

Interplay of hadronic τ decays with BSM physics

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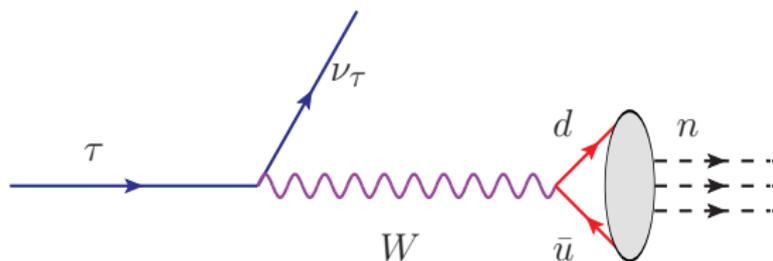
GDR-InF annual workshop 2021
16/11/2021

Based on work with
V. Cirigliano, D. Díaz-Calderón,
A. Falkowski, M. González-Alonso



The hadronic decay of the τ

$$\tau^- \rightarrow n + \nu_\tau, \quad n = \pi^-, \pi^-\pi^0, K^-\pi^0, \dots$$



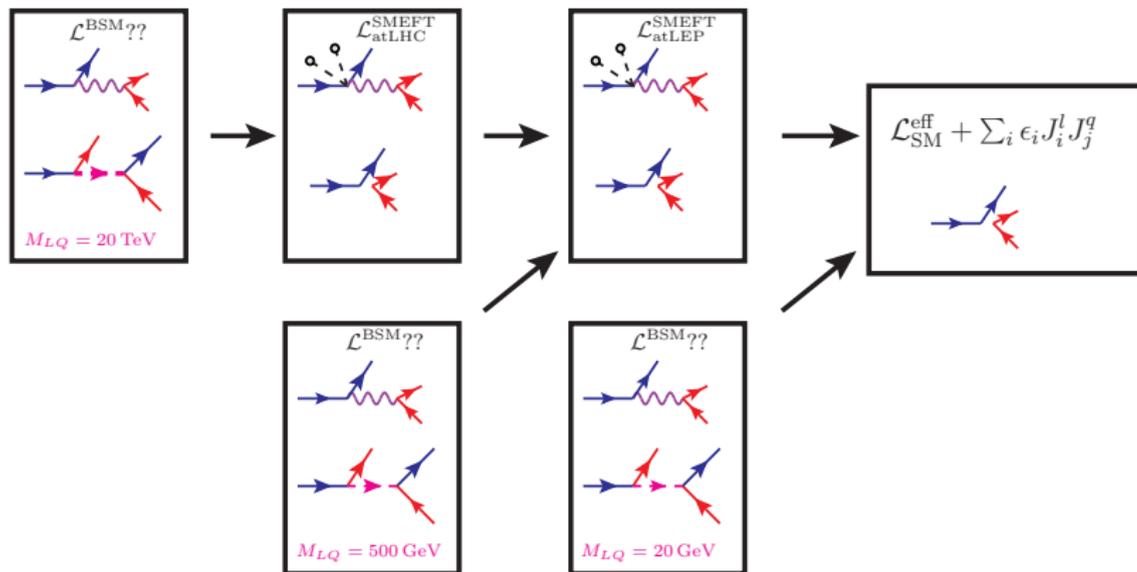
$$\mathcal{L}_{SM} \sim W^\mu J'_\mu + W^\mu J^q_\mu, \quad J^l \sim \bar{\nu}_\tau \Gamma \tau, \quad J^q \sim V_{ud} \bar{D} \Gamma u$$

$$q^2 \ll M_W^2 \sim v^2 \rightarrow \mathcal{L}_{SM}^{\text{eff}} \sim \frac{1}{v^2} J^q \cdot J^l$$

$$\frac{d\Gamma^{(n)}}{dq^2} \sim \sum \text{KIN}_{ij}(q^2) \cdot \rho_{ij}^{(n)}(q^2); \quad \rho_{ij}^{(n)}(q^2) \sim \int d\phi_m \langle n | J_i | 0 \rangle \langle 0 | J_j^\dagger | n \rangle$$

$$\rho_{ij}^{(n)} \text{ mostly a QCD object, e.g. } \rho^{(\pi)} \sim f_\pi^2 \delta^4(q^2 - m_\pi^2)$$

