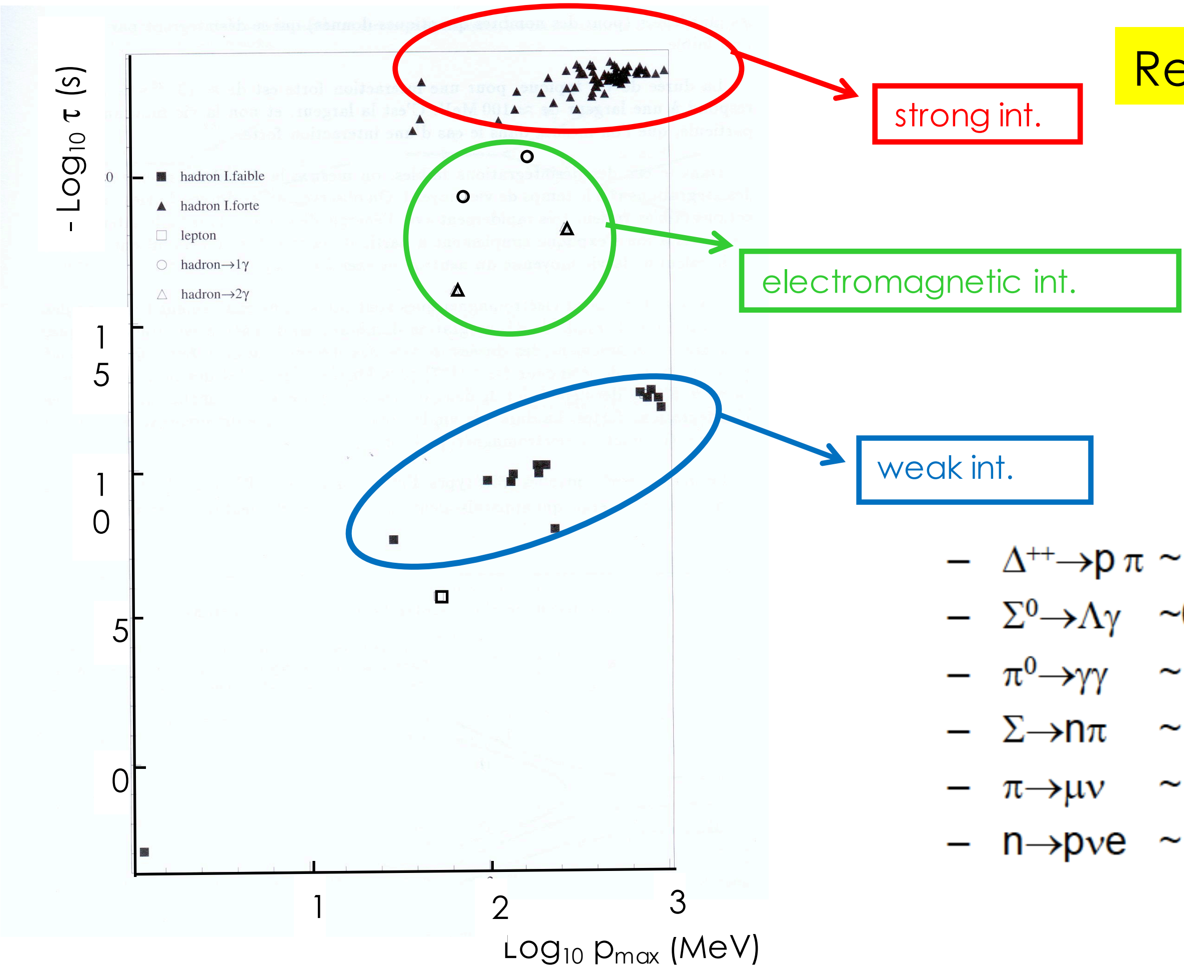
The weak interaction

Remember end of lesson 2



strong int.

electromagnetic int.

weak int.

- $\Delta^{++} \rightarrow p\,\pi$ ~ 10^{-23} sec
- $\Sigma^0 \rightarrow \Lambda\gamma$ $\sim 6\,10^{-20}$ sec
- $\pi^0 \rightarrow \gamma\gamma$ $\sim 10^{-16}$ sec
- $\Sigma \rightarrow n\pi$ $\sim 10^{-10}$ sec
- $\pi \rightarrow \mu\nu$ $\sim 10^{-8}$ sec
- $n \rightarrow p\nu e$ ~15 minutes

strong
Electromagnetic

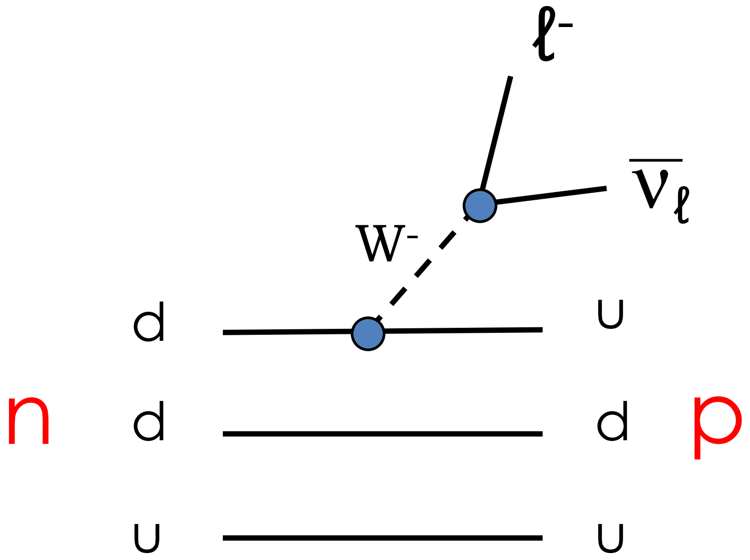
weak

$$\Gamma = \frac{1}{\tau} \propto \left|V_{fi}\right|^2$$

$$\propto \text{coupling constant}^2$$

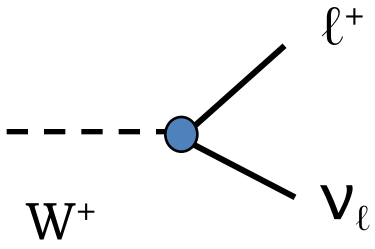
All particles are sensitive to the weak interaction

