Direct CP violation in hadronic τ decays

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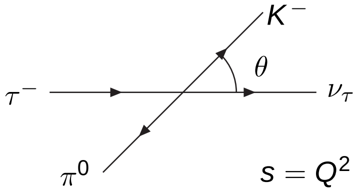
Content of this talk

- The direct CP violation of τ decays $\tau^{\pm} \to K^{\pm} P \nu(\bar{\nu})$ is studied. $P = \pi^0, \eta, \eta'$
- We have computed the CP violation of the forward and backward asymmetries.
- To predict the CP violation, we have used a Chiral Lagrangian including vector and scalar mesons and take into account of η and η' mixing.
- As for new physics with a new source of CP violation, we studied the two Higgs doublet model with non-minimal structure of Yukawa coupling.
- Within the standard model $+$ the form factors with the chiral Lagrangian, we have predicted the distribution of the decays, the foward and backward asymmetries,and branching fraction of $\tau \to \nu K \eta'$

Introduction, CP violation of τ hadronoic decays

To detect CP violation of $\tau \to KP\nu$ decay, the angular distribution and the forward and backward asymmetry are important measurements.



$$s = Q^2 = (p_K + p_\pi)^2$$

$$\frac{d^2\Gamma}{d\sqrt{s}d\cos\theta} = \frac{G_F^2|V_{us}|^2}{2^5\pi^3}\frac{(m_\tau^2 - s)^2}{m_\tau^3}p_K(s)$$

$$\left((\frac{m_\tau^2}{s}\cos^2\theta + \sin^2\theta)p_K(s)^2|F(s)|^2 + \frac{m_\tau^2}{4}|F_s(s)|^2 \right.$$

$$\left. -\frac{m_\tau^2}{\sqrt{s}}p_K(s)\cos\theta \mathrm{Re}(FF_s^*) \right)$$

$p_K(s) =$ three momentum of K or P in hadronic rest frame

Form factors

F and F_S are the vector and the scalar form factors defined below.

$$\langle K^-(p_K)P(p_P)|\bar{s}\gamma_\mu u|0\rangle = F(Q^2)q^\mu$$
$$+ \quad \left(F_S(Q^2) - \frac{\Delta_{KP}}{Q^2}F(Q^2)\right) Q^\mu$$

with $Q^\mu = (p_K + p_P)^\mu$ $q^\mu = (p_K - p_P)^\mu$.
$\Delta_{KP} = m_K^2 - m_P^2$.
F and F_S related to the angular momentum of $L = 1$ and $L = 0$ states of KP system in hadronic rest frame.

The forward and backward asymmetry

To extarct the interference term of F and F_S, one can measure the forward and backward asymmetry. Within the standard model,

$$A_{\rm FB}(s) = \frac{\int_0^1 d\cos\theta \frac{d{\rm Br}}{d\sqrt{s}d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d{\rm Br}}{d\sqrt{s}d\cos\theta}}{\frac{d{\rm Br}}{d\sqrt{s}}}$$

$$= -\frac{\frac{p_K}{\sqrt{s}} \frac{|F_s^{KP}|}{|F^{KP}|} \cos\delta_{\rm st}^{KP}}{\left(\frac{2m_\tau^2}{3s} + \frac{4}{3}\right)\frac{p_K^2}{m_\tau^2} + \frac{1}{2}\left|\frac{F_s^{KP}}{F^{KP}}\right|^2}.$$

Strong phase shift: $\delta_{\rm st}^{KP} = \arg.(\frac{F^{KP}}{F_s^{KP}})$.

