

CP Violation in τ decay

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Outline

- Introduction : τ physics at Belle II
- Puzzle in CP violation in τ decay
- Future Prospect of CP violation measurement
- Conclusions

Introduction

Introduction: τ physics at Belle II

- τ physics is very active research in Belle II!
- Many studies have been done for LFV measurement (e.g. $\tau \rightarrow \mu\mu\mu$, $\tau \rightarrow \mu h$ etc) with early data
- Many analysis on-going on hadronic decays, $\tau \rightarrow 3\pi\nu$ (spectrum measurement), $\tau \rightarrow K\pi\nu$ (V_{us} , CPV measurement) etc...
- More to be done e.g. inclusive measurements (done only at LEP), $\tau \rightarrow 2\pi\nu$ for $g-2$ (the previous Belle analysis is $<100 \text{ fb}^{-1}$ data), heavy neutrino search etc...



*Belle II Physics Week 2024
One of the focus was tau!*

Introduction: τ physics at Belle II

Challenges for hadronic decay measurements

- Both signal/tag sides do NOT make any peak (except for LFV)!
- Channels including π^0 is particularly difficult
- Potentially a large cross-feeds (e.g. background from Cabibbo allowed channels to Cabibbo suppressed channels)
- Still ALEPH result dominates most of the measurements
- MC study very important: **France-Ukraine(-Poland)** collaboration (Krakow=developer of TAUOLA)

Introduction: CP Violation in hadronic tau decays

Belle II Physics Book '18

CP violation : Golden Channel for Belle II Physics!

- Direct CP Violation: non-zero only when two amplitudes have different CP violating and CP conserving (strong) phases
- Triple product: non-zero as long as two amplitudes have different CP violating phase (still you need to measure the difference between tau+ and tau-).

$$\mathcal{A}_\tau = \frac{\Gamma(\tau^+ \rightarrow \pi^+ K_S^0 \bar{\nu}_\tau) - \Gamma(\tau^- \rightarrow \pi^- K_S^0 \nu_\tau)}{\Gamma(\tau^+ \rightarrow \pi^+ K_S^0 \bar{\nu}_\tau) + \Gamma(\tau^- \rightarrow \pi^- K_S^0 \nu_\tau)}$$

$$\mathcal{A}_\tau^{\text{SM}} \simeq 2\text{Re}(\epsilon) \simeq (0.36 \pm 0.01)\% \quad \text{Kaon mixing produces CPV}$$

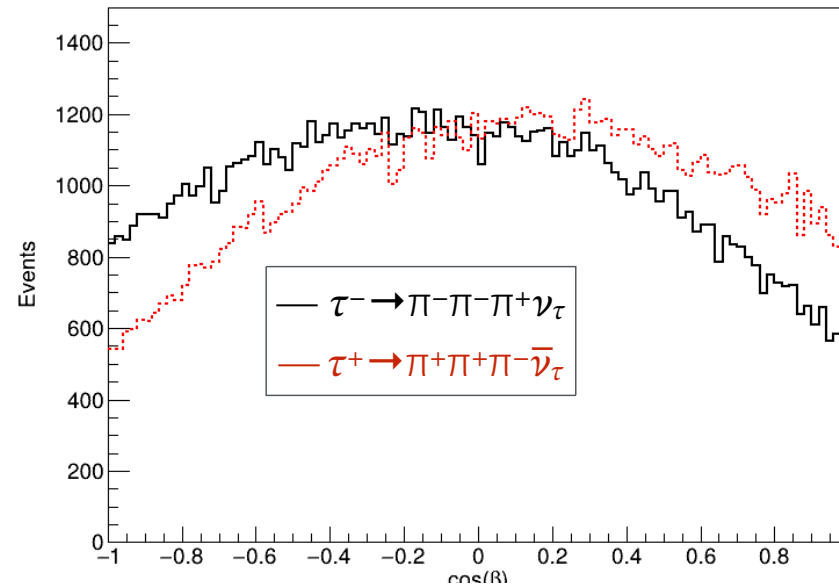
$$\mathcal{A}_\tau = (-0.36 \pm 0.23 \pm 0.11)\% ,$$

Babar measurement 2.8 sigma away...

