



Congratulations !



Model with induced symmetry breaking chain

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What is a scale of New physics?

Before the LHC start we knew a scale **~1 TeV** from

No lose theorem!

From the unitarity of $VV \rightarrow VV$ (V: W,Z) amplitudes: $|\text{Re}(a_l)| \leq \frac{1}{2}$

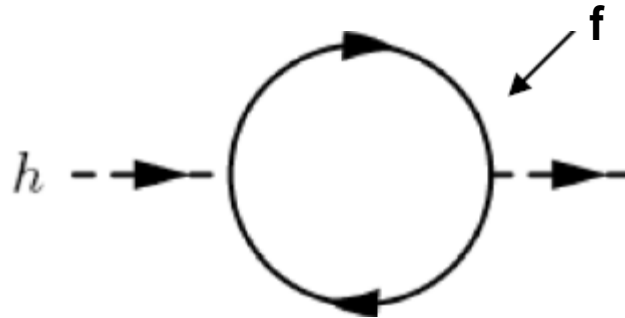
Either light Higgs $M_H \lesssim 710 \text{ GeV}$
or
New Physics at $\sqrt{s} \lesssim 1.2 \text{ TeV}$

The Higgs boson was found !

**We do not have solid arguments for a new scale
We do not know if a new scale (if exists) would be accessible
at the LHC/FCC energies**

SM itself is a renormalizable theory !

Correction to the Higgs mass from a loop containing new particle



$$|M_H^2(\Lambda) - M_H^2(v)| \sim 3/(8\pi^2) y_f^2 M_f^2 \ln(\Lambda^2/v^2) + \dots$$

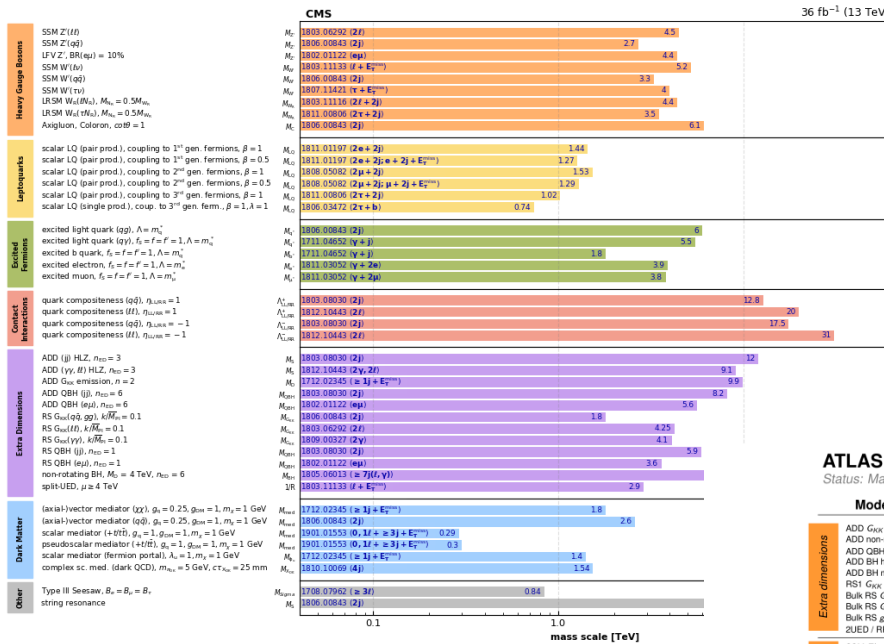
Correction is large for $M_f^2 \sim \Lambda^2$ if the coupling constant y_f is large

