The SMEFT at NLO:
Two-Loop Effects Matter for New Physics

Anders Eller Thomsen

Based on work w/ *L. Born*, *J. Fuentes-Martín*, and *A. Greljo*

Charting EFT Structures to Characterize NP
MITP, 10 September 2026

u^b
UNIVERSITÄT BERN
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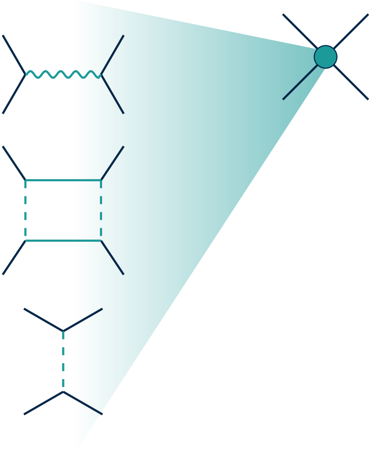
Swiss National Science Foundation

SM Effective Field Theory

High-energy BSM physics manifests as contact interactions in the SMEFT



$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d=5} \sum_{k} \frac{\overbrace{C_{d,k}}^{\text{UV Physics}}}{\underbrace{\Lambda^{d-4}}_{\text{NP scale}}} \mathcal{O}_{d,k}$$

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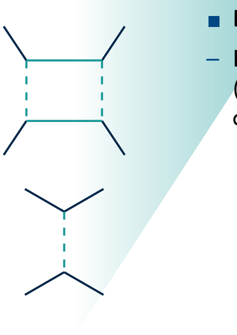

- **Bottom–up:**
  - EFTs allow for a **model-comprehensive** ("model-independent") analysis of deviations from the SM, quantifying possible deviations as an expansion in E/Λ

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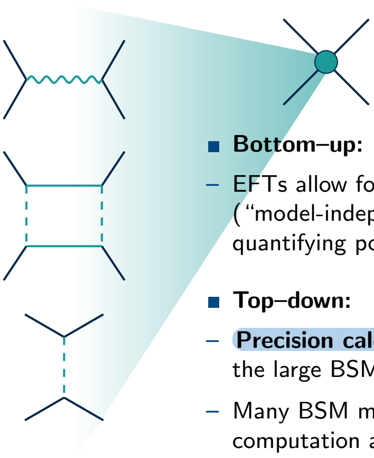

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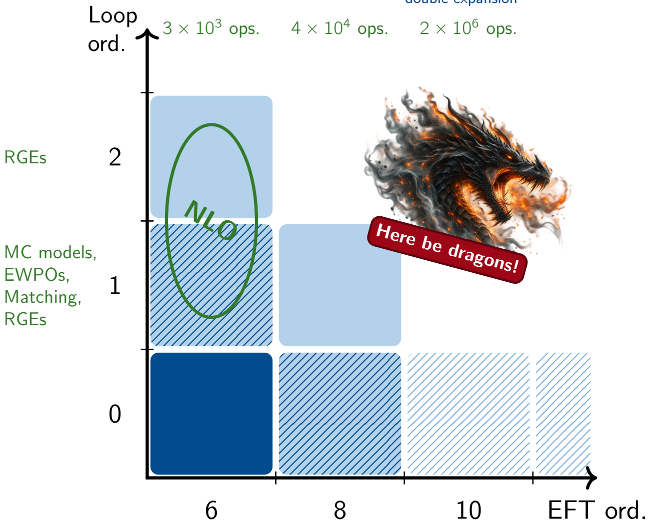
- **Bottom–up:**
  - EFTs allow for a **model-comprehensive** ("model-independent") analysis of deviations from the SM, quantifying possible deviations as an expansion in E/Λ
- **Top–down:**
  - **Precision calculations** necessitates the use of EFTs to separate the large BSM energy scales
  - Many BSM models results in the same EFT, ensuring that computation are **reusable**: you only need to compute once in the EFT

SMEFT as a double expansion

$$\mathcal{L}_{\mathrm{SMEFT}}(\phi) = \mathcal{L}_{\mathrm{SM}}(\phi) + \sum_{d=5}^{\infty}\sum_{\ell=0}^{\infty}\sum_{k} \underbrace{\frac{C^{(\ell)}_{d,k}}{(16\pi^2)^{\ell}\,\Lambda^{d-4}}}_{\text{double expansion}} \mathcal{O}^{(\ell)}_{d,k}(\phi)$$



Why higher-order effects matter

The dimension-six operators change with the renormalization scale:

$$\frac{\mathrm{d}C_i}{\mathrm{d}\ln\mu} = \overset{\text{loop level}}{\gamma_{ij}} C_j$$

γ_{ij} is non-diagonal (operator mixing): **leading effects, not only precision**

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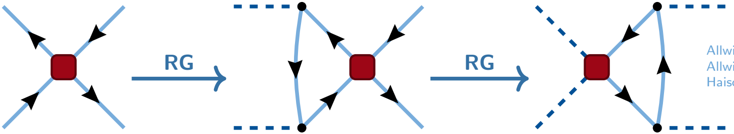
Hard to access at LHC

Constrained by EWPOs



C_{tt} C_{Ht} $C_{HD}^{(\times)}$

$< (1.2\,\mathrm{TeV})^{-2}$ (CMS)

Allwicher *et al.* [2302.11584]; Allwicher *et al.* [2311.00020]; Haisch, Schnell [2410.13304]

$$\delta m_W = 1\,\mathrm{MeV}\cdot\mathrm{TeV}^2\cdot\Big(\underbrace{16\ln\frac{\Lambda}{m_Z}}_{\text{NLO}} - \underbrace{10\ln^2\frac{\Lambda}{m_Z}}_{\text{LO}}\Big) C_{tt}$$

$$|\delta m_W| = \begin{cases} 10\,\mathrm{MeV} & \text{CMS} \\ 0.26\,\mathrm{MeV} & \text{FCC-ee (proj.)} \end{cases}$$

Biekötter, Pecjak [2503.07724]; Born, Fuentes-Martín, **AET** [2601.19974]

2-Loop SMEFT RGEs

/w Lukas Born and Javier Fuentes-Martín [arXiv:2601.19974]

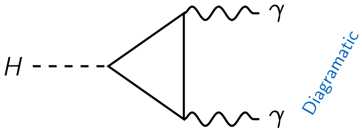
($\not{B}$ part by Banik *et al.* [arXiv:2510.08682])

Why functional methods? The master formula

One-loop matching is the classical use-case of functional methods

Henning *et al.* [1412.1837]; Drozd *et al.* [1512.03003]; Fuentes-Martín *et al.* [1607.02142];...

$\mathcal{L}_{\mathrm{UV}} \xrightarrow{\text{recipe}}$



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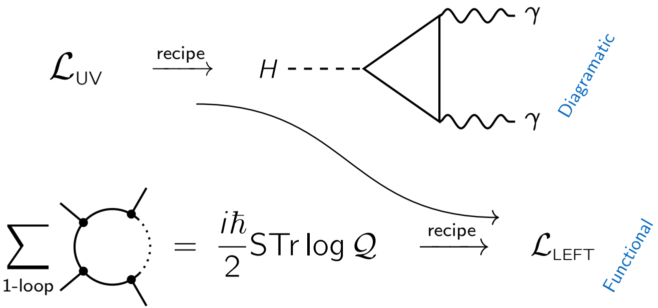


- **Bookkeeping:** organization by topology/internal propagators
- **Manifest covariance:** There is no need to separate out

$$D_\mu = \partial_\mu - iA_\mu$$

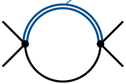
- **Recycling:** the methods recycle known loop-integral techniques

Matching and RG

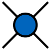
- EFT matching—extraction of EFT couplings

UV field

Changed high-k int



$$\sim \int_k \frac{1}{(k^2 - M^2)} \frac{1}{(k+p)^2 - m^2} \sim \frac{-1}{M^2} \int_k \frac{1}{(k+p)^2 - m^2} +$$



local EFT vertex

Matching and RG

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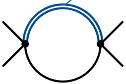

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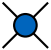
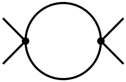


local EFT vertex

- Renormalization/RG functions—extraction of counterterms



$$\sim \int \frac{\mathrm{d}^4 k}{(2\pi)^4} \frac{1}{(k^2 - M^2)^2} \longrightarrow \int \frac{\mathrm{d}^d k}{(2\pi)^d} \frac{1}{(k^2 - M^2)^2} + \boldsymbol{\delta\lambda}$$

local UV counterterm

Matching and RG

- EFT matching—extraction of EFT couplings

UV field

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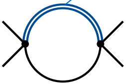

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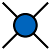

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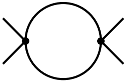

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local UV counterterm

- Amplitudes? Why not?!

  But there might be little point... and some *trouble* $\leftrightsquigarrow$ non-local

Semi-classical approximation

The loop-expansion is a polynomium of tensor contractions

Fuentes-Martín, Palavrić, **AET** [2311.13630]; Fuentes-Martín, Moreno-Sánchez, Palavrić, **AET** [2412.12270]

$$\Gamma[\hat{\eta}] = \widehat{S} + \frac{i\hbar}{2} \overbrace{\zeta_{II} \big(\log \widehat{\mathcal{Q}} \big)_{II}}^{\mathrm{STr}\log \mathcal{Q}}$$

or as supergraphs

$$\Gamma = S + \frac{i}{2} \log \bigcirc$$

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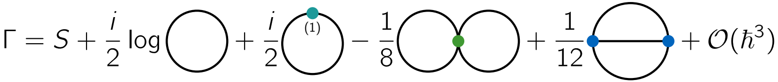
$$+ \frac{\hbar^2}{12} \zeta_{IM}\zeta_{JN}\zeta_{IN} \hat{\mathcal{Q}}^{-1}_{LI} \hat{\mathcal{Q}}^{-1}_{MJ} \hat{\mathcal{Q}}^{-1}_{NK} \hat{\mathcal{V}}^{(0)}_{IJK} \hat{\mathcal{V}}^{(0)}_{LMN} + \mathcal{O}(\hbar^3)$$

Spin statistics: ± 1

or as supergraphs



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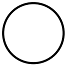
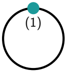
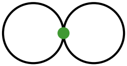
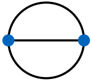
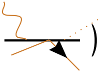
$\Gamma = S + \frac{i}{2} \log$  $+ \frac{i}{2}$ 

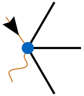
$- \frac{1}{8}$  $+ \frac{1}{12}$  $+ \mathcal{O}(\hbar^3)$

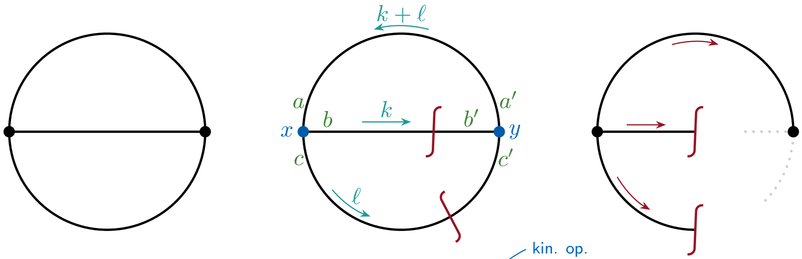
All **vertices and propagators are fully dressed** with background fields

$$\mathcal{Q}_{IJ}[\hat{\eta}] = \frac{\delta^2 S^{(0)}}{\delta\eta^I \delta\eta^J}[\hat{\eta}] = \Big(\quad \Big)^{-1}$$



$$\mathcal{V}^{(0)}_{IJK}[\hat{\eta}] =$$





kin. op.

