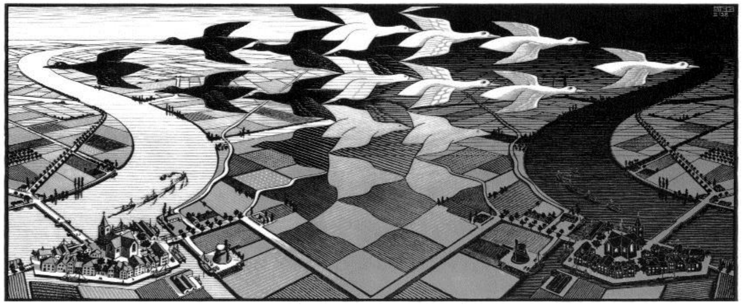

CP-Violation in Heavy Flavour Physics
Lecture 2 (part I)

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Introduction, i.e., the Big Picture

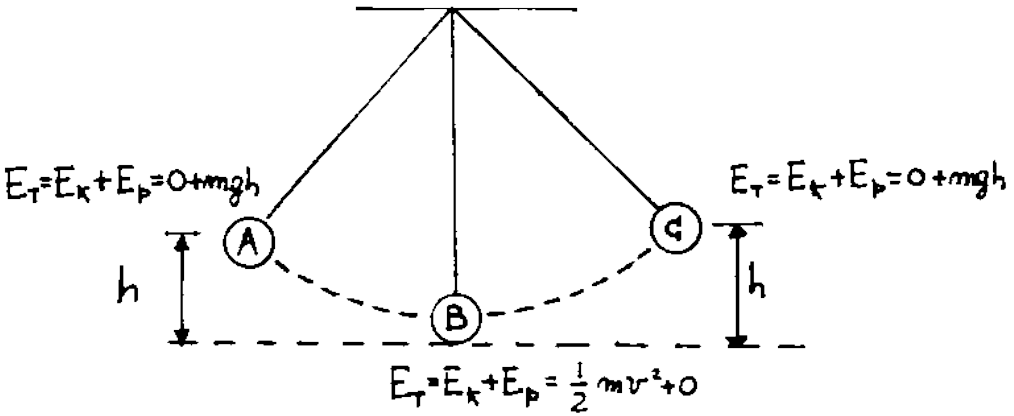
- What seems to be the **trouble**? Well, there is **something wrong** with the Universe we know…
- If matter and anti-matter are always produced in the **same amount** why do not we see any **anti-matter left** after the Big Bang (BB)?
- We know that the Universe **is not empty**…

$$\frac{N_{Baryons}}{N_{Photons}} \approx 10^{-10}$$

- but…, the Universe **is almost empty**! For each $10 \cdot 10^9\, q$ and $10 \cdot 10^9\, \bar{q}$ created in the BB **ONE! q survived**
- How bizarre…

Introduction, i.e., the Big Picture

- The way to attack this problem in HEP is to understand
  - What the Universe is built of – „**matter particles**”
  - How these matter particles interact – **forces** (also particles…)
- The most successful recipe is the **Standard Model** which is based on principle of **gauge invariance** = symmetry
- In other words – **forces** are **consequence** of various **symmetries**, in order to study them we need to understand their invariance principles
- Let check this out – familiar example – **energy conservation**



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Macroscopic (classic) **gravity force** is **invariant** under **time translation**

Symmetry w.r.t. time translations = **conservation** of Energy

Introduction, i.e., the Big Picture

- The way to attack this problem in HEP is to understand
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- In other words – **forces** are **consequence** of various **symmetries**, in order to study them we need to understand their invariance principles
- Let check this out – and not so familiar example…

Invariance w.r.t. **arbitrary change** of a wave function **phase** – **electric charge** conservation (gauge transformation)

Absolute phase of a quantum state cannot be measured

Introduction, i.e., the Big Picture

- There is more… Discrete symmetries! $\mathcal{C}, \mathcal{P}, \mathcal{T}$
  - $\mathcal{C}$ – particle anti-particle conjugation (change sign of all additive quantum numbers…, eh, not quite classical…)
  - $\mathcal{P}$ – mirror symmetry (reflection in a plane mirror and a rotation by 180^o)
  - $\mathcal{T}$ – time reversal (formal reversing the sign of the time axis)
- Known and used in classical physics for quite some time, regarded as just something curies (quantum physics made them great!)
- Classical physics treats time and charge conjugations as trivial
- More interesting stuff going on with the parity

$$\mathcal{P}\vec{r} \to -\vec{r}$$

Polar vector

$$\boxed{\vec{v} = \frac{d\vec{r}}{dt}, \vec{p} = m\vec{v}, \vec{F} = \frac{d\vec{p}}{dt}}$$

Introduction, i.e., the Big Picture

$$\vec{F}_L = q\left(\vec{E} + \vec{v} \times \vec{B}\right) \rightarrow \mathcal{P}\vec{F}_L = -\vec{F}_L \rightarrow \mathcal{P}\vec{B} = \vec{B}$$

