Summary and prospects Physics Programme

8th FCC Physics Workshop, CERN

Guilherme Guedes

The FCC physics programme

Different paradigm today than before LHC:

No no-lose theorems

Questions more profound than ever

Moving into the unknown:

Test the SM in spectacular conditions

Probe the UV landscape

Our narrative: Integrate a strategy of **precision** (where new physics *cannot* hide) and **high-E** (to probe directly any hint we may find).

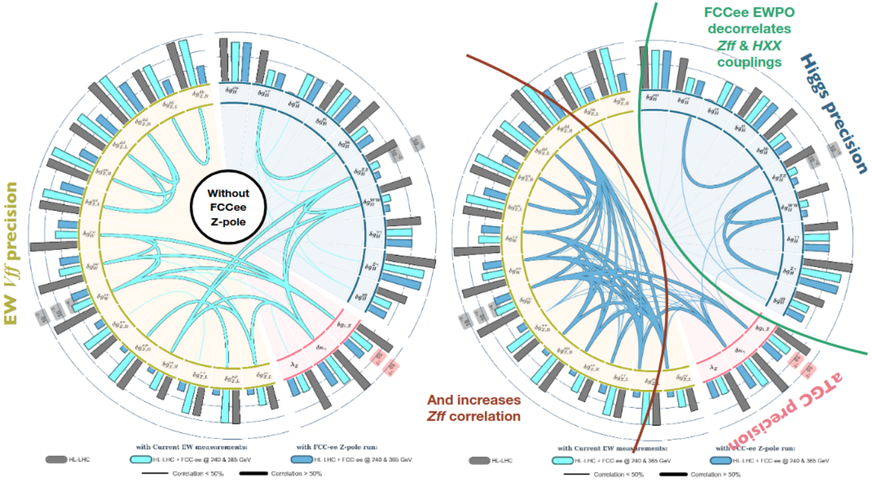
The Tera-Z: model agnostic

Spectacular power to probe new physics indirectly through SMEFT!

Global SMEFT fit results in FCC feasibility report

Characterization of Higgs boson & role of EW

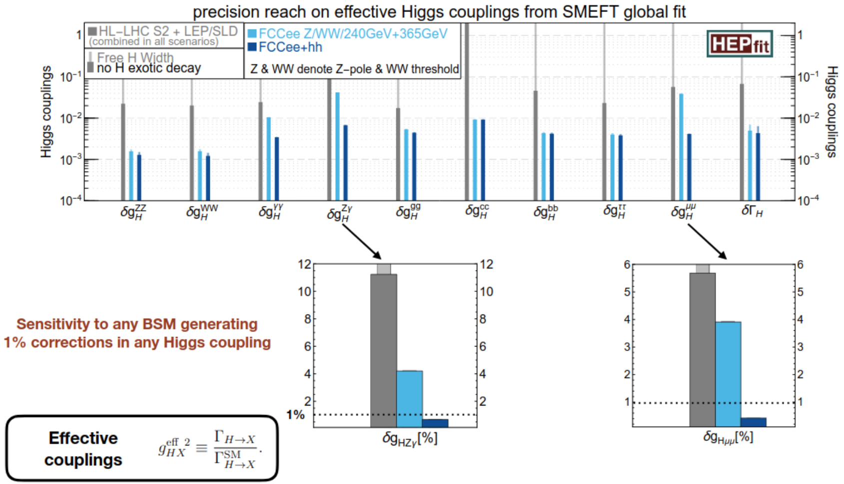
- Made more precise the interplay between Z-pole and Higgs measurements



Global SMEFT fit results in FCC feasibility report

Characterization of Higgs boson & role of EW

- Updated to the current baseline (4IP) and luminosities and in combination with FCC-hh (Higgs)



See talk by Jorge De Blas

The Tera-Z: which UV?

Organising the UV

Suppose dim-6 SMEFT operators arise at tree-level:

$$\mathcal{O}_1(SM) \underset{\chi_{\rm BSM}}{\longrightarrow} \mathcal{O}_2(SM) \Rightarrow \mathcal{O}_{\rm SMEFT}$$

Is it possible to categorise all possible states? Yes!

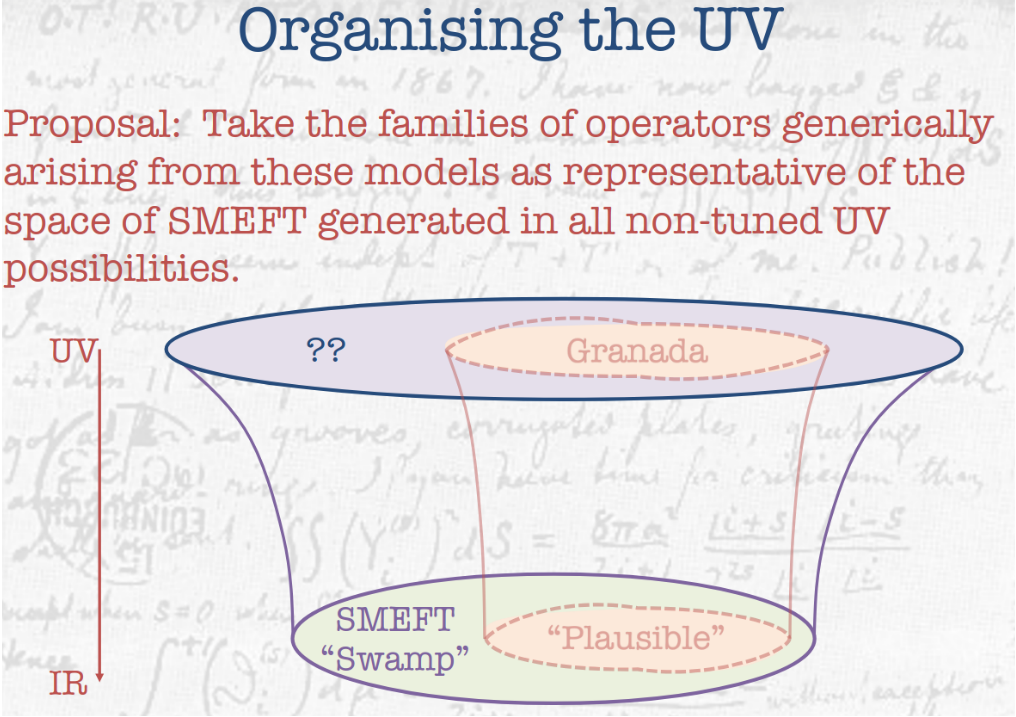
Effective description of general extensions of the Standard Model: the complete tree-level dictionary

J. de Blas, J. C. Criado, M. Perez-Victoria, J. Santiago

"Granada Dictionary".

See talk by Matthew Mccullough

The Tera-Z: which UV?



See talk by Matthew Mccullough

Where is Granada?

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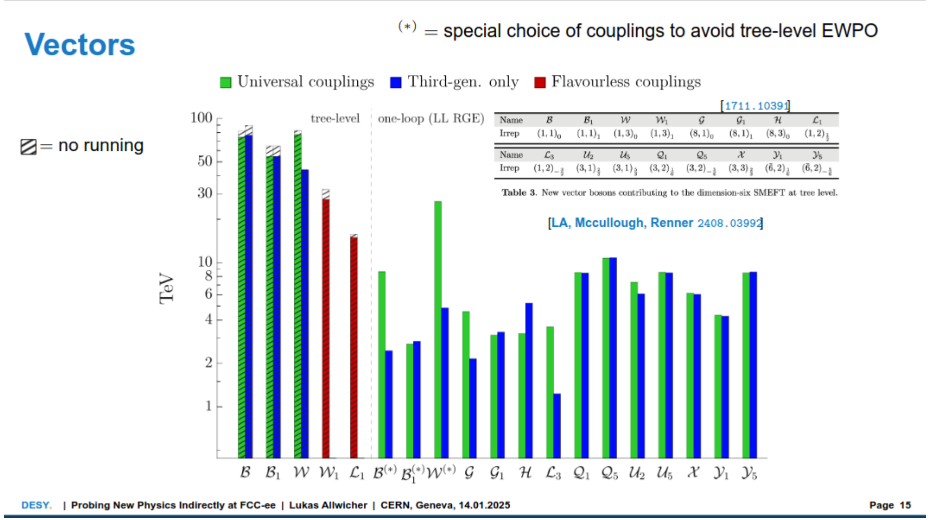
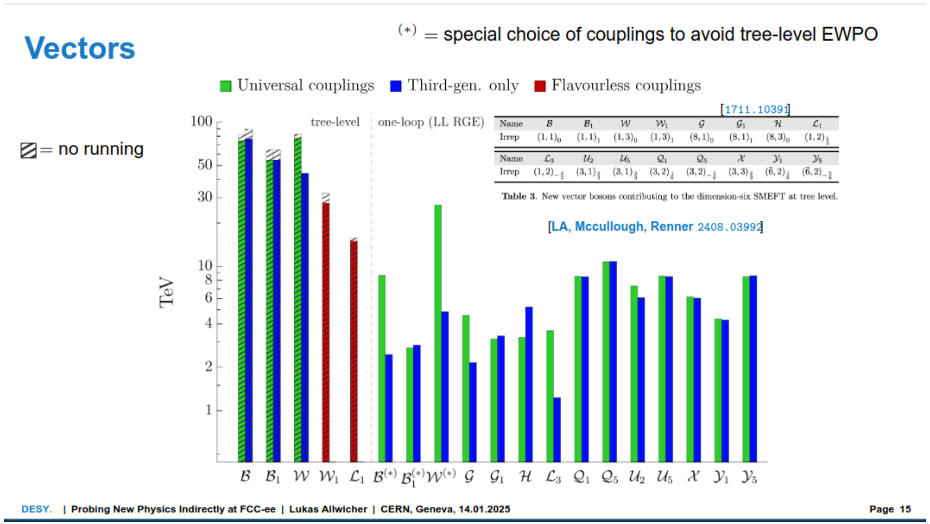


