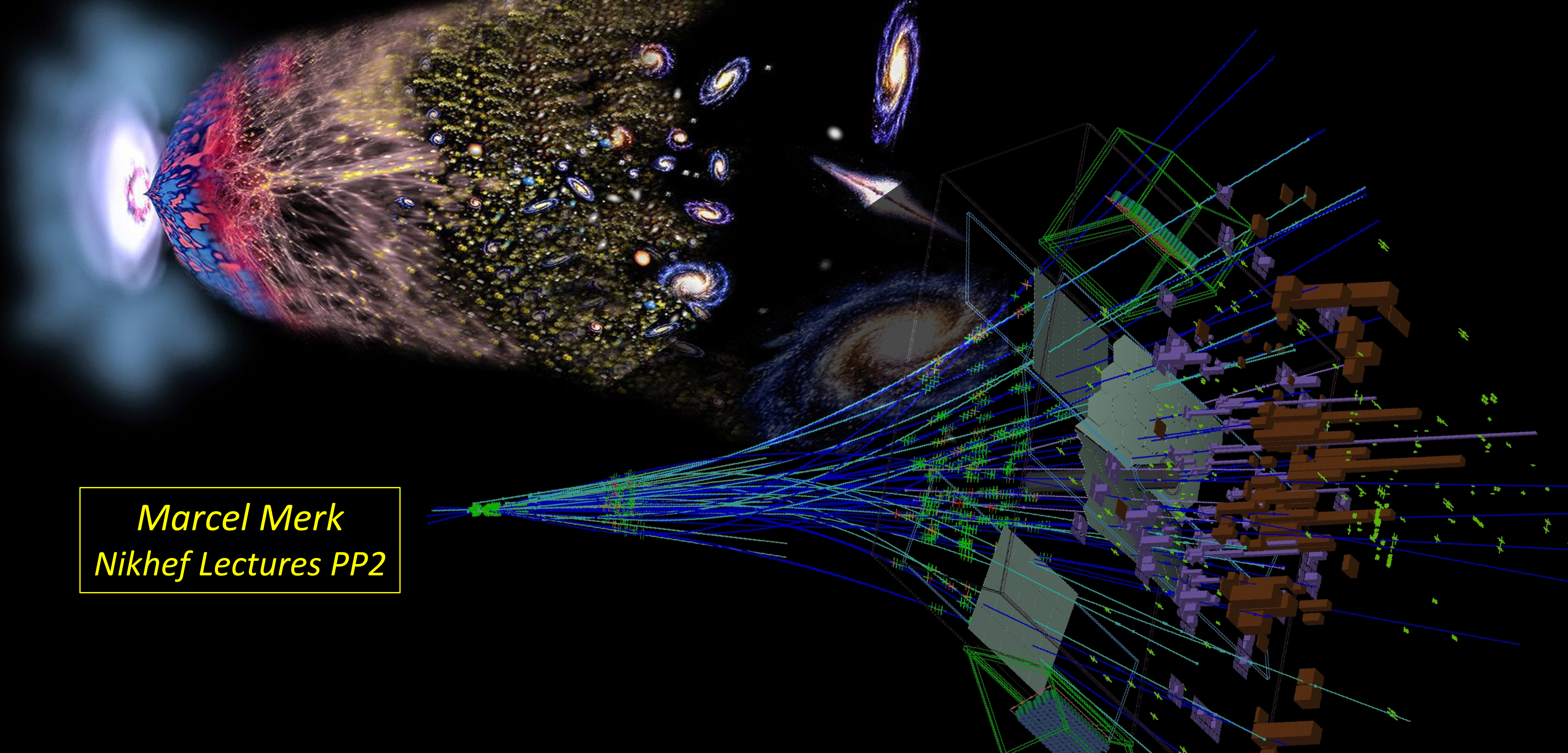
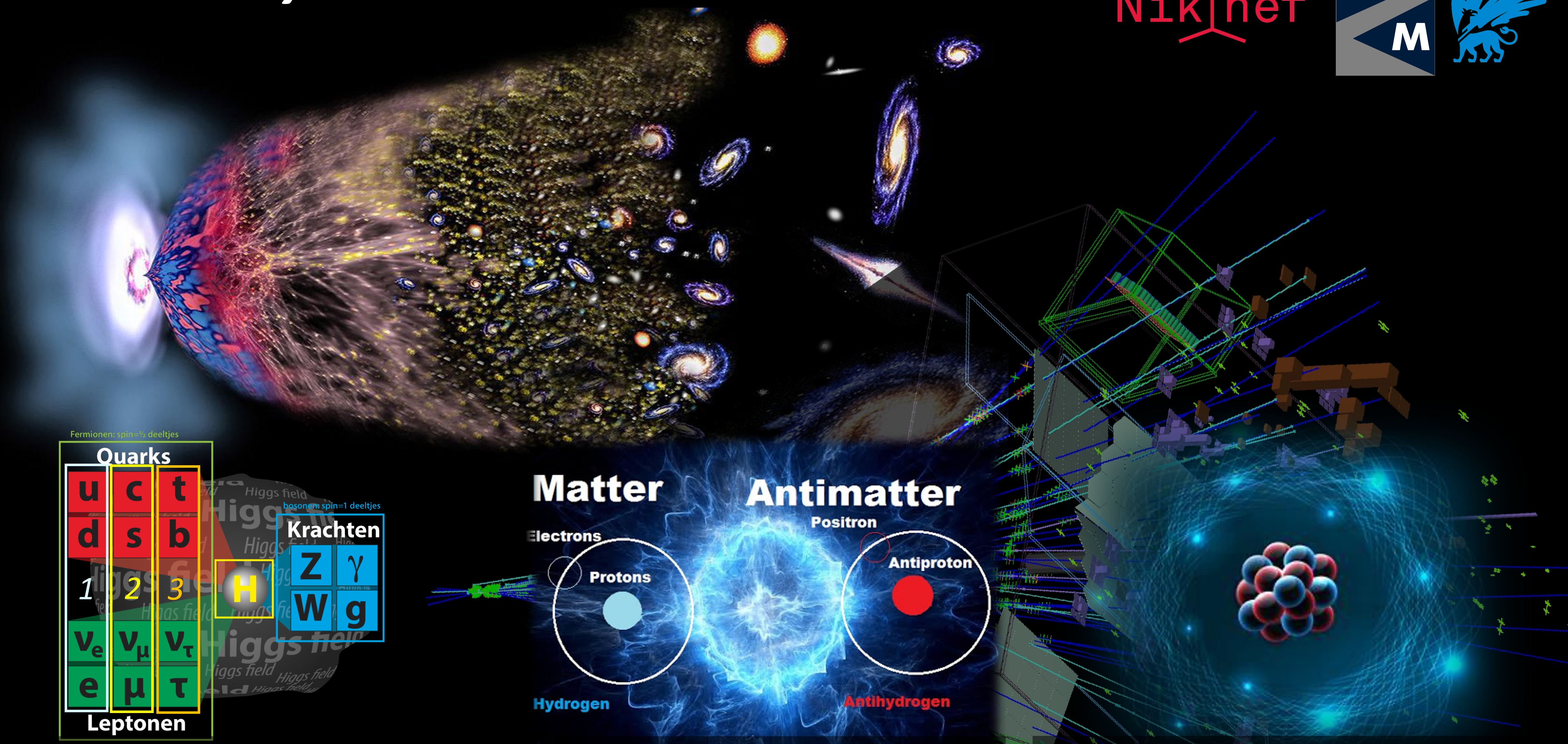
Flavour Physics and CP Violation



Marcel Merk

Nikhef Lectures PP2

Flavour Physics and CP Violation



Why three generations of particles? *Why is there no antimatter?* *Why is an atom electric neutral?*

Introducing the lecturers

Lecturer:

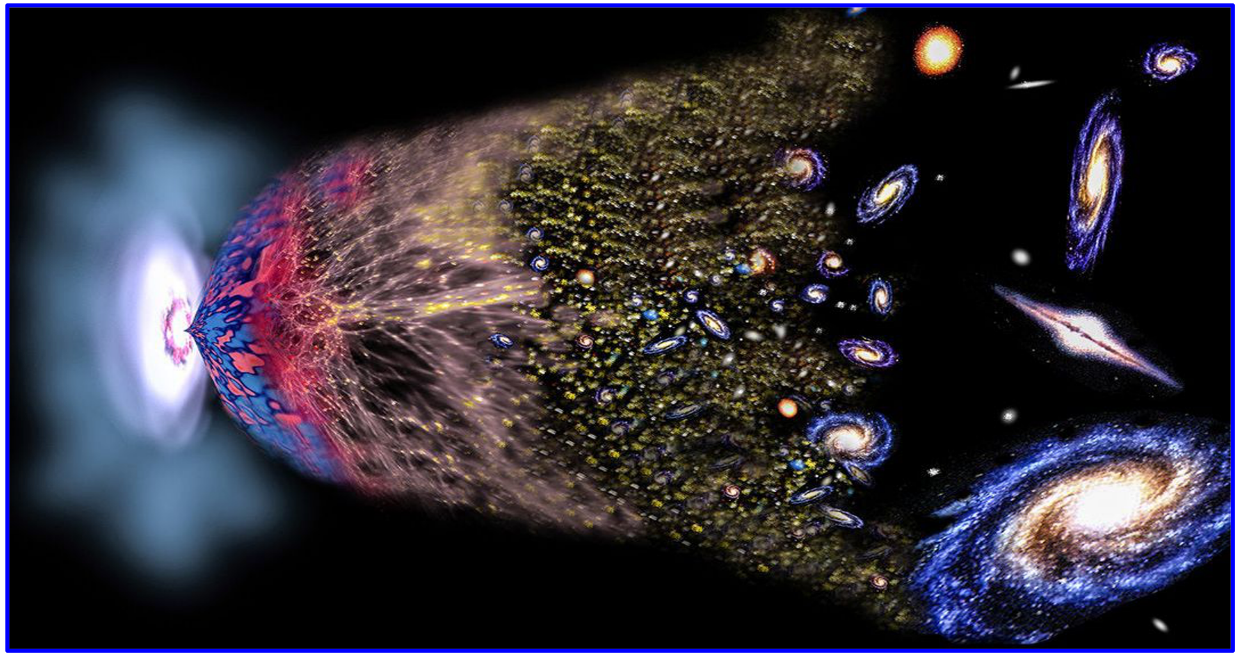
- Marcel Merk

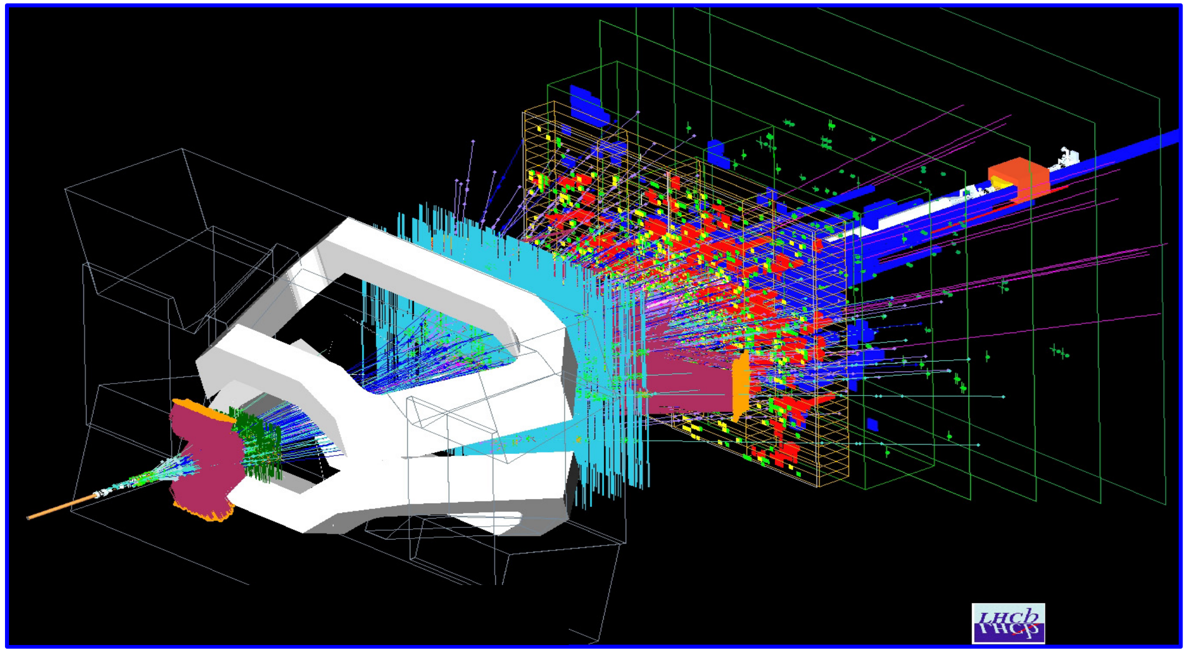
Tutors:

- Silvia Ferreres
- Miriam Lucio Martinez

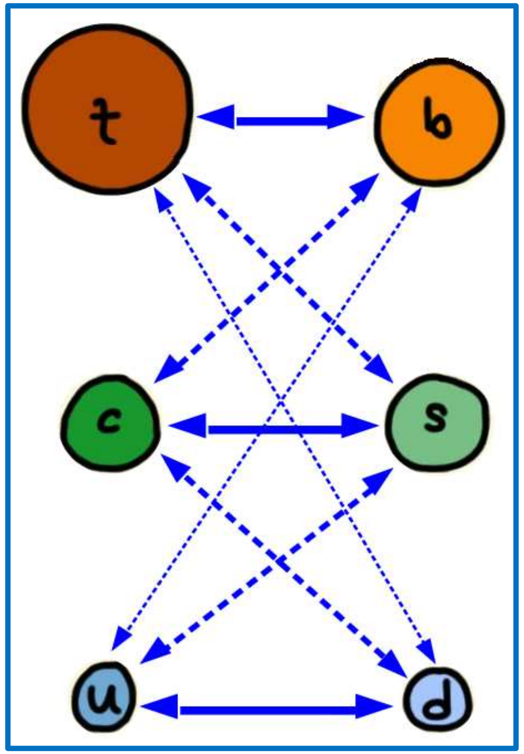
Research (theoretical):
- Why a *matter-vs-antimatter asymmetry* in nature?
- Why do we have *three generations* of particles?

Research (experimental):
- Detector technology at the *Large Hadron Collider.*
- *Measurements of CP violation rare decays*





The Antimatter Mystery


t
b
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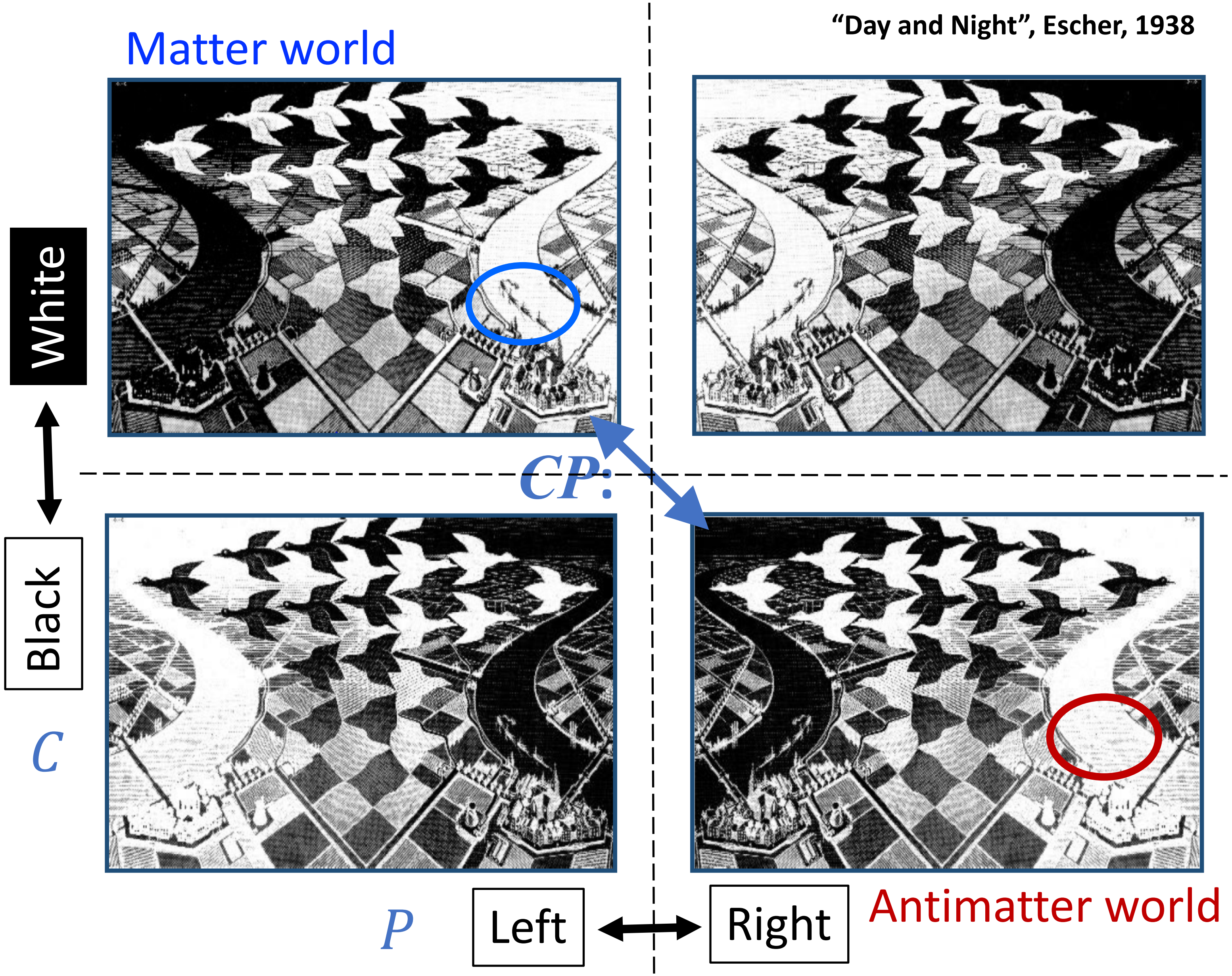
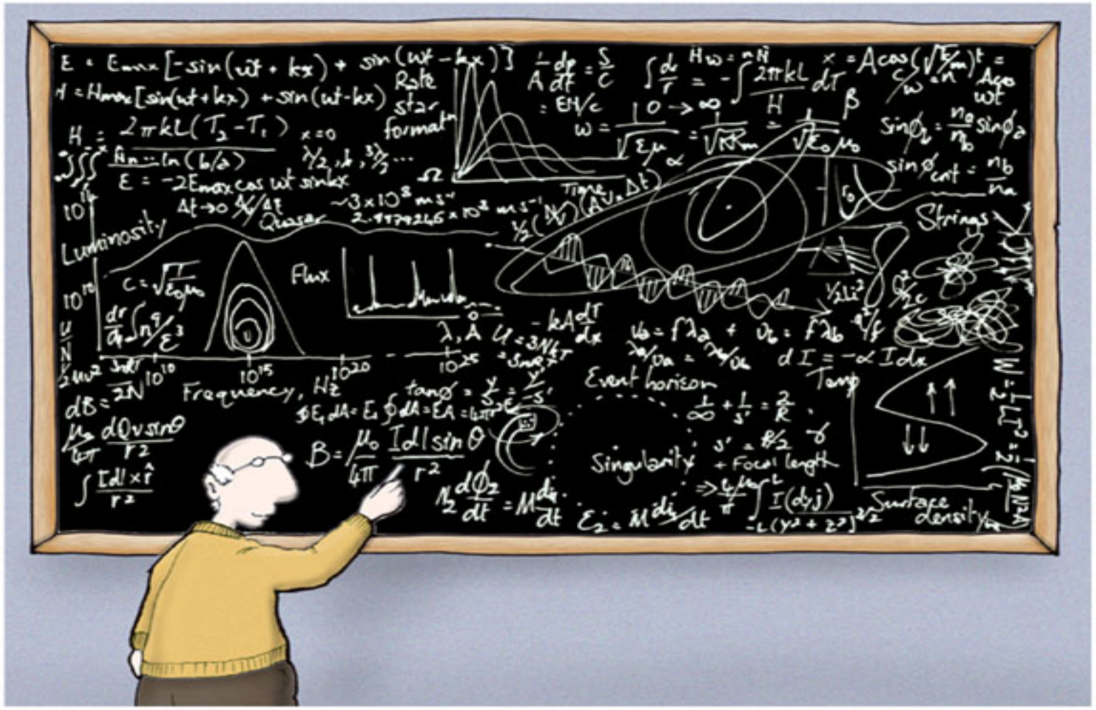

"Day and Night", Escher, 1938
Matter world
White
Black
C
CP:
P
Left
Right
Antimatter world

Contents per Week:

1. CP Violation
   a) Discrete Symmetries
   b) CP Violation in the Standard Model
   c) Jarlskog Invariant and Baryogenesis
2. B-Mixing
   a) CP violation and Interference
   b) B-mixing and time dependent CP violation
   c) Experimental Aspects: LHC vs B-factory
3. B-Decays
   a) Effective Hamiltonian
   b) Lepton Flavour Non-Universality



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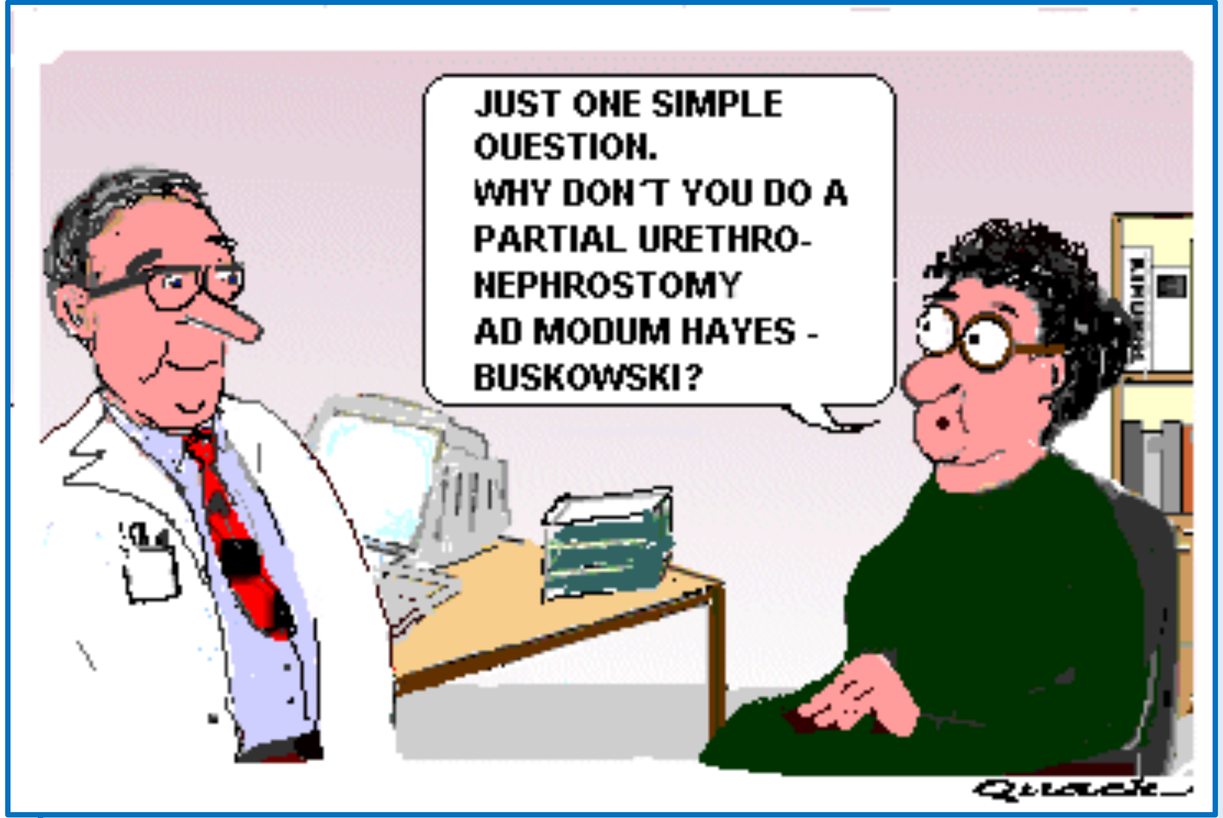
Don't be afraid to ask questions...



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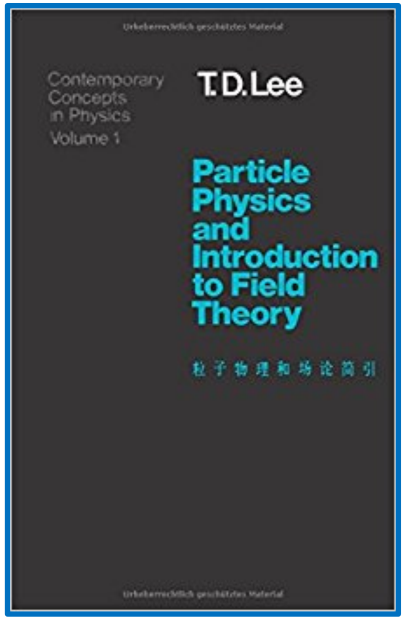
Symmetry and non-Observables

T.D.Lee: "The root to all *symmetry* principles lies in the assumption that it is impossible to observe certain basic quantities; the *non-observables*"

There are four main types of symmetry:

- Permutation symmetry:
  Bose-Einstein and Fermi-Dirac Statistics
- Continuous space-time symmetries:
  translation, rotation, velocity, acceleration,…
- Discrete symmetries:
  space inversion, time reversal, charge conjugation,…
- Unitary symmetries: gauge invariances:
  U_1(charge), SU_2(isospin), SU_3(color),…



$\Rightarrow$ If a quantity is fundamentally non-observable it is related to an *exact* symmetry

$\Rightarrow$ If it could in principle be observed by an improved measurement; the symmetry is said to be *broken*

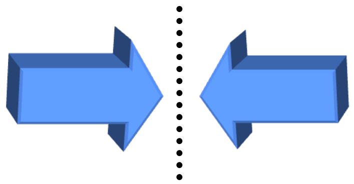
Noether Theorem: symmetry $\Longleftrightarrow$ conservation law

Symmetry and non-observables

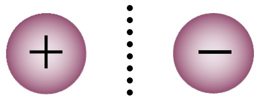
Non-observables	Symmetry Transformations	Conservation Laws or Selection Rule
Difference between identical particles	Permutation	B.-E. or F.-D. statistics
Absolute spatial position	Space translation: $\vec{r} \to \vec{r} + \vec{\Delta}$	momentum
Absolute time	Time translation: $t \to t + \tau$	energy
Absolute spatial direction	Rotation: $\vec{r} \to \vec{r}'$	angular momentum
Absolute velocity	Lorentz transformation	generators of the Lorentz group
Absolute right (or left)	$\vec{r} \to -\vec{r}$	parity
Absolute sign of electric charge	$e \to -e$	charge conjugation
Relative phase between states of different charge Q	$\psi \to e^{i\theta Q}\psi$	charge
Relative phase between states of different baryon number B	$\psi \to e^{i\theta N}\psi$	baryon number
Relative phase between states of different lepton number L	$\psi \to e^{i\theta L}\psi$	lepton number
Difference between different coherent mixture of p and n states	$\binom{p}{n} \to U\binom{p}{n}$	isospin

C, P, T Symmetries

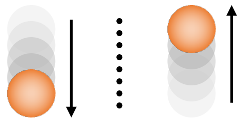
- Parity, P: *unobservable: (absolute handedness)*
  - Reflects a system through the origin. Converts right-handed to left-handed.
    - $\vec{x} \to -\vec{x}$, $\vec{p} \to -\vec{p}$ (vectors) but $\vec{L} = \vec{x} \times \vec{p}$ (axial vectors)



- Charge Conjugation, C: *unobservable: (absolute charge)*
  - Turns internal charges to opposite sign.
    - $e^+ \to e^-$, $K^- \to K^+$



- Time Reversal, T: *unobservable: (direction of time)*
  - Changes direction of motion of particles
    - $t \to -t$



- CPT Theorem:
  - All interactions are invariant under combined C, P and T operation
  - A particle ***is*** an antiparticle travelling backward in time
  - Implies e.g. particle and anti-particle have equal masses and lifetimes

Classical Mirror Worlds → Invariant!

