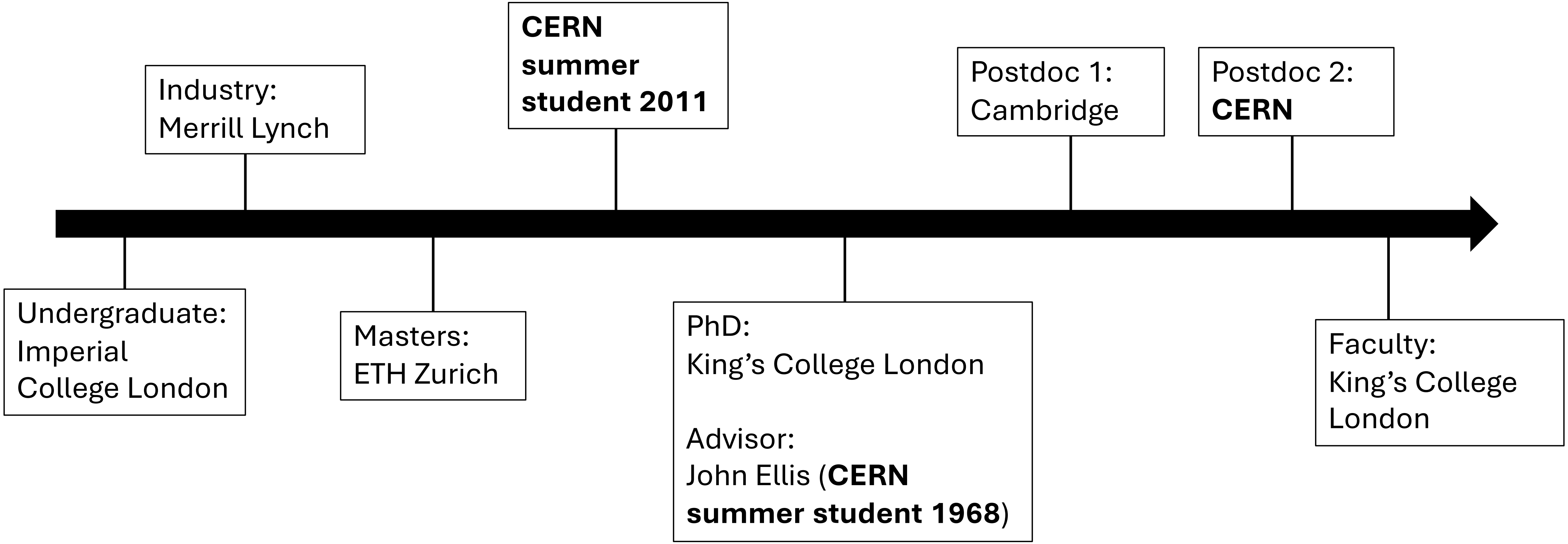
CERN summer student programme, 30th July 2024

# Beyond the Standard Model

Tevong You

# My World Line



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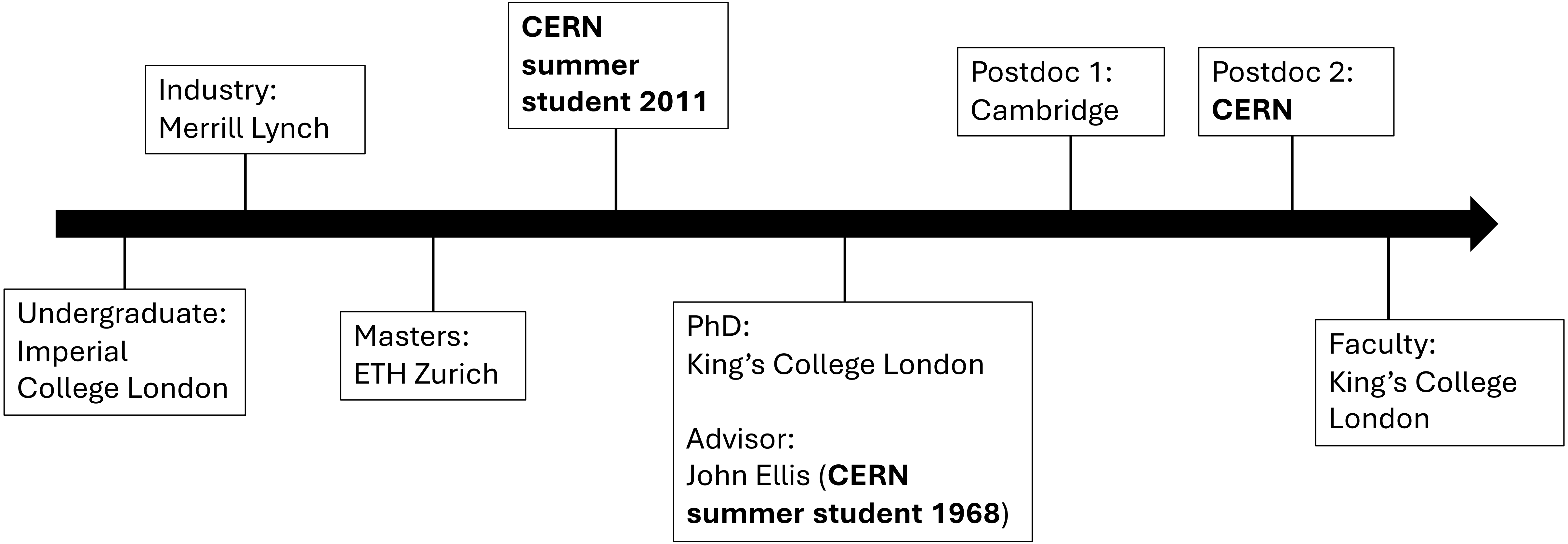


CERN is a very special place — humanity coming together for the exploration of *inner space*

# Oppenheimer and the birth of CERN


One day, Oppenheimer told me of a problem that was very much on his mind. Most of America's best physicists, he said, had like him been trained, or had worked, in Europe's pre-war laboratories. He believed that Europe's shaken nations did not have the resources to rebuild their basic physics infrastructure. He felt they would no longer be able to remain scientific leaders unless they pooled their money and talent. Oppenheimer also believed that it would be "basically unhealthy" if Europe's physicists had to go to the United States or the Soviet Union to conduct their research.

The solution, Oppenheimer felt, was to find a way to enable Europe's physicists to collaborate.

Francois de Rose, "Paris 1951: the birth of CERN", Nature (2008)
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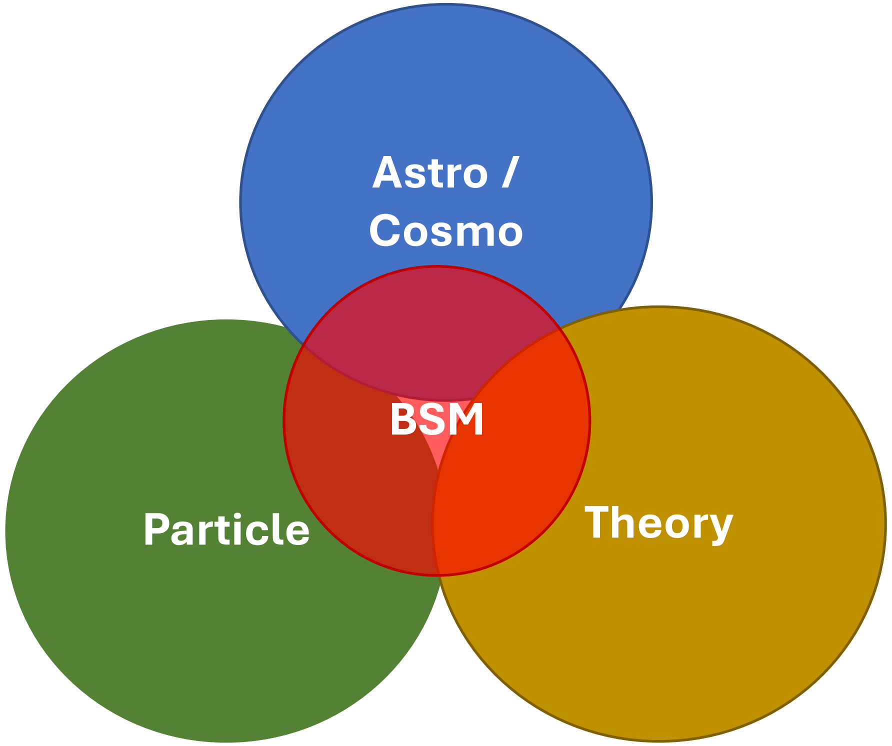
# Why BSM?

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




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

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

# Outline

**Part I**

1. Lessons in how we got here
2. Naturalness — what's the big deal?
3. Problems of the SM: arbitrary / unnatural / incomplete / inconsistent

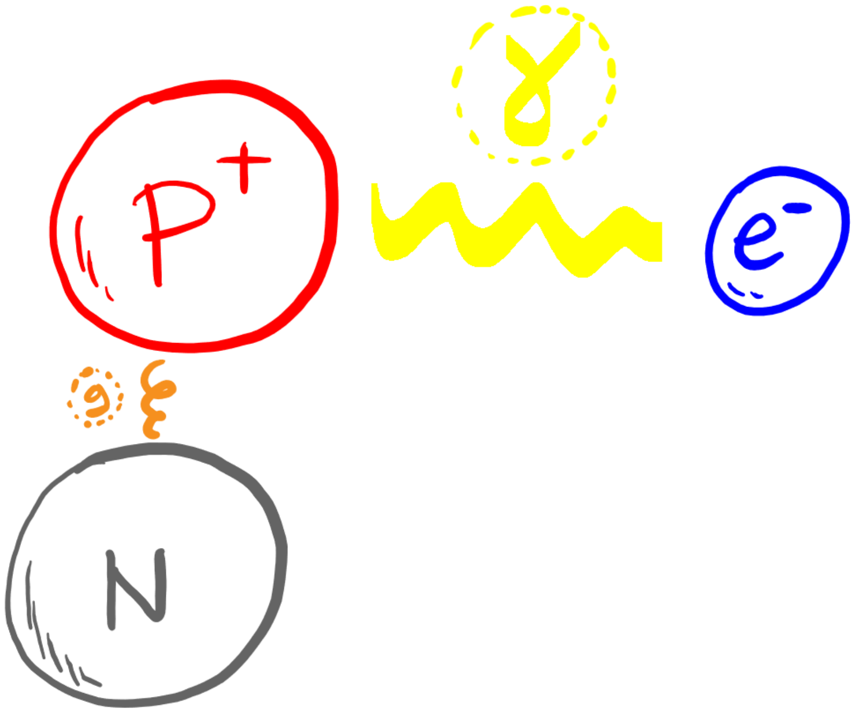
**Part 2**

1. The SM EFT gateway to BSM (and the "totalitarian principle")
2. Supersymmetry, WIMPs, GUTs
3. Cosmological solutions to naturalness problems

# How we got here

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

*Minimal, economical theory?*




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

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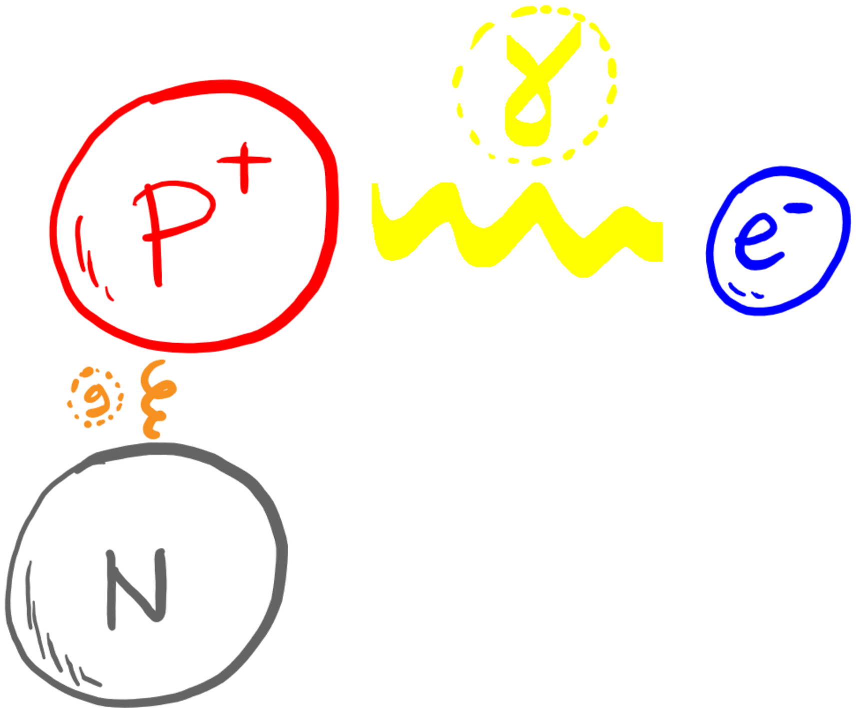
- *1930s*: *everything* is made of **protons**, **neutrons**, and **electrons**




"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

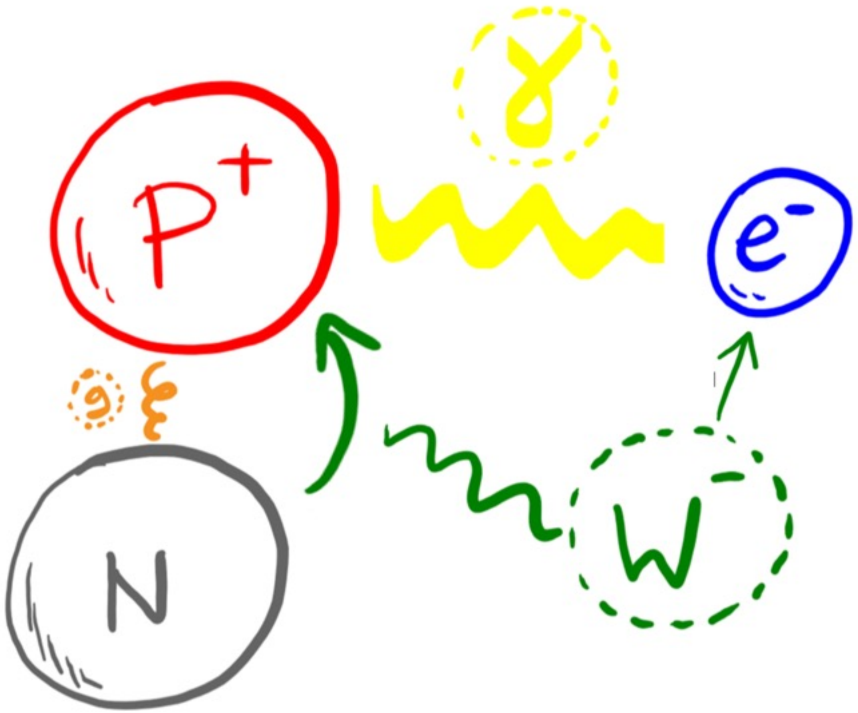
(From D. Tong slide)

