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

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SUSY 2021, Shanghai, China

August 23rd 2021

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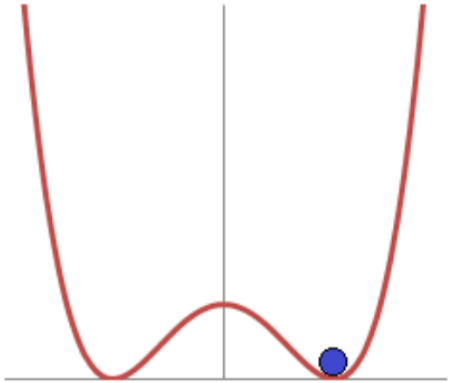
QUANTUM UNIVERSE

EW vacuum stability

The EW vacuum in the Standard Model



[wikipedia]

Only one scalar field

After EWSB the EW vacuum is stable (assuming $\lambda > 0$).

The shape of the potential does not allow for other local minima

$\rightarrow$ Only a 'parametrization' of EWSB

$\rightarrow$ Experimentally: location and curvature at EW minimum

The EW vacuum in SUSY models

[wikipedia]

$\rightarrow$ Explains origin of the shape of the Higgs potential

Large number of scalar fields

Potential is bounded from below

BUT: Possiblity of numerous local (unphysical) minima

$\rightarrow$ The EW minimum is not always the global minimum

$\rightarrow$ The EW vacuum can be short-lived

The analysis of EW vacuum stability gives rise to important constraints

Some context

MSSM: Possibility of charge/colour-breaking minima

[Nucl.Phys.B 222 (1983) 11-19, Nucl.Phys.B 228 (1983) 501-528, Phys.Lett.B 157 (1985) 164-168, Nucl.Phys.B 306 (1988) 1-13, Phys.Lett.B 215 (1988) 323-327, ...]

Strong impact on allowed parameter space (mainly in terms of $A_{\tilde{f}}$, $m^2_{\tilde{f}}$ and μ)

[hep-ph/9507294, hep-ph/9604417, hep-ph/9602414, ...]

Parameter points can still be viable when decay rate of EW vacuum is large compared to the age of the universe

[1405.7376, 1310.4174, 1407.2814, 1812.04644, ...]

NMSSM: Possibility of new types of "neutral" unphysical minima due to additional singlet field

[Nucl.Phys.B 237 (1984) 307-328, hep-ph/9611251...]

$\mu\nu$SSM: Three singlet(=right-handed sneutrino) fields $\rightarrow$ Much more complicated potential

[hep-ph/0508297, 0909.5140...]

False minima with (at least) one sneutrino vev vanishing were found

[0810.1507]

Here: (1) Determination of all local minima of the neutral CP-even scalar potential of the $\mu\nu$SSM at tree level

(2) Estimation of lifetime of non-global EW vacua

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

Right-handed neutrino superfields $\hat{\nu}_i^c$

Define neutrino Yukawa coupling Y_{ij}^{ν}
Gauge-singlets $\rightarrow \lambda_i$- and κ_{ijk}-terms
Sneutrinos acquire vev during EWSB

No scales - Z_3 symmetry

No explicit Majorana masses
No explicit μ-term(s)
No tadpole terms

$$W = \epsilon_{ab}\left(Y_{ij}^{e}\,\hat{H}_d^a\,\hat{L}_i^b\,\hat{e}_j^c + Y_{ij}^{d}\,\hat{H}_d^a\,\hat{Q}_i^b\,\hat{d}_j^c + Y_{ij}^{u}\,\hat{H}_u^b\,\hat{Q}_i^a\,\hat{u}_j^c\right)$$
$$+\epsilon_{ab}\left(Y_{ij}^{\nu}\,\hat{H}_u^b\,\hat{L}_i^a\,\hat{\nu}_j^c - \lambda_i\,\hat{\nu}_i^c\,\hat{H}_u^b\hat{H}_d^a\right) + \frac{1}{3}\kappa_{ijk}\,\hat{\nu}_i^c\hat{\nu}_j^c\hat{\nu}_k^c$$

EW Seesaw

$\Lambda_\nu \sim \Lambda_{\rm EWSB}$
$\Rightarrow Y^{\nu} \lesssim Y^{e} \sim 10^{-6}$

