# HEP Lecture: Flavour Physics

**DESY Summer Student Lectures, 23.08.2022**

**Lu Cao**

*lu.cao@desy.de*


https://indico.desy.de/event/35182/

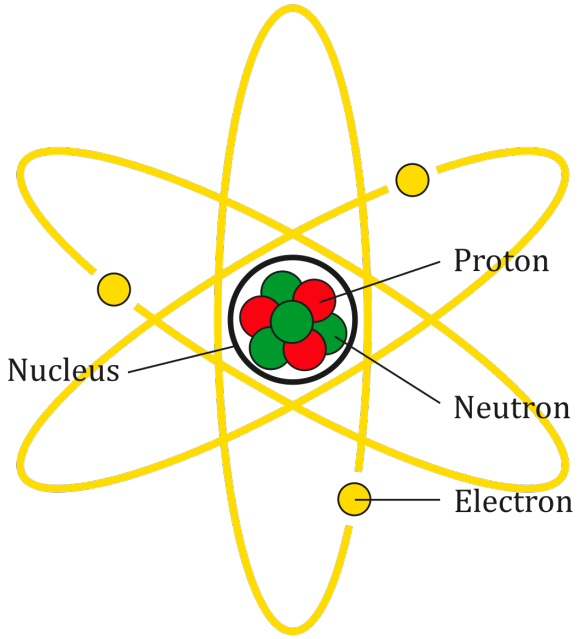
PART 1: What does flavour physics explore?

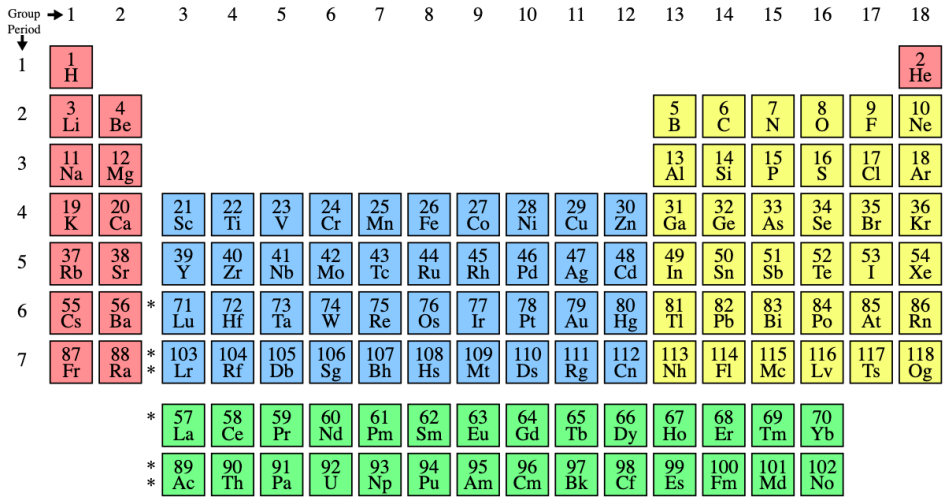
PART 2: OK… then, how to measure?

# PART 1: What does flavour physics explore?

# PART 2: OK… then, how to measure?

# Towards the Fundamental Building Blocks



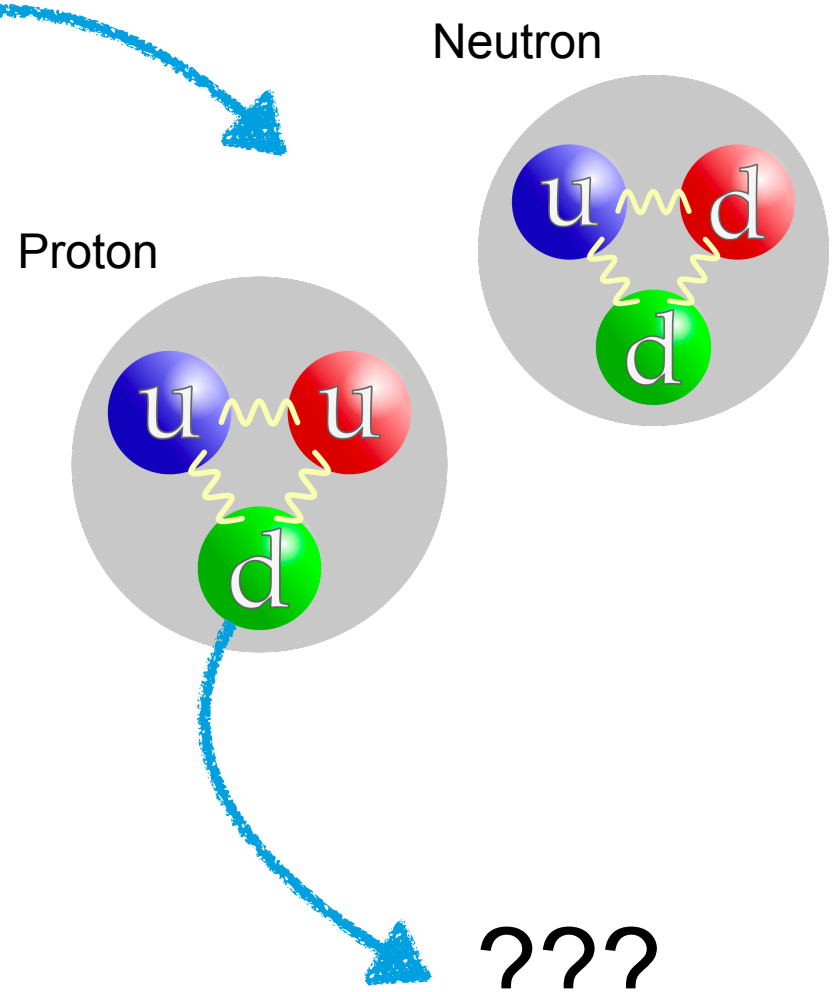






Figure: Wikimedia Commons

# Particles of the Standard Model

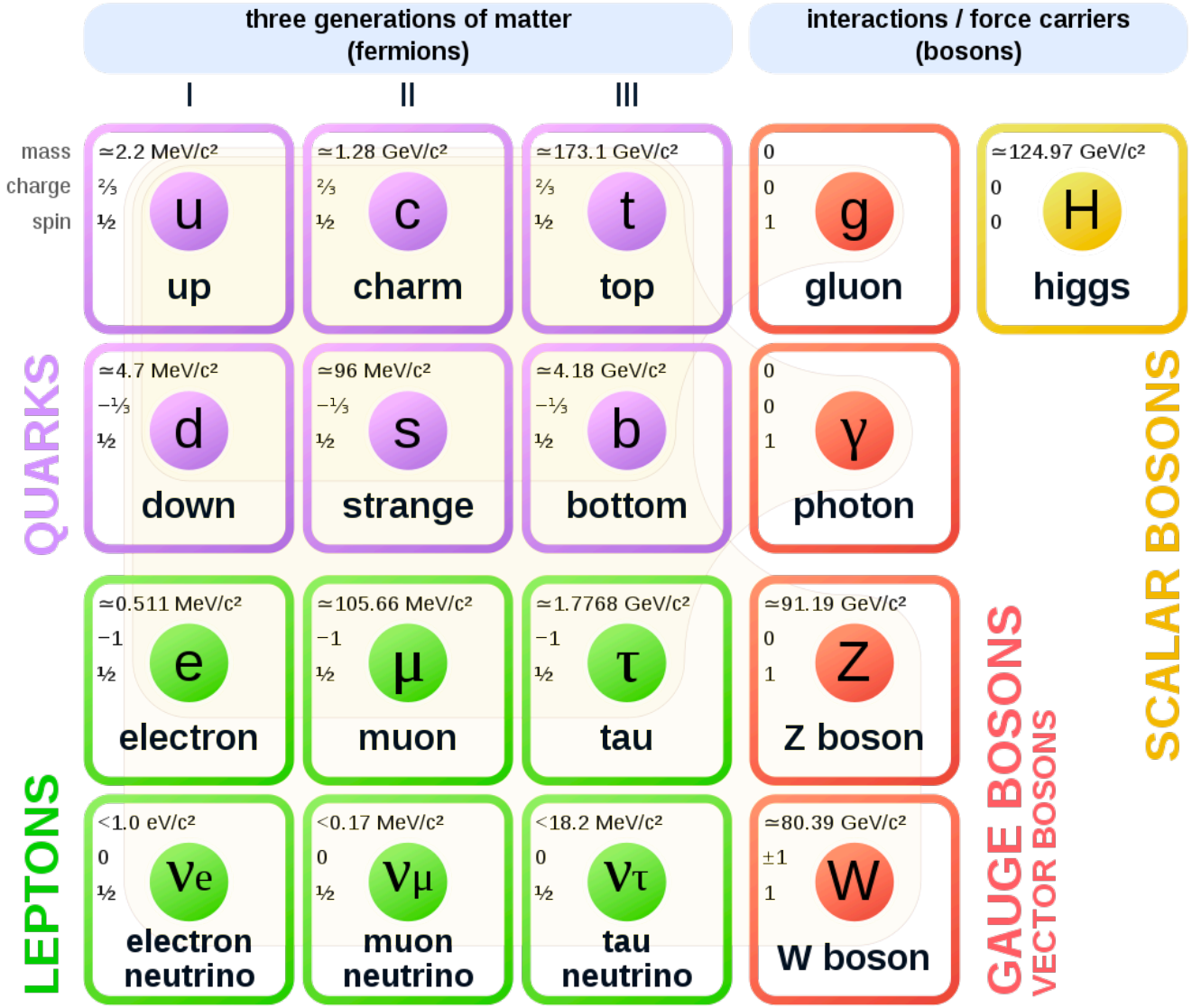





Figure: Wikimedia Commons

# Particles of the Standard Model (Verbose)

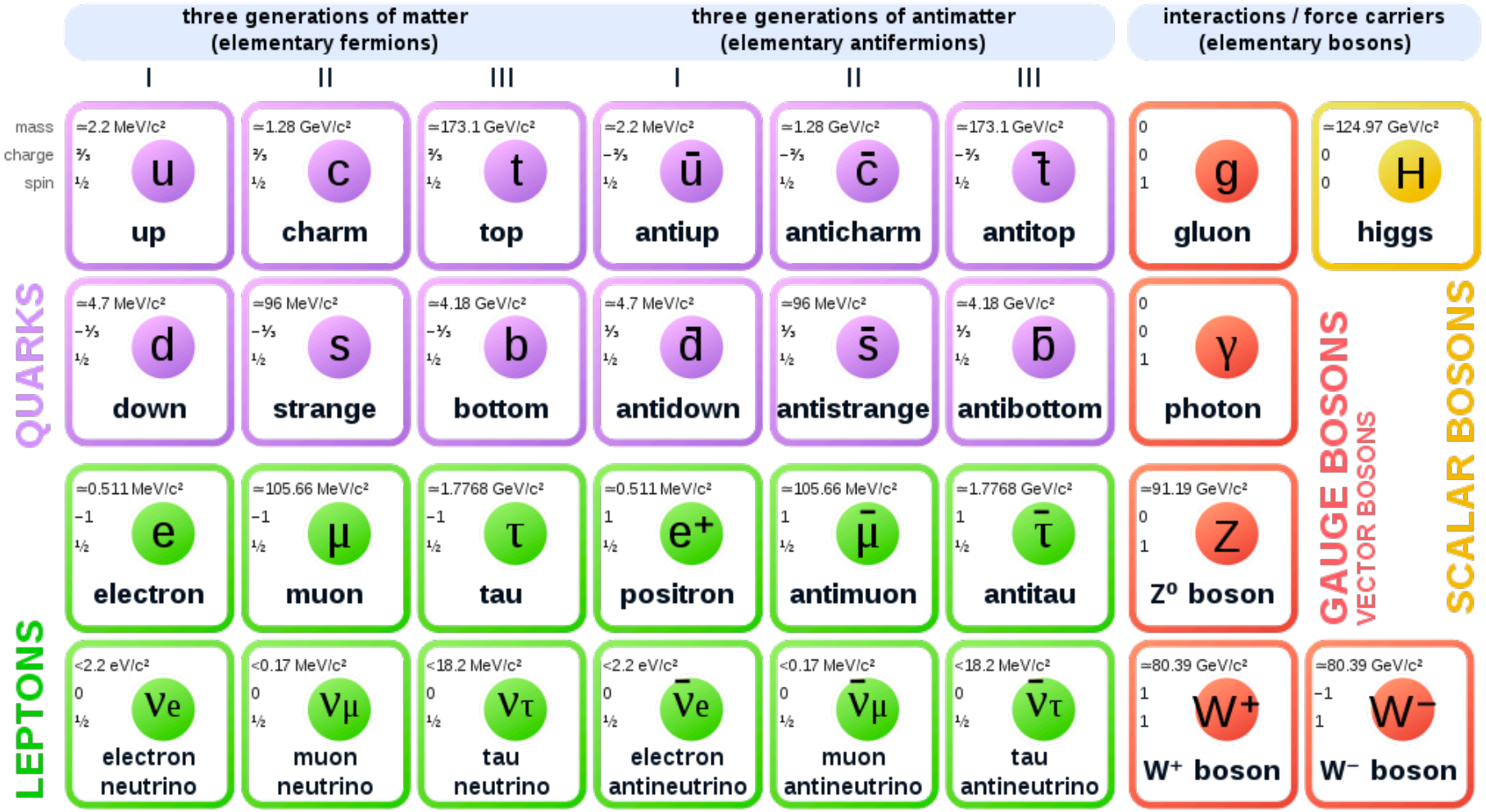
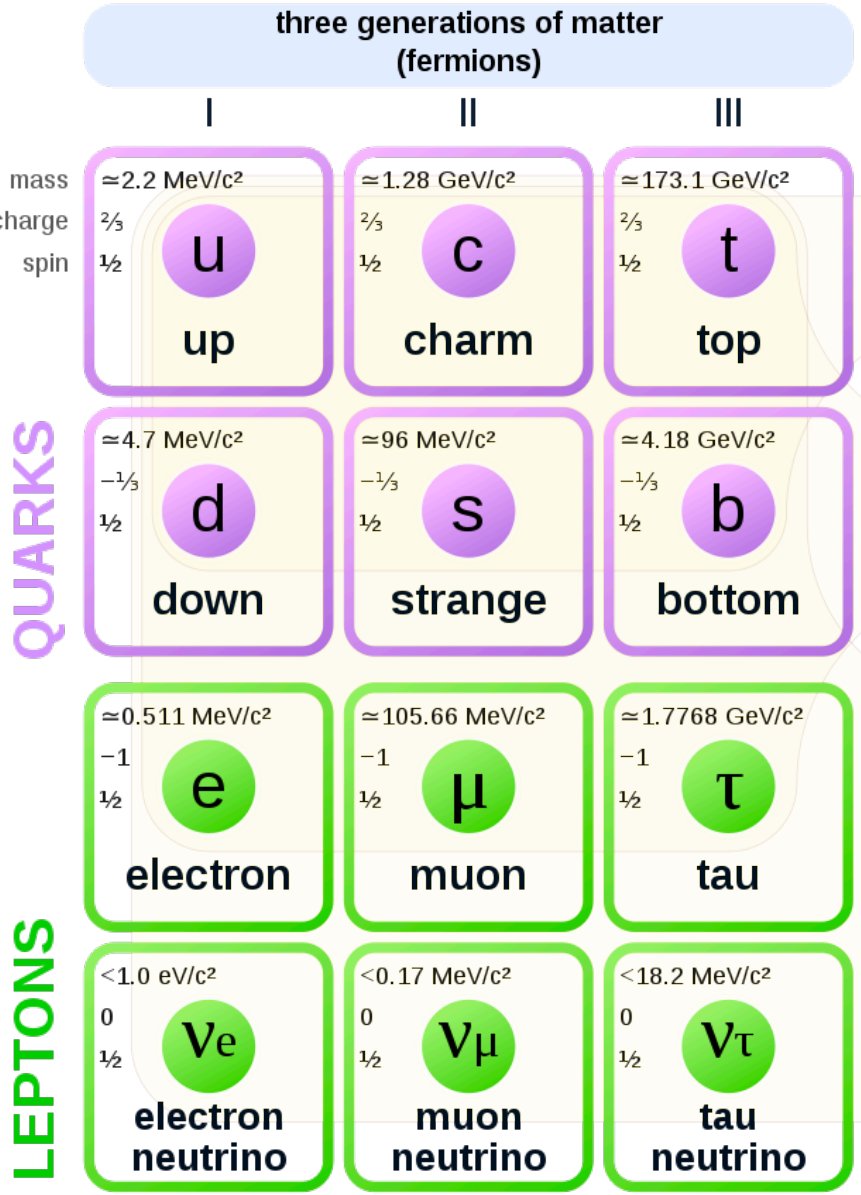
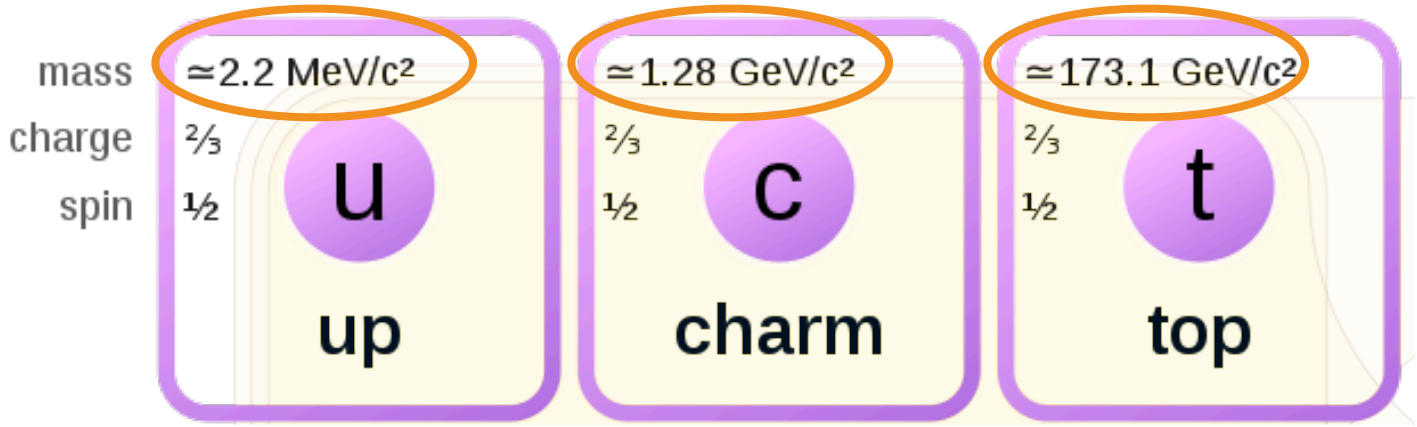



