$\tau^- \to \omega\pi^-\nu_\tau$ decay in RχT with tensor sources

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2025.11.25

based on Feng-Zhi Chen, Xin-Qiang Li, Shi-Can Peng, Ya-Dong Yang, Yuan-He Zou, 2407.00700

The 7th International Workshop on Future Tau-Charm Facilities, Huangshan

Outline

Outline

Hadronic τ decays

- Play an important role in testing the SM
  - Determine the QCD coupling constant $\alpha_s(m_\tau)$

    M. Davier, A. Hocker and Z. Zhang, The Physics of Hadronic Tau Decays, Rev. Mod. Phys. 78 (2006) 1043.
    A. Pich, Precision Tau Physics, Prog. Part. Nucl. Phys. 75 (2014) 41.
  - Extract the CKM matrix element V_{us}

    D. d'Enterria et al., The strong coupling constant: State of the art and the decade ahead, J. Phys. G 51 (2024) 090501.
  - Probing CPV in $\tau \to K_S \pi \nu_\tau$

    I. I. Bigi and A. I. Sanda, A "known"CP asymmetry in tau decays, Phys. Lett. B 625, 47 (2005).
    Y. Grossman and Y. Nir, CP Violation in $\tau \to \nu_\tau \pi K_S$ and $D \to \pi K_S$: The Importance of $K_S - K_L$, JHEP 04 (2012) 002.
  - ...
- Also the ideal place to explore BSM physics
  - Lepton flavor/number violation
  - CPV of $\tau \to K_S \pi \nu_\tau$ in both decay-rate and angular distribution; F. Z. Chen, X. Q. Li, Y. D. Yang and X. Zhang, CP asymmetry in $\tau \to K_S \pi \nu_\tau$ decays within the Standard Model and beyond, Phys. Rev. D 100 (2019) 113006.
  - Second-class currents
  - ...

    A. Pich, Precision Tau Physics, Prog. Part. Nucl. Phys. 75 (2014) 41.
    Belle-II collaboration, The Belle II Physics Book, PTEP 2019 (2019) 123C01.

Status of $\tau \to VP\nu_\tau$ decay

- $\tau \to (nP)^- \nu_\tau$ $(P = \pi, K, \eta^{(\prime)})$ have been extensively studied both within the SM and beyond
  - $\tau^- \to \pi^- \nu_\tau$, $\tau^- \to K^- \nu_\tau$
  - $\tau^- \to \pi^- \pi^0 \nu_\tau$, $\tau^- \to K\pi^- \nu_\tau$, $\cdots$
  - $\tau^- \to (3\pi)^- \nu_\tau$, $\tau^- \to (K\pi\pi)^- \nu_\tau$, $\cdots$
  - $\cdots$
- Only few dedicated investigations on $\tau \to VP\nu_\tau$ $(V = \rho, K^*, \omega, \phi)$, focusing on
  - Branching ratios and angular distributions in $\tau \to \omega\pi\nu_\tau$ decay

    R. Decker and E. Mirkes, Angular distributions in the $\tau \to \omega\pi\nu_\tau$ decay mode, Z. Phys. C 57 (1993) 495.
  - VP form factors calculated in the vector-meson dominance (VMD) model

    G. López Castro and D.A. Lopez Falcon, VMD description of $\tau \to (\omega, \phi)\pi^- \nu_\tau$ decays and the $\omega - \phi$ mixing angle, Phys. Rev. D 54 (1996) 4400.
  - VP form factors calculated in the extended Nambu-Jona-Lasinio (NJL) model

    M.K. Volkov, A.B. Arbuzov and D.G. Kostunin, The decay $\tau \to \pi\omega\nu_\tau$ in the extended NJL model, Phys. Rev. D 86 (2012) 057301.
  - VP form factors calculated in χPT and RχT

    Z.-H. Guo, Study of $\tau \to VP\nu_\tau$ in the framework of resonance chiral theory, Phys. Rev. D 78 (2008) 033004.
  - Second-class current effects from isospin breaking in $\tau \to \omega\pi\nu_\tau$

    N. Paver and Riazuddin, Second-class current effects from isospin breaking in $\tau \to \omega\pi\nu_\tau$, Phys. Rev. D 86 (2012) 037302.

First- and second-class currents

- Hadronic currents classified as first- (FCC) and second-class (SCC) currents according to their total angular momentum J, parity P, and G-parity $G \equiv \mathcal{C}\, e^{i\pi I_2}$ quantum numbers (J^{PG})

$$J^{PG} = \begin{cases} 0^{++},\, 0^{--},\, 1^{+-},\, 1^{-+}, & \text{FCC} \\ 0^{+-},\, 0^{-+},\, 1^{++},\, 1^{--}, & \text{SCC} \end{cases}$$

S. Weinberg, Charge symmetry of weak interactions, Phys. Rev. 112 (1958) 1375.

Edmond L. Berger, Harry J. Lipkin, Classification and J^{PG} Selection Rules for Weak Currents, Phys. Rev. Lett. 59 (1987) 1394.

