# Towards the best limit on non-standard charged current tensor interactions at Belle-II

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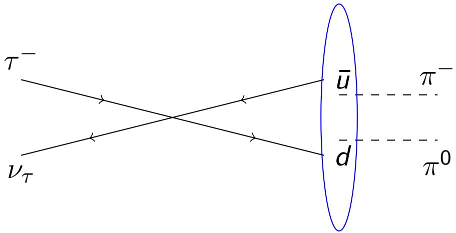
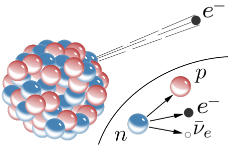
XXXII Reunión Anual de la División de Partículas y Campos de la SMF



# Contents

# Motivation

- By 1911, experiments indicated that $\beta$ decay violated the conservation of energy.
- In 1930 Wolfgang Pauli proposed a hypothetical weakly coupled neutral particle, dubbed the neutrino by Enrico Fermi.



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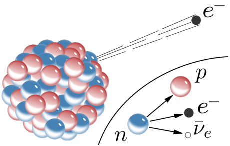


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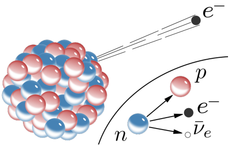
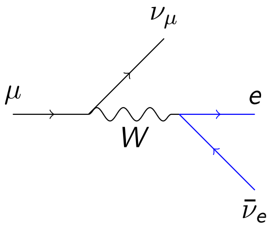



- Fermi proposed a contact interaction model based on QED's vector current interaction.
- It has been modified over the years to incorporate parity violation and the V-A theory; $\mu$ and $\tau$ decays; strangeness changing decays; the quark model; heavy quarks and mixing (CKM) matrix; and neutrino mass and mixing.

# Motivation

- $\mu^- \to e^- \bar{\nu}_e \nu_\mu$ decays receive contribution from $W$-exchange diagrams.
- Interaction between leptons is universal.




$$\mathcal{L} = -\frac{G_F}{\sqrt{2}} \left[\bar{e}\gamma^\mu \left(1-\gamma_5\right)\nu_e\right] \left[\bar{\nu}_\mu \gamma_\mu \left(1-\gamma_5\right)\mu\right] + h.c.,$$

$$\left(\mu^- \to e^- \bar{\nu}_e \nu_\mu,\ \mu^- \bar{\nu}_\mu \to e^- \bar{\nu}_e,\ \mu^- \nu_e \to e^- \nu_\mu,\ e^+ \to \mu^+ \nu_e \bar{\nu}_\mu,\ \cdots\right)$$

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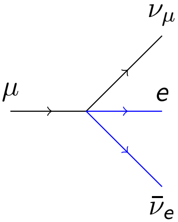


That's an EFT!

- Since the momentum transfer of the process is limited by the muon mass value, which is much smaller than $M_W$, the $W$-propagator shrinks to a point becoming a point-like effective interaction.

# Motivation

- The hadronic current doesn't seem to be universal.
- For $n \to p e^- \nu_e$ decays ($p \to n e^+ \bar{\nu}_e$).

$$\mathcal{L} = -\frac{G_F}{\sqrt{2}} \left[\bar{p}\gamma^\mu \left(1 - g_A\gamma_5\right) n\right] \left[\bar{\nu}_\mu\gamma_\mu \left(1 - \gamma_5\right) \mu\right] + h.c.,$$

where $g_A \sim 1.27$ is a strong interaction correction from QCD.

# Motivation

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$$\mathcal{L} = -\frac{G_F}{\sqrt{2}} \left[\bar{u}\gamma^{\mu}\left(1-\gamma_5\right)d'\right]\left[\bar{\nu}_{\mu}\gamma_{\mu}\left(1-\gamma_5\right)\mu\right] + h.c.,$$

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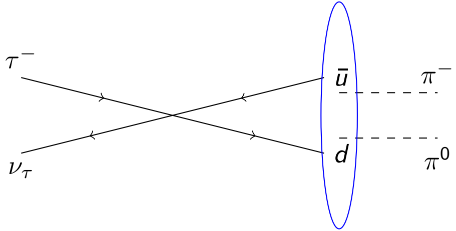
Today (semi)leptonic charged current decays are precision probes of the SM (Michel parameters, n/$\Lambda$ decays, $\pi$ $\mathrm{F}_{V/A}$, $\cdots$).



