Katowice, Poland, Matter to the Deepest conference, 19th September 2025

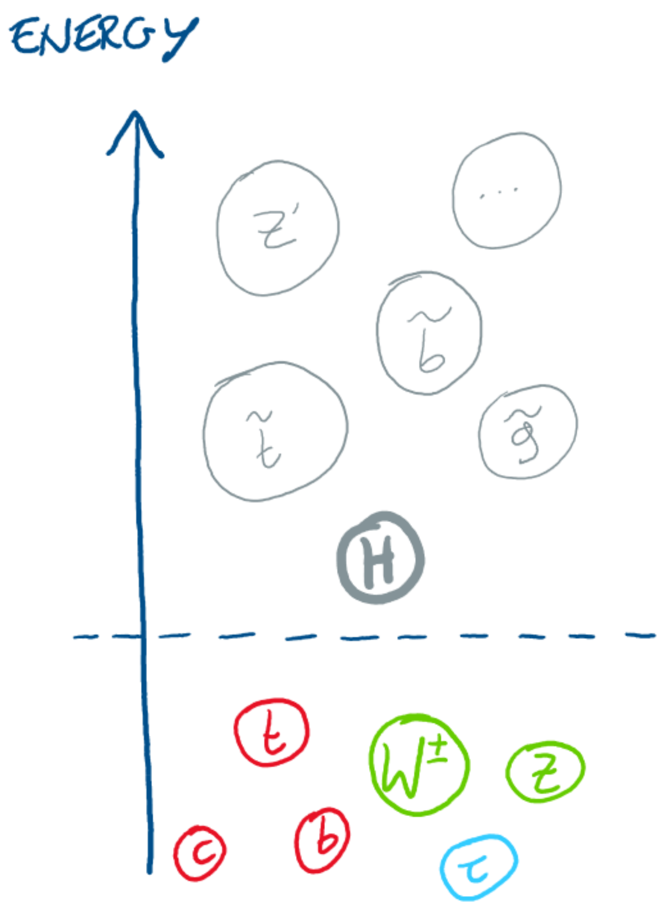
Quantum exploration of the TeV scale at FCC-ee

Tevong You

Contents

Why EFT and naturalness?

- Until now, there had been a **clear roadmap**



Pre-LHC: **high anticipation** of accompanying BSM particles expected to appear together with the Higgs.

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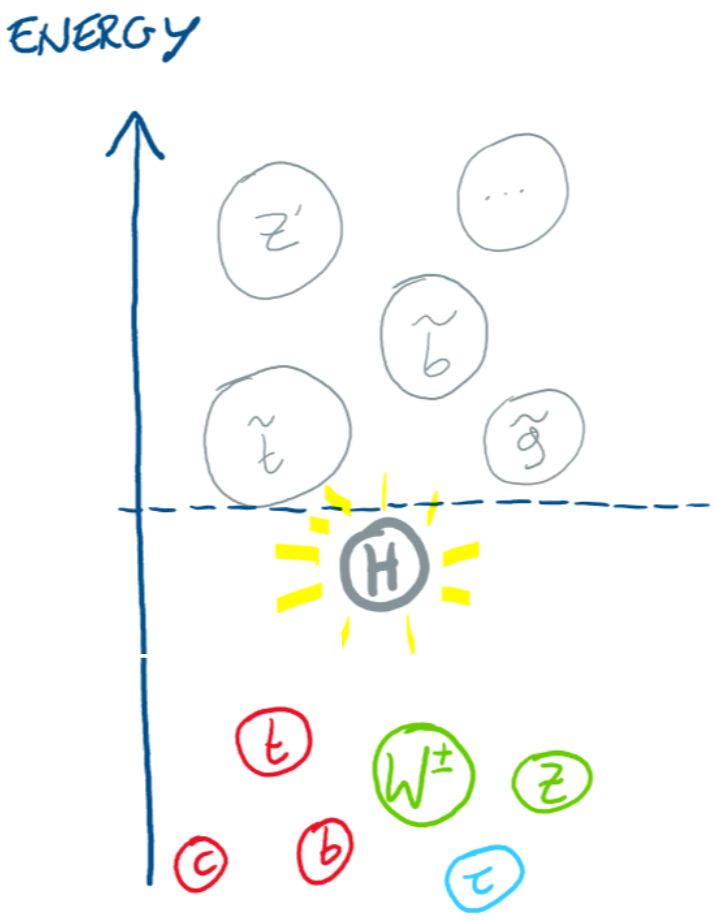

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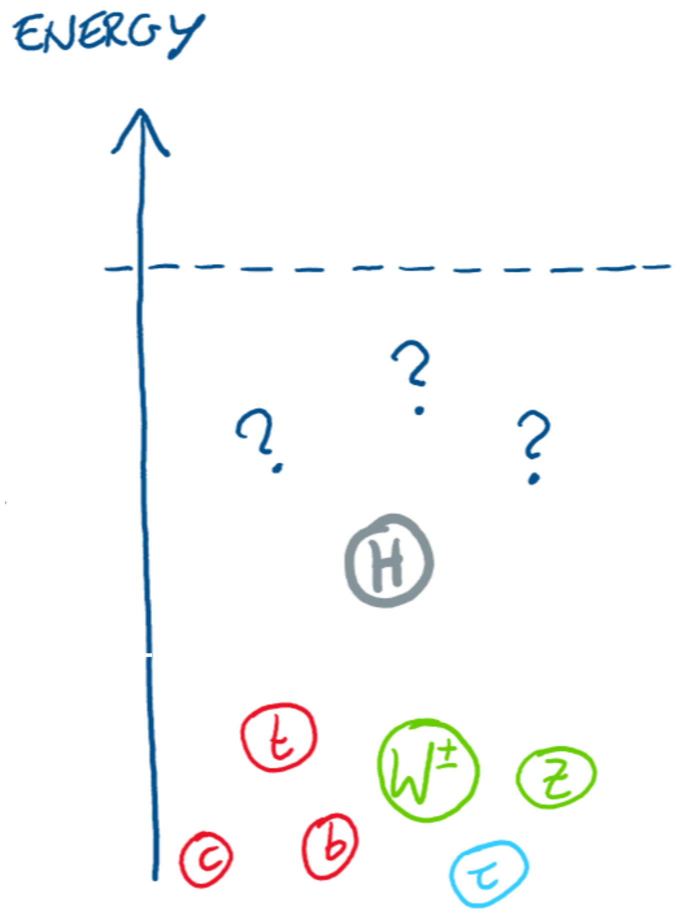

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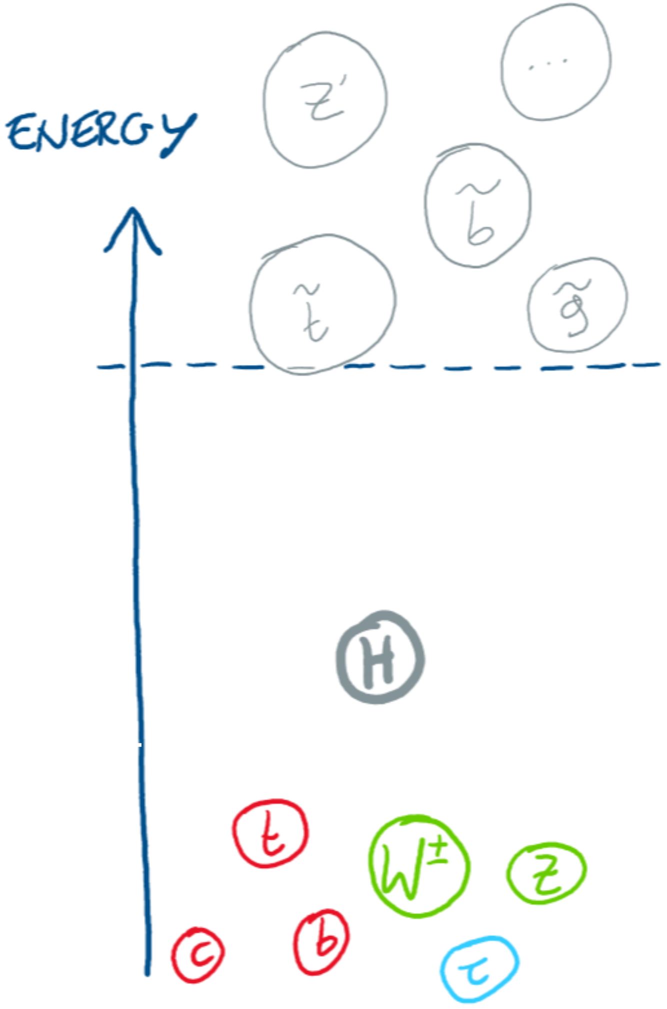

Maybe **just around the corner…**

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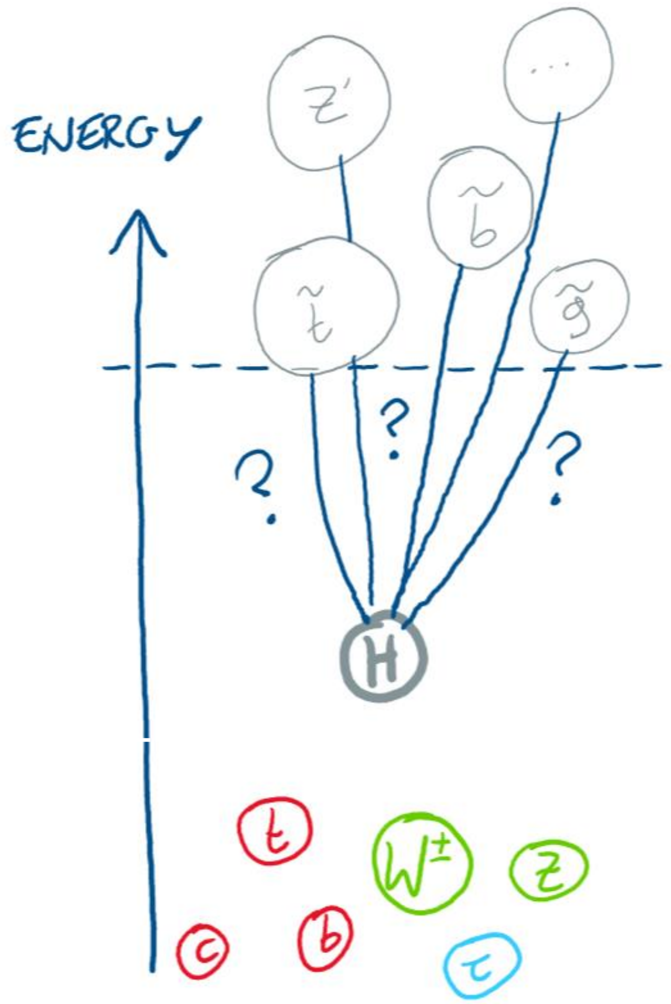

...but the larger the **separation of scales**, the more unnaturally **fine-tuned** the *underlying* theory is!

The Higgs' naturalness problem is **even more perplexing** in the absence of new physics at the LHC.

Our **Michelson-Morley moment?**

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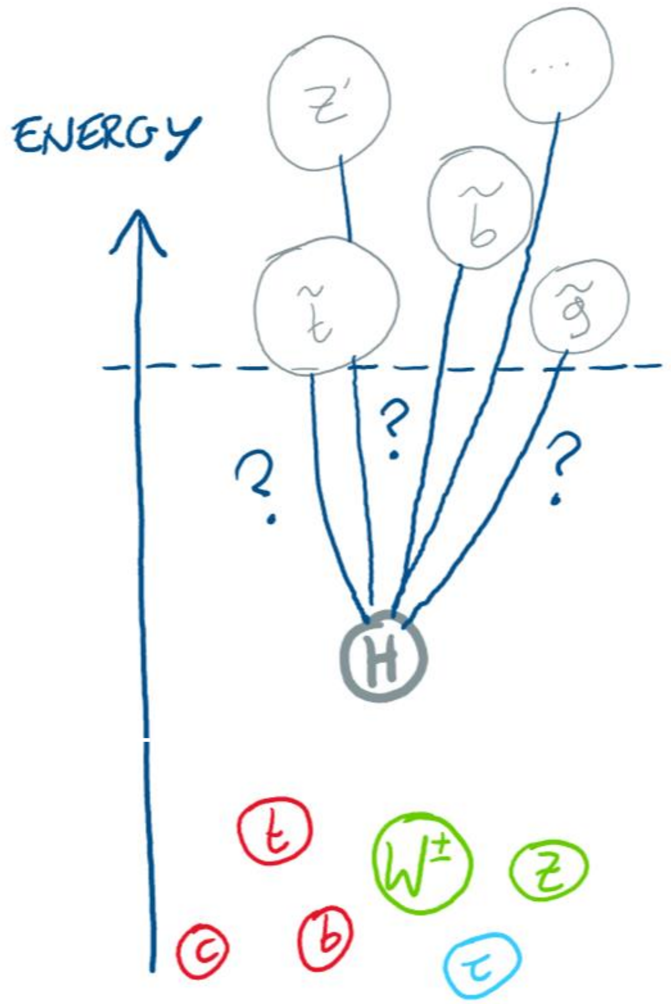

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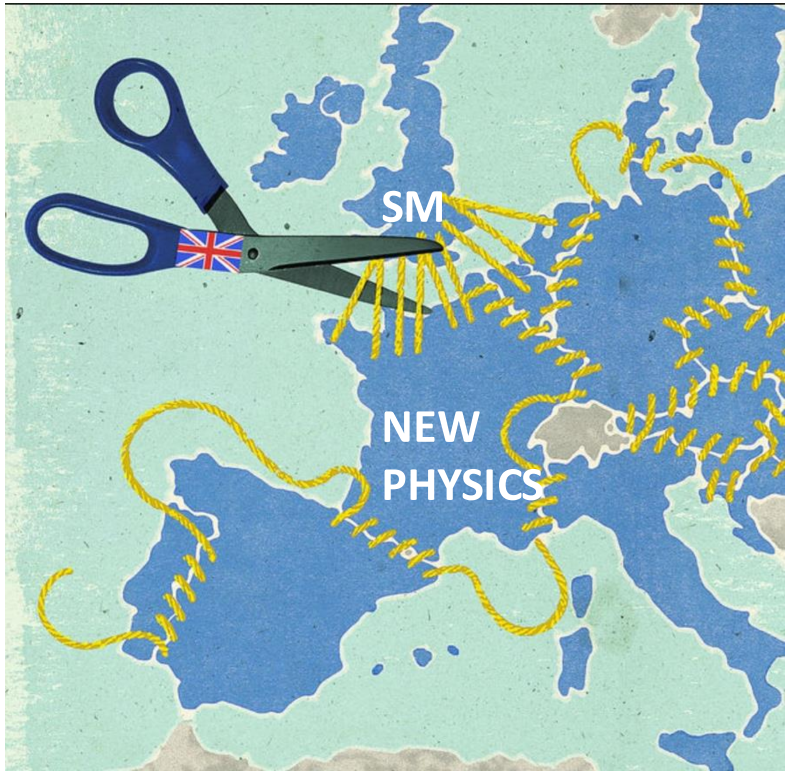
Why EFT and naturalness?

SM EFT is the framework for a **separation of scales** decoupling heavy new physics and the SM:

SMEXIT



Effective Field Theory

$$\boxed{\mathcal{L} = \Lambda^4 + \Lambda^2\mathcal{O}^{(2)} + m\mathcal{O}^{(3)} + \mathcal{O}^{(4)}} + \cancel{\frac{1}{\Lambda}\mathcal{O}^{(5)} + \frac{1}{\Lambda^2}\mathcal{O}^{(6)} + \frac{1}{\Lambda^3}\mathcal{O}^{(7)} + \frac{1}{\Lambda^4}\mathcal{O}^{(8)}} + \ldots$$

1960s point of view: renormalisability of a *finite* number of parameters is essential

Modern point of view: our QFTs are really EFTs - include *all* operators allowed by symmetries

Symmetries dictate EFT structure and natural expectations for sizes of coefficients

Effective Field Theory

$$\mathcal{L}_{SM} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y \qquad ,$$

$$\begin{aligned}
\mathcal{L}_m &= \bar{Q}_L i\gamma^\mu D^L_\mu Q_L + \bar{q}_R i\gamma^\mu D^R_\mu q_R + \bar{L}_L i\gamma^\mu D^L_\mu L_L + \bar{l}_R i\gamma^\mu D^R_\mu l_R \\
\mathcal{L}_G &= -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} \\
\mathcal{L}_H &= (D^L_\mu \phi)^\dagger (D^{L\mu}\phi) - V(\phi) \\
\mathcal{L}_Y &= y_d \bar{Q}_L \phi q^d_R + y_u \bar{Q}_L \phi^c q^u_R + y_L \bar{L}_L \phi l_R + \text{h.c.} \qquad ,
\end{aligned}$$

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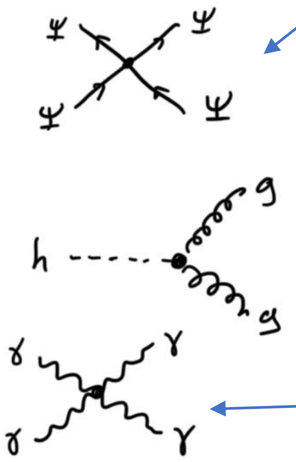
…umber of par…

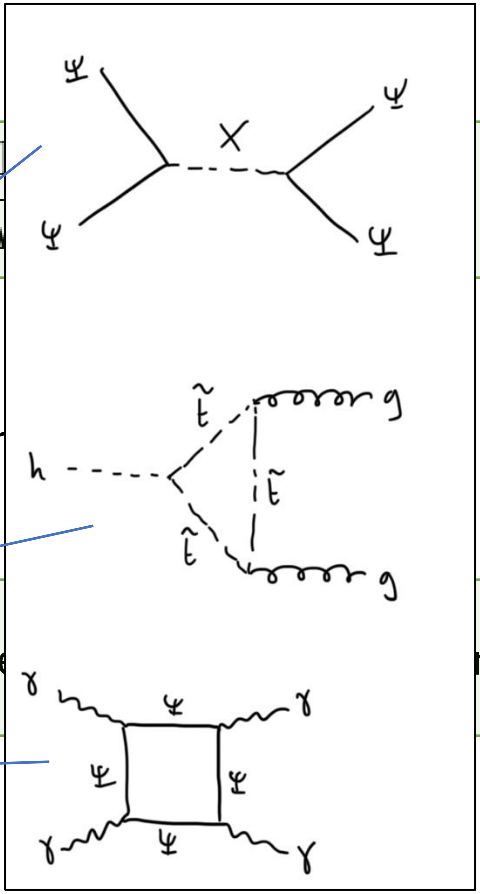
…nclude *all* ope… …metries

e.g. $\mathcal{L}^{\text{dim-6}}_{\text{4-fermion}} = \frac{c_{4f}}{\Lambda^2}\bar{\Psi}\Psi\bar{\Psi}\Psi$

$\mathcal{L}^{\text{dim-6}}_{hgg} = \frac{c_g}{\Lambda^2}|H|^2 G_{\mu\nu}G^{\mu\nu}$

$\mathcal{L}^{\text{dim-8}}_{\gamma\gamma\gamma\gamma} = \frac{c_{4\gamma}}{\Lambda^4}(F_{\mu\nu}F^{\mu\nu})^2$





Symmetries dictate EFT structure and natural expectations for sizes of coefficients

Effective Field Theory

SM EFT coefficients are a **map of the uncharted BSM territory** to explore!

