

# 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  $\tau \rightarrow K_S \pi \nu_\tau$  are given respectively by <sup>1</sup>:

## BABAR ANOMALY

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

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

this sign difference corresponds to a  $2.8\sigma$  deviation.

## NEW MEASUREMENT (BELLE-II)

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

<sup>1</sup>see: arXiv:1110.3790, arXiv:1101.0349, arXiv:2604.23757. 

# HOW TO GET CPV ?

To get CPV, interference between amplitudes is needed

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

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

with relative weak and strong phases given by

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

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]<sup>2</sup> challenged this possibility.

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<sup>2</sup>arXiv:1712.06595, arXiv:1902.08143, arXiv:1909.05543 

# LOW-ENERGY EFFECTIVE FIELD THEORY COMPUTATION

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

## MOST GENERAL FERMI-LIKE LAGRANGIAN

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

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

<sup>3</sup>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

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

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

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

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

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

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

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

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

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

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].

<sup>4</sup>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  $\tau^\pm \rightarrow K^\pm K_S \nu_\tau$  case, this observable is dominated by the SM contribution, according to [6]<sup>5</sup>

$$A_{CP}^{rate} = \frac{A_{CP}^{rate}|_{SM} + A_{CP}^{rate}|_{NP}}{1 + A_{CP}^{rate}|_{SM} \times A_{CP}^{rate}|_{NP}}. \quad (16)$$

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<sup>5</sup>arXiv:1308.4383.

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

The  $FB$  asymmetry actually fulfills the relation

$$A_{FB}(s) = 3/2 \langle \cos\alpha \rangle (s), \quad (18)$$

with

$$\langle \cos\alpha \rangle (s) = \frac{\int_{-1}^1 \cos\alpha \left( \frac{d^2\Gamma(\tau^- \rightarrow K_S \pi^- \nu_\tau)}{ds d\cos\alpha} d\cos\alpha \right)}{\int_{-1}^1 \left( \frac{d^2\Gamma(\tau^- \rightarrow K_S \pi^- \nu_\tau)}{ds d\cos\alpha} d\cos\alpha \right)} = \frac{N(s)}{D(s)}. \quad (19)$$

# CP OBSERVABLES, $FB$ asymmetry

The previous nominator and denominator are

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

# 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]<sup>6</sup>.

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

$$F_T^{\pi\pi}(s) = \exp \left[ \frac{s}{\pi} \int_{4m_\pi^2}^{\infty} \frac{ds'}{s'} \frac{\delta_T(s')}{s' - s - i0} \right], \quad (21)$$

$$F_0^{\pi\pi}(s) = \exp \left[ \frac{s}{\pi} \int_{4m_\pi^2}^{\infty} \frac{ds'}{s'} \frac{\delta_0(s')}{s' - s - i0} \right]. \quad (22)$$

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<sup>6</sup>arXiv:1902.02273, 1301.6973, 1806.09547, 1307.7908, 1407.6590, 2007.11019, 2411.07696, 1601.03989, 1304.8134.

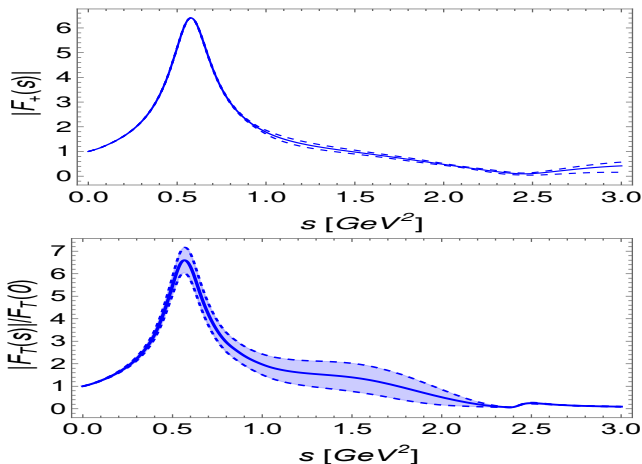
# TENSOR FORM FACTOR PHASE.