$$E^{(\underline{m_i},\underline{n_j})}_{a_i b_j}(x, P_x + k) \equiv (-1)^{m_i}\,(P_x + k)^{\overleftarrow{\underline{m_i}}} Q^{-1}_{a_i b_j}(x, P_x + k)(P_x + k)^{\underline{n_j}}$$

cov. devs. from vertices

Sunset master formula:

$$\frac{\hbar^2}{12}\sum_{m_i,n_i}\int_x\!\!\int_{k\ell} E^{(0,0)}_{aa'}(y, P_y - k - \ell)\, V^{(\underline{m_1},\underline{n_1})}_{abc}(x) V^{(\underline{m_2},\underline{n_2})}_{a'b'c'}(y)$$
$$\times \left[E^{(\underline{m_1},\underline{m_2})}(x, P_x + k)\, U(x,y)\right]_{bb'}\left[E^{(\underline{n_1},\underline{n_2})}(x, P_x + \ell)\, U(x,y)\right]_{cc'}\Big|_{y=x}$$

Wilson line: reinstates gauge-invariance

Grassmanian factor: $\zeta_{aa'}\zeta_{bb'}\zeta_{cc'}\zeta_{ab}\zeta_{ac}\zeta_{a'b}\zeta_{a'c}\zeta_{bc'}\zeta_{a'b'}\zeta_{a'c'} = \pm 1$

Two-loop counterterms

An application of functional methods at multi-loop order

Born, Fuentes-Martín, Kvedaraitė, **AET** [2410.07320]

$$\delta\widehat{S}^{(2)} = \frac{1}{8}\boldsymbol{K}\bar{\boldsymbol{R}}^{*}\boldsymbol{T}\Big[\widehat{\mathcal{V}}^{(0)}_{IJKL}\widehat{\mathcal{Q}}^{-1}_{IJ}\widehat{\mathcal{Q}}^{-1}_{KL}\Big] - \frac{1}{12}\boldsymbol{K}\bar{\boldsymbol{R}}^{*}\boldsymbol{T}\Big[\widehat{\mathcal{V}}^{(0)}_{IJK}\widehat{\mathcal{Q}}^{-1}_{IL}\widehat{\mathcal{Q}}^{-1}_{JM}\widehat{\mathcal{Q}}^{-1}_{KN}\widehat{\mathcal{V}}^{(0)}_{LMN}\Big]$$

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Evaluation recipe:

i) Construct gauge-invariant graphs w/ full background field dependence

ii) Expand in the hard loop-momentum region

iii) Subtract subdivergences w/ a local version of $\boldsymbol{R}^*$-operation — Herzog, Ruijl [1703.03776]

iv) Evaluate single-scale tadpole loop diagrams

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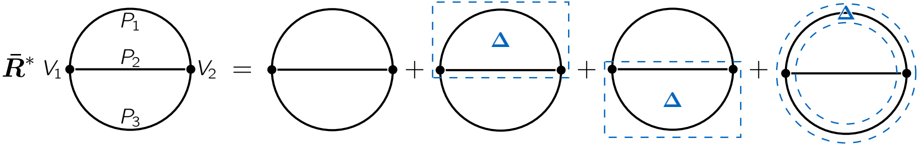

Keeping track of the operator basis

Scehme	d-dimensional $\overline{\text{MS}}$ $\overline{d}$
Op. basis	$\{O_i\}$
Examples	$(\bar{\ell}\gamma_\mu \ell)(\bar{e}\gamma^\mu e)$ $(\bar{\ell}e)(\bar{e}\ell)$
Cts.	$\{\delta g_i\}$

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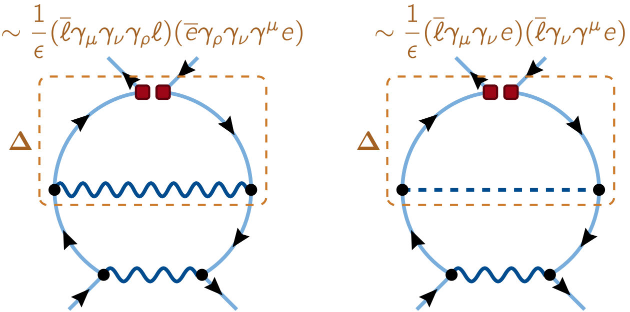

$\bar{\boldsymbol{R}}^*$ counterterm insertions not in the "correct" operator basis!

Naterop, Stoffer [2412.13251]; Born, Fuentes-Martín, **AET** [2601.19974]

Keeping track of the operator basis

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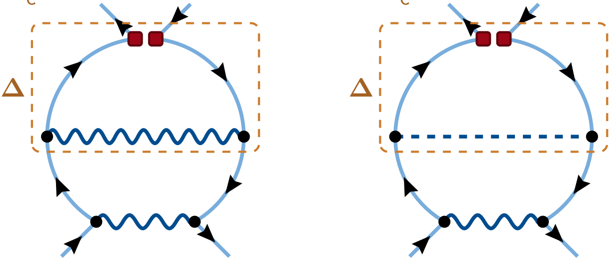
Op. basis	$\{O_i\}$	$\{Q_a,\, E_\alpha\}$
Examples	$(\bar{\ell}\gamma_\mu \ell)(\bar{e}\gamma^\mu e)$ $(\bar{\ell}e)(\bar{e}\ell)$	$(\bar{\ell}\gamma_\mu \ell)(\bar{e}\gamma^\mu e)$ $(\bar{\ell}\gamma_\mu \ell)(\bar{e}\gamma^\mu e) + \frac{1}{2}(\bar{\ell}e)(\bar{e}\ell)$
Cts.	$\{\delta g_i\}$	$\{\delta\lambda_a,\, \delta\eta_\alpha\}$

$(1\text{-loop})^2$

$\sim \frac{1}{\epsilon}(\bar{\ell}\gamma_\mu\gamma_\nu\gamma_\rho\ell)(\bar{e}\gamma_\rho\gamma_\nu\gamma^\mu e)$ $\qquad$ $\sim \frac{1}{\epsilon}(\bar{\ell}\gamma_\mu\gamma_\nu e)(\bar{\ell}\gamma_\nu\gamma^\mu e)$



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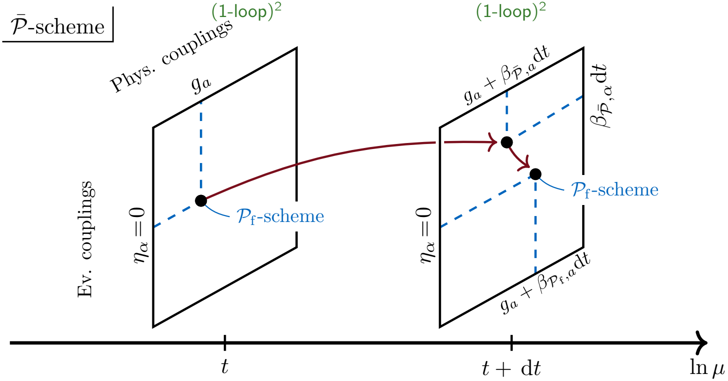
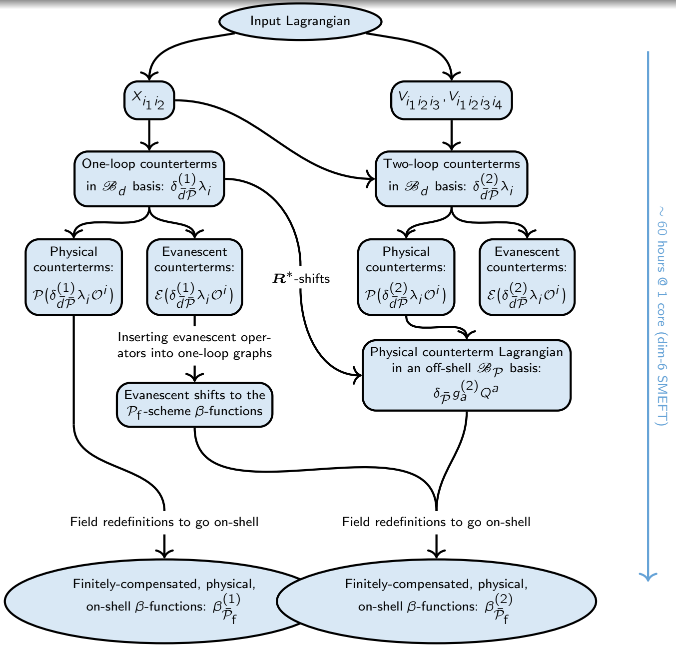
Op. basis	$\{O_i\}$	$\{Q_a,\, E_\alpha\}$	$\{Q_a,\, E_\alpha\}$
Examples	$(\bar{\ell}\gamma_\mu \ell)(\bar{e}\gamma^\mu e)$ $(\bar{\ell}e)(\bar{e}\ell)$	$(\bar{\ell}\gamma_\mu \ell)(\bar{e}\gamma^\mu e)$ $(\bar{\ell}\gamma_\mu \ell)(\bar{e}\gamma^\mu e) + \frac{1}{2}(\bar{\ell}e)(\bar{e}\ell)$	$(\bar{\ell}\gamma_\mu \ell)(\bar{e}\gamma^\mu e)$ $(\bar{\ell}\gamma_\mu \ell)(\bar{e}\gamma^\mu e) + \frac{1}{2}(\bar{\ell}e)(\bar{e}\ell)$
Cts.	$\{\delta g_i\}$	$\{\delta\lambda_a,\, \delta\eta_\alpha\}$	$\{\delta\lambda_a + \Delta\lambda_a,\, \delta\eta_\alpha\}$

(1-loop)^2 (1-loop)^2

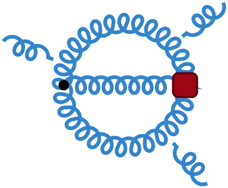


Computation



Fully automated counterterm calculation

Bespoke version of MATCHETE



```
L = FreeLag[] + cGt[] Gtilde;
L // NiceForm
```

iceForm=

$$-\frac{1}{4}G^{\mu\nu x2}+\left(D_\mu\,\bar{c}_G{}^x\cdot D_\mu\,c_G{}^x\right)+g\,G^{\mu y}\left(\bar{c}_G{}^x\cdot D_\mu\,c_G{}^z\right)f^{xyz}+\boxed{\frac{1}{6}\,\mathrm{cGt}\,G^{\mu\rho y}\,G^{\nu\rho z}\,G^{\sigma\kappa x}\,f^{xyz}\,\varepsilon^{\mu\nu\sigma\kappa}}$$

```
ctlag = CountertermLagrangian[L, EFTOrder → 6] // EchoTiming;
ctlag // NiceForm
```

» Added new CG cg1 with indices {SU3c[adj], SU3c[adj], SU3c[adj], SU3c[adj]}

» Added new CG cg2 with indices {SU3c[adj], SU3c[adj], SU3c[adj], SU3c[adj], SU3c[adj]}