- Parity: $\vec{x} \to -\vec{x}$
  - Mass m — $P\,m = m$: scalar
  - Force $\vec{F}$ $(\vec{F} = d\vec{p}/dt)$ — $P\,\vec{F} = P\,d\vec{p}/dt = -\,d\vec{p}/dt = -\vec{F}$: vector
  - Acceleration $\vec{a}$ $(\vec{a} = d^2\vec{x}/dt^2)$ — $P\,\vec{a} = -\,d^2x/dt^2 = -\vec{a}$: vector
  - Angular momentum $\vec{L}, \vec{S}, \vec{J}$ $(\vec{L} = \vec{x} \times \vec{p})$ — $P\;\vec{L} = -\vec{x} \times -\vec{p} = \vec{L}$: axial vector

- Parity: Newton's law is *invariant* under P-operation (i.e. the same in the mirror world):

$$\vec{F} = m\,\vec{a} \xrightarrow{P} -\vec{F} = -m\vec{a} \;\Leftrightarrow\; \vec{F} = m\vec{a}$$

- Charge: Lorentz Force in the C-mirror world is *invariant*:

$$\vec{F} = q\,[\vec{E} + \vec{v}\times\vec{B}] \xrightarrow{C} \vec{F} = -q[-\vec{E} + \vec{v}\times-\vec{B}]$$

- Time: laws of physics are also *invariant* unchanged under T-reversal, since:

$$\vec{F} = m\,\vec{a} = m\,\frac{d^2\vec{x}}{dt^2} \xrightarrow{T} \vec{F} = m\frac{d^2\vec{x}}{d(-t)^2} \;\Leftrightarrow\; \vec{F} = m\vec{a}$$

  - QM: Consider Schrodinger's equation $(t \to -t)$: $i h\dfrac{\partial\psi}{\partial t} = -\dfrac{\vec{\nabla}^2\psi}{2m}$

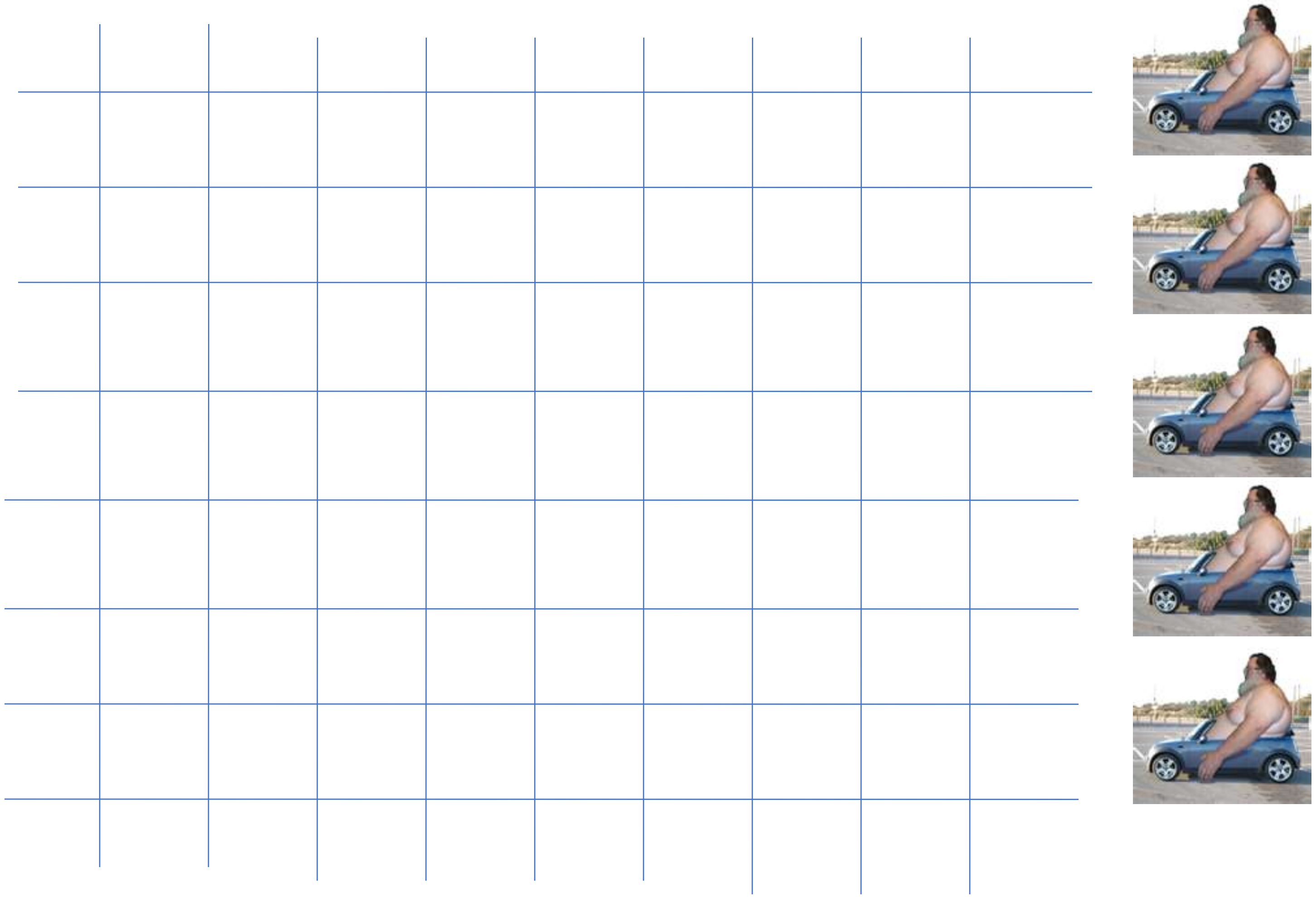
  Complex conjugation is required to stay invariant: $\psi \xrightarrow{T} \psi^*$

C-, P-, T- Symmetry

- Classical Theory is invariant under C, P, T operations; i.e. they conserve C, P, T symmetry
  - Newton mechanics, Maxwell electrodynamics.

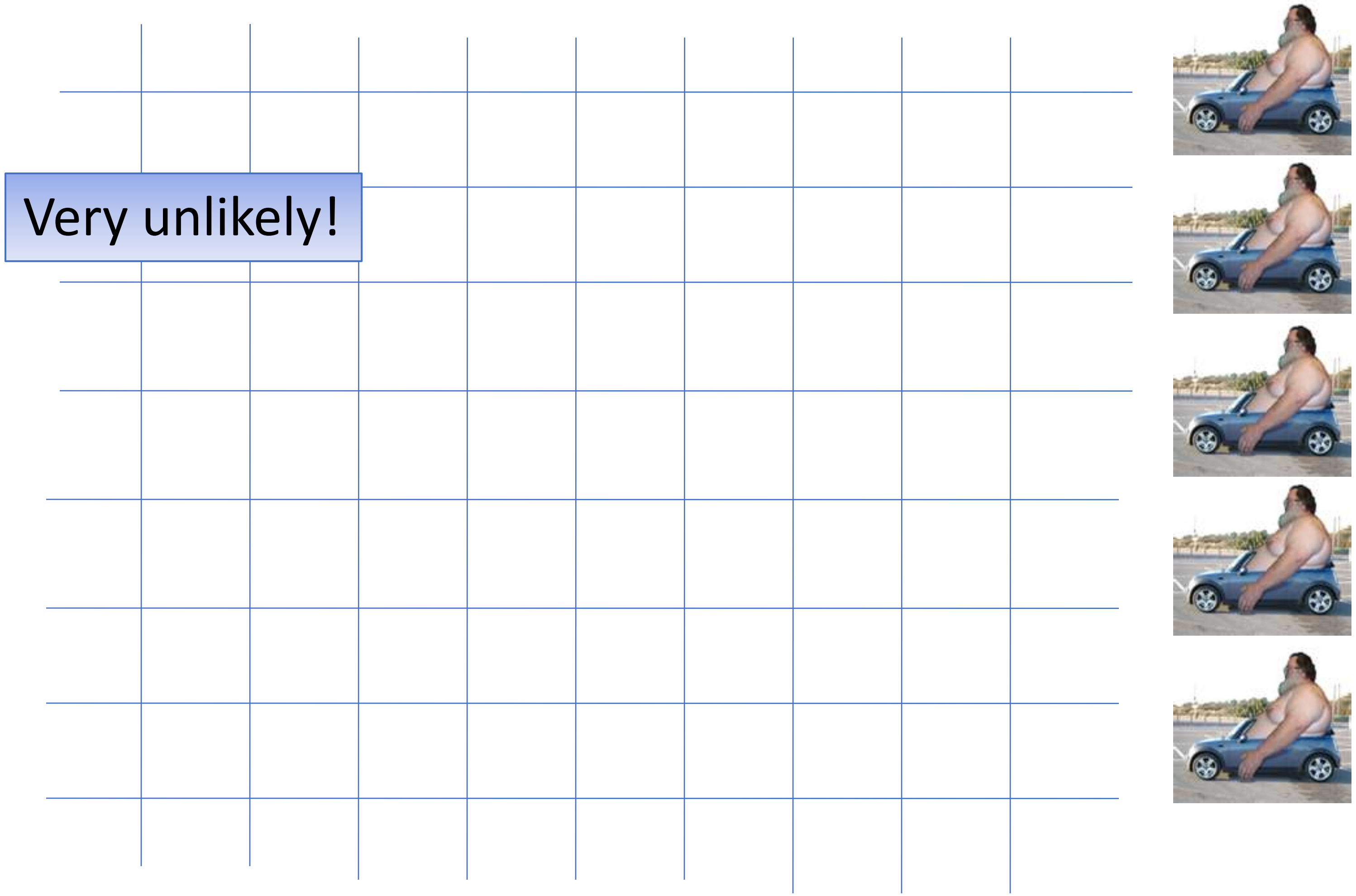
- Suppose we watch some physical event. Can we determine unambiguously whether:
  - We are watching the event where all ***charges are reversed*** or not?
  - We are watching the event ***in a mirror*** or not?
    - Macroscopic biological asymmetries are considered *accidents of evolution* rather than fundamental asymmetry in the laws of physics.
  - We are watching the event in a ***film running backwards*** or not?
    - The arrow of time is due to thermodynamics: i.e. the realization of a macroscopic final state is *statistically more probable* than the initial state

Macroscopic time reversal (T.D. Lee)



- At each crossing: 50% - 50% choice to go left or right
- After many decisions: reverse the velocity of the final state and return
- Do we end up with the initial state?

Macroscopic time reversal (T.D. Lee)



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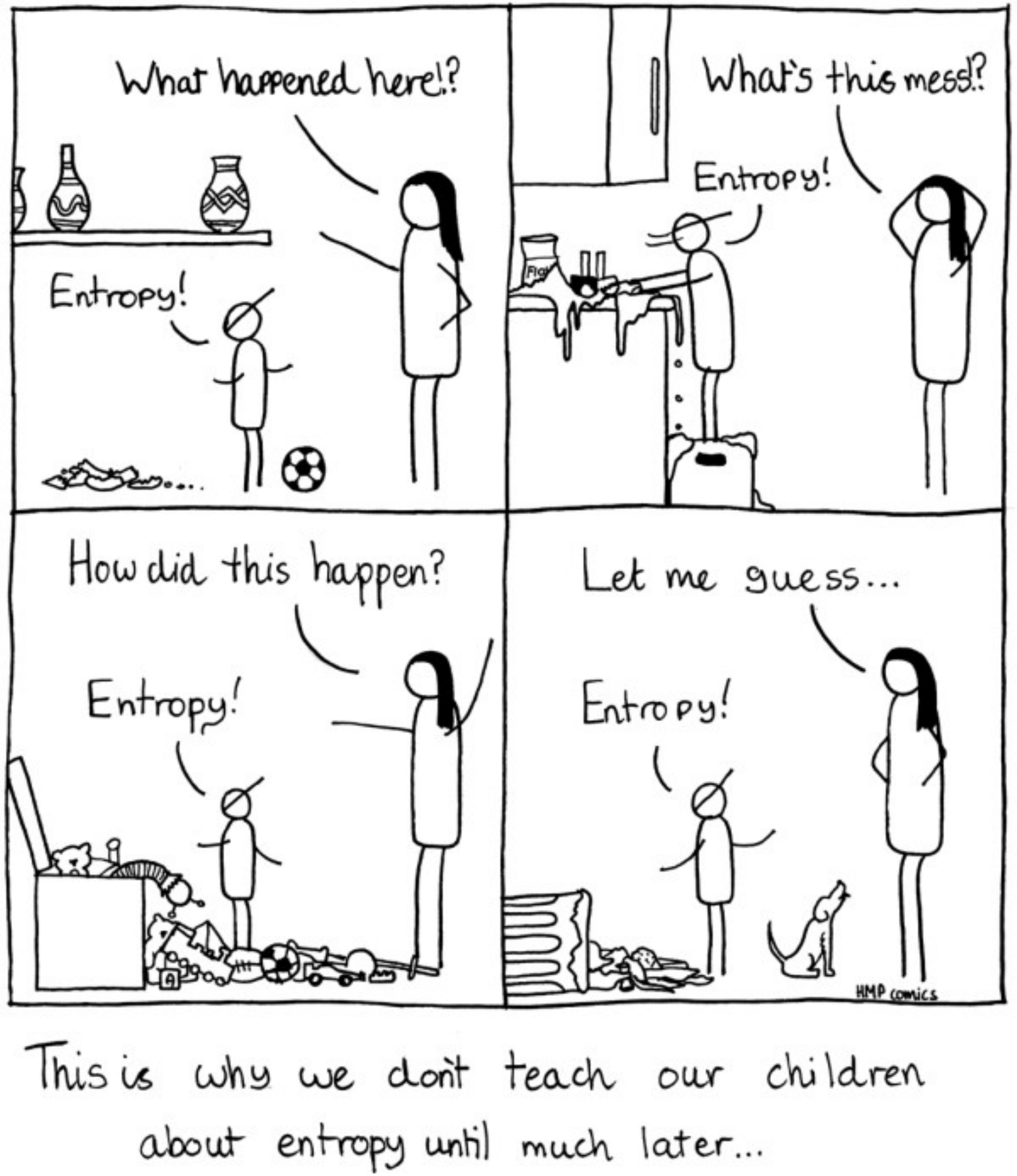
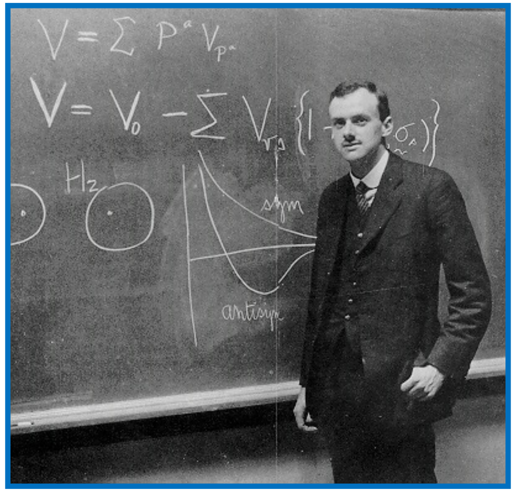
Macroscopic time reversal



C, P operations and Dirac theory (QED)



- In Dirac theory particles are represented as spinors

$$\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix}$$

ψ_1, ψ_2 → +1/2, -1/2 helicity solutions for the particle

ψ_3, ψ_4 → +1/2, -1/2 helicity solutions for the antiparticle

Antimatter!

- Implementation of P and C operators in Dirac theory:

$$P: \quad \psi \to \psi' = \gamma^0 \psi(-\vec{x}, t)$$

$$\begin{pmatrix} \left[\left(i\gamma^0\partial_0 - i\gamma^i\partial_{x_i}\right) - m\right]\psi(\vec{x}, t) = 0 \\ \gamma^0\left[\left(i\gamma^0\partial_0 + i\gamma^i\partial_{x_i}\right) - m\right]\psi'(-\vec{x}, t) = 0 \end{pmatrix}$$

$$C: \quad \psi \to \psi' = i\gamma^2\psi^*(\vec{x}, t)$$

$$\begin{pmatrix} \text{Elect. } \psi: & \left[\gamma^\mu\left(i\partial_\mu + eA_\mu\right) - m\right]\psi = 0 \\ \text{Posit. } \psi': & \left[\gamma^\mu\left(i\partial_\mu - eA_\mu\right) - m\right]\psi' = 0 \end{pmatrix}$$

- QED (Dirac theory) is symmetric under C, P conjugation. Reversing electric charges keeps electrodynamics invariant. See lecture notes for more details.

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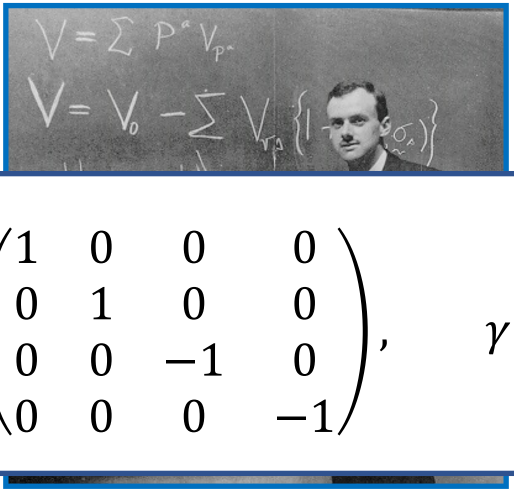

- In Dirac theory particles are represented as spinors

$$\gamma^0 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}, \quad \gamma^1 = \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{pmatrix}, \quad \gamma^2 = \begin{pmatrix} 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \\ 0 & i & 0 & 0 \\ -i & 0 & 0 & 0 \end{pmatrix}, \quad \gamma^3 = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$$

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C, P operations and Dirac theory (QED)

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- In Dirac equation: $\left[\left(i\gamma^0\partial_0 - i\gamma^i\partial_{x_i}\right) - m\right]\psi(\vec{x},t) = 0$
- Implementation of P operator in Dirac: $\vec{x} \to -\vec{x}$; $\partial x_i \to -\partial x_i$

$P \; : \; \psi \to \psi' = \psi(-\vec{x},t)$ $\quad \left[\left(i\gamma^0\partial_0 + i\gamma^i\partial_{x_i}\right) - m\right]\psi(-\vec{x},t) = 0$ Does not work!

Instead: $\psi \to \psi' = \gamma^0\psi(-\vec{x},t)$ $\quad \left[\left(i\gamma^0\partial_0 + i\gamma^i\partial_{x_i}\right) - m\right]\gamma^0\psi(-\vec{x},t) = 0$

$$\gamma^0\left[\left(i\gamma^0\partial_0 - i\gamma^i\partial_{x_i}\right) - m\right]\psi'(-\vec{x},t) = 0$$ OK

- Implementation of C operator in Dirac: $C \; : q \to -q$; $\psi \to \psi' = i\gamma^2\psi^*(\vec{x},t)$

$\psi \; : \quad \left[\gamma^\mu\left(i\partial_\mu - qA_\mu\right) - m\right]\psi = 0$

$\psi' \; : \quad \left[\gamma^\mu\left(i\partial_\mu + qA_\mu\right) - m\right]^*\psi' = 0$

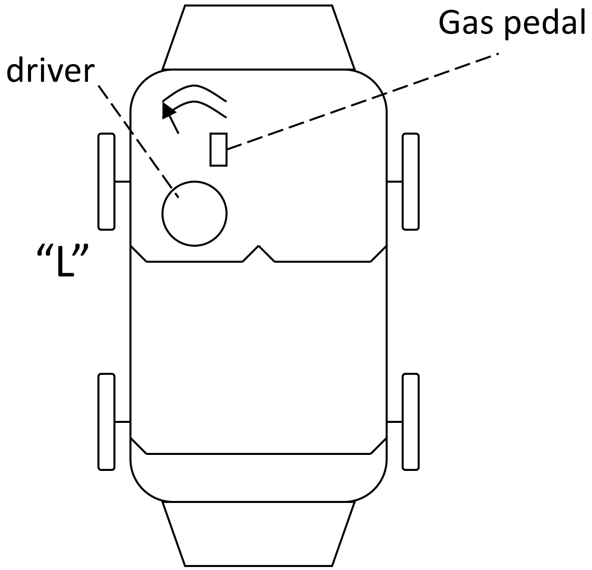
$\psi' \; : \quad \left[\gamma^{\mu *}\left(-i\partial_\mu + qA_\mu\right) - m\right]i\gamma^2\psi^* = 0$

$\psi' \; : \quad i\gamma^2\left[\gamma^\mu\left(i\partial_\mu + qA_\mu\right) - m\right]\psi^* = 0$ OK

Parity Violation

Before 1956 physicists were **convinced** that the laws of nature were left-right symmetric. Strange?

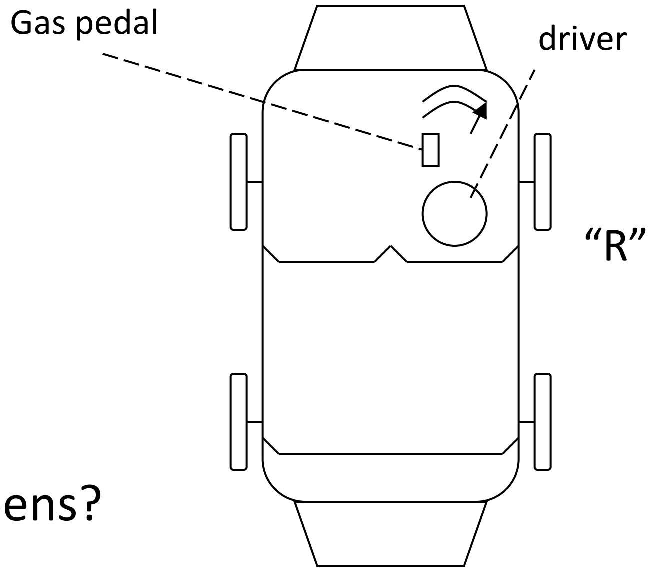
A “gedanken” experiment: consider two perfectly mirror symmetric cars:



“L” and “R” are fully symmetric,
Each nut, bolt, molecule etc.
However the engine is a black box

Person “L” gets in, starts, ….. 60 km/h

Person “R” gets in, starts, ….. What happens?



What happens in case the ignition mechanism uses, say, Co^{60} β decay?

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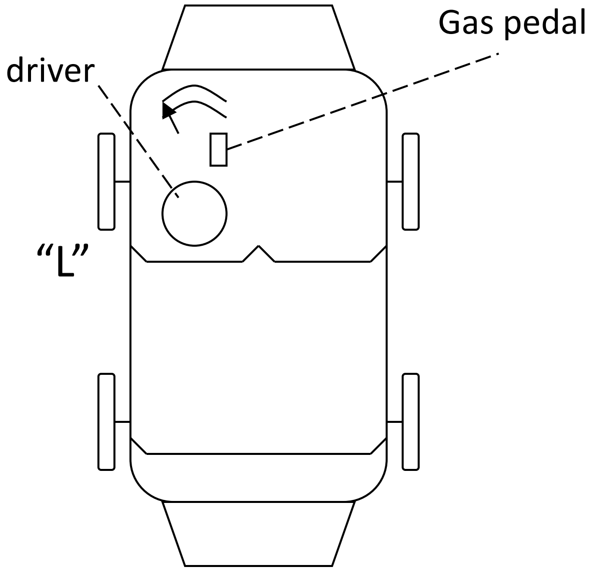
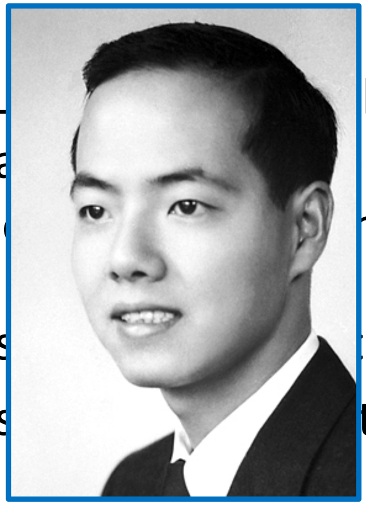


T.D. Lee

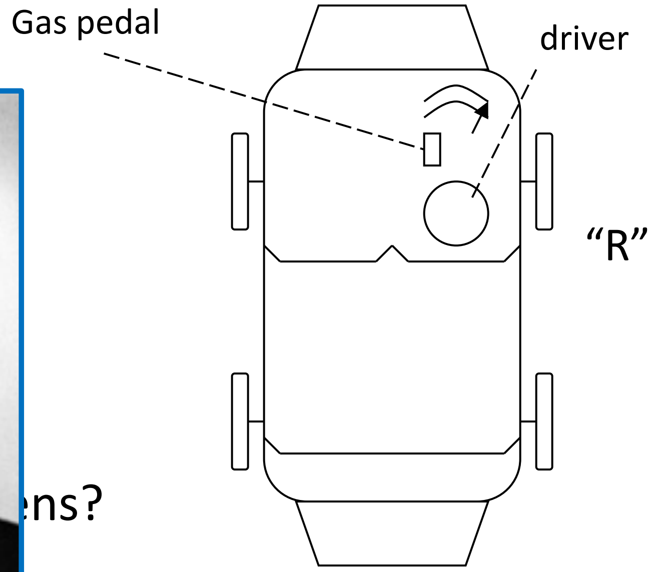


C.N. Yang

“L ... ly sy
Ea ... lecul
H ... he is

Pers ... arts,

Pers ... tarts ... ns?



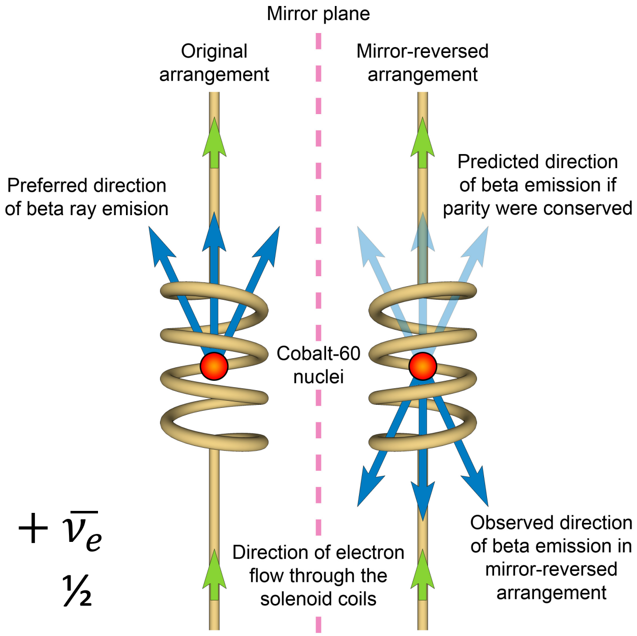
What happens in case the ignition mechanism uses, say, Co^{60} β decay?

Discovery of Parity Violation

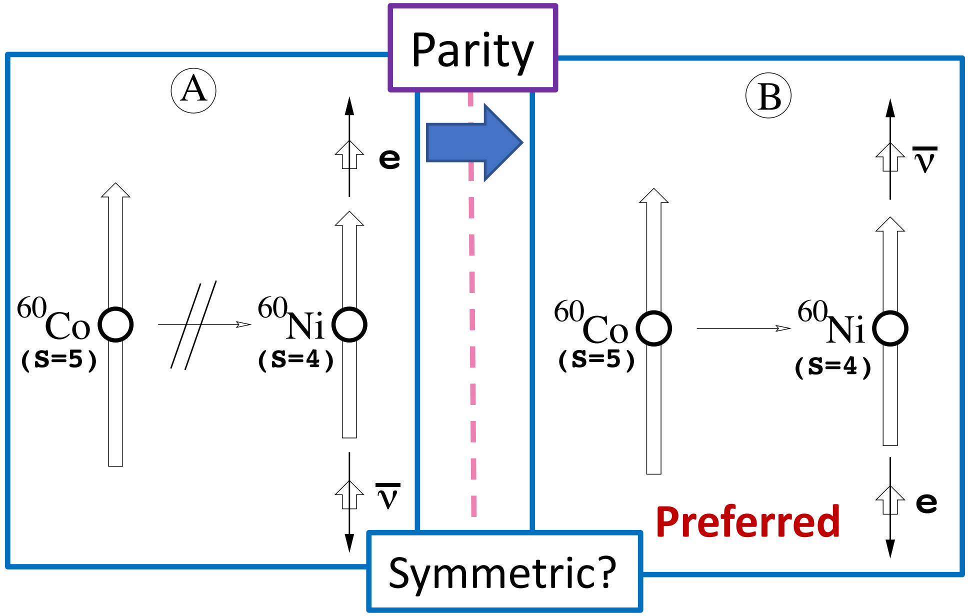
Spin is pseudoscalar, P: $\vec{S} \rightarrow \vec{S}$

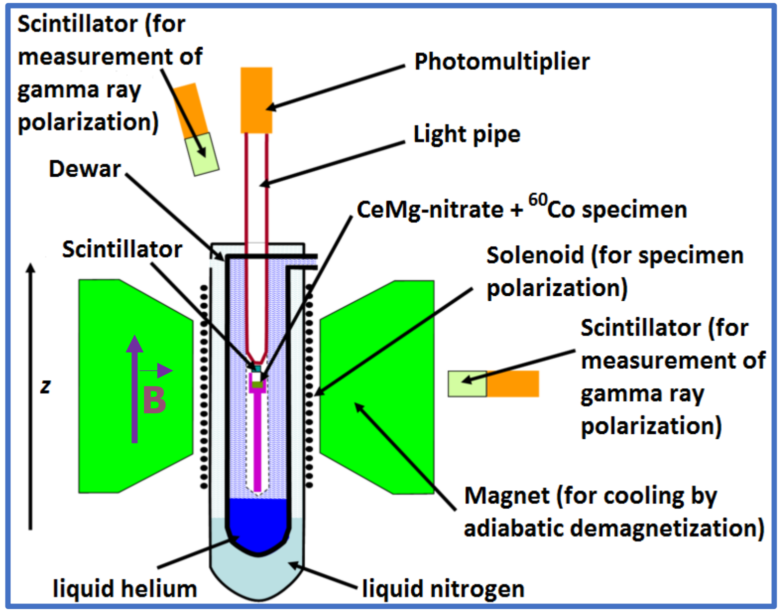
$^{60}_{27}Co \rightarrow {}^{60}_{28}Ni + e^- + \bar{\nu}_e$

S: 5 4 ½ ½



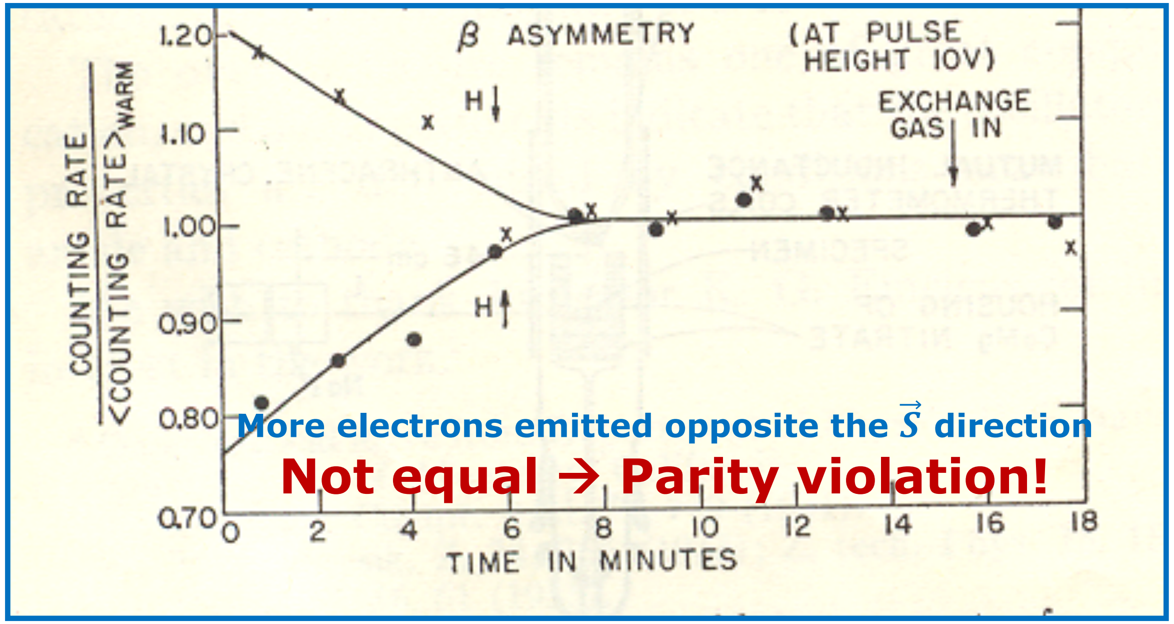
B-field





Is physics is parity invariant?

