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

Tevong You
1) Why the Higgs boson?

2) Why Tera-Z?

3) Why colliders?
Naturalness

Take fine-tuning problems seriously.

Example 1

\[(m_e c^2)_{\text{obs}} = (m_e c^2)_{\text{bare}} + \Delta E_{\text{Coulomb}}, \quad \Delta E_{\text{Coulomb}} = \frac{e^2}{4\pi \varepsilon_0 r_e}.\]

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

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Example 2

Divergence in pion mass: 

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

Experimental value is \( m_{\pi^\pm}^2 - m_{\pi^0}^2 \sim (35.5 \text{ MeV})^2 \)

Expect new physics at \( \Lambda \sim 850 \text{ MeV} \) to avoid fine-tuned cancellation.

\( \rho \) meson appears at 775 MeV!
Naturalness

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Example 3

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

\[ m_{K_L^0} - m_{K_S^0} \approx \frac{1}{16\pi^2} m_K f_K^2 G_F^2 \sin^2 \theta_C \cos^2 \theta_C \times \Lambda^2. \]

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

Gaillard & Lee in 1974 predicted the charm quark mass!
Naturalness

Take fine-tuning problems seriously.

**Higgs?**

Higgs also has a quadratically divergent contribution to its mass

\[ \Delta m_H^2 = \frac{\Lambda^2}{16\pi^2} \left( -6y_t^2 + \frac{9}{4} g_2^2 + \frac{3}{4} g_2' + 6\lambda \right) \]

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

As \( \Lambda \) 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.

e.g. 2205.05708 N. Craig - Snowmass review, 1307.7879 G. Giudice - Naturalness after LHC
Why is unnatural fine-tuning such a big deal? An intuitive picture:

Everything does not depend on everything else equally.

(Otherwise, we would need a Theory of Everything to calculate anything)
Naturalness is still a fundamental problem

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

Effective theory at each energy scale $E$ is **predictive** as a **self-contained** theory at that scale.
Naturalness is still a fundamental problem

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

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

- Planetary dynamics, thermodynamics, fluid dynamics, ...
- Chemistry, atomic physics, nuclear physics, ...
- Strong / weak interactions, ...

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? An intuitive picture:
- Indicates an unprecedented breakdown of the effective theory structure of nature

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

**Unnatural Higgs** means the next layer is no longer predictive without including contributions from much smaller scales.
Naturalness is still a fundamental problem

1. Why is unnatural fine-tuning such a big deal? An intuitive picture:
2. Indicates an unprecedented breakdown of the effective theory structure of nature

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

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.*
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Higgs mass, cosmological constant indicate we don’t understand physics within the regime of our current effective theories!
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- **Incomplete:**

  *Experimental & observational evidence*: dark matter, neutrino mass.

- **Inconsistent:**

  *Theoretical evidence*: quantum gravity, black hole information paradox.
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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**.

Higgs mass, cosmological constant and black hole information paradox indicate we don’t understand physics **within the regime of our current effective theories**!
A Higgs factory can answer definitive questions

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

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?

- 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?

Uncertainty can be reduced from $O(10^6)$ down to a factor of $\sim 2$! Potential implications for BSM.
A Higgs factory can answer definitive questions

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

**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?

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

Rough NLO/LO improvement factor:

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

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

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

2412.14241 Maura, Stefanek, TY

4f operator projections from 2411.02485 Greijo, Tiblom, Valenti
Why Tera-Z?

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 $C_{HD}$.

