Counting the Building Blocks of the Universe

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Johns Hopkins University QuarkNet Physics Workshop

Fundamental Particles

- How many elementary particles do we know?

Fundamental Fermions

- How many fundamental fermions do we know?

    A. 6

    B. 12

    C. 24

    D. 48

    E. 56

Fundamental Fermions

- How many fundamental fermions do we know?

A. 6

B. 12

C. 24

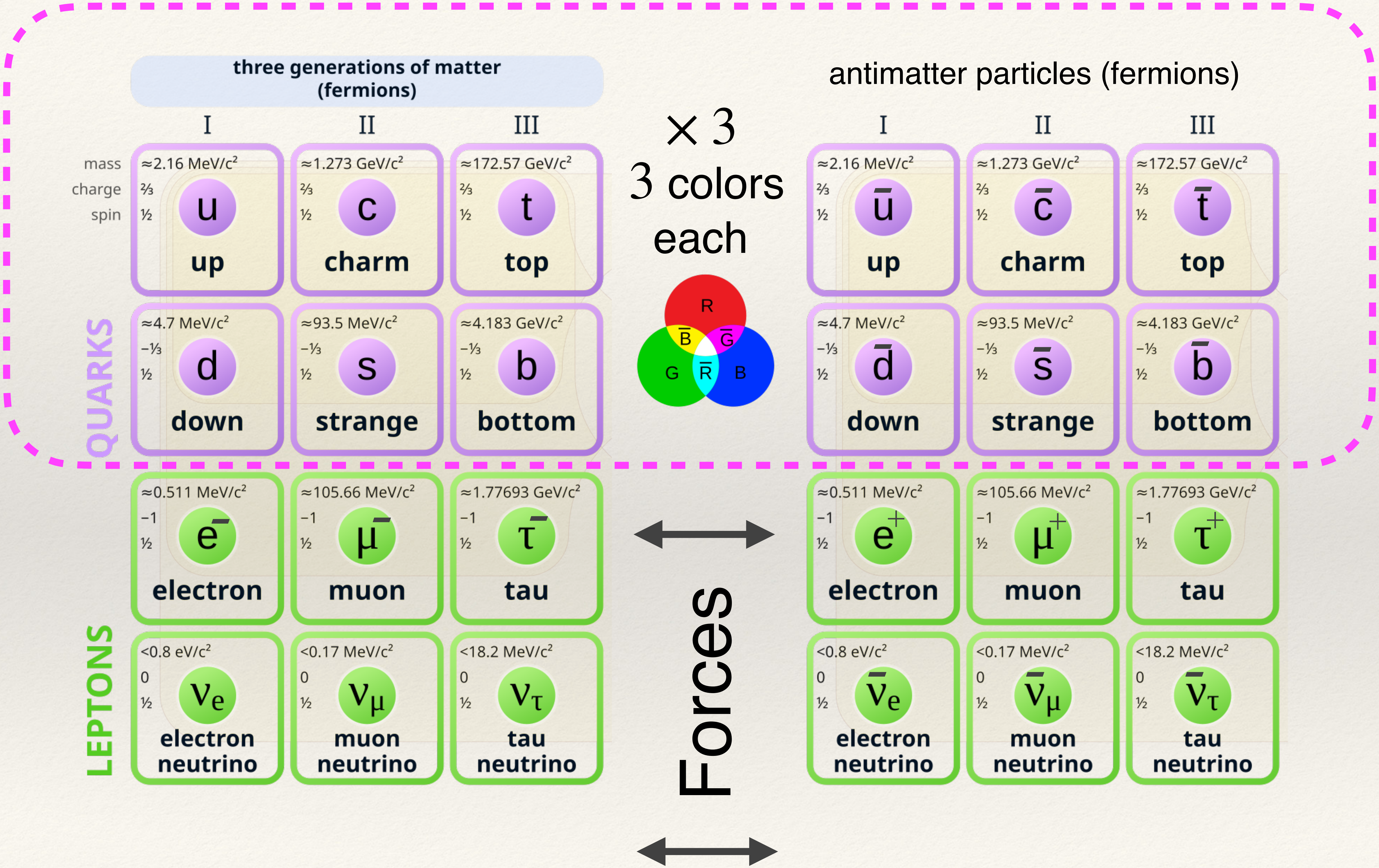
D. 48

E. 56

Hint: did you think about colors…

Hint: did you think about antimatter…

The Matter and Antimatter



Fundamental Fermions

- How many fundamental fermions do we know?

A. 6

B. 12

C. 24

D. 48

E. 56

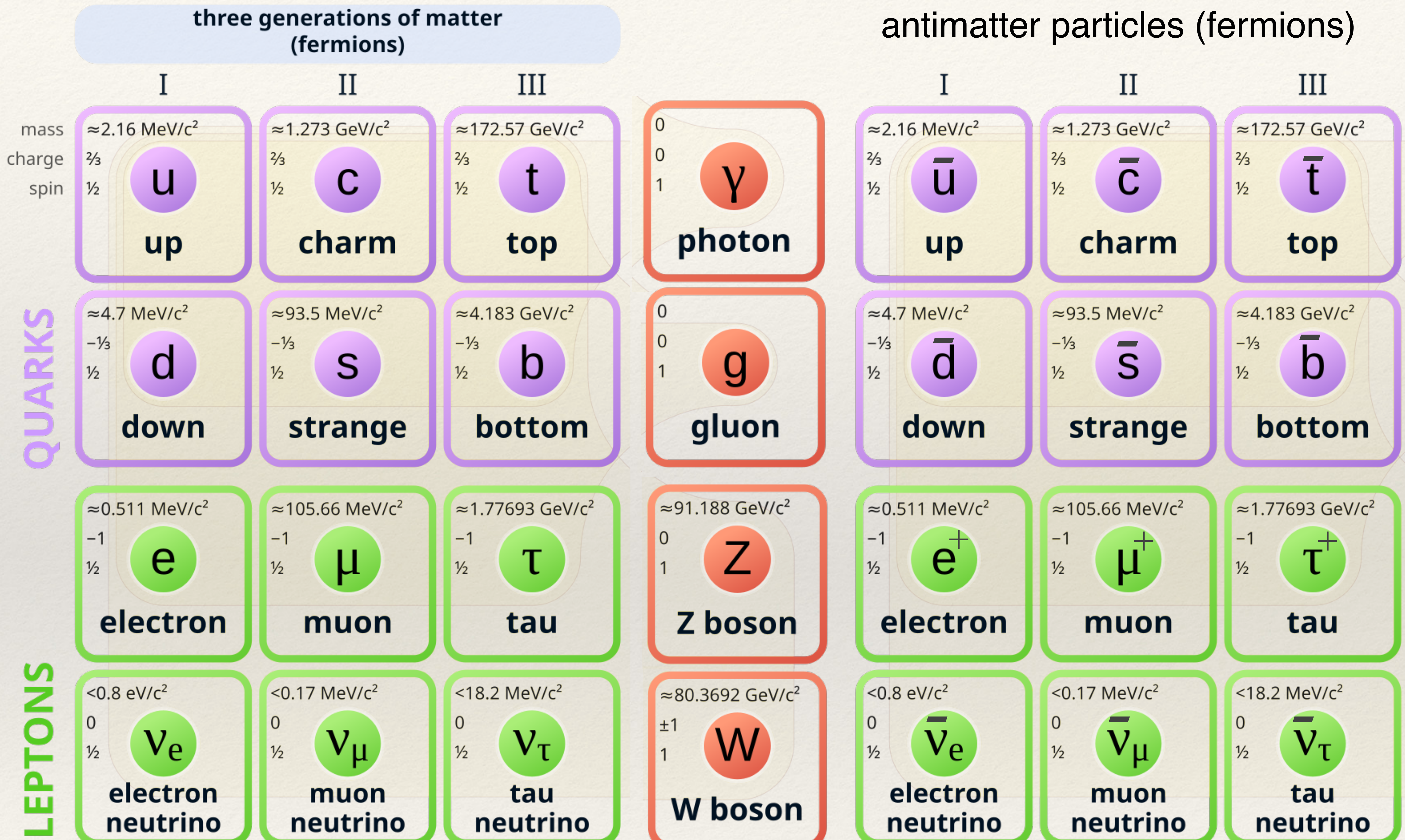
Hint: did you think about colors…

$$3 \times 6 + 6 = 24$$

Hint: did you think about antimatter…

$$2 \times (3 \times 6 + 6) = 48$$

The Matter and the Forces



(Antiparticles are often taken for granted)

Discoveries of the 20th Century

- Which fundamental particle was the final one discovered in the 20th century?

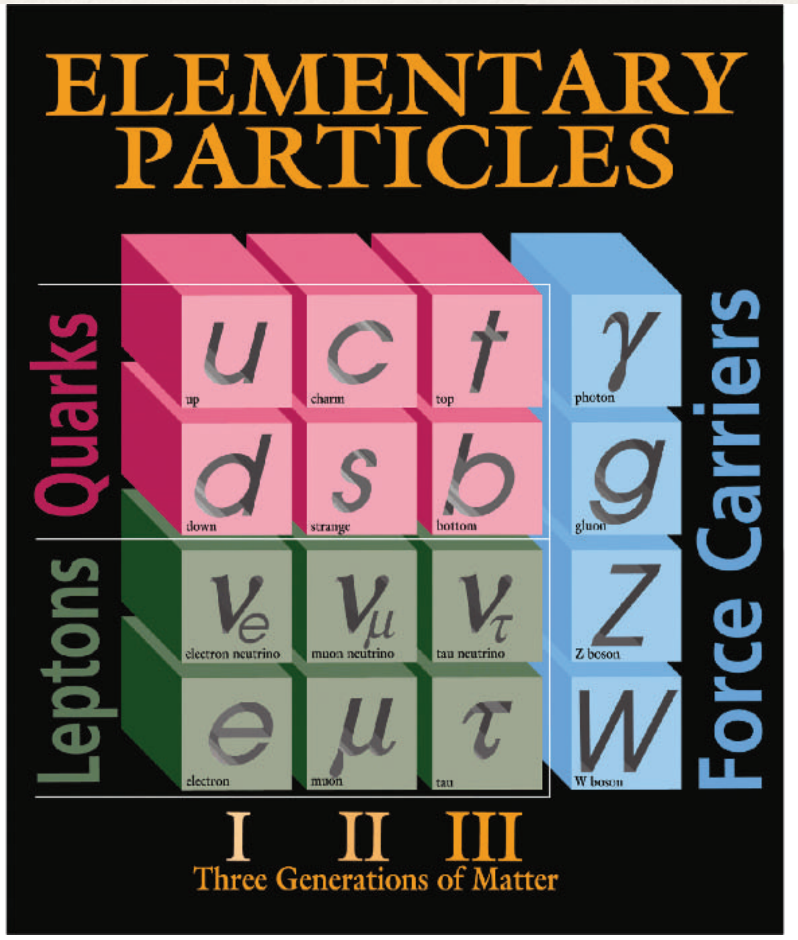
A. Z boson

B. W boson

C. Top quark t

D. Tau neutrino ν_τ

E. Tau lepton τ



(Antiparticles are often taken for granted)

Discoveries of the 20th Century

- Which fundamental particle was the final one discovered in the 20th century?

