

# Electroweak corrections to Higgs decays to dark matter in the N2HDM

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# The Standard Model and dark matter

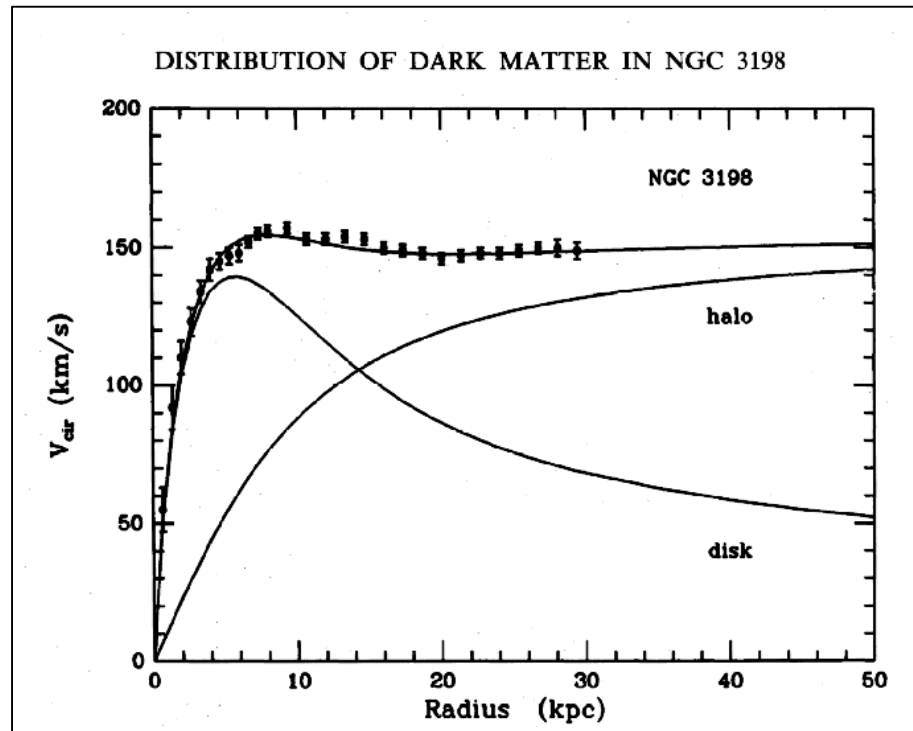
mass →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0	$\approx 126 \text{ GeV}/c^2$
charge →	$2/3$	$2/3$	$2/3$	0	0
spin →	$1/2$	$1/2$	$1/2$	1	0
	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon	<b>H</b> Higgs boson
<b>QUARKS</b>	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	$-1/3$	$-1/3$	$-1/3$	0	
	$1/2$	$1/2$	$1/2$	1	
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>γ</b> photon	
<b>LEPTONS</b>	$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$	$91.2 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$1/2$	$1/2$	$1/2$	1	
	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>Z</b> Z boson	
<b>LEPTONS</b>	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$80.4 \text{ GeV}/c^2$	
	0	0	0	$\pm 1$	
	$1/2$	$1/2$	$1/2$	1	
	<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>W</b> W boson	
				<b>GAUGE BOSONS</b>	

The Standard Model (SM) is one of the most accurate models in Physics. It has exceptional agreement with experimental measurements.