# Formalism

$$\mathcal{L}^{(eff)} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \cdots$$

$$\mathcal{L}_n = \sum_i \alpha_i^{(n)} O_i^{(n)},$$

[a]

[a] Cirigliano, Jenkins & González-Alonso Nucl.Phys. B830 (2010) 95-115

Hypothesis:

- $v \ll \Lambda$ ($\Lambda \sim M_{NP}$)

$$\mathcal{L}^{(eff)} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i \alpha_i O_i \quad \rightarrow \quad \mathcal{L}_{SM} + \frac{1}{v^2}\sum_i \hat{\alpha}_i O_i$$

[a]

[a] Cirigliano, Jenkins & González-Alonso Nucl.Phys. B830 (2010) 95-115

with $\hat{\alpha}_i = (v^2/\Lambda^2)\alpha_i$, which are $\mathcal{O}(10^{-3})$ for $\Lambda \sim 1\mathrm{TeV}$.

$$\mathcal{L}^{(eff)}_{BW} = \mathcal{L}_{SM} + \sum_{i=1}^{77} \frac{\alpha_i}{\Lambda^2} O_i,$$

[a]

[a] Büchmuller-Wyler '85; Grzadkowski, Iskrzynski, Misiak & Rosiek '10

$$\mathcal{L}_{CC} = -\frac{4G_F}{\sqrt{2}} V_{ud} \Big[ (1 + [v_L]_{\ell\ell}) \bar{\ell}_L \gamma_\mu \nu_{\ell L}\, \bar{u}_L \gamma^\mu d_L + [v_R]_{\ell\ell}\, \bar{\ell}_L \gamma_\mu \nu_{\ell L}\, \bar{u}_R \gamma^\mu d_R$$
$$+ [s_L]_{\ell\ell}\, \bar{\ell}_R \nu_{\ell L}\, \bar{u}_R d_L + [s_R]_{\ell\ell}\, \bar{\ell}_R \nu_{\ell L}\, \bar{u}_L d_R$$
$$+ [t_L]_{\ell\ell}\, \bar{\ell}_R \sigma_{\mu\nu} \nu_{\ell L}\, \bar{u}_R \sigma^{\mu\nu} d_L \Big] + h.c.,$$

[a]

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with $\sigma^{\mu\nu} \equiv i[\gamma^\mu, \gamma^\nu]/2$.

$v_L = v_R = s_L = s_R = t_L = 0$ gives the SM effective Lagrangian.

We introduce equivalent effective couplings
$\epsilon_{L,R} = v_{L,R}$, $\epsilon_S = s_L + s_R$, $\epsilon_P = s_L - s_R$ and $\epsilon_T = t_L$

$$\mathcal{L}_{CC} = -\frac{G_F}{\sqrt{2}} V_{ud}(1+\epsilon_L+\epsilon_R)\left\{\bar{\ell}\gamma_\mu(1-\gamma^5)\nu_\ell\,\bar{u}\left[\gamma^\mu - (1-2\hat{\epsilon}_R)\gamma^\mu\gamma^5\right]d \right.$$
$$\left. + \bar{\ell}(1-\gamma^5)\nu_\ell\,\bar{u}(\hat{\epsilon}_S - \hat{\epsilon}_P\gamma^5)d + 2\hat{\epsilon}_T\,\bar{\ell}\sigma_{\mu\nu}(1-\gamma^5)\nu_\ell\,\bar{u}\sigma^{\mu\nu}d\right\} + h.c.,$$

with $\hat{\epsilon}_I \equiv \epsilon_I/(1+\epsilon_L+\epsilon_R)$ for $I = R, S, P, T$.