$\mathcal{L} =$ … $\frac{1}{\Lambda^3}\mathcal{O}^{(7)} + \frac{1}{\Lambda^4}\mathcal{O}^{(8)} + \dots$

X^3		H^6 and H^4D^2		$\psi^2 H^3$	
$\mathcal{O}_G$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_H$	$(H^\dagger H)^3$	$\mathcal{O}_{eH}$	$(H^\dagger H)(\bar l_p e_r H)$
$\mathcal{O}_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
$\mathcal{O}_W$	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^\star(H^\dagger D_\mu H)$	$\mathcal{O}_{dH}$	$(H^\dagger H)(\bar q_p d_r H)$
$\mathcal{O}_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

X^2H^2		$\psi^2 XH$		ψ^2H^2D	
$\mathcal{O}_{HG}$	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I H W_{\mu\nu}^I$	$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p\gamma^\mu l_r)$
$\mathcal{O}_{H\widetilde G}$	$H^\dagger H\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar l_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar l_p\tau^I\gamma^\mu l_r)$
$\mathcal{O}_{HW}$	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde H\, G_{\mu\nu}^A$	$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p\gamma^\mu e_r)$
$\mathcal{O}_{H\widetilde W}$	$H^\dagger H\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde H\, W_{\mu\nu}^I$	$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p\gamma^\mu q_r)$
$\mathcal{O}_{HB}$	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{uB}$	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde H\, B_{\mu\nu}$	$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar q_p\tau^I\gamma^\mu q_r)$
$\mathcal{O}_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dG}$	$(\bar q_p\sigma^{\mu\nu}T^A d_r)H\, G_{\mu\nu}^A$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u_p\gamma^\mu u_r)$
$\mathcal{O}_{HWB}$	$H^\dagger\tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I H\, W_{\mu\nu}^I$	$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d_p\gamma^\mu d_r)$
$\mathcal{O}_{H\widetilde WB}$	$H^\dagger\tau^I H\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar q_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	$\mathcal{O}_{Hud}$	$i(\widetilde H^\dagger D_\mu H)(\bar u_p\gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
$\mathcal{O}_{ll}$	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$\mathcal{O}_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$\mathcal{O}_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$\mathcal{O}_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$\mathcal{O}_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
$\mathcal{O}_{ledq}$	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$\mathcal{O}_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	$\mathcal{O}_{qqu}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$\mathcal{O}_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$\mathcal{O}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$\mathcal{O}_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$\mathcal{O}_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar q_s^k\sigma^{\mu\nu}u_t)$		

196 … rameters is essential

Moc … erators allowed by symmetries

… quantum totalitarian principle”)

Sym … sizes of coefficients

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$$\mathcal{L} = \overbrace{\Lambda^4 + \Lambda^2\mathcal{O}^{(2)}}^{\text{Naturalness violation?}} + m\mathcal{O}^{(3)} + \mathcal{O}^{(4)} + \frac{1}{\Lambda}\mathcal{O}^{(5)} + \frac{1}{\Lambda^2}\mathcal{O}^{(6)} + \frac{1}{\Lambda^3}\mathcal{O}^{(7)} + \frac{1}{\Lambda^4}\mathcal{O}^{(8)} + \ldots$$

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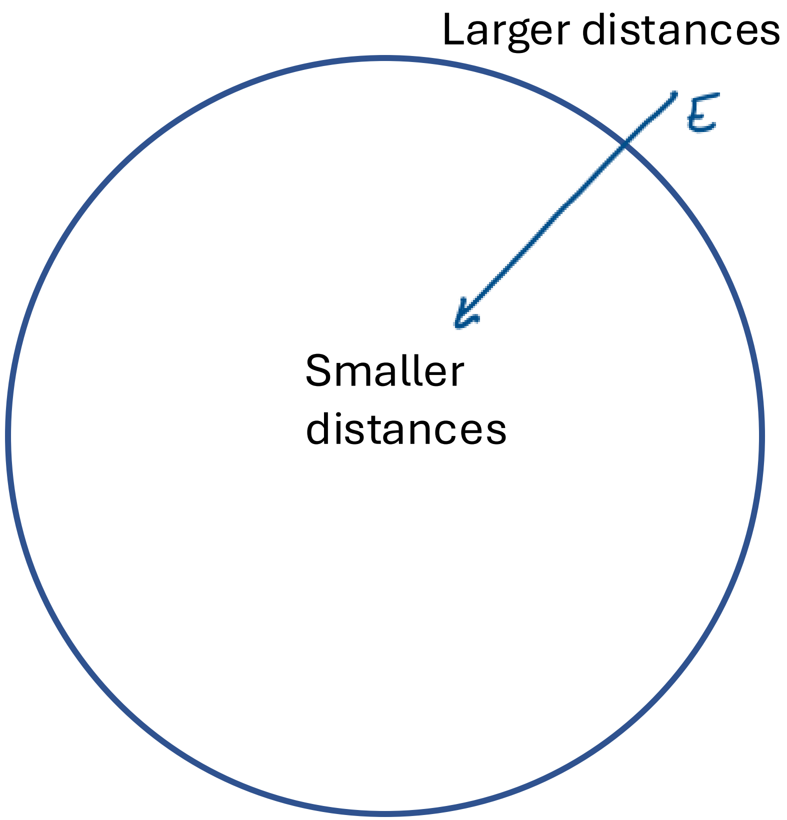
Naturalness is still a fundamental problem

- *Why is unnatural fine-tuning such a big deal?* An intuitive picture:

Physical theories govern a huge range of phenomena across vast scales



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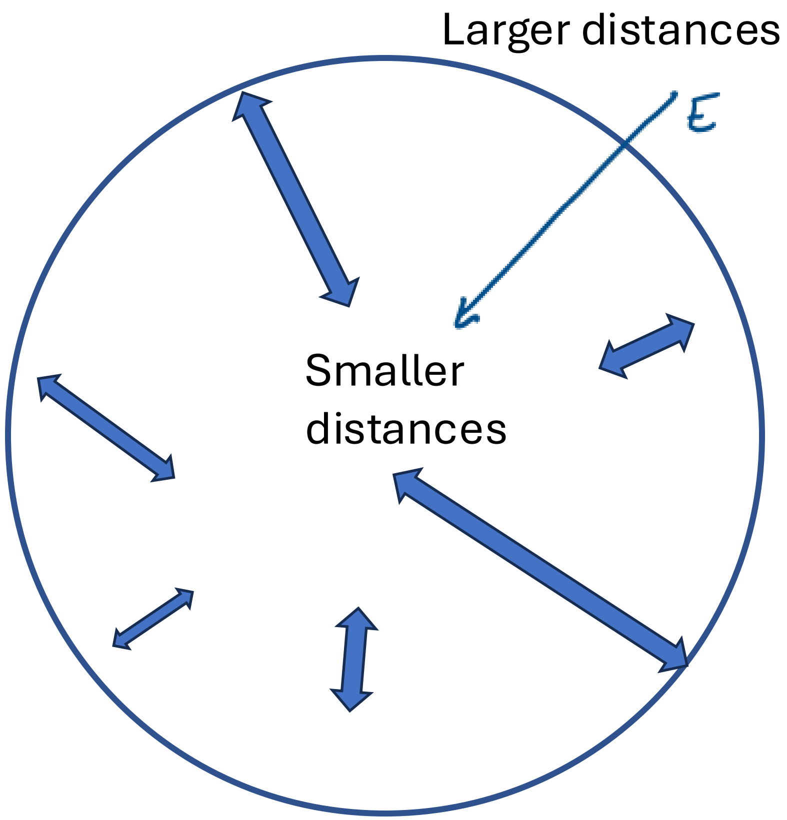
Everything does **not** depend on everything else equally.

(Otherwise, we would need a Theory of Everything to calculate anything)



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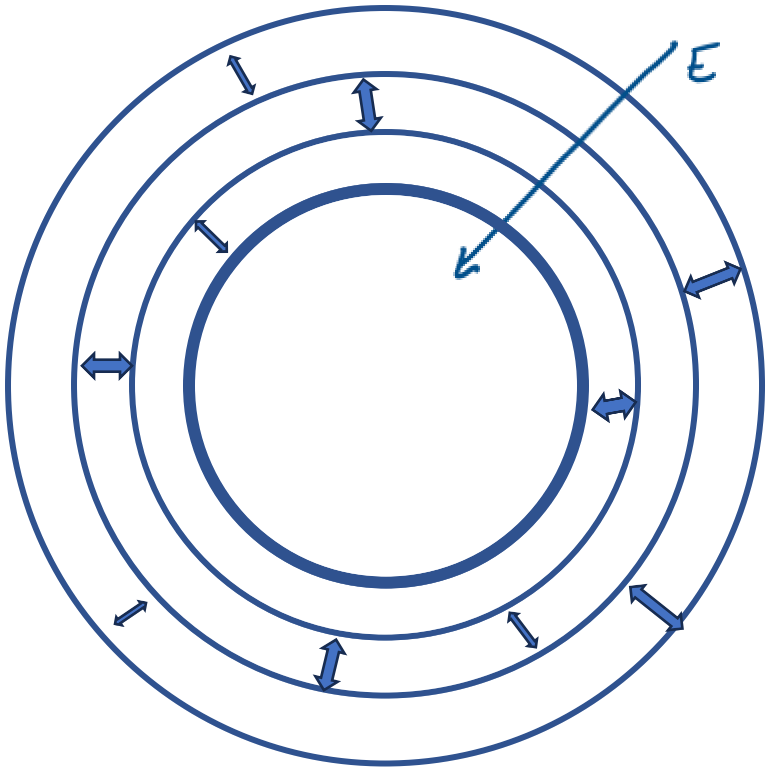
Effective theory at each energy scale E is **predictive** as a **self-contained** theory at that scale



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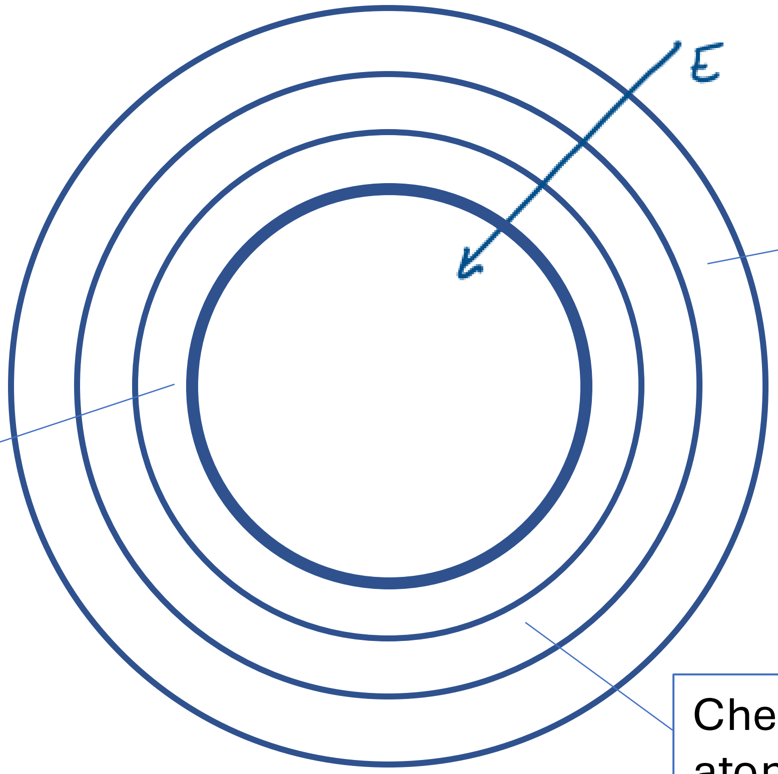

Planetary dynamics, thermodynamics, fluid dynamics, …

Strong / weak interactions, …

Chemistry, atomic physics, nuclear physics, …

In **all theories so far**, no contributions from **smaller scales** compete with **similar magnitude** to effects **on larger scales**

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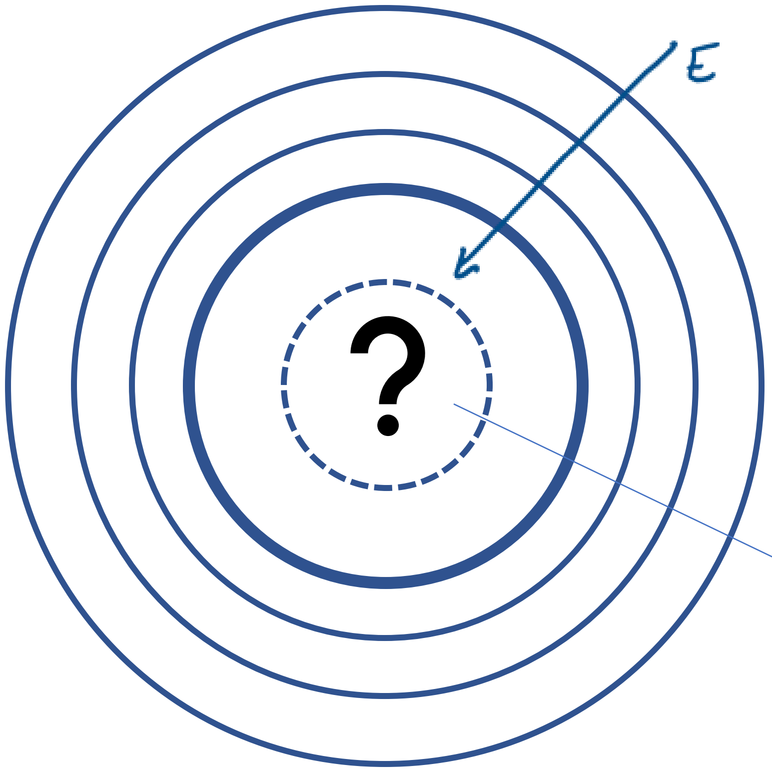

Unnatural Higgs means the next layer **is no longer predictive** without including contributions **from much smaller scales**

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- Indicates **an unprecedented breakdown** of the **effective theory** structure of nature

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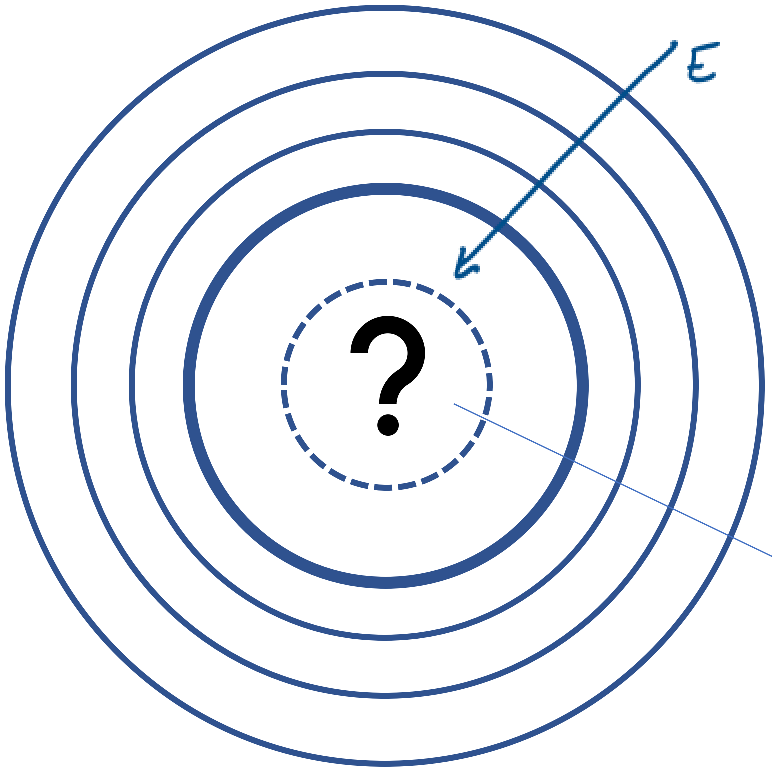

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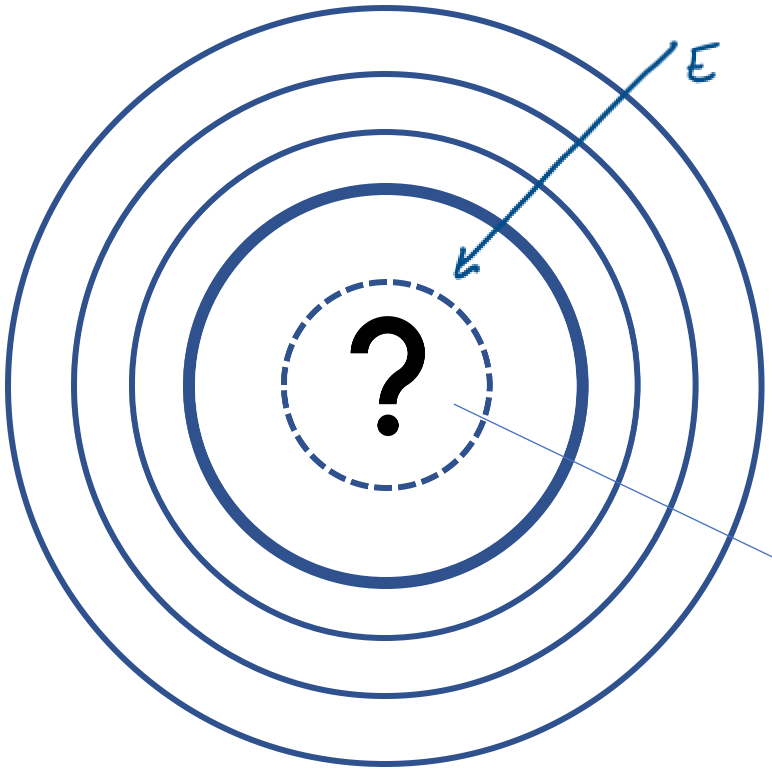


Unnatural Higgs means the next layer **is no longer predictive** without including contributions **from much smaller scales**

- **Future colliders** are **essential** for finding out experimentally **what nature actually does** at higher energies