Figure: Wikimedia Commons

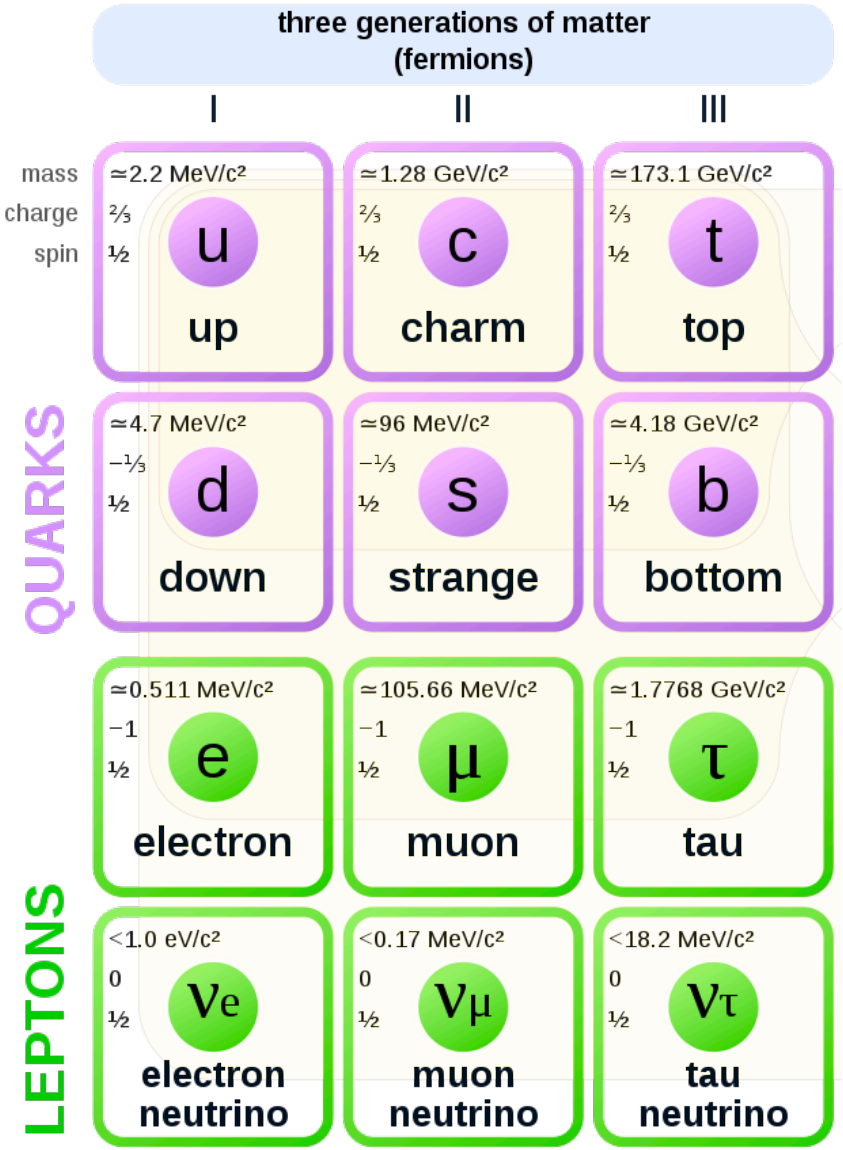
# Generation




- Two types of fundamental fermions: quarks and leptons.
- Generation refers to the columns.
- Both quarks and leptons have 3 generations ("copies").
- Mass of particles increases with generation.



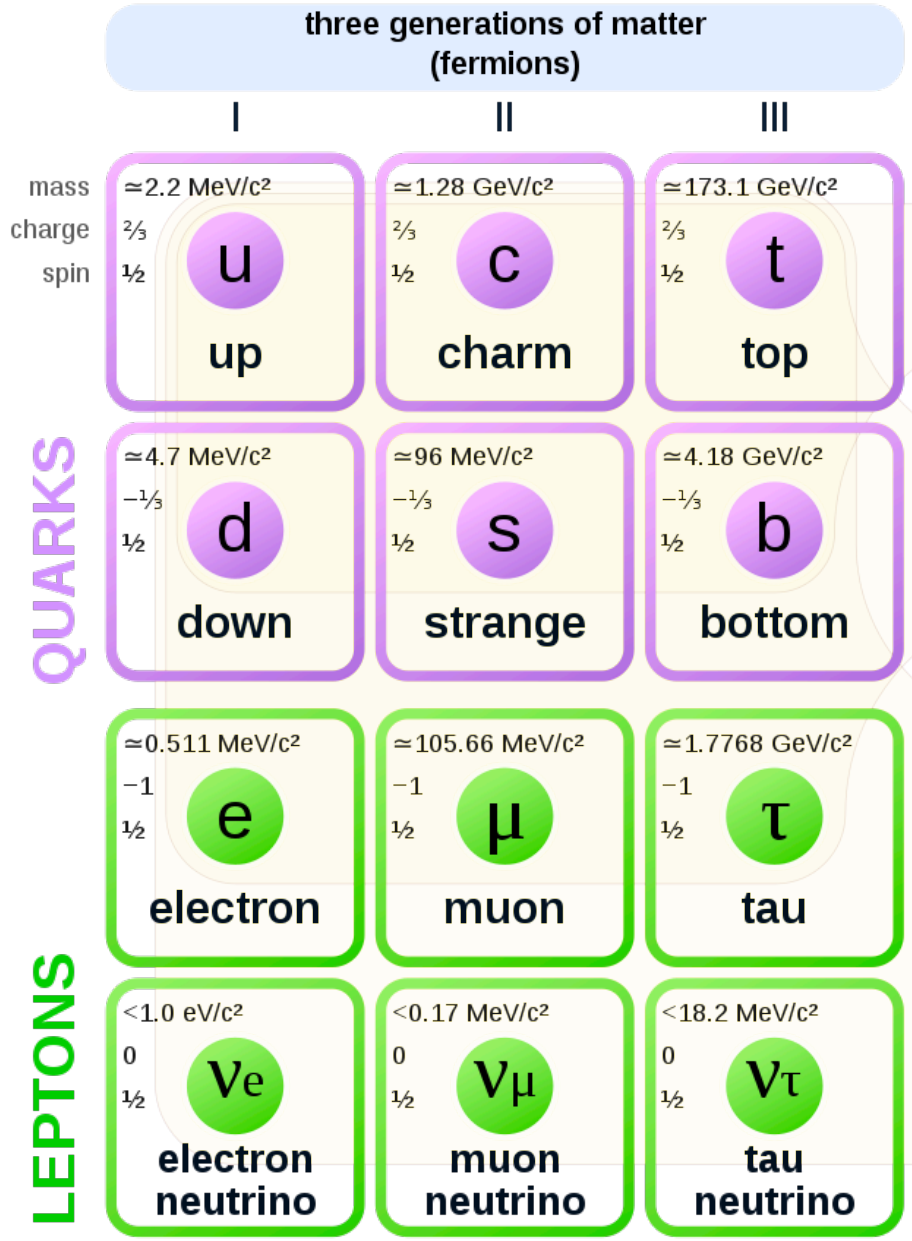
# Flavour




- Flavour refers to the individual cells.
- "electron flavour", "tau flavour", "charm flavour" etc.
- Both quarks and leptons come in six flavours.

# Some Open Questions:

- Why are there three generations?
- Are their additional undiscovered generations?
- Why are there six flavours of quarks and leptons?



# Interactions in the Standard Model

- Interactions are mediated by the gauge bosons.
- A particle must have the corresponding charge to interact.
  - ➡ Electromagnetic (photon) – electric charge
  - ➡ Strong nuclear force (gluon) – colour charge
  - ➡ Weak nuclear force (W and Z) – weak isospin/ hypercharge
  - ➡ Higg's interactions (H) – mass

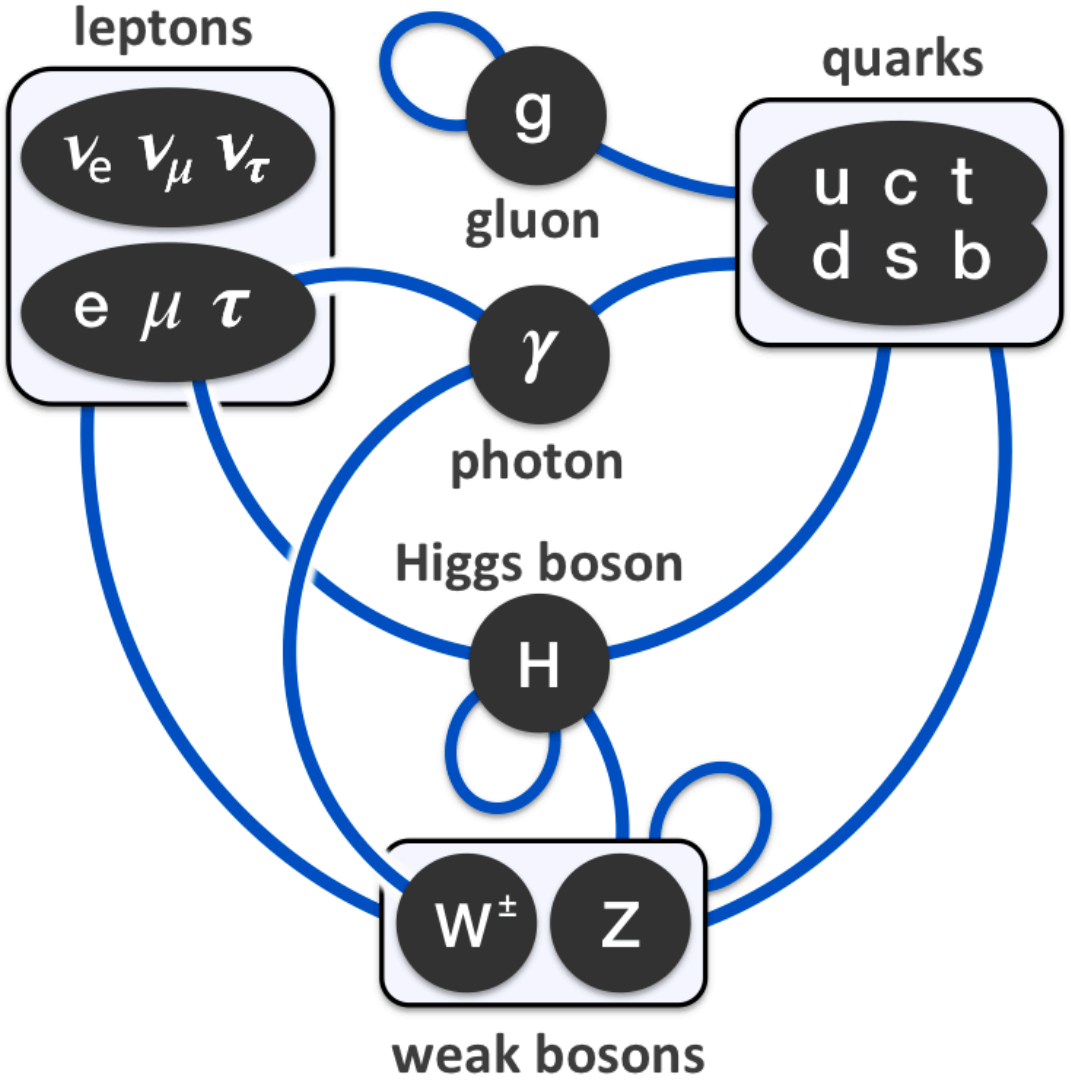
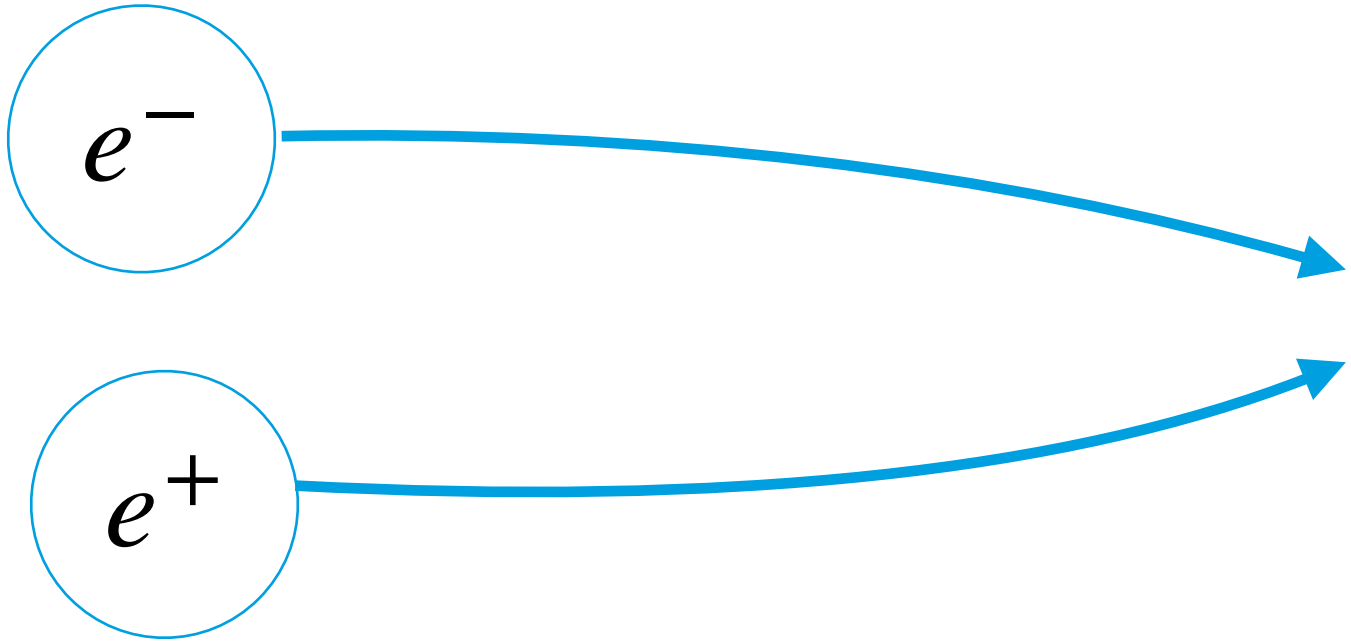


