CERN summer student programme, 25th July 2023

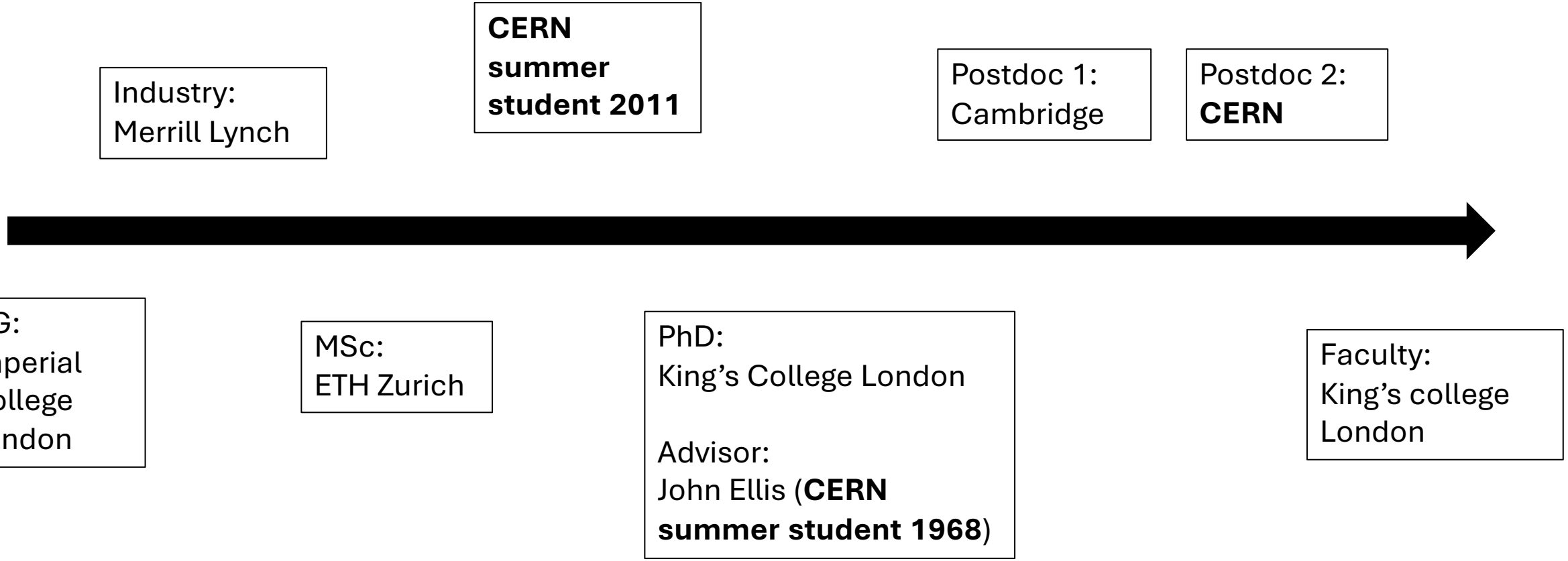
The Branco Weiss Fellowship Society in Science

King's College London

Beyond the Standard Model

Tevong You

My World Line



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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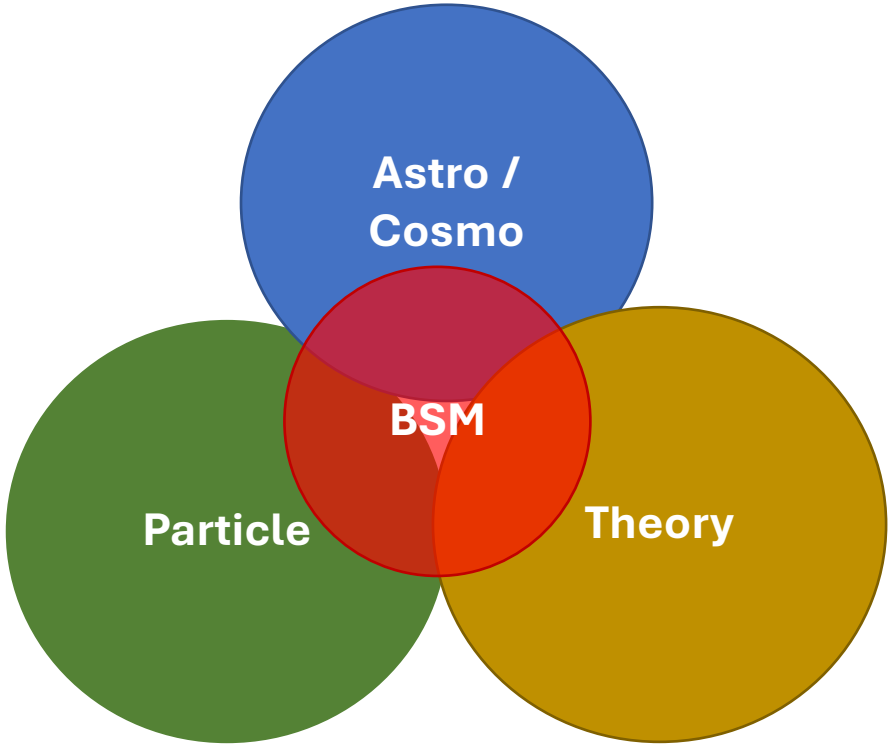
Why BSM?

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



Empirical evidence that the universe is a **unified description** — *not just wishful thinking!*

We *are* getting closer, though **many unanswered problems** remain.

Outline

Part I (slides)

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

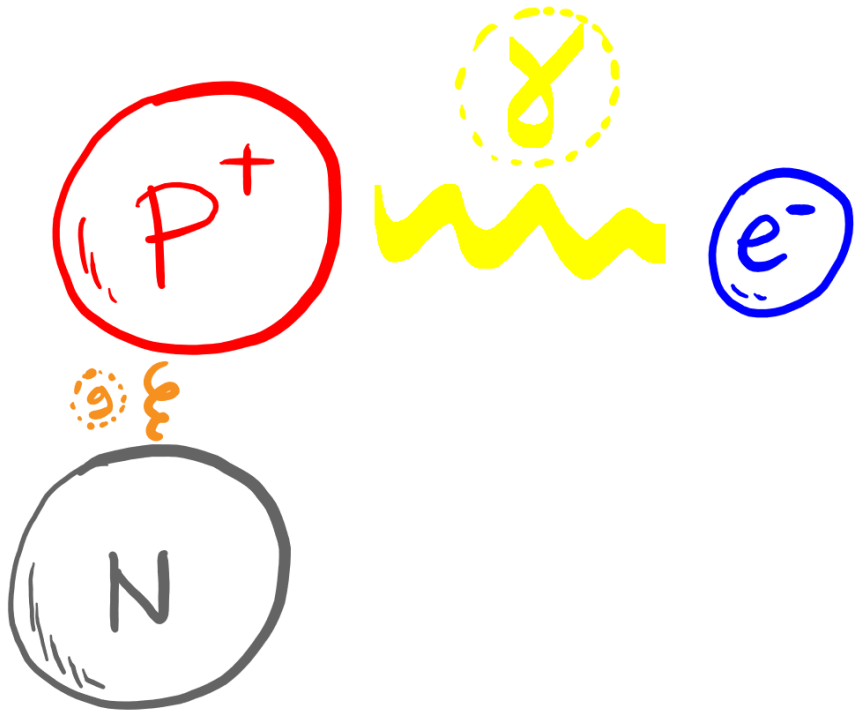
Part 2 (blackboard)

