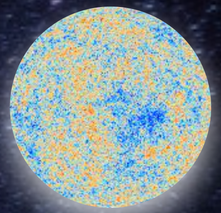
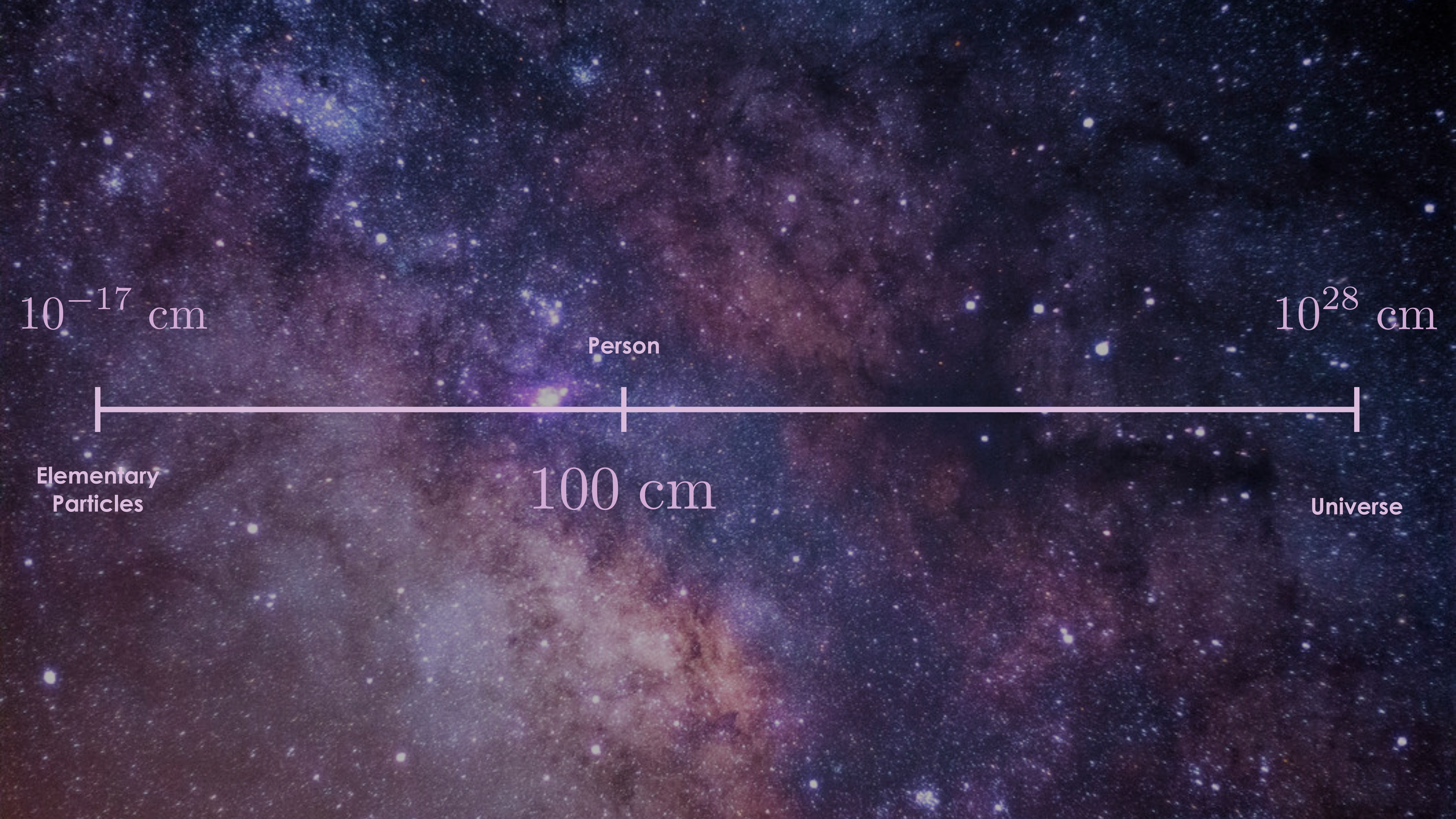

60 YEARS BEHIND AND
BEYOND
THE STANDARD MODEL

Person

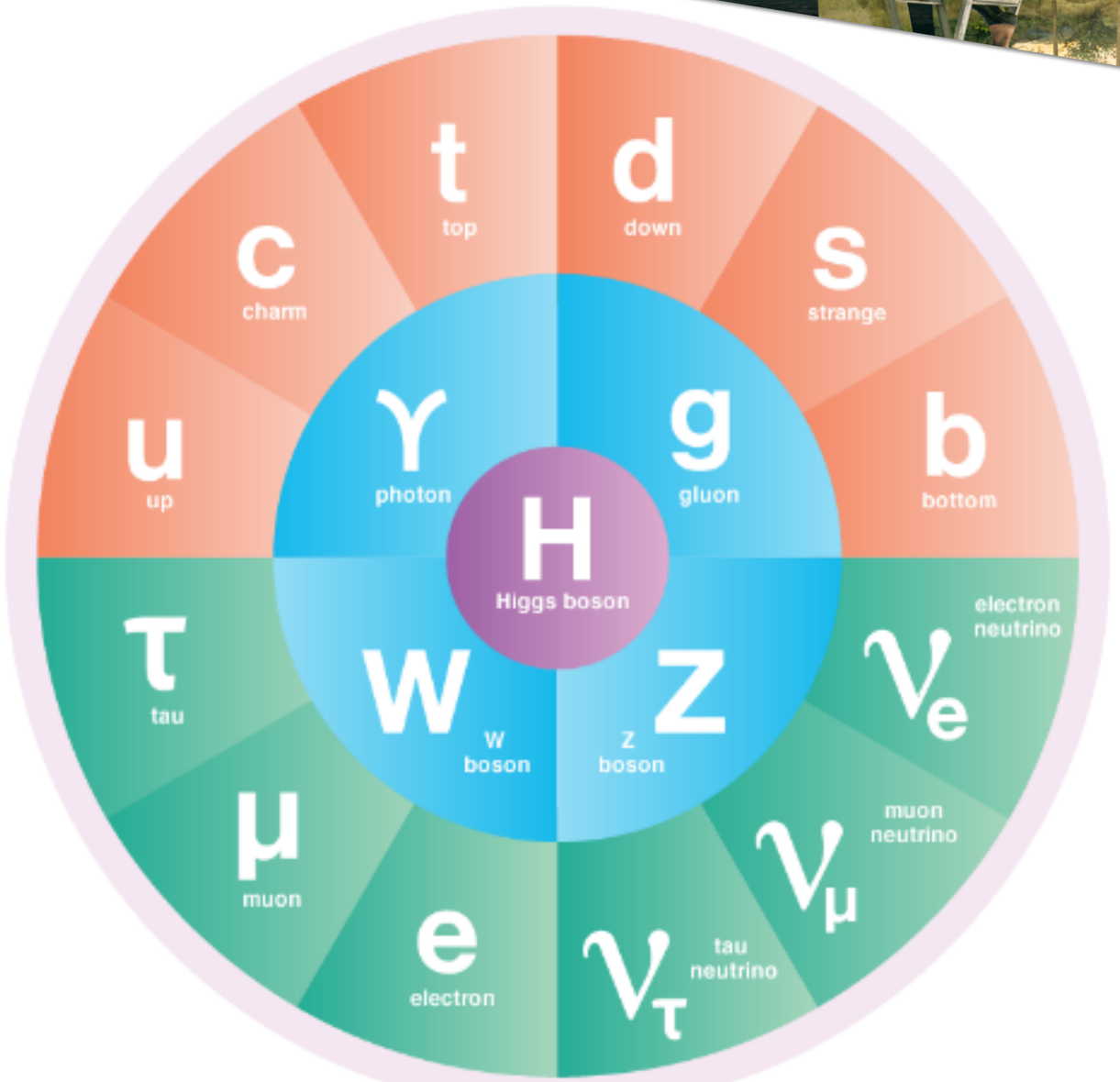


Elementary Particles

Universe


10^{-17} cm
Person
10^{28} cm
Elementary Particles
100 cm
Universe

TODAY



QUARKS LEPTONS BOSONS HIGGS BOSON

+GENERAL RELATIVITY

TODAY

$$\mathcal{L} = \mathcal{L}_G + \mathcal{L}_Y + \mathcal{L}_H$$

$$\mathcal{L}_G = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W^i_{\mu\nu} W^{\mu\nu i} - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu a} + i\overline{\Psi}\gamma^\mu D_\mu \Psi$$

$$\mathcal{L}_Y = -Y_u Q H u^c - Y_d Q H^\dagger d^c - Y_e L H^\dagger e^c + \text{h.c.}$$

