Probing New Physics Indirectly at FCC-ee

Prospects from Electroweak and Flavour Observables

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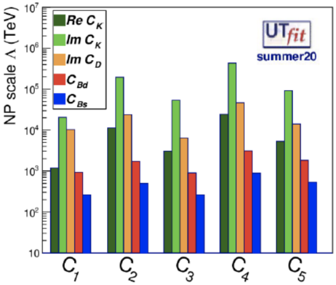
HELMHOLTZ

DESY.

The importance of indirect searches

- No direct discovery at high energies so far (after the Higgs)
- Historically, indirect searches have often preceded direct discovery
  - CP violation in K-$\bar{K}$
  - More recently, hints of the Higgs boson before LHC
- Can point to much higher scales than the ones currently probed at the LHC
- Today, look at:
  - Rare processes: FCNCs, LFV
  - Lepton-flavour universality tests: accident of the SM
- With higher precision, comeback also of flavour-conserving transitions
- **Assumption**: heavy New Physics (above the EW scale), decoupling

[**Barbieri** 2103.15635]



SMEFT

> At and around the EW scale, heavy NP can be integrated out
> Resulting EFT has the SM degrees of freedom and symmetry
> NP effects in higher-dimensional operators

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda_{\text{NP}}^2} \sum_i \mathcal{C}_i^{(6)} \mathcal{O}_i^{(6)} + \cdots$$ [1008.4884]

> Consistent framework allowing for (somewhat) model-independent explorations
> Correct way of dealing with scale hierarchies: one-loop RGE known
> Useful to discuss classes of models [1308.2627,1310.4838,1312.2014]

Indirect searches at FCC-ee

Working point	Z years 1-2	Z, later	WW	HZ	$t\bar{t}$		(s-channel H)
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163	240	340–350	365	m_H
Lumi/IP ($10^{34}\,cm^{-2}s^{-1}$)	115	230	28	8.5	0.95	1.55	(30)
Lumi/year (ab^{-1}, 2 IP)	24	48	6	1.7	0.2	0.34	(7)
Physics goal (ab^{-1})	150		10	5	0.2	1.5	(20)
Run time (year)	2	2	2	3	1	4	(3)
Number of events	5×10^{12} Z		10^8 WW	10^6 HZ + 25k WW $\to$ H	10^6 $t\bar{t}$ +200k HZ +50k WW $\to$ H		(6000)

Z pole (+ WW)

- **EWPOs**
- **Flavour**: $Z \to b\bar{b}, \tau^+\tau^-$

$ZH + t\bar{t}$

- Higgs trilinear: Sally Dawson's talk
- Off-pole EWPOs: new observables with tops

(see talk by Alessandro Valenti)

EWPOs at FCC-ee

- Measure Z- and W boson couplings to fermions through partial decay widths
- Current measurements largely from LEP, $\mathcal{O}(1‰)$ precision
- Expect an improvement by 10-100 at FCC-ee

	Observable	Definition
Z-pole	Γ_Z	$\sum_f \Gamma(Z \to f\bar{f})$
	σ_{had}	$\frac{12\pi}{m_Z} \frac{\Gamma(Z\to e^+e^-)\Gamma(Z\to q\bar{q})}{\Gamma_Z^2}$
	$R_f \; (f = e, \mu, \tau, c, b)$	$\frac{\Gamma(Z\to f\bar{f})}{\sum_q \Gamma(Z\to q\bar{q})}$
	$A_f \; (f = e, \mu, \tau, s, c, b)$	$\frac{\Gamma(Z\to f_L\bar{f}_L)-\Gamma(Z\to f_R\bar{f}_R)}{\Gamma(Z\to f\bar{f})}$
	$A_{\text{FB}}^{0,\ell} \; (\ell = e, \mu, \tau)$	$\frac{3}{4}A_e A_\ell$
	$A_q^{\text{FB}} \; (q = c, b)$	$\frac{3}{4}A_e A_q$
W-pole	m_W	$\sum_{f_1,f_2} \Gamma(W \to f_1 f_2)$
	Γ_W	
	$\text{Br}(W \to \ell\nu) \; (\ell = e, \mu, \tau)$	

[Table from 2404.12809]

