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# A no-go theorem for non-standard explanations of the $\tau \to K_S \pi \nu_\tau$ CP asymmetry

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# Outline

- 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 τ decays

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

- Semi-leptonic tau decays offer several possibilities

Bigi 1210.2968

- 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

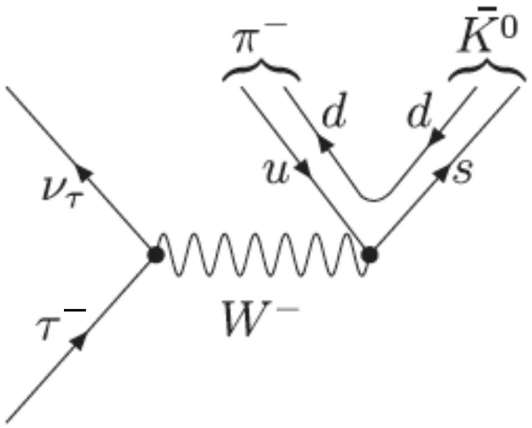
Bigi-Sanda hep-ph/0506037

Grossman-Nir 1110.3790

# $\tau \to K_S \pi \nu_\tau$: 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
  - $\tau^+$ [$\tau^-$] decays into at $K^0$ [$\overline{K}^0$]




  - Reconstruct $K^0(t)$ [$\overline{K}^0(t)$] $\to \pi^+\pi^-$ over a time interval $t_1 < \tau_S < t_2$

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

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# $\tau \to K_S \pi \nu_\tau$: 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**

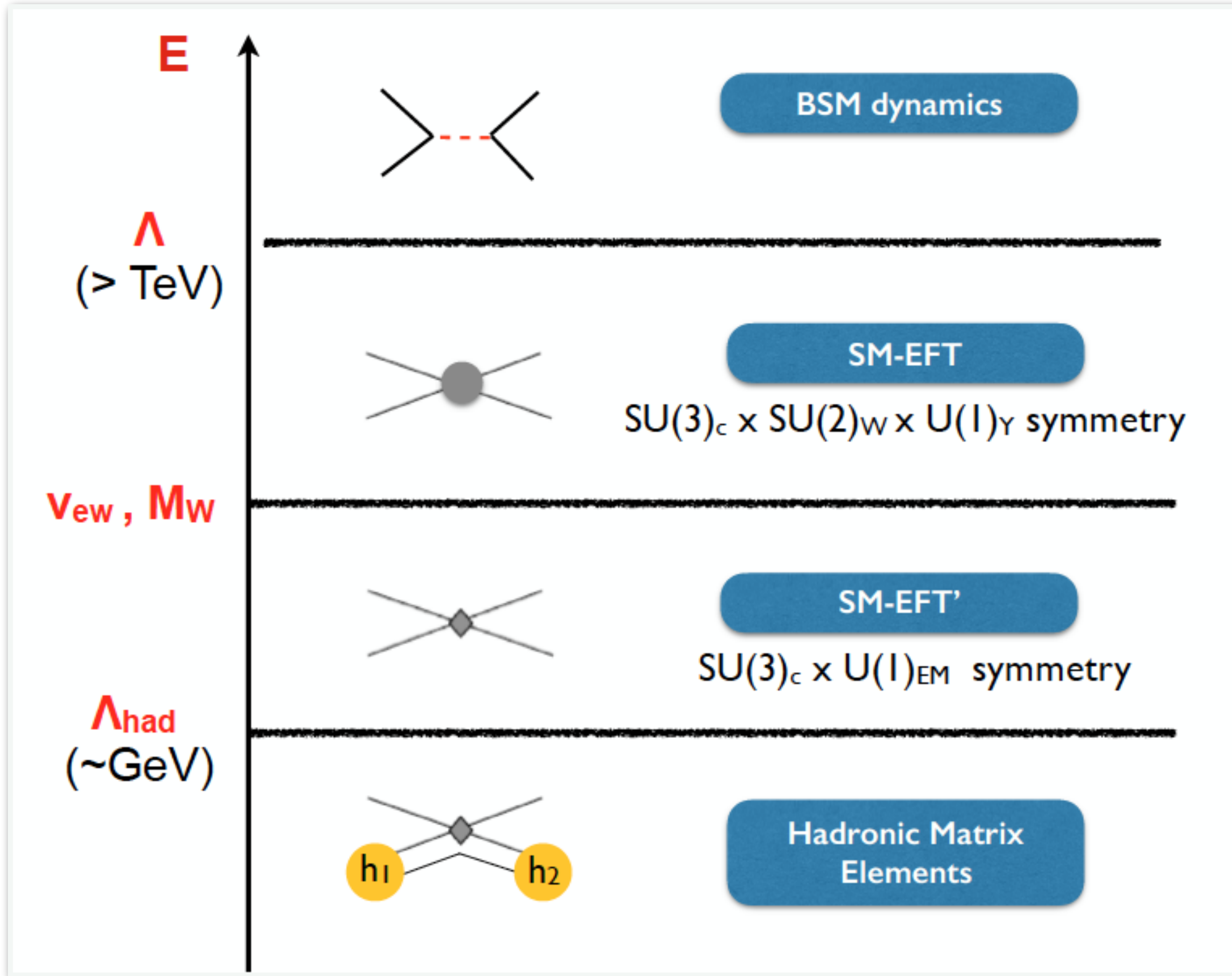
$$A_{CP}^{\tau,\mathrm{SM}} = 3.6(1) \times 10^{-3} \qquad A_{CP}^{\tau,\mathrm{exp}} = -3.6(2.3)(1.1) \times 10^{-3}$$