1. The SM EFT gateway to BSM (and the "totalitarian principle")
2. Composite Higgs / Supersymmetry
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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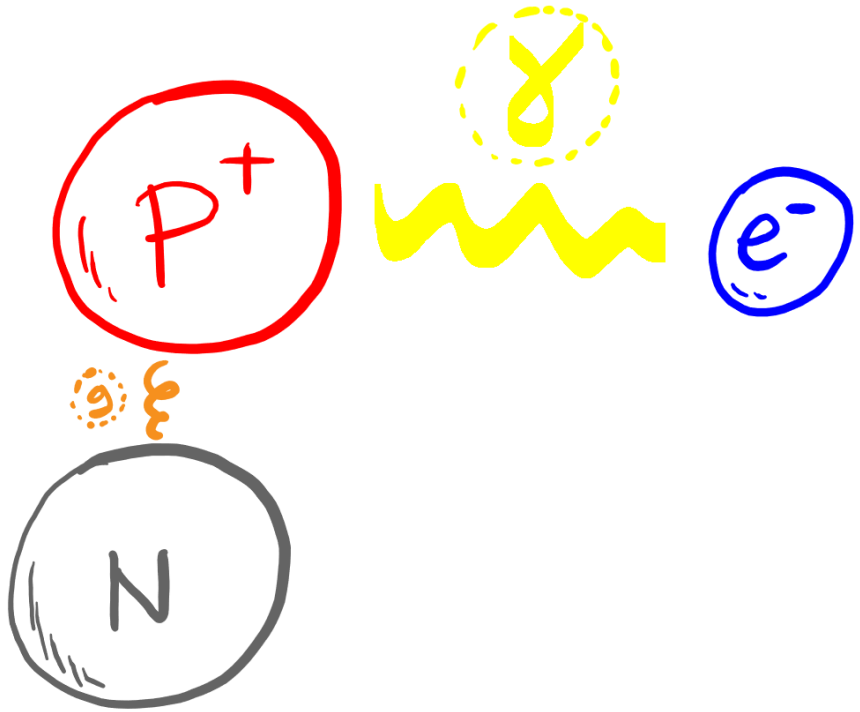


"If we consider protons and neutrons as elementary particles, we would have three kinds of elementary particles [p,n,e]…. This number may seem large but, from that point of view, two is already a large number."

Paul Dirac 1933 Solvay Conference

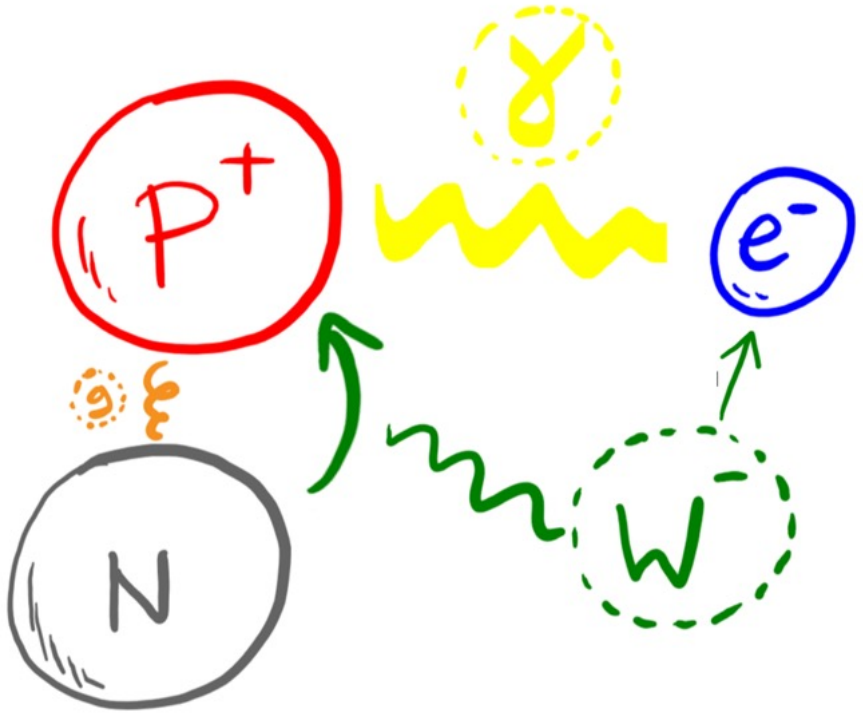
(From D. Tong slide)

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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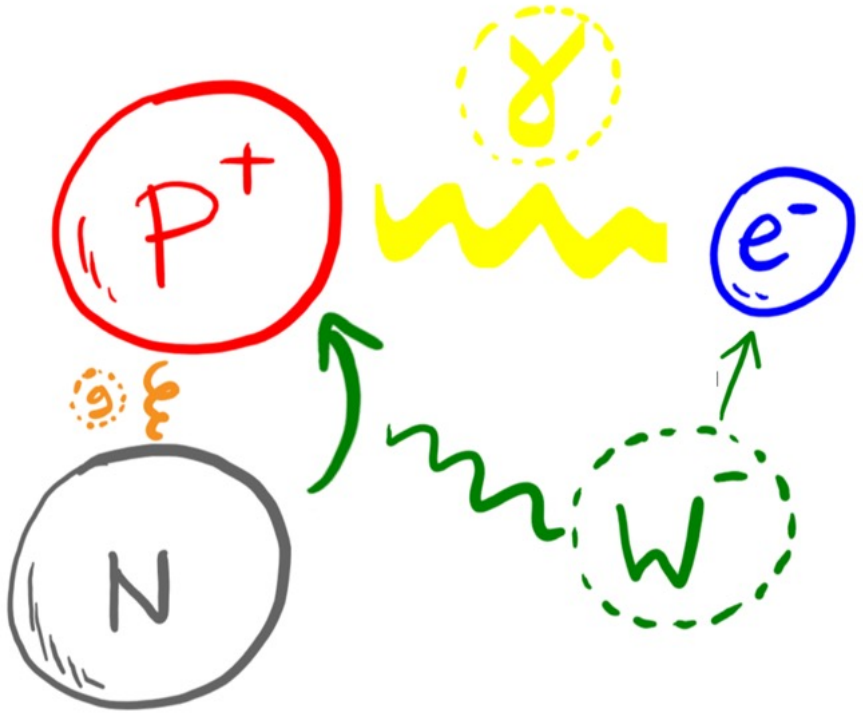

Missing energy? Pauli postulates *"a desperate remedy"*

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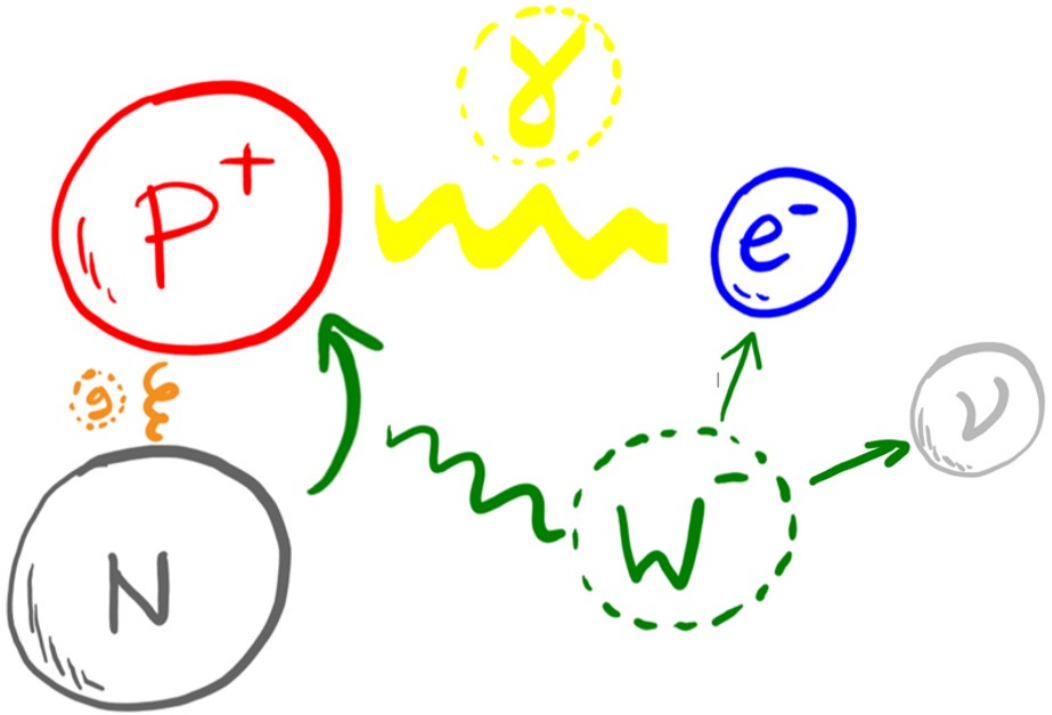

