Matter, anti-matter & the SM

https://en.wikipedia.org/wiki/Girl_before_a_Mirror

Experimental aspects covered by Andrii Usachov

Mara Senghi Soares　**6/June/2023**　**Topical Lectures on LHC physics - Nikhef**

Most particle physics lectures start with the Standard Model

Innovation: today I will start with a question

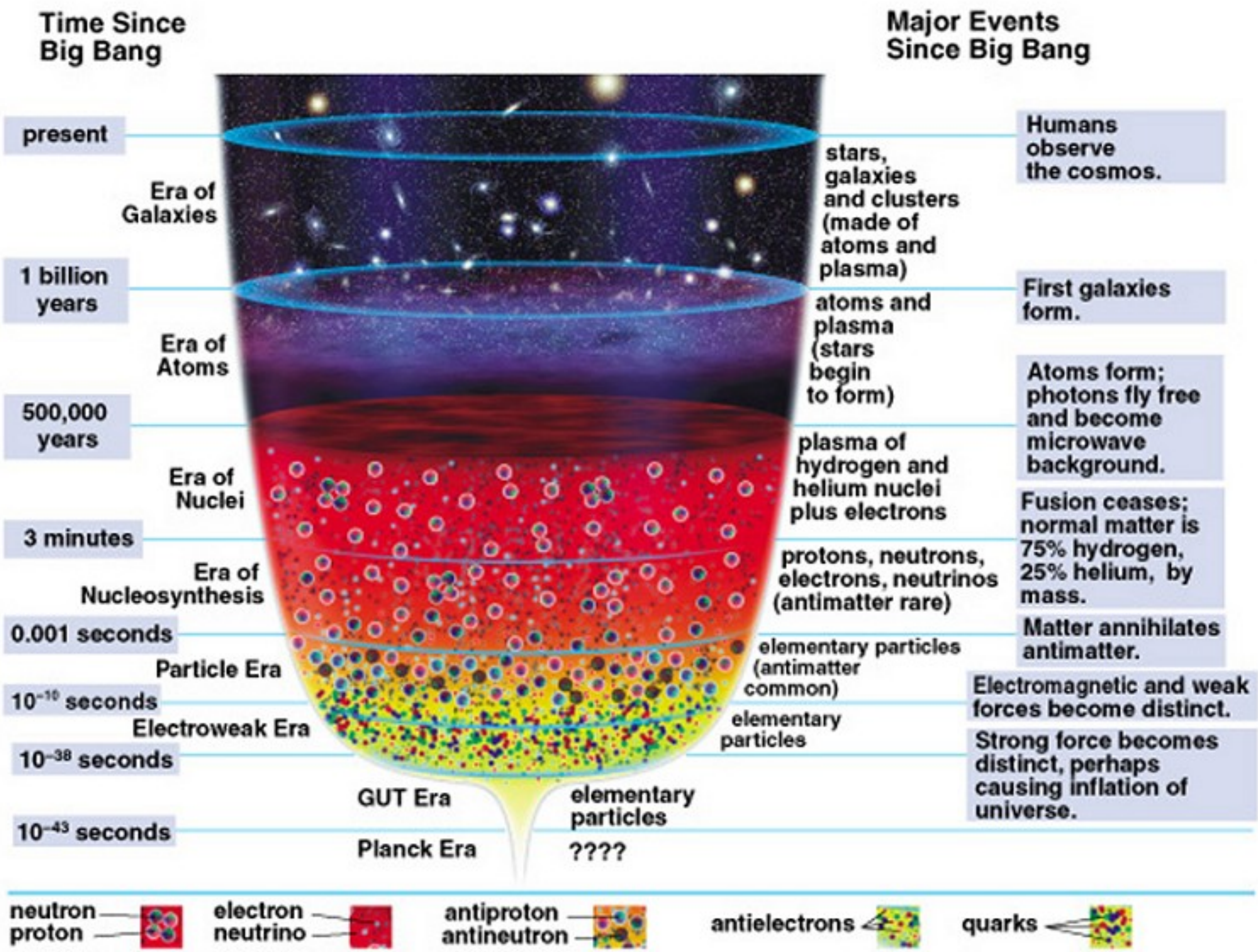
The origin of matter

Do we actually know what the universe is made of?

The origin of matter

Do we actually know what the universe is made of?

"The Essential Cosmic Perspective", by Bennett et al.



Disclaimer: I'm not a cosmologist

The origin of matter

how ?

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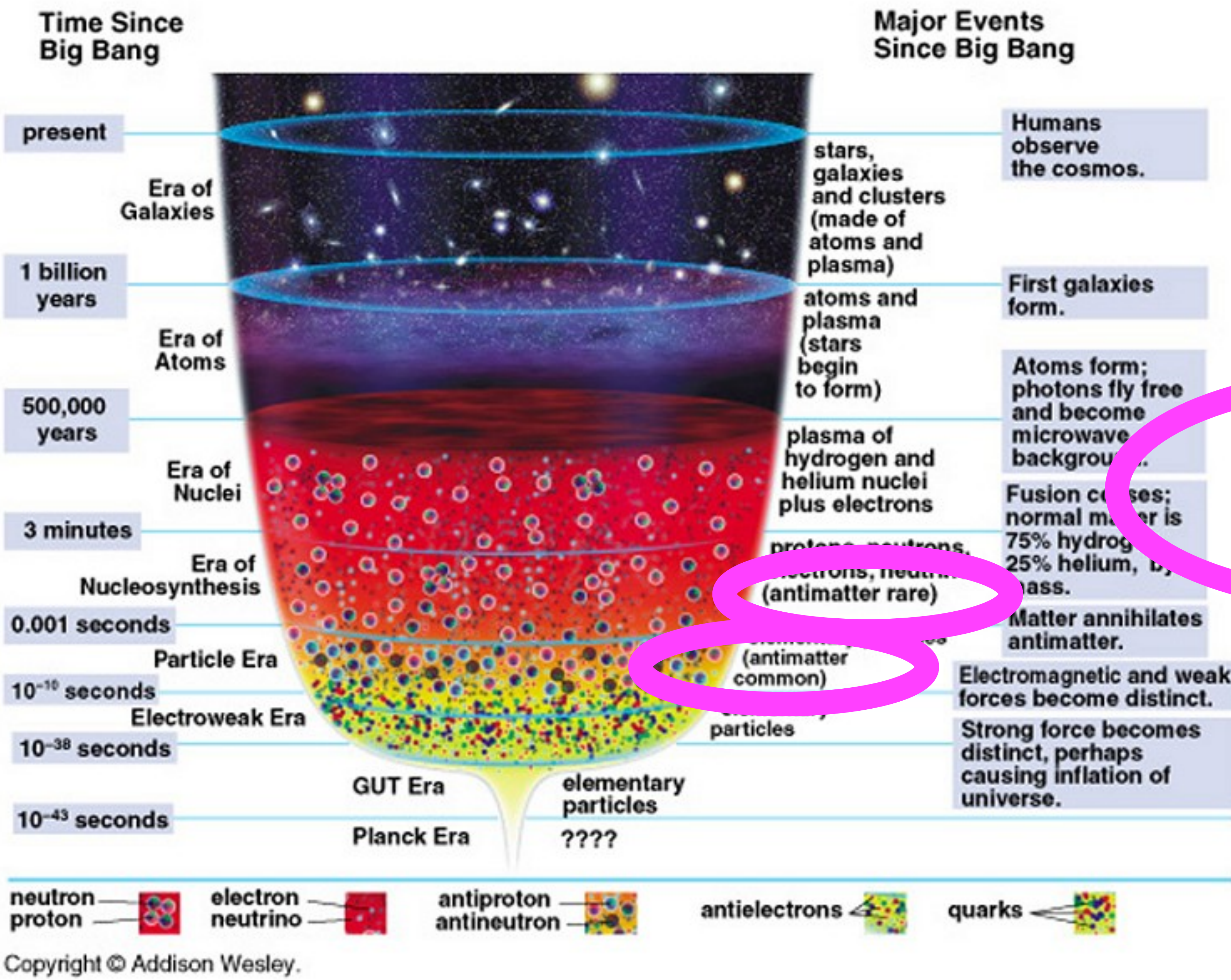


How??

Disclaimer: I'm not a cosmologist

the follow up question is

Can particle physics provide an answer?

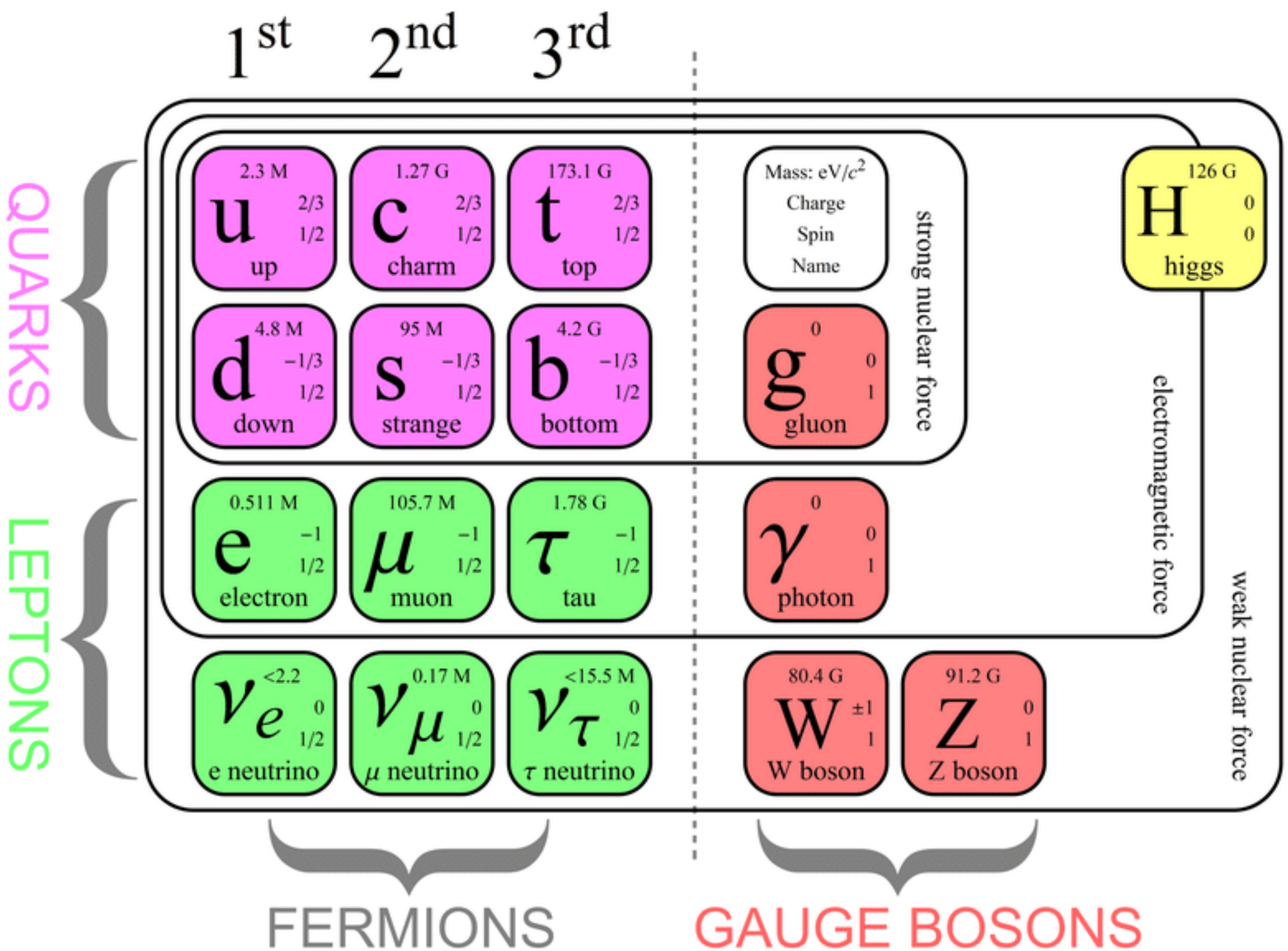
Ok, I was bluffing!

Of course I start with the standard model

elementary particles and their masses

Elementary particles: what are they?

Flavour structure: three generations



Matter particles: **three copies with same quantum numbers**

(three generations)

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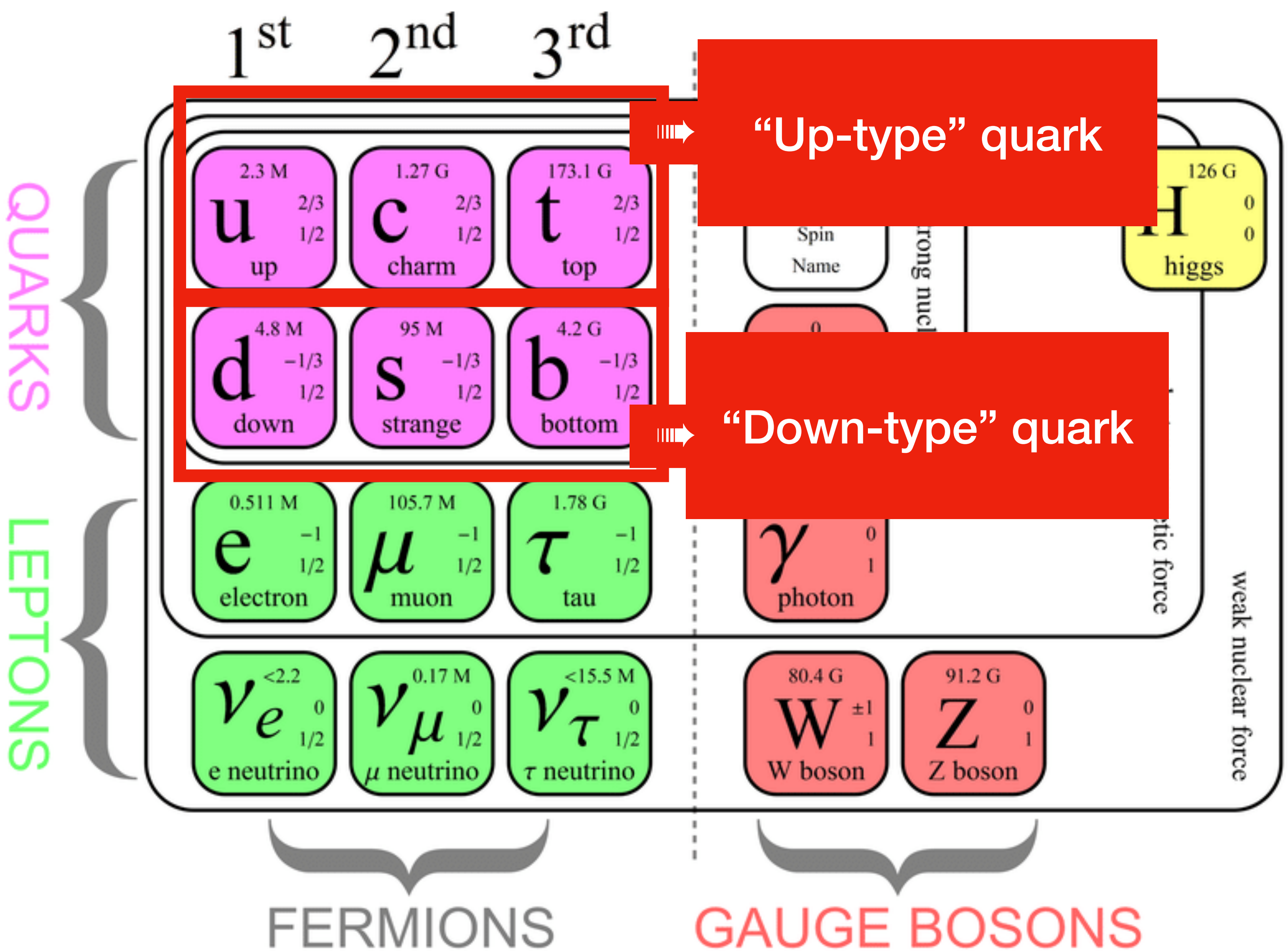


Matter particles: **three copies with same quantum numbers**

(three generations)

— different <u>flavours</u> —

the "copies" :

utterly different masses

identical in** almost **everything else

Elementary particles: what are they?