FCC-ee

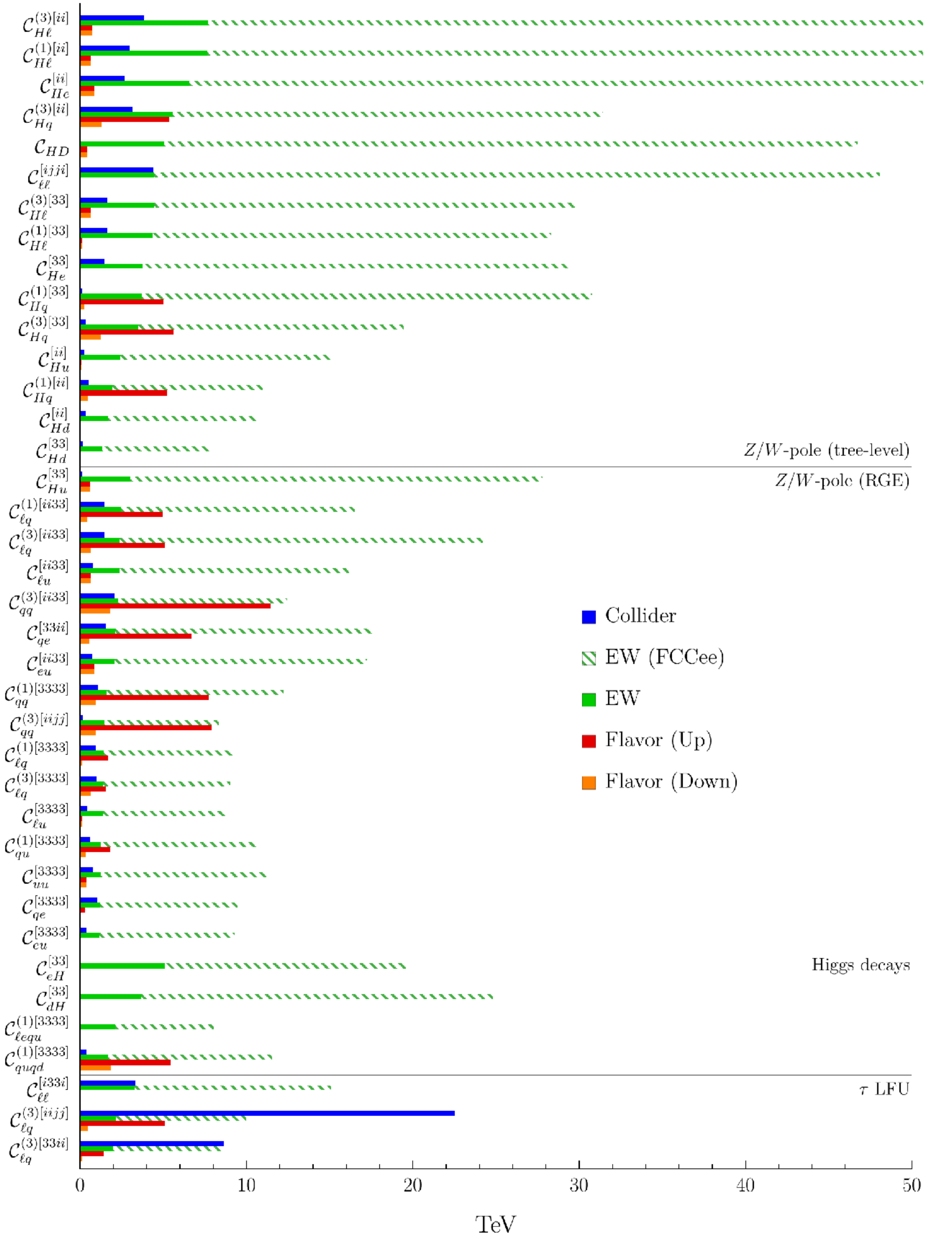
There is a **misconception** that FCC-hh is the really exciting frontier of high energy exploration while FCC-ee is relatively boring.

Nothing could be further from the truth – even if indirect, **FCC-ee is exquisitely sensitive to an extremely wide variety of generic new physics at high energy scales far beyond the LHC**.

Tera-Z statistics on the Z pole is a vital part of this programme of **quantum exploration**.

Why Tera-Z?

2311.00020 Allwicher, Cornella, Isidori, Stefanek



Quantum exploration of the O(10) TeV scale.

Even for TeV-scale new physics **coupling only to third generation**!

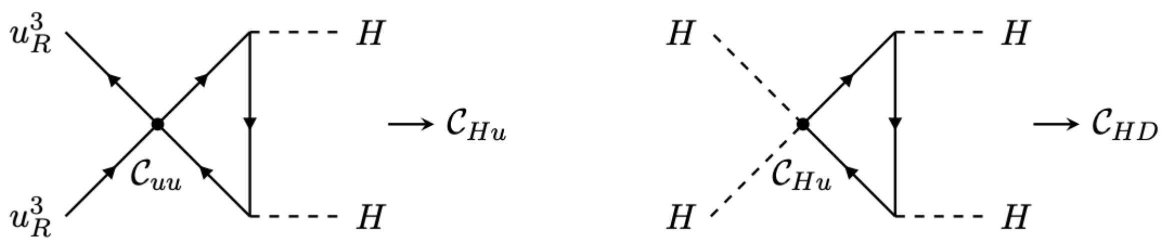


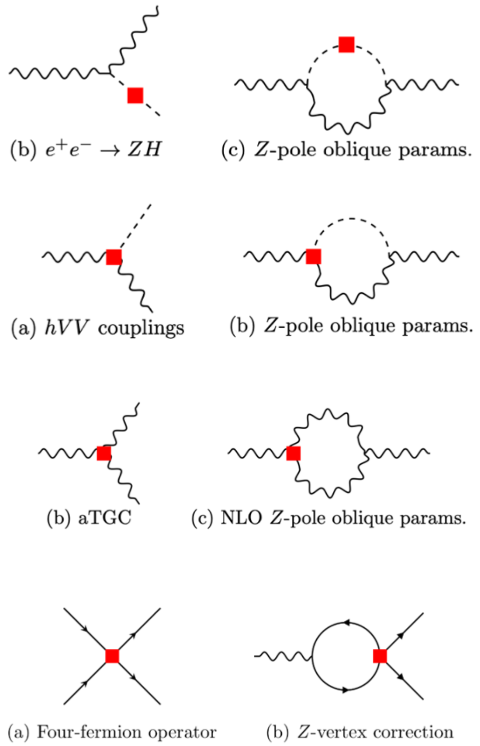
Figure 1. Next-to-leading log running of four-quark operators into $\mathcal{C}_{HD}$.

Naturalness a major motivation for fully exploring 3rd gen @ TeV.

See also 2407.09593 Stefanek

Why Tera-Z?

Quantum loops probe physics not typically thought to be constrained at Z pole, **now accessible by ultra-high electroweak precision**.



Rough NLO/LO improvement factor:

$$\Delta_{Z/ZH}^{NLO/LO} \equiv \frac{1}{16\pi^2}\frac{\epsilon_Z}{\epsilon_{ZH}}\sqrt{\frac{N_Z}{N_{ZH}}} \gtrsim 1$$

$N_Z \sim 10^{12}$ $\quad N_{ZH} \sim 10^6$ $\quad \epsilon_Z \sim 10^{-1}$ $\quad \epsilon_{ZH} \sim 1,$

2412.14241 Maura, Stefanek, **TY**

Accuracy complements energy: On-Z-pole precision at NLO has **comparable** and **complementary** sensitivity to LO above-pole measurements!

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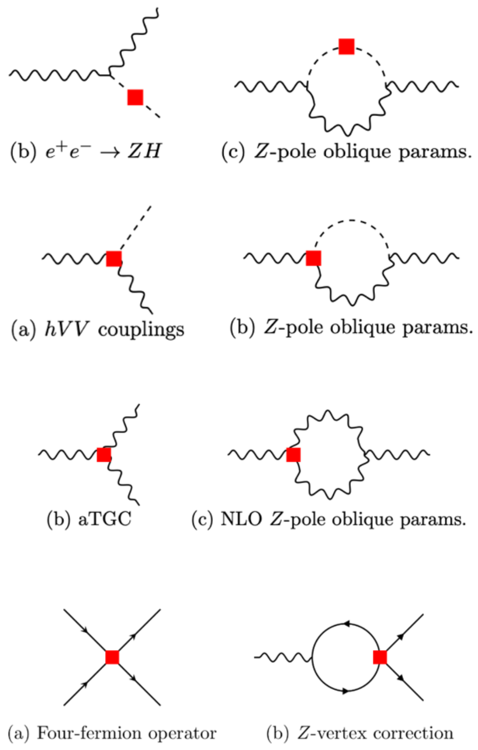

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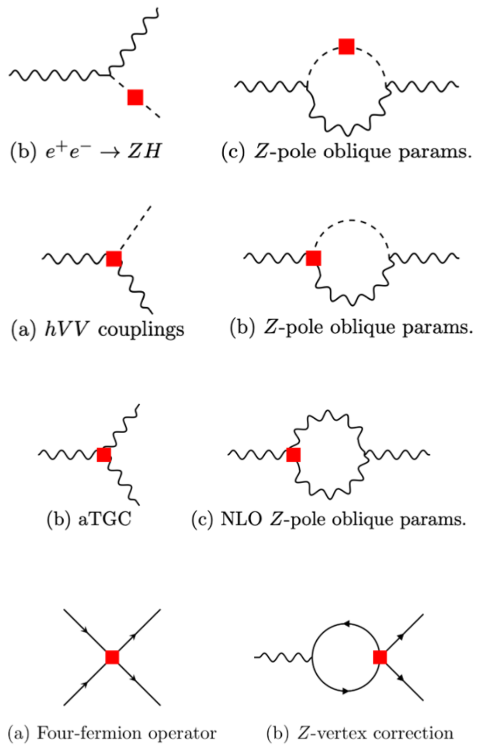

Suppression by loop factor...

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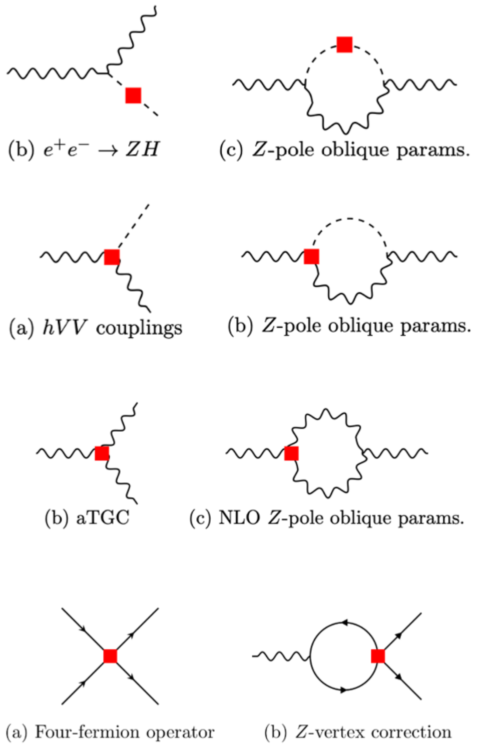

… compensated by enhancement in Z pole statistics

$$\Delta^{NLO/LO}_{Z/ZH} \equiv \frac{1}{16\pi^2}\frac{\epsilon_Z}{\epsilon_{ZH}}\boxed{\sqrt{\frac{N_Z}{N_{ZH}}}} \gtrsim 1$$

$$N_Z \sim 10^{12} \qquad N_{ZH} \sim 10^6 \qquad \epsilon_Z \sim 10^{-1} \qquad \epsilon_{ZH} \sim 1,$$

2412.14241 Maura, Stefanek, **TY**

Accuracy complements energy: On-Z-pole precision at NLO has **comparable** and **complementary** sensitivity to LO above-pole measurements!

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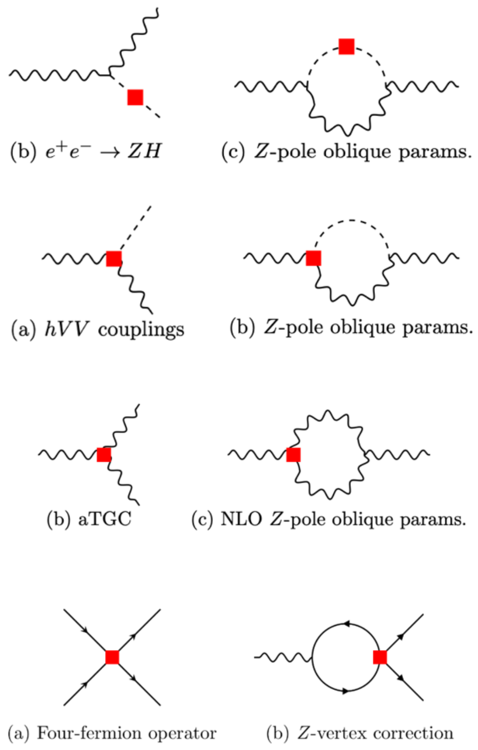

(even accounting for systematics)

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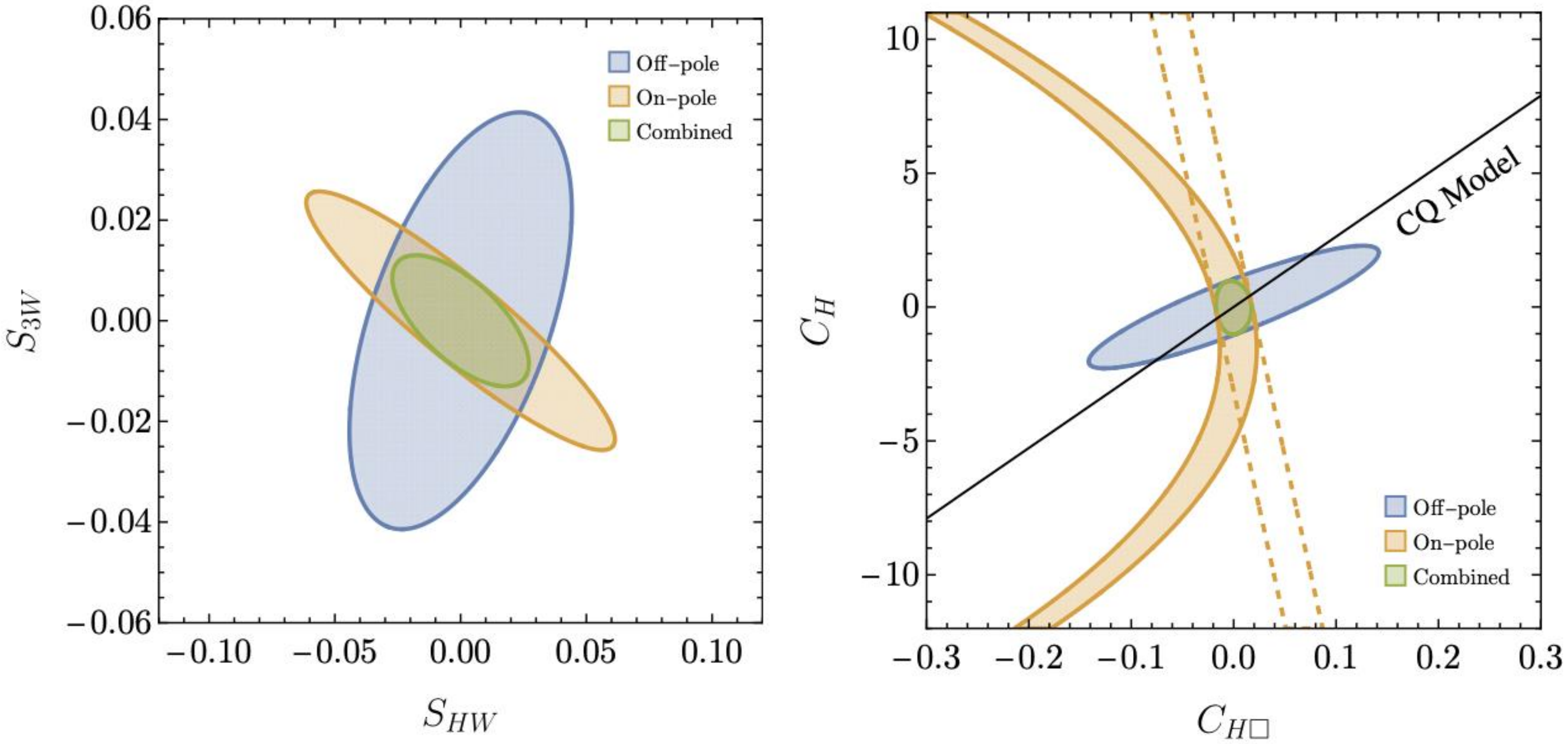
Tera-Z statistics probes physics **not typically thought to best be constrained at Z pole**



2412.14241 Maura, Stefanek, **TY**

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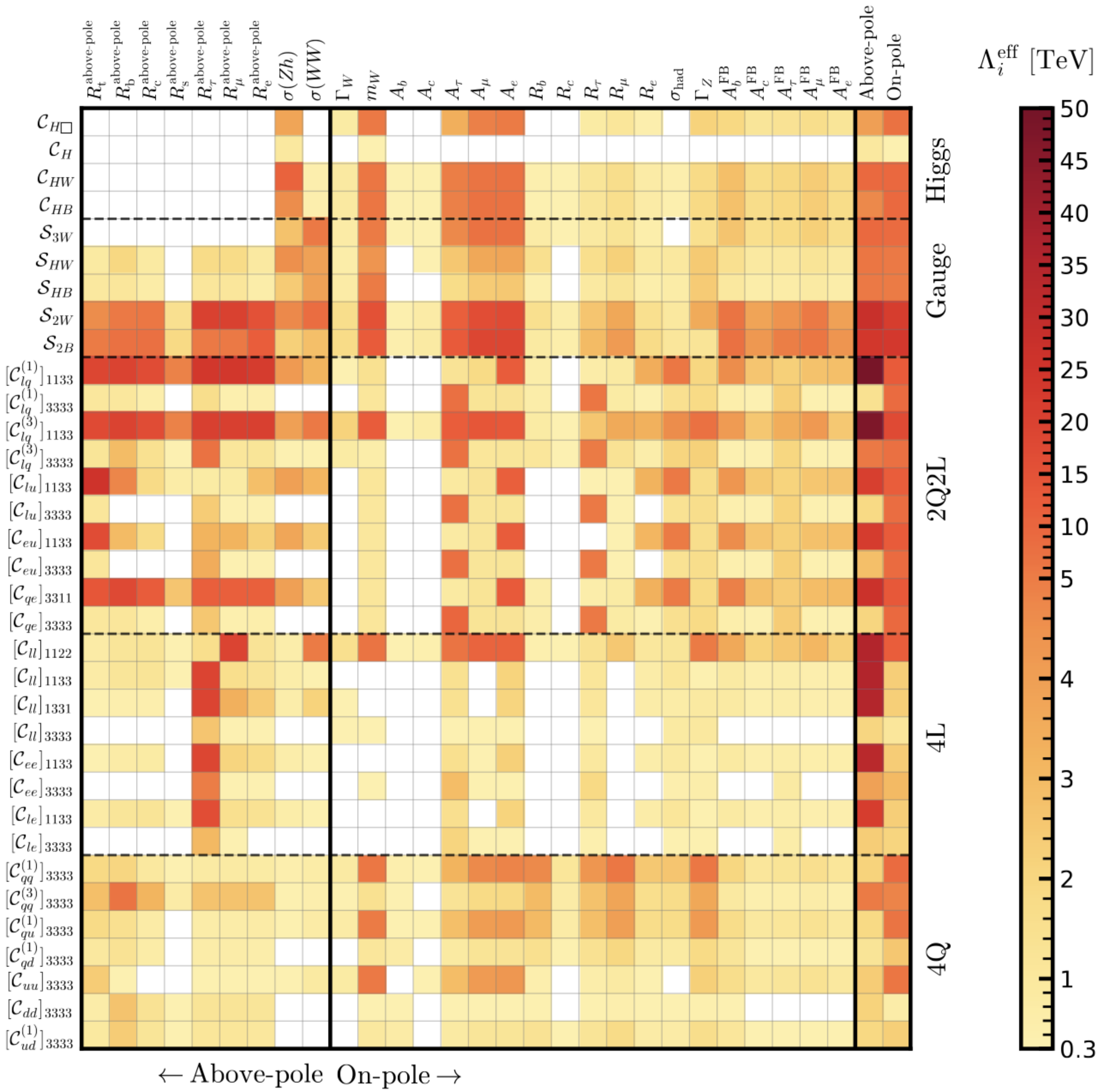
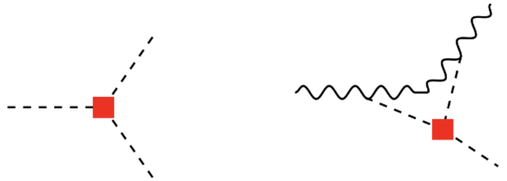