Only if electron decay rate is symmetric wrt spin direction!

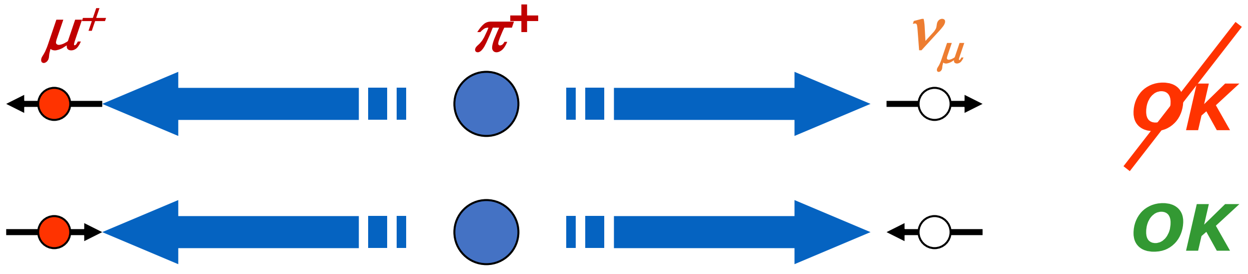


More electrons emitted opposite the $\vec{S}$ direction

Not equal → Parity violation!

So P is violated, what's next?

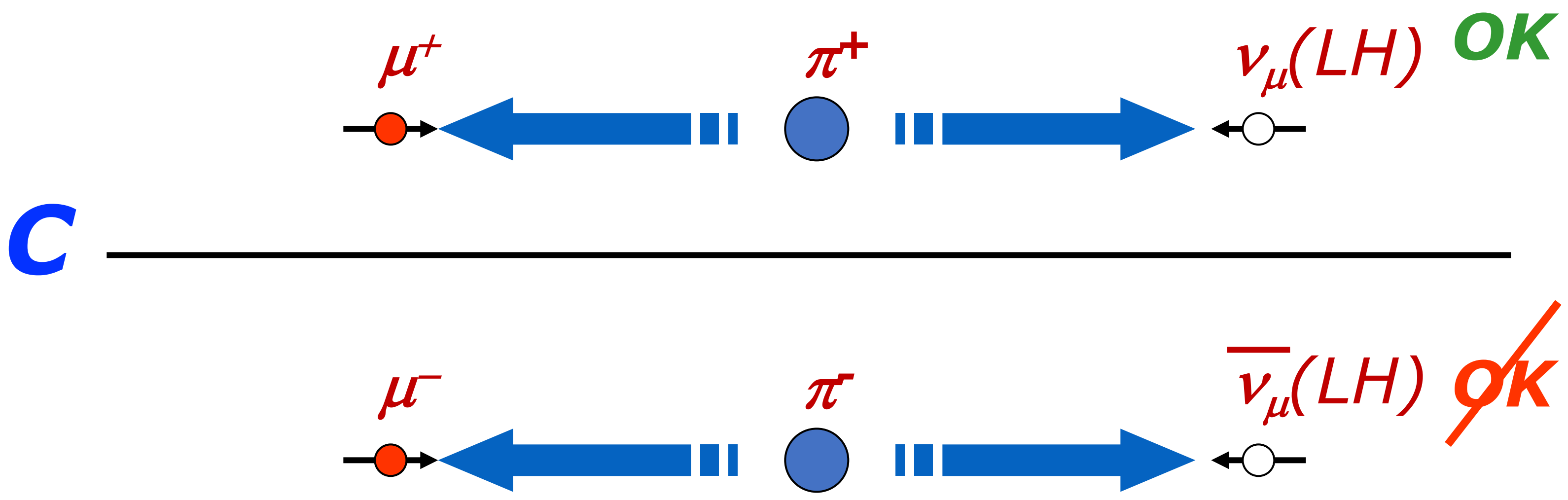
- Wu's experiment was shortly followed by another clever experiment by L. Lederman: Look at decay $\pi^+ \rightarrow \mu^+ \nu_\mu$
  - Pion has spin 0, μ, ν_μ both have spin ½
    → spin of decay products must be oppositely aligned
    → Helicity of muon is same as that of neutrino.



- Ledermans result: All neutrinos are left-handed and all anti-neutrinos are right-handed

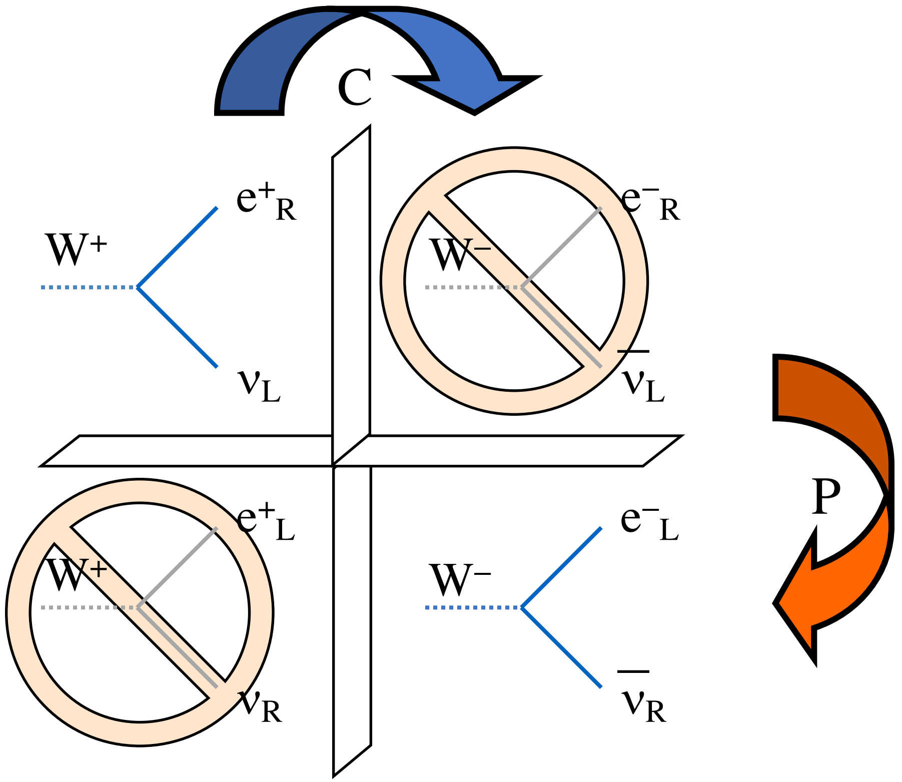
Charge conjugation symmetry?

- Introducing C-symmetry
  - The C(harge) conjugation is the operation which exchanges **particles and anti-particles** (not just electric charge)
  - It is a discrete symmetry, just like P, i.e. $C^2 = 1$



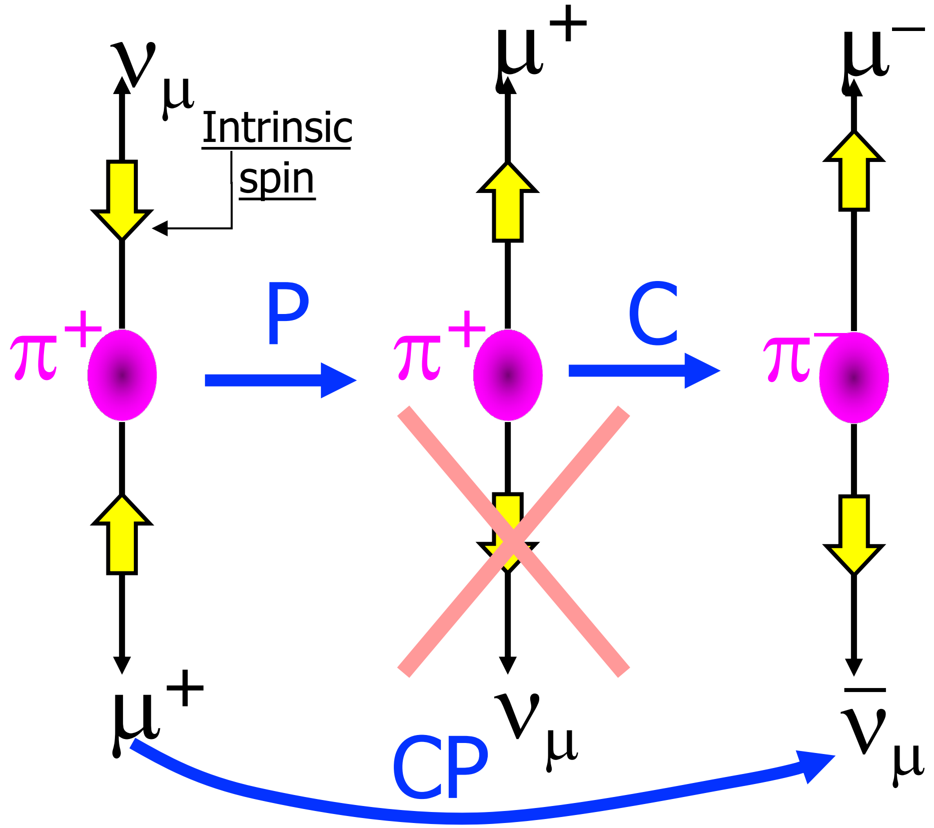
- C symmetry is broken by the weak interaction
  - Just like P

Weak Force breaks C and P, is CP really OK?



- Weak interaction breaks ***C*** and ***P*** symmetry maximally!
  - Nature is left-handed for matter and right-handed for antimatter.
- Despite *maximal* violation of ***C*** and ***P***, combined ***CP*** seems *conserved.*
- Is combined ***CP*** really exactly conserved?

The Weak force and CP violation

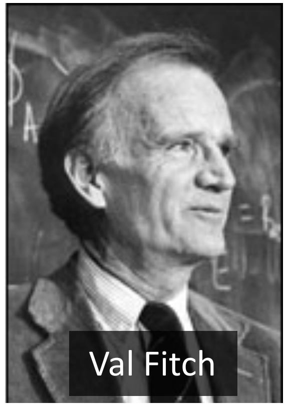


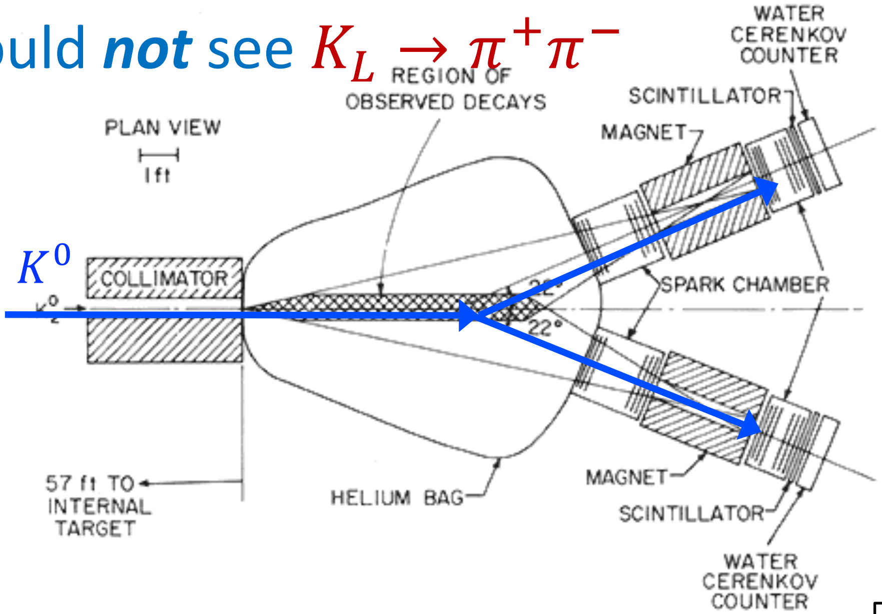
- Combined $C + P \equiv CP$ symmetry?
  - CP symmetry is parity conjugation: $(x, y, z \rightarrow -x, -y, -z)$ followed by charge conjugation: $(\psi \rightarrow \overline{\psi})$
- CP symmetry *appears* to be preserved in the weak interaction
- But in 1964, Christenson, Cronin, Fitch and Turlay observed CP *violation* in decays of neutral kaons…

Discovery of CP-Violation with K^0 decays

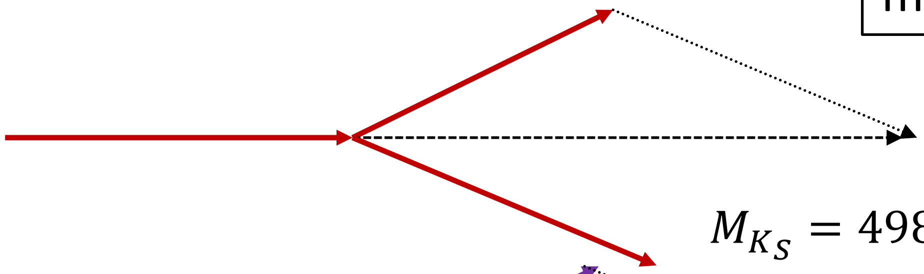
- Create a pure K_L beam ("wait" for K_S to decay)
- If CP is conserved, should ***not*** see $K_L \to \pi^+\pi^-$

K_S: Short-lived is CP even:
$K_1^0 \to \pi^+\pi^-$ (fast)
K_L: Long-lived is CP odd:
$K_2^0 \to \pi^+\pi^-\pi^0$ (slow)





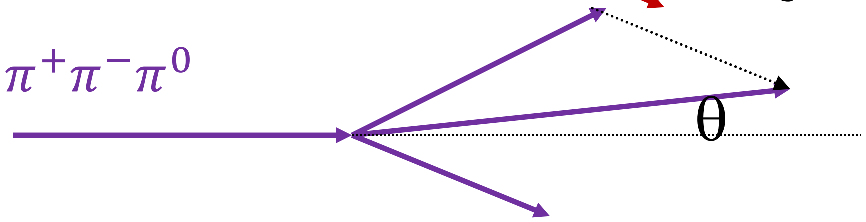
Signal: $K_L \to \pi^+\pi^-$

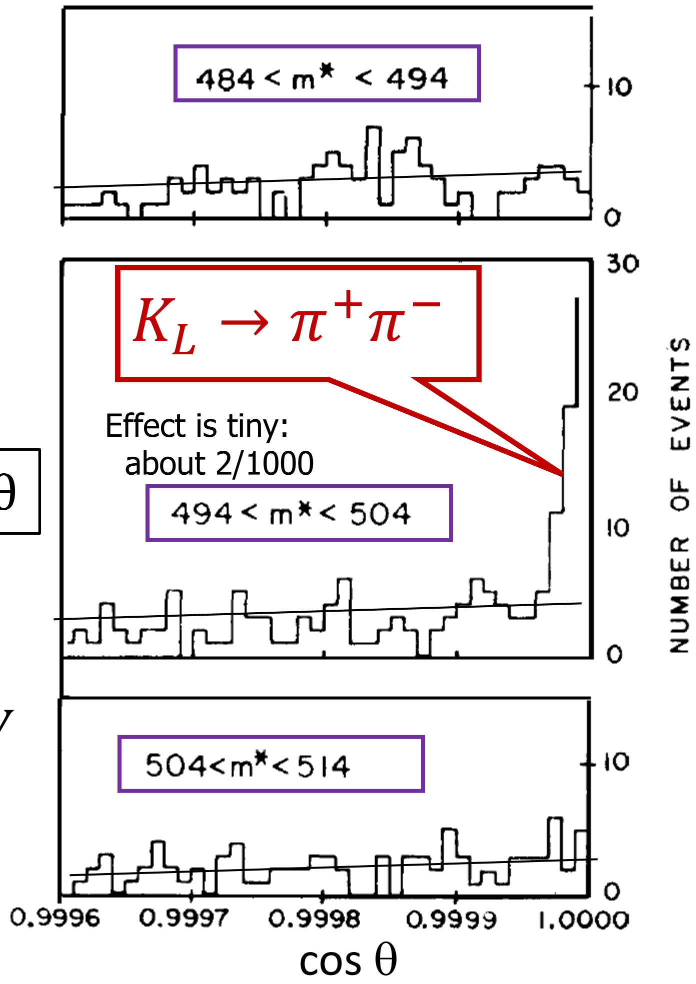


mass, θ

$M_{K_S} = 498\ MeV$

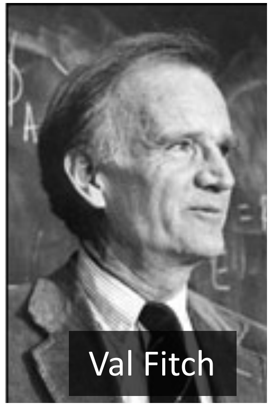
Background: $K_L \to \pi^+\pi^-\pi^0$





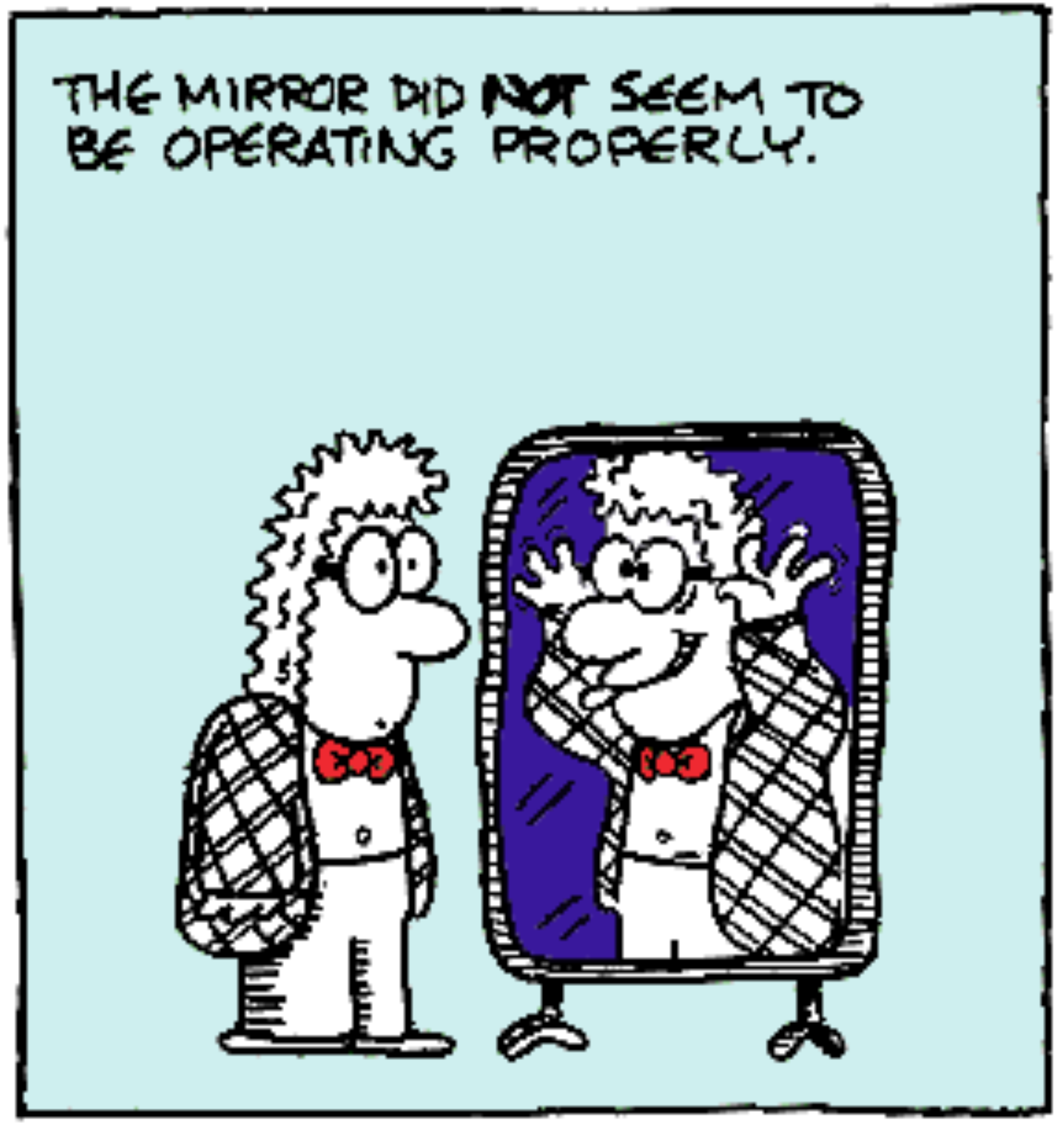
Discovery of CP-Violation with K^0 decays

- Create a pure K_L beam (“wait” for K to decay)
- If CP is conserved,

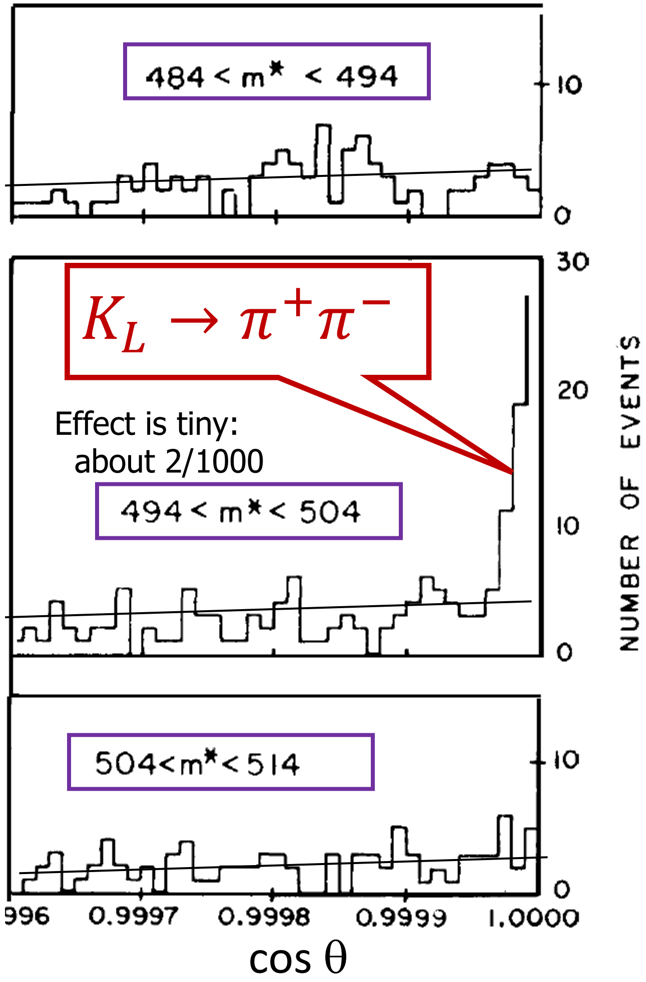


Signal: $K_1^0 \rightarrow \pi$

Background: K



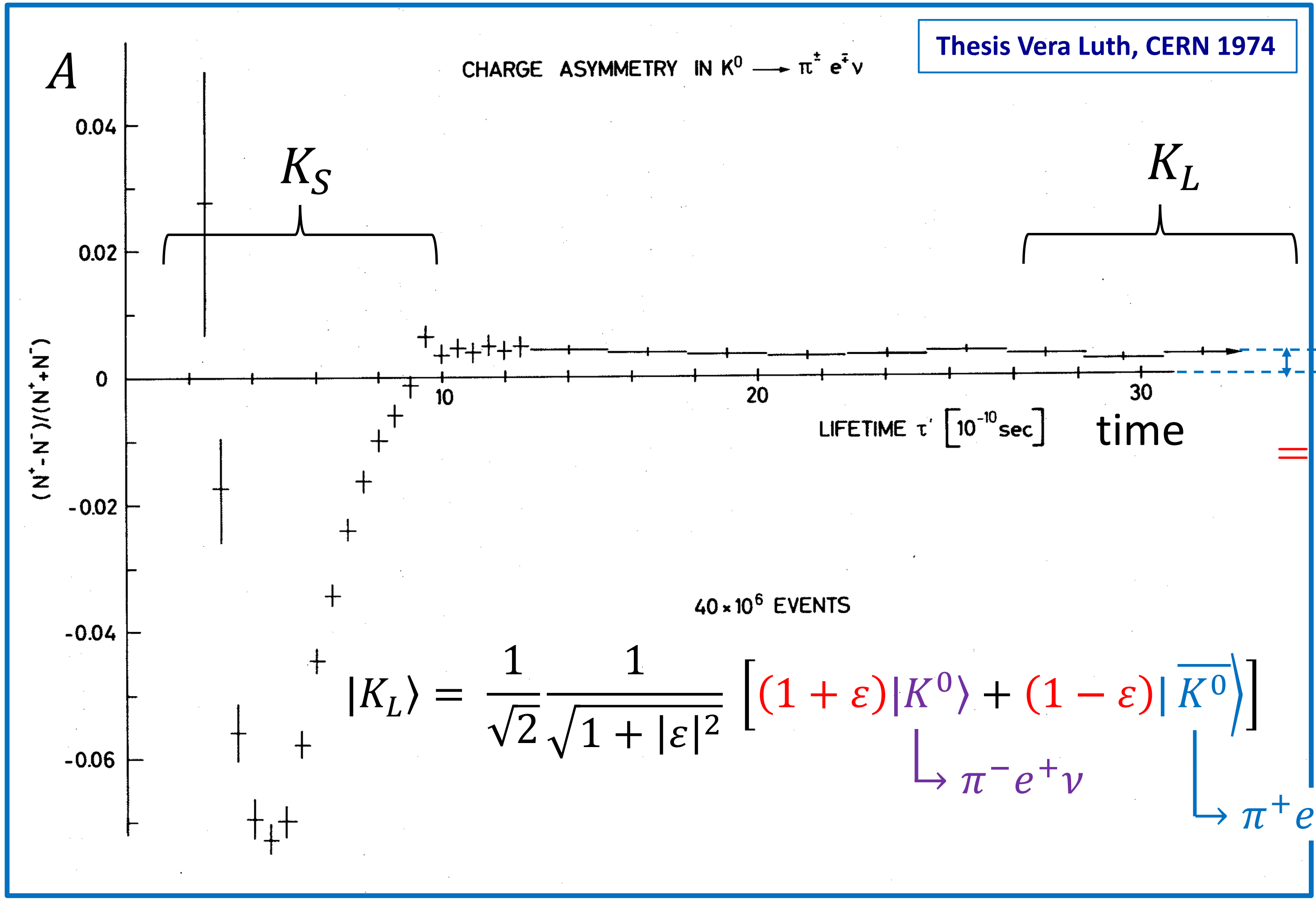
K_S: Short-lived is CP even:
$K_1^0 \rightarrow \pi^+\pi^-$ (fast)
K_L: Long-lived is CP odd:
$K_2^0 \rightarrow \pi^+\pi^-\pi^0$ (slow)



Alternative: Charge Asymmetry in K^0 decays

Measure $A = \frac{N^+ - N^-}{N^+ + N^-}$ with $N^+ = K^0 \to \pi^- e^+ \nu$, $N^- = \overline{K^0} \to \pi^+ e^- \bar{\nu}$ vs the K^0 decay time

$$\frac{N^+ - N^-}{N^+ + N^-} = A$$



$$|K_L\rangle = \frac{1}{\sqrt{2}} \frac{1}{\sqrt{1 + |\varepsilon|^2}} \left[(1+\varepsilon)|K^0\rangle + (1-\varepsilon)|\overline{K^0}\rangle \right]$$

$(1+\varepsilon)|K^0\rangle \to \pi^- e^+ \nu$

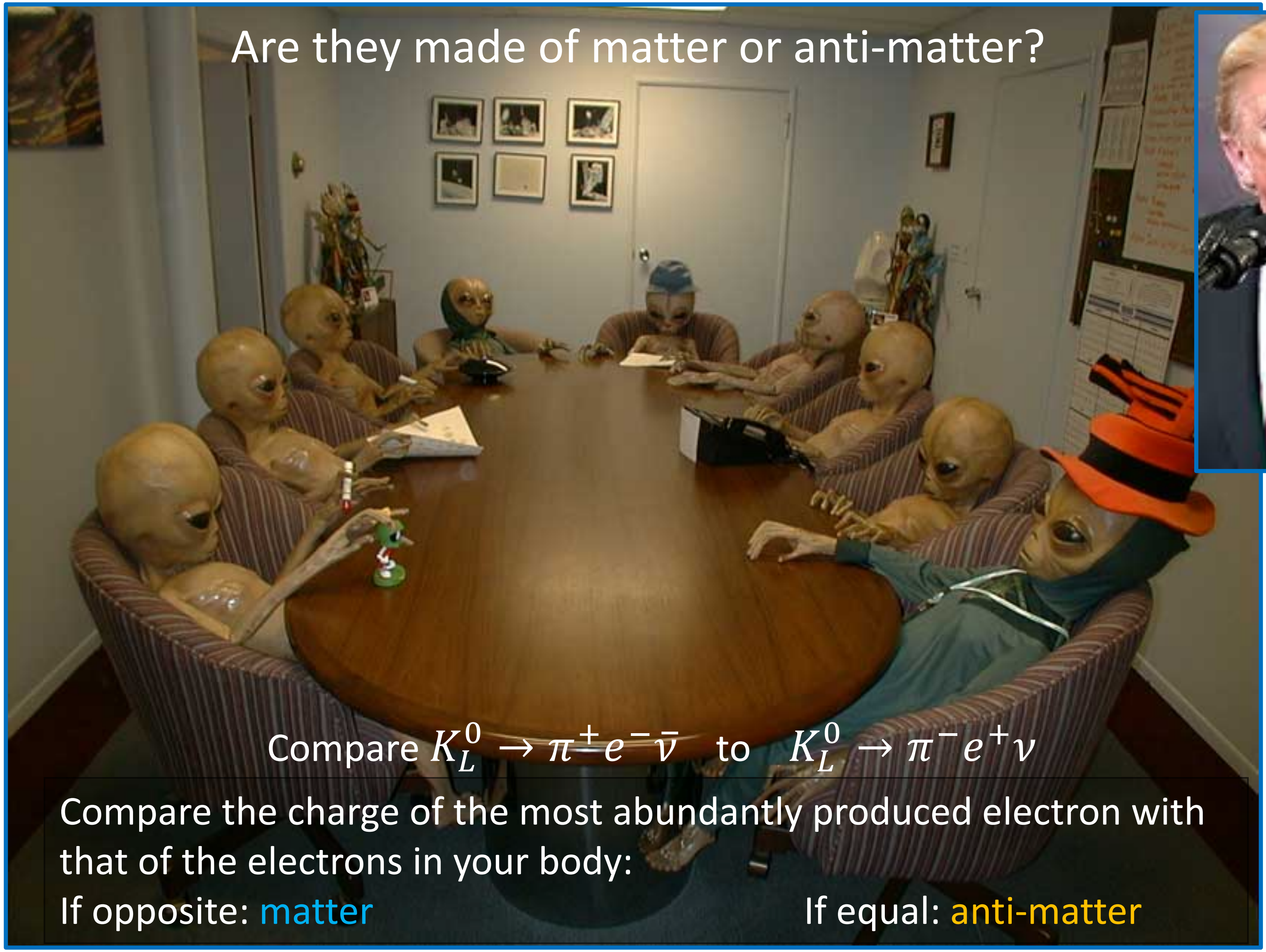
$(1-\varepsilon)|\overline{K^0}\rangle \to \pi^+ e^- \bar{\nu}$

$4\Re(\varepsilon)$

$$= \left| \frac{(1+\varepsilon)}{(1-\varepsilon)} \right|^2$$

CP violation in meson mixing.