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with $\hat{\epsilon}_I \equiv \epsilon_I/(1+\epsilon_L+\epsilon_R)$ for $I = R, S, P, T$.

($\epsilon_L \pm \epsilon_R$ affect the overall normalization of $G_F$ in $V/A$ processes.)
Nuclear physics is only sensitive to $(1-2\hat{\epsilon}_R)g_A/g_V$.

# Amplitude $\tau^-(p) \to \pi^-(p_{\pi^-})\pi^0(p_{\pi_0})\nu_\tau(p')$

$$\begin{aligned}\mathcal{M} &= \mathcal{M}_V + \mathcal{M}_S + \mathcal{M}_T \\ &= \frac{G_F V_{ud}\sqrt{S_{EW}}}{\sqrt{2}}\,(1+\epsilon_L+\epsilon_R)\left[L_\mu H^\mu + \hat{\epsilon}_S L H + 2\hat{\epsilon}_T L_{\mu\nu} H^{\mu\nu}\right],\end{aligned}$$

($\epsilon_{L,R,S,T}$ scale dependence is cancelled by that of the hadron matrix elements)

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\end{aligned}
$$

where we have defined the following leptonic currents

$$
\begin{aligned}
L_\mu &= \bar{u}(P')\gamma^\mu(1-\gamma^5)u(P), \\
L &= \bar{u}(P')(1+\gamma^5)u(P), \\
L_{\mu\nu} &= \bar{u}(P')\sigma_{\mu\nu}(1+\gamma^5)u(P),
\end{aligned}
$$

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and the hadronic matrix elements

$$\begin{aligned}H^\mu &= \langle \pi^0\pi^-|\bar{d}\gamma^\mu u|0\rangle = C_V Q^\mu F_+(s) + C_S\left(\frac{\Delta_{\pi^-\pi^0}}{s}\right) q^\mu F_0(s), \\ H &= \langle \pi^0\pi^-|\bar{d}u|0\rangle \equiv F_S(s), \\ H^{\mu\nu} &= \langle \pi^0\pi^-|\bar{d}\sigma^{\mu\nu} u|0\rangle = iF_T(s)(P^\mu_{\pi^0}P^\nu_{\pi^-} - P^\mu_{\pi^-}P^\nu_{\pi^0}),\end{aligned}$$

where $q^\mu = (P_{\pi^-} + P_{\pi^0})^\mu$, $Q^\mu = (P_{\pi^-} - P_{\pi^0})^\mu + (\Delta_{\pi^0\pi^-}/s)q^\mu$, $s = q^2$ and $\Delta_{ij} = m_i^2 - m_j^2$.

# Amplitude $\tau^-(p) \to \pi^-(p_{\pi^-})\pi^0(p_{\pi_0})\nu_\tau(p')$

If we take the divergence of the vector hadronic current we find

$$F_S(s) = C_S \frac{\Delta_{\pi^-\pi^0}}{(m_d - m_u)} F_0(s)$$

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also we use $L = L_\mu q^\mu / M_\tau$, and reabsorb the $F_S$ form factor

$$C_S \frac{\Delta_{\pi^-\pi^0}}{s} \to C_S \frac{\Delta_{\pi^-\pi^0}}{s} \left[1 + \frac{s\,\hat{\epsilon}_S}{m_\tau(m_d - m_u)}\right]$$

# Amplitude $\tau^-(p) \to \pi^-(p_{\pi^-})\pi^0(p_{\pi_0})\nu_\tau(p')$

- In Garcés, Hernández, López & Roig JHEP 1712 (2017) 027, they considered that $F_T(s) = F_T$ because $\tau^- \to \eta^{(\prime)}\pi^-\nu_\tau$ decays are good for $\hat{\epsilon}_S$ but not for $\hat{\epsilon}_T$.

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- Based on the fact that the $\pi \to e\nu_e\gamma$ decays are good to set competitive constraints on $\hat{\epsilon}_T$, we calculate for the very first time $F_T = F_T(s)$ using info from chiral symmetry and asymptotic QCD.