- The intrinsic P and G parities of mesons

meson	π	$\eta^{(\prime)}$	ρ	ω	ϕ	b_1	a_0	$\cdots$
$P = (-1)^{L+1}$	-1	-1	-1	-1	-1	$+1$	$+1$	$\cdots$
$G = (-1)^{L+S+I}$	-1	$+1$	$+1$	-1	-1	-1	$+1$	$\cdots$

- In the SM, only hadron systems with the same G-parity as that of the weak left-handed quark current are allowed and easily produced, while those with "wrong" G-parity are suppressed

- Examples of SCC in τ decays: $\tau^- \to b_1(1235)^-(\to \omega\pi^-)\nu_\tau$, $\tau^- \to a_0(980)^-(\to \eta\pi^-)\nu_\tau$, $\cdots$

$\tau^- \to \omega\pi^-\nu_\tau$ decay

- Usually employed to test the existence of SCC

  S. Weinberg, Charge symmetry of weak interactions, Phys. Rev. 112 (1958) 1375.

  Edmond L. Berger, Harry J. Lipkin, Classification and J^{PG} Selection Rules for Weak Currents, Phys. Rev. Lett. 59 (1987) 1394.

- In the SM, assuming isospin and thus G-parity conservation, only the vector FCC with $J^{PG} = 1^{-+}$ contributes, while the axial-vector SCC with $J^{PC} = 1^{+-}$ arises due to small isospin-breaking effect

- Axial-vector SCC with $J^{PC} = 1^{+-}$ contribution: $\mathcal{B}(\tau \to \omega\pi\nu_\tau)^{\rm th}_{\rm SCC} \approx (2.3 \sim 2.8) \times 10^{-5}$ based on VMD

  N. Paver and Riazuddin, Second-class current effects from isospin breaking in $\tau \to \omega\pi\nu_\tau$, Phys. Rev. D 86 (2012) 037302.

- Upper experimental limit on the SCC effect: $B(\tau \to \omega\pi\nu_\tau)^{\rm ex}_{\rm SCC} \leq 1.4 \times 10^{-4}$ @ 90% C.L.

  BaBar Collaboration, Phys. Rev. Lett. 103 (2009) 041802.

- Total experimental branching ratio: $\mathcal{B}(\tau^- \to \omega\pi^-\nu_\tau) = (1.95 \pm 0.06)\%$

  S. Navas *et al.* (Particle Data Group), Phys. Rev. D 110 (2024) 030001.

- While still space for genuine SCC non-standard interactions, they must be suppressed with respect to FCC;

  $\Rightarrow$ How about the G-parity-conserving FCC non-standard interactions?

Outline

Model-independent analysis of $\tau \to \omega\pi^-\nu_\tau$ decay in LEFT

- The most general LEFT Lagrangian with $SU(3)_C \otimes U(1)_{\rm em}$ symmetry and Lorentz invariance

$$\mathcal{L}_{\rm eff} = -\frac{G_F^0 V_{ud}}{\sqrt{2}}(1+\epsilon_L+\epsilon_R)\Big\{\bar\tau\gamma_\mu(1-\gamma_5)\nu_\tau\cdot[\bar u\gamma^\mu d-(1-2\,\hat\epsilon_R)\bar u\gamma^\mu\gamma_5 d]$$
$$+\bar\tau(1-\gamma_5)\nu_\tau\cdot[\hat\epsilon_S\,\bar u d-\hat\epsilon_P\,\bar u\gamma_5 d]+\hat\epsilon_T\,\bar\tau\sigma_{\mu\nu}(1-\gamma_5)\nu_\tau\cdot\bar u\sigma^{\mu\nu}(1-\gamma_5)d\Big\}+\text{h.c.}$$

- To see which operators contribute to $\tau \to \omega\pi^-\nu_\tau$ decay, we use the selection rules based on J^{PG}: X.-D. Ji and R.F. Lebed, Phys. Rev. D 63 (2001) 076005; M. Papucci and D. J. Robinson, Phys. Rev. D 105 (2022) 016027.
  - Angular momentum-parity (J^P) decompositions of quark bilinears $\mathcal{O} = \bar d\Gamma u$

$$J^P(\mathcal{O}_S)=0^+,\quad J^P(\mathcal{O}_P)=0^-,\quad J^P(\mathcal{O}_V)=0^+\oplus 1^-,\quad J^P(\mathcal{O}_A)=0^-\oplus 1^+,\quad J^P(\mathcal{O}_T)=1^+\oplus 1^-$$

  - The G-parity transformation of quark bilinears $\mathcal{O} = \bar d\Gamma u$ ($\psi=(u,d)^T$, $\sigma_-=(\sigma_1-i\sigma_2)/2$)

$$G\{\mathcal{O}_S,\mathcal{O}_P,\mathcal{O}_V,\mathcal{O}_A,\mathcal{O}_T\}G^{-1}=\{-\mathcal{O}_S,-\mathcal{O}_P,+\mathcal{O}_V,-\mathcal{O}_A,+\mathcal{O}_T\}$$

