

Theory review / speculations: BSM @ TeV (in connection with the hierarchy problem)

Tevong You

Theory

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OPTICKS:

OR, A

TREATISE

OF THE

REFLEXIONS, REFRACTIONS,
INFLEXIONS and COLOURS

OF

LIGHT.

ALSO

TWO TREATISES

OF THE

SPECIES and MAGNITUDE

OF

Curvilinear Figures.

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Printed for SAM. SMITH, and BENJ. WALFORD,
Printers to the Royal Society, at the *Prince's Arms* in
St. Paul's Church-yard. MDCCIV.

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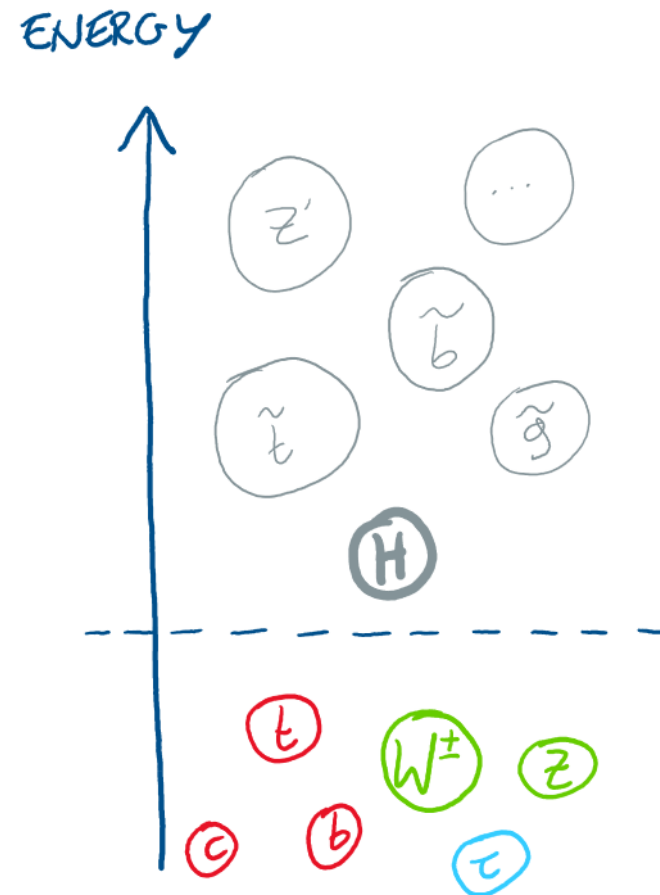
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Contents

- **Review** of the situation
- **EFT** and the connection to **the hierarchy problem**
- **Speculations** on BSM @ TeV scale

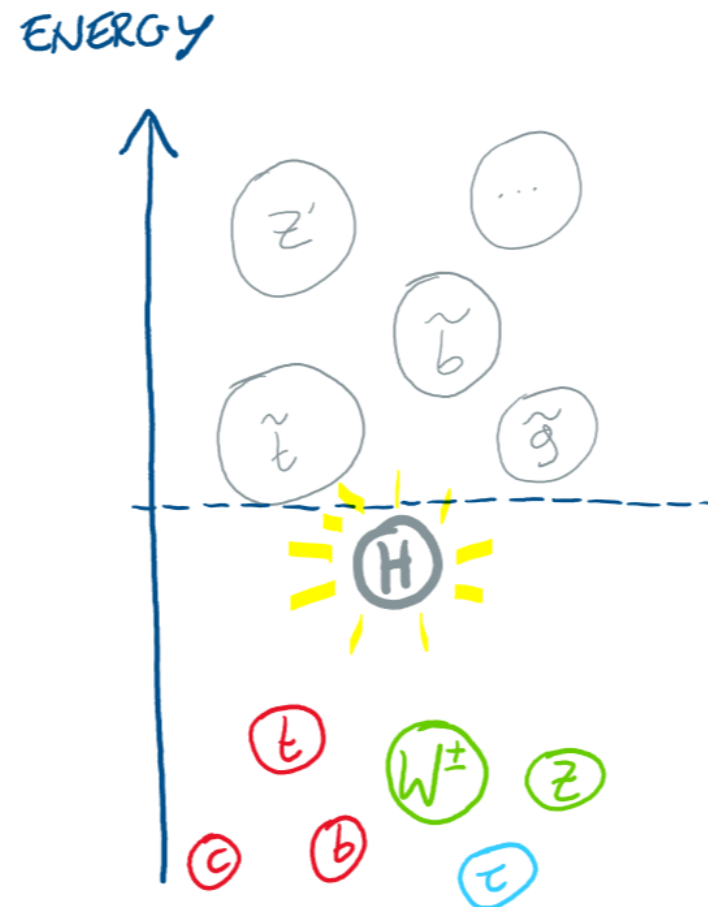
Motivation

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



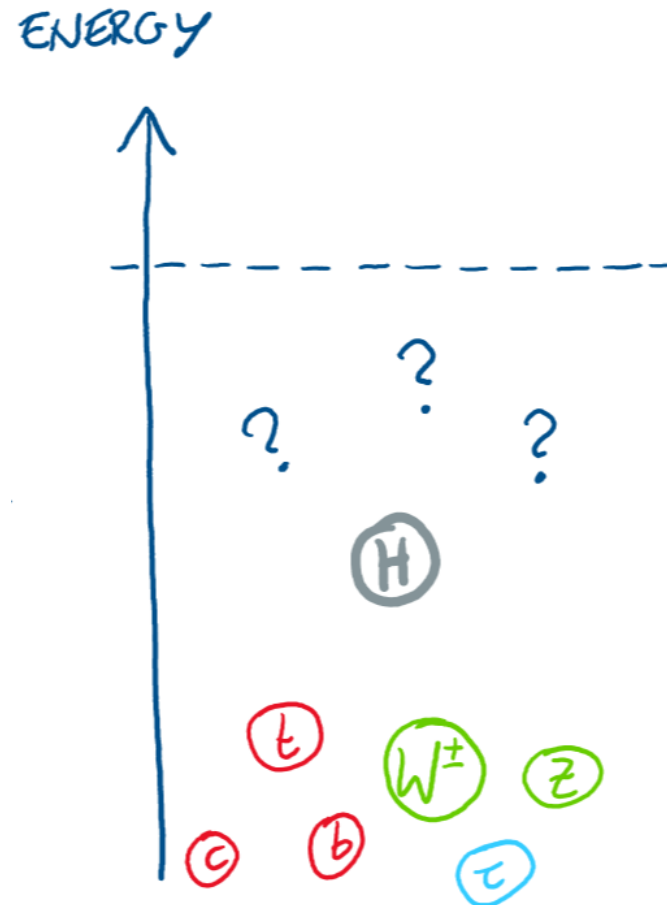
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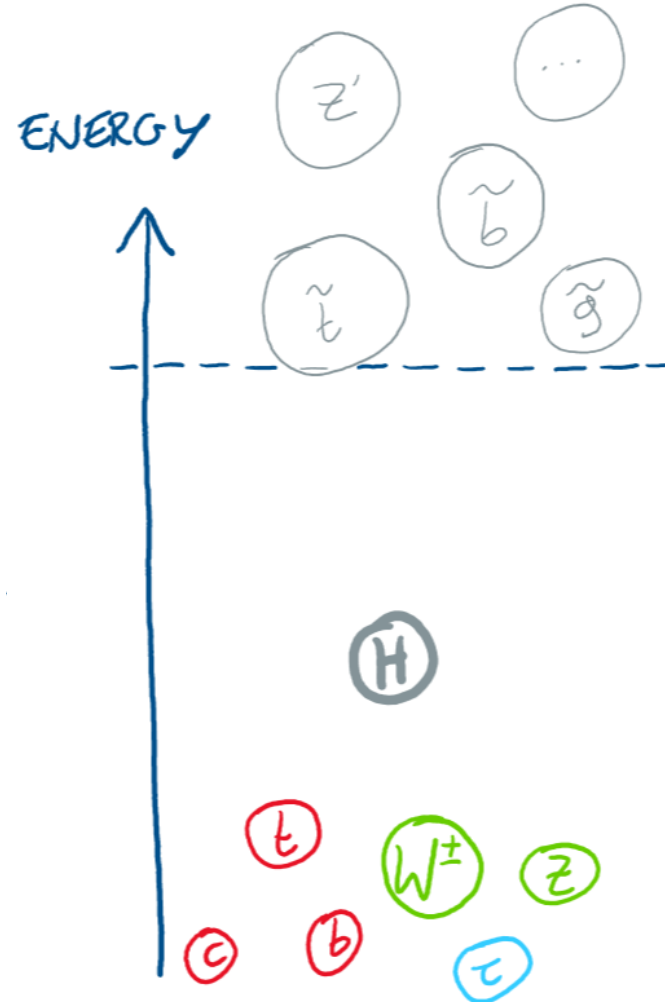
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Conventional
symmetry-based
solutions *have not*
shown up!

Motivation

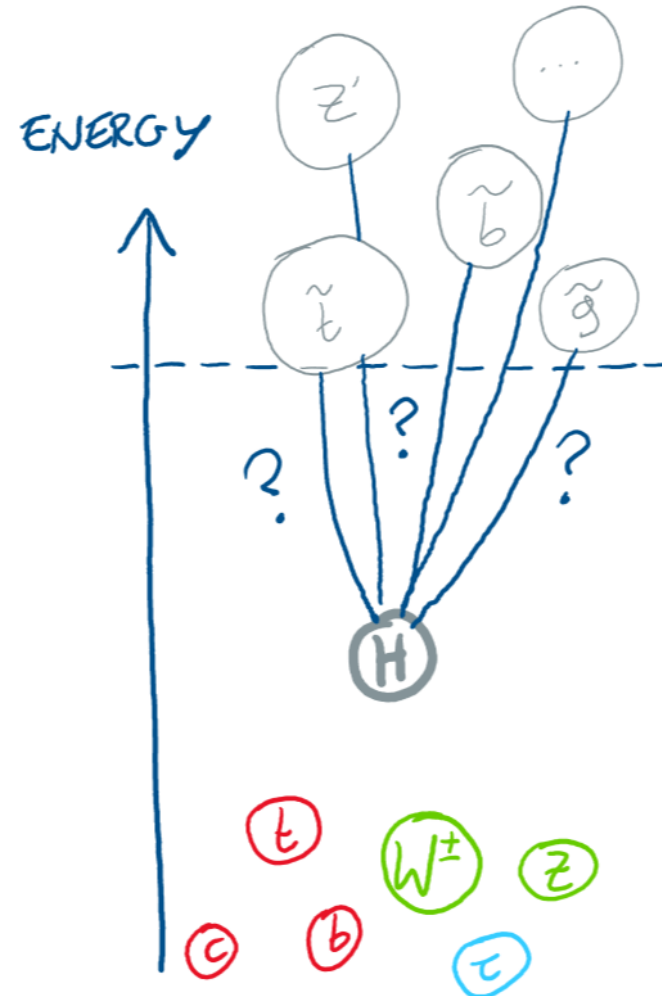
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Maybe **just around the corner...**

Motivation

- 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.