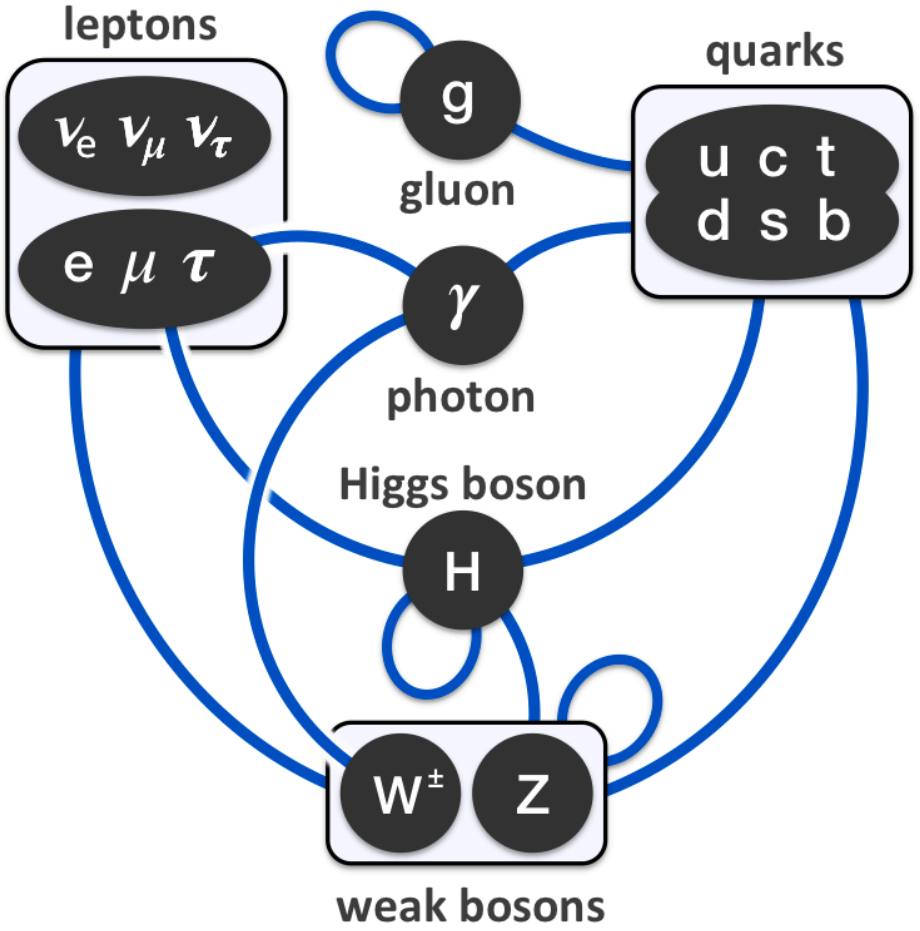



Figure: Wikimedia Commons

# Example Interaction: $e^+e^- \rightarrow e^+e^-$

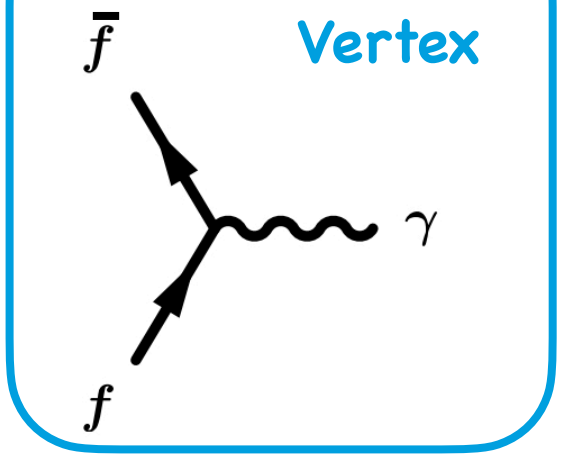
- An electron and positron are observed to scatter.
- Which Standard Model interaction could this be?
- Which boson could mediate this interaction?

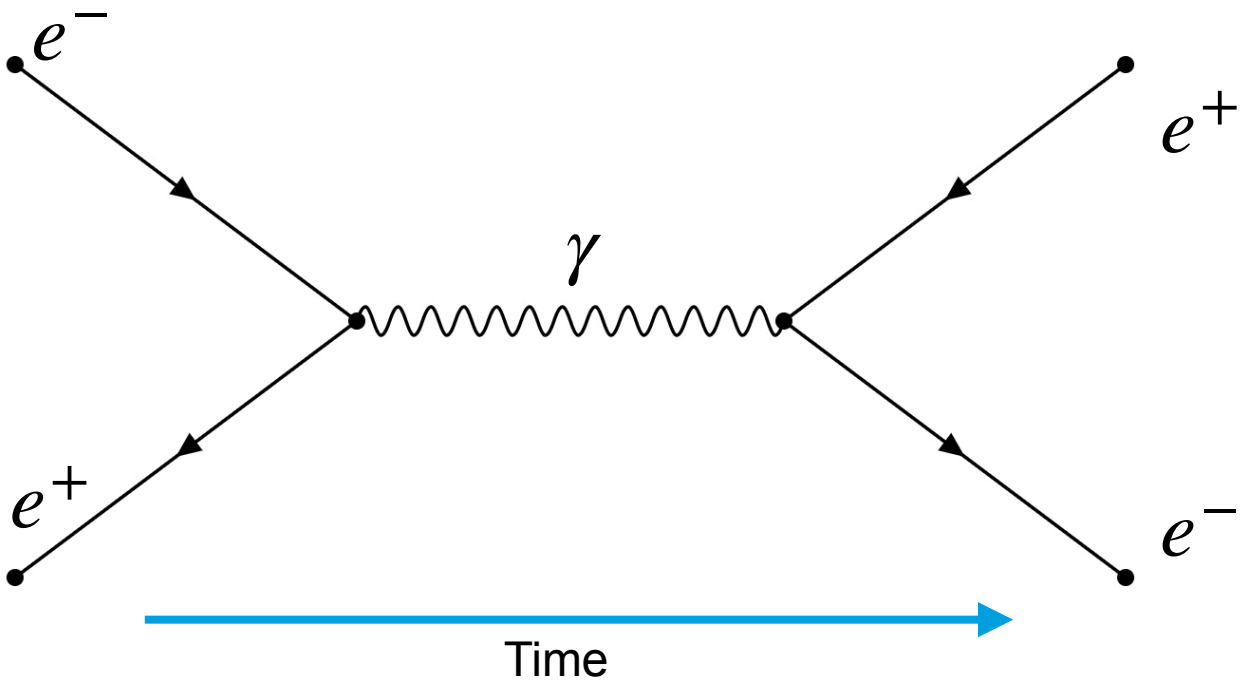


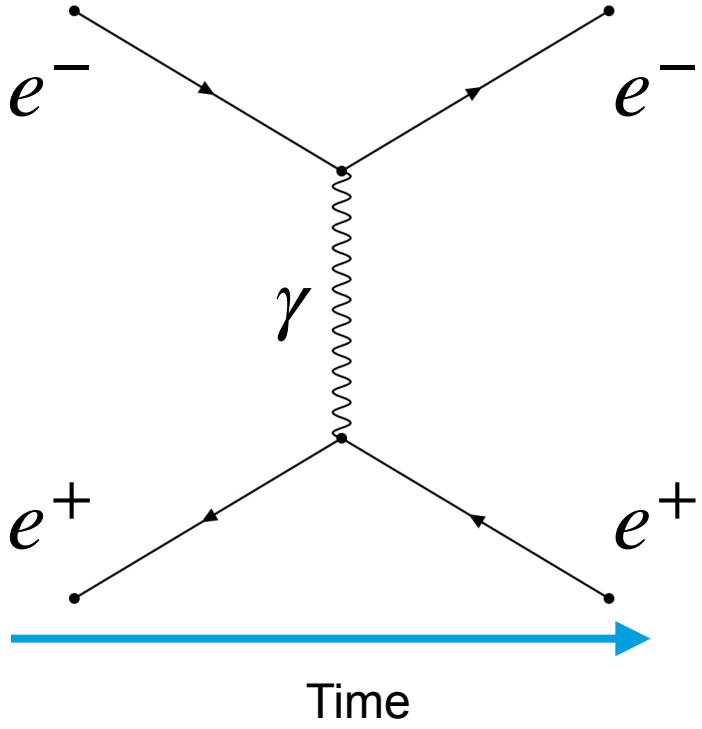



# Feynman diagrams

- Can help visualize how an interaction could proceed.
  - ➡Technically represent an equation in a perturbative expansion.
- Each interaction has a set of **fundamental vertices**.
  - ➡Diagrams constructed by connecting fundamental vertices.
- Two examples for $e^+e^- \to e^+e^-$:



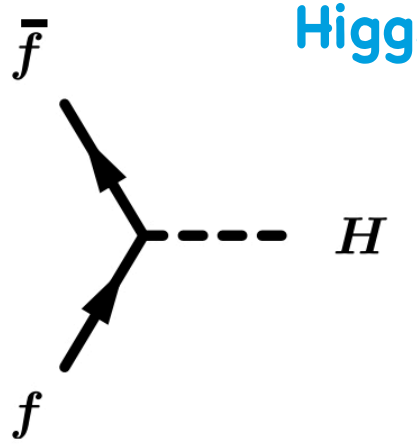



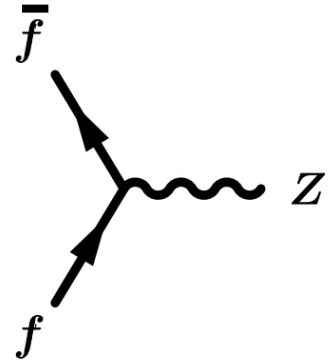
# Vertices for Quark/Lepton Interactions

Which of these interactions appears unique from the others?

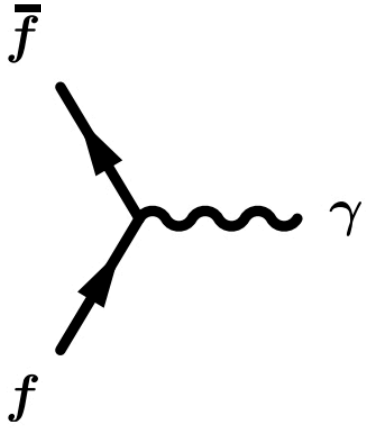
## Higgs



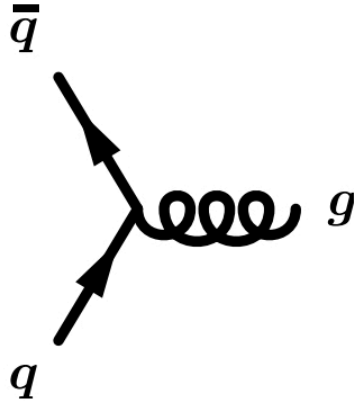

## Weak Force (Neutral Current)




## Electromagnetic




## Strong Force




## Weak Force (Charged Current)

i,j = quark flavour

V = CKM Matrix

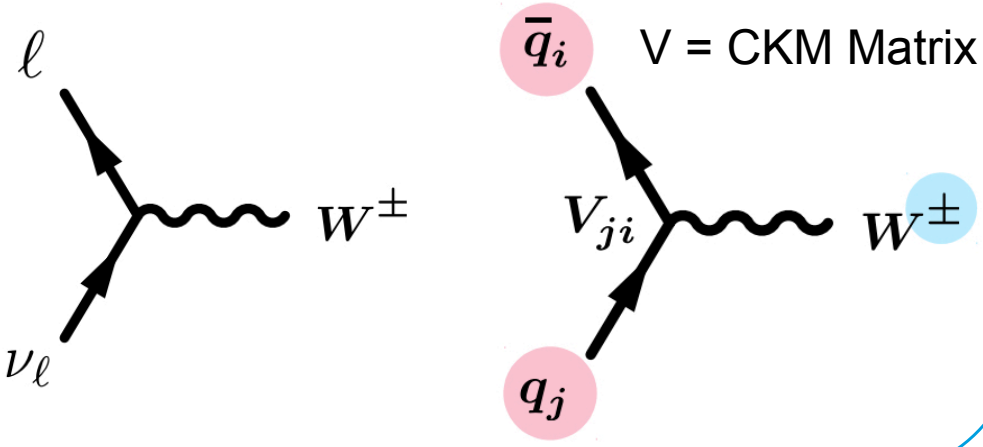
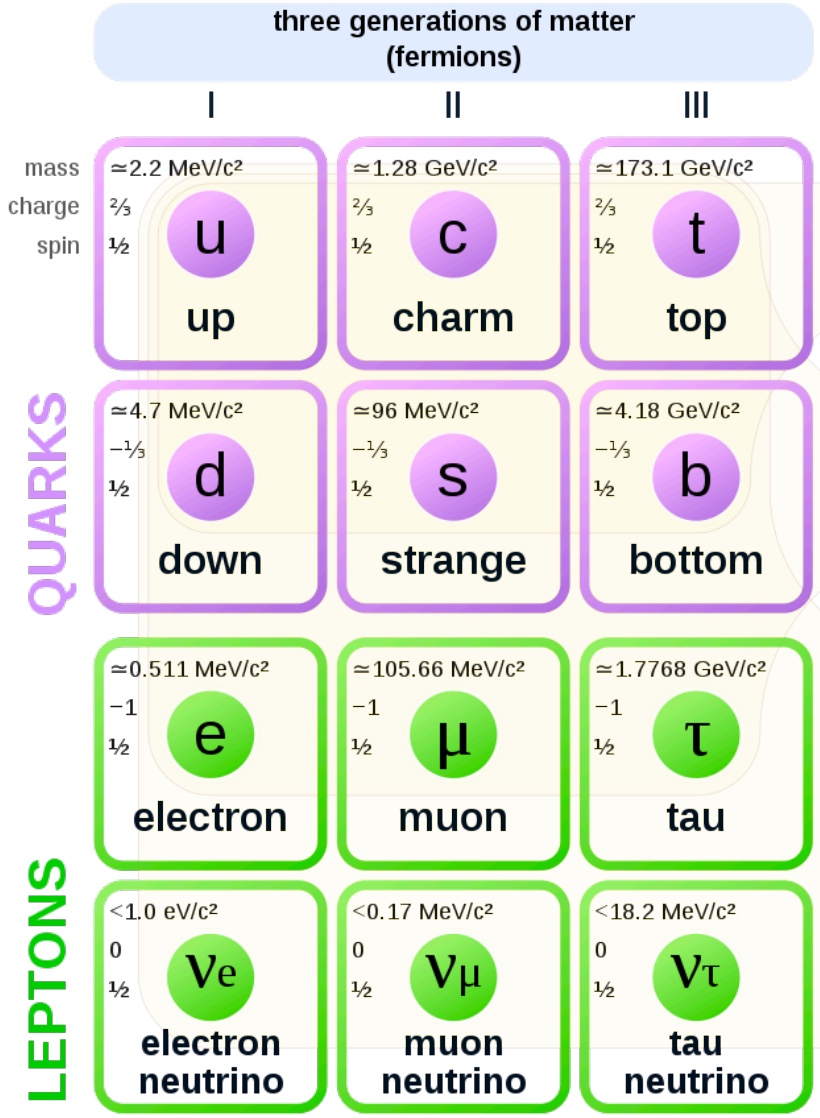


