# The Standard Model – Part 3:
## ”I Came So Far to Get Lost at Sea…”

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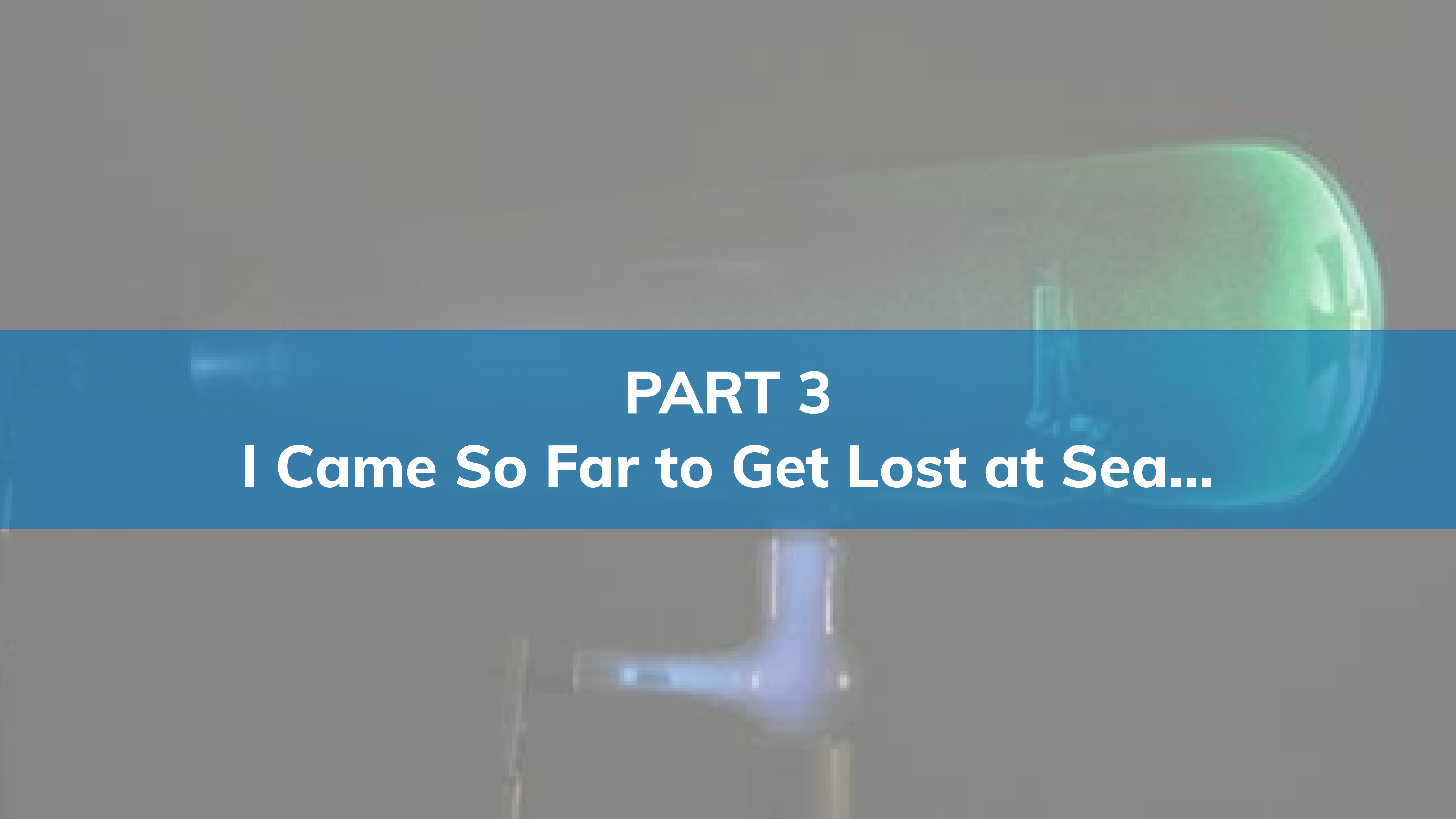
# PROGRAMME

- Part 1:
  ”Cut the Shackles …
  Changed My Name”
- Part 2:
  ”This Way to Gold”
- Part 3:
  ”I Came So Far to Get Lost at Sea…”

*”So I cut the shackles and changed my name*
*And I shed my past like skin on a snake*
*But I came so far to get lost at sea*
*Oh, where the hell am I supposed to be?*

*And the sirens scream down every road*
*While the signs light up, ‘This way to gold’*
*But I'm attached to my worst enemy*
*Oh, who the hell am I supposed to be?”*

Alice Merton, “Run Away Girl”

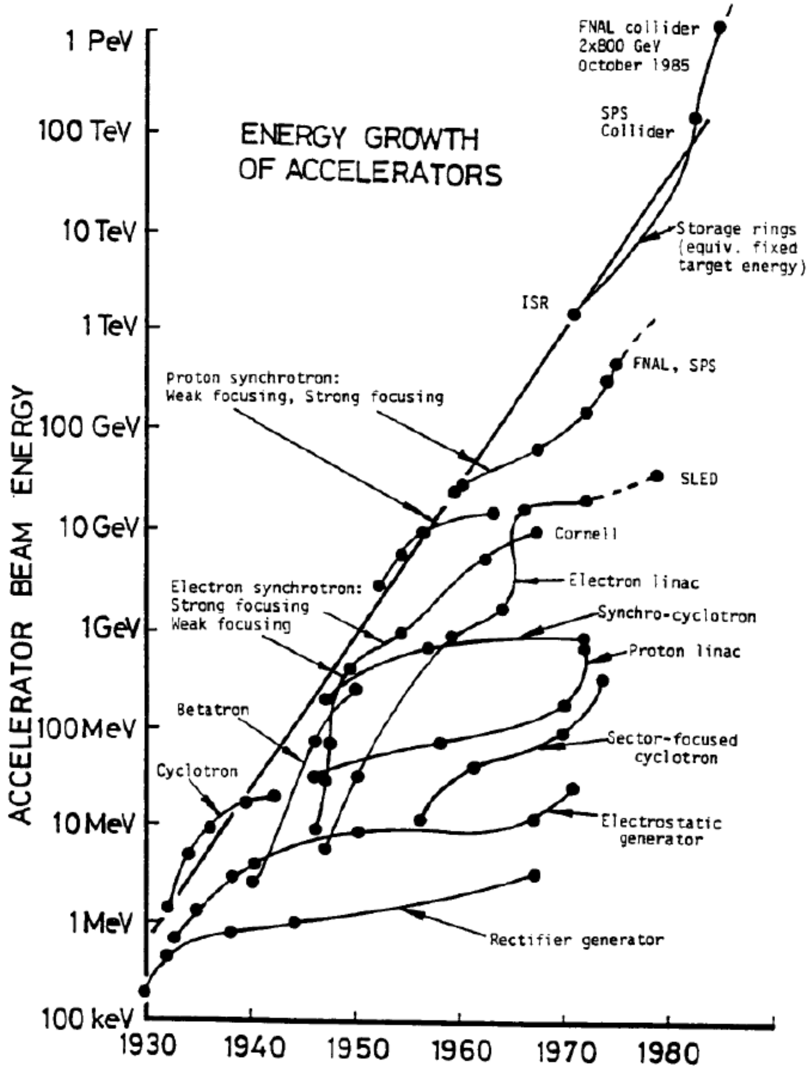


# PART 3
# I Came So Far to Get Lost at Sea...

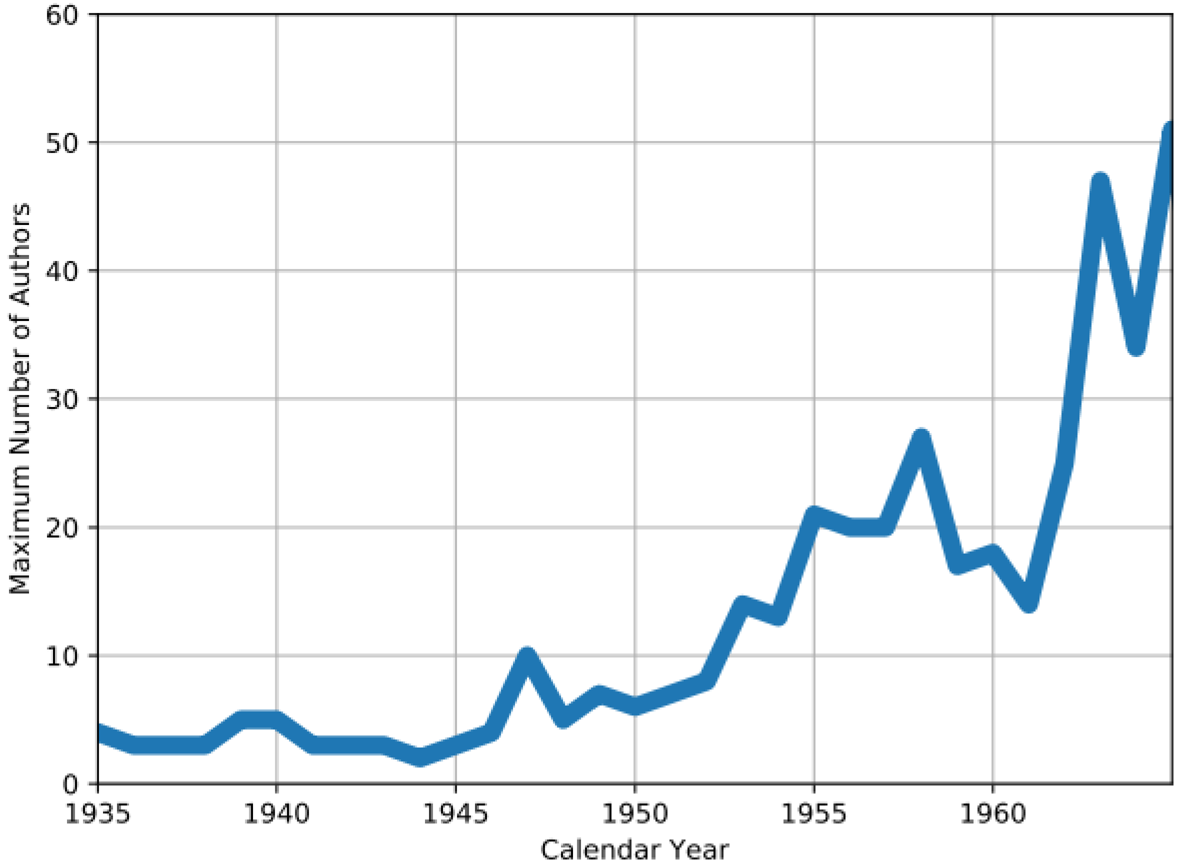
July 4, 2012. Early morning.


# "Global Effort → Global Success"

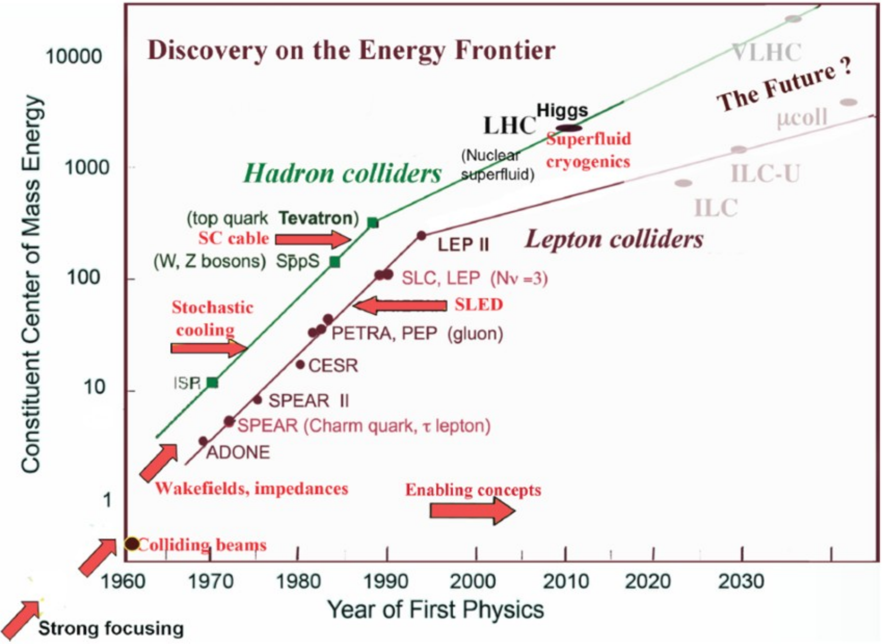
The Standard Model has been an incredible success story.

