Global EFT fits for future lepton colliders

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Effective Field Theory

Energy

UV physics (heavy particles) $\mathcal{L}_{NP}(\phi, \underbrace{\boldsymbol{Z'}, \boldsymbol{X}, \boldsymbol{Q}, \boldsymbol{S}}_{\textbf{new}} \ldots)$

Λ

Effective Field Theory $\mathcal{L}_{SM}(\phi) \boxed{+ \mathcal{L}_{dim6}(\phi)} + \ldots$

Standard Model $\mathcal{L}_{SM}(\phi)$

Effective Field Theory reveals high energy physics through precise measurements at low energy.

EFT pathway to New Physics

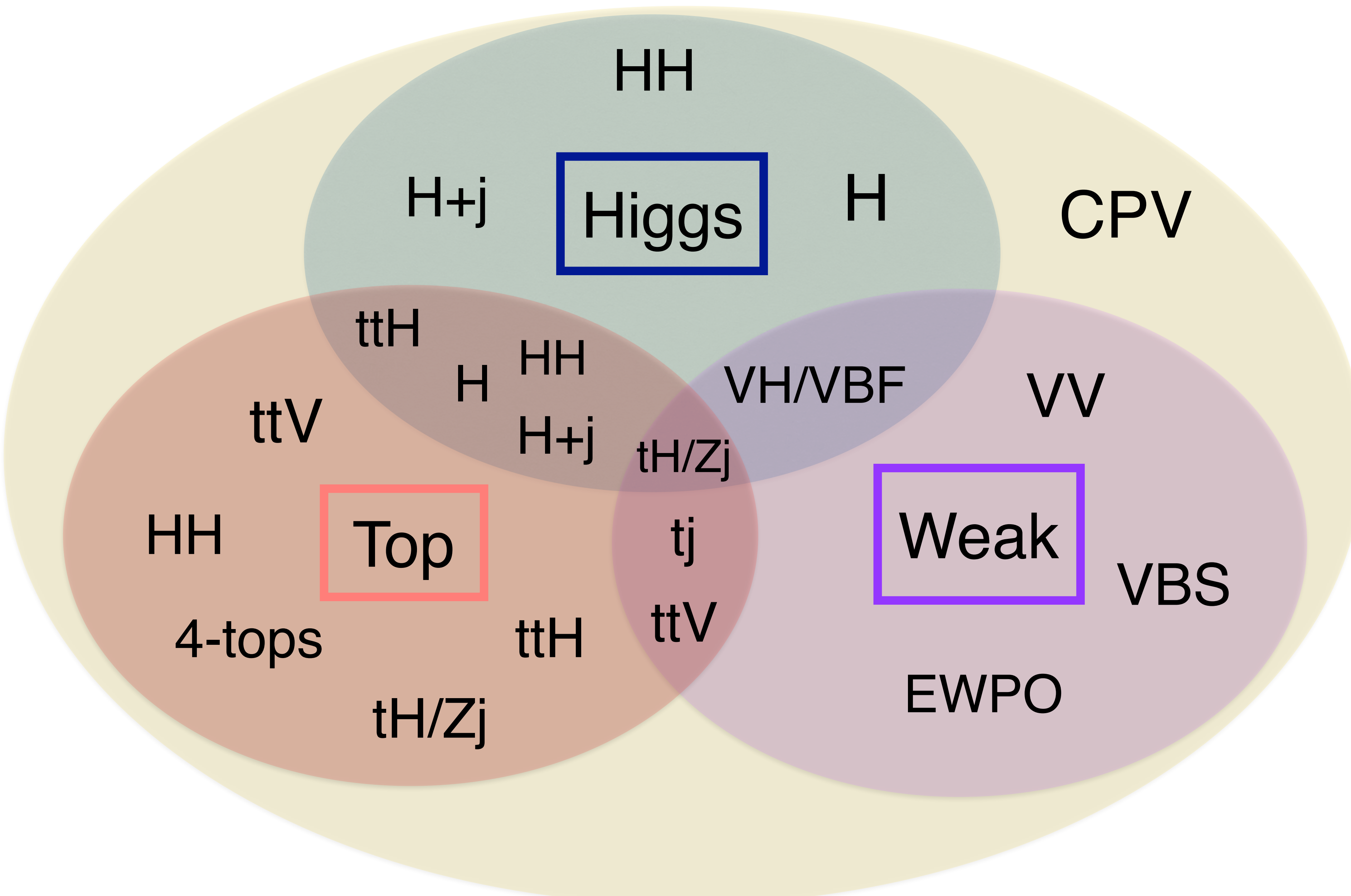
$$\Delta \mathrm{Obs}_n = \mathrm{Obs}_n^{\mathrm{EXP}} - \mathrm{Obs}_n^{\mathrm{SM}} = \frac{1}{\Lambda^2} \sum_i c_i^6(\mu) a_{n,i}^6(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Precise EFT predictions

Precise SM predictions

Precise experimental measurements

Global nature of EFT



Adapted from K. Mimasu

Global fit Setup

Theory

Accurate predictions for the SM and the EFT

SM: (N)NLO QCD + NLO EW

EFT: NLO QCD, linear and quadratics, with SMEFT@NLO NNPDF4.0 no top

Experimental data

445 data points from: Higgs, top, diboson (LHC) & EWPO (LEP).

Inclusive and differential: mostly parton level

Experimental uncertainties and their correlations as provided by experiments

SMEFiT

Giani, Magni, Rojo arXiv:2302.06660

Methodology

Nested Sampling for quadratic fits
Analytic solution for linear fits
Faithful uncertainty estimate
Avoid under- and over-fitting, validated on pseudo-data (closure test)

Output

Fit reports with bounds on coefficients, posterior distributions, PCA, Fisher information
Constraints on New Physics scale
Fit results can be used to bound specific UV complete models

Experimental input

LEP & LHC

Category	Processes	$n_{\rm dat}$ SMEFiT2.0	$n_{\rm dat}$ SMEFiT3.0
Top quark production	$t\bar{t}+X$	94	115
	$t\bar{t}Z$, $t\bar{t}W$	14	21
	$t\bar{t}\gamma$	-	2
	single top (inclusive)	27	28
	tZ, tW	9	13
	$t\bar{t}t\bar{t}$, $t\bar{t}b\bar{b}$	6	12
	Total	**150**	**191**
Higgs production and decay	Run I signal strengths	22	22
	Run II signal strengths	40	36 (*)
	Run II, differential distributions & STXS	35	71
	Total	**97**	**129**
Diboson production	LEP-2	40	40
	LHC	30	41
	Total	**70**	**81**
EWPOs	LEP-2	-	44
Baseline dataset	**Total**	**317**	**445**

SMEFiT3.0 Celada, Giani, Mantani, Rojo, Rossia, Thomas, EV, ter Hoeve arXiv:2404.12809

SMEFiT2.0: Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, EV and Zhang arXiv:2105.00006

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Which operators?

Flavour assumption:

$\mathrm{U}(2)_q \times \mathrm{U}(3)_d \times \mathrm{U}(2)_u \times (\mathrm{U}(1)_\ell \times \mathrm{U}(1)_e)^3$ + Yukawa of bottom, charm and tau

Operator	Coefficient	Definition	Operator	Coefficient	Definition
3rd generation quarks					
$\mathcal{O}_{\varphi Q}^{(1)}$	$c_{\varphi Q}^{(1)}$ (*)	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{Q}\gamma^\mu Q)$	$\mathcal{O}_{tW}$	c_{tW}	$i(\bar{Q}\tau^{\mu\nu}\tau_I t)\tilde{\varphi} W^I_{\mu\nu}$ + h.c.
$\mathcal{O}_{\varphi Q}^{(3)}$	$c_{\varphi Q}^{(3)}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi)(\bar{Q}\gamma^\mu \tau^I Q)$	$\mathcal{O}_{tB}$	c_{tB} (*)	$i(\bar{Q}\tau^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$ + h.c.
$\mathcal{O}_{\varphi t}$	$c_{\varphi t}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{t}\gamma^\mu t)$	$\mathcal{O}_{tG}$	c_{tG}	$ig_S(\bar{Q}\tau^{\mu\nu} T_A t)\tilde{\varphi} G^A_{\mu\nu}$ + h.c.
$\mathcal{O}_{t\varphi}$	$c_{t\varphi}$	$(\varphi^\dagger\varphi)\bar{Q}t\tilde{\varphi}$ + h.c.	$\mathcal{O}_{b\varphi}$	$c_{b\varphi}$	$(\varphi^\dagger\varphi)\bar{Q}b\varphi$ + h.c.
1st, 2nd generation quarks					
$\mathcal{O}_{\varphi q}^{(1)}$	$c_{\varphi q}^{(1)}$ (*)	$\sum_{i=1,2} i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{q}_i\gamma^\mu q_i)$	$\mathcal{O}_{\varphi d}$	$c_{\varphi d}$	$\sum_{i=1,2,3} i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{d}_i\gamma^\mu d_i)$
$\mathcal{O}_{\varphi q}^{(3)}$	$c_{\varphi q}^{(3)}$	$\sum_{i=1,2} i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi)(\bar{q}_i\gamma^\mu \tau^I q_i)$	$\mathcal{O}_{c\varphi}$	$c_{c\varphi}$	$(\varphi^\dagger\varphi)\bar{q}_2 c\tilde{\varphi}$ + h.c.
$\mathcal{O}_{\varphi u}$	$c_{\varphi u}$	$\sum_{i=1,2} i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{u}_i\gamma^\mu u_i)$			
two-leptons					
$\mathcal{O}_{\varphi \ell_i}$	$c_{\varphi \ell_i}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{\ell}_i\gamma^\mu \ell_i)$	$\mathcal{O}_{\varphi\mu}$	$c_{\varphi\mu}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{\mu}\gamma^\mu \mu)$
$\mathcal{O}_{\varphi \ell_i}^{(3)}$	$c_{\varphi \ell_i}^{(3)}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi)(\bar{\ell}_i\gamma^\mu \tau^I \ell_i)$	$\mathcal{O}_{\varphi\tau}$	$c_{\varphi\tau}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{\tau}\gamma^\mu \tau)$
$\mathcal{O}_{\varphi e}$	$c_{\varphi e}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{e}\gamma^\mu e)$	$\mathcal{O}_{\tau\varphi}$	$c_{\tau\varphi}$	$(\varphi^\dagger\varphi)\bar{\ell}_3 \tau\varphi$ + h.c.
four-leptons					
$\mathcal{O}_{\ell\ell}$	$c_{\ell\ell}$	$(\bar{\ell}_1\gamma_\mu\ell_2)(\bar{\ell}_2\gamma^\mu\ell_1)$			