	$\mathcal{O}_S$	$\mathcal{O}_P$	$\mathcal{O}_V$	$\mathcal{O}_A$	$\mathcal{O}_T$	$\omega\pi\,\vert_{L=0}$	$\omega\pi\,\vert_{L=1}$	$\omega\pi\,\vert_{L=2}$
J^{PG}	0^{+-}	0^{--}	$0^{++}\oplus 1^{-+}$	$0^{--}\oplus 1^{+-}$	$1^{++}\oplus 1^{-+}$	1^{++}	$0^{-+}\oplus 1^{-+}\oplus 2^{-+}$	$1^{++}\oplus 2^{++}\oplus 3^{++}$

- Since $\omega\pi^-$ system has a G-parity of $+1$, when assuming G-parity conservation, only the 1^{-+} component of either vector or tensor operator has a non-zero FCC contribution

Decay amplitude

- For $\tau^- \to \omega\pi^-\nu_\tau$, only the two hadronic matrix elements $\langle\omega\pi^-|\mathcal{O}_V|0\rangle$ and $\langle\omega\pi^-|\mathcal{O}_T|0\rangle$ relevant
- The decay amplitude for $\tau^- \to \omega\pi^-\nu_\tau$

$$\mathcal{M} = \mathcal{M}_V + \mathcal{M}_T = -i\frac{G_F^0 V_u d^* \sqrt{S_{EW}}}{\sqrt{2}}(1+\epsilon_L^* + \epsilon_R^*)[L_\mu H^\mu + \hat{\epsilon}_T^* L_{\mu\nu} H^{\mu\nu}]$$

- Leptonic currents

$$L_\mu = \bar{u}_{\nu_\tau}(p_3)\gamma_\mu(1-\gamma_5)u_\tau(p)$$
$$L_{\mu\nu} = \bar{u}_{\nu_\tau}(p_3)\sigma_{\mu\nu}(1+\gamma_5)u_\tau(p)$$

- Hadronic matrix elements

$$H^\mu = \langle\omega(p_2,\varepsilon)\pi^-(p_1)|\bar{d}\gamma^\mu u|0\rangle = iF_V(s)\epsilon^{\mu\nu\rho\sigma}\varepsilon_\nu^* p_{1\rho}p_{2\sigma} \,,$$
$$H^{\mu\nu} = \langle\omega(p_2,\varepsilon)\pi^-(p_1)|\bar{d}\sigma^{\mu\nu} u|0\rangle = F_{T1}(s)\epsilon^{\mu\nu\rho\sigma}(\varepsilon^*\cdot p_1)p_{1\rho}p_{2\sigma} - F_{T2}(s)\epsilon^{\mu\nu\rho\sigma}\varepsilon_\rho^* p_{1\sigma} - F_{T3}(s)\epsilon^{\mu\nu\rho\sigma}\varepsilon_\rho^* p_{2\sigma}$$

- $F_V(s)$: the $\omega\pi$ vector form factor calculated in RχT; Z.-H. Guo, Phys. Rev. D 78 (2008) 033004.
- $F_{T1,2,3}$: the $\omega\pi$ tensor form factors calculated by us in RχT with tensor sources; Feng-Zhi Chen, Xin-Qiang Li, Shi-Can Peng, Ya-Dong Yang, Yuan-He Zou, 2407.00700.

Observables

- To probe the non-standard tensor interactions, we consider the following two observables:
  - The differential decay width

$$\frac{d\Gamma(\tau^- \to \omega\pi^-\nu_\tau)}{ds} = \frac{G_F^2|V_{ud}|^2(m_\tau^2 - s)^2 S_{EW}}{1536\pi^3 s^2 m_\tau^3}\lambda^{3/2}(s, M_\omega^2, M_\pi^2) \times \left\{(m_\tau^2 + 2s)|F_V(s)|^2 + 24 m_\tau \hat{\epsilon}_T \mathrm{Re}\left[F_V(s)\left(F_{T3}^*(s) - F_{T2}^*(s)\right)\right]\right\}$$

  - The forward-backward asymmetry

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

$$= \frac{-12 m_\tau \hat{\epsilon}_T \left\{\mathrm{Re}\left[F_V(s)F_{T2}^*(s)\right](s - \Delta_{\omega\pi}) + \mathrm{Re}\left[F_V(s)F_{T3}^*(s)\right](s + \Delta_{\omega\pi})\right\}}{\lambda^{\frac{1}{2}}(s, M_\omega^2, M_\pi^2)\left\{(2s + m_\tau^2)|F_V(s)|^2 + 24 m_\tau \hat{\epsilon}_T \mathrm{Re}\left[F_V(s)(F_{T3}^*(s) - F_{T2}^*(s))\right]\right\}}$$

- $A_{\mathrm{FB}}(s)$: being directly proportional to $\hat{\epsilon}_T$, and hence an ideal observable to probe the non-standard tensor interaction!

