Purely tauonic decay of charged pseudoscalar mesons

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- Quan-Yi Hu, JHEP 12 (2024) 229
- Quan-Yi Hu, arXiv:2601.12883, submitted to JHEP

SM

Decay rate (neglecting radiative corrections)

$$\Gamma(P \to l\bar{\nu}_l)_{\text{SM}} = \frac{G_F^2}{8\pi} f_P^2 |V_{q_1 q_2}|^2 m_P m_l^2 \left(1 - \frac{m_l^2}{m_P^2}\right)^2$$

QED corrections to $B \to \mu\bar{\nu}$: a few percent. [C. Cornella, M. Ferré, M. König and M. Neubert, arXiv:2601.14361]

CKM suppression	
$\lvert V_{cs}\rvert^2 : \lvert V_{cd}\rvert^2 : \lvert V_{cb}\rvert^2 : \lvert V_{ub}\rvert^2 \simeq 1 : 5.1 \times 10^{-2} : 1.8 \times 10^{-3} : 1.5 \times 10^{-5}$	
Helicity suppression and phase-space factor $m_l^2 \left(1 - m_l^2/m_P^2\right)^2$	
P	$e\bar{\nu}_e : \mu\bar{\nu}_\mu : \tau\bar{\nu}_\tau$
D_s^-	$2.4 \times 10^{-6} : 0.1 : 1$
D^-	$8.8 \times 10^{-6} : 0.4 : 1$
B_c^-	$9.8 \times 10^{-8} : 4.2 \times 10^{-3} : 1$
B^-	$1.1 \times 10^{-7} : 4.5 \times 10^{-3} : 1$

EXP

- $D_s \to \tau\bar{\nu}_\tau$
  $\tau \to \pi\nu_\tau$: CLEO, '09; Belle, '13; BESIII, '16, '21, '23
  $\tau \to \rho\nu_\tau$: CLEO, '09; BESIII, '21
  $\tau \to e\bar{\nu}_e\nu_\tau$: CLEO, '09; BaBar, '10; Belle, '13; BESIII, '21
  $\tau \to \mu\bar{\nu}_\mu\nu_\tau$: BaBar, '10; Belle, '13; BESIII, '23
- $D \to \tau(\to \pi\nu_\tau)\bar{\nu}_\tau$: BESIII, '19, '24
- $B \to \tau\bar{\nu}_\tau$ Belle II, '25 significance of 3.0σ
  All four reconstructed channels (accounting for over 70% of the total τ width)

- Cascade decays

$$P \to \tau(\to \pi\nu_\tau, \rho\nu_\tau, e\bar{\nu}_e\nu_\tau, \mu\bar{\nu}_\mu\nu_\tau)\bar{\nu}_\tau,$$

where $P = D_s, D, B, B_c$.

- Theoretical framework

$$\mathcal{H}_{\text{eff}}^{q_2\to q_1\tau\nu_\tau} = \sqrt{2}G_F V_{q_1q_2} \sum_{B=L,R} \Big[(g_{V,B}^{q_1q_2}\bar{q}_1\gamma^\mu q_2 + g_{A,B}^{q_1q_2}\bar{q}_1\gamma^\mu\gamma_5 q_2)\bar{\tau}\gamma_\mu P_B\nu_\tau$$
$$+ (g_{S,B}^{q_1q_2}\bar{q}_1 q_2 + g_{P,B}^{q_1q_2}\bar{q}_1\gamma_5 q_2)\bar{\tau}P_B\nu_\tau$$
$$+ g_{T,B}^{q_1q_2}(\bar{q}_1\sigma^{\mu\nu}P_B q_2)\bar{\tau}\sigma_{\mu\nu}P_B\nu_\tau\Big] + \text{H.c.},$$

