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CP asymmetries in $\tau \to K_S \pi \nu_\tau$ decays

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based on:

Feng-Zhi Chen, Xin-Qiang Li, Shi-Can Peng, Ya-Dong Yang, Hong-Hao Zhang, JHEP 01 (2022) 108

Feng-Zhi Chen, Xin-Qiang Li, Ya-Dong Yang, JHEP 05 (2020) 151

Feng-Zhi Chen, Xin-Qiang Li, Ya-Dong Yang, Xin Zhang, PRD 100 (2019) 113006

Outline

- ☐ Introduction
- ☐ CP asymmetries in $\tau \to K_S \pi \nu_\tau$ decays within the SM
- ☐ CP asymmetries in $\tau \to K_S \pi \nu_\tau$ decays in a general EFT
- ☐ Summary

$$A_{\rm CP}^{\rm rate} \equiv \frac{\Gamma(\tau^+ \to [\pi^+\pi^-]_{\text{“}K_S\text{”}}\pi^+\bar{\nu}_\tau) - \Gamma(\tau^- \to [\pi^+\pi^-]_{\text{“}K_S\text{”}}\pi^-\nu_\tau)}{\Gamma(\tau^+ \to [\pi^+\pi^-]_{\text{“}K_S\text{”}}\pi^+\bar{\nu}_\tau) + \Gamma(\tau^- \to [\pi^+\pi^-]_{\text{“}K_S\text{”}}\pi^-\nu_\tau)}$$

BaBar Collaboration, PRD 85 (2012) 031102

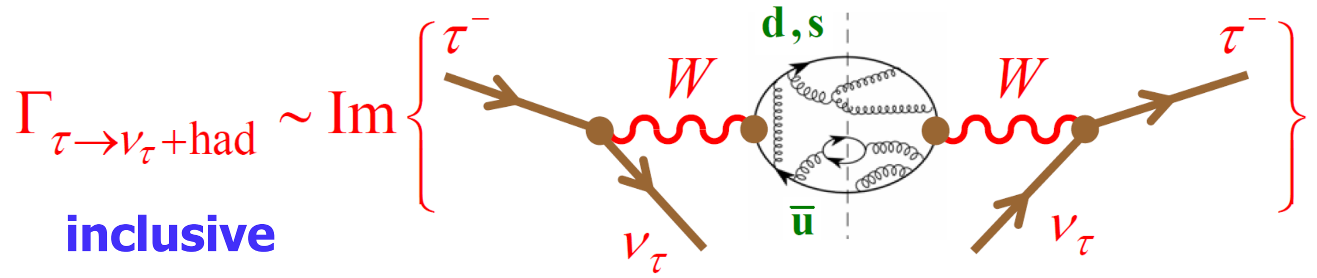
- ➢ commonly discussed decay-rate asymmetry
- ➢ CP asymmetry in the angular distribution

$$A_{CP}^i = \frac{\int_{s_{1,i}}^{s_{2,i}} \int_{-1}^{1} \cos\alpha \left[\frac{d^2\Gamma(\tau^-\to K_S\pi^-\nu_\tau)}{ds\, d\cos\alpha} - \frac{d^2\Gamma(\tau^+\to K_S\pi^+\bar{\nu}_\tau)}{ds\, d\cos\alpha}\right] ds\, d\cos\alpha}{\frac{1}{2}\int_{s_{1,i}}^{s_{2,i}} \int_{-1}^{1} \left[\frac{d^2\Gamma(\tau^-\to K_S\pi^-\nu_\tau)}{ds\, d\cos\alpha} + \frac{d^2\Gamma(\tau^+\to K_S\pi^+\bar{\nu}_\tau)}{ds\, d\cos\alpha}\right] ds\, d\cos\alpha}$$

Belle Collaboration, PRL 107 (2011) 131801

Semi-leptonic (hadronic) tau decays

- **Can be used to extract the fundamental SM parameters: $\alpha_s(m_\tau)$, m_s, $|V_{us}|$, …**

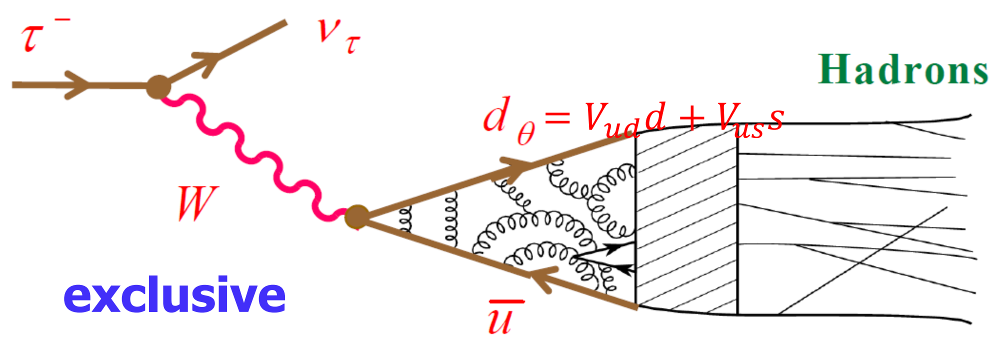


$\alpha_s(m_\tau) = 0.3235^{+0.0138}_{-0.0126}$

RGE ↓ 2203.08271

$\alpha_s(m_Z) = 0.1191 \pm 0.0016$

- **An ideal low-energy QCD-testing laboratory: how QCD currents are hadronized, and further information about the hadronic resonance parameters (M_R, Γ_R), …**



Decay channel	Resonances
$\tau^- \to \pi^-\pi^0\nu_\tau$	$\rho(770), \rho(1450), \rho(1700)$
$\tau^- \to K^-K_S\nu_\tau$	$\rho(770), \rho(1450), \rho(1700)$
$\tau^- \to K_S\pi^-\nu_\tau$	$K^*(892), K^*(1410)$
$\tau^- \to K^-\eta^{(\prime)}\nu_\tau$	$K^*(1410)$
$\tau^- \to \pi^-\eta^{(\prime)}\nu_\tau$	$a_0(980)$

- **Offer further possibilities of studying CPV effects** [I. I. Bigi, 1210.2968; 2111.08126]

Semi-leptonic (hadronic) tau decays

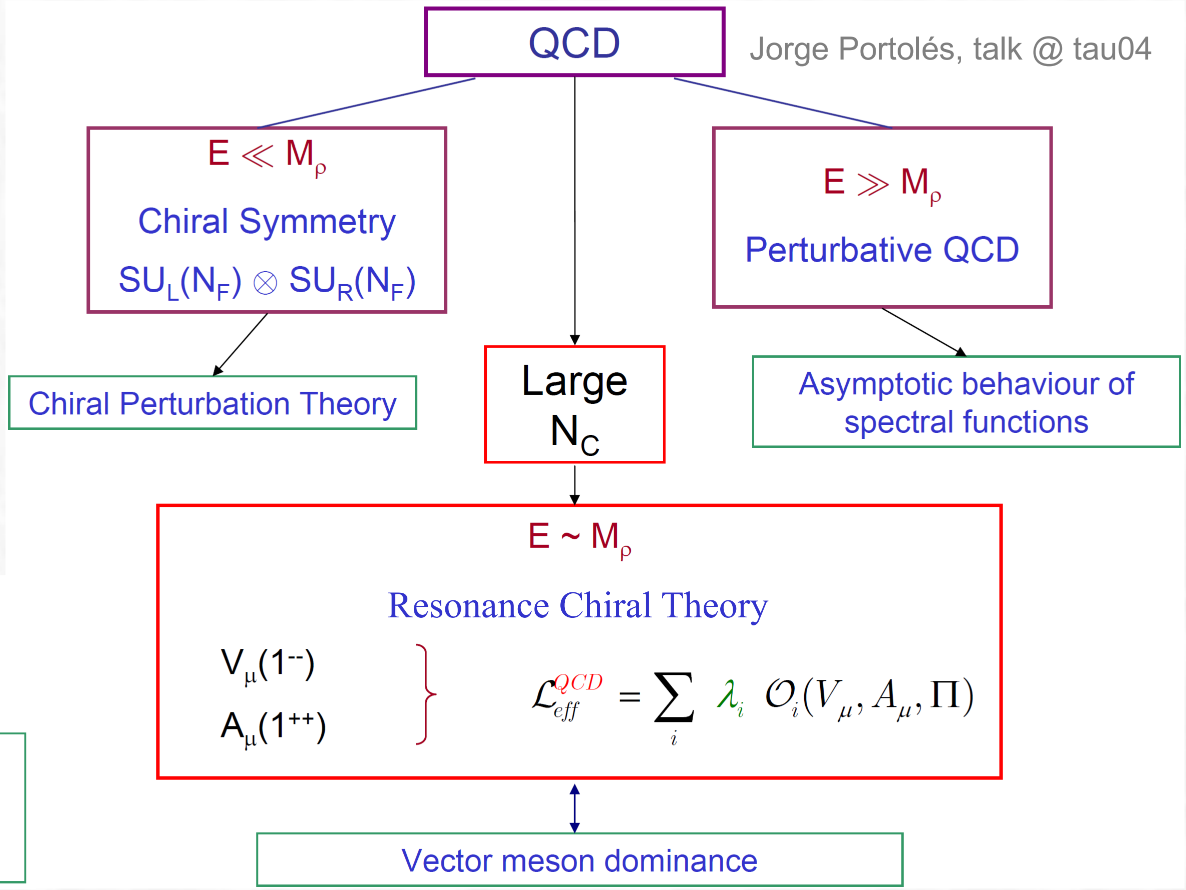
- **For a general hadronic decay, the decay amplitude can be written as:**

$$\mathcal{M}(\tau \to H\nu_\tau) = \frac{G_F}{\sqrt{2}} V_{CKM} [\bar{u}_{\nu_\tau}\gamma^\mu(1-\gamma_5)u_\tau]\, H_\mu$$

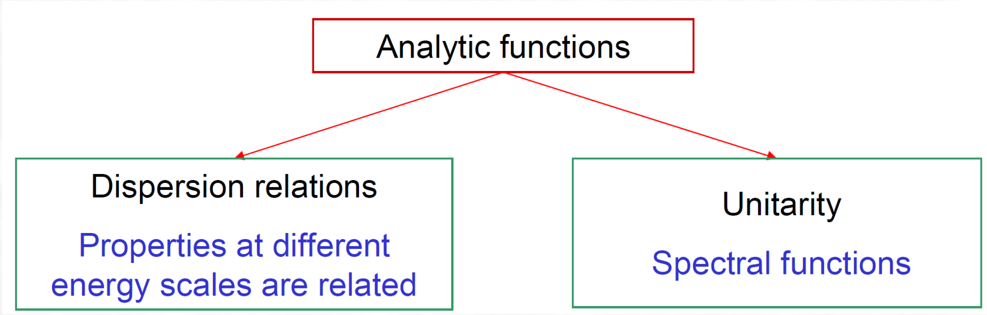
$$H_\mu = \langle H|(\mathcal{V}_\mu - \mathcal{A}_\mu)\, e^{i\mathcal{L}_{QCD}}|0\rangle$$

$$= \sum_i \underbrace{(\ldots\ldots\ldots\ldots\ldots)^i_\mu}_{\text{Lorentz structure}}\ \overbrace{F_i(q^2,\ldots)}^{\text{Form factor}}$$

strong interaction effects

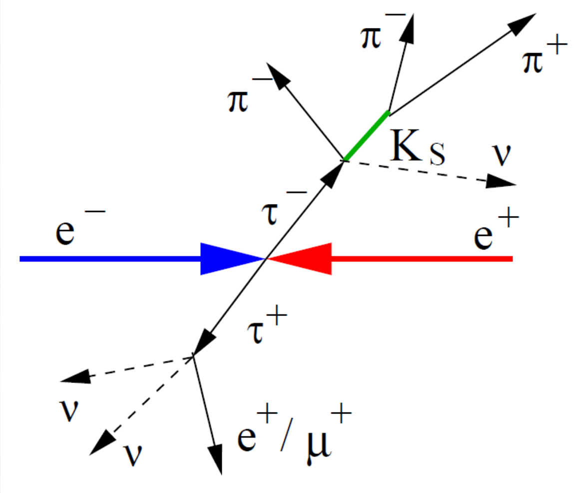


- **Main tasks: determine these FFs**



Why $\tau \to K_S \pi \nu_\tau$ decays

- **Have the largest Br among semi-lep. decays with 1 kaon** [D. Epifanov et al. [Belle], PLB 654 (2007) 65]

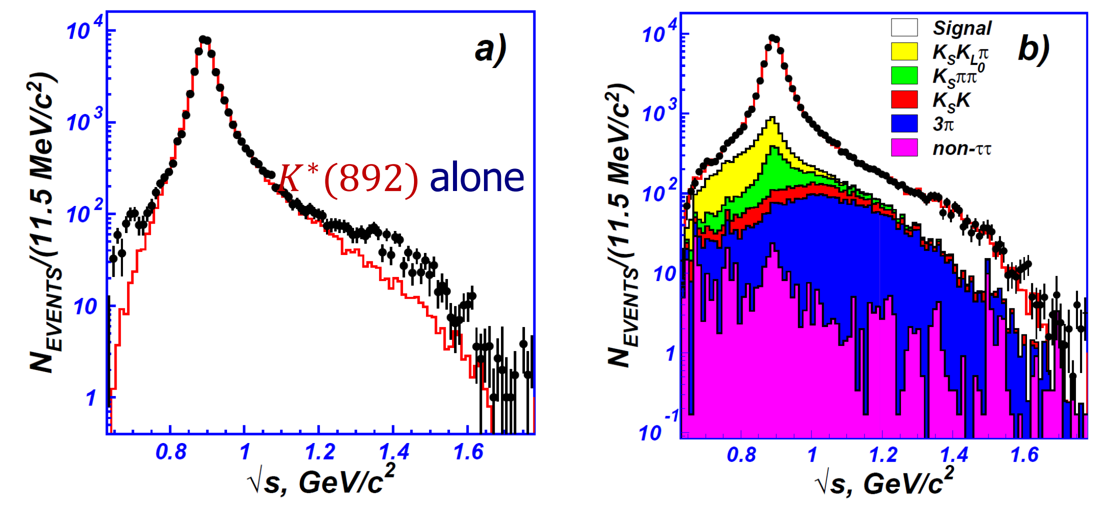


$$\mathbf{Br}(\tau \to K_S \pi \nu_\tau) = (0.404 \pm 0.002(\text{stat.}) \pm 0.013(\text{syst.}))\%$$

