Why is Parity ***RESTORED*** ?

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Why is parity restored ? …

a somewhat provocative title, since we would more usually ask « Why is parity violated? »

In this talk, I plan to show that

- Parity violation is the **default expectation** in gauge theories
- Parity violation has nothing to do with the presence/absence of right-handed neutrinos

and ask the question:

- Since ***we were fooled for centuries*** to think parity was a good symmetry, **why is it indeed restored at the large distances then accessible**?
- And then…is some *fairly long distance* P violation possible?

Parity violation

For centuries, getting to the root of physical law has let us to assume that Parity was a law of nature, with **exceptions linked to biological life (seen as boundary conditions).**

This abstraction proved right for **gravitation, for mechanics**.

It also proved correct **for electromagnetism** and later for **nuclear forces**.

Remark : Electromagnetism is a bit tricky, since we seem to introduce a «right-hand rule » to define B, but this is only an intermediate construction, the convention applies twice to calculate any physical process …

Parity is Broken

The discovery of P violation was a real shock

It was first met with disbelief, in **a purely hadronic context**

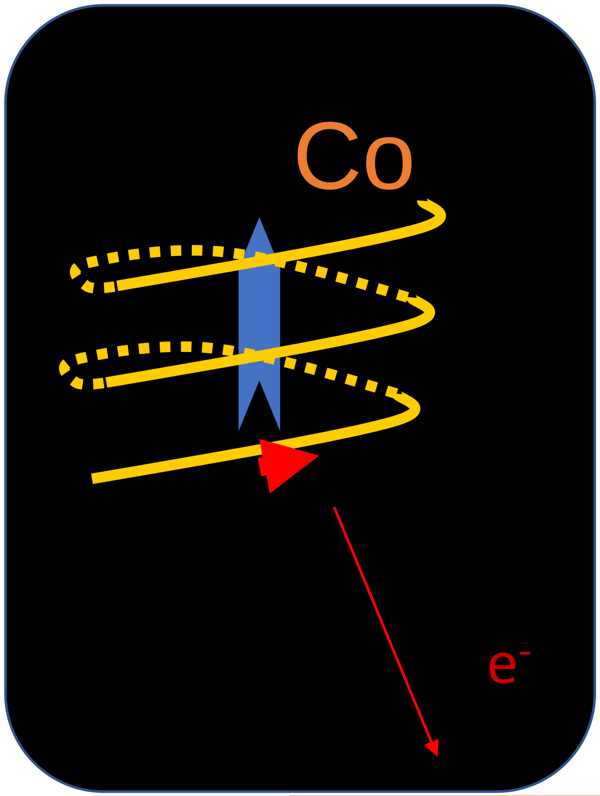
2 particles, then called Theta and Tau (nothing to do with the lepton) were observed with similar masses….close to 500 MeV

The $\tau \rightarrow 3\,\pi$ and the $\Theta \rightarrow 2\,\pi$,

Since the decays were in S wave and the p parity was known to be (-) there were 2 possibilities

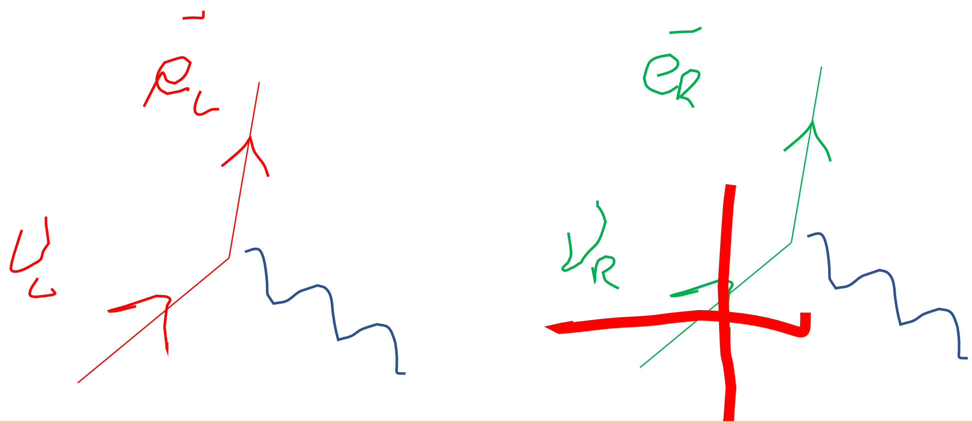
- **Θ and τ** were 2 distinct particles, with identical mass and production (parity doubling)
- OR they were the same particle (K^+) **with broken parity?**

It was so hard to accept the breaking of Parity (Lee and Yang) ,
that a "demonstration" experiment was conceived , the famous Wu experiment.



P violation was clearly demonstrated in the Wu experiment ..

It is easy to explain if only left-handed electrons are produced in a charged vector current.



Killing the right-handed neutrino allows for parity violation in charged currents, even if the coupling is pure vector

The WU experiment was convinced …
……………….but led to a wrong track!