Z-pole EWPOs ($\sqrt{s} = 91.2$ GeV)		
$\mathcal{O}_i$	$\delta/\Delta\ \mathcal{O}_i$ FCC-ee	CEPC
$\alpha(m_Z)^{-1}\,(\times 10^3)$	$\Delta = 2.7$ (1.2)	$\Delta = 17.8$
Γ_W (MeV)	$\Delta = 0.85$ (0.3)	$\Delta = 1.8$ (0.9)
Γ_Z (MeV)	$\Delta = 0.0028$ (0.025)	$\Delta = 0.005$ (0.025)
$A_e\,(\times 10^5)$	$\Delta = 0.5$ (2)	$\Delta = 1.5$
$A_\mu\,(\times 10^5)$	$\Delta = 1.6$ (2.2)	$\Delta = 3.0$ (1.8)
$A_\tau\,(\times 10^5)$	$\Delta = 0.35$ (20)	$\Delta = 1.2$ (6.9)
$A_b\,(\times 10^5)$	$\Delta = 1.7$ (21)	$\Delta = 3$ (21)
$A_c\,(\times 10^5)$	$\Delta = 14$ (15)	$\Delta = 6$ (30)
σ^0_{had} (pb)	$\Delta = 0.025$ (4)	$\Delta = 0.05$ (2)
$R_e\,(\times 10^3)$	$\delta = 0.0028$ (0.3)	$\delta = 0.003$ (0.2)
$R_\mu\,(\times 10^3)$	$\delta = 0.0021$ (0.05)	$\delta = 0.003$ (0.1)
$R_\tau\,(\times 10^3)$	$\delta = 0.0021$ (0.1)	$\delta = 0.003$ (0.1)
$R_b\,(\times 10^3)$	$\delta = 0.001$ (0.3)	$\delta = 0.005$ (0.2)
$R_c\,(\times 10^3)$	$\delta = 0.011$ (1.5)	$\delta = 0.02$ (1)

EWPOs in SMEFT at tree level

- Sensitive to 23 parameters

$[\mathcal{O}_{H\ell}^{(1)}]_{pr} =$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{\ell}_p \gamma^\mu \ell_r)$	$[\mathcal{O}_{Hu}]_{pr} =$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
$[\mathcal{O}_{H\ell}^{(3)}]_{pr} =$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{\ell}_p \tau^I \gamma^\mu \ell_r)$	$[\mathcal{O}_{Hd}]_{pr} =$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
$[\mathcal{O}_{Hq}^{(1)}]_{pr} =$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	$\mathcal{O}_{HD} =$	$\lvert H^\dagger D_\mu H \rvert^2$
$[\mathcal{O}_{Hq}^{(3)}]_{pr} =$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	$\mathcal{O}_{HWB} =$	$(H^\dagger \tau^I H) W^I_{\mu\nu} B^{\mu\nu}$
$[\mathcal{O}_{He}]_{pr} =$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	$[\mathcal{O}_{\ell\ell}]_{1221} =$	$(\bar{\ell}_1 \gamma^\mu \ell_2)(\bar{\ell}_2 \gamma^\mu \ell_1)$

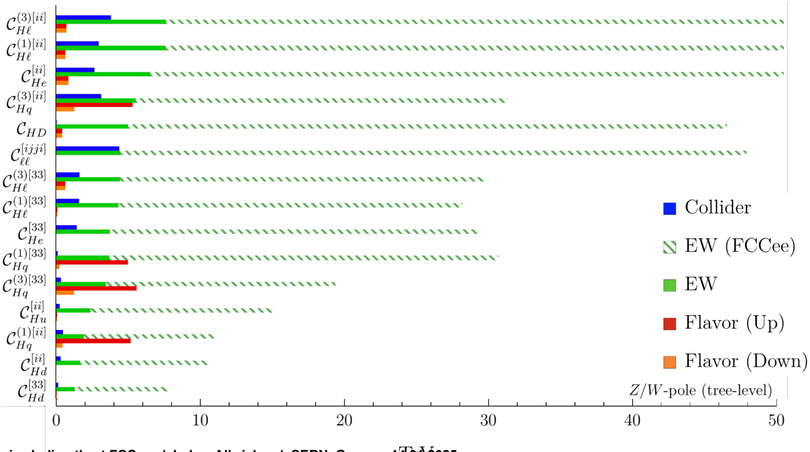
- $\mathcal{A} = \mathcal{A}_0 \left(\frac{g_{\text{SM}}}{m_W^2} + \frac{g_{\text{NP}}}{\Lambda_{\text{NP}}^2} \right)$
- 10^5 improvement in statistics: $\Lambda_{\text{NP}} \to \simeq 20 \Lambda_{\text{NP}}^{\text{now}}$
- Naive scaling, systematics (and theory errors) have an effect at such precision

(see talk by Jaco ter Hoeve)

Projections for tree-level operators

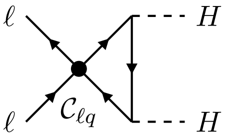
[LA, Cornella, Isidori, Stefanek 2311.00020]

- $U(2)^5$ symmetry acting on the light generations imposed on SMEFT
- From current $\mathcal{O}$(few)TeV to 30 TeV range at FCC



The importance of RGE effects

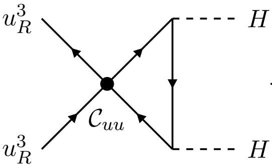
- Loop suppression $\frac{1}{16\pi^2} g^2 \log \frac{m_Z}{\Lambda} \simeq -(0.14)^2$ for $g = 1$ and $\Lambda = 2$ TeV
- Can still probe loop-suppressed effects up to the few TeV range
- LL effects:



