Electroweak input schemes in Standard Model effective field theory

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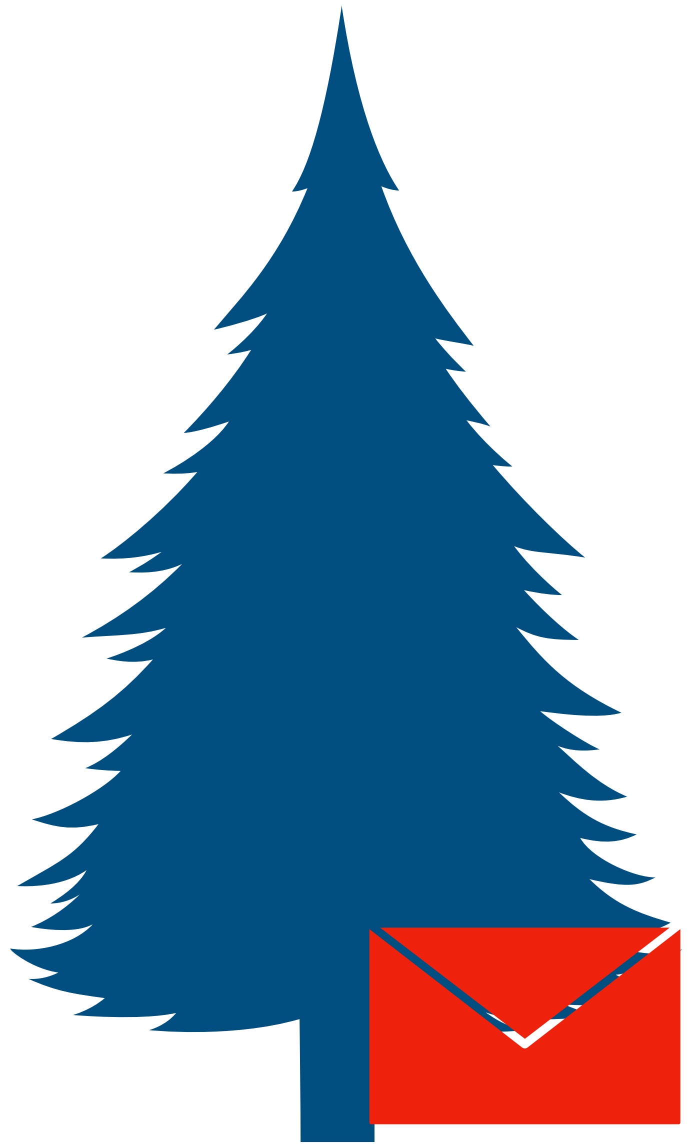
Unterstützt von / Supported by
Alexander von Humboldt Stiftung/Foundation

Particle physics seminar @ Universität Wien - 12 December 2023

Beyond the Standard Model Wishlist



Dear Santa, could you please send us…

… a dark matter candidate

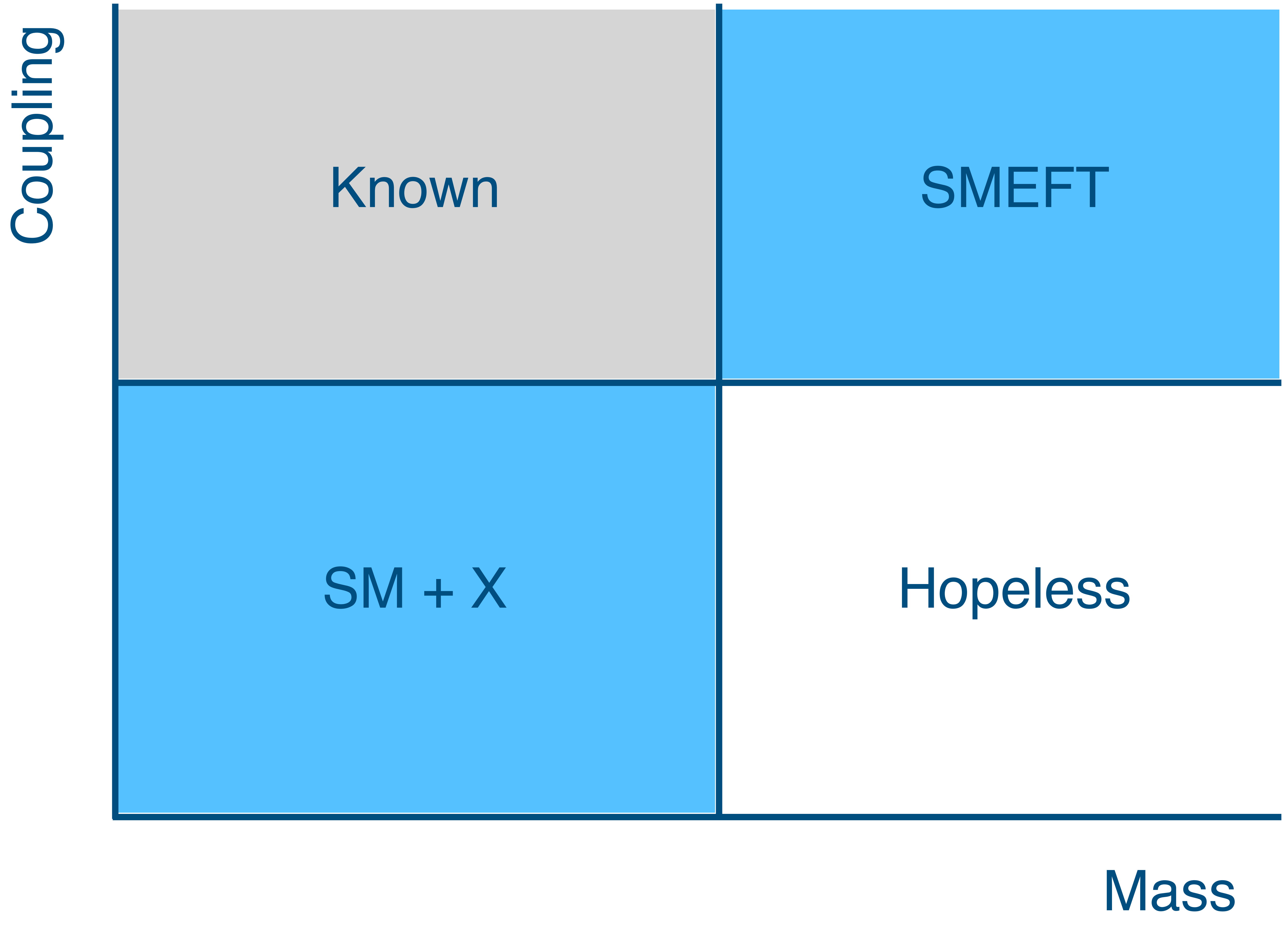
… an explanation for the flavor hierarchy

… an explanation for the matter-antimatter asymmetry of the universe

… a solution to the strong CP problem (preferably an axion)

[adapted from Gavin Salam]