Outline

QCD Lagrangian extended with external sources

- To calculate these form factors, we extend the massless QCD Lagrangian $\mathcal{L}^0_{\rm QCD}$ with the external sources:

$$\mathcal{L}_{\rm QCD} = \mathcal{L}^0_{\rm QCD} + \bar{\psi}\gamma_\mu(v^\mu + a^\mu\gamma_5)\psi - \bar{\psi}(s - ip\gamma_5)\psi + \bar{\psi}\sigma_{\mu\nu}\bar{t}^{\mu\nu}\psi$$

- The external tensor fields $\bar{t}^{\mu\nu} = P_L^{\mu\nu\lambda\rho}t_{\lambda\rho} + P_R^{\mu\nu\lambda\rho}t^\dagger_{\lambda\rho}$ satisfy the local chiral and discrete symmetries, and have the same chiral power counting as of the scalar fields

$$t_\pm^{\mu\nu} \to h t_\pm^{\mu\nu} h^\dagger\,, \qquad t_\pm^{\mu\nu}(\vec{x},t) \xrightarrow{\mathcal{P}} \pm t_\pm^{\mu\nu}(-\vec{x},t)\,, \qquad t_\pm^{\mu\nu}(\vec{x},t) \xrightarrow{\mathcal{C}} -t_\pm^{\mu\nu\top}(\vec{x},t)\,, \qquad t_\pm^{\mu\nu}(\vec{x},t) \sim \mathcal{O}(p^2)$$

- Properties of all the building blocks for constructing the χPT and RχT Lagrangian

$\mathcal{O}$	Dim	$\mathcal{P}$	$\mathcal{C}$	h.c.
$V^{\mu\nu}$	0	$V_{\mu\nu}$	$-(V^{\mu\nu})^T$	$V^{\mu\nu}$
u^μ	1	$-u^\mu$	$(u^\mu)^T$	u^μ
$\chi_\pm$	2	$\pm\chi_\pm$	$(\chi_\pm)^T$	$\pm\chi_\pm$
$f_\pm^{\mu\nu}$	2	$\pm f_{\pm\mu\nu}$	$\mp(f_\pm^{\mu\nu})^T$	$f_\pm^{\mu\nu}$
$t_\pm^{\mu\nu}$	2	$\pm t_{\pm\mu\nu}$	$-(t_\pm^{\mu\nu})^T$	$\pm t_\pm^{\mu\nu}$

The total Lagrangian in χPT and RχT with tensor sources

- The most relevant chiral Lagrangian at the LO in the large N_C expansion

$$\mathcal{L} = \mathcal{L}_\chi^{(2)} + \mathcal{L}_{kin}(V) + \mathcal{L}_{2V} + \mathcal{L}_{VVP} + \mathcal{L}_{VJP} + \mathcal{L}_{VV_1P} + \mathcal{L}_{VT} + \mathcal{L}_{VTP}$$

$$= \mathcal{L}_\chi^{(2)} + \mathcal{L}_{kin}(V) + \mathcal{L}_{2V} + \sum_i^4 d_i O_i + \sum_i^7 c_i O_i + \sum_a^f d_a O_a + F_V^T \langle V_{\mu\nu} t_+^{\mu\nu} \rangle + \sum_i^{15} b_i O_i$$

P. D. Ruiz-Femenia, A. Pich and J. Portoles, JHEP 07 (2003) 003; V. Cirigliano, G. Ecker, M. Eidemuller, A. Pich and J. Portoles, Phys. Lett. B 596 (2004) 96.

- $\mathcal{L}_{VT} = F_V^T \langle V_{\mu\nu} t_+^{\mu\nu} \rangle$: interactions between vector meson and external tensor sources
- $\mathcal{L}_{VTP} = \sum_i^{15} b_i O_i$: interactions among pseudo-scalar, vector, and vector resonances, and given by