Flavour structure: three generations

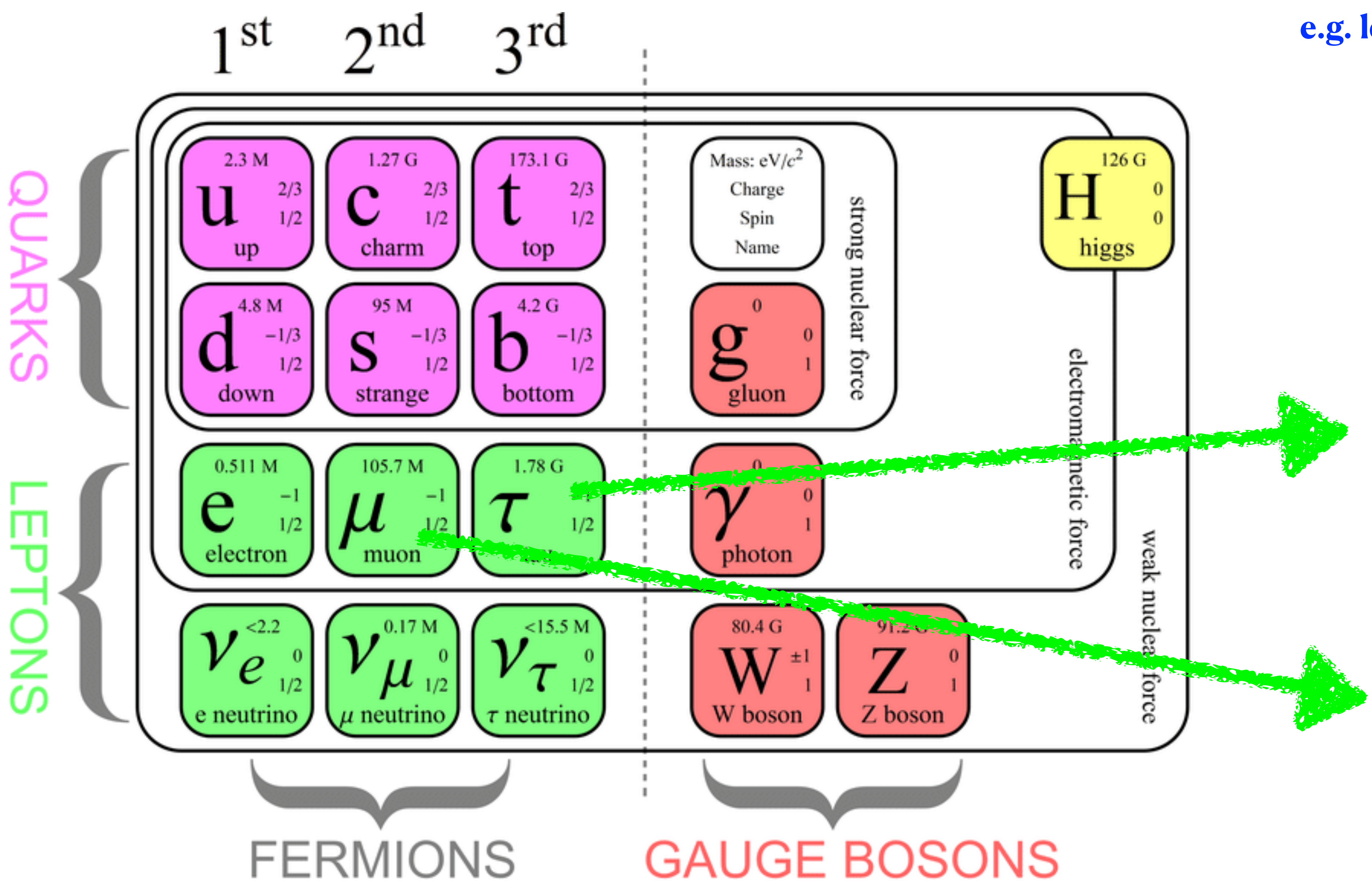
Second and third generation decay

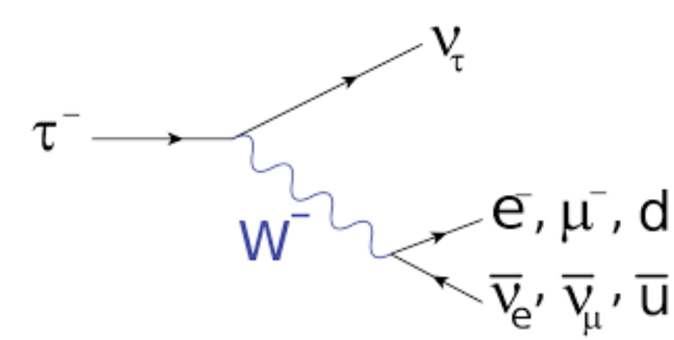
elementary matter particles of higher generations “disintegrate” instantly

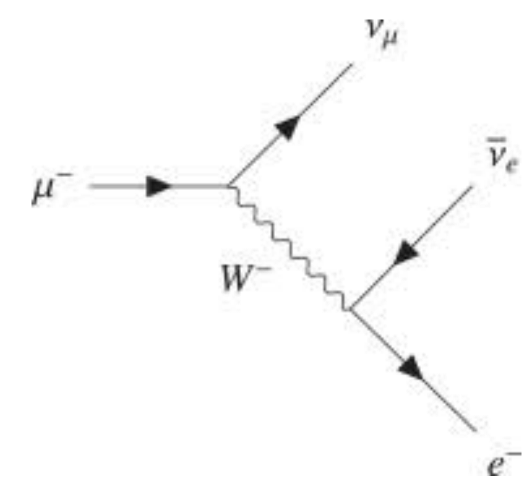
e.g. lepton lifetimes:

Tau	290×10^{-15}
Muon	2.197×10^{-6}
Electron	$> 6.6\ 10^{28}$

(electrons stable!)







Elementary particles: what are they?

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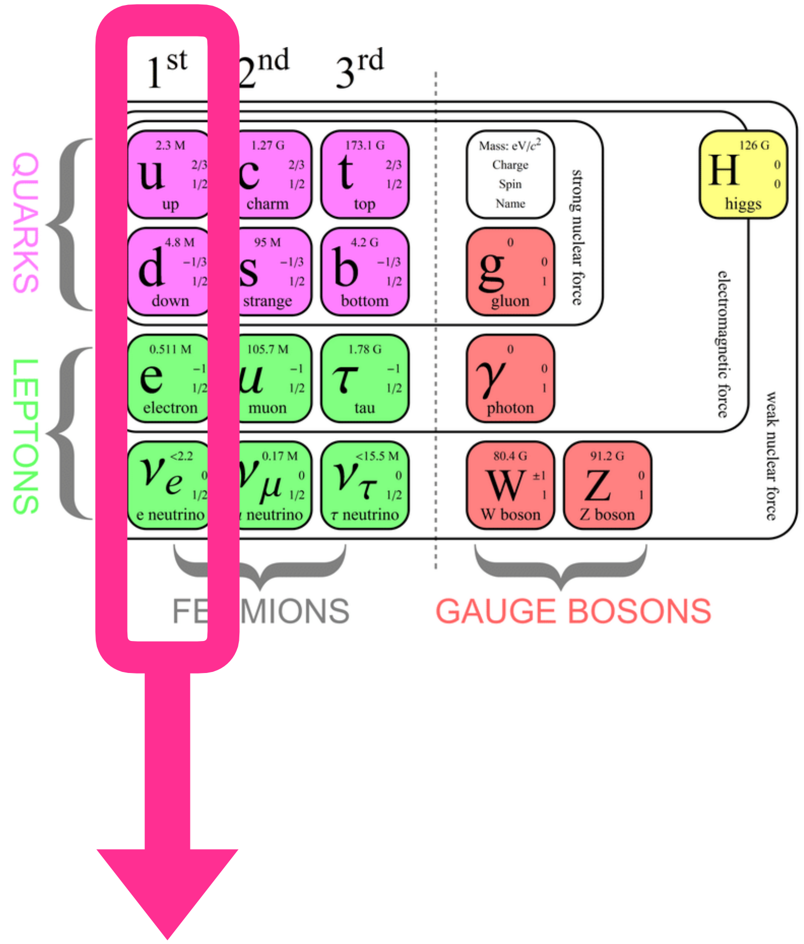
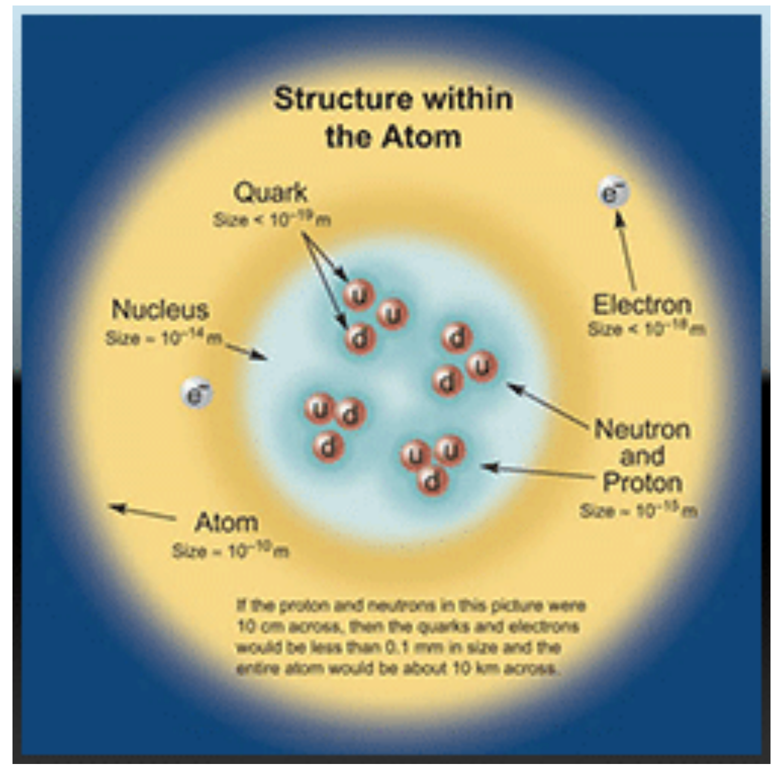


Only first generation is <u>stable</u> **:**

only "good material" to form atoms and all visible matter!



https://particleadventure.org/

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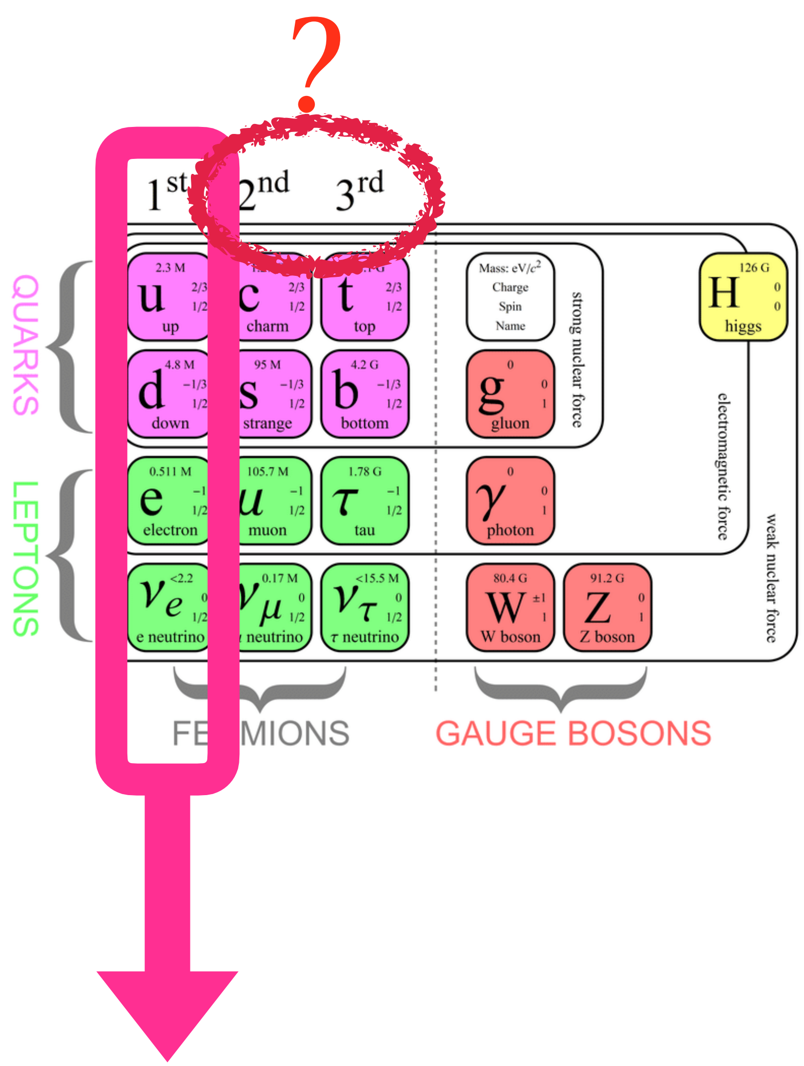

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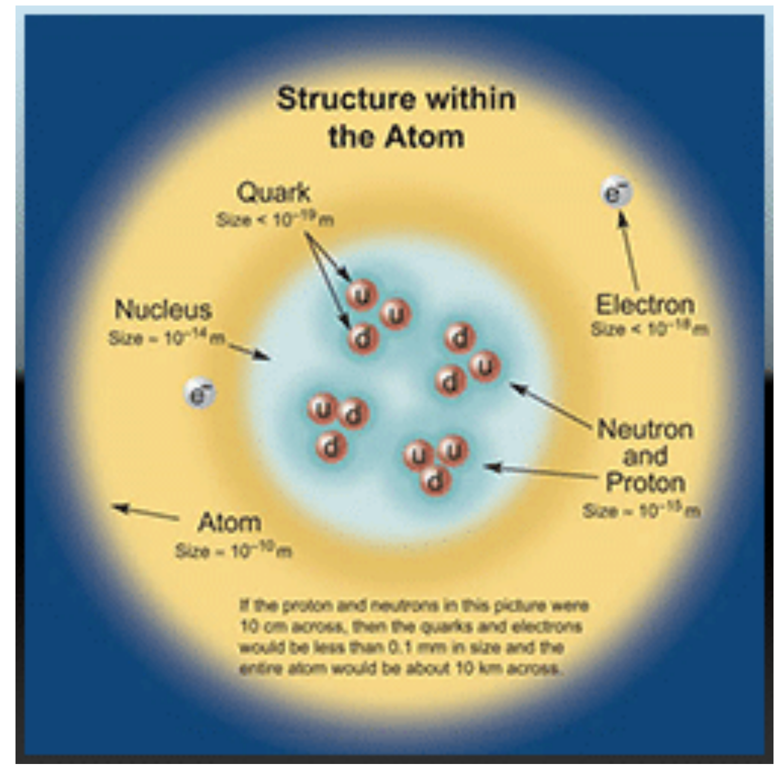


https://particleadventure.org/

If only one generation is needed to form matter why do we have 3?

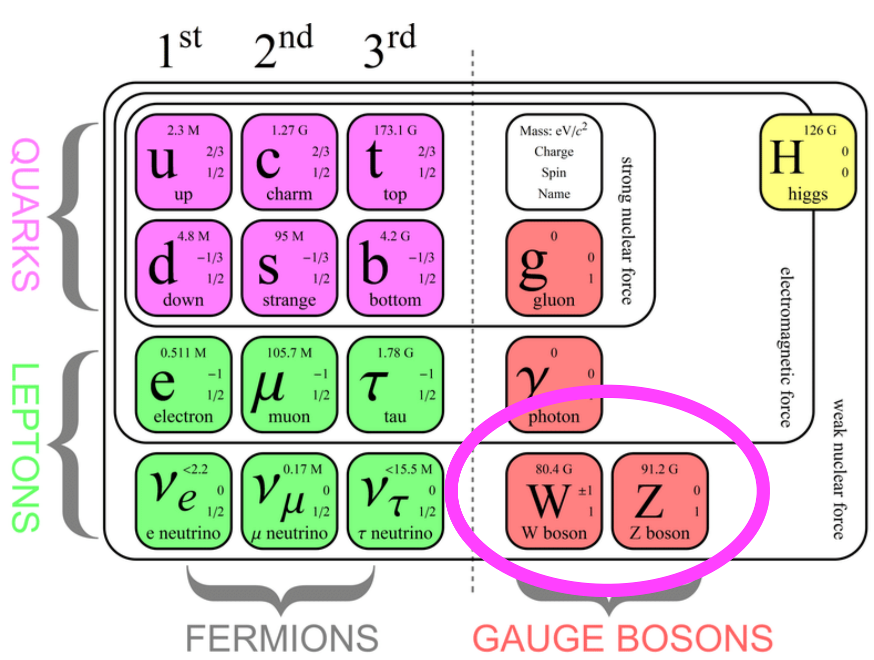
are there "new generations" to be discovered?

