Higher-order corrections in SMEFT

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6th LHC EFT WG meeting - 17 November 2023

Outline

- SMEFT precision
  - N(N)LO QCD
  - NLO EW
  - Sensitivity and degeneracies

- Electroweak input parameters and their influence on one-loop calculations in the SMEFT
  - Size of NLO corrections
  - Number of operators appearing at NLO

Based on 2305.03763 with
Benjamin Pecjak, Darren Scott and Tommy Smith

Precision in SMEFT

$$\mathcal{A} = \mathcal{A}_{\text{SM}} + a_i \frac{C_i^{(6)}}{\Lambda^2}$$

Precision in SMEFT

[Trott (2106.13794)]

$$\mathcal{A} = \mathcal{A}_{\rm SM} + a_i \frac{C_i^{(6)}}{\Lambda^2} + b_{jk} \frac{C_j^{(6)} C_k^{(6)}}{\Lambda^4} + c_l \frac{C_l^{(8)}}{\Lambda^4} + \frac{1}{16\pi^2} \left[d_m \frac{C_m^{(6)}}{\Lambda^2} + e_n \frac{C_n^{(6)}}{\Lambda^2} \log\left(\frac{\mu^2}{\Lambda^2}\right) \right] + \cdots$$

Precision in SMEFT

Dim6^2 effects

Dim8 effects

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SMEFT@NLO

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New sensitivities + new degeneracies

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New sensitivities + new degeneracies

Dim8 effects

[Ellis, Mimasu, Zampedri (2304.06663)]

[Corbett, Desai, Eboli, Gonzalez-Garcia, Martines, Reimitz (2304.03305)]

[Degrande, Li (2303.10493)]

[Dawson, Fontes, Houiller, Sullivan (2205.01561)]

SMEFT truncation, Dim6^2

[Heinrich, Lang (2212.00711)]

[Asteriadis, Dawson, Fontes (2212.03258)]

geoSMEFT

[Corbett, Martin (2306.00053)]

[Martin, Trott (2305.05879)]

Precision in SMEFT

RG running (beyond one loop)
[Aoude, Maltoni, Mattelaer, Severi, Vryonidou (2212.05067)]
[Bern, Parra-Martinez, Sawyer (2005.12917)]
[Cao, Herzog, Melia, Roosmale Nepveu (2303.07391)]
[Jenkins, Manohar, Naterop, Pagès (2310.19883)]

Dim6^2 effects
Dim8 effects

SMEFT@NLO

[Trott (2106.13794)]

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N(N)LO QCD effects

+ extensive preparatory work!

See also summary in [Durieux (HEFT2023)]

- In MC generators
  - Vh [Alioli, (Cirigliano), Dekens, (de Vries, Girard), Merghetti (1703.04751), (1804.07407)]
  - hh [Heinrich, (Jang), (Jones), (Kerner), Scyboz (2006.16877), (2204.13045)]
  - WW/WZ [Baglio, Dawson, (Homiller), (Lewis) (1812.00214), (1909.11576)], […]
- NLO QCD automated [Degrande, Durieux, Maltoni, Mimasu, Vryonidou, Zhang (2008.11743)]
  - $gg \to hh/Zh/ZZ/WW$ [Rossia, Thomas, Vryonidou (2306.09963)]
  - […]

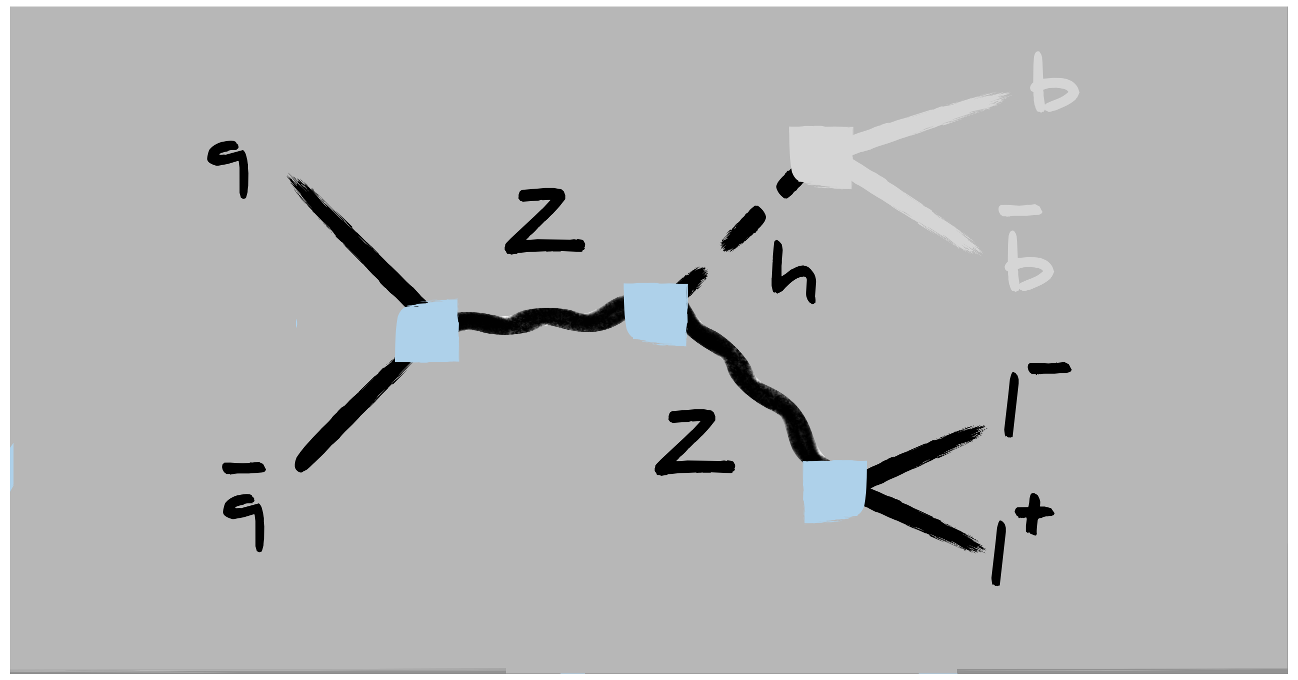
See [Marion's talk (LHC EFT/Higgs WG)]

- NNLO QCD SMEFT results
  - $pp \to Zh \to \ell^+\ell^- b\bar{b}$ (6 ops) [Haisch, Scott, Wesemann, Zanderighi, Zanoli (2204.00663)], (17 ops) [Gauld, Haisch, Schnell (2311.06107)]
  - $t\bar{t}$ (1 op) [Kidonakis, Tonero (2309.16758)]

NNLO QCD effects in Vh

[Gauld, Haisch, Schnell (2311.06107)]

[Luc's talk at (Higgs WG)]

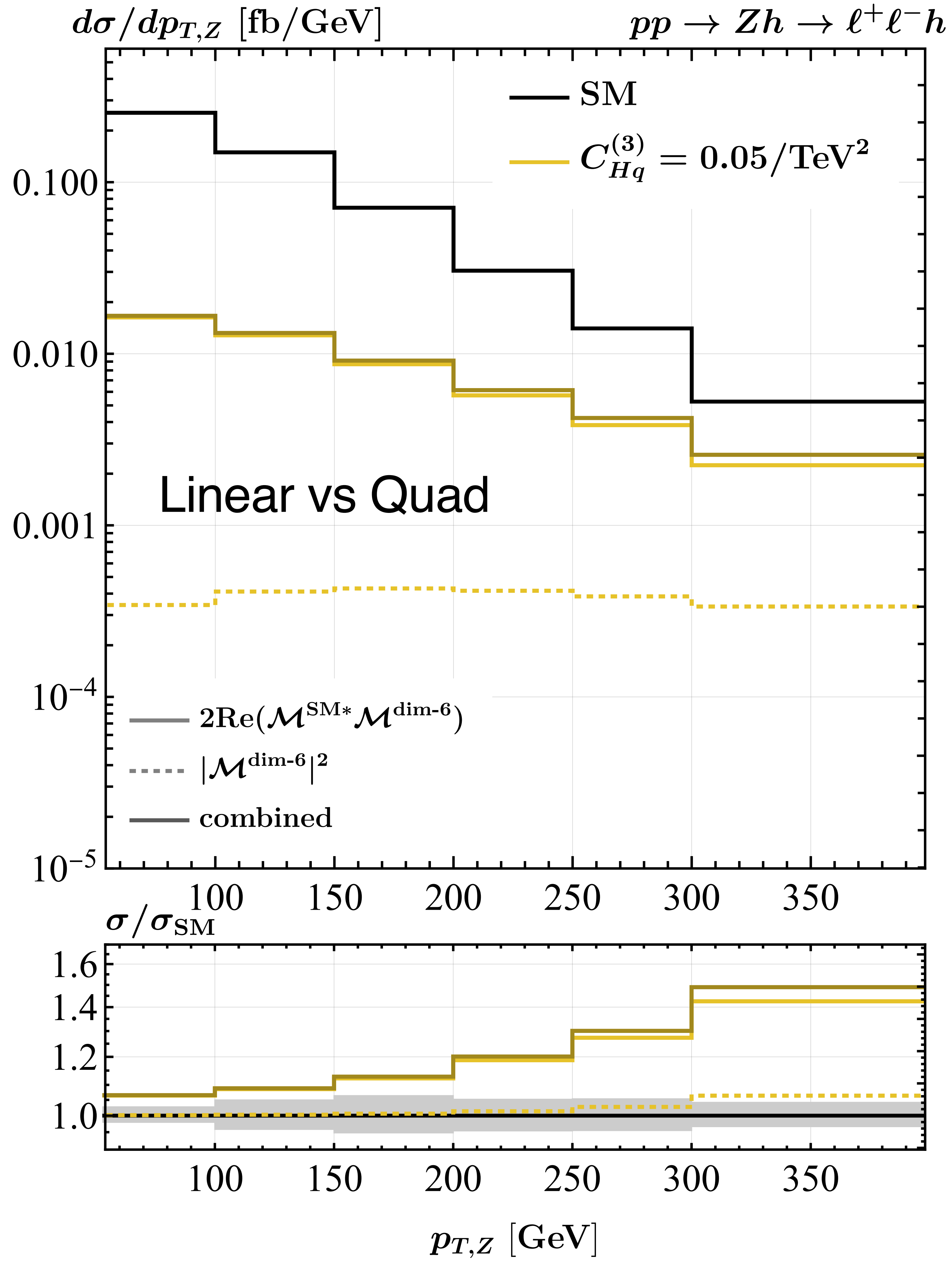


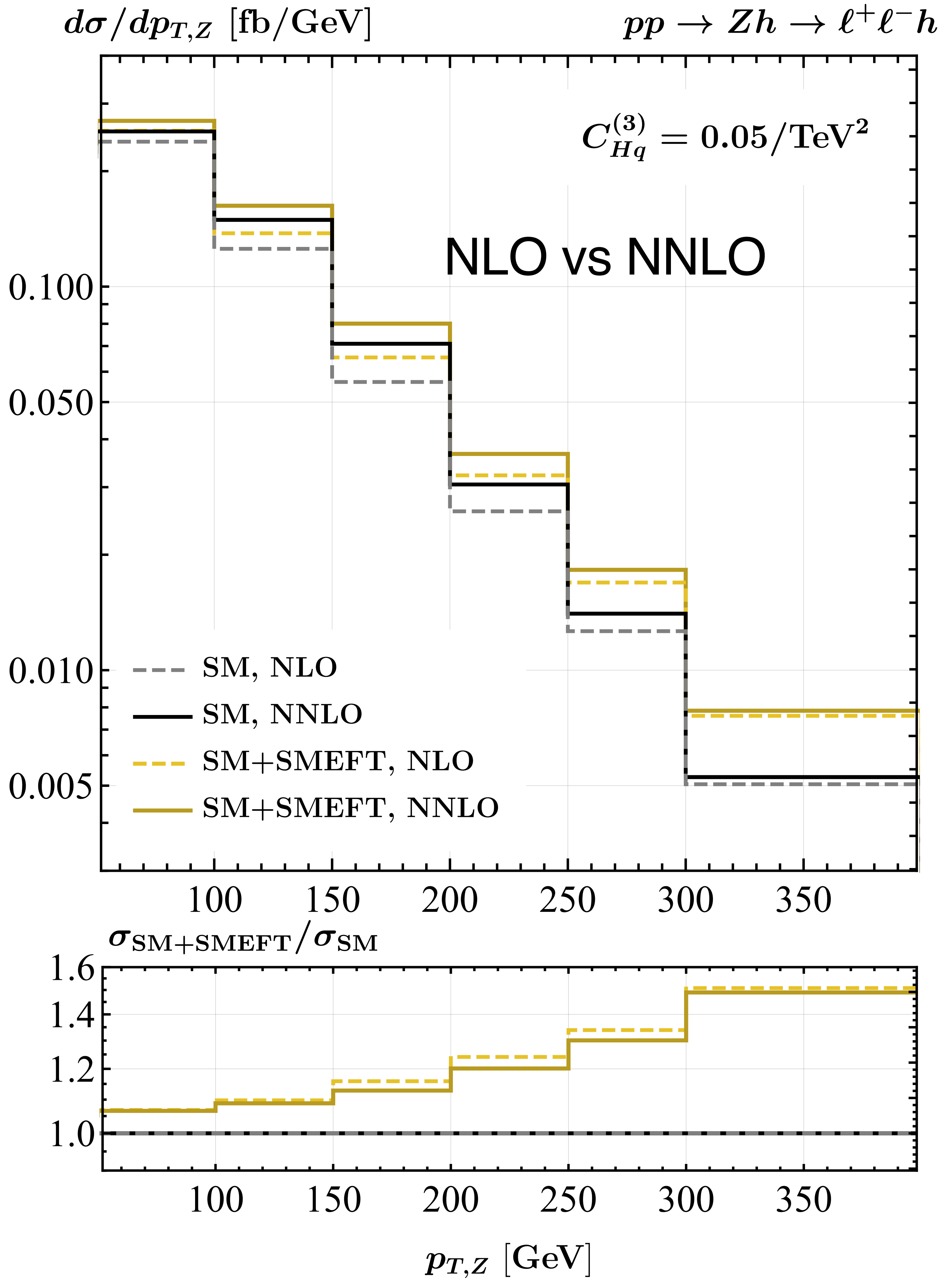
[Haisch, Scott, Wesemann, Zanderighi, Zanoli (2204.00663)]

[Gauld, Haisch, Schnell (2311.06107)]

Linear and quadratic SMEFT contributions in three different EW input schemes

NLO QCD: [Alioli, Dekens, Girard, Mereghetti (1804.07407)]





NLO EW effects

- EWPO [(Bellafronte), Dawson, Giardino (1909.02000), (2201.09887), (2304.00029)],
  Partial results: [Hartmann, Shepherd, Trott (1611.09879)], [Biekötter, Pecjak, Scott, Smith (2305.03763)]
- $h \to b\bar{b}$ [(Cullen), (Gauld), Peciak, Scott (1904.06358), (1607.06354), (1512.02508)]
- $h \to \gamma\gamma$ [Dawson, Giardino (1807.11504); Dedes et al. (1805.00302); Hartmann, Trott (1507.03568), (1505.02646)]
- $h \to \gamma Z$ [Corbett, Rasmussen (2110.03694)]
  On-shell: [Dawson, Giardino (1801.01136); Dedes, Suxho, Trifyllis (1903.12046)]
- $h \to ZZ$ [Dawson, Giardino (1801.01136)]
- $h \to WW$ [Dawson, Giardino (1807.11504)]
- Drell-Yan (partial) [Dawson, Giardino, Ismail (1811.12260)]
- $pp \to t\bar{t}/t\bar{t}H/tH$ [Martini, (Pan), Schulze, (Xiao) (1911.11244), (2104.04277)]
- 4-quark ops in $gg \to h,\ h \to b\bar{b},\ pp \to t\bar{t}h$ [Alasfar, de Blas, Gröber (2202.02333)]

NLO EW effects

How large are the NLO effects?

How are NLO degeneracies affecting global fit results?

- EWPO [(Bellafronte), Dawson, Giardino (1909.02000), (2201.09887), (2304.00029)],
  Partial results: [Hartmann, Shepherd, Trott (1611.09879)], [Biekötter, Pecjak, Scott, Smith (2305.03763)]
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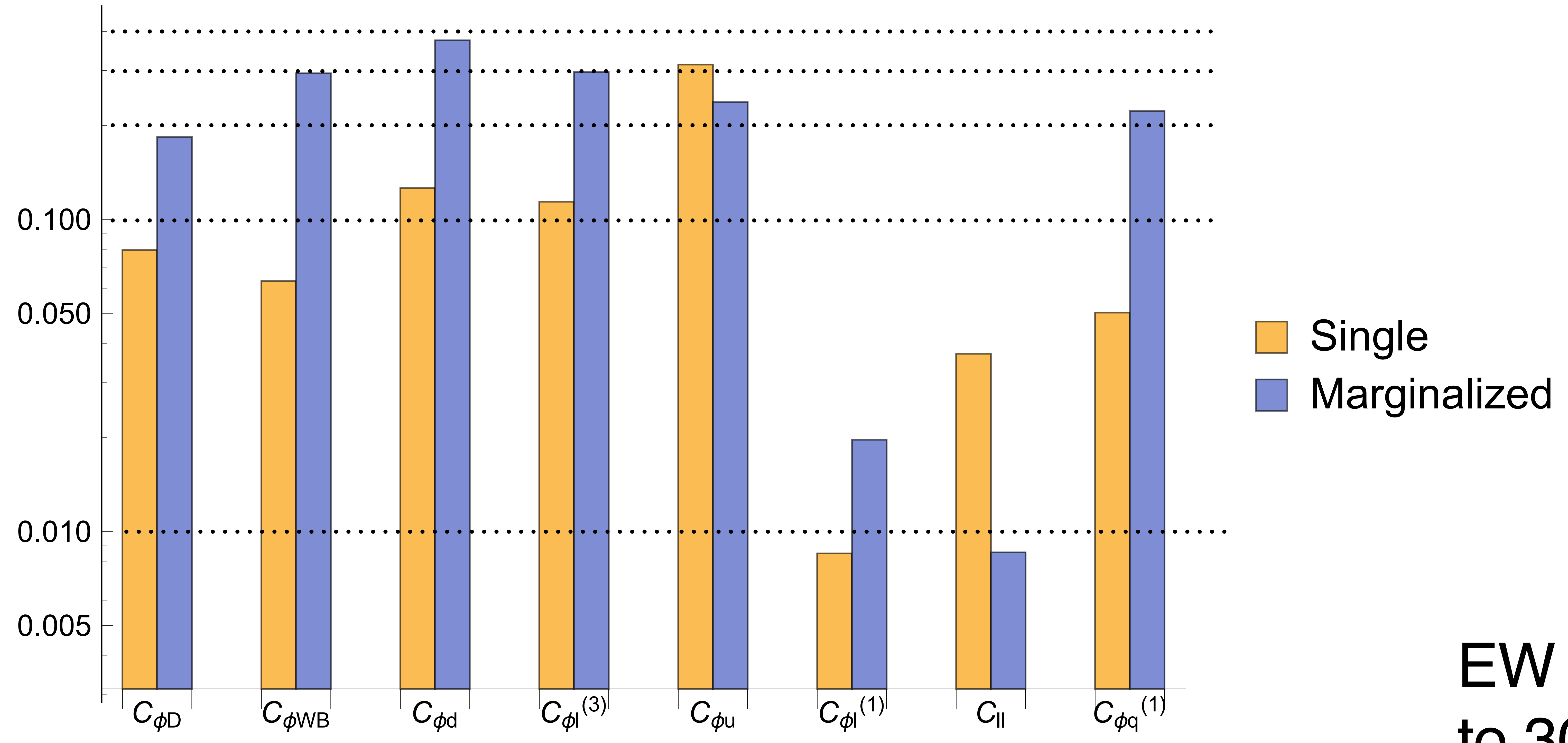
Size of NLO SMEFT effects in EWPO

[Dawson, Giardino (1909.02000)]
[Giardino (HEFT2020)]

$$\left|\frac{\mathscr{C}^{\mathrm{NLO}} - \mathscr{C}^{\mathrm{LO}}}{\mathscr{C}^{\mathrm{LO}}}\right|$$



(8-parameter fit)

EW corrections cause up to 30% effects in fits!

