CERN, 25th - 29th July 2022

The Branco Weiss Fellowship Society in Science

Beyond the Standard Model

Tevong You

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CERN → KING'S College LONDON

Contents

- Lecture 1: Introduction/high-level overview
- Lecture 2: Effective Field Theory (EFT)/naturalness
- Lecture 3: Supersymmetry/extra-dimensions/composite Higgs
- Lecture 4: Neutrinos/Dark matter/QCD axion/relaxion

Lecture 1: introduction/high-level overview

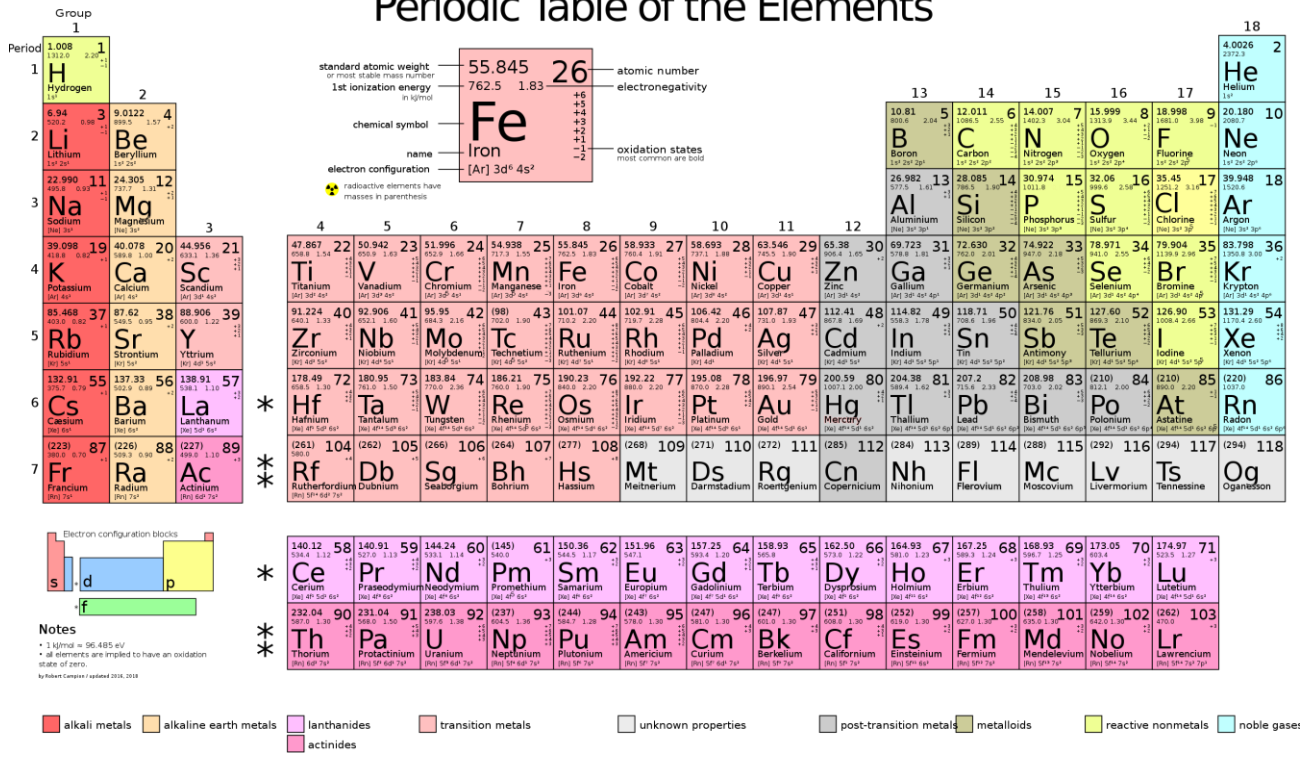
Introduction

- 1900: Almost all data agree spectacularly with the fundamental framework of the time, *no reason to doubt its universal applicability or completeness*.

- 1920s: A combination of **precision measurements** (Mercury), **aesthetic arguments** (relativity) supported by **null experimental results** (Michelson-Morley), and **theoretical inconsistencies** (Rayleigh-Jeans UV catastrophe) lead to an overhaul of the fundamental picture at **smaller scales** and **higher energies** after *pushing the frontiers of technology and theory into new regimes.*

Particle physics in 5 minutes

- *Only **92*** stable elements



- *Everything you see around you* is a combination of these elements

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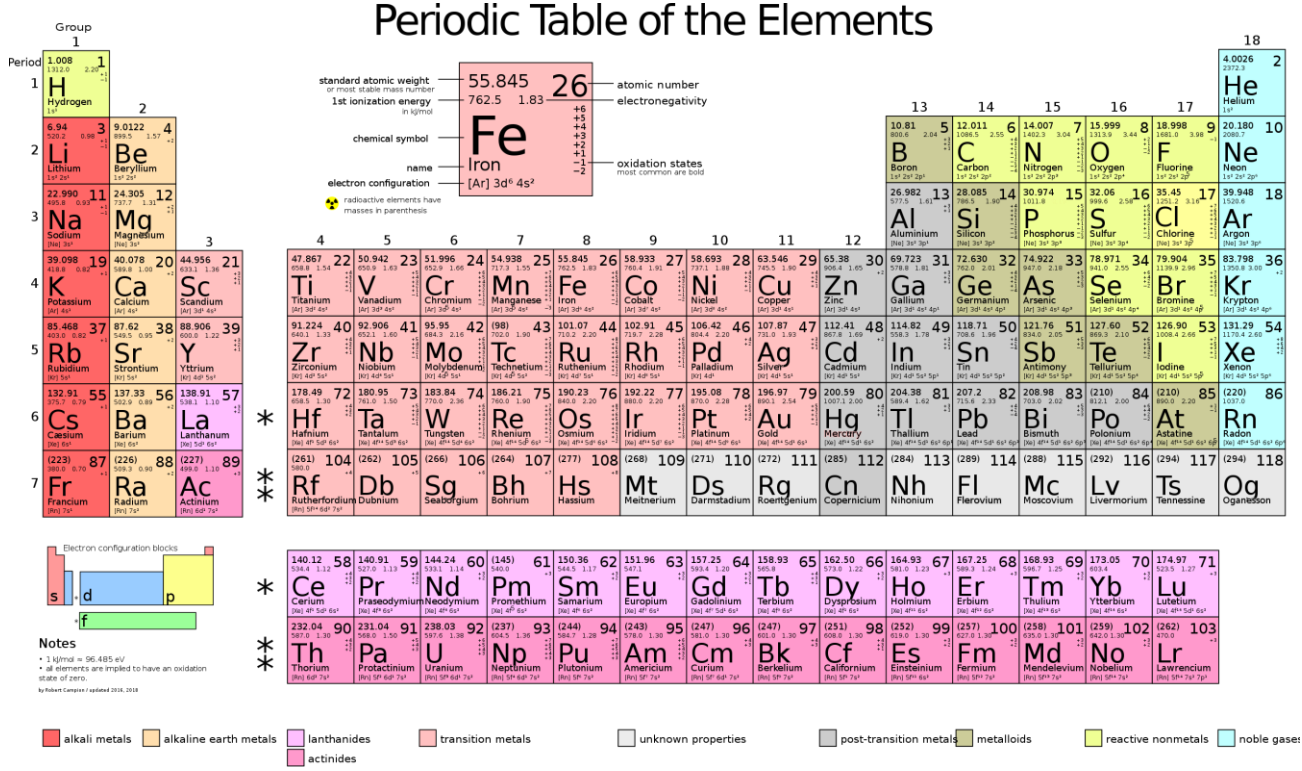
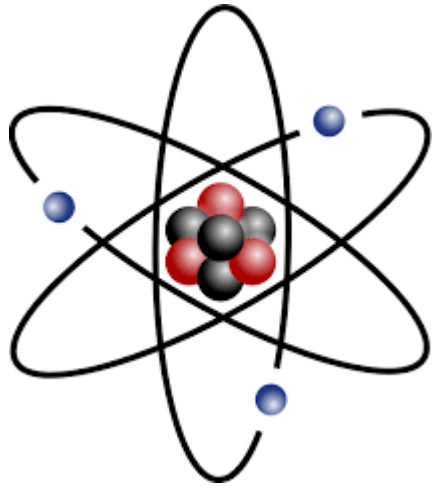


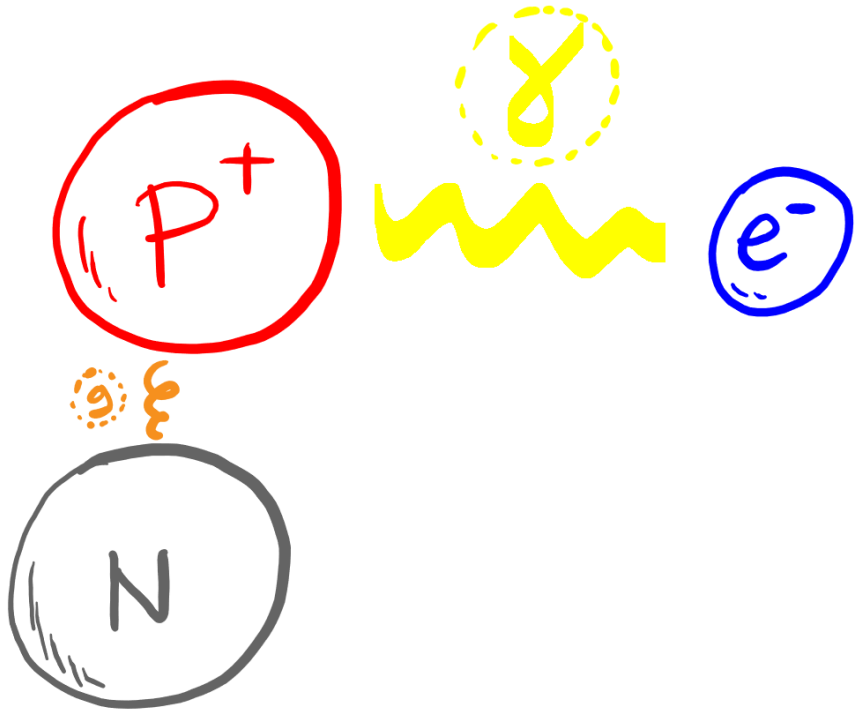


Each element is made of protons and neutrons in the nucleus, surrounded by electrons

