Electroweak Symmetry Restoration induced by Domain Walls in the N2HDM

2HDM Group Meeting
01/02/2024

Introduction to Domain Walls

- **Domain walls** are a type of **topological defects** that arise after a **spontaneous symmetry breaking (SSB)** of a theory with a discrete symmetry.

- After **spontenous symmetry breaking**, different regions of the universe can **fall into different vacua** which are **degenerate** with each other.

Example:

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

$$\mathbf{Z_2}: \ \phi \rightarrow -\phi$$

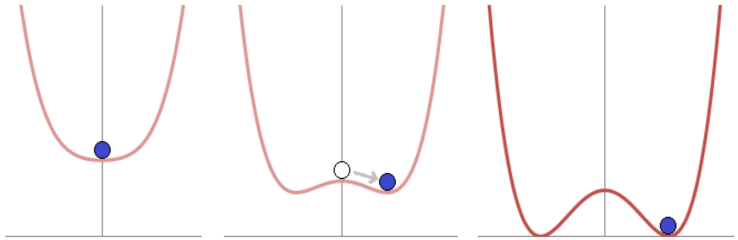


Fig. from wikipedia

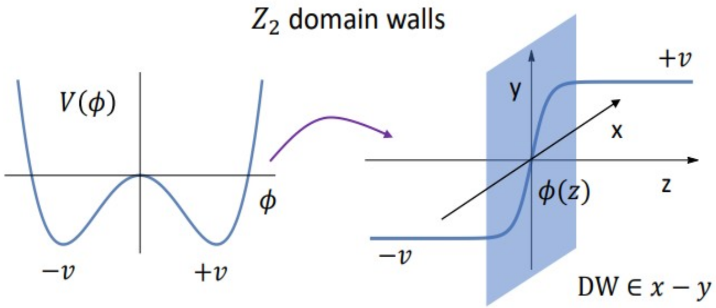


Fig. from Blasi talk

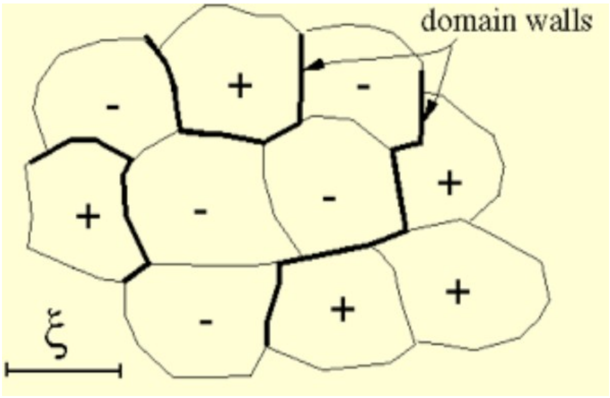


Fig. from

The universe gets divided to **separate cells** after a **phase transition**. Regions which are **causally disconnected** fall into **random vacua** (either positive or negative)

$$G \longrightarrow H$$

SSB of G to subgroup H

The **space of all cosets G/H** gives the **vacuum manifold of all degenerate vacuas**

$$M = G/H$$

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

The N2HDM allows for 2 discrete symmetries:

Z_2 :

$$\Phi_1 \to \Phi_1$$
$$\Phi_2 \to -\Phi_2$$
$$\Phi_s \to \Phi_s$$

Z'_2 :

$$\Phi_1 \to \Phi_1$$
$$\Phi_2 \to \Phi_2$$
$$\Phi_s \to -\Phi_s$$

3 possible domain wall solutions :

1) **Z_2 domain walls**, stable for $m_{12} = 0$.

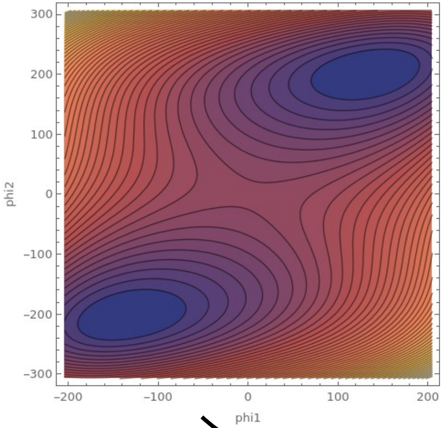
2) **Z'_2 domain walls**, stable in the N2HDM with the given potential.

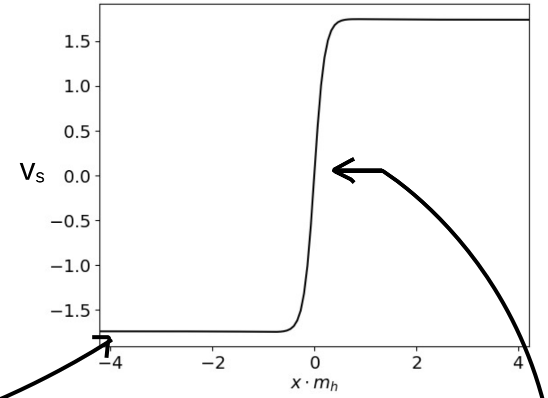
3) **both Z_2 and Z'_2 domain walls**.