DoF	Definition (in Warsaw basis notation)	DoF	Definition (in Warsaw basis notation)
c^1_{QQ}	$2c_{qq}^{1(3333)} - \frac{2}{3}c_{qq}^{3(3333)}$	c^8_{QQ}	$8c_{qq}^{3(3333)}$
c^1_{Qt}	$c_{qu}^{1(3333)}$	c^8_{Qt}	$c_{qu}^{8(3333)}$
$c^{1,8}_{Qq}$	$c_{qq}^{1(i33i)} + 3c_{qq}^{3(i33i)}$	$c^{1,1}_{Qq}$	$c_{qq}^{1(ii33)} + \frac{1}{6}c_{qq}^{1(i33i)} + \frac{1}{2}c_{qq}^{3(i33i)}$
$c^{3,8}_{Qq}$	$c_{qq}^{1(i33i)} - c_{qq}^{3(i33i)}$	$c^{3,1}_{Qq}$	$c_{qq}^{3(ii33)} + \frac{1}{6}(c_{qq}^{1(i33i)} - c_{qq}^{3(i33i)})$
c^8_{tq}	$c_{qu}^{8(ii33)}$	c^1_{tq}	$c_{qu}^{1(ii33)}$
c^8_{tu}	$2c_{uu}^{(i33i)}$	c^1_{tu}	$c_{uu}^{(ii33)} + \frac{1}{3}c_{uu}^{(i33i)}$
c^8_{Qu}	$c_{qu}^{8(33ii)}$	c^1_{Qu}	$c_{qu}^{1(33ii)}$
c^8_{td}	$c_{ud}^{8(33jj)}$	c^1_{td}	$c_{ud}^{1(33jj)}$
c^8_{Qd}	$c_{qd}^{8(33jj)}$	c^1_{Qd}	$c_{qd}^{1(33jj)}$

Operator	Coefficient	Definition	Operator	Coefficient	Definition
$\mathcal{O}_{\varphi G}$	$c_{\varphi G}$	$(\varphi^\dagger\varphi)G_A^{\mu\nu}G^A_{\mu\nu}$	$\mathcal{O}_{\varphi\Box}$	$c_{\varphi\Box}$	$\partial_\mu(\varphi^\dagger\varphi)\partial^\mu(\varphi^\dagger\varphi)$
$\mathcal{O}_{\varphi B}$	$c_{\varphi B}$	$(\varphi^\dagger\varphi)B^{\mu\nu}B_{\mu\nu}$	$\mathcal{O}_{\varphi D}$	$c_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\dagger(\varphi^\dagger D_\mu\varphi)$
$\mathcal{O}_{\varphi W}$	$c_{\varphi W}$	$(\varphi^\dagger\varphi)W_I^{\mu\nu}W^I_{\mu\nu}$	$\mathcal{O}_W$	c_{WWW}	$\epsilon_{IJK}W^I_{\mu\nu}W^{J,\nu\rho}W^{K,\mu}_\rho$
$\mathcal{O}_{\varphi WB}$	$c_{\varphi WB}$	$(\varphi^\dagger\tau_I\varphi)B^{\mu\nu}W^I_{\mu\nu}$			

50 degrees of freedom

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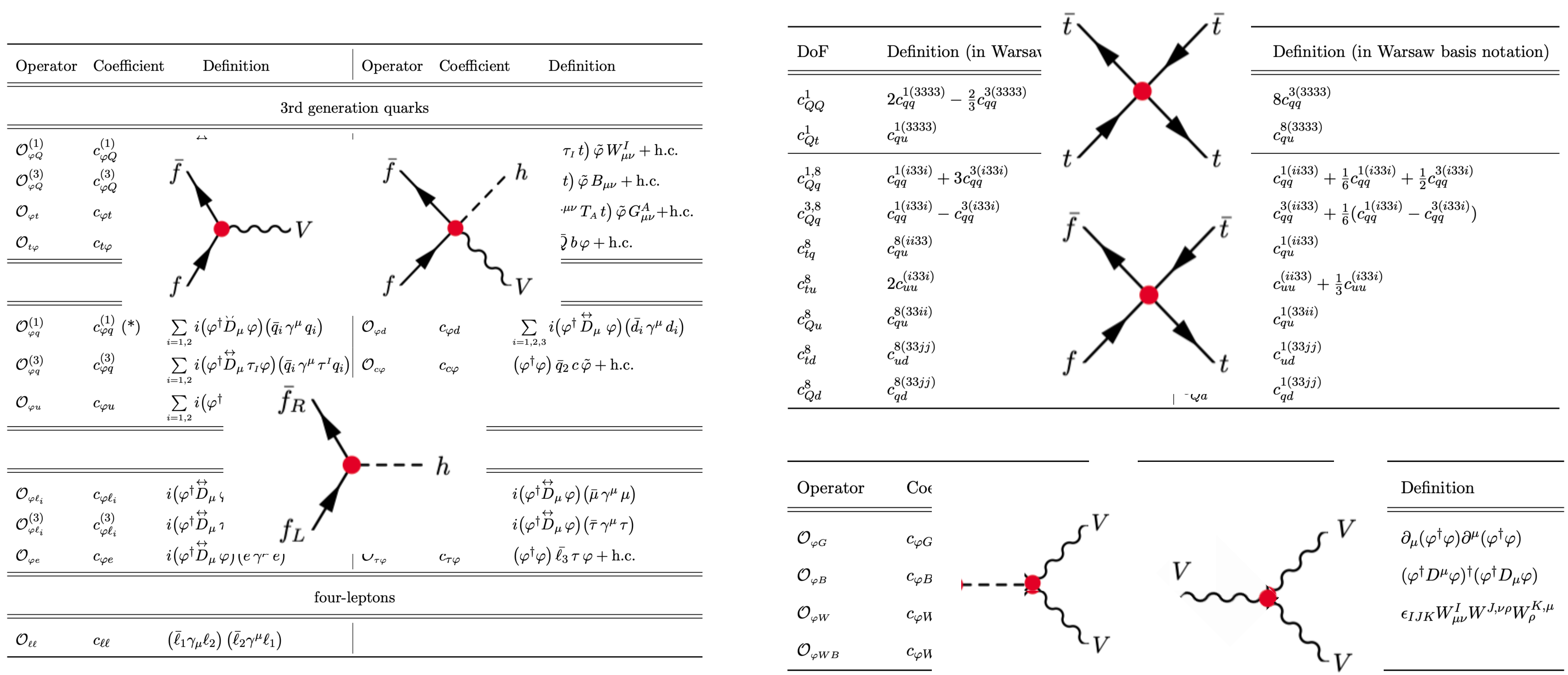
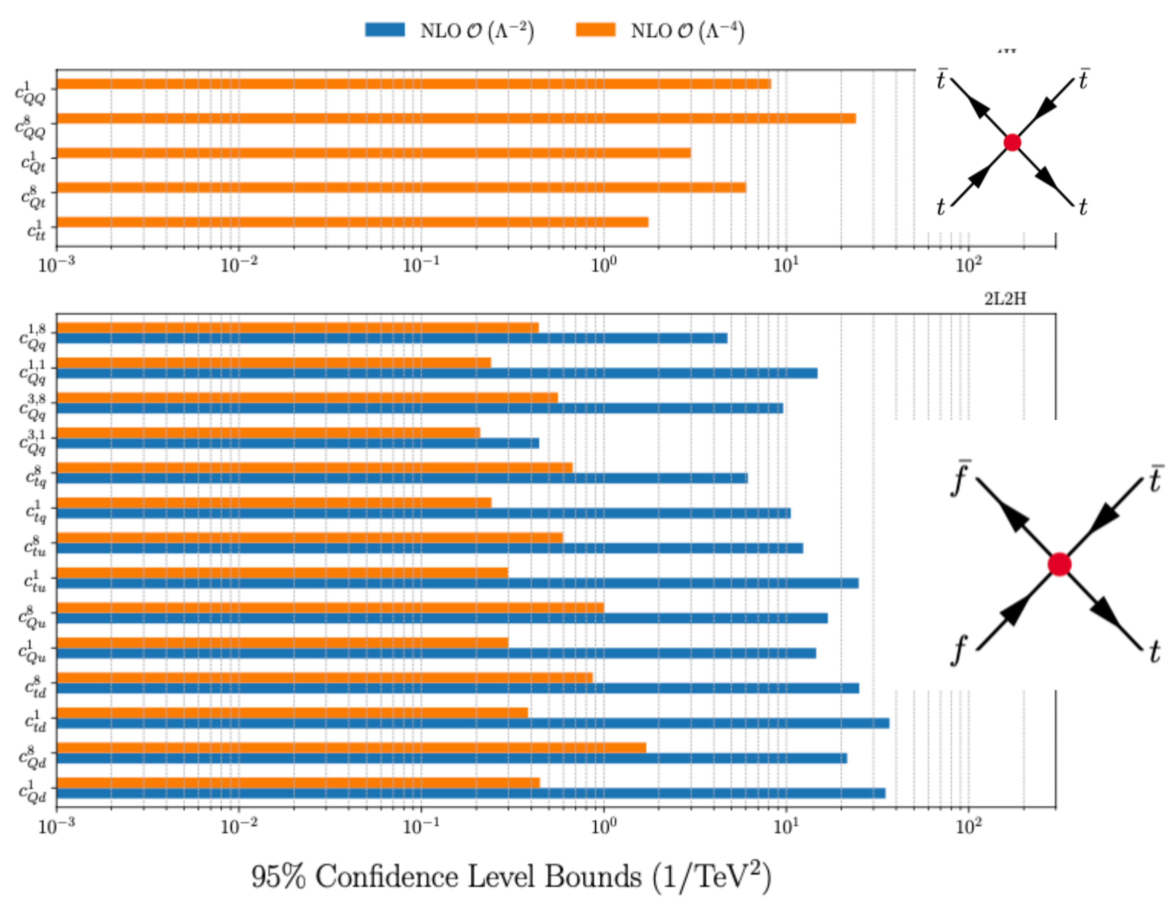
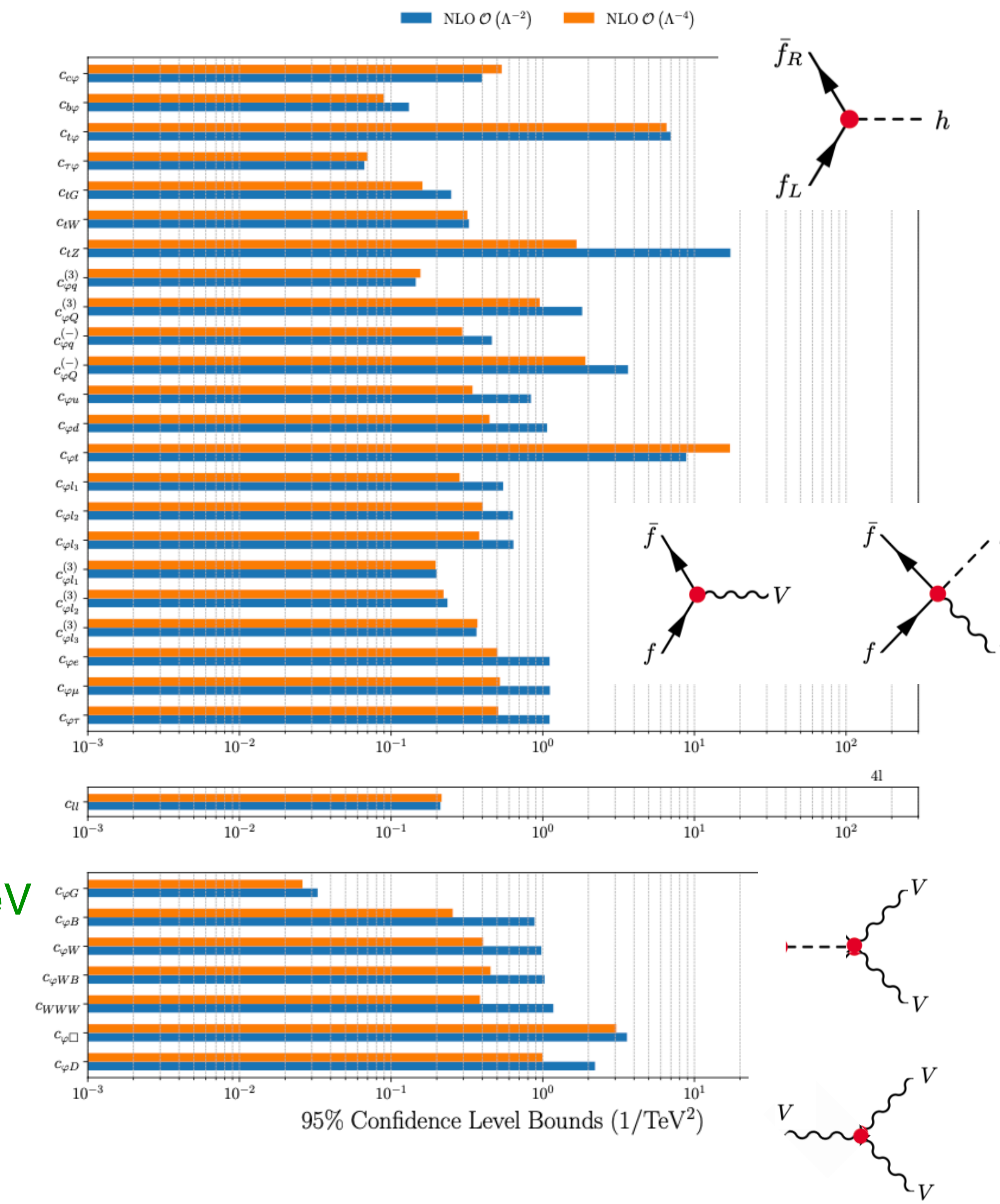


