CP violation in tau decays induced by heavy new physics.

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State of the issue

The theoretical value and experimental measurement made by BaBar of the CP asymmetry in the decay width of $\tau \to K_s \pi \nu_\tau$ are given respectively by [1]:

Babar anomaly

$$A_{CP}^{\mathrm{SM}} = 3.32(6) \times 10^{-3}, \quad (1)$$

$$A_{CP}^{\mathrm{exp}} = -3.6(2.3)(1.1) \times 10^{-3}, \quad (2)$$

this sign difference corresponds to a 2.8σ deviation.

New measurement (Belle-II)

$$A_{CP}^{\mathrm{exp}} = 7.1(2.6)(0.6)(1.5) \times 10^{-3}. \quad (3)$$

now the current uncertainty corresponds to a 1.24σ deviation.

[1] see: arXiv: 1109.1527, 1110.3790, 1101.0349, 2604.23757.

How to get CPV ?

To get CPV, interference between amplitudes is needed

$$\mathcal{A}_j = |\mathcal{A}_j|\, e^{i\delta_j^s} e^{i\delta_j^w}, \tag{4}$$

$$\begin{aligned} A_{CP} &\propto |\mathcal{A}_1 + \mathcal{A}_2|^2 - \left|\bar{\mathcal{A}}_1 + \bar{\mathcal{A}}_2\right|^2 \\ &= -4\,|\mathcal{A}_1|\,|\mathcal{A}_2| \sin\delta^s \sin\delta^w, \end{aligned} \tag{5}$$

with relative weak and strong phases given by

$$\delta^{s(w)} = \delta_1^{s(w)} - \delta_2^{s(w)}. \tag{6}$$

Relying on this simple fact, Ref. [6], considered heavy new physics effects in the form of interactions between tensor (NP) and SM currents to explain the anomaly. Later on, effective field theory methods [7, 8, 9] [2] challenged this possibility.

[2] arXiv:1712.06595, arXiv:1902.08143, arXiv:1909.05543

Low-energy Effective Field Theory Computation

The most general Lagrangian for the $\tau^- \to \bar{u}D\nu_\tau (D = d, s)$ decays is given by [10, 7]

Most general Fermi-like Lagrangian

$$\mathcal{L}_{EFT} = -\frac{G_F^0 V_{uD}}{\sqrt{2}}(1+\epsilon_L^D+\epsilon_R^D)\{\bar{\tau}\gamma_\mu(1-\gamma_5)\nu_\tau \cdot \bar{u}[\gamma^\mu - (1-2\hat{\epsilon}_R^D)\gamma^\mu\gamma_5]D + \bar{\tau}(1-\gamma_5)\nu_\tau \cdot \bar{u}[\hat{\epsilon}_S^D - \hat{\epsilon}_P^D\gamma_5]D + 2\hat{\epsilon}_T^D\bar{\tau}\sigma_{\mu\nu}(1-\gamma_5)\nu_\tau \cdot \bar{u}\sigma^{\mu\nu}D\} + \mathrm{h.c.}, \quad (7)$$

$$\mathcal{M}(\tau^- \to K^-\pi^0\nu_\tau) = \frac{1}{2} G_F V_{us}\left[L_\mu H^\mu + \hat{\epsilon}_S^* L H + 2\hat{\epsilon}_T^* L_{\mu\nu}H^{\mu\nu}\right], [3] \quad (8)$$

[3] The other interesting decay channels are trivially obtained from the $K^0\pi$ one, replacing the $1/2$ factor in eq. (8) by $1/\sqrt{2}$ for the K^-K^0 and $\bar{K}^0\pi^-$ modes, and by 1 in the $\pi^-\pi^0$ channel.

Low-energy Effective Field Theory Computation

where the lepton and hadron currents are defined as

$$L = \bar{u}(p_{\nu_\tau})(1+\gamma_5)u(p_\tau)\,, \tag{9}$$

$$L_\mu = \bar{u}(p_{\nu_\tau})\gamma_\mu(1-\gamma_5)u(p_\tau)\,, \tag{10}$$

$$L_{\mu\nu} = \bar{u}(p_{\nu_\tau})\sigma_{\mu\nu}(1+\gamma_5)u(p_\tau)\,, \tag{11}$$

and ($q^\mu = (p_\pi + p_K)^\mu$, $s = q^2$, $\Delta_{K\pi} = m_K^2 - m_\pi^2$)

$$H = \left\langle \pi^0(p_\pi)K^-(p_K)|\bar{s}d|0\right\rangle = \frac{\Delta_{K\pi}}{m_s - m_u}F_0(s)\,, \tag{12}$$

$$\begin{aligned} H^\mu &= \left\langle \pi^0(p_\pi)K^-(p_K)|\bar{s}\gamma^\mu d|0\right\rangle \\ &= \left[(p_\pi - p_K)^\mu + \frac{\Delta_{K\pi}}{s}q^\mu\right]F_+(s) - \frac{\Delta_{K\pi}}{s}q^\mu F_0(s)\,, \end{aligned} \tag{13}$$

$$\begin{aligned} H^{\mu\nu} &= \left\langle \pi^0(p_\pi)K^-(p_K)|\bar{s}\sigma^{\mu\nu} d|0\right\rangle \\ &= iF_T(s)(p_\pi^\mu p_K^\nu - p_K^\mu p_\pi^\nu)\,. \end{aligned} \tag{14}$$

