CERN summer student programme, 30th July 2024

The Branco Weiss Fellowship Society in Science

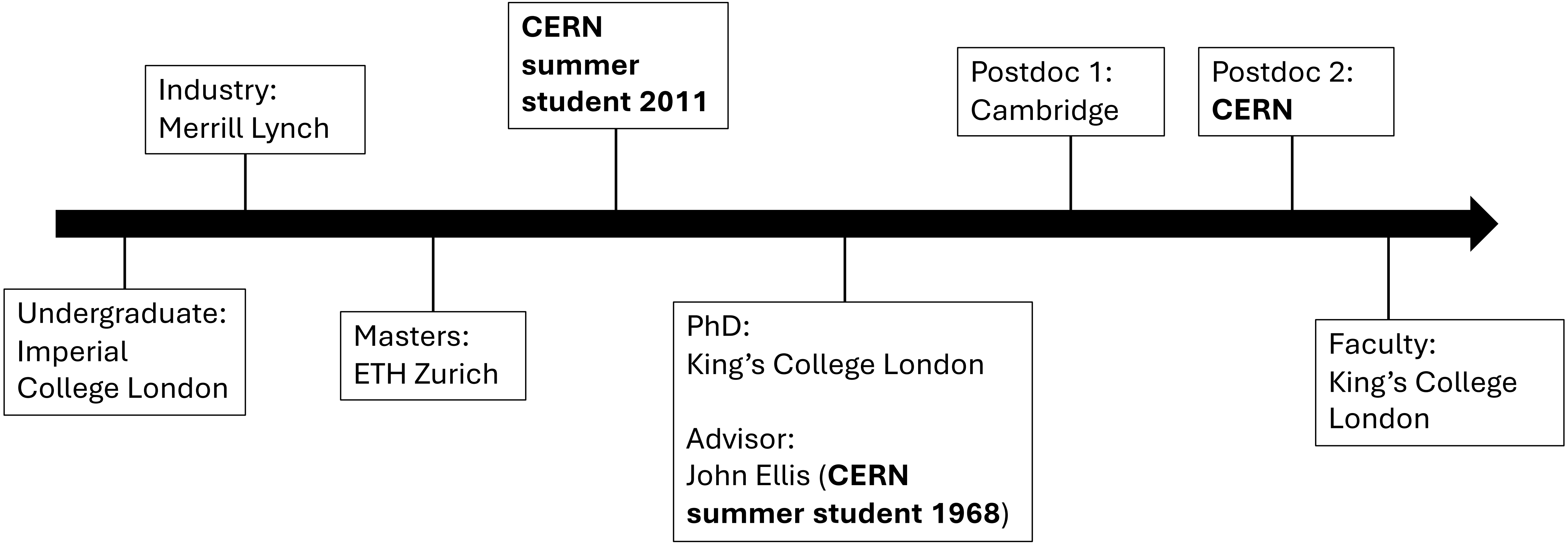
KING'S College LONDON

Beyond the Standard Model

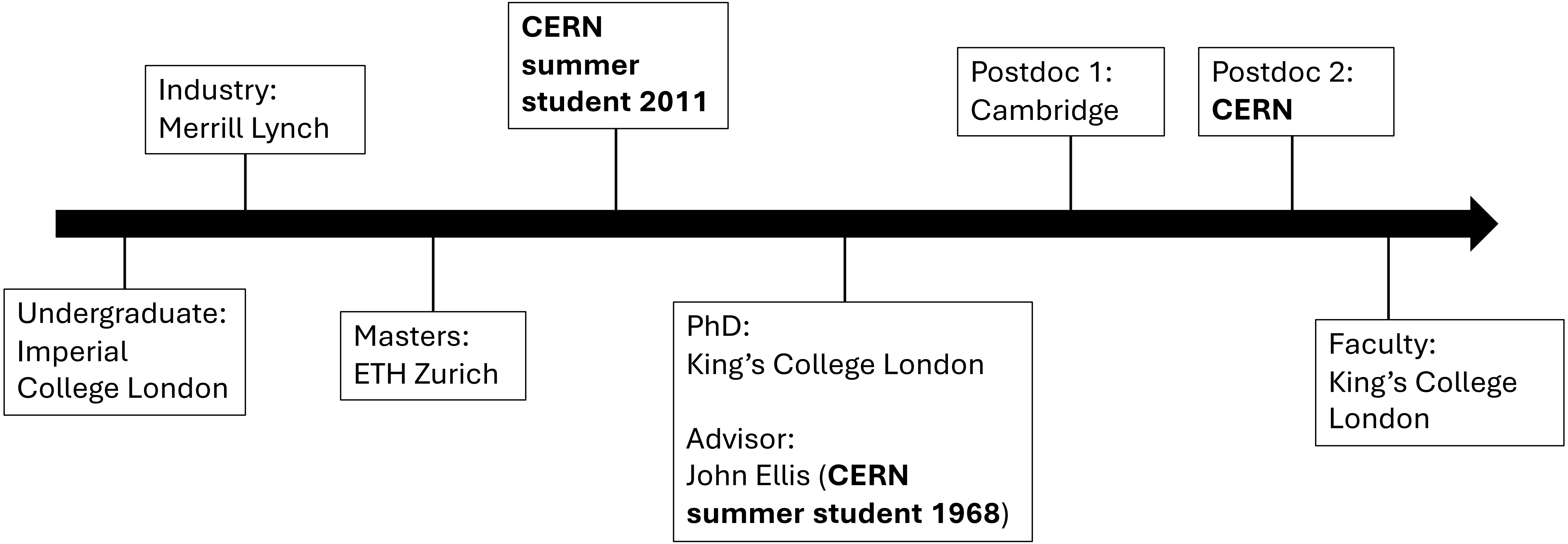
Tevong You

Lecture 1

My World Line



My World Line



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)
https://www.nature.com/articles/455174a

Oppenheimer and the birth of CERN

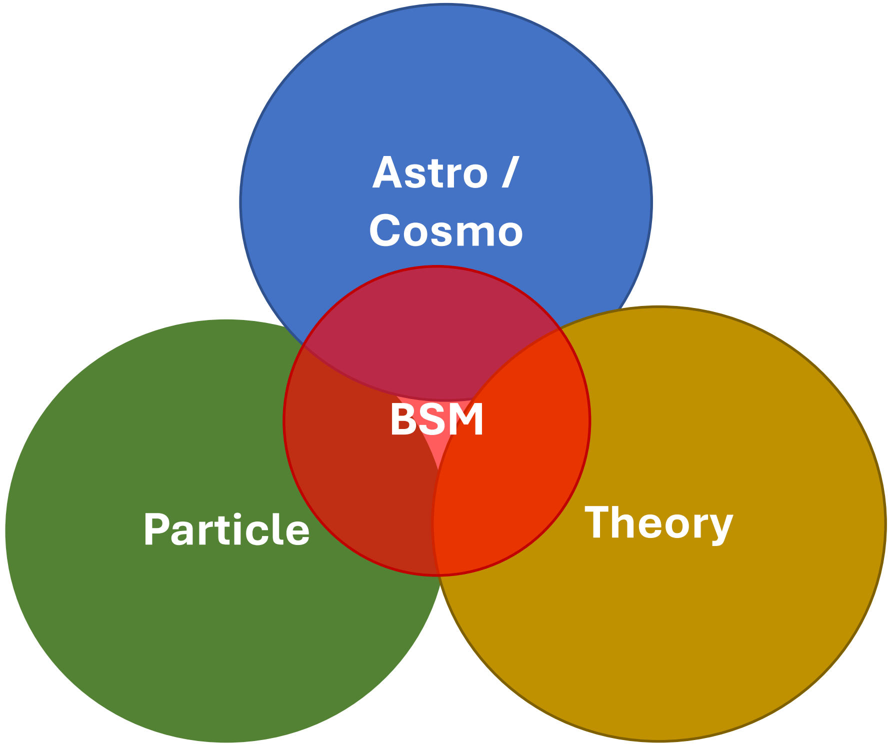
One day, Oppenheimer told me of a problem that was very much on his mind. Most of America's best physicists, he said, had like him been trained, or had worked, in Europe's pre-war laboratories. He believed that Europe's shaken nations did not have the resources to rebuild their basic physics infrastructure. 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) https://www.nature.com/articles/455174a

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

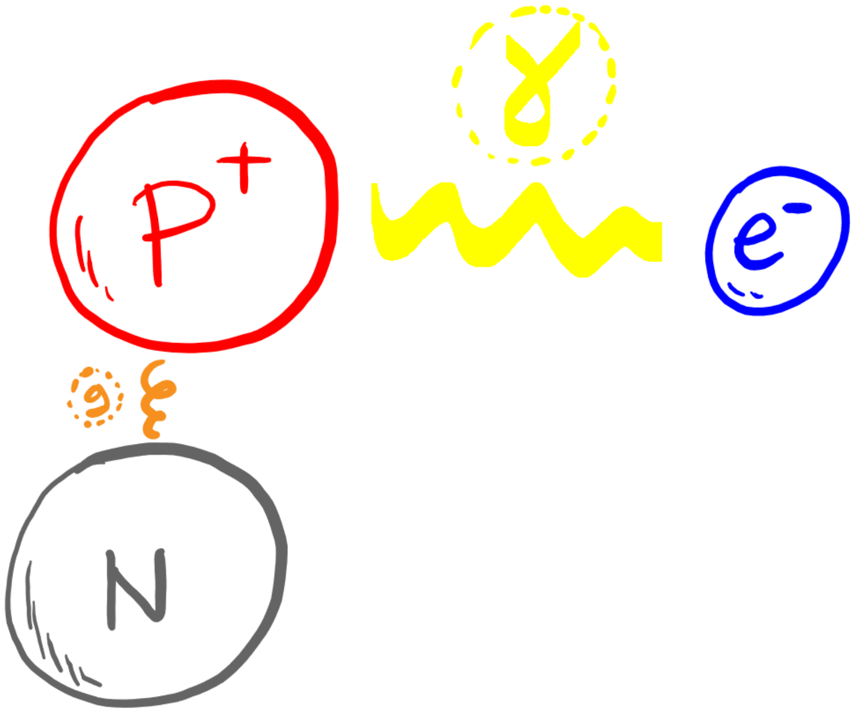
Part 2

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**

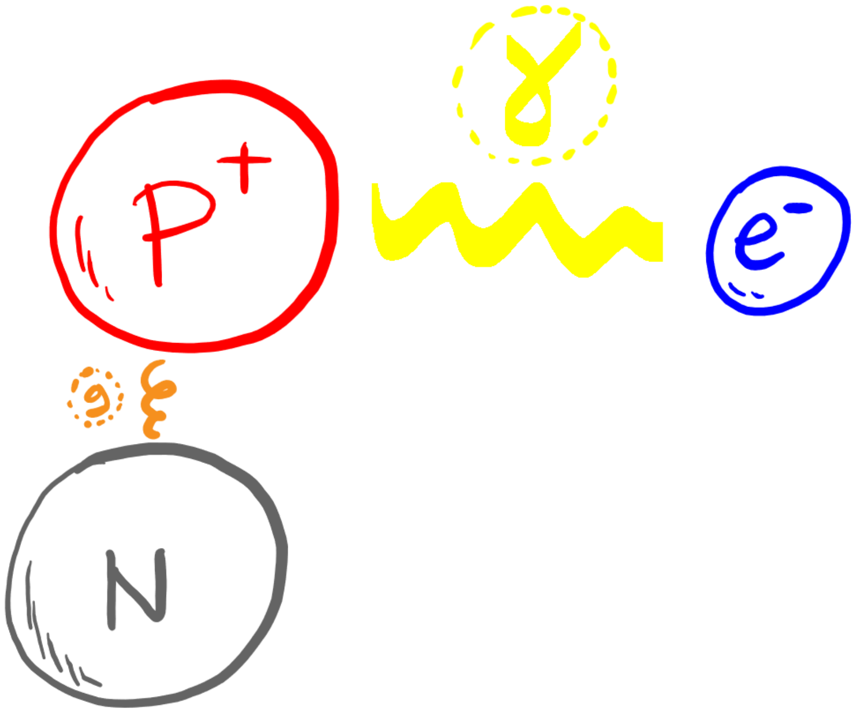
Minimal, economical theory?



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

How we got here

- *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

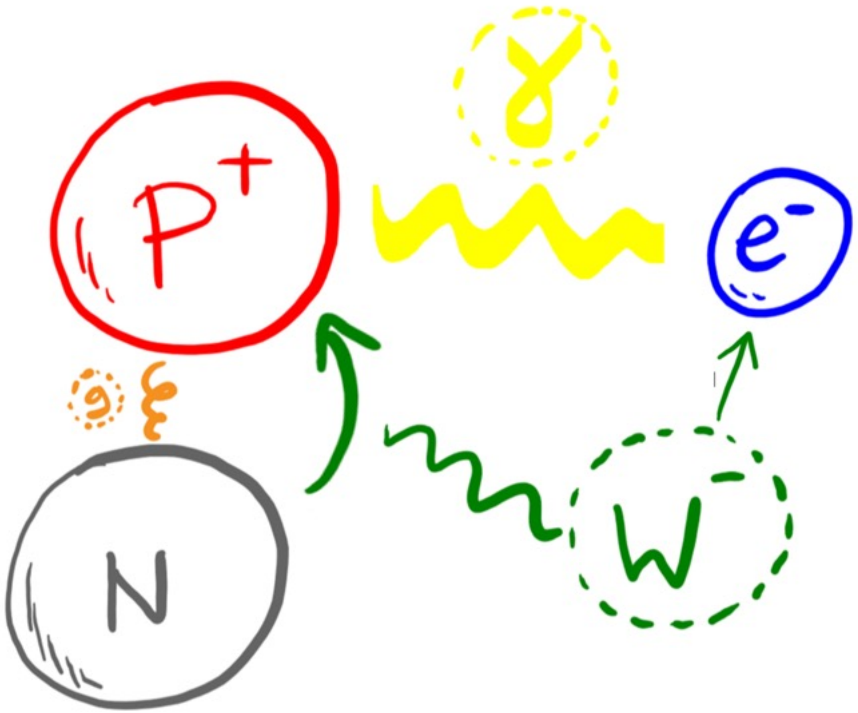
(From D. Tong slide)

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

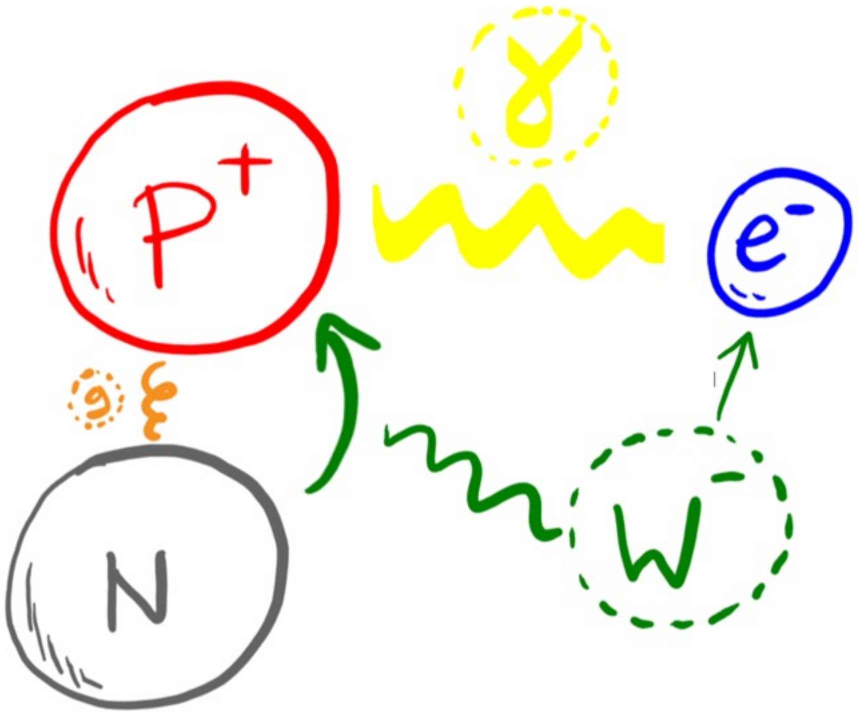
- **Weak force** explains *radioactivity*



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

How we got here

- **Weak force** explains *radioactivity*



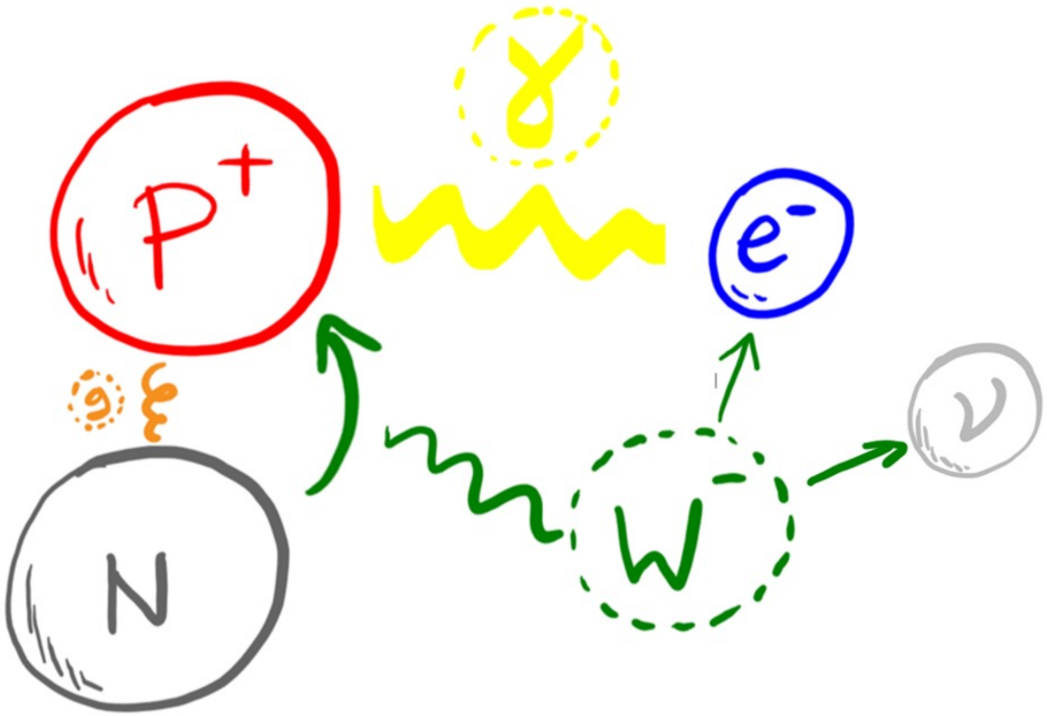
- **Neutron** can change into **proton**, emitting **electron**

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

How we got here

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

Missing energy? Pauli postulates *“a desperate remedy”*

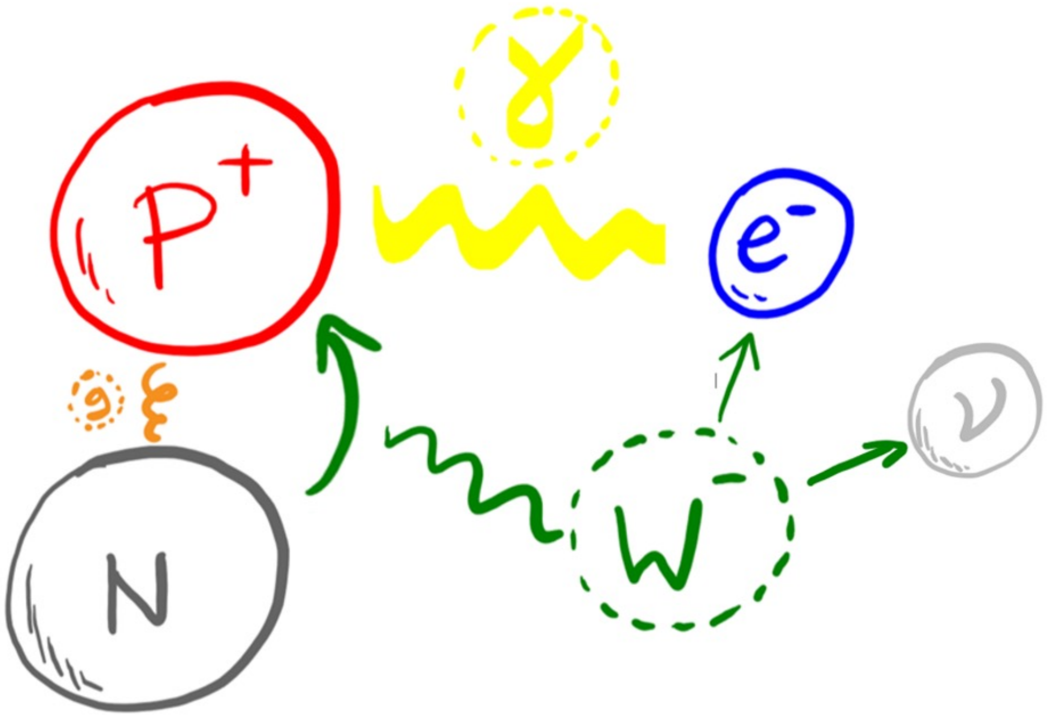


- **Neutron** can change into **proton**, emitting **electron** *and elusive* **neutrino**