A fascinating mystery of the Standard Model

elementary particles and their interactions

elementary particles and their interactions

electroweak

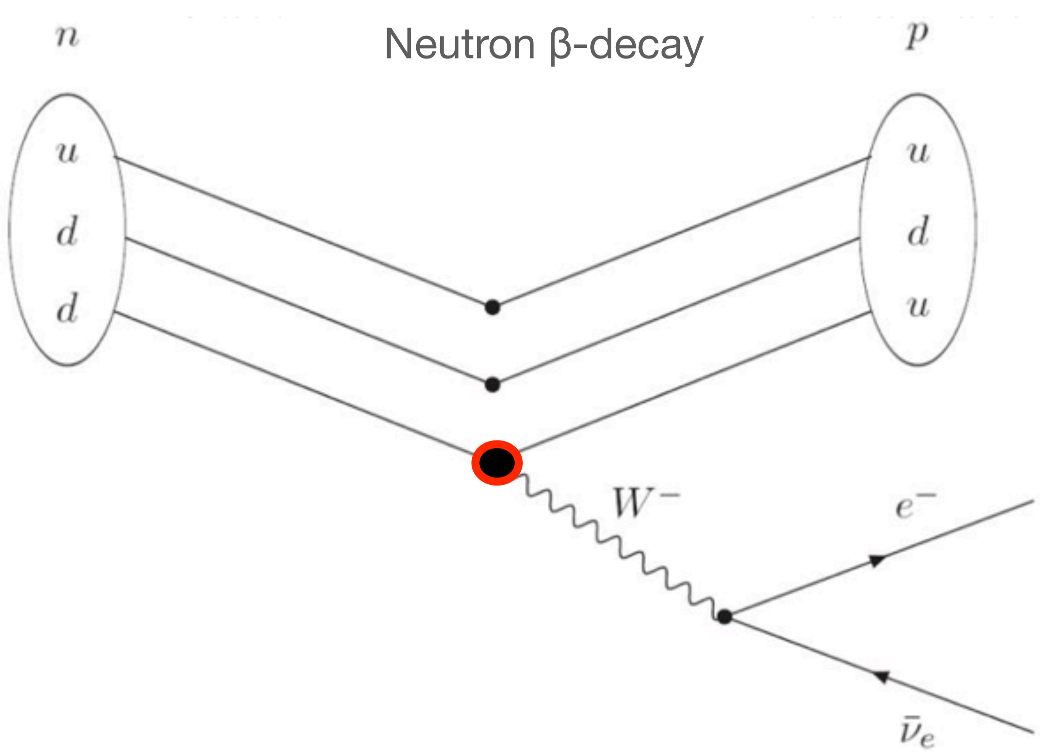


Flavour structure and quarks

A QUARK "BORN" OF A GIVEN FLAVOUR

CAN "DIE" A DIFFERENT FLAVOUR

via interaction



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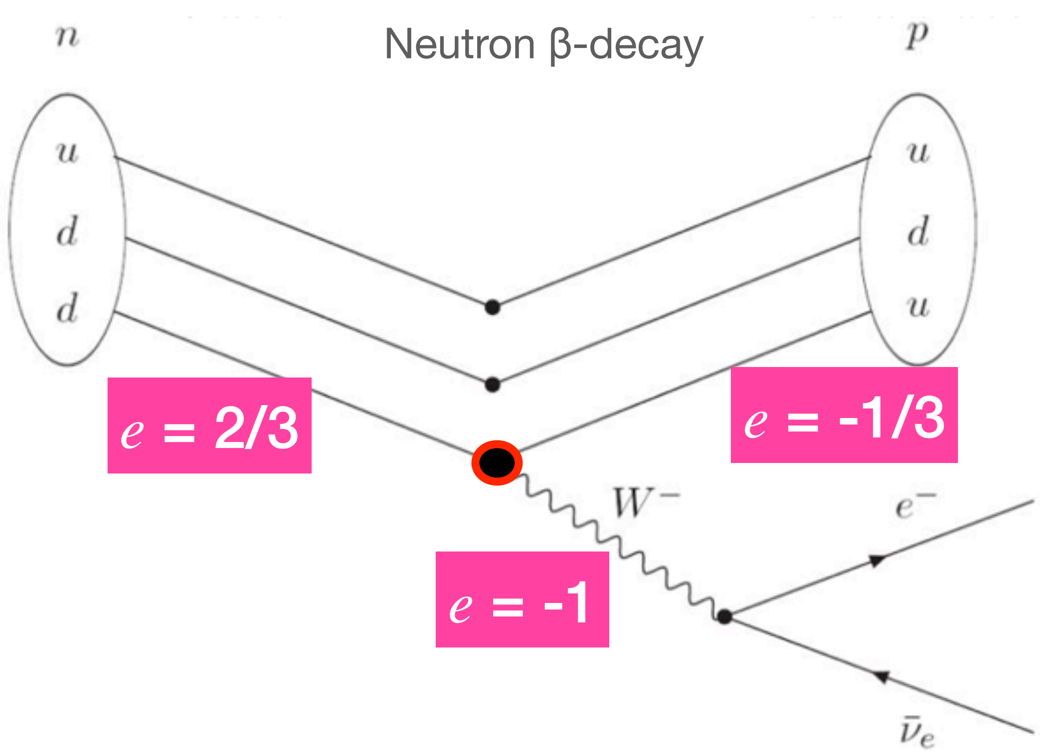
electrical charge
conserved in the transition

Neutron β-decay



Flavour structure and quarks

Mass versus interaction eigenstates

mass eigenstate $\neq$ interaction eigenstate

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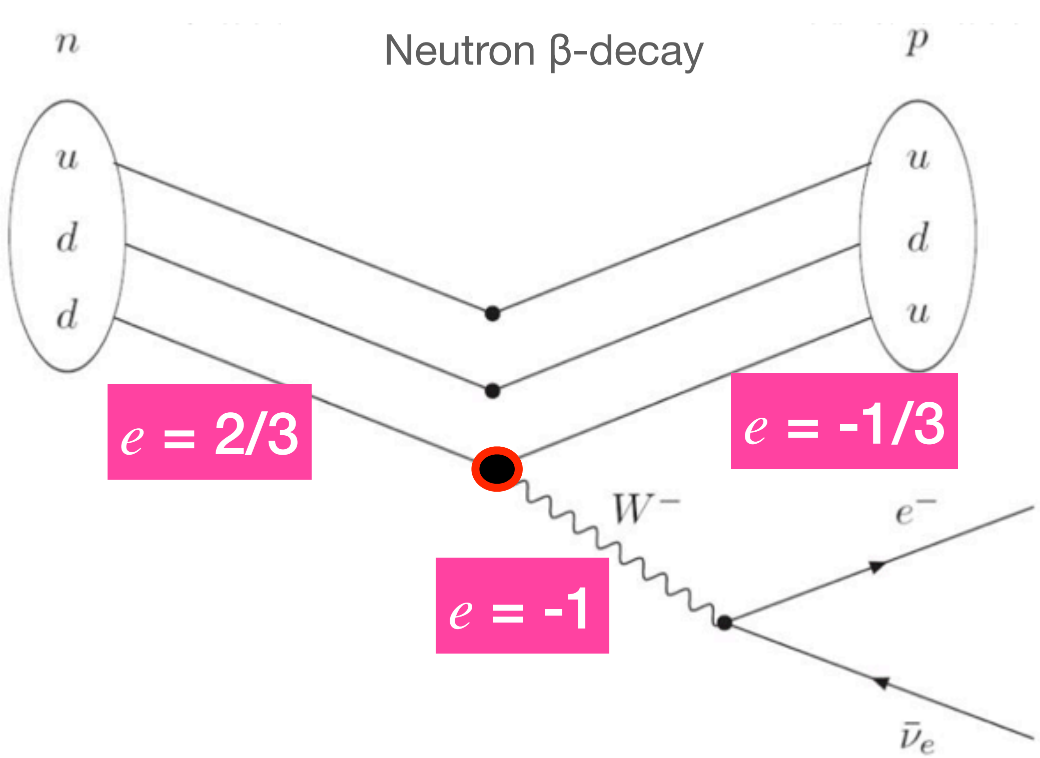
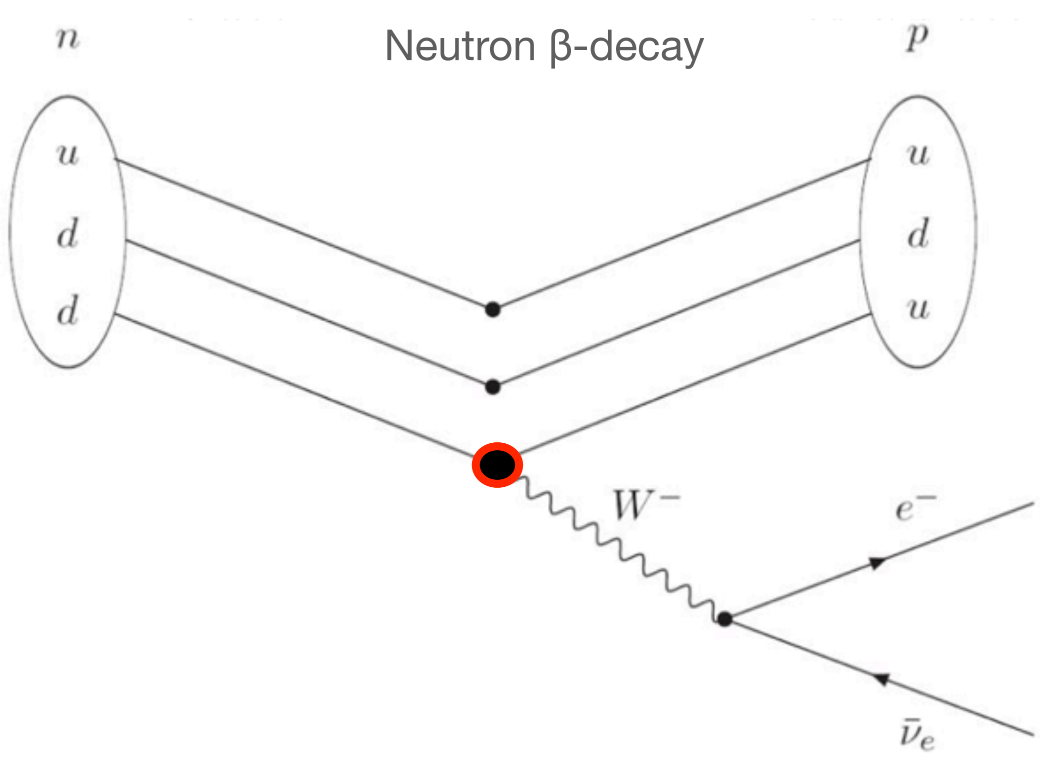


{Parenthesis for jargon clarification}

"Interaction strength"



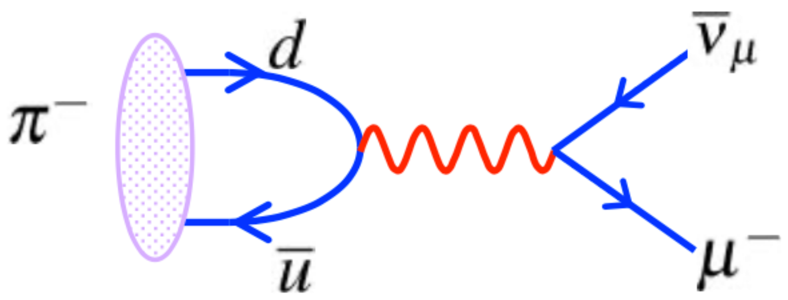
We call "interaction strength" the probability that ● occurs

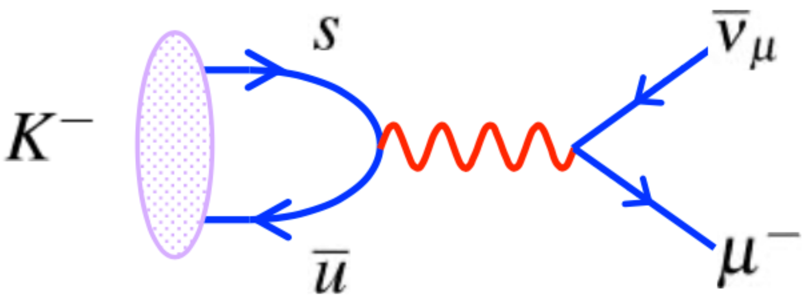
This probability is key input to calculations e.g. how often a process like

$n \to p\ e\ \nu$

occurs

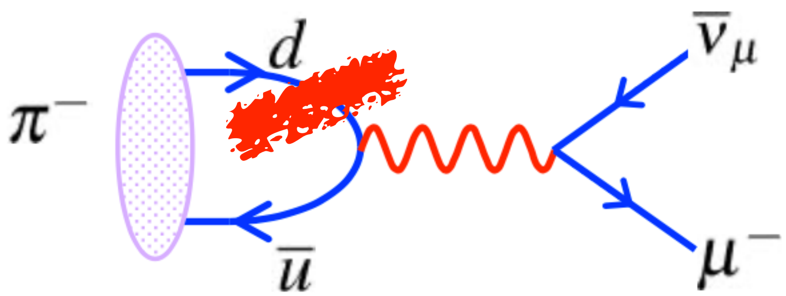
History of quark mixing

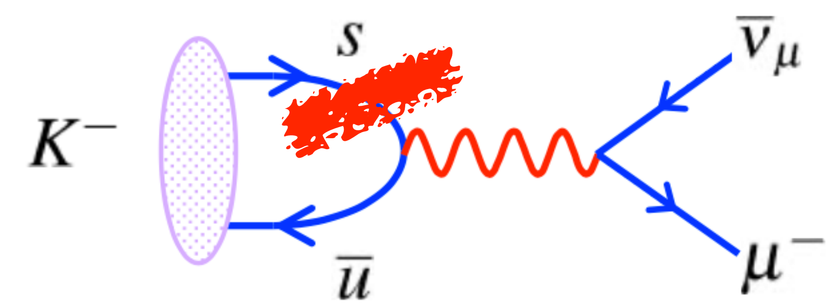




some history

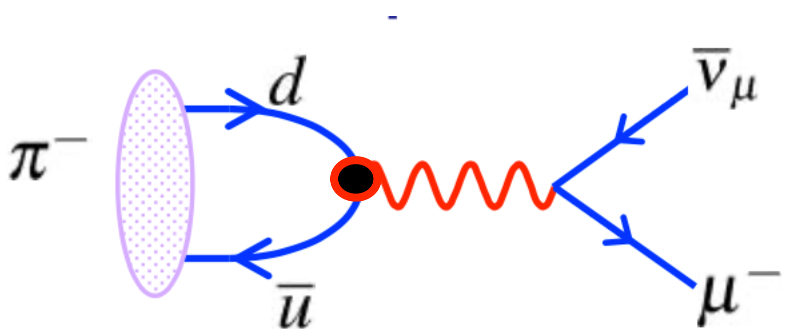
History of quark mixing

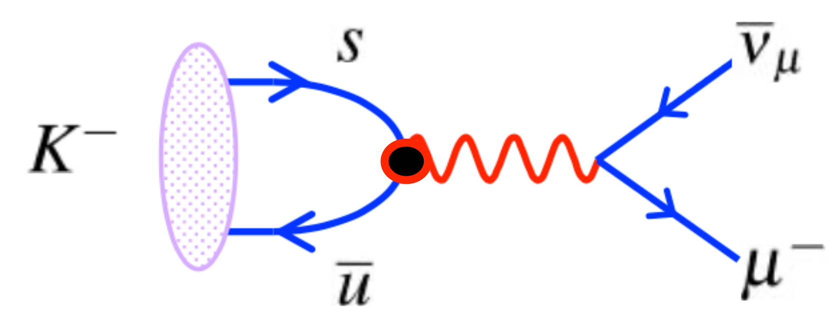




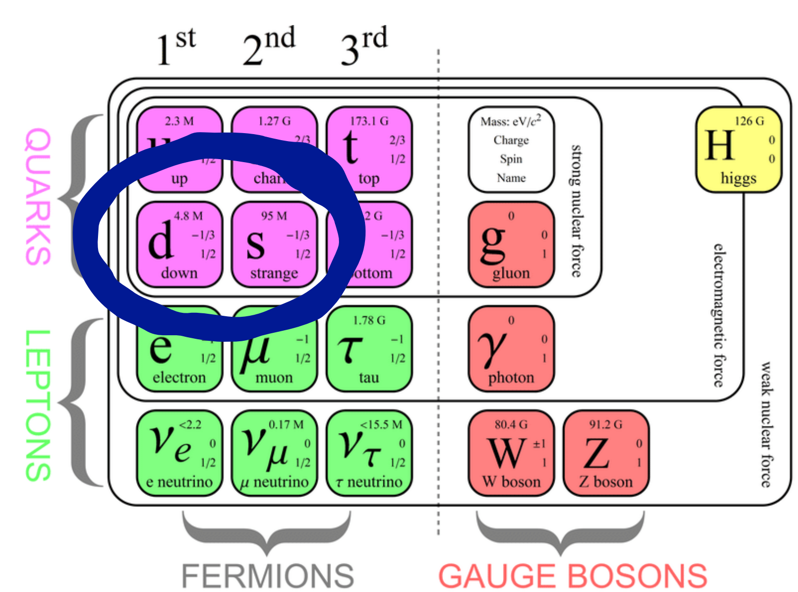
same electroweak interaction via W boson exchange *some history*

History of quark mixing





- d and s are two “copies” of the same ‘object’ (“down-type” quarks)
- interaction strength : the same (right?)