CP Observables, *CP asymmetry rate*

From the latter matrix elements it is straightforward to obtain the *CP-asymmetry rate* and the *Forward-Backward asymmetry* [11, 12][4]

$$A_{CP}^{\rm rate}(\tau^\pm \to K^\pm \pi^0 \nu_\tau) = \frac{\Gamma(\tau^+ \to K^+\pi^0\bar{\nu}_\tau) - \Gamma(\tau^- \to K^-\pi^0\nu_\tau)}{\Gamma(\tau^+ \to K^+\pi^0\bar{\nu}_\tau) + \Gamma(\tau^- \to K^-\pi^0\nu_\tau)}$$
$$= \frac{\Im m[\hat{\epsilon}_T] G_F^2 |V_{us}|^2 S_{EW}}{128\pi^3 M_\tau^2 \Gamma(\tau \to K\pi^0\nu_\tau)} \int_{(m_K+m_\pi)^2}^{M_\tau^2} \mathrm{d}s \left(1 - \frac{M_\tau^2}{s}\right)^2$$
$$\lambda^{3/2}(s, m_K^2, m_\pi^2) \times |F_T(s)||F_+(s)| \sin[\delta_T(s) - \delta_+(s)]\,. \quad (15)$$

The constraints on $\delta_T(s) - \delta_+(s)$ (given by Watson's theorem) and on $\Im m[\hat{\epsilon}_T]$ (from $D - \bar{D}$ mixing and the neutron edm) preclude a natural explanation of the BaBar asymmetry by *heavy new physics* [7].

[4] arXiv:2003.05735, arXiv:2107.12310

The expression in the second and third lines of eq. (15) corresponds to the new physics (NP) contribution to A_{CP}^{rate}, which coincides with A_{CP}^{rate} for those modes **without** neutral Kaons. In the $\tau^{\pm} \to K^{\pm} K_S \nu_\tau$ case, this observable is dominated by the SM contribution, according to [6][5]

$$A_{CP}^{rate} = \frac{A_{CP}^{rate}|_{SM} + A_{CP}^{rate}|_{NP}}{1 + A_{CP}^{rate}|_{SM} \times A_{CP}^{rate}|_{NP}} \,. \tag{16}$$

[5] arXiv:1308.4383.

$$A_{FB}^{\tau^-\to K_S\pi^-\nu_\tau}(s) = \frac{\int_0^1 \frac{\mathrm{d}^2\Gamma(\tau^-\to K_S\pi^-\nu_\tau)}{\mathrm{d}s\,\mathrm{d}\cos\alpha}\mathrm{d}\cos\alpha - \int_{-1}^0 \frac{\mathrm{d}^2\Gamma(\tau^-\to K_S\pi^-\nu_\tau)}{\mathrm{d}s\,\mathrm{d}\cos\alpha}\mathrm{d}\cos\alpha}{\int_0^1 \frac{\mathrm{d}^2\Gamma(\tau^-\to K_S\pi^-\nu_\tau)}{\mathrm{d}s\,\mathrm{d}\cos\alpha}\mathrm{d}\cos\alpha + \int_{-1}^0 \frac{\mathrm{d}^2\Gamma(\tau^-\to K_S\pi^-\nu_\tau)}{\mathrm{d}s\,\mathrm{d}\cos\alpha}\mathrm{d}\cos\alpha}, \tag{17}$$

The *FB asymmetry* actually fulfills the relation

$$A_{FB}(s) = 3/2 < \cos\alpha > (s), \tag{18}$$

with

$$< \cos\alpha > (s) = \frac{\int_{-1}^1 \cos\alpha \left(\frac{\mathrm{d}^2\Gamma(\tau^-\to K_S\pi^-\nu_\tau)}{\mathrm{d}s\,\mathrm{d}\cos\alpha}\mathrm{d}\cos\alpha\right)}{\int_{-1}^1 \left(\frac{\mathrm{d}^2\Gamma(\tau^-\to K_S\pi^-\nu_\tau)}{\mathrm{d}s\,\mathrm{d}\cos\alpha}\mathrm{d}\cos\alpha\right)} = \frac{N(s)}{D(s)}. \tag{19}$$