2412.14241 Maura, Stefanek, **TY**

4f operator projections from
2411.02485 Greljo, Tiblom, Valenti



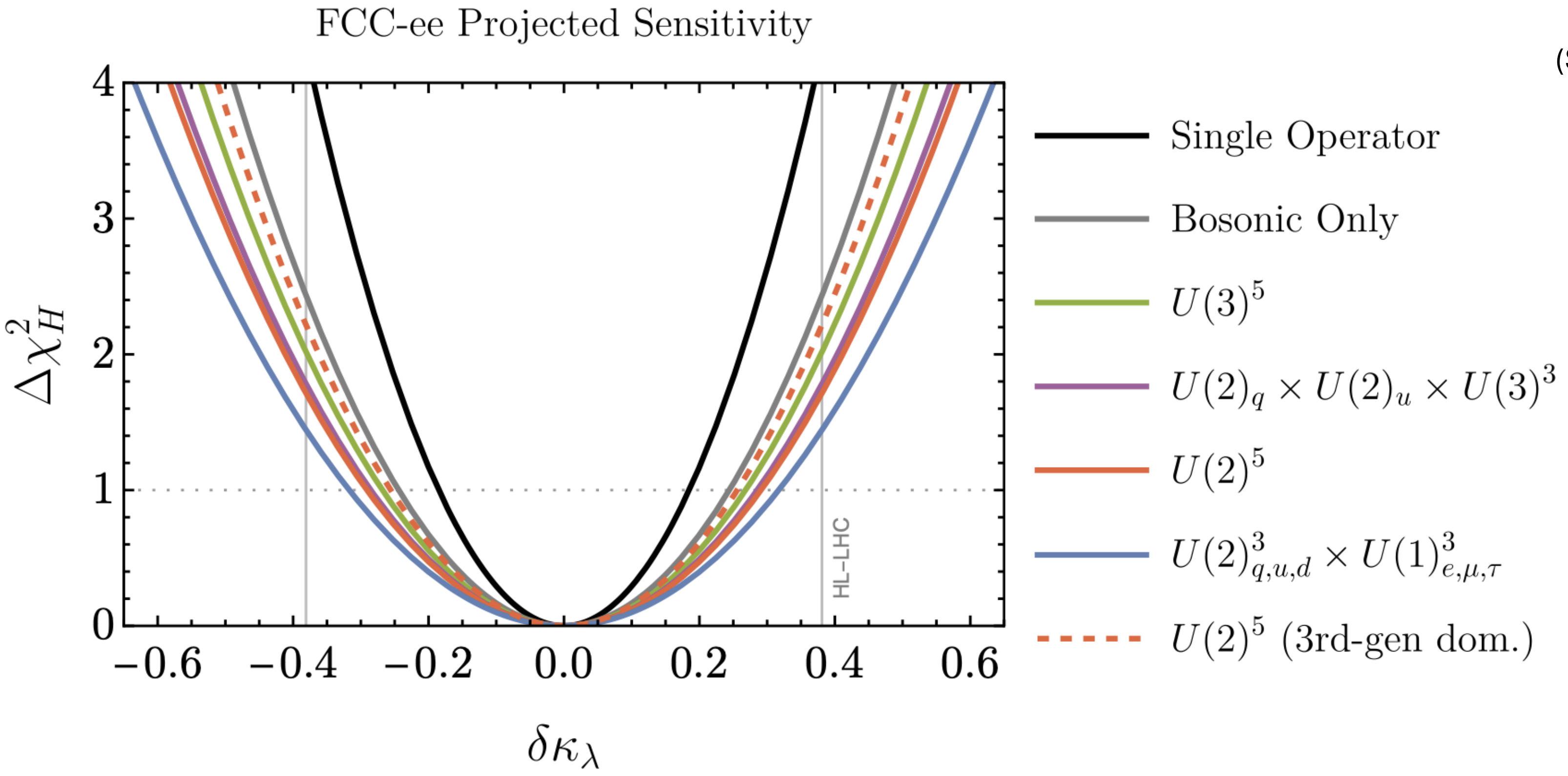
(a) Higgs self-coupling (b) $e^+e^- \to ZH$

Why Tera-Z?

Indirect sensitivity to the Higgs self-coupling at NLO benefits from Tera-Z, marginalised over other effects:

2503.13719 Maura, Stefanek, **TY**

(See also 2502.20453 Hoeve et al)



Note: self-coupling modification correlated with coupling modification; natural upper bound on their ratio, $|\delta_{h^3}/\delta_{VV}| \lesssim 600.$ implies electroweak precision generically a better probe than Higgs self-coupling

2209.00666 Durieux, McCullough, Salvioni

Linear SM extensions at Tera-Z

Simplified models are another way of quantifying the sensitivity of a Tera-Z factory.

e.g. BSM that couple *linearly* (tree level) to the SM form a finite set:

1711.10391 de Blas, Criado, Perez-Victoria, Santiago

Scalars

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	$(6,1)_{\frac{1}{3}}$	$(6,1)_{-\frac{2}{3}}$	$(6,1)_{\frac{4}{3}}$	$(6,3)_{\frac{1}{3}}$	$(8,2)_{\frac{1}{2}}$

Fermions

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	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$	$(3,3)_{\frac{2}{3}}$

Vectors

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

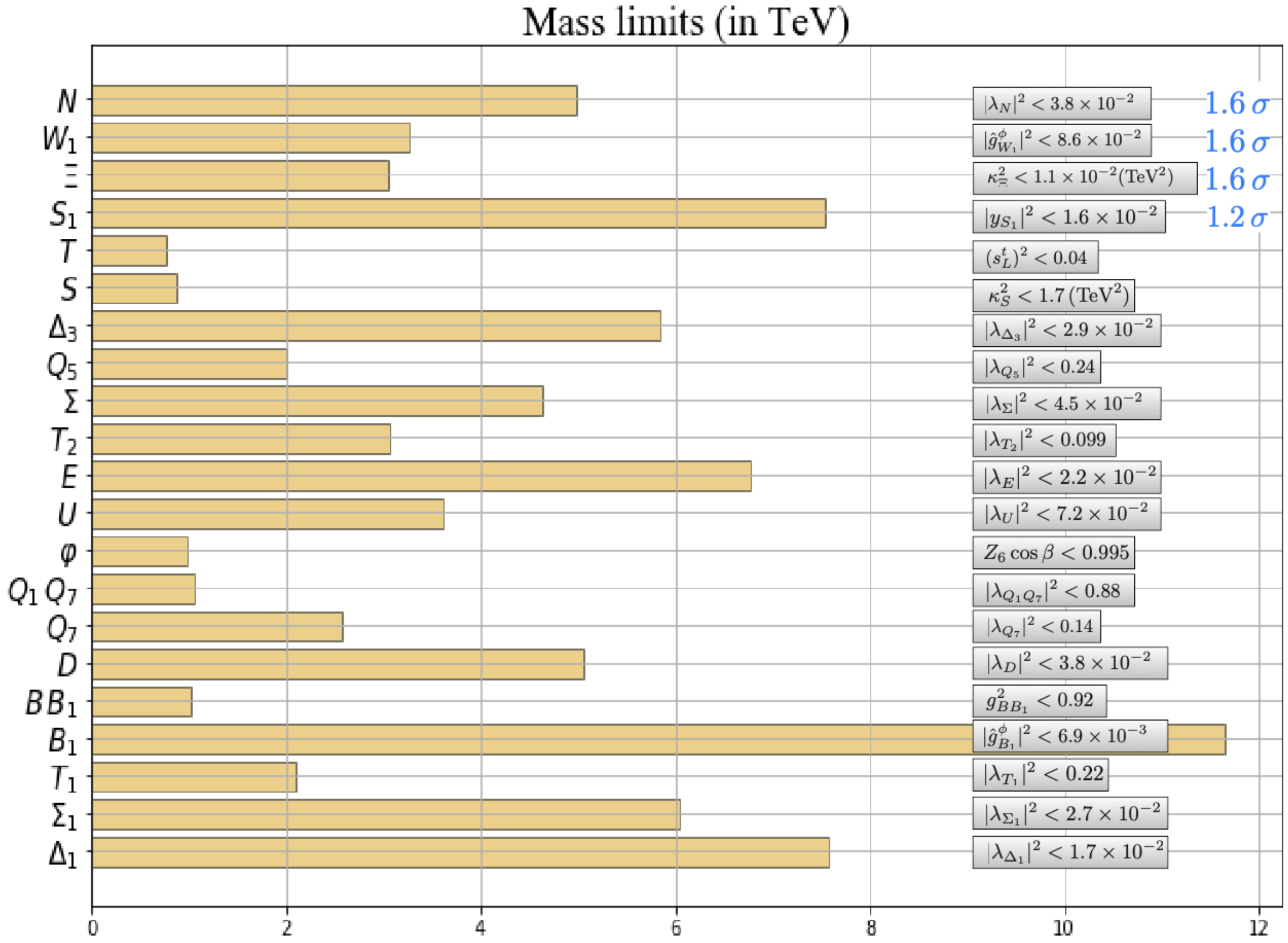
Name	$\mathcal{L}_3$	$\mathcal{U}_2$	$\mathcal{U}_5$	$\mathcal{Q}_1$	$\mathcal{Q}_5$	$\mathcal{X}$	$\mathcal{Y}_1$	$\mathcal{Y}_5$
Irrep	$(1,2)_{-\frac{3}{2}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,3)_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$

Linear SM extensions at Tera-Z

Tree-level SMEFT structure and current **LEP+LHC** constraints:

2012.02779 Ellis, Madigan, Mimasu, Sanz, **TY**

Model	C_{HD}	C_{ll}	C^3_{Hl}	C^1_{Hl}	C_{He}	$C_{H\Box}$	$C_{\tau H}$	C_{tH}	C_{bH}
S						$-\frac{1}{2}$			
S_1		1							
Σ			$\frac{1}{16}$	$\frac{3}{16}$			$\frac{y_\tau}{4}$		
Σ_1			$-\frac{1}{16}$	$-\frac{3}{16}$			$\frac{y_\tau}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_\tau}{2}$		
Δ_1					$\frac{1}{2}$		$\frac{y_\tau}{2}$		
Δ_3					$-\frac{1}{2}$		$\frac{y_\tau}{2}$		
B_1	1					$-\frac{1}{2}$	$-\frac{y_\tau}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
Ξ	-2					$\frac{1}{2}$	y_τ	y_t	y_b
W_1	$-\frac{1}{4}$					$-\frac{1}{8}$	$-\frac{y_\tau}{8}$	$-\frac{y_t}{8}$	$-\frac{y_b}{8}$
φ							$-y_\tau$	$-y_t$	$-y_b$
$\{B, B_1\}$						$-\frac{3}{2}$	$-y_\tau$	$-y_t$	$-y_b$
$\{Q_1, Q_7\}$								y_t	
Model	C^3_{Hq}	C^1_{Hq}	$(C^3_{Hq})_{33}$	$(C^1_{Hq})_{33}$	C_{Hu}	C_{Hd}	C_{tH}	C_{bH}	
U	$-\frac{1}{4}$	$\frac{1}{4}$	$-\frac{1}{4}$	$\frac{1}{4}$			$\frac{y_t}{2}$		
D	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{4}$				$\frac{y_b}{2}$	
Q_5						$-\frac{1}{2}$		$\frac{y_b}{2}$	
Q_7					$\frac{1}{2}$		$\frac{y_t}{2}$		
T_1	$-\frac{1}{16}$	$-\frac{3}{16}$	$-\frac{1}{16}$	$-\frac{3}{16}$			$\frac{y_t}{4}$	$\frac{y_b}{8}$	
T_2	$-\frac{1}{16}$	$\frac{3}{16}$	$-\frac{1}{16}$	$\frac{3}{16}$			$\frac{y_t}{8}$	$\frac{y_b}{4}$	
T			$-\frac{1}{2}\frac{M_T^2}{v^2}$	$\frac{1}{2}\frac{M_T^2}{v^2}$			$y_t \frac{M_T^2}{v^2}$		



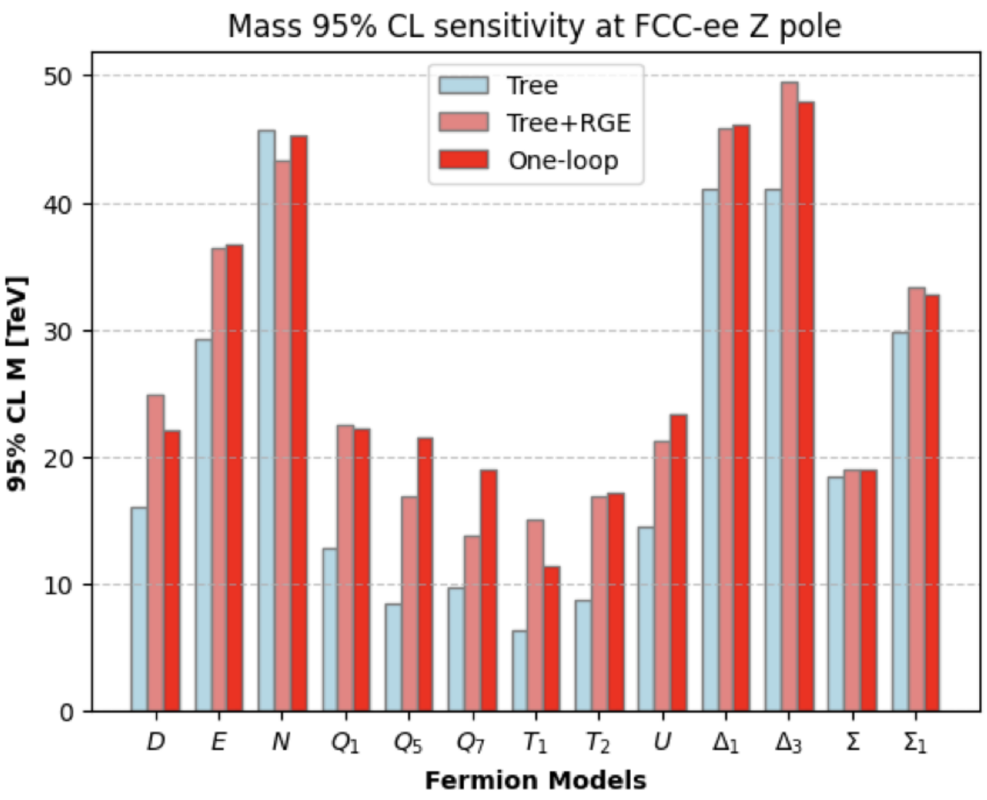
Linear SM extensions at Tera-Z

One-loop SMEFT structure and **Tera-Z** constraints:

2412.01759 Gargalionis, Vuong, Quevillon, **TY**

	$\mathcal{O}_{HWB}$	$\mathcal{O}_{HD}$	$\mathcal{O}_{ll}$	$\mathcal{O}_{Hl}^{(3)}$	$\mathcal{O}_{Hl}^{(1)}$	$\mathcal{O}_{He}$	$\mathcal{O}_{Hq}^{(3)}$	$\mathcal{O}_{Hq}^{(1)}$	$\mathcal{O}_{Hu}$	$\mathcal{O}_{Hd}$
S	κ_S	κ_S		κ_S	κ_S	κ_S	κ_S	κ_S	κ_S	κ_S
S_1			y_{S_1}	y_{S_1}	y_{S_1}	y_{S_1}				
S_2				y_{S_2}	y_{S_2}	y_{S_2}				
φ	$\hat{\lambda}'_\varphi$	$\hat{\lambda}'_\varphi$	$y_{\varphi e}$	$y_{\varphi e}$	$y_{\varphi e}$	$y_{\varphi e}$	$y_{\varphi d}$, $y_{\varphi u}$	$y_{\varphi d}$, $y_{\varphi u}$	$y_{\varphi d}$, $y_{\varphi u}$	$y_{\varphi d}$, $y_{\varphi u}$
Ξ		κ_Ξ, λ_Ξ		κ_Ξ	κ_Ξ	κ_Ξ	κ_Ξ	κ_Ξ	κ_Ξ	κ_Ξ
Ξ_1	κ_{Ξ_1}, λ'_{Ξ_1}	κ_{Ξ_1}, λ_{Ξ_1}, λ'_{Ξ_1}	y_{Ξ_1}	κ_{Ξ_1}, y_{Ξ_1}	κ_{Ξ_1}, y_{Ξ_1}	κ_{Ξ_1}, y_{Ξ_1}	κ_{Ξ_1}	κ_{Ξ_1}	κ_{Ξ_1}	κ_{Ξ_1}
Θ_1	$\hat{\lambda}'_{\Theta_1}$	$\hat{\lambda}''_{\Theta_1}$, $\hat{\lambda}'_{\Theta_1}$, λ_{Θ_1}								
Θ_3	$\hat{\lambda}'_{\Theta_3}$	$\hat{\lambda}'_{\Theta_3}$, λ_{Θ_3}								
ω_1			$y_{q\ell\Omega_1}$	$y_{eu\Omega_1}$, $y_{q\ell\Omega_1}$	$y_{eu\Omega_1}$, $y_{q\ell\Omega_1}$	$y_{eu\Omega_1}$, $y_{q\ell}$	$y_{du\Omega_1}$, $y_{eu\Omega_1}$, $y_{q\ell\Omega_1}$, $y_{qq\Omega_1}$	$y_{du\Omega_1}$, $y_{eu\Omega_1}$, $y_{q\ell\Omega_1}$, $y_{qq\Omega_1}$	$y_{du\Omega_1}$, $y_{eu\Omega_1}$, $y_{q\ell\Omega_1}$, $y_{qq\Omega_1}$	$y_{du\Omega_1}$, $y_{q\ell\Omega_1}$, $y_{qq\Omega_1}$
ω_2							y_{Ω_2}	y_{Ω_2}		y_{Ω_2}
ω_4				$y_{ed\Omega_4}$	$y_{ed\Omega_4}$	$y_{ed\Omega_4}$	$y_{ed\Omega_4}$, $y_{uu\Omega_4}$	$y_{ed\Omega_4}$, $y_{uu\Omega_4}$	$y_{uu\Omega_4}$	$y_{ed\Omega_4}$
Π_1	$\hat{\lambda}'_{\Pi_1}$	$\hat{\lambda}'_{\Pi_1}$	y_{Π_1}	y_{Π_1}	y_{Π_1}	y_{Π_1}	y_{Π_1}	y_{Π_1}		y_{Π_1}
Π_7	$\hat{\lambda}'_{\Pi_7}$	$\hat{\lambda}'_{\Pi_7}$	$y_{\ell u\Pi_7}$	$y_{eq\Pi_7}$, $y_{\ell u\Pi_7}$	$y_{eq\Pi_7}$, $y_{\ell u\Pi_7}$	$y_{eq\Pi_7}$, $y_{\ell u}$	$y_{eq\Pi_7}$, $y_{\ell u\Pi_7}$	$y_{eq\Pi_7}$, $y_{\ell u\Pi_7}$	$y_{eq\Pi_7}$, $y_{\ell u\Pi_7}$	$y_{eq\Pi_7}$
ζ	$\hat{\lambda}'_\zeta$	$\hat{\lambda}'_\zeta$	$y_{q\ell\zeta}$	$y_{q\ell\zeta}$	$y_{q\ell\zeta}$	$y_{q\ell\zeta}$	$y_{q\ell\zeta}$, $y_{qq\zeta}$	$y_{q\ell\zeta}$, $y_{qq\zeta}$	$y_{q\ell\zeta}$, $y_{qq\zeta}$	$y_{q\ell\zeta}$, $y_{qq\zeta}$
Ω_1							$y_{qq\Omega_1}$, $y_{ud\Omega_1}$	$y_{qq\Omega_1}$, $y_{ud\Omega_1}$	$y_{qq\Omega_1}$, $y_{ud\Omega_1}$	$y_{qq\Omega_1}$, $y_{ud\Omega_1}$
Ω_2							y_{Ω_2}	y_{Ω_2}		y_{Ω_2}
Ω_4							y_{Ω_4}	y_{Ω_4}	y_{Ω_4}	
Υ	$\hat{\lambda}'_\Upsilon$	$\hat{\lambda}'_\Upsilon$					y_Υ	y_Υ	y_Υ	y_Υ
Φ	$\hat{\lambda}'_\Phi$	$\hat{\lambda}'_\Phi$, $\hat{\lambda}''_\Phi$					$y_{qd\Phi}$, $y_{qu\Phi}$	$y_{qd\Phi}$, $y_{qu\Phi}$	$y_{qd\Phi}$, $y_{qu\Phi}$	$y_{qd\Phi}$, $y_{qu\Phi}$
N	λ_N	λ_N	λ_N	λ_N	λ_N	λ_N	λ_N	λ_N	λ_N	λ_N
E	λ_E	λ_E	λ_E	λ_E	λ_E	λ_E	λ_E	λ_E	λ_E	λ_E
Δ_1	λ_{Δ_1}	λ_{Δ_1}		λ_{Δ_1}	λ_{Δ_1}	λ_{Δ_1}	λ_{Δ_1}	λ_{Δ_1}	λ_{Δ_1}	λ_{Δ_1}
Δ_3	λ_{Δ_3}	λ_{Δ_3}		λ_{Δ_3}	λ_{Δ_3}	λ_{Δ_3}	λ_{Δ_3}	λ_{Δ_3}	λ_{Δ_3}	λ_{Δ_3}
Σ	λ_Σ	λ_Σ	λ_Σ	λ_Σ	λ_Σ	λ_Σ	λ_Σ	λ_Σ	λ_Σ	λ_Σ
Σ_1	λ_{Σ_1}	λ_{Σ_1}	λ_{Σ_1}	λ_{Σ_1}	λ_{Σ_1}	λ_{Σ_1}	λ_{Σ_1}	λ_{Σ_1}	λ_{Σ_1}	λ_{Σ_1}
U	λ_U	λ_U		λ_U	λ_U	λ_U	λ_U	λ_U	λ_U	λ_U
D		λ_D		λ_D	λ_D	λ_D	λ_D	λ_D	λ_D	λ_D
Q_1	λ_{dQ_1}, λ_{uQ_1}	λ_{dQ_1}, λ_{uQ_1}		λ_{dQ_1}, λ_{uQ_1}	λ_{dQ_1}, λ_{uQ_1}	λ_{dQ_1}, λ_{u}	λ_{dQ_1}, λ_{uQ_1}	λ_{dQ_1}, λ_{uQ_1}	λ_{dQ_1}, λ_{uQ_1}	λ_{dQ_1}, λ_{uQ_1}
Q_5	λ_{Q_5}	λ_{Q_5}		λ_{Q_5}	λ_{Q_5}	λ_{Q_5}	λ_{Q_5}	λ_{Q_5}	λ_{Q_5}	λ_{Q_5}
Q_7	λ_{Q_7}	λ_{Q_7}		λ_{Q_7}	λ_{Q_7}	λ_{Q_7}	λ_{Q_7}	λ_{Q_7}	λ_{Q_7}	λ_{Q_7}
T_1	λ_{T_1}	λ_{T_1}		λ_{T_1}	λ_{T_1}	λ_{T_1}	λ_{T_1}	λ_{T_1}	λ_{T_1}	λ_{T_1}
T_2	λ_{T_2}	λ_{T_2}		λ_{T_2}	λ_{T_2}	λ_{T_2}	λ_{T_2}	λ_{T_2}	λ_{T_2}	λ_{T_2}

e.g. Fermions:

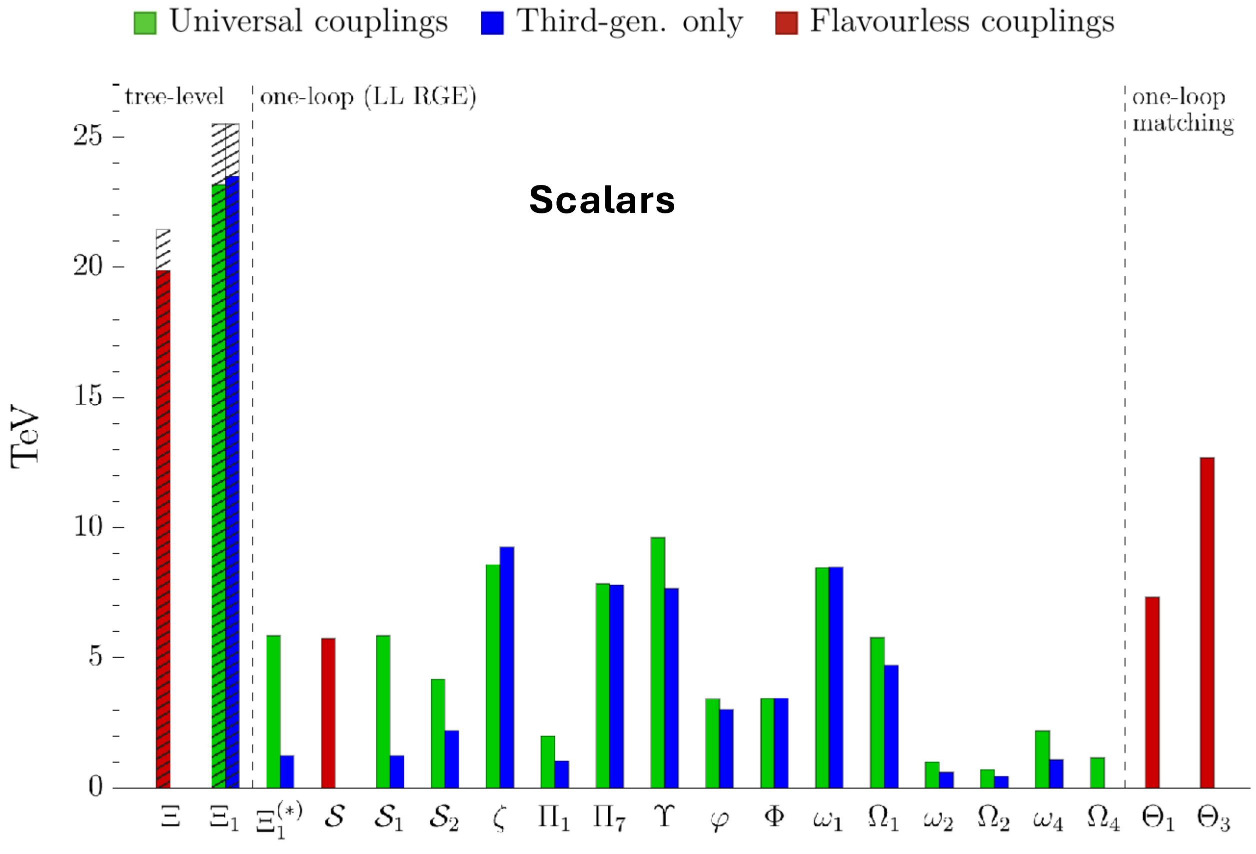


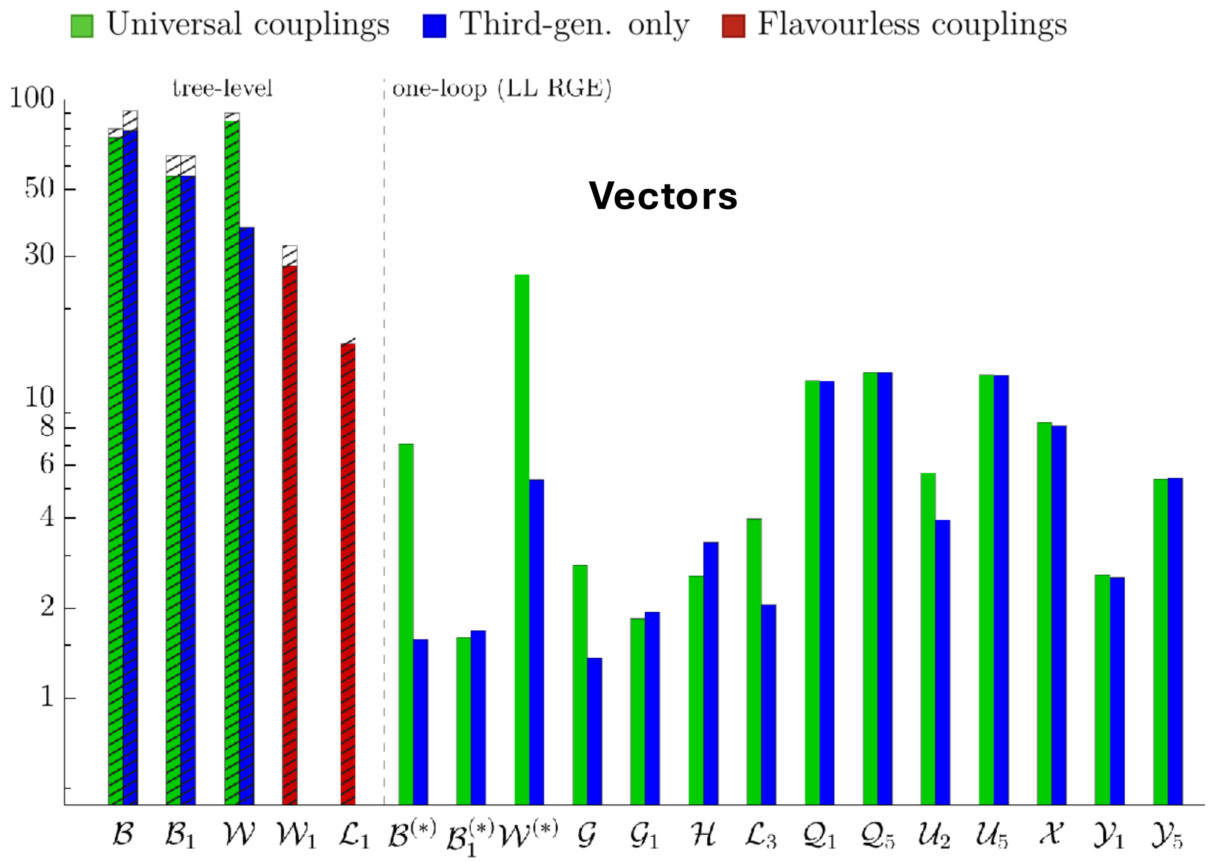
Linear SM extensions at Tera-Z

Linear SM extensions extensively probed by **Z-pole** at Tera-Z – a **quantum leap** in sensitivity.

“Tera-Z is argued to provide an almost inescapable probe of heavy new physics”

2408.03992 Allwicher, McCullough, Renner





Radically new BSM?

Energy

Direct exploration by **hadron** / **muon** collider

$\boldsymbol{\Lambda}$ $\mathcal{L}_{UV} = ?$

$\boldsymbol{E < \Lambda}$ $\mathcal{L}_{IR} = \Lambda^4 + \Lambda^2 \mathcal{O}^{(2)} + m\mathcal{O}^{(3)} + \mathcal{O}^{(4)} + \frac{c_5}{\Lambda}\mathcal{O}^{(5)} + \frac{c_6}{\Lambda^2}\mathcal{O}^{(6)} + \frac{c_7}{\Lambda^3}\mathcal{O}^{(7)} + \frac{c_8}{\Lambda^4}\mathcal{O}^{(8)} + \dots$

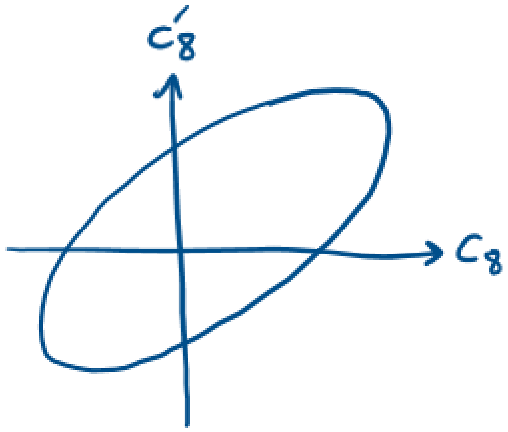
Indirect exploration by **e+e-**

Radically new BSM?

Energy

Direct exploration by **hadron** / **muon** collider

$\boldsymbol{\Lambda}$ $\mathcal{L}_{UV} = ?$



e.g. Consider future indirect sensitivity to UV theory in dimension-8 SMEFT operators

See e.g.
2009.02212 Fuks, Liu, Zhang, Zhou
2009.14298 Ellis, He, Xiao;
2011.03055 Gu, Wang, Zhang;
2308.06226 Davighi, Melville, Mimasu, **TY;**
2404.15937 Liu et al.

$\boldsymbol{E < \Lambda}$

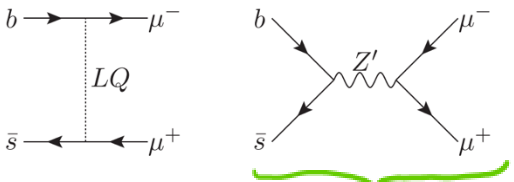
$$\mathcal{L}_{IR} = \Lambda^4 + \Lambda^2\mathcal{O}^{(2)} + m\mathcal{O}^{(3)} + \mathcal{O}^{(4)} + \frac{c_5}{\Lambda}\mathcal{O}^{(5)} + \frac{c_6}{\Lambda^2}\mathcal{O}^{(6)} + \frac{c_7}{\Lambda^3}\mathcal{O}^{(7)} + \boxed{\frac{c_8}{\Lambda^4}\mathcal{O}^{(8)}} + \dots$$

Indirect exploration by **e+e-** collider

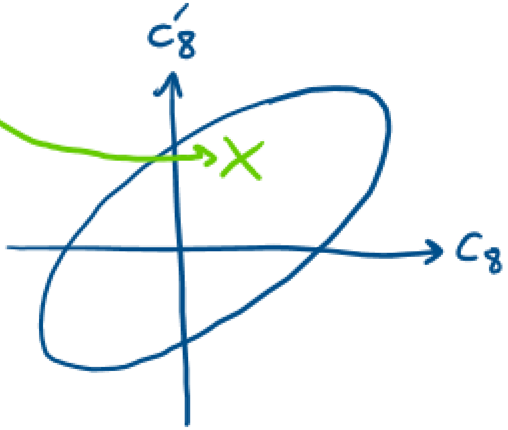
Radically new BSM?

Energy

$\boldsymbol{\Lambda}$ $\mathcal{L}_{UV} = ?$



Direct exploration by **hadron** / **muon** collider



Matching explicit UV models populates a **subspace** of SMEFT coefficient space

$\boldsymbol{E < \Lambda}$

$$\mathcal{L}_{IR} = \Lambda^4 + \Lambda^2 \mathcal{O}^{(2)} + m\mathcal{O}^{(3)} + \mathcal{O}^{(4)} + \frac{c_5}{\Lambda}\mathcal{O}^{(5)} + \frac{c_6}{\Lambda^2}\mathcal{O}^{(6)} + \frac{c_7}{\Lambda^3}\mathcal{O}^{(7)} + \boxed{\frac{c_8}{\Lambda^4}\mathcal{O}^{(8)}} + \ldots$$

Indirect exploration by **e+e-** collider

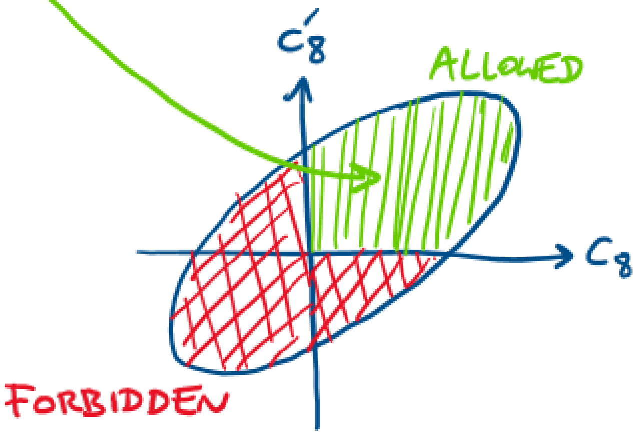
Radically new BSM?

Energy

Direct exploration by **hadron** / **muon** collider

$\boldsymbol{\Lambda}$ — $\mathcal{L}_{UV} = ?$

Unitarity | Locality | Causality | ...