BSM in hadronic τ decays: EFT approach



$$\frac{d\Gamma^{(n)}}{dq^2} \sim \underbrace{\sum \text{KIN}_{ij}(q^2) \cdot \rho_{ij}^{(n)}(q^2)}_{\text{SM}} (1 + c_A \epsilon_A) + \sum \epsilon_A \cdot \text{KIN}'_{ij}(q^2) \cdot \rho'_{ij}{}^{(n)}(q^2)$$

$$\rho_{ij}^{(n)}(q^2) \sim \int d\phi_m \langle n | J_i^{SM} | 0 \rangle \langle 0 | J_j^{SM\dagger} | n \rangle; \quad \rho'_{ij}{}^{(n)}(q^2) \sim \int d\phi_m \langle n | J_i^{SM} | 0 \rangle \langle 0 | J_j^{BSM\dagger} | n \rangle$$

$$\frac{d\Gamma^{(n)}}{dq^2} \sim \underbrace{\sum \text{KIN}_{ij}(q^2) \cdot \rho_{ij}^{(n)}(q^2)}_{\text{SM}} (1 + c_A \epsilon_A) + \sum \epsilon_A \cdot \text{KIN}'_{ij}(q^2) \cdot \rho'_{ij}(q^2)$$

$$\epsilon_A = c_A \cdot \underbrace{\frac{q^2}{M_{\text{BSM}}^2}}_{\text{BSM suppression}} / \underbrace{\frac{q^2}{M_W^2}}_{\text{SM suppression}} = c_A \cdot \frac{M_W^2}{M_{\text{BSM}}^2}$$

For example $c_A \sim 1, \epsilon_A \lesssim 10^{-2} \rightarrow M_{\text{BSM}} \gtrsim 1 \text{ TeV}$

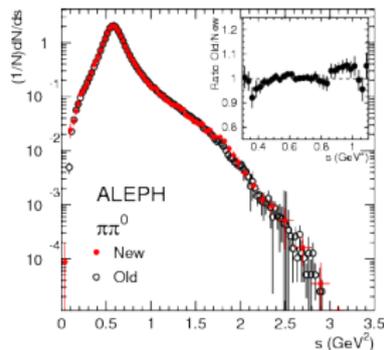
BSM sensitivity? Two possibilities...

- **Further SM Suppression.** For example $\tau \rightarrow \eta \pi \nu_\tau$. $|\epsilon_S| \lesssim 10^{-2}$ [JHEP 12 \(2017\) 027](#)
- **SM and experiment precisely known:** $\tau \rightarrow \pi \nu_\tau$

$$|\epsilon_L^{d\tau} - \epsilon_L^{de} - \epsilon_R^{d\tau} - \epsilon_R^{de} - \frac{B_0^d}{m_\tau} \epsilon_P^{d\tau}| = \left| \frac{\Gamma_{\text{exp}} - \Gamma_{\text{SM}}}{2\Gamma_{\text{exp}}} \right| \lesssim 10^{-2, -3}$$

Exclusive decays: two-pion decay

$$\frac{d\Gamma}{ds} = \left[\frac{d\tilde{\Gamma}}{ds} \right]_{\text{SM}} \left(1 + 2(\epsilon_L^{d\tau} + \epsilon_R^{d\tau} - \epsilon_L^{de} - \epsilon_R^{de}) + a_T(s) \epsilon_T^{d\tau} \right)$$

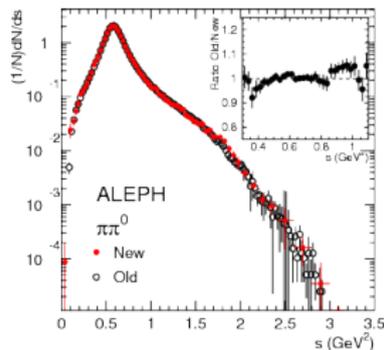


Eur.Phys.J.C 74 (2014) 3, 2803

- Precise $d\Gamma_{exp}$? ✓
- SM precisely known? Need $\langle \pi^0 \pi^- | \bar{d} \gamma_\mu u | 0 \rangle$
Parameterizations can give hints JHEP 11 (2018) 038
- But not ultimate evidence for (no) BSM...