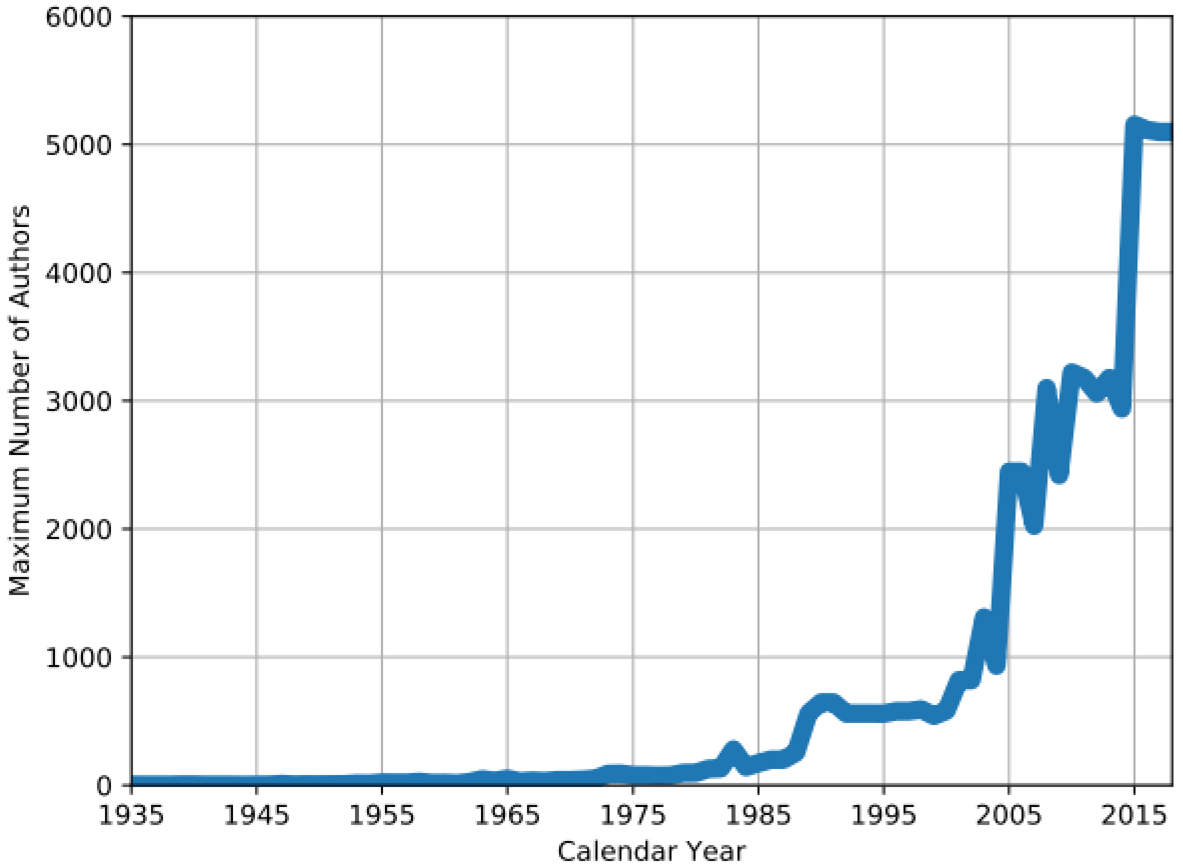


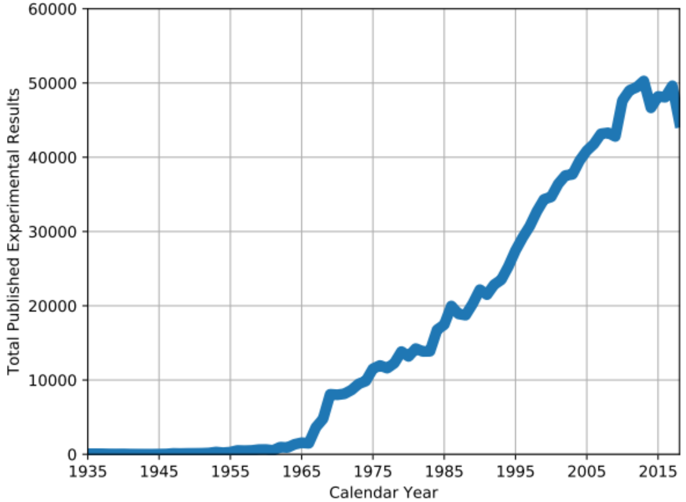

***Note: the above plot charts total beam energy (sum of all beam constituent energies).***




(Left) A "Livingston Plot" ca 1985. (Above) The growth of experimental collaborations from 1935-1965, determined using data from INSPIREHEP.net for particle experiment-based papers published in journals. This is the maximum number of authors per year for any journal paper, vs. year.

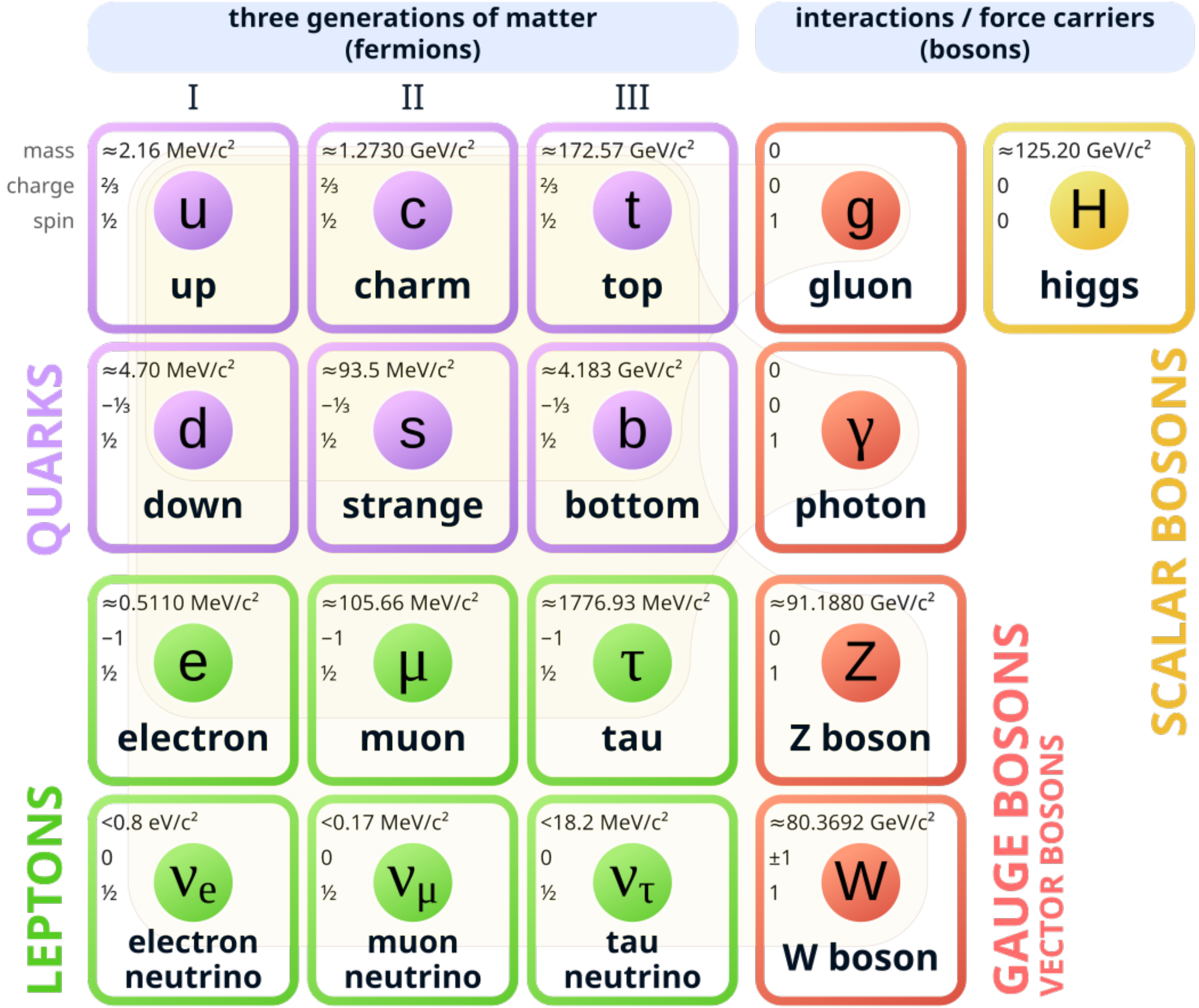



(Top-Left) A "Livingston Plot" from the 2013 Snowmass "Planning the Future" document. (Bottom-Left) The total number of particle experiment journal publications vs. year. (Above) The maximum number of authors per such paper vs. year. Data from INSPIREHEP.net.

# Standard Model of Elementary Particles




## The modern understanding, based on a century of discovery.

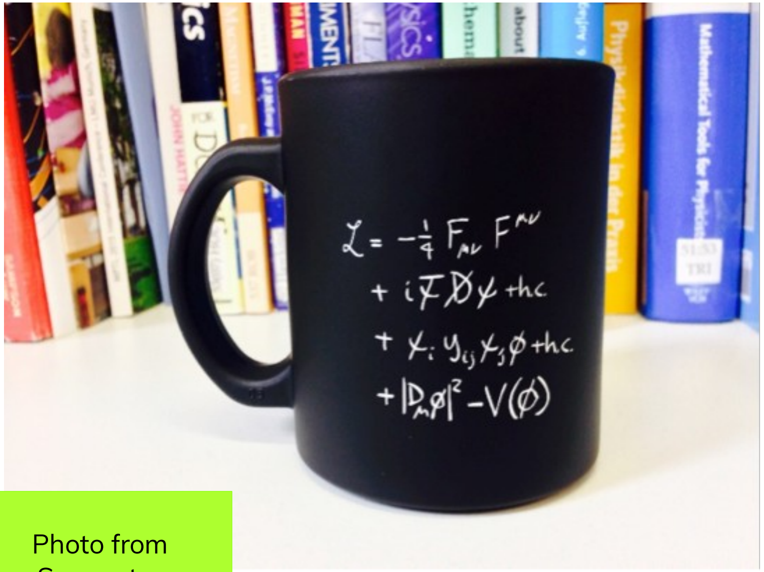
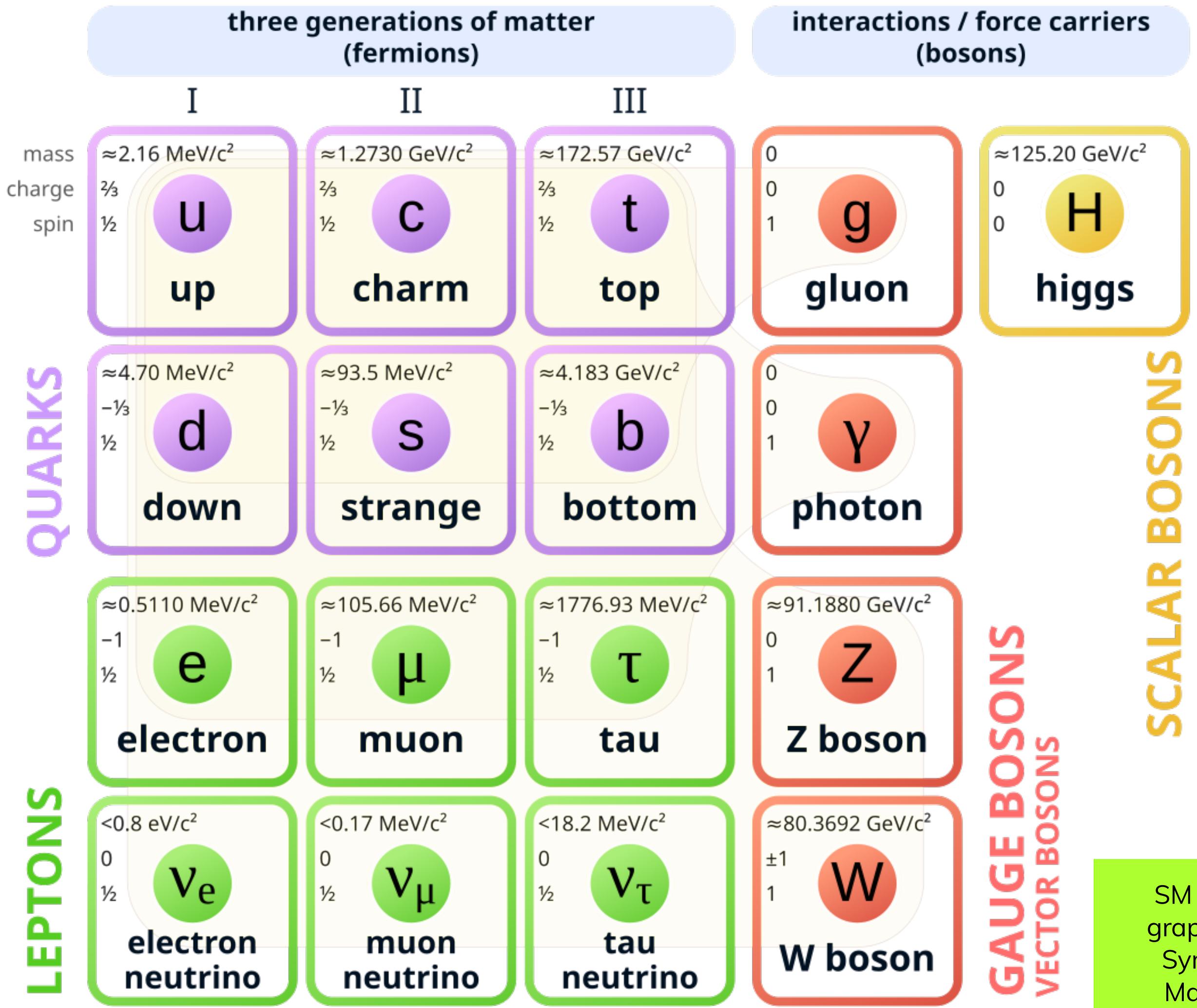