NLO degeneracies

EWPO: 10 ops @LO, 32 ops @NLO
(suppressing flavour indices)

[Dawson, Giardino (1909.02000)]

$$\delta\Gamma(Z \to l^+l^-)^{LO} = \frac{v^2}{\Lambda^2}\Big\{-0.1408\mathcal{C}_{\phi e} + 0.191\mathcal{C}^{(1)}_{\phi l} - 0.037\mathcal{C}^{(3)}_{\phi l} + 0.114\mathcal{C}_{ll} - 0.057\mathcal{C}_{\phi D} -0.0713\mathcal{C}_{\phi WB}\Big\}\ \mathrm{GeV}$$

$$\delta\Gamma(Z \to l^+l^-)^{NLO} = \frac{v^2}{\Lambda^2}\Big\{-0.1596\mathcal{C}_{\phi e} + 0.1834\mathcal{C}^{(1)}_{\phi l} - 0.0221\mathcal{C}^{(3)}_{\phi l} + 0.0985\mathcal{C}_{ll} - 0.0508\mathcal{C}_{\phi D} -0.0349\mathcal{C}_{\phi WB} - 0.0001\mathcal{C}_{\phi W} - 0.0002\mathcal{C}_{ed} - 0.0005\mathcal{C}_{ee} + 0.0035\mathcal{C}_{eu} -0.0002\mathcal{C}_{\phi d} - 0.0042\mathcal{C}^{(1)}_{\phi q} + 0.0032\mathcal{C}^{(3)}_{\phi q} + 0.0049\mathcal{C}_{\phi u} + 0.0002\mathcal{C}_{ld} +0.0001\mathcal{C}_{le} + 0.0034\mathcal{C}^{(1)}_{lq} - 0.0031\mathcal{C}^{(3)}_{lq} - 0.0045\mathcal{C}_{lu} - 0.0001\mathcal{C}_{\phi\Box} -0.0027\mathcal{C}_{qe} - 0.0007\mathcal{C}_{uB} - 0.0007\mathcal{C}_{uW} - 0.0001\mathcal{C}_{W}\Big\}\ \mathrm{GeV}$$

NLO degeneracies

Assuming a $U(3)^5$ symmetry at the high scale

EWPO+Higgs+Top+Dijets+Flavour+Drell-Yan

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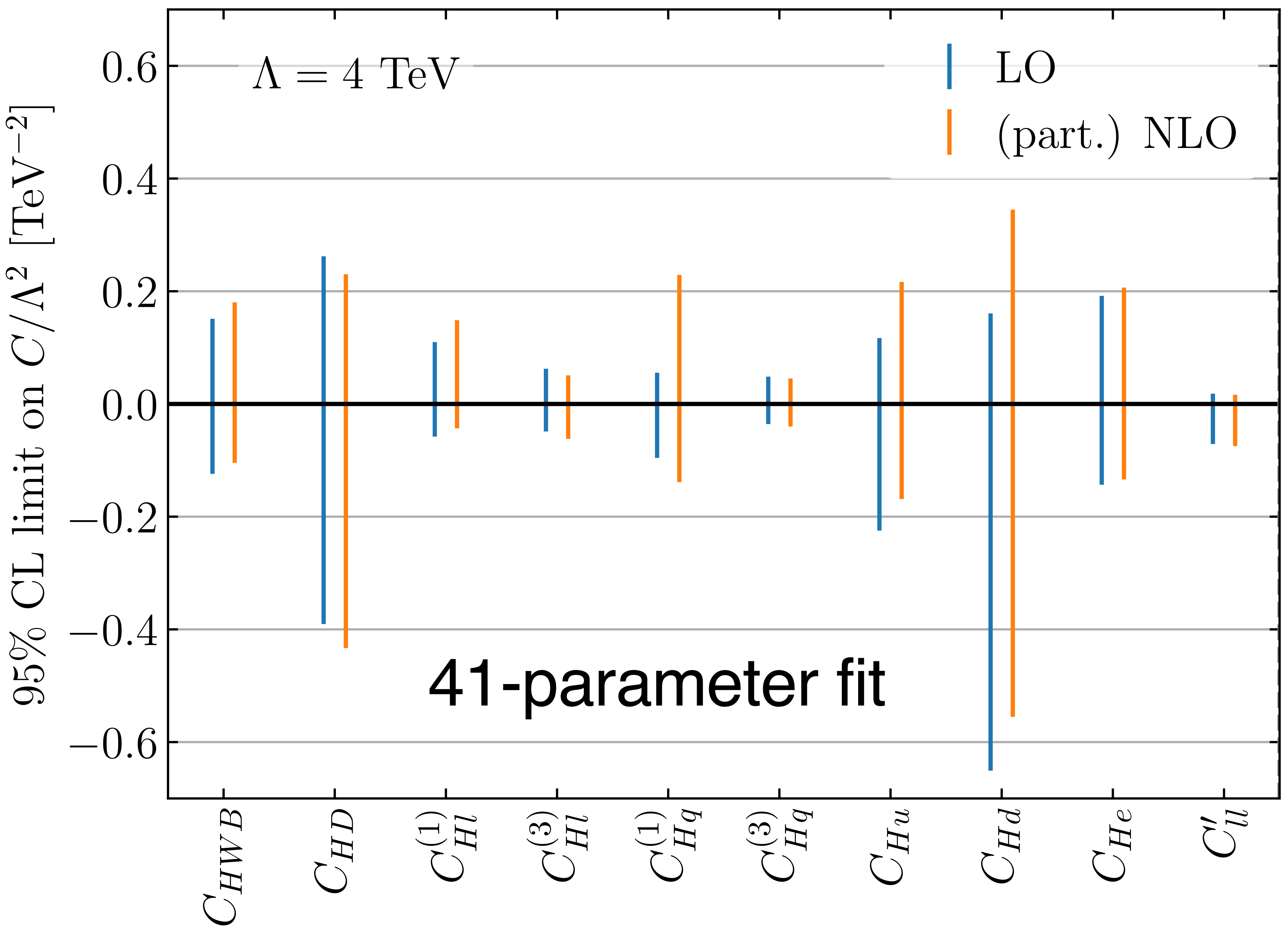
[Bartocci, AB, Hurth (2311.04963)]



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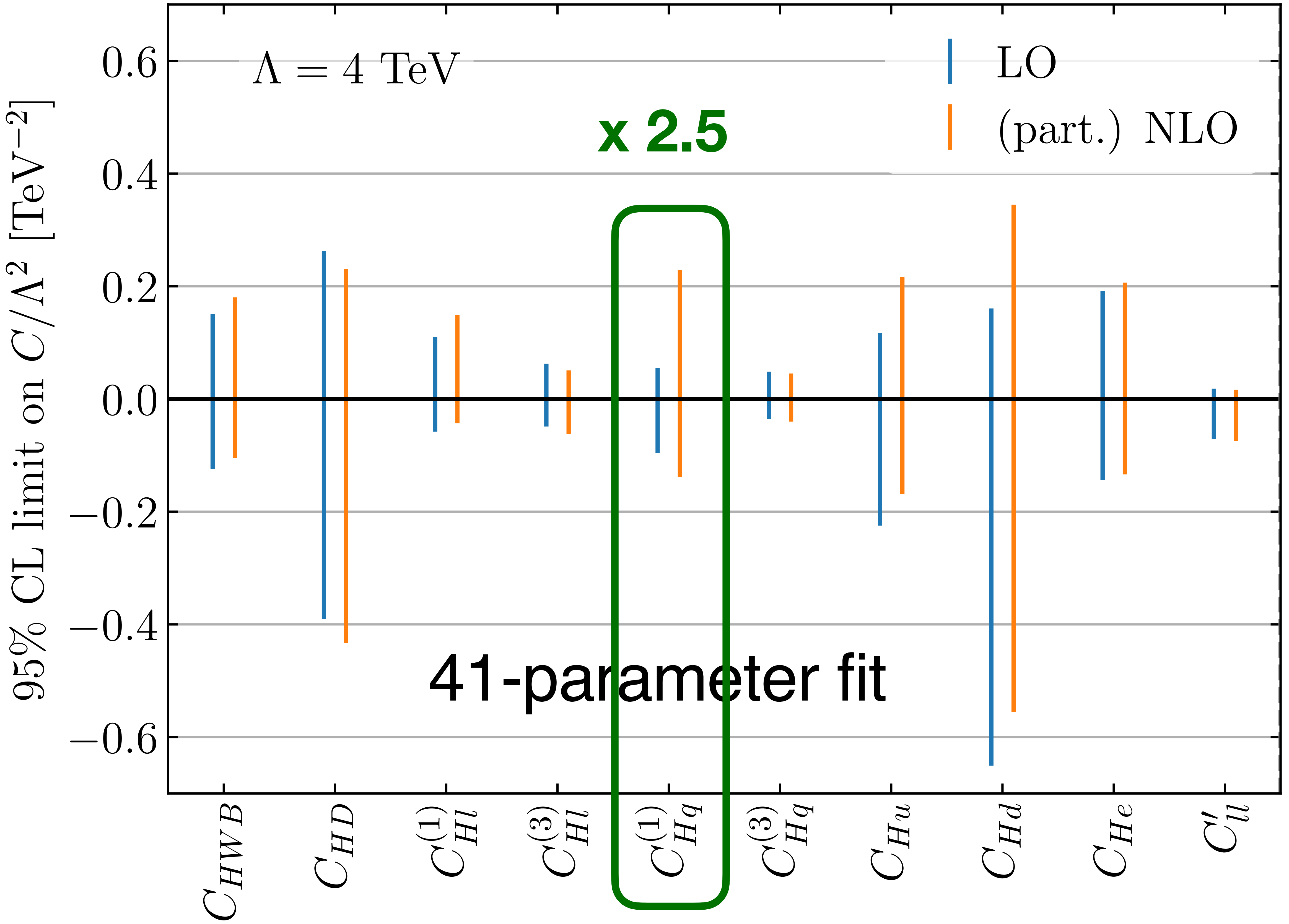

NLO degeneracies

Higgs self coupling [Alasfar, de Blas, Gröber (2202.02333)]

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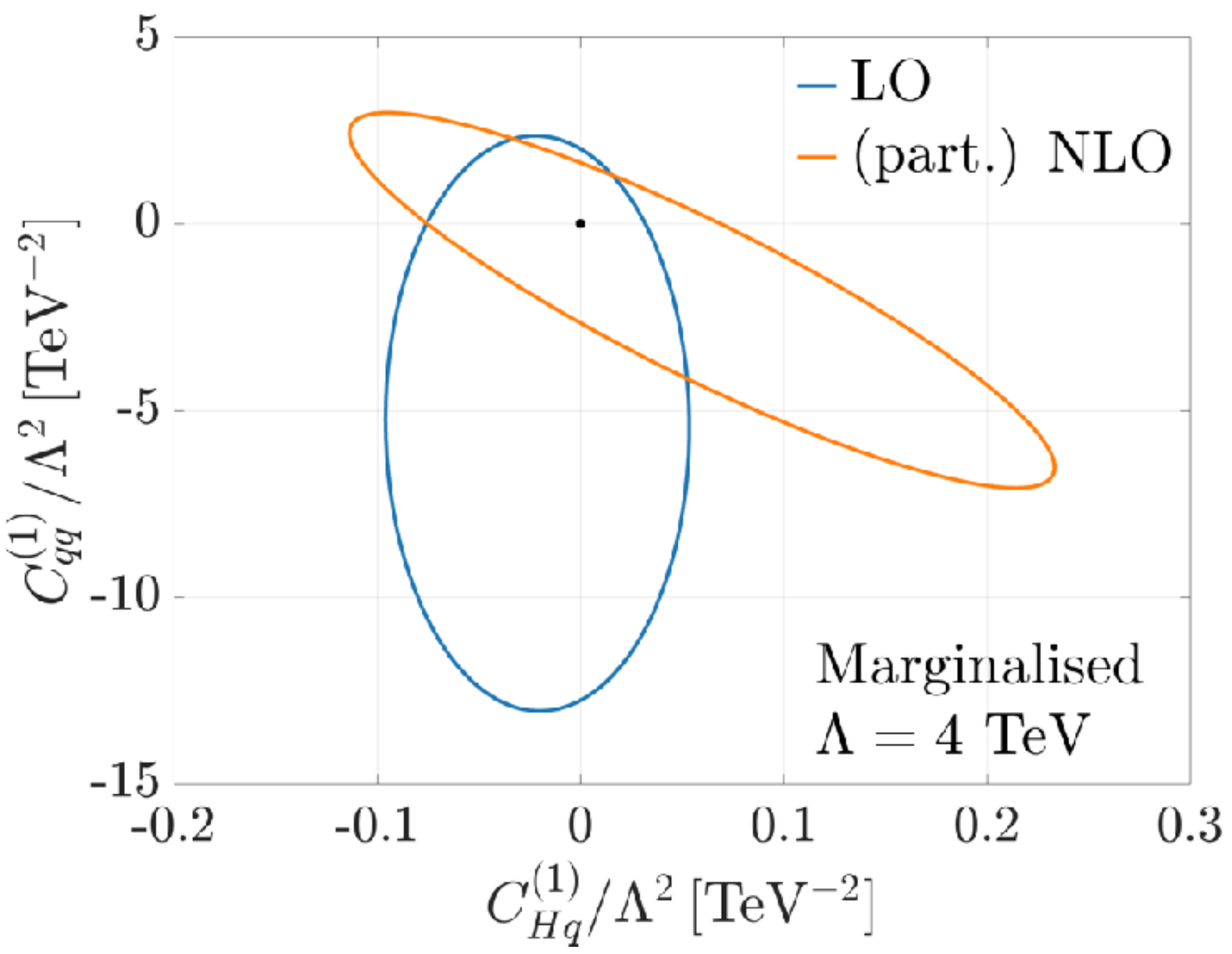

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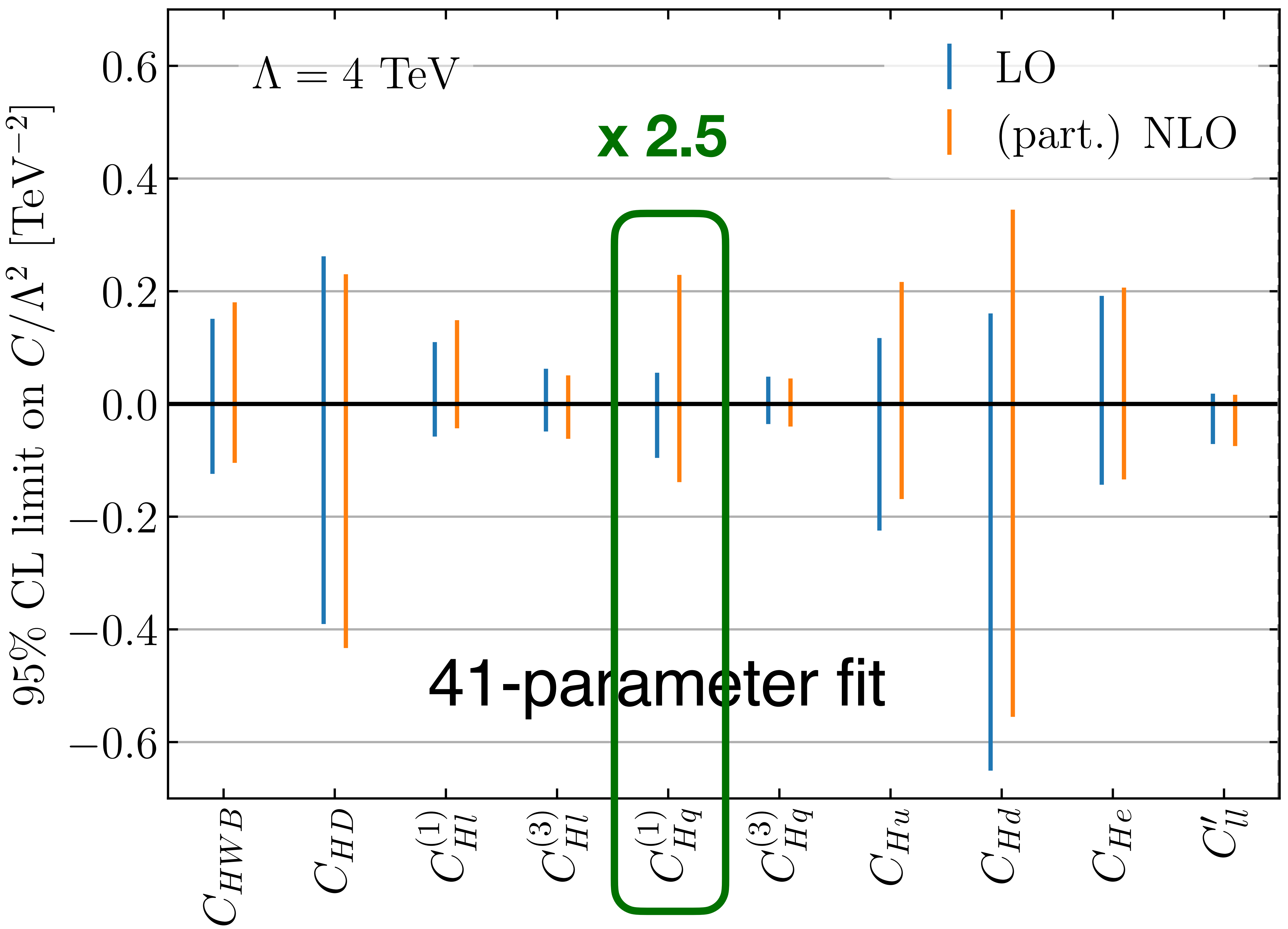

