China Hangzhou CEPC workshop, 23rd October 2024

Beyond the Standard Model at a Higgs and Tera-Z factory

Tevong You

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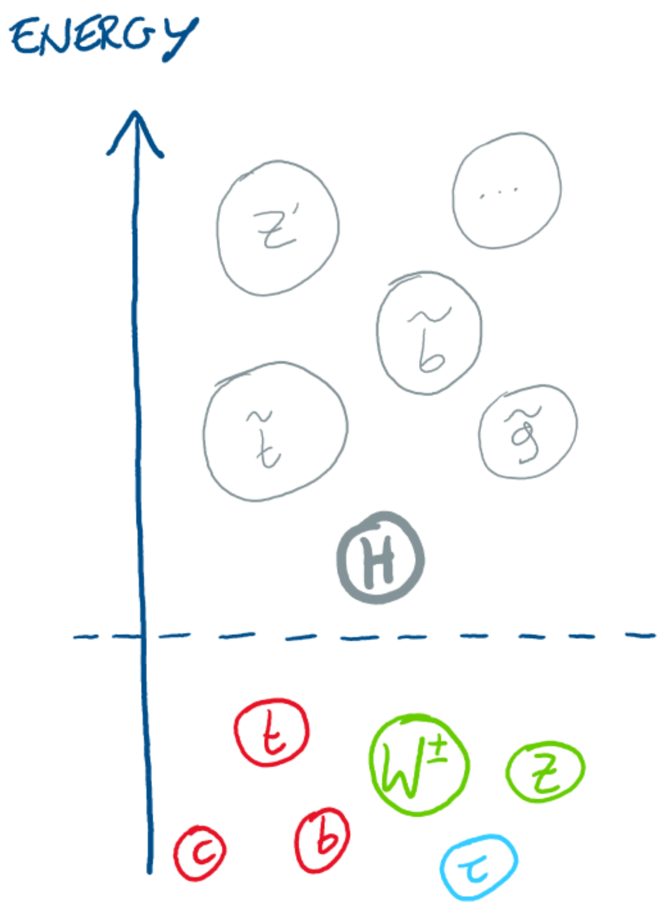
2) Why **Tera-Z**?

3) Why **colliders**?

Why the Higgs boson?

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



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

Why the Higgs boson?

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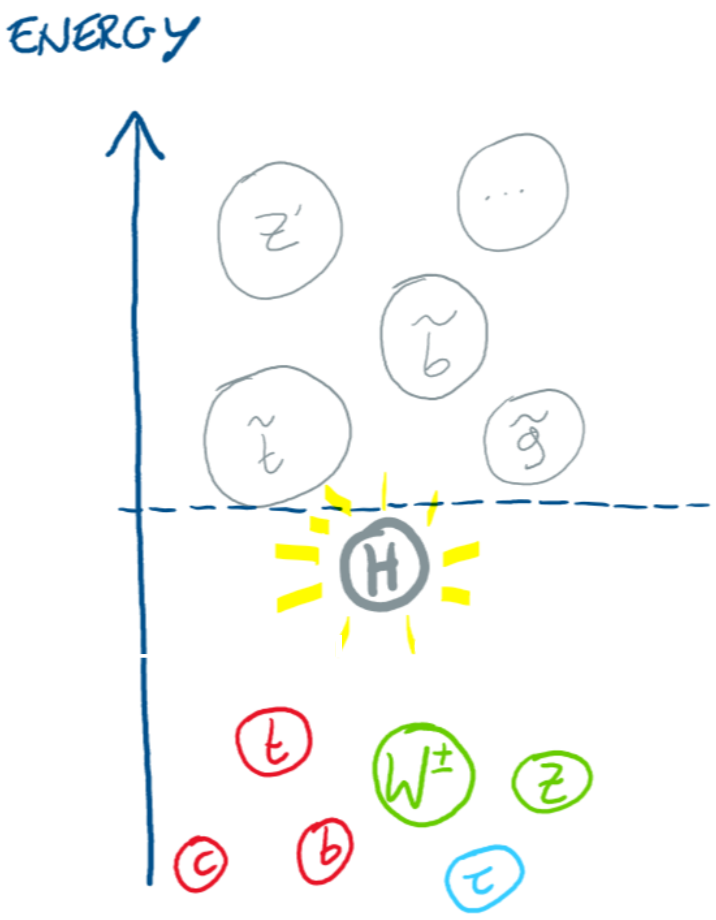

Why the Higgs boson?

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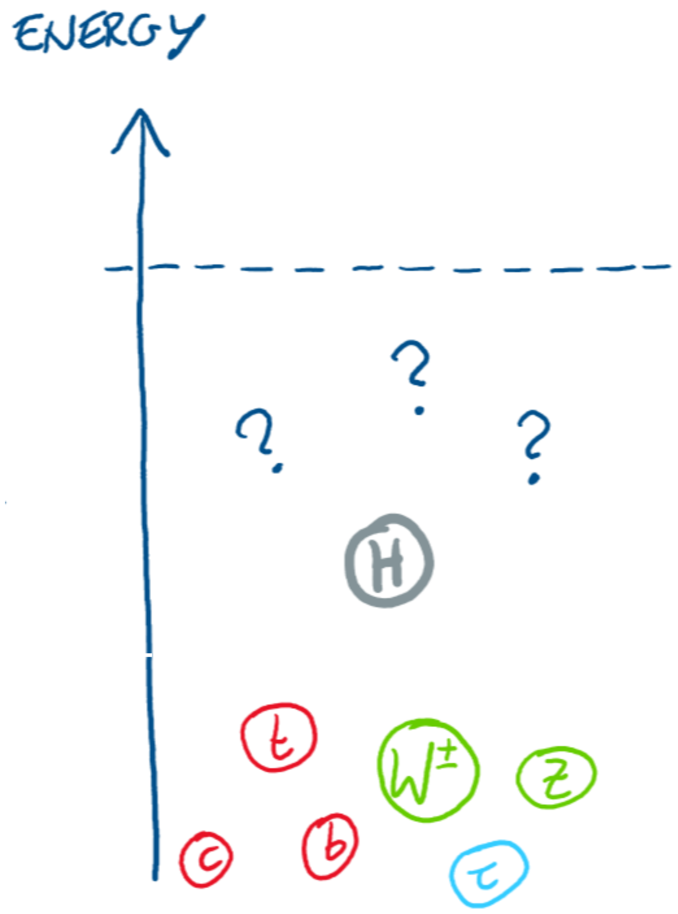

Conventional **symmetry-based** solutions *have not shown up*!

Why the Higgs boson?

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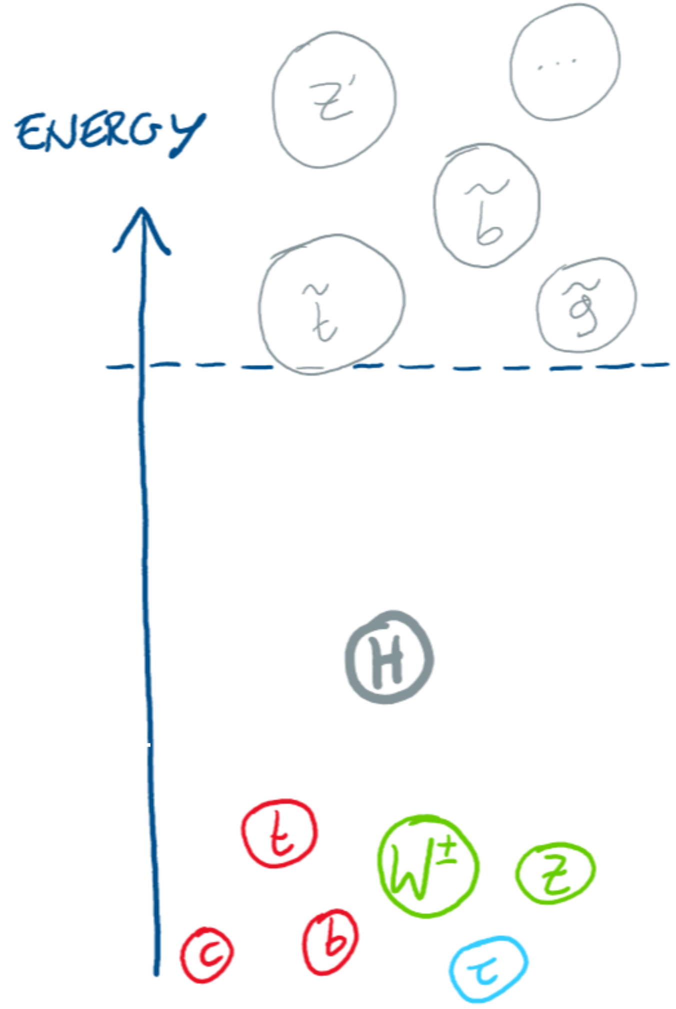
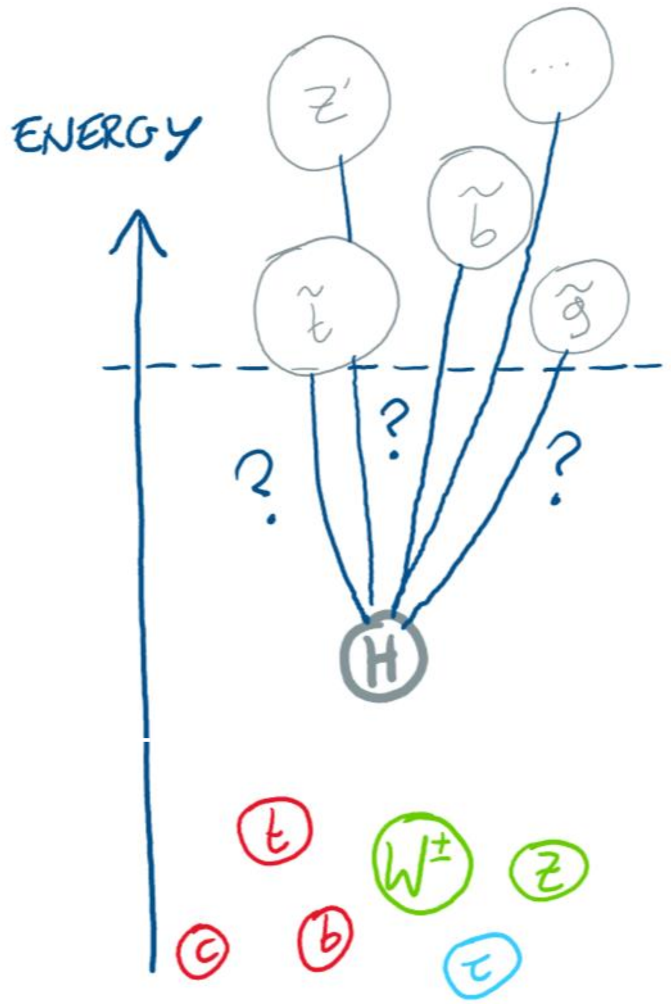


Maybe **just around the corner…**

Why the Higgs boson?