Vector bosons of the weak interaction : W and Z^0

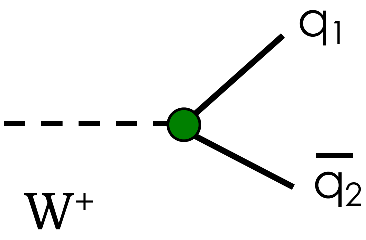


All particles are sensitive to the weak interaction

Gauge bosons W^+, W^- and Z^0



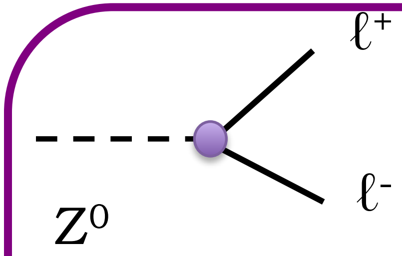
ℓ=e, μ or τ



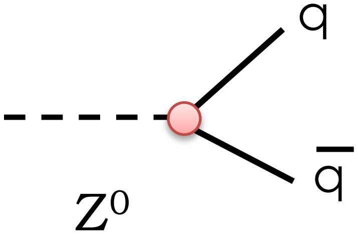
$Q(q_1)$: 2/3

$Q(q_2)$: -1/3

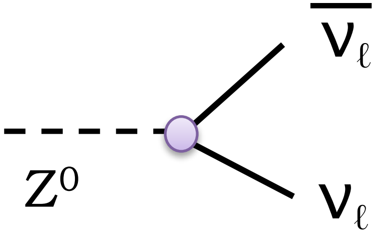
q_i=u,d,s,c,b,t



ℓ=e, μ ou τ



q=u,d,s,c,b,t



Weak interaction : not universal for quarks

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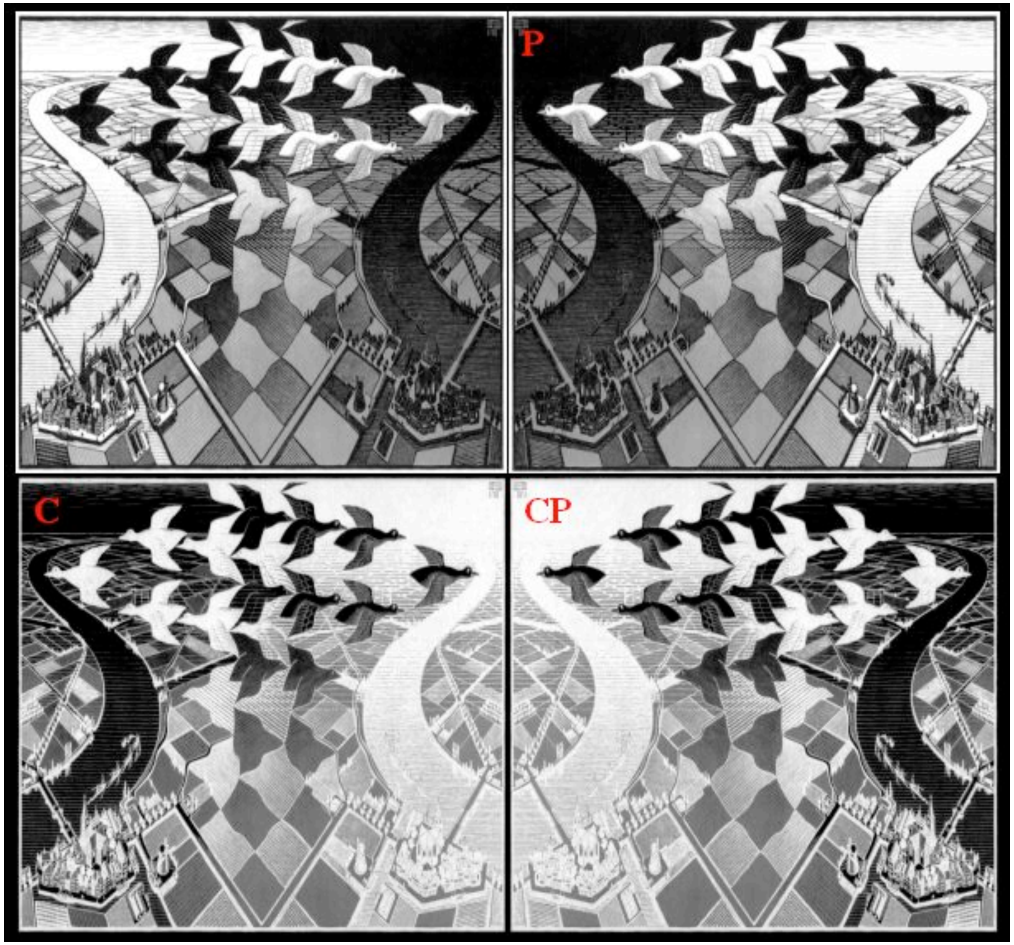
symmetries



Relationship between conservation laws and symmetries

In classical mechanics :

symmetry principle → non observable quantity → invariance

Absolute position non observable → Invariance under translation → Momentum conservation law

Absolute direction non observable → Invariance under rotation → Angular momentum conservation

=> Noether's theorem :

For any continuous symmetry for a given system corresponds a conservation law for this system.

E. Noether

In classical mechanics:

symetry principle ↔ non observable quantity ↔ invariance

- No absolute coordinate
- The absolute position of a point cannot be observed
- Physics laws are invariant under translation

$$V\left(\overrightarrow{r_1} + \vec{d}, \overrightarrow{r_2} + \vec{d}\right) = V(\overrightarrow{r_1}, \overrightarrow{r_2})$$

$$\Longrightarrow V(\overrightarrow{r_1}, \overrightarrow{r_2}) = V(\overrightarrow{r_1} - \overrightarrow{r_2})$$

$$\frac{d\overrightarrow{p_1}}{dt} = -\frac{\partial V}{\partial r_1} = \frac{\partial V}{\partial r_2} = -\frac{d\overrightarrow{p_2}}{dt}$$

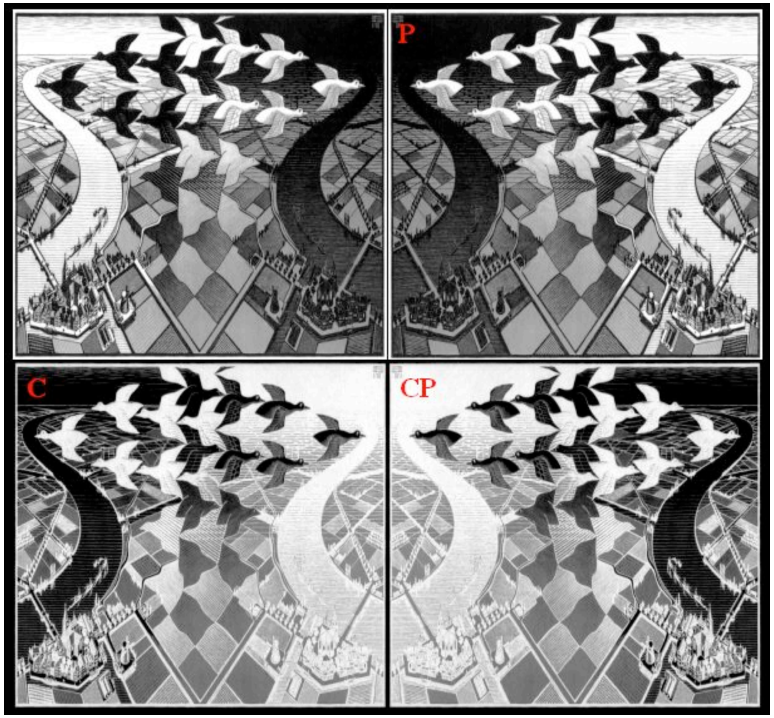
$$\Longrightarrow \frac{d}{dt}(\overrightarrow{p_1} + \overrightarrow{p_2}) = \vec{0}$$