Electroweak input schemes in SMEFT

Based on 2305.03763 with
Benjamin Pecjak, Darren Scott and Tommy Smith

  

Input schemes

[Brivio et al. (2111.12515)]

WG note recommends $\{G_F,\, M_W,\, M_Z\}$

- Lagrangian written in terms of $\{g_1,\, g_w,\, v\}$
- Choice of input parameters

$$\{g_1,\, g_w,\, v\} \to \{\text{input 1, input 2, input 3}\}$$

- Typical choices

M_W	$80.433(9)$ GeV
M_Z	$91.1876(21)$ GeV
G_F	$1.1663797(6)\ \times 10^{-5}$ GeV^2
$\alpha(M_Z)$	$0.007127(2)$

Considerations:

- Number of Wilson coefficients appearing

  (at LO and at higher orders)
- **Convergence in term of the Wilson coefficients**

Meet the schemes

- **The α_μ scheme -** $\{G_F,\, M_W,\, M_Z\}$
  - M_W and M_Z are renormalised on-shell
  - G_F is renormalised through muon decay
  - Sometimes called "M_W scheme" in the SMEFT
- **The α scheme -** $\{\alpha,\, M_W,\, M_Z\}$
  - M_W and M_Z are renormalised on-shell
  - α is renormalised in $\overline{\mathrm{MS}}$-lite scheme [Cullen, Pecjak, Scott (1904.06358)]
- **The LEP scheme -** $\{\alpha,\, G_F,\, M_Z\}$
  - Inputs renormalised as above
  - Sometimes called "α scheme" in the SMEFT

- Wilson coefficients renormalised in $\overline{\mathrm{MS}}$ scheme

The α_μ vs α schemes

α_μ scheme

- Inputs $\{G_F,\, M_W,\, M_Z\}$
- G_F or v_μ is renormalised by requiring that Fermi decay is exact to all orders

$$\frac{1}{v_{T,0}^2} = \frac{1}{v_\mu^2}\left[1 - v_\mu^2 \Delta v^{(6,0,\mu)} - \frac{1}{v_\mu^2}\Delta v_\mu^{(4,1,\mu)} - \Delta v_\mu^{(6,1,\mu)}\right]$$

Tree-level SMEFT	One-loop SM	One-loop SMEFT

The α_μ vs α schemes

α_μ scheme

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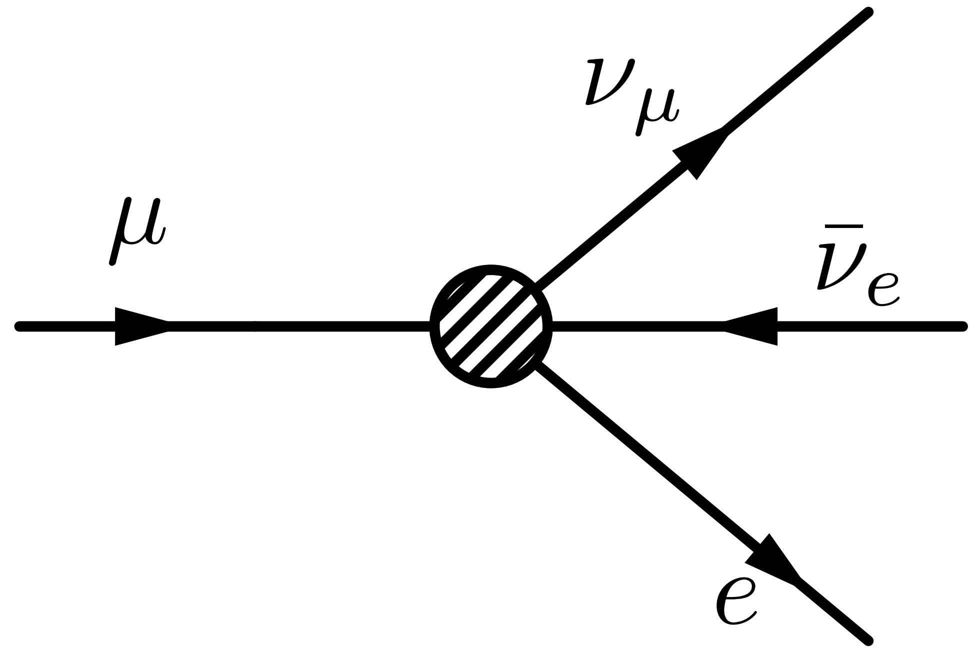
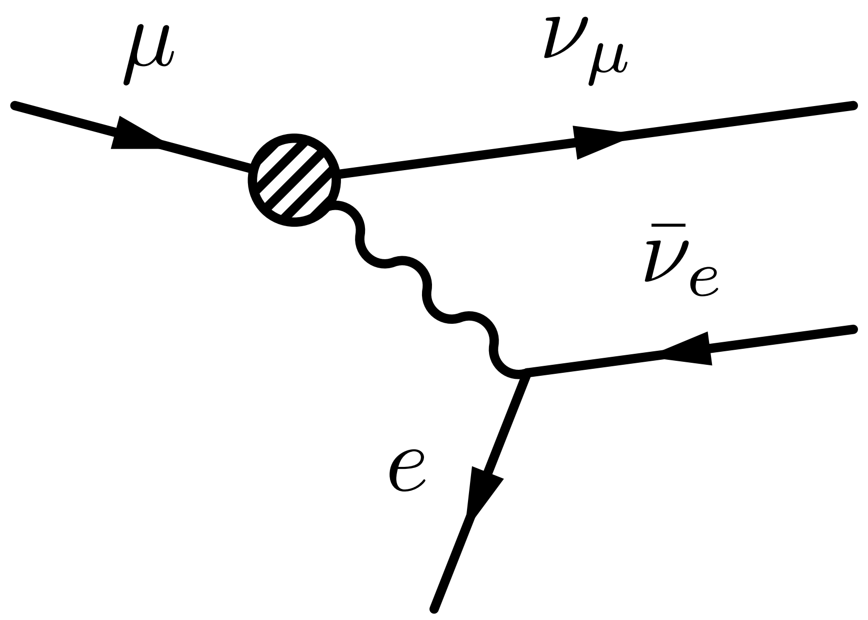




$$\frac{1}{v_{T,0}^2} = \frac{1}{v_\mu^2}\left[1 - \boxed{v_\mu^2 \Delta v^{(6,0,\mu)}} - \frac{1}{v_\mu^2}\Delta v_\mu^{(4,1,\mu)} - \Delta v_\mu^{(6,1,\mu)}\right]$$

Tree-level	One-loop	One-loop
SMEFT	SM	SMEFT

$$\Delta v^{(6,0,\mu)} = C_{\substack{Hl\\11}}^{(3)} + C_{\substack{Hl\\22}}^{(3)} - C_{\substack{ll\\1221}}$$

The α_μ vs α schemes

α_μ scheme

- Inputs $\{G_F,\, M_W,\, M_Z\}$
- G_F or v_μ is renormalised by requiring that Fermi decay is exact to all orders

$$\frac{1}{v_{T,0}^2} = \frac{1}{v_\mu^2}\left[1 - \boxed{v_\mu^2 \Delta v^{(6,0,\mu)}} - \frac{1}{v_\mu^2}\Delta v_\mu^{(4,1,\mu)} - \Delta v_\mu^{(6,1,\mu)}\right]$$

Tree-level SMEFT | One-loop SM | One-loop SMEFT

α scheme

- Inputs $\{\alpha,\, M_W,\, M_Z\}$
- Differs from the α_μ scheme through the way we renormalise the vev
- v_α is a derived parameter

$$v_\alpha = \frac{2M_W s_W}{\sqrt{4\pi\alpha}}$$

$$\frac{\delta v_\alpha}{v_\alpha} \equiv \frac{\delta M_W}{M_W} + \frac{\delta s_W}{s_W} - \frac{\delta e}{e}$$

$$\frac{v_\alpha^2}{v_\mu^2} \equiv 1 + \Delta r$$

NLO corrections

- Process dependent pieces and scheme dependent pieces
- Counterterms contain tadpoles and divergences ⊖

Physical processes

- Tadpole and divergence free ⊕
- Look at decay rates
  - $W \to l\nu_l$
  - $Z \to l^+l^-$
  - $H \to b\bar{b}$

[Dawson, Giardino (1909.02000), (2201.09887)]

$$\Gamma^{(4,0)}_{W\tau\nu} = \frac{M_W}{12\pi}\frac{M_W^2}{v_T^2}$$

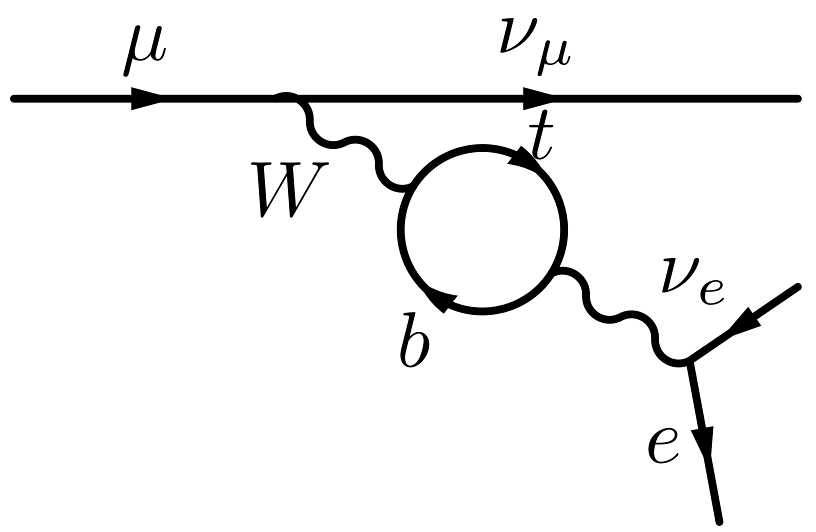
[Cullen, Pecjak, Scott (1512.02508)]

Large-MT corrections for W decay - SM

$$\left.\frac{M_{W,0}^2}{v_{T,0}^2} z_W\right|_{m_t\to\infty} \equiv \frac{M_W^2}{v_\sigma^2}\left[1 + v_\sigma^2 K_W^{(6,0,\sigma)} + \frac{1}{v_\sigma^2} K_W^{(4,1,\sigma)} + K_W^{(6,1,\sigma)}\right]$$

Tadpole and divergence free

$$K_W^{(4,1,\sigma)} = -\Delta v_{\sigma,t}^{(4,1,\sigma)} + 2\Delta M_{W,t}^{(4,1)}$$

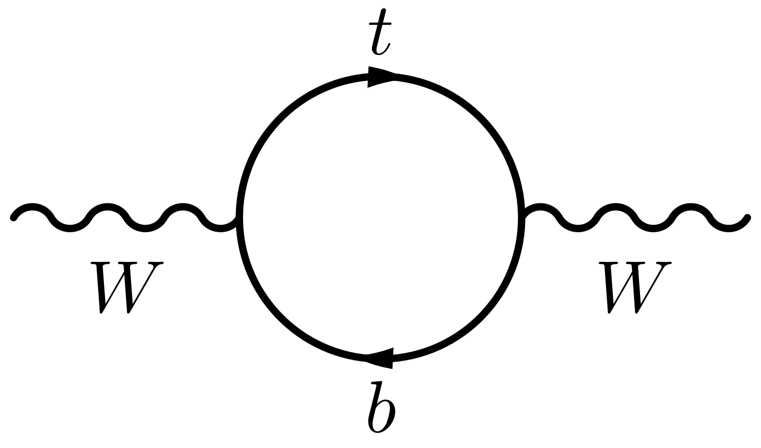


α $\quad K_W^{(4,1,\alpha)} = \Delta r_t^{(4,1)} \approx -3.4\%$

α_μ $\quad K_W^{(4,1,\mu)} = 0$

LEP $\quad \hat{K}_W^{(4,1,\mu)} = -\frac{s_w^2}{c_{2w}} \Delta r_t^{(4,1)} \approx 1.5\%$

$W \to \tau\nu_\tau$	SM
α	-4.2%
α_μ	-0.3%
LEP	2.0%



$$\frac{v_\alpha^2}{v_\mu^2} \equiv 1 + \Delta r$$

Corrections for W decay - SMEFT

$W \to \tau\nu_\tau$	SM	C_{HD}	C_{HWB}	$C^{(3)}_{\substack{Hl\\jj}}$	$C^{(3)}_{\substack{Hl\\33}}$	$C_{\substack{ll\\1221}}$
α	-4.2%	-1.7%	-3.0%	—	2.2%	—
α_μ	-0.3%	—	—	2.5%	2.2%	-0.2%
LEP	2.0%	8.1%	3.2%	5.1%	4.6%	2.5%

$$\Gamma^{(4,0)}_{W\tau\nu} + \Gamma^{(6,0)}_{W\tau\nu} = \frac{M_W}{12\pi}\frac{M_W^2}{v_T^2}\left(1 + 2v_T^2 C^{(3)}_{\substack{Hl\\33}}\right)$$

Corrections for W decay - SMEFT

$W \to \tau\nu_\tau$	SM	C_{HD}	C_{HWB}	$C^{(3)}_{\substack{Hl\\jj}}$	$C^{(3)}_{\substack{Hl\\33}}$	$C_{\substack{ll\\1221}}$
α	-4.2%	-1.7%	-3.0%	—	2.2%	—
α_μ	-0.3%	—	—	2.5%	2.2%	-0.2%
LEP	2.0%	8.1%	3.2%	5.1%	4.6%	2.5%

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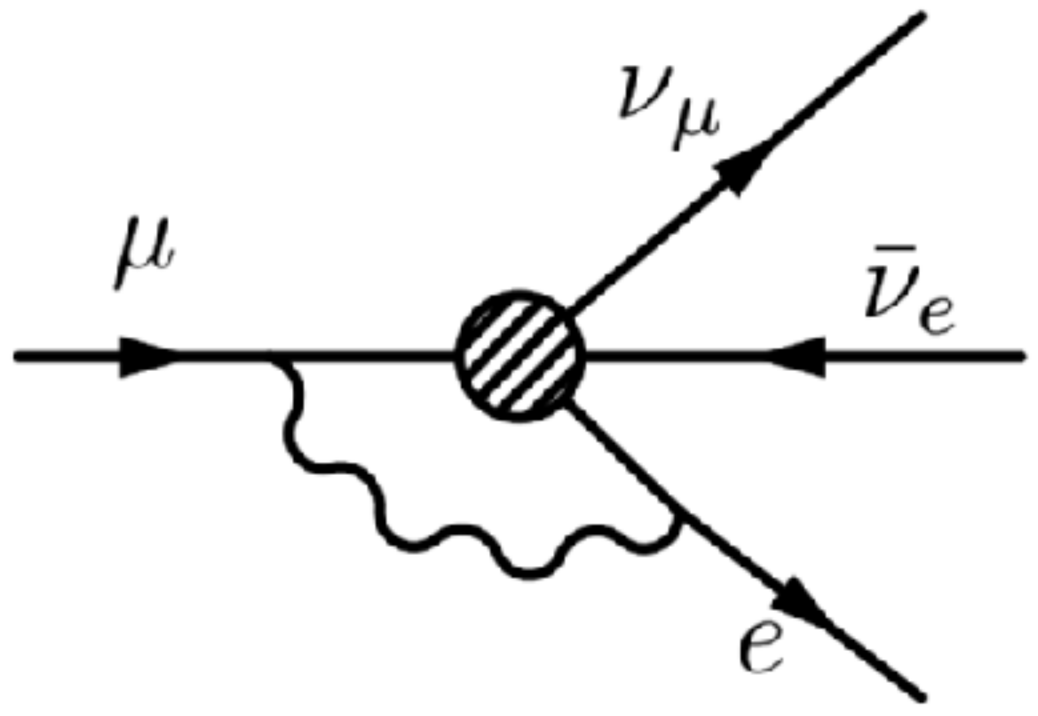
No large MT contribution



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No vT dependence

$$\Gamma^{(4,0)}_{W\tau\nu} + \Gamma^{(6,0)}_{W\tau\nu} = \frac{M_W}{12\pi}\frac{M_W^2}{v_T^2}\left(1 + 2v_T^2 C^{(3)}_{\substack{Hl\\33}}\right)$$