50 degrees of freedom

Current global fit results





- Bounds varying between operators
- Most Wilson coefficient bounds below 1 for Λ=1 TeV
- Quadratic terms important
- Least constrained coefficients are 4-top operators

arXiv:2404.12809

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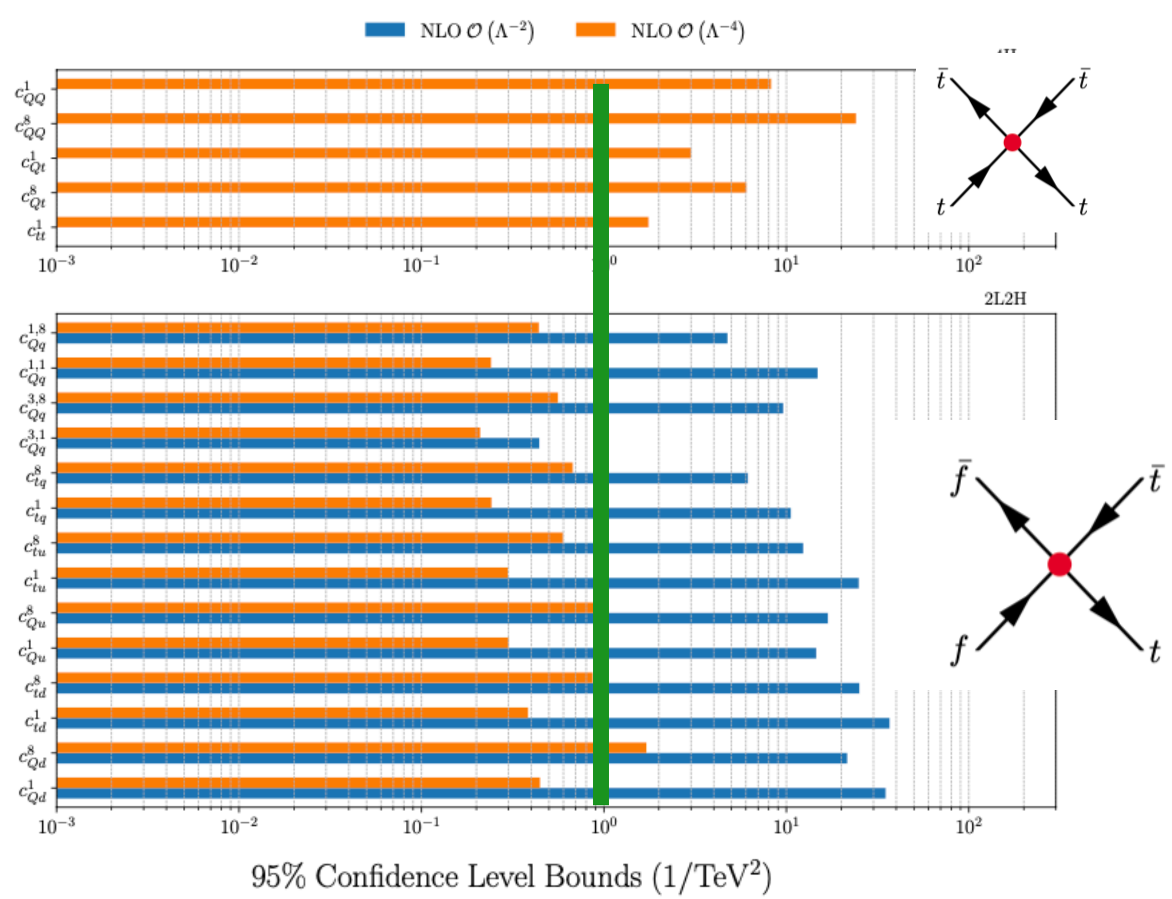