Taking into account experimental conditions and time-dependent efficiencies

BaBar 1109.1527

# BSM contributions?

- BSM physics can induce direct CP violation
- Parameterize "heavy" new physics contributions through effective Lagrangian
- Relevant terms at the hadronic scale:




$$c_V^{\rm SM} = -c_A^{\rm SM} = +1$$

$$\mathcal{L}_{\rm eff} \supset -\frac{G_F}{\sqrt{2}} V_{us} \Big[ c_V (\bar{s}\gamma^\mu u)(\bar{\nu}\gamma_\mu \ell) + c_A (\bar{s}\gamma^\mu u)(\bar{\nu}\gamma_\mu\gamma_5 \ell)$$

$$+ \; c_S (\bar{s}u)(\bar{\nu}\ell) + i c_P (\bar{s}u)(\bar{\nu}\gamma_5 \ell) + c_T (\bar{s}\sigma^{\mu\nu} u)(\bar{\nu}\sigma_{\mu\nu}(1+\gamma_5)\ell) \Big] + \text{h.c.}$$

# Decay rate and asymmetry

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

$$V(s) = f_+(s) c_V - T(s) \qquad S(s) = f_0(s)\left(c_V + \frac{s}{m_\tau(m_s - m_u)} c_S\right) \qquad T(s) = \frac{3s}{m_\tau^2 + 2s} \frac{m_\tau}{M_K} c_T B_T(s)$$

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

$$A_{CP} \propto |\mathcal{A}_1 + \mathcal{A}_2|^2 - |\bar{\mathcal{A}}_1 + \bar{\mathcal{A}}_2|^2$$
$$= -4 |\mathcal{A}_1| |\mathcal{A}_2| \sin(\delta_1^{\rm s} - \delta_2^{\rm s}) \sin(\delta_1^{\rm w} - \delta_2^{\rm w})$$

