Electroweak Symmetry Restoration induced by Domain Walls in the N2HDM

Mohamed Younes Sassi in collaboration with **Gudrid Moortgat-Pick**

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DESY.

Motivation and main idea

Problem

- **Matter anti-matter asymmetry** cannot be solved using physics from the **standard model alone.**

- **Conventional electroweak baryogenesis is in “trouble”**, due to **EDM experiments** constraining the possibility of **CP-violation**.

Proposed solution

- Using domain walls in the Next-To-Two-Higgs-Doublet model to generate the matter-antimatter asymmetry:

  Scalar Higgs doublets VEVs get **very small and even vanish inside** the domain wall. The **sphaleron rate** is therefore **much less suppressed** inside the wall than outside if it.

- **CP-violating vacuum condensates** are generated dynamically **in the vicinity of the wall**.

- In the case of **annihilating domain walls**, all the **Sakharov conditions** for baryogenesis are fulfilled. Providing an interesting new idea for probing **baryogenesis via domain walls**.

Introduction to Domain Walls

Simple definition

- **Domain walls** are a type of **topological defects** that arise after **spontaneous symmetry breaking** (SSB) of a **discrete symmetry** in the early universe.
- After SSB, **different regions** of the universe end up in different **degenerate vacua**. The universe is then divided into seperate cells with the **boundary between** them called a **"domain wall"**.

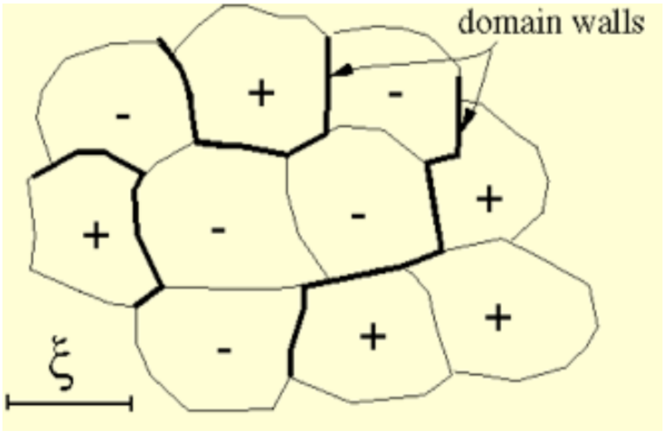


Fig from https://www.ctc.cam.ac.uk/outreach/origins/cosmic_structures_two.php

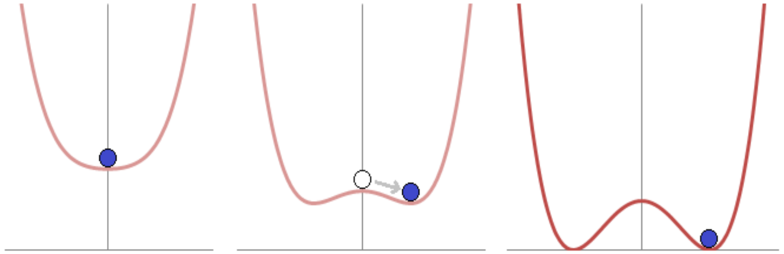


Fig from wikipedia

Simplest example (real singlet scalar)

$$V(\phi) = \mu\phi^2 + \lambda\phi^4$$

V(Φ) is **invariant** under **Z_2:** $\phi \to -\phi$

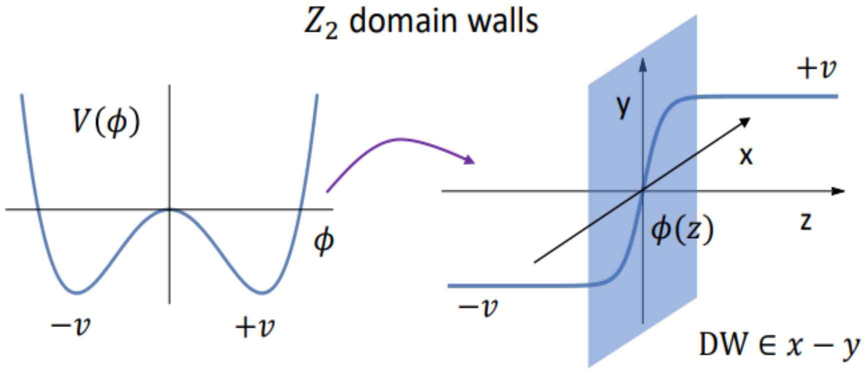


Fig from S.Blasi talk at DESY

- Universe gets **seperated into different cells** with **positive** and **negative minima** having the same probability to occur.

The next-to-two-Higgs-doublet-model (N2HDM)

Add one extra doublet and one extra singlet to the Standard Model.

$$V_{N2HDM} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + m_{12}^2 (\Phi_1^\dagger \Phi_2 + h.c) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger \Phi_2\right)^2$$

$$+ \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) + \left[\frac{\lambda_5}{2}\left(\Phi_1^\dagger \Phi_2\right)^2 + h.c\right]$$

Two Higgs doublets

$$+ \frac{m_S^2}{2}\Phi_s^2 + \frac{\lambda_6}{8}\Phi_s^4 + \frac{\lambda_7}{2}\Phi_s^2(\Phi_1^\dagger \Phi_1) + \frac{\lambda_8}{2}\Phi_s^2(\Phi_2^\dagger \Phi_2).$$

Singlet scalar component

The N2HDM admits several discrete symmetries

- **Z_2 Symmetry:** $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$, $\Phi_s \to \Phi_s$ (**softly broken by m_{12} term**). Used to forbid **Flavor-Changing-Neutral-Currents** at **tree level** when extended to the quarks in the Yukawa sector.

- **Z'_2 Symmetry:** $\Phi_1 \to \Phi_1$, $\Phi_2 \to \Phi_2$, $\Phi_s \to -\Phi_s$. **Unbroken** in the **standard N2HDM**. Leads to the formation of stable domain walls that are **cosmologically forbidden**. Problem solved by adding small soft breaking terms:

$$a\Phi_s,\ b\Phi_s^3,\ c_1\Phi_s\Phi_1^2,\ c_2\Phi_s\Phi_2^2,\ c_3\Phi_s\Phi_1\Phi_2,\ \ldots$$

- We assume those terms are **very small** making them irrelevant for the **DW profiles (only relevant for determining the annihilation time of the DW network)**

The next-to-two-Higgs-doublet-model (N2HDM)

Possible types of vacua in the N2HDM:

$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \qquad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} v_+ \\ \pm v_2 e^{i\xi} \end{pmatrix}, \qquad \langle\Phi_s\rangle = \pm v_s.$$

The N2HDM admits several types of vacua after SSB:

- **Electrically charged vacuum:** $\mathbf{v_+ \neq 0}$. Breaks $\mathbf{U(1)_{em}}$ and leads to **photons being massive → unphysical.**
- **CP-Violating vacuum:** $\boldsymbol{\xi \neq 0}$. **CP-violation** due to phase between the doublets **→ constrained by EDM**
- **Neutral vacuum:** $\mathbf{v_+ = 0, \xi = 0}$. Same behavior as the SM Higgs vacuum **→ used throughout this work**
- It was shown that it is possible to have **CP-violating** or **electric charge breaking vacua** localized **inside domain walls** of the **2HDM** (see **Pilaftsis, Law [2110.12550] PRD** and **MYS, Moortgat-Pick [2309.12398] JHEP**).
- Similar behavior in the **N2HDM** → Opportunity for **electroweak baryogenesis via domain walls**.