Contact with Aliens !



Are they made of matter or anti-matter?

Compare $K_L^0 \to \pi^+ e^- \bar{\nu}$ to $K_L^0 \to \pi^- e^+ \nu$

Compare the charge of the most abundantly produced electron with that of the electrons in your body:

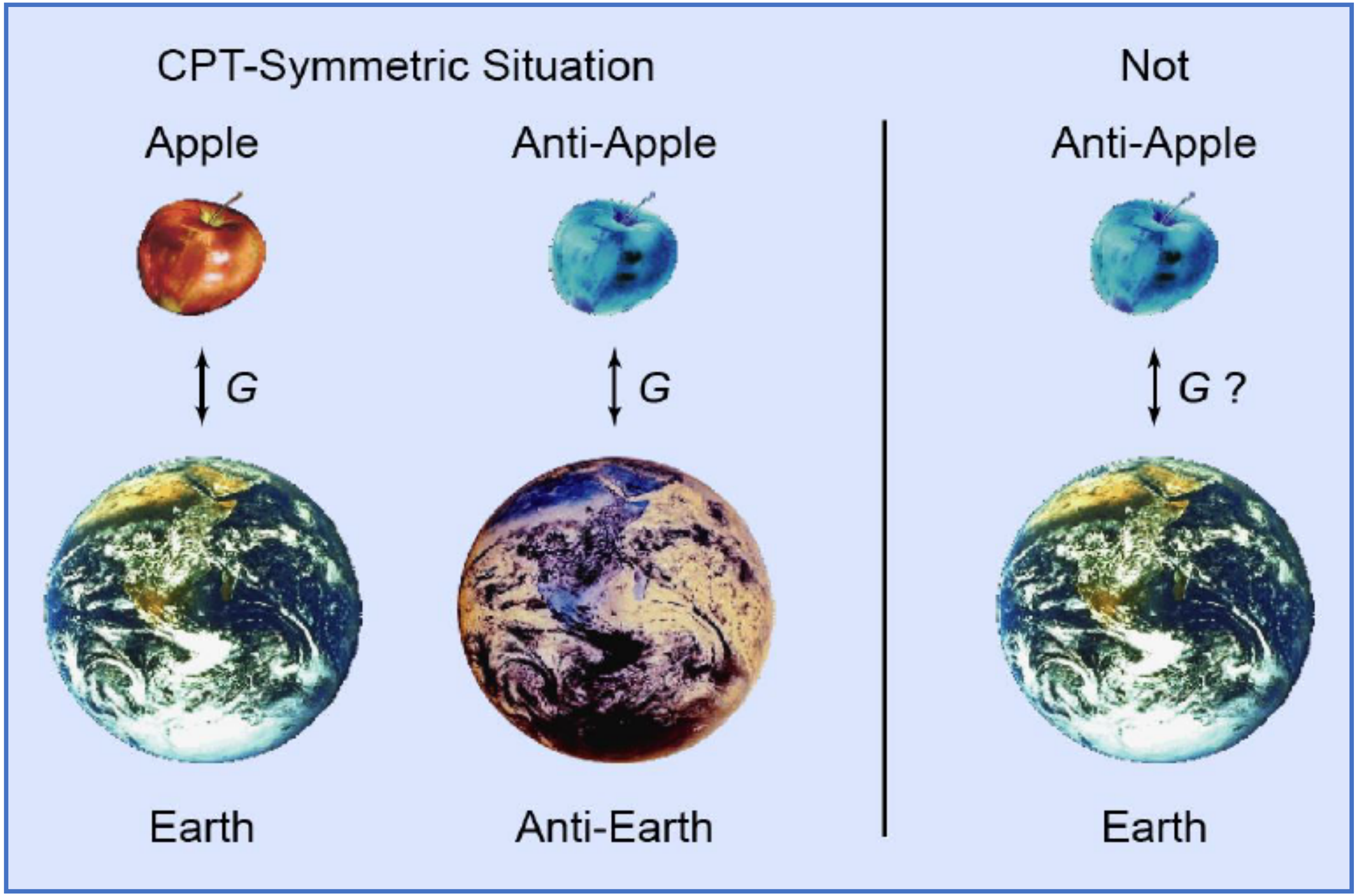
If opposite: matter

If equal: anti-matter

CPT Violation...

CPT symmetry implies that an antiparticle is ***identical*** to a particle travelling backwards in time.

CPT is conserved, but does anti-matter fall down?



Contents per Week:

1. CP Violation
   a) **Discrete Symmetries**
   b) CP Violation in the Standard Model
   c) Jarlskog Invariant and Baryogenesis
2. B-Mixing
   a) CP violation and Interference
   b) B-mixing and time dependent CP violation
   c) Experimental Aspects: LHC vs B-factory
3. B-Decays
   a) Effective Hamiltonian
   b) Lepton Flavour Non-Universality

Contents per Week:

Weak interaction in three Flavour Generations

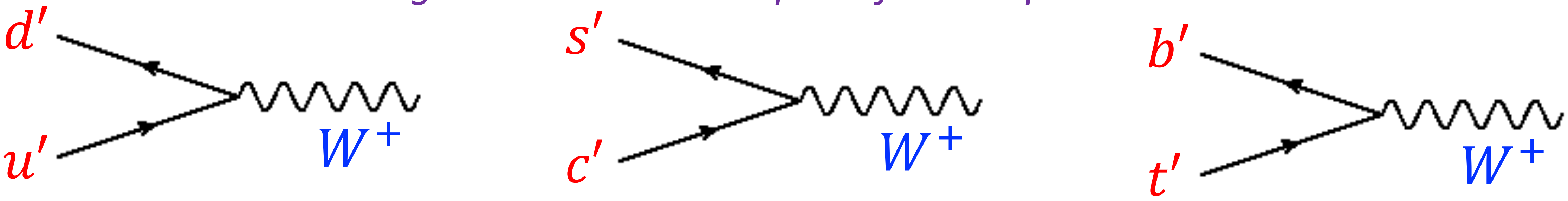

Wolfgang Pauli

- Weak Interaction is 100% parity violating.
  - Wolfgang Pauli: *"I cannot believe God is a weak left-hander."*

- Implement an SU(2)$_L$ symmetry for *massless* particles:

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} u'_L \gamma_\mu W^\mu d'_L \qquad \text{x3 !}$$

- Flavour universality: *identical interactions* in three generations.
  - In fact: *how to distinguish a massless d' quark from s' quark?*



- There is *no CP violation* in these massless interactions
  - What happens when particles acquire mass?

Spontaneous Symmetry Breaking→ Origin of Mass

- Yukawa couplings to massless particles:

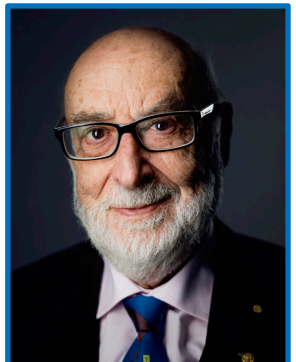
$$\mathcal{L}_Y = Y_{ij}^{d}\,\left(\overline{u}_i', \overline{d}_i'\right)_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} d_{jR}' + Y_{ij}^{u}\,\left(\overline{u}_i', \overline{d}_i'\right)_L \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} u_{jR}'$$

- Yukawa interaction is *not* flavour universal!

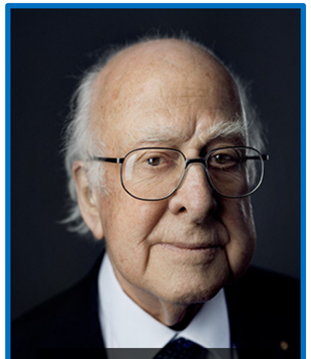
→*Unknown origin of Yukawa matrix acting on generations "i" and "j"*

- SSB: B-E-H Mechanism:

Robert Brout



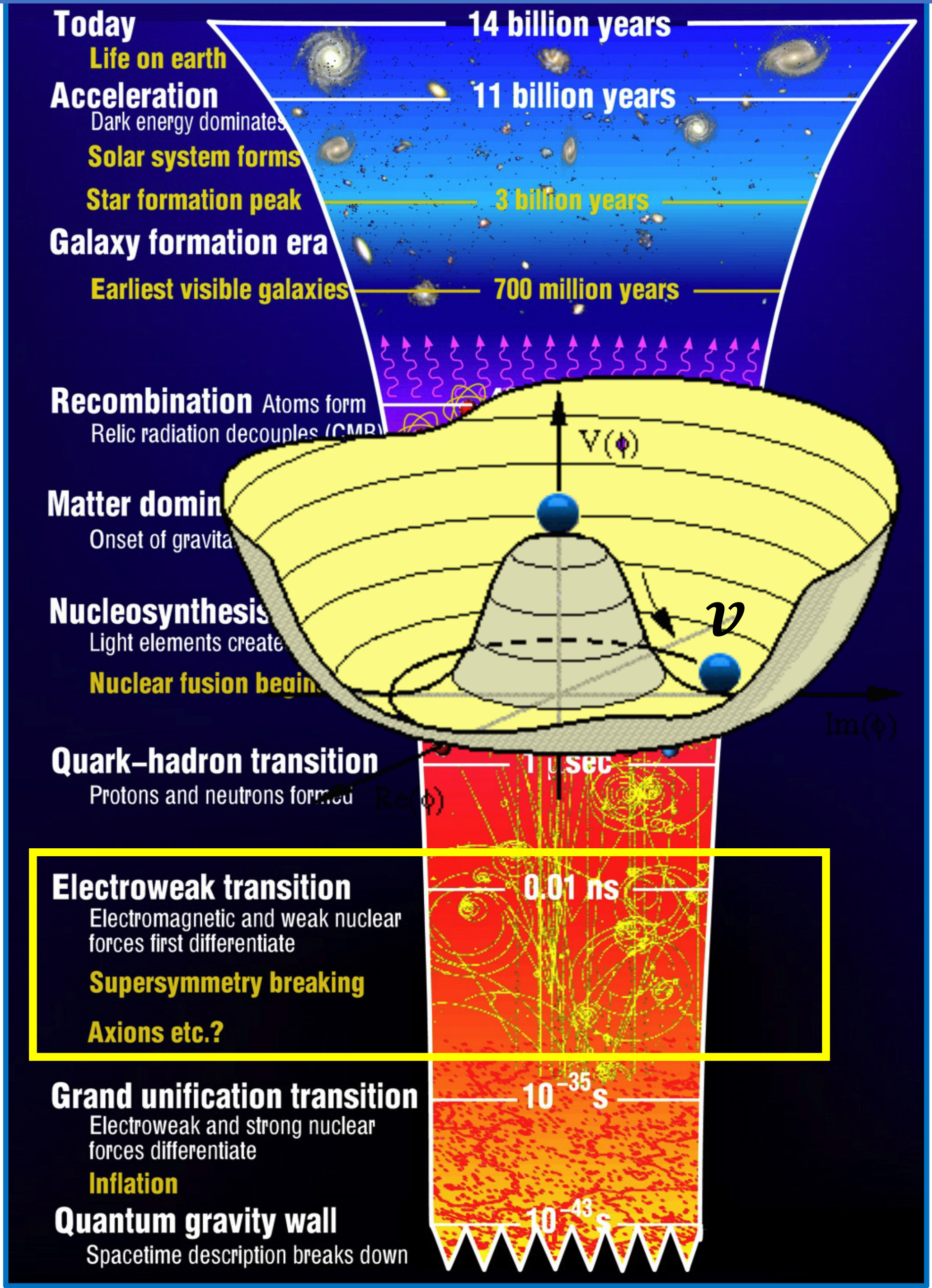
Francois Englert



Peter Higgs

$$\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \rightarrow \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

➔ Massive W- and Z- bosons



Spontaneous Symmetry Breaking → Origin of Mass

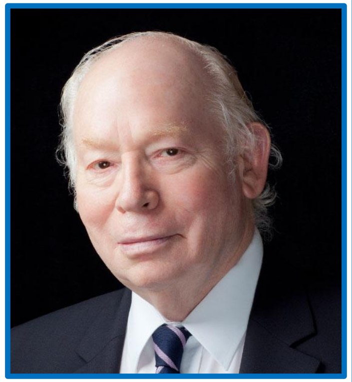
- Yukawa couplings to massless particles (Weinberg):

$$\mathcal{L}_Y = Y_{ij}^d \left(\overline{u_i'}, \overline{d_i'}\right)_L \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} d_{jR}' + Y_{ij}^u \left(\overline{u_i'}, \overline{d_i'}\right)_L \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix} u_{jR}'$$

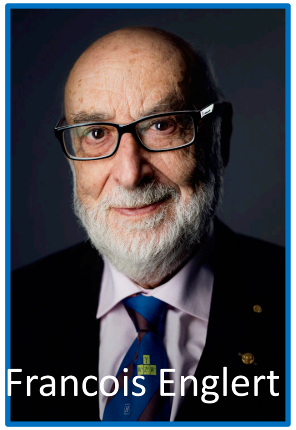
- Yukawa interaction is *not* flavour universal!

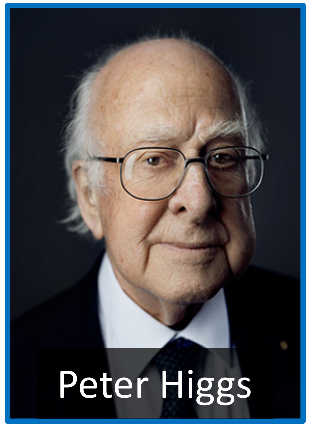
→ *Unknown origin of Yukawa matrix acting on generations "i" and "j"*

➔ Massive fermions



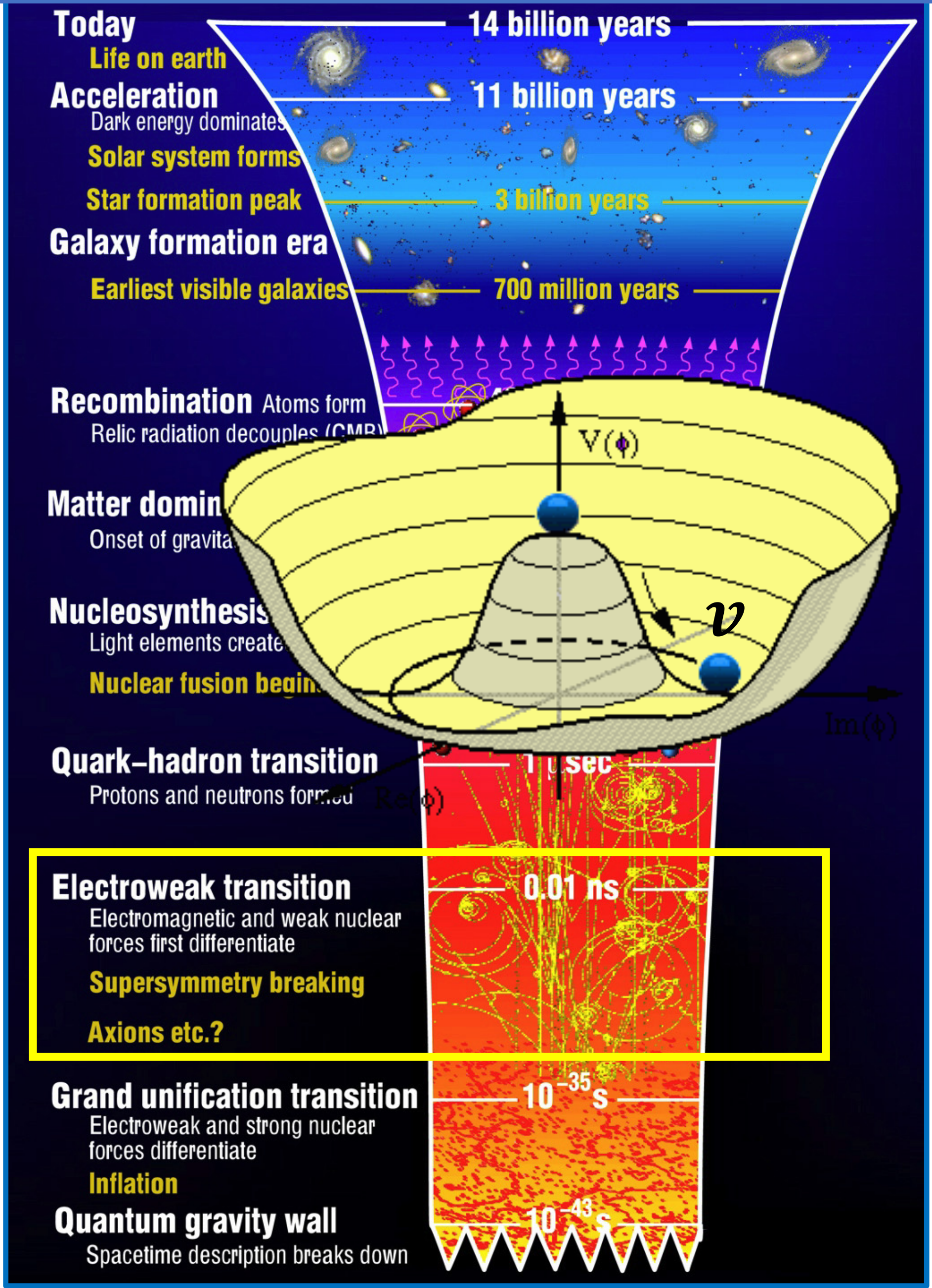
- SSB: B-E-H Mechanism:





$$\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \rightarrow \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

➔ Massive W- and Z- bosons



Spontaneous Symmetry Breaking → Origin of Mass

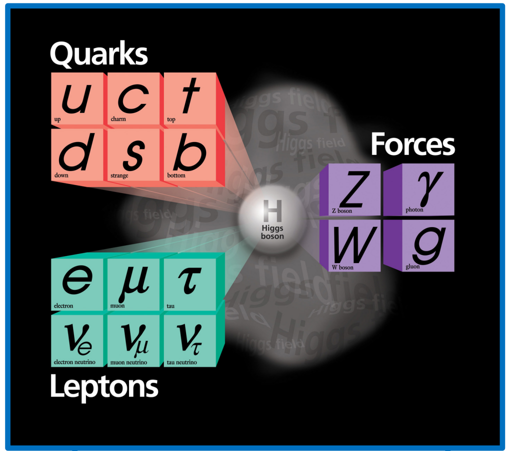
- Yukawa couplings to massless particles:

$$\mathcal{L}_Y = Y^d_{ij}\ \left(\overline{u'_i}, \overline{d'_i}\right)_L \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} d'_{jR} + Y^u_{ij}\ \left(\overline{u'_i}, \overline{d'_i}\right)_L \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix} u'_{jR}$$

- Diagonalize Y_{ij} :

  $u_i = (V^u)_{ij}\, u'_j$ and $d_i = (V^d)_{ij}\, d'_j$

  → mass and flavour eigenstates

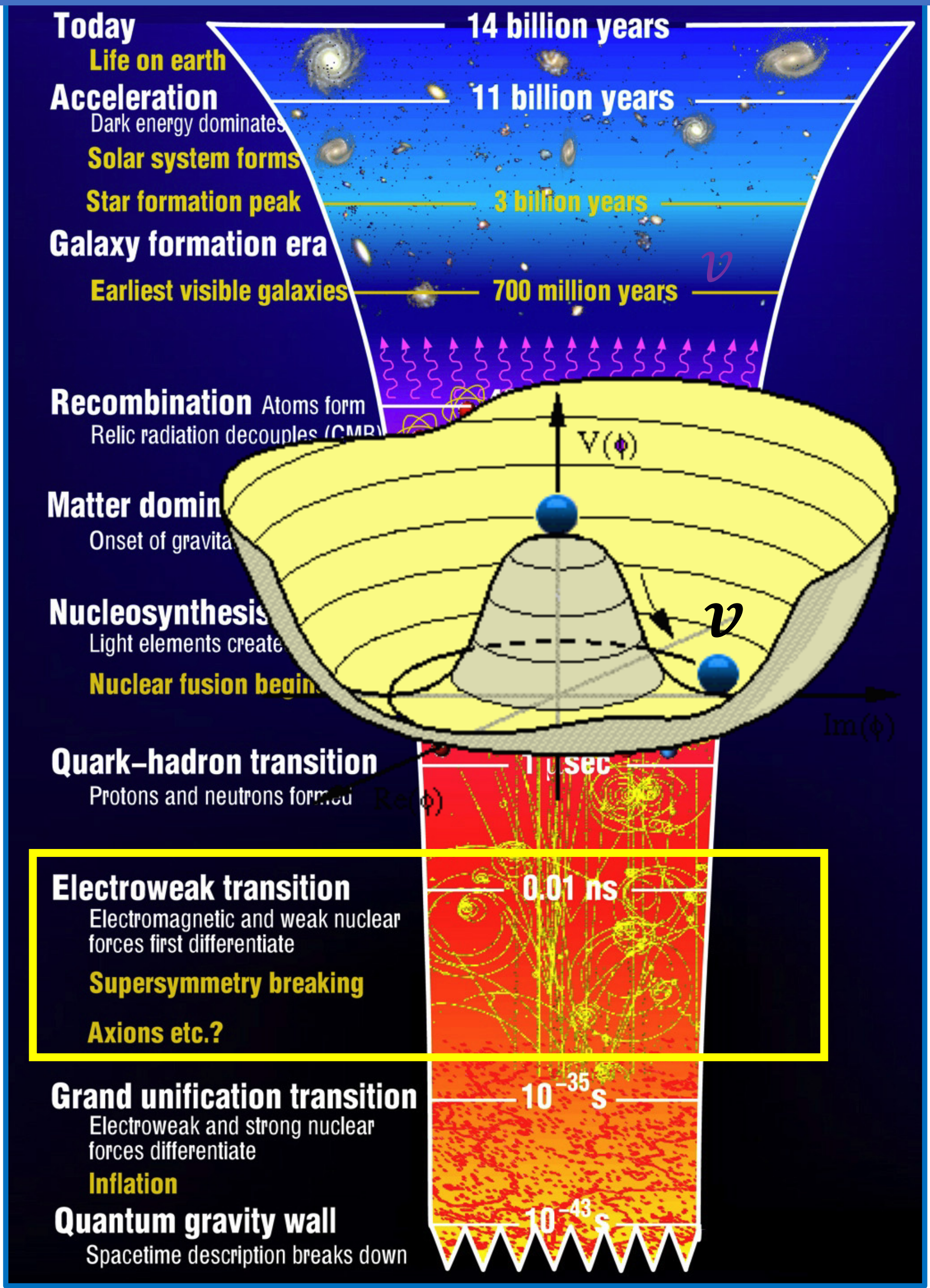


Physical particles

- Mass terms: $M_{ij} = Y_{ij}\, v/\sqrt{2}$

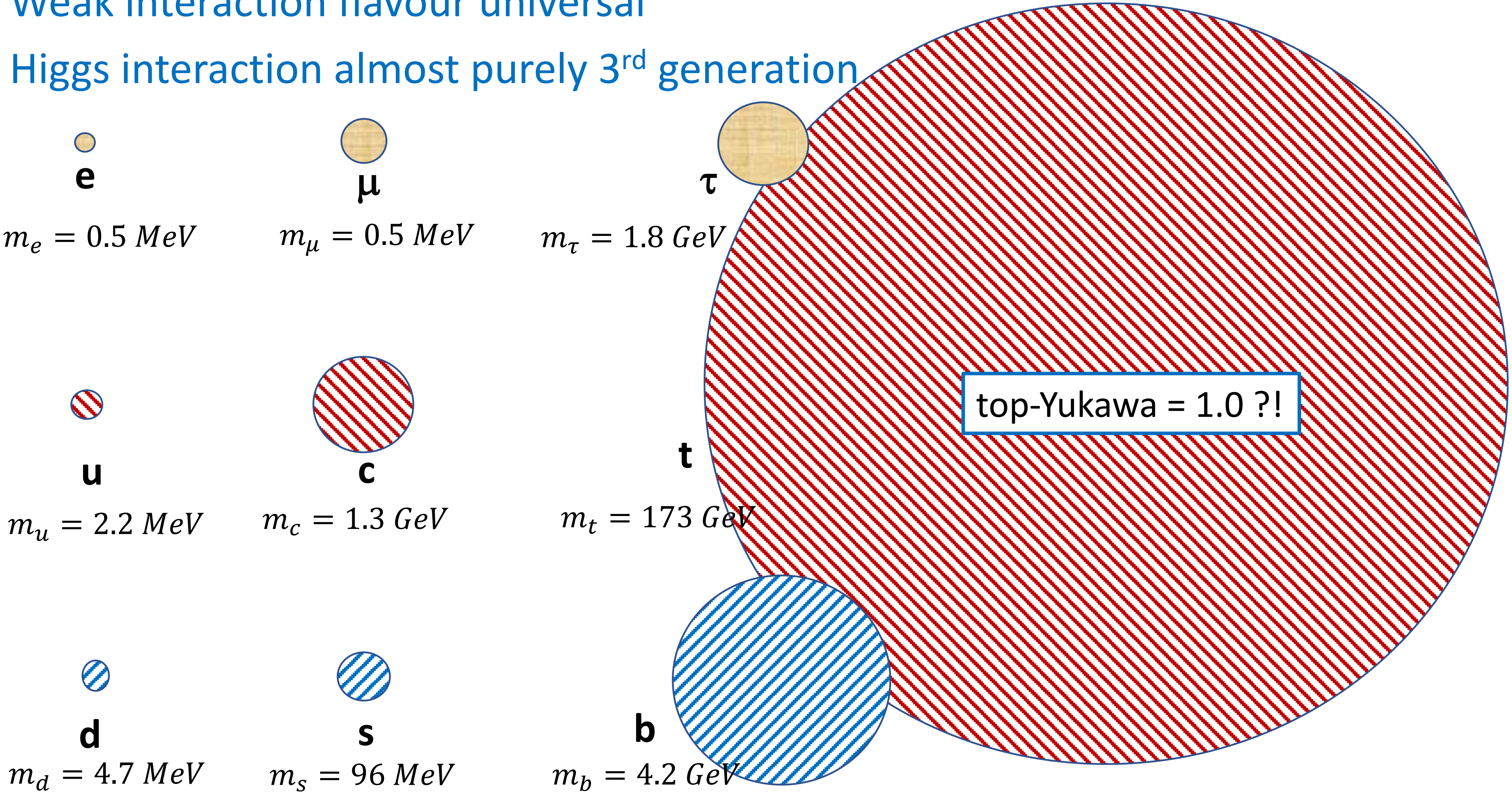
$$\mathcal{L}_Y \to \mathcal{L}_H = m_d\, d_L\, d_R + m_u\, u_L\, u_R$$

- Top quark mass: $m_{top} = 1.0\, v/\sqrt{2}$
  - *To first order Higgs couples only to top with coupling strength 1.0 !*
    - *Very* flavour non-universal



Flavour Puzzle: particle masses? Origin Yukawa couplings?