How we got here

- *Weak force* explains *radioactivity*

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

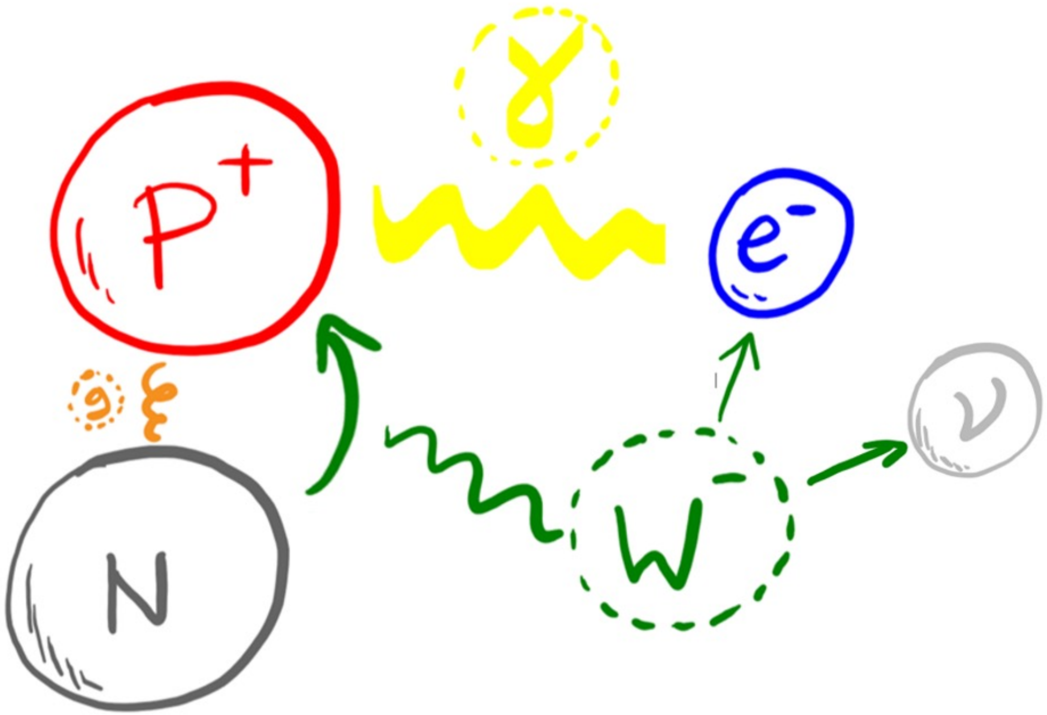


Lesson 2: *perceived* prospect of experimental confirmation is *not a useful scientific criteria* for establishing **what nature actually does**

- **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"*

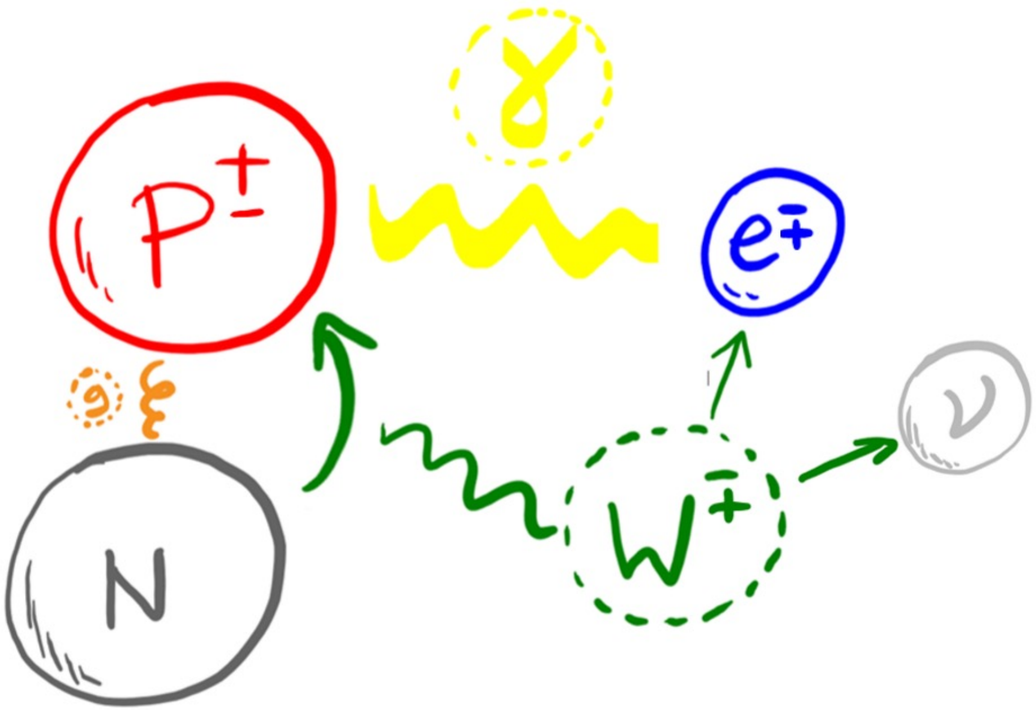
(Bohr postulates fundamental *violation of energy conservation)*

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

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

How we got here

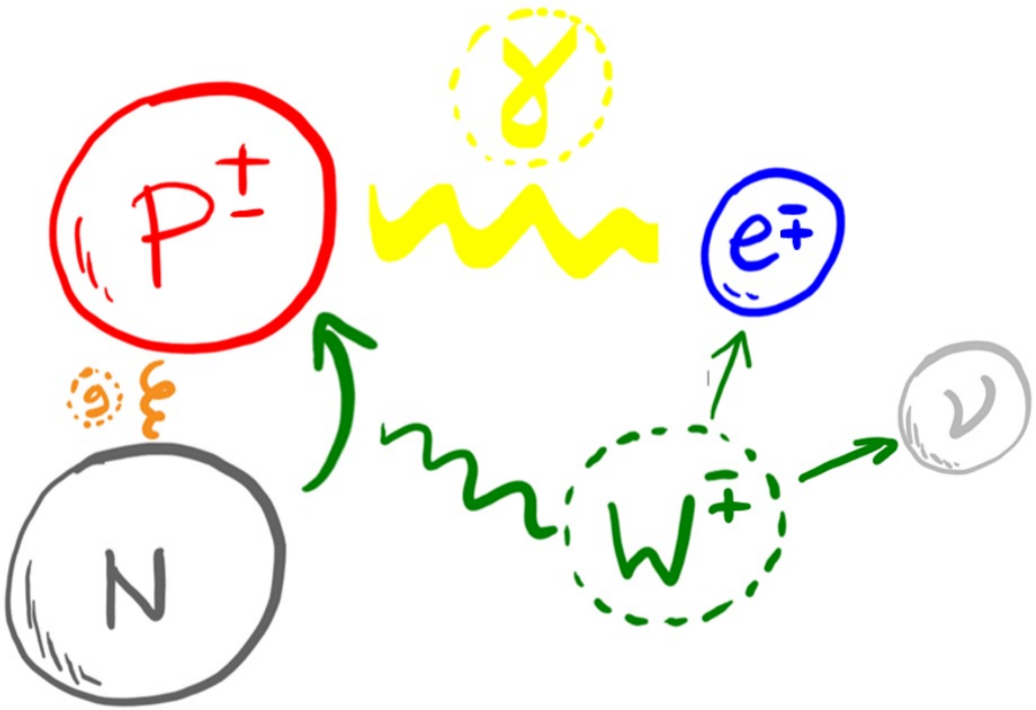
- Dirac: **relativity** + **quantum mechanics** = **antiparticles**



- *Every particle has an oppositely charged antiparticle partner*

How we got here

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

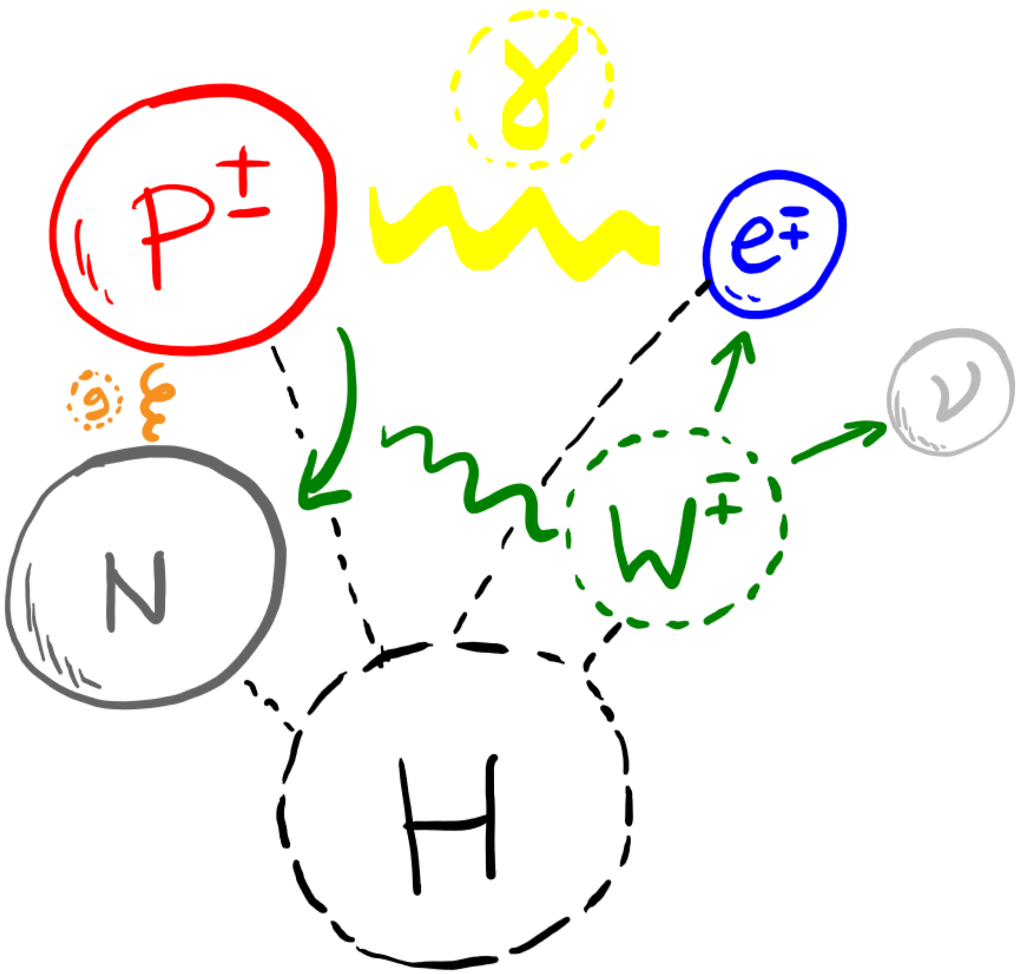


c.f. **Lesson 1**: antiparticles *double the particle spectrum*. Nevertheless, the theory is **much tighter**, **less arbitrary**, and **more elegant**

- *Every particle has an oppositely charged antiparticle partner*

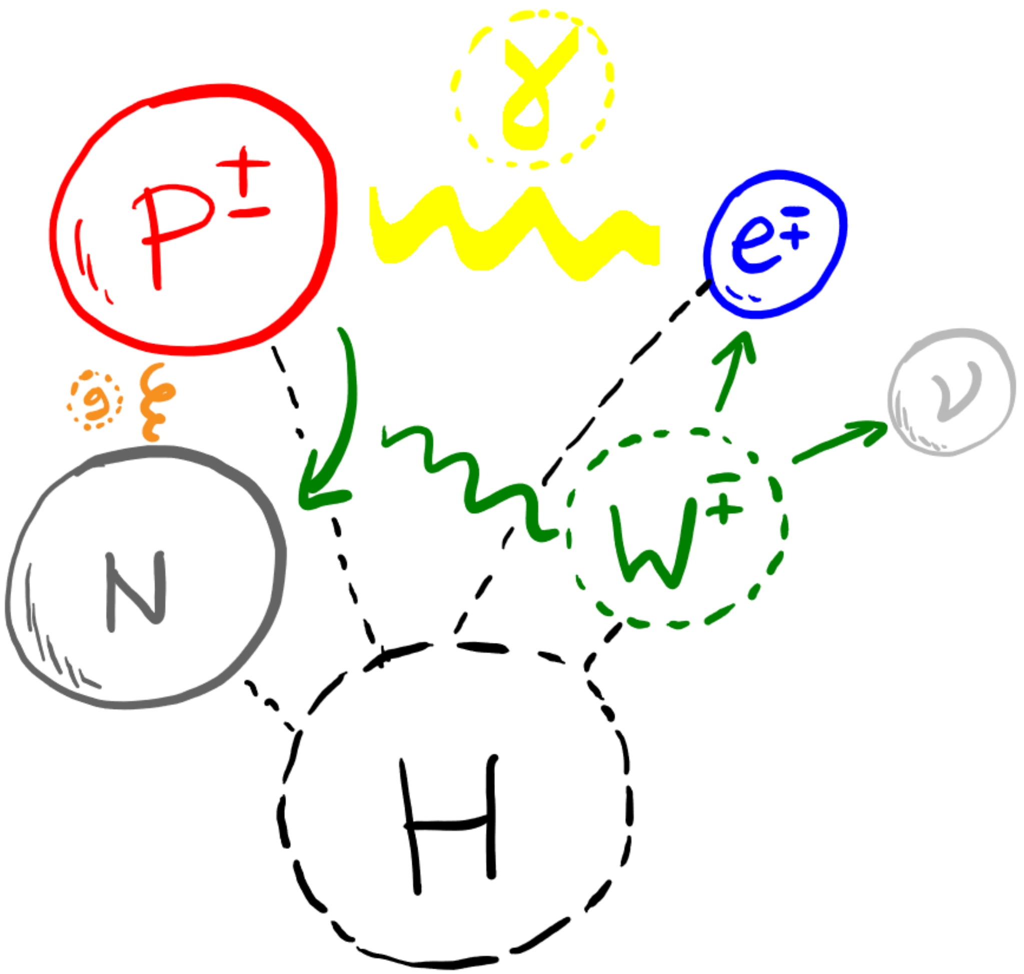
How we got here

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



How we got here

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



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*.

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*.

See BBC Horizon 1964 documentary *“Strangeness minus three”:* 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*.

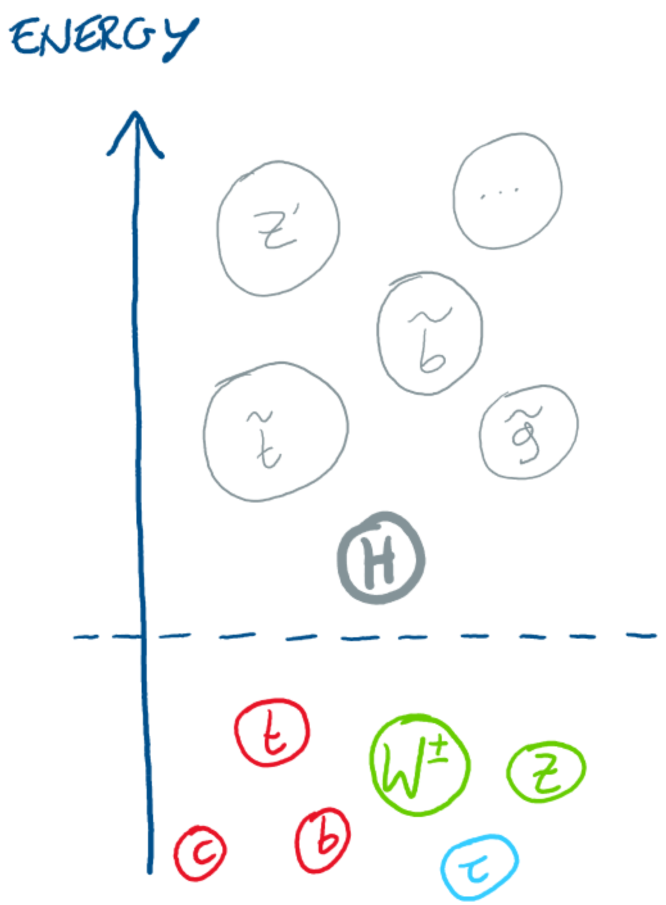
- 1980s:

  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**

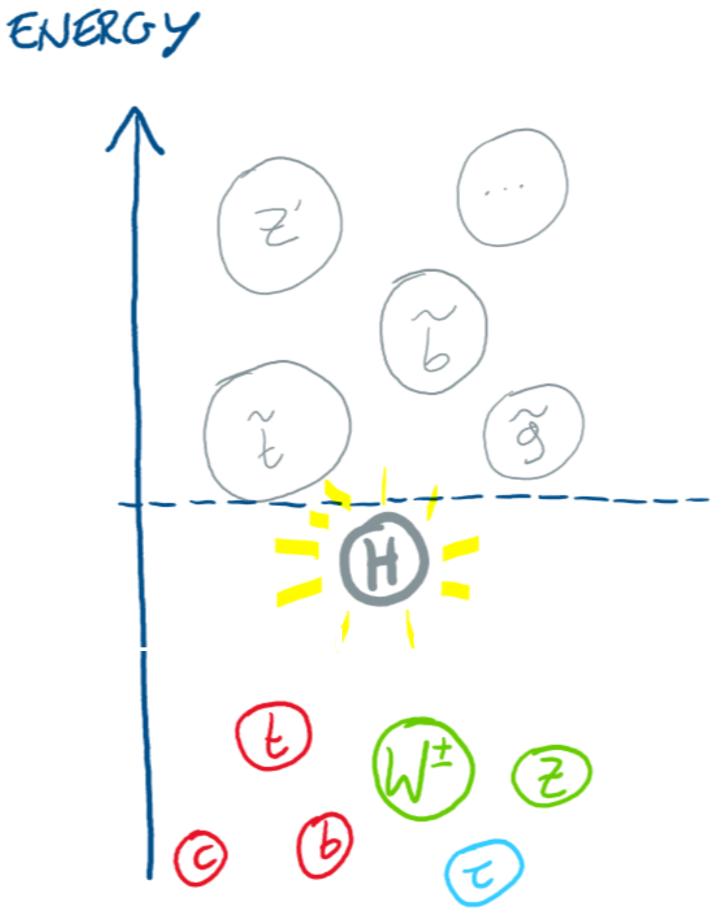


No-lose theorem: Higgs (or something) *guaranteed* to appear.

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

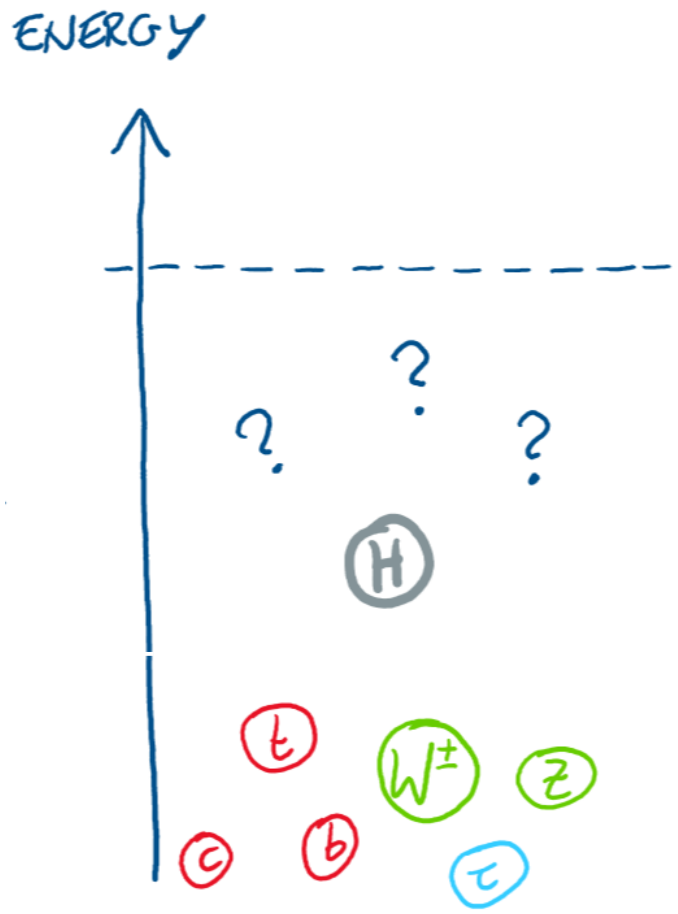
A crisis in particle physics?