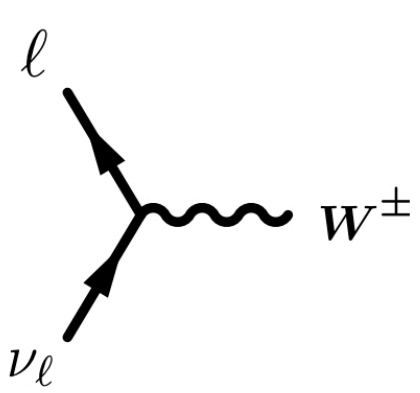


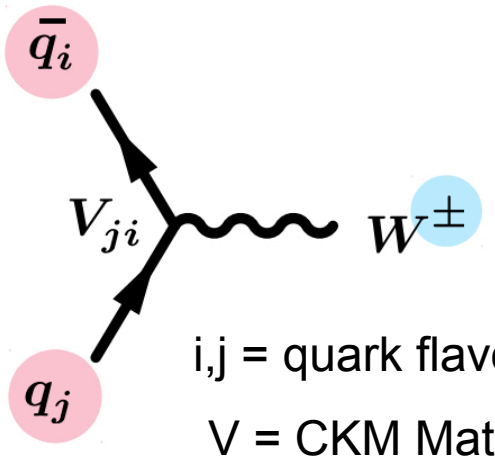

Image: S. Cunliffe

# Charged-Current Weak Interactions




## Weak Force (Charged Current)



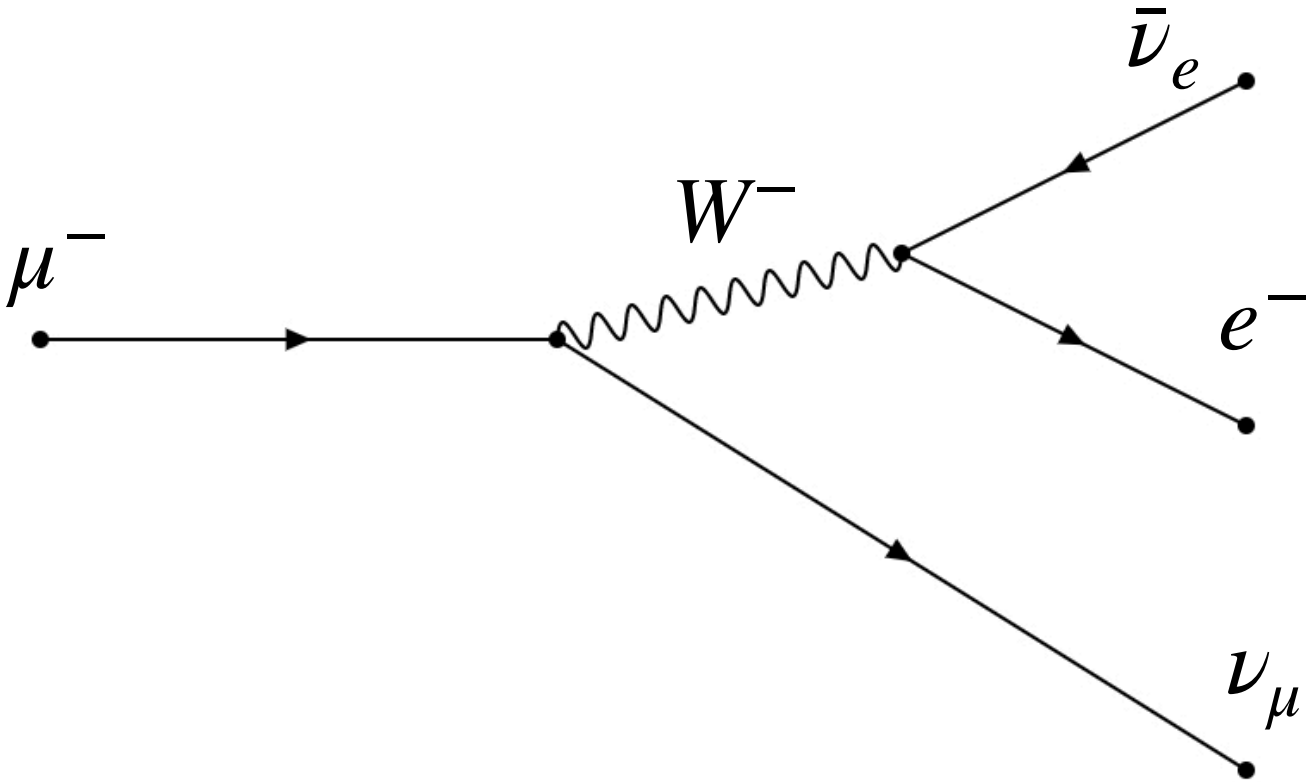



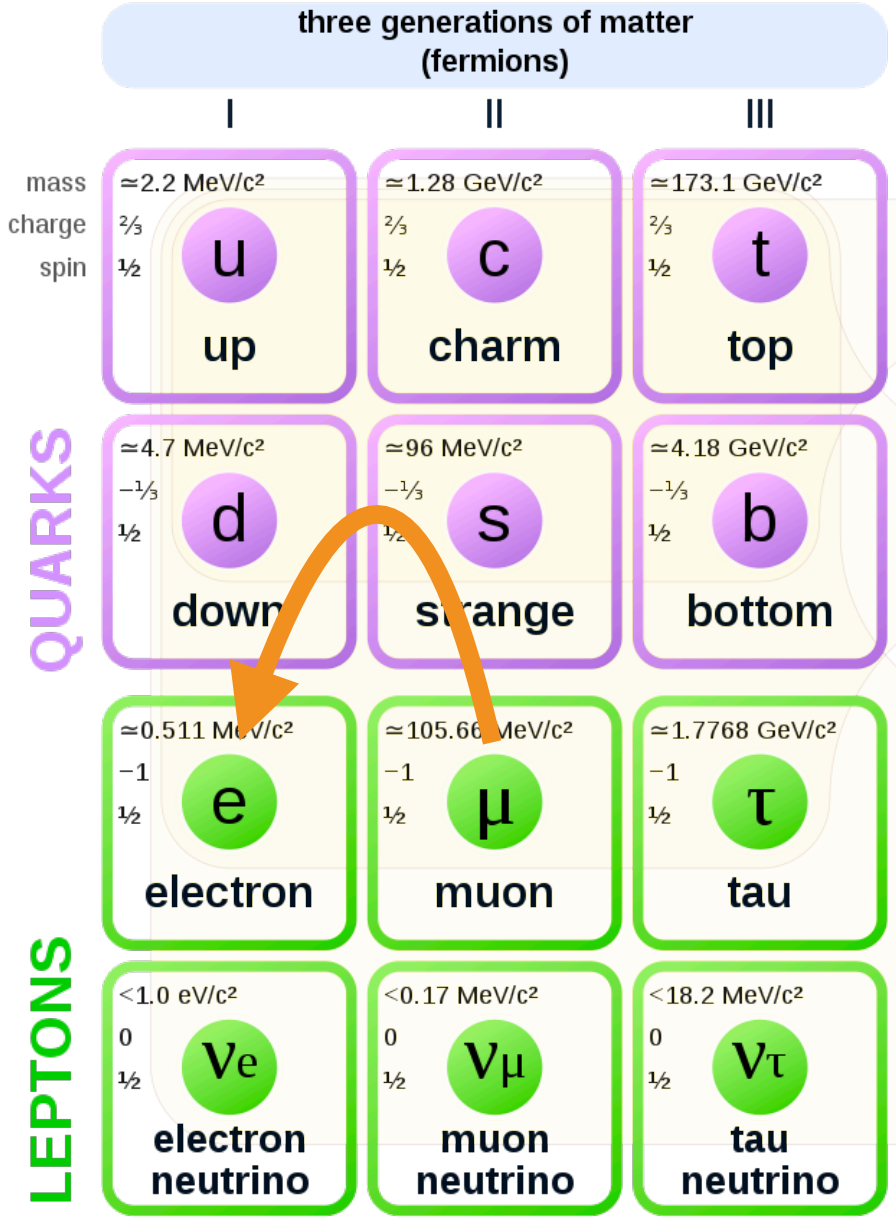

i,j = quark flavour

V = CKM Matrix

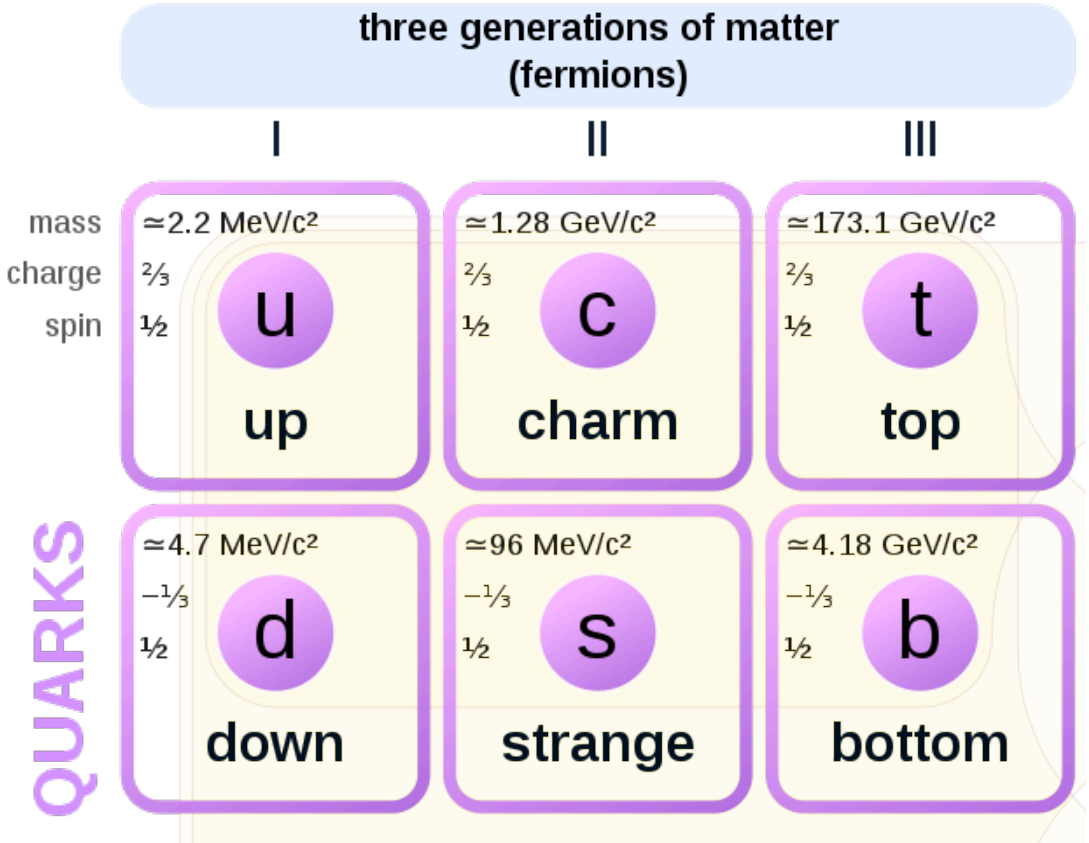
# Example: Muon Decay

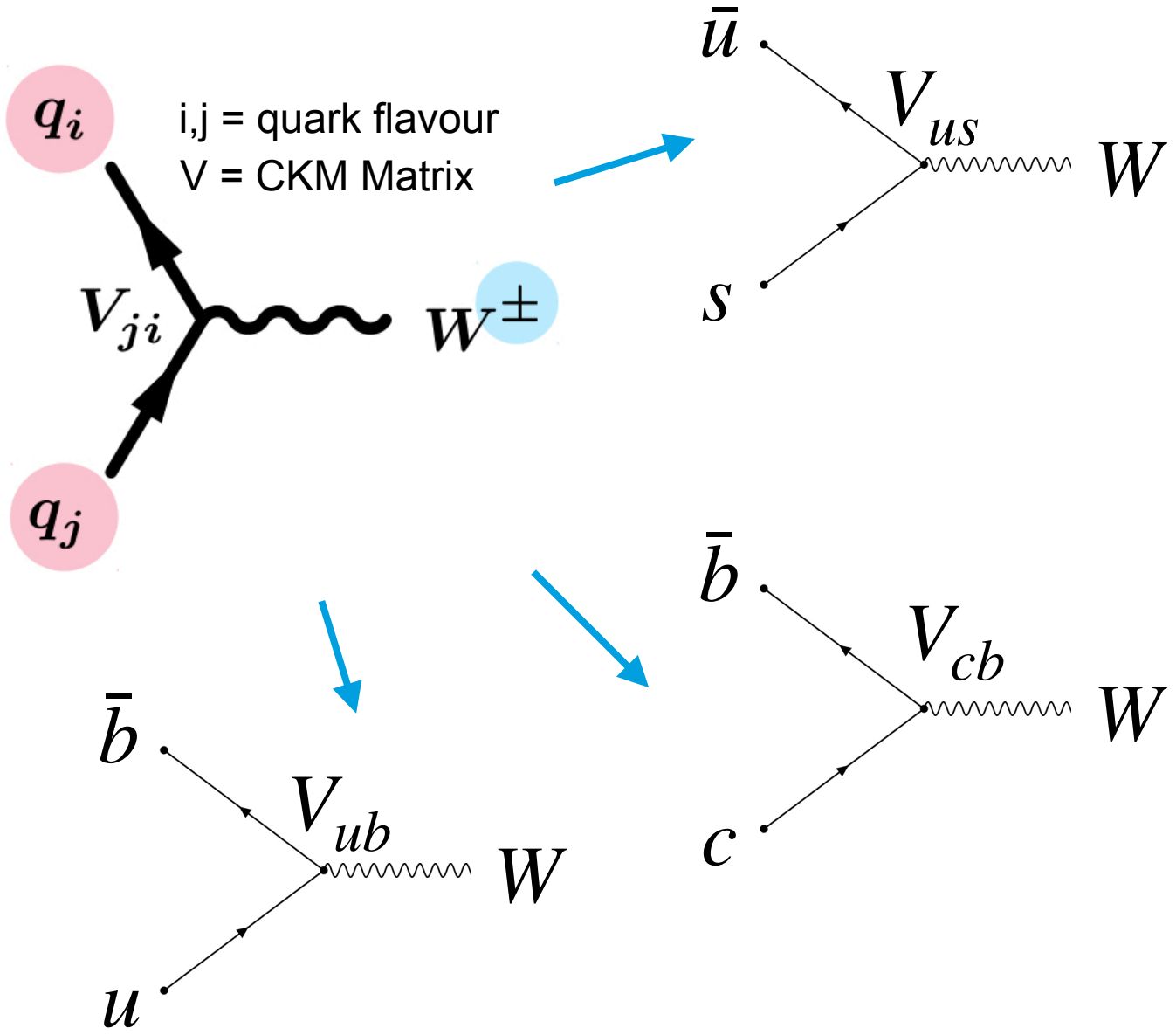
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$



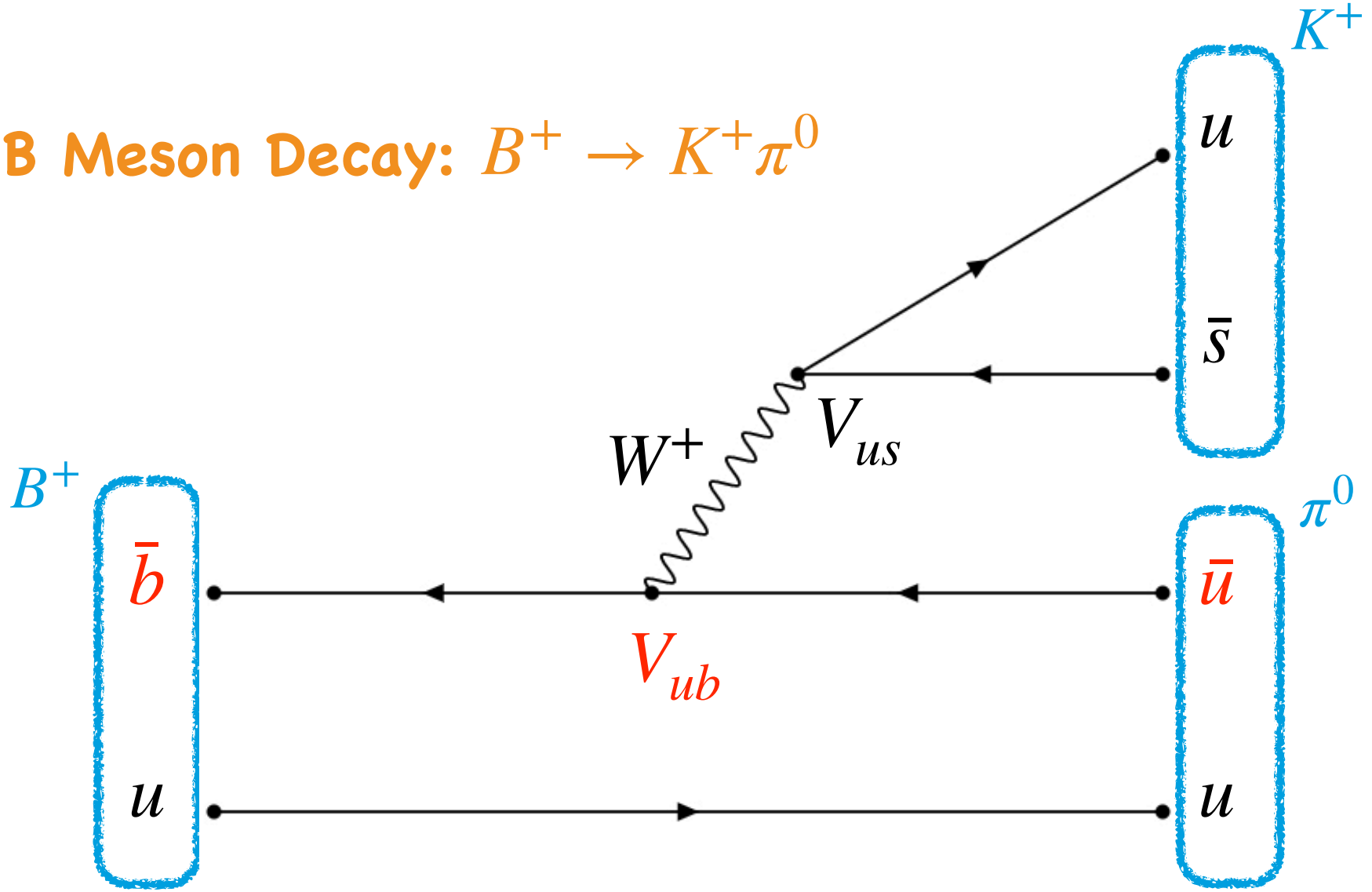
# Quark Flavour Changing Interactions

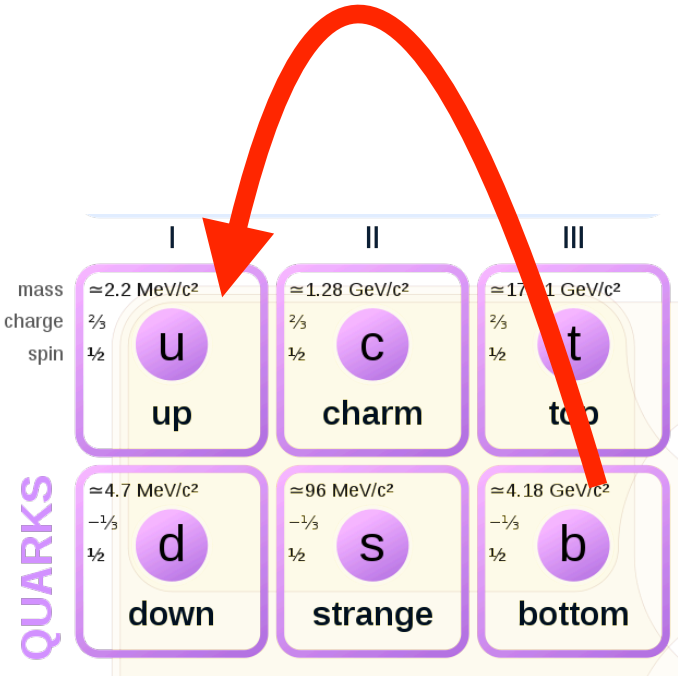


# Example of Quark Flavour Changing Interactions

## B Meson Decay: $B^+ \rightarrow K^+\pi^0$



# The Cabibbo–Kobayashi–Maskawa Matrix

- Matrix value gives measure of the interaction strength
- CKM matrix is unitary (i.e. rotation of mass states into interaction states) $V_{\mathrm{CKM}} V_{\mathrm{CKM}}^{\dagger} = 1$
- Values cannot be predicted by Standard Model

  ➡ Must be measured experimentally!

