Vacuum (meta-)stability in the $\mu\nu$SSM

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The μ-from-ν Supersymmetric Standard Model ($\mu\nu$SSM)

A particularly well motivated **SUSY** model is the μ-from-ν Supersymmetric Standard Model ($\mu\nu$SSM) [1, 2]. Beyond the well-known appealing features of commonly studied SUSY models, in the $\mu\nu$SSM the tiny neutrino masses and their mixings can be accommodated via an **electroweak (EW) seesaw mechanism**, where it is required that the matter content is enlarged w.r.t. the Standard Model (SM) by (three) **right-handed neutrinos**.

We perform an analysis of the **EW vacuum stability** taking into account the **neutral scalar potential** V of the $\mu\nu$SSM. As an example scenario, we discuss the alignment-without-decoupling limit of the $\mu\nu$SSM.

V contains D- and F-terms from the neutral part of the **superpotential**

$$W = \epsilon_{ab}\left(Y^{\nu}_{ij}\,\hat{H}^b_u\,\hat{L}^a_i\,\hat{\nu}^c_j - \lambda_i\,\hat{\nu}^c_i\,\hat{H}^b_u\hat{H}^a_d\right) + \frac{1}{3}\kappa_{ijk}\hat{\nu}^c_i\hat{\nu}^c_j\hat{\nu}^c_k + \dots\ , \tag{1}$$

where $\hat{H}^T_d = (\hat{H}^0_d, \hat{H}^-_d)$ and $\hat{H}^T_u = (\hat{H}^+_u, \hat{H}^0_u)$ are the Higgs doublet superfields, $\hat{L}_i$ are the left-chiral lepton superfields with the left-chiral neutrino superfields $\hat{\nu}_i$ in the upper component, and $\hat{\nu}^c$ are the right-chiral neutrino superfields. In addition, the **soft SUSY-breaking Lagrangian** contributes to V with the terms

$$\begin{aligned}-\mathcal{L}_{\text{soft}} = \epsilon_{ab}&\left(T^{\nu}_{ij}\,H^b_u\,\widetilde{L}^a_{iL}\widetilde{\nu}^*_{jR} - T^{\lambda}_i\,\widetilde{\nu}^*_{iR}\,H^a_dH^b_u + \frac{1}{3}T^{\kappa}_{ijk}\,\widetilde{\nu}^*_{iR}\widetilde{\nu}^*_{jR}\widetilde{\nu}^*_{kR}\ + \text{h.c.}\right)\\ &+\left(m^2_{\widetilde{L}}\right)_{ij}\widetilde{L}^{a*}_{iL}\widetilde{L}^a_{jL} + \left(m^2_{\widetilde{\nu}}\right)_{ij}\widetilde{\nu}^*_{iR}\widetilde{\nu}_{jR} + m^2_{H_d}H^{a*}_dH^a_d + m^2_{H_u}H^{a*}_uH^a_u + \dots\ ,\end{aligned} \tag{2}$$

where H_d, H_u, $\widetilde{\nu}_{iL}$ and $\widetilde{\nu}_{iR}$ denote the scalar components of the superfields $\hat{H}_d$, $\hat{H}_u$, $\hat{\nu}_i$ and $\hat{\nu}^c_i$, respectively.

The Higgs sector

One of the key features of the $\mu\nu$SSM is the mixing of the two Higgs doublet fields H_d and H_u with the three left-handed and right-handed sneutrino fields $\widetilde{\nu}_{iL}$ and $\widetilde{\nu}_{iR}$. In the **EW vacuum** the scalar components of all the **eight neutral fields have a vev**:

$$H^0_{d,u} = \frac{1}{\sqrt{2}}\left(H^{\mathcal{R}}_{d,u} + v_{d,u} + H^{\mathcal{I}}_{d,u}\right)\ ,\quad \widetilde{\nu}_{iR,L} = \frac{1}{\sqrt{2}}\left(\widetilde{\nu}^{\mathcal{R}}_{iR,L} + v_{iR,L} + \widetilde{\nu}^{\mathcal{I}}_{iR,L}\right)\ ,\quad v_{iL} \ll v_d\,, v_u\,, v_{iR} \tag{3}$$

Is the EW minimum the global one?
If not, is the EW vacuum sufficiently long-lived?