A. Z boson	1983 (at CERN)
B. W boson	1983 (at CERN)
C. Top quark t	1995 (at Fermilab)
D. Tau neutrino ν_τ	2000 (at Fermilab)
E. Tau lepton τ	1975 (at SLAC)

Note: The 21st century began on January 1, 2001

DONUT experiment

[article in Symmetry](#)

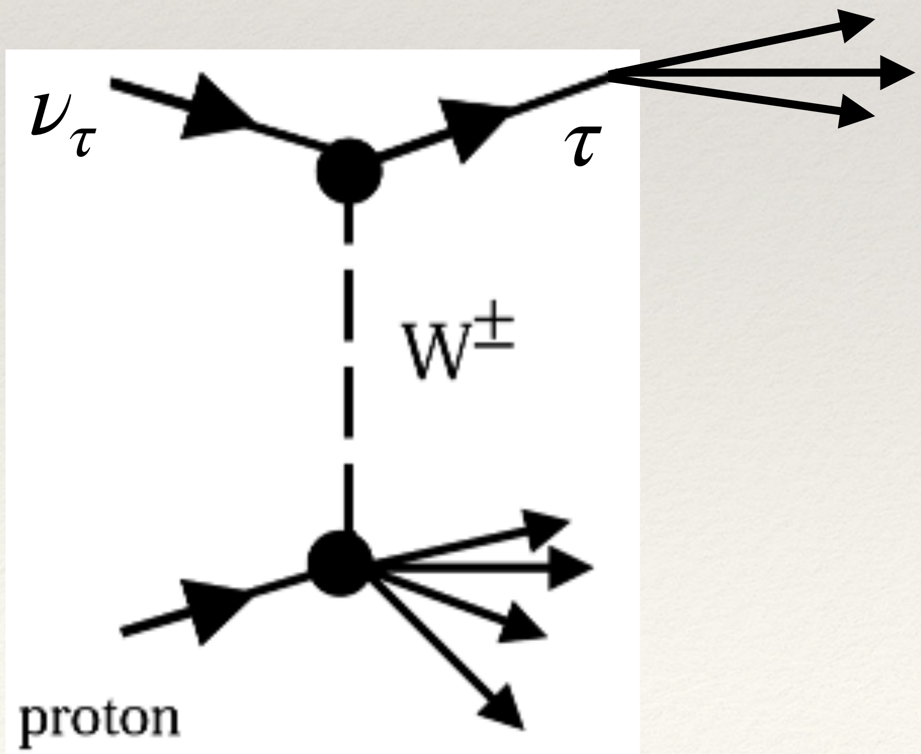
- Direct observation of the nu tau — DONUT (2000)

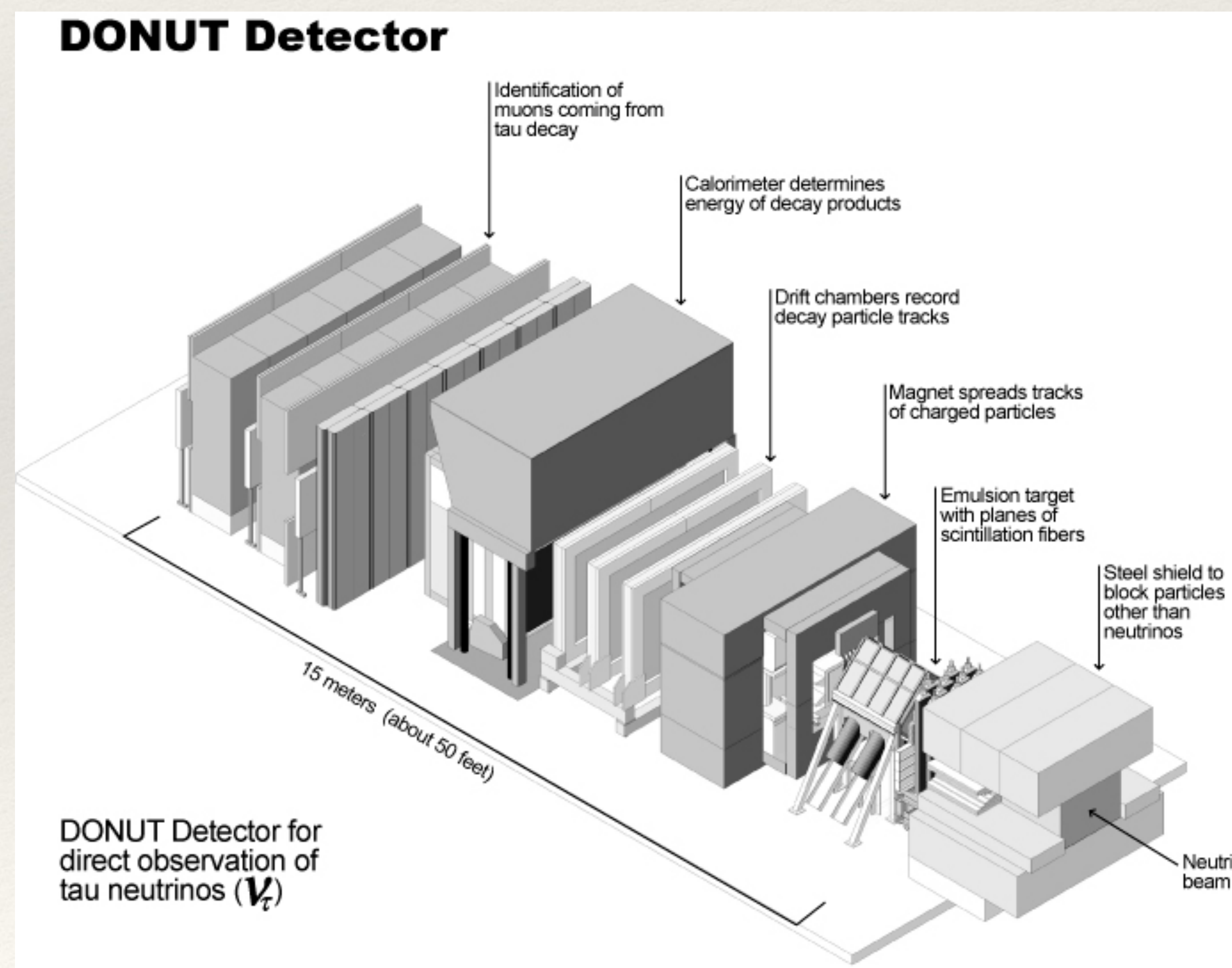
Production of ν_τ:

Tevatron $\quad p + \text{Target} \ \rightarrow \ D_s^\pm + X$

$$D_s^+(c\bar{s}) \ \rightarrow \ \tau^+ + \nu_\tau$$
$$\tau^+ \ \rightarrow \ \bar{\nu}_\tau + X$$

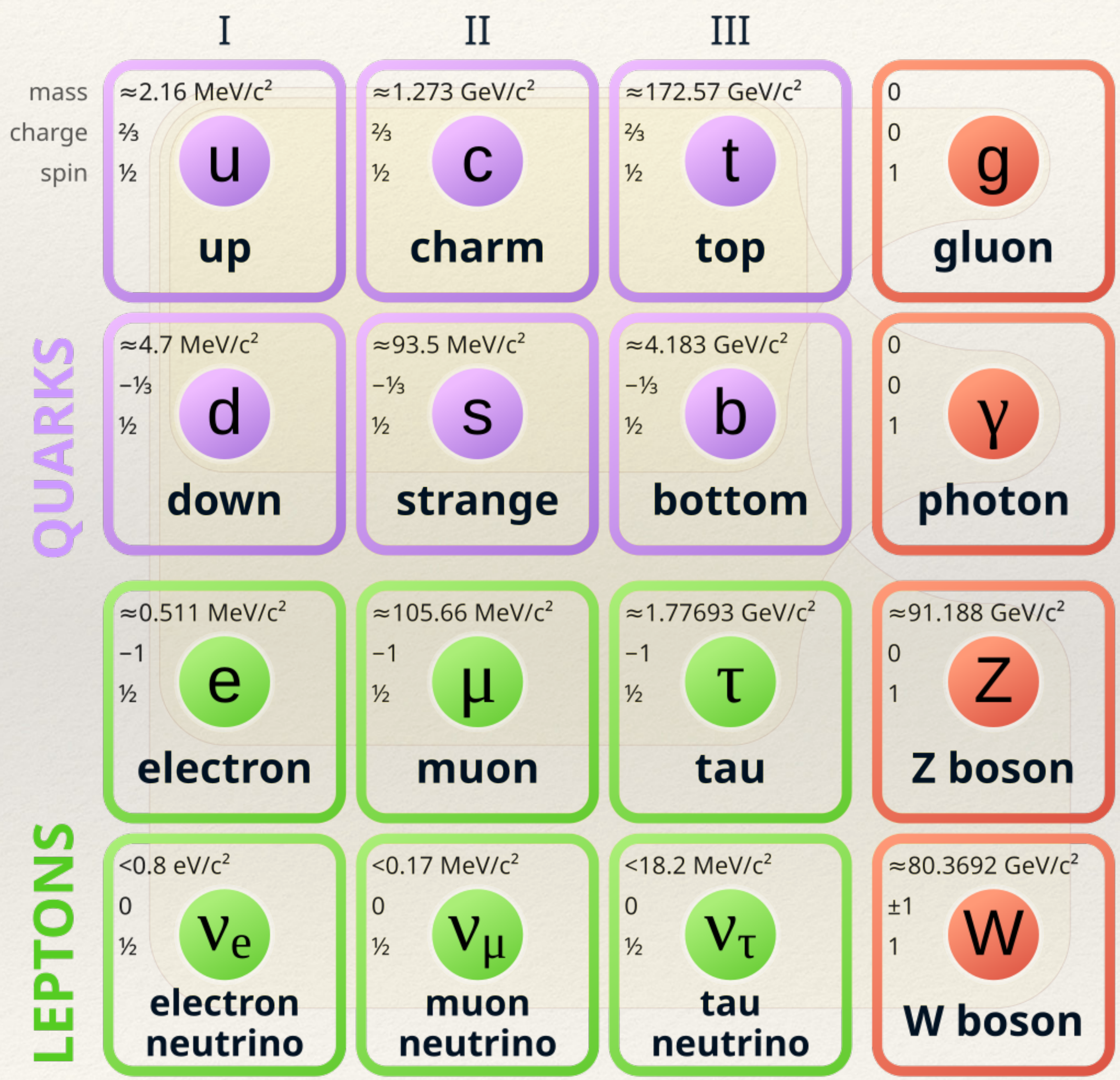
Detection of ν_τ: $\quad \nu_\tau + N \ \rightarrow \ \tau^- + X$