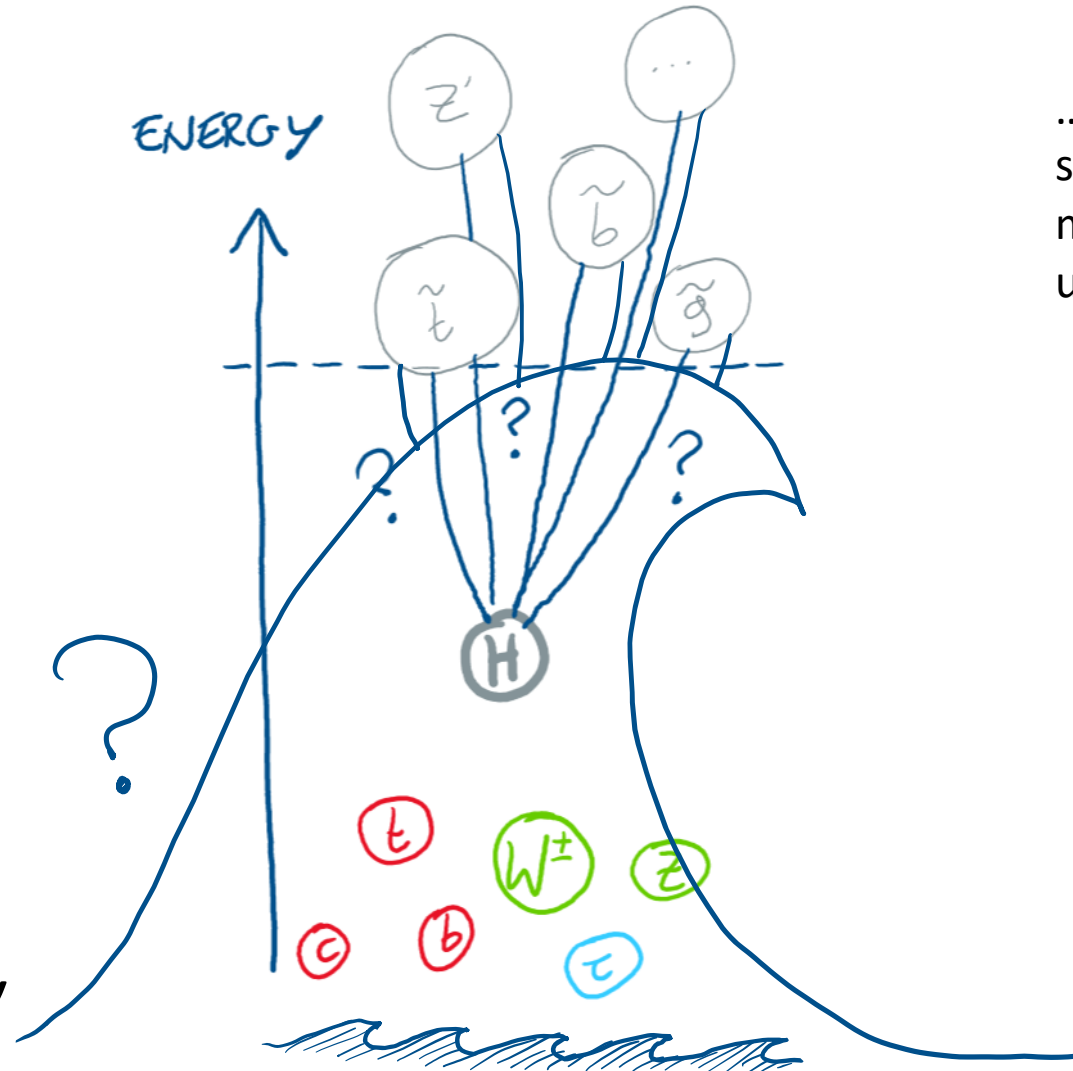
Our **Michelson-Morley moment?**

Motivation

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

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

Vacuum energy is also *peculiarly tiny*



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?**

Effective Field Theory

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

Symmetries control sizes of parameters – naturalness expectations

Effective Field Theory

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

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

Effective Field Theory

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Effective Field Theory

Suppressed!

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

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Effective Field Theory

Naturalness?

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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

Effective Field Theory

The SM *is* an Effective Field Theory - SMEFT is the Fermi theory of the 21st century

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

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

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

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

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

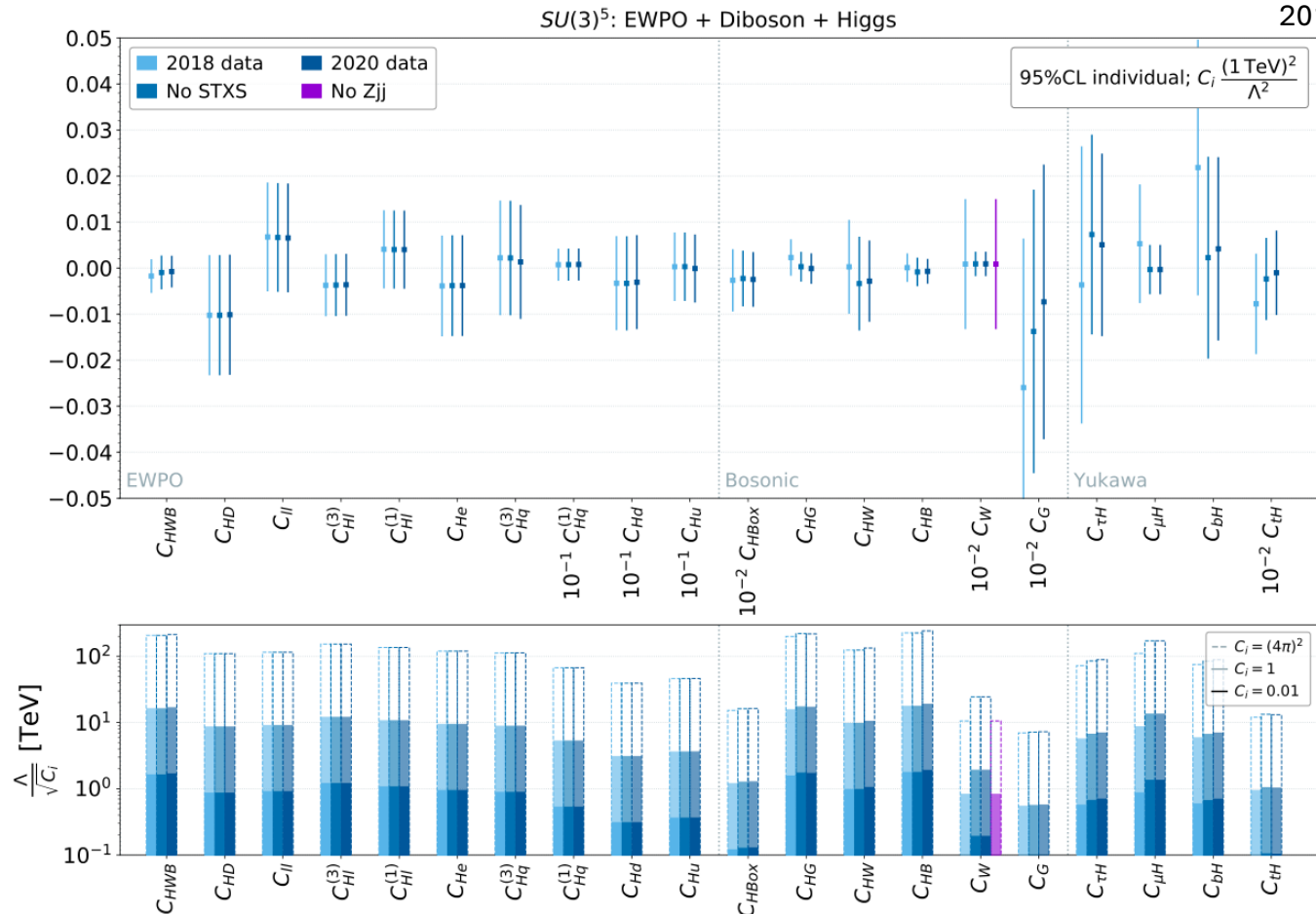
Explore heavy BSM physics in this framework

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).