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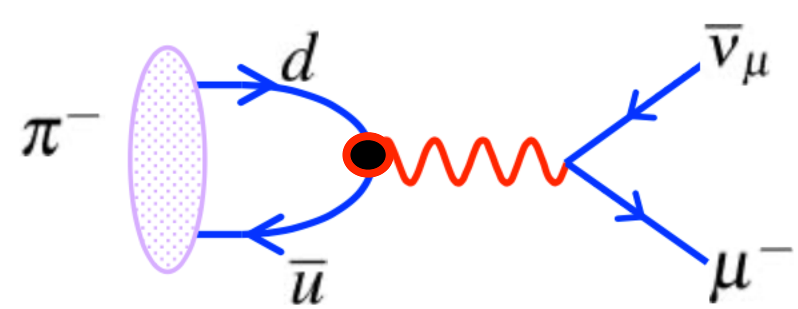
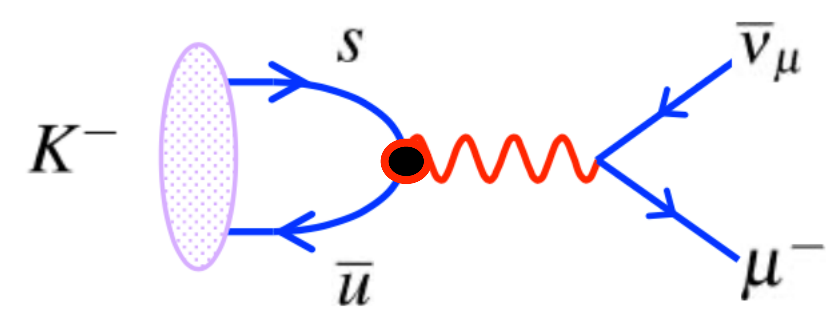


20X MORE LIKELY THAN



- d and s are two “copies” of the same ‘object’ (“down-type” quarks)
- interaction strength : NOT the same ~~(right?)~~

some history

Cabibbo’s idea (1963)

History of quark mixing

- Interacting quarks = superposition of ‘mass quarks’ quantum states

some history

Cabibbo's idea (1963)

History of quark mixing

- Interacting quarks = superposition of 'mass quarks' quantum states

why not?!

like cats when they enter in a box

https://twitter.com/flippyfeets/status/988771139517231105

some history

Cabibbo's idea (1963)

History of quark mixing

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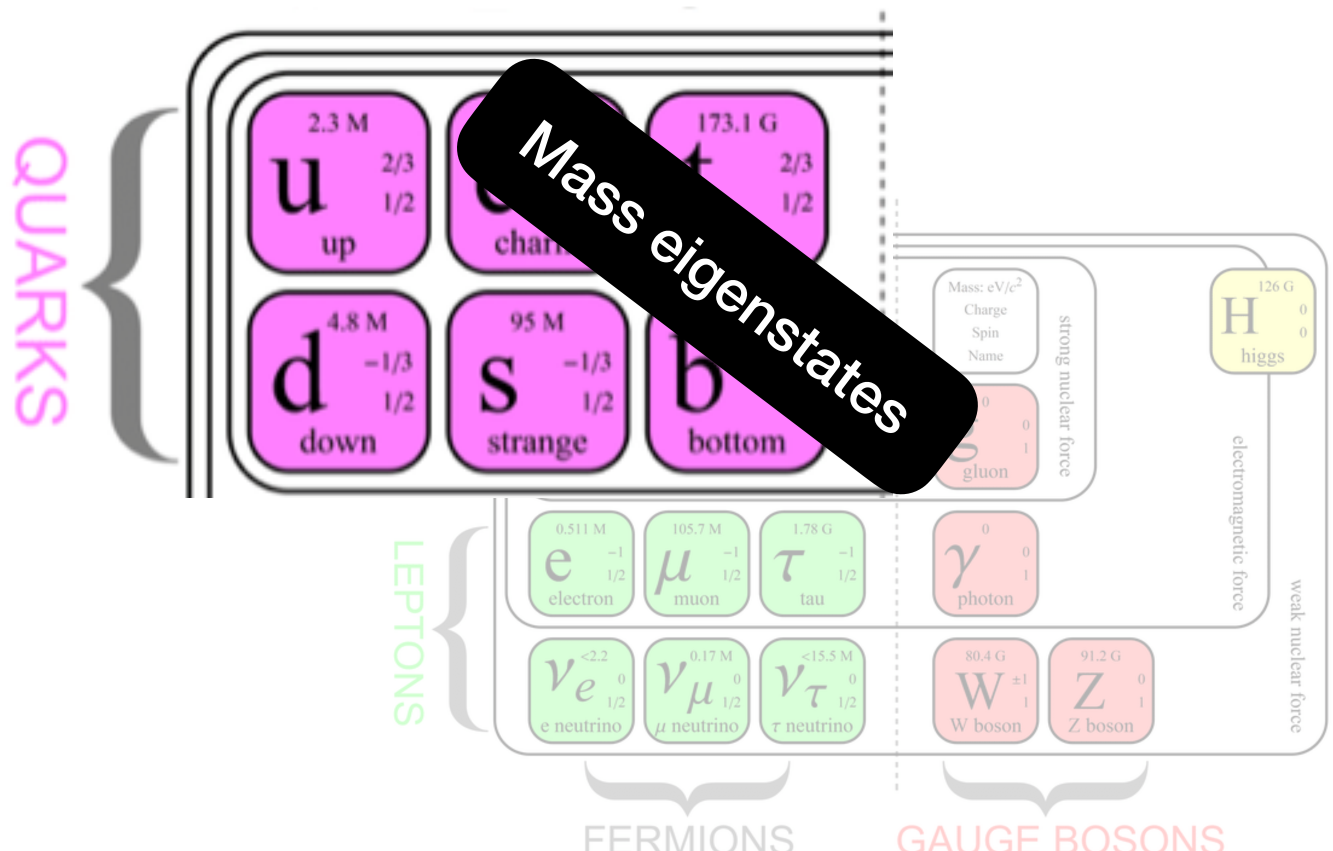

$$|u>,\ |d>,\ |s>, \ldots$$

Cabibbo's idea (1963)

History of quark mixing

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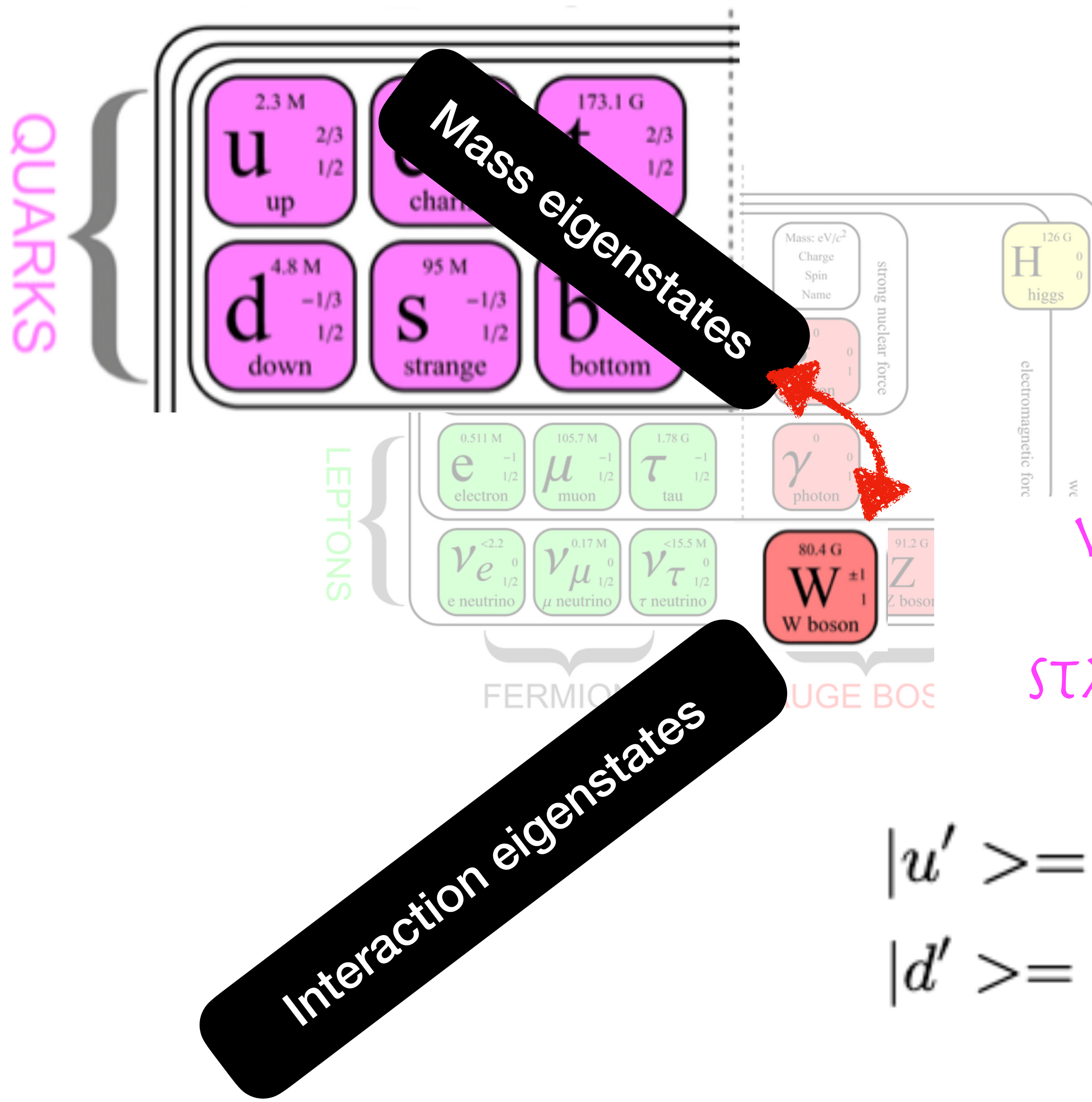

$$|u>,\ |d>,\ |s>, \ldots$$

WHEN INTERACTING VIA **W**, QUANTUM STATES $|u>,\ |d>$ BECOME

$$|u'>=|u>$$

$$|d'>=\cos(\theta_C)|d>+\sin(\theta_C)|s>$$

some history

Cabibbo’s idea   (1963)

“Corrected” interaction strengths

- Interaction states instead of mass states:

$$|\bar{u'}>=|\bar{u}>$$
$$|d'>=\cos(\theta_C)|d>+\sin(\theta_C)|s>$$

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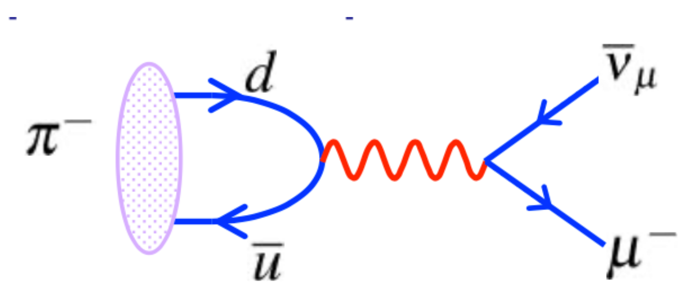
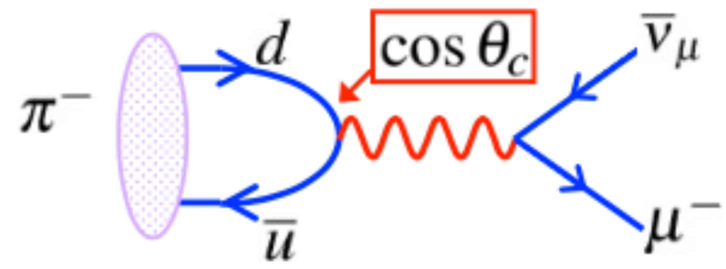


becomes



$$\boxed{\Gamma(\pi^- \to \mu^- \overline{\nu}_\mu) \propto |M|^2 \propto \cos^2\theta_c}$$

some history

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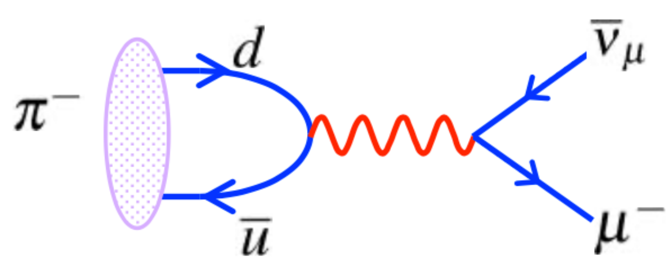

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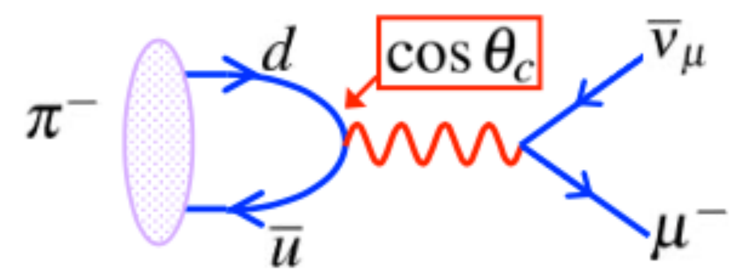

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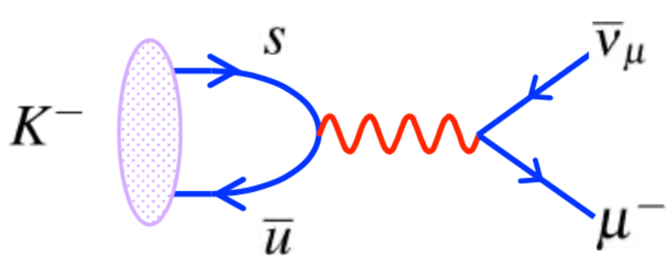

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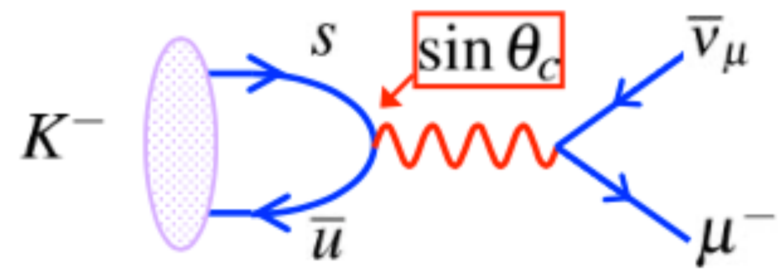

$$\Gamma(K^- \to \mu^- \overline{\nu}_\mu) \propto |M|^2 \propto \sin^2\theta_c$$

some history

Cabibbo's idea (1963)

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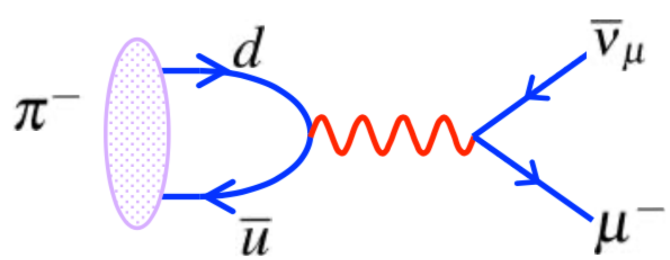

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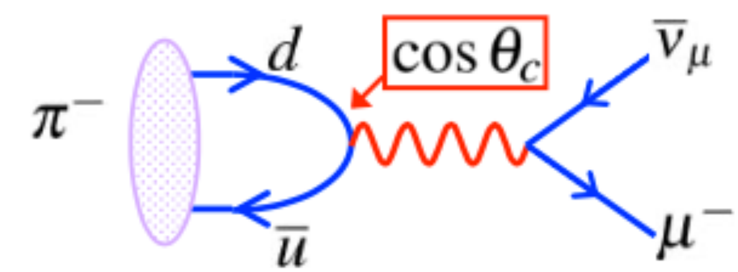
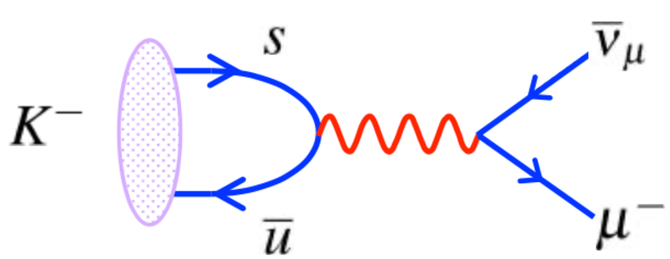


$$\Gamma(\pi^- \to \mu^- \bar{\nu}_\mu) \propto |M|^2 \propto \cos^2\theta_c$$

with $\theta_c = 13.1$
$\cos^2\theta_c / \sin^2\theta_c \cong 20$



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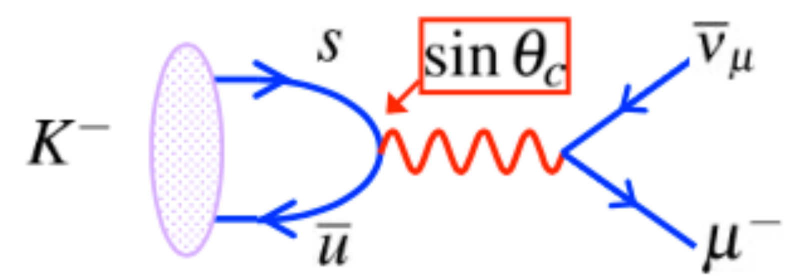

$$\Gamma(K^- \to \mu^- \bar{\nu}_\mu) \propto |M|^2 \propto \sin^2\theta_c$$

Experimental mystery solved!

this +many other 'puzzles' solved, 1 example for sake of time https://physicsworld.com/a/overlooked-for-the-nobel-nicola-cabibbo/

Brilliant idea - but no Nobel prize

PARTICLES AND INTERACTIONS | BLOG

Overlooked for the Nobel: Nicola Cabibbo

01 Oct 2020 Michael Banks

The 2020 Nobel Prize for Physics will be announced on Tuesday 6 October. In the run-up to the announcement, *Physics World* editors have picked some of the people who they think have been overlooked for a prize in the past

Missing out Should Nicola Cabibbo have shared the 2008 Nobel Prize for Physics (Courtesy: ICTP Photo Archive)

In 2008 three physicists bagged that year's Nobel Prize for Physics for developing predictions and concepts on symmetry breaking that became the cornerstones of the Standard Model of Particle Physics.