- *Everything you see around you* is a combination of these elements

Particle physics in 5 minutes

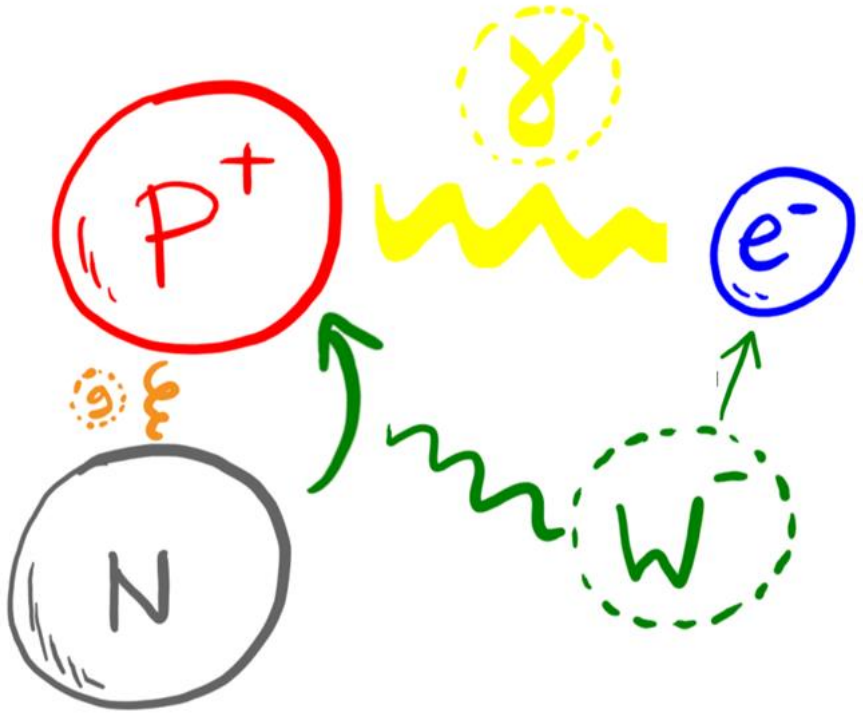
- *1930s*: *everything* is made of **protons**, **neutrons**, and **electrons**



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

Particle physics in 5 minutes

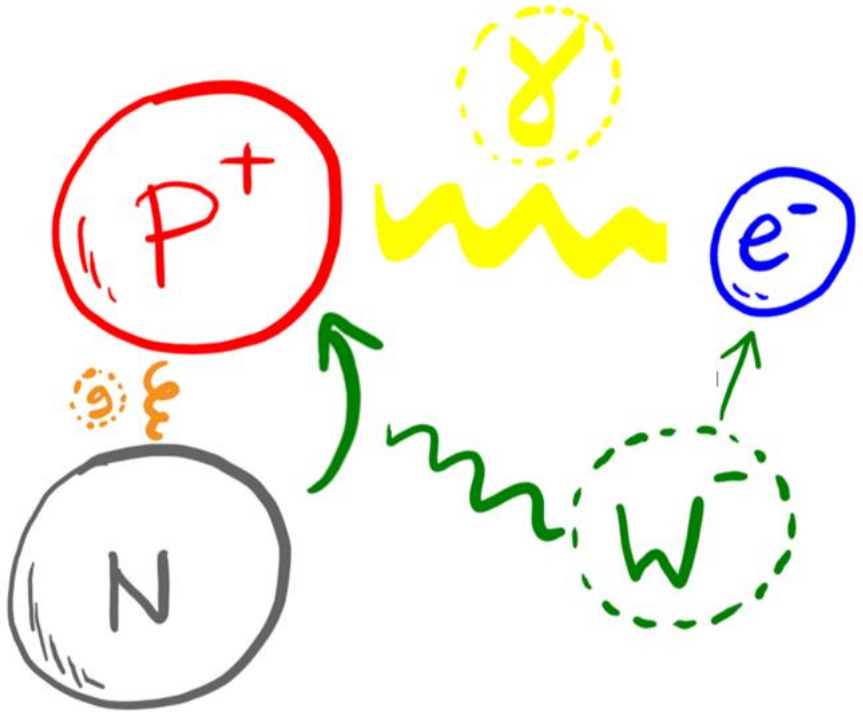
- **Weak force** explains *radioactivity*



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

Particle physics in 5 minutes

- **Weak force** explains *radioactivity*



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

(Bohr suggests fundamental violation of energy conservation principle)

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Particle physics in 5 minutes

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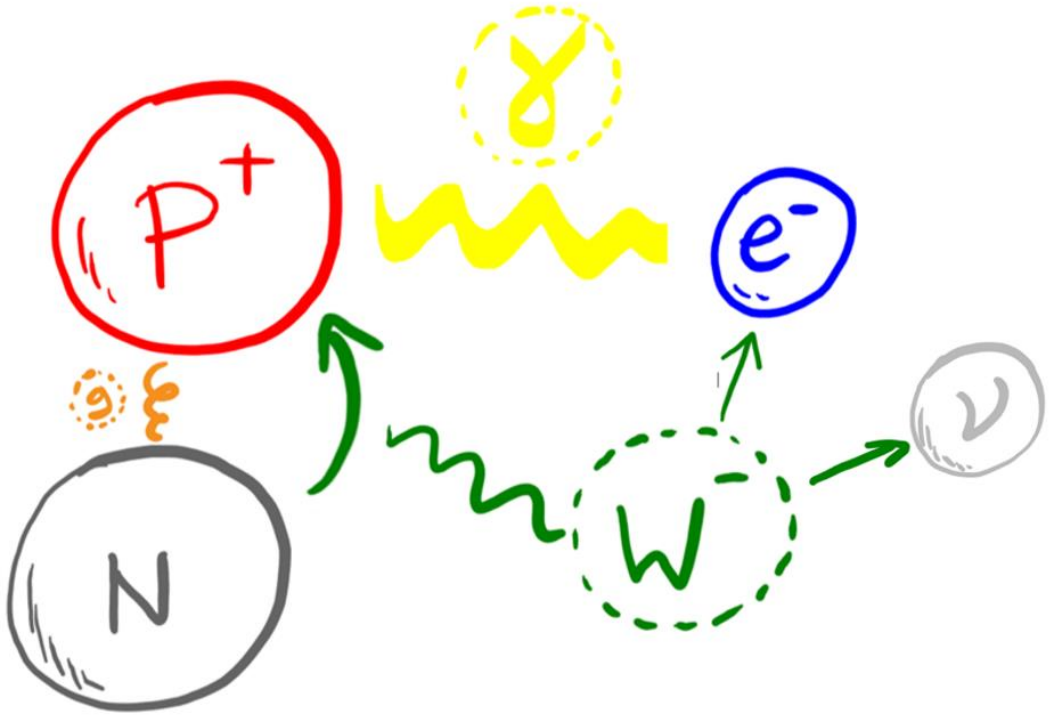


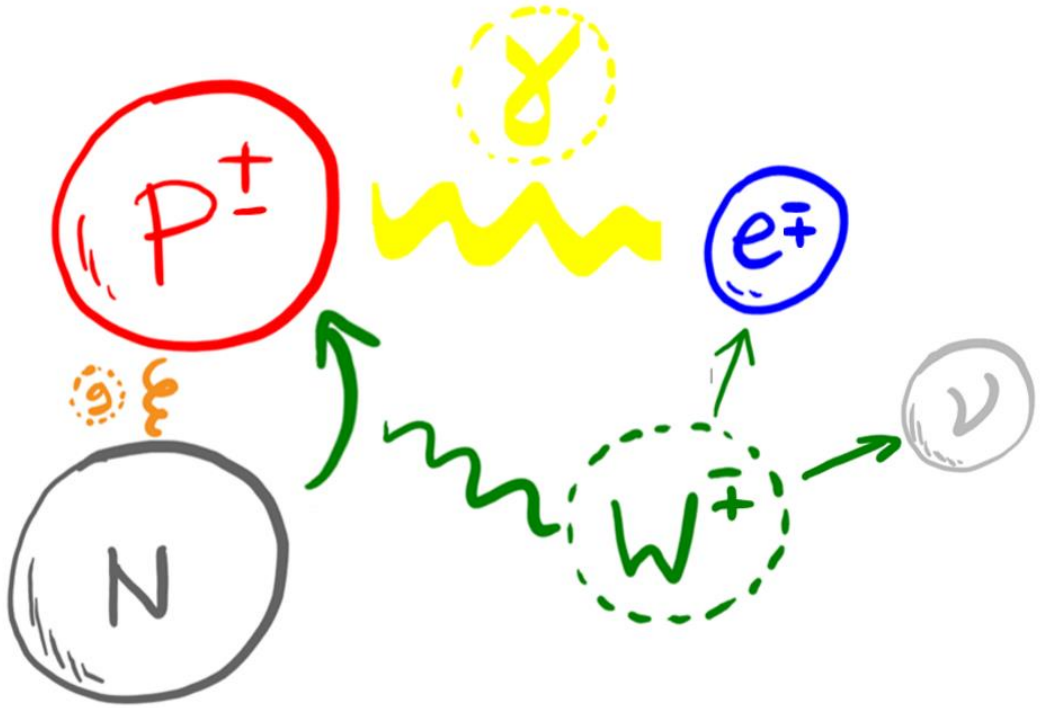
Missing energy? Pauli postulates *"a desperate remedy"*

(Bohr suggests fundamental violation of energy conservation principle)

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

Particle physics in 5 minutes

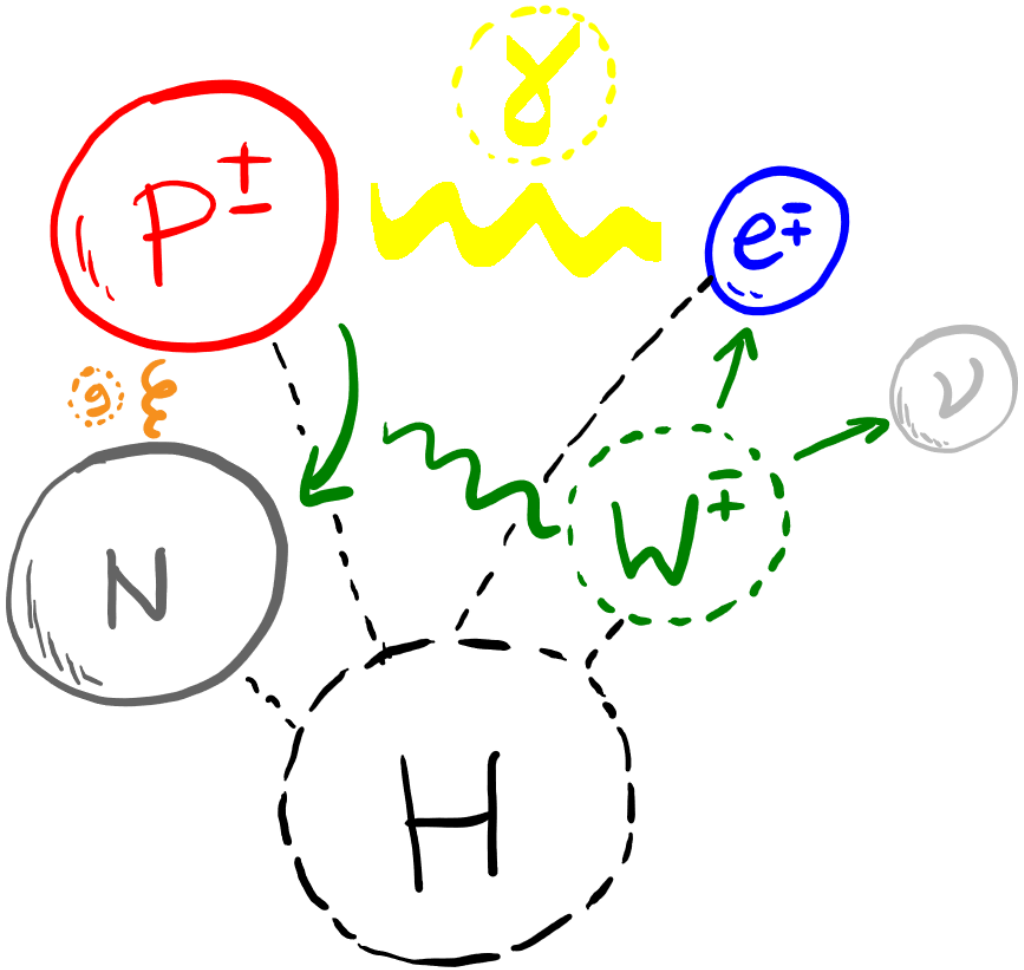
- *Paul Dirac*: Einstein's **relativity** + **quantum mechanics** = **antiparticles**