- Analytical results $d\Gamma/dE_a$, $a = \pi, \rho, e, \mu$

Neglect neutrino mass

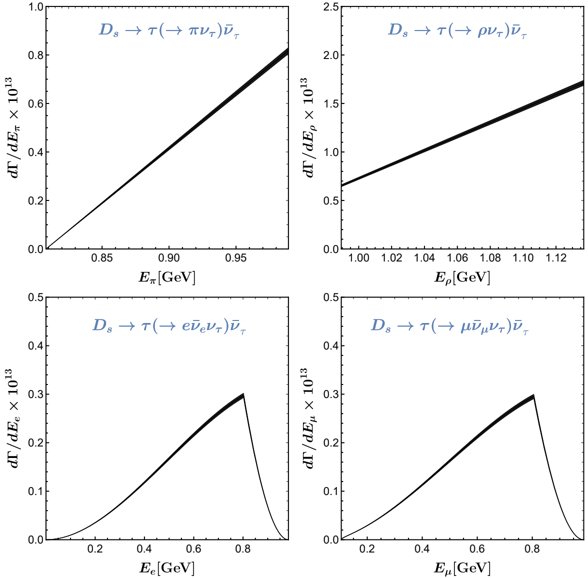
$$\frac{d\Gamma}{dE_\pi} = \frac{G_F^2|V_{q_1q_2}|^2 f_P^2 m_\tau^4 \mathcal{B}(\tau\to\pi\nu_\tau)}{4\pi m_P^2(m_\tau^2-m_\pi^2)^2}\Bigg[\left(m_P^2-m_\tau^2\right)\left(m_\tau^2-m_\pi^2\right)\left(|g_L^{q_1q_2}|^2+|g_R^{q_1q_2}|^2\right) + 4m_P m_\tau^2\left(|g_L^{q_1q_2}|^2-|g_R^{q_1q_2}|^2\right)\left(E_\pi-\frac{E_\pi^-+E_\pi^+}{2}\right)\Bigg].$$

$$\frac{d\Gamma}{dE_\rho} = \frac{G_F^2|V_{q_1q_2}|^2 f_P^2 m_\tau^4 \mathcal{B}(\tau\to\rho\nu_\tau)}{4\pi m_P^2(m_\tau^2-m_\rho^2)^2(m_\tau^2+2m_\rho^2)}\Bigg[\left(m_P^2-m_\tau^2\right)\left(m_\tau^4+m_\tau^2m_\rho^2-2m_\rho^4\right)\left(|g_L^{q_1q_2}|^2+|g_R^{q_1q_2}|^2\right) + 4m_P m_\tau^2\left(m_\tau^2-2m_\rho^2\right)\left(|g_L^{q_1q_2}|^2-|g_R^{q_1q_2}|^2\right)\left(E_\rho-\frac{E_\rho^-+E_\rho^+}{2}\right)\Bigg].$$

Here $g_B^{q_1q_2} \equiv \frac{m_P^2}{m_\tau(m_{q_1}+m_{q_2})} g_{P,B}^{q_1q_2} - g_{A,B}^{q_1q_2}\ (B=L,R)$

$d\Gamma/dE_\ell = \cdots$ [Quan-Yi Hu, JHEP 12 (2024) 229]

In the SM, $P = D_s$. [Quan-Yi Hu, arXiv:2601.12883]



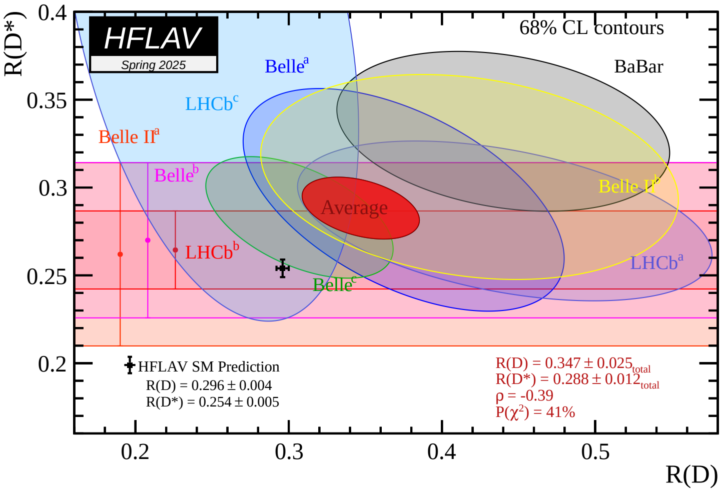
n-th order energy moment [Quan-Yi Hu, arXiv:2601.12883]

