decays

Higgs, *Bellafronte, Del Pio et al.*
2608.28464, 2601.09599, 1801.01136
Z, W
Dawson et al. 2605.18679, 1909.02000, 1808.05948

MadGraph5_aMC@NLO can perform NLO QED computations *Frixione et al. 1804.10017, 2108.10261*

and a large set of UFO models exist *Pagani et al. 2106.02059, Durieux, Mimasu et al. 2008.11743* but ...



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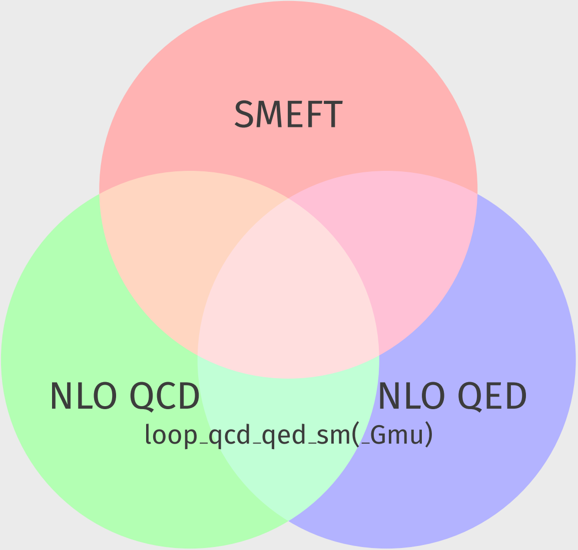

What is automated ?

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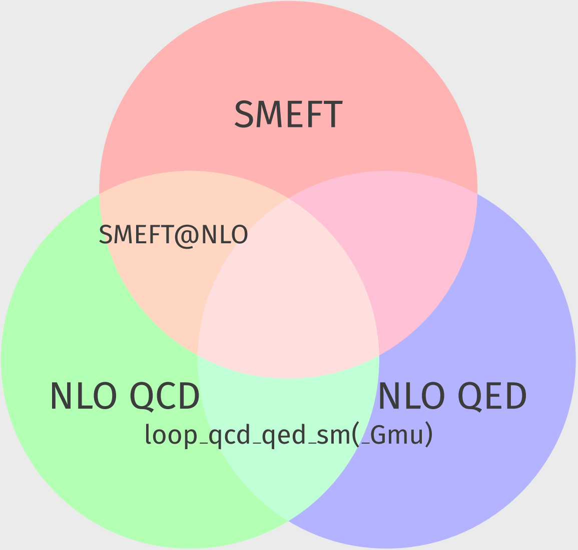

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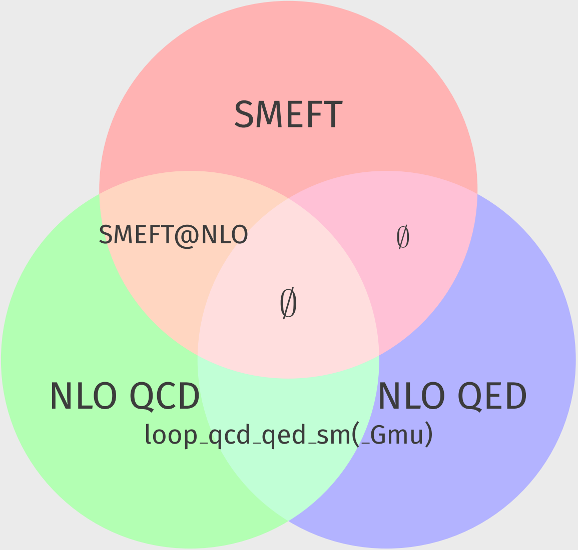