**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 |  |  |  |  |  |  |  |  |
|---------|---|---|---|---|---|---|---|---|
| Irrep   | S | S₁ | S₂ | φ | Ξ | Ξ₁ | Θ₁ | Θ₁ |
| (1, 1)₀ | (1, 1)₁ | (1, 1)₂ | (1, 2)⁻¹₂ | (1, 3)₀ | (1, 3)₁ | (1, 4)⁻¹₂ | (1, 4)₁ |
| Name    |  |  |  |  |  |  |  |  |
| ω₁      |  |  |  |  |  |  |  |  |
| Irrep   | (3, 1)⁻¹₂ | (3, 1)₁₂ | (3, 1)⁻¹₂ | (3, 2)₀ | (3, 2)⁻¹₂ | (3, 3)₁₂ | (3, 3)⁻¹₂ |

| Scalars |  |  |  |  |  |  |  |  |
|---------|---|---|---|---|---|---|---|---|
| Irrep   | Ω₁ | Ω₂ | Ω₄ | Ψ | Φ |  |  |  |
| (6, 1)⁻¹₂ | (6, 1)₁₂ | (6, 1)⁻¹₂ | (6, 3)₀ | (8, 2)⁻¹₂ |

| Fermions |  |  |  |  |  |  |  |  |
|----------|---|---|---|---|---|---|---|---|
| Name     | N | E | Δ₁ | Δ₃ | Σ | Σ₁ |
| Irrep    | (1, 1)₀ | (1, 1)₁⁻ | (1, 2)⁻¹₂ | (1, 2)⁻¹₂ | (1, 3)₀ | (1, 3)₁⁻ |
| Name     |  |  |  |  |  |  |  |  |
| U        |  |  |  |  |  |  |  |  |
| Irrep    | (3, 1)⁻¹₂ | (3, 1)₁⁻ | (3, 2)₀ | (3, 2)⁻¹₂ | (3, 3)₀ | (3, 3)⁻¹₂ |

| Vectors |  |  |  |  |  |  |  |  |
|---------|---|---|---|---|---|---|---|---|
| Name    | B | B₁ | W | W₁ | G | G₁ | H | L₁ |
| Irrep   | (1, 1)₀ | (1, 1)₁⁻ | (1, 3)₀ | (1, 3)₁⁻ | (8, 1)₀ | (8, 1)₁⁻ | (8, 3)₀ | (1, 2)⁻¹₂ |
| Name    |  |  |  |  |  |  |  |  |
| L₃      |  |  |  |  |  |  |  |  |
| Irrep   | (1, 2)⁻¹₂ | (3, 1)⁻¹₂ | (3, 1)₁⁻ | (3, 2)₀ | (3, 2)⁻¹₂ | (3, 3)₀ | (3, 3)⁻¹₂ | (6, 2)⁻¹₂ | (6, 2)⁻¹₂ |
Linear SM extensions at Tera-Z

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

| Model | $C_{HH}$ | $C_{ll}$ | $C_{Hl}^{3}$ | $C_{Hl}^{1}$ | $C_{He}$ | $C_{He}^{2}$ | $C_{He}^{1}$ | $C_{lH}$ | $C_{bH}$ |
|-------|-----------|-----------|--------------|--------------|-----------|--------------|--------------|-----------|-----------|
| $S$   |           |           | $-\frac{1}{2}$ |               |           |               |               |           |           |
| $S_1$ |           |           | $\frac{1}{4}$ | $\frac{3}{16}$ |           |               |               |           |           |
| $\Sigma$ | $\frac{1}{16}$ | $\frac{3}{16}$ |               |               |           |               |               |           |           |
| $\Sigma_1$ | $\frac{1}{16}$ | $\frac{3}{16}$ |               |               |           |               |               |           |           |
| $N$   | $\frac{1}{4}$ | $\frac{1}{4}$ |               |               |           |               |               |           |           |
| $E$   | $\frac{1}{4}$ | $\frac{1}{4}$ |               |               |           |               |               |           |           |
| $\Delta_1$ | $\frac{1}{2}$ |               |               |               |           |               |               |           |           |
| $\Delta_3$ |               | $\frac{1}{2}$ | $\frac{1}{8}$ |               |               |               |               |           |           |
| $B_1$ | 1 |          | $-\frac{1}{2}$ | $-\frac{y_t}{2}$ |               |               |               |           |           |
| $\Xi$ | $\frac{1}{2}$ |               |               | $y_t$ | $y_t$ | $y_t$ |               |           |           |
| $W_1$ | $\frac{1}{8}$ |               |               | $-\frac{y_t}{2}$ | $-\frac{y_t}{2}$ |               |               |           |           |
| $\varphi$ |               |               | $-\frac{y_t}{2}$ | $-\frac{y_t}{2}$ | $-\frac{y_t}{2}$ |               |               |           |           |
| $\{B_1, B_1\}$ |               |               | $-\frac{3}{2}$ |               | $-\frac{y_t}{2}$ | $-\frac{y_t}{2}$ | $-\frac{y_t}{2}$ |           |           |
| $\{Q_1, Q_7\}$ |               |               |               |               |               |               |               |           |           |