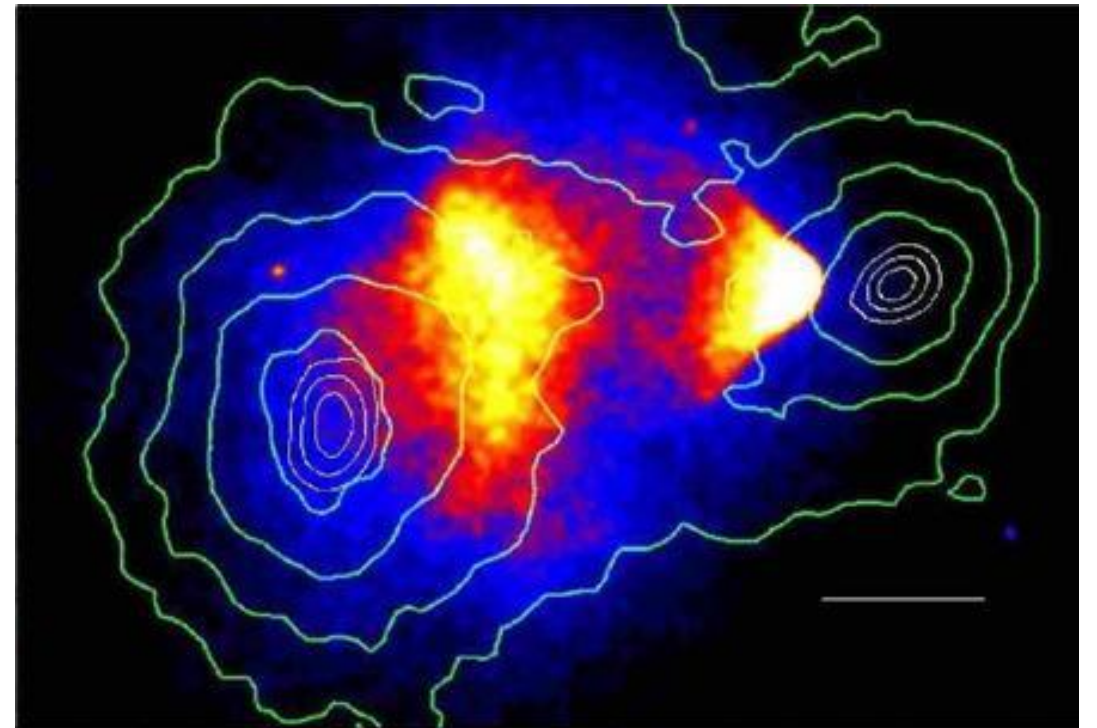
Still can't explain some experimental observations (neutrino masses, matter/anti-matter asymmetry, dark matter...)

# Evidence for dark matter

## Galaxy rotation curves



## Gravitational lensing



Separate observations point towards the existence of “hidden” matter

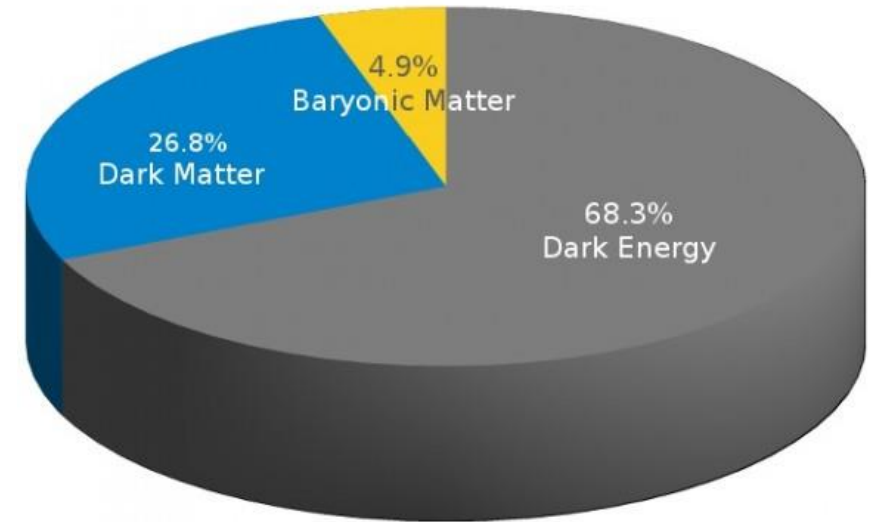
# What is dark matter?