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



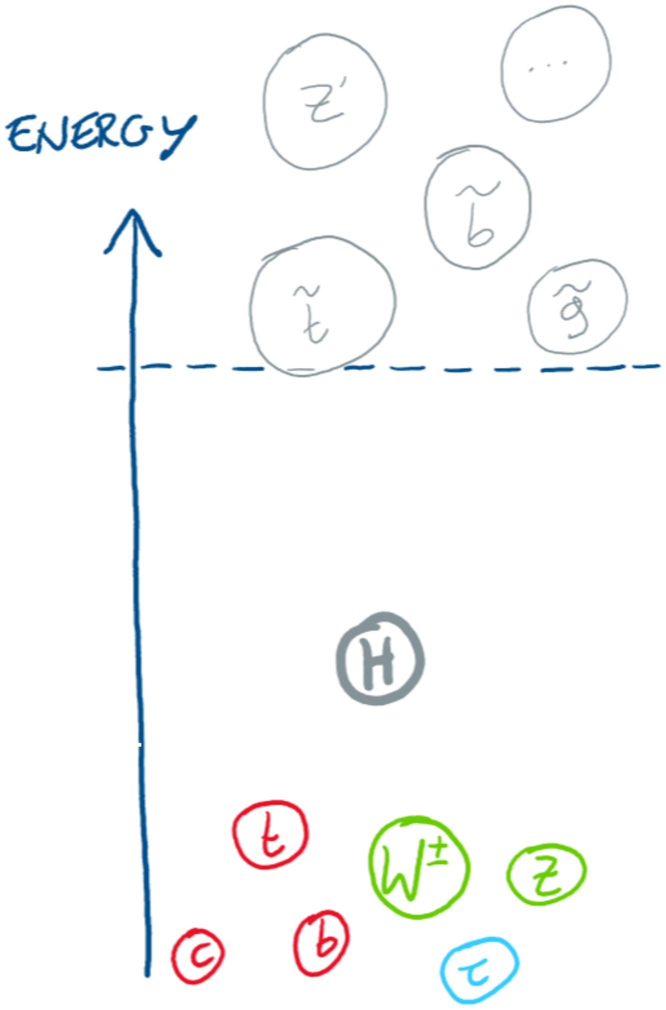
A crisis in particle physics?

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



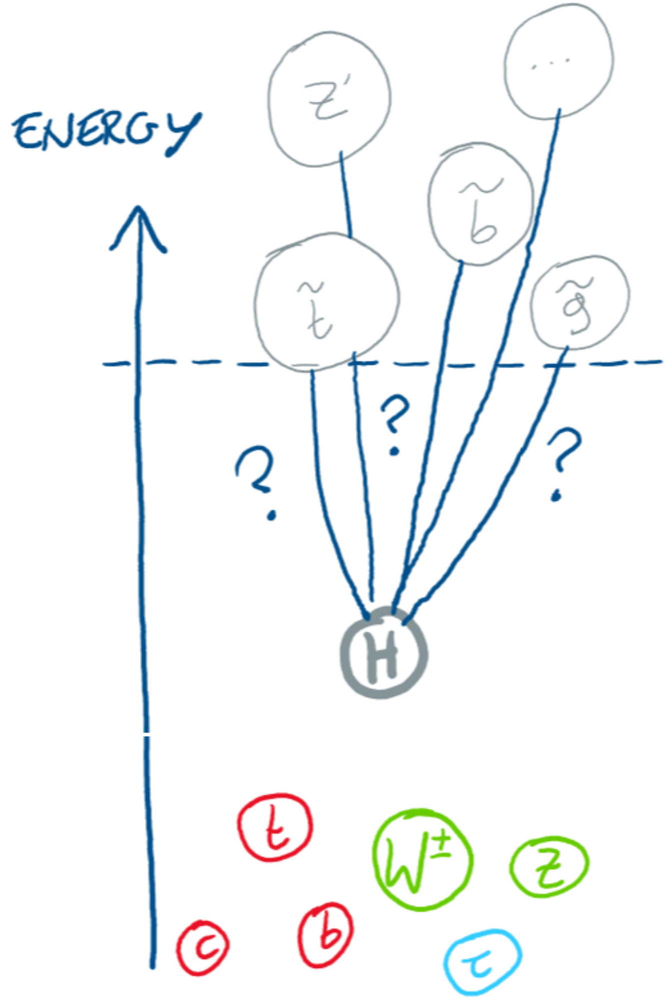
A crisis in particle physics?

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



A crisis in particle physics?

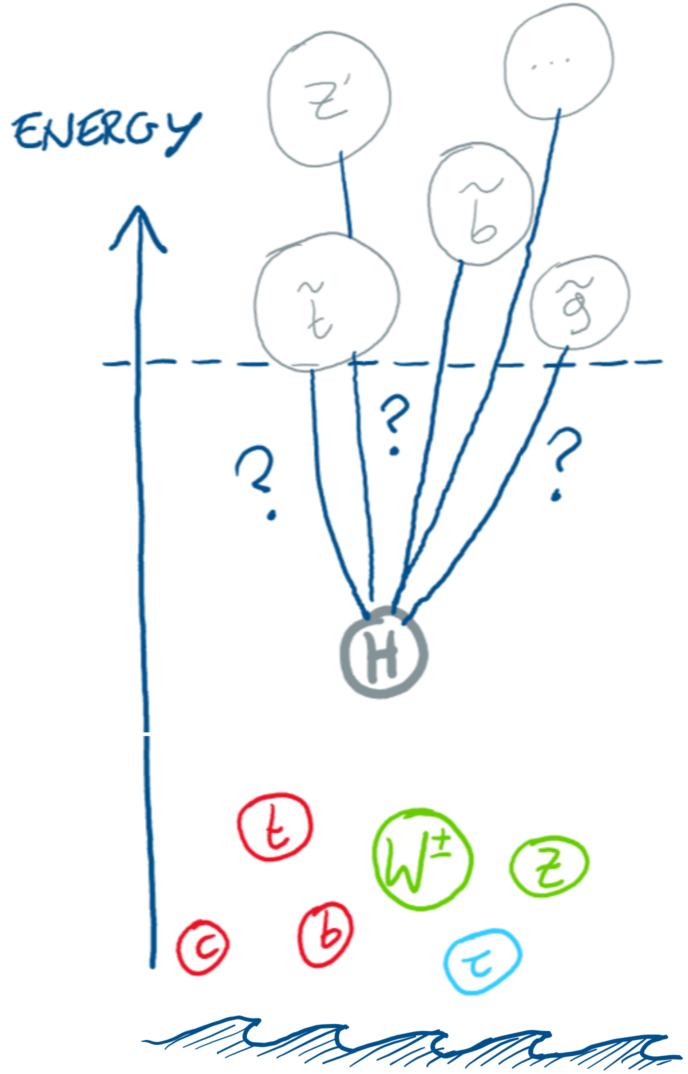
- Until now, there had been a **clear roadmap**



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

A crisis in particle physics?

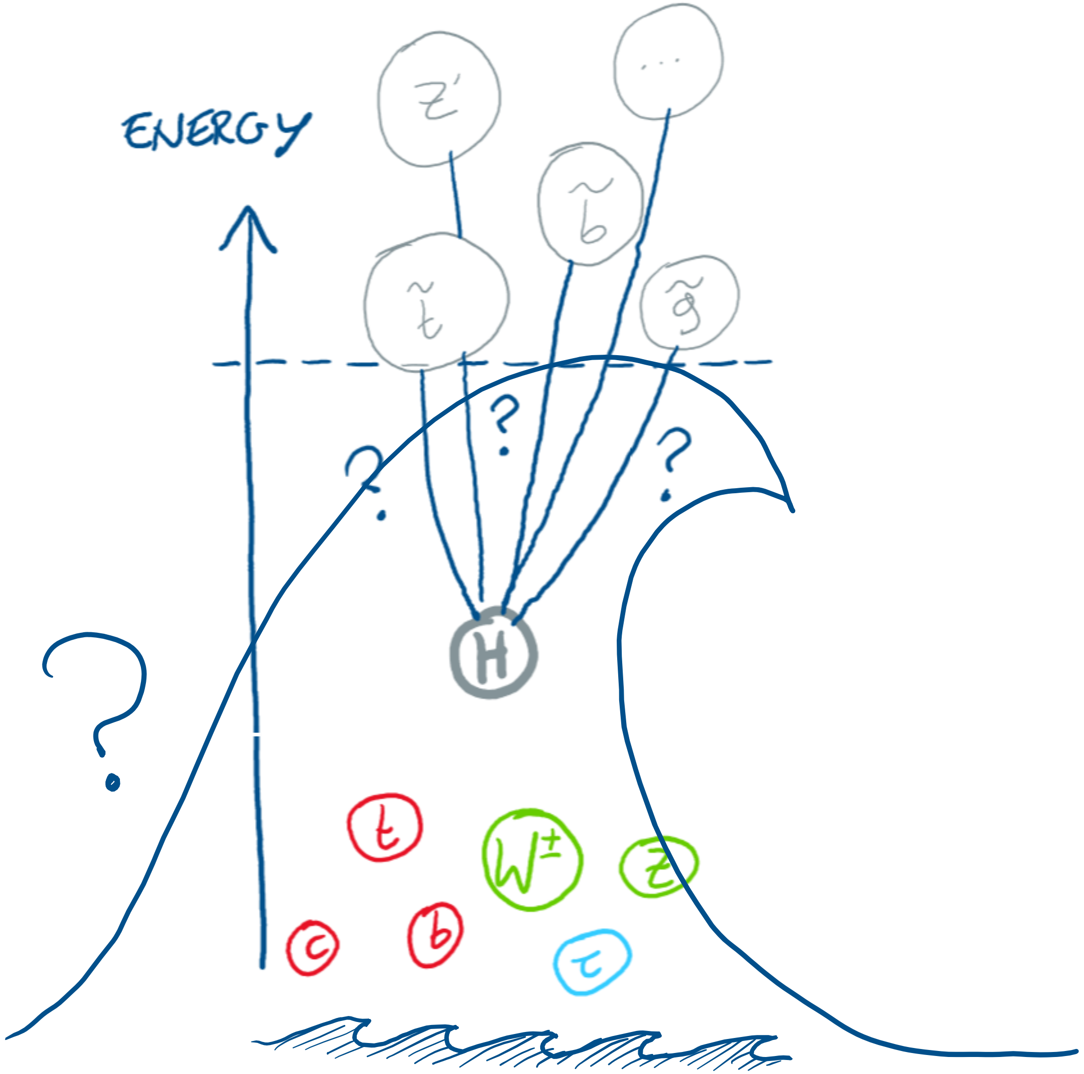
- Until now, there had been a **clear roadmap**



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

A crisis in particle physics?

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

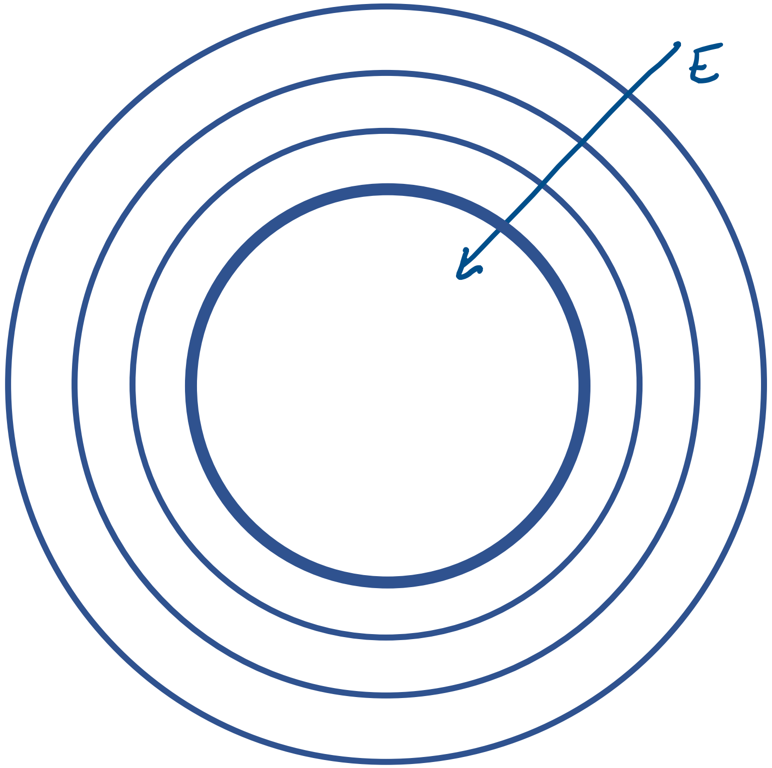


The cosmological constant problem of a tiny vacuum energy is far worse!

Naturalness is still a fundamental problem

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

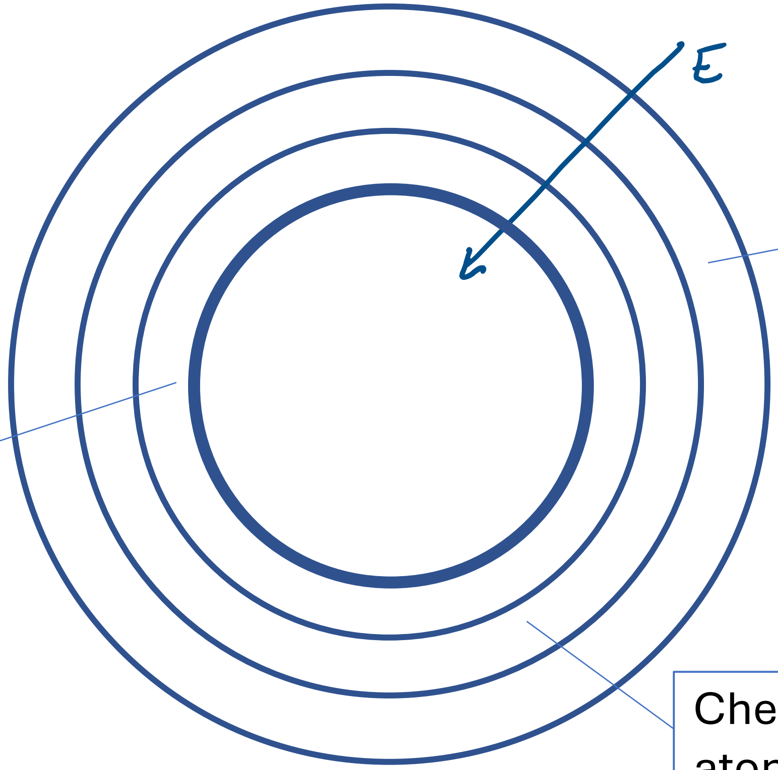
Effective theory at each energy scale E is **predictive** as a **self-contained** theory at that scale



Naturalness is still a fundamental problem

- *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



Planetary dynamics, thermodynamics, fluid dynamics, …

Strong / weak interactions, …

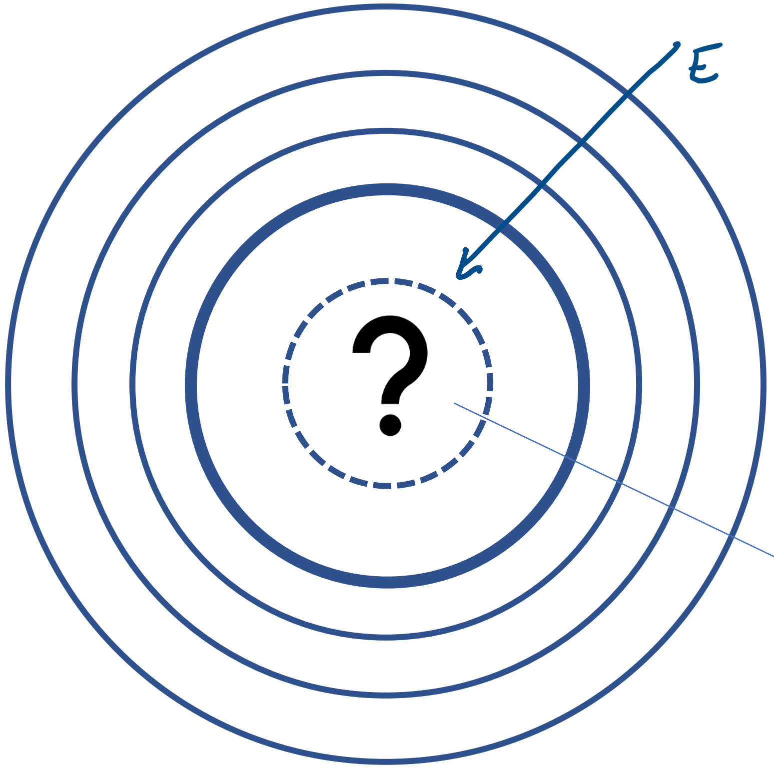
Chemistry, atomic physics, nuclear physics, …

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

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

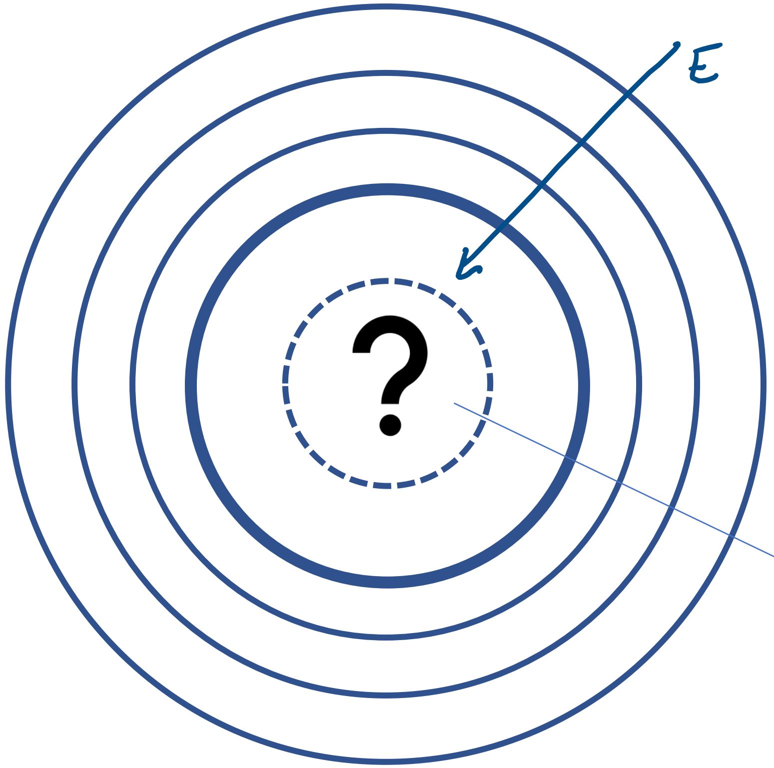


Unnatural Higgs means the next layer *is no longer predictive* without including contributions *from much smaller scales*

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

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

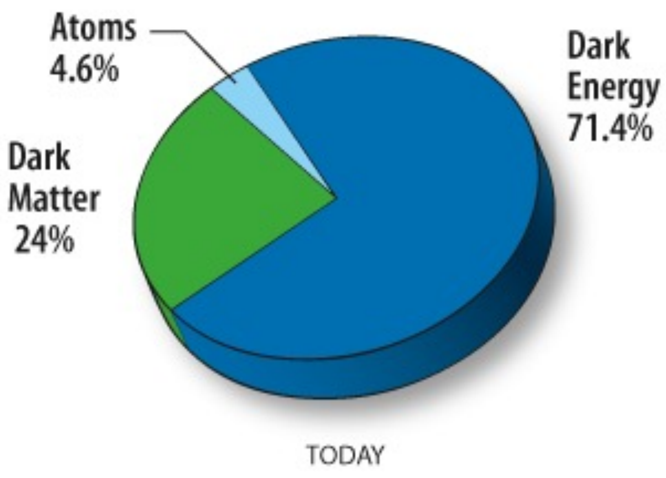


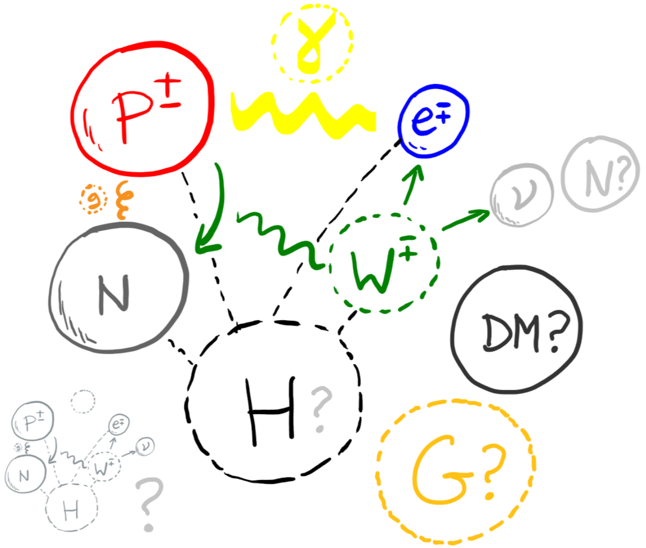
Unnatural Higgs means the next layer *is no longer predictive* without including contributions *from much smaller scales*

- 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

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

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

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

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.