Absolute position cannot be observed ⇔ Invariance under translation ⇔ Momentum is conserved

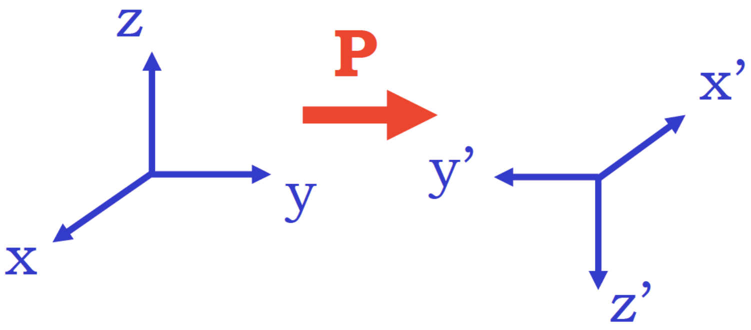
Three discrete symmetries : C, P et T

- C : inverse the charge (all quantum numbers)

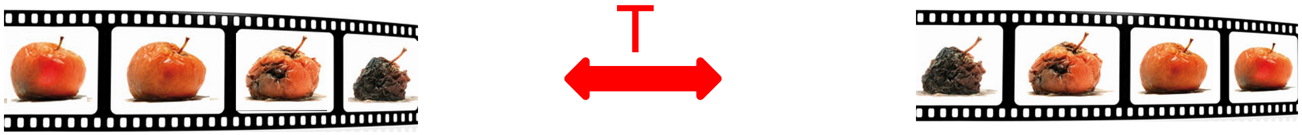
e^- (electron)	$\xleftrightarrow{C}$	e^+ (positron)
p (proton)		$\bar{p}$ (anti-proton)
quark u		anti-quark $\bar{u}$
quark d		anti-quark $\bar{d}$