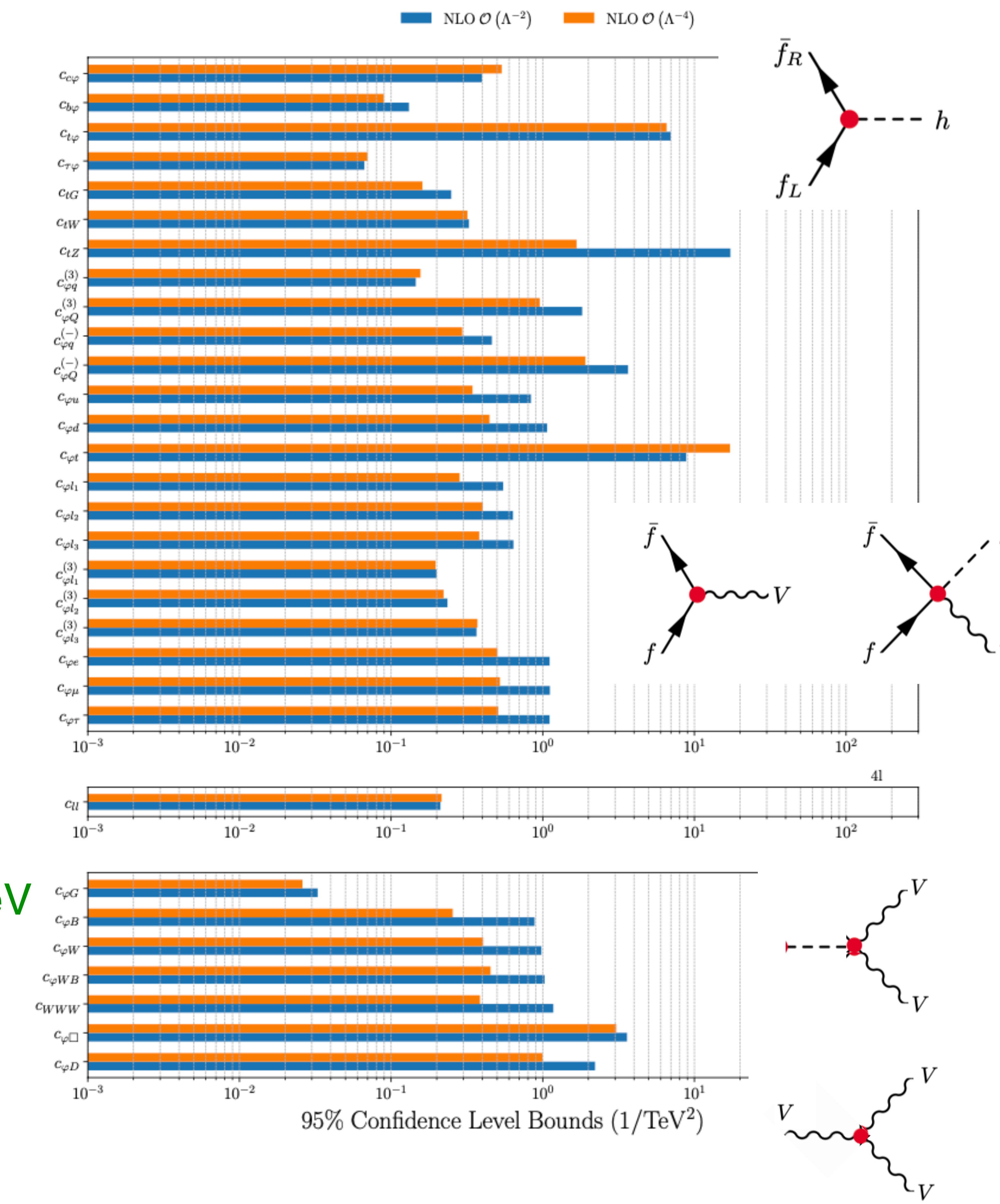

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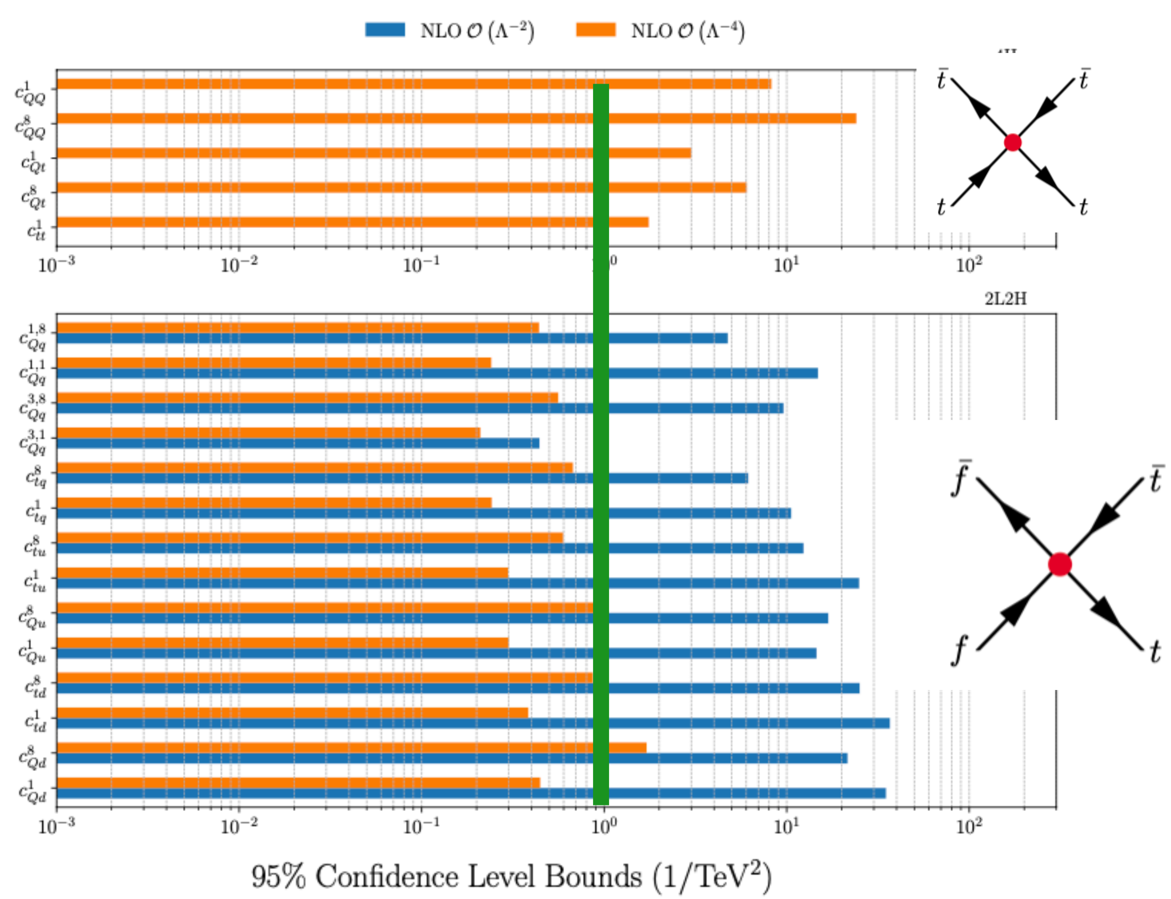

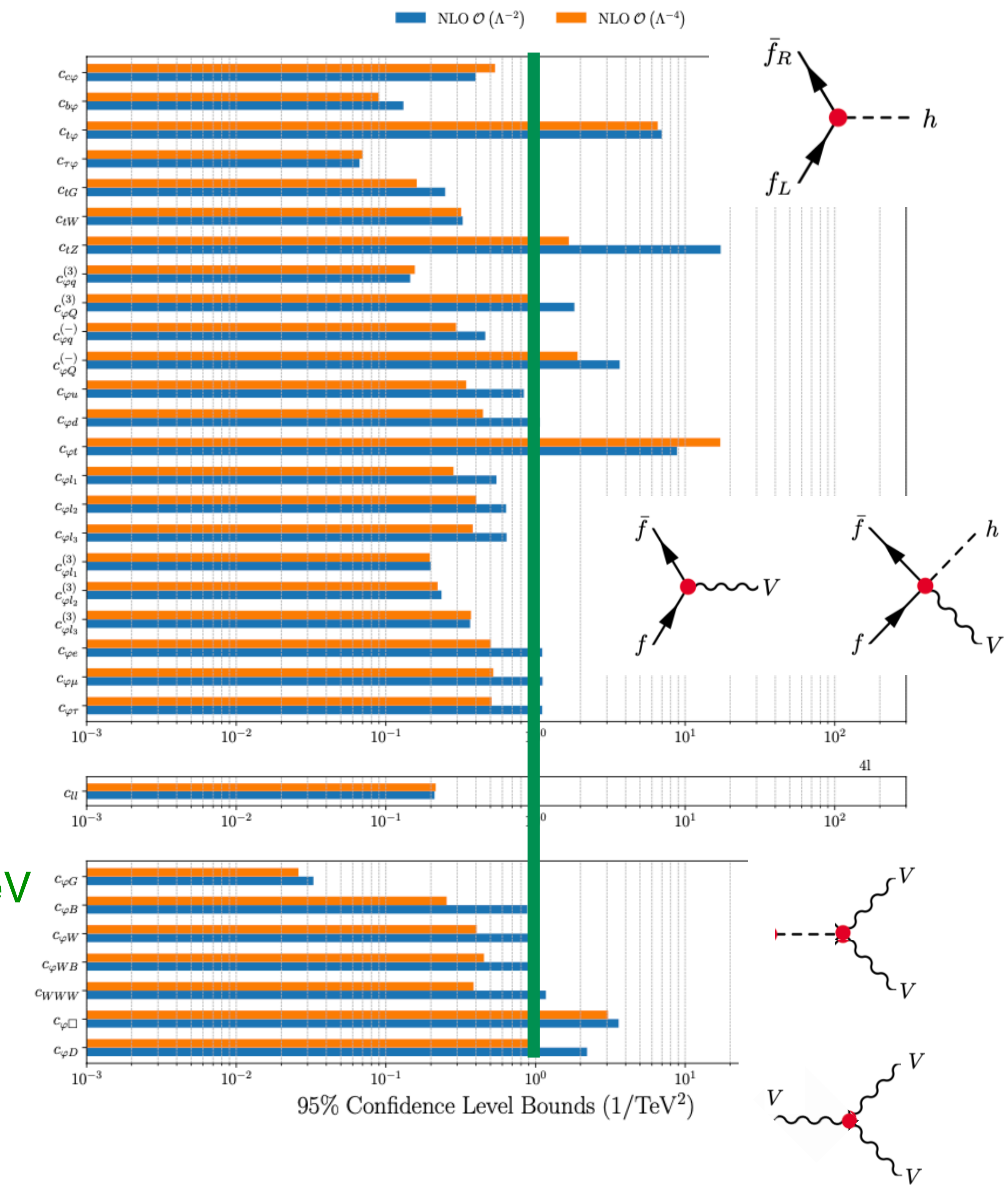

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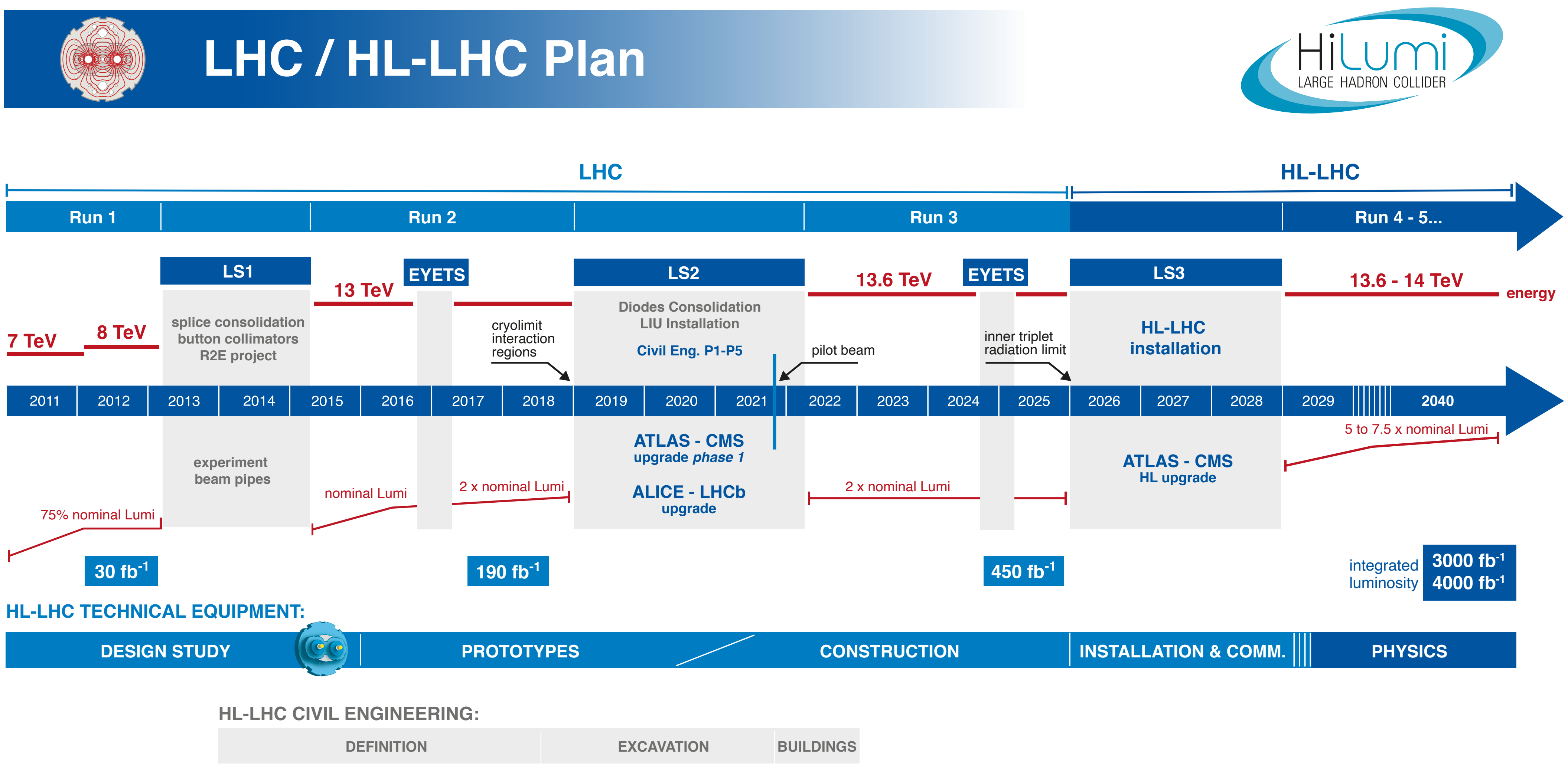
How about the HL-LHC?

