A no-go theorem for non-standard explanations of the \( \tau \rightarrow K_S \pi \nu_\tau \) CP asymmetry

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FOR

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• The CP asymmetry in $\tau \to K_S \pi \nu_\tau$: Standard Model vs experiment

• Non-standard contribution from “heavy” new physics using EFT
  • Suppression of direct CP asymmetry
  • Connection to neutron EDM and D meson mixing

• Conclusions / implications

V. Cirigliano, A. Crivellin, M. Hoferichter, 1712.06595, Phys. Rev. Lett. 120 (2018) no.18, 141803
CPV in $\tau$ decays

- CPV observables are particularly interesting because of potential connections to baryogenesis mechanisms

- Semi-leptonic tau decays offer several possibilities

- One of the simplest asymmetries

$$A_{CP}^\tau = \frac{\Gamma(\tau^+ \to \pi^+ K_S \bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_S \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S \bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_S \nu_\tau)}$$

Predicted to be non-zero in the Standard Model

Bigi-Sanda hep-ph/0506037  
Grossman-Nir 1110.3790
$\tau \rightarrow K_S \pi \nu_\tau$: SM vs experiment

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

- In the SM, asymmetry controlled by CPV in neutral kaon mixing
  - $\tau^+$ [$\tau^-$] decays into at $K^0$ [$\bar{K}^0$]
  - Reconstruct $K^0(t)$ [$\bar{K}^0(t)$] $\rightarrow \pi^+\pi^-$ over a time interval $t_1 < \tau_S < t_2$

$$A_{CP}^\tau(t_1, t_2) = \frac{\int_{t_1}^{t_2} dt [\Gamma(K^0(t) \rightarrow \pi\pi) - \Gamma(\bar{K}^0(t) \rightarrow \pi\pi)]}{\int_{t_1}^{t_2} dt [\Gamma(K^0(t) \rightarrow \pi\pi) + \Gamma(\bar{K}^0(t) \rightarrow \pi\pi)]}$$

Grossman-Nir 1110.3790
$\tau \to K_S \pi \nu_\tau$: SM vs experiment

\[ A_{CP}^\tau = \frac{\Gamma(\tau^+ \to \pi^+ K_S \bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_S \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S \bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_S \nu_\tau)} \]

- In the SM, asymmetry controlled by CPV in neutral kaon mixing

- SM versus measurement: 2.8$\sigma$ tension

$$A_{CP}^{\tau,SM} = 3.6(1) \times 10^{-3} \quad \quad A_{CP}^{\tau,exp} = -3.6(2.3)(1.1) \times 10^{-3}$$

Taking into account experimental conditions and time-dependent efficiencies

BaBar 1109.1527
• BSM physics can induce direct CP violation
• Parameterize “heavy” new physics contributions through effective Lagrangian
• Relevant terms at the hadronic scale:

\[ \mathcal{L}_{\text{eff}} \supset -\frac{G_F}{\sqrt{2}} V_{us} \left[ c_V (\bar{s} \gamma^\mu u)(\bar{\nu} \gamma_\mu \ell) + c_A (\bar{s} \gamma^\mu u)(\bar{\nu} \gamma_\mu \gamma_5 \ell) + c_S (\bar{s} u)(\bar{\nu} \ell) + ic_P (\bar{s} u)(\bar{\nu} \gamma_5 \ell) + c_T (\bar{s} \sigma^{\mu\nu} u)(\bar{\nu} \sigma_{\mu\nu} (1 + \gamma_5) \ell) \right] + \text{h.c.} \]
Decay rate and asymmetry

\[
\frac{d\Gamma}{ds} = G_F^2 |V_{us}|^2 S_{EW} \frac{\lambda_{\pi K}^{1/2}(s)(m_T^2 - s)^2(M_K^2 - M_\pi^2)^2}{1024\pi^3 m_T s^3}
\times \left[ \xi(s) \left( |V(s)|^2 + |A(s)|^2 + \frac{4(m_T^2 - s)^2}{9s m_T^2} |T(s)|^2 \right) + |S(s)|^2 + |P(s)|^2 \right]
\]

\[V(s) = f_+(s)c_V - T(s) \quad S(s) = f_0(s) \left( c_V + \frac{s}{m_T(m_s - m_u)} c_S \right) \quad T(s) = \frac{3s}{m_T^2 + 2s M_K} c_T B_T(s)\]
Decay rate and asymmetry