Domain Wall solutions in the N2HDM

We focus on domain walls related to the Z'_2 symmetry breaking:

To get the domain wall solution:

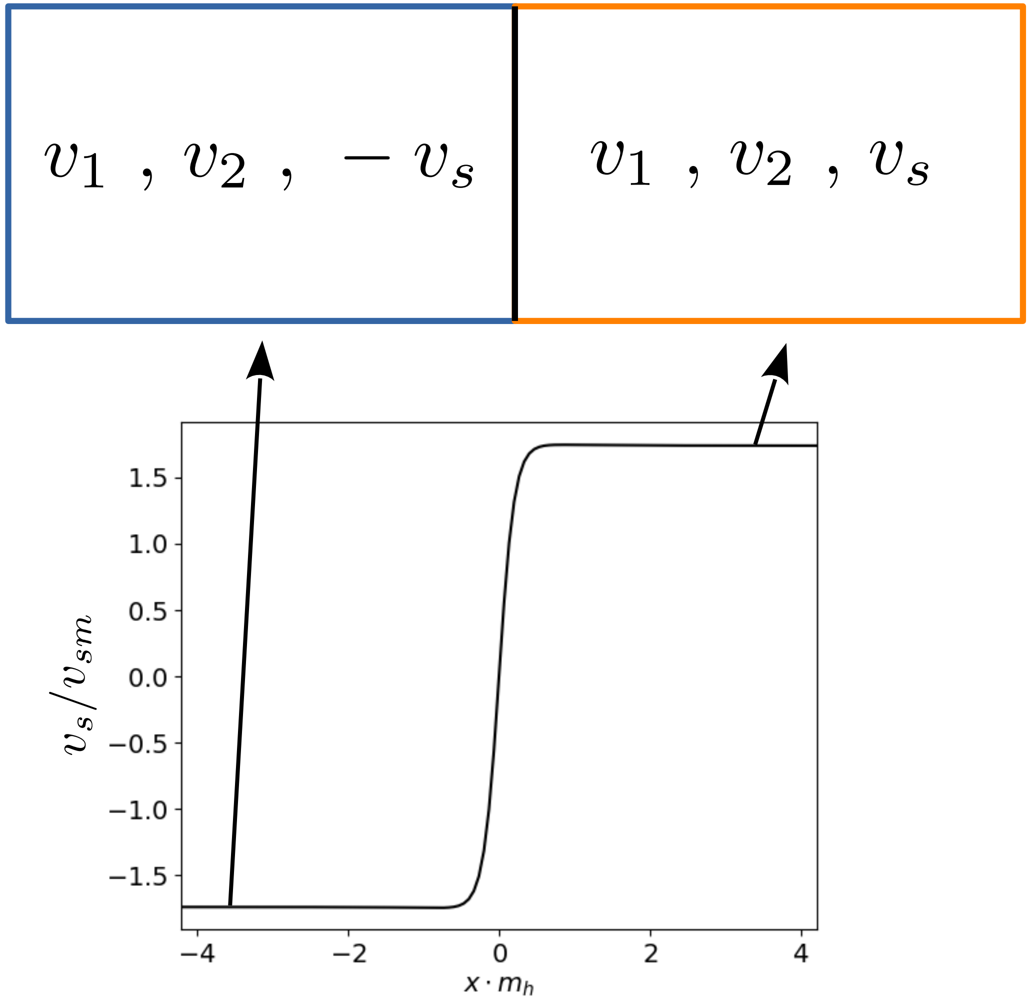
- Determine the boundary conditions
- Solve the equation of motion of the scalar fields:

$$\frac{d^2 v_s}{dx^2} - \frac{dV_{N2HDM}}{dv_s} = 0$$

$$\frac{d^2 v_1}{dx^2} - \frac{dV_{N2HDM}}{dv_1} = 0$$

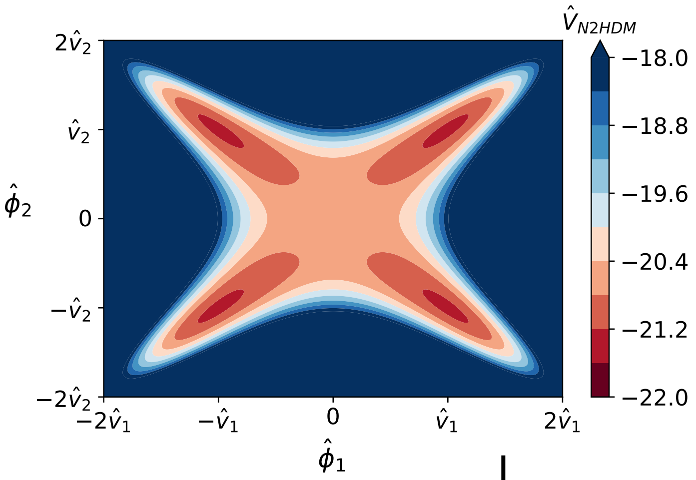
$$\frac{d^2 v_2}{dx^2} - \frac{dV_{N2HDM}}{dv_2} = 0$$

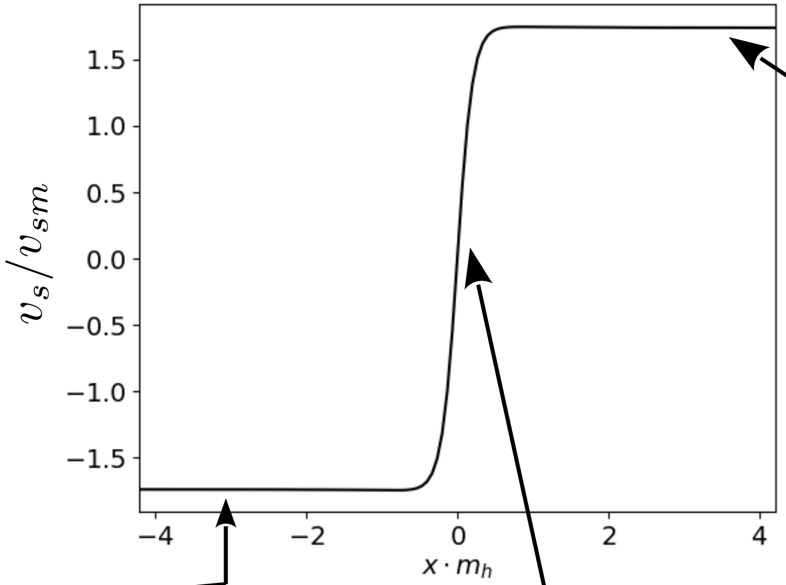
- This is done numerically using the gradient flow algorithm, see **Battye, Brawn, Pilaftsis 2011 (JHEP)**



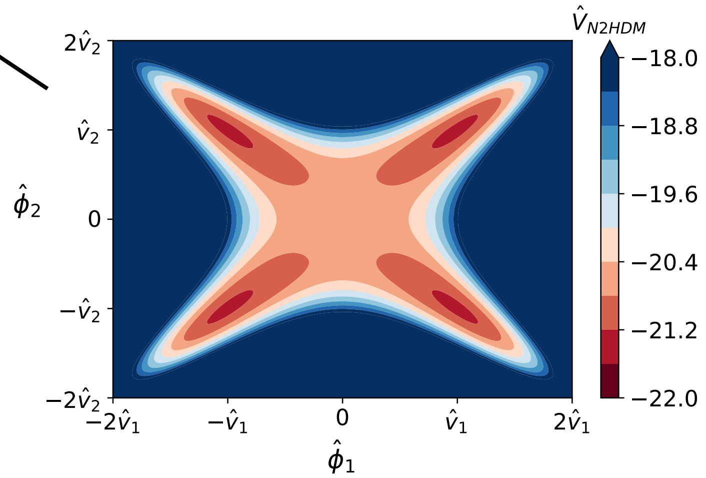
The potential for the Higgs doublets is now space-dependent

Potential at -∞ ($-v_s$)

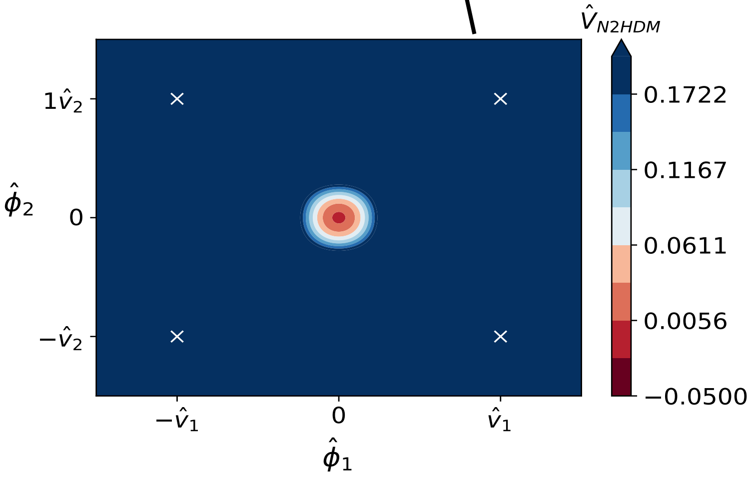




Potential at +∞ (v_s)



Potential at x=0
($v_s = 0$)



- The **minima** of the potential for the **Higgs doublets** inside the wall are **0**.

