Introduction to Nuclear and Particle Physics

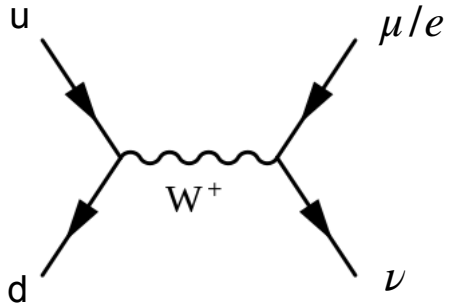
Lesson 10

parity violation

symmetries

Warm-up question 1

$$\pi^+ = \mu^+ + \nu_\mu$$
$$\pi^+ = e^+ + \nu_e$$



The pion can decay in two ways into leptons.
Which statements are correct?

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B) The massive anti-lepton (e^+/μ^+) that is produced must be right-chiral.

C) The neutrinos in the final state will for sure be left-chiral.

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Warm-up question 2

Which statement about symmetries is correct?

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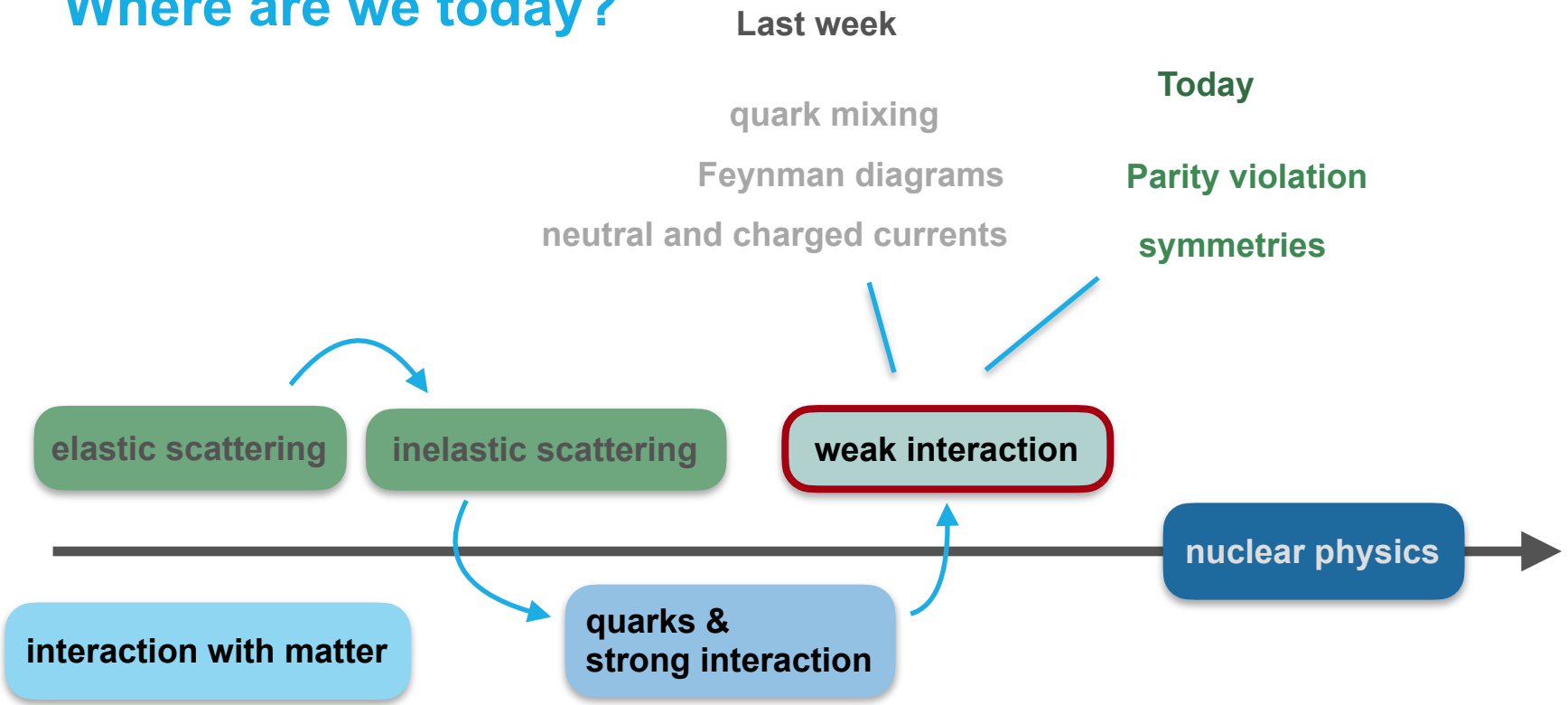
B) The CP symmetry is maximally violated in the weak interaction.