- *Every particle has an oppositely charged antiparticle partner*

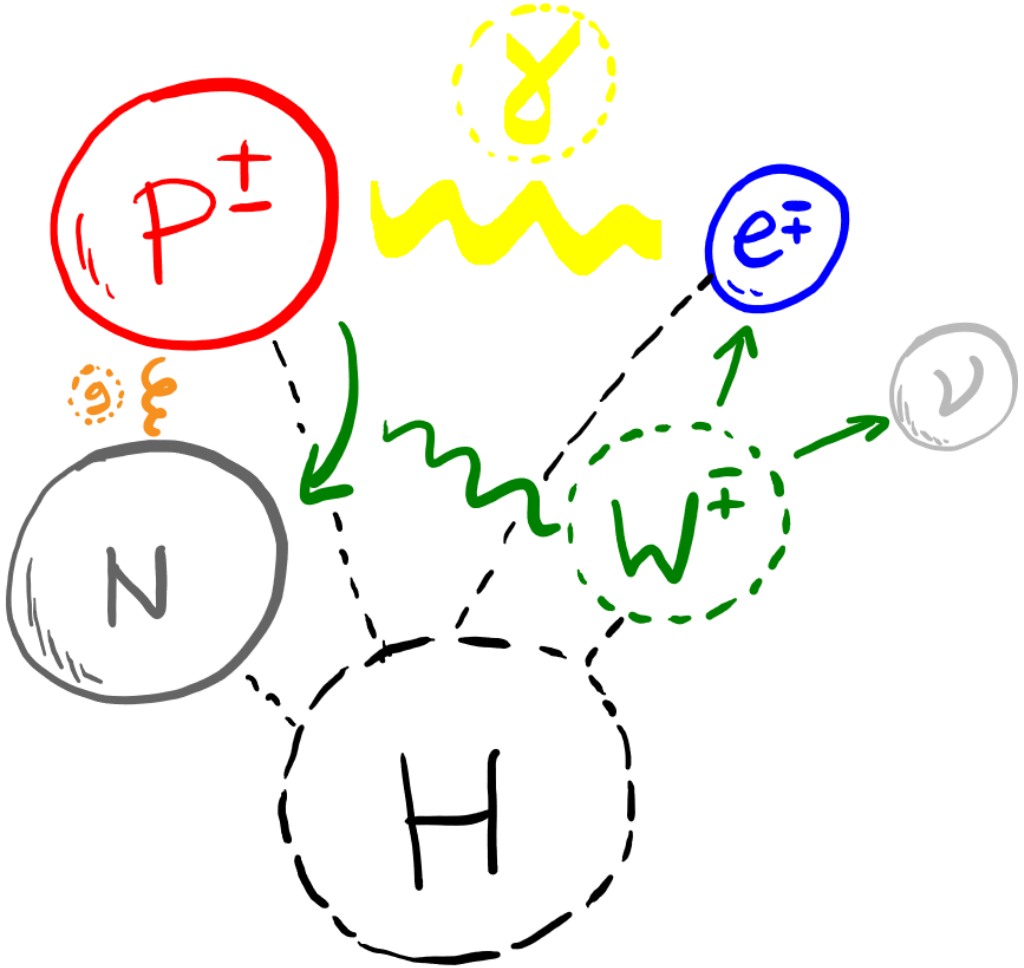
Particle physics in 5 minutes

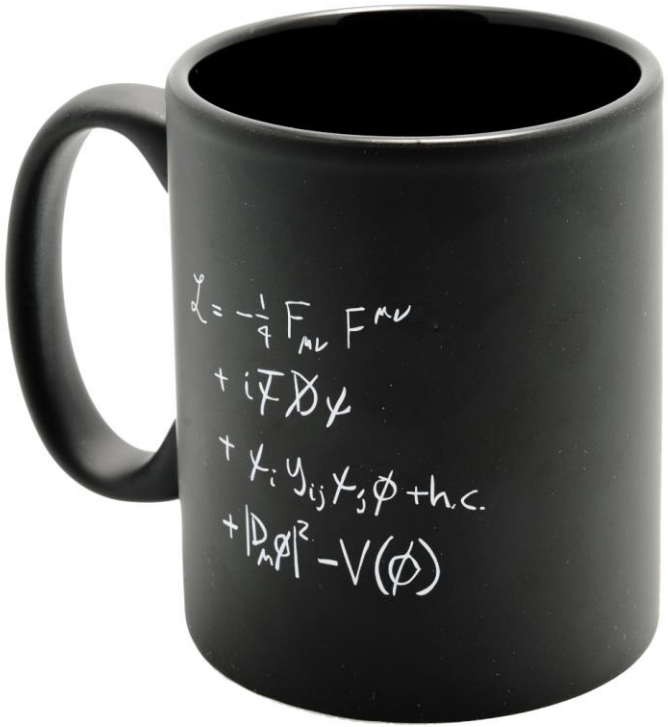
- *Higgs(+Brout+Englert):* **particle masses** require a new **bosonic particle H**



Particle physics in 5 minutes

- The **Standard Model** of particle physics: *the most successful theory ever*





Particle physics in 5 minutes

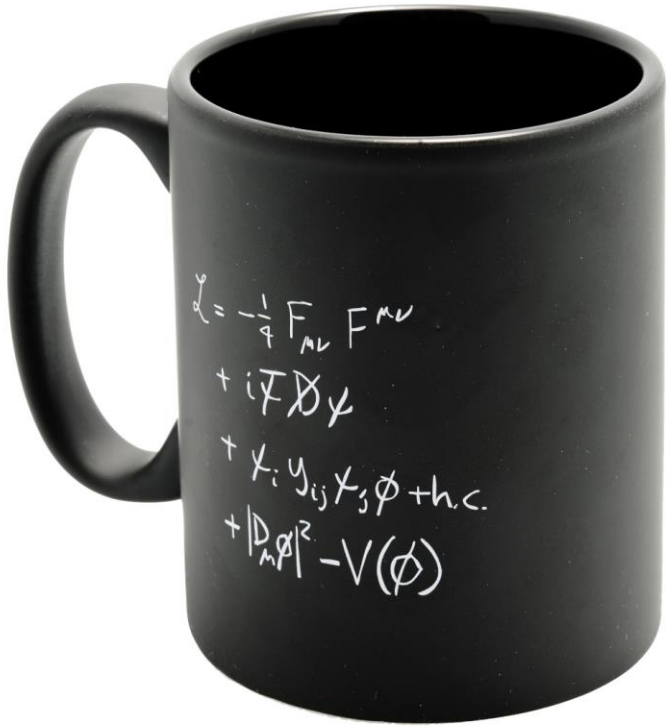
- The **Standard Model** of particle physics: *the most successful theory ever*

$$\mu_e^{\mathrm{QED}} = \frac{e}{2m_e}\frac{g}{2} = \frac{e}{2m_e}\left\{ \underbrace{1}_{\text{Dirac}} + \underbrace{\frac{1}{2}\frac{\alpha}{\pi}}_{\text{Schwinger}} \underbrace{-0.388\frac{\alpha^2}{\pi^2}}_{\text{Petermann}} + \underbrace{1.18\frac{\alpha^3}{\pi^3}}_{\text{Laporta/Remiddi}} \right\}$$

$$= \frac{e}{2m_e}\{1.00115965214 65(270)\} \quad \textbf{Standard Model theory}$$

$$\mu_e^{\mathrm{exp.}} = \frac{e}{2m_e}\{1.00115965218 83(42)\}, \quad \textbf{Experiment}$$

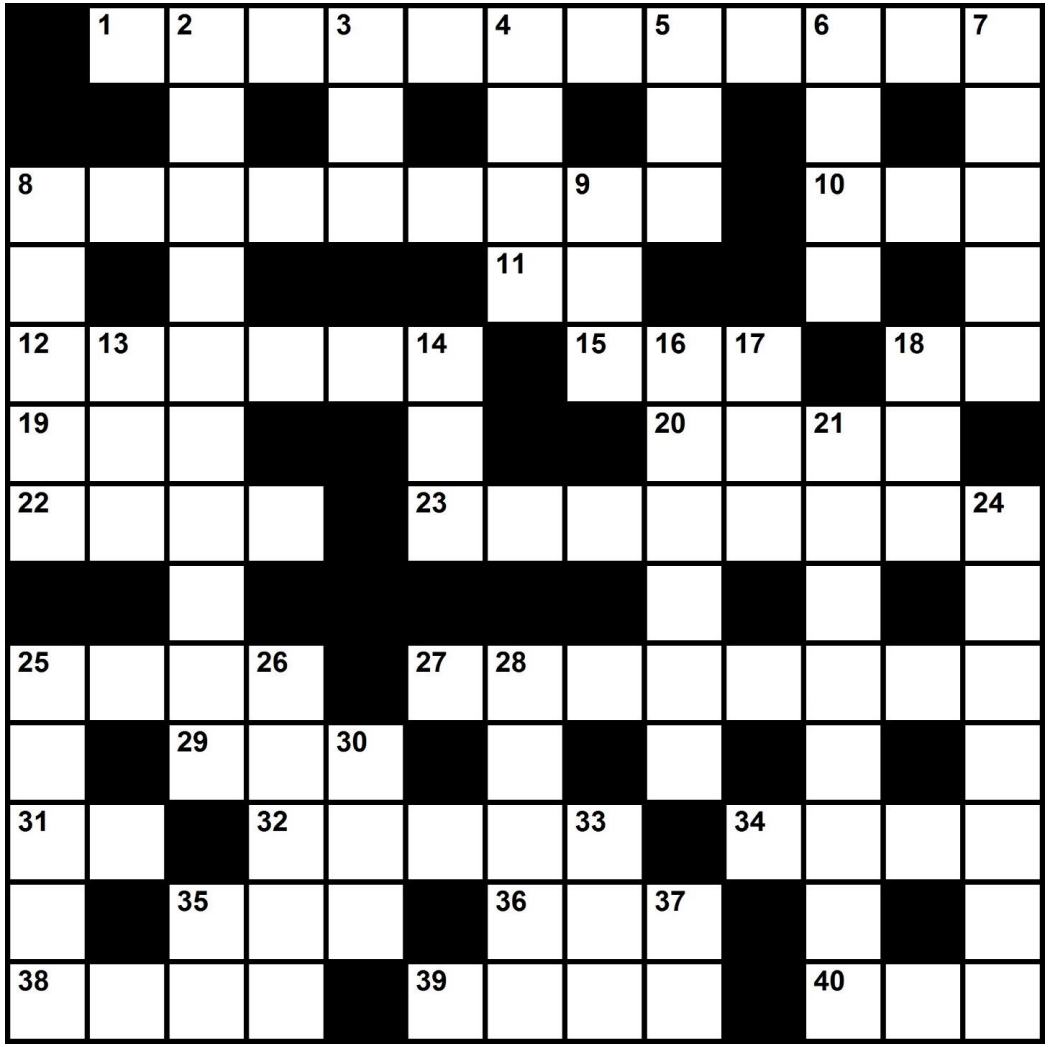
where the experimental value was obtained by Van Dyck, Schwinberg and Dehn



- Agrees with experiment up to **10 decimal places**!

