The Branco Weiss Fellowship Society in Science

Challenges and Opportunities in Theoretical Physics

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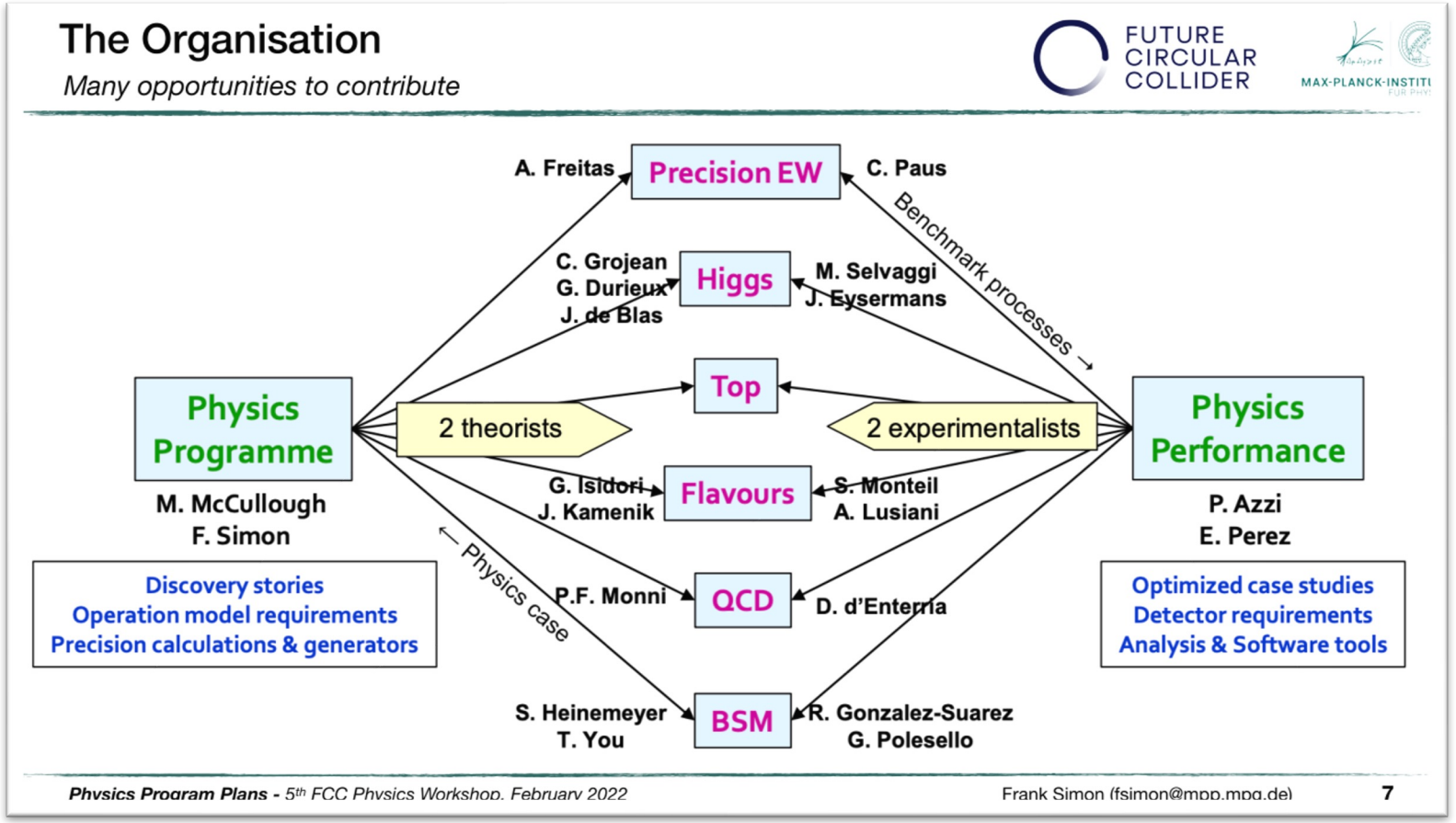
Introduction

- **Challenges**: shifting the narrative and perception of particle physics
- **Opportunities**: high energy and high precision particle collisions are the most comprehensive and wide-ranging probes of fundamental physics
- The prospect of seeing *terra incognita* data from future colliders is amongst the most exciting in all of science!
- *Disclaimer*: as a BSM convenor for the FCC feasibility study, to me **future colliders = FCC**

Introduction

- **FCC feasibility study** under way, to be reviewed/**completed** by end of 2023/**2025**



Slide by Frank Simon

- **Open to suggestions** for BSM studies at FCC

Introduction

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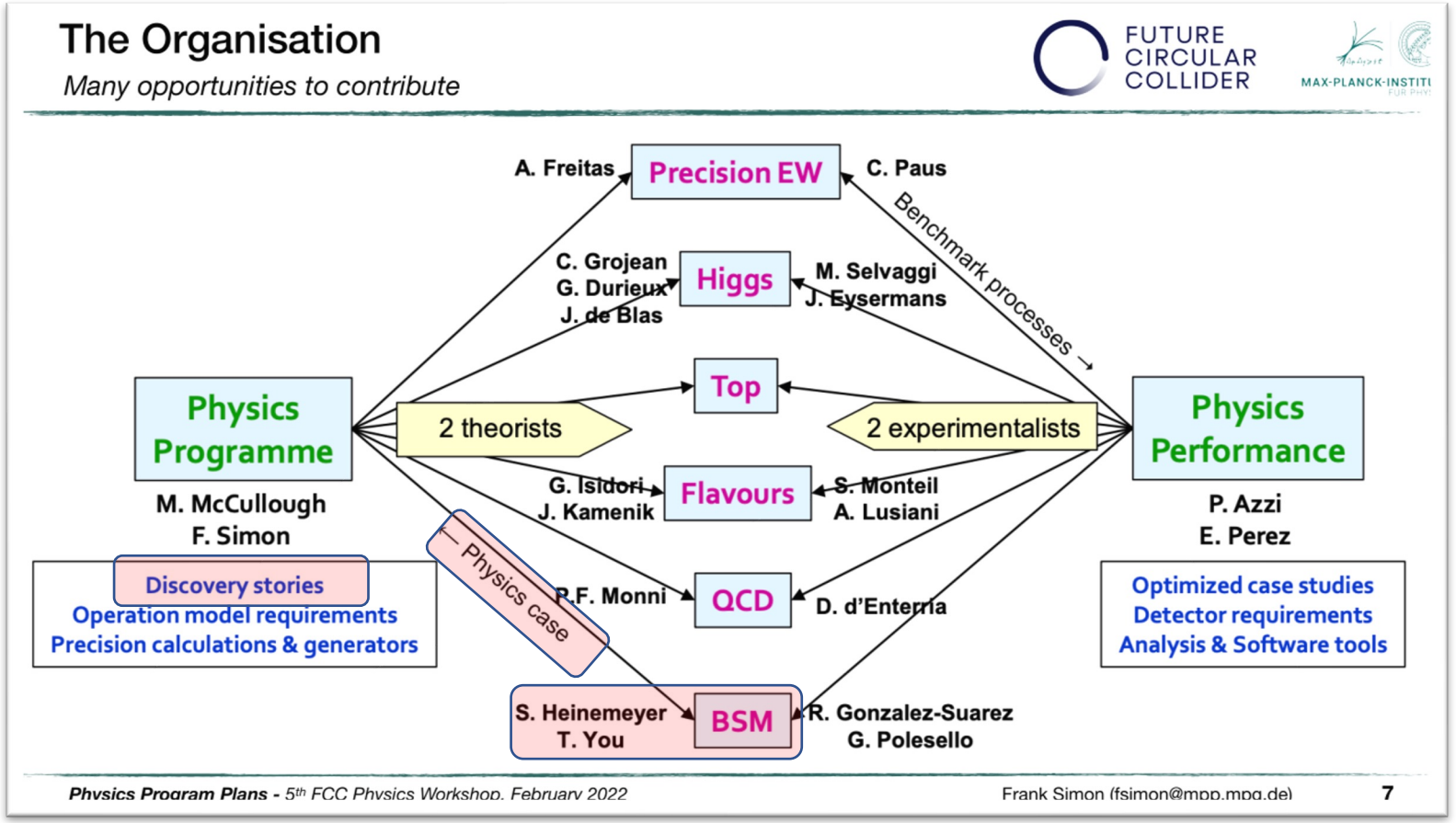


Slide by Frank Simon

- **Note**: *JWST or LIGO did not promise to discover exotic new physics or break GR*

“Discovery stories” → “Exploring origins”

- What is the **purpose** of the FCC?