$$\mathcal{L}_H = |D_\mu H|^2 + m_h^2 |H|^2 - \frac{\lambda}{2} |H|^2$$

TODAY

$$a_e^{\text{theory}} = 0.00115965218164\,3 \pm 0.000000000000764$$

TODAY

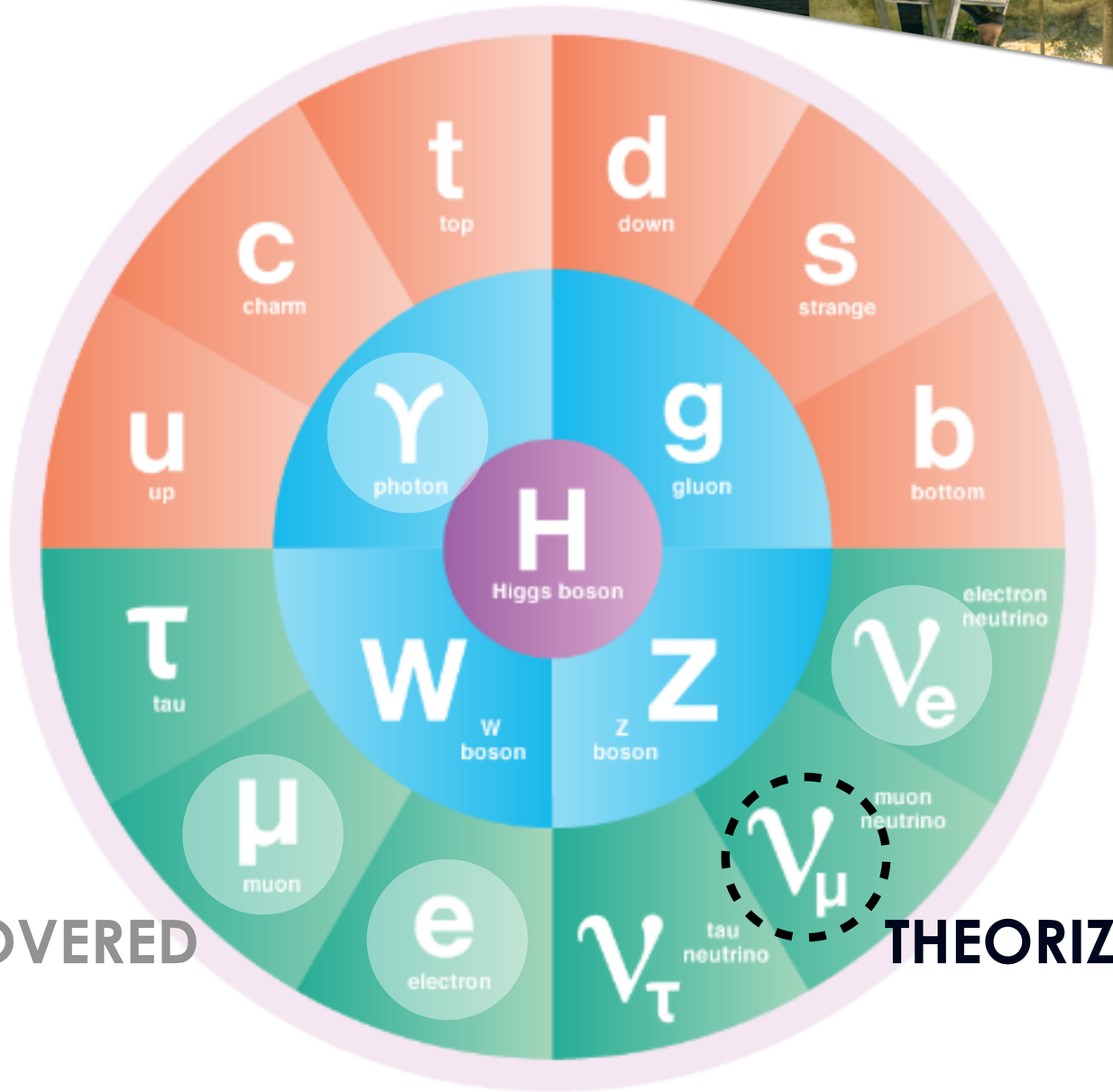
$$a_e^{\text{theory}} = 0.00115965218164\,3 \pm 0.00000000000076\,4$$