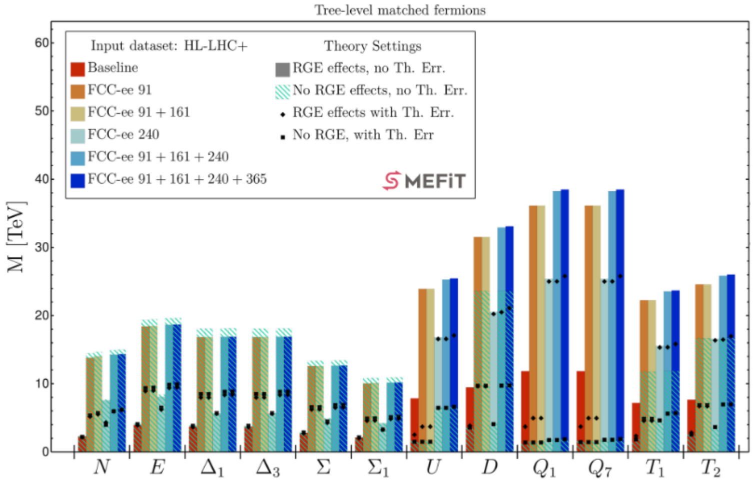
See talk by Lukas Allwicher,
Jaco ter Hoeve, Hoa Vuong

EWPO at the FCC-ee can indirectly test these UVs at O(10) TeV

Where is Granada?



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	$(1,2)_{-\frac{3}{2}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,3)_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$



See talk by Lukas Allwicher,
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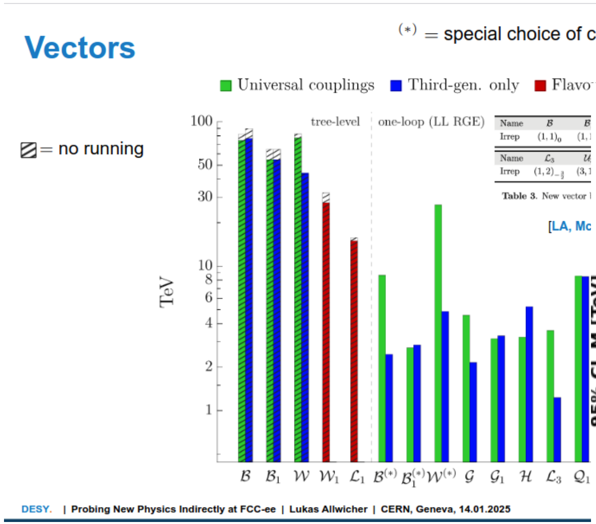
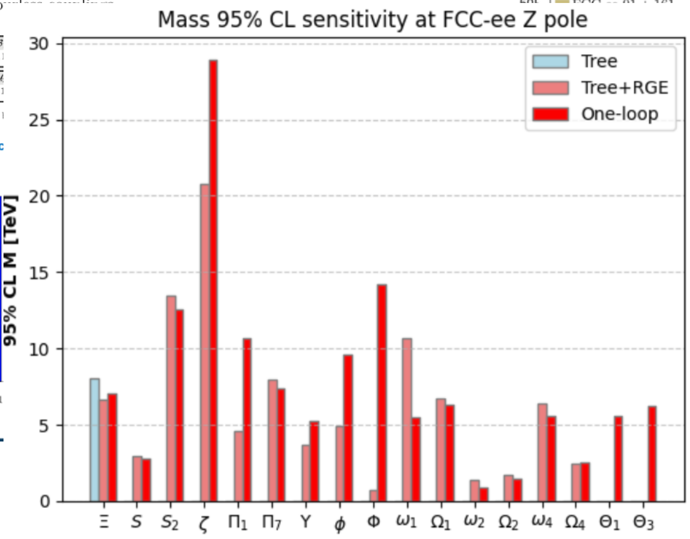
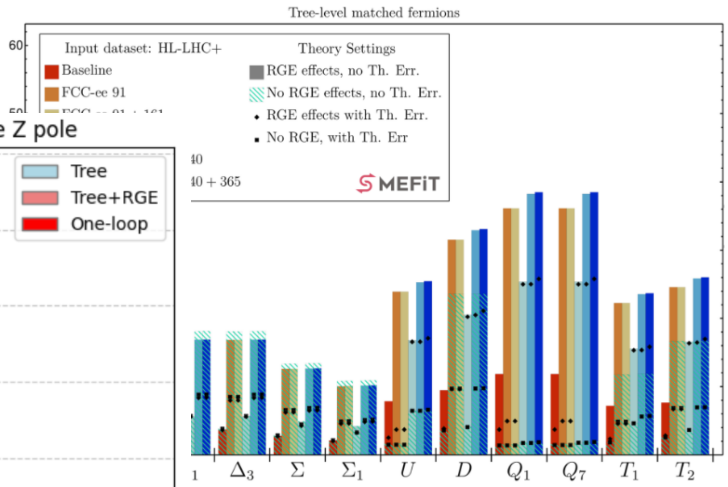
EWPO at the FCC-ee can indirectly test these UVs at O(10) TeV

Where is Granada?







See talk by Lukas Allwicher, Jaco ter Hoeve, Hoa Vuong

EWPO at the FCC-ee can indirectly test these UVs at O(10) TeV

What's next?

Beyond Granada?
NLO EFT observables
Higher-orders?
Flavour
Connection with hh

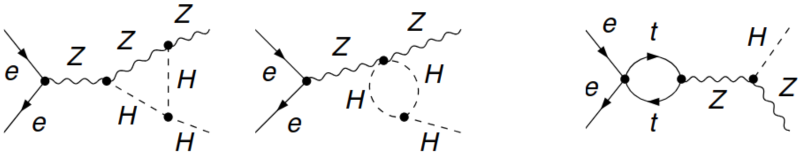
SOLD

GG, Jose Santiago, Pablo Olgoso, 2303.16965
GG, Pablo Olgoso, 2412.14253

The importance of going NLO

Higgstrahlung at NLO EW SMEFT

- Complete NLO calculation including all dimension-6 operators
  - (~70 SMEFT operators contribute in ~ 35 combinations)
- Sensitive to poorly constrained interactions that first arise at NLO
- One-loop virtual + tree level real photon emission
  - Generate with FeynArts → FeynCalc → Package-X
  - Renormalize on-shell for M_W, M_Z, $\overline{\mathrm{MS}}$ for Wilson Coefficients, $C_i(\mu)$



Higgs tri-linear coupling, C_ϕ

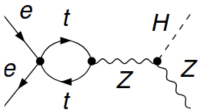
4-fermion operators, C_{eu}

S. Dawson

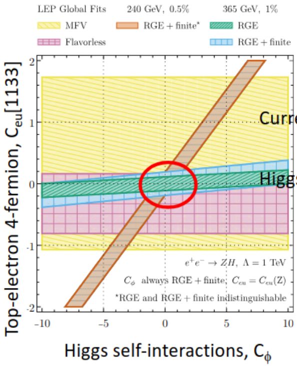
* Complete results at https://gitlab.com/smeft/eehz

e^+e^- → ZH is window to many new interactions

- Sensitivity to Higgs tri-linear correlated with other contributions
  - Calculate to $1/\Lambda^2$ so results are linear bands
- How do future constraints compare with existing information?
  - Assume .5% accuracy on total cross section measurement at √s=240 GeV, 1% at √s=365 GeV
- Limits from Z-pole depend on flavor assumptions
  - Compare with global fits using MFV and flavor-blind operators



Observables at different scales: Z pole observables at M_Z, Higgstrahlung at √s



Power of measurement at 2 different energies

2406.03557

S. Dawson

* C's in plot evaluated at $\mu = M_Z$

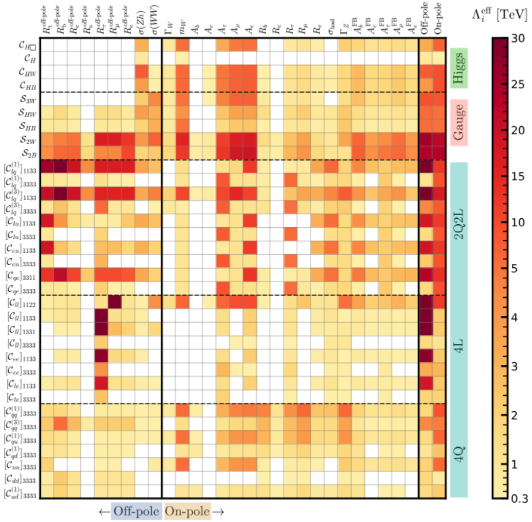
See talk by Sally Dawson

Accuracy complements energy

Accuracy complements energy: EFT summary plot

Some comments

- All Z-pole contributions are NLO except W+Y.
- Still, the typical sensitivity is in the 10 TeV ballpark.
- Most important Z-pole observables: m_W, A_l
- Good complementarity on and off the pole for the Higgs and gauge sectors.
- Z-pole always wins or competes for 4F operators with tops.
- Off pole wins for operators with electrons, otherwise the two are complementary.