Z'_2 domain wall solutions

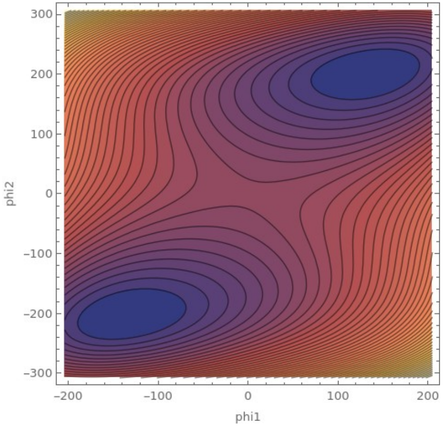
$v_1>0$, $v_2>0$, $v_s<0$	$v_1>0$, $v_2>0$, $v_s>0$

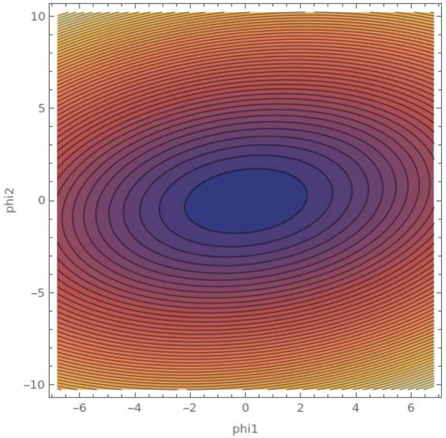
Potential at $-v_s$





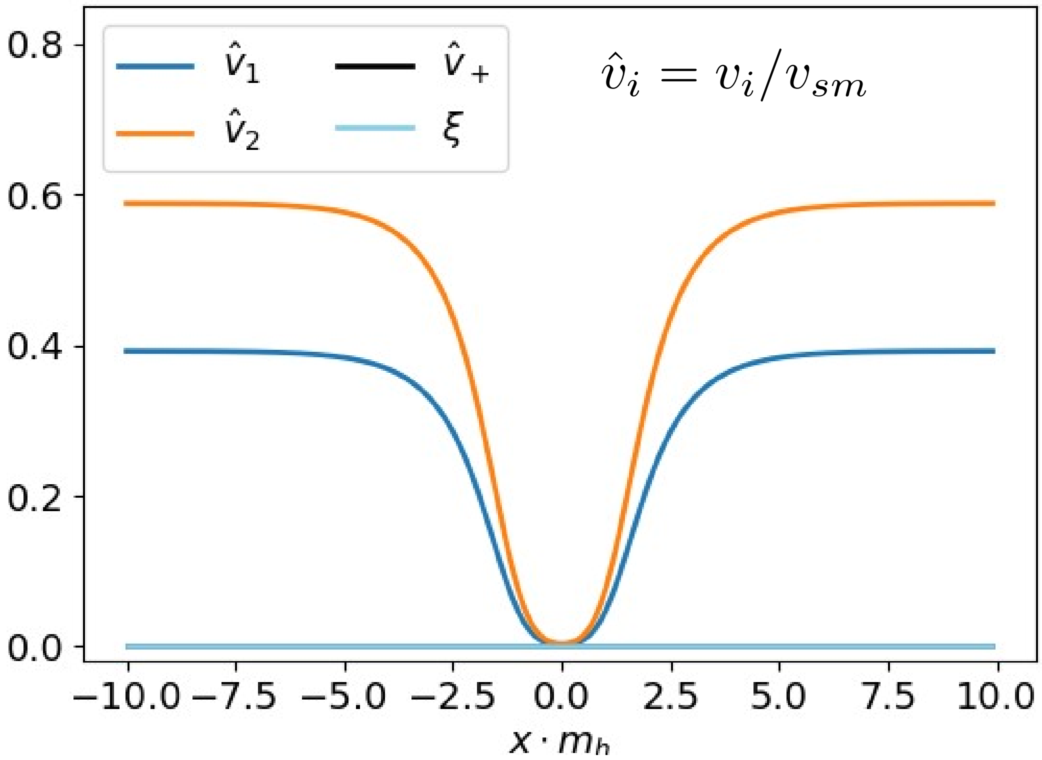
Potential at v_s





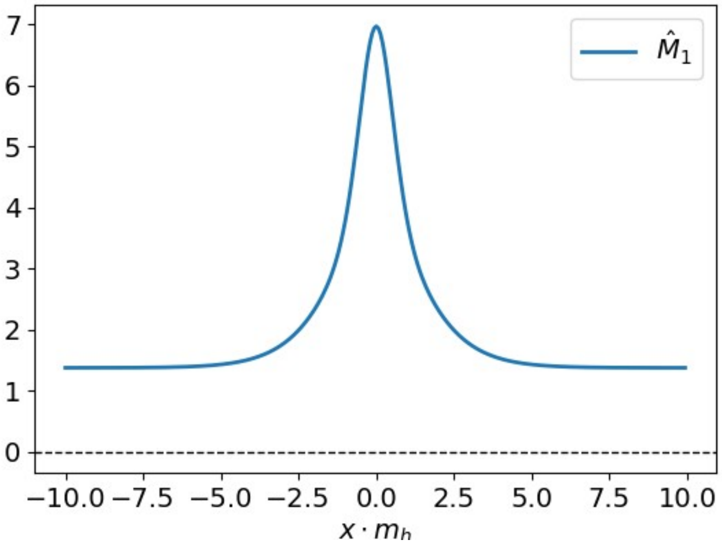
Potential at $v_s = 0$

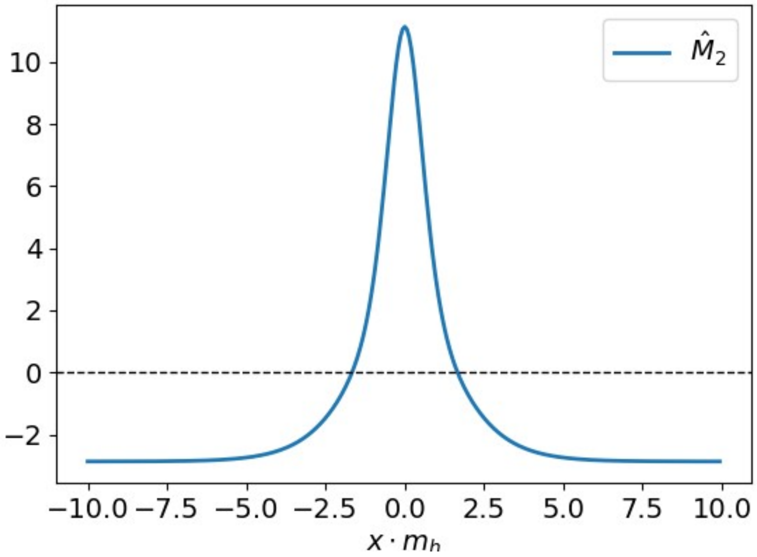
Spatial field configuration for $v_1(x)$ and $v_2(x)$:



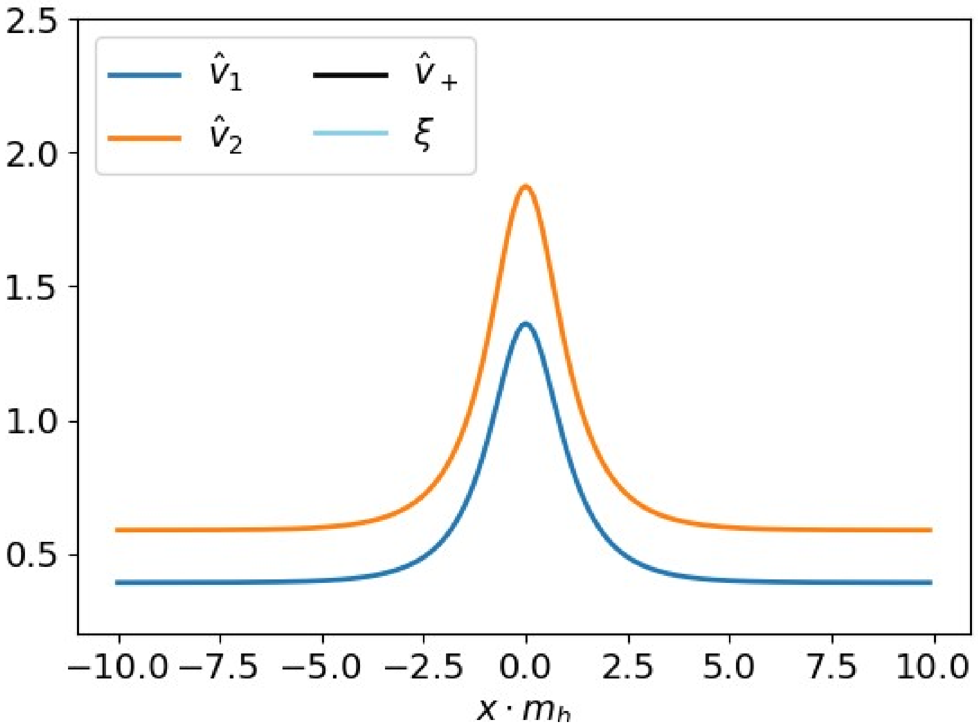
Explanation

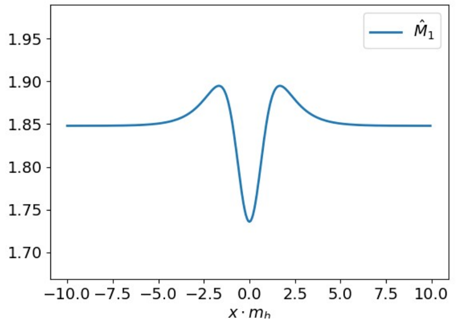
$$M_{eff,1} = \frac{m_{11}^2}{2} + \lambda_{345} v_2^2(x) + \frac{\lambda_7}{2} v_s^2(x) \qquad M_{eff,2} = \frac{m_{22}^2}{2} + \lambda_{345} v_1^2(x) + \frac{\lambda_8}{2} v_s^2(x)$$

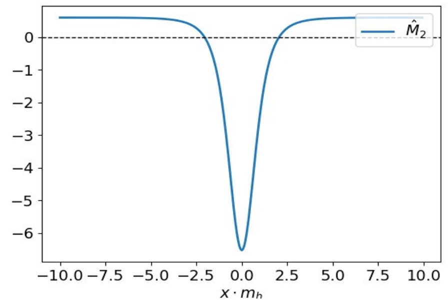




Opposite effect can also occur :