13 695.1 — Mathematica, single core

'/NiceForm=

$$-\frac{11}{4}\hbar\,\frac{1}{\epsilon}\,g^2\,G^{\mu\nu x2}-\frac{51}{4}\hbar^2\,\frac{1}{\epsilon}\,g^4\,G^{\mu\nu x2}-3\,\hbar\,\frac{1}{\epsilon}\,\mathrm{cGt}\,g^2\,G^{\mu\nu x}\,G^{\rho\sigma y}\,G^{\sigma\kappa z}\,f^{xyz}\,\varepsilon^{\mu\nu\rho\kappa}-$$
$$\frac{21}{2}\hbar^2\,\frac{1}{\epsilon^2}\,\mathrm{cGt}\,g^4\,G^{\mu\nu x}\,G^{\rho\sigma y}\,G^{\sigma\kappa z}\,f^{xyz}\,\varepsilon^{\mu\nu\rho\kappa}-\frac{425}{24}\hbar^2\,\frac{1}{\epsilon}\,\mathrm{cGt}\,g^4\,G^{\mu\nu x}\,G^{\rho\sigma y}\,G^{\sigma\kappa z}\,f^{xyz}\,\varepsilon^{\mu\nu\rho\kappa}$$

Born, Fuentes-Martín, Kvedaraitė, **AET** [2410.07320]

γ_5-ambiguities and the limits of NDR

NDR assumptions: $(d = 4 - 2\epsilon)$

$$\{\gamma_\mu, \gamma_\nu\} = 2g_{\mu\nu}, \qquad \{\gamma_\mu, \gamma_5\} = 0, \qquad \gamma_5^2 = \mathbb{1},$$

$$\mathrm{Tr}\big[\gamma_\mu\gamma_\nu\gamma_\rho\gamma_\sigma\gamma_5\big] \xrightarrow[\epsilon\to 0]{} -4i\varepsilon_{\mu\nu\rho\sigma}.$$

Reading point ambiguity/loss of cyclicity (for γ_5-odd traces):

$$\begin{aligned} \mathrm{Tr}\big[\gamma_\alpha\gamma_\mu\gamma_\nu\gamma_\rho\gamma_\sigma\gamma^\alpha\gamma_5\big] &= 4(4+2\epsilon)i\varepsilon_{\mu\nu\rho\sigma} \\ -\,\mathrm{Tr}\big[\gamma^\alpha\gamma_\alpha\gamma_\mu\gamma_\nu\gamma_\rho\gamma_\sigma\gamma_5\big] &= 4(4-2\epsilon)i\varepsilon_{\mu\nu\rho\sigma} \end{aligned}$$

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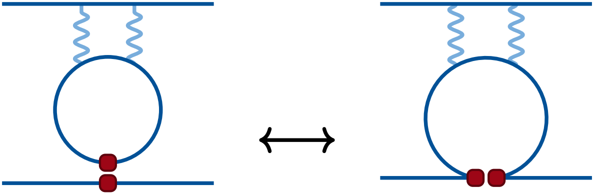
$$-\,\mathrm{Tr}\big[\gamma^\alpha\gamma_\alpha\gamma_\mu\gamma_\nu\gamma_\rho\gamma_\sigma\gamma_5\big] = 4(4-2\epsilon)i\varepsilon_{\mu\nu\rho\sigma}$$

Operator class	Problematic diagrams	Affected β-functions
Reading point at the dimension-six vertex		
Scalar ψ^4	—	—
Vector ψ^4	—	—
$\psi^2 H^2 D$	—	—
$\psi^2 H^3$	1	CP-odd X^2H^2
$\psi^2 XH$	11	$\psi^2 XH$, CP-odd X^2H^2, and CP-odd X^3
Averaging over vertex reading points		
Scalar ψ^4	1	CP-odd X^2H^2
$\psi^2 XH$	1	$\psi^2 XH$
H^2X^2	1	$\psi^2 H^3$
X^3 and H^4D^2	—	—
Weinberg operator	—	—

Example: how some ambiguities can resolved

The reading-point for almost all four-fermion operators can be **verified through Fierzing** to another operator basis

Strategy devised for the LEFT: Buras *et al.* [hep-ph/9211304]; Aebischer *et al.* [2501.08384]



$$\left(\overline{e}\gamma_\mu e\right)\left(\overline{d}\gamma_\mu d\right) \quad\longleftrightarrow\quad \left(\overline{e}\gamma_\mu d\right)\left(\overline{d}\gamma_\mu e\right)$$

Example: how some ambiguities can resolved

The reading-point for almost all four-fermion operators can be **verified through Fierzing** to another operator basis

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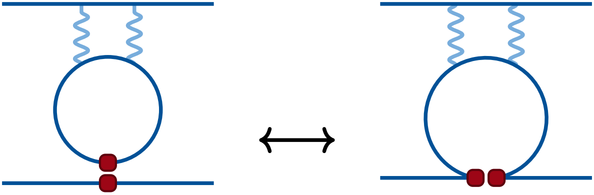

$$(\bar{e}\gamma_\mu e)(\bar{d}\gamma_\mu d) \longleftrightarrow (\bar{e}\gamma_\mu d)(\bar{d}\gamma_\mu e)$$

Fierzing tensor-current operators involves an ambiguous evanescent contribution causing the trick to fail: **we abandon the Warsaw basis**

The “Mainz” basis

$(\bar{L}L)(\bar{R}R)$	
$O_{\ell e}^{prst}$	$(\bar{\ell}^p \gamma_\mu \ell^r)(\bar{e}^s \gamma^\mu e^t)$
$O_{\ell u}^{prst}$	$(\bar{\ell}^p \gamma_\mu \ell^r)(\bar{u}^s \gamma^\mu u^t)$
$O_{\ell d}^{prst}$	$(\bar{\ell}^p \gamma_\mu \ell^r)(\bar{d}^s \gamma^\mu d^t)$
O_{qe}^{prst}	$(\bar{q}^p \gamma_\mu q^r)(\bar{e}^s \gamma^\mu e^t)$
$O_{qu}^{(\parallel)\,prst}$	$(\bar{q}^p \gamma_\mu q^r)(\bar{u}^s \gamma^\mu u^t)$
$O_{qu}^{(\times)\,prst}$	$(\bar{q}_a^p \gamma_\mu q^{br})(\bar{u}_b^s \gamma^\mu u^{at})$
$O_{qd}^{(\parallel)\,prst}$	$(\bar{q}^p \gamma_\mu q^r)(\bar{d}^s \gamma^\mu d^t)$
$O_{qd}^{(\times)\,prst}$	$(\bar{q}_a^p \gamma_\mu q^{br})(\bar{d}_b^s \gamma^\mu d^{at})$

$(\bar{R}R)(\bar{R}R)$	
O_{ee}^{prst}	$(\bar{e}^p \gamma_\mu e^r)(\bar{e}^s \gamma^\mu e^t)$
O_{uu}^{prst}	$(\bar{u}^p \gamma_\mu u^r)(\bar{u}^s \gamma^\mu u^t)$
O_{dd}^{prst}	$(\bar{d}^p \gamma_\mu d^r)(\bar{d}^s \gamma^\mu d^t)$
O_{eu}^{prst}	$(\bar{e}^p \gamma_\mu e^r)(\bar{u}^s \gamma^\mu u^t)$
O_{ed}^{prst}	$(\bar{e}^p \gamma_\mu e^r)(\bar{d}^s \gamma^\mu d^t)$
$O_{ud}^{(\parallel)\,prst}$	$(\bar{u}^p \gamma_\mu u^r)(\bar{d}^s \gamma^\mu d^t)$
$O_{ud}^{(\times)\,prst}$	$(\bar{u}_a^p \gamma_\mu u^{br})(\bar{d}_b^s \gamma^\mu d^{at})$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$	
$O_{\ell edq}^{prst}$	$(\bar{\ell}_j^p e^r)(\bar{d}^s q_j^t)$
$O_{quqd}^{(\parallel)\,prst}$	$(\bar{q}_i^p u^r)\varepsilon^{ij}(\bar{q}_j^s d^t)$
$O_{quqd}^{(\times)\,prst}$	$(\bar{q}_{ai}^p u^{br})\varepsilon^{ij}(\bar{q}_{bj}^s d^{at})$
$O_{\ell equ}^{prst}$	$(\bar{\ell}_i^p e^r)\varepsilon^{ij}(\bar{q}_j^s u^t)$
$O_{\ell uqe}^{prst}$	$(\bar{\ell}_i^p u^r)\varepsilon^{ij}(\bar{q}_j^s e^t)$

$(\bar{L}L)(\bar{L}L)$	
$O_{\ell\ell}^{prst}$	$(\bar{\ell}^p \gamma_\mu \ell^r)(\bar{\ell}^s \gamma^\mu \ell^t)$
$O_{qq}^{(\parallel)\,prst}$	$(\bar{q}^p \gamma_\mu q^r)(\bar{q}^s \gamma^\mu q^t)$
$O_{qq}^{(\times)\,prst}$	$(\bar{q}_i^p \gamma_\mu q^{jr})(\bar{q}_j^s \gamma^\mu q^{it})$
$O_{\ell q}^{(\parallel)\,prst}$	$(\bar{\ell}^p \gamma_\mu \ell^r)(\bar{q}^s \gamma^\mu q^t)$
$O_{\ell q}^{(\times)\,prst}$	$(\bar{\ell}_i^p \gamma_\mu \ell^{jr})(\bar{q}_j^s \gamma^\mu q^{it})$

See also `https://github.com/NewSMEFTBasis/basis-proposal` and discussions in the LHC EFT Working Group

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O_{dd}^{prst}	$(\bar{d}^p \gamma_\mu d^r)(\bar{d}^s \gamma^\mu d^t)$
O_{eu}^{prst}	$(\bar{e}^p \gamma_\mu e^r)(\bar{u}^s \gamma^\mu u^t)$
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$O_{ud}^{(\times)\,prst}$	$(\bar{u}_a^p \gamma_\mu u^{br})(\bar{d}_b^s \gamma^\mu d^{at})$

Avoiding uncontrolled γ_5 traces from tensor currents:

$$Q_{\ell equ}^{(3)} = (\bar{\ell}_i \sigma_{\mu\nu} e)\varepsilon^{ij}(\bar{q}_j \sigma^{\mu\nu} u) \quad \longrightarrow \quad O_{\ell uqe} = (\bar{\ell}_i u)\varepsilon^{ij}(\bar{q}_j e)$$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$	
$O_{\ell edq}^{prst}$	$(\bar{\ell}_j^p e^r)(\bar{d}^s q_j^t)$
$O_{quqd}^{(\parallel)\,prst}$	$(\bar{q}_i^p u^r)\varepsilon^{ij}(\bar{q}_j^s d^t)$
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$O_{\ell equ}^{prst}$	$(\bar{\ell}_i^p e^r)\varepsilon^{ij}(\bar{q}_j^s u^t)$
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The "Mainz" basis

X^3	
O_W	$g_L^3 f^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
O_G	$g_s^3 f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$O_{\widetilde{W}}$	$g_L^3 f^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$O_{\widetilde{G}}$	$g_s^3 f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$

H^4D^2 and H^6	
O_H	$(H^\dagger H)^3$
$O_{HD}^{(\parallel)}$	$(H^\dagger H)(D_\mu H^\dagger D^\mu H)$
$O_{HD}^{(\times)}$	$H_i^* H^j D_\mu H_j^* D^\mu H^i$

$\psi^2 H^3$	
O_{eH}^{pr}	$(H^\dagger H)(\bar{\ell}^p e^r H)$
O_{uH}^{pr}	$(H^\dagger H)(\bar{q}^p u^r \widetilde{H})$
O_{dH}^{pr}	$(H^\dagger H)(\bar{q}^p d^r H)$