$\Rightarrow \mu\,\hat{H}_u^b\hat{H}_d^a$

$\mu = \dfrac{\lambda_i v_{iR}}{\sqrt{2}}$
Scale $\mu \sim \mathcal{O}(\text{EW})$

$\Rightarrow M_{ij}^{M}\nu_{iR}\nu_{jR}$

Majorana masses $M_{ij}^{M} \sim \kappa_{ijk}v_{kR}$

Higgs sector

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

$$\mathcal{L}^{\text{Higgs}}_{\text{soft}} = \epsilon_{ab}\left(T^{\nu}_{ij}\,H^b_u\,\widetilde{L}^a_{iL}\widetilde{\nu}^*_{jR} - T^{\lambda}_i\,\widetilde{\nu}^*_{iR}\,H^a_d H^b_u + \frac{1}{3}T^{\kappa}_{ijk}\,\widetilde{\nu}^*_{iR}\widetilde{\nu}^*_{jR}\widetilde{\nu}^*_{kR} + \text{h.c.}\right)$$

$$+\left(m^2_{\widetilde{L}_L}\right)_{ij}\widetilde{L}^{a*}_{iL}\widetilde{L}^a_{jL} + \left(m^2_{\widetilde{\nu}_R}\right)_{ij}\widetilde{\nu}^*_R\widetilde{\nu}_R + m^2_{H_d}H^{a*}_d H^a_d + m^2_{H_u}H^{a*}_u H^a_u$$

Assuming CP conservation:

$$H^0_d = \frac{1}{\sqrt{2}}\left(H^{\mathcal{R}}_d + v_d + \mathrm{i}\,H^{\mathcal{I}}_d\right) \qquad H^0_u = \frac{1}{\sqrt{2}}\left(H^{\mathcal{R}}_u + v_u + \mathrm{i}\,H^{\mathcal{I}}_u\right)$$

$$\widetilde{\nu}_{iR} = \frac{1}{\sqrt{2}}\left(\widetilde{\nu}^{\mathcal{R}}_{iR} + v_{iR} + \mathrm{i}\,\widetilde{\nu}^{\mathcal{I}}_{iR}\right) \qquad \widetilde{\nu}_{iL} = \frac{1}{\sqrt{2}}\left(\widetilde{\nu}^{\mathcal{R}}_{iL} + v_{iL} + \mathrm{i}\,\widetilde{\nu}^{\mathcal{I}}_{iL}\right)$$

$\rightarrow$ EW vacuum defined by vevs v_d, v_u, v_{iR} and $v_{iL} \ll v_d, v_u, v_{iR}$

$\rightarrow$ Define $v^2 = v_d^2 + v_u^2 + v_{1L}^2 + v_{2L}^2 + v_{3L}^2 = 246\text{GeV}$ and $\tan\beta = v_u/v_d$

Using the vevs as input parameters, the existence of a physical EW vacuum can always be ensured

BUT: The CP-even neutral scalar potential is a polynomial of degree four in eight dimensions

$\rightarrow$ Stationary conditions have $3^8 = 6561$ in the complex plane $\rightarrow$ Other local minima

Question 1: Is the EW minimum the global minium?

Question 2: If not, is the EW vacuum short-lived/unstable or long-lived/(meta-)stable

Determination of EW vacuum stability

Question 1: Is the EW minimum the global minimum?

→ Find all real solutions of the stationary conditions (tadpole equations)
We use the polyhedral continuation method using the public code `Hom4PS2`

→ Calculate the Hessian of the potential at each stationary point
If all eigenvalues of the Hessian are positive we found a local minimum

→ Calculate the potential value (depth) for each local minimum
Compare to depth of EW minimum to check whether the EW minimum is the global one

1st possibility: EW minimum is global → EW vacuum is stable :)

2nd possibility: EW minimum is not global → EW vacuum is potentially short-lived → Estimate lifetime :I

Determination of lifetime of non-global EW vacuum

Question 2: Is the non-global EW vacuum short-lived?