Exclusive decays: two-pion decay

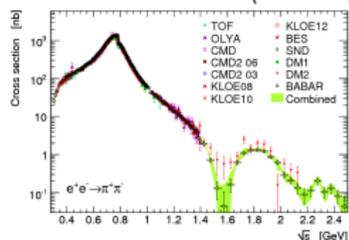
$$\frac{d\Gamma}{ds} = \left[\frac{d\tilde{\Gamma}}{ds} \right]_{\text{SM}} \left(1 + 2(\epsilon_L^{d\tau} + \epsilon_R^{d\tau} - \epsilon_L^{de} - \epsilon_R^{de}) + a_T(s) \epsilon_T^{d\tau} \right)$$



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Unless we take $\langle \pi^0 \pi^- | \bar{d} \gamma_\mu u | 0 \rangle$ from $e^+ e^- \rightarrow \pi^+ \pi^-$ (plus tiny IB corrections)



Eur.Phys.J.C 77 (2017) 12, 827

- From the HVP integral: sub-percent level bound
Phys.Rev.Lett. 122 (2019) 22, 221801
- Per-mil level? Need IB from the lattice

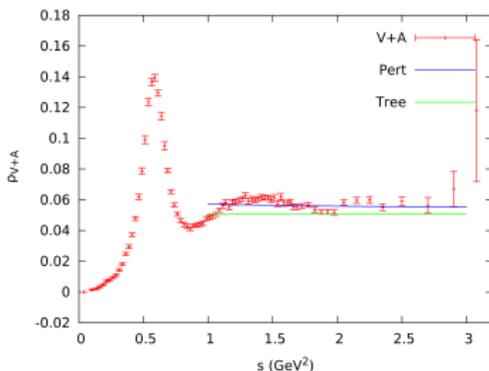
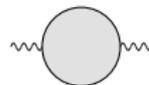
Non-strange inclusive decays

$$\frac{d\Gamma^{(n)}}{dq^2} \sim \underbrace{\sum \text{KIN}_{ij}(q^2) \cdot \rho_{ij}^{(n)}(q^2)}_{\text{SM}} (1 + c_A \epsilon_A) + \sum \epsilon_A \cdot \text{KIN}'_{ij}(q^2) \cdot \rho_{ij}'^{(n)}(q^2)$$

$$\rho_{ij}^{(n)}(q^2) \sim \int d\phi_m \langle n | J_i^{SM} | 0 \rangle \langle 0 | J_j^{SM\dagger} | n \rangle ; \rho_{ij}'^{(n)}(q^2) \sim \int d\phi_m \langle n | J_i^{SM} | 0 \rangle \langle 0 | J_j^{BSM\dagger} | n \rangle$$

• Rest of channels? **Resonance jungle...**

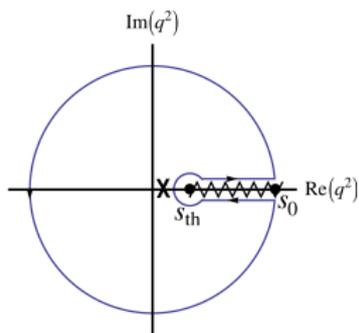
• But $\sum_n \rho_{ij}^{(n)}(q^2) \sim \text{Im} \Pi_{ij}(q^2)$, $\Pi_{ij}(q^2) \sim \int d^4x e^{-iqx} \langle T(J_i(x) J_j(0)) \rangle$



• ALEPH '14. Figure from PhysRevD.94.034027

• **No BSM contamination assumed**

Non-strange inclusive decays



$$\underbrace{\int_{s_{\text{th}}}^{s_0} \frac{ds}{s_0} \omega(s) \frac{1}{\pi} \text{Im} \Pi(s)}_{\text{data}} + \underbrace{\frac{1}{2\pi i} \oint_{|s|=s_0} \frac{ds}{s_0} \omega(s) \Pi(s)}_{\sim \text{OPE}} = 2 \frac{F_\pi^2}{s_0} \omega(M_\pi^2)$$