## Properties

- Does not interact with regular matter
- Interacts weakly with itself
- Stable

## What dark matter is not

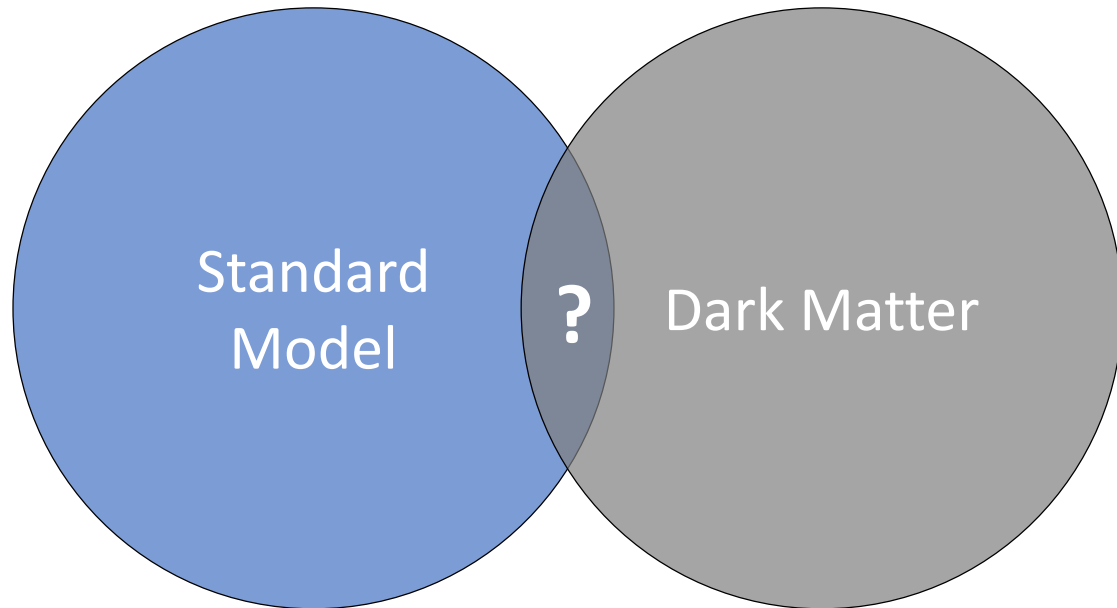
- Barionic matter
- Neutrinos



## What dark matter might be

- Particle → WIMP
- Something else → Modified gravity models

# Standard Model Extensions



To include dark matter in the Standard Model we need to extend it.

Extensions to the SM will be very constrained by experimental measurements.

The N2HDM is one of the simplest Standard Model extensions that allows the existence of dark matter candidates.

# Next to Minimal 2-Higgs Doublet Model (N2HDM)

Standard Model

$$V_{scalar} = \boxed{m_{11}^2 \Phi_1^\dagger \Phi_1 + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2} + m_{22}^2 \Phi_2^\dagger \Phi_2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + h.c.) + \lambda_3 \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 \\ + \lambda_4 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 + \frac{\lambda_5}{2} \left( (\Phi_1^\dagger \Phi_2)^2 + h.c. \right) + \frac{1}{2} m_S^2 \Phi_S^2 + \frac{\lambda_6}{8} \Phi_S^4 + \frac{\lambda_7}{2} \Phi_1^\dagger \Phi_1 \Phi_S^2 + \frac{\lambda_8}{2} \Phi_2^\dagger \Phi_2 \Phi_S^2$$

$$\Phi_1 = \begin{pmatrix} \Phi_1^+ \\ \frac{1}{\sqrt{2}} (v_1 + \rho_1 + i\eta_1) \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} \Phi_2^+ \\ \frac{1}{\sqrt{2}} (v_2 + \rho_2 + i\eta_2) \end{pmatrix} \quad \Phi_S = v_S + \rho_S$$

Vacuum expectation value (VEV)

