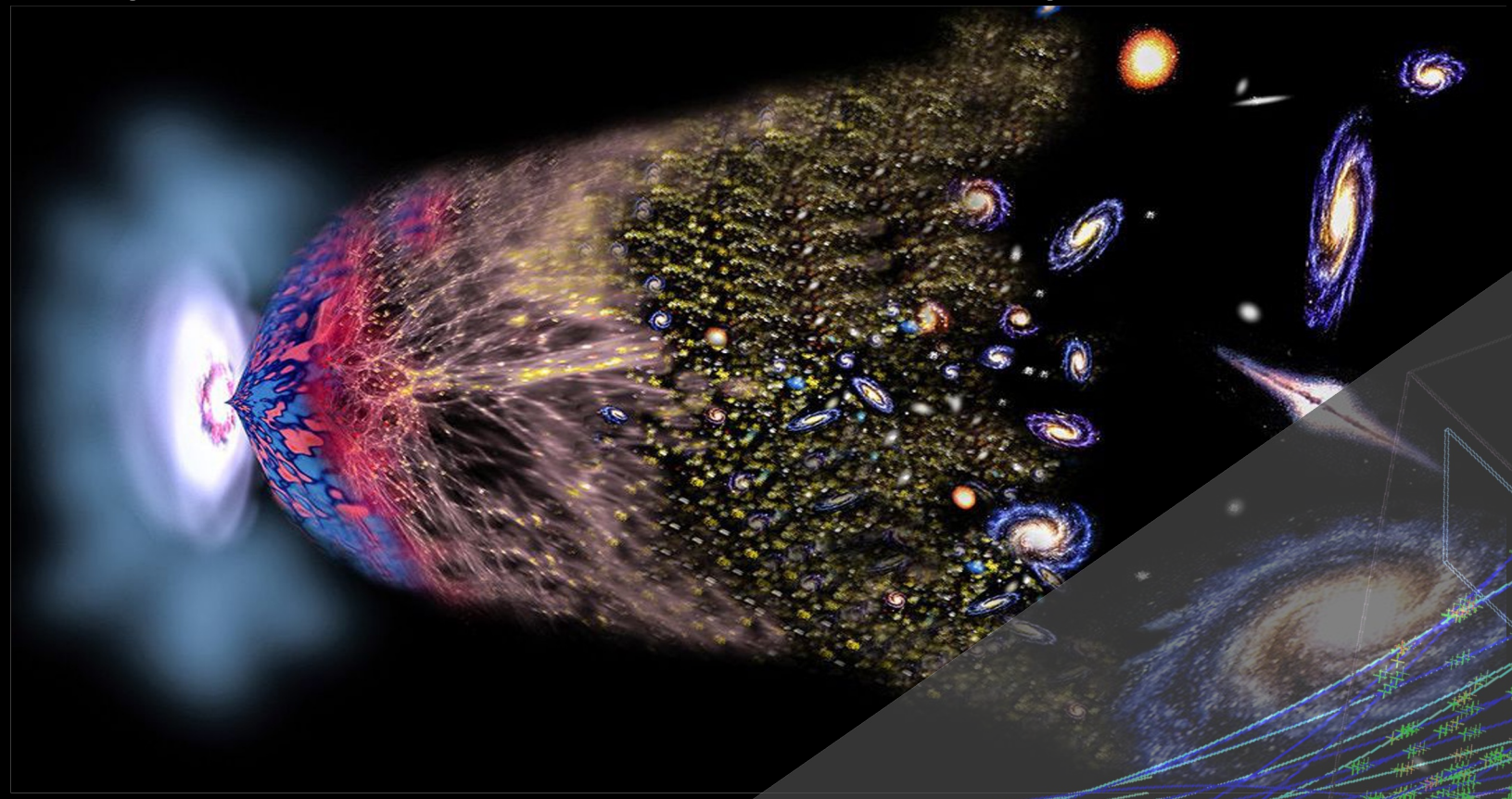
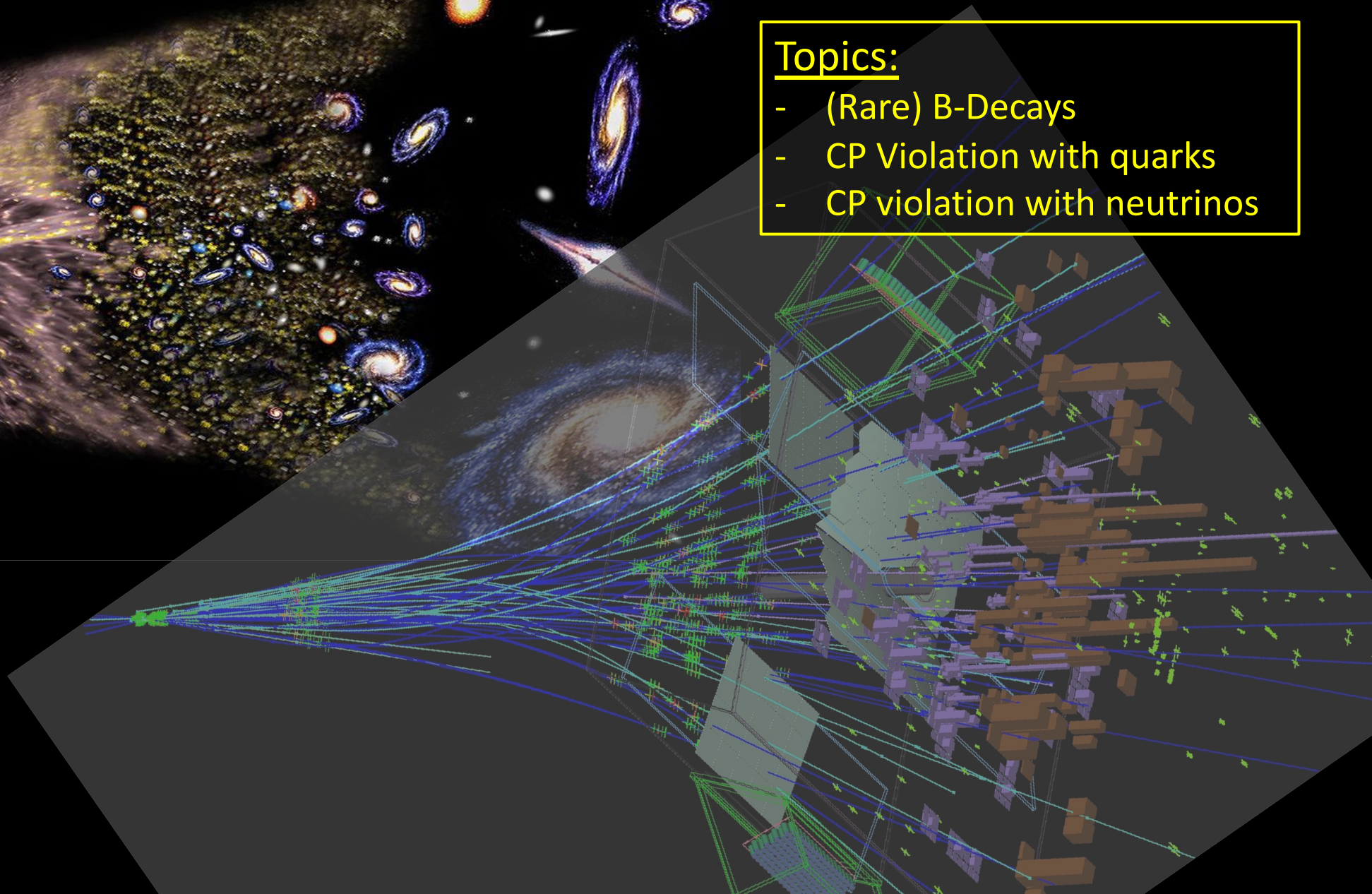
Topical Lectures: Flavour Physics and CP Violation

Nikhef





Topics:

- (Rare) B-Decays
- CP Violation with quarks
- CP violation with neutrinos

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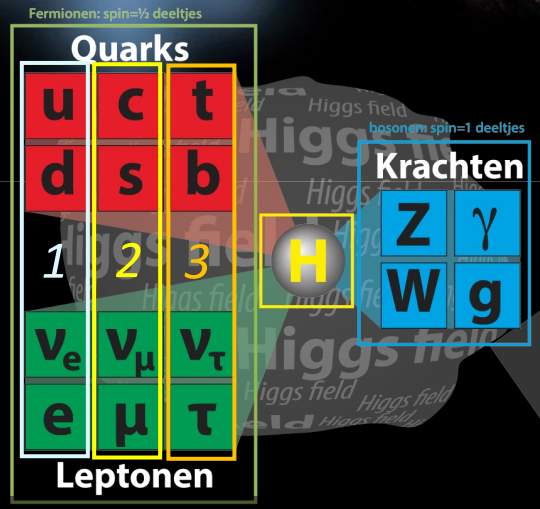
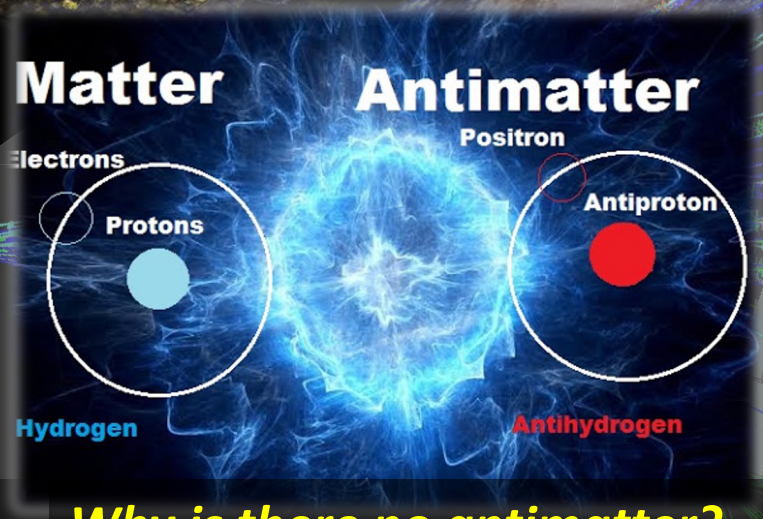
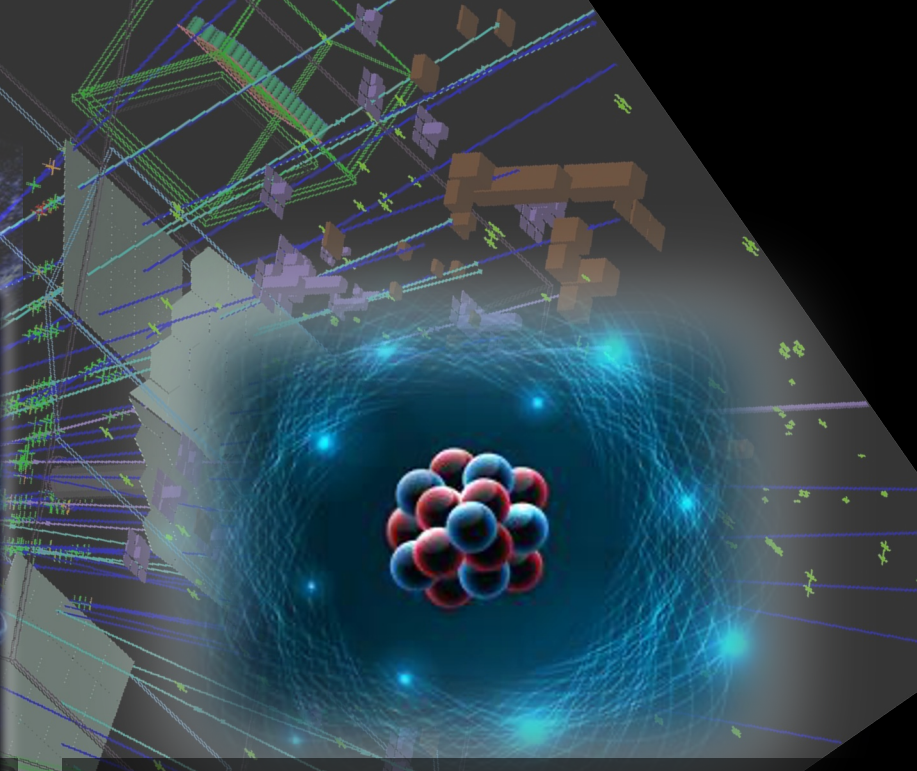


Why three generations of particles?



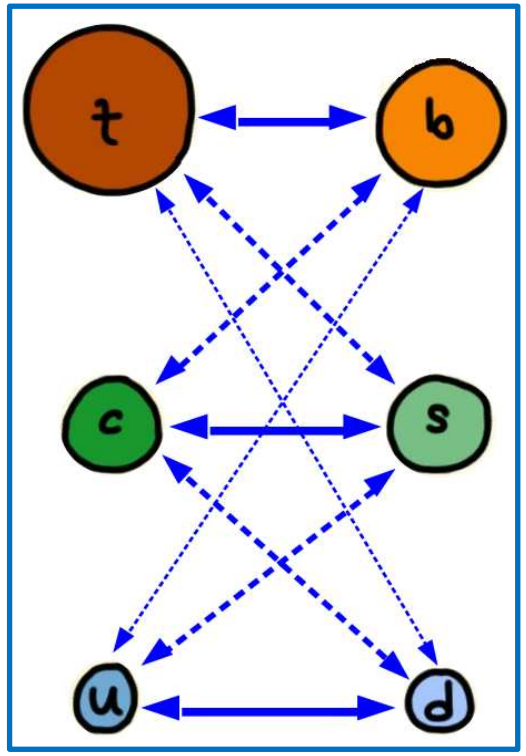
Why is there no antimatter?



Why is an atom electric neutral?

The Antimatter Mystery

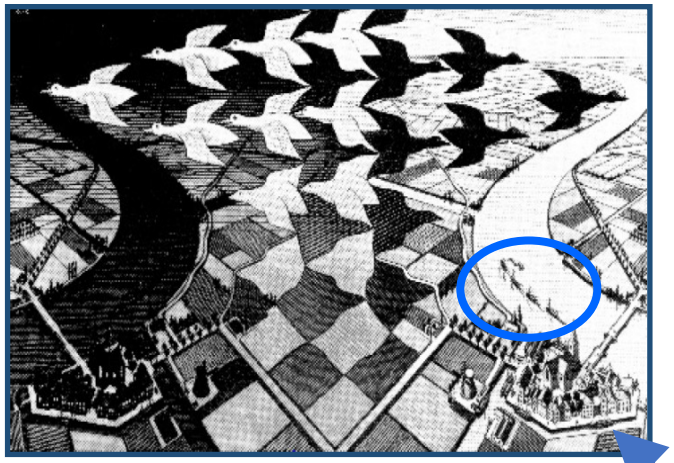
Flavour Physics and CP Violation



Complex amplitudes
in Weak interaction?!

"Day and Night", Escher, 1938

"Matter world"



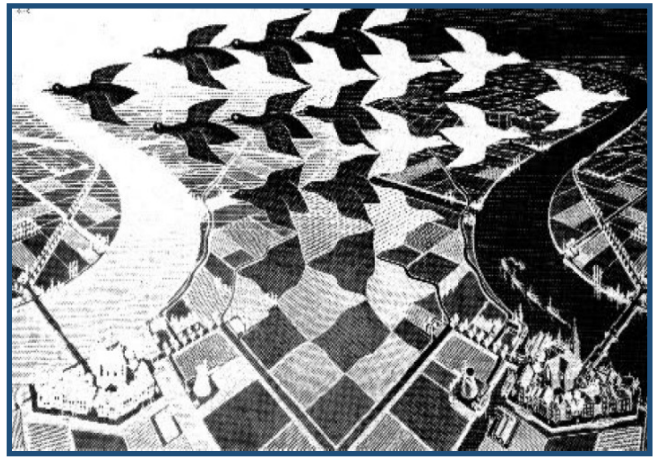
White

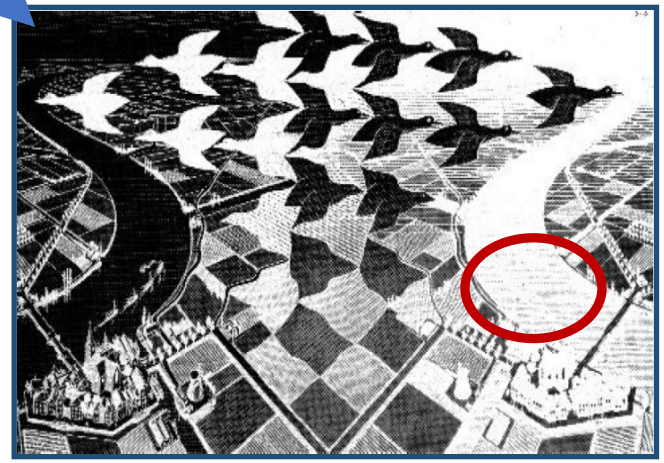
Black

C

CP:

CP Violation!





P

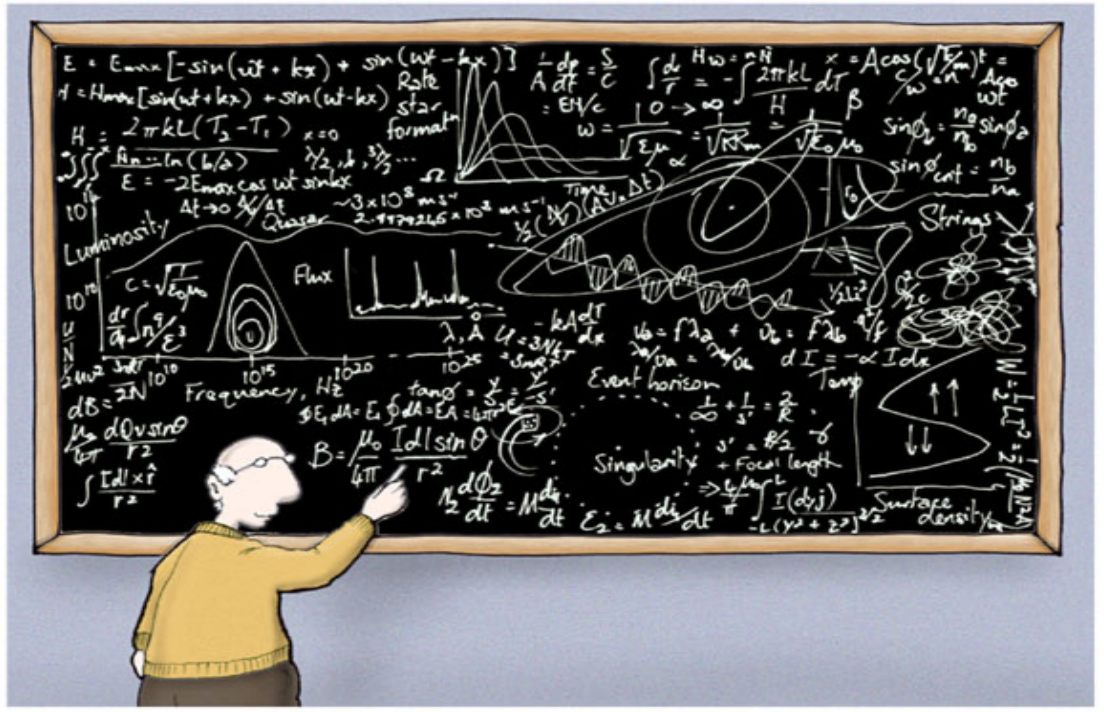
Left

Right

"Antimatter world"

Contents Today & Tomorrow:

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



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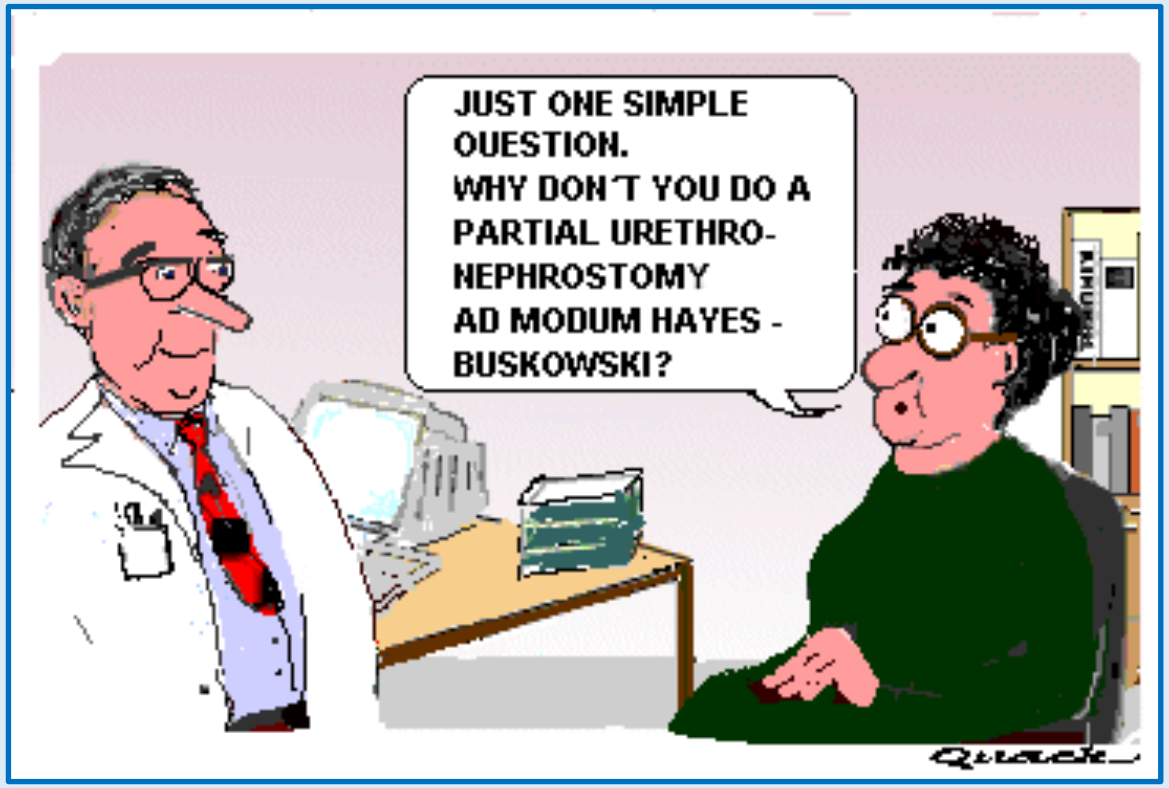
Don't be afraid to ask questions…



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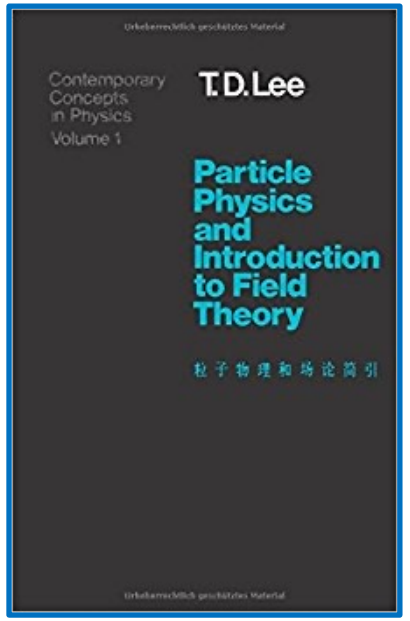
Symmetry and non-Observables

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),…



⇒ If a quantity is fundamentally non-observable it is related to an *exact* symmetry

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

Noether Theorem: symmetry ⇔ conservation law

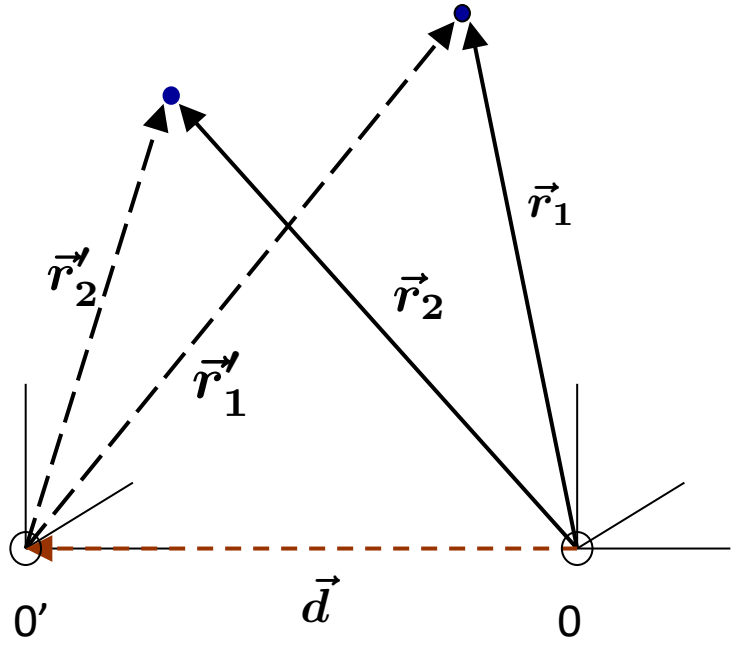
Symmetry and non-Observables

- Simple example: potential energy V between two charged particles:

Absolute position is a non-observable:
The interaction is independent on the choice of the origin 0.

Symmetry:
V is invariant under arbitrary space translations:

$$\vec{r_1} \to \vec{r_1} + \vec{d} \qquad \vec{r_2} \to \vec{r_2} + \vec{d}$$



Consequently:

$$V = V\left(\vec{r}_1 - \vec{r}_2\right)$$

Total momentum is conserved:

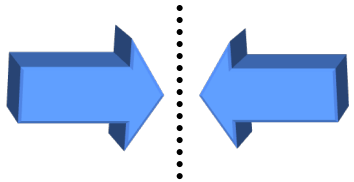
$$\frac{d}{dt}\underbrace{\left(\vec{p}_1 + \vec{p}_2\right)}_{\vec{p}_{\mathrm{tot}}} = \vec{F}_1 + \vec{F}_2 = -\left(\vec{\nabla}_1 + \vec{\nabla}_2\right) V = 0$$

Symmetry and non-observables

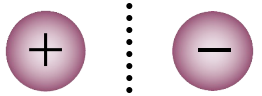
Non-observables	Symmetry Transformations	Conservation Laws or Selection Rule
Difference between identical particles	Permutation	B.-E. or F.-D. statistics
Absolute spatial position	Space translation: $\vec{r} \to \vec{r} + \vec{\Delta}$	momentum
Absolute time	Time translation: $t \to t + \tau$	energy
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	$\begin{pmatrix} p \\ n \end{pmatrix} \to U \begin{pmatrix} p \\ n \end{pmatrix}$	isospin

C, P, T Discrete Symmetries

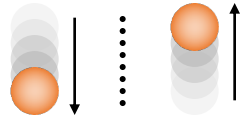
- Parity, P: *unobservable: (absolute handedness)*
  - Reflects a system through the origin.
    Converts right-handed to left-handed.
    - $\vec{x} \to -\vec{x}$, $\vec{p} \to -\vec{p}$ (vectors) but $\vec{L} = \vec{x} \times \vec{p}$ (axial vectors)



- 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 operator P: $\vec{x} \to -\vec{x}$
  - Mass m — $P\,m = m$: scalar
  - Force $\vec{F}$ $(\vec{F} = d\vec{p}/dt)$; $\vec{p} = m d\vec{x}/dt$ — $P\,\vec{F} = P\,d\vec{p}/dt = -d\vec{p}/dt = -\vec{F}$: 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):

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

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

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

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

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

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

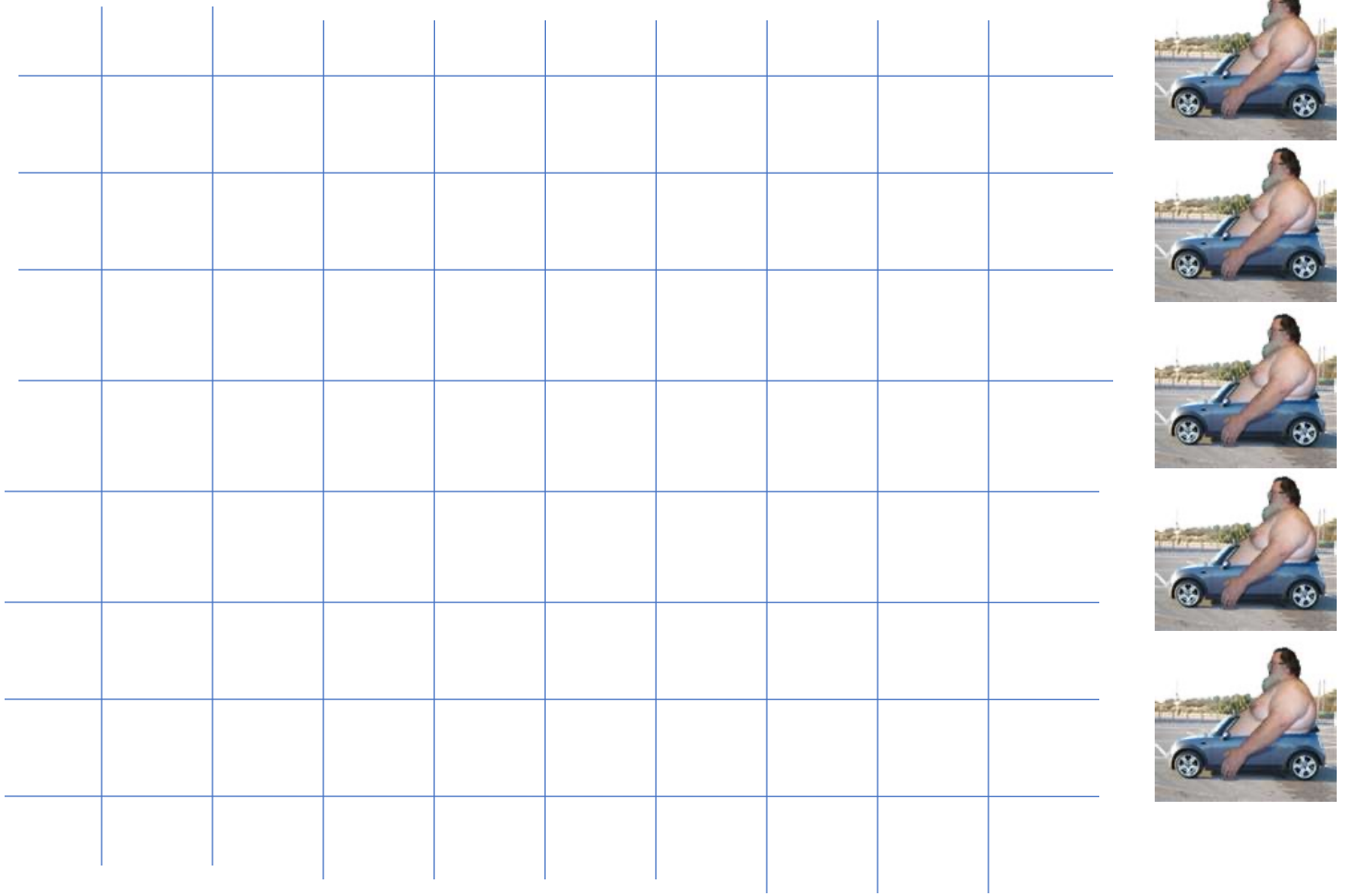
    Complex conjugation of the equation is required to stay invariant: $\quad \psi \xrightarrow{T} \psi^*$

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.