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\]

- Direct CPV from BSM physics? Need both strong and weak phases

\[
A_{CP} \propto |A_1 + A_2|^2 - |ar{A}_1 + \bar{A}_2|^2 = -4|A_1||A_2| \sin(\delta_s^1 - \delta_s^2) \sin(\delta_w^1 - \delta_w^2)
\]

\[
A_j = |A_j|e^{i\delta_s^j}e^{i\delta_w^j}
\]
Decay rate and asymmetry

\[ \frac{d\Gamma}{ds} = G_F^2 |V_{us}|^2 S_{EW} \frac{\lambda_{\pi K}^{1/2}(s)(m_T^2 - s)^2(M_K^2 - M_\pi^2)^2}{1024\pi^3 m_T s^3} \times \left[ \xi(s) \left( |V(s)|^2 + |A(s)|^2 + \frac{4(m_T^2 - s)^2}{9s m_T^2} |T(s)|^2 \right) + |S(s)|^2 + |P(s)|^2 \right] \]

\[ V(s) = f_+(s)c_V - T(s) \quad S(s) = f_0(s) \left( c_V + \frac{s}{m_T(m_s - m_u)} c_S \right) \quad T(s) = \frac{3s}{m_T^2 + 2s} \frac{m_T}{M_K} c_T B_T(s) \]

- **Vector-scalar interference**: no strong phase (same form factor, \( f_0(s) \))
- **Vector-tensor interference**: strong relative phase of \( B_T(s) \) and \( f_+(s) \)

\[ A_{CP}^{\tau, BSM} = \frac{\sin \delta_T^w |c_T|}{\Gamma_{\tau \rightarrow K_S\pi\nu_\tau}} \times \int_{s_{\pi K}}^{m_\tau^2} ds' \kappa(s') |f_+(s')| |B_T(s')| \sin (\delta_+(s') - \delta_T(s')) \]

Devi et al., 1308.4383
Tensor form factor

- Normalization from lattice QCD: $B_T(0)/f_+(0) = 0.678(27)$
- Phase info from unitarity relations: $\pi K$ intermediate state contribution

\[ \text{arg } B_T(s) = \text{arg } f_+(s) = \delta_1^{1/2}(s) \]

Vector-tensor interference vanishes up to inelastic corrections
Estimating inelastic corrections

- $f_+(s)$ dominated by elastic $K^*(892)$ resonance
- Inelastic corrections around $K^*(1410)$
Estimating inelastic corrections

- $f_+(s)$ dominated by elastic $K^*(892)$ resonance
- Inelastic corrections around $K^*(1410)$
- Assuming $\delta_+(s) - \delta_T(s) \sim 2\delta_+^{\text{inel}}(s)$

\[ |A_{CP}^{\tau\text{BSM}}| \lesssim 0.03|\text{Im } c_T| \]

~2 orders of magnitude suppression compared to analysis assuming $\delta_T=0$

(e.g. Devi et al., 1308.4383)
Constraints on $\text{Im}(c_T)$

- Tensor current originates from $\text{SU}(2)_W \times \text{U}(1)_Y$ invariant operator

$$\mathcal{L}_T = C_{abcd} \bar{L}^i_{La} \sigma_{\mu\nu} e_{Rb} \epsilon^{ij} \bar{q}^j_{Lc} \sigma^{\mu\nu} u_{Rd} + \text{h.c.}$$

$$\supset C_{3321} \left[ (\bar{\nu}_\tau \sigma_{\mu\nu} R\tau) (\bar{s} \sigma^{\mu\nu} R u) - V_{us} (\bar{\tau} \sigma_{\mu\nu} R\tau) (\bar{u} \sigma^{\mu\nu} R u) \right] + \text{h.c.}$$

**Induces u-quark EDM**

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R = (1 + \gamma_5)/2
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**Explanation of tau CP asymmetry requires**

$$\text{Im}(c_T) \sim 0.1 \quad \Rightarrow$$

**Need cancellations in nEDM of one part in $10^4$ !**
Constraints on $\text{Im}(c_T)$ (2)

- Cancellation possible through more general flavor structures ($C_{3311}$)

- But nEDM and D-meson mixing probe ~ orthogonal combinations!

\[
V_{ud} \text{Im} c_{T}^{11} + V_{us} \text{Im} c_{T}^{21} \\
\left( V_{cd} c_{T}^{11} + V_{cs} c_{T}^{21} \right)^2
\]
Constraints on $\Im(c_T)$ (2)

- Cancellation possible through more general flavor structures ($C_{3311}$)

- But nEDM and D-meson mixing probe $\sim$ orthogonal combinations!