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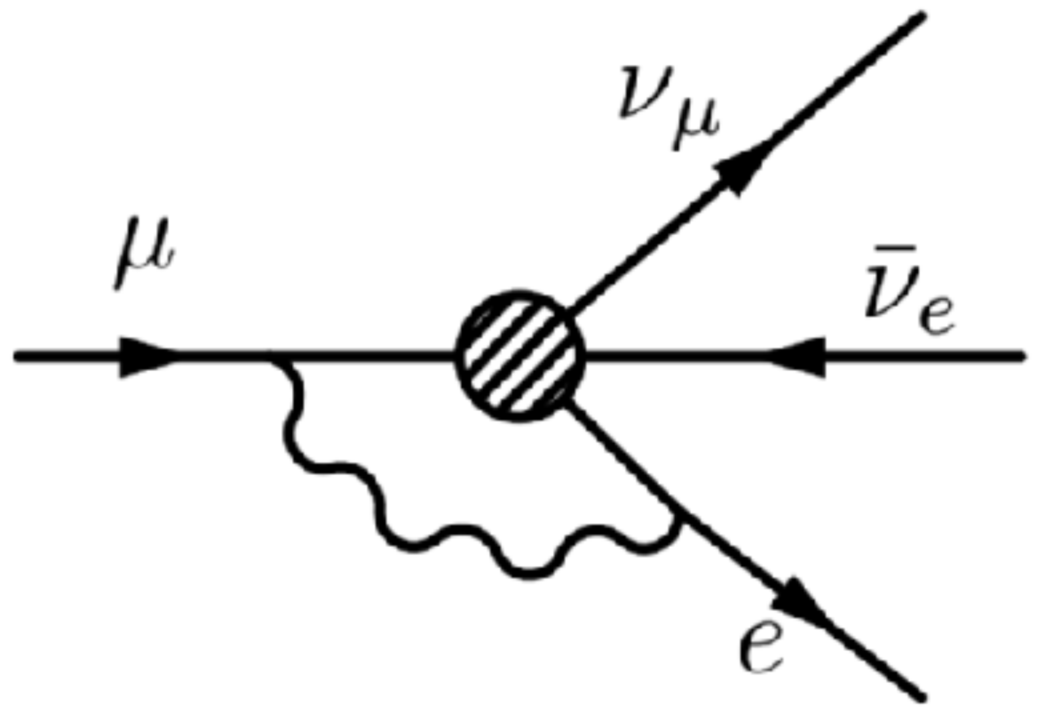

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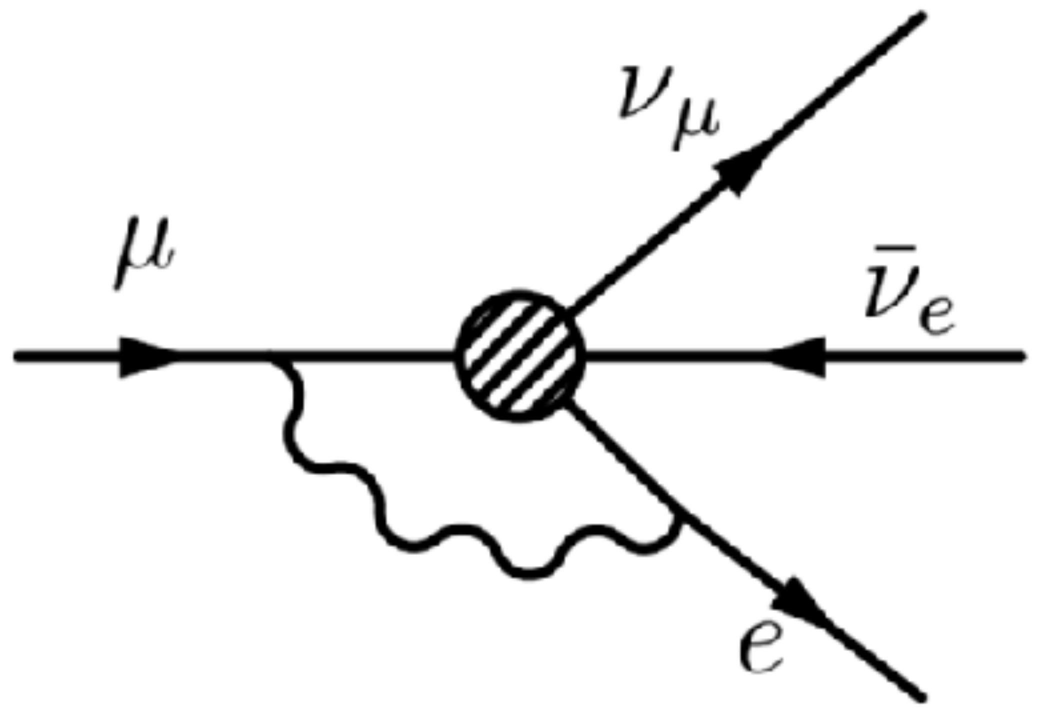
No vT dependence

Similar MW dependence

$$\Gamma^{(4,0)}_{W\tau\nu} + \Gamma^{(6,0)}_{W\tau\nu} = \frac{M_W}{12\pi}\frac{M_W^2}{v_T^2}\left(1 + 2v_T^2 C^{(3)}_{\substack{Hl\\33}}\right)$$

No large MT contribution



H decay α scheme - SMEFT

$$\Gamma^s_{hb\bar{b}}\Big|_{m_t\to\infty} = \frac{3m_b^2 M_H}{8\pi v_\sigma^2}\Big[1 + v_\sigma^2\left(K_H^{(6,0)} + K_W^{(6,0,\sigma)}\right) + \frac{1}{v_\sigma^2}\left(K_H^{(4,1)} + K_W^{(4,1,\sigma)}\right)$$

$$+ K_H^{(6,1)} + \Delta K_H^{(6,1,\sigma)}\Big]$$

H decay α scheme - SMEFT

Scheme independent

$$\Gamma^{s}_{hb\bar{b}}\Big|_{m_t\to\infty} = \frac{3m_b^2 M_H}{8\pi v_\sigma^2}\left[1 + v_\sigma^2\left(K_H^{(6,0)} + K_W^{(6,0,\sigma)}\right) + \frac{1}{v_\sigma^2}\left(K_H^{(4,1)} + K_W^{(4,1,\sigma)}\right) + K_H^{(6,1)} + \Delta K_H^{(6,1,\sigma)}\right]$$

Scheme dependent

H decay α scheme - SMEFT

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Scheme dependent

$$\Delta K_H^{(6,1,\sigma)} = K_W^{(6,1,\sigma)} + 2K_H^{(4,1)}K_W^{(6,0,\sigma)} + \frac{1}{\sqrt{2}}\frac{v_\sigma}{m_b}K_W^{(4,1,\sigma)}C_{\substack{dH\\33}}$$

H decay α scheme - SMEFT

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$$\Delta K_H^{(6,1,\sigma)} = K_W^{(6,1,\sigma)} + 2K_H^{(4,1)} K_W^{(6,0,\sigma)} + \frac{1}{\sqrt{2}}\frac{v_\sigma}{m_b} K_W^{(4,1,\sigma)} C_{\substack{dH\\33}}$$

$$\frac{1}{v_\alpha^2}\left(K_H^{(6,1)} + \Delta K_H^{(6,1,\alpha)}\right) = \Big\{ - C_{HD}(1.6 + 9.7) + (0.0 - 17)C_{HWB} - (3.7 + 6.8)C^{(3)}_{\substack{Hq\\33}} + (0.0 - 8.8)(C_{\substack{Hu\\33}} - C^{(1)}_{\substack{Hq\\33}}) + (0.0 - 3.1)C_{\substack{uB\\33}} + (-4.6 + 0.42)C_{\substack{uW\\33}} - \frac{\sqrt{2}v_\alpha}{m_b}(1.8 + 1.7)\, C_{\substack{dH\\33}}\Big\} \times 10^{-2} + \ldots$$

Scheme dependent corrections larger in most cases

H decay α scheme - SMEFT

Scheme independent

$$\Gamma^{s}_{hb\bar{b}}\Big|_{m_t\to\infty} = \frac{3m_b^2 M_H}{8\pi v_\sigma^2}\left[1 + v_\sigma^2\left(K_H^{(6,0)} + K_W^{(6,0,\sigma)}\right) + \frac{1}{v_\sigma^2}\left(K_H^{(4,1)} + K_W^{(4,1,\sigma)}\right) + K_H^{(6,1)} + \Delta K_H^{(6,1,\sigma)}\right]$$

Scheme dependent

$$\Delta K_H^{(6,1,\sigma)} = K_W^{(6,1,\sigma)} + 2K_H^{(4,1)}K_W^{(6,0,\sigma)} + \frac{1}{\sqrt{2}}\frac{v_\sigma}{m_b}K_W^{(4,1,\sigma)}C_{\substack{dH\\33}}$$

$\frac{1}{v_\alpha^2}$

$- ($ … $2)C_{\substack{uW\\33}}$

$-$ … m_b … $33)$

SMEFT corrections come from several sources but some are common to all processes.

Scheme dependent corrections larger in most cases

Why should I care? Resummation!

- Knowing where the NLO corrections come from allows us to include these in the LO results already

$$\frac{1}{v_{T,0}^2}\Big|_{m_t\to\infty} = \frac{1}{v_\alpha^2}\left[1+\frac{1}{v_{T,0}^2}\Delta r_t^{(4,1)}\right] = \frac{1}{v_\alpha^2}\left[1+\frac{1}{v_\alpha^2}\Delta r_t^{(4,1)}+\frac{1}{v_\alpha^2 v_{T,0}^2}\left(\Delta r_t^{(4,1)}\right)^2+\dots\right]$$
$$= \frac{1}{v_\alpha^2}\left[1-\frac{1}{v_\alpha^2}\Delta r_t^{(4,1)}\right]^{-1} \equiv \frac{1}{\tilde{v}_\alpha^2}$$

- Formulate as replacements for SMEFT

$$\frac{1}{v_T^2} \to \frac{1}{v_\sigma^2}\left[1+v_\sigma^2 K_W^{(6,0,\sigma)}+\frac{K_W^{(4,1,\sigma)}}{v_\sigma^2}+K_W^{(6,1,\sigma)}\right],$$
$$s_w^2 \to s_w^2\left(1-\frac{1}{v_\sigma^2}\Delta r_t^{(4,1)}+\Delta v_\sigma^{(6,0,\sigma)}\Delta r_t^{(4,1)}-2C_{\substack{Hq\\33}}^{(3)}\Delta r_t^{(4,1)}\right),$$
$$c_w^2 \to c_w^2\left(1-\frac{1}{v_\sigma^2}\Delta \rho_t^{(4,1)}+\Delta v_\sigma^{(6,0,\sigma)}\Delta \rho_t^{(4,1)}-2C_{\substack{Hq\\33}}^{(3)}\Delta \rho_t^{(4,1)}\right)$$

Z decay - resummation

$\{G_F,\, M_W,\, M_Z\}$

$Z \to \tau\tau$	$C_{\substack{Hl\\jj}}^{(3)}$	$C_{\substack{lq\\jj33}}^{(3)}$	$C_{\substack{ll\\1221}}$	$C_{\substack{Hq\\33}}^{(3)}$	C_{HD}	C_{HWB}	$C_{\substack{He\\33}}$
NLO	$-1.029^{+0.001}_{-0.000}$	$0.015^{+0.000}_{-0.001}$	$1.006^{+0.000}_{-0.000}$	$0.006^{+0.000}_{-0.002}$	$-0.289^{+0.009}_{-0.007}$	$0.258^{+0.003}_{-0.008}$	$-1.897^{+0.006}_{-0.002}$
NLO_t	$-1.021^{+0.001}_{-0.000}$	$0.015^{+0.004}_{-0.005}$	$1.006^{+0.002}_{-0.002}$	$0.006^{+0.000}_{-0.002}$	$-0.266^{+0.006}_{-0.005}$	$0.272^{+0.002}_{-0.002}$	$-1.864^{+0.005}_{-0.001}$
LO	$-1.000^{+0.015}_{-0.015}$	$0.000^{+0.026}_{-0.026}$	$1.000^{+0.004}_{-0.004}$	$0.000^{+0.001}_{-0.001}$	$-0.169^{+0.011}_{-0.011}$	$0.355^{+0.012}_{-0.012}$	$-1.764^{+0.046}_{-0.046}$
LO_K	$-1.021^{+0.012}_{-0.010}$	$0.015^{+0.000}_{-0.001}$	$1.006^{+0.004}_{-0.004}$	$0.006^{+0.001}_{-0.000}$	$-0.260^{+0.017}_{-0.017}$	$0.267^{+0.009}_{-0.009}$	$-1.838^{+0.048}_{-0.048}$

Resummed LO_K result reproduces NLO result well

NLO_t: large-m_t result

Summary

- Tremendous progress in SMEFT precision calculations!
- SMEFT @NLO is curse and blessing:

    new sensitivities + new degeneracies

EW input schemes

- NLO corrections are scheme and process dependent
- Potential for resummation of scheme-dependent (universal) corrections

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Summary

- Tremendous progress in SMEFT precision calculations!
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- NLO corrections are scheme and process dependent
- Potential for resummation of scheme-dependent (universal) corrections

Thank you for your attention!

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Backup

Tools & Methods

- Calculations performed in unitary gauge and Feynman gauge
- Calculated using in-house FeynRules implementation and cross-checked with SMEFTsim [SMEFTsim: Brivio, (Jiang, Trott) (1709.06492), (2012.11343)]
- Flavour diagonal but not flavour universal
- FJ tadpole scheme [Fleischer, Jegerlehner (1981)]
- Evanescent operators defined in chiral basis, naive dimensional regularisation for γ_5 [Dekens, Stoffer (1908.05295)]
- Tools: FeynRules, FeynArts, FormCalc, LoopTools, PackageX

[Degrande et al. (1108.2040), (1310.1921)]
[Hahn et al. (hep-ph/0012260)]
[Hahn et al. (1604.04611)]

Warsaw basis

[Grzadkowski et al. (1008.4884)]

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

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8: (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$

Plus another 24 four-fermion operators

The LEP scheme

- Inputs $\{\alpha,\, G_F,\, M_Z\}$
- $\hat{M}_W$ is a derived parameter

$$\hat{M}_W^2 = \frac{M_Z^2}{2}\left(1+\sqrt{1-\frac{4\pi\alpha v_\mu^2}{M_Z^2}}\right)$$

$$M_W^2 = \hat{M}_W^2\left[1-\frac{\hat{s}_w^2}{\hat{c}_{2w}}\Delta r-\frac{\hat{c}_w^2\hat{s}_w^4}{\hat{c}_{2w}^3}\Delta r^2\right]+\mathcal{O}\left(\Delta r^3\right)$$

$$\frac{v_\alpha^2}{v_\mu^2} \equiv 1+\Delta r$$

Renormalising α

- $\overline{\alpha}^{(\ell)}(M_Z^2)$: renormalised in five-flavour $\overline{\text{MS}}$-light scheme (all particles heavier than the b quark are decoupled, their corrections are calculated on-shell) [Cullen, Pecjak, Scott (1904.06358)]
- Related to $\alpha(0)$ via

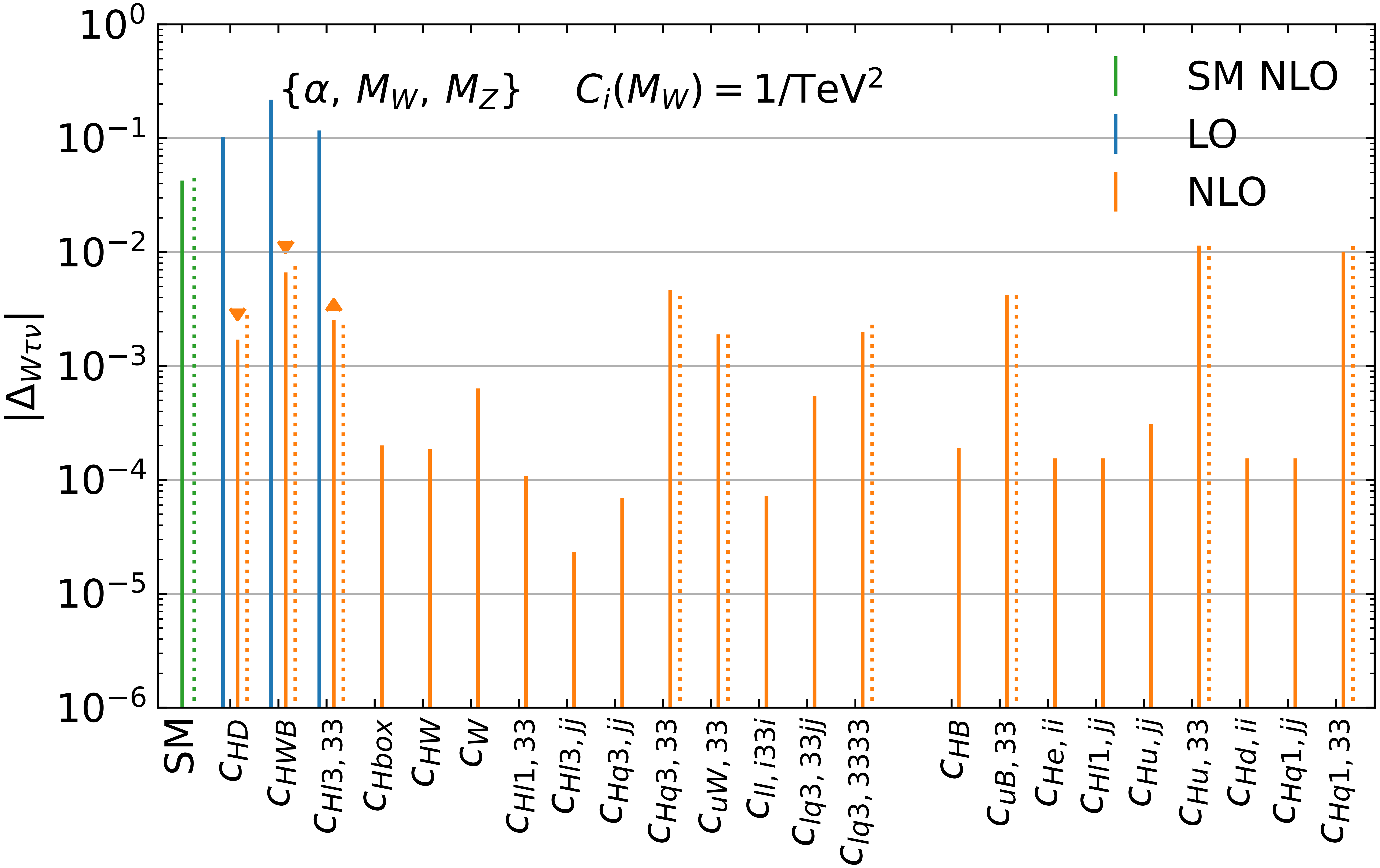
$$\overline{\alpha}^{(\ell)}(M_Z^2) = \frac{\alpha(0)}{1 - \Delta\overline{\alpha}^{(\ell)}(M_Z^2)} \qquad \alpha(M_Z^2) = \frac{\alpha(0)}{1 - \Delta\alpha(M_Z^2)}$$