- P : mirror symmetry

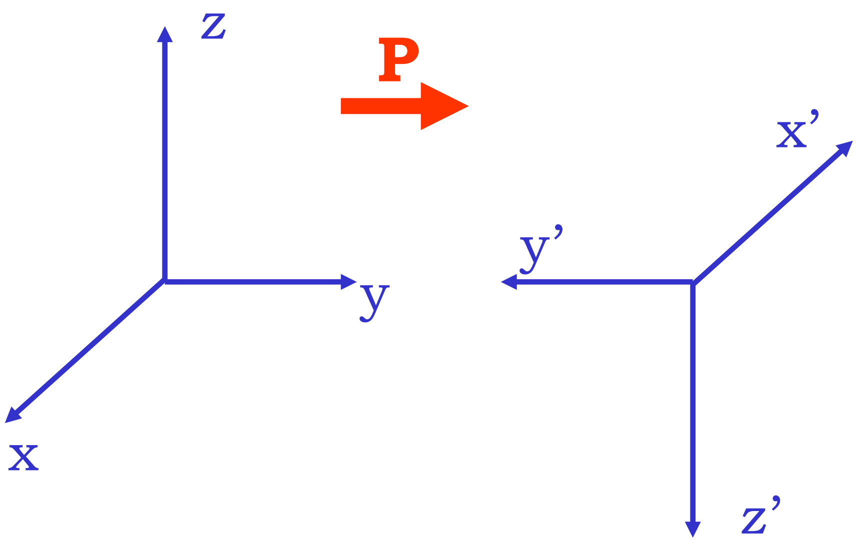


- T : time reversal



All laws of physics are invariant under CPT

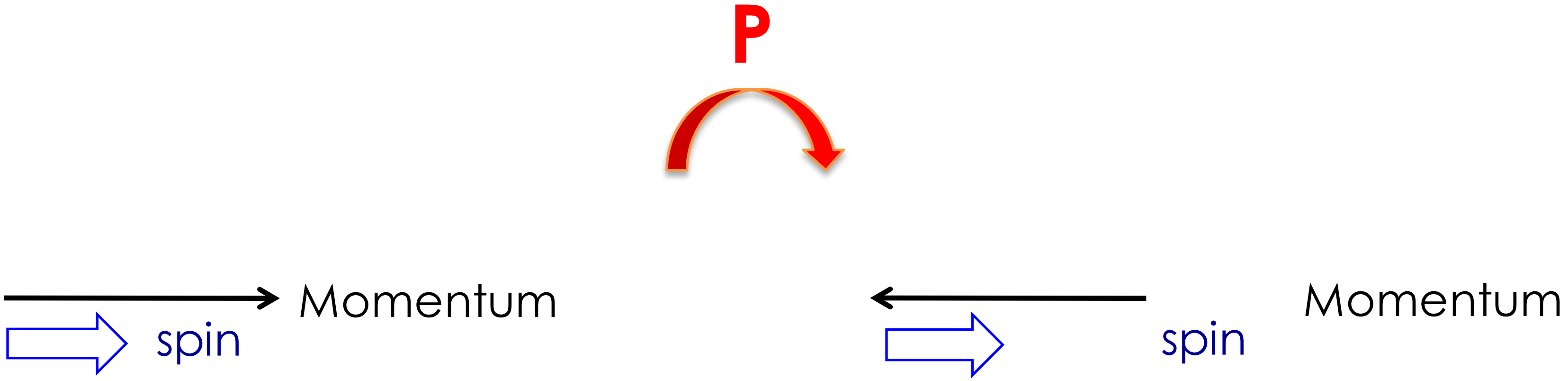
Spin and parity



$$\mathbf{P}\vec{r} = -\vec{r}$$

$$\mathbf{P}(\vec{r}\cdot\vec{p}) = \vec{r}\cdot\vec{p}$$

$$\mathbf{P}(\vec{r}\wedge\vec{p}) = \vec{r}\wedge\vec{p}$$



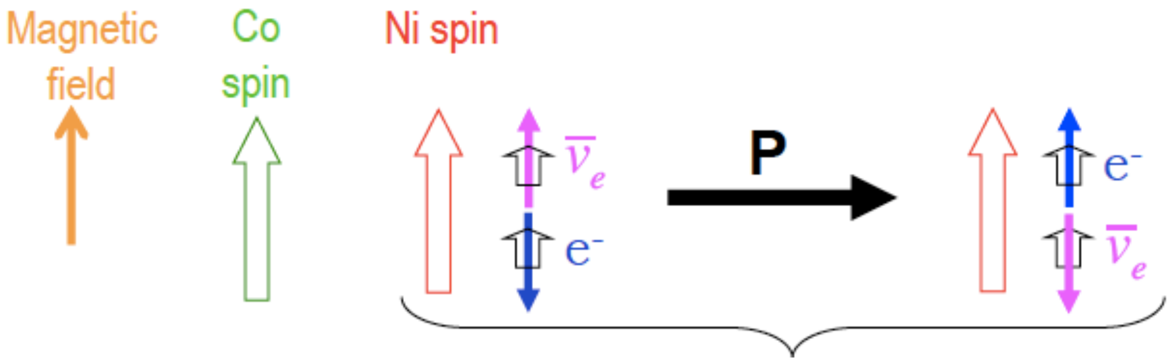
The Wu experiment

Schematical overview of the Co^{60} experiment

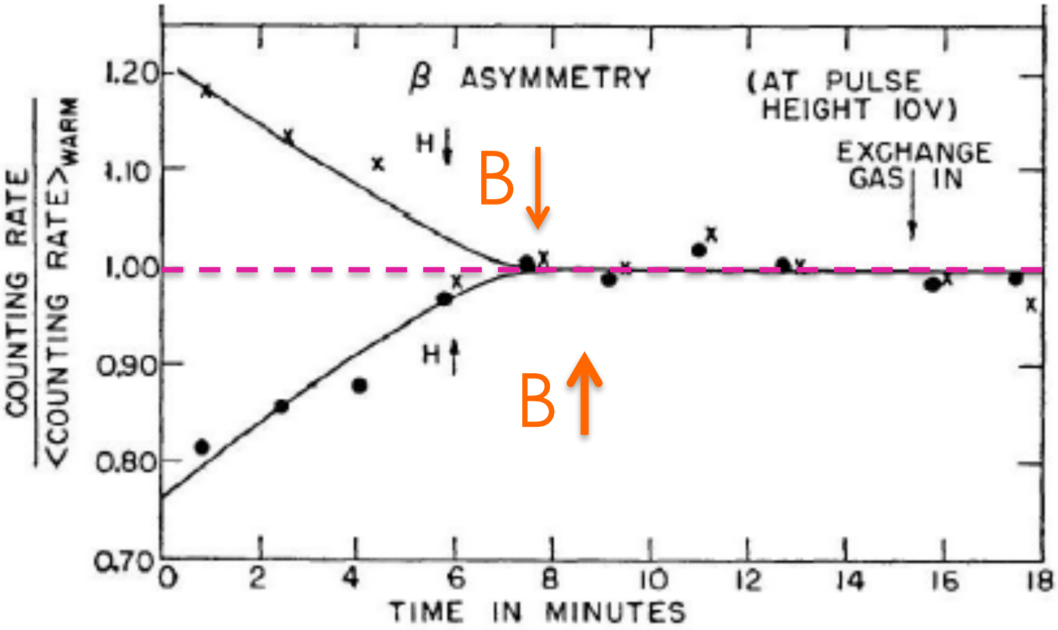
- β decay : $\mathrm{Co}^{60}\ (J=5) \rightarrow \mathrm{Ni}^{60*}\ (J=4)\, e^- \bar{\nu}_e$ $\quad$ $\mathrm{n} \rightarrow \mathrm{p}\, e^- \bar{\nu}_e$
- Wu's experiment :

  - The spin of the Co^{60} atoms are aligned by a magnetic field

  - Record of the direction of the emitted electrons

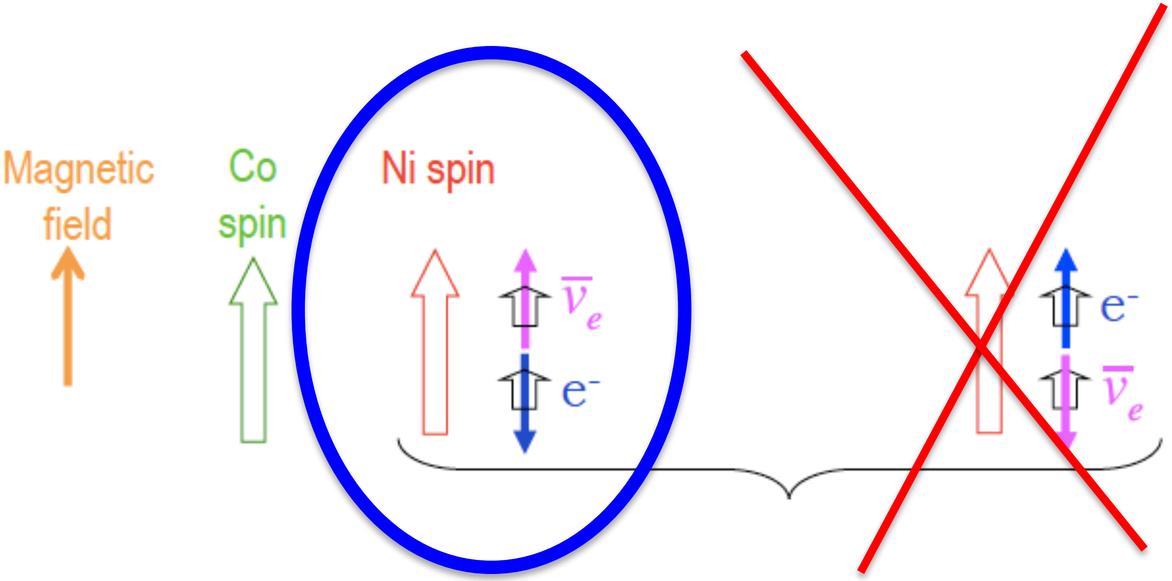


If P is conserved these two configurations should have the same probability



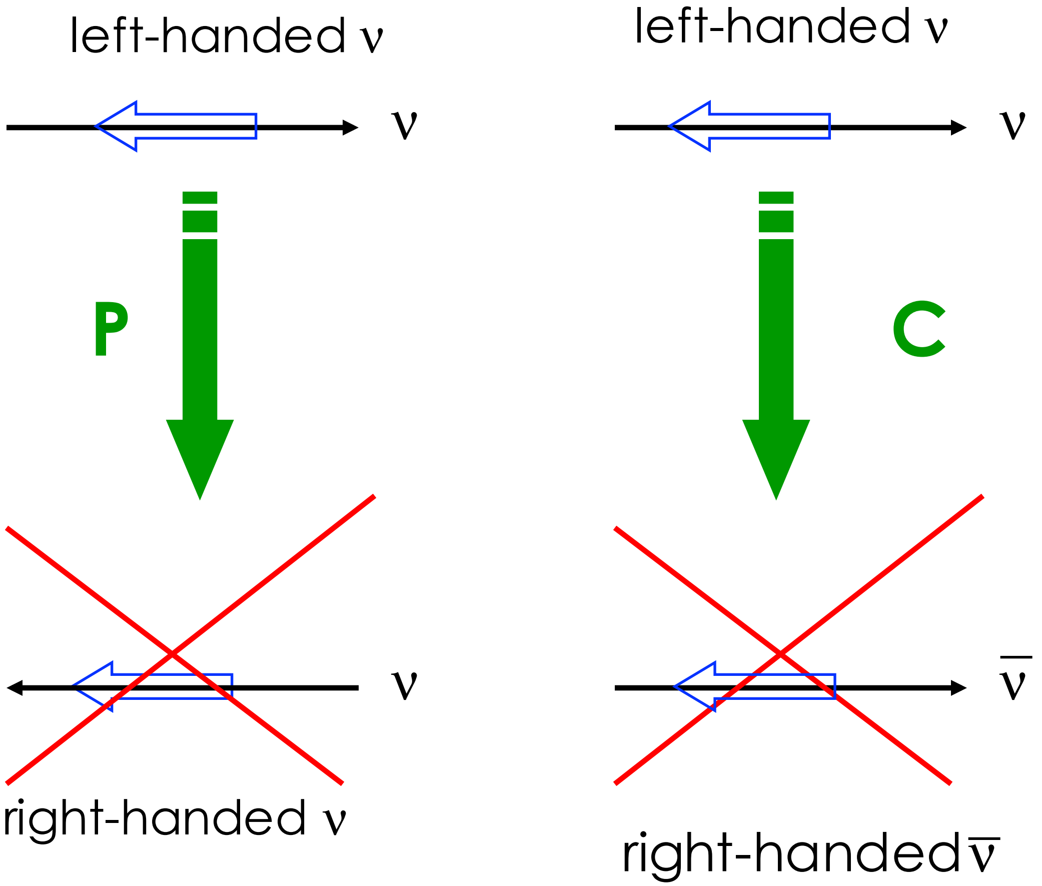
No prefered direction for the emission of the electrons