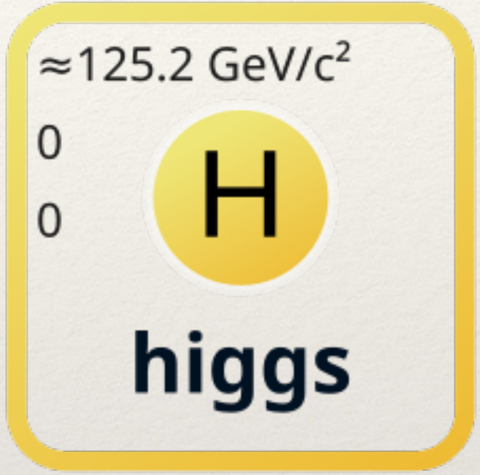


Fundamental Particles

Discovered in the 20th century
(e^- in 1897, almost 20th century, but e^+ in 1932)



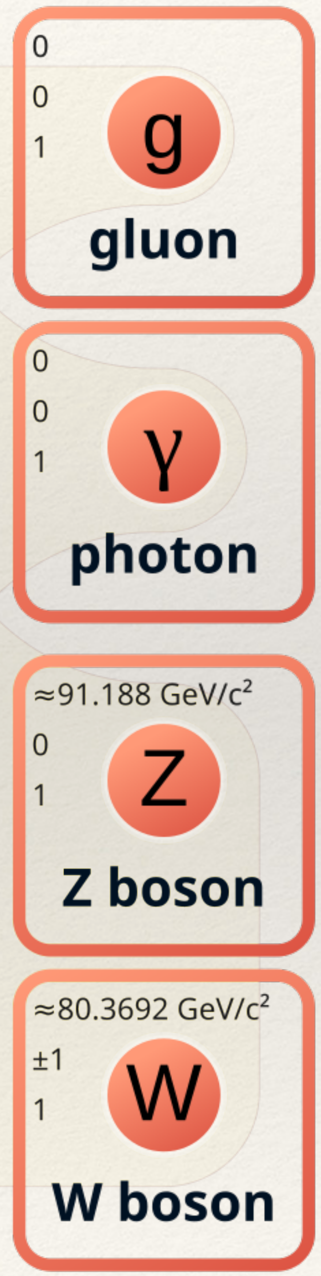
Discovered in
the 21st century



Probably beyond
21st century…

Fundamental Bosons

- How many elementary bosons do we know?

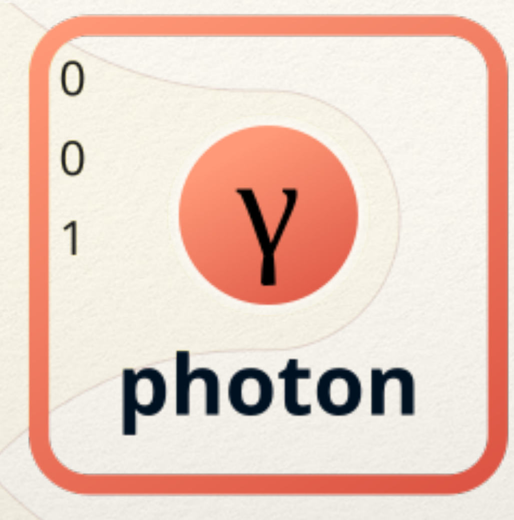


Photon

mass $m_\gamma = 0$

charge $Q_\gamma = 0$

spin $S_\gamma = 1\hbar$



$$E = h\nu$$

— boson (not a matter particle)

— real photons must travel with the speed of light (it is light)

— can also be a virtual particle — appears briefly

then does not have to travel with the speed of light

the uncertainty principle allows shift of energy $E^2 \neq (pc)^2$

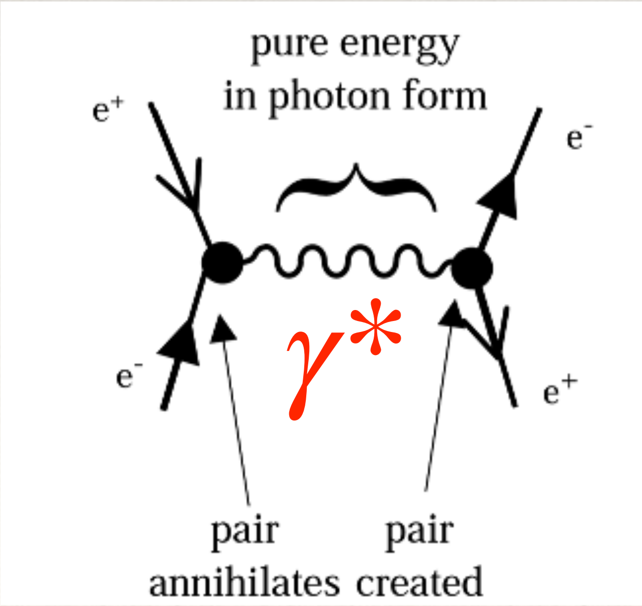
A Virtual Particle

$$E = mc^2$$ — for a particle at rest

$$E^2 = (mc^2)^2 + (pc)^2$$ — for a moving particle

$$E^2 \neq (mc^2)^2 + (pc)^2$$ — for a virtual particle

valid for a brief moment Δt : $$\Delta E \sim \frac{\hbar}{\Delta t}$$



$$E^2 = (m_{\text{inv}}c^2)^2 + (pc)^2$$

$$m_{\text{inv}} \neq m$$

Gluons

8 gluons

mass $m_g = 0$

EM charge $Q_g = 0$

spin $S_g = 1\hbar$

Strong charge:
8 options $r\bar{g},\ g\bar{r},\ r\bar{b},\ b\bar{r},\ g\bar{b},\ b\bar{g},\ \frac{1}{\sqrt{2}}(r\bar{r} - g\bar{g}),\ \frac{1}{\sqrt{6}}(r\bar{r} + g\bar{g} - 2b\bar{b})$

— boson (not a matter particle)

— appears briefly as a virtual particle

does not have to travel with the speed of light

the uncertainty principle allows shift of energy $E^2 \neq (pc)^2$

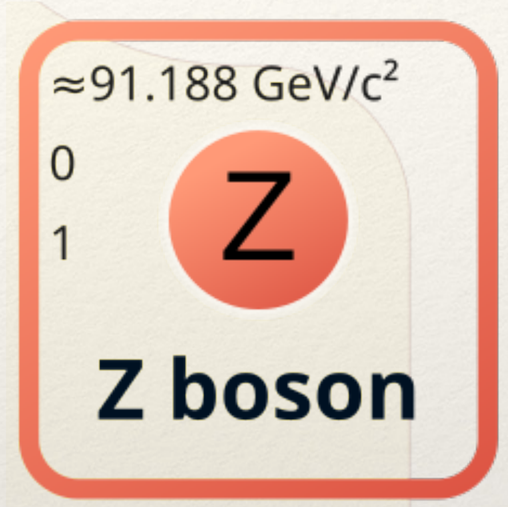
Z boson

- Z boson is like a heavy photon:

mass $$m_Z = 91.2\,\mathrm{GeV}$$

EM charge $$Q_Z = 0$$

spin $$S_Z = 1\hbar$$



Discovered: 1983

— boson (not a matter particle)

— appears briefly as a virtual particle

very massive and decays quickly!

Large Z mass → large energy shift → unlikely → weak interaction

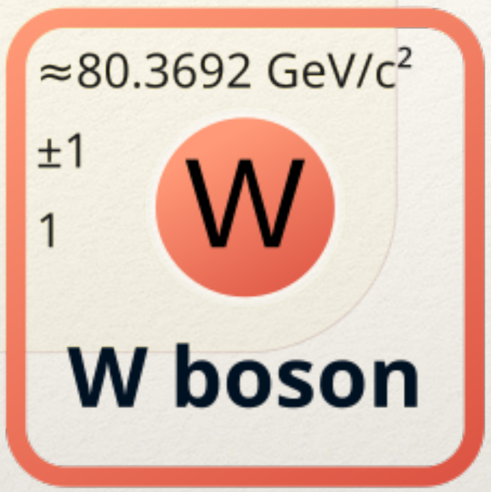
W bosons

- Two bosons: W^+ and W^-

mass $\quad m_W = 80.4\,\mathrm{GeV}$

EM charge $\quad Q_W = \pm 1$

spin $\quad S_W = 1\hbar$



2 bosons: W^+, W^-

Discovered: 1983

— boson (not a matter particle)

— appears briefly as a virtual particle

very massive and decays quickly!

Large W mass → large energy shift → unlikely → weak interaction

Fundamental Particles

- How many elementary particles do we know?

  A. 48

  B. 52

  C. 60

  D. 61

  E. 62

Fundamental Particles

- How many elementary particles do we know?