→ **Electroweak symmetry restoration inside the wall**

Verify the possibility of electroweak symmetry restoration by solving the EOMs of the scalar fields:

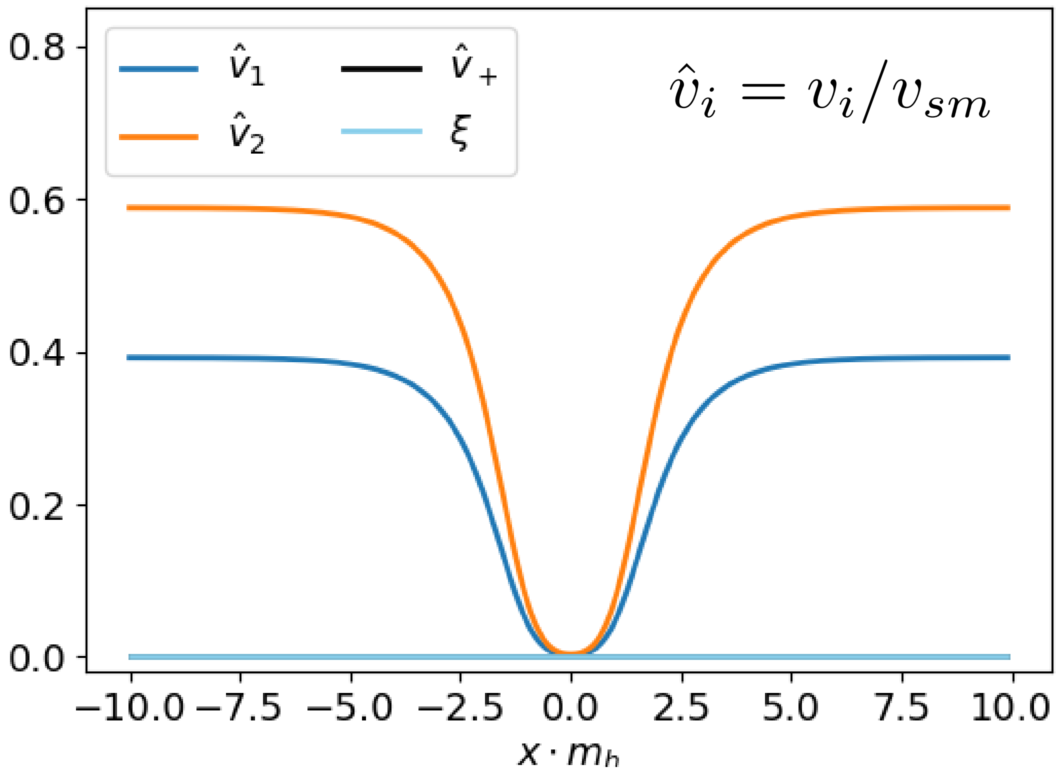
$$\frac{d^2 v_s}{dx^2} - \frac{dV_{N2HDM}}{dv_s} = 0 \qquad \frac{d^2 v_2}{dx^2} - \frac{dV_{N2HDM}}{dv_2} = 0$$

$$\frac{d^2 v_1}{dx^2} - \frac{dV_{N2HDM}}{dv_1} = 0$$

- **Boundary conditions:**

$$\Phi_1(\pm\infty) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix} \qquad \Phi_s(-\infty) = -v_s$$

$$\Phi_2(\pm\infty) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix} \qquad \Phi_s(+\infty) = v_s$$



- Indeed, the profiles of $v_1(x)$ and $v_2(x)$ **vanish inside** the singlet wall → **Electroweak symmetry restoration!**
- **Sphalerons** are **unsuppressed inside the wall.**

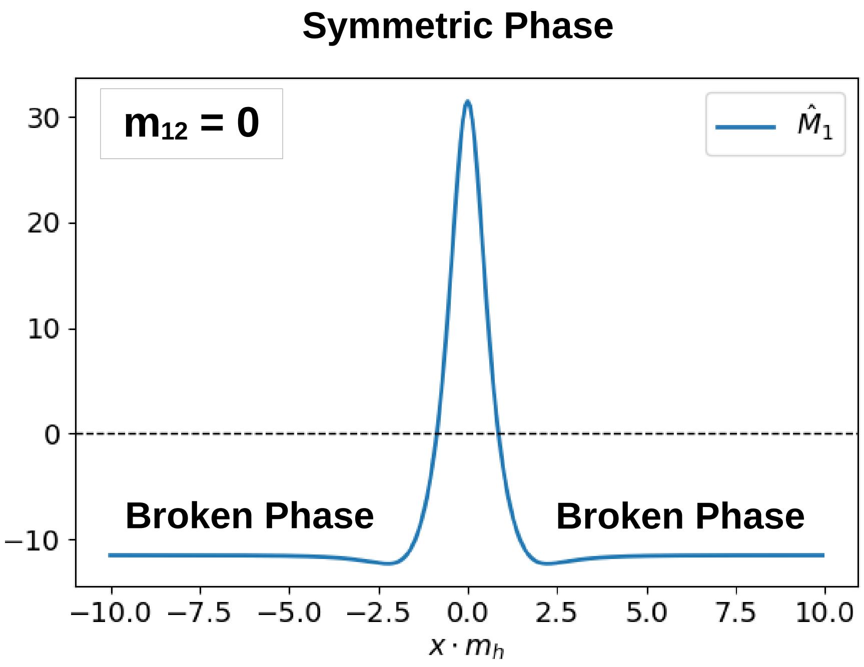
In the N2HDM the effective mass terms are:

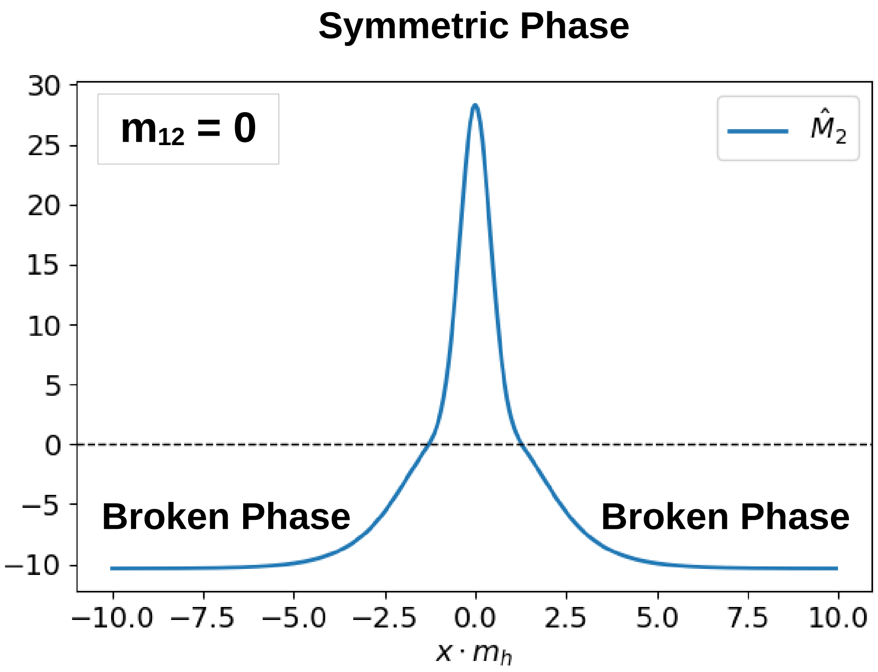
$$V_{N2HDM} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + m_{12}^2 (\Phi_1^\dagger \Phi_2 + h.c) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right)$$
$$+ \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) + \left[\frac{\lambda_5}{2}\left(\Phi_1^\dagger \Phi_2\right)^2 + h.c\right] + \frac{m_S^2}{2}\Phi_s^2 + \frac{\lambda_6}{8}\Phi_s^4 + \frac{\lambda_7}{2}\Phi_s^2 (\Phi_1^\dagger \Phi_1) + \frac{\lambda_8}{2}\Phi_s^2 (\Phi_2^\dagger \Phi_2).$$

- **Extract the effective mass terms for the doublets:**

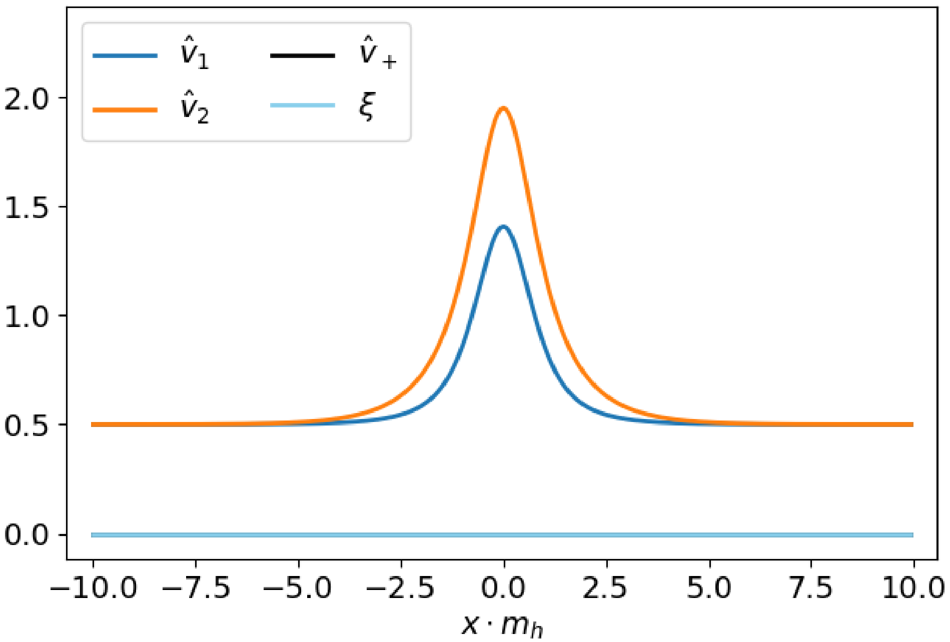
$$M_1 = \frac{m_{11}^2}{2} + \lambda_{345} v_2^2(x) + \frac{\lambda_7}{2} v_s^2(x)$$

$$M_2 = \frac{m_{22}^2}{2} + \lambda_{345} v_1^2(x) + \frac{\lambda_8}{2} v_s^2(x)$$