CP Observables, *FB asymmetry*

The previous nominator and denominator are

$$
\begin{aligned}
N(s) \quad &= -\frac{4}{3}\Delta_{K\pi}\lambda^{1/2}(s,m_K^2,m_\pi^2)\Re e\left[\left(1+\frac{\hat{\epsilon}_S s}{M_\tau(m_s-m_u)}\right)F_+(s)F_0^*(s)\right] \\
&+\frac{8s}{3M_\tau}\Delta_{K\pi}\lambda^{1/2}(s,m_K^2,m_\pi^2)\Re e\left[\hat{\epsilon}_T^*\left(1+\frac{\hat{\epsilon}_S s}{M_\tau(m_s-m_u)}\right)F_T(s)F_0^*(s)\right], \\
D(s) \quad &= \frac{2}{3}\lambda(s,m_K^2,m_\pi^2)\left(1+\frac{2s}{M_\tau^2}\right)|F_+(s)|^2+2\Delta_{K\pi}^2\left|1+\frac{\hat{\epsilon}_S s}{M_\tau(m_s-m_u)}\right|^2 \\
&|F_0(s)|^2+\frac{8}{3}\lambda(s,m_K^2,m_\pi^2)\Bigg[s|\hat{\epsilon}_T|^2\left(2+\frac{s}{M_\tau^2}\right)|F_T(s)|^2 \\
&-\frac{3s}{M_\tau}\Re e[\hat{\epsilon}_T F_+(s)F_T^*(s)]\Bigg].
\end{aligned}
$$

Form-factors input.

We use [1] a dispersive representation for the form factors.
For the pion vector form factor we used a thrice subtracted representation and one subtraction for the scalar and tensor ones (similarly for the other channels, known with less precision) [14, 15, 8, 16, 17, 18, 19, 20, 21][6].

$$F_{+}^{\pi\pi}(s) = \exp\left[\alpha_1 s + \frac{\alpha_2}{2}s^2 + \frac{s^3}{\pi}\int_{4m_\pi^2}^{\infty}\frac{\mathrm{d}s'}{s'^3}\frac{\delta_+(s')}{s'-s-i0}\right], \qquad (20)$$

$$F_{T}^{\pi\pi}(s) = \exp\left[\frac{s}{\pi}\int_{4m_\pi^2}^{\infty}\frac{\mathrm{d}s'}{s'}\frac{\delta_T(s')}{s'-s-i0}\right], \qquad (21)$$

$$F_{0}^{\pi\pi}(s) = \exp\left[\frac{s}{\pi}\int_{4m_\pi^2}^{\infty}\frac{\mathrm{d}s'}{s'}\frac{\delta_0(s')}{s'-s-i0}\right]. \qquad (22)$$

[6] arXiv:1902.02273, 1301.6973, 1806.09547, 1307.7908, 1407.6590, 2007.11019, 2411.07696, 1601.03989, 1304.8134.

As we showed [1], Watson's final state theorem limits our possibilities to observe CPV induced by heavy new physics in these decays. Due to these restrictions we [1] (see also [7, 8, 12]) estimate the phase of the tensor form factor considering

$$\left|\delta_+(s) - \delta_T(s)\right| = 2\delta_+^{\rm inel}(s)\,, \tag{23}$$

where $\delta_+^{inel}(s)$ is given by the inelastic effects arising from the pion vector form factor only (analogously for other channels).

Form-factors input.

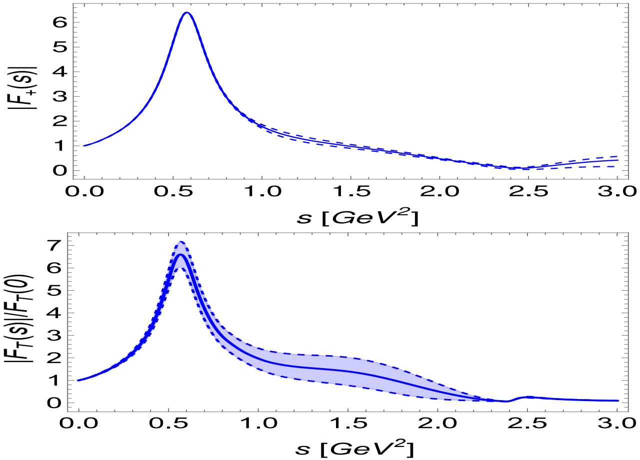


Figure: On top, pion vector form factor. At the bottom, tensor form factor derived from the estimator described in the previous section.