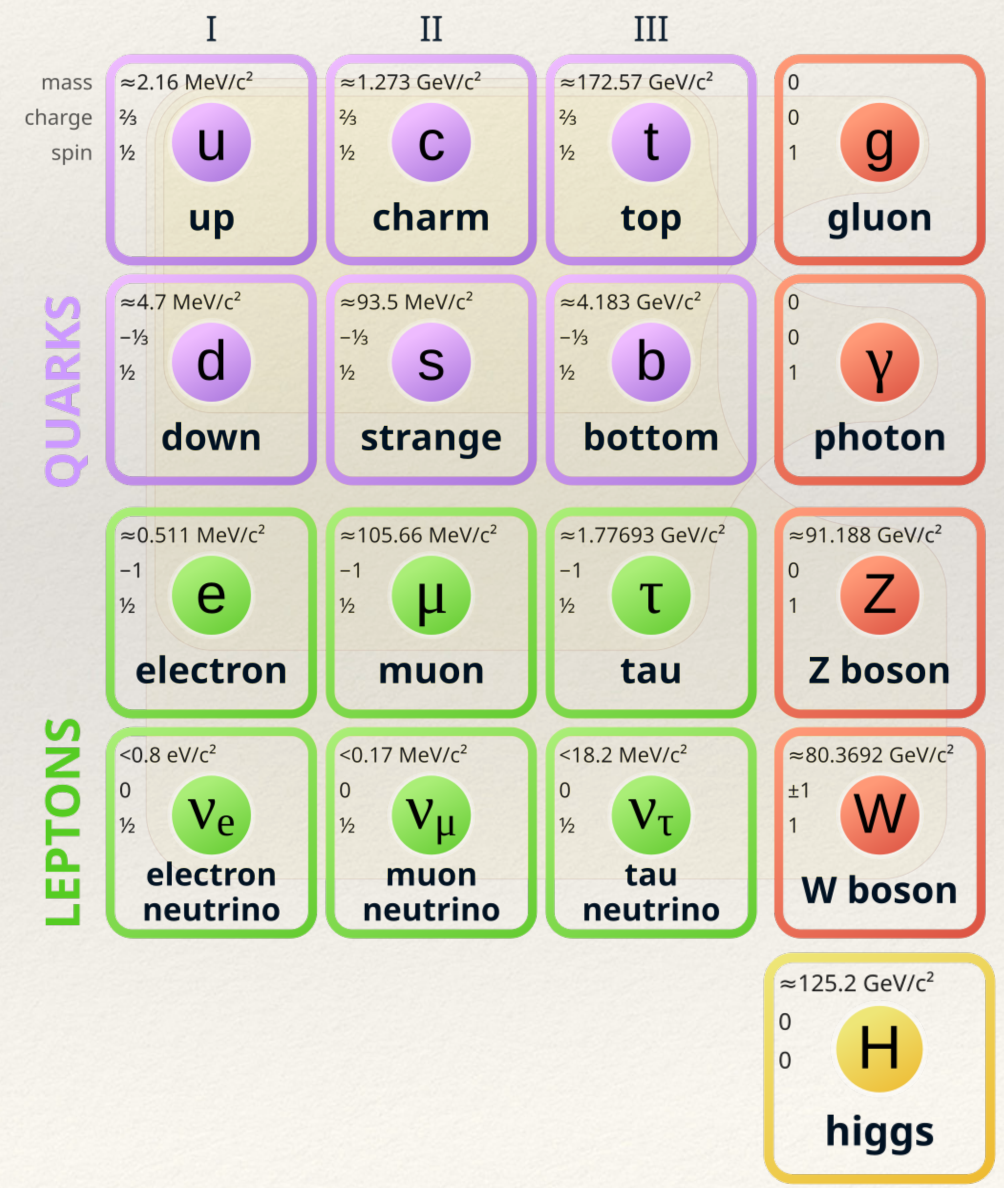
A. 48 — elementary bosons

B. 52 — elementary fermions

C. 60

D. 61 $2\times(6+3\times6)+4+8+1$

E. 62 — if counting graviton, but we do not know



Fundamental Particles

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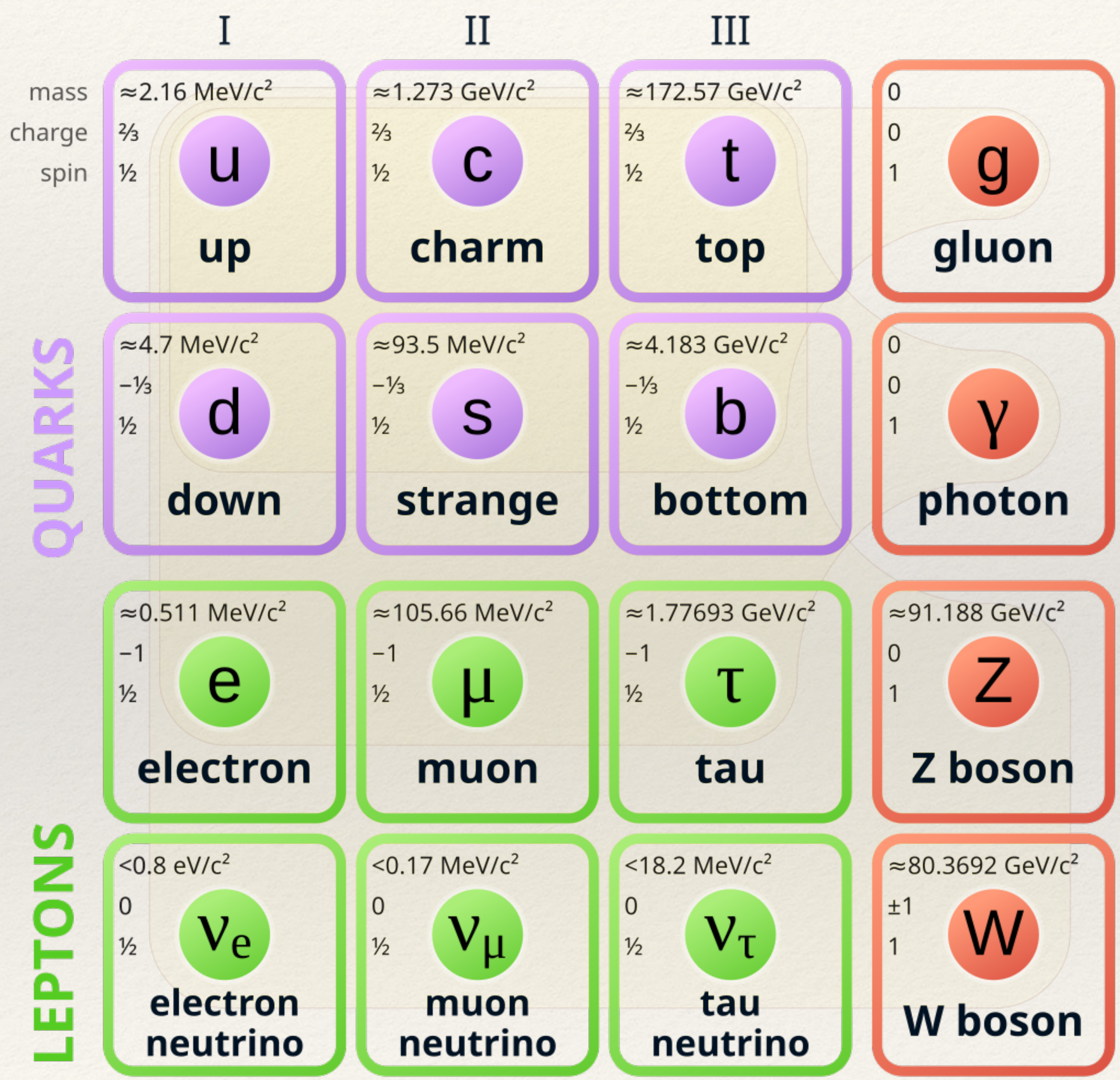
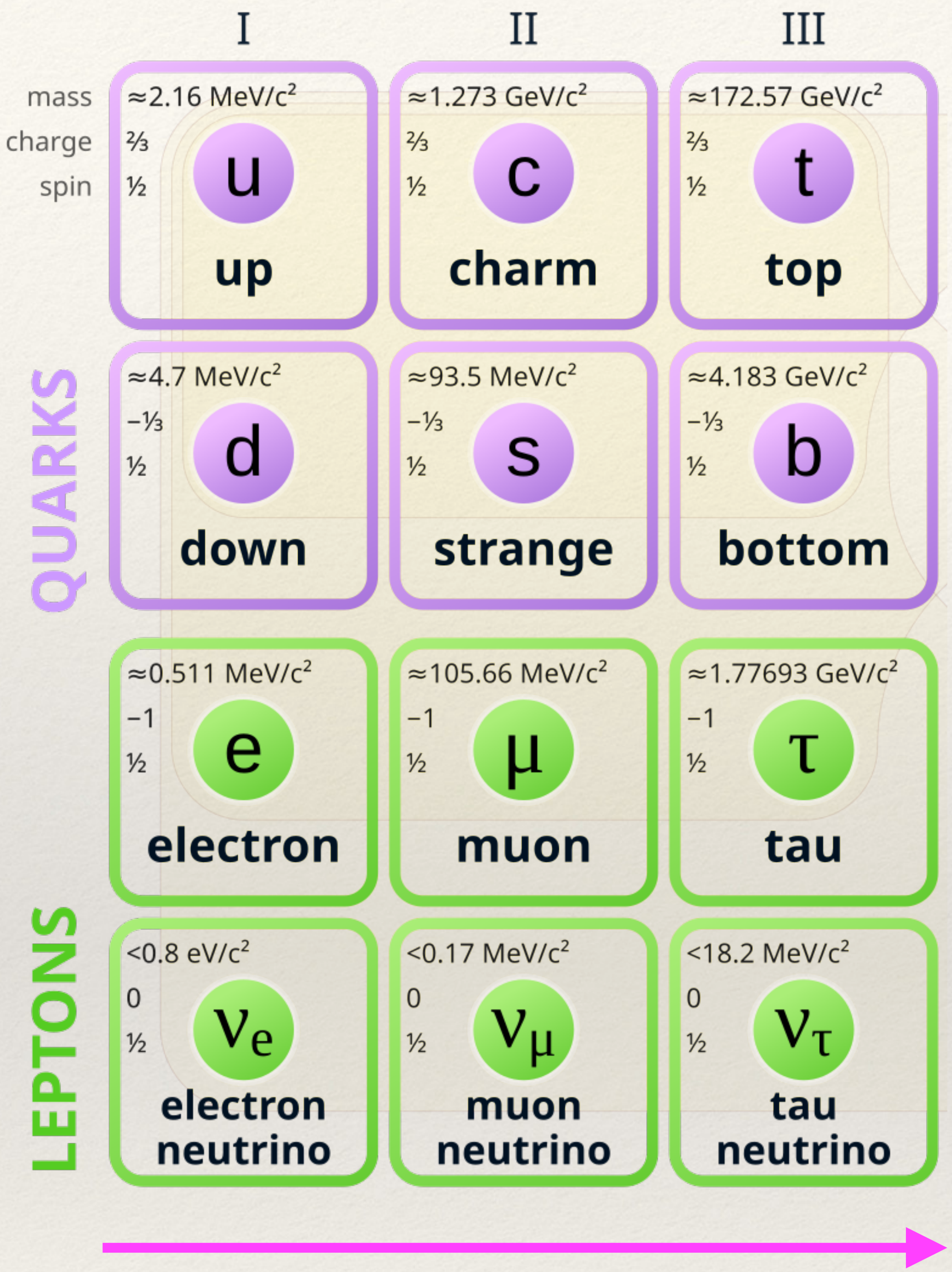
(e^- in 1897, almost 20th century, but e^+ in 1932)