Effective Field Theory

The SM is an Effective Field Theory - SMEFT is the Fermi theory of the 21st century

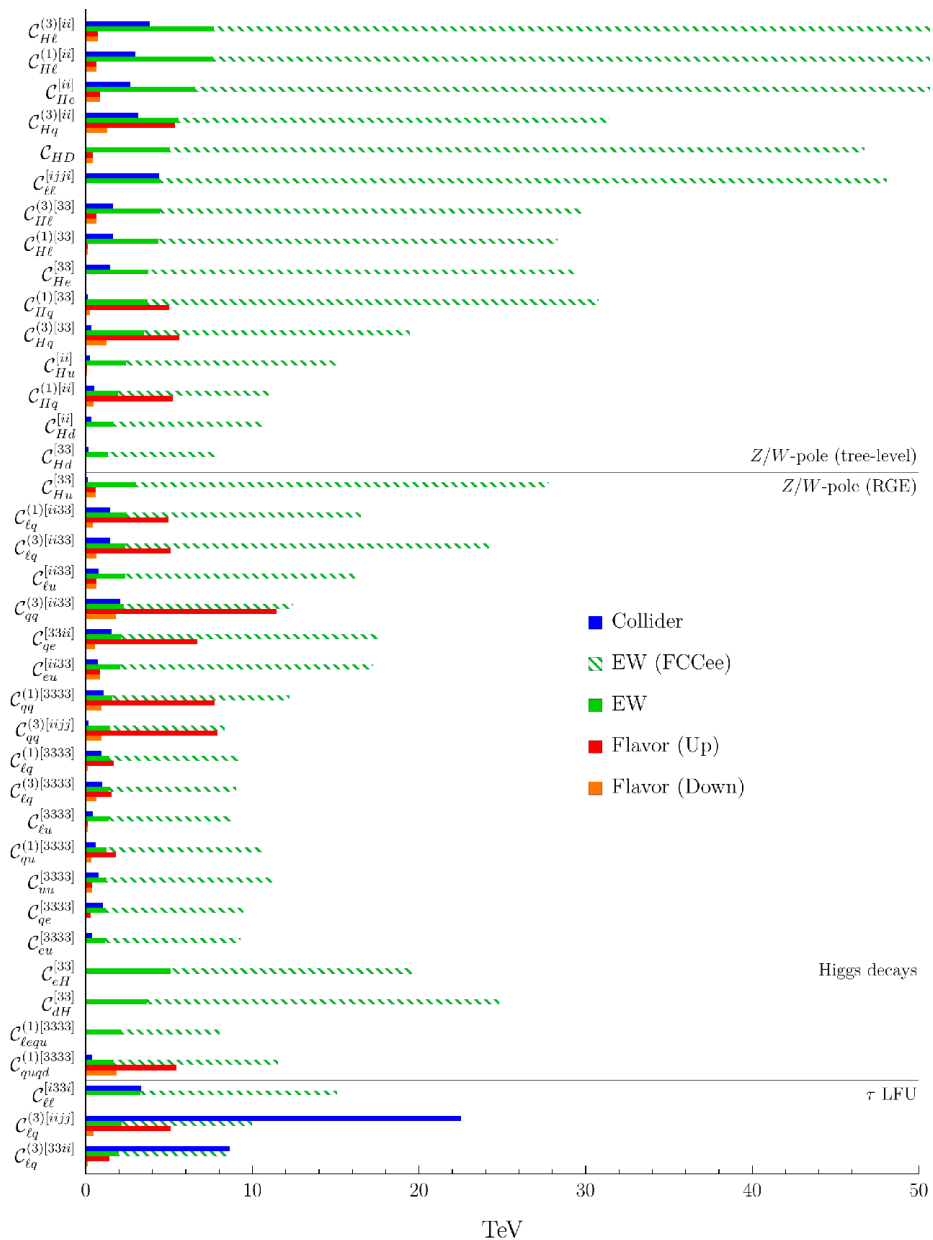


See also other recent global fits, e.g.
 2311.00020 Allwicher, Cornella, Isidori, Stefanek
 2311.04963 Bartocci, Biekotter, Hurth
 2404.12809 SMEFIT collaboration

Indirect evidence preceded direct discovery for nearly all SM particles. May be true of BSM!

Effective Field Theory

2311.00020 Allwicher, Cornella, Isidori, Stefaneke



Powerful indirect exploration of the multi-TeV scale @ FCC-ee

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

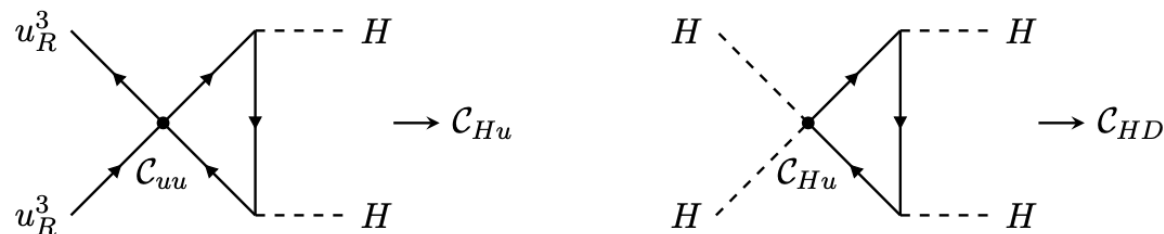


Figure 1. Next-to-leading log running of four-quark operators into C_{HD} .

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

Naturalness

Take aesthetic problems seriously.

Example 1

$$F = m_{inertia}a \qquad F \propto \frac{q_1 q_2}{r^2}$$

Inertial mass and charge have nothing to do with each other, and yet for gravity we arbitrarily set by hand

$$q = m_{inertia}$$

Solution to this equivalence problem took centuries: Newtonian gravity \rightarrow GR

Naturalness

Take fine-tuning problems seriously.

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

Example 2

$$(m_e c^2)_{obs} = (m_e c^2)_{bare} + \Delta E_{Coulomb} \quad \Delta E_{Coulomb} = \frac{1}{4\pi\epsilon_0} \frac{e^2}{r_e}$$

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

$$e^2/(4\pi\epsilon_0 m_e c^2) = 2.8 \times 10^{-13} \text{ cm}$$

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

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

Naturalness

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Example 3

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.

ρ meson appears at 775 MeV!

Naturalness

Take fine-tuning problems seriously.

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

Example 4

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 $\Lambda < 3 \text{ GeV}$.

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??

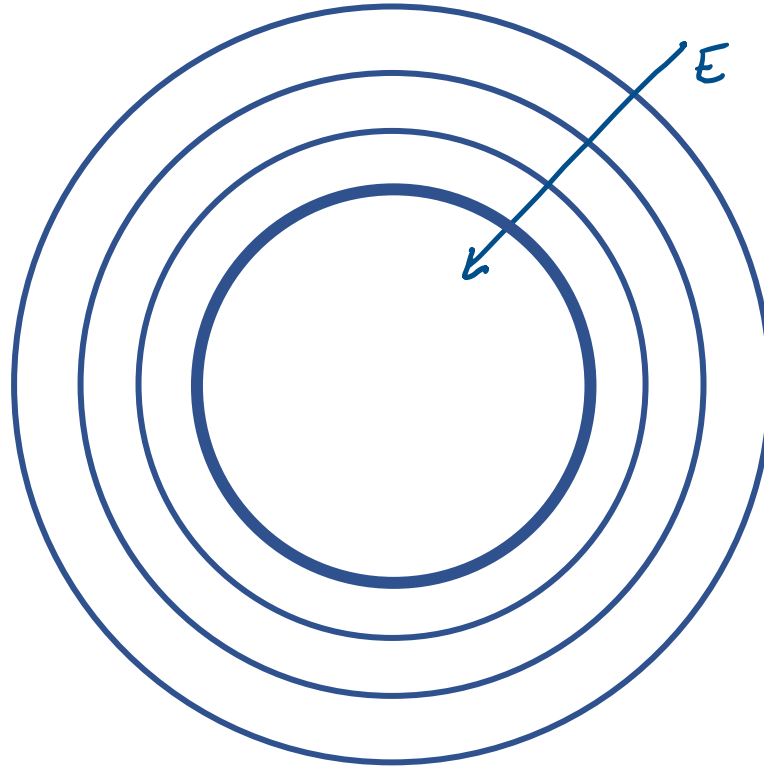
As Λ is pushed to the TeV scale by null results, tuning is around 10% - 1%.

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

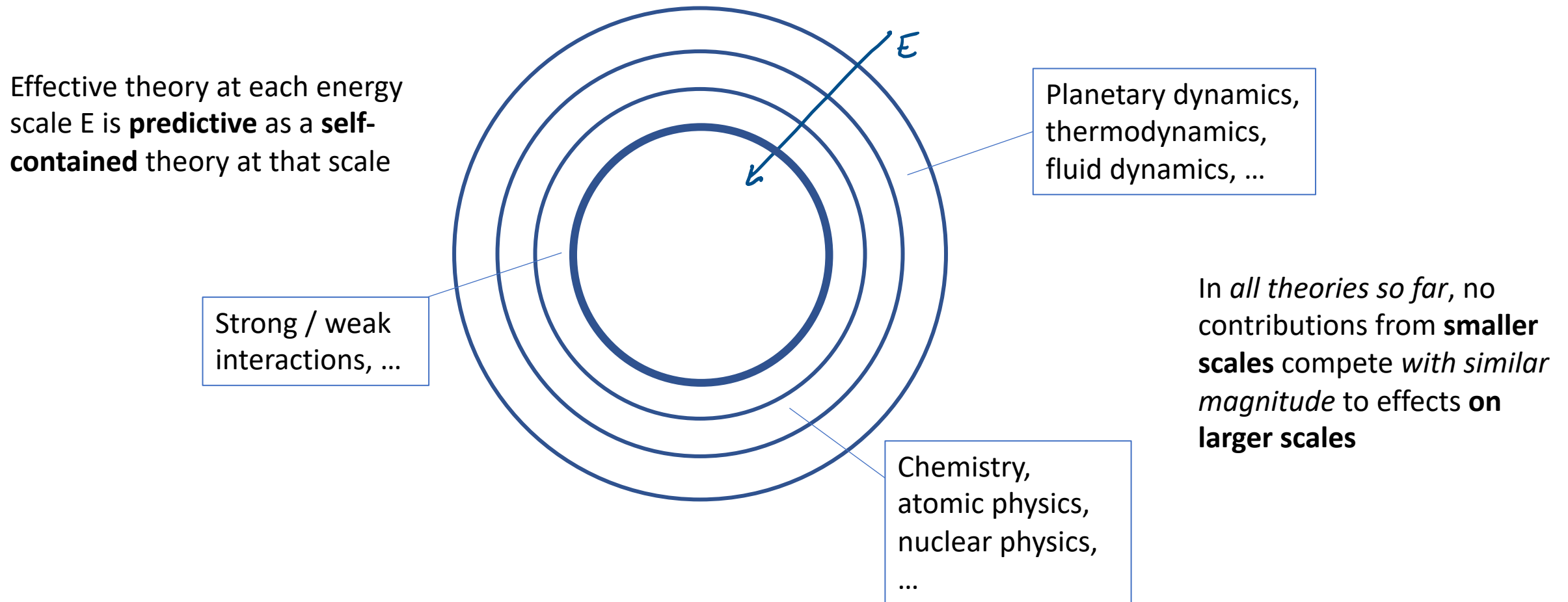
- *Why is unnatural fine-tuning such a big deal?*

