Cosener's house, Abingdon NExT PhD summer school, 15th July 2024

The Branco Weiss Fellowship Society in Science

Beyond the Standard Model

Tevong You

Imperial College London — MERRILL LYNCH — ETH zürich — KING'S College LONDON — UNIVERSITY OF CAMBRIDGE — CERN — KING'S College LONDON

Undergraduate → Industry → MSc → PhD → Junior Research Fellow → Senior Research Fellow → Lecturer

Literature

- -Andrea Wulzer BSM lectures: https://arxiv.org/abs/1901.01017
- -Matthew McCullough BSM lectures: https://inspirehep.net/literature/1684708
- -Hitoshi Murayama supersymmetry phenomenology: https://arxiv.org/abs/hep-ph/0002232
- -Nathaniel Craig review of naturalness: https://arxiv.org/abs/2205.05708
- - Arkani-Hamed, Huang, Huang paper that contains a nice review of the on-shell amplitudes approach to classifying all allowed massless interactions: https://arxiv.org/abs/1709.04891

Contents

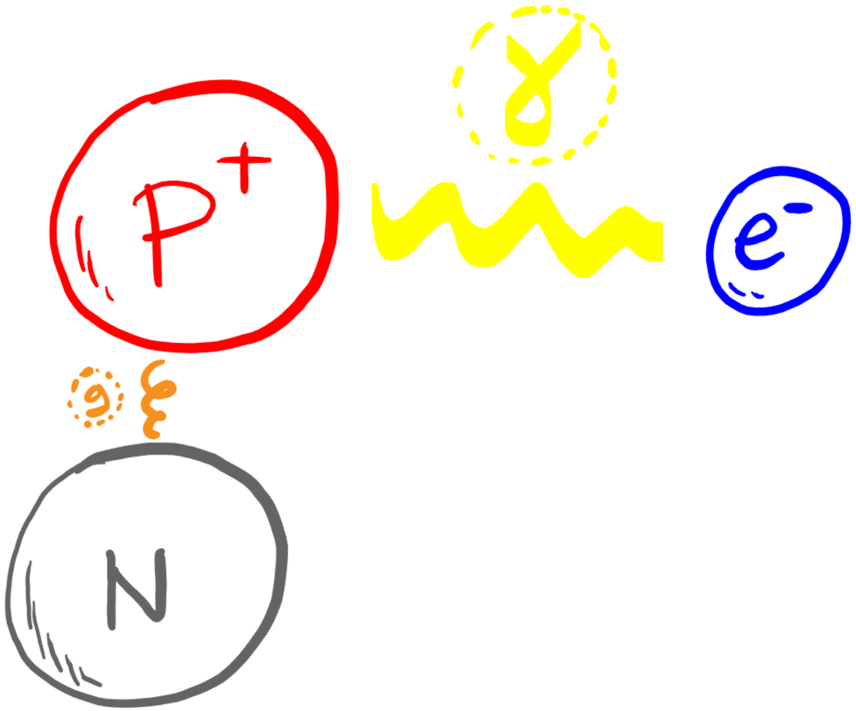
- **Review** of the situation
- **EFT** as a window to BSM
- **Naturalness** and the Higgs boson
- **Speculations** on BSM outcomes for naturalness

Introduction

- **3 lessons** from history

Introduction

- *1930s*: *everything* is made of **protons**, **neutrons**, and **electrons**

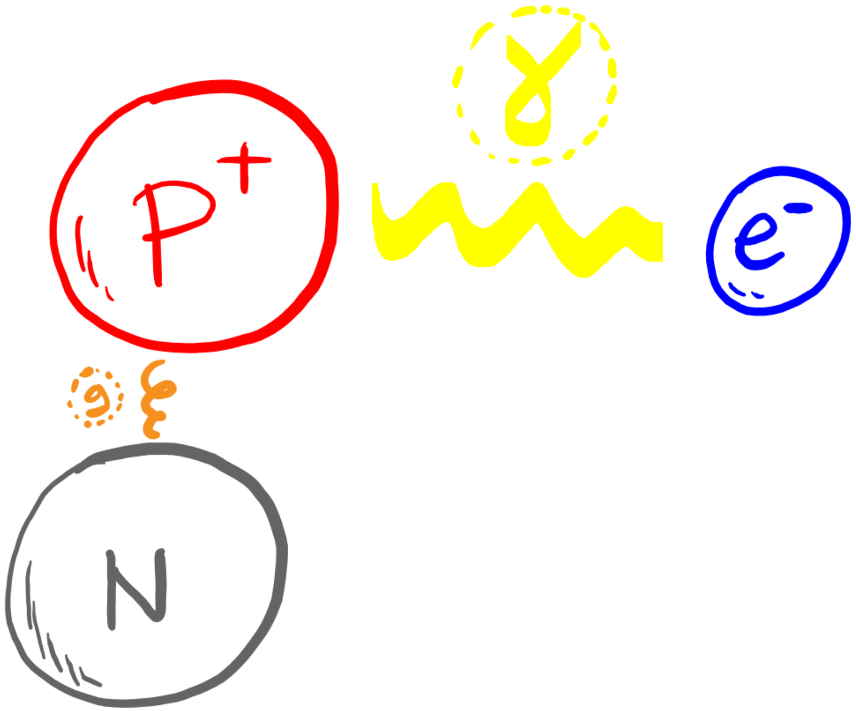


Minimal, economical theory!
However…

- Held together by **electromagnetism** and the **strong force**

Introduction

- *1930s*: *everything* is made of **protons**, **neutrons**, and **electrons**



"If we consider protons and neutrons as elementary particles, we would have three kinds of elementary particles [p,n,e]…. This number may seem large but, from that point of view, two is already a large number."

Paul Dirac 1933 Solvay Conference

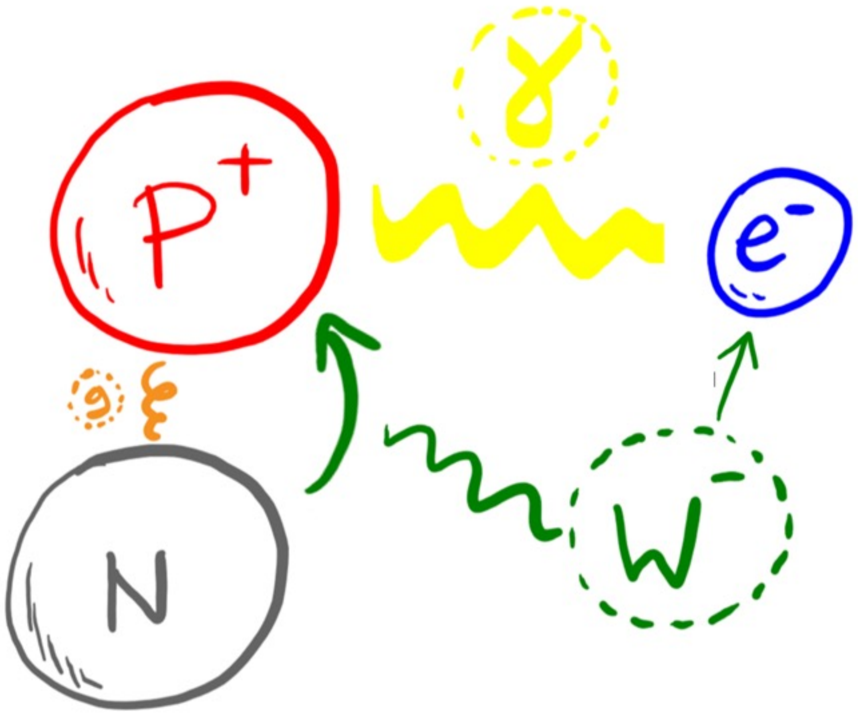
From D. Tong slide

Lesson 1: Beauty in fundamental physics is not an economy of particle multiplicities, it's an *economy of theoretical principles*

- Held together by **electromagnetism** and the **strong force**

Introduction

- **Weak force** explains *radioactivity*

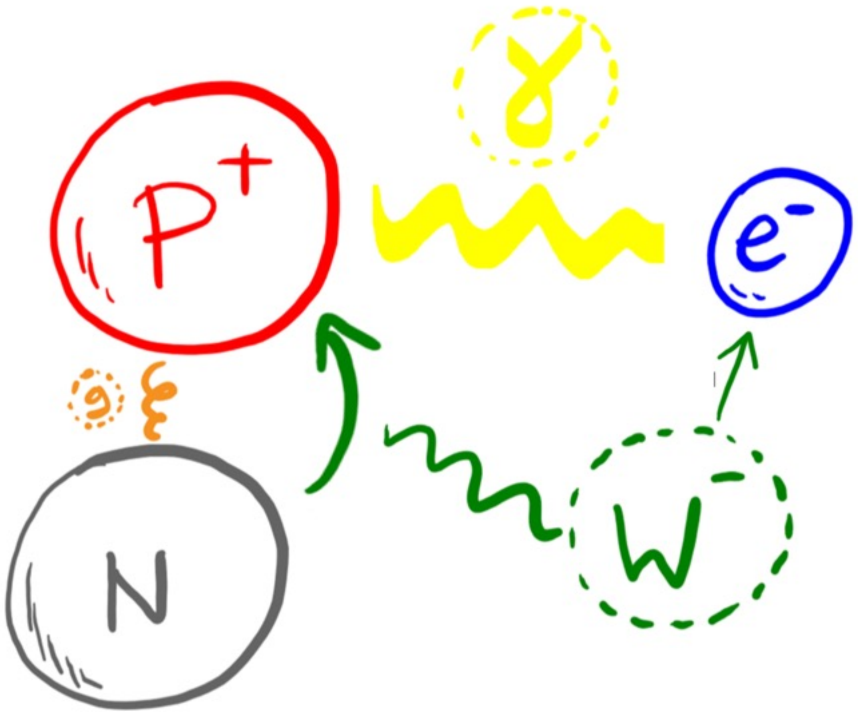


- **Neutron** can change into **proton**, emitting **electron**

Introduction

- **Weak force** explains *radioactivity*

Missing energy? Pauli postulates *"a desperate remedy"*



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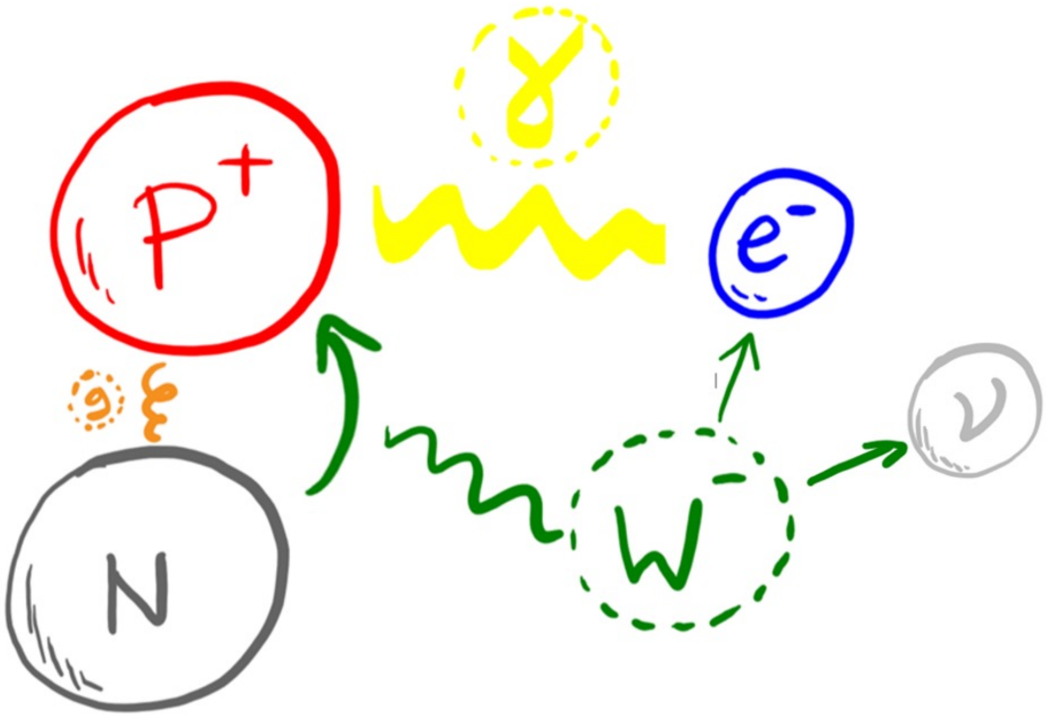

- **Neutron** can change into **proton**, emitting **electron** *and elusive* **neutrino**

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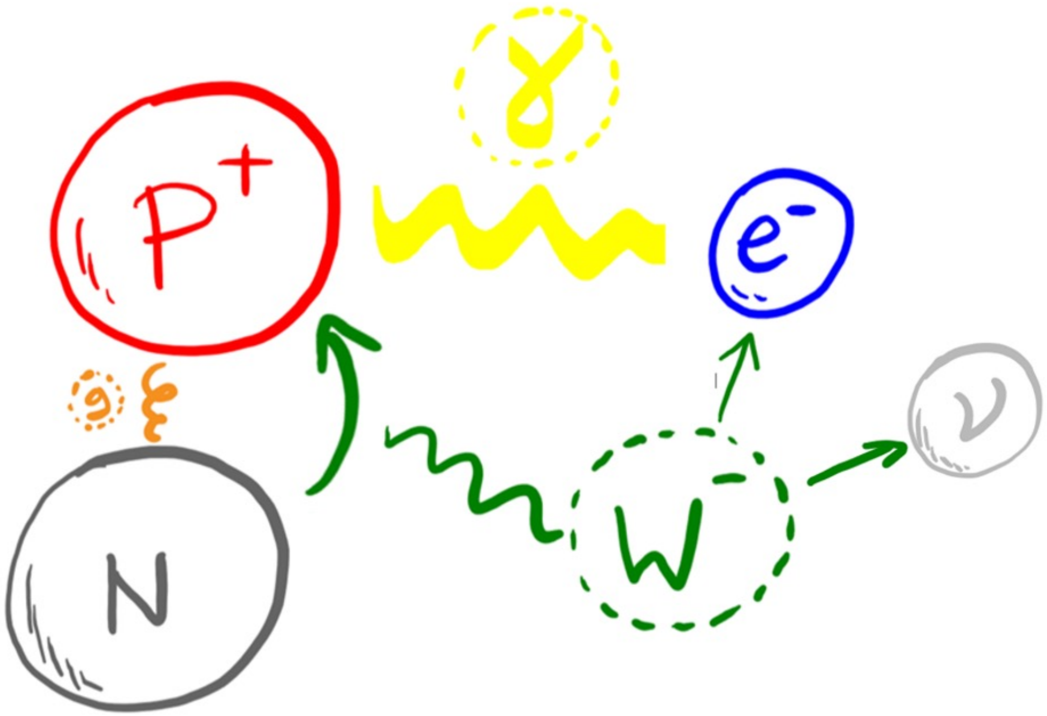

Missing energy? Pauli postulates *"a desperate remedy"*

Lesson 2: *perceived* prospects of experimental confirmation is *not a useful scientific criteria* for establishing **what nature actually does**

- **Neutron** can change into **proton**, emitting **electron** *and elusive* **neutrino**

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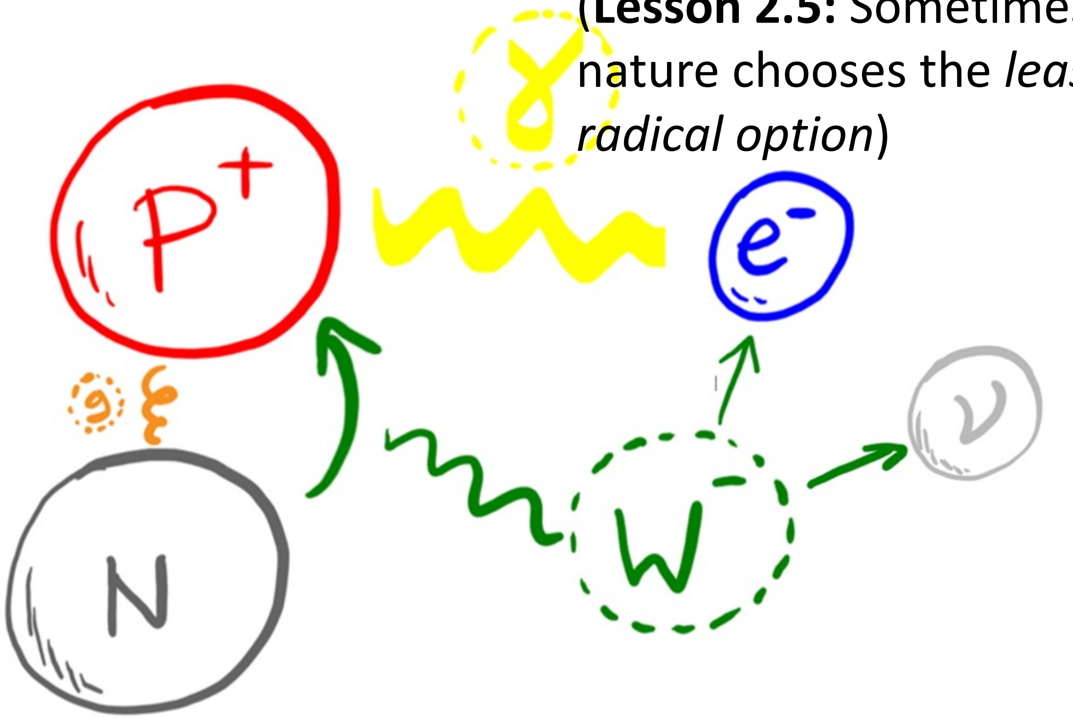
Introduction

- ***Weak force*** explains *radioactivity*

(**Lesson 2.5:** Sometimes nature chooses the *least radical option*)



Missing energy? Pauli postulates *"a desperate remedy"*

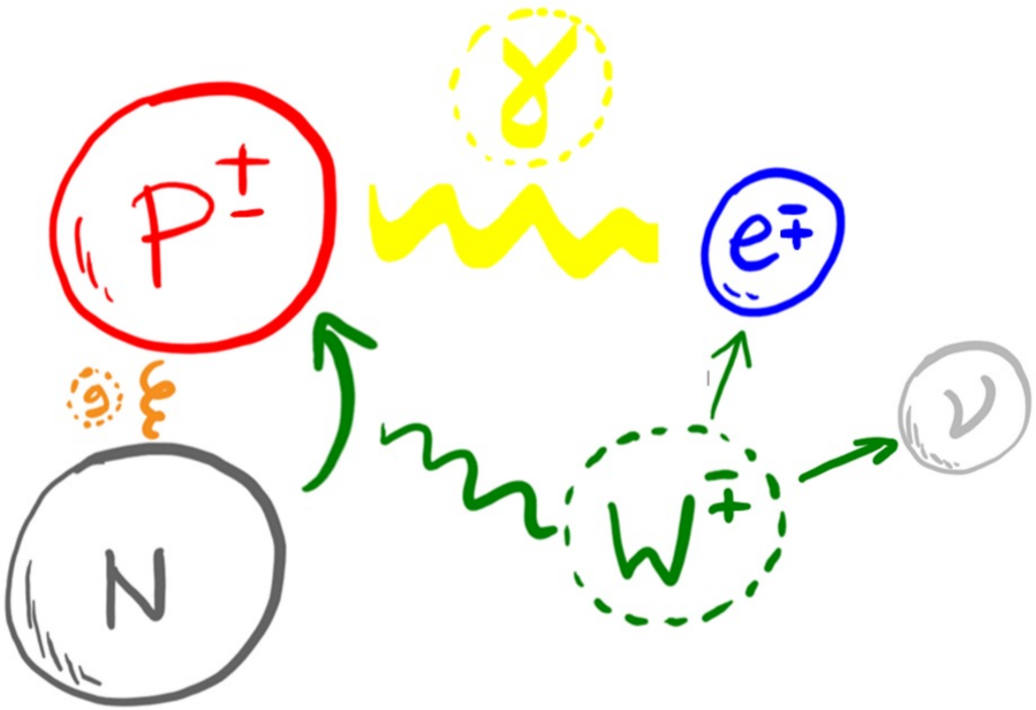
(Bohr suggests fundamental violation of energy conservation principle)

Lesson 2: *perceived* prospects of experimental confirmation is *not a useful scientific criteria* for establishing **what nature actually does**

- **Neutron** can change into **proton**, emitting **electron** *and elusive* **neutrino**

Introduction

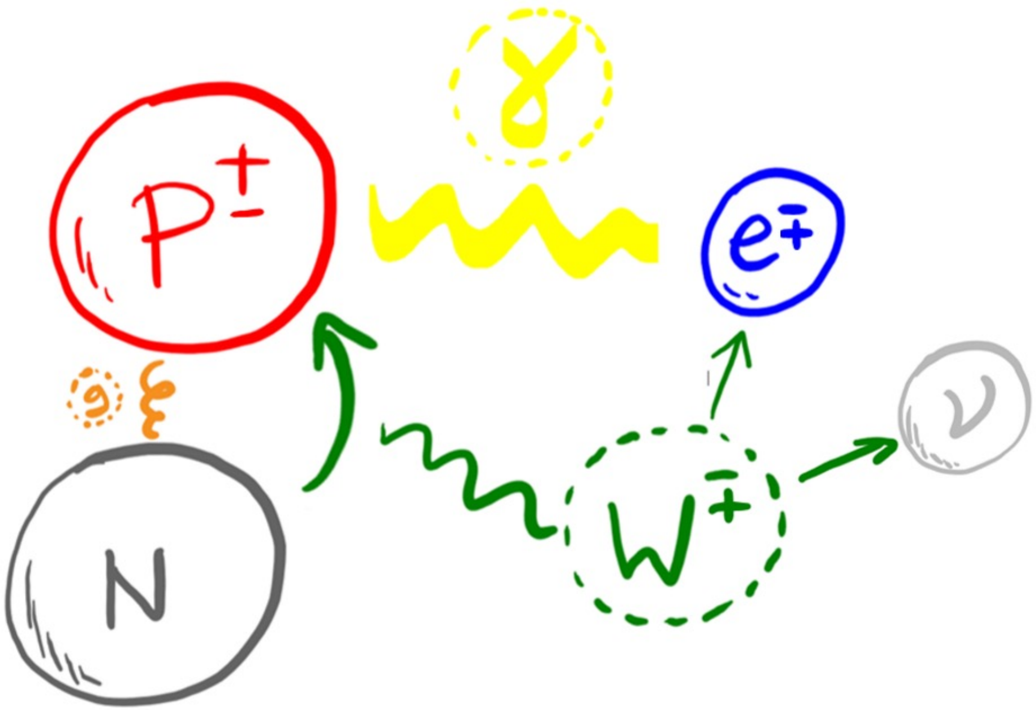
- Dirac: Einstein's **relativity** + **quantum mechanics** = **antiparticles**