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

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.

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!

Problems of the SM

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%.

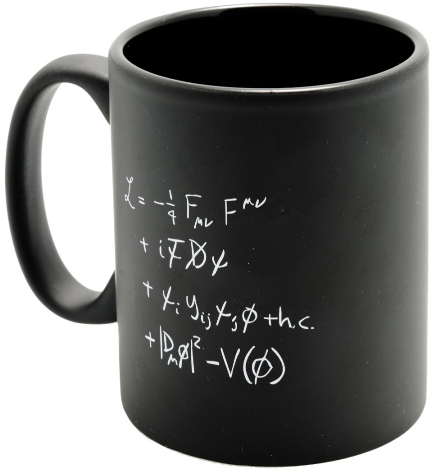
Note for the experts: in the SM the Higgs mass is a parameter to be measured, not calculated. What the quadratic divergence represents (independently of the choice of renormalisation scheme) is the fine-tuning in an underlying theory in which we expect the Higgs mass to be calculable.

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.

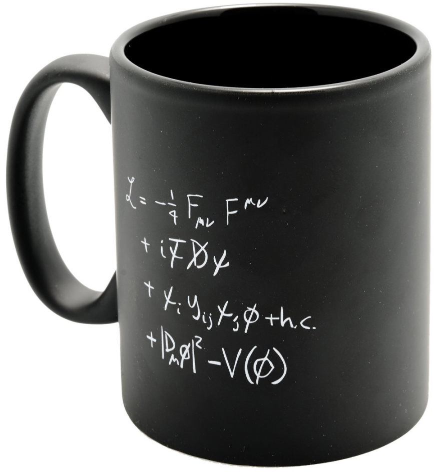


Conclusion

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!



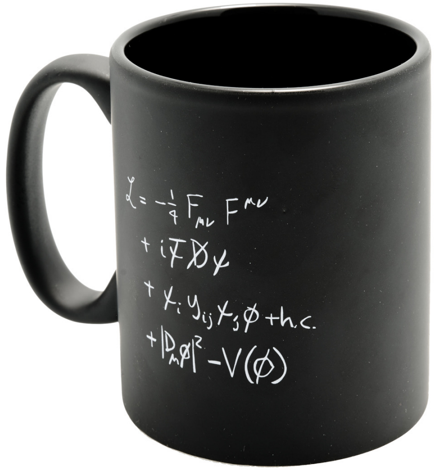
Conclusion

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.



Lecture 2

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"

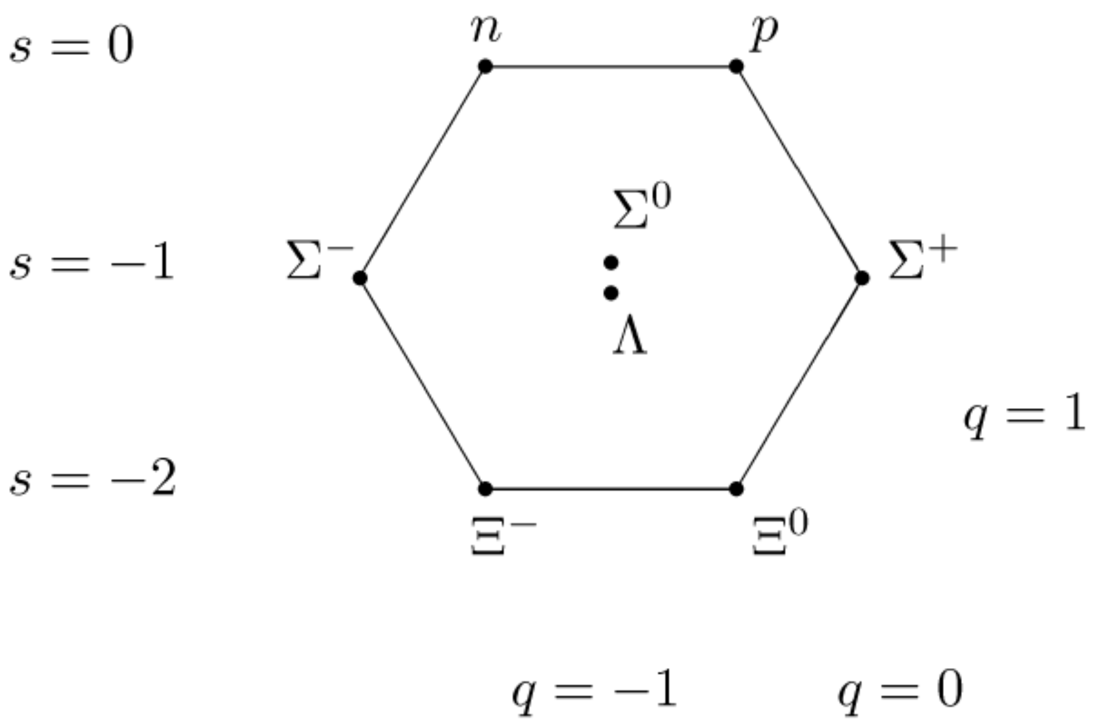
Gell-Mann stated this maxim in relation to quantum mechanics summing over all allowed possibilities.

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

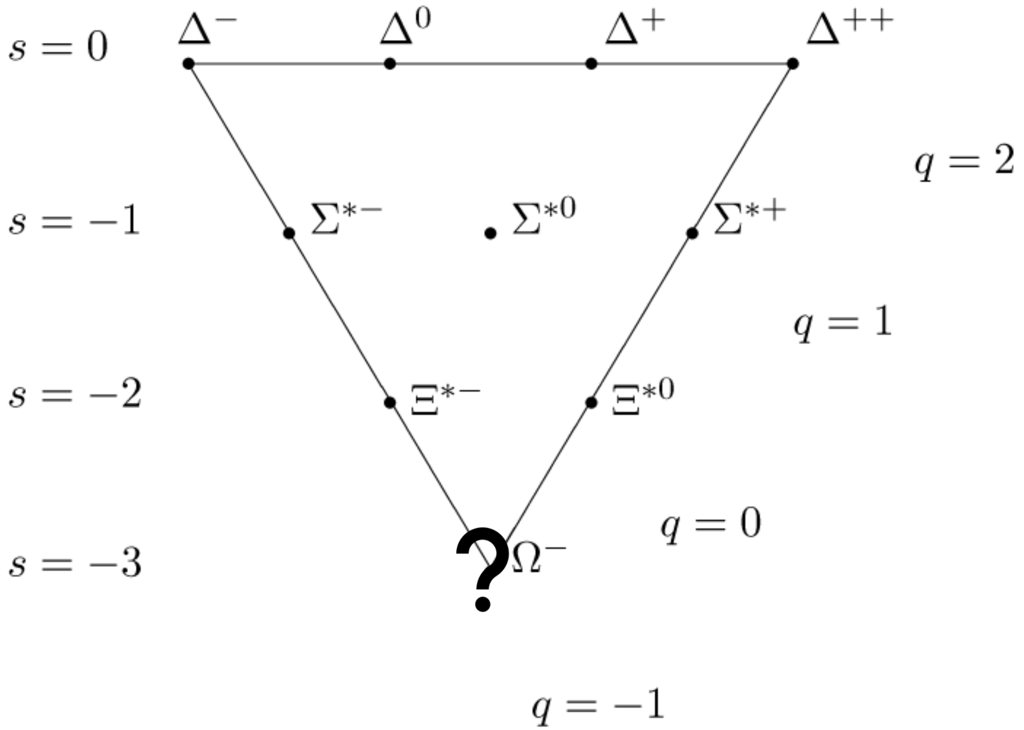
In 1961, Gell-Mann and Ne'eman noticed that hadrons could be organized in a pattern according to their "strangeness" number, s, and electromagnetic charge, q.



Spin ½ baryon octet

Example: the Eightfold way

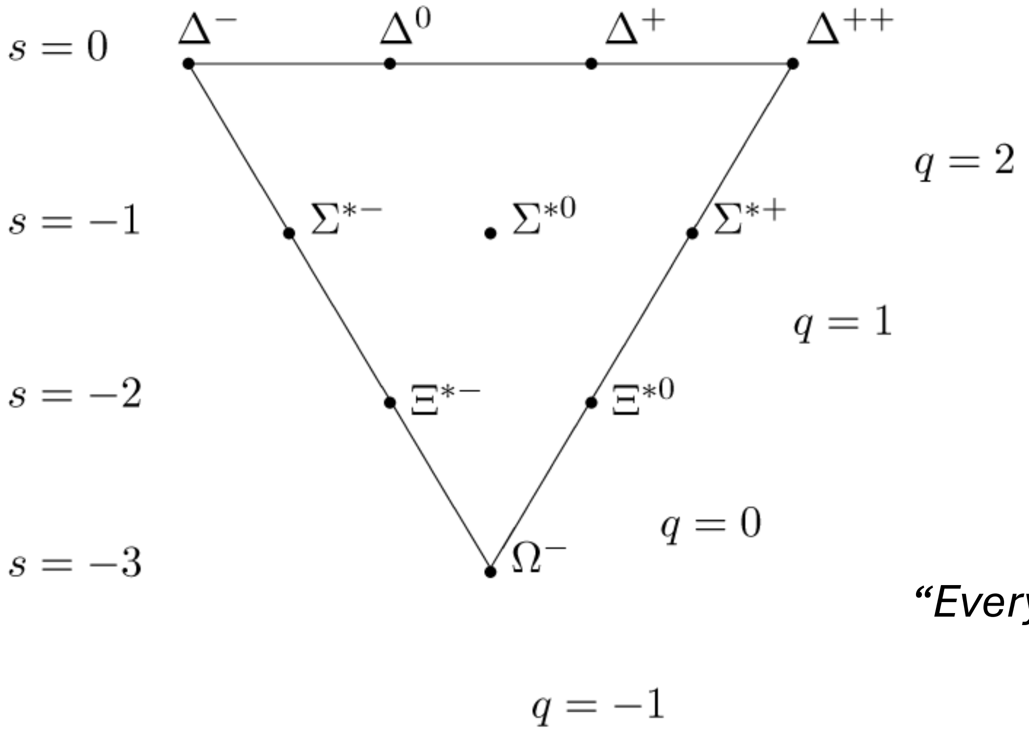
Only one baryon was missing. It would be *extremely strange* (pun not intended) if it weren't there.



Spin 3/2 baryon decuplet

Example: the Eightfold way

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



"Everything not forbidden is compulsory"

Spin 3/2 baryon decuplet

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
ϕ	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$

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

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

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	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$

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

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

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

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

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

Operator dimension = mass dimension in natural units

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

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

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

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**	$\frac{1}{6}$

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

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

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

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

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

"dimensions of"

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

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

$[dt\,dx\,dy\,dz] = M^{-4}$

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

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

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

The Standard Model as an Effective Field Theory

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	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$

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

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

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

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

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

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	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$
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	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$

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

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

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

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

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

“Everything not forbidden is compulsory”

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

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
ϕ	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$

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

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

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

? **Strong-CP problem**

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

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

"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.

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

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

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

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

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

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.

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

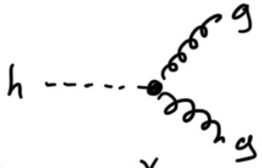
$$\ldots_R + \bar{L}_L i\gamma^\mu D^L_\mu L_L + \bar{l}_R i\gamma^\mu D^R_\mu l_R$$

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

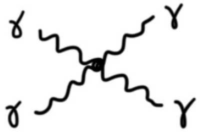
$$\ldots_L \bar{L}_L \phi l_R + \text{h.c.} \quad ,$$

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

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



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

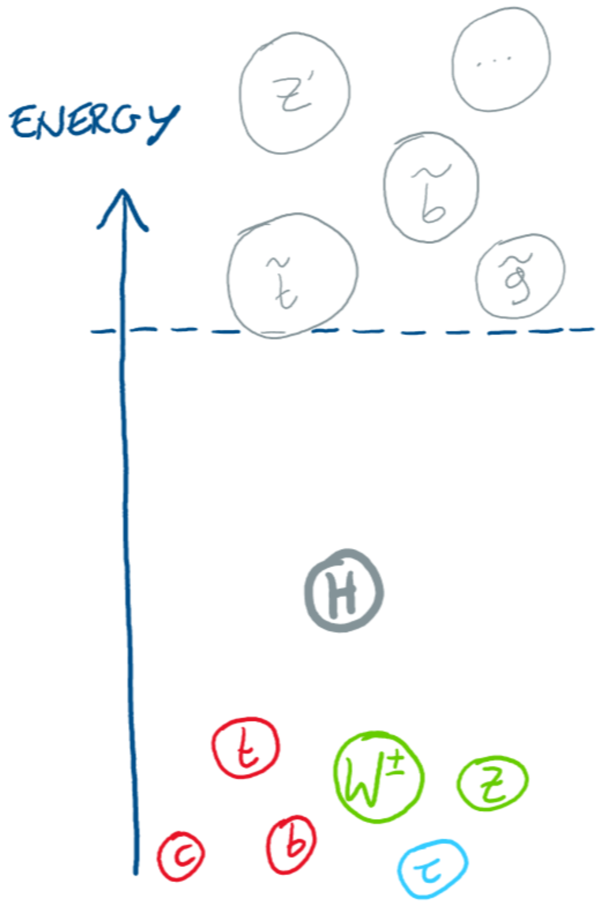


Including operators of **mass dimension** $>$ **4**! This is the "*Standard Model Effective Field Theory*".

Tevong You

The Standard Model as an Effective Field Theory

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



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

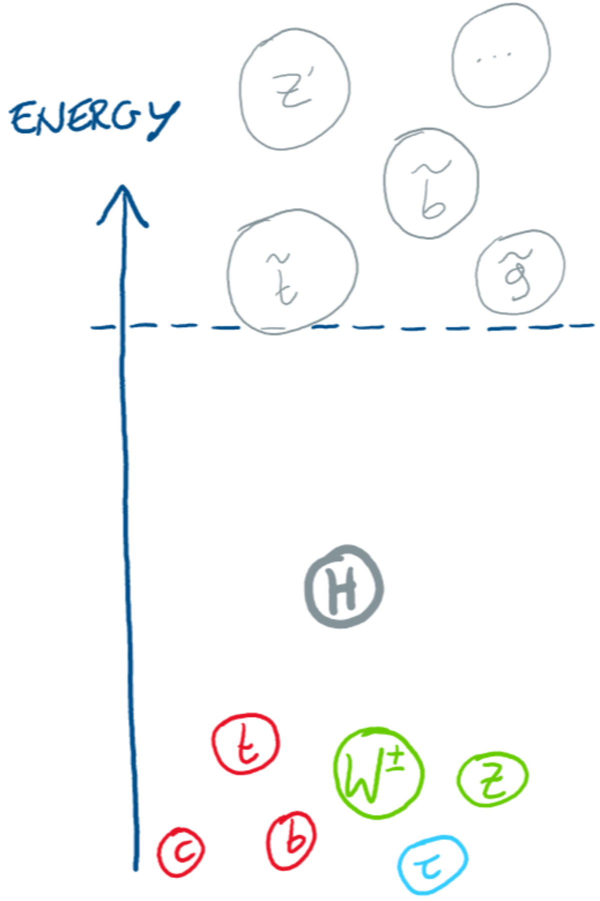
$$\mathcal{L}_{SM} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y \quad ,$$

$$\mathcal{L}_m = \bar{Q}_L i\gamma^\mu D_\mu^L Q_L + \bar{q}_R i\gamma^\mu D_\mu^R q_R + \bar{L}_L i\gamma^\mu D_\mu^L L_L + \bar{l}_R i\gamma^\mu D_\mu^R l_R$$
$$\mathcal{L}_G = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W_{\mu\nu}^a W^{a\mu\nu}$$
$$\mathcal{L}_H = (D_\mu^L \phi)^\dagger (D^{L\mu}\phi) - V(\phi)$$
$$\mathcal{L}_Y = y_d \bar{Q}_L \phi q_R^d + y_u \bar{Q}_L \phi^c q_R^u + y_L \bar{L}_L \phi l_R + \text{h.c.} \quad ,$$

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 $\boldsymbol{\Lambda}$

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

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

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

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

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

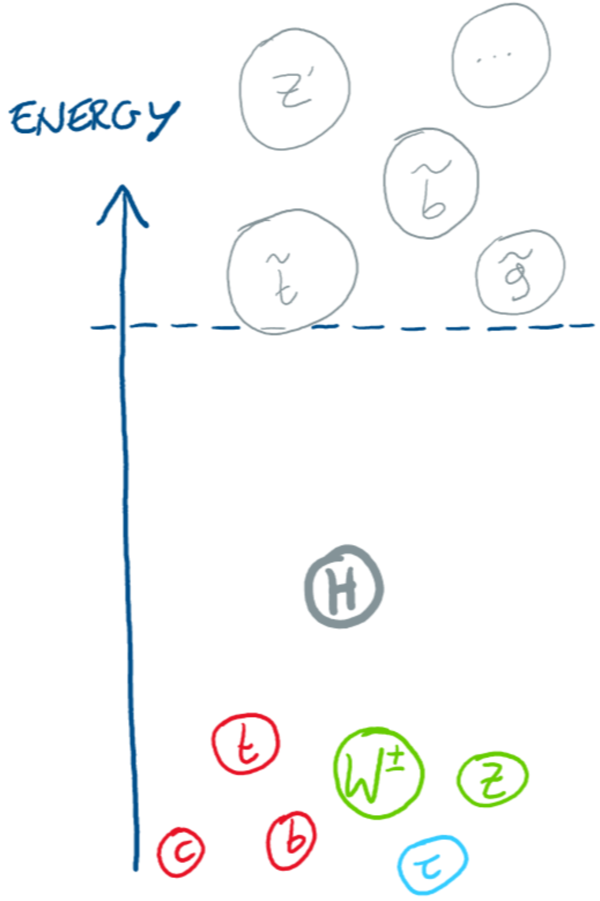
$$\mathcal{L}_Y = y_d\bar{Q}_L\phi q^d_R + y_u\bar{Q}_L\phi^c q^u_R + y_L\bar{L}_L\phi l_R + \text{h.c.} \quad ,$$

Symmetries control sizes of parameters – *naturalness expectations*.

Tevong You

The Standard Model as an 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**, $\boldsymbol{c_i}$?

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

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

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

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

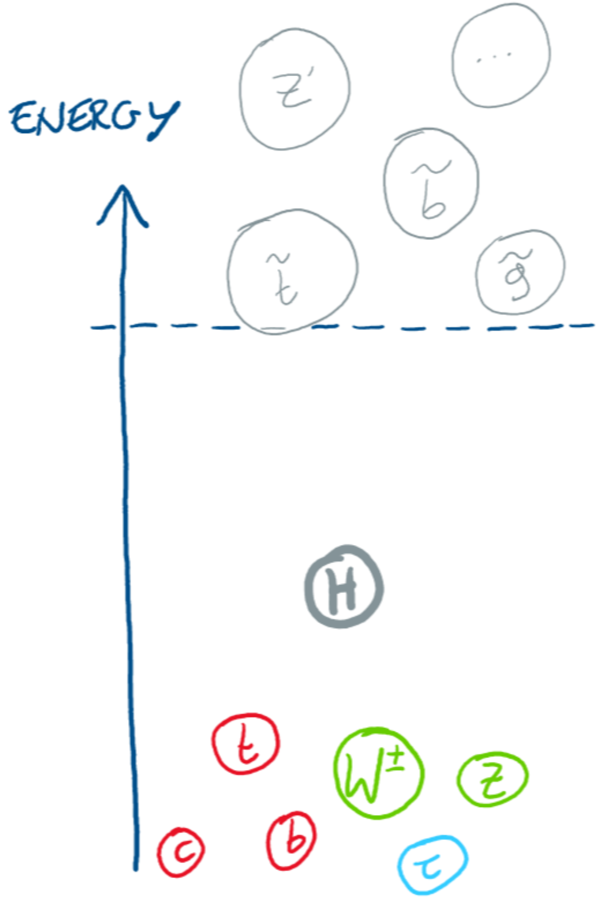
$$\mathcal{L}_H = (D^L_\mu\phi)^\dagger(D^{L\mu}\phi) - V(\phi)$$

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

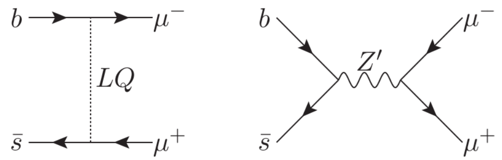
Symmetries control sizes of parameters – *naturalness expectations*.

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**, $\boldsymbol{c_i}$?