- The hadronic currents parametrized by two form factors:

$$J^\mu = F_V(q^2)\left(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}\right)(q_1 - q_2)_\nu + F_S(q^2)q^\mu, \; q^\mu = q_1^\mu + q_2^\mu$$

- The $K^*(892)$ alone not sufficient to describe the $K\pi$ spectrum
- Fitted result with $K^*(892) + K^*(800) + K^*(1410)$ model reproduces data well



- **Promising for searches for CPV both within the SM and beyond** [I. I. Bigi, 1210.2968; 2111.08126]

Why $\tau \to K_S \pi \nu_\tau$ decays

- **Decay-rate asymmetry in $\tau \to K_S \pi \nu_\tau$ decays:**

$$A_{\rm CP}^{\rm rate} \equiv \frac{\Gamma(\tau^+ \to [\pi^+\pi^-]_{\text{“}K_S\text{”}} \pi^+ \bar{\nu}_\tau) - \Gamma(\tau^- \to [\pi^+\pi^-]_{\text{“}K_S\text{”}} \pi^- \nu_\tau)}{\Gamma(\tau^+ \to [\pi^+\pi^-]_{\text{“}K_S\text{”}} \pi^+ \bar{\nu}_\tau) + \Gamma(\tau^- \to [\pi^+\pi^-]_{\text{“}K_S\text{”}} \pi^- \nu_\tau)}$$

2.8σ deviation

$$\begin{cases} A_{\rm CP}^{\rm Exp} = (-3.6 \pm 2.3 \pm 1.1) \times 10^{-3} \\ A_{\rm CP}^{\rm SM} = (3.6 \pm 0.1) \times 10^{-3} \end{cases}$$

BaBar Collaboration, PRD 85 (2012) 031102

I. Bigi and A. I. Sanda PLB 625 (2005) 47
Y. Grossman and Y. Nir, JHEP 04 (2012) 002

- **CP asymmetry in the angular distribution of $\tau \to K_S \pi \nu_\tau$ decays**

$$A_{CP}^i = \frac{\int_{s_{1,i}}^{s_{2,i}} \int_{-1}^{1} \cos\alpha \left[\frac{d^2\Gamma(\tau^- \to K_S \pi^- \nu_\tau)}{ds\, d\cos\alpha} - \frac{d^2\Gamma(\tau^+ \to K_S \pi^+ \bar{\nu}_\tau)}{ds\, d\cos\alpha} \right] ds\, d\cos\alpha}{\frac{1}{2}\int_{s_{1,i}}^{s_{2,i}} \int_{-1}^{1} \left[\frac{d^2\Gamma(\tau^- \to K_S \pi^- \nu_\tau)}{ds\, d\cos\alpha} + \frac{d^2\Gamma(\tau^+ \to K_S \pi^+ \bar{\nu}_\tau)}{ds\, d\cos\alpha} \right] ds\, d\cos\alpha}$$

Belle Collaboration, PRL 107 (2011) 131801

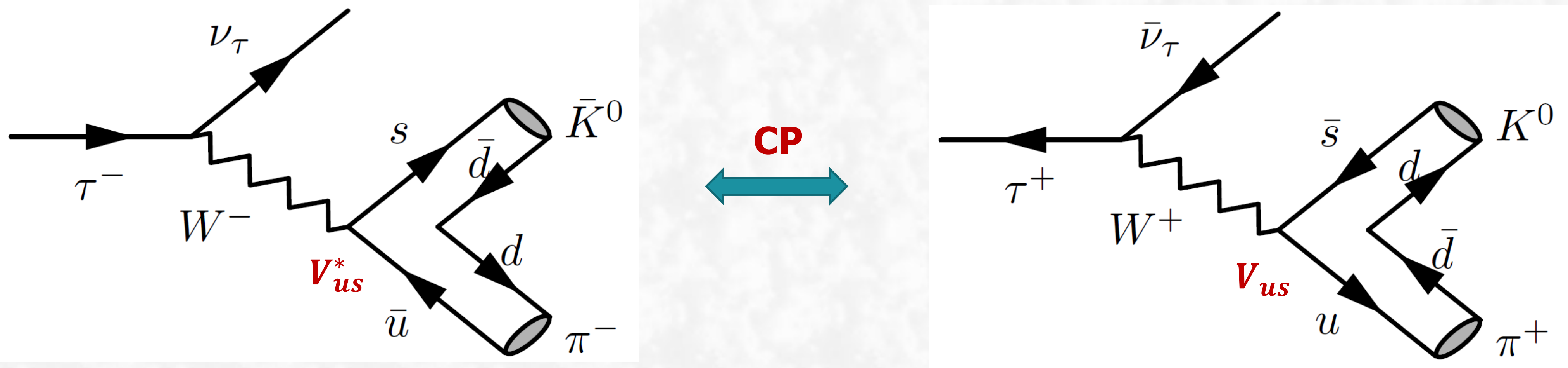
$\sqrt{s}$ [GeV]	$A^{CP}_{{\rm SM},i}$ $[10^{-3}]$	$A^{CP}_{{\rm exp},i}$ $[10^{-3}]$
0.625 − 0.890	0.39 ± 0.01	$7.9 \pm 3.0 \pm 2.8$
0.890 − 1.110	0.04 ± 0.01	$1.8 \pm 2.1 \pm 1.4$
1.110 − 1.420	0.12 ± 0.02	$-4.6 \pm 7.2 \pm 1.7$
1.420 − 1.775	0.27 ± 0.05	$-2.3 \pm 19.1 \pm 5.5$

compatible with zero with a sensitivity of $\mathcal{O}(10^{-3})$

- **Can be used to probe many BSM effects:** $H^{\pm}$, Leptoquark, …

$\tau \to K_S \pi \nu_\tau$ decays within the SM

- **Tree-level Feynman diagrams in weak interaction within the SM:**



- **According to the well-known ΔS = ΔQ rule, τ^- can only decay into $\bar{K}^0$, while τ^+ into K^0**

- **In the SM, V_{us} is real (no weak phase) & the same strong phase between the two CP-related processes**

$$\mathcal{A}(\tau^+ \to K^0 \pi^+ \bar{\nu}_\tau) = \mathcal{A}(\tau^- \to \bar{K}^0 \pi^- \nu_\tau)$$

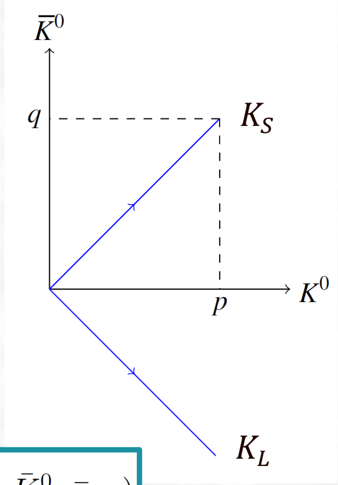
$\tau \to K_S \pi \nu_\tau$ decays within the SM

- **Caution: due to $K^0 - \bar{K}^0$ mixing, the exp. reconstructed kaons are the mass $(|K_S\rangle, |K_L\rangle)$ rather than the flavor $(|K^0\rangle, |\bar{K}^0\rangle)$ eigenstates**

$$|K_S^0\rangle = \frac{(1+\epsilon)|K^0\rangle + (1-\epsilon)|\bar{K}^0\rangle}{\sqrt{2(1+|\epsilon|^2)}}, \qquad |K^0\rangle = \frac{\sqrt{2(1+|\epsilon|^2)}}{2(1+\epsilon)}\left[|K_S^0\rangle + |K_L^0\rangle\right],$$

$$|K_L^0\rangle = \frac{(1+\epsilon)|K^0\rangle - (1-\epsilon)|\bar{K}^0\rangle}{\sqrt{2(1+|\epsilon|^2)}}, \qquad |\bar{K}^0\rangle = \frac{\sqrt{2(1+|\epsilon|^2)}}{2(1-\epsilon)}\left[|K_S^0\rangle - |K_L^0\rangle\right].$$

ϵ: characterizes the amount of CPV in the neutral kaon system



- **In the absence of CPV, $\epsilon = 0$, we have in the SM that :**

$$\mathcal{A}(\tau^+ \to K^0\pi^+\bar{\nu}_\tau) = \mathcal{A}(\tau^- \to \bar{K}^0\pi^-\nu_\tau)$$

$$|K_S\rangle = \frac{|K^0\rangle + |\bar{K}^0\rangle}{\sqrt{2}}, \qquad |K_L\rangle = \frac{|K^0\rangle - |\bar{K}^0\rangle}{\sqrt{2}}$$

$\Rightarrow$

$$\frac{d^2\Gamma(\tau^- \to K_{S,L}\pi^-\nu_\tau)}{ds\, d\cos\alpha} = \frac{1}{2}\frac{d^2\Gamma(\tau^- \to \bar{K}^0\pi^-\nu_\tau)}{ds\, d\cos\alpha}$$

$$\frac{d^2\Gamma(\tau^+ \to K_{S,L}\pi^+\bar{\nu}_\tau)}{ds\, d\cos\alpha} = \frac{1}{2}\frac{d^2\Gamma(\tau^+ \to K^0\pi^+\bar{\nu}_\tau)}{ds\, d\cos\alpha}$$

$\Rightarrow$ **no CP asymmetries in both decay rate & angular distribution**

- **However, CPV in neutral kaon system well established: $|\epsilon| = (2.228 \pm 0.011)\times 10^{-3}$**

$\tau \to K_S \pi \nu_\tau$ decays within the SM

- Once CPV in $K^0 - \bar{K}^0$ mixing considered, non-zero CP asymmetries appear in the decays

- Experimentally, the K_S intermediate states reconstructed via the $\pi^+\pi^-$ final state

- When the kaon decay time is long enough, the $\pi^+\pi^-$ final state can arise not only from K_S, but also from K_L, due to the CPV in $K^0 - \bar{K}^0$ mixing

  → **the interference between K_S & K_L amplitudes important for studying CPV!**

- Time-dependent and doubly differential decay widths:

$$\frac{d^2\Gamma(\tau^- \to K_{S,L}\pi^-\nu_\tau \to [\pi^+\pi^-]\pi^-\nu_\tau)}{ds\, d\cos\alpha} = \frac{d^2\Gamma(\tau^- \to \bar{K}^0\pi^-\nu_\tau)}{ds\, d\cos\alpha}\Gamma(\bar{K}^0(t) \to \pi^+\pi^-),$$
$$\frac{d^2\Gamma(\tau^+ \to K_{S,L}\pi^+\bar{\nu}_\tau \to [\pi^+\pi^-]\pi^+\bar{\nu}_\tau)}{ds\, d\cos\alpha} = \frac{d^2\Gamma(\tau^+ \to K^0\pi^+\bar{\nu}_\tau)}{ds\, d\cos\alpha}\Gamma(K^0(t) \to \pi^+\pi^-),$$

→ s: the $K\pi$ invariant mass squared;

→ α: the angle between the directions of K and τ seen in the $K\pi$ rest frame

Time-dep. CPA in the angular distribution

- **Time-dep. CP asymmetry in the angular distribution:** $(d\omega = ds\,d\cos\alpha)$
  - bin choice $[s_{1,i}, s_{2,i}]$
  - time interval $[t_1, t_2]$
  - exp.-dep. effects parametrized by $F(t)$

$$A_i^{CP}(t_1,t_2) = \frac{\int_{s_{1,i}}^{s_{2,i}}\int_{-1}^{1}\cos\alpha\left[\frac{d\Gamma^{\tau^-}}{d\omega}\int_{t_1}^{t_2}F(t)\bar{\Gamma}_{\pi^+\pi^-}(t)\,dt - \frac{d\Gamma^{\tau^+}}{d\omega}\int_{t_1}^{t_2}F(t)\Gamma_{\pi^+\pi^-}(t)\,dt\right]d\omega}{\frac{1}{2}\int_{s_{1,i}}^{s_{2,i}}\int_{-1}^{1}\left[\frac{d\Gamma^{\tau^-}}{d\omega}\int_{t_1}^{t_2}F(t)\bar{\Gamma}_{\pi^+\pi^-}(t)\,dt + \frac{d\Gamma^{\tau^+}}{d\omega}\int_{t_1}^{t_2}F(t)\Gamma_{\pi^+\pi^-}(t)\,dt\right]d\omega}$$

$$= \frac{\left(\langle\cos\alpha\rangle_i^{\tau^-} + \langle\cos\alpha\rangle_i^{\tau^+}\right)A_K^{CP}(t_1,t_2) + \left(\langle\cos\alpha\rangle_i^{\tau^-} - \langle\cos\alpha\rangle_i^{\tau^+}\right)}{1 + A_K^{CP}(t_1,t_2)\cdot A_{\tau,i}^{CP}}$$

