

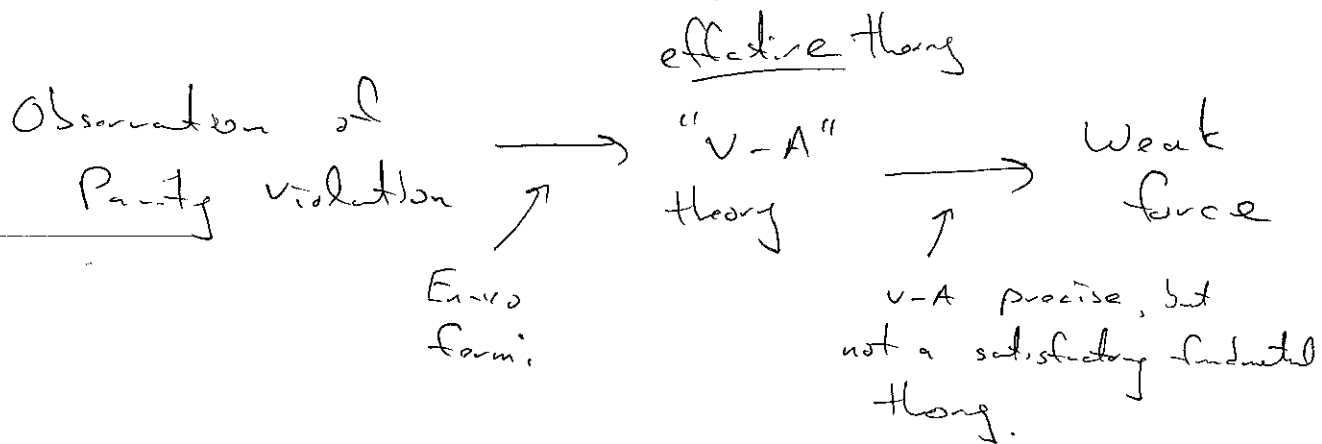
Parity Violation (This is example of a little detail <sup>①</sup> that did not look as expected and the added down a rabbit hole that was only resolved @ the LHC)

1950s

Parity conservation is the idea that physics is unchanged if  $L \leftrightarrow R$  are reversed (Eg. physics ~~is the same~~ can't tell if you're looking in mirror or not).

What was found in 50's was that some particle interactions distinguished  $L \leftrightarrow R$ . Shocking could never happen in Gravity / EM or Strong force

Now force (weak interaction) completely changed our ideas about what a force could be.



Next few lectures we will explore this new force, lead us down a path w/ surprise after surprise ultimately to Higgs boson which <sup>provides a</sup> framework on which all this sits.

# Discrete Lorentz Transformations

Early in course we discussed LT. focus was on continuous LT. Also discrete transformations that leave  $t^2 - x^2$  invariant.

Parity  $P \vec{x} = -\vec{x}$  Can be thought of as act of viewing something through mirror.

Vectors, like position & velocity are flipped by  $P$ .

$$P \vec{v} = -\vec{v} \quad \left( P \left( \frac{dx}{dt} \right) \right)_{t \rightarrow -t} = - \left( \frac{dx}{dt} \right)_{t \rightarrow -t}$$

Other mathematical objects that transform as vectors under continuous LT, but do not pick up "-" sign under  $P$

"Pseudo vectors" (vampire vectors)

Tend to arise from cross products.

Example Angular Momentum

$$\vec{L} = \vec{x} \times \vec{p} \quad P(\vec{L}) = P(\vec{x}) \times P(\vec{p}) \\ = -\vec{x} \times -\vec{p} = \vec{L}$$

{ torque  
B-field

Aside Also notion of Scalars & Pseudo Scalars

$$P n = \begin{matrix} \leftarrow \text{Scalar} \\ + \\ n \\ \leftarrow \text{Pseudoscalar} \end{matrix}$$

Maxwell's equations, invariant to  $\mathbb{P} \leftarrow \boxed{\text{Hw}}$   
 & QED & G.R. are also invariant.