Discovered in the 21st century

Masses of Elementary Particles

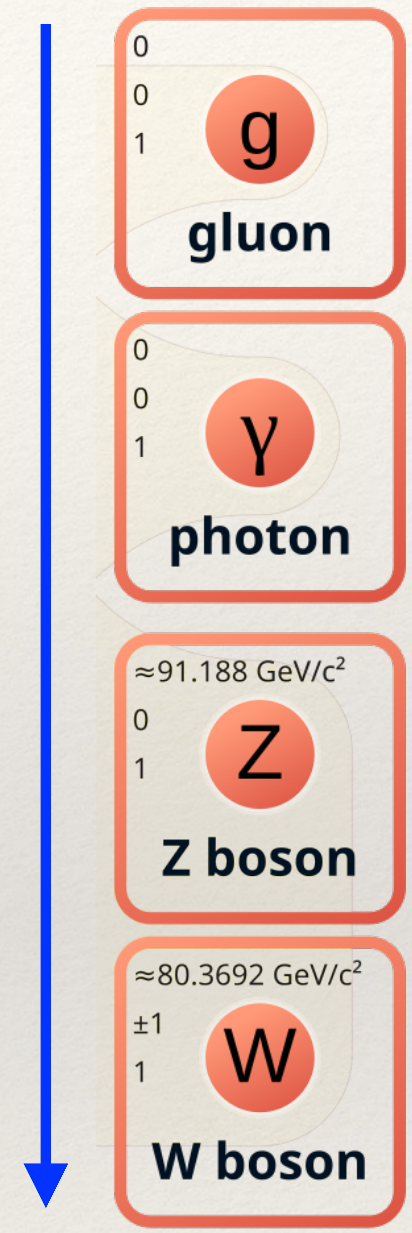


- Why such spread in fermion masses? (matter particles)

$$m_{\nu_e} < 0.8\ \mathrm{eV}/c^2$$

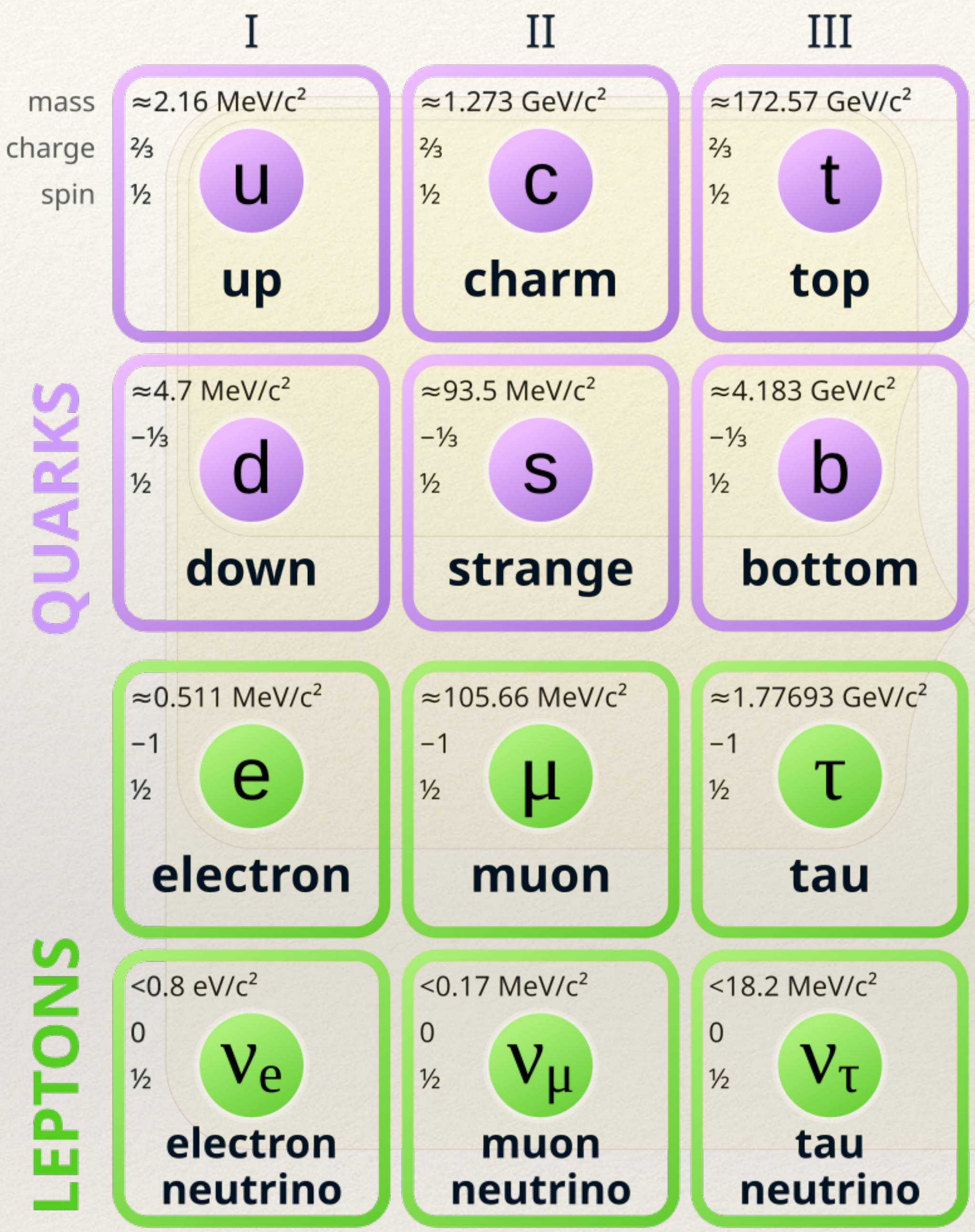
$$m_t \approx 1.7 \times 10^{11}\ \mathrm{eV}/c^2$$

- Why some bosons (force carriers) are massless and others massive?

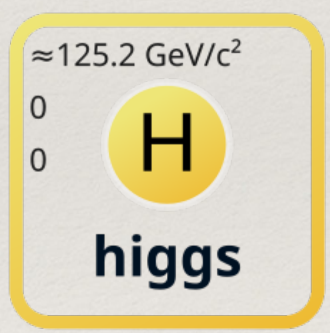


- Why each generation much heavier than the preceding one.

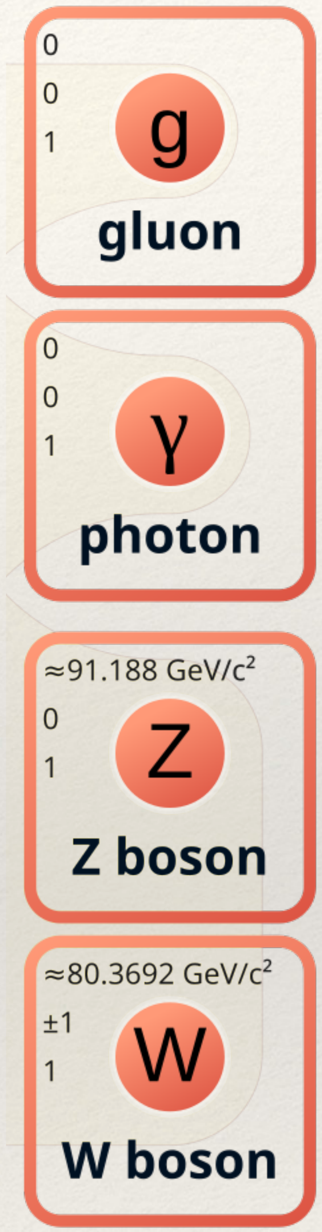
Masses of Elementary Particles



- Why such spread in fermion masses?
- Why some bosons are massless and others massive?



$$m_H c^2 = \sqrt{2\lambda}\, v$$



$$m_f\, c^2 = \frac{y_f\, v}{\sqrt{2}}$$

Higgs field

$$m_W\, c^2 = \frac{1}{2} g\, v$$

Big Questions

- Why are there exactly 3 generations of fermions?
- Why are there leptons and quarks, pairs in each generation?
- Why do masses span huge ranges (e.g. top vs electron)?
- Why are neutrino masses so tiny, are neutrinos special?
- Why are there 4 forces and why is their strength what it is?
- Why is the Higgs mass so small compared to to the Planck $M_{\rm Pl}$
- Why is $v = 246\,\mathrm{GeV}$?
- Why does the Universe contain more matter than antimatter?
- What is dark matter, dark energy, what caused inflation ?..

Big Answers?