L. Beldjoudi and T. N. Truong, Phys. Lett. **B351**, 357 (1995).

CP violation of the Forward and backward asymmetry

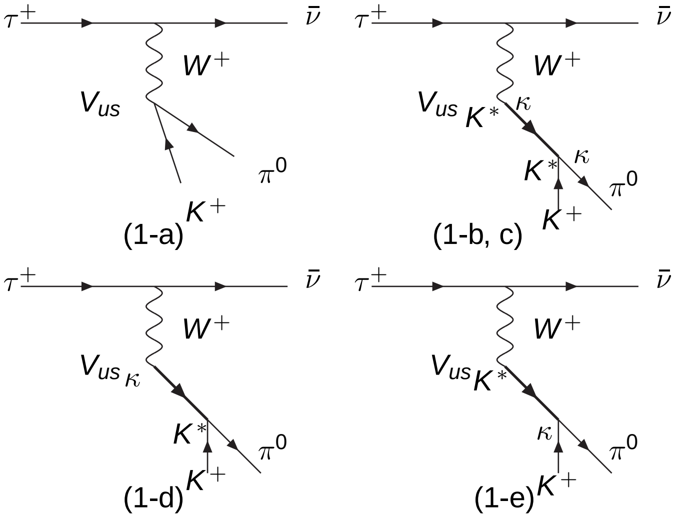
By measuring the forward and backward asymmetries for $\tau^- \to K^-\pi^0\nu$ and $\tau^+ \to K^+\pi^0\bar{\nu}$ and by taking their difference, it is a sensitive quantity to the CP violation.

$$\begin{aligned} A_{FB}(s) - \bar{A}_{FB}(s) &\sim \cos(\delta_{st}^{KP} + \theta_{new}) - \cos(\delta_{st}^{KP} - \theta_{new}) \\ &\sim \sin\delta_{st}^{KP} \sin\theta_{new} \end{aligned}$$

Within the standard model, only a single weak phase of V_{us} contribute, then,the direct CP violation vanishes. $\theta_{new} = 0$. To estimate the direct CP violation of the forward and backward asymmetry, the form factors must be computed including the strong phases.

- J. H. Kuhn. and E. Mirkes, Phys. Lett. **B398**, 407 (1997).
- Y. S. Tsai, Nucl. Phys. Proc. Suppl. **55C**, 293 (1997).

The Feynman diagrams contributing to the form factors



Chiral Lagrangian with vector and scalar resonances

- The model incorporates the effect of η_0 and η_8 octet mixing.
  $\tau \to K\eta\nu$, $\tau \to K\eta'\nu$
- Include the vector and scalar meson intermediate states .
  The decay chains:
  $\tau \to K^*(892)\nu \to (K\pi)_{L=1,0}\nu$ (p,s wave)
  $\tau \to \kappa(800)\nu \to (K\pi)_{L=0}\nu$ (s wave)
- SU(3) breaking of the vector mesons

Here we show the scalar and vector meson nonets.

$$S = \begin{pmatrix} \frac{a^0}{2} + \frac{\sigma}{2} & \frac{a^+}{\sqrt{2}} & \frac{\kappa^+}{\sqrt{2}} \\ \frac{a^-}{\sqrt{2}} & -\frac{a^0}{2} + \frac{\sigma}{2} & \frac{\kappa^0}{\sqrt{2}} \\ \frac{\kappa^-}{\sqrt{2}} & \frac{\overline{\kappa^0}}{\sqrt{2}} & f^0 \end{pmatrix}, \quad V = \begin{pmatrix} \frac{\rho}{2} + \frac{\omega}{2} & \frac{\rho^+}{\sqrt{2}} & \frac{K^{*+}}{\sqrt{2}} \\ \frac{\rho^-}{\sqrt{2}} & -\frac{\rho^0}{2} + \frac{\omega}{2} & \frac{K^{*0}}{\sqrt{2}} \\ \frac{K^{*-}}{\sqrt{2}} & \frac{\overline{K^{*0}}}{\sqrt{2}} & \phi \end{pmatrix}.$$

Effective Lagrangian: $U = \exp(2i\frac{\pi}{f}) = \xi^2$

$$
\begin{aligned}
\mathcal{L} &= \frac{f^2}{4}\mathrm{Tr}DUDU^\dagger + B\mathrm{Tr}M(U+U^\dagger) \\
&- ig_{2p}\mathrm{Tr}\left(\xi M\xi - \xi^\dagger M\xi^\dagger\right)\eta_0 - \frac{M_0^2}{2}\eta_0^2 \\
&+ \mathrm{Tr}D_\mu S D^\mu S - M_\sigma^2 \mathrm{Tr}S^2 \\
&+ \frac{g_1}{4}\mathrm{Tr}(D_\mu U D^\mu U^\dagger)(\xi S\xi^\dagger) + g_2\mathrm{Tr}\left((\xi M\xi + \xi^\dagger M\xi^\dagger)S\right) \\
&- \frac{1}{2}\mathrm{Tr}F_{\mu\nu}F^{\mu\nu} + M_V^2\mathrm{Tr}(V_\mu - \frac{\alpha_\mu}{g})^2 + g_{1V}\mathrm{Tr}S(V_\mu - \frac{\alpha_\mu}{g})^2.
\end{aligned}
$$