Puzzle of τ^+ and τ^- asymmetry

Puzzle of τ^+ and τ^- asymmetry

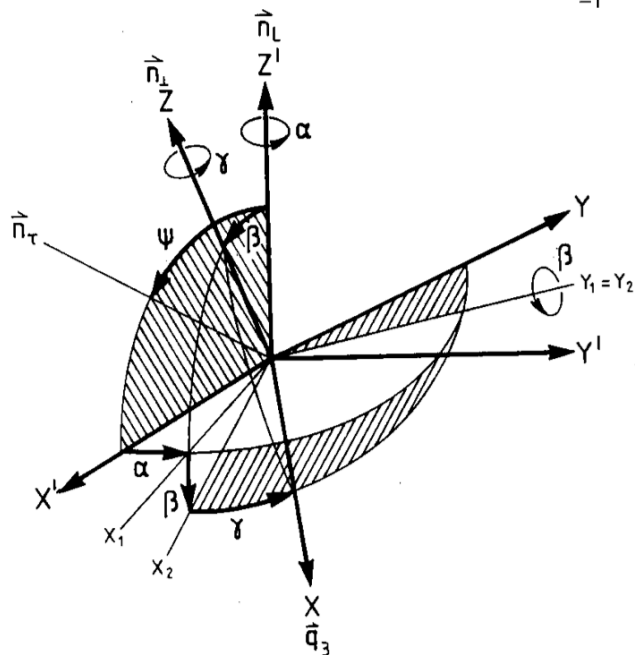
$\tau \rightarrow \pi\pi\pi\nu\tau$ decay in Tauola MC generator



Paper in preparation with
Z. Was (IFJ PAN)

Is this CP Violation?!
(No! CP phase in SM for leptons)

*If not, how can we measure
the “true” CP Violation?*



$\cos\beta$

$$\cos\beta = \vec{n}_L \cdot \vec{n}_\perp$$

$$\cos\gamma = -\frac{\vec{n}_L \cdot \hat{q}_3}{|\vec{n}_L \times \vec{n}_\perp|}$$

$$\sin\gamma = \frac{(\vec{n}_L \times \vec{n}_\perp) \cdot \hat{q}_3}{|\vec{n}_L \times \vec{n}_\perp|}$$

@ hadronic rest frame

✓ n_L : direction of the lab frame

✓ $n_\perp$: direction normal to the
hadronic decay plane

✓ q_3 : direction of a hadron

Puzzle of τ^+ and τ^- asymmetry

Very naively, CP violation should be non-zero A_{CP}

$$A_{CP} = \frac{\bar{\Gamma}(\tau^+ \rightarrow h^+ \bar{\nu}_\tau) - \Gamma(\tau^- \rightarrow h^- \nu_\tau)}{\bar{\Gamma}(\tau^+ \rightarrow h^+ \bar{\nu}_\tau) + \Gamma(\tau^- \rightarrow h^- \nu_\tau)}$$

$$\Gamma(\tau^- \rightarrow h^- \nu_\tau) \propto \mathcal{M}^- \mathcal{M}^{-\dagger}$$

$$\bar{\Gamma}(\tau^+ \rightarrow h^+ \bar{\nu}_\tau) \propto \mathcal{M}^+ \mathcal{M}^{+\dagger}$$

Is CP conservation $(\mathcal{M}^-)^{\text{CP}} = \mathcal{M}^+$?

Hadronic Decays: $\tau^\pm \rightarrow h^\pm \nu_\tau$

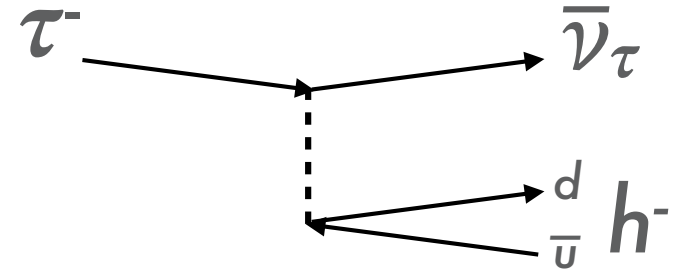
$h = \pi, \pi\pi, \pi\pi\pi, K, K\pi, K\pi\pi, KK, KK\pi, \dots$