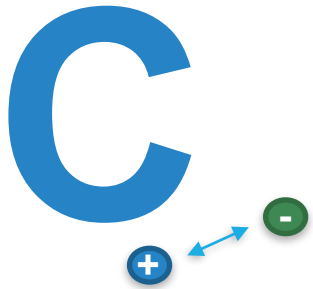
C) Parity violation can be observed, but is not part of the Standard Model.

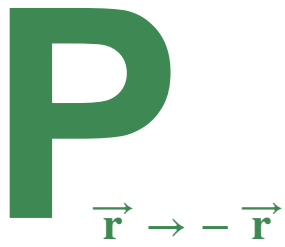
D) So far there is no experimental indication at all for a violation of the CPT symmetry.

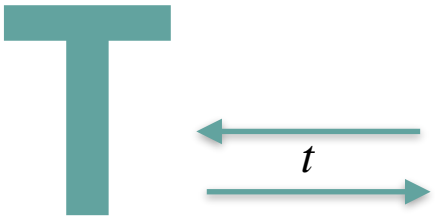
Where are we today?



… but CPT still holds! - violations in the weak sector







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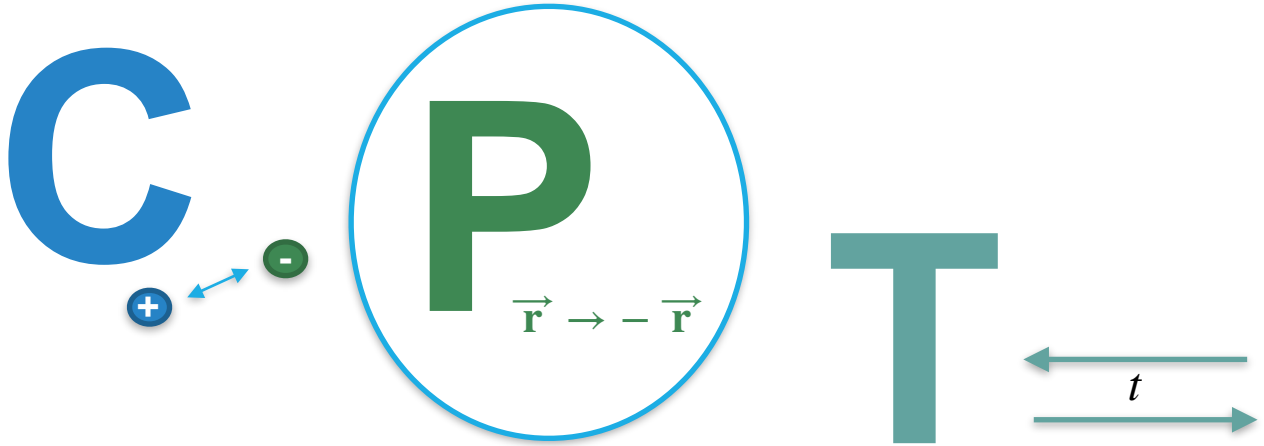
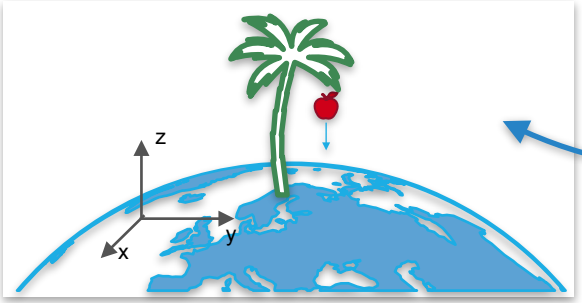
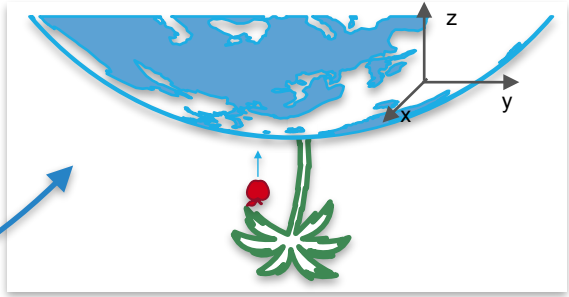


