Domain Walls in The 2HDM and Their Interactions with Standard Model Fermions

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DESY.

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:

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

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

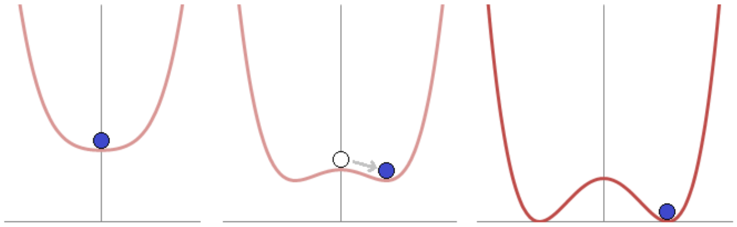


Fig. from wikipedia

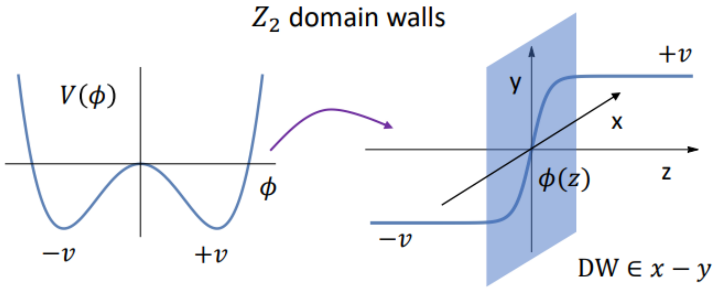


Fig. from Blasi talk

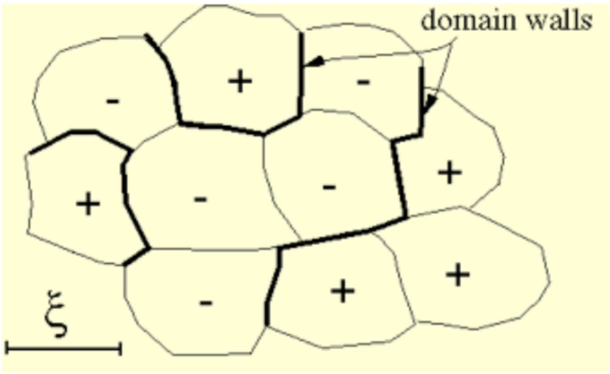


Fig. from https://www.ctc.cam.ac.uk/outreach/origins/cosmic_structures_two.php

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

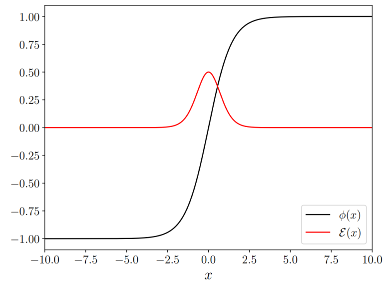
The **space of all cosets G/H** gives the **vacuum manifold of all degenerate vacuas**

$$M = G/H$$

- The vacuum manifold M of the **standard model** is a **3-Sphere**
- M is not **disconnected** and does **not contain holes** :
  No **domain walls or cosmic strings or monopoles** in the standard model.
- **Beyond standard model physics** can have different types of topological defects

But domain walls are problematic in cosmology because their energy "dilutes" slower than matter and radiation and therefore dominates the universe!

$$\rho_{dw} \propto \sigma t^{-1} \qquad \rho_{matter} \propto a^{-3} \qquad \rho_{rad} \propto a^{-4}$$



Leads to **strong bounds** on the energy of domain walls allowed **$\sigma^{1/3}$ < 0.93 MeV** (B. Zel'Dovich, I. Y. Kobzarev, L. B. Okun', Soviet Journal of Experimental and Theoretical Physics 40 (1975) 1)

Domain walls from **approximate discrete symmetries** get **annihilated** and therefore these models are allowed if the annihilation occurs **before** dominating the energy density of the universe.

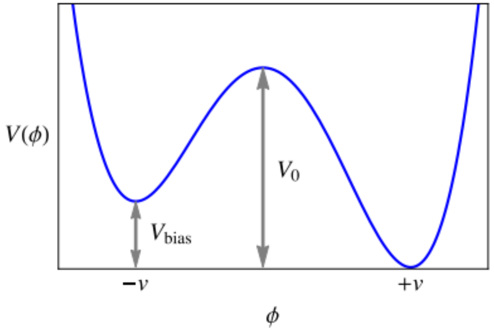


Fig. from 1703.02576

time

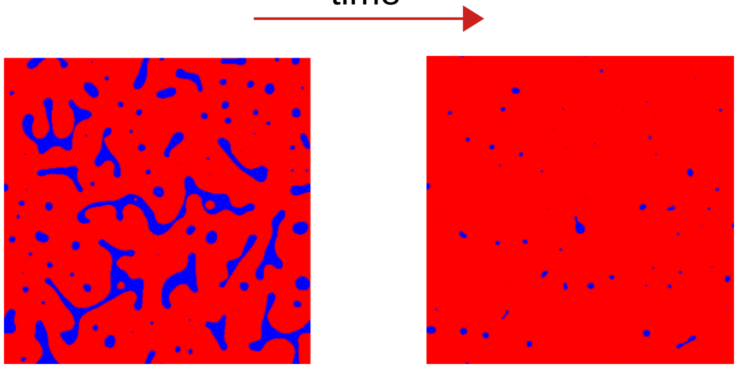
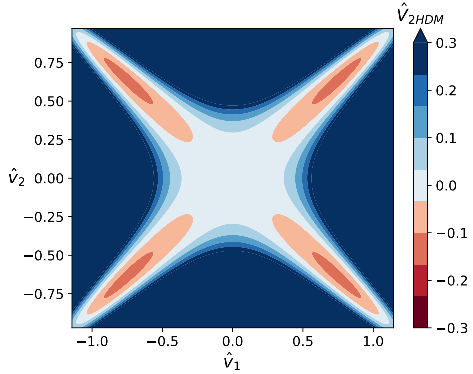
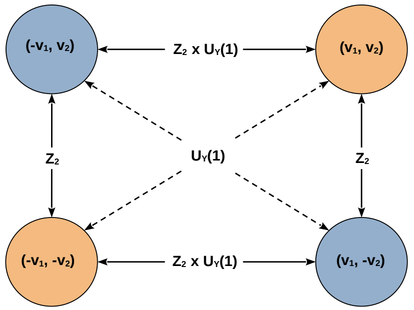


Fig. from Dominic Viatic PhD 2020

Two-Higgs-Doublet Model (2HDM) potential

$$V(\Phi_1,\Phi_2) = m_{11}^2\,|\Phi_1|^2 + m_{22}^2\,|\Phi_2|^2 - m_{12}(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1)$$
$$+\,\frac{\lambda_1}{2}\,|\Phi_1|^4 + \frac{\lambda_2}{2}\,|\Phi_2|^4 + \lambda_3\,|\Phi_1|^2\,|\Phi_2|^2 + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+\,\lambda_5\left[(\Phi_2^\dagger\Phi_1)^2 + (\Phi_2^\dagger\Phi_1)^2\right]$$

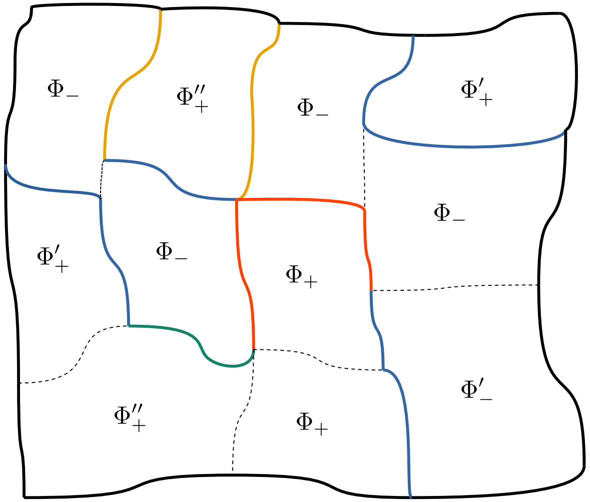




In the following, focus on Z_2 symmetry (softly broken by m^2_{12} term)

In the early universe after SSB, regions that are causally disconnected acquire a random VEV.

Z_2: $\Phi_1 \longrightarrow \Phi_1 \quad , \qquad \Phi_2 \longrightarrow -\Phi_2$



Full symmetry of the model:

$$SU_L(2)\otimes U_Y(1)\otimes Z_2 \longrightarrow U_{em}(1)$$
$$M = SU(2)\otimes Z_2$$ **Two disconnected 3-Spheres**

Possible vacua in the 2HDM

2HDM has 8 scalar degrees of freedom

$$\Phi_i(x) = U(x)\hat{\Phi}_i(x)$$

$$\hat{\Phi}_1(x) = \begin{pmatrix} 0 \\ v_1(x) \end{pmatrix}, \hat{\Phi}_2(x) = \begin{pmatrix} v_+(x) \\ v_2(x)e^{i\xi(x)} \end{pmatrix}$$

$$U(x) = e^{i\theta(x)}\ exp(\frac{ig_i(x)\sigma_i}{2})$$

$$\hat{\Phi}_1 = \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \hat{\Phi}_2 = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

Neutral vacuum

$$\hat{\Phi}_1 = \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \hat{\Phi}_2 = \begin{pmatrix} 0 \\ v_2 e^{i\xi} \end{pmatrix}$$

CP breaking vacuum

$$\hat{\Phi}_1 = \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \hat{\Phi}_2 = \begin{pmatrix} v_+ \\ v_2 \end{pmatrix}$$

Charge breaking vacuum

Here we only consider neutral vacua at the boundaries and take the general Vacuum Parametrization at each point in x (***possibility of getting CP and/or Charge violation inside the domain wall)***

$$\Phi_1(\pm\infty) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1^0 \end{pmatrix}, \qquad \Phi_2(\pm\infty) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \pm v_2^0 \end{pmatrix}$$

How to get domain wall solution ?

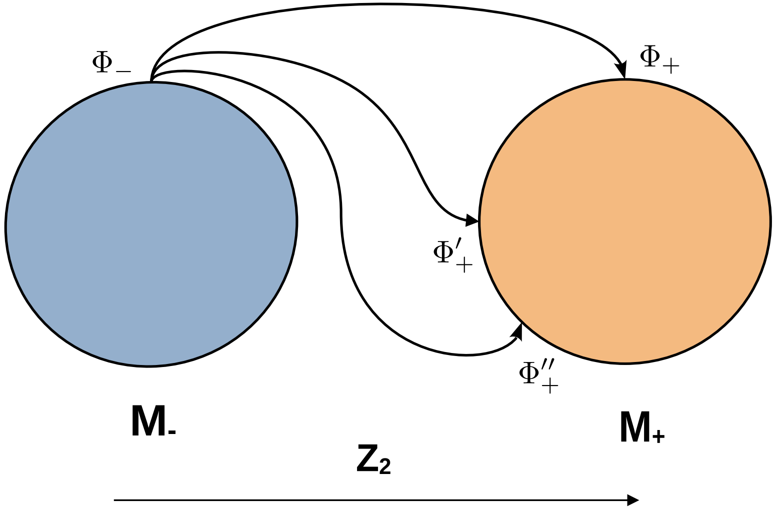
1) Choice of vacua at both domains

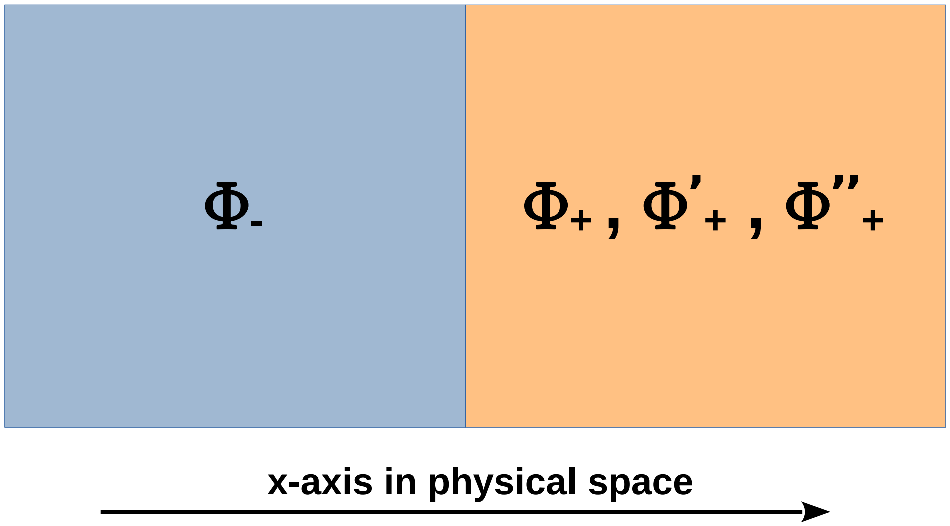
$$\Phi_- = \left[\Phi_1 = \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \Phi_2 = \begin{pmatrix} 0 \\ -v_2 \end{pmatrix}\right]$$

$$\Phi_+ = \left[\Phi_1 = \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \Phi_2 = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}\right]$$

$$\Phi'_+ = \mathrm{U}\Phi_+ \qquad \Phi''_+ = \mathrm{U}'\Phi_+$$

U and U' are elements of $SU_L(2)xU_Y(1)$





Electroweak gauge rotated vacua related by Z_2 symmetry will have different types of domain walls!