- *Every particle has an oppositely charged antiparticle partner*

Introduction

- Dirac: Einstein's **relativity** + **quantum mechanics** = **antiparticles**

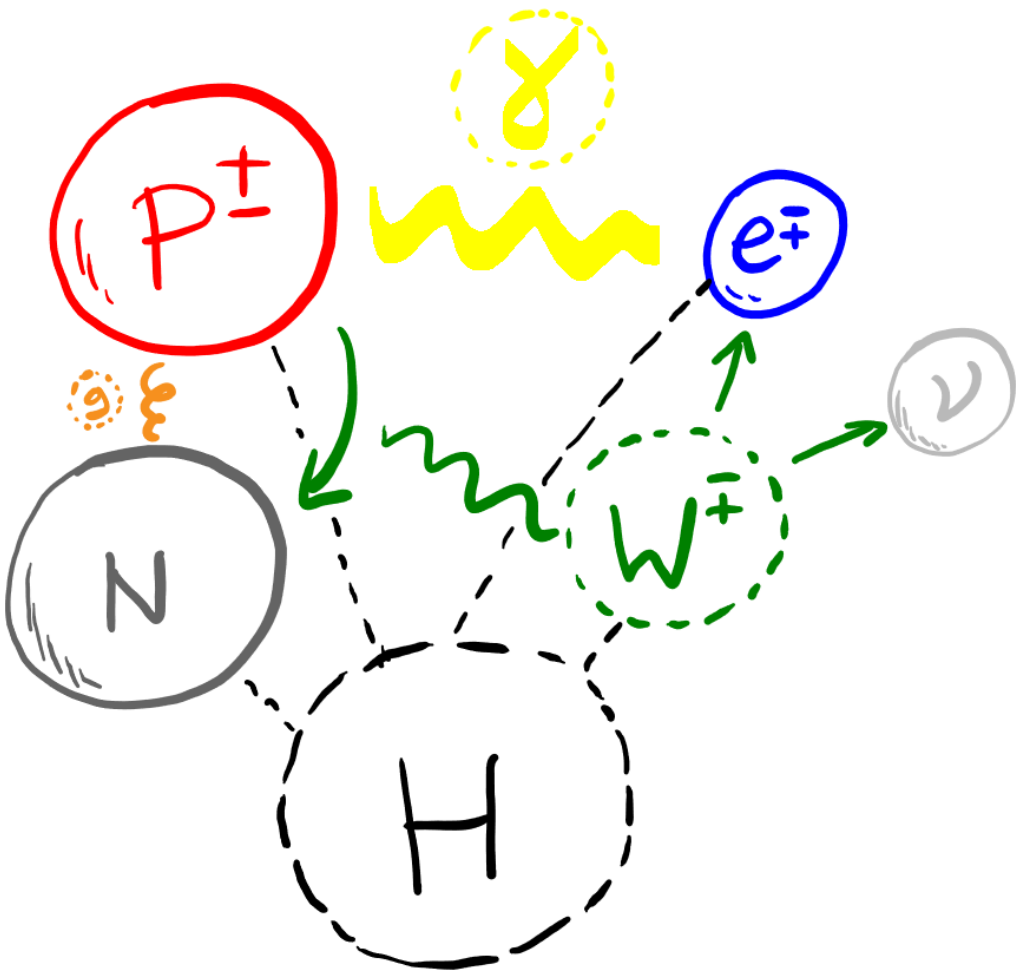


see **Lesson 1**: antiparticles *double the particle spectrum*. Nevertheless, the theory is **much tighter**, **less arbitrary**, and **more elegant**

- *Every particle has an oppositely charged antiparticle partner*

Introduction

- *Higgs(+Brout+Englert):* **particle masses** require a new **scalar boson H**



Introduction

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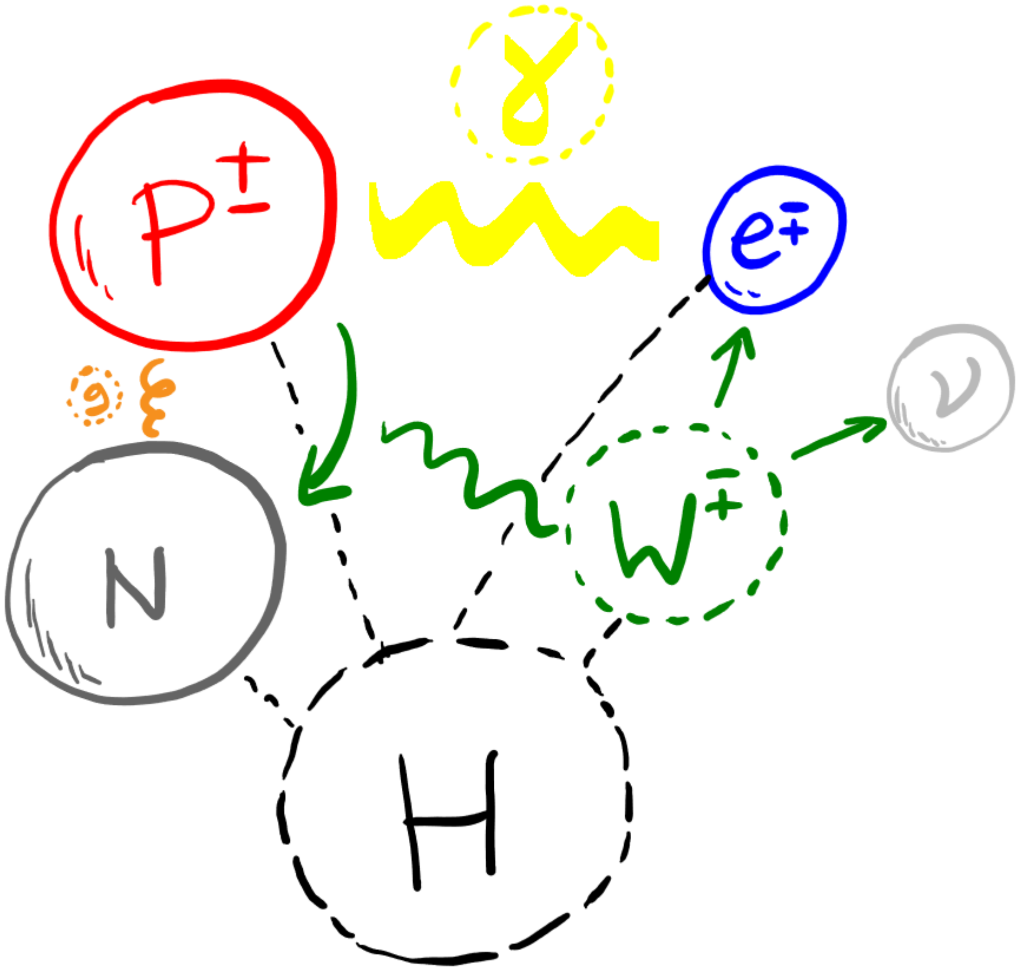


Lesson 3: Keep an open mind.

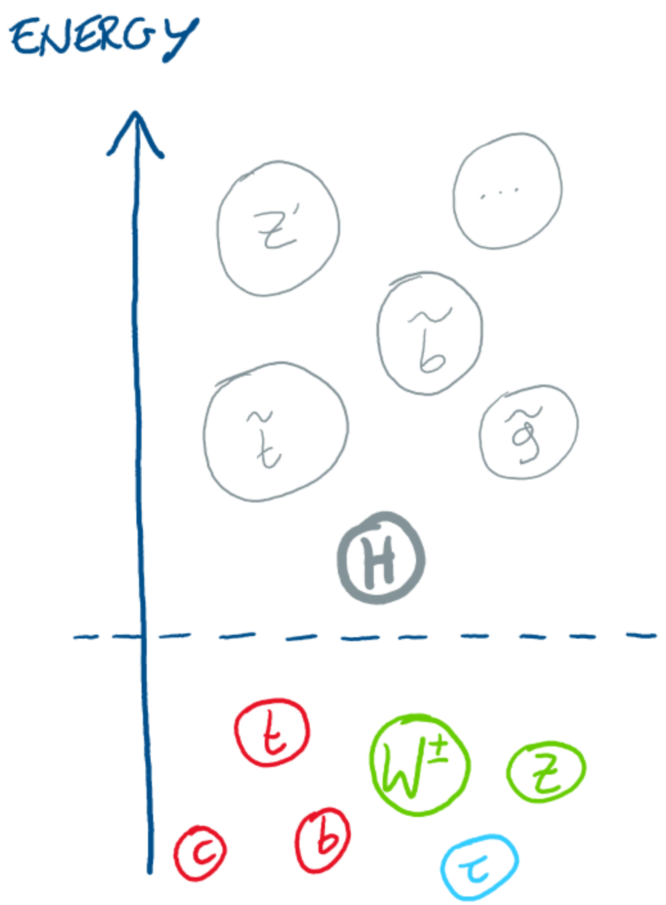
Ideas initially dismissed as **unrealistic** (*e.g.* non-abelian gauge theories because they predicted **unobserved massless** bosons) can later make sense upon further investigation

Introduction

- 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) *violates symmetry expectation*.
- **Tremendous progress** since, *despite lack of BSM*

Motivation

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



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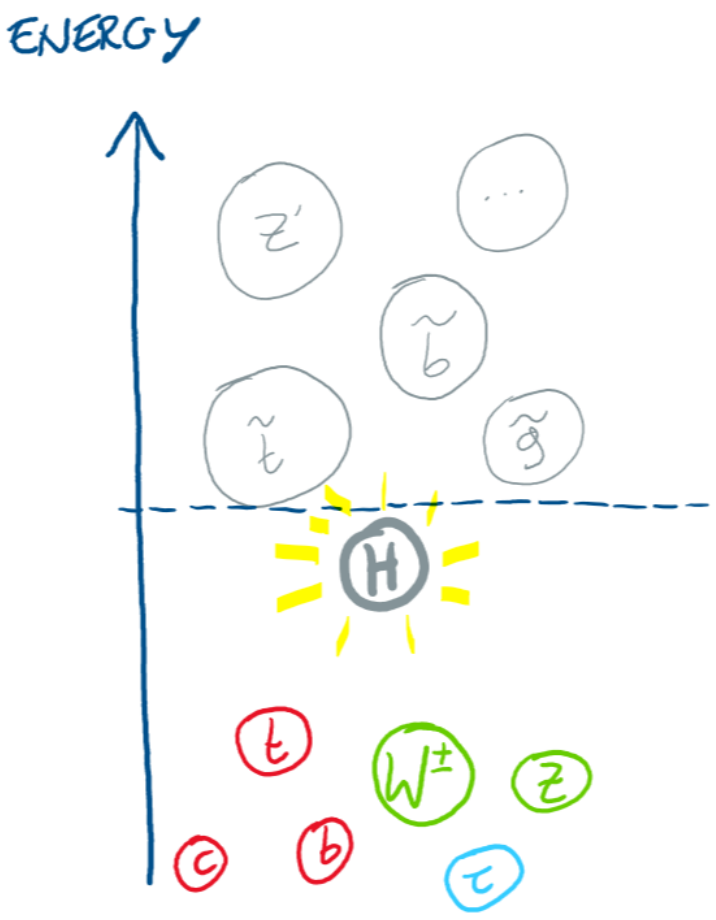

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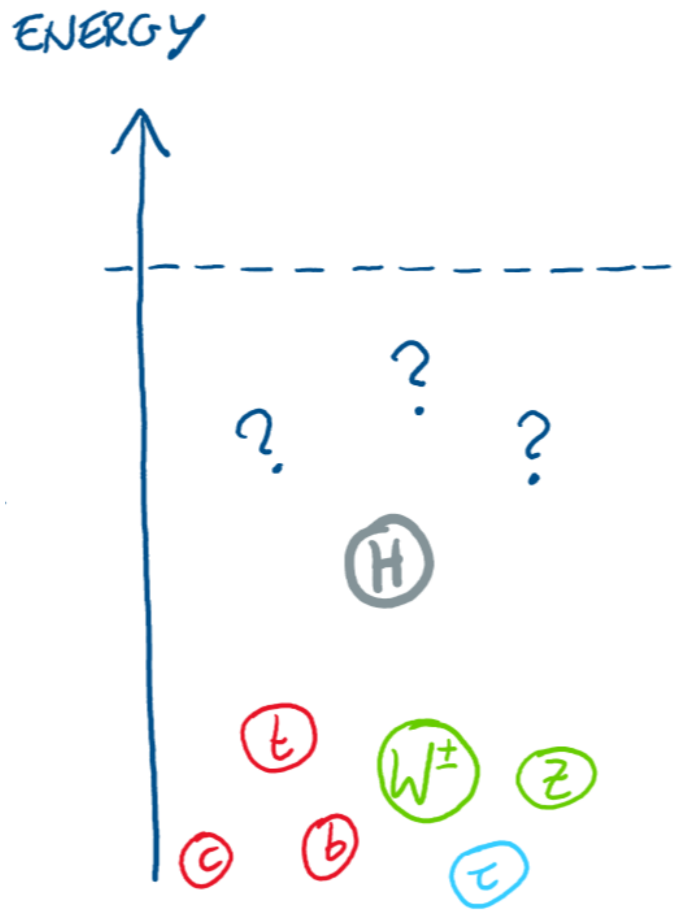

Conventional **symmetry-based** solutions *have not shown up*!

Motivation

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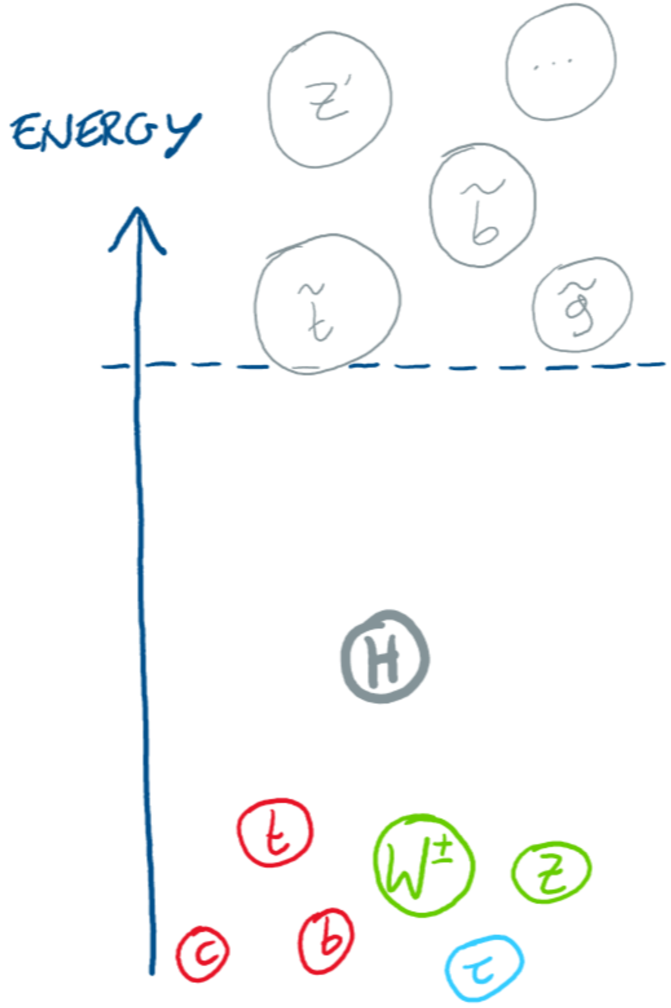

Maybe **just around the corner**…

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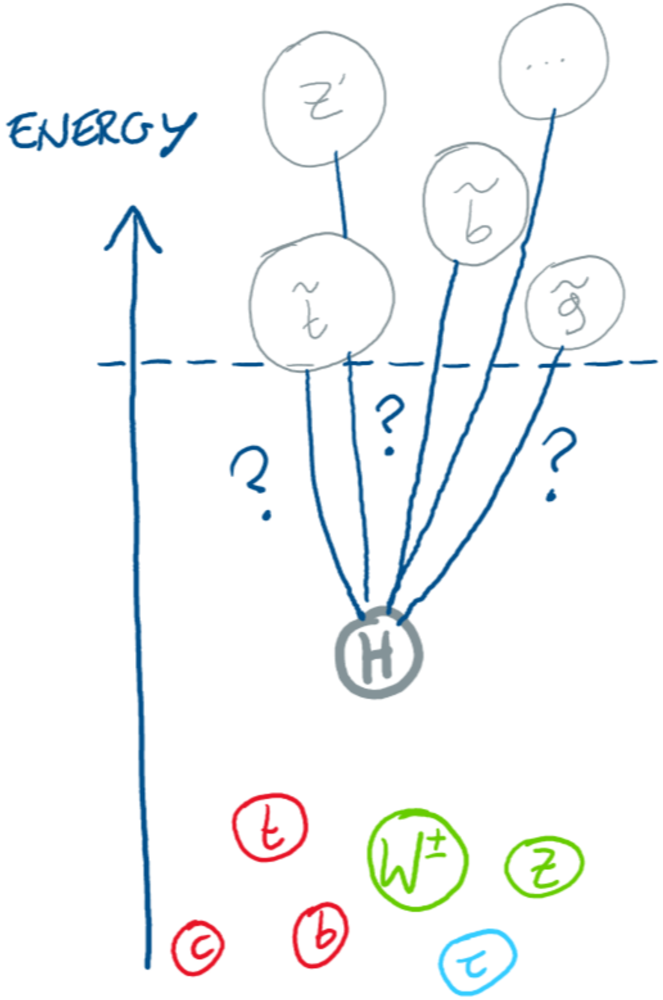

...but the larger the separation of scales, the more **fine-tuned** the *underlying* theory is!

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

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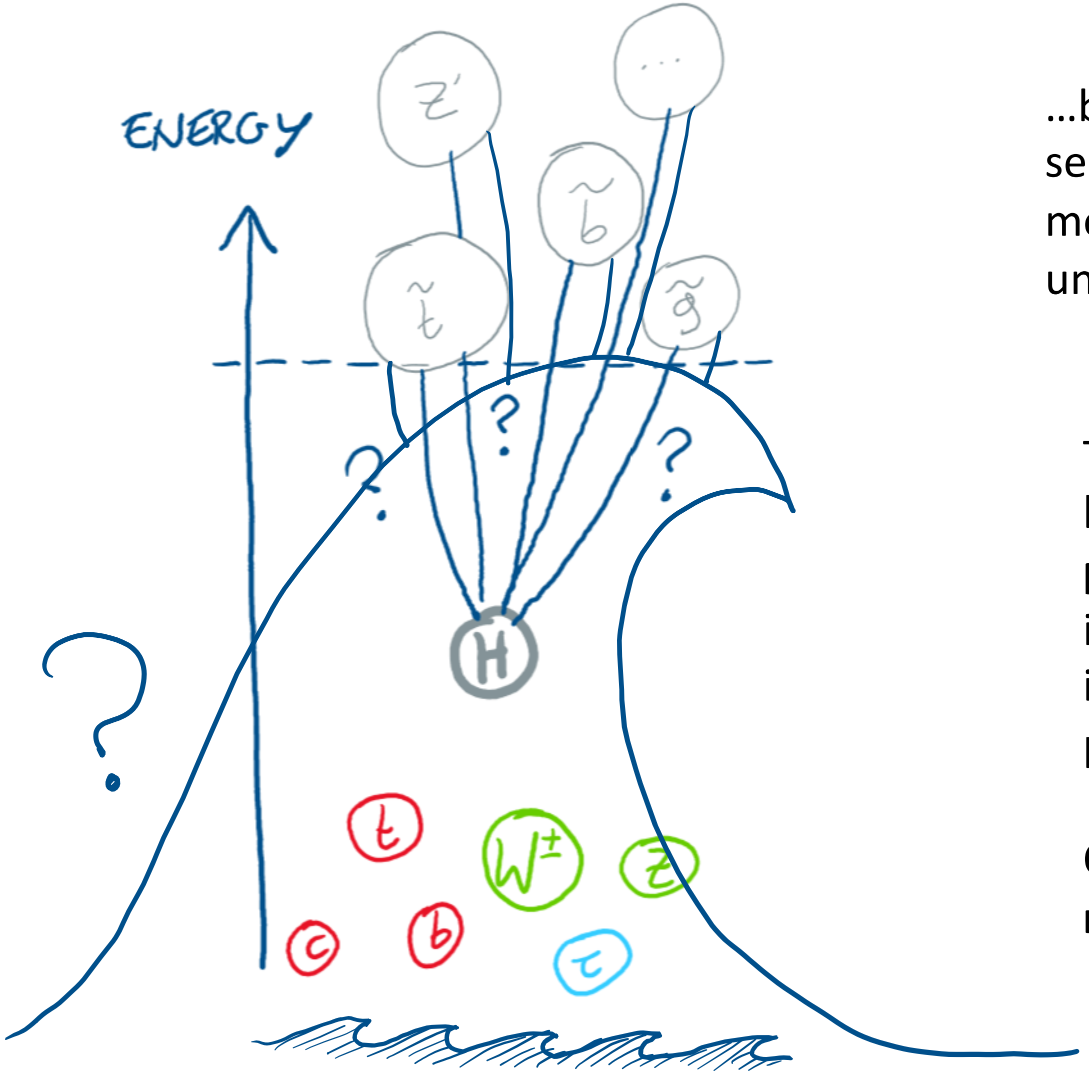


...but the larger the separation of scales, the more **fine-tuned** the underlying theory is

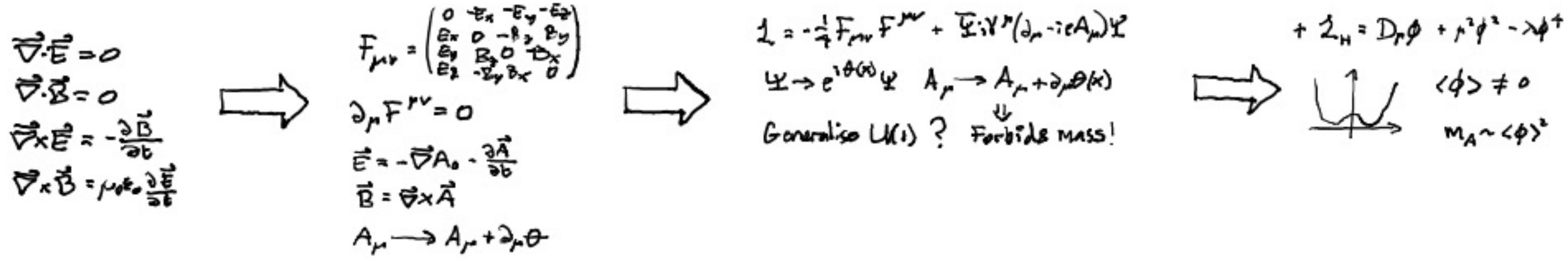
The Higgs boson's hierarchy problem is a **profound mystery**, that is **even more perplexing** in the absence of new physics at the LHC.

Our **Michelson-Morley moment?**

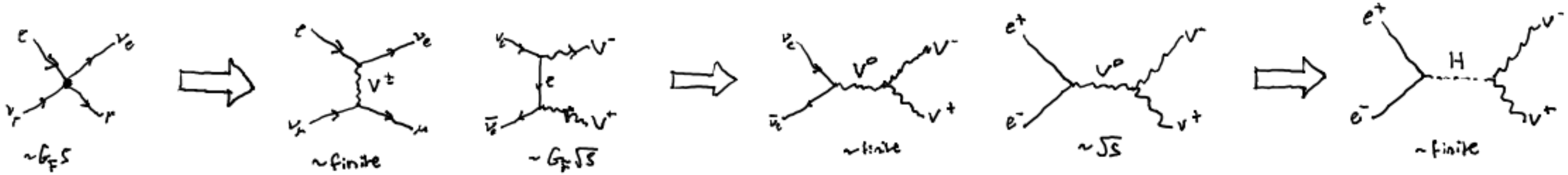
Vacuum energy is also *peculiarly tiny*

From Maxwell to Higgs

- Historically:

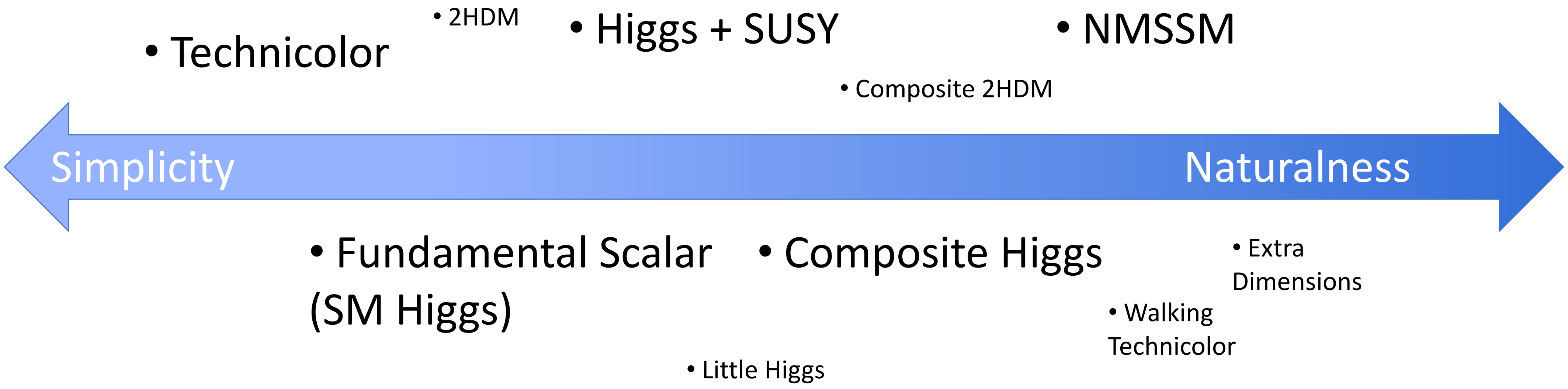


- Inevitably:



Beyond the Standard Model Higgs?