Science: it works

- Science is like a **crossword puzzle**

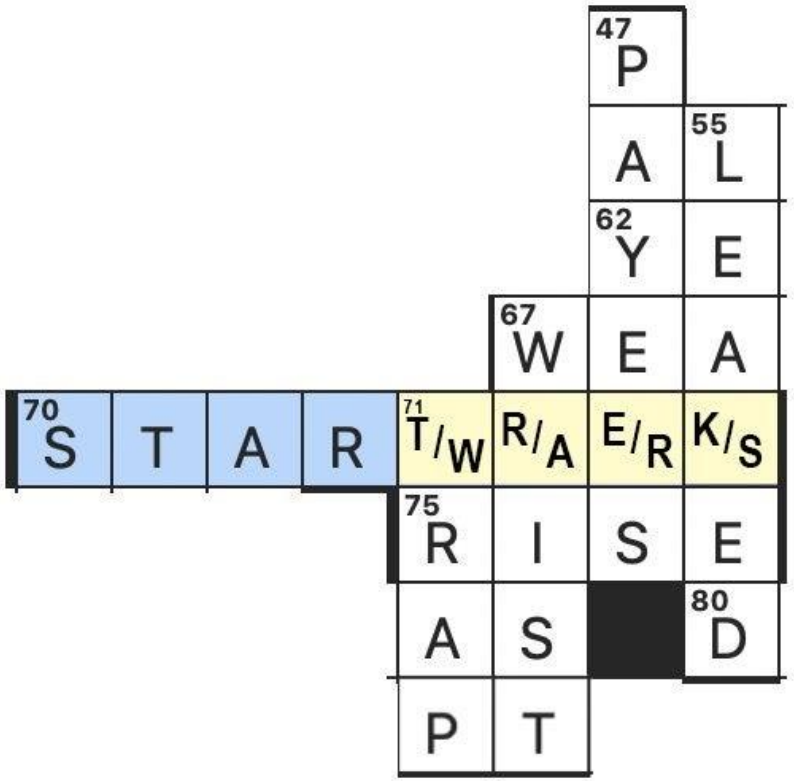


We *know* when we are on **the right track**

Science: it works

- Science is like a **crossword puzzle**

Though sometimes **competing solutions** are *tough to disentangle*…

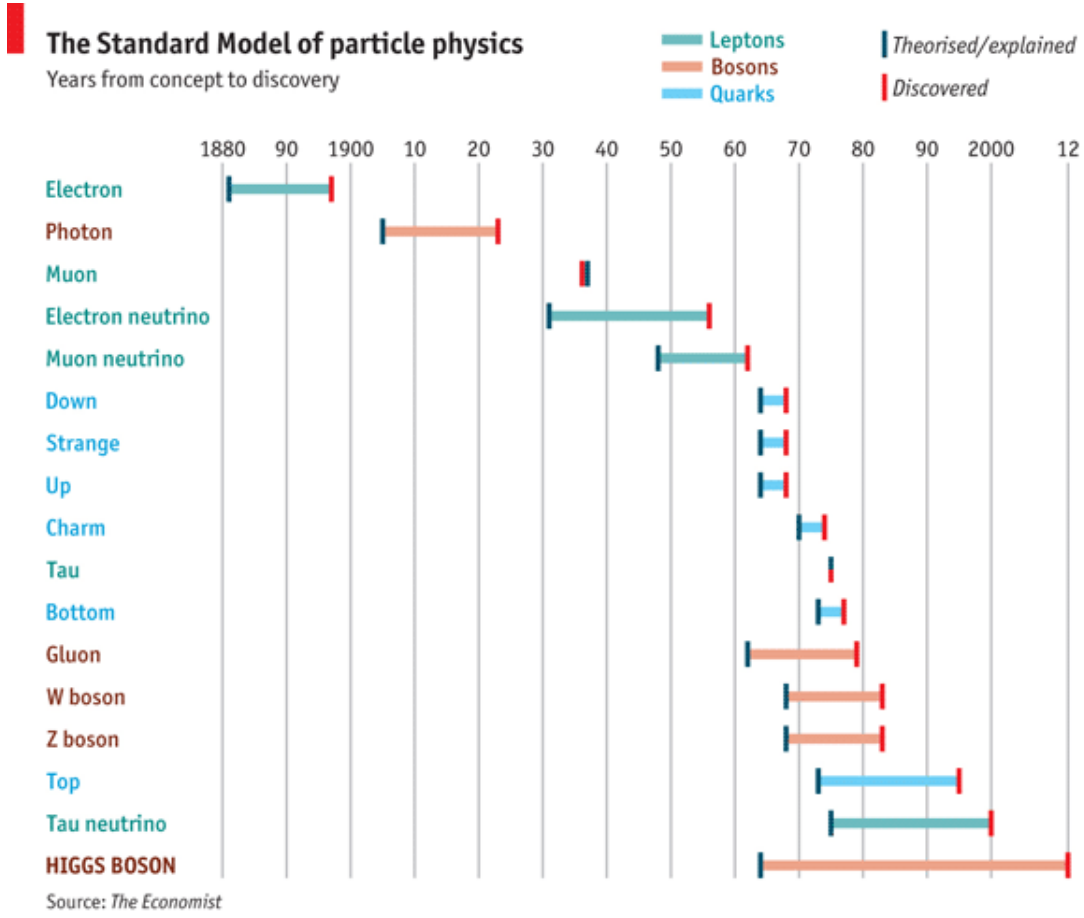


ACROSS:
70. The better of two sci-fi franchises

DOWNS:
71. "It's a ____!"
67. Body part that precedes "band"
47. Ones involved in a transaction
55. Let out, in a way

The Higgs boson discovery

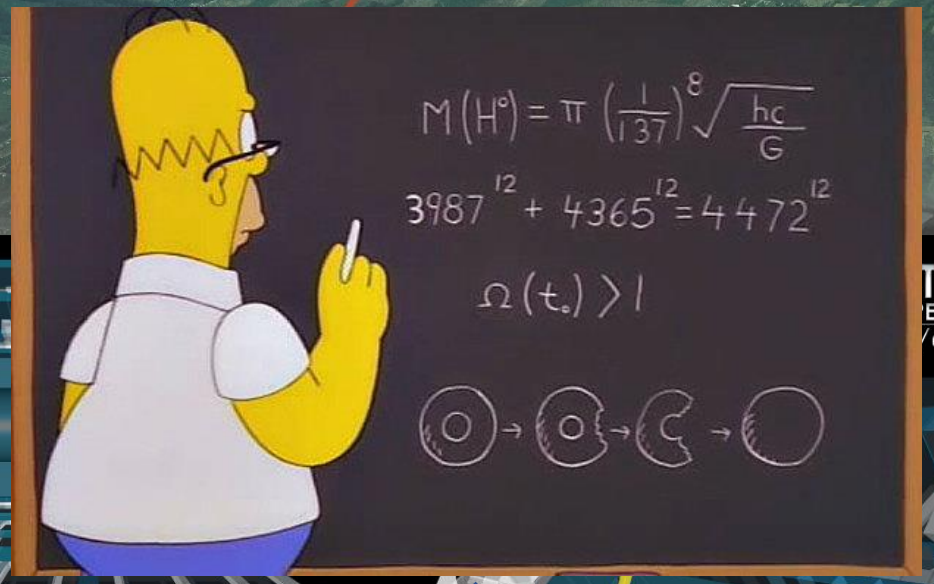
- The **last missing piece** of the Standard Model puzzle

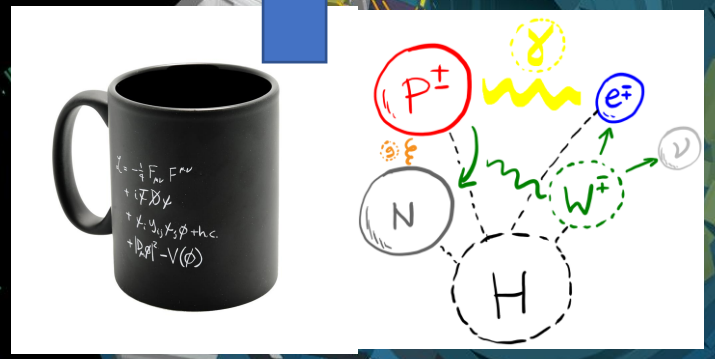


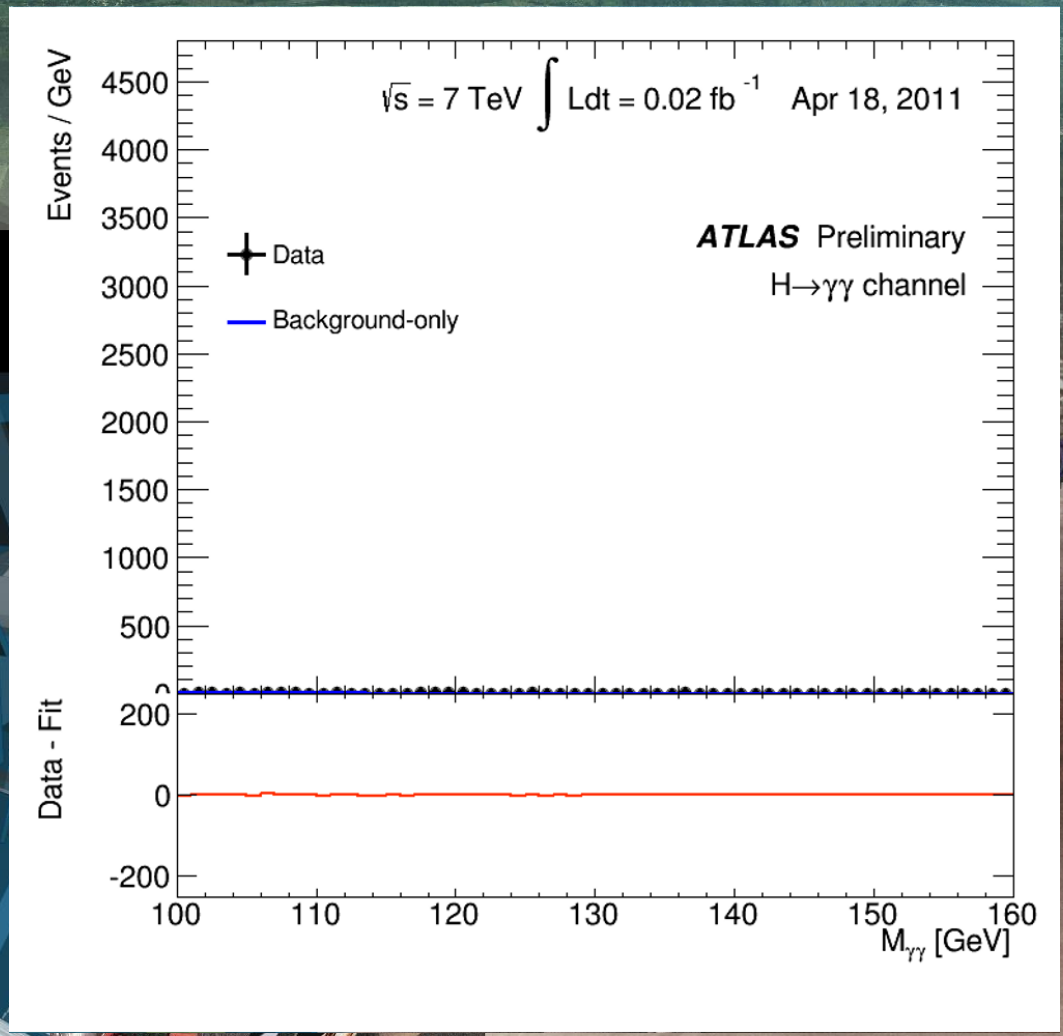
- Caps a **remarkable century** of particle physics