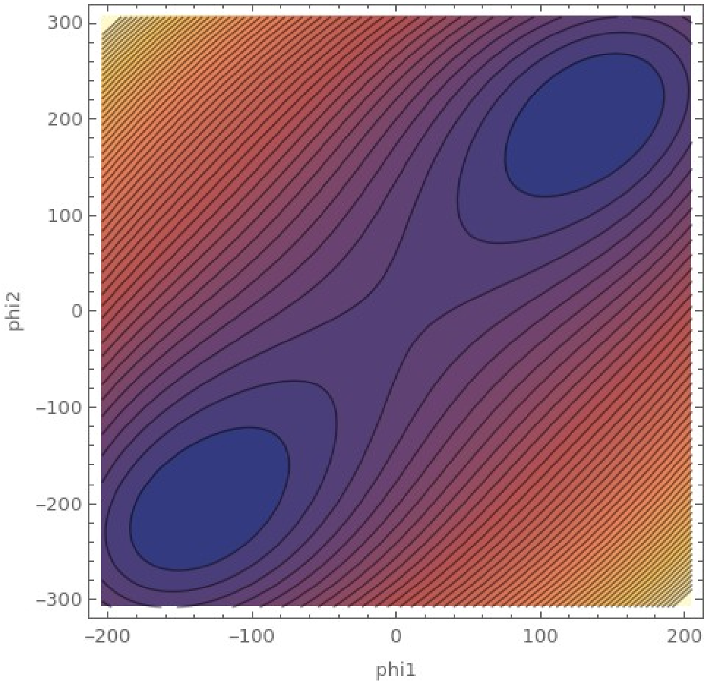


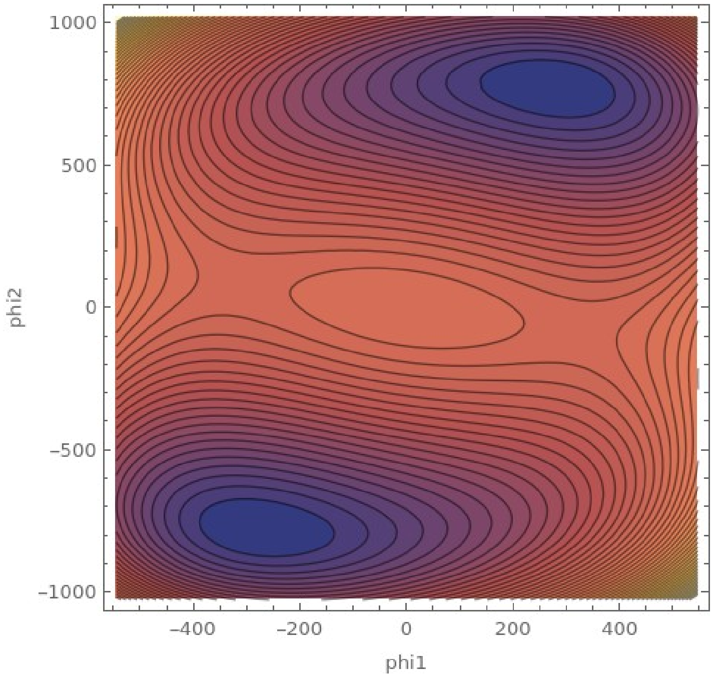


Effective mass terms get smaller inside the wall, leading the minima of the potential to “stretch”.

Vacuum expectation values of the doublets grow bigger **inside the wall**. Most particles get **reflected** off the walls.

Outside the domain wall | **Inside the domain wall**





The minima for v_1 and v_2 inside the domain wall have a higher value than outside.

Relevant parameters for the behavior of $v_1(x)$ and $v_2(x)$ inside the domain walls are :

m_{11}, m_{22}, λ_{345}, 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

Scan over parameter points satisfying **boundedness from below**, **perturbative unitarity** and **vacuum stability:**

$m_{h1} = 125.09$ GeV, 125.09 GeV $< m_{h2} < 500$ GeV, 500 GeV $< m_{h3} < 1200$ GeV,