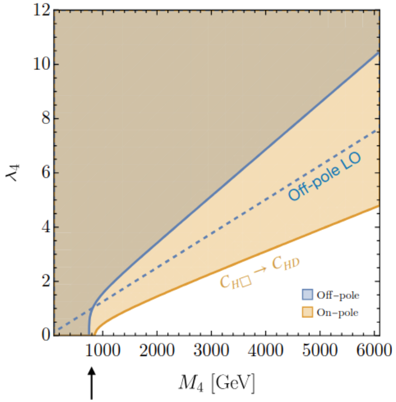


[Maura, BAS, You, 2412.14241]

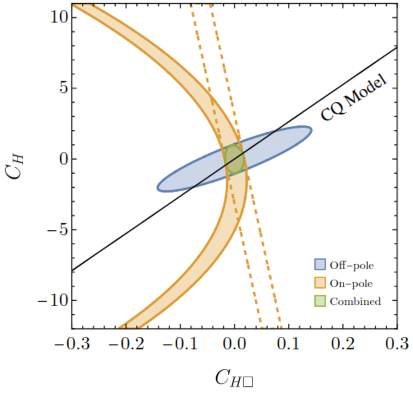
Custodial quadruplet model

[Maura, BAS, You, 2412.14241]

- While $C_{H\Box}$ is 1-loop and C_H is tree, the reverse is true in how they affect $\sigma(ZH)$, so they contribute similarly, but with the opposite sign. Again, partial cancellation!



*Lower λ_4-independent bound on the mass comes from W+Y parameters.



*Off-pole direction not fully flat because we include $\sigma(ZH)$ at 240+365 GeV.

See talk by Ben Stefanek

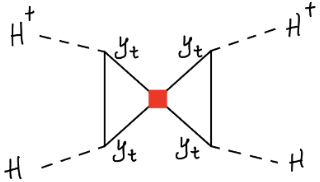
Observables on Z-pole at NLO ~ off-pole at NLO

2-loop effects

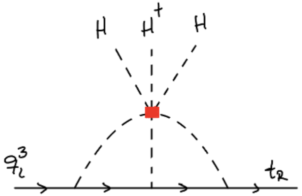
The (SM)EFT software project:

Upgrading from “human computers” to computers

Example of the importance of these corrections:



$$[O_{qq}^{(1)}]_{3333} \rightarrow [O_{Hq}^{(1)}]_{33} \rightarrow O_{HD}$$



[Top-Yukawa correction]

Some results in the bSMEFT at NLL

$$\frac{dC_i}{d\ln\mu} = \frac{\beta_i^{(1)}}{(16\pi^2)} + \frac{\beta_i^{(2)}}{(16\pi^2)^2} + \ldots$$

$$\beta^{(1)}_{C_{HD}} = \left(\frac{9}{2}g_L^2 + 6\lambda - \frac{5}{6}g_Y^2\right)C_{HD} + \frac{20}{3}g_Y^2 C_{H\Box}$$

$$\beta^{(1)}_{C_{H\Box}} = \left(12\lambda - \frac{4}{3}g_Y^2 - 4g_L^2\right)C_{H\Box} + \frac{5}{3}g_Y^2 C_{HD}$$

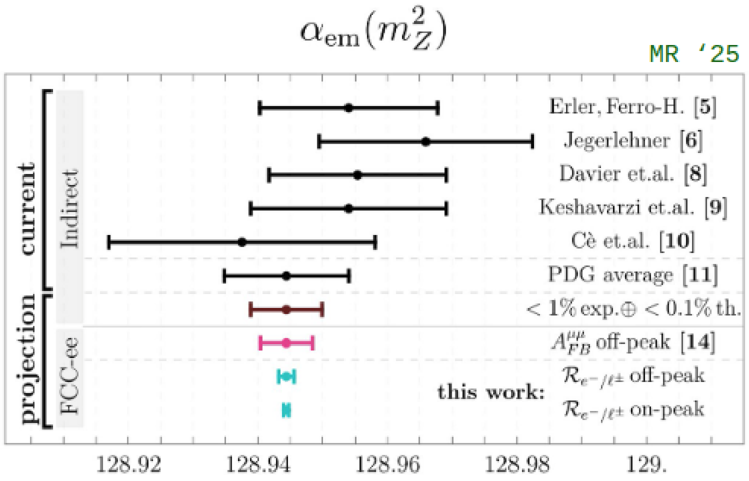
Enlarged mixing: Most operators mix at NLL

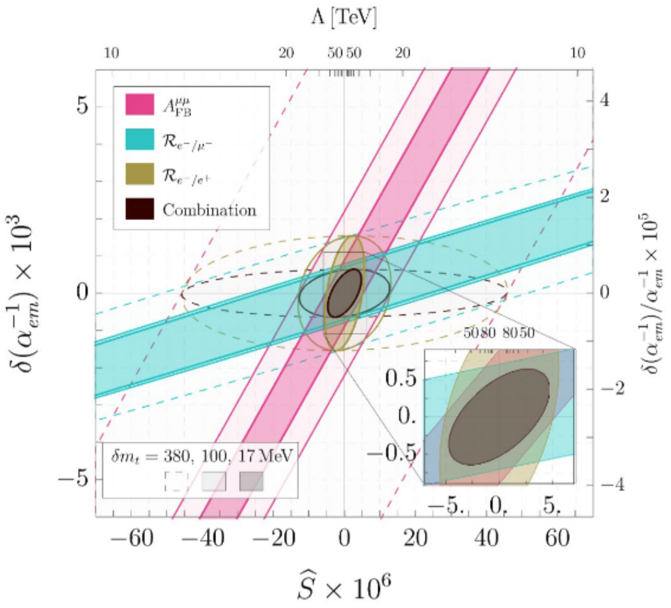
$$\begin{aligned}\beta^{(2)}_{C_{HD}} = &\left[\lambda\left(\frac{5}{2}g_Y^2 - \frac{45}{2}g_L^2\right) + \frac{299}{216}g_Y^4 + \frac{41}{2}g_Y^2 g_L^2 - \frac{1}{8}g_L^4 - 36\lambda^2\right]C_{HD} \\ &+\left(\frac{70}{27}g_Y^4 - \frac{227}{9}g_Y^2 g_L^2 - \frac{136}{3}\lambda g_Y^2\right)C_{H\Box} \\ &+\left(32 g_Y^3 g_L - 68 g_Y g_L^3 - 96\lambda g_Y g_L\right)C_{HWB} \\ &+\left(\frac{32}{3}g_Y^4 + 12 g_Y^2 g_L^2 - 48\lambda g_Y^2\right)C_{HB} \\ &+28 g_Y^2 g_L^2 C_{HW} + 26 g_Y^2 g_L^3 C_W\end{aligned}$$

See talk by Javier Fuentes-Martin

Improving EWPO

See talk by Marc Riembau





Improving sensitivity fundamental to take advantage of EWPO!

Flavour programme

- Flavour **precision** also probes generic BSM extensions b/c you **cannot turn off flavour violation**!