Introduction to Parity





$$P: \begin{pmatrix} x \\ y \\ z \end{pmatrix} \longrightarrow \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix}$$

So far, all our physical theories have been conserving parity

Classical mechanics + electrodynamics

Gravity

QED

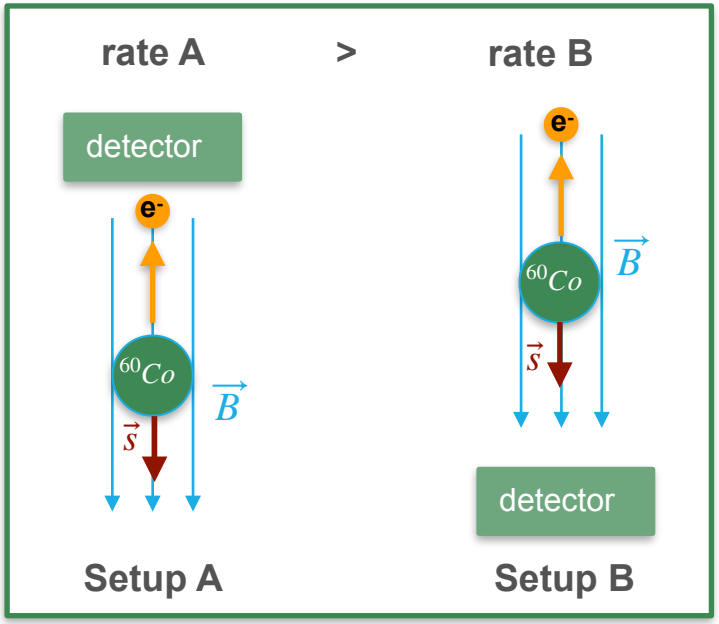
QCD

usually, parity violation is not part of our everyday's experience…

The Wu experiment

Chien-Shiung Wu

Idea: Do a parity transformation with the experimental setup to test whether parity is conserved in weak decays.



in reality: simply change polarization of B-field

Note:

As axial vectors, spin and angular momentum do not change under parity!

$$P\left(\vec{S}\right) = \vec{S}$$

$$P\left(\vec{L}\right) = P\left(\vec{r} \times \vec{p}\right) = -\left(\vec{r}\right) \times \left(-\vec{p}\right) = \vec{L}$$

Observation:

β^- decay strongly favours emission of e- anti-parallel to spin direction of nucleus.

Question about parity

Which statements are correct about the parity transformation?

- ☐ The momentum $\vec{p}$ changes sign under parity transformation.
- ☐ The velocity $\vec{v}$ changes sign under parity transformation.
- ☐ The angular momentum $\vec{L}$ changes sign under parity transformation.
- ☐ The spin $\vec{S}$ changes sign under parity transformation.
- ☐ The kinetic energy changes sign under parity transformation.
- ☐ The helicity of a particle changes sign under parity transformation.

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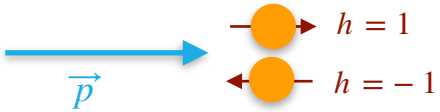
Helicity vs Chirality

Helicity

$$h = \frac{\vec{s} \cdot \vec{p}}{|s|\,|p|}$$

- describes state of spin relative to momentum
- for fermions: $h = \pm 1$
- depends on reference frame!

⇒ **not Lorentz-invariant!**



The Connection

Mass-less particle: $\beta = 1$

Helicity corresponds to Chirality

Massive particle: $\beta < 1$

- Chiral particle is in superposition of $h = \pm 1$ states.
- Probability for left-chiral e^- to be in $h = 1$ state:

$$W(h = 1) = \frac{1}{2}(1 - \beta)$$

Chirality

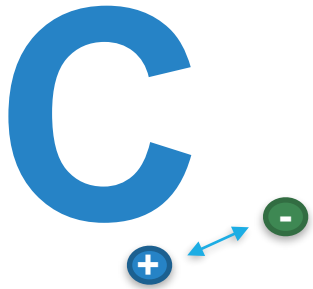
left-chiral / right-chiral

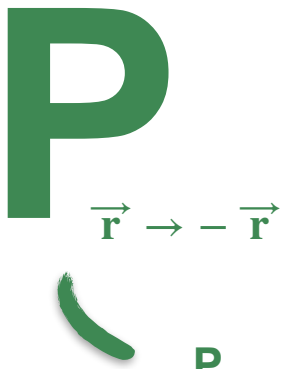
- Fundamental property of particle
- determines interaction of particle with parity-violating interactions