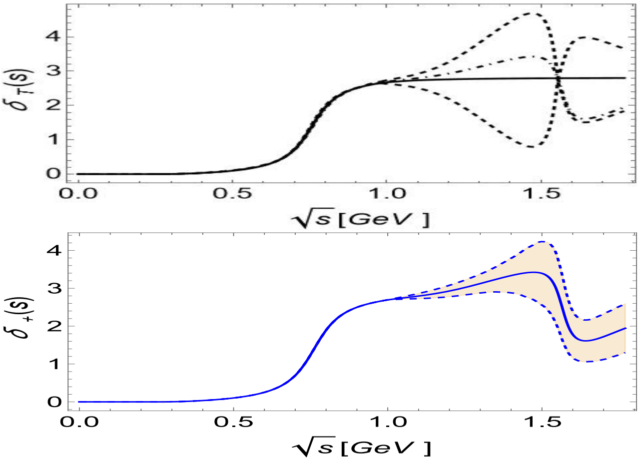


Figure: On top, tensor form factor phase. At the bottom, vector form factor phase.

For the tensor operators, in the weak basis, one has

$$\mathcal{L}_{SMEFT} \supset [C^{(3)}_{\ell equ}]_{klmn}(\bar{\ell}^i_{Lk}\sigma_{\mu\nu}e_{Rl})\epsilon^{ij}(\bar{q}^j_{Lm}\sigma^{\mu\nu}u_{Rn}) + \text{h.c.}$$
$$= [C^{(3)}_{\ell equ}]_{klmn}[(\bar{\nu}_{Lk}\sigma_{\mu\nu}e_{Rl})(\bar{d}_{Lm}\sigma^{\mu\nu}u_{Rn}) - (\bar{e}_{Lk}\sigma_{\mu\nu}e_{Rl})(\bar{u}_{Lm}\sigma^{\mu\nu}u_{Rn})] + \text{h.c}$$

where the left-handed lepton and quark $SU(2)_L$ doublets are $\ell_L = (\nu_L, e_L)^T$ and $q_L = (u_L, d_L)^T$, while the corresponding singlets are e_R and u_R. $SU(2)_L$(family) indices are denoted by latin letters. In the *down* mass basis, one finds

$$\begin{aligned} \mathcal{L}_{SMEFT} &\supset [C^{(3)}_{\ell equ}]_{klmn}[(\bar{\nu}_{Lk}\sigma_{\mu\nu}e_{Rl})(\bar{d}_{Lm}\sigma^{\mu\nu}u_{Rn}) \\ &\quad -V_{am}(\bar{e}_{Lk}\sigma_{\mu\nu}e_{Rl})(\bar{u}_{La}\sigma^{\mu\nu}u_{Rn})] + \text{h.c.} \end{aligned} \quad (25)$$

similar expressions for the scalar operators in the SMEFT can be obtained.

Bounds on real part of WCs.

The real parts of the Wilson coefficients are most effectively constrained by analyzing CP-conserving inclusive and exclusive semi-leptonic tau decays. In the following, we will consider [1] the bounds from the analyses [25, 26] (see also [27, 28])[7], allowing the (signal-maximizing) values

$$\Re e[\epsilon_S^d] = -3.1 \times 10^{-2}\,, \quad \Re e[\epsilon_T^d] = -7.9 \times 10^{-3}\,, \tag{26}$$

and

$$\Re e[\epsilon_S^s] = 2.3 \times 10^{-2}\,, \quad \Re e[\epsilon_T^s] = 1.8 \times 10^{-2}\,. \tag{27}$$

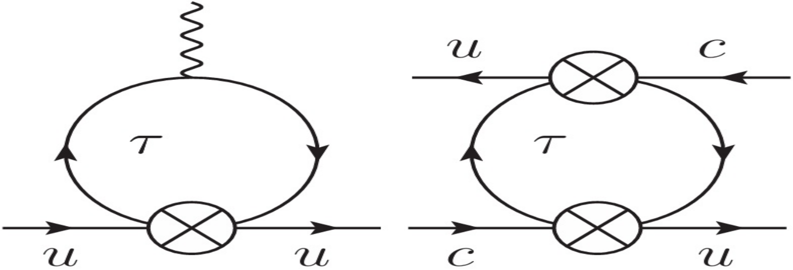
[7] arXiv:2112.02087, arXiv:2303.01362

Bounds on imaginary Part of WCs.

If the neutron EDM [8] is mainly contributed by a single $\hat{\epsilon}_T^D$, then

$$d_u(\mu) = -2\sqrt{2} G_F \frac{eM_\tau}{\pi^2} V_{uD}^2 \Im m[\hat{\epsilon}_T^D(\mu)] \log \frac{\Lambda}{\mu}, \quad (28)$$

which yields $|\Im m[\hat{\epsilon}_T^s]| \lesssim 4 \times 10^{-6}$ and $|\Im m[\hat{\epsilon}_T^d]| \lesssim 8 \times 10^{-5}$ for $\Lambda \gtrsim 100$ GeV and $\mu = 2$ GeV.
In the scalar case, the strongest constraints come from $D^0 - \bar{D}^0$ mixing, implying $\Im m \left[\hat{\epsilon}_S^D\right] \in [-3.1, 1.6] \times 10^{-4}$ at 95% C.L, as can be seen in [12].