  To explore the fundamental origins of our universe and its laws

- **Exploring**, not searching
  - *“Exploring the origins of our universe”* is a more accurate **mission statement**, unlike e.g. *“searching for supersymmetry and dark matter”*
  - *“Exploring the origin of the Higgs”* simpler to convey than **naturalness**

- *“Discovery stories”* risks putting the focus on *promising* to **find new physics**
- *“Exploring origins”* puts the focus on **open BSM questions** to be answered
  - Emphasises the FCC as a **general purpose particle observatory** with a *wide-ranging physics programme,* rather than e.g. an expensive search for supersymmetry

(My proposal: rename FCC to the **International Particle Observatory**)

FCC as an origins explorer

- **Origin of matter**
  - EW phase transition, CP violation, baryogenesis, etc.
- **Origin of the Higgs**
  - BSM in post-naturalness era, supersymmetry, compositeness, etc.
- **Origin of flavour**
  - BSM flavour models, B anomalies, g-2, etc.
- **Origin of dark matter**
  - Including dark sectors more generally
- **Origin of neutrinos**
  - BSM neutrino models, neutrino portal, etc.
- **Origin of the Standard Model**
  - SM is an EFT of an underlying UV theory that it originates from: SMEFT (or HEFT)

Origin of matter

- Open question
  - *matter-antimatter asymmetry*

- BSM models:
  - Higgs+singlet first-order **EW phase transition**
  - *New sources* of **CP violation**

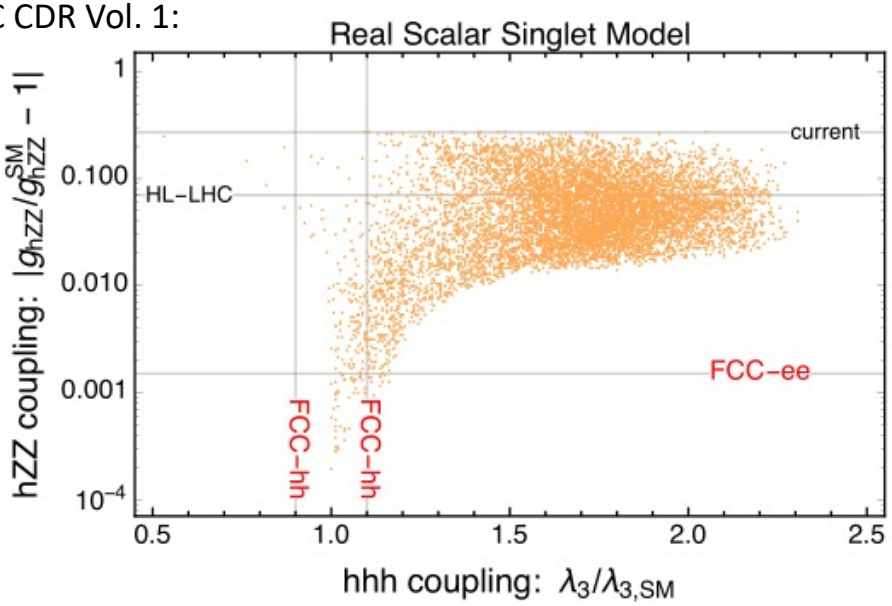
    e.g. 2112.03889 Bonnefoy, Gendy, Grojean, Ruderman
  - **Baryogenesis/Leptogenesis**

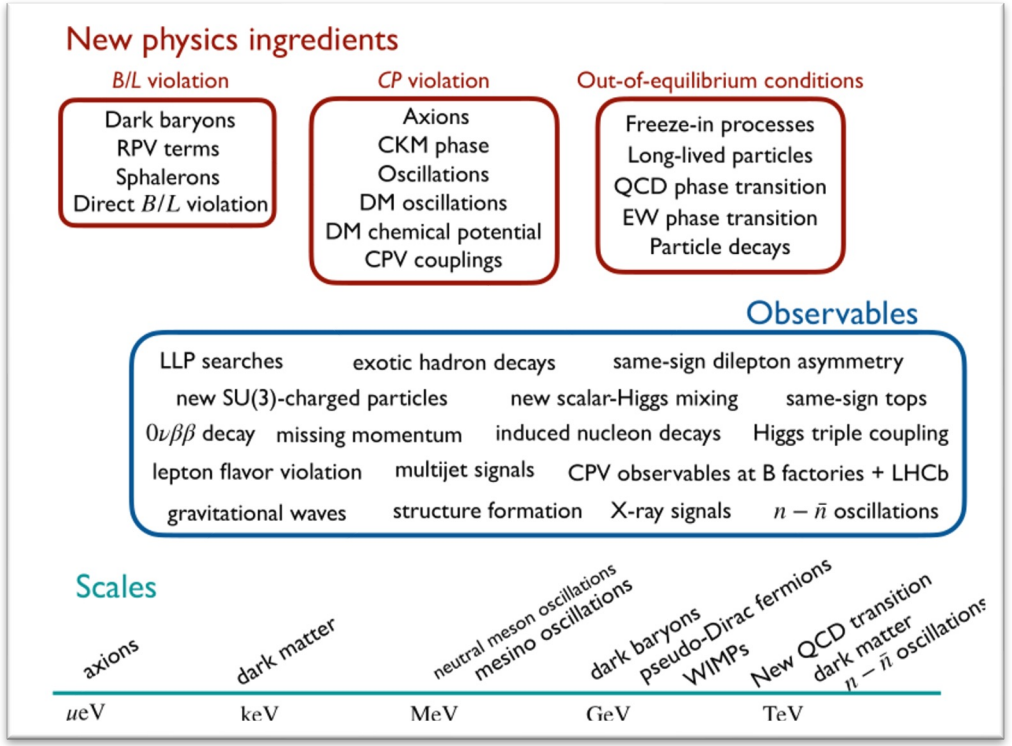
    e.g. 2203.05010 Snowmass white paper:

- Observables:
  - Higgs (self-)couplings, exotics, LFV, etc.

- Connection to other working groups:
  - Higgs, precision EW, top, flavour

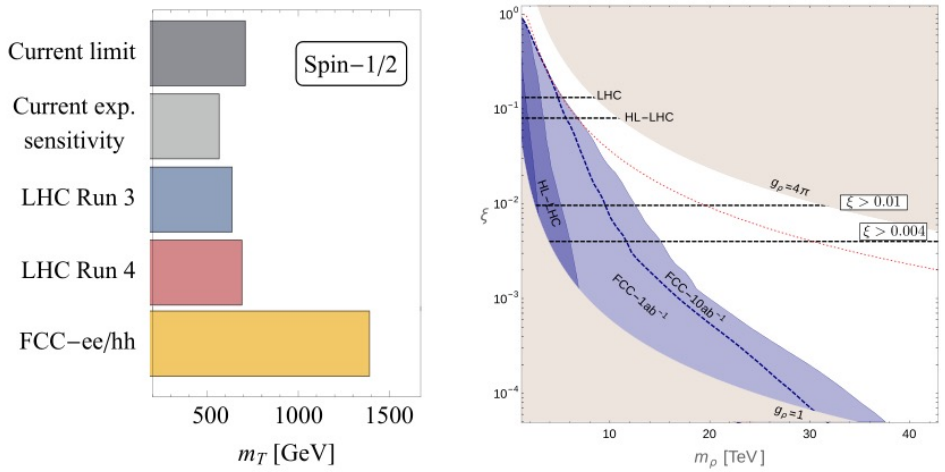
FCC CDR Vol. 1:





Origin of the Higgs

Complementarity between ee and hh:



FCC CDR Vol. 1,
Thamm, Torre, Wulzer, 1502.01701

- Open question
  - Is the Higgs **composite** or **elementary**?
  - Are there **extra spacetime symmetries** or **dimensions**?
  - Do these concepts play a role in *addressing the naturalness problem*?
  - Is a **new principle** at play in the Higgs sector?