Decay rate per Hubble volume for EW vacuum decay:

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

We calculate S_E in a semi-classical straight-path approximation [hep-ph/9302321]

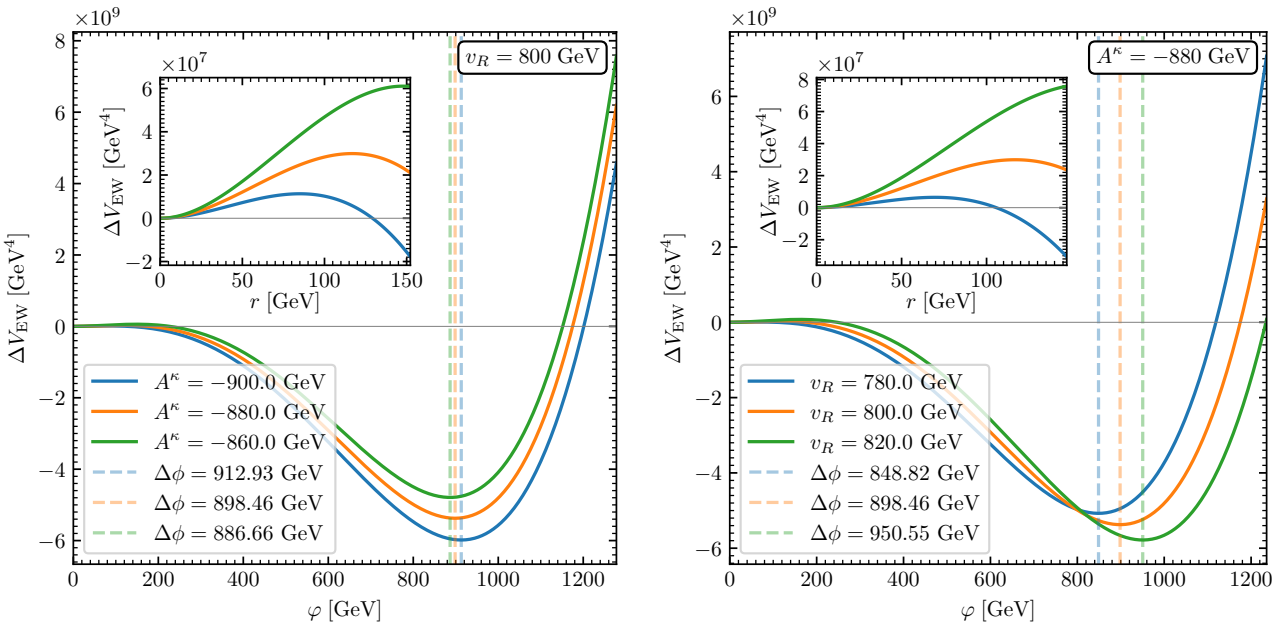


Figure: V along the straight path connecting the EW minimum (at $\varphi = 0$) and an unphysical minimum for different values of A_i^κ (left) and v_{iR} (right). Also indicated are the field space distances $\Delta\phi$ with vertical dashed lines.

Criteria to decide whether a parameter point is viable: [1812.04644]

$$S_E < 390 \ \Rightarrow \ \text{EW vacuum is } \textbf{short-lived, unstable} \ ,$$
$$390 \leq S_E \leq 440 \ \Rightarrow \ \text{EW vacuum is potentially short-lived} \ ,$$
$$S_E > 440 \ \Rightarrow \ \text{EW vacuum is long-lived, (meta-)stable}$$

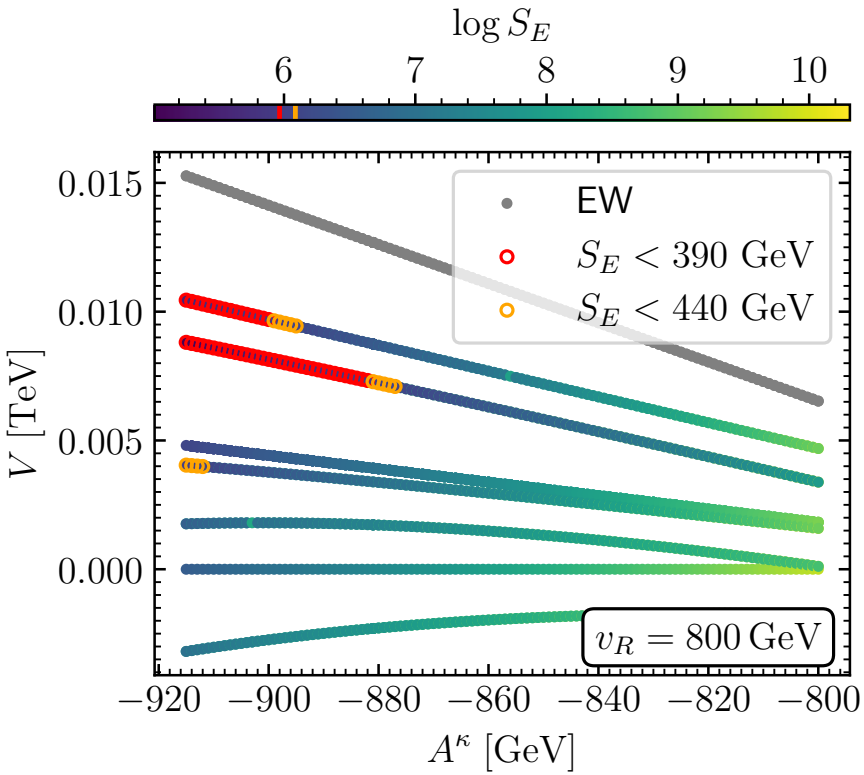
Exploration of the alignment-without-decoupling limit