- A priori many ways to break electroweak symmetry!
- But tension between simplicity and naturalness



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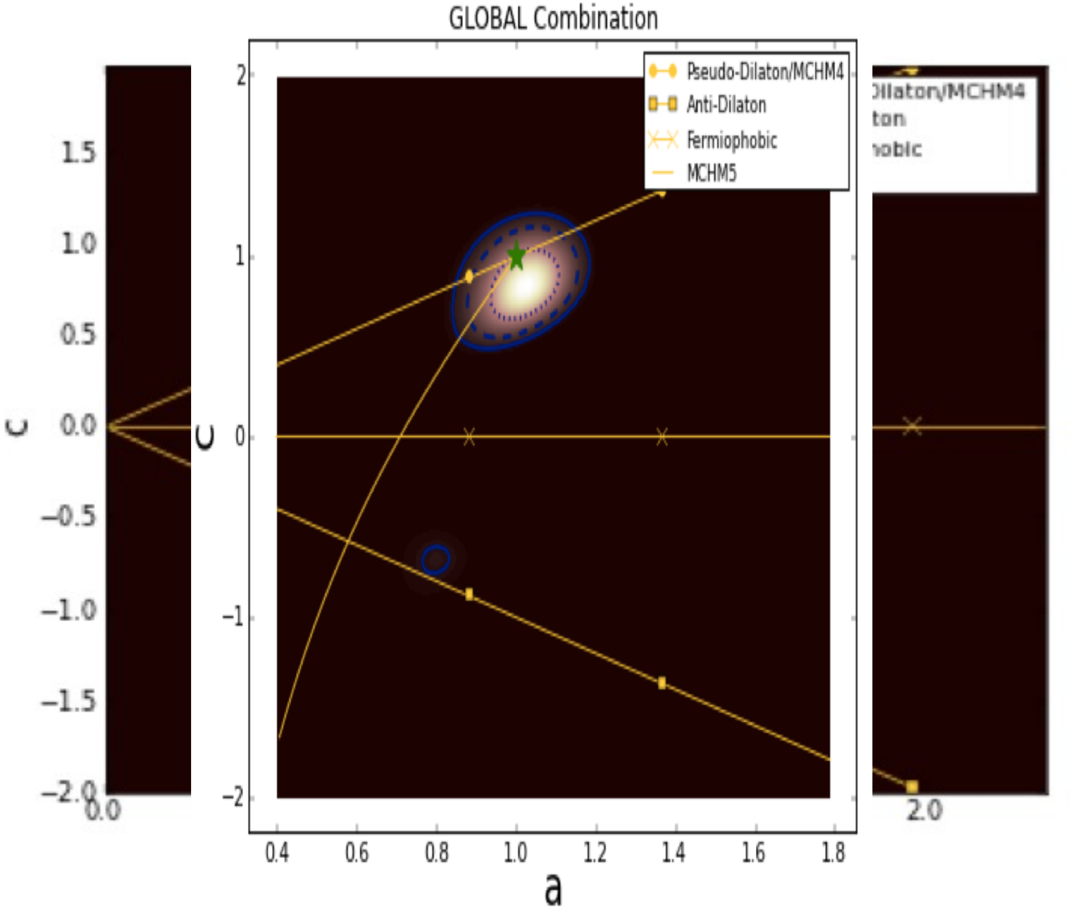
Beyond the Standard Model Higgs?

- Could have had very different coupling



March 2012 pre-discovery

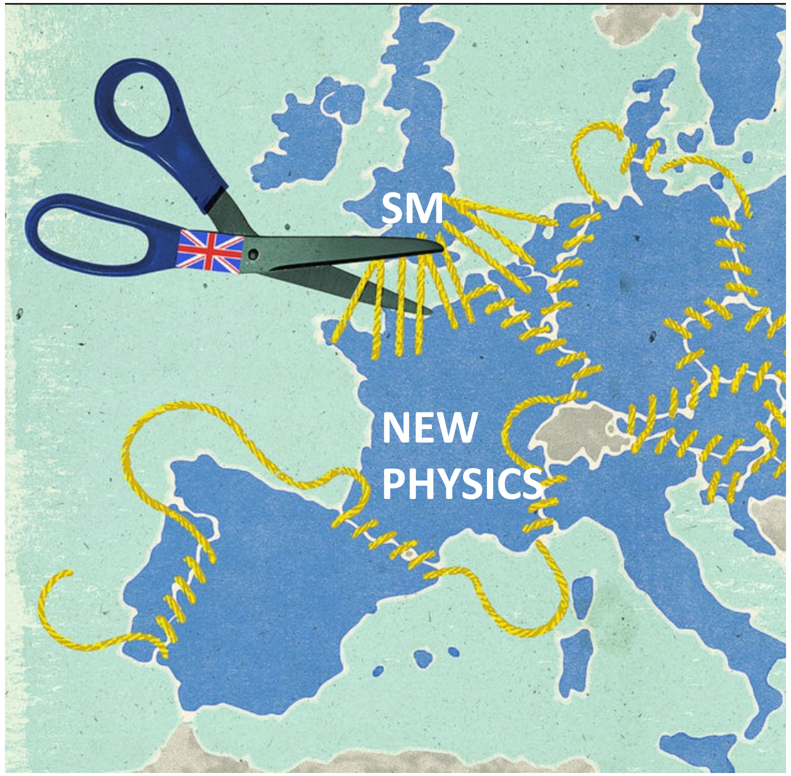
July 2012 post-discovery

J. Ellis and T.Y. [arXiv:1207.1693]

Effective Field Theory

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

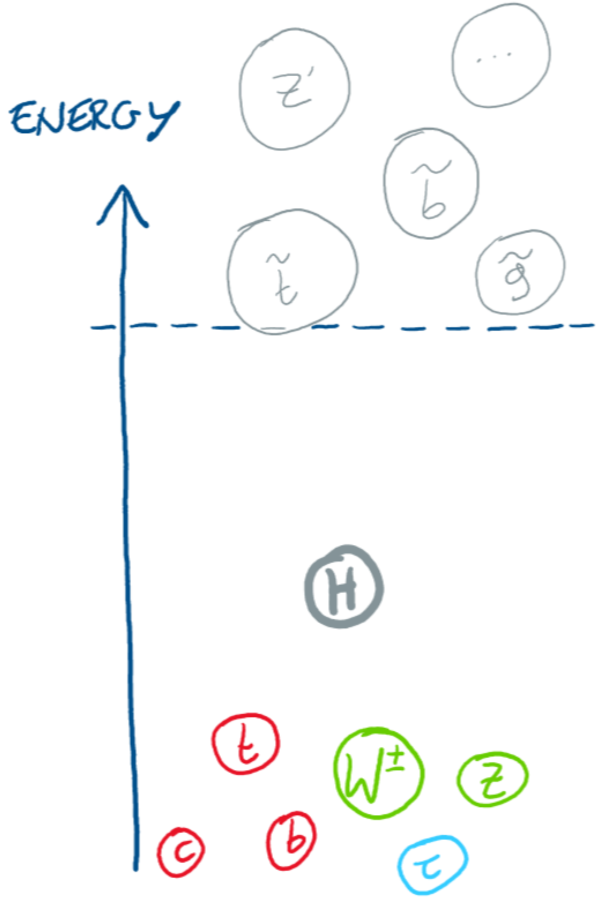
SMEXIT:



Symmetries control sizes of parameters – *naturalness expectations*

Effective Field Theory

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



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

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

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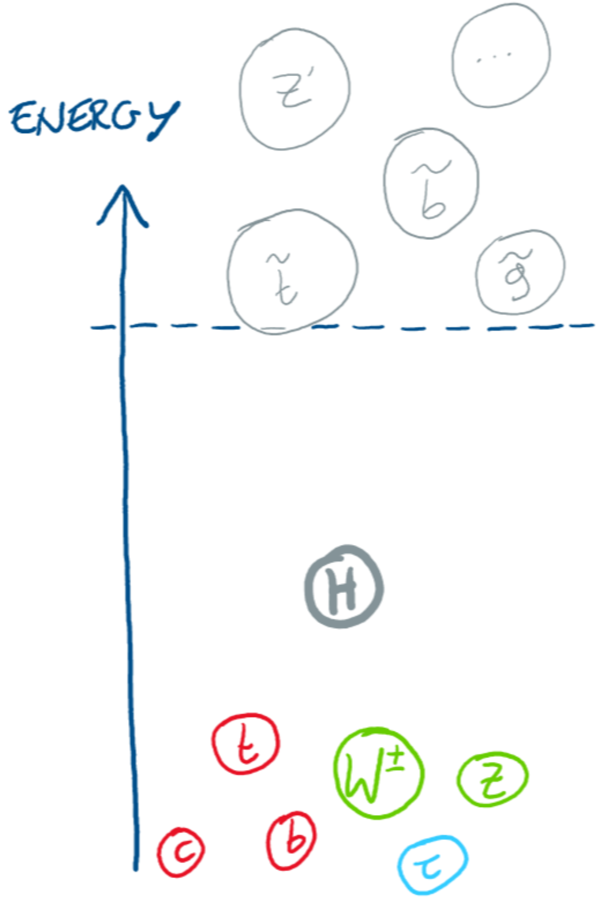
\mathcal{L}_Y &= y_d \bar{Q}_L \phi q^d_R + y_u \bar{Q}_L \phi^c q^u_R + y_L \bar{L}_L \phi l_R + \text{h.c.} \quad ,
\end{aligned}$$

Symmetries control sizes of parameters – *naturalness expectations*

Effective Field Theory

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

- Characterises *heavy* new ultra-violet (**UV**) physics
- Parametrised by coefficients $\boldsymbol{c_i}$ and heavy energy scale $\boldsymbol{\Lambda}$



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

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

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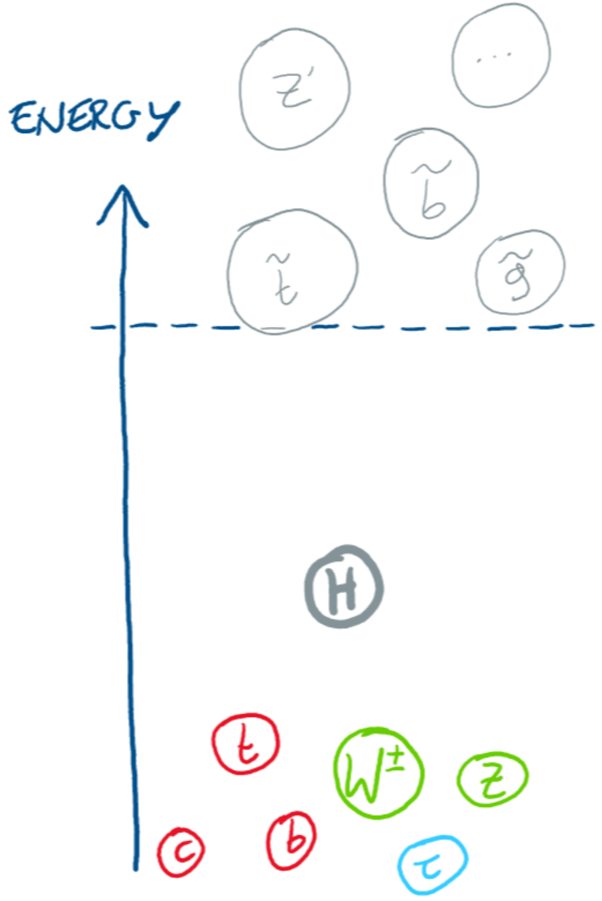
Symmetries control sizes of parameters – *naturalness expectations*

Effective Field Theory

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

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



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Symmetries control sizes of parameters – *naturalness expectations*

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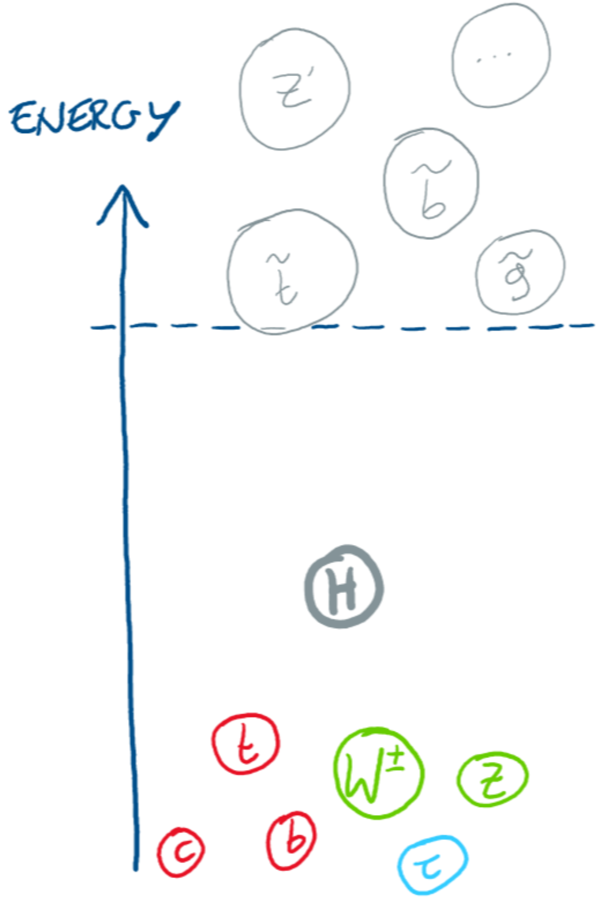

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Symmetries control sizes of parameters – *naturalness expectations*

Effective Field Theory

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

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

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

Effective Field Theory

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Suppressed!

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Naturalness?

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Effective Field Theory

e.g. QED as an EFT includes Fermi theory and Euler-Heisenberg dimension-8 operators

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

Fermi theory
(1933)

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

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

Euler-Heisenberg
(1936)

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

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Fermi theory (1933)

$$+ \sum_i \frac{c_6^{(i)}}{\Lambda^2} (\bar{\Psi} \Gamma^i \Psi)(\bar{\Psi} \Gamma^i \Psi) \qquad \Gamma = \{ \mathbb{1}, \gamma_5, \gamma_\mu, \gamma_\mu \gamma_5, \sigma_{\mu\nu} \}$$

Euler-Heisenberg (1936)

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

Wilson coefficients generated by UV physics

Effective Field Theory

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

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

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

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Up to mass dimension 4, this is “The Standard Model”

Effective Field Theory

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

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

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

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

$$\mathcal{L}_G = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \theta\frac{\alpha_s}{8\pi}G^a_{\mu\nu}\widetilde{G}^{a\mu\nu}$$

? **Strong-CP problem**

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

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

Up to mass dimension 4, this is “The Standard Model”.

Effective Field Theory

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

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

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

$$\mathcal{L}_G = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W_{\mu\nu}^a W^{a\mu\nu} \quad -\theta\frac{\alpha_s}{8\pi}G_{\mu\nu}^a \widetilde{G}^{a\mu\nu}$$

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

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

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).

Operators

- Lagrangian dim-6 operator coefficient normalization: $$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i=1}^{2499} \frac{C_i}{\Lambda^2}\mathcal{O}_i$$

- Warsaw basis

[1008.4884 Grzadkowski et al]

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

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

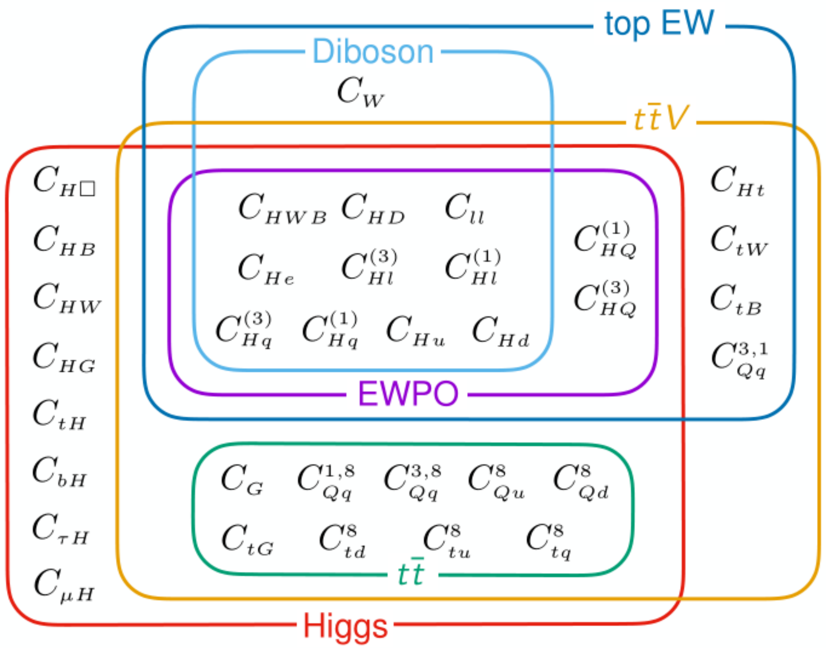
$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{ll}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$\mathcal{O}_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$\mathcal{O}_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

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

Input scheme:

$$\alpha_{EW}^{-1} = 127.95, \quad G_F = 1.16638\times 10^{-5}\,\text{GeV}^{-2},$$
$$m_Z = 91.1876\,\text{GeV}, \quad m_H = 125.09\,\text{GeV}, \quad m_t = 173.2\,\text{GeV}$$

Operators



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

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

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{ll}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$\mathcal{O}_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$\mathcal{O}_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

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

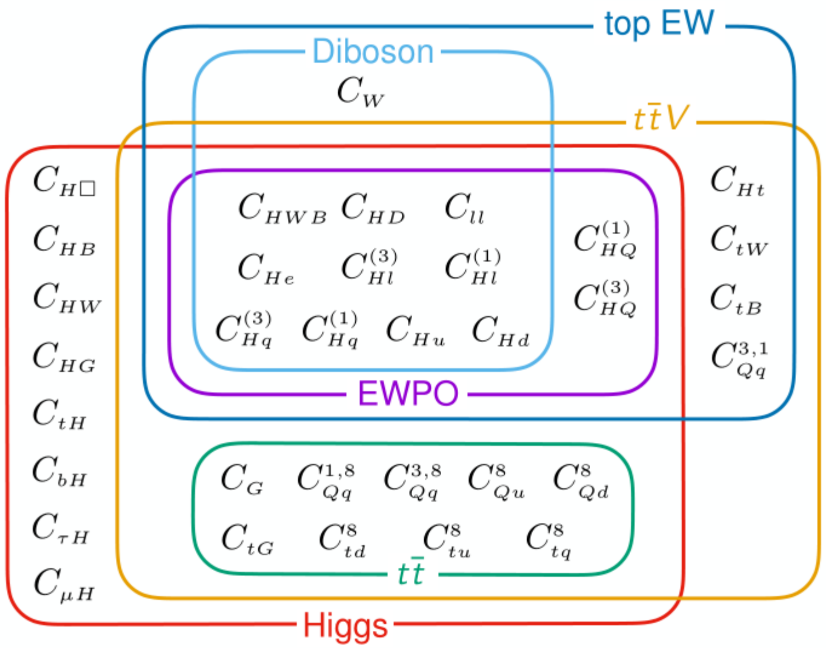
- 20 operators relevant for Higgs, diboson, and EWPO:

EWPO: $\mathcal{O}_{HWB}\,,\ \mathcal{O}_{HD}\,,\ \mathcal{O}_{ll}\,,\ \mathcal{O}_{Hl}^{(3)}\,,\ \mathcal{O}_{Hl}^{(1)}\,,\ \mathcal{O}_{He}\,,\ \mathcal{O}_{Hq}^{(3)}\,,\ \mathcal{O}_{Hq}^{(1)}\,,\ \mathcal{O}_{Hd}\,,\ \mathcal{O}_{Hu}\,,$

Bosonic: $\mathcal{O}_{H\Box}\,,\ \mathcal{O}_{HG}\,,\ \mathcal{O}_{HW}\,,\ \mathcal{O}_{HB}\,,\ \mathcal{O}_{W}\,,\ \mathcal{O}_{G}\,,$

Yukawa: $\mathcal{O}_{\tau H}\,,\ \mathcal{O}_{\mu H}\,,\ \mathcal{O}_{bH}\,,\ \mathcal{O}_{tH}\,.$

Operators



- 20 operators relevant for Higgs, diboson, and EWPO:

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

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

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{ll}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$\mathcal{O}_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$\mathcal{O}_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

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

EWPO: $\mathcal{O}_{HWB}\,,\ \mathcal{O}_{HD}\,,\ \mathcal{O}_{ll}\,,\ \mathcal{O}_{Hl}^{(3)}\,,\ \mathcal{O}_{Hl}^{(1)}\,,\ \mathcal{O}_{He}\,,\ \mathcal{O}_{Hq}^{(3)}\,,\ \mathcal{O}_{Hq}^{(1)}\,,\ \mathcal{O}_{Hd}\,,\ \mathcal{O}_{Hu}\,,$ Can be constrained setting $|H|^2 \to v^2$

Bosonic: $\mathcal{O}_{H\Box}\,,\ \mathcal{O}_{HG}\,,\ \mathcal{O}_{HW}\,,\ \mathcal{O}_{HB}\,,\ \mathcal{O}_{W}\,,\ \mathcal{O}_{G}\,,$

Triple-gauge field strength operators

Yukawa: $\mathcal{O}_{\tau H}\,,\ \mathcal{O}_{\mu H}\,,\ \mathcal{O}_{bH}\,,\ \mathcal{O}_{tH}\,.$

Can only be constrained by Higgs physics

Operators

- Top-specific flavour symmetry:

$$SU(3)^5 \to SU(2)^2 \times SU(3)^3$$
$$= SU(2)_q \times SU(2)_u \times SU(3)_d \times SU(3)_l \times SU(3)_e$$

- + 14 Top operators

See 1802.07237

Top 2F: $\mathcal{O}_{HQ}^{(3)}\,,\ \mathcal{O}_{HQ}^{(1)}\,,\ \mathcal{O}_{Ht}\,,\ \mathcal{O}_{tG}\,,\ \mathcal{O}_{tW}\,,\ \mathcal{O}_{tB}\,,$

Top 4F: $\mathcal{O}_{Qq}^{3,1}\,,\ \mathcal{O}_{Qq}^{3,8}\,,\ \mathcal{O}_{Qq}^{1,8}\,,\ \mathcal{O}_{Qu}^{8}\,,\ \mathcal{O}_{Qd}^{8}\,,\ \mathcal{O}_{tQ}^{8}\,,\ \mathcal{O}_{tu}^{8}\,,\ \mathcal{O}_{td}^{8}$

- 20 operators relevant for Higgs, diboson, and EWPO:

EWPO: $\mathcal{O}_{HWB}\,,\ \mathcal{O}_{HD}\,,\ \mathcal{O}_{ll}\,,\ \mathcal{O}_{Hl}^{(3)}\,,\ \mathcal{O}_{Hl}^{(1)}\,,\ \mathcal{O}_{He}\,,\ \mathcal{O}_{Hq}^{(3)}\,,\ \mathcal{O}_{Hq}^{(1)}\,,\ \mathcal{O}_{Hd}\,,\ \mathcal{O}_{Hu}\,,$ Can be constrained setting $|H|^2 \to v^2$

Bosonic: $\mathcal{O}_{H\Box}\,,\ \mathcal{O}_{HG}\,,\ \mathcal{O}_{HW}\,,\ \mathcal{O}_{HB}\,,\ \mathcal{O}_{W}\,,\ \mathcal{O}_{G}\,,$

Yukawa: $\mathcal{O}_{\tau H}\,,\ \mathcal{O}_{\mu H}\,,\ \mathcal{O}_{bH}\,,\ \mathcal{O}_{tH}\,.$