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



Naturalness is still a fundamental problem

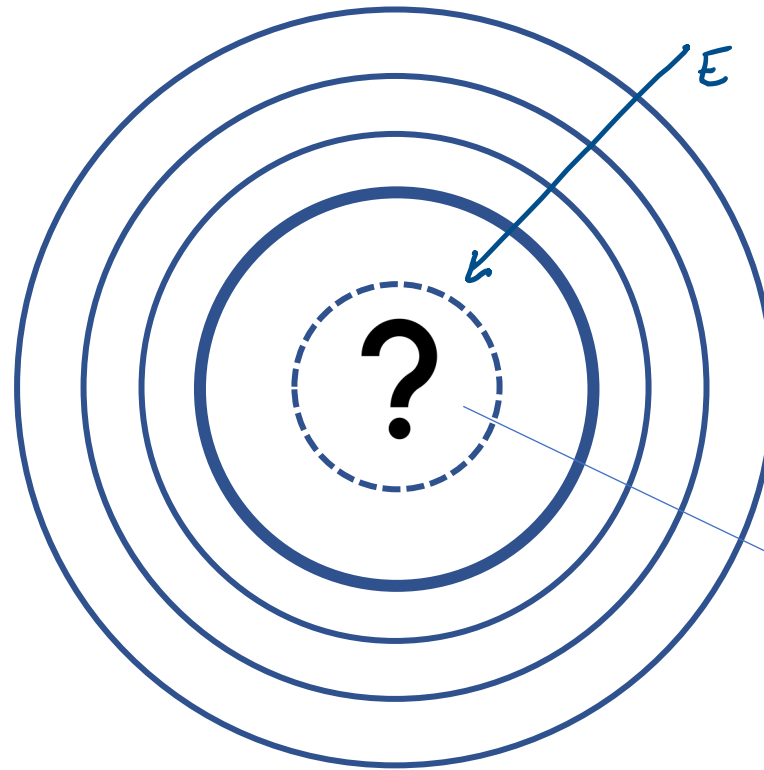
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Naturalness is still a fundamental problem

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

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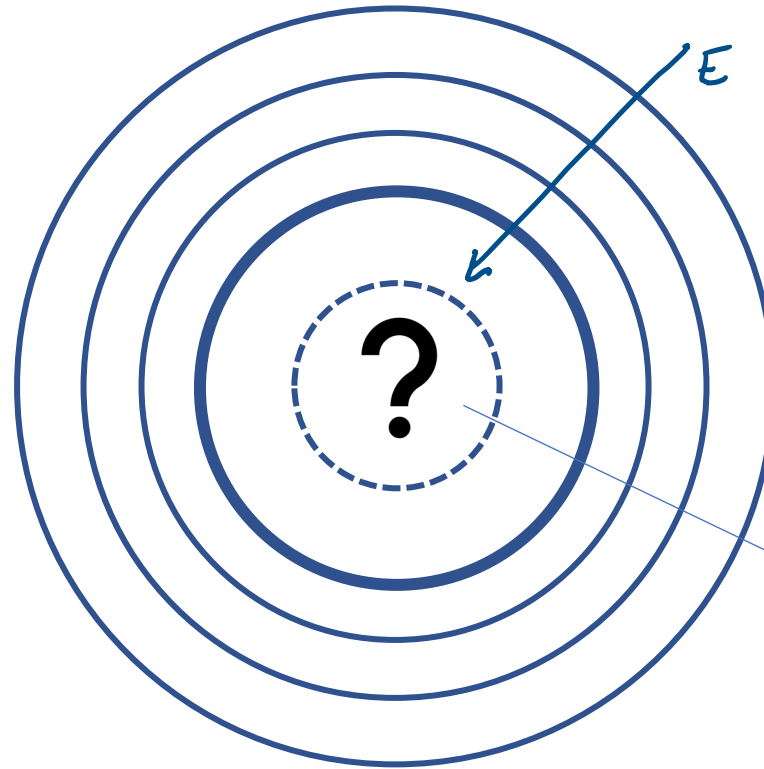


Unnatural Higgs means the next layer *is no longer predictive* without including contributions *from much smaller scales*

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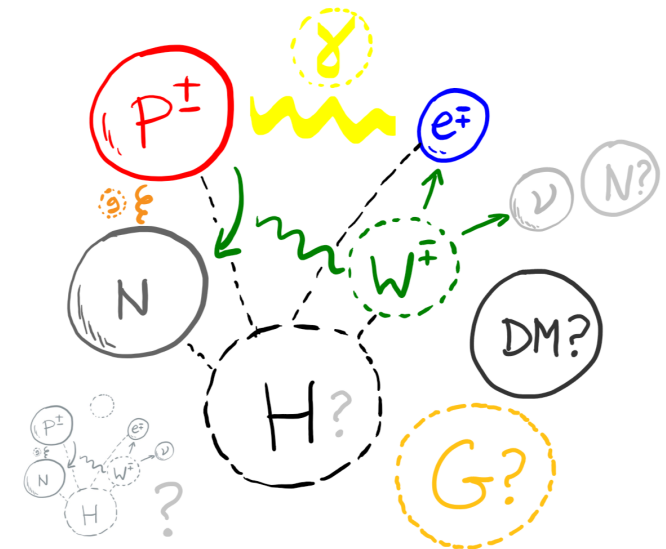
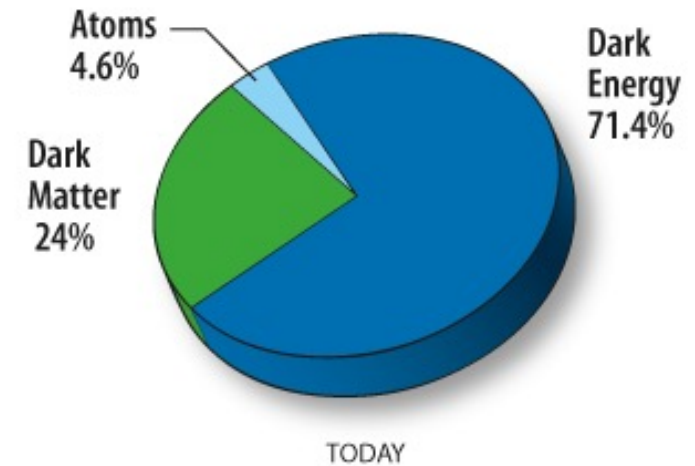


Unnatural Higgs means the next layer *is no longer predictive* without including contributions *from much smaller scales*

- Are we missing a **new** “*post-naturalness*” principle? c.f. null results in search for aether

Naturalness aside, many more open questions

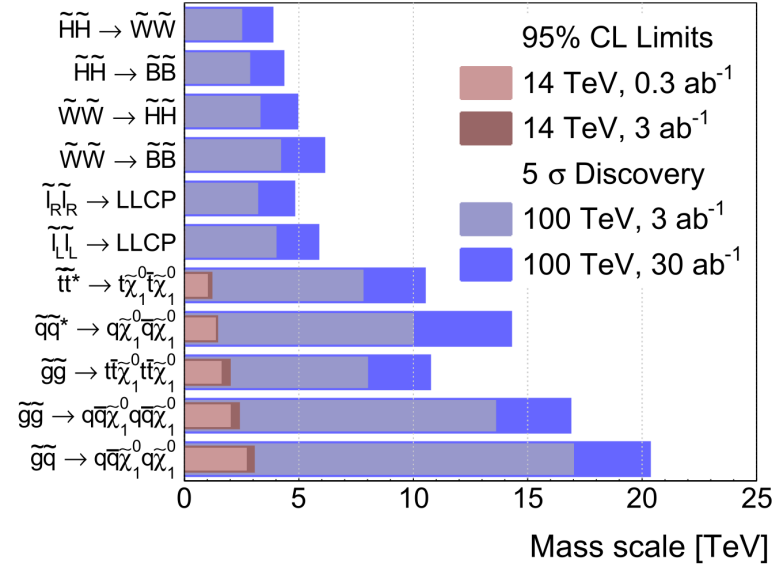
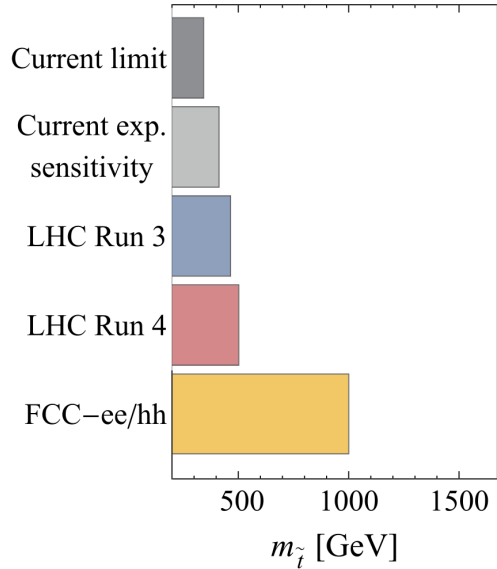
- What is the **origin of the Higgs?**
- What is the **origin of matter?**
- What is the **origin of flavour?**
- What is the **origin of dark matter and dark energy?**
- What is the **origin of neutrino mass?**
- What is the **origin of the Standard Model?**



Origin of the Higgs

FCC CDR Vol. 1

Note: naturalness aside, still motivation in exploring origin of Higgs in models from which it emerges, where its mass is *calculable*