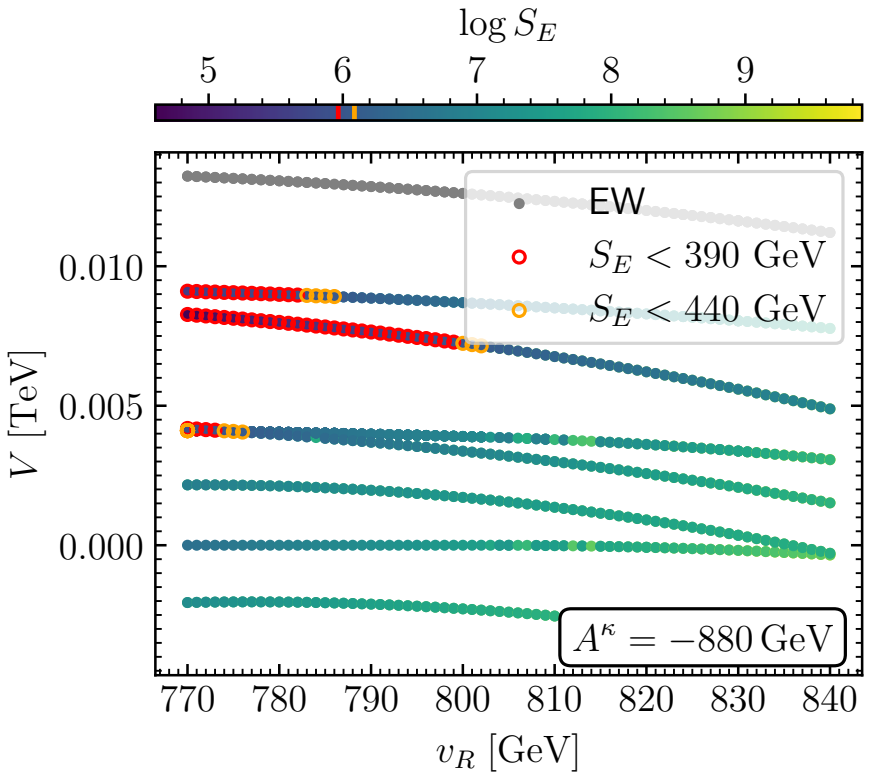
In the $\mu\nu$SSM one can reach the **alignment-without-decoupling limit** by fulfilling the conditions:

$$\lambda_1^2 + \lambda_2^2 + \lambda_3^2 = \frac{m_{h_{125}}^2 - M_Z^2 c_{2\beta}}{v^2 s_\beta^2} \ , \quad A_i^\lambda = \frac{\mu}{c_\beta s_\beta} - \sqrt{2}\kappa_i \nu_{iR} \ , \quad i = 1, 2, 3$$

We perform a scan over A^κ and ν_R in with $\lambda_1 = 0.54$, $\lambda_2 = 0.36$ and $\lambda_3 = 0.005$