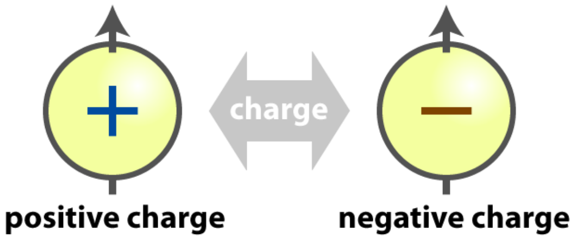
Axial vector

- Already within the framework of the classical physics we can have four classes of quantities with different behavior under parity transformation
  - **Scalars** (m)
  - **(Polar) Vectors** $(\vec{p},\ \vec{F})$
  - **Pseudo-scalars** (e.g., $\vec{E} \cdot \vec{B}$)
  - **(Axial Vectors) Pseudo-vectors** $(\vec{B}, \vec{L})$
- Nice, but let's see what the quantum theory does for us…

Introduction, i.e., the Big Picture

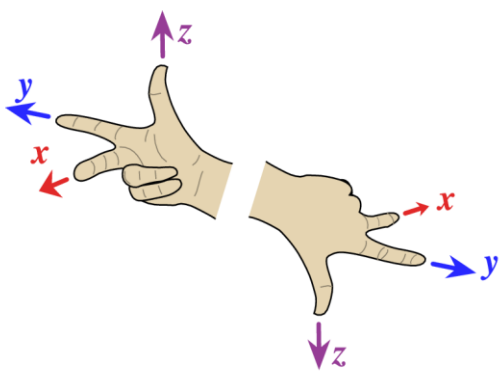
- $\mathcal{C}$ – formally changes a field ϕ into a related one $\phi^\dagger$, the latter one has just all its additive quantum numbers with opposite signs
  - Charge
  - Lepton number
  - Barion number
  - …

- We know based on experimental work that the invariance under $\mathcal{C}$ transformation always holds for the strong and e-m interactions
- Cannot distinguish between matter and anti-matter using any observable related to strong or e-m forces!



Introduction, i.e., the Big Picture

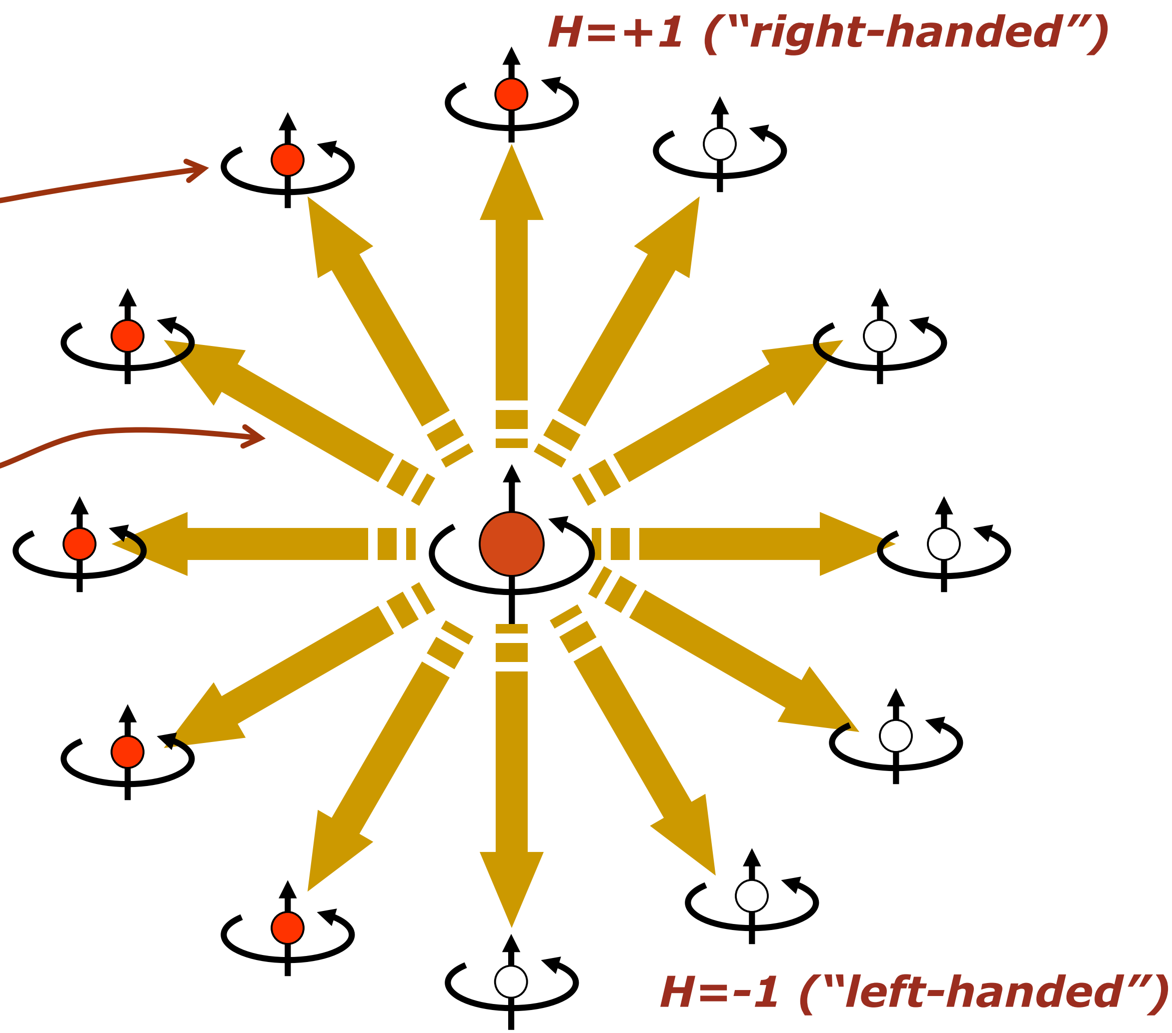
- $\mathcal{P}$ – parity invariance regarded as „common sense”, why physics would distinguish between the real and mirror worlds? No way…
- But, we got so called $\theta - \tau$ puzzle (see the previous lecture)
  - To deal with it, the theorists realised that the weak interactions must be described by quantities that are mixture of vectors and pseudo-vectors (V-A theory)!
  - That was a huge step forward in getting to the SM
  - Now this may lead to quantities that will behave as pseudo-scalars under parity transformation, thus…
  - the difference between the real and mirror world!