$$M_a^{(n)} = \int E_a^n \frac{d\Gamma}{dE_a} dE_a$$

	$\tau \to \pi\nu_\tau$	$\tau \to \rho\nu_\tau$	$\tau \to e\bar{\nu}_e\nu_\tau$	$\tau \to \mu\bar{\nu}_\mu\nu_\tau$
$\frac{\lvert V_{cs}\rvert^2 f_{D_s}^2}{10^{14}} \lvert g_L^{cs}\rvert^2$	$1.33M_\pi^{(1)} - 1.15M_\pi^{(0)}$	$1.54M_\rho^{(1)} - 1.63M_\rho^{(0)}$	$1.70M_e^{(0)} - 2.68M_e^{(1)}$	$1.75M_\mu^{(0)} - 2.72M_\mu^{(1)}$
$\frac{\lvert V_{cs}\rvert^2 f_{D_s}^2}{10^{14}} \lvert g_R^{cs}\rvert^2$	$1.24M_\pi^{(0)} - 1.33M_\pi^{(1)}$	$1.66M_\rho^{(0)} - 1.54M_\rho^{(1)}$	$2.68M_e^{(1)} - 1.65M_e^{(0)}$	$2.72M_\mu^{(1)} - 1.70M_\mu^{(0)}$
$\frac{\lvert V_{cd}\rvert^2 f_D^2}{10^{15}} \lvert g_L^{cd}\rvert^2$	$1.03M_\pi^{(1)} - 0.91M_\pi^{(0)}$	$1.20M_\rho^{(1)} - 1.26M_\rho^{(0)}$	$1.30M_e^{(0)} - 2.08M_e^{(1)}$	$1.34M_\mu^{(0)} - 2.11M_\mu^{(1)}$
$\frac{\lvert V_{cd}\rvert^2 f_D^2}{10^{15}} \lvert g_R^{cd}\rvert^2$	$0.94M_\pi^{(0)} - 1.03M_\pi^{(1)}$	$1.28M_\rho^{(0)} - 1.20M_\rho^{(1)}$	$2.08M_e^{(1)} - 1.28M_e^{(0)}$	$2.11M_\mu^{(1)} - 1.32M_\mu^{(0)}$
$\frac{\lvert V_{ub}\rvert^2 f_B^2}{10^{11}} \lvert g_L^{ub}\rvert^2$	$1.68M_\pi^{(1)} - 1.83M_\pi^{(0)}$	$1.95M_\rho^{(1)} - 3.14M_\rho^{(0)}$	$3.87M_e^{(0)} - 3.38M_e^{(1)}$	$3.99M_\mu^{(0)} - 3.43M_\mu^{(1)}$
$\frac{\lvert V_{ub}\rvert^2 f_B^2}{10^{11}} \lvert g_R^{ub}\rvert^2$	$3.14M_\pi^{(0)} - 1.68M_\pi^{(1)}$	$3.69M_\rho^{(0)} - 1.95M_\rho^{(1)}$	$3.38M_e^{(1)} - 3.08M_e^{(0)}$	$3.43M_\mu^{(1)} - 3.18M_\mu^{(0)}$
$\frac{\lvert V_{cb}\rvert^2 f_{B_c}^2}{10^{11}} \lvert g_L^{cb}\rvert^2$	$1.07M_\pi^{(1)} - 1.31M_\pi^{(0)}$	$1.24M_\rho^{(1)} - 2.28M_\rho^{(0)}$	$2.85M_e^{(0)} - 2.14M_e^{(1)}$	$2.94M_\mu^{(0)} - 2.18M_\mu^{(1)}$
$\frac{\lvert V_{cb}\rvert^2 f_{B_c}^2}{10^{11}} \lvert g_R^{cb}\rvert^2$	$2.33M_\pi^{(0)} - 1.07M_\pi^{(1)}$	$2.71M_\rho^{(0)} - 1.24M_\rho^{(1)}$	$2.14M_e^{(1)} - 2.23M_e^{(0)}$	$2.18M_\mu^{(1)} - 2.30M_\mu^{(0)}$