2) Minimize the energy functional of the vacuum configuration Φ(x)

$$E = \int dx \ \mathcal{E}(x), \qquad \mathcal{E}(x) = \frac{d\Phi_i}{dx}\frac{d\Phi_i^\dagger}{dx} + V(\Phi_1, \Phi_2)$$

$$\Phi_i(x) = U(x)\hat{\Phi}_i(x) \qquad U = e^{i\theta(x)} \ exp(\frac{ig_i(x)\sigma_i}{2})$$

$$\mathcal{E}(x) = \frac{d\tilde{\Phi}_1^\dagger}{dx}\frac{d\tilde{\Phi}_1}{dx} + \frac{d\tilde{\Phi}_2^\dagger}{dx}\frac{d\tilde{\Phi}_2}{dx} + \left(\frac{d\tilde{\Phi}_{1,2}^\dagger}{dx}U^\dagger(x)\frac{dU}{dx}\tilde{\Phi}_{1,2}(x) + \text{h.c}\right) + \tilde{\Phi}_{1,2}^\dagger(x)\frac{dU^\dagger}{dx}\frac{dU}{dx}\tilde{\Phi}_{1,2}(x)$$
$$+ V_{2HDM}(\Phi_1, \Phi_2)$$

Minimization of E yields the **equation of motion for static fields** (analogous to minimizing the action)

$$\frac{d}{dx}\left(\frac{\partial \mathcal{E}}{\partial\left(d\phi_n/dx\right)}\right) - \frac{\partial \mathcal{E}}{\partial \phi_n} = 0$$

Solve numerically using **Gradient flow method**

Richard A. Battye, Gary D. Brawn, Apostolos Pilaftsis (1106.3482) JHEP
Richard A. Battye, Apostolos Pilaftsis, Dominic G. Viatic (2006.13273) JHEP
Apostolos Pilaftsis, Kai Hong Law (2110.12550), Phys.Rev.D

Simplest case : Standard Domain Walls Solution

$$\Phi_- = \left\{ \Phi_1 = \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \Phi_2 = \begin{pmatrix} 0 \\ -v_2 \end{pmatrix} \right\} \qquad \Phi_+ = \left\{ \Phi_1 = \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \Phi_2 = \begin{pmatrix} 0 \\ v_2 \end{pmatrix} \right\} \qquad \mathrm{U}(x) = \text{constant}$$

To get the domain wall solution, minimize the energy functional of the field configuration:

$$E = \int dx\ \mathcal{E}(x), \qquad \mathcal{E}(x) = \frac{d\Phi_i}{dx}\frac{d\Phi_i^\dagger}{dx} + V(\Phi_1, \Phi_2)$$

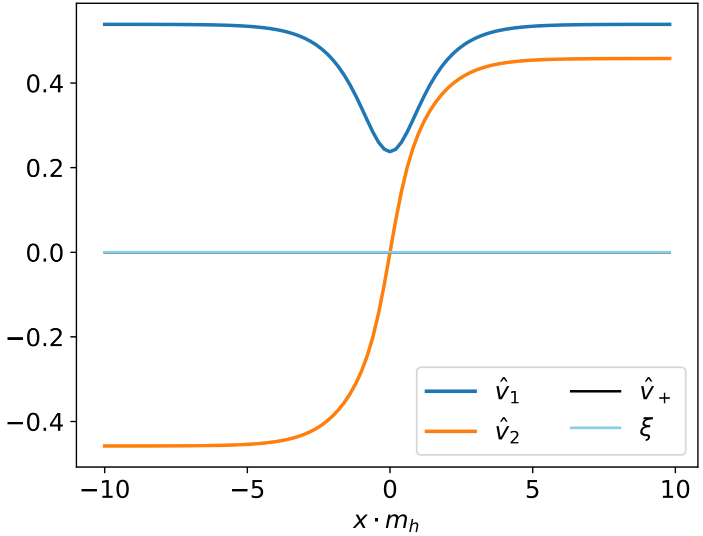
$$\mathcal{E}(x) = \frac{1}{2}(\frac{dv_1}{dx})^2 + \frac{1}{2}(\frac{dv_2}{dx})^2 + \frac{1}{2}(\frac{dv_+}{dx})^2 + \frac{1}{2}v_2^2(x)(\frac{d\xi}{dx})^2 + V_{2hdm}$$

"Equations of motion" for the vacua:

$$\frac{d^2v_1}{dx^2} - \frac{dV_{2hdm}}{dv_1} = 0 \qquad \frac{d^2v_2}{dx^2} - \frac{dV_{2hdm}}{dv_2} = 0 \qquad \frac{d^2v_+}{dx^2} - \frac{dV_{2hdm}}{dv_+} = 0$$

$$\mathrm{v}_2^2(x)\frac{d^2\xi}{dx^2} + 2v_2\frac{dv_2}{dx}\frac{d\xi}{dx} - \frac{dV_{2hdm}}{d\xi} = 0$$

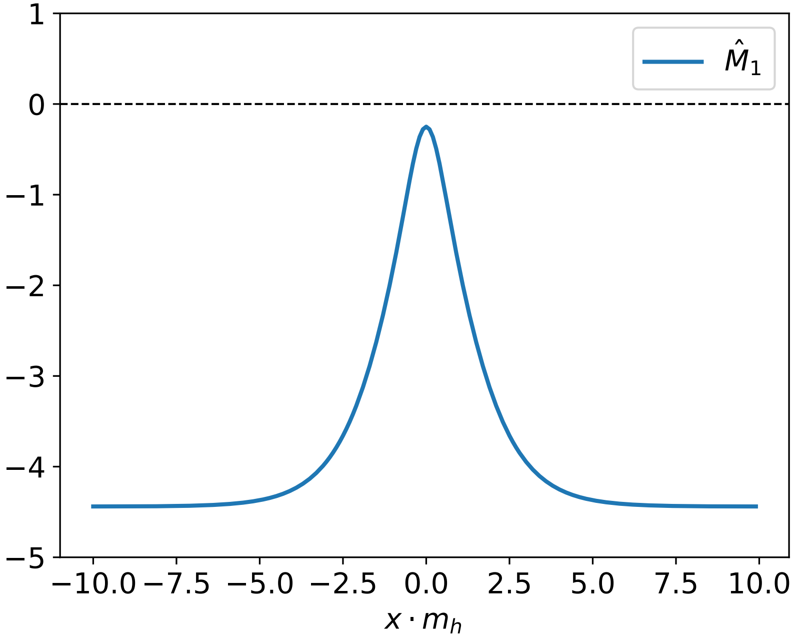
$$\hat{v}_i = v_i/v_{sm}$$



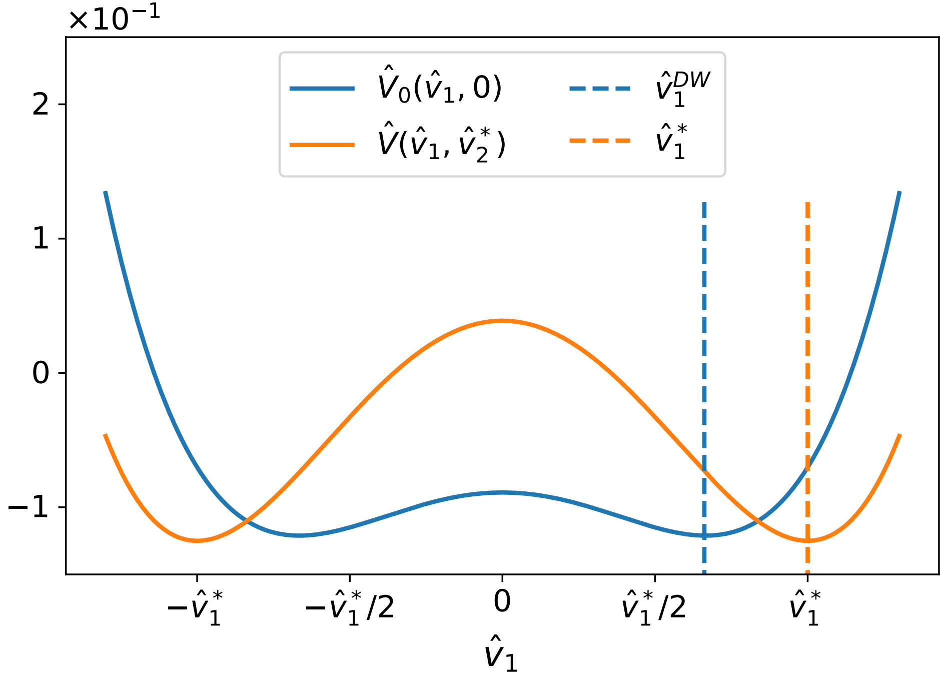
Explaining the behavior of $v_1(x)$

Calculate the **effective mass** term for $v_1(x)$:

$$M_{eff1} = \frac{1}{2}m_{11}^2 + \frac{1}{4}\left[(\lambda_3+\lambda_4)v_2^2(x) + \lambda_3 v_+^2(x) + \lambda_5 v_2^2(x)\cos(2\xi(x))\right]$$



Becomes **bigger (<u>less negative</u>)** **inside** the domain wall !