Amplitude

$$\mathcal{M}^- = g_v \bar{u}(p_\nu) \gamma_\mu (1 + \gamma_{AV} \gamma_5) u(p_\tau) J^\mu$$

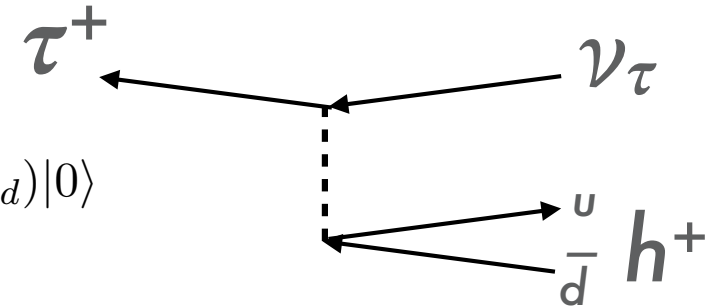
$$\mathcal{M}^+ = g_v \bar{v}(p_\tau) \gamma_\mu (1 + \gamma_{AV} \gamma_5) v(p_\nu) J^\mu$$

$$\gamma_{AV} = g_A/g_V \text{ (in SM it is -1)}$$



Hadronic currents

$$J^\mu = \langle h^- | \bar{u}(p_d) \gamma^\mu (1 - \gamma_5) v(p_u) | 0 \rangle = \langle h^+ | \bar{u}(p_u) \gamma^\mu (1 - \gamma_5) v(p_d) | 0 \rangle$$



Squared amplitude

$$\mathcal{M}^- \mathcal{M}^{-\dagger}$$

$$= 2g_v^2 [(1 + \gamma_{AV}^2) \{p_{\tau\mu}, p_{\nu\nu}\} + 2\gamma_{AV} m_\tau \{p_{\nu\mu}, s_\nu\} - 2i\gamma_{AV} \epsilon_{\alpha\beta\mu\nu} p_{\nu\alpha} p_{\tau\beta} + i(1 + \gamma_{AV}^2) m_\tau \epsilon_{\alpha\beta\mu\nu} s_\alpha p_{\nu\beta}] J^\mu J^{\nu\dagger}$$

$$\mathcal{M}^+ \mathcal{M}^{+\dagger}$$

$$= 2g_v^2 [(1 + \gamma_{AV}^2) \{p_{\tau\mu}, p_{\nu\nu}\} - 2\gamma_{AV} m_\tau \{p_{\nu\mu}, s_\nu\} + 2i\gamma_{AV} \epsilon_{\alpha\beta\mu\nu} p_{\nu\alpha} p_{\tau\beta} + i(1 + \gamma_{AV}^2) m_\tau \epsilon_{\alpha\beta\mu\nu} s_\alpha p_{\nu\beta}] J^\mu J^{\nu\dagger}$$

Hadronic Decays: $\tau^\pm \rightarrow h^\pm \nu_\tau$

$h = \pi, \pi\pi, \pi\pi\pi, K, K\pi, K\pi\pi, KK, KK\pi, \dots$

Amplitude

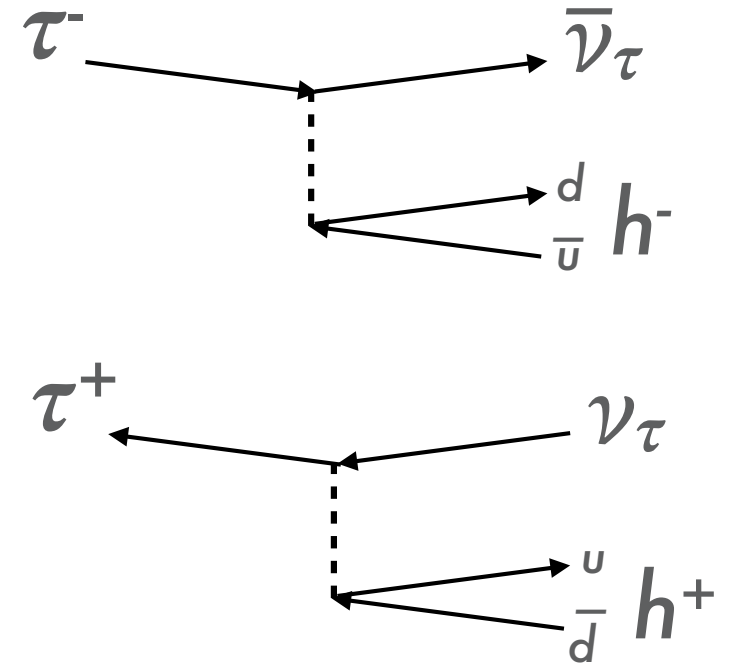
$$\mathcal{M}^- = g_v \bar{u}(p_\nu) \gamma_\mu (1 + \gamma_{AV} \gamma_5) u(p_\tau) J^\mu$$