Photo from Symmetry Magazine

# Standard Model of Elementary Particles




SM formula graphic from Symmetry Magazine

1
$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\frac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$
2
$$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H -$$
$$\frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h\Big[\frac{2M^2}{g^2} +$$
$$\frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\Big] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu -$$
$$W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu -$$
$$W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$
$$g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$
$$\frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] -$$
$$gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$
$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$
$$igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$
$$\frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}_j^\lambda(\gamma\partial + m_u^\lambda)u_j^\lambda -$$
3
$$\bar{d}_j^\lambda(\gamma\partial + m_d^\lambda)d_j^\lambda + igs_w A_\mu\Big[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda\gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda\gamma^\mu d_j^\lambda)\Big] +$$
$$\frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}_j^\lambda\gamma^\mu(\frac{4}{3}s_w^2 -$$
$$1 - \gamma^5)u_j^\lambda) + (\bar{d}_j^\lambda\gamma^\mu(1 - \frac{8}{3}s_w^2 - \gamma^5)d_j^\lambda)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) +$$
$$(\bar{u}_j^\lambda\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d_j^\kappa)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}_j^\kappa C^\dagger_{\lambda\kappa}\gamma^\mu(1 +$$
$$\gamma^5)u_j^\lambda)] + \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] -$$
4
$$\frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}_j^\lambda C_{\lambda\kappa}(1-\gamma^5)d_j^\kappa) +$$
$$m_u^\lambda(\bar{u}_j^\lambda C_{\lambda\kappa}(1+\gamma^5)d_j^\kappa] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}_j^\lambda C^\dagger_{\lambda\kappa}(1+\gamma^5)u_j^\kappa) - m_u^\kappa(\bar{d}_j^\lambda C^\dagger_{\lambda\kappa}(1 -$$
$$\gamma^5)u_j^\kappa] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}_j^\lambda\gamma^5 u_j^\lambda) -$$
$$\frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}_j^\lambda\gamma^5 d_j^\lambda) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 -$$
5
$$\frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- -$$
$$\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y -$$
$$\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ -$$
$$\partial_\mu\bar{X}^- X^-) - \frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2}\bar{X}^0 X^0 H] +$$
$$\frac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] +$$
$$igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

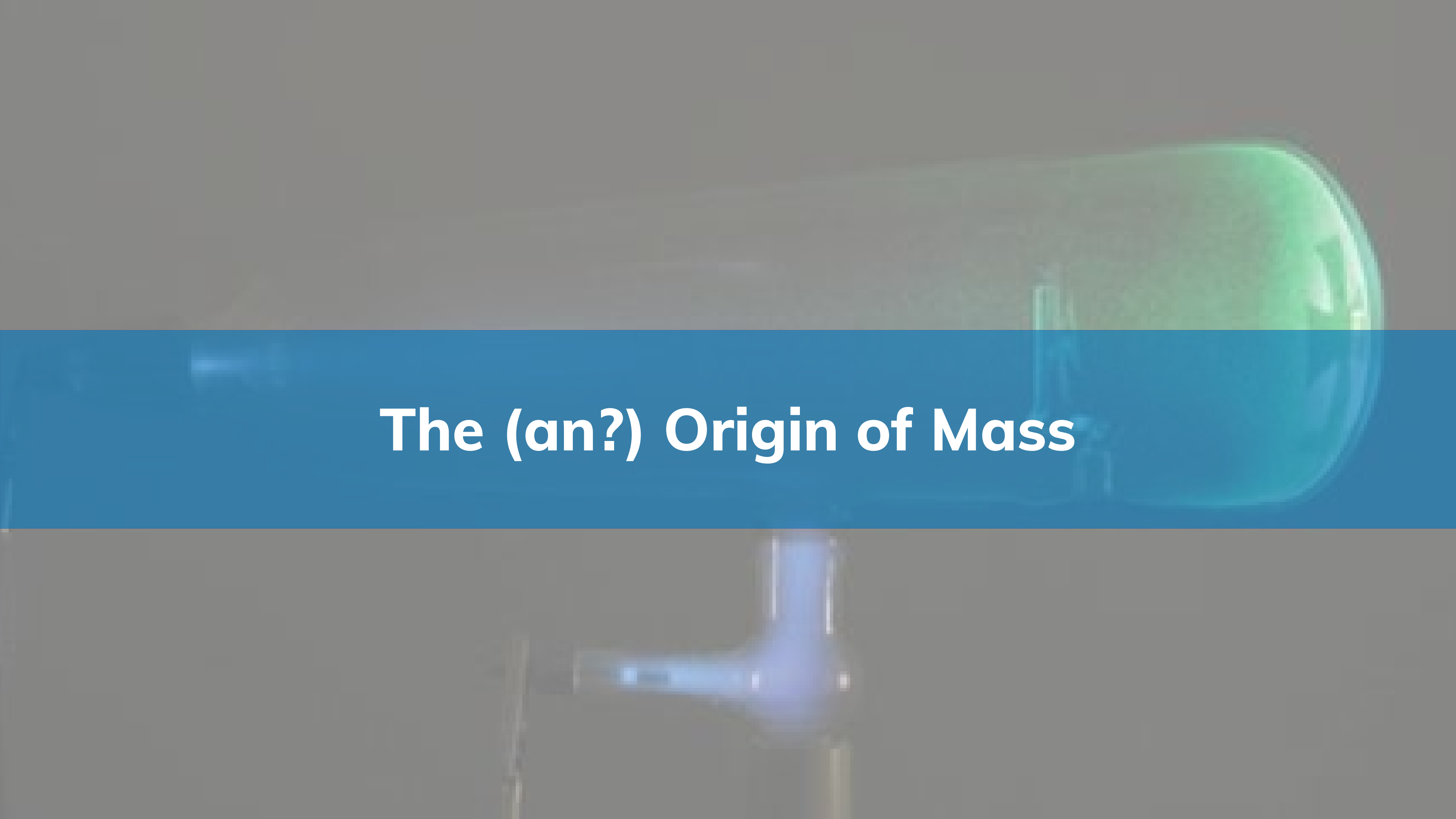
*The Standard Model is the most successful theory of nature ever constructed by humankind.*

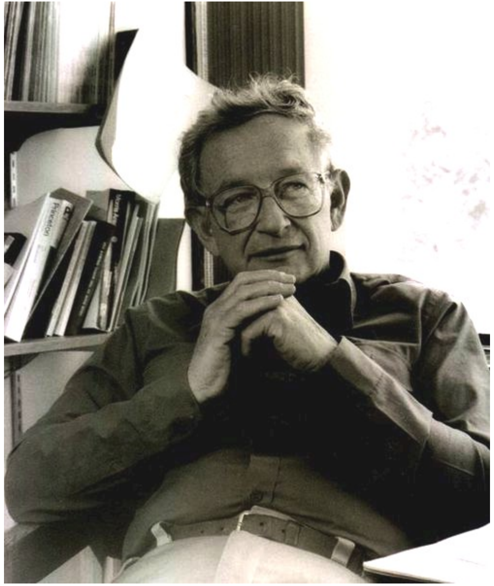
*The Standard Model is a*
*terrible description of the universe.*

*My 11-mile run in 2017 was my most successful attempt at a marathon ever conducted.*

*I did a terrible job of running a marathon in 2017.*

# The (an?) Origin of Mass





Philip Warren Anderson

Left-to-right: Tom Kibble, Gerald Guralnik, Carl Hagen, Francois Englert, Robert Brout, and Peter Higgs.

***<u>1962</u>***: *The photon, the particle that transmits the electromagnetic force (light), has no mass; yet Philip Anderson, studying plasmas, realizes that those phenomena could be best described as if the photon "acquires" a mass; he works out the details in classical field theory ("Plasmons, gauge invariance, and mass"), and speculates that the same mechanism could apply to nuclear forces in a quantum field theory.*

***<u>1964</u>***: *three separate groups - Brout and Englert; Higgs; Guralnik, Hagen, and Kibble – fully work out the math for nuclear forces and set the stage for a almost 50-year quest to test this idea for the source of fundamental mass.*

# The Standard Model

$$\mathscr{L}_{SM} = \mathscr{L}_{EW} + \mathscr{L}_{QCD}$$

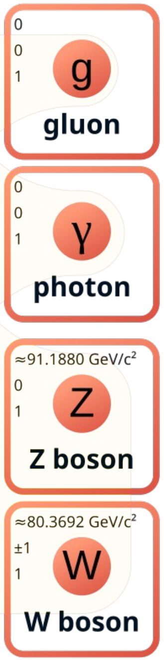
The Standard Model's undrlying quantum field theory structure is based on a set of symmetry groups:

$$SU(3)_{colour} \times SU(2)_{weak} \times U(1)_{em}$$

It was assumed these symmetries were respected. This was the fatal flaw as regards mass for bosons. But how to break the symmetry … specifically, $SU(2) \times U(1)$?

# What is the idea?

**Problem:** **in the 1940s and 1950s, nobody was able to write a self-consistent, well-behaved and predictive quantum field theory of fundamental forces whose transmitters also have mass.**




massless

massless

massive

massive

To break the SU(2)×U(1) symmetry, one can begin by adding to the theory a complex scalar field doublet, H

$$H = \begin{pmatrix} H^{+} \\ H^{0} \end{pmatrix}$$

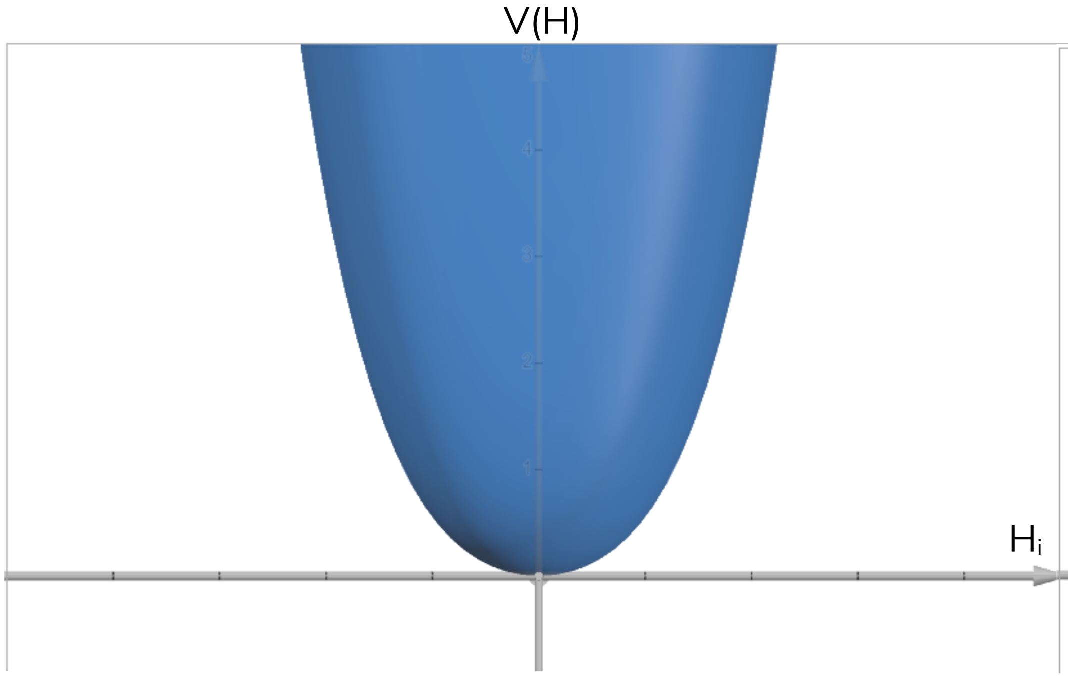
So that:

$$\mathscr{L}_{\text{scalar}} = T - V = \frac{1}{2}(D_{\mu}\phi)^2 - \lambda(H^2 \pm v^2/2)^2$$