The Landscape of (new) physics



New physics has to be…

… very heavy

SMEFT
Leptoquarks
Z’ bosons
Supersymmetry

… (light and) very weakly interacting with the SM

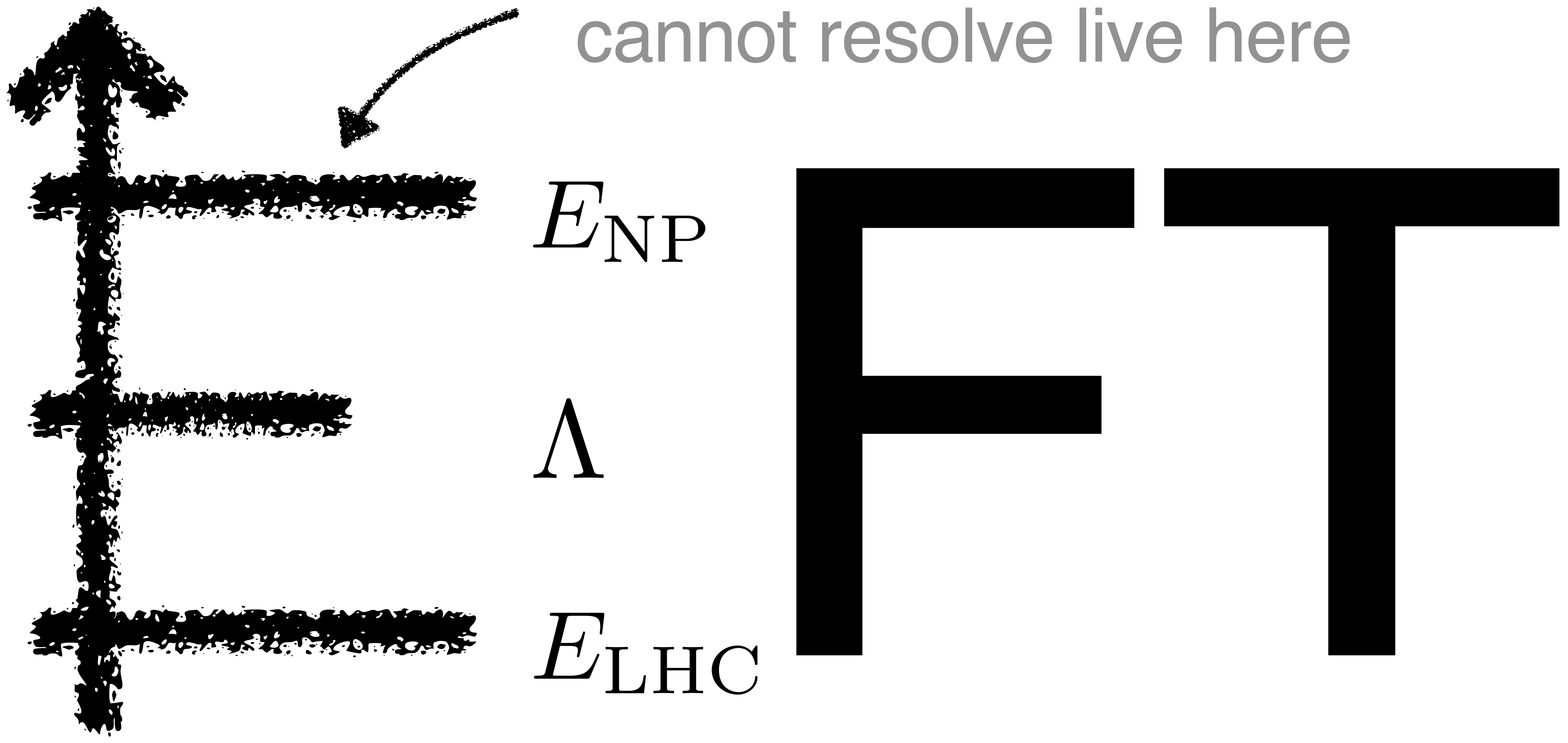
Outline

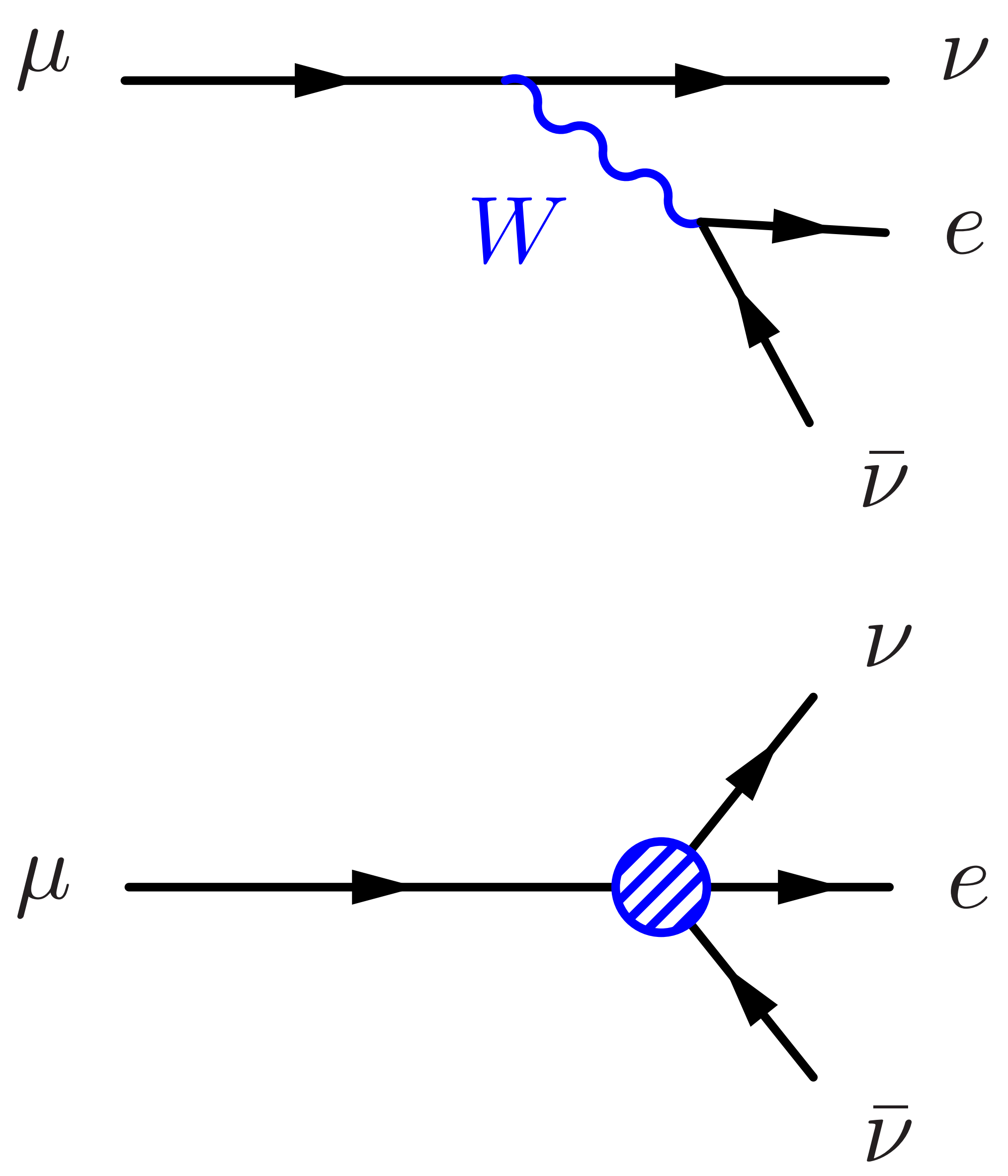
- A brief introduction to effective field theory
- Electroweak input parameters and their influence on one-loop calculations in the SMEFT
  - Size of NLO corrections
  - Number of operators appearing at NLO

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

Effective field theory - EFT

Heavy particles that we cannot resolve live here



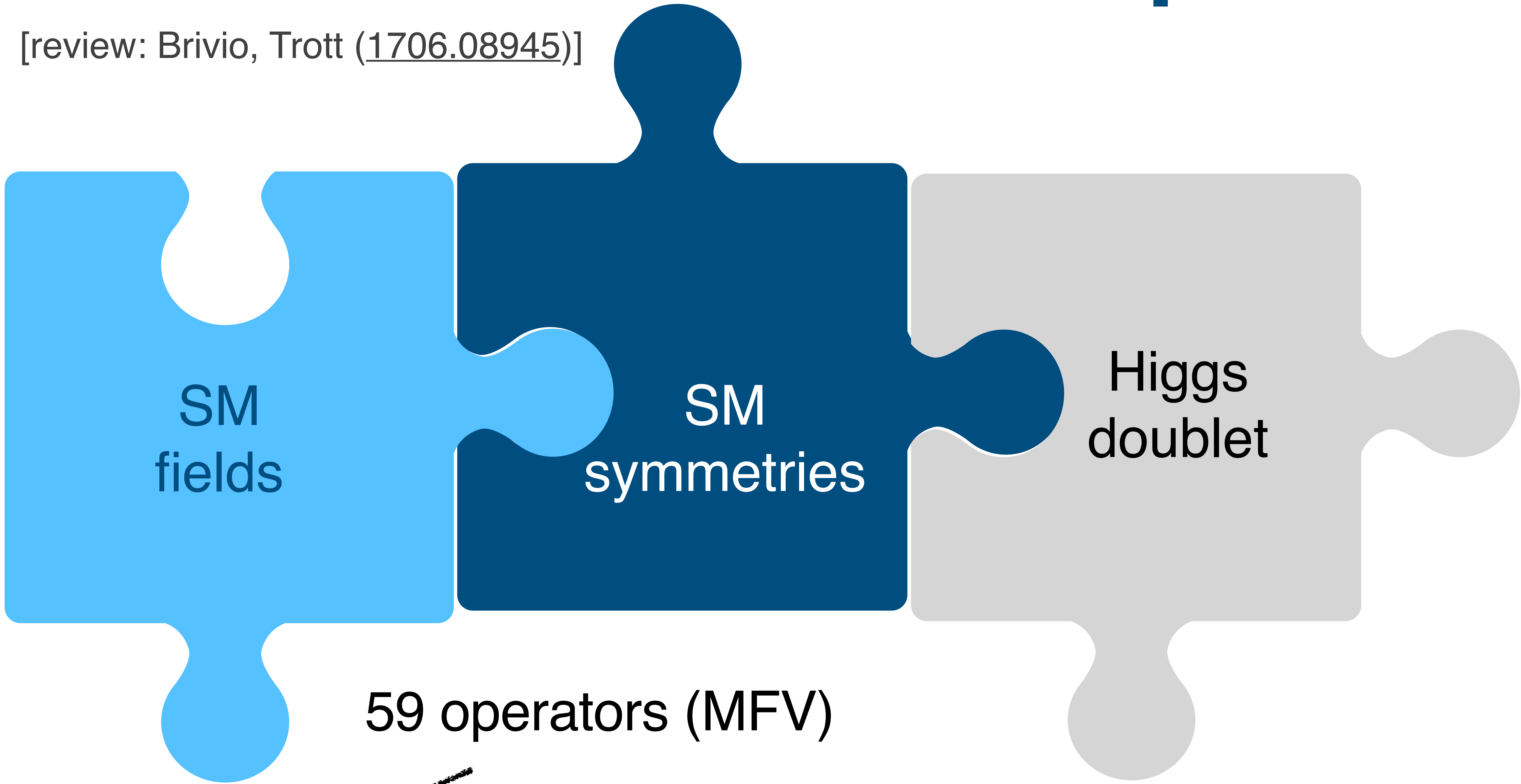


Hierarchy of scales

Describe NP by higher-order interactions of SM fields

EFTs from the bottom-up

[review: Brivio, Trott (1706.08945)]



- **Minimal assumptions** on UV completion
- **Universal language** for data interpretation

59 operators (MFV)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \cdots$$

Odd dimensions violate lepton or baryon number

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	$(H^\dagger H)^3$

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

$5: \psi^2H^3 + \text{h.c.}$	
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}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2H^2$	
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}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

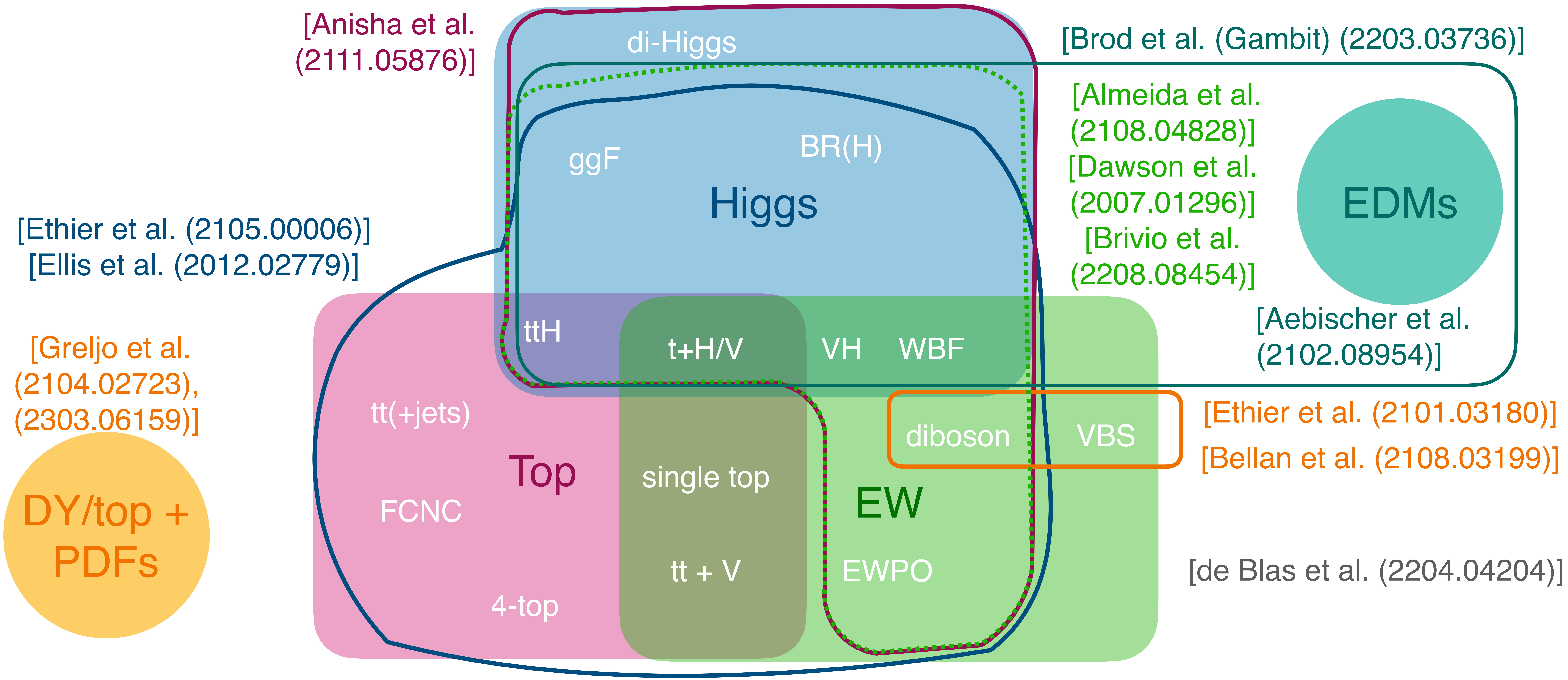
$6: \psi^2XH + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\,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