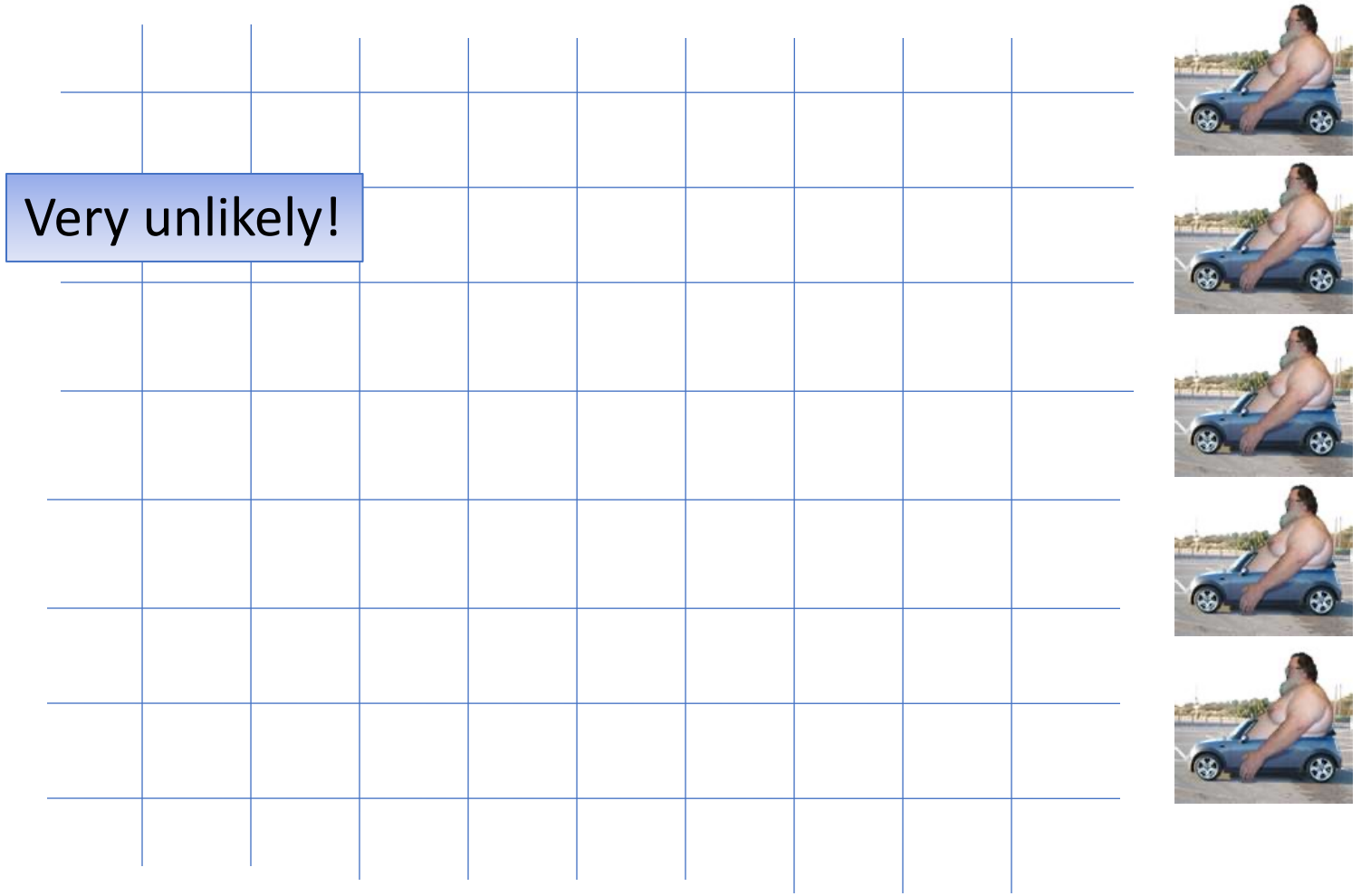
- Suppose we watch some physical event. Can we determine unambiguously whether:
  - We are watching the event where all ***charges are reversed*** or not?
  - We are watching the event ***in a mirror*** or not?
    - Macroscopic biological asymmetries are considered *accidents of evolution* rather than 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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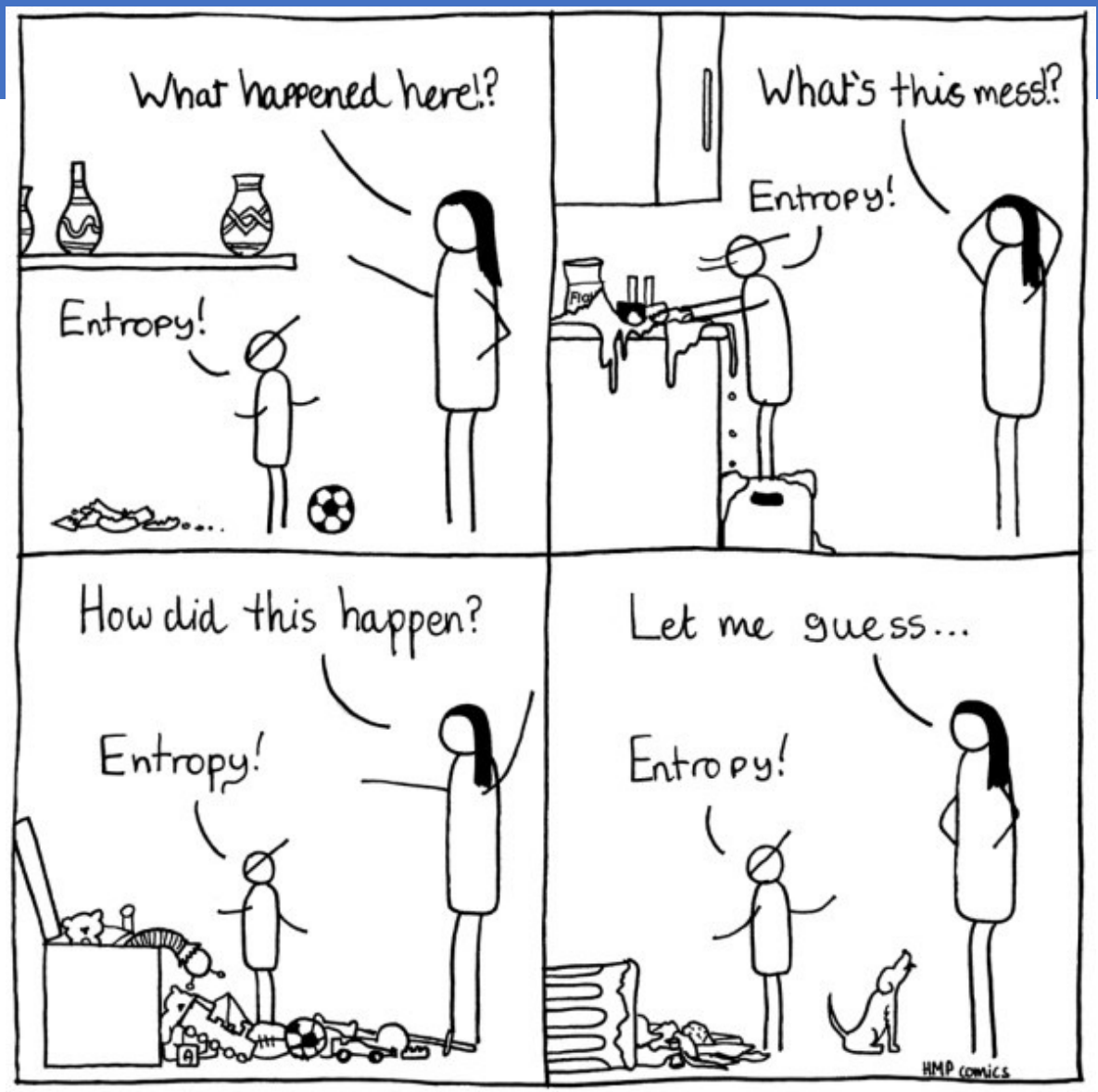
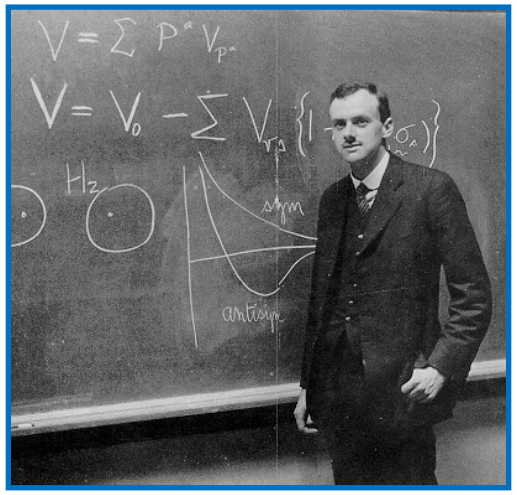
Macroscopic time reversal



This is why we don't teach our children about entropy until much later...

C, P operations and Dirac theory (QED)

$(i\gamma^\mu \partial_\mu - m)\psi(\vec{x}, t) = 0$



- 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:

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

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

$$\begin{pmatrix} \left[\left(i\gamma^0\partial_0 - i\gamma^i\partial_{x_i}\right) - m\right]\psi(\vec{x}, t) = 0 \\ \left[\left(i\gamma^0\partial_0 - i\gamma^i\partial_{x_i}\right) - m\right]\psi'(-\vec{x}, t) = 0 \end{pmatrix} \qquad \begin{pmatrix} \text{Elect. } \psi: & \left[\gamma^\mu\left(i\partial_\mu + eA_\mu\right) - m\right]\psi = 0 \\ \text{Posit. } \psi': & \left[\gamma^\mu\left(i\partial_\mu - eA_\mu\right) - m\right]\psi' = 0 \end{pmatrix}$$

- QED (Dirac theory) is symmetric under C, P conjugation. Reversing electric charges keeps electrodynamics invariant.

C, P operations and Dirac theory (QED)

$(i\gamma^\mu \partial_\mu - m)\psi(\vec{x},t) = 0$

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

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

- 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 : $\psi \to \psi' = \psi(-\vec{x},t)$?

$$\left[\left(i\gamma^0\partial_0 - i\gamma^i\partial_{-x_i}\right) - m\right]\psi(-\vec{x},t) = 0$$

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

Multiply eq by γ^0:

$$\gamma^0\left[\left(i\gamma^0\partial_0 + i\gamma^i\partial_{x_i}\right) - m\right]\psi(-\vec{x},t) = 0$$

Instead: $\psi' = \gamma^0\psi(-\vec{x},t)$!

$$\left[\left(i\gamma^0\partial_0 - i\gamma^i\partial_{x_i}\right) - m\right]\gamma^0\psi(-\vec{x},t) = 0$$ OK!

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

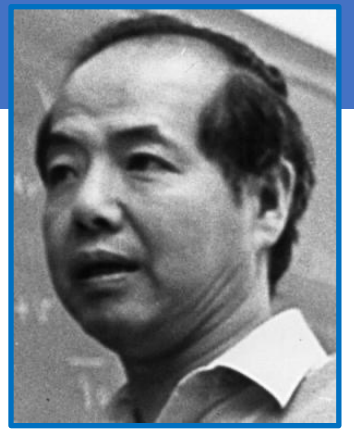
ψ : $\left[\gamma^\mu\left(i\partial_\mu - qA_\mu\right) - m\right]\psi = 0$

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

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

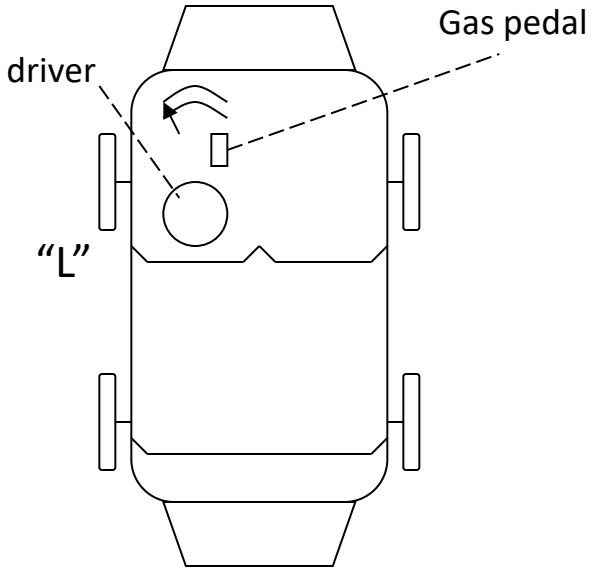
ψ' : $\left[\gamma^\mu\left(i\partial_\mu + qA_\mu\right) - m\right]i\gamma^2\psi^* = 0$ OK

Parity Violation



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

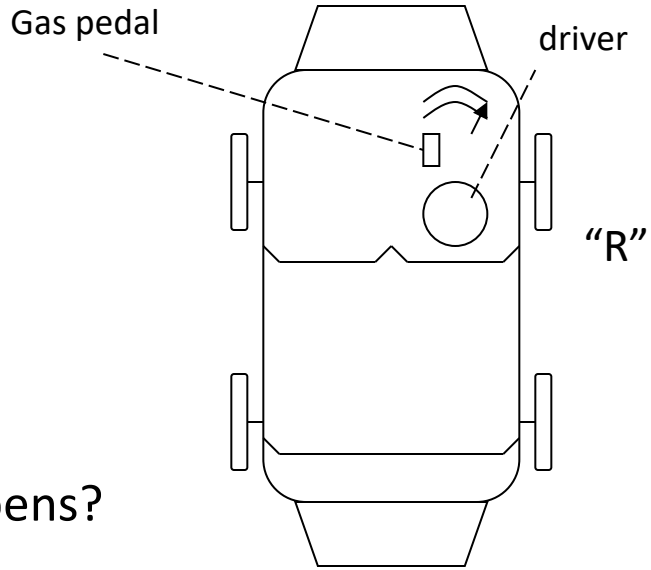
A “gedanken” experiment: consider two perfectly mirror symmetric cars:



“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

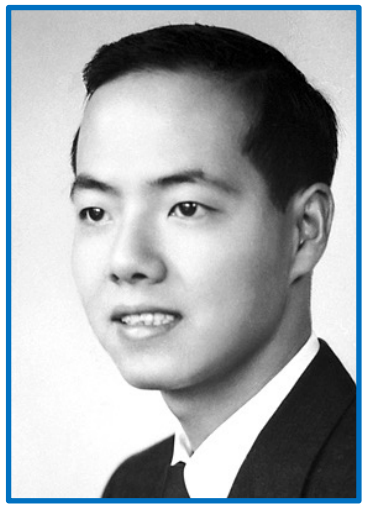
Person “R” gets in, starts, ….. What happens?



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

Parity Violation

T.D. Lee



C.N. Yang

- First to pose Parity violation as a solution of the so-called theta-tau puzzle:
  - Two different particles with exactly same mass and spin but different decay modes?

$\theta^+ \rightarrow \pi^+\pi^0$ (Parity +)

$\tau^+ \rightarrow \pi^+\pi^+\pi^0$ (Parity –)

➢One particle K^+ with parity violating decay

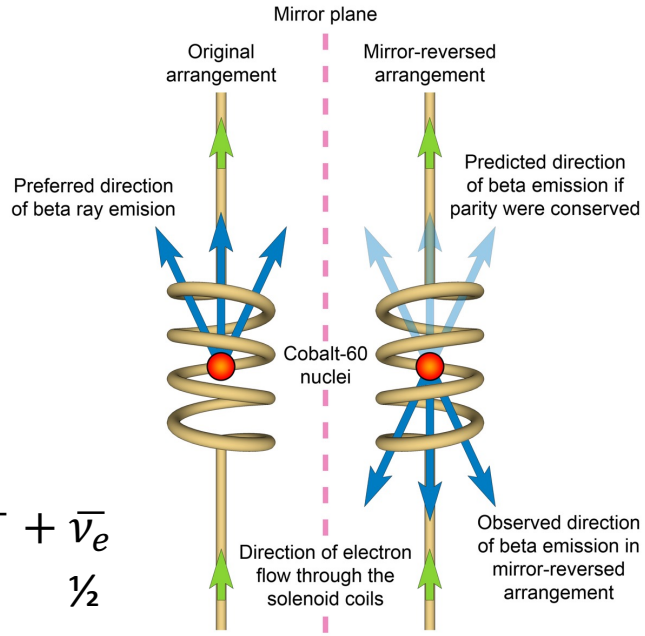
Wolfgang Pauli

"I cannot believe God is a weak left-hander."

Discovery of Parity Violation

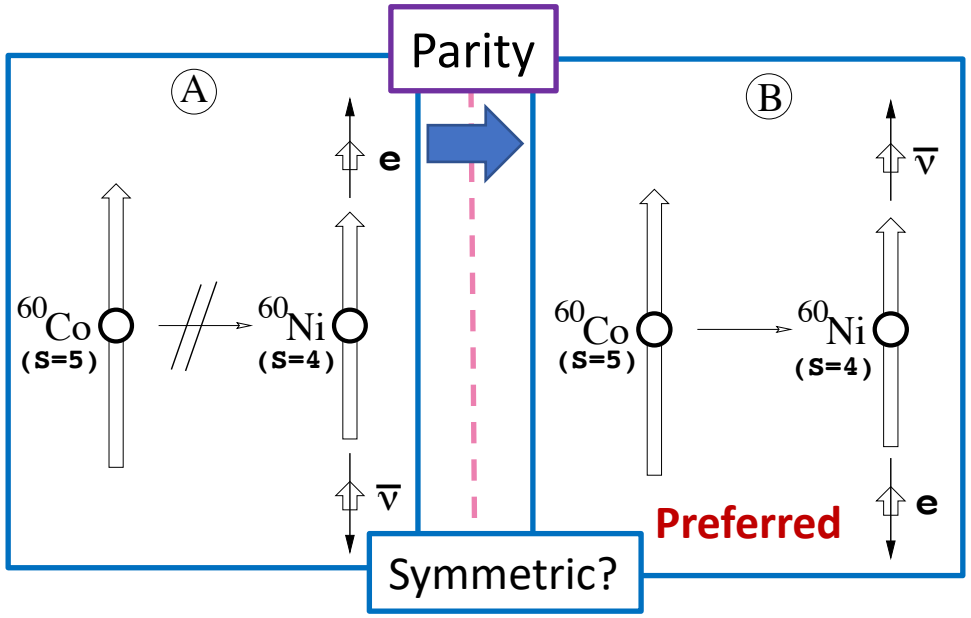
$$^{60}_{27}Co \rightarrow {}^{60}_{28}Ni + e^- + \bar{\nu}_e$$

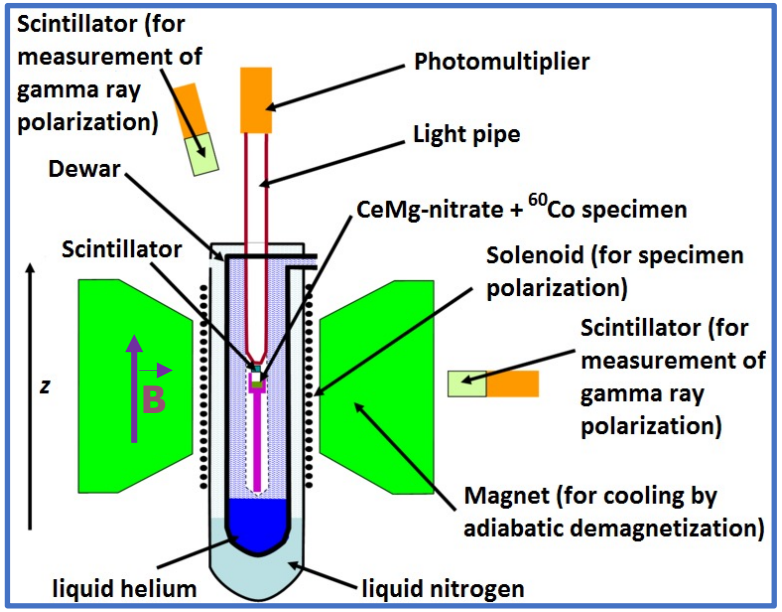
S: 5 4 ½ ½



B-field

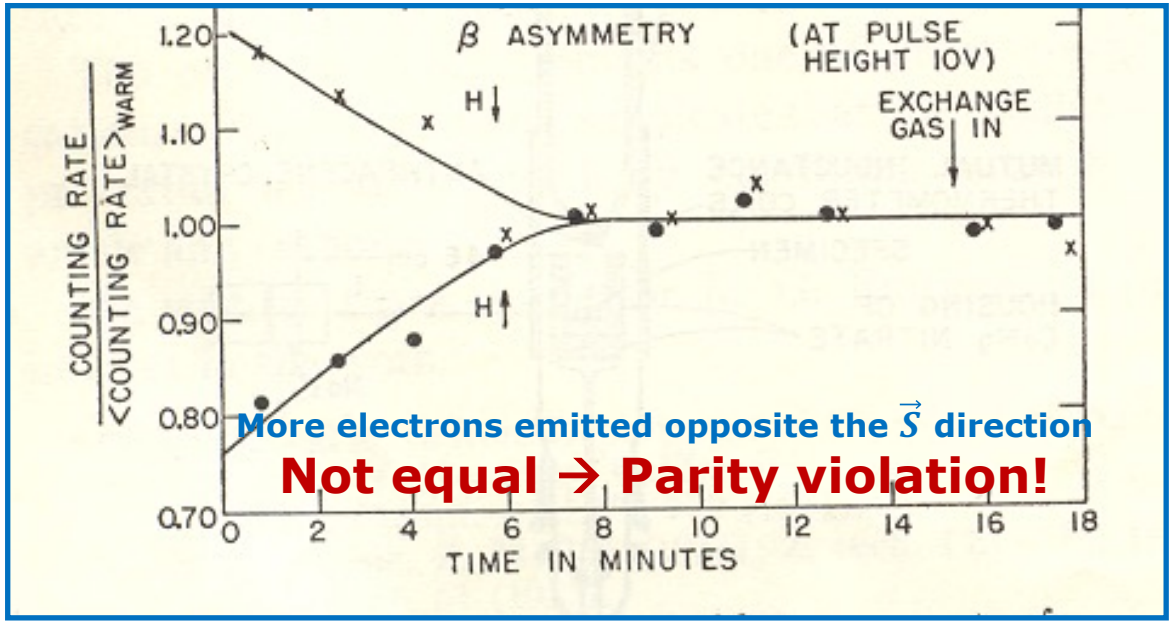
Spin is pseudoscalar, P: $\vec{S} \rightarrow \vec{S}$





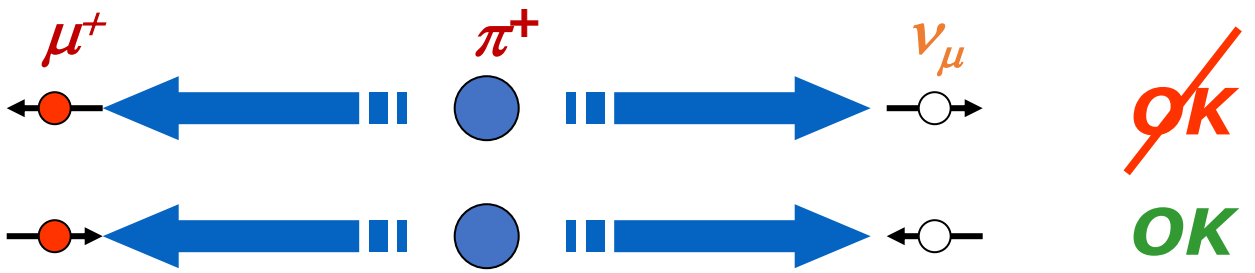
Is physics is parity invariant?

Only if electron decay rate is symmetric wrt spin direction!



So P is violated, what's next…?

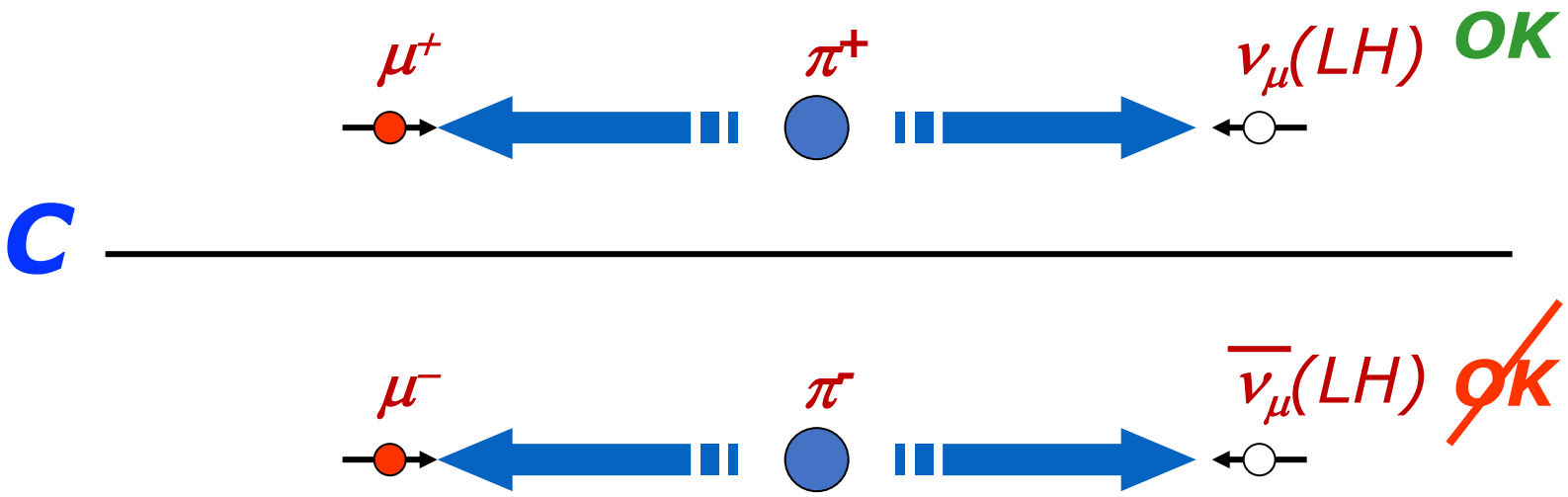
- Wu's experiment was shortly followed by another clever experiment by L. Lederman: Look at decay $\pi^+ \rightarrow \mu^+ \nu_\mu$
  - Pion has spin 0, while μ, ν_μ both have spin ½
    → spin of decay products must be oppositely aligned
    → Helicity of muon is same as that of neutrino.



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

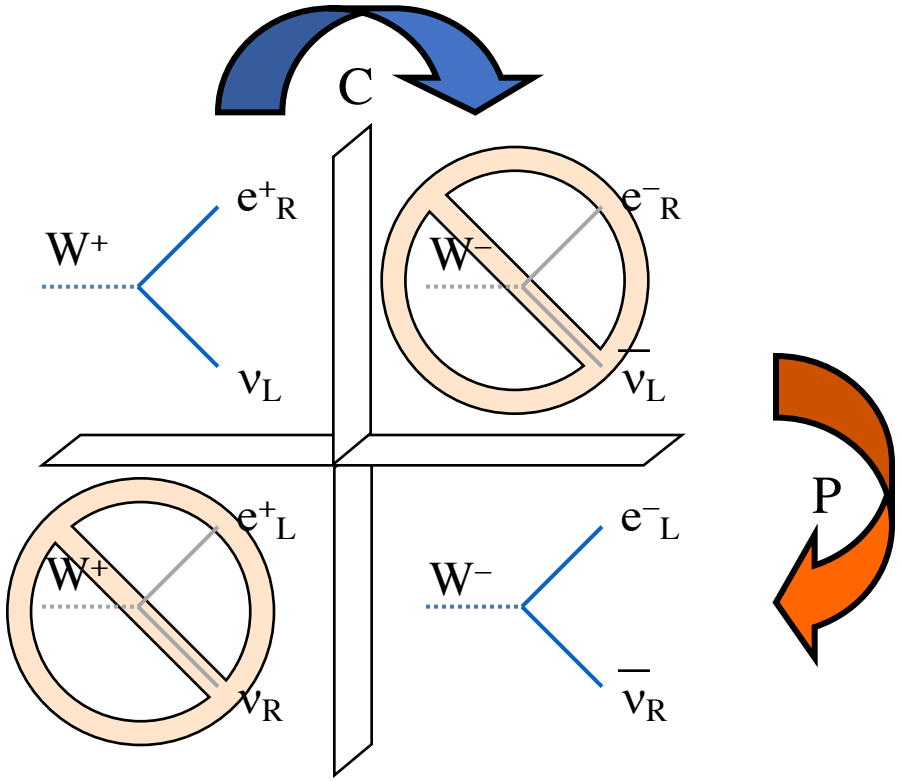
Charge conjugation symmetry?