Triple-gauge field strength operators

Can only be constrained by Higgs physics

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

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

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

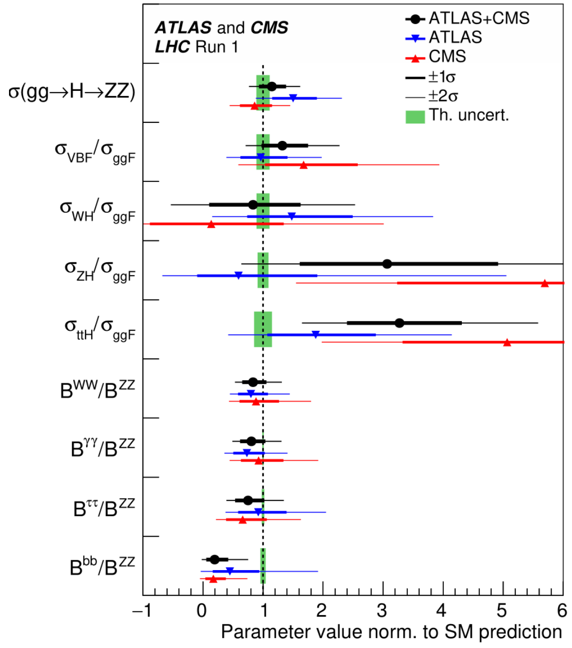
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
$\mathcal{O}_{ledq}$	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$\mathcal{O}_{quqd}^{(1)}$	$(\bar q_p^j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

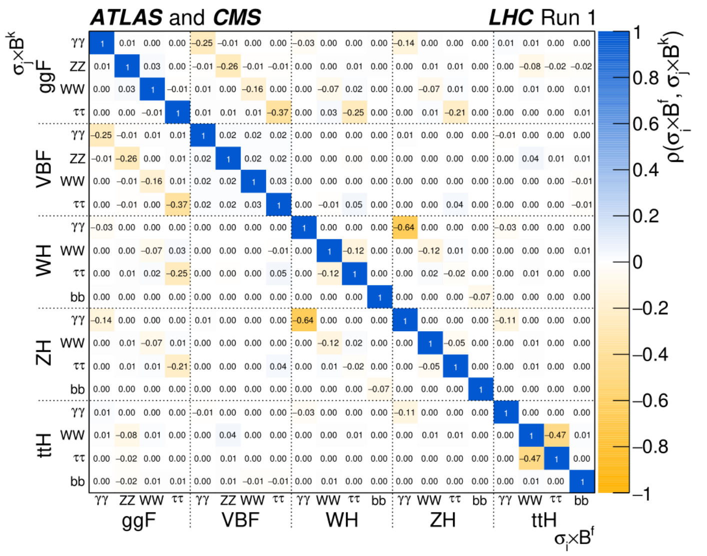
Measurements

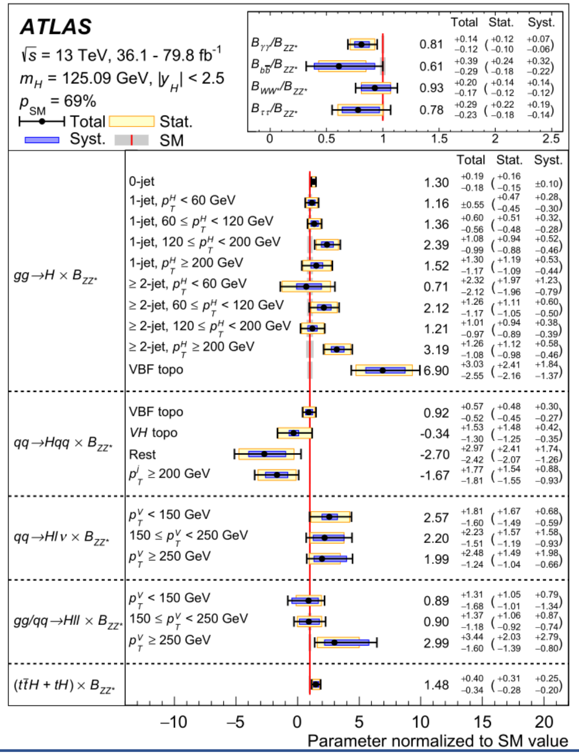
- Higgs:

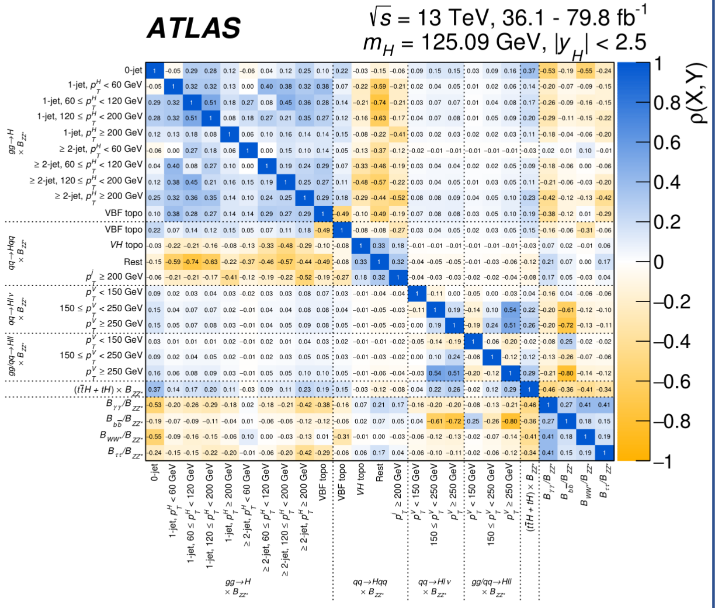
LHC Run 1 Higgs	n_{obs}	Ref.
ATLAS and CMS LHC Run 1 combination of Higgs signal strengths. Production: ggF, VBF, ZH, WH & ttH Decay: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$ & $b\bar{b}$	21	[8]
ATLAS inclusive $Z\gamma$ signal strength measurement	1	[9]

LHC Run 2 Higgs (new)	n_{obs}	Ref.
ATLAS combination of signal strengths and stage 1.0 STXS in $H \to 4\ell$ including ratios of branching fractions to $\gamma\gamma$, WW^*, $\tau^+\tau^-$ & $b\bar{b}$ Signal strengths|coarse STXS bins| fine STXS bins	16|19|25	[10]
CMS LHC combination of Higgs signal strengths. Production: ggF, VBF, ZH, WH & ttH Decay: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$, $b\bar{b}$ & $\mu^+\mu^-$	23	[11]
CMS stage 1.0 STXS measurements for $H \to \gamma\gamma$. 13 parameter fit | 7 parameter fit	13|7	[12]
CMS stage 1.0 STXS measurements for $H \to \tau^+\tau^-$	9	[13]
CMS stage 1.1 STXS measurements for $H \to 4\ell$	19	[14]
CMS differential cross section measurements of inclusive Higgs production in the $WW^* \to \ell\nu\ell\nu$ final state. $\frac{d\sigma}{dn_{\text{jet}}}$ | $\frac{d\sigma}{dp_H^T}$	5|6	[15]
ATLAS $H \to Z\gamma$ signal strength.	1	[16]
ATLAS $H \to \mu^+\mu^-$ signal strength.	1	[17]





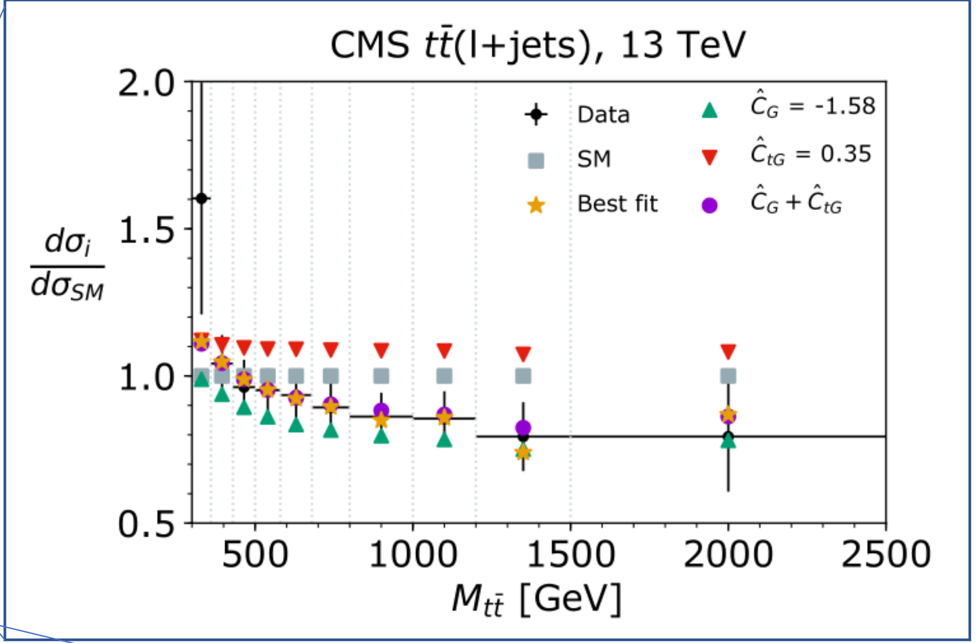


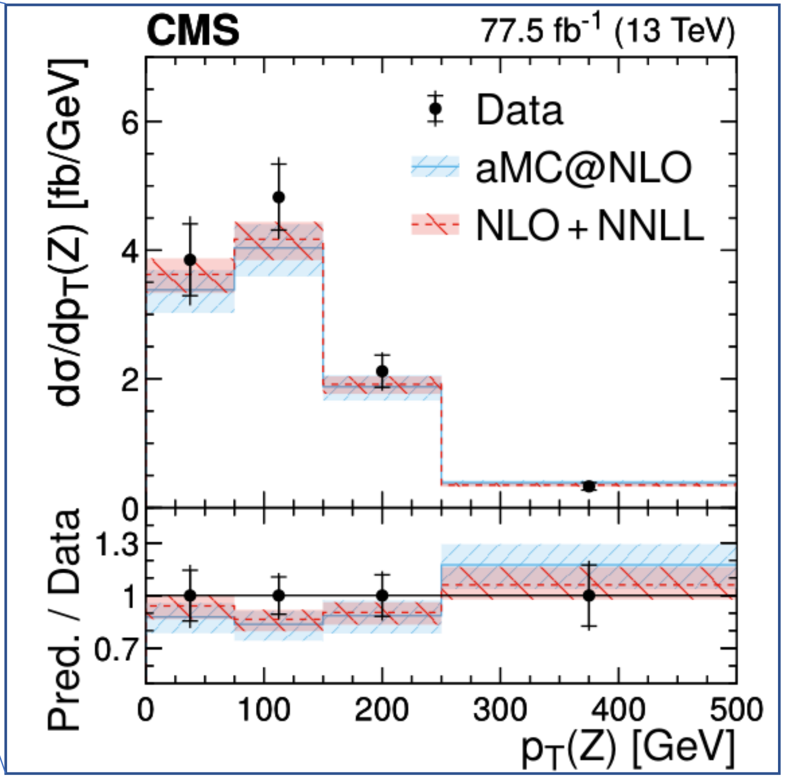


Measurements

- Top:

Run 2 top	n_{obs}	Ref.
CMS $t\bar{t}$ differential distributions in the dilepton channel. $\frac{d\sigma}{dm_{t\bar{t}}}$	6	[36, 230]
CMS $t\bar{t}$ differential distributions in the ℓ+jets channel. $\frac{d\sigma}{dm_{t\bar{t}}}$	10	[37]
ATLAS measurement of differential $t\bar{t}$ charge asymmetry, $A_C(m_{t\bar{t}})$.	5	[38]
ATLAS $t\bar{t}W$ & $t\bar{t}Z$ cross section measurements. $\sigma_{t\bar{t}W} \mid \sigma_{t\bar{t}Z}$	2	[39]
CMS $t\bar{t}W$ & $t\bar{t}Z$ cross section measurements. $\sigma_{t\bar{t}W} \mid \sigma_{t\bar{t}Z}$	$1 \mid 1$	[40]
CMS $t\bar{t}Z$ differential distributions. $\frac{d\sigma}{dp_Z^T} \mid \frac{d\sigma}{d\cos\theta^*}$	$4 \mid 4$	[41]
CMS measurement of differential cross sections and charge ratios for t-channel single-top quark production. $\frac{d\sigma}{dp^T_{t+\bar{t}}} \mid R_t\,(p^T_{t+\bar{t}})$	$5 \mid 5$	[42]
CMS measurement of t-channel single-top and anti-top cross sections. σ_t, $\sigma_{\bar{t}}$, $\sigma_{t+\bar{t}}$ & R_t.	4	[43]
CMS measurement of the t-channel single-top and anti-top cross sections. $\sigma_t \mid \sigma_{\bar{t}} \mid \sigma_{t+\bar{t}} \mid R_t$.	$1 \mid 1 \mid 1 \mid 1$	[44]
CMS t-channel single-top differential distributions. $\frac{d\sigma}{dp^T_{t+\bar{t}}} \mid \frac{d\sigma}{d\lvert y_{t+\bar{t}}\rvert}$	$4 \mid 4$	[45]
ATLAS tW cross section measurement.	1	[46]
CMS tZ cross section measurement.	1	[47]
CMS tW cross section measurement.	1	[48]
ATLAS tZ cross section measurement.	1	[49]
CMS tZ ($Z \to \ell^+\ell^-$) cross section measurement	1	[50]
ATLAS four-top search in the multi-lepton and same-sign dilepton channels.	1	[51]
ATLAS four-top search in the single-lepton and opposite-sign dilepton channels.	1	[52]
CMS four-top search in the multi-lepton and same-sign dilepton channels.	1	[53]
CMS four-top search in the single-lepton and opposite-sign dilepton channels.	1	[54]
CMS $t\bar{t}b\bar{b}$ cross section measurement in the all-jet channel.	1	[55]
CMS $t\bar{t}b\bar{b}$ cross section measurement in the dilepton channel.	1	[56]





Measurements

- EWPO:

EW precision observables	n_{obs}	Ref.
Precision electroweak measurements on the Z resonance. Γ_Z, $\sigma^0_{\text{had.}}$, R^0_ℓ, A^ℓ_{FB}, A_ℓ(SLD), A_ℓ(Pt), R^0_b, R^0_c A^b_{FB}, A^c_{FB}, A_b & A_c	12	[1]
Combination of CDF and D0 W-Boson Mass Measurements	1	[6]
LHC run 1 W boson mass measurement by ATLAS	1	[57]

$$\Gamma_Z = \Gamma_{had} + 3\Gamma_\ell + 3\Gamma_\nu \qquad R_\ell = \frac{\Gamma_{had}}{\Gamma_\ell} \qquad \sigma_{had} = 12\pi \frac{\Gamma_e \Gamma_{had}}{\hat{m}_Z^2 \Gamma_Z^2} \qquad A^f_{FB} = \frac{3}{4} A_e A_f \qquad M_W = c_W M_Z$$

$$R_q = \frac{\Gamma_q}{\Gamma_{had}}$$

$$\Gamma_f = \frac{\sqrt{2} G_F M_Z^2 \hat{M}_Z}{6\pi}\left[(g_L^f)^2 + (g_R^f)^2\right] \qquad A_f = \frac{(g_L^f)^2 - (g_R^f)^2}{(g_L^f)^2 + (g_R^f)^2}$$

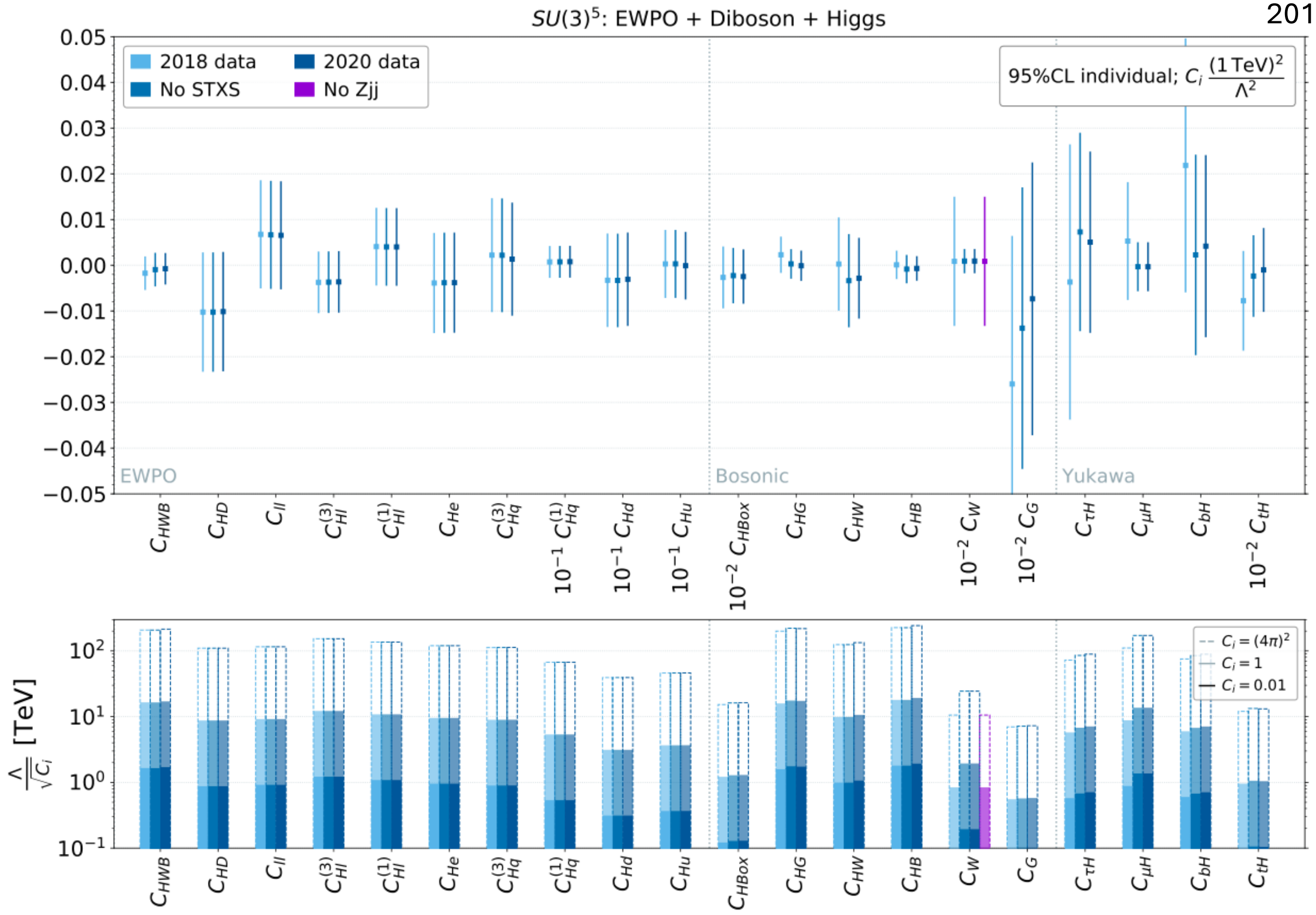
$$g^f = T_f^3 - Q_f s_W^2 \qquad s_W^2 = \frac{1}{2} - \frac{1}{2}\sqrt{1 - \frac{4\pi\alpha}{\sqrt{2} G_F m_Z^2}}$$

$$m_Z^2 = (m_Z^2)^0 (1 + \Pi_{ZZ}) \qquad G_F = G_F^0 (1 - \Pi^0_{WW}) \qquad \alpha(m_Z) = \alpha^0(m_Z)(1 + \Pi'_{\gamma\gamma})$$

Effective Field Theory

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

2012.02779 Ellis, Madigan, Mimasu, Sanz, TY

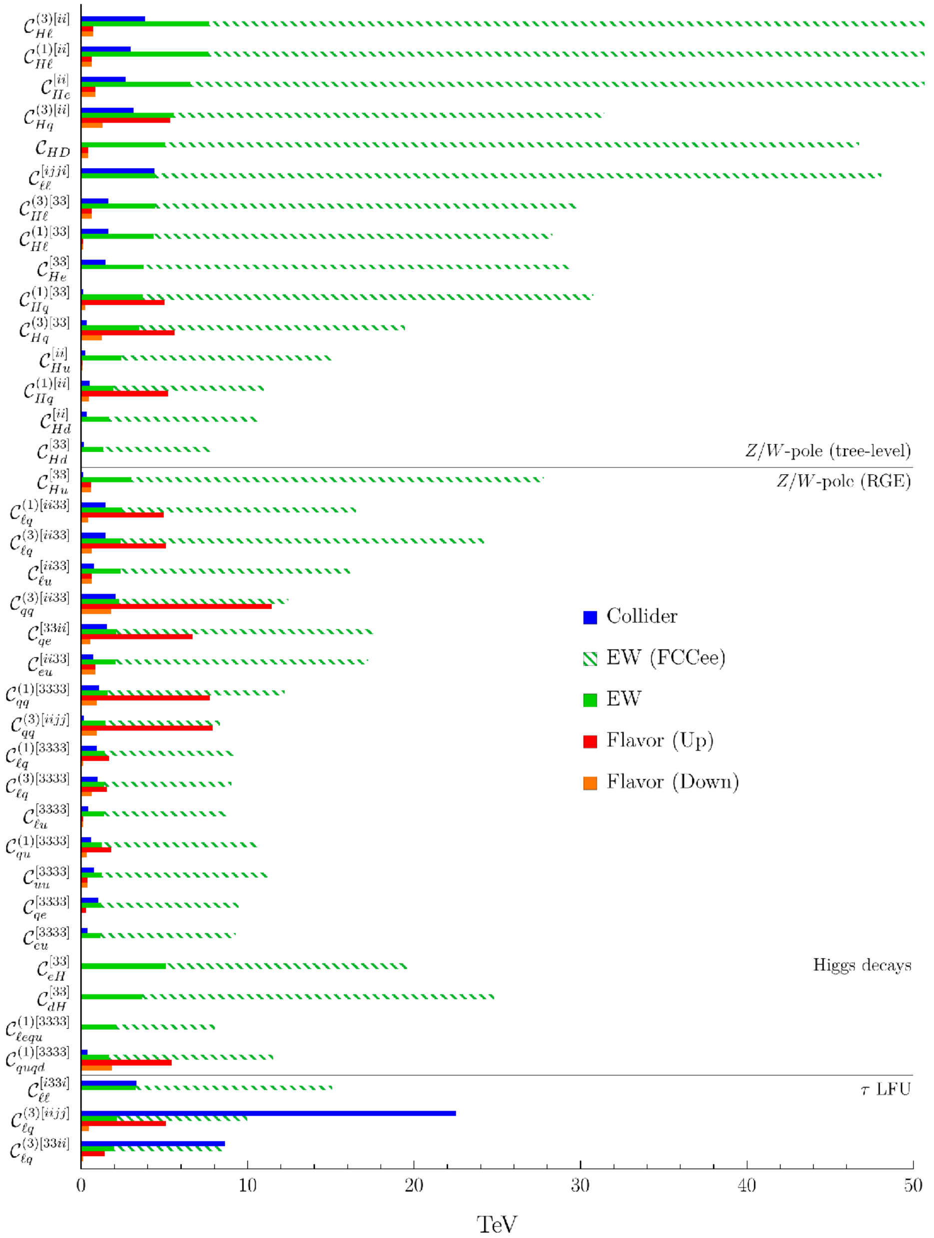


See also other recent global fits, e.g.
2311.00020 Allwicher, Cornella, Isidori, Stefanek
2311.04963 Bartocci, Biekotter, Hurth
2404.12809 SMEFiT collaboration

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

Effective Field Theory

2311.00020 Allwicher, Cornella, Isidori, Stefanek



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

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

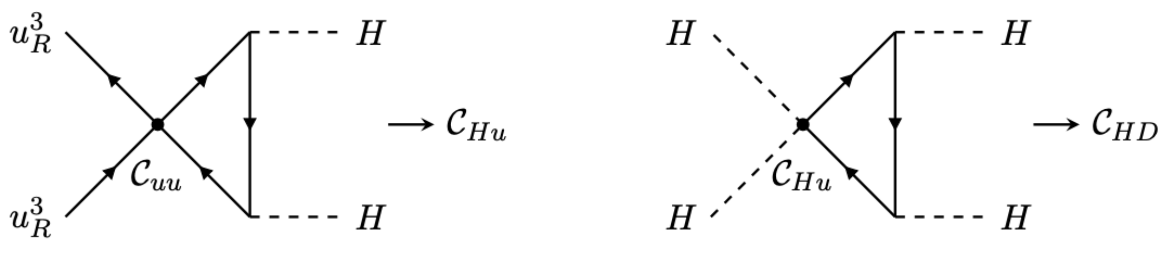


Figure 1. Next-to-leading log running of four-quark operators into $\mathcal{C}_{HD}$.