$7: \psi^2H^2D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p\tau^I\gamma^\mu l_r)$
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.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$

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

Plus another 24 four-fermion operators

Confronting the SMEFT with data

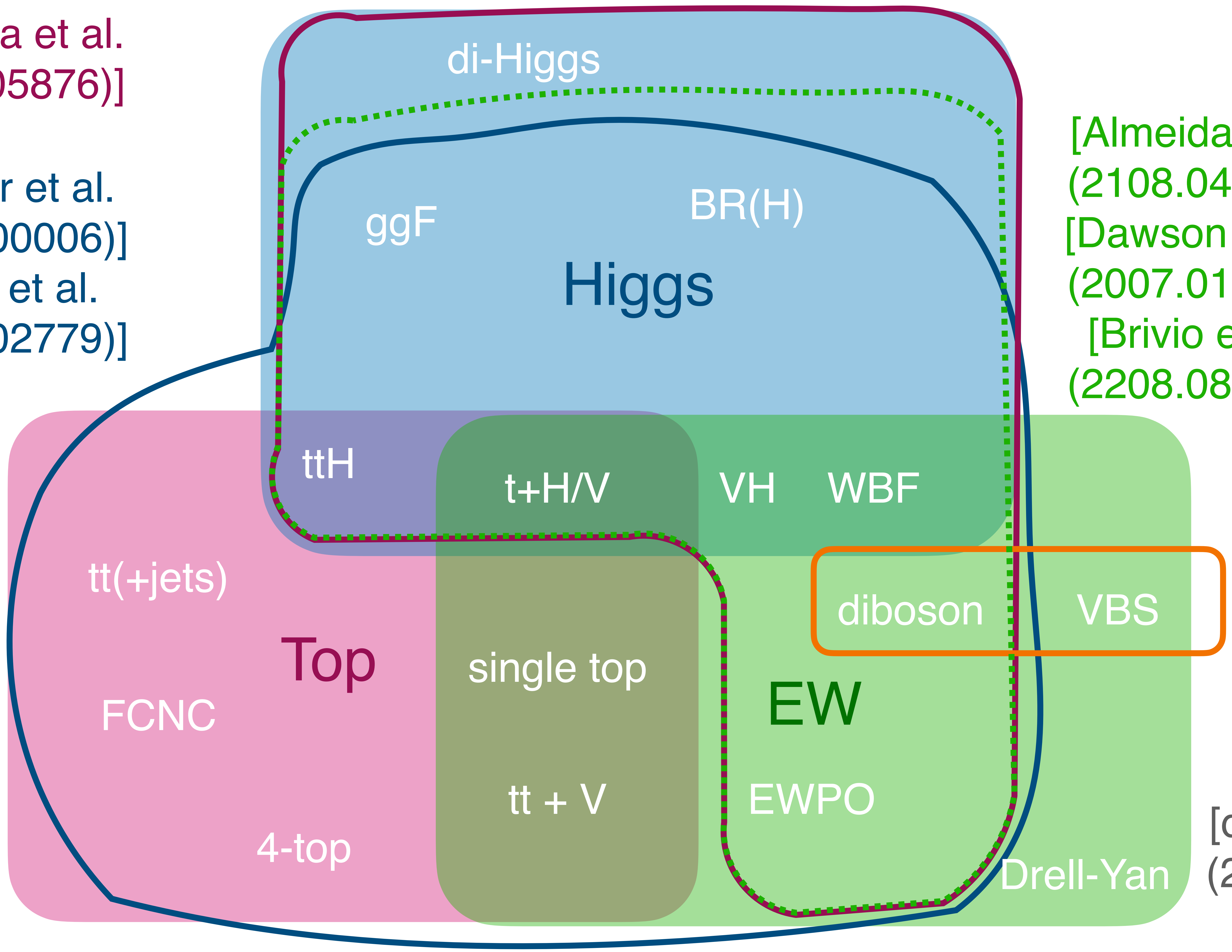


Adapted from Ken Mimasu

Combining LHC and non-LHC observables

[Anisha et al. (2111.05876)]

[Ethier et al. (2105.00006)]
[Ellis et al. (2012.02779)]



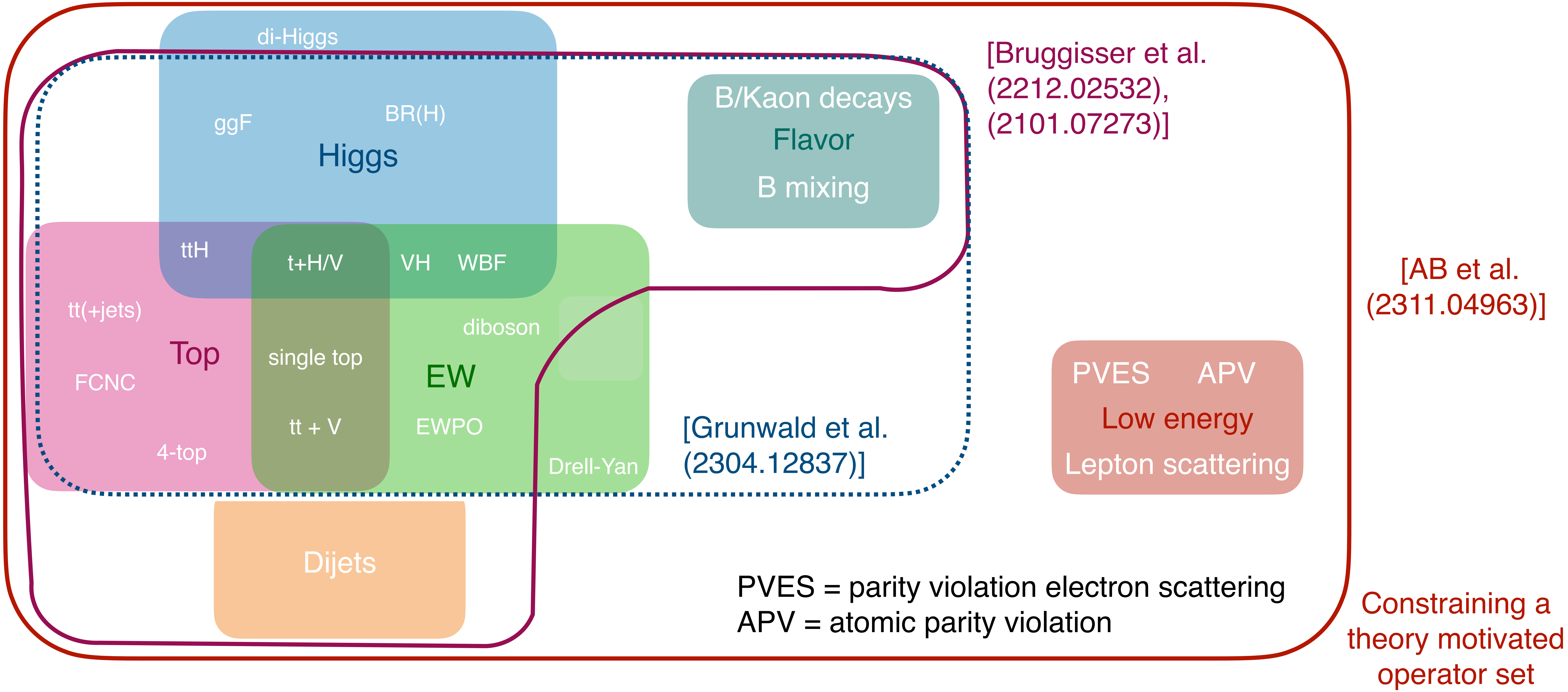
[Almeida et al. (2108.04828)]
[Dawson et al. (2007.01296)]
[Brivio et al. (2208.08454)]

[Ethier et al. (2101.03180)]
[Bellan et al. (2108.03199)]

[de Blas et al. (2204.04204)]

Adapted from Ken Mimasu

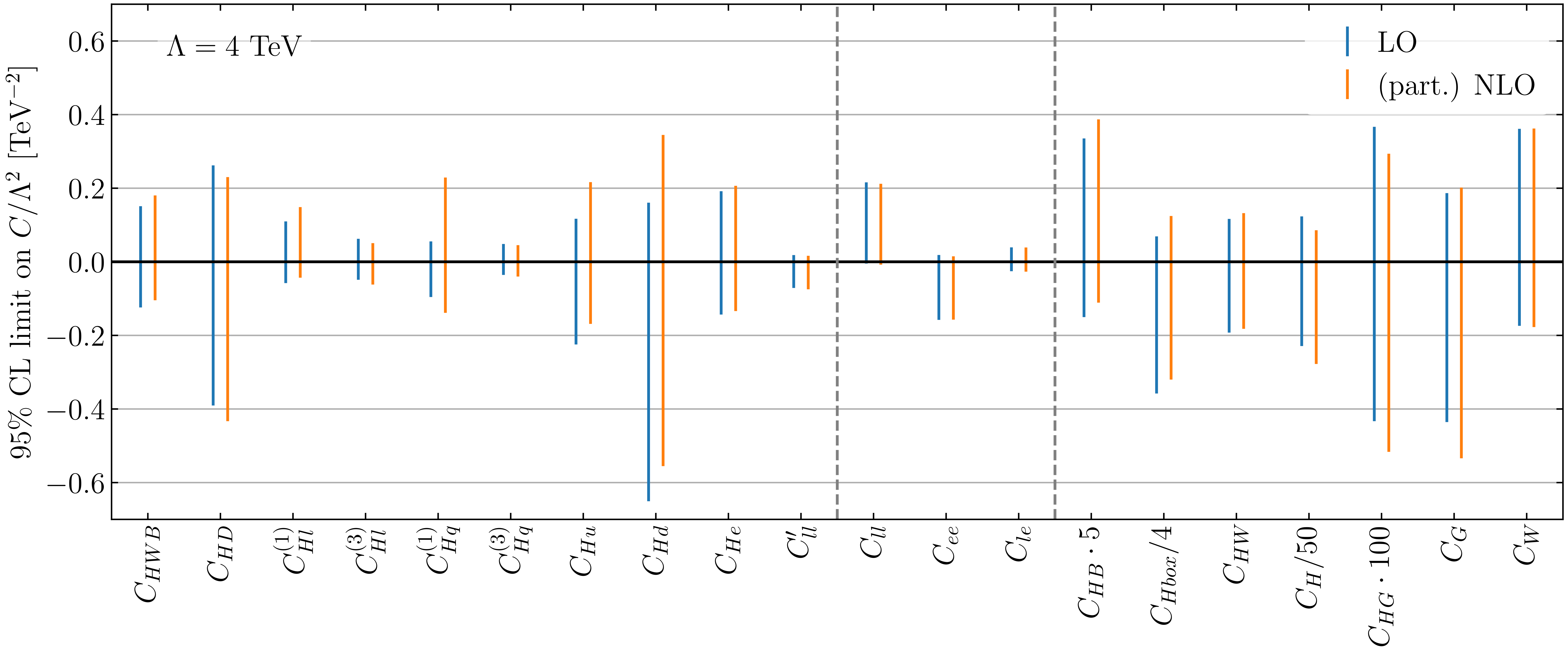
Combining LHC and non-LHC observables



Adapted from Ken Mimasu

Global fits

[Bartocci, AB, Hurth (2311.04963)]