tau decay width weighted by $\cos\alpha$ ⟵

$$\langle\cos\alpha\rangle_i^{\tau^-} + \langle\cos\alpha\rangle_i^{\tau^+} = \frac{\int_{s_{1,i}}^{s_{2,i}}\int_{-1}^{1}\cos\alpha\left[\frac{d\Gamma^{\tau^-}}{d\omega} + \frac{d\Gamma^{\tau^+}}{d\omega}\right]d\omega}{\frac{1}{2}\int_{s_{1,i}}^{s_{2,i}}\int_{-1}^{1}\left[\frac{d\Gamma^{\tau^-}}{d\omega} + \frac{d\Gamma^{\tau^+}}{d\omega}\right]d\omega}$$

$$\langle\cos\alpha\rangle_i^{\tau^-} - \langle\cos\alpha\rangle_i^{\tau^+} = \frac{\int_{s_{1,i}}^{s_{2,i}}\int_{-1}^{1}\cos\alpha\left[\frac{d\Gamma^{\tau^-}}{d\omega} - \frac{d\Gamma^{\tau^+}}{d\omega}\right]d\omega}{\frac{1}{2}\int_{s_{1,i}}^{s_{2,i}}\int_{-1}^{1}\left[\frac{d\Gamma^{\tau^-}}{d\omega} + \frac{d\Gamma^{\tau^+}}{d\omega}\right]d\omega}$$

$$A_K^{CP}(t_1,t_2) = \frac{\int_{t_1}^{t_2}F(t)\left[\bar{\Gamma}_{\pi^+\pi^-}(t) - \Gamma_{\pi^+\pi^-}(t)\right]dt}{\int_{t_1}^{t_2}F(t)\left[\bar{\Gamma}_{\pi^+\pi^-}(t) + \Gamma_{\pi^+\pi^-}(t)\right]dt}$$ ⟶ CPA in kaon decay

$$A_{\tau,i}^{CP} = \frac{\int_{s_{1,i}}^{s_{2,i}}\int_{-1}^{1}\left[\frac{d\Gamma^{\tau^-}}{d\omega} - \frac{d\Gamma^{\tau^+}}{d\omega}\right]d\omega}{\int_{s_{1,i}}^{s_{2,i}}\int_{-1}^{1}\left[\frac{d\Gamma^{\tau^-}}{d\omega} + \frac{d\Gamma^{\tau^+}}{d\omega}\right]d\omega}$$ ⟶ CPA in tau decay

- **Within the SM:**

$$\mathcal{A}(\tau^+ \to K^0\pi^+\bar{\nu}_\tau) = \mathcal{A}(\tau^- \to \bar{K}^0\pi^-\nu_\tau)$$ ⟹

$$\frac{d\Gamma^{\tau^+}}{d\omega} = \frac{d\Gamma^{\tau^-}}{d\omega} \Longrightarrow A_{\tau,i}^{CP} = 0\,,\quad \langle\cos\alpha\rangle_i^{\tau^-} = \langle\cos\alpha\rangle_i^{\tau^+}$$

$$\Downarrow$$

$$A_i^{CP}(t_1,t_2) = 2\,\langle\cos\alpha\rangle_i^{\tau^-}A_K^{CP}(t_1,t_2)$$

Decay-rate asymmetry within the SM

- **Within the SM, since $A_\tau^{CP} = 0$, the direct decay-rate asymmetry is exactly equal to A_K^{CP}:**

$$A_{CP}^{\text{rate}}(t_1,t_2) = \frac{\Gamma_{\tau^+}\int_{t_1}^{t_2} dt F(t)\Gamma\left(K^0(t)\to\pi^+\pi^-\right) - \Gamma_{\tau^-}\int_{t_1}^{t_2} dt F(t)\Gamma\left(\bar{K}^0(t)\to\pi^+\pi^-\right)}{\Gamma_{\tau^+}\int_{t_1}^{t_2} dt F(t)\Gamma\left(K^0(t)\to\pi^+\pi^-\right) + \Gamma_{\tau^-}\int_{t_1}^{t_2} dt F(t)\Gamma\left(\bar{K}^0(t)\to\pi^+\pi^-\right)}$$

$$= \frac{A_\tau^{CP} + A_K^{CP}(t_1,t_2)}{1 + A_\tau^{CP} A_K^{CP}(t_1,t_2)} = A_K^{CP}(t_1,t_2)$$

- $A_K^{CP}(t_1,t_2)$: CPV in $K^0 - \bar{K}^0$ mixing

$$A_K^{\text{CP}}(t_1 \ll \Gamma_S^{-1}, \Gamma_S^{-1} \ll t_2 \ll \Gamma_L^{-1}) \approx -2\text{Re}(\epsilon_K) = -(3.32 \pm 0.06) \times 10^{-3}$$

$$F(t) = \begin{cases} 1 & t_1 < t < t_2 \\ 0 & \text{otherwise.} \end{cases}$$

Y. Grossman and Y. Nir, JHEP 04 (2012) 002

efficiency function $F(t)$ provided by BaBar

$A_{\text{EXP}}^{CP} = (-3.6 \pm 2.3 \pm 1.1)\times 10^{-3}$

[BaBar, PRD 85 (2012) 031102]

- 2.8σ **puzzle still there:** $A_{\text{SM}}^{CP} = (3.6 \pm 0.1)\times 10^{-3}$

Time-dep. CPA in the angular distribution

- **Within the SM, CPA in angular distribution:** $A_i^{CP}(t_1,t_2) = 2\,\langle\cos\alpha\rangle_i^{\tau^-} A_K^{CP}(t_1,t_2)$

$$A_K^{\rm CP}(t_1 \ll \Gamma_S^{-1}, \Gamma_S^{-1} \ll t_2 \ll \Gamma_L^{-1}) \approx -2{\rm Re}(\epsilon_K) = -(3.32 \pm 0.06)\times 10^{-3}$$ **as input!**

- **For $\langle\cos\alpha\rangle_i^{\tau^\pm}$: depending on the two normalized FFs** $\tilde{F}_{+,0}(s) = F_{+,0}(s)/F_+(0)$

$$\langle\cos\alpha\rangle^{\tau^-}(s) = \frac{\int_{-1}^{1}\cos\alpha\left(\frac{d^2\Gamma^{\tau^-}}{ds\,d\cos\alpha}\right)d\cos\alpha}{\int_{-1}^{1}\left(\frac{d^2\Gamma^{\tau^-}}{ds\,d\cos\alpha}\right)d\cos\alpha} = \frac{-2\Delta_{K\pi}\Re e[\tilde{F}_+(s)\tilde{F}_0^*(s)]\lambda^{1/2}(s,M_K^2,M_\pi^2)}{\left|\tilde{F}_+(s)\right|^2\left(1+\frac{2s}{m_\tau^2}\right)\lambda(s,M_K^2,M_\pi^2)+3\Delta_{K\pi}^2\left|\tilde{F}_0(s)\right|^2}$$

$$\langle\bar{K}^0(p_K)\pi^-(p_\pi)\,|\bar{s}\gamma^\mu u|\,0\rangle = \left[(p_K-p_\pi)^\mu - \frac{\Delta_{K\pi}}{s}q^\mu\right]F_+(s) + \frac{\Delta_{K\pi}}{s}q^\mu F_0(s)$$

→ due to interference between vector & scalar FFs

- **Hadronic FFs:**
  - Vector form factor : the thrice-subtracted dispersion representation
    D.R. Boito, R. Escribano and M. Jamin, Eur. Phys. J. C59 (2009) 821

$$F_+(s) = \exp\left\{\lambda'_+\frac{s}{M_{\pi^-}^2} + \frac{1}{2}(\lambda''_+ - \lambda'^2_+)\frac{s^2}{M_{\pi^-}^4} + \frac{s^3}{\pi}\int_{s_{K\pi}}^{s_{cut}} ds'\frac{\delta_+(s')}{(s')^3(s'-s-i\epsilon)}\right\},$$

  - Scalar form factor : the coupled-channel dispersive representation
    M. Jamin, J.A. Oller and A. Pich, Nucl. Phys. B622 (2002) 279

$$F_0^1(s) = \frac{1}{\pi}\sum_{j=1}^{3}\int_{s_j}^{\infty} ds'\frac{\sigma_j(s')F_0^j(s')t_0^{1\to j}(s')^*}{s'-s-i\epsilon}, \ (1\equiv K\pi,\ 2\equiv K\eta,\ \text{and}\ 3\equiv K\eta')$$

For CP studies, the Breit-Wigner form is not applicable, as it violates Watson's theorem and unphysical!

Time-dep. CPA in the angular distribution

- **Numerical results for $A_i^{CP}(t_1, t_2)$ in four mass bins:**

$\sqrt{s}$ [GeV]	$A^{CP}_{SM,i}$ $[10^{-3}]$	$A^{CP}_{exp,i}$ $[10^{-3}]$	n_i/N_s [%]
$0.625 - 0.890$	0.39 ± 0.01	$7.9 \pm 3.0 \pm 2.8$	36.53 ± 0.14
$0.890 - 1.110$	0.04 ± 0.01	$1.8 \pm 2.1 \pm 1.4$	57.85 ± 0.15
$1.110 - 1.420$	0.12 ± 0.02	$-4.6 \pm 7.2 \pm 1.7$	4.87 ± 0.04
$1.420 - 1.775$	0.27 ± 0.05	$-2.3 \pm 19.1 \pm 5.5$	0.75 ± 0.02

SM predictions still below the Belle sensitivity of $\mathcal{O}(10^{-3})$, but expected to be detectable at Belle II, with $\sqrt{70}$ times more sensitive results!

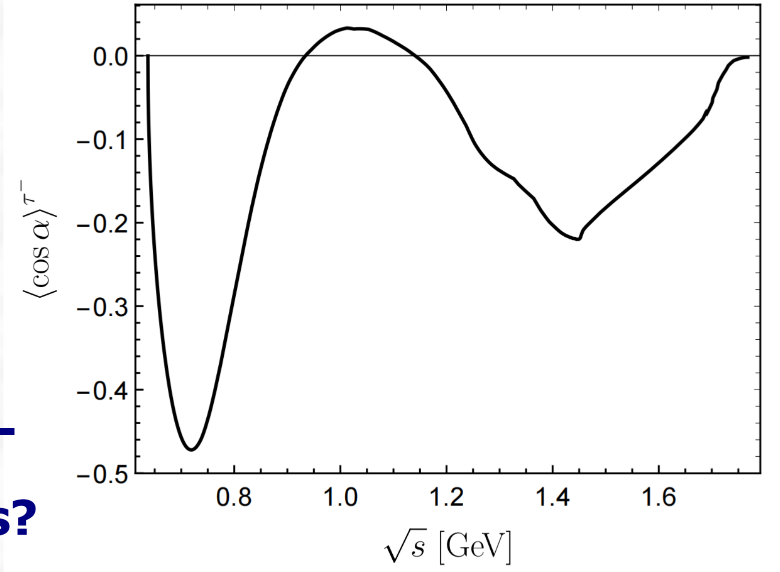
Belle-II, *PTEP* 2019 (2019) 123C01

- **Two more predictions:**

as large as the SM prediction for $A_{CP}^{\rm rate}$

$$A_{\rm SM}^{CP} = (3.6 \pm 0.1) \times 10^{-3}$$

$$A_i^{CP}(t_1, t_2) = \begin{cases} (3.06 \pm 0.06) \times 10^{-3}, & 0.70\,\text{GeV} < \sqrt{s} < 0.75\,\text{GeV} \\ (1.38 \pm 0.18) \times 10^{-3}, & 1.40\,\text{GeV} < \sqrt{s} < 1.50\,\text{GeV} \end{cases}$$



- **Interesting to see if Belle II & STCF can measure the CP-violating angular observables in such two mass intervals?**

$\tau^{\pm} \to K^0(\bar{K}^0)\pi^{\pm}\bar{\nu}_\tau(\nu_\tau)$ in a general EFT

- **When NP presents in tau decays:**

$$\mathcal{A}(\tau^+ \to K^0\pi^+\bar{\nu}_\tau) \neq \mathcal{A}(\tau^- \to \bar{K}^0\pi^-\nu_\tau)$$

$$\frac{d\Gamma^{\tau^+}}{d\omega} \neq \frac{d\Gamma^{\tau^-}}{d\omega} \Longrightarrow A^{CP}_{\tau,i} \neq 0\,, \quad \langle\cos\alpha\rangle_i^{\tau^-} \neq \langle\cos\alpha\rangle_i^{\tau^+}$$

- **CP-violating observables:**

$$A_i^{\rm CP} \simeq \left(\langle\cos\alpha\rangle_i^{\tau^-} + \langle\cos\alpha\rangle_i^{\tau^+}\right) A_K^{\rm CP} + \left(\langle\cos\alpha\rangle_i^{\tau^-} - \langle\cos\alpha\rangle_i^{\tau^+}\right)$$

- **The most general $SU(3)_C \otimes U(1)_{em}$-invariant low-energy effective Lagrangian:**

$$\mathcal{L}_{\rm eff} = -\frac{G_F V_{us}}{\sqrt{2}}\Big\{\bar{\tau}\gamma_\mu(1-\gamma_5)\nu_\tau \cdot \bar{u}\left[\gamma^\mu - (1-2\,\hat{\epsilon}_R)\gamma^\mu\gamma_5\right]s$$

$$+\bar{\tau}(1-\gamma_5)\nu_\tau \cdot \bar{u}\left[\hat{\epsilon}_S - \hat{\epsilon}_P\gamma_5\right]s + 2\,\hat{\epsilon}_T\,\bar{\tau}\sigma_{\mu\nu}(1-\gamma_5)\nu_\tau \cdot \bar{u}\sigma^{\mu\nu}s\Big\} + {\rm h.c.}$$

- **Decay amplitude for $\tau^- \to \bar{K}^0\pi^-\nu_\tau$:**

  scalar operator + tensor operator

$$\mathcal{M} = \mathcal{M}_V + \mathcal{M}_S + \mathcal{M}_T$$

$$= \frac{G_F V_{us}}{\sqrt{2}}\left[L_\mu H^\mu + \hat{\epsilon}_S^* LH + 2\hat{\epsilon}_T^* L_{\mu\nu}H^{\mu\nu}\right]$$