- BSM models:
  - Conventional **symmetry-based** solutions: *e.g. supersymmetry, compositeness/extra-dimensions*
  - **Hidden** symmetry-based solutions: *e.g. Twin Higgs* e.g. 2202.01228 Durieux, McCullough, Salvioni
  - **Post-natural** BSM
    - i.e. *accept large hierarchy of scales*, whether **accidental** or natural via **cosmological dynamics** or some **UV/IR mechanism**
    - *Split supersymmetry, relaxion, self-organised localisation, vacuum metastability, …*

    e.g. 2105.08617 Giudice, McCullough, TY
    2108.09315 Khoury, Steingasser

- Observables:
  - Higgs (self-)couplings, SUSY searches, exotics, VL fermions, BSM triple Higgs couplings …

- Connection to other working groups:
  - Higgs, precision EW, top, flavour

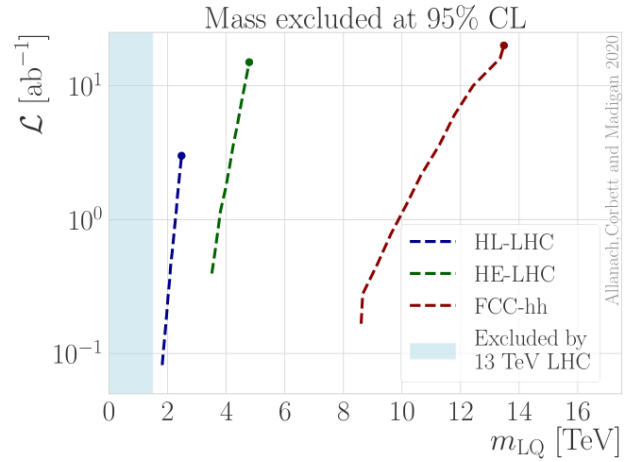
Origin of flavour

- Open question
  - *Structure of Yukawas and CKM?*

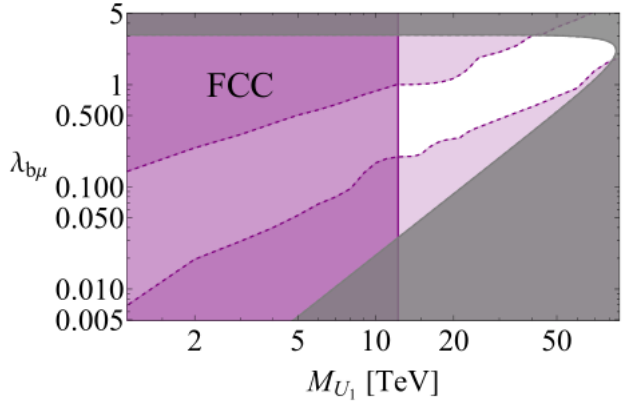
- BSM models:
  - Models addressing **B anomalies** and **muon g-2**
  - *Z', leptoquarks, VL fermions*

- Observables:
  - Higgs (self-)couplings, light yukawas, flavour, top, dileptons, etc.

- Connection to other working groups:
  - Higgs, precision EW, top, flavour, QCD



Allanach, Corbett, Madigan [1911.04455]



Azatov et al [2205.13552]

Table S.4: Expected production yields for b-flavoured particles at FCC-ee at the Z run, and at Belle II (50 ab^{-1}) for comparison.

particle production (10^9)	$B^0/\bar{B}^0$	B^+/B^-	$B_s^0/\bar{B}_s^0$	$\Lambda_b/\bar{\Lambda}_b$	$c\bar{c}$	$\tau^+\tau^-$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-ee	1000	1000	250	250	550	170

FCC CDR Vol. 1

Origin of dark matter

- Open question
  - What is the **microscopic particle nature** of dark matter?
  - Is there an **extended dark sector**?

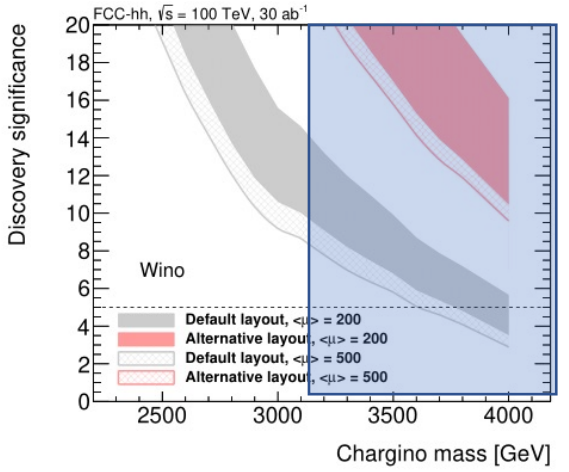
- BSM models:
  - **Higgsino**, **winos**, more general WIMPs
  - **Higgs portal**
  - **ALPs**

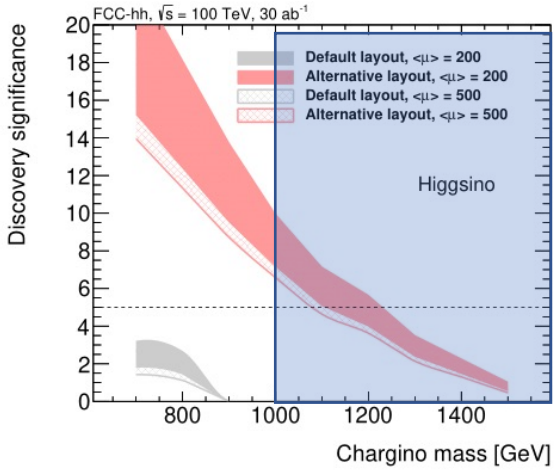
- Observables:
  - Higgs (self-)couplings, Higgs invisible decays, MET, LLPs (**SND/FASER@FCC?),** etc.

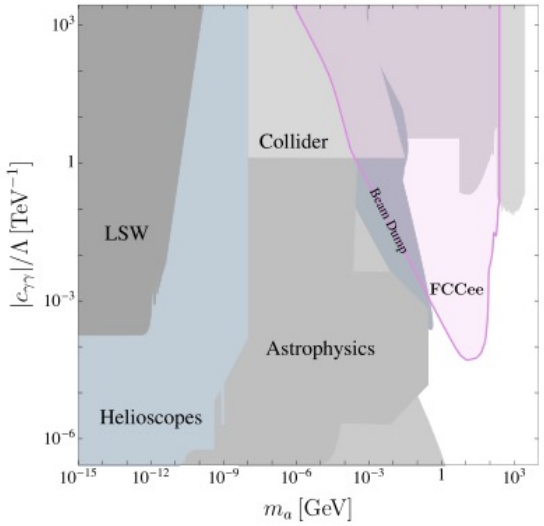
- Connection to other working groups:
  - Higgs, precision EW

FCC-hh: coverage of *entire* thermal WIMP doublet and triplet DM!

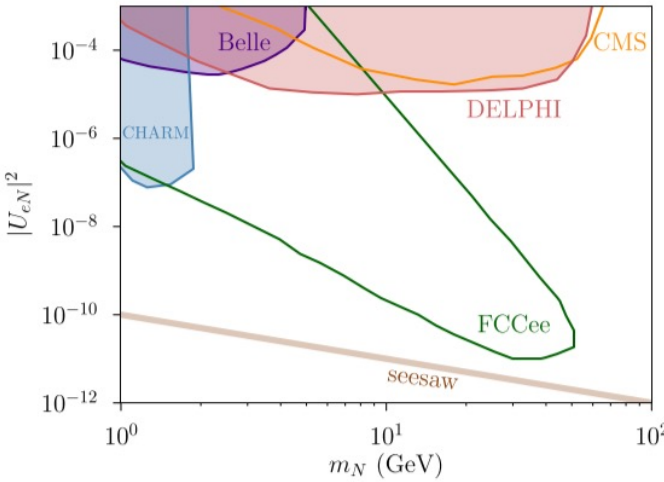
FCC CDR Vol. 1:







Bauer et al 1808.10323



Knapen, Thamm 2108.08949

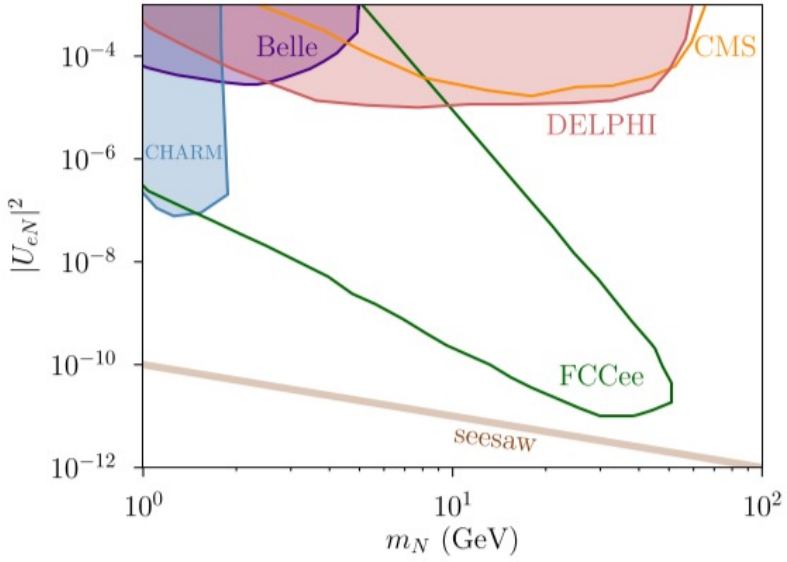
Origin of neutrinos

- Open question
  - Is there an **extended neutrino sector**?