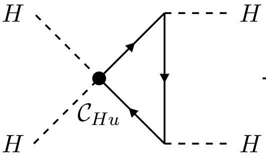
$$[\dot{\mathcal{C}}^{(3)}_{Hl}]_{\alpha\beta} \supset 2N_c [\mathcal{C}^{(3)}_{lq}]_{\alpha\beta kl} [Y_d^\dagger Y_d + Y_u^\dagger Y_u]_{lk}$$

  - Particularly relevant if y_t is involved
  - Effects e.g. in $Z \to \tau\tau$

- Sometimes even NLL effects can be relevant



$\longrightarrow \mathcal{C}_{Hu}$

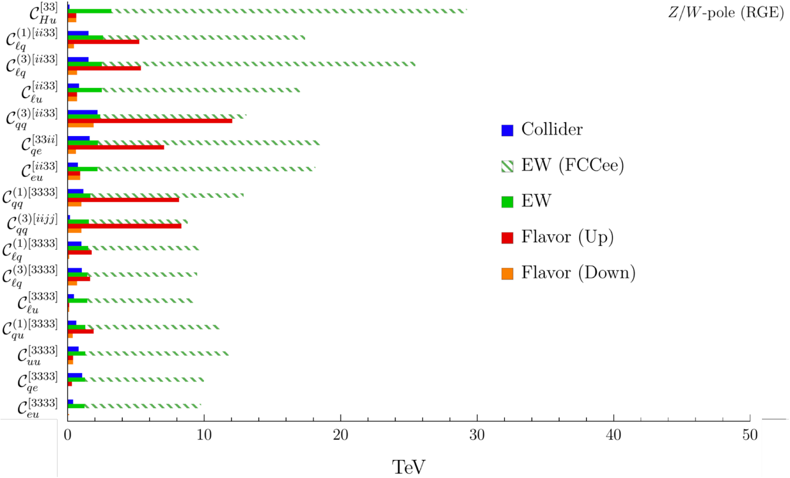


$\longrightarrow \mathcal{C}_{HD} \quad \to \delta m_W$

Projections from loop-level EWPOs

[LA, Cornella, Isidori, Stefanek 2311.00020]

- $\mathcal{O}(10)$ TeV constraints for four-fermion operators (3rd gen. quarks)



From SMEFT to the UV

- SMEFT as a “bookkeeping” tool
- Both single-parameter fits and global fits do not carry the same information as an explicit model
- Not all of the SMEFT parameter space can be spanned by UV models
- In particular, flat directions may not be populated
- Even if populated at tree-level, loops (RGE) will typically break them

Which models with heavy NP can be probed at FCC-ee? Which scales?

Linear extensions of the Standard Model

[De Blas et al. 1711.10391]

- Finite number of new states can couple linearly to the SM fields: *Granada dictionary*
- Matching to SMEFT at $d = 6$ well known

Scalar	$\mathcal{S}$ $(1,1)_0$	$\mathcal{S}_1$ $(1,1)_1$	$\mathcal{S}_2$ $(1,1)_2$	φ $(1,2)_{\frac{1}{2}}$	Ξ $(1,3)_0$	Ξ_1 $(1,3)_1$	Θ_1 $(1,4)_{\frac{1}{2}}$	Θ_3 $(1,4)_{\frac{3}{2}}$
	ω_1 $(3,1)_{-\frac{1}{3}}$	ω_2 $(3,1)_{\frac{2}{3}}$	ω_4 $(3,1)_{-\frac{4}{3}}$	Π_1 $(3,2)_{\frac{1}{6}}$	Π_7 $(3,2)_{\frac{7}{6}}$	ζ $(3,3)_{-\frac{1}{3}}$		
	Ω_1 $(6,1)_{\frac{1}{3}}$	Ω_2 $(6,1)_{-\frac{2}{3}}$	Ω_4 $(6,1)_{\frac{4}{3}}$	Υ $(6,3)_{\frac{1}{3}}$	Φ $(8,2)_{\frac{1}{2}}$			
Fermion	N $(1,1)_0$	E $(1,1)_{-1}$	Δ_1 $(1,2)_{-\frac{1}{2}}$	Δ_3 $(1,2)_{-\frac{3}{2}}$	Σ $(1,3)_0$	Σ_1 $(1,3)_{-1}$		
	U $(3,1)_{\frac{2}{3}}$	D $(3,1)_{-\frac{1}{3}}$	Q_1 $(3,2)_{\frac{1}{6}}$	Q_5 $(3,2)_{-\frac{5}{6}}$	Q_7 $(3,2)_{\frac{7}{6}}$	T_1 $(3,3)_{-\frac{1}{3}}$	T_2 $(3,3)_{\frac{2}{3}}$	
Vector	$\mathcal{B}$ $(1,1)_0$	$\mathcal{B}_1$ $(1,1)_1$	$\mathcal{W}$ $(1,3)_0$	$\mathcal{W}_1$ $(1,3)_1$	$\mathcal{G}$ $(8,1)_0$	$\mathcal{G}_1$ $(8,1)_1$	$\mathcal{H}$ $(8,3)_0$	$\mathcal{L}_1$ $(1,2)_{\frac{1}{2}}$
	$\mathcal{L}_3$ $(1,2)_{-\frac{3}{2}}$	$\mathcal{U}_2$ $(3,1)_{\frac{2}{3}}$	$\mathcal{U}_5$ $(3,1)_{\frac{5}{3}}$	$\mathcal{Q}_1$ $(3,2)_{\frac{1}{6}}$	$\mathcal{Q}_5$ $(3,2)_{-\frac{5}{6}}$	$\mathcal{X}$ $(3,3)_{\frac{2}{3}}$	$\mathcal{Y}_1$ $(\bar{6},2)_{\frac{1}{6}}$	$\mathcal{Y}_5$ $(\bar{6},2)_{-\frac{5}{6}}$