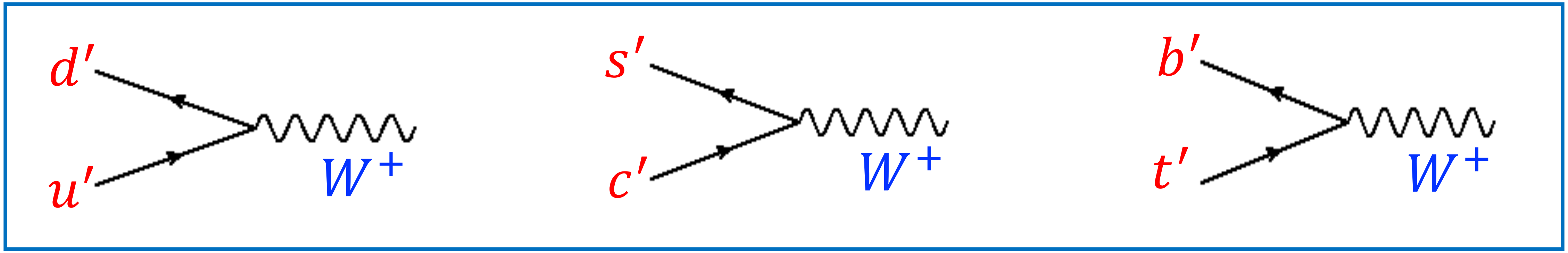
- Weak interaction flavour universal
- Higgs interaction almost purely 3rd generation



The Weak Interaction → Flavour Mixing

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} {u'}_L \gamma_\mu W^\mu {d'}_L$$

- *No CP violation*



Redefine: $u_i' = (V^u)_{ij}\, u_i$ and: $d_i' = \left(V^d\right)^\dagger_{ij} d_i$, such that: $V_{CKM} = \left(V^u V^{d\dagger}\right)_{ij}$ …

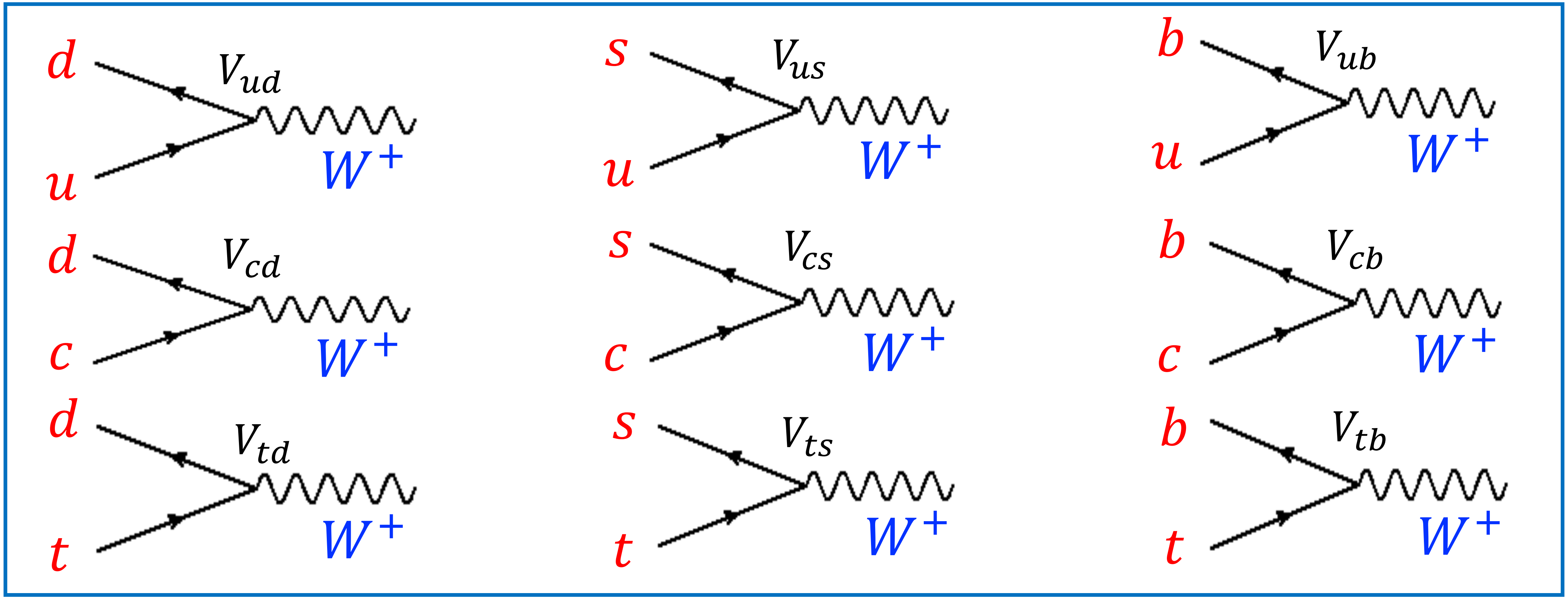
The Weak Interaction → Flavour Mixing

(Interaction basis) (Mass basis)

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} u'_L \gamma_\mu W^\mu d'_L \longrightarrow \mathcal{L}_W = \frac{g}{\sqrt{2}} V_{CKM}\, u_L\, \gamma_\mu W^\mu d_L$$

Redefine: $u'_i = (V^u)_{ij}\, u_i$ and: $d'_i = \left(V^d\right)^\dagger_{ij} d_i$, such that: $V_{CKM} = \left(V^u V^{d\dagger}\right)_{ij}$ …

Generation structure of weak interaction, *now includes CP violation.*



The Weak Interaction → Flavour Mixing

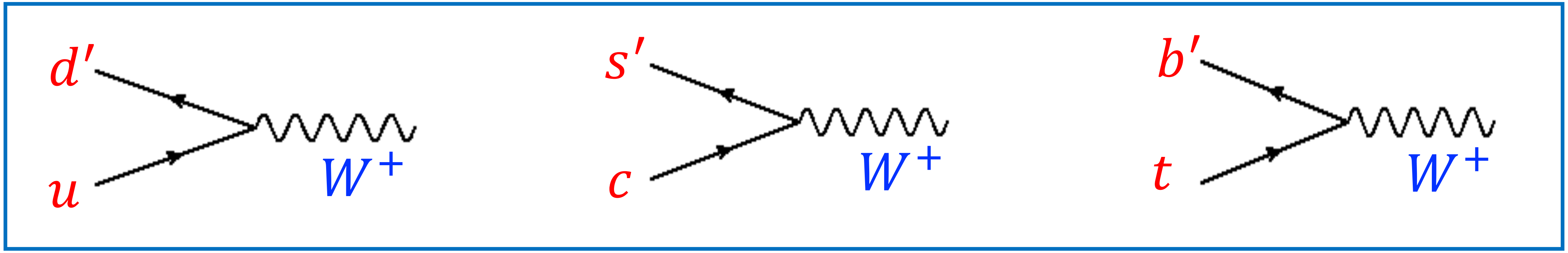
(Interaction basis) (Mass basis)

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} u'_L \gamma_\mu W^\mu d'_L \longrightarrow \mathcal{L}_W = \frac{g}{\sqrt{2}} V_{CKM}\, u_L \gamma_\mu W^\mu d_L$$

Redefine: $u'_i = (V^u)_{ij}\, u_i$ and: $d'_i = \left(V^d\right)^\dagger_{ij} d_i$, such that: $V_{CKM} = \left(V^u V^{d\dagger}\right)_{ij}$ …

Generation structure of weak interaction, *now includes CP violation.*

Convention: instead, we do as if: $u'_i = u_i$ and $d'_i = (V_{CKM})_{ij}\, d_j$



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

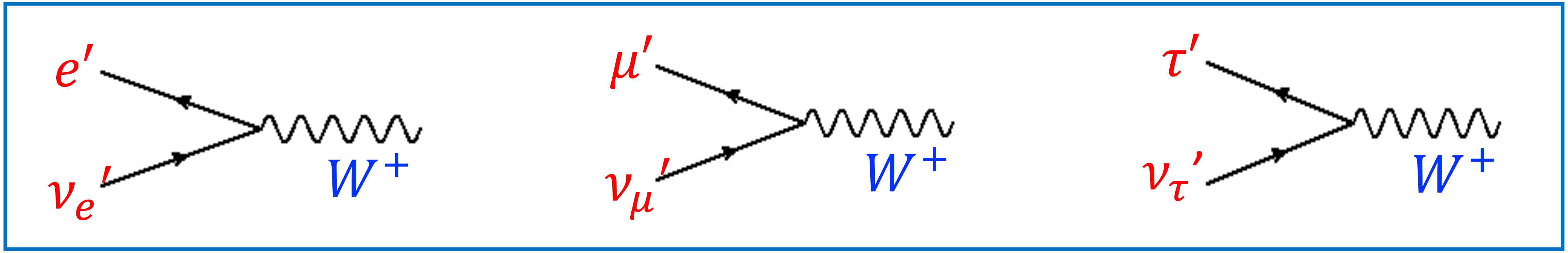
$$|s'\rangle = V_{cd}\,|d\rangle + V_{cs}\,|s\rangle + V_{cb}\,|b\rangle$$

$$|b'\rangle = V_{td}\,|d\rangle + V_{ts}\,|s\rangle + V_{tb}\,|b\rangle$$

How about leptons?

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} \nu'_{e_L} \gamma_\mu W^\mu e'_L$$

- *No CP violation*



Redefine: $\nu_i{}' = (U^\nu)_{ij}\, \nu_i$ and: $l'_i = (U^l)^\dagger_{ij} l_i$, such that: $U_{MNS} = \left(U^\nu U^{l\dagger}\right)_{ij}$ …

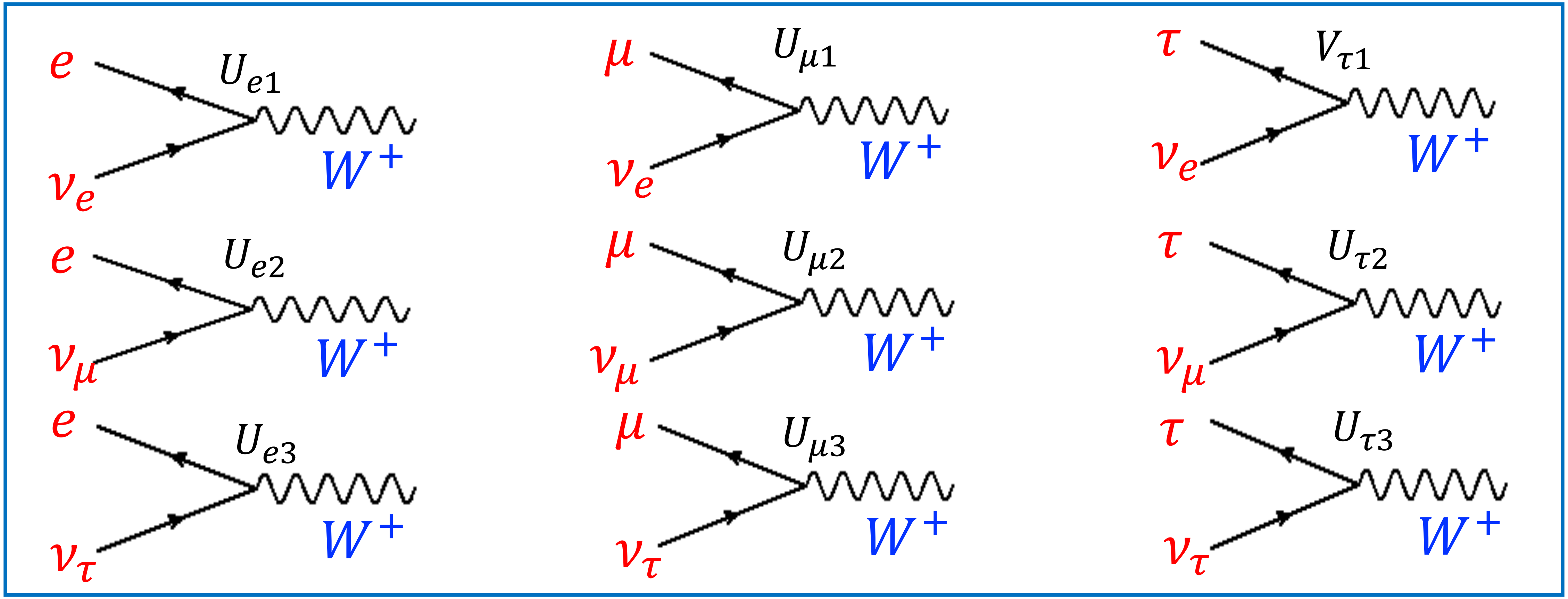
How about leptons?

(Interaction basis) → (Mass basis)

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} \nu'_L \gamma_\mu W^\mu e'_L \longrightarrow \mathcal{L}_W = \frac{g}{\sqrt{2}} U_{MNS} \nu_L \gamma_\mu W^\mu e_L$$

Redefine: $\nu'_i = (U)_{ij}\, \nu_i$ and: $l'_i = \left(U^d\right)^\dagger_{ij} l_i$, such that: $U_{MNS} = \left(U^u U^{d\dagger}\right)_{ij}$ …

Generation structure of weak interaction, *now includes CP violation.*



How about leptons?

(Interaction basis) (Mass basis)

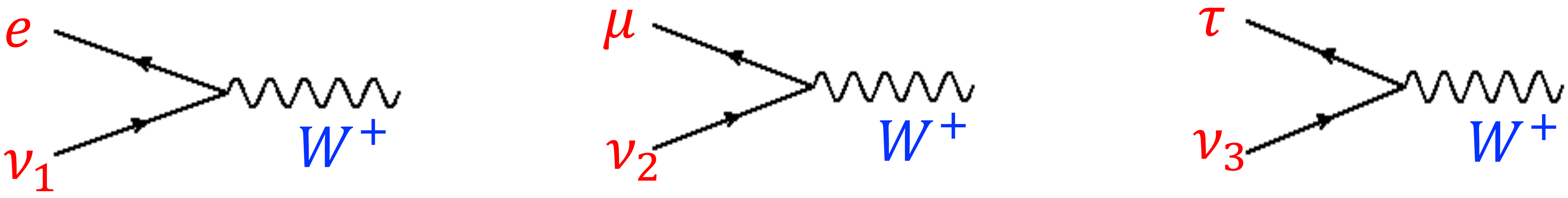
$$\mathcal{L}_W = \frac{g}{\sqrt{2}} \nu'_L \, \gamma_\mu \, W^\mu \, e'_L \longrightarrow \mathcal{L}_W = \frac{g}{\sqrt{2}} U_{MNS} \, \nu_L \, \gamma_\mu \, W^\mu \, e_L$$

Redefine: $\nu'_i = (U)_{ij} \, \nu_i$ and: $l'_i = \left(U^d\right)^\dagger_{ij} l_i$, such that: $U_{MNS} = \left(U^u U^{d\dagger}\right)_{ij}$ …

Generation structure of weak interaction, *now includes CP violation.*

Convention: instead we do as if: $\nu_{1,2,3} = (U_{MNS})_{ij} \, \nu_{e,\mu,\tau}$ and $l_i{}' = l_i$

For neutrinos we label the mass eigenstates as: 1, 2, 3 instead of e, μ, τ



$$|\nu_1\rangle = U_{e1} \, |\nu_e\rangle + U_{\mu 1} \, |\nu_\mu\rangle + U_{\tau 1} \, |\nu_\tau\rangle$$

$$|\nu_2\rangle = U_{e2} \, |\nu_e\rangle + U_{\mu 2} \, |\nu_\mu\rangle + U_{\tau 2} \, |\nu_\tau\rangle$$

$$|\nu_3\rangle = U_{e3} \, |\nu_e\rangle + U_{\mu 3} \, |\nu_\mu\rangle + U_{\tau 3} \, |\nu_\tau\rangle$$

Food for thought: which states mix?

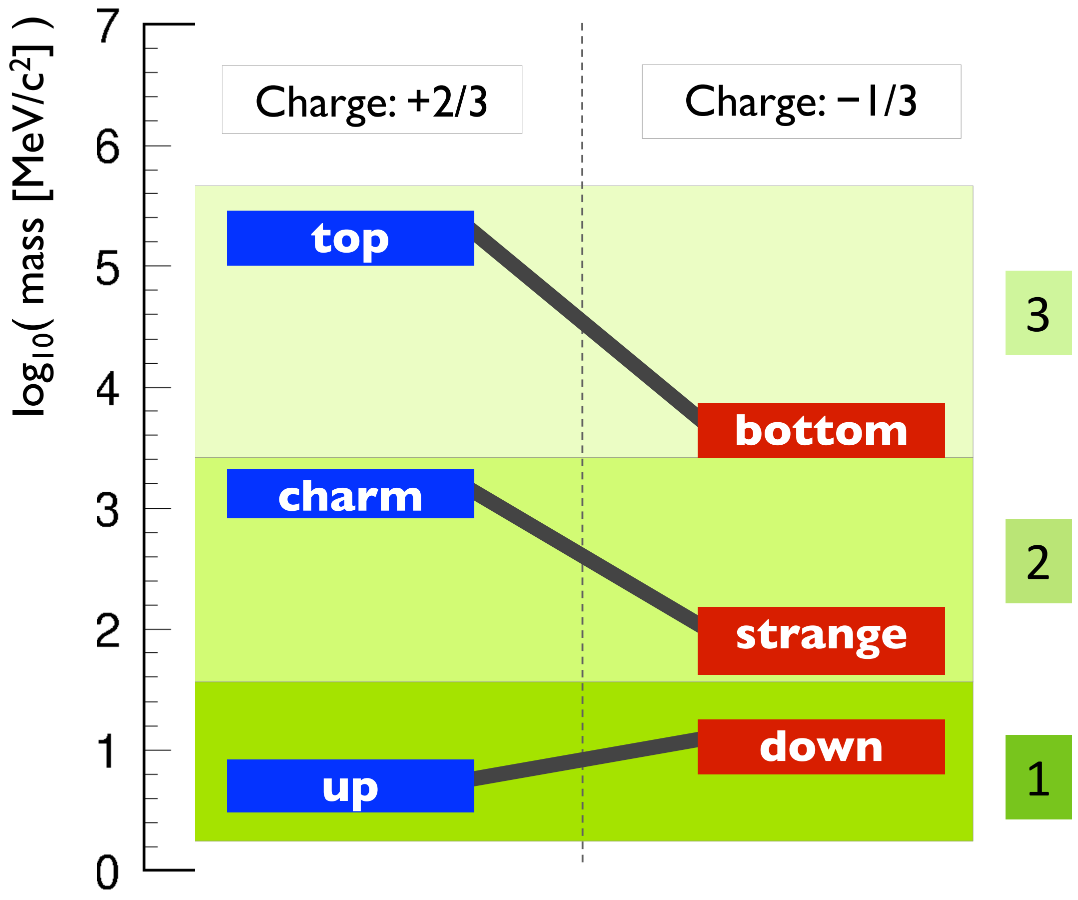
- Quarks: $\binom{u}{d'} = \binom{u}{V_{ud}\, d + V_{us}\, s + V_{ub}\, b}$; We say "the down-type quarks mix".
- Leptons: $\binom{\nu_1}{e} = \binom{U_{e1}\, \nu_e + U_{\mu 1}\, \nu_\mu + U_{\tau 1}\, \nu_\tau}{e}$; We say "the neutrinos mix."

- Why the "down-types" in one case and the "up-types" in another?

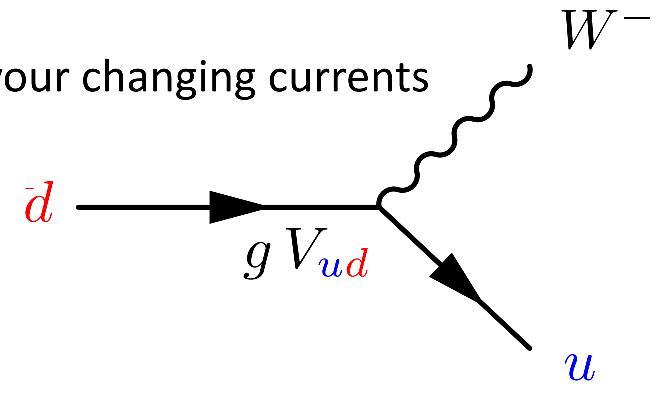
- Answer: it is convention! Both mix individually (in an unknown way).
  - The interaction is always: $\mathcal{L}_W = \frac{g}{\sqrt{2}} V_{CKM}\, u_L\ \gamma_\mu\, W^\mu\, d_L$
  - i.e up and down-type combined!

- Paradox question: does this mean neutrino mixing is unphysical??

Flavour Changing Quark Interactions

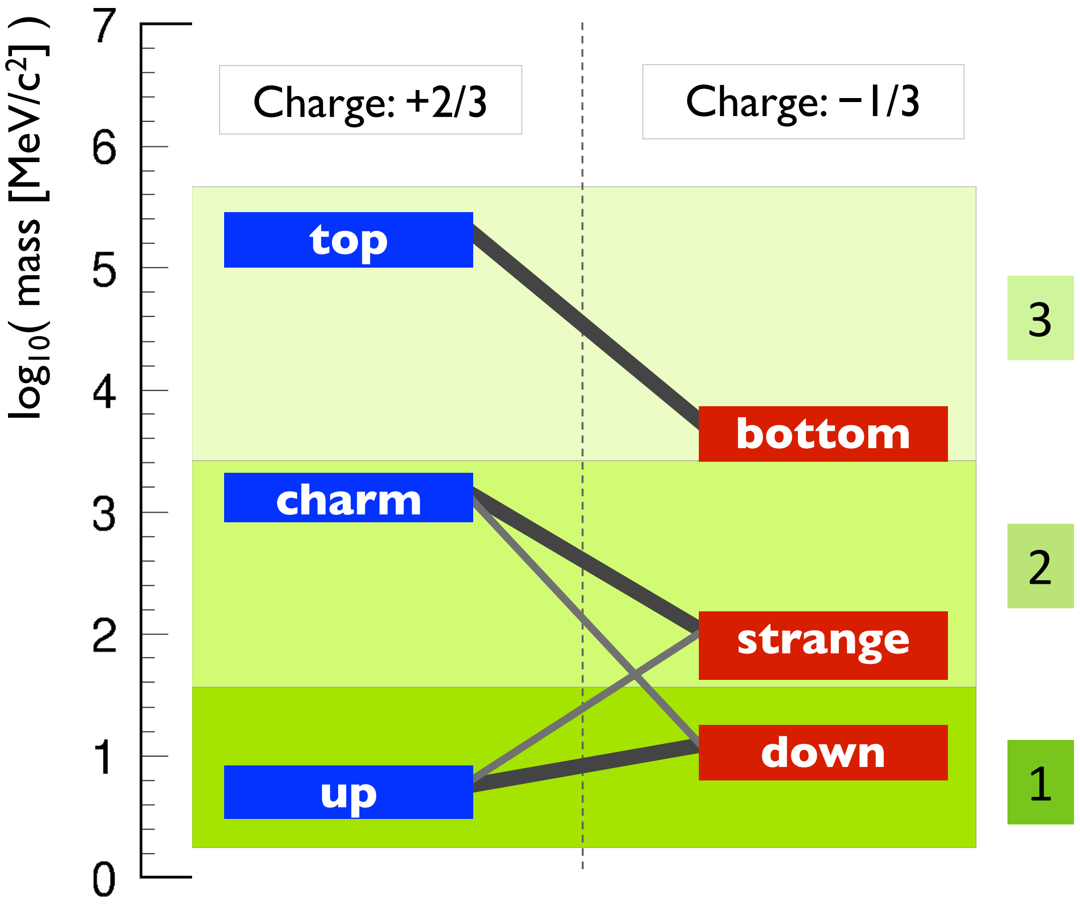


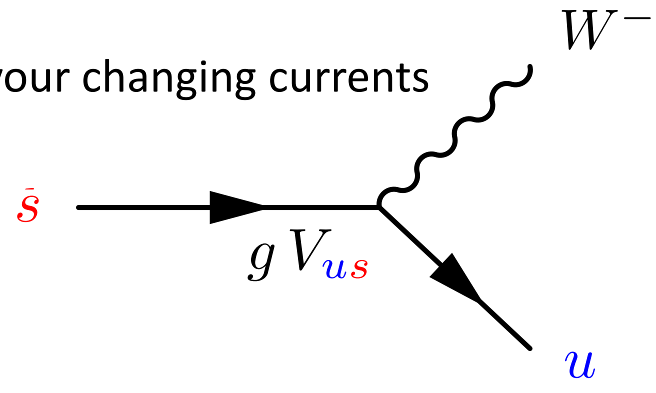
Flavour changing currents



$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & & \\ & V_{cs} & \\ & & V_{tb} \end{pmatrix}$$

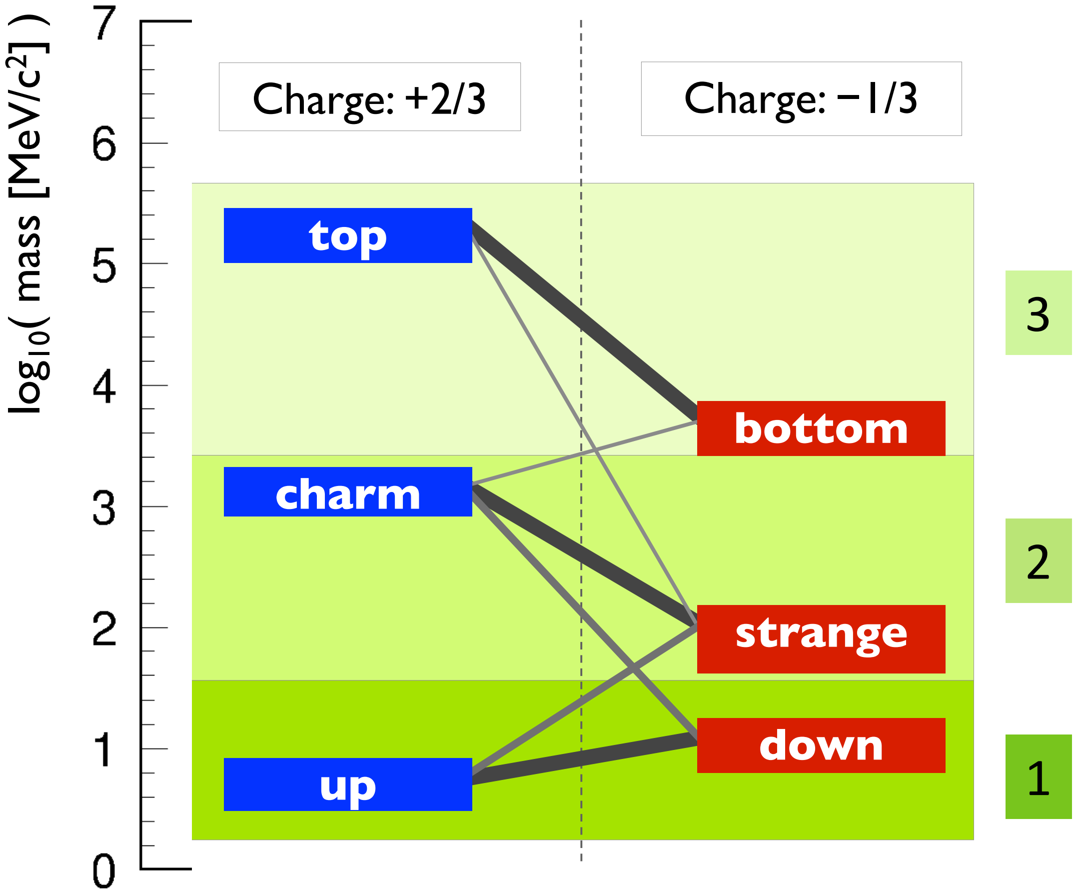
Flavour Changing Quark Interactions



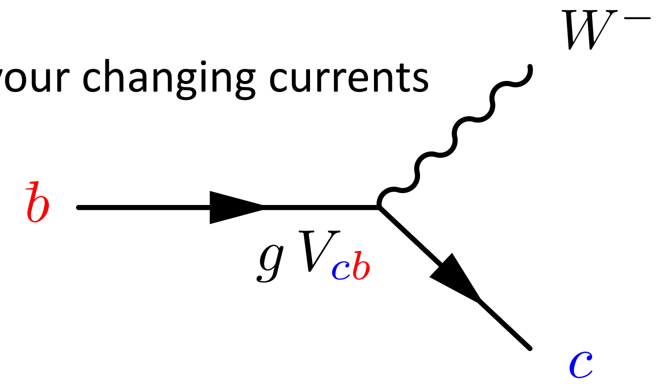


$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & \\ V_{cd} & V_{cs} & \\ & & V_{tb} \end{pmatrix}$$