- 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. $C^2 = 1$



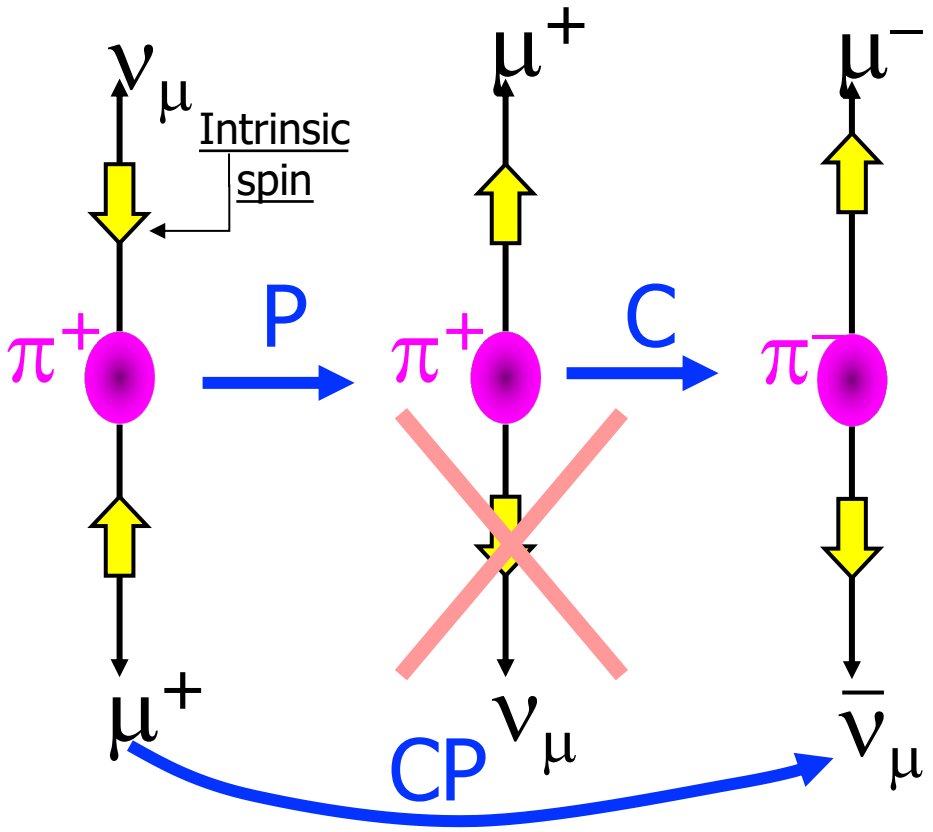
- C symmetry is broken by the weak interaction
  - Just like P

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



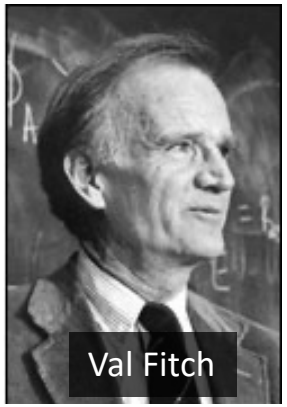
- Combined $\boldsymbol{C + P \equiv CP}$ symmetry?
  - $\boldsymbol{CP}$ symmetry is parity conjugation: $(x, y, z \rightarrow -x, -y, -z)$ followed by charge conjugation: $(\psi \rightarrow \overline{\psi})$
- $\boldsymbol{CP}$ symmetry *appears* to be preserved in the weak interaction
- But in 1964,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

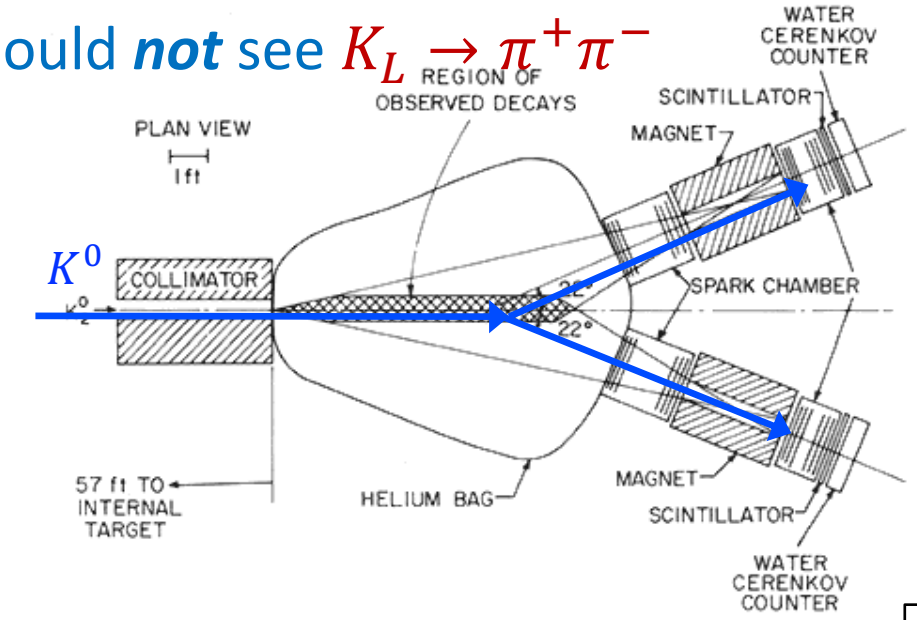
Discovery of CP-Violation with K^0 decays

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

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)

James Cronin

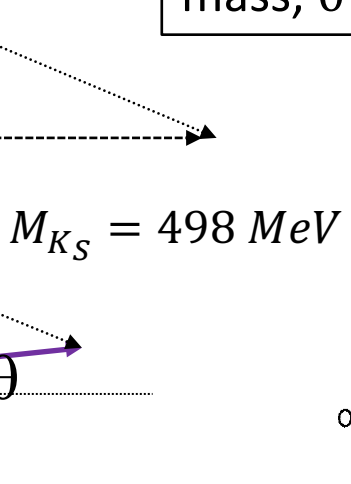

Val Fitch

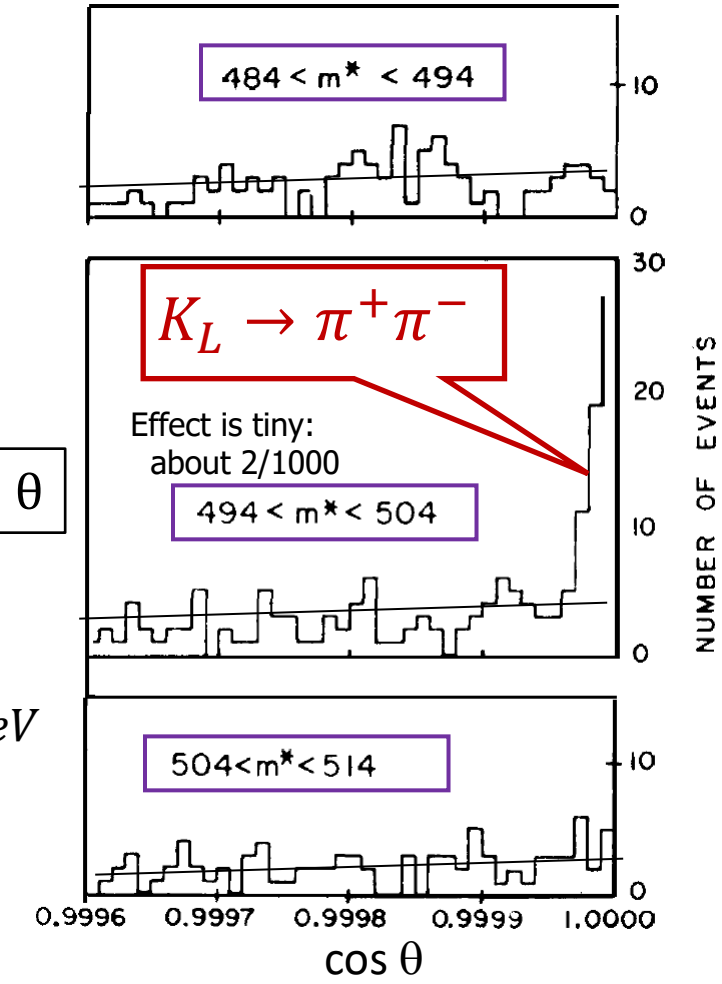


CP violating Signal: $K_L \rightarrow \pi^+\pi^-$

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

π^0 remains undetected





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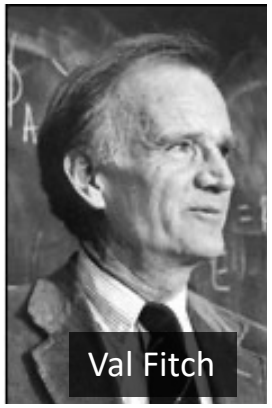
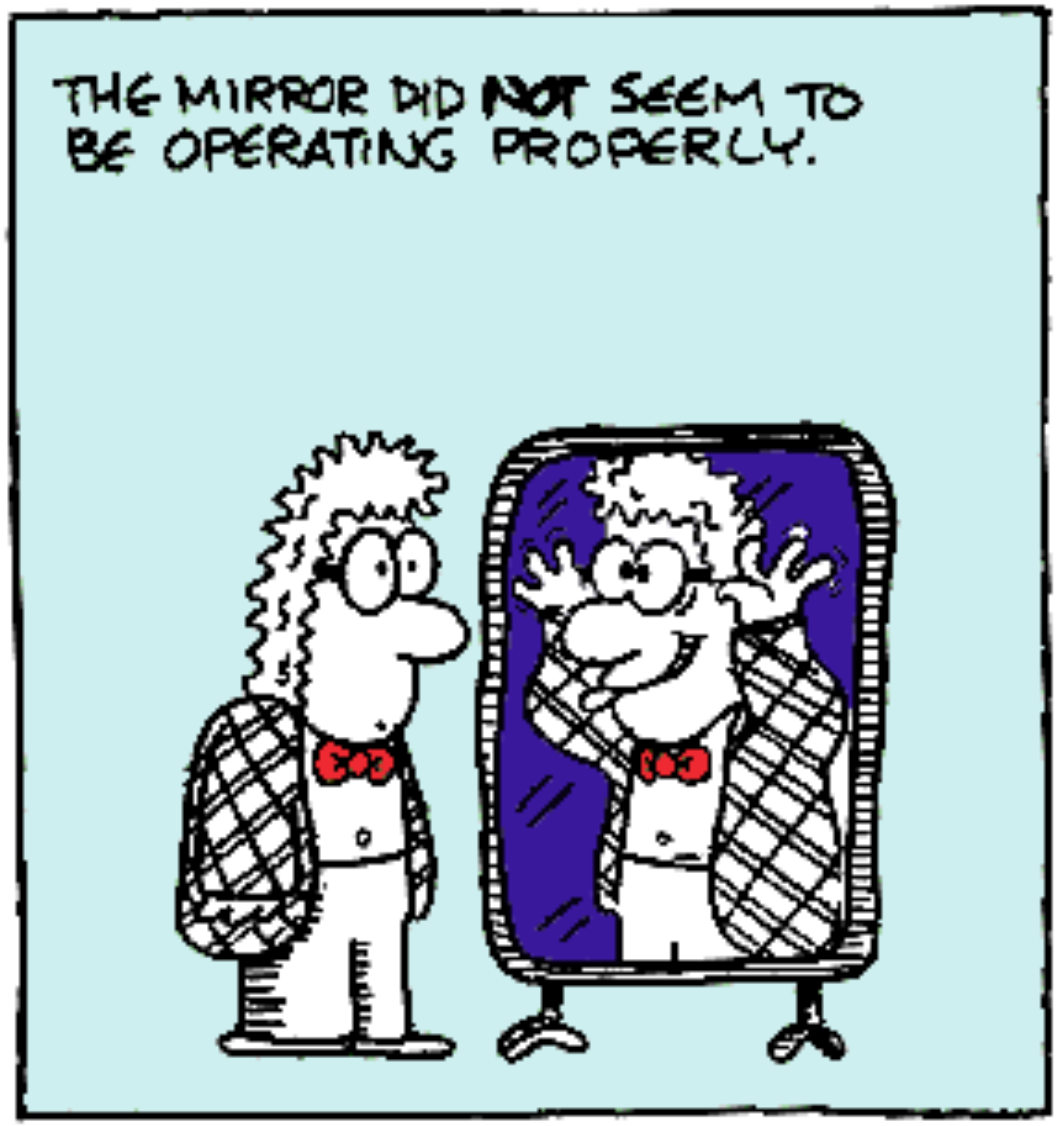
- Create a pure K_L beam ("wait" for K_S to decay)
- If CP is conserved,

James Cronin


Val Fitch

CP violating Signal: K

Background: K



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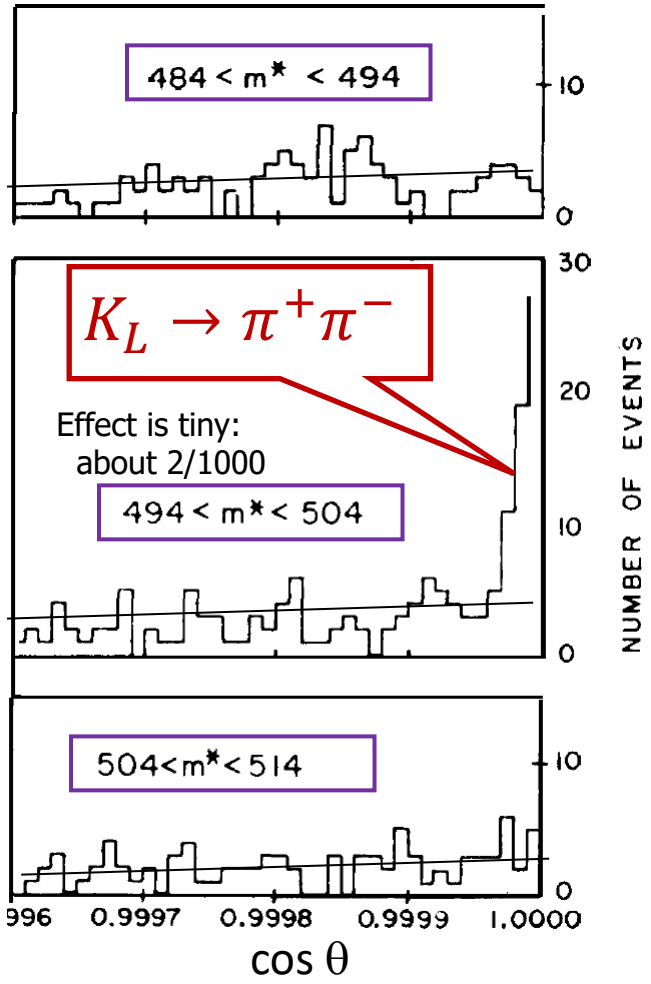
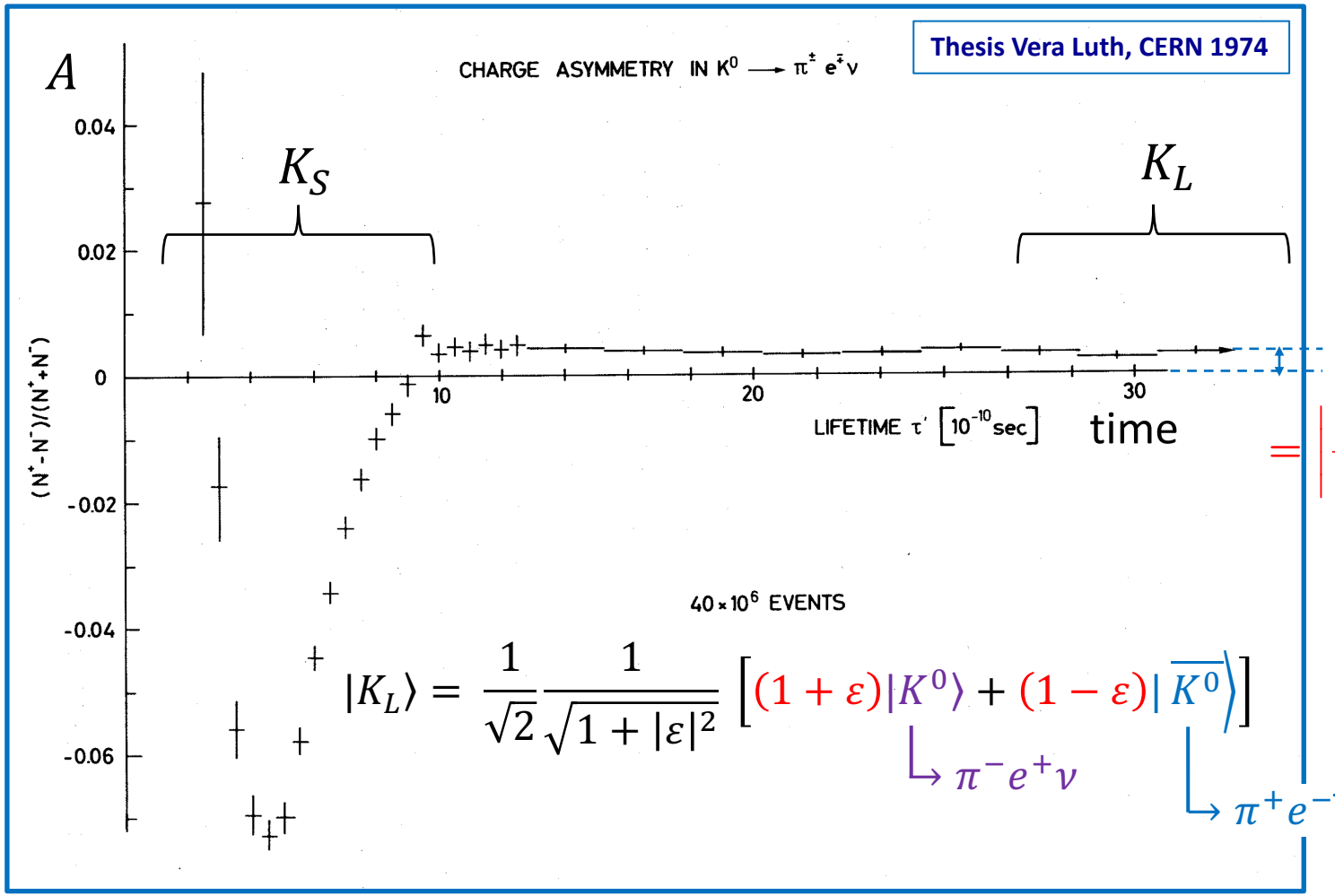


Alternative: Charge Asymmetry in K^0 decays

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

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



$$= \left|\frac{(1+\varepsilon)}{(1-\varepsilon)}\right|^2 \quad 4\Re(\varepsilon)$$

Kaon has $J^P = 0^-$:

$$P|K^0\rangle = -|K^0\rangle$$
$$P|\overline{K^0}\rangle = -|\overline{K^0}\rangle$$

Two CP states:

$$|K_1\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle - |\overline{K^0}\rangle\right]$$
$$|K_2\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle + |\overline{K^0}\rangle\right]$$

Two particles:

$$|K_S\rangle \simeq [|K_1\rangle + \varepsilon|K_2\rangle]$$
$$|K_L\rangle \simeq [|K_2\rangle + \varepsilon|K_1\rangle]$$

CP violation in meson mixing.

Contact with Aliens !

Are they made of matter or anti-matter?

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

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

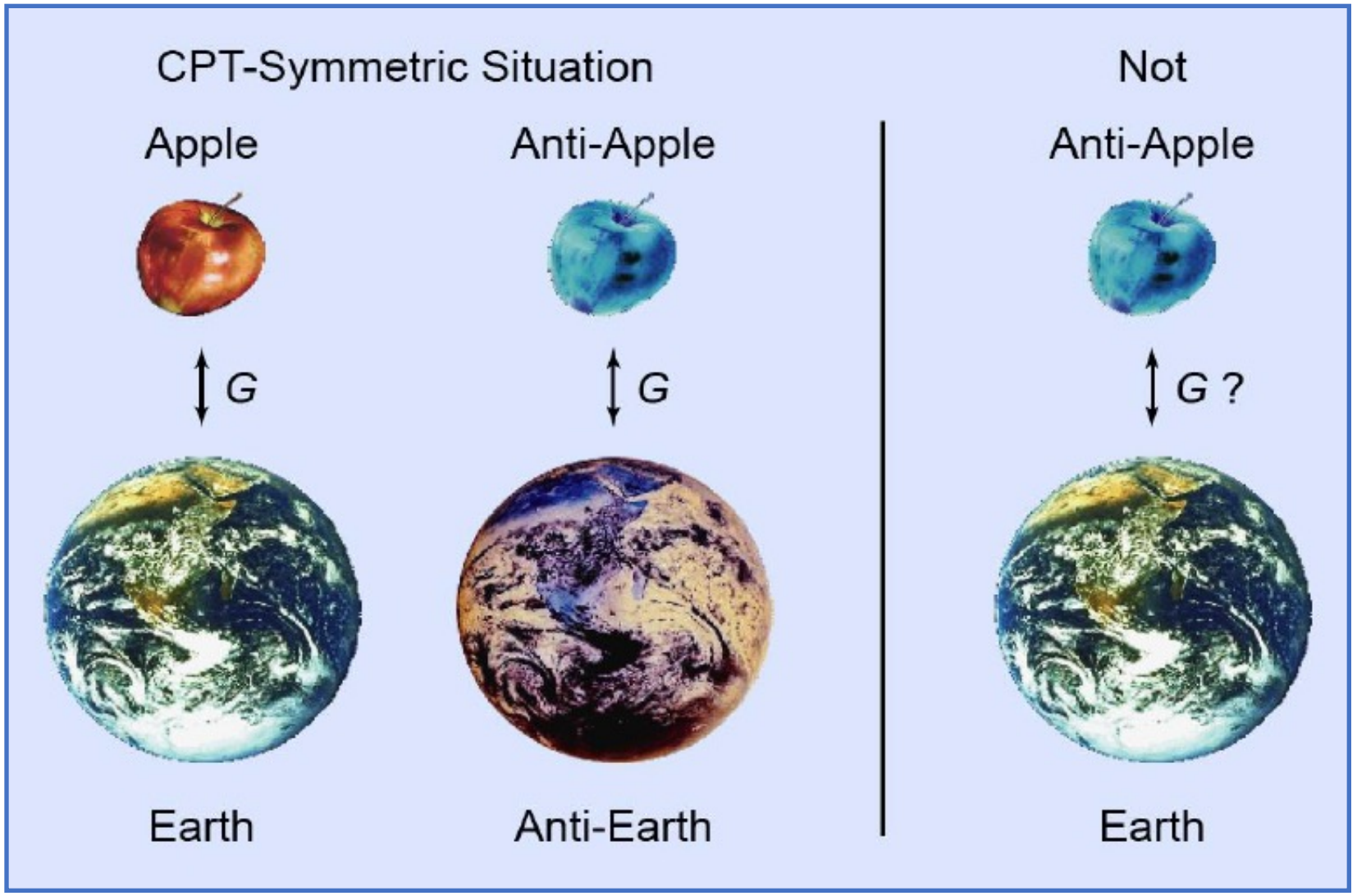
If opposite: matter

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 Today & Tomorrow:

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   a) Discrete Symmetries
   b) CP Violation in the Standard Model
   c) Jarlskog Invariant and Baryogenesis
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Weak interaction in three Flavour Generations

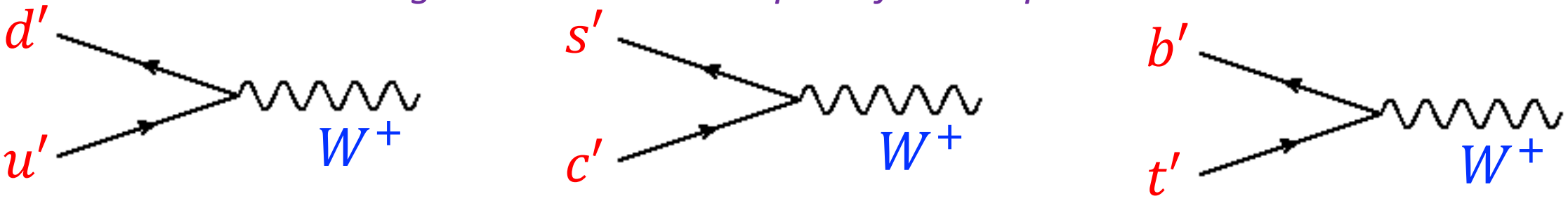
- Weak Interaction is 100% parity violating.
  - Wolfgang Pauli: *"I cannot believe God is a weak left-hander."*

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

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

Note:
$$\psi_L = \frac{1}{2}(1-\gamma^5)\psi$$

- 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

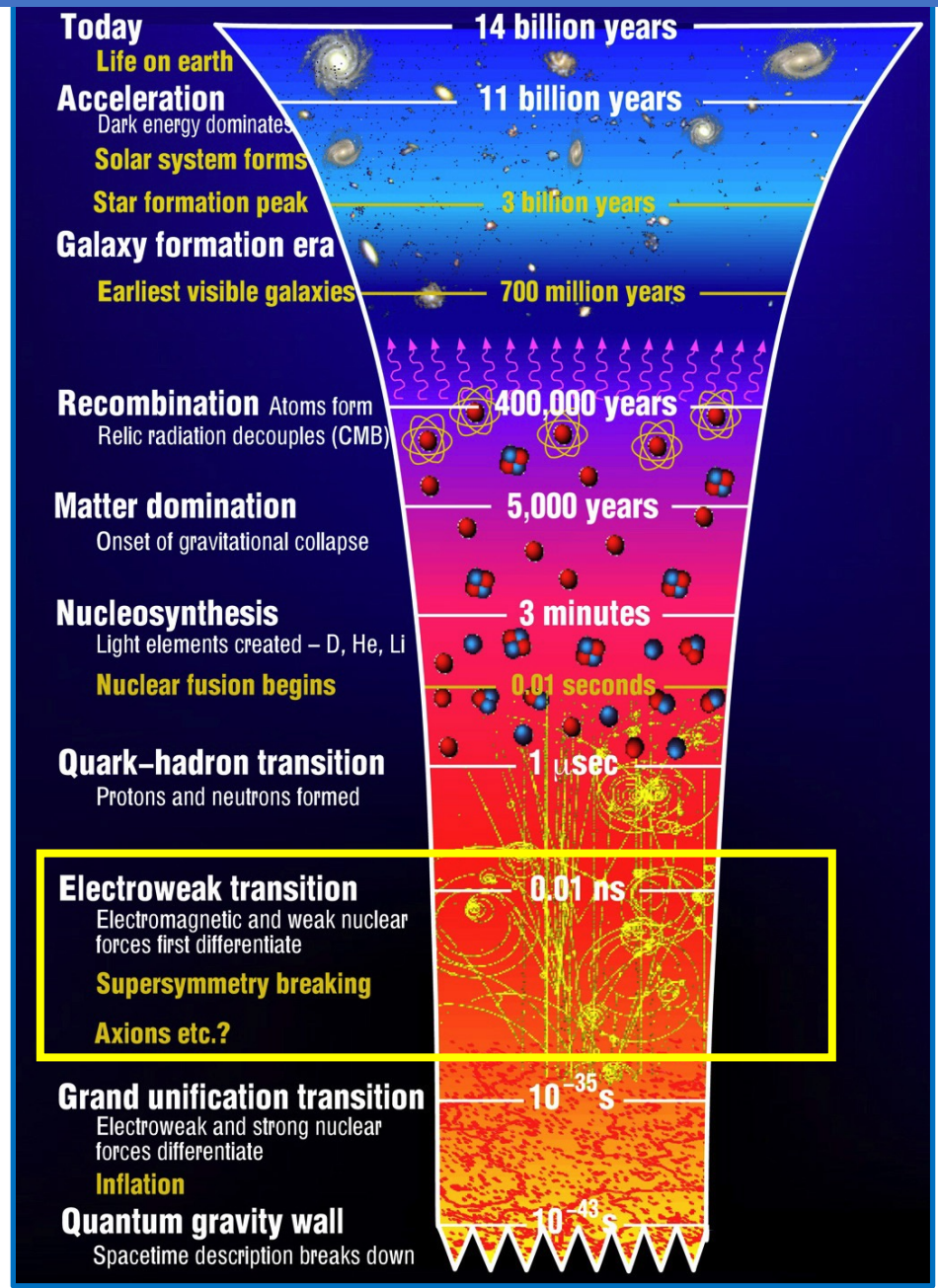
- Yukawa couplings to massless particles (Weinberg):

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

- Yukawa interaction is *not* flavour universal!