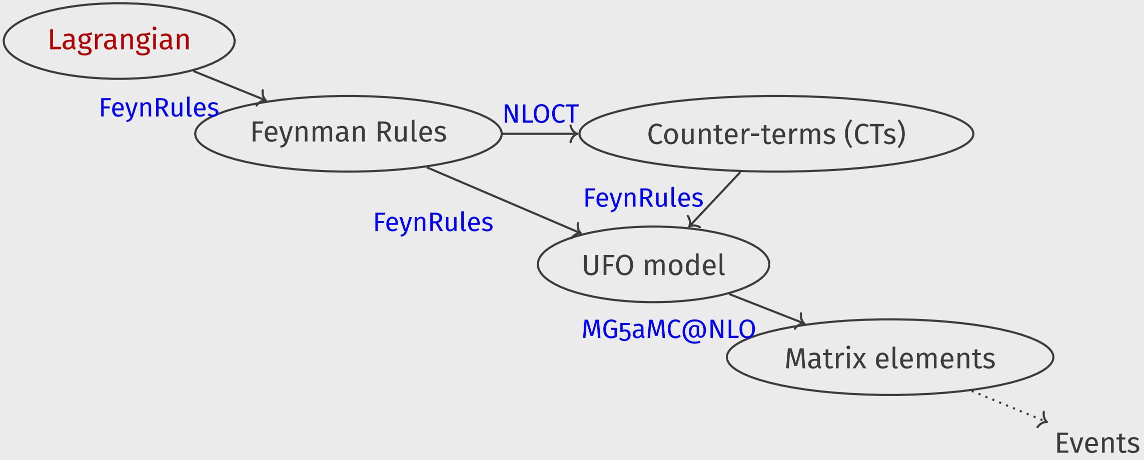
Lagrangian
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Regularization	$\rightarrow$	Dim. reg.

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Renormalization	$\rightarrow$	$\overline{MS}$, OS, CMS ?
Input scheme	$\rightarrow$	α, LEP, α_μ ?
Flavor scheme	$\rightarrow$	5F, 4F ?
γ_5-scheme	$\rightarrow$	BMHV, KKS, NDR ?
Gauge fixing	$\rightarrow$	Unitary, Feynman, R_ξ ?
Tadpoles	$\rightarrow$	PRTS, FJTS, GIVS ?

Biekötter et. al. 2305.03763, 2312.06448

Tadpole schemes 101

For a deeper dive, see *Passarino 0612122, Denner & Lang 1607.07352, Dittmaier 2203.07236*

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Lesson 1 : Vev induced parameters renormalized with Non Momentum based conditions (e.g. $\overline{MS}$) develop a Gauge-Dependence under a naïve tadpole renormalization.

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What tadpole scheme should you use ?

Parameter Renormalized Tadpole Scheme (PRTS) :

👍 few contributions of tadpole CTs $\Rightarrow$ most CTs are small
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Fleischer–Jegerlehner Tadpole Scheme (FJTS) : shift $h \to h + v + \Delta v$ and

$$t_h = \left.\frac{\partial(\mathcal{L} - \mathcal{L}|_{\Delta v=0})}{\partial h}\right|_{h=0}$$

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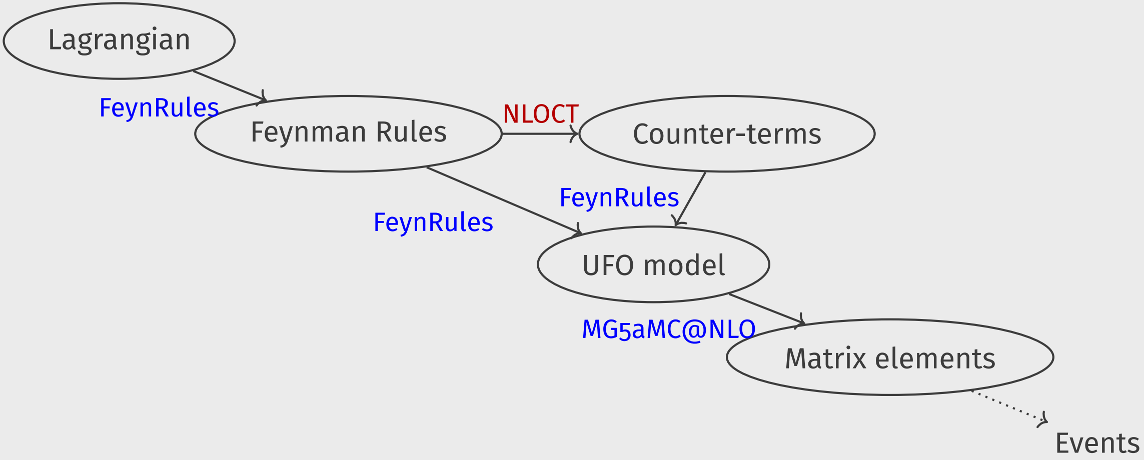
Gauge Invariant Vev Scheme (GIVS) : Non linear Higgs representation + PRTS