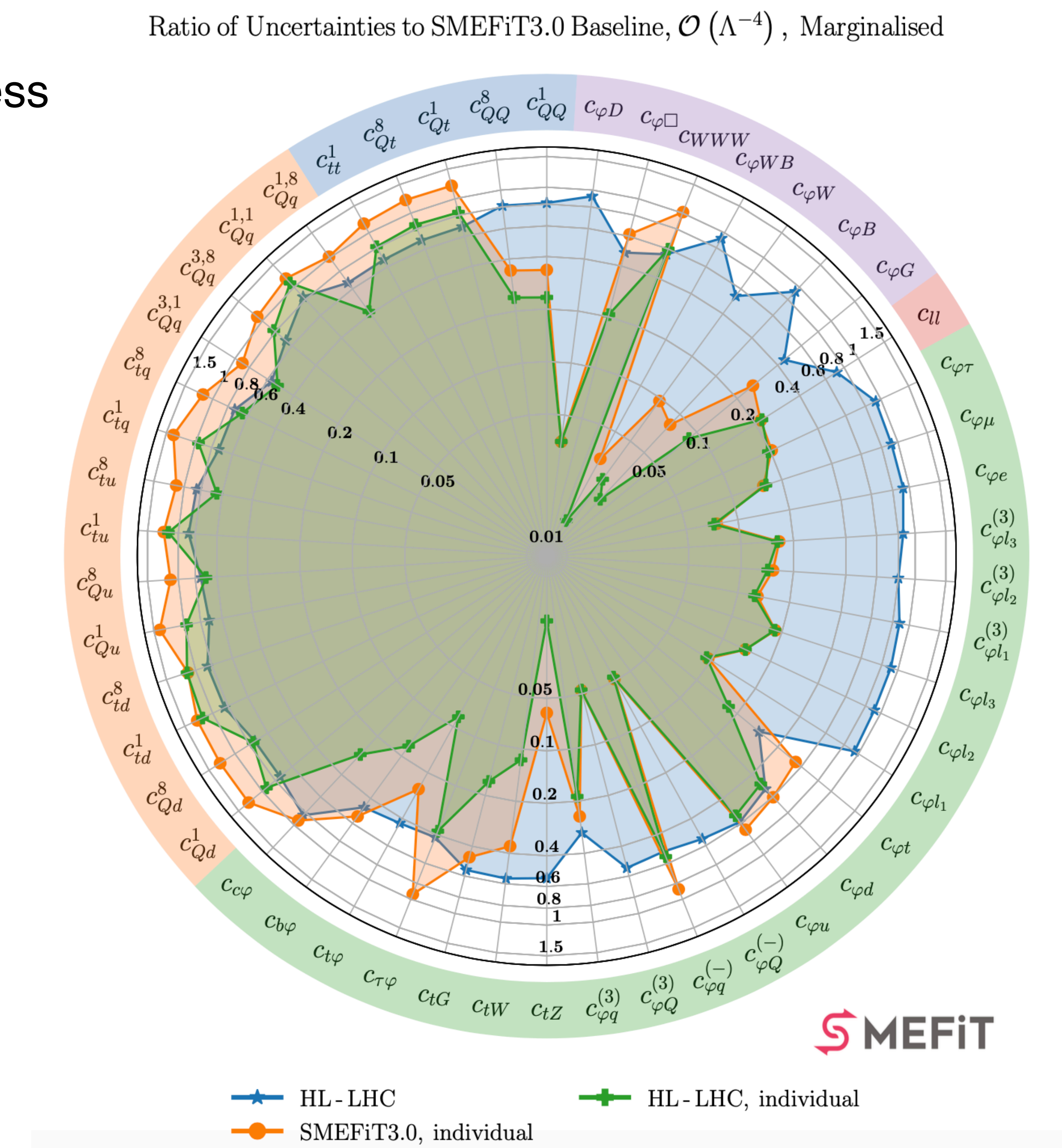


- HL-LHC will collect 3000ab^{-1} over the next 20 years
- Any future project will come after that
- How will the constraints look at the end of the HL-LHC?

Constraints at the HL-LHC

- We project all Run II datasets: one for each process and final state
- Scaling of uncertainties:
  - Statistical ones scaling with Luminosity
  - Systematics reduced by a factor of 2

- Explore relative improvement compared to current LHC fit
- We see an improvement ranging from 20% to a factor of 3 in the marginalised fit
- Improvement also through marginalisation
- No dedicated binning: Expect further improvement over LHC due to access to statistically limited high energy tails



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The future

HiLumi
HL-LHC PROJECT

clic

International
MUON Collider
Collaboration

FCC
hh ee he

CEPC

ilc
international linear collider

The future

Future circular lepton colliders

Energy ($\sqrt{s}$)	$\mathcal{L}_{\rm int}$ (Run time)		$\mathcal{L}_{\rm FCC-ee}/\mathcal{L}_{\rm CEPC}$
	FCC-ee (4 IPs)	CEPC (2 IPs)	
91 GeV (Z-pole)	300 ab^{-1} (4 years)	100 ab^{-1} (2 years)	3
161 GeV ($2\,m_W$)	20 ab^{-1} (2 years)	6 ab^{-1} (1 year)	3.3
240 GeV	10 ab^{-1} (3 years)	20 ab^{-1} (10 years)	0.5
350 GeV	0.4 ab^{-1} (1 year)	0.2 ab^{-1}	2
365 GeV ($2\,m_t$)	3 ab^{-1} (4 years)	1 ab^{-1} (5 years)	3

Future Circular Colliders

What will the FCC-ee measure?

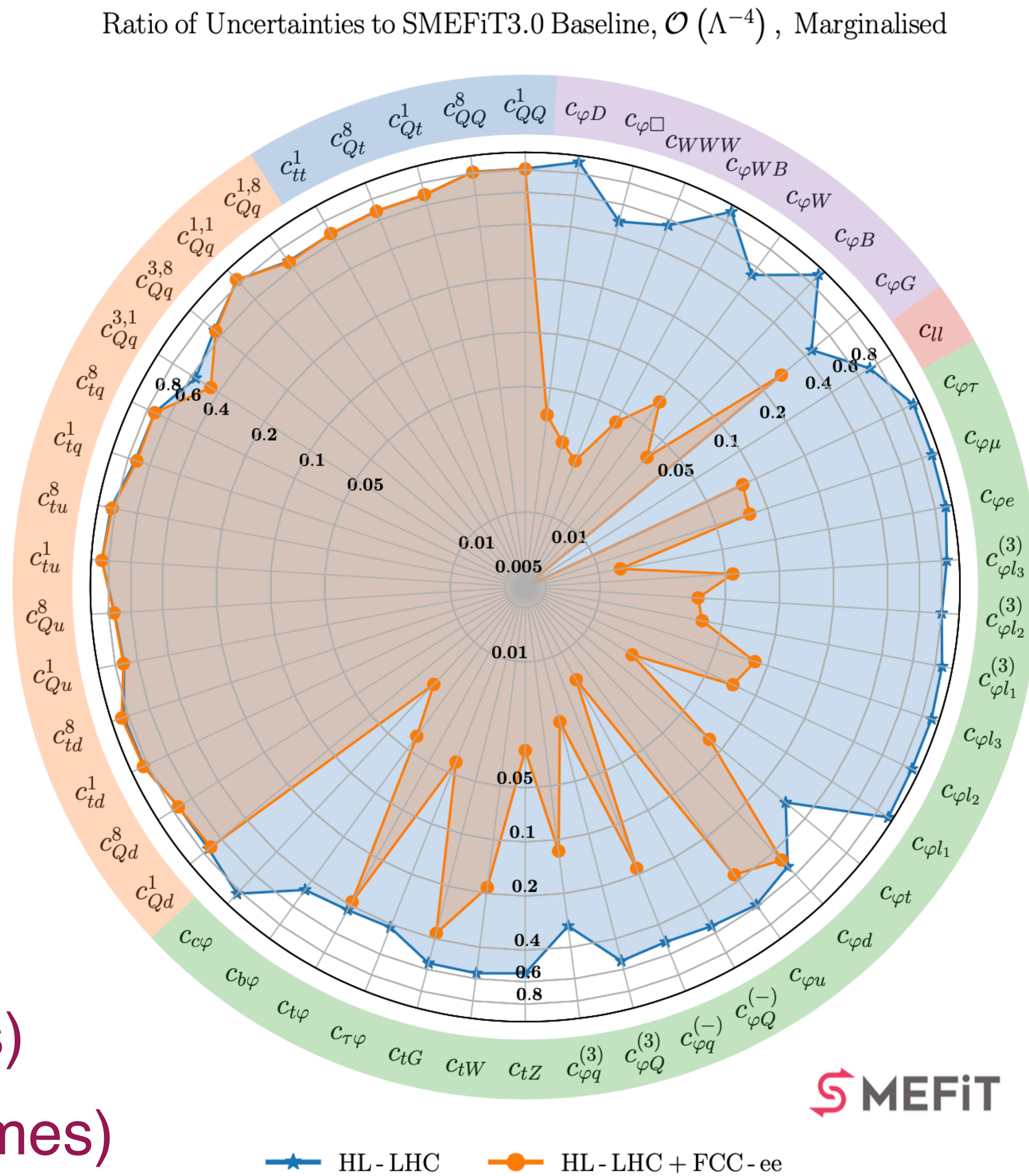
- EWPOs at the Z-pole
- Light fermion pair prediction
- Higgsstrahlung and VBF
- W boson pair production
- Top-quark pair production (365GeV)