$$
\pi = \frac{1}{2}\begin{pmatrix} \pi^0 + \frac{\eta_8}{\sqrt{3}} & \sqrt{2}\pi^+ & \sqrt{2}K^+ \\ \sqrt{2}\pi^- & -\pi^0 + \frac{\eta_8}{\sqrt{3}} & \sqrt{2}K^0 \\ \sqrt{2}K^- & \sqrt{2}\bar{K}^0 & -2\frac{\eta_8}{\sqrt{3}} \end{pmatrix} \quad M = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix}
$$

We assume isospin $m_u = m_d$.

η and η' mixing in the framework

The mass matrix for eta_0 and η_8 sector:

$$(\eta_8, \eta_0) \begin{pmatrix} M_{88}^2 & M_{08}^2 \\ M_{08}^2 & M_{00}^2 \end{pmatrix} \begin{pmatrix} \eta_8 \\ \eta_0 \end{pmatrix}$$

$$\begin{pmatrix} \eta \\ \eta' \end{pmatrix} = \begin{pmatrix} \cos\theta_{08} & -\sin\theta_{08} \\ \sin\theta_{08} & \cos\theta_{08} \end{pmatrix} \begin{pmatrix} \eta_8 \\ \eta_0 \end{pmatrix}.$$

$M_{08}^2 = \frac{4}{\sqrt{3}} \frac{m_s - m_u}{F_8} g_{2p}$ Beacuse the octet mass M_{88} is given by

$$M_{88}^2 = \frac{1}{3F_8^2}\left(\frac{8}{1+\Delta} M_K^2 F_K^2 - \frac{2}{\Delta} M_\pi^2 F_\pi^2 + M_\pi^2 F_\pi^2\right)$$

M_{88}^2 can be determined by F_K, F_π, M_K, M_π and $\Delta = \frac{m_u}{m_s}$. Additional input of two mass eigenvalues M_η $M_{\eta'}$ determines the mixing angle

$$\theta_{08\text{th.}} = -21.49(\Delta = \frac{1}{25}) \ \left(\theta_{08\text{exp.}} = -(22.36^{+1.12}_{-1.21})(J/\psi \to \gamma\eta^{(\prime)})\right)$$

Parameters of the Chiral Lagrangian

$M_\kappa = M_\sigma$ (MeV)	800	840	760
$g_2 m_s$ (MeV^3)	2.65×10^7	2.79×10^7	2.52×10^7
g_1(MeV)	215	225	204
$B m_s$ (MeV^4)	9.24×10^8	9.24×10^8	9.24×10^8
$\Delta = \frac{m_u}{m_s}$	$\frac{1}{25}$	$\frac{1}{25}$	$\frac{1}{25}$
$\Delta S = S_{03} - S_{01}$(MeV)	39.8	37.9	41.9
g_{1V}(MeV)	12200	12800	11600
g	5.90	5.90	5.90

Table: The numerical values for the parameters in the chiral Lagrangian. We use $M_K = 494, M_\pi = 135, F_K = 113, F_\pi = 92.2$ and $\Gamma_{K^*} = 50.8$ as input. g is determined from the width of K^*. g_{1V} is determined by M_{K^*} and M_ϕ as input. In this case M_ρ is predicted as 743 (MeV).

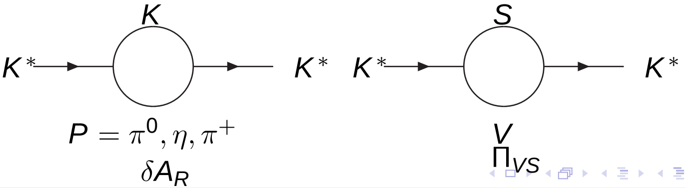
Form factors from the Chiral Lagrangian

Vector Form Factor:(Include loop correction through self-energy of the resonances)

$$F^{K^+\pi^0}(Q^2) = \frac{1}{\sqrt{2}}\left\{-\frac{R+R^{-1}}{2} + \frac{(\Delta S)^2}{2F_K F_\pi} + \frac{M_{K^*}^2}{2g^2 F_K F_\pi}\left(1-\frac{M_{K^*}^2}{A_R}\right) + \frac{\Pi_{VS}^{\mathrm{T}}}{2g^2 F_K F_\pi}\left(1-\frac{2M_{K^*}^2}{A_R}\right)\right\}, R = \frac{F_K}{F_\pi}$$