**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**

# How we got here

- **Weak force** explains *radioactivity*




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

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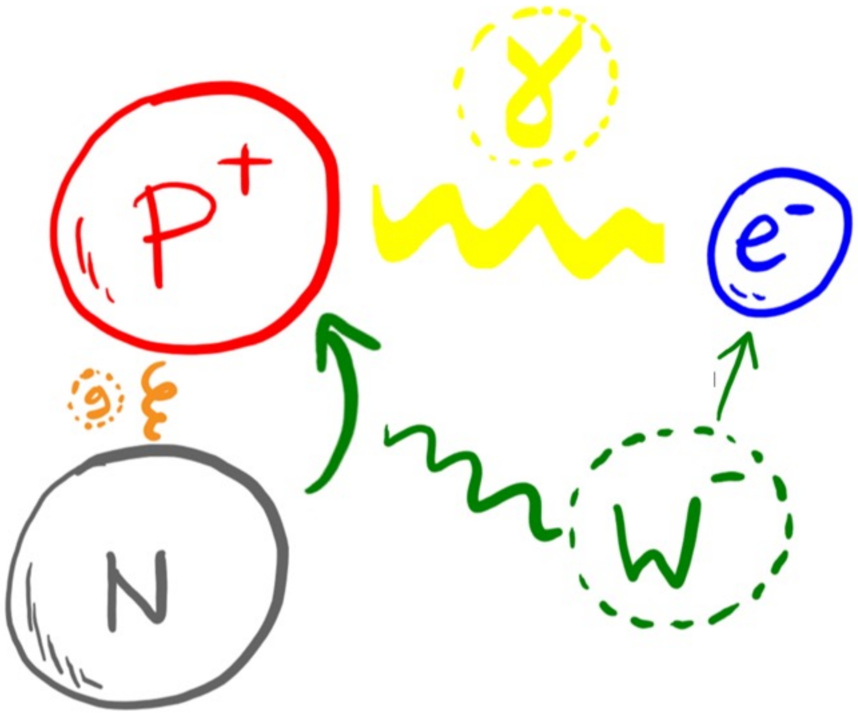


**Missing energy?** Pauli postulates *"a desperate remedy"*

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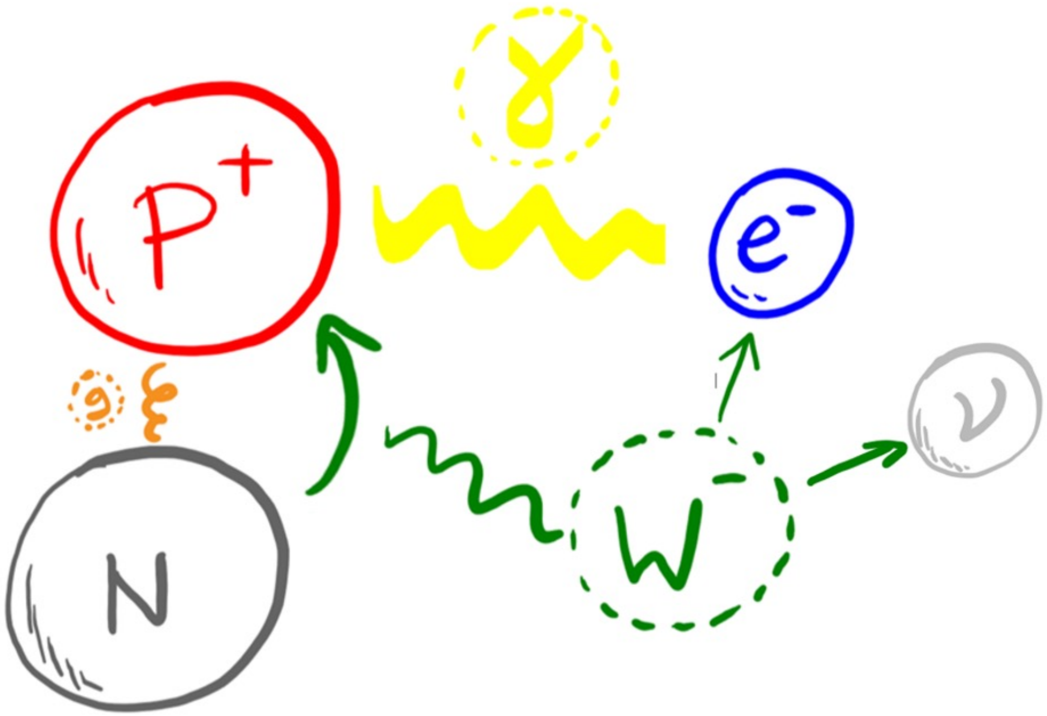


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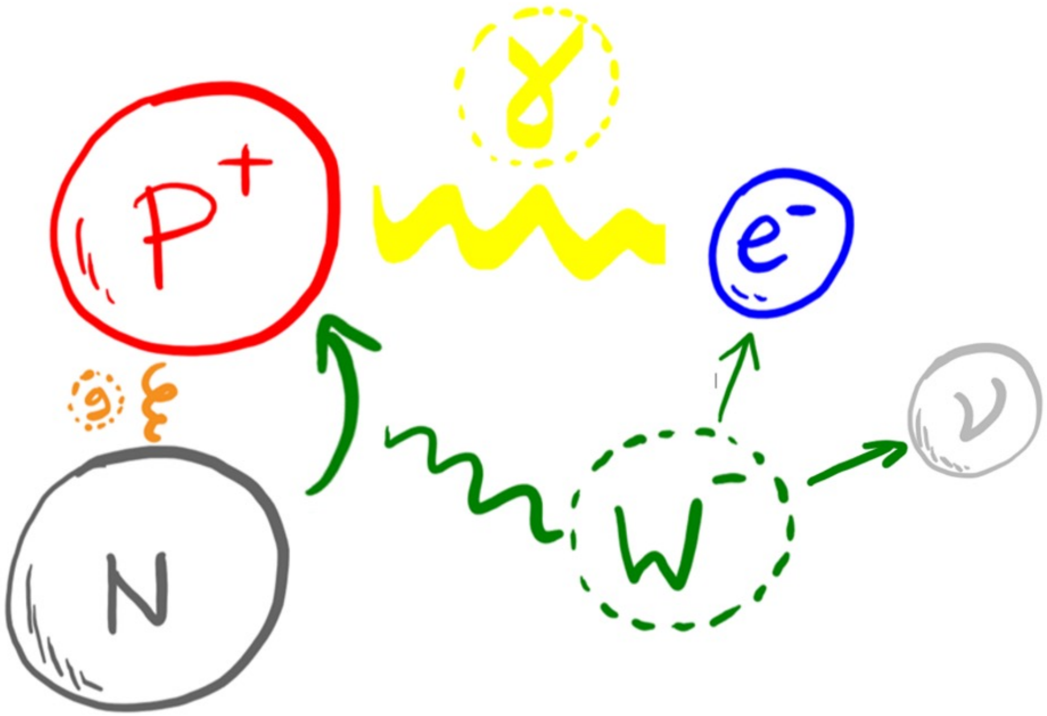


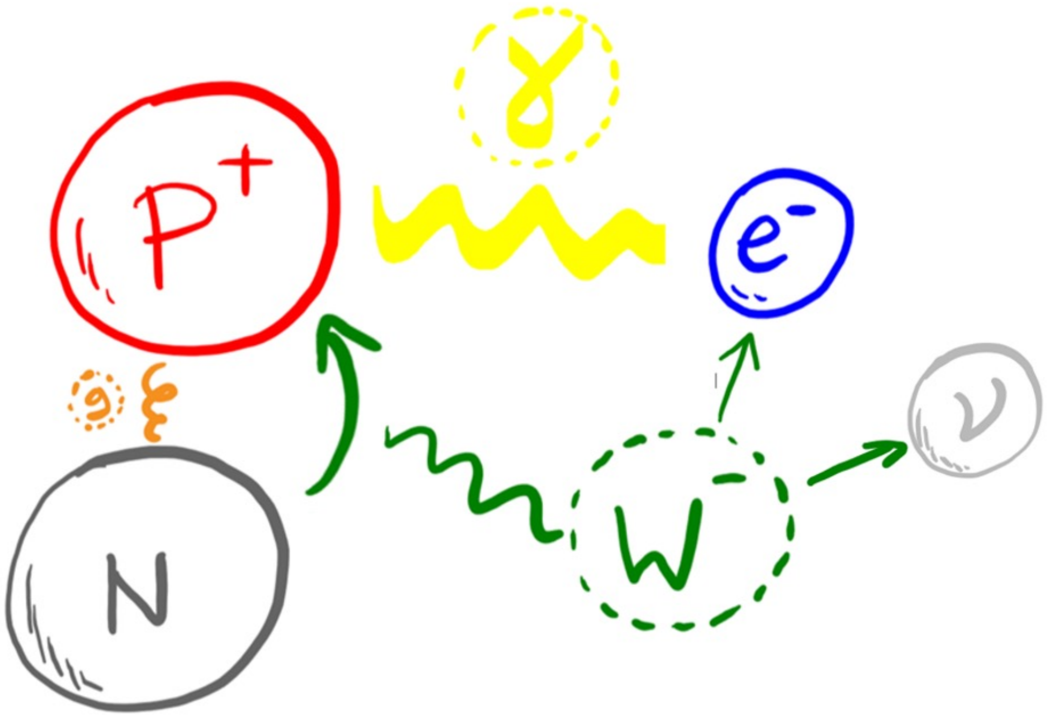

**Missing energy?** Pauli postulates *"a desperate remedy"*

**Lesson 2:** *perceived* prospect 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**

# How we got here

- *Weak force* explains *radioactivity*




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

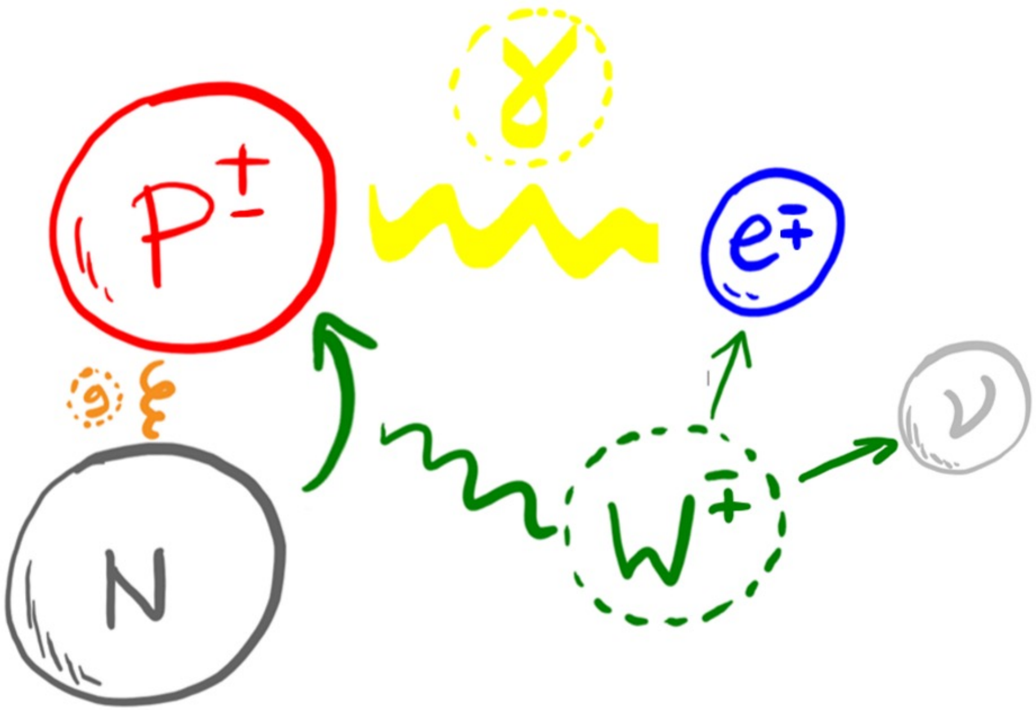
(Bohr postulates fundamental *violation of energy conservation)*