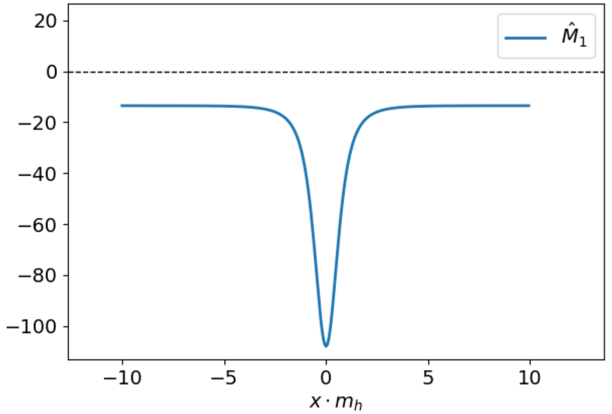




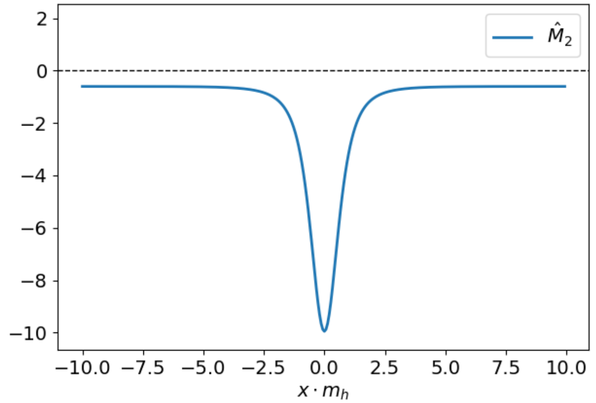
Also opposite behavior occures: VEVs are bigger inside the wall:



$$M_1 = \frac{m_{11}^2}{2} + \lambda_{345} v_2^2(x) + \frac{\lambda_7}{2} v_s^2(x)$$



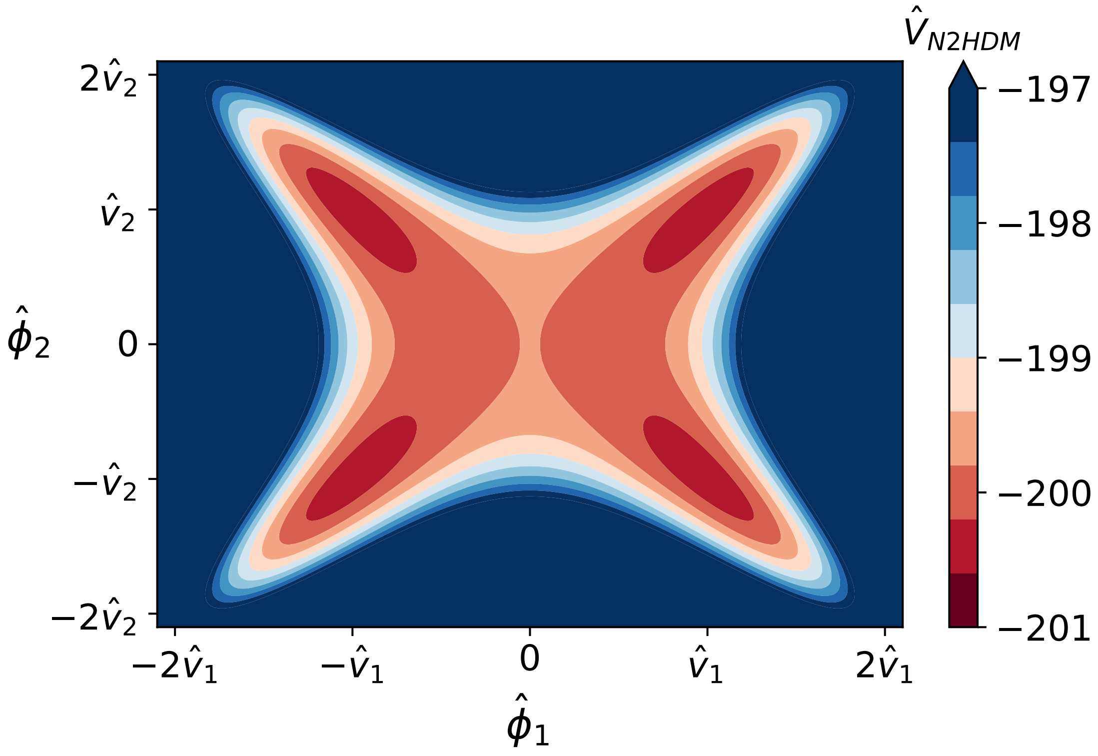
$$M_2 = \frac{m_{22}^2}{2} + \lambda_{345} v_1^2(x) + \frac{\lambda_8}{2} v_s^2(x)$$



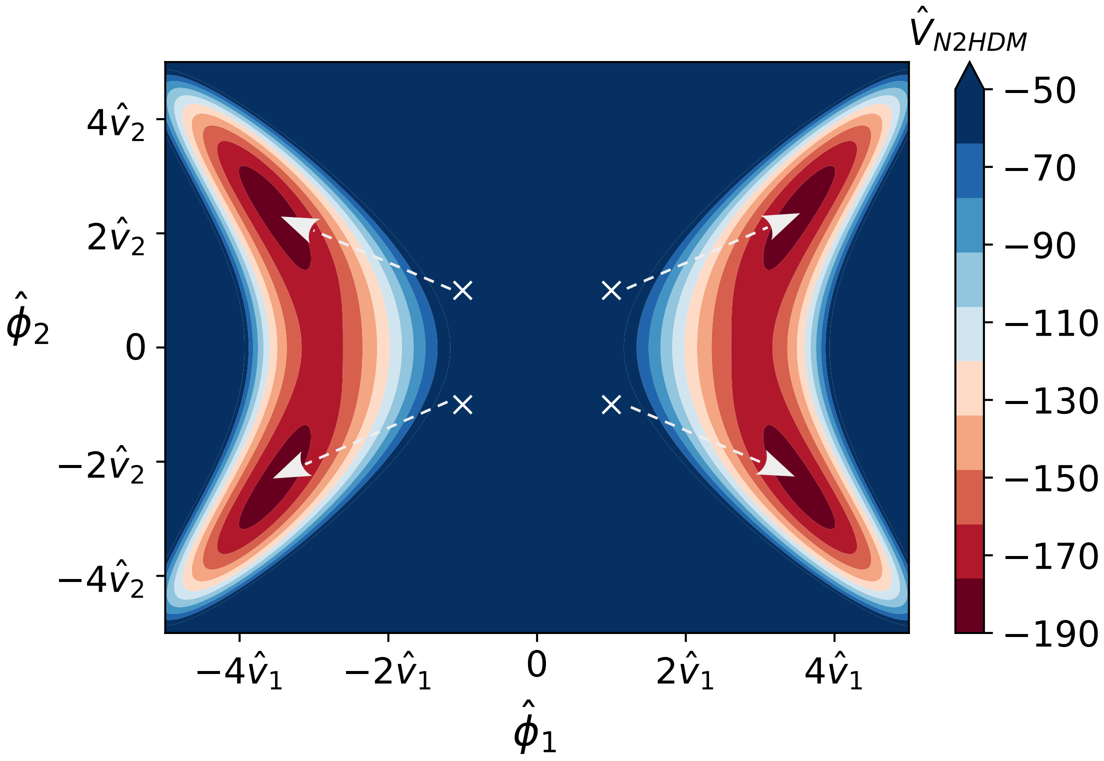
- This occurs when the **effective mass terms** become **more negative** inside the wall.
- Occurs in particular when $\boldsymbol{\lambda_7}$ and $\boldsymbol{\lambda_8}$ are **positive** **(v_s vanishing inside the wall induces a negative contribution)**.
- Most particles get **reflected** off the wall.