- Related to on-shell $\alpha(M_Z^2)$ via

$$\overline{\alpha}^{(\ell)}(\mu^2) = \alpha(M_Z^2)\left[1 + \frac{\alpha(0)}{\pi}\left(\frac{100}{27} - \frac{20}{9}\ln\frac{M_Z^2}{\mu^2}\right)\right]$$

$W \to \tau\nu_\tau$ - SMEFT

$$\Delta_{W\tau\nu} \equiv \frac{\Gamma_{W\tau\nu}}{\Gamma^{(4,0)}_{W\tau\nu}} = 1 + \Delta^{(4,1)}_{W\tau\nu} + \Delta^{(6,0)}_{W\tau\nu} + \Delta^{(6,1)}_{W\tau\nu}$$



Orange triangles:

relative sign of NLO corrections

Dashes lines:

Large-MT limit

Largest contributions from top loops (dashed lines)

$\mu = M_W$

Corrections for H decay - SMEFT

$j = 1,\, 2$

$h \to b\bar{b}$		SM	$C_{H\Box}$	C_{HD}	$C_{\substack{dH\\33}}$	C_{HWB}	$C^{(3)}_{\substack{Hl\\jj}}$	$C_{\substack{ll\\1221}}$
α	NLO QCD	20.3%	20.3%	20.3%	20.3%	20.3%	-	-
	NLO EW	-5.2 %	2.1%	-11.0%	4.2%	-6.7%	-	-
	NLO correction	15.1%	22.4%	9.3%	24.5%	13.6%	-	-
α_μ	NLO QCD	20.3%	20.3%	20.3%	20.3%	-	20.3%	20.3%
	NLO EW	-0.8 %	2.1%	2.0%	1.9%	-	0.9%	-0.8%
	NLO correction	19.5%	22.4%	22.3%	22.2%	-	21.2%	19.5%
LEP	NLO QCD	20.3%	20.3%	20.3%	20.3%	-	20.3%	20.3%
	NLO EW	-0.7 %	2.1%	1.6%	1.9%	-	0.7%	-0.9%
	NLO correction	19.5%	22.3%	21.9%	22.2%	-	21.0%	19.3%

$$\Gamma^{(4,0)}_{hb\bar{b}} + \Gamma^{(6,0)}_{hb\bar{b}} = \frac{3m_b^2 M_H}{8\pi v_T^2}\left[1 + v_T^2\left(2C_{H\Box} - \frac{1}{2}C_{HD} - \sqrt{2}\frac{v_T}{m_b}C_{\substack{dH\\33}}\right)\right]$$

Corrections for H decay - SMEFT

$j = 1, 2$

$h \to b\bar{b}$		SM	$C_{H\Box}$	C_{HD}	$C_{\substack{dH \\ 33}}$	C_{HWB}	$C^{(3)}_{\substack{Hl \\ jj}}$	$C_{\substack{ll \\ 1221}}$
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	NLO correction	19.5%	22.3%	21.9%	22.2%	-	21.0%	19.3%

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Corrections for H decay - SMEFT

$j = 1,\, 2$

$h \to b\bar{b}$		SM	$C_{H\Box}$	C_{HD}	$C_{\substack{dH\\33}}$	C_{HWB}	$C^{(3)}_{\substack{Hl\\jj}}$	$C_{\substack{ll\\1221}}$
α	NLO QCD	20.3%	20.3%	20.3%	20.3%	20.3%	-	-
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	NLO correction	19.5%	22.3%	21.9%	22.2%	-	21.0%	19.3%

MW dependence subdominant

$$\Gamma^{(4,0)}_{hb\bar{b}} + \Gamma^{(6,0)}_{hb\bar{b}} = \frac{3m_b^2 M_H}{8\pi v_T^2}\left[1 + v_T^2\left(2C_{H\Box} - \frac{1}{2}C_{HD} - \sqrt{2}\frac{v_T}{m_b}C_{\substack{dH\\33}}\right)\right]$$

Corrections for H decay - SMEFT

$j = 1,\, 2$

$h \to b\bar{b}$		SM	$C_{H\Box}$	C_{HD}	$C_{\underset{33}{dH}}$	C_{HWB}	$C^{(3)}_{\underset{jj}{Hl}}$	$C_{\underset{1221}{ll}}$
α	NLO QCD	20.3%	20.3%	20.3%	20.3%	20.3%	-	-
	NLO EW	-5.2 %	2.1%	-11.0%	4.2%	-6.7%	-	-
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No vT dependence

MW dependence subdominant

$$\Gamma^{(4,0)}_{hb\bar{b}} + \Gamma^{(6,0)}_{hb\bar{b}} = \frac{3m_b^2 M_H}{8\pi v_T^2}\left[1 + v_T^2\left(2C_{H\Box} - \frac{1}{2}C_{HD} - \sqrt{2}\frac{v_T}{m_b}C_{\underset{33}{dH}}\right)\right]$$

Operators appearing at NLO

	MW	MZ	vT	Total
Alpha	12	29	29	29
alpha_Mu	13	30	12	33
LEP	33	30	23	33

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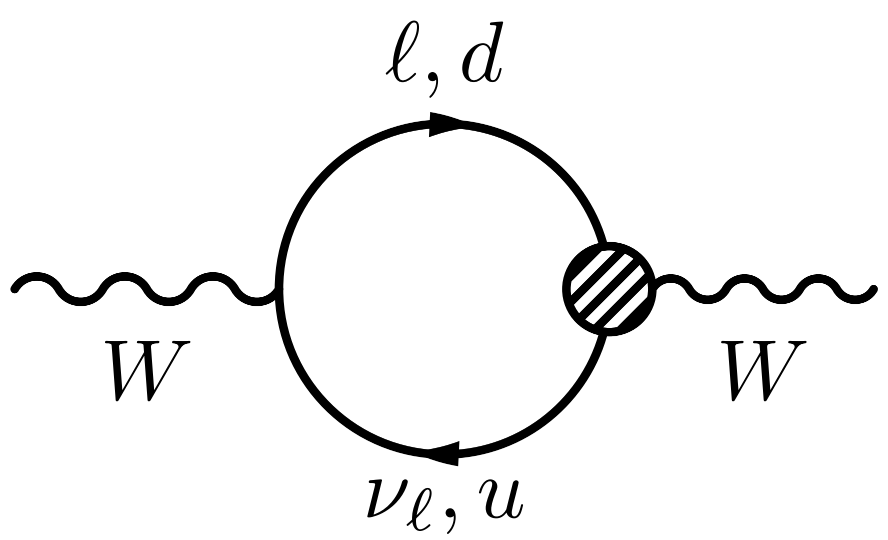

$C^{(3)}_{\substack{Hl\\ii}}, C^{(3)}_{\substack{Hq\\ii}}$

6 ops

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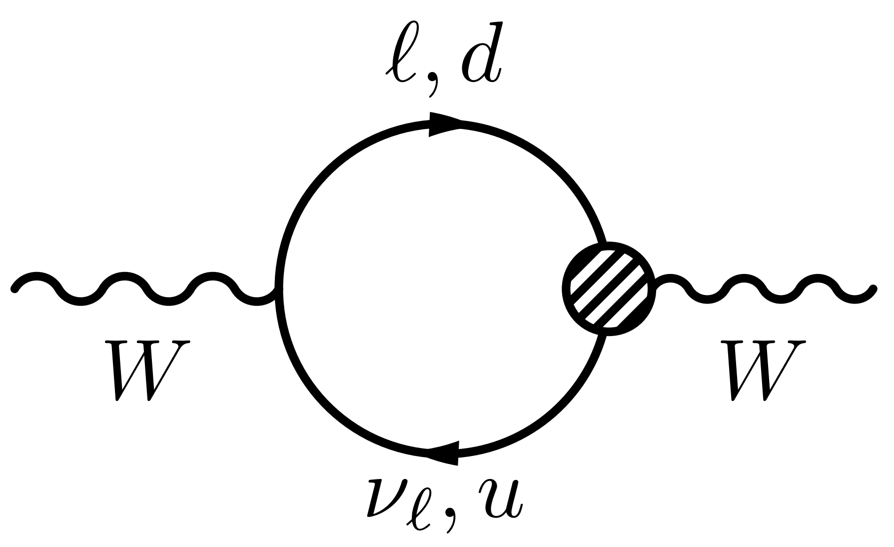

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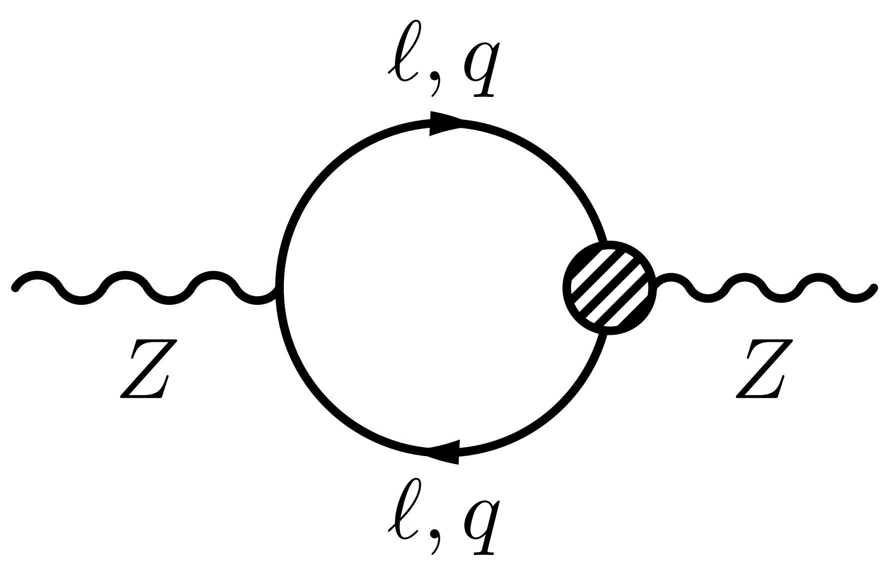
6 ops



$C^{(3)}_{\substack{Hl\\ii}}, C^{(3)}_{\substack{Hq\\ii}}, C^{(1)}_{\substack{Hl\\ii}}, C^{(1)}_{\substack{Hq\\ii}}, C_{\substack{He\\ii}}, C_{\substack{Hu\\ii}}, C_{\substack{Hd\\ii}},$

21 ops

Operators appearing at NLO

	MW	MZ	vT	Total
Alpha	12	29	29	29
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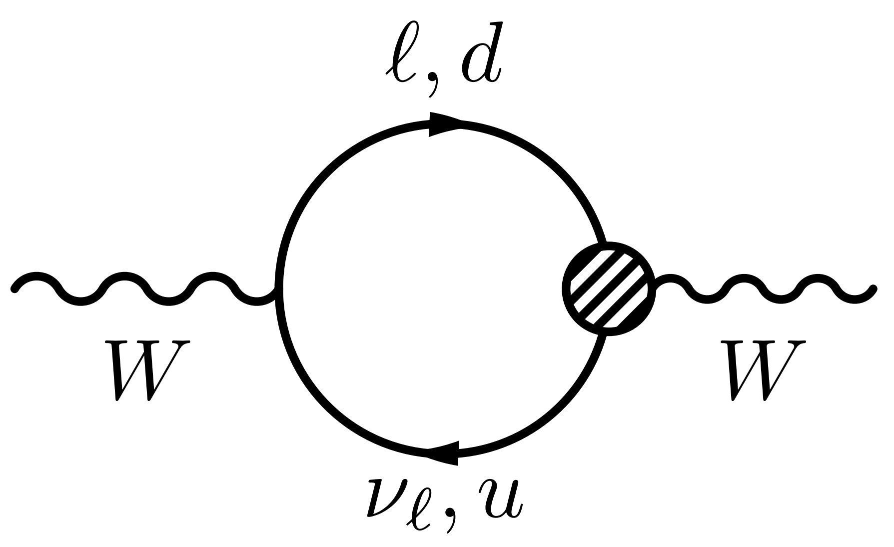
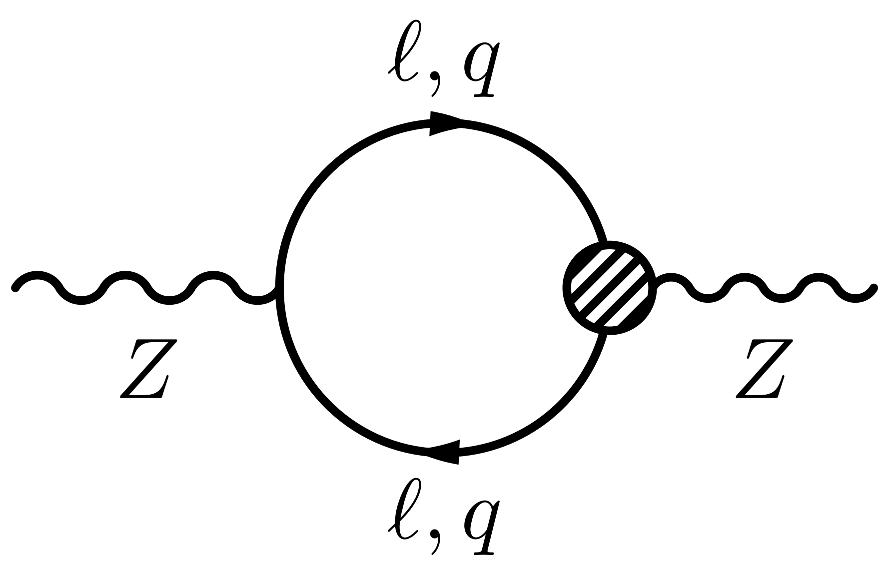


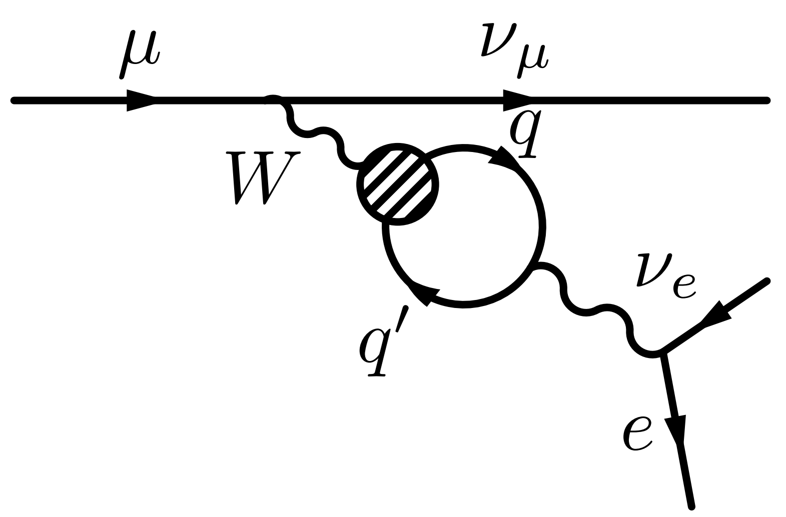
$C^{(3)}_{\substack{Hl\\ii}},\ C^{(3)}_{\substack{Hq\\ii}}$

6 ops



$C^{(3)}_{\substack{Hl\\ii}},\ C^{(3)}_{\substack{Hq\\ii}},\ C^{(1)}_{\substack{Hl\\ii}},\ C^{(1)}_{\substack{Hq\\ii}},\ C_{\substack{He\\ii}},\ C_{\substack{Hu\\ii}},\ C_{\substack{Hd\\ii}},$