$$a_e^{\text{experiment}} = 0.00115965218059 \pm 0.00000000000001\,3$$

1963

IPhT is born

1963



DISCOVERED

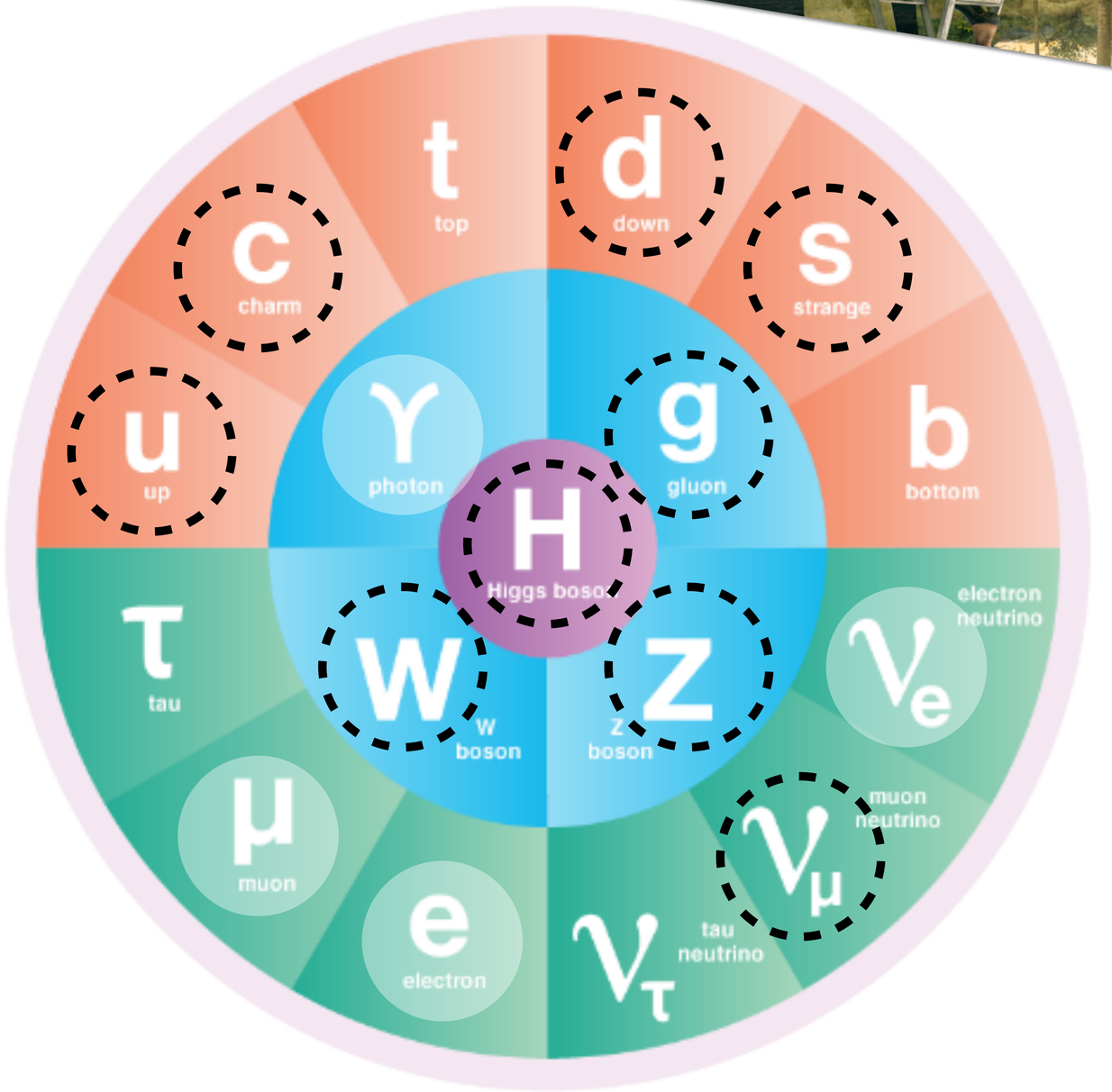
THEORIZED

QUARKS LEPTONS BOSONS HIGGS BOSON

1963 1968

IPhT is born

1968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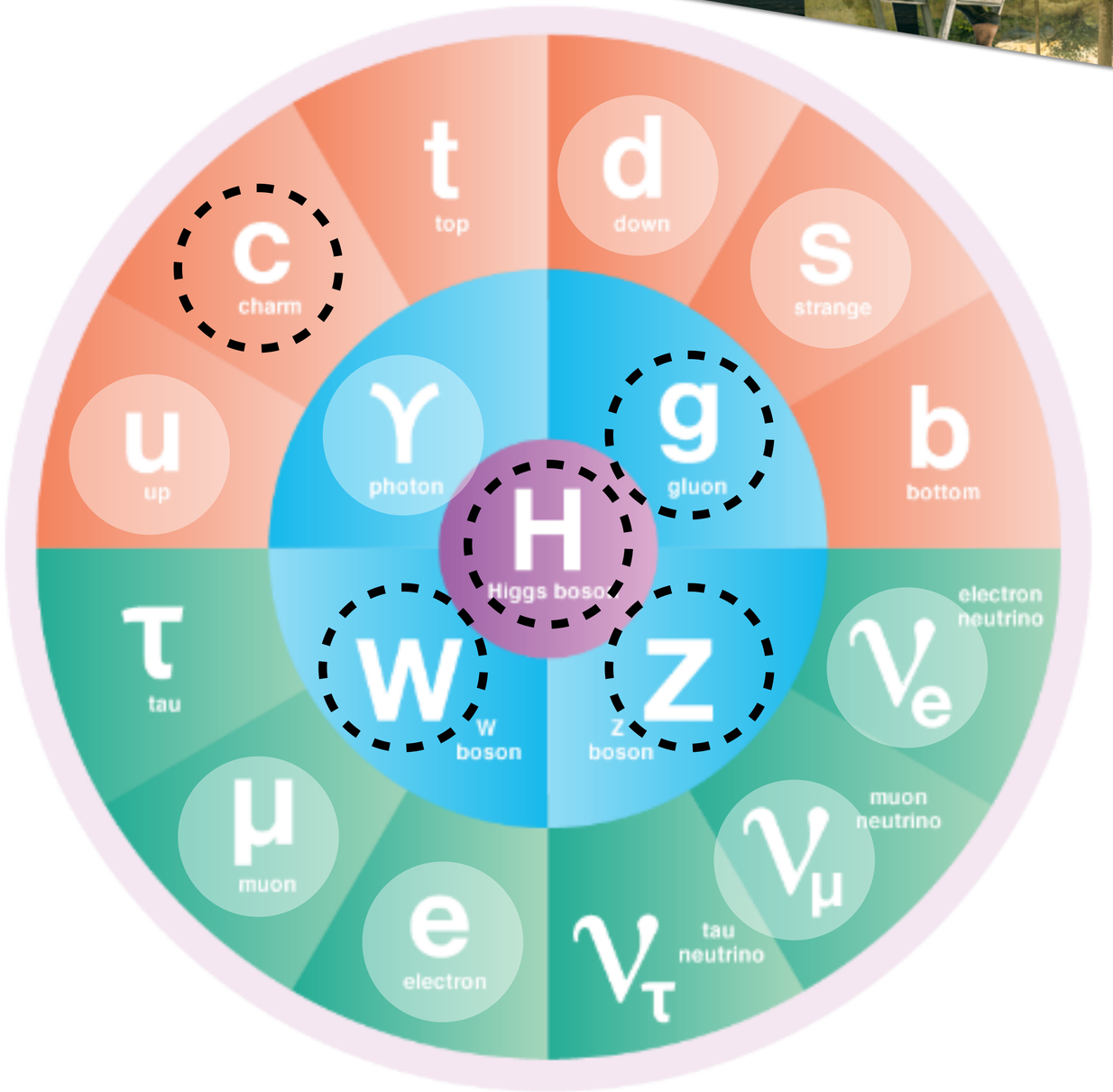
QUARKS
LEPTONS
BOSONS
HIGGS BOSON

1968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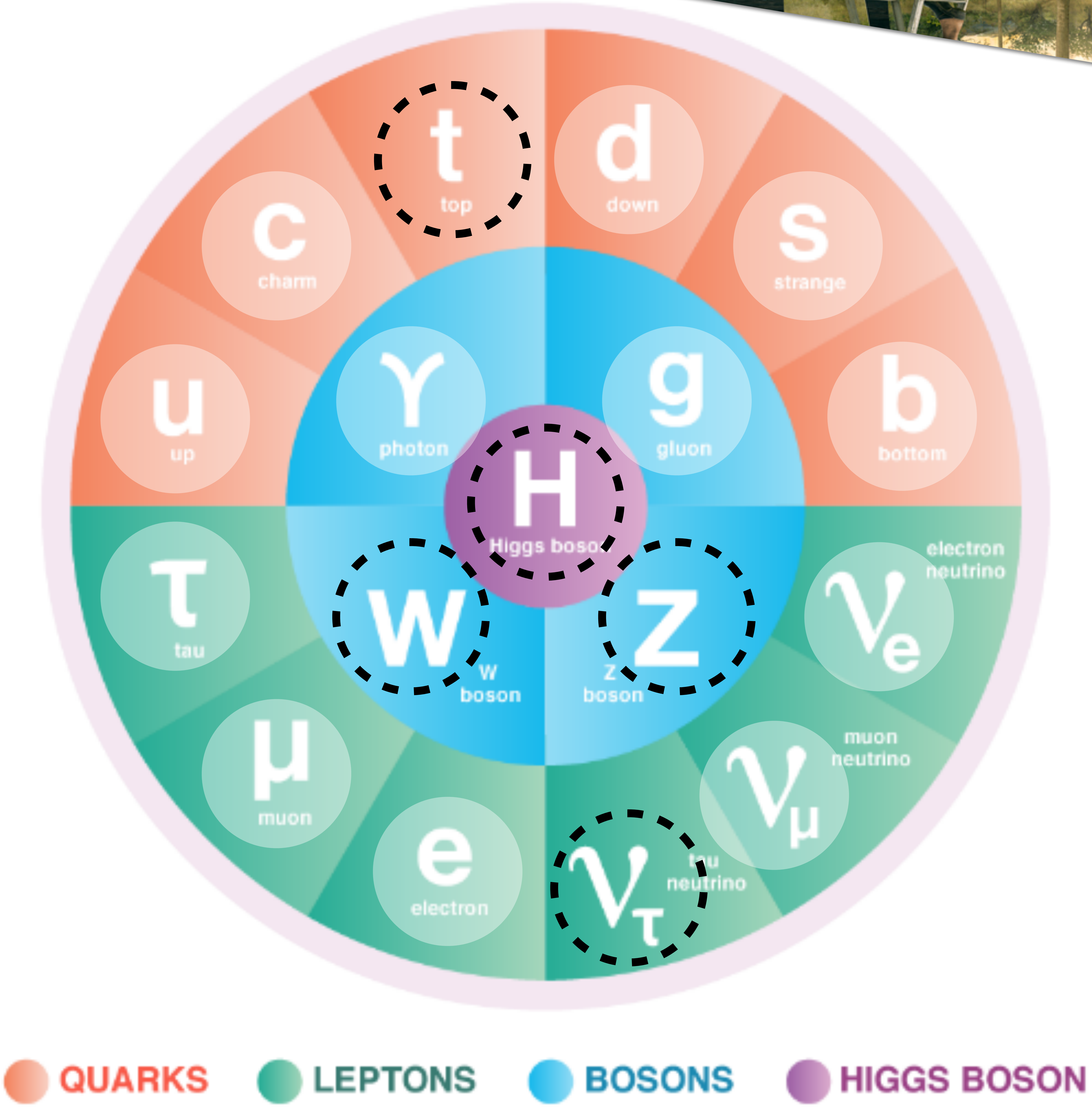
QUARKS
LEPTONS
BOSONS
HIGGS BOSON