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

Interaction states — CKM Matrix — Mass states

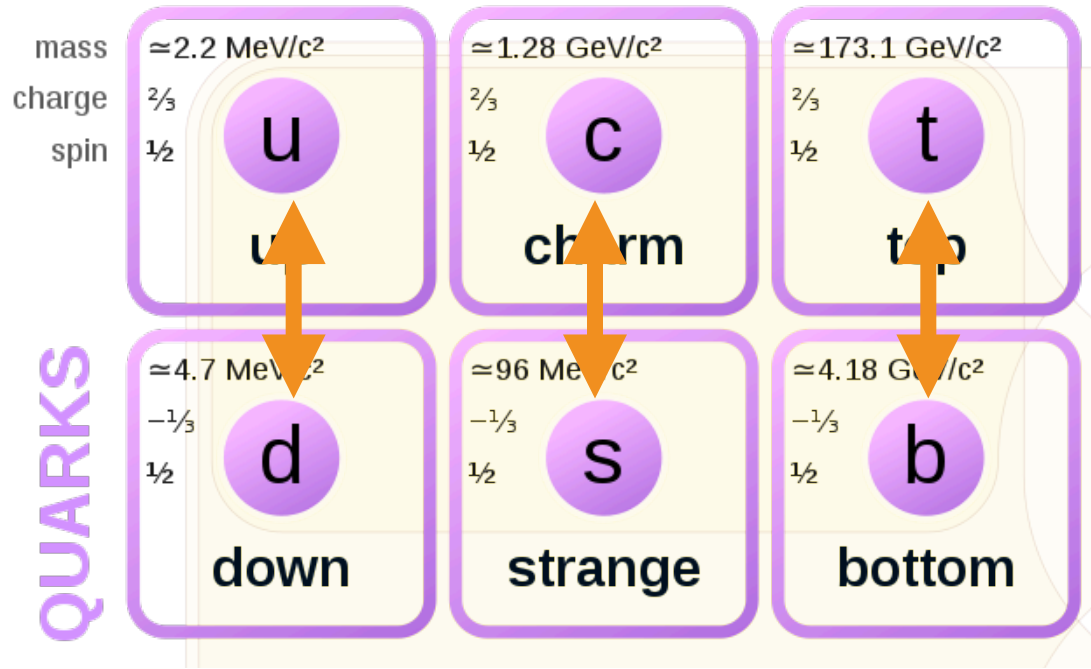
"Cabibbo-Kobayashi-Maskawa Matrix"

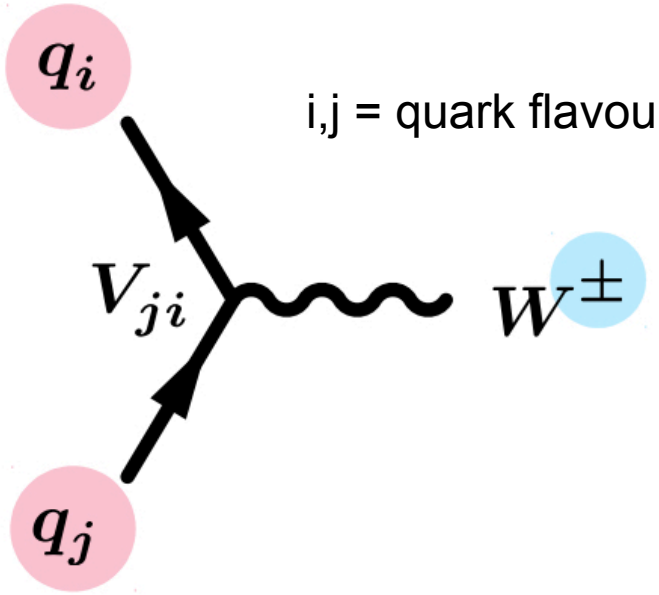
"Quark-mixing matrix" (1973)

Cabibbo matrix

$$V_{\mathrm{CKM}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} \approx \begin{pmatrix} 0.974 & 0.226 & 0.004 \\ 0.23 & 0.96 & 0.04 \\ 0.01 & 0.04 & 0.999 \end{pmatrix}$$

# Changing Quark Flavour

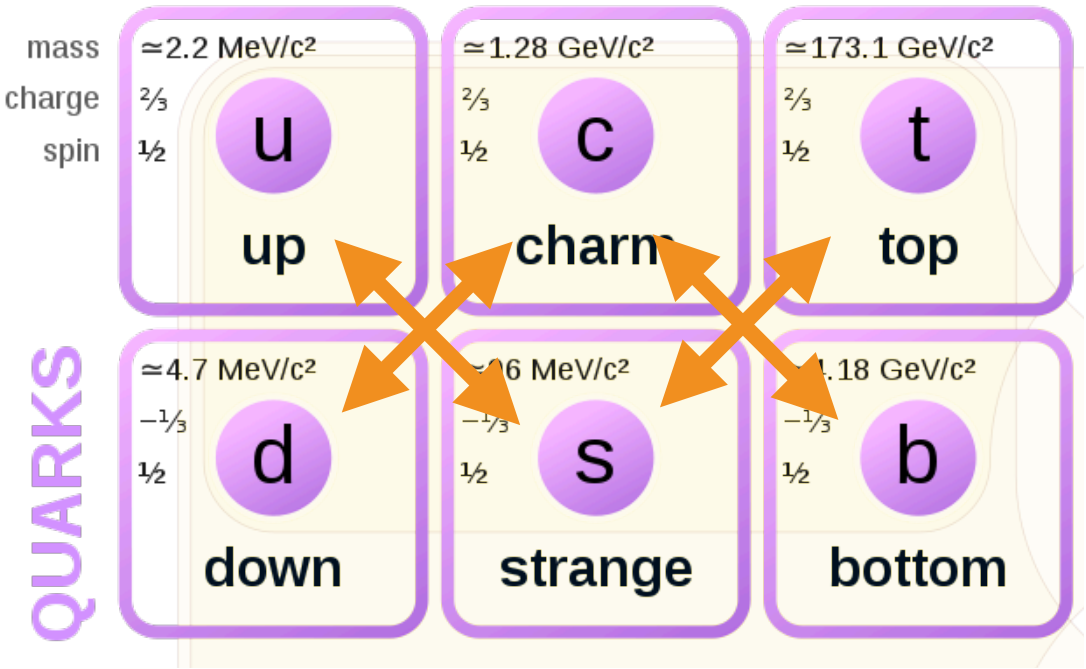


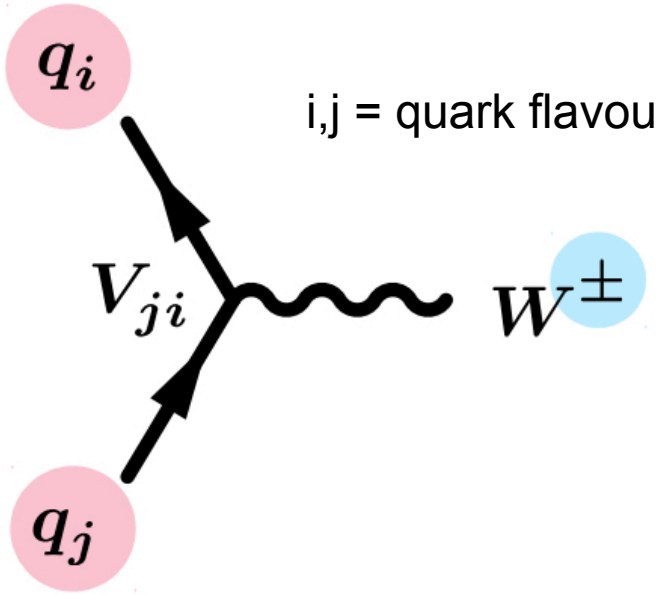




i,j = quark flavour

$$V_{\mathrm{CKM}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} \approx \begin{pmatrix} 0.974 & 0.226 & 0.004 \\ 0.23 & 0.96 & 0.04 \\ 0.01 & 0.04 & 0.999 \end{pmatrix}$$

# Changing Quark Flavour

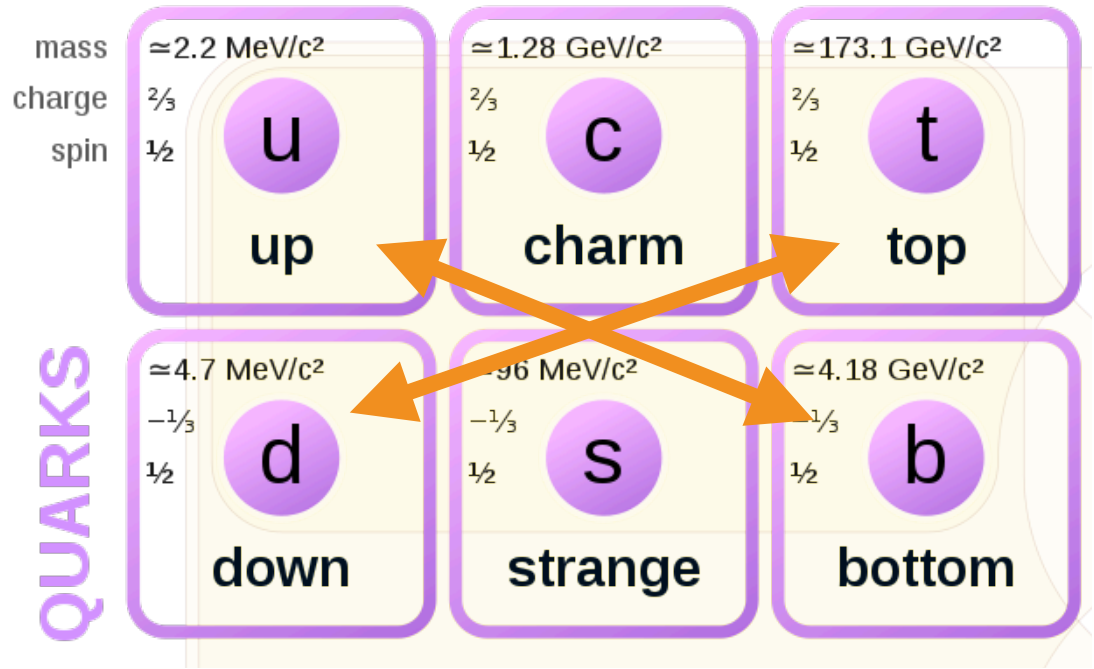


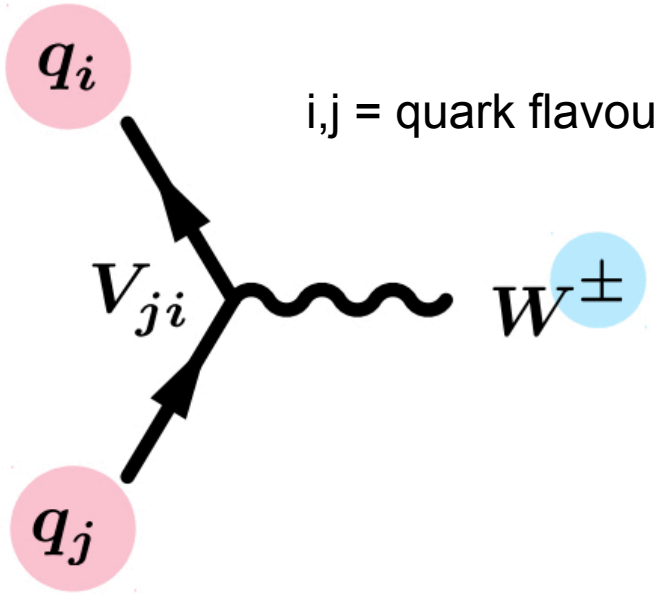




i,j = quark flavour

$$V_{\mathrm{CKM}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} \approx \begin{pmatrix} 0.974 & 0.226 & 0.004 \\ 0.23 & 0.96 & 0.04 \\ 0.01 & 0.04 & 0.999 \end{pmatrix}$$

# Changing Quark Flavour

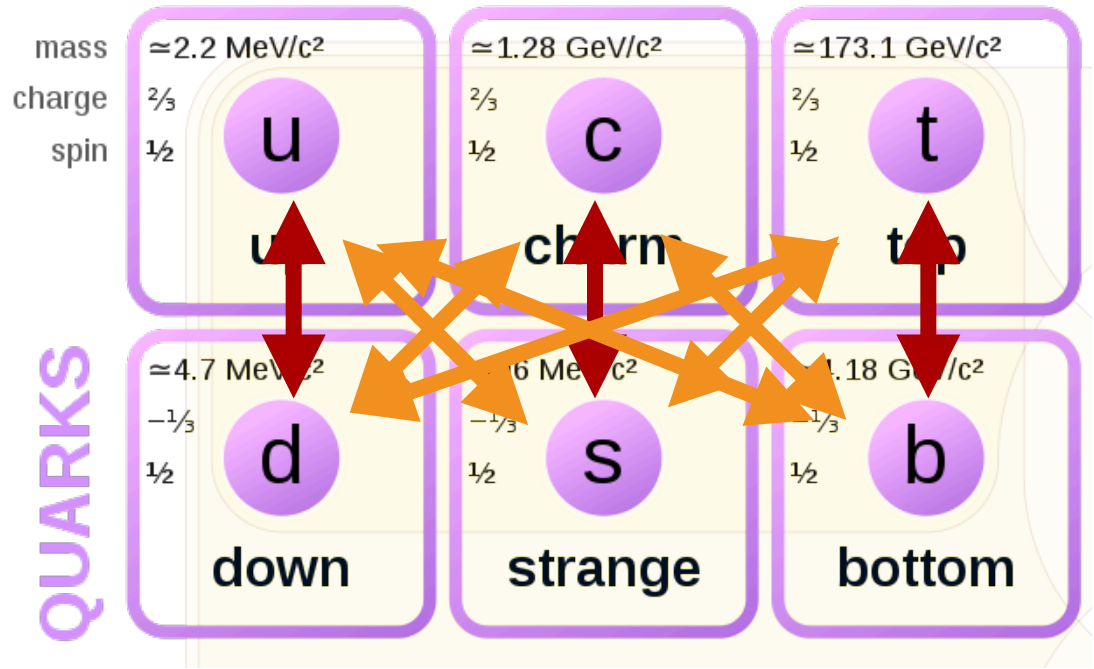



i,j = quark flavour

$$V_{\mathrm{CKM}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} \approx \begin{pmatrix} 0.974 & 0.226 & 0.004 \\ 0.23 & 0.96 & 0.04 \\ 0.01 & 0.04 & 0.999 \end{pmatrix}$$

# Changing Quark Flavour

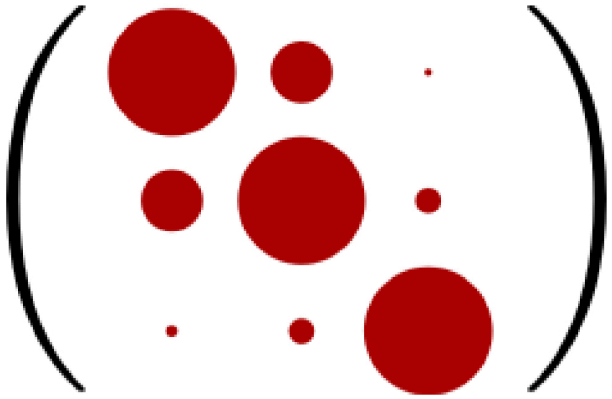



CKM matrix almost diagonal!