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

$$\begin{pmatrix} Y_{11}\overline{(u\ \ d)^I_L}\begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} & Y_{12}\overline{(u\ \ d)^I_L}\begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} & Y_{13}\overline{(u\ \ d)^I_L}\begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} \\ Y_{21}\overline{(c\ \ s)^I_L}\begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} & Y_{22}\overline{(c\ \ s)^I_L}\begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} & Y_{23}\overline{(c\ \ s)^I_L}\begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} \\ Y_{31}\overline{(t\ \ b)^I_L}\begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} & Y_{32}\overline{(t\ \ b)^I_L}\begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} & Y_{33}\overline{(t\ \ b)^I_L}\begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} \end{pmatrix} \cdot \begin{pmatrix} d^I_R \\ s^I_R \\ b^I_R \end{pmatrix}$$



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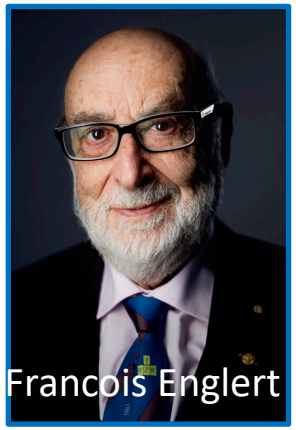
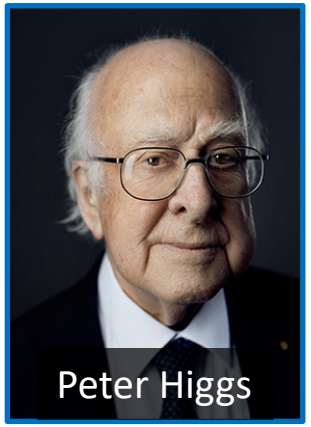
- SSB: B-E-H Mechanism:

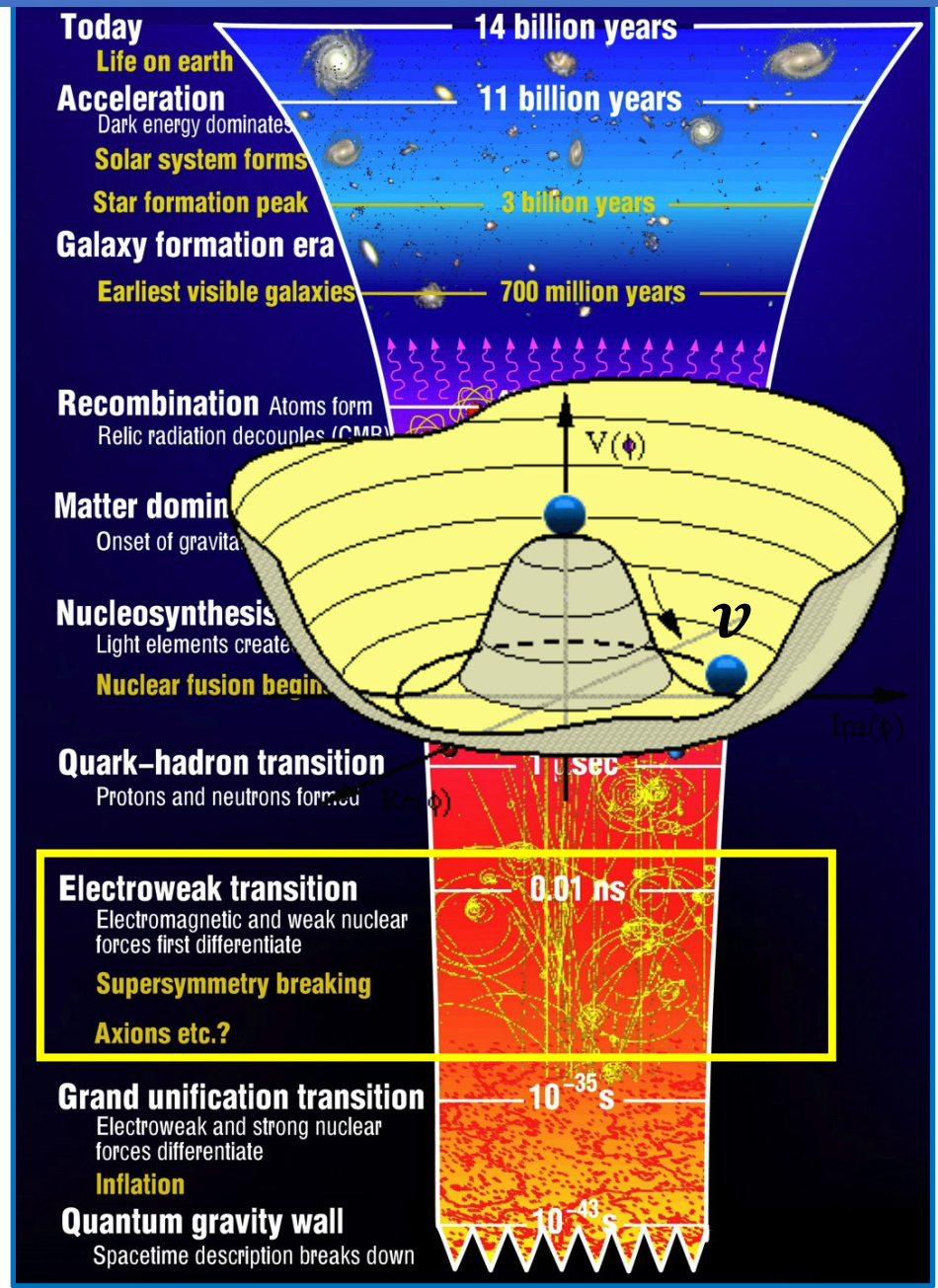
Robert Brout


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



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- Yukawa couplings to massless particles (Weinberg):

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

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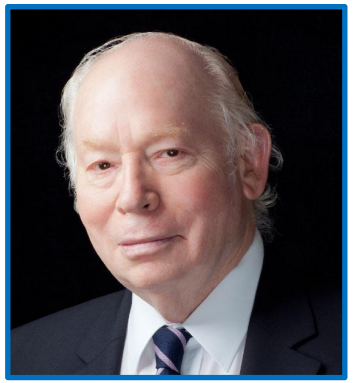

→Massive fermions

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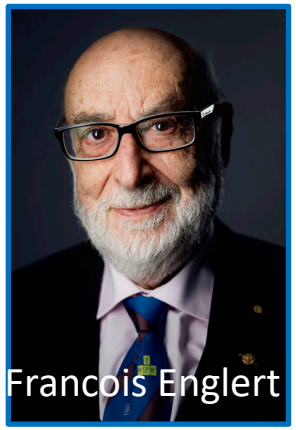

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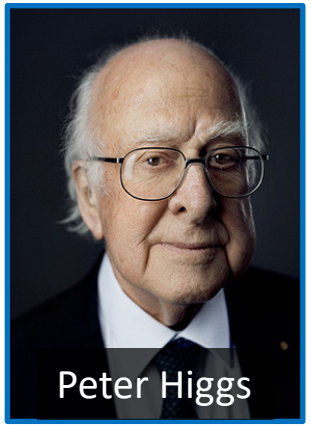

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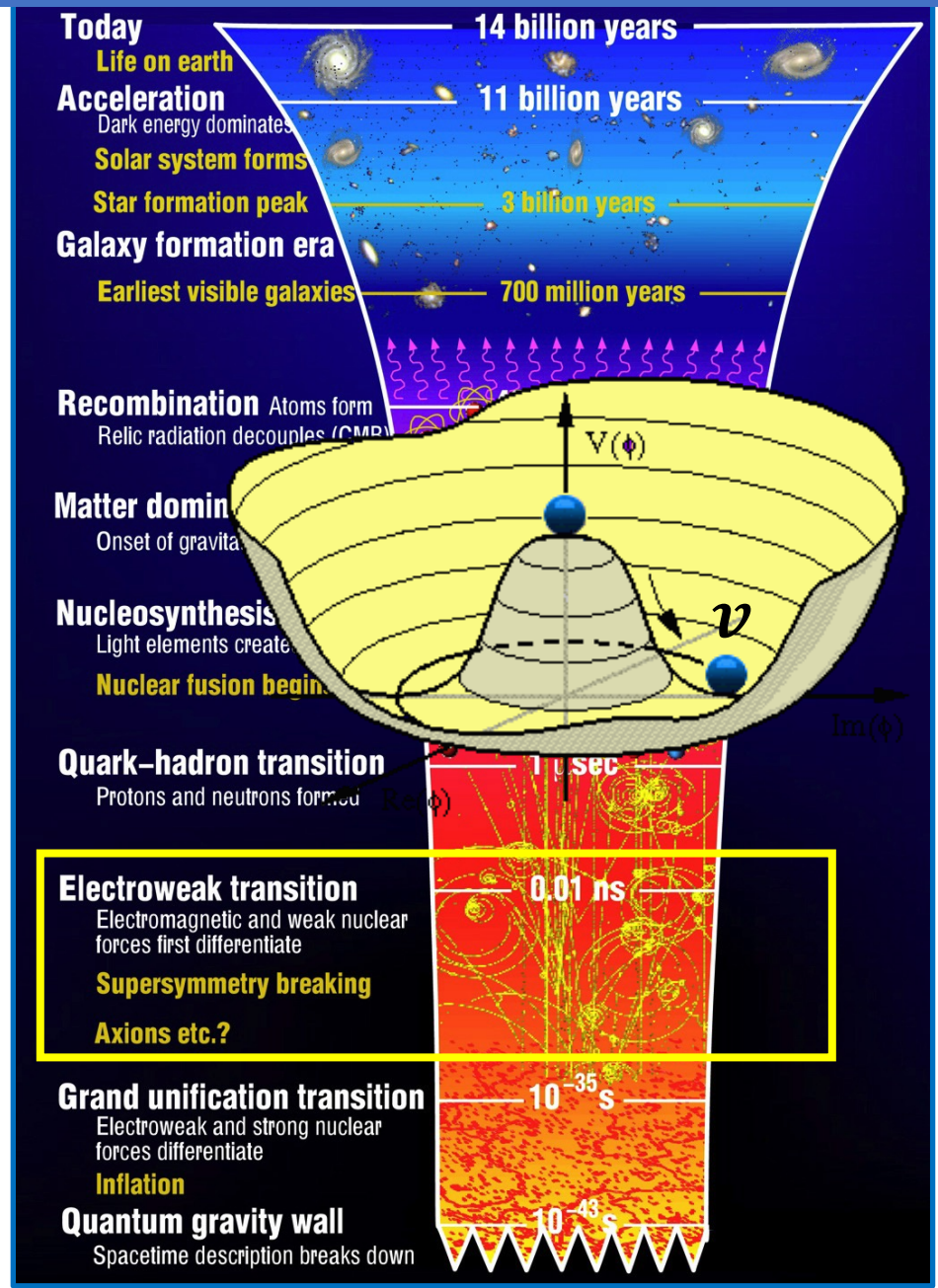

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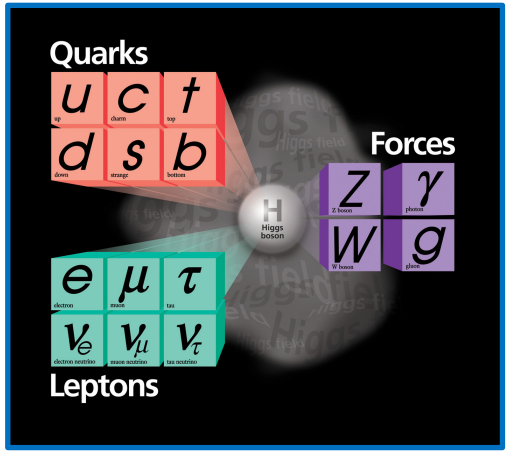
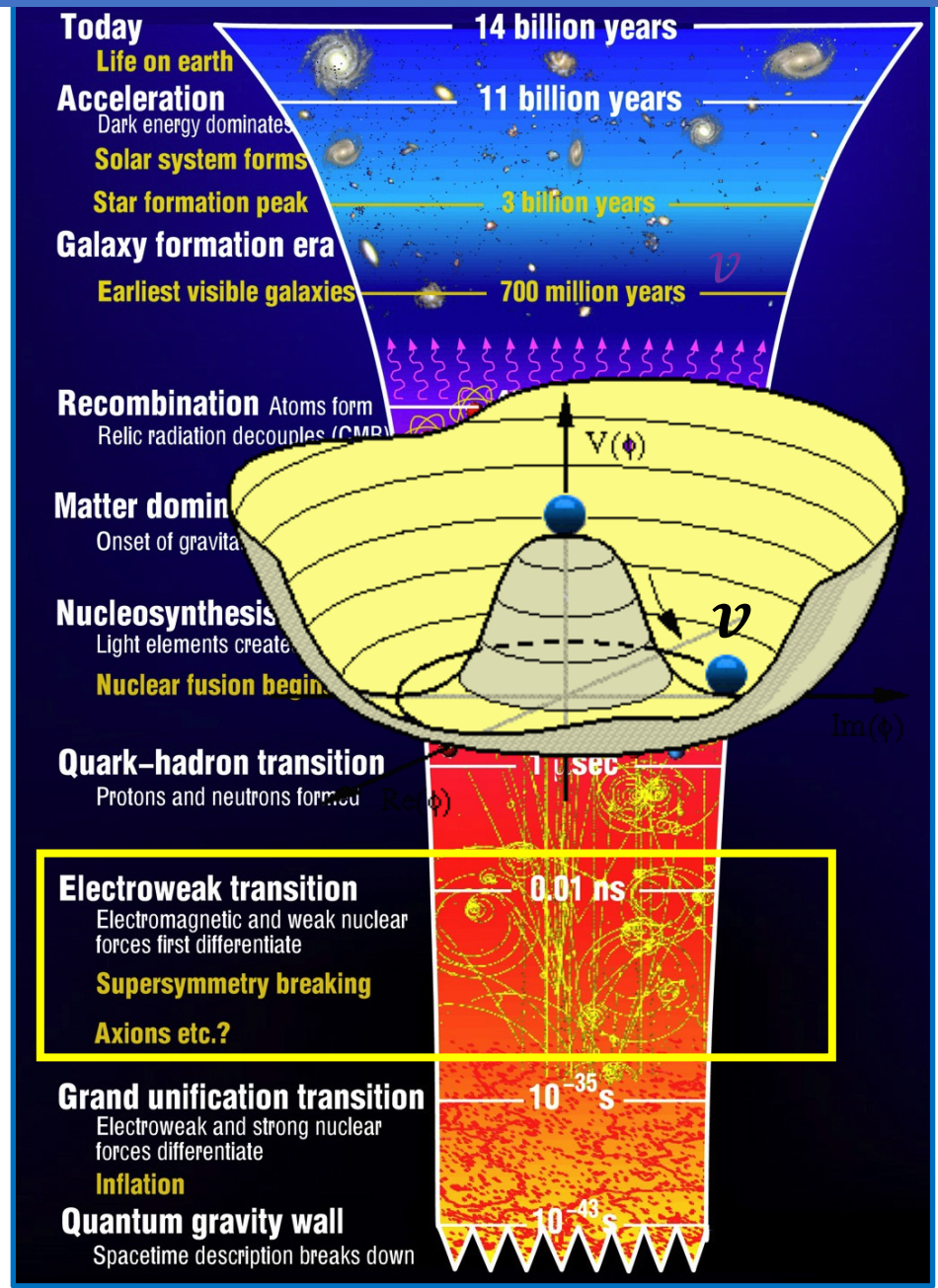
- Diagonalize Y_{ij} :

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

→ mass and flavour eigenstates





Spontaneous Symmetry Breaking→ Origin of Mass

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$$\mathcal{L}_Y = Y^d_{ii}\ (\bar{u}_i, \bar{d}_i)_L \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} d_{iR} + Y^u_{ii}\ (\bar{u}_i, \bar{d}_i)_L \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix} u_{iR}$$

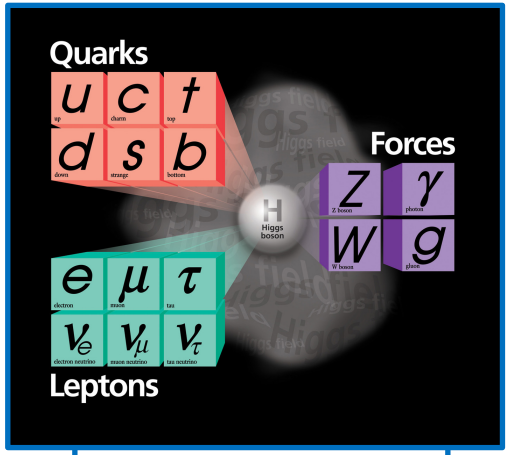
- Diagonalize Y_{ij} :

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

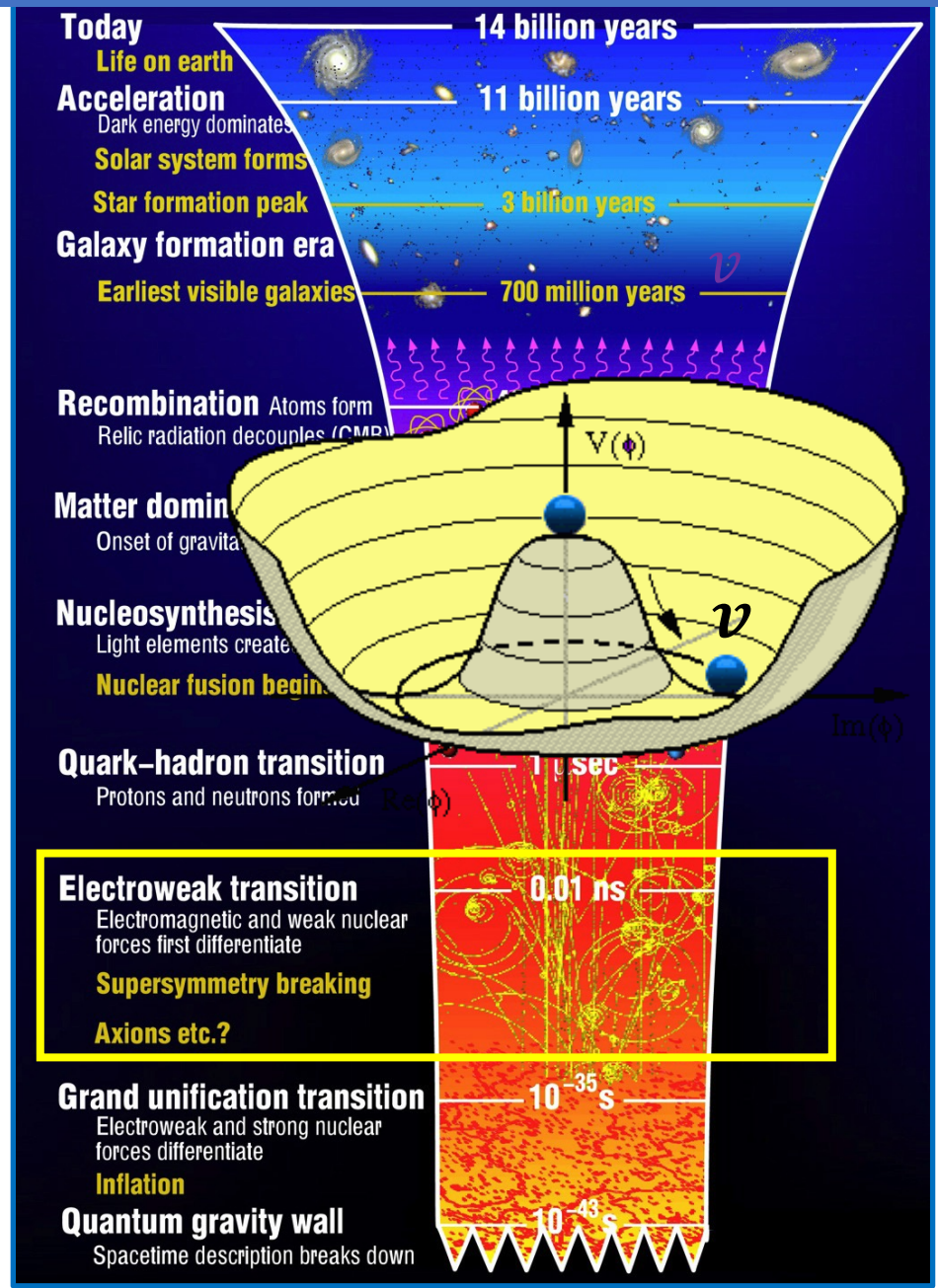
→ mass and flavour eigenstates

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

$$\mathcal{L}_Y \to \mathcal{L}_H = m_d\, \bar{d}_L\, d_R + m_u\, \bar{u}_L\, u_R$$



Physical particles



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  → mass and flavour eigenstates

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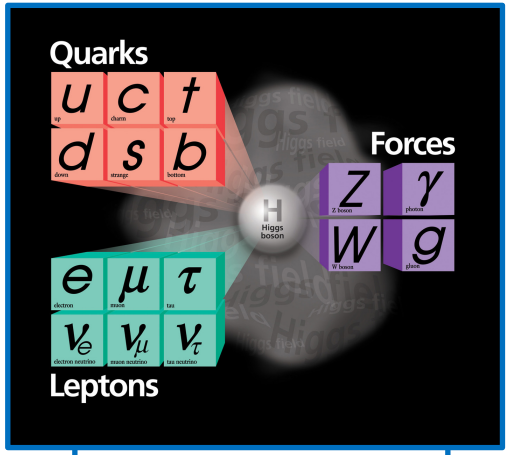
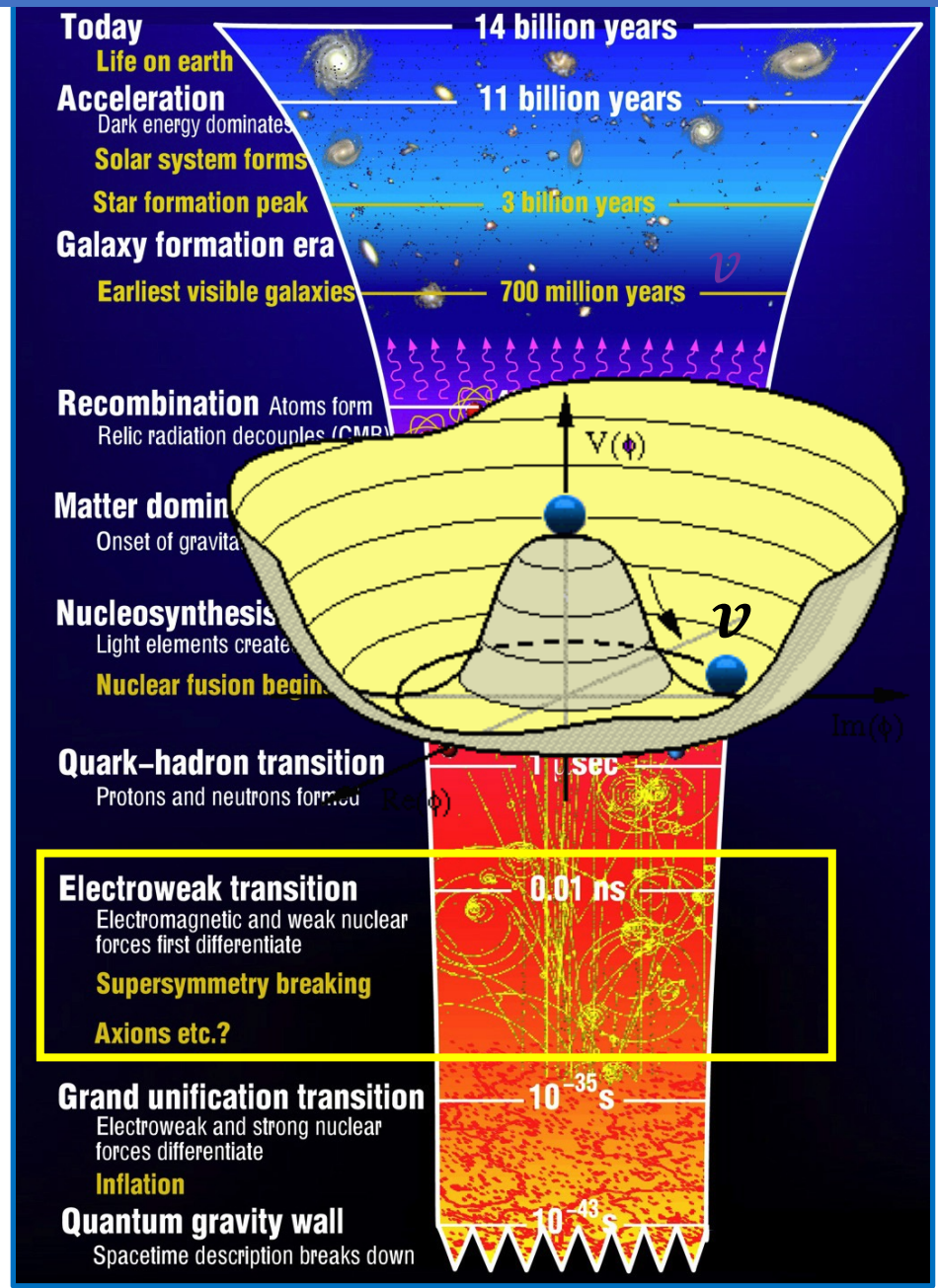


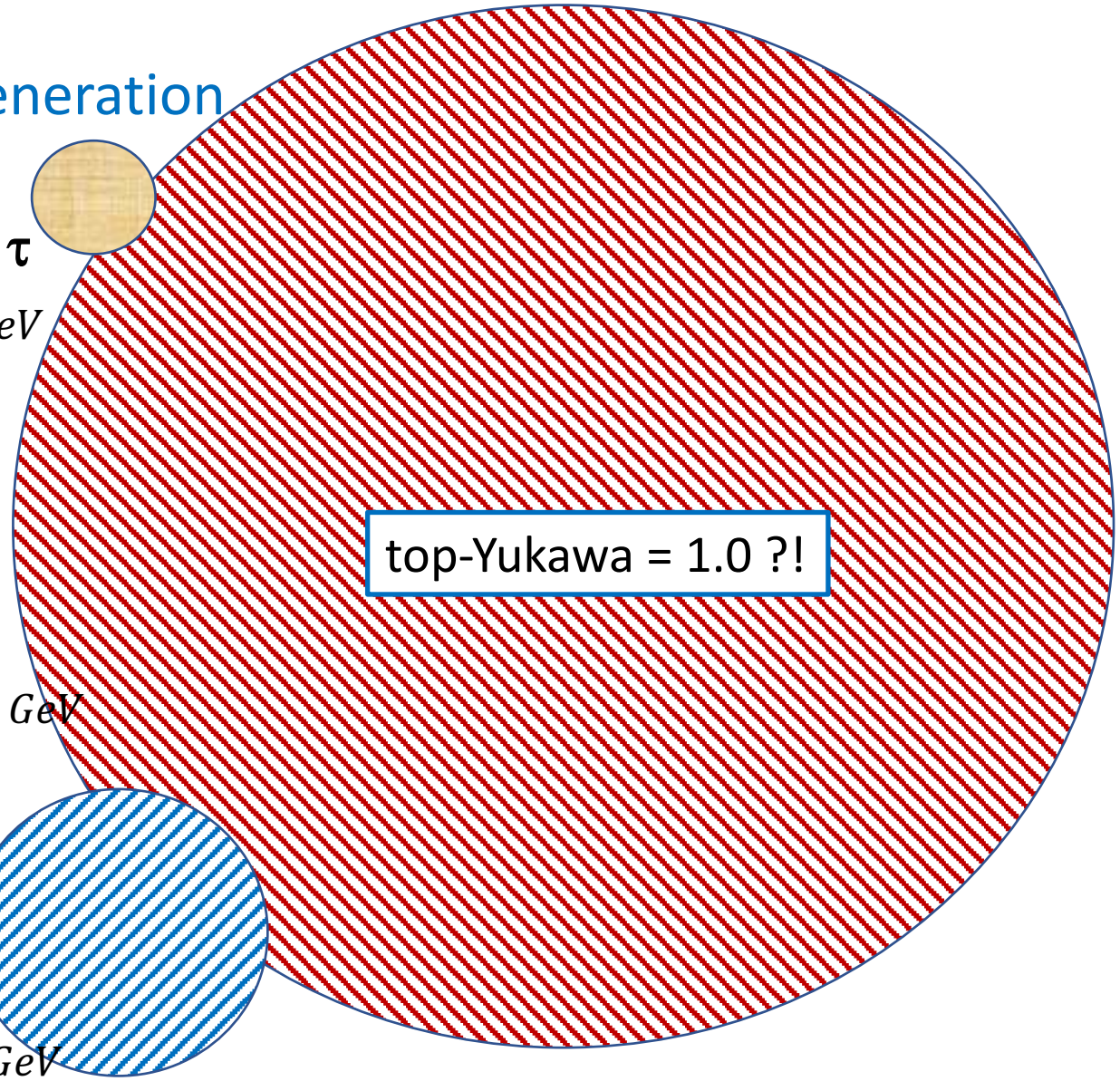
Physical particles

- 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



$m_e = 0.5\ MeV$ $m_\mu = 0.5\ MeV$ $m_\tau = 1.8\ GeV$

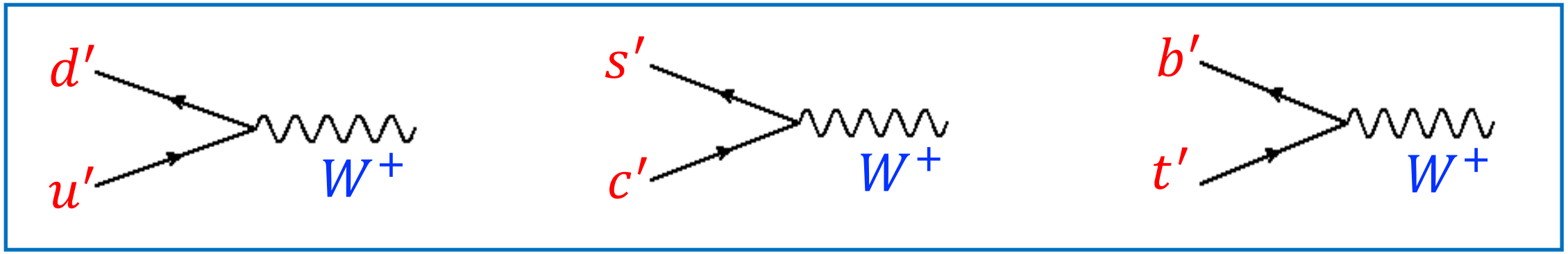
$m_u = 2.2\ MeV$ $m_c = 1.3\ GeV$ $m_t = 173\ GeV$