Flavour Changing Quark Interactions

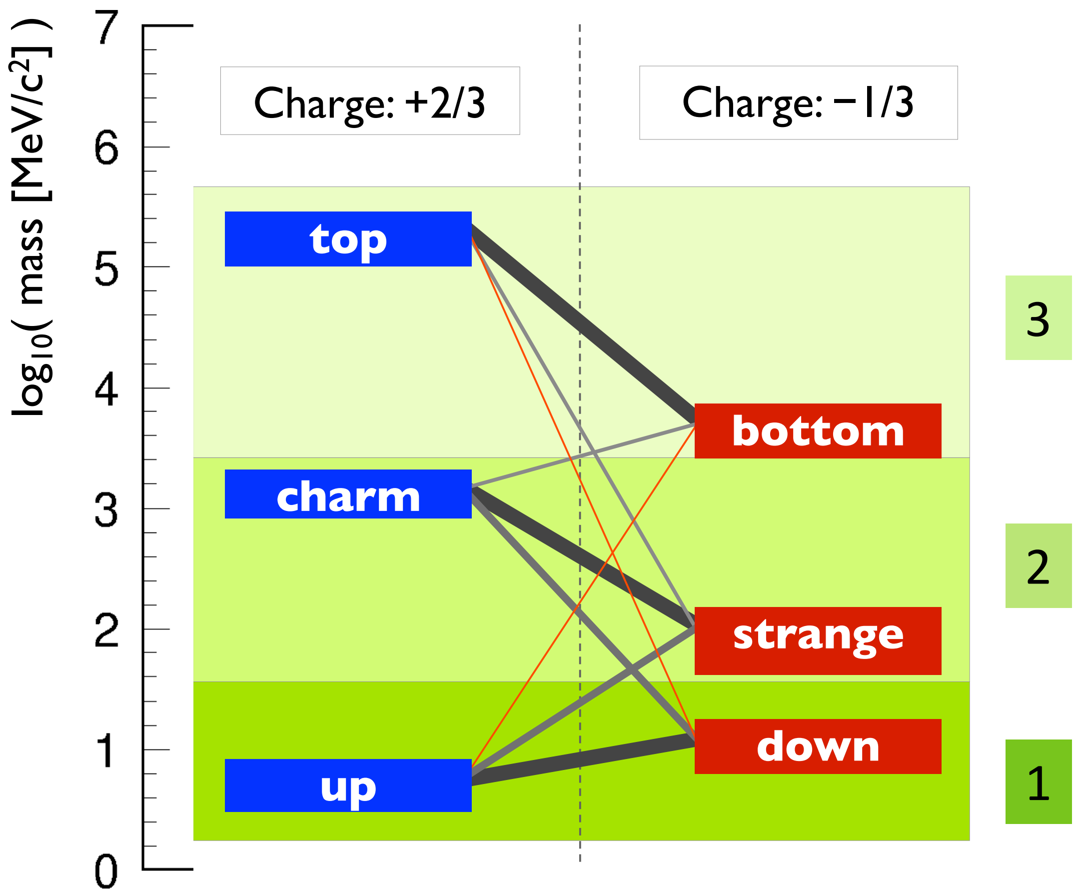


Flavour changing currents

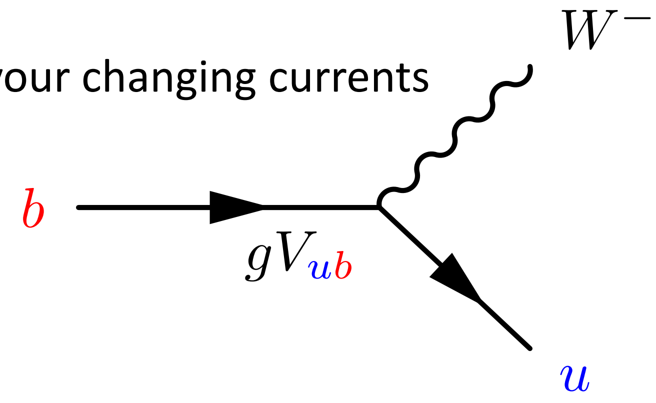


$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & \\ V_{cd} & V_{cs} & V_{cb} \\ & V_{ts} & V_{tb} \end{pmatrix}$$

Flavour Changing Quark Interactions

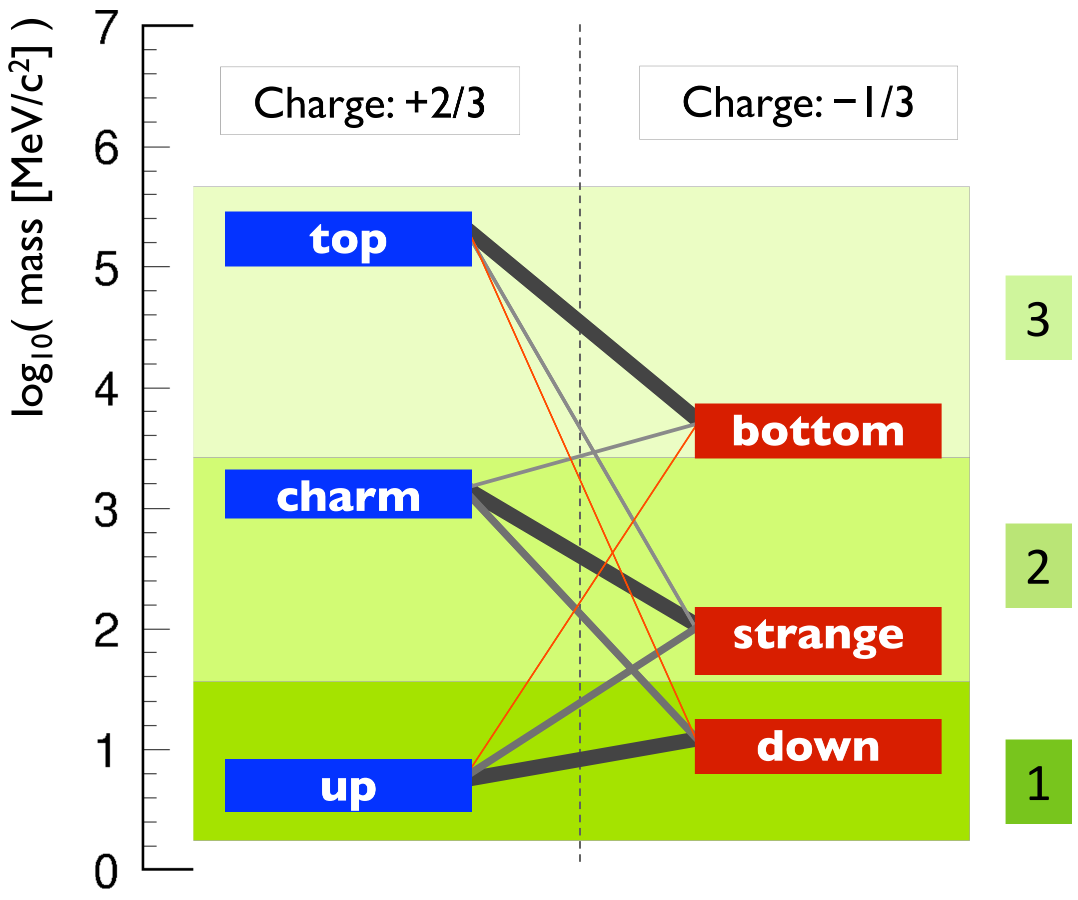


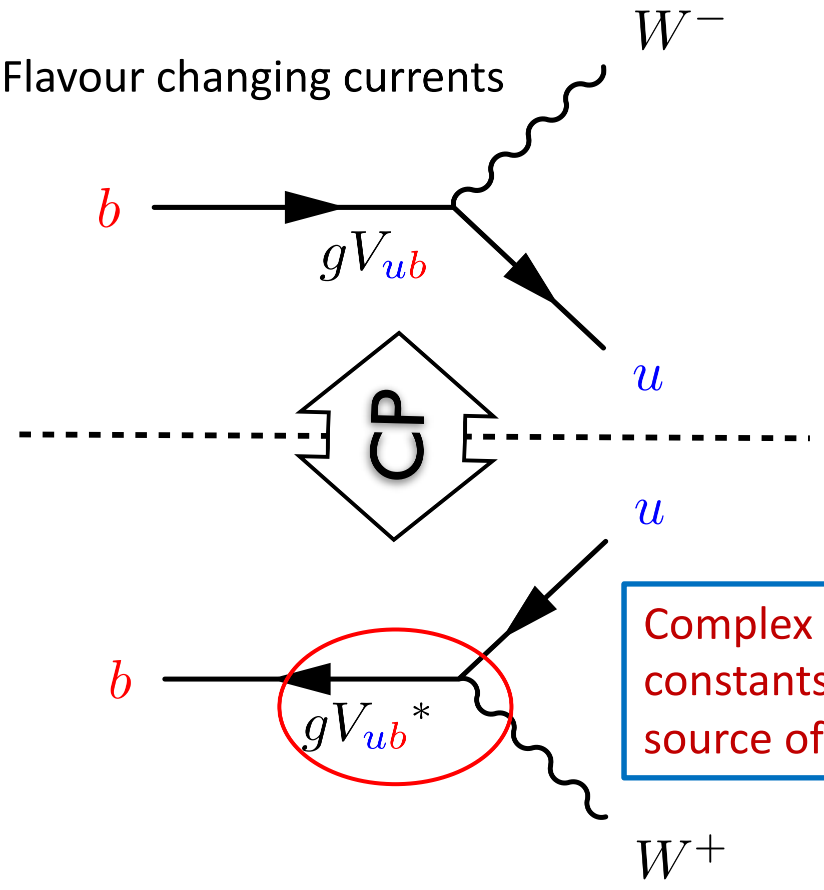
Flavour changing currents



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

Flavour Changing Quark Interactions – CP Violation





Complex coupling constants are the source of CP viol.

- Particles and antiparticles have complex conjugated coupling constants

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

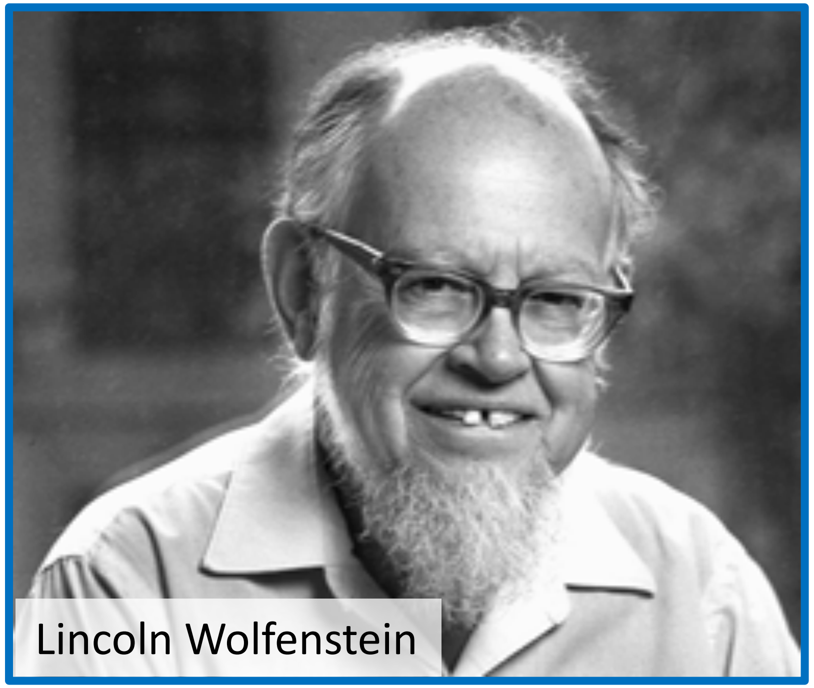
The CKM matrix V_{CKM} - 3 Generations

$$V_{CKM}: \quad \begin{matrix} & d & s & b \\ u & & & \\ c & & & \\ t & & & \end{matrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Wolfenstein parametrization: V_{CKM} =

$$\begin{pmatrix} 1 - {}^{1}/_{2}\,\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - {}^{1}/_{2}\,\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

➔ 1 complex degree of freedom
➔ CP violating phase



Lincoln Wolfenstein

- It follows from unitarity:

$$V_{CKM}^{\dagger}\, V_{CKM} = 1$$

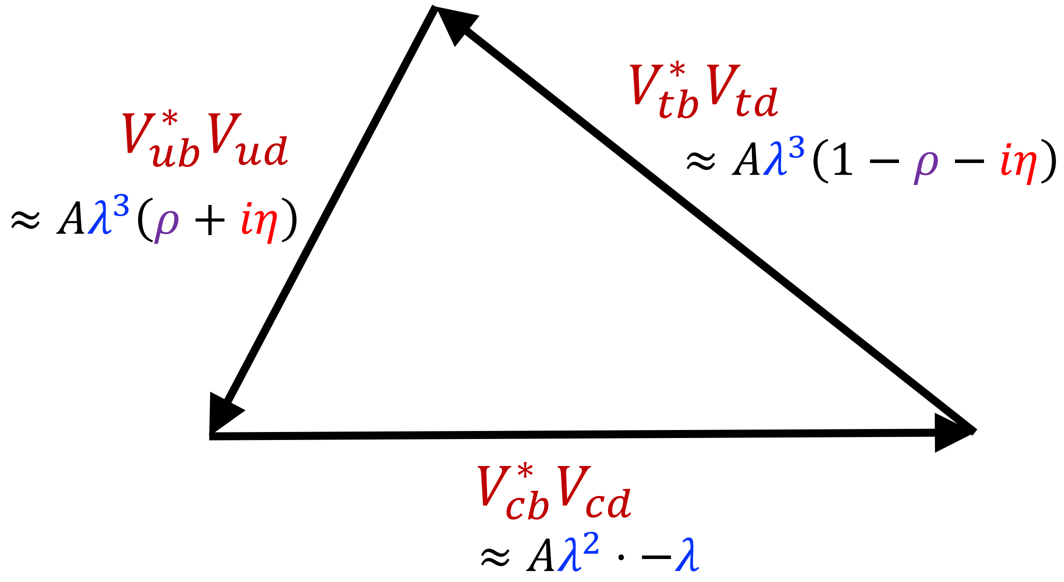
The CKM matrix and unitarity triangle

- The CKM is a mixing matrix, ie. a complex rotation in 3x3 flavour space
  - This implies that the matrix is unitary: $V_{CKM}^{\dagger}\, V_{CKM} = 1$

$$\begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- There are 9 orthonormality equations
  - Example: $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$

Triangle in the complex plane:



- Wolfenstein parametrization:

$$V_{CKM} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\,\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

The CKM matrix and unitarity triangle

- The CKM is a mixing matrix, ie. a complex rotation in 3x3 flavour space
  - This implies that the matrix is unitary: $V_{CKM}^{\dagger} V_{CKM} = 1$

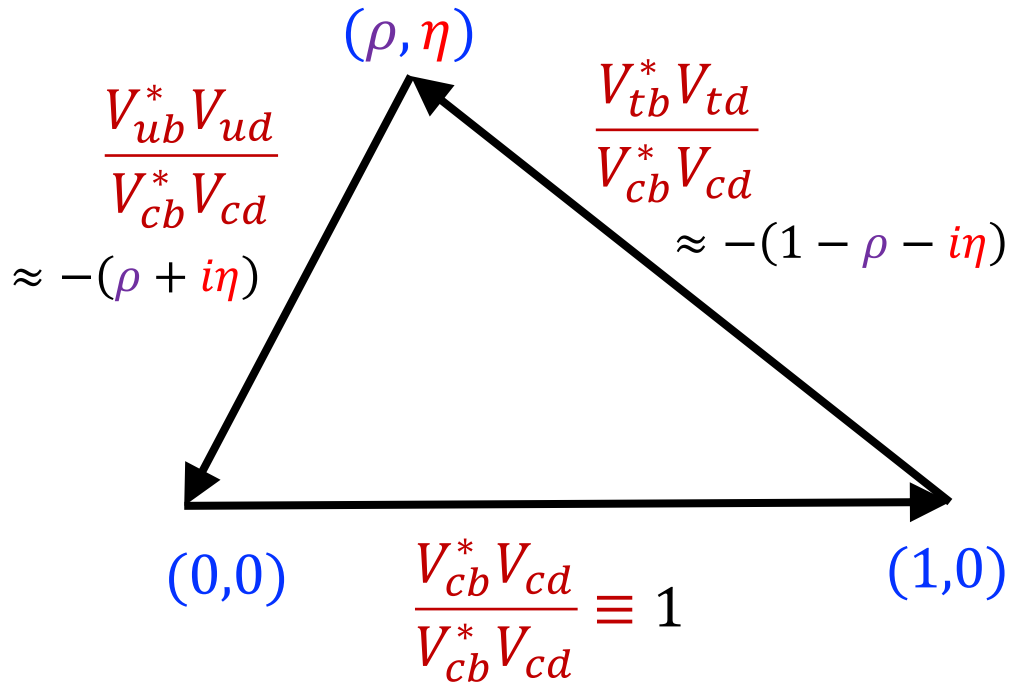
$$\begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- There are 9 orthonormality equations
  - Example: $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$

- Wolfenstein parametrization:

$$V_{CKM} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Triangle in the complex plane:



Renormalize horizontal scale to 1

The CKM matrix and unitarity triangle

- CKM in terms of ***phases***:

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

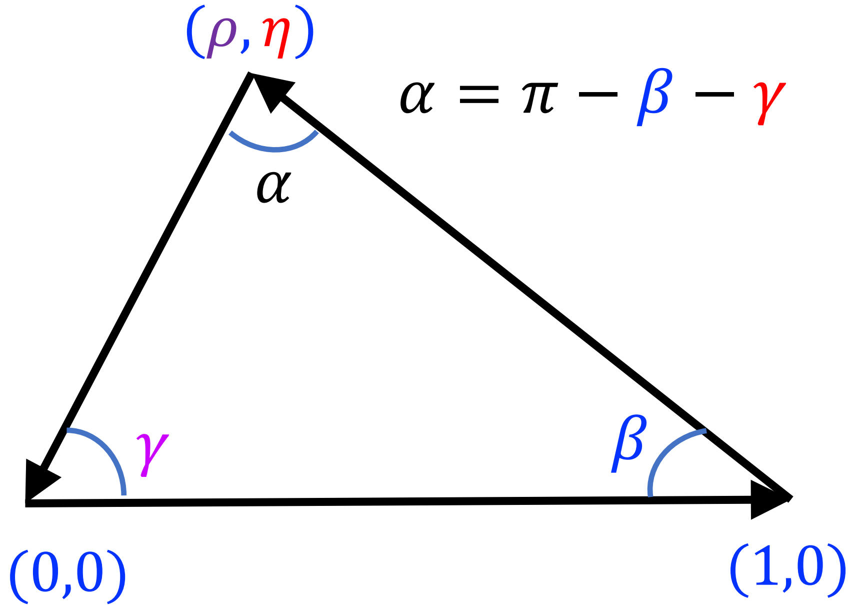
- There are 9 orthonormality equations
  - 9 complex numbers: 9 real + 9 imaginary
  - 5 unobservable *relative* quark phases: $\psi_i' \to e^{\phi_i}\psi_i$
  - 18 – 9 – 5 = 4 degrees of freedom

- Wolfenstein parametrization:

$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\,\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$V_{CKM}^{\dagger} V_{CKM} = 1$$

Triangle in the complex plane:



- There are 4 degrees of freedom:
  - 3 real (Euler angles) and one phase

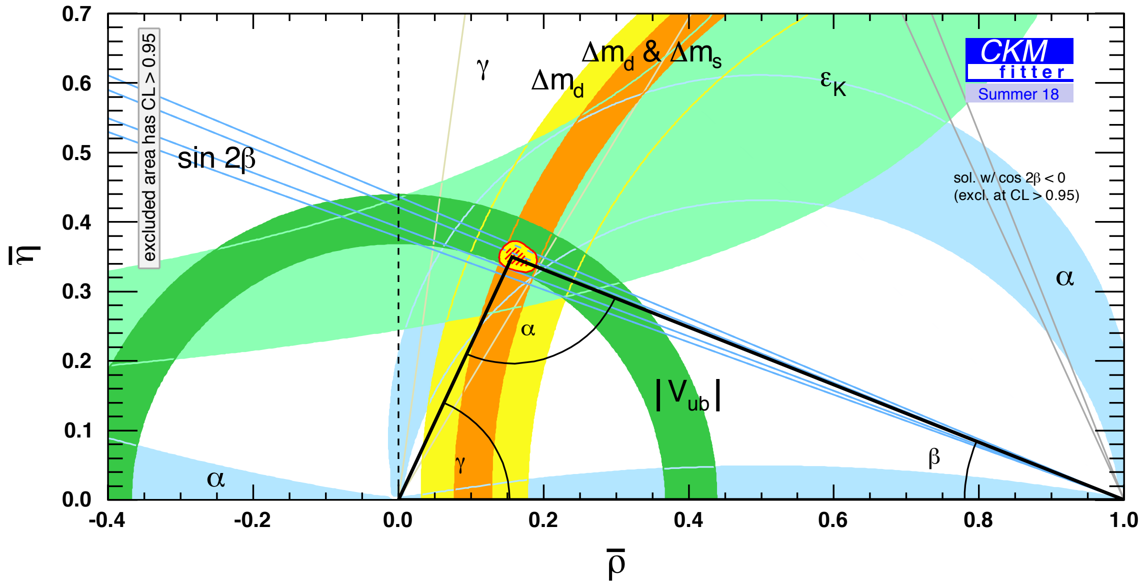
The CKM matrix and unitarity triangle

- CKM in terms of ***phases***:

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

Triangle in the complex plane:

$$V_{CKM}^{\dagger} V_{CKM} = 1$$



- Wolfenstein parametrization:

$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- CP Violation:
  - Non-zero unitary phases
  - Triangle surface $\neq 0$
    - Jarlskog invariant “J”

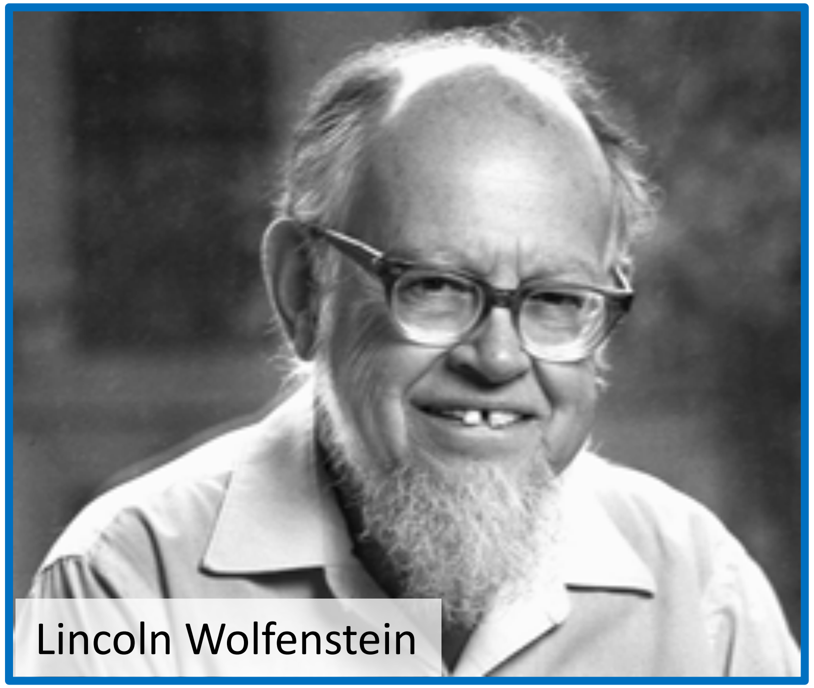
The CKM matrix V_{CKM} - 3 Generations

$$V_{CKM}: \quad \begin{matrix} & d & s & b \\ u & V_{ud} & V_{us} & V_{ub} \\ c & V_{cd} & V_{cs} & V_{cb} \\ t & V_{td} & V_{ts} & V_{tb} \end{matrix}$$

- Wolfenstein parametrization: V_{CKM} =

$$\begin{pmatrix} 1-{}^{1}/_{2}\,\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-{}^{1}/_{2}\,\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

➔ 1 CP violating phase


Lincoln Wolfenstein

The CKM matrix V_{CKM} - 3 vs 2 Generations

$$V_{CKM}: \quad \begin{array}{c|ccc} & d & s & b \\ \hline u & V_{ud} & V_{us} & V_{ub} \\ c & V_{cd} & V_{cs} & V_{cb} \\ t & V_{td} & V_{ts} & V_{tb} \end{array}$$

- Wolfenstein parametrization: V_{CKM} =

$$\begin{pmatrix} 1 - {}^1/_2\,\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - {}^1/_2\,\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

➔ 1 CP violating phase

$$V_{CKM}: \quad \begin{array}{c|cc} & d & s \\ \hline u & V_{ud} & V_{us} \\ c & V_{cd} & V_{cs} \end{array}$$

1 free variable =
8 (4 complex)
– 4 orthonormality
– 3 quark phases

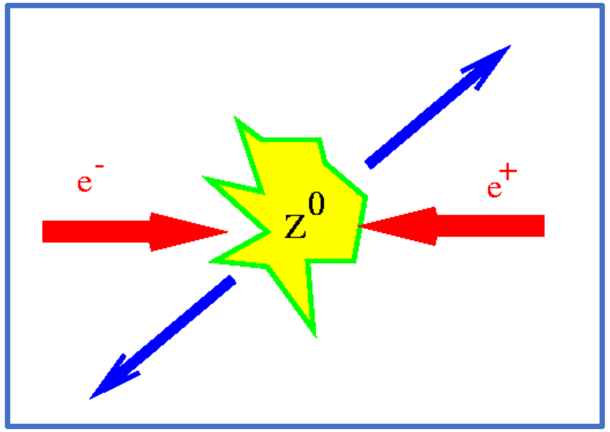
$$V_{CKM} = \begin{pmatrix} 1 - {}^1/_2\,\lambda^2 & \lambda \\ -\lambda & 1 - {}^1/_2\,\lambda^2 \end{pmatrix}$$

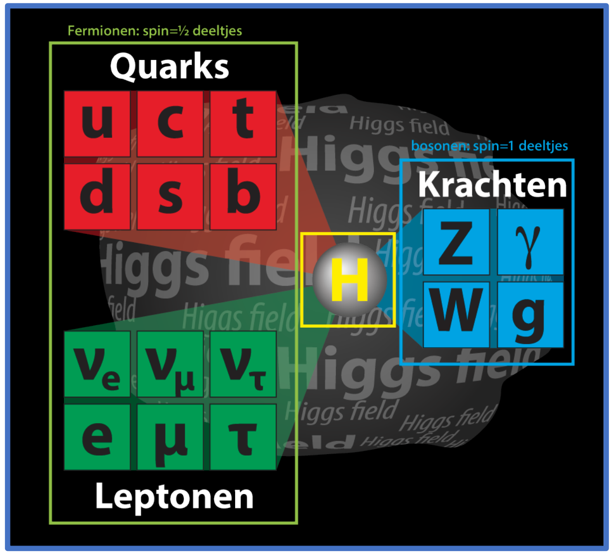
➔ No CP violation

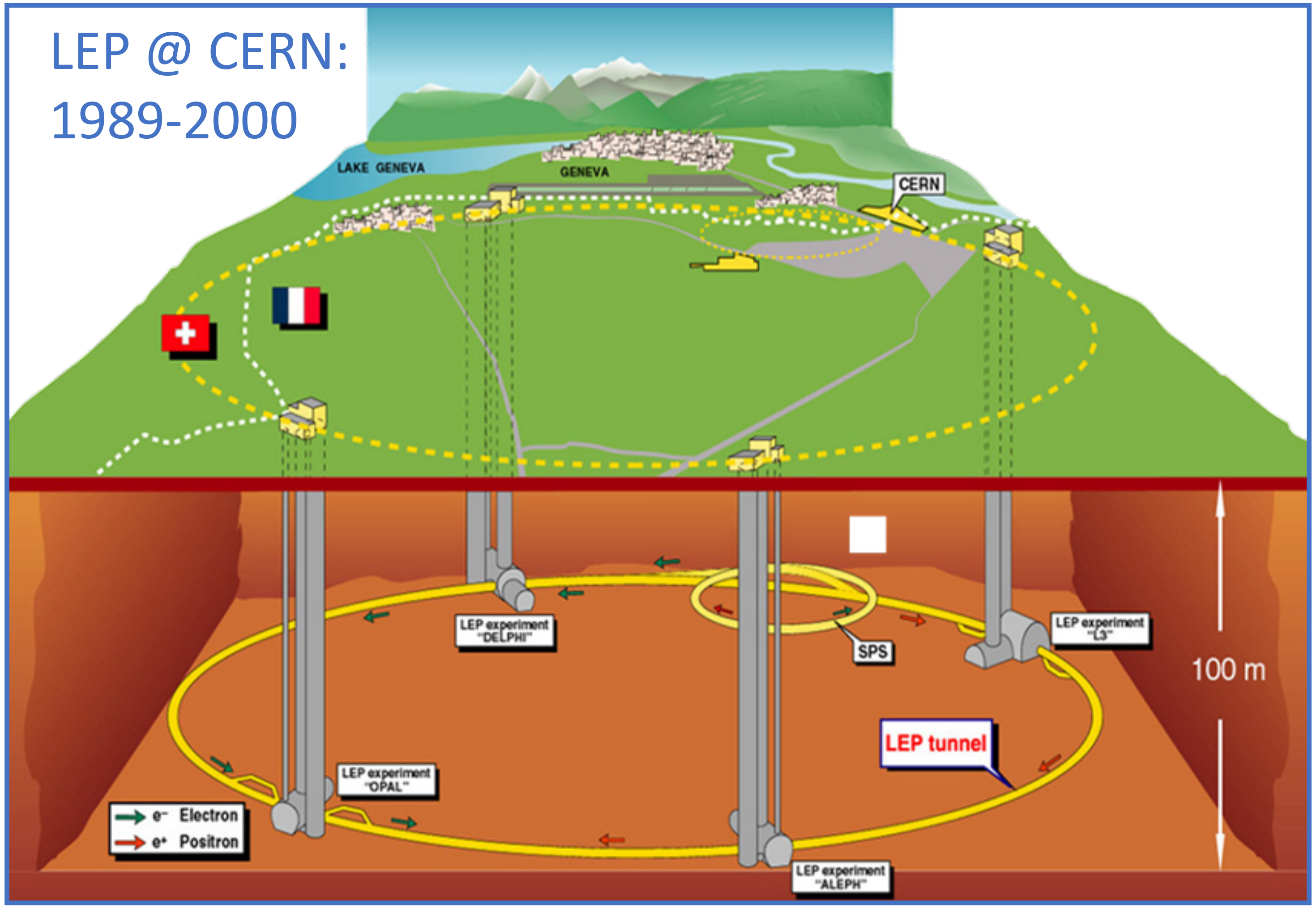
- *3 generations is the minimal particle content to generate CP violation* (In Standard Model).