All (except very few) new states are probed by EWPOs at one-loop

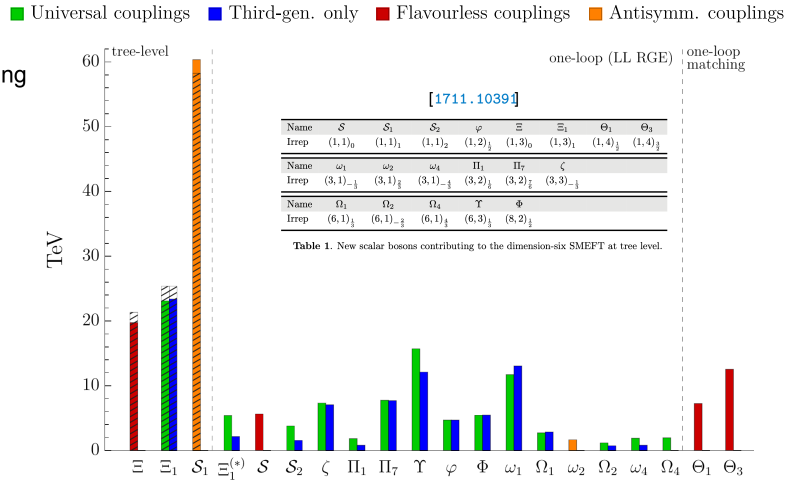
Analysis strategy

- Assume SM central values + FCC-ee expected errors
- Integrate out one state of the Granada dictionary at a time, assuming couplings are defined at a scale $\Lambda = 2$ TeV
- Consider only couplings at $d \leq 4$
- RGE evolve from 2 TeV to m_Z (first LL only)
  $\rightarrow$ use `DsixTools` `[2010.16341]`
- Get bounds on the mediator mass for $y, g, \lambda = 1$
  (dimensionful couplings $\kappa = 5$ TeV)
- Flavour assumptions:
  (a) **Flavour-universal** couplings: $y_{11} = y_{22} = y_{33}$ (or $y_1 = y_2 = y_3$ for fermions), and $y_{ij} = 0$ for $i \neq j$.
  (b) **Third-generation only** couplings: $y_{ij} = y\delta_{i3}\delta_{j3}$

Scalars

$^{(*)}$ = special choice of couplings to avoid tree-level EWPO

▨ = no running



[1711.10391]

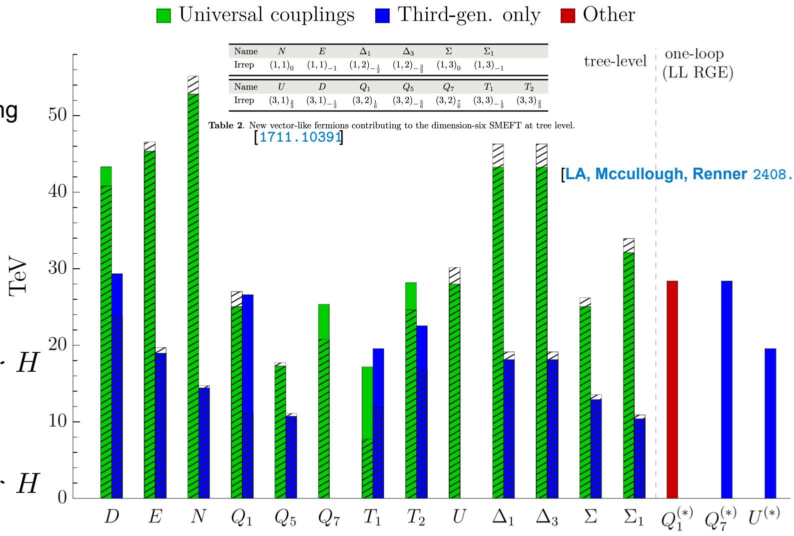
Name	$\mathcal{S}$	$\mathcal{S}_1$	$\mathcal{S}_2$	φ	Ξ	Ξ_1	Θ_1	Θ_3
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,1)_2$	$(1,2)_{\frac{1}{2}}$	$(1,3)_0$	$(1,3)_1$	$(1,4)_{\frac{1}{2}}$	$(1,4)_{\frac{3}{2}}$
Name	ω_1	ω_2	ω_4	Π_1	Π_7	ζ		
Irrep	$(3,1)_{-\frac{1}{3}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{4}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$		
Name	Ω_1	Ω_2	Ω_4	Υ	Φ			
Irrep	$(6,1)_{\frac{1}{3}}$	$(6,1)_{-\frac{2}{3}}$	$(6,1)_{\frac{4}{3}}$	$(6,3)_{\frac{1}{3}}$	$(8,2)_{\frac{1}{2}}$			