CP asymmetries in the $\pi^{\pm}\pi^{0}$ channel.

In this case, the SM contribution is negligible, so using current bounds for the NP part [25], we find

$$\left| A_{CP}^{rate}|_{\pi\pi} \right| \leq 3 \times 10^{-5} \,, \qquad (29)$$

clearly too tiny to be observed soon.
The maximal effect on $A_{FB}|_{\pi\pi}$ is shown by a blue solid line in the figure.

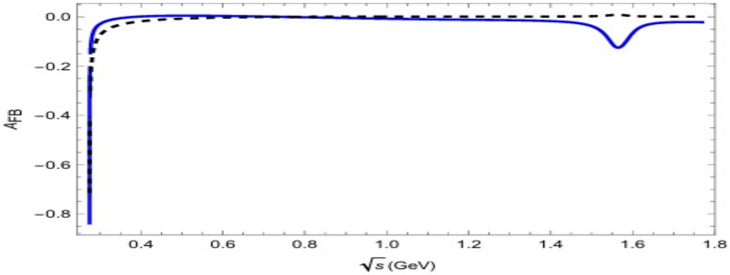


Figure: Maximal effect on $A_{FB}^{\tau\to\pi\pi^0\nu_\tau}(s)$ (blue solid line), corresponding to $\Re e[\epsilon_S^d] = -0.31$, $\Im m[\epsilon_S^d] = -2.7 \times 10^{-4}$, $\Re e[\epsilon_T^d] = -7.9 \times 10^{-3}$ and $\Im m[\epsilon_T^d] = 8 \times 10^{-5}$), compared to the SM (black dashed line).

The most interesting channel is given by the one with $K^{\pm}K_S$ mesons in the final state [29], whose total asymmetry rate (including $K^0 - \bar{K}^0$ oscillation effects in eq. (16)) is given by

$$A^{rate}_{CP,KK} = -3.83 \times 10^{-3}. \tag{30}$$

with a maximal NP contribution given by

$$|A^{rate,NP}_{CP,KK}| \leq 2.3 \times 10^{-4} \tag{31}$$

Noticeably, a 5% precision on the measurement of A^{rate}_{CP} would already be sensitive to the maximum allowed NP contribution in this case. The effect is large because:

- $\Im m[\epsilon^d_S] = -2.7 \times 10^{-4}$ vs. $\Im m[\epsilon^d_T] = 8 \times 10^{-5}$,
- $A^{rate,NP}_{CP,KK} \neq 0$ needs $\Im m[F_V - F_T] \neq 0$, which only happens in the inelastic region, and KK is fully inelastic.

CP asymmetries in the $K^{\pm}K_S$ channel.

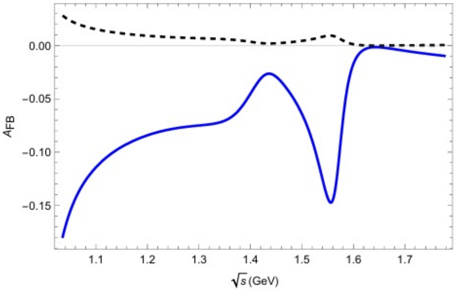


FIGURE: Maximal effect on $A_{FB}^{\tau\to K_S K\nu_\tau}(s)$ (blue solid line), corresponding to $\Re e[\epsilon_S^d] = -0.031$, $\Im m[\epsilon_S^d] = -2.7 \times 10^{-4}$, $\Re e[\epsilon_T^d] = -7.9 \times 10^{-3}$ and $\Im m[\epsilon_T^d] = 8 \times 10^{-5}$, compared to the SM case (black dashed line).

CP asymmetries in the $K^{\pm}\pi^0$ channel.

Finally, the maximal rate for the $K^{\pm}\pi^0$ channel is given by

$$|A_{CP}^{rate}|_{K\pi}| \leq 6 \times 10^{-7} \,. \tag{32}$$

Again, a too small effect to be observed soon.
The corresponding A_{FB} is displayed in the following figure

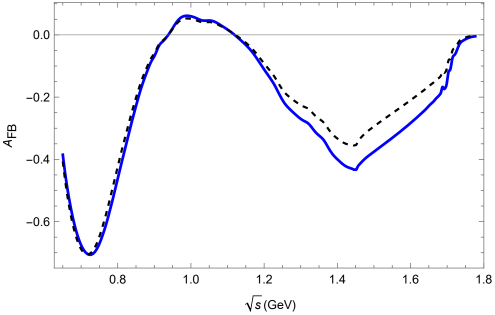


Figure: Maximal effect on $A_{FB}^{\tau\to K\pi^0\nu_\tau}(s)$ (blue solid line), corresponding to $\Re e[\epsilon_S^s] = 2.3 \times 10^{-2}$, $\Im m[\epsilon_S^s] = -2.7 \times 10^{-4}$, $\Re e[\epsilon_T^s] = 1.8 \times 10^{-2}$ and $\Im m[\epsilon_T^s] = 4 \times 10^{-6}$ compared to the SM case (black dashed line).