Tensor form factors

- **Leptonic currents:**

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

- **Hadronic matrix elements:**

$$H = \langle \pi^- \overline{K}^0 \mid \bar{s}u \mid 0\rangle = F_S(s)$$
$$H^\mu = \langle \pi^- \overline{K}^0 \mid \bar{s}\gamma^\mu u \mid 0\rangle = Q^\mu F_+(s) + \frac{\Delta_{K\pi}}{s} q^\mu F_0(s)$$
$$H^{\mu\nu} = \langle \pi^- \overline{K}^0 \mid \bar{s}\sigma^{\mu\nu} u \mid 0\rangle = iF_T(s)\,(p_K^\mu p_\pi^\nu - p_\pi^\mu p_K^\nu)$$

- **$K\pi$ tensor FF: due to lack of enough exp. data, the once-subtracted dispersion representation**

$$F_T(s) = F_T(0)\exp\left\{\frac{s}{\pi}\int_{s_{K\pi}}^{\infty} ds' \frac{\delta_T(s')}{s'(s'-s-i\epsilon)}\right\}$$

- **for $F_T(0)$: obtained from the lowest-order $\chi\mathrm{PT}$ with tensor source**

$$\mathcal{L}_4^{\chi\mathrm{PT}} = \Lambda_1 \langle t_+^{\mu\nu} f_{+\mu\nu}\rangle - i\Lambda_2 \langle t_+^{\mu\nu} u_\mu u_\nu\rangle + \Lambda_3 \langle t_+^{\mu\nu} t^+_{\mu\nu}\rangle + \Lambda_4 \langle t_+^{\mu\nu}\rangle^2$$

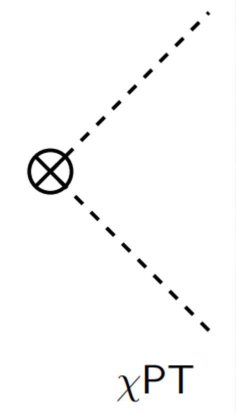
⬇

$$\left\langle \bar{K}^0(p_K)\pi^-(p_\pi)\left|\frac{\delta L_4^{\chi\mathrm{PT}}}{\delta \bar{t}_{\mu\nu}}\right|0\right\rangle = i\frac{\Lambda_2}{F_\pi^2}(p_K^\mu p_\pi^\nu - p_K^\nu p_\pi^\mu)$$

$$F_T(0) = \Lambda_2/F_\pi^2,\ \text{with}\ \Lambda_2 = (11.1 \pm 0.4)\mathrm{MeV}$$

O. Cata and V. Mateu, JHEP 09 (2007) 078

I. Baum *et al.*, PRD 84 (2011) 074503

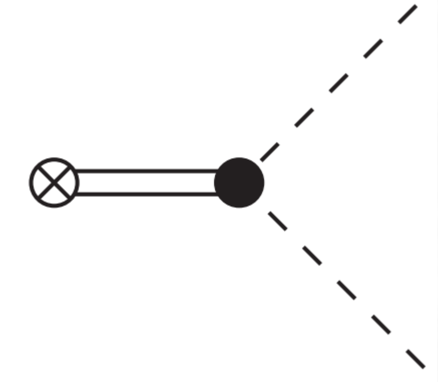


Tensor form factors

- To account for the s-dep. of these FFs, we have included the **two spin-1 resonances** $K^*(892)$ & $K^*(1410)$, both contribute dominantly to $F_+(s)$ & $F_T(s)$

➤ $F_T(s)$: **obtained with RχT including spin-1 resonances**

- $$\mathcal{L}_6^{\mathrm{R}\chi\mathrm{T}} = \mathcal{L}_{kin}(\hat{V}_\mu) - \frac{1}{2\sqrt{2}}\left(f_V\langle\hat{V}_{\mu\nu}f_+^{\mu\nu}\rangle + ig_V\langle\hat{V}_{\mu\nu}[u^\mu, u^\nu]\rangle\right) - f_V^T\langle\hat{V}_{\mu\nu}t_+^{\mu\nu}\rangle$$



Ecker, J. Gasser, H. Leutwyler, A. Pich, and E. de Rafael, PLB 223 (1989) 425

$$F_T(s) = \frac{\Lambda_2}{F_\pi^2}\left[1 + \frac{\sqrt{2}f_V^T g_V}{\Lambda_2}\frac{s}{M_{K^*}^2 - s} + \frac{\sqrt{2}f_V^{T\prime}g_V^\prime}{\Lambda_2}\frac{s}{M_{K^{*\prime}}^2 - s}\right]$$

$$= \frac{\Lambda_2}{F_\pi^2}\left[\frac{M_{K^*}^2 + \beta s}{M_{K^*}^2 - s} - \frac{\beta s}{M_{K^{*\prime}}^2 - s}\right]$$

energy-dep. width $\gamma_n(s)$ →

$$\tilde{F}_T(s) = F_T(s)/F_T(0)$$

$$= \frac{m_{K^*}^2 - \kappa_{K^*}\tilde{H}_{K\pi}(0) + \beta s}{D(m_{K^*}, \gamma_{K^*})} - \frac{\beta s}{D(m_{K^{*\prime}}, \gamma_{K^{*\prime}})}$$

$\beta = \frac{\sqrt{2}f_V^T g_V}{\Lambda_2} - 1 \simeq \pm 0.75\gamma$: characterizes the relative weight of the two resonances, and plays the same role as γ for $F_+(s)$

Feng-Zhi Chen, Xin-Qiang Li, Ya-Dong Yang, Xin Zhang, PRD 100 (2019) 113006

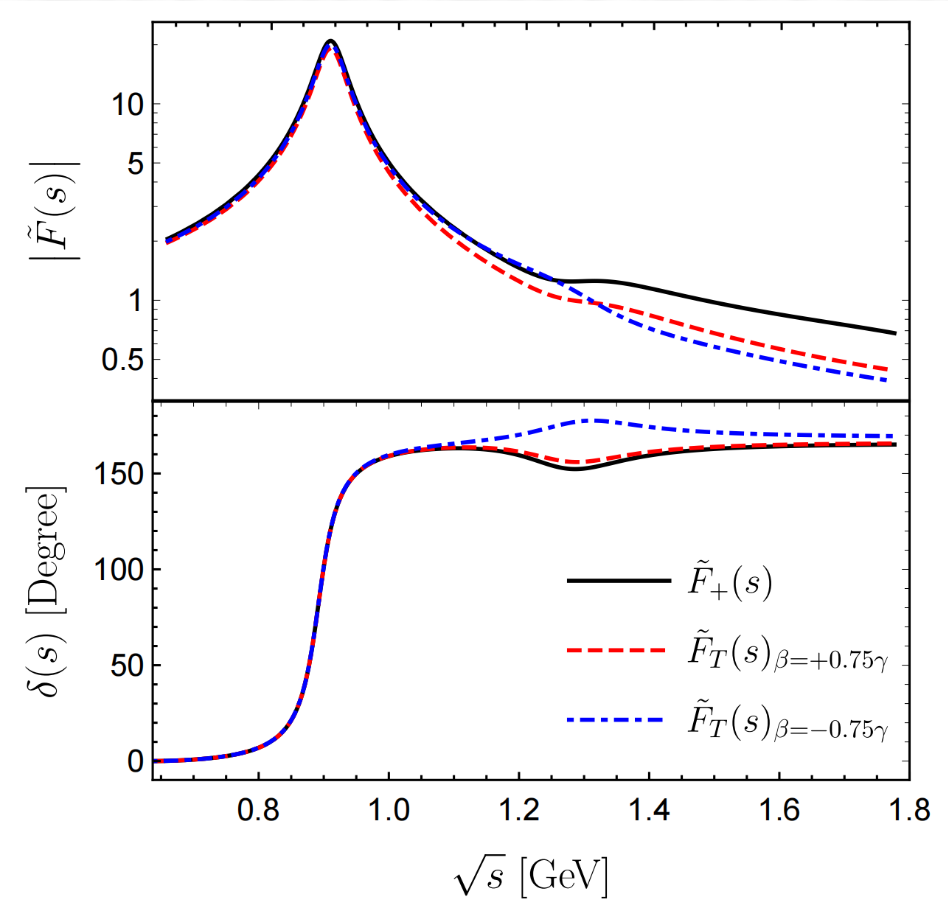
Tensor form factors

- Combining χPT @ low s + RχT @ intermediate s + asymptotic behaviors @ high s, we obtain the once-subtracted dispersion representation:

$$F_T(s) = F_T(0)\exp\left\{\frac{s}{\pi}\int_{s_{K\pi}}^{\infty} ds' \frac{\delta_T(s')}{s'(s'-s-i\epsilon)}\right\}$$

$$\delta_T(s) = \begin{cases} \arctan\left[\frac{\Im m\tilde{F}_T(s)}{\Re e\tilde{F}_T(s)}\right], & s_{K\pi} < s < s_{\text{cut}} \\ n_T\pi, & s \geq s_{\text{cut}} \end{cases}$$

asymptotic $1/s$ as dictated by pQCD



- in elastic region (below ~ 1.2 GeV), $\delta_T(s) = \delta_+(s)$ as required by Watson's theorem [K. M. Watson, Phys. Rev. 95 (1954) 228]

- in inelastic region (above ~ 1.2 GeV), $\delta_T(s)$ and $\delta_+(s)$ start to behave differently due to the different relative weights of the two resonances $K^*(892)$ & $K^*(1410)$

CP-violating observables in the general EFT

- **Decay-rate asymmetry:**

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

only vector-tensor interference as the only possible mechanism

- **CPA in angular distribution:**

$$A_{CP}^i \simeq \Delta_{K\pi}\, S_{\rm EW} \frac{N_s}{n_i} \int_{s_{1,i}}^{s_{2,i}} \left\{ -\frac{{\rm Im}[\hat{\epsilon}_S]}{m_\tau(m_s - m_u)} {\rm Im}[F_+(s)F_0^*(s)] - \frac{2{\rm Im}[\hat{\epsilon}_T]}{m_\tau} {\rm Im}[F_T(s)F_0^*(s)] + \left[\left(\frac{1}{s} + \frac{{\rm Re}[\hat{\epsilon}_S]}{m_\tau(m_s - m_u)}\right) {\rm Re}[F_+(s)F_0^*(s)] - \frac{2{\rm Re}[\hat{\epsilon}_T]}{m_\tau} {\rm Re}[F_T(s)F_0^*(s)]\right] A_K^{CP} \right\} C(s)\, ds\,.$$

both from scalar-vector and scalar-tensor interferences

- **Constraints on ${\rm Re}[\hat{\epsilon}_{S,T}]$: more stringent from decay rates of various exclusive τ decays**

$${\rm Re}[\hat{\epsilon}_S] = (0.8^{+0.8}_{-0.9} \pm 0.3)\%,\ {\rm Re}[\hat{\epsilon}_T] = (0.9 \pm 0.7 \pm 0.4)\%$$

S. Gonzàlez-Solís, A. Miranda, J. Rendón and P. Roig, Phys. Lett. B 804 (2020) 135371

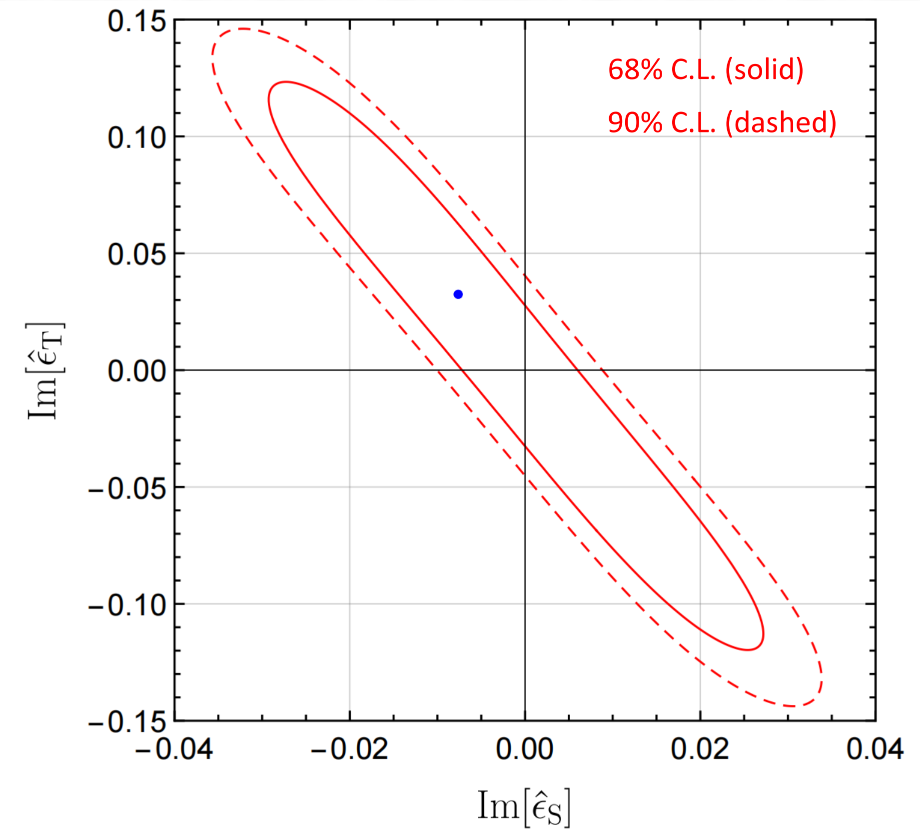
- **Constraints on ${\rm Im}[\hat{\epsilon}_{S,T}]$: more sensitive to these CP-violating observables**