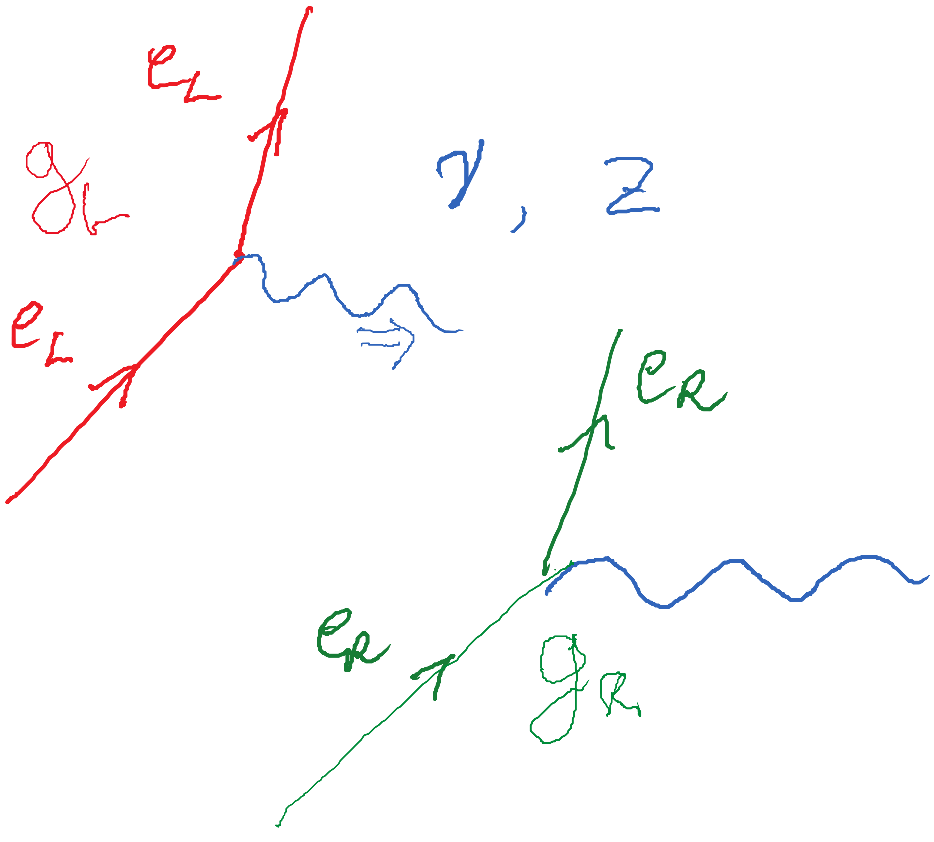
By focusing on neutrinos, and thus on leptons,
it probably led to the often-encountered ***folklore***
that "Parity violation is due to the absence of the right-handed neutrino",

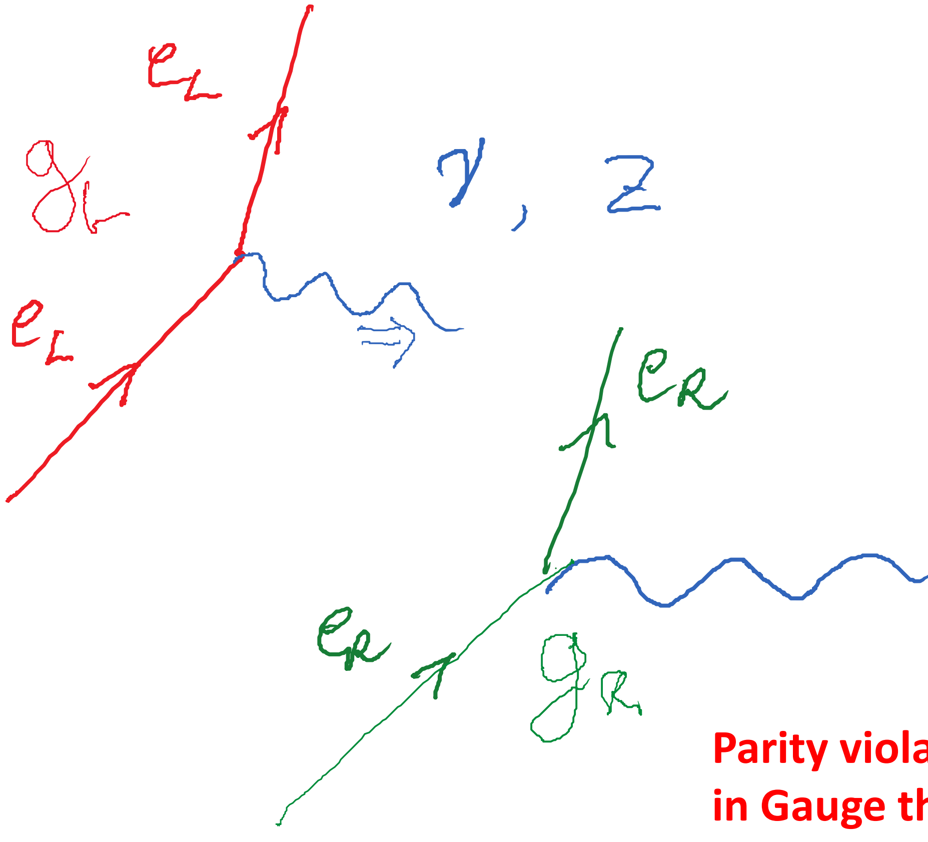
and indirectly to the **artificial exclusion of the** ν_R from the Standard Model.