→ **Coupling** between quarks of **same generation is strongest**

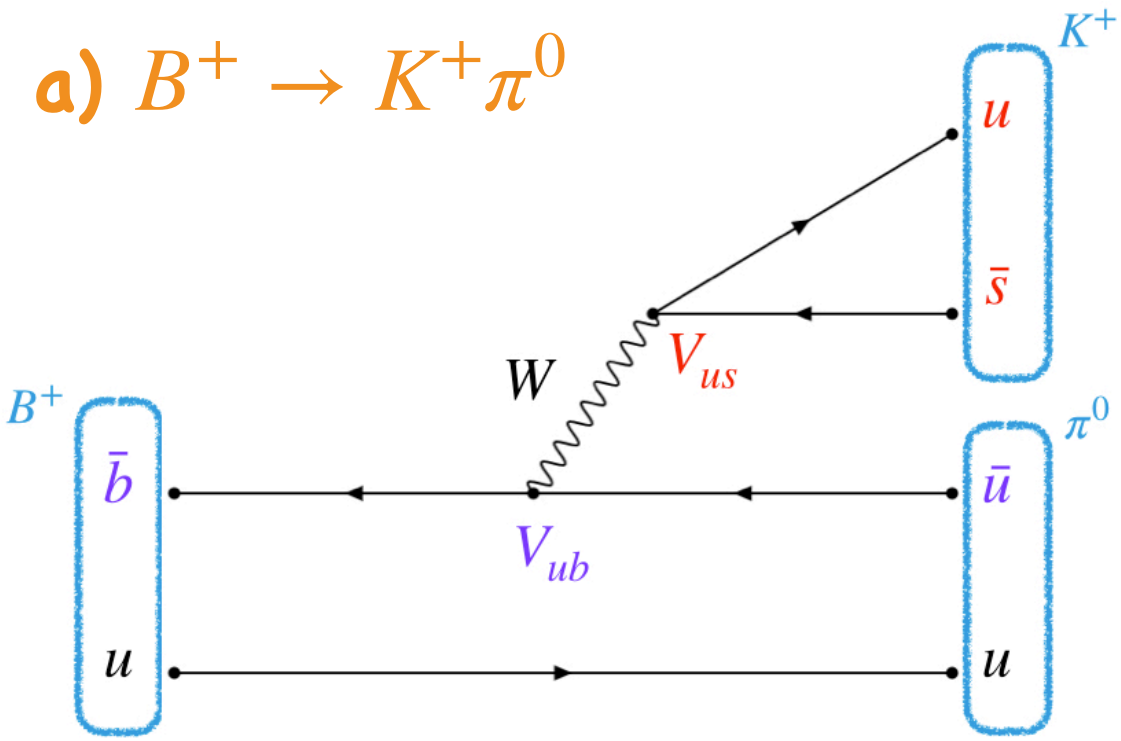
→ **Coupling** between **first** und **third generation** is **small**

$$V_{\mathrm{CKM}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} \approx$$

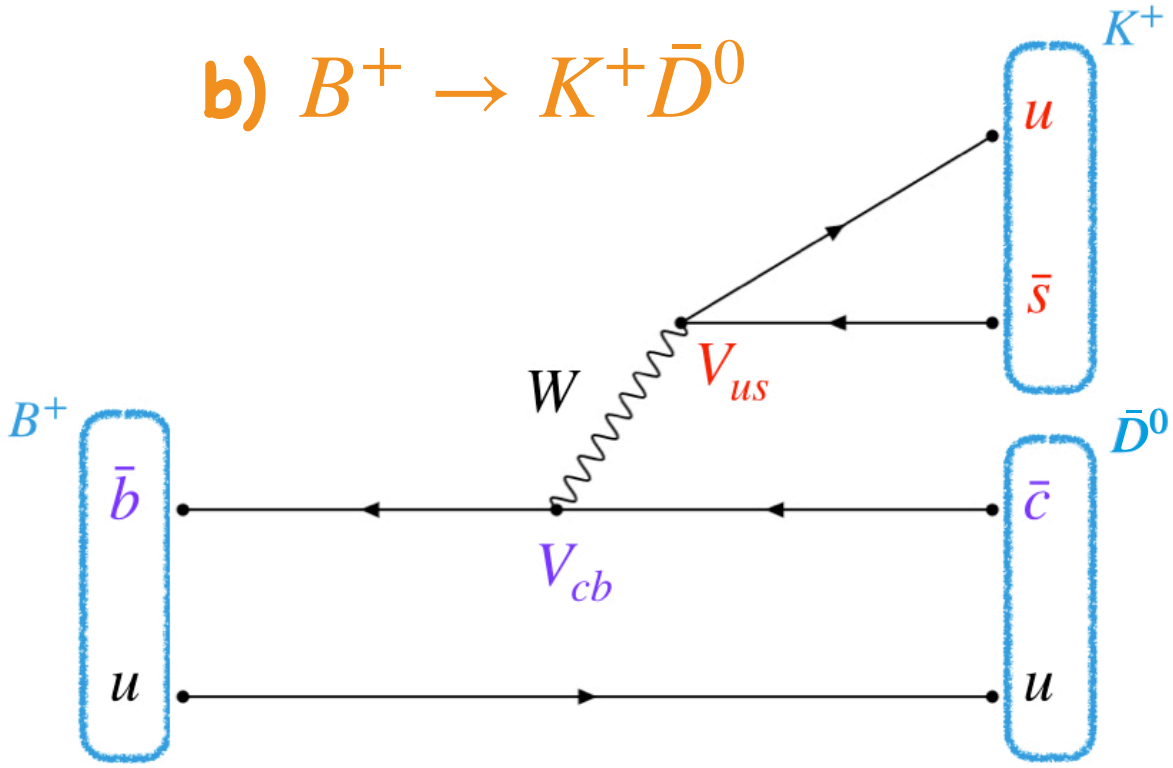


# Q1: Which decay do you expect to have a higher rate?

a) $B^+ \to K^+\pi^0$




b) $B^+ \to K^+\bar{D}^0$




**Hint:**

$$V_{\mathrm{CKM}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} \approx$$

# CKM Matrix Unitarity and 4th Generation?

- For unitarity the CKM matrix must follow the conditions:

$$\sum_i V_{ij} V_{ik}^* = \delta_{jk} \text{ and } \sum_j V_{ij} V_{kj}^* = \delta_{ik}$$

- Recall an open question was: Are their additional undiscovered generations of quarks?

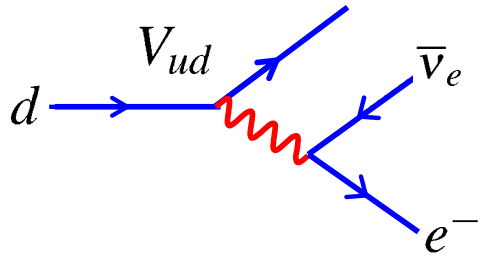
- One way to test for hints of new quark generations is to precisely measure the CKM Matrix and check if the measured values satisfy unitarity.

$$|V_{\mathrm{CKM}}| = \begin{pmatrix} 0.97435 \pm 0.00016 & 0.22500 \pm 0.00067 & 0.00369 \pm 0.00011 \\ 0.22486 \pm 0.00067 & 0.97349 \pm 0.00016 & 0.04182^{+0.00085}_{-0.00074} \\ 0.00857^{+0.00020}_{-0.00018} & 0.04110^{+0.00083}_{-0.00072} & 0.999118^{+0.000031}_{-0.000036} \end{pmatrix}$$

R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)
https://pdg.lbl.gov/2022/reviews/rpp2022-rev-ckm-matrix.pdf

# Determination of the CKM Matrix

1) $|V_{ud}|$ via nuclear beta decay



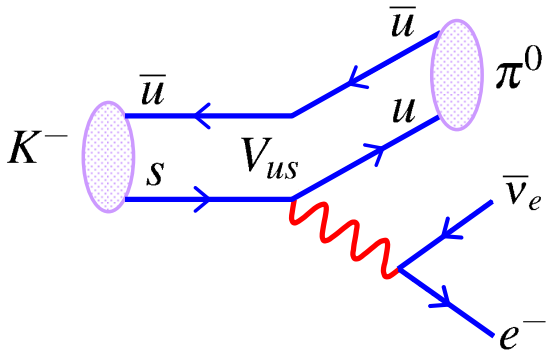

Super allowed $0^+ \rightarrow 0^+$ beta decays are relatively free from theoretical uncertainties

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\Gamma \propto |V_{ud}|^2$$

$$|V_{ud}| = 0.97377 \pm 0.00027$$

2) $|V_{us}|$ from semileptonic Kaon decays




$$\Gamma \propto |V_{us}|^2$$

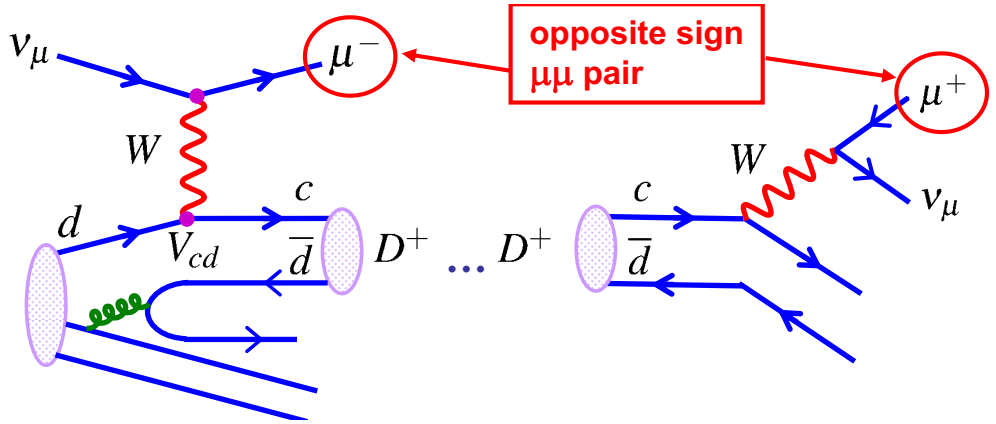
$$|V_{us}| = 0.2257 \pm 0.0021$$

# Determination of the CKM Matrix

3) $|V_{cd}|$ from neutrino scattering $\nu_\mu + N \to \mu^+\mu^- X$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Look at opposite charge di-muon events in $\nu_\mu$ scattering from production and decay of $D^+(c\bar{d})$ meson



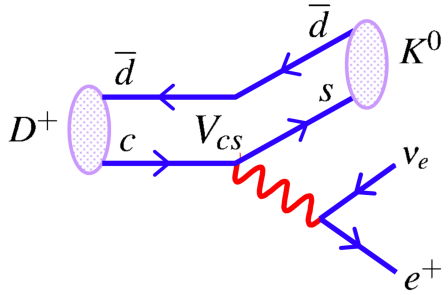

Rate $\propto |V_{cd}|^2 \mathcal{B}(D^+ \to X\mu^+\bar{\nu})$

measured by various collider experiments

$$|V_{cd}| = 0.230 \pm 0.011$$

# Determination of the CKM Matrix

4) $|V_{cs}|$ from semi-leptonic charmed meson decays




$$\Gamma \propto |V_{cs}|^2$$

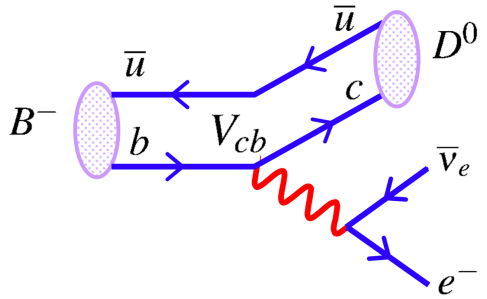
$$|V_{cs}| = 0.957 \pm 0.017 \pm 0.093$$

exp. error

uncertainty dominated by theory error

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

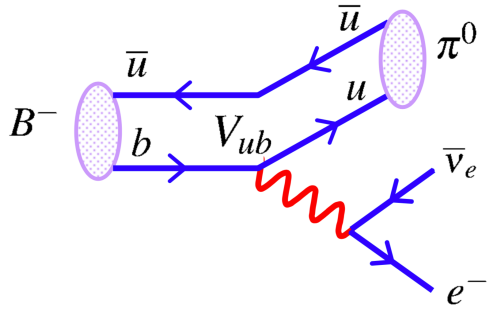
5) $|V_{cb}|$ from semi-leptonic B hadron decays