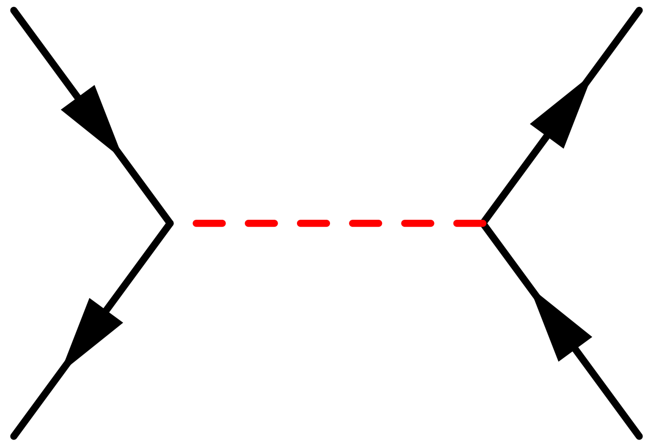


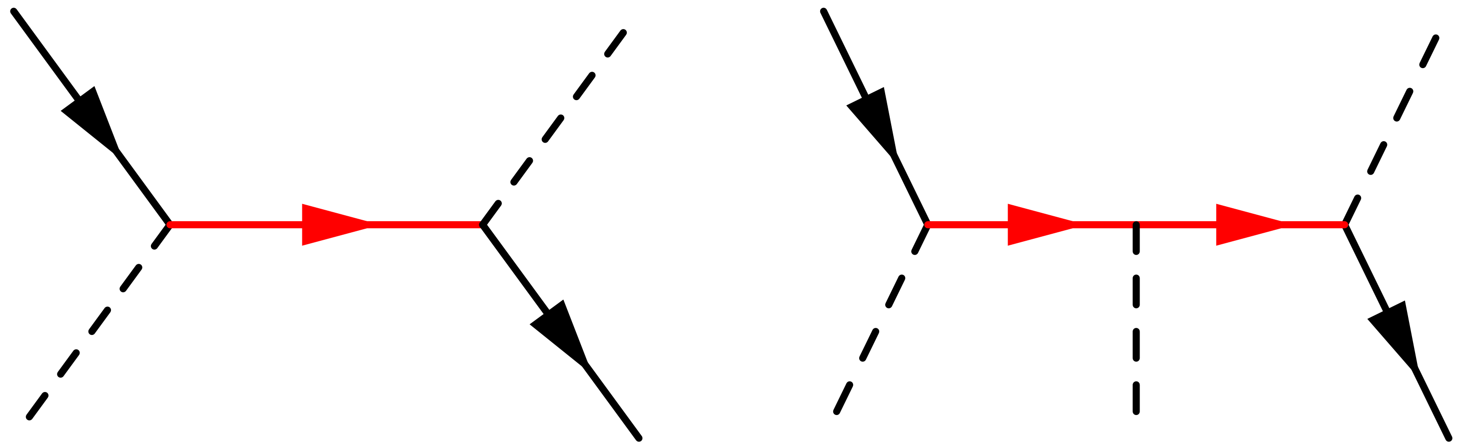
What do EFTs tell us about new physics?

Scalar

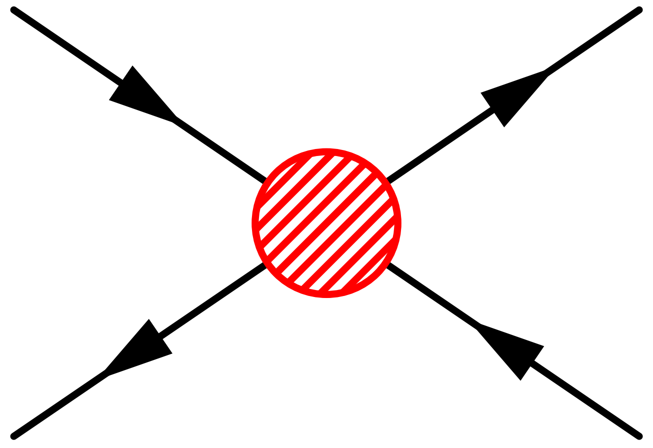
Vector-like lepton

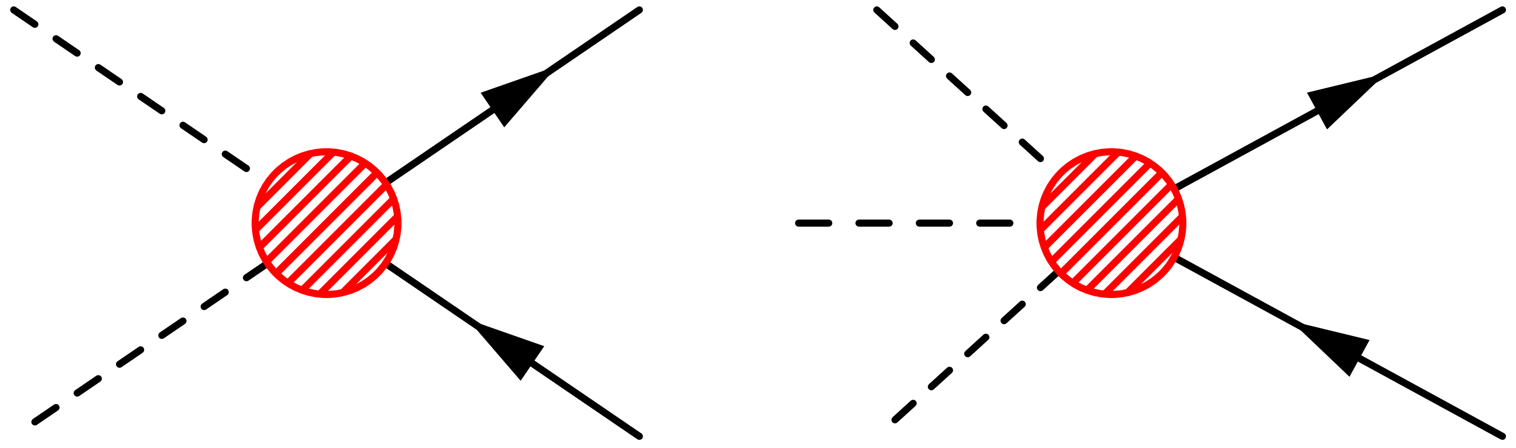
UV model





SMEFT





What do EFTs tell us about new physics?

UV model

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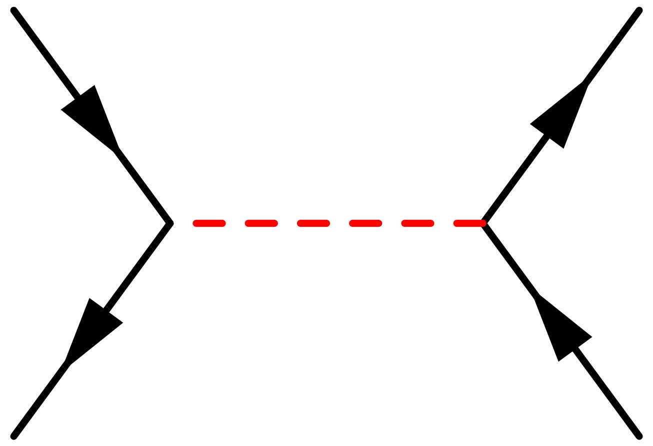
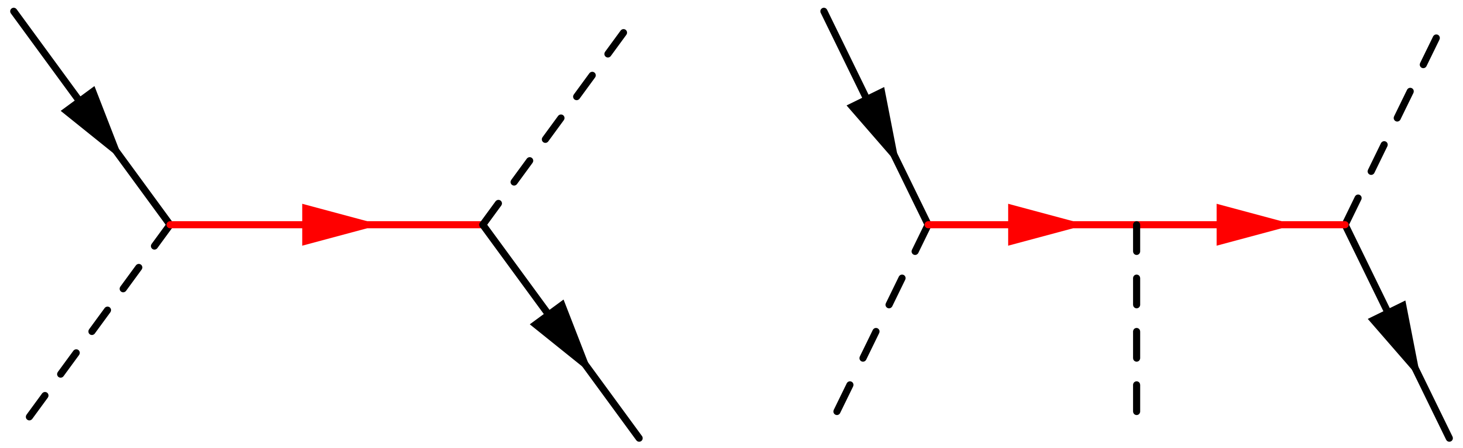
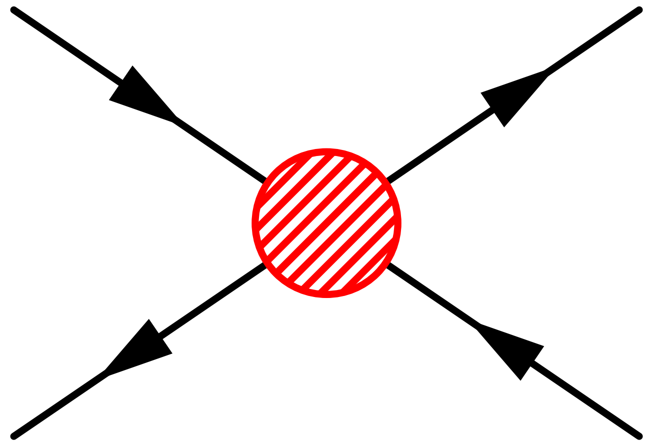
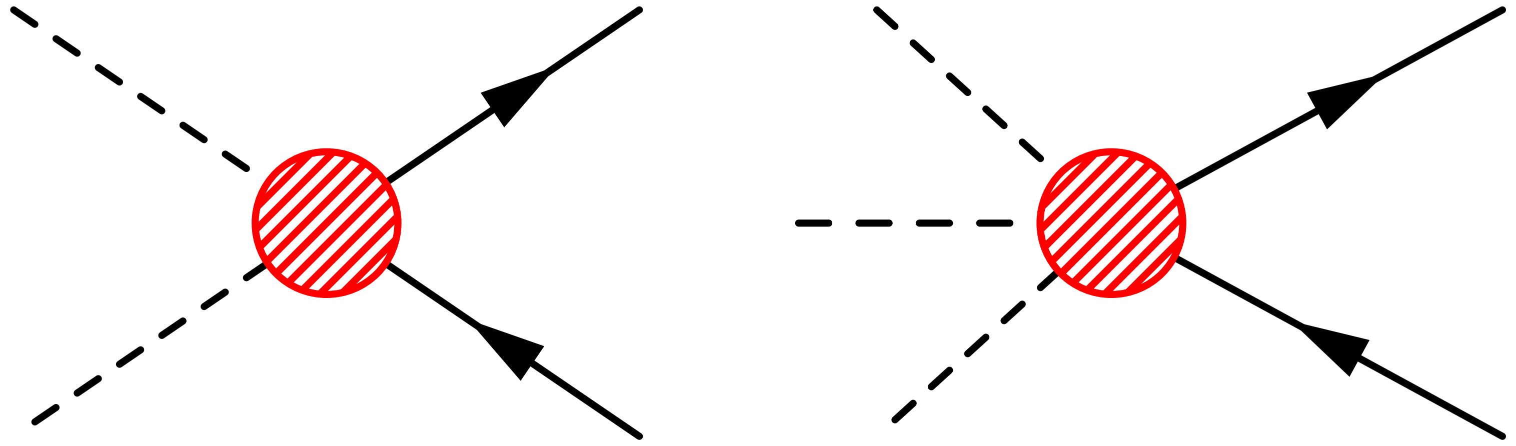