$$v_S = 0$$

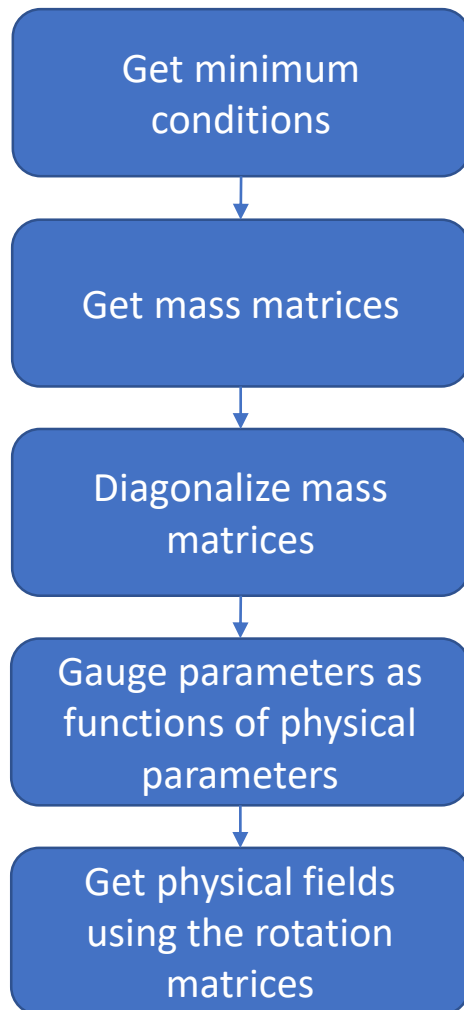
Dark Singlet Phase

$$v_1 = 0$$

Inert Doublet Phase

**Particles and parameters are not physical**

# Change of basis



Solve system of equations:  $\frac{\partial V}{\partial \psi} = 0, \psi \in \{\rho_{1,2,S}, \eta_{1,2}, \Phi_{1,2}^+\}$

$$(M_{even})_{ij} = \left( \frac{\partial^2 V}{\partial \rho_i \partial \rho_j} \right) \quad (M_{odd})_{ij} = \left( \frac{\partial^2 V}{\partial \eta_i \partial \eta_j} \right) \quad (M_+)_{ij} = \left( \frac{\partial^2 V}{\partial \Phi_i^+ \partial \Phi_j^+} \right)$$

$$M_{diag} = \Lambda^{-1} M \Lambda \quad \left\{ \begin{array}{l} \Lambda_{3 \times 3} = R \longrightarrow \text{mixing angle } \alpha \\ \Lambda_{2 \times 2} = U \longrightarrow \text{mixing angle } \beta \end{array} \right.$$

Use conditions from diagonal mass matrices to write gauge parameters as functions of the physical parameters

$$\vec{\rho} = R \vec{\rho}_{ph}$$

$$\vec{\eta} = U \vec{\eta}_{ph}$$

$$\vec{\Phi}^+ = U \vec{\Phi}_{ph}^+$$

# N2HDM - Physical basis

Fields	$h, H_0, X, A_0, H^\pm$
Parameters	Dark Singlet Phase $\rightarrow \{m_h^2, m_H^2, m_X^2, m_{A_0}^2, m_{H^\pm}^2, v, \alpha, \beta, m_{12}^2, \lambda_6, \lambda_7, \lambda_8\}$ Inert Doublet Phase $\rightarrow \{m_h^2, m_H^2, m_X^2, m_{A_0}^2, m_{H^\pm}^2, v, v_S, \alpha, m_{11}^2, \lambda_1, \lambda_7\}$
Interactions	<p>The interaction diagrams show the following vertices:</p> <ul style="list-style-type: none"> <li>Diagram 1: A vertex where a scalar field <math>h</math> splits into two dark singlet fields <math>X</math>.</li> <li>Diagram 2: A vertex where two scalar fields <math>h</math> interact to produce two dark singlet fields <math>X</math>.</li> <li>Diagram 3: A vertex where a scalar field <math>h</math> and a scalar field <math>H_0</math> interact to produce two dark singlet fields <math>X</math>.</li> </ul>

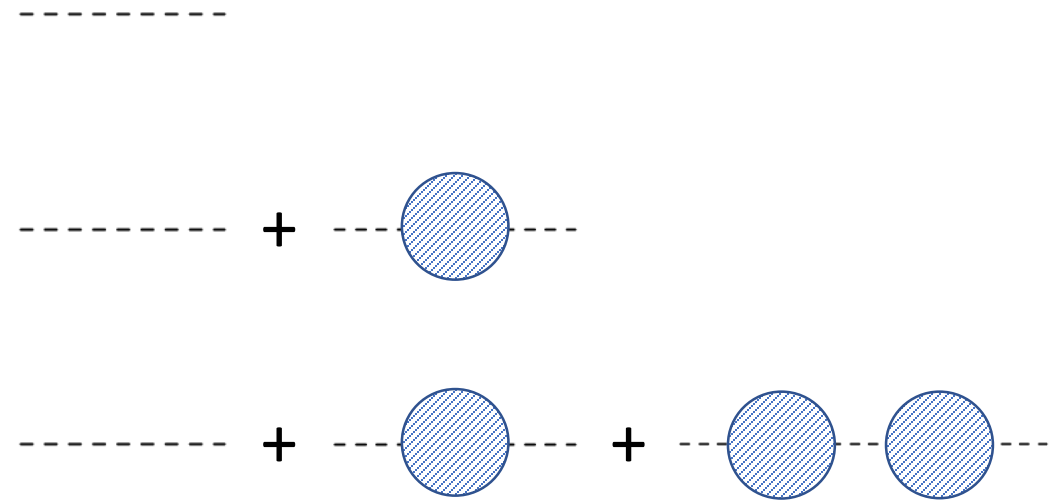
# One-loop corrections

In quantum field theory, higher orders of perturbation theory are represented by sets of Feynman loop diagrams.

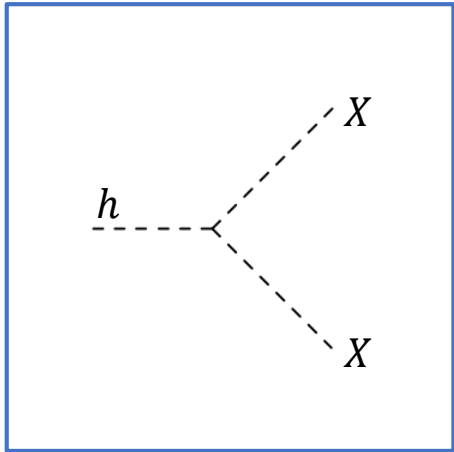
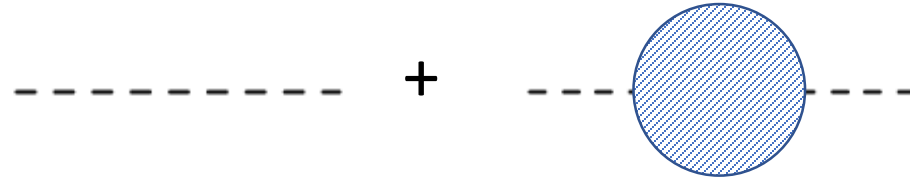
$$\langle \psi_f | \mathbf{G} | \psi_i \rangle_{LO} = g^{(0)}$$