$$\mathcal{A}_j = |\mathcal{A}_j| e^{i\delta_j^{\rm s}} e^{i\delta_j^{\rm w}}$$

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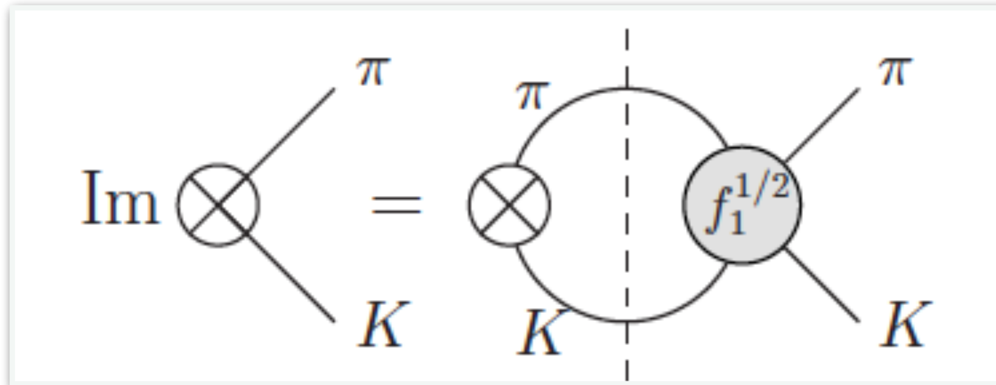
- Vector-scalar interference: no strong phase (same form factor, $f_0(s)$)
- Vector-tensor interference: strong relative phase of $B_T(s)$ and $f_+(s)$

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

Devi et al., 1308.4383

# Tensor form factor




I=1/2
ℓ=1

- Normalization from lattice QCD: $B_T(0)/f_+(0) = 0.678(27)$ Baum et al., 1108.1021
- Phase info from unitarity relations: πK intermediate state contribution

$$\mathrm{Im}\, B_T(s) = \frac{\lambda_{\pi K}^{1/2}(s)}{s} B_T(s) \left(f_1^{1/2}(s)\right)^*$$

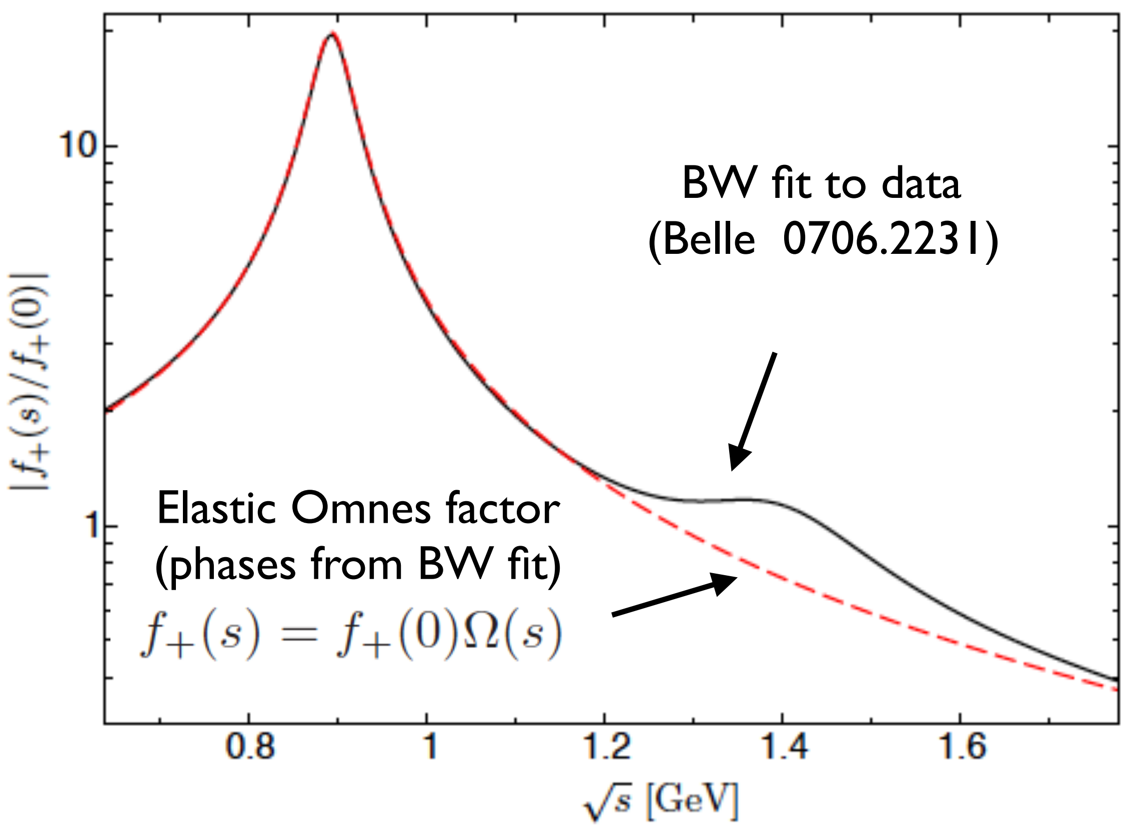
$$\mathrm{Im}\, f_+(s) = \frac{\lambda_{\pi K}^{1/2}(s)}{s} f_+(s) \left(f_1^{1/2}(s)\right)^*$$

