Student Seminar - HUGS 2016: CP Violation in $\tau^{\pm} \to K^{\pm}\pi^{+}\pi^{-}\nu_{\tau}$

Marco Antonio Carrillo Bernal

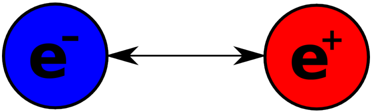
Faculty of Physics, UV Dr. Carlos Vargas

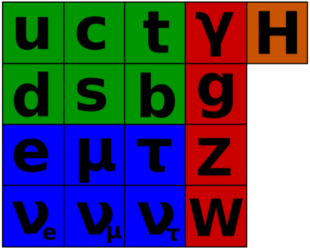
Institute of Physics, UNAM Dr. Genaro Toledo

June 16, 2016

Matter and antimatter

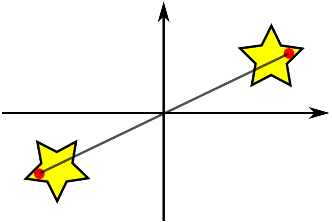
The quantity of matter in our Universe exceeds the quantity of antimatter in our Universe.





The breaking of CP symmetry shows that the physics of particles and antiparticles is not the same.

Parity and Charge Conjugation



$$P^2 = I \Rightarrow P = \pm 1$$

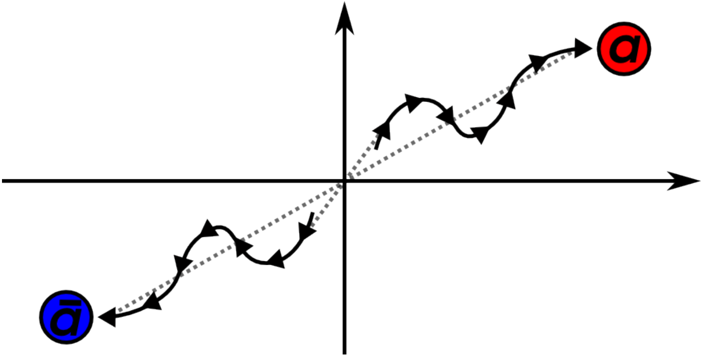
Vector	$P(\mathbf{v}) = -\mathbf{v}$
Axial vector	$P(\mathbf{a}) = \mathbf{a}$
Scalar	$P(s) = s$
Pseudoscalar	$P(p) = -p$

$$C|a\rangle = \pm|\bar{a}\rangle \Rightarrow C^2 = I$$

Particle	C
$\gamma \to \gamma$	-1
$\pi^0 \to \pi^0$	$+1$
$K^0 \to \bar{K}^0$	$e^{i\xi}$

D. Griffiths, Introduction to Elementary Particle Physics (2014).

CP transformation

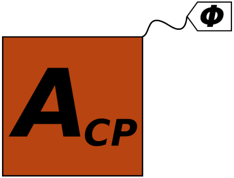


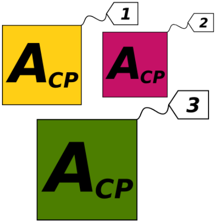
CP	$P=+1$	$P=-1$
$C=+1$	$+1$	-1
$C=-1$	-1	$+1$

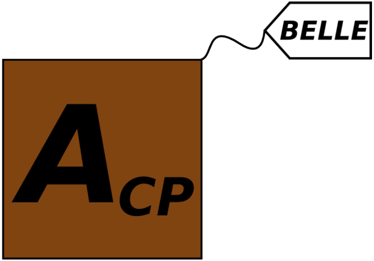
D. Griffiths, Introduction to Elementary Particle Physics (2014).

A small number in the Standard Model

Within the SM, CP Violation arises from a complex phase $e^{i\phi}$ in the CKM Matrix. The CP Asymmetry ($\mathcal{A}_{CP}$) quantifies the difference between a physical process and its CP-conjugated image.