Naturalness a major motivation for fully exploring 3[rd] 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

$$\mathrm{q} = m_{inertia}$$

Solution to this equivalence problem took centuries: Newtonian gravity → GR

Naturalness

Take fine-tuning problems seriously.

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

Example 2

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

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

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

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

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

Naturalness

Take fine-tuning problems seriously.

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

Example 3

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

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

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

ρ meson appears at 775 MeV!

Naturalness

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 $\Lambda < 3$ 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

<u>Higgs?</u>

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??

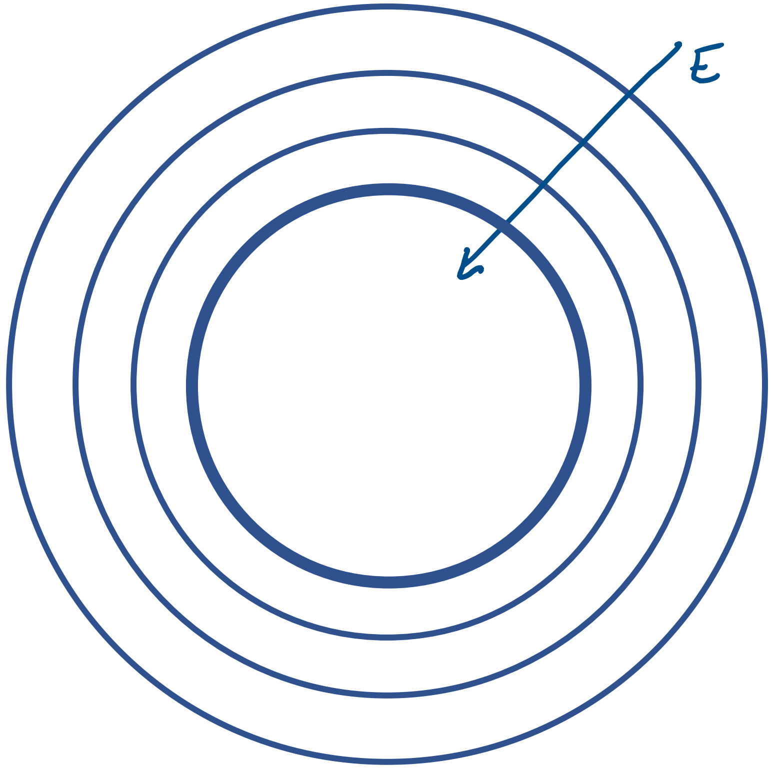
As Λ is pushed to the TeV scale by null results, tuning is around 10% - 1%.

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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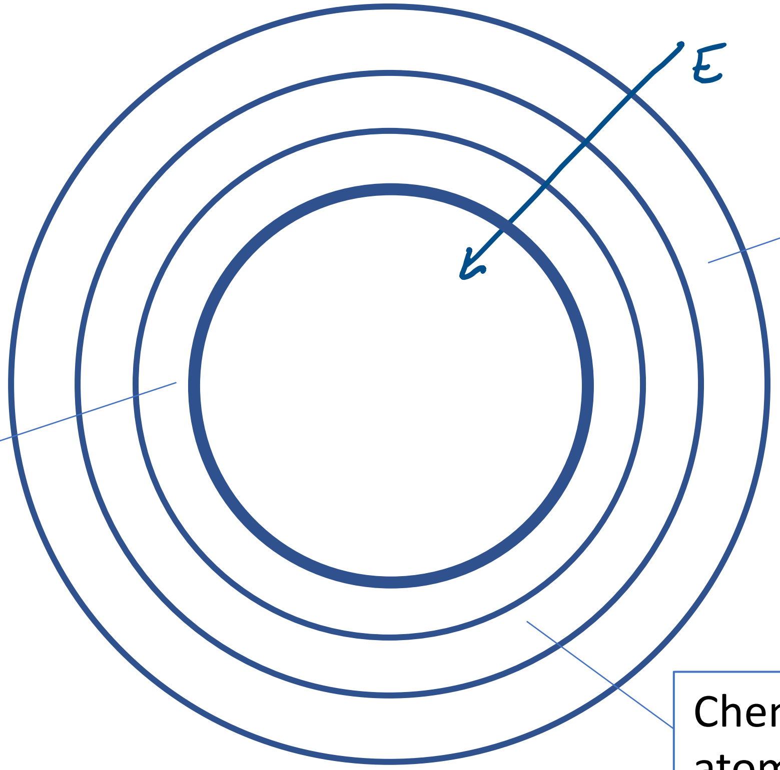

Planetary dynamics, thermodynamics, fluid dynamics, …

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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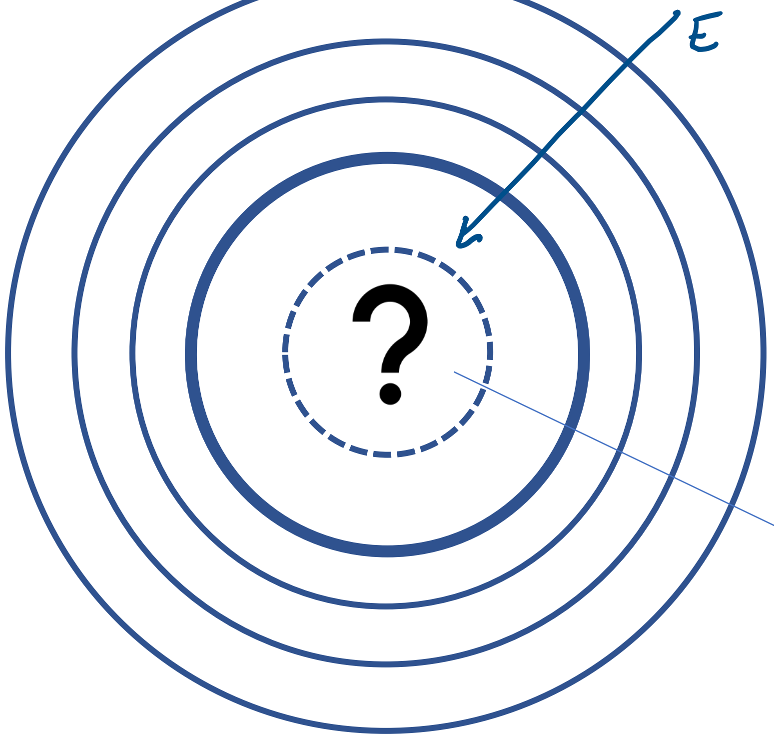

Unnatural Higgs means the next layer *is no longer predictive* without including contributions *from much smaller scales*

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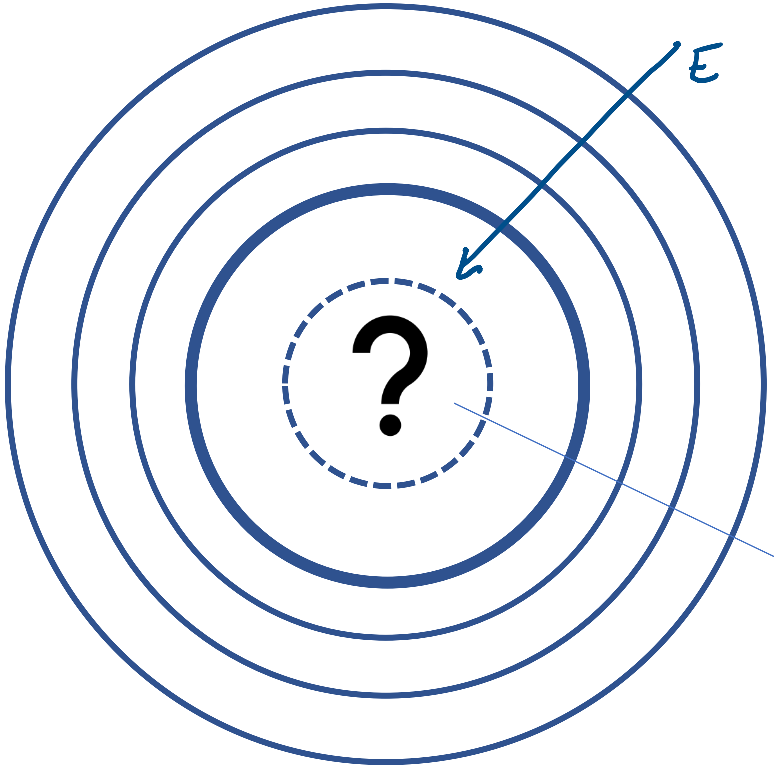


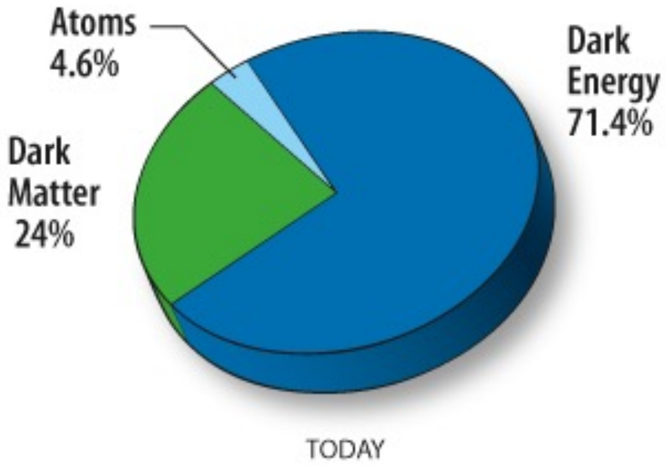
Unnatural Higgs means the next layer *is no longer predictive* without including contributions *from much smaller scales*

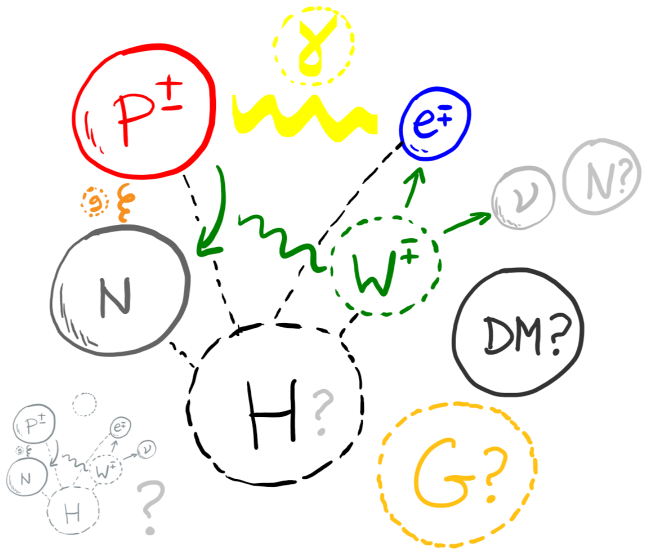
- Are we missing a **new** *"post-naturalness"* principle?

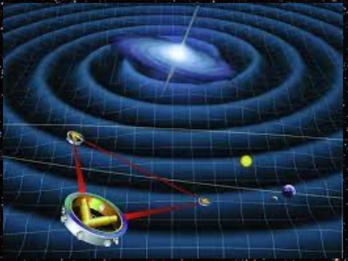
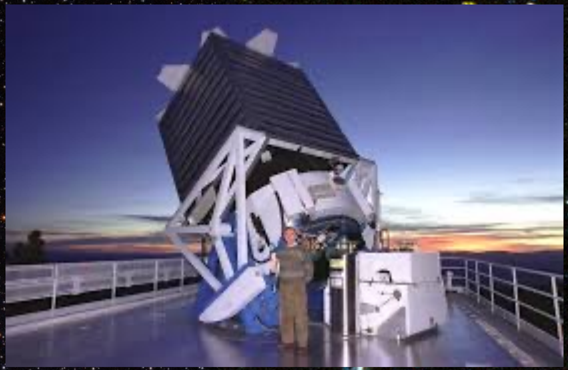
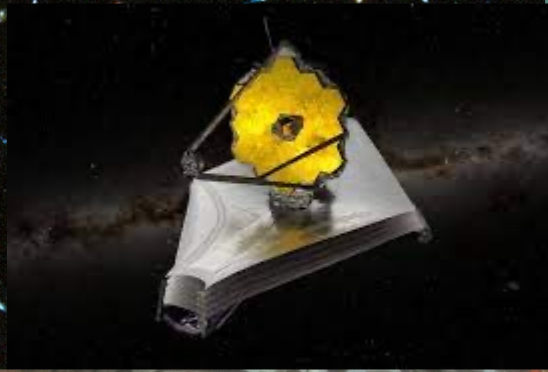
c.f. null results in search for aether

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**?

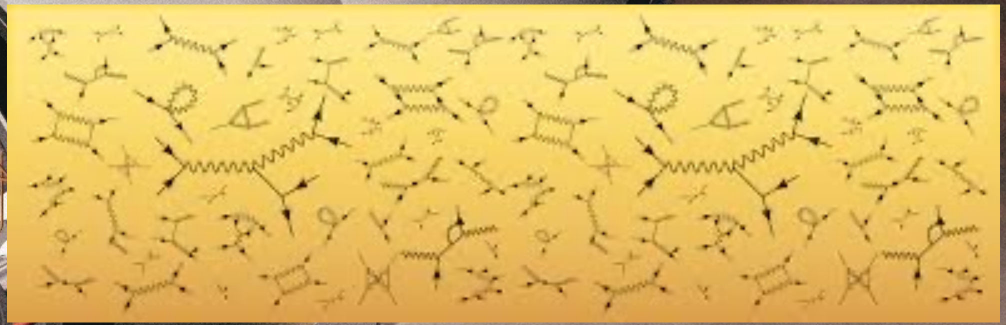




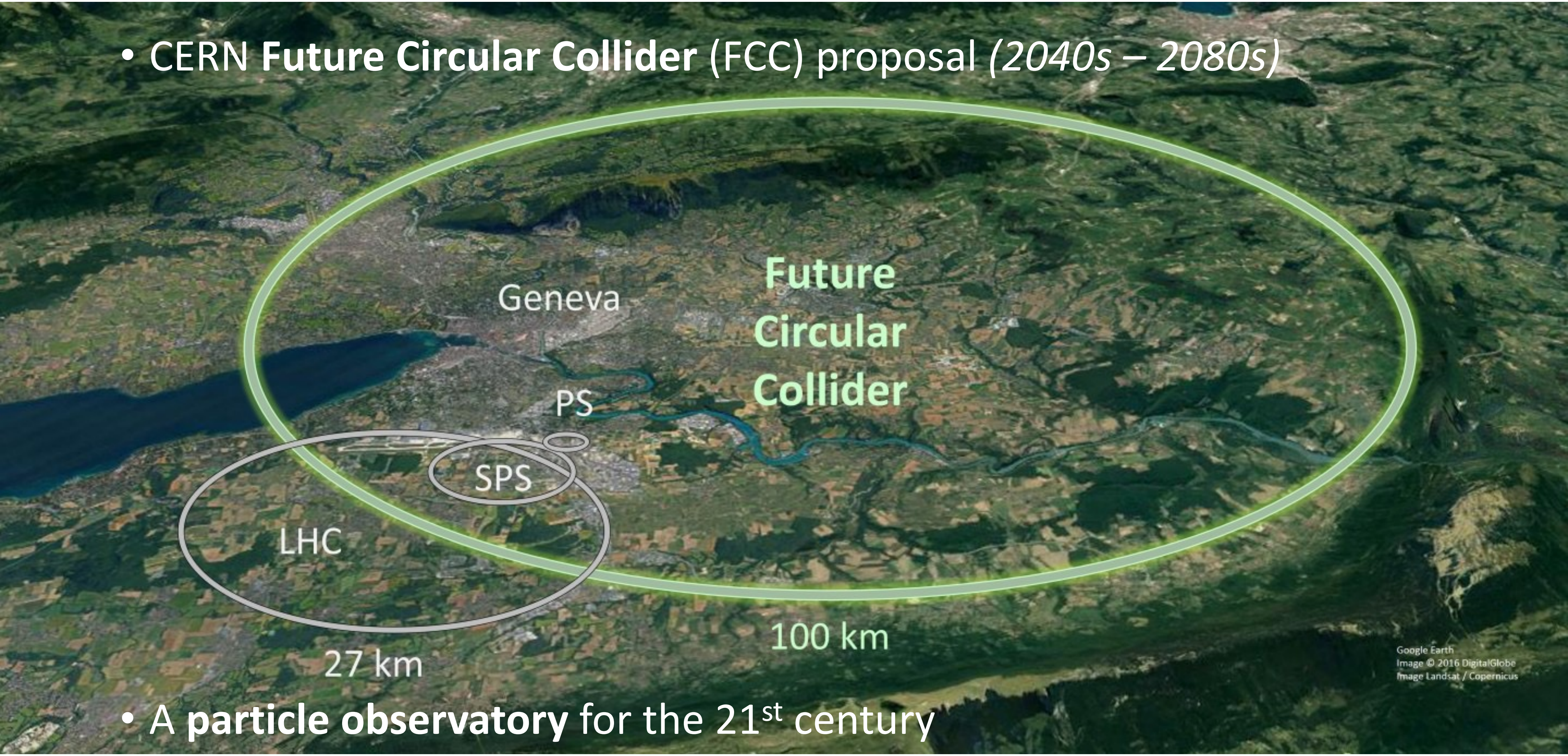
- Telescopes are observatories of the very large
- Colliders observe the very small
- We need *all eyes open* **on all scales** in our universe





FCC-ee → FCC-hh

- CERN **Future Circular Collider** (FCC) proposal *(2040s – 2080s)*



- A **particle observatory** for the 21st century

“BSM discovery prospects” → “Exploring origins”

- What is the **purpose** of a **next-generation particle observatory**?

> *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**

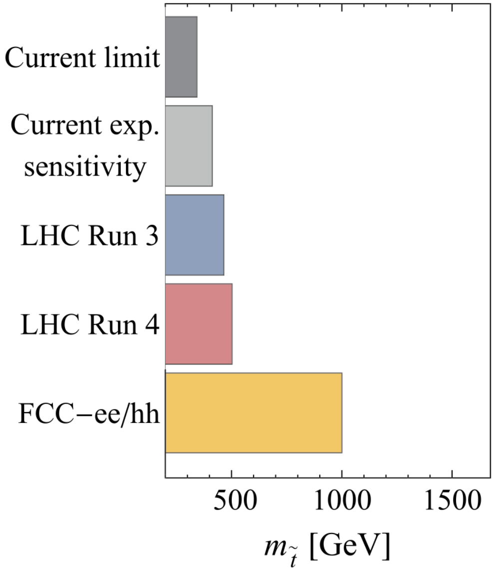
- *“Discovery stories”* risks putting the focus on *promising* to **find new physics**
- *“Exploring origins”* puts the focus on **open BSM questions** to be answered
  - Emphasises colliders as a **general-purpose particle observatory** with a *wide-ranging physics programme*

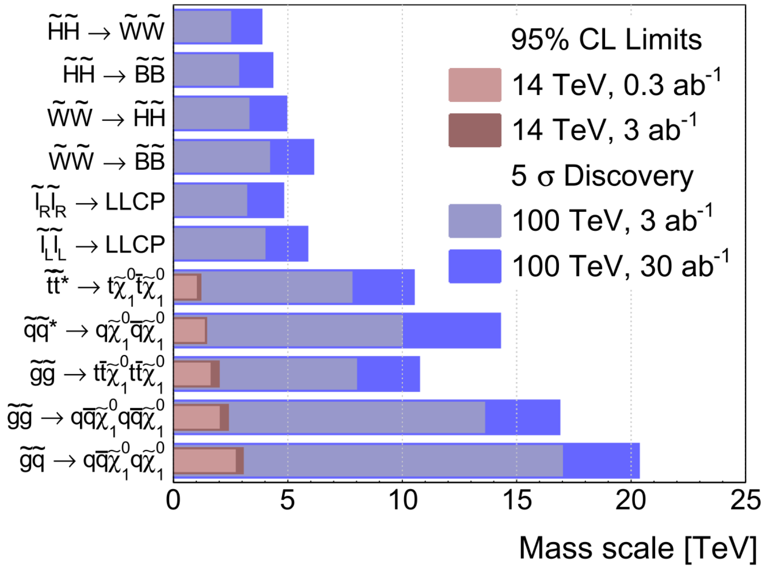
(Rename FCC to the **International Particle Observatory**?) See CERN Courier article: https://cerncourier.com/a/future-colliders-are-particle-observatories/

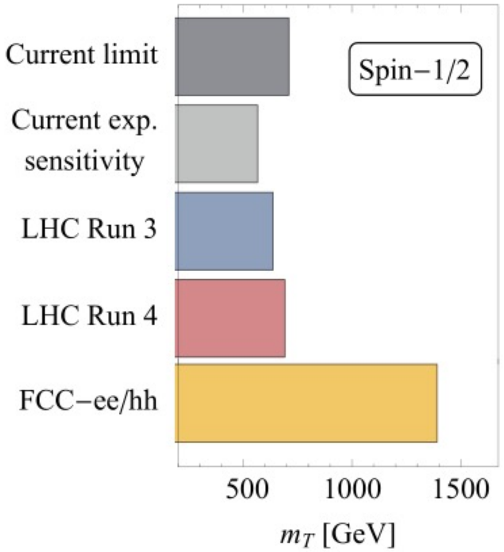
Origin of the Higgs

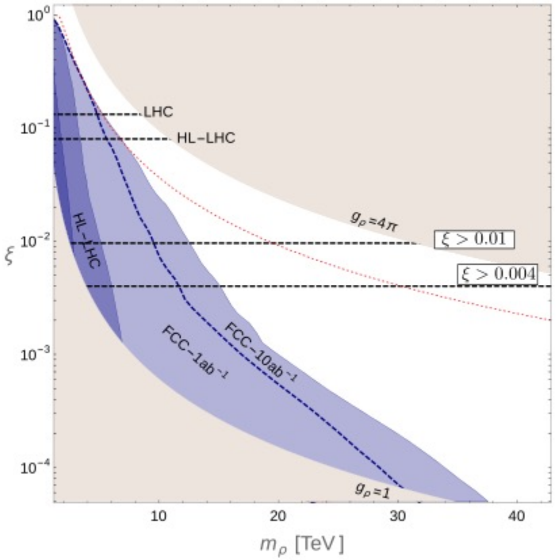
Note: naturalness aside, still motivation in exploring origin of Higgs in models from which it emerges, where its mass is *calculable*

FCC CDR Vol. 1





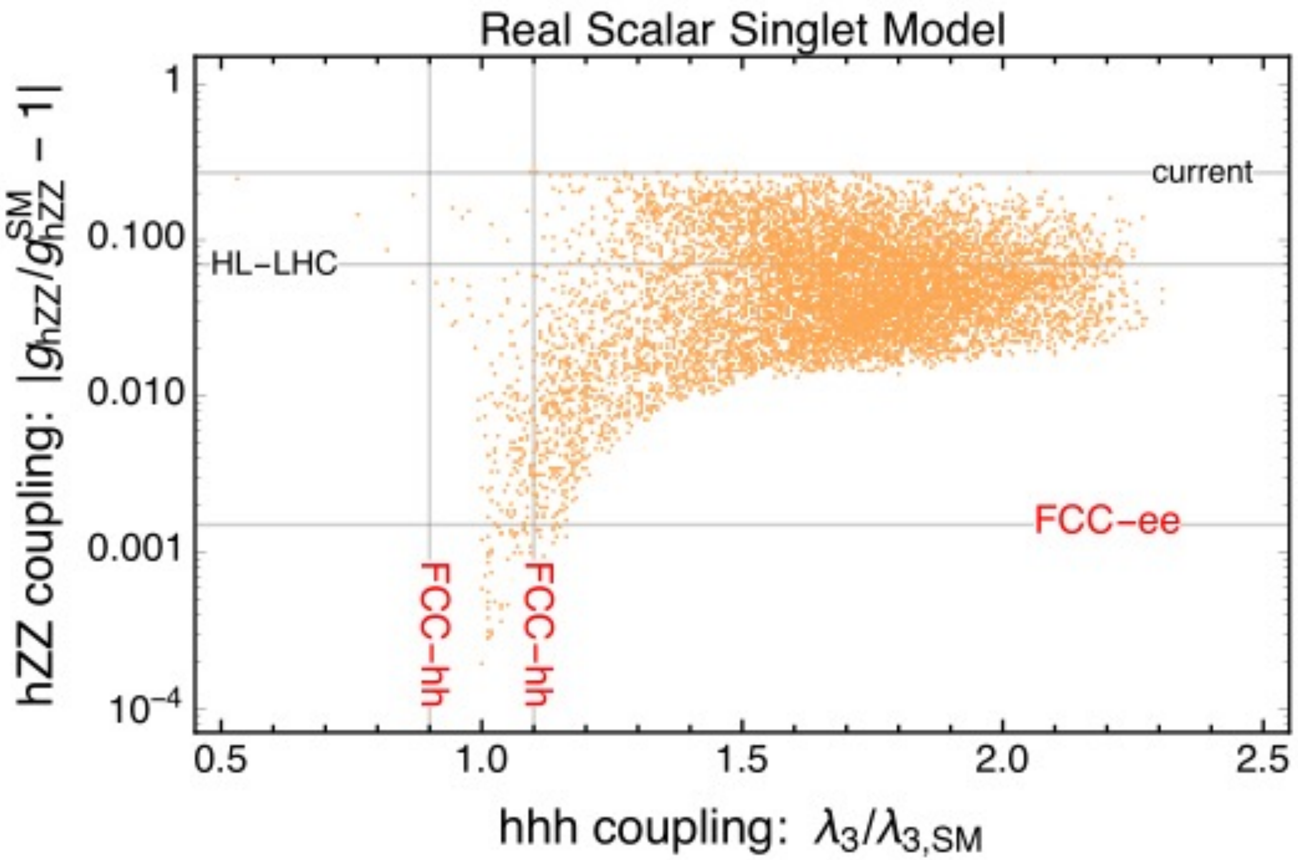




- **Supersymmetry**
  - Massless spins 0, ½, 1, 3/2, 2 *only*
  - Spin 3/2 *must* be supersymmetric
  - (Ir)relevant for solving **naturalness**?
- **Composite Higgs / extra dimensions**
  - Is the Higgs **elementary** or **composite**?
  - Are there *accessible* extra dimensions?