# Observables

Other observables at the backup slides.

$$\Delta \equiv \frac{\Gamma - \Gamma^0}{\Gamma^0} = \alpha\hat{\epsilon}_S + \beta\hat{\epsilon}_T + \gamma\hat{\epsilon}_S^2 + \delta\hat{\epsilon}_T^2,$$

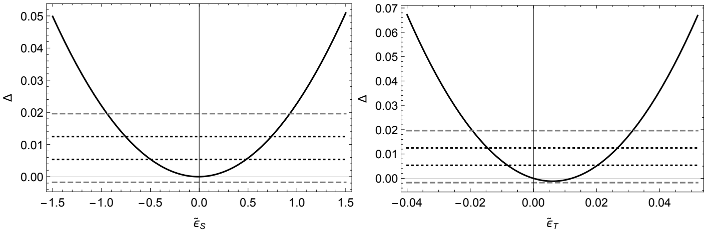


Figure: $\Delta$ as a function of $\hat{\epsilon}_S$ (for $\hat{\epsilon}_T = 0$) and $\hat{\epsilon}_T$ (for $\hat{\epsilon}_S = 0$) for $\tau^- \to \pi^-\pi^0\nu_\tau$ decays. Horizontal lines represent current values of $\Delta$ according to the limits on the branching ratio obtained by Belle (dashed line), and in the hypothetical case of this value being measured by Belle II (dotted line).

# Main Results & Discussions

| $\Delta$ | $\hat{\epsilon}_T$ |
|---|---|
| $\pi^-\pi^0$ | |
| Belle | $[-1.9, 3.1] \cdot 10^{-2}$ |
| Belle II | $[-1.4, -0.8] \cdot 10^{-2} \cup [2.0, 2.7] \cdot 10^{-2}$ |

(LU is assumed)

| (in units of $10^{-2}$) | $\lvert\hat{\epsilon}_T\rvert$ |
|---|---|
| Low energy | 0.1 |
| LHC ($e\nu$) | 0.3 |

Cirigliano, Alonso & Graesser, JHEP 1302 (2013) 046

LHC ($e^+e^-$) leads to $0.1 \times 10^{-2}$

- We find that the different observables would allow to set competitive constraints on tensor interactions.
- For the best fit ($\chi^2/d.o.f. = 1.3$), we get $\hat{\epsilon}_T = (0.51^{+0.09}_{-0.18}) \times 10^{-2}$ which is competitive, and $|\hat{\epsilon}_S| < 0.24$ at 90% C.L.

# Decay rate

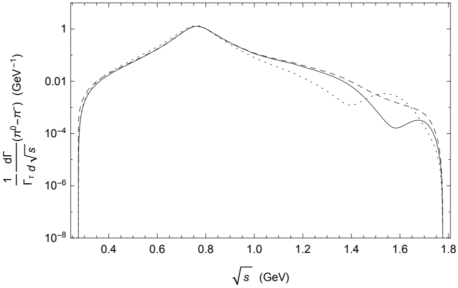


Figure: Hadronic invariant mass distribution for the SM (solid line), $\hat{\epsilon}_S = 0.9281$, $\hat{\epsilon}_T = 0$ (dashed line) and $\hat{\epsilon}_S = 0$, $\hat{\epsilon}_T = 0.0314$ (dotted line).

$$A_{FB} = \frac{\int_0^1 d\cos\theta \frac{d^2\Gamma}{ds\, d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d^2\Gamma}{ds\, d\cos\theta}}{\int_0^1 d\cos\theta \frac{d^2\Gamma}{ds\, d\cos\theta} + \int_{-1}^0 d\cos\theta \frac{d^2\Gamma}{ds\, d\cos\theta}},$$

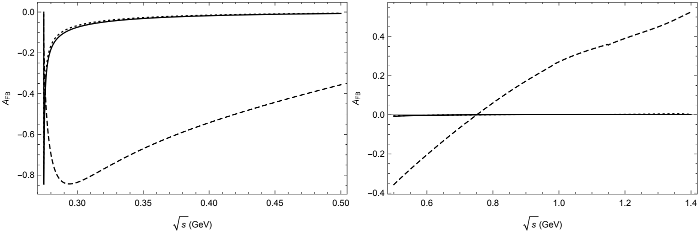


Figure: Forward-backward asymmetry in the $\tau^- \to \pi^-\pi^0\nu_\tau$ decay regarding SM (solid line), ($\hat{\epsilon}_S = 0.9281$, $\hat{\epsilon}_T = 0$) (dashed line) and ($\hat{\epsilon}_S = 0$, $\hat{\epsilon}_T = 0.0314$) (dotted line).