Vector-like lepton



SMEFT





Subset of operators induced

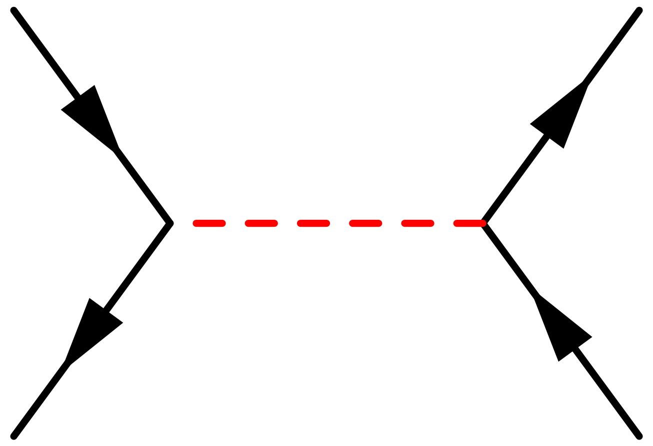
Correlations

C_{ll}

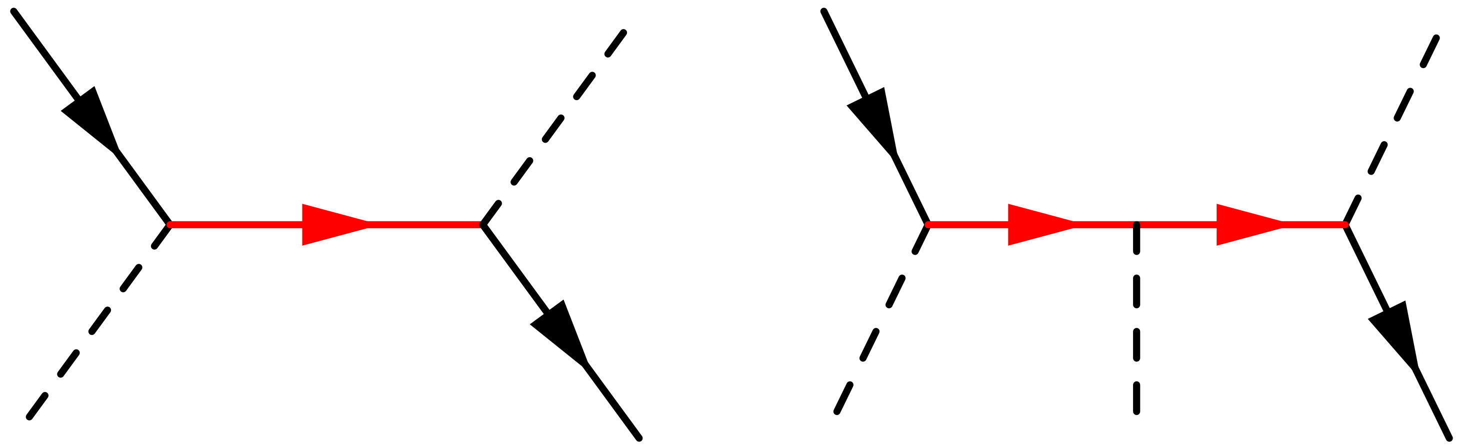
$C_{Hl}^{(3)}\,,\; C_{Hl}^{(1)}\,,\; C_{eH}$

What do EFTs tell us about new physics?

Scalar



Vector-like lepton



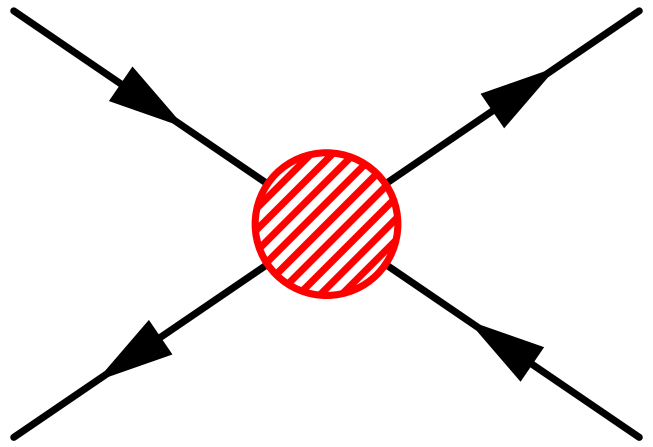
UV model

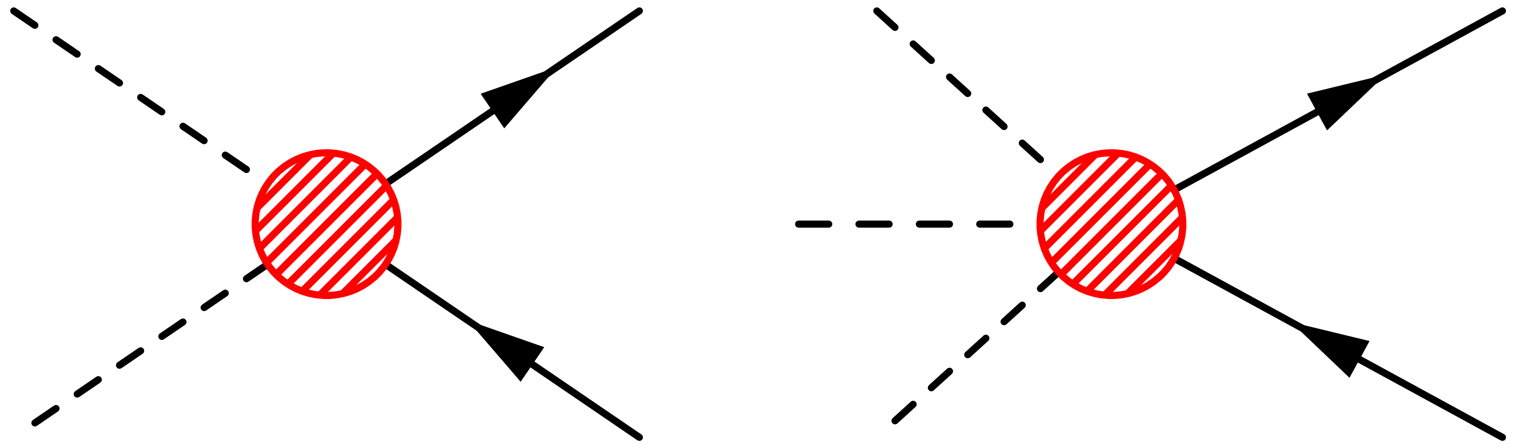
MatchmakerEFT [Carmona et al. (2112.10787)]

CoDEx [Bakshi, Chakrabortty, Patra (1808.04403)]

Matchete [Fuentes-Martín et al. (2212.04510)]

SMEFT





Subset of operators induced

Correlations

C_{ll}

$C^{(3)}_{Hl}\,,\; C^{(1)}_{Hl}\,,\; C_{eH}$

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)]

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

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)]

N(N)LO QCD effects

+ extensive preparatory work!

- 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)]
  - […]
- 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)]

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 do they depend on the input scheme?

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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Electroweak input schemes in SMEFT

Based on 2305.03763 with
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Input schemes

- 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
$\alpha(M_Z)$	$0.007127(2)$	

Why does the choice of input scheme matter?

In the SM:

- Precision of input parameters
- Convergence of the perturbative series

In the SMEFT:

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

Teaser: perturbative convergence for leptonic W decay

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

Different schemes

$W \to \tau\nu_\tau$	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%

Corrections to the LO Wilson coefficients at NLO

Teaser: perturbative convergence for leptonic W decay

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

Different schemes

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Corrections to the LO Wilson coefficients at NLO

Are there patterns and can they be understood?

Meet the schemes

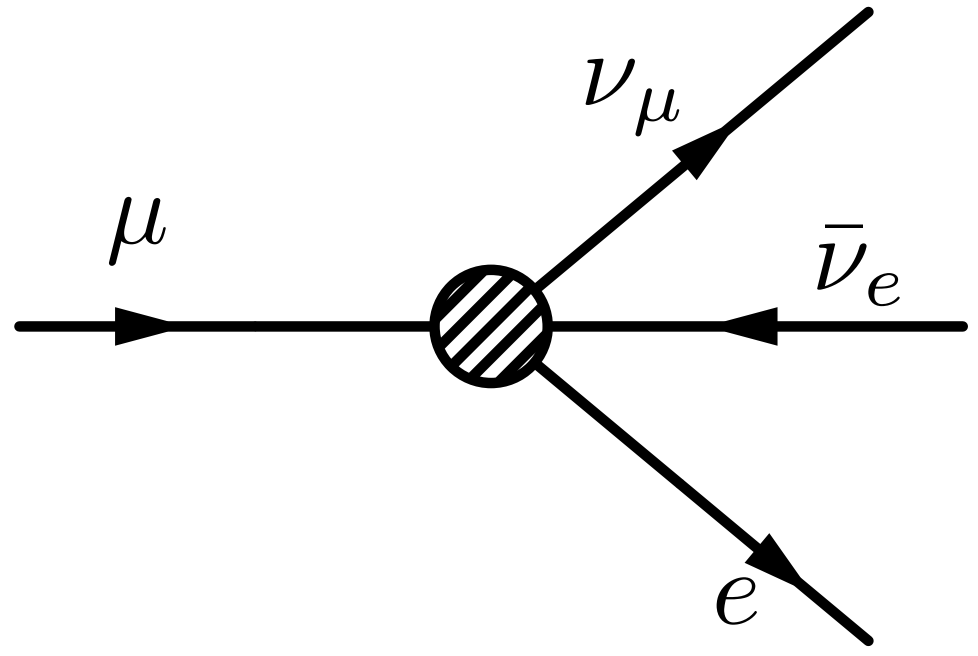
- **The α_μ scheme -** $\{G_F,\ M_W,\ M_Z\}$
  - M_W and M_Z are renormalised on-shell
  - G_F is renormalised through muon decay
  - Sometimes called "M_W scheme" in the SMEFT
- **The α scheme -** $\{\alpha,\ M_W,\ M_Z\}$
  - M_W and M_Z are renormalised on-shell
  - α is renormalised in $\overline{\mathrm{MS}}$-lite 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