- The **effective mass terms** get **smaller inside the wall**, leading the **doublet minima** of the potential to **"stretch"**.

Outside the wall



Inside the wall



Conditions for electroweak symmetry restoration inside the wall

1. Need the **effective mass terms** to be **positive** inside the wall.

Define the change in the effective mass across the wall:

$$\Delta_1 = \lambda_{345}(v_2^2(0) - v_2^2(\pm\infty)) - \frac{\lambda_7}{2} v_s^2(\pm\infty) > 0$$

$$\Delta_2 = \lambda_{345}(v_1^2(0) - v_1^2(\pm\infty)) - \frac{\lambda_8}{2} v_s^2(\pm\infty) > 0$$

2. The **change in the effective mass** across the wall needs to happen in a **large enough space D** in order for the doublet fields to **converge** to a **very small value inside the wall.**

Relevant quantity influencing **D** is the **width of the singlet wall** γ_s :

$$\delta_s \propto (\sqrt{\lambda_6} v_s)^{-1}$$

- Neglecting contributions from terms proportional to $\boldsymbol{\lambda_{345}}$, the dimensionless quantities $\mathbf{B_{1,2} = \lambda_{7,8} / \lambda_6}$ provide a good **parameter** for the **amount of symmetry restoration** inside the wall.

Verifying the different behaviors of the doublet fields inside the singlet wall

- Relevant **potential parameters** are: **m_{11}, m_{22}, m_{12}, λ_{345}, λ_6, λ_7, λ_8 and v_s.**

- Relevant **physical parameters** are then: **m_{h1}, m_{h2}, m_{h3}, α_1, α_2, α_3, v_s and m_{12}.**

→ Perform a random parameter scan using **ScannerS** (20000 points) varying the **CP-even Higgs masses**, **mixing angles**, **v_s** and **m_{12}**.

- All points satisfy **theoretical constraints** of **boundedness from below**, **vacuum stability** and **perturbative unitarity**.
- All points satisfy the **experimental constraints** of **flavor physics**, **electroweak precision measurements S,T and U**.
- Also require **Z'_2 symmetry restoration** in the early universe.

Scan Parameters

$m_{h1} = 125.09$ GeV
150 GeV < m_{h2} < 400 GeV
500 GeV < m_{h3} < 1100 GeV

$0.7 < \alpha_1 < 1.1$
$-0.6 < \alpha_2 < -0.6$
$0.5 < \alpha_3 < 1.57$

200 GeV < v_s < 3000 GeV
75000 GeV^2 < m_{12} < 200000 GeV^2

- The results are expressed in terms of:

$$r_{1,2} = \frac{v_{1,2}(0)}{v_{1,2}(\pm\infty)}$$

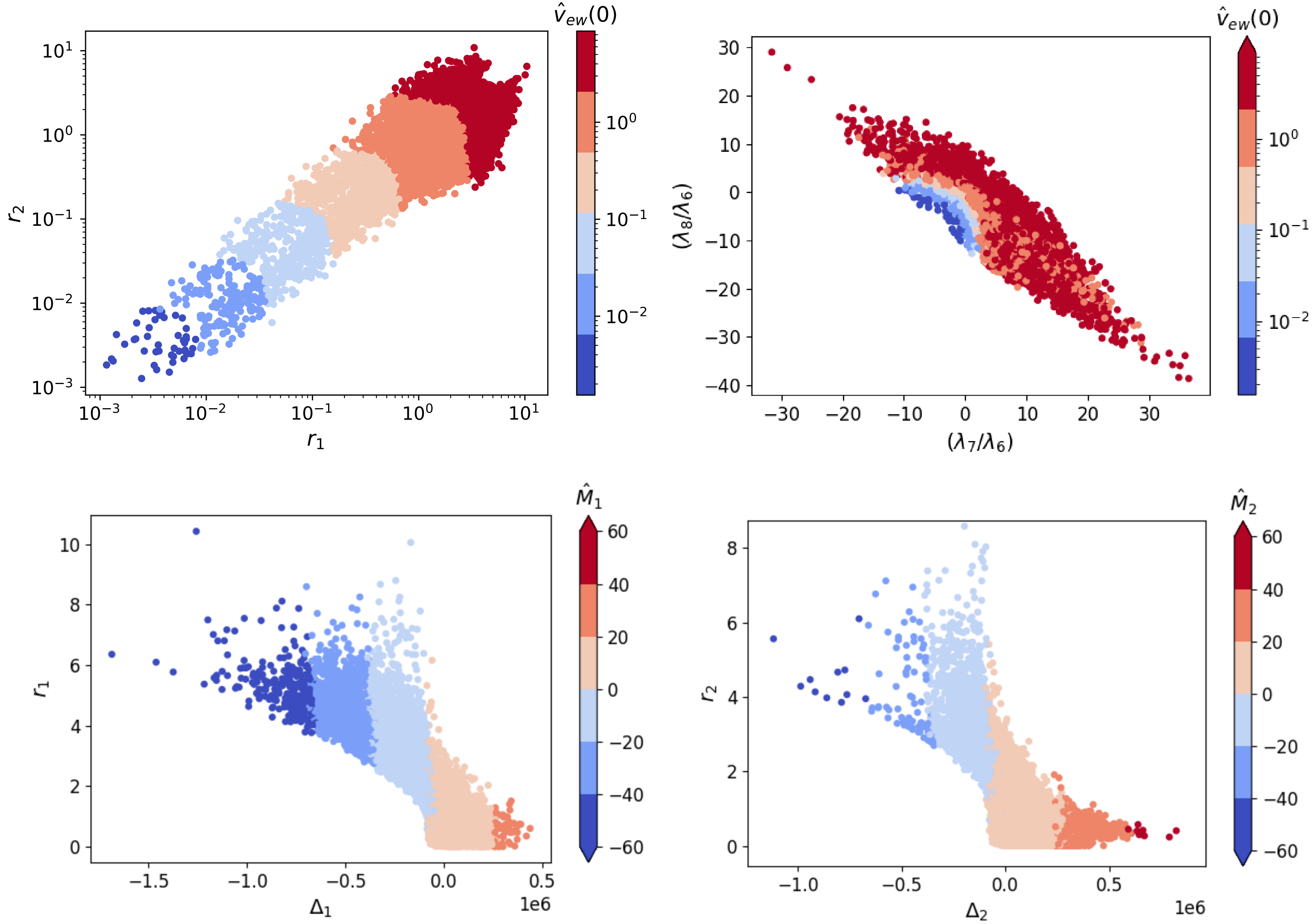
Ratio of the VEVs inside and outside the wall

$$\hat{v}_{ew}(0) = \frac{\sqrt{v_1^2(0) + v_2^2(0)}}{v_{sm}}$$

Measure of electroweak symmetry restoration

Results

- The results of the scan show that $\mathbf{r_1}$ and $\mathbf{r_2}$ can range from nearly **0.001** to **10**.
- Ratios **smaller than 1** possible mainly when $\boldsymbol{\lambda_7}$ and $\boldsymbol{\lambda_8}$ **negative**.
- **Negative** $\boldsymbol{\Delta_{1,2}}$ mainly lead to ratios **bigger** than 1.
- **Positive** $\boldsymbol{\Delta_{1,2}}$ mainly lead to ratios **smaller** than 1.
- Some **anomalous points** where the opposite behavior happens. Mainly due to $\mathbf{m_{12} \neq 0}$.



Width of the wall :

- For a model with only a real scalar singlet, the width of the wall is given by $\delta_s = (\frac{\sqrt{\lambda_6}}{2} v_s)^{-1}$

- In the case of the **N2HDM**, the **backreaction of the doublet fields** can substantially change the width of the singlet wall → **Need to evaluate the width numerically.**

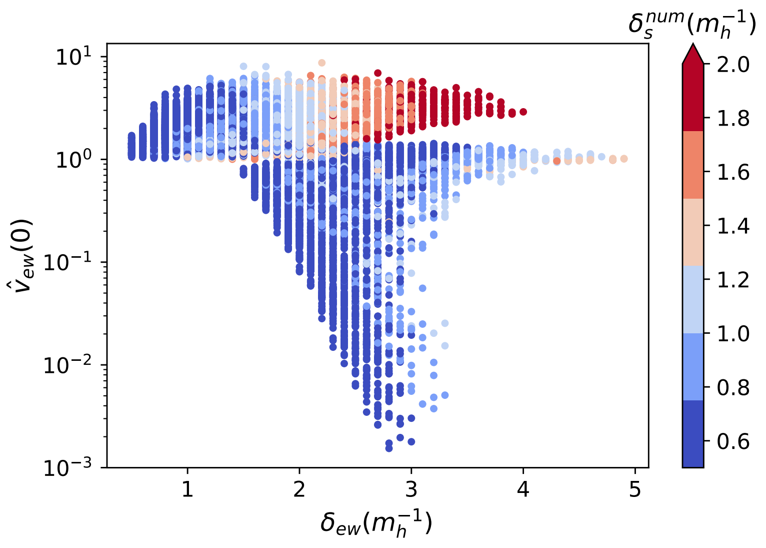
- $\delta_s = (\frac{\sqrt{\lambda_6}}{2} v_s)^{-1}$ Is a good approximation in case of Higgs doublet decoupling or when $v_{1,2}(0) = 0$ inside the wall.