1963 1968 1979

IPhT is born

IPhT goes to Primary School

1979



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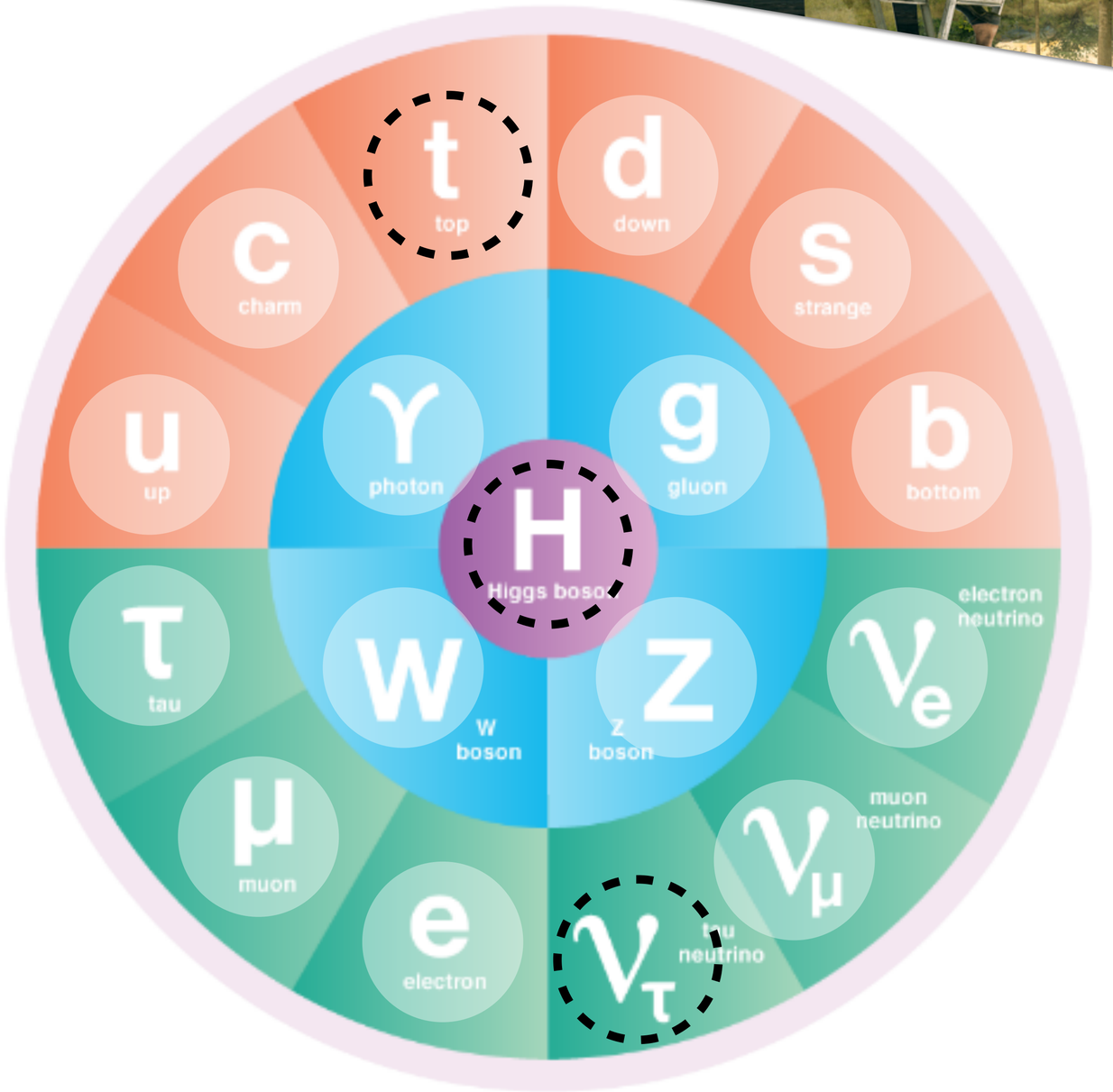
QUARKS
LEPTONS
BOSONS
HIGGS BOSON

1963 1968 1979 1983

IPhT is born

IPhT goes to Primary School

1983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QUARKS
LEPTONS
BOSONS
HIGGS BOSON

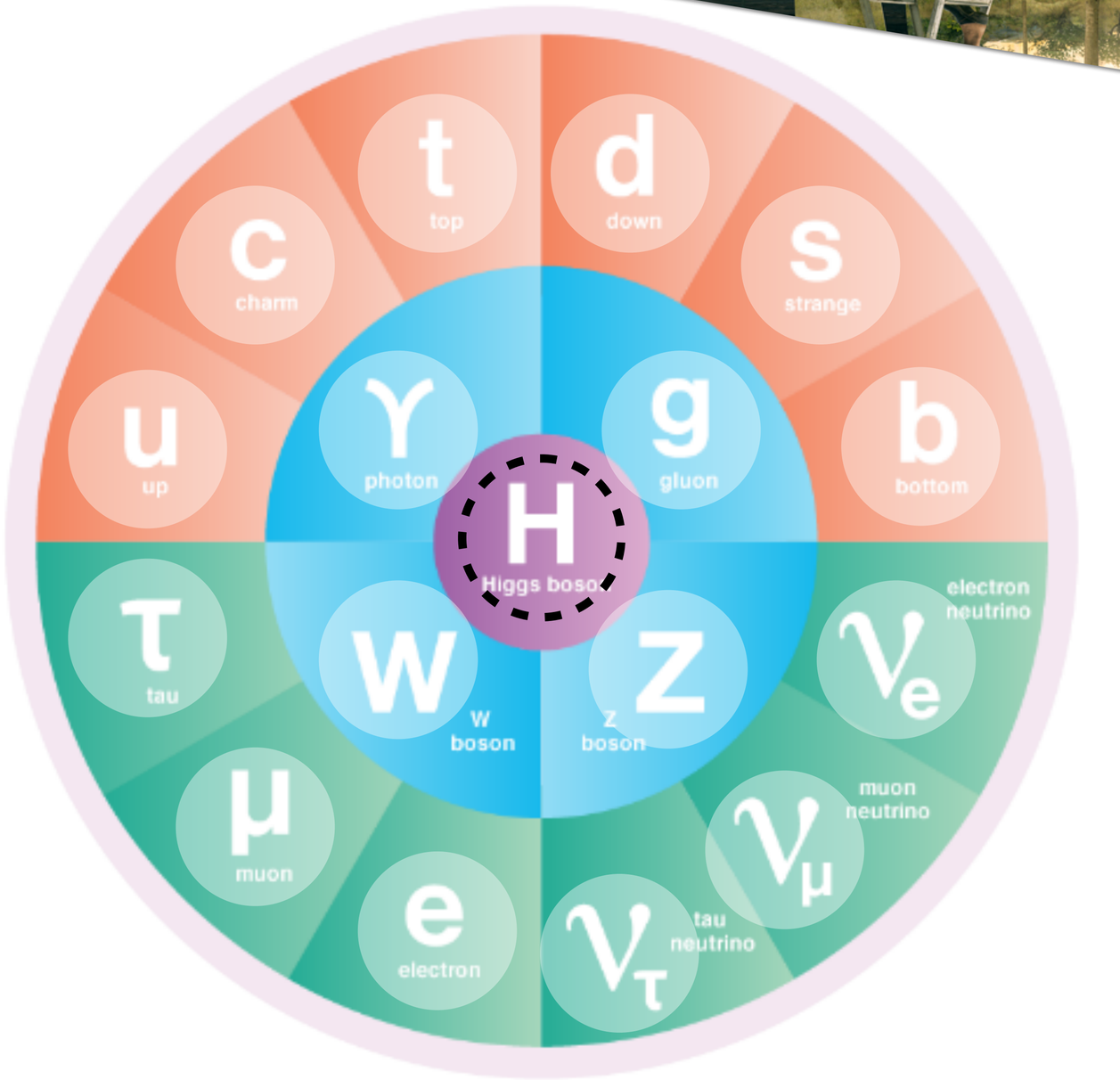
1963 1968 1979 1983 2000

IPhT is born

IPhT goes to Primary School

IPhT goes to University

2000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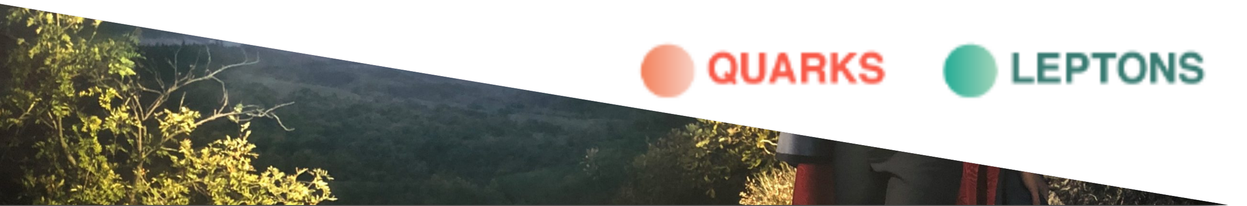