The Higgs boson discovery

- **High energy colliders** probe *directly* the smallest scales







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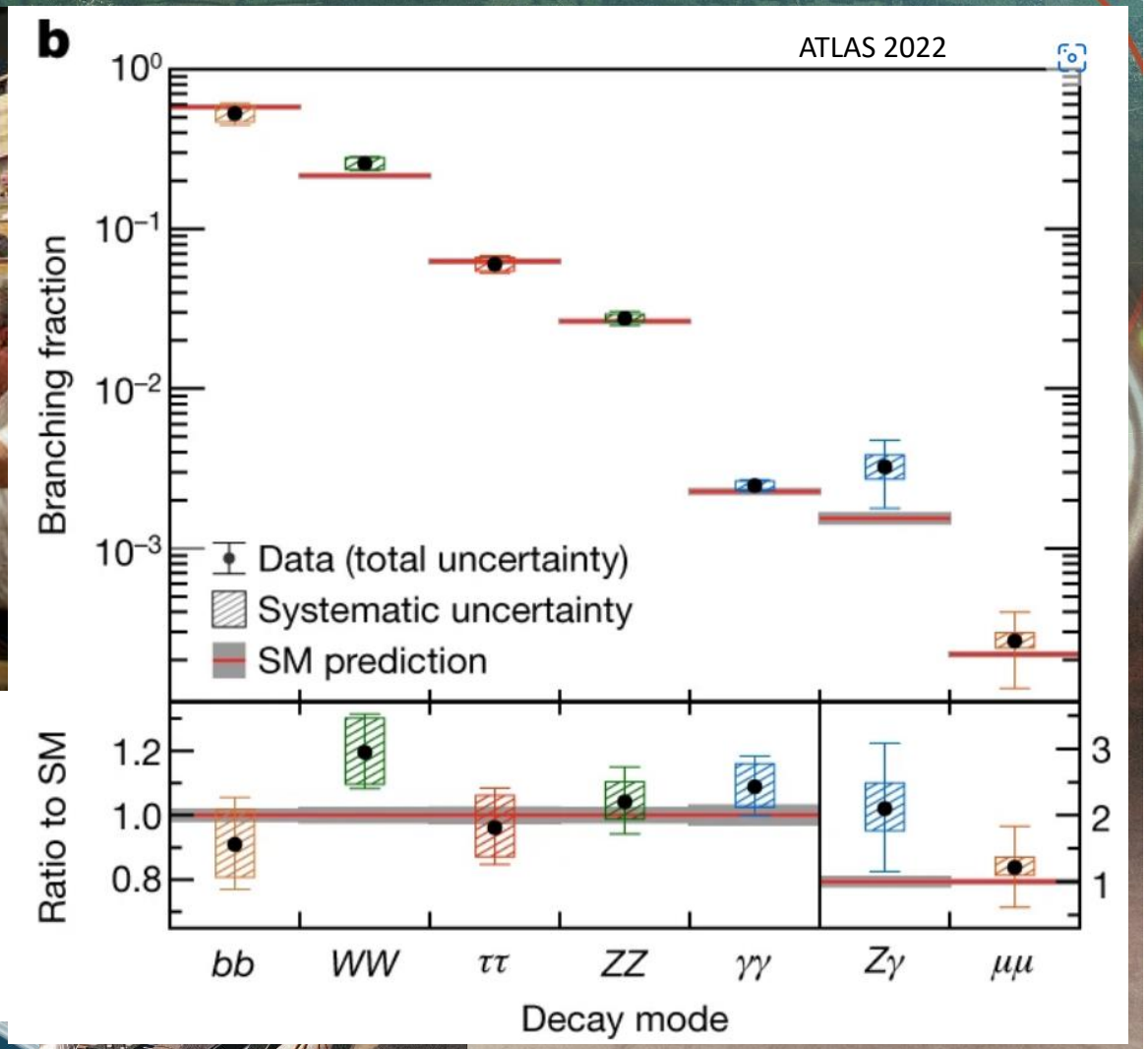
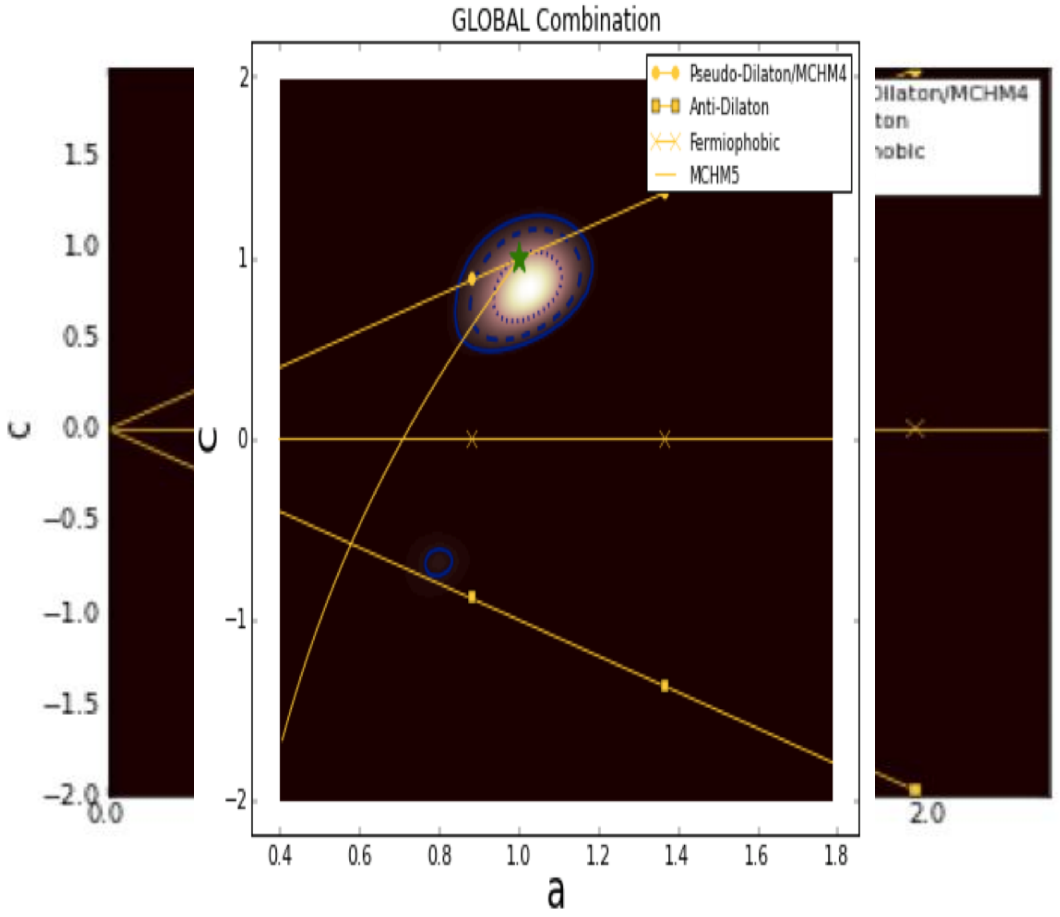


A BSM Higgs boson?

- Couplings *could* have been **very different** from vanilla SM Higgs!

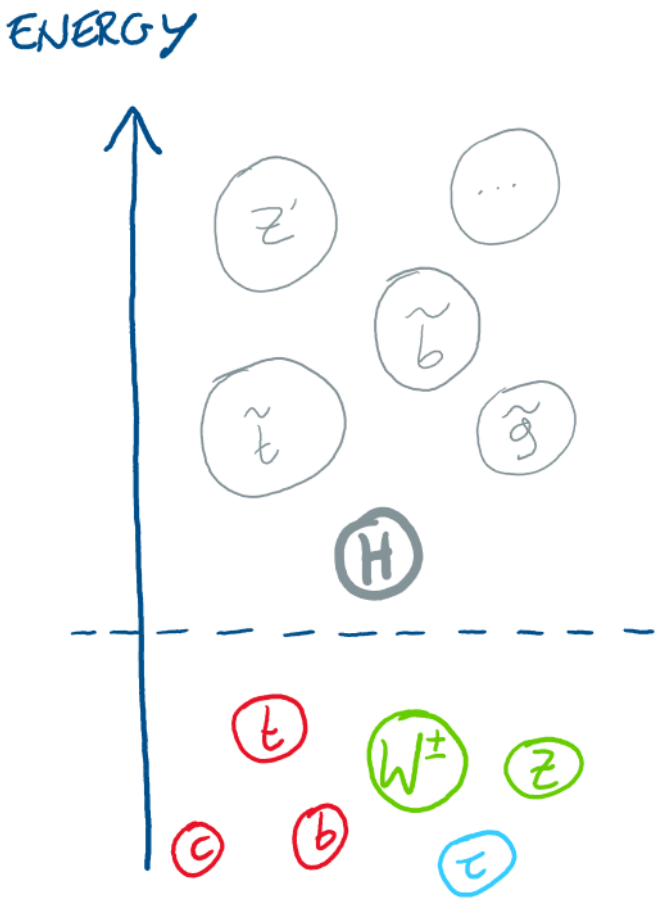


More precision needed to further **explore BSM** in Higgs couplings

March 2013 re-discovery
July 2012 post-discovery
J. Ellis and T.Y. [arXiv:1303.0679]

What next?