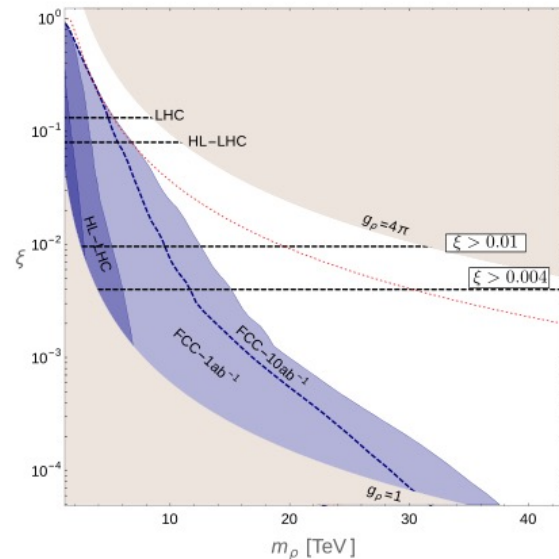
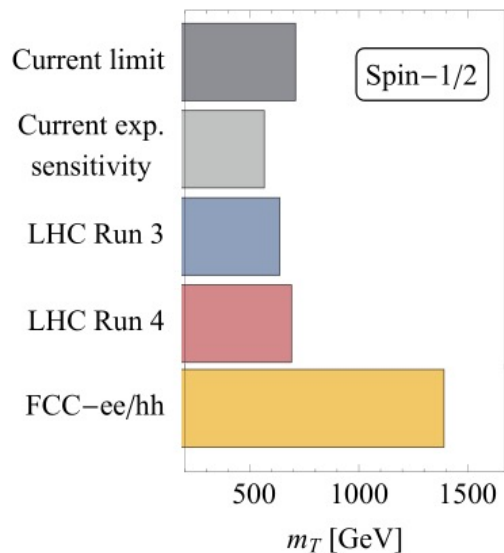


• Supersymmetry

- Massless spins 0, $\frac{1}{2}$, 1, $\frac{3}{2}$, 2 *only*
- Spin $\frac{3}{2}$ *must* be supersymmetric
- (Ir)relevant for solving **naturalness**?

• Composite Higgs / extra dimensions

- Is the Higgs **elementary** or **composite**?
- Are there *accessible* extra dimensions?



Potential BSM outcomes for naturalness at TeV scale

- **Radically conservative:** naturalness restored just around the corner
 - Natural supersymmetry
 - Composite Higgs/extra dimensions
- **Creatively conservative**
 - Twin Higgs
 - Stealth supersymmetry
- **Post-naturalness BSM**
 - Split supersymmetry
 - Vector-like fermions only
 - Higgs criticality
 - Cosmological dynamics
- **Radically new?**
 - Hard to imagine what form this might take, by definition
 - How might this show up?

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“Radically conservative” historical precedent

- 1930-40s: Success of QED. **QFT** emerges as the *new fundamental description of Nature*.
- 1960s: QFT is **unfashionable**, non-Abelian theory dismissed as an **unrealistic generalisation** of local symmetry-based forces. Widely believed a **radically new framework** will be required *e.g. to understand the strong force*.
- 1970s: **QFT triumphs** following Yang-Mills+Higgs+asymptotic freedom+renormalisation. Nature is **radically conservative**, *but more unified than ever*.
- 1980s: Success of SM. QFT understood as **most general EFT consistent with symmetry**. Higgs and cosmological constant *violate this symmetry principle*.

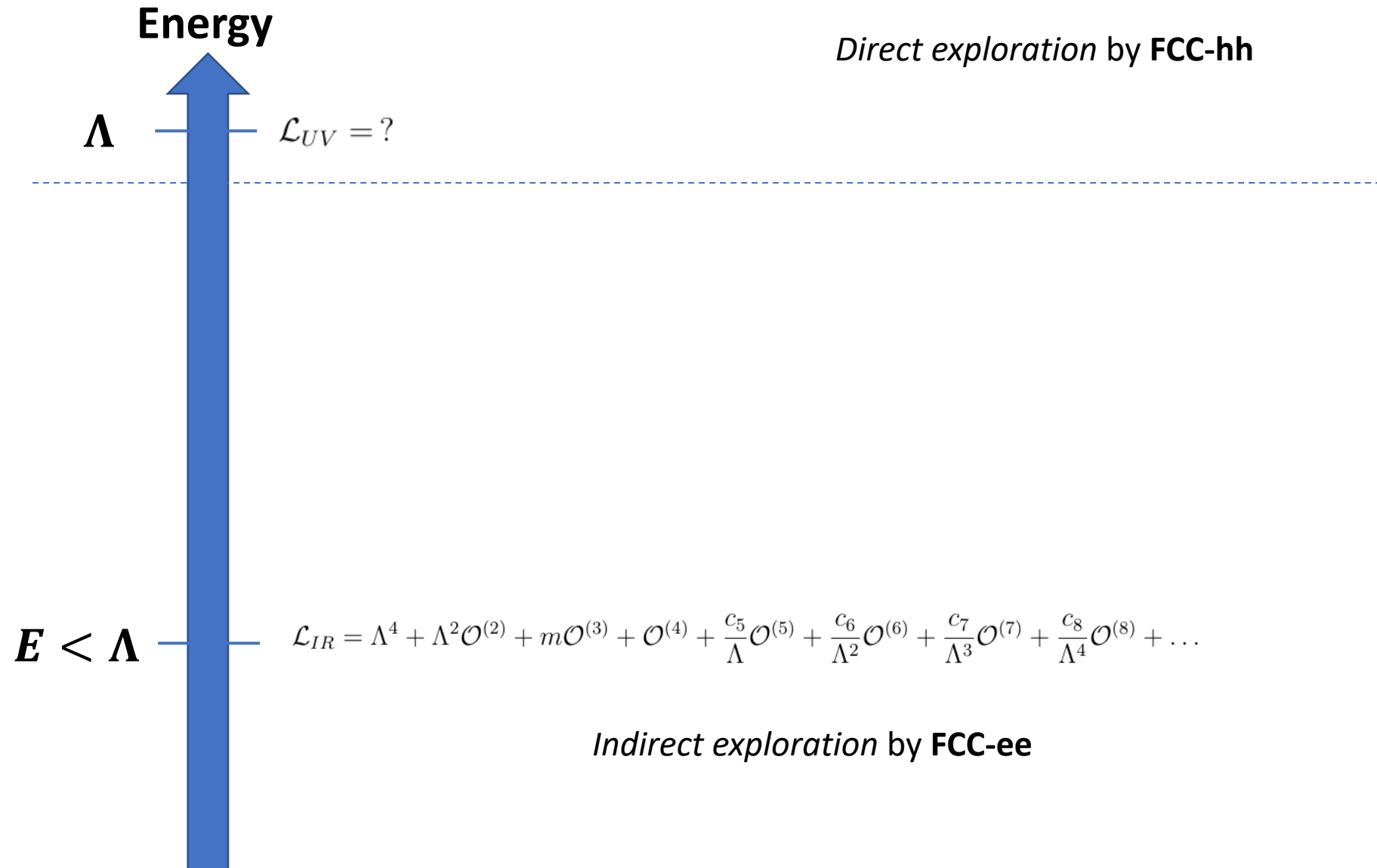
“Radically conservative” naturalness solution at TeV scale?

- 1980-2020s: Success of SM, established as the *fundamental description of Nature up to TeV scale*.
- 2040s: QFT is **unfashionable**, supersymmetry theory dismissed as an **unrealistic generalisation** of symmetry principles. Widely believed a **radically new framework** will be required *e.g. to understand naturalness*.
- 2060s: **QFT triumphs** following Yang-Mills+Higgs+asymptotic freedom+renormalisation+**supersymmetry**. Nature is **radically conservative**, *but more unified than ever*.
- 2080s: Success of MSSM?

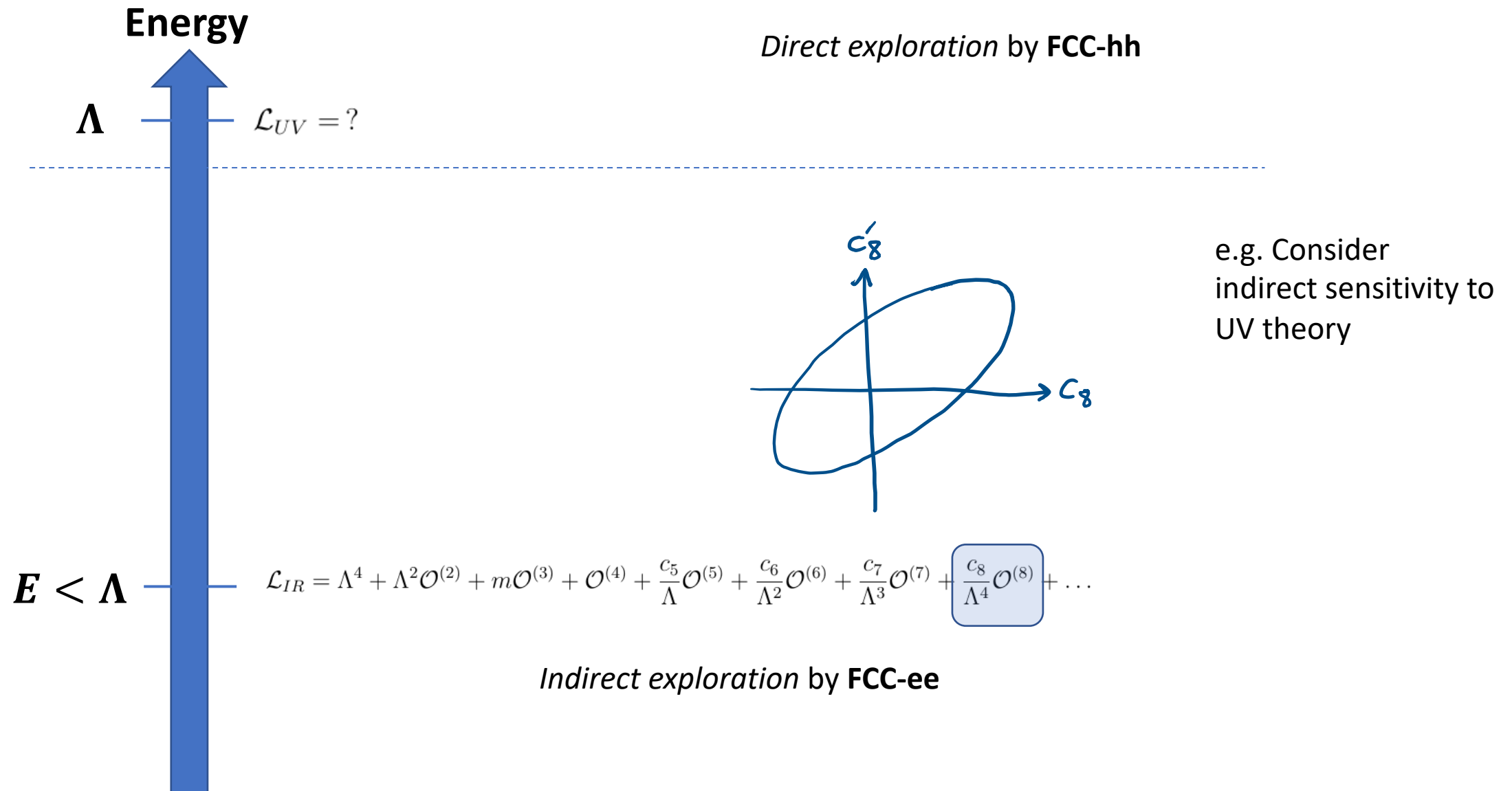
Potential BSM outcomes for naturalness at TeV scale

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 - Natural supersymmetry
 - Composite Higgs/extra dimensions
- **Creatively conservative**
 - Twin Higgs
 - Stealth supersymmetry
- **Post-naturalness BSM**
 - Split supersymmetry
 - Vector-like fermions only
 - Lowered vacuum instability scale
 - Weak-scale new physics for cosmological dynamics
- **Radically new?**
 - Hard to imagine what form this might take, by definition
 - How might this show up?

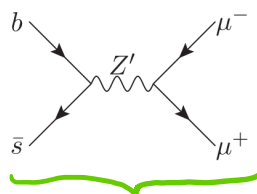
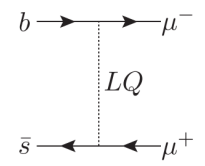
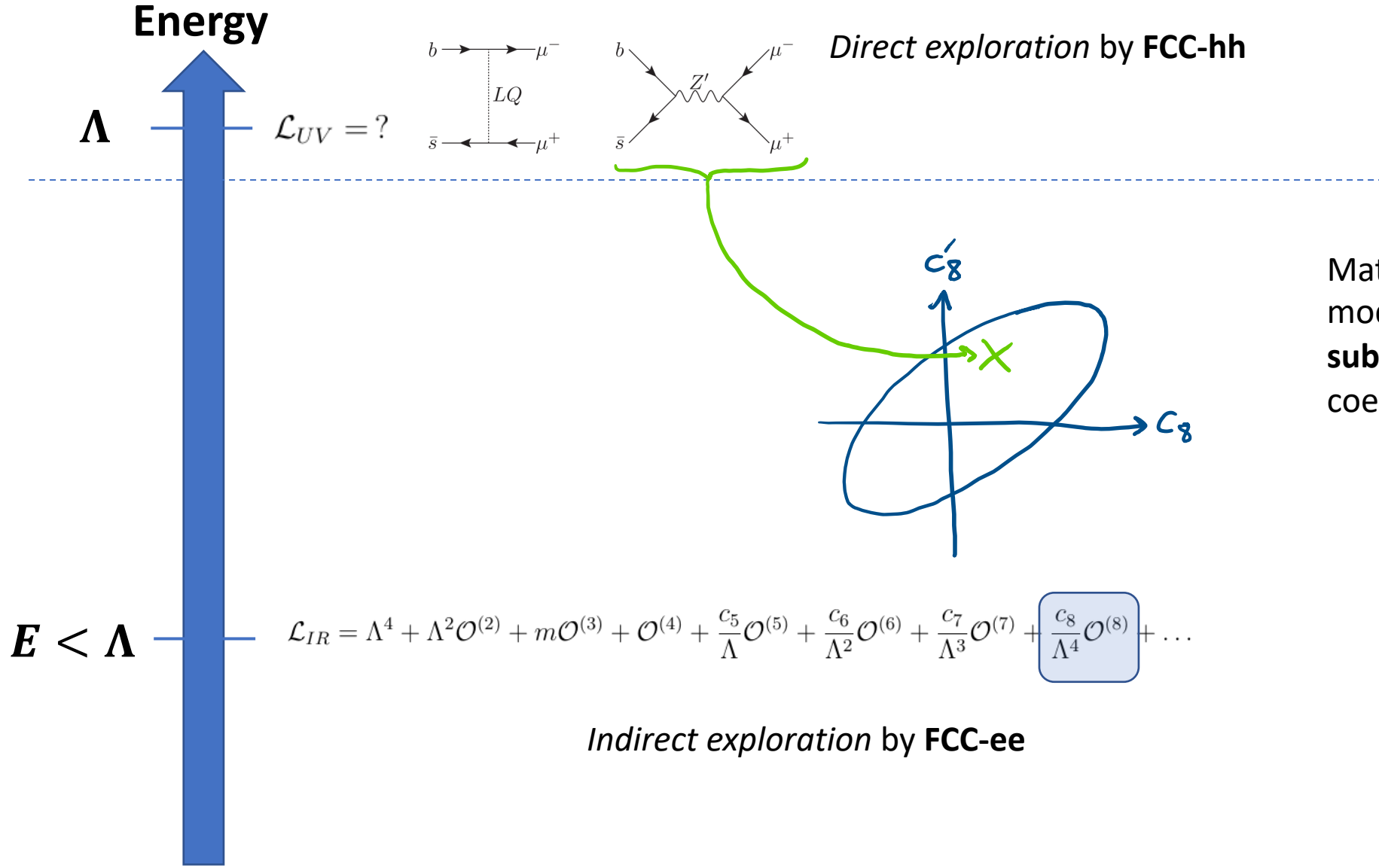
Radically new BSM?



Radically new BSM?



Radically new BSM?