Leads **$v_1(0)$ getting a smaller value** **inside** the domain wall

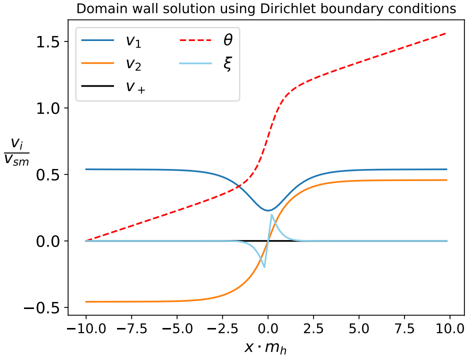
Case when θ(x) is non-constant :

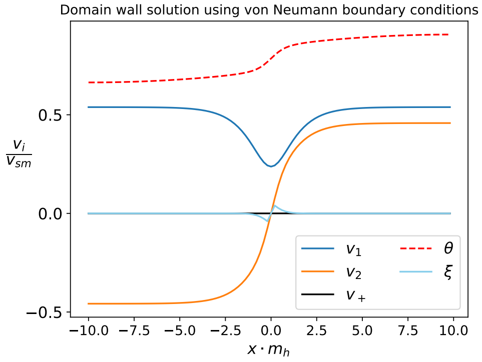
$$\Phi_- = \left\{ \Phi_1 = \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \Phi_2 = \begin{pmatrix} 0 \\ -v_2 \end{pmatrix} \right\}$$

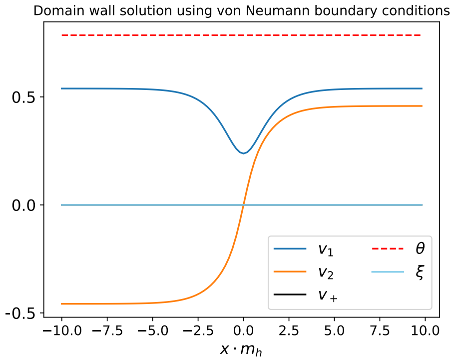
$$\Phi'_+ = \left\{ \Phi_1 = e^{i\theta} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \Phi_2 = e^{i\theta} \begin{pmatrix} 0 \\ v_2 \end{pmatrix} \right\}$$

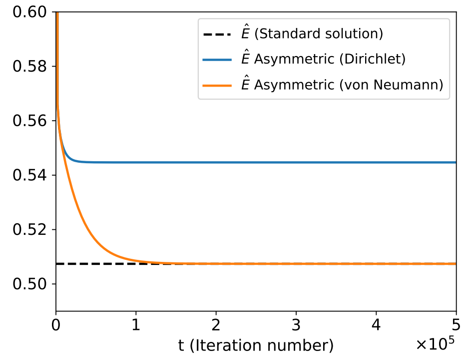
Kinetic part of $\mathcal{E}(\mathbf{x})$ is now dependent on θ:

$$\mathcal{E}(x) = \frac{1}{2}(\frac{dv_1}{dx})^2 + \frac{1}{2}(\frac{dv_2}{dx})^2 + \frac{1}{2}(\frac{dv_+}{dx})^2 + \frac{1}{2}v_2^2(x)\left(\frac{d\xi}{dx}\right)^2 + \frac{1}{2}v_1^2(x)(\frac{d\theta}{dx})^2 + \frac{1}{2}v_2^2(x)\left((\frac{d\theta}{dx})^2 + 2\frac{d\theta}{dx}\frac{d\xi}{dx}\right) + \frac{1}{2}v_+^2(x)(\frac{d\theta}{dx})^2 + V_{2hdm}(v_1, v_2, v_+, \xi)$$









This leads to the **phase ξ(x)** between the two doublets being **non zero inside** the domain wall.

CP violation inside the domain wall

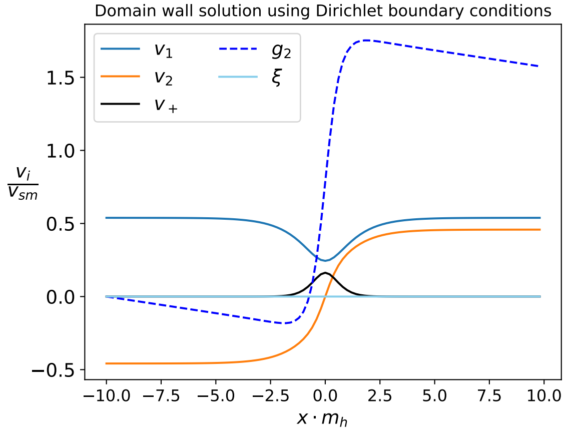
This CP-violation inside the wall is unstable and after some time we end up with the standard domain wall solution

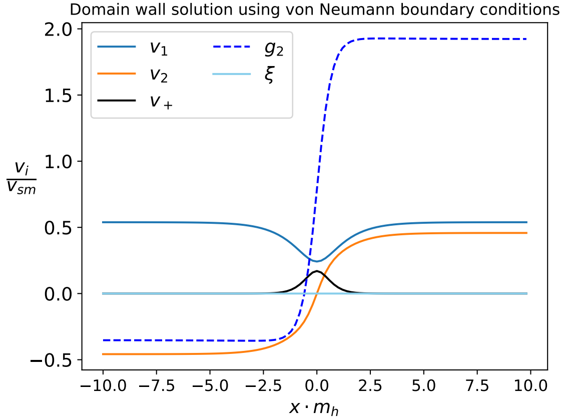
Case when $g_2(x)$ is non-constant :

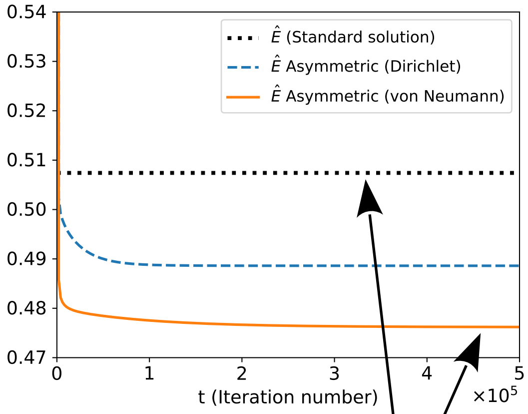
$$U(x) = \exp\left(\frac{i g_2(x) \sigma_2}{2}\right)$$

As an example take

$$g_2(x) = \left\{ \begin{array}{l} 0 \text{ at } -\infty \\ \frac{\pi}{2} \text{ at } +\infty \end{array} \right\}$$







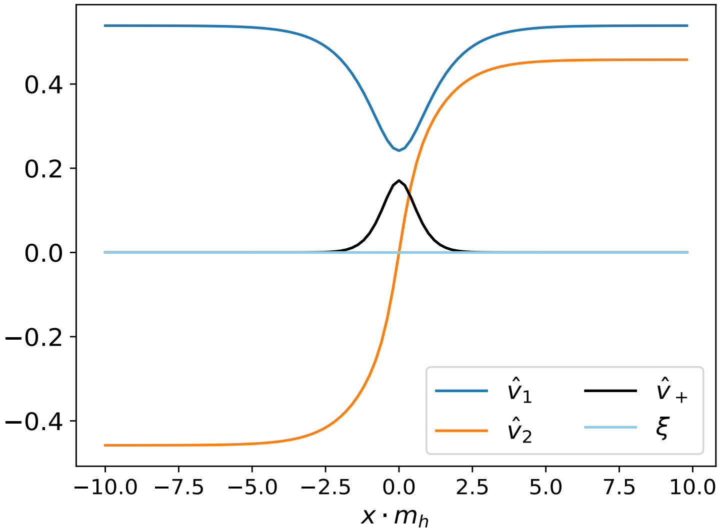
$v_+(x) \neq 0$ **inside** the domain wall.

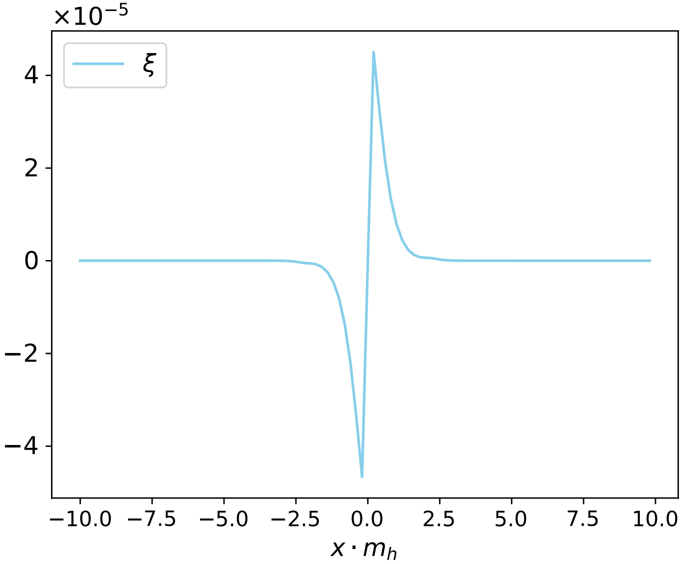
This leads to charge breaking effects and a massive photon inside the domain wall.

Energy of **charge breaking vacuum configuration lower** than the energy of the **standard configuration**.

Charge violation is stable

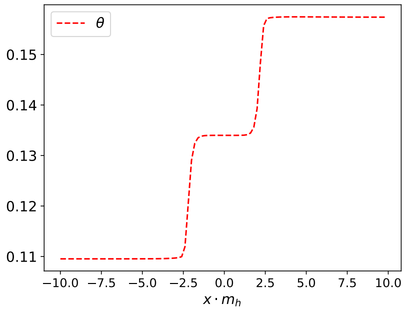
Random values for Goldstone and hypercharge modes

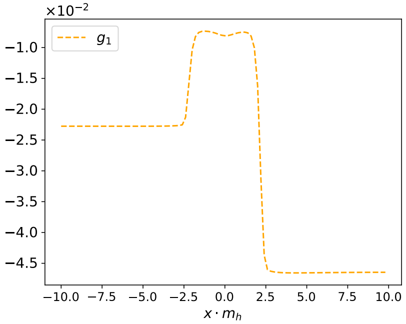


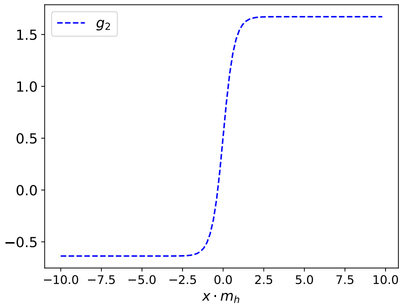


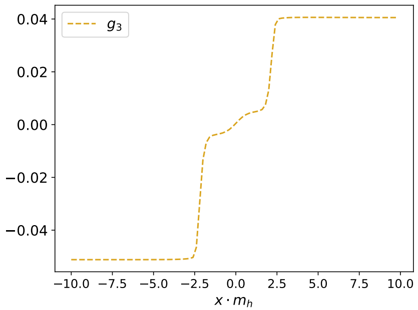
Charge violating vacuum inside the wall

CP-violating vacuum inside the wall









Fermion Scattering off Domain Walls

(Example for type-2 2HDM for up type quarks)

$$\mathcal{L}_{fermion} = i\bar{Q}_L(\gamma^\mu D_\mu)Q_L + i\bar{u}_R(\gamma^\mu D_\mu)u_R + i\bar{d}_R(\gamma^\mu D_\mu)d_R$$
$$- y_2\bar{Q}_L U(x)\begin{pmatrix} v_+(x) \\ v_2(x)e^{i\xi(x)} \end{pmatrix} u_R - y_1\bar{Q}_L U(x)\begin{pmatrix} 0 \\ v_1(x) \end{pmatrix} d_R + h.c$$

$$U = e^{i\theta(x)}\ exp(\frac{i\gamma_i(x)\sigma_i}{2})$$

Solve the Dirac equation in the background of a scalar field domain wall, the mass terms are then x-dependent!