Introduction, i.e., the Big Picture

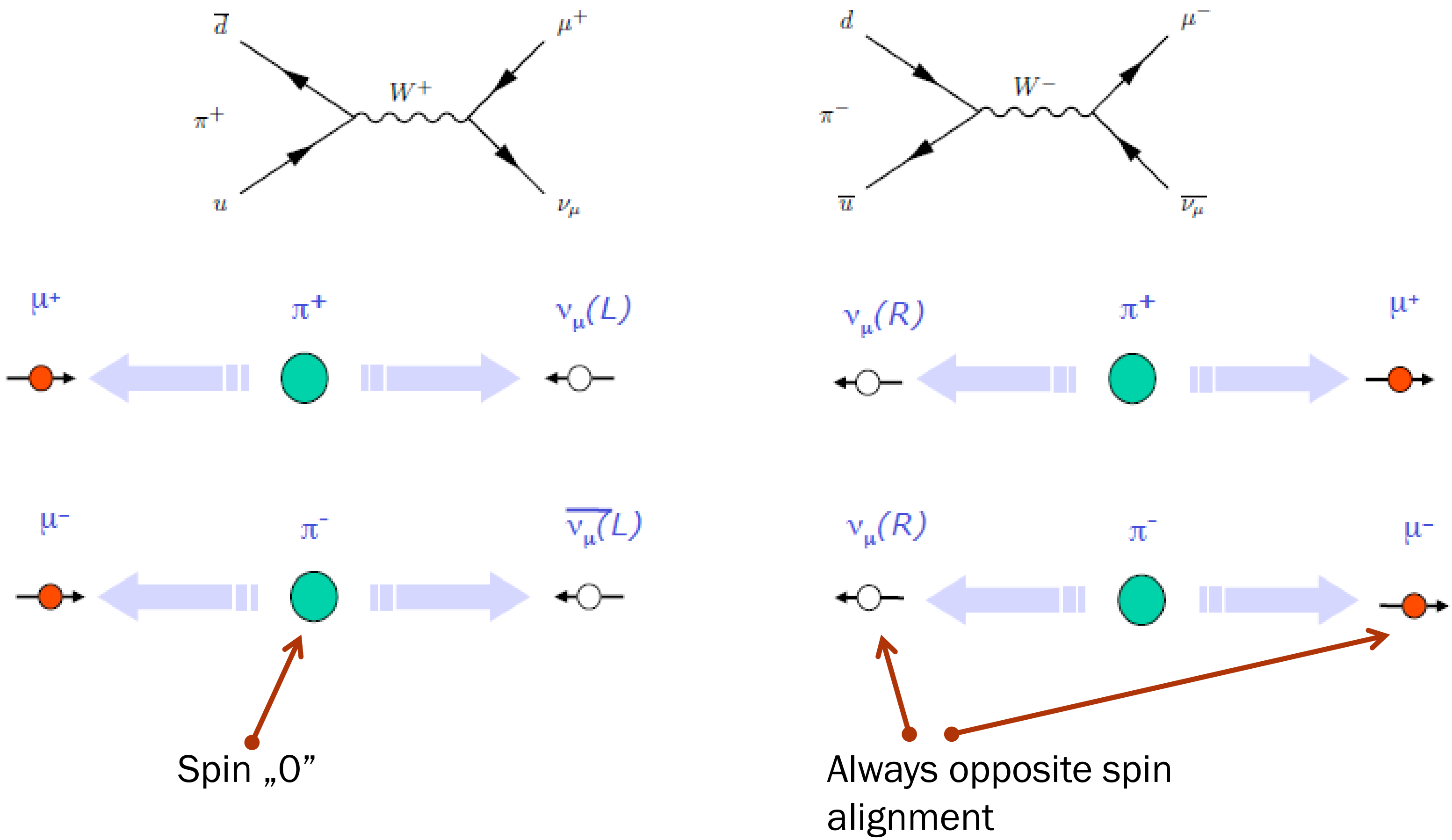
- So, what such **pseudo-scalar observable** would look like? Meet the fantastic **helicity**! (Well, meet it the second time, see the last lecture…)