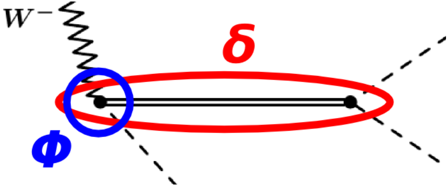






Odd and Even CP phases

$$M(P \to f) = M_1 + M_2 = |M_1|e^{i(\delta_1+\phi_1)} + |M_2|e^{i(\delta_2+\phi_2)}$$

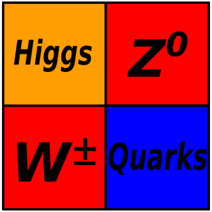


Even or strong $\mathbf{e^{i\delta}}$:
Do not change of sign under *CP* and arise from the intermediate states of a decay.

Odd or weak $\mathbf{e^{i\phi}}$:
Change of sign under *CP* and arise from the weak couplings with $W^{\pm}$.

Bigi y Sanda, CP Violation (2009), PDG, Review of Particle Physics, Chin. Phys. C 38 090001 (2014).

The CKM Matrix



$$\mathcal{L}_Y = \frac{-g_W}{\sqrt{2}}(\bar{u},\bar{c},\bar{t})_L \gamma^{\mu} W^{\pm}_{\mu} V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L + \dots$$

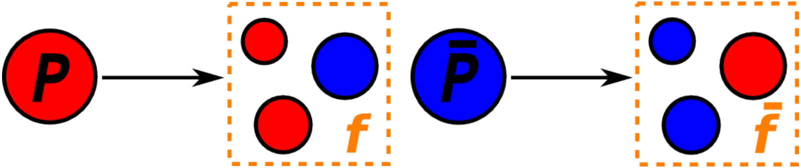
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$V_{uj}V^{*}_{uk} + V_{cj}V^{*}_{ck} + V_{tj}V^{*}_{tk} = \delta_{jk}$$
$$V_{jd}V^{*}_{kd} + V_{js}V^{*}_{ks} + V_{jb}V^{*}_{kb} = \delta_{jk}$$

PDG, Review of Particle Physics, Chin. Phys. C 38 090001 (2014).

CP asymmetry in a decay

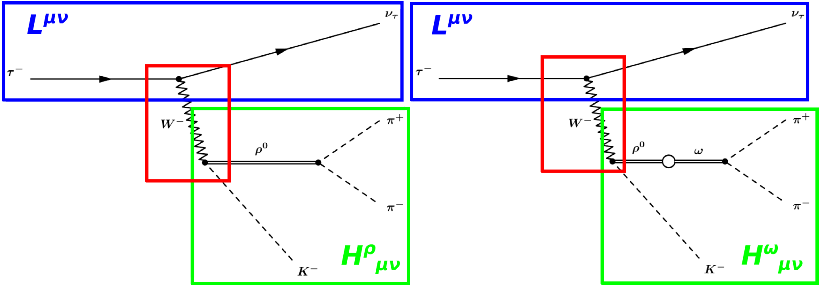
$$M(P \to f) = |M_1| e^{i(\delta_1 + \phi_1)} + |M_2| e^{i(\delta_2 + \phi_2)}$$
$$\bar{M}(\bar{P} \to \bar{f}) = |M_1| e^{i(\delta_1 - \phi_1)} + |M_2| e^{i(\delta_2 - \phi_2)}$$



$$\mathcal{A}_{CP} \equiv \frac{\Gamma(\bar{P} \to \bar{f}) - \Gamma(P \to f)}{\Gamma(\bar{P} \to \bar{f}) + \Gamma(P \to f)} = \frac{|\bar{M}|^2 - |M|^2}{|\bar{M}|^2 + |M|^2}$$
$$= \frac{-2|M_1 M_2| \sin(\delta_2 - \delta_1) \sin(\phi_2 - \phi_1)}{|M_1|^2 + |M_2|^2 + 2|M_1 M_2| \cos(\delta_2 - \delta_1) \cos(\phi_2 - \phi_1)}$$

Bigi y Sanda, CP Violation (2009), PDG, Review of Particle Physics, Chin. Phys. C 38 090001 (2014).