21 ops

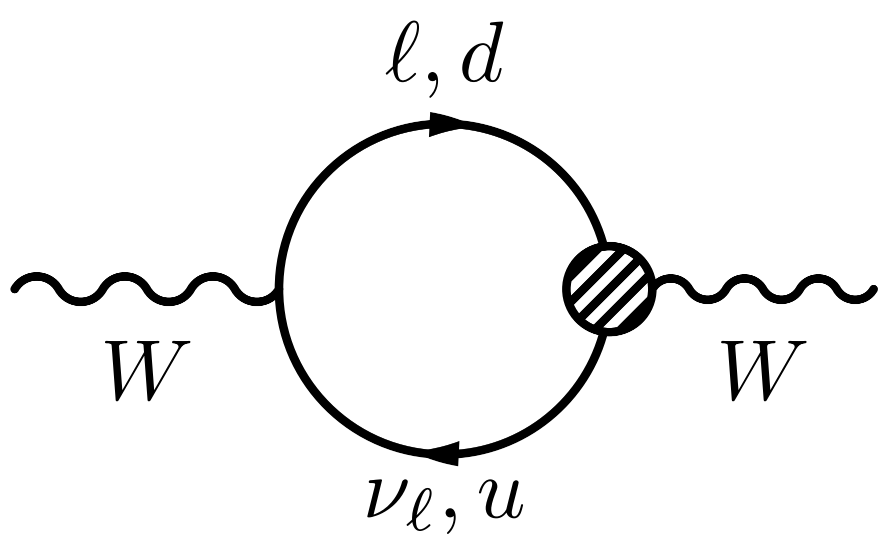


$C^{(3)}_{\substack{Hq\\33}}$

1 op

Operators appearing at NLO

	MW	MZ	vT	Total
Alpha	12	29	29	29
alpha_Mu	13	30	12	33
LEP	33	30	23	33

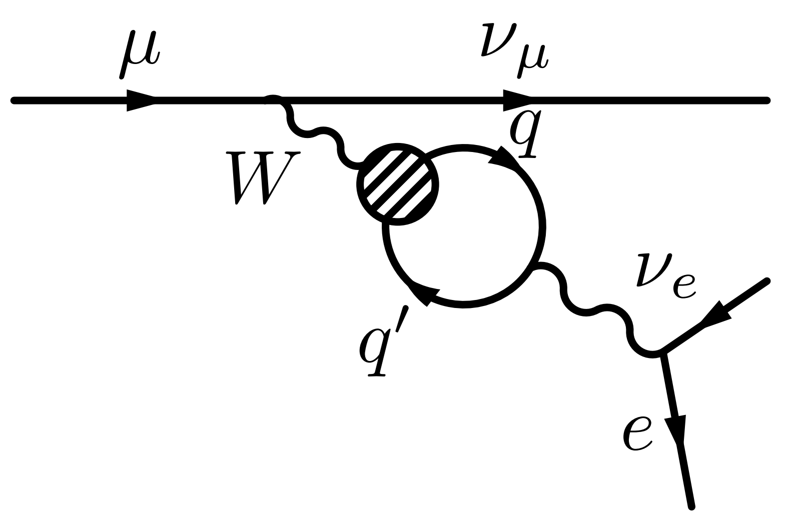


$C^{(3)}_{\substack{Hl\\ii}}, C^{(3)}_{\substack{Hq\\ii}}$

6 ops

Operators overlap between different inputs

Operators may overlap with those appearing in the bare matrix elements



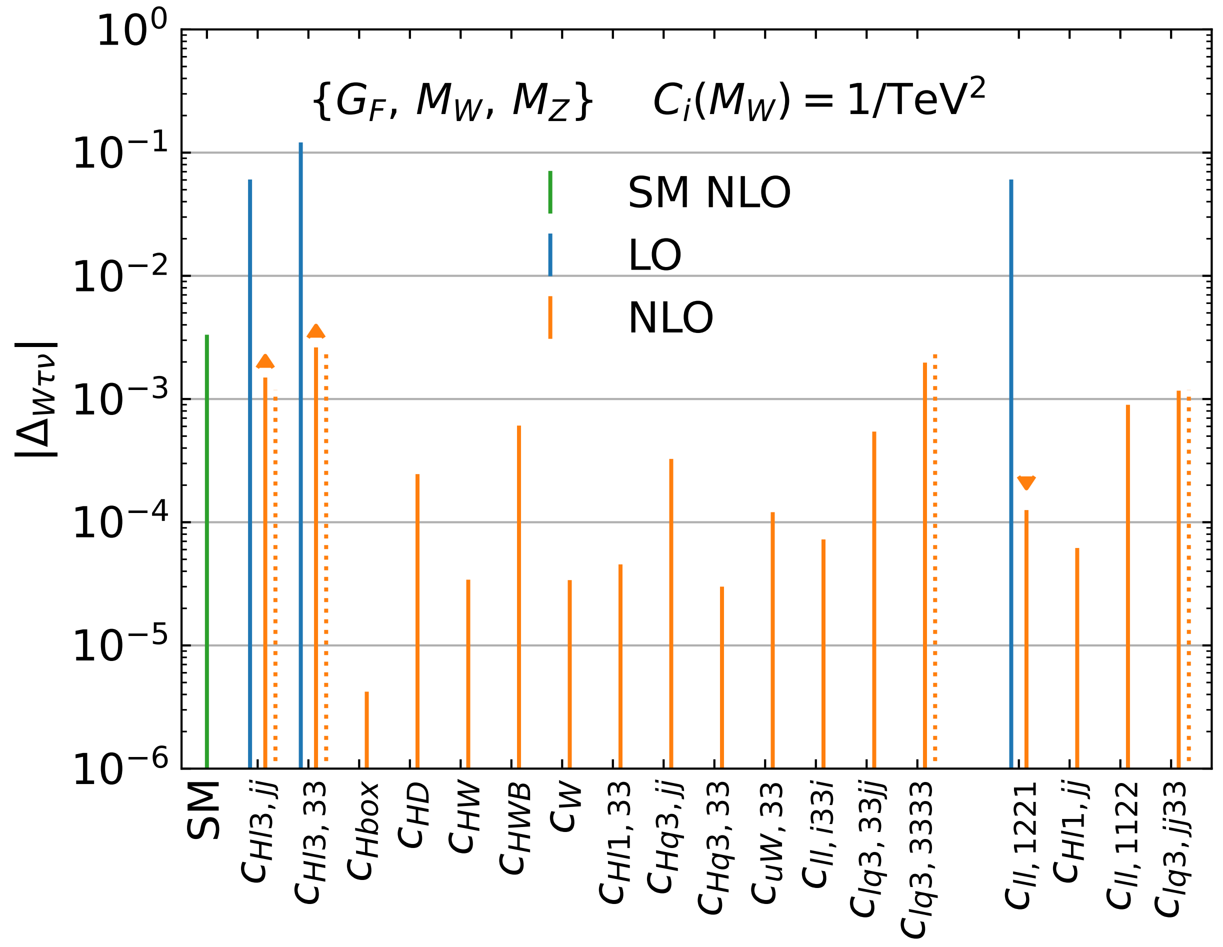
$C^{(3)}_{\substack{Hq\\33}}$

1 op

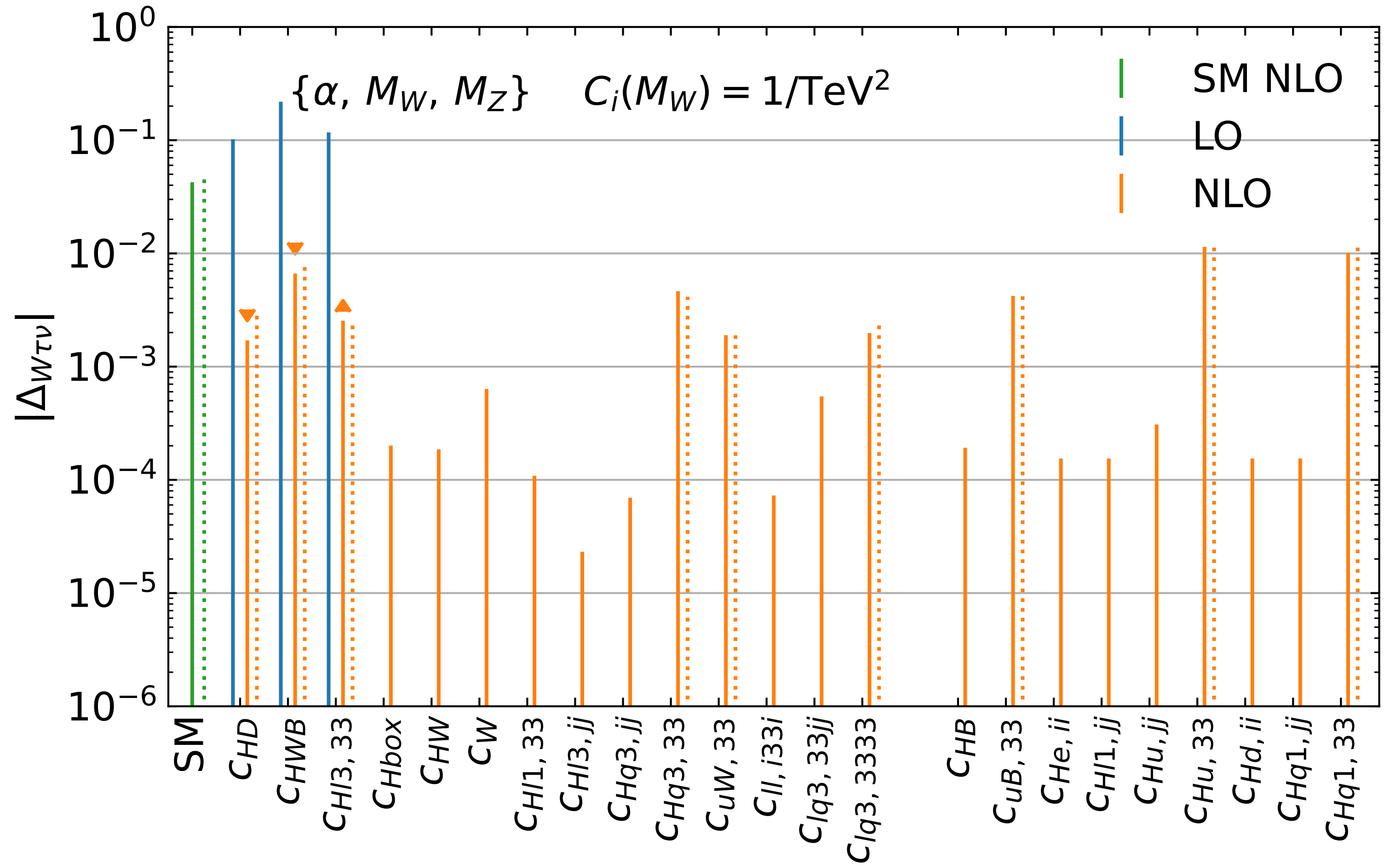
$W \to \tau\nu_\tau$ - SMEFT

$\mu = M_W$

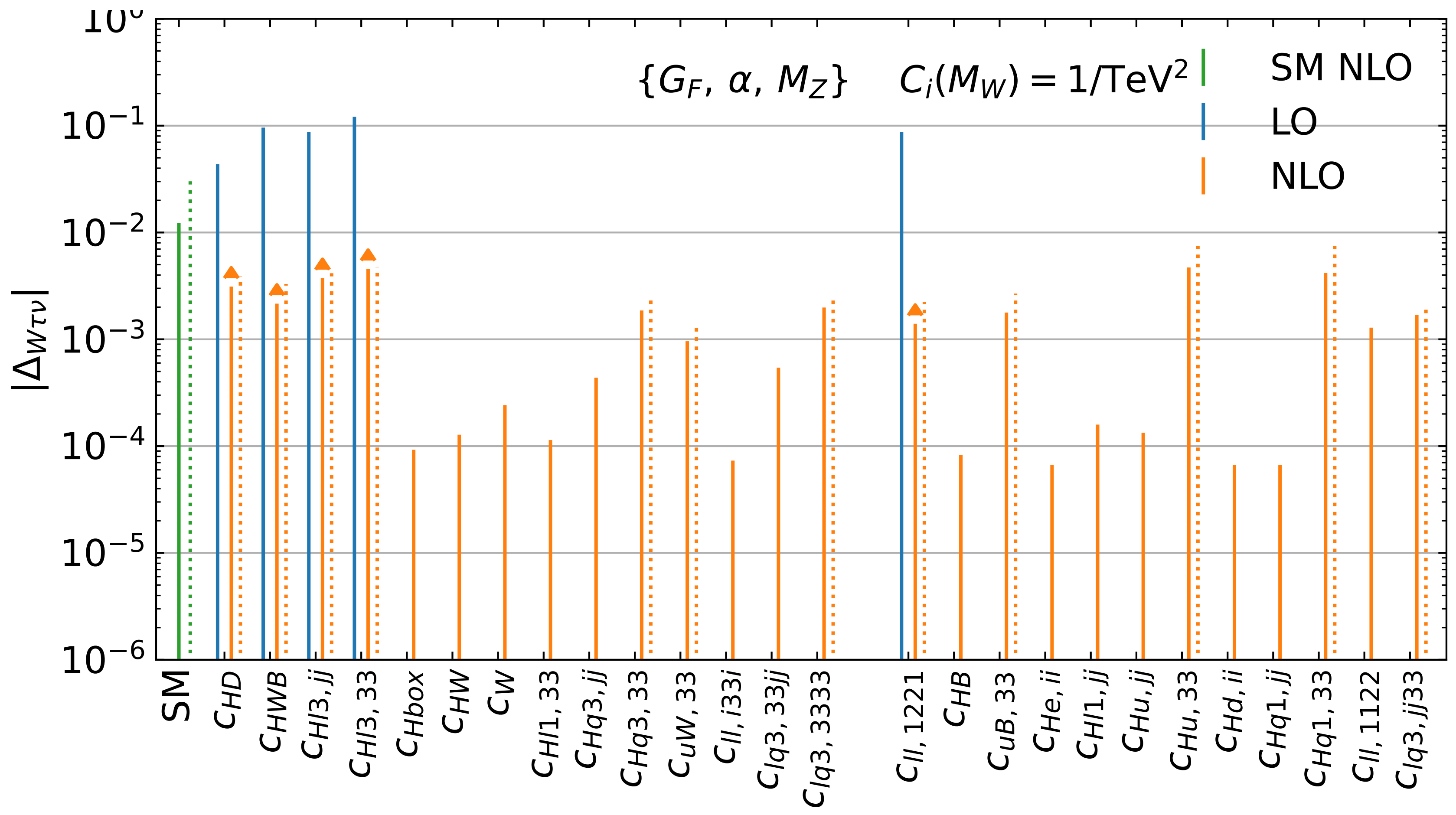
$$\Delta_{W\tau\nu} \equiv \frac{\Gamma_{W\tau\nu}}{\Gamma^{(4,0)}_{W\tau\nu}} = 1 + \Delta^{(4,1)}_{W\tau\nu} + \Delta^{(6,0)}_{W\tau\nu} + \Delta^{(6,1)}_{W\tau\nu}$$



α_μ



α



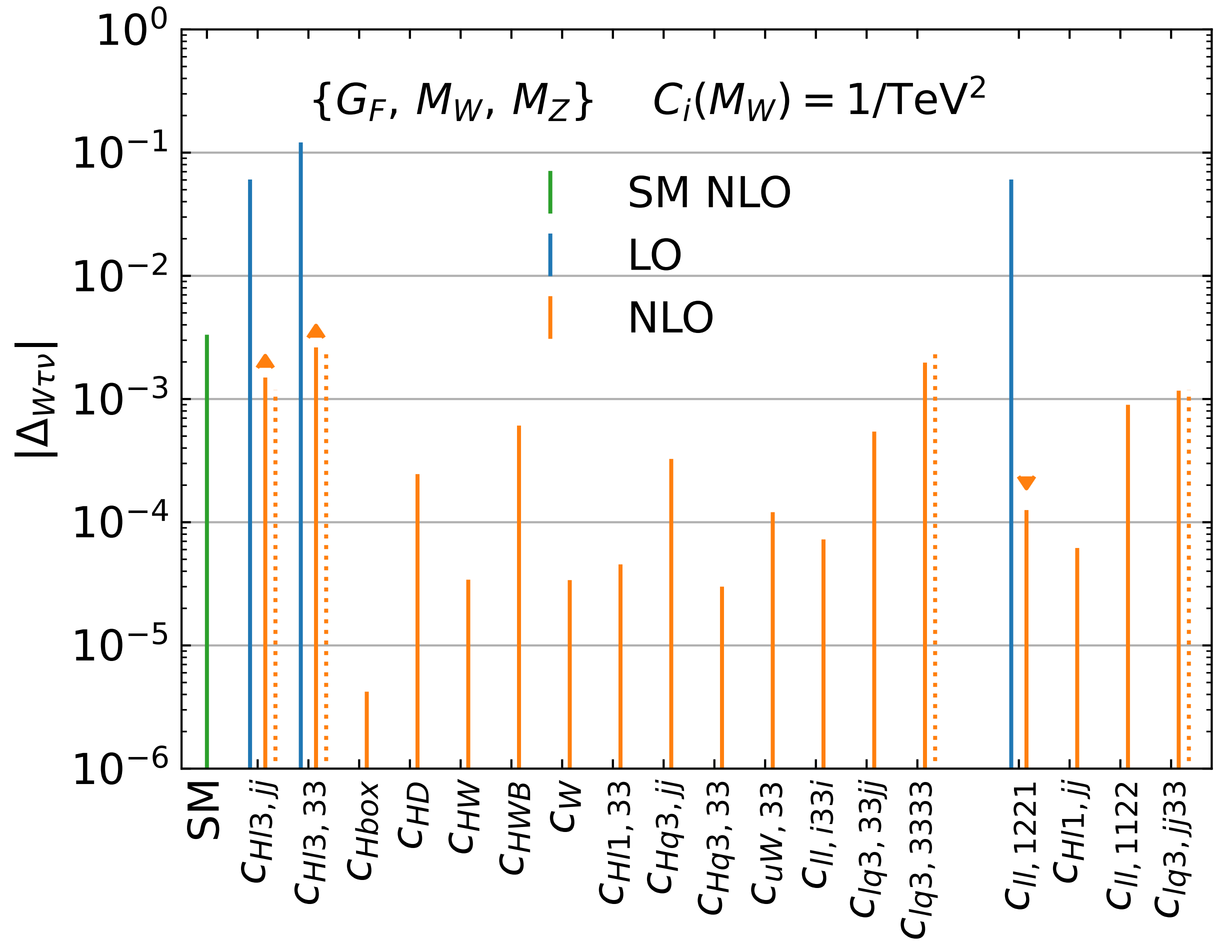
LEP

Lowest number of operators at NLO in α_μ scheme

$W \to \tau\nu_\tau$ - SMEFT

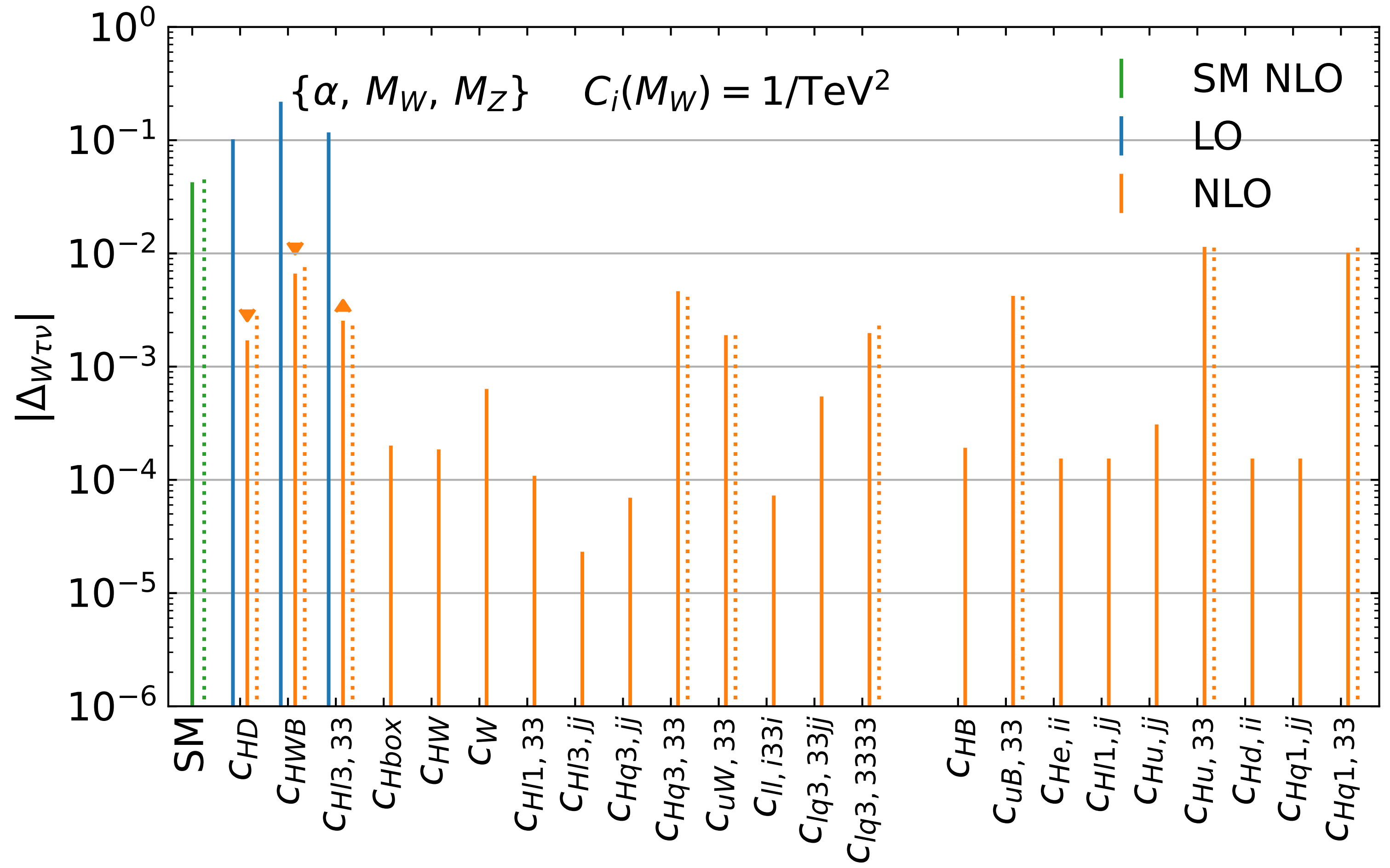
$\mu = M_W$

$$\Delta_{W\tau\nu} \equiv \frac{\Gamma_{W\tau\nu}}{\Gamma^{(4,0)}_{W\tau\nu}} = 1 + \Delta^{(4,1)}_{W\tau\nu} + \Delta^{(6,0)}_{W\tau\nu} + \Delta^{(6,1)}_{W\tau\nu}$$