Result of the experiment: the e^- are preferentially emitted in the direction opposite to the Co spin (asymmetry)



The weak interaction **maximally** violates **P**

Elementary particle of matter with a mass = 0, spin ½



only left-handed massles particle of matter and right-handed particles of antimatter

Interactions and Quantum numbers : conservation, non-conservation

Now you have different interactions and we also have quantum number which can be or not conserved

THE ONLY REASON A PARTICLE IS STABLE AND/OR NOT INTERACTING IS BECAUSE THERE IS SOME QUANTUM NUMBER CONSERVATION

- Some rules work for all interactions :
  - Baryon number conservation
  - Lepton number conservation
  - Electric charge conservation

- What about…?? :
  - The parity P
  - The charge conjugation C
  - CP
  - The strangeness S

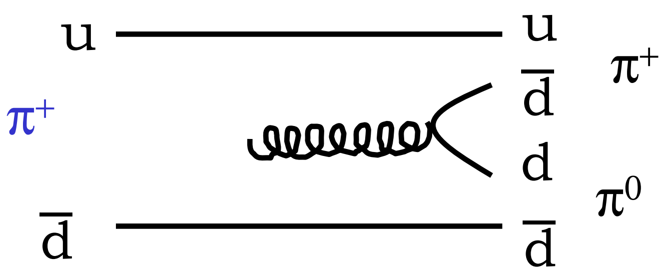
The violation of parity has experimental consequences !

Example of the π+ decay (lighest hadron)
Let’s try to fond out its decay modes !

The violation of parity has experimental consequences !

Example of the π+ decay (lighest hadron)
Let’s try to fond out its decay modes !

Strong interaction ?



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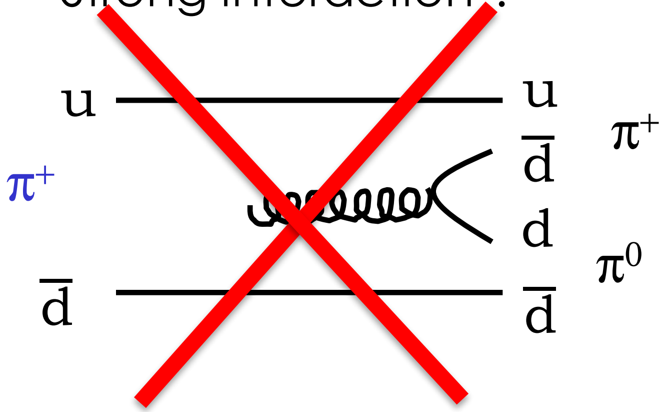

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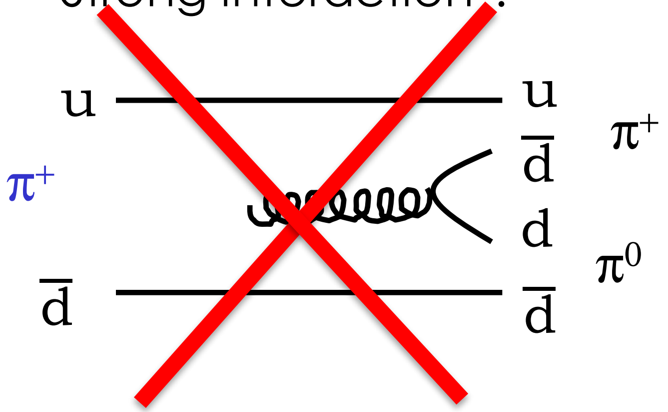
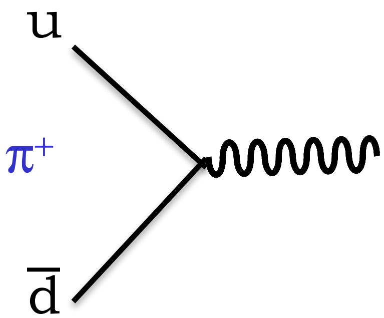


Elm interaction ?



The violation of parity has experimental consequences !

Example of the π+ decay (lighest hadron)
Let’s try to fond out its decay modes !

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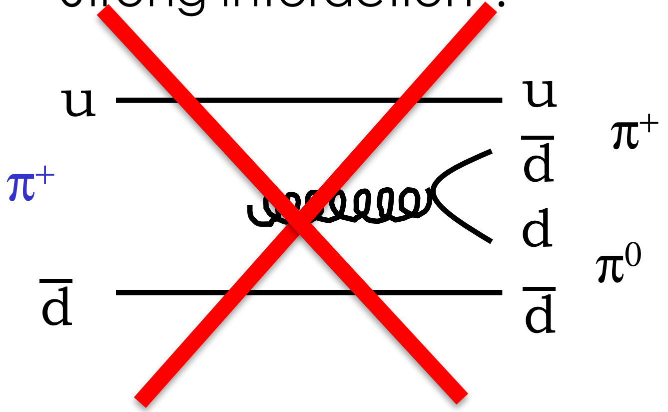
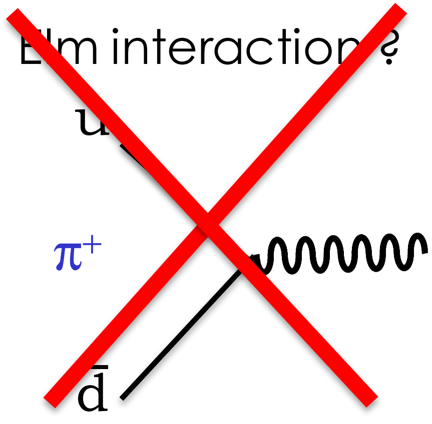
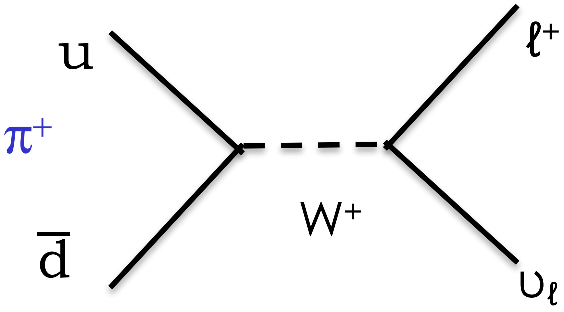


Elm interaction ?