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

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

# How we got here

- Dirac: **relativity** + **quantum mechanics** = **antiparticles**




- *Every particle has an oppositely charged antiparticle partner*

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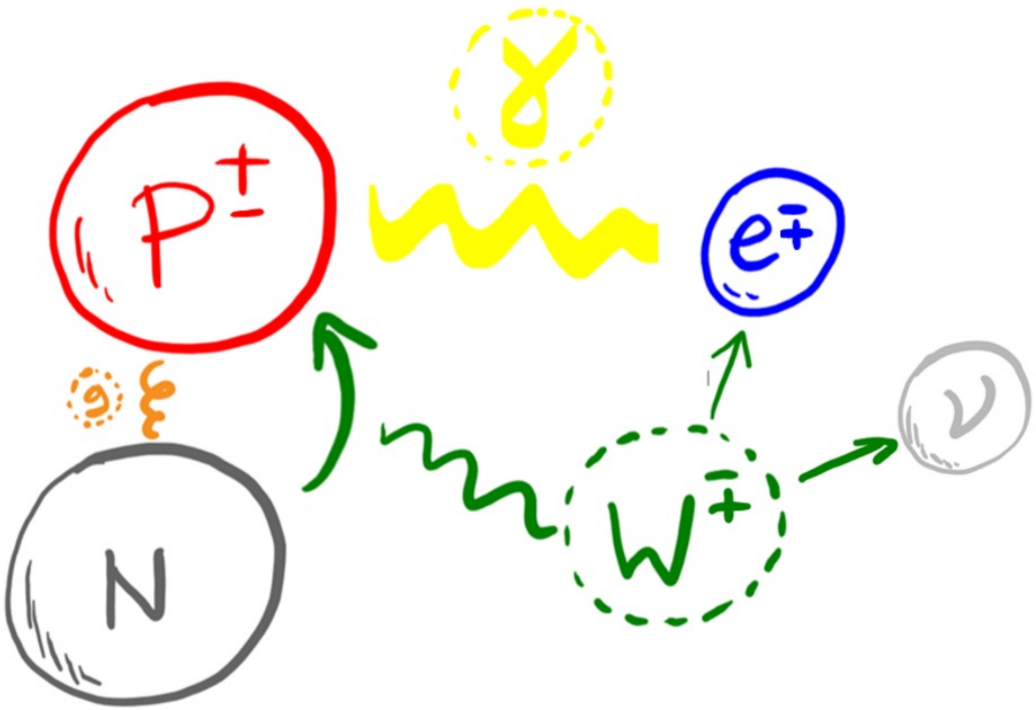
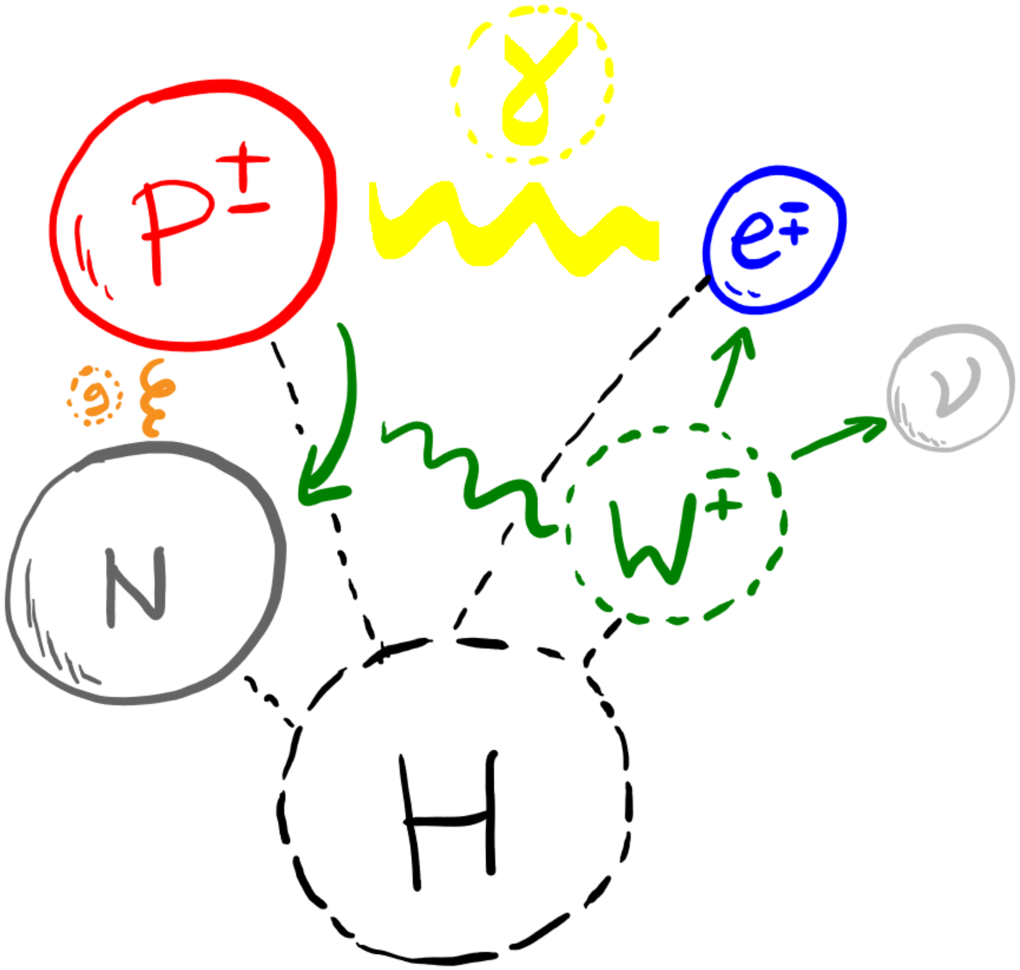


*c.f.* **Lesson 1**: antiparticles *double the particle spectrum*. Nevertheless, the theory is **much tighter**, **less arbitrary**, and **more elegant**

- *Every particle has an oppositely charged antiparticle partner*

# How we got here

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



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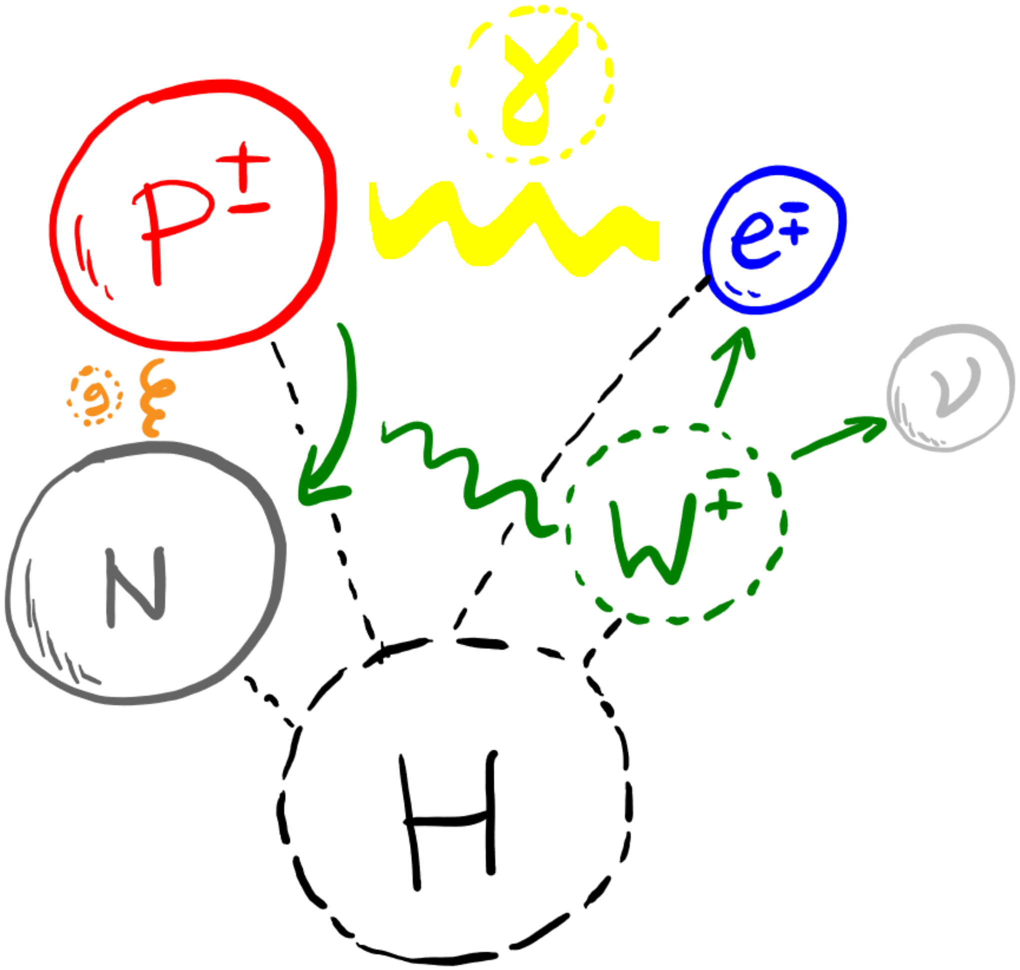


**Lesson 3:** Keep an open mind.

Ideas initially dismissed as **unrealistic** (*e.g.* non-abelian gauge theories and spontaneous symmetry breaking, because they predicted **unobserved massless** bosons) can turn out to be correct eventually

# How we got here

- 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*.

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See BBC Horizon 1964 documentary *“Strangeness minus three”:*
[https://www.bbc.co.uk/programmes/p01z4p1j](https://www.bbc.co.uk/programmes/p01z4p1j)

# How we got here

- 1970s:

  **QFT triumphs** following Yang-Mills+Higgs+asymptotic freedom+renormalisation. Nature is **radically conservative**, *but more unified than ever*.

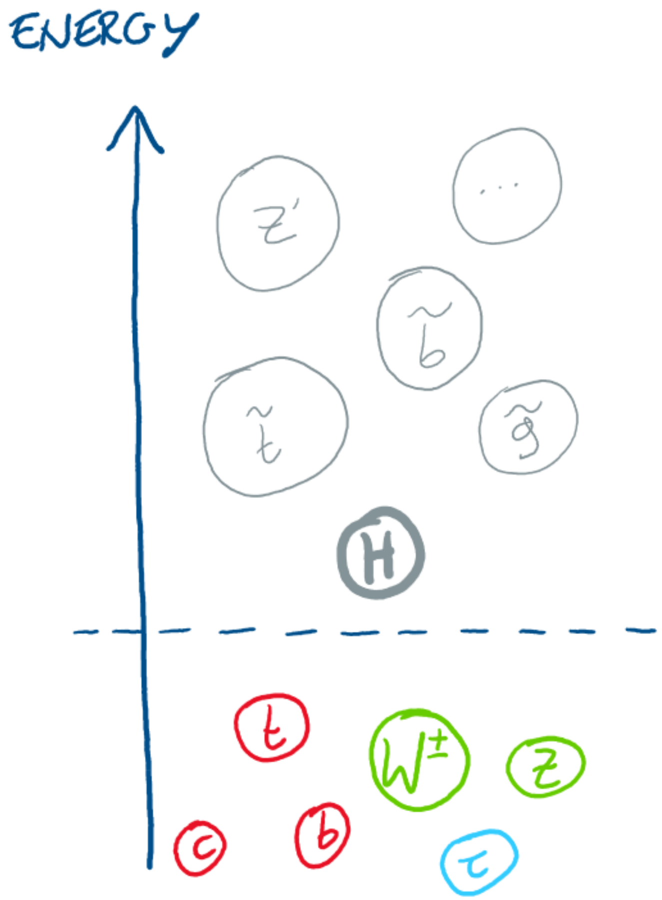
- 1980s:

  Success of SM. QFT understood as **most general Effective Field Theory (EFT) consistent with symmetry**. *Higgs and cosmological constant violates symmetry expectation*.

- **Tremendous progress** since, *despite lack of BSM*.

# A crisis in particle physics?

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




**No-lose theorem:** Higgs (or something) *guaranteed* to appear.

**High anticipation** of accompanying BSM particles *expected* to appear.

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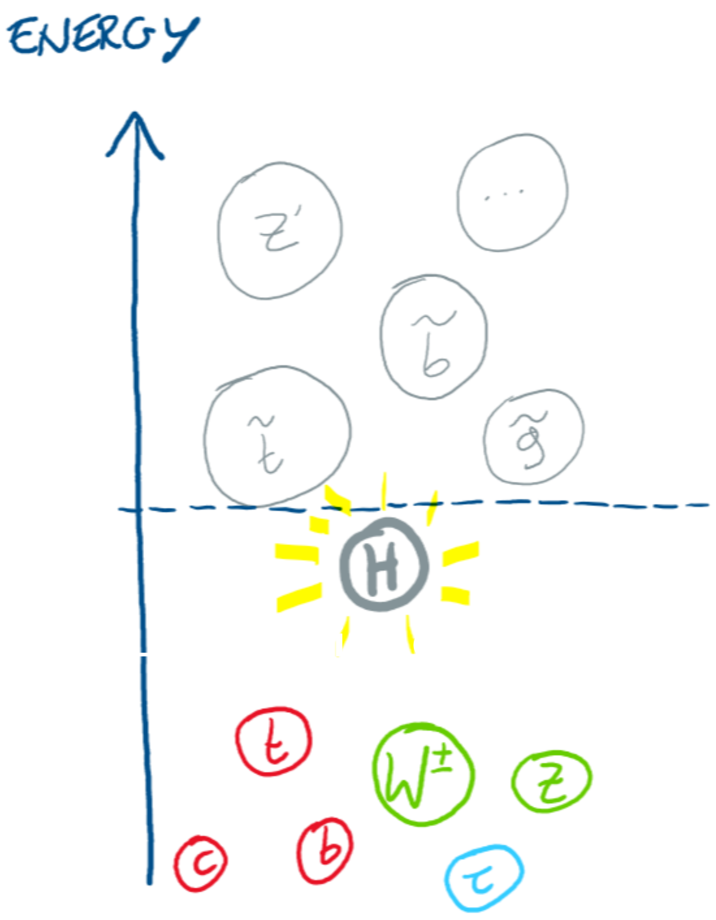

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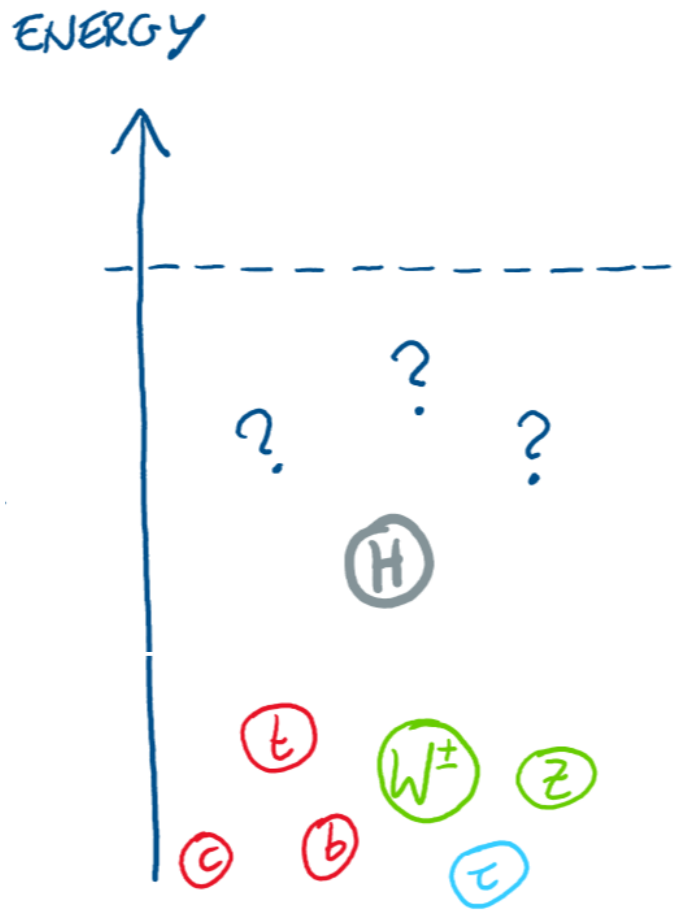

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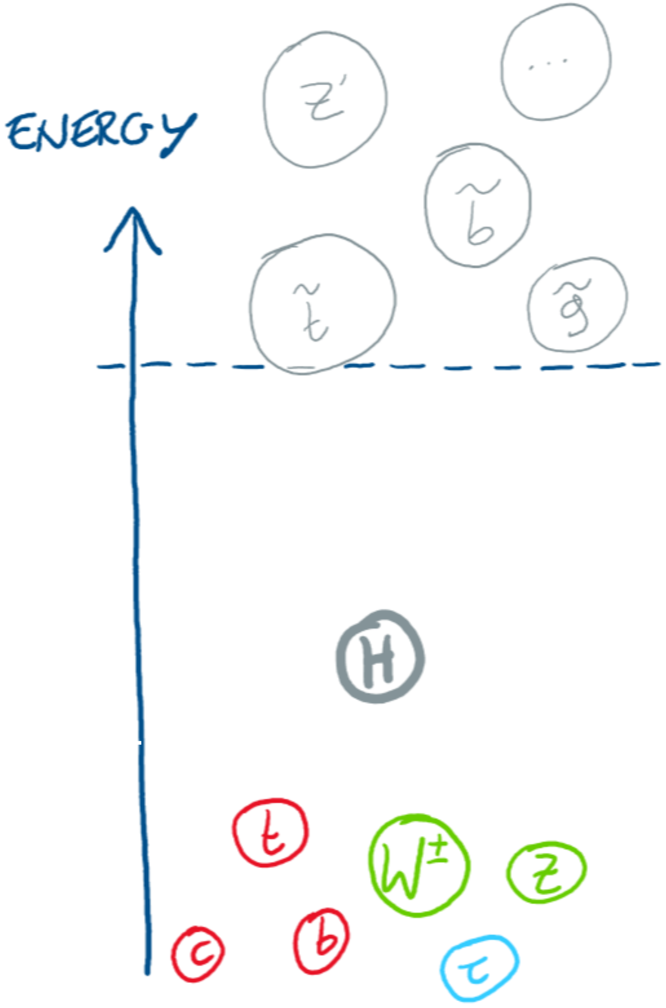

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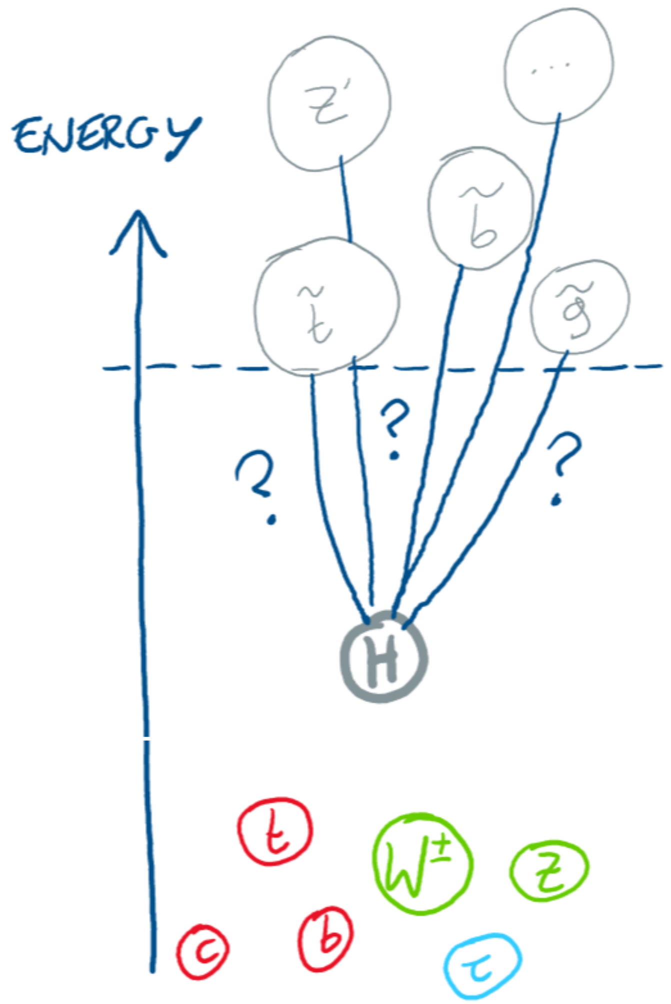


The hierarchy / naturalness problem of the Higgs is more puzzling than ever

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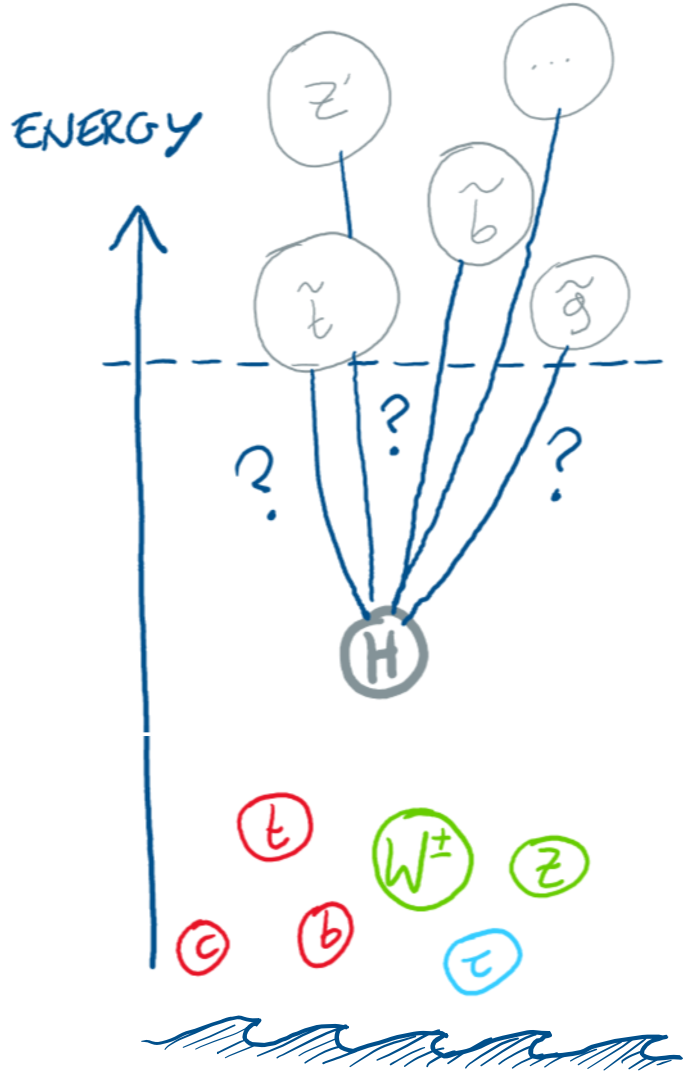


The cosmological constant problem of a tiny vacuum energy is far worse!

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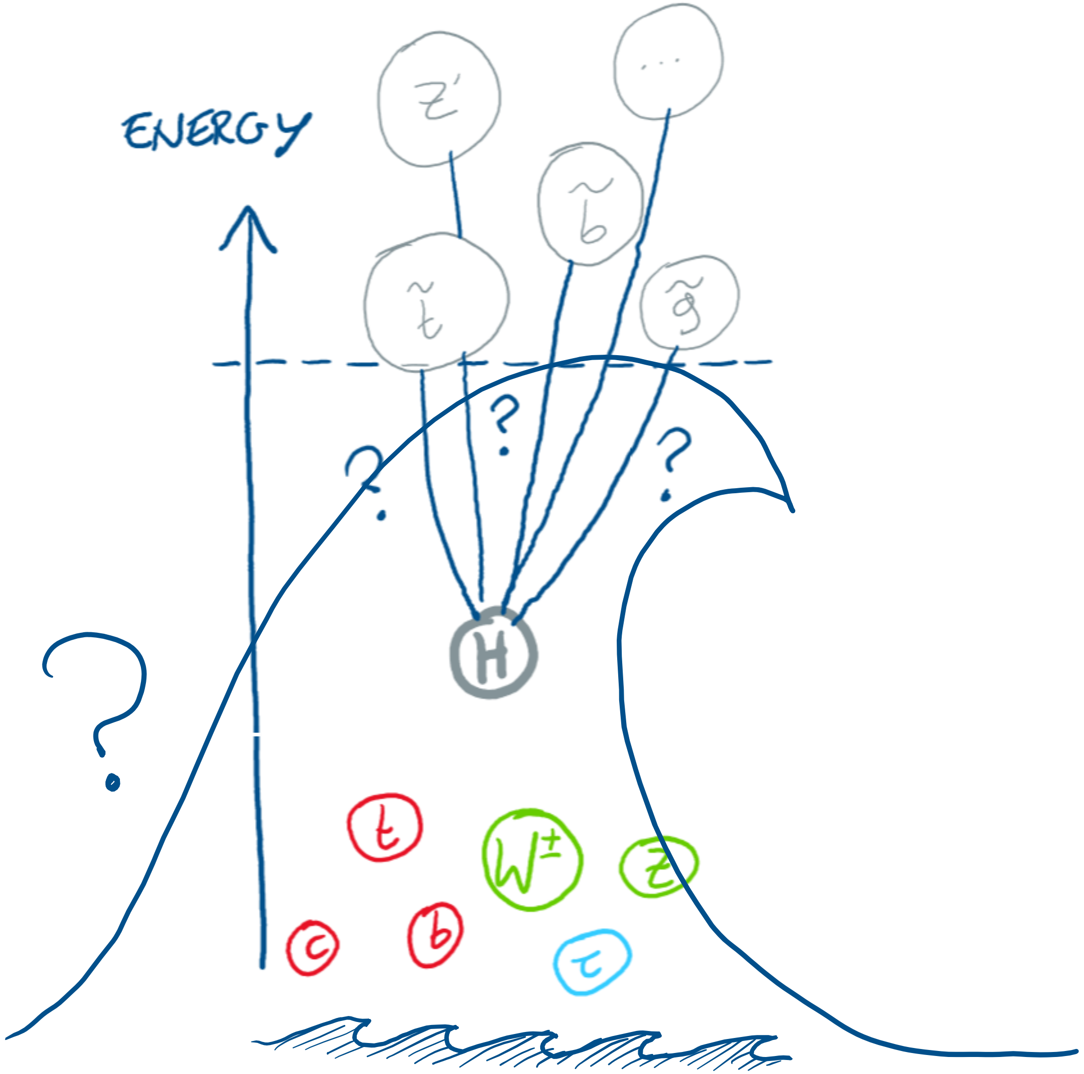


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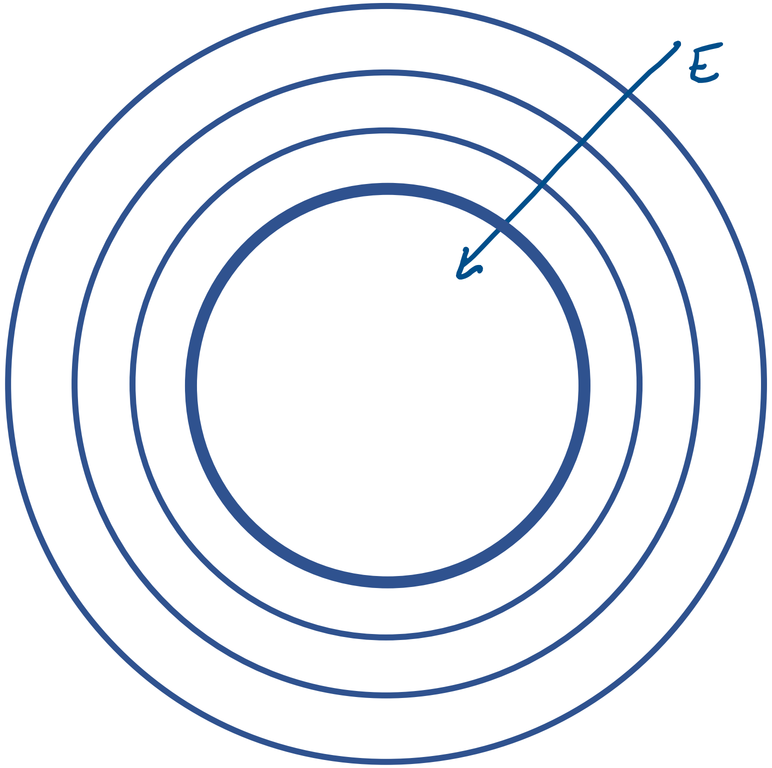
# Naturalness is still a fundamental problem

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

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



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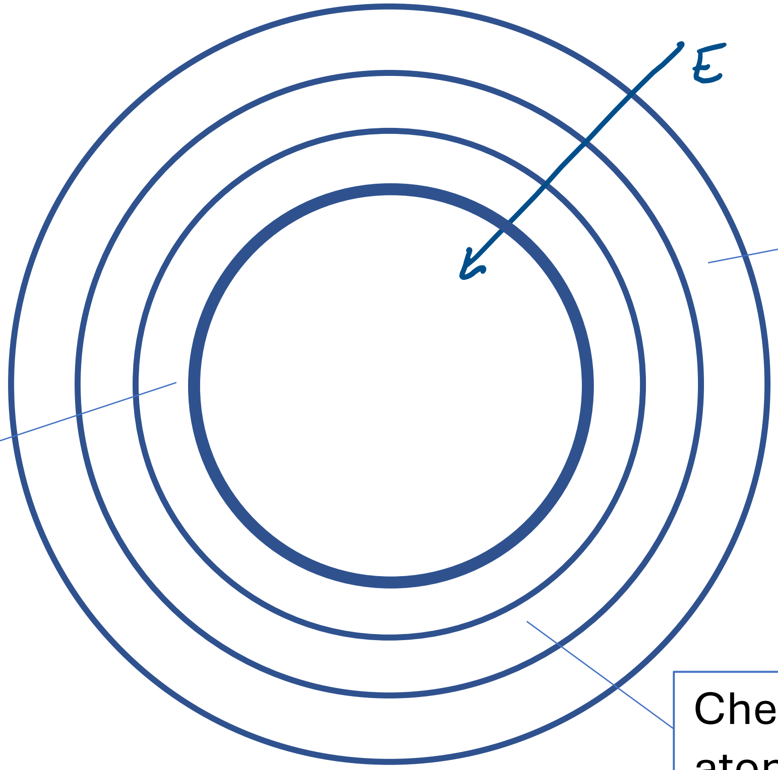


In *all theories so far*, no contributions from **smaller scales** compete *with similar magnitude* to effects **on larger scales**

# Naturalness is still a fundamental problem

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- Indicates *an unprecedented breakdown* of the **effective theory** structure of nature

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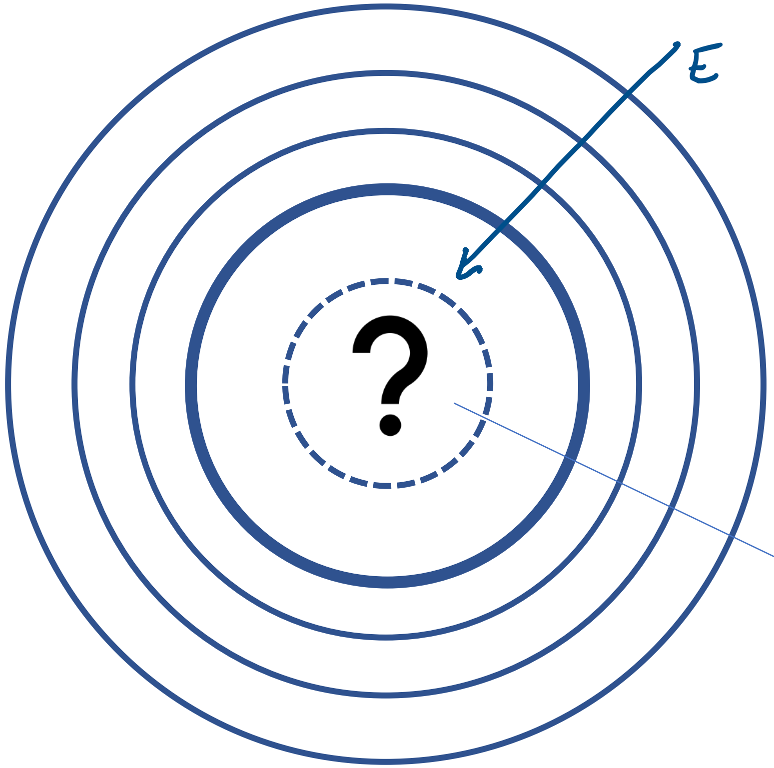


**Unnatural Higgs** means the next layer *is no longer predictive* without including contributions *from much smaller scales*

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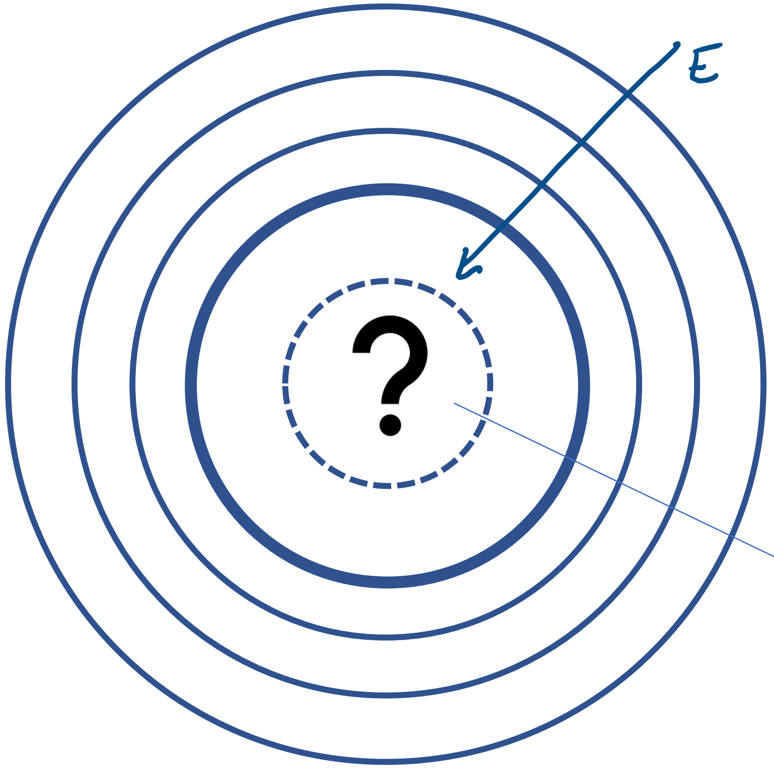
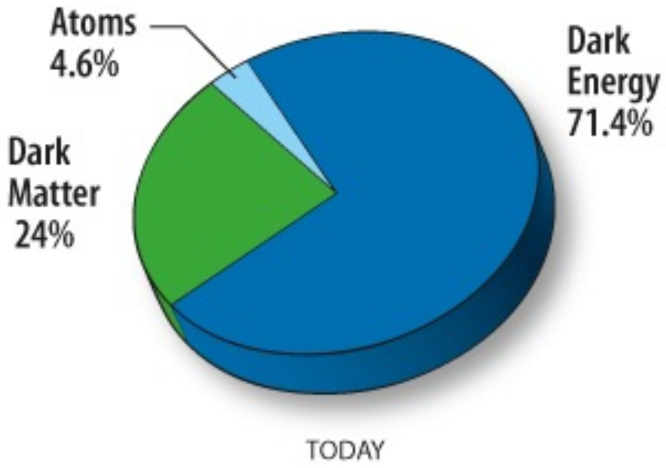


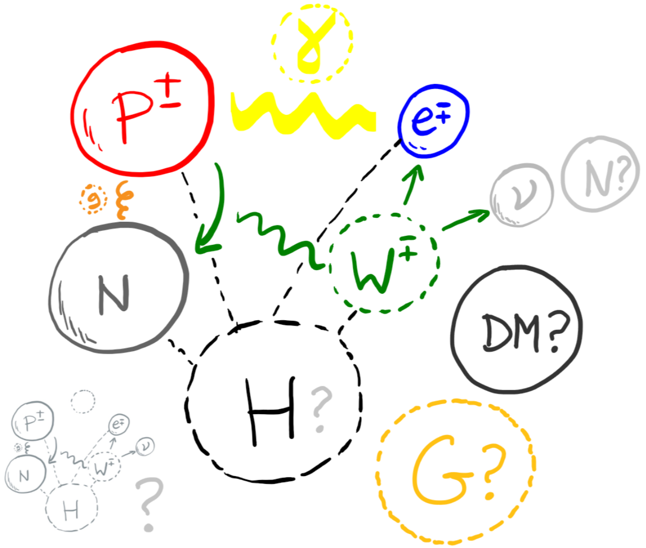

**Unnatural Higgs** means the next layer *is no longer predictive* without including contributions *from much smaller scales*

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

# 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**?
- …



# Problems of the SM

- **Arbitrary:**

Higgs potential, yukawa couplings, flavour structure, quantized hypercharges, matter-antimatter asymmetry – *arbitrary parameters put in by hand*.

- **Unnatural:**

Higgs mass, cosmological constant, strong-CP problem – *fine-tuned cancellations between independent contributions*.

# Problems of the SM

- **Incomplete:**

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

- **Inconsistent:**

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

# Problems of the SM

Take problems of arbitrariness seriously.

Example 0

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

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

$$q = m_{inertia}$$

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

# Problems of the SM

Take structural theoretical problems seriously.

Example 1

Maxwell's equations of electromagnetism did not satisfy the principle of Galilean relativity.

$$\nabla \cdot \mathbf{E} = \rho/\epsilon_0$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}\right)$$

No inconsistencies – one could calculate perfectly well EM phenomena.

*Aether* medium expected to reconcile Maxwell with Galileo.

Resolution to this structural problem: Galilean relativity → Special relativity

# Problems of the SM

Take fine-tuning problems seriously.

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

Example 2

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

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

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

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

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

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Example 3

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

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

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

$\rho$ meson appears at 775 MeV!

# Problems of the SM

Take fine-tuning problems seriously.

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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!

# Problems of the SM

Take fine-tuning problems seriously.

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Higgs?

Higgs also has a quadratically divergent contribution to its mass

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

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

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

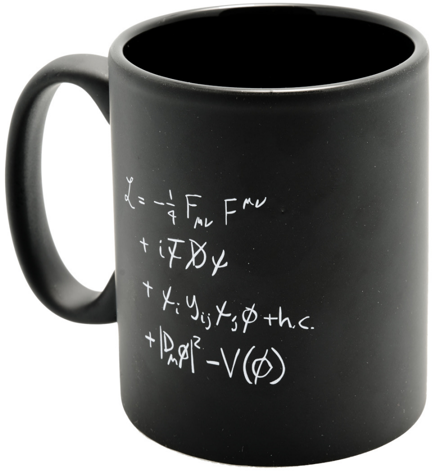
Note for the experts: in the SM the Higgs mass is a parameter to be measured, not calculated. What the quadratic divergence represents (independently of the choice of renormalisation scheme) is the fine-tuning in an underlying theory in which we expect the Higgs mass to be calculable.

# Conclusion

What are we looking for in a satisfying explanation?

Gauge theory of spin-1 vector bosons have the quality we seek in a satisfying theory.

Not just a phenomenological parametrization of independent vector boson interactions.

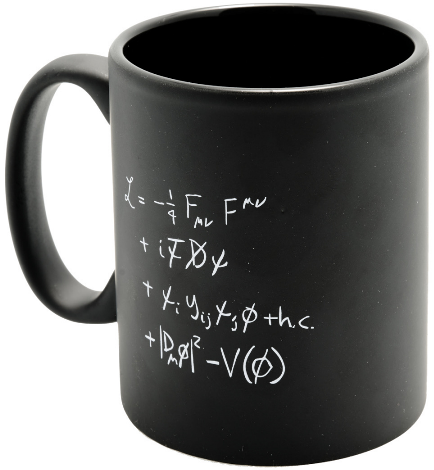


# Conclusion

In contrast, everything to do with the Higgs in the SM is arbitrary; more like a parametrisation than an explanation of electroweak symmetry breaking.

We seek to better understand the origin of the Higgs in an underlying theory from which it emerges, where we can calculate its potential in terms of more fundamental principles.
(*c.f.* condensed matter Higgs)

| |
|---|
| Avoiding fine-tuning in underlying theory = expect new physics around weak scale! |



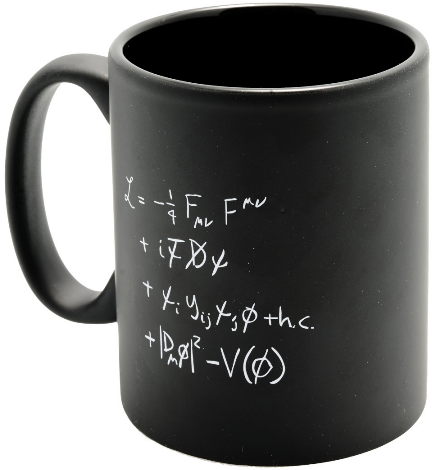
# Conclusion

The SM has many arbitrary features put in by hand which hint at underlying structure.

Maybe it just is what it is ¯_(ツ)_/¯

But we would like a deeper understanding, an explanation for why things are the way they are.

| |
|---|
| Science is about *removing arbitrariness* from explanations. |



# Outline

**Today**

1. The Totalitarian Principle

2. The Standard Model as an Effective Field Theory

3. The Higgs no-lose theorem

# The Totalitarian Principle

*"Everything not forbidden is compulsory"*

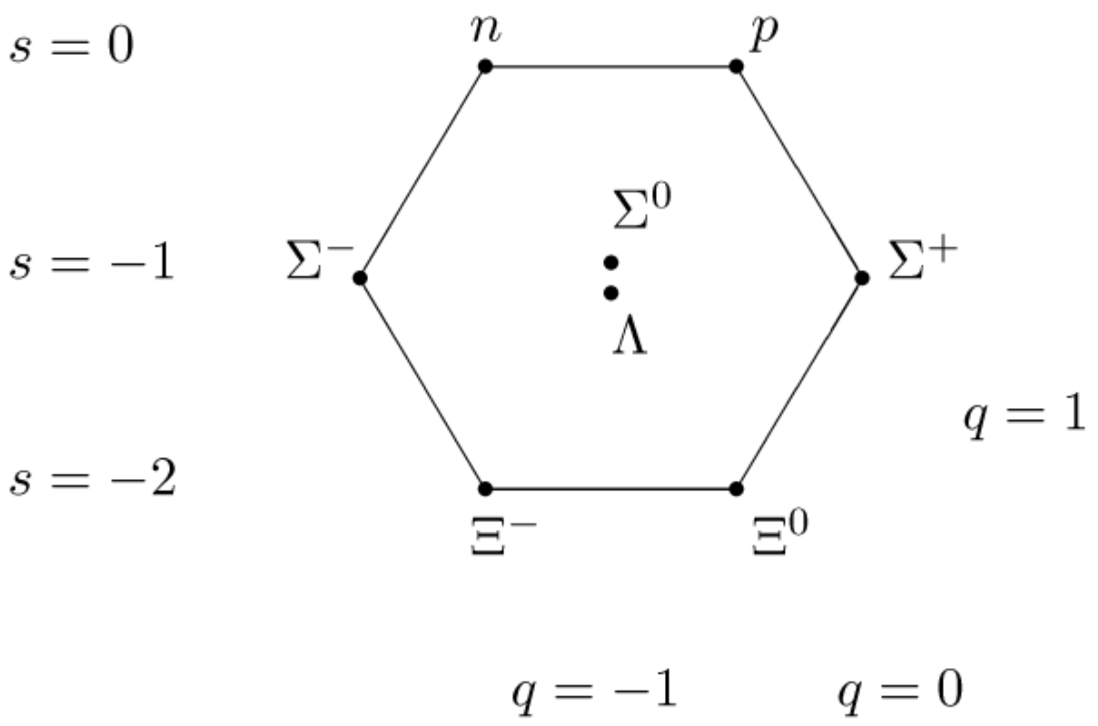
Gell-Mann stated this maxim in relation to quantum mechanics summing over all allowed possibilities.

I will use this principle more generally as a **theoretical rule of thumb**.

When there is a *finite* set of possibilities, this can be a compelling argument for motivating BSM.

# Example: the Eightfold way

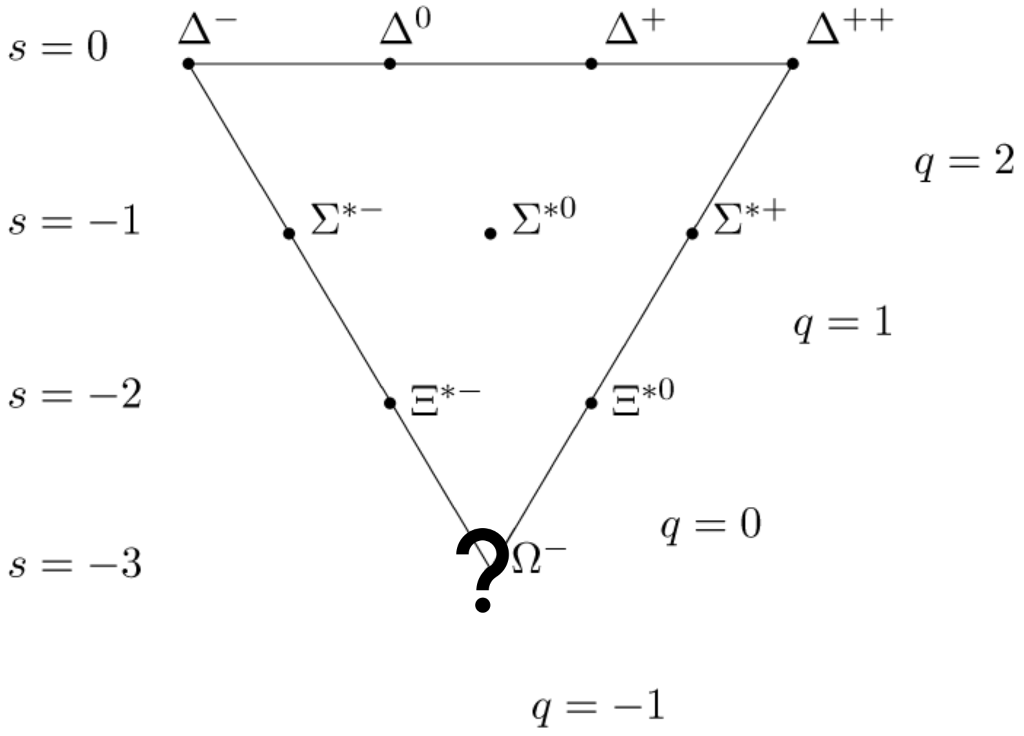
In 1961, Gell-Mann and Ne'eman noticed that hadrons could be organized in a pattern according to their "strangeness" number, s, and electromagnetic charge, q.




Spin ½ baryon octet

# Example: the Eightfold way

Only one baryon was missing. It would be *extremely strange* (pun not intended) if it weren't there.




Spin 3/2 baryon decuplet

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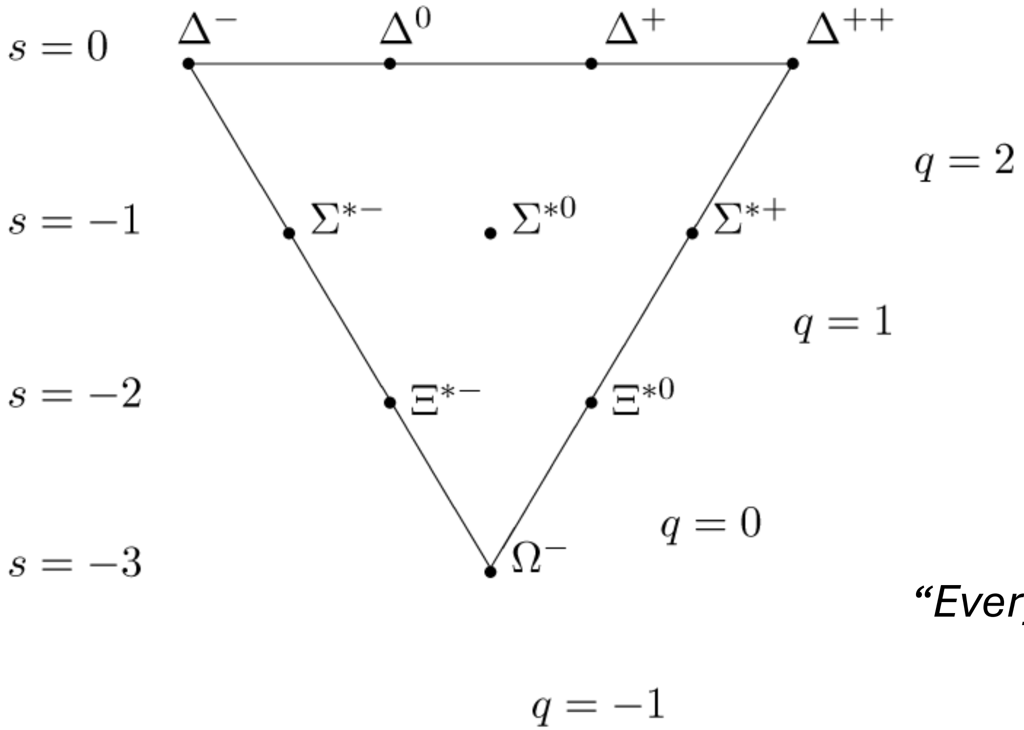


*"Everything not forbidden is compulsory"*

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# The Standard Model as an Effective Field Theory

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

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

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

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

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

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

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

Up to **mass dimension 4**, this is what we typically call *“The Standard Model”*.

# The Standard Model as an 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** | $\frac{1}{6}$ |

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

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

$$= -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu}$$

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

$$= y_d \bar{Q}_L \phi q^d_R + y_u \bar{Q}_L \phi^c q^u_R + y_L \bar{L}_L \phi l_R + \text{h.c.} \quad ,$$

Operator dimension = mass dimension in natural units

$E = mc^2$ $\quad$ $[E] = [m] \equiv M$

$E = hf$ $\quad \xrightarrow{\hbar = c = 1}$ $\quad [E] = [T^{-1}] \Rightarrow [T] = M^{-1}$

$E = hc/\lambda$ $\quad$ $[E] = [L^{-1}] \Rightarrow [L] = M^{-1}$

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Action $S$ is in exponent, $e^{iS}$. $[S] = M^0$ (dimensionless) — "dimensions of"

$S = \int dt\,dx\,dy\,dz\, \mathcal{L}$, $\quad [dt\,dx\,dy\,dz] = M^{-4}$ $\quad \Rightarrow [\mathcal{L}] = M^4$

e.g. $\mathcal{L} = m_H^2 \phi^2 \qquad [\phi] = M$

$\mathcal{L} = y\phi\bar{\Psi}\Psi \qquad [\Psi] = M^{3/2} \qquad [y] = M^0$

Up to **mass dimension 4**, this is what we typically call *“The Standard Model”*.

# The Standard Model as an Effective Field Theory

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| $q_R^d$ | $\mathbf{3}$ | $\mathbf{1}$ | $-\frac{1}{3}$ |
| $L_L$ | $\mathbf{1}$ | $\mathbf{2}$ | $-\frac{1}{2}$ |
| $l_R$ | $\mathbf{1}$ | $\mathbf{1}$ | $-1$ |
| $\phi$ | $\mathbf{1}$ | $\mathbf{2}$ | $\frac{1}{2}$ |

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

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

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

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

*"Everything not forbidden is compulsory"*

Up to **mass dimension 4**, this is what we typically call *"The Standard Model"*.

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

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

**Strong-CP problem**

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

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

*“Everything not forbidden is compulsory”*

Up to **mass dimension 4**, this is what we typically call *“The Standard Model”*.

# The Standard Model as an Effective Field Theory

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

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

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

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

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

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

Including operators of **mass dimension** $>$ **4**! This is the "*Standard Model Effective Field Theory*".

# The Standard Model as an Effective Field Theory

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

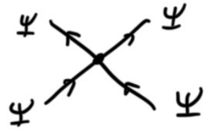
$$\mathcal{L}_{SM}^{EFT} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y + \frac{c_5}{\Lambda}\mathcal{O}^{(5)} + \frac{c_6}{\Lambda^2}\mathcal{O}^{(6)} + \frac{c_7}{\Lambda^3}\mathcal{O}^{(7)} + \frac{c_8}{\Lambda^4}\mathcal{O}^{(8)} + \ldots$$

$$\ldots_R + \bar{L}_L i\gamma^\mu D^L_\mu L_L + \bar{l}_R i\gamma^\mu D^R_\mu l_R$$

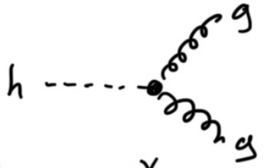
$$-\theta\frac{\alpha_s}{8\pi}G^a_{\mu\nu}\widetilde{G}^{a\mu\nu}$$

$$\ldots_L\bar{L}_L\phi l_R + \text{h.c.} \quad ,$$

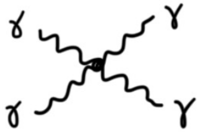
e.g. $\mathcal{L}^{\text{dim-6}}_{\text{4-fermion}} = \frac{c_{4f}}{\Lambda^2}\bar{\Psi}\Psi\bar{\Psi}\Psi$




$\mathcal{L}^{\text{dim-6}}_{hgg} = \frac{c_g}{\Lambda^2}|H|^2 G_{\mu\nu}G^{\mu\nu}$



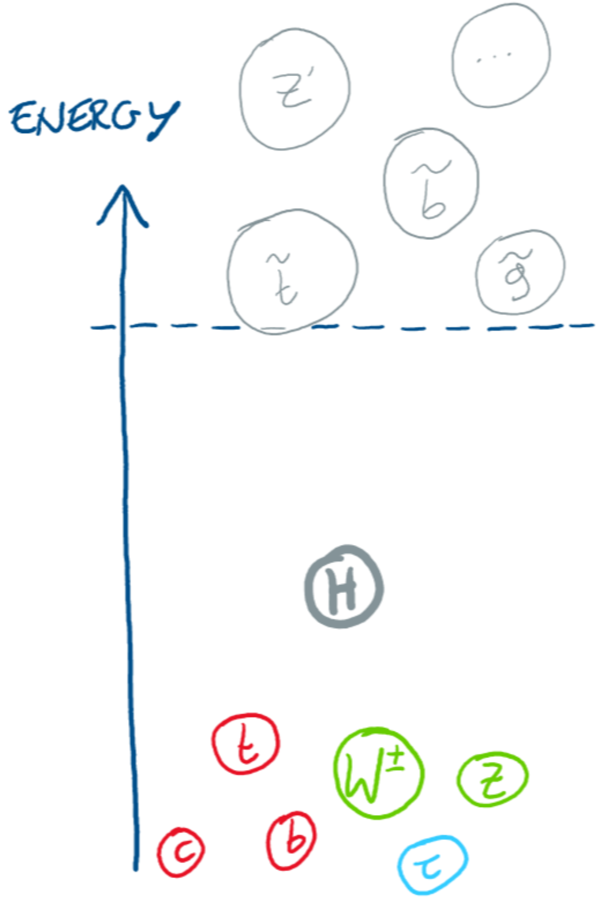

$\mathcal{L}^{\text{dim-8}}_{\gamma\gamma\gamma\gamma} = \frac{c_{4\gamma}}{\Lambda^4}(F_{\mu\nu}F^{\mu\nu})^2$




Including operators of **mass dimension > 4**! This is the "*Standard Model Effective Field Theory*".

# The Standard Model as an Effective Field Theory

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




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

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

$$\mathcal{L}_m = \bar{Q}_L i\gamma^\mu D^L_\mu Q_L + \bar{q}_R i\gamma^\mu D^R_\mu q_R + \bar{L}_L i\gamma^\mu D^L_\mu L_L + \bar{l}_R i\gamma^\mu D^R_\mu l_R$$
$$\mathcal{L}_G = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu}$$
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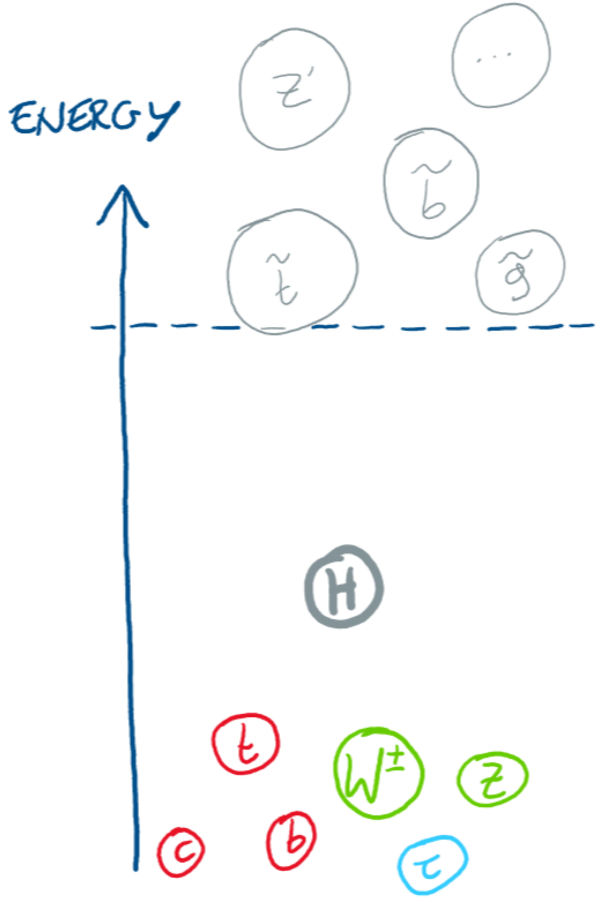
**Symmetries** control sizes of parameters – *naturalness expectations.*

# The Standard Model as an 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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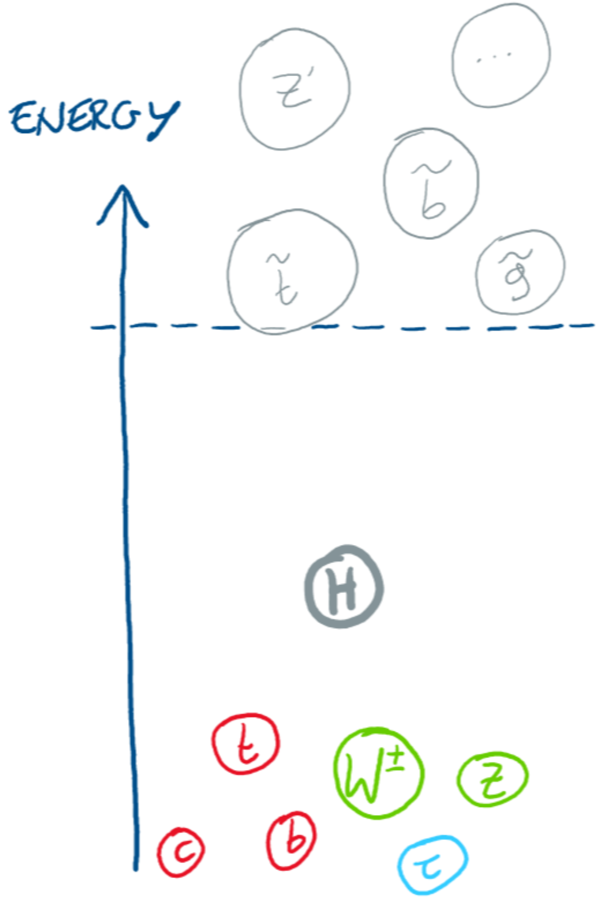
**EFT** is the framework for a **separation of scales** between heavy new physics and the SM.