CP-violating observables in general EFT

- **Fit results on $\mathrm{Im}[\hat{\epsilon}_{S,T}]$ from $\mathcal{B}^{\tau^-}_{\mathrm{exp}}$ and $A^{CP}_{\mathrm{exp},i}$ in four different bins from Belle:**

$$\chi^2 = \sum_{i=1}^{4} \left(\frac{A^{CP}_{\mathrm{exp},i} - A^{CP}_{\mathrm{th},i}}{\sigma_i} \right)^2 + \left(\frac{\mathcal{B}^{\tau^-}_{\mathrm{exp}} - \mathcal{B}^{\tau^-}_{\mathrm{th}}}{\sigma_{\mathcal{B}}} \right)^2$$

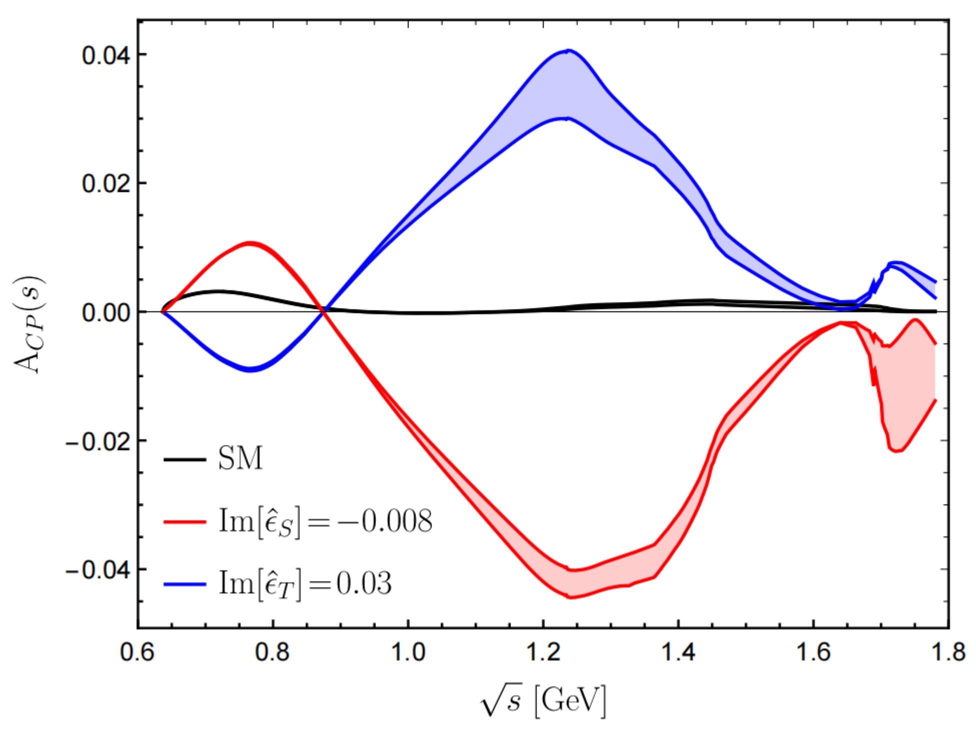
$$\chi^2_{\mathrm{min}} = 4.20, \quad \mathrm{Im}[\hat{\epsilon}_S] = -0.008 \pm 0.027, \quad \mathrm{Im}[\hat{\epsilon}_T] = 0.03 \pm 0.12$$



- remarkably negative correlation between $\mathrm{Im}[\hat{\epsilon}_S]$ & $\mathrm{Im}[\hat{\epsilon}_T]$, as both vector & tensor FFs dominated by $K^*(892)$ and $K^*(1410)$, and hence have almost the same phases, especially in elastic region
- bound on $\mathrm{Im}[\hat{\epsilon}_S]$ consistent with $|\mathrm{Im}(\eta_S)| < 0.026$ @ 90% C.L. obtained by Belle [PRL 107 (2011) 131801]
- upper bound on $\mathrm{Im}[\hat{\epsilon}_T]$ only of $\mathcal{O}(10^{-1})$, much weaker than $2|\mathrm{Im}[\hat{\epsilon}_T]| \leq 10^{-5}$ from neutron EDM & $D^0 - \bar{D}^0$ mixing [V. Cirigliano *et al.*, PRL 120 (2018) 141803]

CP-violating observables in general EFT

- A_i^{CP} in the presence of non-standard scalar & tensor interactions:



- with best-fit values of $\mathrm{Im}[\hat{\epsilon}_S]$ and $\mathrm{Im}[\hat{\epsilon}_T]$, the CPA distributions have almost the same magnitude but opposite in sign in whole $K\pi$ invariant-mass region
- the non-standard scalar & tensor contributions are about one order of magnitude larger than the SM prediction

- **We strongly suggest the future experiments, especially Belle II & STCF, to make more precise measurement of these CP asymmetries in the angular distributions**

Belle-II, *PTEP* **2019** (2019) 123C01; H. Sang, X. Shi, X. Zhou, X. Kang and J. Liu, *CPC* **45** (2021) 053003

Constraints on Im[$\hat{\epsilon}_{S,T}$] from other processes

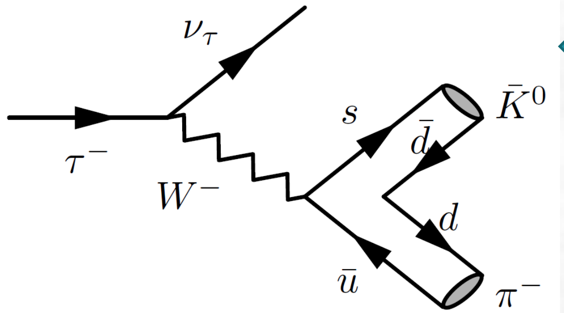
- ☐ **If BSM interactions originate from a weakly-coupled heavy NP well above the EW scale**

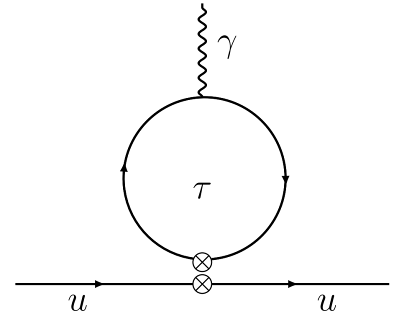
  ↳ **$SU(2)_L$ invariance of $\mathcal{L}_{eff}$ implies other processes to put further limits on Im[$\hat{\epsilon}_{S,T}$]**

- ☐ **For the tensor operator:** $\mathcal{L}_{\rm SMEFT} \supset [C^{(3)}_{\ell equ}]_{klmn} (\bar{\ell}^i_{Lk} \sigma_{\mu\nu} e_{Rl}) \epsilon^{ij} (\bar{q}^j_{Lm} \sigma^{\mu\nu} u_{Rn}) + \text{h.c.}$

  ↓ dim-6 SMEFT operator

$$[C^{(3)}_{\ell equ}]_{klmn} [(\bar{\nu}_{Lk} \sigma_{\mu\nu} e_{Rl})(\bar{d}_{Lm} \sigma^{\mu\nu} u_{Rn}) - V_{am} (\bar{e}_{Lk} \sigma_{\mu\nu} e_{Rl})(\bar{u}_{La} \sigma^{\mu\nu} u_{Rn})] + \text{h.c.}$$





$\tau \to K_S \pi \nu_\tau$ & neutron EDM share the same WC:

$$d_u(\mu) = -2\sqrt{2} G_F \frac{e m_\tau}{\pi^2} V_{us}^2 \, \text{Im}[\hat{\epsilon}_T(\mu)] \log \frac{\Lambda}{\mu}$$

$$[C^{(3)}_{\ell equ}]_{3321} = -2\sqrt{2} G_F V_{us} \hat{\epsilon}^*_T$$

➢ **Assuming the neutron EDM receives contribution only from $\hat{\epsilon}_T$, we get:**

$$|d_n = g_T^u(\mu) d_u(\mu)| < 1.8\times10^{-26} e \text{ cm} \Rightarrow |\text{Im}[\hat{\epsilon}_T]| \leq \frac{1.5\times10^{-5}}{\ln\left(\frac{\Lambda}{\mu_\tau}\right)} \lesssim 4\times10^{-6} \text{ for } \Lambda \gtrsim 100\text{GeV} \ \& \ \mu_\tau = 2\text{GeV}$$

nEDM collaboration, PRL 124 (2020) 081803

$A^i_{CP}|_{\max} \sim \mathcal{O}(10^{-6})$ ← **strongest limit obtained so far!**

Constraints on $\mathrm{Im}[\hat{\epsilon}_{S,T}]$ from other processes

- **Caveat: tensor operator $(\bar{\tau}\sigma_{\mu\nu}\tau_R)(\bar{u}_L\sigma^{\mu\nu}u_R)$ can also associate with the WC combination**

$$V_{ud}\,\mathrm{Im}[C^{(3)}_{\ell equ}]_{3311} + V_{us}\,\mathrm{Im}[C^{(3)}_{\ell equ}]_{3321} = 2\sqrt{2}G_F\left(V_{ud}^2\,\mathrm{Im}[\epsilon_T]_{3311} + V_{us}^2\,\mathrm{Im}[\epsilon_T]_{3321}\right)$$

$$d_u(\mu) = -2\sqrt{2}G_F\,\frac{em_\tau}{\pi^2}\left(V_{ud}^2\,\mathrm{Im}[\epsilon_T]_{3311} + V_{us}^2\,\mathrm{Im}[\epsilon_T]_{3321}\right)\log\frac{\Lambda}{\mu}$$

- when delicate cancellation exists between them, stringent limit on $\mathrm{Im}[\hat{\epsilon}_T]$ can be diluted

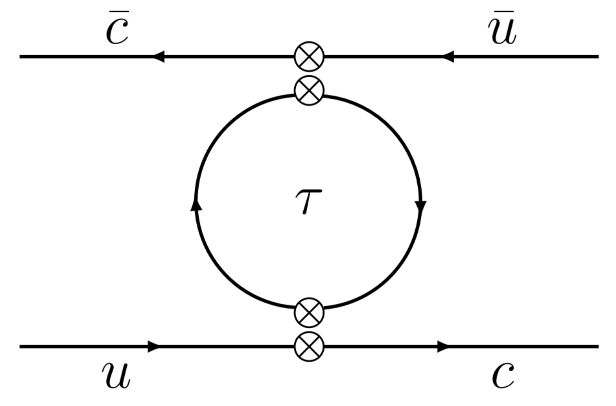
- **In this case, another interesting constraint on $(\bar{\tau}\sigma_{\mu\nu}\tau_R)(\bar{c}_L\sigma^{\mu\nu}u_R)$ from $D^0-\bar{D}^0$ mixing:**

$$V_{cd}[C^{(3)}_{\ell equ}]_{3311} + V_{cs}[C^{(3)}_{\ell equ}]_{3321} = V_{ud}V_{cd}[\epsilon_T]_{3311} + V_{us}V_{cs}[\epsilon_T]_{3321}$$

double insertion

$$M_{12}^{\mathrm{NP}} = \frac{1}{2M_D}\left[C_2'(\mu)\langle D^0|(\bar{c}_L^\alpha u_R^\alpha)(\bar{c}_L^\beta u_R^\beta)|\bar{D}^0\rangle(\mu) + C_3'(\mu)\langle D^0|(\bar{c}_L^\alpha u_R^\beta)(\bar{c}_L^\beta u_R^\alpha)|\bar{D}^0\rangle(\mu)\right]$$

$$C_2' = \frac{1}{2}C_3' = 16G_F^2\,\frac{m_\tau^2}{\pi^2}\left(V_{ud}V_{cd}\,[\epsilon_T]_{3311} + V_{us}V_{cs}\,[\epsilon_T]_{3321}\right)^2\log\frac{\Lambda}{\mu_\tau}$$



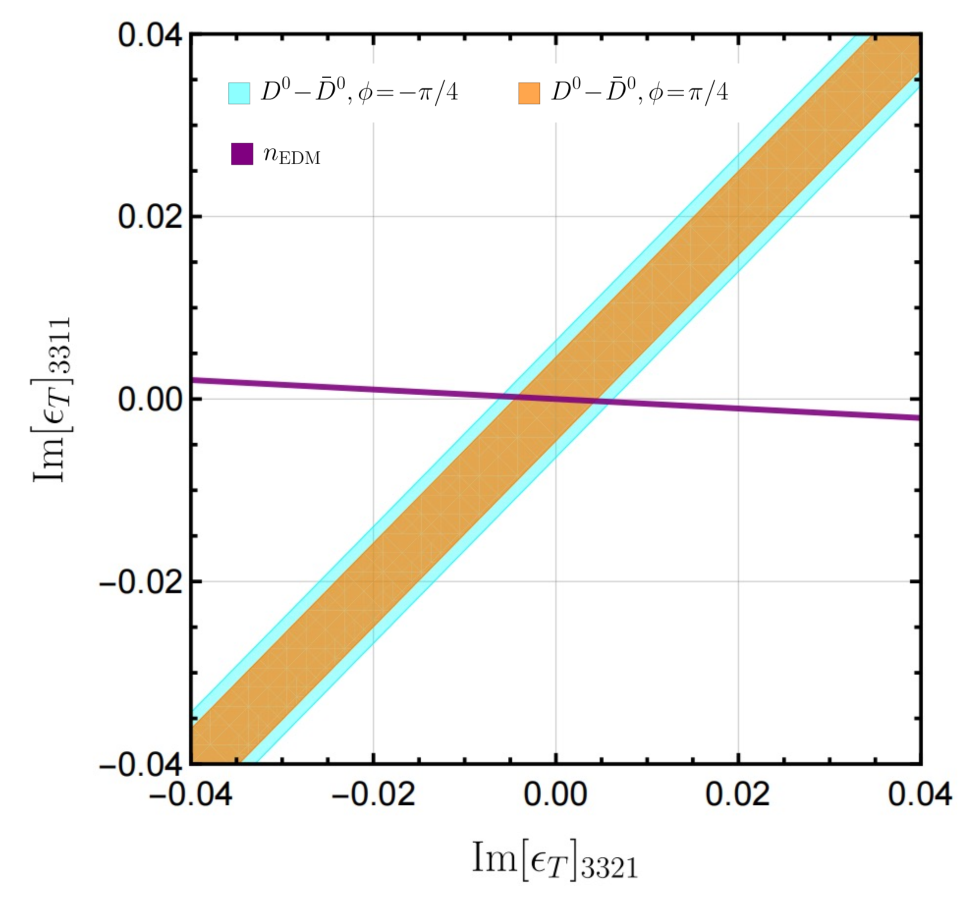
$$x_{12} = \frac{2|M_{12}|}{\Gamma_D} = (0.409 \pm 0.048)\%, \qquad \phi_{12} = \arg\left(\frac{M_{12}}{\Gamma_{12}}\right) = (0.58^{+0.91}_{-0.90})^{\mathrm{o}}$$

we can get further constraint on $\mathrm{Im}[\hat{\epsilon}_T]$!