Makoto Kobayashi of the KEK lab and Toshihide Maskawa from the University of Kyoto, both in Japan, shared one half of prize for their work in 1972 on the mechanism of broken symmetry, which led to the prediction of a new family of quarks. Yoichiro Nambu of the University of Chicago in the US, who died in 2015, bagged the other half of the prize for realizing in 1960 how to apply spontaneous symmetry breaking to particle physics. Nambu's work described how the vacuum is not the most symmetrical state, work that underpinned the mechanism for the Higgs field.

https://physicsworld.com/a/overlooked-for-the-nobel-nicola-cabibbo/

Brilliant idea - but no Nobel prize

Kobayashi and Maskawa got it instead

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… for the CKM matrix: whole picture

Cabibbo, Kobayashi, Maskawa

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$|d' >= V_{ud}|d > +V_{us}|s > +V_{ub}|b >, \ldots$$

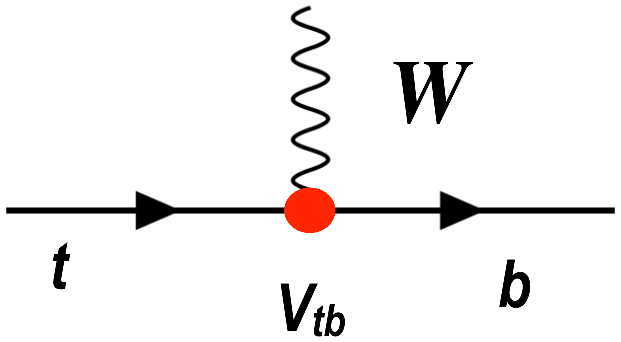
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1, \ldots$$

what does it have to do with the initial matter-antimatter issue?

What does it have to do with anti-matter?

A few possible mixings

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



What does it have to do with anti-matter?

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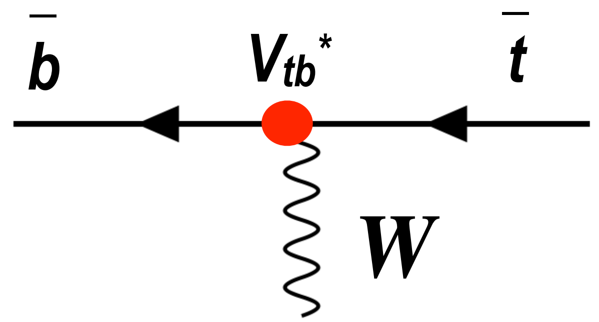

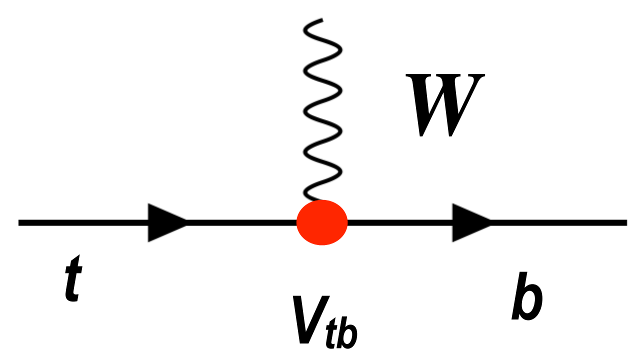

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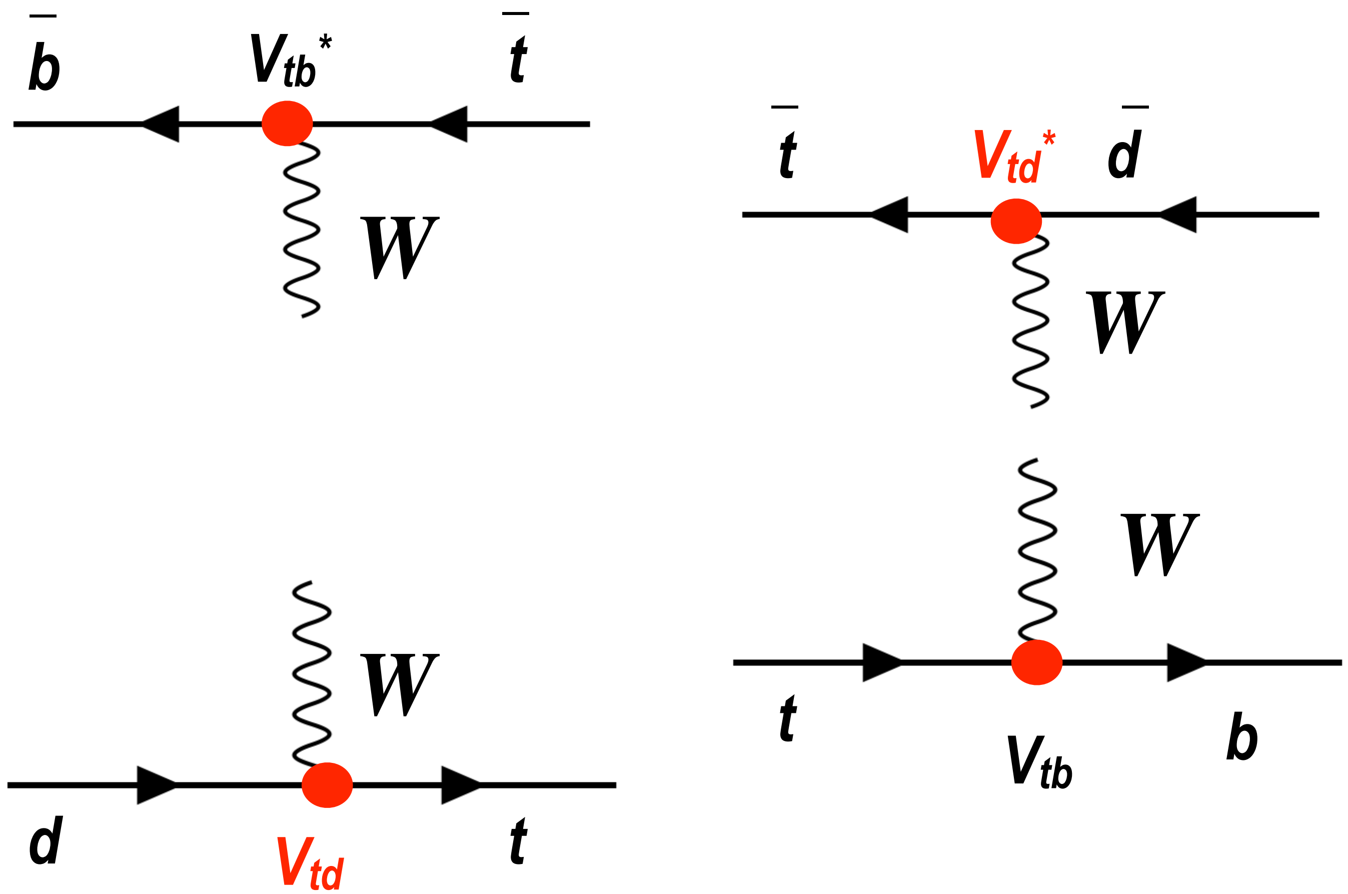
A few possible mixings



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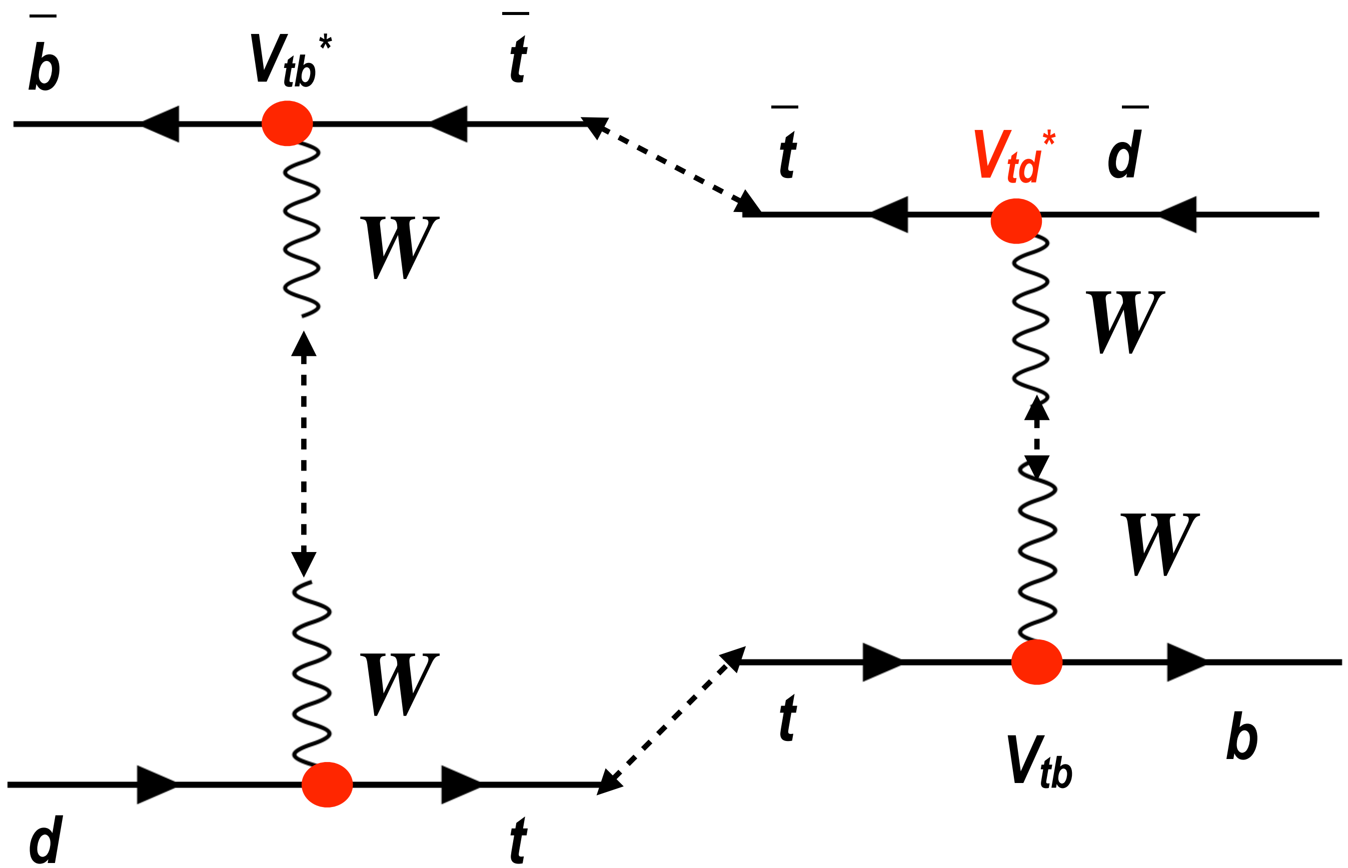
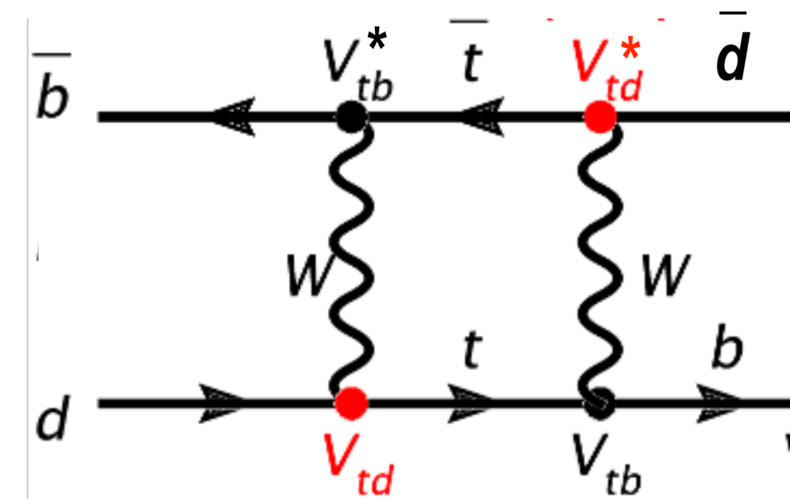
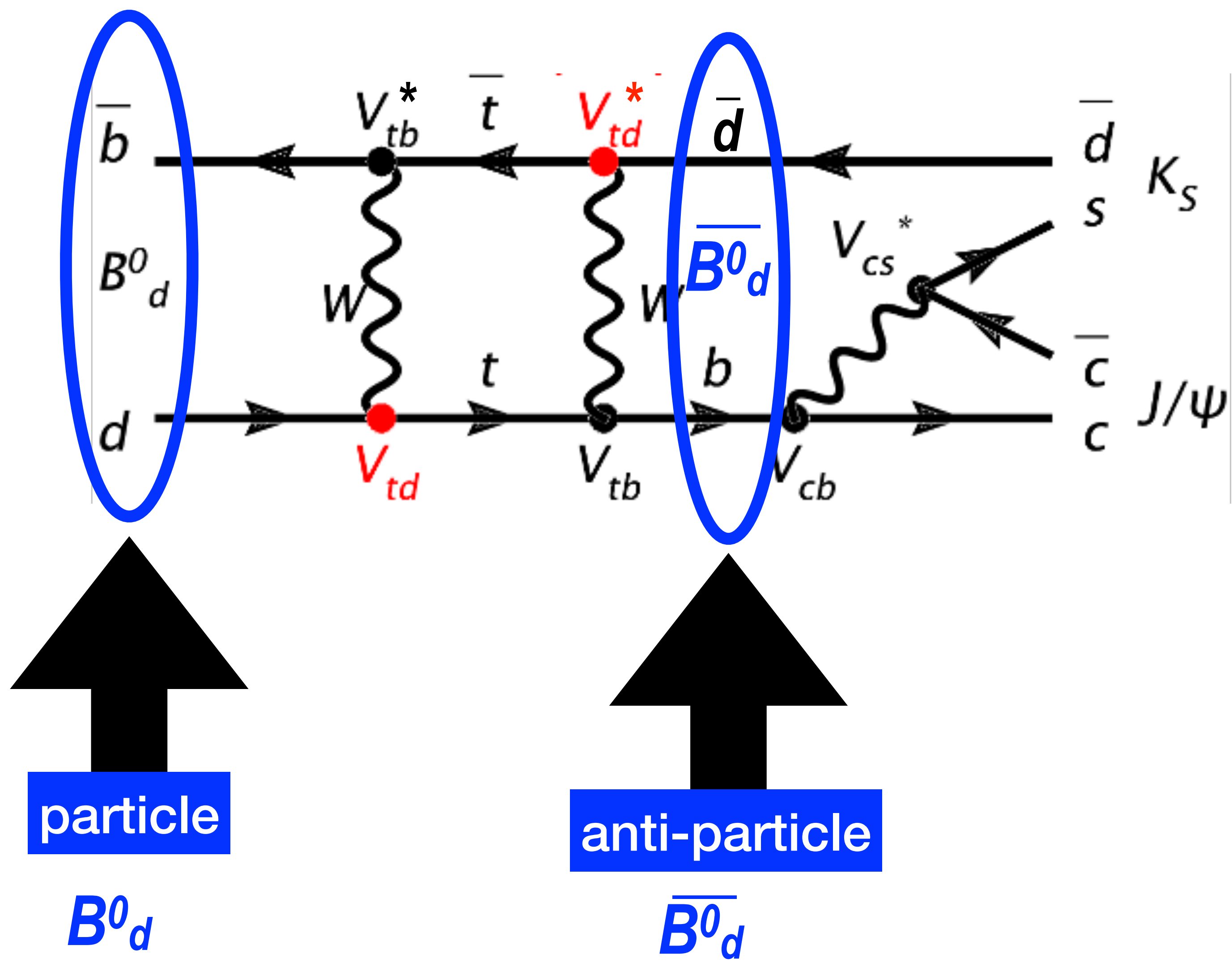




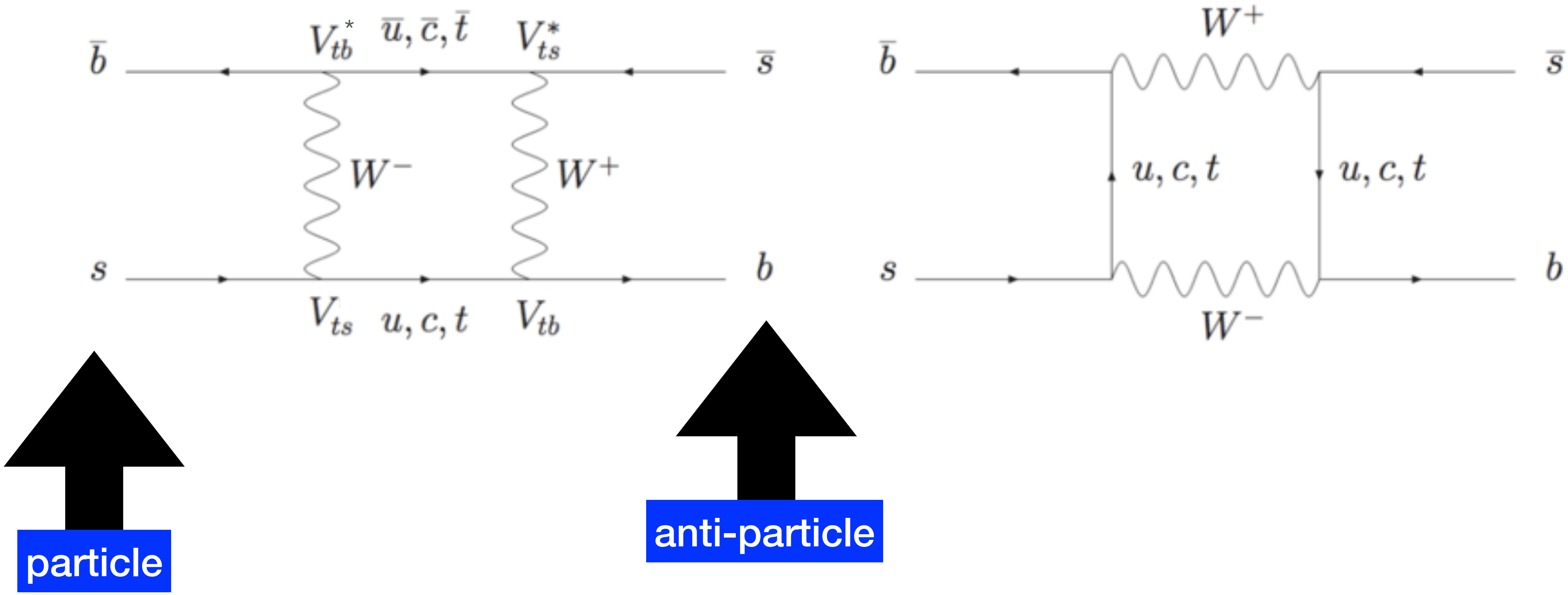
What does it have to do with anti-matter?

