Exercice III

1. $K^- \to \pi^- \pi^0$

$m(K^-) \simeq 500\ \text{MeV} > m(\pi^-) + m(\pi^0) \simeq 275\ \text{MeV}$

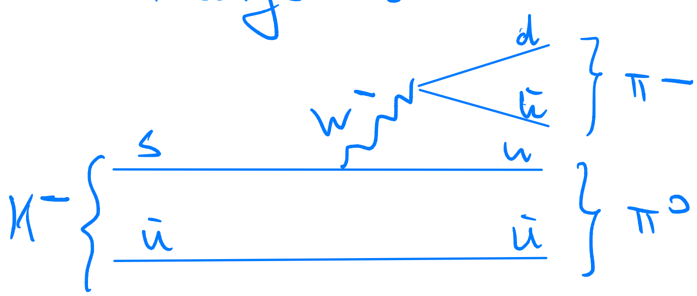
$Q_i = Q_f = -1$

Baryon and lepton quantum numbers do not intervene

↳ process allowed

$S_i = -1 \neq S_f = 0$

Strangeness is not conserved ⇒ WI



2. $J/\psi \to e^+ e^-$

$m(J/\psi) \simeq 3100\ \text{MeV} > 2 m_e \simeq 1\ \text{MeV}$

$Q_i = Q_f = 0$

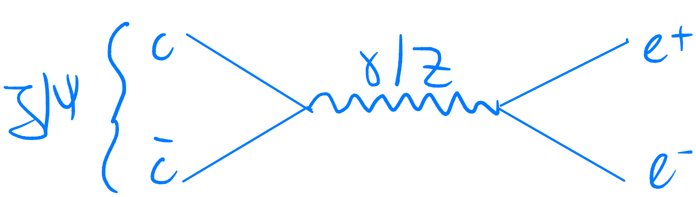
$L_{e,i} = L_{e,f} = 0$

Baryon number does not intervene

↳ process allowed

$C_i = C_f = 0$, other flavours do not intervene.

⇒ flavour conserved. Leptons participate, so it cannot be the SI.



The interaction occurs by the exchange of γ/Z.
At the energy scale of $m(J/\psi)$ the γ is dominant
$\Rightarrow$ EM interaction

3. $\Lambda \to n\, \tau^- \nu_\tau$

$m(\Lambda) \simeq 1115\ \text{MeV} < m(n) + m(\tau) \approx 2700\ \text{MeV}$

$L_{\tau,i} = 0 \neq L_{\tau,f} = 2$

$\hookrightarrow$ forbidden by non-conservation of energy and τ lepton number.