$\tau^{-} \to K^{-}\rho^{0}(\omega)\nu_{\tau} \to K^{-}\pi^{+}\pi^{-}\nu_{\tau}$



$\tau^{-} \to K^{-}\rho^{0}\nu_{\tau} \to K^{-}\pi^{+}\pi^{-}\nu_{\tau}$

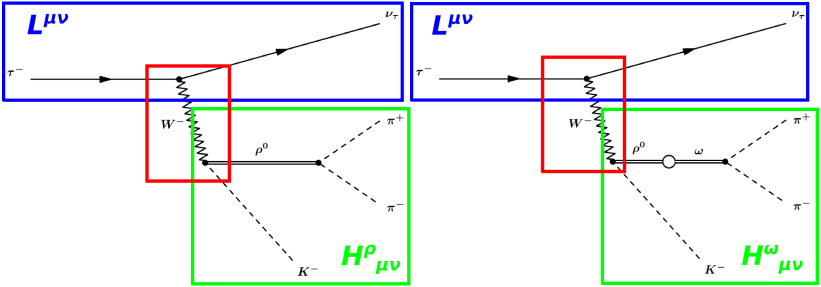
Invariant mass of $\pi^{+}\pi^{-}$ close to the ρ^{0} resonance, $\sqrt{s} \sim m_{\rho}$.

$\tau^{-} \to K^{-}(\rho^{0} - \omega)\nu_{\tau} \to K^{-}\pi^{+}\pi^{-}\nu_{\tau}$

Invariant mass of $\pi^{+}\pi^{-}$ close to the ω resonance, $\sqrt{s} \sim m_{\omega}$.

Chao Wang *et al*, Eur. Phys. J. C 74 (2014) 3140

$\tau^- \to K^-\rho^0(\omega)\nu_\tau \to K^-\pi^+\pi^-\nu_\tau$

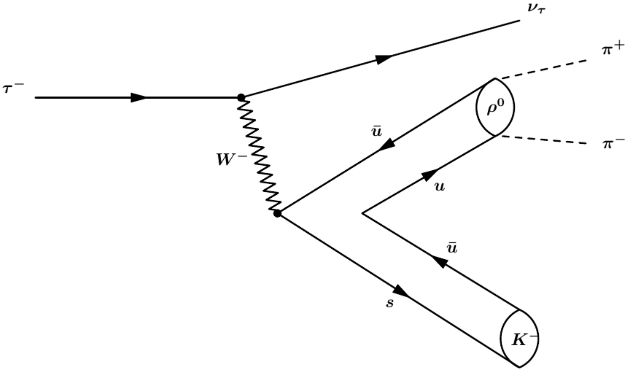


$$M_\rho = \frac{G_F}{\sqrt{2}} g_{\rho\pi\pi} s_\rho L^\mu H^\rho_\mu \qquad M_{\rho-\omega} = \frac{G_F}{\sqrt{2}} g_{\rho\pi\pi} s_\omega \tilde{\Pi}(s) L^\mu H^\omega_\mu$$

Chao Wang *et al*, Eur. Phys. J. C 74 (2014) 3140

Leading order in G_F

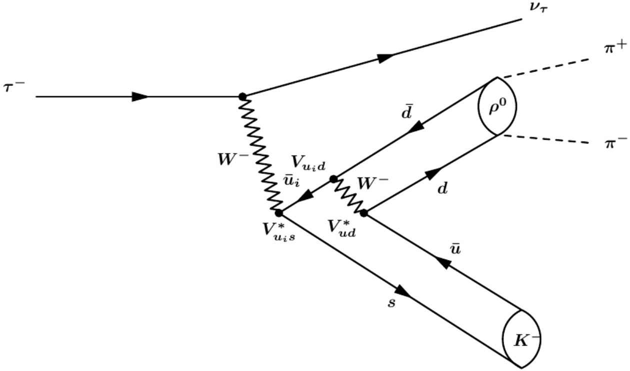
$M_0 \propto G_F, \qquad |M_0|^2 \propto |V_{us}|^2$



No weak CP phase $\Rightarrow$ No CP violation

Second order in G_F (1)