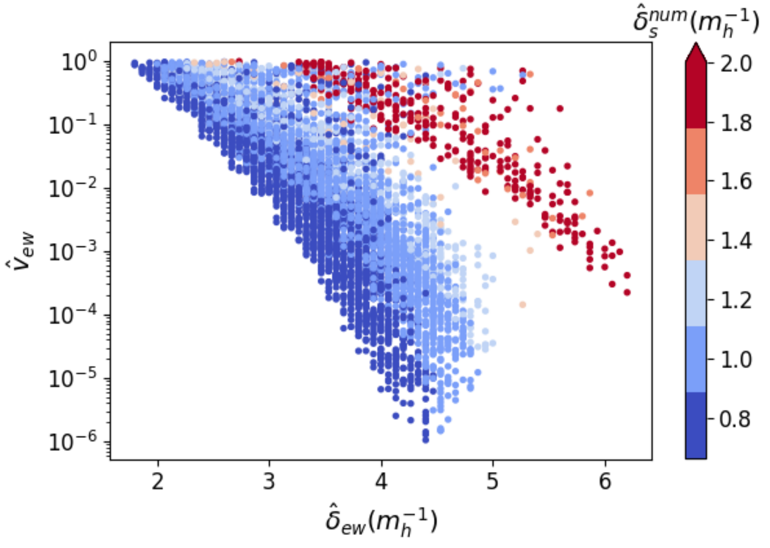
What about the width of doublet profiles in the vicinity of the wall ?

- Only possible to evaluate it numerically in a complex models such as the N2HDM.

- Proportional to the width of the singlet wall γ_s .

- Increases with **smaller v_{ew}(0)**. Electroweak symmetry restoring parameters usually have a **large width**.





Results from another scan with negative $\lambda_{7,8}$

Focus on scenarios that lead to electroweak symmetry breaking in a large region around the wall:

- **Smaller $v_{ew}(0)$** can be obtained for **large positive $\Delta_{1,2}$** and a **large region** where the effective mass term changes across the wall.
- When neglecting **λ_{345} , $\Delta_{1,2}$ x D** proportional to **$\lambda_{7,8}/\lambda_6$**
- Large ratios **$\lambda_{7,8}/\lambda_6$** lead to very small $v_{1,2}(0)$ in a large region around the wall.
- Using the mass basis for the couplings:

$$R = \begin{pmatrix} c_{\alpha_1} c_{\alpha_2} & s_{\alpha_1} c_{\alpha_2} & s_{\alpha_2} \\ -(c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} + s_{\alpha_1} c_{\alpha_3}) & c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_2} s_{\alpha_3} \\ -c_{\alpha_1} s_{\alpha_2} c_{\alpha_3} + s_{\alpha_1} s_{\alpha_3} & -(c_{\alpha_1} s_{\alpha_3} + s_{\alpha_1} s_{\alpha_2} c_{\alpha_3}) & c_{\alpha_2} c_{\alpha_3} \end{pmatrix}$$

CP-even Higgs Mixing angles

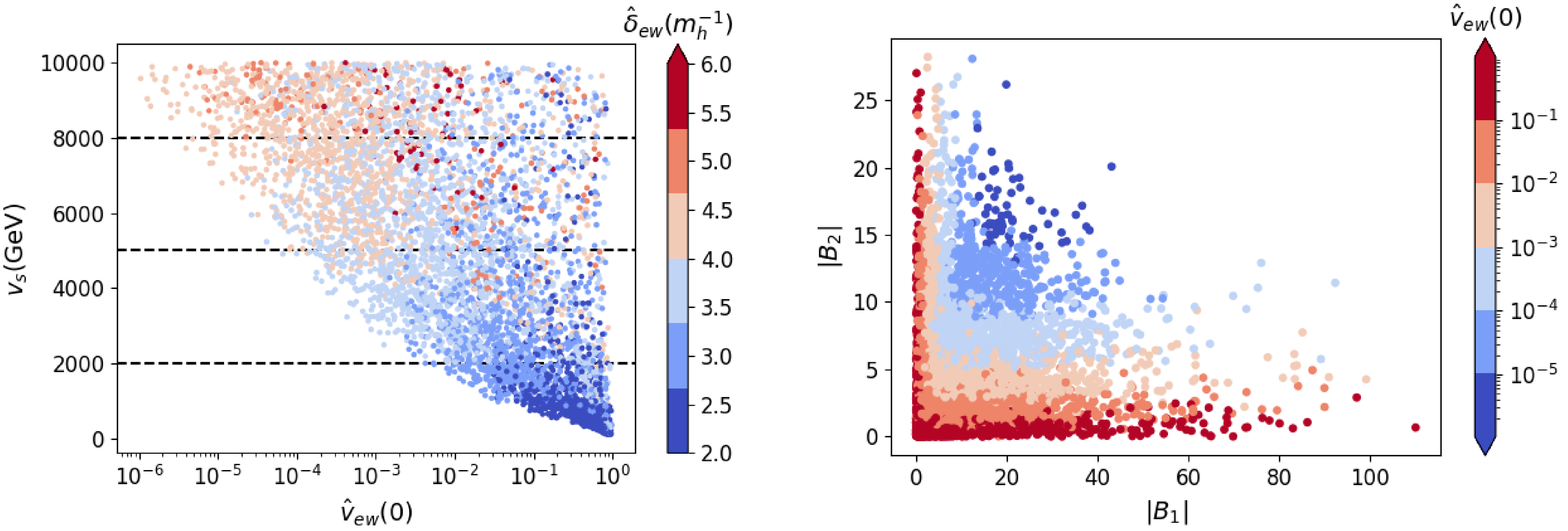
$$\lambda_6 = \frac{m_{h_1}^2 R_{13}^2 + m_{h_2}^2 R_{23}^2 + m_{h_3}^2 R_{33}^2}{v_s^2} \qquad \lambda_7 = \frac{R_{13}R_{11}m_{h_1}^2 + R_{23}R_{21}m_{h_2}^2 + R_{33}R_{31}m_{h_3}^2}{v_1 v_s} \qquad \lambda_8 = \frac{R_{13}R_{12}m_{h_1}^2 + R_{23}R_{22}m_{h_2}^2 + R_{33}R_{32}m_{h_3}^2}{v_2 v_s}$$

$$\rightarrow \quad \lambda_7/\lambda_6 = \left(\frac{v_s}{v_1}\right)\left(\frac{R_{13}R_{11}m_{h_1}^2 + R_{23}R_{21}m_{h_2}^2 + R_{33}R_{31}m_{h_3}^2}{m_{h_1}^2 R_{13}^2 + m_{h_2}^2 R_{23}^2 + m_{h_3}^2 R_{33}^2}\right)$$

- Look for **large v_s**
- Look for parameter points with **small λ_6**. For example **small masses**.