SUPPLEMENTARIES

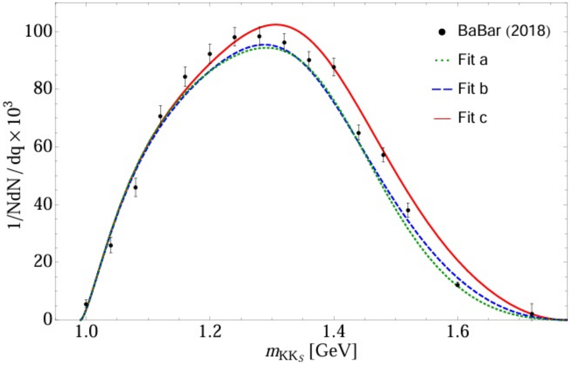


FIGURE: BaBar data for $\tau \to K^- K_S \nu_\tau$ as compared to the fits from [18] (arxiv:1902.02273)

Supplementaries

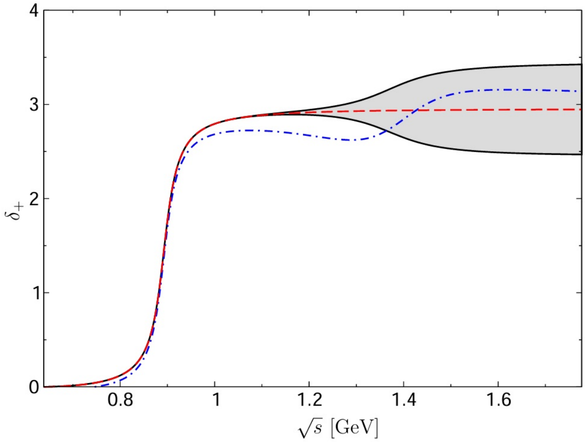


Figure: δ^+ from a BW approximation for the K*(892) (red dashed line) in comparison to the phase from the experimental fit (blue dot-dashed line). The band represents the estimates made in [7] (arXiv:1712.06595).

- D. A. L. Aguilar, J. Rendón and P. Roig, JHEP **01** (2025), 105.
- B. Aubert *et al.* [BaBar], "Observation of CP violation in the B^0 meson system," Phys. Rev. Lett. **87** (2001), 091801.
- Y. Grossman and Y. Nir, JHEP **04** (2012), 002.
- M. Bischofberger *et al.* [Belle], Phys. Rev. Lett. **107** (2011), 131801.
- A. D. Sakharov, "Violation of CP Invariance, C asymmetry, and baryon asymmetry of the universe," Pisma Zh. Eksp. Teor. Fiz. **5** (1967), 32-35.
- H. Z. Devi, L. Dhargyal and N. Sinha, "Can the observed CP asymmetry in $\tau \to K\pi\nu_\tau$ be due to nonstandard tensor interactions?," Phys. Rev. D **90** (2014) no.1, 013016.
- V. Cirigliano, A. Crivellin and M. Hoferichter, "No-go theorem for nonstandard explanations of the $\tau \to K_S\pi\nu_\tau$ CP asymmetry," Phys. Rev. Lett. **120** (2018) no.14, 141803.

- J. Rendón, P. Roig and G. Toledo Sánchez, "Effective-field theory analysis of the $\tau^- \to (K\pi)^- \nu_\tau$ decays," Phys. Rev. D **99** (2019) no.9, 093005.
- F. Z. Chen, X. Q. Li, Y. D. Yang and X. Zhang, Phys. Rev. D **100** (2019) no.11, 113006.
- E. A. Garcés, M. Hernández Villanueva, G. López Castro and P. Roig, JHEP **12** (2017), 027.
- F. Z. Chen, X. Q. Li and Y. D. Yang, "*CP* asymmetry in the angular distribution of $\tau \to K_S \pi \nu_\tau$ decays," JHEP **05** (2020), 151.
- F. Z. Chen, X. Q. Li, S. C. Peng, Y. D. Yang and H. H. Zhang, "CP asymmetry in the angular distributions of $\tau \to K_S \pi \nu_\tau$ decays. Part II. General effective field theory analysis," JHEP **01** (2022), 108.
- J. H. Kühn and E. Mirkes, "Structure functions in tau decays," Z. Phys. C **56** (1992), 661-672 [erratum: Z. Phys. C **67** (1995), 364].