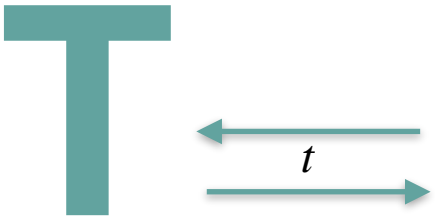
Lorentz-invariant quantity

e_R e_L

… but CPT still holds! - violations in the weak sector







maximally violated

Weak bosons see only:
- left-chiral particles,
- right-chiral anti-particles

Wu experiment **$\pi^{\pm}$ decay**

Question 19 (*2 Points*) A particle is moving along the $+x$-axis of a reference system K with helicity $H = +1$ and energy E. Its velocity is thus $\vec{v} = +|v|\vec{e}_x$. A second reference system K' moves along the $+x$-axis of the reference system K. The velocity of the reference system K' in K is $+|v_{RF}|\vec{e}_x$. The axes of the two reference systems point in the same directions, i.e., $\vec{e}_x = \vec{e}_{x'}$ etc.
Which statements are correct?

A. The energy E of the particle is an invariant, i.e., independent of the reference system.

B. The mass of the particle is an invariant.

C. The spin in K points in $+\vec{e}_x$-direction, i.e., $\vec{S} = +|S|\vec{e}_x$.

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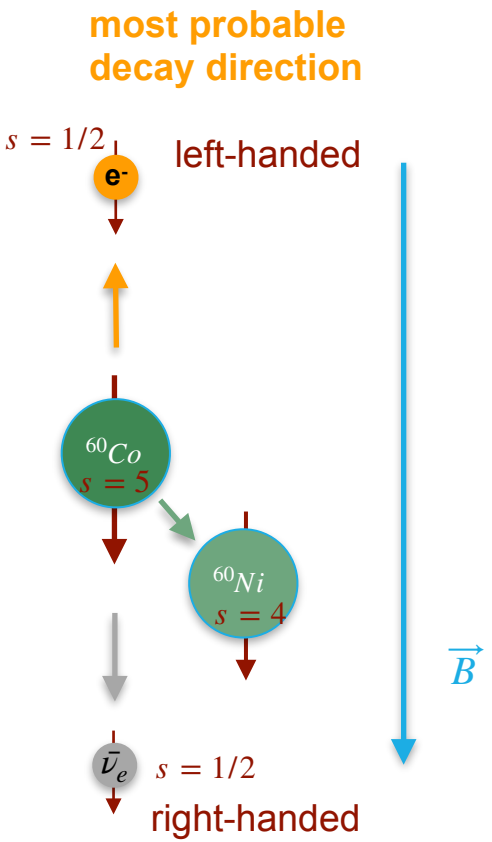
Maximal Parity Violation and Wu's experiment

W bosons only couple to left-chiral particles and right-chiral anti-particles.

⇒ anti-neutrino from decay must be right-handed!

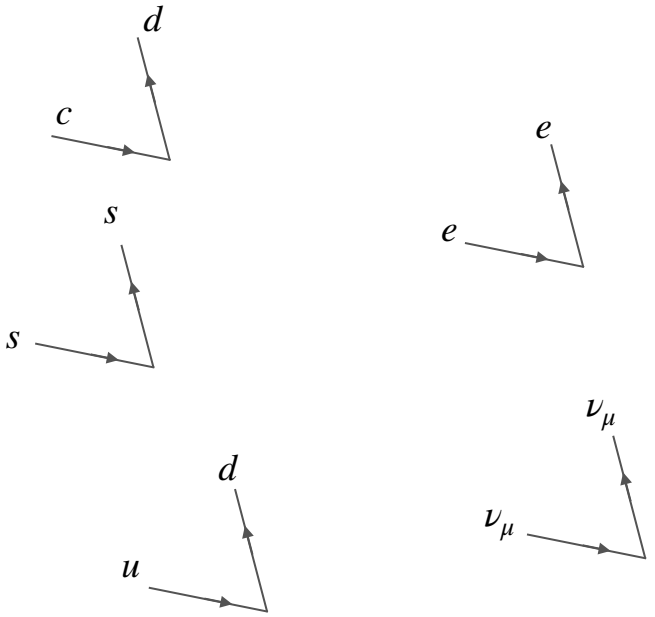
Link to Wu's observation:

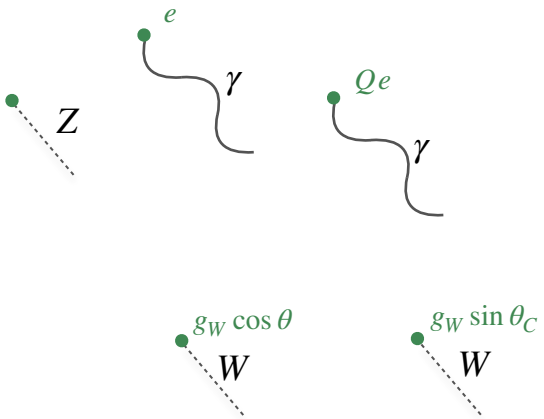
- ^{60}Co are spin-polarized by external B field.
- Parity Violation: decay produces left-chiral electron and right-chiral anti-neutrino
- Due to angular momentum conservation: electrons ejected anti-parallel to spin!



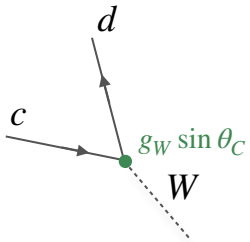
Group work

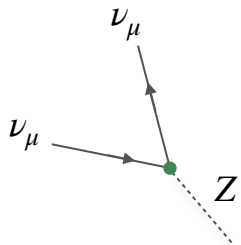
Please match the bosons with the correct vertex factors from the right to the corresponding fermion lines on the left.

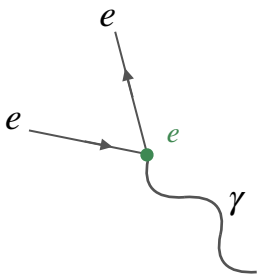


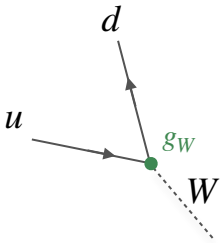


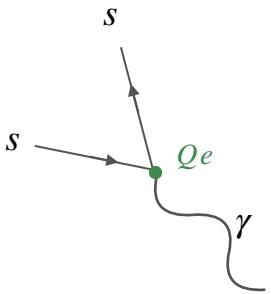
Group work - results







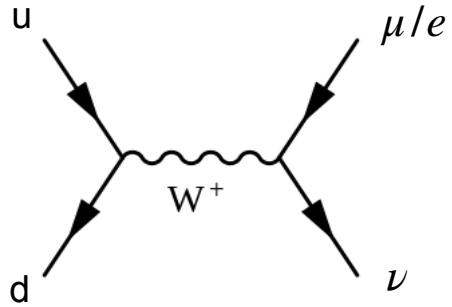




The decay of the charged pion

Which of the following decay channels is dominant?

$$\pi^+ = \mu^+ + \nu_\mu$$
$$\pi^+ = e^+ + \nu_e$$



A) Comparison of phase space:

$$\Gamma_{i\to f} \sim \left|M_{fi}\right|^2 \rho(E)$$

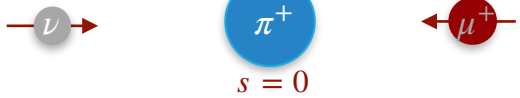
density of states: number of states per unit energy

$$\rho(E) \sim \frac{\mathrm{d}^3 p}{\mathrm{d}E} \sim p^2 \frac{\mathrm{d}p}{\mathrm{d}E}$$

$$\frac{\rho_e(E)}{\rho_\mu(E)} \approx 3.3$$

B) Helicity suppression:

Neutrino is left-handed



μ^+/e^+ needs to be right-chiral, but in $h = -1$

$$W(h=-1) = \frac{1}{2}(1-\beta)$$

$$W_e(h=-1) \approx 0$$

Positron channel is helicity-suppressed!