$m_d = 4.7\ MeV$ $m_s = 96\ MeV$ $m_b = 4.2\ GeV$

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

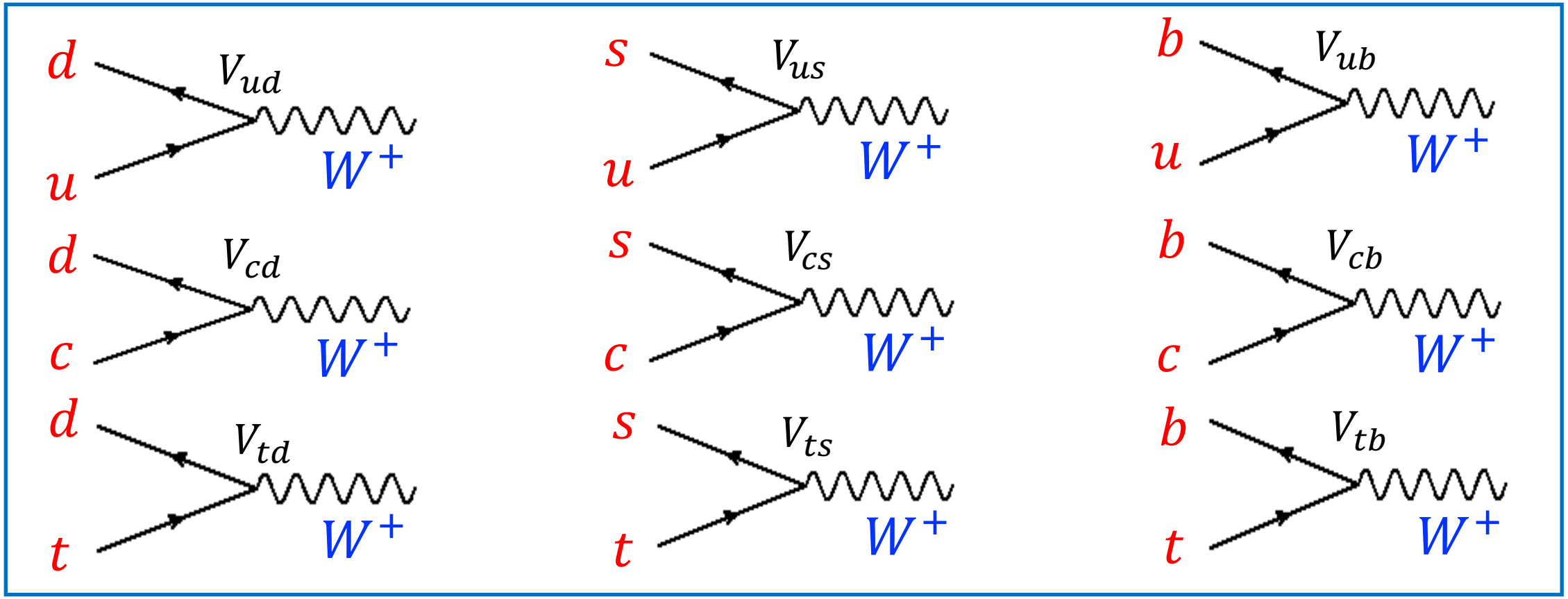
The Weak Interaction → Flavour Mixing

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

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



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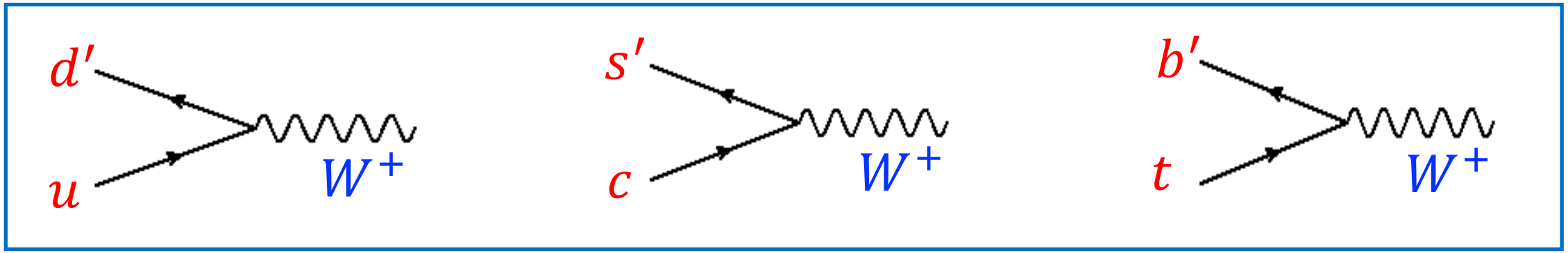
Generation structure of weak interaction, *now includes CP violation.*

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



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

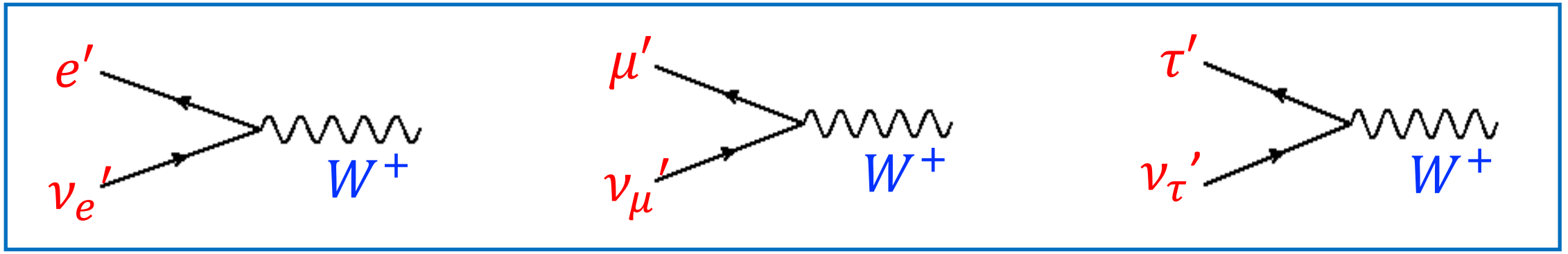
$$|s'\rangle = V_{cd}|d\rangle + V_{cs}|s\rangle + V_{cb}|b\rangle$$

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

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: $U_{MNS} = (U^\nu U^{l\dagger})_{ij}$ …

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: $U_{MNS} = \left(U^u U^{d\dagger}\right)_{ij}$ …

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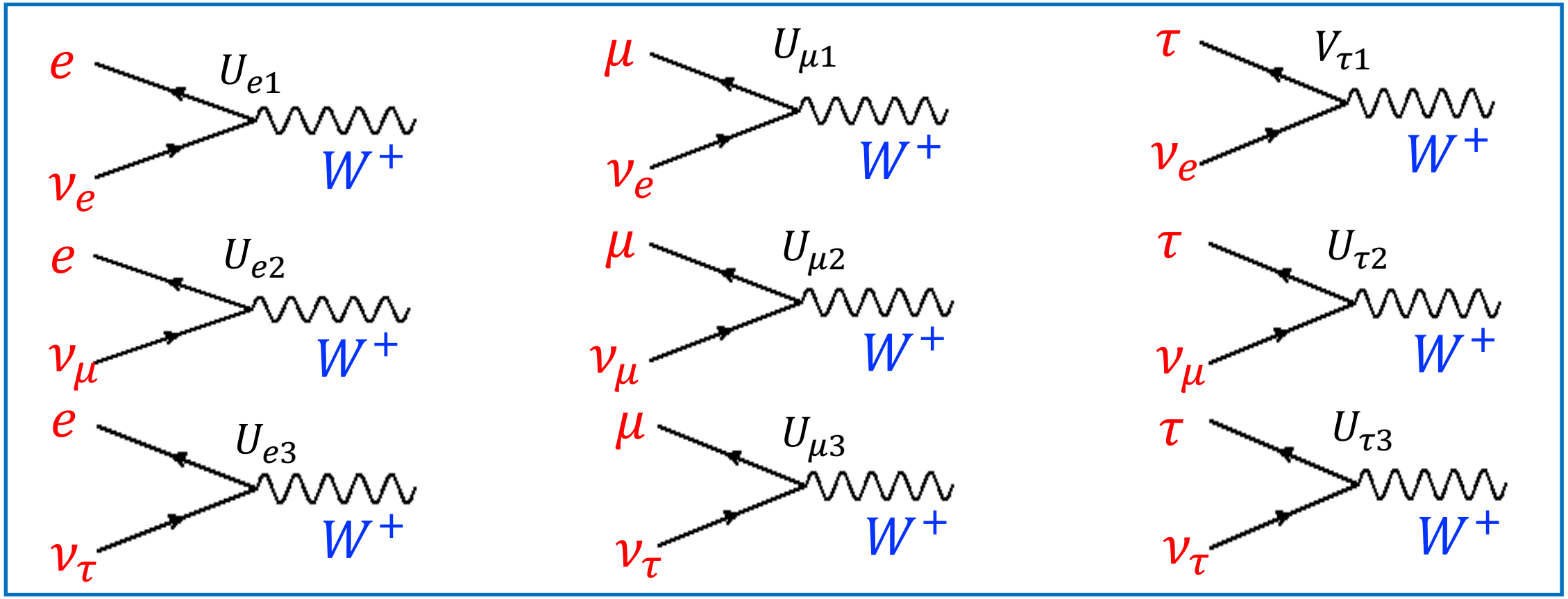

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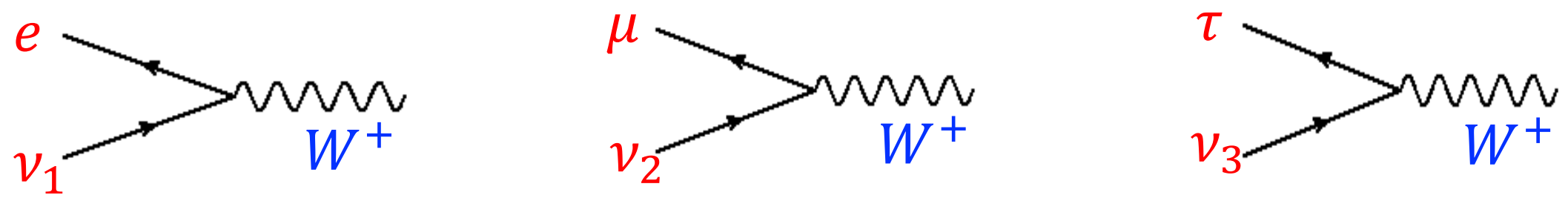
Generation structure of weak interaction, *now includes CP violation.*

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-1: which states mix?

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

Food for thought-2: Where did the CP violation come from?

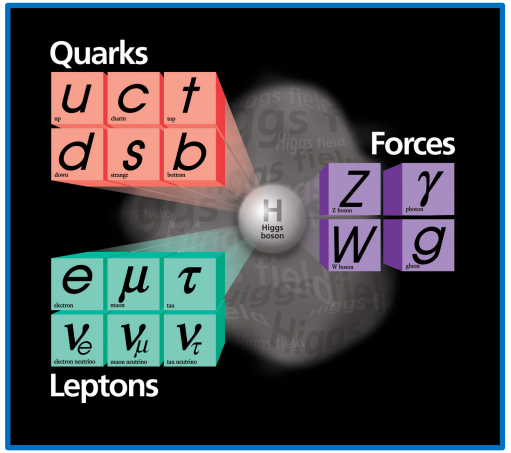
- Yukawa couplings to massless particles:

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

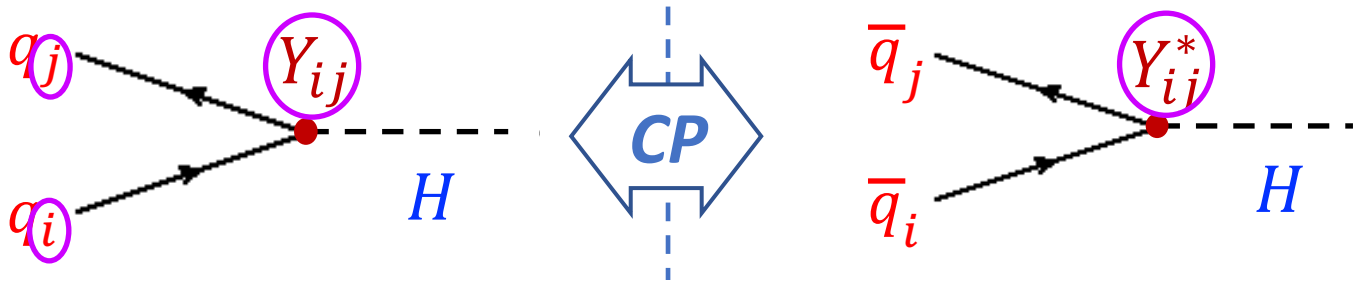
- Diagonalize Y_{ij} :

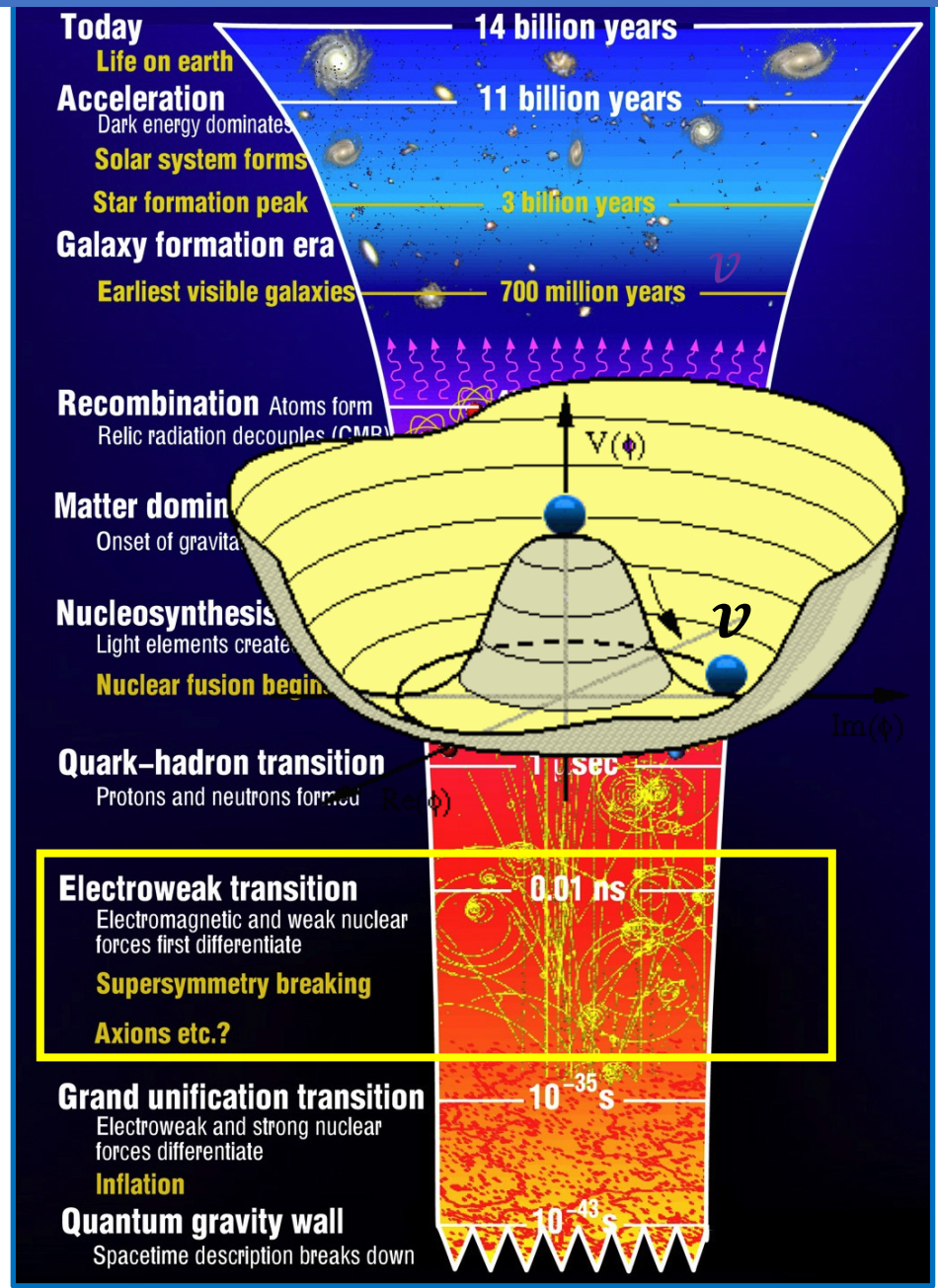
$u_i = (V^u)_{ij}\, u'_j$ and $d_i = (V^d)_{ij}\, d'_j$

→ mass and flavour eigenstates



- Universality violation: Higgs !
  - Higgs coupling is *not universal*, and mixes generations
  - Complex couplings: allows for CP Violation!





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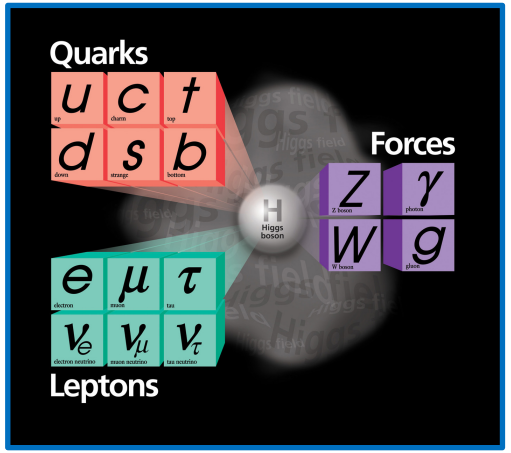
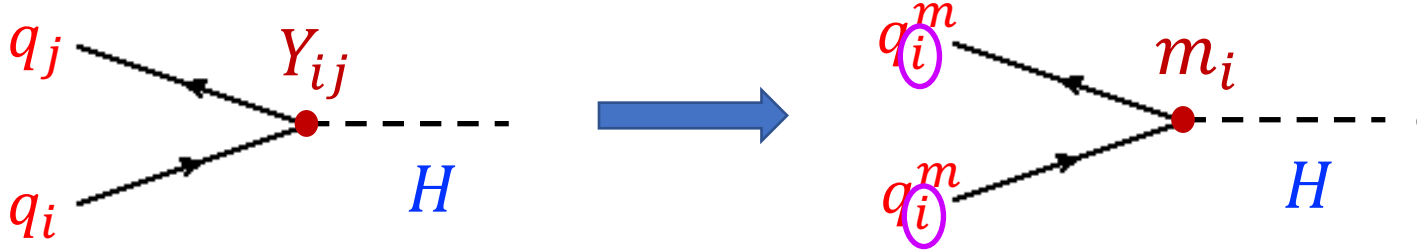
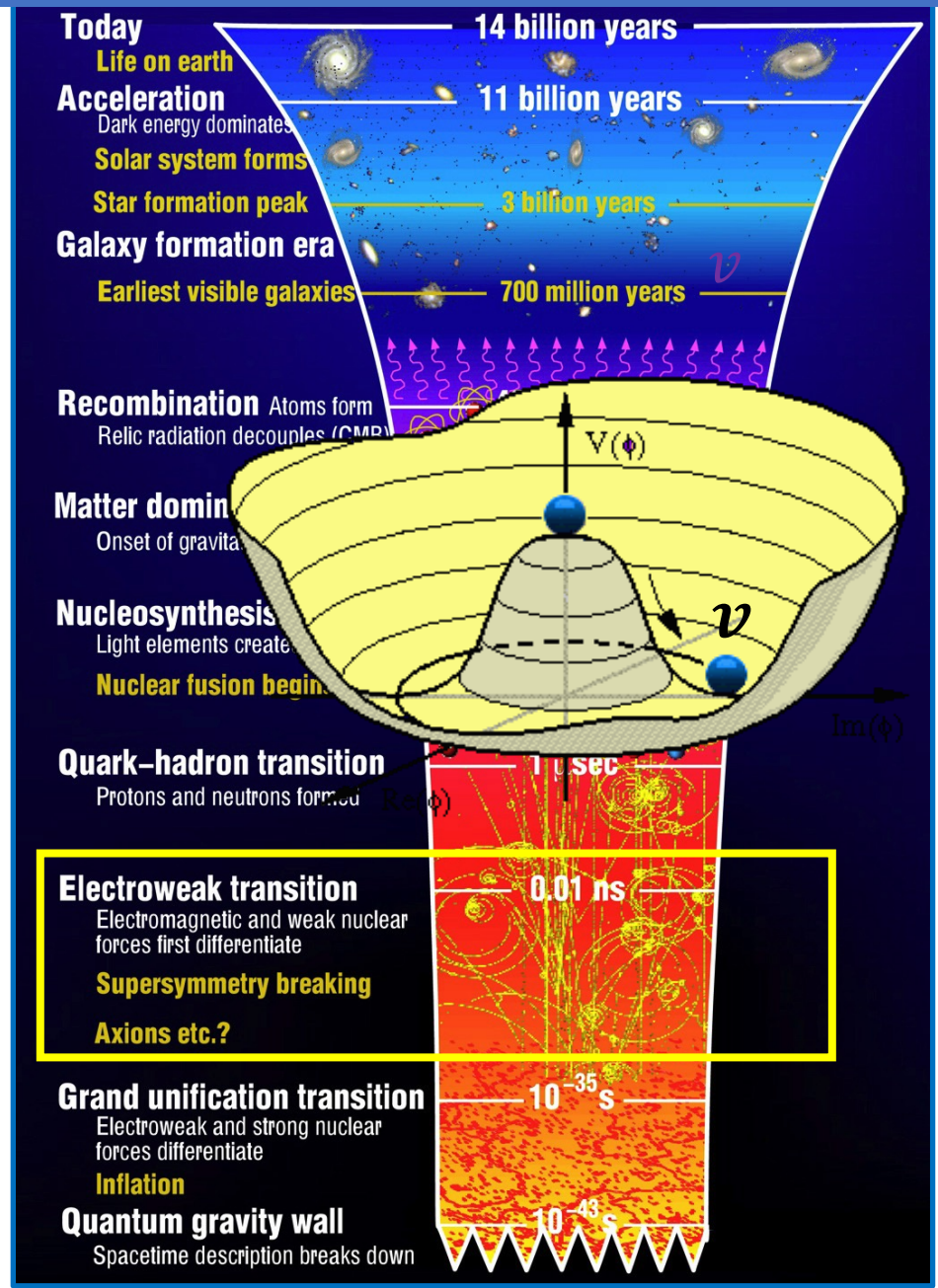


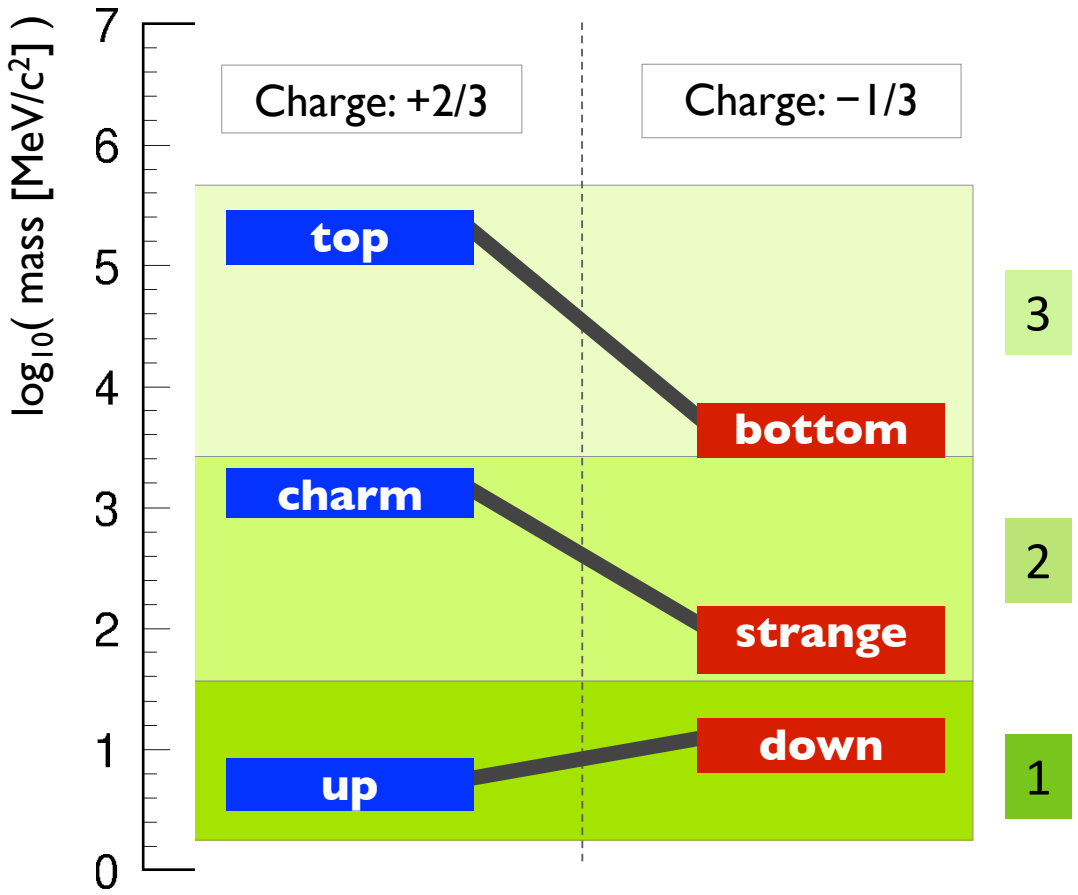
- Higgs: redefines quarks states in mass eigenstates $(i \leftrightarrow i)$

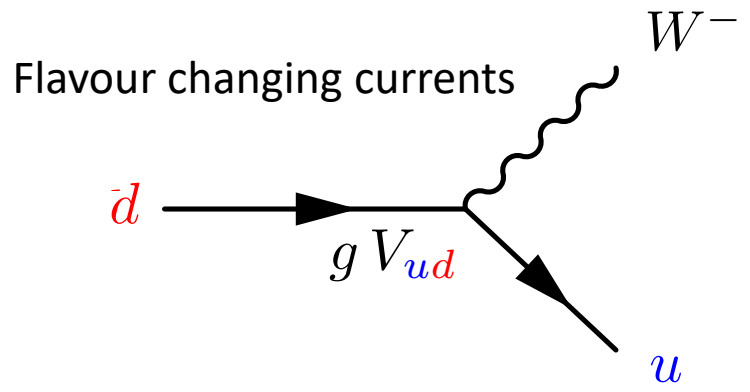
m_i : Real couplings only! → No CP violation





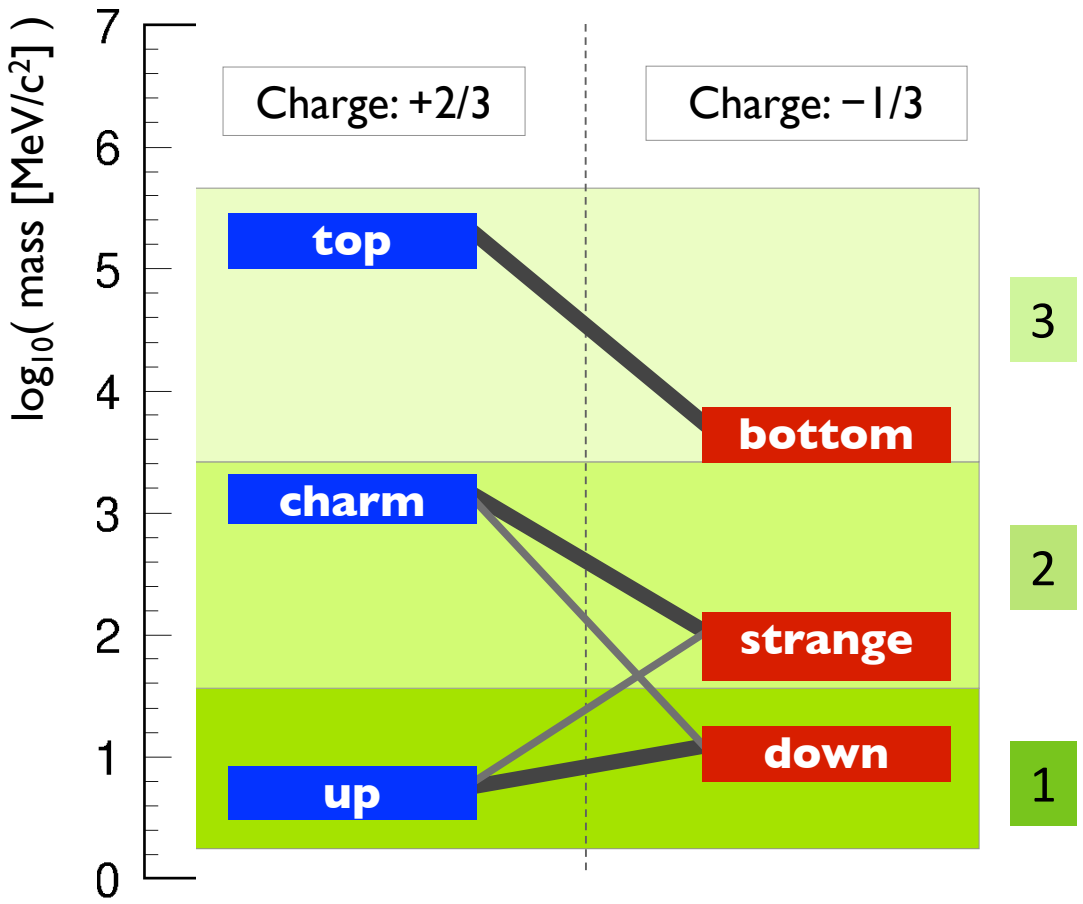
Flavour Changing Quark Interactions

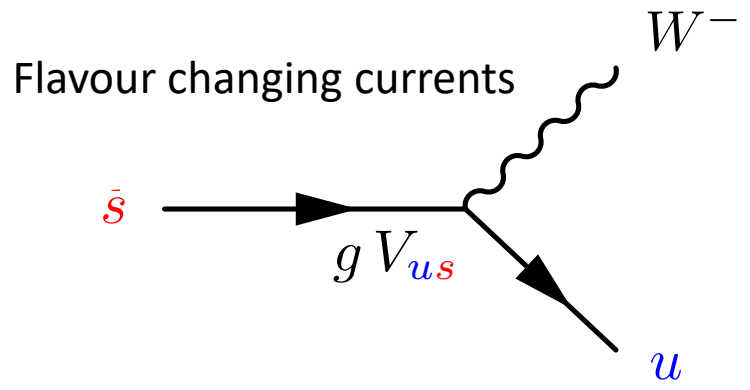




$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & & \\ & V_{cs} & \\ & & V_{tb} \end{pmatrix}$$