$$\mathcal{M}^+ = g_v \bar{v}(p_\tau) \gamma_\mu (1 + \gamma_{AV} \gamma_5) v(p_\nu) J^\mu$$

$$\gamma_{AV} = g_A/g_V \text{ (in SM it is -1)}$$

u : particle

v : anti-particle



Let's take CP transformation to the M^- amplitude

CP transformation

P transformation:

$$\bar{\psi}_1 \gamma^\mu (1 - \gamma^5) \psi_2 \longrightarrow \bar{\psi}_1 \gamma^\mu (1 + \gamma^5) \psi_1 \Big|_{p \rightarrow \hat{p}} \quad \hat{p} = (p_0, -\vec{p})$$

C transformation:

$$\bar{\psi}_1 \gamma^\mu (1 - \gamma^5) \psi_2 \longrightarrow -\bar{\psi}_2 \gamma^\mu (1 + \gamma^5) \psi_1$$

$$\psi(x) = \int \frac{d^3 \vec{p}}{(2\pi)^{\frac{3}{2}}} \sqrt{\frac{m}{E}} \sum_{s=\pm} \left[b(\vec{p}, s) u(\vec{p}, s) e^{-ipx} + d^\dagger(\vec{p}, s) v(\vec{p}, s) e^{+ipx} \right]$$

$$\bar{\psi}(x) = \int \frac{d^3 \vec{p}}{(2\pi)^{\frac{3}{2}}} \sqrt{\frac{m}{E}} \sum_{s=\pm} \left[b^\dagger(\vec{p}, s) \bar{u}(\vec{p}, s) e^{-ipx} + d(\vec{p}, s) \bar{v}(\vec{p}, s) e^{+ipx} \right]$$

$b^\dagger(d^\dagger)$ is the creation operator for (anti-)particle

$b(d)$ is the annihilation operator for (anti-)particle

CP transformation

(Anti-)particle Projection

$$\begin{aligned}\Lambda^+ \psi &= u, & \bar{\psi} \Lambda^+ &= \bar{u} \\ \Lambda^- \psi &= v, & \bar{\psi} \Lambda^- &= \bar{v}\end{aligned}\quad \Lambda^\pm = (\not{p} \pm m)$$

Spin Projection

$$\mathcal{P}^+ = u(p_\tau) \bar{u}(p_\tau) = \frac{1}{2}(\not{p}_\tau + m_\tau)(1 + \gamma_5 \not{s})$$

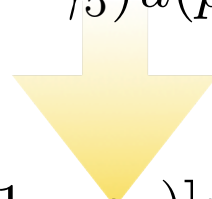
Amplitude

$$\mathcal{M}^- = g_v V_{ud}^* \bar{\psi}_\nu [\Lambda^+ \gamma_\mu (1 - \gamma_5) \mathcal{P}^+ \Lambda^+] \psi_\tau J^\mu$$

$$J^\mu = \langle h^- | \bar{\psi}_d [\Lambda^+ \gamma^\mu (1 - \gamma_5) \Lambda^-] \psi_u | 0 \rangle$$

Amplitude

$$\mathcal{M}^- = g_v V_{ud}^* \bar{u}(p_\nu) \gamma_\mu (1 - \gamma_5) u(p_\tau) \langle h^- | \bar{u}_d \gamma^\mu (1 - \gamma_5) v_u | 0 \rangle$$



$$(\mathcal{M}^-)^{CP} = g_v V_{ud}^* \bar{v}_\tau [\mathcal{P}^+ \gamma^\mu (1 - \gamma_5)] v_\nu \langle h^+ | \bar{u}_u [\gamma_\mu (1 - \gamma_5)] v_d | 0 \rangle \Big|_{p \rightarrow \hat{p}}$$