Positivity bounds forbid **negative signs** of dim-8 SMEFT coefficients *assuming only general fundamental principles* in the UV

$\boldsymbol{E < \Lambda}$ — $$\mathcal{L}_{IR} = \Lambda^4 + \Lambda^2\mathcal{O}^{(2)} + m\mathcal{O}^{(3)} + \mathcal{O}^{(4)} + \frac{c_5}{\Lambda}\mathcal{O}^{(5)} + \frac{c_6}{\Lambda^2}\mathcal{O}^{(6)} + \frac{c_7}{\Lambda^3}\mathcal{O}^{(7)} + \boxed{\frac{c_8}{\Lambda^4}\mathcal{O}^{(8)}} + \ldots$$

Indirect exploration by **e+e-** collider

Measuring the *"wrong" sign* experimentally would have **truly revolutionary** consequences for the underlying theory!

Radically new BSM?

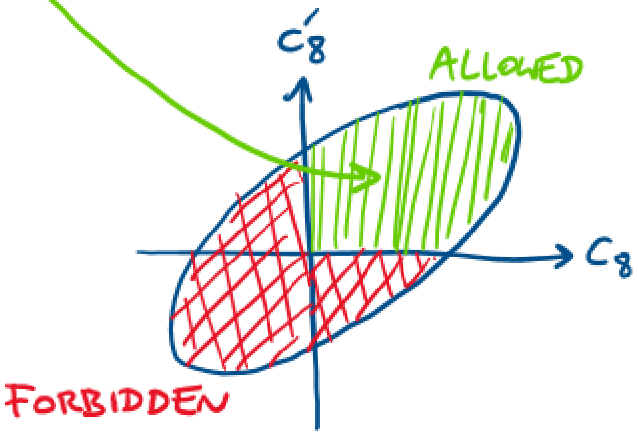
Energy

May not even have a Lagrangian/QFT description

Direct exploration by **hadron** / **muon** collider

Λ

$\boxed{\mathcal{L}_{UV} = ?}$ | Unitarity | Locality | Causality | ...



Positivity bounds forbid **negative signs** of dim-8 SMEFT coefficients *assuming only general fundamental principles* in the UV

$E < \Lambda$

$$\mathcal{L}_{IR} = \Lambda^4 + \boxed{\Lambda^2\mathcal{O}^{(2)}} + m\mathcal{O}^{(3)} + \mathcal{O}^{(4)} + \frac{c_5}{\Lambda}\mathcal{O}^{(5)} + \frac{c_6}{\Lambda^2}\mathcal{O}^{(6)} + \frac{c_7}{\Lambda^3}\mathcal{O}^{(7)} + \boxed{\frac{c_8}{\Lambda^4}\mathcal{O}^{(8)}} + \dots$$

Indirect exploration by **e+e-** collider

Measuring the *"wrong" sign* experimentally would have **truly revolutionary** consequences for the underlying theory!

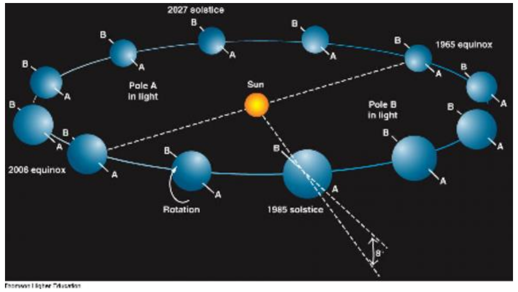
Could potentially be related to hierarchy problem

2308.06226 Davighi, Melville, Mimasu, **TY**

Conclusion

Sometimes an anomaly in **indirect precision** measurement = *something missing*:

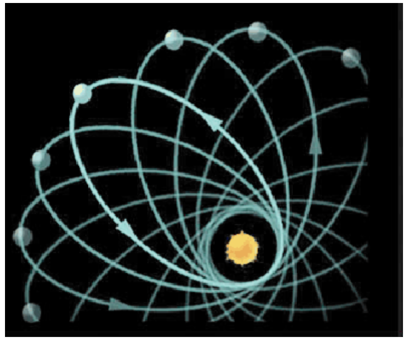
Anomaly in orbit of Uranus

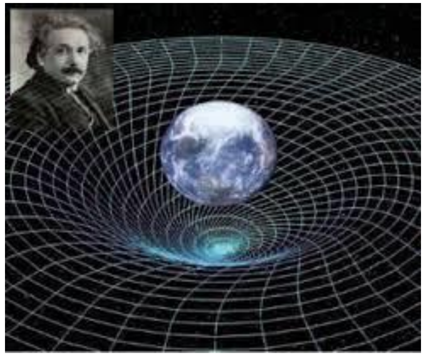


Discovery of Neptune

Other times its implications are *far more radical*:

Anomaly in orbit of Mercury





Explained by General Relativity

(Could have been **anticipated** by **Effective Theory** and **naturalness**!) 1106.1568 J.D. Wells

Conclusion

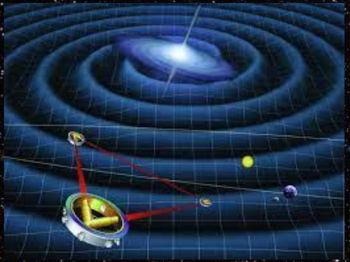
An unnaturally small cosmological constant and Higgs mass may be indicating that **something fundamentally different is going on** at shorter distances that we don‘t understand yet.

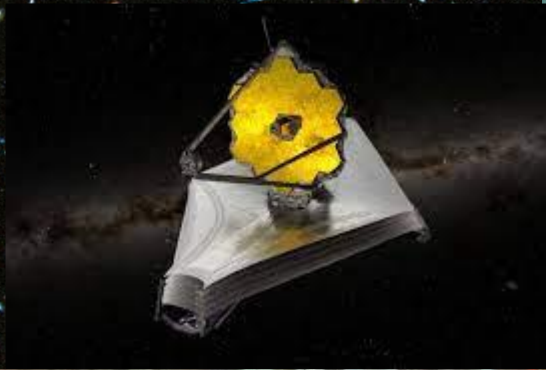
FCC-ee can indirectly **probe a wide variety of generic new physics at higher energy scales** far beyond the reach of the LHC: **quantum exploration of the TeV scale**.

Almost all SM particles **first appeared indirectly** before being discovered directly; **same may be true of BSM!**

Backup

Concluding Remarks





- Telescopes are **space observatories** for exploring *outer space*
- Colliders are *experimental* **particle observatories** for exploring *inner space*
- We need **all eyes open on all scales** in our universe to make progress

Concluding Remarks

Future colliders are **not just a wild punt for BSM**, any more than JWST or LISA is only about breaking ΛCDM. Particle physics must be reframed in same way as astro/cosmo: **about doing good science**.

They are scientific laboratories for doing all kinds of fundamental experiments on small scales – a general-purpose *"particle observatory"* for the zeptoscopic world.

The wealth of information they provide about the most fundamental quantum processes we can directly access experimentally make colliders a unique, irreplaceable, and crucial instrument for the job of fundamental physics: **to better understand our universe**.

https://cerncourier.com/a/future-colliders-are-particle-observatories/

Concluding Remarks

- *"What would be the use of such extreme refinement in the science of measurement? […] The more important fundamental laws and facts of physical science have all been discovered, and these are so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote.* […]*"*

–A. Michelson 1903

Concluding Remarks

- *"What would be the use of such extreme refinement in the science of measurement?* ***Very briefly and in general terms the answer would be that in this direction the greater part of all future discovery must lie.*** *The more important fundamental laws and facts of physical science have all been discovered, and these are so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote.* ***Nevertheless, it has been found that there are apparent exceptions to most of these laws, and this is particularly true when the observations are pushed to a limit, i.e., whenever the circumstances of experiment are such that extreme cases can be examined.****"*

  –A. Michelson 1903

Effective Field Theory

e.g. QED as an EFT includes Fermi theory (at operator mass dimension 6) and Euler-Heisenberg (at dimension 8)

$$\mathcal{L}^{EFT}_{QED} = \bar{\Psi} i \gamma^\mu D_\mu \Psi - m \bar{\Psi}\Psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

Fermi theory
(1933)

$$+ \sum_i \frac{c_6^{(i)}}{\Lambda^2} (\bar{\Psi} \Gamma \Psi)(\bar{\Psi} \Gamma \Psi)$$

$$\Gamma = \{\mathbb{1}, \gamma_5, \gamma_\mu, \gamma_\mu\gamma_5, \sigma_{\mu\nu}\}$$

Euler-Heisenberg
(1936)

$$+ \frac{c_8^{(1)}}{\Lambda^4} (F_{\mu\nu} F^{\mu\nu})^2 + \frac{c_8^{(2)}}{\Lambda^4} F_{\mu\nu} F^{\nu\rho} F_{\rho\lambda} F^{\lambda\mu} + \dots$$

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Wilson coefficients generated by UV physics

The Standard Model as an Effective Field Theory

Given particle content, write down *all* terms allowed by symmetries.

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
Q_L	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$
q_R^u	$\mathbf{3}$	$\mathbf{1}$	$\frac{2}{3}$
q_R^d	$\mathbf{3}$	$\mathbf{1}$	$-\frac{1}{3}$
L_L	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$
l_R	$\mathbf{1}$	$\mathbf{1}$	-1
ϕ	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$

$$\mathcal{L}_{SM} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y \quad ,$$

$$\mathcal{L}_m = \bar{Q}_L i\gamma^\mu D^L_\mu Q_L + \bar{q}_R i\gamma^\mu D^R_\mu q_R + \bar{L}_L i\gamma^\mu D^L_\mu L_L + \bar{l}_R i\gamma^\mu D^R_\mu l_R$$

$$\mathcal{L}_G = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu}$$

$$\mathcal{L}_H = (D^L_\mu\phi)^\dagger(D^{L\mu}\phi) - V(\phi)$$

$$\mathcal{L}_Y = y_d\bar{Q}_L\phi q_R^d + y_u\bar{Q}_L\phi^c q_R^u + y_L\bar{L}_L\phi l_R + \text{h.c.} \quad ,$$

Up to **mass dimension 4**, this is what we typically call *"The Standard Model"*.

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Strong-CP problem

$$\mathcal{L}_H = (D_\mu^L\phi)^\dagger(D^{L\mu}\phi) - V(\phi)$$

$$\mathcal{L}_Y = y_d\bar{Q}_L\phi q_R^d + y_u\bar{Q}_L\phi^c q_R^u + y_L\bar{L}_L\phi l_R + \text{h.c.} \qquad ,$$

"Everything not forbidden is compulsory"

Up to **mass dimension 4**, this is what we typically call *"The Standard Model"*.

The Standard Model as an Effective Field Theory

Given particle content, write down *all* terms allowed by symmetries - including operators of **mass dimension** $>$ **4**.

$$\mathcal{L}_{SM}^{EFT} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y \boxed{+ \frac{c_5}{\Lambda}\mathcal{O}^{(5)} + \frac{c_6}{\Lambda^2}\mathcal{O}^{(6)} + \frac{c_7}{\Lambda^3}\mathcal{O}^{(7)} + \frac{c_8}{\Lambda^4}\mathcal{O}^{(8)} + \dots}$$

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"Everything not forbidden is compulsory"

This is the *"Standard Model Effective Field Theory"* (**SMEFT).**

See e.g. 1706.08945, 2303.16922 for reviews

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Given particle content, write down *all* terms allowed by symmetries - including operators of **mass dimension** $>$ **4**.

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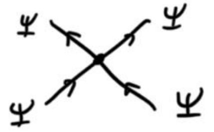
$$\ldots_R + \bar{L}_L i\gamma^\mu D^L_\mu L_L + \bar{l}_R i\gamma^\mu D^R_\mu l_R$$

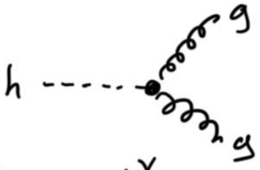
$$- \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} - \theta \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

$$\ldots_L \bar{L}_L \phi l_R + \text{h.c.} \quad ,$$

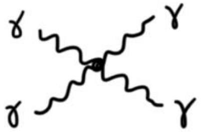
e.g. $\mathcal{L}^{\text{dim-6}}_{\text{4-fermion}} = \frac{c_{4f}}{\Lambda^2} \bar{\Psi}\Psi\bar{\Psi}\Psi$



$\mathcal{L}^{\text{dim-6}}_{hgg} = \frac{c_g}{\Lambda^2} |H|^2 G_{\mu\nu} G^{\mu\nu}$



$\mathcal{L}^{\text{dim-8}}_{\gamma\gamma\gamma\gamma} = \frac{c_{4\gamma}}{\Lambda^4} (F_{\mu\nu} F^{\mu\nu})^2$



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The Standard Model as an Effective Field Theory

Given particle content, write down *all* terms allowed by symmetries - including operators of **mass dimension** > 4.

$$\mathcal{L}^{EFT}_{SM} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y \boxed{+ \frac{c_5}{\Lambda}\mathcal{O}^{(5)} + \frac{c_6}{\Lambda^2}\mathcal{O} \; \dots + \dots}$$

$$+ \bar{L}_L i\gamma \dots$$

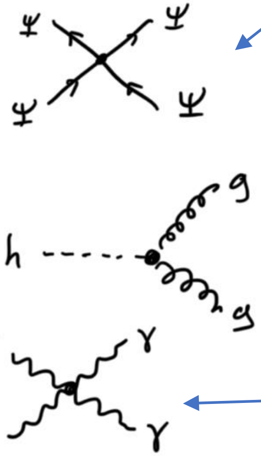
$$- \frac{1}{4}G^a_{\mu\nu} \dots$$

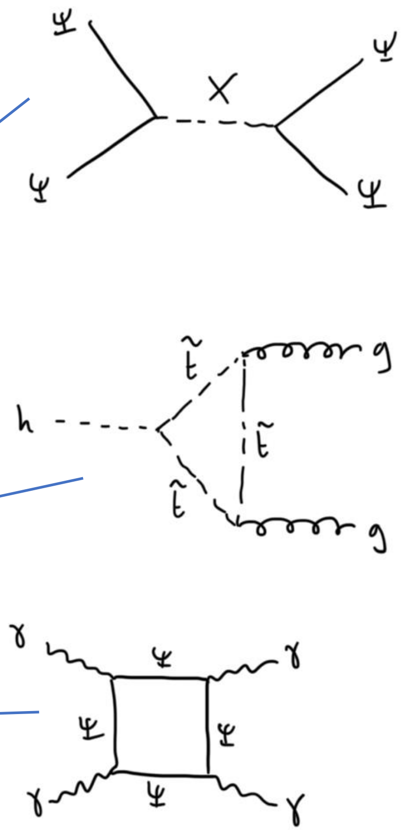
$$\bar{L}_L \phi l_R + \dots$$

e.g. $\mathcal{L}^{\text{dim-6}}_{\text{4-fermion}} = \frac{c_{4f}}{\Lambda^2}\bar{\Psi}\Psi\bar{\Psi}\Psi$

$\mathcal{L}^{\text{dim-6}}_{hgg} = \frac{c_g}{\Lambda^2}|H|^2 G_{\mu\nu}G^{\mu\nu}$

$\mathcal{L}^{\text{dim-8}}_{\gamma\gamma\gamma\gamma} = \frac{c_{4\gamma}}{\Lambda^4}(F_{\mu\nu}F^{\mu\nu})^2$





This is the “*Standard Model Effective Field Theory*” (**SMEFT**).

See e.g. 1706.08945, 2303.16922 for reviews

The Standard Model as an Effective Field Theory

The SMEFT is the **Fermi theory of the 21st century**.

$$\mathcal{L}_{SM}^{EFT} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y \boxed{+ \frac{c_5}{\Lambda}\mathcal{O}^{(5)} + \frac{c_6}{\Lambda^2}\mathcal{O}^{(6)} + \frac{c_7}{\Lambda^3}\mathcal{O}^{(7)} + \frac{c_8}{\Lambda^4}\mathcal{O}^{(8)} + \ldots}$$

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Explore heavy BSM physics in this framework.

This does not exclude the possibility of light new physics; just add those fields in as part of the EFT if desired or discovered.

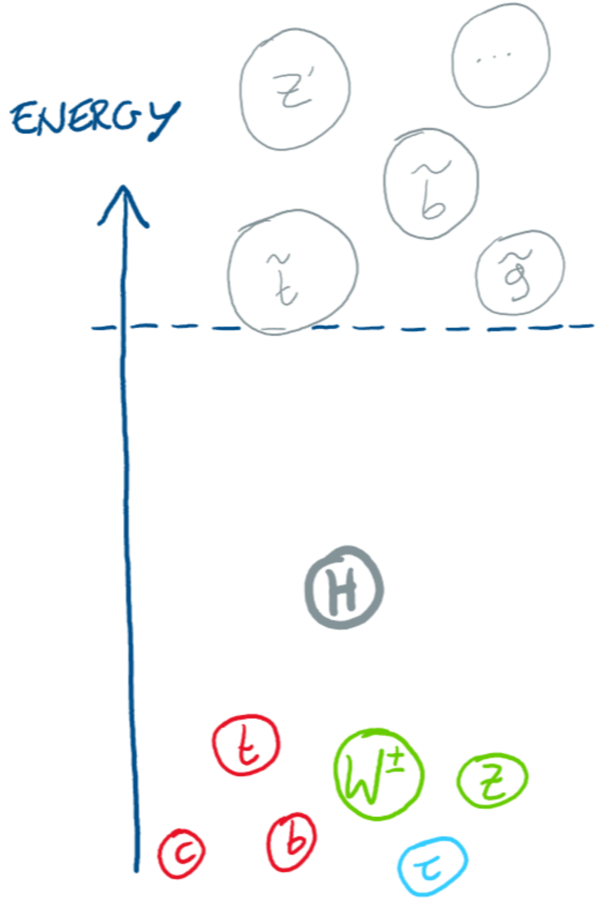
Non-linear chiral electroweak lagrangian + singlet scalar is a more general EFT framework (known as HEFT).

The Standard Model as an Effective Field Theory

EFT is the framework for a **separation of scales** between heavy new physics and the SM.

- What are the experimental constraints on the **energy scale** of new physics, $\boldsymbol{\Lambda}$?