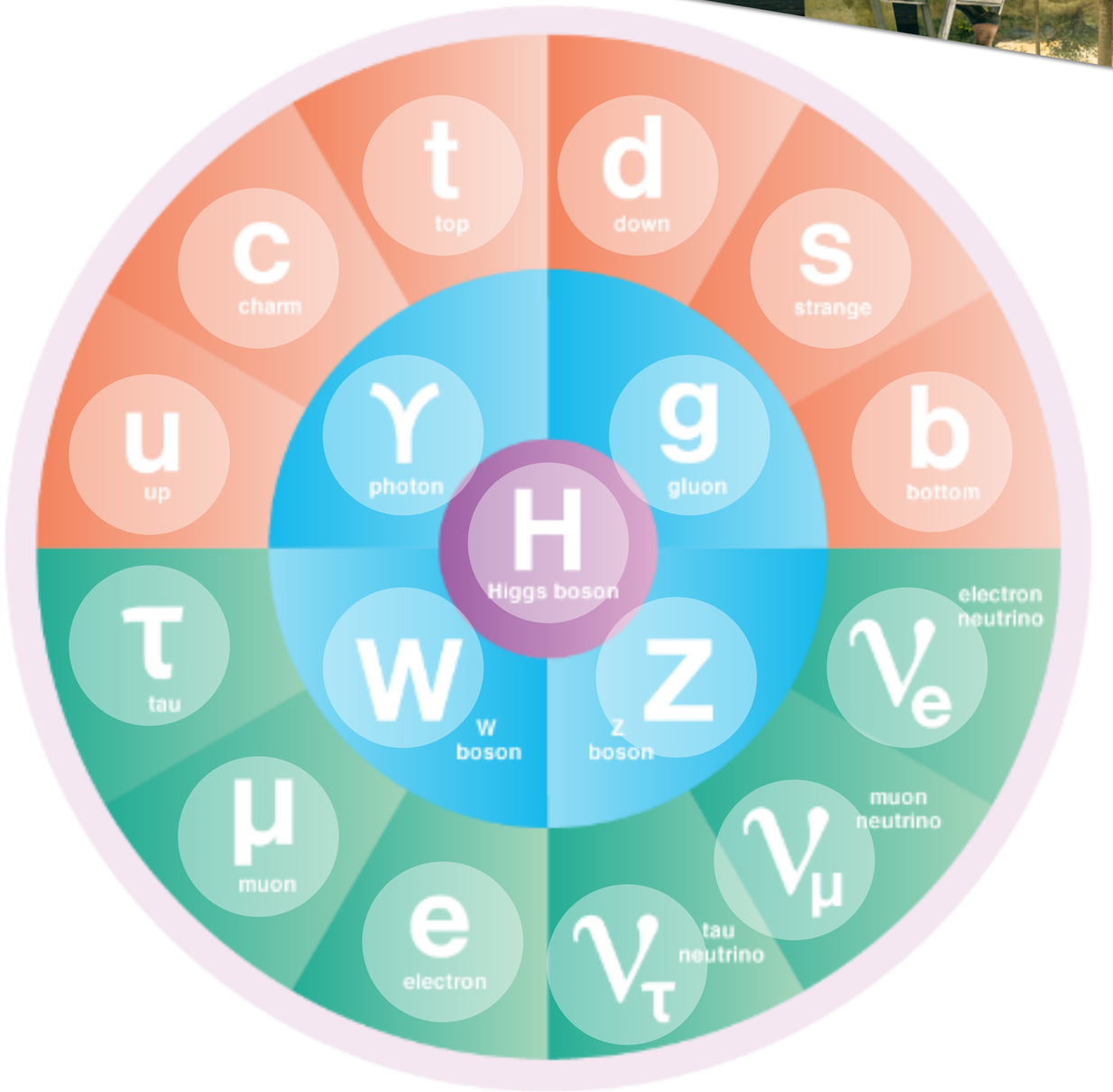
1963 1968 1979 1983 2000 2012

IPhT is born

IPhT goes to Primary School

IPhT goes to University

2012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QUARKS
LEPTONS
BOSONS
HIGGS BOSON