CP transformation

CP transformation

$$\mathcal{M}^- = g_v V_{ud}^* \bar{u}(p_\nu) \gamma_\mu (1 - \gamma_5) u(p_\tau) \langle h^- | \bar{u}_d \gamma^\mu (1 - \gamma_5) v_u | 0 \rangle$$



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$$(\mathcal{M}^-)^{CP} = \mathcal{M}^+ \Big|_{p \rightarrow \hat{p}, V_{ud} \rightarrow V_{ud}^*}$$

Hadronic Decays: $\tau^\pm \rightarrow h^\pm \nu_\tau$

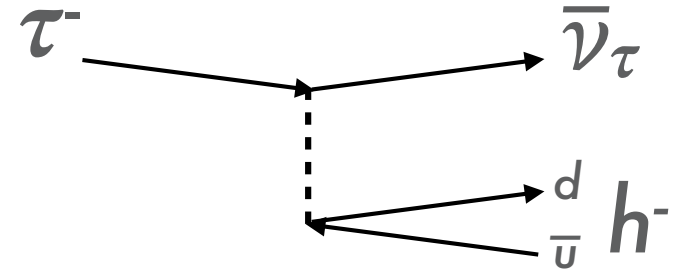
$h = \pi, \pi\pi, \pi\pi\pi, K, K\pi, K\pi\pi, KK, KK\pi, \dots$

Amplitude

$$\mathcal{M}^- = g_v \bar{u}(p_\nu) \gamma_\mu (1 + \gamma_{AV} \gamma_5) u(p_\tau) J^\mu$$

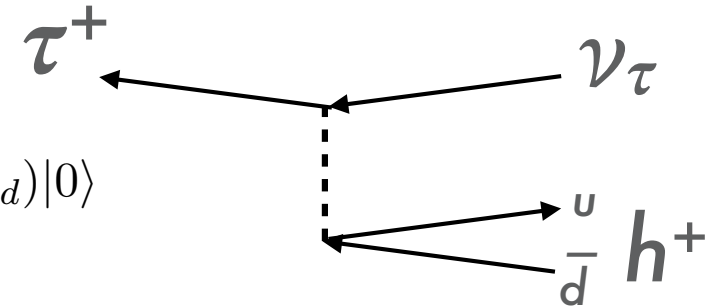
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Squared amplitude

$$\mathcal{M}^- \mathcal{M}^{-\dagger}$$

$$= 2g_v^2 [(1 + \gamma_{AV}^2) \{p_{\tau\mu}, p_{\nu\nu}\} + 2\gamma_{AV} m_\tau \{p_{\nu\mu}, s_\nu\} - 2i\gamma_{AV} \epsilon_{\alpha\beta\mu\nu} p_{\nu\alpha} p_{\tau\beta} + i(1 + \gamma_{AV}^2) m_\tau \epsilon_{\alpha\beta\mu\nu} s_\alpha p_{\nu\beta}] J^\mu J^{\nu\dagger}$$

$$\mathcal{M}^+ \mathcal{M}^{+\dagger}$$

$$= 2g_v^2 [(1 + \gamma_{AV}^2) \{p_{\tau\mu}, p_{\nu\nu}\} - 2\gamma_{AV} m_\tau \{p_{\nu\mu}, s_\nu\} + 2i\gamma_{AV} \epsilon_{\alpha\beta\mu\nu} p_{\nu\alpha} p_{\tau\beta} + i(1 + \gamma_{AV}^2) m_\tau \epsilon_{\alpha\beta\mu\nu} s_\alpha p_{\nu\beta}] J^\mu J^{\nu\dagger}$$