Table 1. New scalar bosons contributing to the dimension-six SMEFT at tree level.

[LA, Mccullough, Renner 2408.03992]

Fermions

$^{(*)}$ = special choice of couplings to avoid tree-level EWPO

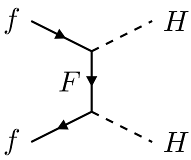


Name	N	E	Δ_1	Δ_3	Σ	Σ_1	
Irrep	$(1,1)_0$	$(1,1)_{-1}$	$(1,2)_{-\frac{1}{2}}$	$(1,2)_{-\frac{3}{2}}$	$(1,3)_0$	$(1,3)_{-1}$	
Name	U	D	Q_1	Q_5	Q_7	T_1	T_2
Irrep	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$	$(3,3)_{\frac{2}{3}}$

Table 2. New vector-like fermions contributing to the dimension-six SMEFT at tree level.
[1711.10391]

[**LA, Mccullough, Renner** 2408.03992]

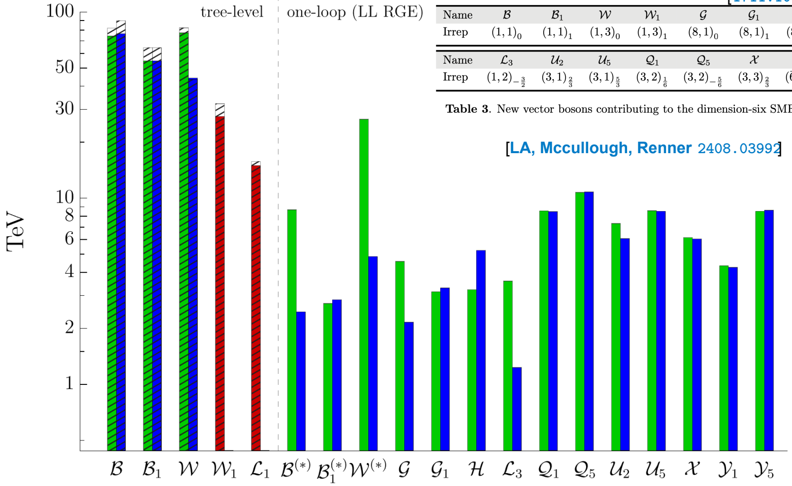
▨ = no running



Vectors

$^{(*)}$ = special choice of couplings to avoid tree-level EWPO

▨ = no running



[1711.10391]

Name	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{W}$	$\mathcal{W}_1$	$\mathcal{G}$	$\mathcal{G}_1$	$\mathcal{H}$	$\mathcal{L}_1$
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,3)_0$	$(1,3)_1$	$(8,1)_0$	$(8,1)_1$	$(8,3)_0$	$(1,2)_{\frac{1}{2}}$

Name	$\mathcal{L}_3$	$\mathcal{U}_2$	$\mathcal{U}_5$	$\mathcal{Q}_1$	$\mathcal{Q}_5$	$\mathcal{X}$	$\mathcal{Y}_1$	$\mathcal{Y}_5$
Irrep	$(1,2)_{-\frac{3}{2}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,3)_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$

Table 3. New vector bosons contributing to the dimension-six SMEFT at tree level.

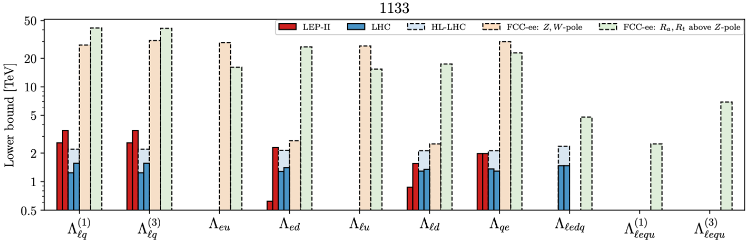
[LA, Mccullough, Renner 2408.03992]

EWPOs off the pole: four-fermion operators

Energy-enhancement compensates luminosity

- Four-fermion operators, e.g. $eebb$, have negligible contribution on the pole to e.g. R_b
- Off the pole, energy-enhanced amplitudes in the EFT
- Comparable sensitivity w.r.to the pole (loop effects)
- Can dominate when the RGE effect is smaller (e.g. gauge coupling running)
- At $t\bar{t}$, define $R_t = \sigma(e^+e^- \to t\bar{t})/\sigma(e^+e^- \to q\bar{q})$