Moving Forward
in Time

1963 1968 1979 1983 2000 2012

=

Moving Up
in Energy

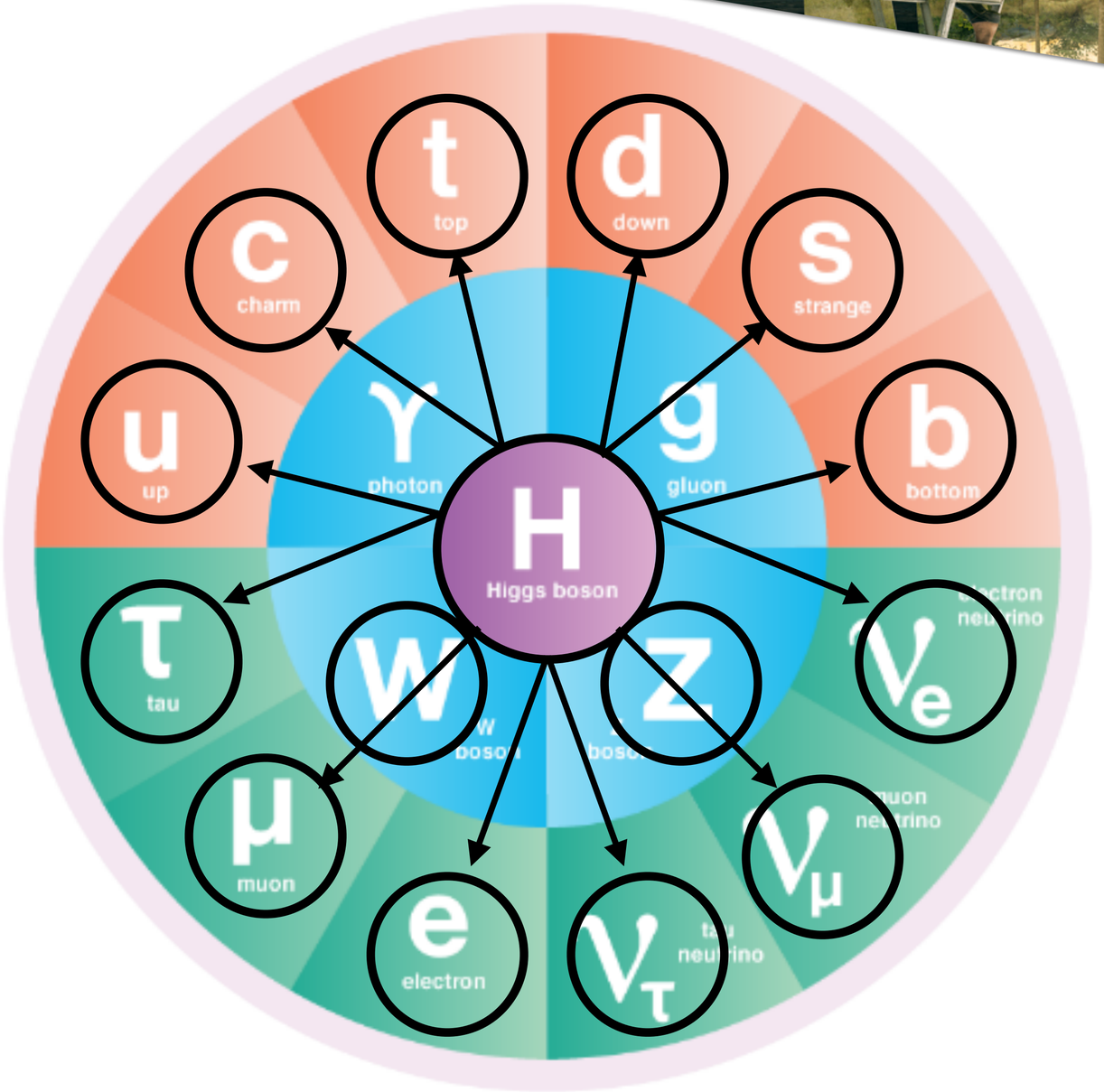
Today — CERN LHC
13.6 TeV

1971 — CERN ISR
62 GeV

E(Today)/E(1971) ~ 219


BEYOND
THE STANDARD MODEL

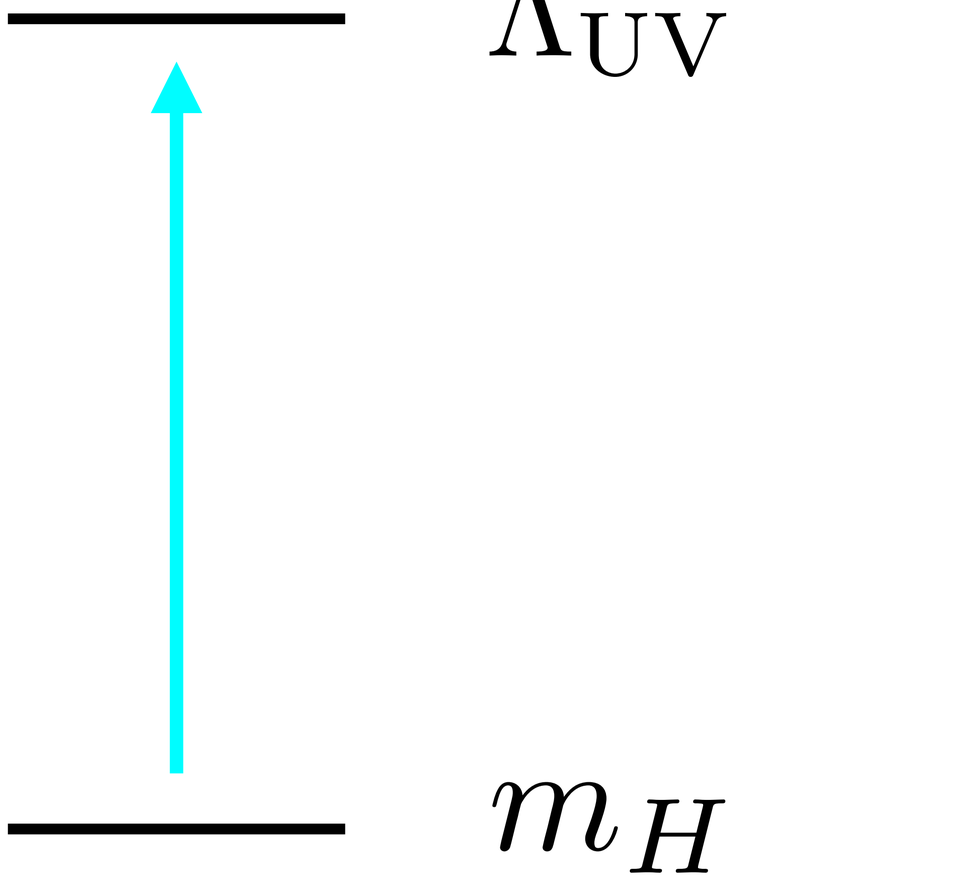
TODAY



QUARKS LEPTONS BOSONS HIGGS BOSON

m_H

TODAY


$\Lambda_{\rm UV}$
m_H

$\Lambda_{\rm UV}$

m_H

PREDICTION

$$\mathcal{L} = c\Lambda_{\rm UV}^{4-\Delta} O^{\Delta}$$

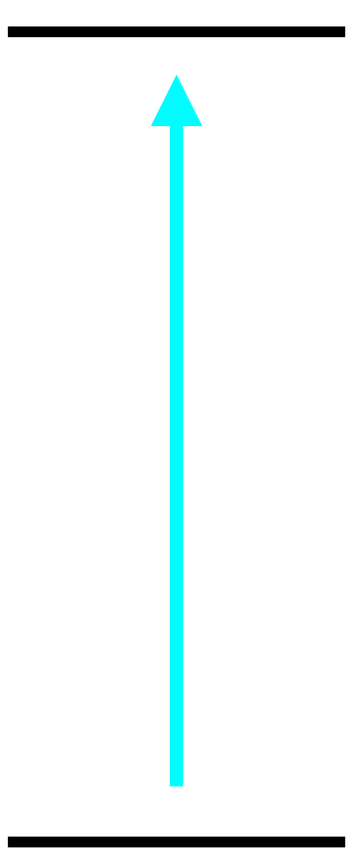
$\Lambda_{\rm UV}$

m_H

$$\mathcal{L} = c\Lambda_{\rm UV}^{4-\Delta} O^{\Delta}$$

$$\Delta_{m_H^2} = 2$$

$$m_H^2 = c\Lambda_{\rm UV}^2$$



$$m_H^2 = c\Lambda_{\rm UV}^2$$

WE HAVE A CONTRADICTION

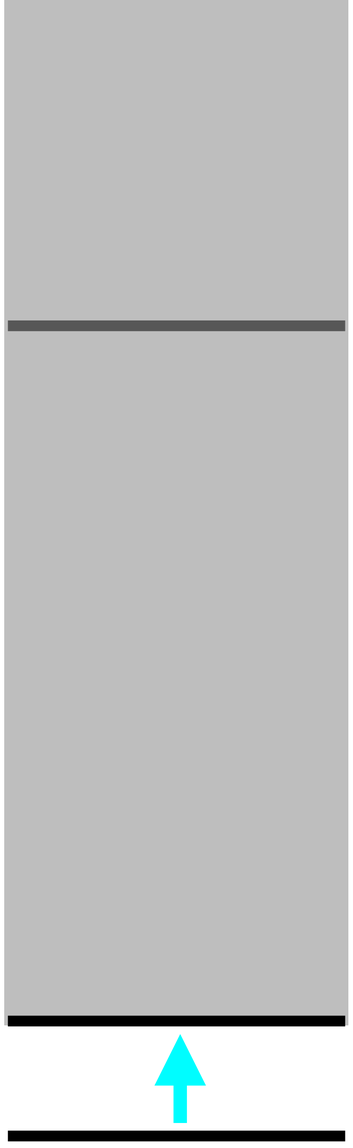
$$\sqrt{c}\Lambda_{\rm UV} \gg m_H^{\rm exp}$$

$$m_H^2 = c\Lambda_{\rm UV}^2$$

WE HAVE A CONTRADICTION

$$\sqrt{c}\Lambda_{\rm UV} \gg m_H^{\rm exp}$$

All Possible Explanations Change Radically
our outlook on Nature

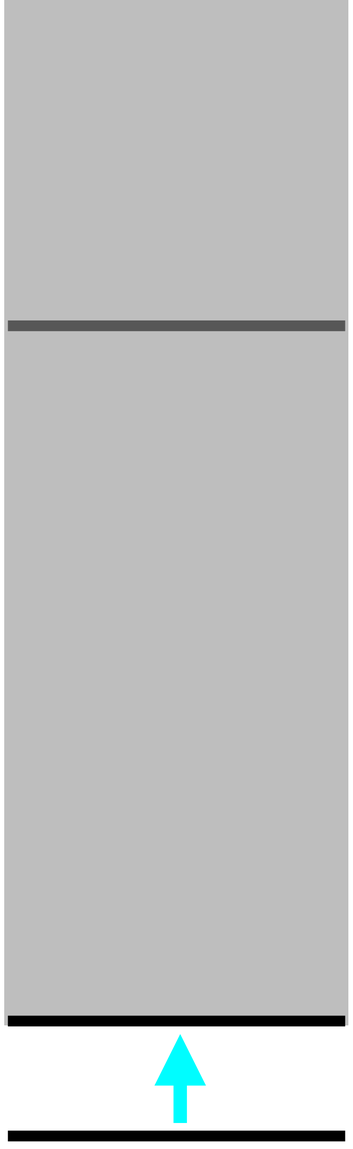


$\Lambda_{\rm UV}$

Λ_S

m_H

1. SYMMETRY



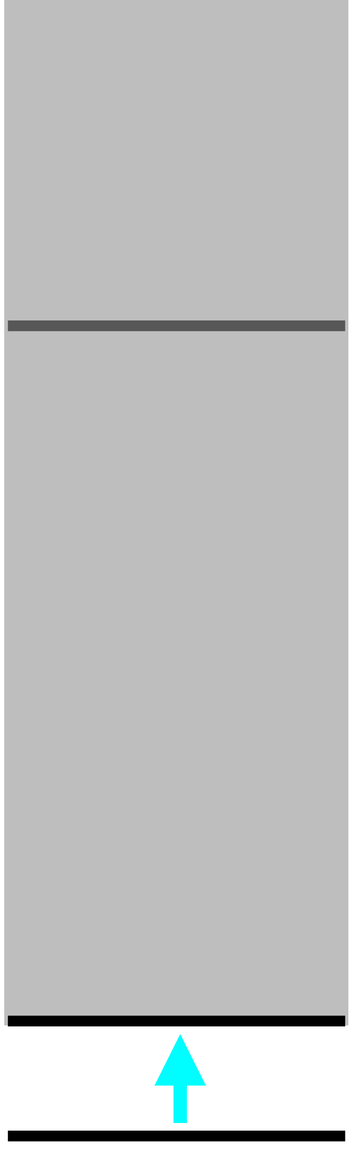
$\Lambda_{\rm UV}$

Λ_S

m_H

1. SYMMETRY (SUPERSYMMETRY OR SCALE INVARIANCE)

Many new particles



$\Lambda_{\rm UV}$

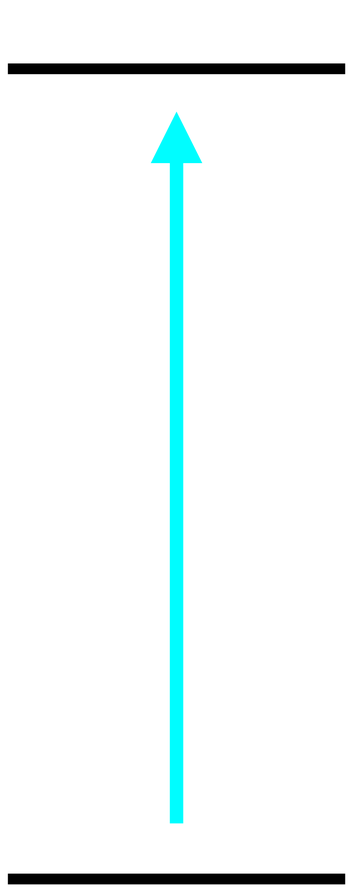
Λ_S

m_H

1. SYMMETRY

(NON-INVERTIBLE)