Of course, this was in contradiction to the initial observation of the K → 2 pi vs K → 3 pi Parity violation!

Soon, the experiments establishing the Standard Model proved

- The existence of neutral currents (they could have been included in the Fermi Lagrangian, but were still considered proof of the SM)
- The violation of parity in neutral current interactions (atomic parity violation) .





Parity violation is indeed the EXPECTED SITUATION in Gauge theories ! **(In 3+1 dimensions)**

They are purely chiral, with L spinors speaking only to L spinors and R to R

$$g_L \neq g_R$$

In fact, the mystery would rather be ….
Why is Parity respected around us?

Take for example the SU(5) unification … (or any SuSy approach)

All fermions are re-written in terms of the Left-Handed spinors

e.g; $((u_R)^c)_L$ …. In 10 and $\bar{5}$

Is it an accident that after breaking, the « long-distance » gauge interactions (in which I would include U(1)em but also the unbroken SU(3)color) are parity invariant ???

…with the result that we have been fooled for many centuries in believing in Parity as an exact symmetry?

I have no (complete, satisfactory) answer ! …

The mathematical coherence of the theory may give some hints.

- Anomaly conservation
- Gauge invariance of mass term for long-distance interactions
- Singularities in massless gauge bosons coupling with massless fermions prevent the existence of the latter.

- Anomaly conservation

The discussion must involve the U(1) em and the SU(3) long distance forces (unbroken symmetries)

Let us assume that we start from a grand-unified theory, say SU(5) (not parity-conserving) or SO (10)

For all the gauged currents, the quantum anomalies must cancel, and the same must remain true after symmetry breaking.

IF we have only relatively small representations, this matching can only be done for SU(3) by compensating 3 by $\bar{3}$ …(no other representation like 6 present) …which would lead to Parity restauration .

- Only massive fermions have long-distance interactions
  (one neutrino could be massless, but it does not have long-distance interactions)

Hence a mass term in the Lagrangian must invariant under the corresponding gauge transformation (rotation by φ)

$$m \bar{\psi}_L \psi_R + h.c$$

$$\bar{\psi}_L \to e^{-i\alpha_L \varphi} \qquad \psi_R \to e^{i\alpha_R \varphi}$$

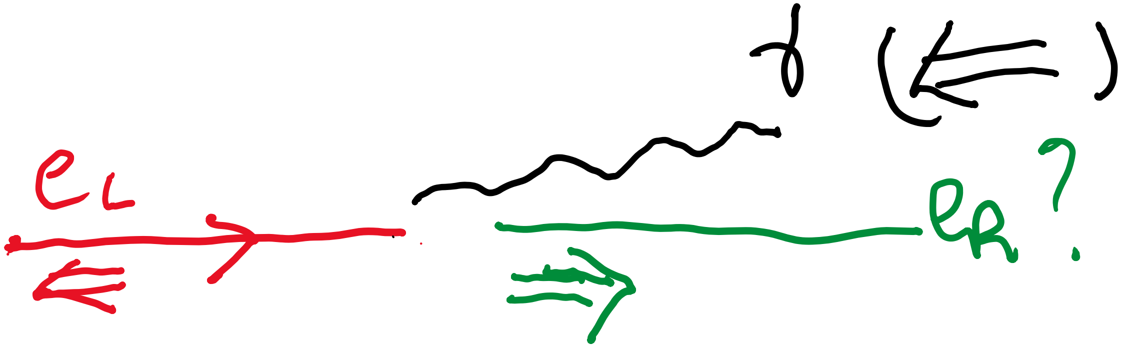
$$\alpha_R = \alpha_L$$

This brings us to an old question :
The problem of parity restauration is solved if only maasive fermions
can have charges under long-distance interactions (massless gauge bosons)

Indeed, there are singularities,

For instance consider the longitudinal emission, either from a fermion with m → 0

or a massless fermion



The L R transition
is only possible with
a small mass term …

Could we still have some « residual » *fairly long-distance* P violation?