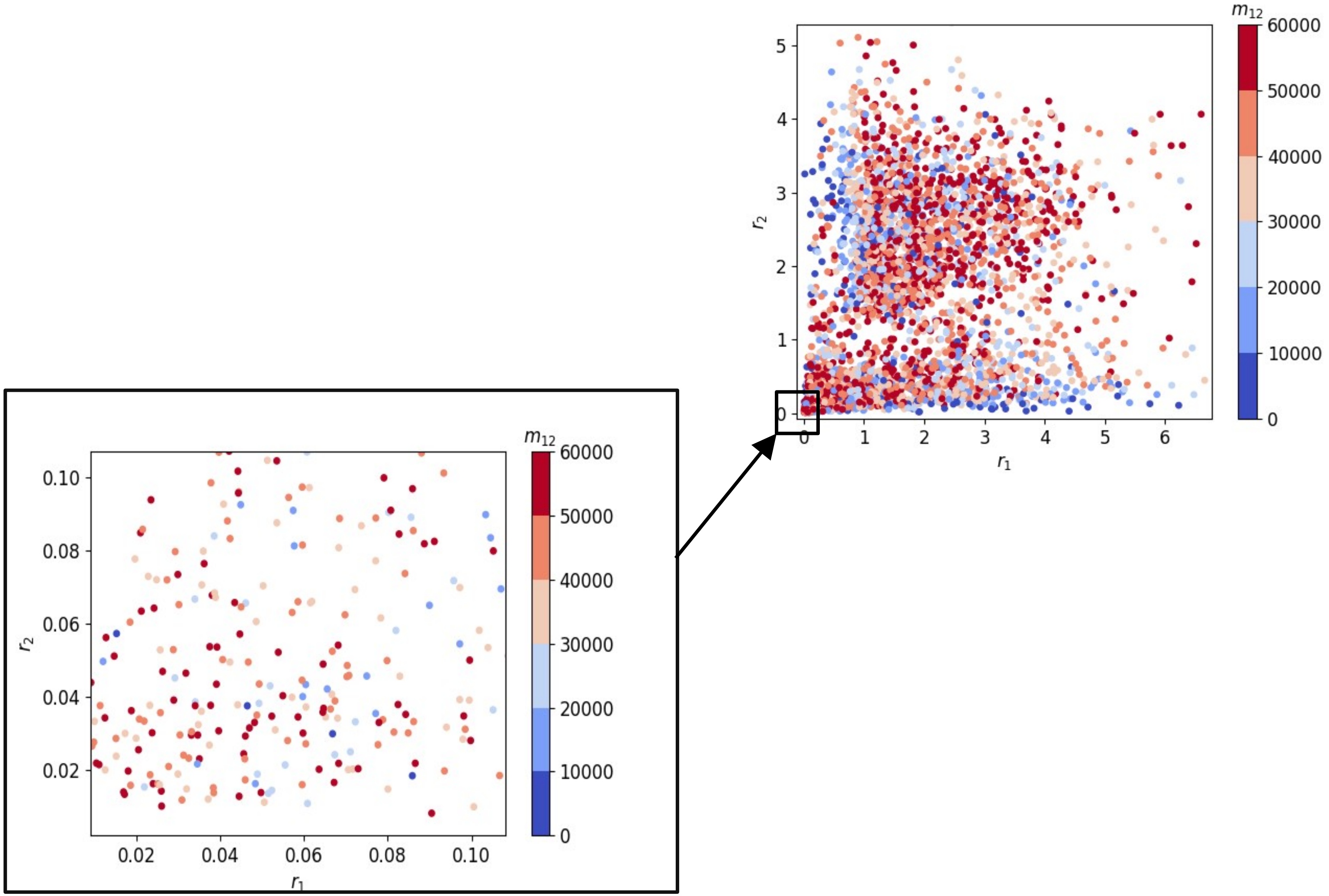
$0.6 < Ch_aVV < 1.0$
$0.6 < Ch_att < 1.2$
$-1 < Rb3 < 1$

tan(beta) = 1.5
200 GeV $< v_s <$ 1500 GeV
0 GeV^2 $< m_{12} <$ 60000 GeV^2

Yukawa type 2

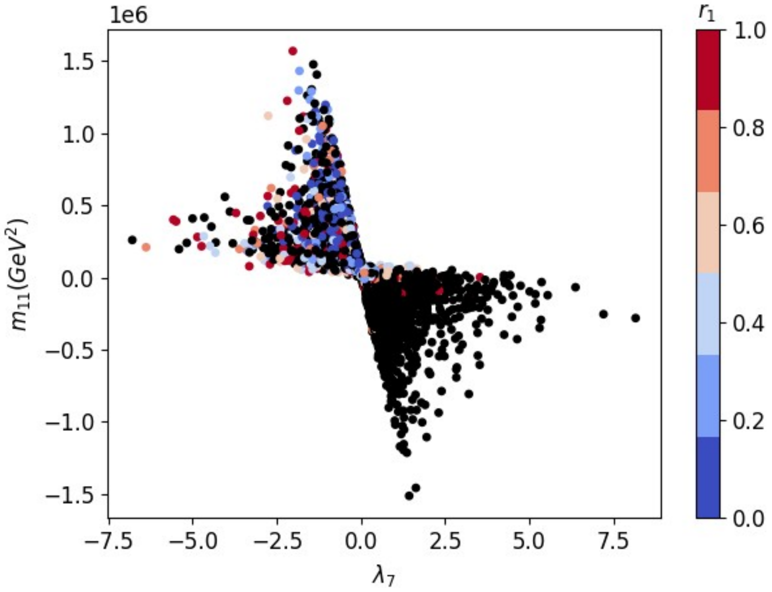
Generate 4000 points satisfying theoretical constraints and then calculate the domain wall profile