Flavour Changing Quark Interactions





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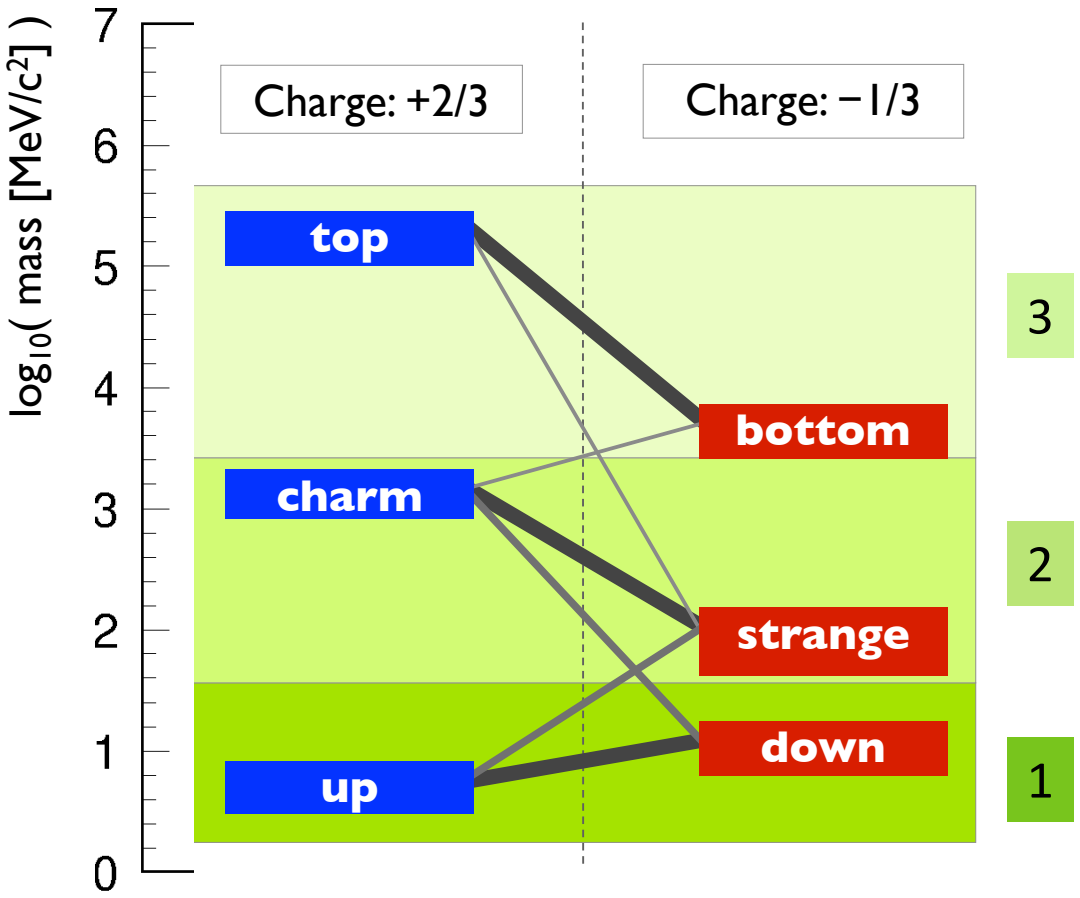

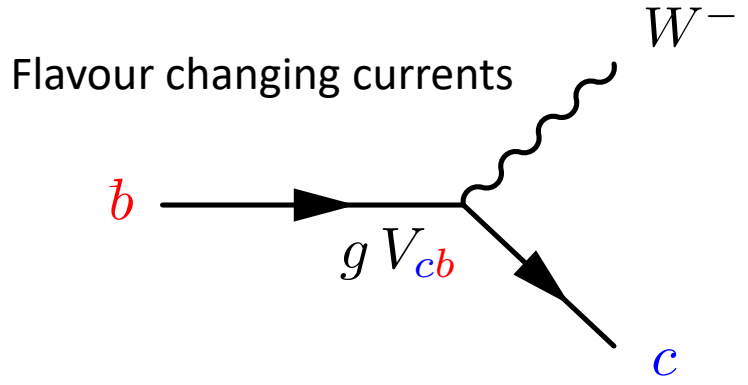

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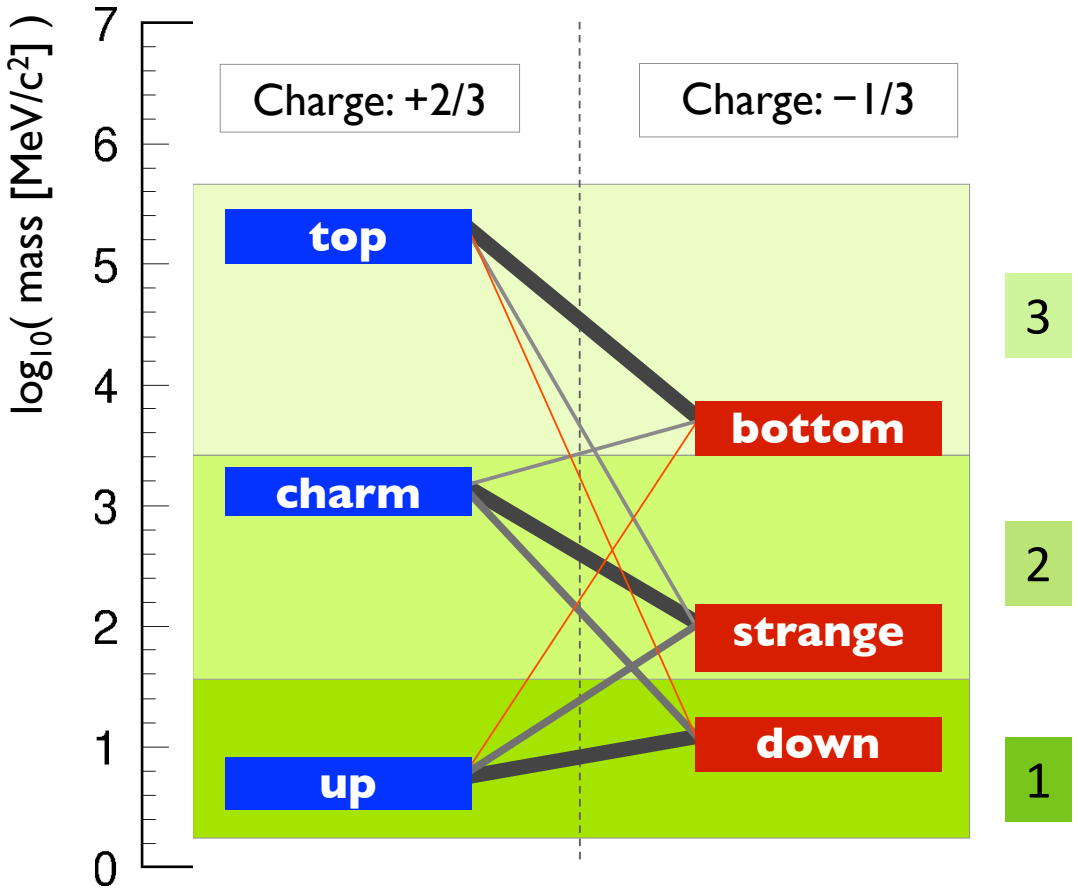
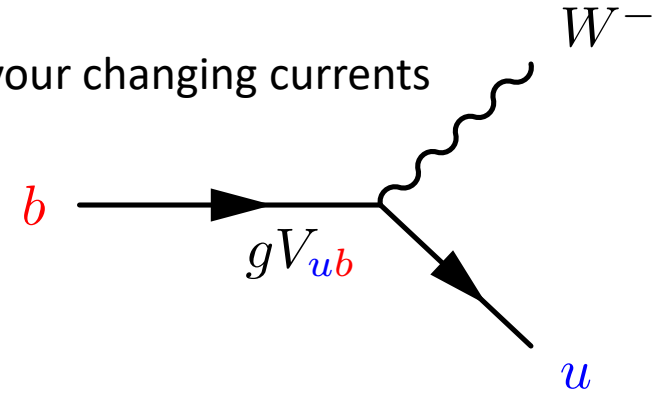
Flavour Changing Quark Interactions

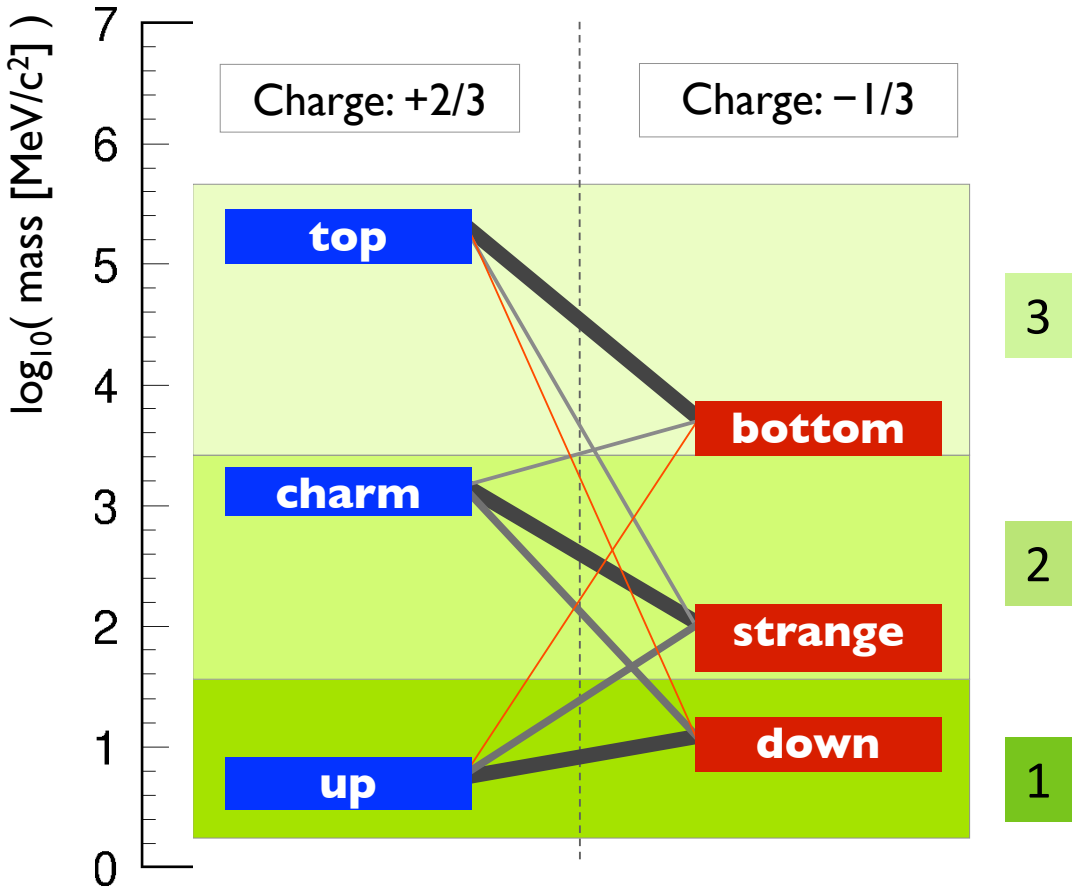


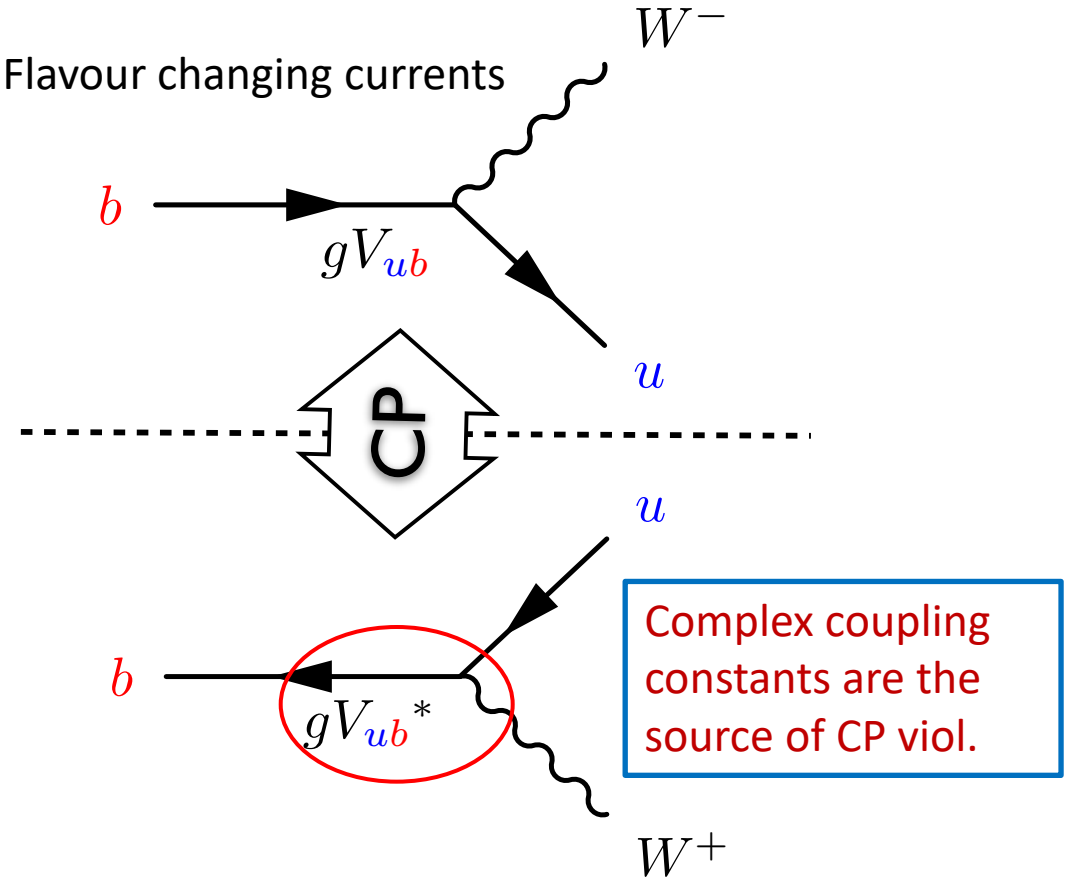
Flavour changing currents



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

Flavour Changing Quark Interactions – CP Violation





- 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

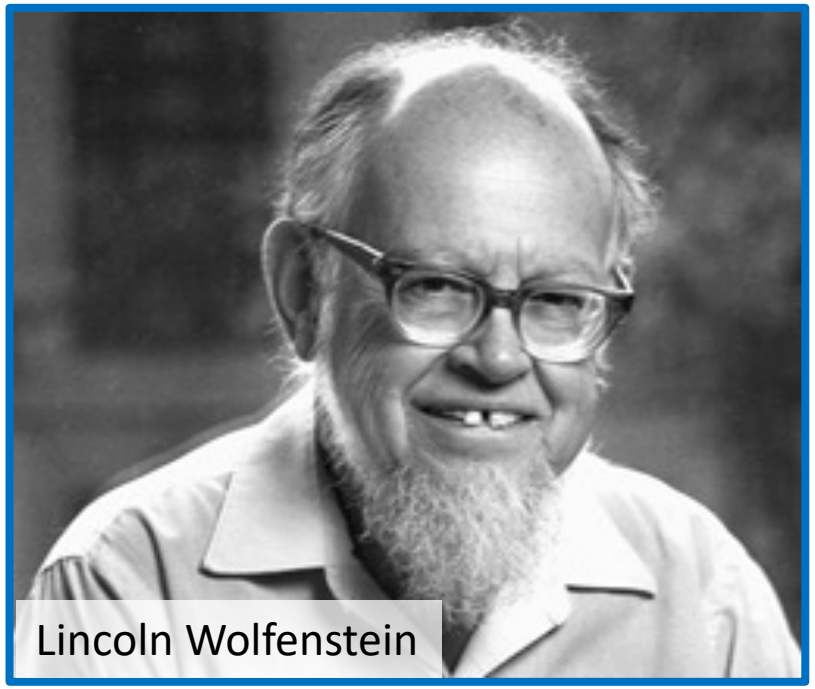
V_{CKM}:

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

- 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:

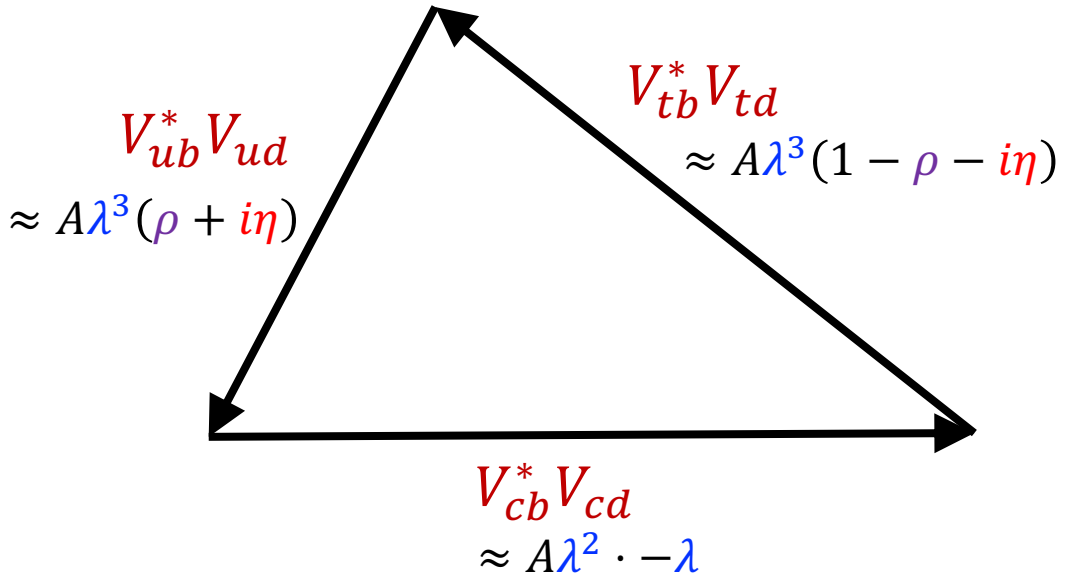
$$V_{CKM}^{\dagger}\, V_{CKM} = 1$$

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

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

Triangle in the complex plane:



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

- Wolfenstein parametrization:

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

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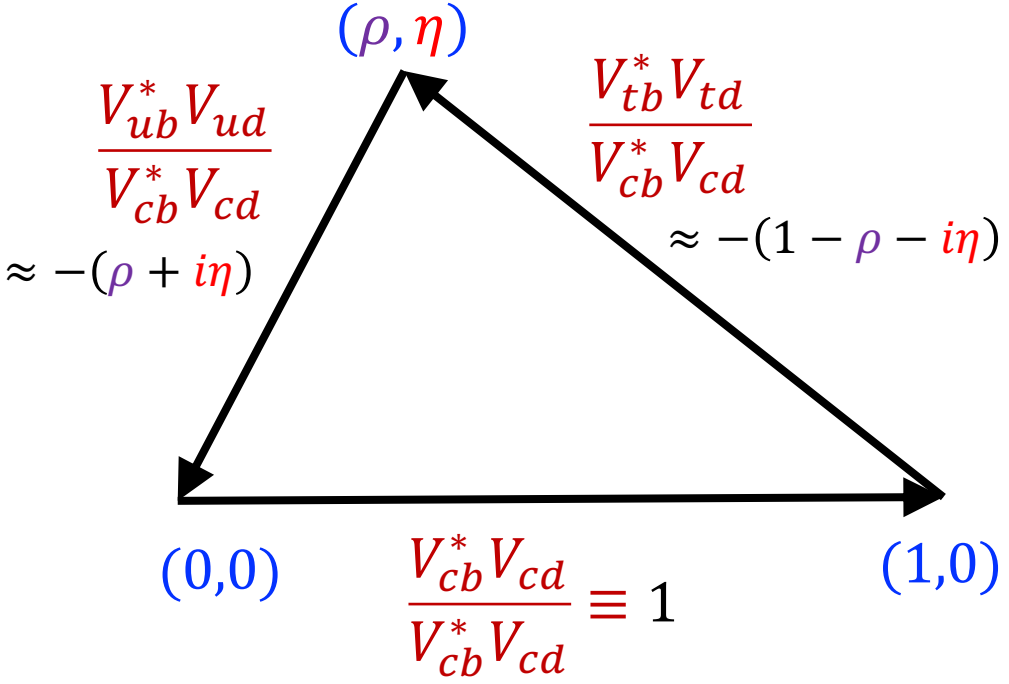

Renormalize horizontal scale to 1

- Wolfenstein parametrization:

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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:

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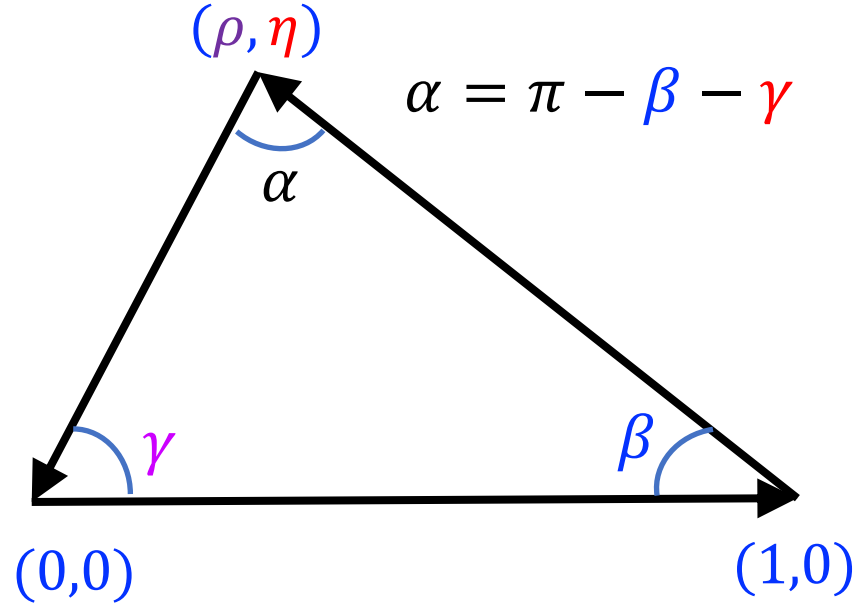

- There are 4 degrees of freedom:
  - 3 real (Euler angles) and one phase

The CKM matrix and unitarity triangle

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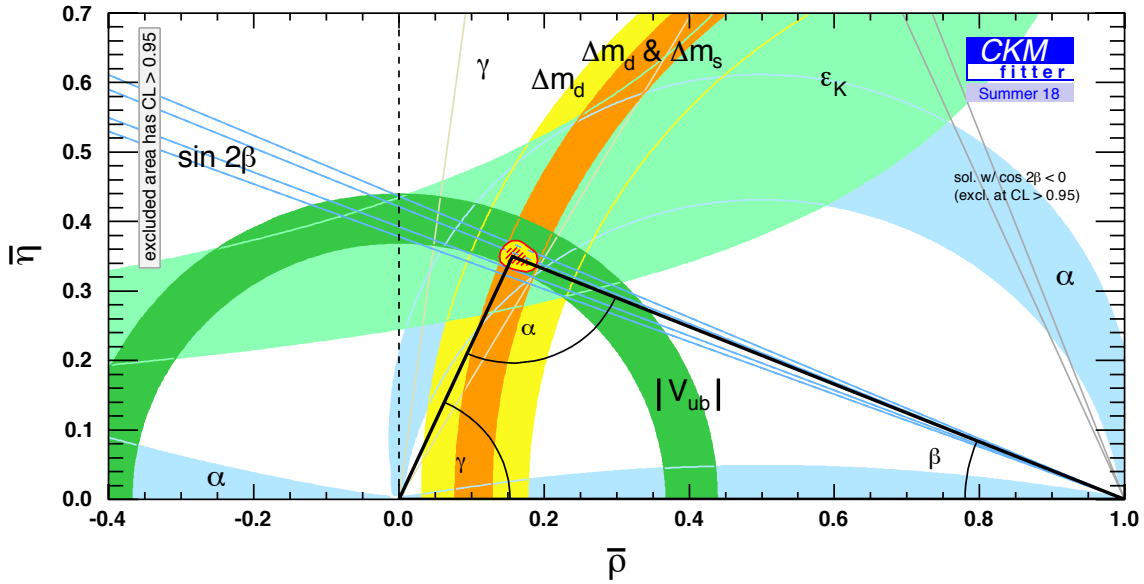
Triangle in the complex plane:

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



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- CP Violation:
  - Non-zero unitary phases
  - Triangle surface ≠ 0
    - Jarlskog invariant "J"

The CKM matrix V_{CKM} - 3 Generations

V_{CKM}:

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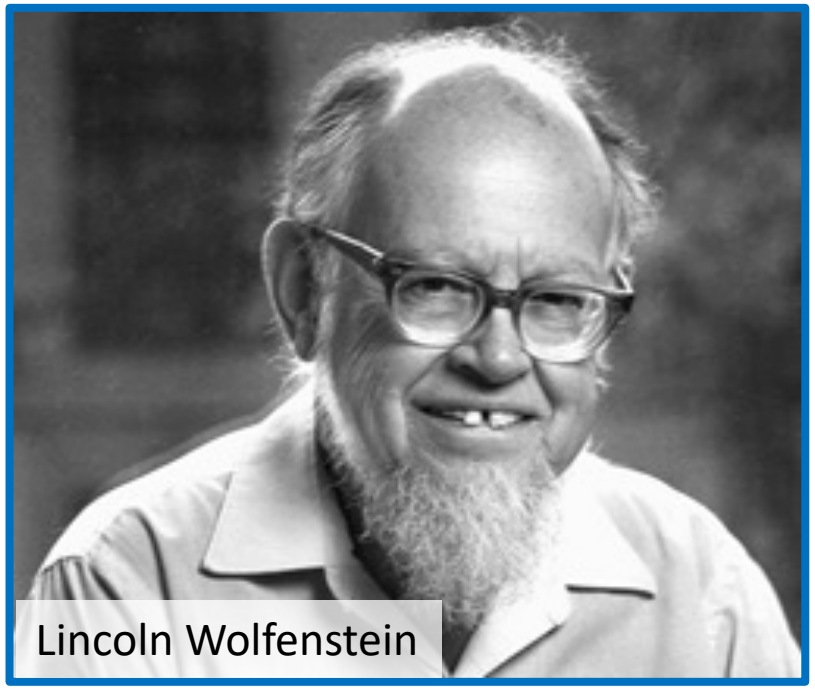
➔ 1 CP violating phase



Lincoln Wolfenstein

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

V_{CKM}:

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

- Wolfenstein parametrization: $V_{CKM} =$

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➔ 1 CP violating phase

V_{CKM}:

$$\begin{array}{c} \\ u \\ c \end{array} \begin{array}{c} \begin{array}{cc} d & s \end{array} \\ \begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} \end{array}$$

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

$V_{CKM} =$

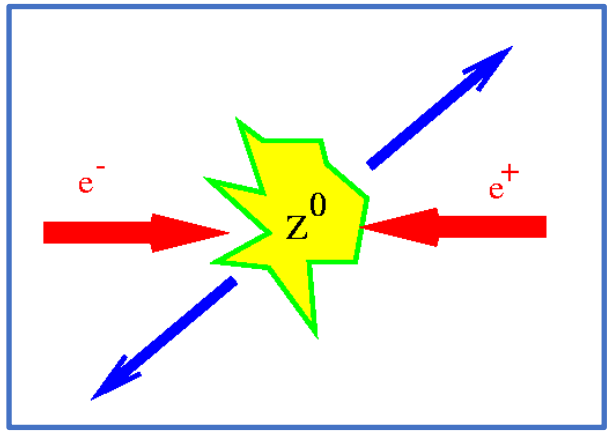
$$\begin{pmatrix} 1 - {}^1\!/_2\,\lambda^2 & \lambda \\ -\lambda & 1 - {}^1\!/_2\,\lambda^2 \end{pmatrix}$$

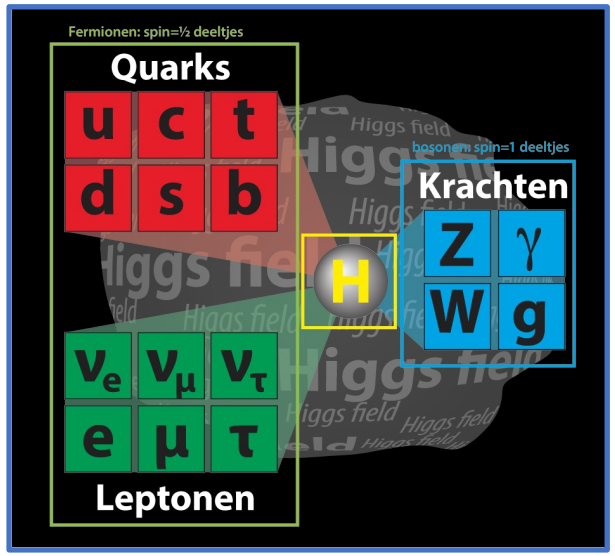
➔ No CP violation

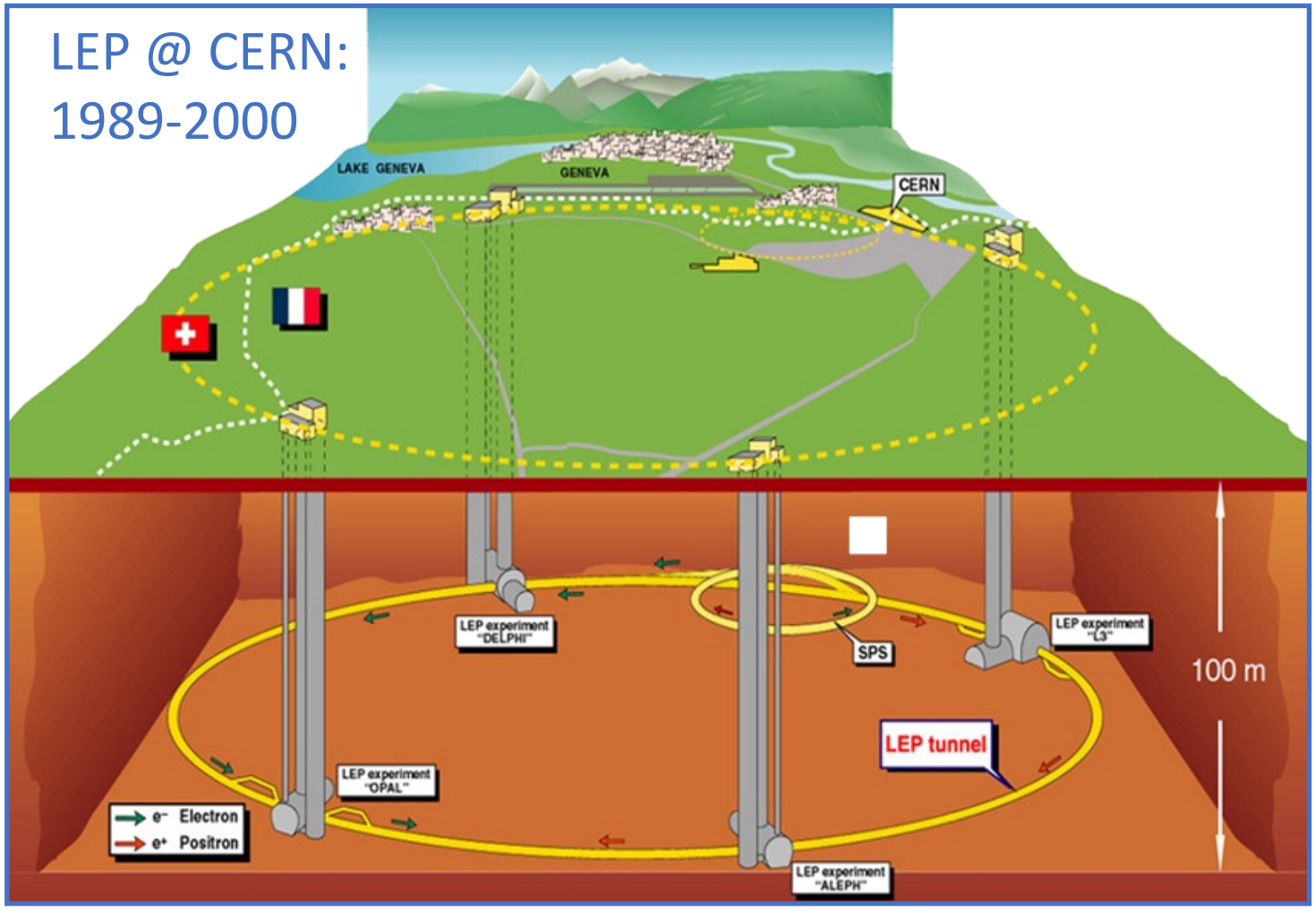
- *3 generations is the minimal particle content to generate CP violation* (In Standard Model).