Parameter scan for small masses and large v_s

94 GeV < m_{h1} < 98 GeV
m_{h2} = 125.09 GeV
300 GeV < m_{h3} < 400 GeV



- Parameter points with **larger v_s** can lead to **electroweak symmetry restoration** in a **large region** around the wall

Different Goldstone modes on both domains

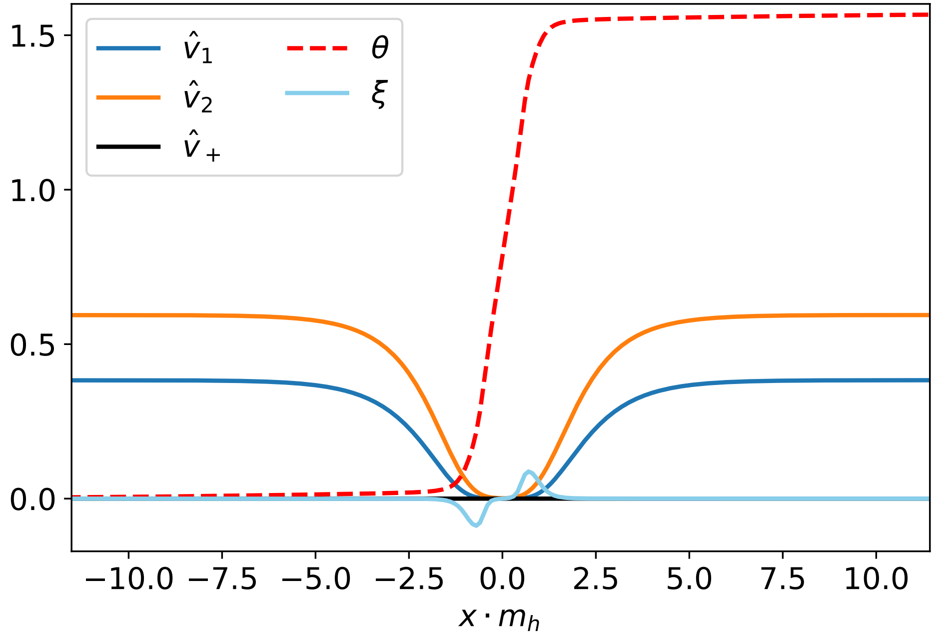
$$\langle \Phi_1 \rangle = U \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix},$$

$$\langle \Phi_2 \rangle = U \frac{1}{\sqrt{2}} \begin{pmatrix} v_+ \\ \pm v_2 e^{i\xi} \end{pmatrix},$$

$$U = exp(i\theta) exp[(g_i \sigma_i)/(2 v_{sm})].$$

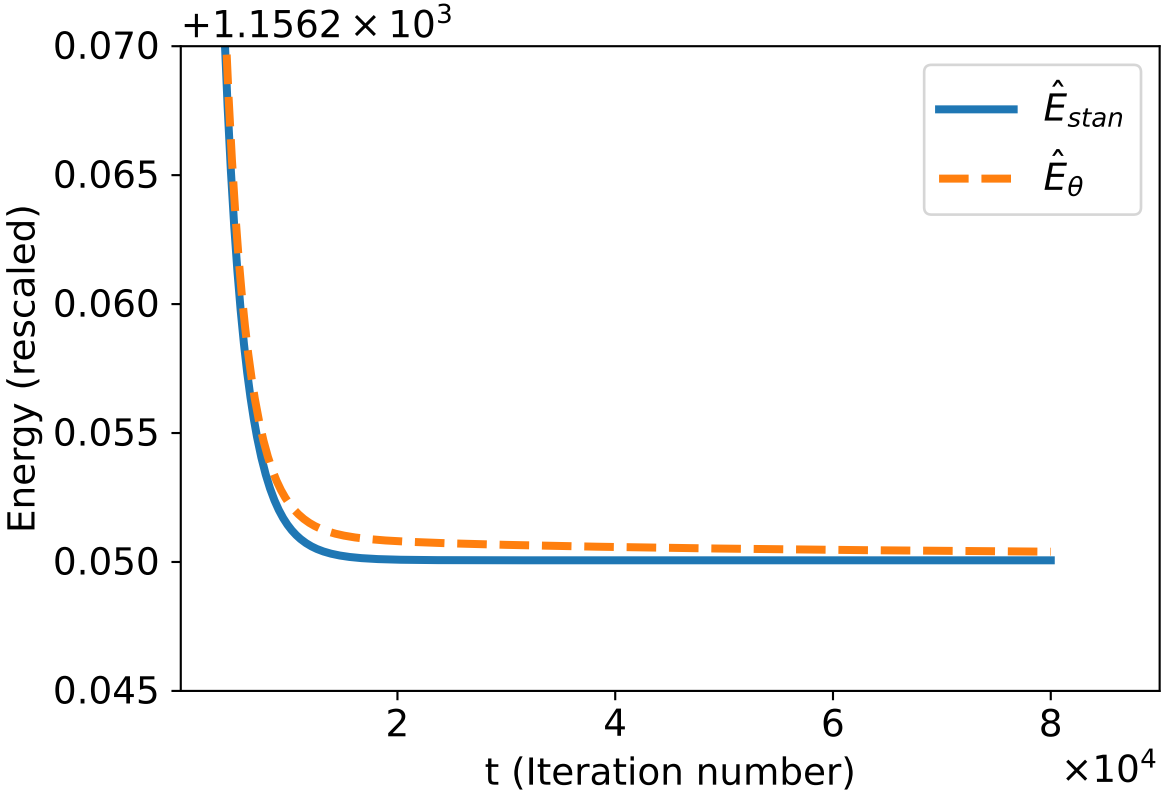
v_1 , v_2 , $-v_s$	v_1 , v_2 , v_s
$\theta = 0$	$\theta = \pi/2$

- **θ** and **g_i** are the **Goldstone modes** related to **$U(1)_Y$** and **$SU(2)_L$**
- In the early universe **different domains** can have **random values of the Goldstone modes**.
- Different Goldstone modes can induce **CP-violating and/or charge breaking vacua** located **inside** the wall.
- E.g. having **different θ** induces **CP-violating vacua localized in the vicinity of the wall.**
- This effect happens when the **EW symmetry** and the **Z'_2** are spontaneously broken at the **same time (one step phase transition)**.



From EOM of the Goldstone mode **θ(x)** → $$\frac{d\theta}{dx} = \frac{-v_2^2}{v_1^2 + v_2^2 + v_+^2}\frac{d\xi}{dx}$$ **Pilaftsis, Law (2021)**

- Solution with **CP-violation** has **higher energy** than the **standard solution**.
- CP-violating solution of the doublet fields will **decay** to the standard solution.



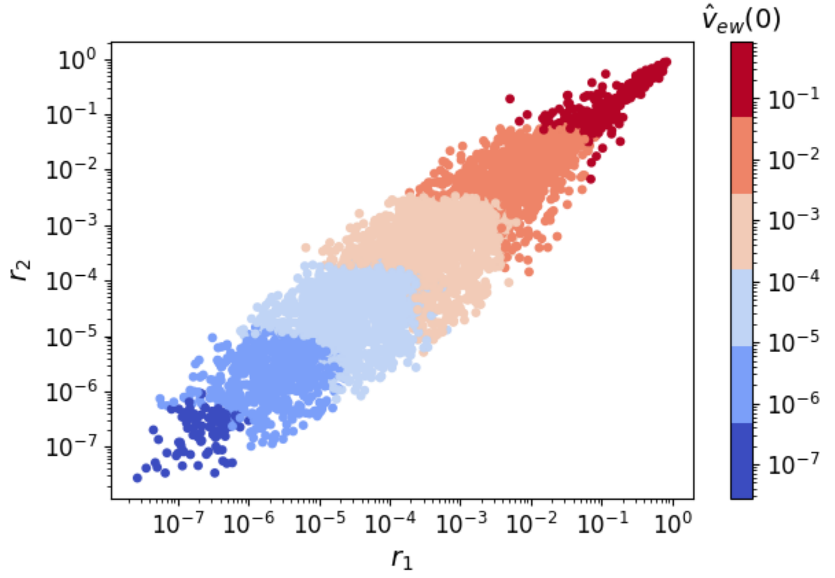
Summary and conclusions

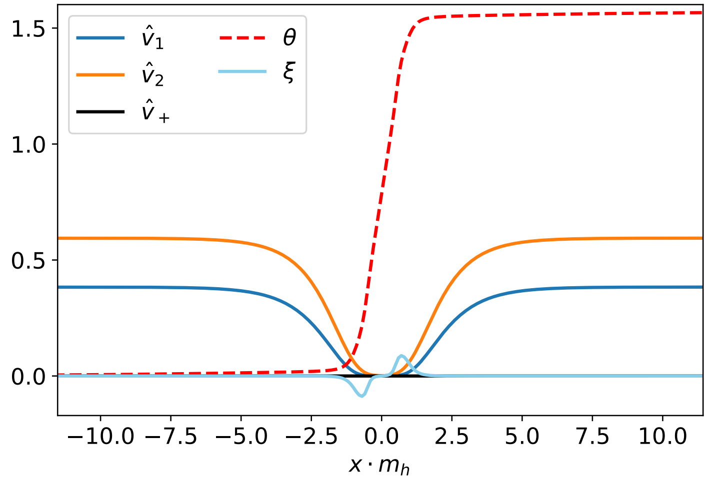
1) In the N2HDM the **vacuum expectation values for the Higgs doublets** can be **substantially lower** inside the domain wall of the singlet **than outside of it**. Making **sphaleron rates** inside the wall **much less supressed**.

2) Possible to achieve **very small values** for the ratio of the VEVs inside over those outside the wall for parameter points that satisfy **theoretical and experimental constraints**.

3) Relevant variables are the **masses and mixing angles of the CP-even** Higgs bosons.