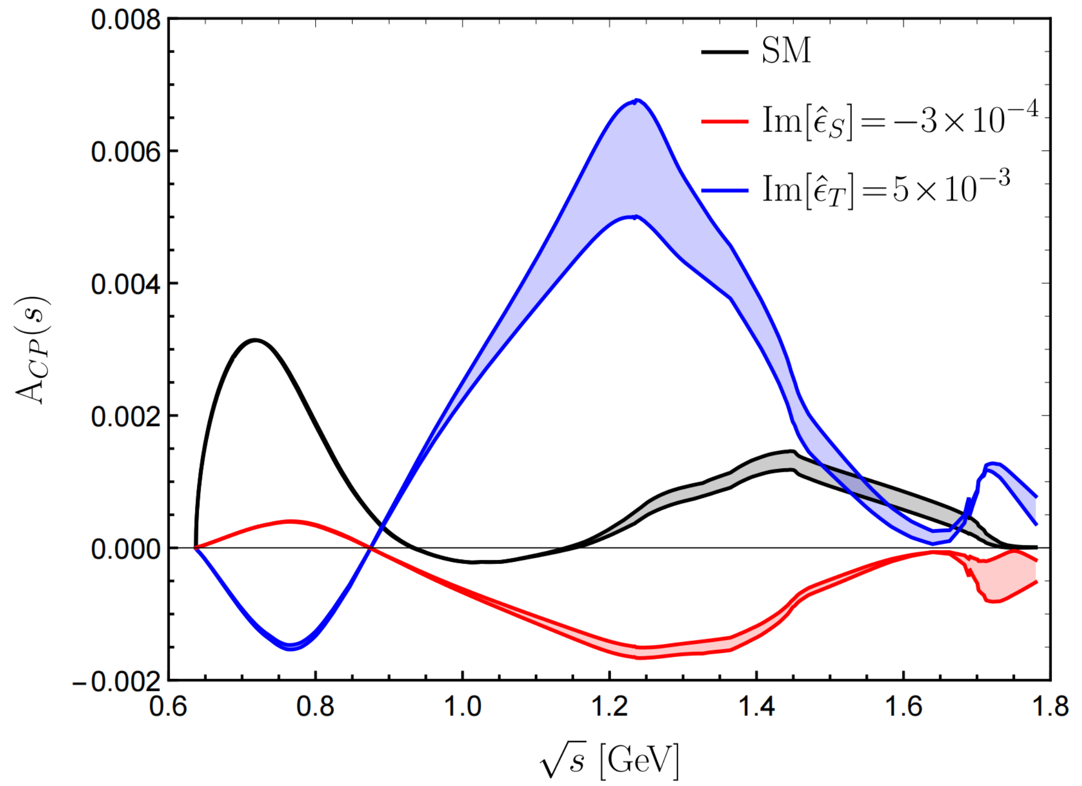
Constraints on $\mathrm{Im}[\hat{\epsilon}_{S,T}]$ from other processes

- **Combined constraints from d_n & $D^0 - \bar{D}^0$ mixing:**

$|\mathrm{Im}[\hat{\epsilon}_T]| \lesssim 4\times 10^{-6}$



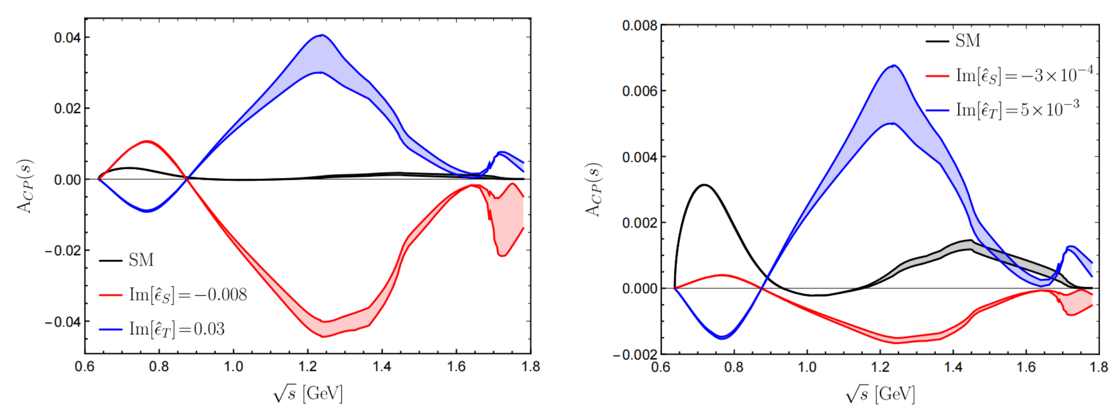
➢ upper limit: $|\mathrm{Im}[\epsilon_T]| \sim 5\times 10^{-3}$, significantly diluted



- **Prediction for CPA with $|\mathrm{Im}[\epsilon_T]| = 5\times 10^{-3}$:** ***still has a significant impact on the CPA!***

Summary

- $\tau \to K_S \pi \nu_\tau$ **decays: very promising for CP studies**
  - In the SM, there exist both decay-rate asymmetry & CP asymmetry in angular distribution due to CPV in $K^0 - \bar{K}^0$ mixing, with results of $\mathcal{O}(10^{-3})$ and detectable @ Belle II & STCF
  - Within a general EFT, only vector-tensor interference produces a direct decay-rate asymmetry, while both scalar-vector & scalar-tensor interferences possible for CPA in the angular distribution
- **With other bounds considered, 2.8σ deviation for A_{CP}^{rate} not easily explained by heavy NP**
- **CP asymmetry in the angular distribution in three different cases:**



sensitive to BSM scalar & tensor interactions!

- **Measurable @ Belle II & STCF?**

Thank you for your attention!

Backup

Tau lepton physics

- τ : **discovered in 1975 by Martin Perl *et al.* (SLAC-LBL)**
  - Mass: $m_\tau = 1776.86 \pm 0.12\ \mathrm{MeV}$
  - Lifetime: $\tau_\tau = (2.903 \pm 0.005)\times 10^{-13}\mathrm{s}$

PDG 2023

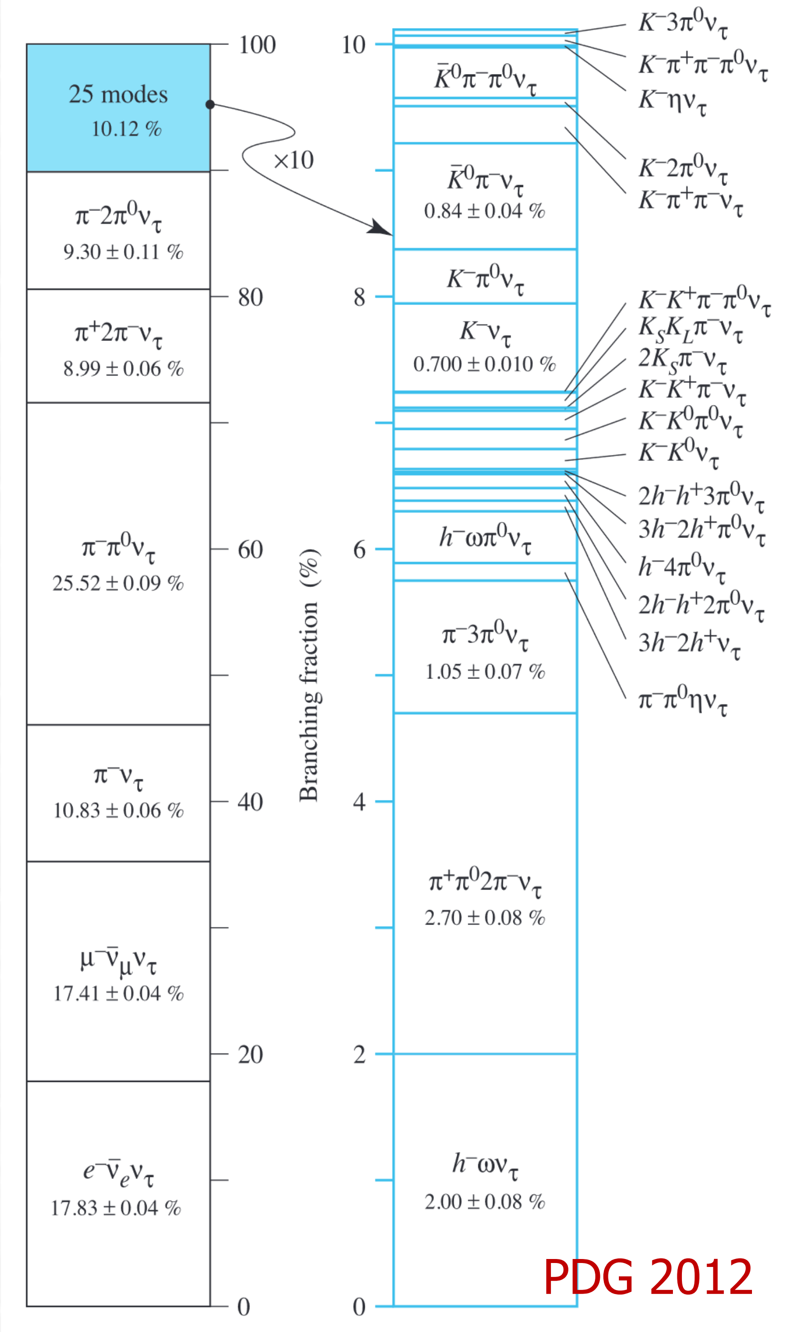
- **In SM, tau decays via charged-current weak interaction:**
  - purely leptonic: $\tau \to \nu_\tau \ell \bar{\nu}_\ell$, $\tau \to \nu_\tau \ell \bar{\nu}_\ell \gamma$, …
  - semi-leptonic (hadronic): $\tau \to \nu_\tau \pi$, $\tau \to \nu_\tau K\pi$, …
  - rare and forbidden: LFV, LNV, BNV, …

six modes account for 90%, 25 modes for the last 10%

- τ : **the only lepton heavy enough to decay into hadrons:**

$$\mathrm{Br} \simeq 66\%!$$

- **Very rich phenomenology: see *biennial tau workshops!***



Experimental facilities for tau physics

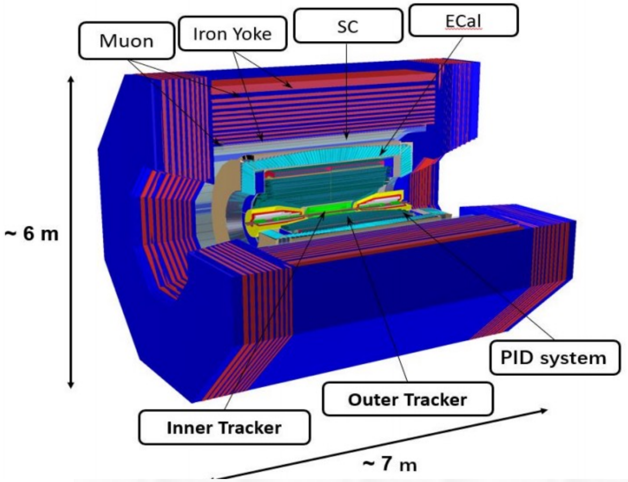
- **Many dedicated facilities, with large tau samples** [C. Z. Yuan, talk @ IAS Program on HEP 2021]

Experiment	Integrated luminosity (fb^{-1})	Cross section (nb)	Number of produced τ pairs (10^9)	Typical tag efficiency	Tagged τ pairs (10^9)	Fraction of Non-τ background
BESIII	50	0 ~ 3.6	~ 0.15	10%	0.015	<1%
BaBar+Belle	1,500	0.9	1.35	33%	0.45	8%
LEP (ALEPH, DELPHI, L3, OPAL)	0.20×4	1.5	0.0012	79% (ALEPH), 92% within $\lvert\cos\theta\rvert<0.90$	0.0007	1.2% (ALEPH)
STCF/SCT	10,000	2.5	25	10%=BESIII	1.5	<1%=BESIII
Belle II	50,000	0.9	45	33%=Belle	15	8%=Belle
CEPC	45,000	1.5	70	87% (↑10% over ALEPH)	60	<1.2%@ALEPH
FCC-ee	115,000	1.5	170	87% (↑10% over ALEPH)	150	<1.2%@ALEPH

- **With these large tau samples, lots of tau physics projects: see *biennial tau workshops!***