$R(D^{(*)})$ anomaly [3.8σ]

$$R(D^{(*)}) \equiv \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$



BP1 : $C_{LL}^{V}=0.077;$ BP2 : $C_{RL}^{V}=-0.065;$ BP3 : $C_{LL}^{S}=0.167$

BP4 : $C_{RL}^{S}=0.181;$ BP5 : $C_{RL}^{V}=0.01+0.41i;$ BP6 : $C_{LL}^{S}=-0.55+0.86i$

BP7 : $C_{LL}^{V}=0.07,\ C_{RL}^{S}=0.03,$ for the singlet vector LQ U_1

BP8 : $C_{LL}^{V}=0.07,\ C_{LL}^{S}=0.2i,$ for the singlet scalar LQ S_1

BP9 : $C_{RL}^{V}=0.65i,\ C_{LL}^{S}=0.02-0.61i,$ for the doublet scalar LQ R_2

BP10 : $C_{RR}^{V}=0.37,$ for the mediator $V^{\mu}\sim(1,1,-1)$

BP11 : $C_{LR}^{S}=-0.06,\ C_{RR}^{S}=0.46,$ for the mediator $\Phi\sim(1,2,1/2)$

BP12 : $C_{RR}^{V}=0.39,\ C_{LR}^{S}=-0.1,$ for the singlet vector LQ U_1

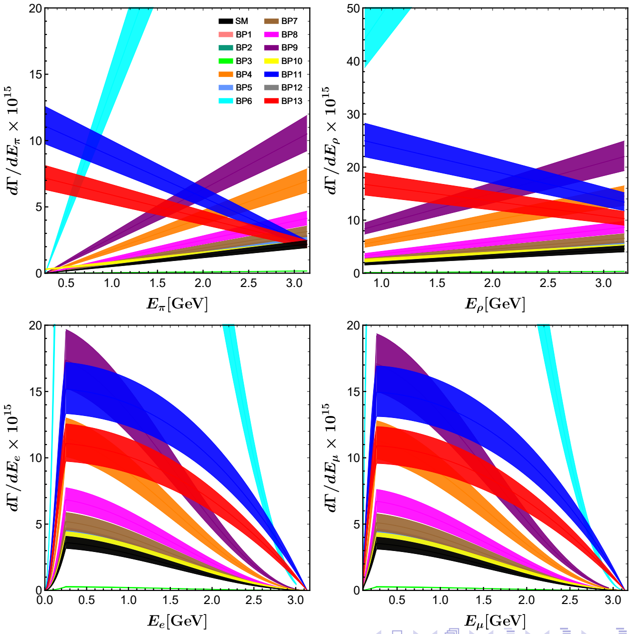
BP13 : $C_{LR}^{S}=0.418,$ for the doublet vector LQ $\tilde{V}_2$

Purely LH neutrino:BP1∼9 [S.Iguro, T.Kitahara and R.Watanabe,PRD110(2024)075005]
Purely RH neutrino:BP10∼13 [R.Mandal, C.Murgui, A.Peñuelas and A.Pich, JHEP08(2020)022]

The impact of NP on

$$B_c \to \tau(\to \pi\nu_\tau, \rho\nu_\tau, \ell\bar{\nu}_\ell\nu_\tau)\bar{\nu}_\tau$$

[Quan-Yi Hu, JHEP 12 (2024) 229]