Perform the gauge transformation to get rid of U(x) in the Yukawa sector:

$$\Phi_1(x) \to U^{-1}(x)\Phi_1(x) = \begin{pmatrix} 0 \\ v_1(x) \end{pmatrix}$$

$$\Phi_2(x) \to U^{-1}(x)\Phi_2(x) = \begin{pmatrix} v_+(x) \\ v_2(x)e^{i\xi(x)} \end{pmatrix}$$

But at the cost of having “pure gauge” gauge fields

$$G_\mu \to G_\mu + \frac{i}{g}U^{-1}(x)\partial_\mu U(x)$$

Gauge fields B^μ, W^μ_i living inside the domain walls

Dirac Equations :

$$i\Big(\gamma^\mu\partial_\mu + iY_L\gamma^\mu\partial_\mu\theta(x)\Big)u_L - y_2 v_2(x)e^{i\xi(x)}u_R = 0$$
$$i\Big(\gamma^\mu\partial_\mu + iY_R\gamma^\mu\partial_\mu\theta(x)\Big)u_R - y_2 v_2(x)e^{-i\xi(x)}u_L = 0$$

CP-Violating case

$$i\not\partial d + \frac{i}{2}(\not\partial_x g_2(x))P_L u - y_d v_1(x)d + y_u v_+(x)P_R u = 0$$
$$i\not\partial u - \frac{i}{2}(\not\partial_x g_2(x))P_L d - y_u v_2(x)u + y_u v_+(x)P_L d = 0$$

Charge-Violating case

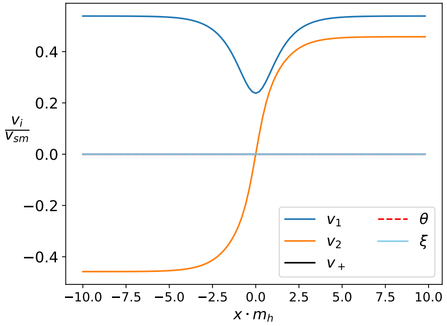
Standard Domain Walls (no CP or Charge violation in the VEV)

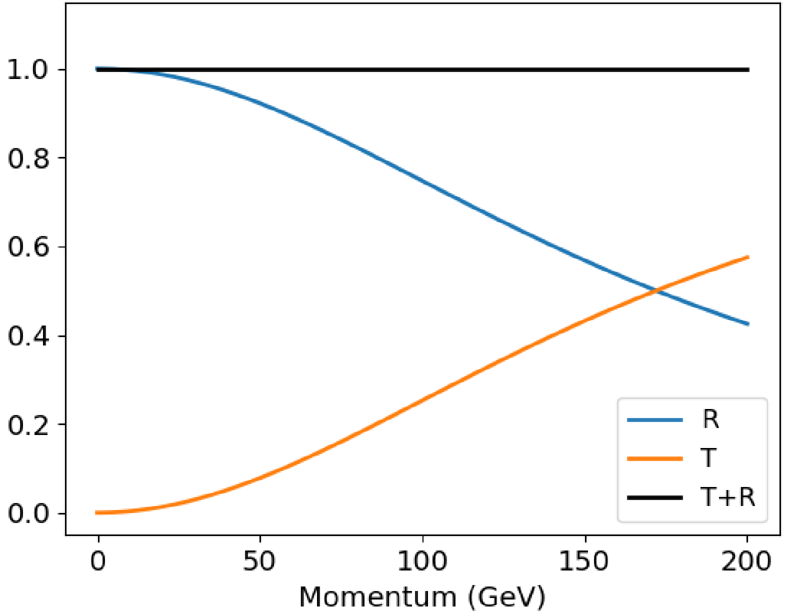
Dirac equation: $i\gamma^{\mu}\partial_{\mu}u - y_2 v_2(x)u = 0$

Take ansatz of a **plane wave solution**

$$u_-(x) = \begin{pmatrix} u_1^r \\ u_2^r \\ u_3^r \\ u_4^r \end{pmatrix} e^{ipx} + u_{inc}e^{-ipx} \qquad u_+(x) = \begin{pmatrix} u_1^t \\ u_2^t \\ u_3^t \\ u_4^t \end{pmatrix} e^{-ipx}$$

Solve the Dirac equation **away from the wall** for x>0 and x<0 then **match the two solutions in both regions at x = 0**, using the **continuity** of the wave function at x=0

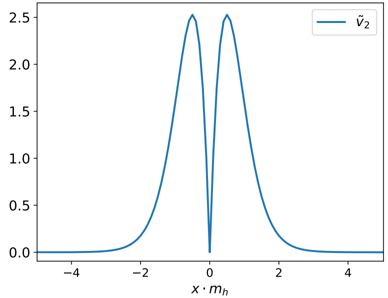




$$R = \frac{m^2}{E^2} \qquad T = \frac{p^2}{E^2}$$

Nearly all non relativistic particles get reflected off the domain wall.
Particle **trapping** in pockets of **false vacuum regions** ?
Evolution of light domain walls interacting with dark matter **Phys. Rev. D 43, 346 (1990)**

Case with CP violation



In the thin wall approximation :

$$\partial_\mu \theta(x) = \Delta\theta\delta(x)$$

$$v_2(x)e^{i\xi(x)} \simeq v_2(x) + iv_2(x)\xi(x)$$
$$= v_2(x) + i(\tilde{v}_2\delta(x-\epsilon) + \tilde{v}_2\delta(x+\epsilon))$$

Presence of delta-distribution leads to **discontinuity** of the **wave function** at **x = 0**

- Dirac equation can be written as :

$$\partial_x u(x) = \Big[-i\gamma_1\partial_x\theta(x)(Y_L P_L + Y_R P_R) + i\gamma_1 m_{re}(x) - m_{im}(x)\gamma_1\gamma_5 \Big] u(x) =: \hat{G}(x)u(x)$$

- Matching both solutions at x>0 and x<0 requires integrating the Dirac equation between -ϵ and ϵ

$$u(\epsilon) = \hat{P}\ \ exp\left(\int_{-\epsilon}^{\epsilon} dx'\hat{G}(x')\right)u(-\epsilon)$$

$$u(\epsilon) = exp(-\frac{i\Delta\theta}{2}(Y_L + Y_R))\left(cosh(a)\mathbf{\hat{1}} - \frac{sinh(a)}{a}\mathbf{\hat{A}}\right)u(-\epsilon)$$

$$\hat{A} = \begin{pmatrix} 0 & 2\tilde{v}_2 & i\frac{\Delta\theta(Y_R - Y_L)}{2} & 0 \\ 2\tilde{v}_2 & 0 & 0 & i\frac{\Delta\theta(Y_R - Y_L)}{2} \\ i\frac{\Delta\theta(Y_R - Y_L)}{2} & 0 & 0 & -2\tilde{v}_2 \\ 0 & i\frac{\Delta\theta(Y_R - Y_L)}{2} & -2\tilde{v}_2 & 0 \end{pmatrix}$$

$$a = \sqrt{4\tilde{v}_2^2 - \frac{\Delta\theta^2(Y_R - Y_L)^2}{4}}$$

$$a_1 = 2\tilde{v}_2$$

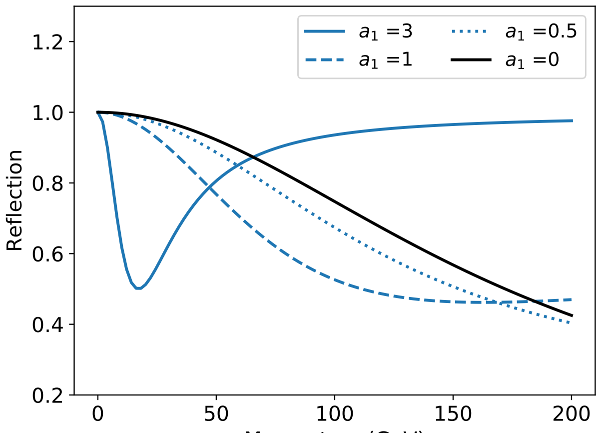
$$b_2 = \Delta\theta(Y_R - Y_L)$$

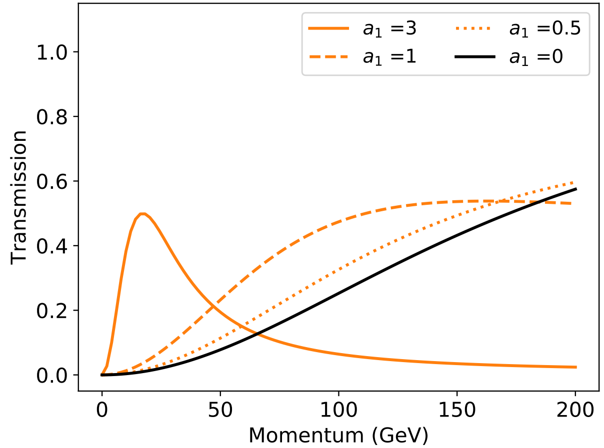
$$a_1 = 2\tilde{v}_2 \qquad b_2 = \Delta\theta(Y_R - Y_L)$$

For $a_1 \gg b_2$

$$\hat{\mathrm{R}}(\mathrm{p}) = \frac{4m_u^2E^2 + p^4(\cosh^2(2a_1) - 1)}{[(E^2 + m_u^2) + p^2\cosh(2a_1)]^2}$$

$$\hat{\mathrm{T}}(\mathrm{p}) = \frac{2p^2(p^2 + (E^2 + m^2)\cosh(2a_1))}{[(E^2 + m_u^2) + p^2\cosh(2a_1)]^2}$$

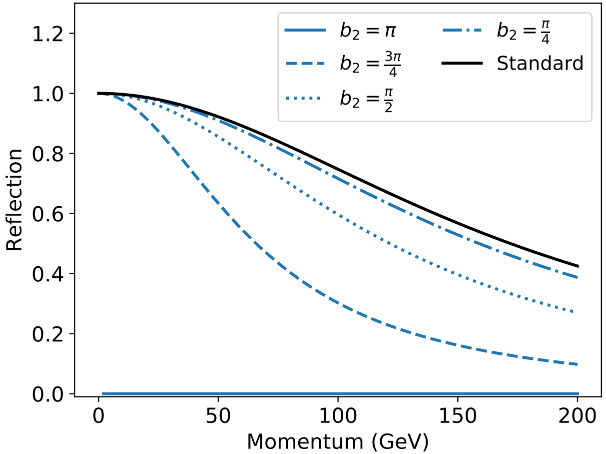


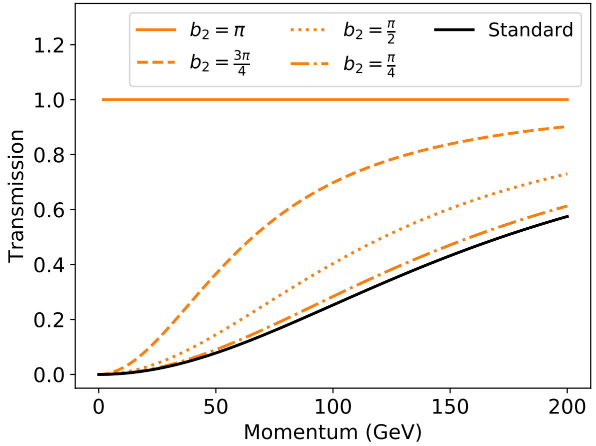


For $b_2 \gg a_1$

$$\hat{\mathrm{R}}(\mathrm{p}) = \frac{2m_u^2\cos^2(\frac{b_2}{2})}{m_u^2 + 2p^2 + m_u^2\cos(b_2)}$$

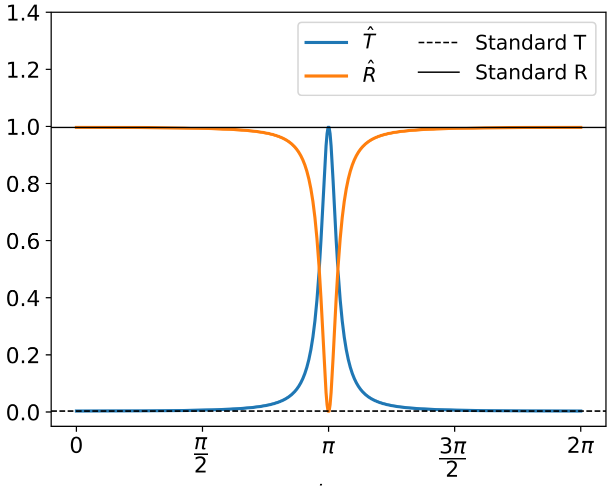
$$\hat{\mathrm{T}}(\mathrm{p}) = \frac{2p^2}{m_u^2 + 2p^2 + m_u^2\cos(b_2)}$$



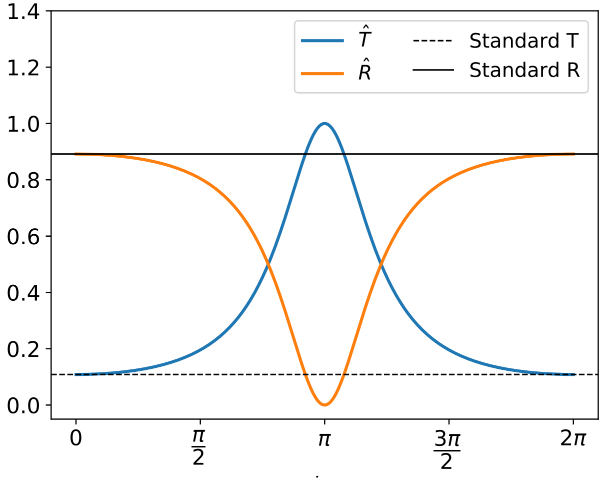


Transmission and reflection rates for top quarks (m=172 GeV) as a function of b_2 for a fixed momentum.