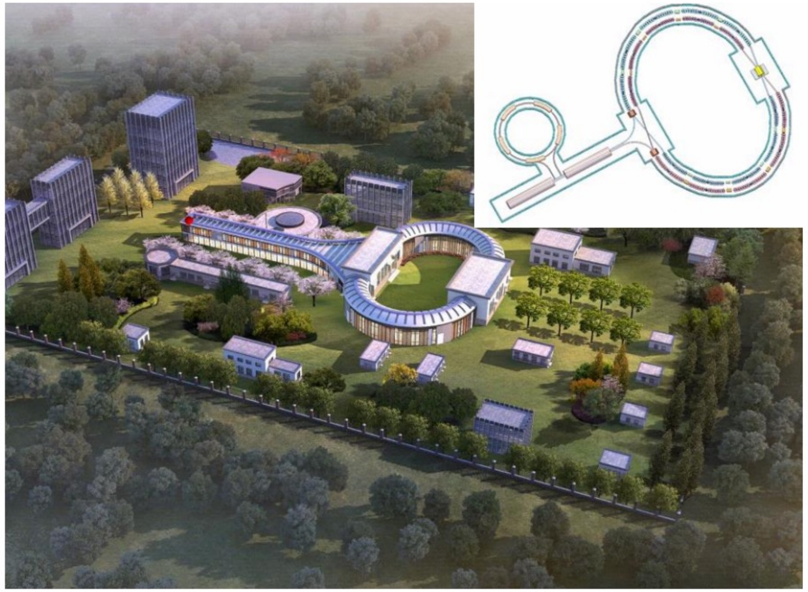
Super Tau-Charm Facility (STCF) in China

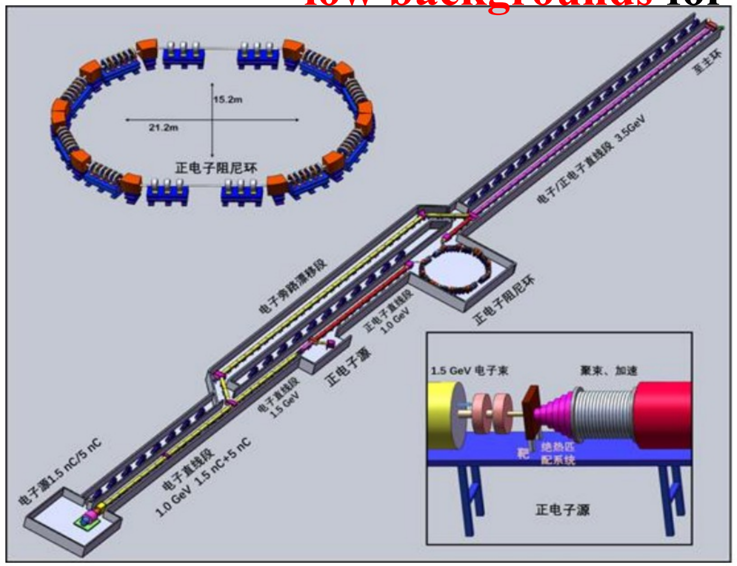
- Peaking luminosity >0.5×10^{35} $cm^{-2}s^{-1}$ at 4 GeV
- Energy range E_{cm} = 2-7 GeV
- Potential to increase luminosity and realize beam polarization
- A nature extension and a viable option for China accelerator project in the post BEPCII/BESIII era



expected to have higher detection efficiency and low backgrounds for productions at threshold

excellent resolution, kinematic constraining





1 ab^{-1} data expected per year

Xiaorong Zhou, talk @ charm 2020

The CPV sensitivity with 1ab^{-1} @ 4.26 GeV[1]:

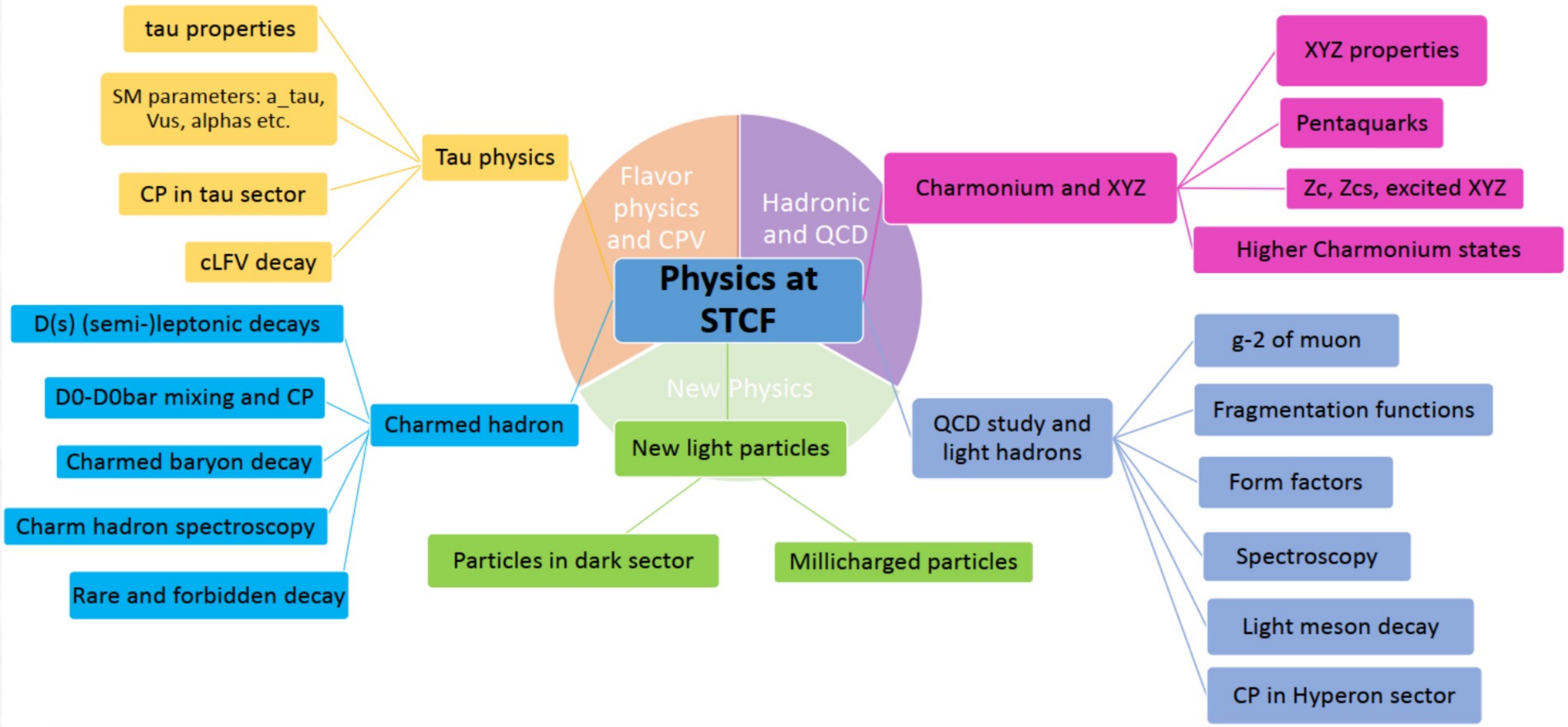
$A_{STCF} \sim 9.7 \times 10^{-4}$

With 10 ab^{-1} data:

$A_{STCF} \sim 3.1 \times 10^{-4}$

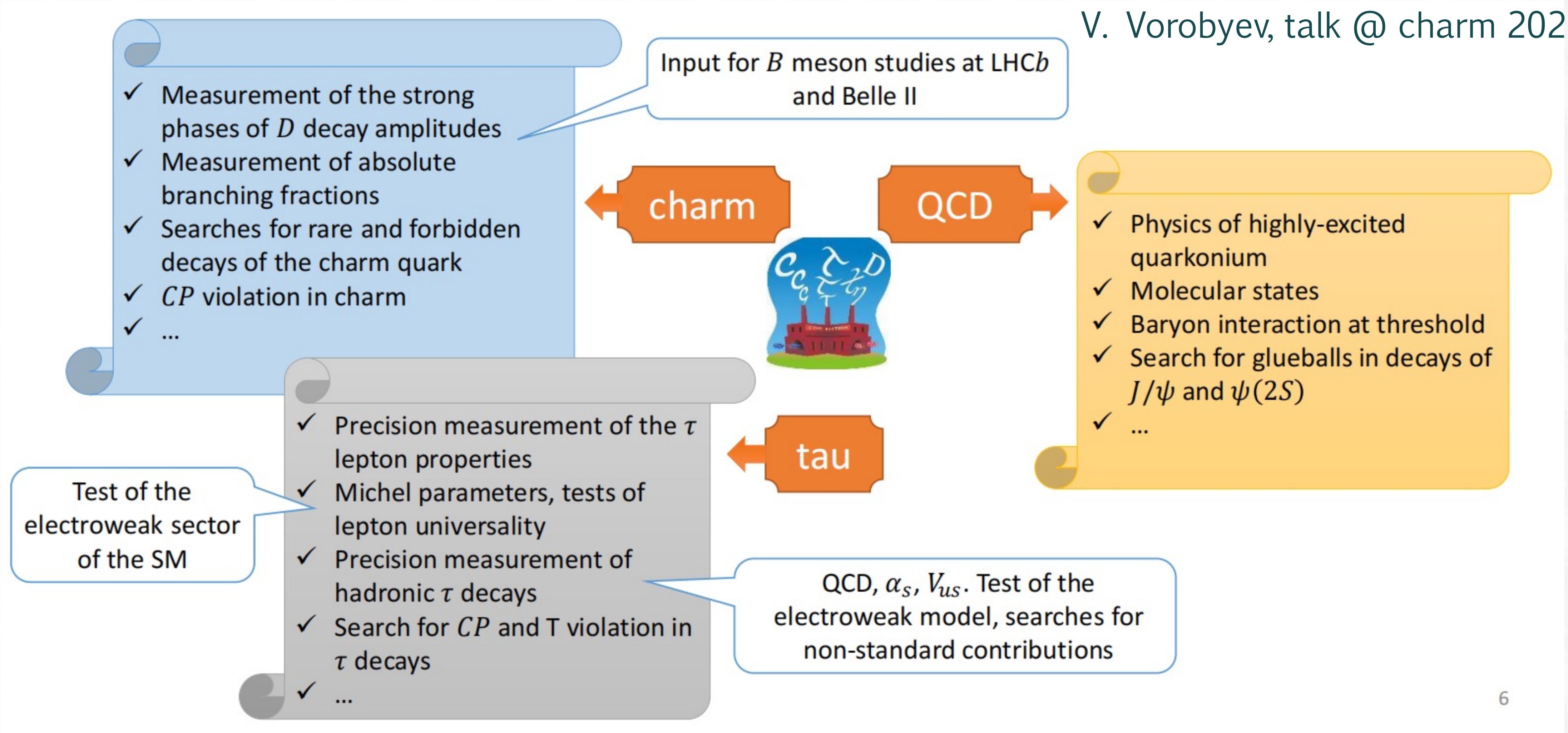
Physics at STCF

Xiaorong Zhou, talk @ charm 2020



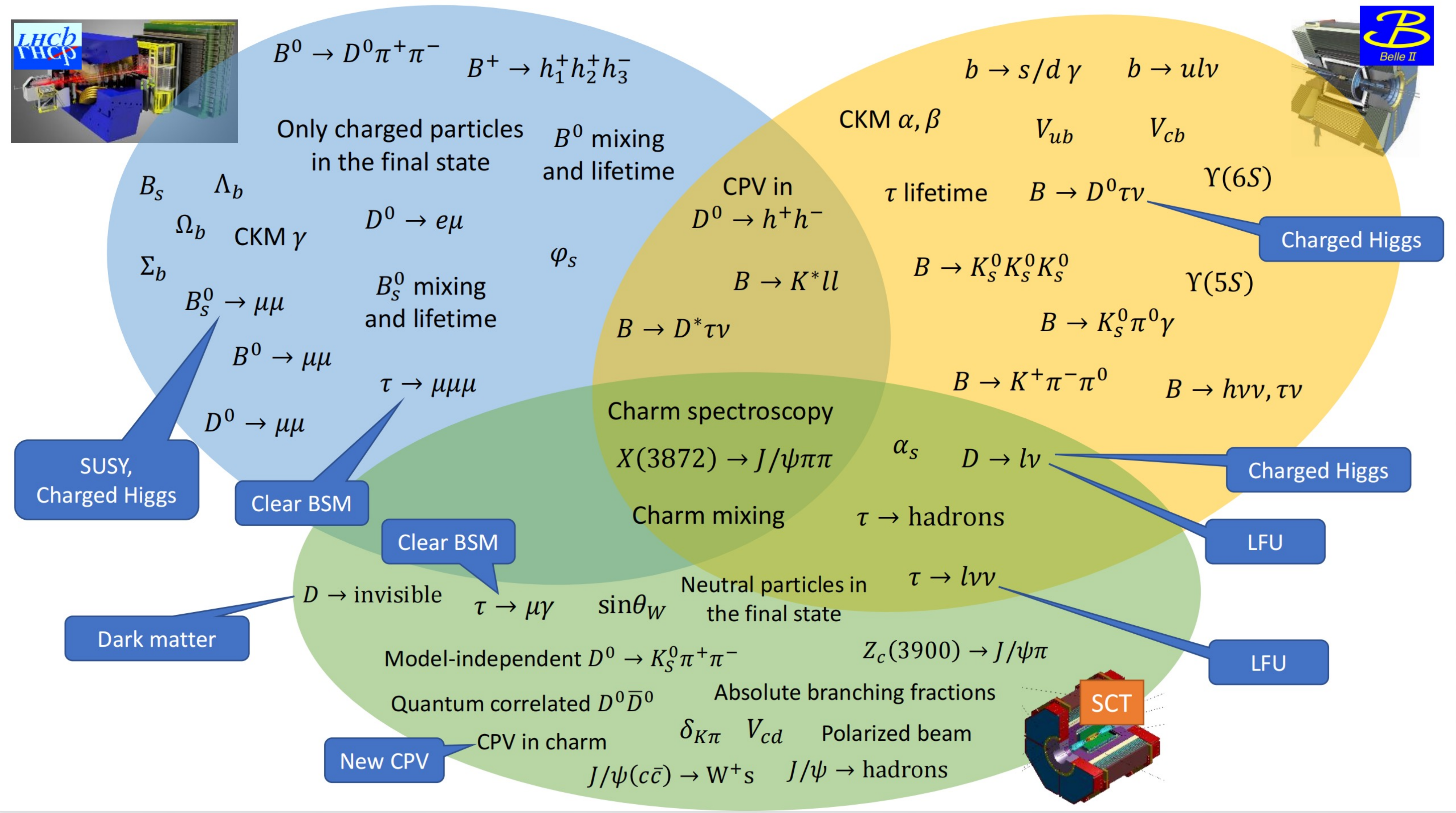
- **rich of physics program, unique for physics with c quark and τ leptons,**
- **important playground for study of QCD, exotic hadrons, flavor and search for new physics.**