3 Generations of particles – How do we know?

LEP: The heavy Z boson decays into 3 light neutrino types.



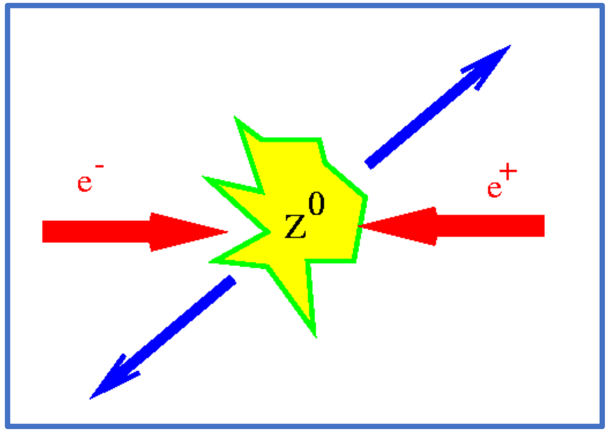


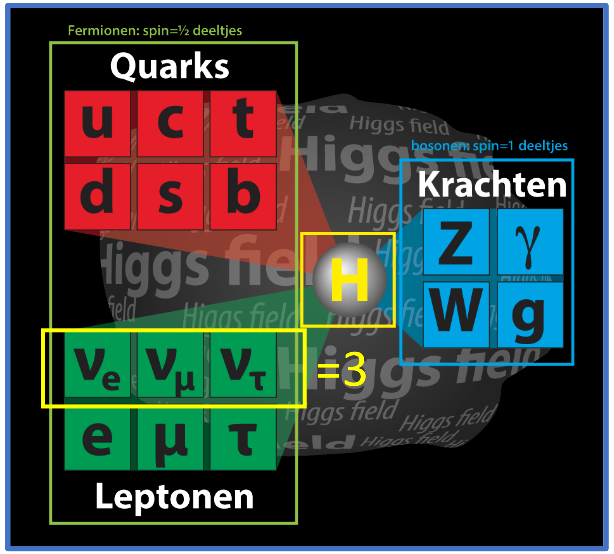


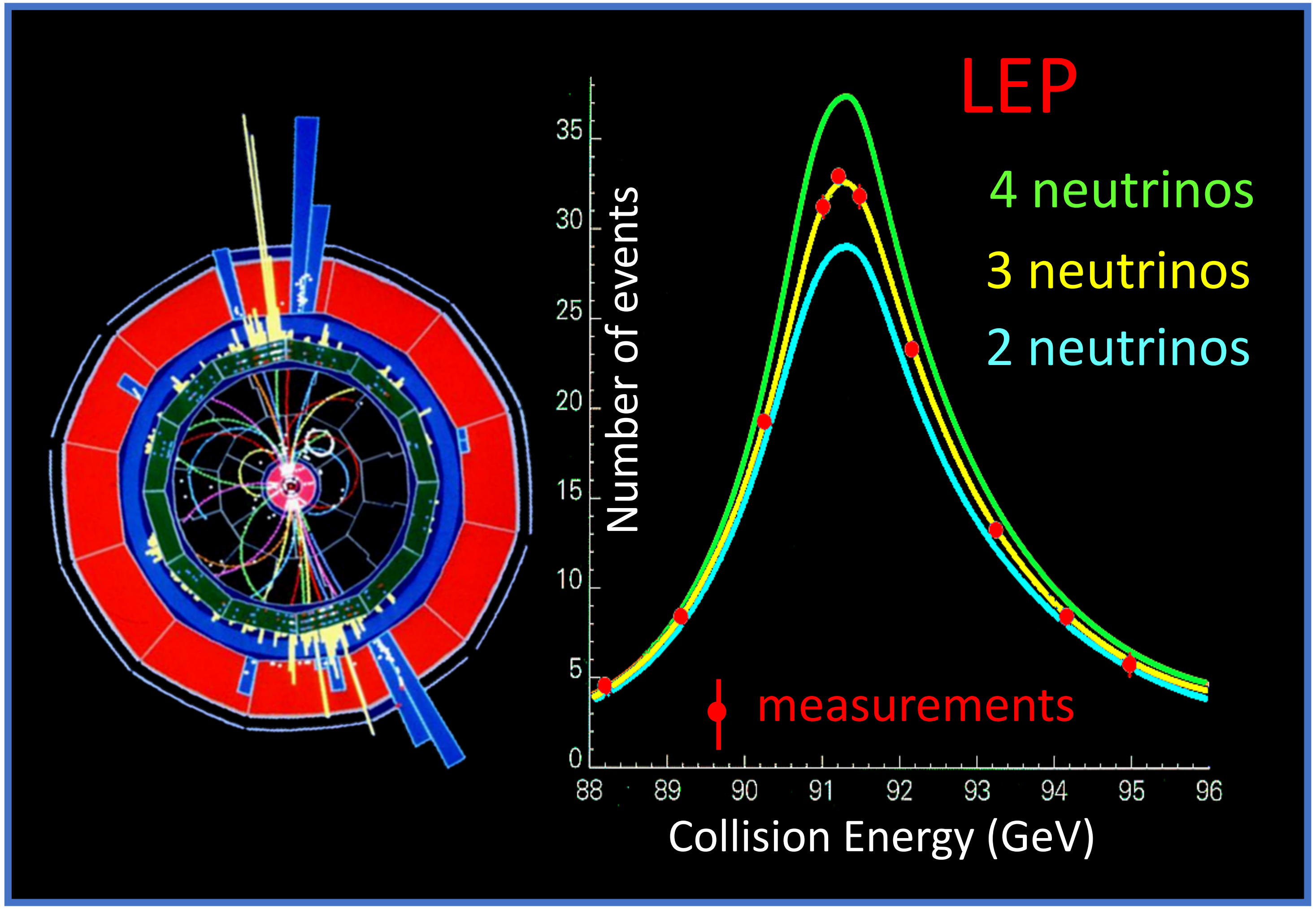
- *No additional weakly interacting **light fermion** generations.*

3 Generations of particles – How do we know?

LEP: The heavy Z boson decays into 3 light neutrino types.





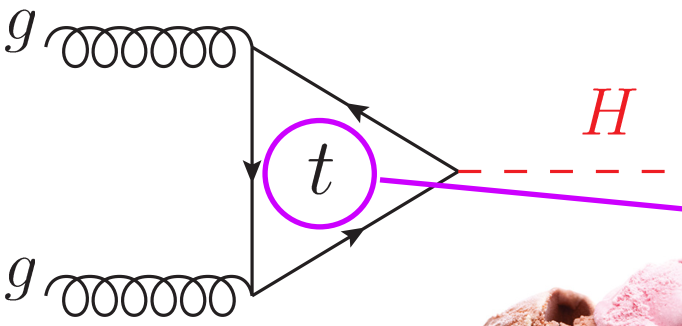


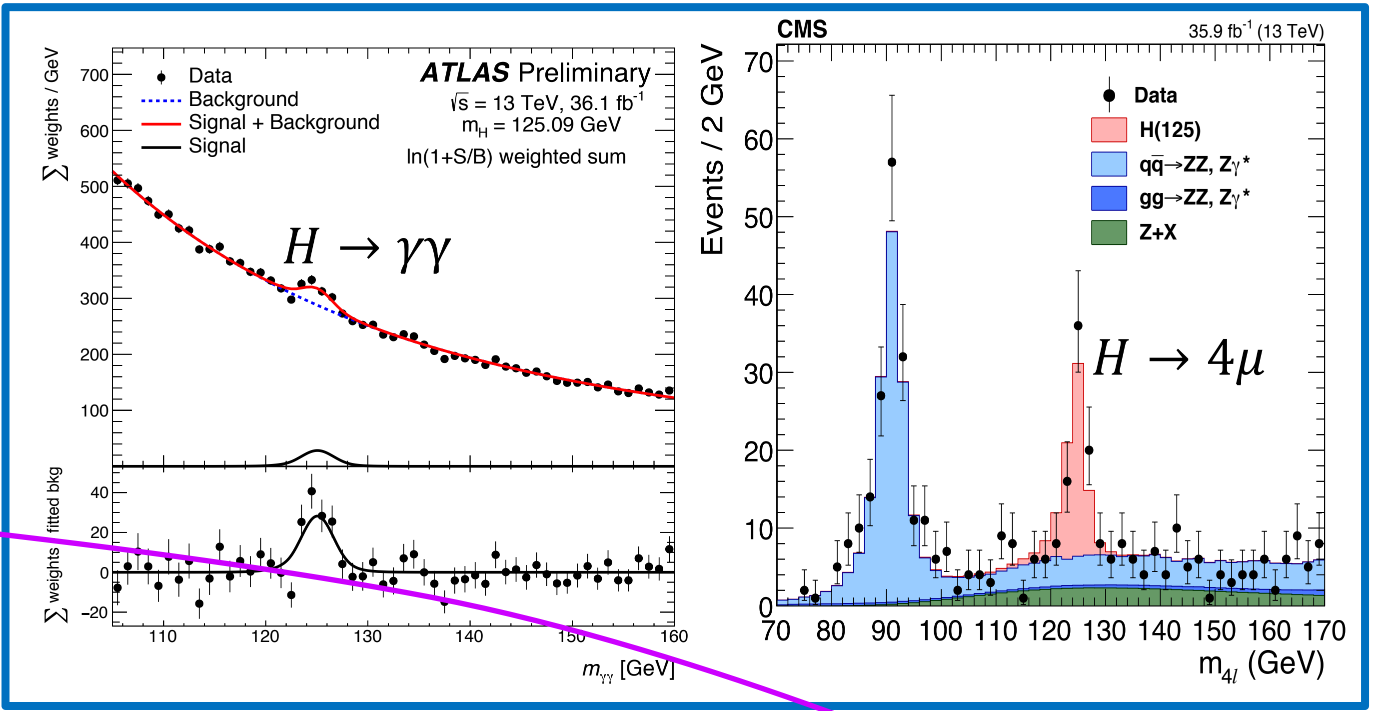
- *No additional weakly interacting **light fermion** generations.*

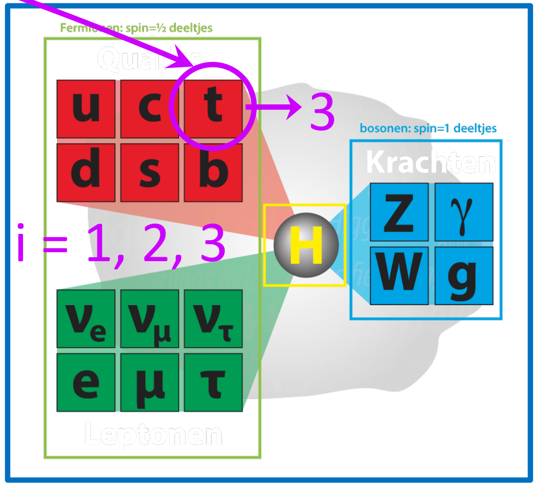
3 Generations of particles – How do we know?

LHC: Higgs production:

Loop diagram is proportional to the mass of the heaviest fermion.







- *Top is the **heaviest fermion** flavour.*

➢ *3 Flavour generations*

How about leptons?

- Equivalent of CKM-Matrix V_{CKM} for leptons is PMNS-Matrix
  - Pontecorvo-Maki-Nakagawa-Sakata matrix: U_{PMNS}

- Neutrinos: U_{PMNS}

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

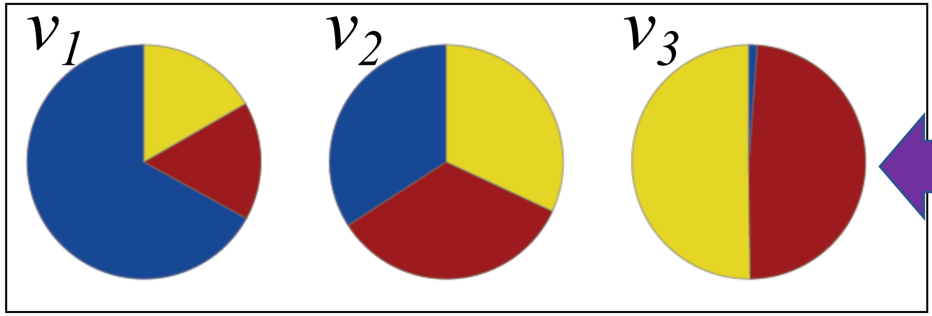
$$U_{MNSP} \approx \begin{pmatrix} 0.82 & 0.55 & 0.15 \\ 0.37 & 0.57 & 0.70 \\ 0.39 & 0.59 & 0.69 \end{pmatrix}$$

- Quarks: V_{CKM}

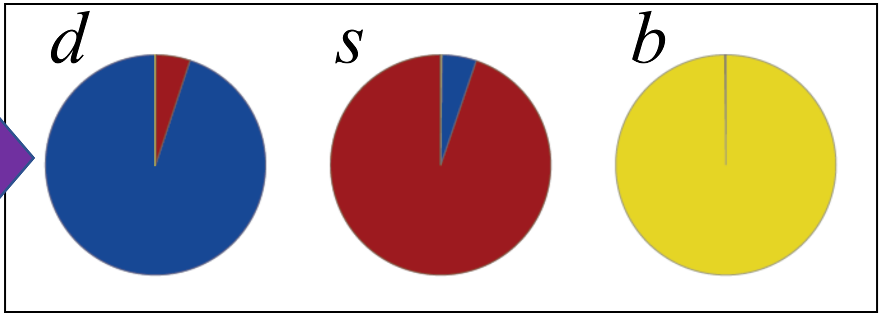
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

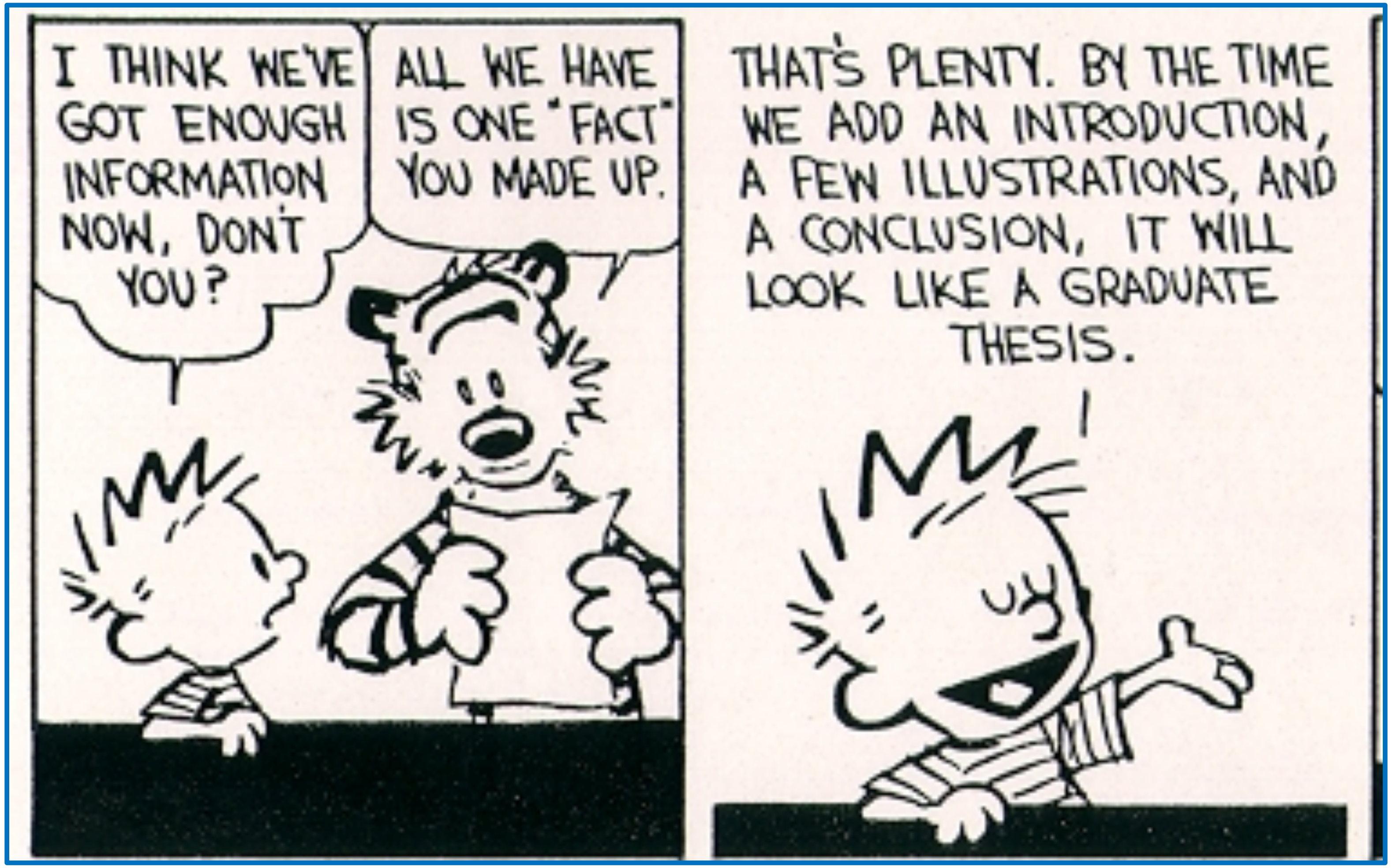
$$V_{CKM} = \begin{pmatrix} 0.97446 & 0.22452 & 0.00365 \\ 0.22438 & 0.97359 & 0.04214 \\ 0.00896 & 0.04133 & 0.99911 \end{pmatrix}$$

?



Completely different hiearchy




I THINK WE'VE GOT ENOUGH INFORMATION NOW, DON'T YOU?
ALL WE HAVE IS ONE "FACT" YOU MADE UP.
THAT'S PLENTY. BY THE TIME WE ADD AN INTRODUCTION, A FEW ILLUSTRATIONS, AND A CONCLUSION, IT WILL LOOK LIKE A GRADUATE THESIS.

Contents per Week:

1. CP Violation
   a) Discrete Symmetries
   b) CP Violation in the Standard Model
   c) Jarlskog Invariant and Baryogenesis
2. B-Mixing
   a) CP violation and Interference
   b) B-mixing and time dependent CP violation
   c) Experimental Aspects: LHC vs B-factory
3. B-Decays
   a) Effective Hamiltonian
   b) Lepton Flavour Non-Universality

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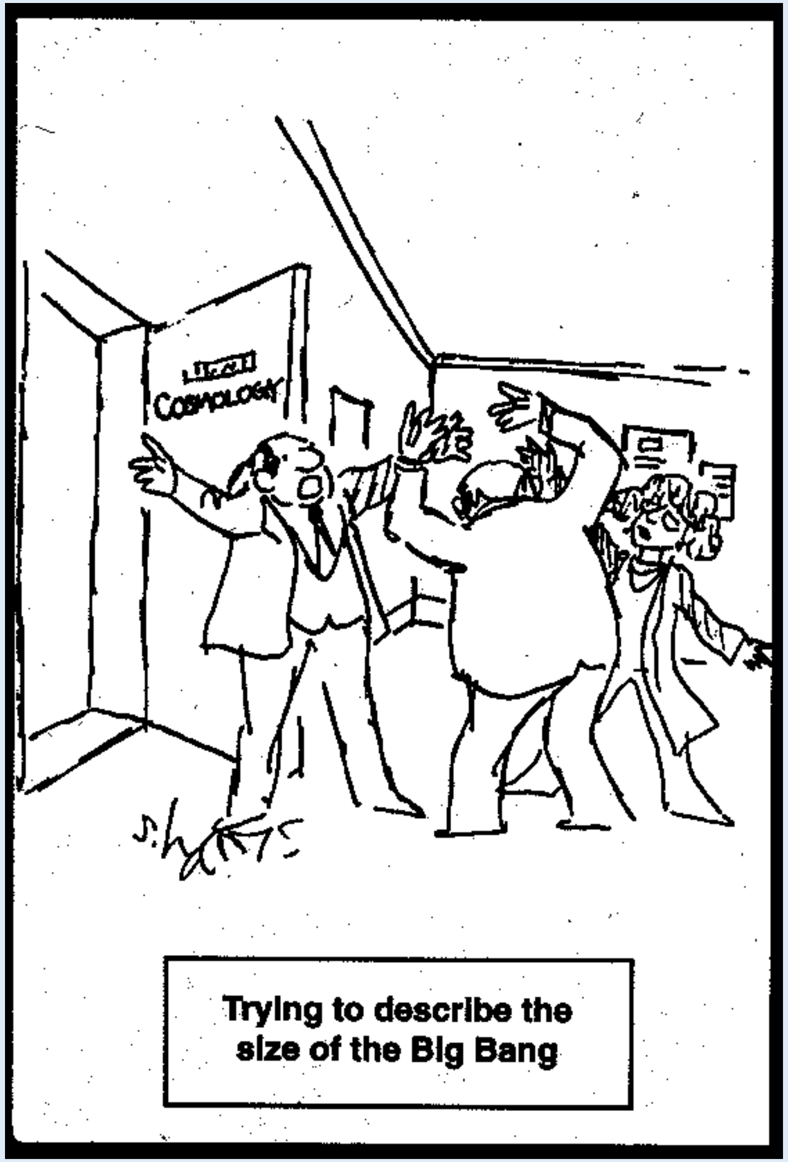
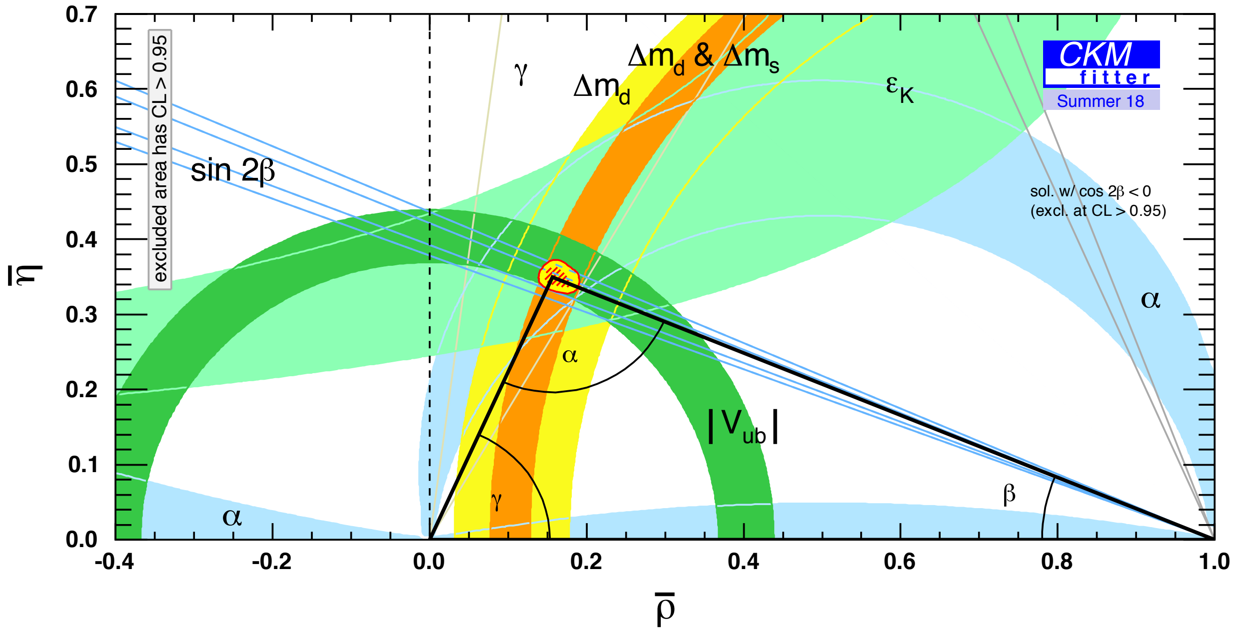


How large is CP violation?

- Large CP violation requires *large mixing* and *large phases* in the CKM matrix.
  - Surface of unitarity triangle
  - Jarlskog invariant: $J = 3 \times 10^{-5}$



- CP violation also requires three generations with non-zero quark masses
  - In fact, ***different*** masses are required:
    - $m_u \neq m_c$; $m_c \neq m_t$; $m_t \neq m_u$
    - $m_d \neq m_s$; $m_s \neq m_b$; $m_b \neq m_d$

- Jarlskog criterion (1987) for amount of CP violation:
  - $\det[M_u M_u^\dagger, M_d M_d^\dagger] = 2\,i\,J\,(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_u^2 - m_t^2)$
    $\times\,(m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_d^2 - m_b^2)$

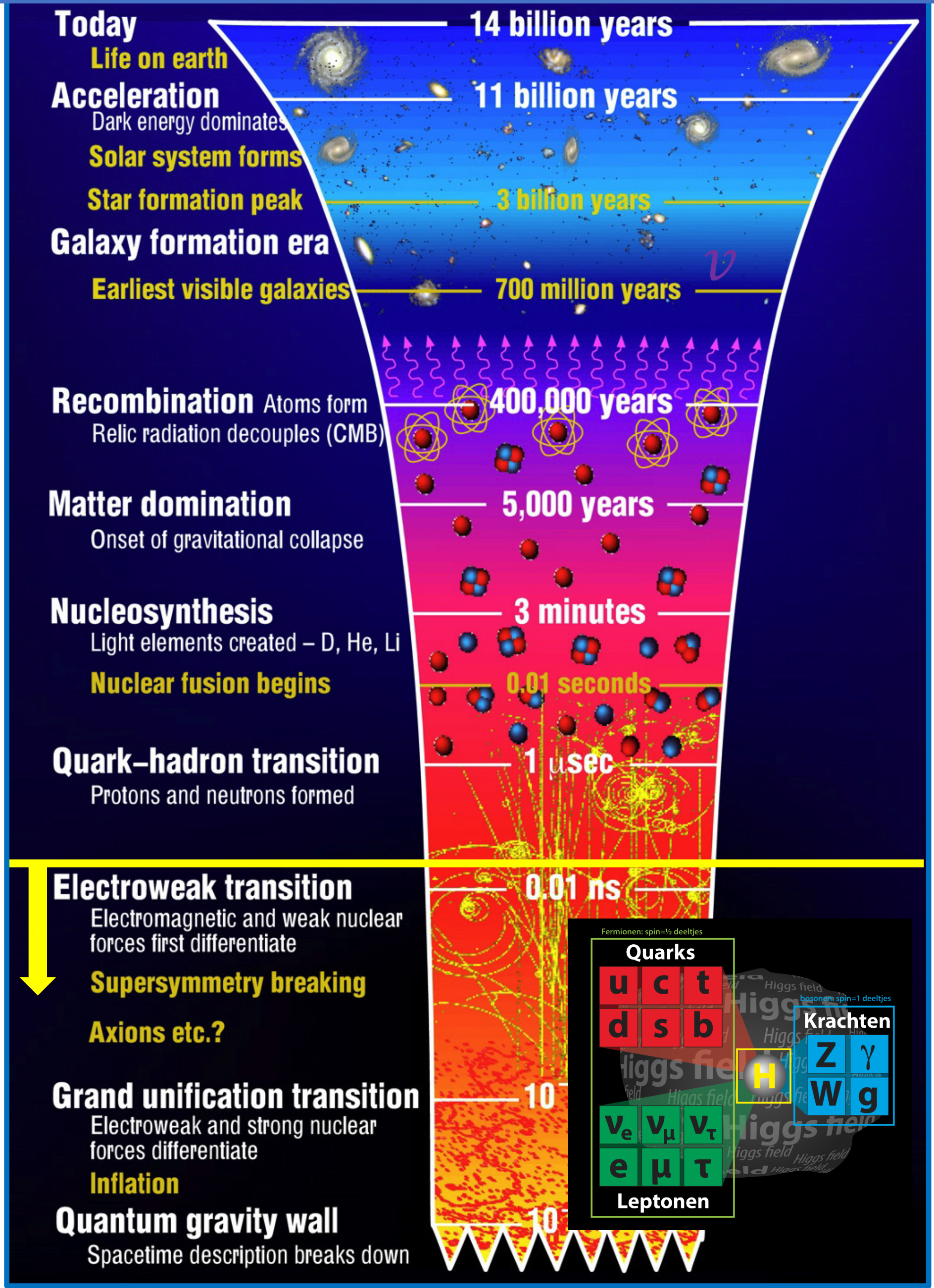
$M_{ij} = Y_{ij}\, v/\sqrt{2}$


Cecile Jarlskog

SU(2)

- W interaction flavour universal

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} u'_L \gamma_\mu W^\mu d'_L$$