→ **For no parameter point of our scan the EW minimum is the global one**





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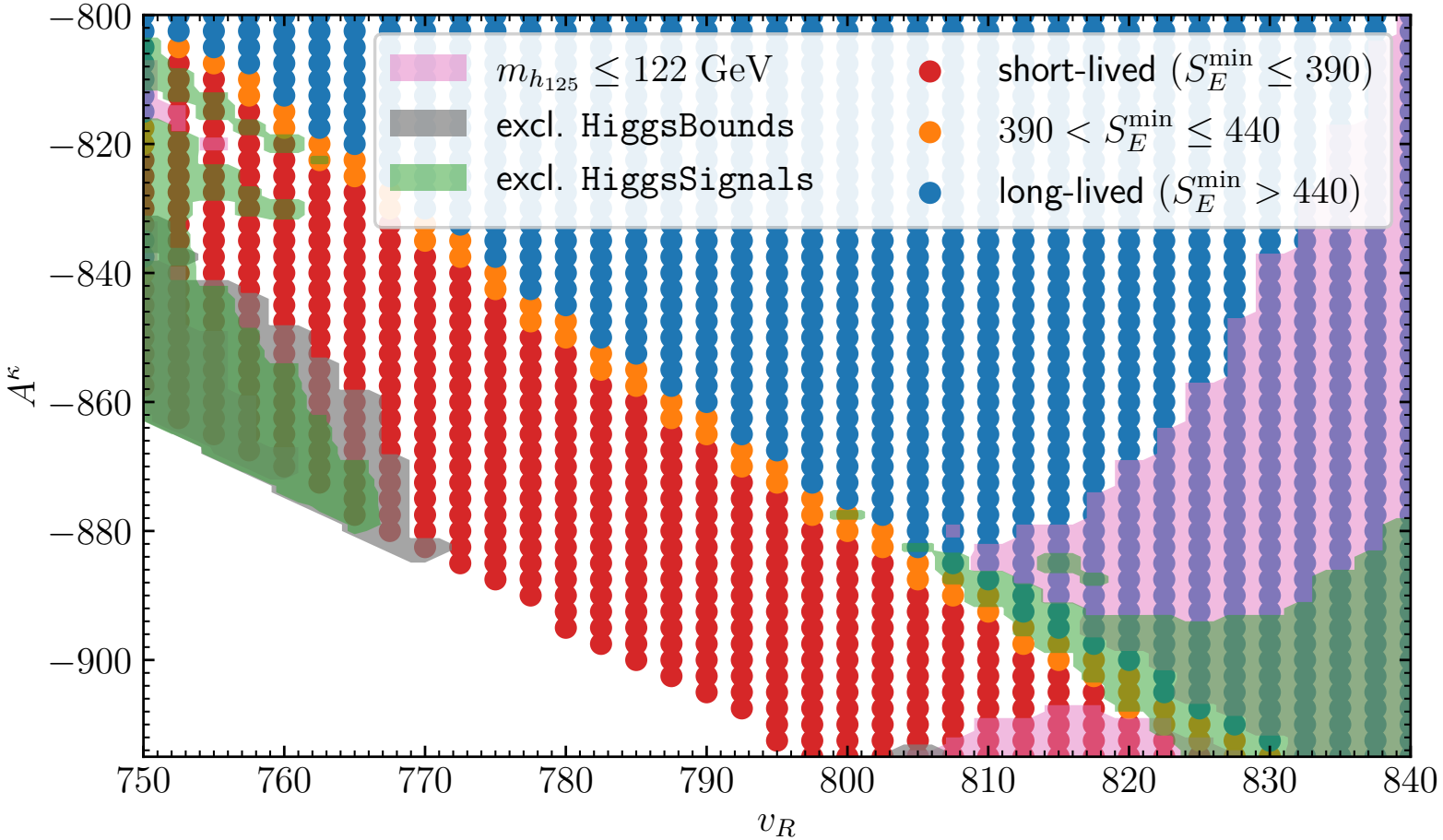


Figure: Blue points have a sufficiently long-lived EW vacuum, while red points have a rapidly decaying EW vacuum. The orange points have a potentially short-lived EW vacuum. The gray and green areas indicate excluded regions based on the `HiggsBounds` and `HiggsSignals` constraints, and the pink area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