$$\begin{aligned}
\mathcal{L}_{VTP} = {} & b_1 \epsilon_{\mu\nu\rho\sigma} \langle \{ V^{\mu\nu}, t_+^{\rho\alpha} \} \nabla_\alpha u^\sigma \rangle + b_2 \epsilon_{\mu\nu\rho\sigma} \langle \{ V^{\mu\alpha}, t_+^{\nu\rho} \} \nabla_\alpha u^\sigma \rangle + i b_3 \epsilon_{\mu\nu\rho\sigma} \langle \{ V^{\mu\nu}, t_+^{\rho\sigma} \} \chi_- \rangle \\
& + i b_4 \epsilon_{\mu\nu\rho\sigma} \langle \{ V^{\mu\nu}, t_-^{\rho\sigma} \} \chi_+ \rangle + b_5 \epsilon_{\mu\nu\rho\sigma} \langle \{ \nabla_\alpha V^{\mu\nu}, t_+^{\rho\alpha} \} u^\sigma \rangle + b_6 \epsilon_{\mu\nu\rho\sigma} \langle \{ \nabla_\alpha V^{\mu\alpha}, t_+^{\nu\rho} \} u^\sigma \rangle \\
& + b_7 \epsilon_{\mu\nu\rho\sigma} \langle \{ \nabla^\mu V^{\nu\rho}, t_+^{\sigma\alpha} \} u_\alpha \rangle + i b_8 \epsilon_{\mu\nu\rho\sigma} \langle V^{\mu\nu} t_-^{\rho\sigma} \rangle \langle \chi_+ \rangle + b_9 \epsilon_{\mu\nu\rho\sigma} \langle V^{\mu\nu} \nabla_\alpha u^\rho \rangle \langle t_+^{\sigma\alpha} \rangle \\
& + b_{10} \epsilon_{\mu\nu\rho\sigma} \langle V^{\mu\alpha} \nabla_\alpha u^\nu \rangle \langle t_+^{\rho\sigma} \rangle + i b_{11} \epsilon_{\mu\nu\rho\sigma} \langle V^{\mu\nu} \chi_- \rangle \langle t_+^{\rho\sigma} \rangle + i b_{12} \epsilon_{\mu\nu\rho\sigma} \langle V^{\mu\nu} \chi_+ \rangle \langle t_-^{\rho\sigma} \rangle \\
& + b_{13} \epsilon_{\mu\nu\rho\sigma} \langle \nabla_\alpha V^{\mu\nu} u^\rho \rangle \langle t_+^{\sigma\alpha} \rangle + b_{14} \epsilon_{\mu\nu\rho\sigma} \langle \nabla_\alpha V^{\mu\alpha} u^\nu \rangle \langle t_+^{\rho\sigma} \rangle + b_{15} \epsilon_{\mu\nu\rho\sigma} g_{\alpha\beta} \langle \nabla^\mu V^{\nu\alpha} u^\rho \rangle \langle t_+^{\sigma\beta} \rangle
\end{aligned}$$

Remarks for the Lagrangian

- The spin-1 vector resonances are described by the anti-symmetric tensor fields; G. Ecker, J. Gasser, A. Pich and E. de Rafael, Nucl. Phys. B 321 (1989) 311.

- The lowest-lying pseudo-scalar and vector octets are given by

$$\Phi = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{1}{\sqrt{6}}\eta_8 & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{1}{\sqrt{6}}\eta_8 & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta_8 \end{pmatrix}, \qquad V_{\mu\nu} = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}_{\mu\nu}$$

- To obtain a minimal and irredundant operator basis, we have made use of the Schouten identity, the equations of motion for the lowest-order χPT Lagrangian, and other relations about the derivatives

  P. D. Ruiz-Femenia, A. Pich and J. Portoles, JHEP 07 (2003) 003; V. Cirigliano, G. Ecker, M. Eidemuller, A. Pich and J. Portoles, Phys. Lett. B 596 (2004) 96.

- Once the relevant Lagrangian is fixed, the quark bilinear hadronization is then determined by taking the functional derivatives of the χPT and RχT actions with respect to the external fields and, afterwards, by setting all the external currents to zero

$\omega\pi$ vector and tensor form factors in RχT

- Vector form factor $F_V(s)$:

$$F_V(s) = \frac{2\sqrt{2}}{FM_\omega}\left[2d_3F_V + d_sF_{V_1}\right] + \frac{4\sqrt{2}F_V}{FM_\omega}\left[(d_1+8d_2)M_\pi^2 + d_3(M_\omega^2 - M_\pi^2 + s)\right]D_\rho(s)$$

$$+ \frac{2\sqrt{2}F_{V_1}}{FM_\omega}\left[d_mM_\pi^2 + d_MM_\omega^2 + d_ss\right]D_{\rho_1}(s),$$

$$D_V(s) \equiv 1/(M_V^2 - s - iM_V\Gamma_V(s)) :$$ resonance propagator with energy-dependent width $\Gamma_V(s)$

Z.-H. Guo, Study of $\tau \to VP\nu_\tau$ in the framework of resonance chiral theory, Phys. Rev. D 78 (2008) 033004.

- Tensor form factor $F_{T1}(s)$:

$$F_{T1}(s) = \frac{4F_V^T}{FM_\omega M_\rho^2}\left[d_{12}M_\pi^2 + d_3\left(\Delta_{\omega\pi} + M_\rho^2\right)\right]D_\rho(s)$$

$$- \frac{4F_{V_1}^T}{FM_\omega M_{\rho_1}^2}\left[d_dM_\omega^2 - (d_b+4d_f)\,M_\pi^2 - (d_a - d_b)\,M_{\rho_1}^2\right]D_{\rho_1}(s)\,,$$