- What are the experimental constraints on their **interaction strengths**, $\boldsymbol{c_i}$?



$$\mathcal{L}_{UV} = ?$$

$$\mathcal{L}_{SM} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y + \frac{c_5}{\Lambda}\mathcal{O}^{(5)} + \frac{c_6}{\Lambda^2}\mathcal{O}^{(6)} + \frac{c_7}{\Lambda^3}\mathcal{O}^{(7)} + \frac{c_8}{\Lambda^4}\mathcal{O}^{(8)} + \dots$$

$$\begin{aligned}
\mathcal{L}_m &= \bar{Q}_L i\gamma^\mu D^L_\mu Q_L + \bar{q}_R i\gamma^\mu D^R_\mu q_R + \bar{L}_L i\gamma^\mu D^L_\mu L_L + \bar{l}_R i\gamma^\mu D^R_\mu l_R \\
\mathcal{L}_G &= -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} \\
\mathcal{L}_H &= (D^L_\mu\phi)^\dagger(D^{L\mu}\phi) - V(\phi) \\
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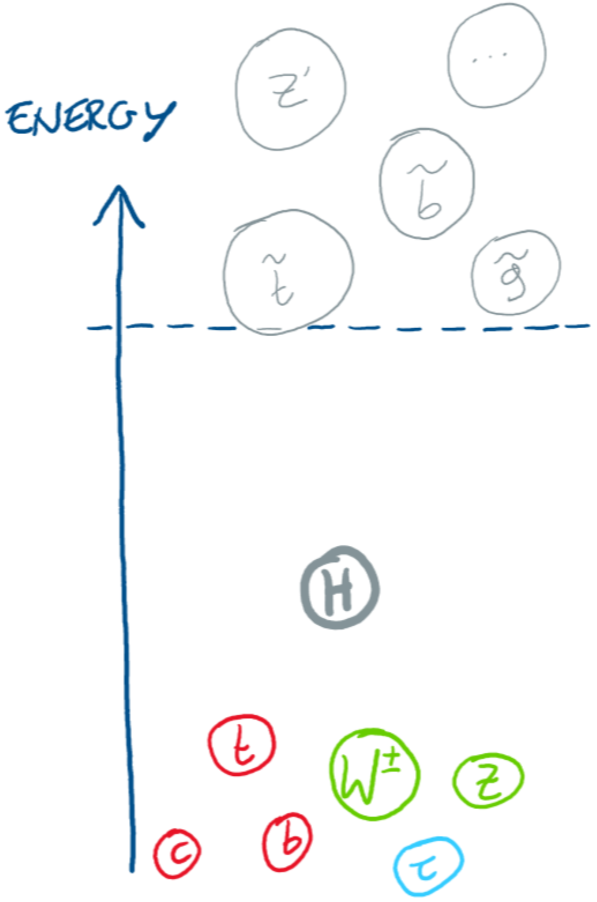
\end{aligned}$$

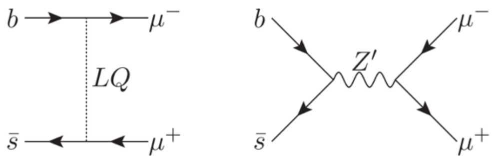
Structure of UV determined through **IR precision measurements**.

The Standard Model as an Effective Field Theory

EFT is the framework for a **separation of scales** between heavy new physics and the SM.



e.g. leptoquarks or Z'



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- What are the experimental constraints on their **interaction strengths**, $\boldsymbol{c_i}$?

$$\mathcal{L}_{SM} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y \; + \frac{c_6}{\Lambda^2}(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t) + \ldots$$

$$\mathcal{L}_m = \bar{Q}_L i\gamma^\mu D^L_\mu Q_L + \bar{q}_R i\gamma^\mu D^R_\mu q_R + \bar{L}_L i\gamma^\mu D^L_\mu L_L + \bar{l}_R i\gamma^\mu D^R_\mu l_R$$
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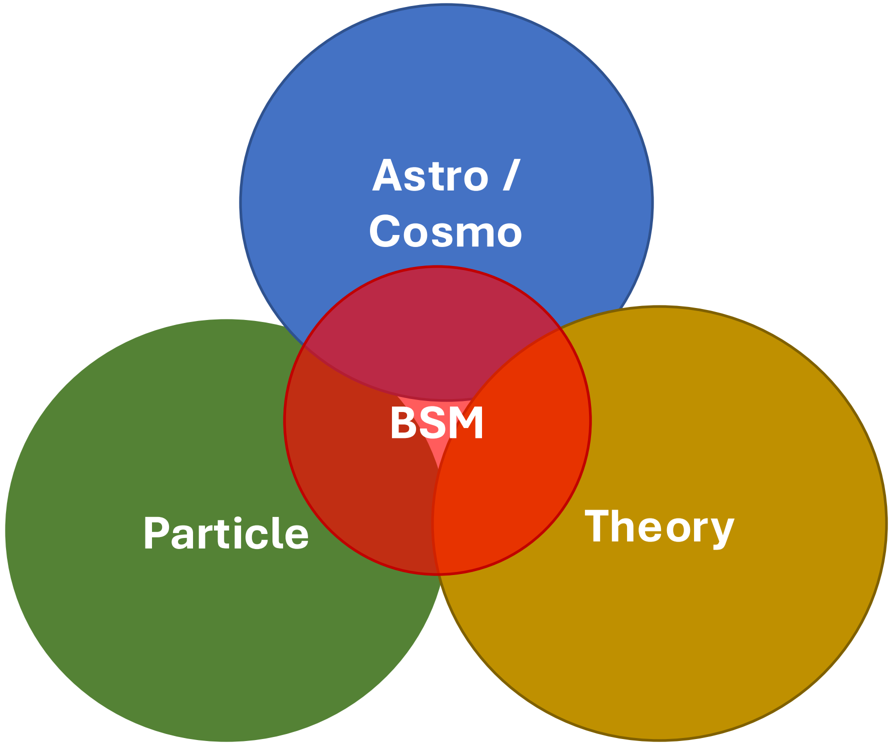
Structure of UV determined through **IR precision measurements**.

Why Colliders?

The ultimate goal of fundamental physics is to go **Beyond the Standard Model** (BSM).

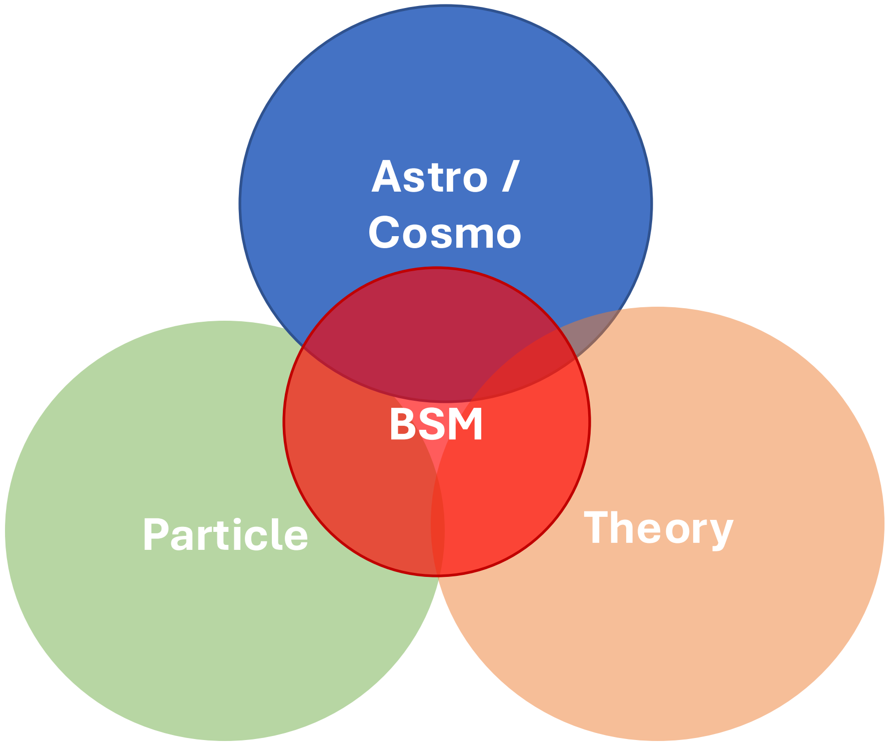


BSM combines our **experimental**, **observational**, and **theoretical** knowledge of the Universe.

We *are* getting closer to the ultimate truth, empirically, though **many unanswered problems** remain.

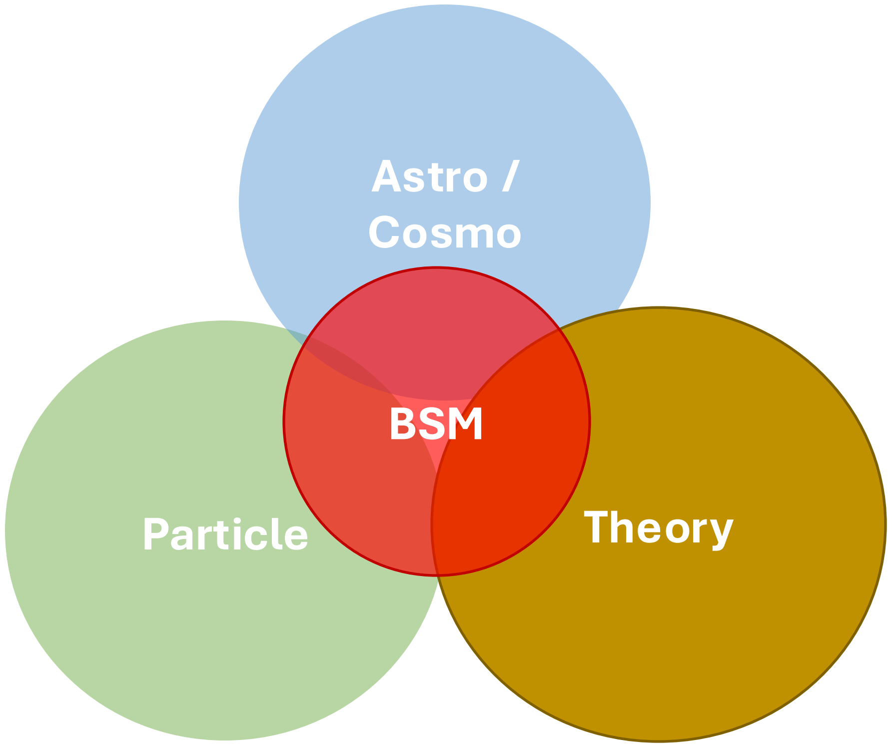
Why Colliders?

Astrophysics and **Cosmology** probe *indirectly* some of the highest energies or weakest interactions.



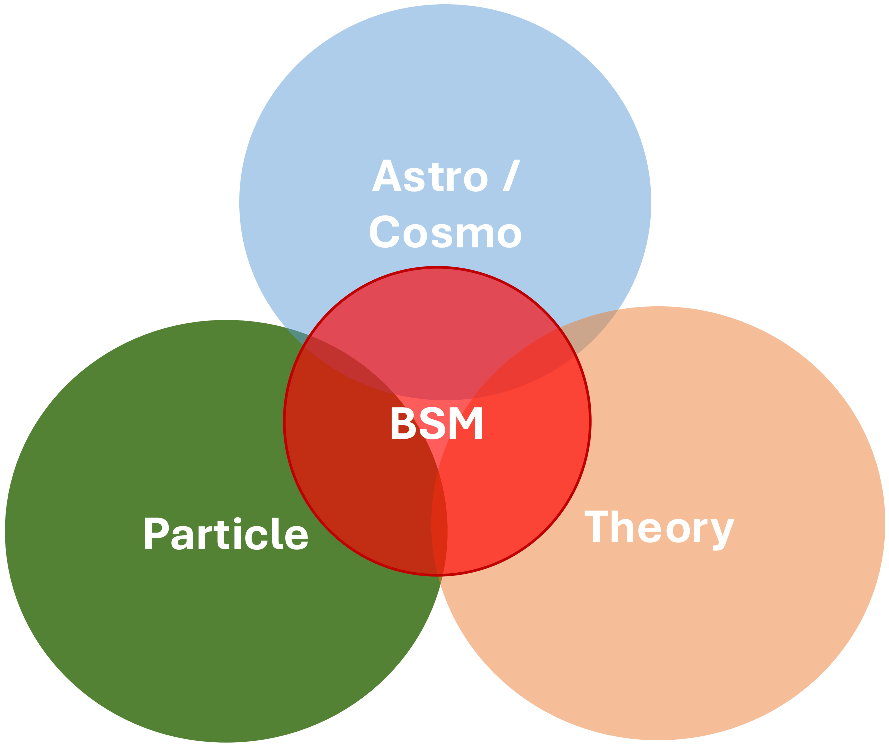
Why Colliders?

Theoretical consistency can be a fruitful guide for making progress.



Why Colliders?

Particle physics plays a *unique role* in enabling *experimental* access to small scales.



Exploring the fundamental nature of reality at the zeptoscale is a true **frontier of the unknown**.

Concluding Remarks

There is **value in pushing frontiers** – *definite questions are answered*, and we learn something regardless of the outcome.

A **new generation** of improved measurements, analysis techniques, theoretical calculations, data management, hardware development, cutting-edge engineering, large international collaboration, and popular culture inspiration **can only benefit humanity** regardless of our own short-sighted disappointment at lack of BSM. **Doing good science is its own reward.**

Maintain a **spirit of curiosity** to **explore the “final frontier”**.

https://cerncourier.com/a/future-colliders-are-particle-observatories/

Naturalness

Take fine-tuning problems seriously.

e.g. 2205.05708 N. Craig - Snowmass review,
1307.7879 G. Giudice - Naturalness after LHC

Example 1

$$(m_e c^2)_{obs} = (m_e c^2)_{bare} + \Delta E_{\text{Coulomb}}. \qquad \Delta E_{\text{Coulomb}} = \frac{1}{4\pi\varepsilon_0} \frac{e^2}{r_e}.$$

Avoiding cancellation between “bare” mass and divergent self-energy in classical electrodynamics requires new physics around

$$e^2/(4\pi\varepsilon_0 m_e c^2) = 2.8 \times 10^{-13}\ \text{cm}$$

Indeed, the positron and quantum-mechanics appears just before!

$$\Delta E = \Delta E_{\text{Coulomb}} + \Delta E_{\text{pair}} = \frac{3\alpha}{4\pi} m_e c^2 \log \frac{\hbar}{m_e c r_e}$$

Naturalness

Take fine-tuning problems seriously.

e.g. 2205.05708 N. Craig - Snowmass review,
1307.7879 G. Giudice - Naturalness after LHC

Example 2

Divergence in pion mass: $$m^2_{\pi^\pm} - m^2_{\pi^0} = \frac{3\alpha}{4\pi}\Lambda^2$$

Experimental value is $m^2_{\pi^\pm} - m^2_{\pi_0} \sim (35.5\,\mathrm{MeV})^2$

Expect new physics at $\Lambda \sim 850$ MeV to avoid fine-tuned cancellation.

ρ meson appears at 775 MeV!

Naturalness

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e.g. 2205.05708 N. Craig - Snowmass review,
1307.7879 G. Giudice - Naturalness after LHC

Example 3

Divergence in Kaons mass difference in a theory with only up, down, strange:

$$m_{K_L^0} - m_{K_S^0} = \simeq \frac{1}{16\pi^2} m_K f_K^2 G_F^2 \sin^2\theta_C \cos^2\theta_C \times \Lambda^2$$

Avoiding fine-tuned cancellation requires $\Lambda < 3$ GeV.

Gaillard & Lee in 1974 predicted the charm quark mass!

Naturalness

Take fine-tuning problems seriously.

e.g. 2205.05708 N. Craig - Snowmass review,
1307.7879 G. Giudice - Naturalness after LHC

Higgs?

Higgs also has a quadratically divergent contribution to its mass

$$\Delta m_H^2 = \frac{\Lambda^2}{16\pi^2}\left(-6y_t^2 + \frac{9}{4}g^2 + \frac{3}{4}g'^2 + 6\lambda\right)$$

Avoiding fine-tuned cancellation requires $\Lambda < O(100)$ GeV??

As Λ is pushed to the TeV scale by null results, tuning is around 10% - 1%.

Note: in the SM the Higgs mass is a parameter to be measured, not calculated. What the quadratic divergence represents (independently of the choice of renormalisation scheme) is the fine-tuning in an underlying theory in which we expect the Higgs mass to be calculable.

Many more open questions

The Standard Model is arbitrary, unnatural, incomplete, and inconsistent.

- **Arbitrary:**

Higgs potential, yukawa couplings, flavour structure, quantized hypercharges, matter-antimatter asymmetry – *arbitrary parameters put in by hand*.

- **Unnatural:**

Higgs mass, cosmological constant, strong-CP problem – *fine-tuned cancellations between independent contributions*.

Many more open questions

The Standard Model is arbitrary, unnatural, incomplete, and inconsistent.

- **Incomplete:**

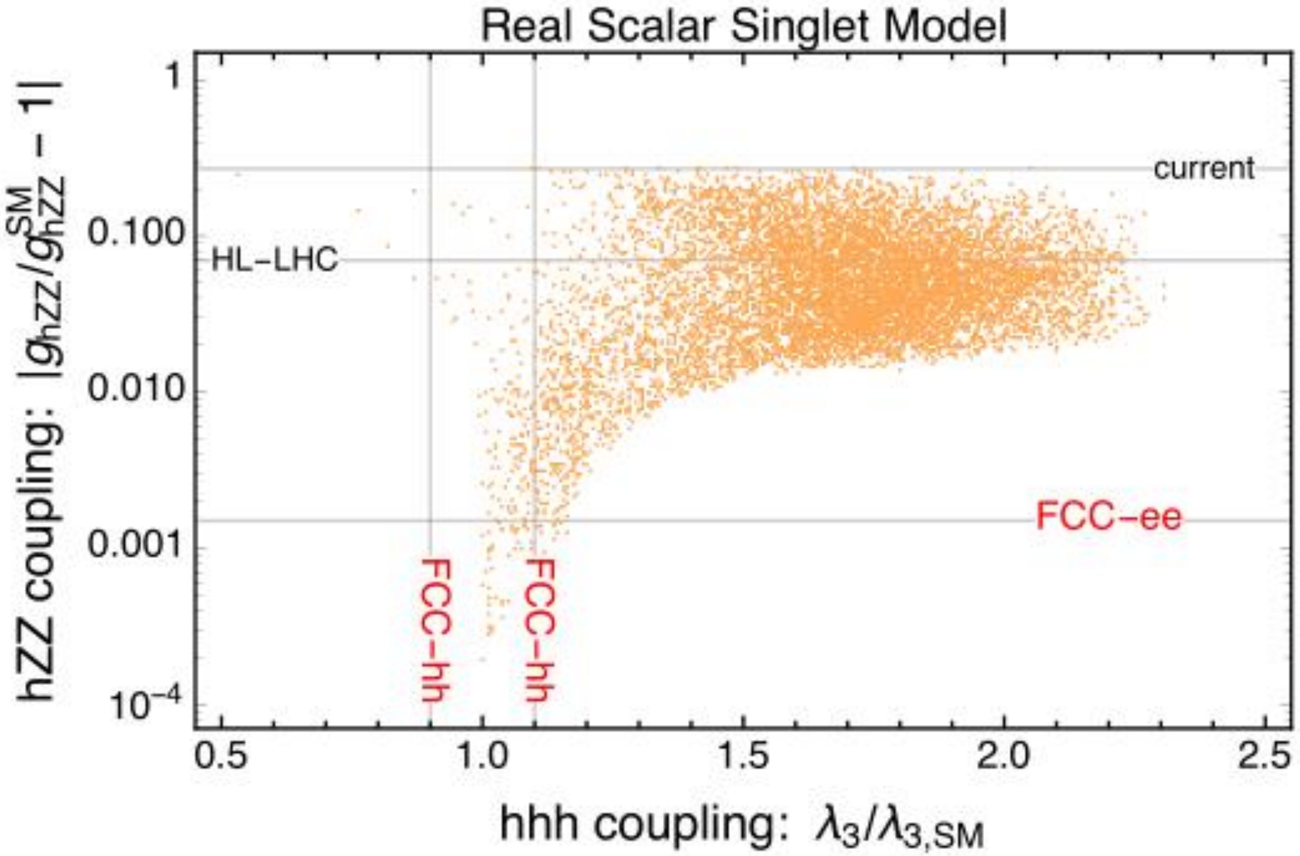
Experimental & observational evidence: dark matter, neutrino mass.