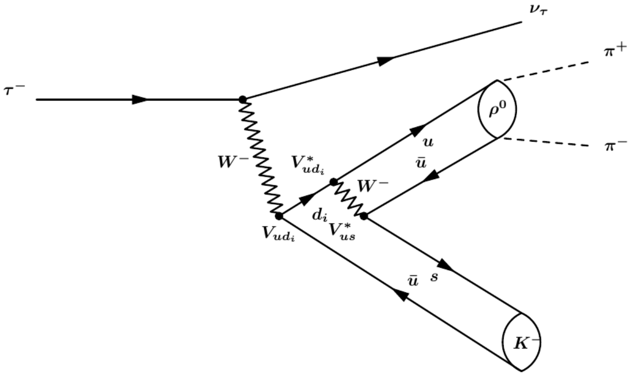
$$M_1 \propto G_F^2, \qquad M_0 M_1^{\dagger} \propto V_{us}^{*} V_{u_i s} V_{u_i d}^{*} V_{ud} \to V_{us}^{*} V_{ts} V_{td}^{*} V_{ud}$$



Weak CP phase ⇒ CP violating term

Second order in G_F (2)

$$M_2 \propto G_F^2, \qquad M_0 M_2^\dagger \propto |V_{us}|^2 |V_{ud_i}|^2$$



No weak CP phase $\Rightarrow$ No CP violation

CP asymmetry

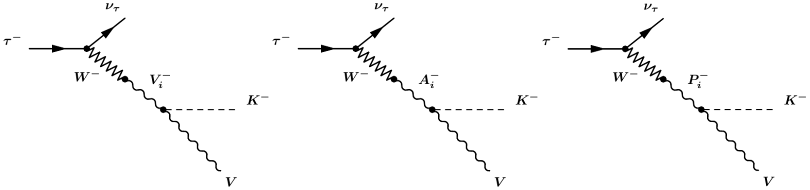
$$
\begin{aligned}
\mathcal{A}_{CP} &= \frac{|M|^2 - |\bar{M}|^2}{|M|^2 + |\bar{M}|^2} \\
&= \frac{(M_0 M_1^\dagger + M_1 M_0^\dagger) - (M_0 \bar{M}_1^\dagger + \bar{M}_1 M_0^\dagger)}{|M_0|^2 + \mathcal{O}(G_F^3)}
\end{aligned}
$$

$$
\begin{aligned}
M_0 M_0^\dagger &\propto L^{\mu\nu}\left\{ H_{\mu\nu}^{0\rho 0\rho} + s_\omega^* \tilde{\Pi}_{\rho\omega}^* H_{\mu\nu}^{0\rho 0\omega} + s_\omega \tilde{\Pi}_{\rho\omega} H_{\mu\nu}^{0\omega 0\rho} + |s_\omega \tilde{\Pi}_{\rho\omega}|^2 H_{\mu\nu}^{0\omega 0\omega} \right\} \\
M_0 M_1^\dagger &\propto L^{\mu\nu}\left\{ H_{\mu\nu}^{0\rho 1\rho} + s_\omega^* \tilde{\Pi}_{\rho\omega}^* H_{\mu\nu}^{0\rho 1\omega} + s_\omega \tilde{\Pi}_{\rho\omega} H_{\mu\nu}^{0\omega 1\rho} + |s_\omega \tilde{\Pi}_{\rho\omega}|^2 H_{\mu\nu}^{0\omega 1\omega} \right\}
\end{aligned}
$$

$$
H_{\mu\nu}^{iVjV'} \equiv H_\mu^{iV}\left(H_\nu^{jV'}\right)^\dagger, \qquad H_\mu^{0\rho}, H_\mu^{0\omega}, H_\mu^{1\rho}, H_\mu^{1\omega}
$$