$X^2 H^2$	
O_{HG}	$g_s^2 (H^\dagger H) G^{A\mu\nu} G_{\mu\nu}^A$
$O_{H\widetilde{G}}$	$g_s^2 (H^\dagger H) G^{A\mu\nu} \widetilde{G}_{\mu\nu}^A$
O_{HW}	$g_L^2 (H^\dagger H) W^{I\mu\nu} W_{\mu\nu}^I$
$O_{H\widetilde{W}}$	$g_L^2 (H^\dagger H) W^{I\mu\nu} \widetilde{W}_{\mu\nu}^I$
O_{HB}	$g_Y^2 (H^\dagger H) B^{\mu\nu} B_{\mu\nu}$
$O_{H\widetilde{B}}$	$g_Y^2 (H^\dagger H) B^{\mu\nu} \widetilde{B}_{\mu\nu}$
O_{HWB}	$g_Y g_L (H^\dagger t^I H) B^{\mu\nu} W_{\mu\nu}^I$
$O_{H\widetilde{W}B}$	$g_Y g_L (H^\dagger t^I H) B^{\mu\nu} \widetilde{W}_{\mu\nu}^I$

$\psi^2 X H$	
O_{eW}^{pr}	$g_L (\bar{\ell}^p \sigma^{\mu\nu} e^r t^I H) W_{\mu\nu}^I$
O_{eB}^{pr}	$g_Y (\bar{\ell}^p \sigma^{\mu\nu} e^r H) B_{\mu\nu}$
O_{uG}^{pr}	$g_s (\bar{q}^p \sigma^{\mu\nu} T^A u^r \widetilde{H}) G_{\mu\nu}^A$
O_{uW}^{pr}	$g_L (\bar{q}^p \sigma^{\mu\nu} u^r t^I \widetilde{H}) W_{\mu\nu}^I$
O_{uB}^{pr}	$g_Y (\bar{q}^p \sigma^{\mu\nu} u^r \widetilde{H}) B_{\mu\nu}$
O_{dG}^{pr}	$g_s (\bar{q}^p \sigma^{\mu\nu} T^A d^r H) G_{\mu\nu}^A$
O_{dW}^{pr}	$g_L (\bar{q}^p \sigma^{\mu\nu} d^r t^I H) W_{\mu\nu}^I$
O_{dB}^{pr}	$g_Y (\bar{q}^p \sigma^{\mu\nu} d^r H) B_{\mu\nu}$

$\psi^2 H^2 D$	
$O_{H\ell}^{(\parallel)\,pr}$	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{\ell}^p \gamma^\mu \ell^r)$
$O_{H\ell}^{(\times)\,pr}$	$i(H_i^* \overleftrightarrow{D}_\mu H^j)(\bar{\ell}_j^p \gamma^\mu \ell^{ir})$
O_{He}^{pr}	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}^p \gamma^\mu e^r)$
$O_{Hq}^{(\parallel)\,pr}$	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{q}^p \gamma^\mu q^r)$
$O_{Hq}^{(\times)\,pr}$	$i(H_i^* \overleftrightarrow{D}_\mu H^j)(\bar{q}_j^p \gamma^\mu q^{ir})$
O_{Hu}^{pr}	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}^p \gamma^\mu u^r)$
O_{Hd}^{pr}	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}^p \gamma^\mu d^r)$
O_{Hud}^{pr}	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}^p \gamma^\mu d^r)$

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H^4D^2 and H^6	
O_H	$(H^\dagger H)^3$
$O_{HD}^{(\parallel)}$	$(H^\dagger H)(D_\mu H^\dagger D^\mu H)$
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$\psi^2 H^3$	
O_{eH}^{pr}	$(H^\dagger H)(\bar{\ell}^p e^r H)$
O_{uH}^{pr}	$(H^\dagger H)(\bar{q}^p u^r \widetilde{H})$
O_{dH}^{pr}	$(H^\dagger H)(\bar{q}^p d^r H)$

$X^2 H^2$	
O_{HG}	$g_s^2 (H^\dagger H) G^{A\mu\nu} G^A_{\mu\nu}$
$O_{H\widetilde{G}}$	$g_s^2 (H^\dagger H) G^{A\mu\nu} \widetilde{G}^A_{\mu\nu}$
O_{HW}	$g_L^2 (H^\dagger H) W^{I\mu\nu} W^I_{\mu\nu}$
$O_{H\widetilde{W}}$	$g_L^2 (H^\dagger H) W^{I\mu\nu} \widetilde{W}^I_{\mu\nu}$
O_{HB}	$g_Y^2 (H^\dagger H) B^{\mu\nu} B_{\mu\nu}$
$O_{H\widetilde{B}}$	$g_Y^2 (H^\dagger H) B^{\mu\nu} \widetilde{B}_{\mu\nu}$
O_{HWB}	$g_Y g_L (H^\dagger t^I H) B^{\mu\nu} W^I_{\mu\nu}$
$O_{H\widetilde{W}B}$	$g_Y g_L (H^\dagger t^I H) B^{\mu\nu} \widetilde{W}^I_{\mu\nu}$

$\psi^2 X H$	
O_{eW}^{pr}	$g_L (\bar{\ell}^p \sigma^{\mu\nu} e^r t^I H) W^I_{\mu\nu}$
O_{eB}^{pr}	$g_Y (\bar{\ell}^p \sigma^{\mu\nu} e^r H) B_{\mu\nu}$
O_{uG}^{pr}	$g_s (\bar{q}^p \sigma^{\mu\nu} T^A u^r \widetilde{H}) G^A_{\mu\nu}$
O_{uW}^{pr}	$g_L (\bar{q}^p \sigma^{\mu\nu} u^r t^I \widetilde{H}) W^I_{\mu\nu}$
O_{uB}^{pr}	$g_Y (\bar{q}^p \sigma^{\mu\nu} u^r \widetilde{H}) B_{\mu\nu}$
O_{dG}^{pr}	$g_s (\bar{q}^p \sigma^{\mu\nu} T^A d^r H) G^A_{\mu\nu}$
O_{dW}^{pr}	$g_L (\bar{q}^p \sigma^{\mu\nu} d^r t^I H) W^I_{\mu\nu}$
O_{dB}^{pr}	$g_Y (\bar{q}^p \sigma^{\mu\nu} d^r H) B_{\mu\nu}$

$\psi^2 H^2 D$	
$O_{H\ell}^{(\parallel)pr}$	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{\ell}^p \gamma^\mu \ell^r)$
$O_{H\ell}^{(\times)pr}$	$i(H_i^* \overleftrightarrow{D}_\mu H^j)(\bar{\ell}_j^p \gamma^\mu \ell^{ir})$
O_{He}^{pr}	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}^p \gamma^\mu e^r)$
$O_{Hq}^{(\parallel)pr}$	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{q}^p \gamma^\mu q^r)$
$O_{Hq}^{(\times)pr}$	$i(H_i^* \overleftrightarrow{D}_\mu H^j)(\bar{q}_j^p \gamma^\mu q^{ir})$
O_{Hu}^{pr}	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}^p \gamma^\mu u^r)$
O_{Hd}^{pr}	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}^p \gamma^\mu d^r)$
O_{Hud}^{pr}	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}^p \gamma^\mu d^r)$

Remove derivatives acting on multiple fields

$$Q_{\Box H} = (H^\dagger H)\Box(H^\dagger H) \quad \longrightarrow \quad O_{HD}^{(\parallel)} = (H^\dagger H)(D_\mu H^\dagger D^\mu H)$$

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$\psi^2 H^3$	
O_{eH}^{pr}	$(H^\dagger H)(\bar{\ell}^p e^r H)$
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$\psi^2 X H$	
O_{eW}^{pr}	$g_L (\bar{\ell}^p \sigma^{\mu\nu} e^r t^I H) W_{\mu\nu}^I$
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O_{dW}^{pr}	$g_L (\bar{q}^p \sigma^{\mu\nu} d^r t^I H) W_{\mu\nu}^I$
O_{dB}^{pr}	$g_Y (\bar{q}^p \sigma^{\mu\nu} d^r H) B_{\mu\nu}$

$\psi^2 H^2 D$	
$O_{H\ell}^{(\parallel)pr}$	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{\ell}^p \gamma^\mu \ell^r)$
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O_{He}^{pr}	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}^p \gamma^\mu e^r)$
$O_{Hq}^{(\parallel)pr}$	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{q}^p \gamma^\mu q^r)$
$O_{Hq}^{(\times)pr}$	$i(H_i^* \overleftrightarrow{D}_\mu H^j)(\bar{q}_j^p \gamma^\mu q^{ir})$
O_{Hu}^{pr}	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}^p \gamma^\mu u^r)$
O_{Hd}^{pr}	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}^p \gamma^\mu d^r)$
O_{Hud}^{pr}	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}^p \gamma^\mu d^r)$

See also https://github.com/NewSMEFTBasis/basis-proposal and discussions in the LHC EFT Working Group

The "Mainz" basis

X^3	
O_W	$g_L^3 f^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
O_G	$g_s^3 f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$O_{\widetilde{W}}$	$g_L^3 f^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$O_{\widetilde{G}}$	$g_s^3 f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$

$H^4 D^2$ and H^6	
O_H	$(H^\dagger H)^3$
$\boxed{O_{HD}^{(\parallel)}}$	$\boxed{(H^\dagger H)(D_\mu H^\dagger D^\mu H)}$
$O_{HD}^{(\times)}$	$H_i^* H^j D_\mu H_j^* D^\mu H^i$

$\psi^2 H^3$	
O_{eH}^{pr}	$(H^\dagger H)(\bar{\ell}^p e^r H)$
O_{uH}^{pr}	$(H^\dagger H)(\bar{q}^p u^r \widetilde{H})$
O_{dH}^{pr}	$(H^\dagger H)(\bar{q}^p d^r H)$

$X^2 H^2$	
O_{HG}	$g_s^2 (H^\dagger H) G^{A\mu\nu} G_{\mu\nu}^A$
$O_{H\widetilde{G}}$	$g_s^2 (H^\dagger H) G^{A\mu\nu} \widetilde{G}_{\mu\nu}^A$
O_{HW}	$g_L^2 (H^\dagger H) W^{I\mu\nu} W_{\mu\nu}^I$
$O_{H\widetilde{W}}$	$g_L^2 (H^\dagger H) W^{I\mu\nu} \widetilde{W}_{\mu\nu}^I$
O_{HB}	$g_Y^2 (H^\dagger H) B^{\mu\nu} B_{\mu\nu}$
$O_{H\widetilde{B}}$	$g_Y^2 (H^\dagger H) B^{\mu\nu} \widetilde{B}_{\mu\nu}$
$\boxed{O_{HWB}}$	$\boxed{g_Y g_L (H^\dagger t^I H) B^{\mu\nu} W_{\mu\nu}^I}$
$\boxed{O_{H\widetilde{W}B}}$	$\boxed{g_Y g_L (H^\dagger t^I H) B^{\mu\nu} \widetilde{W}_{\mu\nu}^I}$

$\psi^2 X H$	
O_{eW}^{pr}	$g_L (\bar{\ell}^p \sigma^{\mu\nu} e^r t^I H) W_{\mu\nu}^I$
O_{eB}^{pr}	$g_Y (\bar{\ell}^p \sigma^{\mu\nu} e^r H) B_{\mu\nu}$
O_{uG}^{pr}	$g_s (\bar{q}^p \sigma^{\mu\nu} T^A u^r \widetilde{H}) G_{\mu\nu}^A$
$\boxed{O_{uW}^{pr}}$	$\boxed{g_L (\bar{q}^p \sigma^{\mu\nu} u^r t^I \widetilde{H}) W_{\mu\nu}^I}$
O_{uB}^{pr}	$g_Y (\bar{q}^p \sigma^{\mu\nu} u^r \widetilde{H}) B_{\mu\nu}$
O_{dG}^{pr}	$g_s (\bar{q}^p \sigma^{\mu\nu} T^A d^r H) G_{\mu\nu}^A$
$\boxed{O_{dW}^{pr}}$	$\boxed{g_L (\bar{q}^p \sigma^{\mu\nu} d^r t^I H) W_{\mu\nu}^I}$
O_{dB}^{pr}	$g_Y (\bar{q}^p \sigma^{\mu\nu} d^r H) B_{\mu\nu}$