- We have no answers to these questions

  — but we are looking for answers

(1) obtain experimental data to challenge Standard Model

(2) propose new Models which

— consistent with existing data

— explains existing puzzles

— has predictive power

Big Ideas

- Symmetry as the organizing principle

  example: Spontaneous symmetry breaking → generates masses

- Grand Unification Theories (GUTs)

  — all forces unify at high energy

- Supersymmetry (SUSY)

  — every particle has a partner (fermion ↔ boson)

- Extra dimensions

  — warped extra dimensions of space beyond 3 familiar ones

- String theory

  — particles = vibrating strings

Big Ideas, Part 2

- Emergence / deeper principles
  — what we think is fundamental may not be fundamental
- Anthropic principle (multiverse)
  — parameters vary across universes, ours are compatible with life

https://www.youtube.com/watch?v=om2lIWXLLN4&t=3s

Fundamental Parameters

Fundamental Parameters

- How many fundamental parameters do we need?

A. 5

B. 6

C. 20

D. 26

E. 61

Example: mass of an electron

Counting Parameters: Quarks

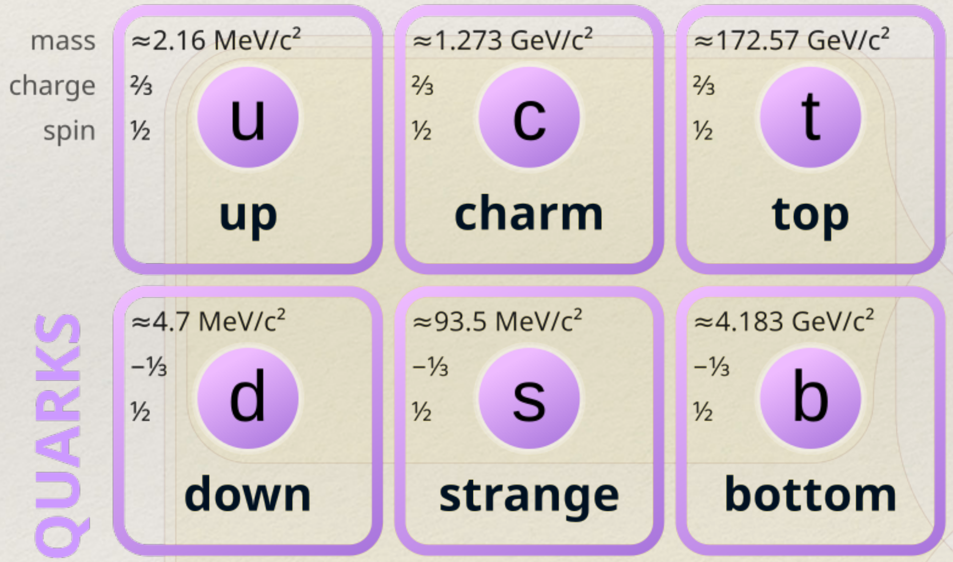
- Mass of each quark is a parameter which we cannot predict

  — may be there is a deeper theory
  which will make predictions / relationship

  — for now 6 parameters of the theory
  which we must measure in experiment

6 parameters:

$$m_d, m_u, m_s, m_c, m_b, m_t$$

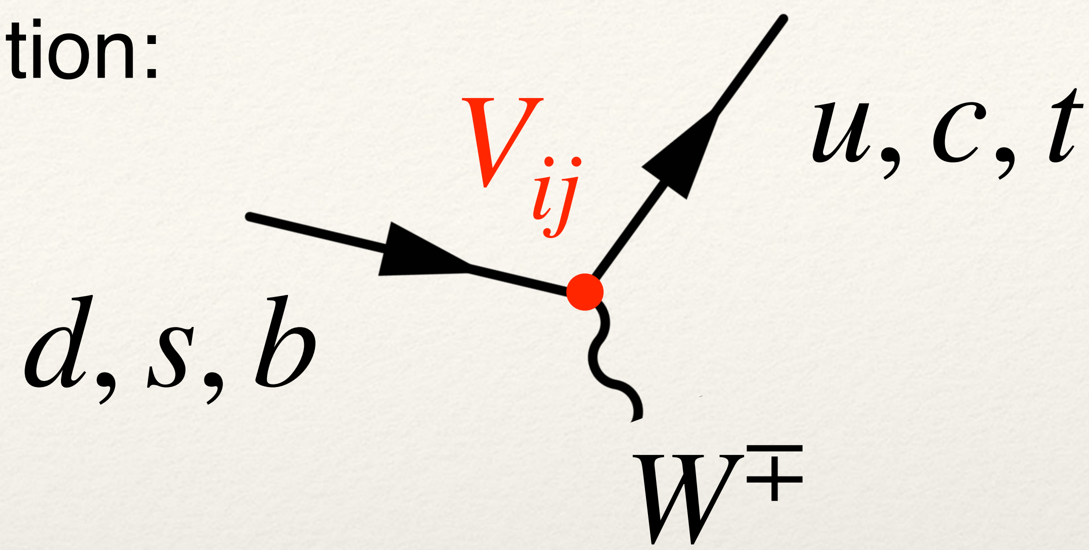


- Masses of particle and antiparticle are equal

  — fundamental CPT theorem…

Counting Parameters: Quarks

- 4 parameters which describe transition:

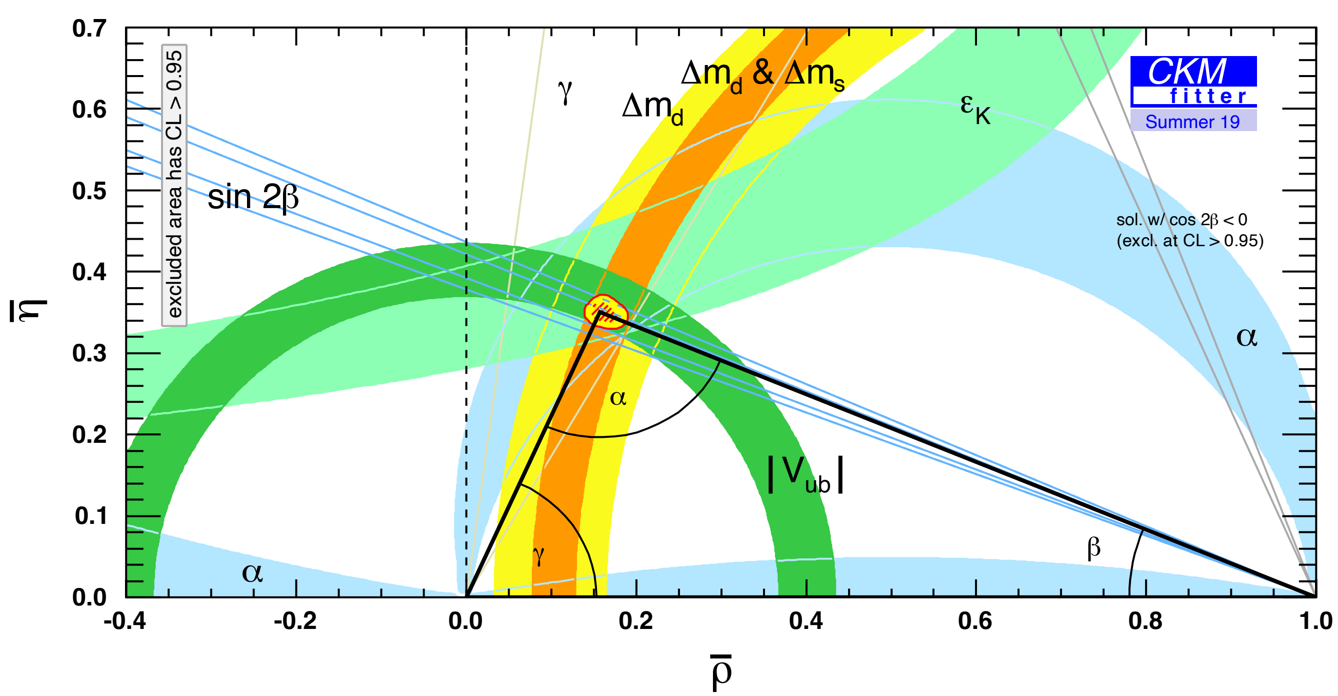


  - Matrix V_{ij} must preserve probability, described by
    - 3 angles and 1 phase which can tell matter from antimatter (responsible for CP or Time symmetry violation)

$$\begin{pmatrix} u \\ c \\ t \end{pmatrix} \leftrightarrow \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{\mathrm{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Nobel Prize in Physics 2008

- The only known source of CP violation (difference matter-antimatter)
  - in the Quark sector (completion of the Standard Model in this sector)



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The Nobel Prize in Physics 2008

Photo: University of Chicago
Yoichiro Nambu
Prize share: 1/2

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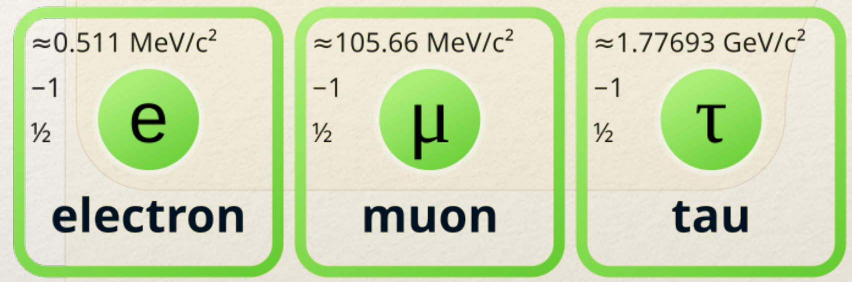
Photo: U. Montan
Makoto Kobayashi
Prize share: 1/4

© The Nobel Foundation
Photo: U. Montan
Toshihide Maskawa
Prize share: 1/4

The Nobel Prize in Physics 2008 was divided, one half awarded to Yoichiro Nambu *"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"*, the other half jointly to Makoto Kobayashi and Toshihide Maskawa *"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"*.