- BSM models:
  - *Symmetry-protected* **pseudo-Dirac neutrinos**, low type-I **see-saw**?
  - Connection to **leptogenesis**, **Higgs**, **dark sectors**?

- Observables:
  - Higgs decays, final state leptons, exotics, LLPs, …

- Connection to other working groups:
  - Higgs, precision EW



Knapen, Thamm 2108.08949

Origin of the SM

- Open question
  - What is the **scale of the underlying theory** that *the SM originates from*?
  - Are there other particles that get most of their mass from the Higgs?

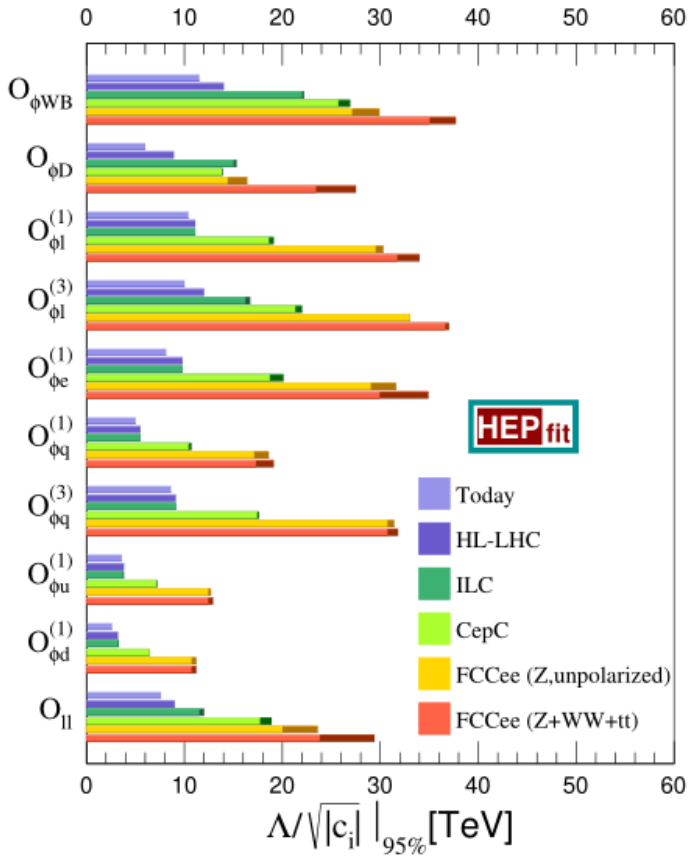
e.g. 2110.02967 Banta, Cohen, Craig, Lu, Sutherland

- BSM models:
  - **SMEFT** framework
  - Simplified models for SM extensions
  - **Positivity**, BSM *beyond EFT/QFT*?, …

    e.g. 2011.03055 Gu, Wang, Zhang

- Observables:
  - Higgs (self-)couplings, longitudinally polarized vector bosons, multi-bosons, direct searches, etc.

e.g. 1812.09299 Henning, Lombardo, Riembau, Riva

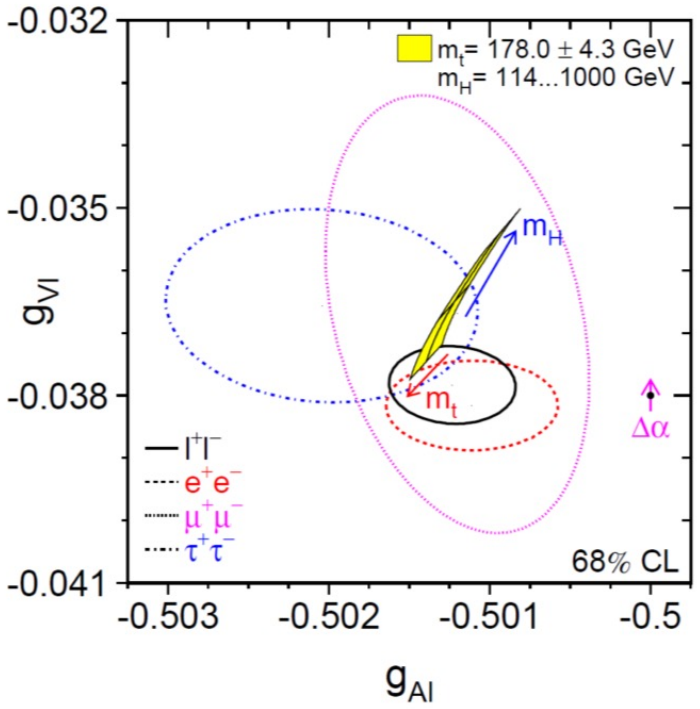


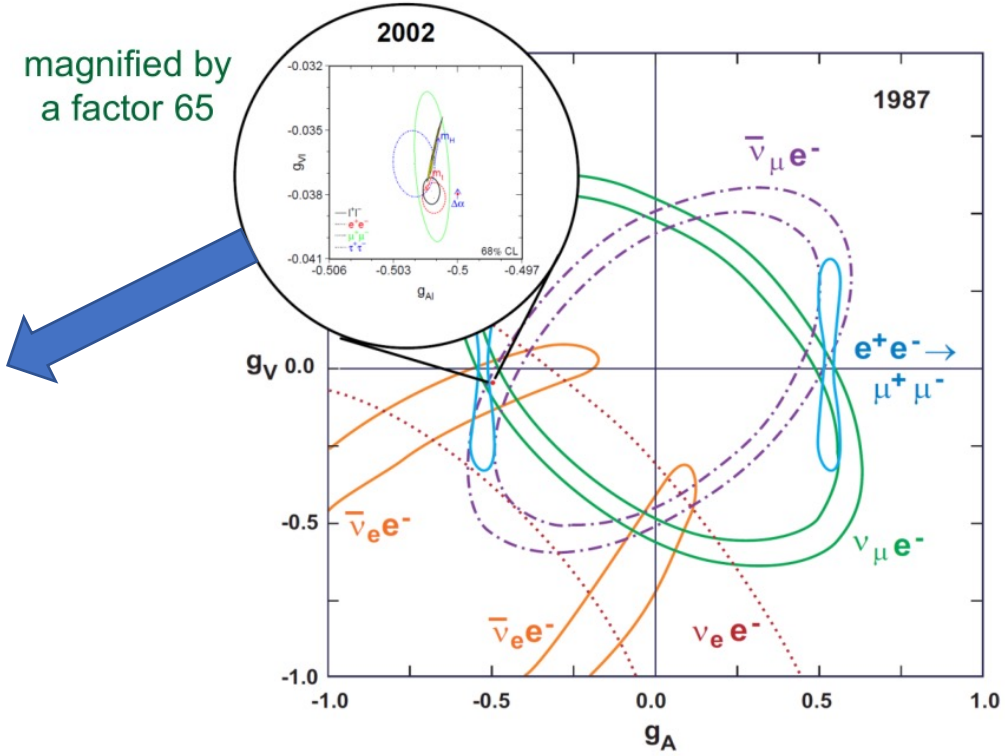
1611.05354 de Blas et al

- Connection to other working groups:
  - Higgs, precision EW, top, flavour, QCD

No BSM is still a success story

- 1980-1990s: LEP physics programme **a resounding success**
- Improved our fundamental picture of nature *by orders of magnitude*