In the Standard Model , particles are transformed into anti-particles **via mixing!**



What does it have to do with anti-matter?

Meson B_s turns into its anti-particle via mixing



What does it have to do with anti-matter?

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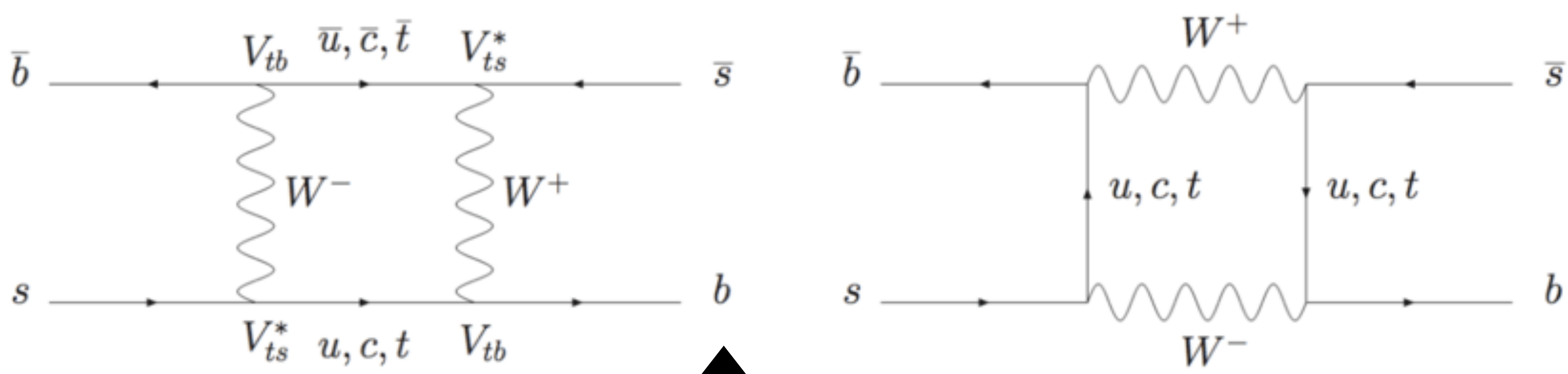


particle

anti-particle

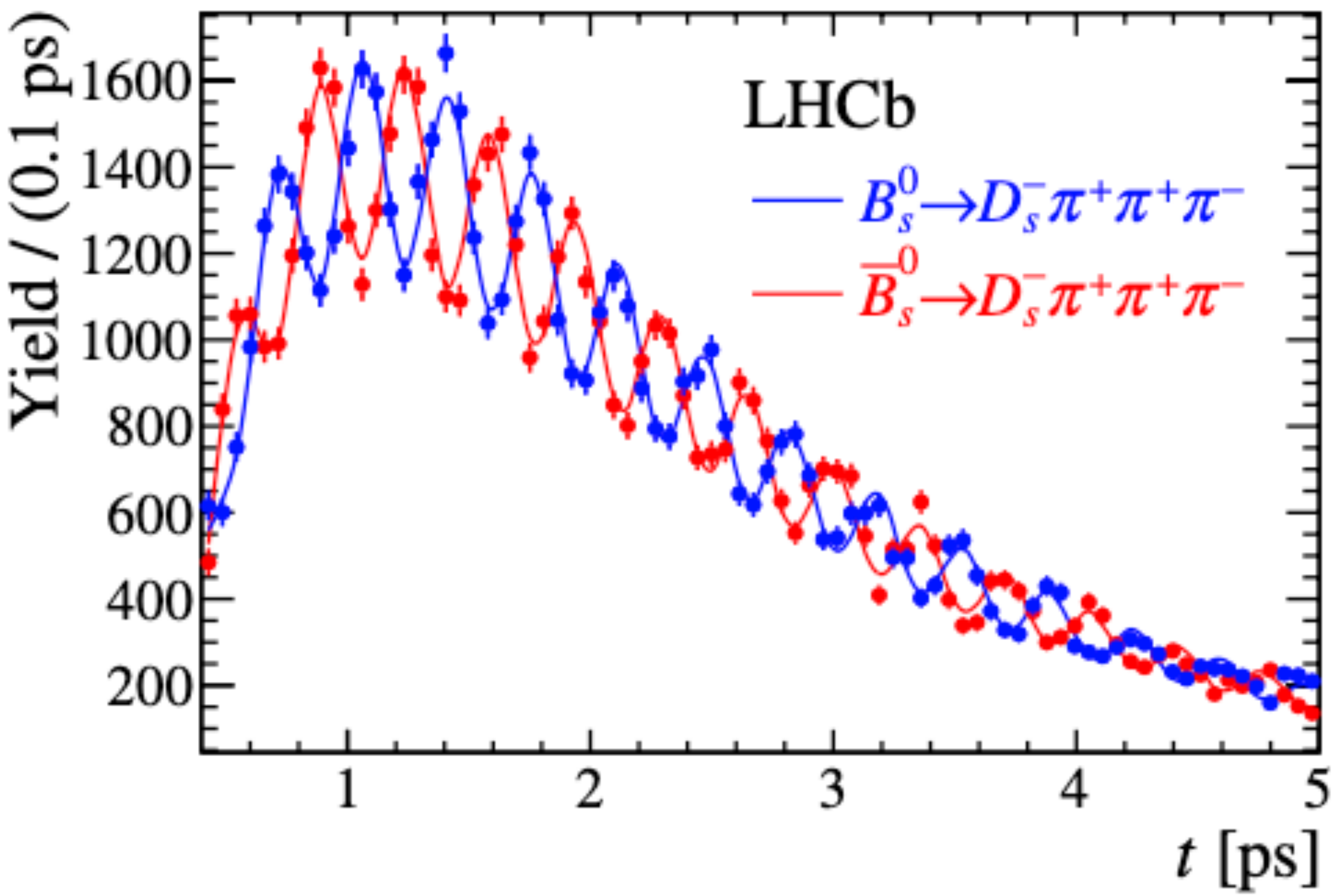
The LHCb experiment is specialised in transforming matter in antimatter (via mixing) in a controlled way

Nikhef/VU PhD thesis: Michele Veronesi

https://cds.cern.ch/record/2790773?ln=en

LHCb measurement

Quantum mechanics in action, see with bare eyes



what else can mixing or, the SM say about matter-antimatter?

Quark-antiquark transition probabilities

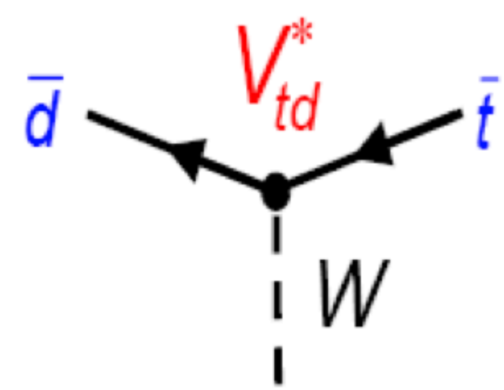
Quarks

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CP

Anti-quarks:

$$\begin{pmatrix} \bar{d}' \\ \bar{s}' \\ \bar{b}' \end{pmatrix} = \begin{pmatrix} V^*_{ud} & V^*_{us} & V^*_{ub} \\ V^*_{cd} & V^*_{cs} & V^*_{cb} \\ V^*_{td} & V^*_{ts} & V^*_{tb} \end{pmatrix} \begin{pmatrix} \bar{d} \\ \bar{s} \\ \bar{b} \end{pmatrix}$$

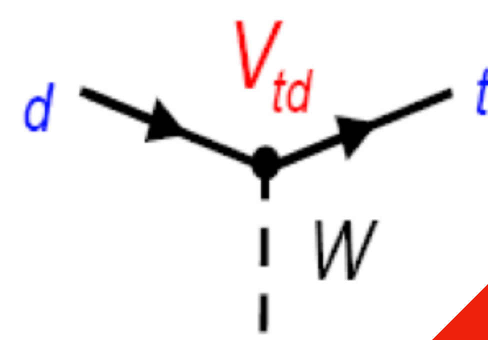


Quark-antiquark transition probabilities

Excellent starting point to understand why amounts of matter-antimatter differ in nature

Quarks

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



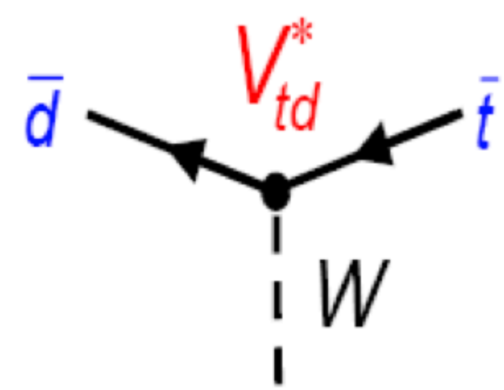
$q \rightarrow \bar{q} \neq \bar{q} \rightarrow q$

CP

complex matrix!!!

Anti-quarks:

$$\begin{pmatrix} \bar{d}' \\ \bar{s}' \\ \bar{b}' \end{pmatrix} = \begin{pmatrix} V^*_{ud} & V^*_{us} & V^*_{ub} \\ V^*_{cd} & V^*_{cs} & V^*_{cb} \\ V^*_{td} & V^*_{ts} & V^*_{tb} \end{pmatrix} \begin{pmatrix} \bar{d} \\ \bar{s} \\ \bar{b} \end{pmatrix}$$

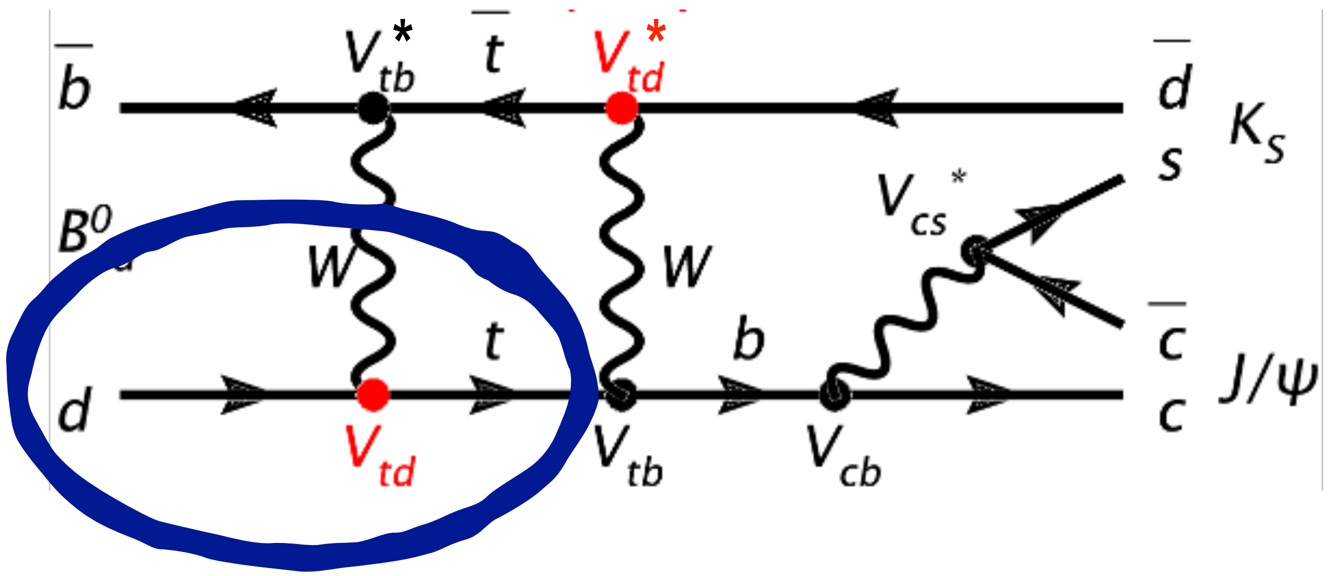


"CP-violation"!

lllllllooooops

Loops: quantum fluctuations

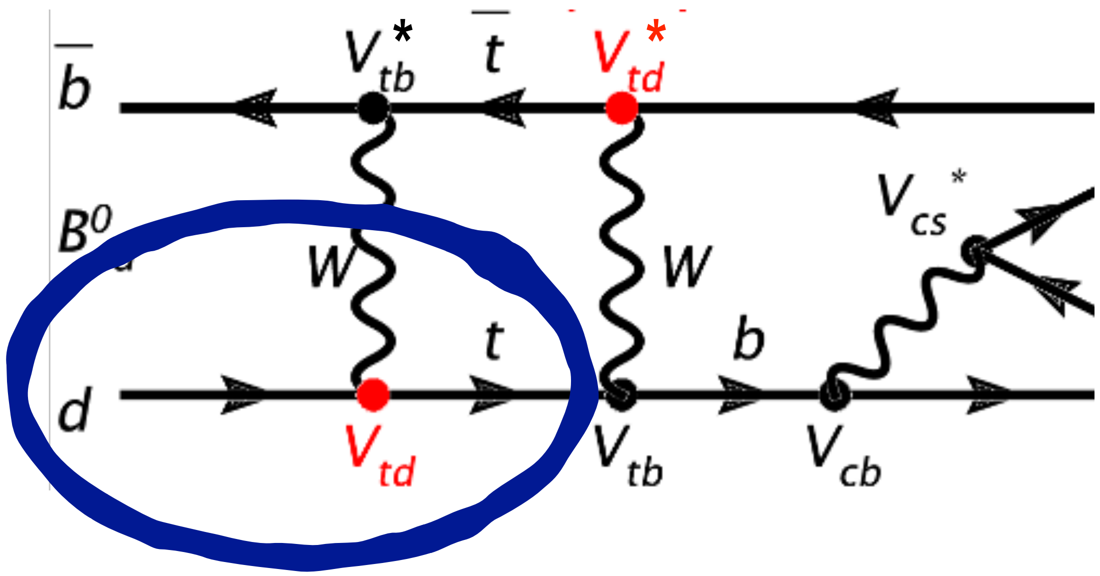
probe higher masses



A d quark
"giving birth" to
a top quark?