Weak interaction !

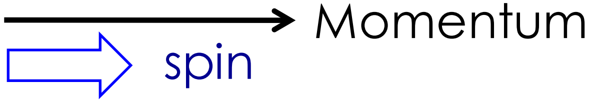


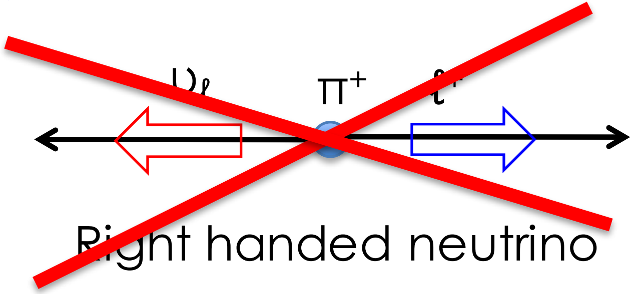
Only one allowed !

$\pi \rightarrow \ell\ \nu_\ell$

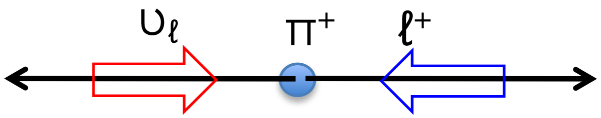
Spin of the pion : 0
Spin of the lepton and neutrino : ½

m_e = 0.5 MeV
m_μ = 105 MeV
m_π = 135 MeV





~~Right handed neutrino~~



Left handed neutrino

if the ℓ^+ is massless this is not possible !

$$\Gamma = \frac{1}{8\pi} G^2 f_\pi^2 m_\pi m_l^2 \left(1 - \frac{m_l^2}{m_\pi^2}\right)^2$$

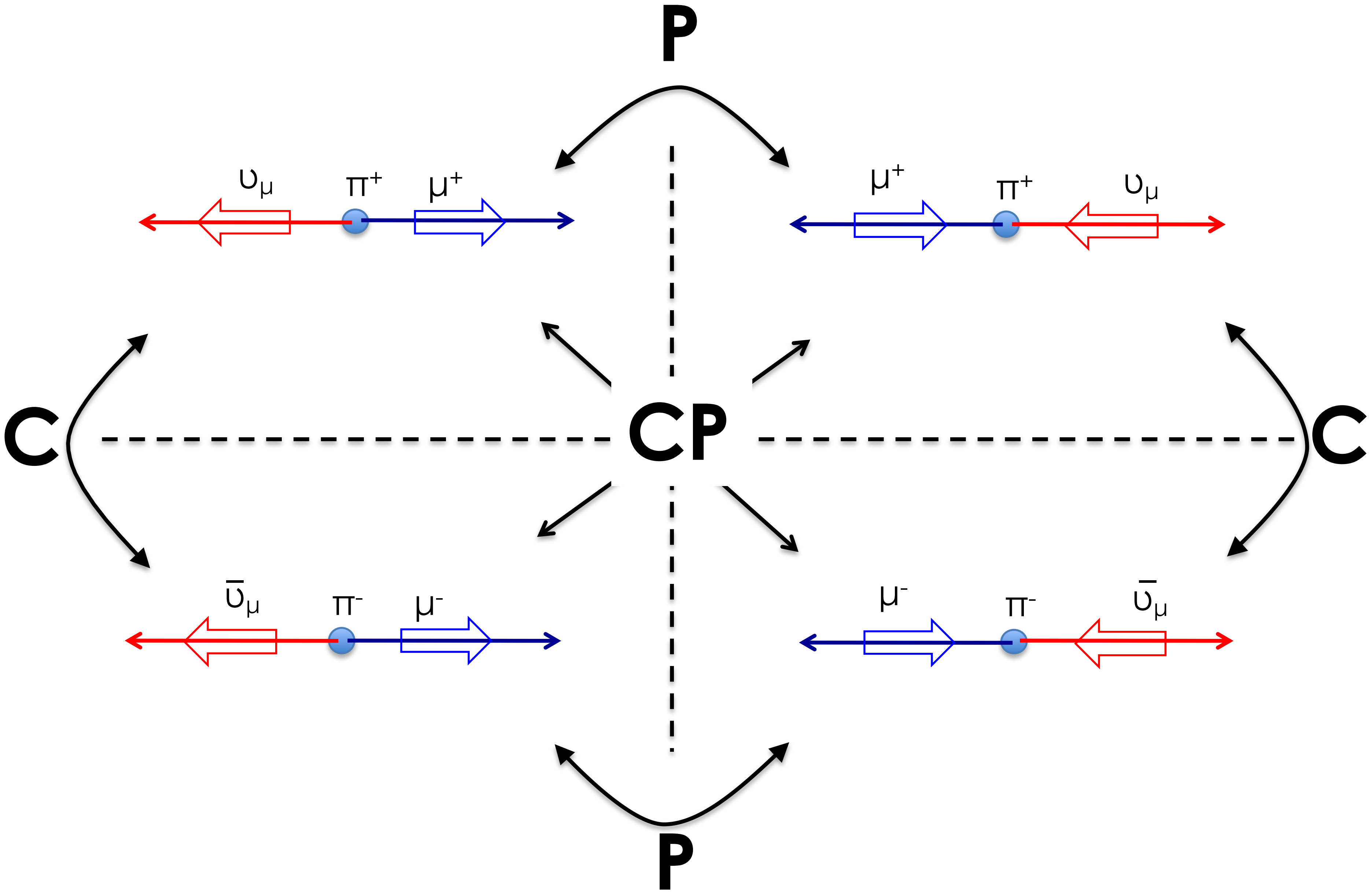
$$\frac{\Gamma_e}{\Gamma_\mu} \propto \left(\frac{m_e}{m_\mu}\right)^2 \frac{1}{\left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^2} : 1.27\ 10^{-4}$$