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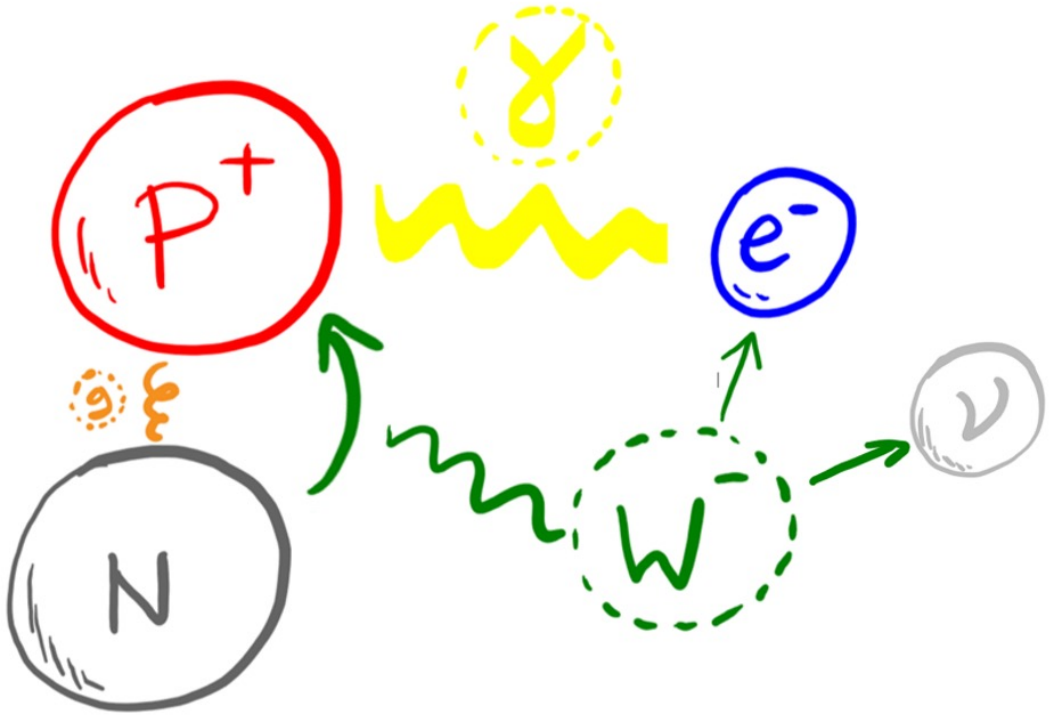


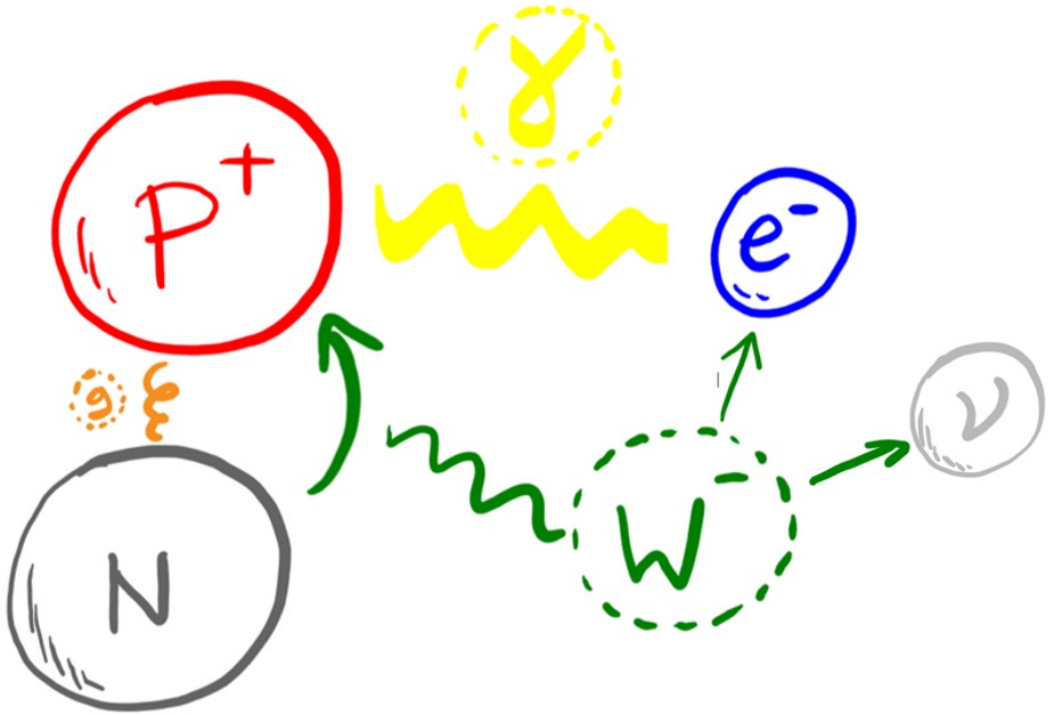
Missing energy? Pauli postulates *"a desperate remedy"*

Lesson 2: *perceived* 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**

How we got here

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



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

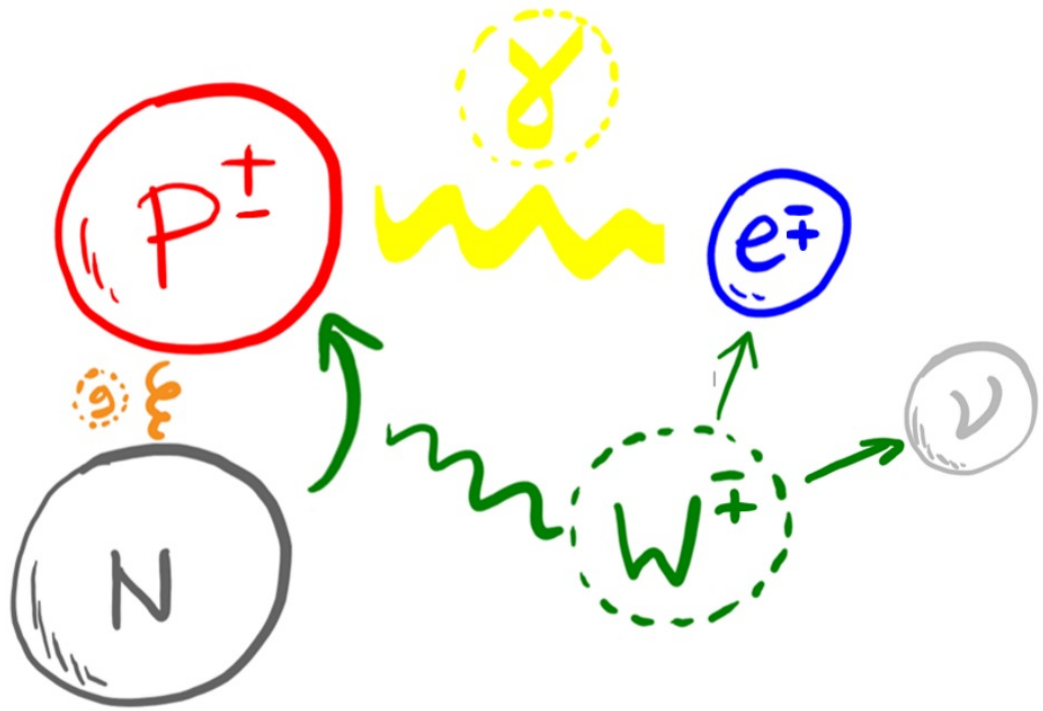
(Bohr postulates fundamental *violation of energy conservation)*