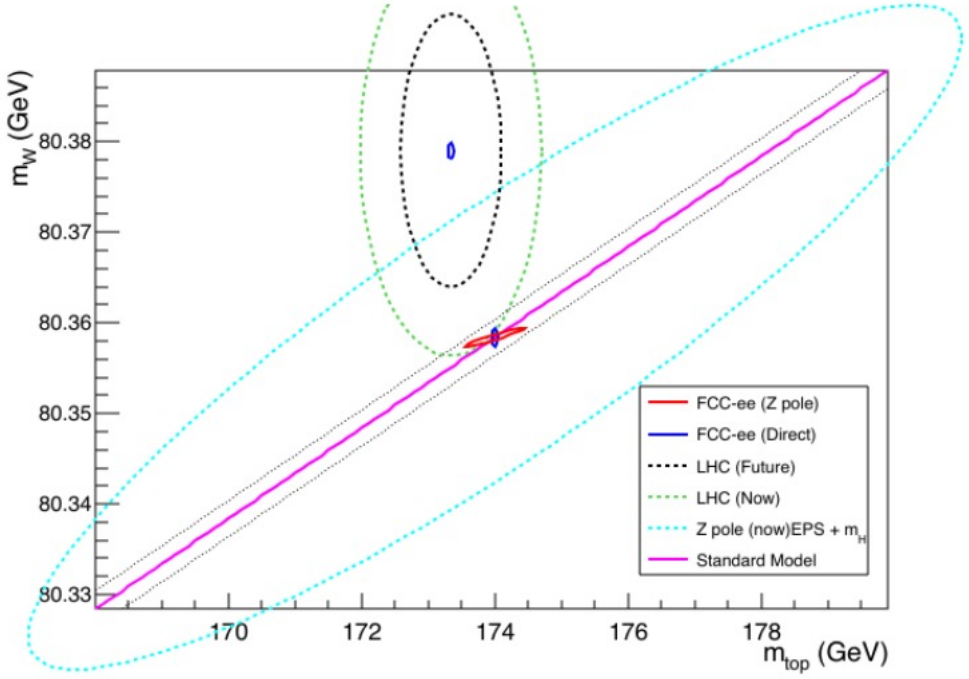


Guy Wilkinson slide

- *Indirect precision probe* of physics at **higher energies**

No BSM or new discoveries at FCC-ee

- Further **zooming in** on our fundamental picture of nature



- **Rich physics programme** covering Higgs, top, electroweak, multi-bosons, flavour, rare decays, neutrinos, QCD, heavy ions *and more*.

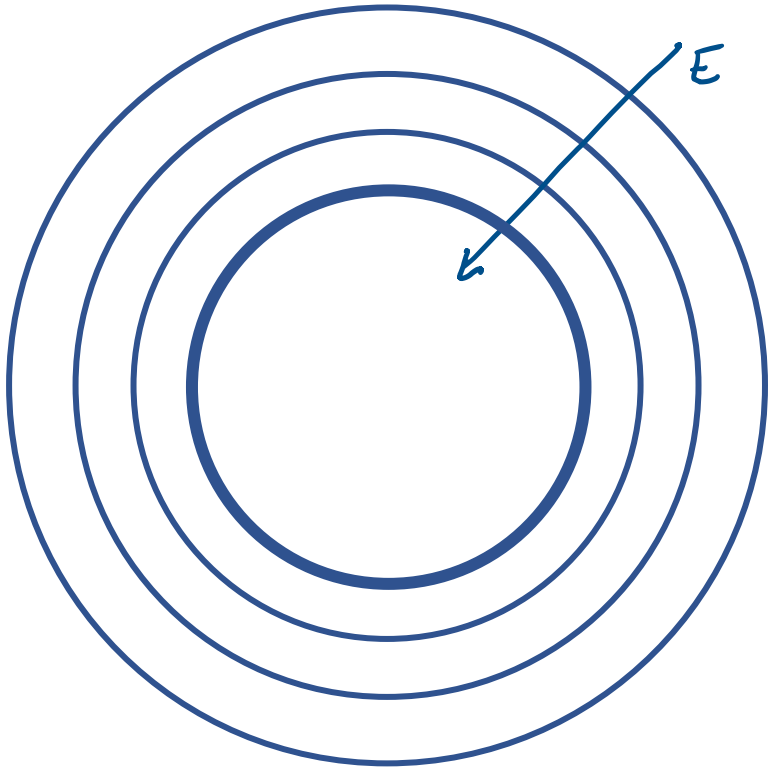
No guarantee of new discoveries at FCC-hh

- **No guarantee of discovery** at Tevatron either. Hadron collisions thought by some *to be too messy to do physics*.
- **Value in pushing frontiers**: we learn something *regardless of outcome*
- **Definite questions** are answered, *even if in the negative*
- Science is about *continually refining existing knowledge* and *exploring the unknown*
- **A new generation** of data management, analysis techniques, improved measurements, theoretical calculational tools, hardware development, cutting-edge engineering, large international collaboration, popular culture inspiration, and spirit of fundamental exploration**, can only benefit humanity** regardless of our own short-sighted disappointment at lack of BSM. *Doing good science is its own reward.*

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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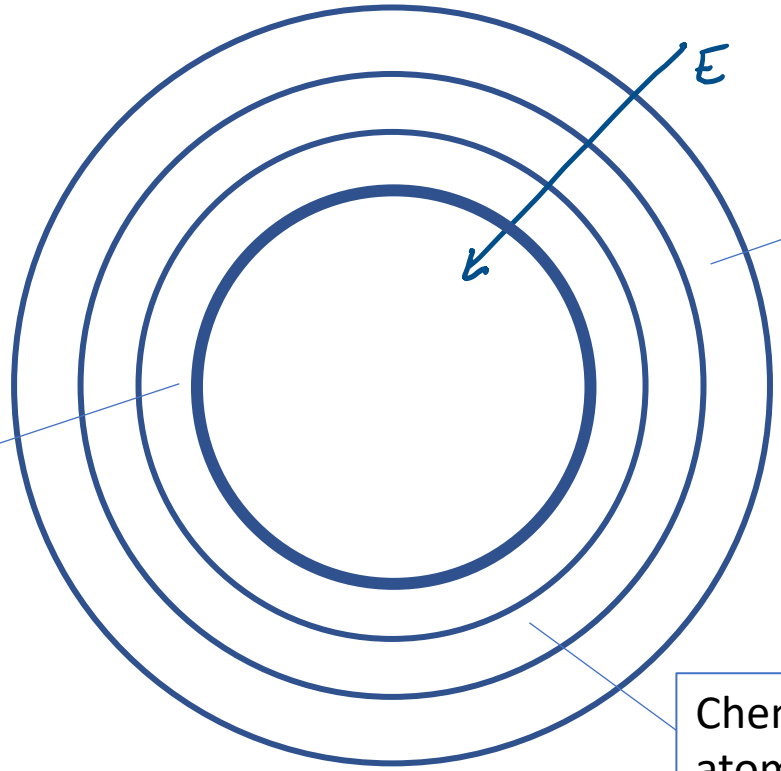

Planetary dynamics, thermodynamics, fluid dynamics, …

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**

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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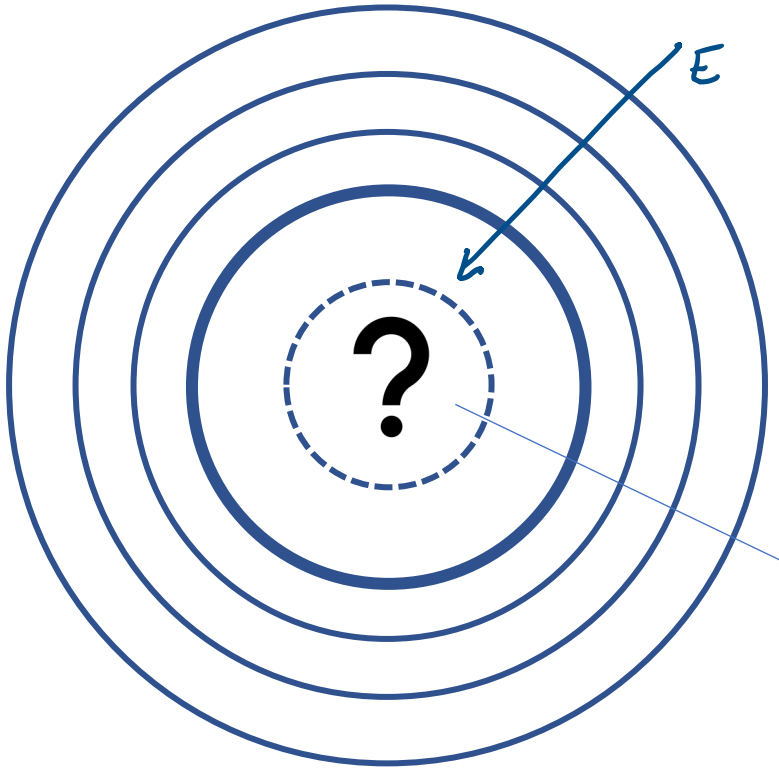

Unnatural Higgs means the next layer *is no longer predictive* without including contributions *from much smaller scales*