$$\langle \psi_f | \mathbf{G} | \psi_i \rangle_{NLO} = g^{(0)} + g^{(1)}$$

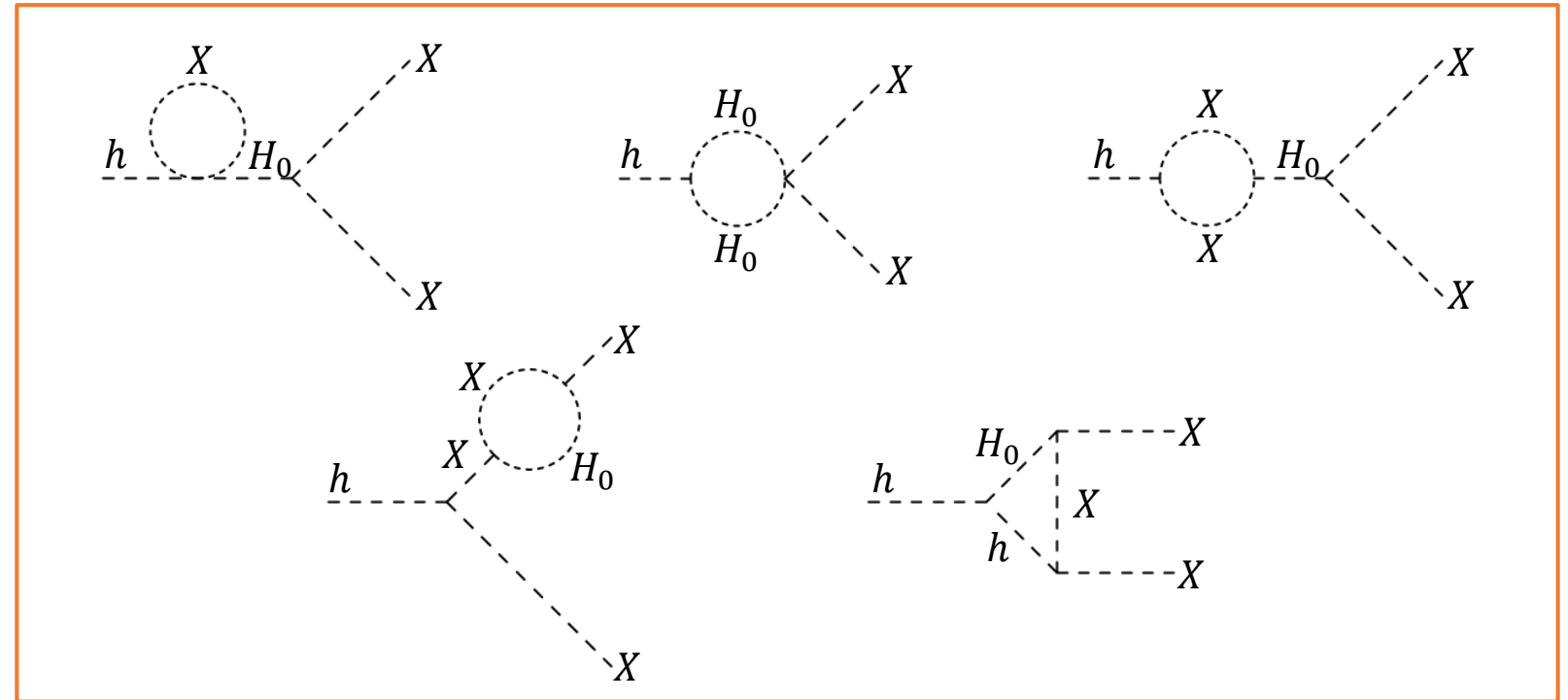
$$\langle \psi_f | \mathbf{G} | \psi_i \rangle_{NNLO} = g^{(0)} + g^{(1)} + g^{(2)}$$



# One-loop corrections



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# One-loop corrections

- Experiments are becoming more precise so theorists must reduce errors in their predictions to keep up.
- Leading order (LO) in perturbation theory is mostly not enough so we need to go at least to NLO.
- Calculation of loop contributions often leads to divergences:

$$\int_0^{\infty} \frac{d^4 p}{(2\pi)^4} \frac{1}{p^2 - m^2} \xrightarrow{\text{UV divergence } (p \rightarrow \infty)} \boxed{\text{Renormalization}}$$

# Renormalization

- Method to treat divergences that arise from loop calculations.
- The divergences are isolated through the process of **regularization**.

$$\int_0^\infty \frac{d^4 p}{(2\pi)^4} \frac{1}{p^2 - m^2} \xrightarrow{\text{Regularization}} \infty + \textit{finite terms}$$

- The divergences are absorbed by renormalizing the fields and parameters of the model.

# Renormalization

Parameters are shifted and fields are rescaled:

$$\lambda_0 = \hat{\lambda} + \delta\lambda$$

Diagram illustrating the renormalization of a parameter  $\lambda$ :

- $\lambda_0$  is labeled "bare" parameter.
- $\hat{\lambda}$  is labeled "renormalized parameter".
- $\delta\lambda$  is labeled "counterterm".

$$\phi_0 = \left(1 + \frac{\delta Z}{2}\right) \hat{\phi}$$

The counterterms absorb the divergences.

For  $n$  parameters and  $m$  fields, we need  $(n + m)$  renormalization conditions in order to fix all the counterterms.

After renormalization, all UV divergences should cancel out.

# What's next?

- Complete the renormalization of the model.
- Scan the parameter space in order to apply experimental constraints.
- Study the constrained model with respect to the Higgs invisible decays.