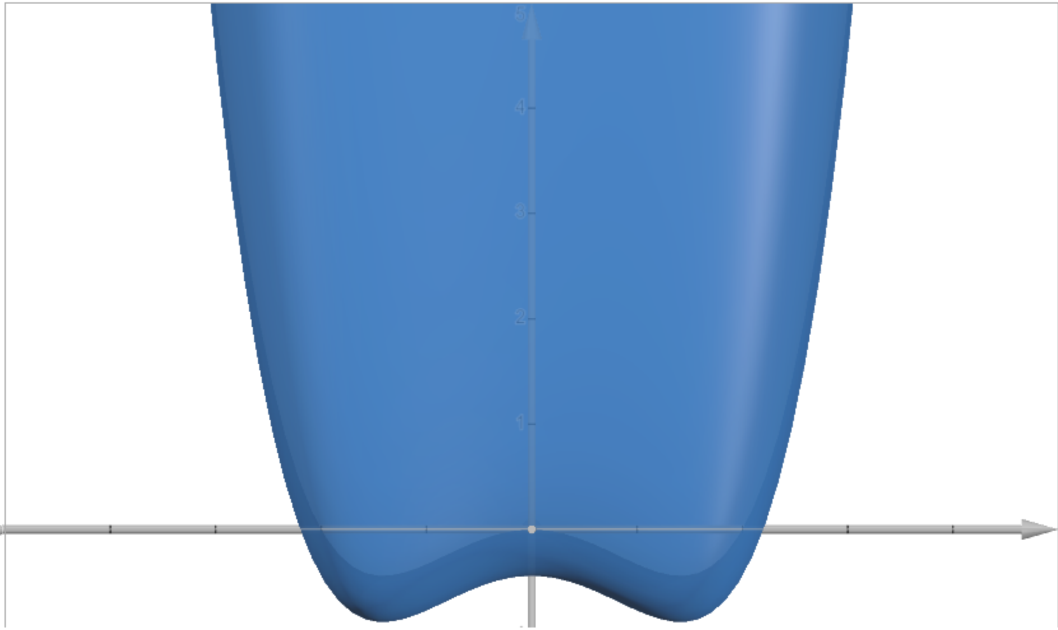
# Choose Your Potential

$$V(H)=\frac{\lambda}{4}\left(H^2\pm v^2/2\right)^2$$

**If you choose "+"**

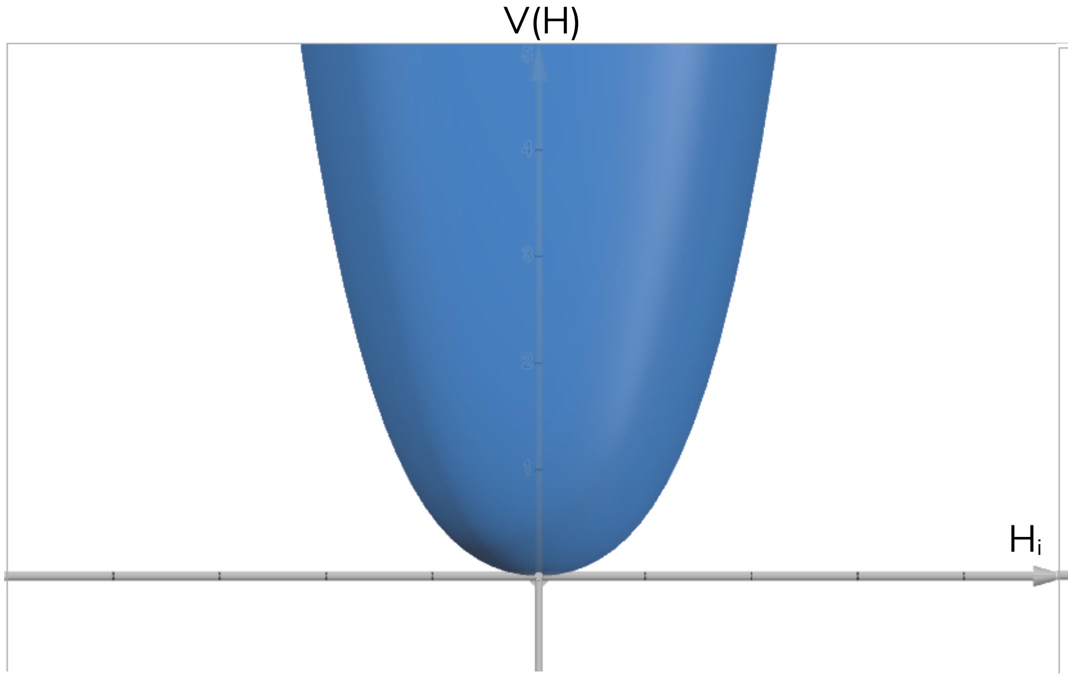



**If you choose "-"**

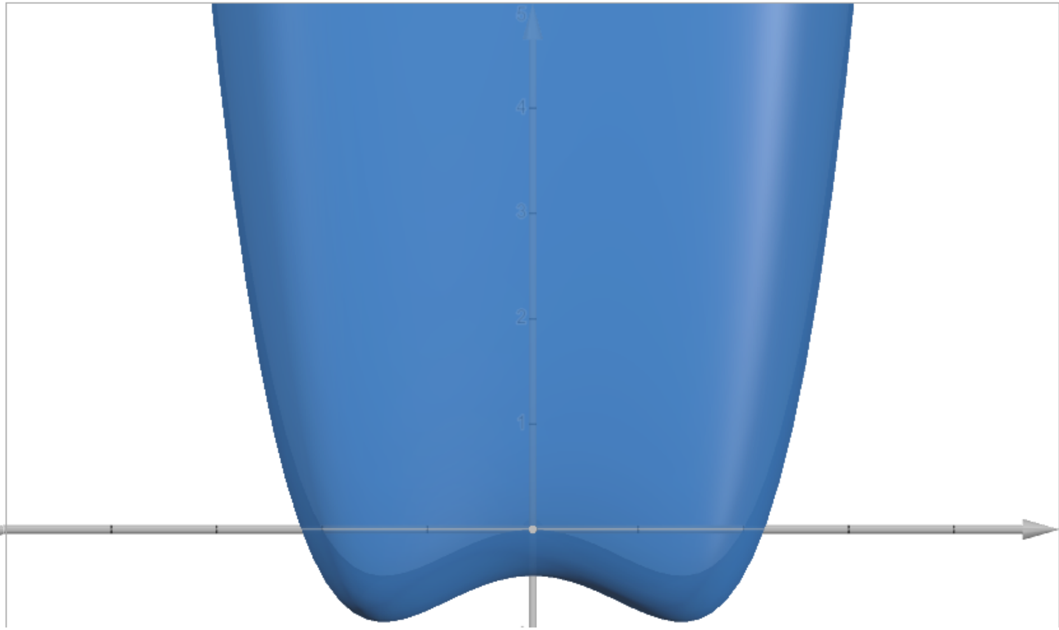


# Choose Your Potential

Minimum still at V(H)=0. Perturbations about the minimum still result in massless gauge fields.




An infinite number of minima in two dimension at V(H)=v. Nature spontaneously "chose" one of these. Massive gauge fields possible, at a cost.



# Consequences

The W field of the ElectroWeak Lagrangian has three components. Two of them mix (with angle $\theta_W$) to make each of the W+ and W- physical states (both massive). The third component of W mixes with the B field to make the massive Z and massless photon. The relationships between parameters of the theory and the W and Z are as given in the previous lecture:

$$M_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F} \rightarrow M_W \approx 80\, GeV/c^2 \qquad M_Z = M_W/\cos\theta_W \approx 90\, GeV$$

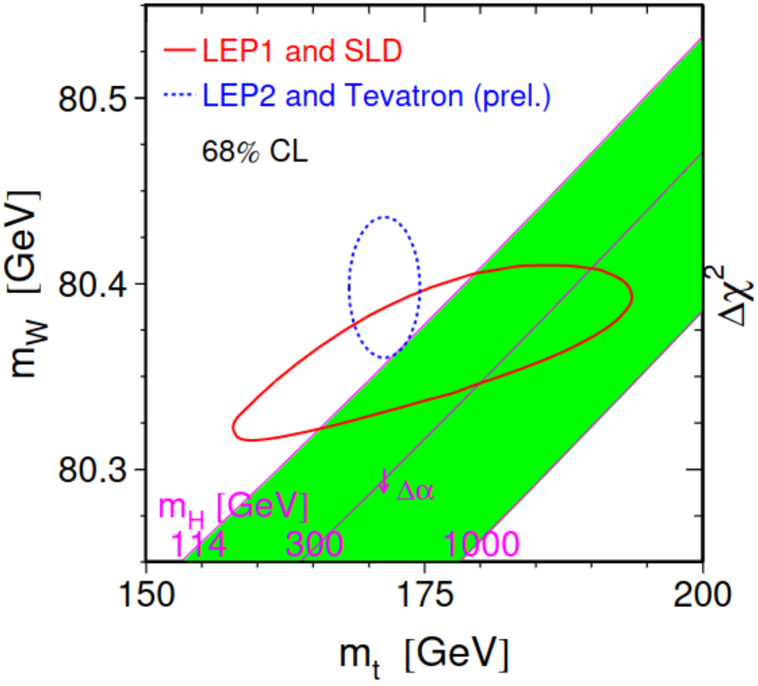
The scalar potential minimum at v is given by $v \equiv 1/\sqrt{\sqrt{2}G_F} \approx 246\ \text{GeV}$

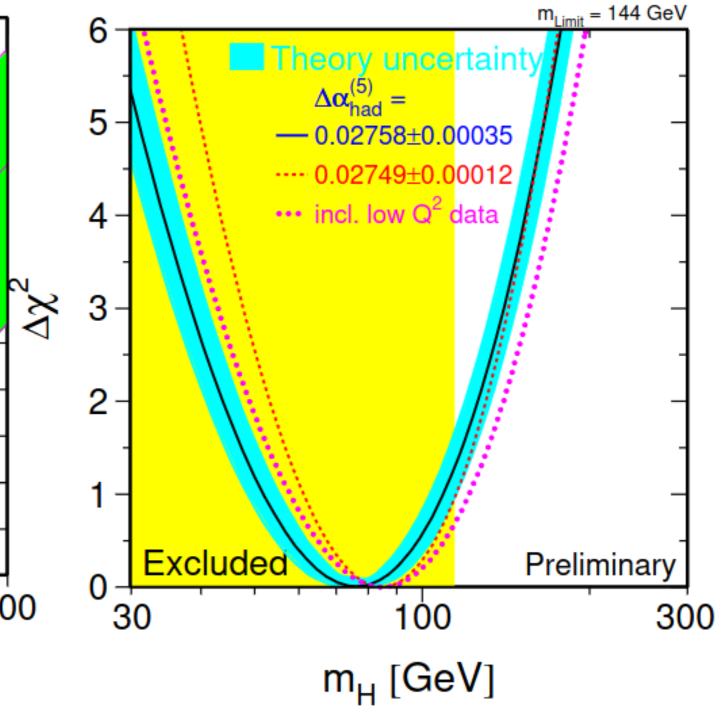
There is one remaining “degree of freedom” after the dust settles, which behaves like a massive scalar boson with

$$m_{scalar} = \sqrt{2\lambda}\, v$$

# Precision Electroweak Bounds on Higgs Mass

Higher order diagrams involving Higgs Bosons enter as corrections to Standard Model predictions for electroweak processes.




Higgs mass $M_H = 85^{+39}_{-28}$ GeV

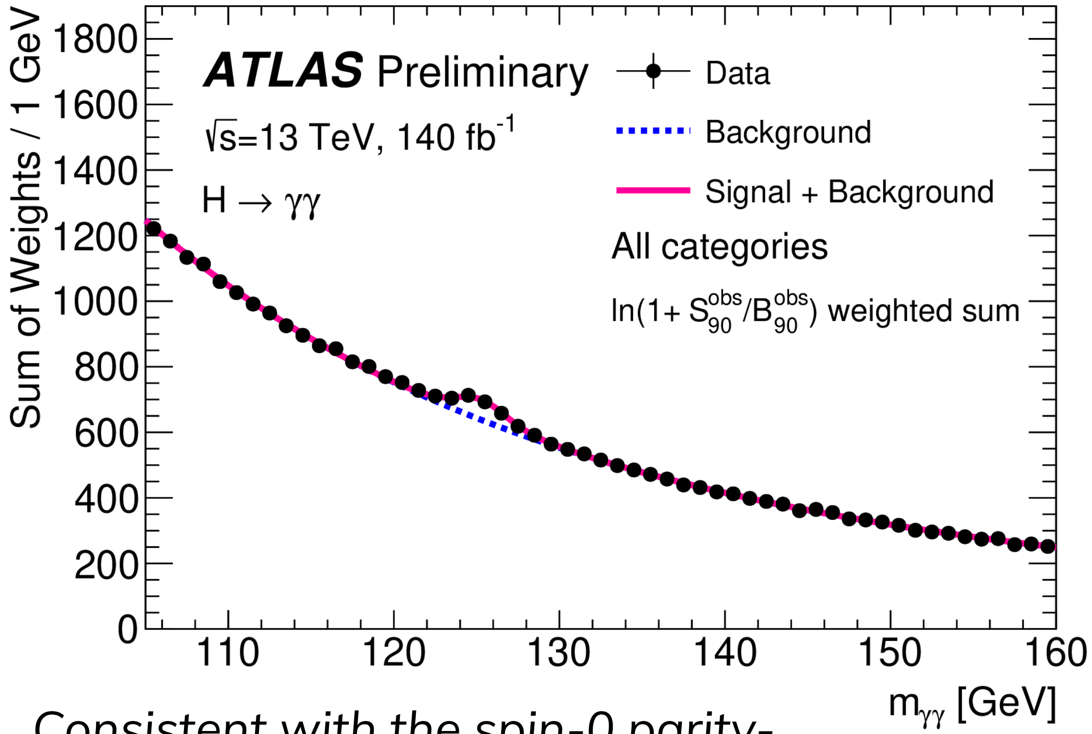
$M_H < 144$ GeV (90% C.L.)