Uncertainty projections from Snowmass study: arXiv:2206.08326

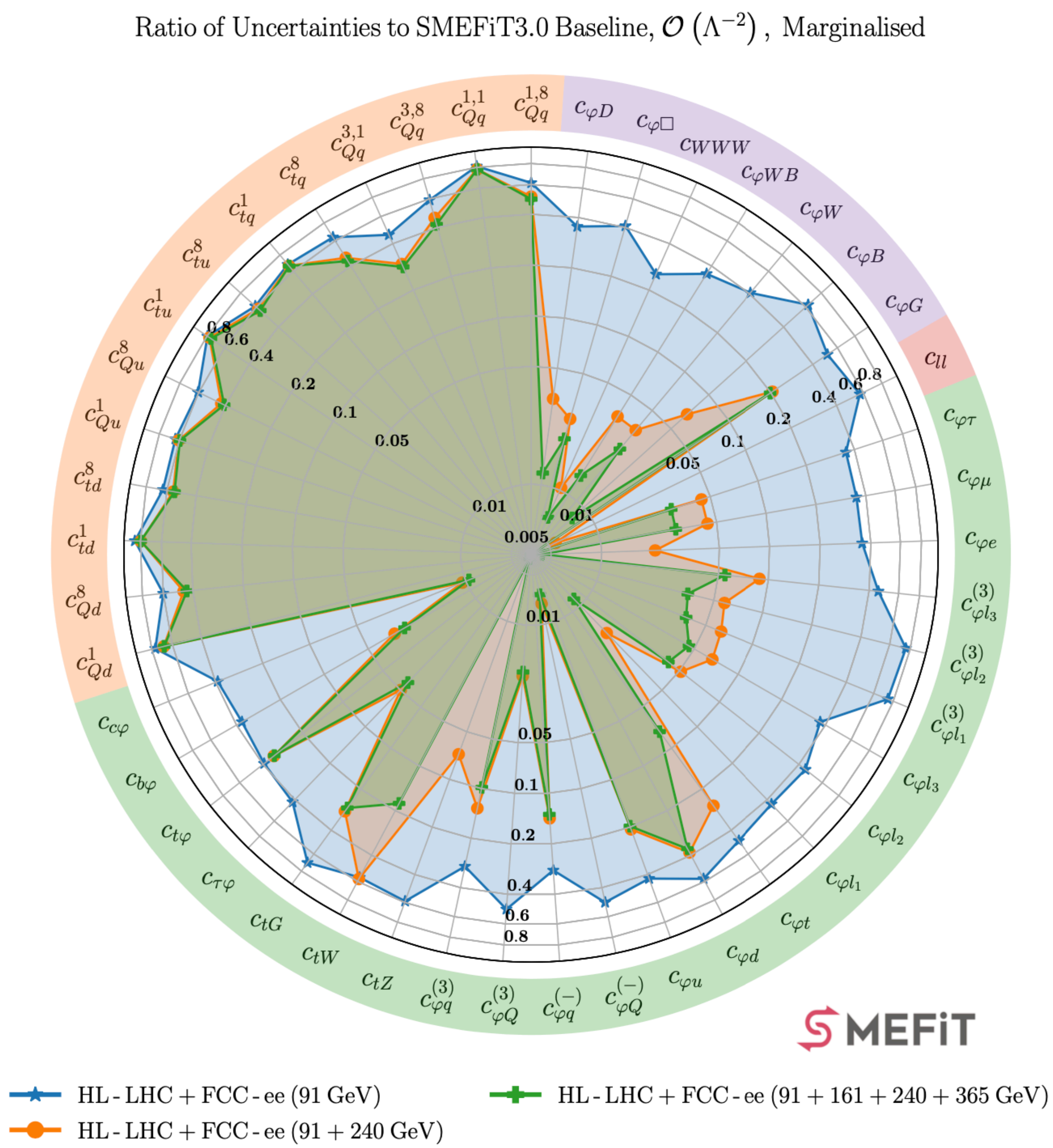
See also Jorge's talk on Monday

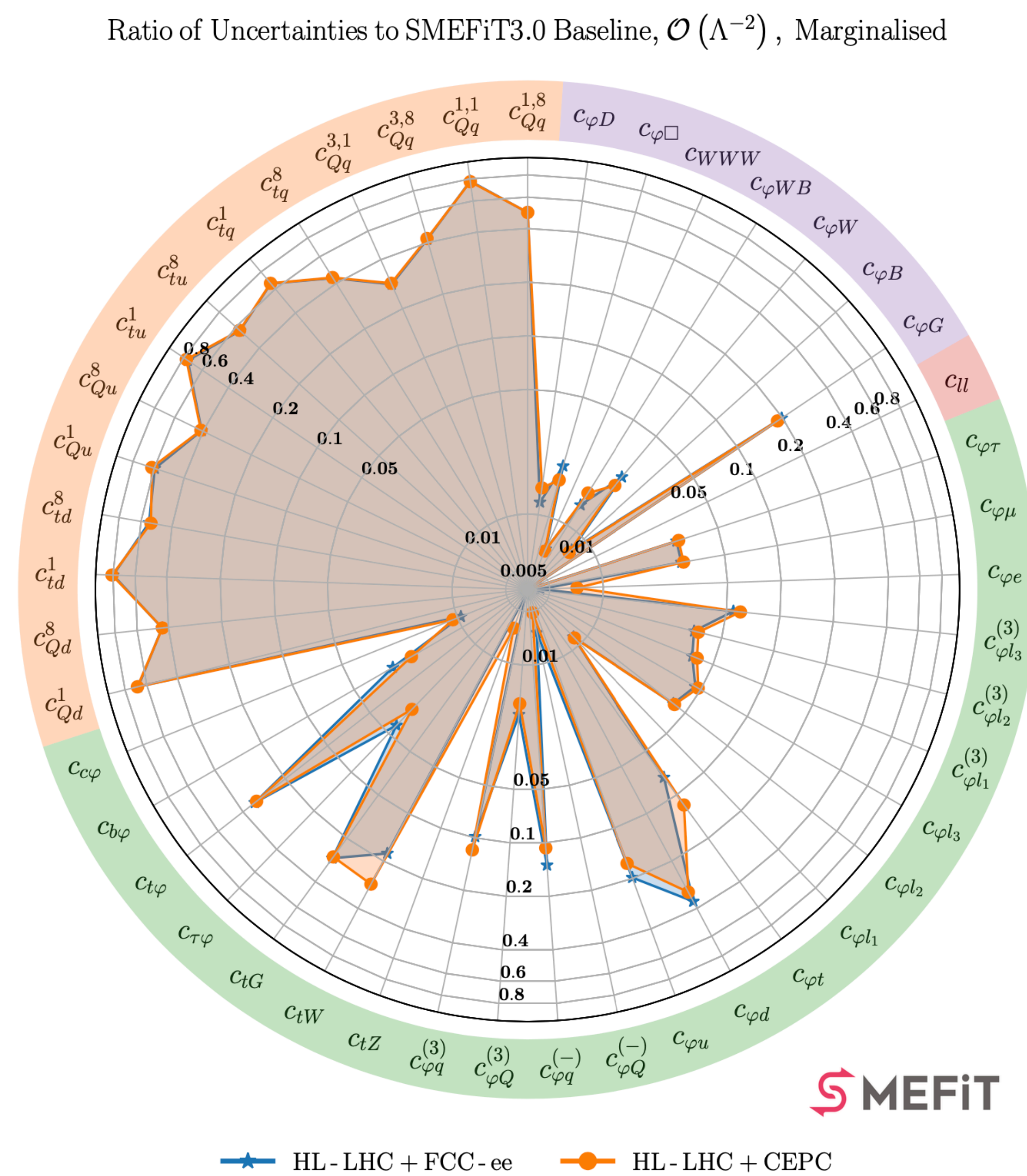
Significant improvement for:

- gauge operators (up to 30 times)
- 2-fermion operators (up to 50 times)



FCC-ee: Energy Runs & CEPC



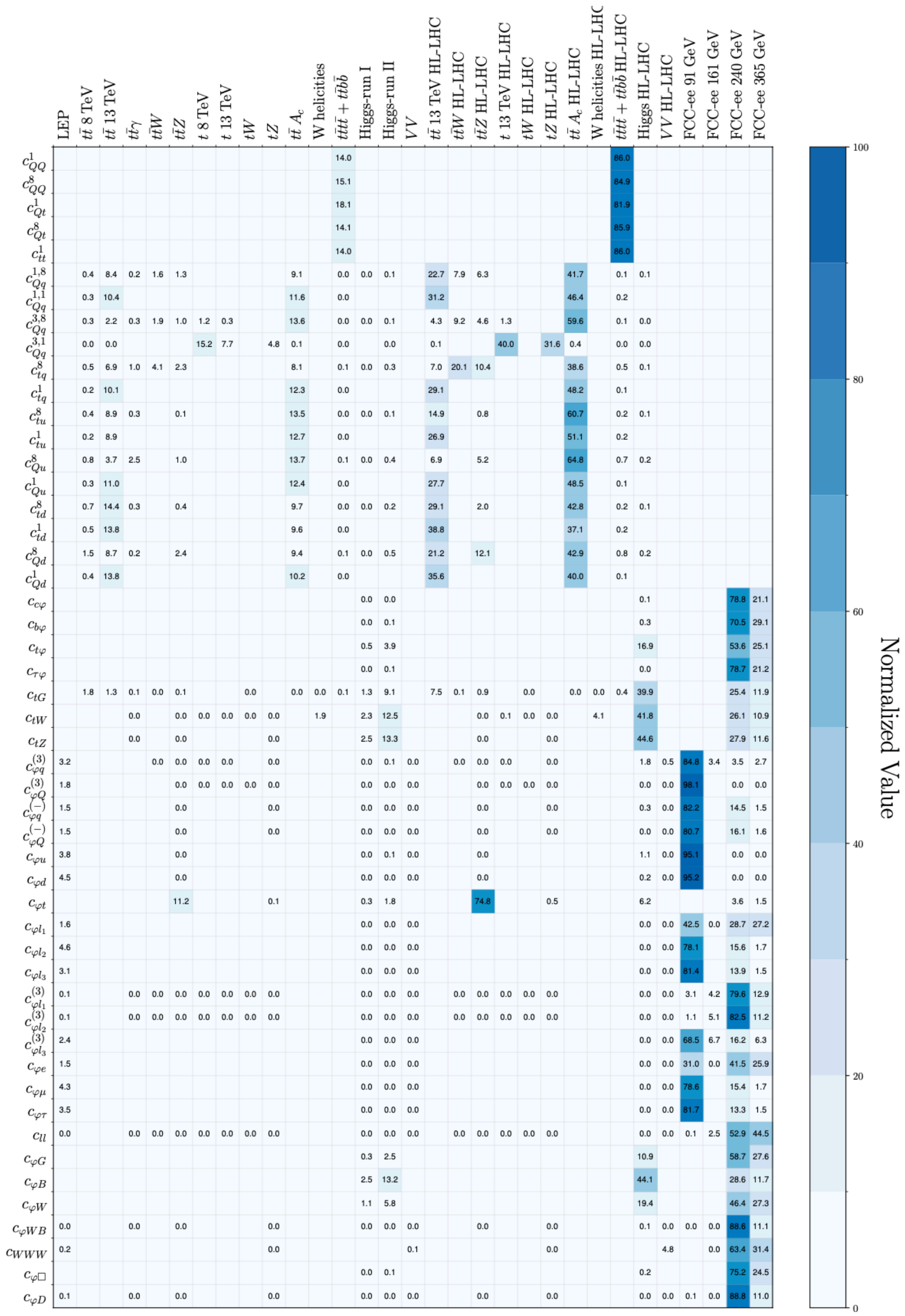


Significant impact of 240 GeV run, 365 GeV run also helps

Very similar results for CEPC

arXiv:2404.12809

Fisher information



- Fisher information shows which process gives more sensitivity for a given operator
- Proxy for a linear individual fit
- FCC-ee dominates nearly all operators except for 4-quark operators, only accessible at in pp collisions (tree level)
- Global fit picture more complicated due to correlations
- Both Z-pole run and run at 240 GeV important to pin down 2-fermion and gauge operators

What do we learn from global fits?

Bounds on new physics scale vary from 0.1 TeV (unconstrained) to 10s of TeV.
Bounds depend on:

- the operator
- assumption of a strongly or weakly coupled theory
- individual or marginalised bounds (reality is somewhere in-between)
- linear or quadratic bounds

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constraint: $\frac{c_i^6(\mu)}{\Lambda^2} = \frac{\lambda^2}{M^2} < X$