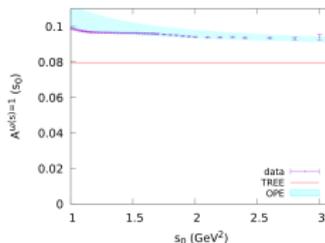
Nucl.Phys.B 373 (1992) 581-612

Kinematic weight

$$I^{\text{exp}} = 25.051(74)$$

$$I^{\text{SM}} = 24.80(49)$$

$\omega = 1$ weight



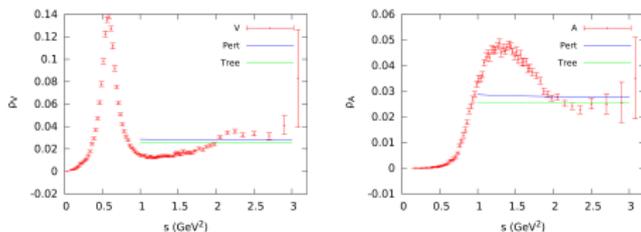
• **SM**: Most precise phenomenological determination of α_s PDG '20

• **BSM**. Take α_s^{latt}

$$\epsilon_{L+R}^{d\tau} - \epsilon_{L+R}^{de} - 0.76 \epsilon_R^{d\tau} + 1.96(62) \epsilon_T^{d\tau} = (5 \pm 10) \times 10^{-3}$$

$$\epsilon_{L+R}^{d\tau} - \epsilon_{L+R}^{de} - 0.88 \epsilon_R^{d\tau} + 1.08(36) \epsilon_T^{d\tau} = (9.4 \pm 8.8) \times 10^{-3}$$

Non-strange inclusive decays: Weinberg sum rules

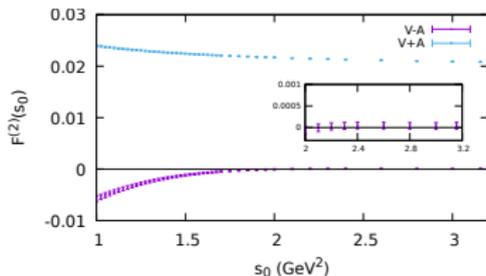


Weinberg 1967: • $\int \rho_V \approx \int \rho_A + \text{pion}$, • $\int q^2 \rho_V \approx \int q^2 \rho_A \rightarrow M_{a1} \approx \sqrt{2} M_\rho$

54 years of iterations later (QCD, OPE, LEP, EFTs, DVs, lattice,...):

$$F_{V-A}^{(2)}(s_0) \equiv \int_{s_{\text{th}}}^{s_0} \frac{ds}{s_0} \left(1 - \frac{s}{s_0}\right)^2 \frac{1}{\pi} \text{Im} \Pi_{V-A}(s) - 2 \frac{F_\pi^2}{s_0} \left(1 - \frac{M_\pi^2}{s_0}\right)^2 - \frac{\langle \mathcal{O}_{6,V-A}^d(s_0) \rangle'}{s_0^3} \underbrace{=}_0 \quad s_0 \sim m_\tau^2$$

JHEP 06 (2021) 005



$$\epsilon_{L+R}^{d\tau} - \epsilon_{L+R}^{de} + 1.93 \epsilon_R^{d\tau} + 6.4(5.9) \epsilon_T^{d\tau} = (7.1 \pm 9.5) \times 10^{-3}$$

Strange decays

- $\tau \rightarrow K\nu_\tau$. $|\epsilon_L^{sT} - \epsilon_L^{se} - \epsilon_R^{sT} - \epsilon_R^{se} - \frac{B_0^s}{m_\tau} \epsilon_P^{sT}| = \left| \frac{\Gamma_{\text{exp}} - \Gamma_{SM}}{2\Gamma_{\text{exp}}} \right| \lesssim 10^{-2, -3}$
- $\tau \rightarrow K\pi\nu_\tau$. SM analysis in [JHEP 10 \(2013\) 070](#) fit the shape, predict normalization. Recycled to

$$\epsilon_{L+R}^{sT} - \epsilon_{L+R}^{se} + f(\epsilon_S^{s\ell}, \epsilon_T^{s\ell}) = 0.002 \pm 0.018 \quad \text{Preliminary}$$