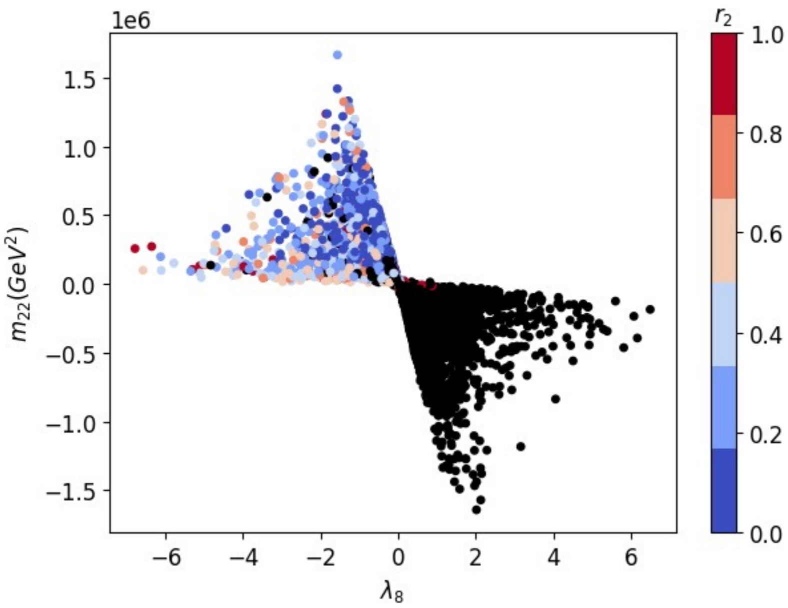
The relevant results are the ratio $r_i = v_i(0)/v_i(\infty)$



$$M_{eff,1} = \frac{m_{11}^2}{2} + \lambda_{345} v_2^2(x) + \frac{\lambda_7}{2} v_s^2(x)$$

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

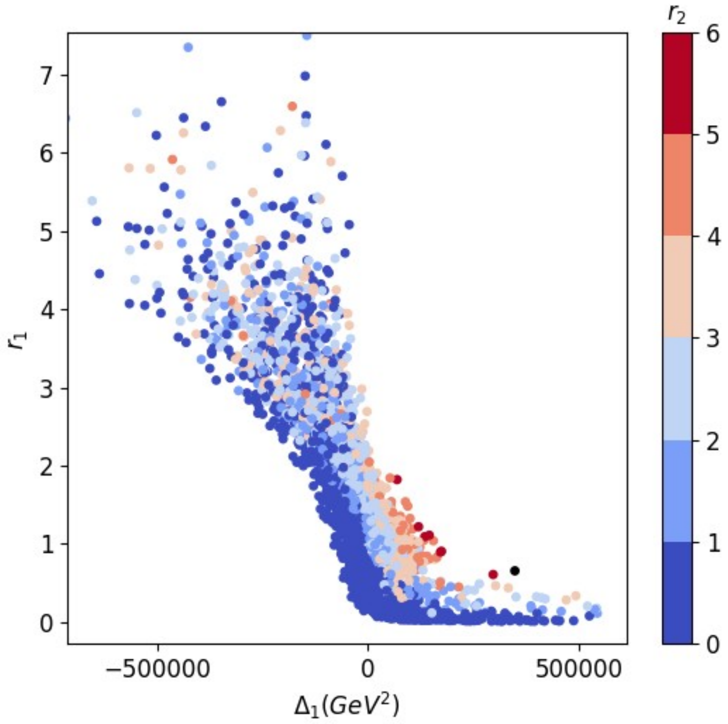


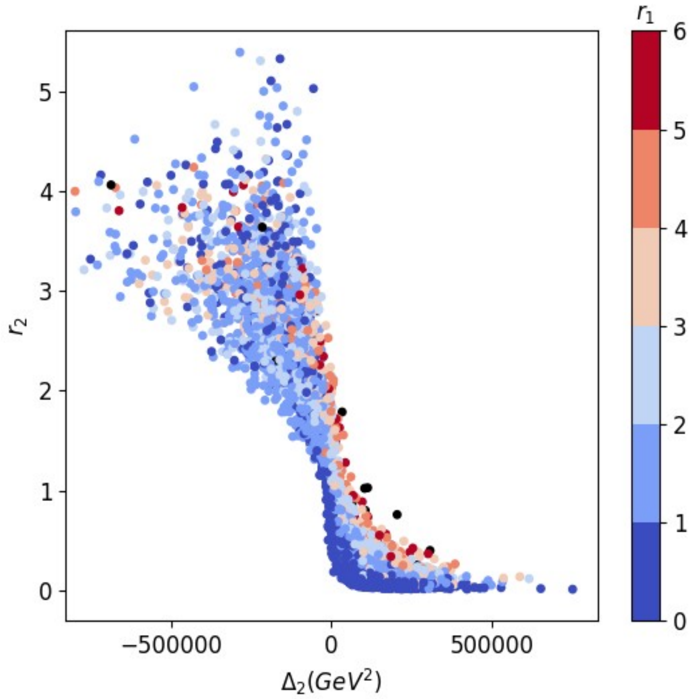


r_i >1 shown in black

$$\Delta_i = M_{eff,i}(x=0) - M_{eff,i}(\pm\infty)$$

Δ_i the difference in the effective mass inside and outside the domain wall.