4. $p\, \pi^- \to \Lambda\, K^0$

$Q_i = Q_f = 0$

$B_i = B_f = 1$

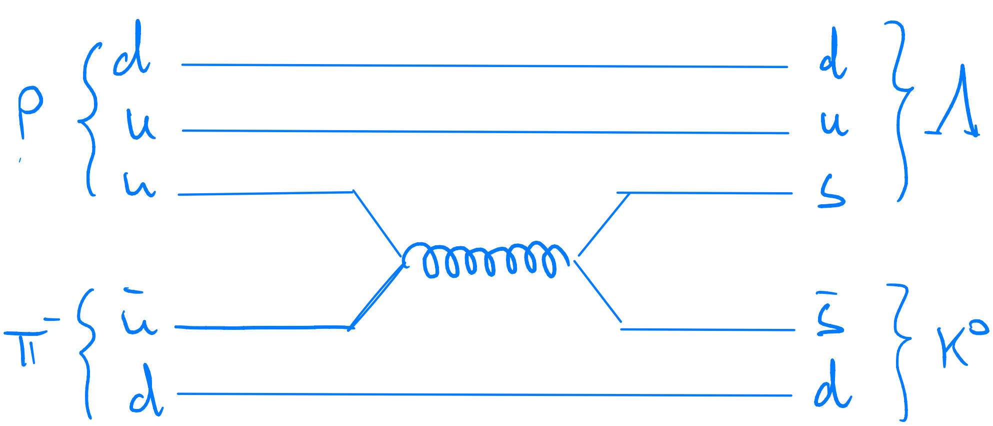
Lepton numbers do not intervene

$\hookrightarrow$ allowed

$S_i = S_f = 0$, other flavours do not intervene

Only hadrons interact and flavours conserved

$\Rightarrow$ SI



5. $\bar{D}^0 \to e^+ e^-$

$m(\bar{D}^0) \approx 1800 \text{ MeV} > 2m(e) \approx 1 \text{ MeV}$

$Q_i = Q_f = 0$

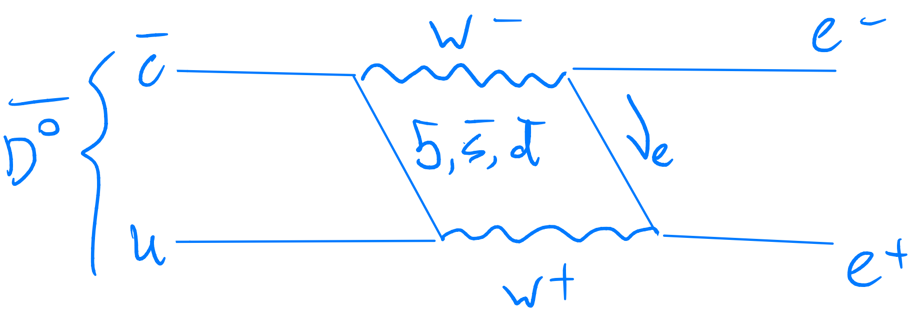
$L_{e,i} = L_{e,f} = 0$

Baryon number and other lepton numbers do not intervene.

$\Rightarrow$ Process allowed

$C_i = +1 \neq C_f = 0$ (charm not conserved)

$\Rightarrow$ WI



Exercice IV

1. Experimental considerations

1(a) The $p\bar{p}$ mode is the only two-body decay of the η_c consisted of two stable particles which are directly detectable. Moreover, these particles are charged (tracks: easier than neutrals)
[We can also appreciate the fact that the $p\bar{p}$ BF is measured at the level of 10%, (uncertainty / central value). This is related to the reasons above]

1(b) * Both η_c and J/ψ decay into $p\bar{p}$, and therefore their peaks are visible in the $p\bar{p}$ invariant mass histogram.
* The centers of the peaks correspond to the masses of the decaying particles ($m(J/\psi) \simeq 3097$ MeV, $m(\eta_c) \simeq 2984$ MeV)
* In the plot, the FWHM of the J/ψ and η_c are approximately 0.01 GeV and 0.04 GeV, (10 and 40 MeV) respectively.

From the PDG:

$\Gamma(J/\psi) \simeq 93$ keV and $\Gamma(\eta_c) \simeq 32$ MeV

Thus the J/ψ peak width is essentially due to the experimental resolution, $R \simeq 10\,MeV$ and that of the η_c width is $\sim \Gamma(\eta_c) + R$.

⊛ The <u>integrals of the peaks</u> are interpretable considering the corresponding BFs of the B decays and of the $J/\psi / \eta_c$ decays (together with their total widths).

This is a higher level answer (<u>bonus</u>)

1.(c) ⊛ <u>$p\bar{p}K^+\pi^-$</u> spectrum, for the B^0 meson reconstruction.

⊛ <u>$p\bar{p}\pi^-$</u> for the X^- search

⊛ $K^+\pi^-$ spectrum to look for K^* decays (bonus)

⊛ $p\bar{p}K^+K^-$, $p\bar{p}\pi^+\pi^-$... to identify background events for in which π/K are misidentified. (bonus)

2. Quantum numbers of the X^- hadron

2(a) The charges that are always conserved:

Q, B, L_ℓ.

Thus:
$$\begin{cases} Q(X^-) = Q(\eta_c) + Q(\pi^-) = -1 \\ B(X^-) = B(\eta_c\,\pi^-) = 0 \\ L_\ell(X^-) = L_\ell(\eta_c\,\pi^-) = 0 \quad \text{(3 lepton nb}^{\text{s}}\text{)} \end{cases}$$

$$J(\eta_c) = 0 \quad ; \quad J(\pi^-) = 0$$

$$\vec{J}(X^-) = \underbrace{\vec{J}(\eta_c) + \vec{J}(\pi^-)}_{\vec{0}} + \vec{L}$$

$$J(X^-) = \ell$$

2(b) ⊛ If the decay is due to SI also flavours are conserved. all of them are 0 for the final state, thus:

$$S(X^-) = C(X^-) = B(X^-) = 0$$

and

$$Y(X^-) = 0$$

⊛ SI conserves isospin.

$$I(\pi) = 1 \quad ; \quad I_3(\pi^-) = -1 \quad ; \quad I(\eta_c) = 0$$

$$I_3(X^-) = I_3(\pi^-) + I_3(\eta_c) = -1$$

$$I(X^-) = I(\pi) = 1$$

$$|X^-\rangle = |1\ -1\rangle$$

2(c) $J^{PC}(\eta_c) = 0^{-+}$; $J^P(\pi^-) = 0^-$

SI conserves P (C is not relevant here)

$$P(X) = \underbrace{P(\eta_c) \cdot P(\pi^-)}_{+1} \cdot (-1)^\ell = (-1)^\ell$$