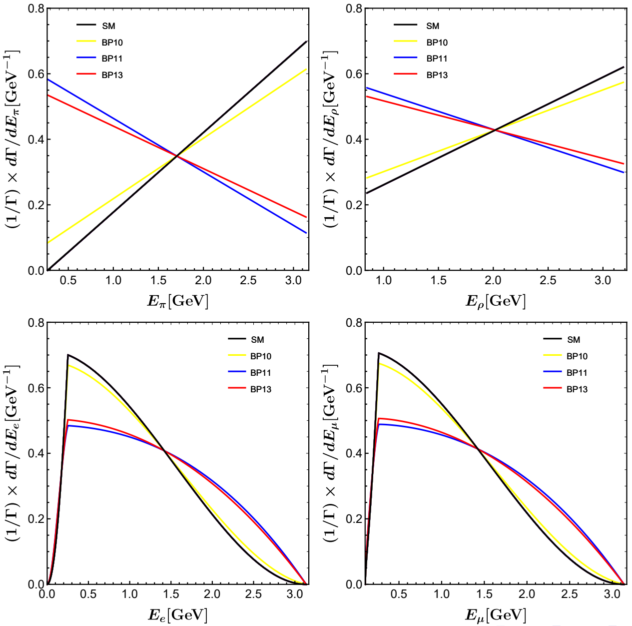


Normalized distribution

$$\frac{1}{\Gamma}\frac{d\Gamma(B_c \to \tau(\to \pi\nu_\tau, \rho\nu_\tau, \ell\bar{\nu}_\ell\nu_\tau)\bar{\nu}_\tau)}{dE_{\pi,\rho,\ell}}$$

There exist fixed points!

[Quan-Yi Hu, JHEP 12 (2024) 229]



The position of the fixed point is not affected by any heavy NP.

Cascade decay $P \to \tau(\to h\nu_\tau)\bar{\nu}_\tau$ ($h = \pi$ or ρ). Only one fixed point exists.

$$E_h = \frac{\left(m_P^2 + m_\tau^2\right)\left(m_h^2 + m_\tau^2\right)}{4 m_P m_\tau^2}, \frac{1}{\Gamma}\frac{d\Gamma}{dE_h} = \frac{2 m_P m_\tau^2}{\left(m_P^2 - m_\tau^2\right)\left(m_\tau^2 - m_h^2\right)}.$$

Cascade decay $P \to \tau(\to \ell\bar{\nu}_\ell\nu_\tau)\bar{\nu}_\tau$ ($\ell = e$ or μ). Two fixed points exist.

[Quan-Yi Hu, arXiv:2601.12883]

	π	ρ	e	μ
D_s	$(0.8986, 5.525)$	$(1.063, 6.782)$	$(0.3314, 0.7077)$ $(0.8259, 1.878)$	$(0.3431, 0.7247)$ $(0.8294, 1.909)$
D	$(0.8951, 11.13)$	$(1.059, 13.66)$	$(0.3327, 0.7111)$ $(0.8511, 2.060)$	$(0.3444, 0.7282)$ $(0.8544, 2.095)$
B	$(1.478, 0.4299)$	$(1.749, 0.5277)$	$(0.2015, 0.4003)$ $(1.227, 0.4923)$	$(0.2165, 0.4046)$ $(1.233, 0.4989)$
B_c	$(1.705, 0.3487)$	$(2.017, 0.4280)$	$(0.1747, 0.3434)$ $(1.418, 0.4079)$	$(0.1911, 0.3436)$ $(1.424, 0.4133)$

[Quan-Yi Hu, arXiv:2601.12883]

Summary

- The differential distributions of $P \to \tau(\to \pi\nu_\tau, \rho\nu_\tau, e\bar{\nu}_e\nu_\tau, \mu\bar{\nu}_\mu\nu_\tau)\bar{\nu}_\tau$ decays have been calculated for the first time.
- Energy moments and method for measuring NP couplings $g_L^{q_1 q_2}$ and $g_R^{q_1 q_2}$.
- Normalized distribution $d\Gamma/(\Gamma dE)$ and fixed point.

Thank you!