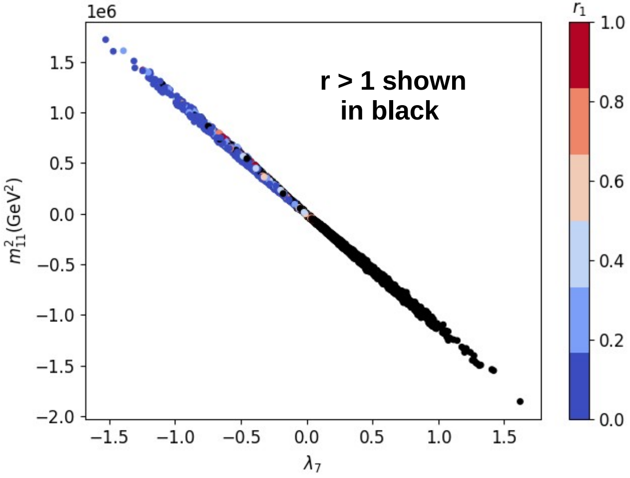


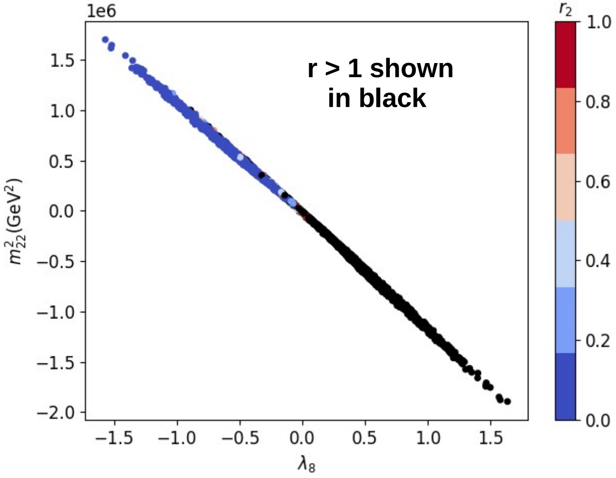
Negative Δ_i "stretches" the potential : the VEVs get bigger inside the wall.
Positive Δ_i "shrinks" the potential : the VEVs become smaller inside the wall

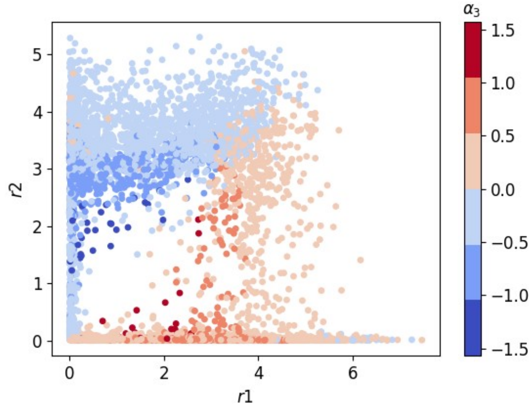
Few parameter points show a different behavior!

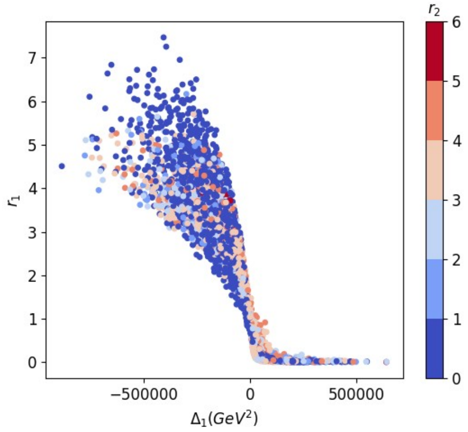
Situation for m_{12} = 0

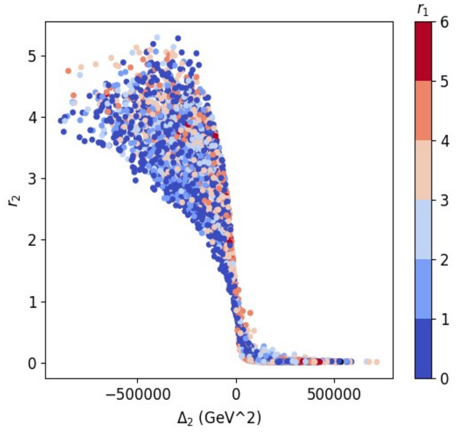
Scan for 5000 points satisfying theoretical constraints with m_{12} = 0.