Connection to dualities in Statistical Mechanics



2. MULTIVERSE

$$\text{——} \quad \Lambda_{\mathrm{UV}}$$

$$m_H^2 = c\Lambda_{\mathrm{UV}}^2$$

$$= (c_1 + c_2 + c_3 + ...)\Lambda_{\mathrm{UV}}^2$$

$$\text{——} \quad m_H$$

2. MULTIVERSE

$\langle h \rangle \simeq v$

$\langle h \rangle \simeq v$

$\langle h \rangle \simeq v$

$\langle h \rangle \simeq v$

$\langle h \rangle \simeq v$

$\langle h \rangle \simeq v$

$$m_H^2 = c\Lambda_{\rm UV}^2$$

$$= (c_1 + c_2 + c_3 + ...)\Lambda_{\rm UV}^2$$

2. MULTIVERSE

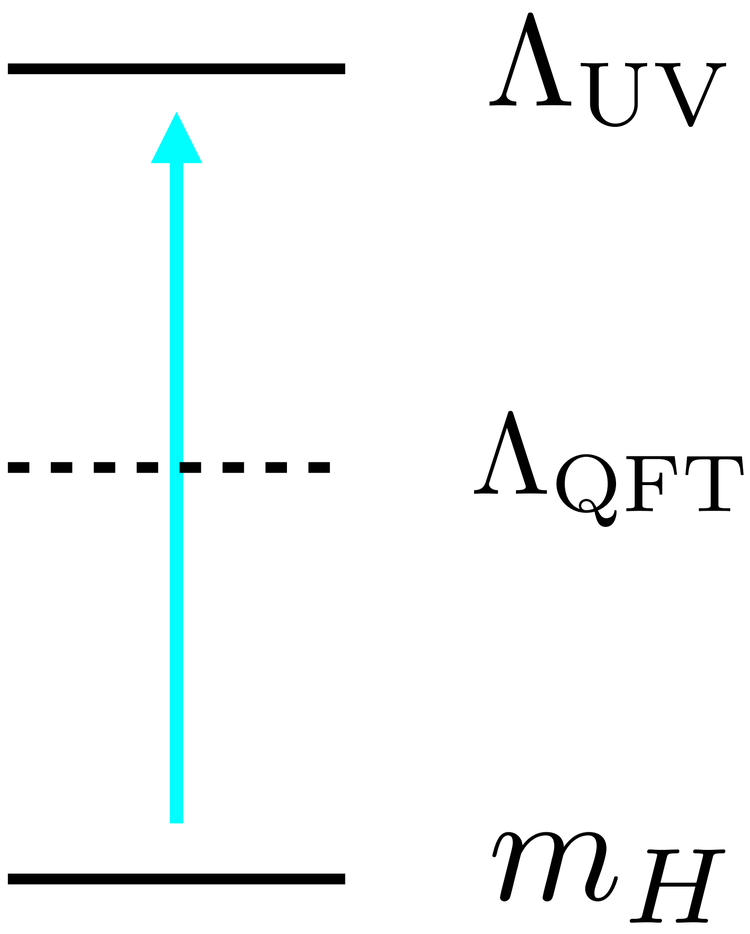
Statistical

Anthropic

Observers

Dynamical

= measured Higgs mass



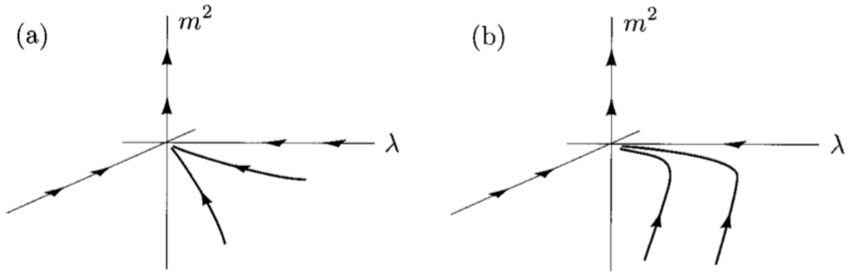
3. BREAKDOWN OF QUANTUM FIELD THEORY

$$m_H^2 = c\Lambda_{\mathrm{UV}}^2$$

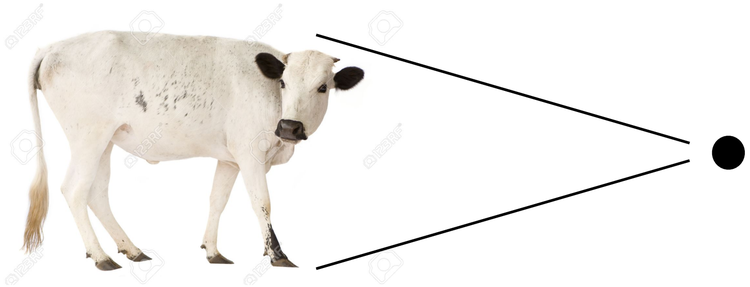
ASSUMPTION:
You don’t need to know the mass of the proton
to calculate the trajectory of a football

In Quantum Field Theory:
Systematic way of integrating out high energy degrees of freedom to obtain a simplified low energy theory

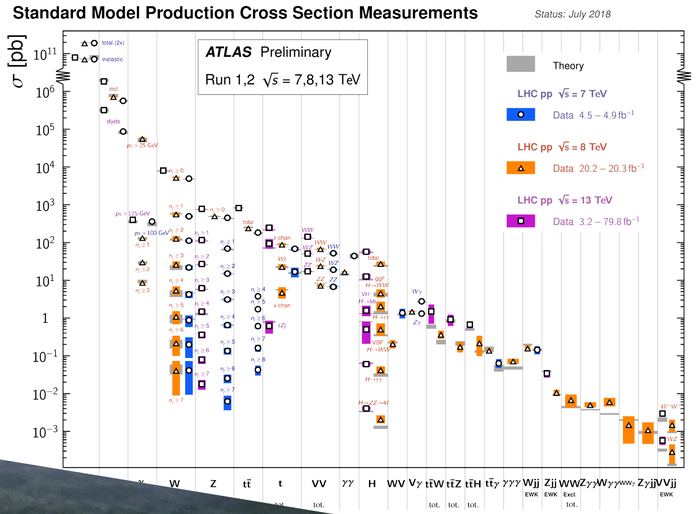
RENORMALIZATION



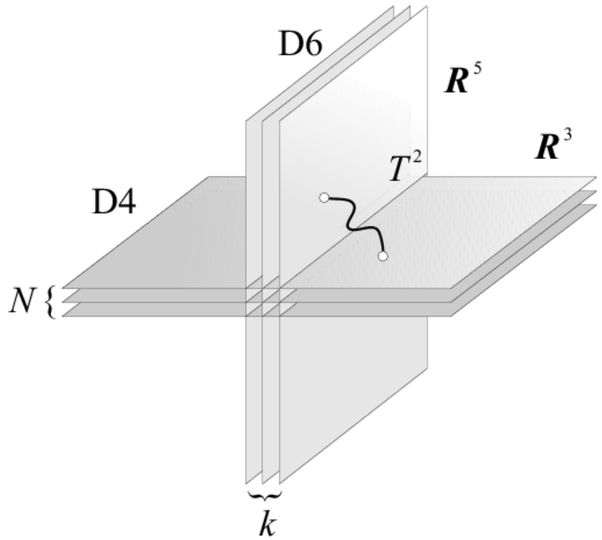
SYMMETRIES FROM COARSE GRAINING

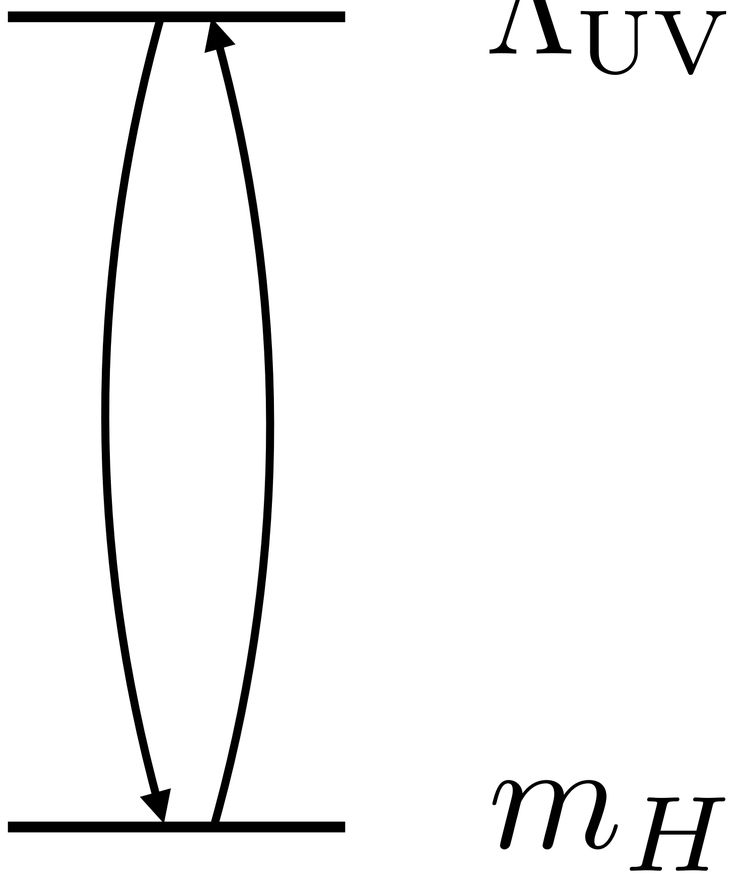


PRECISION CALCULATIONS

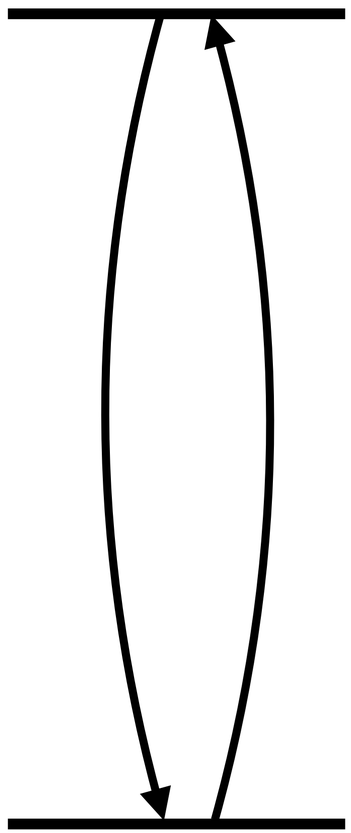


QFT INSIGHTS FROM STRING THEORY





3. BREAKDOWN OF QUANTUM FIELD THEORY (UV/IR Mixing)



Λ_{UV}

m_H

CONCRETE EXAMPLE:
Non-commutative spacetime

3. BREAKDOWN OF QUANTUM FIELD THEORY (UV/IR Mixing)

CHALLENGE:
Write a model that does not break what we know
(i.e. Lorentz Symmetry)