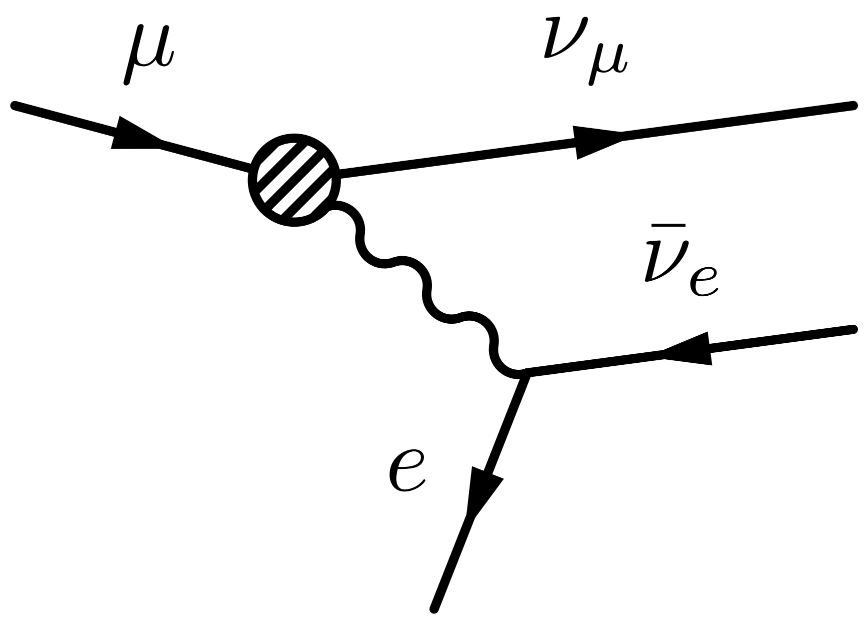
- Wilson coefficients renormalised in $\overline{\mathrm{MS}}$ scheme

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	One-loop	One-loop
SMEFT	SM	SMEFT

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

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	One-loop	One-loop
SMEFT	SM	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

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

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

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

The LEP scheme

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

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

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

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

NLO corrections

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

Physical processes

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

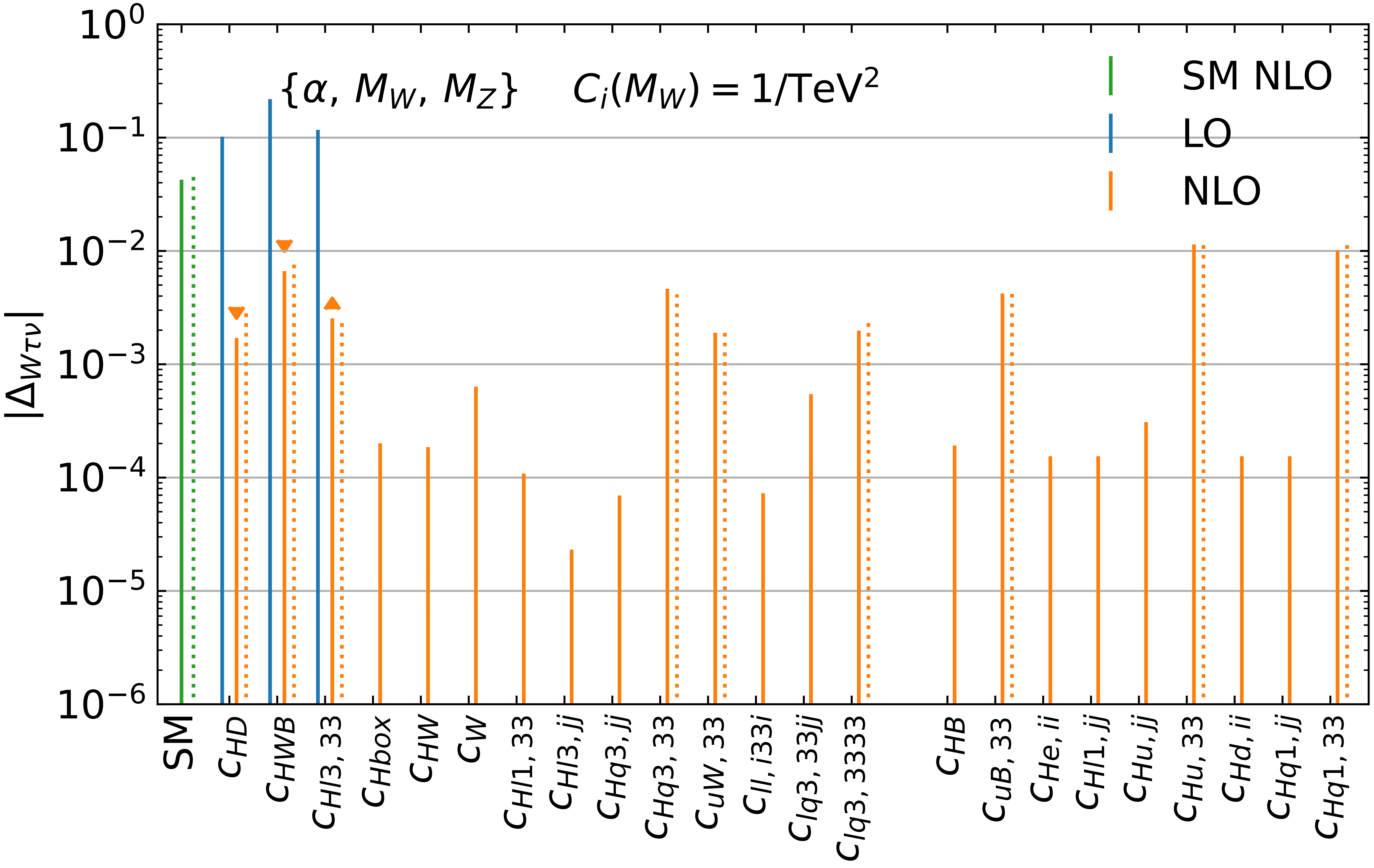
[Dawson, Giardino (1909.02000), (2201.09887)]

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

[Cullen, Pecjak, Scott (1512.02508)]

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

$\mu = M_W$

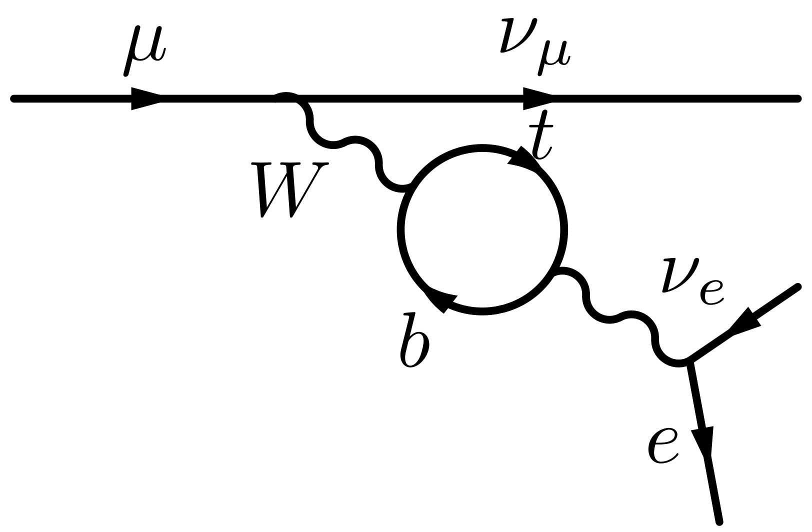
Corrections for W decay - SM

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

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

Tadpole and divergence free

$$K_W^{(4,1,\sigma)} = -\Delta v^{(4,1,\sigma)}_{\sigma,t} + 2\Delta M^{(4,1)}_{W,t}$$

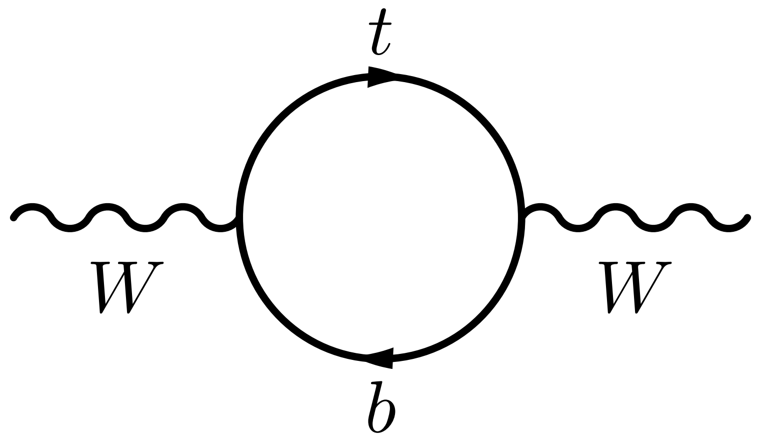


$$K_W^{(4,1,\alpha)} = \Delta r_t^{(4,1)} \approx -3.4\%$$

$$K_W^{(4,1,\mu)} = 0$$

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

$W \to \tau\nu_\tau$	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

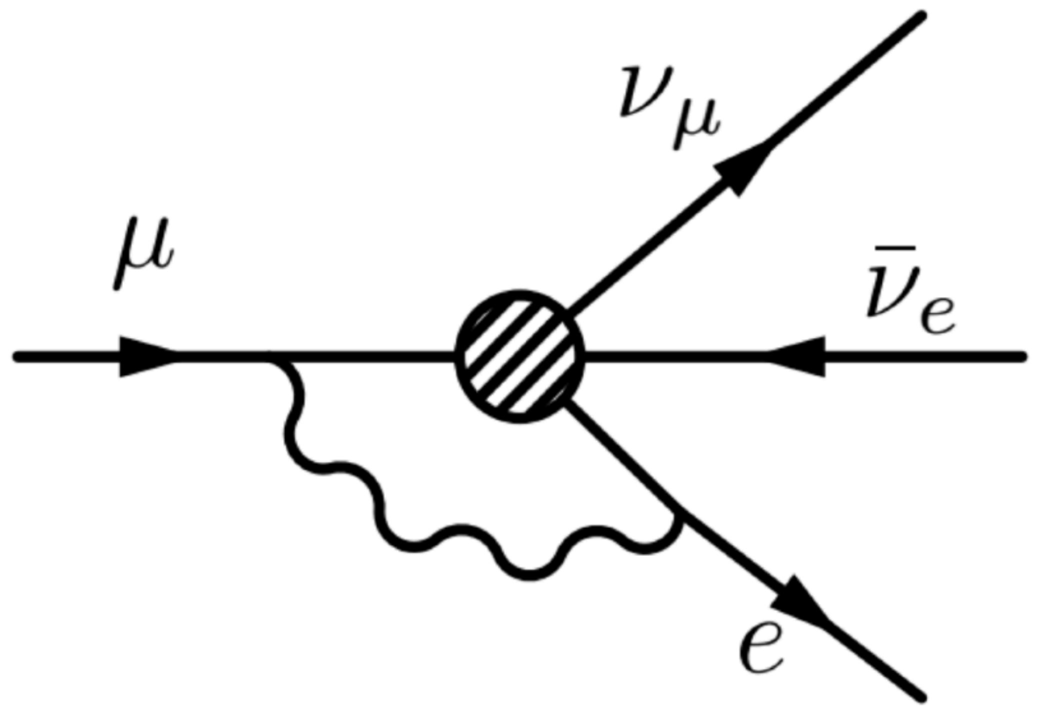
$W \to \tau\nu_\tau$	SM	C_{HD}	C_{HWB}	$C^{(3)}_{\substack{Hl\\jj}}$	$C^{(3)}_{\substack{Hl\\33}}$	$C_{\substack{ll\\1221}}$
α	-4.2%	-1.7%	-3.0%	—	2.2%	—
α_μ	-0.3%	—	—	2.5%	2.2%	-0.2%
LEP	2.0%	8.1%	3.2%	5.1%	4.6%	2.5%