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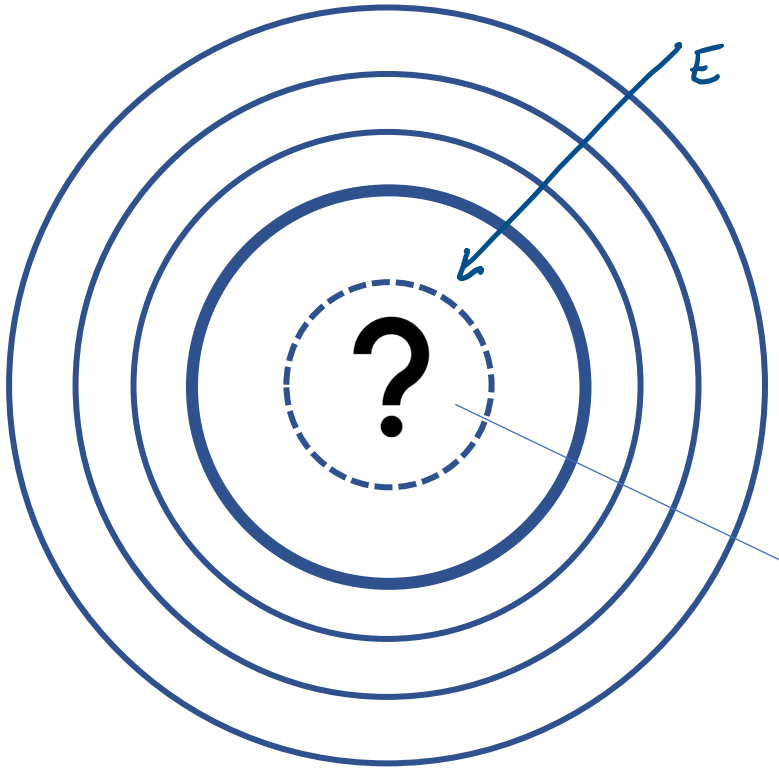


Unnatural Higgs means the next layer *is no longer predictive* without including contributions *from much smaller scales*

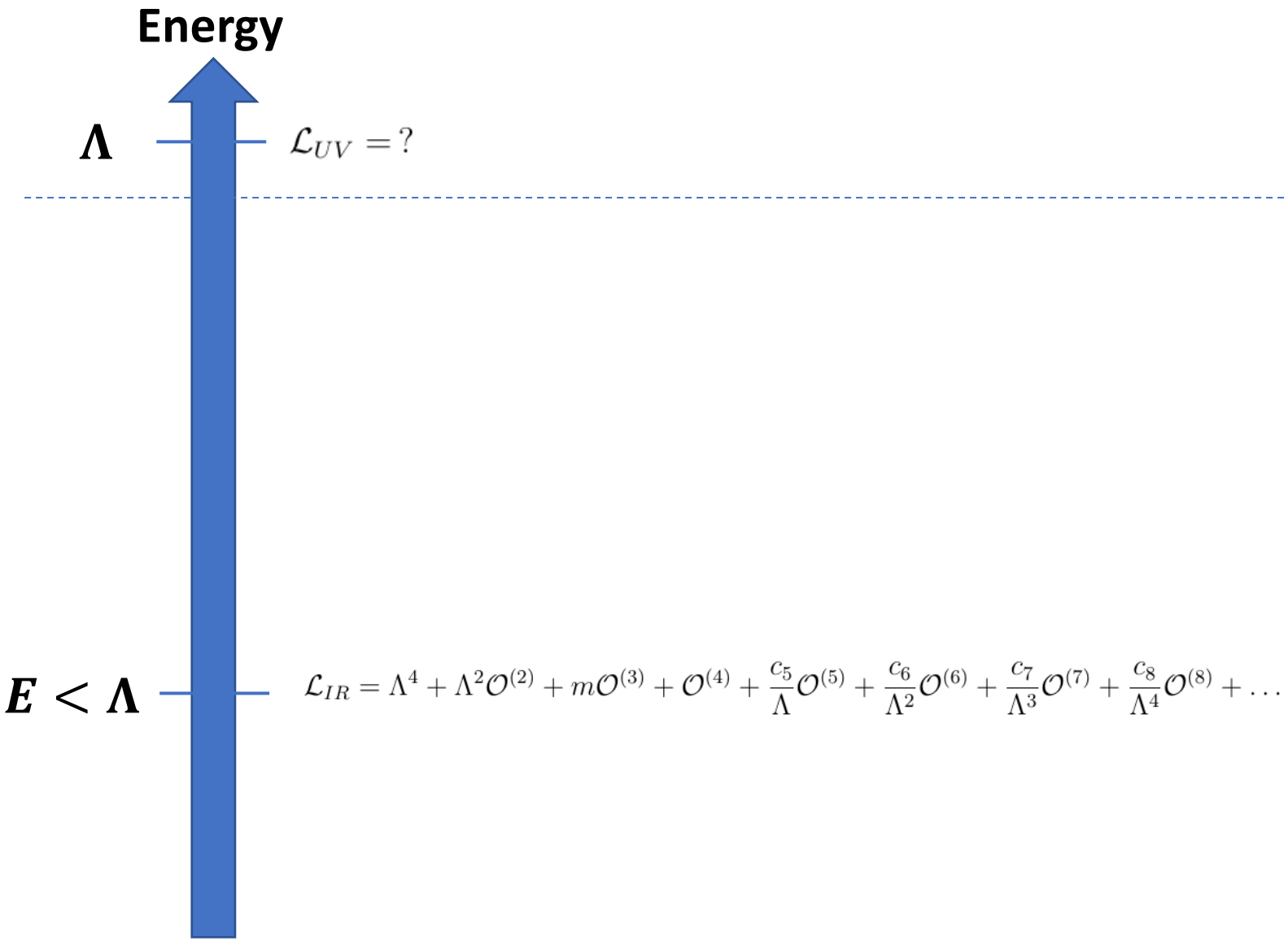
- Are we missing a **fundamentally new** *"post-naturalness"* principle?

c.f. null results in search for aether

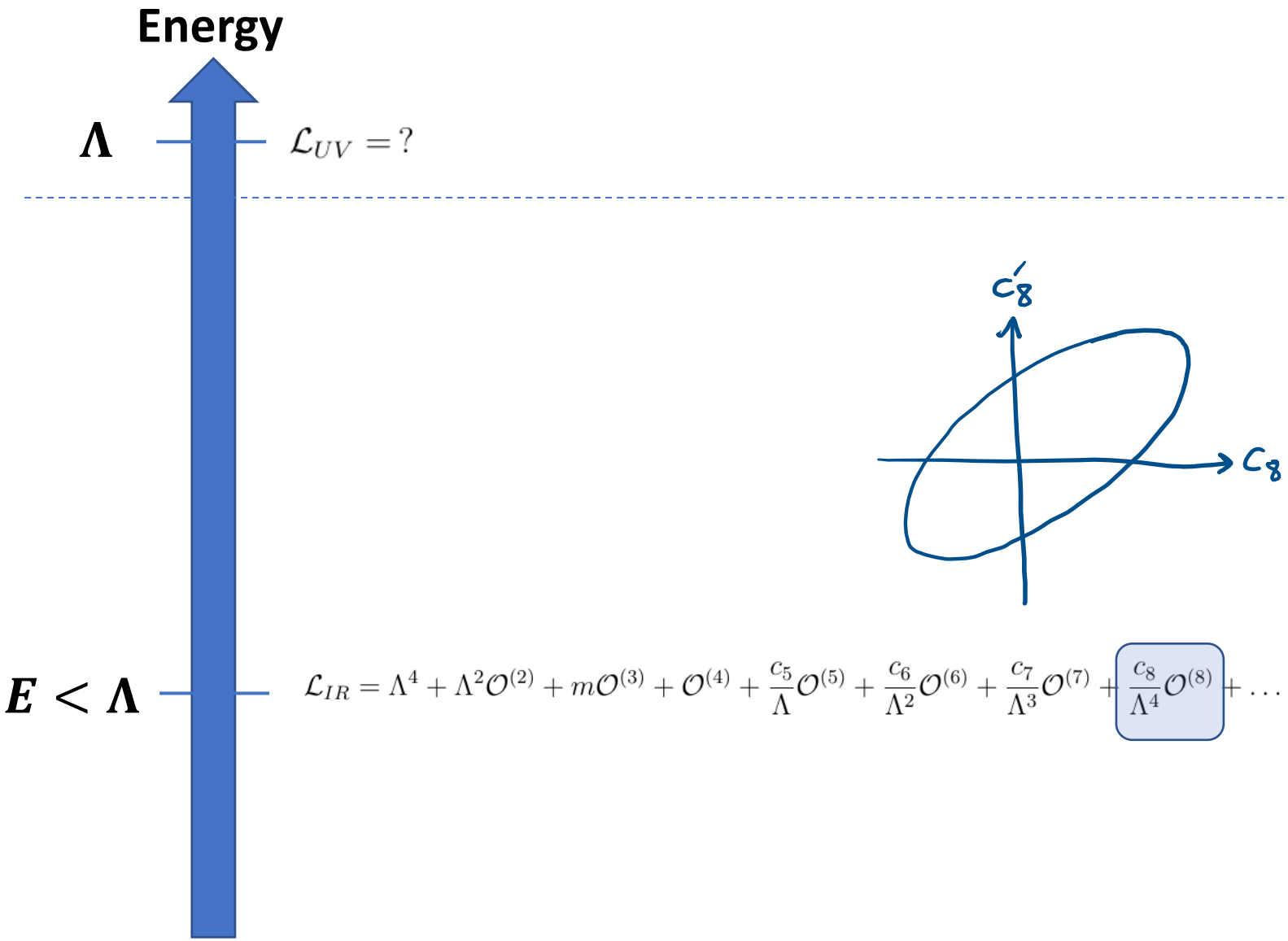
Potential BSM outcomes for naturalness at FCC

- **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
  - 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?