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



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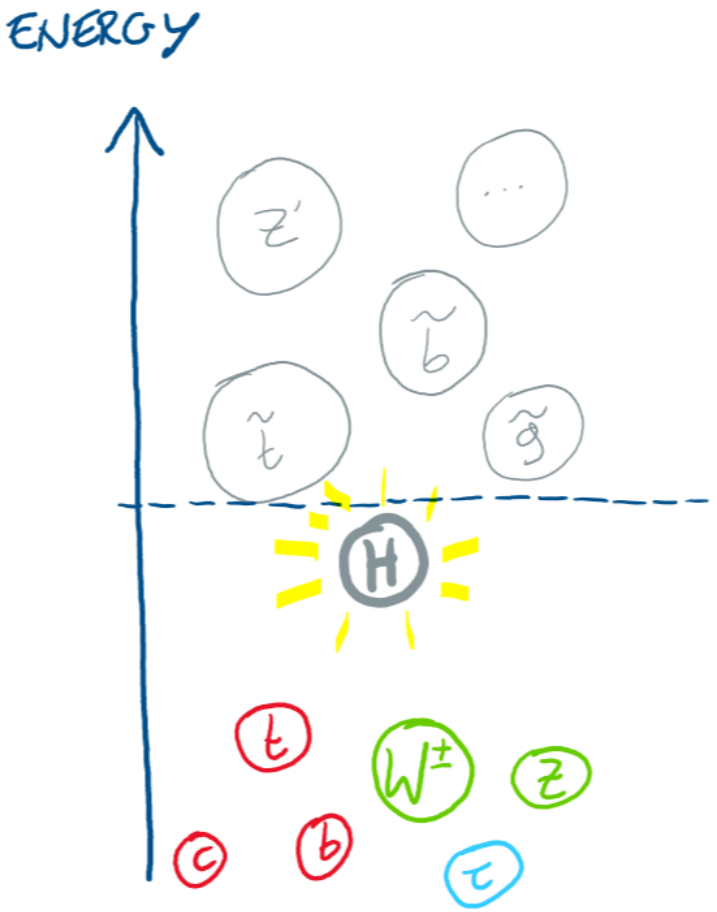

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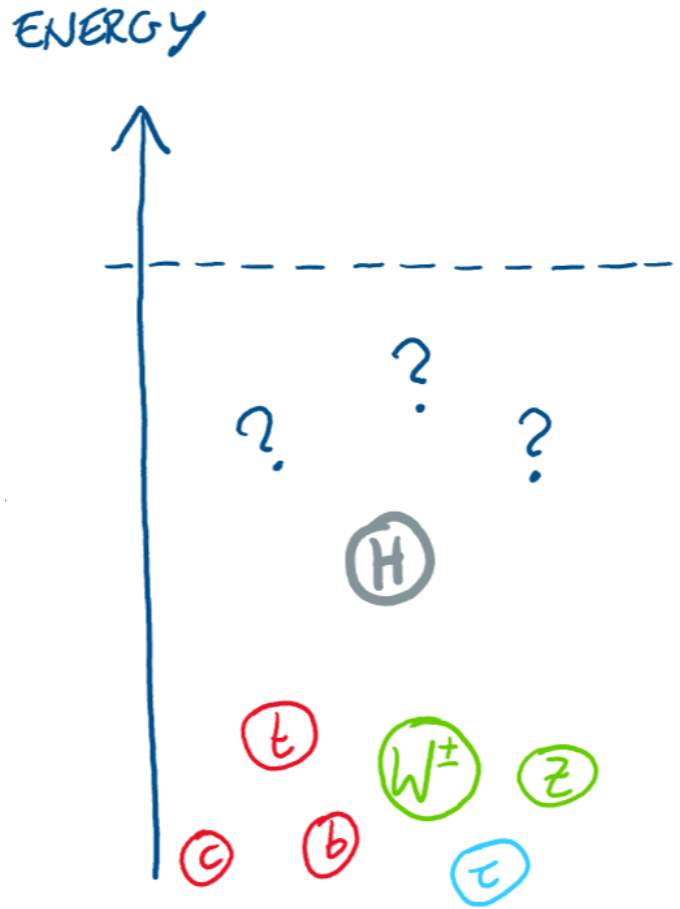

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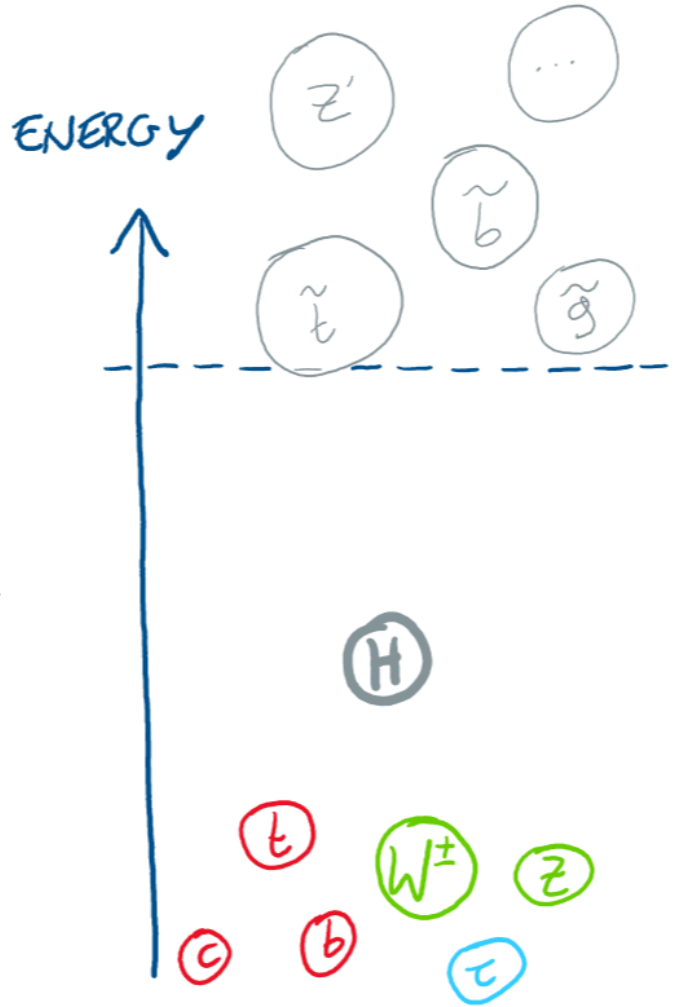

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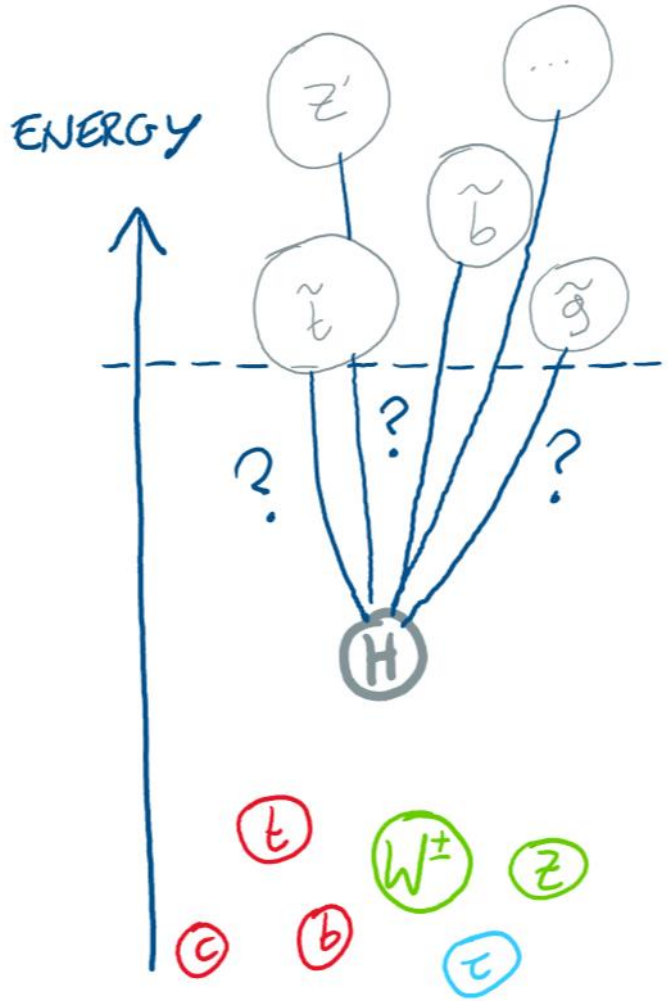

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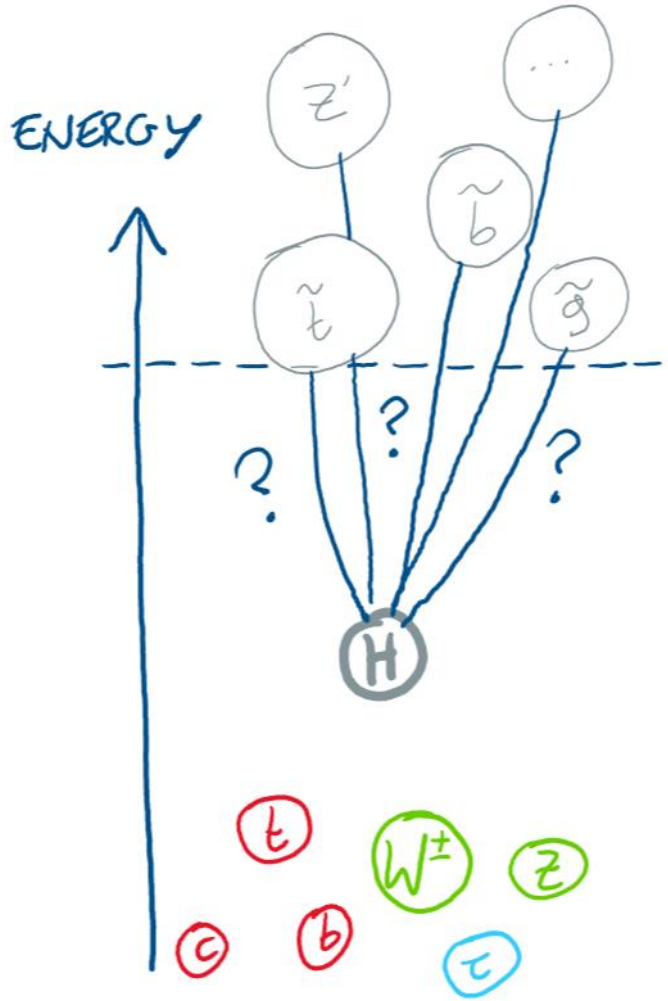

The Higgs is **more mysterious** than ever!

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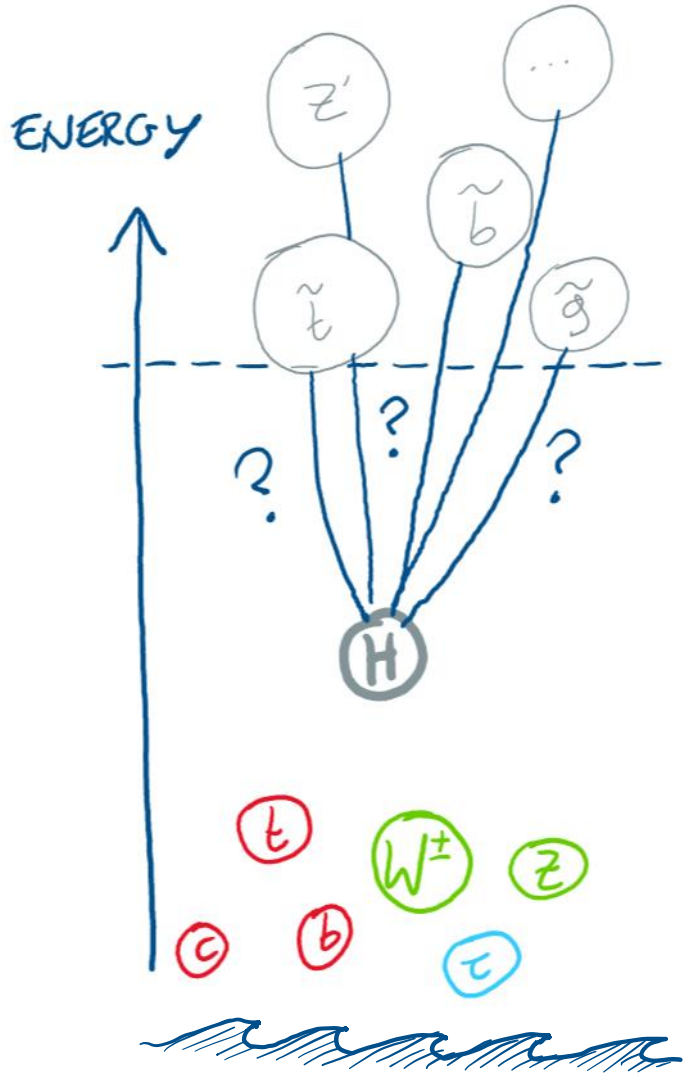