3 Generations of particles – How do we know?

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



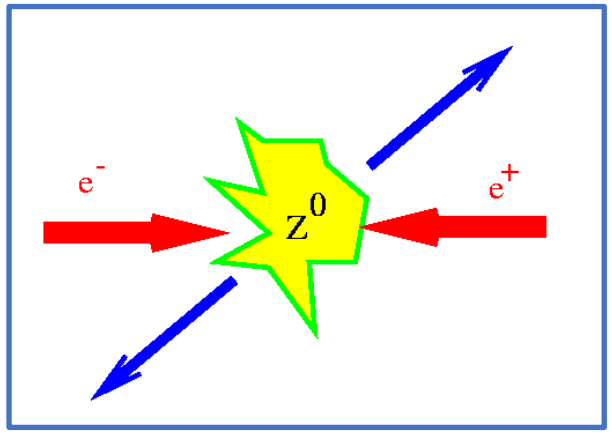


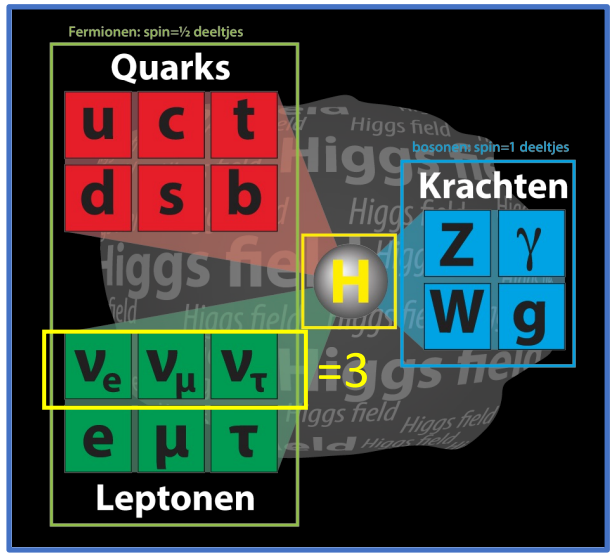


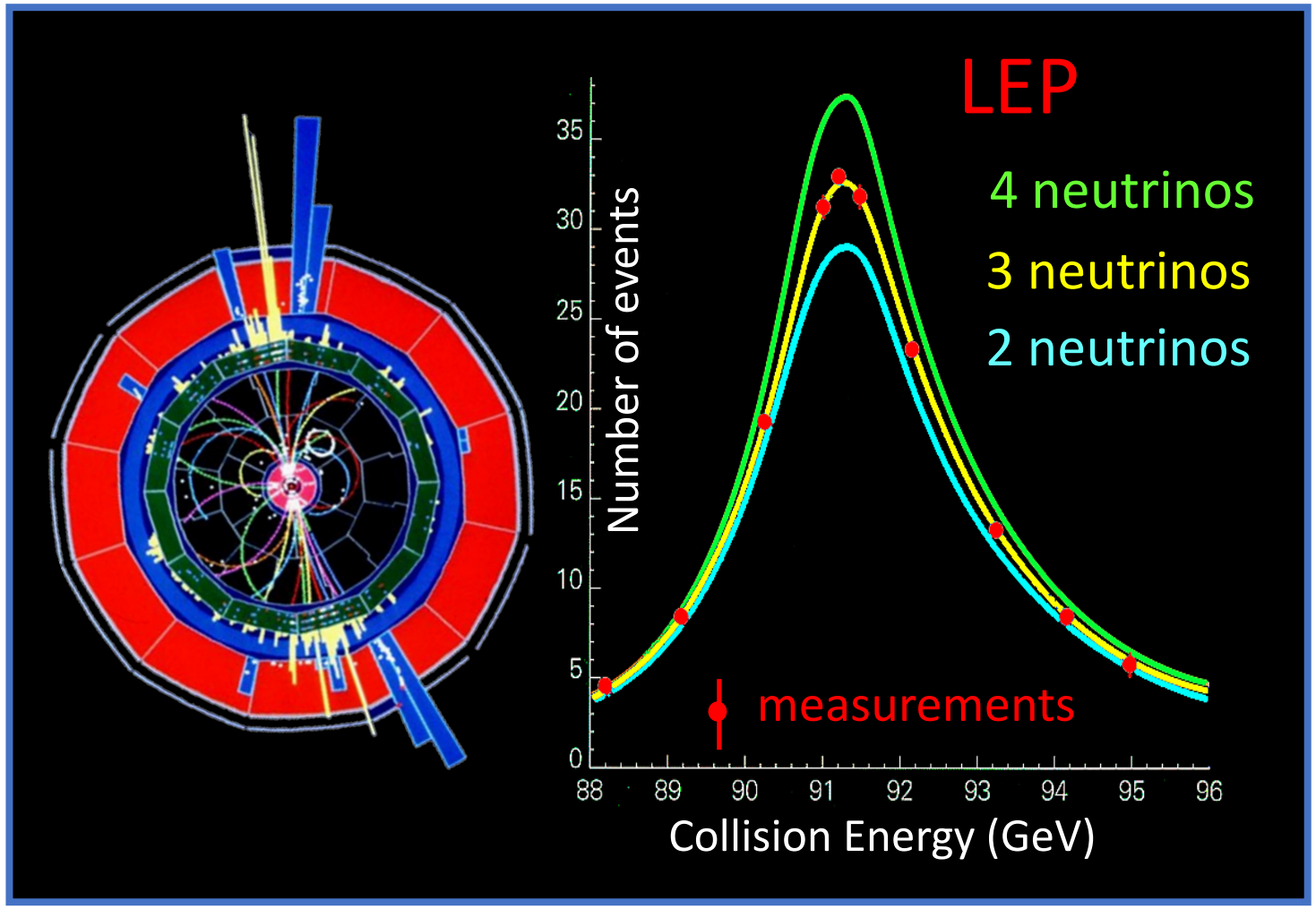
- *No additional weakly interacting **light fermion** generations.*

3 Generations of particles – How do we know?

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





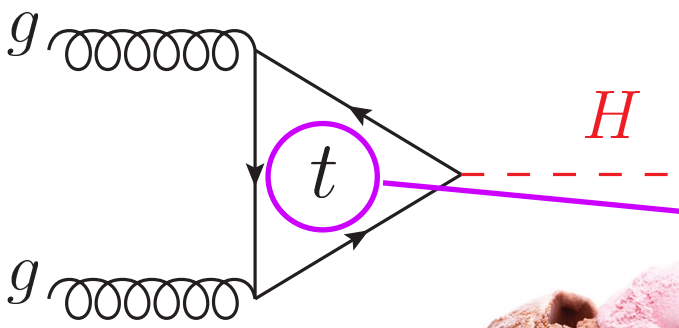


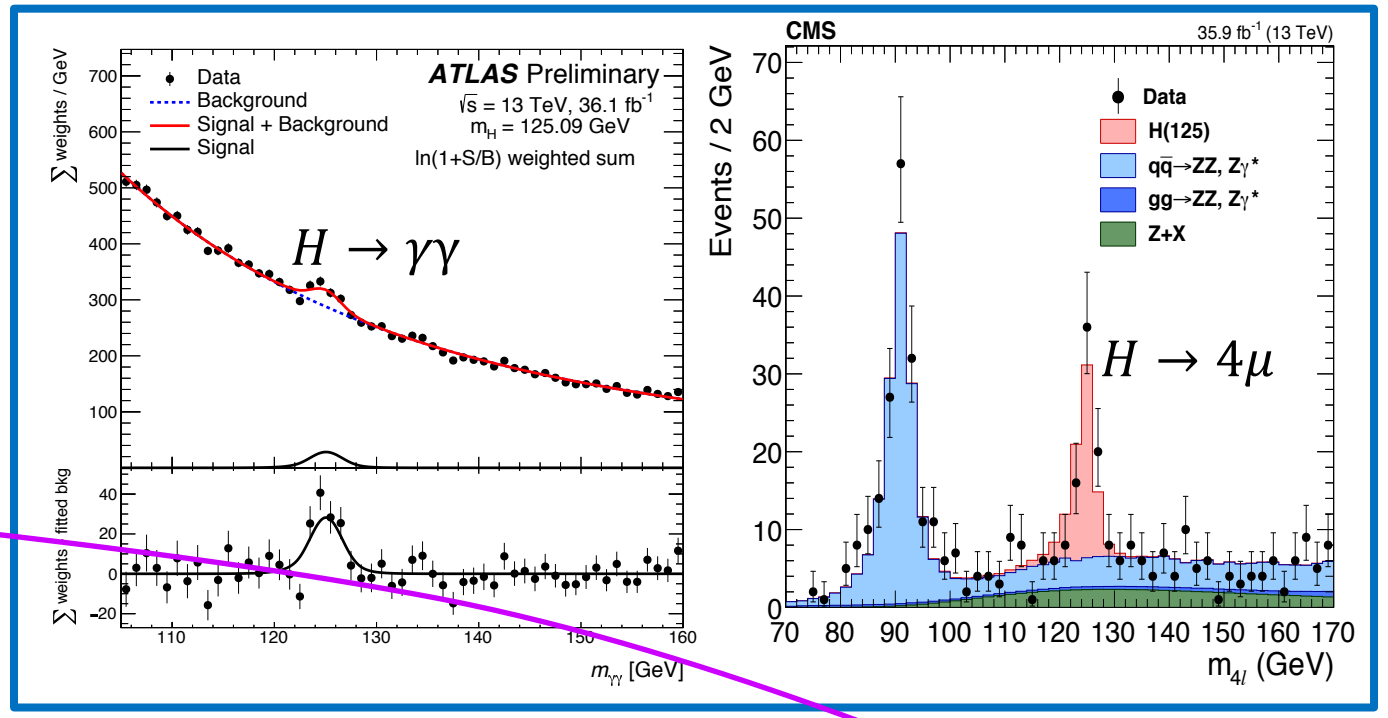
- *No additional weakly interacting **light fermion** generations.*

3 Generations of particles – How do we know?

LHC: Higgs production:

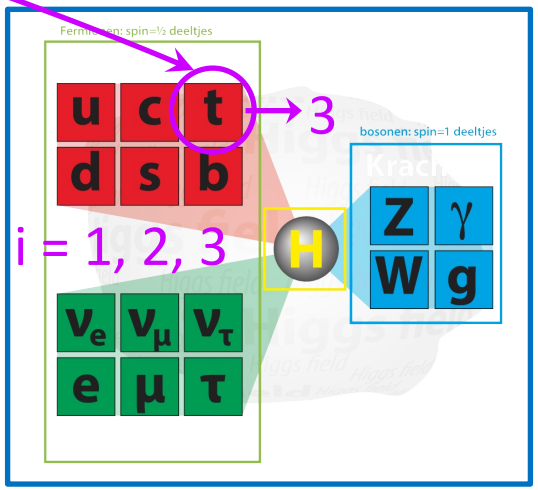
Loop diagram is proportional to the mass of the heaviest fermion.





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

➢ *3 Flavour generations*



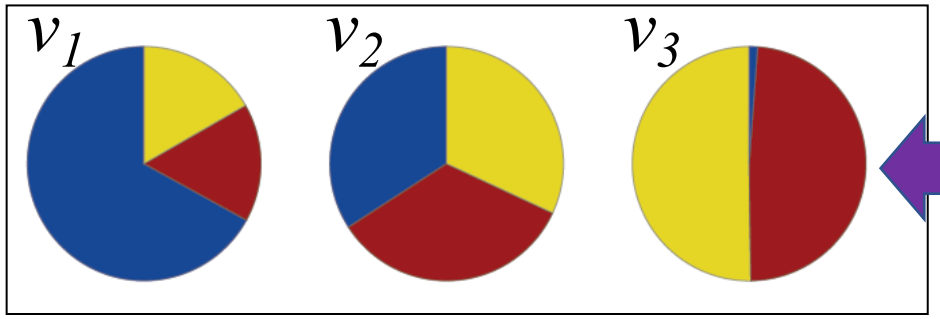
How about leptons?

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

- Neutrinos: U_{PMNS}

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

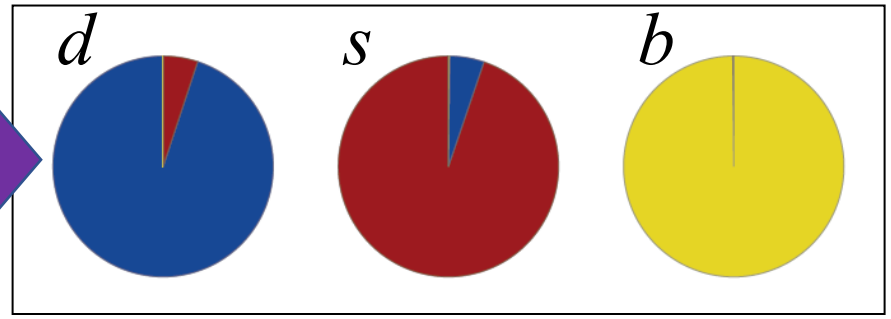
$$U_{MNSP} \approx \begin{pmatrix} 0.82 & 0.55 & 0.15 \\ 0.37 & 0.57 & 0.70 \\ 0.39 & 0.59 & 0.69 \end{pmatrix}$$



- Quarks: V_{CKM}

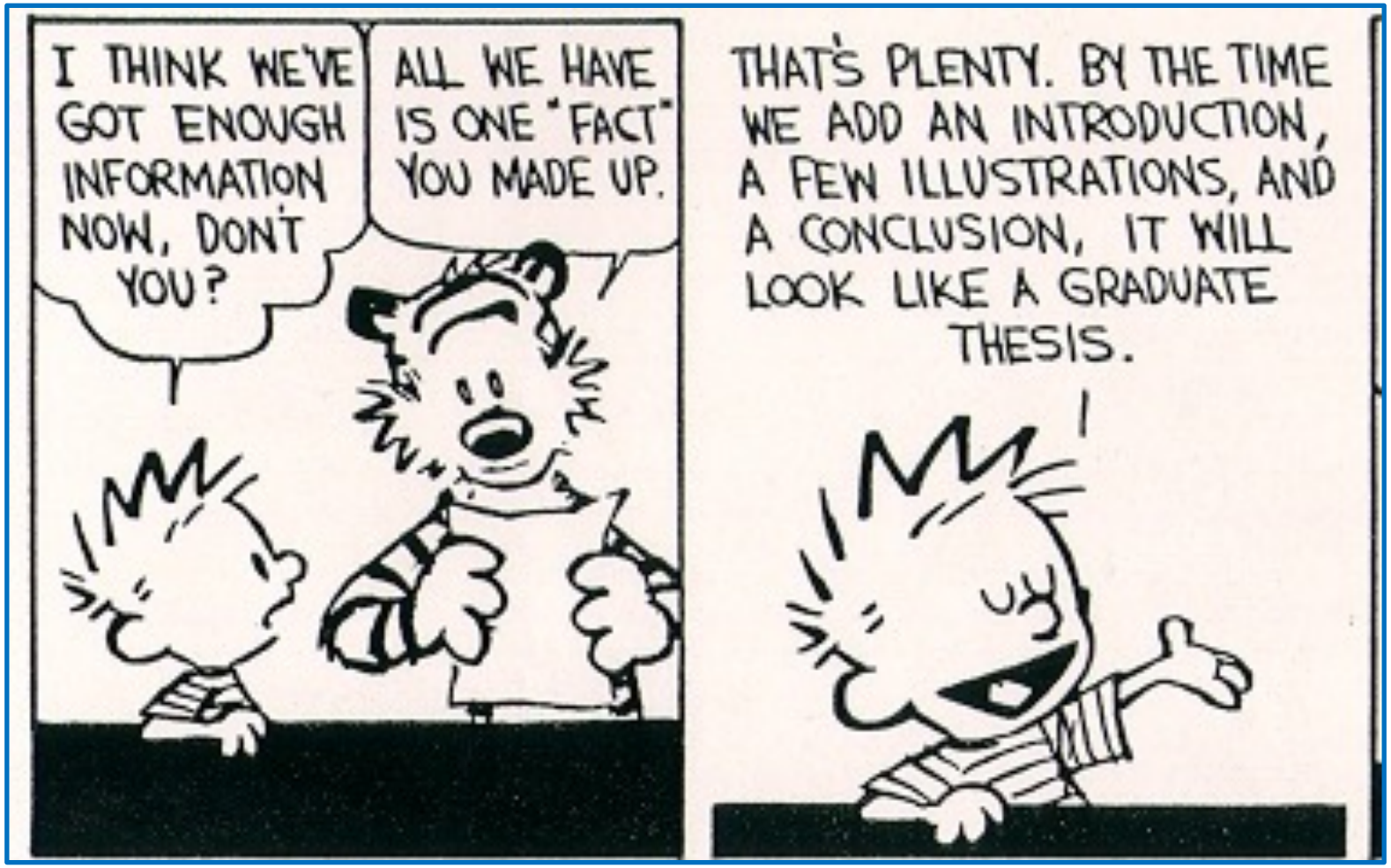
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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



?

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 Today & Tomorrow:

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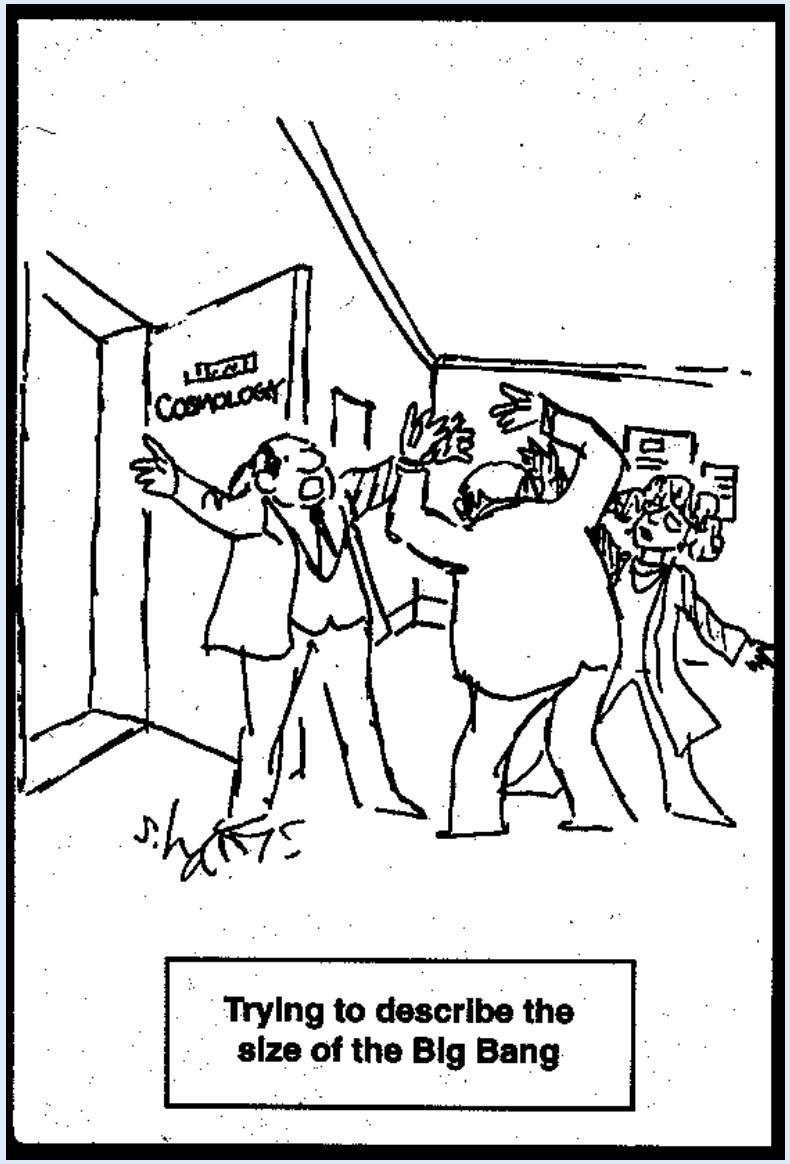
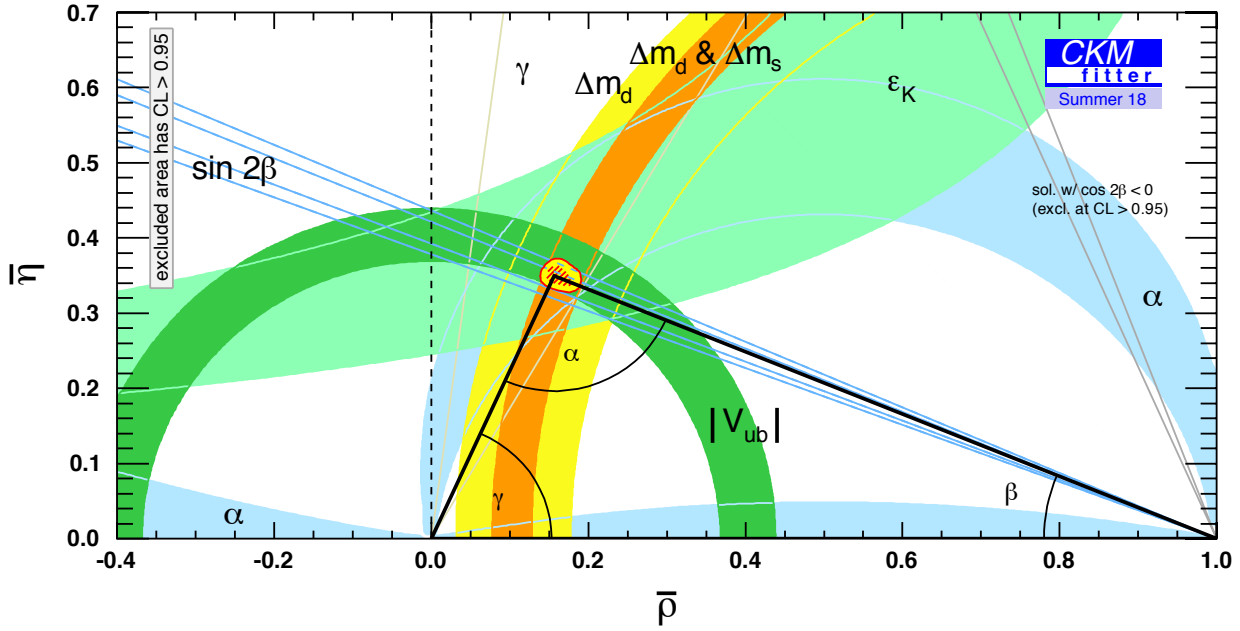


How large is CP violation?