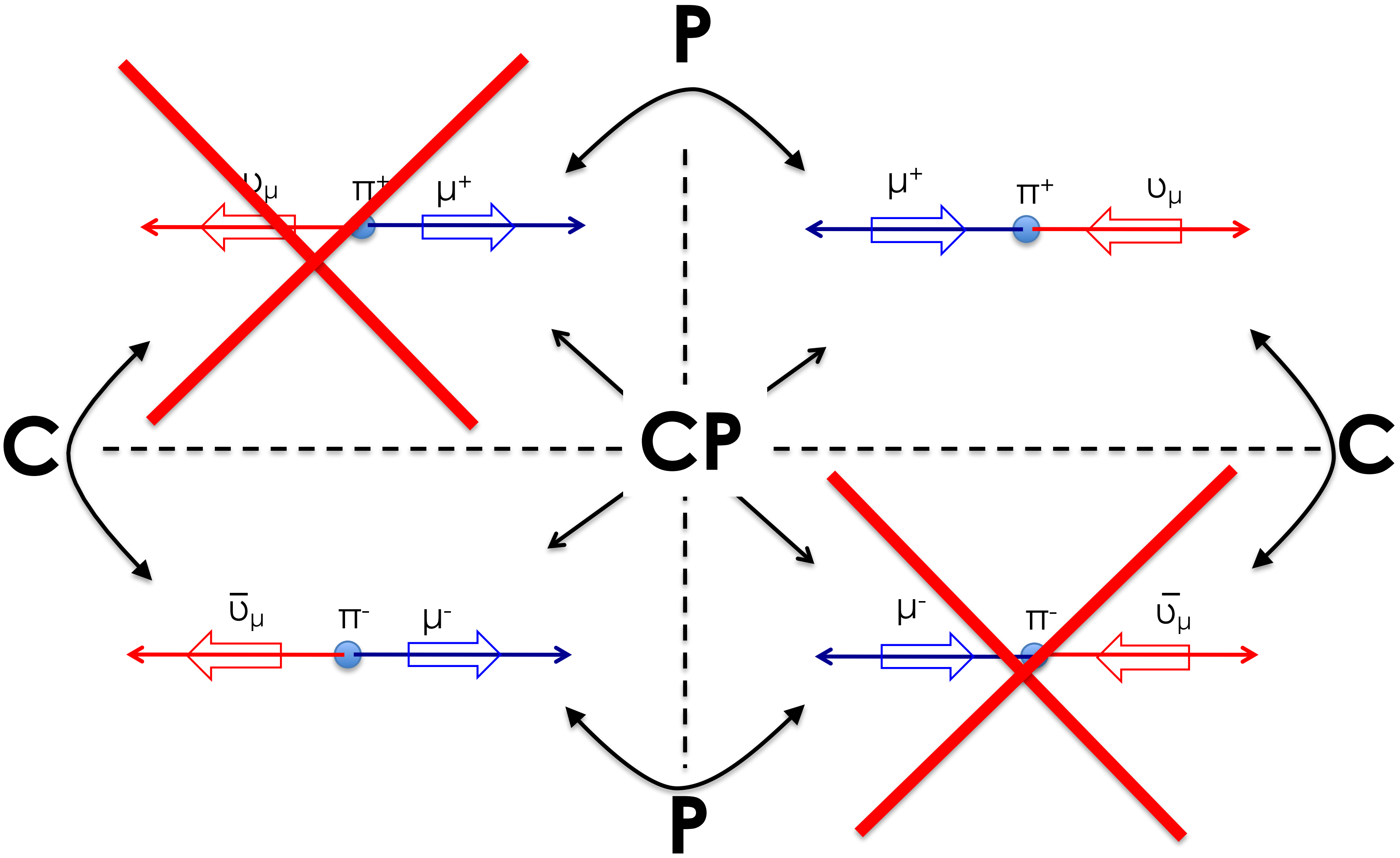
Measurement:

$$\frac{\Gamma\left(\pi^+ \to e^+ \nu_e\right)}{\Gamma\left(\pi^+ \to \mu^+ \nu_\mu\right)} = (1.230 \pm 0.004)\ 10^{-4}$$

Despite the much larger phase space, the electronic mode is strongly disfavored

But what could be a proper symmetry ?

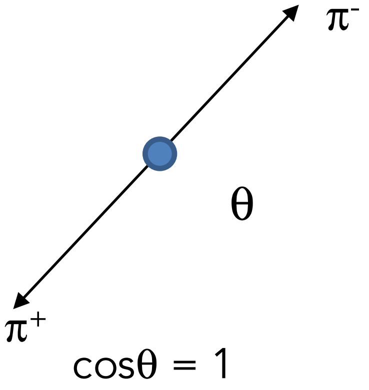

P
υ_μ
π^+
μ^+
μ^+
π^+
υ_μ
C
CP
C
$\bar{\upsilon}_\mu$
π^-
μ^-
μ^-
π^-
$\bar{\upsilon}_\mu$
P

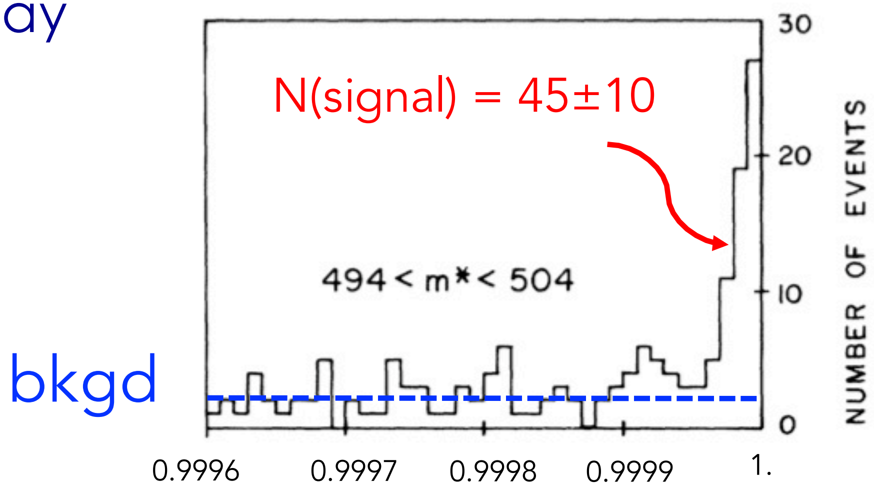


The ν is left handed (the anti-neutrino is right handed)

1964 Cronin, Fitch, Christensen et Turlay

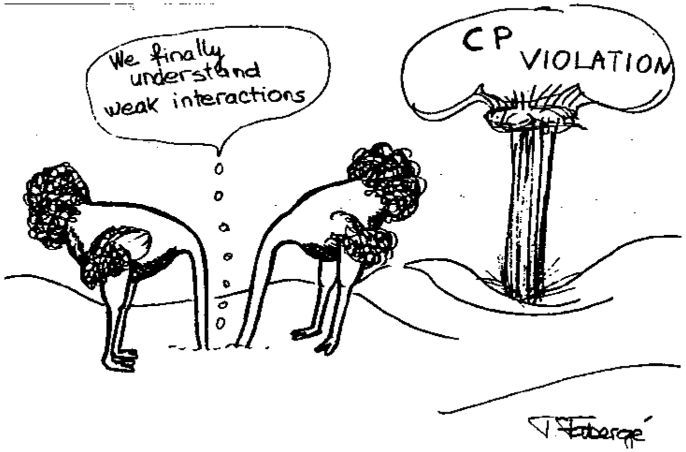
Observation of $K_L^0 \to \pi\pi$ which is forbidden if CP is conserved