Loops: quantum fluctuations

probe higher masses

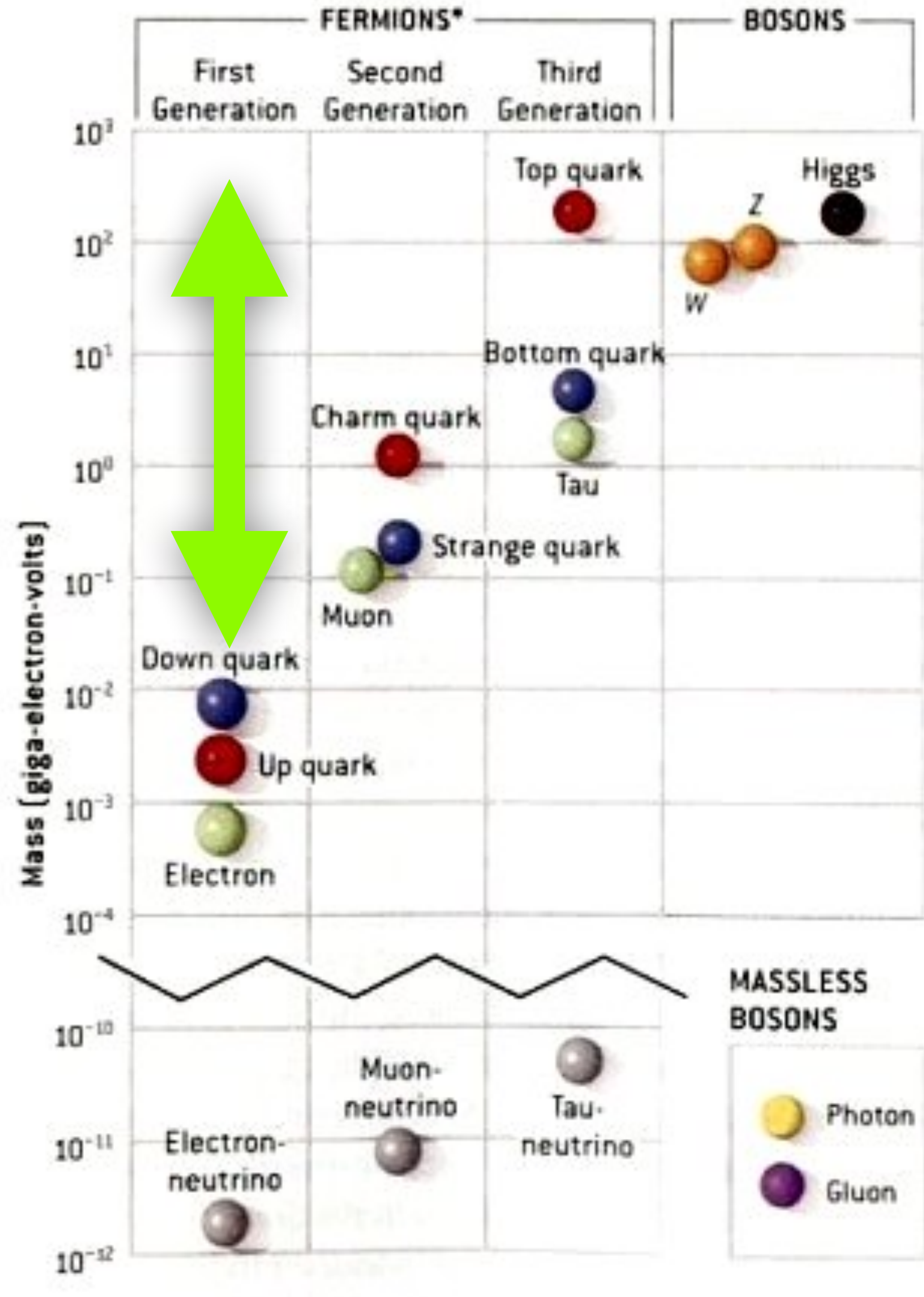


A d quark "giving birth" to a top quark?

Orders of magnitude difference

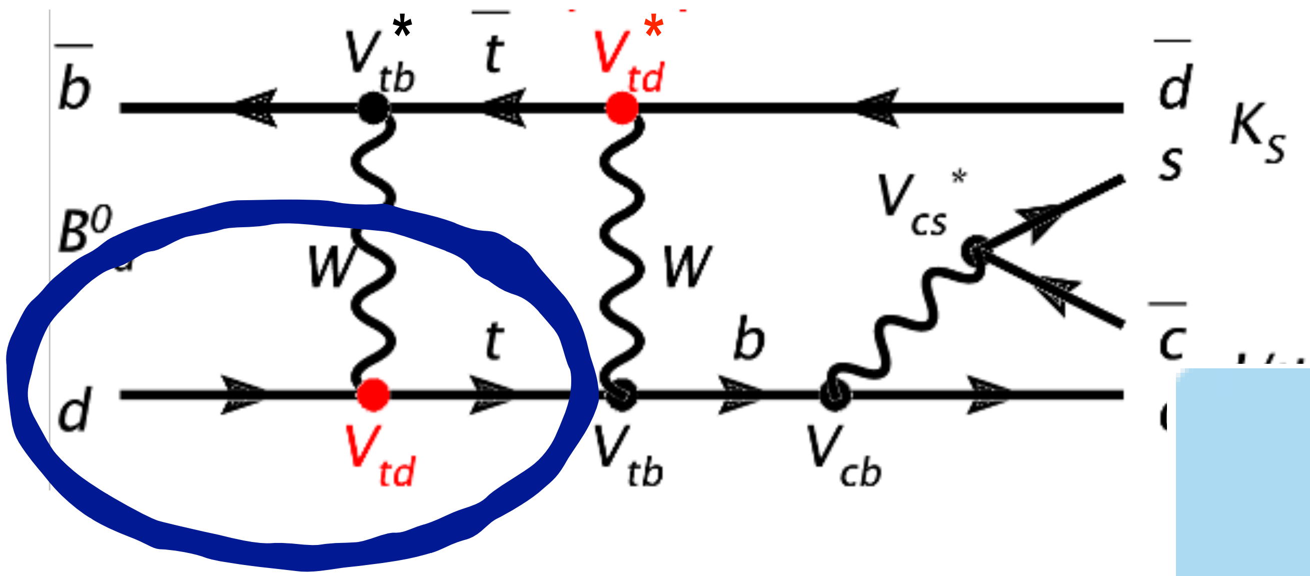
Mass of elementary particles :

(log scale)

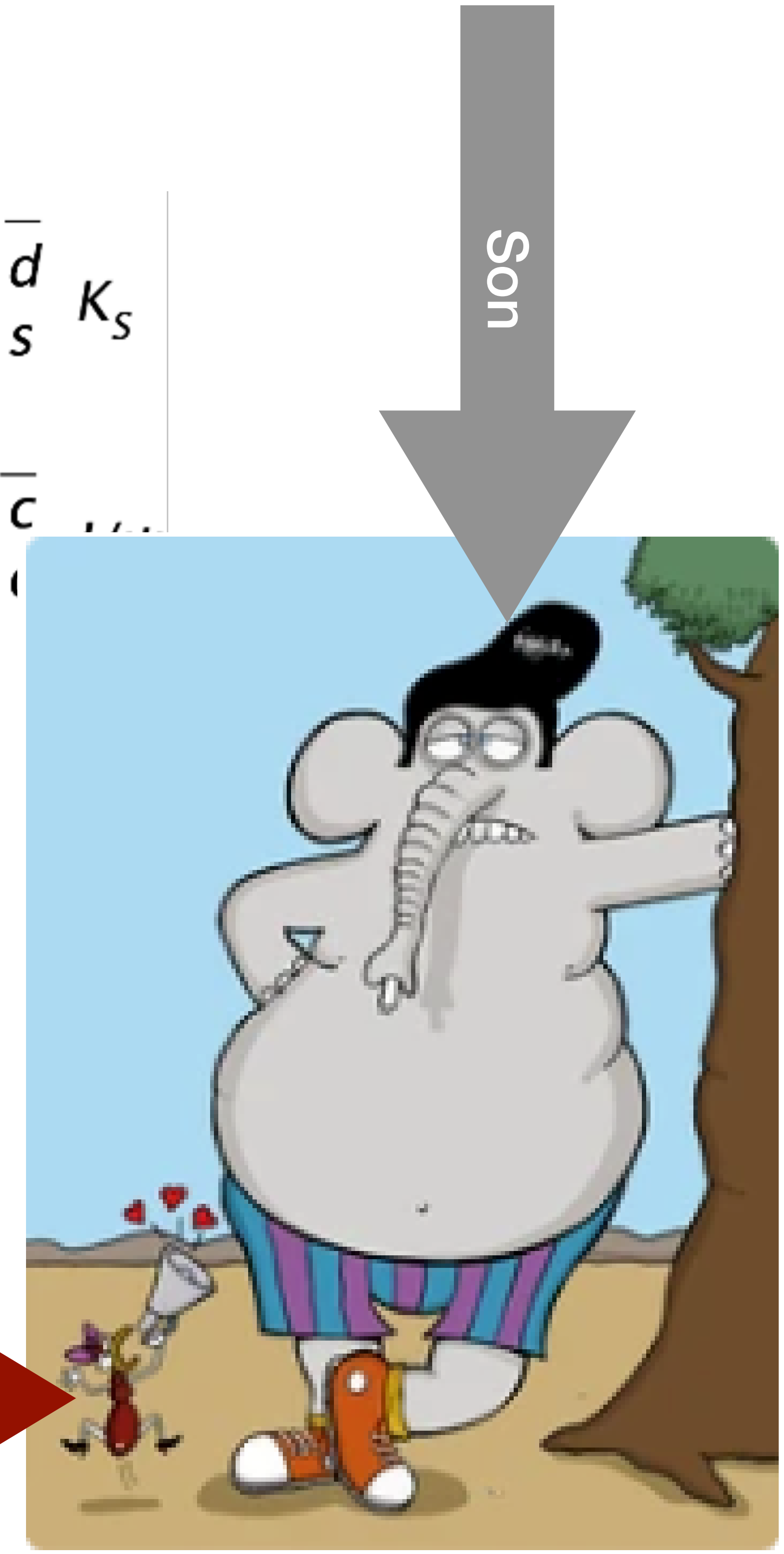


Loops: quantum fluctuations

probe higher masses

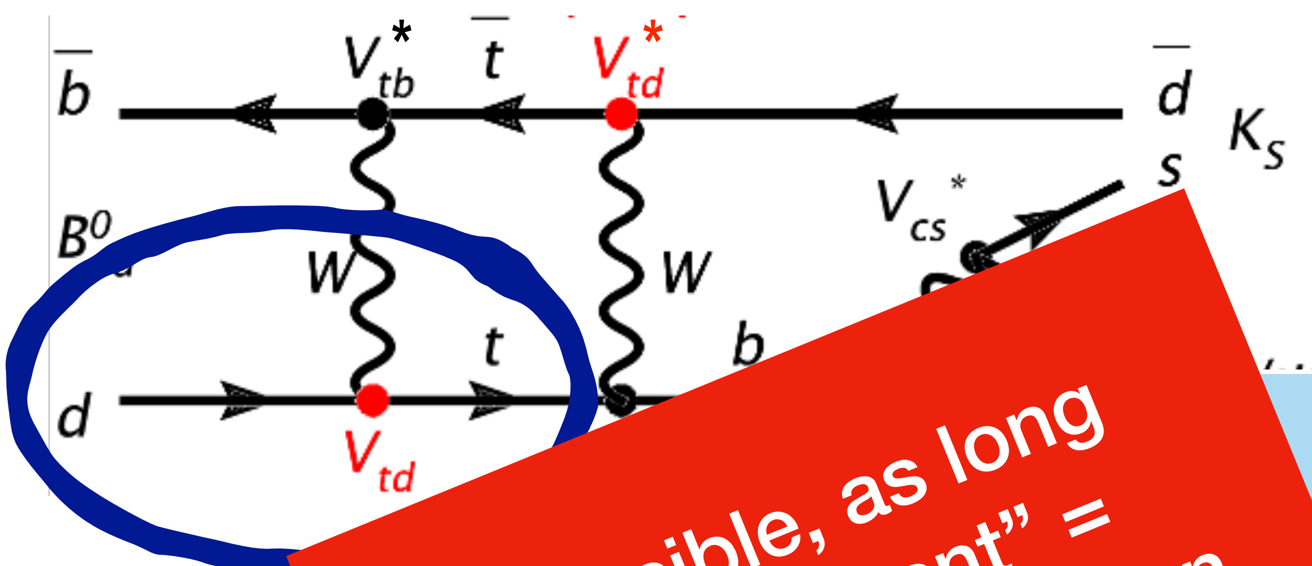


A d quark "giving birth" to a top quark?



Loops: quantum fluctuations

probe higher masses



Possible, as long as "elephant" = quantum fluctuation

not on its mass shell

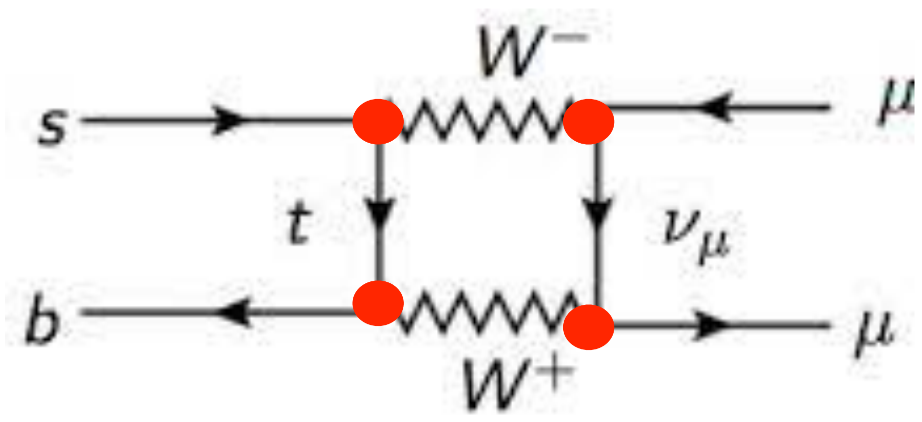
A d quark "giving birth" to a top quark?

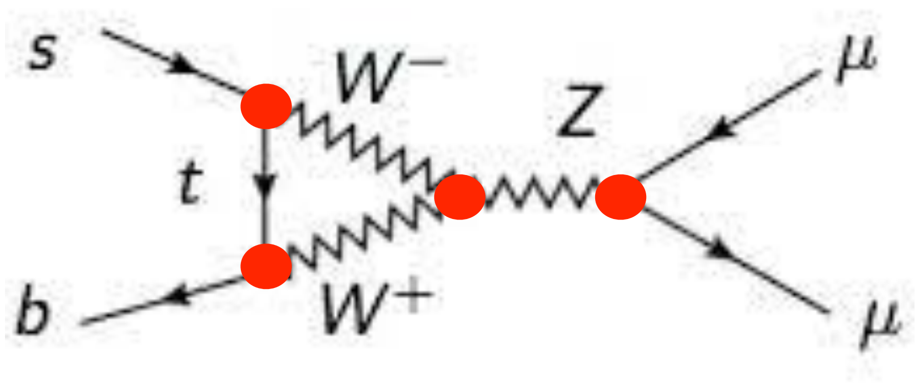
Son

Mother

Loops: quantum fluctuations

probe higher masses: $B_{s} \rightarrow \mu\mu$ example

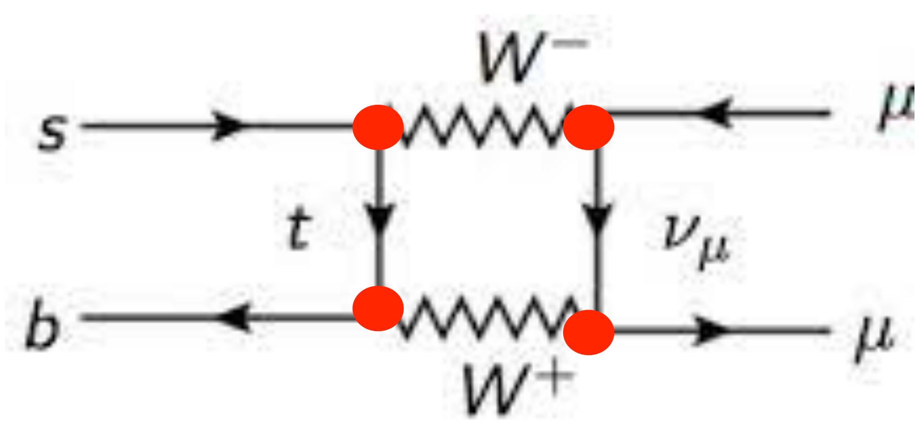




- Interaction strength: each vertex
- Extremely low-probability decay
    - 1 time every 10^{-9} of all B_s
- No “direct decay” possible
    - must involve a loop

Loops: quantum fluctuations

probe higher masses: $B_{s\to}\mu\mu$ example



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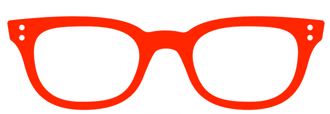