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



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

The Higgs boson's hierarchy problem is a **profound mystery**, that is **even more perplexing** in the absence of new physics at the LHC.

Our **Michelson-Morley moment?**

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: $m_{\pi^\pm}^2 - m_{\pi^0}^2 = \frac{3\alpha}{4\pi}\Lambda^2$

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

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??

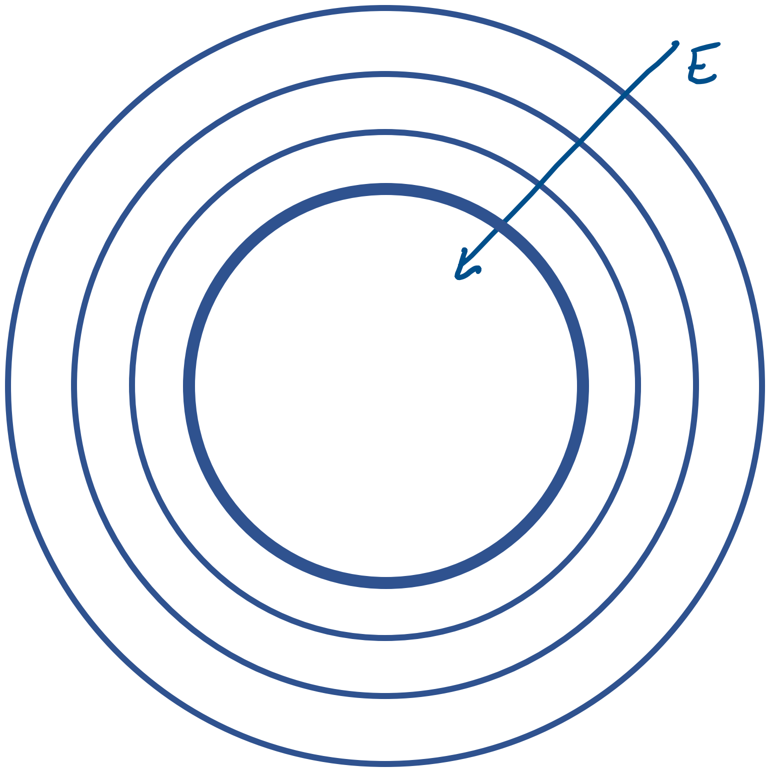
As Λ is pushed to the TeV scale by null results, tuning is around 10% - 1%.

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.

Naturalness is still a fundamental problem

- *Why is unnatural fine-tuning such a big deal?*

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



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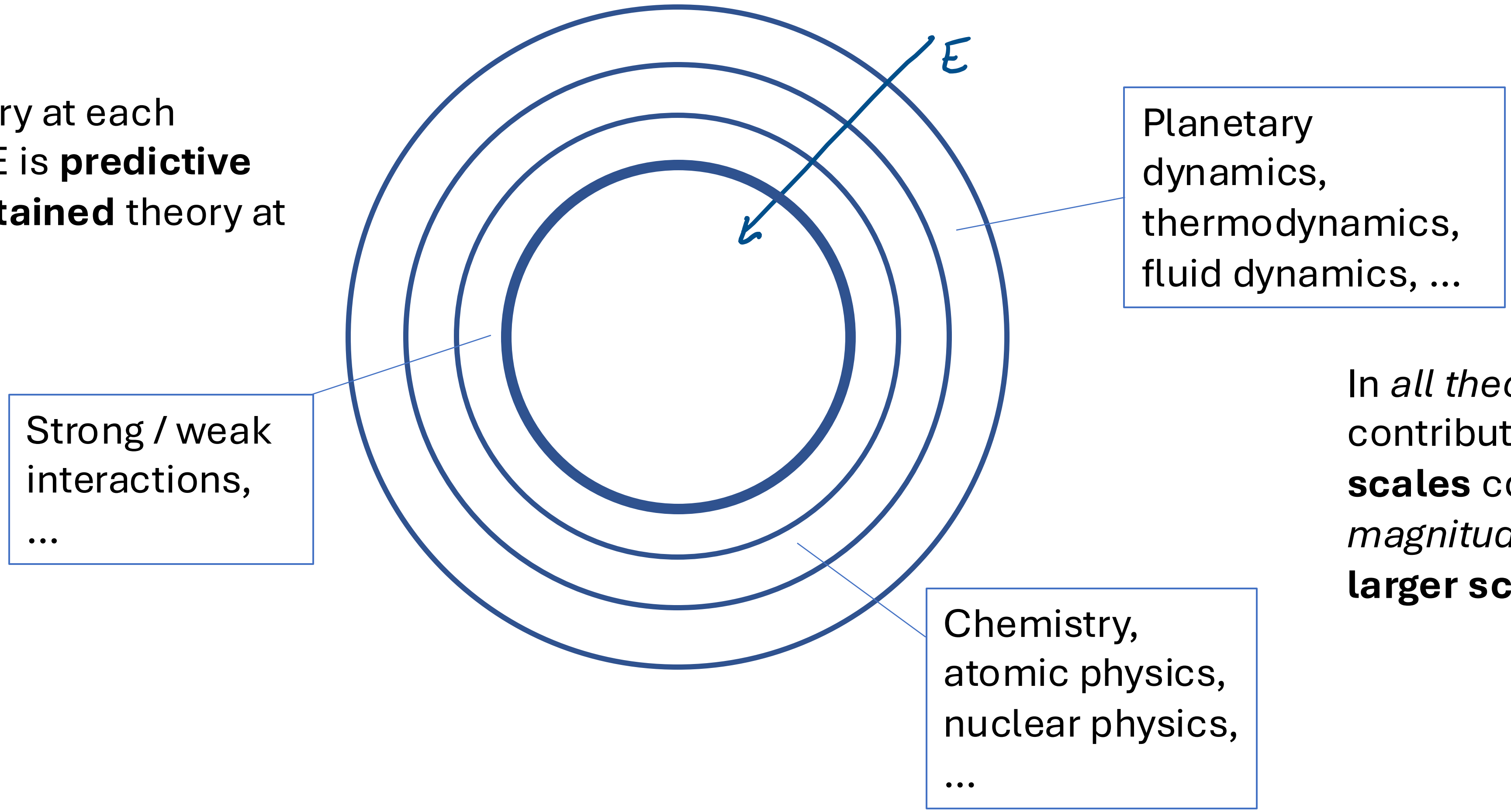

In *all theories so far*, no contributions from **smaller scales** compete *with similar magnitude* to effects **on larger scales**

Naturalness is still a fundamental problem

- *Why is unnatural fine-tuning such a big deal?*
- Indicates *an unprecedented breakdown* of the **effective theory** structure of nature

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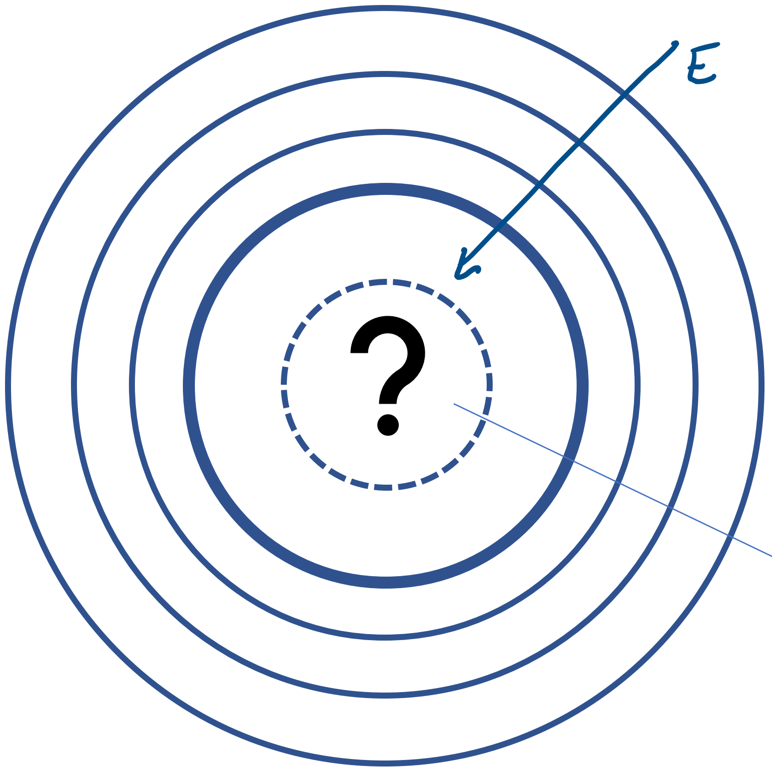

Unnatural Higgs means the next layer *is no longer predictive* without including contributions *from much smaller scales*

Naturalness is still a fundamental problem

- *Why is unnatural fine-tuning such a big deal?*
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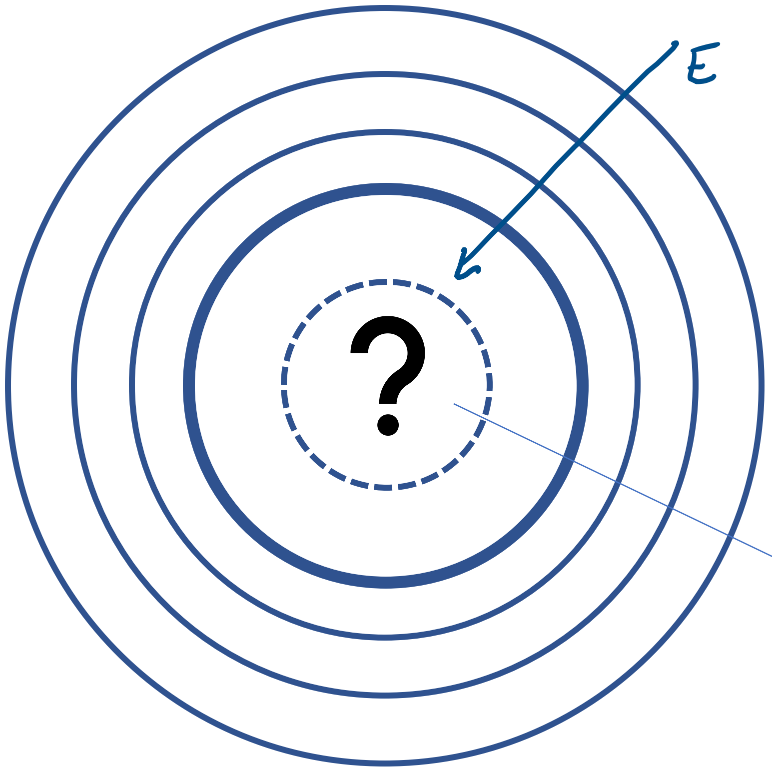