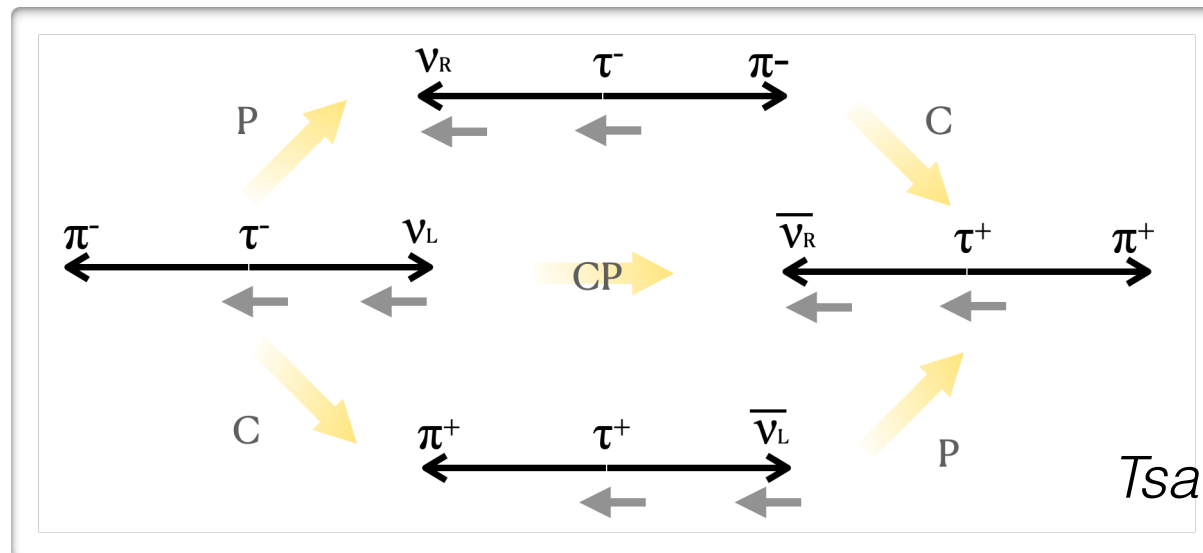
Hadronic Decays: $\tau^\pm \rightarrow \pi^\pm \nu_\tau$

$$\mathcal{M}^- \mathcal{M}^{-\dagger} = 16g_v^2 f_\pi^2 m_\tau |p|^3 \left(1 + \frac{\vec{s} \cdot \vec{p}_\pi}{|p|} \right)$$

$$\mathcal{M}^+ \mathcal{M}^{+\dagger} = 16g_v^2 f_\pi^2 m_\tau |p|^3 \left(1 - \frac{\vec{s} \cdot \vec{p}_\pi}{|p|} \right)$$

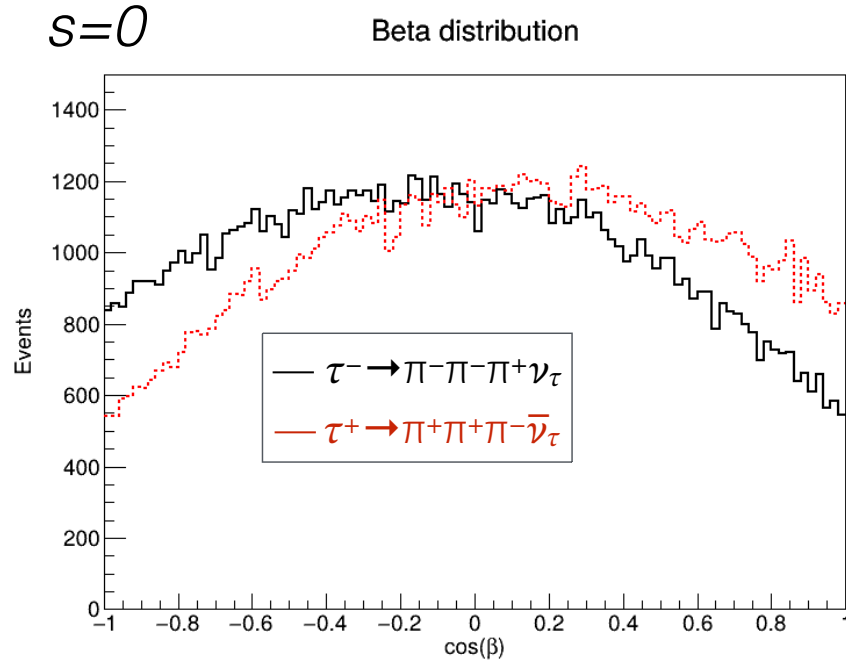
CP Conservation!

$$\mathcal{M}^- \mathcal{M}^{-\dagger} = \mathcal{M}^+ \mathcal{M}^{+\dagger} \Big|_{p \rightarrow \hat{p}, V_{ud} \rightarrow V_{ud}^*}$$