D. Gómez Dumm and P. Roig, "Dispersive representation of the pion vector form factor in $\tau \to \pi\pi\nu_\tau$ decays," Eur. Phys. J. C **73** (2013) no.8, 2528.

J. A. Miranda and P. Roig, "Effective-field theory analysis of the $\tau^- \to \pi^-\pi^0\nu_\tau$ decays," JHEP **11** (2018), 038.

R. Escribano, S. Gonzàlez-Solís and P. Roig, "$\tau^- \to K^-\eta^{(\prime)}\nu_\tau$ decays in Chiral Perturbation Theory with Resonances," JHEP **10** (2013), 039.

R. Escribano, S. González-Solís, M. Jamin and P. Roig, "Combined analysis of the decays $\tau^- \to K_S\pi^-\nu_\tau$ and $\tau^- \to K^-\eta\nu_\tau$," JHEP **09** (2014), 042.

S. Gonzàlez-Solís and P. Roig, "A dispersive analysis of the pion vector form factor and $\tau^- \to K^-K_S\nu_\tau$ decay," Eur. Phys. J. C **79** (2019) no.5, 436.

J. A. Miranda and P. Roig, “New τ-based evaluation of the hadronic contribution to the vacuum polarization piece of the muon anomalous magnetic moment,” Phys. Rev. D **102** (2020), 114017.

G. L. Castro, A. Miranda and P. Roig, “Isospin breaking corrections in 2π production in tau decays and e+e- annihilation: Consequences for the muon g-2 and conserved vector current tests,” Phys. Rev. D **111** (2025) no.7, 073004.

R. Escribano, S. Gonzàlez-Solís and P. Roig, “Predictions on the second-class current decays $\tau^- \to \pi^- \eta^{(\prime)} \nu_\tau$,” Phys. Rev. D **94** (2016) no.3, 034008.

T. Bhattacharya, V. Cirigliano, R. Gupta, H. W. Lin and B. Yoon, “Neutron Electric Dipole Moment and Tensor Charges from Lattice QCD,” Phys. Rev. Lett. **115** (2015) no.21, 212002.

R. Gupta, B. Yoon, T. Bhattacharya, V. Cirigliano, Y. C. Jang and H. W. Lin, “Flavor diagonal tensor charges of the nucleon from (2+1+1)-flavor lattice QCD,” Phys. Rev. D **98** (2018) no.9, 091501.

C. Abel *et al.* "Measurement of the Permanent Electric Dipole Moment of the Neutron," Phys. Rev. Lett. **124** (2020) no.8, 081803.

V. Cirigliano, D. Díaz-Calderón, A. Falkowski, M. González-Alonso and A. Rodríguez-Sánchez, JHEP **04** (2022), 152.

R. Escribano, J. A. Miranda and P. Roig, "Radiative corrections to the $\tau^- \to (P_1 P_2)^- \nu_\tau$ $(P_{1,2} = \pi, K)$ decays," Phys. Rev. D **109** (2024) no.5, 053003.

V. Cirigliano, A. Falkowski, M. González-Alonso and A. Rodríguez-Sánchez, "Hadronic τ Decays as New Physics Probes in the LHC Era," Phys. Rev. Lett. **122** (2019) no.22, 221801.

S. Gonzàlez-Solís, A. Miranda, J. Rendón and P. Roig, "Exclusive hadronic tau decays as probes of non-SM interactions," Phys. Lett. B **804** (2020), 135371.

S. Gonzàlez-Solís, A. Miranda, J. Rendón and P. Roig, "Effective-field theory analysis of the $\tau^- \to K^-(\eta^{(\prime)}, K^0)\nu_\tau$ decays," Phys. Rev. D **101** (2020) no.3, 034010.

- J. H. Kühn and E. Mirkes, Z. Phys. C **56** (1992), 661-672 [erratum: Z. Phys. C **67** (1995), 364]. doi:10.1007/BF01474741
- J. H. Kühn and E. Mirkes, Phys. Lett. B **398** (1997), 407-414 doi:10.1016/S0370-2693(97)00233-5. [arXiv:hep-ph/9609502 [hep-ph]].
- J. H. Kühn and E. Mirkes, Phys. Lett. B **286** (1992), 381-386. doi:10.1016/0370-2693(92)91791-7
- S. Arteaga, Master Thesis (Cinvestav, Mexico City), 2019.
- S. Arteaga, L. Y. Dai, A. Guevara and P. Roig, Phys. Rev. D **106** (2022) no.9, 096016. doi:10.1103/PhysRevD.106.096016
- J. M. Roney, SciPost Phys. Proc. **17** (2025), 012. doi:10.21468/SciPostPhysProc.17.012
- H. Z. Devi, L. Dhargyal and N. Sinha, Phys. Rev. D **90** (2014) no.1, 013016. doi:10.1103/PhysRevD.90.013016