Origin of matter

- Nature of the **electroweak phase transition**: *first* or *second order*?

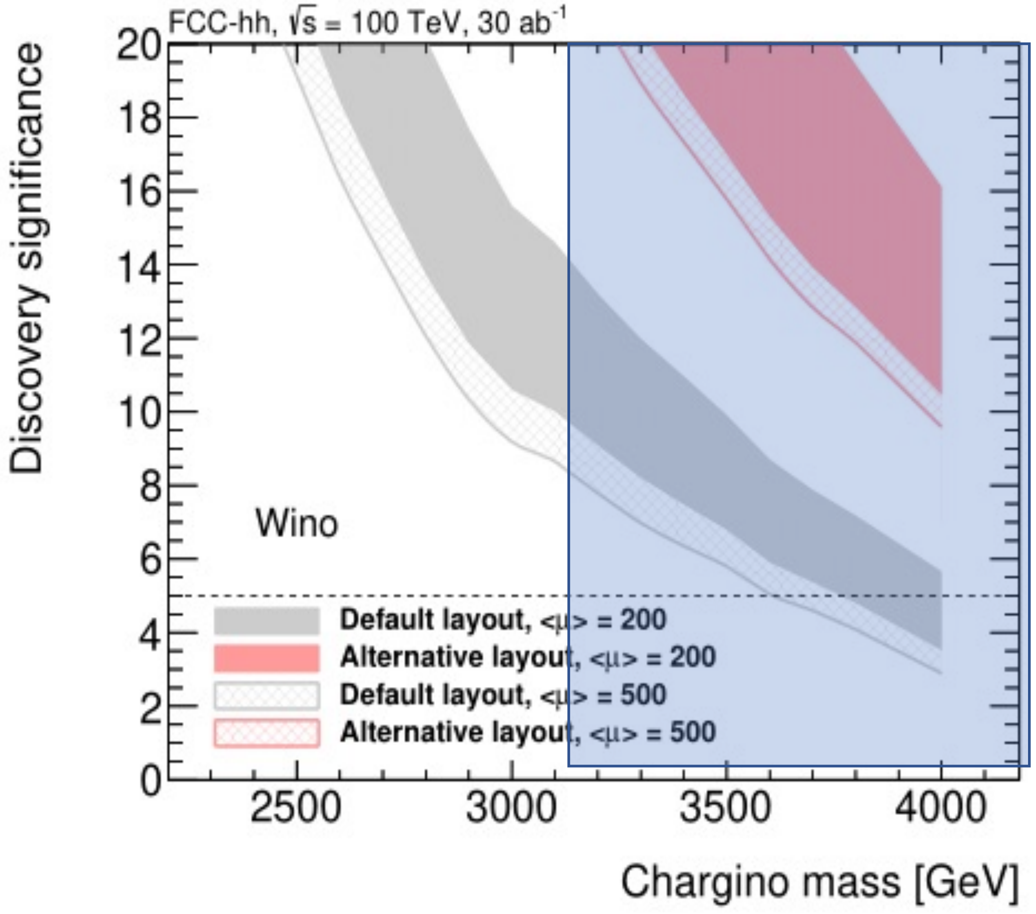


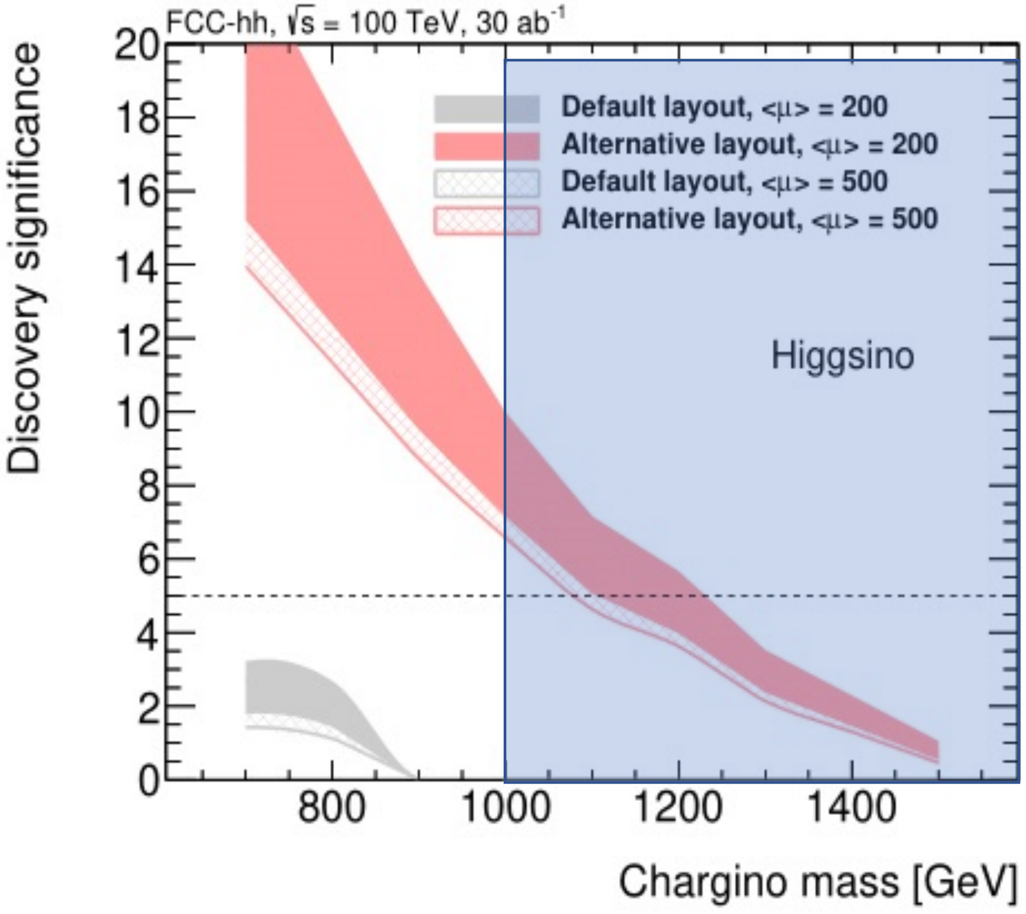
FCC CDR Vol. 1

- *Potential corroboration* with **gravitational wave signal** at LISA

Origin of dark matter

- FCC-hh coverage of *entire* **doublet** and **triplet thermal WIMP** mass range

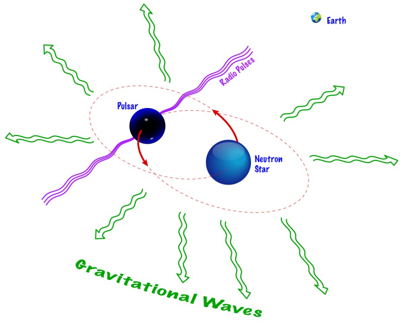




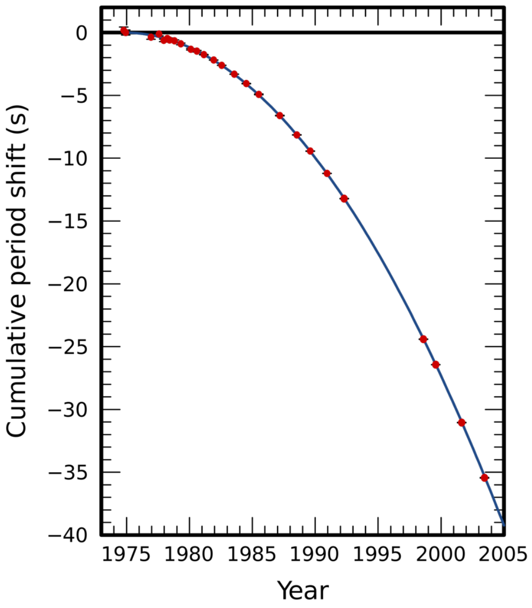
FCC CDR Vol. 1

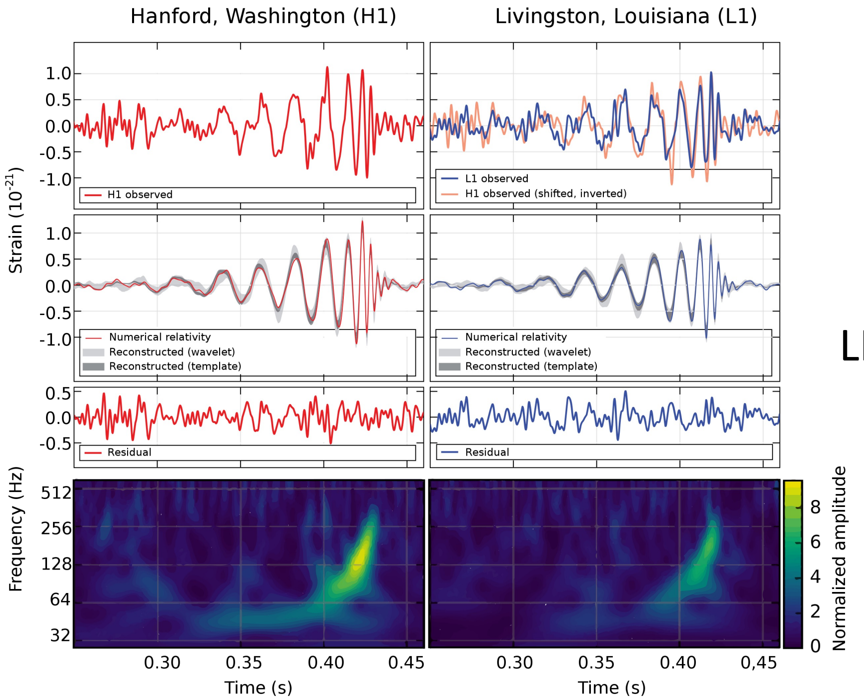
Why high energy after high precision?

- Follow up **indirect observations** with **direct exploration**



Hulse-Taylor binary
neutron+pulsar system



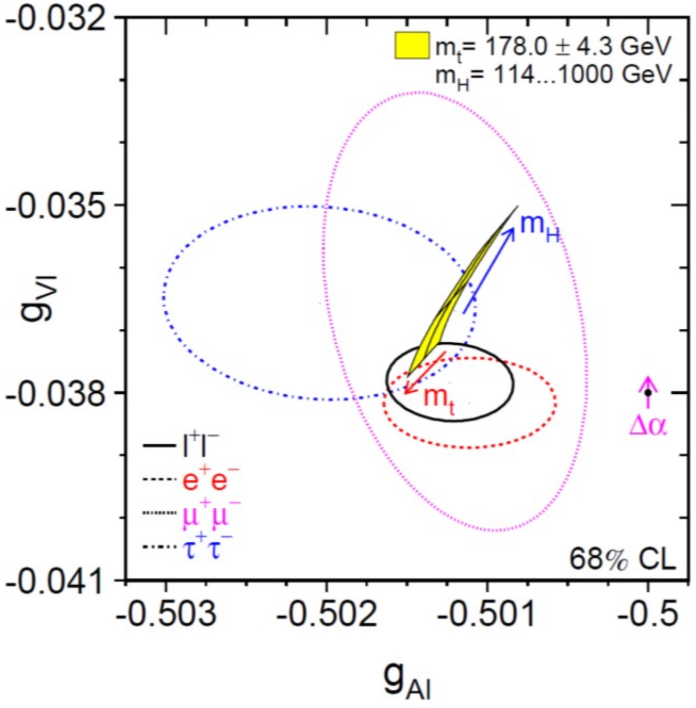


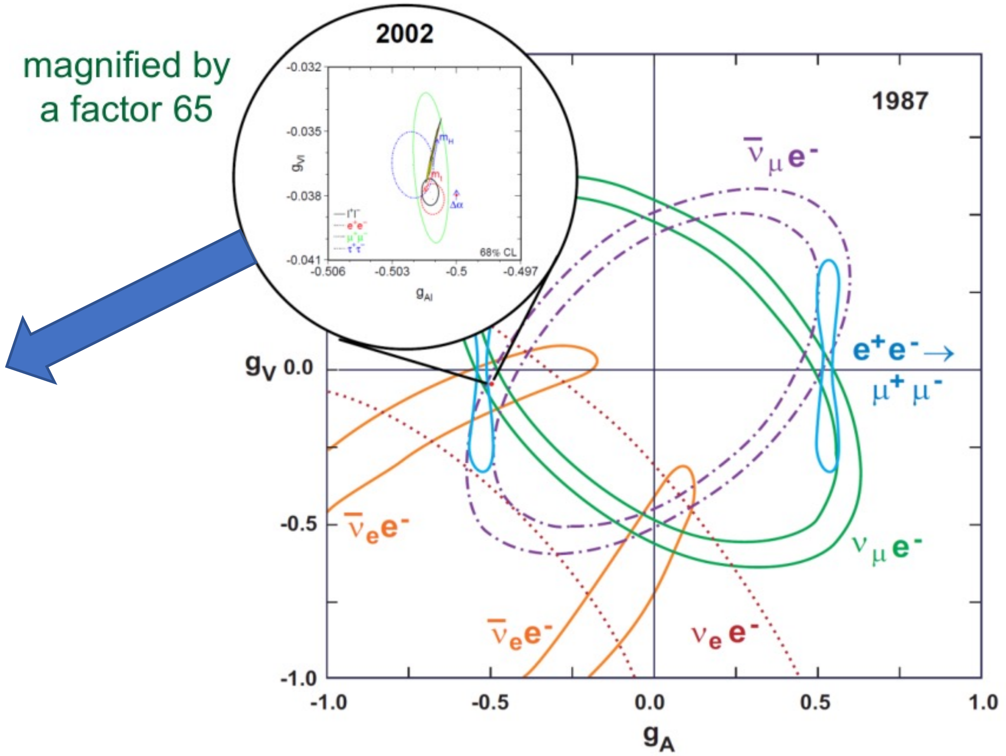
LIGO+VIRGO

- **Note:** in astro/cosmo, observing *known* objects and processes **in new regimes** or to **better accuracy** is reason enough to keep making progress!

No BSM or new discoveries at LEP

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



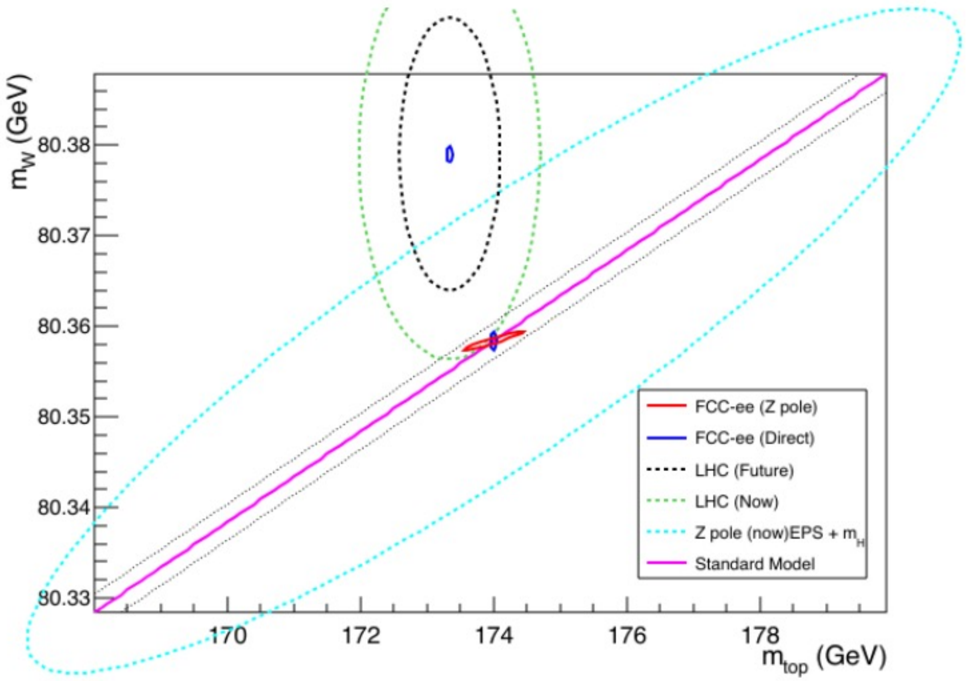


Guy Wilkinson slide

- *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?

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

- **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.*

Potential BSM outcomes for naturalness

- **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

- 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?

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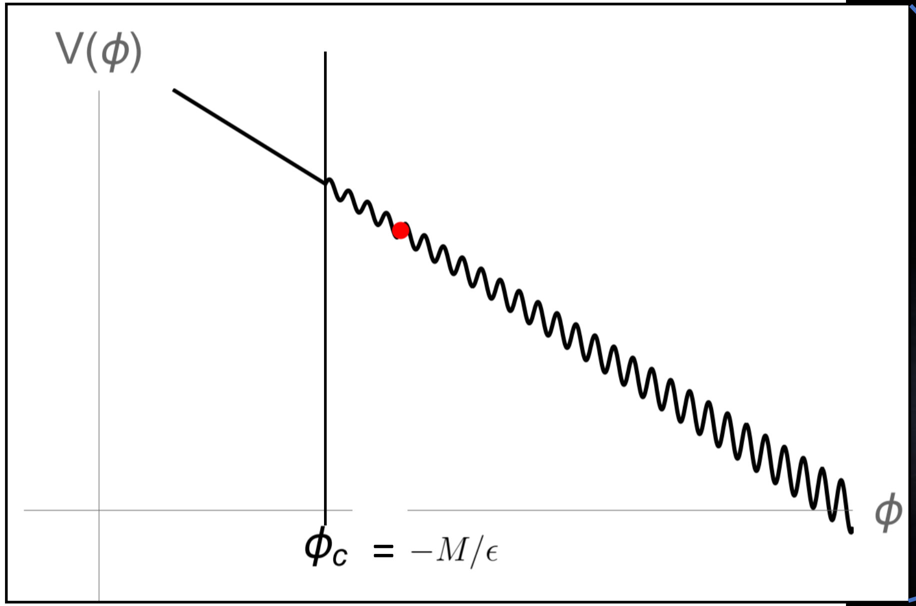
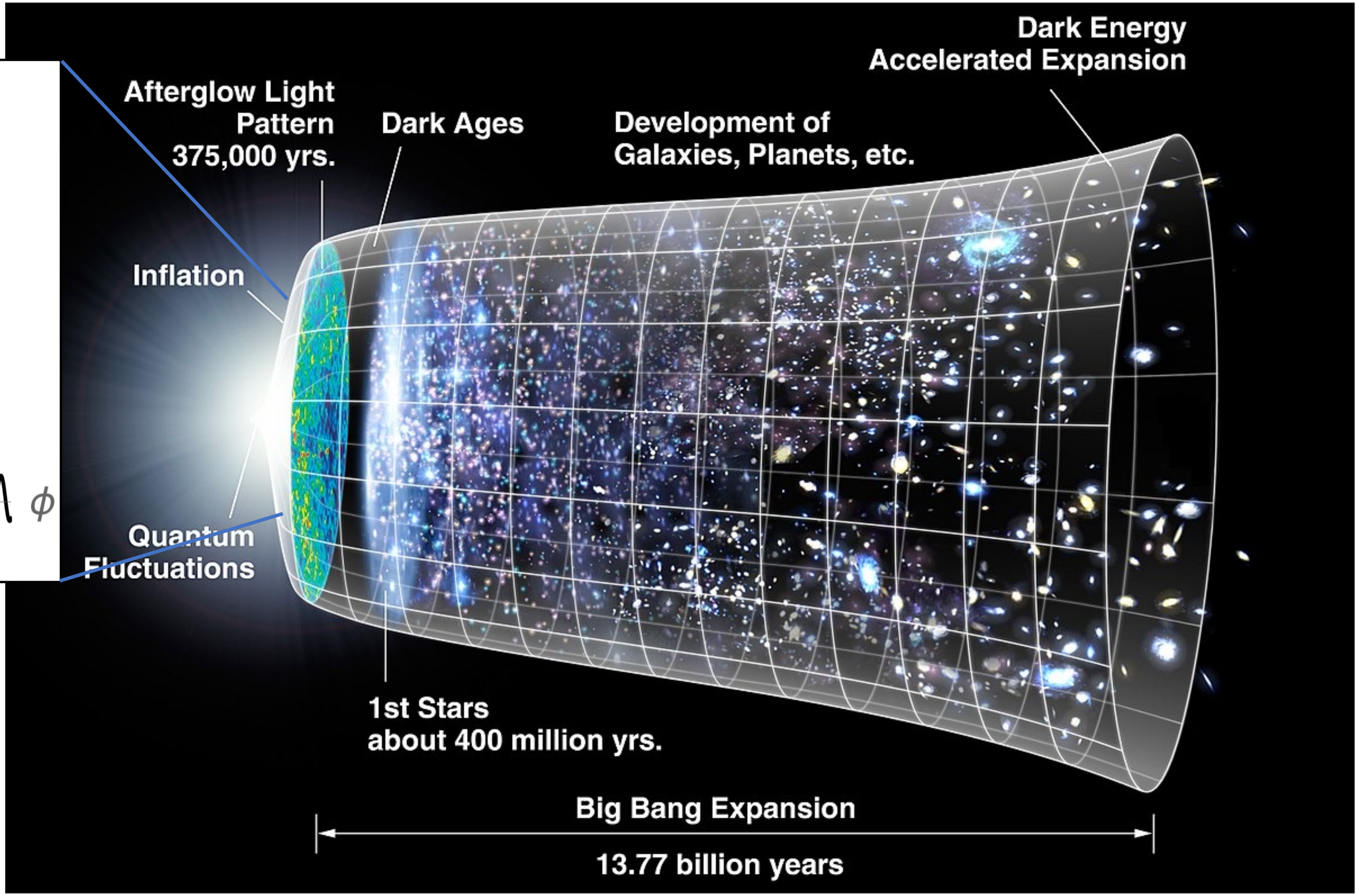
Cosmological solutions to naturalness problems