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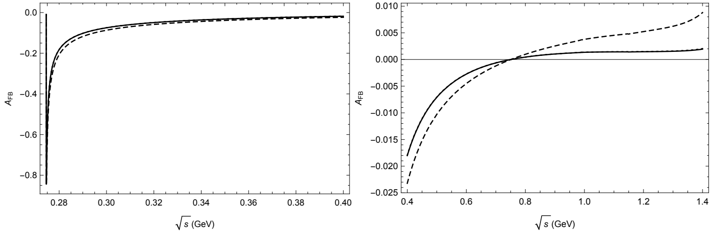


Figure: Forward-backward asymmetry in the $\tau^- \to \pi^- \pi^0 \nu_\tau$ decay regarding SM (solid line), scalar interaction (dashed line) and tensor interaction (dotted line) with the constraints on $\hat{\epsilon}_S$ and $\hat{\epsilon}_T$, respectively.

# Conclusions

- The $\tau^- \to \pi^-\pi^0\nu_\tau$ is the most likely tau decay.
- Branching ratio and form factors for $\tau^- \to \pi^-\pi^0\nu_\tau$ decays are known with precision.

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- Dalitz plots are not good to differentiate between SM & BSM.
- Decay spectra can distinguish between SM & BSM.

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- Within an EFT framework possible NP can be characterized model-independently.
- Dalitz plots are not good to differentiate between SM & BSM.
- Decay spectra can distinguish between SM & BSM.
- Belle-II tau analysis is lead by Mexican researchers.

# References


- J. Miranda Hernández, Ms. Sc. Thesis, *Effective field theory analysis of the $\tau^- \to \pi^-\pi^0\nu_\tau$ decays.*(2018) Cinvestav, México.
- E. A. Garcés, M. Hernández Villanueva, G. López Castro and P. Roig, *Effective-field theory analysis of the $\tau^- \to \eta^{(\prime)}\pi^-\nu_\tau$ decays*, (2017). arXiv: 1708.07802v2 [hep-ph]

- This work should be submitted soon for publication in JHEP.

# $F_T(s)$

There are only four operators at the leading chiral order, $\mathcal{O}(p^4)$, that include the tensor current:

$$\mathcal{L} = \Lambda_1 \langle t^{\mu\nu} f_{+\mu\nu} \rangle - i\Lambda_2 \langle t_+^{\mu\nu} u_\mu u_\nu \rangle + \ldots ,$$

[a]

[a] O. Catá, V. Mateu. JHEP (2007) 078

the coupling between the vector resonance and tensor sources at $\mathcal{O}(p^2)$ is given by

$$\mathcal{L}_2 \left[ V(1^{--}) \right] = F_V^T M_V \langle V_{\mu\nu} \, t_+^{\mu\nu} \rangle + \cdots ,$$

# $F_T(s)$

We get for the tensor form factor

$$F_T(s) = \frac{\sqrt{2}\Lambda_2}{F^2}\left[1 + \frac{G_V F_V^T}{\Lambda_2}\frac{M_V}{M_V^2 - s}\right],$$

In order to reduce the number of independent parameters in the model, we can invoke large-$N_C$ arguments through the analysis of the correlators $\langle VV \rangle$, $\langle TT \rangle$ and $\langle VT \rangle$. We found $F_V^T/F_V = 1/\sqrt{2}$, and we can rewrite $F_T(s)$ as

$$F_T(s) = \frac{\sqrt{2}\Lambda_2}{F^2}\left[1 + \frac{F^2}{\sqrt{2}\Lambda_2}\frac{M_V}{M_V^2 - s}\right],$$

where we have used the relation $G_V F_V = F^2$.