So, FCC-ee combines the USPs (for flavour) of B factories & LHC

New opportunities

Doing this not only allows comparable/better measurements at FCC-ee in the familiar channels suited to Belle II and LHC

➢ It also opens some completely new frontiers i.e. processes we have never measured before

See talk by Joe Davighi

Flavour programme

Survey of studies

The following flagship channels have received dedicated studies, with detector simulation (IDEA baseline) and background modelling:

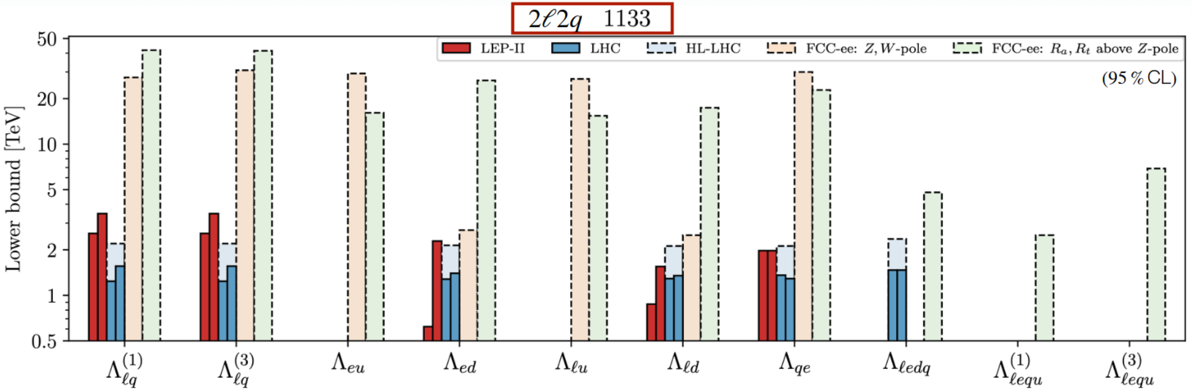
1. $B \to K^* \tau\tau$ — new frontier!
2. $B_{c/u} \to \tau\nu$ — new frontier!
3. $b \to s\bar{\nu}\nu$ — pushing back the Belle II frontier: 10% to 1% precision

See talk by Joe Davighi

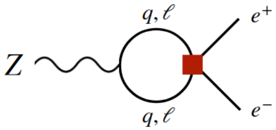
Flavour complementarity with EWPO

See talk by Alessandro Valenti

$$R_b = \frac{\sigma(e^+e^- \to \bar{b}b)}{\sum_{q=u,d,s,c,b}\sigma(e^+e^- \to \bar{q}q)} \qquad + R_c, R_s, R_t, R_\ell$$



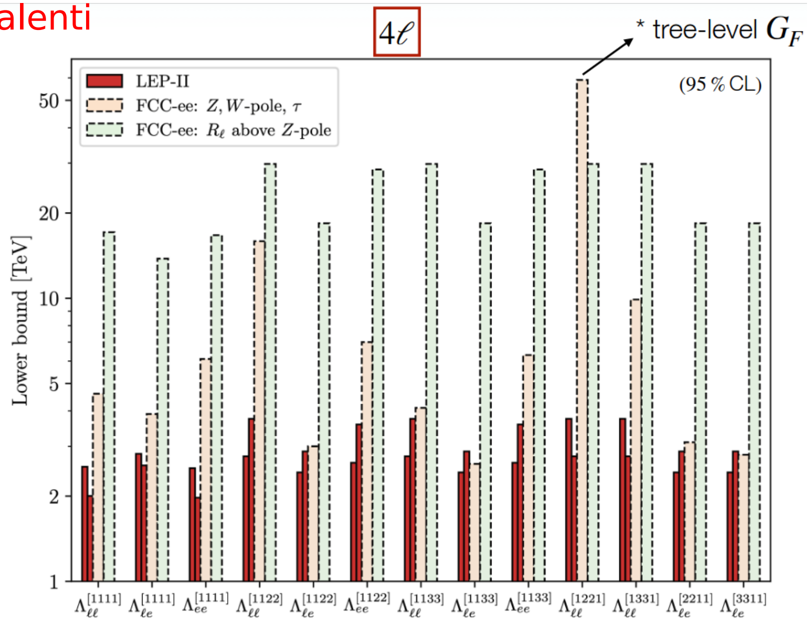
- LEP-II: R_a ratios
- (HL-)LHC: high-p_T $\bar{q}q \to e^+e^-$ tails
- **FCC-ee Z-pole**: **1-loop RGE** →



(y_t^2 for top, gauge others)

Flavour complementarity with EWPO

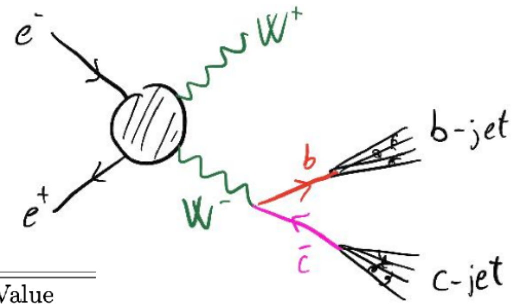
See talk by Alessandro Valenti



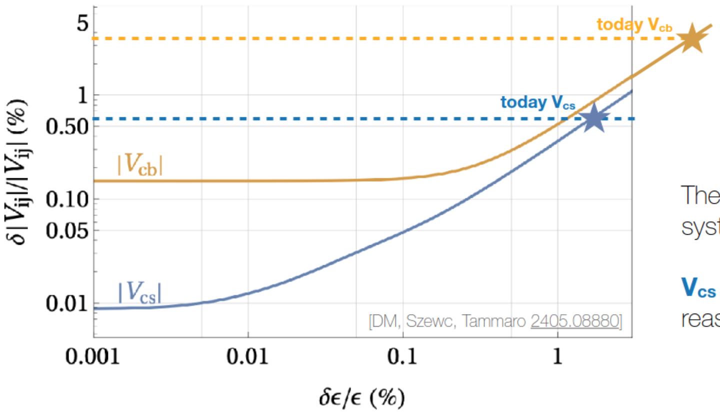
Flavour tagging crucial to assess expected FCC-ee precision

CKM measurement

See talk by David Marzocca



Fixing the **efficiencies working point** at the **FCC (IDEA)** one.



Parameter	Value
N_{WW}	3×10^8
$\mathrm{Br}(W \to \mathrm{had})$	0.6741
$\mathrm{Br}(W \to \ell\nu)$	0.3278
$\mathcal{A}_W$	0.9

The precision on V_{cb} saturates at per-mille level of systematic uncertainties, due to limited statistics.

V_{cs} instead is never statistically limited for any reasonable value of systematic uncertainties.

Considerable improvement in V_{cb} and V_{cs} extraction compared to present (and future) measurements are expected, **for any systematic uncertainty below the 1% level**.

H/Z flavor violating decays

See talk by Arman Korajac

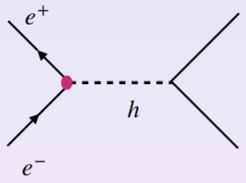
Decay	SM prediction	exp. bound	indir. constr.	FCC-ee bound
$\mathcal{B}(h \to bs)$	$(8.9 \pm 1.5) \cdot 10^{-8}$	0.16 ▲	2×10^{-3} ★	9.6×10^{-4}
$\mathcal{B}(h \to bd)$	$(3.8 \pm 0.6) \cdot 10^{-9}$	0.16 ▲	10^{-3} ★	5×10^{-3}
$\mathcal{B}(h \to cu)$	$(2.7 \pm 0.5) \cdot 10^{-20}$	0.16 ▲	2×10^{-2} ★	2.5×10^{-3}
$\mathcal{B}(Z \to bs)$	$(4.2 \pm 0.7) \cdot 10^{-8}$	2.9×10^{-3} ■	6×10^{-8} ●	$\mathcal{O}(10^{-6})$
$\mathcal{B}(Z \to bd)$	$(1.8 \pm 0.3) \cdot 10^{-9}$	2.9×10^{-3} ■	6×10^{-8} ●	$\mathcal{O}(10^{-6})$
$\mathcal{B}(Z \to cu)$	$(1.4 \pm 0.2) \cdot 10^{-18}$	2.9×10^{-3} ■	4×10^{-7} ●	2.3×10^{-3}

Light fermion Yukawas

See talk by Ramona Groeber

Electron Yukawa coupling

FCC-ee can directly measure the electron Yukawa coupling by dedicated run at Higgs pole mass



probes $\kappa_e < 1.6$

[d'Enterria, Poldaru, Wojcik '21]

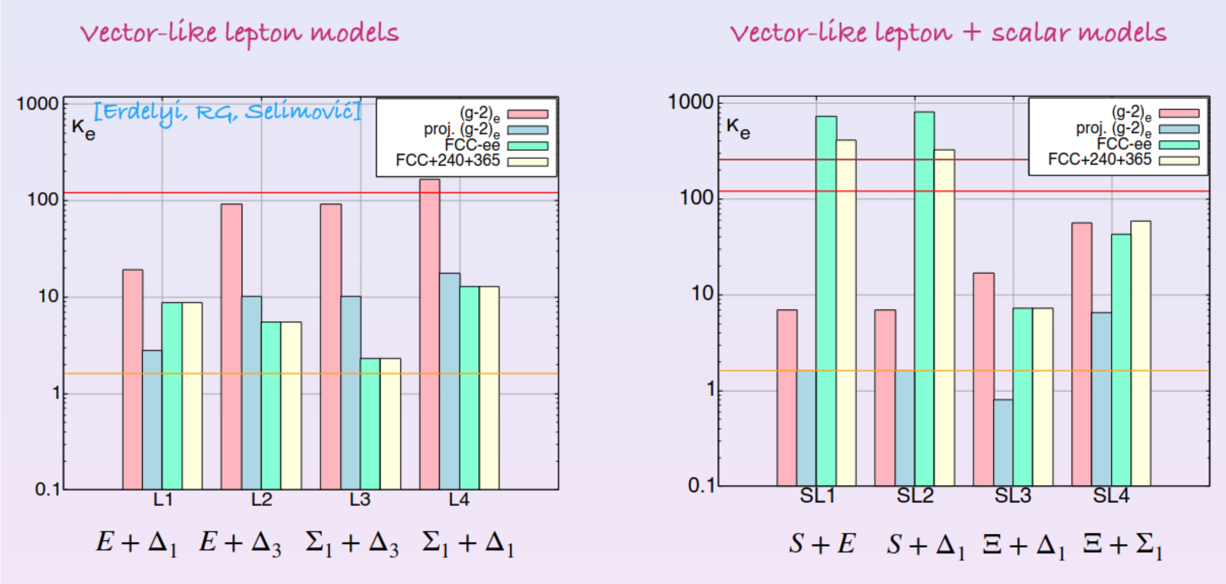
requires monocromatised e^+e^- beam,
precise knowledge of Higgs boson mass,
extended timeline

And which models are probed?