$V(\phi)$ is (at leading order) a polynomial function of degree four in eight field dimensions $\phi = (H^{\mathcal{R}}_d, H^{\mathcal{R}}_u, \widetilde{\nu}^{\mathcal{R}}_{iR}, \widetilde{\nu}^{\mathcal{R}}_{iL})$, $i = 1,2,3$. Such a function has in general numerous local minima. Whenever there are **unphysical minima deeper than the EW minimum**, a calculation of the **decay rate of the EW vacuum** is required in order to decide whether a parameter point is viable or not.

Alignment without decoupling

In the next-to-minimal supersymmetric SM (NMSSM) it was shown that there can be a scalar state at 125 GeV that is aligned with the SM vev, thus resembling a SM Higgs boson, without a decoupling of the remaining Higgs bosons [3]. In the $\mu\nu$SSM one can reach the **alignment-without-decoupling limit** by fulfilling the conditions (see also [4]):

$$\lambda_1^2 + \lambda_2^2 + \lambda_3^2 = \frac{m^2_{h_{125}} - M_Z^2 c_{2\beta}}{v^2 s^2_\beta}\ ,\qquad A^\lambda_i = \frac{\mu}{c_\beta s_\beta} - \sqrt{2}\kappa_i v_{iR}\ ,\qquad i = 1,2,3 \tag{4}$$

In the light of the SM-likeness of the discovered Higgs boson, we chose this limit in order to explore the impact of vacuum stability constraints in the $\mu\nu$SSM.

Strategy: Estimation of the lifetime of the EW vacuum

We solve the stationary conditions of the potential to determine all local minima of V using the **homotopy continuation method** (`Hom4PS-2` [5]) When deeper minima are present (see figure 1) we calculate the **decay rate per Hubble volume for the EW vacuum decay** into each deeper minimum:

$$\frac{\Gamma}{V} = K\mathrm{e}^{-S_E}\ ,\quad S_E:\ \text{Euclidean bounce action}\ ,\quad K:\ \text{Higher-order terms, only estimated} \tag{5}$$

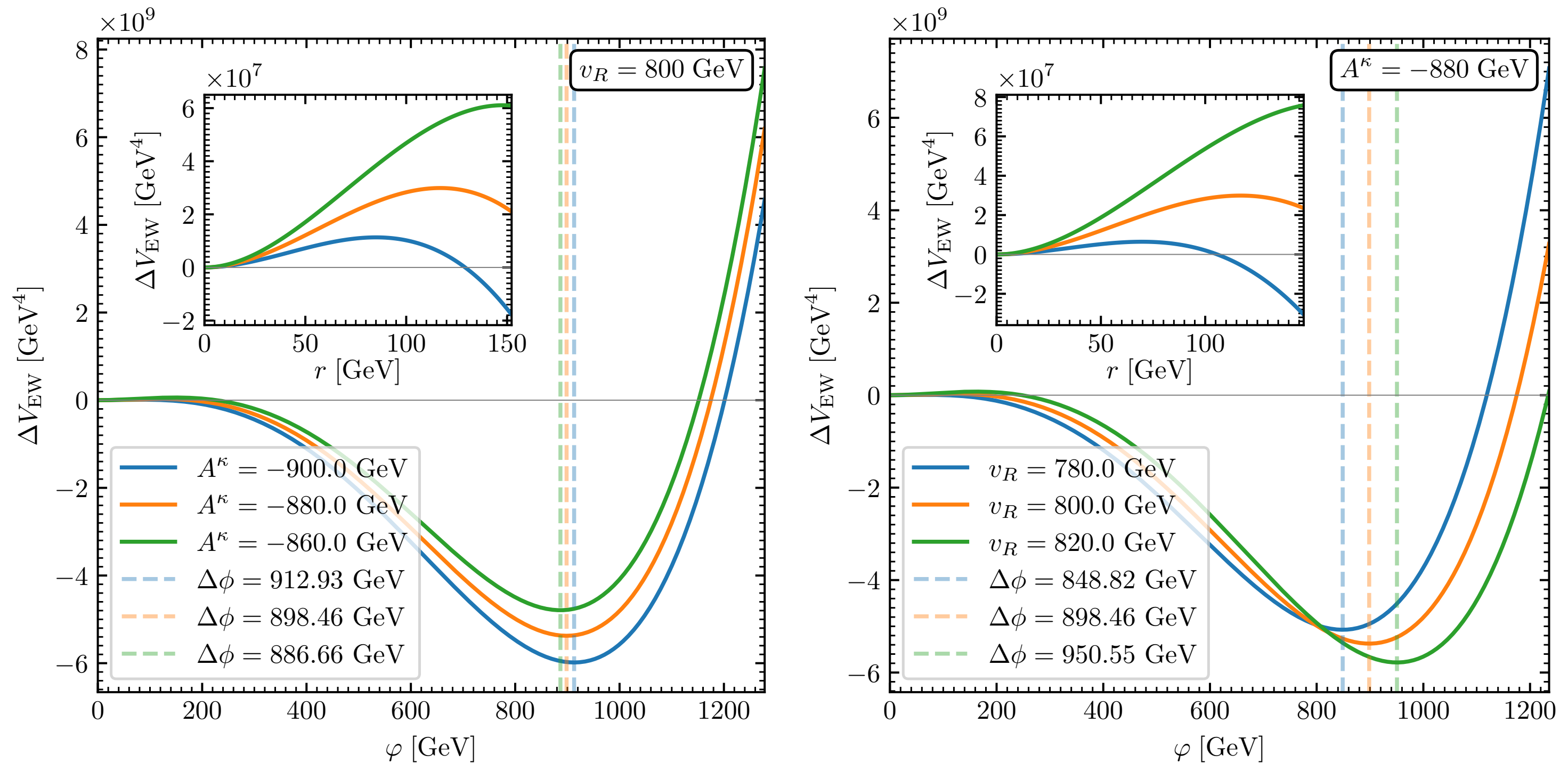

Figure 1. V_{EW} along the straight path connecting the EW minimum (at $\varphi = 0$) and an unphysical minimum for different values of A^κ_i (left) and v_{iR} (right). Also indicated are the field space distances $\Delta\phi$ with vertical dashed lines.

We calculate S_E in a semi-classical straight-path approximation [6]. Based on the comparison of the lifetime of the EW vacuum compared to the age of the universe, we follow the following **criteria to decide whether a parameter point is viable** [7]:

$$\begin{aligned} S_E < 390 &\ \Rightarrow\ \text{short-lived, unstable}\ ,\\ 390 \le S_E \le 440 &\ \Rightarrow\ \text{potentially short-lived}\ ,\\ S_E > 440 &\ \Rightarrow\ \text{long-lived, stable}\end{aligned} \tag{6}$$

Results

We perform a scan over A^κ and v_R in the alignment-without decoupling limit with $\lambda_1 = 0.54$, $\lambda_2 = 0.36$ and $\lambda_3 = 0.005$. We find that **for no parameter point the EW minimum is the global minimum.**