Unnatural Higgs means the next layer *is no longer predictive* without including contributions *from much smaller scales*

- Are we missing a **fundamentally new** *"post-naturalness"* principle? *(c.f. null results in search for aether)*

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:**

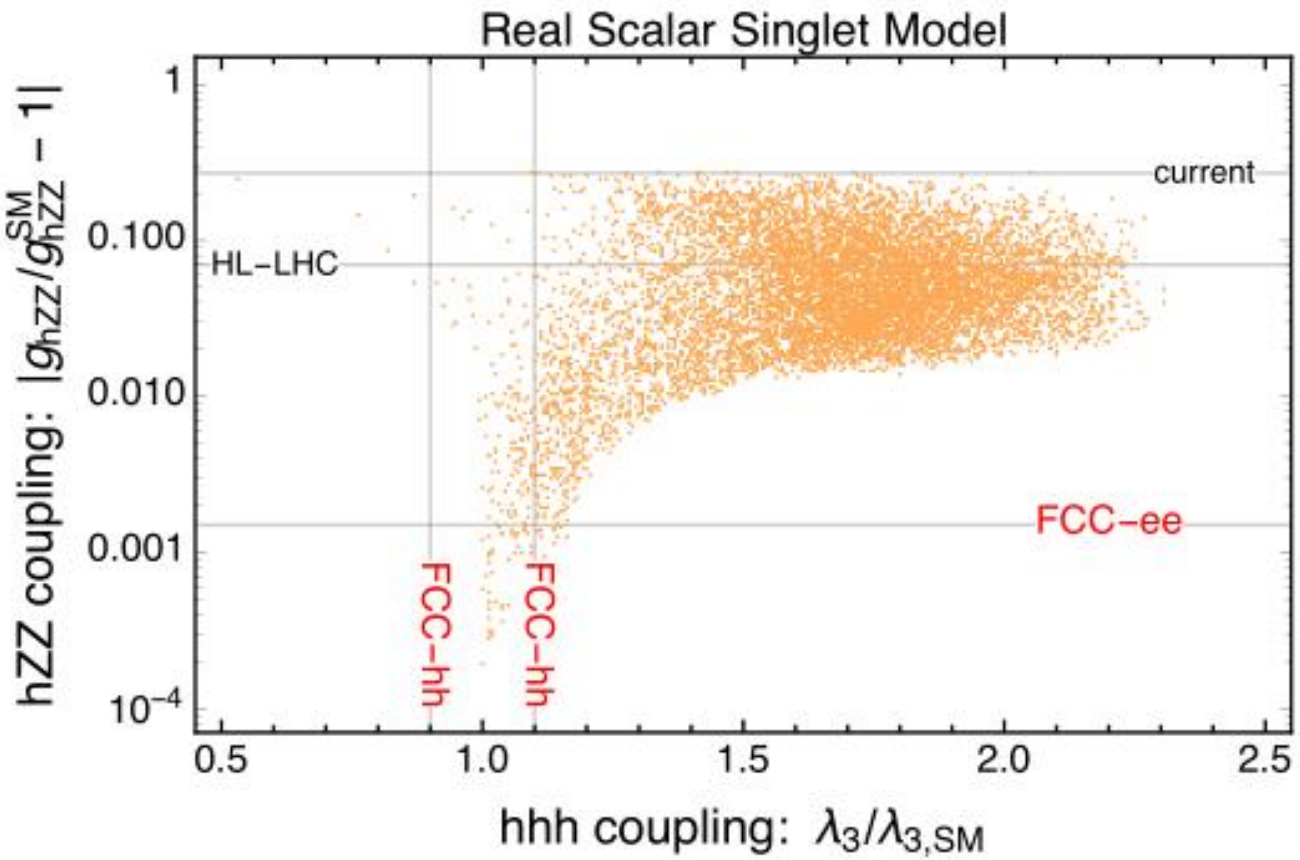
Experimental & observational evidence: dark matter, neutrino mass.

- **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 or second order?*



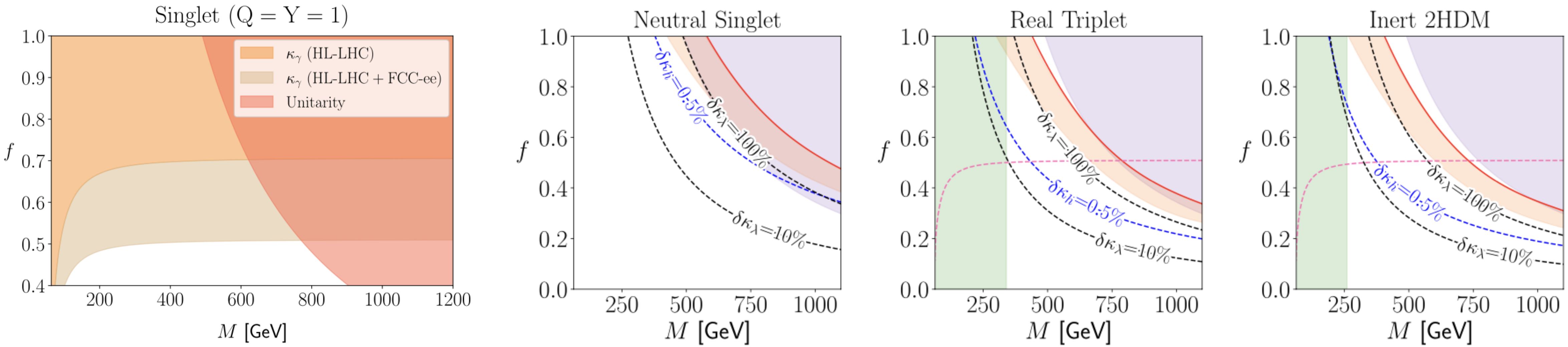
FCC CDR Vol. 1

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?

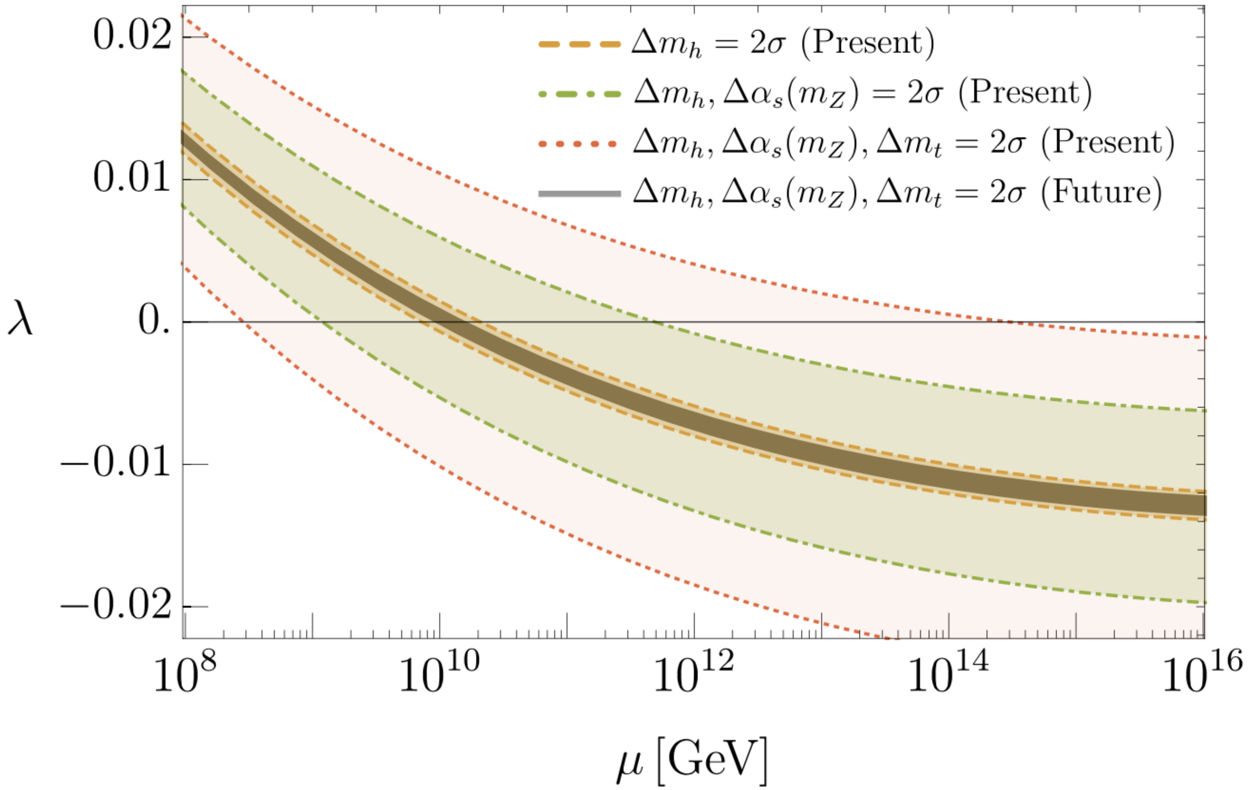
2110.02967 Banta, Cohen, Craig, Lu, Sutherland
2409.18177 Crawford, Sutherland



- 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?