Magnetic Moments

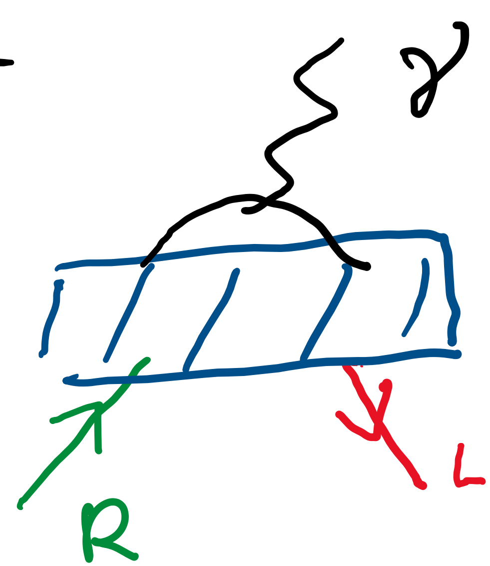
$\mu \, \vec{S} \cdot \vec{B}$

As LR transitions, diagonal magnetic moments are intrinsically P conserving.

$$\bar{f}_L \sigma^{\mu\nu} f_R \, F_{\mu\nu} + h.c$$

Transition Magnetic Moments

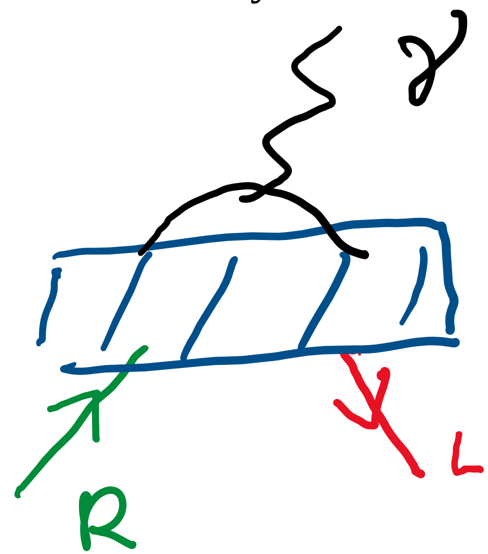
$$\mu \quad \bar{d}_L \sigma^{\mu\nu} s_R + h.c$$



Electric Dipole Moments

EDMs are intrinsically P violating for an *elementary particle*,
as they must align with the spin* but can be induced by local forces.

$\vec{S} \cdot \vec{E}$

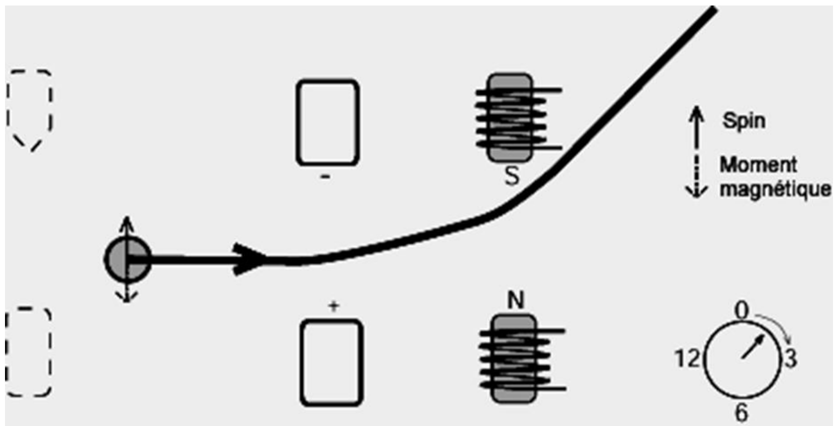


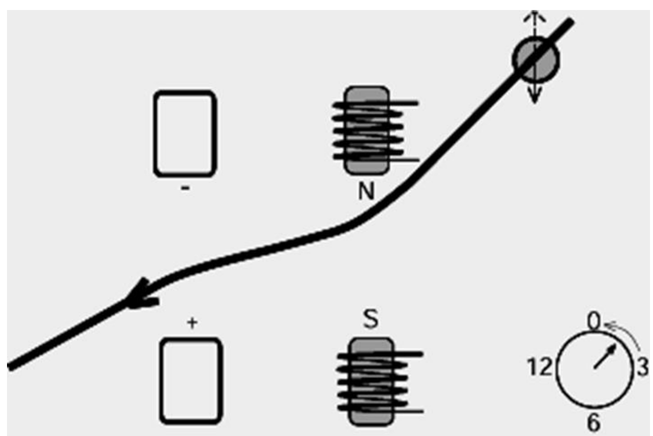
They violate P, CP and T .