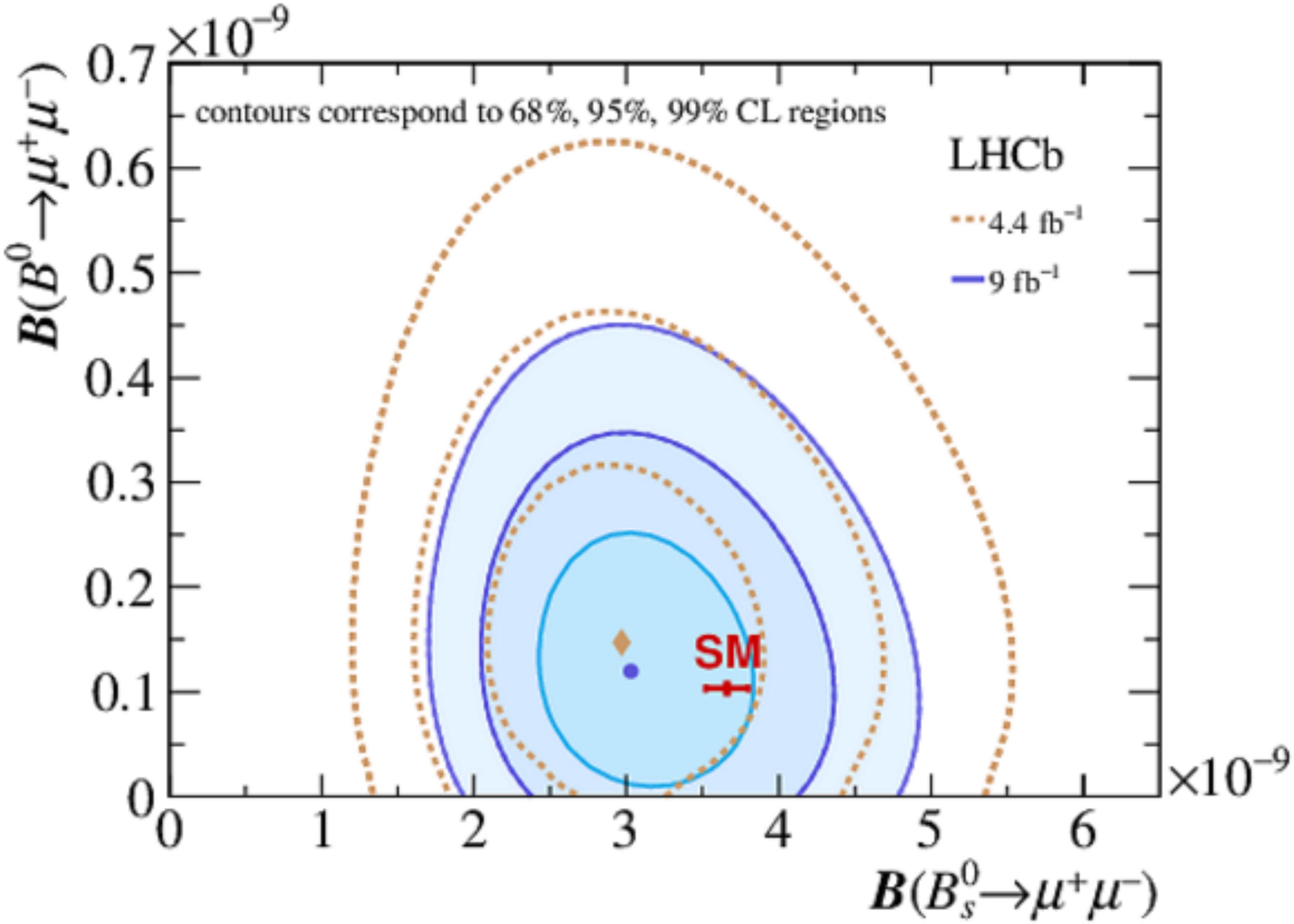
Look carefully: loop may be hiding a heavy new physics particle

- No “direct decay” possible
  - must involve a loop

Excellent testing ground for new physics

Decay rates involving loop

$B_s \to \mu\mu$ example



https://en.wikipedia.org/wiki/Girl_before_a_Mirror

Summary

Matter, anti-matter & the SM

- An obvious, fundamental question begging for an answer
- Observations from particle accelerator vs cosmology are complementary

- Our contribution : controlled production of anti-matter in the laboratory
    - LHCb experiment an excellent testing ground for matter-antimatter studies

- Extremely heavy particles can be produced via quantum fluctuation in loops
    - LHCb experiment an excellent testing ground for detecting new physics

Extra slides

C P T

the three symmetries

https://en.wikipedia.org/wiki/Girl_before_a_Mirror

Charge conjugation, Parity, Time reversal
How was that again?

Charge conjugation:
transforms a particle and it's anti-particle

more than electrical charge flip

Parity transformation:
transforms a right-handed particle into left-handed

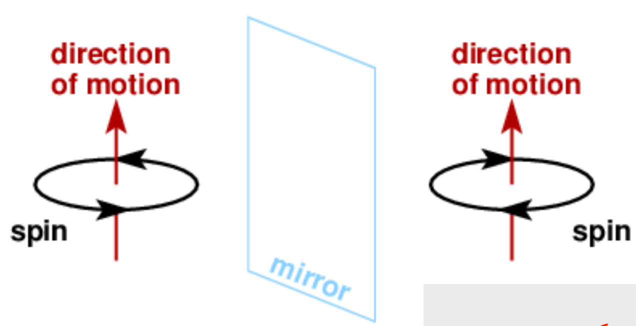
parity transformation:

Vectors change sign

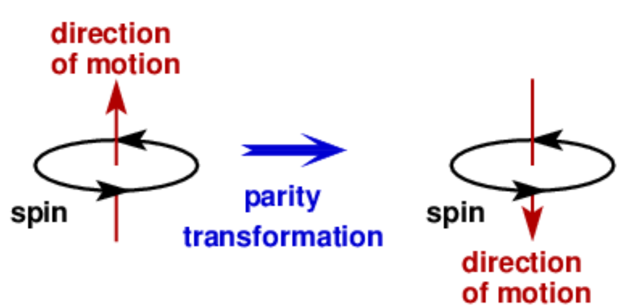
$$\vec{r} \xrightarrow{\hat{P}} -\vec{r}$$
$$\vec{p} \xrightarrow{\hat{P}} -\vec{p} \qquad (p_x = \frac{\partial}{\partial x}, \ etc.)$$

Axial-Vectors unchanged

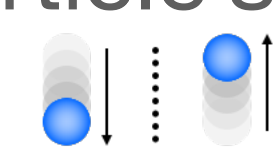
$$\vec{L} \xrightarrow{\hat{P}} \vec{L} \qquad (\vec{L} = \vec{r} \wedge \vec{p})$$
$$\vec{\mu} \xrightarrow{\hat{P}} \vec{\mu} \qquad (\vec{\mu} \propto \vec{L})$$



more than simple mirror image

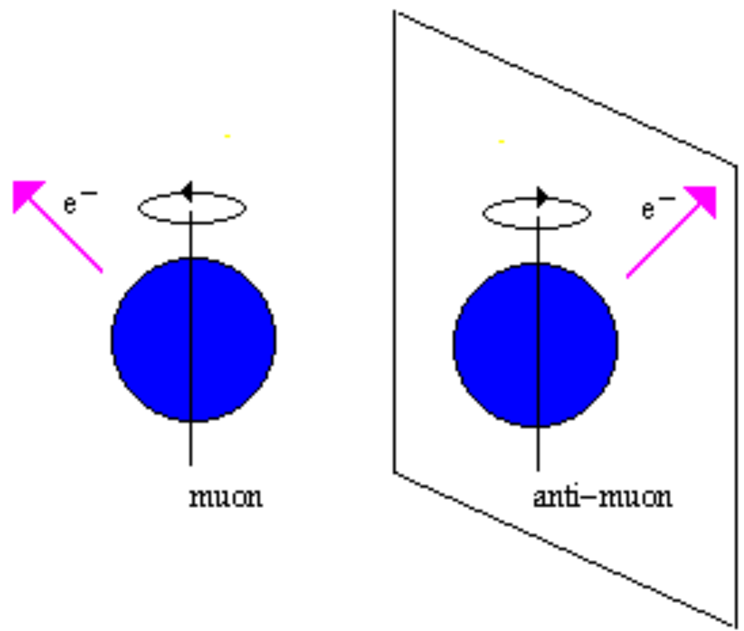


Time reversal:
changes e.g. the particle's direction of motion

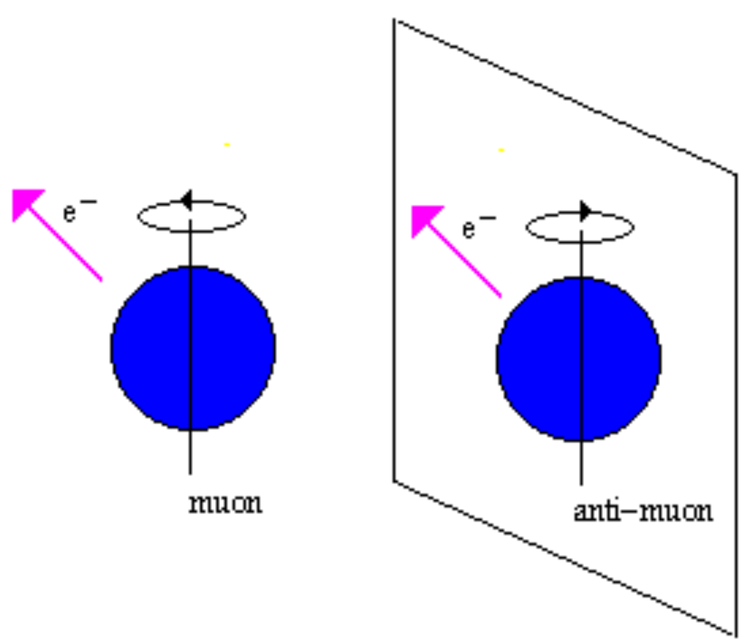


Conserved or not conserved?!

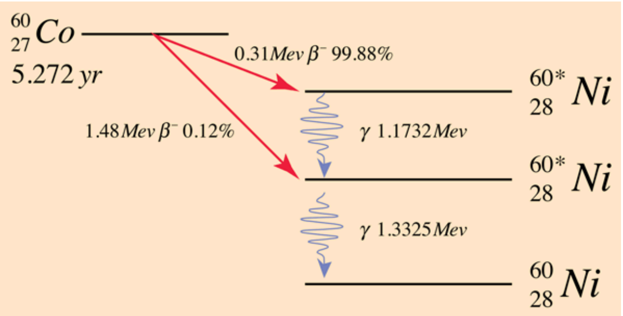
Parity, for elementary particles, can be defined with respect to the direction in which they emit decay particles. A muon will typically emit an electron to the right. If the parity is reversed, then the muon should emit the electron to the left, the mirror image.



One time out of a thousand, an anti−muon will decay to the right, a violation of the charge−parity or CP rule.



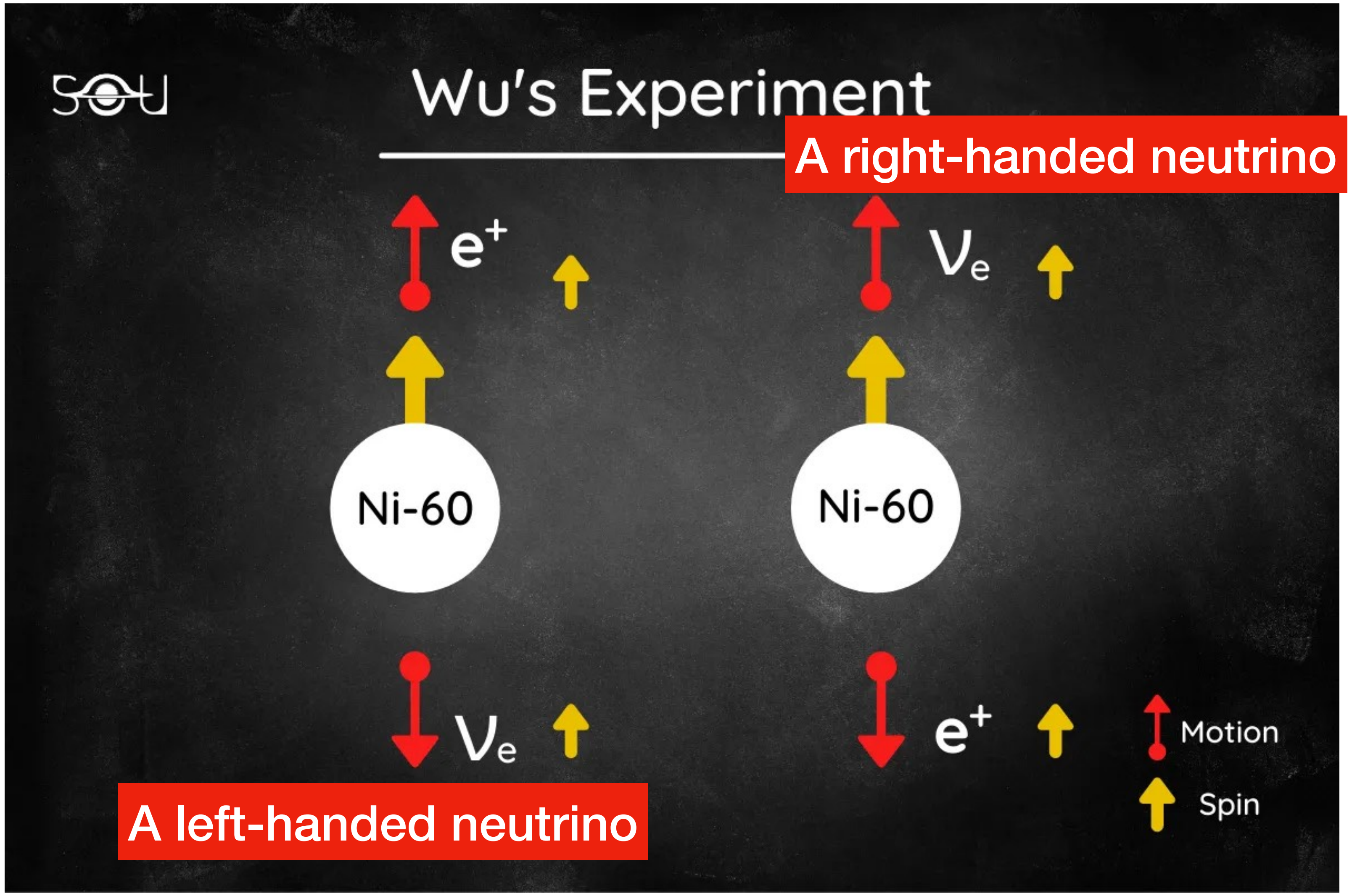
The Wu experiment



β decay of polarized 60-Cobalt nuclei

$$^{60}Co \rightarrow {}^{60}Ni + e^- + \bar{\nu}_e$$

- Cobalt : spin 5
- Nickel : spin 4
- electron: spin 1/2
- anti-neutrino: spin 1/2



In case of parity-conserving decay: same amounts of left- and right-handed particles is produced

Check the direction of the electron!!

Charge conjugation operator

Particle fields : “spinors”

Charge conjugation operator is defined as

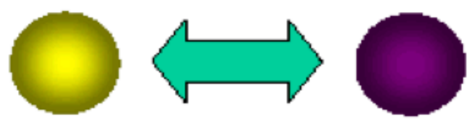
$$\psi' = \hat{C}\psi = i\gamma^2\psi^* = i\begin{pmatrix} 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \\ 0 & i & 0 & 0 \\ -i & 0 & 0 & 0 \end{pmatrix}\psi^*$$

Quantity	Notation	P	C	T
Position	$\vec{r}$	-1	+1	+1
Momentum (Vector)	$\vec{p}$	-1	+1	-1
Spin (Axial Vector)	$\vec{\sigma} = \vec{r} \times \vec{p}$	+1	+1	-1
Helicity	$\vec{\sigma}.\vec{p}$	-1	+1	+1
Electric Field	$\vec{E}$	-1	-1	+1
Magnetic Field	$\vec{B}$	+1	-1	-1
Magnetic Dipole Moment	$\vec{\sigma}.\vec{B}$	+1	-1	+1
Electric Dipole Moment	$\vec{\sigma}.\vec{E}$	-1	-1	-1
Transverse Polarization	$\vec{\sigma}.(\vec{p_1} \times \vec{p_2})$	+1	+1	-1

Completing the table: C, P, T

Charge conjugation

Recall Particle Physics I — check lecture notes



Particle to antiparticle transformation

C operator acts on a state $|\psi(x, t)>$ as

$$C|\Psi(\mathbf{r},t)\rangle = |\Psi^C(\mathbf{r},t)\rangle$$

$$C^2|\Psi(\mathbf{r},t)\rangle = |\Psi(\mathbf{r},t)\rangle$$

Only a particle that is its own antiparticle can be eigenstate of C !

$\pi^0, \eta, \eta', \rho^0, \phi, \omega, \psi$ and photon

$C\,|\pi^+> = C\,|u\bar{d}> = |\bar{u}d>$ ➨ $q'\bar{q}$ not eigenstates of C

For mesons what are their own antiparticles (qqbar): $C = (-1)^{L+S}$ where L = angular momentum, S=spin eigenvalues

Example: π^0 has spin 0 : $C\,|\pi^0> = +1$

From symmetry of electromagnetic fields: photon has C = -1

How to compute P eigenstates

and intrinsic parity

Parity operator is identified as $P = \gamma^0$

$$\psi(\vec{r},t) = \gamma^0 \psi(-\vec{r},t) = \begin{pmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{0} & -\mathbf{I} \end{pmatrix} \psi(-\vec{r},t)$$

$$Pu_1 = Pu_2 = +1 \qquad Pv_1 = Pv_2 = -1$$

Parity of fermions $P_f = +1$

Parity of antifermions $P_{\bar{f}} = -1$

Parity of bosons = Parity of anti-bosons

- Parity is a *multiplicative* quantum number for composites
  - For composite AB the parity is P(A)*P(B), Thus:
  - Baryons have P=1*1*1=1, anti-baryons have P=-1*-1*-1=-1
  - (Anti-)mesons have P=1*-1 = -1
- Excited states (with orbital angular momentum)
  - Get an extra factor $(-1)^{l}$ where *l* is the orbital L quantum number
  - Note that parity formalism is parallel to total angular momentum J=L+S formalism, it has an *intrinsic* component and an *orbital* component
- Photon (spin-1, see table 2 pages before) : intrinsic P of -1