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



- *Every particle has an oppositely charged antiparticle partner*

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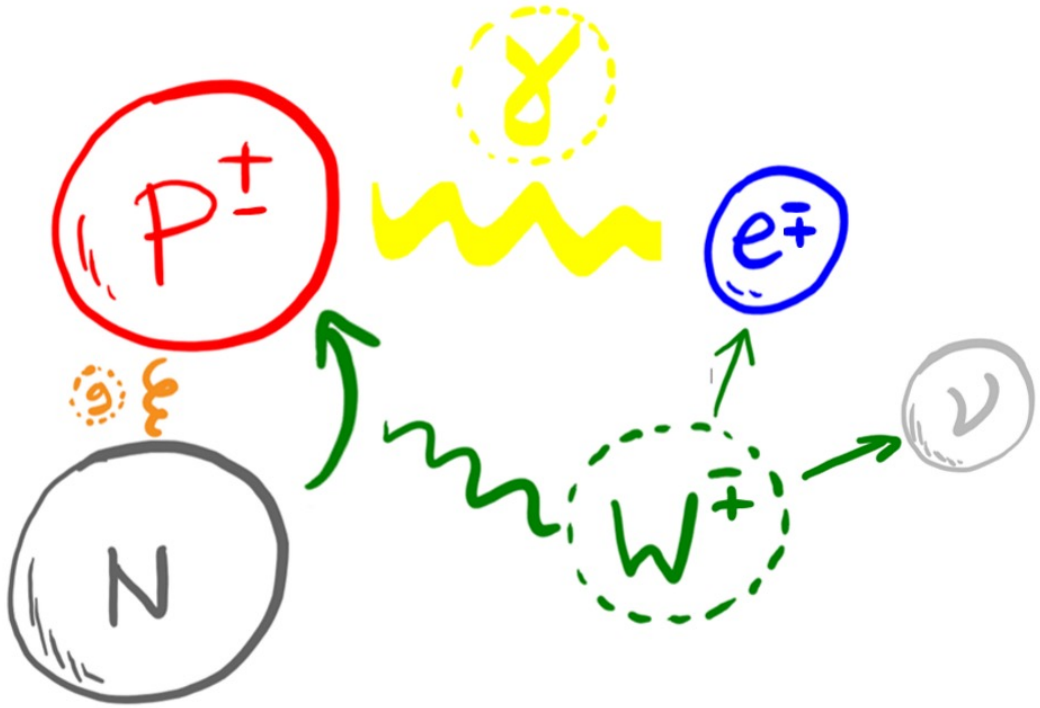
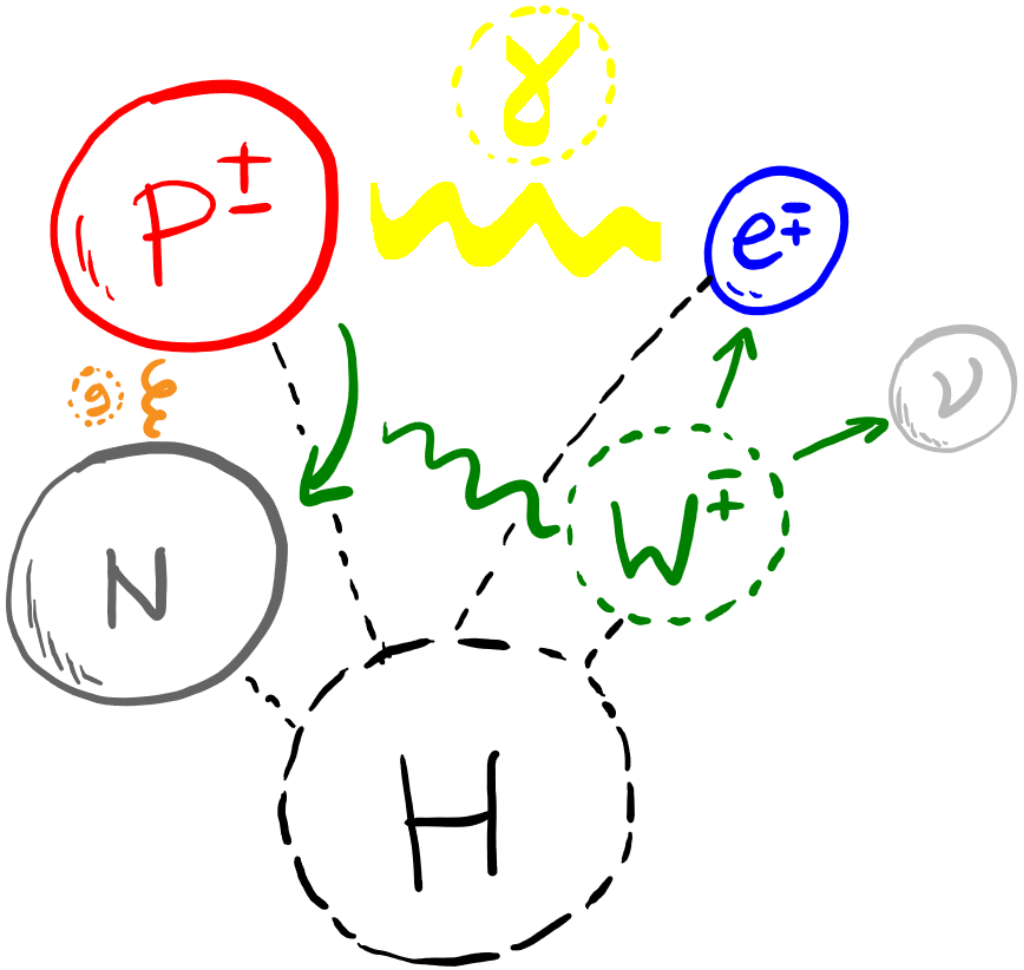


c.f. **Lesson 1**: antiparticles *double the particle spectrum*. Nevertheless, the theory is **much tighter**, **less arbitrary**, and **more elegant**

- *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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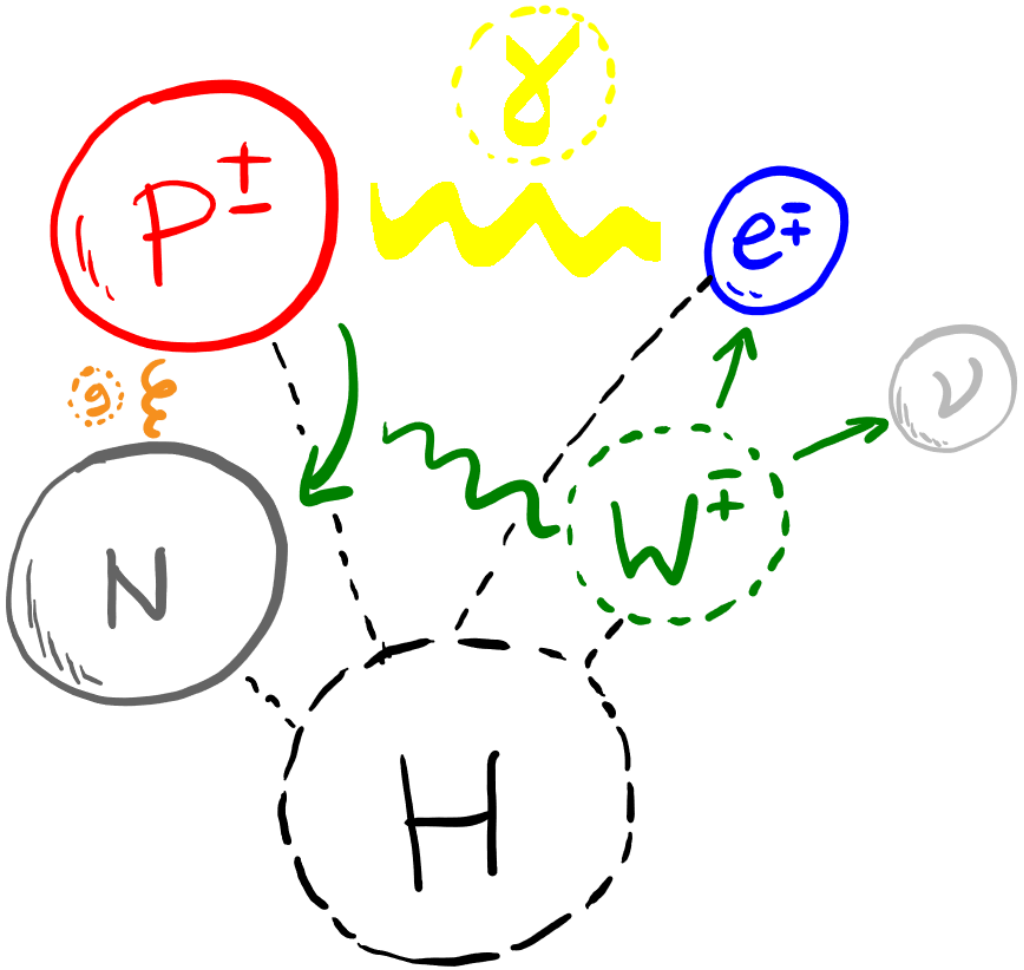


Lesson 3: Keep an open mind.

Ideas initially dismissed as **unrealistic** (*e.g.* non-abelian gauge theories and spontaneous symmetry breaking, because they predicted **unobserved massless** bosons) can click together suddenly and make sense

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*.

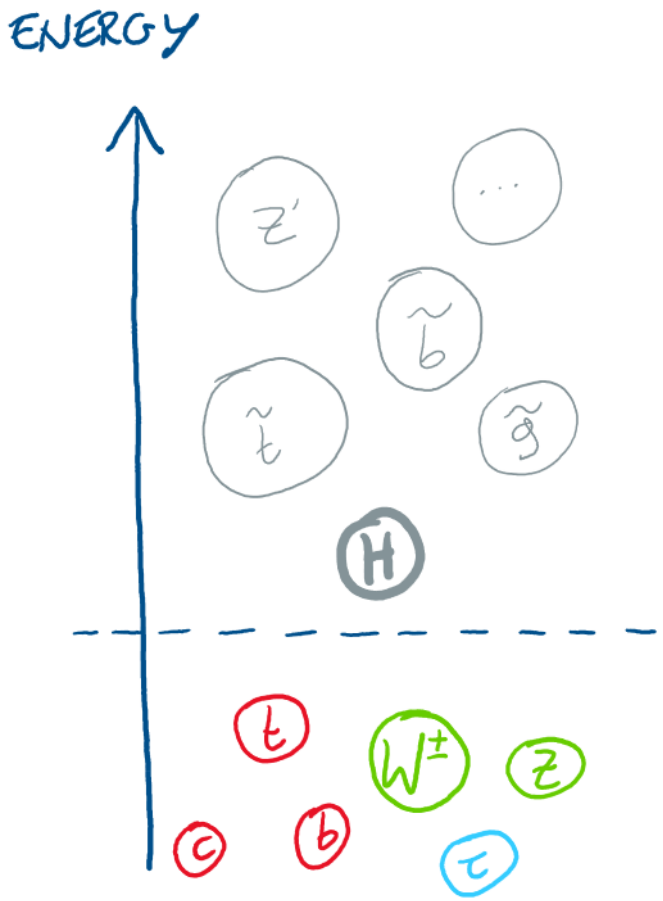
- 1970s: **QFT triumphs** following Yang-Mills+Higgs+asymptotic freedom+renormalisation. Nature is **radically conservative**, *but more unified than ever*.

- 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*.

A crisis in particle physics?

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



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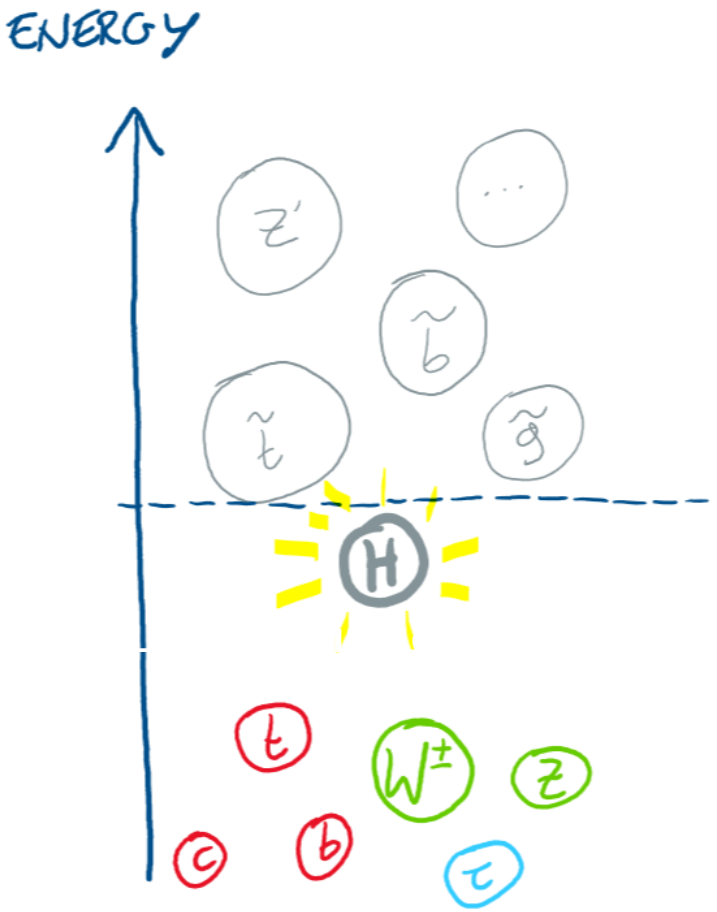

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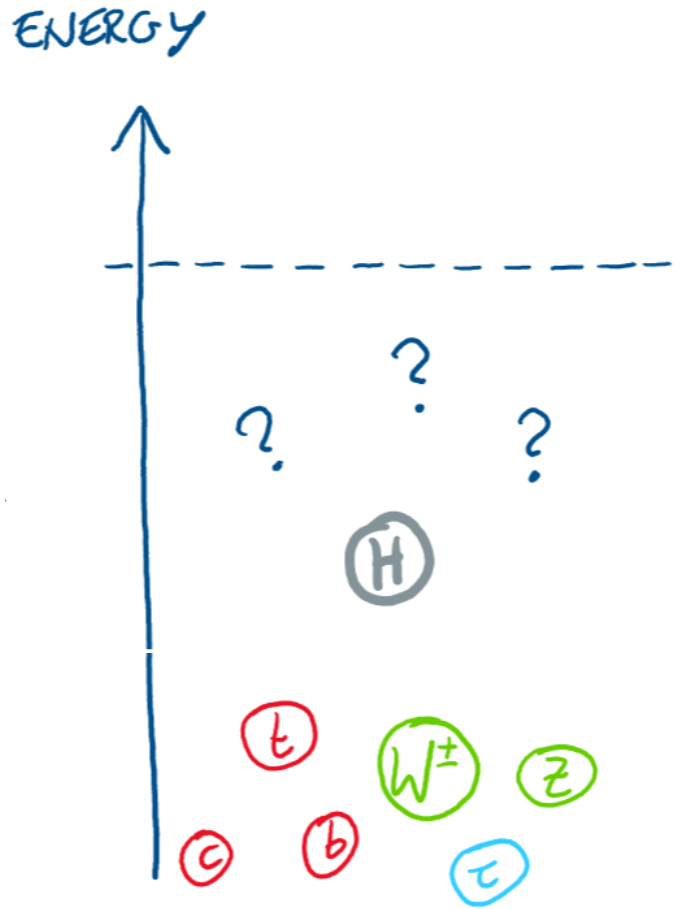

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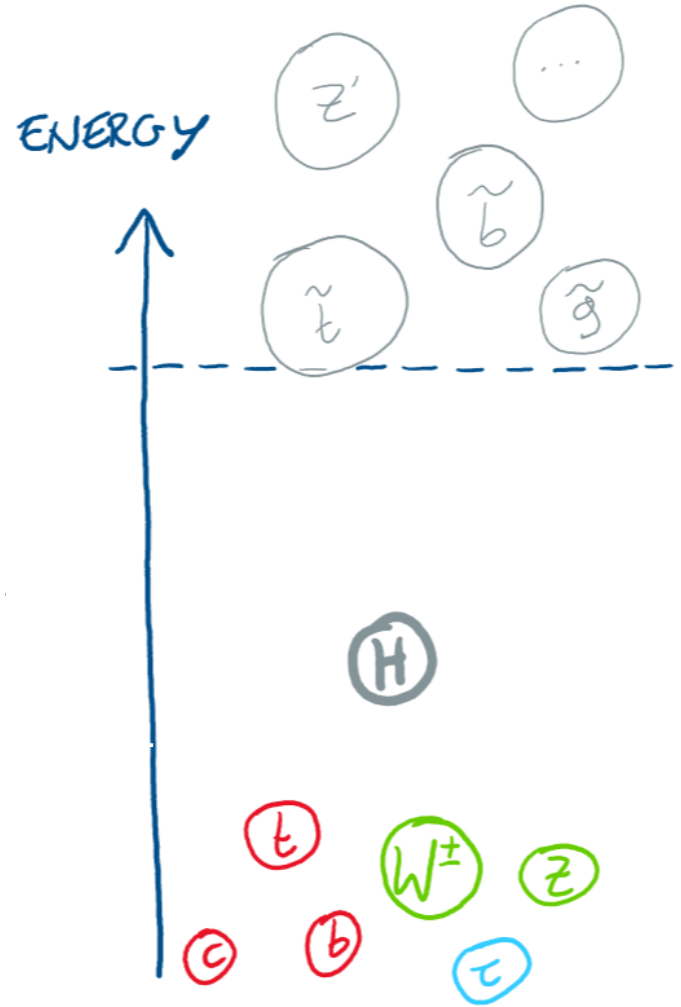

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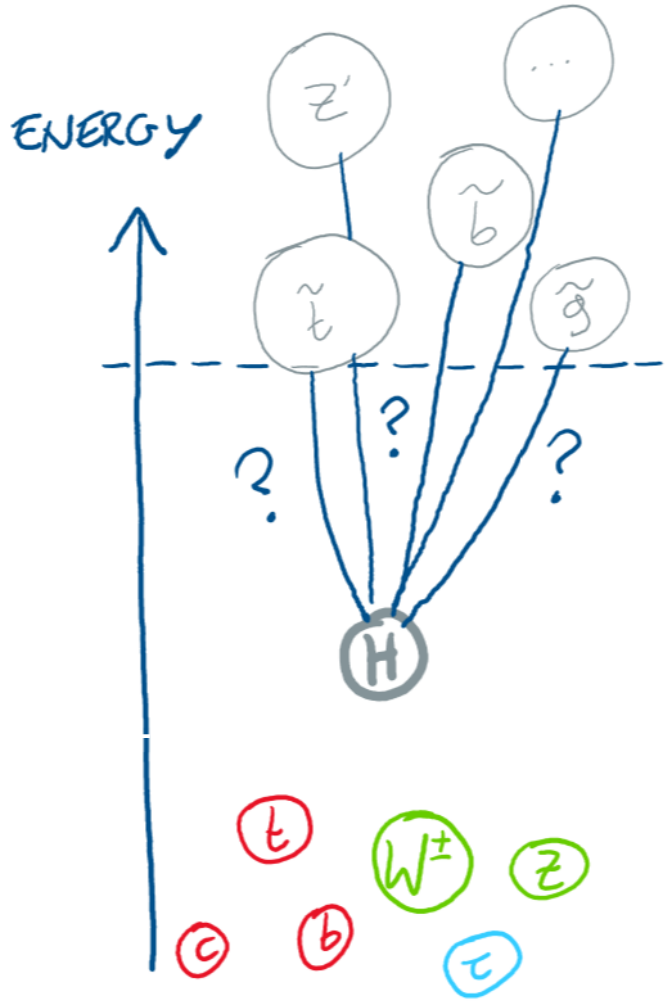

The hierarchy / naturalness problem of the Higgs is more puzzling than ever

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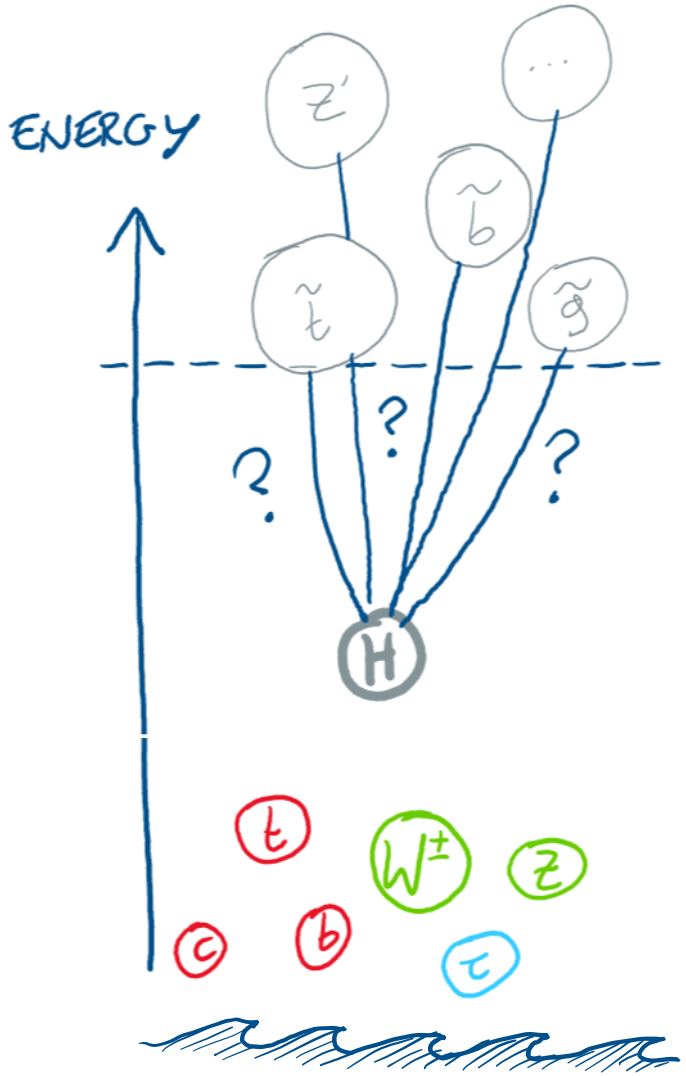

The cosmological constant problem of a tiny vacuum energy is far worse!