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

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

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

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

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

Symmetries control sizes of parameters – *naturalness expectations.*

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		ψ^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		ψ^2XH		ψ^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			
$\mathcal{O}_{ledq}$	$(\bar{l}^j_p e_r)(\bar{d}_s q^j_t)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(q^{\gamma j}_s)^T C l^k_t\right]$		
$\mathcal{O}^{(1)}_{quqd}$	$(\bar{q}^j_p u_r)\varepsilon_{jk}(\bar{q}^k_s d_t)$	$\mathcal{O}_{qqu}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(u^\gamma_s)^T C e_t\right]$		
$\mathcal{O}^{(8)}_{quqd}$	$(\bar{q}^j_p T^A u_r)\varepsilon_{jk}(\bar{q}^k_s T^A d_t)$	$\mathcal{O}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$		
$\mathcal{O}^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\varepsilon_{jk}(\bar{q}^k_s u_t)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(u^\gamma_s)^T C e_t\right]$		
$\mathcal{O}^{(3)}_{lequ}$	$(\bar{l}^j_p\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}^k_s\sigma^{\mu\nu}u_t)$				

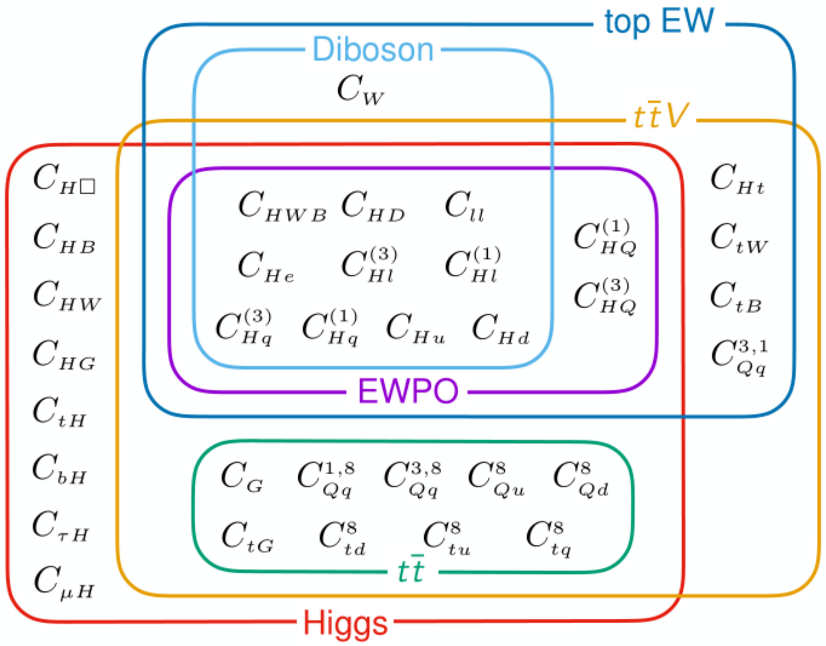
Tevong You

The Standard Model as an Effective Field Theory

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



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

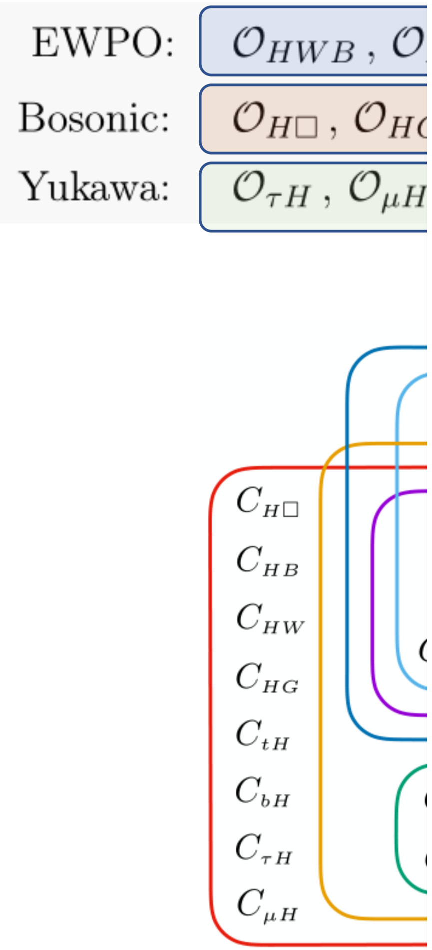
X^2H^2		ψ^2XH		ψ^2H^2D	
$\mathcal{O}_{HG}$	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I H W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$
$\mathcal{O}_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$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

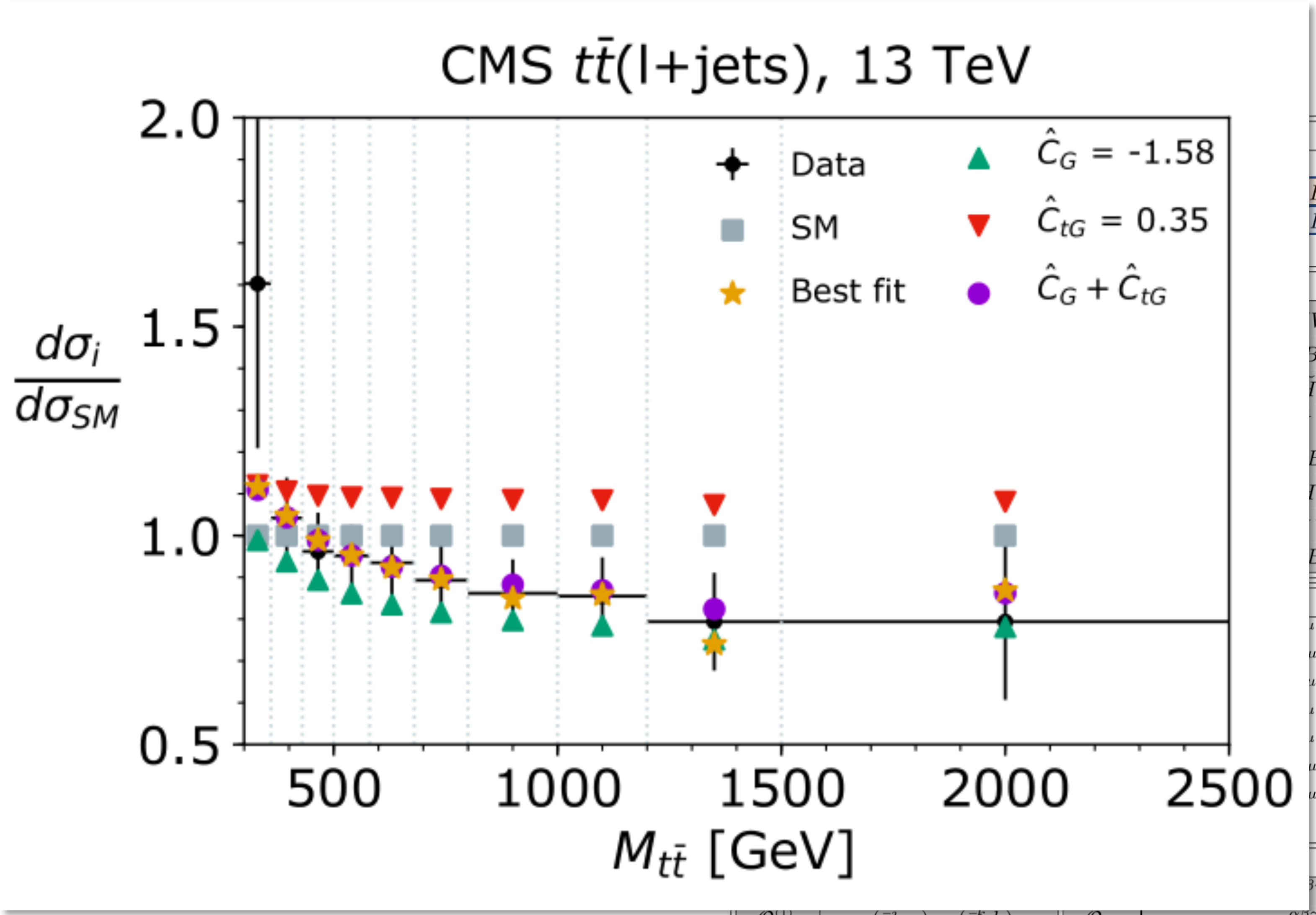
$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{ll}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}^{(1)}_{qq}$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

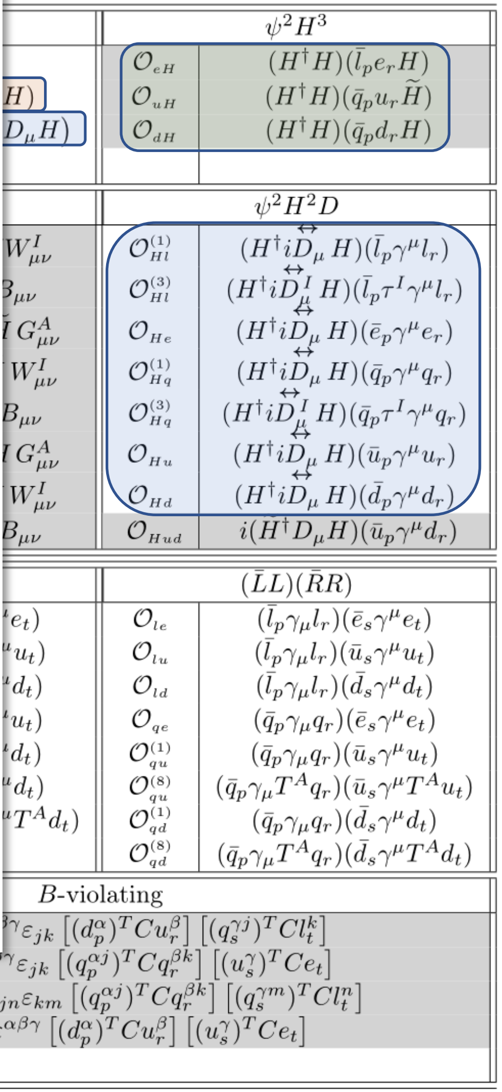
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
$\mathcal{O}_{ledq}$	$(\bar{l}^j_p e_r)(\bar{d}_s q^j_t)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(q^{\gamma j}_s)^T C l^k_t\right]$
$\mathcal{O}^{(1)}_{quqd}$	$(\bar{q}^j_p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

Constrained by global fit to experimental data.

The Standard Model as an Effective Field Theory





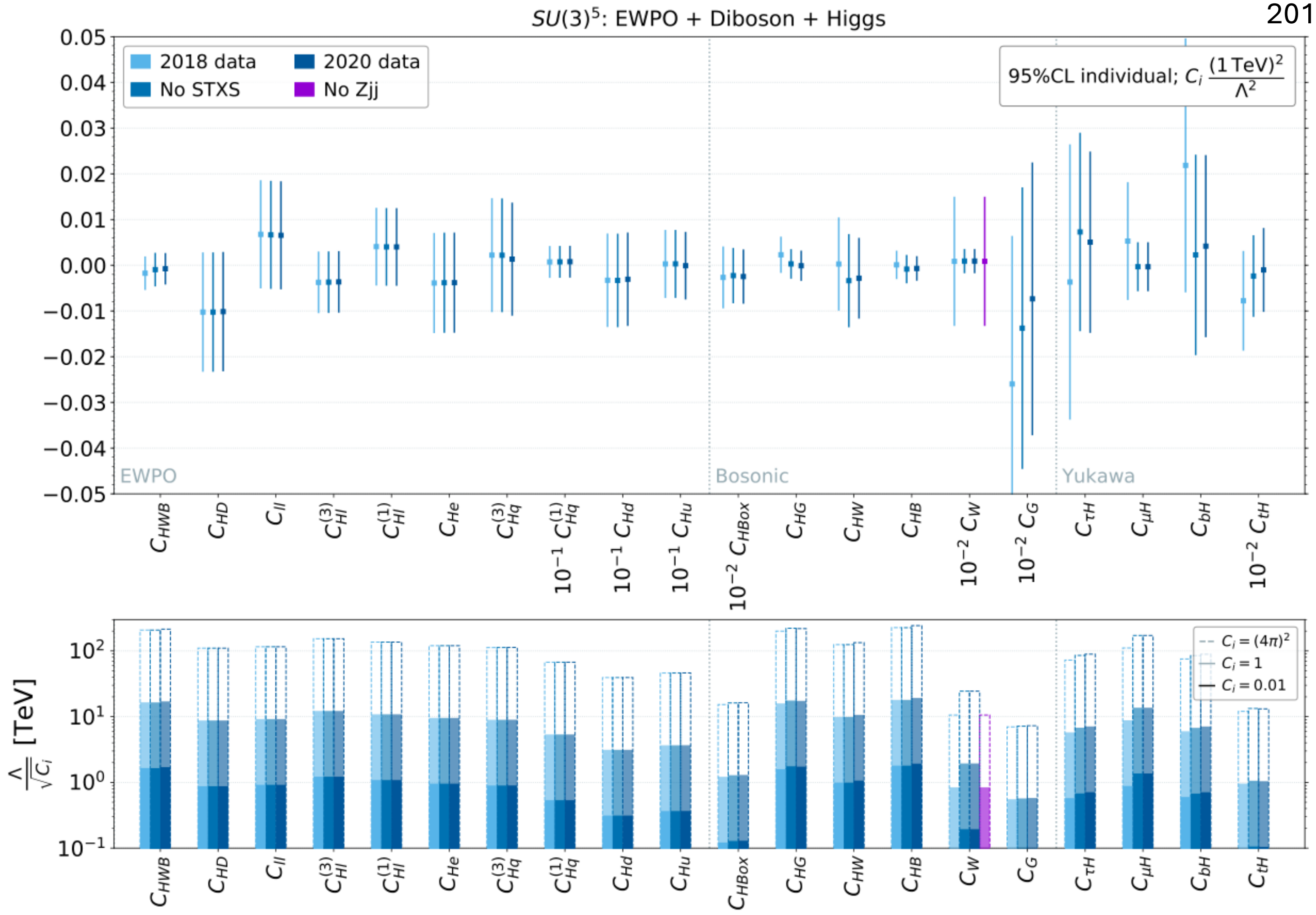


Constrained by global fit to experimental data. e.g. top data

Tevong You

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

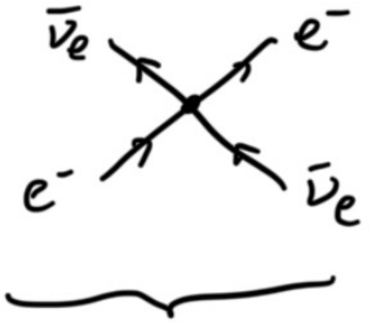
Indirect evidence preceded direct discovery for nearly all SM particles. May be true of BSM!

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.

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



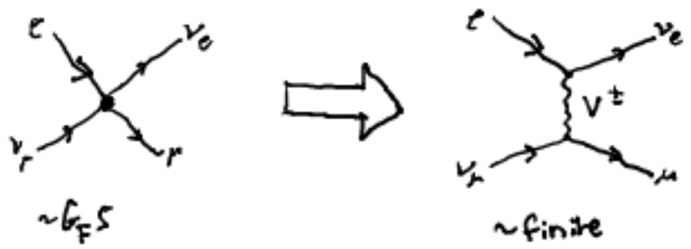
$2 \to 2$ scattering amplitude is dimensionless: $[\mathcal{A}_{2\to 2}] = 0$

$$\Rightarrow \quad \mathcal{A}_{e^-\bar{\nu}_e \to e^-\bar{\nu}_e} \sim \frac{c}{\Lambda^2} E^2$$

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.

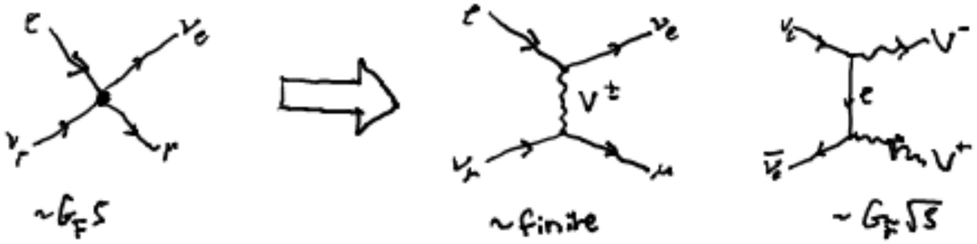


By analogy with photon of QED, add spin 1 intermediate vector boson (with mass and charge).

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.

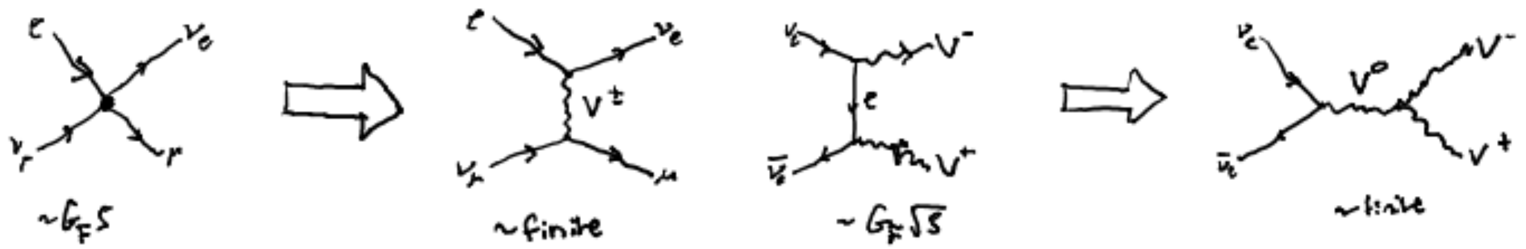


Makes scattering process finite, but introduces another process with divergent energy growth.

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.

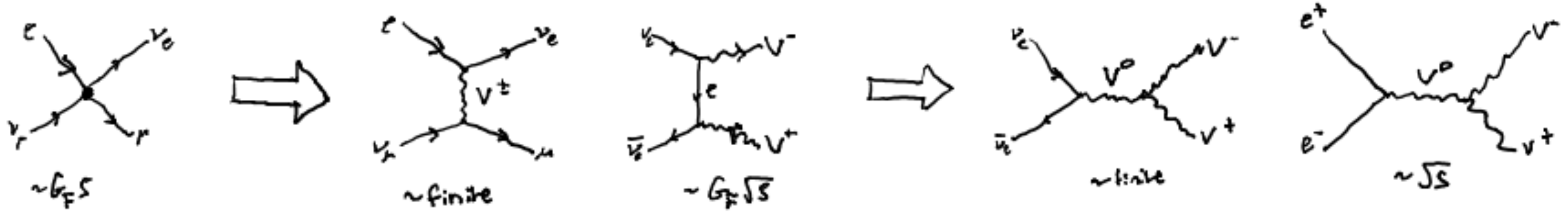


Add neutral spin 1 vector boson with appropriate couplings to make this scattering process finite.

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.

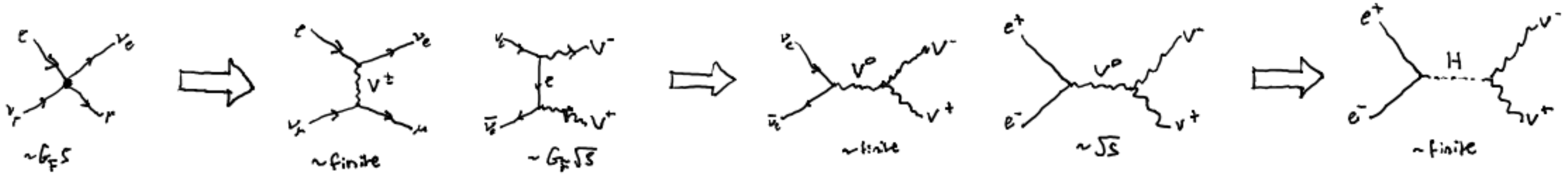


But another amplitude now grows unbounded with energy.

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.

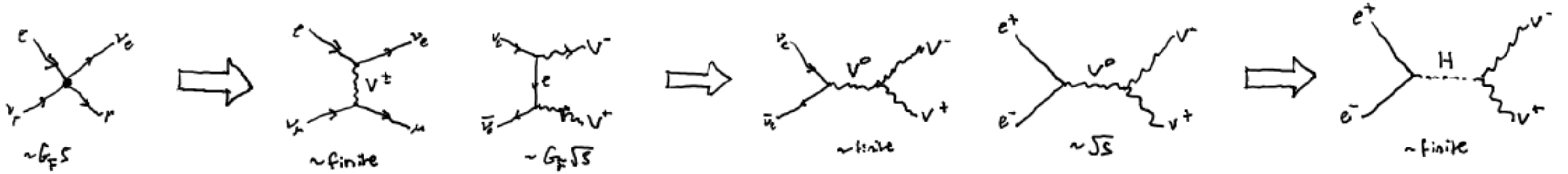


Add a scalar spin 0 boson.

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.