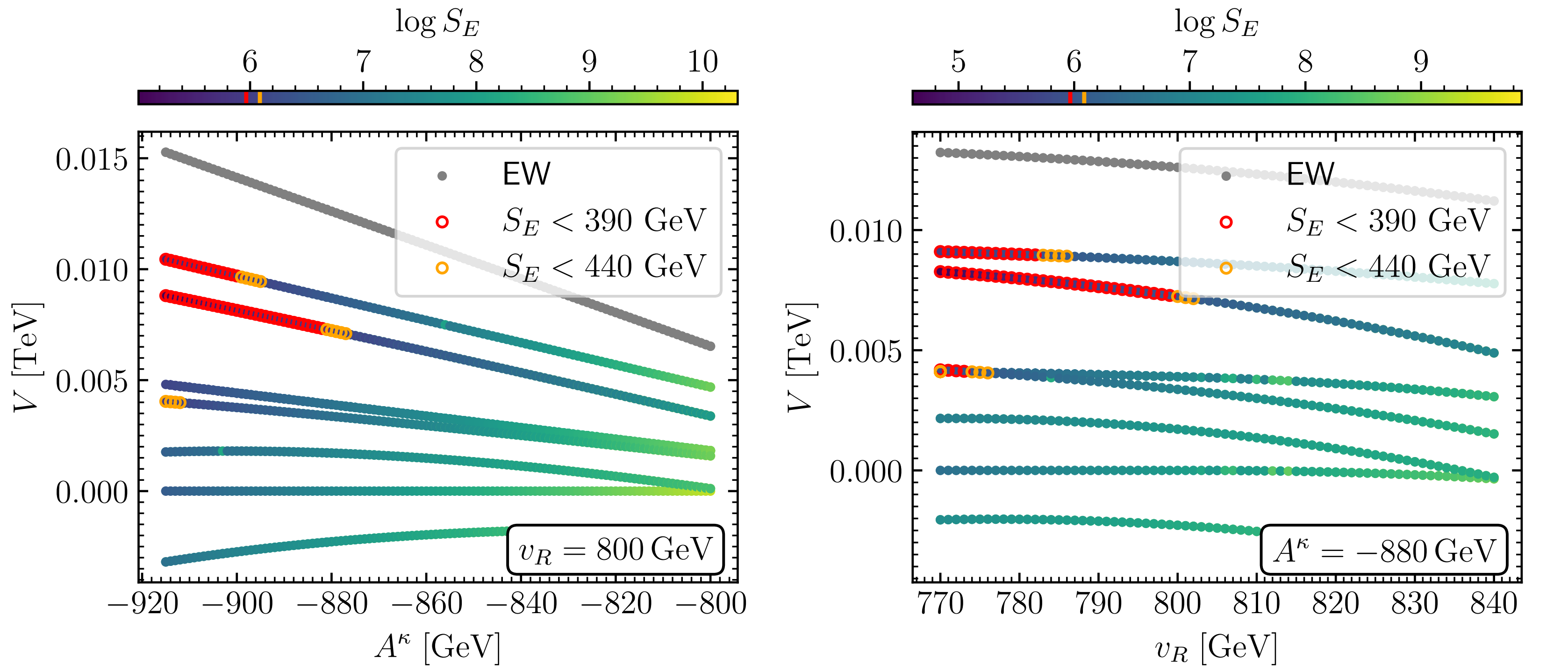

Figure 2. EW minimum and deeper unphysical minima as a function of A^κ for fixed v_R (left) and as a function of v_R for fixed A^κ (right). Shown are the potential values V of each local minimum,. The colors of the points indicate the value of the euclidean bounce action S_E. Points with $S_E < 390$ are highlighted with a red edge and points with $390 \le S_E \le 440$ are highlighted with a yellow edge. The EW minima are shown in gray.

The parameter points with the smallest values of v_R and A^κ are short-lived and should be rejected. Nevertheless, **in large parts of the parameter space the (meta-stable) EW vacuum is sufficiently long lived.** and the points should not be rejected.

A scan in the v_R-A^κ plane shows (see figure 3) that the **impact of the vacuum stability analysis** can reach stronger exclusions compared to the ones obtained from experimental searches for the Higgs bosons (as checked with **`HiggsBounds`**) or from the measurements of the signal rates of the Higgs boson at 125 GeV (as checked with **`HiggsSignals`**).