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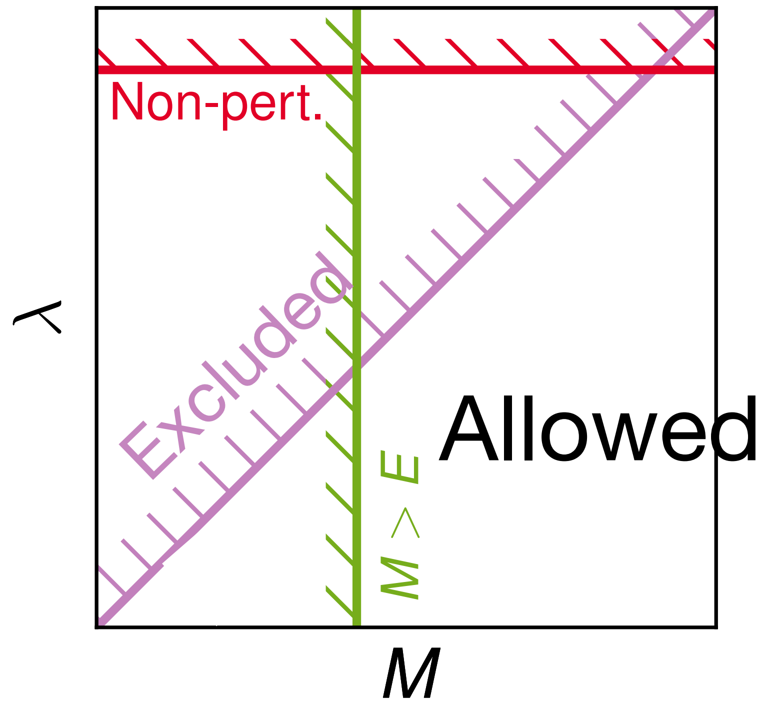
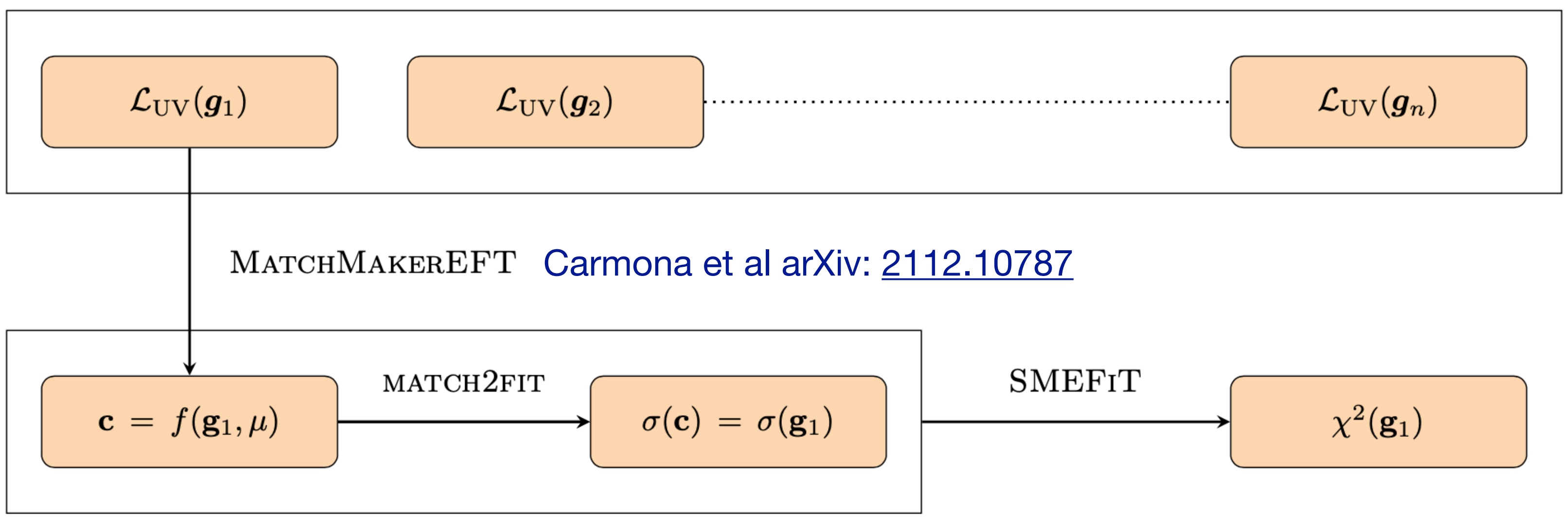


From SMEFT to the UV

Global fit constrains parameters of UV models

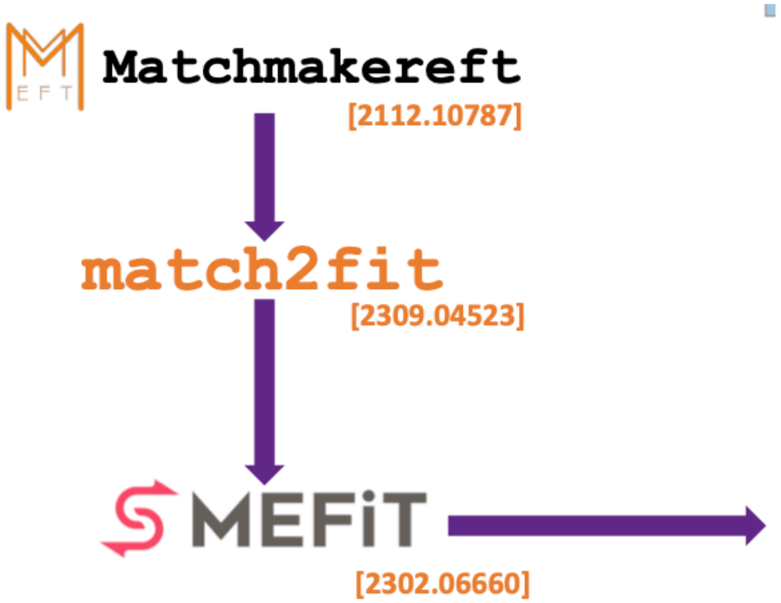
Matching condition ← $$\frac{c_i^6(\mu)}{\Lambda^2} = \frac{\lambda^2}{M^2} < X$$



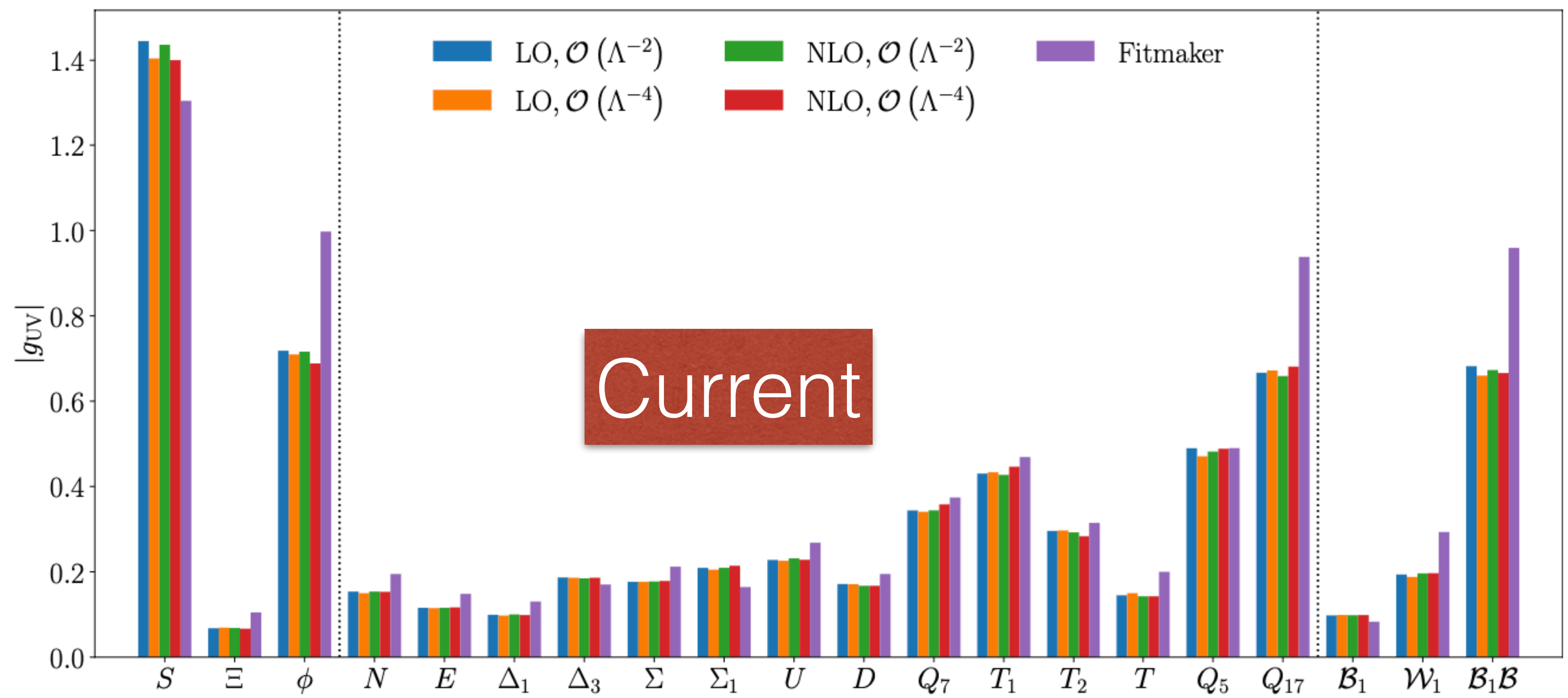
- Automate chain with final output constraints on the UV parameters
- Simplest case: single-field extensions of the SM de Blas arXiv:1711.10391
- Assume mass, constrain the coupling or vice versa

ter Hoeve, Magni, Rojo, Rossia, EV arXiv: 2309.04523

What can we learn from these fits?



Scalars		Fermions		Vectors	
Particle	Irrep	Particle	Irrep	Particle	Irrep
$\mathcal{S}$	$(1,1)_0$	N	$(1,1)_0$	$\mathcal{B}$	$(1,1)_0$
$\mathcal{S}_1$	$(1,1)_1$	E	$(1,1)_{-1}$	$\mathcal{B}_1$	$(1,1)_1$
ϕ	$(1,2)_{1/2}$	Δ_1	$(1,2)_{-1/2}$	$\mathcal{W}$	$(1,3)_0$
Ξ	$(1,3)_0$	Δ_3	$(1,2)_{-3/2}$	$\mathcal{W}_1$	$(1,3)_1$
Ξ_1	$(1,3)_1$	Σ	$(1,3)_0$	$\mathcal{G}$	$(8,1)_0$
ω_1	$(3,1)_{-1/3}$	Σ_1	$(1,3)_{-1}$	$\mathcal{H}$	$(8,3)_0$
ω_4	$(3,1)_{-4/3}$	U	$(3,1)_{2/3}$	$\mathcal{Q}_5$	$(8,3)_0$
ζ	$(3,3)_{-1/3}$	D	$(3,1)_{-1/3}$	$\mathcal{Y}_5$	$(\bar{6},2)_{-5/6}$
Ω_1	$(6,1)_{1/3}$	Q_1	$(3,2)_{1/6}$		
Ω_4	$(6,1)_{4/3}$	Q_7	$(3,2)_{7/6}$		
Υ	$(6,3)_{1/3}$	T_1	$(3,3)_{-1/3}$		
Φ	$(8,2)_{1/2}$	T_2	$(3,3)_{2/3}$		
		Q_5	$(3,2)_{-5/6}$		



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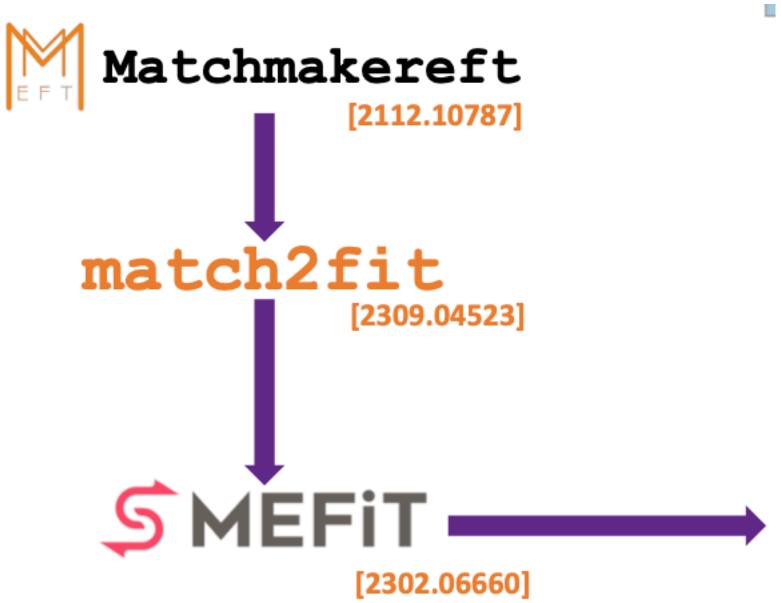
Automated constraints on UV models (also 1-loop and multiparticle models) from global EFT fit

Current mass constraints on single particle extensions: 1TeV to 10TeV

Best constraints for models modifying EWPOs, worst for those only changing 4-top operators

What can we learn from these fits?