Rate : (2.0 ± 0.4) 10^{-3}

It was a huge surprise …. and has a lot of consequences



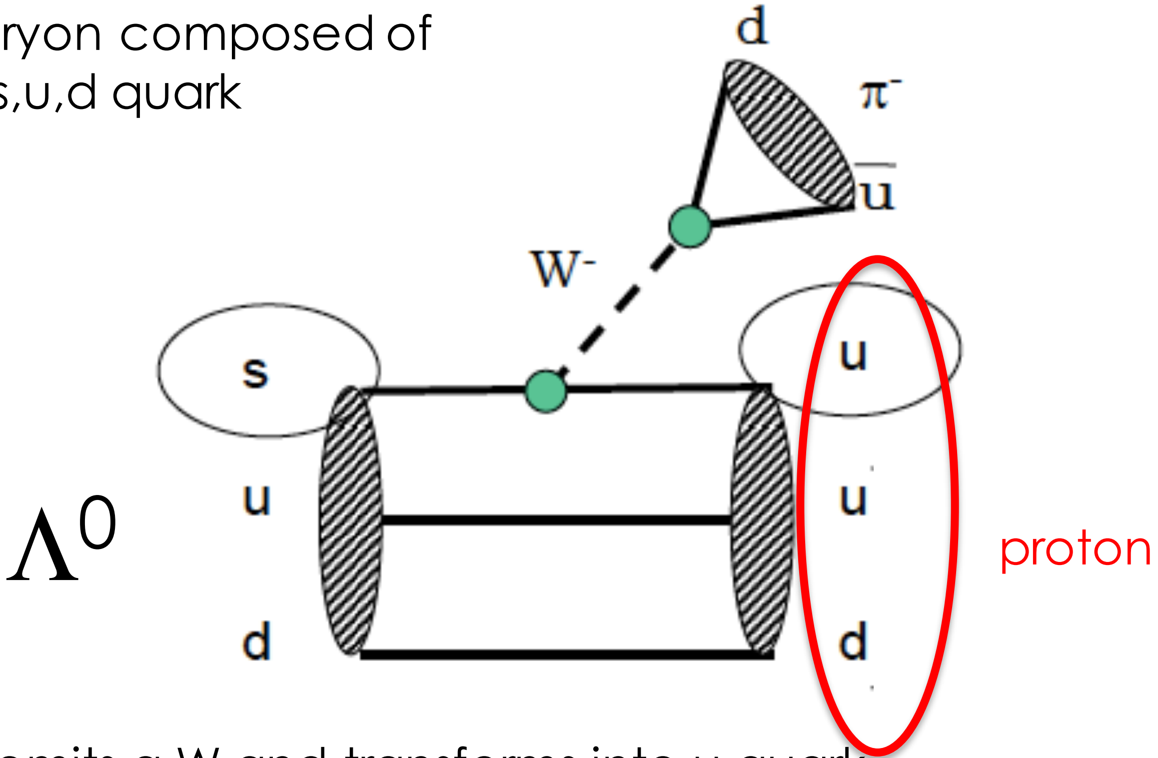
In 2019 : (2.271 ± 0.017) 10^{-3}

Shown in1966 by N. Cabibbo

)

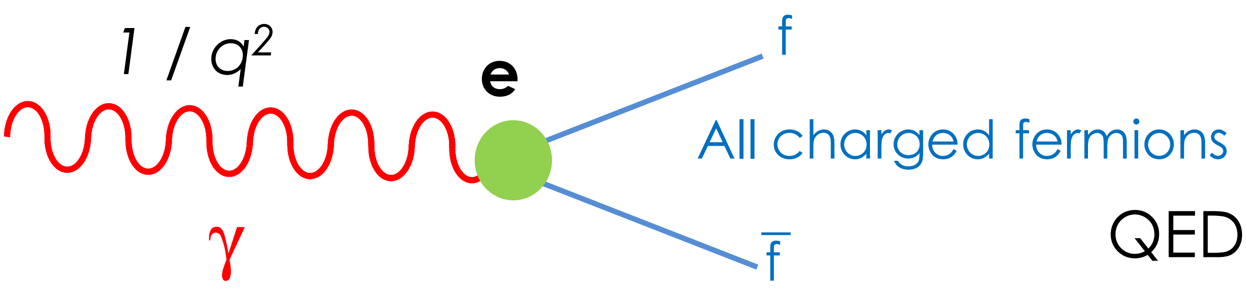
A typical weak decay

Λ^0 : A baryon composed of
s,u,d quark



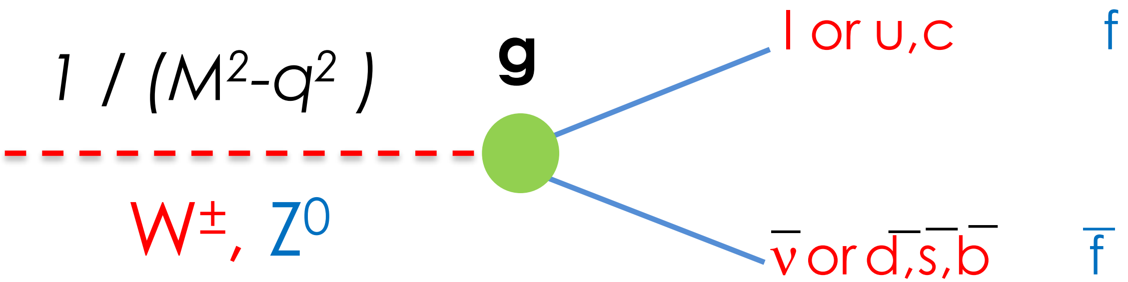
- ✓ The quark s emits a W and transforms into u quark
- ✓ The u quark meets the u and d initial quark and form a proton
- ✓ The W is virtual and
  - ☐ **no decay** : W is reabsorbed by the same quark s
  - ☐ **decay $\Lambda^0 \rightarrow$ p,π^- :** W transforms into a pair of $(u,\bar{d})=\pi^-$

$$\boxed{\alpha = \frac{e^2}{4\pi\varepsilon_0 hc} = \frac{1}{137}}$$



QED Coupling ~e^2/q^2

QED Electromagnetism
$M_\gamma=0$
$e=(\sqrt{\alpha})\sim 0.1$



Weak Coupling ~g^2/M^2

Weak interaction
$M_W=80$ GeV
$M_Z\sim 90$GeV
$g\sim e$

The weak interaction is not weak because of *g<<e* but because of the large value for the W mass (very different of what happens with QED and the photon)

Weak interaction in summary

- All quarks and leptons are sensitive to the weak interaction
- Two gauge bosons of high mass : M_W~M_Z~80-90 GeV → short range
- Extremely weak : (~ 10^{-8} smaller intensity than the strong interaction at a distance of 1 fm)
- Non universal couplings
- Irrespectful interaction
  - violates maximally C and P
  - does not conserve the flavour
  - Exhibits a tiny CP violation