Chao Wang *et al*, Eur. Phys. J. C 74 (2014) 3140

Leading order hadronic element $H_{\mu}^{0\rho(\omega)}$



$$H_{\mu}^{0\rho(\omega)} = V_{us}^{*}\left[-g\varepsilon_{\mu\lambda\alpha\beta}p_1^{\alpha}p_2^{\beta} - ifg_{\mu\lambda} - i(a_1 p_{1\mu} + a_2 p_{2\mu})Q_{\lambda}\right]\epsilon^{*\lambda}$$

$$f = -\frac{1}{2}(Q^2 + m_{\rho(\omega)}^2 - m_K^2)\sum_i \frac{h_{A_i}t_{A_i}}{D_{A_i}(Q^2)},$$

$$a_1 = \frac{5}{2}\sum_i \frac{h_{P_i}t_{P_i}}{D_{P_i}(Q^2)} + \frac{1}{2}\sum_i \frac{h_{A_i}t_{A_i}}{D_{A_i}(Q^2)}, \qquad g = \frac{1}{2}\sum_i \frac{h_{V_i}t_{V_i}}{D_{V_i}(Q^2)},$$

$$a_2 = \frac{3}{2}\sum_i \frac{h_{P_i}t_{P_i}}{D_{P_i}(Q^2)} + \frac{1}{2}\sum_i \frac{h_{A_i}t_{A_i}}{D_{A_i}(Q^2)}.$$

A. Flores-Tlalpa y G. López, Phys. Rev. D 77 113011 (2008), Chao Wang *et al*, Eur. Phys. J. C 74 (2014) 3140.

Second order hadronic element $H_{\mu}^{1\rho(\omega)}$

$$H_{\mu}^{1\rho(\omega)} = C^{\rho(\omega)} \left[-A_1 \varepsilon_{\mu\lambda\alpha\beta} p_1^{\alpha} p_2^{\beta} - iC_{AB} g_{\mu\lambda} + i(A_1 p_{1\mu} + 2B_1 p_{2\mu}) Q_{\lambda} \right] \epsilon^{*\lambda}$$

Chao Wang *et al*, Eur. Phys. J. C 74 (2014) 3140, Xing-Gang Wu *et al*, Eur. Phys. J. C 52 (2007) 561-570.

$$C^{\rho(\omega)} = +(-) \frac{6\sqrt{2}(2\pi)^3 \sqrt{m_u m_d^2 m_s} G_F V_{ts}^* V_{td} V_{ud}^*}{m_K}$$

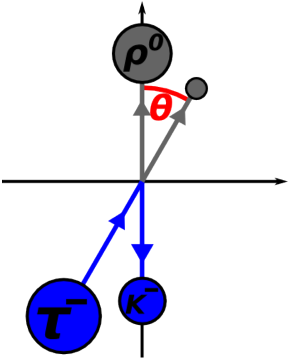
$$H_{\mu}^{0\omega} = H_{\mu}^{0\rho}, \qquad H_{\mu}^{1\omega} = -H_{\mu}^{1\rho}$$

$$M_0 M_0^{\dagger} \propto L^{\mu\nu} H_{\mu\nu}^{0\rho 0\rho} \left\{ 1 + s_{\omega}^* \tilde{\Pi}_{\rho\omega}^* + s_{\omega} \tilde{\Pi}_{\rho\omega} + |s_{\omega} \tilde{\Pi}_{\rho\omega}|^2 \right\}$$

$$M_0 M_1^{\dagger} \propto L^{\mu\nu} H_{\mu\nu}^{0\rho 1\rho} \left\{ 1 - s_{\omega}^* \tilde{\Pi}_{\rho\omega}^* + s_{\omega} \tilde{\Pi}_{\rho\omega} - |s_{\omega} \tilde{\Pi}_{\rho\omega}|^2 \right\}$$

Hadronic rest-frame

$$
\begin{aligned}
\rho(\omega) &\rightarrow & p_1^{\mu} &= (E_1, 0, 0, P),\\
K^{-} &\rightarrow & p_2^{\mu} &= (E_2, 0, 0, -P),\\
\nu_{\tau} &\rightarrow & p_3^{\mu} &= (K, K\sin\theta, 0, K\cos\theta),\\
\tau &\rightarrow & p_4^{\mu} &= (E_4, K\sin\theta, 0, K\cos\theta),\\
& & Q^{\mu} &= (E_1 + E_2, 0, 0, 0).
\end{aligned}
$$