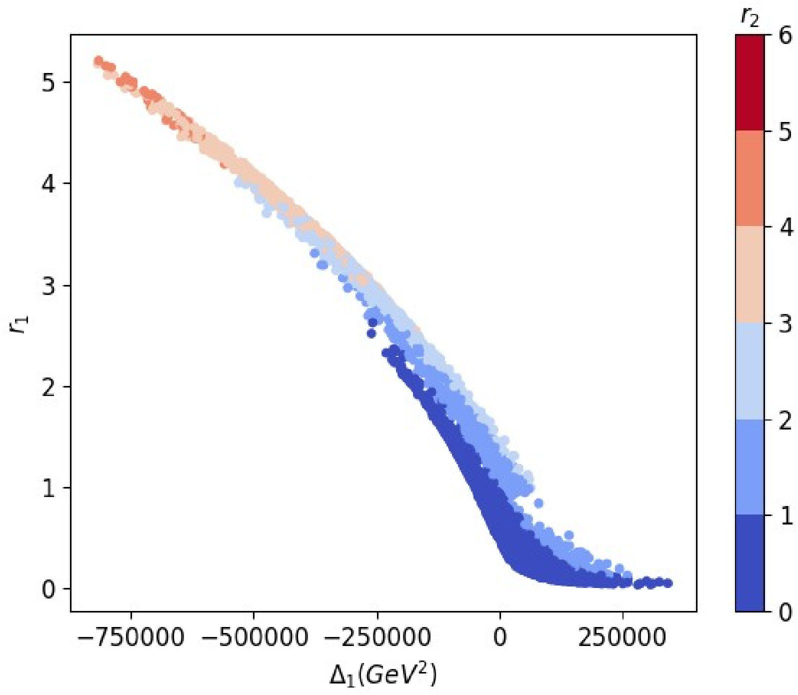


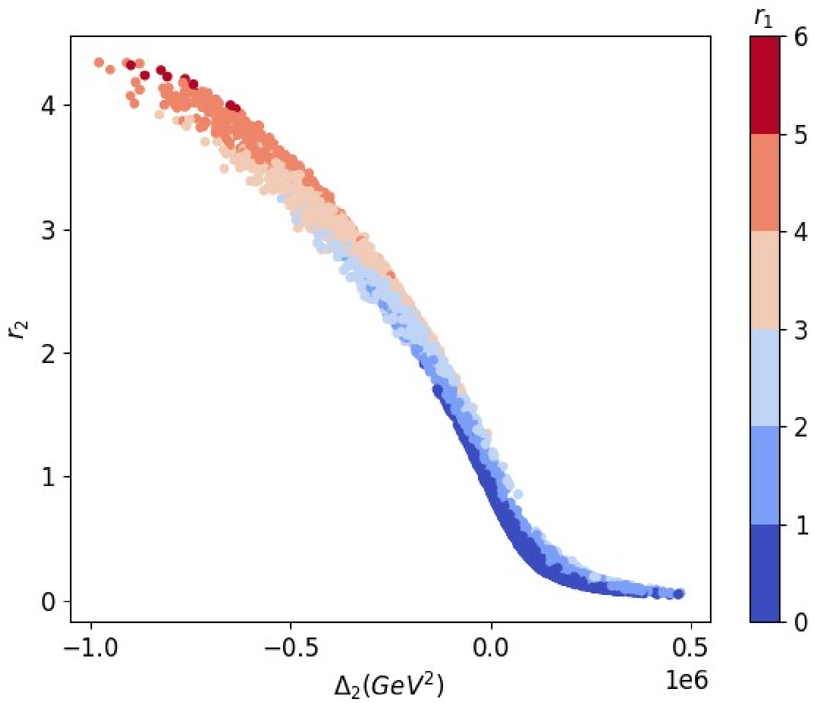




Effect of negative λ_{345}

$$M_{eff,1} = \frac{m_{11}^2}{2} + \lambda_{345} v_2^2(x) + \frac{\lambda_7}{2} v_s^2(x)$$



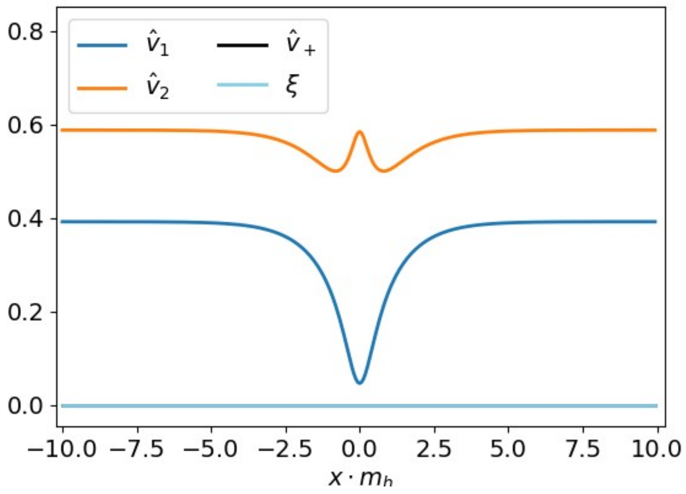


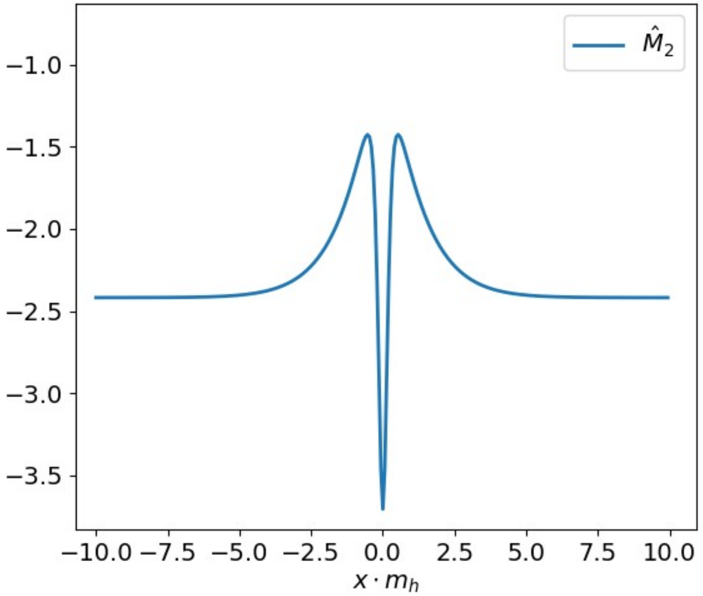
Some parameter points have **$r_i < 0$** even for **$\Delta_i < 0$** (and the opposite).

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!