$\psi^2 H^2 D$	
$O_{H\ell}^{(\parallel)pr}$	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{\ell}^p \gamma^\mu \ell^r)$
$\boxed{O_{H\ell}^{(\times)pr}}$	$\boxed{i(H_i^* \overleftrightarrow{D}_\mu H^j)(\bar{\ell}_j^p \gamma^\mu \ell^{ir})}$
O_{He}^{pr}	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}^p \gamma^\mu e^r)$
$O_{Hq}^{(\parallel)pr}$	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{q}^p \gamma^\mu q^r)$
$\boxed{O_{Hq}^{(\times)pr}}$	$\boxed{i(H_i^* \overleftrightarrow{D}_\mu H^j)(\bar{q}_j^p \gamma^\mu q^{ir})}$
O_{Hu}^{pr}	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}^p \gamma^\mu u^r)$
O_{Hd}^{pr}	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}^p \gamma^\mu d^r)$
O_{Hud}^{pr}	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}^p \gamma^\mu d^r)$

Canonical gauge coupling normalization:

$$X_{\mu\nu} \longrightarrow g_X X_{\mu\nu}$$

See also https://github.com/NewSMEFTBasis/basis-proposal and discussions in the LHC EFT Working Group

Results: pdf

$$\beta^{(2)}_{C^{pr}_{dB}} = \Big\{ \frac{1}{72} g_Y^2 Y_d^{pr} + \frac18 (Y_d Y_d^\dagger Y_d)^{pr} + \frac14 g_L^2 Y_d^{pr} - \frac13 (Y_u Y_u^\dagger Y_d)^{pr} \Big\} C_{HD}^{(\|)} + \Big\{ \frac13 (Y_u Y_u^\dagger Y_d)^{pr} - \frac{5}{144} g_Y^2 Y_d^{pr} - \frac18 (Y_d Y_d^\dagger Y_d)^{pr} - \frac{3}{16} g_L^2 Y_d^{pr}\Big\} C_{HD}^{(\times)}$$

$$+ \Big\{ \frac{29}{108} g_Y^4 Y_d^{pr} + \frac12 \lambda g_Y^2 Y_d^{pr} + g_Y^2 \Big(\frac{1}{12}(Y_u Y_u^\dagger Y_d)^{pr} + \frac16 \mathrm{T}_2 Y_d^{pr} + \frac14 (Y_d Y_d^\dagger Y_d)^{pr}\Big) + \frac83 g_Y^2 g_s^2 Y_d^{pr} - \frac18 g_Y^2 g_L^2 Y_d^{pr}\Big\} C_{HB} + \Big\{ \frac{i}{8} g_Y^2 g_L^2 Y_d^{pr}$$

$$+ g_Y^2 \Big(\frac{19i}{12}(Y_uY_u^\dagger Y_d)^{pr} - \frac{i}{6} \mathrm{T}_2 Y_d^{pr} - \frac{i}{4}(Y_dY_d^\dagger Y_d)^{pr}\Big) - \frac{29i}{108} g_Y^4 Y_d^{pr} - \frac{i}{2}\lambda g_Y^2 Y_d^{pr} - \frac{8i}{3} g_Y^2 g_s^2 Y_d^{pr}\Big\} C_{H\widetilde B} + \frac18 g_L^4 C_{HW} Y_d^{pr} - \frac{i}{8} g_L^4 C_{H\widetilde W} Y_d^{pr}$$

$$+ \frac43 g_s^4 C_{HG} Y_d^{pr} - \frac{4i}{3} g_s^4 C_{H\widetilde G} Y_d^{pr} + \Big\{ \frac{9}{32} g_Y^2 g_L^2 Y_d^{pr} + \frac{425}{96} g_L^4 Y_d^{pr} - \frac38 \lambda g_L^2 Y_d^{pr} - g_L^2\Big(\frac38 \mathrm{T}_2 Y_d^{pr} + \frac{9}{16}(Y_dY_d^\dagger Y_d)^{pr} + \frac{15}{16}(Y_uY_u^\dagger Y_d)^{pr}\Big)$$

$$- 6 g_s^2 g_L^2 Y_d^{pr}\Big\} C_{HWB} + \Big\{ \frac{3i}{8}\lambda g_L^2 Y_d^{pr} + g_L^2\Big(\frac{3i}{16}(Y_uY_u^\dagger Y_d)^{pr} + \frac{3i}{8} \mathrm{T}_2 Y_d^{pr} + \frac{9i}{16}(Y_dY_d^\dagger Y_d)^{pr}\Big) + 6i g_s^2 g_L^2 Y_d^{pr} - \frac{9i}{32} g_Y^2 g_L^2 Y_d^{pr}$$

$$- \frac{425i}{96} g_L^4 Y_d^{pr}\Big\} C_{H\widetilde W B} - \frac{21}{4} g_L^6 C_W Y_d^{pr} + \frac{35i}{12} g_L^6 C_{\widetilde W} Y_d^{pr} + 2 g_s^6 C_G Y_d^{pr} - \frac{26i}{9} g_s^6 C_{\widetilde G} Y_d^{pr} + \Big\{ \frac38 \delta^{pa}\delta^{rb} g_L^2 - \frac18 \delta^{pa}\delta^{rb} g_Y^2 - \frac18 \delta^{pa}(Y_d^\dagger Y_d)^{br}$$

$$- \frac18 \delta^{rb}(Y_dY_d^\dagger)^{pa}\Big\} C_{dH}^{ab} + \Big\{\frac54 g_Y^2 Y_e^{*ab} Y_d^{pr} + \frac94 g_L^2 Y_e^{*ab} Y_d^{pr}\Big\} C_{eB}^{ab} - \frac94 g_L^2 Y_e^{*ab} C_{eW}^{ab} Y_d^{pr} + \Big\{ \frac12 \mathrm{T}_2 \delta^{pa}(Y_u^\dagger Y_d)^{br} + g_L^2\Big(\frac94 Y_u^{*ab} Y_d^{pr} - \frac{39}{8}\delta^{pa}(Y_u^\dagger Y_d)^{br}\Big)$$

$$+ g_Y^2\Big(\frac{5}{12} Y_u^{*ab} Y_d^{pr} - \frac{11}{24}\delta^{pa}(Y_u^\dagger Y_d)^{br}\Big) + \frac52 (Y_u^\dagger Y_d)^{br}(Y_uY_u^\dagger)^{pa} + \frac52 \delta^{pa}(Y_u^\dagger Y_u Y_u^\dagger Y_d)^{br} - \frac12 (Y_u^\dagger Y_d)^{br}(Y_dY_d^\dagger)^{pa} - \delta^{pa}(Y_u^\dagger Y_d Y_d^\dagger Y_d)^{br}\Big\} C_{uB}^{ab}$$

$$+ C_{uB}^{*ab}\Big\{ \frac12 Y_u^{pb}(Y_uY_u^\dagger Y_d)^{ar} + \mathrm{T}_2 Y_d^{ar} Y_u^{pb} + g_Y^2\Big(\frac{5}{12} Y_d^{pr} Y_u^{ab} - \frac29 Y_d^{ar} Y_u^{pb}\Big) + \frac52 Y_d^{ar}(Y_uY_u^\dagger Y_u)^{pb} - Y_u^{pb}(Y_dY_d^\dagger Y_d)^{ar} - 2Y_d^{ar}(Y_dY_d^\dagger Y_u)^{pb} - \frac94 g_L^2 Y_d^{ar} Y_u^{pb}$$

$$- 8 g_s^2 Y_d^{ar} Y_u^{pb}\Big\} - \frac58 \delta^{pa} g_L^2 C_{uW}^{ab}(Y_u^\dagger Y_d)^{br} + g_L^2 C_{uW}^{*ab}\Big\{\frac{15}{8} Y_d^{pr} Y_u^{ab} - \frac18 Y_d^{ar} Y_u^{pb}\Big\} + \frac83 \delta^{pa} g_s^2 C_{uG}^{ab}(Y_u^\dagger Y_d)^{br} + \frac{44}{9} g_s^2 C_{uG}^{*ab} Y_d^{ar} Y_u^{pb}$$

$$+ \Big\{ g_L^2\Big(\frac{9}{16}\delta^{rb}(Y_uY_u^\dagger)^{pa} + \frac{15}{8} \mathrm{T}_2\delta^{pa}\delta^{rb} + \frac{27}{4} Y_d^{*ab} Y_d^{pr} + 9\delta^{pa}(Y_d^\dagger Y_d)^{br} + \frac{237}{16}\delta^{rb}(Y_dY_d^\dagger)^{pa}\Big) + g_Y^2\Big(\frac{5}{12} Y_d^{*ab} Y_d^{pr} + \frac{601}{144}\delta^{rb}(Y_dY_d^\dagger)^{pa}$$

$$+ \frac{349}{72}\delta^{pa}(Y_d^\dagger Y_d)^{br} + \frac{39}{8}\delta^{pa}\delta^{rb}\,\mathrm{Tr}\Big[Y_e^\dagger Y_e\Big] - \frac38 \delta^{pa}\delta^{rb}\,\mathrm{Tr}\Big[Y_d^\dagger Y_d\Big] - \frac{101}{144}\delta^{rb}(Y_uY_u^\dagger)^{pa} - \frac{29}{8}\delta^{pa}\delta^{rb}\,\mathrm{Tr}\Big[Y_u^\dagger Y_u\Big]\Big) + g_s^2\Big(20\delta^{pa}\delta^{rb}\,\mathrm{Tr}\Big[Y_d^\dagger Y_d\Big]$$

$$+ 20\delta^{pa}\delta^{rb}\,\mathrm{Tr}\Big[Y_u^\dagger Y_u\Big] - \frac{16}{3}\delta^{rb}(Y_dY_d^\dagger)^{pa} - \frac{16}{3}\delta^{rb}(Y_uY_u^\dagger)^{pa} - \frac{32}{3}\delta^{pa}(Y_d^\dagger Y_d)^{br}\Big) + \frac54 \mathrm{T}_2\delta^{rb}(Y_uY_u^\dagger)^{pa} + \frac54\delta^{pa}(Y_d^\dagger Y_d Y_d^\dagger Y_d)^{br} + \frac54 \delta^{rb}(Y_dY_d^\dagger Y_dY_d^\dagger)^{pa}$$

$$+ \frac32\delta^{pa}\delta^{rb}\lambda^2 + \frac32\delta^{pa}\delta^{rb}\,\mathrm{Tr}\Big[Y_d^\dagger Y_d Y_u^\dagger Y_u\Big] + \frac{103}{48}\delta^{pa}\delta^{rb} g_Y^2 g_L^2 + \frac{11}{4}\delta^{rb}(Y_uY_u^\dagger Y_uY_u^\dagger)^{pa} + \frac{172}{3}\delta^{pa}\delta^{rb} g_s^4 - \frac14 \delta^{pa}(Y_d^\dagger Y_u Y_u^\dagger Y_d)^{br}$$

$$- \frac12\delta^{rb}(Y_dY_d^\dagger Y_uY_u^\dagger)^{pa} - \lambda\Big(\frac32\delta^{pa}\delta^{rb} g_Y^2 + 6\delta^{pa}(Y_d^\dagger Y_d)^{br} + 6\delta^{rb}(Y_dY_d^\dagger)^{pa}\Big) - \delta^{rb}(Y_uY_u^\dagger Y_dY_d^\dagger)^{pa} - \frac{31}{27}\delta^{pa}\delta^{rb} g_Y^2 g_s^2 - \frac{1577}{1296}\delta^{pa}\delta^{r}$$