Chao Wang *et al*, Eur. Phys. J. C 74 (2014) 3140,

D. Griffiths, Introduction to Elementary Particles (2010).

$$\tilde{\Pi}_{\rho\omega}(s) \approx \tilde{\Pi}_{\rho\omega}(m_{\omega}^2) + (s - m_{\omega})\tilde{\Pi}'_{\rho\omega}(m_{\omega}^2).$$

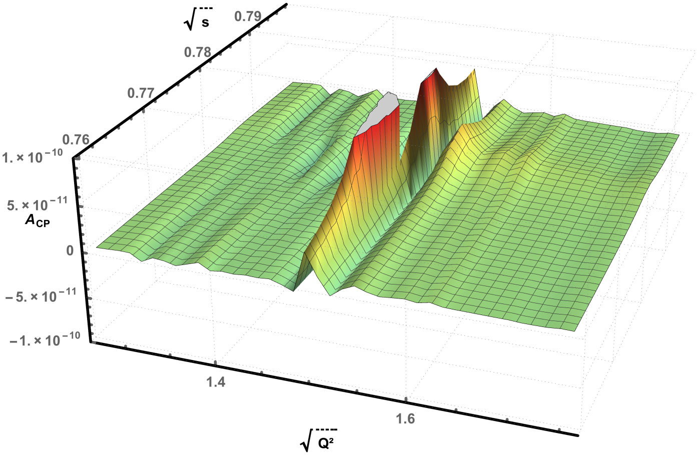
$$E_1 = \frac{Q^2 + m_K^2 - m_\rho^2}{2\sqrt{Q^2}}, \qquad E_2 = \frac{Q^2 - m_K^2 - m_\rho^2}{2\sqrt{Q^2}},$$

$$P = \frac{\sqrt{m_K^4 + m_\rho^4 - 2m_K^2 Q^2 - 2m_K^2 Q^2 - 2m_\rho^2 Q^2}}{2\sqrt{Q^2}},$$

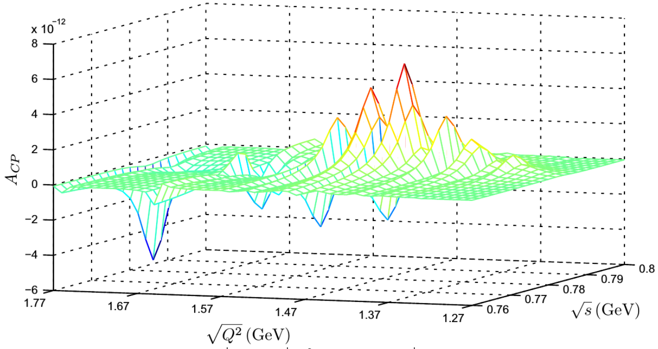
$$K = \frac{m_\tau^2 - Q^2}{2\sqrt{Q^2}}, \qquad E_4 = \frac{m_\tau^2 - Q^2}{2\sqrt{Q^2}}.$$

$$1.27\,\text{GeV} < \sqrt{Q^2} < 1.77\,\text{GeV}, \qquad 0.76\,\text{GeV} < \sqrt{s} < 0.80\,\text{GeV}$$

CP asymmetry surface



CP asymmetry surface (Wang, et.al.)



Chao Wang *et al*, *Direct CP violation in* $\tau^{\pm} \to K^{\pm}\rho^{0}(\omega)\nu_{\tau} \to K^{\pm}\pi^{+}\pi^{-}\nu_{\tau}$, Eur. Phys. J. C 74 (2014) 3140, Fig. 4.

$$A_{CP}^{\Omega} = \frac{\int_{\Omega} dQ^2 ds(|M|^2 - |\bar{M}|^2)}{\int_{\Omega} dQ^2 ds(|M|^2 + |\bar{M}|^2)}$$