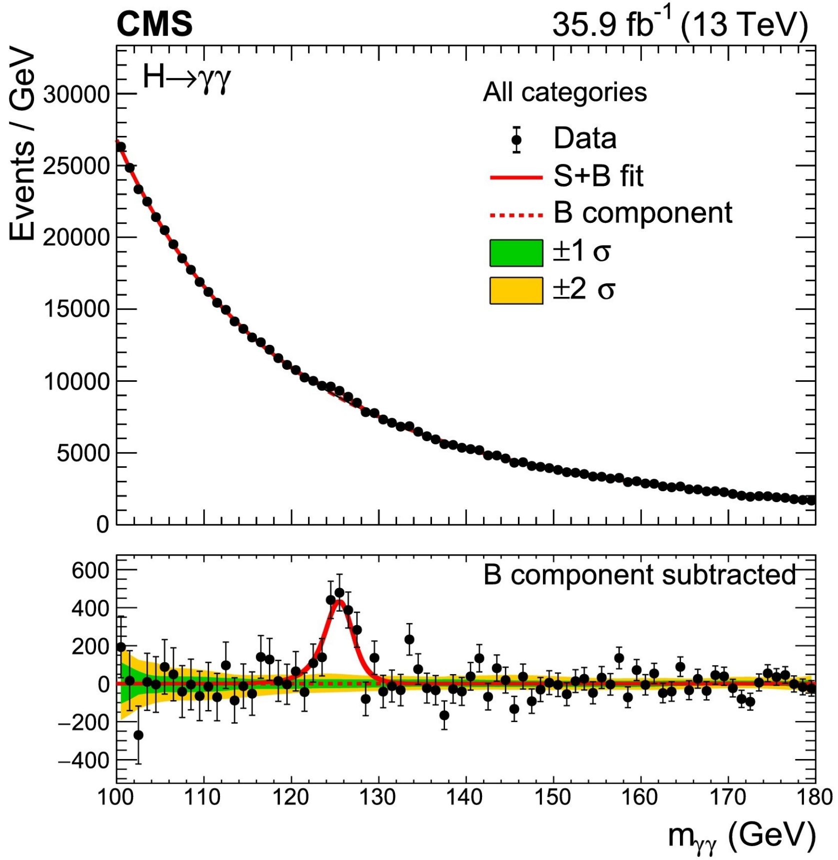
SNOLAB

**Slide from Prof. Steve Playfer (Univ. of Edinburgh), Lecture 17 of his Particle Physics course, Spring 2009!**

# The Higgs Particle

$m_H$ = 125.11 GeV (± 0.08%)



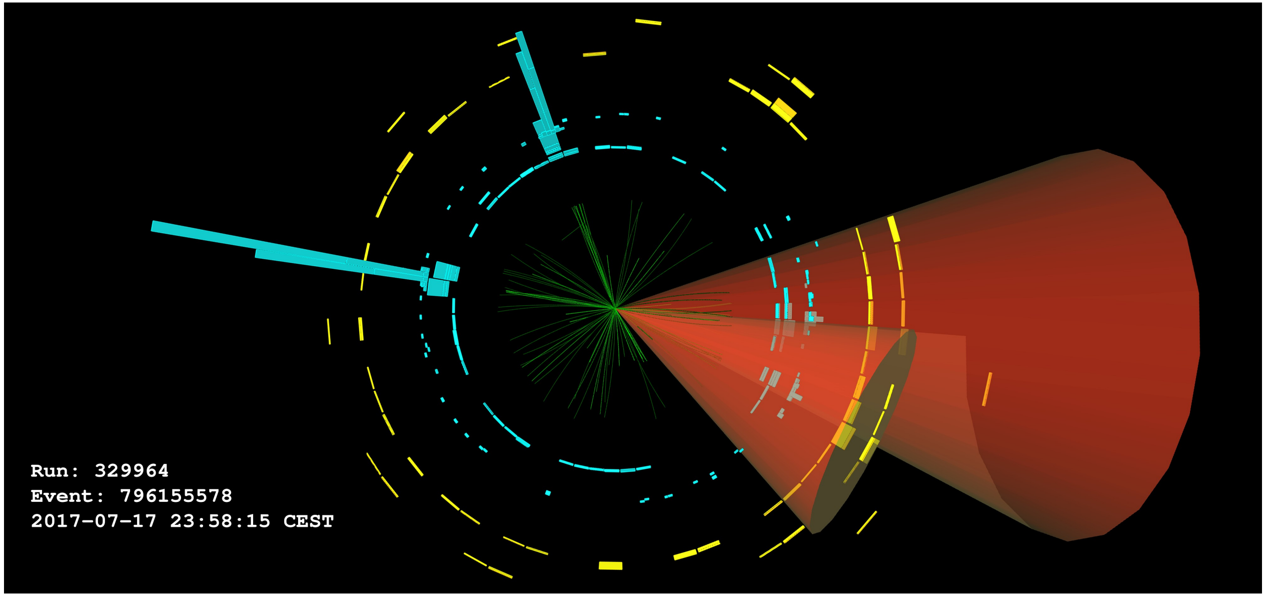




*Consistent with the spin-0 parity-even boson predicted by SM.*

# What is Next?

**There is only one free parameter of the original Standard Model left:** λ (the Higgs self-interaction strength, which is what sets its own mass). This is now predicted to be

$$\lambda = m_H^2 / (2 v^2) = 0.129$$




**"Di-Higgs Production" is a major experimental target of the LHC program for the next 10+ years. Talk to Michael Kagan to learn more – he's an expert!**

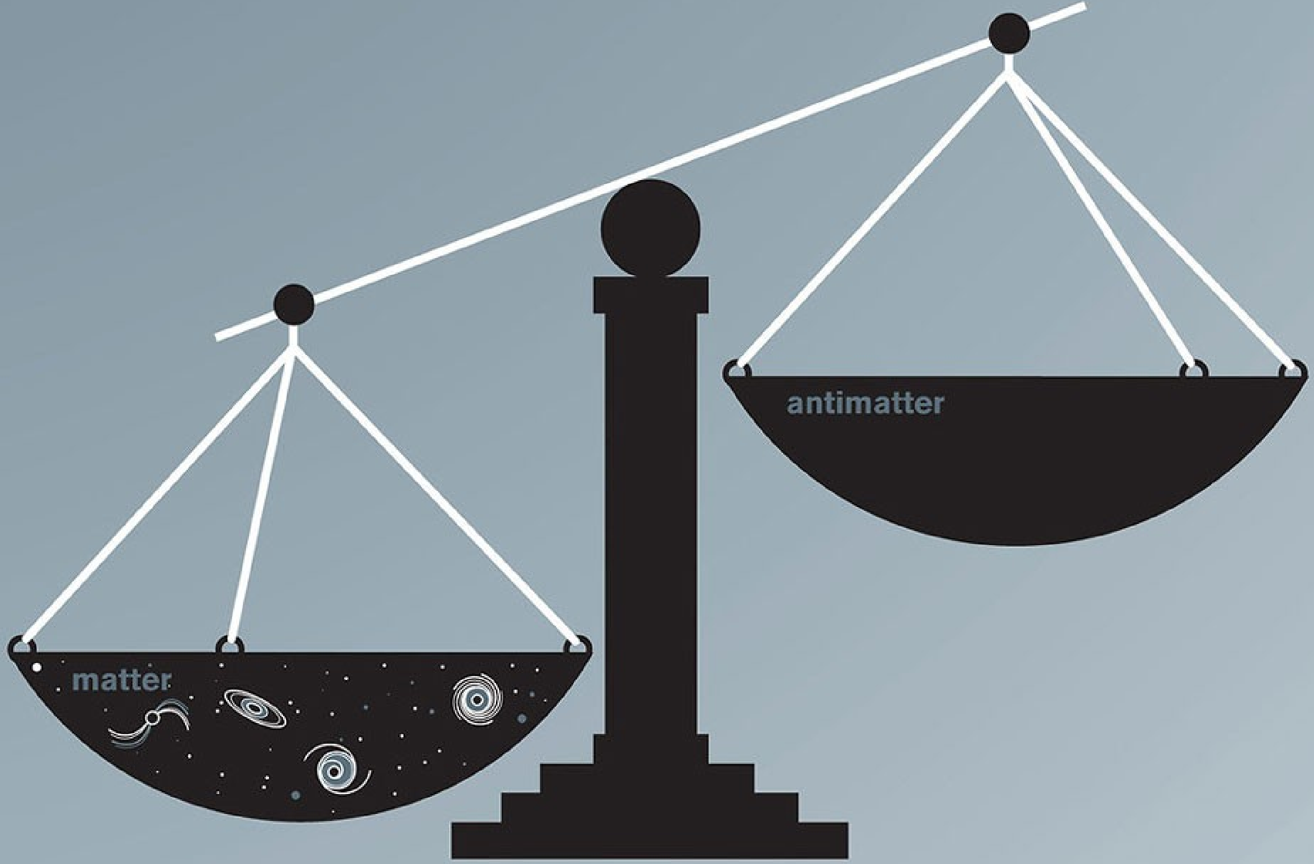
The Higgs particle's "self interaction" manifests in a particle collider as the production of a pair of Higgs particles. These events should be exceedingly rare (1000 times rarer than the single-Higgs production processes that led to the 2012 discovery)

*The Standard Model has been terrifically successful at describing the structure of baryonic matter and much of leptonic physics.*

*Here are some places where it fails.*
*(or, at least, makes you go "Huh".)*

# The Matter-Antimatter Balance of the Cosmos

There is far more matter in the universe than antimatter.




The observed photon-to-baryon ratio is about a billion-to-one, suggesting there was cataclysmic matter/antimatter annihilation early on and that remaining matter is the leftover asymmetry in the universe…

**Image credit: Fermilab**

# How to get such a cosmic asymmetry?

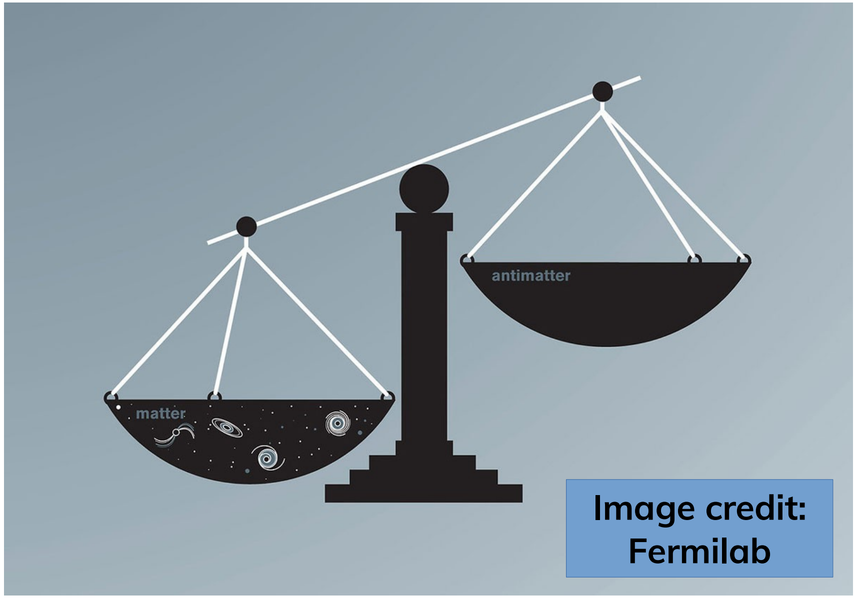
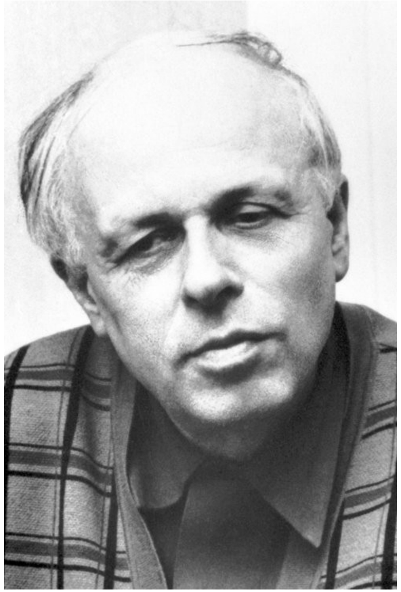



Image credit: Fermilab



Andrei Sakharov
Photo credit:
Nobel Prize Foundation

## The Sakharov Conditions:

- Baryon number violation
- Charge Parity (CP) and Charge (C) Symmetry violation
- Interactions out of thermal equilibrium

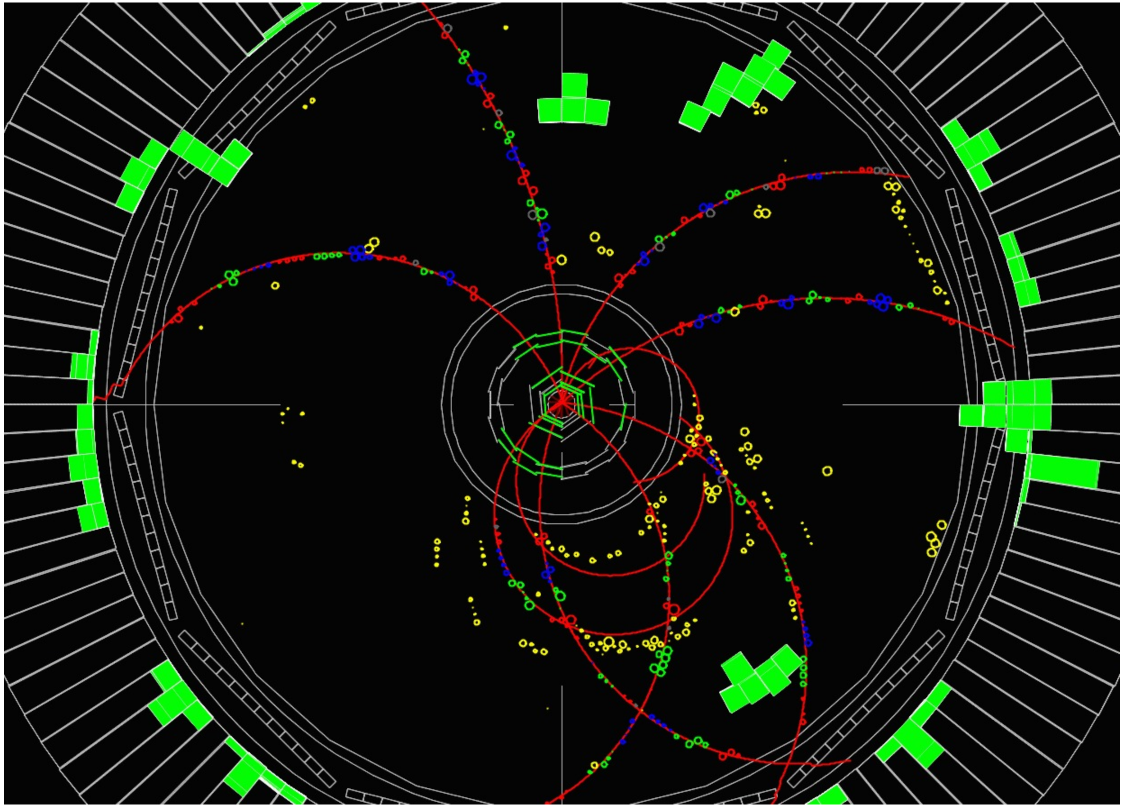
**Baryon number** is an "accidental symmetry" of the Standard Model, and at the quantum level **weak processes CAN violate B conservation**(*) but the effects are so small as to be unobservable...