- **Cosmological evolution** during inflation could play a role





Cosmological solutions to naturalness problems

- The **good**: QCD axion solution of strong CP problem
- The **bad**: Abbott relaxation of cosmological constant
- The **ugly**: Cosmological relaxation of weak scale
- The **exotic**: Self-Organised Localisation

Cosmological solutions to naturalness problems

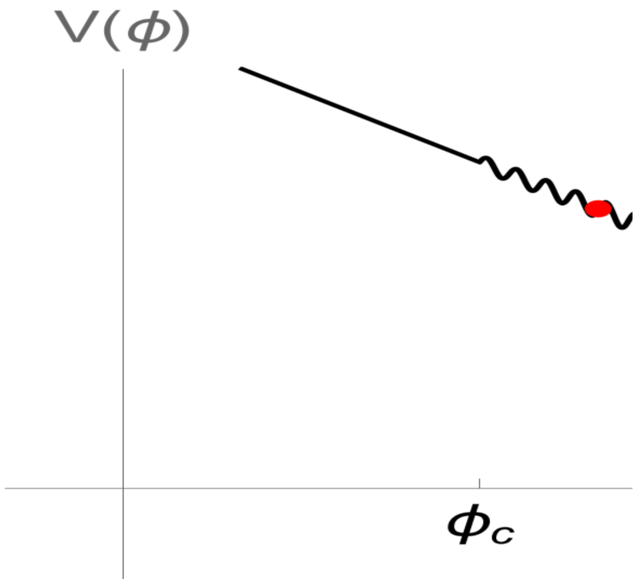
- The **good**: QCD axion solution of strong CP problem
  - Most likely candidate for existing in nature
- The **bad**: Abbott relaxation of cosmological constant
  - Doesn't work
- The **ugly**: Cosmological relaxation of weak scale
  - Works, but wouldn't bet on it yet
- The **exotic**: Self-Organised Localisation
  - Requires eternal inflation

QCD axion

$$\mathcal{L} \supset \Lambda_p^4 \cos\left(\frac{\phi}{f_p}\right)$$

- Needs no introduction – **widely accepted** cosmological solution
- First incarnation (Weinberg-Wilczek axion) ruled out ⇒ DFSZ / KSVZ **invisible axion**
- Has a *'halo of truth'* to it, but also lack of attractive alternatives
- Still a PQ **quality problem**: requires additional UV model-building

Abbott model



L. F. Abbott, Phys. Lett. B 150 (1985) 427

$$\mathcal{L} \supset \epsilon M^3\phi + ... + \Lambda_p^4 \cos\left(\frac{\phi}{f_p}\right)$$

- Vacuum energy relaxed by ϕ
- Periodic potential barriers **suppressed** by Hawking temperature
- **Unsuppressed** for small enough vacuum energy density ⇒ **trapped at small CC**

- However, ends in **cold empty universe**
- Reheating requires *e.g. null energy condition violation*

Alberte et al 1608.05715
Graham, Kaplan, Rajendran 1902.06793

Cosmological relaxation

P. W. Graham, D. E. Kaplan and S. Rajendran, [arXiv:1504.07551]

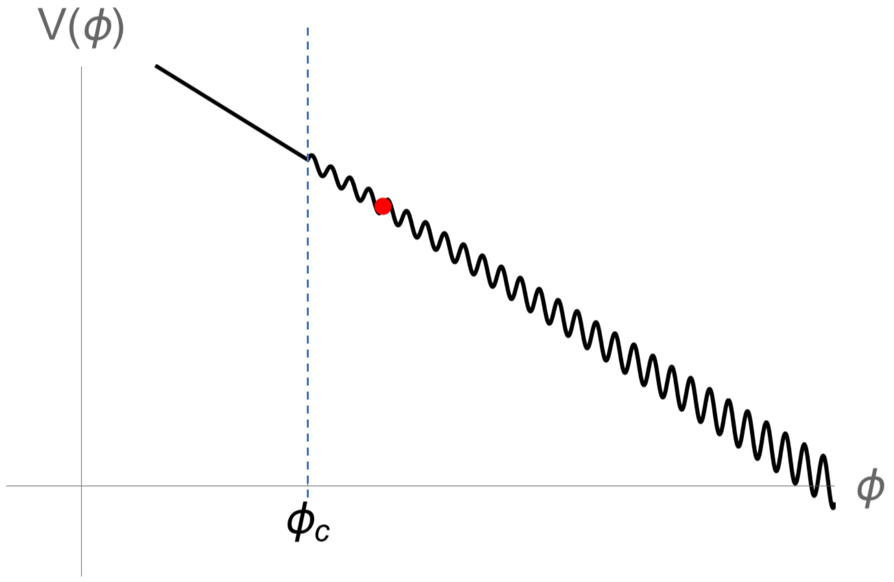
- Assume Higgs mass is naturally large at cut-off M

$$\mathcal{L} \supset (M^2 + \epsilon M\phi)|h|^2 + \epsilon M^3\phi + ... + \Lambda_p^{4-n} v^n \cos\left(\frac{\phi}{f_p}\right)$$

- Higgs quadratic term scanned by axion-like field ϕ during inflation

- ϕ protected by shift symmetry, explicitly broken by small parameter ε

- Backreaction when $< h > \sim v$ stops ϕ evolution at small electroweak scale v



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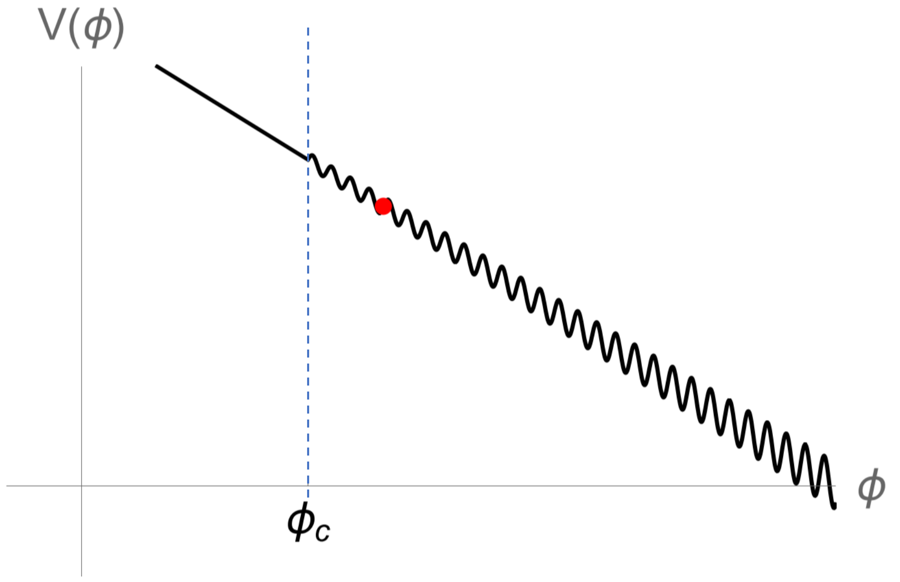

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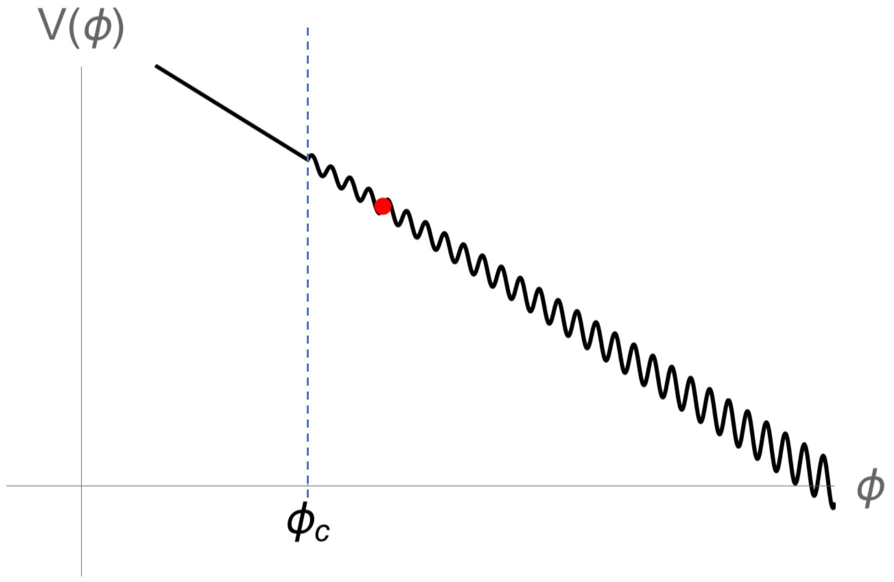

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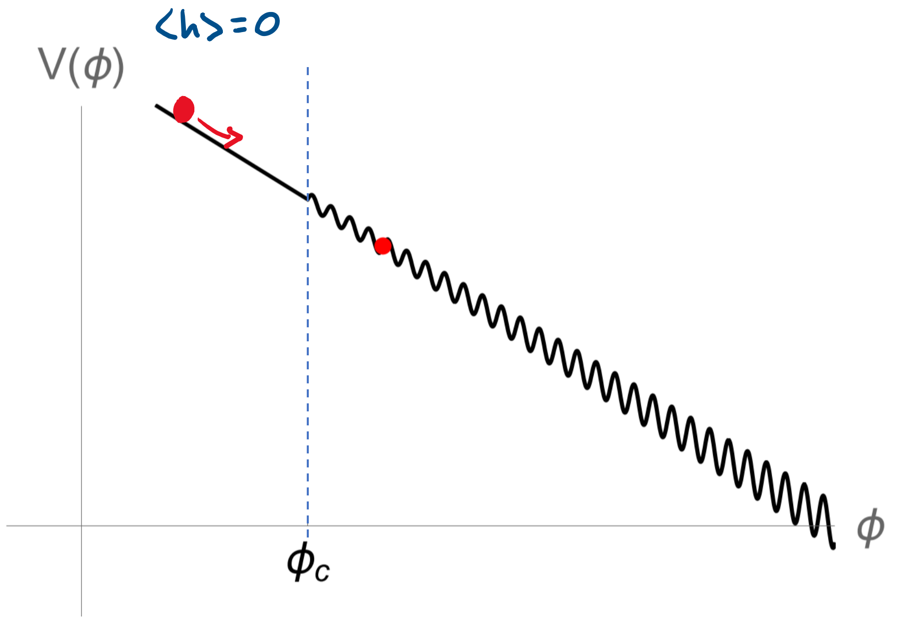

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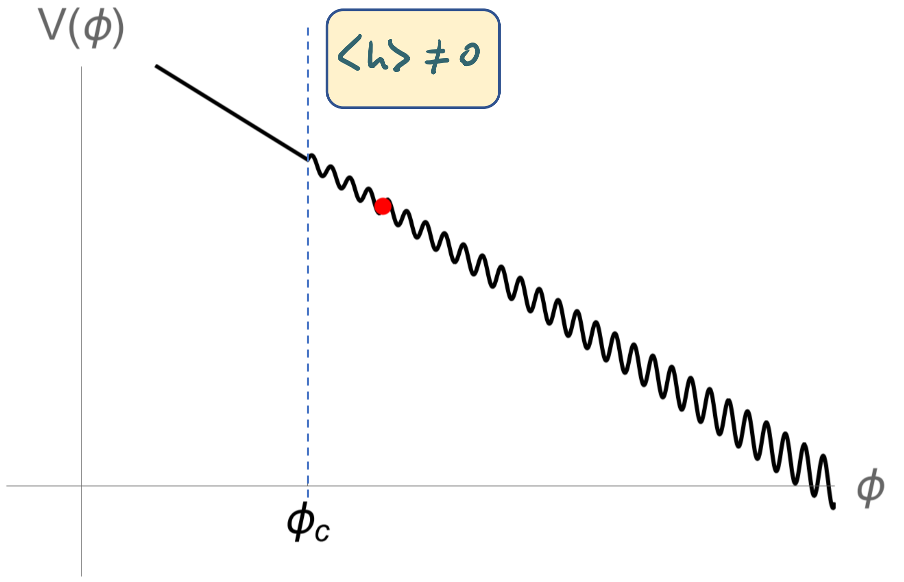

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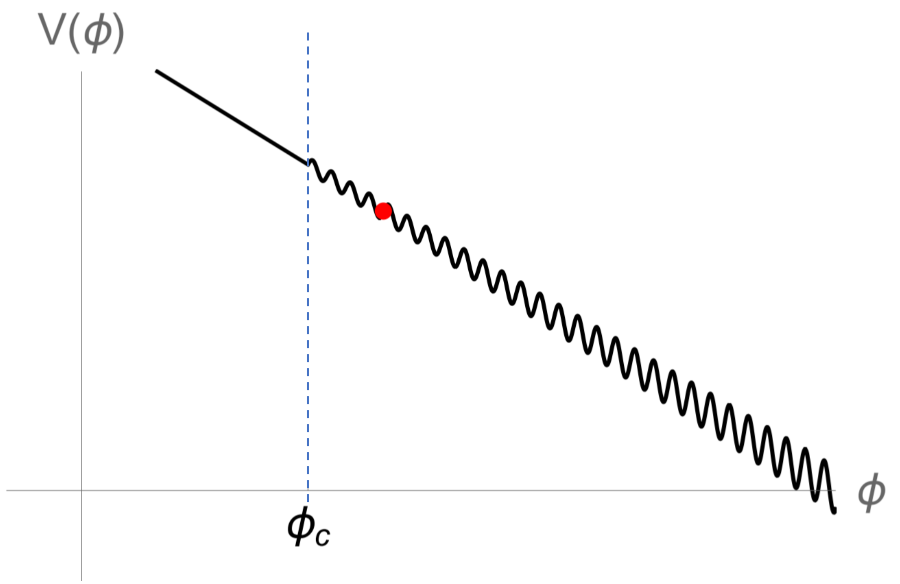
Cosmological relaxatio

Constraints: $H < v$, classical rolling vs quantum, inflaton energy density dominates relaxion, etc.

Very small ε and natural scanning range lead to super-planckian field excursions, exponential e-foldings…

- Assume Higgs mass is naturally l

$$\mathcal{L} \supset (M^2 + \epsilon M \phi)|h|^2 + \epsilon M^3 \phi + \ldots + \Lambda_p^{4-n} v^n \cos\left(\frac{\phi}{f_p}\right)$$



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Cosmological relaxation

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- **n=1** models Graham et al [1504.07551]
    - Confining gauge group G=QCD: Need additional ingredients to overcome **strong-CP problem**

      See e.g. most recently: Chatrchyan, Servant [2210.01148]
    - New gauge group G: **coincidence problem**

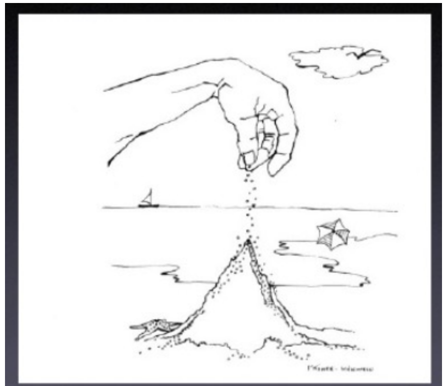
- **n=2** models Espinosa et al [1506.09217]
    - G can be at higher scales, raises M cut-off too
    - **Requires second scalar** to relax relaxion barriers: double-scanning mechanism

- **n=0** models Hook and Marques-Tavares [1607.01786], **TY** [1701.09167]
    - **More promising**, make use of axial gauge coupling

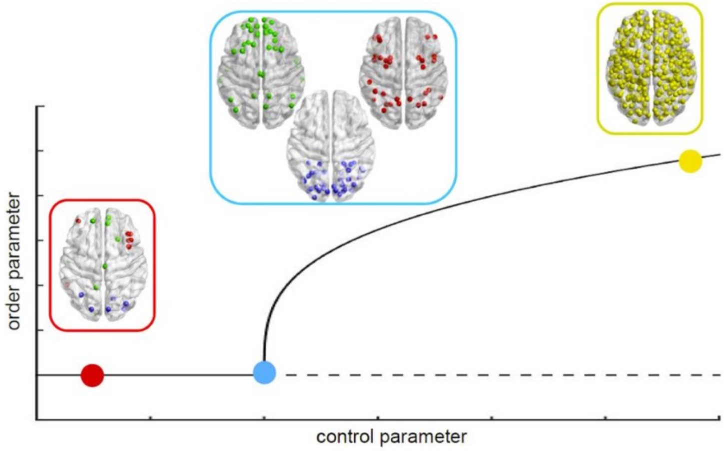
$$\mathcal{L} = \frac{1}{32\pi^2}\frac{a}{f}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}G_{\mu\nu}G_{\rho\sigma}$$

Self-Organised Criticality

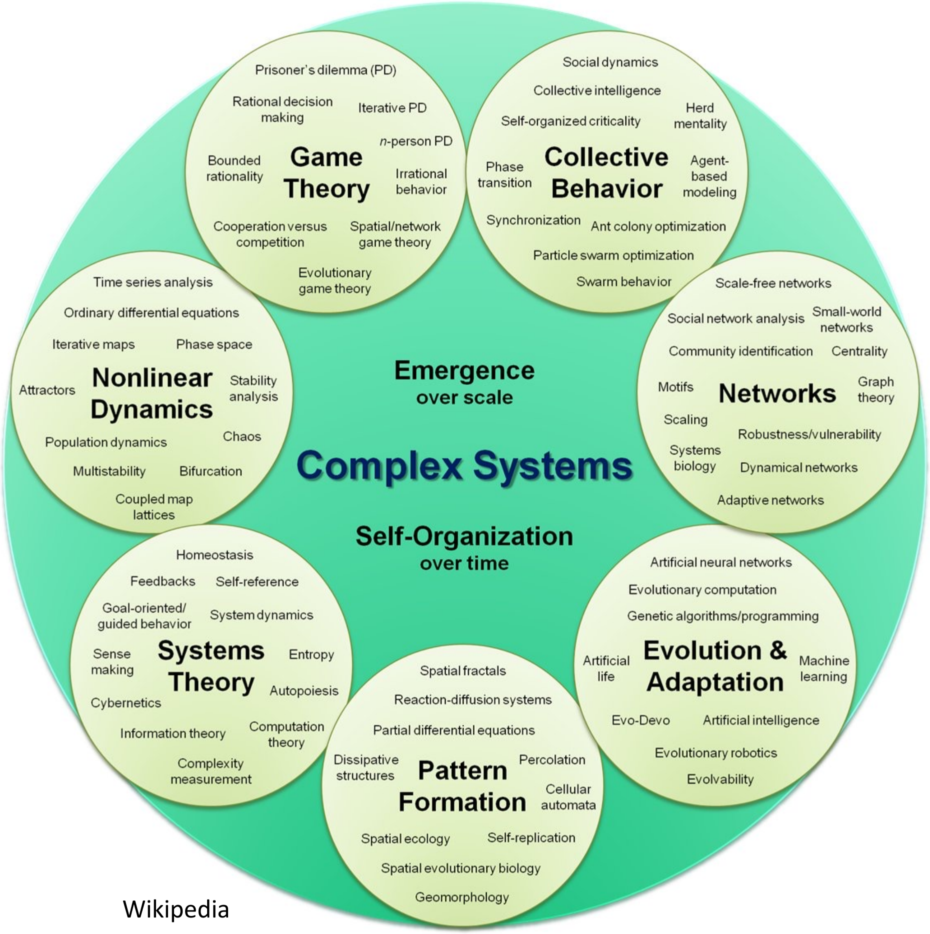
- Many systems in nature **self-tuned** to live near criticality



Bak, Tang and Weisenfeld (1989)



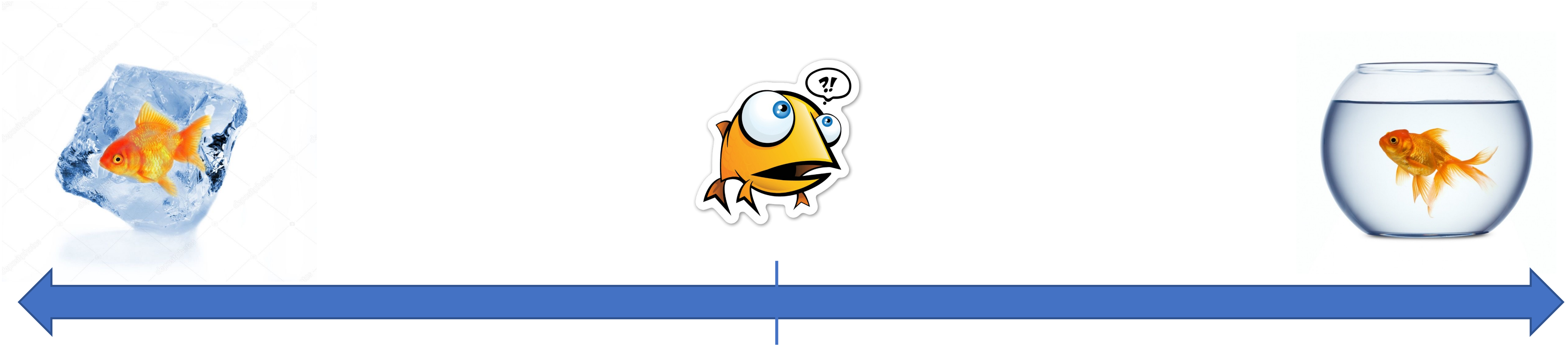
https://www.quantamagazine.org/toward-a-theory-of-self-organized-criticality-in-the-brain-20140403/



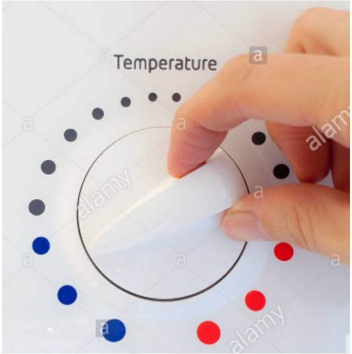
Wikipedia

Critical points

- To be at the **critical point** of a classical phase transition **requires tuning**



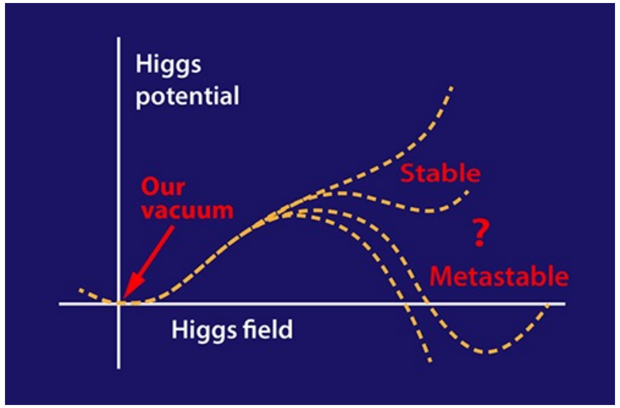
- Living **near criticality** is highly **non-generic**!