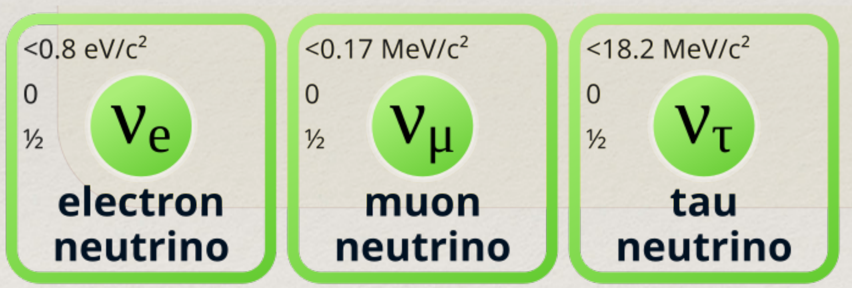
Counting Parameters: Leptons

- Mass of each lepton is a parameter which we cannot predict
- In the original Standard Model neutrinos have no mass $m_\nu = 0$
  - would bring only 3 parameters: m_e, m_μ, m_τ



  - no "CKM" matrix

$$m_{\nu_e} = m_{\nu_\mu} = m_{\nu_\tau} = 0$$



Nobel Prize in Physics 2015

- Discovery of neutrino "oscillations" $\Rightarrow$ $m_\nu \neq 0$

interact propagate

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = V_{\mathrm{MNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

conclusive result in 2001

from two experiments:

Super-Kamiokande (Japan)

Sudbury Neutrino Observatory (SNO, in Canada)

Nobel Prize in Physics 2015

© Nobel Prize Outreach. Photo: A. Mahmoud

Takaaki Kajita

Prize share: 1/2

© Nobel Prize Outreach. Photo: A. Mahmoud

Arthur B. McDonald

Prize share: 1/2

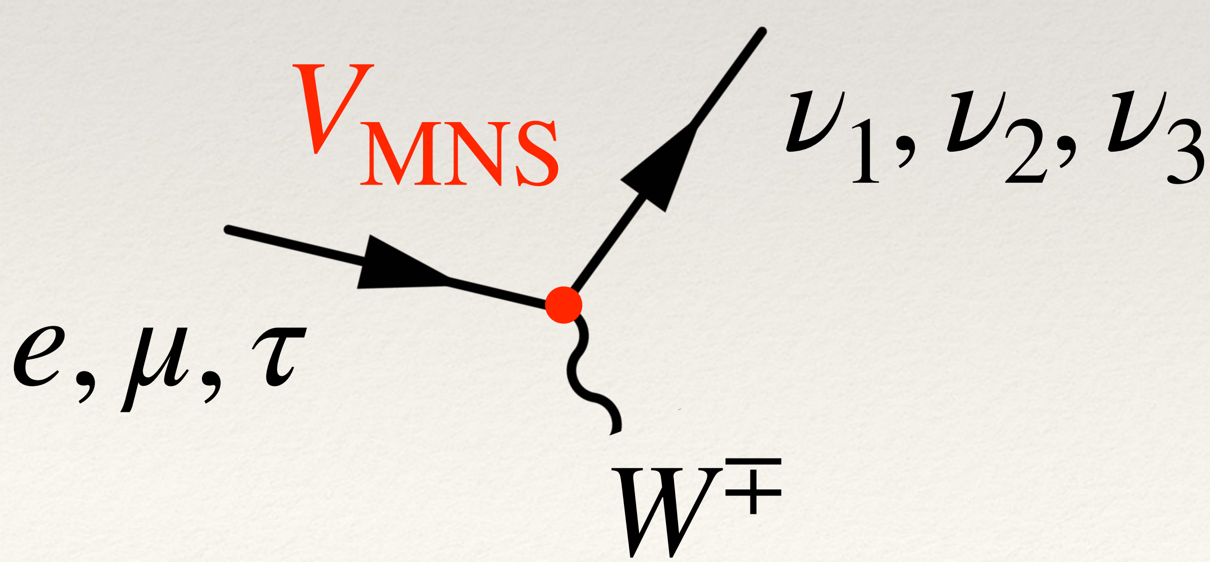
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass"

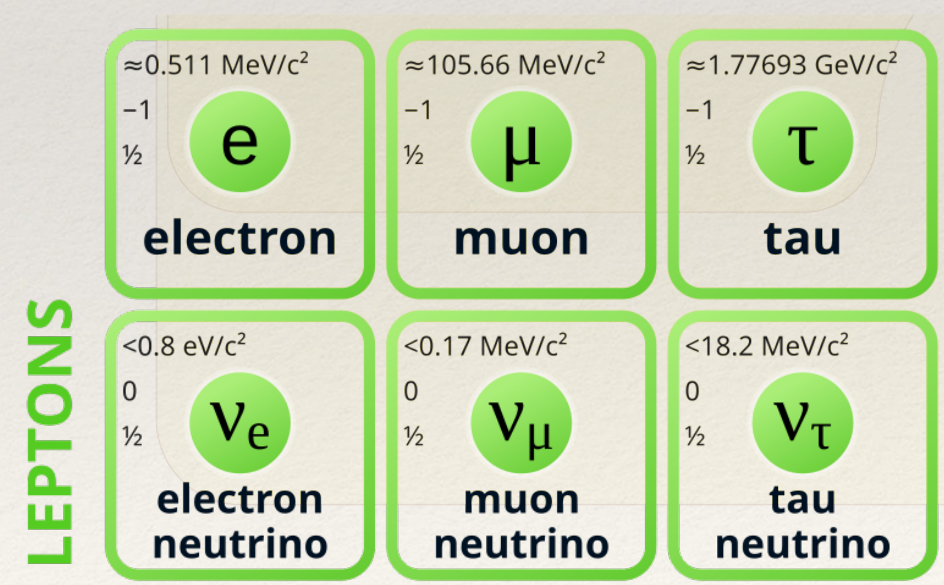
Counting Parameters: Leptons

- Mass of each lepton is a parameter which we cannot predict
- In original Standard Model neutrinos have no mass $m_\nu = 0$
  - — would bring only 3 parameters: m_e, m_μ, m_τ
- However, it was discovered that neutrinos have mass

10 parameters: 6 masses $m_e, m_\mu, m_\tau, m_1, m_2, m_3$

3 angles and 1 phase





Fundamental Parameters

- How many fundamental parameters do we need to describe fundamental fermions?

    A. 5

    B. 6

    C. 20

    D. 26

    E. 61

Fundamental Parameters

- How many fundamental parameters do we need to describe fundamental fermions?

A. 5

B. 6

C. $\boxed{20}$

D. 26

E. 61

$$6 + 4 + 6 + 4$$

$$m_d, m_u, m_s, m_c, m_b, m_t$$

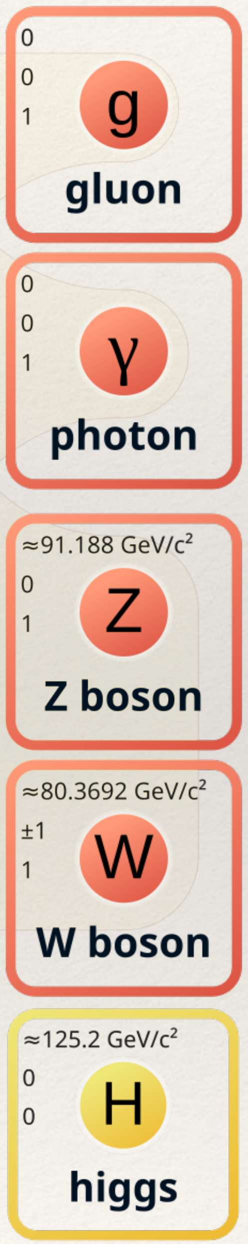
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$m_e, m_\mu, m_\tau, m_1, m_2, m_3$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = V_{\text{MNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Counting Parameters: Bosons

- One could (naively) define boson masses as parameters, but:



$$m_g = 0$$

$$m_\gamma = 0$$

$$m_Z = 91.2\ \mathrm{GeV}$$

$$m_{W+} = m_{W-} = 80.4\ \mathrm{GeV}$$

$$m_H = 125\ \mathrm{GeV}$$

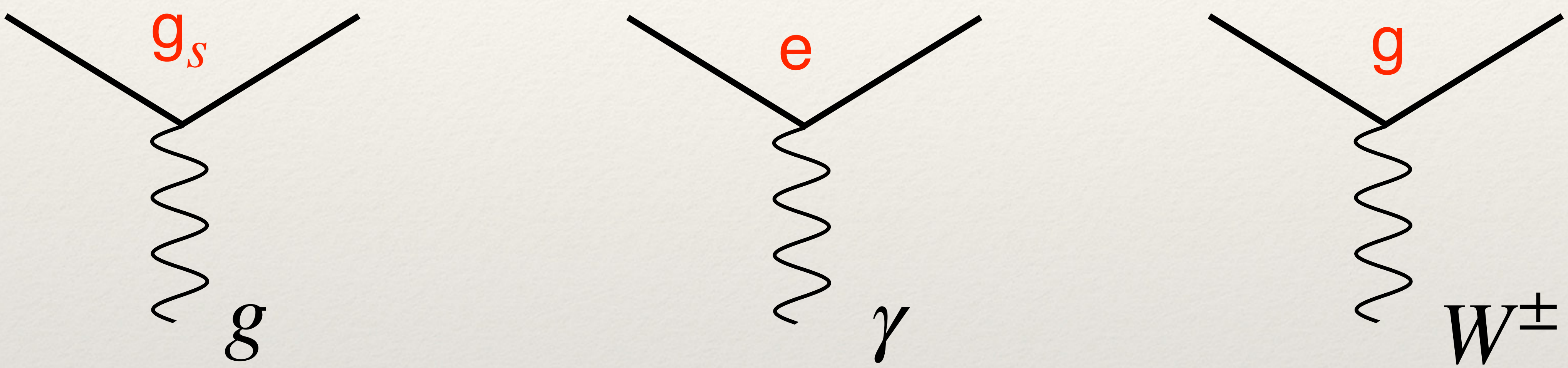
a different approach is taken…

because boson masses are derived, e.g. $m_W c^2 = \frac{1}{2} g\, v$

Strength of Interactions

- 3 parameters of strength

strong interactions   electromagnetic   weak interactions



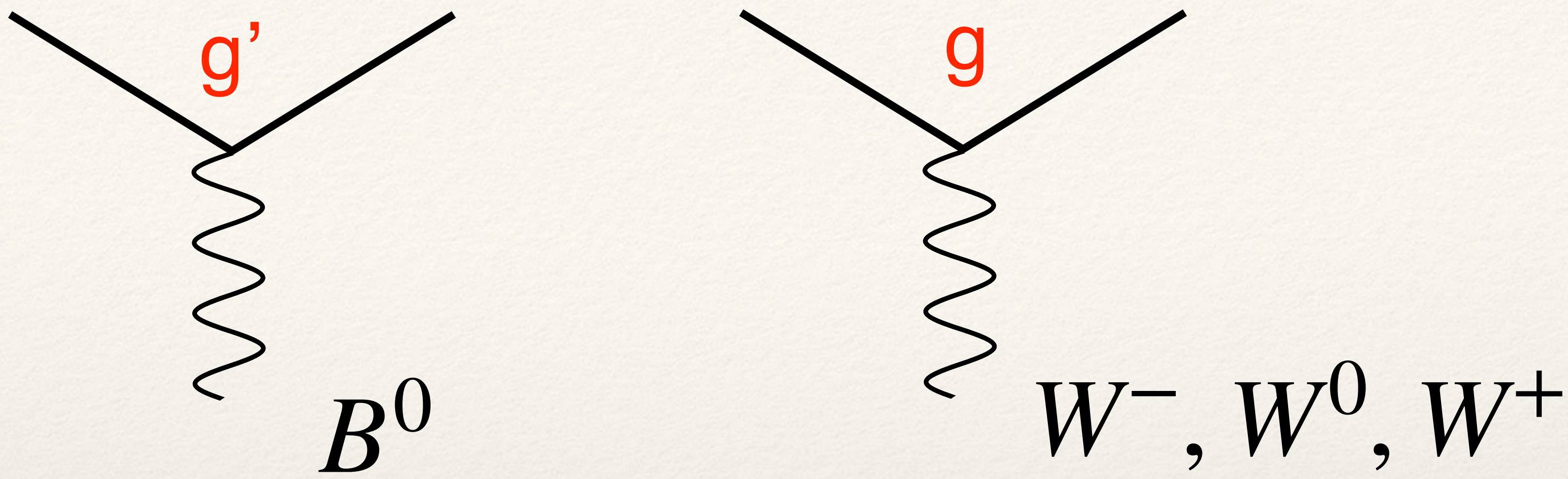
(why did we skip the Z boson ?..)

- 1 parameter that describes CP (Time) symmetry violation

  in strong interactions θ_{QCD}

  no evidence of non-zero value…

Electroweak Interactions



- There are four “original” bosons: B^0 and W^-, W^0, W^+

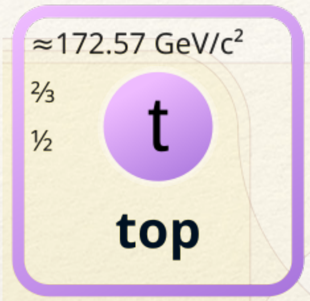
$$\begin{pmatrix} Z \\ \gamma \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W \\ \sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} W^0 \\ B^0 \end{pmatrix}$$

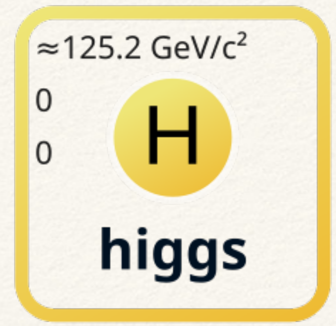
- Electroweak symmetry breaks (recall Higgs mechanism)

  — one boson remains massless (γ)

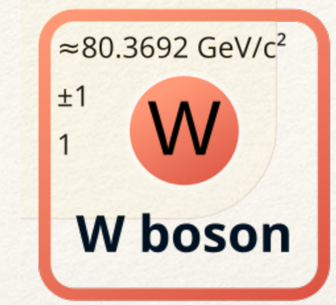
  — three bosons acquire mass (Z, W^+, W^-)

The Higgs Mechanism





$$m_H c^2 = \sqrt{2\lambda}\, v$$



$$m_f\, c^2 = \frac{y_f\, v}{\sqrt{2}}$$

Higgs field

$$m_W\, c^2 = \frac{1}{2} g\, v$$

- This idea was around since 1964-67
  - — gave explanation to all elementary particle masses
  - — why no Nobel Prize for nearly 50 years?
- Needed to prove its predictive power
  - — H discovered in 2012, Nobel Prize in 2013

Fundamental Parameters

- How many fundamental parameters do we need to describe fundamental bosons (interactions)?

    A. 5

    B. 6

    C. 20

    D. 26

    E. 61

Fundamental Parameters

- How many fundamental parameters do we need to describe fundamental bosons (interactions)?

A. 5

$\boxed{\text{B. } 6}$ $= 3 + 1 + 2$

C. 20

D. 26

E. 61

— three strengths g_s,g',g

— strong CP parameter θ_{QCD}

— Higgs boson self-coupling λ

— Higgs field expectation value (vev) v

Fundamental Parameters

- How many fundamental parameters do we need?

    A. 5

    B. 6

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Fundamental Parameters

- How many fundamental parameters do we need?

A. 5

B. 6

C. 20

D. $\boxed{26}$ $= 20 + 6$

E. 61

20 parameters describe fundamental fermions

6 parameters describe fundamental bosons

Fundamental Parameters

- We need 26 fundamental parameters in Subatomic World

  — if neutrinos are special, may be even more

- If we add gravity (General relativity), 2 more parameters:

  — Cosmological constant Λ (vacuum / dark energy density)

  — Newton's constant G_N (strength of gravity)

Planck mass: $$M_{\rm Pl} = \sqrt{\frac{\hbar c}{G_N}} \approx 1.22 \times 10^{19}\ \mathrm{GeV}$$

compared to weak scale: $$v = 2.46 \times 10^2\,\mathrm{GeV}$$

Fundamental Physics

- 61(+1) fundamental particles & 26(+2) fundamental parameters

  explain all measurements across the vast range of temperatures and cover all familiar phenomena by complexity and scale:

  — Physics (from Elementary Particles to Classical Physics)

  — Chemistry ("complicated Atomic Physics")

  — Biology ("complex Chemistry")

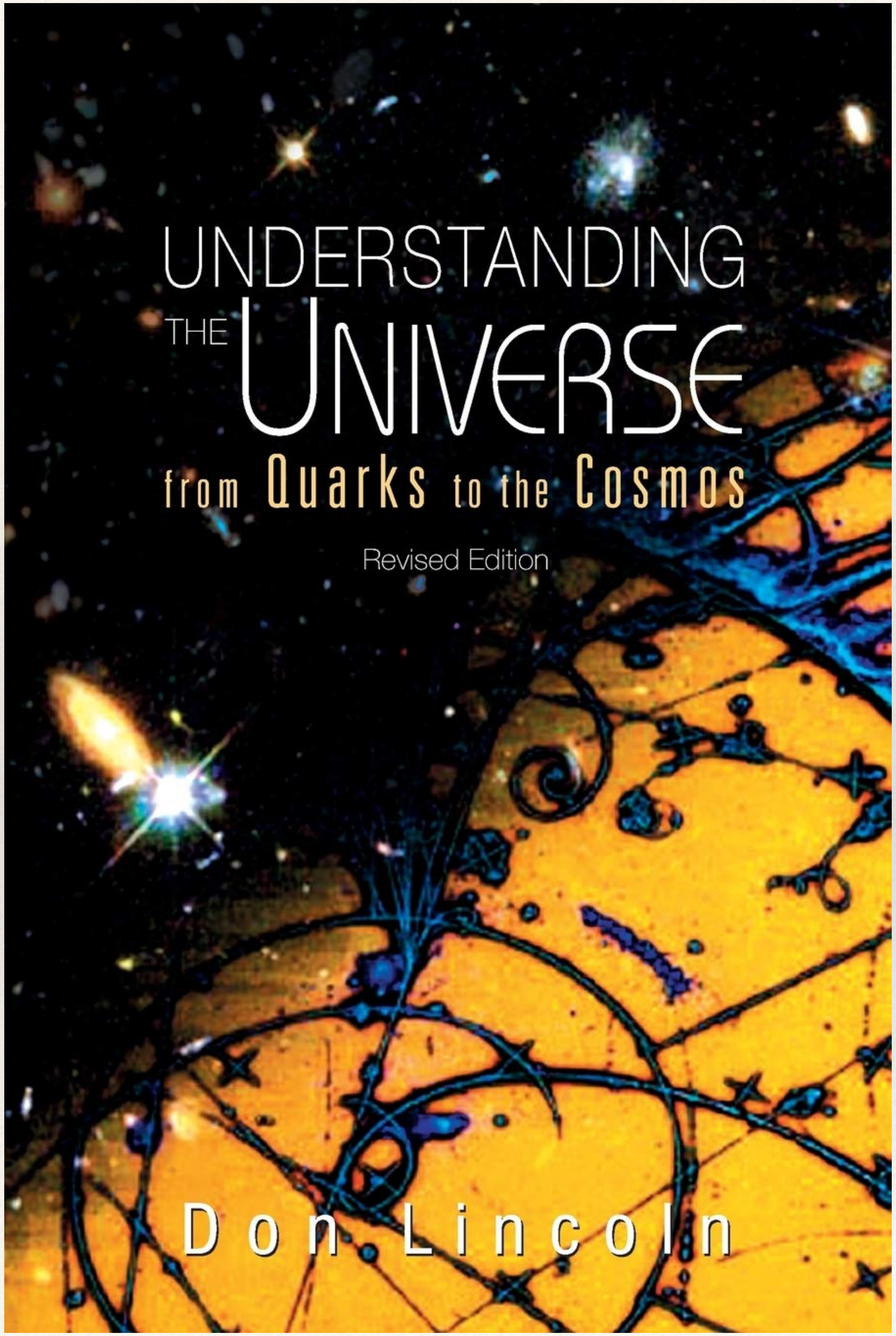
  — Astronomy ("large-scale Physics")

  — Cosmology ("Universe-level Astronomy")

- Why do these 26 parameters have the values that they have?

  — what if they were different?

Credits


UNDERSTANDING
THE UNIVERSE
from Quarks to the Cosmos
Revised Edition
Don Lincoln

YouTube channel with Don Lincoln: