IL NUOVO CIMENTO **44 C** (2021) 183
DOI 10.1393/ncc/i2021-21183-5

Colloquia: La Thuile 2021

Flavour and collider signals from a singly charged scalar

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received 16 September 2021

Summary. — A singly charged $SU(2)_L$ scalar singlet can only have flavour off-diagonal couplings to neutrinos and charged leptons and therefore necessarily violates lepton flavour (universality) (LF(U)). We study its phenomenology in light of the hints for LFU violation emerging from the measurements of $\tau \to \mu\bar{\nu}\nu/\tau(\mu) \to e\bar{\nu}\nu$ and from the discrepancies between the different determinations of V_{us}, the so called "Cabibbo-Angle Anomaly". Interestingly, the singly charged scalar has only three free couplings and is therefore very predictive: it violates LF(U), leads to a positive definite effect in $\ell \to \ell'\bar{\nu}\nu$, as preferred by data, and allows us to make predictions for radiative lepton decays and 3-body charged lepton decays. Finally, we look at the collider bounds, recasting ATLAS searches for sleptons and dark matter searches with mono-photon signatures at LEP. Even though these bounds are not yet competitive with flavour bounds, they can be significantly improved at future e^+e^- colliders. In fact, we find that FCC-hh projections push the predicted value for Br$[\tau \to e\mu\mu]$ towards the region observable by BELLE II and FCC-ee, providing a prime example of complementarity between low energy precision experiments and direct searches for NP.

1. – Introduction

In the recent years, even though no new particle has been discovered after the Higgs boson at the LHC, intriguing indirect hints for the violation of lepton flavour universality (LFU) were accumulated. The long standing tension in the anomalous magnetic moment of the muon, recently confirmed by the $g-2$ experiment at Fermilab, as well as global fits to $b \to s\ell^+\ell^-$ and $b \to c\tau\nu$ data, convincingly point towards new physics (NP) with a significance of $\approx 4.2\,\sigma$, $>5\,\sigma$ and $>3\,\sigma$, respectively. Recently, this very coherent pattern has been enriched by the deficit in first row Cabibbo Kobayashi Maskawa (CKM) unitarity [1-3], known as the Cabibbo Angle Anomaly (CAA), which can be interpreted as a sign of LFU violation [3-9].

Interestingly, the CAA can be explained by a constructive NP contribution to the SM $\mu \to e\nu_\mu\bar{\nu}_e$ amplitude, preferred at the $2\,\sigma$ level [10] also by data on the analogous tau decays $\tau \to \mu\nu_\tau\bar{\nu}_\mu$. Such an effect can be naturally generated at tree level, and there are only four possible NP candidates(1): vectorlike leptons [11,12], a left-handed vector $SU(2)_L$ triplet [13], a left-handed Z' with flavour violating couplings [14], and a singly charged $SU(2)_L$ singlet scalar.

The last option even gives a necessarily constructive effect and, due to Hermiticity of the Lagrangian, automatically violates lepton flavour (universality). Furthermore, as a singly charged scalar cannot couple to quarks and only generates charged lepton flavour violation at the loop level, it is weakly constrained experimentally by other processes and can therefore potentially explain the CAA and the hints for LFU violation in τ decays. In these proceedings, we present a comprehensive analysis of the collider and flavour phenomenology of the singly charged $SU(2)_L$ singlet scalar in light of the hints for LFU violation, following ref. [6]. Singly charged scalars have been proposed within the Babu-Zee model and often studied as part of a larger NP spectrum, mostly with the aim of generating neutrino masses at loop level, while here we focus on the SM supplemented only by the singly charged scalar (note that this already constitutes a UV complete model).

2. – The model

As motivated in the Introduction, we supplement the SM by a $SU(2)_L \times SU(3)_C$ singlet ϕ^+ with hypercharge +1. Interestingly, this allows only for Yukawa-type interactions with leptons

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - \left(\lambda_{ij}/2\,\bar{L}^c_{a,i}\,\varepsilon_{ab}\,L_{b,j}\,\Phi^+ + \text{h.c.}\right)\,, \tag{1}$$

but not with quarks. Here L is the left-handed $SU(2)_L$ lepton doublet, c stands for charge conjugation, a and b are $SU(2)_L$ indices, i and j are flavour indices and ε_{ab} is the two-dimensional antisymmetric tensor. Note that, without loss of generality, λ_{ij} can be chosen to be antisymmetric in flavour space, $\lambda_{ji} = -\lambda_{ij}$, such that $\lambda_{ii} = 0$ and our free parameters are λ_{12}, λ_{13}, and λ_{23}. In addition, there can be a coupling to the SM Higgs doublet $\lambda H^\dagger H \phi^+\phi^-$, which contributes to the mass m_ϕ but otherwise only has a significant impact on $h \to \gamma\gamma$.

3. – Collider searches

3·1. *LHC searches.* – The singly charged $SU(2)_L$ singlet scalar has the same quantum numbers as the right-handed slepton in supersymmetry. Therefore, bounds from direct searches for smuons and selectrons can be recast to set bounds on our model. The dominant contribution is given by the Drell-Yan pair production of $\phi^\pm$. We assume that interference with the SM background (mostly W^+W^- production in this case) can be neglected in the limit of a large enough m_ϕ and a narrow $\phi^\pm$ width. For the reinterpretation of the bounds, we consider the most recent ATLAS analysis [15] with 139 fb^{-1} of data, searching for final states with an oppositely charged lepton pair (e^+e^- or $\mu^+\mu^-$) and missing transverse energy. The search targets sleptons decaying into leptons and neutralinos, which corresponds to our setup in the case of a vanishing neutralino mass. The ATLAS bounds on the right-handed slepton mass in this limit is ≈ 425 GeV

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(1) Also a $SU(2)_L$ triplet scalar gives rise to a SM-like amplitude but interferes destructively.

for both the e^+e^- and $\mu^+\mu^-$ channels and for a 100% branching ratio of the slepton into the given channel. To reinterpret this result, we simulated the pair production cross section at leading order with MG5_aMC [16] and rescaled it with a constant K-factor, obtained by matching our values with the production cross section to the one given by ATLAS (for a right-handed slepton mass of 500 GeV). A conservative error of 10% was added on the cross section to account for the differences in the simulation procedures. fig. 1 shows the bounds in the m_ϕ–$\mathrm{Br}(\phi^\pm \to \mathrm{e}^\pm(\mu^\pm)\nu)$ plane extracted from the analysis of the e^+e^- and $\mu^+\mu^-$ channels of ATLAS. The red (green) hatched region is excluded by the e^+e^- $(\mu^+\mu^-)$ channel. The coloured bands indicate the change in the mass limit obtained by linearly varying the efficiency calculated on the value of the ATLAS bound by ±40%, between 200 GeV and 425 GeV, for m_ϕ. The solid line corresponds to the estimated limit without taking into account the additional uncertainties discussed above. Due to the antisymmetry of the couplings, the sum of the branching ratio to muons and electrons can never be smaller than 1/2 and can set a coupling-independent limit of ≈ 230 GeV on m_ϕ.

3·2. *Mono photon searches.* – LEP-searches for dark matter (DM) with monophoton signatures allow us to set a lower limit on $|\lambda^2_{12,13}|/m^2_\phi$. Using the DELPHI analysis of refs. [17, 18] and ref. [19], we were able to exploit the kinematic distributions to obtain a bound of ≈ 480 GeV for zero DM mass on the DM mediator mass for unit coupling strength and vectorial interactions (in the effective theory). Taking into account that we have neutrinos and therefore interference with the SM, this translates into a bound of $\approx 1\,\text{TeV}$. Assuming that m_ϕ is sufficiently above the LEP production threshold, as suggested by LHC searches discussed above, we can recast these results. Taking into account that we have a left-handed vector current, we find $(|\lambda^2_{12,13}|)/m^2_\phi \lessapprox 1/(175\,\text{GeV})^2$. This bound would be strengthened for λ_{12} and λ_{13} simultaneously nonzero, but further weakened as m_ϕ approaches the LEP beam energy. Therefore, it is not yet competitive with flavour bounds but could be significantly improved at future e^+e^- colliders.

4. – Flavour observables

4·1. $\ell \to \ell'\nu\nu$. – The SM decay of a charged lepton into a lighter one and a pair of neutrinos is modified at tree level by the exchange of a $\phi^\pm$. Applying Fierz identities, one can remove the charge conjugation and transform the amplitude to the $V-A$ structure of the corresponding SM amplitude. Taking only into account interfering effects with the SM we have

$$\delta(\ell_i \to \ell_j\nu\nu) = \frac{\mathcal{A}_{NP}(\ell_i \to \ell_j\nu_i\bar{\nu}_j)}{\mathcal{A}_{SM}(\ell_i \to \ell_j\nu_i\bar{\nu}_j)} = \frac{|\lambda^2_{ij}|}{g^2_2}\frac{m^2_W}{m^2_\phi}\,, \tag{2}$$

where the necessarily positive effect given by our setup is shown. This has to be compared to $\frac{\mathcal{A}(\tau\to\mu\nu\bar{\nu})}{\mathcal{A}(\mu\to e\nu\bar{\nu})}|_{\mathrm{EXP}} = 1.0029(14)$, $\frac{\mathcal{A}(\tau\to\mu\nu\bar{\nu})}{\mathcal{A}(\tau\to e\nu\bar{\nu})}|_{\mathrm{EXP}} = 1.0018(14)$ and $\frac{\mathcal{A}(\tau\to e\nu\bar{\nu})}{\mathcal{A}(\mu\to e\nu\bar{\nu})}|_{\mathrm{EXP}} = 1.0010(14)$ [10] (with the correlations given in ref. [10]). Furthermore, the effect in $\mathcal{A}(\mu \to e\,\nu_\mu\bar{\nu}_e)$ leads to a modification of the Fermi constant, which enters not only the electroweak (EW) precision observables, but also the determination of V_{ud} from beta decays. Superallowed beta decays provide the most precise determination of V_{ud}, leading to $V^\beta_{us} = 0.2280(6)$ [20] .This value of V^β_{ud}, together with V_{us} from kaon [21] and tau decays [10] and V_{ub} shows a $\sim 3\sigma$ tension with respect to the assumption of CKM

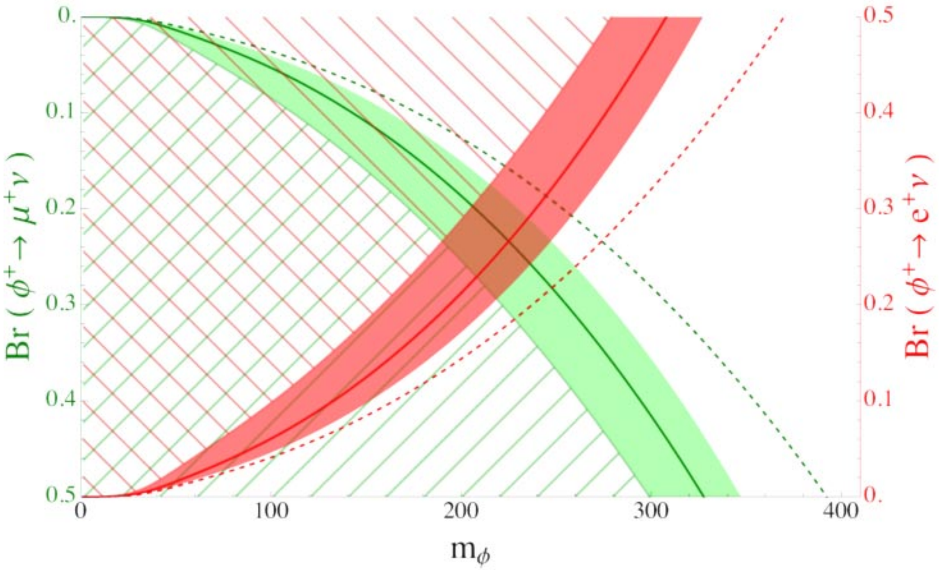


Fig. 1.: Recast ATLAS bounds on m_ϕ and BR($\phi^+ \to \ell^+\nu$). The red (green) region is excluded by e^+e^- ($\mu^+\mu^-$) searches (see main text for details). The dashed lines represent the projected exclusion reach for an integrated luminosity of 3 ab^{-1} at the High-Luminosity (HL) LHC.

unitarity [22], known as the Cabibbo Angle Anomaly

$$|V_{us}|^2 + |V_{ud}|^2 + |V_{ub}|^2 = 0.9985(5)\,. \tag{3}$$

This tension can be alleviated by the NP effect given by $V_{ud}^{\beta} = V_{ud}\big[1 - \delta(\mu \to e\nu\nu)\big]$. As G_F enters also the calculation of the EW gauge boson masses and Z pole observables, a global fit is necessary. Adding the determinations of the CKM elements to the standard EW observables (see, *e.g.*, ref. [23] for details on our input and implementation) calculated by HEPfit [24], we find

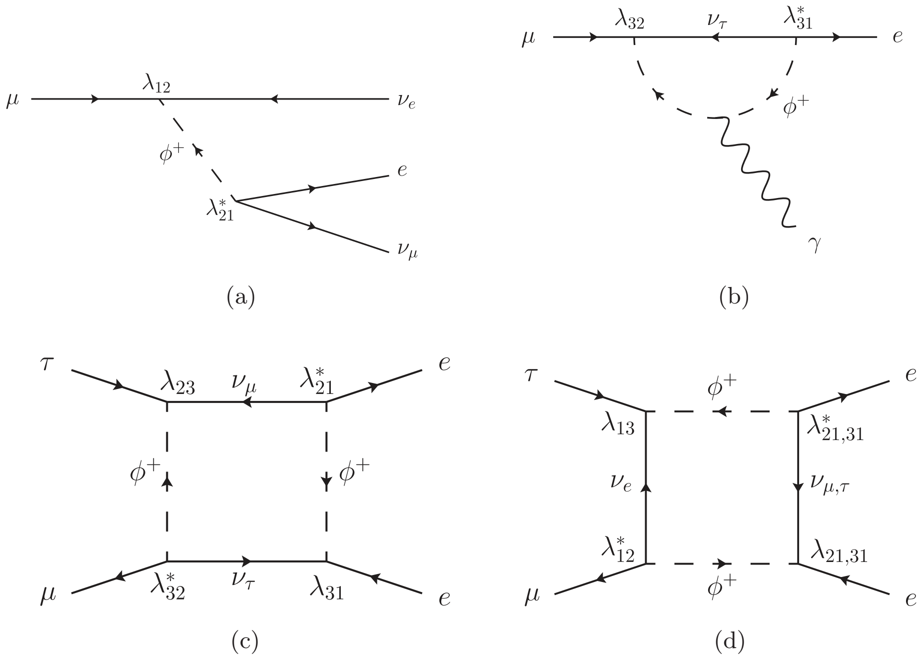
$$\delta(\mu \to e\nu\nu) = 0.00065(15)\,. \tag{4}$$

4·2. $\ell \to \ell'\gamma$. – The singly charged scalar generates $\ell \to \ell'\gamma$ (see fig. 2). Here, we obtain

$$\mathrm{Br}[\mu \to e\gamma] = \frac{m_\mu^3}{4\pi\Gamma_\mu}\left(|c_L^{e\mu}|^2 + |c_R^{e\mu}|^2\right)\,, \tag{5}$$

with Γ_μ being the total width of the muon, and $c_{L(R)}^{e\mu} = \frac{e\,\lambda_{13}^*\,\lambda_{23}}{384\,\pi^2}\frac{m_{e(\mu)}}{m_\phi^2}$. The expressions for $\tau \to \mu(e)\gamma$ can be obtained by a straightforward exchange of indices. The current experimental limits at 90% C.L. are [25-27]:

$$\mathrm{Br}[\mu \to e\gamma] \le 4.2 \times 10^{-13}\,, \qquad \mathrm{Br}[\tau \to \mu\gamma] \le 4.4 \times 10^{-8}\,, \qquad \mathrm{Br}[\tau \to e\gamma] \le 3.3 \times 10^{-8}\,.$$



(a) (b)

(c) (d)

Fig. 2.: Feynman diagrams showing the contribution of $\phi^\pm$ to (a) $\mu \to e\nu_\mu\bar{\nu}_e$, (b) $\mu \to e\gamma$, and ((c), (d)) $\tau \to \mu ee$. The corresponding diagrams for analogous processes with different flavours are not depicted but can be deduced by straightforward substitutions.

4·3. $\ell \to \ell' \ell'^{(\prime)} \ell'^{(\prime)}$. – The singly charged scalar contributes to three-body decays to charged leptons at loop level. Here the dominant contribution for sizable couplings λ is the box diagram shown in fig. 2. For concreteness, we give the results for $\tau \to 3e$ and $\tau \to \mu ee$, while the other decays can be obtained by an appropriate exchange of the flavour indices

$$\mathrm{Br}[\tau \to e\mu\mu] = \frac{m_\tau^5}{1536\,\pi^3\,\Gamma_\tau} \left| \frac{\lambda_{12}^*\,\lambda_{23}\left(\left|\lambda_{12}^2\right| + \left|\lambda_{23}^2\right| - \left|\lambda_{13}^2\right|\right)}{64\,\pi^2\,m_\phi^2} \right|^2 ,$$

$$\mathrm{Br}[\tau \to eee] = \frac{m_\tau^5}{768\,\pi^3\,\Gamma_\tau} \left| \frac{\lambda_{12}^*\,\lambda_{23}\left(\left|\lambda_{12}^2\right| + \left|\lambda_{13}^2\right|\right)}{64\,\pi^2\,m_\phi^2} \right|^2 , \tag{6}$$

where Γ_τ is the total decay width of the tau. Here we did not include the small on- and off-shell photon contributions (they are given in ref. [6], together with the results for $\mu \to e$ conversion), and we do not consider the branching ratios for the decays involving more than one flavour change (such as $\tau \to e\mu e$), which must be tiny in our model due to the measured smallness of $\mu \to e\gamma$. The corresponding experimental bounds (95% C.L.)

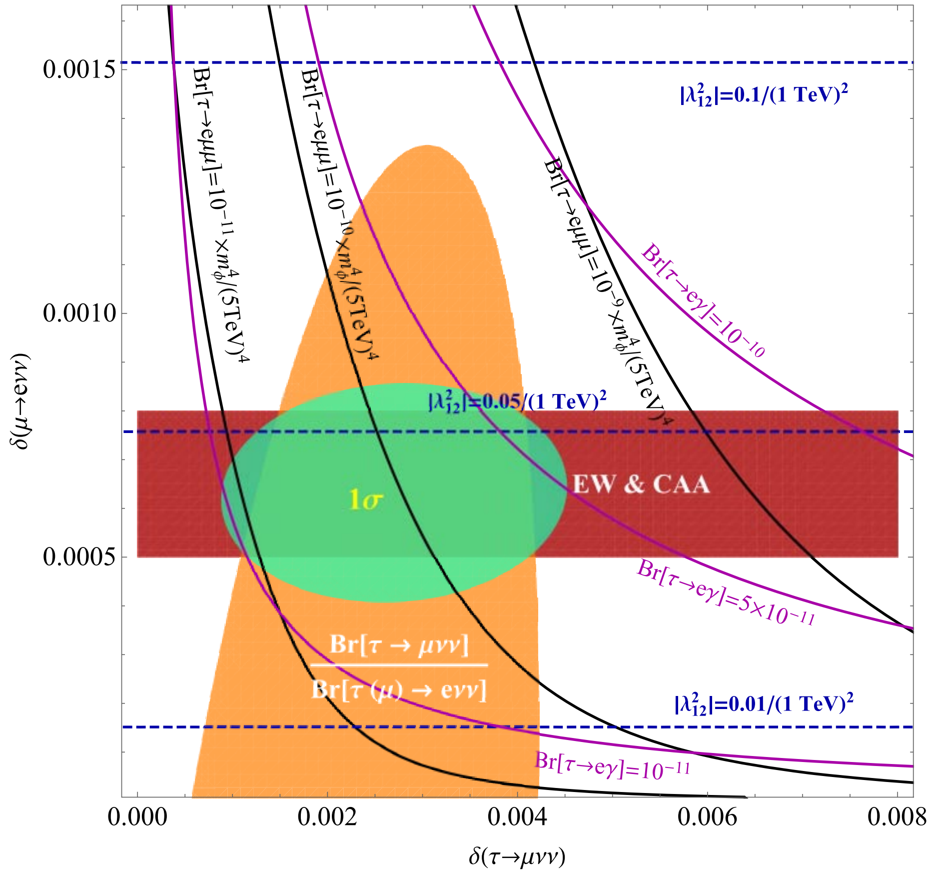


Fig. 3.: Preferred regions at the 1σ level in the $\delta(\tau\to\mu\nu\nu)$–$\delta(\mu\to e\nu\nu)$ plane together with the predictions for $\tau\to e\gamma$ (magenta), $\tau\to e\mu\mu$ (black) and $|\lambda_{12}^2|/m_\phi^2$ (blue) which can be constrained from monophoton searches at future e^+e^- colliders.

are [28-31, 10]

$$\begin{aligned}
&\mathrm{Br}[\mu^-\to e^-e^+e^-]\le 1.0\times10^{-12}\,, &&\mathrm{Br}[\tau^-\to e^-e^+e^-]\le 1.4\times10^{-8}\,,\\
&\mathrm{Br}[\tau^-\to e^-\mu^+\mu]\le 1.6\times10^{-8}\,, &&\mathrm{Br}[\tau^-\to \mu^-e^+e^-]\le 1.1\times10^{-8}\,,\\
&\mathrm{Br}[\tau^-\to \mu^-\mu^+\mu^-]\le 1.1\times10^{-8}\,. &&
\end{aligned} \tag{7}$$

5. – Phenomenology

We start by considering the NP effect in $\tau\to\mu\nu\nu$ and $\mu\to e\nu\nu$. fig. 3 shows the regions preferred by data (at the $1\,\sigma$ level) for $\delta(\tau\to\mu\nu\nu)$ and $\delta(\mu\to e\nu\nu)$ in orange and red, respectively. The combined region at the 68% C.L is shown in green. As a first result, we find that for any point within the combined region, λ_{13} must be vanishingly small in order not to violate the bounds from $\mu\to e\gamma$ or $\mu\to e$ conversion. Therefore, we can neglect its effect in the following.

Assuming ($\lambda_{13} \simeq 0$), we have $\mathrm{Br}(\phi^+ \to \mu^+\nu) = 0.5$, which leads to a bound of ≈ 300 GeV from the $\mu^+\mu^-$ channel, as shown in Fig 1. This bound could be further improved at the HL-LHC [32] (by around 30%, where the ATLAS bounds are rescaled for an integrated luminosity of 3 ab^{-1}) or at the Future Circular hadron Collider (FCC-hh) [33] where we estimate a potential improvement of up to a factor of few [34].

Furthermore, we can correlate $\delta(\tau \to \mu\nu\nu)$ and $\delta(\mu \to e\nu\nu)$ directly to $\tau \to e\gamma$ and indirectly to $\tau \to e\mu\mu$ (here there is also a dependence on m_ϕ), as indicated by the magenta and black lines in fig. 3. The predicted branching ratio for $\tau \to e\gamma$ is of the order of a few times 10^{-11} while we find $\mathrm{Br}[\tau \to e\mu\mu] \approx 10^{-10} m_\phi^4/(5\,\mathrm{TeV})^4$, which, interestingly, lies within the reach of BELLE II [35] or the Future Circular electron-positron Collider (FCC-ee) [36]. We also depict constant values of $|\lambda_{12}^2|/m_\phi^2$ as dashed blue lines. Even though their values are significantly below the LEP bounds discussed above, future e^+e^- colliders like the International Linear Collider (ILC) [37], the Compact Linear Collider (CLIC) [38], the Circular Electron Positron Collider (CEPC) [39] or the FCC-ee [40] could test the predicted monophoton signature. In particular, the ILC can improve the bound on the Wilson coefficient by a factor of 50 [41], CEPC by a factor 40 [42] and even bigger improvements could be expected at CLIC and at FCC-ee, for which a dedicated study is strongly motivated.

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