They are expected to be tiny in SM, but are predicted (and currently bound by experiment) in most extensions (SuSy, LR, …)

***except maybe in some non-commutative geometries.**

T-violating effect of hypothetical electric dipole moment (gedanken experiment)



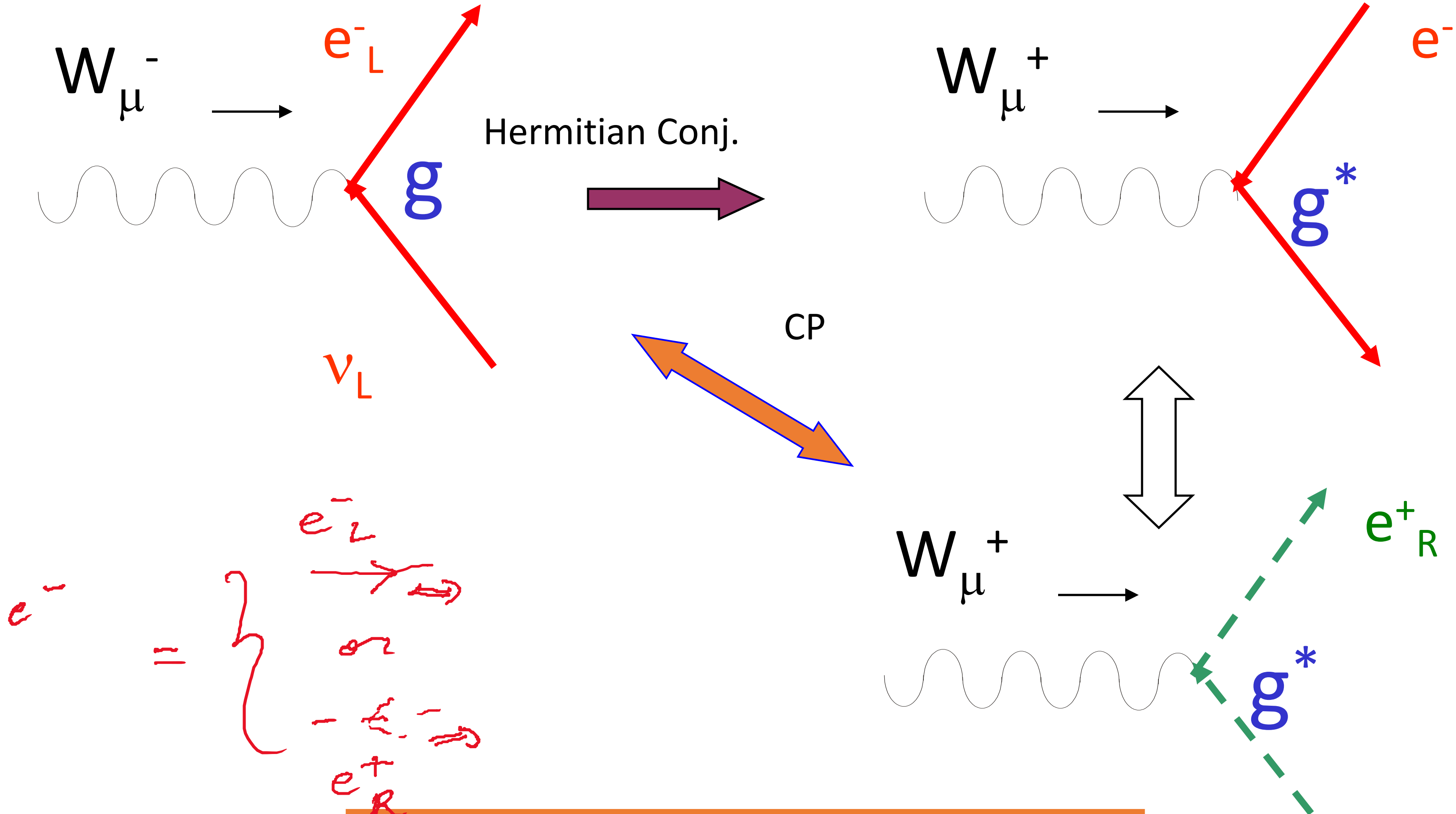



Parity restoration
due
to fermion masses ?
Some fairly long-disance
P violation
could persist through
dipole moments.

If time allows … a few words about CP violation

- CP is the natural symmetry of pure gauge interactions of fermions
  (no scalar or mass terms)
- After the discovery of P violation, CP violation was expected (predicted)
  by theorists (in particular Lev B. Okun, who had to counter Landau’s opposition)
  and the K decay experiments were suggested
- CP violation is due to something different: the feeble Scalar interaction
  (there are no weak interactions, but still feeble ones)

CP is the intrinsic symmetry of gauge interactions in 3+1 dimensions
see Basic Building Bloc : chiral fermion and gauge boson



$g=g^*$ ⟺ CP conservation

The feeble interaction (H)

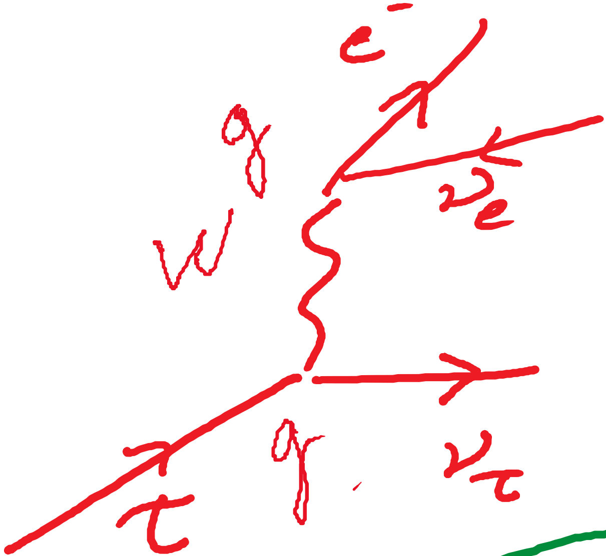
Naïve question: where is the border between « weak » and « strong »?