+ another 296 pages

Results: interactive notebook

Conventions | Interactive ADM | β–functions | ADM columns | SM β–functions

ADM columns

Full version | Only top Yukawa and gauge couplings

Display only the one–loop running:

Display the ADM column corresponding to $C_{uG}{}^{ab}$

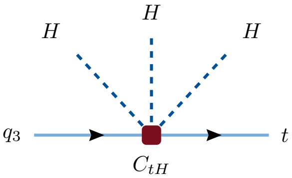
Result Copy result

	$C_{uG}{}^{ab}$
C_H	$\hbar^2 C_{uG}{}^{ab}\left(-128 g_s^2 \bar{Y}_u^{ar} \bar{Y}_u^{st} \bar{Y}_u^{ub} Y_u^{sr} Y_u^{ut} + \lambda\left(\frac{32}{3} g_s^2 g_L^2 \bar{Y}_u^{ab} + \frac{32}{3} g_s^2 g_Y^2 \bar{Y}_u^{ab} + 16 g_s^2 \bar{Y}_u^{ar} \bar{Y}_u^{sb} Y_u^{sr}\right) - 16 g_s^2 \lambda^2 \bar{Y}_u^{ab}\right)$
$C_{HD}^{(\shortparallel)}$	$\hbar^2 C_{uG}{}^{ab}\left(-32 g_s^2 g_L^2 \bar{Y}_u^{ab} - \frac{32}{3} g_s^2 g_Y^2 \bar{Y}_u^{ab} + g_s^2\left(96 \bar{Y}_d^{ar} Y_d^{sr} \bar{Y}_u^{sb} + 96 \bar{Y}_u^{ar} \bar{Y}_u^{sb} Y_u^{sr}\right)\right)$
$C_{HD}^{(\times)}$	$\hbar^2 C_{uG}{}^{ab}\left(-\frac{64}{3} g_s^2 g_Y^2 \bar{Y}_u^{ab} + g_s^2\left(-96 \bar{Y}_d^{ar} Y_d^{sr} \bar{Y}_u^{sb} + 96 \bar{Y}_u^{ar} \bar{Y}_u^{sb} Y_u^{sr}\right)\right)$
C_{HB}	$-\frac{16}{9} \hbar^2 g_s^2 \bar{Y}_u^{ab} C_{uG}{}^{ab}$
$C_{H\tilde{B}}$	$-\frac{179 i}{18} \hbar^2 g_s^2 \bar{Y}_u^{ab} C_{uG}{}^{ab}$
C_{HW}	0
$C_{H\tilde{W}}$	$-\frac{73 i}{6} \hbar^2 g_s^2 \bar{Y}_u^{ab} C_{uG}{}^{ab}$
C_{HG}	$2 \hbar \bar{Y}_u^{ab} C_{uG}{}^{ab} + \hbar^2 C_{uG}{}^{ab}\left(\frac{3}{2} g_L^2 \bar{Y}_u^{ab} + 46 g_s^2 \bar{Y}_u^{ab} + \frac{37}{18} g_Y^2 \bar{Y}_u^{ab} + 2 \bar{Y}_d^{ar} Y_d^{sr} \bar{Y}_u^{sb} - 15 \bar{Y}_u^{ar} \bar{Y}_u^{sb} Y_u^{sr} + 3 \lambda \bar{Y}_u^{ab}\right)$
$C_{H\tilde{G}}$	$2 i \hbar \bar{Y}_u^{ab} C_{uG}{}^{ab} + \hbar^2 C_{uG}{}^{ab}\left(\frac{3 i}{2} g_L^2 \bar{Y}_u^{ab} + 22 i g_s^2 \bar{Y}_u^{ab} + \frac{37 i}{18} g_Y^2 \bar{Y}_u^{ab} + 4 i \bar{Y}_d^{ar} Y_d^{sr} \bar{Y}_u^{sb} - 9 i \bar{Y}_u^{ar} \bar{Y}_u^{sb} Y_u^{sr} + 3 i \lambda \bar{Y}_u^{ab}\right)$
C_{HWB}	$\frac{32}{3} \hbar^2 g_s^2 \bar{Y}_u^{ab} C_{uG}{}^{ab}$
$C_{H\tilde{W}B}$	$34 i \hbar^2 g_s^2 \bar{Y}_u^{ab} C_{uG}{}^{ab}$
C_W	0
$C_{\tilde{W}}$	0
C_G	$\hbar^2 \bar{Y}_u^{ab} C_{uG}{}^{ab}$
$C_{\tilde{G}}$	$-\frac{i}{3} \hbar^2 \bar{Y}_u^{ab} C_{uG}{}^{ab}$
$C_{eH}{}^{ij}$	$\hbar^2 C_{uG}{}^{ab}\left(\frac{16}{3} g_s^2 g_L^2 Y_e^{ij} \bar{Y}_u^{ab} + \frac{16}{3} g_s^2 g_Y^2 Y_e^{ij} \bar{Y}_u^{ab} - 16 \lambda g_s^2 Y_e^{ij} \bar{Y}_u^{ab}\right)$
$C_{uH}{}^{ij}$	$\hbar g_s^2 C_{uG}{}^{ab}\left(16 \bar{Y}_u^{pb} Y_u^{pj} \delta_{ai} + 16 \bar{Y}_u^{ar} Y_u^{ir} \delta_{bj}\right) + \hbar^2 C_{uG}{}^{ab}\Big(4 g_s^2 g_L^4 \delta_{ai} \delta_{bj} - \frac{92}{27} g_s^2 g_Y^4 \delta_{ai} \delta_{bj} + g_s^2 g_L^2\left(\frac{16}{3} \bar{Y}_u^{ab} Y_u^{ij} - \frac{26}{3} \bar{Y}_u^{pb} Y_u^{pj} \delta_{ai} - \frac{56}{3} \bar{Y}_d^{ar} Y_d^{ir} \delta_{bj} - \frac{82}{3} \bar{Y}_u^{ar} Y_u^{ir} \delta_{bj}\right) + g_s^2 g_Y^2\left(\frac{16}{3} \bar{Y}_u^{ab} Y_u^{ij} - \frac{614}{27} \bar{Y}_u^{pb} Y_u^{pj} \delta_{ai} - \frac{254}{27} \bar{Y}_u^{ar} Y_u^{ir} \delta_{bj}\right) + g_s^2\Big(-\frac{8}{3} \bar{Y}_d^{ar} Y_d^{ir} \bar{Y}_u^{sb} Y_u^{sj} + 16 \bar{Y}_u^{ar} \bar{Y}_u^{sb} Y_u^{sr} Y_u^{ij} + 36 \bar{Y}_d^{pr} Y_d^{sr} \bar{Y}_u^{sb} Y_u^{pj} \delta_{ai} - \frac{340}{3} \bar{Y}_u^{pb} \bar{Y}_u^{st} Y_u^{pt} Y_u^{sj} \delta_{ai} + 16 \bar{Y}_d^{pr} Y_d^{ir} \bar{Y}_u^{at} Y_u^{pt} \delta_{bj} - \frac{332}{3} \bar{Y}_u^{at} \bar{Y}_u^{pr} Y_u^{pt} Y_u^{ir} \delta_{bj} + \frac{100}{3} \bar{Y}_d^{ar} Y_d^{sr} \bar{Y}_u^{st} Y_u^{it} \delta_{bj} + \frac{152}{9} g_L^2 g_Y^2 \delta_{ai} \delta_{bj}\Big) + g_s^4\left(-\frac{64}{3} \bar{Y}_u^{ab} Y_u^{ij} + \frac{2488}{9} \bar{Y}_u^{pb} Y_u^{pj} \delta_{ai} + \frac{2488}{9} \bar{Y}_u^{ar} Y_u^{ir} \delta_{bj} - 128 \bar{Y}_d^{pr} Y_d^{pr} \delta_{ai} \delta_{bj} - 128 \bar{Y}_u^{pr} Y_u^{pr} \delta_{ai} \delta_{bj}\right) + \lambda\left(-8 g_s^2 g_L^2 \delta_{ai} \delta_{bj} + \frac{224}{9} g_s^4 \delta_{ai} \delta_{bj} + \frac{56}{27} g_s^2 g_Y^2 \delta_{ai} \delta_{bj} + g_s^2\left(-16 \bar{Y}_u^{ab} Y_u^{ij} + \frac{152}{3} \bar{Y}_u^{pb} Y_u^{pj} \delta_{ai} + \frac{16}{3} \bar{Y}_d^{ar} Y_d^{ir} \delta_{bj} + \frac{160}{3} \bar{Y}_u^{ar} Y_u^{ir} \delta_{bj}\right)\right)\Big)$
$C_{dH}{}^{ij}$	$\hbar^2 C_{uG}{}^{ab}\Big(-\frac{64}{3} g_s^4 Y_d^{ij} \bar{Y}_u^{ab} + \frac{16}{3} g_s^2 g_Y^2 Y_d^{ij} \bar{Y}_u^{ab} + g_s^2 g_L^2\left(\frac{16}{3} Y_d^{ij} \bar{Y}_u^{ab} - \frac{40}{3} Y_d^{pj} \bar{Y}_u^{pb} \delta_{ai}\right) + \lambda g_s^2\left(-16 Y_d^{ij} \bar{Y}_u^{ab} + 8 Y_d^{pj} \bar{Y}_u^{pb} \delta_{ai}\right) + g_s^2\left(-8 \bar{Y}_d^{ar} Y_d^{sj} Y_d^{ir} \bar{Y}_u^{sb} + \frac{32}{3} Y_d^{sj} \bar{Y}_u^{ar} \bar{Y}_u^{sb} Y_u^{ir} + \frac{40}{3} \bar{Y}_d^{pr} Y_d^{pj} Y_d^{sr} \bar{Y}_u^{sb} \delta_{ai} + \frac{8}{3} Y_d^{sj} \bar{Y}_u^{pb} \bar{Y}_u^{st} Y_u^{pt} \delta_{ai}\right)\Big)$
$C_{eB}{}^{ij}$	0
$C_{eW}{}^{ij}$	0
$C_{uB}{}^{ij}$	$\frac{40}{9} \hbar g_s^2 C_{uG}{}^{ab} \delta_{ai} \delta_{bj} + \hbar^2 C_{uG}{}^{ab}\left(-\frac{5}{3} g_s^2 g_L^2 \delta_{ai} \delta_{bj} + \frac{820}{27} g_s^4 \delta_{ai} \delta_{bj} - \frac{205}{81} g_s^2 g_Y^2 \delta_{ai} \delta_{bj} + g_s^2\left(-\frac{70}{9} \bar{Y}_u^{pb} Y_u^{pj} \delta_{ai} + \frac{16}{9} \bar{Y}_d^{ar} Y_d^{ir} \delta_{bj} - \frac{26}{9} \bar{Y}_u^{ar} Y_u^{ir} \delta_{bj}\right)\right)$
$C_{uW}{}^{ij}$	$\frac{16}{3} \hbar g_s^2 C_{uG}{}^{ab} \delta_{ai} \delta_{bj} + \hbar^2 C_{uG}{}^{ab}\left(-\frac{14}{3} g_s^2 g_L^2 \delta_{ai} \delta_{bj} + \frac{328}{9} g_s^4 \delta_{ai} \delta_{bj} - \frac{82}{27} g_s^2 g_Y^2 \delta_{ai} \delta_{bj} + g_s^2\left(-\frac{4}{3} \bar{Y}_u^{pb} Y_u^{pj} \delta_{ai} - \frac{16}{3} \bar{Y}_d^{ar} Y_d^{ir} \delta_{bj} - \frac{28}{3} \bar{Y}_u^{ar} Y_u^{ir} \delta_{bj}\right)\right)$
$C_{uG}{}^{ij}$	$\hbar C_{uG}{}^{ab}\left(2 \bar{Y}_u^{pb} Y_u^{pj} \delta_{ai} - \frac{3}{2} \bar{Y}_d^{ar} Y_d^{ir} \delta_{bj} + \frac{5}{2} \bar{Y}_u^{ar} Y_u^{ir} \delta_{bj} - \frac{9}{4} g_L^2 \delta_{ai} \delta_{bj} + \frac{4}{3} g_s^2 \delta_{ai} \delta_{bj} - \frac{19}{36} g_Y^2 \delta_{ai} \delta_{bj} + 3 \bar{Y}_d^{pr} Y_d^{pr} \delta_{ai} \delta_{bj} + \bar{Y}_e^{pr} Y_e^{pr} \delta_{ai} \delta_{bj} + 3 \bar{Y}_u^{pr} Y_u^{pr} \delta_{ai} \delta_{bj}\right) + \hbar^2 C_{uG}{}^{ab}\Big(-3 \bar{Y}_u^{ar} \bar{Y}_u^{sb} Y_u^{sj} Y_u^{ir} - \frac{1}{4} \bar{Y}_d^{pr} Y_d^{sr} \bar{Y}_u^{sb} Y_u^{pj} \delta_{ai} - 9 \bar{Y}_u^{pb} \bar{Y}_u^{st} Y_u^{pj} Y_u^{st} \delta_{ai} - 9 \bar{Y}_d^{pr} Y_d^{pr} \bar{Y}_u^{sb} Y_u^{sj} \delta_{ai} - 3 \bar{Y}_e^{pr} Y_e^{pr} \bar{Y}_u^{sb} Y_u^{sj} \delta_{ai} + \frac{5}{4} \bar{Y}_u^{pb} \bar{Y}_u^{st} Y_u^{pt} Y_u^{sj} \delta_{ai} +$