$$H = \frac{\vec{s}\cdot\vec{p}}{|\vec{s}\cdot\vec{p}|}$$



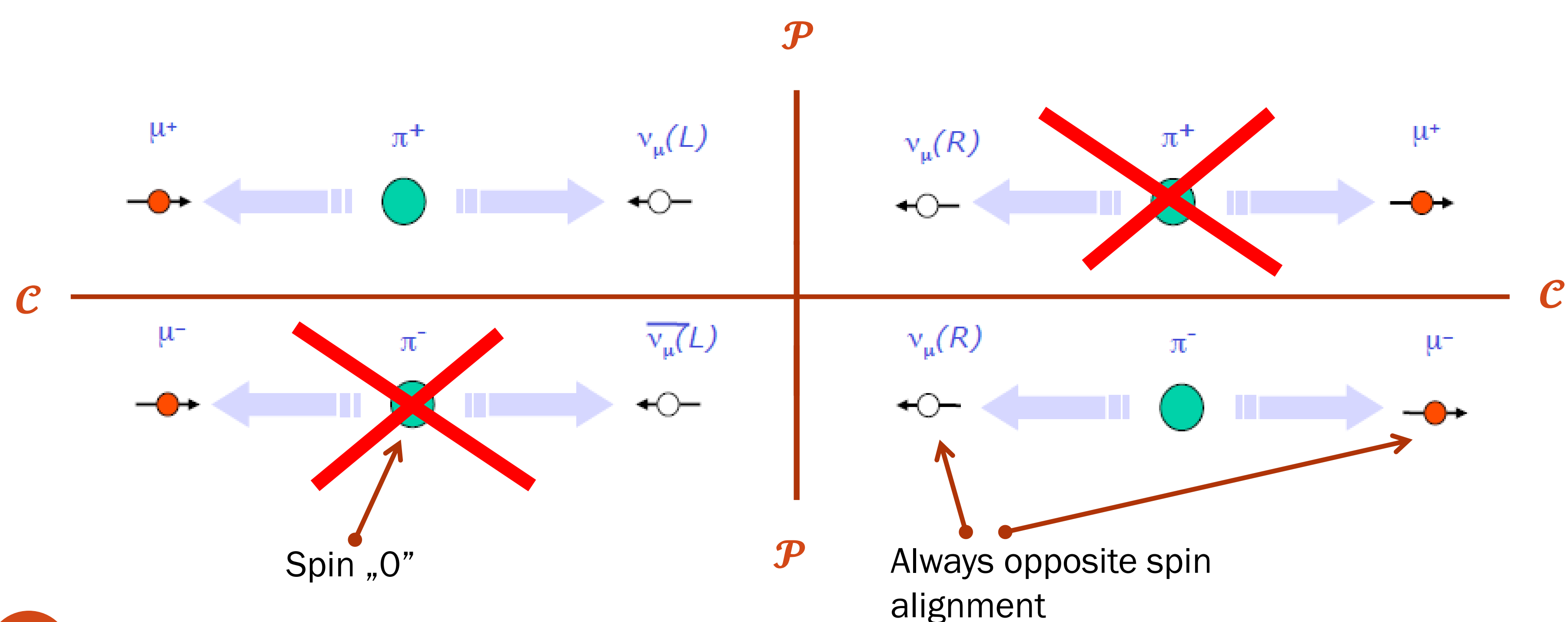
Introduction, i.e., the Big Picture

- Now, how this new „handedness” observable make things exciting?
- Lederman experiment: $\pi^+ \rightarrow \mu^+ + \nu_\mu$, $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$