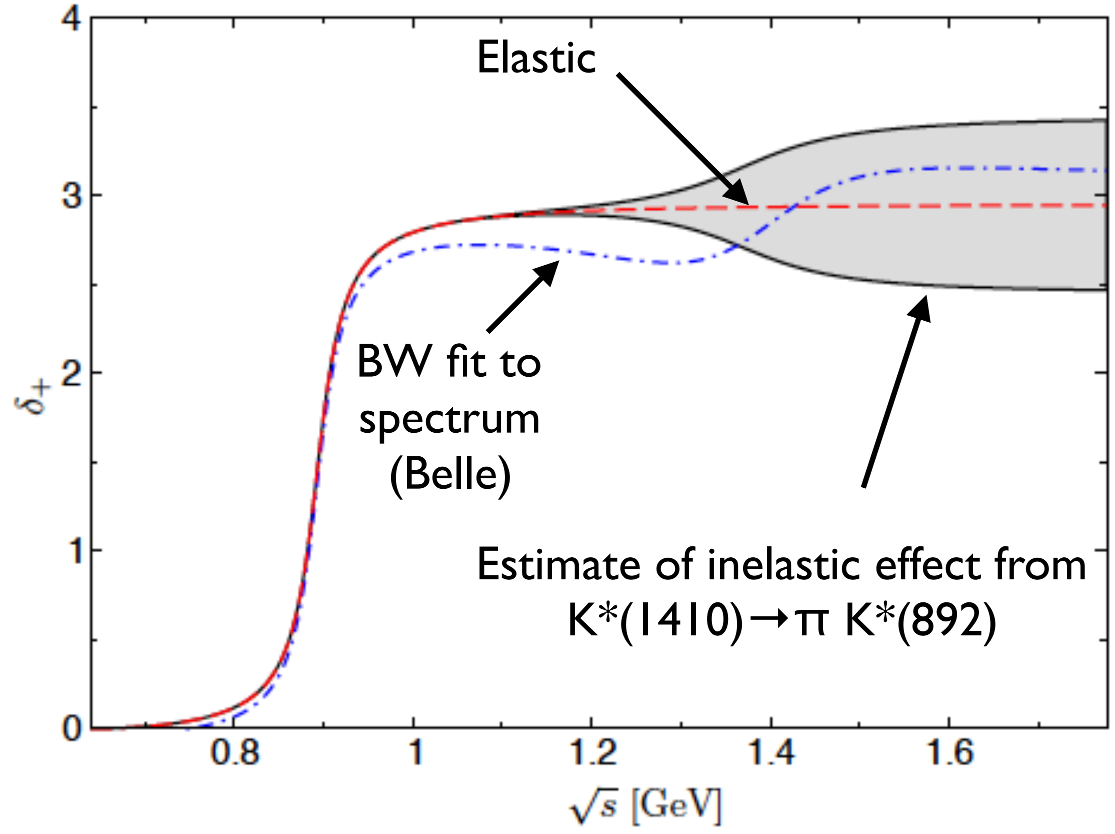
$$\arg B_T(s) = \arg f_+(s) = \delta_1^{1/2}(s)$$

Dominated by K*(892)