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

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

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

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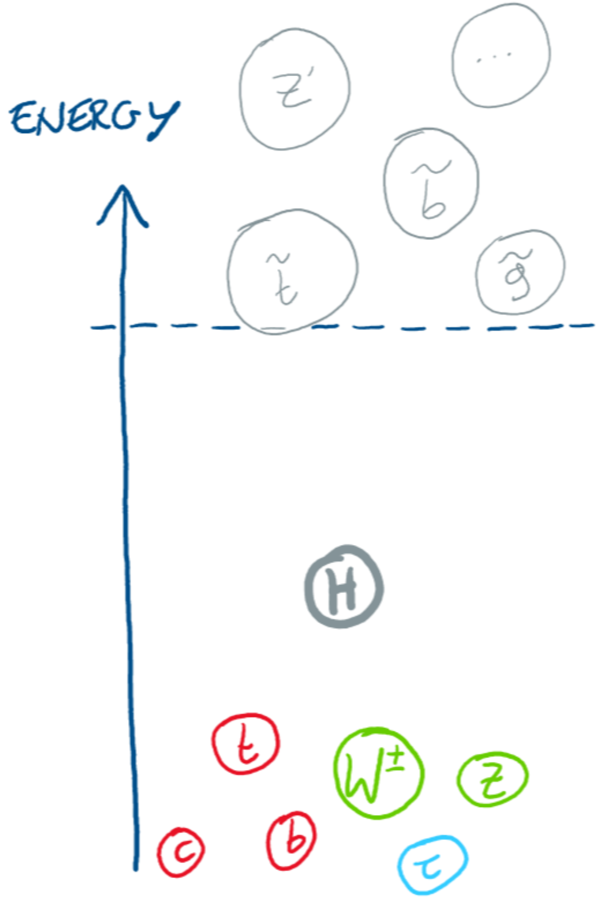
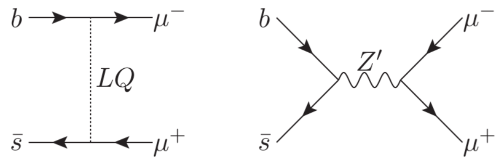
**Symmetries** control sizes of parameters – *naturalness expectations*.

# The Standard Model as an Effective Field Theory

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




e.g. leptoquarks or Z’




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

$$\mathcal{L}_{SM} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y + \frac{c_6}{\Lambda^2}(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t) + \dots$$

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

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

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# The Standard Model as an Effective Field Theory

Operators of mass dimension 6:

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

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

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

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

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

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

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

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

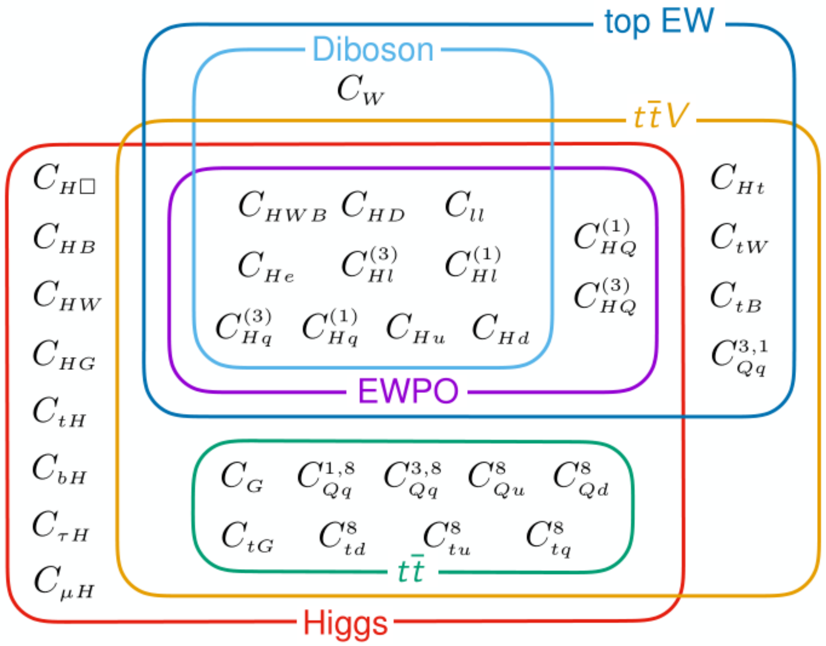
| $(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$ | | $B$-violating | |
|---|---|---|---|
| $\mathcal{O}_{ledq}$ | $(\bar{l}^j_p e_r)(\bar{d}_s q^j_t)$ | $\mathcal{O}_{duq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(q^{\gamma j}_s)^T C l^k_t\right]$ |
| $\mathcal{O}^{(1)}_{quqd}$ | $(\bar{q}^j_p u_r)\varepsilon_{jk}(\bar{q}^k_s d_t)$ | $\mathcal{O}_{qqu}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(u^\gamma_s)^T C e_t\right]$ |
| $\mathcal{O}^{(8)}_{quqd}$ | $(\bar{q}^j_p T^A u_r)\varepsilon_{jk}(\bar{q}^k_s T^A d_t)$ | $\mathcal{O}_{qqq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$ |
| $\mathcal{O}^{(1)}_{lequ}$ | $(\bar{l}^j_p e_r)\varepsilon_{jk}(\bar{q}^k_s u_t)$ | $\mathcal{O}_{duu}$ | $\varepsilon^{\alpha\beta\gamma}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(u^\gamma_s)^T C e_t\right]$ |
| $\mathcal{O}^{(3)}_{lequ}$ | $(\bar{l}^j_p\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}^k_s\sigma^{\mu\nu}u_t)$ | | |

# The Standard Model as an Effective Field Theory

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

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

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




Constrained by global fit to experimental data.

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

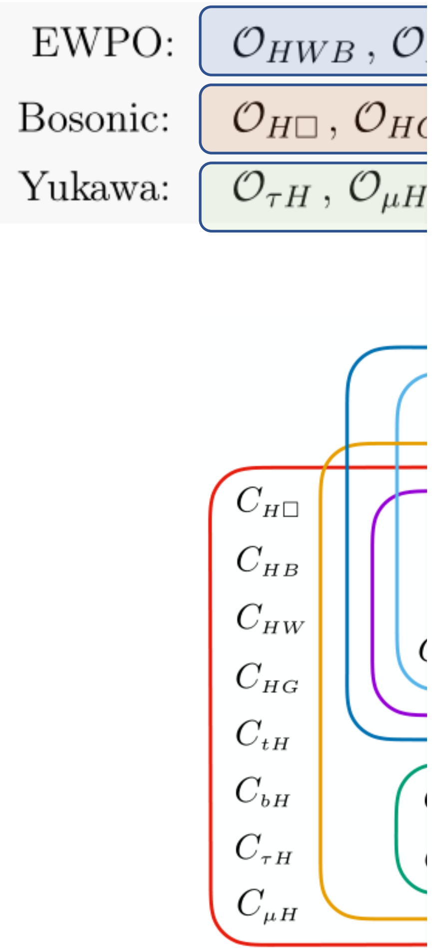
| $X^2H^2$ | | $\psi^2XH$ | | $\psi^2H^2D$ | |
|---|---|---|---|---|---|
| $\mathcal{O}_{HG}$ | $H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$ | $\mathcal{O}_{eW}$ | $(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I H W^I_{\mu\nu}$ | $\mathcal{O}^{(1)}_{Hl}$ | $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu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

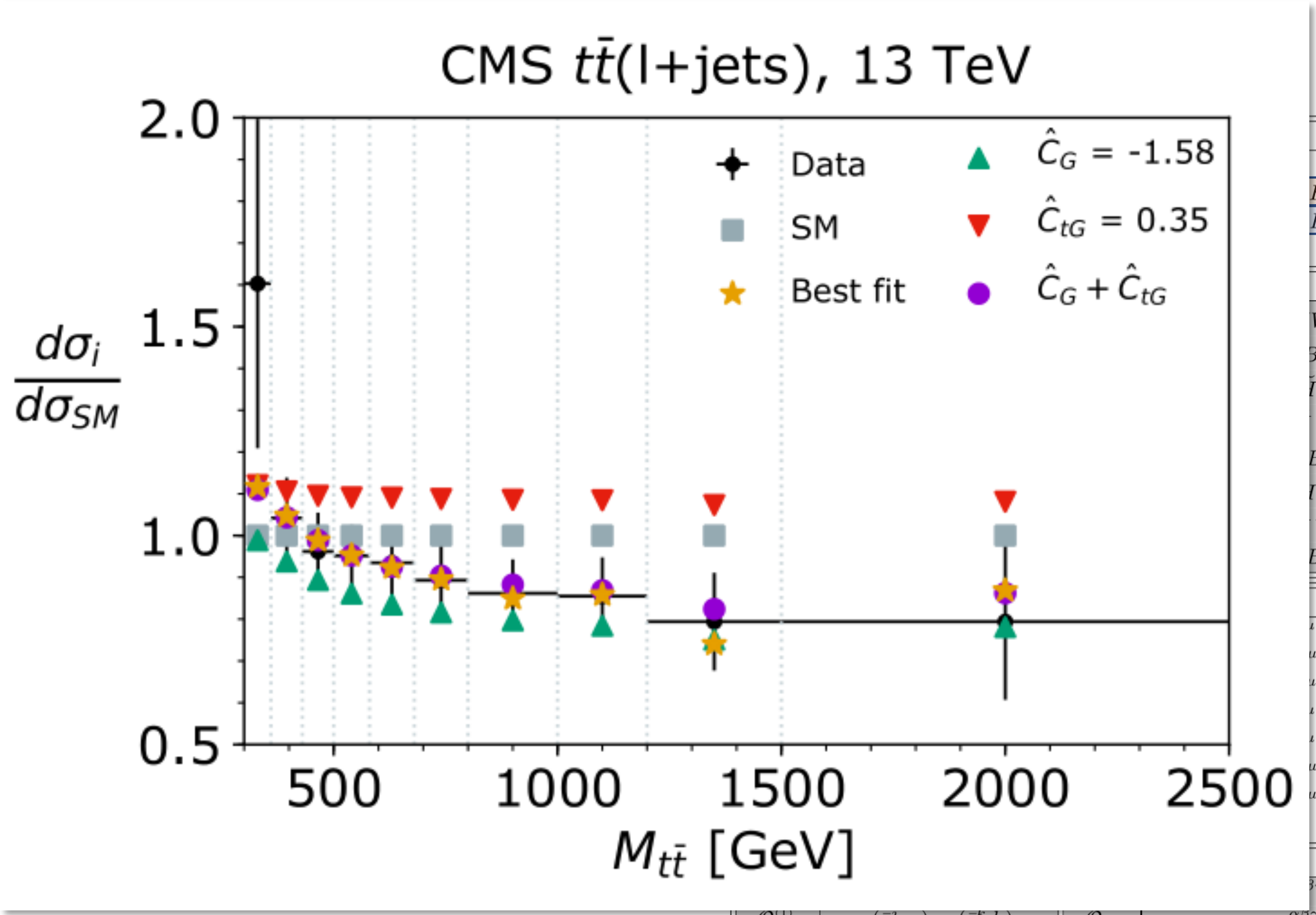
| $(\bar{L}L)(\bar{L}L)$ | | $(\bar{R}R)(\bar{R}R)$ | | $(\bar{L}L)(\bar{R}R)$ | |
|---|---|---|---|---|---|
| $\mathcal{O}_{ll}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$ | $\mathcal{O}_{ee}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$ | $\mathcal{O}_{le}$ | $(\bar{l}_p\gamma_\mu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

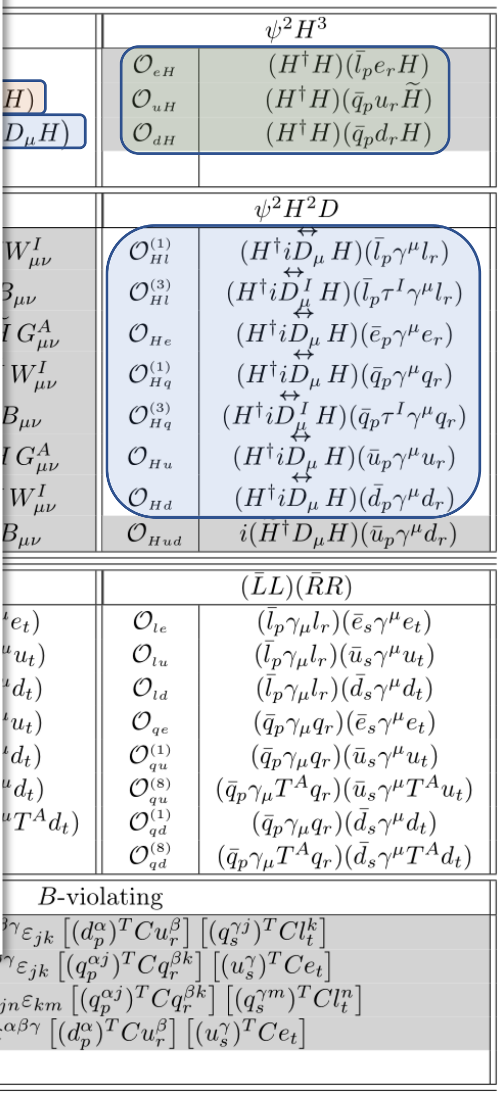
| $(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$ | | $B$-violating | |
|---|---|---|---|
| $\mathcal{O}_{ledq}$ | $(\bar{l}^j_p e_r)(\bar{d}_s q^j_t)$ | $\mathcal{O}_{duq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(q^{\gamma j}_s)^T C l^k_t\right]$ |
| $\mathcal{O}^{(1)}_{quqd}$ | $(\bar{q}^j_p u_r)\varepsilon_{jk}(\bar{q}^k_s d_t)$ | $\mathcal{O}_{qqu}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(u^\gamma_s)^T C e_t\right]$ |
| $\mathcal{O}^{(8)}_{quqd}$ | $(\bar{q}^j_p T^A u_r)\varepsilon_{jk}(\bar{q}^k_s T^A d_t)$ | $\mathcal{O}_{qqq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$ |
| $\mathcal{O}^{(1)}_{lequ}$ | $(\bar{l}^j_p e_r)\varepsilon_{jk}(\bar{q}^k_s u_t)$ | $\mathcal{O}_{duu}$ | $\varepsilon^{\alpha\beta\gamma}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(u^\gamma_s)^T C e_t\right]$ |
| $\mathcal{O}^{(3)}_{lequ}$ | $(\bar{l}^j_p\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}^k_s\sigma^{\mu\nu} u_t)$ | | |