See also talk by Francis Petriello to see how polarization can be important.

Light fermion Yukawas

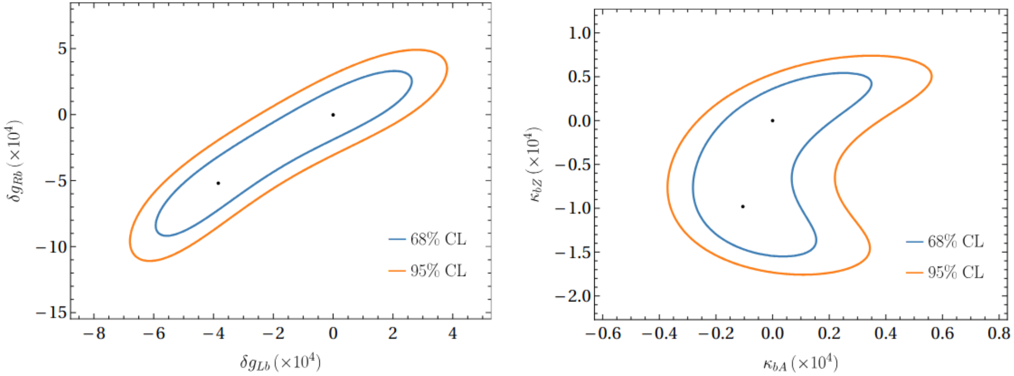
See talk by Ramona Groeber



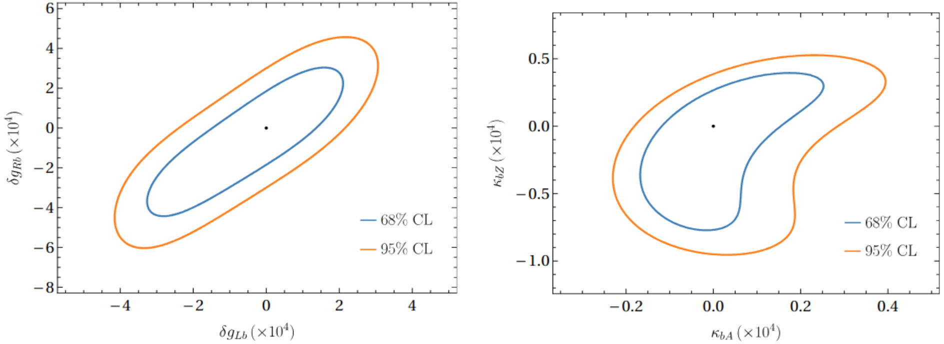
High correlation with (g-2)e

Dipoles at the FCC

Z pole + 240 GeV



Z pole + 240 + 360 GeV



See talk by Xiaoze Tan

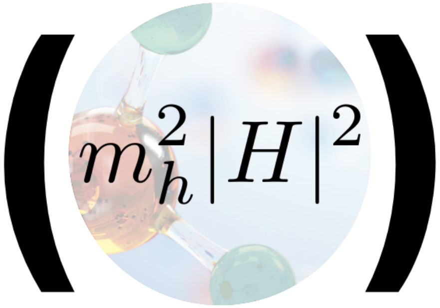
Interesting complementarity between different runs!

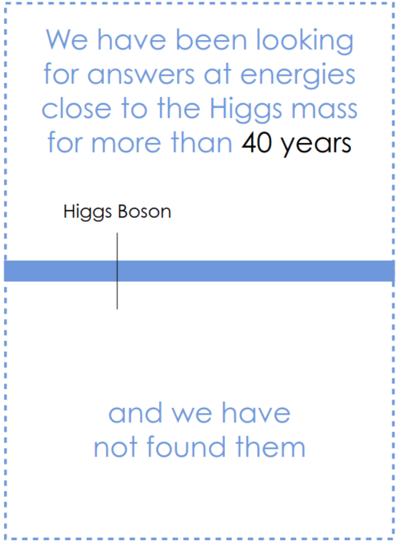
See also talk by Michael Pitt on tau dipole.

Into more concrete questions

What’s up with the Higgs?

See talk by Raffaele D’Agnolo





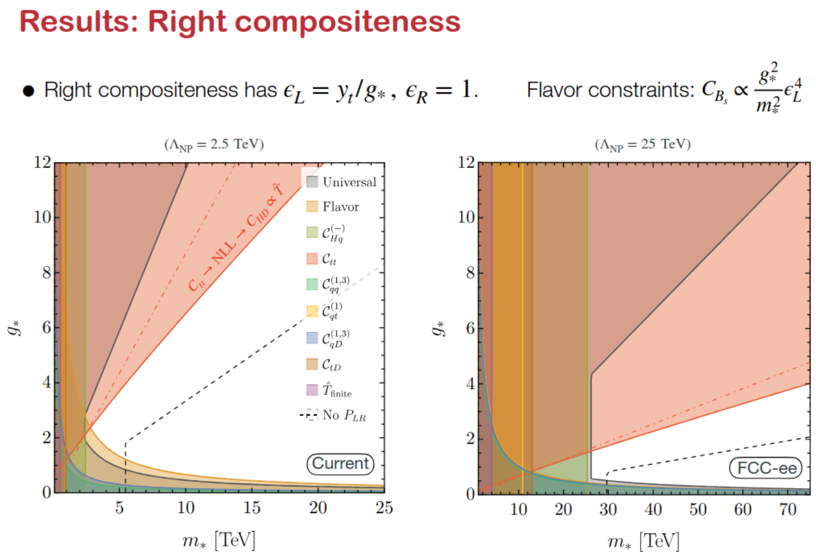
What’s up with the Higgs?

See talk by Raffaele D’Agnolo

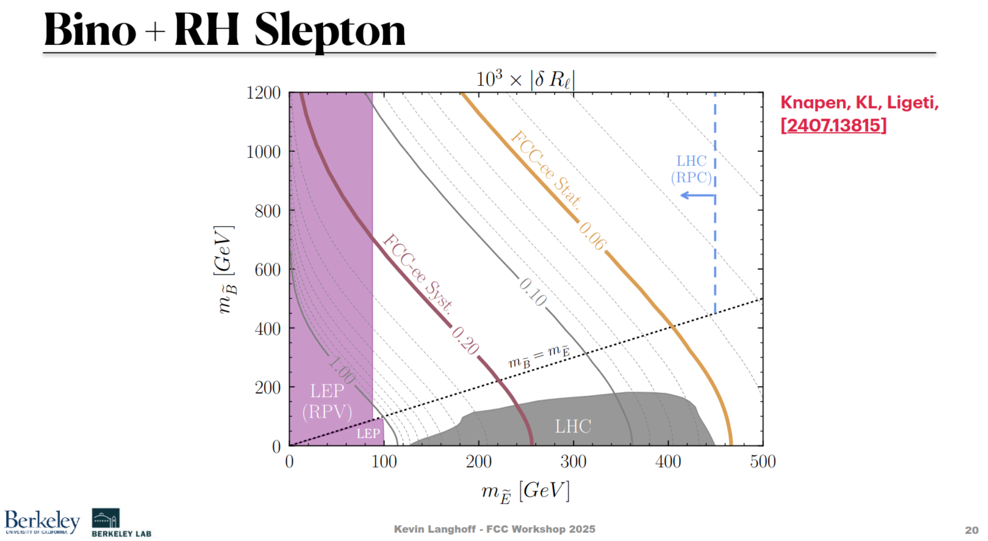
1. We tune
2. There is no mass scale beyond the SM [1305.6939]
3. The Higgs mass and the CC are inputs
4. UV/IR Mixing [1909.01365]
5. Swampland on steroids

What's up with the Higgs?