Physics @ a STCF in a nutshell



Interplay with B physics

V. Vorobyev, talk @ charm 2021



Constraints on Im$[\hat{\epsilon}_{S,T}]$ from other processes

- **For the scalar operator: originate from the following two SMEFT operators**

$$\mathcal{L}_{\rm SMEFT} \supset [C^{(1)}_{\ell equ}]_{klmn}(\bar{\ell}^i_{Lk} e_{Rl})\epsilon^{ij}(\bar{q}^j_{Lm} u_{Rn}) + [C_{\ell edq}]_{klmn}(\bar{\ell}^i_{Lk} e_{Rl})(\bar{d}_{Rm} q^i_{Ln}) + \text{h.c.}$$

dim-6 SMEFT operator

$$\supset [C^{(1)}_{\ell equ}]_{klmn}\left[(\bar{\nu}_{Lk} e_{Rl})(\bar{d}_{Lm} u_{Rn}) - V_{am}(\bar{e}_{Lk} e_{Rl})(\bar{u}_{La} u_{Rn})\right] \rightarrow (\bar{\nu}_\tau \tau_R)(\bar{s}_L u_R)$$

$$+ [C_{\ell edq}]_{klmn}\left[V^*_{an}(\bar{\nu}_{Lk} e_{Rl})(\bar{d}_{Rm} u_{La}) + (\bar{e}_{Lk} e_{Rl})(\bar{d}_{Rm} d_{Ln})\right] + \text{h.c.} \rightarrow (\bar{\nu}_\tau \tau_R)(\bar{s}_R u_L)$$

scalar operator

$(\bar{\nu}_\tau \tau_R)(\bar{s} u)$

$$-2\sqrt{2} G_F V^*_{us} \hat{\epsilon}^*_S = \left[C^{(1)}_{\ell equ}\right]_{3321} + V^*_{ud}\left[C_{\ell edq}\right]_{3321} + V^*_{us}\left[C_{\ell edq}\right]_{3322} + V^*_{ub}\left[C_{\ell edq}\right]_{3323}$$

  - constraint on $\hat{\epsilon}_S$ can be obtained from other processes;
  - when potential cancellations exist between $C^{(1)}_{\ell equ}$ & $C_{\ell edq}$, the allowed values of $\hat{\epsilon}_S$ can be diluted

- **Mixing between scalar and tensor operators:**

$$\hat{\epsilon}_S = -\frac{[C^{(1)}_{\ell equ}]^*_{3321}}{2\sqrt{2} G_F V_{us}}, \qquad \hat{\epsilon}_T = -\frac{[C^{(3)}_{\ell equ}]^*_{3321}}{2\sqrt{2} G_F V_{us}}$$

$$\begin{pmatrix} \hat{\epsilon}_S \\ \hat{\epsilon}_T \end{pmatrix}_{(\mu=2\ \text{GeV})} = \begin{pmatrix} 1.72 & -0.0242 \\ -2.17\times 10^{-4} & 0.825 \end{pmatrix} \begin{pmatrix} \hat{\epsilon}_S \\ \hat{\epsilon}_T \end{pmatrix}_{(\mu=m_Z)}, \quad \begin{pmatrix} C^{(1)}_{\ell equ} \\ C^{(3)}_{\ell equ} \end{pmatrix}_{(\mu=m_Z)} = \begin{pmatrix} 1.20 & -0.185 \\ -0.00381 & 0.959 \end{pmatrix} \begin{pmatrix} C^{(1)}_{\ell equ} \\ C^{(3)}_{\ell equ} \end{pmatrix}_{(\mu=1\ \text{TeV})}$$

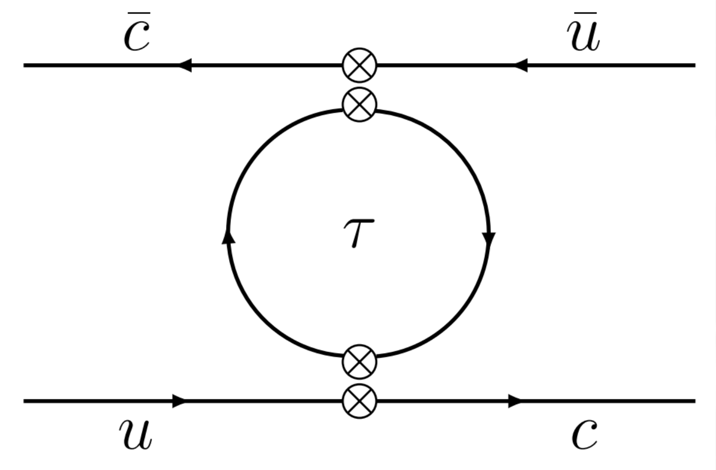
Constraints on $\mathrm{Im}[\hat{\epsilon}_{S,T}]$ from other processes

- **For scalar operator: no direct contribution to d_n, but can mix into tensor operator via RGE**

$|\mathrm{Im}[\hat{\epsilon}_T]| \lesssim 4\times10^{-6}$ ⟶ $|\mathrm{Im}[\hat{\epsilon}_S(\mu_\tau)]| \lesssim 2.3\times10^{-3}$, comparable to $\mathrm{Im}[\hat{\epsilon}_S] = -0.008 \pm 0.027$

- **The scalar operator $(\bar{\tau}_L \tau_R)(\bar{c}_L u_R)$ contributes to $D^0 - \bar{D}^0$ mixing:**

double insertion



$$M_{12}^{\mathrm{NP}} = \frac{1}{2M_D}\left[C_2'(\mu)\langle D^0|(\bar{c}_L^\alpha u_R^\alpha)(\bar{c}_L^\beta u_R^\beta)|\bar{D}^0\rangle(\mu)\right]$$

$$C_2' = -G_F^2 \frac{m_\tau^2}{\pi^2}(V_{us}V_{cs}\,\hat{\epsilon}_S)^2 \log\frac{\Lambda}{\mu_\tau}$$

$$x_{12} = \frac{2|M_{12}|}{\Gamma_D} = (0.409 \pm 0.048)\%,$$

$$\phi_{12} = \arg\left(\frac{M_{12}}{\Gamma_{12}}\right) = (0.58^{+0.91}_{-0.90})^{\mathrm{o}}$$

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$$\mathrm{Im}[\hat{\epsilon}_S(\mu_\tau)] \in [-3.1, 1.6]\times10^{-4} \text{ @ } 2\sigma$$

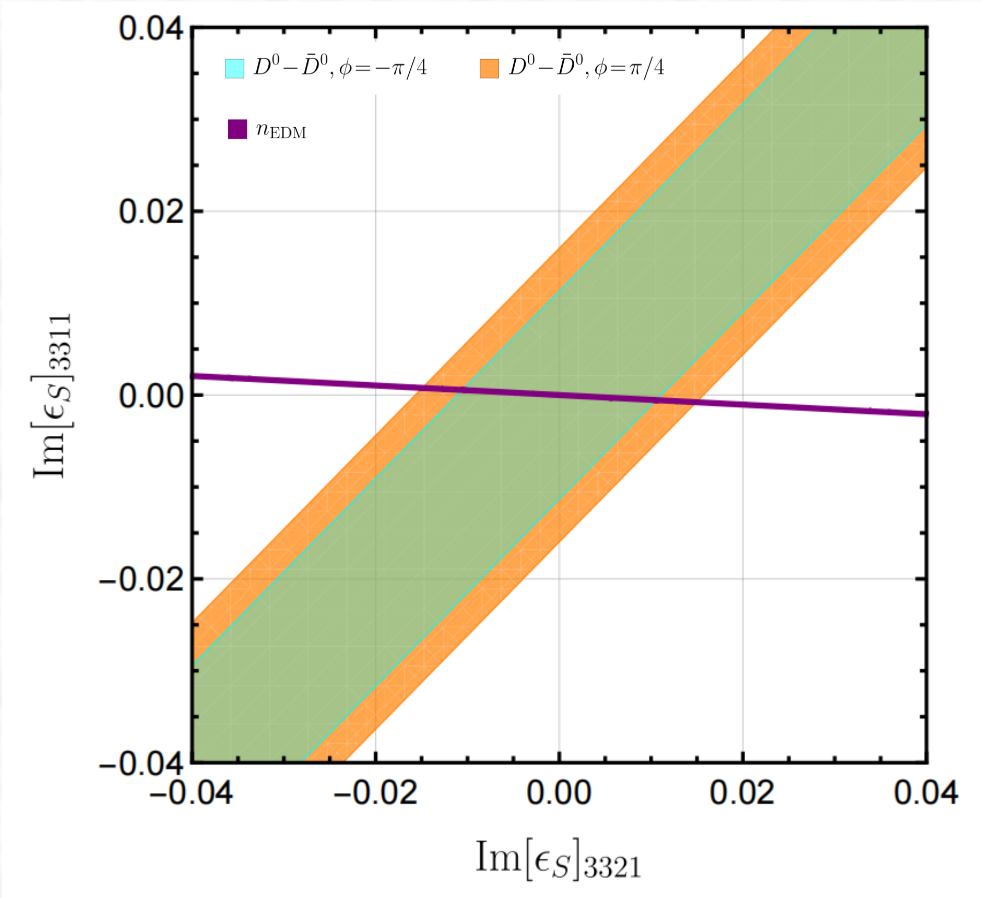
- Constraint from $D^0 - \bar{D}^0$ mixing is one order of magnitude stronger than from neutron EDM
- $A_{CP}^i|_{\max} \sim \mathcal{O}(10^{-3})$: of the same order as A_{SM}^{CP}

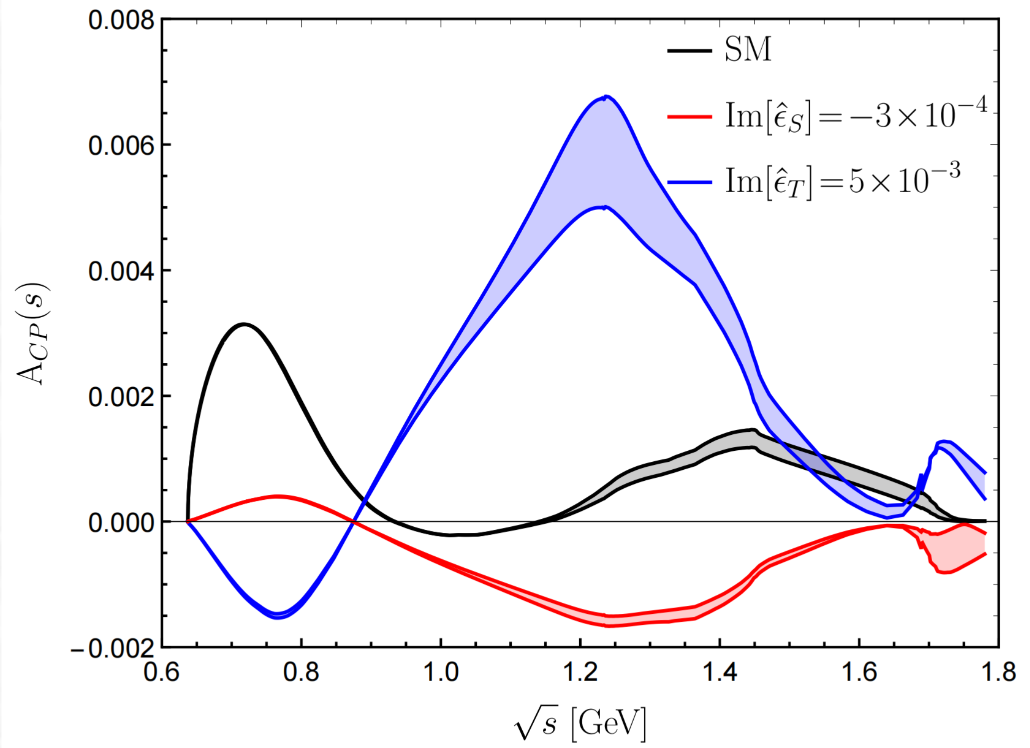
Constraints on $\mathrm{Im}[\hat{\epsilon}_{S,T}]$ from other processes

- **Caveat: once cancellations occur, bounds diluted**

$V_{ud}\mathrm{Im}[C^{(1)}_{\ell equ}]_{3311}+V_{us}[C^{(1)}_{\ell equ}]_{3321}$ (for d_n),

$V_{cd}[C^{(1)}_{\ell equ}]_{3311}+V_{cs}[C^{(1)}_{\ell equ}]_{3321}$ (for $D^0-\bar{D}^0$ mixing)





- **Predictions for CPA with $\mathrm{Im}[\hat{\epsilon}_S(\mu_\tau)]=-3\times10^{-4}$: slightly smaller than the SM prediction**