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Ξ	$(1,3)_0$	Δ_3	$(1,2)_{-3/2}$	$\mathcal{W}_1$	$(1,3)_1$
Ξ_1	$(1,3)_1$	Σ	$(1,3)_0$	$\mathcal{G}$	$(8,1)_0$
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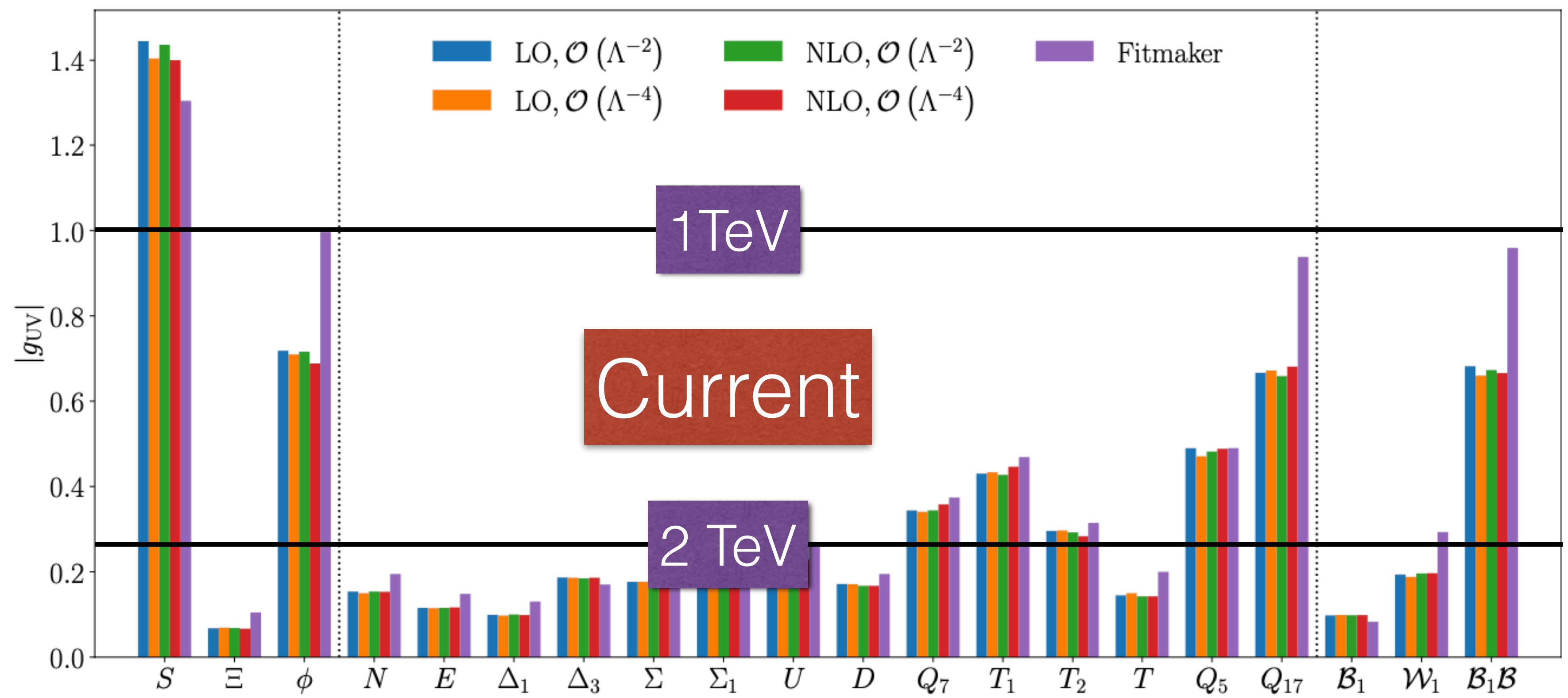
ζ	$(3,3)_{-1/3}$	D	$(3,1)_{-1/3}$	$\mathcal{Y}_5$	$(\bar{6},2)_{-5/6}$
Ω_1	$(6,1)_{1/3}$	Q_1	$(3,2)_{1/6}$		
Ω_4	$(6,1)_{4/3}$	Q_7	$(3,2)_{7/6}$		
Υ	$(6,3)_{1/3}$	T_1	$(3,3)_{-1/3}$		
Φ	$(8,2)_{1/2}$	T_2	$(3,3)_{2/3}$		
		Q_5	$(3,2)_{-5/6}$		



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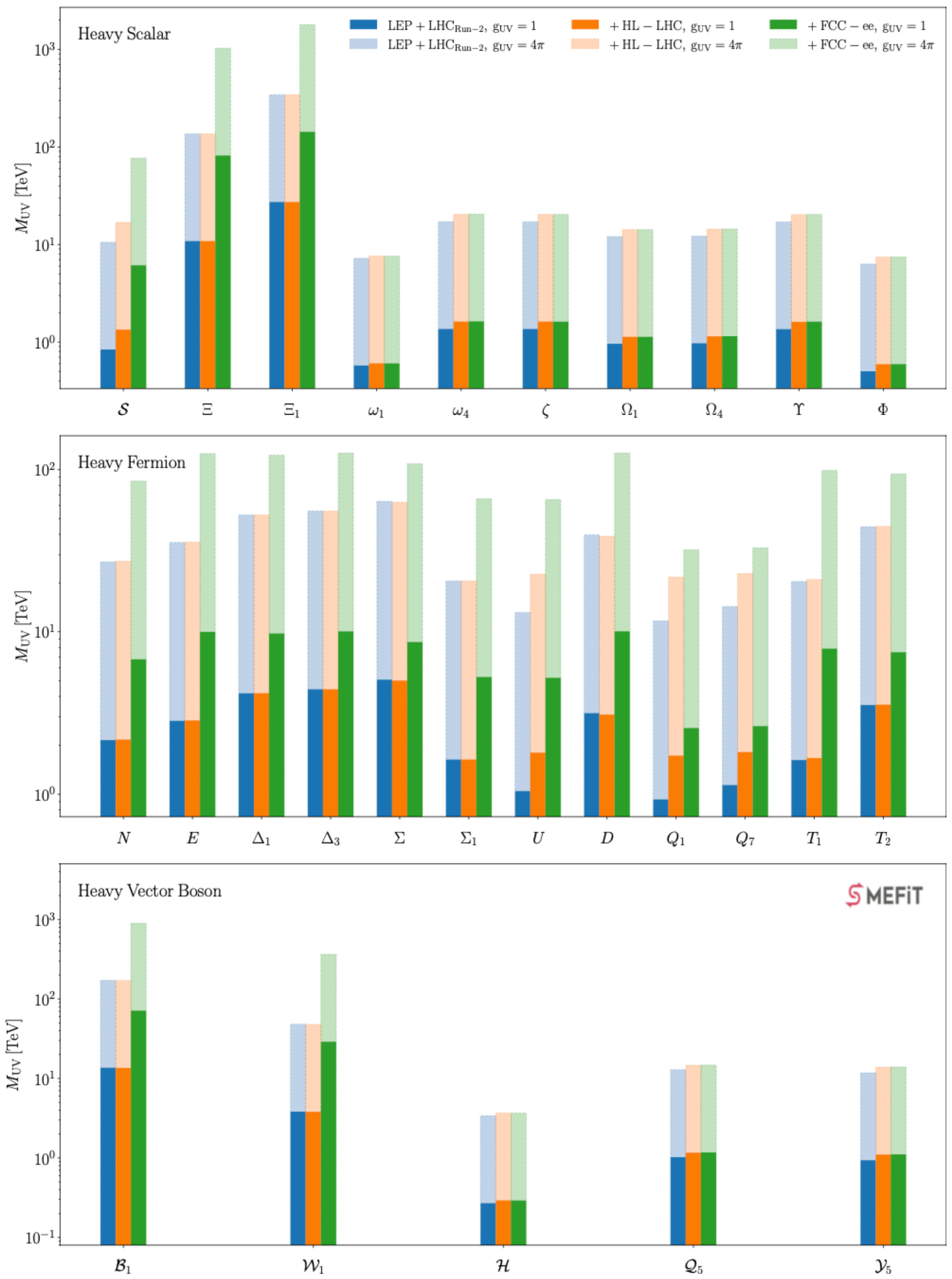
Best constraints for models modifying EWPOs, worst for those only changing 4-top operators

From SMEFT to the UV



arXiv:2404.12809

Scalars		Fermions		Vectors	
Particle	Irrep	Particle	Irrep	Particle	Irrep
$\mathcal{S}$	$(1,1)_0$	N	$(1,1)_0$	$\mathcal{B}$	$(1,1)_0$
$\mathcal{S}_1$	$(1,1)_1$	E	$(1,1)_{-1}$	$\mathcal{B}_1$	$(1,1)_1$
ϕ	$(1,2)_{1/2}$	Δ_1	$(1,2)_{-1/2}$	$\mathcal{W}$	$(1,3)_0$
Ξ	$(1,3)_0$	Δ_3	$(1,2)_{-3/2}$	$\mathcal{W}_1$	$(1,3)_1$
Ξ_1	$(1,3)_1$	Σ	$(1,3)_0$	$\mathcal{G}$	$(8,1)_0$
ω_1	$(3,1)_{-1/3}$	Σ_1	$(1,3)_{-1}$	$\mathcal{H}$	$(8,3)_0$
ω_4	$(3,1)_{-4/3}$	U	$(3,1)_{2/3}$	$\mathcal{Q}_5$	$(8,3)_0$
ζ	$(3,3)_{-1/3}$	D	$(3,1)_{-1/3}$	$\mathcal{Y}_5$	$(\bar{6},2)_{-5/6}$
Ω_1	$(6,1)_{1/3}$	Q_1	$(3,2)_{1/6}$		
Ω_4	$(6,1)_{4/3}$	Q_7	$(3,2)_{7/6}$		
Υ	$(6,3)_{1/3}$	T_1	$(3,3)_{-1/3}$		
Φ	$(8,2)_{1/2}$	T_2	$(3,3)_{2/3}$		
		Q_5	$(3,2)_{-5/6}$		

- Large improvements in mass reach for models modifying EWPOs at the FCC
- Bounds reaching 100 TeV for some models at the FCC-ee
- HL-LHC improving models generating 4-quark operators (expect better improvement with dedicated HL-LHC analysis)

Conclusions

- SMEFT is a consistent way to look for new interactions
- Global fits results already available: important to combine as many processes as possible to extract maximal information
- Eventually global fit results give us a clear indication of the scale of potential new physics and the reach of future colliders
- Significant improvements in New Physics reach at the HL-LHC and especially at future circular lepton colliders
- Plan to extend this to other future projects

https://lhcfitnikhef.github.io/smefit_release/previous_releases/smefit30.html

Thank you for your attention