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



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%	-	-
	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%

No vT dependence

MW dependence subdominant

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

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

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

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

Scheme dependent corrections larger in most cases

H decay α scheme - SMEFT

Scheme independent

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

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

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

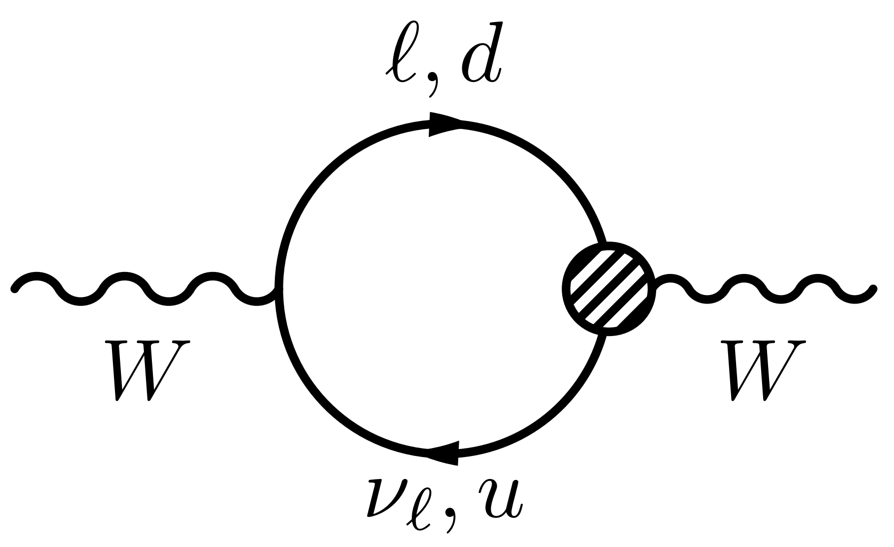
Z decay - resummation

$Z \to \tau\tau$	$C^{(3)}_{\substack{Hl \\ jj}}$	$C^{(3)}_{\substack{lq \\ jj33}}$	$C_{\substack{ll \\ 1221}}$	$C^{(3)}_{\substack{Hq \\ 33}}$	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	$-1.021^{+0.012}_{-0.010}$	$0.015^{+0.000}_{-0.001}$	$1.006^{+0.004}_{-0.004}$	$0.006^{+0.001}_{-0.000}$	$-0.260^{+0.017}_{-0.017}$	$0.267^{+0.009}_{-0.009}$	$-1.838^{+0.048}_{-0.048}$

Operators appearing at NLO

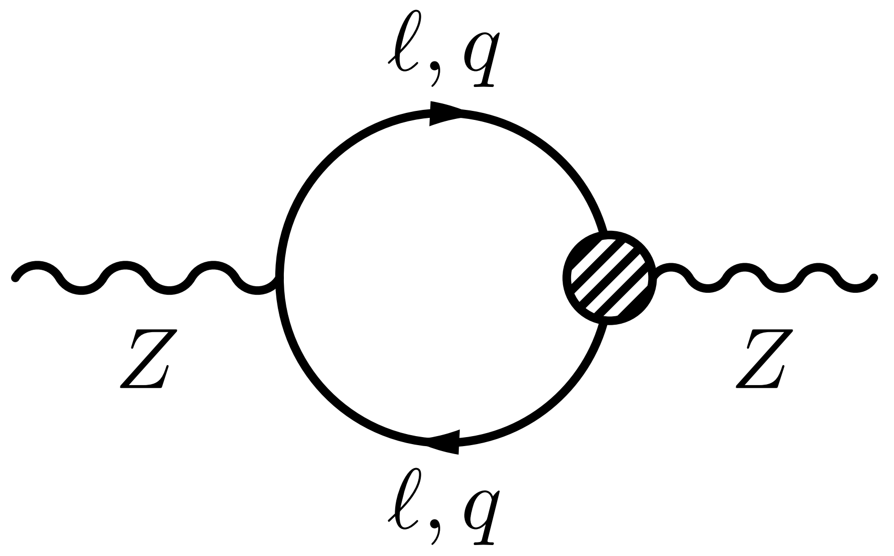
	MW	MZ	vT	Total
α	12	29	29	29
α_μ	13	30	12	33
LEP	33	30	12	33

$$M_{Z,0} = M_Z \left(1 + \frac{1}{v_\sigma^2} \Delta M_Z^{(4,1)} + \Delta M_Z^{(6,1)} - \Delta v_\mu^{(6,0,\sigma)} \Delta M_Z^{(4,1)}\right)$$



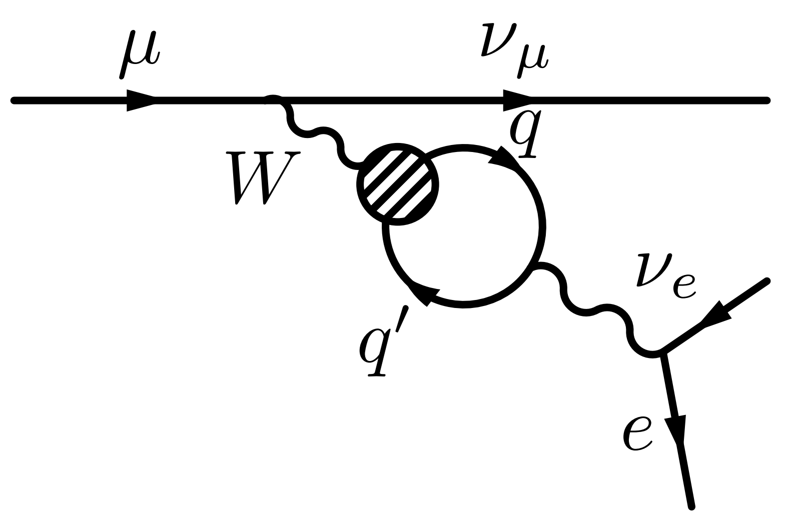
$C^{(3)}_{\substack{Hl\\ii}}$, $C^{(3)}_{\substack{Hq\\ii}}$

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

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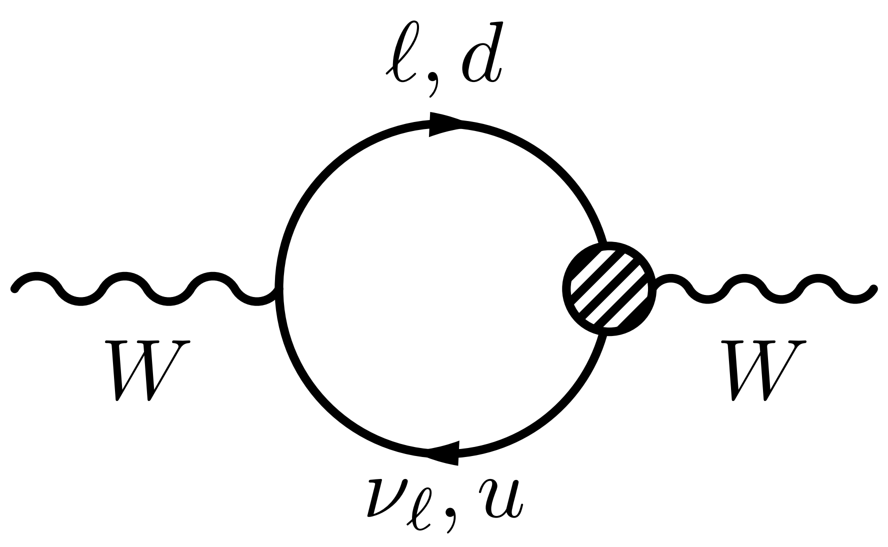
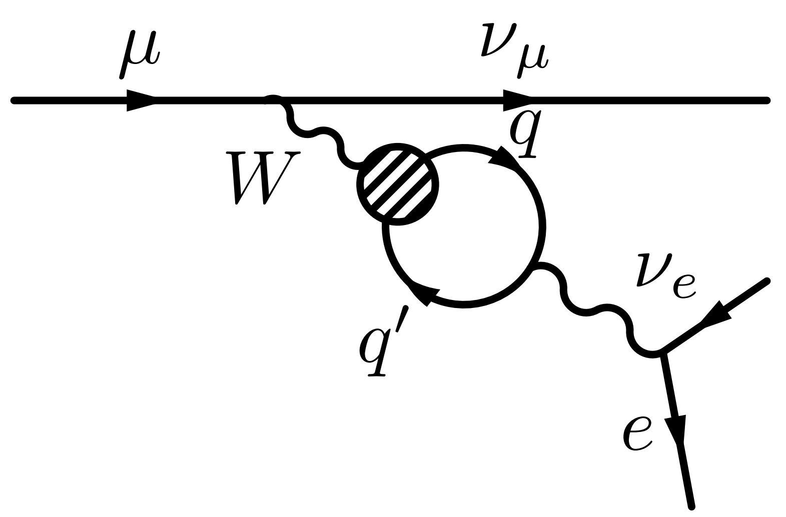


$C^{(3)}_{\substack{Hl\\ii}}, C^{(3)}_{\substack{Hq\\ii}}$

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

Electroweak schemes

- Compared three schemes
  - α_μ scheme - $\{G_F,\, M_W,\, M_Z\}$
  - α scheme - $\{\alpha,\, M_W,\, M_Z\}$
  - LEP scheme - $\{\alpha,\, G_F,\, M_Z\}$

- Scheme dependence of NLO corrections is process dependent
- However, **some corrections are universal** (potential for resummation)
- As a byproduct, we have derived relations that allow to shift from one scheme to another (based on the analytic result)

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What is the influence of SMEFT@NLO on global fits?