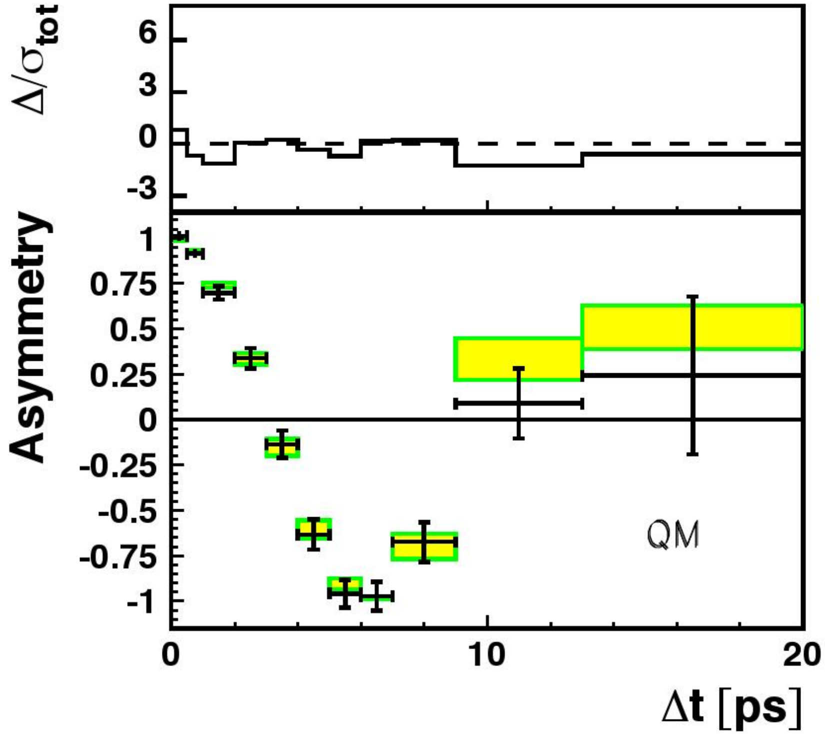
**Interactions being out of thermal equilibrium** is "early universe stuff" ... let's leave that to the cosmologists for now. That's not a SM problem, per se ...

What about **C and CP violation**? You bet! The SM violates CP and C left and right (pun intended) ((it was only funny to me))

(*) G. 't Hooft, Phys. Rev. Lett. 37, 8 (1976).

$$e^+e^- \rightarrow B^0(\bar{b}d)\bar{B}^0(b\bar{d})$$






How the flavour of the meson changes with time is beautifully described by the SM (quantum mechanics, QM). This process can be used to study CP violation. This and related processes have discovered CP violation in Kaons (1950s) and B mesons (2000s).

**The B and anti-B are in a quantum superposition when they are created. When one decays, this "collapses" the other B into a definite state of either B or $\bar{\text{B}}$. From there, we can look at how the meson evolves in time (see upper right plot).**

# Is there enough CP violation?

- Nope. Not in the quark sector of the Standard Model. Not enough to explain how our universe became so matter-dominated.
- Neutrino mixing may lead us to evidence for CP violation in the neutrino/lepton sector, but that is a topic for a different lecture(r).
- And, anyway, neutrino mass and mixing is generally considered “beyond the Standard Model” and so … also a subject for other lecture(r)s.

# Whoa, wait. Neutrino Mass is “Beyond the Standard Model”?

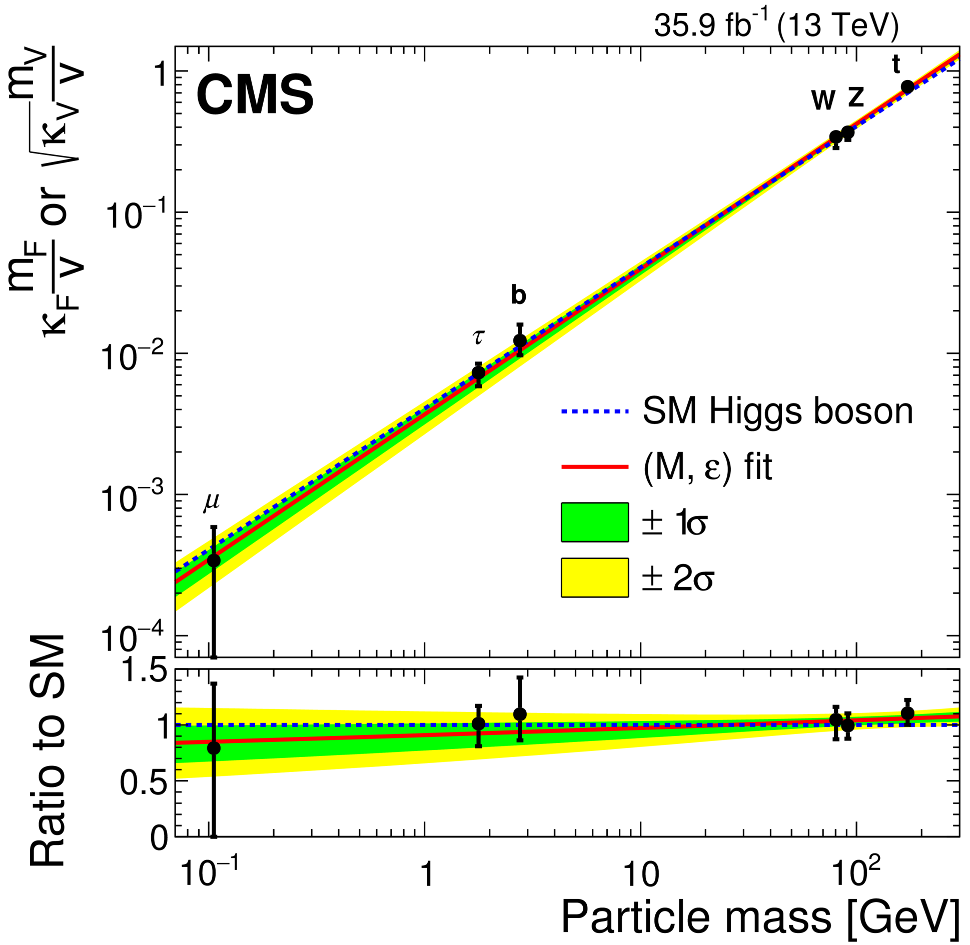
# Maybe. Fine. Let's Look at It.

The fermions acquire mass in the Standard Model through the Higgs field, which couples left-handed to right-handed fermions fields with a strength $g_f$ for each of the fermions,

$$m_f = g_f \cdot v/2$$

In the SM, one expects a linear relationship between the rate of $H \to f\bar{f}$ and $m_f$, which is so-far observed in experiment (see right).

$$\mathcal{L}_f = \frac{g_f}{\sqrt{2}}(\bar{f}_L f_R + \bar{f}_R f_L)v + \frac{g_f}{\sqrt{2}}(\bar{f}_L f_R + \bar{f}_R f_L)h$$



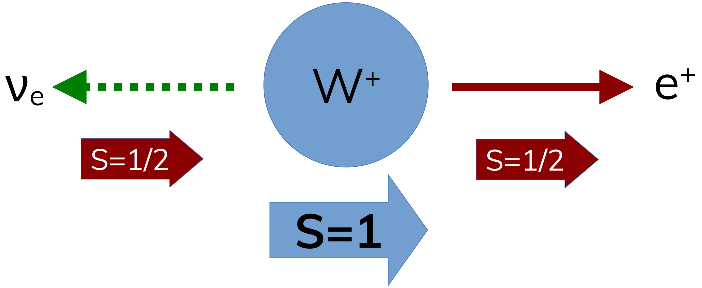
# Chirality, Helicity, and Neutrinos

- Chirality (left- or right-handed fields) is determined by whether or not a fermion field transforms under a left-handed or right-handed representation of the Poincare group. It is a deeply theoretical feature of fields.
- In the massless limit (e.g. “classical neutrinos”), helicity and chirality are the same thing, where helicity is:

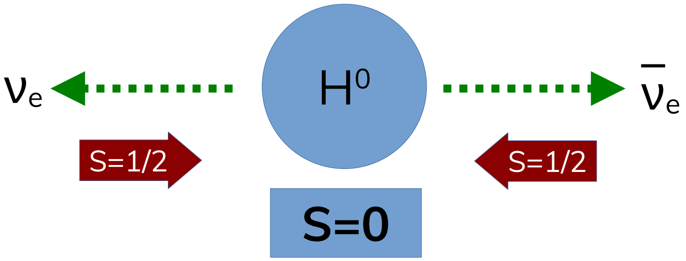
$$\mathrm{sgn}(\vec{s} \cdot \vec{p}) = \pm 1$$

  The W boson only couples to left-handed particles and right-handed antiparticles.
- Chirality is Lorentz invariant, while helicity is not (although helicity commutes with the Hamiltonian).
- Due to the smallness of the neutrino mass, most neutrinos are helicity -1 and most antineutrinos are helicity +1 and are almost entirely in their chiral states.

# Chirality, Helicity, W, and H

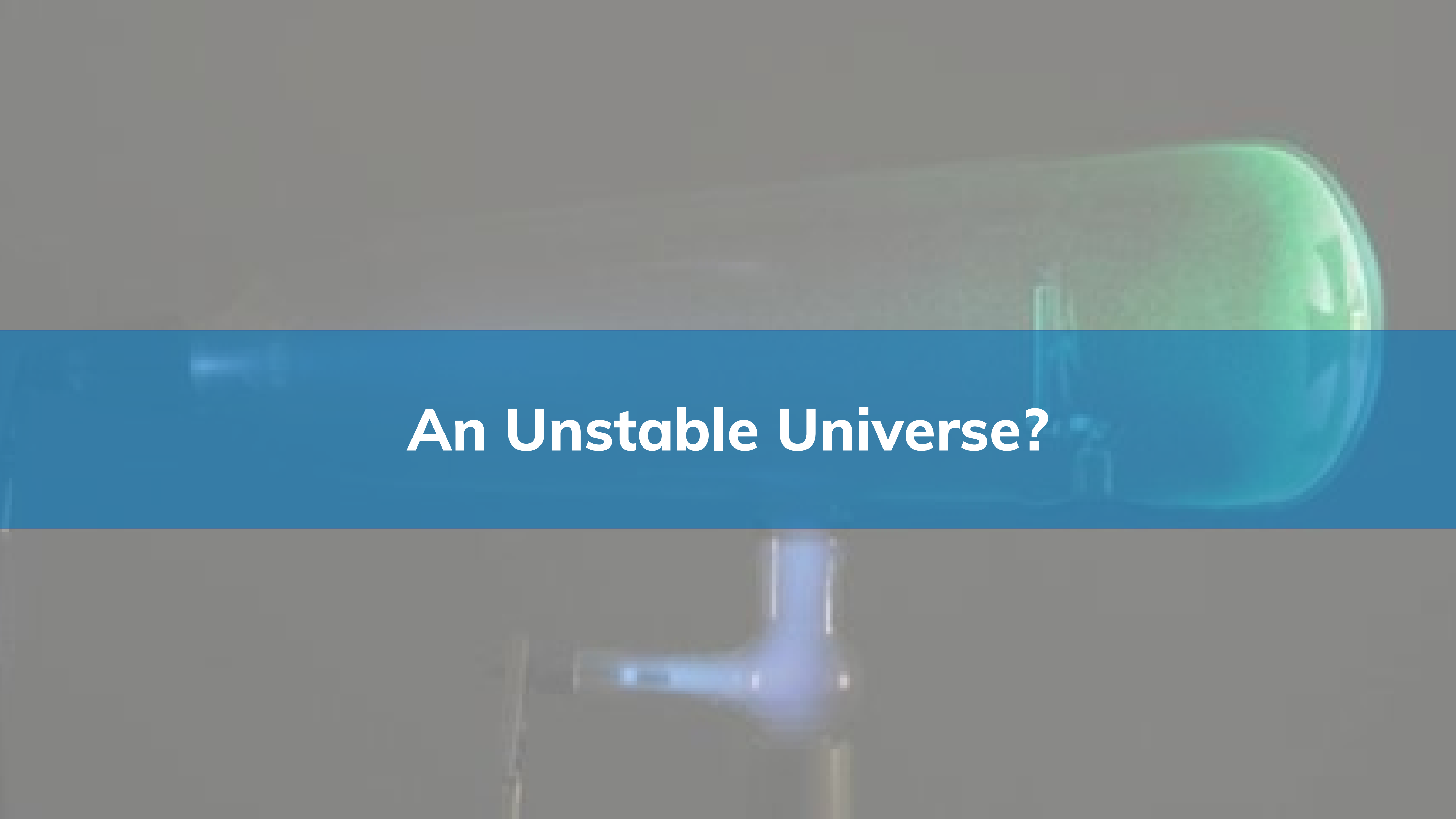



This is a perfectly acceptable decay in the SM, so long as the spins of the leptons align to yield the spin-1 of the W. The electron has a small mass, so this won’t work out quite every time but, again, helicity and chirality are only the same in the massless limit.




The Higgs is spinless, so the spin orientations of the outgoing leptons have to cancel. This results in a left-handed neutrino and a left-handed antineutrino, or a right-handed antineutrino and a right-handed neutrino.