👍 small CTs,
tadpole amplitudes are Gauge-Invariant !
👎 too young (2022), not yet used in the SMEFT EW community.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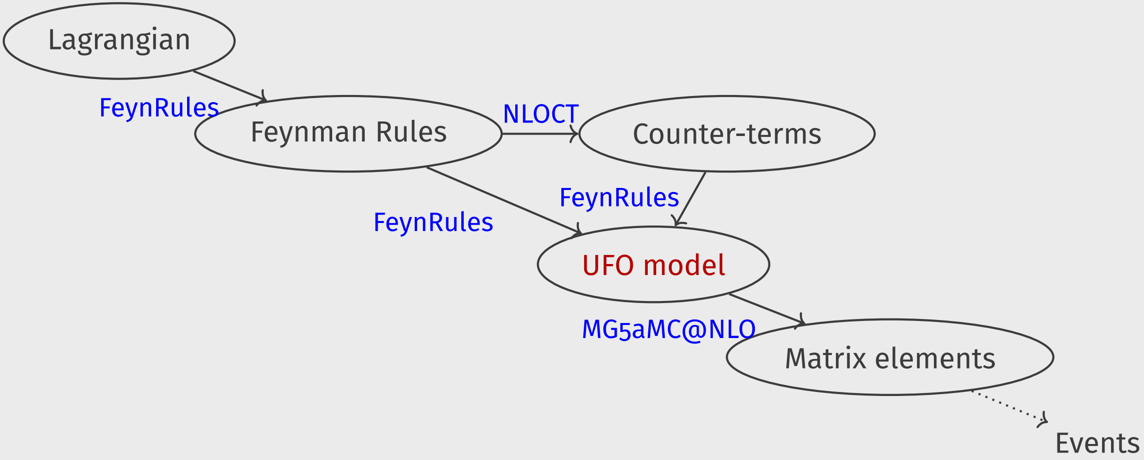
NLOCT

UFO models need both UV and R2 CTs (automatically generated by NLOCT).

Most of the 1-loop EW machinery is already implemented (γ_5, dim. reg., 2 and 3-pts renormalization) except :

- FJTS (hybrid tadpole scheme, see OnShellRenormalization[])
- G_μ-renormalization

Pipeline of automated computations



First models : unlocking the Higgs sector

Build the broken SM lagrangian in interaction basis (g_1, g_2, v, λ)+Warsaw basis

$$\begin{aligned}\mathcal{L}_H =&(D_\mu H^\dagger)(D^\mu H) - \lambda(H^\dagger H - v^2/2)^2 \\ &+ C_{H\Box}(H^\dagger H)\Box(H^\dagger H) + C_{HD}(H^\dagger D_\mu H)^*(H^\dagger D^\mu H) + C_H(H^\dagger H)^3\end{aligned}$$

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- $v_T = v\left(1 + \frac{3C_H v^2}{8\lambda}\right)$.
- kinetic term shift $\{h, G0\} \to \{(1 + C_{H,\text{kin}})h, (1 - v^2 C_{HD}/4)G0\}$
- $M_H^2 = 2\lambda v_T^2\left(1 - \frac{3C_H v^2}{2\lambda} + 2C_{H,\text{kin}}\right)$ where $C_{H,\text{kin}} \equiv v^2(C_{H\Box} - C_{HD}/4)$.
- $M_Z^2 = \frac{v_T^4}{4}(g_1^2 + g_2^2)\left(1 + \frac{C_{HD}v^2}{2\Lambda^2}\right)$