- 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:
    - $m_u \neq m_c \;\; ; \;\; m_c \neq m_t \;\; ; \;\; m_t \neq m_u$
    - $m_d \neq m_s \;\; ; \;\; m_s \neq m_b \;\; ; \;\; m_b \neq m_d$

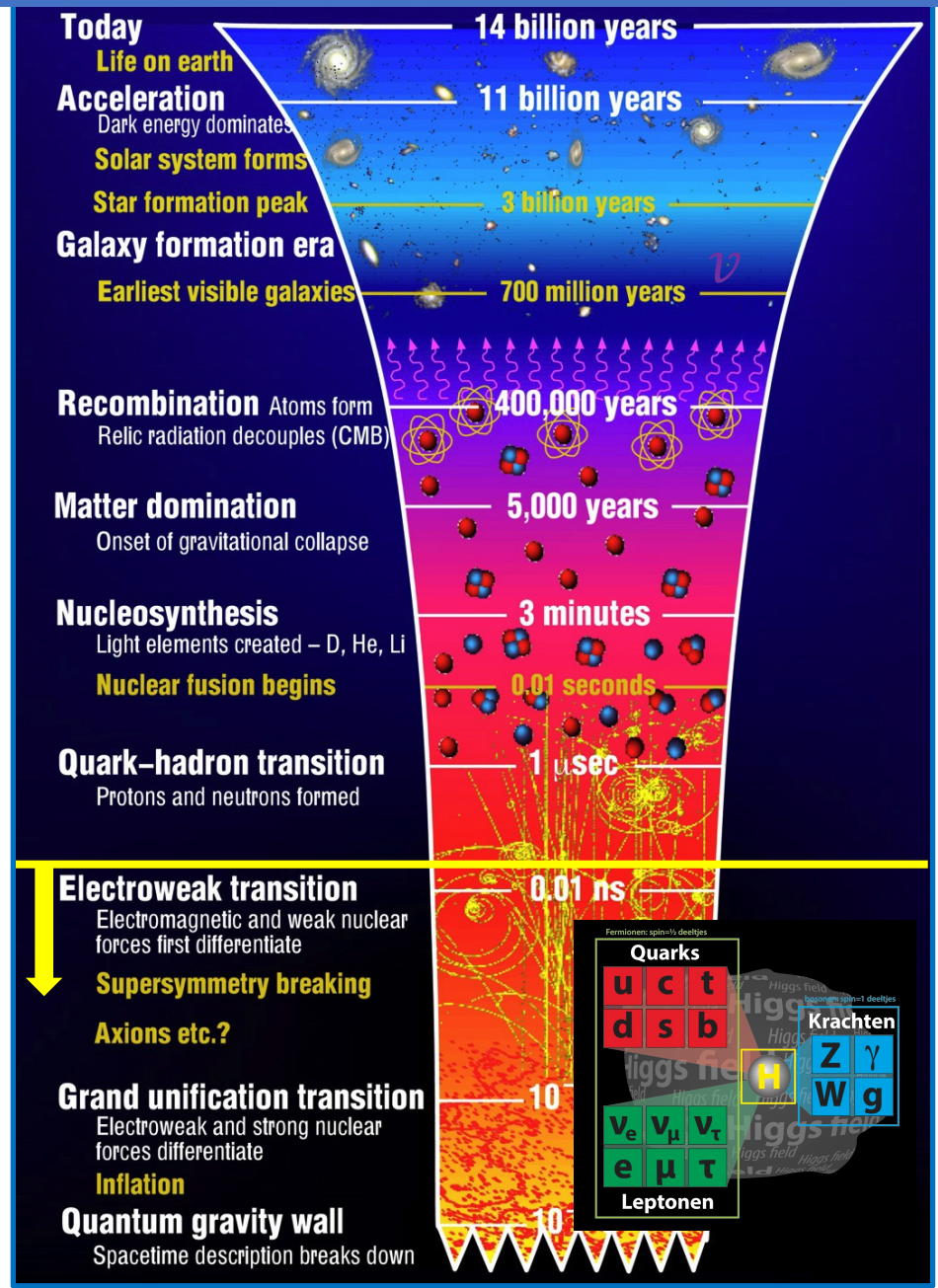
- Jarlskog criterion (1987) for amount of CP violation:
  - $\det\left[M_u M_u^\dagger, M_d M_d^\dagger\right] = 2\,i\,J\,(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_u^2 - m_t^2) \times (m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_d^2 - m_b^2)$

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

SU(2)

- W interaction flavour universal

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



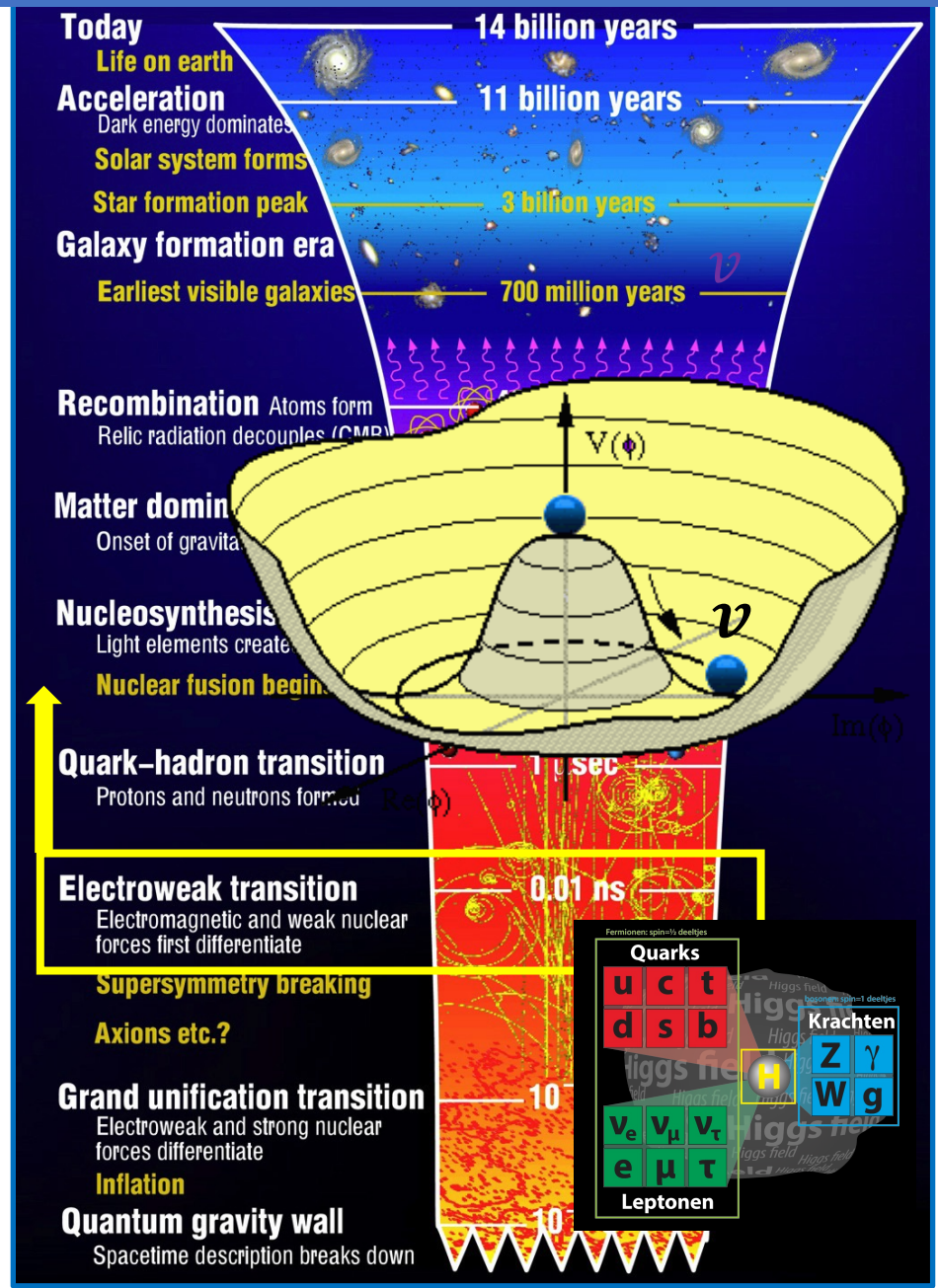
SU(2) → Higgs vev

- W interaction flavour universal

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

- Higgs interaction *not* flavour universal

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



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

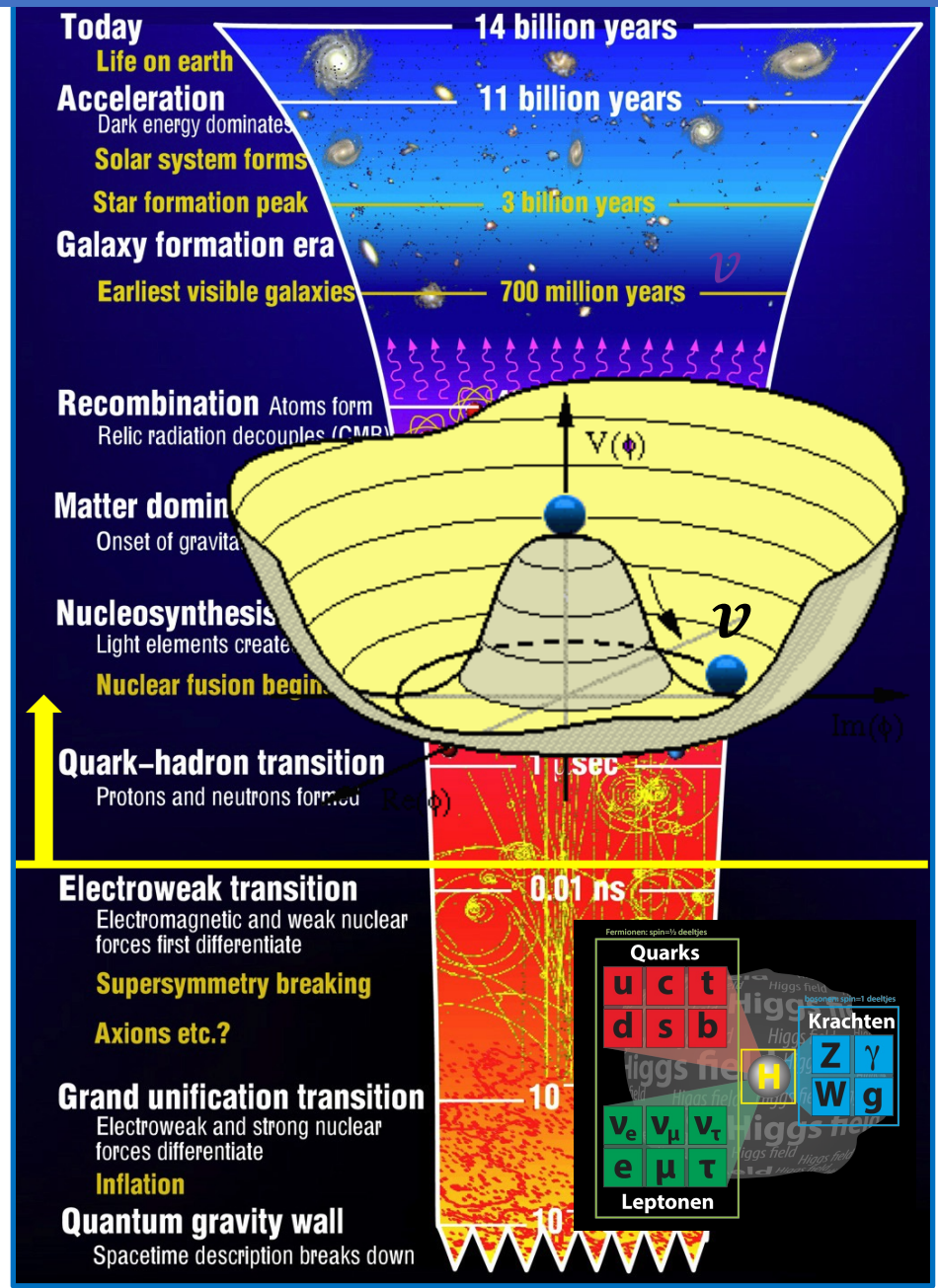
$$\mathcal{L}_H = Y^d_{ij} \left(\overline{u'_i}, \overline{d'_i}\right)_L \begin{pmatrix} 0 \\ v \end{pmatrix} d'_{jR} + Y^u_{ij} \left(\overline{u'_i}, \overline{d'_i}\right)_L \begin{pmatrix} v \\ 0 \end{pmatrix} u'_{jR}$$

- Mass vs Interaction states:

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

- Amount of CP violation:

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



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

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

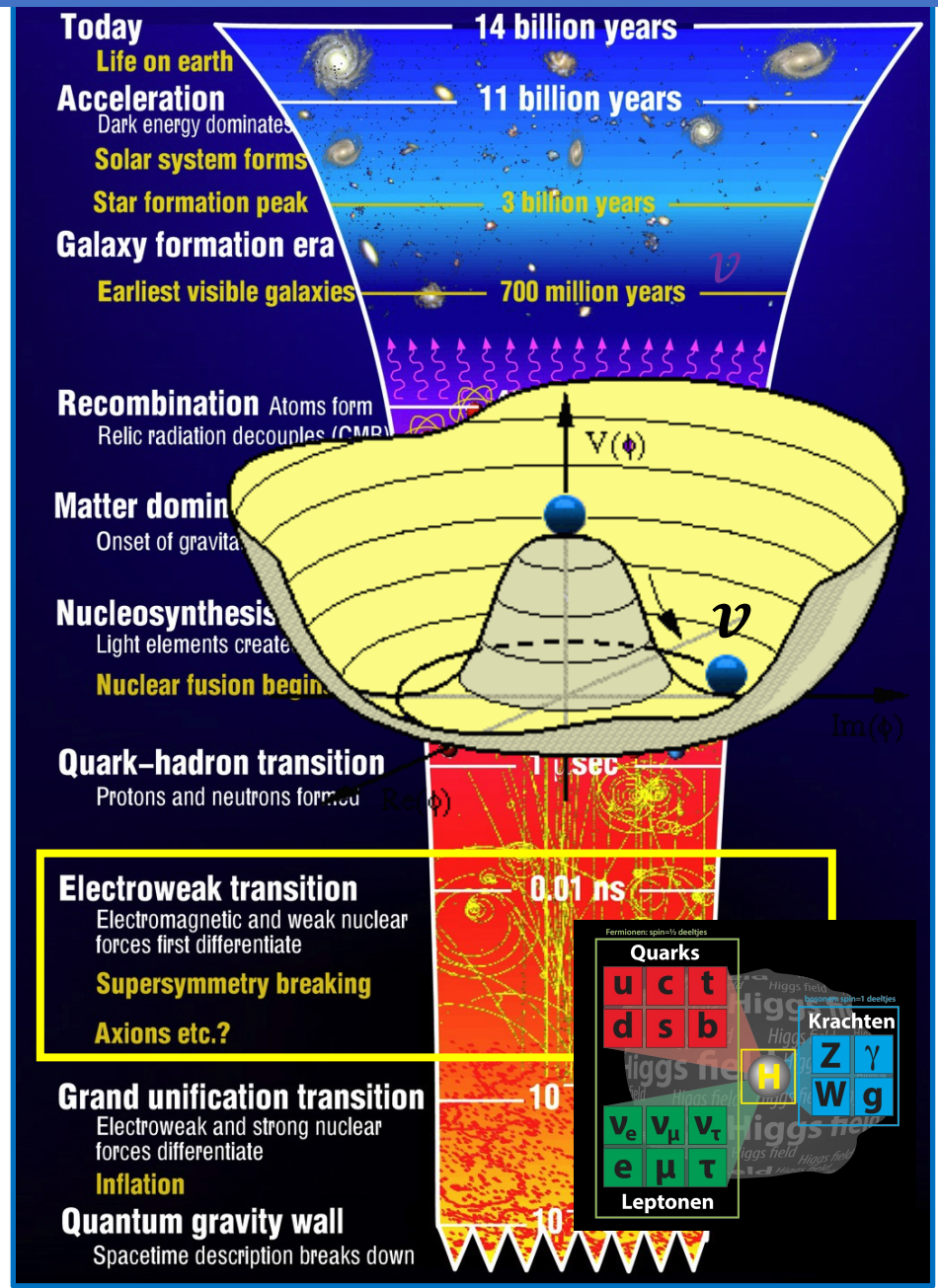
- Mass vs Interaction states:

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

- 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

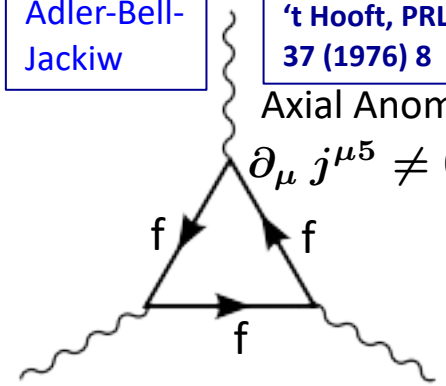
✓ Baryon Number Violation

Adler-Bell-Jackiw

't Hooft, PRL 37 (1976) 8

Axial Anomaly:

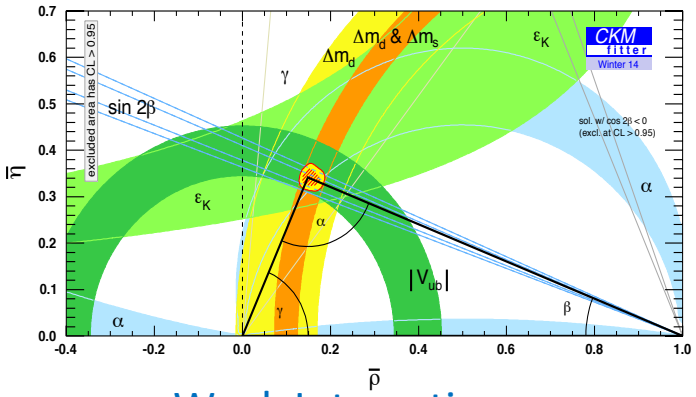
$$\partial_\mu j^{\mu 5} \neq 0$$



Quantum anomaly

Matter - antimatter asymmetry

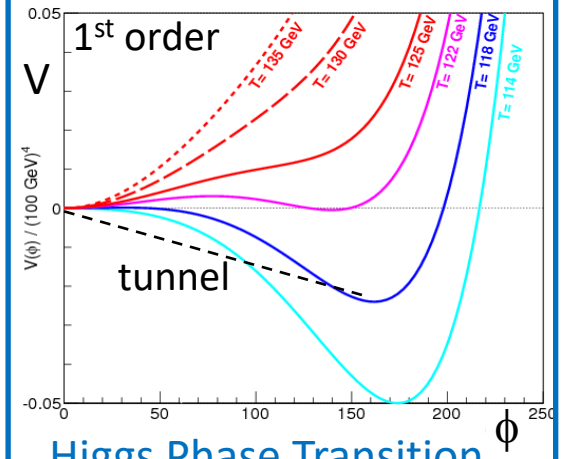
✓ C and CP Violation



Weak Interaction

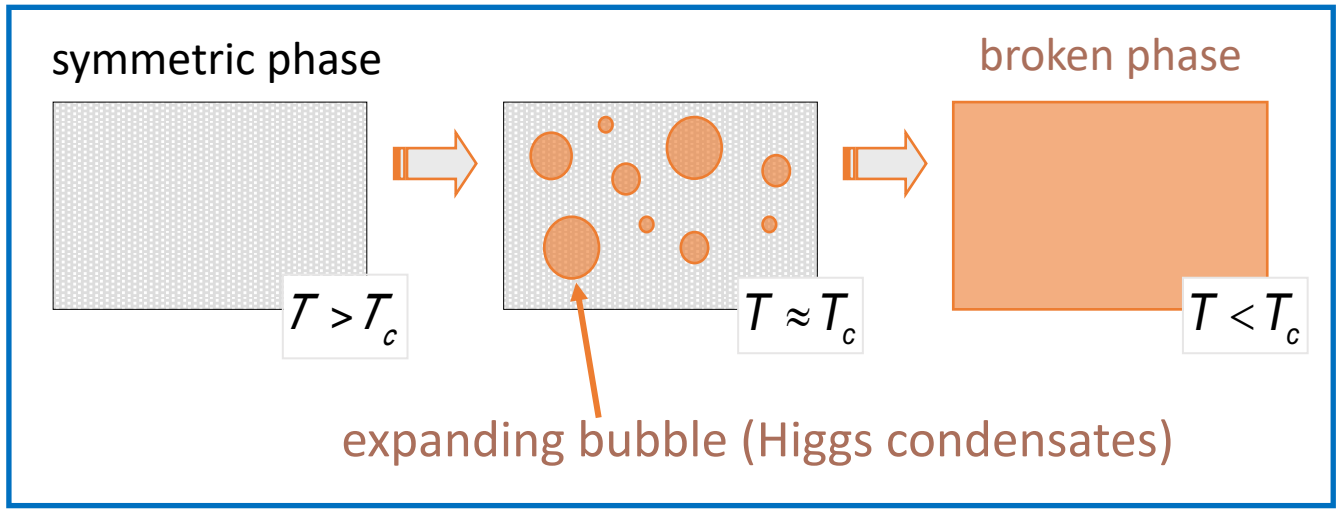
Non - reversal

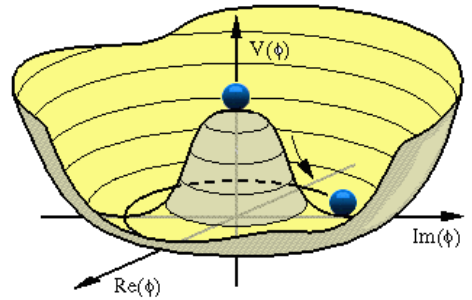
✓ Thermal non-equilibrium



Higgs Phase Transition

- Baryogenesis from Higgs symmetry breaking?





The Baryogenesis Puzzle – Electroweak Baryogenesis?

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

Baryon asymmetry

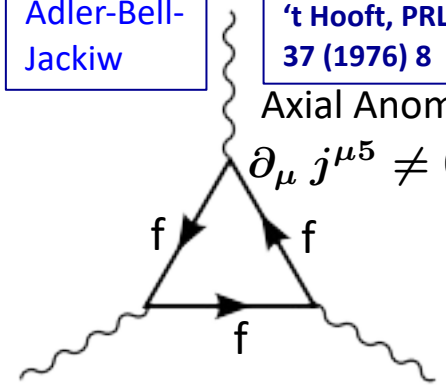
✓ Baryon Number Violation

Adler-Bell-Jackiw

't Hooft, PRL 37 (1976) 8

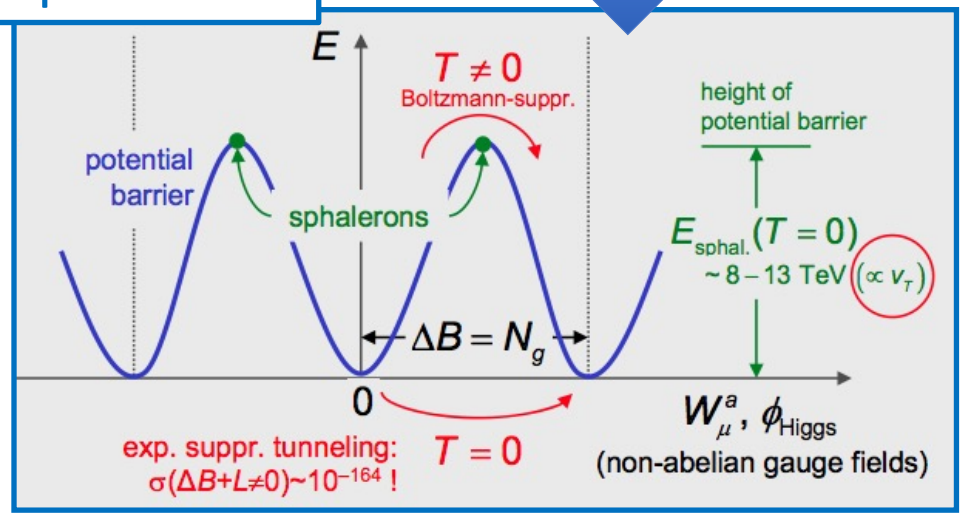
Axial Anomaly:

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



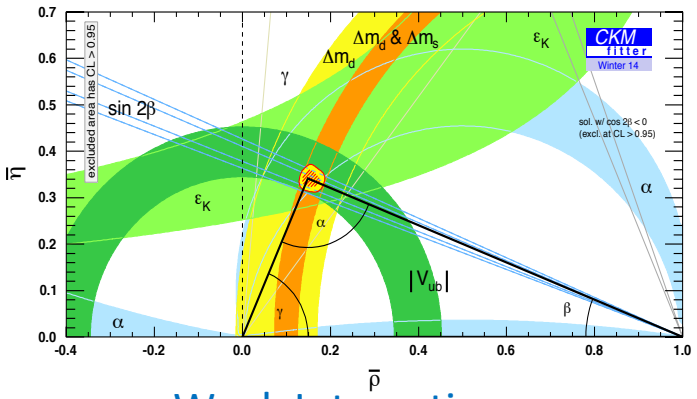
Quantum anomaly

✓ Sphalerons



Matter - antimatter asymmetry

✗ C and CP Violation



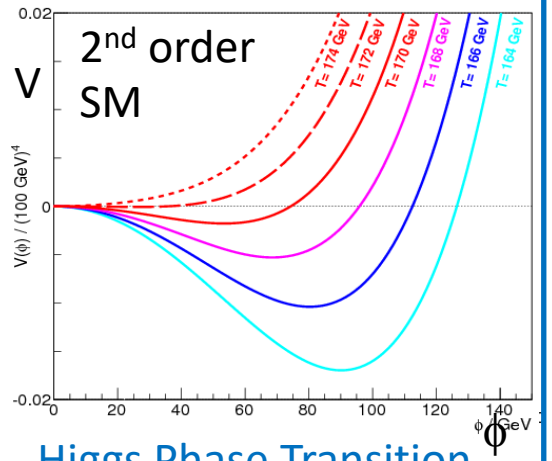
Weak Interaction

✗ 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

Non - reversal

✗ Thermal non-equilibrium



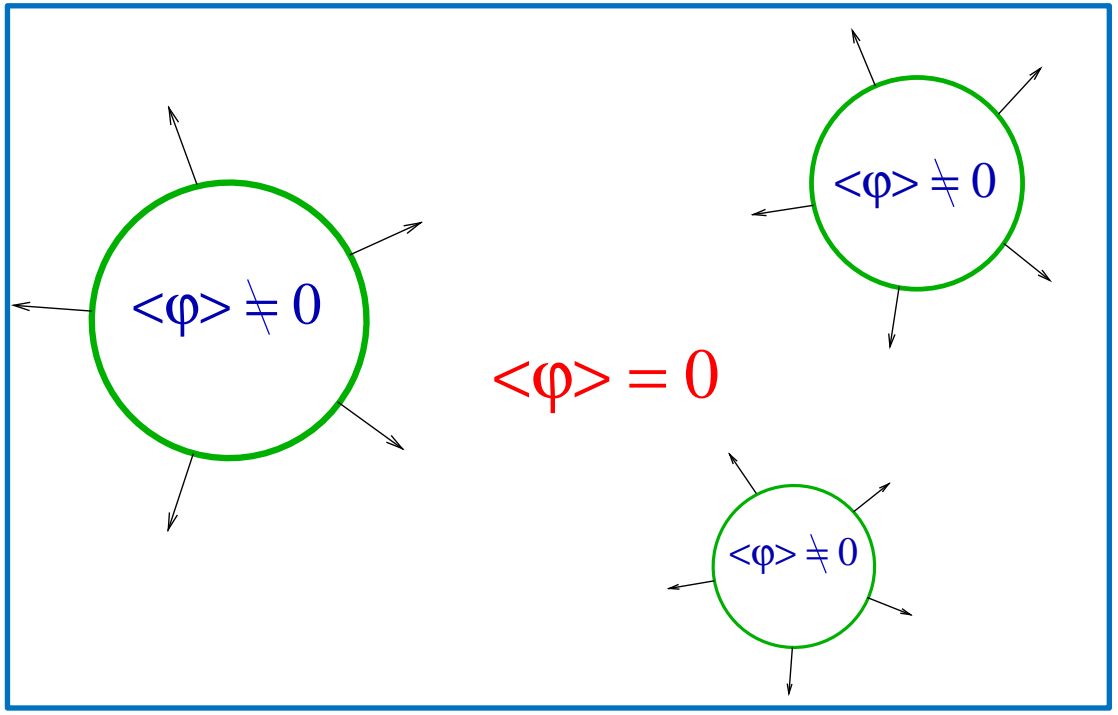
Higgs Phase Transition

✗ 1st order?

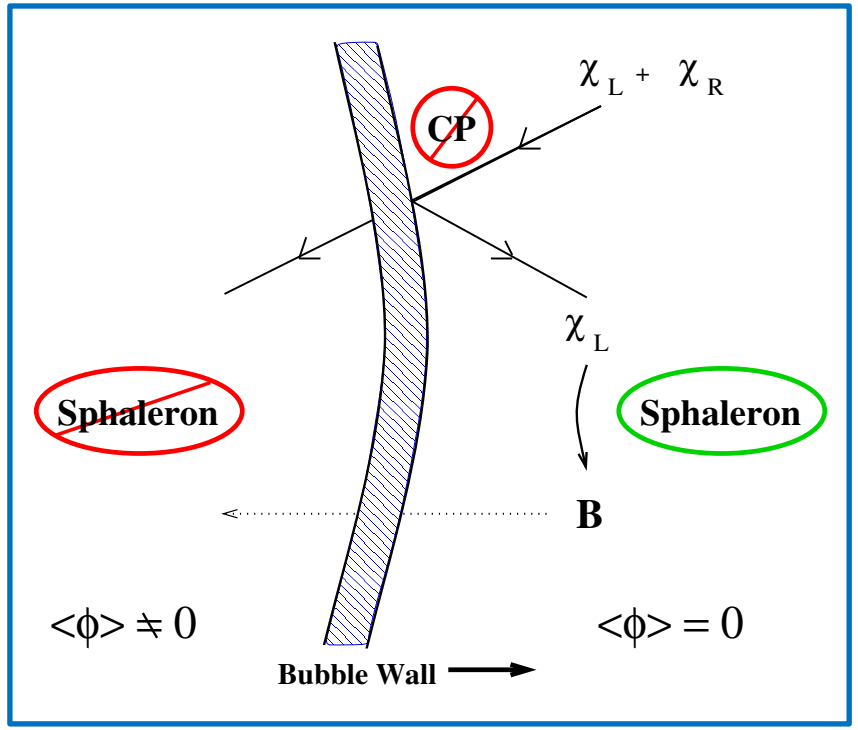
- SM: M_H < ~70 GeV
- THDM: M_H ~ 125 OK

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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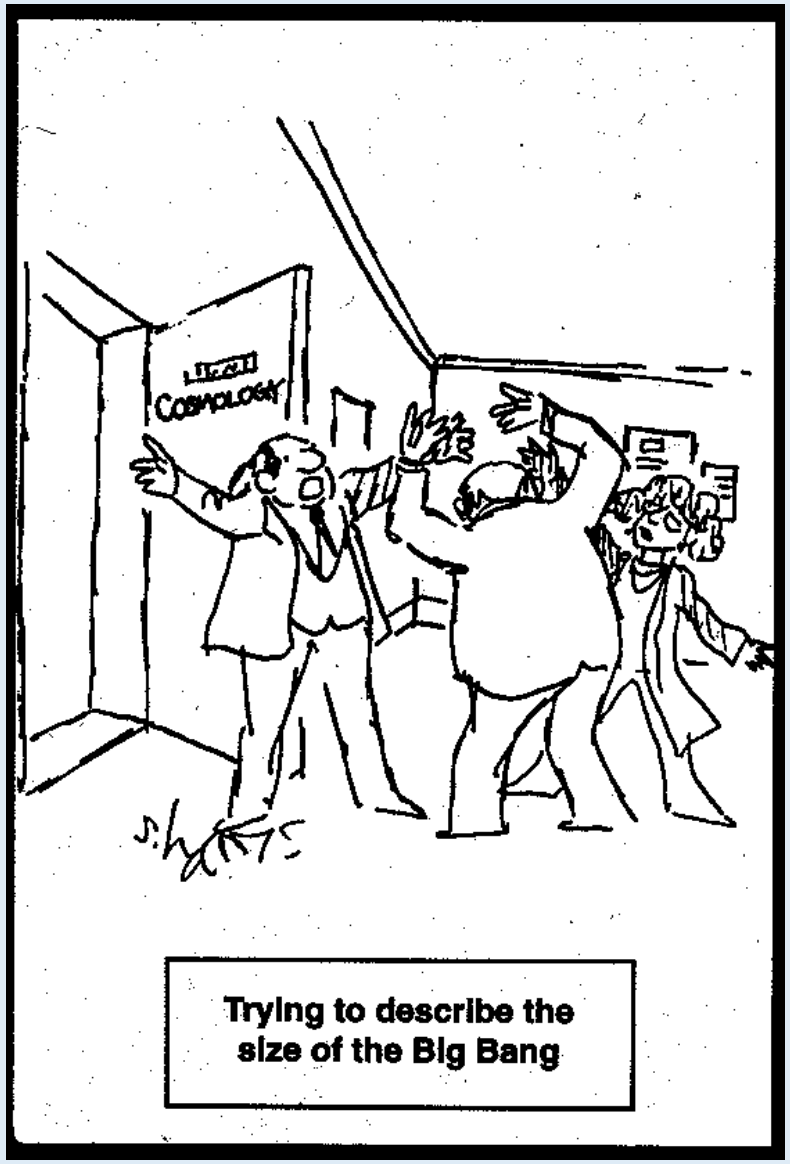
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