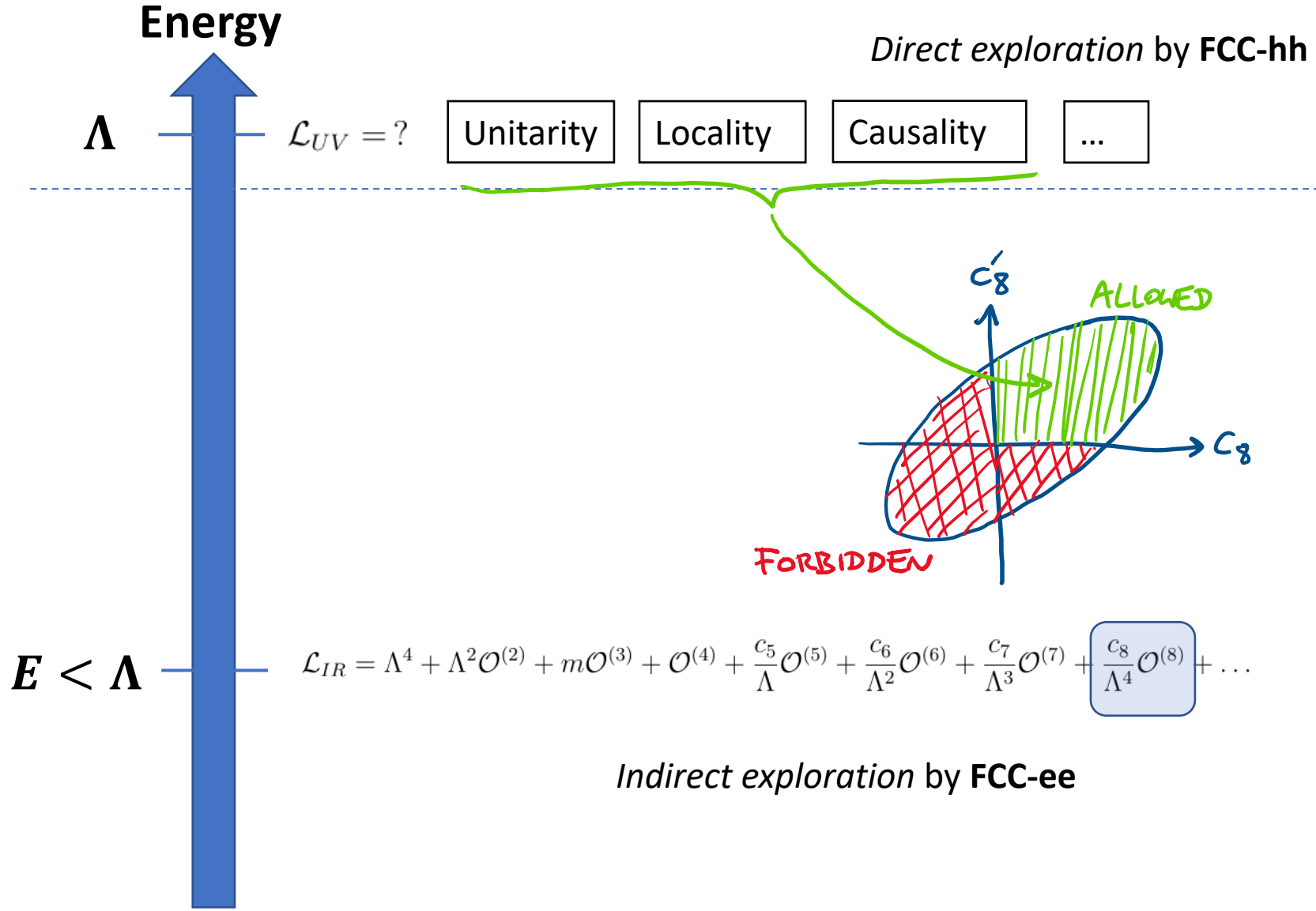


Direct exploration by FCC-hh

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

Indirect exploration by FCC-ee

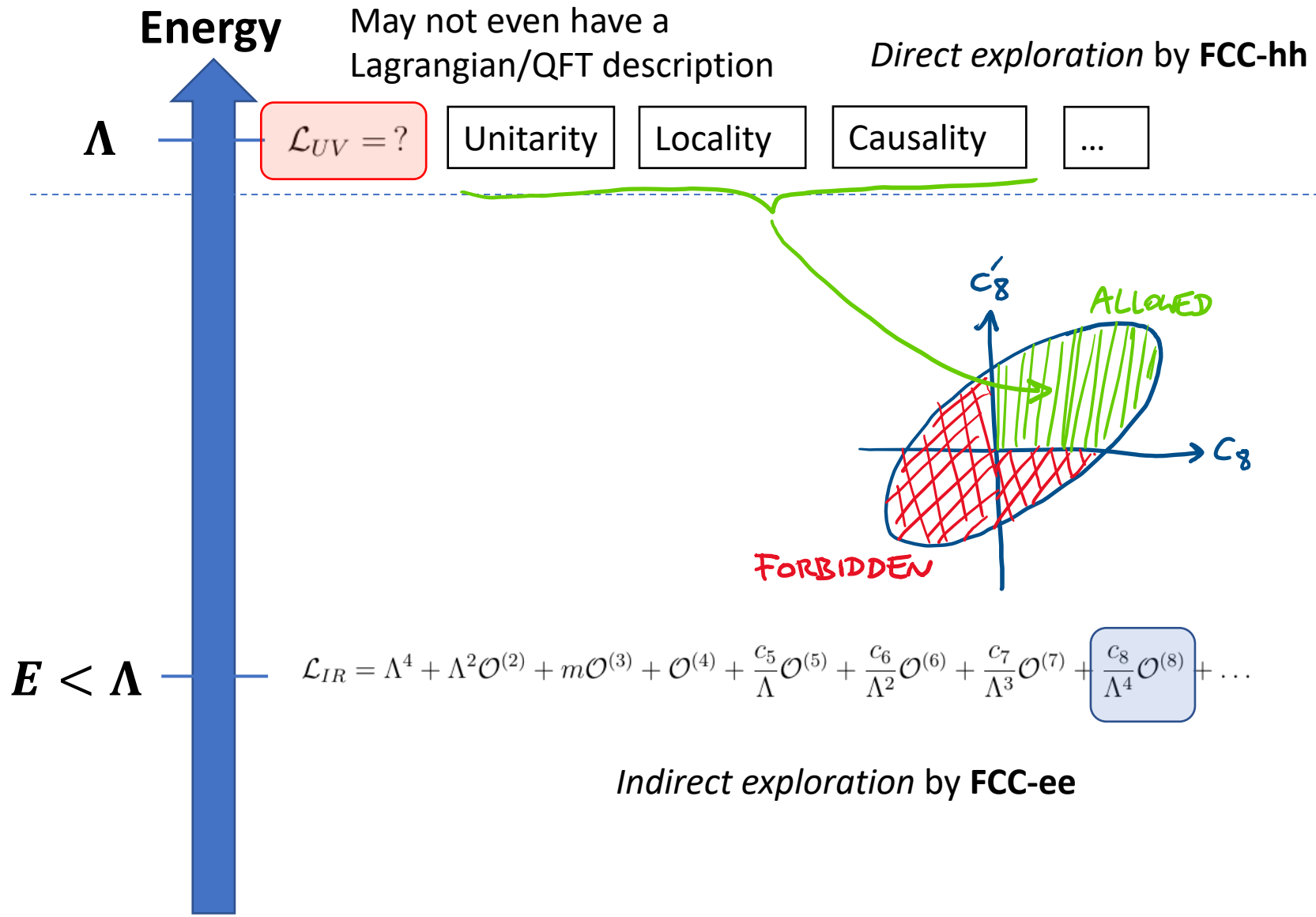
Radically new BSM?



Positivity bounds forbid **negative signs** of 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?



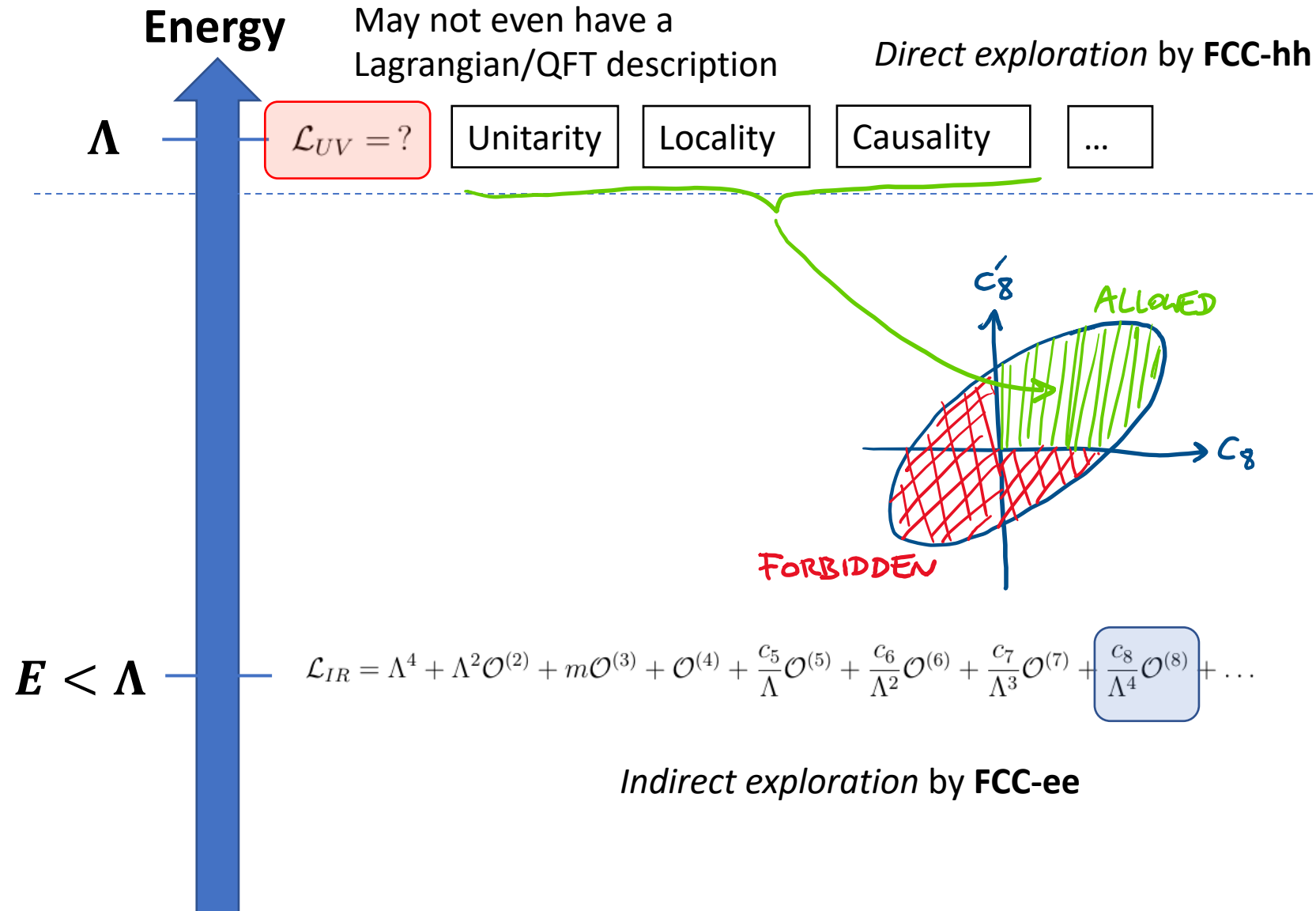
Positivity bounds forbid **negative signs** of SMEFT coefficients assuming only general fundamental principles in the UV

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Radically new BSM?

Positivity may correlate EFT with the electroweak hierarchy problem

2308.06226 Davighi, Melville, Mimasu, TY



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

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

Potential Positivity Bounds

2308.06226 Davighi, Melville, Mimasu, TY

Scalar potentials with a stable vev can contribute to positivity bounds

$$\mathcal{L}_{\text{EFT}}[H] = c_8 \frac{\mathcal{O}_8}{\Lambda^4} + c_{10} \frac{|H|^2 \mathcal{O}_8}{\Lambda^6}$$