Answer (ca 1970) …didn't you realize they are 10 orders of magnitude apart ???

particule	**Mass (GeV/c²)**	**« lifetime »**
π (1800)	1.8	3.3 10^{-24} s
lepton τ	1.777	2.9 10^{-13} s
neutron	0.9396	880 s
proton	0.938	> 10^{+31} years
muon	0.113	2.2 10^{-6} s

« Dimensional analysis » expectation ….

1 GeV $T = 6.58\ 10^{-25}$ s



$$T \sim \frac{1}{m_\tau} * (1/g)^4 * (\frac{M_W}{m_\tau})^4$$

Playing either on MW or g allows to fit lifetimes, but to fit all, a combination of M of order 100GeV and **g of oder of the electric charge** is needed….

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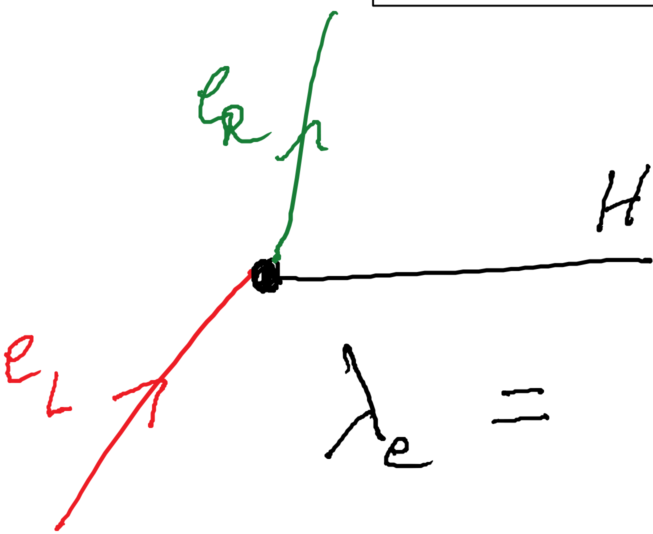
ENTERS THE *feeble* FORCE

The Scalar Boson (B-E-H) which was introduced
to give mass to the gauge bosons … finds a new use.
It is also responsible for the fermion masses!