- Tensor form factor $F_{T2}(s)$:

$$F_{T2}(s) = -\frac{2F_V^T}{FM_\omega M_\rho^2}\left\{\left[d_{12}M_\pi^2 - d_3\left(\Sigma_{\omega\pi} - M_\rho^2\right)\right]\right.$$

$$+\left[d_{12}M_\pi^2(s+\Delta_{\omega\pi}) - d_3\left(s\Sigma_{\omega\pi} - \Delta_{\omega\pi}^2 + M_\rho^2\left(2M_\omega^2 + s + \Delta_{\omega\pi}\right)\right)\right]D_\rho(s)\Big\}$$

$$-\frac{2F_{V_1}^T}{FM_\omega M_{\rho_1}^2}\left\{\left[d_d M_\omega^2 + (d_b+4d_f)\,M_\pi^2 + (d_a-d_b)\,M_{\rho_1}^2\right](1+(s-\Sigma_{\omega\pi})D_{\rho_1}(s))\right.$$

$$\left.+2M_\omega^2\left[(d_b+d_d+4d_f)\,M_\pi^2 + (d_a-d_b-d_d)\,M_{\rho_1}^2\right]D_{\rho_1}(s)\right\}\ ,$$

- Tensor form factor $F_{T3}(s)$:

$$F_{T3}(s) = -\frac{2F_V^T}{FM_\omega M_\rho^2}\left\{\left[d_{12}M_\pi^2 - d_3\left(\Sigma_{\omega\pi} + M_\rho^2\right)\right]\right.$$

$$+\left[d_{12}M_\pi^2\left(M_{s\omega\pi} - 2M_\rho^2\right) - d_3\left(s\Sigma_{\omega\pi} - \Delta_{\omega\pi}^2 + M_\rho^2(s-\Sigma_{\omega\pi})\right)\right]D_\rho(s)\Big\}$$

$$-\frac{2F_{V_1}^T}{FM_\omega M_{\rho_1}^2}\left\{\left[d_d M_\omega^2 + (d_b+4d_f)\,M_\pi^2 - (d_a-d_b)\,M_{\rho_1}^2\right](1+(s-\Sigma_{\omega\pi})D_{\rho_1}(s))\right.$$

$$\left.+2M_\pi^2\left[(d_b+d_d+4d_f)\,M_\omega^2 - (d_a+4d_f)\,M_{\rho_1}^2\right]D_{\rho_1}(s)\right\}$$

Constraints on resonance couplings

- Too many undetermined resonance couplings involved in these form factors
- Constraints from QCD short-distance behaviors: these form factors $F_i(s)$ should vanish smoothly for $s \to \infty$
  S. J. Brodsky and G. R. Farrar, Scaling Laws at Large Transverse Momentum, Phys. Rev. Lett. 31 (1973) 1153;
  G. P. Lepage and S. J. Brodsky, Exclusive Processes in Perturbative Quantum Chromodynamics, Phys. Rev. D 22 (1980) 2157.

$$c_1 - c_2 + c_5 = c_1 + 4c_3 = d_4 = d_a - d_b - d_c = b_1 - b_2 = b_5 = 0\,,$$

$$c_6 - c_5 = \frac{2d_3 F_V + d_s F_{V_1}}{2\sqrt{2} M_\omega^2} M_V,$$

$$b_6 = \frac{F_V^T}{M_\omega^2 M_\rho^2}\left[d_{12} M_\pi^2 - d_3\left(\Sigma_{\omega\pi} - M_\rho^2\right)\right] + \frac{F_{V_1}^T}{M_\omega^2 M_{\rho'}^2}\left[d_d M_\omega^2 + (d_b + 4d_f)\, M_\pi^2 + (d_a - d_b)\, M_{\rho'}^2\right]$$

$$b_1 + 4(b_3 + b_4 + b_8) = \frac{F_V^T}{M_\pi^2 M_\rho^2}\left[d_{12} M_\pi^2 - d_3\left(\Sigma_{\omega\pi} + M_\rho^2\right)\right] + \frac{F_{V_1}^T}{M_\pi^2 M_{\rho'}^2}\left[d_d M_\omega^2 + (d_b + 4d_f)\, M_\pi^2 - d_c M_{\rho'}^2\right]$$

- These relations have been exploited when expressing the form factors $F_i(s)$, and they depend only on the resonance couplings d_i in $\mathcal{O}(p^4)$ odd-intrinsic-parity RχT

Constraints on resonance couplings and LECs

- For d_3, d_s, d_M and d_m: obtained by fitting the SM predicted $\tau^- \to \omega\pi^-\nu_\tau$ spectral function to the experimental data; CLEO collaboration, Phys. Rev. D 61 (2000) 072003.
- For the remaining d_i: obtained by matching $\mathcal{O}(p^4)$ odd-intrinsic-parity RχT onto $\mathcal{O}(p^6)$ χPT with the vector resonances integrated out