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

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

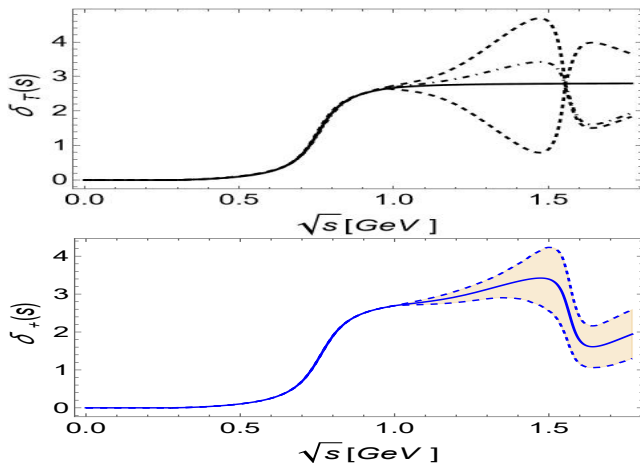
where  $\delta_+^{inel}(s)$  is given by the inelastic effects arising from the pion vector form factor only (analogously for other channels).

# 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.

# VECTOR AND TENSOR FORM-FACTORS.



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

# BOUNDS TO THE NEW PHYSICS COEFFICIENTS

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

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

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

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

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])<sup>7</sup>, allowing the (signal-maximizing) values

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

and

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

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<sup>7</sup>arXiv:2112.02087, arXiv:2303.01362

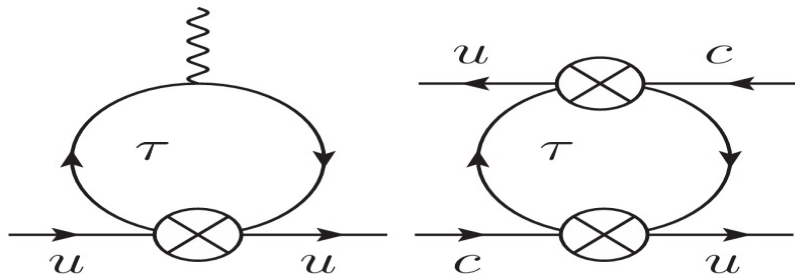
# BOUNDS ON IMAGINARY PART OF WCs.

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

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

which yields  $|\Im m[\hat{e}_T^s]| \lesssim 4 \times 10^{-6}$  and  $|\Im m[\hat{e}_T^d]| \lesssim 8 \times 10^{-5}$  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  $\Im m[\hat{e}_S^D] \in [-3.1, 1.6] \times 10^{-4}$  at 95% C.L, as can be seen in [12].



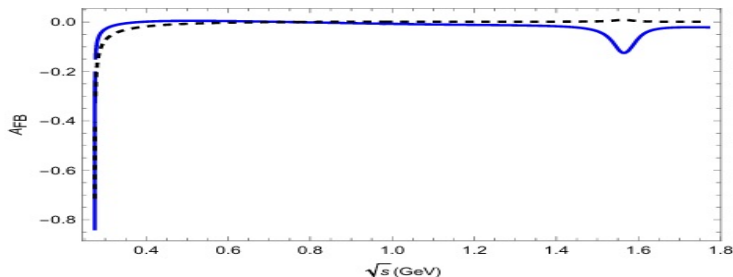
# CP ASYMMETRIES IN THE $\pi^\pm\pi^0$ CHANNEL.

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

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

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  $A_{FB}^{\tau \rightarrow \pi\pi^0\nu\tau}(s)$  (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).