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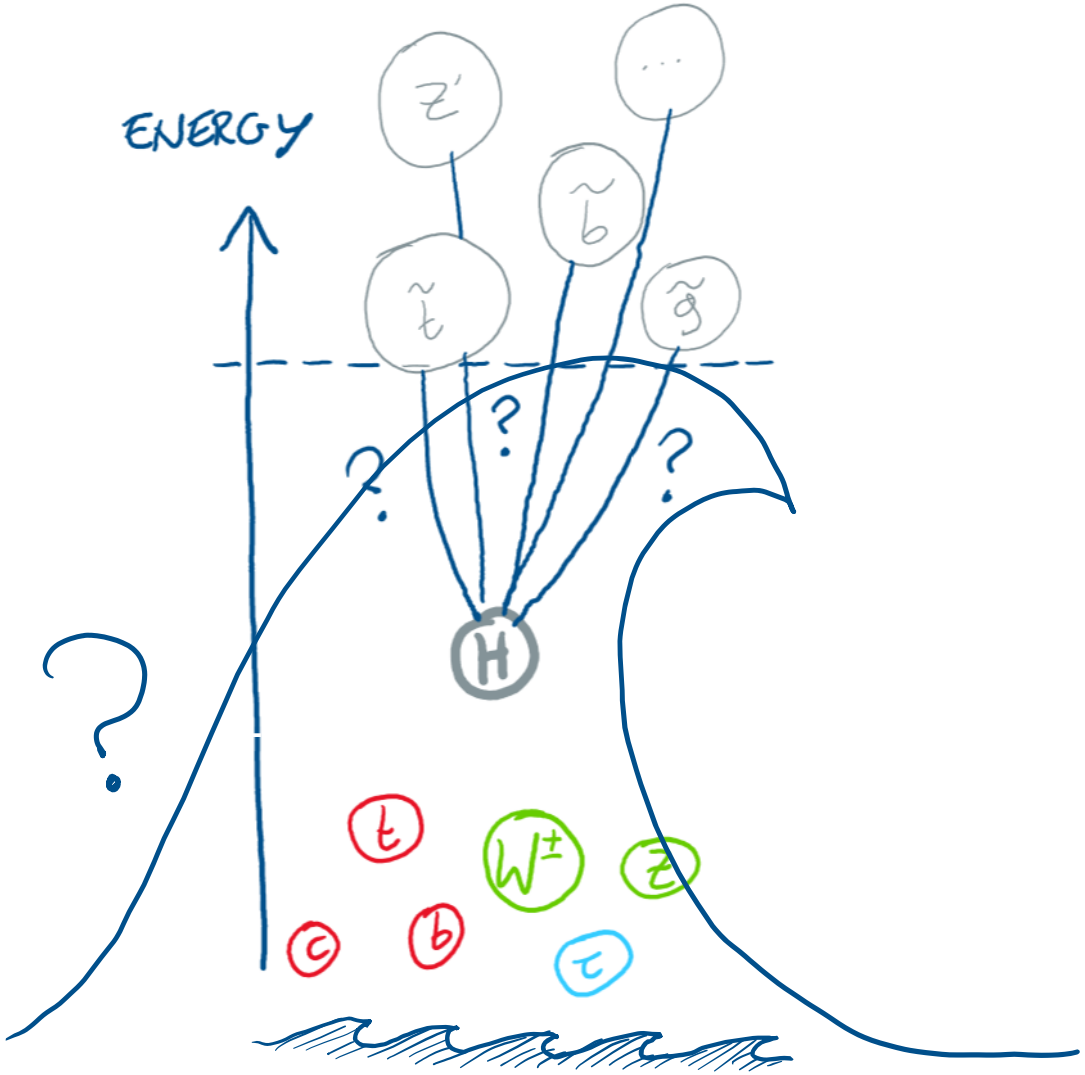

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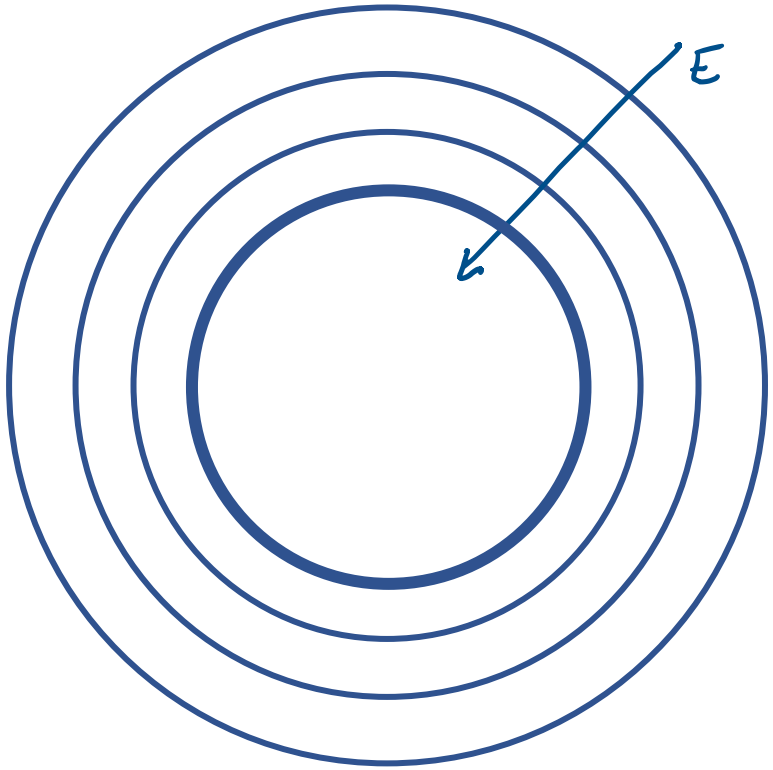
Naturalness is still a fundamental problem

- *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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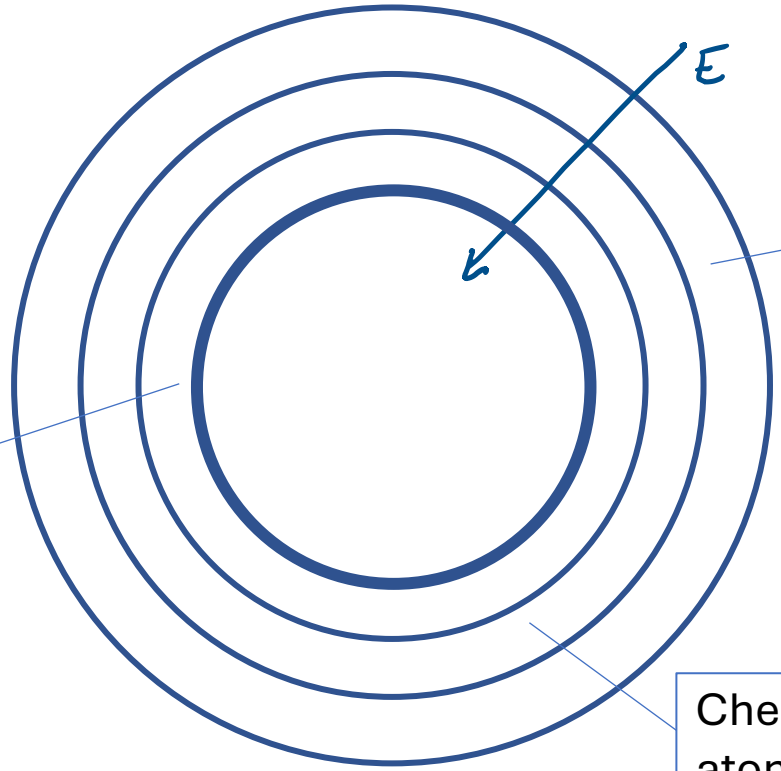