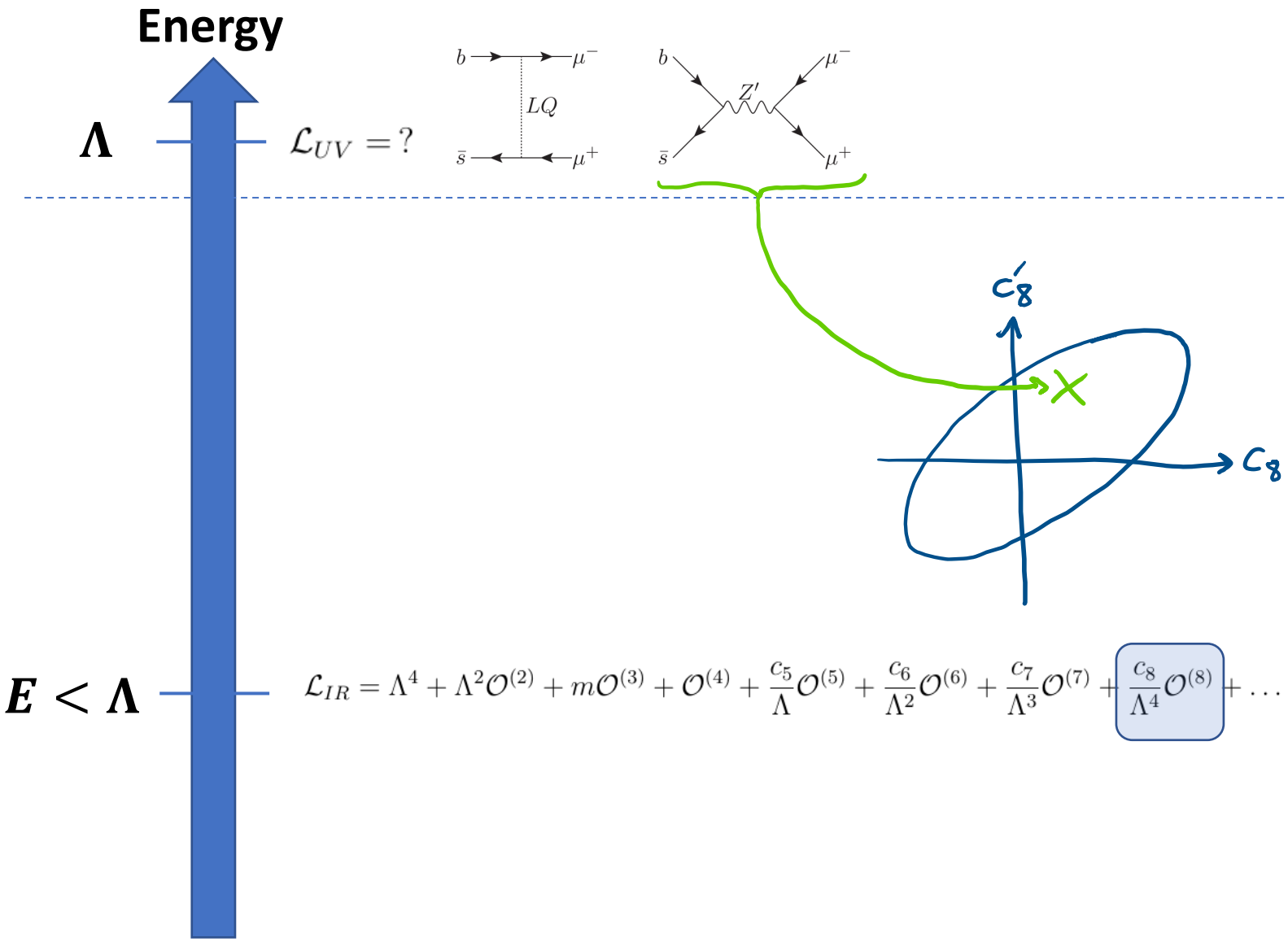


Radically new BSM?



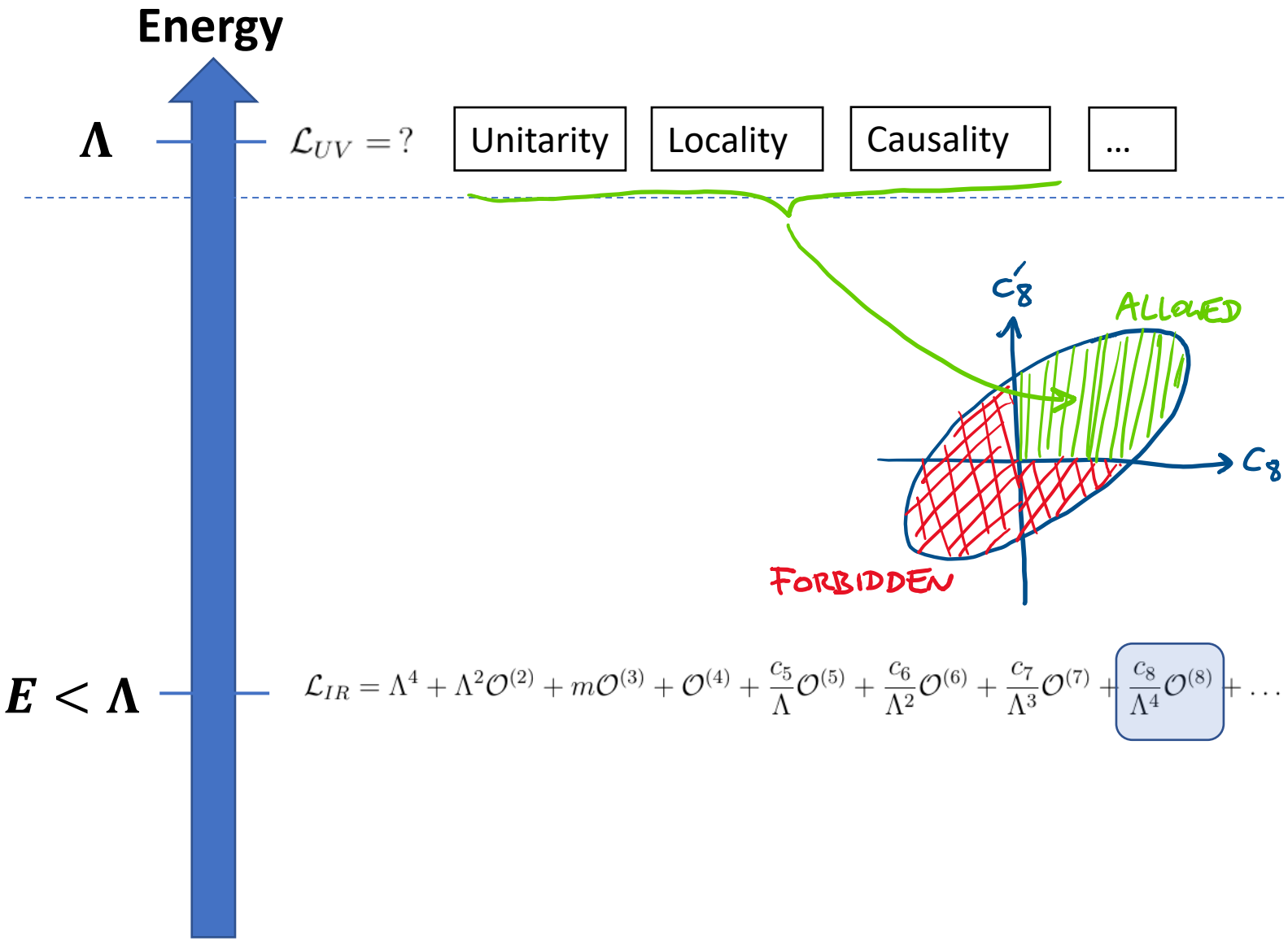
e.g. Consider indirect sensitivity to UV theory

Radically new BSM?