Explanation of tau CP asymmetry requires non-trivial conspiracy of couplings
Conclusions

• BaBar measurement of CP asymmetry in $\tau \rightarrow K_S \pi \nu_\tau$ differs from Standard Model at 2.8$\sigma$

• Non-standard explanation from “heavy” new physics runs into trouble
  • It can only come from tensor-vector interference: but “strong phase” is greatly suppressed (Watson’s theorem)
  • It requires large “weak phase” in conflict with neutron EDM and D meson mixing

• If confirmed at Belle-II, this would point to “light” BSM physics
Backup
Effect of final state interactions

- QED corrections \text{\cite{Antonelli et al. 2013}} produce non-vanishing \text{vector–scalar} interference
- Suppressed by
  - $f_0(s)$ vs. $f_+(s)$
  - Kinematics
  - $O(\alpha/\pi)$
- Final estimate
  \[ |A_{CP}^{\tau, BSM}| \lesssim 10^{-4} |\text{Im} \ c_S| \]
- From $\tau \to K_S\pi\nu_\tau$ spectrum: $|\text{Im} \ c_S| \lesssim 1$
  \[ \rightarrow \text{phenomenologically irrelevant} \]
Form factors and kinematics

\[ \langle \bar{K}^0(p_K)\pi^-(p_\pi)|\bar{s}\gamma^\mu u|0 \rangle = (p_K - p_\pi)^\mu f_+(s) + (p_K + p_\pi)^\mu f_-(s), \]

\[ \langle \bar{K}^0(p_K)\pi^-(p_\pi)|\bar{s}u|0 \rangle = \frac{M_K^2 - M_\pi^2}{m_s - m_u} f_0(s), \]

\[ \langle \bar{K}^0(p_K)\pi^-(p_\pi)|\bar{s}\sigma^{\mu\nu} u|0 \rangle = i \frac{p_K^\mu p_\pi^\nu - p_\pi^\mu p_K^\nu}{M_K} B_T(s). \]

\[ f_-(s) = \frac{M_K^2 - M_\pi^2}{s} (f_0(s) - f_+(s)) \]

\[ \xi(s) = \frac{(m_\tau^2 + 2s)\lambda_{\pi K}(s)}{3m_\tau^2(M_K^2 - M_\pi^2)^2} \]

\[ \kappa(s) = G_F^2 |V_{us}|^2 S_{EW} \frac{\lambda_{\pi K}^{3/2}(s)(m_\tau^2 - s)^2}{256\pi^3 m_\tau^2 M_K s^2}. \]

\[ \lambda_{\pi K}(s) = \lambda(s, M_\pi^2, M_K^2) \]

\[ \lambda(a, b, c) = a^2 + b^2 + c^2 - 2(ab + ac + bc) \]
Elastic form factors

\[ f_+(s) = f_+(0) \Omega(s), \quad B_T(s) = B_T(0) \Omega(s), \]

\[ \Omega(s) = \exp \left\{ \frac{s}{\pi} \int_{s_{\pi K}}^{\infty} \frac{\delta(s')}{s'(s' - s)} \right\}. \]
Induced neutron EDM

\[
d_u(\mu) = \frac{e m_\tau V_{us}^2}{v^2} \frac{V_{us}^2}{\pi^2} \text{Im} c_T(\mu) \log \frac{\Lambda}{\mu}
\]

\[
\simeq 3.0 \times \text{Im} c_T(\mu) \log \frac{\Lambda}{\mu} \times 10^{-21} \text{ e cm}
\]

\[
d_n = g_T^u(\mu) d_u(\mu)
\]

\[
g_T^u(\mu = 2 \text{ GeV}) = -0.233(28)
\]

Bhattacharya et al., 1506.04196