Vector-tensor interference vanishes up to inelastic corrections

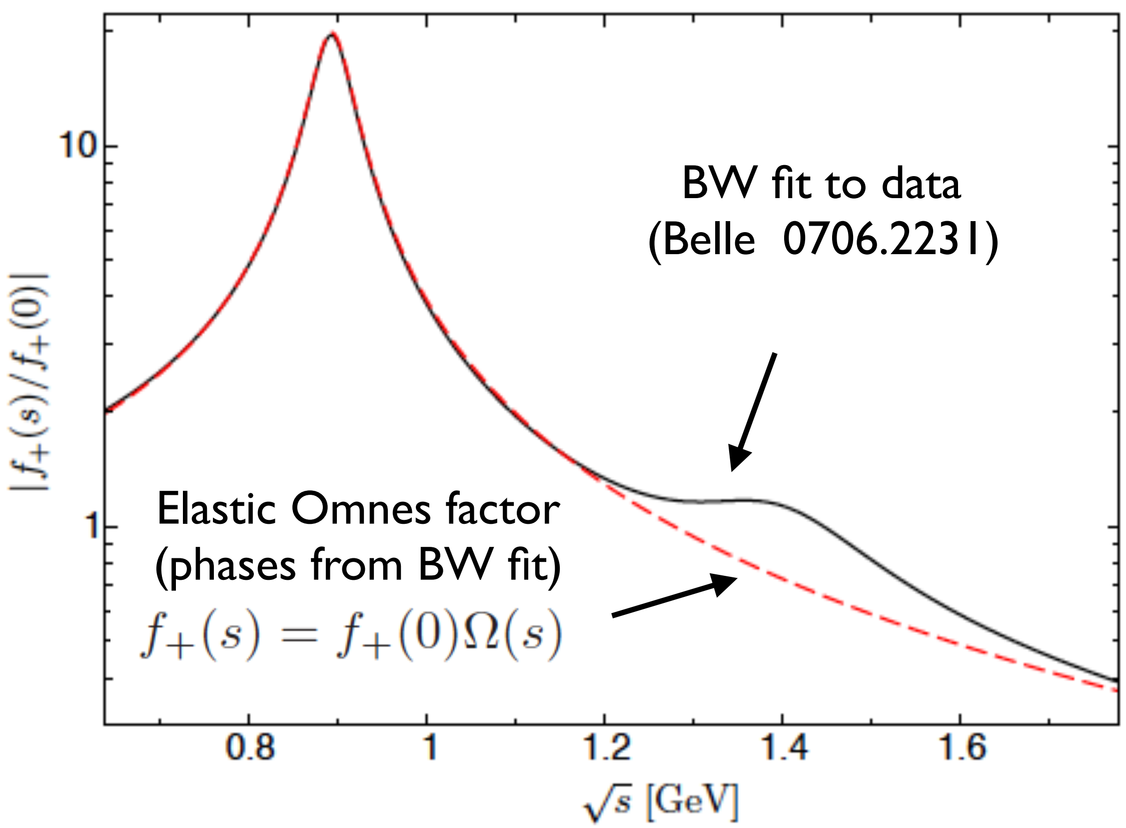
# Estimating inelastic corrections

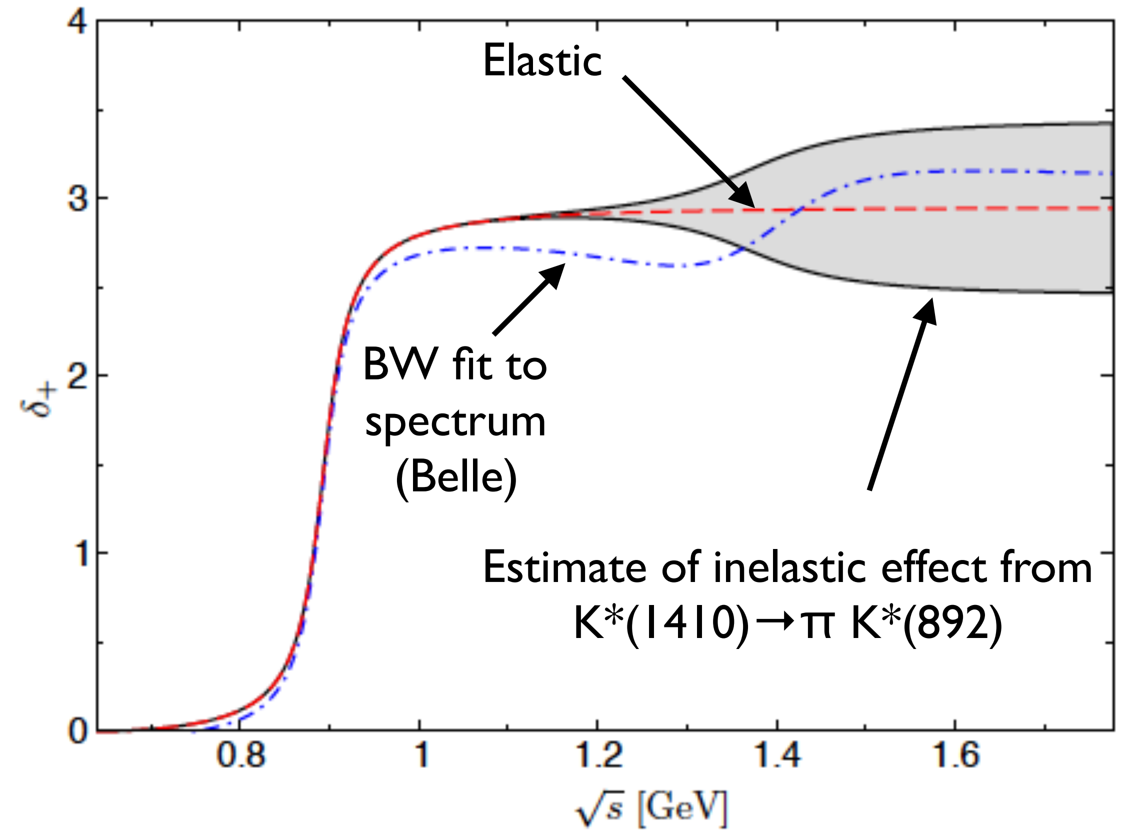



- $f_+(s)$ dominated by elastic K*(892) resonance
- Inelastic corrections around K*(1410)

# Estimating inelastic corrections




- $f_+(s)$ dominated by elastic K*(892) resonance
- Inelastic corrections around K*(1410)
- Assuming $\delta_+(s) - \delta_T(s) \sim 2\delta_+^{inel}(s) \Rightarrow$ $|A_{CP}^{\tau,BSM}| \lesssim 0.03 |\mathrm{Im}\, c_T|$

**~2 orders of magnitude suppression compared to analysis assuming $\delta_T$=0**
**(e.g. Devi et al., 1308.4383)**

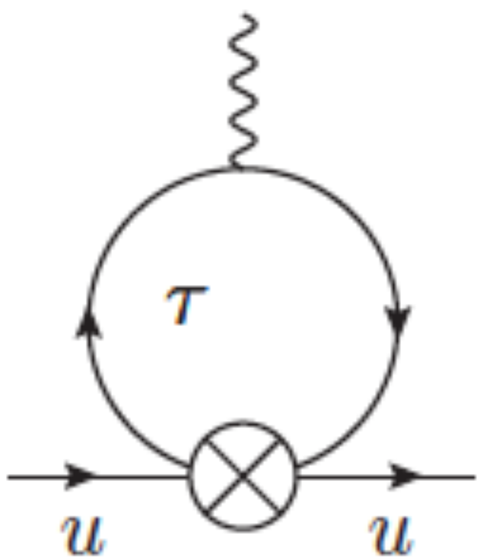
# Constraints on Im($c_T$)

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

$$\mathcal{L}_T = C_{abcd}\, \bar{L}^i_{La}\sigma_{\mu\nu}e_{Rb}\,\epsilon^{ij}\,\bar{q}^j_{Lc}\sigma^{\mu\nu}u_{Rd} \ + \ \text{h.c.} \qquad R = (1+\gamma_5)/2$$

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

Induces u-quark EDM
→ neutron EDM




$$|\text{Im}\, c_T(\mu_\tau)| \leq \frac{4.4\times 10^{-5}}{\log\frac{\Lambda}{\mu_\tau}} \lesssim 10^{-5}$$

Explanation of tau CP asymmetry requires
Im($c_T$) ~ 0.1 ⇒

Need cancellations in nEDM of one part in $10^4$ !