4) Possibility of having **metastable CP-violating condensates** inside the walls separating domains with **different Goldstone modes**.





Outlook

- Calculation of the **generated baryogenesis** via the motion of the **domain walls** in the early universe **until their annihilation** (all Sakharov conditions are satisfied).

Backup

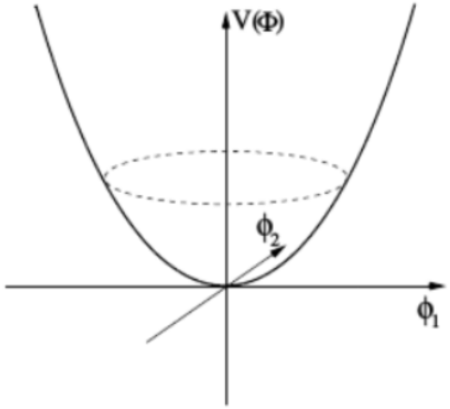
- For potentials of the form:

$$V = a_i \phi_i^2 + b_i \phi_i^4 + c_{ij} \phi_i \phi_j$$

- When c_{ij} **terms vanish**, the **phase** of the potential (**symmetric or broken**) is determined by the **sign** of the **mass term** a_i multiplying the **quadratic** field terms.

- For positive a_i the potential is in the **symmetric phase.**

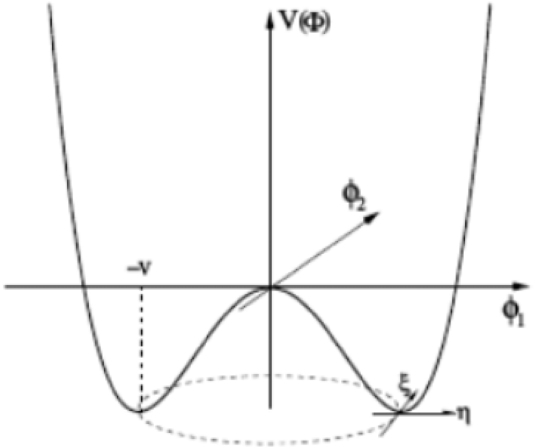
- For negatif a_i the potential is in the **broken phase.**



$a_i > 0$

$b_i > 0$

Symmetric phase



$a_i < 0$

$b_i > 0$

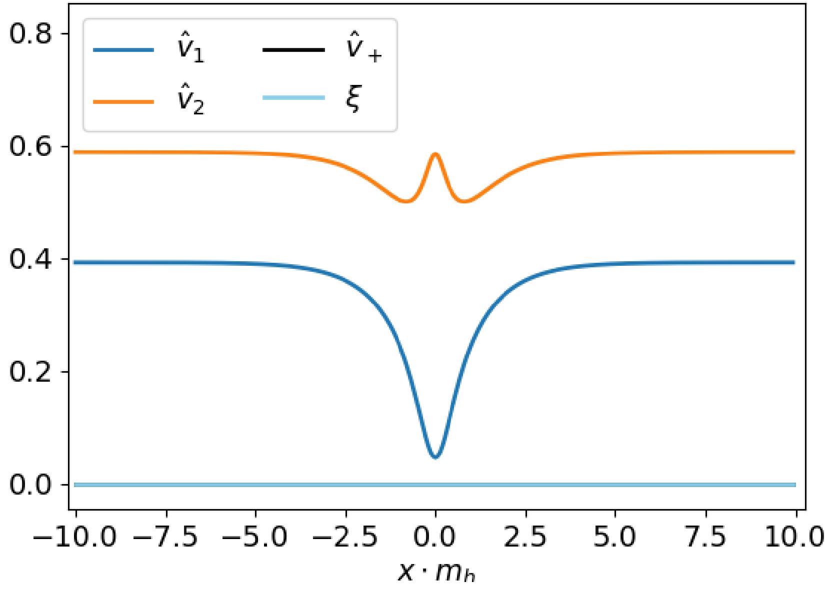
Broken phase

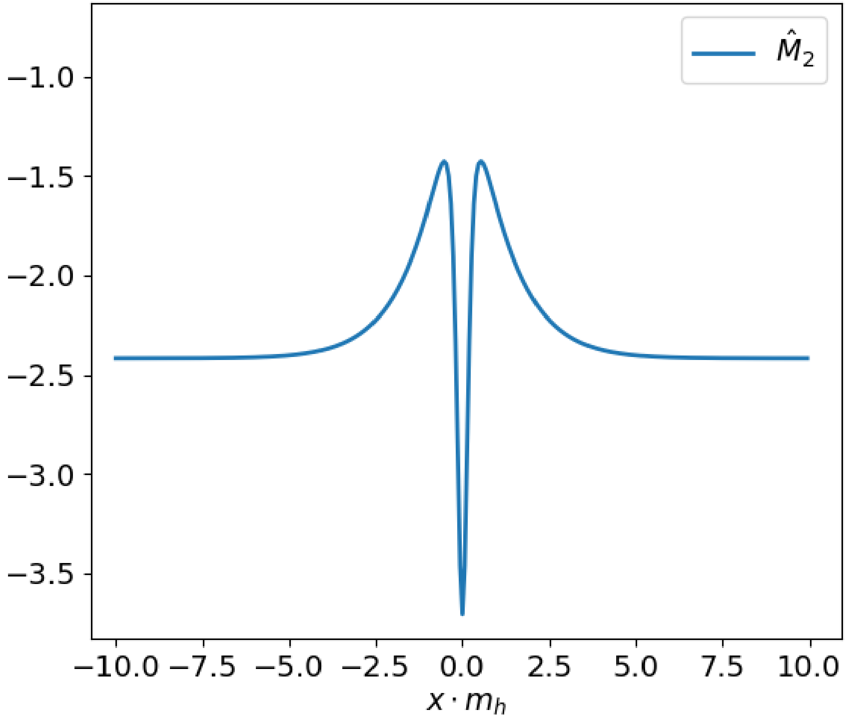
Some parameter points have $r_i < 1$ even for $\Delta_i < 0$ (and the opposite).

This is because the contribution of λ_{345} to the effective mass can be big for $x \approx 0$.

This behavior occurs for λ_8 positive and a thin domain wall, making the contribution from λ_8 to the effective mass localized at x = 0.

$$M_{eff,2} = \frac{m_{22}^2}{2} + \lambda_{345} v_1^2(x) + \frac{\lambda_8}{2} v_s^2(x)$$



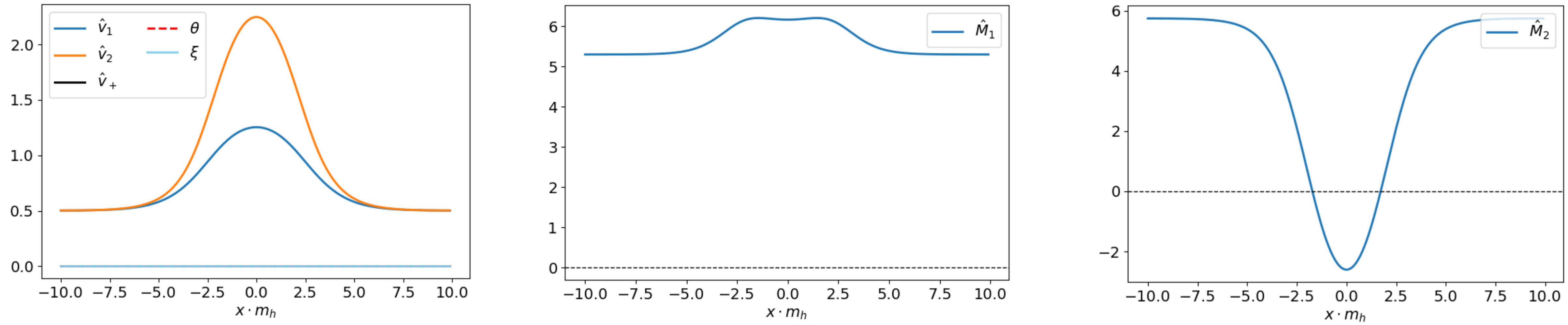


$v_2(x=0)$ inside the wall is smaller than outside the wall. But Δ_2 is negative!

m_{12} anomalies

- Because $m_{12}\neq 0$, some parameter points will not have the minima of the 2HDM potential at x=0 (v_s=0) at the origin ($v_{1,2}$=0) even though the effective masses are **positive and higher inside the wall**.

- The minima of the Higgs doublets at x=0 will then converge to those **non-zero vevs**.



Same behavior for parameter points with $\Delta_2 > 0$ but $r_2 > 1$.

Thank you

Contact

Deutsches Elektronen-Synchrotron DESY

www.desy.de

Mohamed Younes Sassi

mohamed.younes.sassi@desy.de