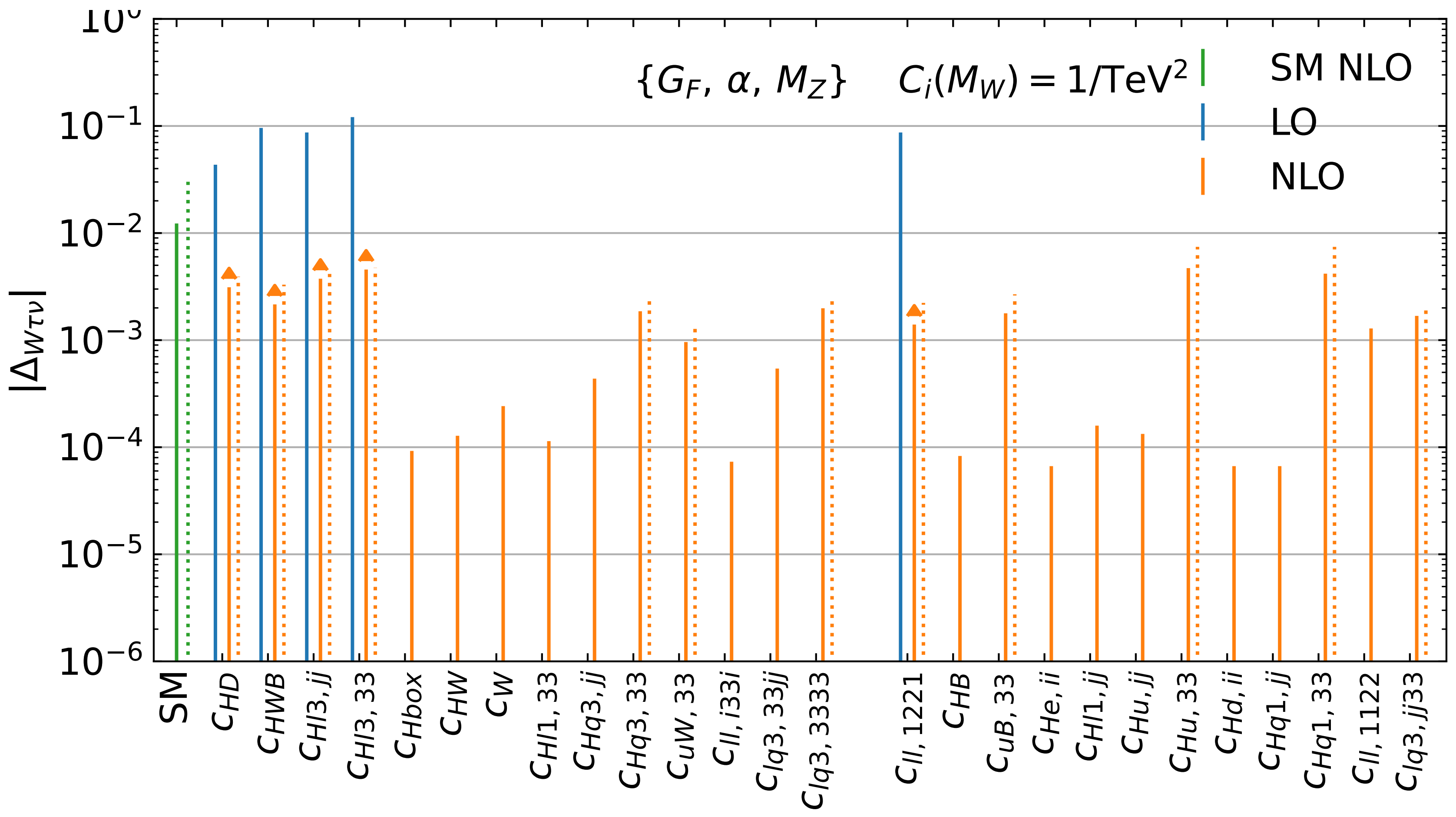
α_μ

Lowest number of operators at NLO in α_μ scheme



α

Smallest SMEFT NLO corrections in α_μ scheme



LEP

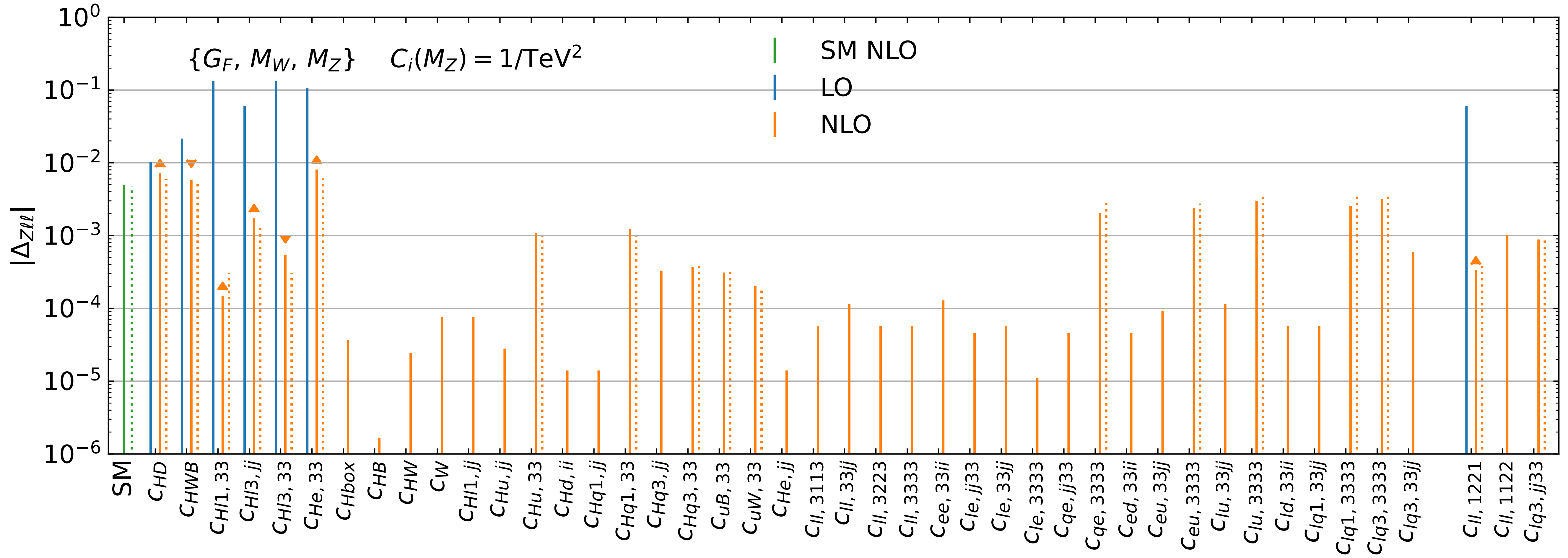
$Z \to \tau\tau$ - SMEFT

α scheme does not contain some 4f operators
(appearing in muon decay)

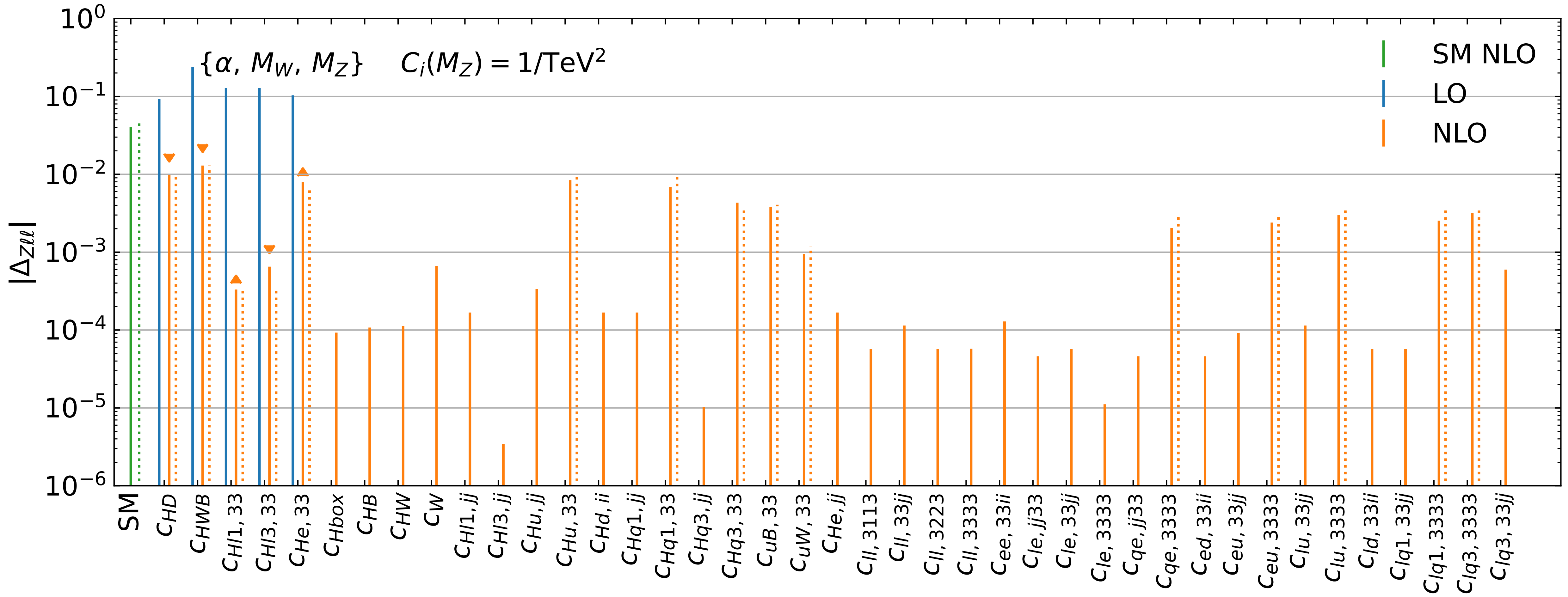
Largest absolute SMEFT NLO corrections in α scheme

Large relative SMEFT NLO corrections in α_μ scheme (LR interference effect)