| Model | $C_{HH}^3$ | $C_{HH}^1$ | $(C_{HH}^3)_{33}$ | $(C_{HH}^3)_{133}$ | $C_{Hl}^3$ | $C_{Hl}^1$ | $C_{He}^3$ | $C_{He}^1$ | $C_{lH}$ | $C_{bH}$ |
|-------|-------------|-------------|------------------|------------------|------------|------------|------------|------------|-----------|-----------|
| $U$   | $-\frac{1}{4}$ | $\frac{1}{4}$ |               |               | $\frac{y_t}{2}$ |               |               |           |           |           |
| $D$   | $-\frac{1}{4}$ | $-\frac{1}{4}$ |               |               | $\frac{y_t}{2}$ |               |               |           |           |           |
| $Q_5$ | $-\frac{1}{4}$ | $-\frac{1}{4}$ |               |               | $\frac{y_t}{2}$ |               |               |           |           |           |
| $Q_7$ | $\frac{1}{2}$ |               |               |               | $\frac{y_t}{2}$ |               |               |           |           |           |
| $T_1$ | $\frac{1}{16}$ | $-\frac{3}{16}$ |               |               | $\frac{y_t}{4}$ |               |               |           |           |           |
| $T_2$ | $\frac{1}{16}$ | $\frac{3}{16}$ |               |               | $\frac{y_t}{4}$ |               |               |           |           |           |
| $T$   | $\frac{1}{2}$ | $\frac{1}{2}$ | $\frac{1}{2}$ | $\frac{1}{2}$ | $\frac{y_t}{2}$ | $\frac{y_t}{2}$ | $\frac{y_t}{2}$ |           |           |           |

Mass limits (in TeV):

![Mass limits graph](image_url)
# Linear SM extensions at Tera-Z

One-loop SMEFT structure and Tera-Z constraints:

| $O_{HWW}$ | $O_{HD}$ | $O_8$ | $O_{H1}^{(0)}$ | $O_{H1}^{(1)}$ | $O_{H6}$ | $O_{H8}^{(0)}$ | $O_{H8}^{(1)}$ | $O_{H10}$ | $O_{H4}$ |
|------------|----------|--------|----------------|----------------|---------|---------------|---------------|-----------|--------|
| $S$        | $\kappa_S$ | $\kappa_S$ | $\bar{y}_S$ | $\bar{y}_S$ | $\bar{y}_S$ | $\bar{y}_S$ | $\bar{y}_S$ | $\bar{y}_S$ | $\bar{y}_S$ |
| $S_1$      | $\kappa_{S_1}$ | $\kappa_{S_1}$ | $\bar{y}_{S_1}$ | $\bar{y}_{S_1}$ | $\bar{y}_{S_1}$ | $\bar{y}_{S_1}$ | $\bar{y}_{S_1}$ | $\bar{y}_{S_1}$ | $\bar{y}_{S_1}$ |
| $S_2$      | $\kappa_{S_2}$ | $\kappa_{S_2}$ | $\bar{y}_{S_2}$ | $\bar{y}_{S_2}$ | $\bar{y}_{S_2}$ | $\bar{y}_{S_2}$ | $\bar{y}_{S_2}$ | $\bar{y}_{S_2}$ | $\bar{y}_{S_2}$ |
| $\varphi$  | $\lambda_{\varphi}$ | $\lambda_{\varphi}$ | $\bar{y}_{\varphi}$ | $\bar{y}_{\varphi}$ | $\bar{y}_{\varphi}$ | $\bar{y}_{\varphi}$ | $\bar{y}_{\varphi}$ | $\bar{y}_{\varphi}$ | $\bar{y}_{\varphi}$ |
| $\Xi_1$    | $\kappa_{\Xi_1}$ | $\kappa_{\Xi_1}$ | $\bar{y}_{\Xi_1}$ | $\bar{y}_{\Xi_1}$ | $\bar{y}_{\Xi_1}$ | $\bar{y}_{\Xi_1}$ | $\bar{y}_{\Xi_1}$ | $\bar{y}_{\Xi_1}$ | $\bar{y}_{\Xi_1}$ |
| $\Theta_1$ | $\lambda_{\Theta_1}$ | $\lambda_{\Theta_1}$ | $\bar{y}_{\Theta_1}$ | $\bar{y}_{\Theta_1}$ | $\bar{y}_{\Theta_1}$ | $\bar{y}_{\Theta_1}$ | $\bar{y}_{\Theta_1}$ | $\bar{y}_{\Theta_1}$ | $\bar{y}_{\Theta_1}$ |
| $\Theta_2$ | $\lambda_{\Theta_2}$ | $\lambda_{\Theta_2}$ | $\bar{y}_{\Theta_2}$ | $\bar{y}_{\Theta_2}$ | $\bar{y}_{\Theta_2}$ | $\bar{y}_{\Theta_2}$ | $\bar{y}_{\Theta_2}$ | $\bar{y}_{\Theta_2}$ | $\bar{y}_{\Theta_2}$ |
| $\omega_1$ | $\omega_{\omega_1}$ | $\omega_{\omega_1}$ | $\bar{y}_{\omega_1}$ | $\bar{y}_{\omega_1}$ | $\bar{y}_{\omega_1}$ | $\bar{y}_{\omega_1}$ | $\bar{y}_{\omega_1}$ | $\bar{y}_{\omega_1}$ | $\bar{y}_{\omega_1}$ |
| $\omega_2$ | $\omega_{\omega_2}$ | $\omega_{\omega_2}$ | $\bar{y}_{\omega_2}$ | $\bar{y}_{\omega_2}$ | $\bar{y}_{\omega_2}$ | $\bar{y}_{\omega_2}$ | $\bar{y}_{\omega_2}$ | $\bar{y}_{\omega_2}$ | $\bar{y}_{\omega_2}$ |
| $\Pi_1$    | $\Pi_{\Pi_1}$ | $\Pi_{\Pi_1}$ | $\bar{y}_{\Pi_1}$ | $\bar{y}_{\Pi_1}$ | $\bar{y}_{\Pi_1}$ | $\bar{y}_{\Pi_1}$ | $\bar{y}_{\Pi_1}$ | $\bar{y}_{\Pi_1}$ | $\bar{y}_{\Pi_1}$ |
| $\Pi_2$    | $\Pi_{\Pi_2}$ | $\Pi_{\Pi_2}$ | $\bar{y}_{\Pi_2}$ | $\bar{y}_{\Pi_2}$ | $\bar{y}_{\Pi_2}$ | $\bar{y}_{\Pi_2}$ | $\bar{y}_{\Pi_2}$ | $\bar{y}_{\Pi_2}$ | $\bar{y}_{\Pi_2}$ |
| $\zeta_1$  | $\zeta_{\zeta_1}$ | $\zeta_{\zeta_1}$ | $\bar{y}_{\zeta_1}$ | $\bar{y}_{\zeta_1}$ | $\bar{y}_{\zeta_1}$ | $\bar{y}_{\zeta_1}$ | $\bar{y}_{\zeta_1}$ | $\bar{y}_{\zeta_1}$ | $\bar{y}_{\zeta_1}$ |
| $\zeta_2$  | $\zeta_{\zeta_2}$ | $\zeta_{\zeta_2}$ | $\bar{y}_{\zeta_2}$ | $\bar{y}_{\zeta_2}$ | $\bar{y}_{\zeta_2}$ | $\bar{y}_{\zeta_2}$ | $\bar{y}_{\zeta_2}$ | $\bar{y}_{\zeta_2}$ | $\bar{y}_{\zeta_2}$ |
| $\omega_4$ | $\omega_{\omega_4}$ | $\omega_{\omega_4}$ | $\bar{y}_{\omega_4}$ | $\bar{y}_{\omega_4}$ | $\bar{y}_{\omega_4}$ | $\bar{y}_{\omega_4}$ | $\bar{y}_{\omega_4}$ | $\bar{y}_{\omega_4}$ | $\bar{y}_{\omega_4}$ |
| $\Omega_1$ | $\Omega_{\Omega_1}$ | $\Omega_{\Omega_1}$ | $\bar{y}_{\Omega_1}$ | $\bar{y}_{\Omega_1}$ | $\bar{y}_{\Omega_1}$ | $\bar{y}_{\Omega_1}$ | $\bar{y}_{\Omega_1}$ | $\bar{y}_{\Omega_1}$ | $\bar{y}_{\Omega_1}$ |
| $\Omega_2$ | $\Omega_{\Omega_2}$ | $\Omega_{\Omega_2}$ | $\bar{y}_{\Omega_2}$ | $\bar{y}_{\Omega_2}$ | $\bar{y}_{\Omega_2}$ | $\bar{y}_{\Omega_2}$ | $\bar{y}_{\Omega_2}$ | $\bar{y}_{\Omega_2}$ | $\bar{y}_{\Omega_2}$ |