A_R : inverse propagator for K^* including the self-energy corrections.

$$A_R(s) = M_{K^*}^2 - s - iM_{K^*}\Gamma_{K^*}(s) + \mathrm{Re.}(\delta A_R(s)) + \Pi_{VS}^{\mathrm{T}} + (a_0+k_0) + (a_1+k_1)s.$$



Renormalization

The self energy corrections are divergent. We define the finite parts δA_R by subtraction at zero momentum.

$$\delta A_R(s) = \delta A(s) - \delta A(0) - s\delta A'(0)$$

Then we added the polynominals.

$$a_0 + a_1 s.$$

Similar polynomials $(k_0 + k_1 s)$ for Π^T_{VS}.
There are many finite constants, 10 in total. We only work within the subset of the finite constants and keep only 6 constants non-vanishing. $(a_0, a_1, k_0, k_1, d_0, d_1)$. We require the (real part) one loop corrected inverse propagators have zero at physical mass of K^* and κ and the residues of their propagators at their pole are unities.
One can have the four constraints. Then the numbers of the free parameters (k_0, k_1) to be adjusted is just two.

Determination of the free parameters and prediction.

M_κ (MeV)	760	800	840
$a_1 + k_1$	0.340	0.345	0.351
$a_0 + k_0$	-63500.	-56800	-52500
d_1	-0.139	-0.140	-0.134
d_0	6490	-1870	-16400
k_0	-4.16×10^5	-4.03×10^5	-3.92×10^5
k_1	0.656	0.656	0.656
$\mathrm{Br}(K\pi^0)$	0.00416	0.00416	0.00416
$\mathrm{Br}(K\eta)$	0.000162	0.000162	0.000162
$\mathrm{Br}(K\eta')$	4.14×10^{-6}	3.87×10^{-6}	3.95×10^{-6}

Table: The prediction of $\mathrm{Br}(\tau \to K\eta'\nu)$ The numerical values for the finite renormalization constants. They are chosen so that the the branching fractions of $\tau \to K\pi\nu$ and $\tau \to K\eta\nu$ can be reproduced. The unit of a_0, k_0, d_0 are MeV^2. The others are dimensionless.

Prediction of the hadronic invariant mass distribution

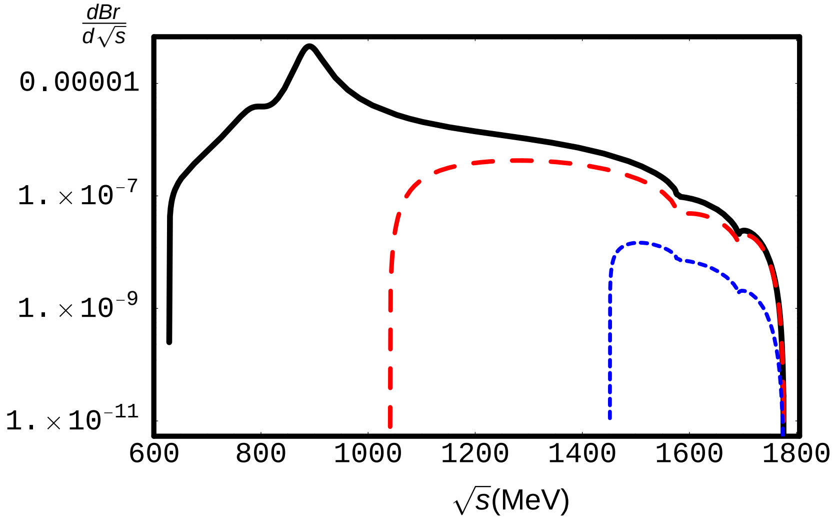


Figure: The hadronic invariant spectrum $\frac{d\mathrm{Br}}{d\sqrt{s}}$ for $K\pi^0$(black), $K\eta$ (red) and $K\eta'$ (blue) cases. We choose $M_\kappa = 800$ (MeV)

$$A_{\rm FB}(s) = -\frac{\frac{p_K}{\sqrt{s}}\frac{|F_S^{KP}|}{|F^{KP}|}\cos\delta_{\rm st}^{KP}}{\left(\frac{2m_\tau^2}{3s}+\frac{4}{3}\right)\frac{p_K^2}{m_\tau^2}+\frac{1}{2}\left|\frac{F_S^{KP}}{F^{KP}}\right|^2}.$$