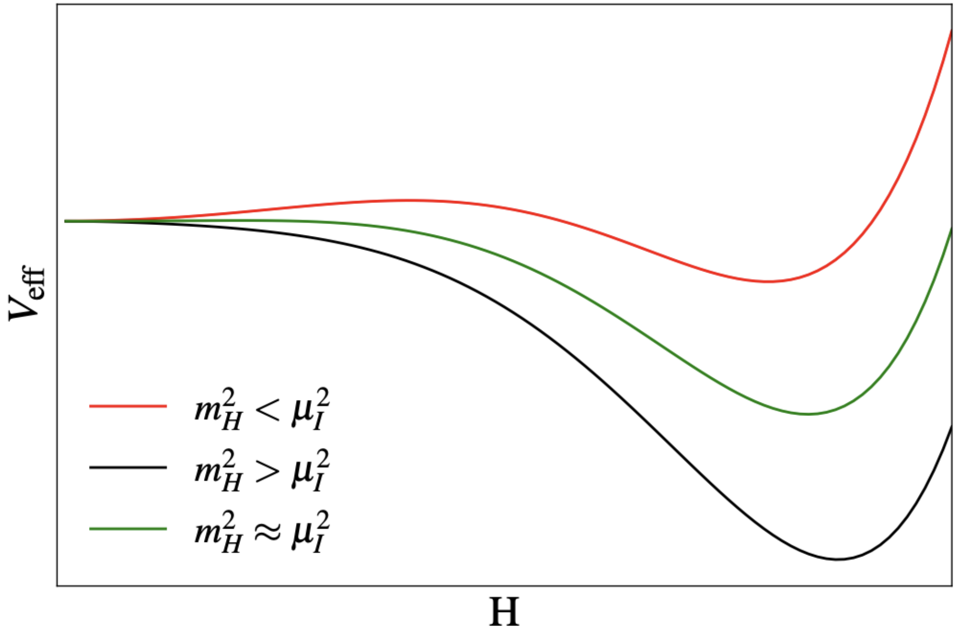
Snowmass 2021
Dunsky, Harigaya, Hall

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

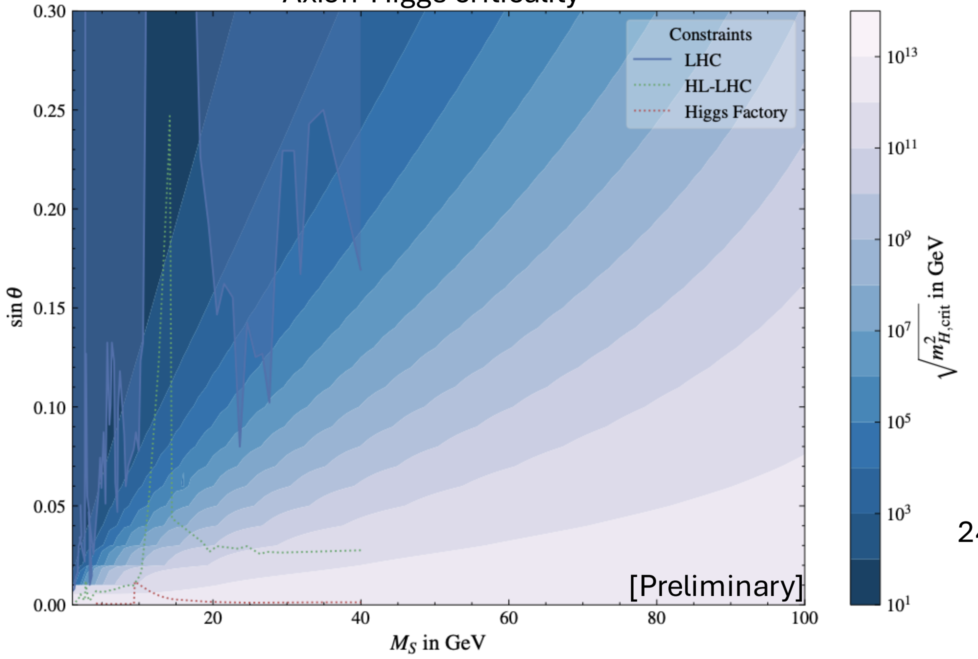
A Higgs factory can answer definitive questions

e.g. Is the Higgs mass set by **cosmological self-organised criticality**?

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



Axion-Higgs criticality



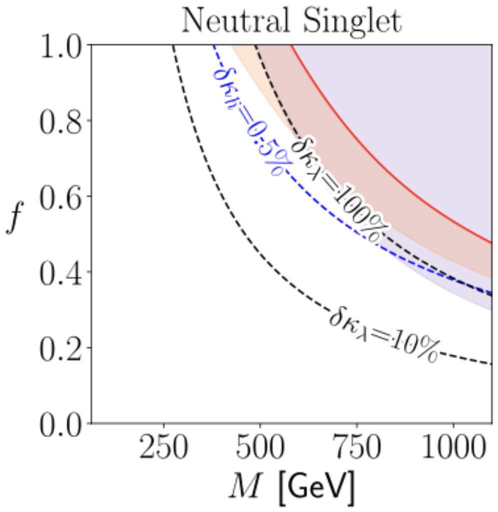
24xx.xxxx Detering, **TY**

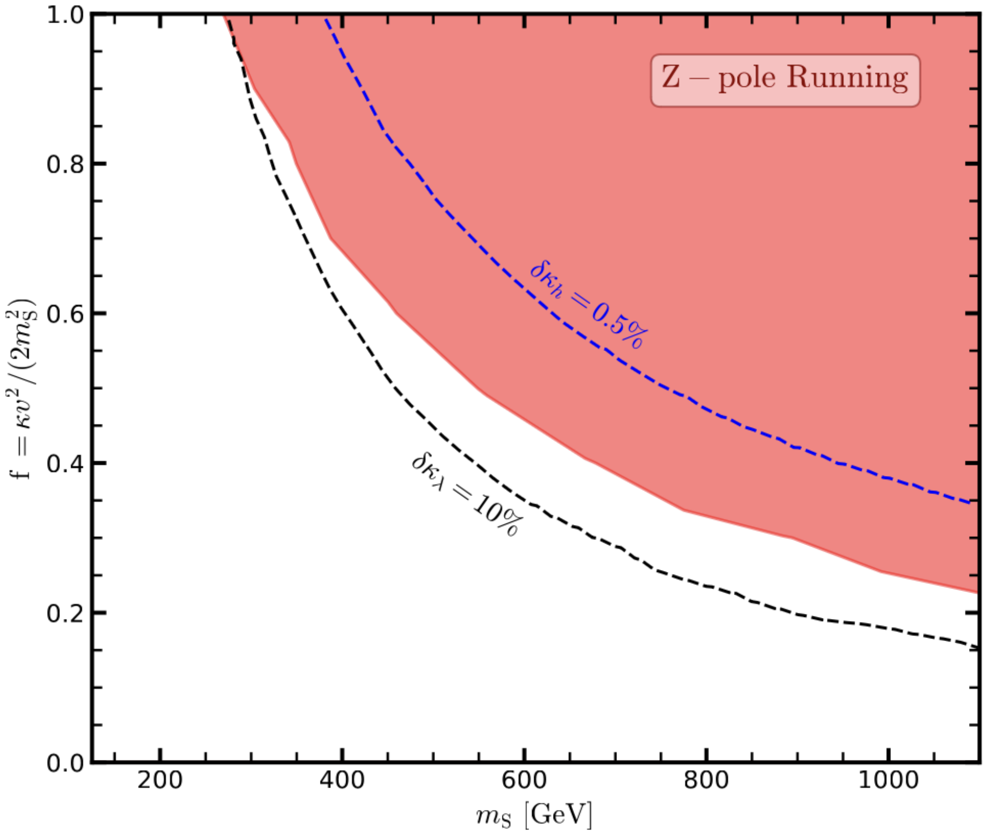
Vacuum instability scale sets Higgs mass upper bound, must be lowered by light BSM particles.

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

Why Tera-Z?

“Quantum totalitarian principle” at loop level **mixes in physics** not typically thought to be constrained at Z pole, **now accessible by ultra-high electroweak precision**.



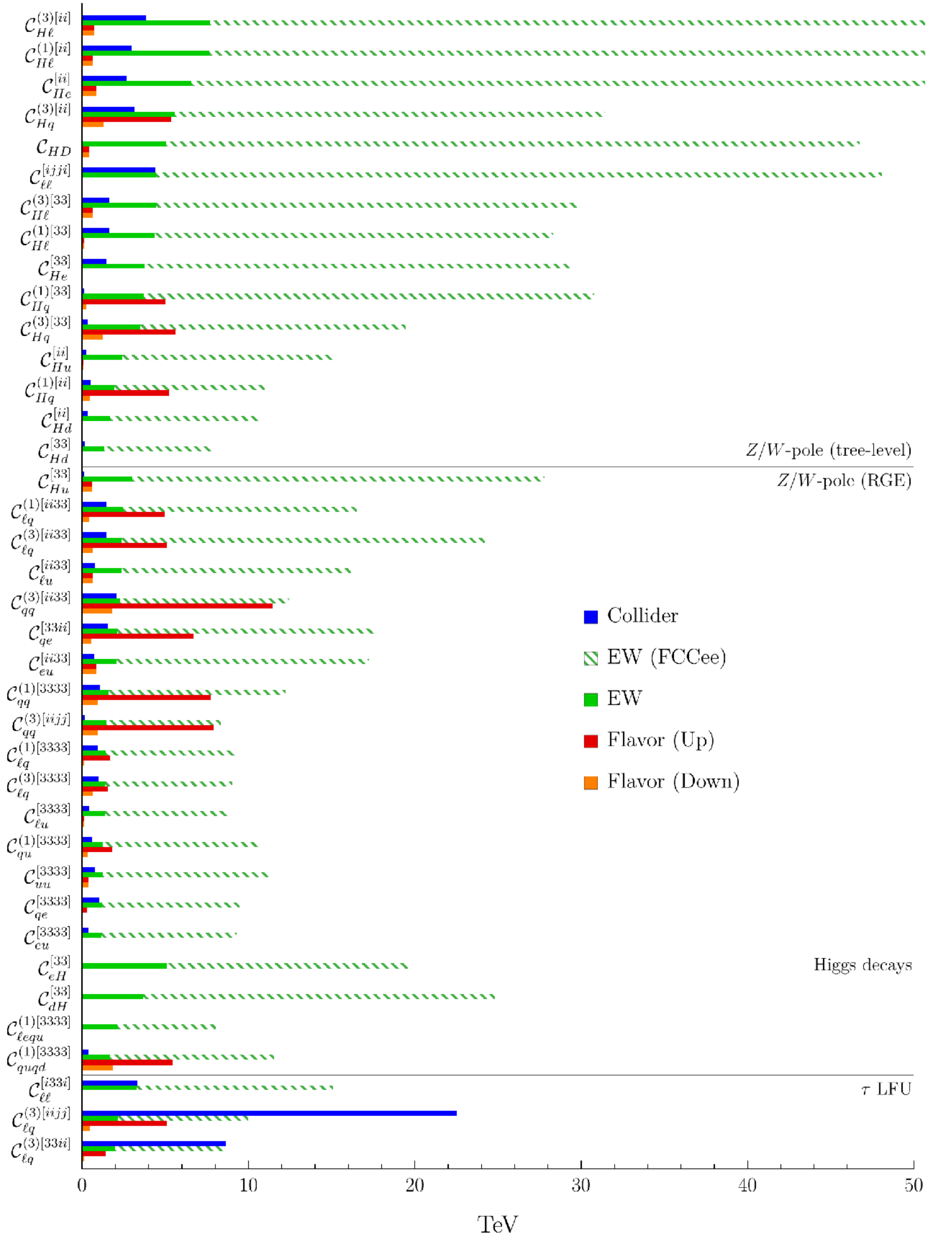


24xx.xxxx Maura, Stefanek, **TY**

e.g. Singlet scalar *even with custodial symmetry* can now be constrained by T parameter at Next-to-Leading Log.

Why Tera-Z?

2311.00020 Allwicher, Cornella, Isidori, Stefanek



Powerful indirect exploration of the multi-TeV scale @ Tera-Z.