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

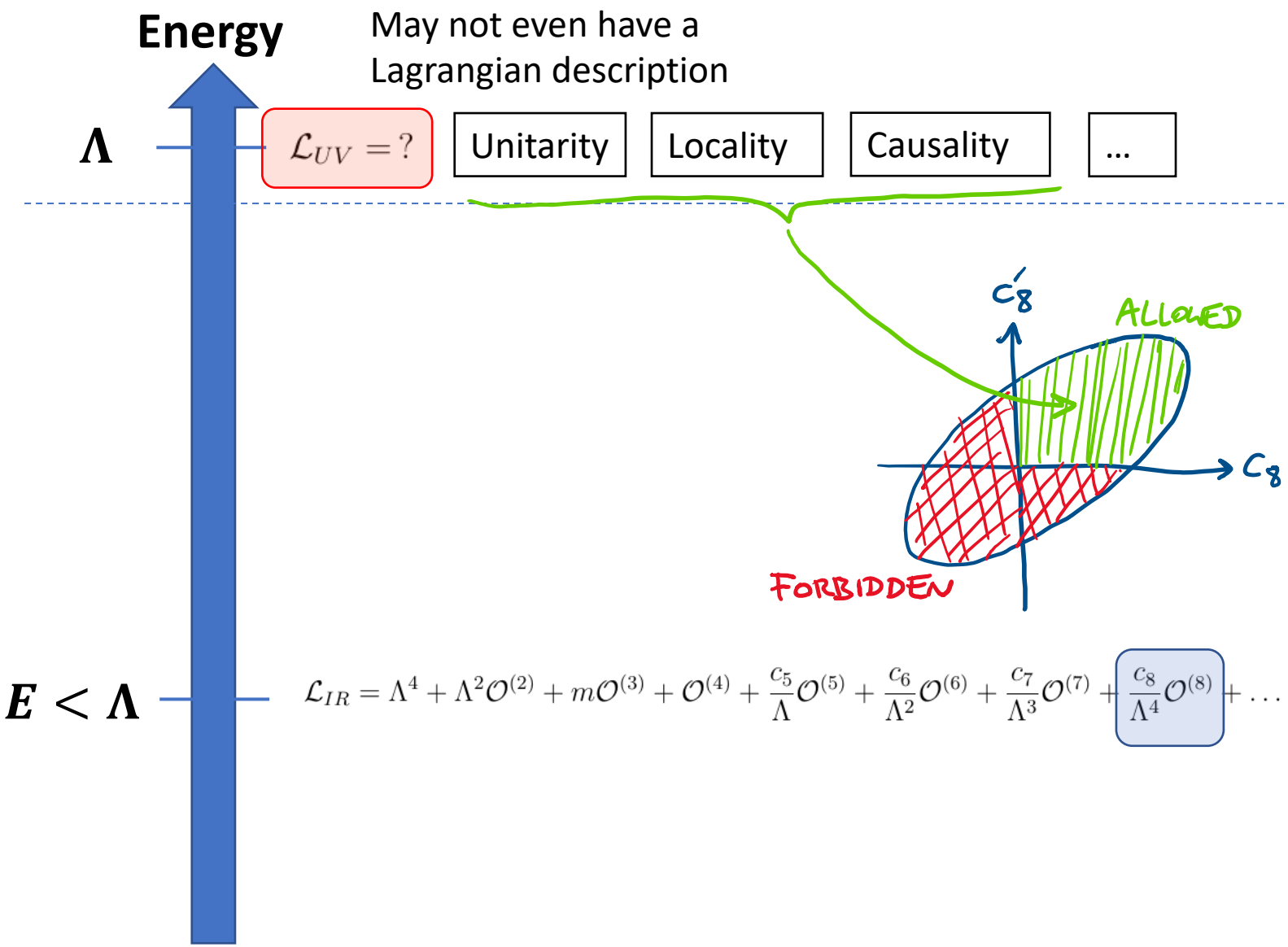
Radically new BSM?



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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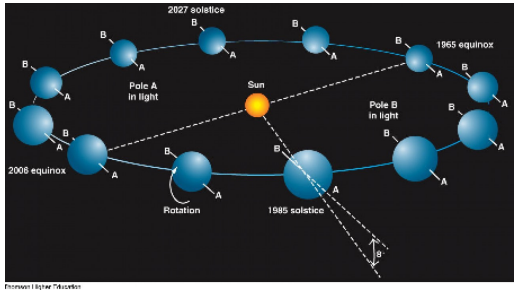
Radically new BSM?

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

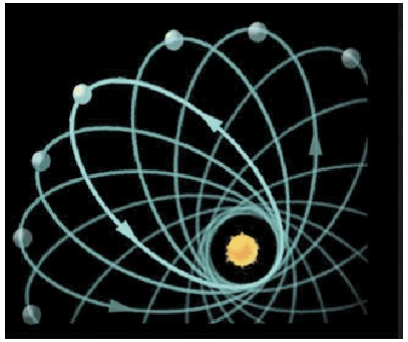
Anomaly in orbit of Uranus

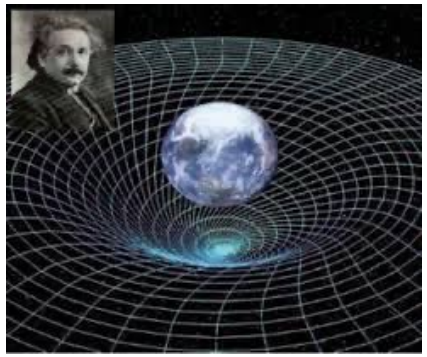


Discovery of Neptune

- Sometimes its implications are *far more radical*

Anomaly in orbit of Mercury



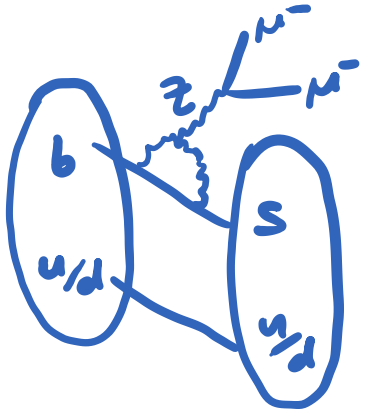


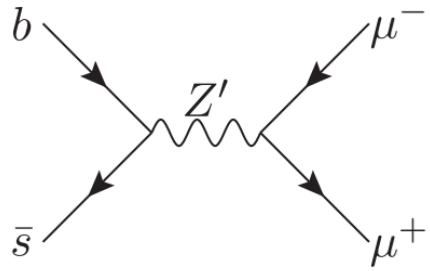
Explained by General Relativity

Radically new BSM?

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

Anomaly in Flavour physics

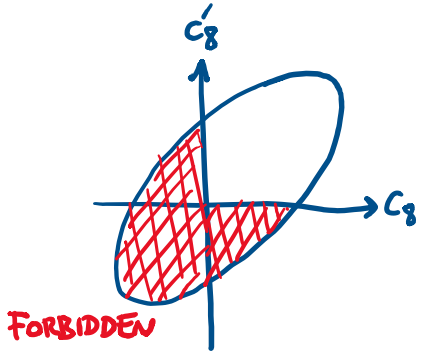




Discovery of Z'?

- Sometimes its implications are *far more radical*

Anomaly in positivity bounds?



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

Explained by ???

Conclusion

- **FCC** is *vital* to the **future of fundamental physics**
  - *No realistic alternative to FCC-ee+hh combined physics case x feasibility*
- Emphasise *narrative*, not models
- New cases for BSM benchmarks?
  - e.g. probing the origin of gravitational waves in TeV scale phase transitions
- Blind spots in design decisions?
- FCC BSM e-group mailing list:

https://e-groups.cern.ch/e-groups/EgroupsSubscription.do?egroupName=FCC-PED-PhysicsGroup-BSM

Backup

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** (B mesons, 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*.

Potential BSM outcomes at FCC

- 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*.

Potential BSM outcomes at FCC

- 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

This slightly facetious example is nevertheless one possible scenario…