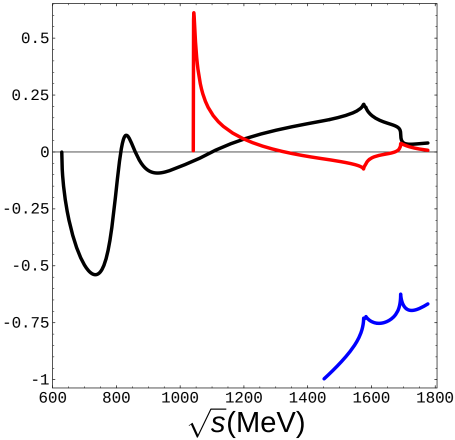


Figure: The predictions of the forward and backward asymmtries of $\tau \to K\pi\nu$(black) $\tau \to K\eta\nu$(red) and $\tau \to K\eta'\nu$ (blue) in the standard model.

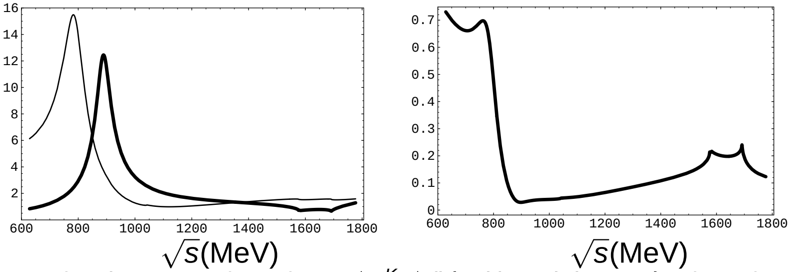


Figure: Left: The vector form factor $|F^{K\pi}|$ (black) and the scalar form factor $10 \times |F_s^{K\pi}|$ (thin solid). Right: The ratio $\frac{|F_s^{K\pi}|}{|F^{K\pi}|}$.

Strong phase shift: $\delta_{st} = \delta_V - \delta_S$

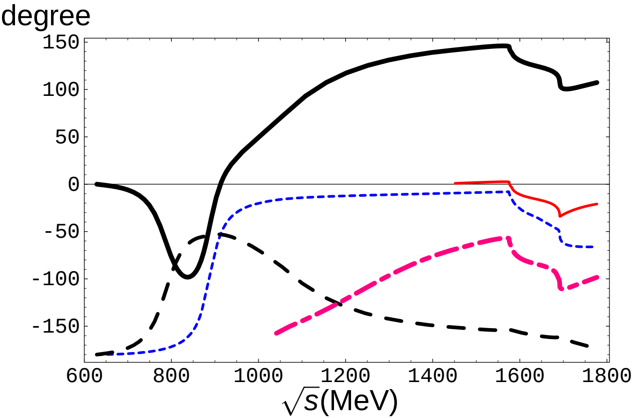


Figure: The phase of the vector form factor: $\delta_V^{K\pi} = \arg.F^{K\pi}$ (blue) and the phase of the scalar form factor $\delta_S^{K\pi} = \arg.F_s^{K\pi}$ (black). The strong phase shift $\delta_{st}^{K\pi} = \delta_V^{K\pi} - \delta_S^{K\pi}$ is shown with red line. $\delta_{st}^{K\eta}$ and $\delta_{st}^{K\eta'}$ are shown with magenta line and green line respectively.

New Physics and the CP violation of the forward and backward asymmetry

- The two Higgs doublet model with the natural flavor conservation, the charged Higgs coupling to the τ lepton and τ neutrino is real as in the standard charged current interaction. Therefore within the scheme, we may not have the CP phase. Then we relax the condition of natural flavor condition as

$$
\begin{aligned}
-\mathcal{L} &= y_{1ij}\overline{e_{Ri}}\tilde{H_1}^{\dagger} l_{Lj} + y_{2ij}\overline{e_{Ri}}H_2^{\dagger} l_{Lj} \\
&+ y^{\nu}_{2i}\overline{\nu_{Ri}}\tilde{H_2}^{\dagger} l_{Li} + \mathrm{h.c.}.
\end{aligned}
$$