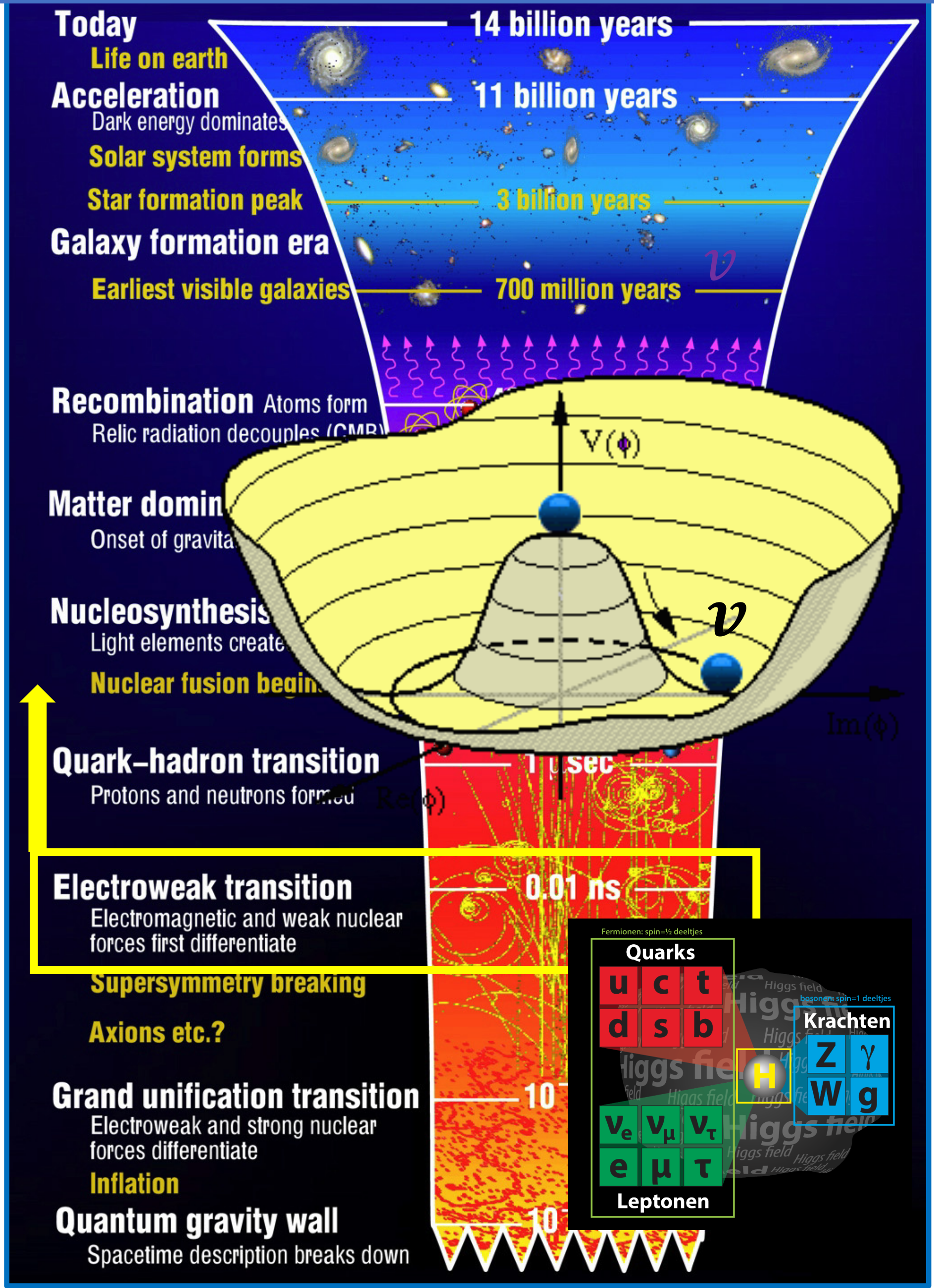
SU(2) → Higgs vev

- W interaction flavour universal

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} u'_L \, \gamma_\mu \, W^\mu \, d'_L$$

- Higgs interaction *not* flavour universal

$$\mathcal{L}_H = Y^d_{ij} \left(\bar{u}'_i, \bar{d}'_i\right)_L \binom{0}{v} \, d'_{jR} + Y^u_{ij} \left(\bar{u}'_i, \bar{d}'_i\right)_L \binom{v}{0} \, u'_{jR}$$



SU(2) → Higgs vev → Origin of Mass

- W interaction flavour universal

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} u'_L \, \gamma_\mu \, W^\mu \, d'_L$$

- Higgs interaction *not* flavour universal

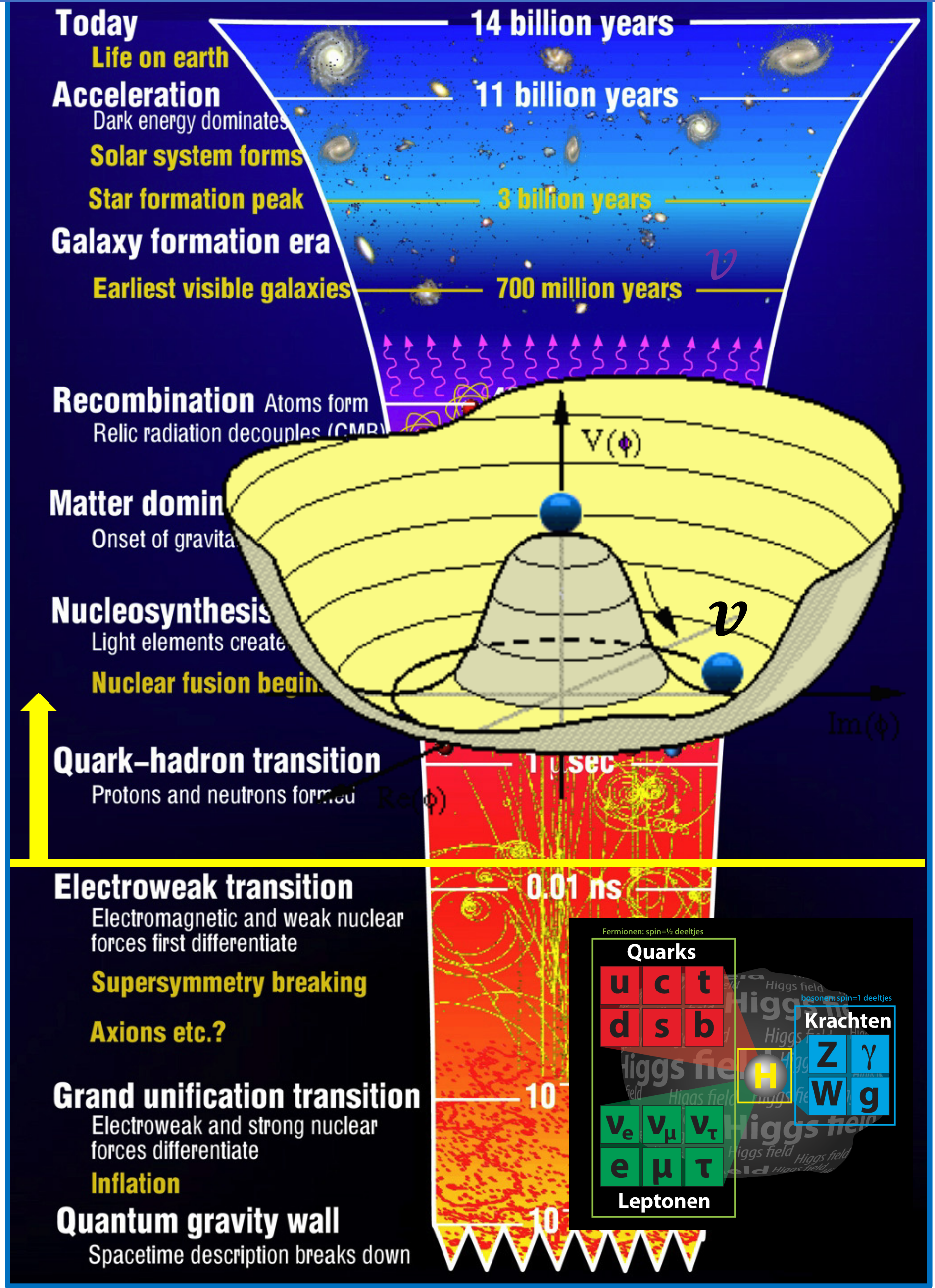
$$\mathcal{L}_H = Y^d_{ij} \left(\overline{u'_i}, \overline{d'_i}\right)_L \begin{pmatrix} 0 \\ v \end{pmatrix} d'_{jR} + Y^u_{ij} \left(\overline{u'_i}, \overline{d'_i}\right)_L \begin{pmatrix} v \\ 0 \end{pmatrix} u'_{jR}$$

- Mass vs Interaction states:

$$u_i = (V^u)_{ij} \, u'_j \qquad\qquad d_i = \left(V^d\right)_{ij} \, d'_j$$

- Amount of CP violation:

$$\det\left[M_u M_u^\dagger , M_d M_d^\dagger\right] = 2\, i\, J \,(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_u^2 - m_t^2) \times (m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_d^2 - m_b^2)$$



SU(2) → Higgs vev → Origin of Mass → Origin of CP violation?

- W interaction flavour universal

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} u'_L \gamma_\mu W^\mu d'_L$$

- Higgs interaction *not* flavour universal

$$\mathcal{L}_H = Y_{ij}^d \left(\overline{u'_i}, \overline{d'_i}\right)_L \begin{pmatrix} 0 \\ v \end{pmatrix} d'_{jR} + Y_{ij}^u \left(\overline{u'_i}, \overline{d'_i}\right)_L \begin{pmatrix} v \\ 0 \end{pmatrix} u'_{jR}$$

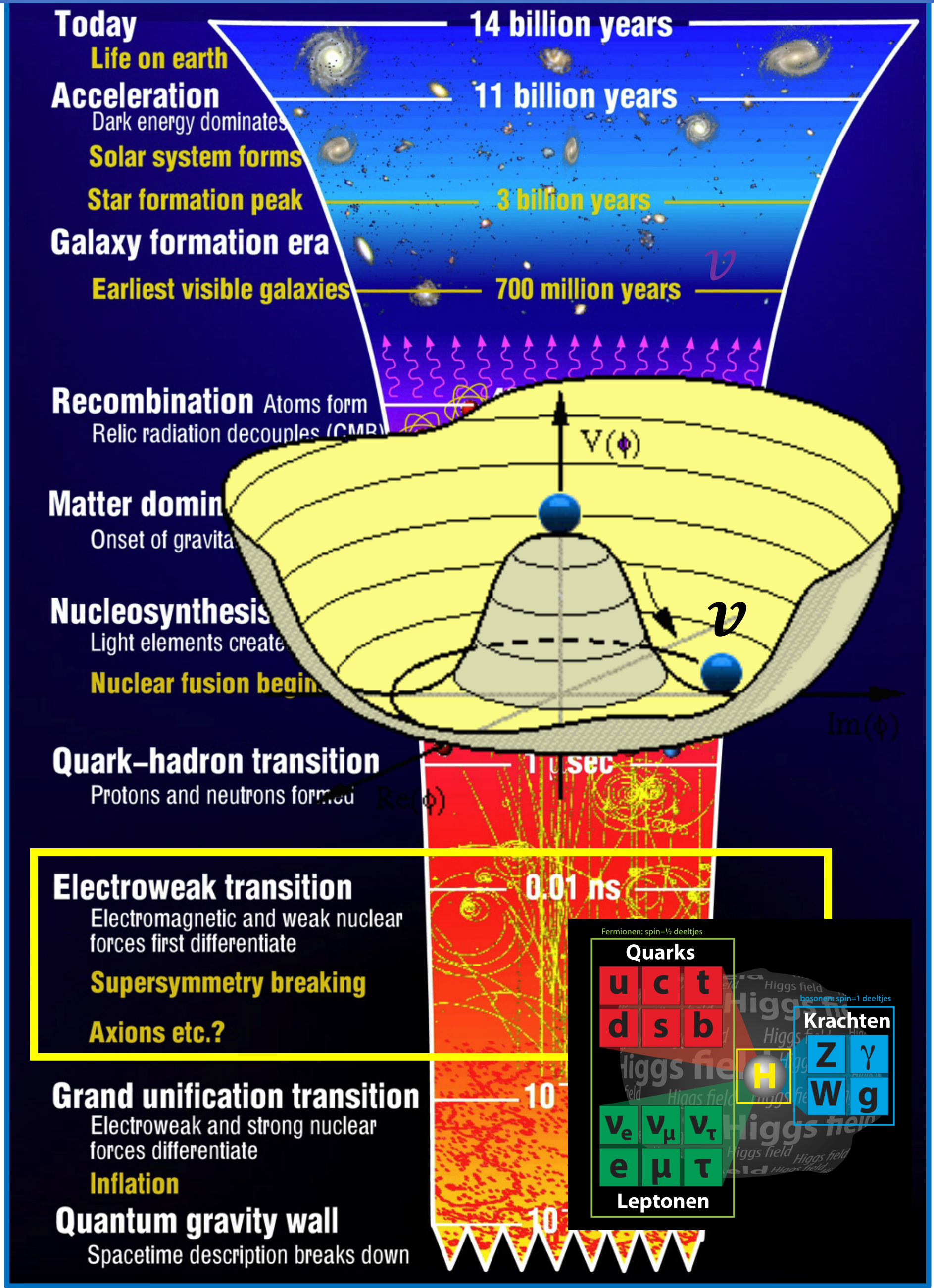
- Mass vs Interaction states:

$$u_i = (V^u)_{ij}\, u'_j \qquad\qquad d_i = (V^d)_{ij}\, d'_j$$

- Amount of CP violation:

$$\det\left[M_u M_u^\dagger, M_d M_d^\dagger\right] = 2\, i\, J\, (m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_u^2 - m_t^2) \times (m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_d^2 - m_b^2)$$

- *Does the Standard Model include CP violation **before** symmetry breaking?*
  - *Is CP violation perhaps an emergent phenomenon?*



The Baryogenesis Puzzle – Electroweak Baryogenesis?

- Sacharov Conditions
  - ✓All present in S.M.

Baryon asymmetry

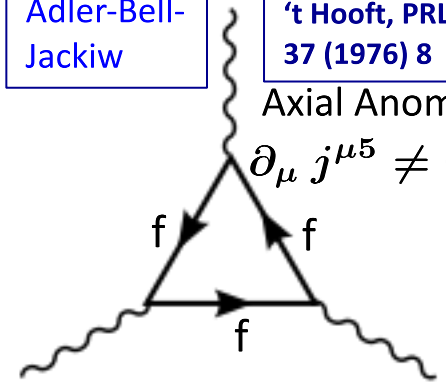
✓ Baryon Number Violation

Adler-Bell-Jackiw

't Hooft, PRL 37 (1976) 8

Axial Anomaly:

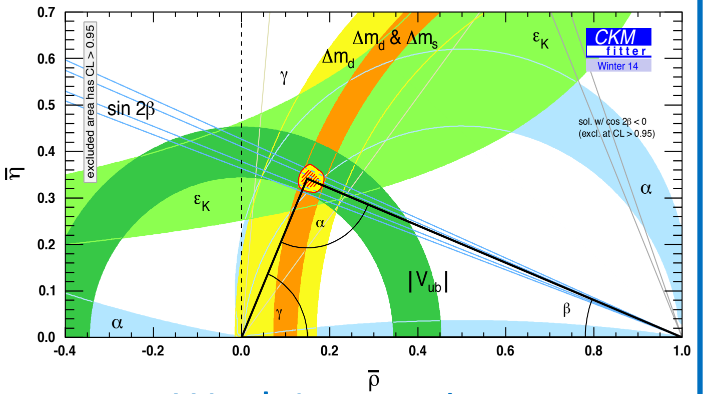
$$\partial_\mu j^{\mu 5} \neq 0$$



Quantum anomaly

Matter - antimatter asymmetry

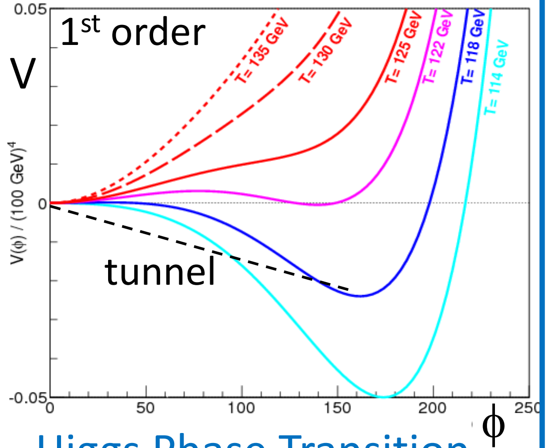
✓ C and CP Violation



Weak Interaction

Non - reversal

✓ Thermal non-equilibrium

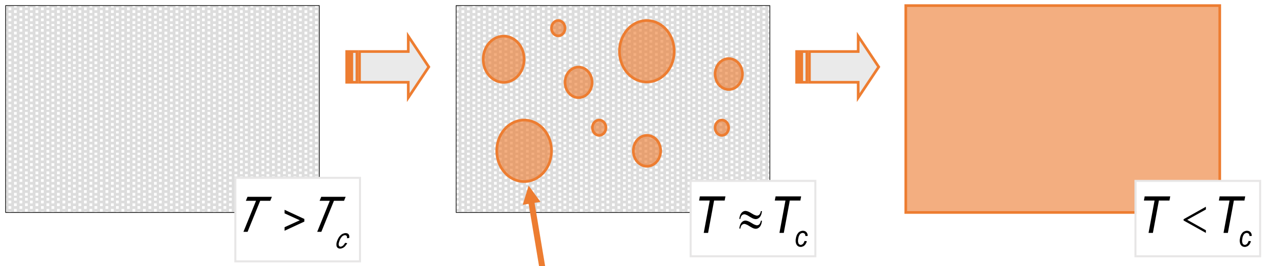


Higgs Phase Transition

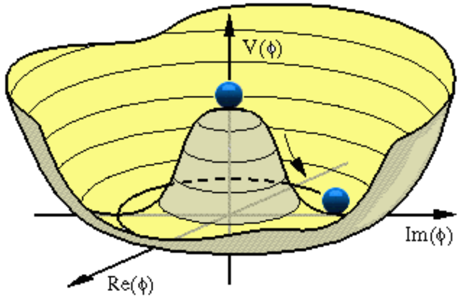
- Baryogenesis from Higgs symmetry breaking?

symmetric phase

broken phase



expanding bubble (Higgs condensates)



The Baryogenesis Puzzle – Electroweak Baryogenesis?

- Sacharov Conditions
  - ✓ All present in S.M.
  - ✗ Not Enough?

Baryon asymmetry

✓ **Baryon Number Violation**

Adler-Bell-Jackiw

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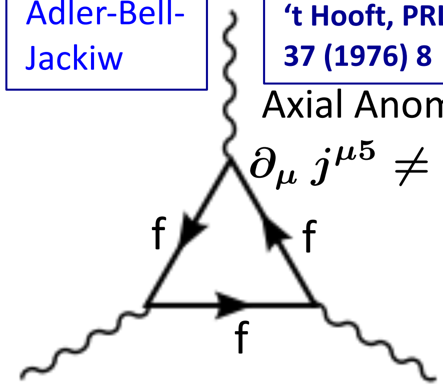
Axial Anomaly:

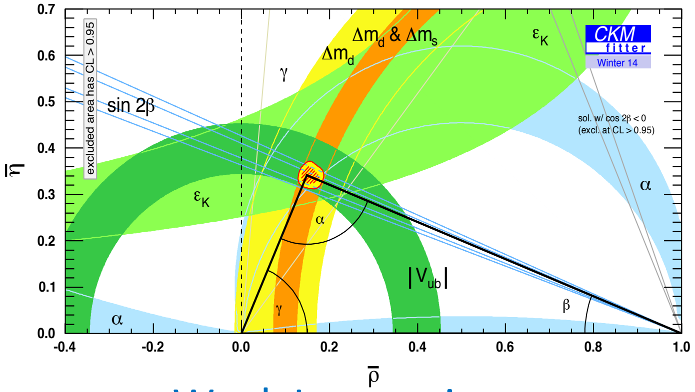
$$\partial_\mu j^{\mu 5} \neq 0$$



Quantum anomaly

Matter - antimatter asymmetry

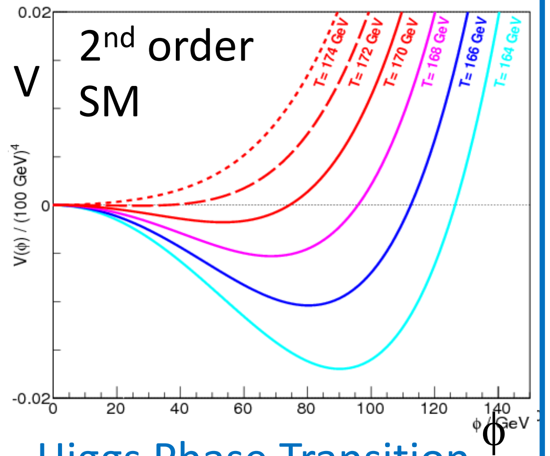
✗ **C and CP Violation**



Weak Interaction

Non - reversal

✗ **Thermal non-equilibrium**

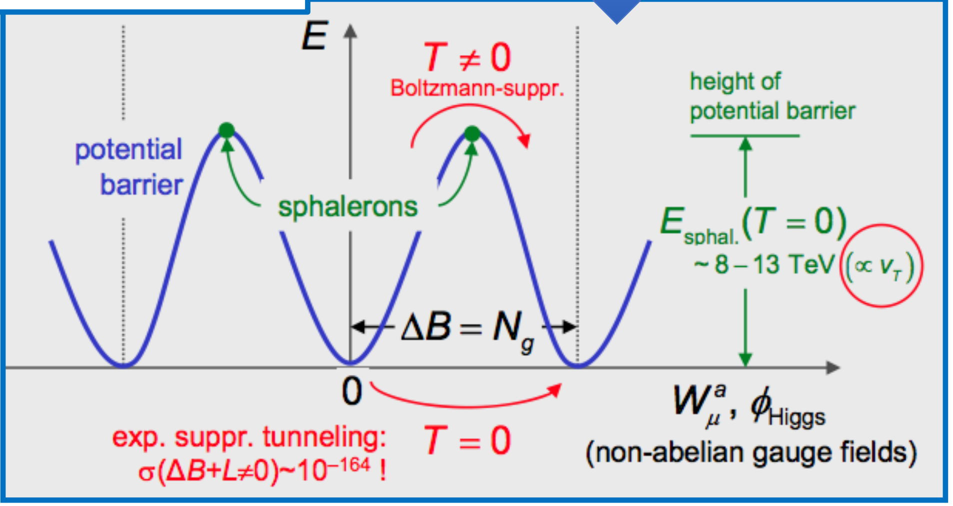


Higgs Phase Transition

✗ 1st order?

- SM: $M_H <$ ~70 GeV
- THDM: M_H ~ 125 OK

✓ Sphalerons

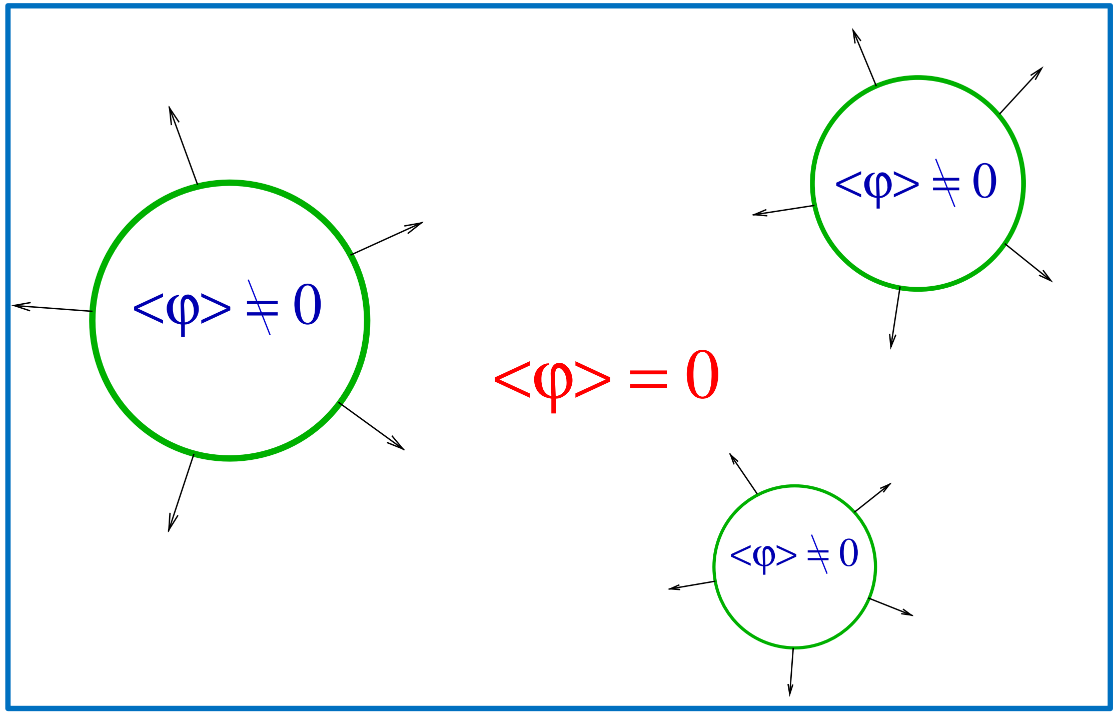


✗ CPV from CKM

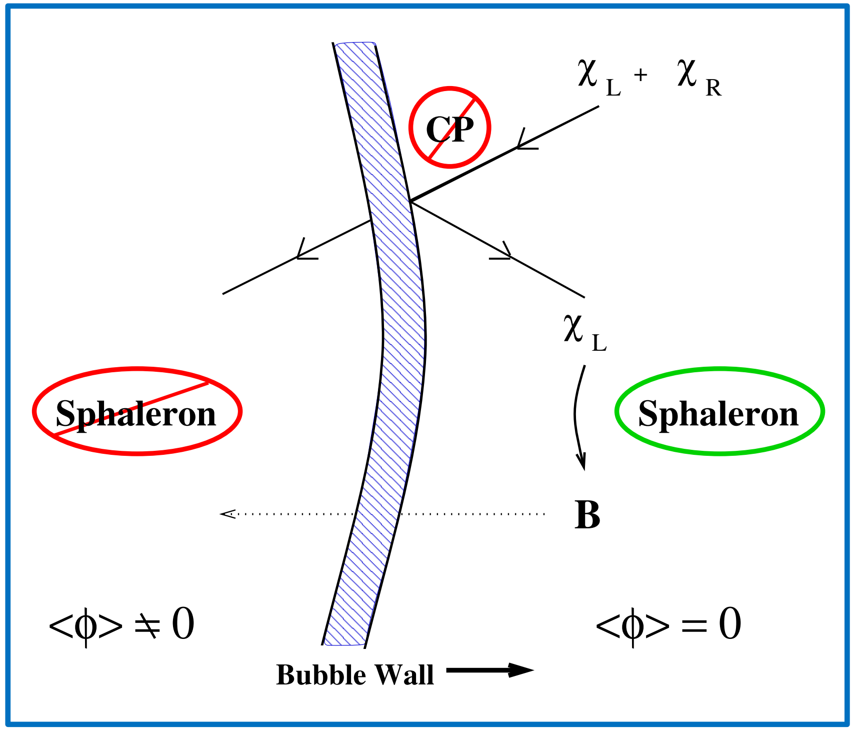
- BAU: $\frac{\Delta n_B}{n_\gamma} \approx 10^{-10}$
- $A_{CP} = J_{inv} \times (m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_u^2 - m_t^2) \times (m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_d^2 - m_b^2)$
  - From CKM: $A_{CP}/T_c^{12} \approx 10^{-20}$ → Too small
  - Used $T_c \sim 100$ GeV

The Baryogenesis Puzzle – Electroweak Baryogenesis?

Expanding bubbles of broken phase
In a medium of symmetric phase



Baryon production in
front of bubble wall



➔ *Was the phase transition in the early universe of 1st order?*

➔ *Higgs potential?*

➔ *If new physics is abundant in thermal plasma of early universe:*

➔ *Likely to be of TeV energy scale.*

Alternative Explanation…

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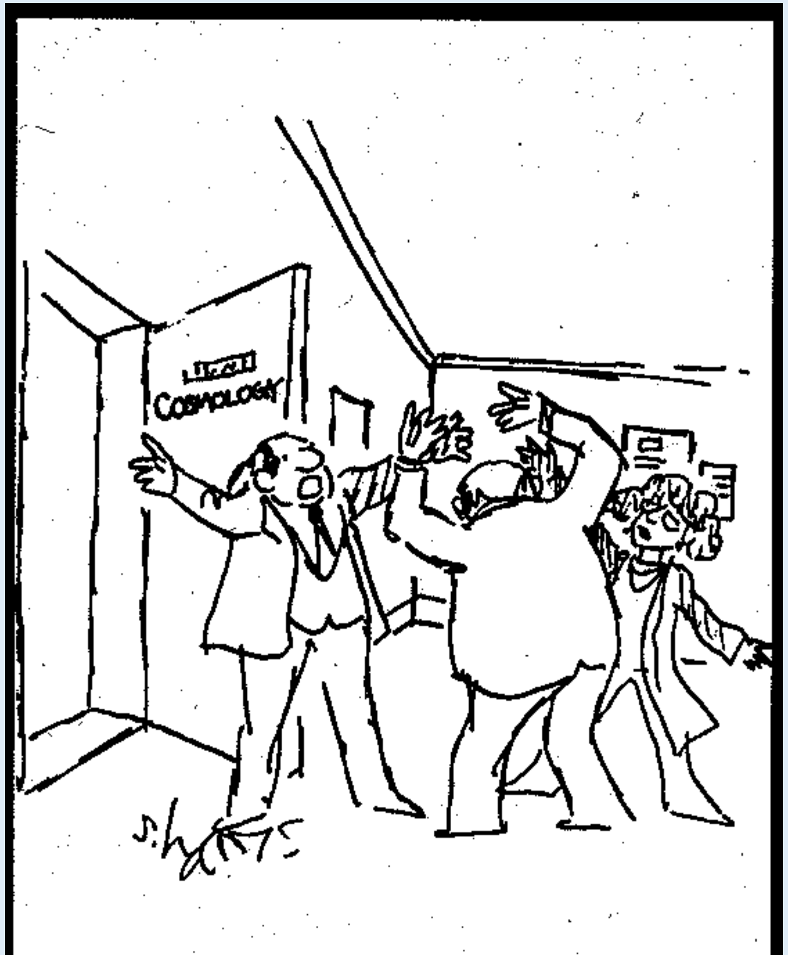
   a) Effective Hamiltonian
   b) Lepton Flavour Non-Universality



Trying to describe the size of the Big Bang