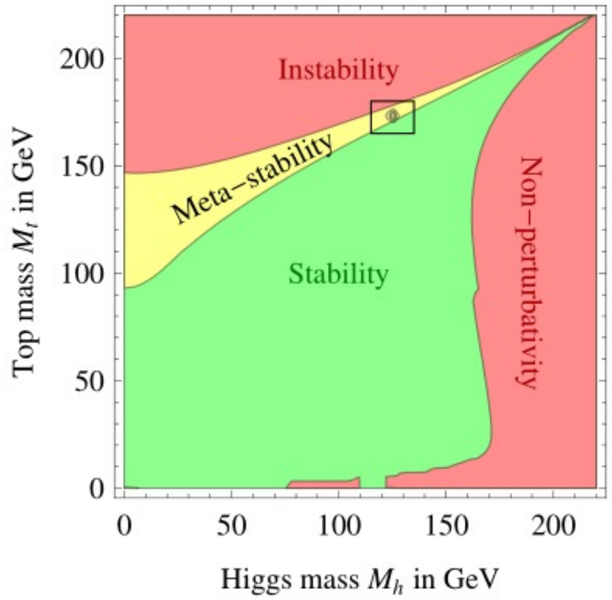


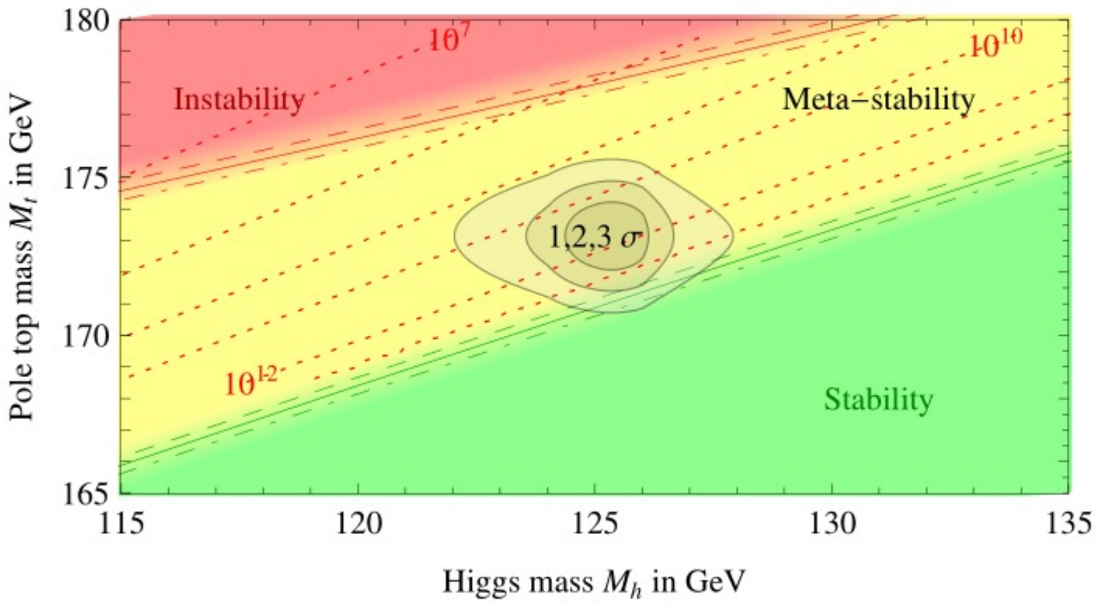
3 hints for **near-criticality** of our Universe

- 1) Higgs potential **metastability** in SM

1205.6497 Degrassi et al







- Living on critical boundary of **two phases coexisting**

3 hints for **near-criticality** of our Universe

- 1) Higgs potential **metastability** in SM

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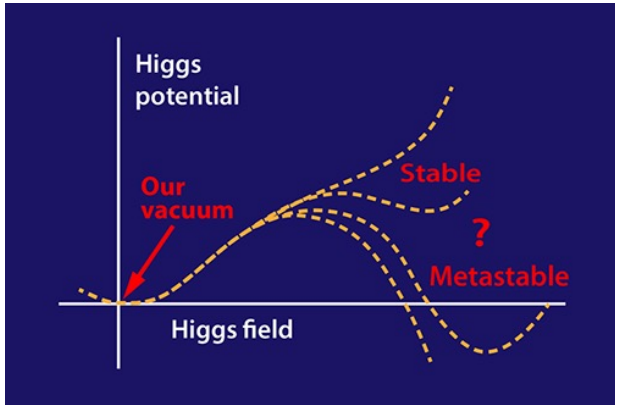
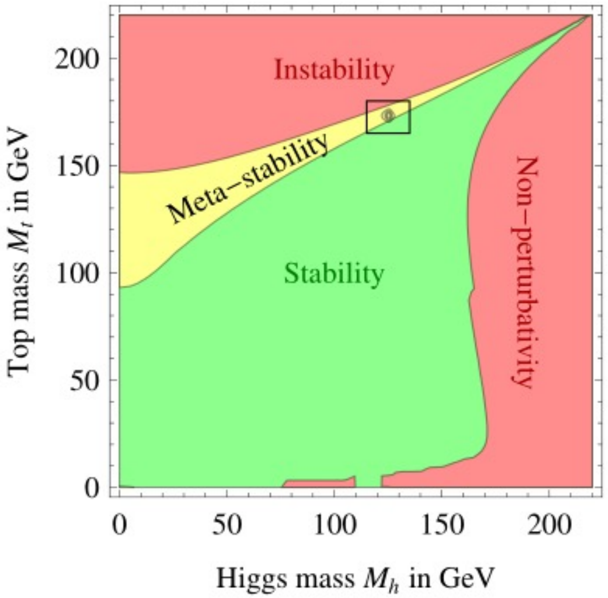
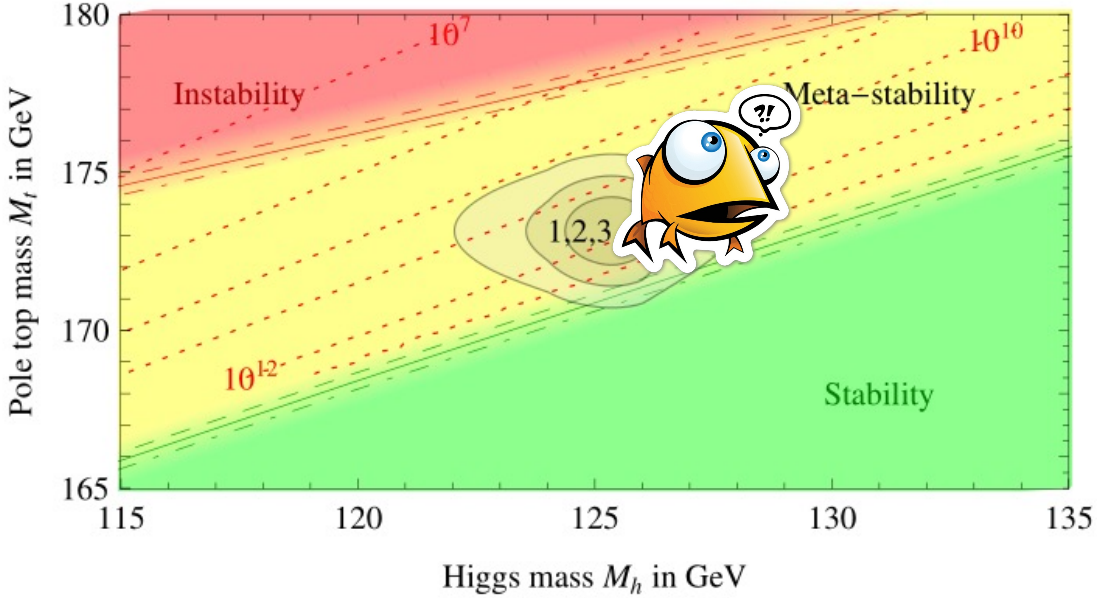


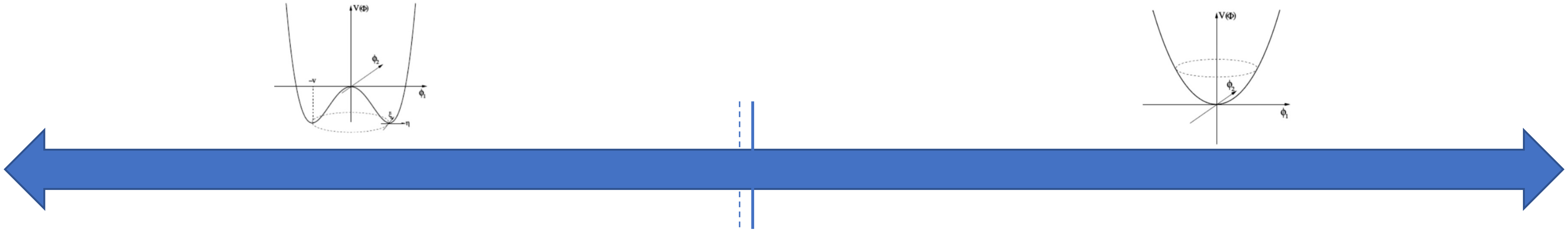




- Living on critical boundary of **two phases coexisting**

3 hints for **near-criticality** of our Universe

- 2) **Higgs mass**

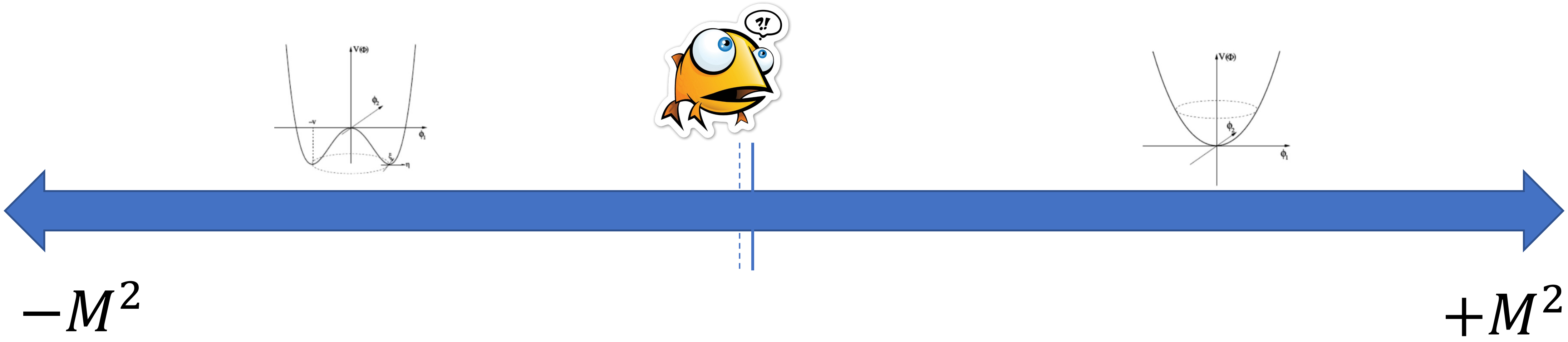


$-M^2$ $+M^2$

- Tuned close to boundary between **ordered** and **disordered** phase

3 hints for **near-criticality** of our Universe

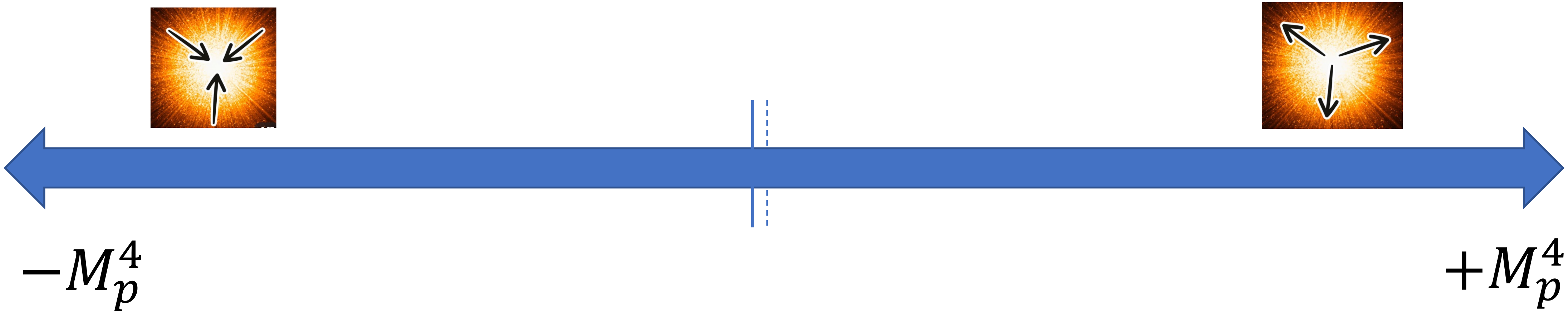
- 2) **Higgs mass**



- Tuned close to boundary between **ordered** and **disordered** phase

3 hints for **near-criticality** of our Universe

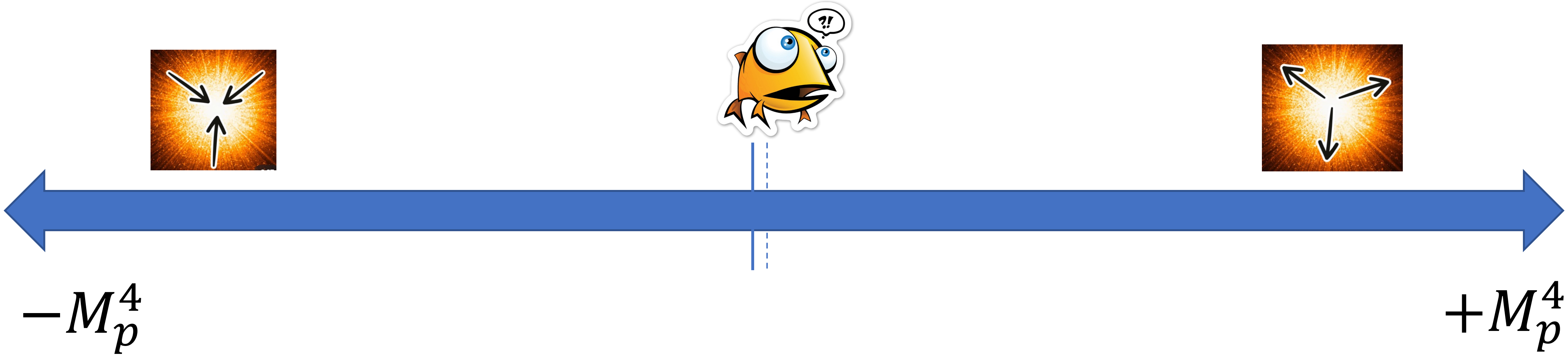
- 3) **Cosmological constant**



- Tuned close to boundary between **implosion** and **explosion**

3 hints for **near-criticality** of our Universe

- 3) **Cosmological constant**



- Tuned close to boundary between **implosion** and **explosion**

3 hints for **near-criticality** of our Universe

- Why do we appear to live at a **special point** close to criticality?

- Conventional explanations:
    - 1) **Metastability**: heavy new physics restores stability?
    - 2) **Higgs mass**: new symmetries?
    - 3) **Cosmological constant**: anthropics?

- Alternatively, hints for a **new principle** *beyond EFT expectations* at play?

Self-Organised Criticality

- **Fundamental** self-organised criticality in our universe?

- Need a **mechanism** for self-organisation of **fundamental parameters**

e.g. Self-Organized Criticality in eternal inflation landscape: J. Khoury et al 1907.07693, 1912.06706, 2003.12594

- **Self-Organised Localisation (SOL):**
  - cosmological **quantum phase transitions** localise fluctuating scalar fields during inflation at critical points

Giudice, McCullough, TY 2105.08617

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
  - 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?

Energy

Direct exploration by **FCC-hh**

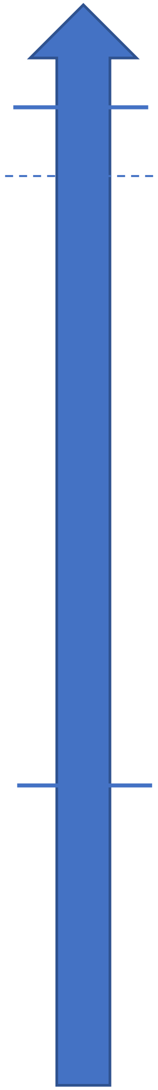
$\boldsymbol{\Lambda}$ — $\mathcal{L}_{UV} = ?$

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

Indirect exploration by **FCC-ee**

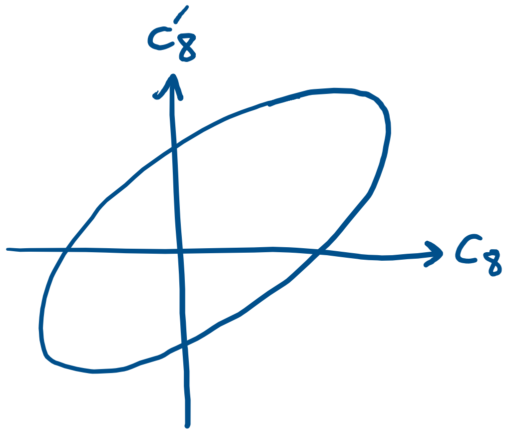
Radically new BSM?

Energy



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

Direct exploration by **FCC-hh**



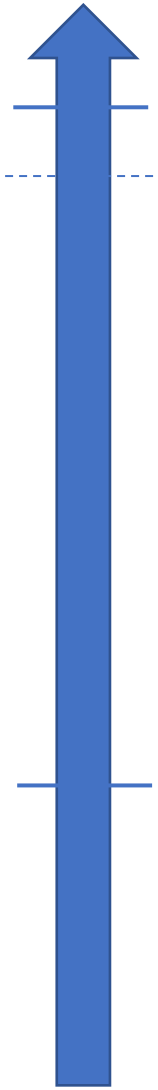
e.g. Consider indirect sensitivity to UV theory

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

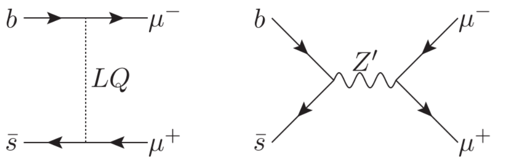
Indirect exploration by **FCC-ee**

Radically new BSM?

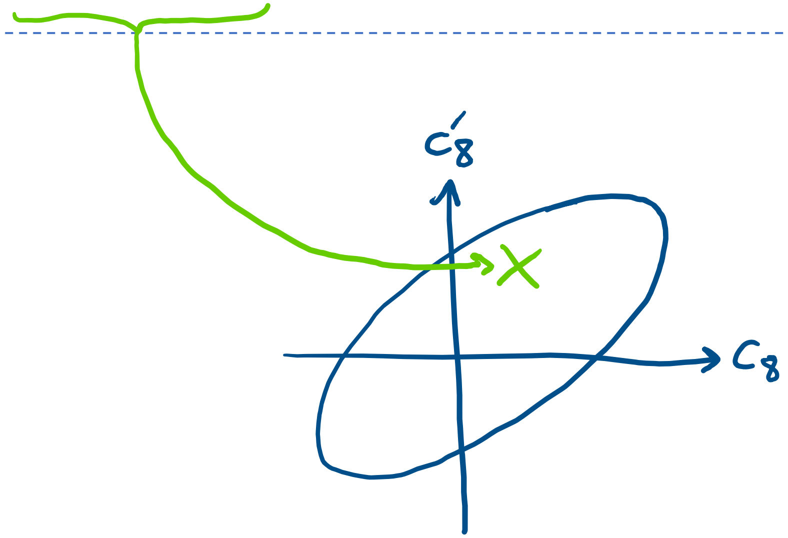
Energy



Λ $\mathcal{L}_{UV} = ?$



Direct exploration by **FCC-hh**



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

$E < \Lambda$

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

Indirect exploration by **FCC-ee**

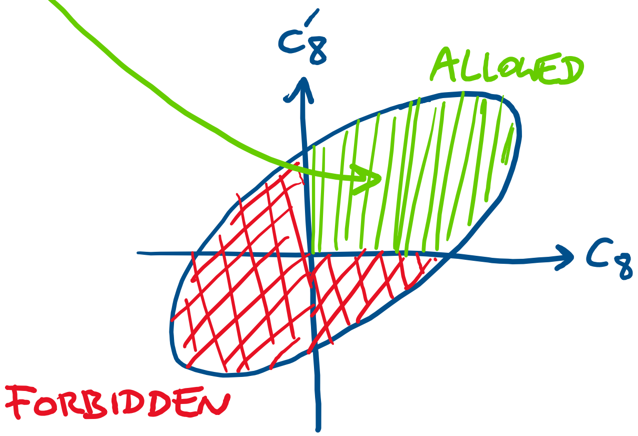
Radically new BSM?

Energy

Direct exploration by **FCC-hh**

Λ — $\mathcal{L}_{UV} = ?$

Unitarity | Locality | Causality | ...



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

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Indirect exploration by **FCC-ee**

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

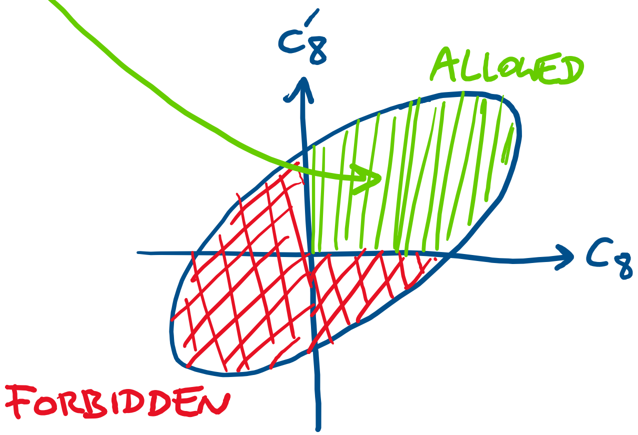
Radically new BSM?

Energy

May not even have a Lagrangian/QFT description

Direct exploration by **FCC-hh**

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



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Indirect exploration by **FCC-ee**

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Radically new BSM?

Positivity may correlate EFT with the electroweak hierarchy problem

2308.06226 Davighi, Melville, Mimasu, TY

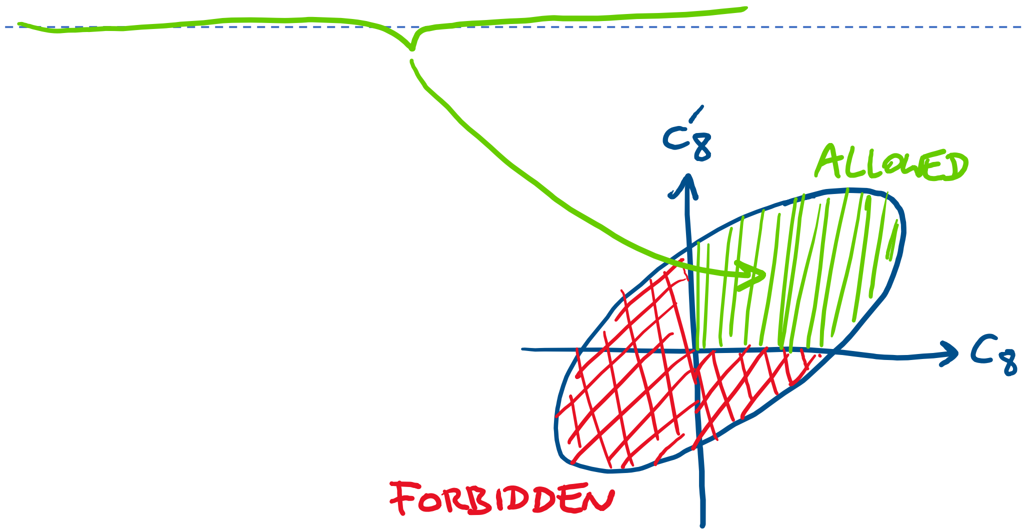
Energy

May not even have a Lagrangian/QFT description

Direct exploration by **FCC-hh**

Λ

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



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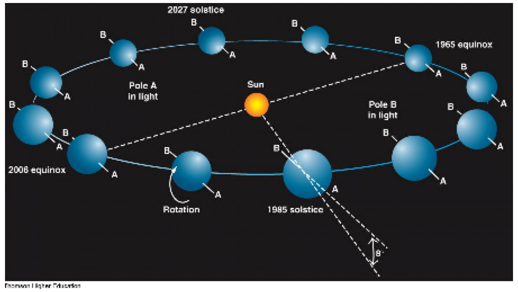
Indirect exploration by **FCC-ee**

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

Radically new BSM?

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

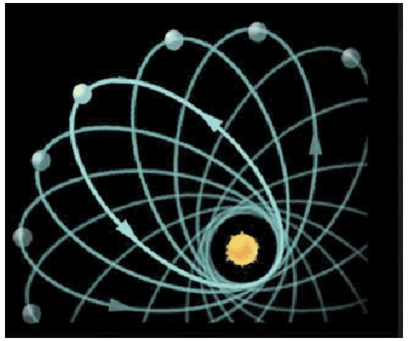
Anomaly in orbit of Uranus

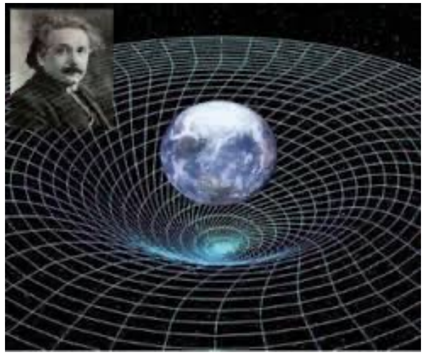


Discovery of Neptune

- 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

See CERN Courier article: https://cerncourier.com/a/future-colliders-are-particle-observatories/

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*.