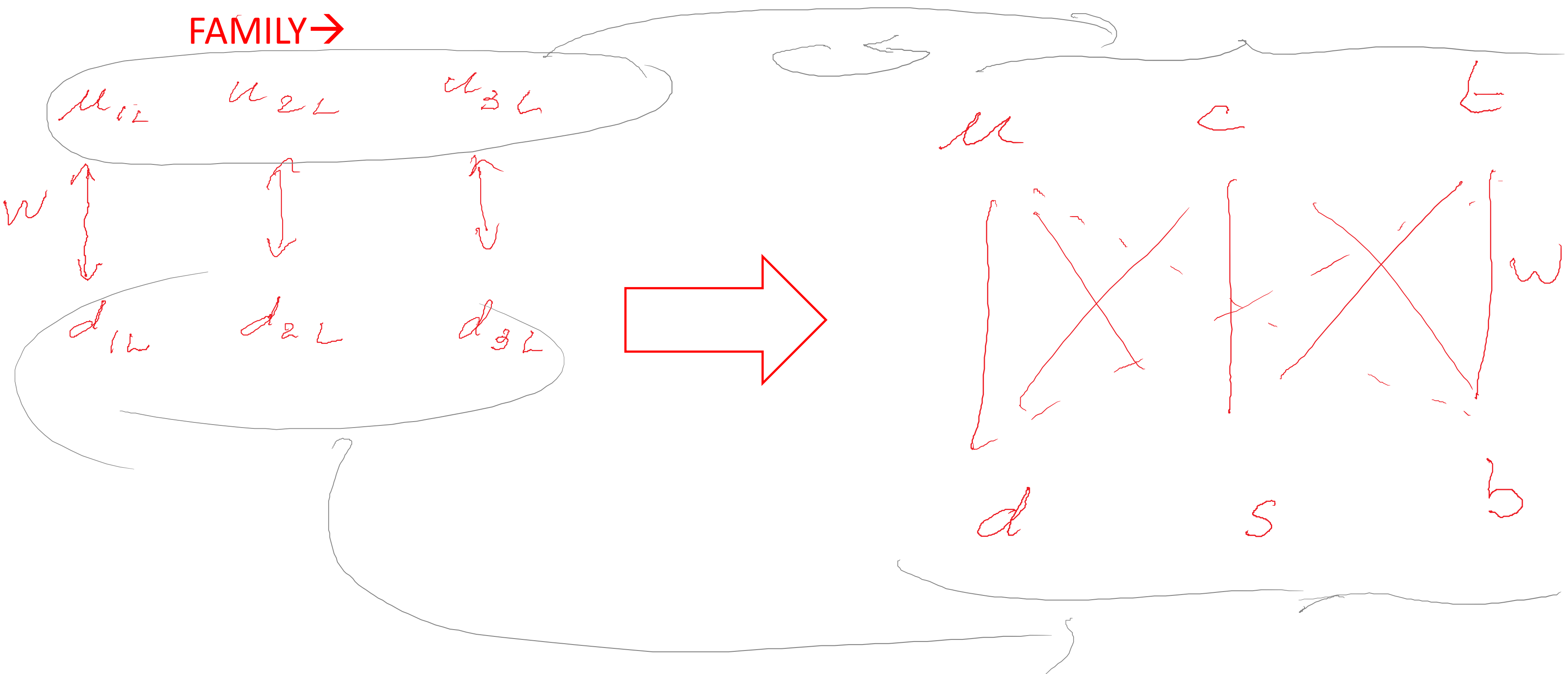
A priori, 2 different roles, BUT

- SU(2) breaking is needed to split masses in a multiplet
- Such splitting necessarily contributes to the W and Z masses



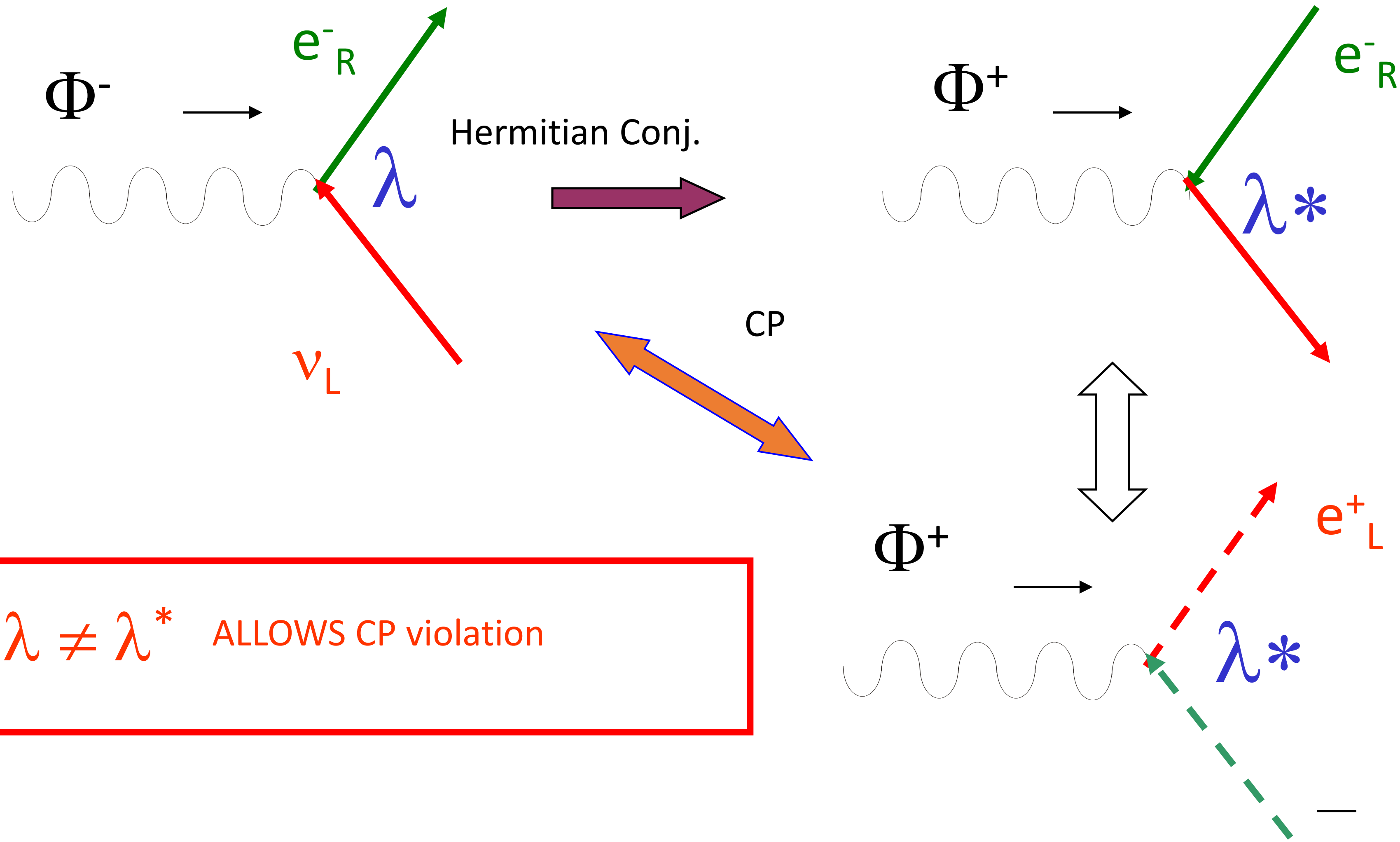
$$\lambda_e = \frac{g}{\sqrt{2}} \frac{m_e}{M_W} \simeq 6.10^{-6} \frac{g}{\sqrt{2}}$$

Moving from a « current » basis to a « mass basis »,
the Scalar (feeble) interaction accounts for the instability of the heavy flavours ..