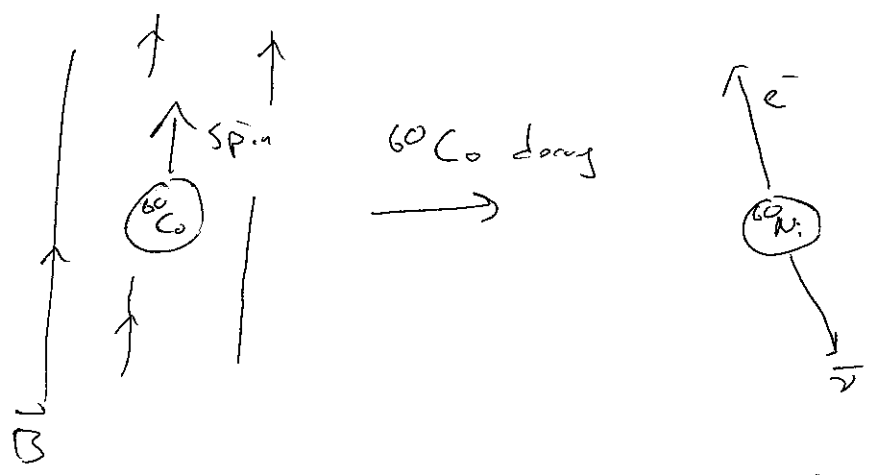
Other Discrete L.T.s

$\overline{\mathbb{T}}$  - time Reversal  $\overline{\mathbb{T}} t = -t$

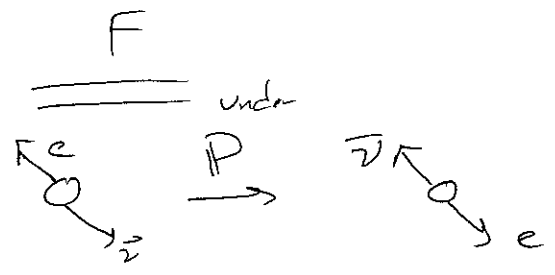
$\mathbb{C}$  - Charge Conjugation  $\mathbb{C} q = -q$

Maxwell's equations invariant under  $\mathbb{C} \overline{\mathbb{T}}$   $\leftarrow \boxed{\text{Hw}}$

$\overline{\mathbb{T}}$  needs to be defined  $\overline{\mathbb{T}} i = -i$  to have  
 the Schrodinger<sup>\*</sup> eq invariant.  $\leftarrow \boxed{\text{Hw}}$



I  
 Invariant under  $\mathbb{P}$

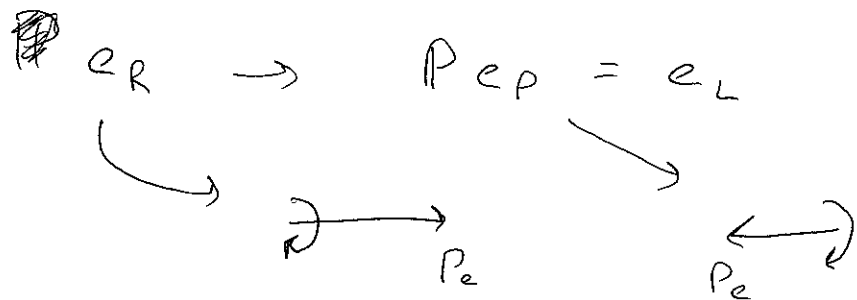


So under  $\mathbb{P}$  the experimental setup is unchanged by the  
 final configuration is flipped. So if  $\mathbb{P}$  conserved  
 you should see both final configuration w/ equal prob

Shocking Result C.S.W. more electrons emitted opposite to the direction of the spin. (4)

Force that governs nuclear decays violates parity

Now



If parity violated by weak interaction, we would expect different numbers of  $e_R$  &  $e_L$  produced in the  $^{60}\text{Co}$  decays.

~~It~~ In fact experiments showed that the  $\beta$  produced electrons are Always left-handed.

IP not just violated, but maximally violated.

Turns out  $\bar{\nu}$  is always right-handed

$\nu$ 's only interact w/ weak interaction. These interactions only involve  $\nu_L$  &  $\bar{\nu}_R$  Suggests that only one helicity of  $\nu$ 's exist.

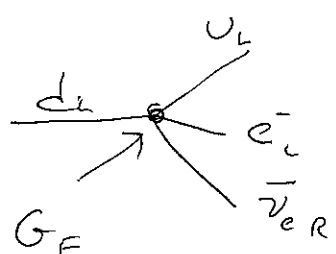
Weird & unexpected. eg we know from study of  $e^+e^- \rightarrow \mu^+\mu^-$  scattering that  $e$ 's &  $\mu$ 's can be L or R leads to observed  $1 + \cos^2\theta$  cross section

Fundamental Process in  $^{60}\text{Co} \rightarrow ^{60}\text{Ni}$  is  $n \rightarrow p$

or

$$d \rightarrow u + e^- + \bar{\nu}_e$$

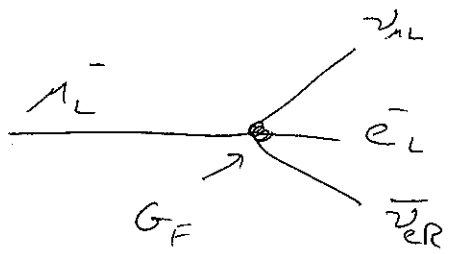
"V-A" theory "Fermi" theory was invented to describe this



$$\mathcal{L} \supset G_F \bar{\nu}_e e_L d_L u_L$$

$\hookrightarrow$  Fermi constant units  $\text{GeV}^{-2}$

Also describes the decay of  $\mu^-$ s (easier to measure, cleaner to calculate)



$$\Gamma = \frac{G_F^2 m_\mu^5}{192 \pi^3}$$

Can apply Feynman rules to ~~the~~ <sup>Fermi</sup> theory  $\uparrow$

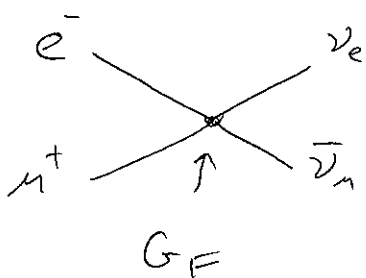
which is in very good agreement with observations.

However, there are problems built in to this Fermi theory.

- ) Postulate about 4-fermion interaction
- ) In QCD & EM 4-fermion is controlled by Spin-1 Bosons ~~that~~
- ) Tip of the ice berg. will find
  - Structure Fermi theory requires massive force carriers
  - Seems to violate gauge invariance
  - Can maintain GI by adding new particles

(6)

Problems w/ Fermi theory. Consider cross section to produce  $\nu_e$  &  $\bar{\nu}_\mu$  from  $e\mu$  collision.



$$\sigma \sim |M|^2 \sim G_F^2$$

$\sigma$  needs units of Area  $\sim \text{GeV}^{-2}$

$$\Rightarrow \sigma \sim G_F^2 E_{cm}^2$$

$\hookrightarrow$  weird cross section diverges w  $E_{cm}$ .

Doesn't make physical sense (e &  $\mu$  wavelengths shrink w/  $E$ )

$\sigma$  should get smaller.

Eg

$$\sigma(ee \rightarrow \mu\mu) \sim \frac{1}{E_{cm}^2} \quad \text{As expected}$$

## Force Carrier

Assume force carrier associated w/ interaction. Spin 1

$G_F$  arise from force carrier, more importantly needs right mass dimension  $\Rightarrow$  force carriers are massive

$$G_F = \frac{1}{m_F^2}$$

$$G_F \sim 10^{-5} \text{ GeV}^2$$

$\hookrightarrow$  "Fermi Mass"

$$\Rightarrow m_F \sim 300 \text{ GeV}$$

Problematic mass terms for force carriers are not gauge invariant  $m^2 A^2$

Crisis