- We allows the charged lepton acquires mass from two Higgs H_1 and H_2. One can, in general, take the following parametrizations for Higgs fields,

$$
H_1 = e^{i\frac{\theta_{CP}}{2}} \begin{pmatrix} \frac{v_1+h_1-i\sin\beta A}{\sqrt{2}} \\ -\sin\beta H^- \end{pmatrix}, \quad H_2 = e^{i\frac{\theta_{CP}}{2}} \begin{pmatrix} -\cos\beta H^+ \\ \frac{v_2+h_2-i\cos\beta A}{\sqrt{2}} \end{pmatrix}.
$$

CP violating coupling of charged Higgs and τ, ν_τ

$$\mathcal{L} = H^+ \overline{\nu_{Li}} l_{Rj} \left(\frac{Y^*_{2ji} e^{+i\frac{\theta_{CP}}{2}}}{\cos\beta} - \delta_{ij} \frac{g \tan\beta m_j}{\sqrt{2} M_W} \right)$$

where $Y_2 = V_R y_2 V_L^\dagger$ and V_R and V_L. $y_2 \to 0$ reduced to the two Higgs doublet model with natural flavor conservation.

$$-H^+ \overline{\nu_{L\tau}} \tau_R \frac{g \tan\beta m_\tau}{\sqrt{2} M_W} (1 - r_{2\tau\tau}) \quad (1)$$

CP violation for the forward and backward asymmetry

$$A_{FB} - \bar{A}_{FB} = \frac{2\frac{p_K}{\sqrt{s}}\frac{|F_s^{KP}|}{|F^{KP}|}\sin\delta_{st}}{\left(\frac{2m_\tau^2}{3s} + \frac{4}{3}\right)\frac{p_K^2}{m_\tau^2} + \frac{1}{2}\sum_i \frac{|F_{si\tau}^{KP}|^2}{|F_{\tau\tau}^{KP}|^2}} \left(\frac{Q^2}{M_H^2}\frac{\tan^2\beta}{\sin\beta}\right)|r_{2\tau\tau}|\sin\theta_{2\tau\tau},$$

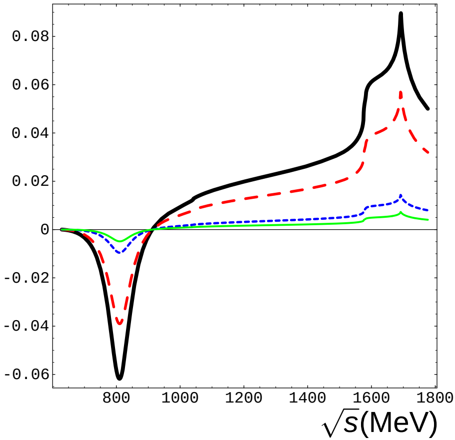


Figure: CP violation for the forward and backward asymmetries of $\tau \to K\pi^0\nu$. The charged Higgs boson mass is changed as $M_H(\mathrm{GeV}) = 200$(black),250(red),500(blue) and 700(green). The other parameters are $\tan\beta = 50$, $|r_{2\tau\tau}| = 1$ and $\theta_{2\tau\tau} = \frac{\pi}{2}$.

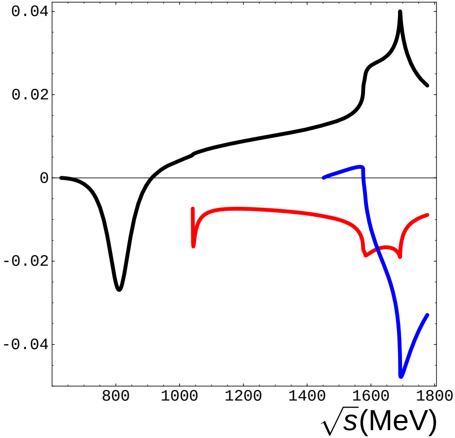


Figure: CP violation for the forward and backward asymmetries of $\tau \to K\pi^0\nu$(black) ,$\tau \to K\eta\nu$ (blue) and $\tau \to K\eta'\nu$ (red). We choose the parameters as $M_H = 300$, $\tan\beta = 50$ $|r_{2\tau\tau}| = 1$, $\theta_{2\tau\tau} = \frac{\pi}{2}$