$$c_8 + \frac{v^2}{\Lambda^2} c_{10} \geq 0$$

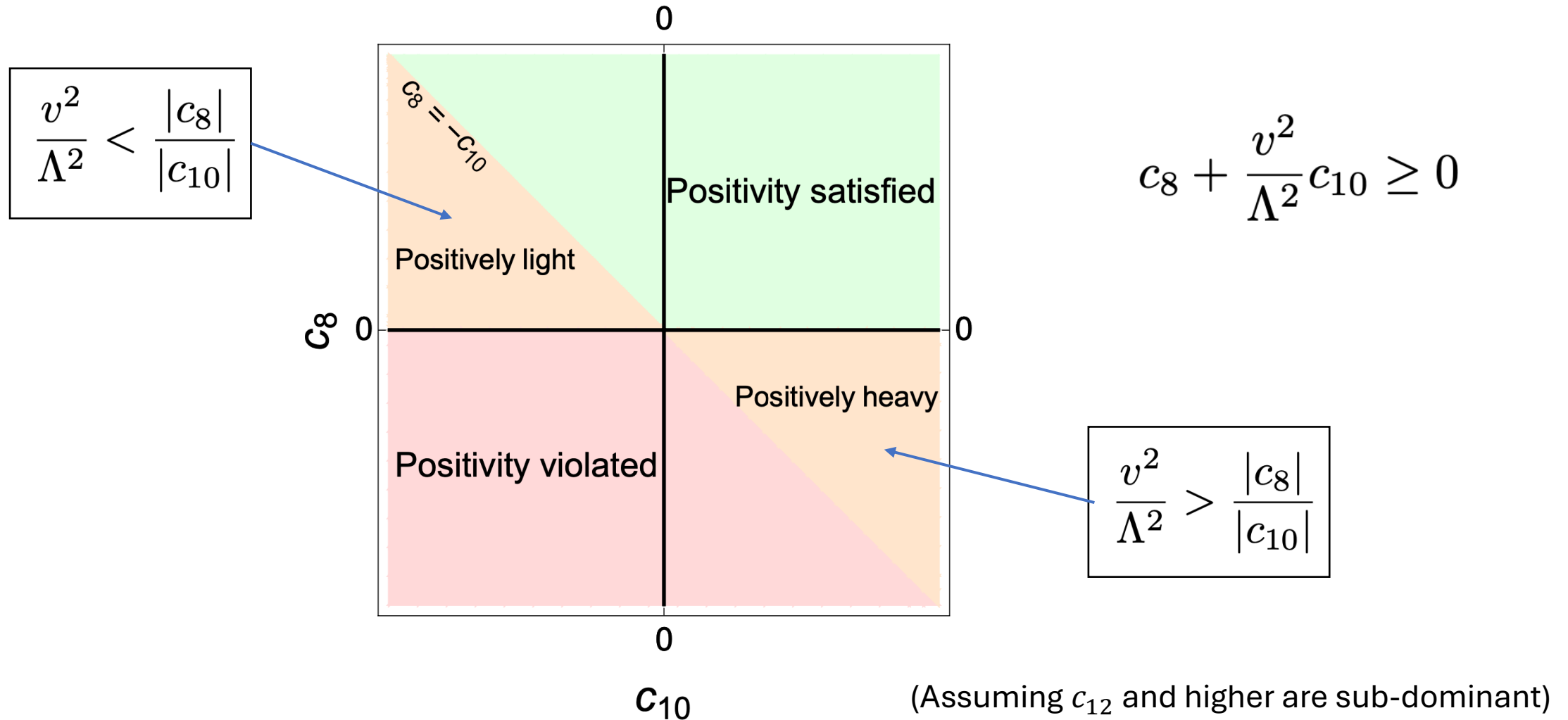
(Assume higher-dimensional operators to be suppressed, though can include them too)

Positivity mandated by unitarity, locality, causality (and Lorentz invariance) of UV

Positively light Higgs

2308.06226 Davighi, Melville, Mimasu, TY

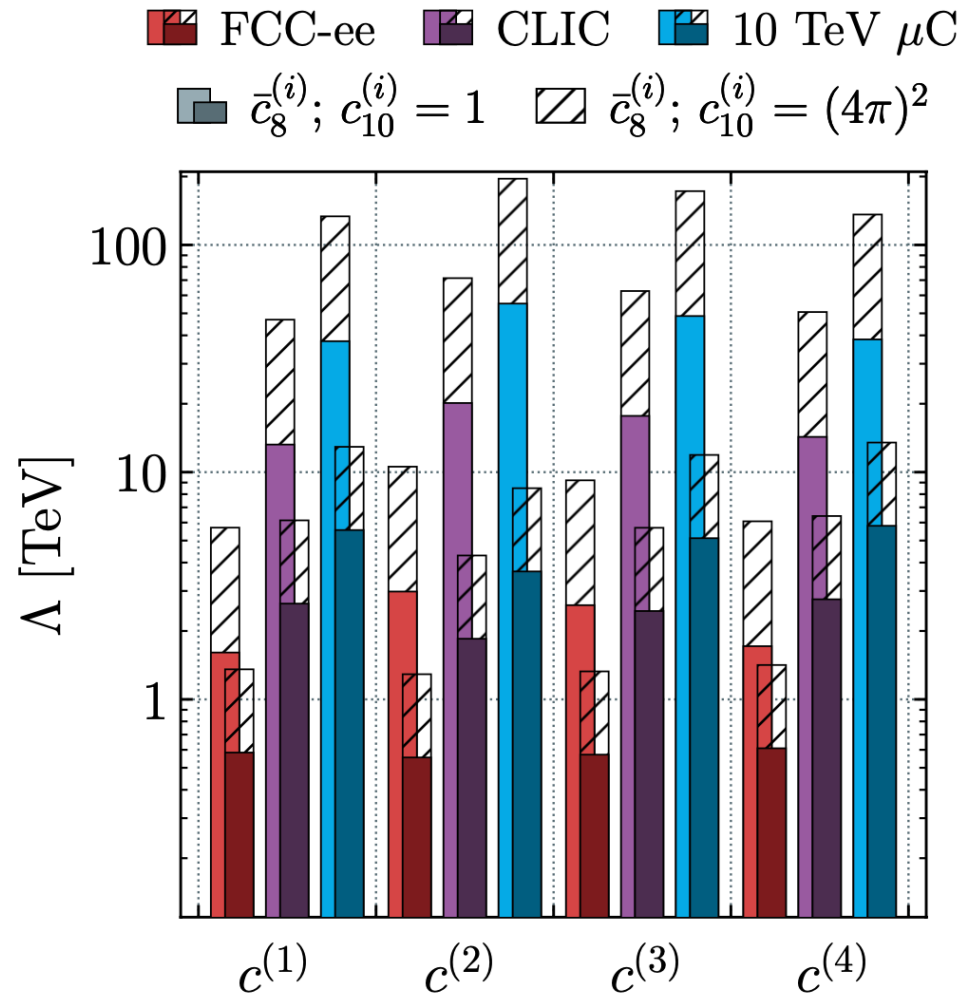
A unitary, local, and causal UV theory that lives in $|c_8| \ll |c_{10}|$ EFT parameter space *necessarily* has restricted vev v



Positively light Higgs

2308.06226 Davighi, Melville, Mimasu, TY

This scenario could *in principle* be established experimentally for a little hierarchy up to O(10) TeV



$$\mathcal{L}_{\text{EFT}}[H] = c_8 \frac{\mathcal{O}_8}{\Lambda^4} + c_{10} \frac{|H|^2 \mathcal{O}_8}{\Lambda^6}$$

$$\mathcal{O}_8^{(1)} = \partial^\nu (\bar{e}_i \gamma^\mu e_i) \partial_\nu (\bar{e}_i \gamma_\mu e_i) ,$$

$$\mathcal{O}_8^{(2)} = \partial^\nu (\bar{e}_i \gamma^\mu e_i) \partial_\nu (\bar{L}_i \gamma_\mu L_i) ,$$

$$\mathcal{O}_8^{(3)} = D^\nu (\bar{e}_i L_i) D_\nu (\bar{L}_i e_i) ,$$

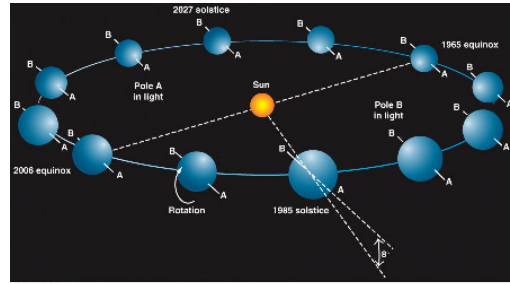
$$\mathcal{O}_8^{(4)} = \partial^\nu (\bar{L}_i \gamma^\mu L_i) \partial_\nu (\bar{L}_i \gamma_\mu L_i) ,$$

See also 2009.02212 Fuks, Liu, Zhang, Zhou

Radically new BSM?

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

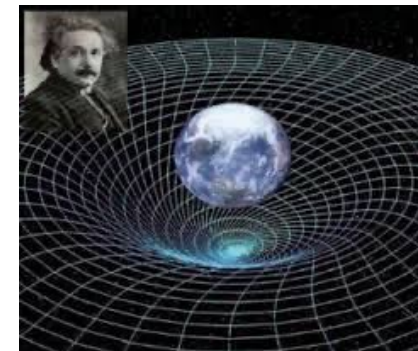
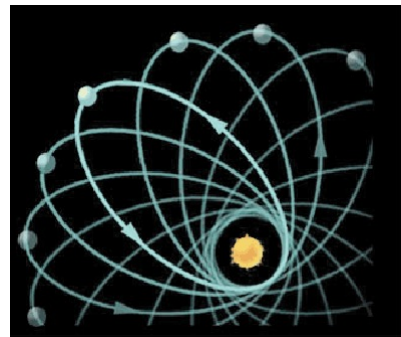
Anomaly in orbit of Uranus



Discovery of Neptune

- Sometimes its implications are *far more radical*

Anomaly in orbit of Mercury



Explained by General Relativity

Conclusion

- TeV scale is the new frontier we should be excited to explore
 - New phenomena every time we reach a new energy scale
- Doing good science is the main motivation
 - Colliders are general-purpose tools for a wide-ranging physics programme
- BSM is just one potential outcome
 - Not the be all and end all --- see every other field of science
- Keep an open mind
 - Spirit of pushing fundamental knowledge and exploration as far as possible

Conclusion

- *“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

Conclusion

- *“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

Conclusion

- 1900: Almost all data agree spectacularly with the fundamental framework of the time, *no reason to doubt its universal applicability or completeness.*
- 1920s: A combination of **precision measurements** (Mercury), **aesthetic arguments** (relativity) supported by **null experimental results** (Michelson-Morley), and **theoretical inconsistencies** (Rayleigh-Jeans UV catastrophe) lead to an overhaul of the fundamental picture at **smaller scales** and **higher energies** after *pushing the frontiers of technology and theory into new regimes.*

Conclusion

- 2020: Almost all data agree spectacularly with the fundamental framework of the time, *no reason to doubt its universal applicability or completeness.*
- 2050s: A combination of **precision measurements** (MW, Hubble), **aesthetic arguments** (naturalness) supported by **null experimental results** (LHC), and **theoretical inconsistencies** (black hole information paradox) lead to an overhaul of the fundamental picture at **smaller scales** and **higher energies** after *pushing the frontiers of technology and theory into new regimes.*