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

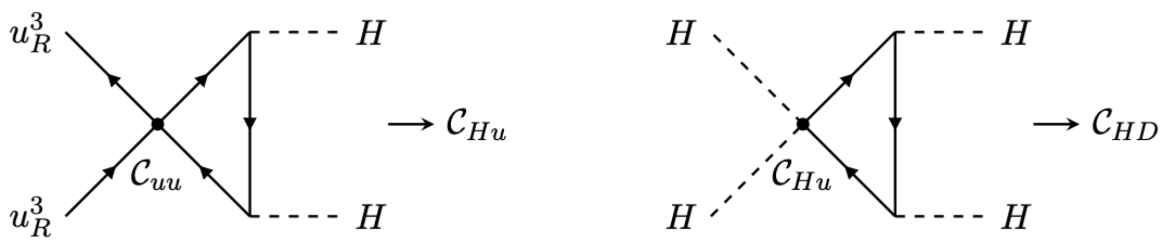


Figure 1. Next-to-leading log running of four-quark operators into $\mathcal{C}_{HD}$.

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

See also 2407.09593 Stefanek

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* 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	$(1,1)_0$	$(1,1)_1$	$(1,3)_0$	$(1,3)_1$	$(8,1)_0$	$(8,1)_1$	$(8,3)_0$	$(1,2)_{\frac{1}{2}}$

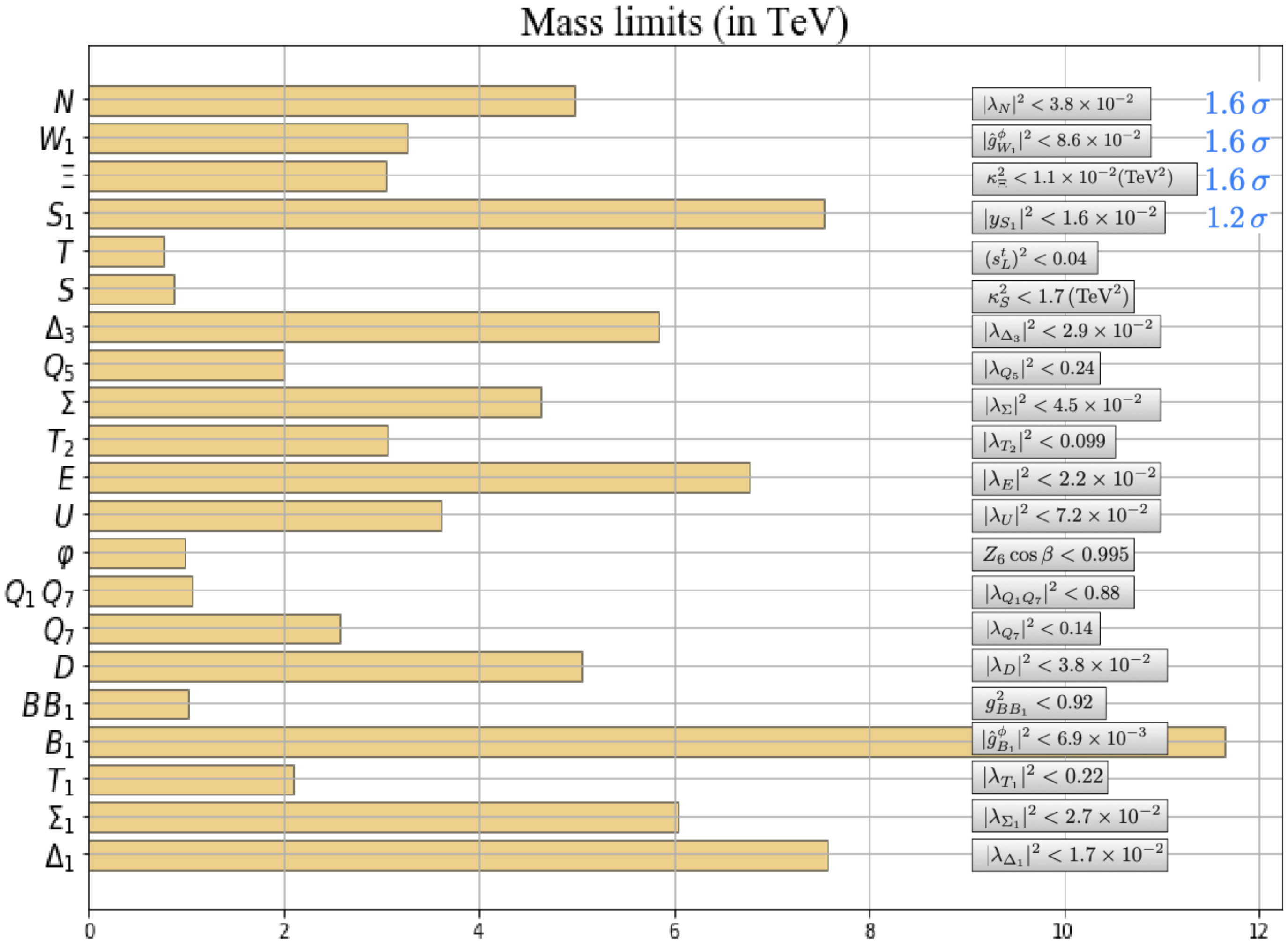
Name	$\mathcal{L}_3$	$\mathcal{U}_2$	$\mathcal{U}_5$	$\mathcal{Q}_1$	$\mathcal{Q}_5$	$\mathcal{X}$	$\mathcal{Y}_1$	$\mathcal{Y}_5$
Irrep	$(1,2)_{-\frac{3}{2}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,3)_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$

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			$-\frac{1}{2}\frac{M_T^2}{v^2}$	$\frac{1}{2}\frac{M_T^2}{v^2}$			$y_t\frac{M_T^2}{v^2}$		



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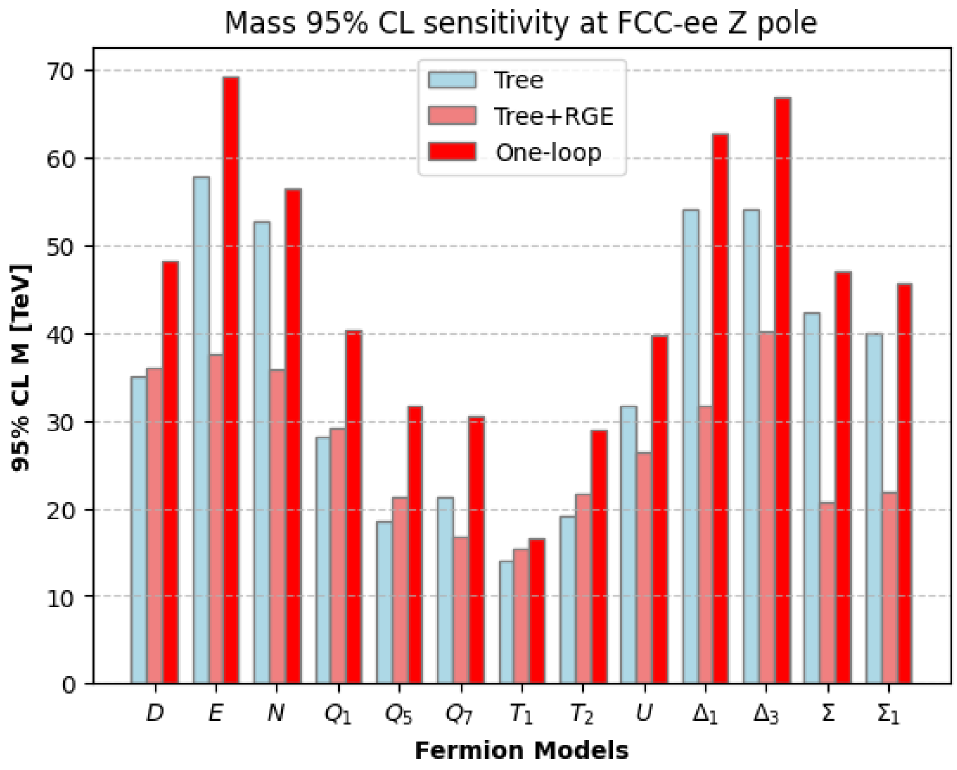
Linear SM extensions at Tera-Z

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

24xx.xxxx 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_{uQ}	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:



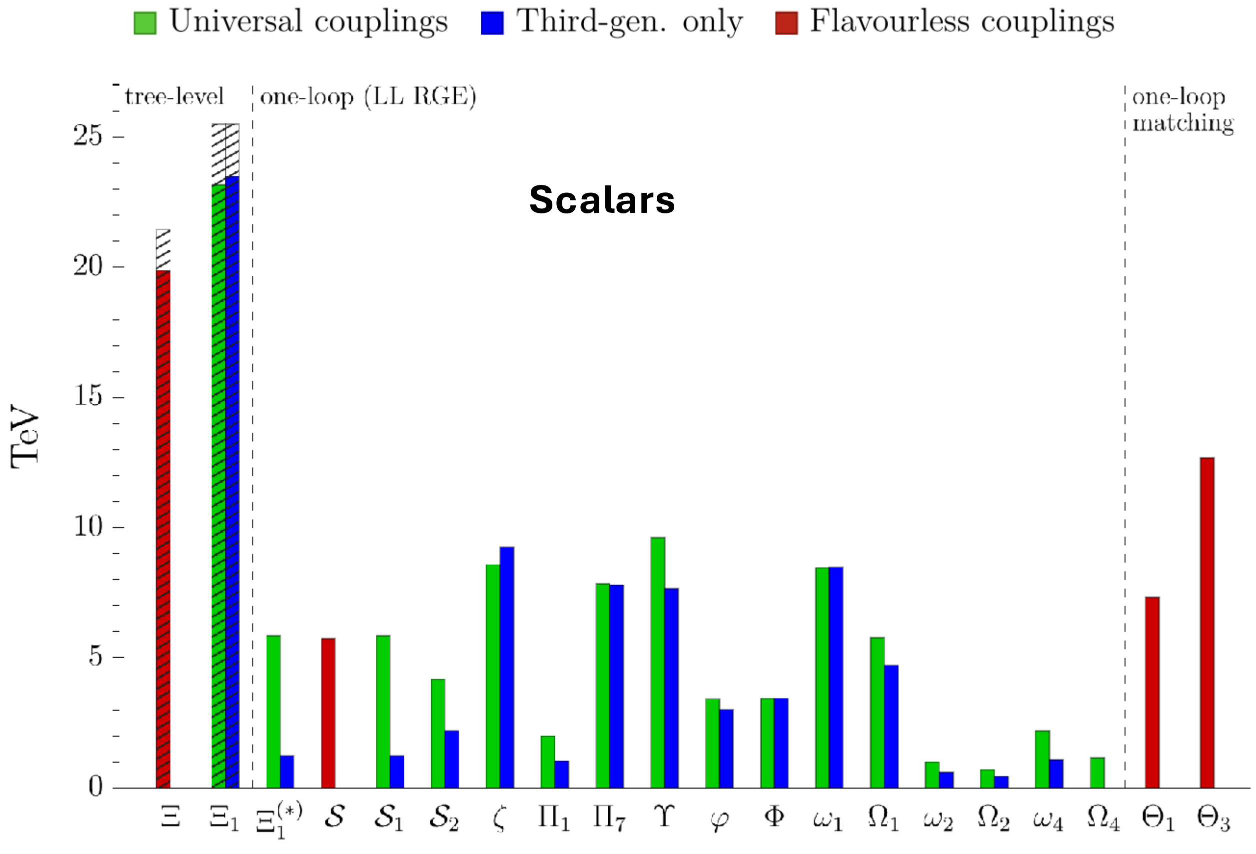
(Preliminary)