- **Inclusive strange**

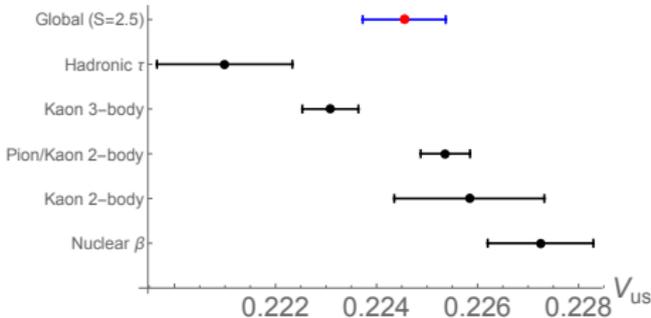
- ▶ SM but with $m_s \rightarrow m_d$: $\frac{\Gamma^d}{|V_{ud}|^2} = \frac{\Gamma^s}{|V_{us}|^2}$
- ▶ Real SM: $\frac{\Gamma^d}{|V_{ud}|^2} = \frac{\Gamma^s}{|V_{us}|^2} + \delta R_{th}^{SM} \rightarrow V_{us}$ [HFLAV '18](#)
- ▶ BSM: $\frac{\Gamma^d}{|V_{ud}|^2} (1 + 2\delta_{BSM,d}^{inc}) = \frac{\Gamma^s}{|V_{us}|^2} (1 + 2\delta_{BSM,s}^{inc}) + \delta R_{th}^{SM}$

$$\begin{aligned} \epsilon_{\tau \rightarrow \nu_\tau s\bar{u}} &= 1.00 (\epsilon_{L+R}^{sT} - \epsilon_{L+R}^{se}) - 1.03 \epsilon_R^{sT} - 0.39 \epsilon_P^{sT} + 1.6(5) \epsilon_T^{sT} + 0.08(1) \epsilon_S^{sT} \\ &\quad - 1.07 (\epsilon_{L+R}^{dT} - \epsilon_{L+R}^{de}) + 1.04 \epsilon_R^{dT} + 0.30 \epsilon_P^{dT} - 1.7(5) \epsilon_T^{dT} \\ &= -(0.0179 \pm 0.0085), \end{aligned}$$

Preliminary

$$\begin{pmatrix} \epsilon_L^{d\tau/e} + \epsilon_R^{d\tau} - \epsilon_R^{de} \\ \epsilon_R^{d\tau} \\ \epsilon_P^{d\tau} \\ \hat{\epsilon}_T^{d\tau} \\ \epsilon_L^{s\tau/e} - \epsilon_R^{s\tau} - \epsilon_R^{se} - \frac{m_{K^\pm}^2}{m_\tau(m_u+m_s)} \epsilon_P^{s\tau} \\ \epsilon_L^{s\tau/e} + \epsilon_R^{s\tau} - \epsilon_R^{se} + 0.08(1)\epsilon_S^{s\tau} - 0.39\epsilon_P^{s\tau} + 1.6(5)\epsilon_T^{s\tau} \end{pmatrix} = \begin{pmatrix} 2.2 \pm 2.6 \\ 0.6 \pm 1.4 \\ 0.4 \pm 1.0 \\ -2.8 \pm 6.0 \\ -0.3 \pm 1.0 \\ -1.3 \pm 1.2 \end{pmatrix} \times 10^{-2},$$

- Far better sensitivity in simplified scenarios
- ϵ_X^e from V_{ud} and V_{us} input from β and K and π decays
- Full likelihood with explicit dependence on V_{ud} , V_{us} , f_K , f_π consistently kept



- Cabibbo Anomalies? **HFLAV '18**
- Underestimated uncertainties **cannot** be discarded
- But full **translation into BSM EFT** is, for the first time, implemented
- Exploring favored? directions

Very preliminary exploration

	$\epsilon_X^{de} \times 10^3$	$\epsilon_X^{se} \times 10^3$	$\epsilon_X^{d\mu} \times 10^3$	$\epsilon_X^{s\mu} \times 10^3$	$\epsilon_X^{d\tau} \times 10^3$	$\epsilon_X^{s\tau} \times 10^3$
L	-0.77(25)	0.6(1.2)	0.44(88)	0.5(1.2)	5.3(2.6)	18.6(6.1)
R	0.61(25)	-5.2(1.7)	0.61(25)	-5.2(1.7)	0.61(25)	-5.2(1.7)
S	1.38(65)	x	x	-0.26(44)	(-21, 10)	-27(10)
P	0.00018(17)	-0.00044(36)	0.016(32)	0.032(64)	2.0(2.6)	11.0(5.5)
\hat{T}	0.28(82)	x	x	1(18)	28.6(10.1)	-13.7(5.1)

Table: $\epsilon_X^{D\ell}$ values in 10^{-3} units, fitting one parameter at a time.