QUANTUM MECHANICS: If you put a lot of energy in one point you will explore short distances

$$L \simeq \frac{\hbar}{p}$$

QUANTUM MECHANICS: If you put a lot of energy in one point you will explore short distances

$$L \simeq \frac{\hbar}{p}$$

GRAVITY: You cannot put a lot of energy in one point, you will make a big black hole (large distances)

$$L \simeq G_N E$$

1. SYMMETRY → Simple and Clean Answer
2. MULTIVERSE
3. BREAKDOWN OF QFT

PREDICTION: A future full of discoveries

2012 — 2023

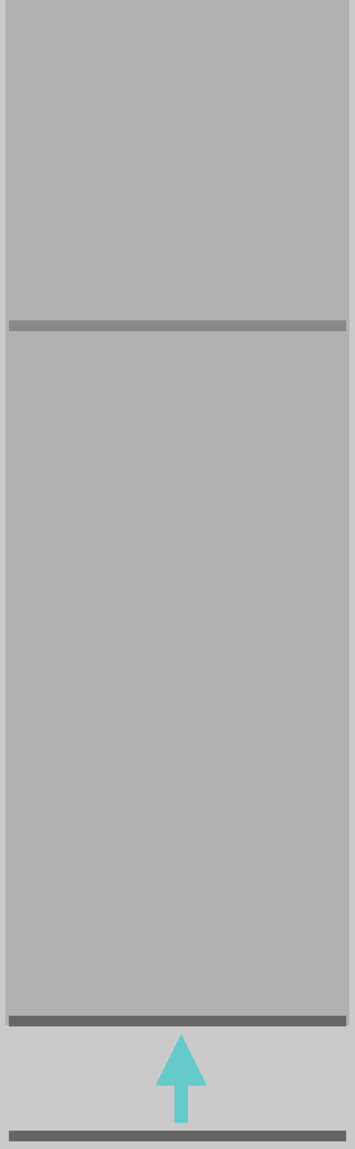
1. SYMMETRY
2. MULTIVERSE
3. BREAKDOWN OF QFT

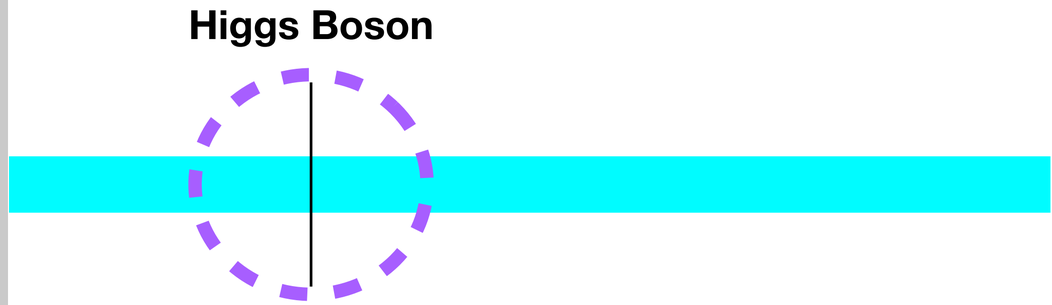
Speculative and not Fully Well-Defined

PREDICTION: A future full of uncertainty

2012

2023





Problem 1: We have not seen these symmetries yet

Experiment

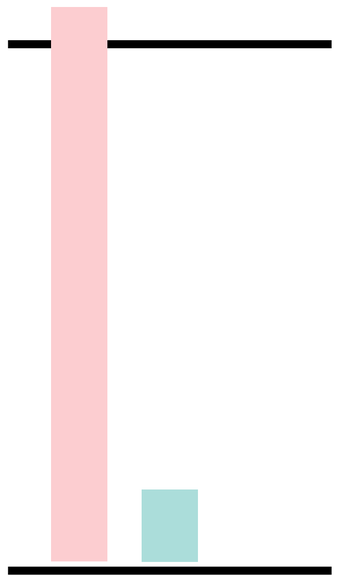
$m_h^{\rm exp}$

Symmetry?

Λ^4

Problem 2: it does not work for the size of the Universe

Experiment



$m_h^{\rm exp}$

Λ^4

The only thing that works is a Multiverse

Cosmological Constant

$$\Lambda^4$$

SIZE OF THE UNIVERSE

Higgs Mass Squared

$$m_h^2 |H|^2$$

WEAK FORCE, STRUCTURE OF NUCLEI, COMPLEX CHEMISTRY, …

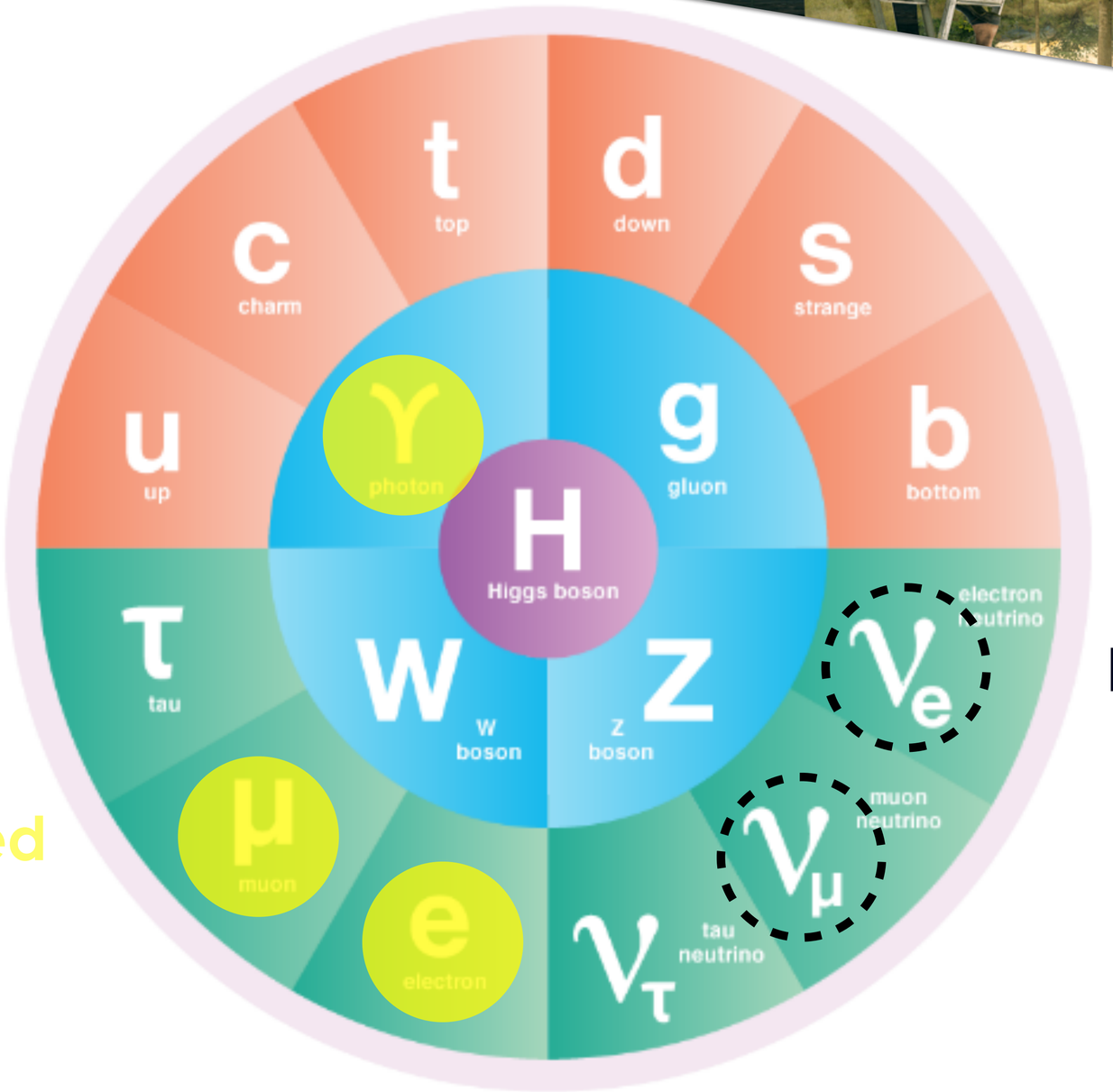
1. SYMMETRY
2. MULTIVERSE
3. BREAKDOWN OF QFT

PREDICTION: A future full
of uncertainty and excitement

BACKUP

1953

1953



Predicted

Discovered