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Vacuum energy is also peculiarly tiny

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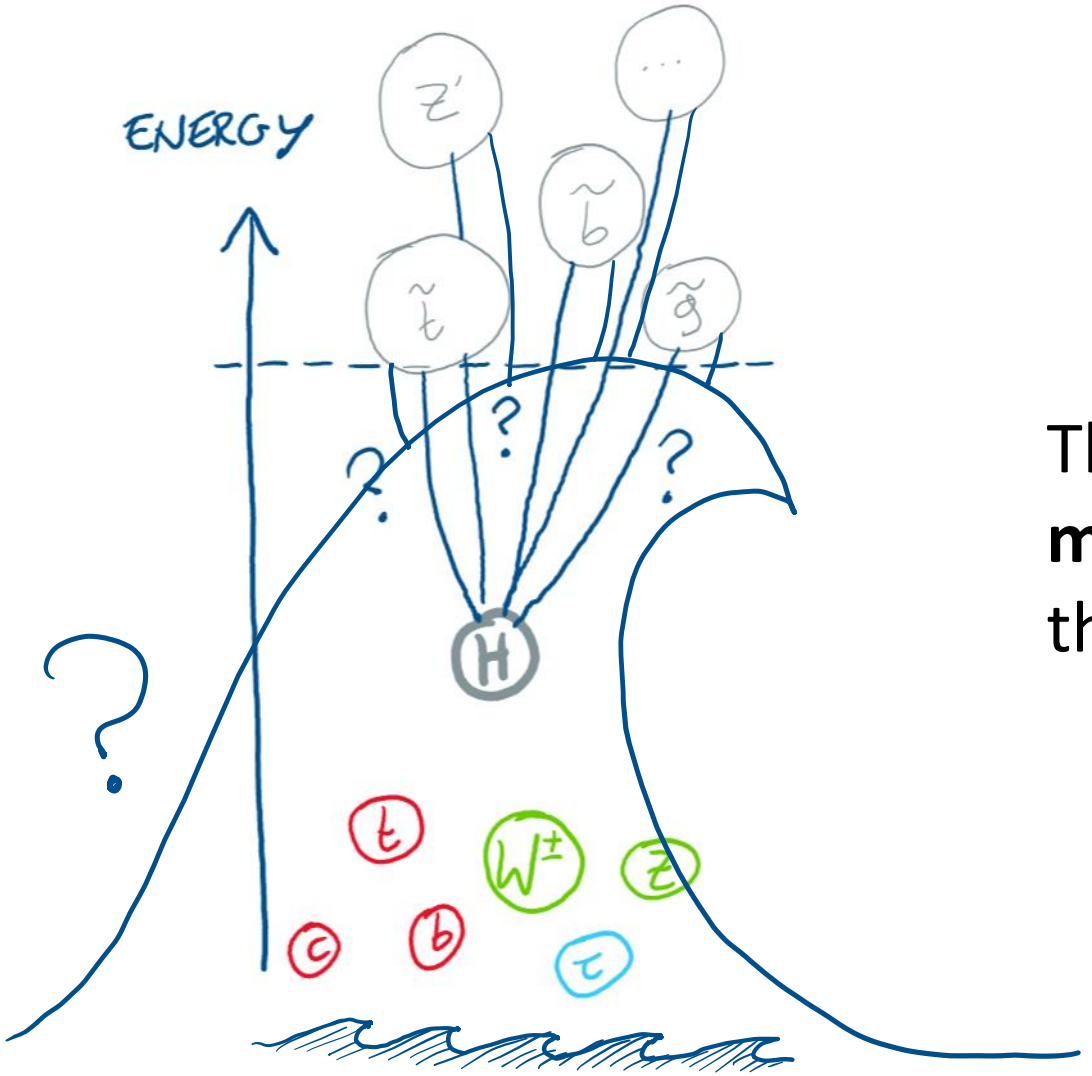
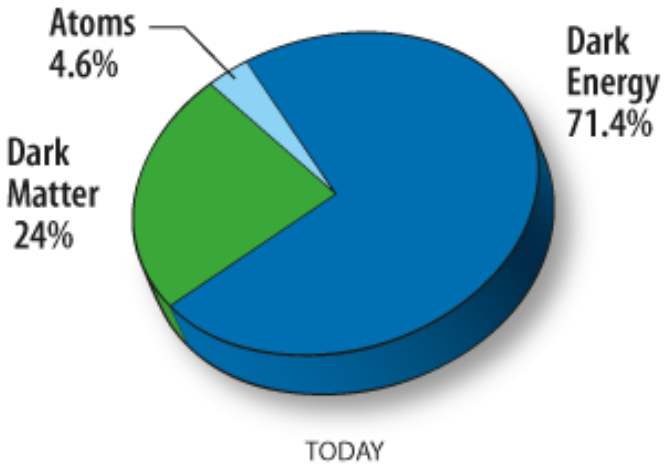


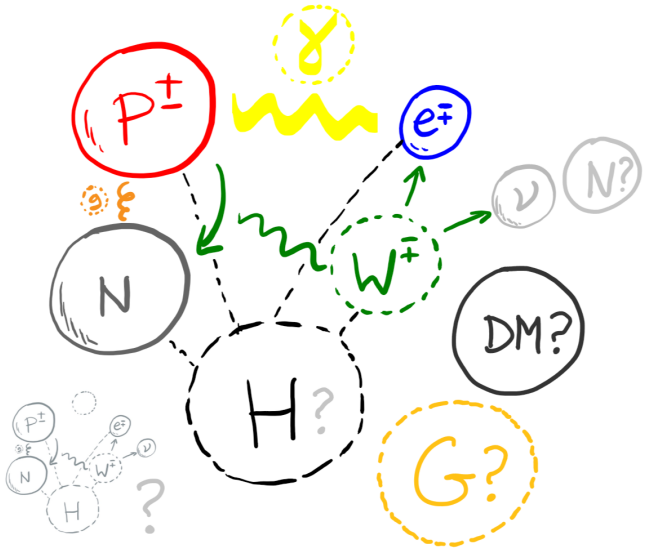
The Higgs is **more mysterious** than ever!

Vacuum energy is also peculiarly tiny

The Standard Model is not enough

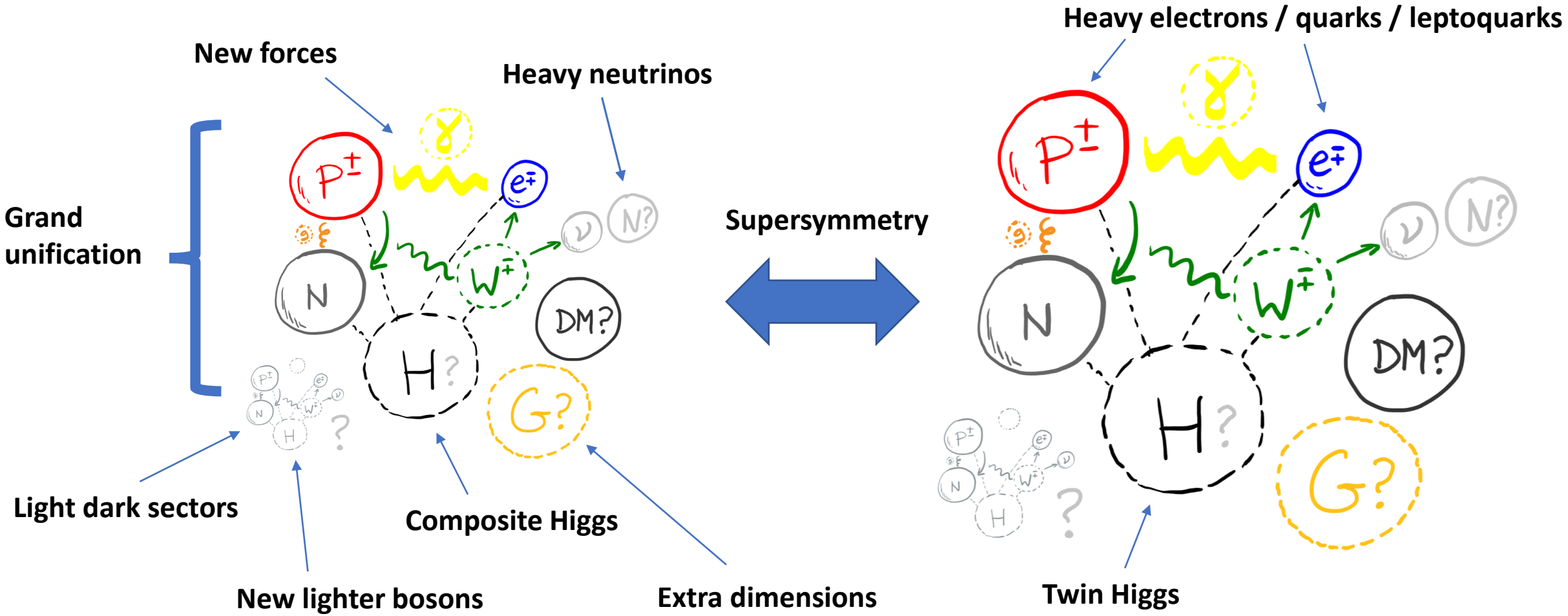
- What is the **origin of the Higgs**?
- What is the **origin of matter**?
- What is the **origin of flavour**?
- What is the **origin of dark matter** and **dark energy**?
- What is the **origin of neutrino mass**?
- What is the **origin of the Standard Model**?





Going beyond the Standard Model

- Many theories to address these questions



- *New approaches* involving **cosmological evolution**

All allowed theories of massless particles

- BSM physics is **creativity** within *a straightjacket*

- *Consistency* of **relativity** + **quantum mechanics**:
  - Spin 0
  - Spin 1/2
  - Spin 1
  - Spin 3/2
  - Spin 2
  - Spin > 2 – **Forbidden** for elementary massless particles

All allowed theories of massless particles

- BSM physics is **creativity** within *a straightjacket*

- *Consistency* of **relativity** + **quantum mechanics**:
  - Spin 0 – **Higgs**
  - Spin 1/2 – **Matter**
  - Spin 1 – **Forces**, interactions *must obey* **Yang-Mills** structure
  - Spin 3/2 – ?
  - Spin 2 – **Graviton**, must couple *universally* → **General Relativity**
  - Spin > 2 – **Forbidden** for elementary massless particles

All allowed theories of massless particles

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  - Spin 0 – **Higgs**
  - Spin 1/2 – **Matter**
  - Spin 1 – **Forces**, interactions *must obey* **Yang-Mills** structure
  - Spin 3/2 – Must couple **supersymmetrically**!
  - Spin 2 – **Graviton**, must couple *universally* → **General Relativity**
  - Spin > 2 – **Forbidden** for elementary massless particles