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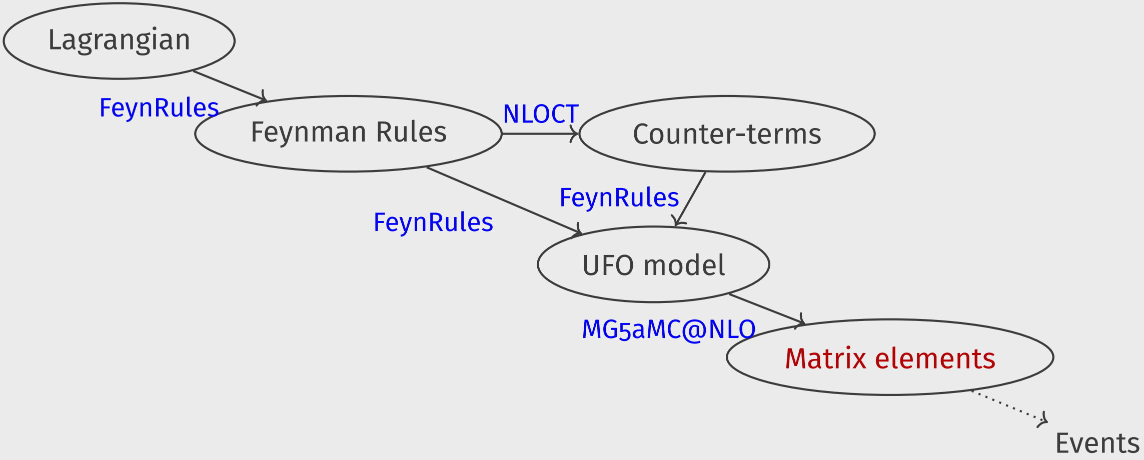
Including $M_W^2 = \frac{g_2^2 v_T^2}{4}$ and $e = \frac{g_1 g_2}{\sqrt{g_1^2+g_2^2}}$ gives the usual mass basis (e, M_W, M_Z, M_H).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$h \to ff$

Pecjak et al. (2016, **2019**, 2020, **2023**)

$$\Gamma_{h\to f\bar{f}} = \int \frac{d\phi_2}{2m_H}|\mathcal{M}_{h\to f\bar{f}}|^2 + \int \frac{d\phi_3}{2m_H}|\mathcal{M}_{h\to f\bar{f}(g,\gamma)}|^2$$
$$= B_f(m_f)(\Gamma_f^{(4,0)} + \Gamma_f^{(6,0)} + \Gamma_f^{(4,1)} + \Gamma_f^{(6,1)})$$

$$i\mathcal{M}_f = -i\bar{u}(p_f)v(p_{\bar{f}})\left[A_f^{(4,0)} + A_f^{(6,0)} + \frac{1}{16\pi^2}(A_f^{(4,1)} + A_f^{(6,1)})\right]$$

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$$\Gamma_f^{(4,0)} = A_f^{(4,0)}.A_f^{(4,0)}, \qquad \Gamma_f^{(4,1)} = \frac{1}{16\pi^2}2A_f^{(4,0)}.A_f^{(4,1)}$$

$$\Gamma_f^{(6,0)} = 2A_f^{(4,0)}.A_f^{(6,0)}, \qquad \Gamma_f^{(6,1)} = \frac{1}{16\pi^2}2(A_f^{(6,0)}.A_f^{(4,1)} + A_f^{(4,0)}.A_f^{(6,1)})$$

Papers/Tools	Input	m_b Renorm.
1904.06358	α, M_W, M_Z	*OnShell*/$\overline{MS}$
2305.03763	$G_F, M_W, M_Z/\alpha, M_W, M_Z/\alpha, G_F, M_Z$	$\overline{MS}$
NLOCT	α, M_W, M_Z	*OnShell*/$\overline{MS}$
MG5	$G_F, M_W, M_Z/\alpha, M_W, M_Z/\alpha, G_F, M_Z$	$\times$
MG5@NLO	$G_F, M_W, M_Z/\alpha, M_W, M_Z$	*OnShell*

Table: Schemes

OnShell renormalization is mandatory for M_W in MG5@NLO $\Rightarrow$ excludes LEP input scheme at NLO.