… but CPT still holds! - violations in the weak sector

violated

Oscillations of B mesons

CP

slightly violated

- Neutral Kaon decays

"direct"

$$|K_L\rangle = |K_2\rangle \quad (CP = -1)$$

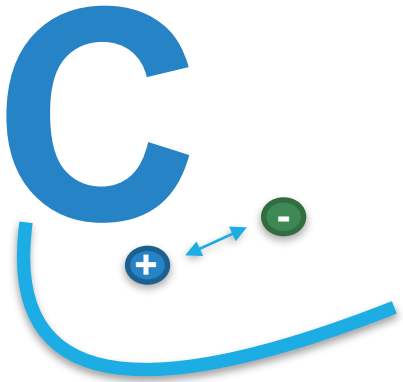
$\pi\pi\pi$ $(CP = -1)$ $\pi\pi$ $(CP = +1)$

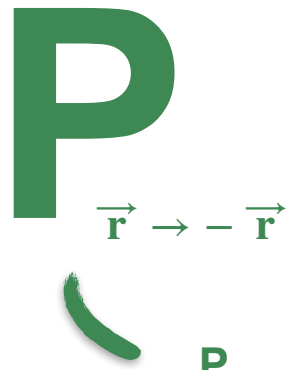
"indirect"

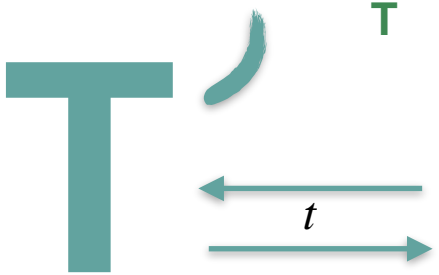
$$|K_L\rangle \sim |K_2\rangle + \varepsilon |K_1\rangle$$

$\pi\pi\pi$ $(CP = -1)$ $\pi\pi$ $(CP = +1)$

- B Meson decays







maximally violated

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Wu experiment $\pi^{\pm}$ **decay**

Nice video

https://www.youtube.com/watch?v=Elt0Gt9Cb6Q

Warm-up question 1

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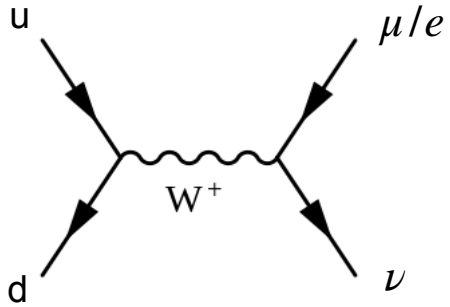

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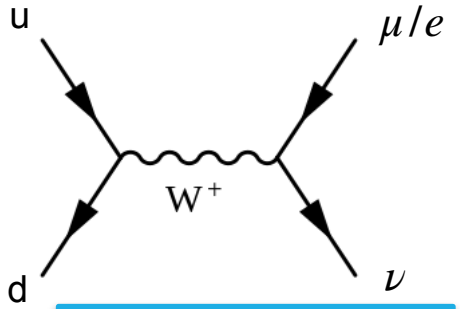

Muon channel is more likely because of that

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The massive anti-lepton (e^+/μ^+) that is produced must be right-chiral.

The neutrinos in the final state will for sure be left-chiral.

The helicity can also be h=-1 since the e/μ both have mass.

D) The helicity of the produced e^+/μ^+ must be h=+1.

E) The weak W bosons couple only to particles with helicity h=-1.

W distinguishes for chirality, not helicity.

Warm-up question 2

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B) The CP symmetry is maximally violated in the weak interaction.

C) Parity violation can be observed, but is not part of the Standard Model.

D) So far there is no experimental indication at all for a violation of the CPT symmetry.

Warm-up question 2

Which statement about symmetries is correct?

A) The spin changes its direction under the parity transformation. Does not change

B) The CP symmetry is maximally violated in the weak interaction. Only slightly violated

C) Parity violation can be observed, but is not part of the Standard Model. Is part of the SM!

So far there is no experimental indication at all for a violation of the CPT symmetry.