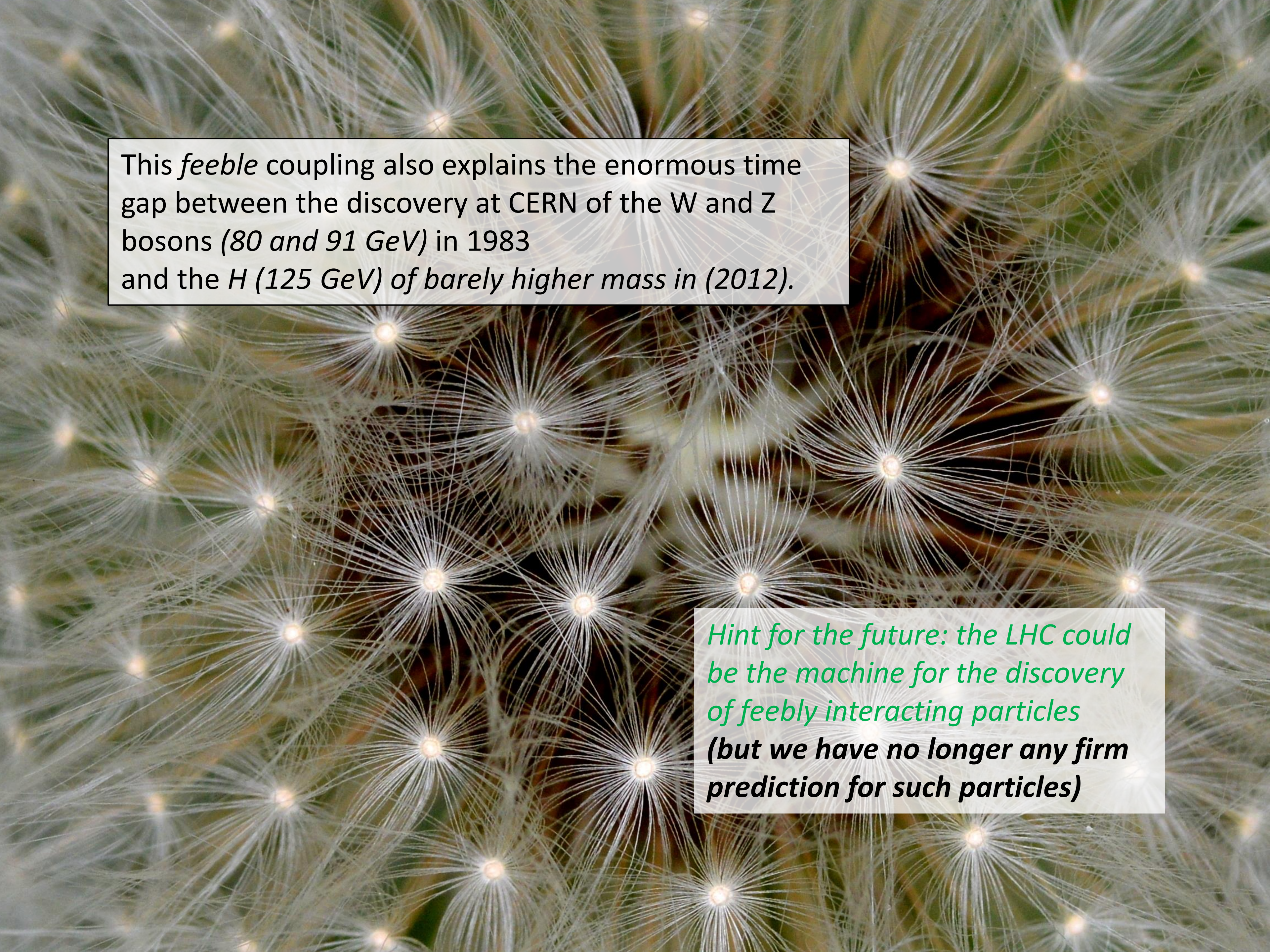


Mixing

But CP violation is easily introduced by arbitrary, complex couplings



$\lambda \neq \lambda^*$ ALLOWS CP violation


This *feeble* coupling also explains the enormous time gap between the discovery at CERN of the W and Z bosons *(80 and 91 GeV)* in 1983
and the *H (125 GeV) of barely higher mass in (2012).*
Hint for the future: the LHC could be the machine for the discovery of feebly interacting particles
(but we have no longer any firm prediction for such particles)