Planetary dynamics, thermodynamics, fluid dynamics, …

Strong / weak interactions, …

Chemistry, atomic physics, nuclear physics, …

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

Naturalness is still a fundamental problem

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

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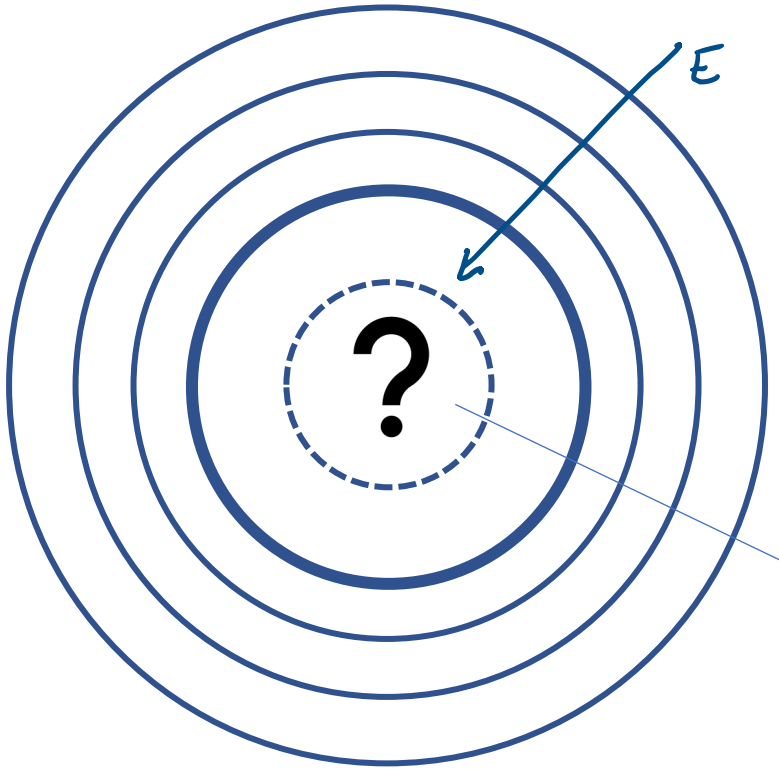

Unnatural Higgs means the next layer *is no longer predictive* without including contributions *from much smaller scales*

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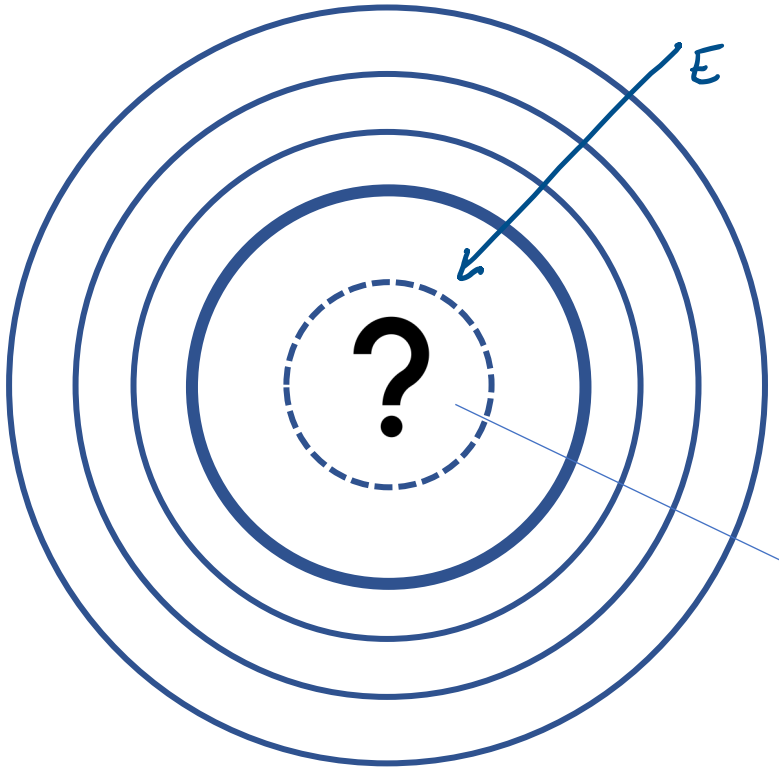
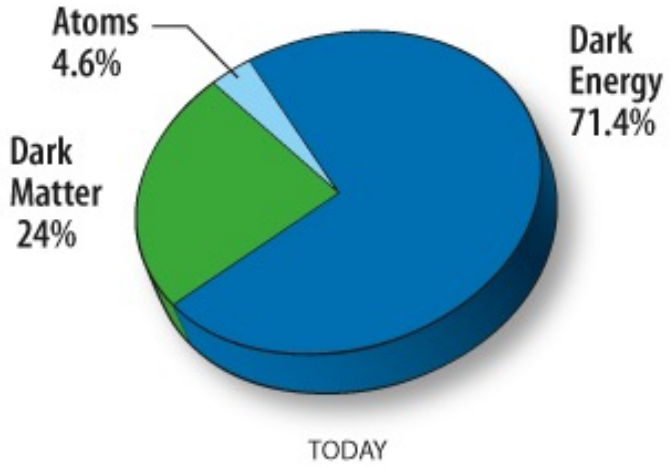


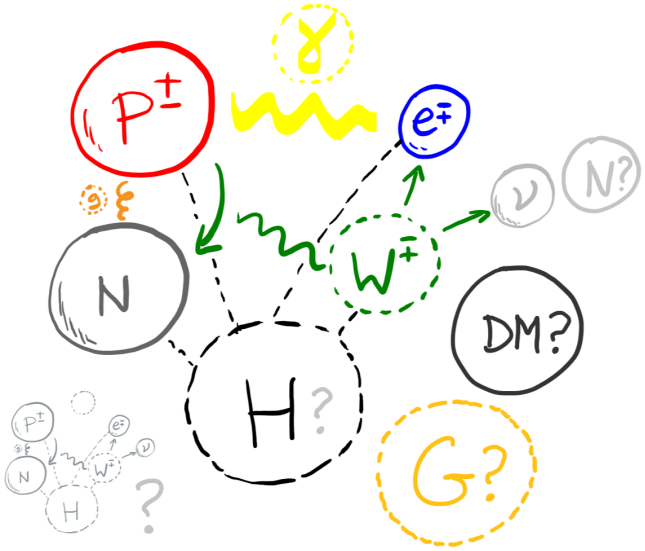
Unnatural Higgs means the next layer *is no longer predictive* without including contributions *from much smaller scales*

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

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

- **Aesthetic:**

  Higgs potential, yukawa couplings, flavour structure, quantized hypercharges, are all *arbitrary parameters put in by hand*.

- **Unnatural:**

  Higgs mass, cosmological constant, strong-CP problem.

- **Inconsistent:**

  Experimental/observational: dark matter, neutrino mass, matter-antimatter asymmetry.

  Theoretical: quantum gravity, black hole information paradox.

Problems of the SM

Take aesthetic problems seriously.

Example 1

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

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

$$q = m_{inertia}$$

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

Problems of the SM

Take fine-tuning problems seriously.

Example 2

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

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!

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

Problems of the SM

Take fine-tuning problems seriously.

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.

ρ meson appears at 775 MeV!

Problems of the SM

Take fine-tuning problems seriously.

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.

Higgs?

Higgs also has a quadratically divergent contribution to its mass

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

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

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

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

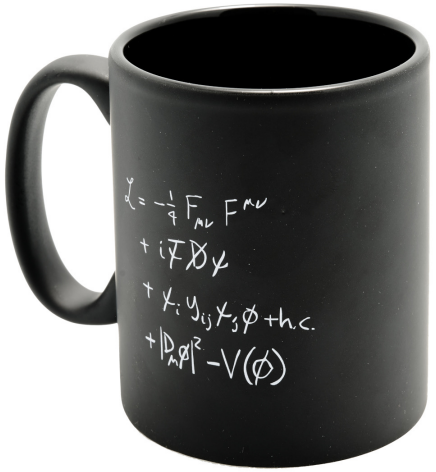
Problems of the SM

Gauge theories have the quality we seek in a satisfying theory.

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 such new physics to appear close to the weak scale!



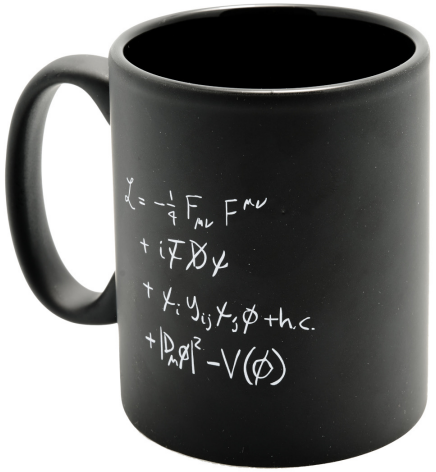
Conclusion

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.



Questions?