# CP ASYMMETRIES IN THE $K^\pm K_S$ CHANNEL.

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

$$A_{CP, KK}^{rate} = -3.83 \times 10^{-3}. \quad (30)$$

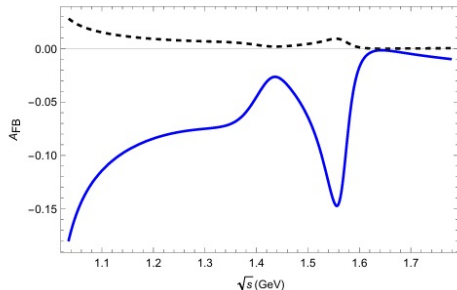
with a maximal NP contribution given by

$$|A_{CP, KK}^{rate, NP}| \leq 2.3 \times 10^{-4} \quad (31)$$

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

- $\Im m[\epsilon_S^d] = -2.7 \times 10^{-4}$  vs.  $\Im m[\epsilon_T^d] = 8 \times 10^{-5}$ ,
- $A_{CP, KK}^{rate, NP} \neq 0$  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  $A_{FB}^{\tau \rightarrow K_S K \nu \tau}(s)$  (blue solid line), corresponding to  $\Re[\epsilon_S^d] = -0.031$ ,  $\Im m[\epsilon_S^d] = -2.7 \times 10^{-4}$ ,  $\Re[\epsilon_T^d] = -7.9 \times 10^{-3}$  and  $\Im m[\epsilon_T^d] = 8 \times 10^{-5}$ , compared to the SM case (black dashed line).

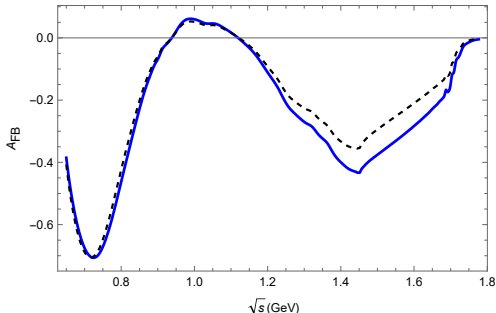
# CP ASYMMETRIES IN THE $K^\pm\pi^0$ CHANNEL.

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

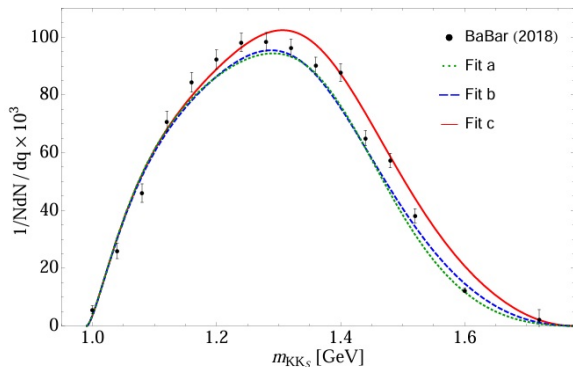
$$|A_{CP}^{rate}|_{K\pi} \leq 6 \times 10^{-7}. \quad (32)$$

Again, a too small effect to be observed soon.

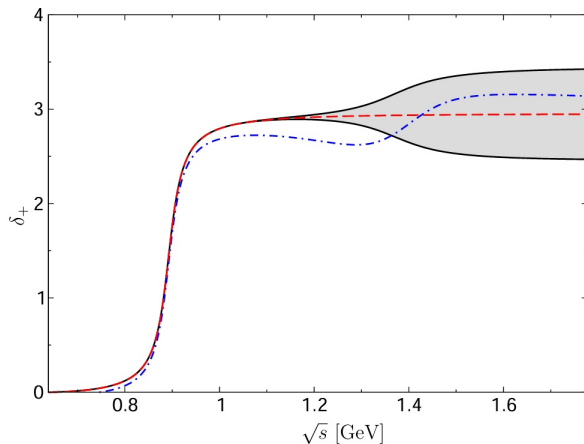
The corresponding  $A_{FB}$  is displayed in the following figure










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














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














**FIGURE:**  $\delta^+$  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).








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