**So if the Higgs diagram exists (the Higgs gives mass to neutrinos), every Higgs interaction would change the “handedness” of the neutrino and leave a large population of wrong-handed neutrinos that cannot interact with the W boson … they effectively decouple from many/most weak interactions. <u>This is not ideal as models go.</u>**

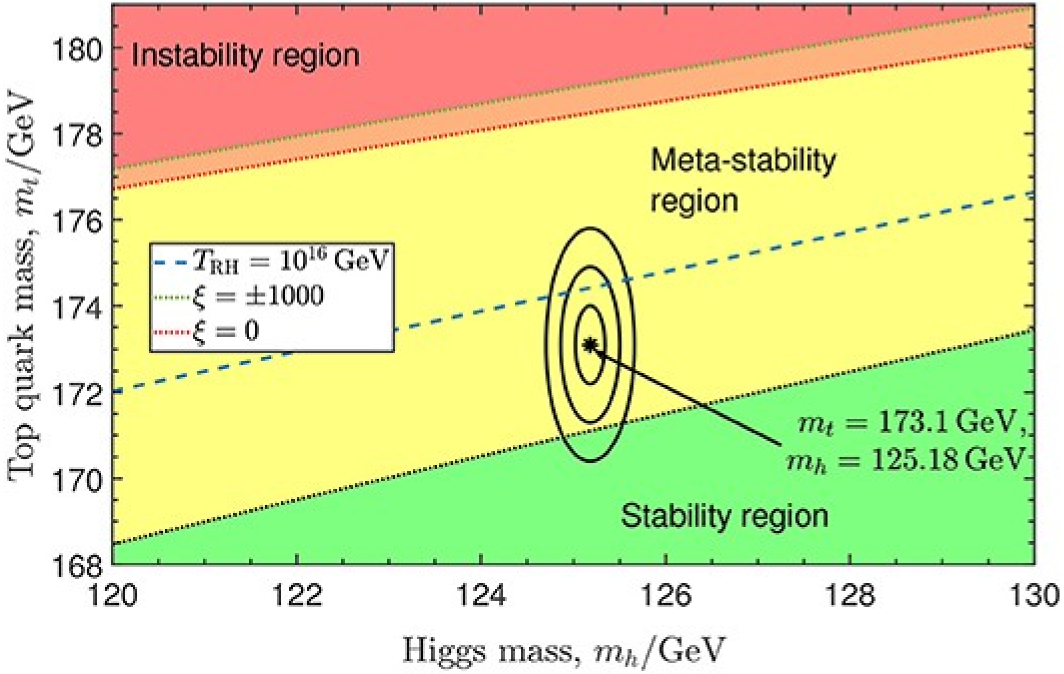


# An Unstable Universe?

# Metastability of the Universe?

The Higgs potential tells us about the vacuum of the electroweak theory. Is the universe in a stable minimum of the vacuum?

If the SM is the final theory of nature … **then maybe not.** A universe with this set of parameters favours being in a metastable state. If the universe ever falls into the actual minimum, the energy release would wipe out the cosmos … the “electroweak vacuum catastrophe”.

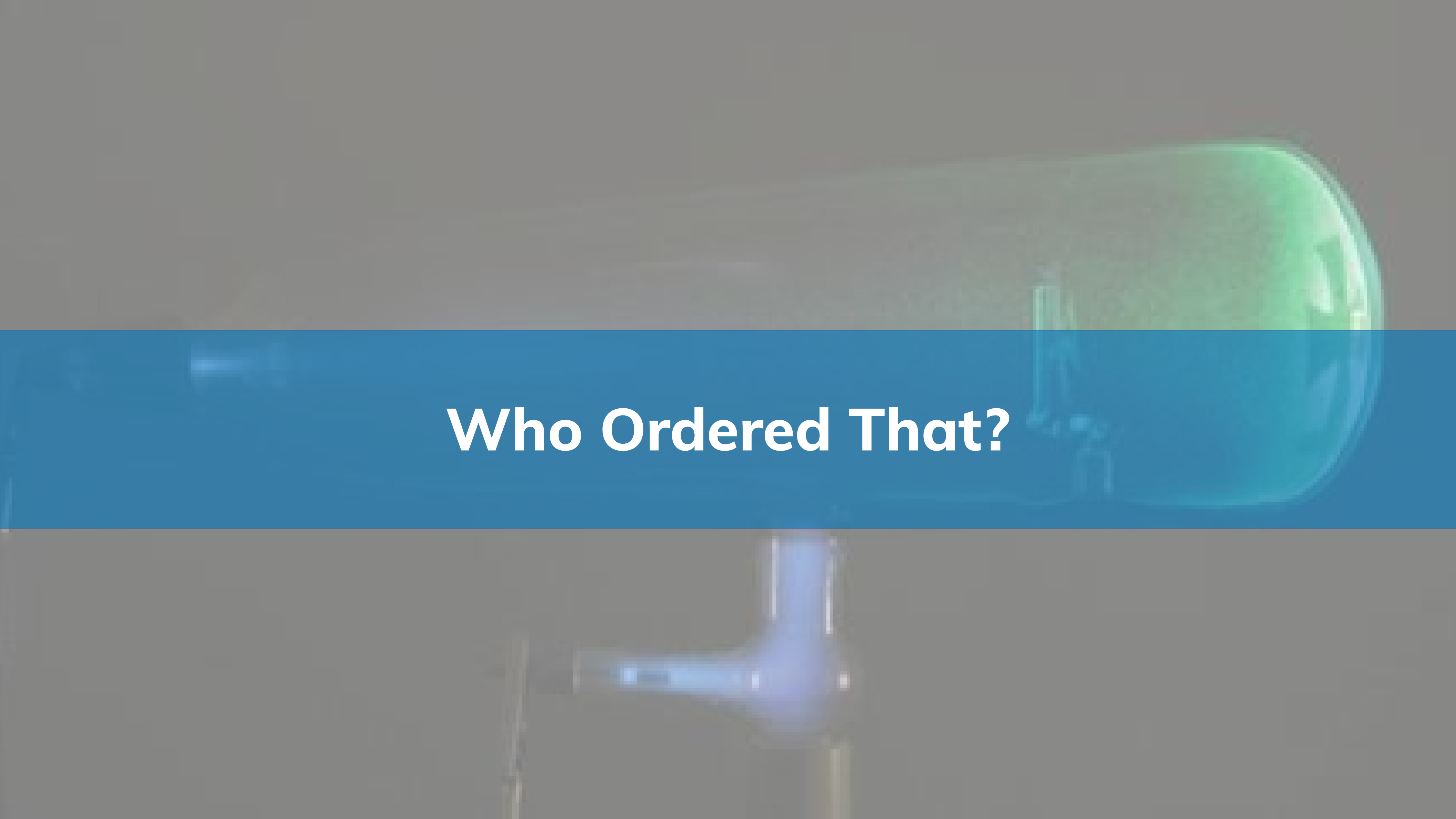



**I choose to interpret this as meaning the SM is NOT the final theory of nature, and the real final theory won’t suffer from this.**

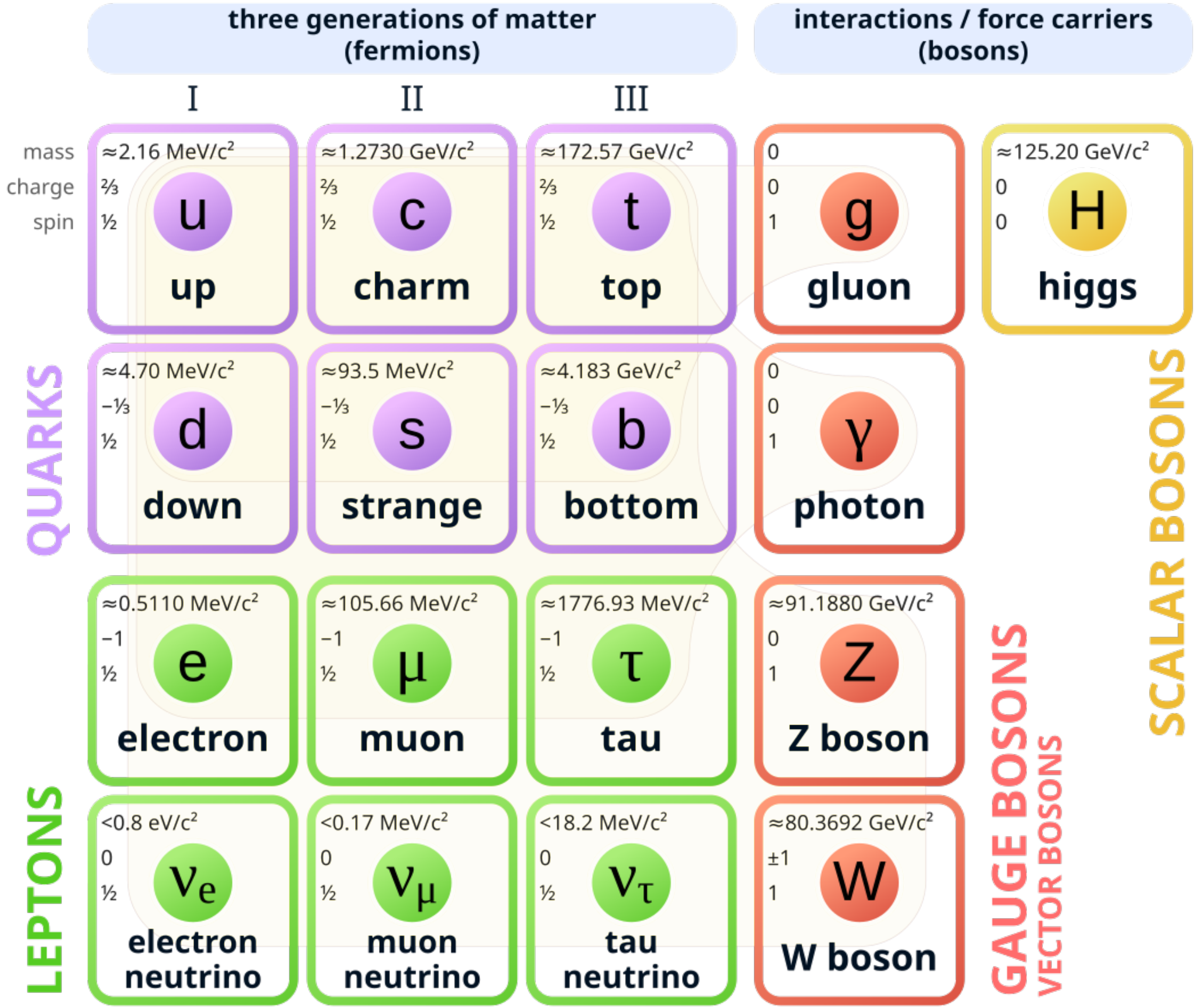


Markkanen, Tommi; Rajantie, Arttu; Stopyra, Stephen (2018). "Cosmological Aspects of Higgs Vacuum Metastability". Frontiers in Astronomy and Space Sciences. 5: 40. arXiv:1809.06923

# Who Ordered That?



# Standard Model of Elementary Particles




## The Standard Model is, itself, not predictive on a number of subjects:

- The origin of families. Why are there quarks ***and*** leptons, and why are they so different?
- The origin of generations. Why are there three, and are there more?
- The origin of the coupling of the Higgs to fermions and bosons. We traded "Why is there mass?" for "Who set these couplings?".
- Why are masses so different?
- Why are these forces so different?
- Hey, where's gravity? Does it need to be here?

# The Mass Hierarchy Problem

- Why are the Yukawa couplings of the fermions to the Higgs field so radiacally different? What sets these couplings?
- Why are neutrinos massive and why are their masses so vastly different from the quarks and charged leptons?