(We tune.) Symmetry-based solutions



See talk by Ben Stefanek

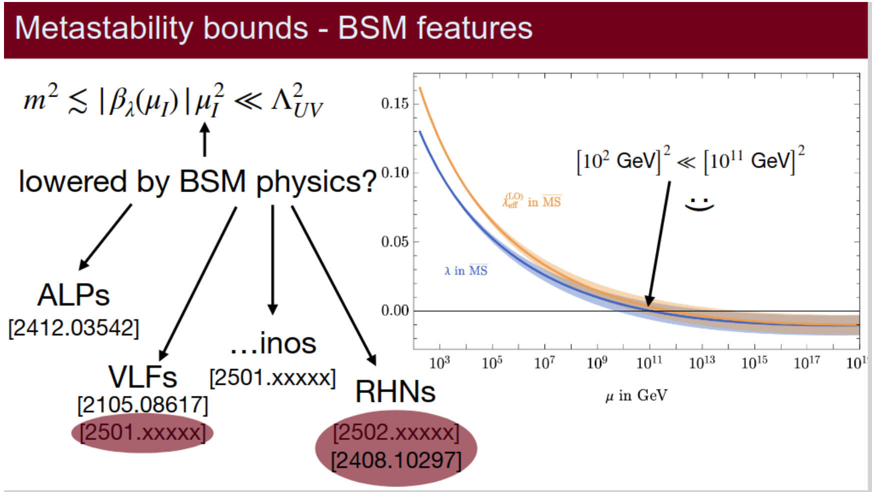


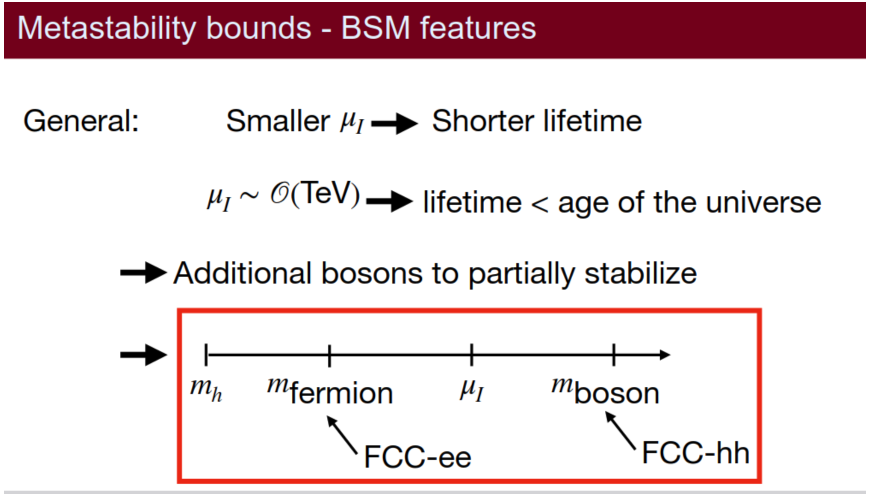
See talk by Kevin Langhoff

Not observing anything at the FCC-ee is still valuable information!

What's up with the Higgs?

Something different.





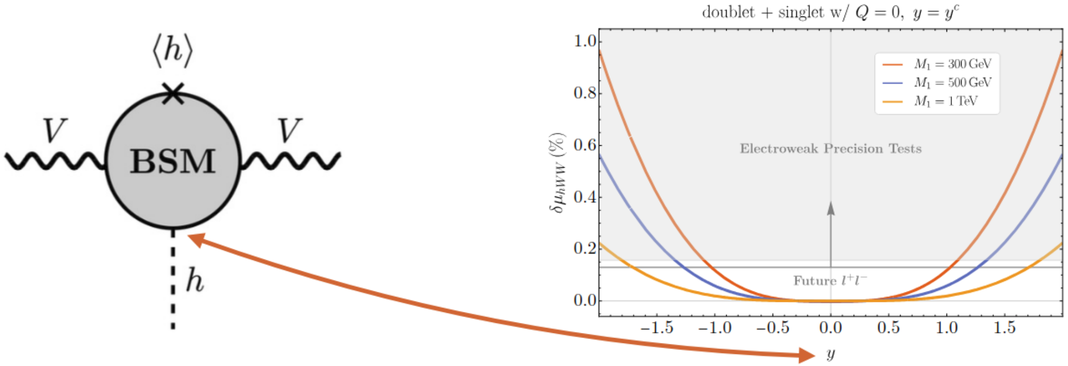
See talk by Thomas Steingasser

Finding these two d.o.f. could point to a solution to naturalness

What’s up with the Higgs?

See talk by Raffaele D’Agnolo

Imagine that you observed a deviation in hWW and have then discovered the fermions that generate it



Large Yukawa couplings are “bad”

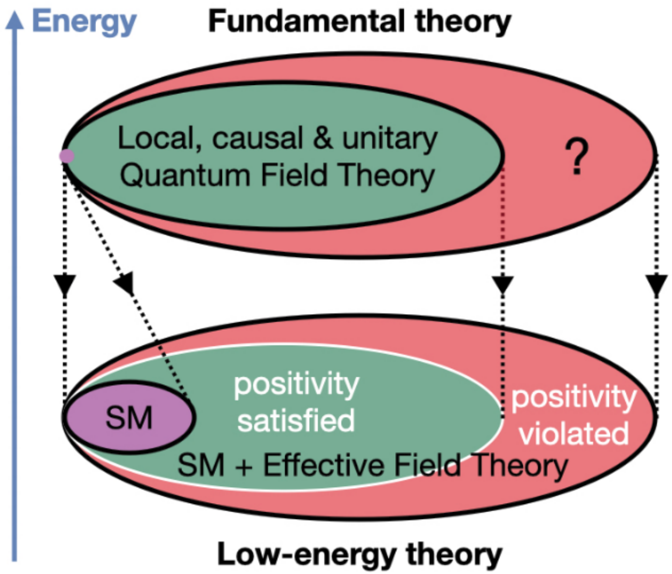
$$\frac{d\lambda}{d\log E} \sim -\frac{y^4}{16\pi^2}$$

$$\frac{dy}{d\log E} \sim \frac{y^3}{16\pi^2}$$

If you see a deviation in hWW or hZZ at HL-LHC or FCC-ee you will detect new bosons at FCC-hh (at the latest)

RTD, F. Nortier, G. Rigo, P. Sesma ’23

Positivity tests



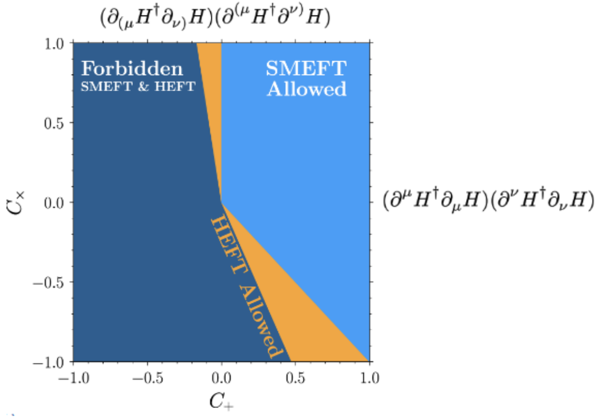
See talk by Ken Mimasu

Search for **positivity violation**

"Test fundamental principles of QFT in the UV"

- What kind of exotic UV theory?
- Something revolutionary!
- More down to earth: **HEFT vs SMEFT**

[Remmen & Rodd; 2412.07827]



Future collider potential is largely unexplored

- Important part of the EFT programme beyond dim-6

BSM particle searches: vectors

See talk by Riccardo Torre

Simplified models

- Heavy Vector Triplet

Pappadopulo et al., 1402.4431

$$\begin{aligned}\mathcal{L}_V \;=\;& -\frac{1}{4} D_{[\mu}V^a_{\nu]} D^{[\mu}V^{\nu]\,a} + \frac{m_V^2}{2} V^a_\mu V^{\mu\,a} \\ & + i\, g_V c_H V^a_\mu H^\dagger \tau^a \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_F V^a_\mu J^{\mu\,a}_F \\ & + \frac{g_V}{2} c_{VVV}\, \epsilon_{abc} V^a_\mu V^b_\nu D^{[\mu}V^{\nu]\,c} + g_V^2 c_{VVHH} V^a_\mu V^{\mu\,a} H^\dagger H - \frac{g}{2} c_{VVW} \epsilon_{abc} W^{\mu\nu\,a} V^b_\mu V^c_\nu \,.\end{aligned}$$

- Heavy Vector Singlets

$$\begin{aligned}\mathcal{L}_{\mathcal{V}^+} =& -\frac{1}{2} D_{[\mu}\mathcal{V}^+_{\nu]} D^{[\mu}\mathcal{V}^{-\,\nu]} + m^2_{\mathcal{V}^+}\mathcal{V}^+_\mu \mathcal{V}^{-\mu} \\ & - i\frac{g_V}{\sqrt{2}} c^+_H \mathcal{V}^+_\mu H^\dagger \overleftrightarrow{D}^\mu \tilde{H} + \frac{g_V}{\sqrt{2}} c^+_q \mathcal{V}^+_\mu J^\mu_q + \text{h.c.} \\ & + 2 g_V^2 c^+_{VVHH} \mathcal{V}^+_\mu \mathcal{V}^{-\mu} H^\dagger H + i g' c^+_{VVB} B_{\mu\nu}\mathcal{V}^{+\mu}\mathcal{V}^{-\nu}\end{aligned}$$