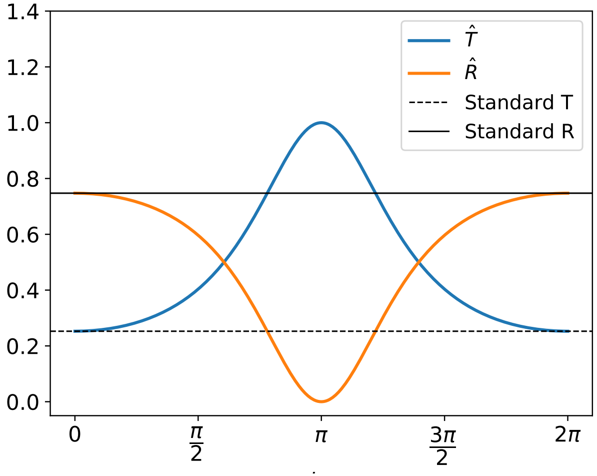
p = 10 GeV

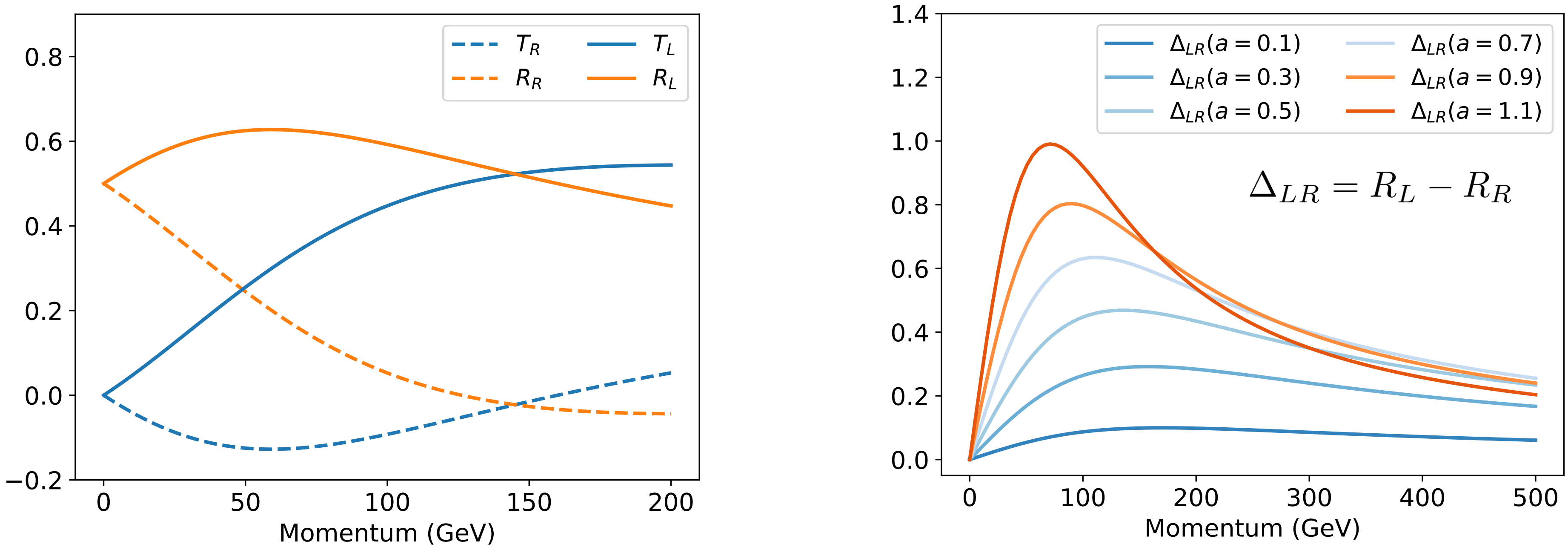


p = 60 GeV



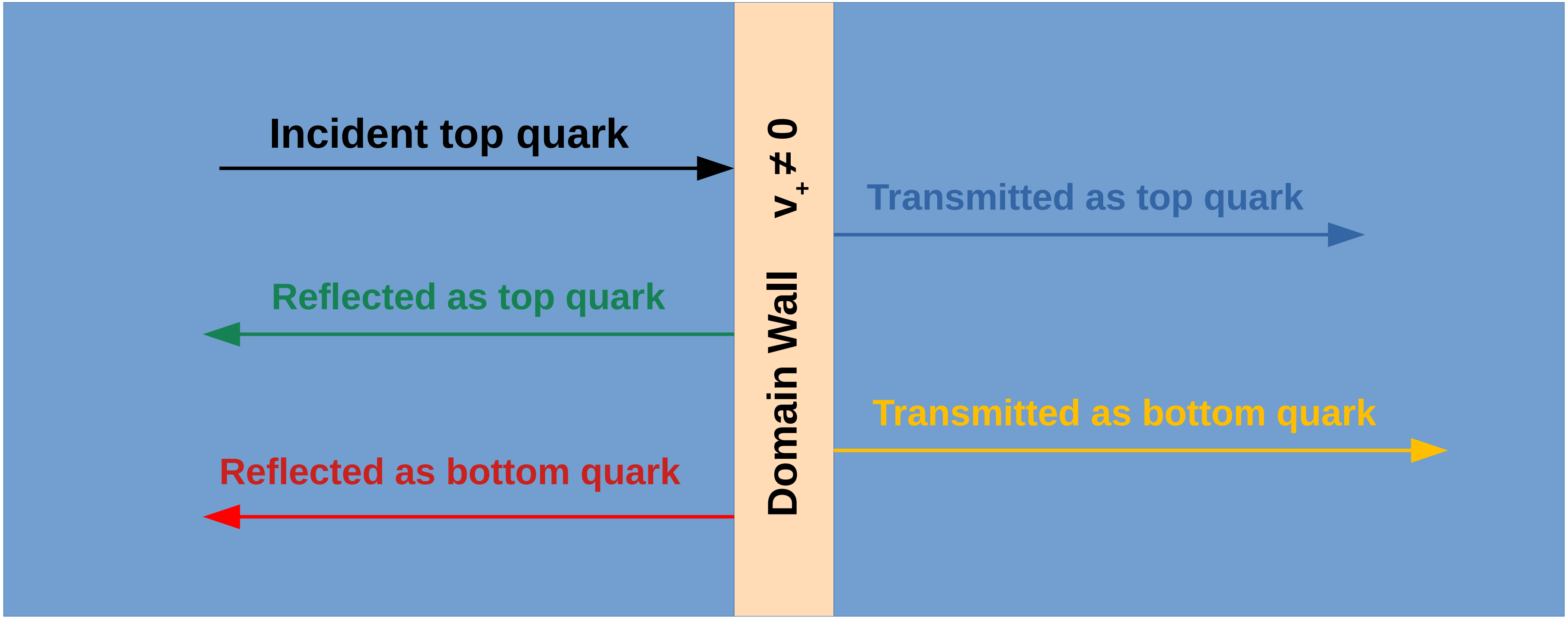
p = 100 GeV





Right and left handed particles get reflected and transmitted with a different rate!

Case with charge violation ($v_+ \neq 0$)



The charge gets carried by the gauge bosons living inside the domain wall

Similar work done for **$SU(5)xZ_2$ Domain Walls** D.A.Steer, T.Vachaspati [0602130]

Case with charge violation ($v_+ \neq 0$)

Take example of charge violation due to $g_2(x)$

$$\Phi_1(x) = \frac{U(x)}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1(x) \end{pmatrix}, \qquad \Phi_2(x) = \frac{U(x)}{\sqrt{2}} \begin{pmatrix} v_+(x) \\ v_2(x) e^{i\xi(x)} \end{pmatrix} \qquad U(x) = \begin{pmatrix} cos(g_2(x)) & sin(g_2(x)) \\ -sin(g_2(x)) & cos(g_2(x)) \end{pmatrix}$$

Use a **gauge transformation** to remove the matrix U(x) from the Yukawa sector

Dirac equations:

$$i\partial\!\!\!/ d + \frac{i}{2}(\partial\!\!\!/_x g_2(x))P_L u - y_d v_1(x) d + y_u v_+(x) P_R u = 0$$
$$i\partial\!\!\!/ u - \frac{i}{2}(\partial\!\!\!/_x g_2(x))P_L d - y_u v_2(x) u + y_u v_+(x) P_L d = 0$$

Solve this equation for x far away from the domain wall in both regions

for x>0 :

$$i\partial\!\!\!/ d - y_d v_1 d = 0$$
$$i\partial\!\!\!/ u + y_u v_2 u = 0$$

for x<0 :

$$i\partial\!\!\!/ d - y_d v_1 d = 0$$
$$i\partial\!\!\!/ u - y_u v_2 u = 0$$

Rewrite in this form

$$\partial_x \begin{pmatrix} u(x) \\ d(x) \end{pmatrix} = \hat{G}(x) \begin{pmatrix} u(x) \\ d(x) \end{pmatrix} = \begin{pmatrix} -iE\gamma_1\gamma_0 + i\gamma_1 m_u(x) & i\gamma_1 \hat{G}_2(x) \\ i\gamma_1 \hat{G}_1(x) & iE\gamma_1\gamma_0 + i\gamma_1 m_d(x) \end{pmatrix} \begin{pmatrix} u(x) \\ d(x) \end{pmatrix}$$

$$G_1(x) = -\frac{i}{2}(\partial\!\!\!/_x g_2(x))P_L - y_u v_+(x) P_R,$$
$$G_2(x) = \frac{i}{2}(\partial\!\!\!/_x g_2(x))P_L - y_u v_+(x) P_L.$$

Matching condition for x>0 and x<0 :

$$\begin{pmatrix} u(+\epsilon) \\ d(+\epsilon) \end{pmatrix} = \hat{P} \exp\left(\int_{-\epsilon}^{+\epsilon} dx \;\; \hat{G}(x) \right) \begin{pmatrix} u(-\epsilon) \\ d(-\epsilon) \end{pmatrix} \dashrightarrow \begin{pmatrix} u(+\epsilon) \\ d(+\epsilon) \end{pmatrix} = \begin{pmatrix} M_1 & M_2 \\ M_3 & M_4 \end{pmatrix} \begin{pmatrix} u(-\epsilon) \\ d(-\epsilon) \end{pmatrix}$$

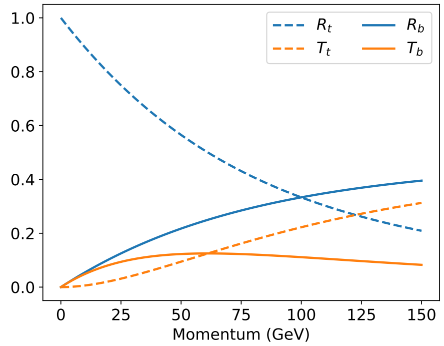
Distinguish two cases:

Yukawa term dominant $\mathbf{k = \frac{yv_+}{1GeV} >> m = \Delta g_2/2}$

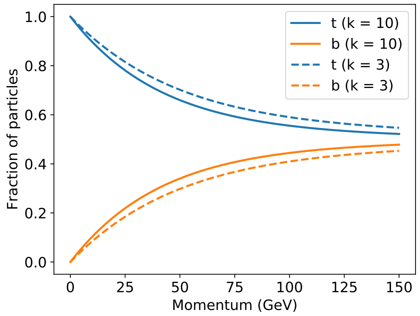
$$i\gamma_1 \partial_x d - y_d v_1(x) d + y_u v_+(x) P_R u = 0$$

$$i\gamma_1 \partial_x u - y_u v_2(x) u + y_u v_+(x) P_L d = 0$$

Reflection and transmission coefficients



Fraction of particles after interaction with the domain walls

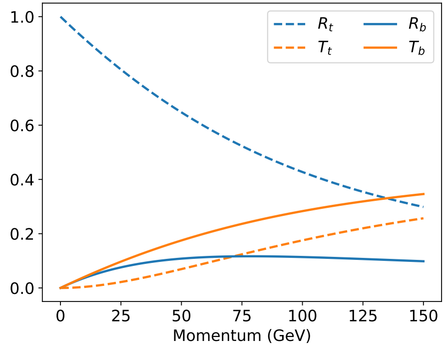


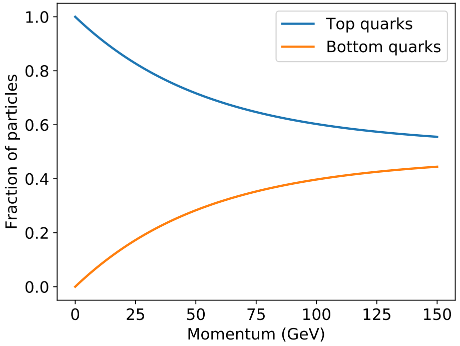
Gauge term dominant $\mathbf{k = \frac{yv_+}{1GeV} << m = \Delta g_2/2}$

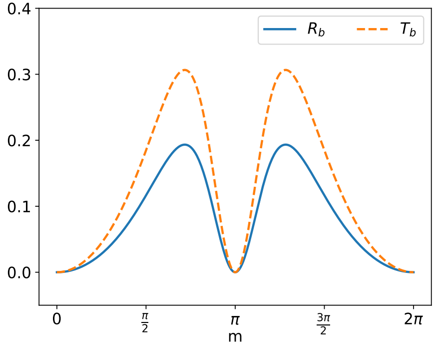
$$i\gamma_1 \partial_x d + \frac{i}{2}\big(\gamma_1 \partial_x g_2(x)\big) P_L u - y_d v_1(x) d = 0$$

$$i\gamma_1 \partial_x u - \frac{i}{2}\big(\gamma_1 \partial_x g_2(x)\big) P_L d - y_u v_2(x) u = 0$$

In this case the transmission as down-type quarks gets higher with energy.

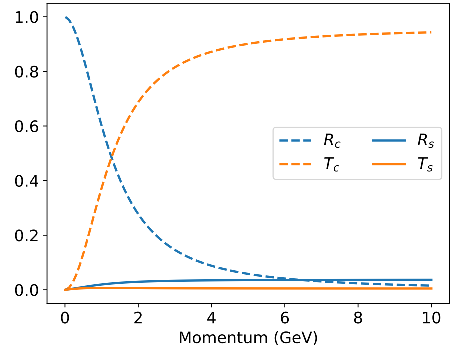


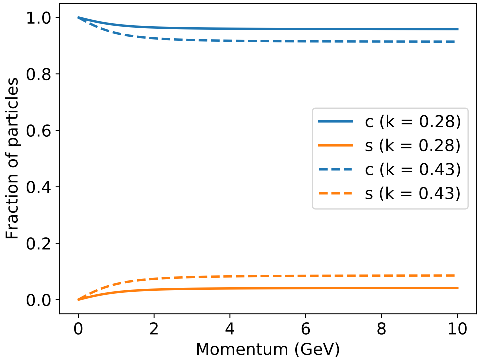




Situation for second generation quarks:

- $y\tilde{v}_+$ small
- Δg_2 small





Situation for second generation quarks:

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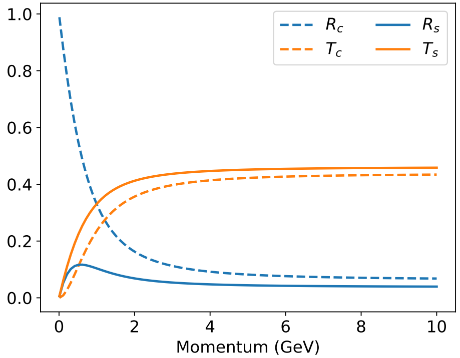
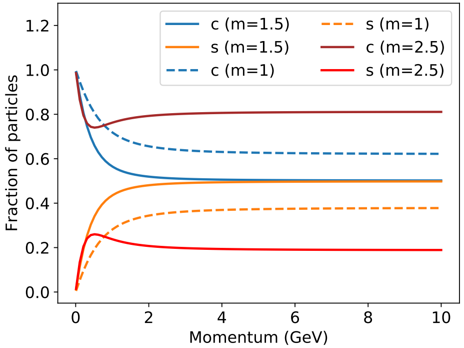
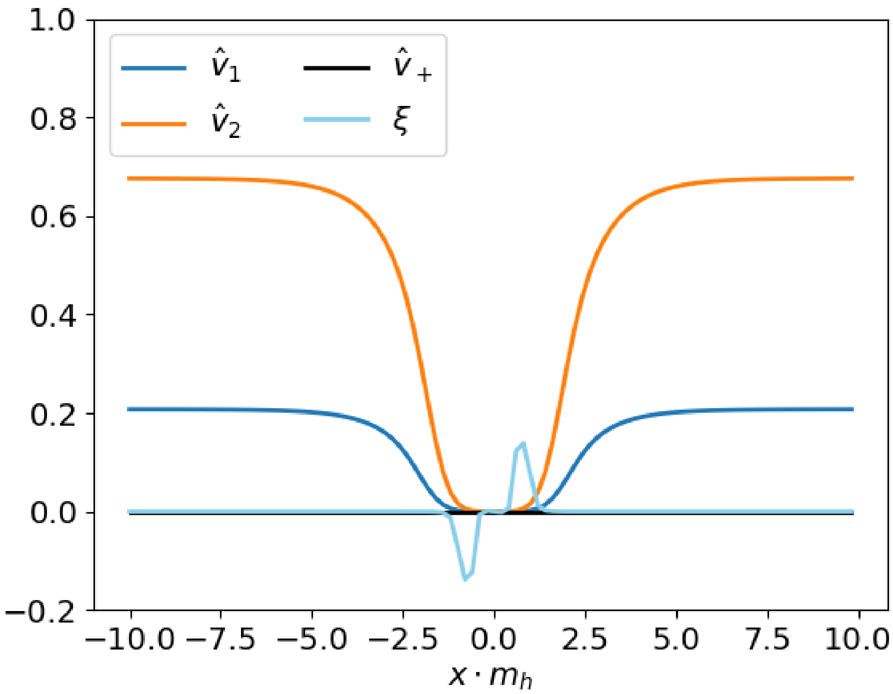




- **For a fixed v_+, the effect of charge violation is much higher for 3rd generation quarks than 2nd or 1st generation quarks!**
- **For a fixed Δg_2, the effect is mostly similar for all generations.**

Electroweak Symmetry Restoration in the N2HDM

The electroweak symmetry can be restored inside Inside the domain wall of the singlet.



Conclusions and Outlook

- Due to **breaking SU(2)xU(1)** symmetry **at the same time with** the **Z_2 symmetry**, the domain walls in the 2HDM can have **CP and Charge violation inside the wall**.

- **SM Fermion scattering off the domain walls** can **break charge** and **CP**.

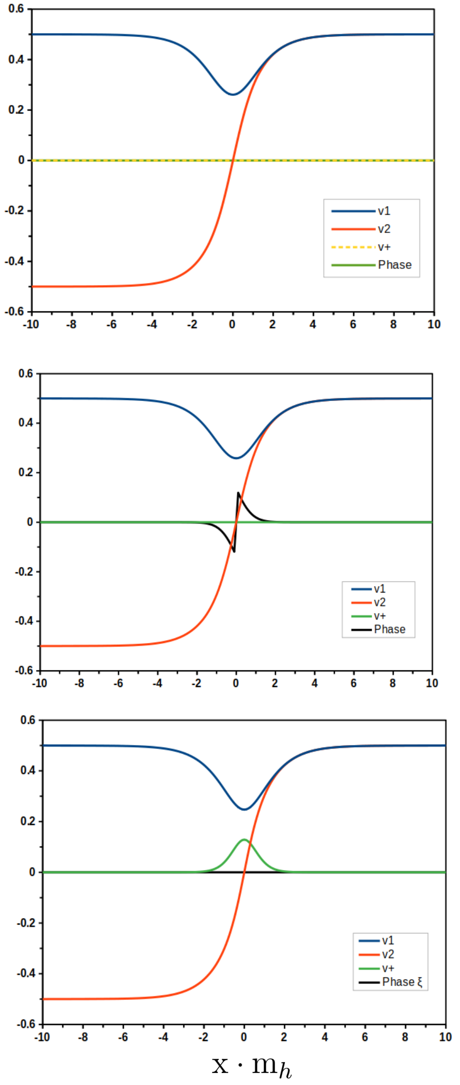
- Possible future directions include :

1) **Electroweak Baryogenesis** using the **domain walls.**

2) **Fermionic bound states** on the walls.

3) **Using charge violation** inside the domain wall to **constrain** the model.

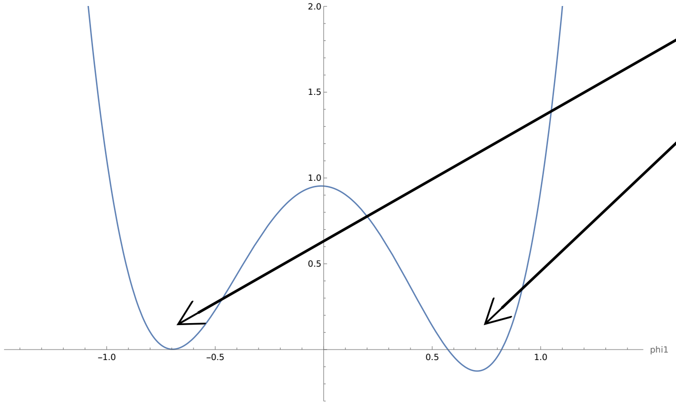
4) **Probing gravitational wave** spectrum from the annihilation **of the different types of domain walls.**

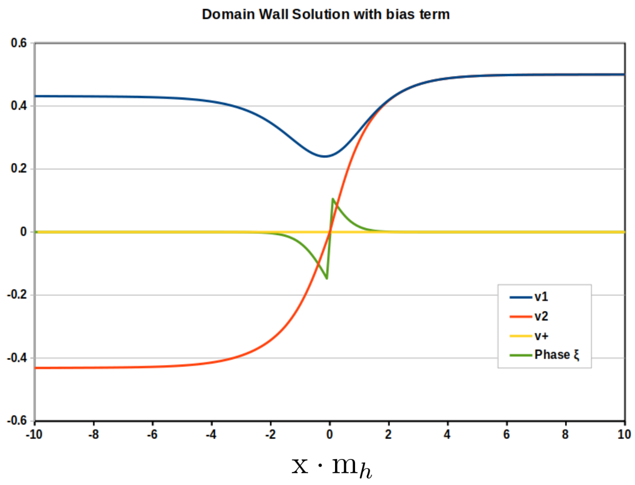


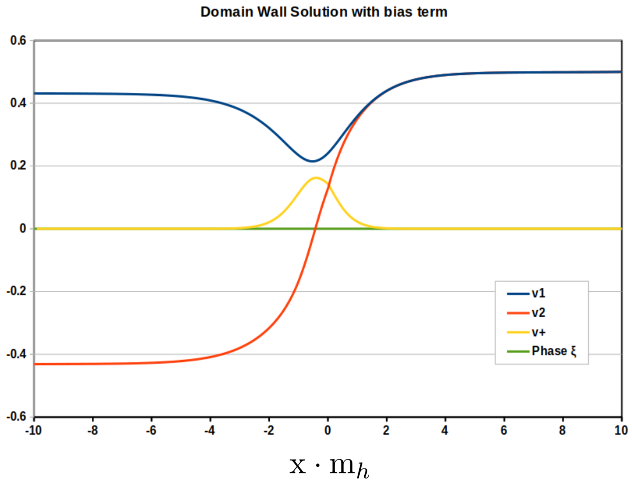
Backup

For $m_{12} \neq 0$, the Z_2 **symmetry is then approximate** and we get **asymmetric domain walls**:

The minima are not degenerate anymore







From the differential equation of θ(x) one can derive:

$$\frac{d\theta}{dx} = \frac{-v_2^2}{v_1^2 + v_2^2 + v_+^2}\frac{d\xi}{dx}$$

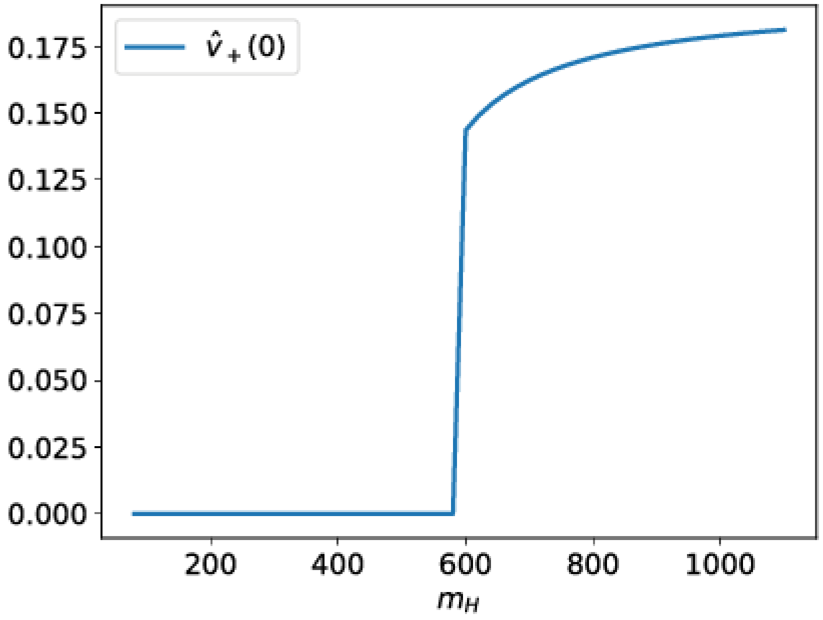
Variation in the hypercharge across the wall leads to <u>CP-violating phase inside the wall.</u>

From the differential equation of g_2(x) one can derive:

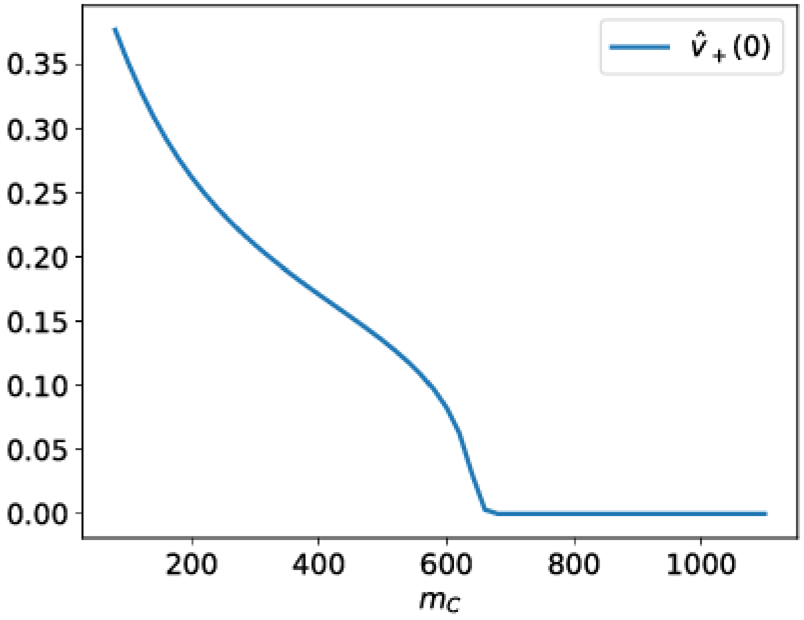
$$\frac{dg_2}{dx} = \frac{-2v_2^2\cos^2(\xi)}{v_1^2 + v_2^2 + v_+^2}\frac{d}{dx}\left(\frac{v_+}{v_2\cos(\xi)}\right)$$

Variation in g_2 across the wall leads to <u>charge violating vacuum inside the wall.</u>

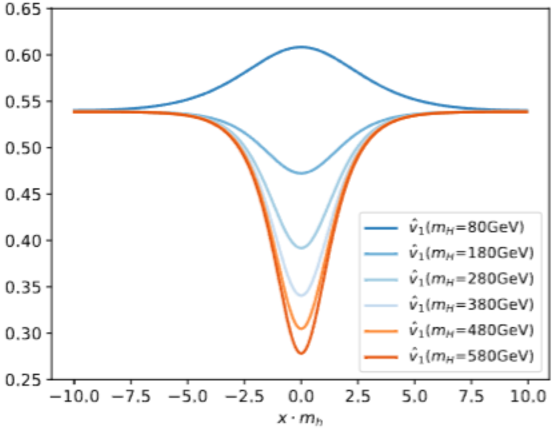
$m_C = 400$ GeV



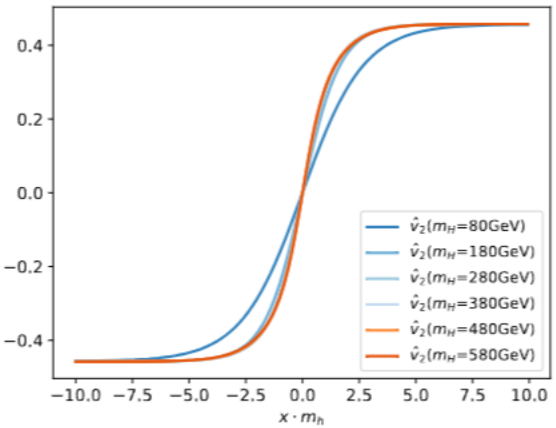
$m_H = 800$ GeV



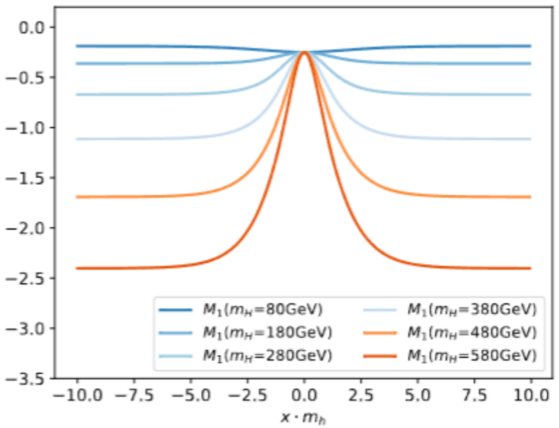
Dependance of the **maximal charge violating vacuum inside the wall $v_+(0)$** on the **mass parameters**. **No dependance on the mass of the CP-odd Higgs mass was found!**



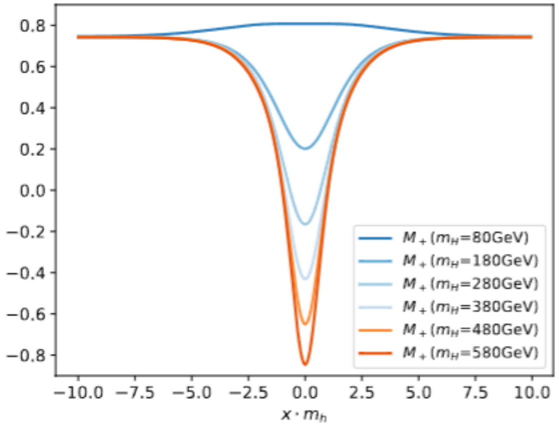
(a) Dependence of v_1 on m_H.



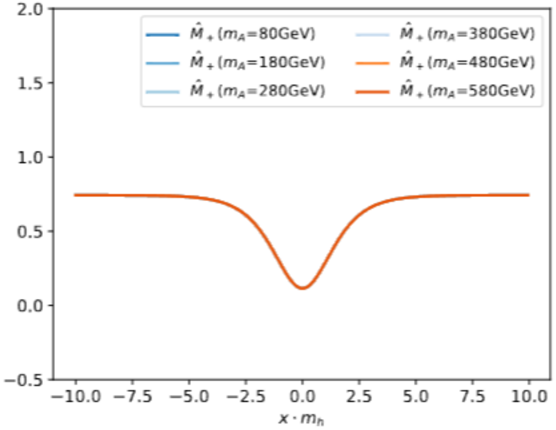
(b) Dependence of v_2 on m_H.



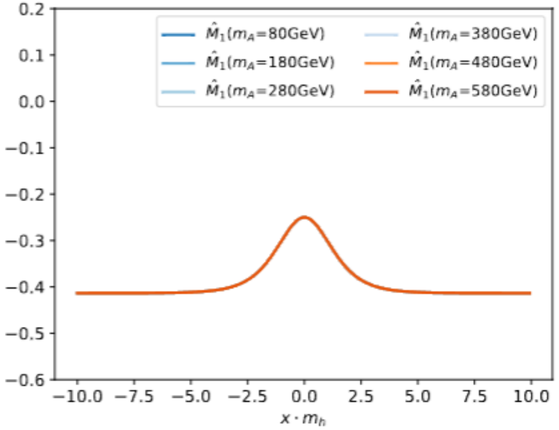
(c) Dependence of M_1 on m_H.



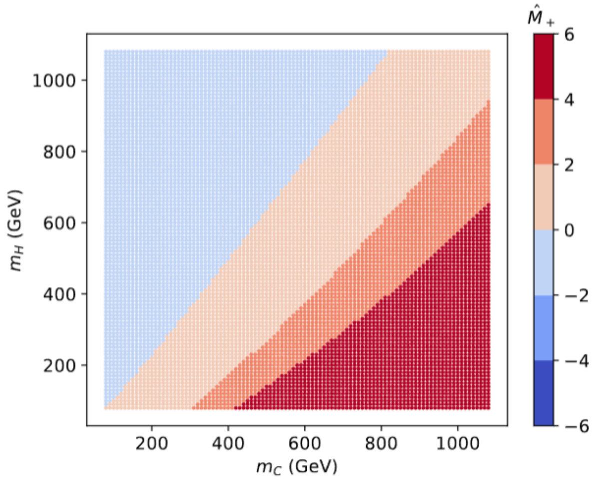
(d) Dependence of M_+ on m_H.



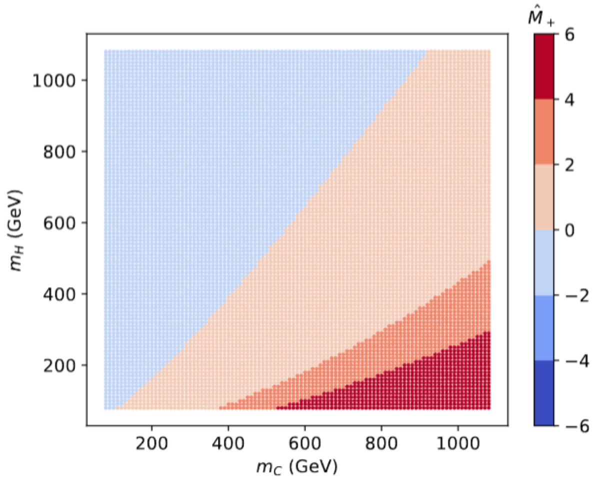
(e) Dependence of $\hat{M}_+$ on m_A.