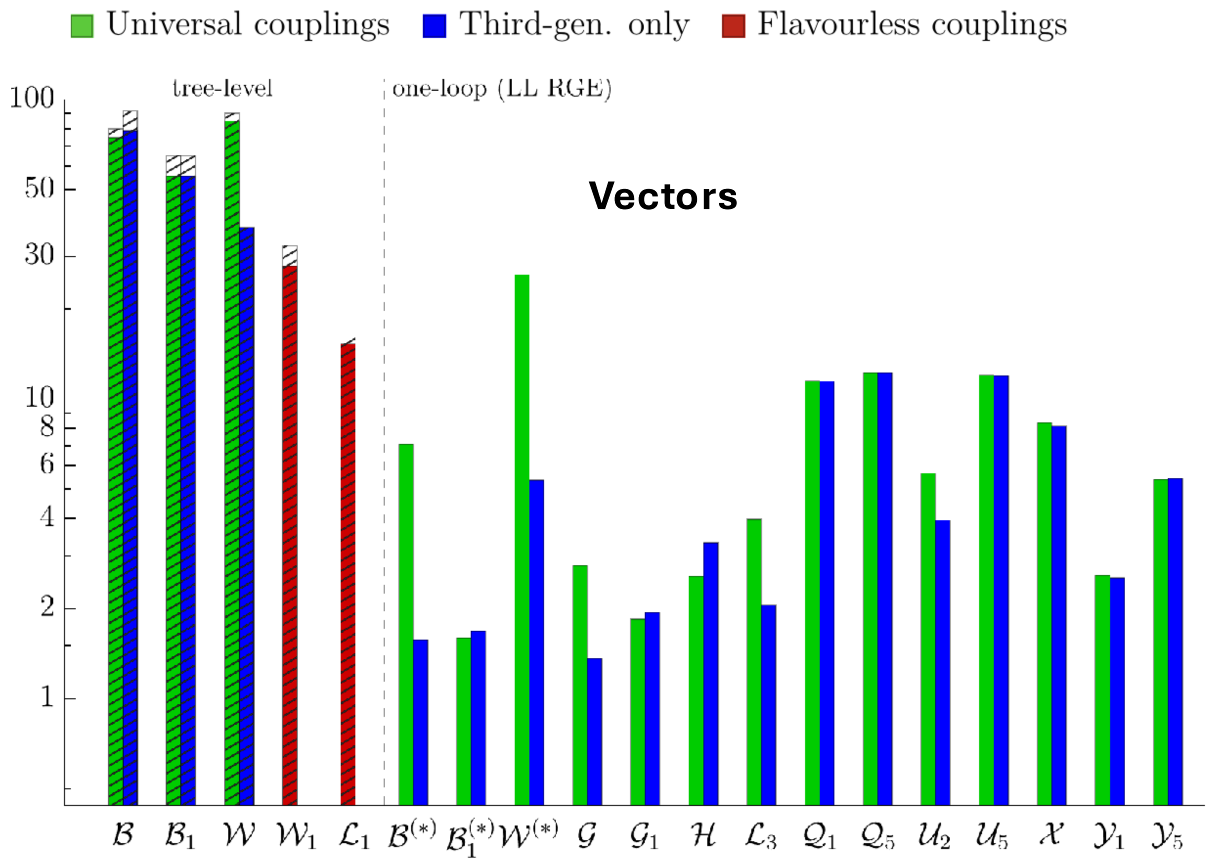
Linear SM extensions at Tera-Z

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"

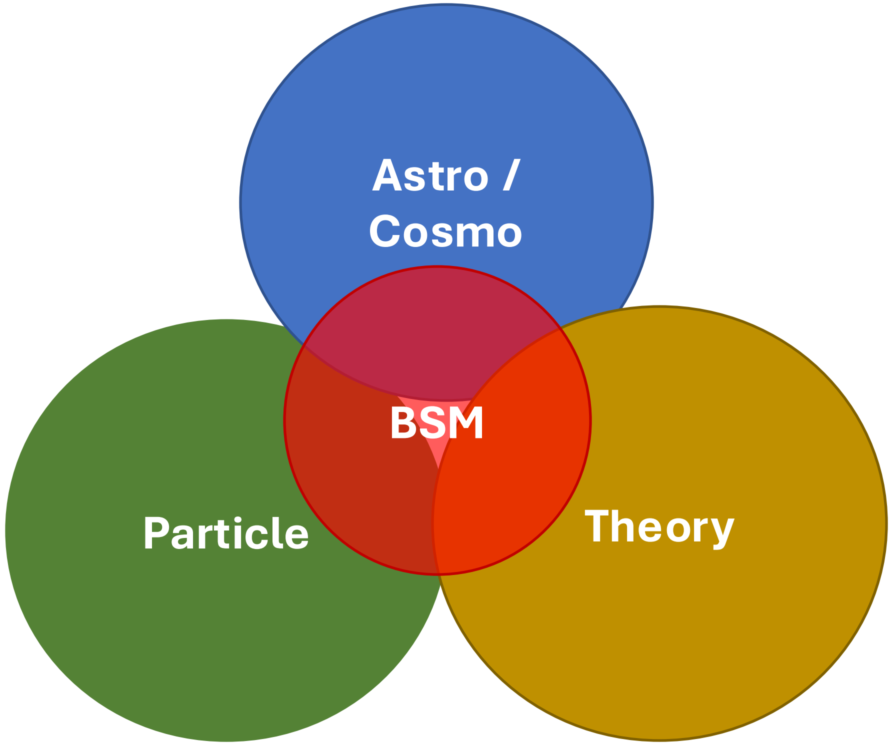
2408.03992 Allwicher, McCullough, Renner





Why Colliders?

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

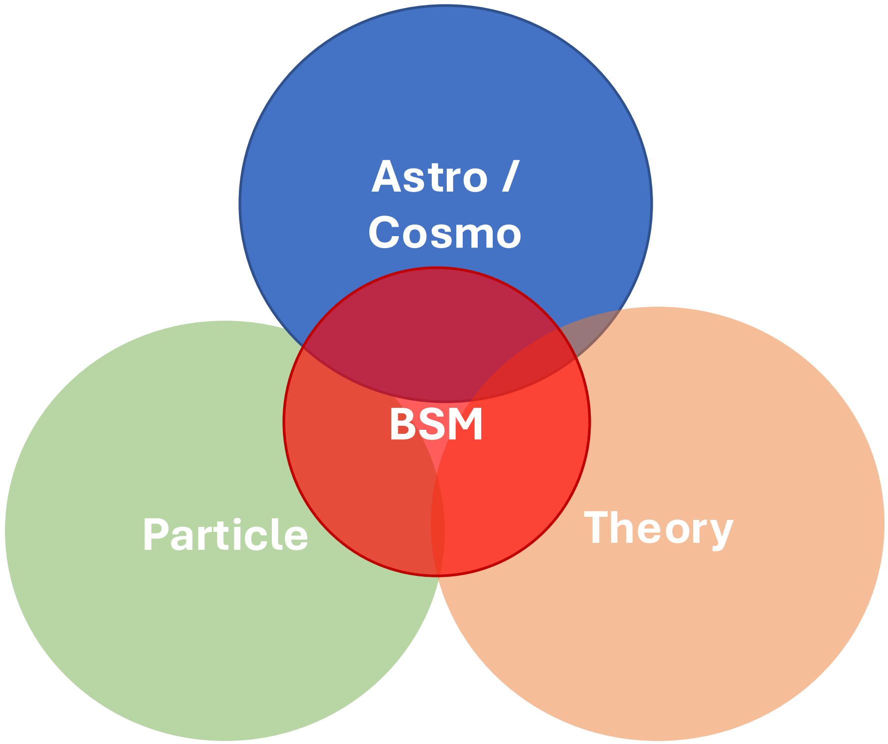


BSM combines our **experimental**, **observational**, and **theoretical** knowledge of the Universe.

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

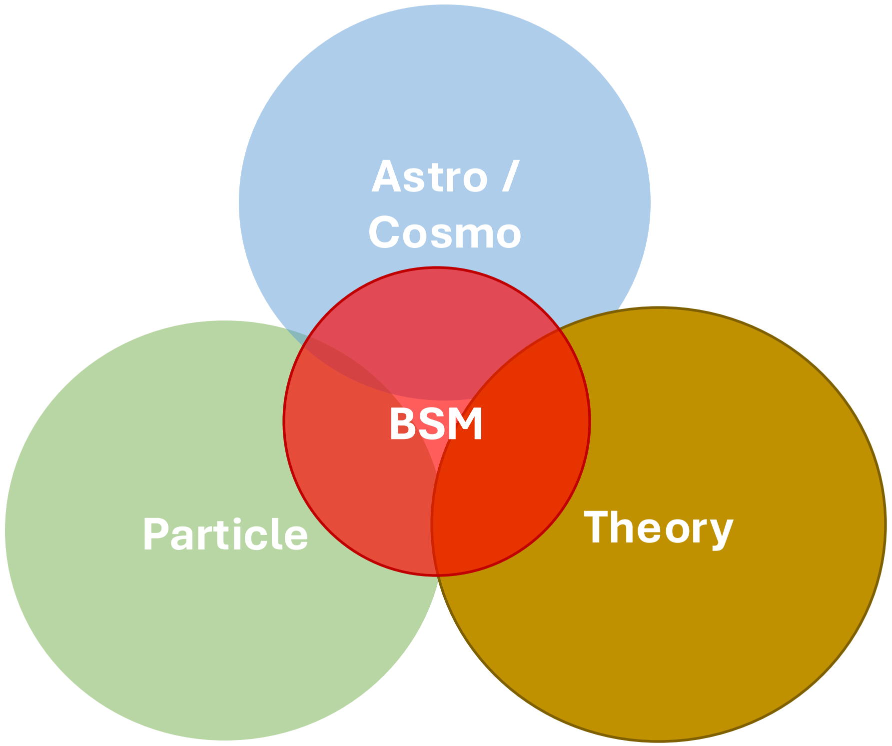
Why Colliders?