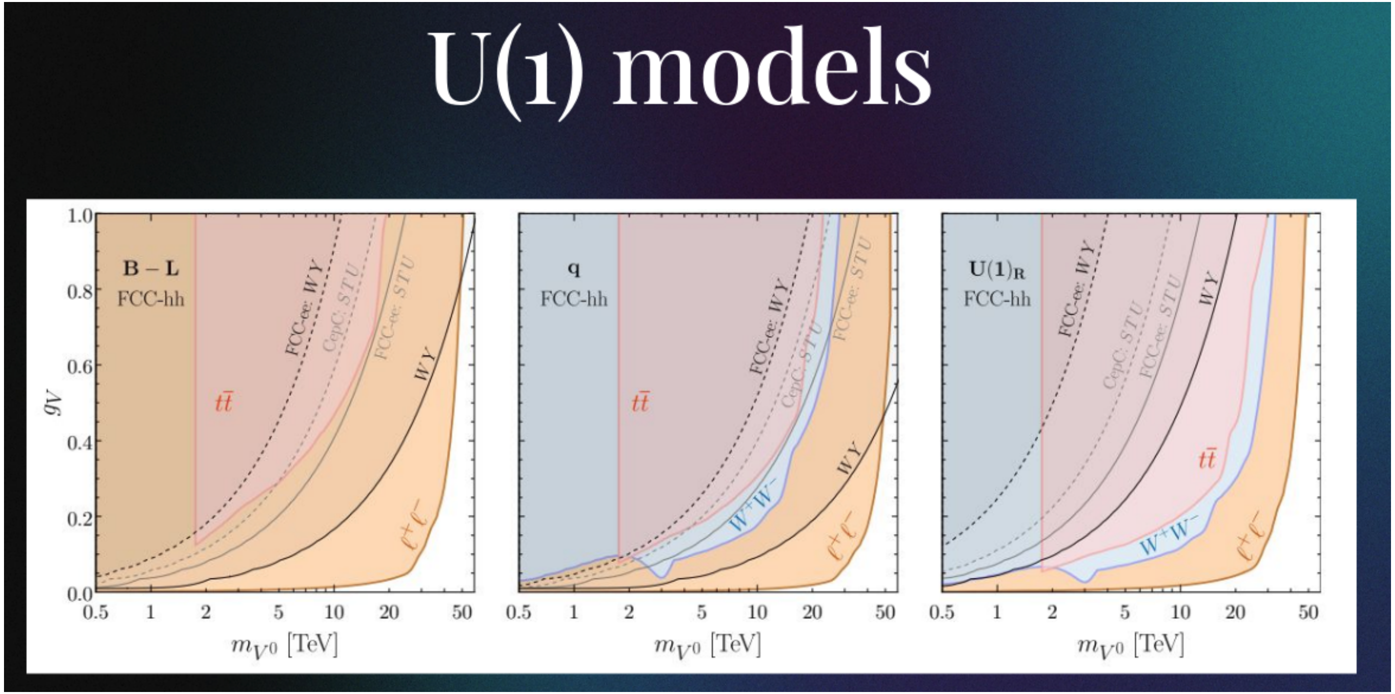
$$\begin{aligned}\mathcal{L}_{\mathcal{V}^0} =& -\frac{1}{4} \partial_{[\mu}\mathcal{V}^0_{\nu]}\partial^{[\mu}\mathcal{V}^{0\,\nu]} + \frac{m^2_{\mathcal{V}^0}}{2}\mathcal{V}^0_\mu\mathcal{V}^{0\,\mu} \\ & + i\frac{g_V}{2} c^0_H \mathcal{V}^0_\mu H^\dagger \overleftrightarrow{D}^\mu H + \sum_{\Psi=Q,L,U,D,E} \frac{g_V}{2} c^0_\Psi \mathcal{V}^0_\mu J^\mu_\Psi \\ & + g_V^2 c^0_{VVHH}\mathcal{V}^0_\mu \mathcal{V}^{0\,\mu} H^\dagger H\end{aligned}$$

$$\mathcal{L}_{\text{mix}} = (i g_V c^+_{VVV} D_{[\mu}\mathcal{V}^-_{\nu]}\mathcal{V}^{0\,\mu}\mathcal{V}^{+\,\nu} + \text{h.c.}) + i g_V c^0_{VVV}\partial_{[\mu}\mathcal{V}^0_{\nu]}\mathcal{V}^{+\,\mu}\mathcal{V}^{-\,\nu}$$