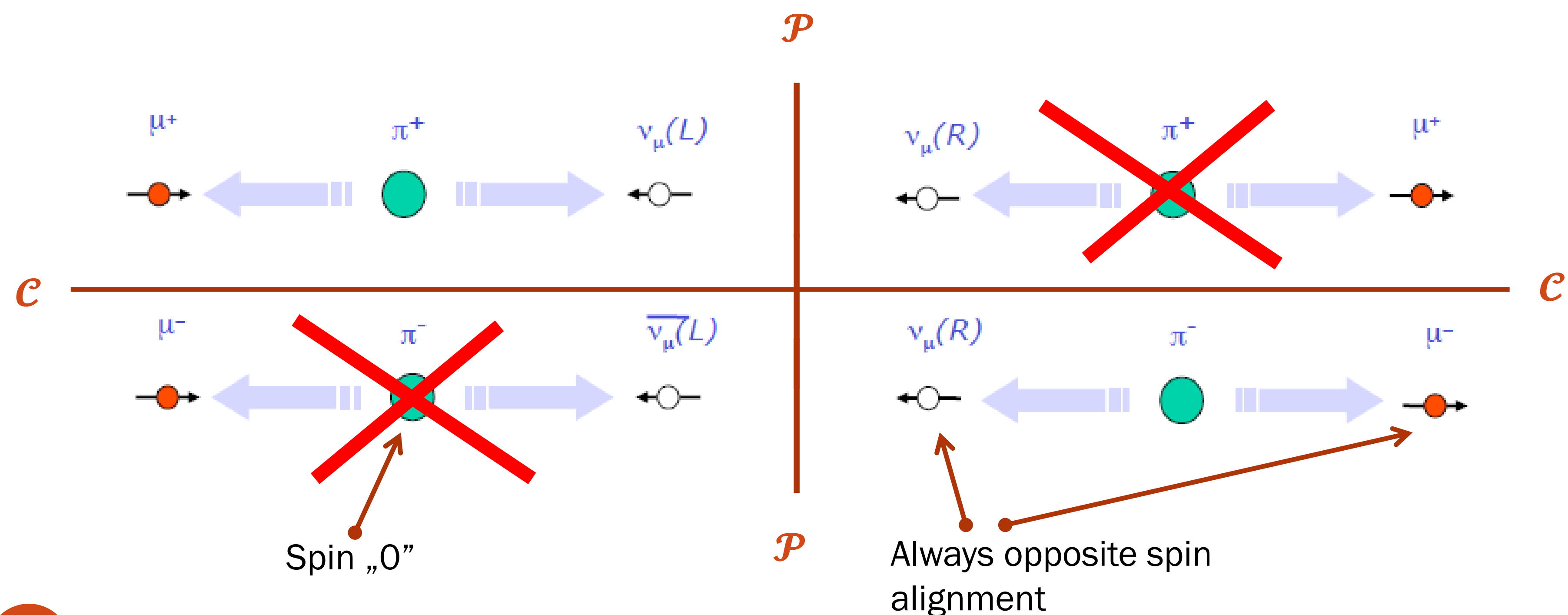
Introduction, i.e., the Big Picture

- Now, how this new „handedness" observable make things exciting?
- Lederman experiment: $\pi^+ \rightarrow \mu^+ + \nu_\mu$, $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
- Note! **Helicity of muon always the same as that for neutrino**



Introduction, i.e., the Big Picture

- Now, how this new „handedness" observable make things exciting?
- Lederman experiment: $\pi^+ \to \mu^+ + \nu_\mu$, $\pi^- \to \mu^- + \bar{\nu}_\mu$
- **Maximal (100%) violation of parity and charge conjugation!**
- **CP seems to be good symmetry (matter – anti-matter)**



A Small Detour – Parity Operator

- $\mathcal{P}$ – operator and its eigenstates
  - Two successive parity transformation leave a vector unchanged

$$\mathcal{P}\vec{r} \to -\vec{r}, \mathcal{P}(-\vec{r}) \to \vec{r}$$

  - this gives us:

$$\mathcal{P}\ \mathcal{P}|\alpha\rangle = \mathcal{P}^2|\alpha\rangle = +1|\alpha\rangle$$

  - this is known fact – parity operator eigenvalues can only be ± 1
- So, for any **parity invariant** Hamiltonian the following is true:

$$\boxed{\left[\mathcal{P}, \widehat{H}\right] = 0}$$

- If both operators **commute** the eigenstates of the Hamiltonian are also eigenstates of parity operator with eigenvalues of either $+1$ or -1
- Since wave function transforms under parity as follow: $\mathcal{P}\alpha(\vec{r}) = \alpha(-\vec{r})$, this implies that any stationary eigenstates of parity invariant Hamiltonian **have definite parity**!
- We call them **odd** and **even** states

Oscillations of Neutral Mesons

- We saw that the weak interactions **maximally violate** charge and space parities
- Also, there was a hint that the **combined symmetry** $\mathcal{CP}$ may be **exact** one
- Invariance under $\mathcal{CP}$ implies **matter – anti-matter symmetry**
- Ok, wait a moment… we know this is **not true**! Just look out in the night! The Universe is **dominated** by matter…
- So, $\mathcal{CP}$ cannot be the exact symmetry of the Universe! Are there any hints regarding **breaking the combined symmetry**?
- Let's have a look at $\theta - \tau$ puzzle again…

$$\theta^0 \to \pi^0 + \pi^0$$

$$\theta^0 \to \pi^+ + \pi^-$$

$$\tau^0 \to \pi^0 + \pi^0 + \pi^0$$

$$\tau^0 \to \pi^+ + \pi^- + \pi^0$$

What is the connection with neutral **Kaons**?