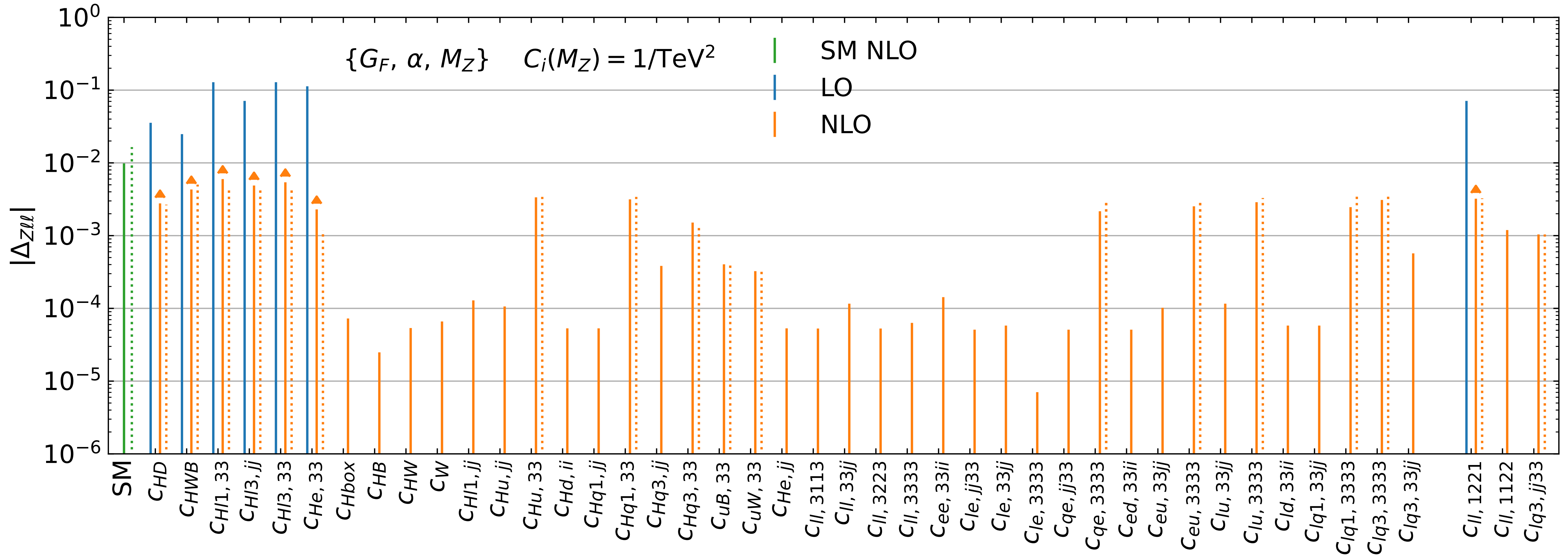
$\mu = M_Z$



α_μ

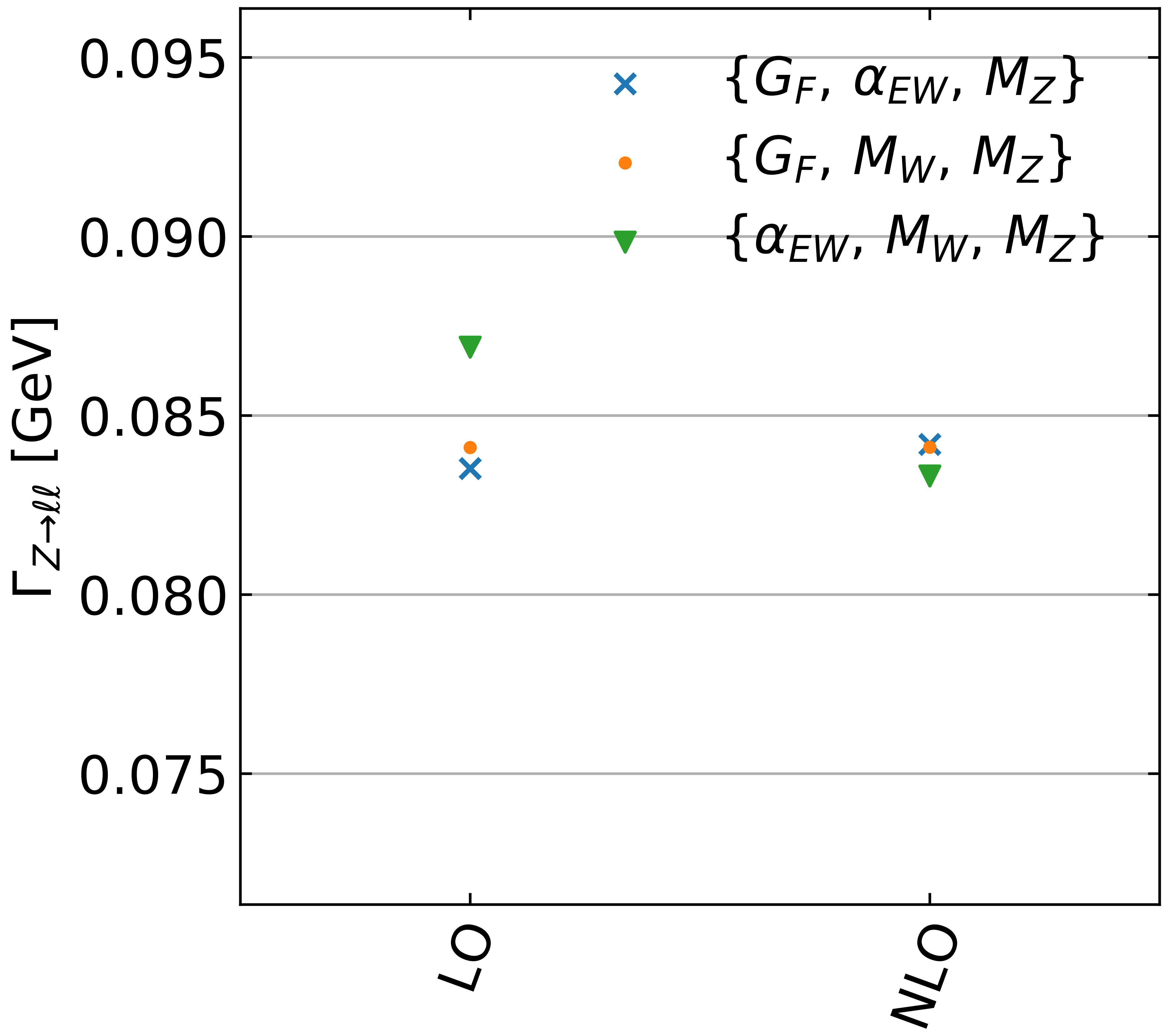


α



LEP

$Z \to \tau\tau$ - SM

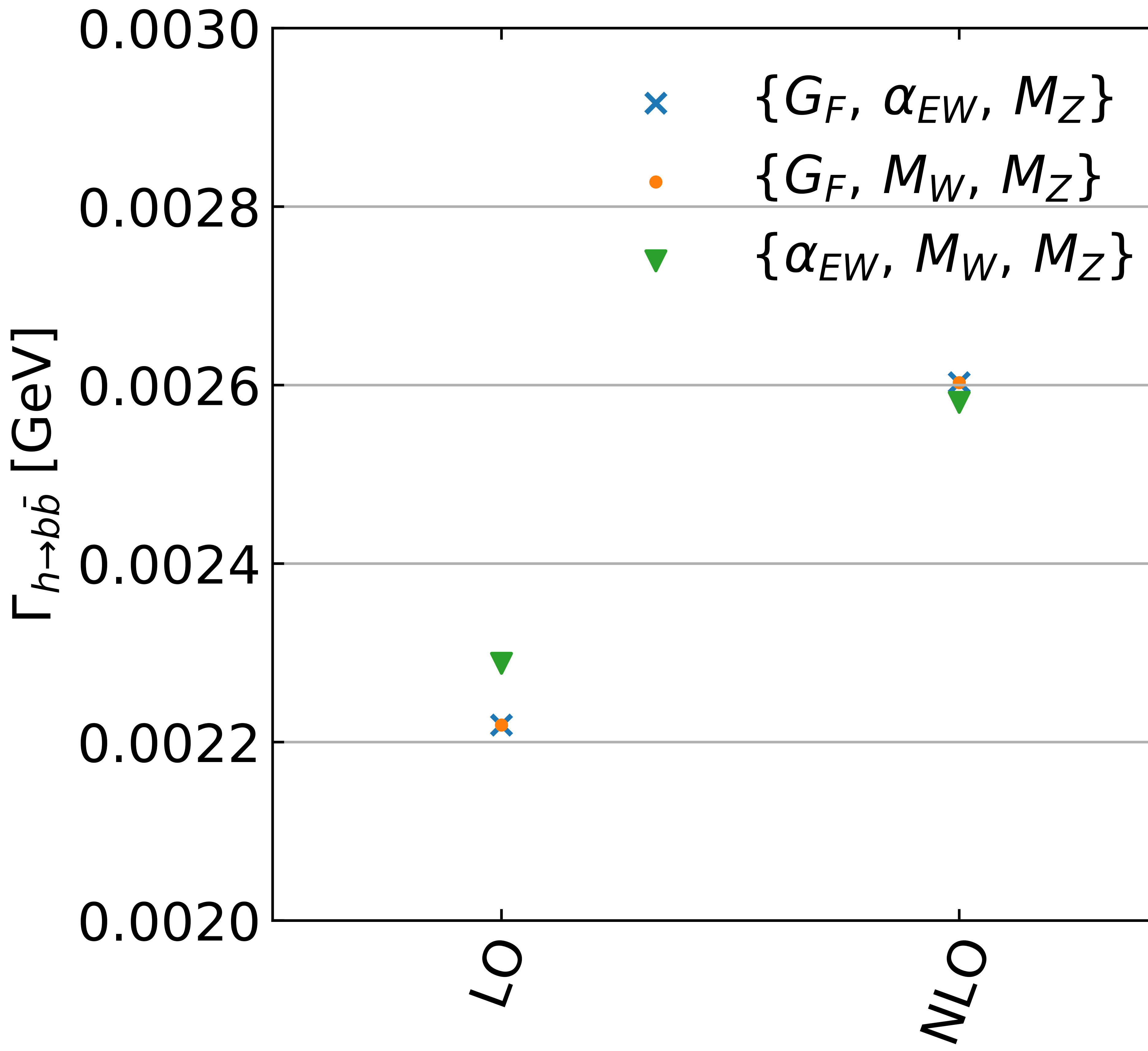


Large differences between schemes at LO (5 %)

Schemes closer at NLO

Largest correction given to alpha scheme

$H \to b\bar{b}$ - SM



Large NLO corrections

LEP and α_μ scheme are identical

$$\mathcal{M}_0^{(4,0)} = \frac{m_b}{v_T}$$

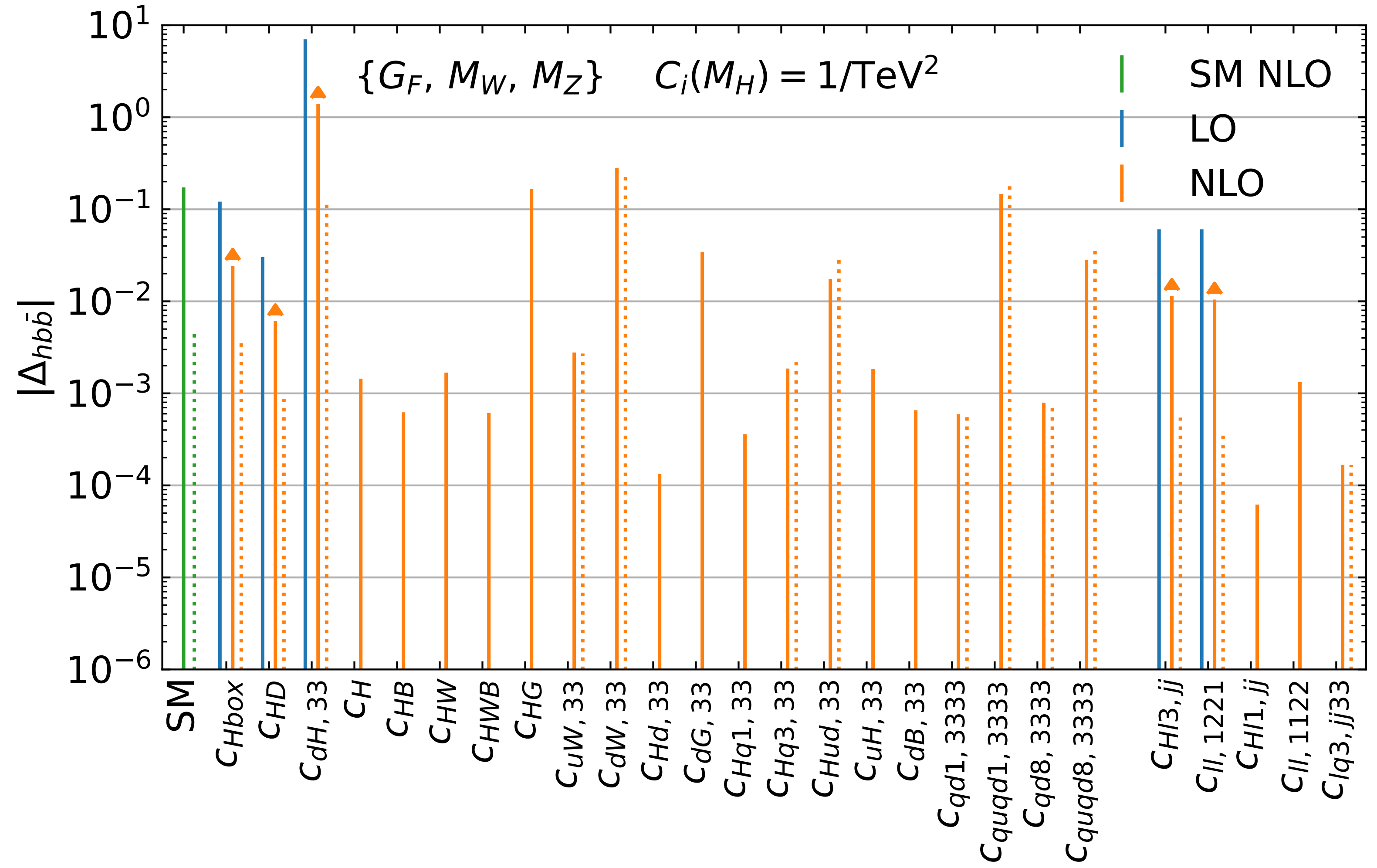
$H \to b\bar{b}$ - SMEFT

LEP and α_μ scheme are identical (up to numerics)

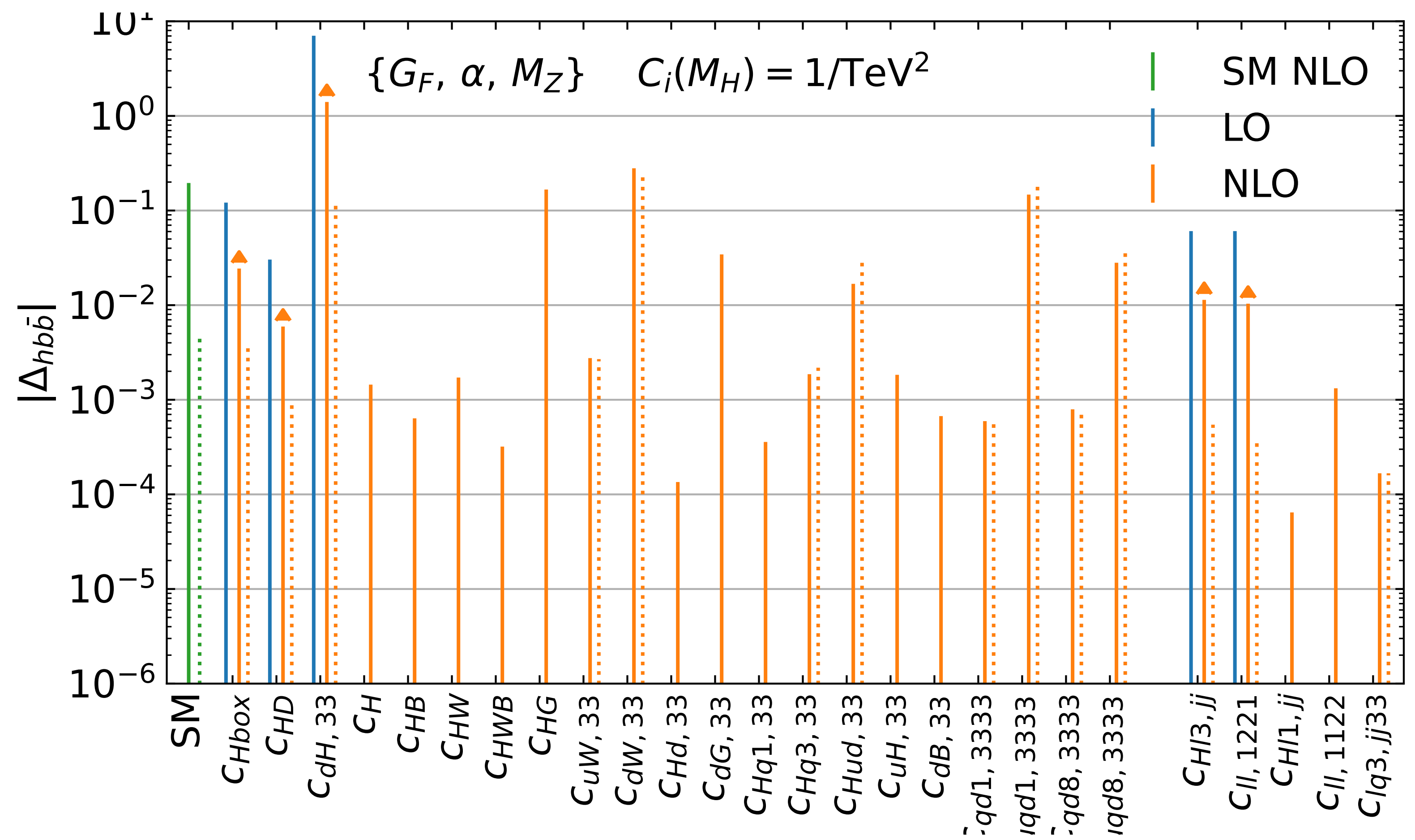
More operators contribute in the α scheme

$$\Gamma^{(4,0)}_{hb\bar{b}} + \Gamma^{(6,0)}_{hb\bar{b}} = \frac{3m_b^2 M_H}{8\pi v_T^2}\left[1 + v_T^2\left(2C_{H\Box} - \frac{1}{2}C_{HD} - \sqrt{2}\frac{v_T}{m_b}C_{\substack{dH\\33}}\right)\right]$$

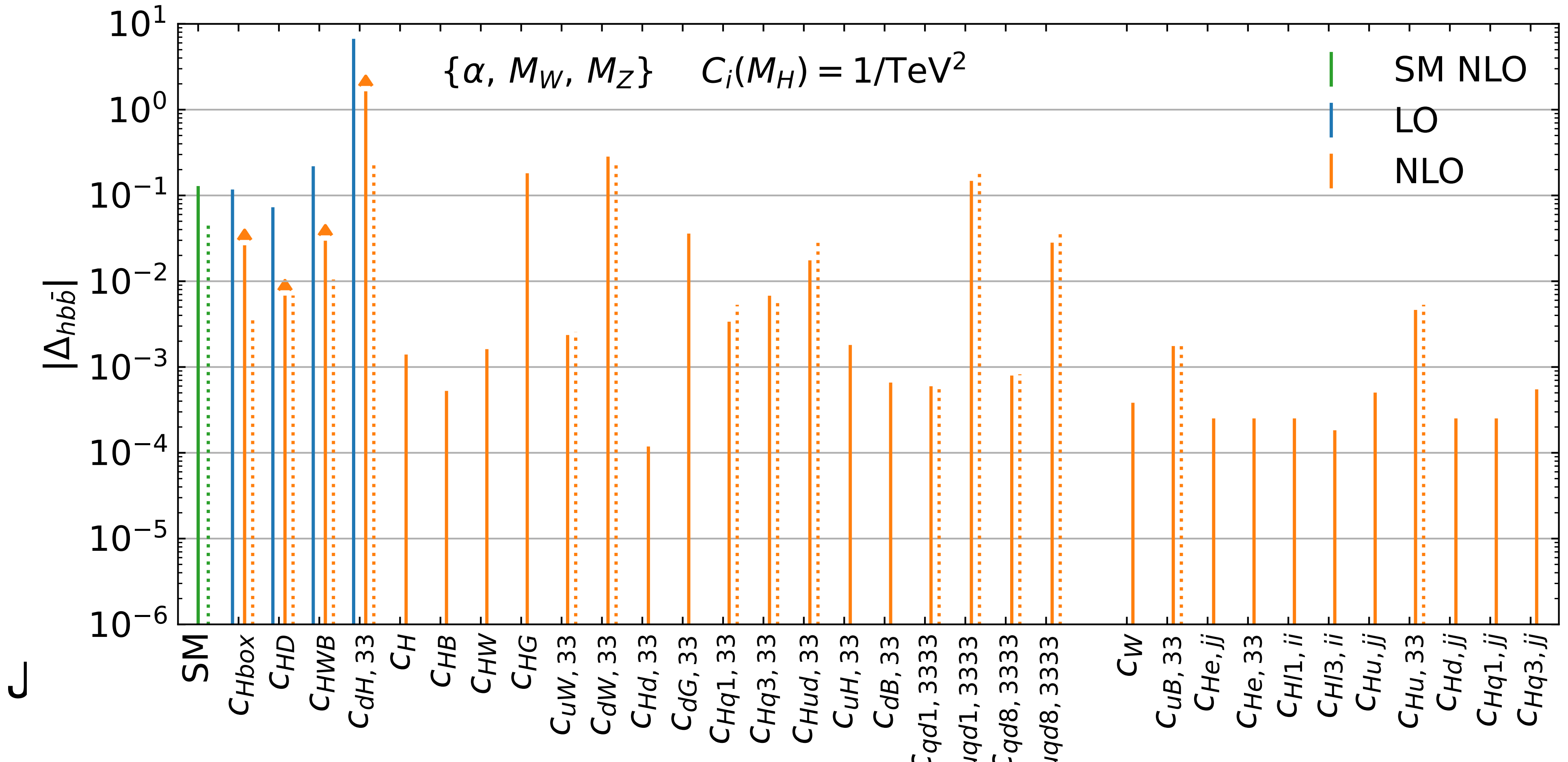
$$\mu = M_H$$



α_μ



α



LEP

Resummation for W decay

	C_{HD}	C_{HWB}	$C^{(3)}_{\substack{Hq\\33}}$	$C_{\substack{Hu\\33}}$	$C^{(1)}_{\substack{Hq\\33}}$	$C_{\substack{uB\\33}}$	$C_{\substack{uW\\33}}$
NLO	$1.713^{+0.000}_{-0.011}$	$3.621^{+0.000}_{-0.011}$	$-0.079^{+0.018}_{-0.012}$	$-0.195^{+0.038}_{-0.000}$	$0.172^{+0.000}_{-0.033}$	$-0.072^{+0.008}_{-0.000}$	$-0.032^{+0.005}_{-0.000}$
LO	$1.742^{+0.120}_{-0.120}$	$3.733^{+0.131}_{-0.131}$	$0.000^{+0.008}_{-0.008}$	$0.000^{+0.182}_{-0.182}$	$0.000^{+0.189}_{-0.189}$	$0.000^{+0.066}_{-0.066}$	$0.000^{+0.059}_{-0.059}$
$\tilde{\text{LO}}$	$1.617^{+0.110}_{-0.110}$	$3.540^{+0.123}_{-0.123}$	$0.000^{+0.008}_{-0.008}$	$0.000^{+0.168}_{-0.168}$	$0.000^{+0.175}_{-0.175}$	$0.000^{+0.062}_{-0.062}$	$0.000^{+0.056}_{-0.056}$
$\tilde{\text{LO}}_K$	$1.697^{+0.031}_{-0.031}$	$3.610^{+0.033}_{-0.033}$	$-0.063^{+0.003}_{-0.003}$	$-0.193^{+0.018}_{-0.018}$	$0.193^{+0.023}_{-0.023}$	$-0.068^{+0.121}_{-0.121}$	$-0.031^{+0.110}_{-0.110}$
$\tilde{\text{LO}}'_K$	$1.666^{+0.040}_{-0.053}$	$3.542^{+0.070}_{-0.074}$	$-0.065^{+0.010}_{-0.000}$	$-0.200^{+0.029}_{-0.000}$	$0.200^{+0.000}_{-0.032}$	$-0.070^{+0.124}_{-0.120}$	$-0.032^{+0.113}_{-0.110}$