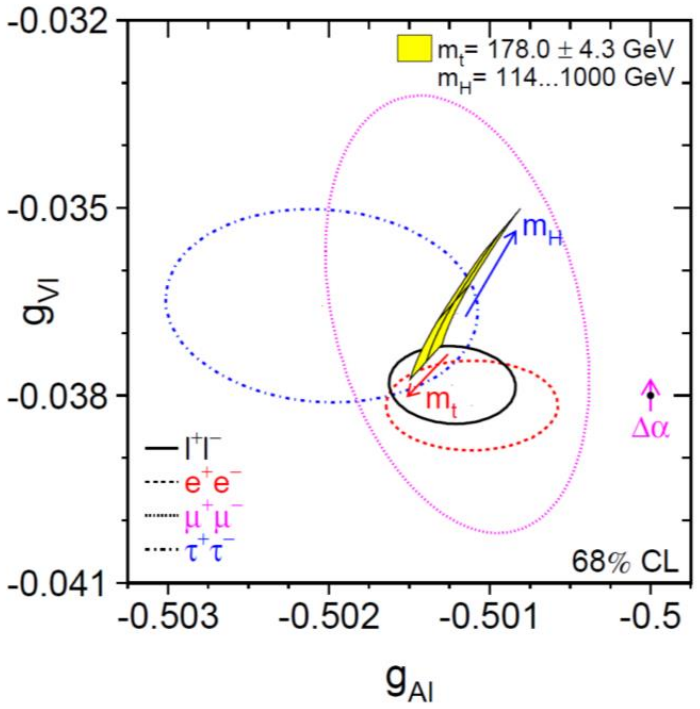
- Supersymmetry **emerges** from *same consistency principles* as SM
  - Though it *need not solve the Higgs mass problem* or *be at accessible scales*

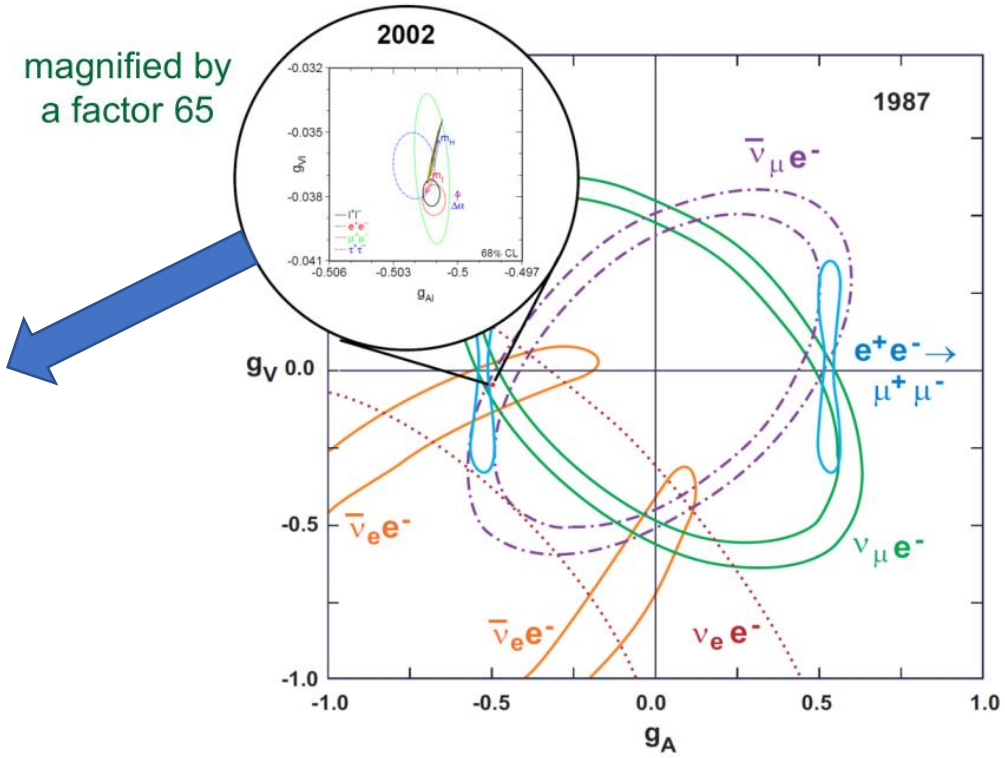
No guarantee of new discoveries

- **No guarantee of discovery** at Tevatron either. Hadron collisions thought by some *to be too messy to do physics*.
- **Value in pushing frontiers**: we learn something *regardless of outcome*
- **Definite questions** are answered, *even if in the negative*
- Science is about *continually refining existing knowledge* and *exploring the unknown*
- **A new generation** of data management, analysis techniques, improved measurements, theoretical calculational tools, hardware development, cutting-edge engineering, large international collaboration, popular culture inspiration, and spirit of fundamental exploration**, can only benefit humanity** regardless of our own short-sighted disappointment at lack of BSM. *Doing good science is its own reward.*

No BSM or new discoveries at LEP

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



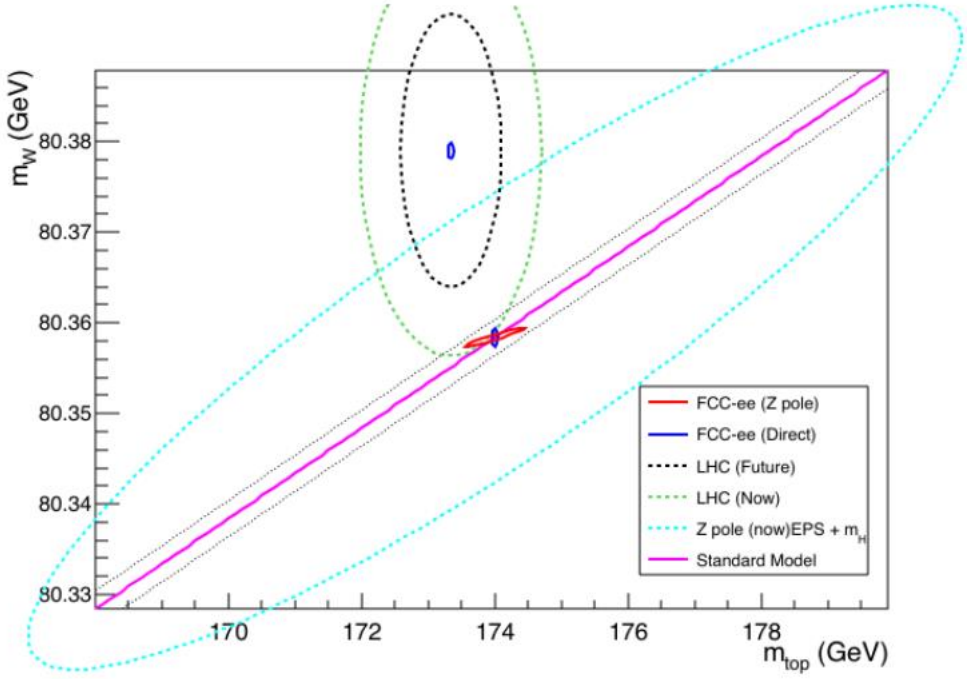


Guy Wilkinson slide

- *Indirect precision probe* of physics at **higher energies**

No BSM or new discoveries guaranteed at FCC-ee

- Further **zooming in** on our fundamental picture of nature

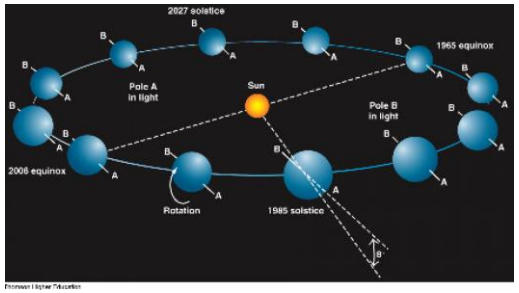


- **Rich physics programme** covering Higgs, top, electroweak, multi-bosons, flavour, rare decays, neutrinos, QCD, heavy ions *and more*.

Radically new BSM?

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

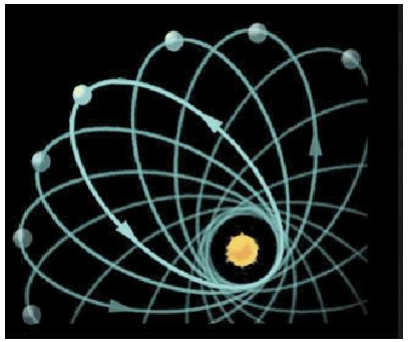
Anomaly in orbit of Uranus

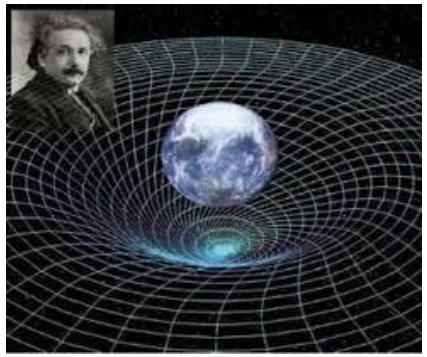


Discovery of Neptune

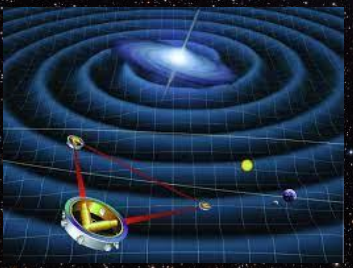
- Sometimes its implications are *far more radical*

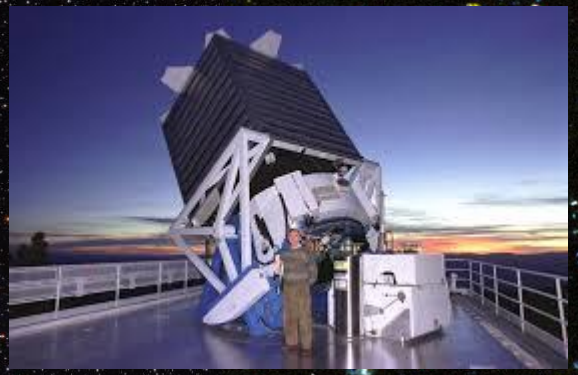
Anomaly in orbit of Mercury

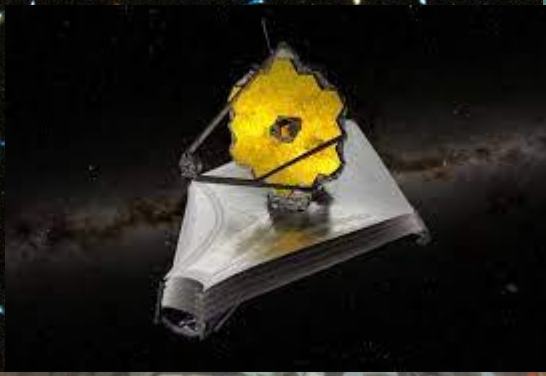




Explained by General Relativity







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

Introduction

- 1900: Almost all data agree spectacularly with the fundamental framework of the time, *no reason to doubt its universal applicability or completeness*.

- 1920s: A combination of **precision measurements** (Mercury), **aesthetic arguments** (relativity) supported by **null experimental results** (Michelson-Morley), and **theoretical inconsistencies** (Rayleigh-Jeans UV catastrophe) lead to an overhaul of the fundamental picture at **smaller scales** and **higher energies** after *pushing the frontiers of technology and theory into new regimes.*

Conclusion

- 2020: Almost all data agree spectacularly with the fundamental framework of the time, *no reason to doubt its universal applicability or completeness*.

- 2050s: A combination of **precision measurements** (B mesons, Hubble), **aesthetic arguments** (naturalness) supported by **null experimental results** (LHC), and **theoretical inconsistencies** (black hole information paradox) lead to an overhaul of the fundamental picture at **smaller scales** and **higher energies** after *pushing the frontiers of technology and theory into new regimes*.