Tevong You

# The Standard Model as an Effective Field Theory



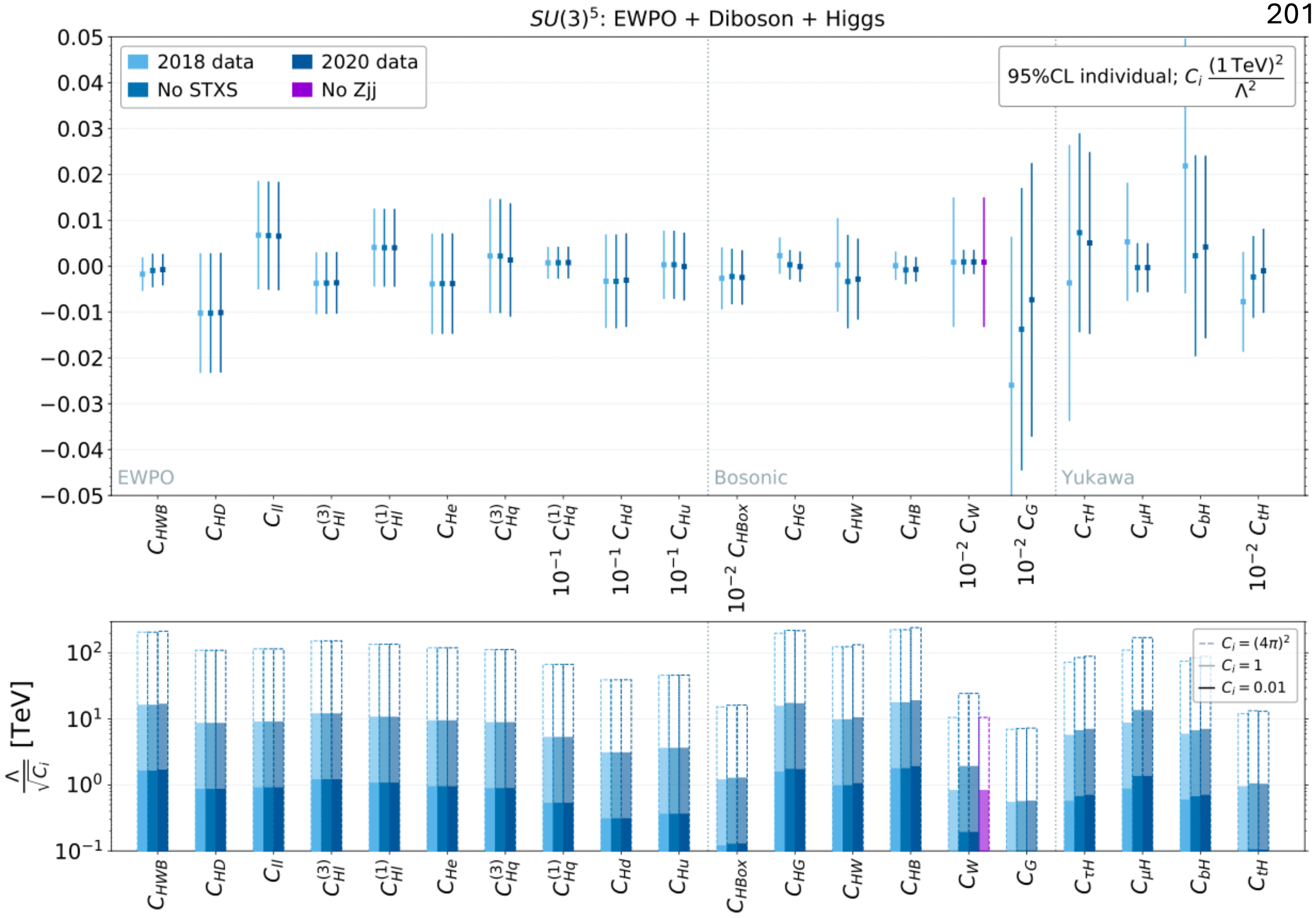




Constrained by global fit to experimental data. e.g. top data

# The Standard Model as an Effective Field Theory

Experimental constraints on SMEFT from LEP electroweak observables and LHC measurements:

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

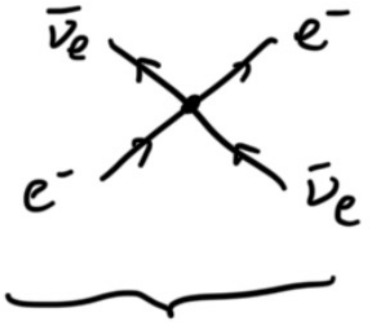
*Indirect evidence preceded direct discovery* for nearly all SM particles. May be true of BSM!

# The Higgs no-lose theorem

In the 1940s, Fermi theory was the Effective Field Theory (EFT) of the weak interactions at ~10 GeV.

EFT breaks down at higher energies by predicting nonsense when calculating scattering processes.

$$\mathcal{L}^{\text{dim-6}}_{\text{Fermi}} = \frac{c_{4f}}{\Lambda^2}\bar{\Psi}\Psi\bar{\Psi}\Psi$$




$2\to2$ scattering amplitude is dimensionless: $[\mathcal{A}_{2\to2}]=0$ $\Rightarrow$ $\mathcal{A}_{e^-\bar{\nu}_e\to e^-\bar{\nu}_e} \sim \frac{c}{\Lambda^2}E^2$

# The Higgs no-lose theorem

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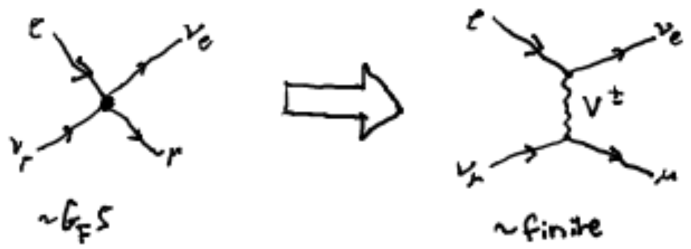

By analogy with photon of QED, add spin 1 intermediate vector boson (with mass and charge).

# The Higgs no-lose theorem

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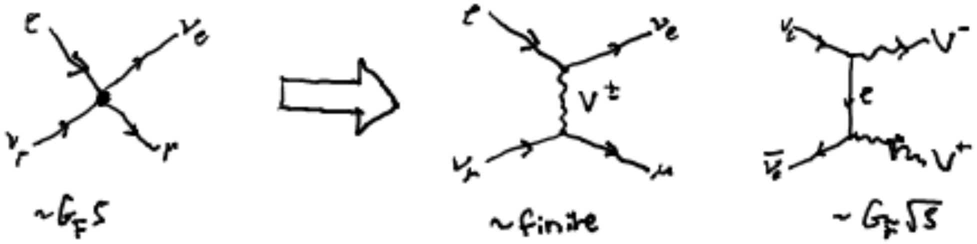
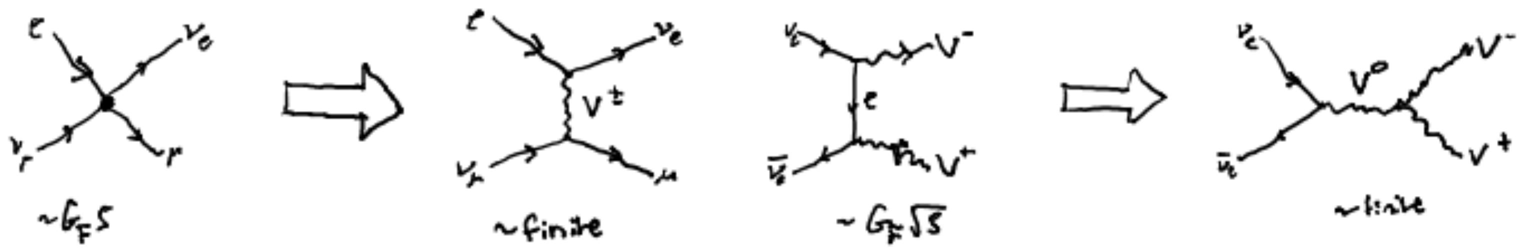



Makes scattering process finite, but introduces another process with divergent energy growth.

# The Higgs no-lose theorem

In the 1940s, Fermi theory was the Effective Field Theory (EFT) of the weak interactions at ~10 GeV.

EFT breaks down at higher energies by predicting nonsense when calculating scattering processes.

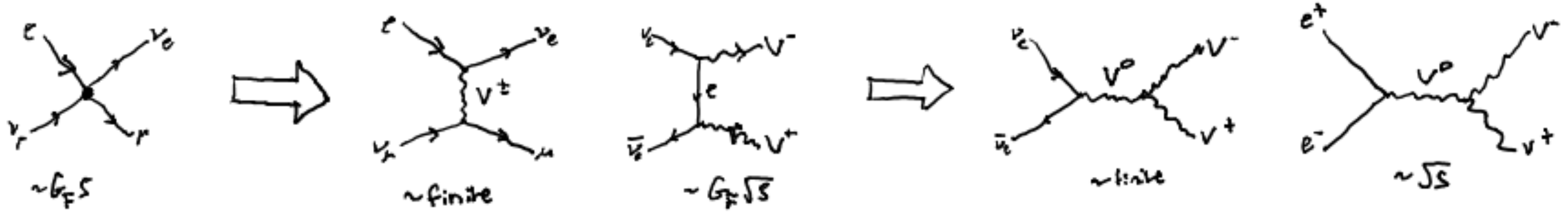



Add neutral spin 1 vector boson with appropriate couplings to make this scattering process finite.

# The Higgs no-lose theorem

In the 1940s, Fermi theory was the Effective Field Theory (EFT) of the weak interactions at ~10 GeV.

EFT breaks down at higher energies by predicting nonsense when calculating scattering processes.

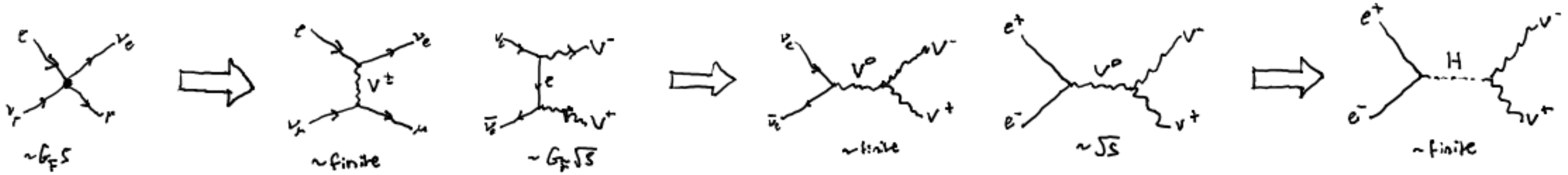



But another amplitude now grows unbounded with energy.

# The Higgs no-lose theorem

In the 1940s, Fermi theory was the Effective Field Theory (EFT) of the weak interactions at ~10 GeV.

EFT breaks down at higher energies by predicting nonsense when calculating scattering processes.

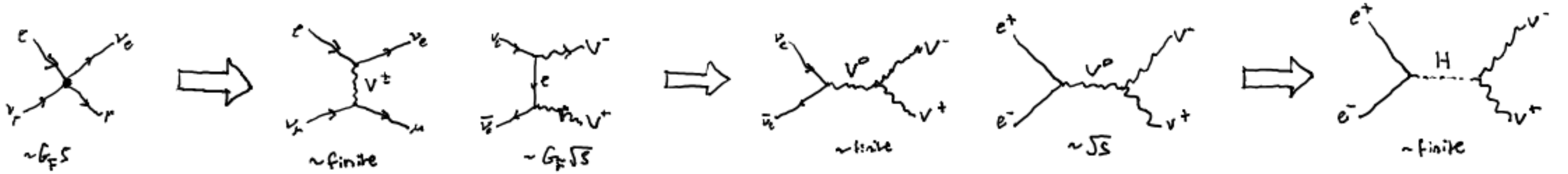



Add a scalar spin 0 boson.

# The Higgs no-lose theorem

In the 1940s, Fermi theory was the Effective Field Theory (EFT) of the weak interactions at ~10 GeV.

EFT breaks down at higher energies by predicting nonsense when calculating scattering processes.

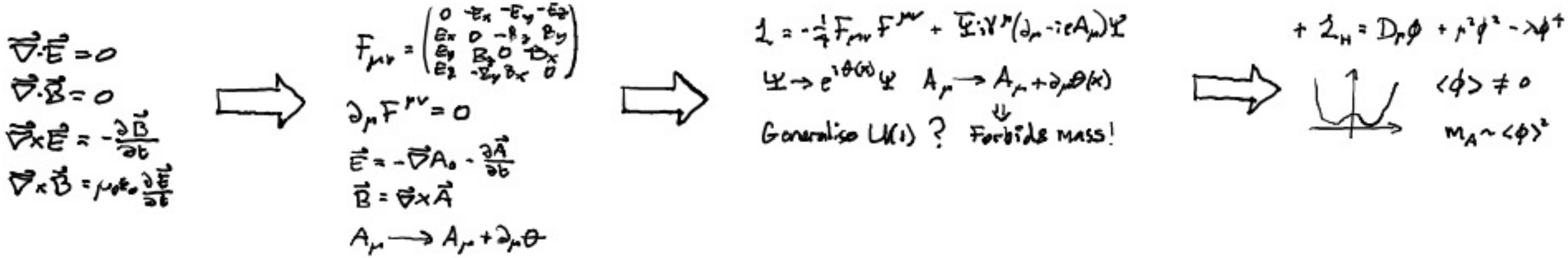



Adding spin 1 and spin 0 particles with couplings fixed to cancel divergent energy contributions *recovers the Standard Model theory* of non-Abelian gauge bosons and Higgs mechanism!

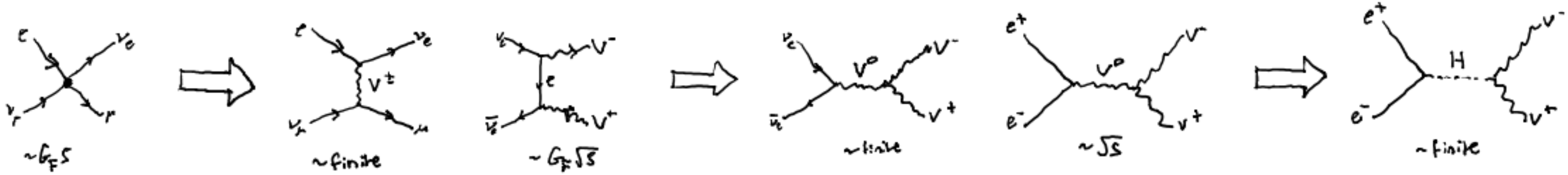
Without the Higgs, the theory breaks down around 1 TeV: **LHC guaranteed to discover something new**.

# The Higgs no-lose theorem

Historically:




Inevitably:




**Theoretical self-consistency** can be a powerful guide to extending our fundamental frameworks.

# Conclusion

The totalitarian principle is not to be taken too seriously, but gives a sense of pleasing theoretical reasoning.

The Standard Model, like Fermi theory before it, is an Effective Field Theory.

Theoretical reasoning is powerful, but only experiment can tell us what the underlying theory will be.

# Questions?

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