# Dalitz Plot

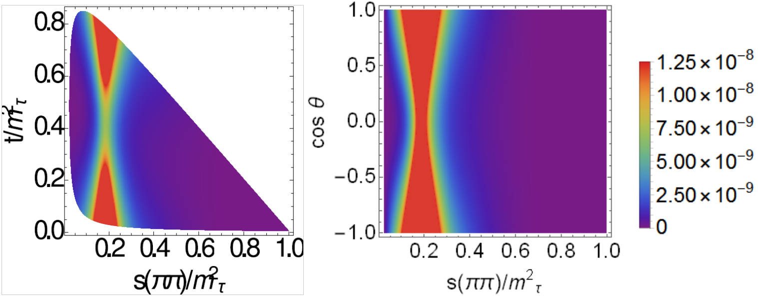


Figure: Dalitz plot distribution for $\tau^- \to \pi^-\pi^0\nu_\tau$ decays as a function of s and t (left) and as a function of s and $\cos\theta$ (right) for SM.

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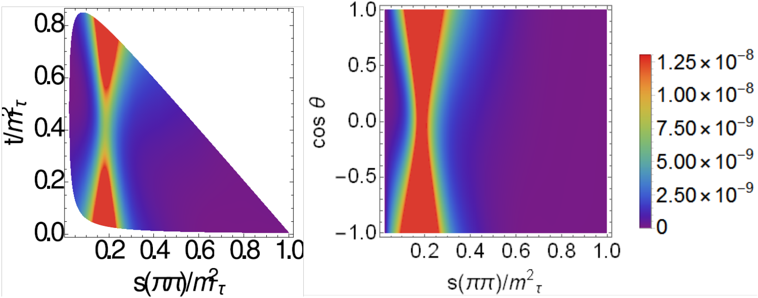


Figure: Dalitz plot distribution for $\tau^- \to \pi^-\pi^0\nu_\tau$ decays as a function of s and t (left) and as a function of s and $\cos\theta$ (right) with $\hat{\epsilon}_S = 0.9281$, $\hat{\epsilon}_T = 0$.

# Dalitz Plot

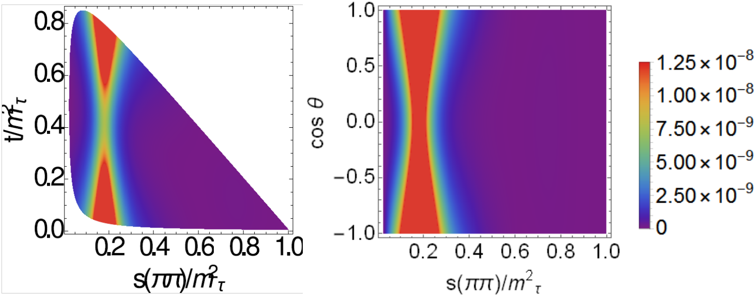


Figure: Dalitz plot distribution for $\tau^- \to \pi^-\pi^0\nu_\tau$ decays as a function of s and t (left) and as a function of s and $\cos\theta$ (right) with $\hat{\epsilon}_S = 0$, $\hat{\epsilon}_T = 0.0314$.

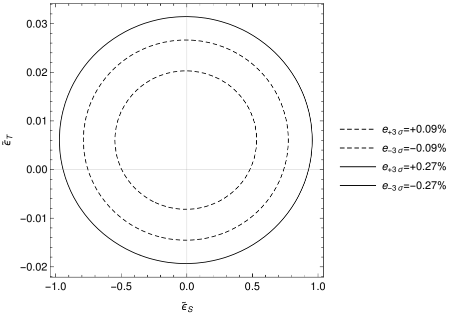


Figure: Constraints on scalar and tensor couplings obtained from $\Delta(\tau^- \to \pi^-\pi^0\nu_\tau)$ values using current experimental limits on branching ratio (solid line), and in the hypothetical case of this value being measured by Belle II.