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



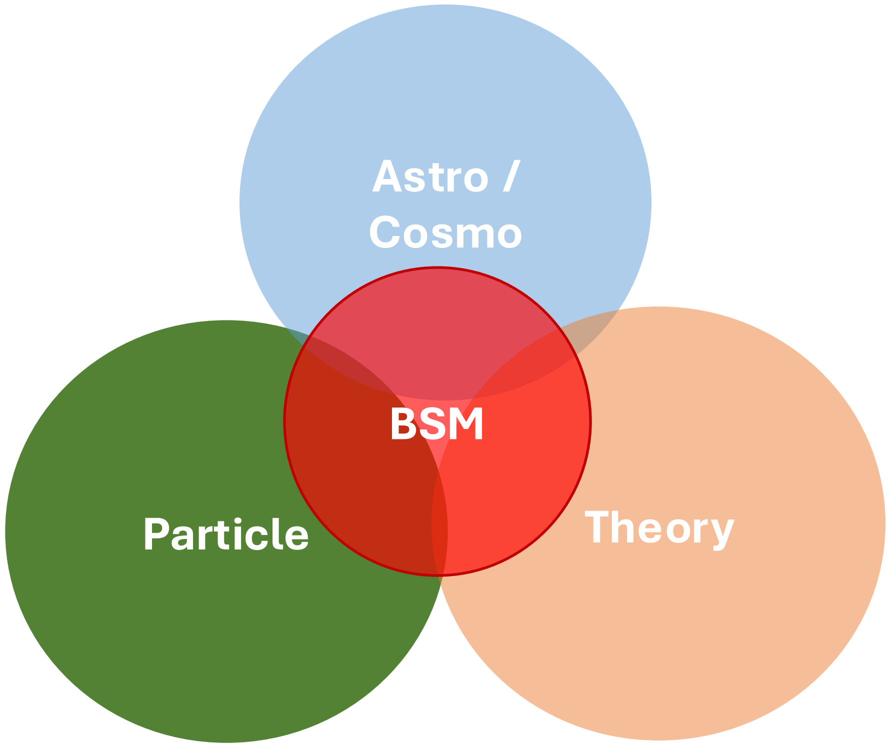
Why Colliders?

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.

Radically new BSM?

Energy

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

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

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

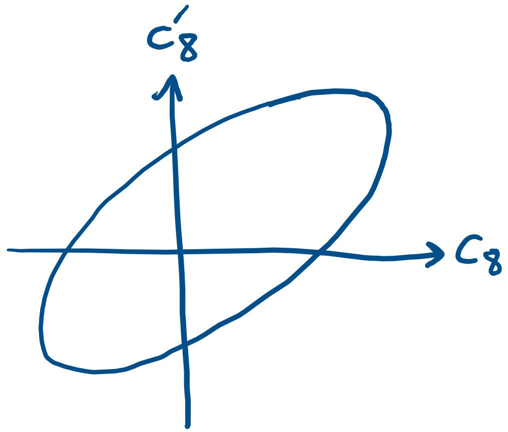
Indirect exploration by **e+e-**

Radically new BSM?

Energy

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

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



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

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

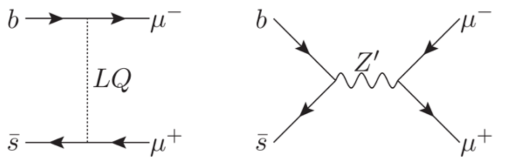
Indirect exploration by **e+e-** collider

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.

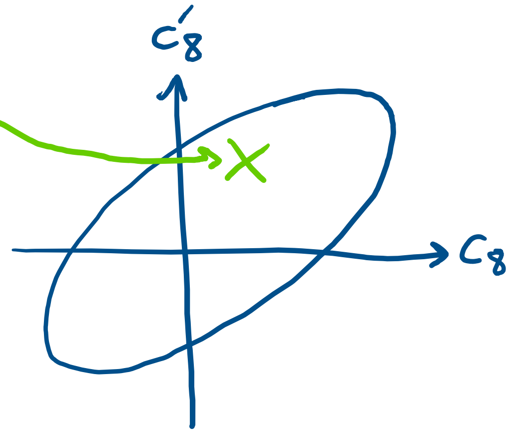
Radically new BSM?

Energy

Λ $\qquad \mathcal{L}_{UV} = ?$



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



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

$E < \Lambda$

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

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

Tevong You

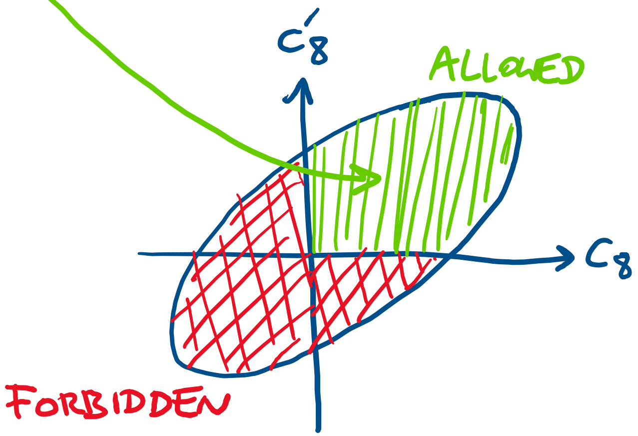
Radically new BSM?

Energy

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

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

Unitarity	Locality	Causality	...



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

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

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

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

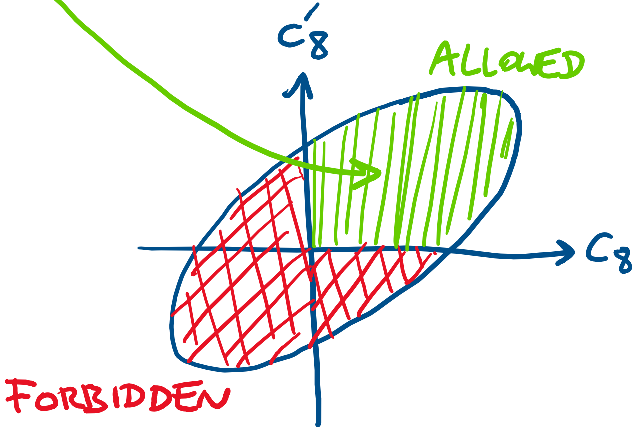
Radically new BSM?

Energy

May not even have a Lagrangian/QFT description

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

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



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

$E < \Lambda$

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

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

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

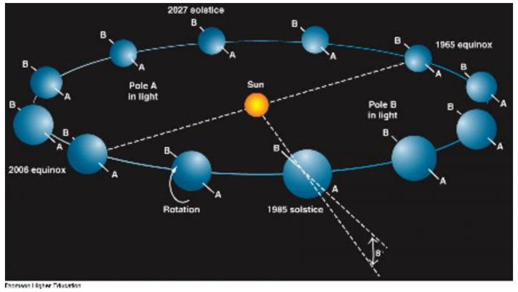
Could potentially be related to hierarchy problem

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

Radically new BSM?

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

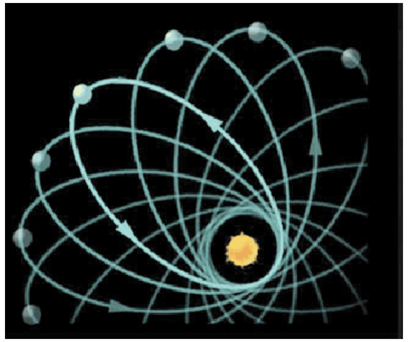
Anomaly in orbit of Uranus

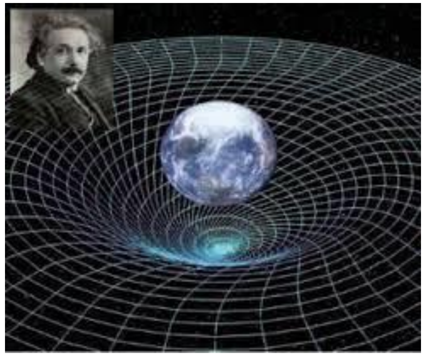


Discovery of Neptune

Other times its implications are *far more radical*:

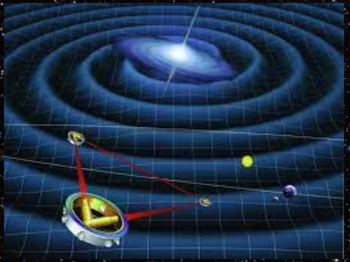
Anomaly in orbit of Mercury

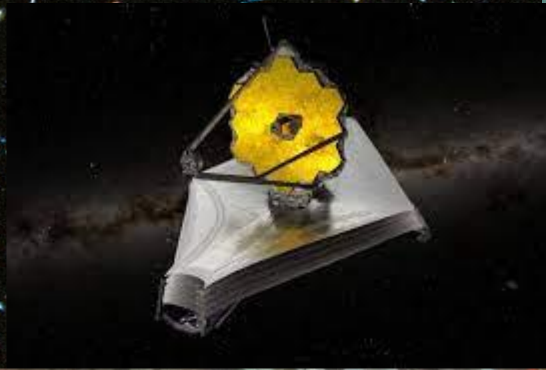




Explained by General Relativity

Concluding Remarks

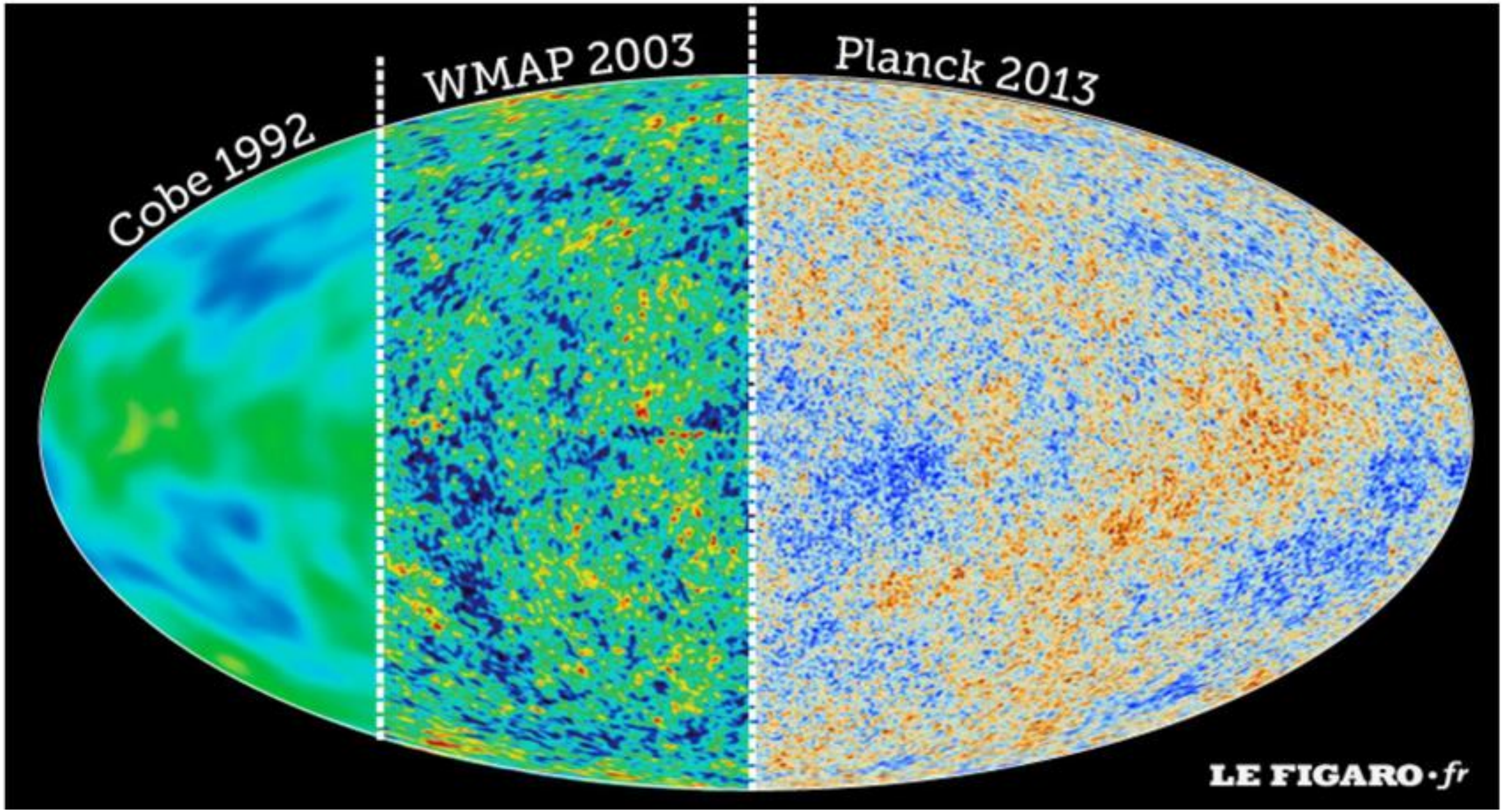




- Telescopes are **space observatories** for exploring *outer space*
- Colliders are *experimental* **particle observatories** for exploring *inner space*
- We need **all eyes open on all scales** in our universe to make progress

Concluding Remarks

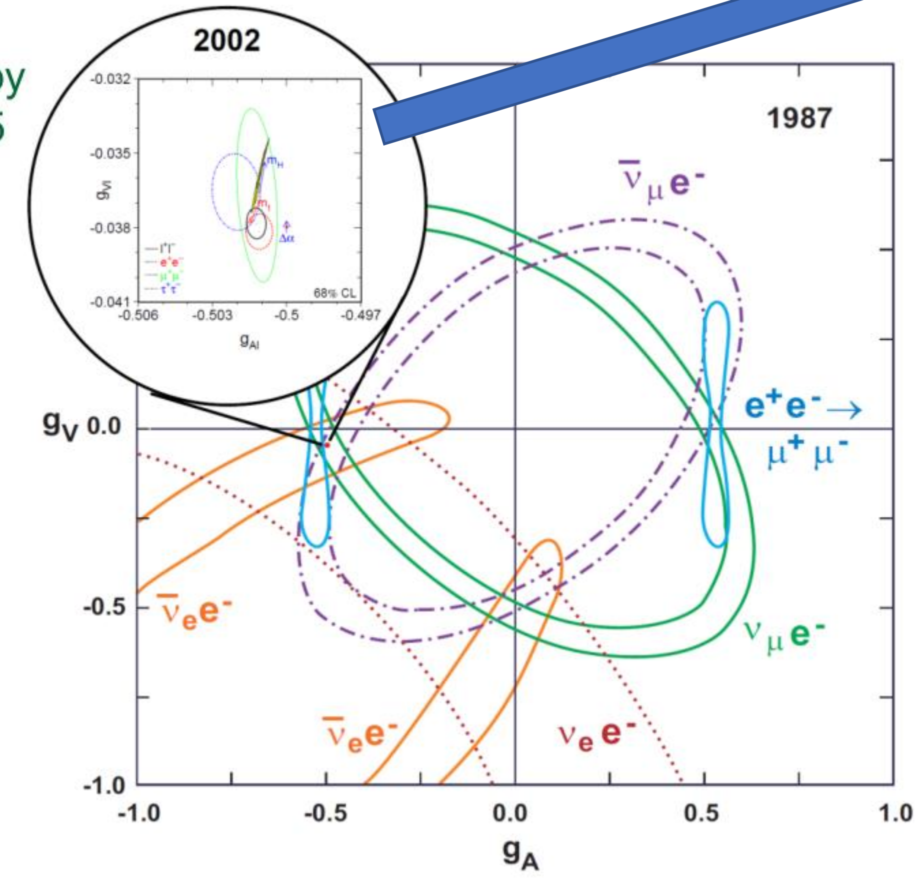
Sharpen our picture of the Universe, *e.g. before and after Planck*.

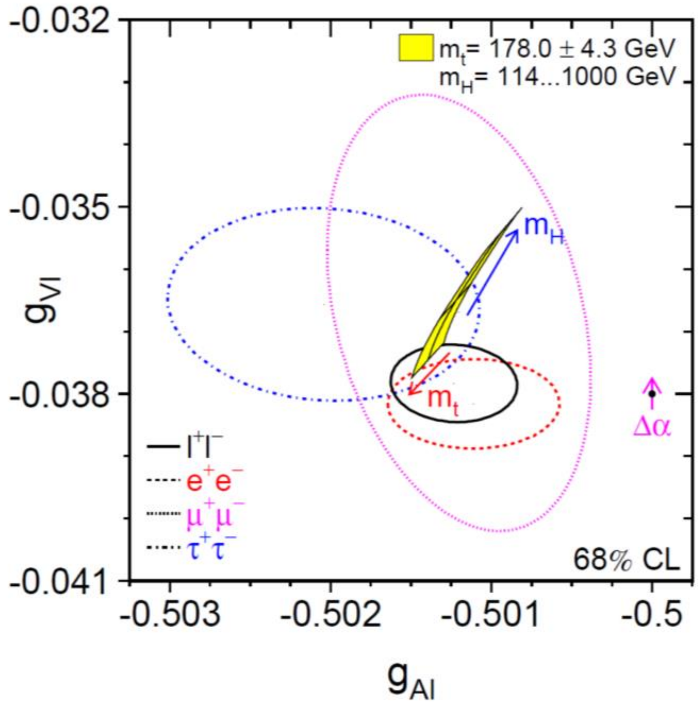


Concluding Remarks

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

magnified by
a factor 65

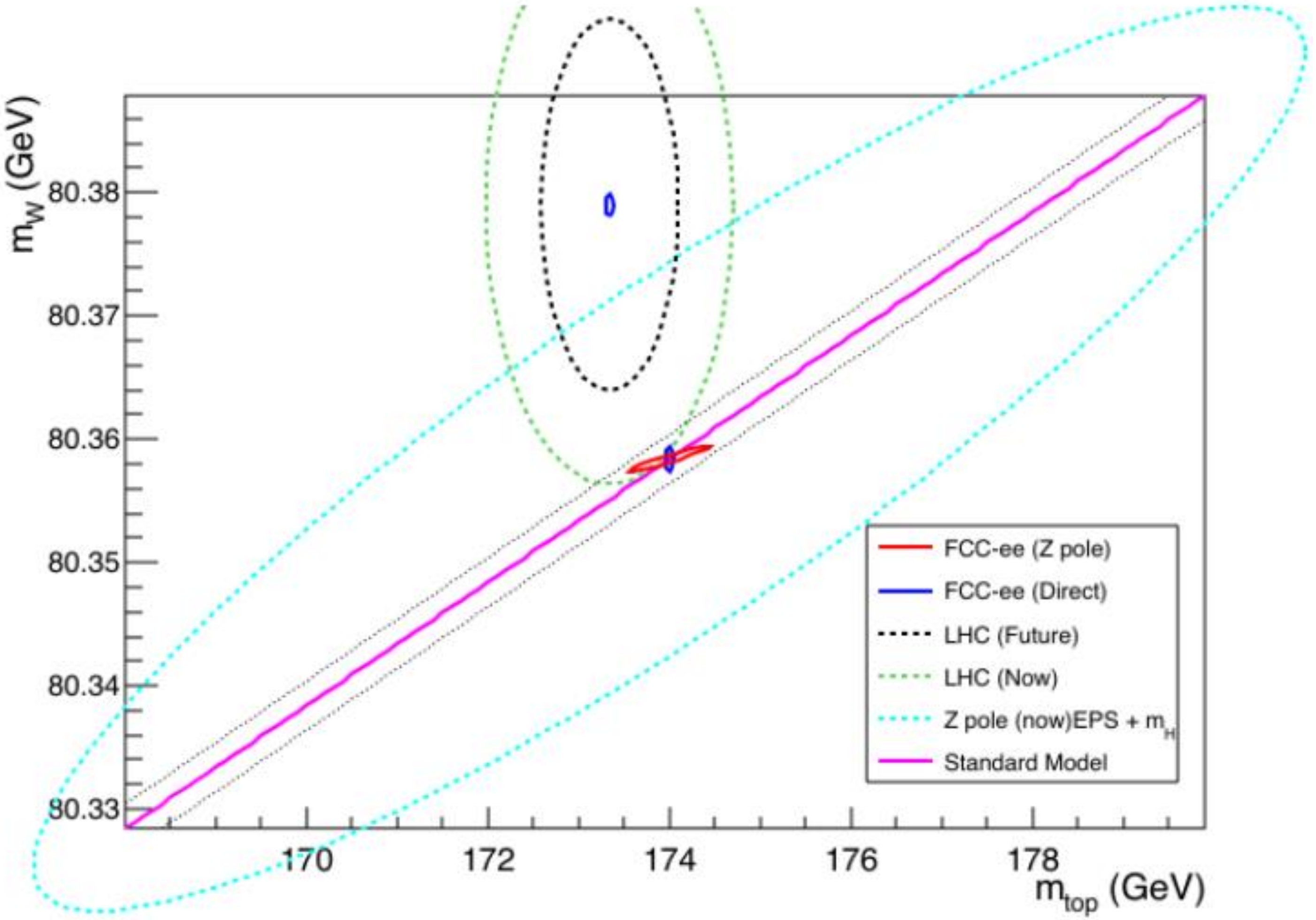




Guy Wilkinson slide

Concluding Remarks

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



Concluding Remarks

Indirect precision measurements are of fundamental importance, complementary to direct searches.

Indirect evidence preceded direct discovery for nearly all SM particles – **same may be true of BSM**.

However, there are **no guarantees** of BSM discovery at future colliders; there are no guarantees of BSM discovery *anywhere else* either.

What we can guarantee is a **rich and wide-ranging programme** of fundamental physics that will significantly advance our understanding of the Universe.

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

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** and of **exploring the unknown**.

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