- **Inconsistent:**

Theoretical evidence: quantum gravity, black hole information paradox.

A Higgs factory can answer definitive questions

e.g. Nature of the **electroweak phase transition**: first order?



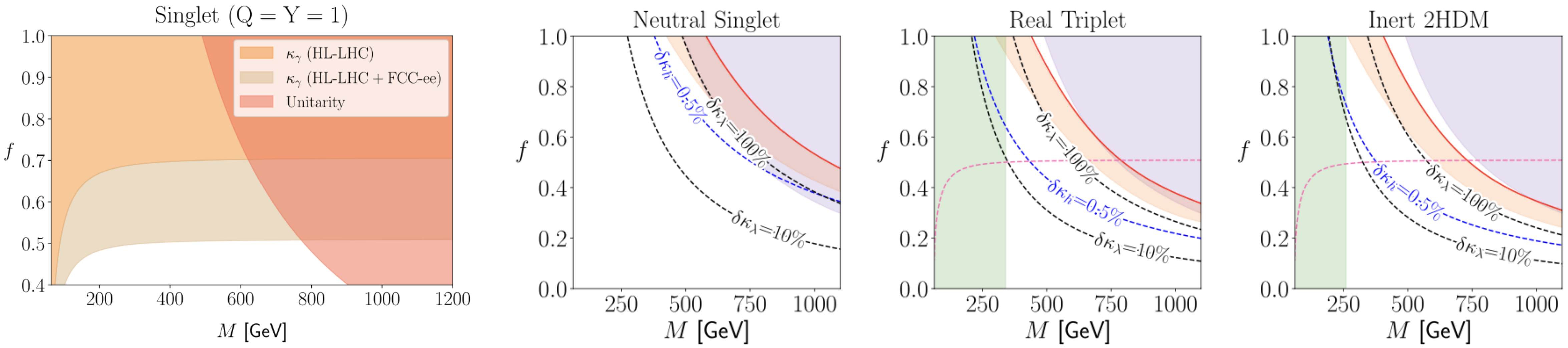
FCC CDR Vol. 1

Potential gravitational wave signal in range accessible by LISA

A Higgs factory can answer definitive questions

e.g. Does the Higgs boson give any other particles *most* of their mass?

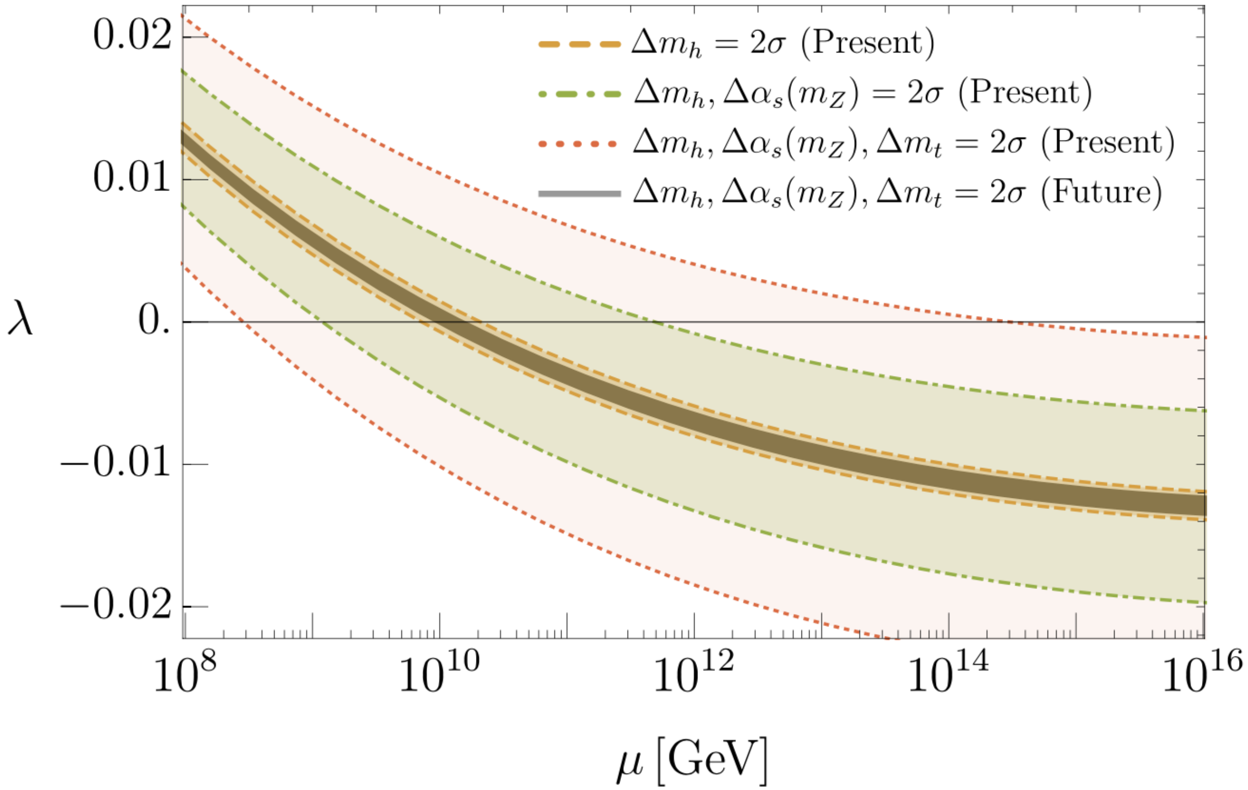
2110.02967 Banta, Cohen, Craig, Lu, Sutherland
2409.18177 Crawford, Sutherland



- Mass fraction $f > 0.5$ obtained from Higgs can be almost entirely excluded.

A Higgs factory can answer definitive questions

e.g. What is the **vacuum instability scale** in the SM?



Snowmass 2021
Dunsky, Harigaya, Hall

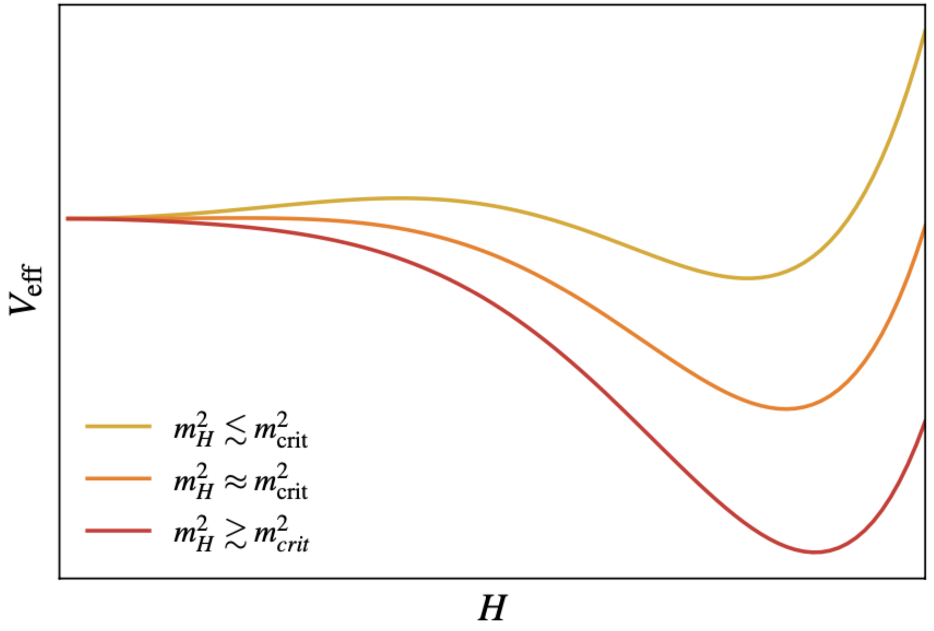
See also e.g. 2203.17197
Franceschini, Strumia, Wulzer

Uncertainty can be reduced from $O(10^6)$ down to *a factor of* ***~2!*** Potential implications for BSM.

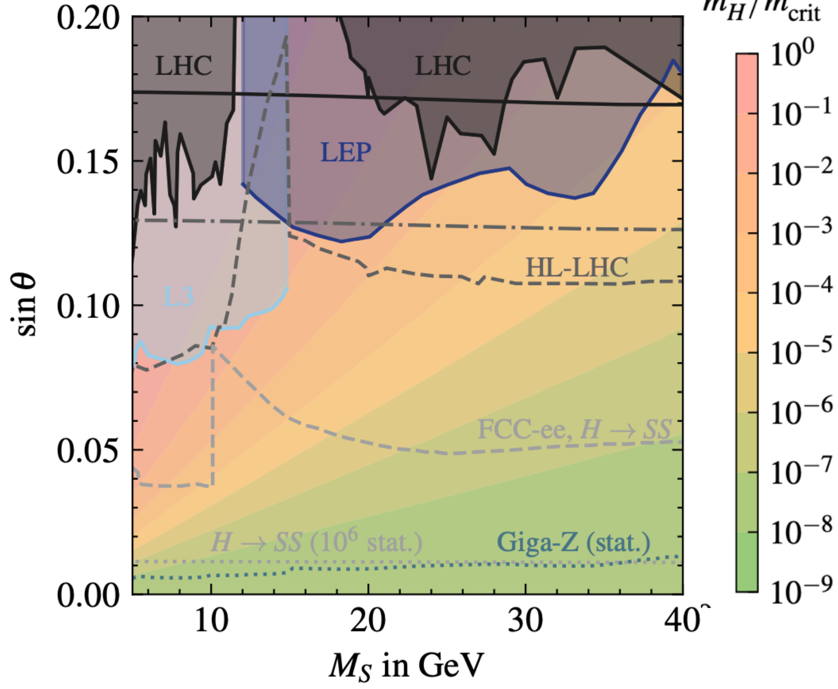
A Higgs factory can answer definitive questions

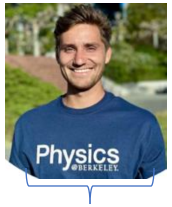
e.g. Is the Higgs mass due to **cosmological self-organised criticality**?

1907.07693 Khoury et al,
2105.08617 Giudice, McCullough, **TY**
2108.09315 Khoury, Steingasser



Axion-Higgs criticality





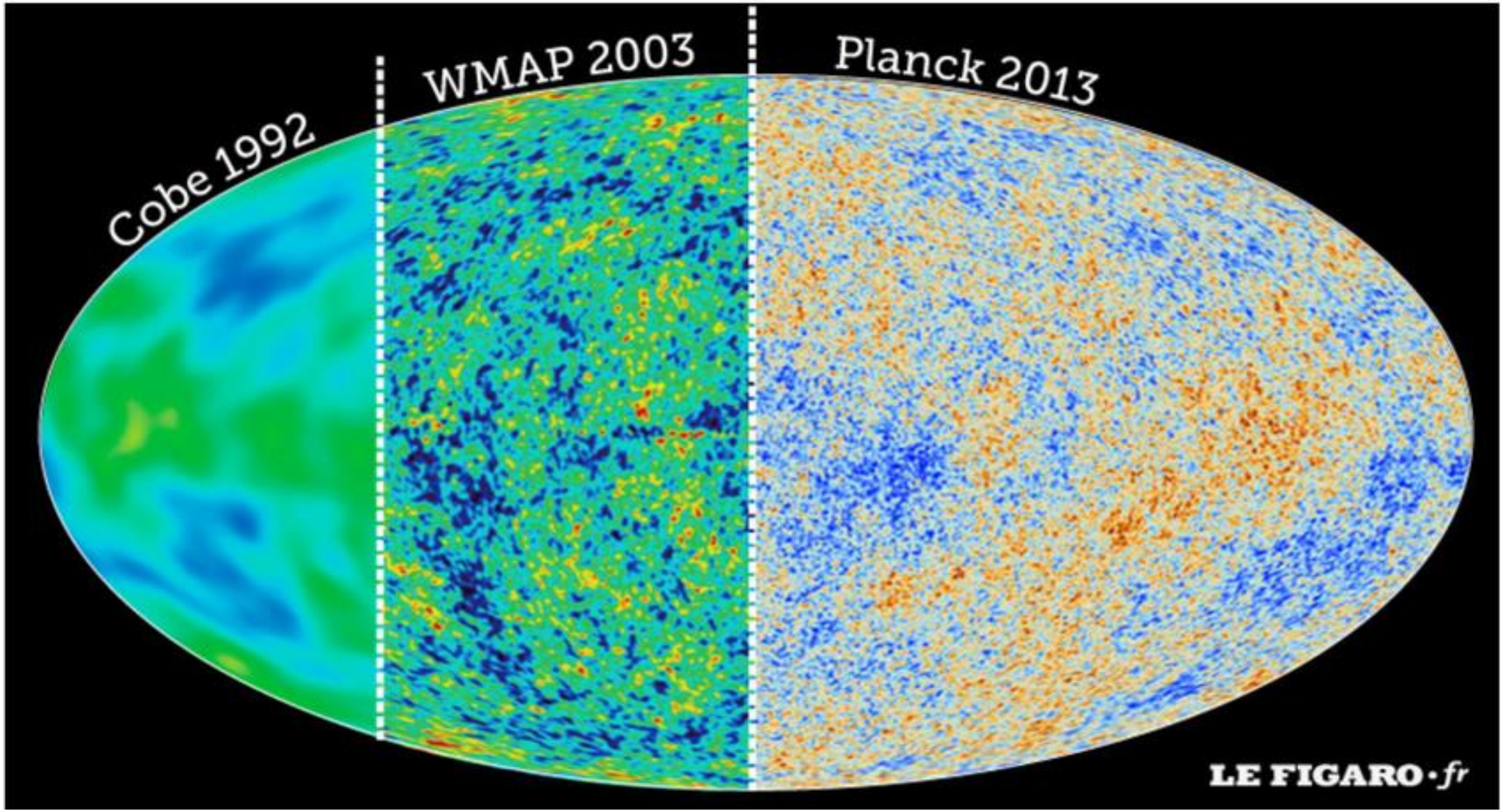
2412.03542 Detering, **TY**

Vacuum instability scale sets **Higgs mass upper bound**, must be lowered by **light BSM particles**.

Finite parameter space comprehensively probed by Higgs factory and Tera-Z.

Concluding Remarks

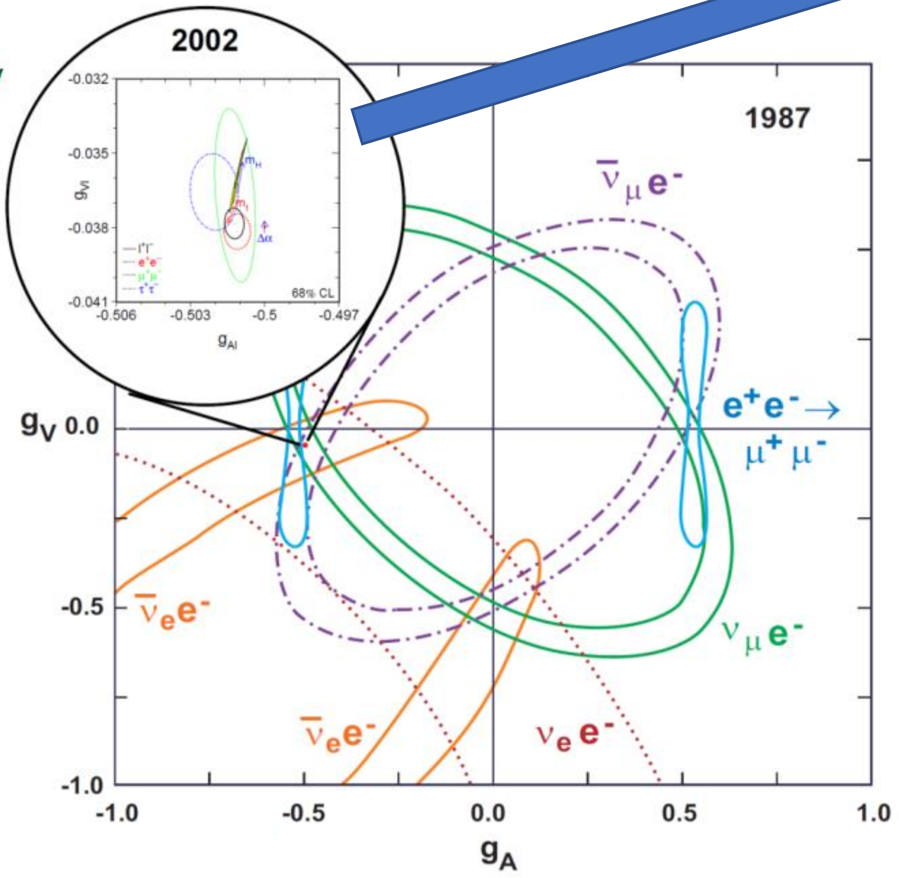
Sharpen our picture of the Universe, *e.g. before and after Planck*.

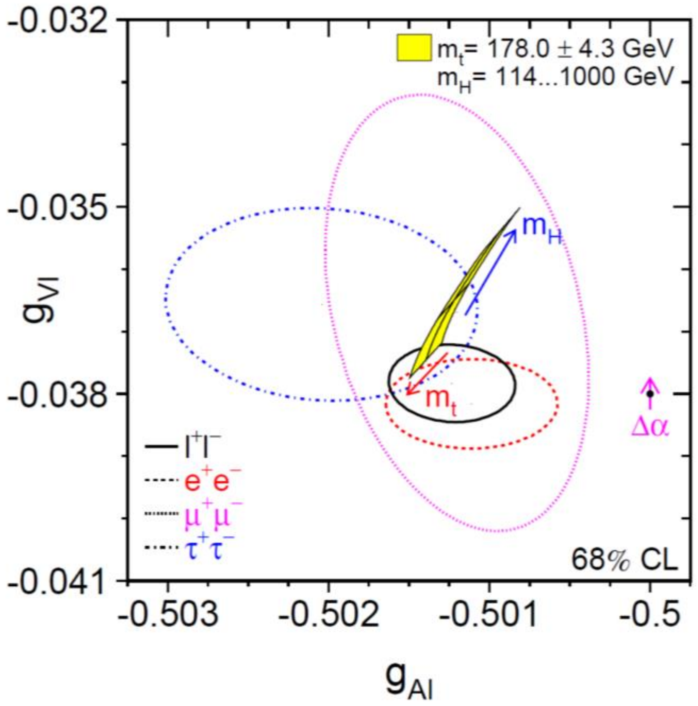


Concluding Remarks

Sharpen our picture of the Universe, *e.g. before and after LEP*.

magnified by
a factor 65





Guy Wilkinson slide

Concluding Remarks

Sharpen our picture of the Universe, *e.g. before and after FCC-ee / CEPC*.