Focus on $h \to b\bar{b}$

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$h \to b\bar{b}$

$$\Delta_f^{NLO} = 1 + \frac{\Gamma_f^{(6,0)} + \Gamma_f^{(4,1)} + \Gamma_f^{(6,1)}}{\Gamma_f^{(4,0)}}$$

Δ_f^{LO}	SM	SM+$O_{\phi\Box}$	SM+$O_{\phi D}$
2023	1	1.117	1.073
2019	1	1.115	1.071
MG5	1	1.117	1.073

Table: LO, α-scheme

Δ_f^{NLO}	SM	SM+$O_{\phi\Box}$	SM+$O_{\phi D}$
2019	0.602	0.684	0.644
MG5@NLO	0.596	0.664	0.626

Table: Total NLO corrections, OnShell, α-scheme

Dawson and Giardino 1801.01136

Complete 1-loop SMEFT computation

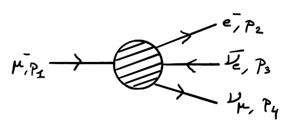
- Warsaw basis,
- Input scheme $(M_H, M_W, M_Z, G_\mu, C_i)$,
- OnShell for SM parameters,
- $\overline{MS}$ for Wilson coefs.

$\mathcal{O}_W$	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$\mathcal{O}_\phi$	$(\phi^\dagger\phi)^3$	$\mathcal{O}_{\phi\Box}$	$(\phi^\dagger\phi)\Box(\phi^\dagger\phi)$
$\mathcal{O}_{\phi D}$	$(\phi^\dagger D^\mu\phi)^* (\phi^\dagger D_\mu\phi)$	$\underset{p,r}{\mathcal{O}_{u\phi}}$	$(\phi^\dagger\phi)(\bar{q}'_p u'_r \widetilde{\phi})$	$\mathcal{O}_{\phi W}$	$(\phi^\dagger\phi)\, W_{\mu\nu}W^{\mu\nu}$
$\mathcal{O}_{\phi B}$	$(\phi^\dagger\phi)\, B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi WB}$	$(\phi^\dagger\tau^I\phi)\, W^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar{q}'_p\sigma^{\mu\nu}u'_r)\tau^I\widetilde{\phi}\, W^I_{\mu\nu}$
$\underset{p,r}{\mathcal{O}_{uB}}$	$(\bar{q}'_p\sigma^{\mu\nu}u'_r)\widetilde{\phi}\, B_{\mu\nu}$	$\underset{p,r}{\mathcal{O}^{(1)}_{\phi l}}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{l}'_p\gamma^\mu l'_r)$	$\underset{p,r}{\mathcal{O}^{(3)}_{\phi l}}$	$(\phi^\dagger i\overleftrightarrow{D}^I_\mu\phi)(\bar{l}'_p\tau^I\gamma^\mu l'_r)$
$\underset{p,r}{\mathcal{O}_{\phi e}}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{e}'_p\gamma^\mu e'_r)$	$\underset{p,r}{\mathcal{O}^{(1)}_{\phi q}}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{q}'_p\gamma^\mu q'_r)$	$\underset{p,r}{\mathcal{O}^{(3)}_{\phi q}}$	$(\phi^\dagger i\overleftrightarrow{D}^I_\mu\phi)(\bar{q}'_p\tau^I\gamma^\mu q'_r)$
$\underset{p,r}{\mathcal{O}_{\phi u}}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{u}'_p\gamma^\mu u'_r)$	$\underset{p,r}{\mathcal{O}_{\phi d}}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{d}'_p\gamma^\mu d'_r)$	$\underset{p,r,s,t}{\mathcal{O}_{ll}}$	$(\bar{l}'_p\gamma_\mu l'_r)(\bar{l}'_s\gamma^\mu l'_t)$
$\underset{p,r,s,t}{\mathcal{O}^{(3)}_{lq}}$	$(\bar{l}'_p\gamma_\mu\tau^I l'_r)(\bar{q}'_s\gamma^\mu\tau^I q'_t)$				

Figure: Table I : 19 Wilson coef. contributing at 1-loop.