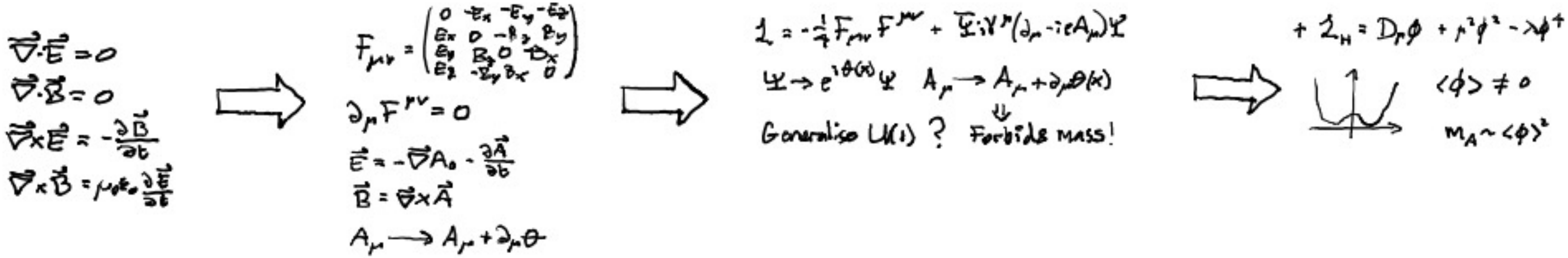


Adding spin 1 and spin 0 particles with couplings fixed to cancel divergent energy contributions *recovers the Standard Model theory* of non-Abelian gauge bosons and Higgs mechanism!

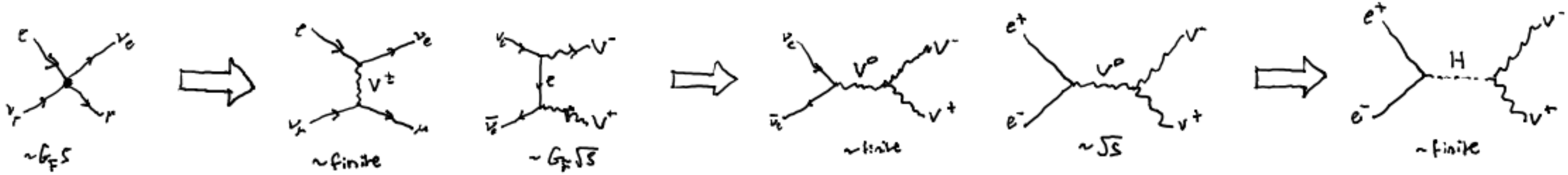
Without the Higgs, the theory breaks down around 1 TeV: **LHC guaranteed to discover something new**.

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.

Lecture 3

Outline

Today

1. Neutrino masses
2. Grand Unified Theories
3. WIMP dark matter
4. Supersymmetry

Neutrino masses

Neutrino oscillations imply neutrinos have mass.

The **Standard Model** does not allow a mass term for neutrinos to be written down.

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

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

Neutrino masses

Neutrino oscillations imply neutrinos have mass.

The **Standard Model** does not allow a mass term for neutrinos to be written down.

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

$$\begin{aligned}
\mathcal{L}_m &= \bar{Q}_L i\gamma^\mu D_\mu^L Q_L + \bar{q}_R i\gamma^\mu D_\mu^R q_R + \bar{L}_L i\gamma^\mu D_\mu^L L_L + \bar{l}_R i\gamma^\mu D_\mu^R l_R \\
\mathcal{L}_G &= -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W_{\mu\nu}^a W^{a\mu\nu} \\
\mathcal{L}_H &= (D_\mu^L\phi)^\dagger(D^{L\mu}\phi) - V(\phi) \\
\mathcal{L}_Y &= y_d\bar{Q}_L\phi q_R^d + y_u\bar{Q}_L\phi^c q_R^u + y_L\bar{L}_L\phi l_R + \text{h.c.} \qquad ,
\end{aligned}$$

The **Standard Model Effective Field Theory**, on the other hand, enables more operator combinations at higher mass dimensions.

When the Higgs gets a vacuum expectation value, these could generate a dimension 2 neutrino mass term.

Neutrino masses

The Standard Model EFT has a *unique* dimension 5 operator – **the Weinberg operator**.

$$\mathcal{L}_{\text{dim-5}} = \frac{c_5}{\Lambda}(\bar{L} H^c)(L^c H^c)$$

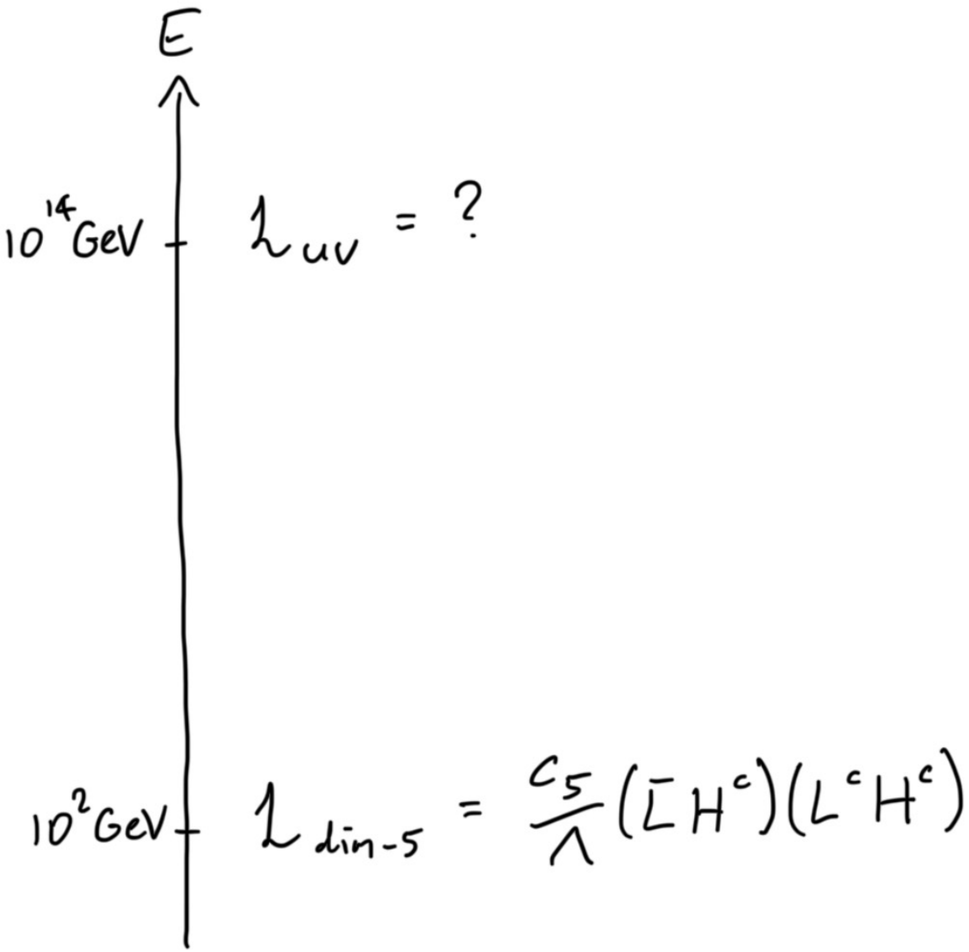
After electroweak symmetry breaking, when the Higgs gains a non-zero vacuum expectation value, the Weinberg operator **gives neutrinos a small mass** suppressed by v/Λ.

$$\frac{c_5}{\Lambda}(\bar{L} H^c)(L^c H^c) \xrightarrow[\langle H \rangle \sim v]{} m_\nu = \frac{c_5}{\Lambda} v^2$$

For $m_\nu \sim 0.1$ eV, if $c_5 \sim O(1)$ then expect new physics that generates this operator to be at $\boldsymbol{\Lambda \sim 10^{14}}$ **GeV**.

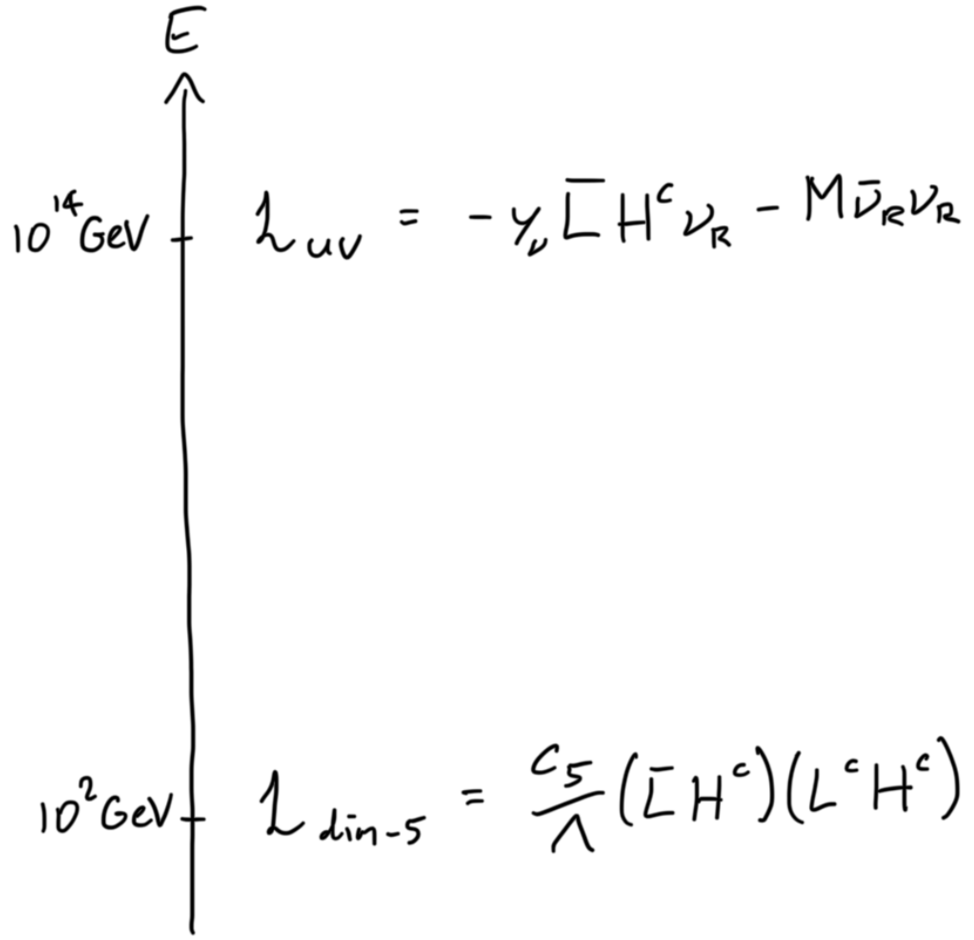
Neutrino masses

What kind of **new physics** could generate the Weinberg operator?



Neutrino masses

Add a new completely *neutral* fermion $\boldsymbol{\nu_R}$ to the SM particle content.



Neutrino masses

Add a new completely *neutral* fermion $\boldsymbol{\nu_R}$ to the SM particle content.

E

10^{14} GeV

$$\mathcal{L}_{UV} = -y_\nu \bar{L} H^c \nu_R - M \bar{\nu}_R \nu_R$$

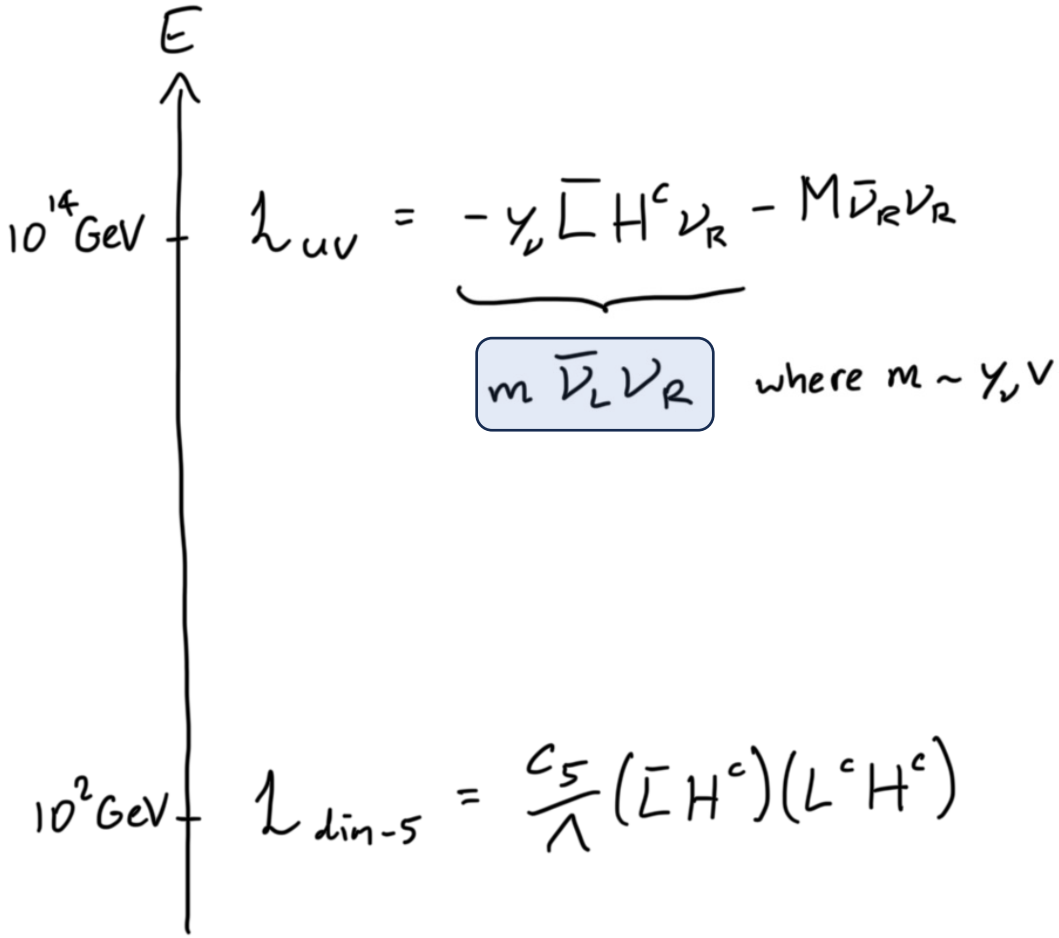
10^{2} GeV

$$\mathcal{L}_{dim\text{-}5} = \frac{c_5}{\Lambda} (\bar{L} H^c)(L^c H^c)$$

Note that it already has a mass M that we fix to be $\sim 10^{14}$ GeV.

Neutrino masses

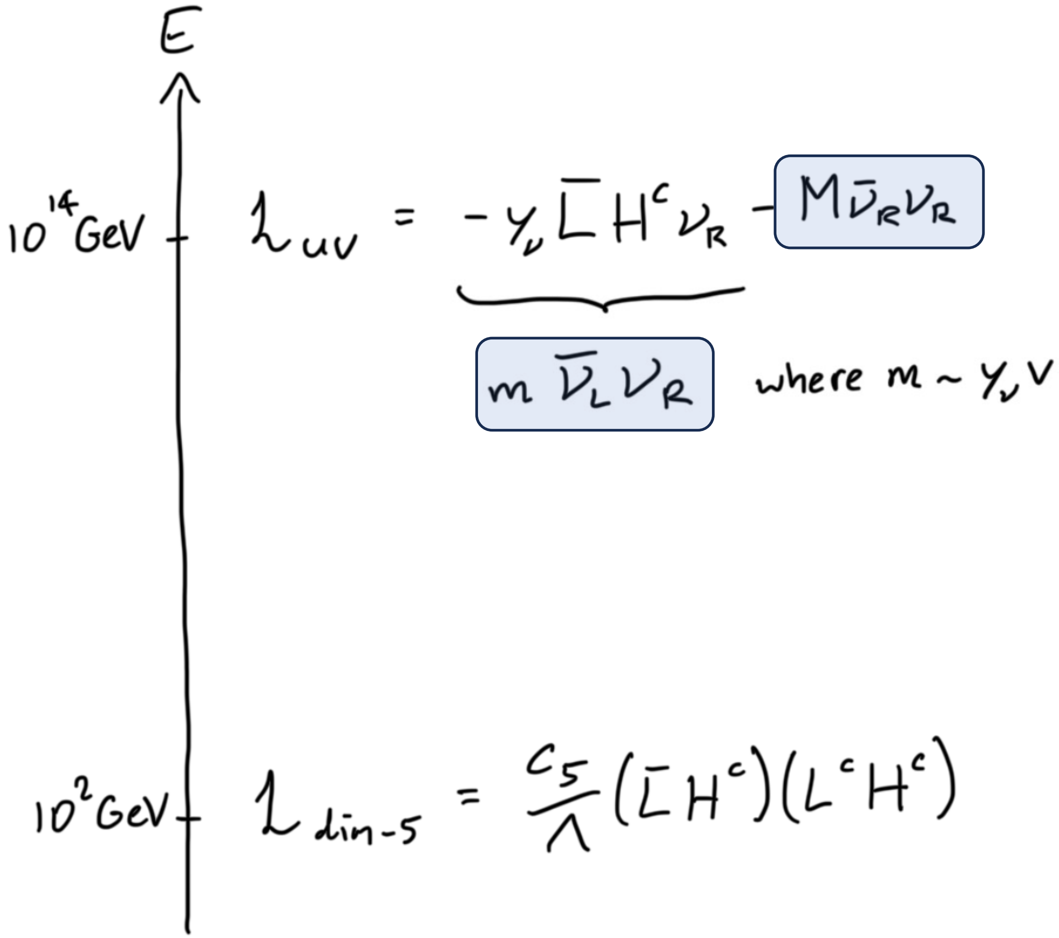
Add a new completely *neutral* fermion $\boldsymbol{\nu_R}$ to the SM particle content.



After electroweak symmetry breaking, the **Higgs yukawa coupling** generates *another neutrino mass* term.

Neutrino masses

Add a new completely *neutral* fermion $\boldsymbol{\upsilon_R}$ to the SM particle content.



We diagonalise the 2 x 2 mass matrix in the Lagrangian to obtain the **physical mass eigenstates**.

Neutrino masses

Add a new completely *neutral* fermion $\boldsymbol{\nu_R}$ to the SM particle content.

$$\mathcal{L}_{\text{see-saw}} \supset -m\bar{\nu}_L \nu_R - M\bar{\nu}_R \nu_R + \text{h.c.}$$

$$= -(\bar{\nu}_L, \bar{\nu}_R)\begin{pmatrix} 0 & m \\ m & M \end{pmatrix}\begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

$$= -(\bar{\nu}, \bar{N})\begin{pmatrix} m_\nu & 0 \\ 0 & M_N \end{pmatrix}\begin{pmatrix} \nu \\ N \end{pmatrix}$$

where

$$m_\nu = \frac{1}{2}\left(M - \sqrt{M^2 + 4m^2}\right) \simeq -\frac{m^2}{M} \qquad M_N = \frac{1}{2}\left(M + \sqrt{M^2 + 4m^2}\right) \simeq M$$

when $M \gg m$.

We diagonalise the 2 x 2 mass matrix in the Lagrangian to obtain the **physical mass eigenstates**.