Tsai's argument

Hadronic Decays: $\tau^\pm \rightarrow \pi^\mp \pi^\pm \pi^\pm \nu_\tau$



$$\begin{aligned} \mathcal{M}^- \mathcal{M}^{-\dagger} &\propto i\gamma_{AV} \epsilon_{\alpha\beta\mu\nu} p_{\nu\alpha} p_{\tau\beta} J^\mu J^{*\nu} \\ &= -\gamma_{AV}(Q)_0 \left(\vec{p}_\tau \cdot \text{Im}(\vec{J} \times \vec{J}^*) \right)_z \end{aligned}$$

$$\begin{aligned} \mathcal{M}^+ \mathcal{M}^{+\dagger} &\propto -i\gamma_{AV} \epsilon_{\alpha\beta\mu\nu} p_{\nu\alpha} p_{\tau\beta} J^\mu J^{*\nu} \\ &= +\gamma_{AV}(Q)_0 \left(\vec{p}_\tau \cdot \text{Im}(\vec{J} \times \vec{J}^*) \right)_z \end{aligned}$$

$$\cos \beta = n_L \cdot \frac{p_1 \times p_2}{|p_1 \times p_2|}$$

$P_{1,2} : \pi \text{ momentum}$

T odd triple product: it requires imaginary part to be non-zero

New physics search with CP Violation

$$\begin{aligned}\mathcal{M}^- &= g_v \bar{u}(p_\nu) \gamma_\mu (1 - \gamma_5) u(p_\tau) J^\mu + \eta_P \bar{u}(p_\nu) (1 + \gamma_5) u(p_\tau) J' \\ \mathcal{M}^+ &= g_v \bar{v}(p_\tau) \gamma_\mu (1 - \gamma_5) v(p_\nu) J^\mu + \eta_P^* \bar{v}(p_\tau) (1 - \gamma_5) v(p_\nu) \hat{J}'\end{aligned}$$

Interference term

$$\mathcal{M}_1^- \mathcal{M}_2^{-\dagger} + \mathcal{M}_2^- \mathcal{M}_1^{-\dagger}$$

E.K. and A Korchin, preliminary

$$= \text{Re} \left\{ 4g_v \eta_P [m(p_\nu \cdot J^\dagger) + (s \cdot p_\nu)(p_\tau \cdot J^\dagger) - (p_\nu \cdot p_\tau)(s \cdot J^\dagger) + i\epsilon_{\alpha\beta\nu\mu} s^\alpha p_\nu^\beta p_\tau^\nu J^{\mu\dagger}] J' \right\}$$

$$\mathcal{M}_1^- \mathcal{M}_2^{-\dagger} + \mathcal{M}_2^- \mathcal{M}_1^{-\dagger} \Big|_{\text{CP}}$$

$$J' = -\hat{J}'$$

$$= \text{Re} \left\{ 4g_v \eta_P^* [-m(p_\nu \cdot J^\dagger) + (s \cdot p_\nu)(p_\tau \cdot J^\dagger) - (p_\nu \cdot p_\tau)(s \cdot J^\dagger) - i\epsilon_{\alpha\beta\nu\mu} s^\alpha p_\nu^\beta p_\tau^\nu J^{\mu\dagger}] \hat{J}' \right\}$$

difference

$$= 8g_v m \text{Im}[\eta_P^*] \times \text{Im}[(p_\nu \cdot J^\dagger) J']$$

~~CP~~

$$= 8g_v \text{Re}[\eta_P^*] \times \text{Re}[(s \cdot p_\nu)(p_\tau \cdot J^\dagger) J']$$

CP

$$= 8g_v \text{Re}[\eta_P^*] \times \text{Re}[-(p_\nu \cdot p_\tau)(s \cdot J^\dagger) J']$$

CP

$$= 8g_v m \text{Im}[\eta_P^*] \times \text{Im}[(p_\nu \cdot J^\dagger) J']$$

~~CP~~

Conclusions

- Differential decay rates for τ^+ and τ^- are different even if CP is conserved.
- It disappears with flipping the sign of 3-momentum
- New physics can break CP in tau decay. We look for a specific differential decay rate to distinguish the CPV and CPC contributions.