- J. P. Lees *et al.* [BaBar], Phys. Rev. D **85** (2012), 031102 [erratum: Phys. Rev. D **85** (2012), 099904]. doi:10.1103/PhysRevD.85.031102.
- V. Cirigliano, A. Crivellin and M. Hoferichter, Phys. Rev. Lett. **120** (2018) no.14, 141803. doi:10.1103/PhysRevLett.120.141803.
- J. Rendón, P. Roig and G. Toledo Sánchez, Phys. Rev. D **99** (2019) no.9, 093005. doi:10.1103/PhysRevD.99.093005.
- F. Z. Chen, X. Q. Li, S. C. Peng, Y. D. Yang and H. H. Zhang, JHEP **01** (2022), 108. doi:10.1007/JHEP01(2022)108.
- D. A. L. Aguilar, J. Rendón and P. Roig, JHEP **01** (2025), 105. doi:10.1007/JHEP01(2025)105.
- E. A. Garcés, M. Hernández Villanueva, G. López Castro and P. Roig, JHEP **12** (2017), 027. doi:10.1007/JHEP12(2017)027
- J. A. Miranda and P. Roig, JHEP **11** (2018), 038. doi:10.1007/JHEP11(2018)038.

V. Cirigliano, A. Falkowski, M. González-Alonso and A. Rodríguez-Sánchez, Phys. Rev. Lett. **122** (2019) no.22, 221801. doi:10.1103/PhysRevLett.122.221801

S. Gonzàlez-Solís, A. Miranda, J. Rendón and P. Roig, Phys. Rev. D **101** (2020) no.3, 034010. doi:10.1103/PhysRevD.101.034010

S. Gonzàlez-Solís, A. Miranda, J. Rendón and P. Roig, Phys. Lett. B **804** (2020), 135371. doi:10.1016/j.physletb.2020.135371.

M. A. Arroyo-Ureña, G. Hernández-Tomé, G. López-Castro, P. Roig and I. Rosell, Phys. Rev. D **104** (2021) no.9, L091502. doi:10.1103/PhysRevD.104.L091502.

M. A. Arroyo-Ureña, G. Hernández-Tomé, G. López-Castro, P. Roig and I. Rosell, JHEP **02** (2022), 173. doi:10.1007/JHEP02(2022)173.

V. Cirigliano, D. Díaz-Calderón, A. Falkowski, M. González-Alonso and A. Rodríguez-Sánchez, JHEP **04** (2022), 152. doi:10.1007/JHEP04(2022)152.

- R. Escribano, J. A. Miranda and P. Roig, Phys. Rev. D **109** (2024) no.5, 053003. doi:10.1103/PhysRevD.109.053003.
- R. Barate *et al.* [ALEPH], Eur. Phys. J. C **4** (1998), 409-431. doi:10.1007/s100520050217
- T. E. Browder *et al.* [CLEO], Phys. Rev. D **61** (2000), 052004. doi:10.1103/PhysRevD.61.052004
- R. Akers *et al.* [OPAL], Z. Phys. C **67** (1995), 45-56. doi:10.1007/BF01564820
- K. Ackerstaff *et al.* [OPAL], Z. Phys. C **75** (1997), 593-605. doi:10.1007/s002880050505
- A. Pich, Prog. Part. Nucl. Phys. **75** (2014), 41-85 doi:10.1016/j.ppnp.2013.11.002 [arXiv:1310.7922 [hep-ph]].
- A. Rodríguez-Sánchez, to appear in the Encyclopedia of Particle Physics, [arXiv:2504.21732 [hep-ph]].

V. Cirigliano, J. Jenkins and M. González-Alonso, Nucl. Phys. B **830** (2010), 95-115. doi:10.1016/j.nuclphysb.2009.12.020

O. Catà and V. Mateu, JHEP **09** (2007), 078. doi:10.1088/1126-6708/2007/09/078

V. Shtabovenko, R. Mertig and F. Orellana, Comput. Phys. Commun. **256** (2020), 107478. doi:10.1016/j.cpc.2020.107478

Pich Antonio", Effective field theory: Course, Les Houches Summer School in Theoretical Physics, Session 68: Probing the Standard Model of Particle Interactions, hep-ph/9806303, (1998).

G. Ecker, J. Gasser, A. Pich and E. de Rafael, Nucl. Phys. B **321** (1989), 311-342. doi:10.1016/0550-3213(89)90346-5

G. Ecker, J. Gasser, H. Leutwyler, A. Pich and E. de Rafael, Phys. Lett. B **223** (1989), 425-432. doi:10.1016/0370-2693(89)91627-4

A. Pich, P. Roig, I. Rosell,