Modified Top-Yukawa

/w Born and Greljo: [arXiv:2604.26817]

Top-Yukawa feeding into EWPO @ 2 loops



$$\delta\kappa_t = -\frac{v^2 C_{tH}}{y_t}$$

$$|\delta\kappa_t| = \begin{cases} 0.11 & \text{ATLAS, CMS} \\ 0.034 & \text{HL-LHC (proj.)} \end{cases}$$

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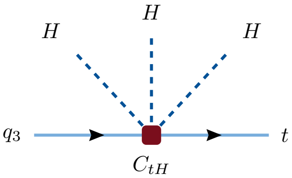

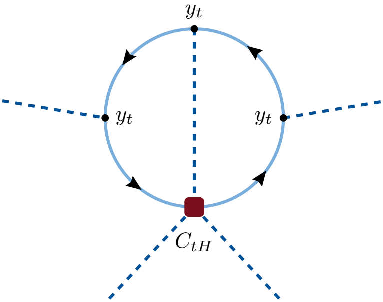

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$$\frac{\mathrm{d}C_{HD}^{(\times)}}{\mathrm{d}\ln\mu} \supset -\frac{18}{(4\pi)^4}|y_t|^2\,\mathrm{Re}\big[y_t^* C_{tH}\big]$$

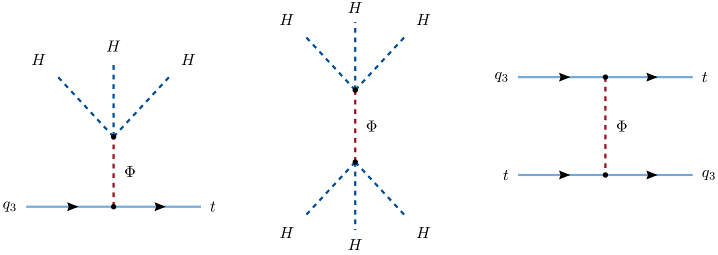
$$\delta m_W = 16.1\,\mathrm{MeV}\cdot\delta\kappa_t \ln\frac{\Lambda}{m_Z}$$

$$|\delta m_W| = \begin{cases} 10\,\mathrm{MeV} & \text{CMS} \\ 0.26\,\mathrm{MeV} & \text{FCC-ee (proj.)} \end{cases}$$

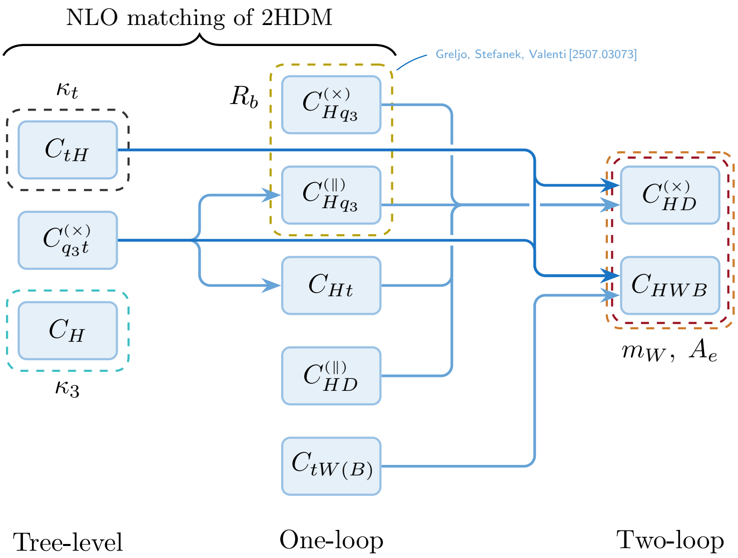
UV realization of the $C_{tH} \to C_{HD}^{(\times)}$ effect:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{kin}}^{\Phi} - \Big[\lambda_{\Phi} (\Phi^{\dagger} H)(H^{\dagger} H) + y_{\Phi} \overline{q}_3 \widetilde{\Phi} t_R \; + \; \mathrm{H.c.} \Big] + \ldots$$

Integrating the heavy Higgs Φ out in the decoupling limit:

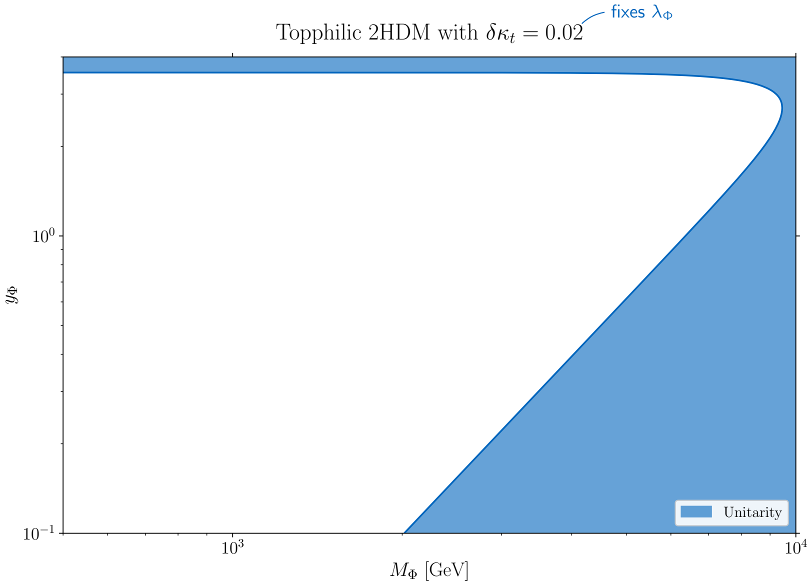


EWPOs in the top-philic 2HDM



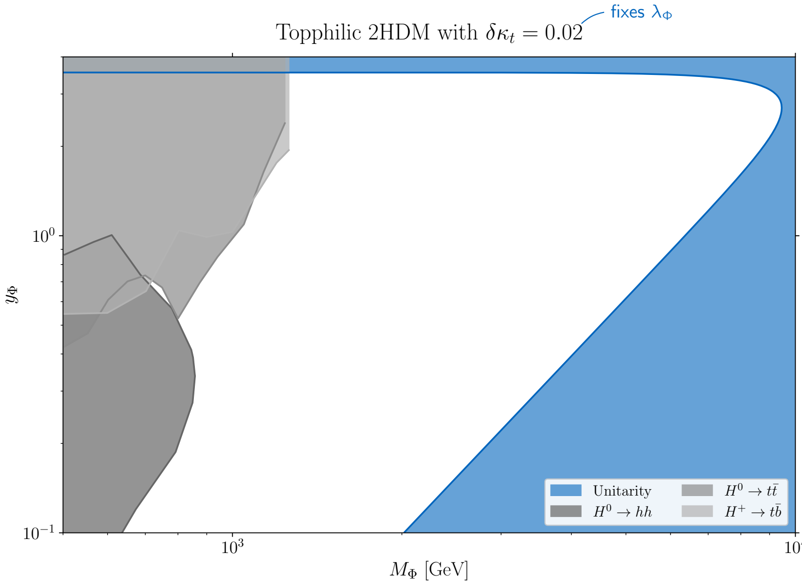
Our analysis uses the 2-loop running (no resummation) of Born, Fuentes-Martín, **AET** [2601.19974], 1-loop matching with `Matchete` [2212.04510] and 1-loop determination of EWPOs Biekötter, Pecjak [2503.07724]

parameter space for the top-philic 2HDM



Born, Greljo, **AET** [2604.26817]

parameter space for the top-philic 2HDM



Born, Greljo, **AET** [2604.26817]

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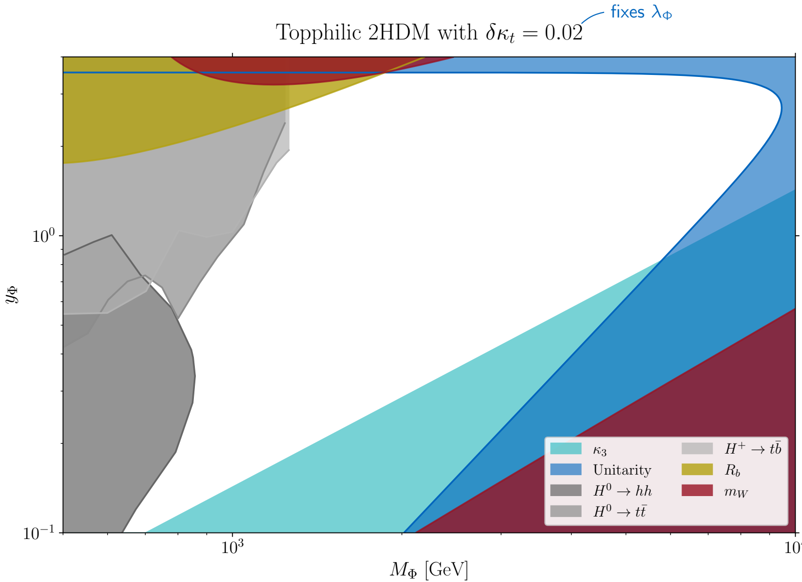