totally 18 terms too long to display here

$$\begin{cases} B_1 = & -\frac{G_V^2}{4M_V^4}(2d_1+16d_2-3d_3) - \frac{G_V G_{V_1}}{4M_V^2 M_{V_1}^2}(2d_a+2d_b-3d_c+5d_d+8d_f) \\ & +\frac{\sqrt{2}G_V}{M_V^3}(g_3-2g_9+g_{10}), \\ B_2 = & -\frac{1}{2\sqrt{2}M_V^3}\left[4G_V c_4 - F_V g_4\right], \\ \vdots & \\ B_{21} = & -\frac{1}{12M_V^4}\left[2F_V G_V(2d_3-3d_4)-3F_V^2 d_4\right] \\ & -\frac{1}{12M_V^2 M_{V_1}^2}\left[2G_V F_{V_1}(3d_c-d_d-3d_e)+2F_V G_{V_1}(d_c-3d_d)-3F_V F_{V_1} d_e\right] \\ & +\frac{1}{6\sqrt{2}M_V^3}\left[2G_V(3c_5-c_6+3c_7)-F_V(3c_7+4g_5+2g_6-6g_7+2g_8)\right], \\ B_{22} = & -\frac{F_V^2}{2M_V^4}d_3 - \frac{F_V F_{V_1}}{2M_V^2 M_{V_1}^2}(d_c-d_d)+\frac{F_V}{\sqrt{2}M_V^3}(c_5-c_6), \end{cases}$$

- B_i: LECs of $\mathcal{O}(p^6)$ χPT, and taken from S.-Z. Jiang, Z.-L. Wei, Q.-S. Chen and Q. Wang, Phys. Rev. D 92 (2015) 025014

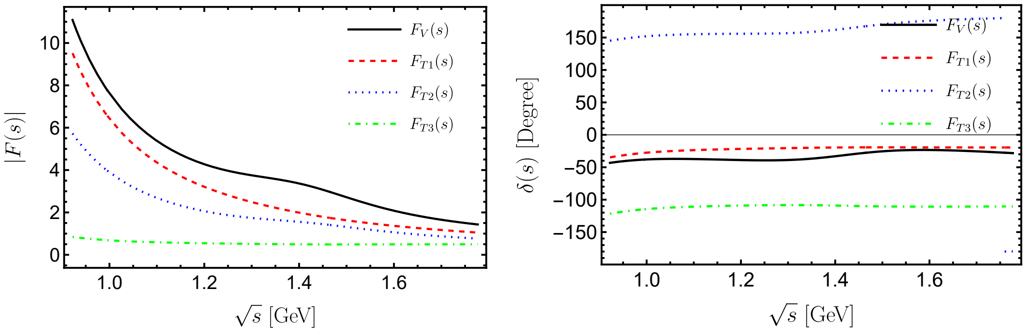
Outline

Numerical results of the resonance couplings in $\mathcal{O}(p^4)$ odd-intrinsic-parity RχT Lagrangian

- With $d_3 = -0.229 \pm 0.008$, $d_s = -0.259 \pm 0.039$, $d_m M_\pi^2 + d_M M_\omega^2 = 0.525 \pm 0.067$ and B_i input, we obtain numerical results of the resonance couplings in $\mathcal{O}(p^4)$ odd-intrinsic-parity RχT Lagrangian

$c_1 = -7.44 \times 10^{-3}$	$d_1 = 6.08 \times 10^{-1}$	$g_1 = -2.71 \times 10^{-3}$
$c_2 = -3.45 \times 10^{-3}$	$d_2 = -7.99 \times 10^{-2}$	$g_2 = 5.76 \times 10^{-3}$
$c_3 = 1.86 \times 10^{-3}$	$d_3 = -2.29 \times 10^{-1}$	$g_3 = 8.81 \times 10^{-3}$
$c_4 = -9.59 \times 10^{-3}$	$d_4 = 0$	$g_4 = -3.23 \times 10^{-2}$
$c_5 = 3.99 \times 10^{-3}$	$d_a = 2.73$	$g_5 = 2.79 \times 10^{-2}$
$c_6 = 2.16 \times 10^{-2}$	$d_b = 2.86$	$g_6 = -6.99 \times 10^{-2}$
$c_7 = -3.40 \times 10^{-1}$	$d_c = -1.29 \times 10^{-1}$	$g_7 = -5.99 \times 10^{-2}$
	$d_d = -4.33 \times 10^{-1}$	$g_8 = -2.60 \times 10^{-3}$
	$d_e = 7.19 \times 10^{-1}$	$g_9 = 3.79 \times 10^{-3}$
	$d_f = 7.49 \times 10^{-1}$	$g_{10} = 3.53 \times 10^{-2}$
		$g_{18} = 8.96 \times 10^{-3}$

Moduli (left) and phases (right) of $\omega\pi$ form factors as a function of $\omega\pi$ invariant mass $\sqrt{s}$



- A slight bump around $\sqrt{s} \sim 1.4$ GeV in vector FF $F_V(s)$, indicating the existence of $\rho(1450)$ resonance
- The same $\rho(1450)$ bump not quite obvious for tensor FFs $F_{T1,2,3}$, due to its small weight to these FFs
- The $\rho(770)$ peak absent in all these FFs, because the $\omega\pi$ mass threshold is higher than the $\rho(770)$ mass
- The FF phases display only a small variation with respect to $\sqrt{s}$ in the whole $\omega\pi$ invariant mass range