$h \to ZZ$ & $Z\gamma$

G_μ input scheme: One-loop computation of μ^- decay in zero-momentum scheme.



$$G_\mu + \frac{C_{ll}}{\sqrt{2}\Lambda^2} - \sqrt{2}\frac{C_{\phi l}^{(3)}}{\Lambda^2} \equiv \frac{1}{\sqrt{2}v_0^2}(1+\Delta r) := \frac{-1}{2\sqrt{2}}\mathcal{A}$$

Making the above relation valid at any order defines Δr perturbatively as

$$\Delta r = 2v^2\mathcal{B} + \mathcal{V}\left(1 + \frac{v^2 C_{\phi l}^{(3)}}{\Lambda^2}\right) + \delta Z\left(1 + \frac{v^2(2C_{\phi l}^{(3)} - C_{ll})}{\Lambda^2}\right) - \frac{\Pi_W(0)}{M_W^2}\left(1 + \frac{2v^2 C_{\phi l}^{(3)}}{\Lambda^2}\right) + A.D.$$

and is equivalent to the renormalization condition for v :

$$v^2 = v_0^2 - \delta v^2, \quad \delta v^2 = \frac{\Delta r}{\sqrt{2}G_\mu}\left(1 - \frac{C_{ll}}{\sqrt{2}G_\mu\Lambda^2} + \sqrt{2}\frac{C_{\phi l}^{(3)}}{G_\mu\Lambda^2}\right)$$

Take home message

Be kind with your tadpoles, check wether your vev induced $\overline{MS}$ parameters are gauge invariant,

One completely automatised scheme for UFO generation : (α, M_W, M_Z)

G_μ models are being tested for $h \to f\bar{f}$, $h \to ZV$ and $e^+e^- \to Zh$

NLOCT might receive an upgrade ...

Thank you for your attention !

Backup : Fermi Model

Effective theory of the SM below the EW scale :

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QED}} + \mathcal{L}_{\text{QCD}} - 2\sqrt{2}G_F[\bar{\nu}_\mu \gamma_\mu P_L \mu][\bar{e}\gamma^\mu P_L \nu_e]$$

In this theory, the tree-level amplitude of the muon decay at vanishing external momentum is :

$$\mathcal{A}^{(0)} = -2\sqrt{2}G_F[\bar{u}(0)\gamma_\nu P_L u(0)][\bar{u}(0)\gamma^\nu P_L v(0)]$$

Δr

Results for $\Delta r_{\mathrm{SM}} = 16\pi^2 \frac{\sqrt{2}}{G_\mu} \Delta r$:

$$\Delta r_{\mathrm{SM}} = \frac{6M_W^2 A_0(M_H^2)}{M_H^2 - M_W^2} - M_H^2 - 4N_c A_0(M_t^2) + 2N_c M_t^2 + A_0(M_Z^2)\left(14 + \frac{6M_Z^2}{M_W^2 - M_Z^2}\right) - M_Z^2$$
$$+ A_0(M_W^2)\left(2 - \frac{3M_W^2}{M_W^2 - M_Z^2} - \frac{6M_W^2}{M_H^2 - M_W^2}\right) - 2M_W^2$$

One-loop automation : state of the art

1/ NLOCT

What ? Package that computes R2-rational (see OPP) and UV CTs.

How ?

- Dimensional regularization,
- anticommuting γ_5 & no trace's cyclicity, 'reading point' (Kreimer's scheme),
- "Hybride" tadpole renormalization,
- On-Shell/Complex Mass / $\overline{MS}$ scheme for 2pt-functions,
- $\overline{MS}$ / Zero-Momentum scheme (+Ward Id) for 3pt-functions,
- Feynman Gauge.

One-loop automation : state of the art

2/ SMEFT@NLO

What ?
List of R2-rational and UV CTs for QCD & 4fermions loops in SMEFT (up to 5pt).

How ?

- On-Shell scheme for 2pt-functions,
- $\overline{MS}$ for 3pt-functions and Wilson coefficients,
- covariant anomaly scheme (preserves QCD Ward Id),
- evanescent operators (see Buras).