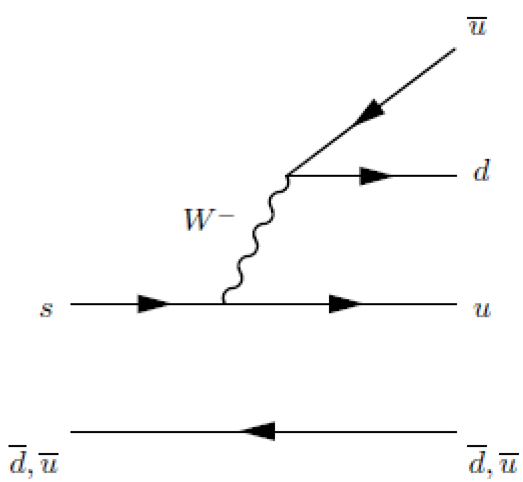
$$K^- + p = \bar{K}^0 + n$$

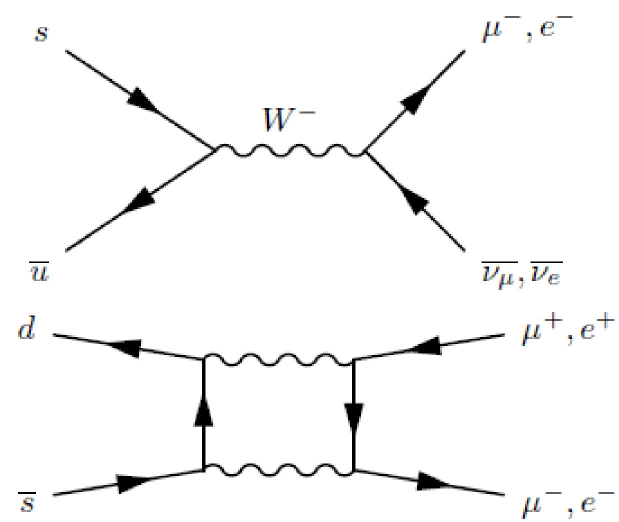
$$K^+ + n = K^0 + p$$

$$\pi^- + p = \Lambda^0 + K^0$$

Oscillations of Neutral Mesons

- The real questions here:
  - How (θ^0, τ^0) are related to $(K^0, \overline{K}^0)$?
  - Are K^0 different than $\overline{K}^0$?
- This is not trivial…
- Using purely hadronic and leptonic decays, we cannot distinguish them…



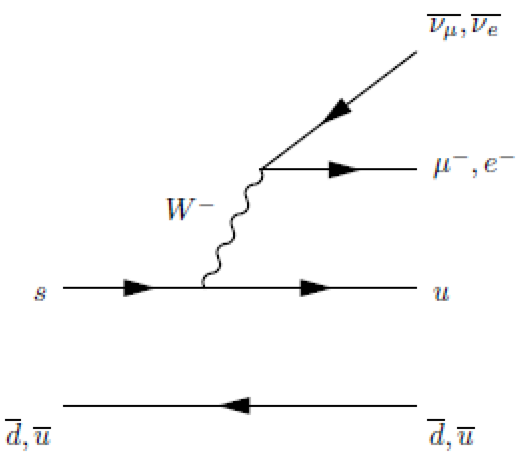


$$
\begin{array}{ccl}
K^+ & \rightarrow & \pi^+\pi^0,\ \pi^+\pi^-\pi^+,\ \pi^+\pi^0\pi^0 \\
K^- & \rightarrow & \pi^-\pi^0,\ \pi^-\pi^+\pi^-,\ \pi^-\pi^0\pi^0 \\
K^0 & \rightarrow & \pi^0\pi^0,\ \pi^0\pi^0\pi^0,\ \pi^+\pi^-,\ \pi^+\pi^-\pi^0 \\
\overline{K^0} & \rightarrow & \pi^0\pi^0,\ \pi^0\pi^0\pi^0,\ \pi^+\pi^-,\ \pi^+\pi^-\pi^0
\end{array}
$$

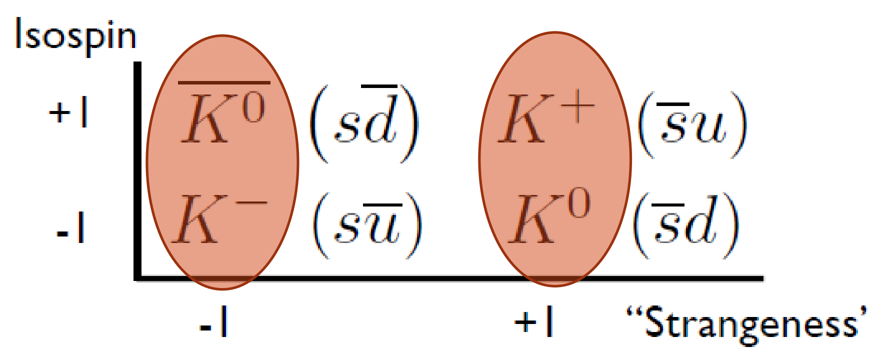
$$
\begin{array}{ccl}
K^+ & \rightarrow & \mu^+\nu_\mu,\ e^+\nu_e \\
K^- & \rightarrow & \mu^-\overline{\nu_\mu},\ e^-\overline{\nu_e} \\
K^0 & \rightarrow & \mu^-\mu^+,\ e^-e^+ \\
\overline{K^0} & \rightarrow & \mu^+\mu^-,\ e^+e^-
\end{array}
$$