Neutrino masses

Add a new completely *neutral* fermion $\boldsymbol{\nu_R}$ to the SM particle content.

$$\mathcal{L}_{\text{see-saw}} \supset -m\bar{\nu}_L\nu_R - M\bar{\nu}_R\nu_R + \text{h.c.}$$

$$= -(\bar{\nu}_L, \bar{\nu}_R)\begin{pmatrix} 0 & m \\ m & M \end{pmatrix}\begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

$$= -(\bar{\nu}, \bar{N})\begin{pmatrix} m_\nu & 0 \\ 0 & M_N \end{pmatrix}\begin{pmatrix} \nu \\ N \end{pmatrix}$$

where

$$m_\nu = \tfrac{1}{2}\left(M - \sqrt{M^2+4m^2}\right) \qquad M_N = \tfrac{1}{2}\left(M + \sqrt{M^2+4m^2}\right)$$

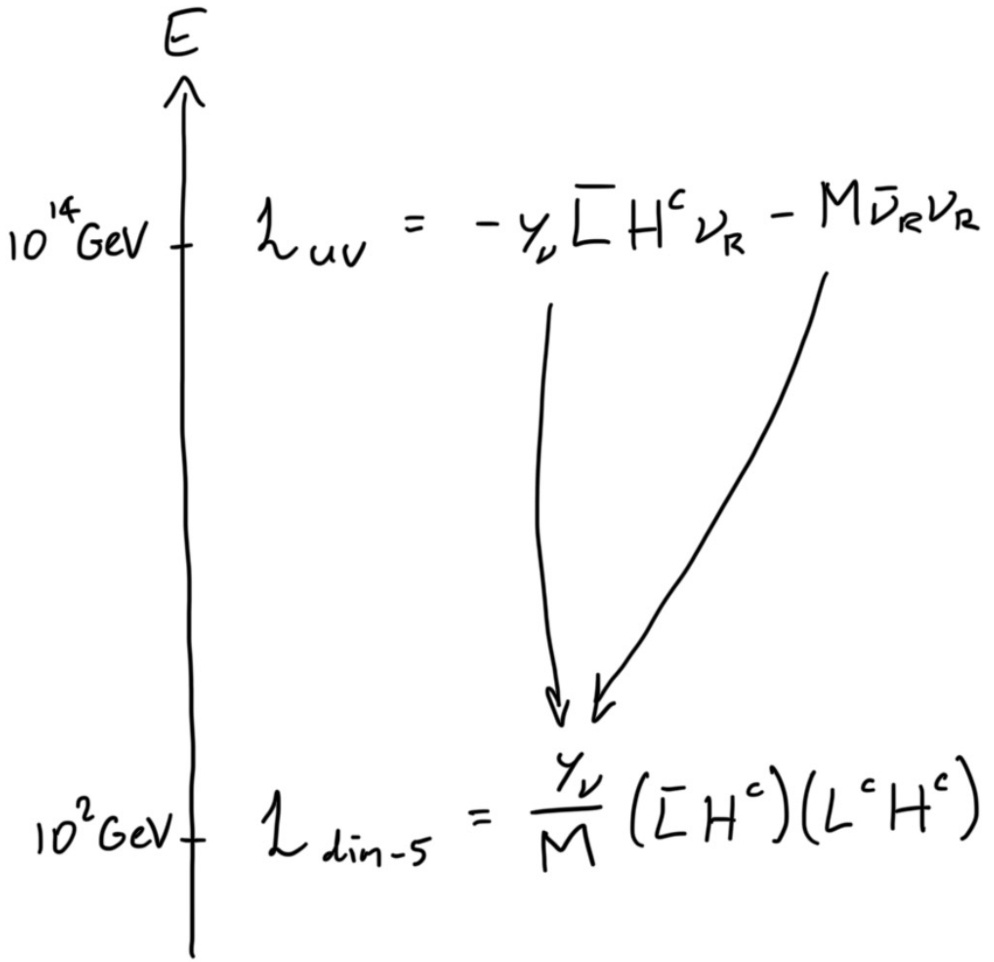
$$\simeq -\frac{m^2}{M} \qquad\qquad \simeq M$$

when $M \gg m$.

We diagonalise the 2 x 2 mass matrix in the Lagrangian to obtain the **physical mass eigenstates**.

Neutrino masses

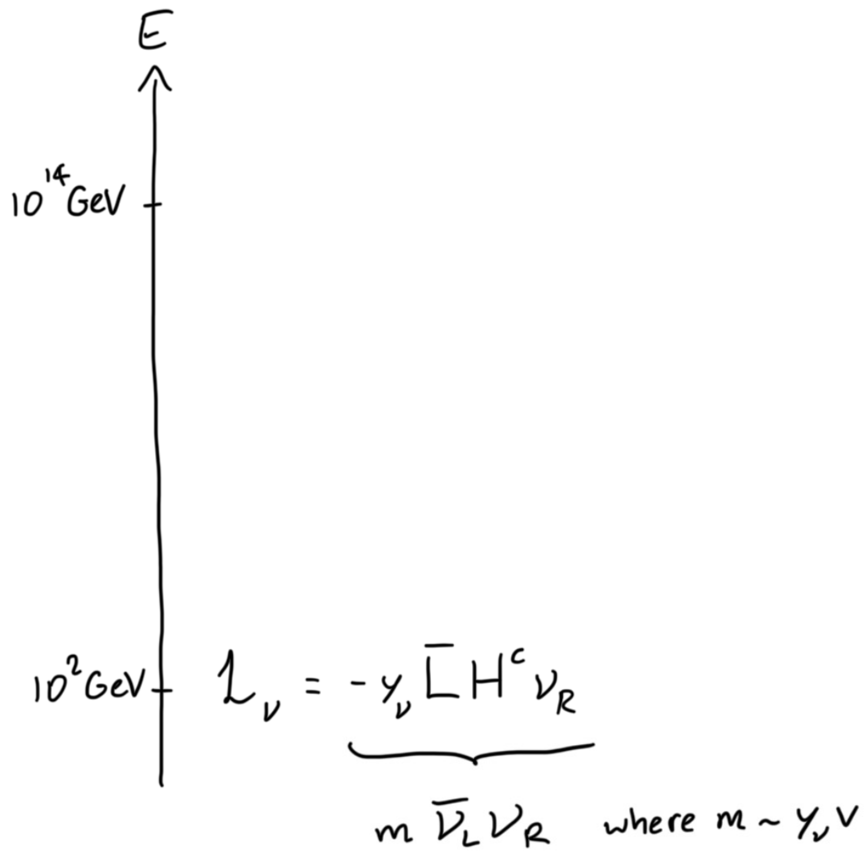
Add a new completely *neutral* fermion $\boldsymbol{\nu_R}$ to the SM particle content.



This UV theory generates the Weinberg operator with $c_5 \sim y_\nu$, $\Lambda \sim M$ in the SM EFT.

Neutrino masses

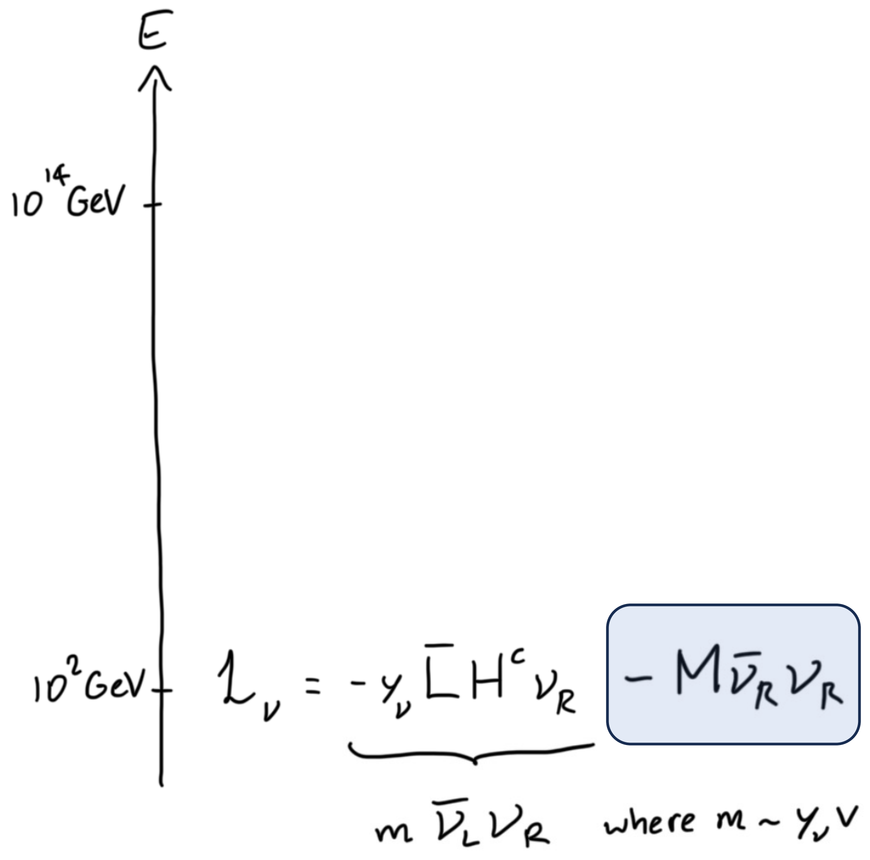
Why didn't we just add the neutral fermion $\boldsymbol{\nu_R}$ with only one mass term through the Yukawa coupling?



With $y_\nu \sim 10^{-12}$ this gives a neutrino mass $m \sim 0.1$ eV as required.

Neutrino masses

Why didn't we just add the neutral fermion $\boldsymbol{\nu_R}$ with only one mass term through the Yukawa coupling?



But the other mass term is **necessarily there**! *"Everything not forbidden is compulsory"*

Lepton number

The Weinberg operator violates a **Lepton number** symmetry that is *accidentally* conserved by operators of mass dimension ≤ 4.

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

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

The Standard Model Effective Field Theory provides *an explanation* for small Lepton number violation.

Baryon number

There exist operators at dimension 6 that violate a **Baryon number** symmetry that is *accidentally* conserved by operators of mass dimension ≤ 4.

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

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

Just like Lepton number violation at dimension 5, Baryon number violation at dimension 6 is expected.

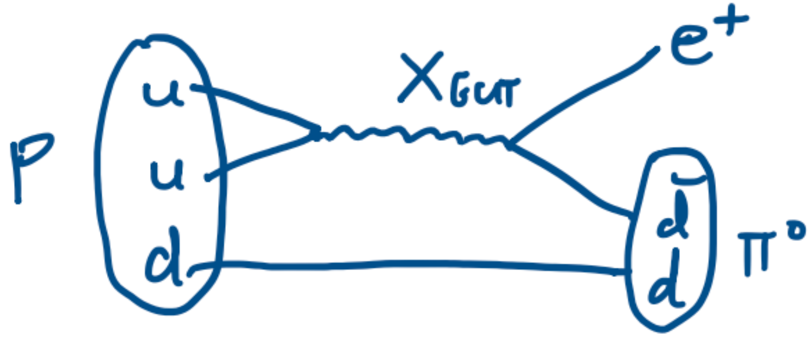
$$\text{e.g. } \mathcal{L}^{\text{dim-6}}_{\not{B}} = \frac{c}{\Lambda^2} \overline{Q}^c_L Q_L \overline{u}^c_R e_R$$

Lack of proton decay in experiments such as Super-Kamiokande implies $\Lambda > 10^{15}$ GeV.

Grand Unified Theories

Grand Unified Theories (GUTs) unify all SU(3) x SU(2) x U(1) into a single GUT group, e.g. SO(10), at higher energies.

Proton decay via a GUT gauge boson is a generic consequence:

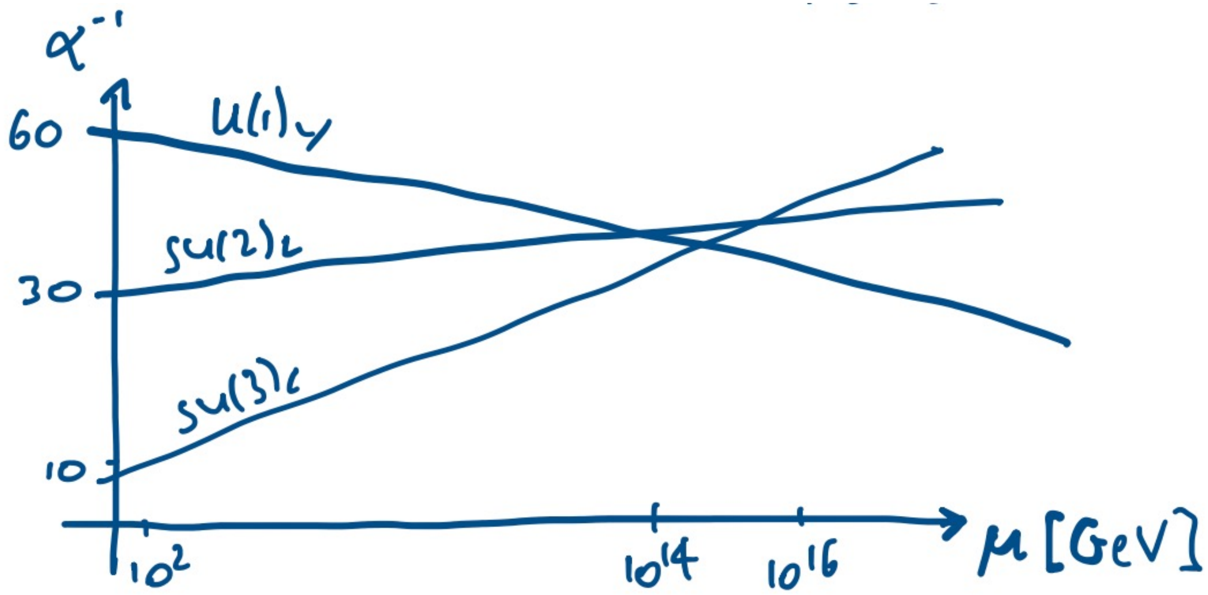


GUT scale must therefore be at least 10^{15} GeV.

Grand Unified Theories

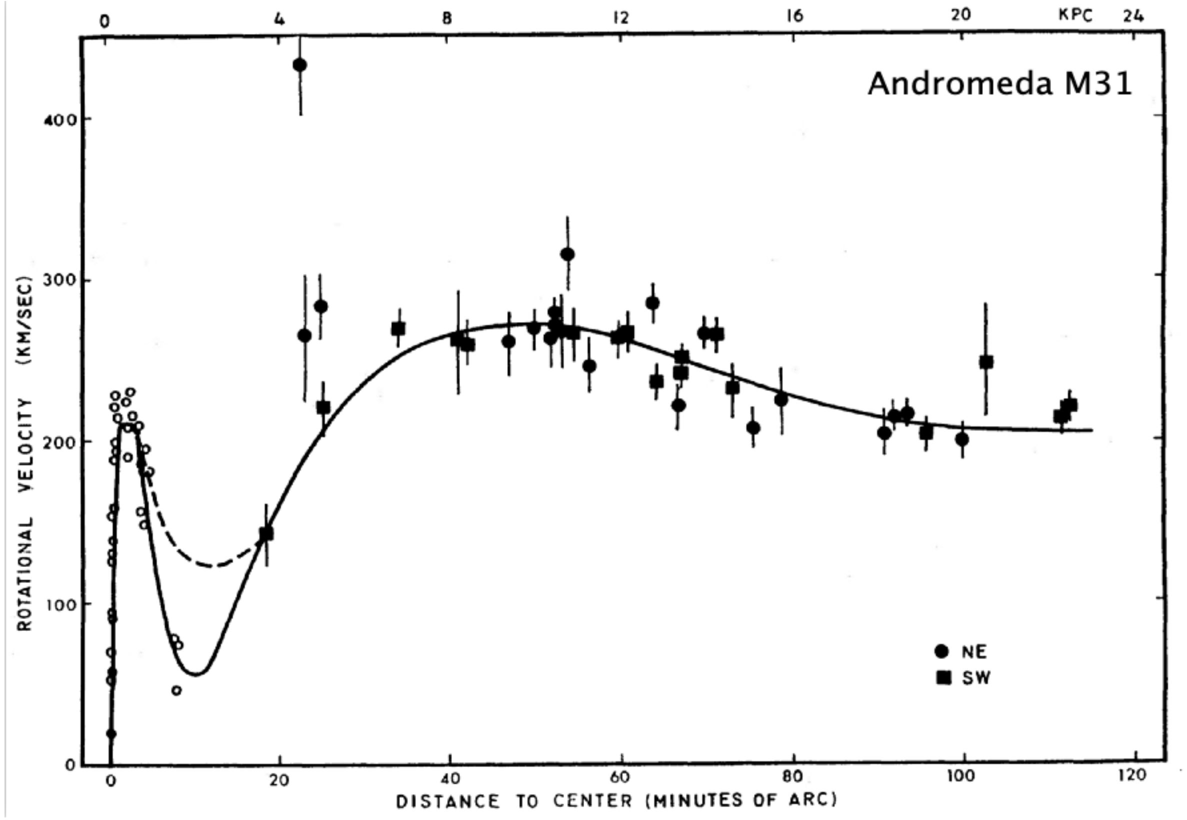
GUTs are desirable rather than necessary. However, there are hints suggesting this may be the case:

- Electroweak unification makes it reasonable to consider unifying the strong force too.
- U(1) hypercharges of SM particles are quantised with fractional charges.
- Standard Model particle content fits neatly into multiplets of GUT group representations.
- Running of gauge couplings suggest they meet at high energy scales ~ 10^{15} GeV (*but not quite*).



Dark Matter

Multiple independent observational evidence for dark matter on all scales:

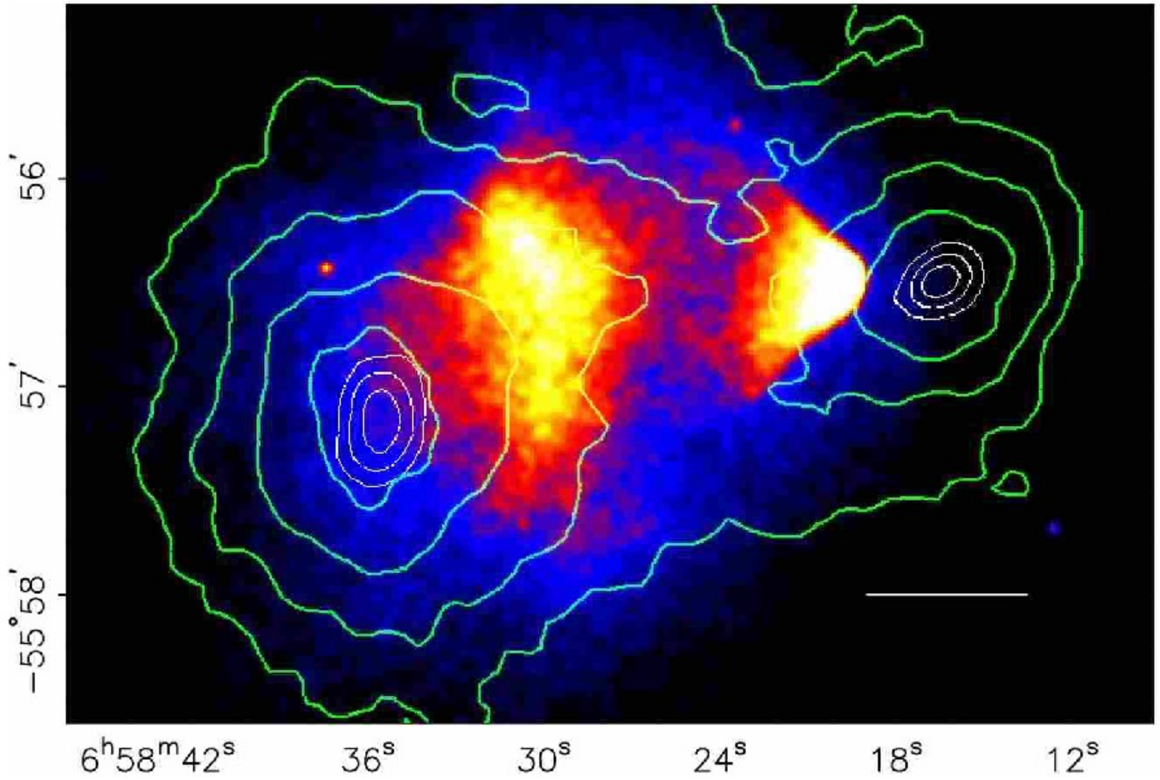


Rubin and Ford 1970

See e.g. 2406.01705 Cirelli, Strumia, Zupan for a comprehensive review.