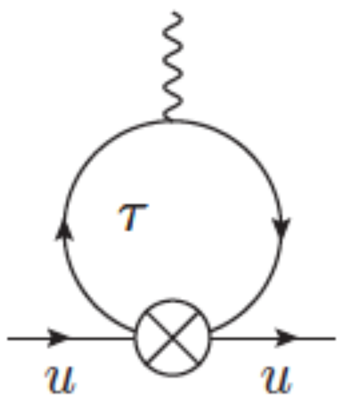
# Constraints on Im($c_T$) (2)

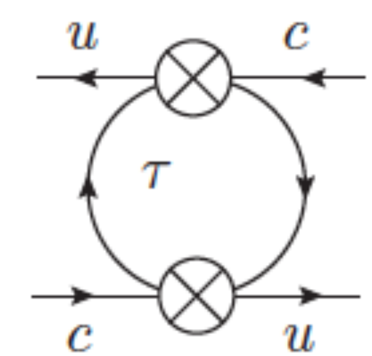
- Cancellation possible through more general flavor structures ($C_{3311}$)

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

$$V_{ud}\mathrm{Im}\, c_T^{11} + V_{us}\mathrm{Im}\, c_T^{21}$$ nEDM

$$\left(V_{cd}c_T^{11} + V_{cs}c_T^{21}\right)^2$$ D mixing



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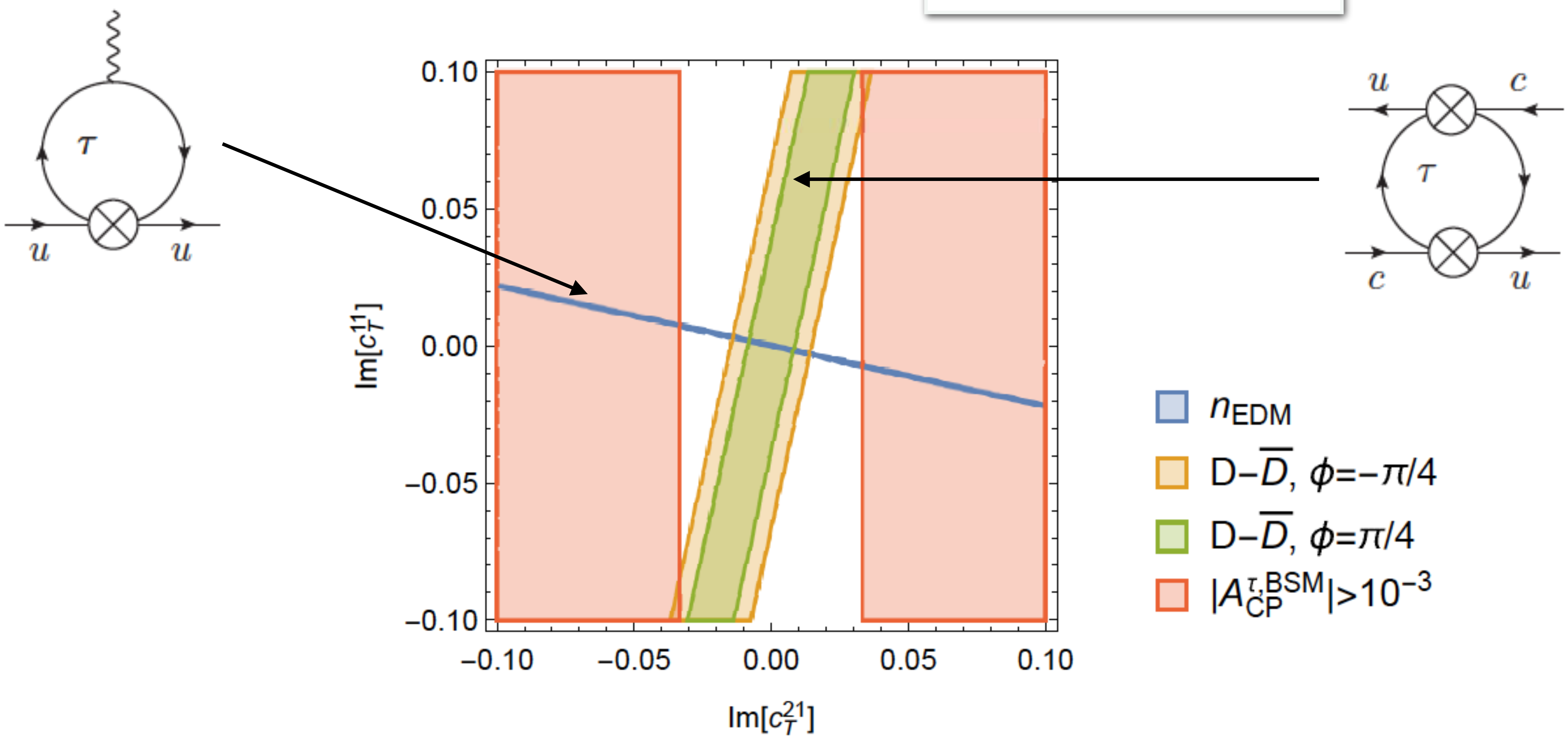