- Scheme dependence of NLO corrections is process dependent
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- As a byproduct, we have derived relations that allow to shift from one scheme to another (based on the analytic result)

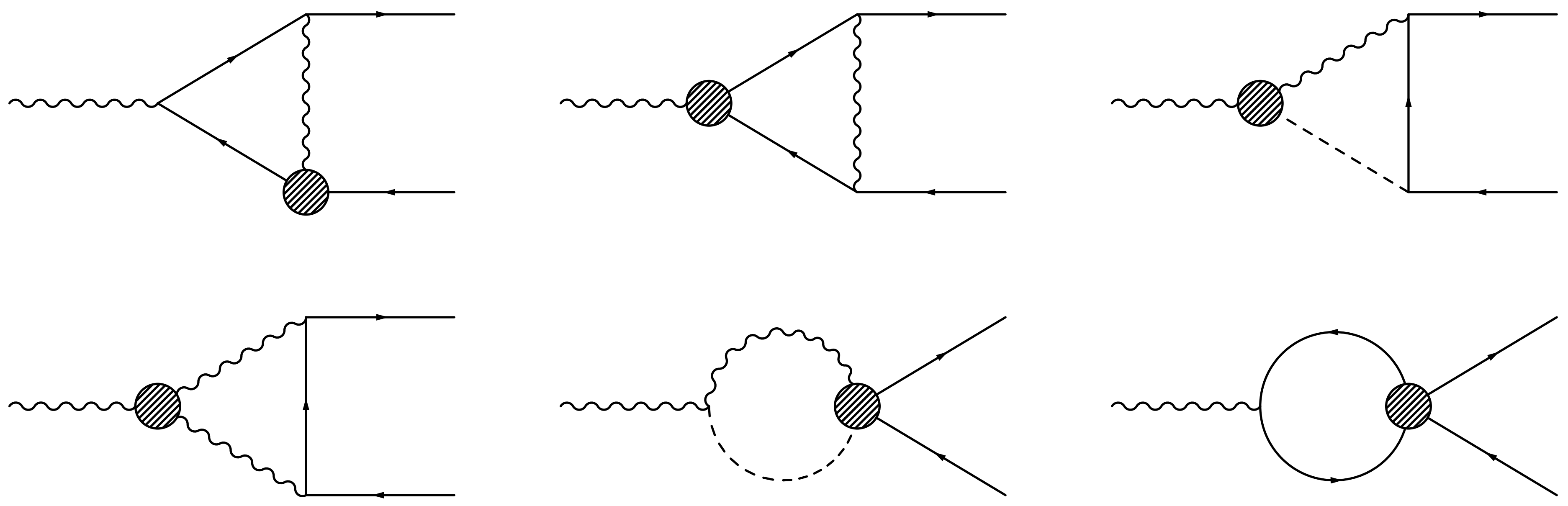
SMEFT EWPO@NLO: degeneracies

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

[Dawson, Giardino (1909.02000)], [AB, Pecjak, Scott, Smith (2305.03763)]

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

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



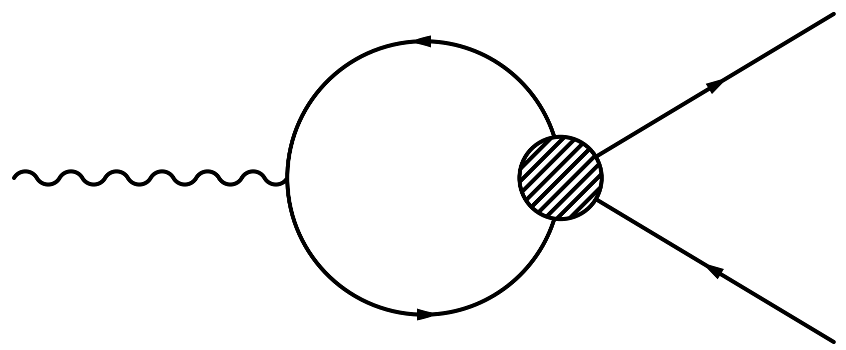
SMEFT@NLO: blessing & curse

precision & degeneracies

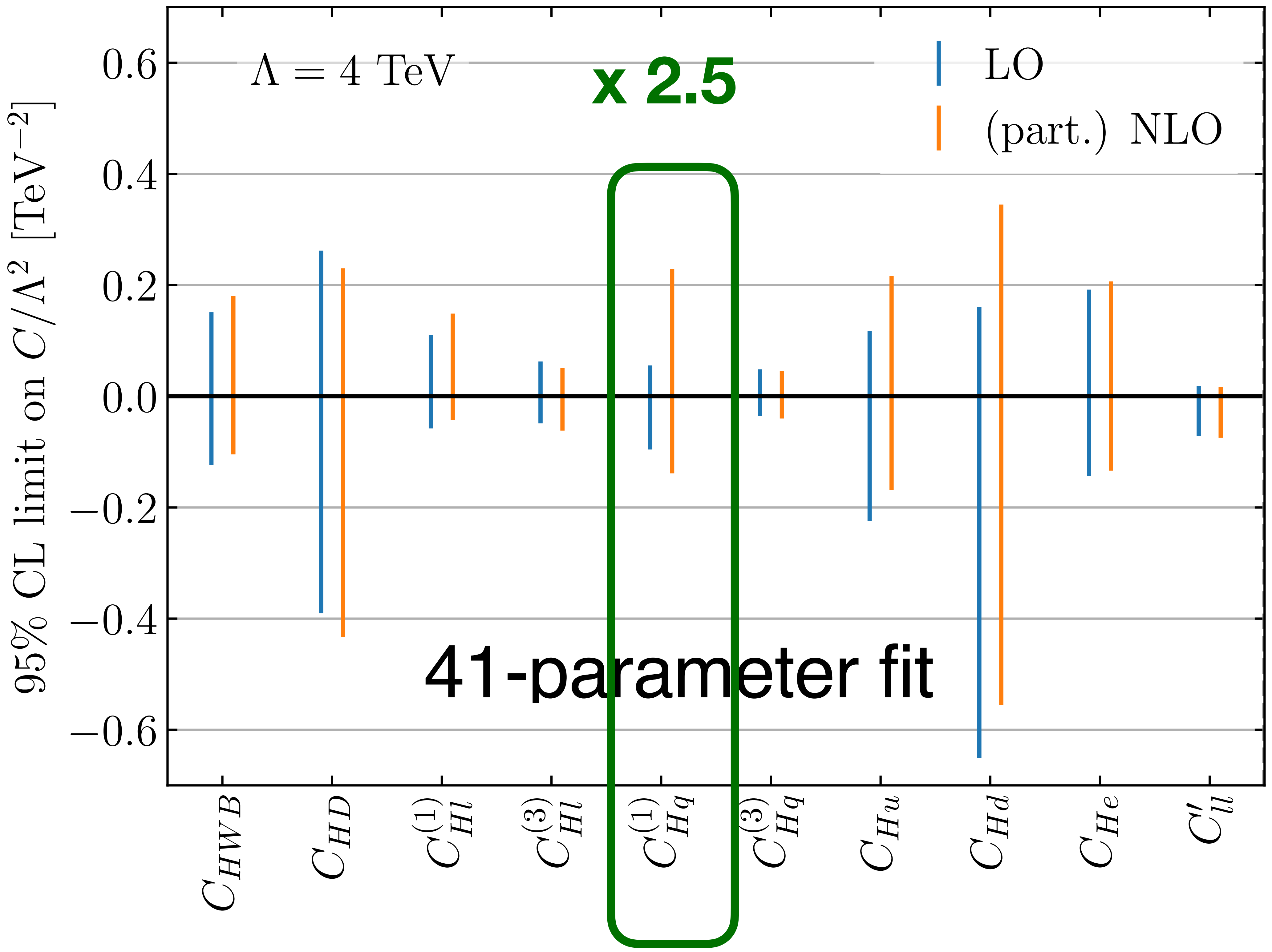
EWPO@NLO

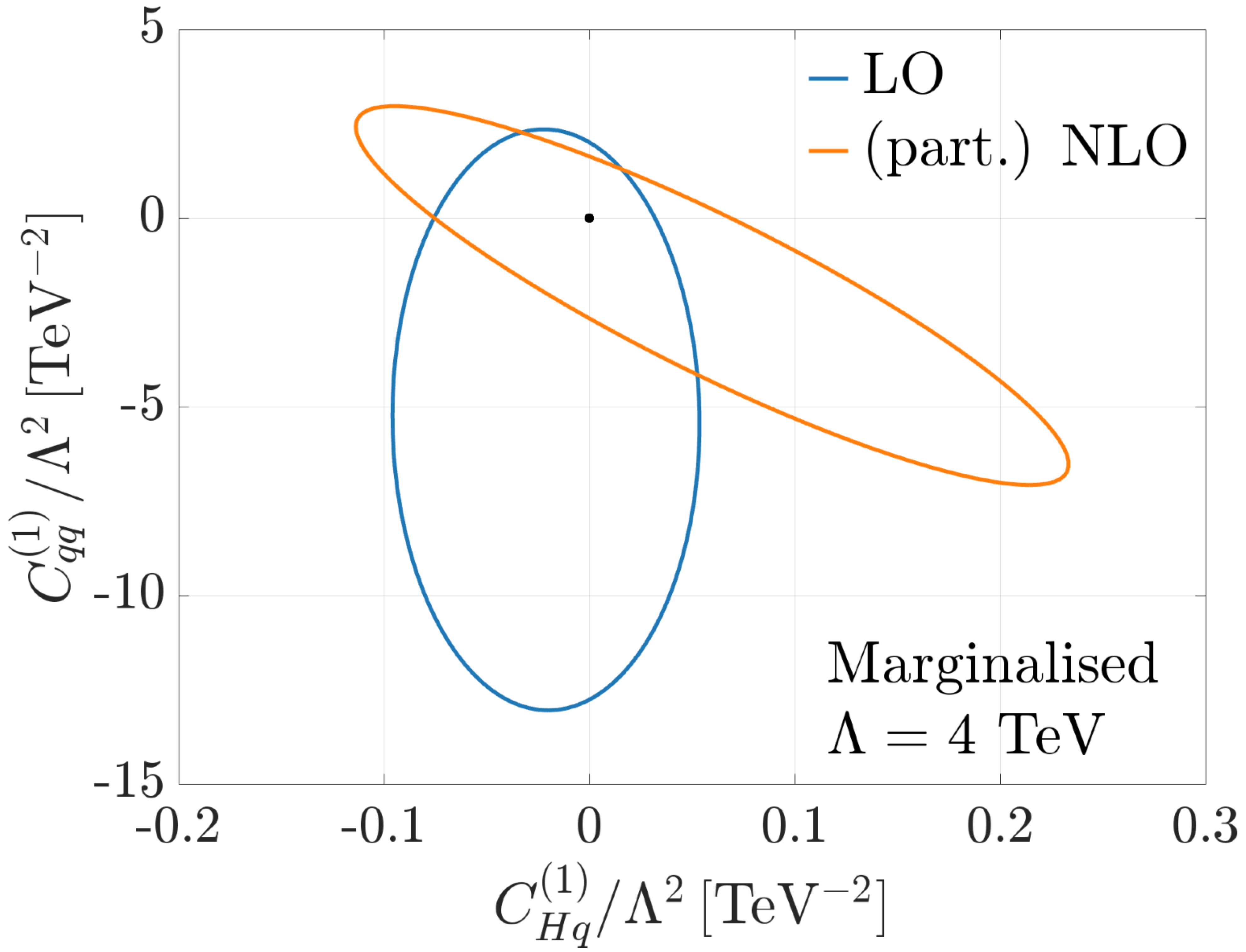
Assuming a $U(3)^5$ symmetry at the high scale

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



[Bartocci, AB, Hurth (2311.04963)]





Conclusions

EW input schemes for the SMEFT

- Corrections can be understood in the large-MT limit
- Possible to resum (some) corrections

- Ready to promote predictions to NLO accuracy in global fits

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Thank you for your attention!