Possible J^P with $\ell \in \{0, 1, 2\}$:

$\ell = 0$ $\quad J^P(X) = 0^+$

$\ell = 1$ $\quad J^P(X) = 1^-$

$\ell = 2$ $\quad J^P(X) = 2^+$

2(d) $C(X^-)$ cannot be determined from this decay because π^- is not a $\hat{C}$ eigenstate.

2(e) The quark contents of the final-state particles are $\bar{u}d$ for π^- and $c\bar{c}$ for the η_c. The lowest level diagram necessarily leaves these flavours unchanged and thus we can assume that X^- is a $c\bar{c}\bar{u}d$ state.

2(f) SI decay $\Rightarrow$ G conservation

$$G(X) = G(\eta_c) \times G(\pi^-) = (+1)(-1) = -1$$

Examples of decays which do not conserve G:

$X^- \to J/\psi\, \pi^-$ $\quad (G(J/\psi) = -1)$

$X^- \to \eta_c\, \rho^-$ $\quad (G(\rho^-) = +1)$

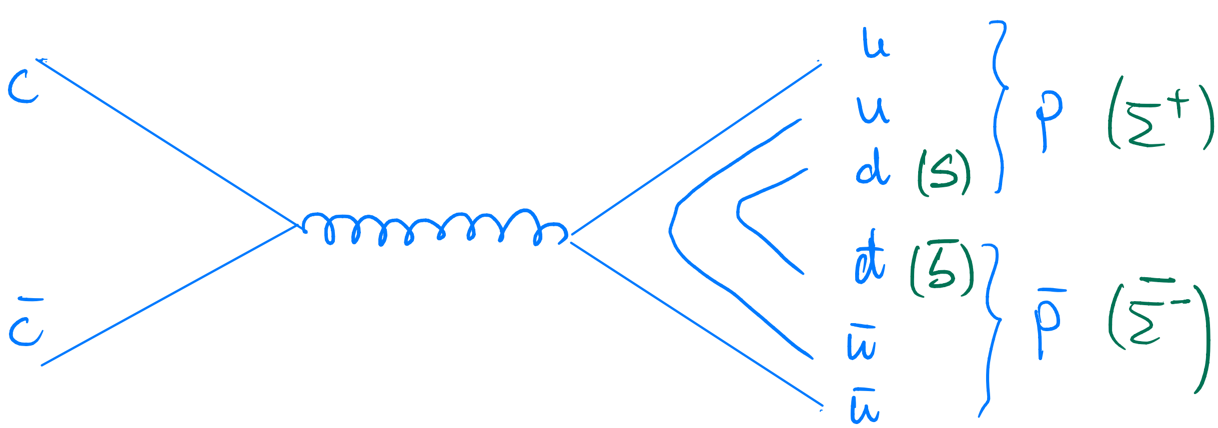
3. Aspects of the η_c decay

3(a) $\eta_c \to p\bar{p}$ (SI process)

$\bar{\Sigma}^-$ is the antibaryon of Σ^+, and is thus a $\bar{u}\bar{u}\bar{s}$ state.

- In both decays, only hadrons participate and there is no flavour violation.
- The BFs of these two η_c decays are similar (phase space has a small influence here
- SU(3) symmetry (p and Σ^+ belong to the same octet). (bonus)

3(b)



3(c) $|\eta_c\rangle = |0,0\rangle$

$|p\rangle = |\tfrac{1}{2}\ \tfrac{1}{2}\rangle \qquad |\bar{p}\rangle = |\tfrac{1}{2}\ -\tfrac{1}{2}\rangle$

$|\Sigma^+\rangle = |1\ 1\rangle \qquad |\bar{\Sigma}^-\rangle = |1\ -1\rangle$

The proton belongs to the doublet (p, n)
The Σ^+ belongs to the triplet $(\Sigma^+, \Sigma^0, \Sigma^-)$
I and I_3 follow.
Anti-particles belong to separate multiplets and their I_3 is opposite to that of their particles.