Dark Matter

Multiple independent observational evidence for dark matter on all scales:

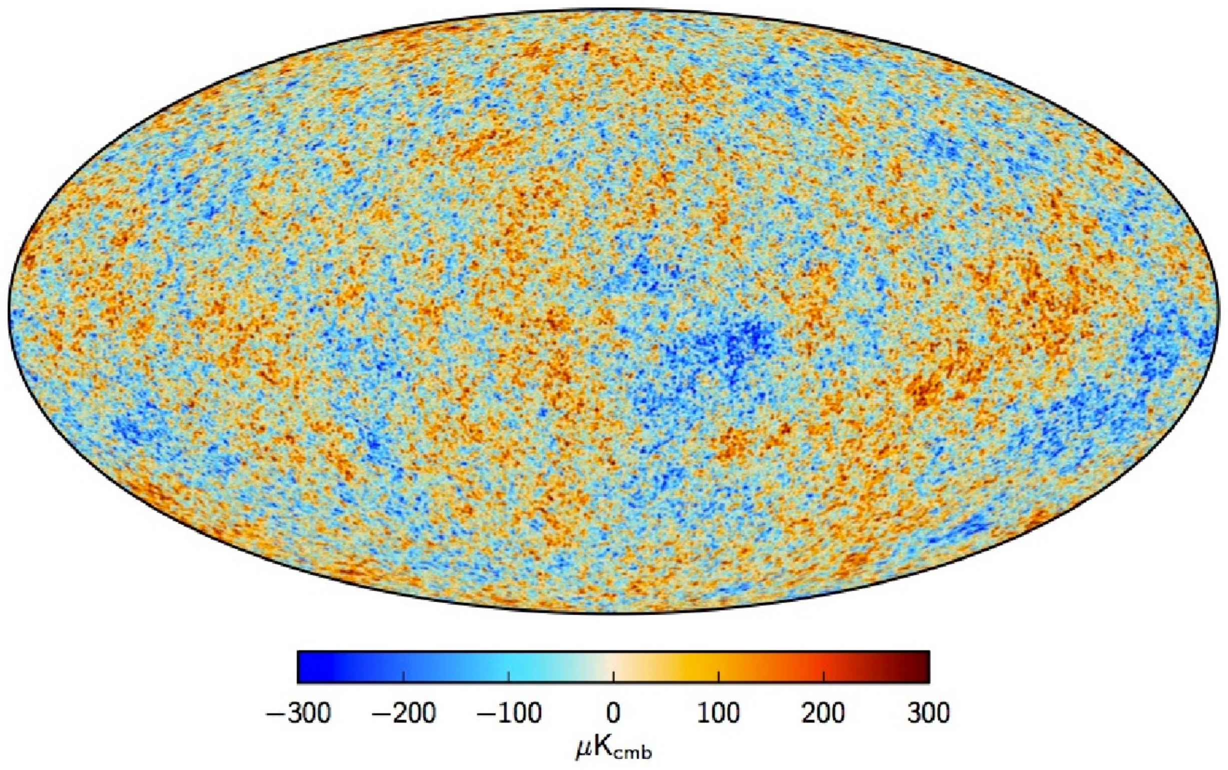


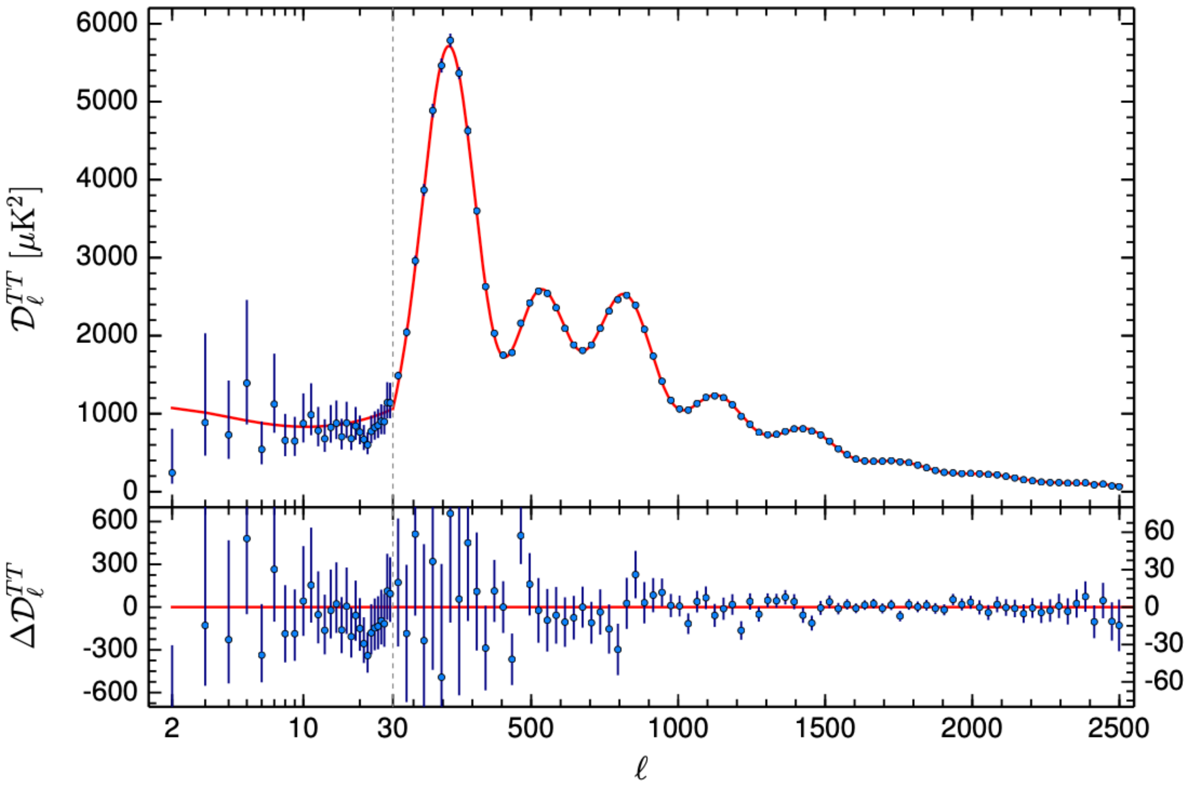
Clowe et al 2006

See e.g. 2406.01705 Cirelli, Strumia, Zupan for a comprehensive review.

Dark Matter

Multiple independent observational evidence for dark matter on all scales:





Planck

See e.g. 2406.01705 Cirelli, Strumia, Zupan for a comprehensive review.

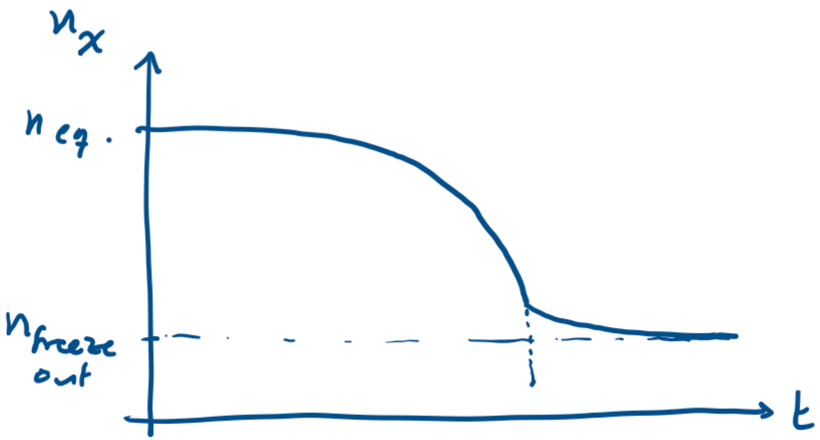
WIMP Dark Matter

Weakly Interacting Massive Particles (WIMP) are a simple candidate for dark matter.

Add to the Standard Model a DM particle χ with mass m and coupling α through which it annihilates.

Its averaged annihilation cross-section is $< \sigma v > \sim \frac{\alpha^2}{m^2}$.

Relic abundance of DM is set by thermal freeze-out as the Universe expands and temperature falls.



$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{eq}^2)$$

WIMP Dark Matter

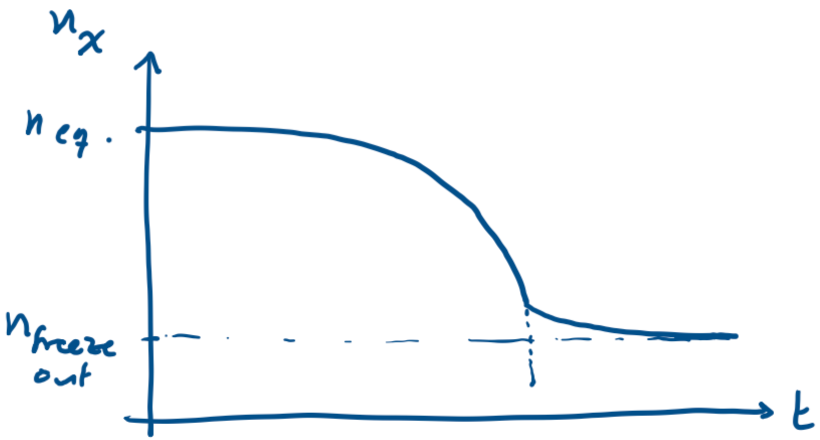
Weakly Interacting Massive Particles (WIMP) are a simple candidate for dark matter.

Add to the Standard Model a DM particle χ with mass m and coupling α through which it annihilates.

Its averaged annihilation cross-section is $< \sigma v > \sim \frac{\alpha^2}{m^2}$.

Relic abundance of DM is set by thermal freeze-out as the Universe expands and temperature falls.

This gives the observed relic abundance for a typical weak coupling with weak-scale mass!



$$\frac{dn}{dt} + 3Hn = -\langle\sigma v\rangle(n^2 - n_{eq}^2)$$

$$\Omega_\chi h^2 \sim \frac{10^{-26}\,\text{cm}^3/\text{s}}{\langle\sigma v\rangle} \simeq 0.1\left(\frac{0.01}{\alpha}\right)^2\left(\frac{m}{100\,\text{GeV}}\right)^2$$

Supersymmetry

Historically, the success of classifying particles into representations of symmetry groups led to a search for a symmetry that included not just matter particles but also the force particles.

Coleman-Mandula theorem: **impossible**.

- Fermions and bosons behave differently under Lorentz transformations.
- A symmetry that interchanges them therefore doesn’t commute with Lorentz generators.
- But internal (non-spacetime) symmetry generators must be Lorentz scalars.

Haag-Lopuzanski-Sohnius: **possible**, *only if the supersymmetry generators are fermionic*.

Supersymmetry is the **unique extension** allowed of spacetime symmetries.

Supersymmetry

Supersymmetrising the Standard Model introduces a *superpartner* for every SM particle – the **Minimal Supersymmetric Standard Model** (MSSM).

<u>Immediate benefits</u>

Fermion superpartners of the Higgs and weak gauge bosons can be WIMP dark matter!

Controls quantum corrections to the Higgs mass to **solve the unnatural fine-tuning problem**:

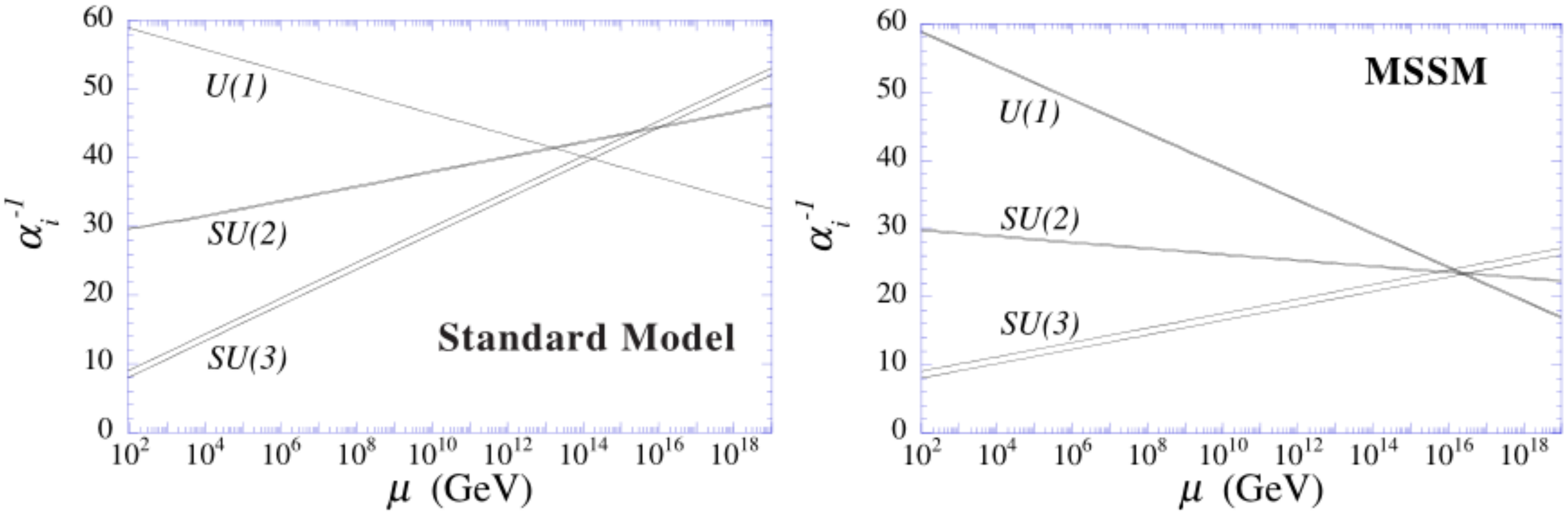
$$\sim -6\,\frac{y_t^2}{4\pi^2}\left(m_{\tilde t}^2 - m_t^2\right)\log\left(\frac{m_{\tilde t}^2}{m_t^2}\right)$$

Supersymmetry

Supersymmetrising the Standard Model introduces a *superpartner* for every SM particle – the **Minimal Supersymmetric Standard Model** (MSSM).

Immediate benefits

Gauge couplings unify at a single GUT scale!



Supersymmetry

Supersymmetrising the Standard Model introduces a *superpartner* for every SM particle – the **Minimal Supersymmetric Standard Model** (MSSM).

<u>But also downsides</u>

- A degree of arbitrariness is reintroduced by supersymmetry breaking.
- Many more free parameters due to ignorance of supersymmetry breaking mechanism.
- Extra structure must be imposed to control violation of symmetries that were automatically small in the Standard Model Effective Field Theory.
- *No WIMPs discovered yet?*
- *No superpartners discovered yet?*

Supersymmetry

Perhaps supersymmetry does not solve the Higgs fine-tuning problem but still exists at some energy scale in nature. *Is this just wishful thinking?*

The historical line of reasoning may make it seem that way:

Generalising **Abelian** gauge theories to **non-Abelian** gauge theories,

$$[B_r, B_s] = 0 \longrightarrow [B_r, B_s] = iC^t_{rs} B_t$$

Generalising the **Poincare** algebra to a **supersymmetry** algebra,

$$\begin{aligned} [P_\mu, P_\nu] &= 0 \\ [M_{\mu\nu}, M_{\rho\sigma}] &= ig_{\nu\rho}M_{\mu\sigma} - ig_{\mu\rho}M_{\nu\sigma} - ig_{\nu\sigma}M_{\mu\rho} + ig_{\mu\sigma}M_{\nu\rho} \\ [M_{\mu\nu}, P_\rho] &= -ig_{\rho\mu}P_\nu + ig_{\rho\nu}P_\mu \end{aligned} \longrightarrow$$

$$\begin{aligned} [P_\mu, Q^I_\alpha] &= 0 \\ [P_\mu, \bar{Q}^I_{\dot\alpha}] &= 0 \\ \{Q^I_\alpha, Q^J_\beta\} &= \epsilon_{\alpha\beta} Z^{IJ} \\ \{\bar{Q}^I_{\dot\alpha}, \bar{Q}^J_{\dot\beta}\} &= \epsilon_{\dot\alpha\dot\beta} (Z^{IJ})^* \\ \{Q^I_\alpha, \bar{Q}^J_{\dot\beta}\} &= 2\sigma^\mu_{\alpha\dot\beta} P_\mu \delta^{IJ} \\ [M_{\mu\nu}, Q^I_\alpha] &= i(\sigma_{\mu\nu})^\beta_\alpha Q^I_\beta \\ [M_{\mu\nu}, \bar{Q}^{I\dot\alpha}] &= i(\bar\sigma_{\mu\nu})^{\dot\alpha}_{\dot\beta} \bar{Q}^{I\dot\beta} \end{aligned}$$

Supersymmetry

Perhaps supersymmetry does not solve the Higgs fine-tuning problem but still exists at some energy scale in nature. *Is this just wishful thinking?*

Consider all allowed interactions of *massless* particles:

Relativity + quantum mechanics forbids all but the following possibilities:

- spin 0
- spin ½
- spin 1
- spin 3/2
- spin 2

Spin > 2 is not allowed.

Supersymmetry

Perhaps supersymmetry does not solve the Higgs fine-tuning problem but still exists at some energy scale in nature. *Is this just wishful thinking?*

Consider all allowed interactions of *massless* particles:

Relativity + quantum mechanics forbids all but the following possibilities:

- spin 0
- spin ½
- spin 1 – can only self-interact consistently as a Yang-Mills non-Abelian gauge theory.
- spin 3/2
- spin 2 – can only interact universally as in General Relativity.

Spin $>$ 2 is not allowed.

Supersymmetry

Perhaps supersymmetry does not solve the Higgs fine-tuning problem but still exists at some energy scale in nature. *Is this just wishful thinking?*

Consider all allowed interactions of *massless* particles:

Relativity + quantum mechanics forbids all but the following possibilities:

- spin 0 – Higgs boson.
- spin ½ – matter.
- spin 1 – can only self-interact consistently as a Yang-Mills non-Abelian gauge theory.
- spin 3/2
- spin 2 – can only interact universally as in General Relativity.

Spin $>$ 2 is not allowed.

Supersymmetry

Perhaps supersymmetry does not solve the Higgs fine-tuning problem but still exists at some energy scale in nature. *Is this just wishful thinking?*

Consider all allowed interactions of *massless* particles:

Relativity + quantum mechanics forbids all but the following possibilities:

- spin 0 – Higgs boson.
- spin ½ – matter.
- spin 1 – can only self-interact consistently as a Yang-Mills non-Abelian gauge theory.
- spin 3/2 – ?
- spin 2 – can only interact universally as in General Relativity.

Spin $>$ 2 is not allowed.

Supersymmetry

Perhaps supersymmetry does not solve the Higgs fine-tuning problem but still exists at some energy scale in nature. *Is this just wishful thinking?*

Consider all allowed interactions of *massless* particles:

Relativity + quantum mechanics forbids all but the following possibilities:

- spin 0 – Higgs boson.
- spin ½ – matter.
- spin 1 – can only self-interact consistently as a Yang-Mills non-Abelian gauge theory.
- spin 3/2 – can only interact **supersymmetrically**!
- spin 2 – can only interact universally as in General Relativity.

Spin > 2 is not allowed.

Supersymmetry

Perhaps supersymmetry does not solve the Higgs fine-tuning problem but still exists at some energy scale in nature. *Is this just wishful thinking?*

Consider all allowed interactions of *massless* particles:

Relativity + quantum mechanics forbids all but the following possibilities:

- spin 0 – Higgs boson. ✓
- spin ½ – matter. ✓
- spin 1 – can only self-interact consistently as a Yang-Mills non-Abelian gauge theory. ✓
- spin 3/2 – can only interact **supersymmetrically**! ?
- spin 2 – can only interact universally as in General Relativity. ✓

Spin $>$ 2 is not allowed.

"Everything not forbidden is compulsory"

Conclusion

Neutrino masses and dark matter are concrete evidence for beyond the Standard Model particles.

Heavy right-handed neutrinos in a see-saw mechanism and WIMP DM are natural, simple candidates.

GUTs are desirable and appealing extensions of the Standard Model, but not necessary.

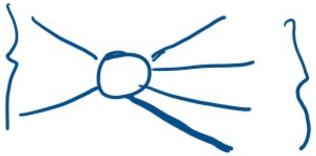
Supersymmetry arises uniquely out of strong theoretical consistency constraints and solves several phenomenological problems automatically. However, there is no experimental evidence for it yet.

Questions?

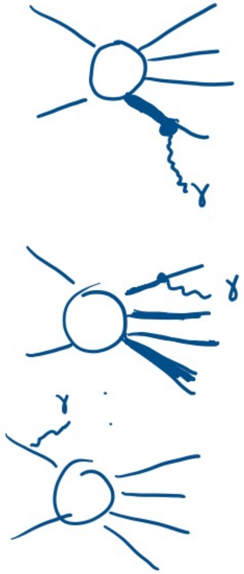
Tevong.you@kcl.ac.uk

Backup

Spin-1 amplitudes

$A_{\alpha\to\beta} =$ 

$\eta = \pm 1$

- $A^{\mu}_{\alpha\to\beta}(q) =$ 

$= A_{\alpha\to\beta} \cdot \sum_n \frac{\eta_n e_n p_n^\mu}{(p_n+q)^2+m^2}$

soft limit $q \to 0$: $\sum_n \frac{\eta_n e_n p_n^\mu}{p_n \cdot q}$

$\sum_n \eta_n e_n = 0$

charge conservation!

- polarisation vector $\epsilon_\mu \to \epsilon_\mu + q_\mu \Rightarrow q_\mu A^\mu_{\alpha\to\beta} = 0$

Backup

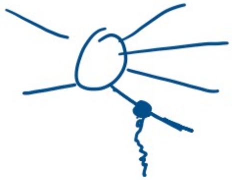
Massless spin-2 amplitudes

$$A^{\mu\nu}_{\alpha\to\beta}(q) \xrightarrow[q\to 0]{} A_{\alpha\to\beta} \sum_n \frac{\eta_n g_n p_n^\mu p_n^\nu}{p_n \cdot q}$$

$$q_\mu A^{\mu\nu} = 0 \implies \sum_n \eta_n g_n p_n^\nu = 0$$

but $\sum_n p_n^\nu = 0$

$g_n = \sqrt{8\pi G_N}$ must be independent of n



$$F = m_{inertial}\, a$$

$$F_{EM} = \frac{q_1 q_2}{4\pi\epsilon_0 r^2} \qquad F_G = g m$$

Backup

Spin ≥ 3

$$\mathcal{A}^{\mu\nu\rho\cdots}_{\alpha+\beta}(q) \xrightarrow[q\to 0]{} \mathcal{A}_{\alpha+\beta} \sum_n \frac{\eta_n g_n p_n^\mu p_n^\nu p_n^\rho \cdots}{p_n \cdot q} = 0 \quad \Rightarrow \quad \sum g_n p_n^\nu p_n^\rho \cdots = 0$$

$q \cdot \mathcal{A}$

$\Rightarrow g_n = 0$

no spins ≥ 3

(massless)