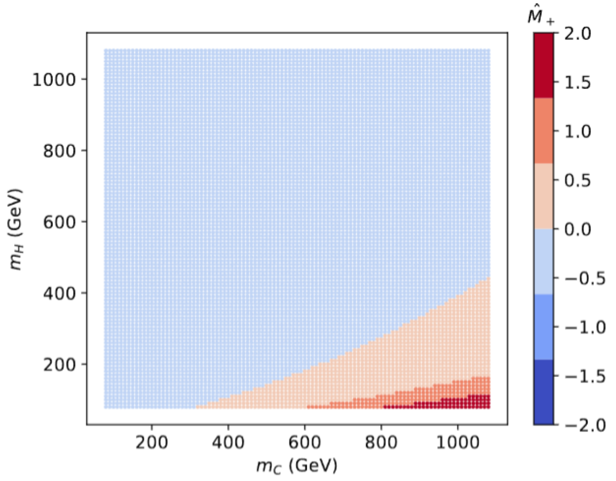
(f) Dependence of $\hat{M}_1$ on m_A.



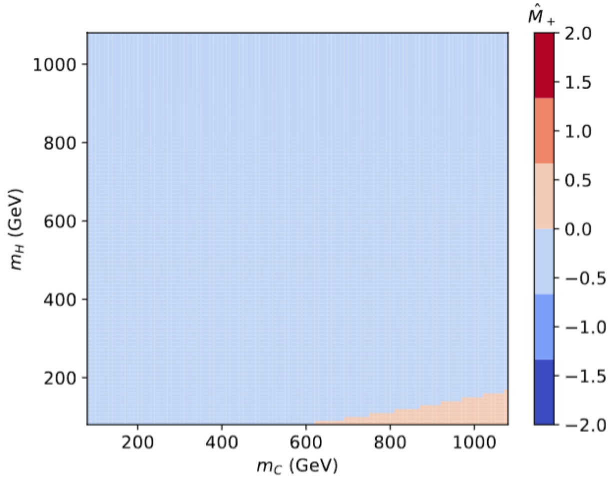
(a) $\tan(\beta) = 0.85$



(b) $\tan(\beta) = 1.5$



(c) $\tan(\beta) = 5$



(d) $\tan(\beta) = 10$

$$M_+(x) = \frac{1}{2}m_{22} + \frac{1}{4}(\lambda_2 v_2^2(x) + \lambda_3 v_1^2(x))$$

Dependence of the **charged effective mass $M_+(0)$** inside the domain wall on the masses **m_C** and **m_H**.
Negative values lead to the possibility of generating a charged vacuum inside the wall.

Example for simplified case where only **θ(x) is non constant** :

$$U(x) = e^{i\theta(x)}$$

$$\mathcal{E}(x) = \frac{1}{2}(\frac{dv_1}{dx})^2 + \frac{1}{2}(\frac{dv_2}{dx})^2 + \frac{1}{2}(\frac{dv_+}{dx})^2 + v_2^2(\frac{d\xi}{dx})^2 + \frac{1}{2}(\frac{d\theta}{dx})^2(v_1^2 + v_2^2 + v_+^2) + v_2^2\frac{d\theta}{dx}\frac{d\xi}{dx} + V(v_1, v_2, v_+, \xi)$$

Leads to the equations of motion:

$$\frac{d^2v_1}{dx^2} - (\frac{d\theta}{dx})^2 v_1 - \frac{dV}{dv_1} = 0$$

$$\frac{d^2v_2}{dx^2} - v_2(\frac{d\xi}{dx} + \frac{d\theta}{dx})^2 - \frac{dV}{dv_2} = 0$$

$$\frac{d^2v_+}{dx^2} - v_+(\frac{d\theta}{dx})^2 - \frac{dV}{dv_+} = 0$$

$$v_2^2\frac{d^2\xi}{dx^2} + v_2^2\frac{d^2\theta}{dx^2} + 2v_2\frac{dv_2}{dx}\frac{d\xi}{dx} + 2v_2\frac{dv_2}{dx}\frac{d\theta}{dx} - \frac{dV}{d\xi} = 0$$

$$(v_1^2 + v_2^2 + v_+^2)\frac{d^2\theta}{dx^2} + 2\frac{d\theta}{dx}(v_1\frac{dv_1}{dx} + v_2\frac{dv_2}{dx} + v_+\frac{dv_+}{dx}) + v_2^2\frac{d^2\xi}{dx^2} + 2v_2\frac{dv_2}{dx}\frac{d\xi}{dx} = 0$$

Solve numerically using
Gradient flow method
Richard A. Battye, Gary D. Brawn, Apostolos Pilaftsis (1106.3482) JHEP
Richard A. Battye, Apostolos Pilaftsis, Dominic G. Viatic (2006.13273) JHEP

Baryogenesis with Topological Defects

Idea discussed in the 90s :

- **Local and nonlocal defect-mediated electroweak baryogenesis**
  hep-ph/9409281

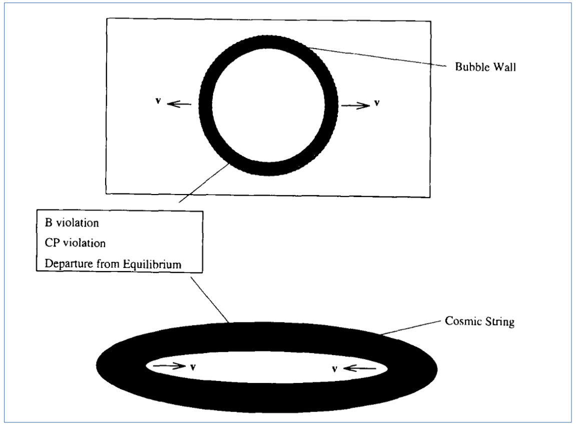
- **Baryogenesis from Domain Walls in the Next-to-Minimal Supersymmetric Standard Model**
  hep-ph/9505241

- **Electroweak Baryogenesis with Cosmic Strings ?**
  Hep-ph/9901310

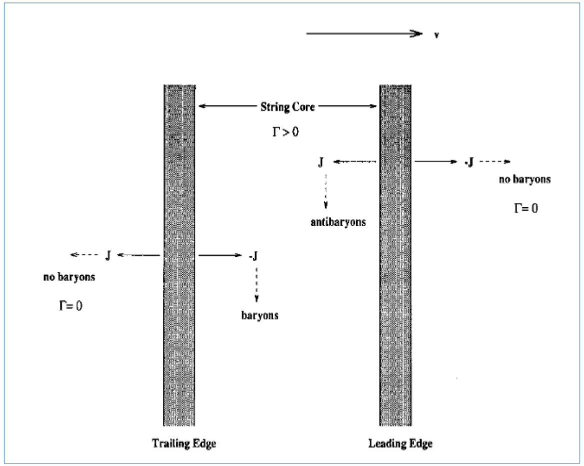
- **...**

Main idea:

- **The topological defect acts as the bubble wall.**
- **Sphalerons** are **less supressed** inside the topological defect
- **CP violation in the defect walls.**



From Physics Letters B 335 (1994) 123-130



Main Problems discussed in past papers:

- **Volume suppression factor** due to defect **not spanning the whole universe.**

$$\boxed{\Delta n_B = \frac{1}{V}\frac{\Gamma_B}{T} V_{\rm BG}\Delta\theta}$$

- **Symmetry restoration region not large enough to contain Sphalerons.**

$$\boxed{R_{restoration} \sim \frac{1}{\sqrt{\lambda}v} \qquad R_{Sphalerons} \sim \frac{1}{g^2T}}$$

For N2HDM/2HDM Domain walls thickness 5-10 times smaller than Sphalerons

For cosmic strings

String-mediated electroweak baryogenesis: A critical analysis

J. M. Cline,[1,*] J. R. Espinosa,[2,†] G. D. Moore,[1,‡] and A. Riotto[2,§]
[1]*Department of Physics, McGill University, 3600 University Street, Montréal, Québec, Canada H3A 2T8*
[2]*CERN TH-Division, CH-1211 Geneva 23, Switzerland*
(Received 6 October 1998; published 22 February 1999)

Very Suppressed!

$$\left[\frac{N_B}{N_\gamma}\right]_{strings} \lesssim 10^{-10}\left[\frac{N_B}{N_\gamma}\right]_{observed}. \qquad (4)$$

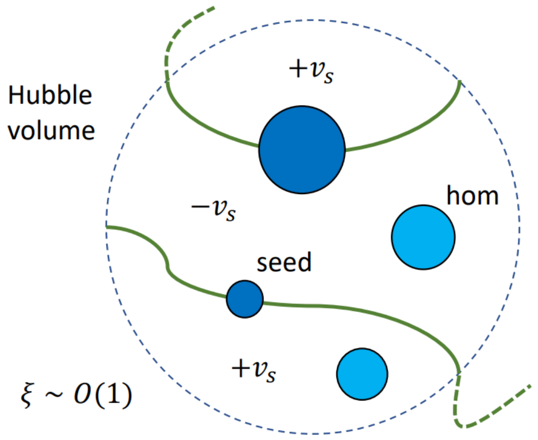
That is, the mechanism just studied is uncapable of generating a sufficiently large matter-antimatter asymmetry.

What about Domain Walls ?

Calculation of sphaleron rate in 2+1 dimensions inside the walls ?

This was already done for the case of SM extended with a singlet scalar

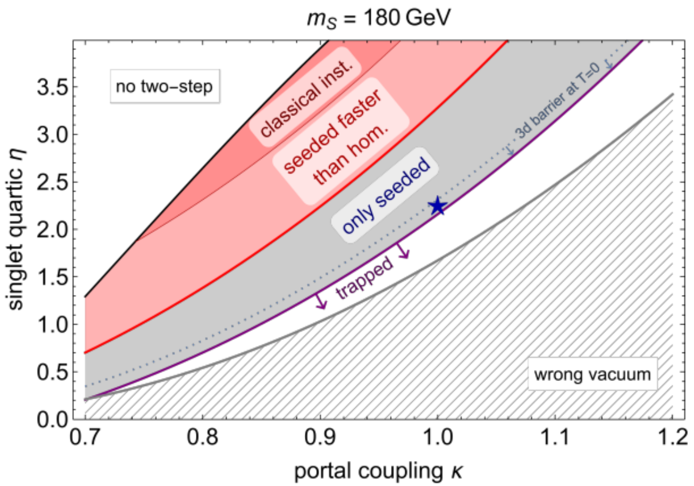
Domain Walls from **singlet Z_2 symmetry breaking** act as **impurities** and **enhance the nucleation of EWSB bubbles.**

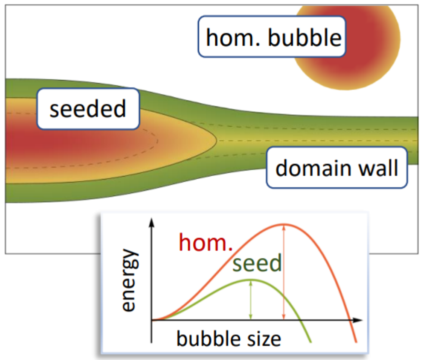


Nucleation prob. no longer the same everywhere, enhanced at DW location

- Different nucleation condition:

$$\frac{S_3}{T} \sim 140 \quad \text{vs} \quad \frac{S_{\rm inh}}{T} \sim 100$$





Figures from Simone Blasi DESY theory Seminar Talk 02.05.22

More informations in **Domain walls seeding the electroweak phase transition arXiv:2203.16450 (Simone Blasi and Alberto Mariotti)**