**Explanation of tau CP asymmetry requires non-trivial conspiracy of couplings**

# Conclusions

- BaBar measurement of CP asymmetry in $\tau \to K_S \pi \nu_\tau$ 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 Antonelli et al. 2013 produce non-vanishing **vector–scalar** interference
- Suppressed by
  - $f_0(s)$ vs. $f_+(s)$
  - Kinematics
  - $\mathcal{O}(\alpha/\pi)$
- Final estimate

$$|A_{CP}^{\tau,\text{BSM}}| \lesssim 10^{-4}|\text{Im}\, c_S|$$

- From $\tau \to K_S\pi\nu_\tau$ spectrum: $|\text{Im}\, c_S| \lesssim 1$

$\hookrightarrow$ phenomenologically irrelevant

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# Form factors and kinematics

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

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

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

$$f_-(s) = \frac{M_K^2 - M_\pi^2}{s}\left(f_0(s) - f_+(s)\right)$$

$$\xi(s) = \frac{(m_\tau^2 + 2s)\lambda_{\pi K}(s)}{3m_\tau^2(M_K^2 - M_\pi^2)^2} \qquad \kappa(s) = G_F^2|V_{us}|^2 S_{\rm EW}\frac{\lambda_{\pi K}^{3/2}(s)(m_\tau^2 - s)^2}{256\pi^3 m_\tau^2 M_K s^2}.$$

$$\lambda_{\pi K}(s) = \lambda(s, M_\pi^2, M_K^2) \qquad \lambda(a,b,c) = a^2 + b^2 + c^2 - 2(ab + ac + bc)$$

# Elastic form factors

$$f_+(s) = f_+(0)\Omega(s), \qquad B_T(s) = B_T(0)\Omega(s),$$

$\delta_1^{1/2}(s)$

$$\Omega(s) = \exp\left\{\frac{s}{\pi}\int_{s_{\pi K}}^{\infty}\frac{\delta(s')}{s'(s'-s)}\right\}.$$

# Induced neutron EDM

$$d_u(\mu) = \frac{e m_\tau}{v^2} \frac{V_{us}^2}{\pi^2} \, \mathrm{Im}\, c_T(\mu) \;\log \frac{\Lambda}{\mu}$$
$$\simeq 3.0 \times \mathrm{Im}\, c_T(\mu) \log \frac{\Lambda}{\mu} \times 10^{-21} \, e\,\mathrm{cm}$$

$$d_n = g_T^u(\mu) d_u(\mu)$$

$$g_T^u(\mu = 2\,\mathrm{GeV}) = -0.233(28)$$

Bhattacharya et al., 1506.04196