Baker et al., 2407.11117

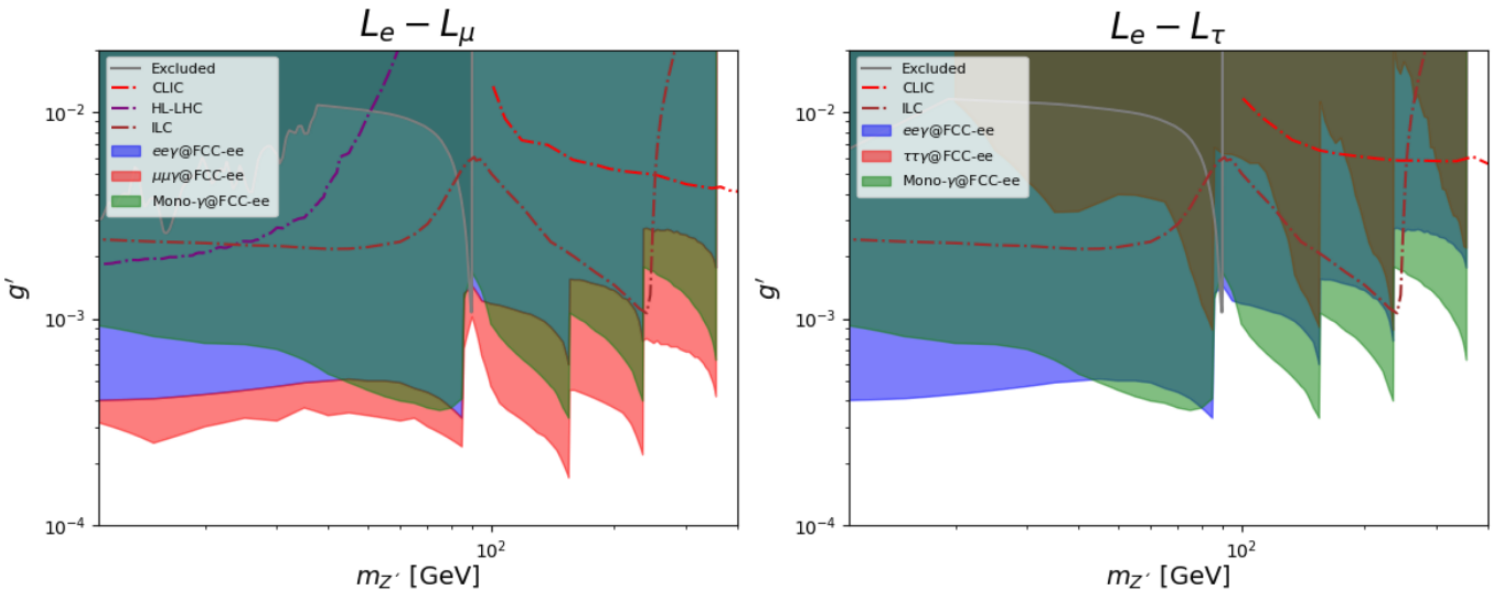
BSM particle searches: vectors

See talk by Riccardo Torre



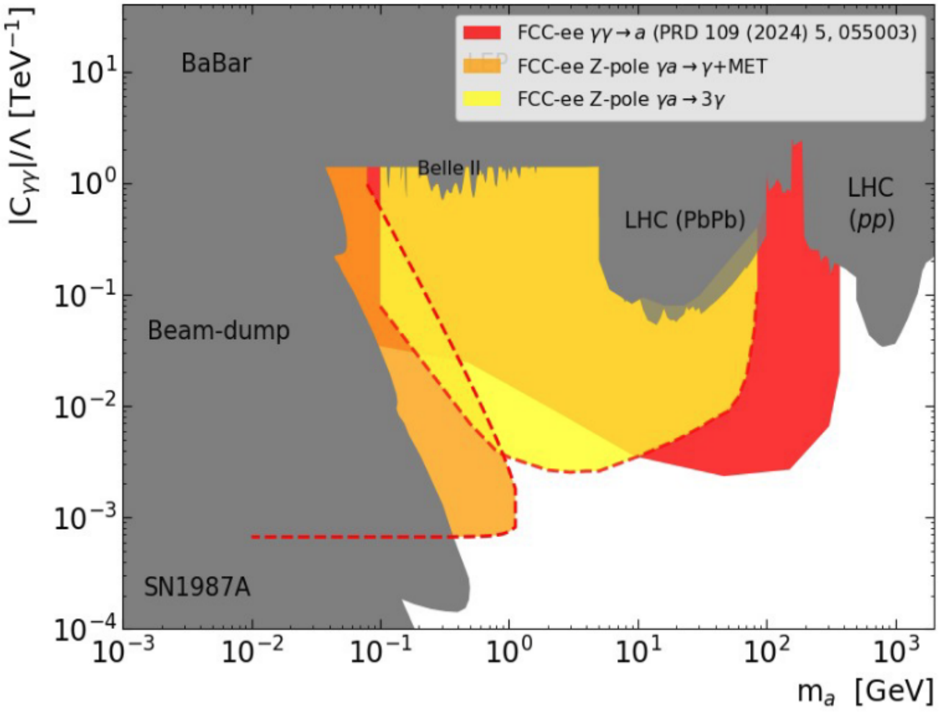
BSM particle searches: vectors

See talk by Jose Zurita



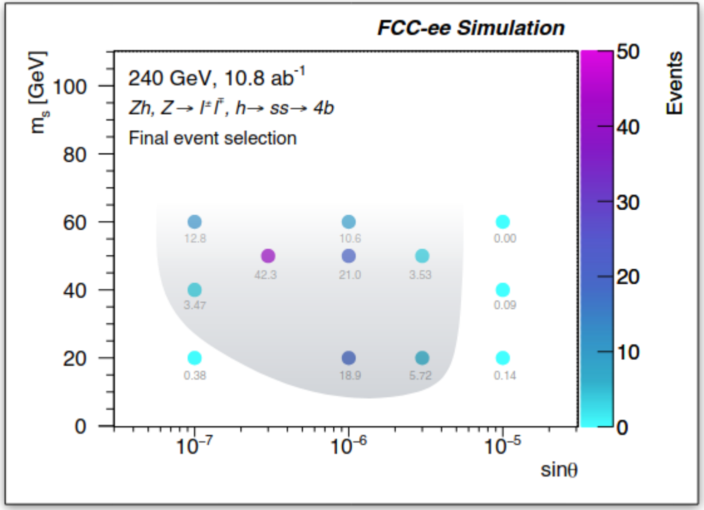
BSM particle searches: ALPs

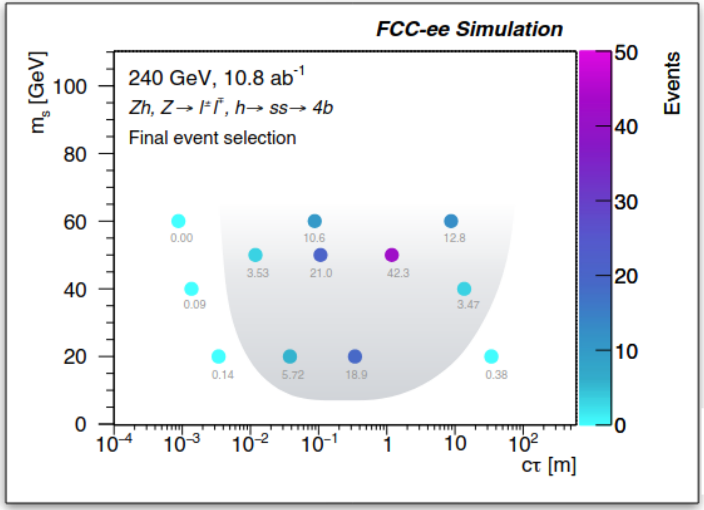
See talk by Giacomo Polesello



BSM particle searches: LLPs

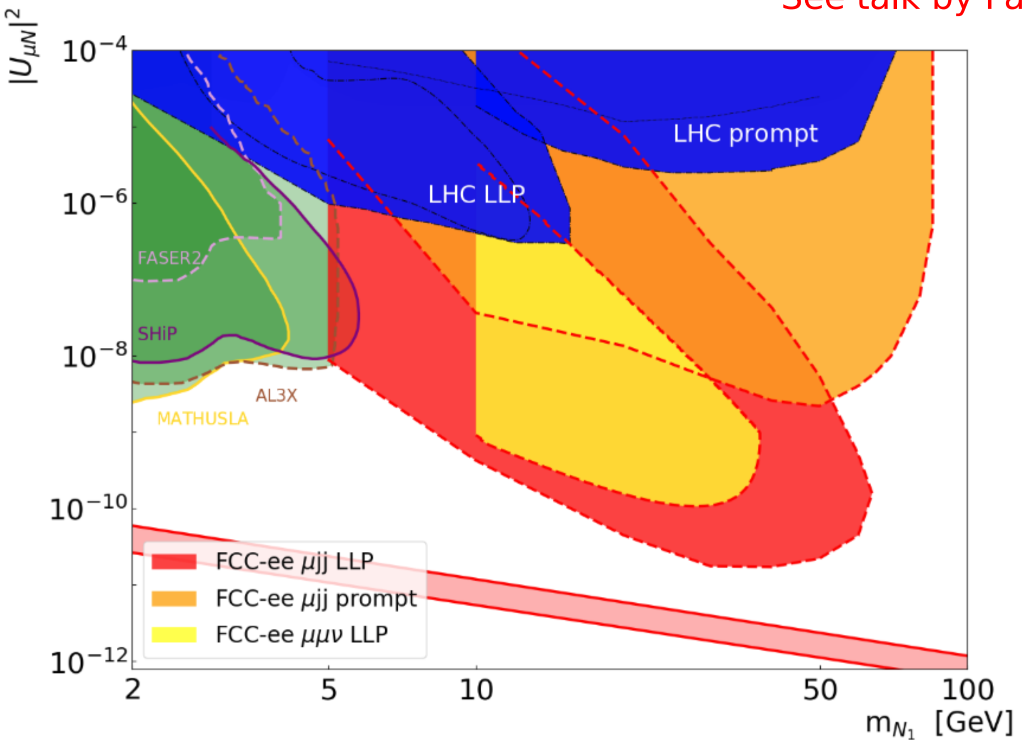
See talk by Axel Gallen





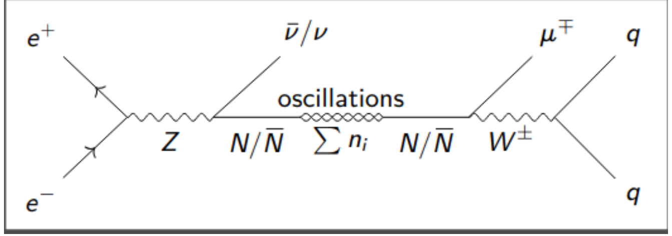
BSM particle searches: HNLs

See talk by Pantelis Kontaxakis



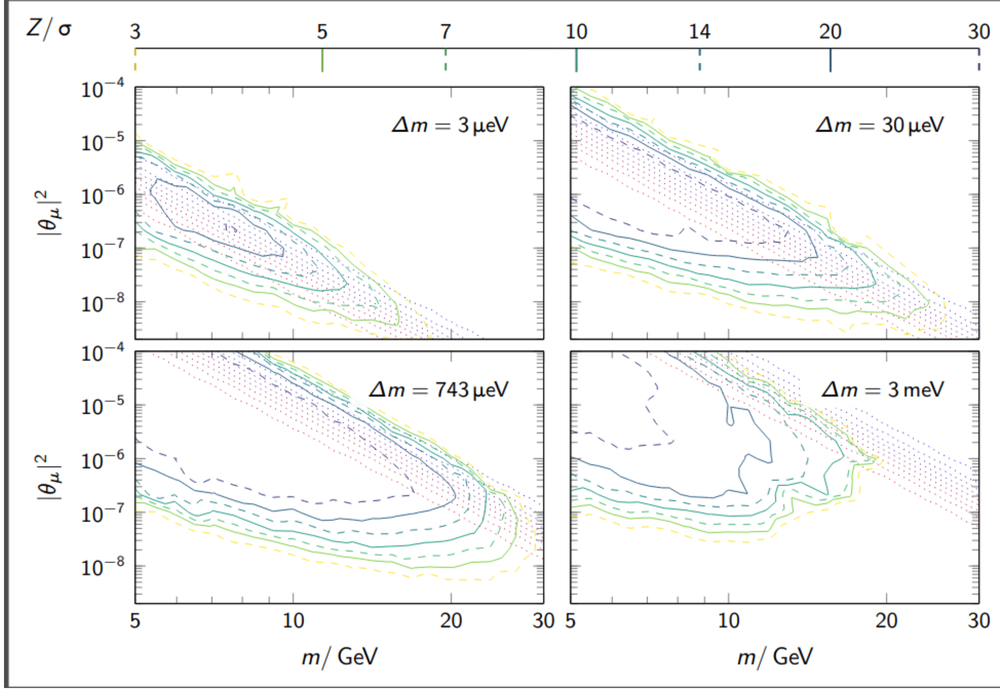
BSM particle searches: HNLs

Single charged lepton



See talk by Jan Hajer

Significance for $N\bar{N}$Os with different mass splittings at the FCC-*ee* [24]



FCC-hh synergies with ee

See talk by Michelangelo Mangano

Key question to address:

given a discovery at FCC-ee (whether **direct,** *eg ALPs, HNL, BSM H decays, …,* or **indirect,** *eg deviations in EWPO or in Higgs properties*), how will FCC-hh contribute to the interpretation of this discovery?

- What information will it add to the study of the properties of new particles observed at FCC-ee?
- How will it uncover the microscopic origin of SM deviations see at FCC-ee?

See talk by Juan Rojo on the power of forward physics facilities.

Conclusions

1. Tera-Z has incredible potential to probe general new physics scenarios up to **multiple TeV**.

2. Naturalness explanations will be pushed to the limit.

3. Flavour at FCC offers avenues to test new channels and increase the sensitivity of several others.

4. There is an important complementarity between the different runs and between FCC-ee and FCC-hh to test BSM.

Without a clear direction, the broad scope of the FCC project is fundamental!