[Greljo, Tiblom, Valenti 2411.02485]

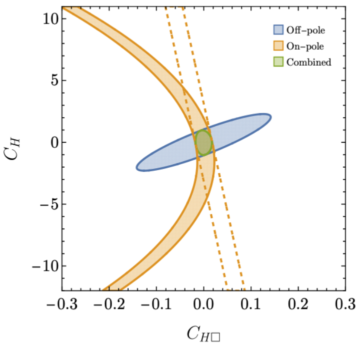


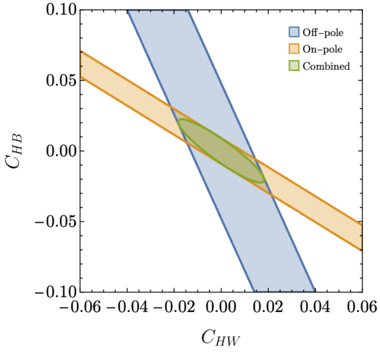
Higgs on the Z-pole

[Maura, Stefanek, You 2412.14241]

Precision against loops

- Modified hVV coupling gives, at NLO, contribution in gauge boson self-energy
- EWPOs on the Z-pole can be sensitive and complementary probes
- See Ben Stefanek's talk for this and more





Summary on EWPOs

The power of flavour-conserving transitions

- EWPOs on the Z-pole powerful probes of NP
  - $\mathcal{O}(> 30)$ TeV bounds for tree-level operators, $\mathcal{O}(1-10)$ TeV for loop level
  - Linear extensions of the SM probed almost entirely
- Here: only tree-level matching + RGE effects, for full one-loop matching see Hoa's talk (scalars + fermions)
- Off-pole measurements can be complementary

Flavour prospects at FCC-ee

Table 7: Expected production yields of heavy-flavored particles at Belle II (50 ab^{-1}) and FCC-ee (Z pole). The $X/\overline{X}$ represents the production of a B-hadron or its charge conjugated state. The Z branching fractions and hadronization rates are taken from [2].

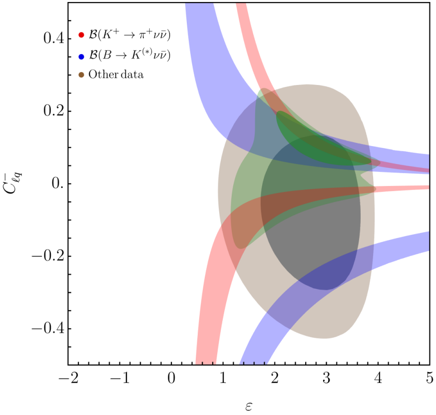
Particle production (10^9)	$B^0/\overline{B}^0$	B^+/B^-	$B_s^0/\overline{B}_s^0$	$B_c^+/\overline{B}_c^-$	$\Lambda_b/\overline{\Lambda}_b$	$c\bar{c}$	$\tau^+\tau^-$
Belle II	27.5	27.5	n/a	n/a	n/a	65	45
FCC-ee	620	620	150	4	130	600	170

- $\sim 10^3$ more $b\bar{b}$ and $\tau^+\tau^-$ w.r.to Belle
- $\sim \times 5$ improvement in Λ_{NP} reach
- ~ 30 more than Belle-II projections
- Access to B_s and B_c
- Great advantage due to clean environment and boosted final states (cf. e.g. missing energy measurements at LHCb)
- Fore example, expect 10^{-4} precision in τ LFU measurements

A case study

Third-generation New Physics in semileptonic transitions

[LA, Bordone, Isidori, Piazza, Stanzione 2410.21444]



- Long-standing tension in R_D/R_{D^*}
- Recently, exp. progress on dineutrino modes: $B \to K\nu\bar{\nu}$ ($K \to \pi\nu\bar{\nu}$)
- Consistent with third-generation NP (ν_τ)
- **How could FCC-ee help?**

Correlated observables: future prospects

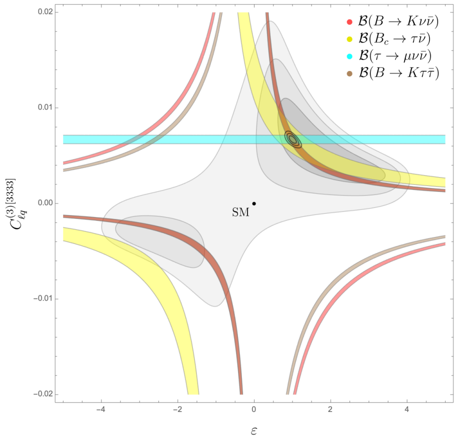
[LA, Isidori, Pešut WIP]