Born, Greljo, **AET** [2604.26817]

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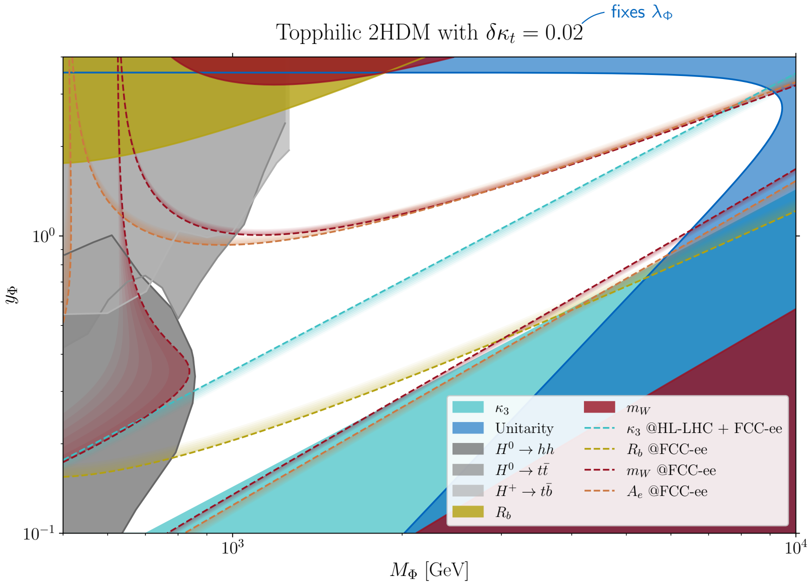

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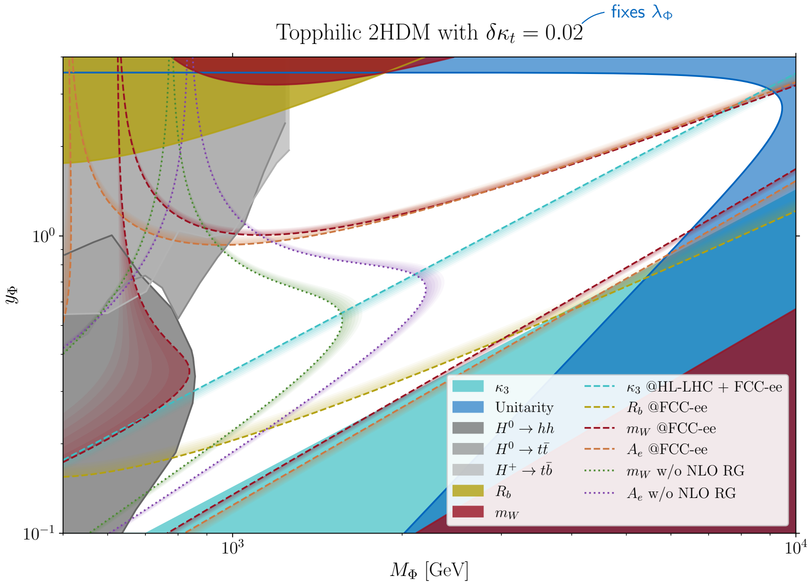
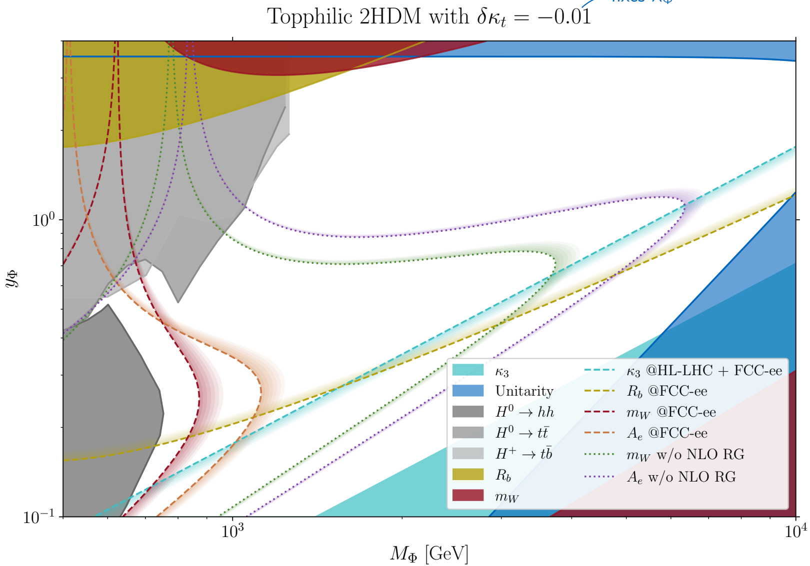


Born, Greljo, **AET** [2604.26817]

parameter space for the top-philic 2HDM

fixes λ_Φ



Born, Greljo, **AET** [2604.26817]

Summary and outlook

- Functional methods provide a strong basis for automated multi-loop calculations of RGEs and matching quantities.
- Results can be adapted to the Warsaw basis at the price of an extra ambiguity
- Remaining ambiguities in the 2-loop SMEFT (such as they are) would have to be resolved in the BMHV scheme: we hope to integrate the code with a BMHV-scheme implementation w/ Adrian Moreno-Sánchez
- Full use of the results will require implementation into SMEFT running codes
- NLO contributions to EWPO can be the best probes of some operators, e.g., C_{tt} and C_{tH}

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Thank you!

Backup

The R-star operation

Any 'diagram' G satisfies

Herzog, Ruijl [1703.03776]

$$\text{finite} = \underbrace{\mathbf{\Delta}}_{\text{counterterm op.}} G + \bar{\boldsymbol{R}}^{*} G = \mathbf{\Delta} G + \sum_{\substack{S \in \overline{W}_{\mathrm{UV}}(G) \\ S' \in W_{\mathrm{IR}}(G) \\ S \cap S' = \emptyset}} \mathbf{\Delta}_{\mathrm{IR}}(S') * \mathbf{\Delta}(S) * G/S \setminus S'$$

The R-star operation

Any ‘diagram’ G satisfies

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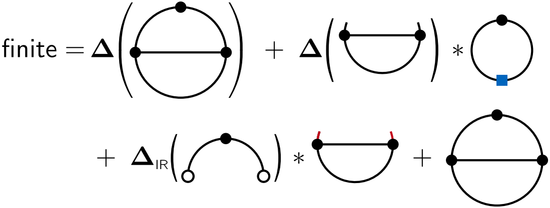
counterterm op.



It is an extension of the $\boldsymbol{R}$ operation, which is used to prove perturbative renormalization

The R-star operation

Any ‘diagram’ G satisfies

Herzog, Ruijl [1703.03776]

$$\text{finite} = \underbrace{\boldsymbol{\Delta}}_{\text{counterterm op.}} G + \bar{\boldsymbol{R}}^* G = \boldsymbol{\Delta} G + \sum_{\substack{S \in \overline{W}_{\mathrm{UV}}(G) \\ S' \in W_{\mathrm{IR}}(G) \\ S \cap S' = \emptyset}} \boldsymbol{\Delta}_{\mathrm{IR}}(S') * \boldsymbol{\Delta}(S) * G/S \setminus S'$$

$$\boldsymbol{\Delta} G = -\underbrace{\boldsymbol{K}}_{\epsilon\text{-pole operator}} \bar{\boldsymbol{R}}^* G$$

The counterterm is polynomial (local)

$$\boldsymbol{\Delta} G = -\boldsymbol{K} \bar{\boldsymbol{R}}^* \underbrace{\boldsymbol{T}^{(\omega(G))}_{\{p_i, m_j^2\}}}_{\text{Taylor expansion}} G$$

IR rearrangement: counterterms are insensitive to momentum routing and masses

$$\boldsymbol{\Delta} G = \boldsymbol{\Delta} G', \qquad \text{for} \quad \omega(G) = 0,\ G' \sim G$$

The R-star operation

Any 'diagram' G satisfies

Herzog, Ruijl [1703.03776]

$$\text{finite} = \underbrace{\mathbf{\Delta}}_{\text{counterterm op.}} G + \bar{\boldsymbol{R}}^* G = \mathbf{\Delta} G + \sum_{\substack{S \in \overline{W}_{\mathrm{UV}}(G) \\ S' \in W_{\mathrm{IR}}(G) \\ S \cap S' = \emptyset}} \mathbf{\Delta}_{\mathrm{IR}}(S') * \mathbf{\Delta}(S) * G/S \setminus S'$$

The counterterm operator $\mathbf{\Delta}$ applied to Γ yields

Counterterm master formula

$$\delta S^{(2)} = \frac{1}{8} \boldsymbol{K} \bar{\boldsymbol{R}}^* \boldsymbol{T} \Big[\mathcal{D}^{(0)}_{IJKL} \mathcal{Q}^{-1}_{IJ} \mathcal{Q}^{-1}_{KL} \Big] - \frac{1}{12} \boldsymbol{K} \bar{\boldsymbol{R}}^* \boldsymbol{T} \Big[\mathcal{C}^{(0)}_{IJK} \mathcal{Q}^{-1}_{IL} \mathcal{Q}^{-1}_{JM} \mathcal{Q}^{-1}_{KN} \mathcal{C}^{(0)}_{LMN} \Big]$$

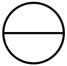
Born, Fuentes-Martín, Kvedaraitė, **AET**: [2410.07320]

- Includes a truncating hard region–like expansion ($\boldsymbol{T}$)
- No need to explicitly calculate counterterm topologies
- *No need to include EOM-vanishing or gauge-violating counterterms!*

R-star in practice

Scaleless integrals do not vanish under the R-star operation

Hard-region expansion

$$-\frac{1}{12}\boldsymbol{K}\bar{\boldsymbol{R}}^*\boldsymbol{T}\Bigg($$  $$\Bigg) \supset -\frac{m^2\lambda^2\phi^2}{4}\boldsymbol{K}\bar{\boldsymbol{R}}^*\int_{k,\ell}\frac{1}{k^4}\frac{1}{\ell^2}\frac{1}{(k+\ell)^2}$$

With **auxiliary mass IR rearrangement**, all IR subdivergences are removed

$$-\frac{m^2\lambda^2\phi^2}{4}\boldsymbol{K}\bar{\boldsymbol{R}}^*\int_{k,\ell}\frac{1}{k^4-a}\frac{1}{\ell^2-a}\frac{1}{(k+\ell)^2-a}$$

$\boldsymbol{K}\bar{\boldsymbol{R}}^*\boldsymbol{T}^{(0)}$ $\qquad\qquad$ i/ϵ

$$-\frac{m^2\lambda^2\phi^2}{4}\boldsymbol{K}\Bigg(\int_{k,\ell}\frac{1}{k^4-a}\frac{1}{\ell^2-a}\frac{1}{(k+\ell)^2-a}+\int_k\frac{1}{k^4-a}\boldsymbol{\Delta}\int_\ell\frac{1}{\ell^2-a}\frac{1}{(k+\ell)^2-a}\Bigg)$$

All dependence on the auxiliary mass vanishes from the counterterm:

$$\delta S^{(2)} \supset \frac{m^2\lambda^2\phi^2}{8}\left(\frac{1}{\epsilon^2}-\frac{1}{\epsilon}\right)$$

Each diagram/graph/integral gives a local counterterm!