$$|p\bar{p}\rangle = |\tfrac{1}{2}\ \tfrac{1}{2}\rangle \otimes |\tfrac{1}{2}\ -\tfrac{1}{2}\rangle = \sqrt{\tfrac{1}{2}}\,|1\,0\rangle + \sqrt{\tfrac{1}{2}}\,|0\,0\rangle$$

$$|\Sigma^+\bar{\Sigma}^-\rangle = |1\ 1\rangle \otimes |1\ -1\rangle =$$
$$= \sqrt{\tfrac{1}{6}}\,|2\,0\rangle + \sqrt{\tfrac{1}{2}}\,|1\,0\rangle + \sqrt{\tfrac{1}{3}}\,|0\,0\rangle$$

$$\frac{\Gamma_{th}(\eta_c \to p\bar{p})}{\Gamma_{th}(\eta_c \to \Sigma^+\bar{\Sigma}^-)} \simeq \underbrace{\frac{PS(\eta_c \to p\bar{p})}{PS(\eta_c \to \Sigma^+\bar{\Sigma}^-)}}_{\approx 1} \cdot \frac{|\langle p\bar{p}|H_f|\eta_c\rangle|^2}{|\langle \Sigma^+\bar{\Sigma}^-|H_f|\eta_c\rangle|^2} \simeq$$

Isospin amplitude of $I=0$.

$$\simeq \frac{\tfrac{1}{2}\,\cancel{f_0}}{\tfrac{1}{3}\,\cancel{f_0}} = \frac{3}{2}$$

Isospin amplitude for $I=0$

H_I connects only states with the same I, I_3, so we only consider the $|00\rangle$ part

2(d) The ratio of the measured BFs is opposite. We note that the PS difference cannot explain this, as it should have done the opposite effect.

Possible comments: the $\Xi^+ \bar{\Xi}^-$ BF has a large uncertainty and is only $< 2\sigma$ away from the predicted ratio.

Also, SU(3)-symmetry breaking may be at play (but should cause an opposite effect).

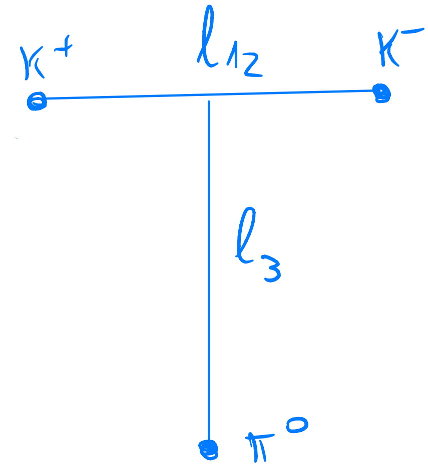
Finally: other interactions may be at play.

2(e) The η_c does not carry colour, while the gluon does! This actually forbidds the diagram drawn above.

The transition may occur via SI but with several gluons to ensure colour conservation.

Thus, the EM interaction, which is the next dominant one at this energy scale, must compete with the SI.

2 (f) $J^P(K^\pm) = 0^-$; $J^{PC}(\pi^0) = 0^{-+}$



$$P_f = \underbrace{(P(K))^2 P(\pi)}_{-1} (-1)^{l_{12}+l_3} =$$

$$= (-1)^{l_{12}+l_3+1}$$

$$C_f = C(K^+ K^-)\, C(\pi^0) =$$

$$= P(K^+ K^-)\, C(\pi^0) = \underbrace{(P(K))^2}_{1} (-1)^{l_{12}} \underbrace{C(\pi^0)}_{1} = (-1)^{l_{12}}$$

$$J_f = J_i = 0$$

2(g) The decay is due to SI as only hadrons are involved and flavours are conserved.
Furthermore, it is the dominant decay of the η_c, and the width of η_c is $\simeq 30$ MeV, which confirms SI.
Even if one suspects a competition with EM int, this interaction still conserves C and P
$\Rightarrow$ C and P are conserved.

$$J^{PC}(\eta_c) = 0^{-+}$$

$$C_i = C(\eta_c) = +1$$

$$C_f = C_i \Rightarrow (-1)^{l_{12}} = +1 \Rightarrow l_{12} \text{ even}$$

$$\vec{J}_i = \underbrace{\vec{J}(K^+) + \vec{J}(K^-) + \vec{J}(\pi^0)}_{\vec{0}} + \vec{L}_{12} + \vec{L}_3$$

$$J_i = J_f \Rightarrow l_{12} = l_3$$

$$P_i = P(\eta_c) = -1$$

$$P_f = (-1)^{\underbrace{l_{12}+l_3}_{\text{even}}+1} = -1$$

$\Downarrow$ no additional constraint from $P_i = P_f$

Possible values of l_{12} and l_3:
$l_{12} = l_3$, both are even.