Oscillations of Neutral Mesons

- The real questions here:
  - How (θ^0, τ^0) are related to $(K^0, \overline{K}^0)$?
  - Are K^0 different than $\overline{K}^0$?
- This is not trivial…
- Now, semileptonic…



$$
\begin{aligned}
K^+ &\rightarrow \pi^0\mu^+\nu_\mu,\ \pi^0 e^+\nu_e \\
K^- &\rightarrow \pi^0\mu^-\overline{\nu_\mu},\ \pi^0 e^-\overline{\nu_e} \\
K^0 &\rightarrow \pi^-\mu^+\nu_\mu,\ \pi^- e^+\nu_e \\
\overline{K^0} &\rightarrow \pi^+\mu^-\overline{\nu_\mu},\ \pi^+ e^-\overline{\nu_e}
\end{aligned}
$$



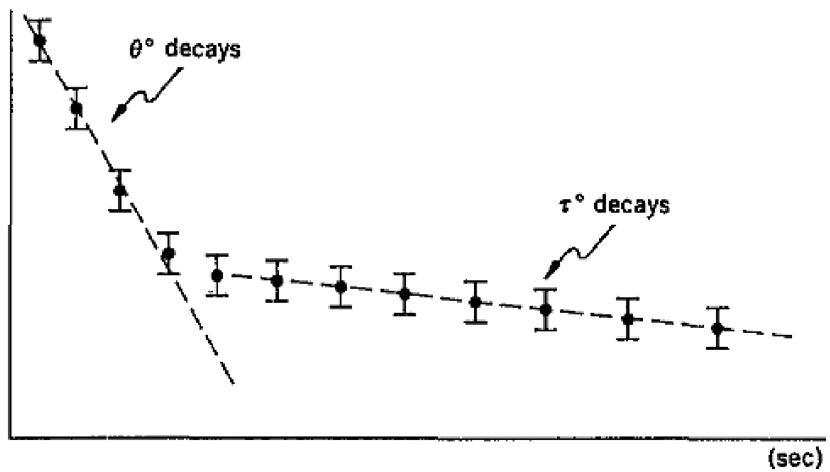
Oscillations of Neutral Mesons

- These neutral kaons are produced in the **strong** interactions with well **defined strangeness**, i.e., as eigenstates of the $\mathcal{S}$ operator

$$\mathcal{S}|K^0\rangle = +1|K^0\rangle, \mathcal{S}|\overline{K}^0\rangle = +1|\overline{K}^0\rangle$$

- Thus, K^0 is an antiparticle of $\overline{K}^0$ and they **can be tell apart** by the value of their strangeness!
- After production by the strong forces the kaons are unstable and decay – we can measure their lifetimes. Since they are antiparticles for each other we expect (the $\mathcal{CPT}$ theorem) that their **masses** and **lifetimes** are the same!
- **Instead a remarkable result**

decays



lifetime

Oscillations of Neutral Mesons

- Instead of **well defined** (single!) lifetime, as expected from a unique eigenstate of free-particle Hamiltonian, the **data** indicate **two distinct** lifetimes related to both K^0 and $\overline{K}^0$
- K^0 and $\overline{K}^0$ must be **superposition** of two distinct states with different lifetimes
- We call them K_1^0 (two pion channels) and K_2^0 (three pion channels)
- The results found for K^0 and $\overline{K}^0$ are then consistent in the sense that the lifetimes found for both their **components** K_1^0 and K_2^0 are **the same**!

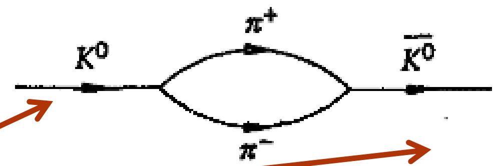
$$\tau_1 \approx 0.9 \times 10^{-10}\ s$$

$$\tau_2 \approx 5.0 \times 10^{-8}\ s$$

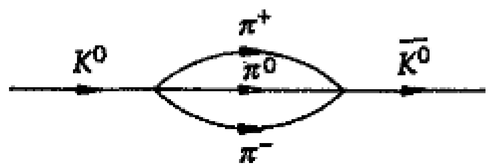
- One more thing, since K^0 and $\overline{K}^0$ share the same decay channels we say that they can **mix with each** other via higher order weak interactions
- Although they are produced as unique states (different S) they propagate in time as a mixture of states (the same decay channels)

Oscillations of Neutral Mesons

- To be more precise: K^0 and $\overline{K}^0$ are produced as orthogonal states
- This orthogonality is then broken by the weak interactions and the transition $K^0 \leftrightarrow \overline{K}^0$ is possible – the weak interaction do not conserve strangeness



Kaons can mix!
Fantastic property!



