Construction of the Standard Model

- Aim : illustrate how experiment guides the construction of theories, which in turn imply new predictions that can be tested.
  - Only simple formulas, used to get actual numbers that can be confronted with data. See theoretical lectures for the rigourous computations!

- Subject :
  - how weak decays suggested the Fermi theory and the IVB hypothesis;
  - the formulation of the Standard Electroweak theory;
  - and its lengthy experimental validation

- Scope : EW sector, fermion/boson interactions
  Not discussed : fermion physics (generations, CP violation)

Outline - 1

- Construction and refinement of Fermi's theory
  - A vector current-current interaction, by analogy to QED
  - Discovery of parity violation, and its inclusion in the theory
  - Successes and limitations
  - The Intermediate Vector Boson hypothesis
- The Electroweak theory
  - Very short summary of steps accomplished beyond Fermi
  - Vertices and couplings
  - Predictions

Outline - 2

- Tests and validation of the theory

  - Neutral currents : search, discovery (neutrino beams)
    - Implications: first prediction of the W and Z boson masses
  - Discovery of the intermediate vector bosons (hadron-hadron collisions)
  - Precise measurement of the Z boson resonance (e^+e^- collisions)
    - implications : prediction of the top quark mass and the Higgs boson mass
  - Discovery of the top quark and Higgs boson (hadron-hadron collisions)

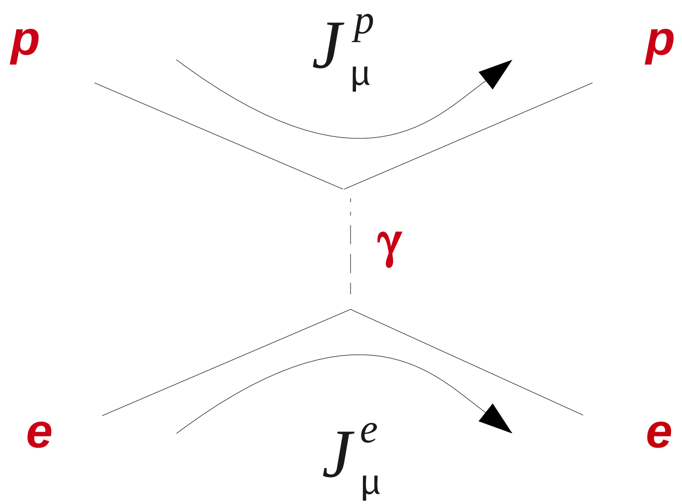
TOWARDS ELECTROWEAK UNIFICATION

Strong and weak interactions

Interaction	Lifetimes	Cross-sectrons	Coupling
Strong	~10^{-23} s	~10 mb	~1
Electromagnetic	~10^{-18} s	~1 μb	~10^{-2}
Weak	~10^{-12}, and up to seconds	~10 pb	~10-6

The Fermi interaction - 1

- Elastic electron-proton scattering, for example :



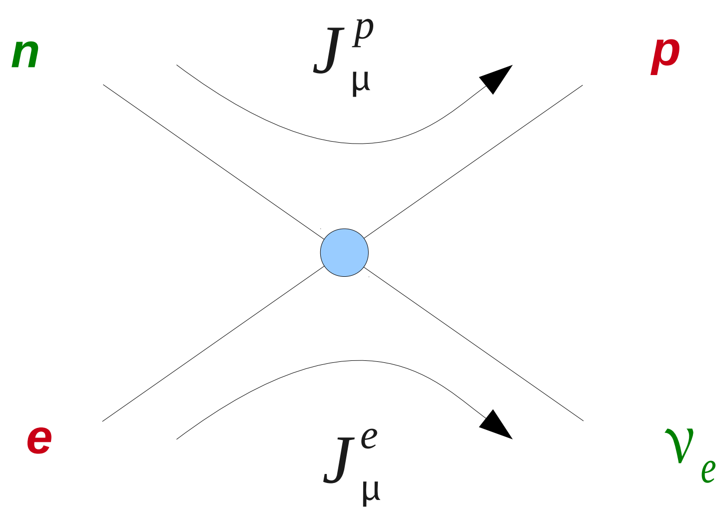
$$p\ e \rightarrow p\ e$$

$$M = \frac{e}{q^2}(\bar{p}\gamma^\mu p)(\bar{e}\gamma_\mu e)$$

- Coupling strength, **e**, determined from cross-section measurements
  - Only parameter of the theory!
- The structure of the interaction (vector currents, propagators, in- and outgoing spinors) is dictated by QFT + requirement of local gauge invariance

The Fermi interaction - 2

- Neutron decay, by analogy : http://inspirehep.net/record/3203



$$J_\mu^p \qquad J_\mu^e$$

$$n \rightarrow p \; e^- \; \bar{\nu}_e$$

$$M = G_F (\bar{n} \gamma^\mu p)(\bar{\nu}_e \gamma_\mu e)$$

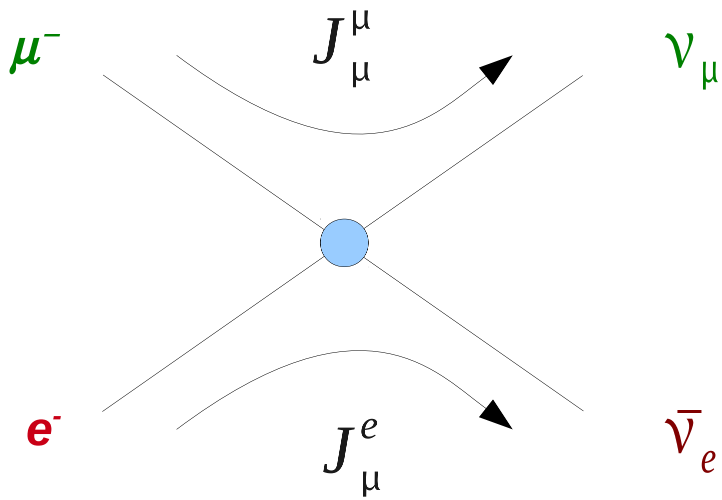
- And atomic β decays:

$$^{10}C \rightarrow {}^{10}Be \; e^+ \; \nu_e$$

$$^{14}O \rightarrow {}^{14}N \; e^+ \; \nu_e \; \ldots$$

The Fermi interaction - 3

- And muon decay :



$$\mu^- \rightarrow e^- \; \bar{\nu}_e \; \nu_\mu$$

$$M = G_\mu (\bar{\mu} \gamma^\mu \nu_\mu)(\bar{\nu}_e \gamma_\mu e)$$

- A consistent picture?
  - The coupling constants are to be measured from the decay times
  - Do we have $G_F = G_\mu$?

The Fermi interaction - 4

- Approximate formulae for the lifetimes (NB : $\tau = 1/\Gamma$)

$$\tau_O = \frac{30\pi^3}{G_F^2 E_0^5}$$

with τ_O the lifetime of ^{14}O, E_0 the available energy

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

with τ_μ the muon lifetime, m_μ the muon mass

- Numerical application
  - **^{14}O** decay : E_0 = 1.81 MeV, τ = 236 s
  - **μ** decay : m_μ = 105 MeV, τ = 2.2 μs

  (WATCH OUT : natural units used above! s $\leftrightarrow$ GeV^{-1} conversion factor?)

The Fermi interaction - 5

- The θ–τ puzzle
- Two particles discovered in the early fifties:

$$\theta^{+} \rightarrow \pi^{+}\pi^{0} \qquad\qquad \tau^{+} \rightarrow \pi^{+}\pi^{+}\pi^{-}$$

- Exercise : what is their parity? The π has spin/parity 0^{-}.
- All interactions are, until then, observed to conserve parity. But, for θ and τ, the mass and lifetime are measured as

$$m_{\theta} \sim m_{\tau} \sim 495\, MeV \qquad\qquad \tau_{\theta} \sim \tau_{\tau} \sim 12\, ns$$

- What does this suggest?

The Fermi interaction - 5

- Paper by Lee & Yang : http://inspirehep.net/record/21787

  Discusses the evidence in favour of parity conservation at that time. Reviewed the all available experimental data and concluded that

  - Parity is actually shown to be conserved in EM and strong interactions
  - But in the case of weak interactions, there is actually no evidence either way!

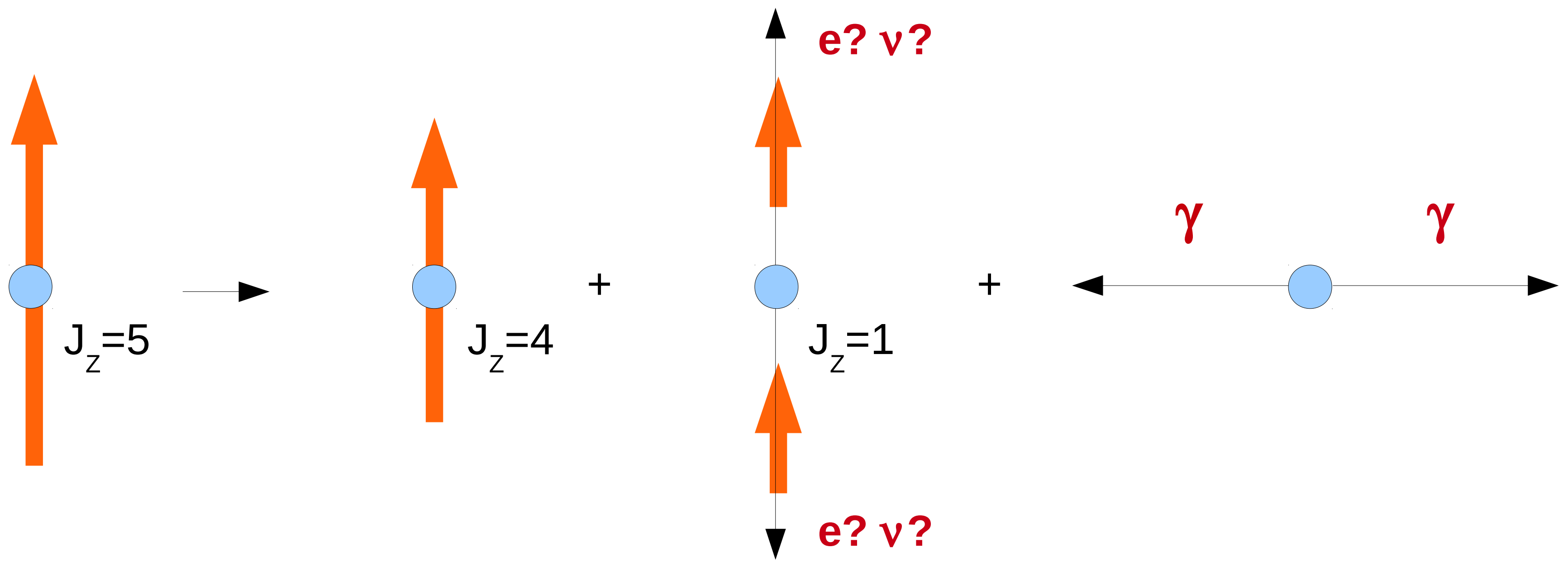
→ hypothesis that parity might be violated, or at least that its conservation needs to be tested! The authors were very cautious:

> … unsupported by experimental evidence. (One might even say that the present $\theta - \tau$ puzzle may be taken as an indication that parity conservation is violated in weak interactions. This argument is, however, not to be taken seriously because of the paucity of our present knowledge concerning the nature of the strange particles. It supplies rather an incentive for an examination of the question of parity conservation.) To decide …

The Fermi interaction - 6

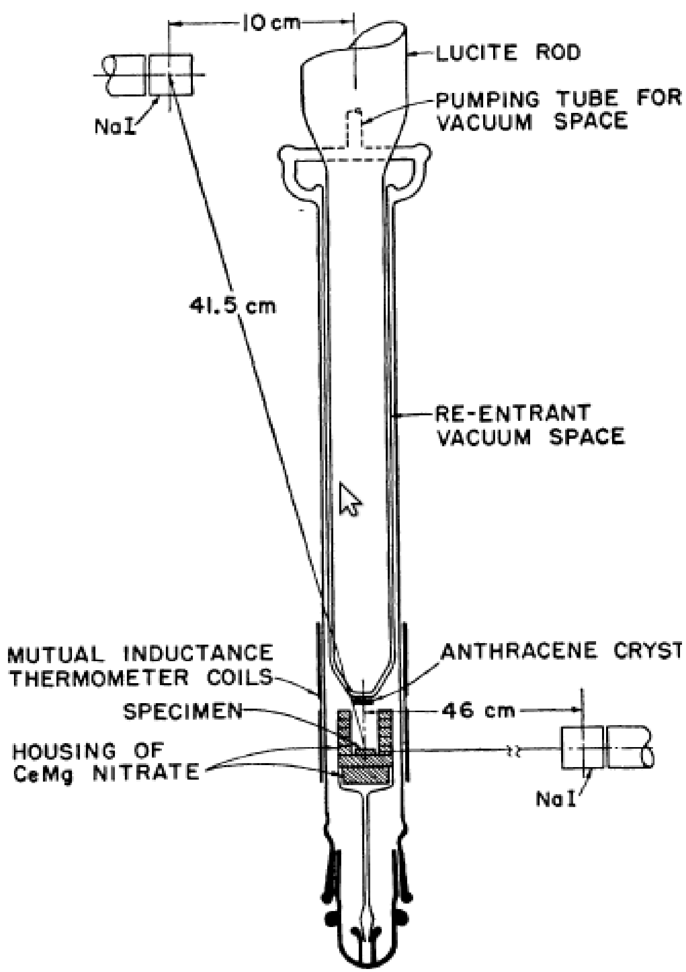
- Parity violation? Consider: $^{60}Co \rightarrow {}^{60}\mathrm{Ni}^{*} \; e^{-} \; \bar{\nu}_{e}$

$$\hookrightarrow {}^{60}\mathrm{Ni} \; \gamma \; \gamma$$



The Fermi interaction - 7

- Experimental setup and results: accumulate and align many nuclides!
  - http://inspirehep.net/record/28182



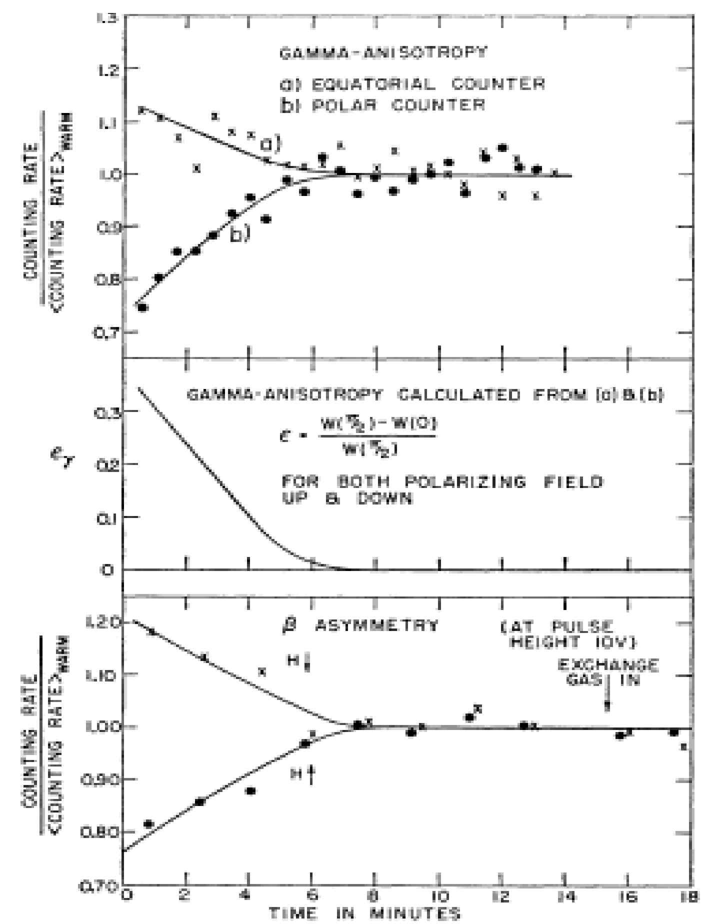
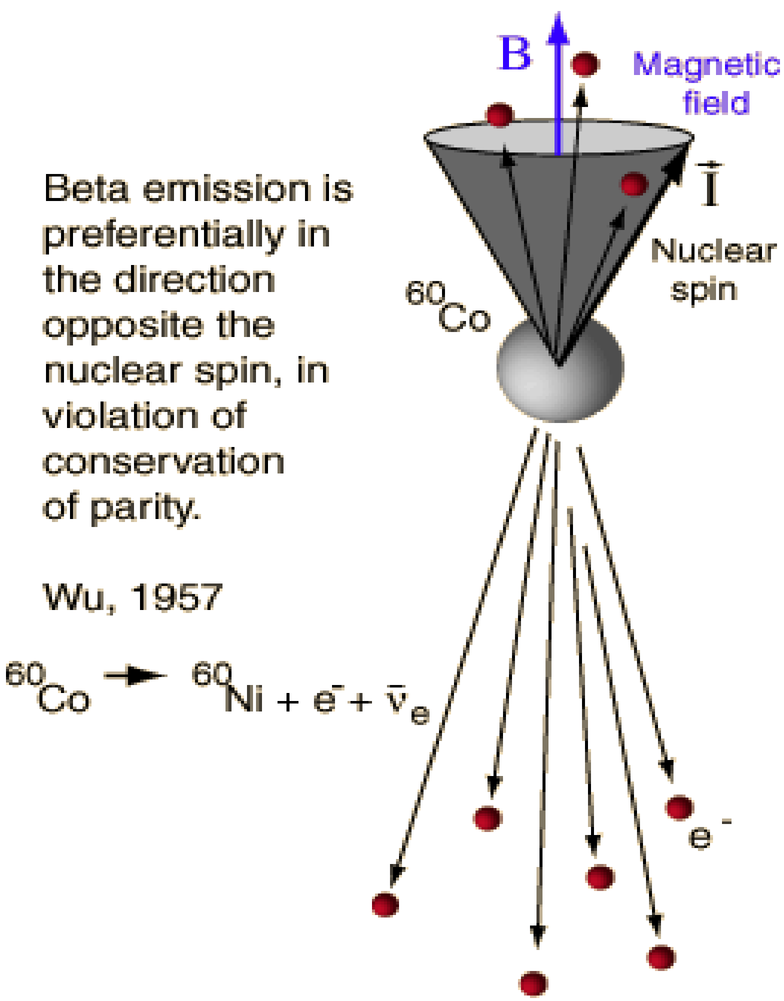


FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.

The Fermi interaction - 7

- Experimental setup and results: accumulate and align many nuclides!



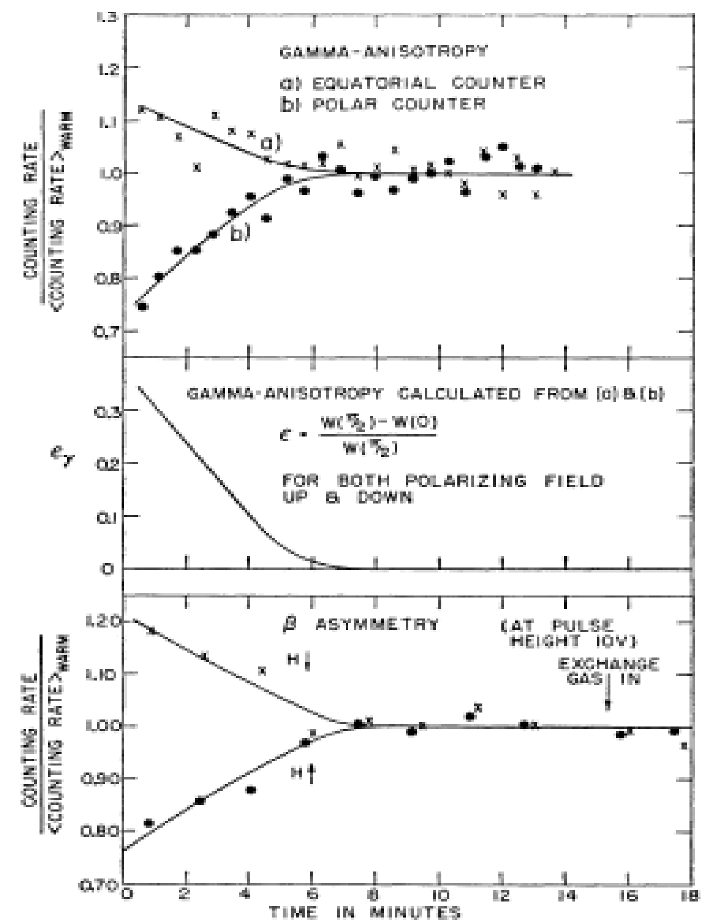


FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.

The Fermi interaction - 8

- Summary, in words

  - By bringing them to very cold temperature,the Cobalt 60 nuclides spins could be partially aligned along the magnetic field
  - The photons from Nickel 60 de-excitation are distributed preferentially along the “equator” of the system, allowing to observe and measure the polarization of the system
  - In this state, the electrons from β decay are distributed preferentially opposite to the magnetic field
  - This indicates parity violation (exercise : apply P to the system)

  - The experimental procedure was checked in two ways
    - The magnetic field was reversed : the electron distribution followed
    - When the system is warmed up : the polarization disappeared, as indicated by the vanishing photon anisotropy; the electron distribution followed simultaneously

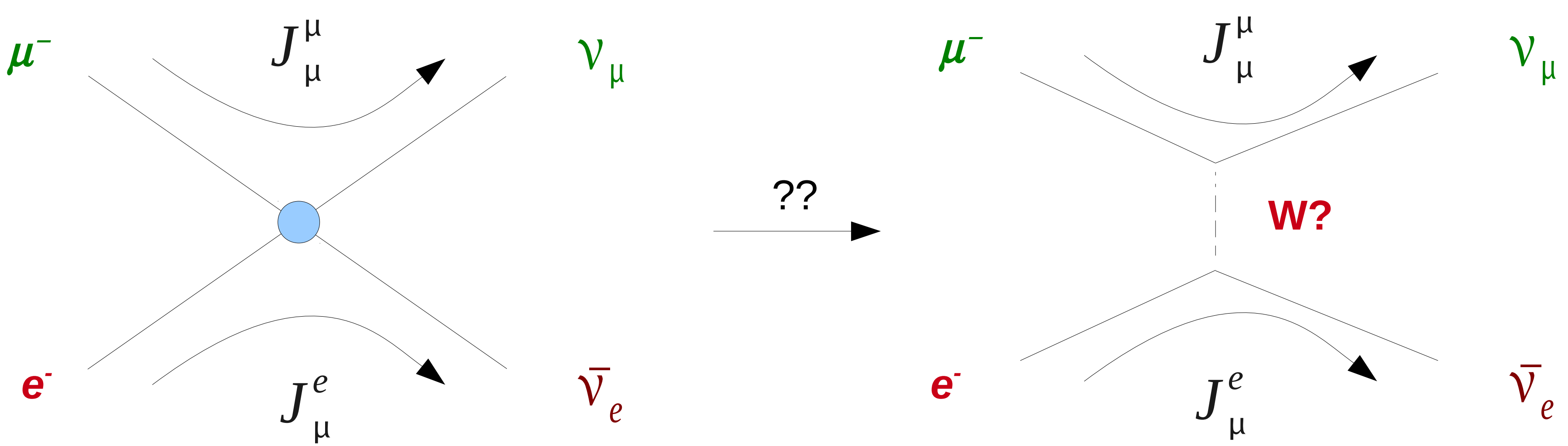
The Fermi interaction - 9

- After all, this requires only a small modification to the Fermi interaction:

$$M = G_F \left(\bar{n}\gamma^{\mu}(1-\gamma^5)p\right)\left(\bar{\nu}_e\gamma_{\mu}(1-\gamma^5)e\right)$$

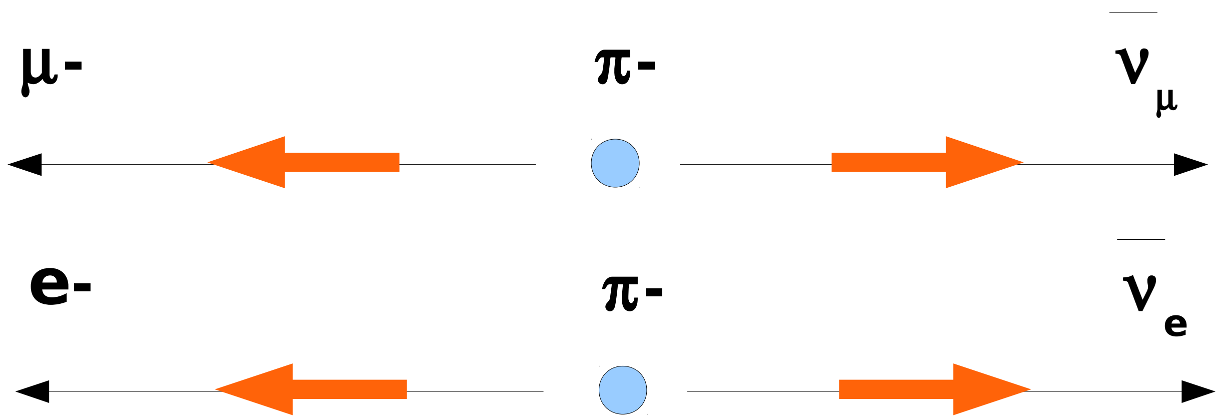
- This operator involves only $e^-_L,\ \nu_L\ (\text{or}\ e^+_R,\ \bar{\nu}_R)$

- The Intermediate Vector Boson hypothesis



The Fermi interaction - 10

- Another consequence : pion decay. A priori, two possible modes:



- For $\pi \rightarrow \mu\, \nu_\mu$, the muon is not very energetic, and helicity ≠ chirality
  So this is OK.
- For $\pi \rightarrow e\, \nu_e$, the electron is ultra-relativistic, and helicity = chirality
  So this is strongly disfavoured!
- Indeed, observation confirms that the electron mode is 10^4 times less frequent than the muon mode.

The Fermi interaction - 11

- Status : what has been achieved
  - EXP Weak interactions observed as slow decays of instable nuclei
  - First version of the Fermi interaction developed by analogy to QED to explain the weak interaction. No new vector boson introduced; absence of propagator compensated by small, dimensionful couplings constant, **$G_F \sim 10^{-5}$ GeV^{-2}**

    TH

    Gives a universal picture of β decays (in nuclei, pion decay, and muon decay), electron capture, ...
  - EXP Parity violation first suggested in K → 2π, 3π decays, then confirmed in β decay
  - This new feature is then accommodated into the Fermi theory.
  - The theory is now very successful, but mathematically flawed

    TH
    - Dimensionful couplings → non-renormalizability; growing cross sections
  - IVB hypothesis introduced to start curing this, again in analogy with QED.
- **Next problem : gauge invariance! How to derive this interaction from symmetry arguments?**

- $1\ \mathrm{GeV} = 1.52 \times 10^{24}\ \mathrm{s}^{-1}$
- $h = 6.62606957(29)\times10^{-34}$

- $G_f = 1.16637(1)\ 10^{-5}\ \mathrm{GeV}^{-2}$