## e.g. Fermions:

Mass 95% CL sensitivity at FCC-ee Z pole

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2412.01759 Gargalionis, Vuong, Quevillon, TY
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

\[ \mathcal{L}_{\text{UV}} = ? \]

\[ \Lambda \]

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

Indirect exploration by e+e-
Radically new BSM?

Direct exploration by hadron / muon collider

\[ E < \Lambda \]

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

Indirect exploration by e+e- collider

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.
Radically new BSM?

Direct exploration by hadron / muon collider

Matching explicit UV models populates a subspace of SMEFT coefficient space

Indirect exploration by e+e- collider
Radically new BSM?

Direct exploration by hadron / muon collider

Indirect exploration by e+e- collider

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

Measuring the “wrong” sign experimentally would have truly revolutionary consequences for the underlying theory!
Radically new BSM?

May not even have a Lagrangian/QFT description

\[ \mathcal{L}_{\text{UV}} = ? \]

Unitarity \quad Locality \quad Causality \quad \ldots

Energy

\[ \Lambda \]

\( E \ll \Lambda \)

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

Direct exploration by hadron / muon collider

Indirect exploration by e^+e^- collider

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

Measuring the “wrong” sign experimentally would have truly revolutionary consequences for the underlying theory!

Related to positivity of entanglement entropy

2308.06226 Davighi, Melville, Mimasu, TY

2402.16956 Aoude, Elor, Remmen, Sumensari

Could potentially be related to hierarchy problem
Radically new BSM?

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

Anomaly in orbit of Uranus  \rightarrow  Discovery of Neptune

Other times its implications are *far more radical*:

Anomaly in orbit of Mercury  \rightarrow  Explained by General Relativity

(Could have been **anticipated by Effective Theory** and **naturalness**!) 1106.1568 J.D. Wells
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 **uniquely rich and vast programme of fundamental physics** that will significantly advance our understanding of the Universe.
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