$$\Gamma \propto |V_{cb}|^2$$

$$|V_{cb}| = 0.0416 \pm 0.0006$$

6) $|V_{ub}|$ from semi-leptonic B hadron decays

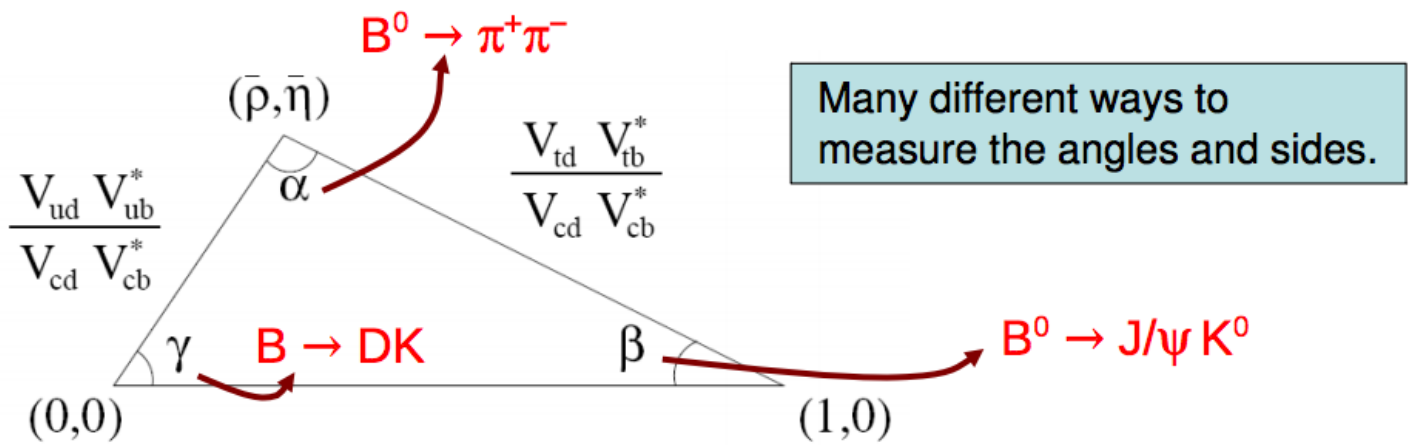



$$\Gamma \propto |V_{ub}|^2$$

$$|V_{ub}| = 0.0043 \pm 0.0003$$

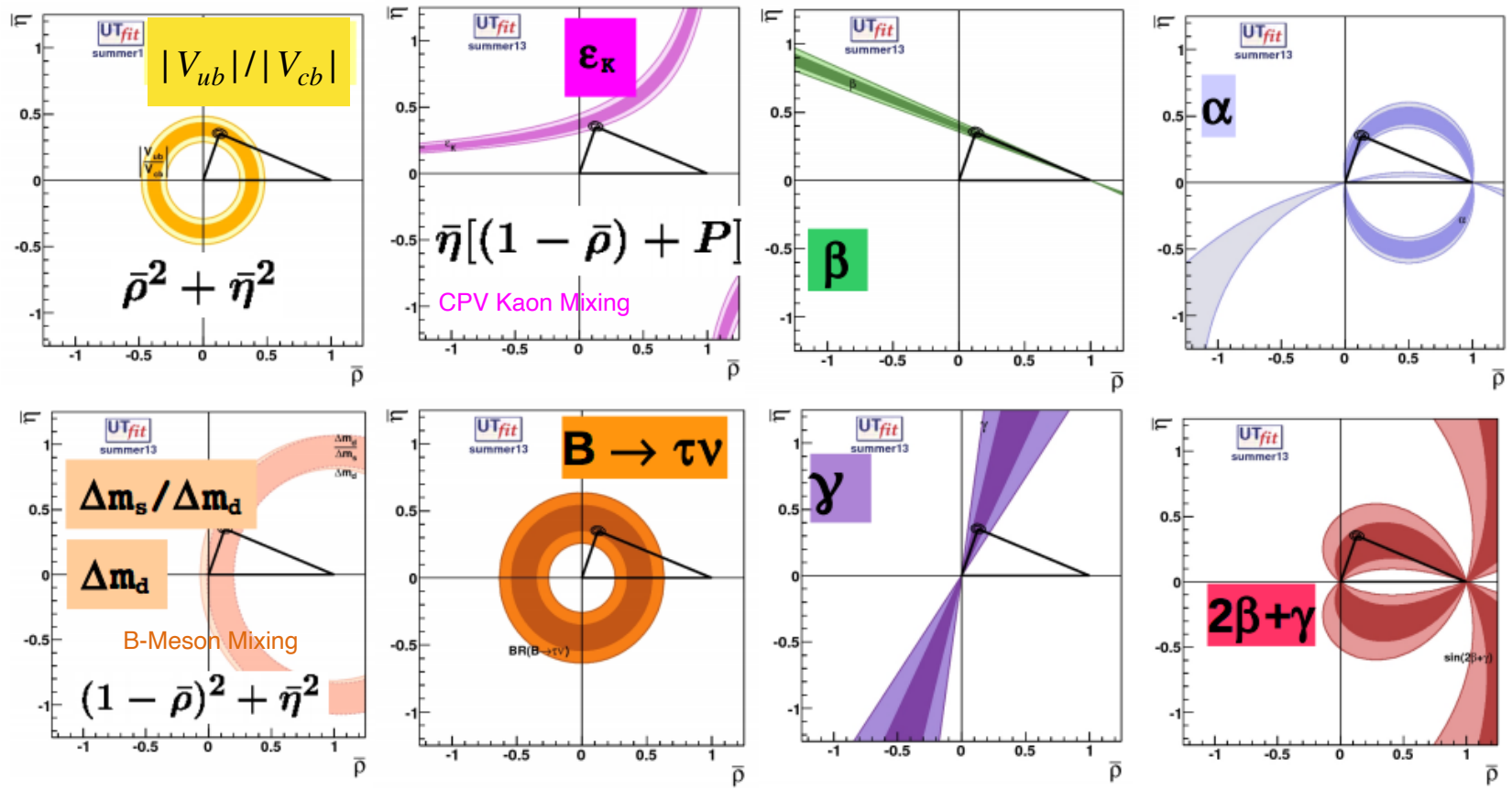
# Testing the CKM Picture

- The sides and angles need to be measured to over-constrain the triangle and test that it closes.
- If there is CP violation the triangle remains open
- All lengths involve b decays

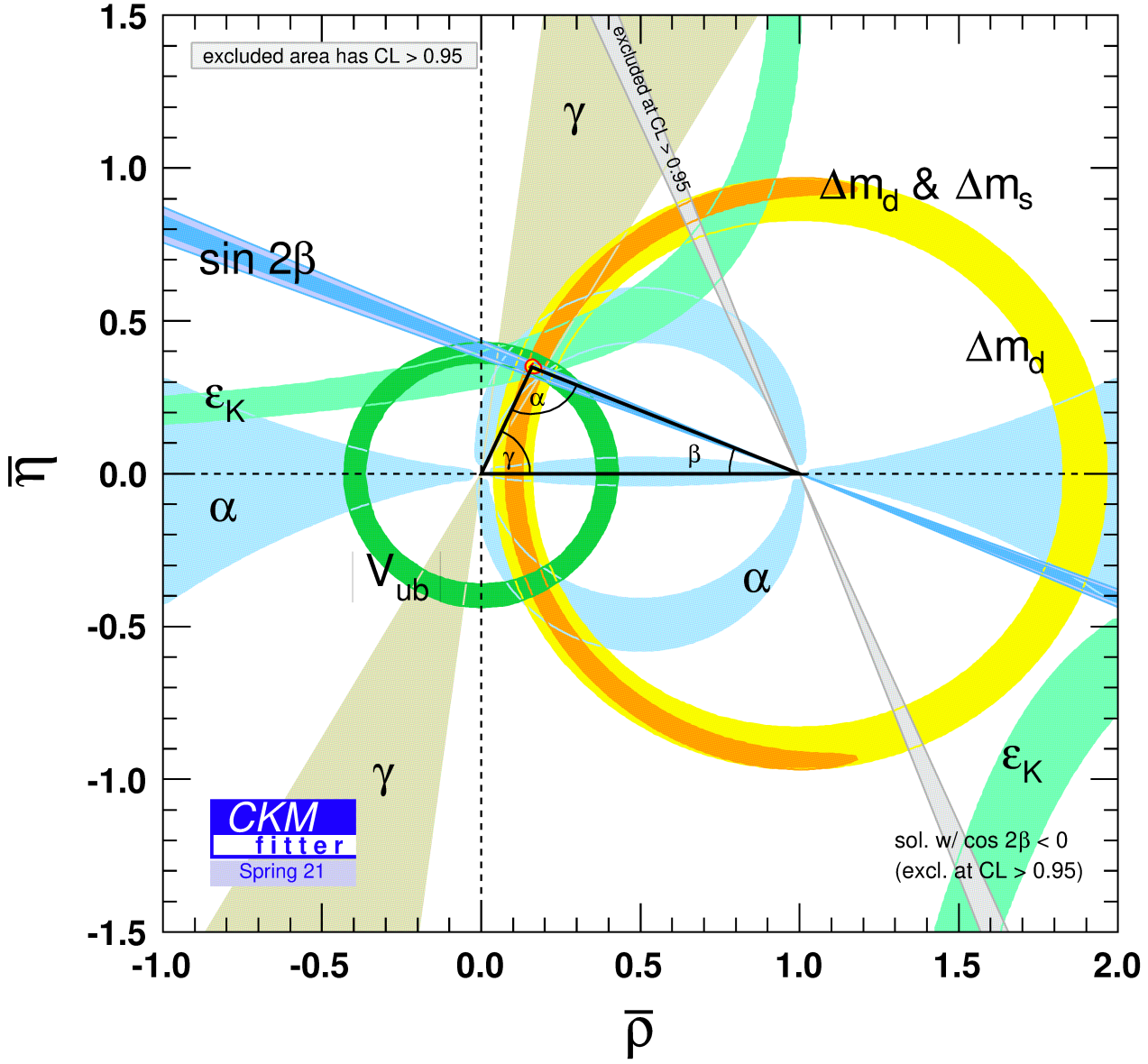


# Testing the CKM Picture

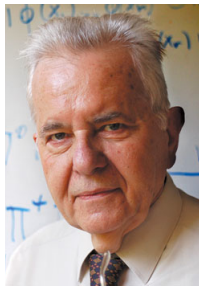
Let's look at some of the constraints from experimental results:




http://www.utfit.org/UTfit/



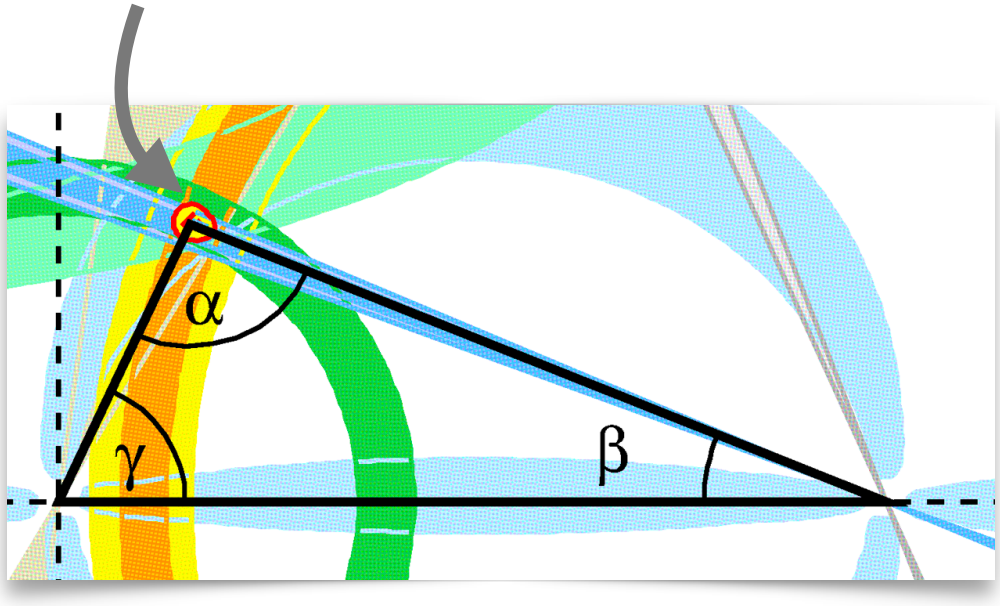

Nobel prize 2008



Nicola **C**abibbo

Makoto **K**obayashi Toshihide **M**asukawa

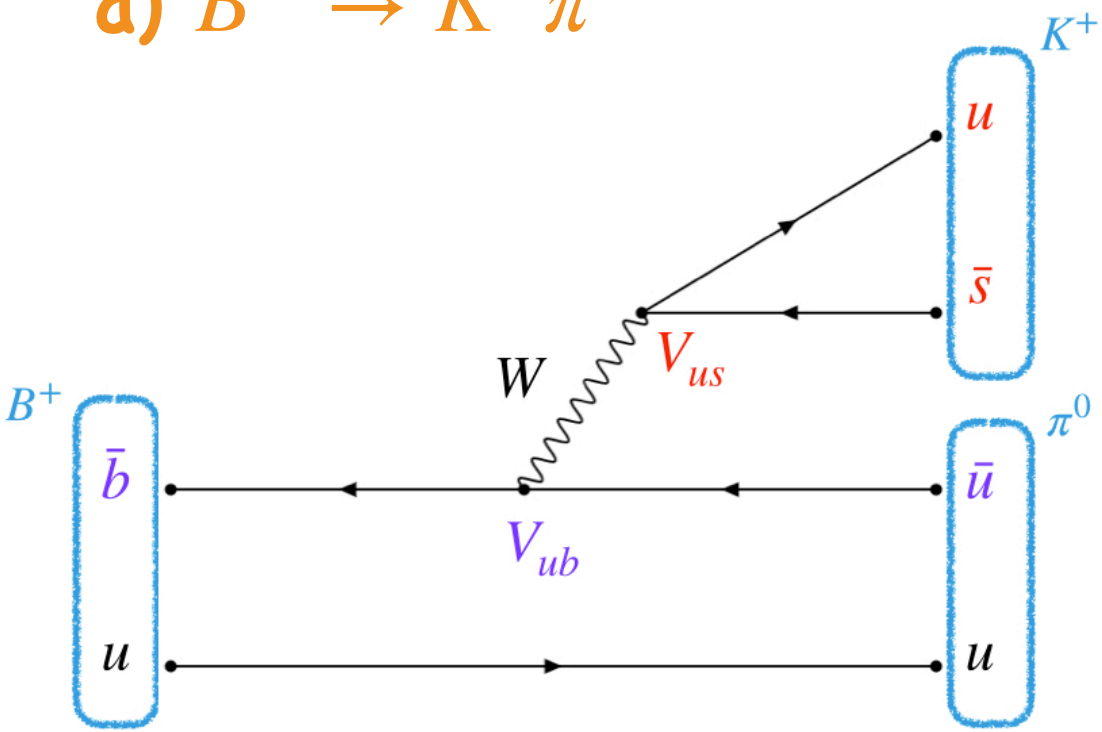
CPV & Kobayashi-Maskawa (KM) mechanism




http://ckmfitter.in2p3.fr/www/results/plots_spring21/ckm_res_spring21.html

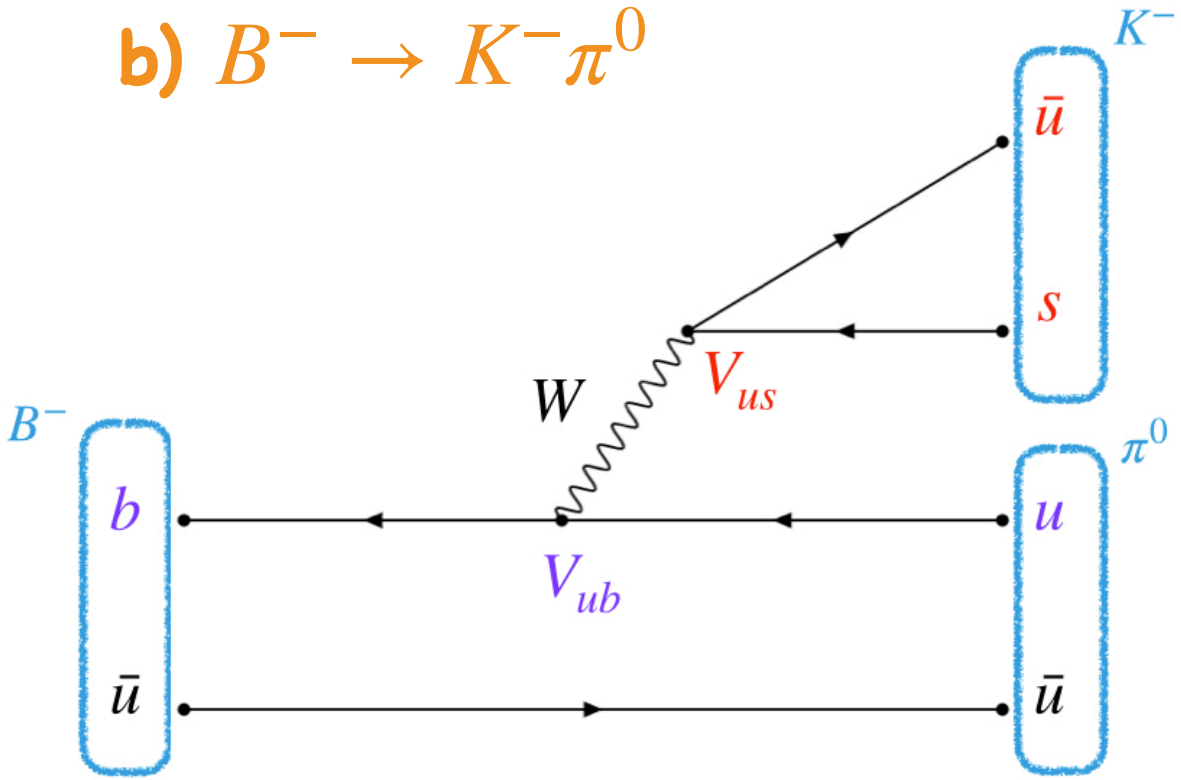
# Q2: Do you expect these decays to have the same rate?

a) $B^+ \to K^+\pi^0$




"Anti-Matter Version"

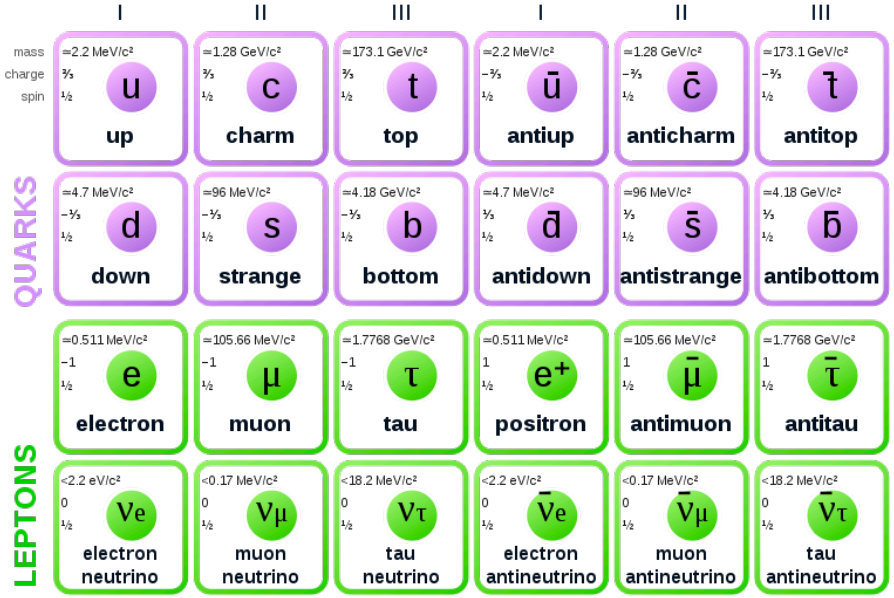
b) $B^- \to K^-\pi^0$

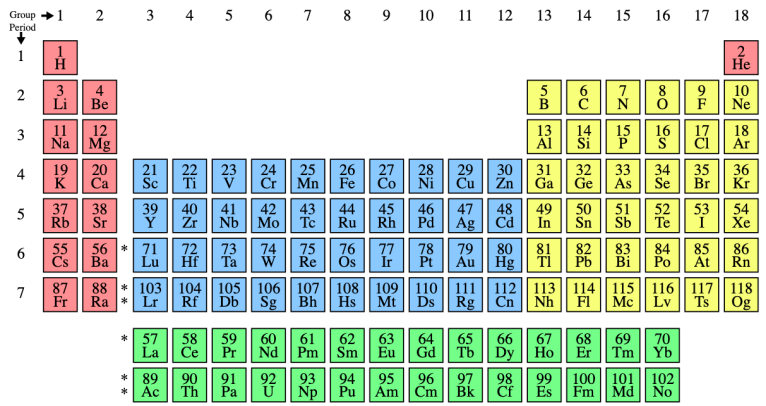



"Matter Version"

# Matter Anti-Matter Asymmetry Universe

- If the universe began with equal parts matter and anti-matter, why is the universe today matter dominated?