- K^0 and $\overline{K}^0$ are the eigenstates of the **strong** hamiltonian but **cannot be** the eigenstates of the **weak** interactions!

$$\langle K^0|\overline{K}^0\rangle = 0 \ \rightarrow \langle K^0|H_{Strong}|\overline{K}^0\rangle = 0$$

$$H_{Strong}|K^0\rangle = m_{K^0}|K^0\rangle \qquad H_{Strong}|\overline{K}^0\rangle = m_{\overline{K}^0}|\overline{K}^0\rangle$$

$$m_{K^0} = m_{\overline{K}^0} \approx 498\ MeV$$

Oscillations of Neutral Mesons

- For the weak interactions we have then

$$\boxed{\langle K^0 | H_{Weak} | \overline{K}^0 \rangle \neq 0}$$

- Kaons decay in weak processes, given that K_1^0 and K_2^0 have unique lifetimes we can treat them as **eigenstates** of H_{Weak}
- Now quantum physics starts twist our brains… Since we used the picture where K^0 and $\overline{K}^0$ are a **mixture** of K_1^0 and K_2^0 to explain the weird lifetime data now we can say that K_1^0 and K_2^0 are **mixture** of K^0 and $\overline{K}^0$ - this makes description of the **mass** states much nicer!
- Just follow to the next slide…

Neutral Mesons and CP

- Let's start with the assumption that $\mathcal{CP}$ is a good symmetry of the weak interactions
- Kaons are pseudo-scalars, thus, have odd intrinsic parities

$$\mathcal{CP}|K^0\rangle = -\mathcal{C}|K^0\rangle = -|\bar{K}^0\rangle$$

$$\mathcal{CP}|\bar{K}^0\rangle = -\mathcal{C}|\bar{K}^0\rangle = -|K^0\rangle$$

- Can use appropriate linear orthonormal combinations that are eigenstates of $\mathcal{CP}$ operator

$$|K_1^0\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle)$$

$$|K_2^0\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle)$$

$$\mathcal{CP}|K_1^0\rangle = \frac{1}{\sqrt{2}}(\mathcal{CP}|K^0\rangle - \mathcal{CP}|\bar{K}^0\rangle) = \frac{1}{\sqrt{2}}(-|\bar{K}^0\rangle + |K^0\rangle) = \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle) = |K_1^0\rangle$$

$$\mathcal{CP}|K_2^0\rangle = \cdots = -|K_2^0\rangle$$

Neutral Mesons and CP

- Now, K_1^0 and K_2^0 can be regarded as **eigenstates of $\mathcal{CP}$** with even and odd eigenvalues respectively
- One extraordinary thing – **cannot** define **unique strangeness** of these states!
- Now can identify them as

$$\boxed{\theta^0 = K_1^0 \rightarrow \pi^0 + \pi^0}$$

$$\boxed{\tau^0 = K_2^0 \rightarrow \pi^0 + \pi^0 + \pi^0}$$

- Since the phase space (density of states) for two body decay is much larger than for three body one
- The rate of decay for K_1^0 should be much larger than for K_2^0
- Or in other words - K_1^0 lifetime should be much shorter than for K_2^0
- This is what the experiment showed us. Great!

Flavour (strangeness) oscillation

- Strong interaction gives us kaons with **definite** strangeness, we write down the following:

$$|K^0\rangle = \frac{1}{\sqrt{2}}\left(|K_1^0\rangle + |K_2^0\rangle\right)$$

$$|\overline{K}^0\rangle = -\frac{1}{\sqrt{2}}\left(|K_1^0\rangle - |K_2^0\rangle\right)$$

- Kaons are **produced** as eigenstates of **strong Hamiltonian** (mixture of weak Hamiltonian states) but **propagate** through time as eigenstates of **weak one**
- In time both components of strong states **decay away** and after a sufficient amount of time we are going to have only $|K_2^0\rangle$ component
- However, since $|K_2^0\rangle$ is a mixture of $|K^0\rangle$ and $|\overline{K}^0\rangle$ states, even starting from pure $|K^0\rangle$ (or $|\overline{K}^0\rangle$) state we end up with a mixture of states of different strangeness
- This phenomenon is called **flavour oscillation**

Flavour (strangeness) oscillation

- This effect can be measured! Just need to put the anti-kaons in some medium and observe them interacting strongly with it (because strong interaction preserve strangeness!)

$$\bar{K}^0 + p \rightarrow \Sigma^+ + \pi^+ + \pi^-$$

$$\bar{K}^0 + p \rightarrow \Lambda^0 + \pi^+ + \pi^0$$

$$K^0 + p \not\rightarrow \Sigma^+ + \pi^+ + \pi^-$$

$$K^0 + p \not\rightarrow \Lambda^0 + \pi^+ + \pi^0$$

- Detecting hiperons is a proof of $\bar{K}^0$ presence!
- Similar oscillation effects for beauty and charm mesons!

Next time...

- Discovering CP-violation
- Framework to the quantitative description of CPV
- CKM matrix – flavour and mass states