Localized integrated CP asymmetry

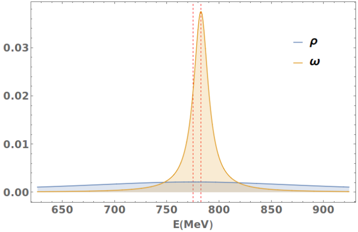
$\sqrt{Q^2}$ (GeV)	$A^{\Omega}_{CP}(10^{-12})$
(1.30,1.35)	0.45
(1.35,1.40)	-0.70
(1.40,1.45)	-0.46
(1.45,1.50)	-10.09
(1.50,1.55)	24.24
(1.55,1.60)	9.54
(1.60,1.65)	7.20
(1.65,1.70)	4.61

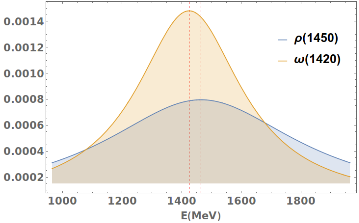
$\sqrt{Q^2}$ (GeV)	$A^{\Omega}_{CP}(10^{-12})$
(1.30,1.35)	3.4
(1.35,1.40)	9.6
(1.40,1.45)	63
(1.45,1.50)	51
(1.50,1.55)	-6.6
(1.55,1.60)	-2.2
(1.60,1.65)	-3.8
(1.65,1.70)	-3.4

Chao Wang *et al*, Eur. Phys. J. C 74 (2014) 3140, Tab. 2.

$\rho(1450) - \omega(1420)$ Mixing

$$\Delta E \Delta t \geq 1/2$$



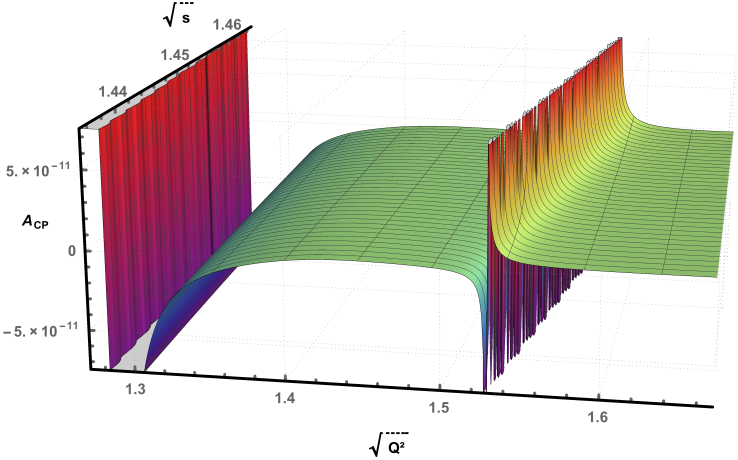


$$\Delta m_{\rho-\omega} \approx 7\,\text{MeV}$$
$$\Delta \Gamma_{\rho-\omega} \approx 140\,\text{MeV}$$

$$\Delta m_{\rho'-\omega'} \approx 45\,\text{MeV}$$
$$\Delta \Gamma_{\rho'-\omega'} \approx 185\,\text{MeV}$$

Y. Nagashima, Elementary Particle Physics (2010).

CP asymmetry surface



Localized integrated CP asymmetry

$\sqrt{Q^2}$ (GeV)	$A^{\Omega}_{CP}(10^{-12})$
(1.30,1.35)	-29.25
(1.35,1.40)	-4.4
(1.40,1.45)	0.94
(1.45,1.50)	0.96
(1.50,1.55)	-1.94
(1.55,1.60)	8.23
(1.60,1.65)	4.08
(1.65,1.70)	3.77

Summary

- The physics of particles and antiparticles is not always the same.
- Weak and strong CP phases are necessary to have a non-vanishing CP asymmetry.
- CP violating effects in $\tau^{\pm} \rightarrow K^{\pm}\pi^{+}\pi^{-}\nu_{\tau}$ are expected to be of order 10^{-11}.
- The overlap in the Lorentz distribution between two resonances does not seem to favor the CP asymmetry.

STUDENT SEMINAR - HUGS 2016

Thank you!

Q & A