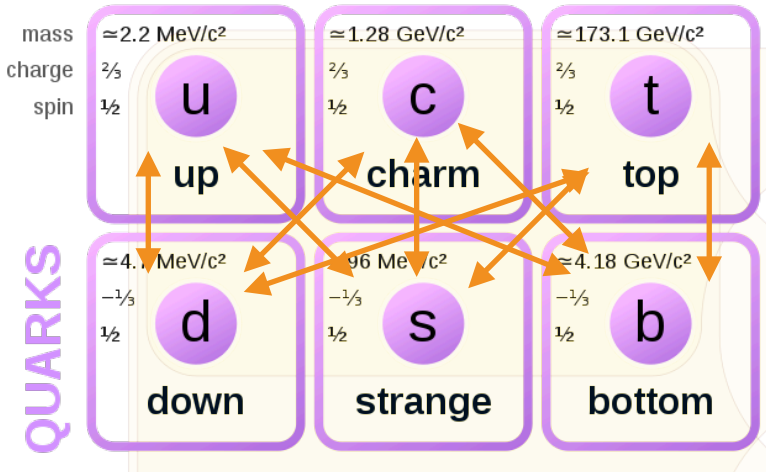



???

# Flavour Changing Currents

We discussed that **Weak charged currents** can change the quark flavour

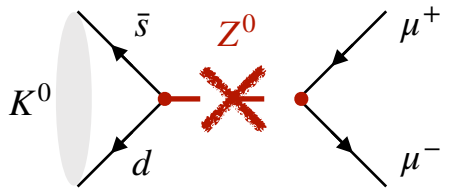



Transitions between

**1st row (charge 2/3) ↔ 2nd row (charge -1/3)**

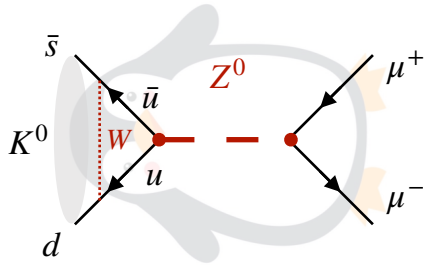
What about **weak neutral-current** transitions?

does not occur at tree-level in nature

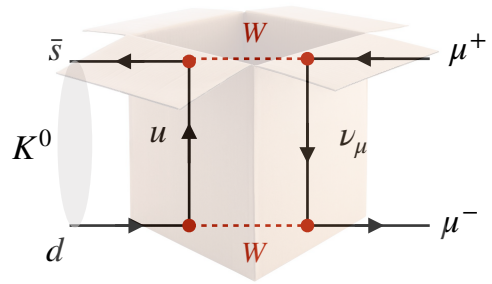



Only **higher-order diagrams** contribute

e.g. **Rare Decay**




or



# The Landscape of Flavour Physics

We denote by **"Flavour physics"** all the phenomena related to the interactions of differentiating the various fermion families.



Image: S. Cunliffe

# The Landscape of Flavour Physics

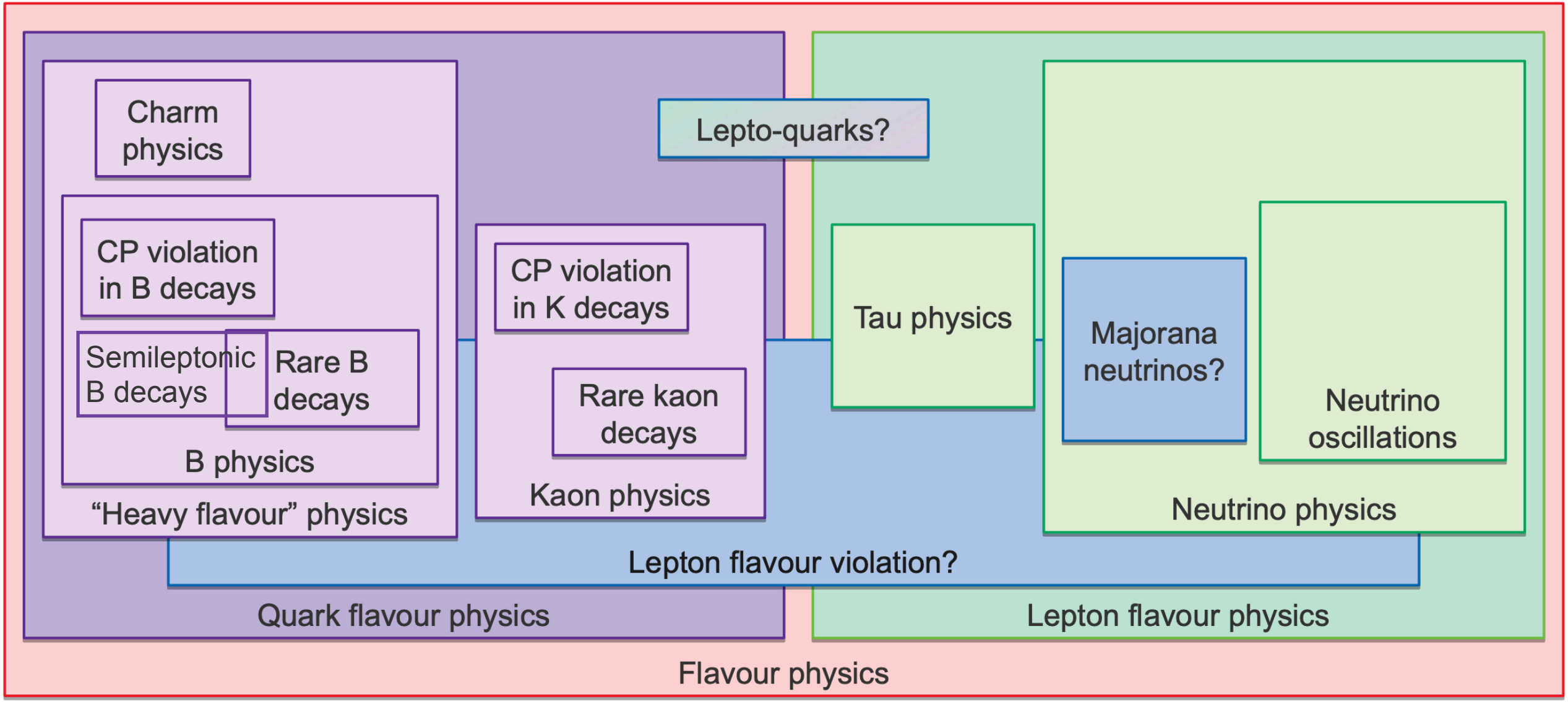
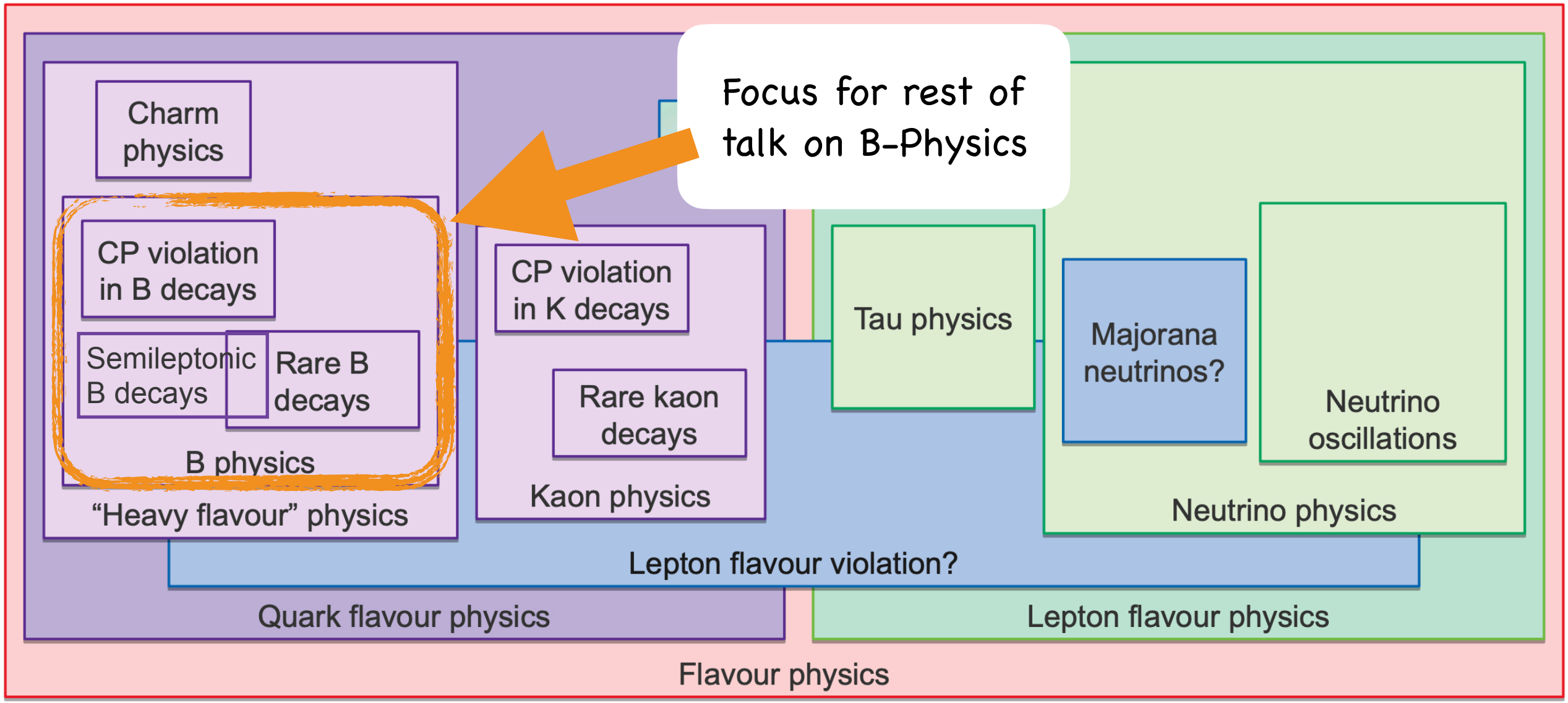



Image: S. Cunliffe

# The Landscape of Flavour Physics



# The Landscape of Flavour Physics

Outside of

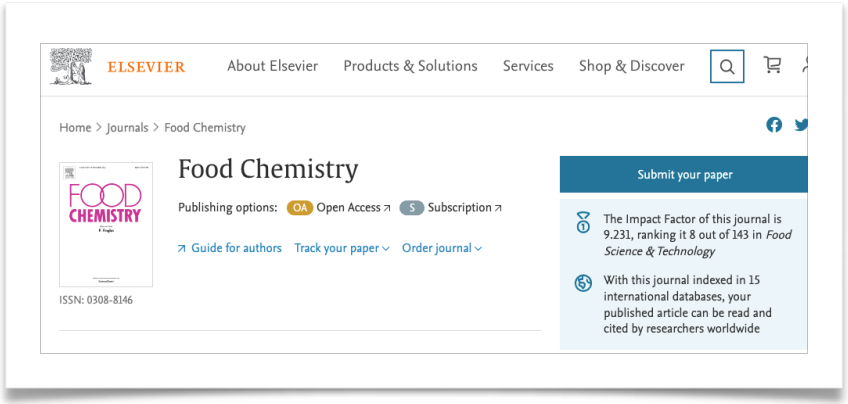
# The Landscape of Flavour Physics

Outside of

**Reviewer Invitation For FOOD CHEMISTRY**

**was received by a flavour-physics expert…**

Title: "Flavor formation and regulation of peas seed milk via enzyme activity inhibition and off-flavour compounds control release"



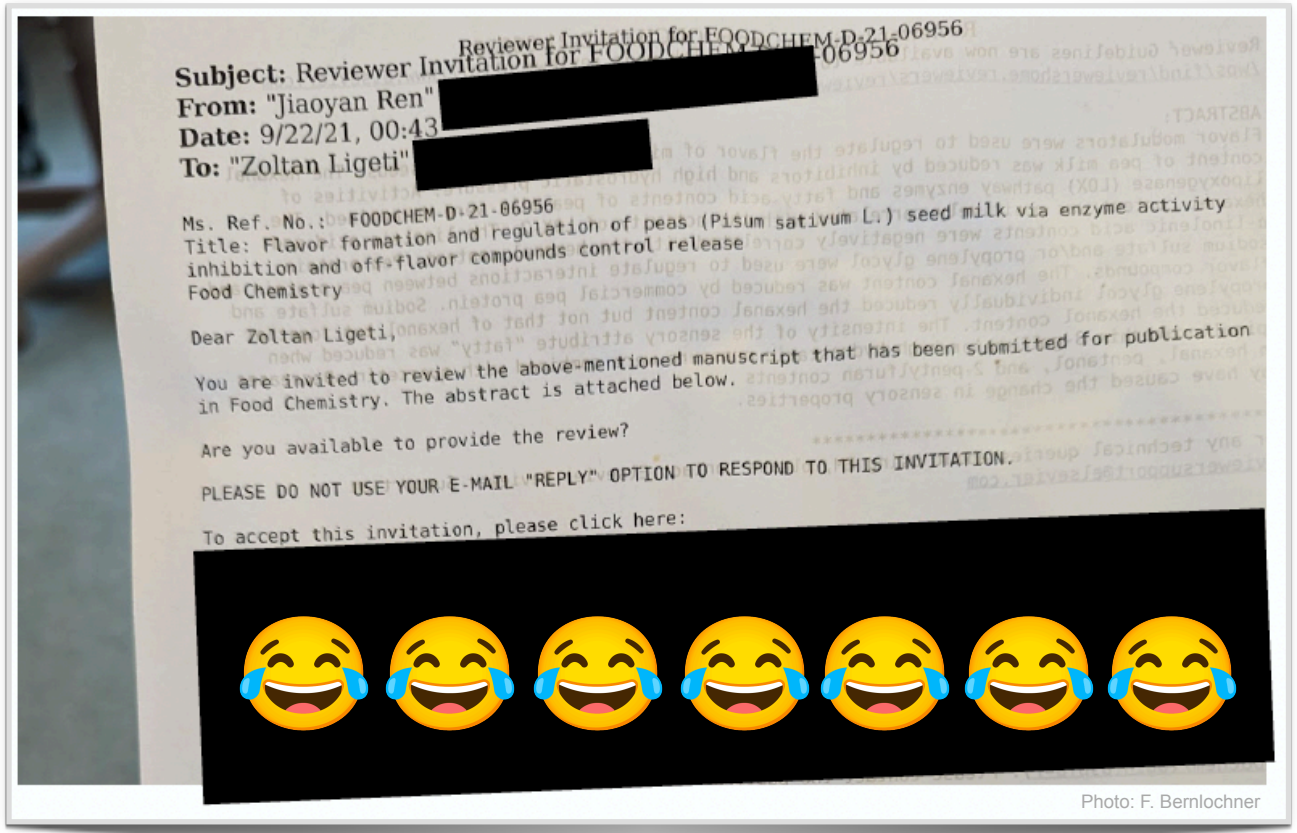




Photo: F. Bernlochner