- Only third-gen. flavour indices:
  $\mathcal{O}_{\ell q}^{(3)} = (\bar{\ell}_L^3 \sigma^I \gamma_\mu \ell_L^3)(\bar{q}_L^3 \sigma^I \gamma^\mu q_L^3)$
- Flavour-violating effects via $U(2)_q$ breaking spurion

$$\tilde{V} = -\varepsilon V_{ts} \begin{pmatrix} V_{td}/V_{ts} \\ 1 \end{pmatrix}$$

- $q_L^3 \to q_L^3 + \tilde{V}_i q_L^i$

Observable	FCC-ee expected precision
$B \to K\nu\bar{\nu}$	5%
$B_c \to \tau\nu$	1%
$\tau \to \mu\nu\bar{\nu}$ (LFU ratio)	10^{-4}
$B \to K\tau\tau$	10%



(see talk by Joe Davighi for a review)

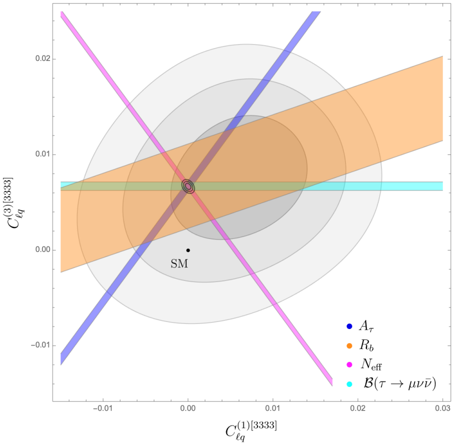
Flavour v. EWPOs

$$\mathcal{O}_{\ell q}^{(1)} = (\bar{\ell}_L^3 \gamma_\mu \ell_L^3)(\bar{q}_L^3 \gamma^\mu q_L^3)$$
$$\mathcal{O}_{\ell q}^{(3)} = (\bar{\ell}_L^3 \sigma^I \gamma_\mu \ell_L^3)(\bar{q}_L^3 \sigma^I \gamma^\mu q_L^3)$$

- Flavour-conserving directions (no spurions) badly probed by flavour
- Interplay with EWPOs: independent probes
- y_t running into $\mathcal{C}_{H\ell}^{(1\pm3)}$

Complementarity!

[LA, Isidori, Pešut WIP]



An explicit (simplified) model

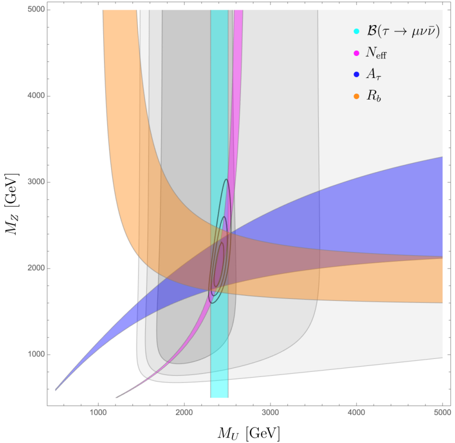
U_1 leptoquark + Z'

[LA, Isidori, Pešut WIP]

- $SU(4)$-unification inspired construction
- Heavy $U_1 \sim (3,1,2/3)$ and Z' vectors with third-gen. coupling

$$\mathcal{L}_{\text{int}} \supset \frac{g_4}{\sqrt{2}}\left[U_\mu\left(\bar{q}_L^3\gamma^\mu\ell_L^3\right) + \text{H.c.}\right] + \frac{g_4}{2\sqrt{6}}Z'_\mu\left(\bar{q}_L^3\gamma^\mu q_L^3\right) - \frac{3}{2}\frac{g_4}{\sqrt{6}}Z'_\mu\left(\bar{\ell}_L^3\gamma^\mu\ell_L^3\right)$$

- $\mathcal{C}_{\ell q}^{(1)[3333]} = \mathcal{C}_{\ell q}^{(3)[3333]} = \frac{g_4^2 v^2}{8M_U^2}$
- $\mathcal{C}_{\ell q}^{(1)[3333]} = -\frac{g_4^2 v^2}{32M_Z^2}$



Summary

- Indirect searches for New Physics can probe much higher scales than direct searches
- FCC-ee, with a leap in precision, will provide an unprecedented opportunity for precision physics
- EWPOs can probe many different NP scenarios
  $\rightarrow$ sensitive to loop effects from heavy NP
- Linear extensions of the SM probed from $\mathcal{O}(1)$ up to $\mathcal{O}(100)$ TeV scale
- Off- and on-pole measurements are in synergy - help remove degeneracies
- (Heavy) flavour prospects complementary to B factories and LHC
- Exciting precision program overall - still much to be explored!

Thank you!