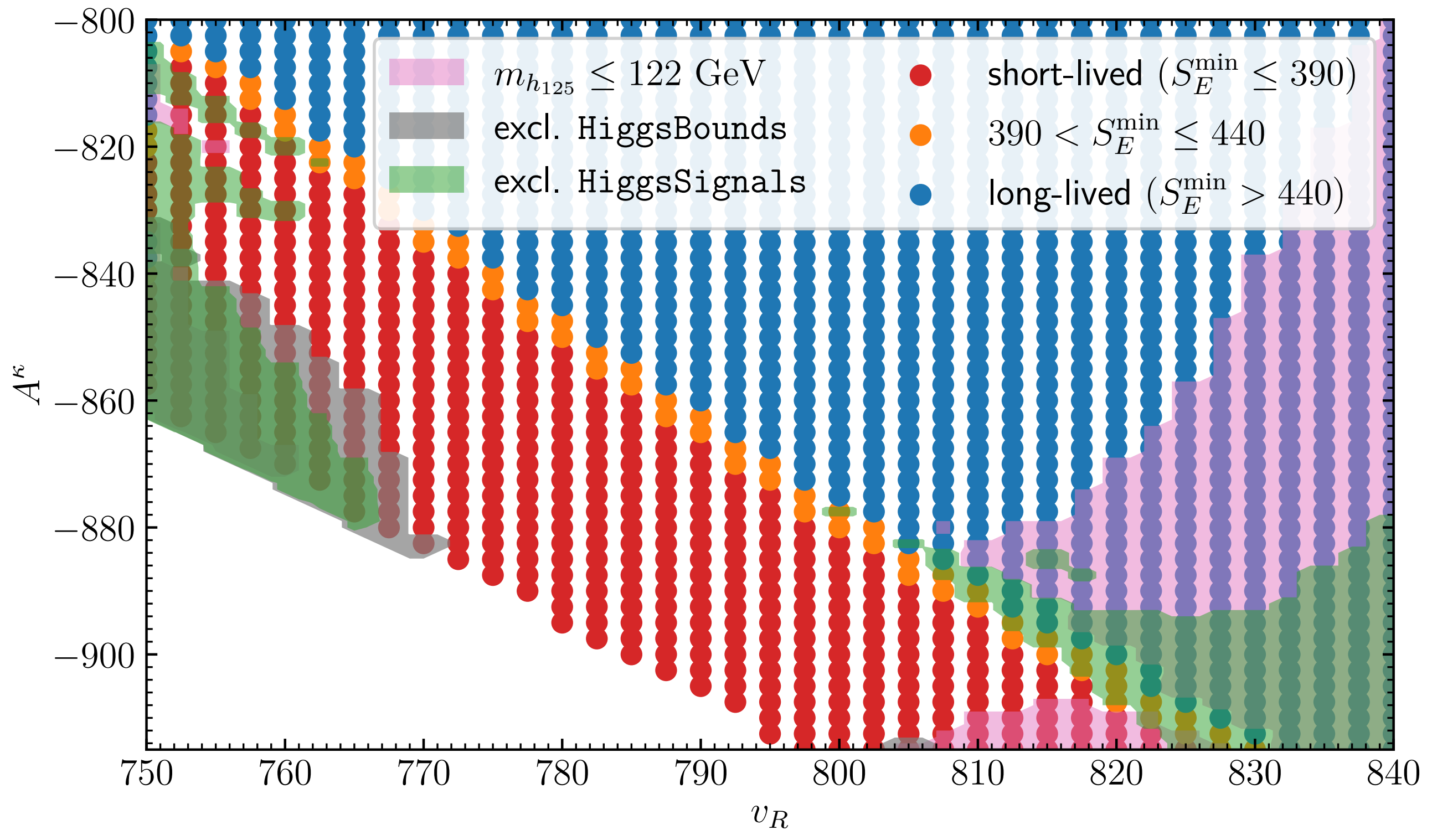

Figure 3. Blue points have a sufficiently long-lived EW vacuum, while red points have a rapidly decaying EW vacuum. The orange points have a potentially short-lived EW vacuum. The gray and green areas indicate excluded regions based on the `HiggsBounds` and `HiggsSignals` constraints (see text for details), and the pink area indicates the parameter region in which $m_{h_{125}} < 122$.

Conclusions and outlook

The EW minimum of the $\mu\nu$SSM is not the global minimum of the scalar potential in large parts of the parameter space. In such cases, a calculation of the lifetime of the EW vacuum has to be performed in order to decide whether a parameter point is viable.

Demanding that the EW minimum is the global minimum would exclude erroneously valid parameter points, because in many cases the meta-stable EW vacuum is sufficiently long-lived.

The python package `munuSSM`

The next version of the code **`munuSSM`** [8] will make the calculation of the lifetime of the EW vacuum available to the public. The code can be downloaded at `https://gitlab.com/thomas.biekoetter/munussm`.

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Enter the $\mu\nu$niverse at http://dark.ft.uam.es/mununiverse/

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