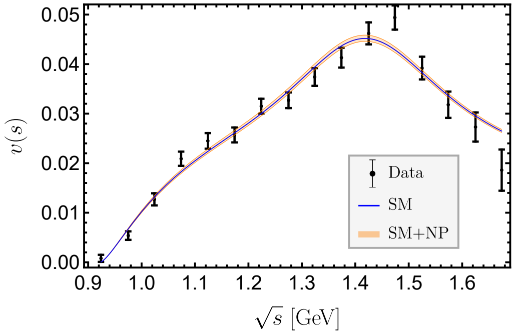
Spectral function and forward-backward asymmetry

- With the form factors at hand, we can now study the non-standard tensor effects in $\tau^- \to \omega\pi^-\nu_\tau$ decay
- $\hat{\epsilon}_T = (0.3 \pm 4.9) \times 10^{-3}$: obtained by fitting to the spectral function $v(s)$ in 16 bins and the branching ratio $\mathcal{B}(\tau^- \to \omega\pi^-\nu_\tau) = 1.95(6)\%$; CLEO collaboration, Phys. Rev. D 61 (2000) 072003.
- $\epsilon_T = (-0.1 \pm 0.2^{+1.1+0.0}_{-1.4-0.1} \pm 0.2) \times 10^{-2}$: obtained from a simultaneous fit to $\tau^- \to \pi^-\nu_\tau, \pi^-\pi^0\nu_\tau, K^-K^0\nu_\tau$ decays; S. Gonzàlez-Solís, A. Miranda, J. Rendón and P. Roig, Phys. Lett. B 804 (2020) 135371.
- Our result is about one order of magnitude stronger than the latter, but both bearing larger uncertainties

- Spectral function $v(s)$ with $\hat{\epsilon}_T$:

$$v(s) = \frac{32\pi^2 m_\tau^3}{G_F^2 |V_{ud}|^2 (m_\tau^2 - s)^2 (m_\tau^2 + 2s)} \times \frac{d\Gamma(\tau^- \to \omega\pi^-\nu_\tau)}{ds}$$

- Compared to SM, the tensor contribution to $v(s)$ is small, and its presence provides very limited improvement on the fit

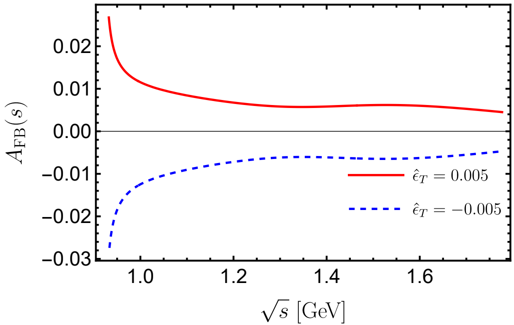


Spectral function and forward-backward asymmetry

- Forward-backward asymmetry $A_{\rm FB}(s)$ with $\hat{\epsilon}_T$:

$$A_{\rm FB}(s) = \frac{-12 m_\tau \hat{\epsilon}_T \left\{ {\rm Re}\left[F_V(s) F^*_{T2}(s)\right](s-\Delta_{\omega\pi}) + {\rm Re}\left[F_V(s) F^*_{T3}(s)\right](s+\Delta_{\omega\pi}) \right\}}{\lambda^{\frac{1}{2}}(s, M_\omega^2, M_\pi^2)\left\{ (2s+m_\tau^2)\,|F_V(s)|^2 + 24 m_\tau \hat{\epsilon}_T {\rm Re}\left[F_V(s)(F^*_{T3}(s) - F^*_{T2}(s))\right] \right\}}$$

- A non-zero $A_{\rm FB}(s)$ arises only in the presence of a non-standard tensor contribution



- The distribution of $A_{\rm FB}(s)$ with respect to $\sqrt{s}$, with two values of $\hat{\epsilon}_T = \pm 0.005$
- A non-vanishing $A_{\rm FB}(s)$ distribution served as a hint of non-standard tensor interaction
- We suggest to perform further detailed studies of $A_{\rm FB}(s)$ at Belle II and STCF

Outline

Summary

- We have performed a model-independent LEFT analysis of $\tau^- \to \omega\pi^-\nu_\tau$ decay
- Assuming G-parity conservation and using the selection rule based on J^{PG} quantum numbers, the dominant BSM contributions arise only from vector and tensor operators
- We have extended the RχT Lagrangian with external tensor sources to describe the interactions of the tensor external fields with pseudoscalar and vector mesons
- The $\omega\pi$ tensor form factors are calculated in the framework of RχT, and the resonance couplings are determined with QCD short-distance constraints and the matching relations between RχT and χPT
- Any measurement of the forward-backward asymmetry $A_{\rm FB}(s)$ with a non-vanishing distribution could be served as a hint of the non-standard tensor interaction

Thank you very much!