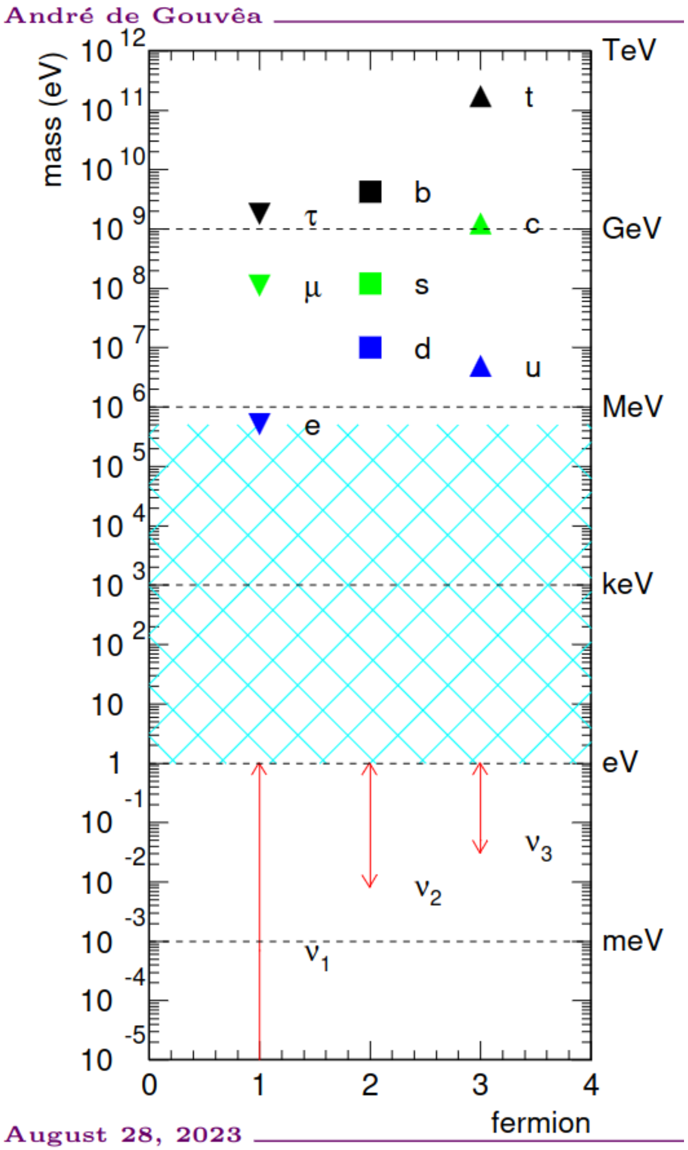
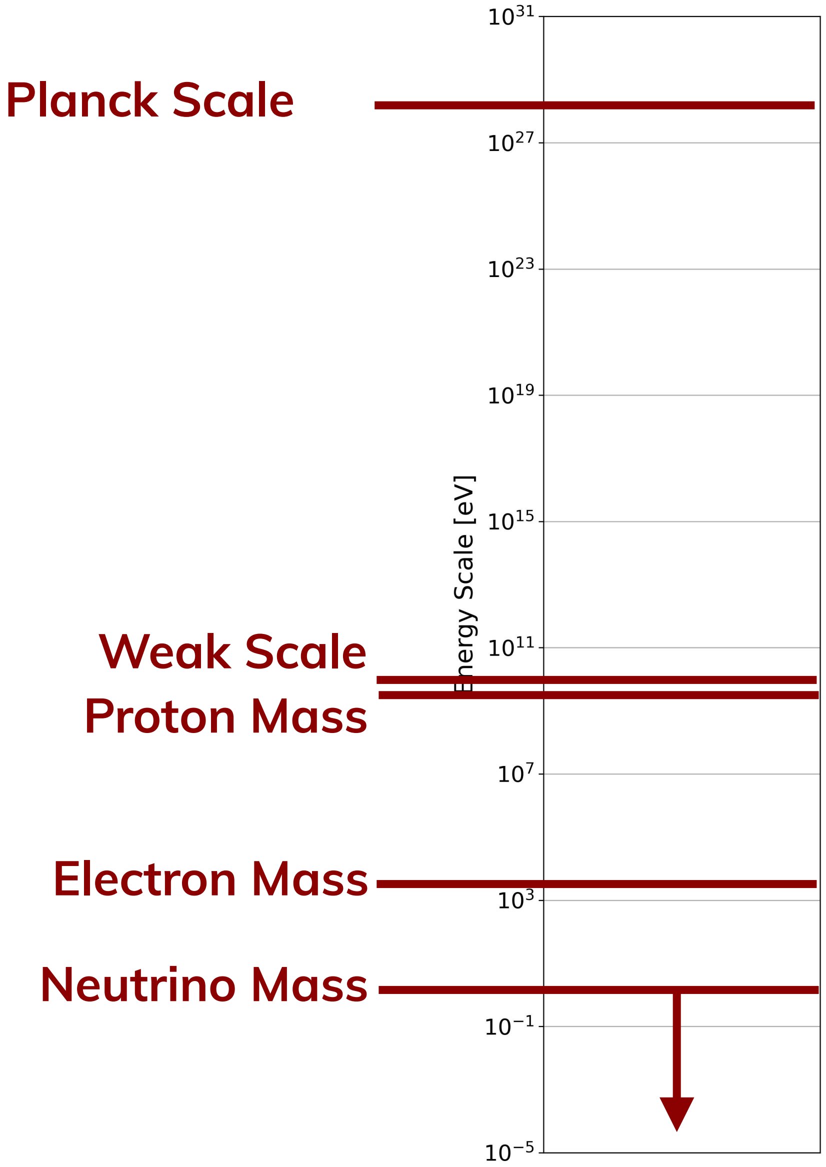



Image by Andre de Gouvea, TAUP 2023

# The Energy Scale Hierarchy Problem

- If gravity and the standard model are ever to be related, one needs to understand the vast energy scale difference between when the EW unification occurs and when gravity would become strong.
- Somewhere in between, maybe EW and QCD unite at a ***Grand Unified Theory (GUT)*** energy scale?
- Are there other energy scales? (c.f. dark matter)



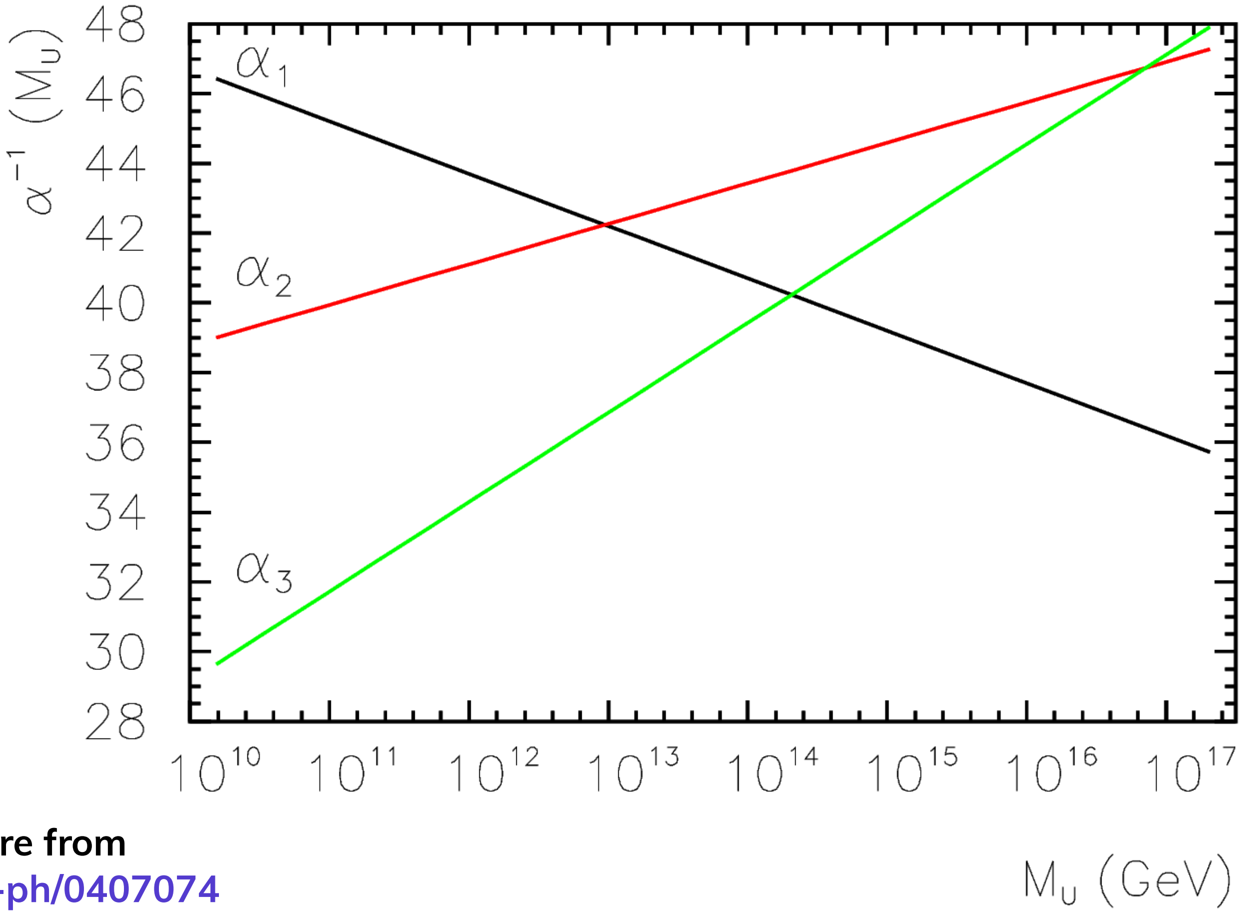
# The Vacuum Energy Problem

SNOLAB

- If one interprets the accelerated expansion of the universe as being due to a cosmologically constant energy density in space, Planck satellite data would suggest $\Lambda \sim 3.35$ GeV/m$^3$.
- The Standard Model is, at best, an effective quantum field theory valid in some energy range (e.g., up to some energy scale above which the effective theory is no longer valid). It predicts corrections to particle masses, etc. due to virtual particles
  - If we assume the energy scale is the Planck scale ($10^{28}$ eV), the energy density of the vacuum would be $10^{120}$ greater than observed.
  - If we were more modest and cut off the theory at the EW scale (246 GeV), then we still are too big by $10^{55}$ or so.
- A safe interpretation: there are things we don't yet understand about the universe, or that we haven't done right in our application of QFT to the universe.

c.f., arXiv:1002.3966

# Such a Disappointment




The Standard Model had some promise early on for delivering a "unified field theory" wherein at high energies $g_{EM} = g_W = g_S$. The electroweak sector of the SM is a partial realization of that dream. Alas, in the baseline theory the strong coupling constant misses uniting with the EW coupling constants.

Do real theories of nature have to unify all forces? This may or may not be a human bias, but it feels clunky in the SM.

**Figure from**
hep-ph/0407074

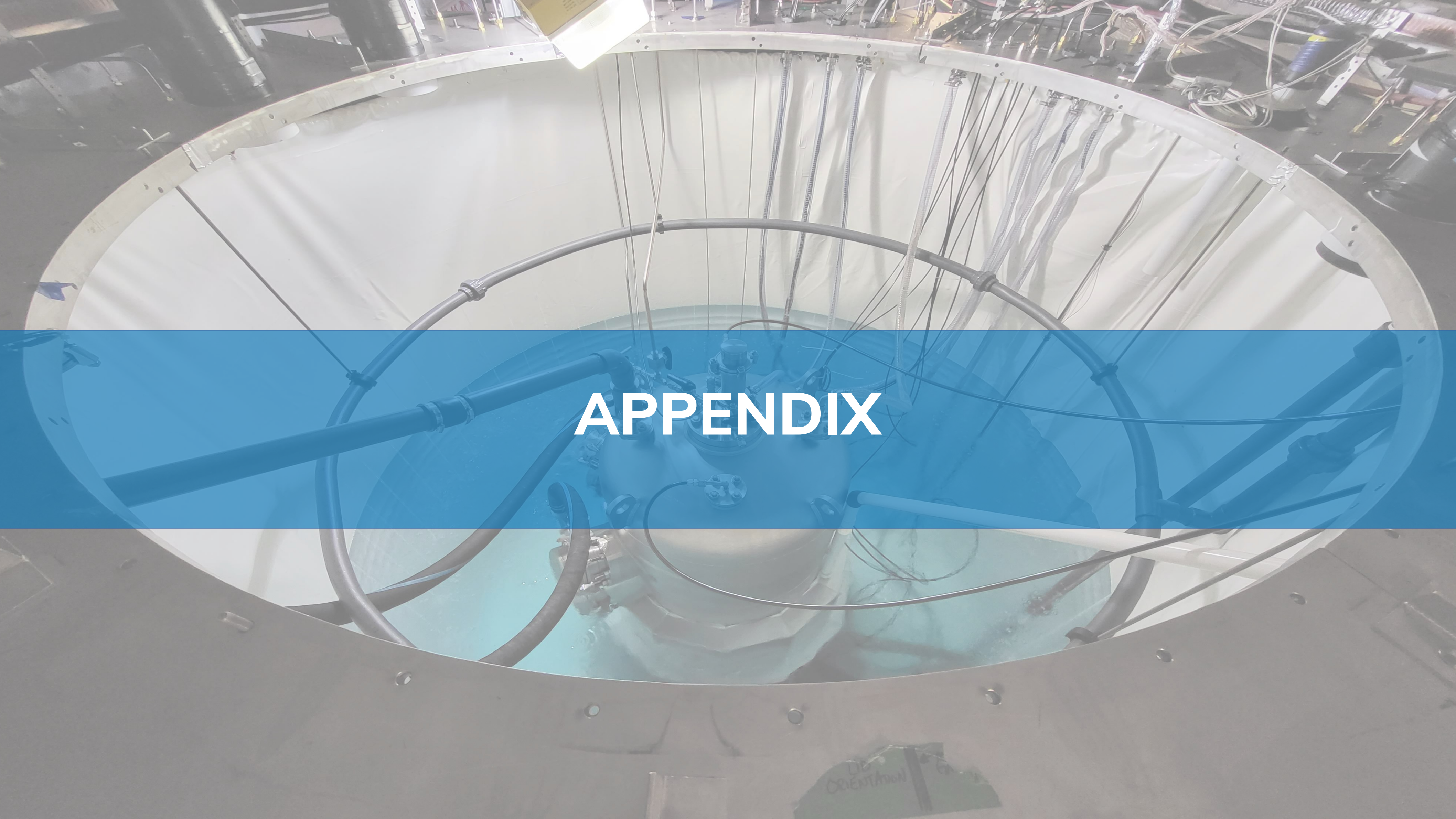
# Lost at Sea

- When I was in high school, Stephen Hawking's "A Brief History of Time" had recently been a best seller, string theory was still all the rage, and there was really just the top quark and the Higgs boson to "sort out". The Standard Model seemed to be a good start on a final theory … if we could just tie up those loose ends … a few annoying puzzles.
- When I went to graduate school in 1998, all that seemed left was the Higgs particle.
- By the time I earned my PhD in 2004, astronomy, astrophysics, and cosmology were pointing to a universe ruled by dark matter and dark energy, and neutrinos had mass (mixing was clearly observed).

# Lost at Sea

- The Standard Model is essentially complete now, in the way it was envisioned in the 1970s and 1980s … but given the pace of experimental/observational discovery it feels like we are no closer to a better theory of nature.
- Remember the lessons of classical mechanics, thermodynamics, and classical field theory (EM): there are good ideas that work really well.
- Let the puzzles of your age lead the way. Follow them, be relentless and undaunted, and look in every corner of the data and the math. Try corners no one else is trying.
- We can do this. We can find our way to a better theory of nature.

# APPENDIX



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