Conclusions

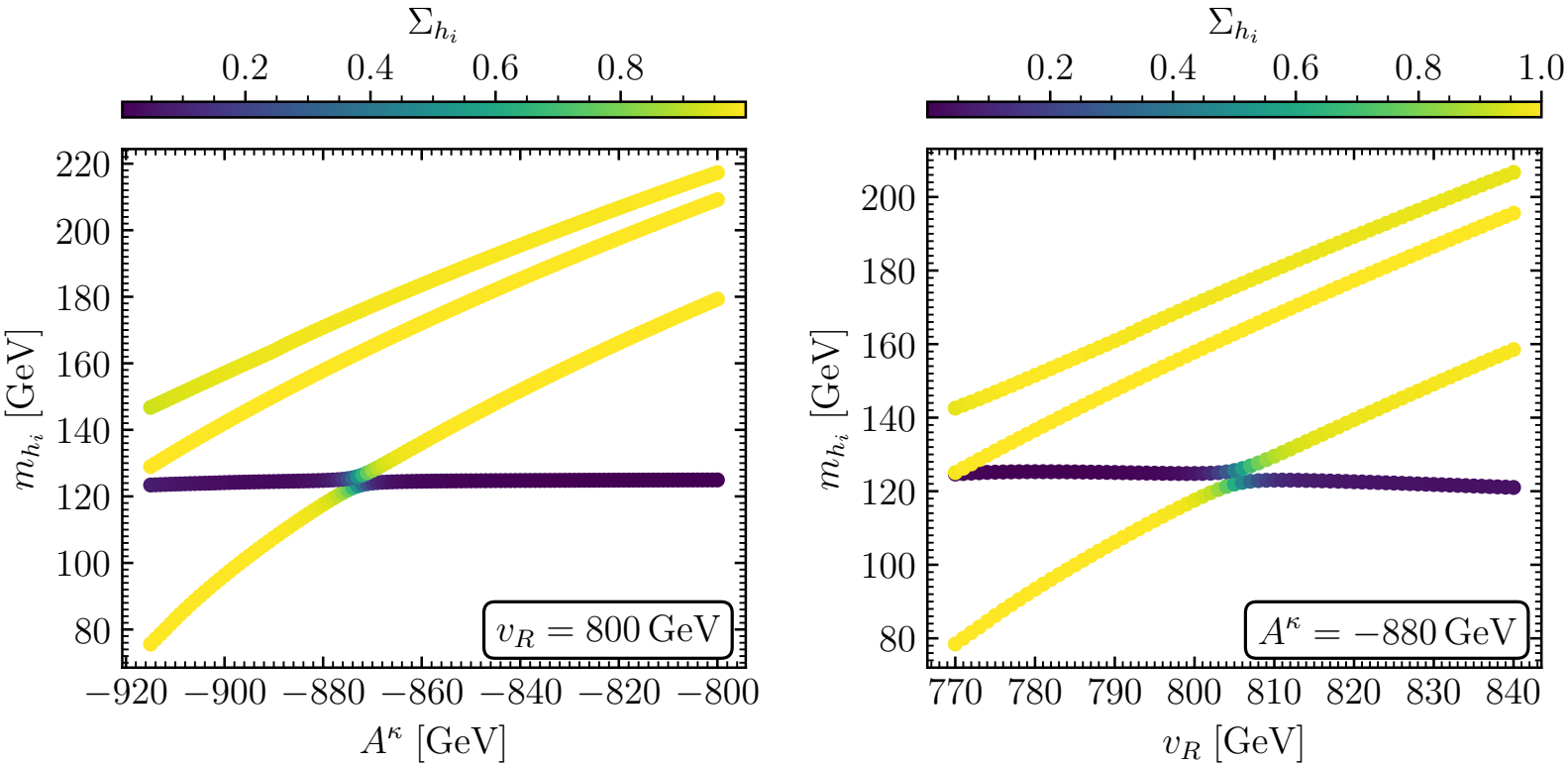
We explored the EW vacuum stability in the alignment-without-decoupling limit of the $\mu\nu$SSM:

- In this limit the EW minimum is not the global minimum of the potential
- $\mathcal{O}(10)$ unphysical minima below the EW minimum
- Often the EW vacuum is long-live and (meta-)stable

$\rightarrow$ An analysis of the $\mu\nu$SSM should take into account an investigation of the EW vacuum stabilty
$\rightarrow$ Demanding that the EW minimum is the global minimum would exclude viable parameter space
$\rightarrow$ Instead a calculation of the lifetime of the EW vacuum should be performed

Thanks!

Higgs-boson spectrum ($h_{1,2,3,4}$) for the scans over A^κ and v_R



Σ_{h_i} : singlet-admixture of h_i