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Backup

Scalars

State	Tree level zero possible?	1-loop RGE zero possible?	Bounding obs.
$\mathcal{S}$	✓	✗	A_e
$\mathcal{S}_1$	✓ if $(y_{\mathcal{S}_1})_{12} = 0$	✗	A_e
$\mathcal{S}_2$	✓	✗	A_e (R_τ)
φ	✓	✗	Γ_Z
Ξ	✗	✗	m_W
Ξ_1	✓ if $\kappa_{\Xi_1} = 0$ & $(y_{\Xi_1})_{12} = 0$	✗	m_W
Θ_1	✓	✓*	m_W
Θ_3	✓	✓*	m_W
ω_1	✓	✗	Γ_Z
ω_2	✓	✗	Γ_Z
ω_4	✓	✗	A_e (R_τ)
Π_1	✓	✗	A_e (R_τ)
Π_7	✓	✗	R_τ
ζ	✓	✗	Γ_Z (R_τ)
Ω_1	✓	✗	Γ_Z
Ω_2	✓	✗	Γ_Z
Ω_4	✓	✓ if $(y_{\Omega_4})_{33} \neq 0$, all else zero	Γ_Z (-)
Υ	✓	✗	Γ_Z
Φ	✓	✗	Γ_Z

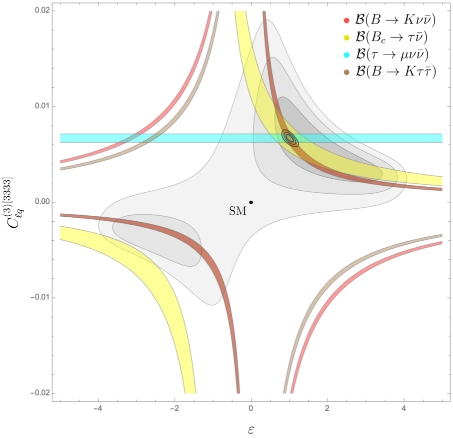
Fermions

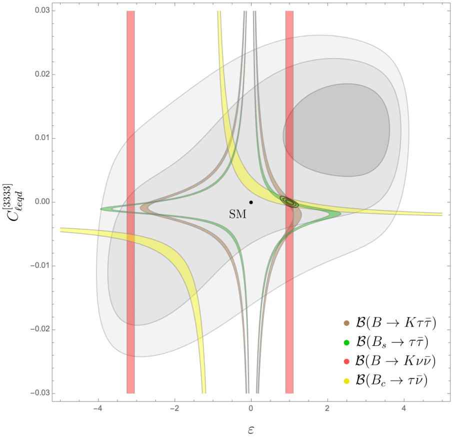
State	Tree level zero possible?	1-loop RGE zero possible?	Bounding obs.
N	✗	✗	A_e (Γ_Z)
E	✗	✗	Γ_Z (R_τ)
Δ_1	✗	✗	A_e (R_τ)
Δ_3	✗	✗	A_e (R_τ)
Σ	✗	✗	Γ_Z (R_τ)
Σ_1	✗	✗	A_e (Γ_Z)
U	✓ if $(\lambda_U)_3 \neq 0$, all else zero	✗	Γ_Z (m_W)
D	✗	✗	Γ_Z
Q_1	✓ if $(\lambda^u_{Q_1})_3 \neq 0$, all else zero	✗	m_W
Q_5	✗	✗	Γ_Z
Q_7	✓ if $(\lambda_{Q_7})_3 \neq 0$, all else zero	✗	m_W
T_1	✗	✗	m_W (Γ_Z)
T_2	✗	✗	Γ_Z

Vectors

State	Tree level zero possible?	1-loop RGE zero possible?	Bounding obs.
$\mathcal{B}$	✓ if $(g^{\phi}_{\mathcal{B}}) = 0$ & $(g^{l}_{\mathcal{B}})_{12} = 0$	✓ if eqns. (**??**)	m_W
$\mathcal{B}_1$	✓ if $(g^{\phi}_{\mathcal{B}_1}) = 0$	✗	m_W
$\mathcal{W}$	✓ if $(g^{\phi}_{\mathcal{W}}) = 0$ & $K_{12}(g^{l}_{\mathcal{W}}) = 0$	✓ if eqns. (**??**)	A_e (Γ_Z)
$\mathcal{W}_1$	✗	✗	m_W
$\mathcal{G}$	✓	✓ if $(g^{u}_{\mathcal{G}})_{33} \neq 0$, all else zero	Γ_Z
$\mathcal{G}_1$	✓	✗	Γ_Z
$\mathcal{H}$	✓	✗	Γ_Z
$\mathcal{L}_1$	✗	✗	A_e
$\mathcal{L}_3$	✓	✗	A_e (A_τ)
$\mathcal{U}_2$	✓	✗	Γ_Z
$\mathcal{U}_5$	✓	✗	R_τ
$\mathcal{Q}_1$	✓	✗	R_τ
$\mathcal{Q}_5$	✓	✗	Γ_Z
$\mathcal{X}$	✓	✗	R_τ
$\mathcal{Y}_1$	✓	✗	Γ_Z
$\mathcal{Y}_5$	✓	✗	Γ_Z

Flavour prospects: SMEFT analysis





Flavour prospects: U_1 + Z' model