But a new fermion may have a very small coupling to the SM Higgs boson

No solid arguments for a new scale

Many limits already in TeV energy range

Overview of CMS EXO results



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2019

ATLAS Preliminary

$$\int \mathcal{L} dt = (3.2 - 139) \text{ fb}^{-1}$$

$$\sqrt{s} = 8, 13 \text{ TeV}$$

Model	ℓ, γ	Jets [†]	E ^{miss} _T	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimensions	ADD $G_{\mu\mu} + g/\eta$	0 e, μ	1-4	Yes	36.1	M_{D_2} 7.7 TeV
	ADD non-resonant $\gamma\gamma$	2 γ	-	Yes	36.7	M_{D_2} 8.6 TeV
	ADD OBH	-	2	-	37.0	M_{D_2} 8.9 TeV
	ADD BH high Σp_T	$\geq 1 e, \mu$	≥ 2	-	3.2	M_{D_2} 8.2 TeV
	ADD BH multiplet	-	≥ 3	-	3.6	M_{D_2} 9.55 TeV
	RS1 $G_{\mu\mu} \rightarrow \gamma\gamma$	2 γ	-	Yes	36.7	$G_{\mu\mu}$ mass 4.1 TeV
	Bulk RS $G_{\mu\mu} \rightarrow WW/ZZ$	multi-channel	-	Yes	36.1	$G_{\mu\mu}$ mass 2.3 TeV
	Bulk RS $G_{\mu\mu} \rightarrow WW \rightarrow q\bar{q}q\bar{q}$	0 e, μ	2 J	-	139	$G_{\mu\mu}$ mass 1.6 TeV
	Bulk RS $G_{\mu\mu} \rightarrow t\bar{t}$	1 e, μ	$\geq 1 b, \geq 1 J/2$	Yes	36.1	$G_{\mu\mu}$ mass 3.9 TeV
	2UED / RPP	1 e, μ	$\geq 2 b, \geq 3 J$	Yes	36.1	KU mass 1.8 TeV
Gauge bosons	SSM Z' $\rightarrow \ell\ell$	2 e, μ	-	Yes	139	Z' mass 5.1 TeV
	SSM Z' $\rightarrow \tau\tau$	2 τ	-	Yes	36.1	Z' mass 2.42 TeV
	Leptophobic Z' $\rightarrow b\bar{b}$	1 e, μ	$\geq 1 b, \geq 1 J/2$	Yes	36.1	Z' mass 2.1 TeV
	Leptophobic Z' $\rightarrow t\bar{t}$	1 e, μ	$\geq 1 b, \geq 1 J/2$	Yes	36.1	Z' mass 3.9 TeV
	SSM W' $\rightarrow \ell\nu$	1 e, μ	-	Yes	139	W' mass 6.9 TeV
	SSM W' $\rightarrow \tau\nu$	1 τ	-	Yes	36.1	W' mass 3.7 TeV
	HVT V' $\rightarrow WZ \rightarrow q\bar{q}q\bar{q}$ model B	0 e, μ	2 J	-	139	V' mass 3.6 TeV
	HVT V' $\rightarrow WH/ZH$ model B	multi-channel	-	Yes	36.1	V' mass 2.93 TeV
	LRSM W ₂ $\rightarrow t\bar{b}$	1 e, μ	1 J	-	36.1	W ₂ mass 3.25 TeV
	LRSM W ₂ $\rightarrow \mu\nu$	2 μ	1 J	-	80	W ₂ mass 5.0 TeV
CI	CI $q\bar{q}q\bar{q}$	-	2	-	37.0	A 21.8 TeV
	CI ($t\bar{t}q\bar{q}$)	2 e, μ	$\geq 1 b, \geq 1 J$	Yes	36.1	A 21.8 TeV
	CI ($t\bar{t}t\bar{t}$)	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 J$	Yes	36.1	A 2.57 TeV
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1-4	Yes	36.1	ρ_{DM} 1.55 TeV
	Colored scalar mediator (Dirac DM)	0 e, μ	1-4	Yes	36.1	ρ_{DM} 1.67 TeV
	VV ₁ EFT (Dirac DM)	0 e, μ	1, J, $\geq 1 J$	Yes	3.2	M_{V_1} 700 GeV
	Scalar reson. $\phi \rightarrow t\bar{t}$ (Dirac DM)	0 e, μ	1 b, 0.1 J	Yes	36.1	M_ϕ 3.4 TeV
LQ	Scalar LQ 1 st gen	1, 2 e, μ	≥ 2	Yes	36.1	LQ mass 1.4 TeV
	Scalar LQ 2 nd gen	1, 2 e, μ	≥ 2	Yes	36.1	LQ mass 1.64 TeV
	Scalar LQ 3 rd gen	2 τ	2 b	-	36.1	LQ mass 1.03 TeV
	Scalar LQ 3 rd gen	0, 1 e, μ	2 b	Yes	36.1	LQ mass 979 GeV
Heavy quarks	VLO $T\bar{T} \rightarrow H\gamma/Z\gamma/W\gamma + X$	multi-channel	-	Yes	36.1	T mass 1.37 TeV
	VLO $B\bar{B} \rightarrow W\gamma/Z\gamma + X$	multi-channel	-	Yes	36.1	B mass 1.34 TeV
	VLO $T_{1/3} T_{1/3} \rightarrow W\gamma + X$	2(SS)/3 e, μ	$\geq 1 b, \geq 1 J$	Yes	36.1	T _{1/3} mass 1.64 TeV
	VLO $V \rightarrow W\gamma + X$	1 e, μ	$\geq 1 b, \geq 1 J$	Yes	36.1	Y mass 1.85 TeV
	VLO $Q \rightarrow H\gamma + X$	0 e, μ	$2\gamma \geq 1 b, \geq 1 J$	Yes	79.8	B mass 1.21 TeV
	VLO $Q\bar{Q} \rightarrow W\gamma W\gamma$	1 e, μ	$\geq 4 J$	Yes	20.3	Q mass 690 GeV
	Excited quark $q^* \rightarrow q\gamma$	-	2 J	-	139	q* mass 6.7 TeV
	Excited quark $q^* \rightarrow q\gamma$	1 γ	1 J	-	36.7	q* mass 5.3 TeV
Excited fermions	Excited quark $q^* \rightarrow b\gamma$	-	1 b, 1 J	-	36.1	q* mass 2.6 TeV
	Excited lepton ℓ^*	3 e, μ, τ	-	-	20.3	q* mass 3.9 TeV
	Excited lepton ℓ^*	3 e, μ, τ	-	-	20.3	q* mass 1.6 TeV
	Excited lepton ℓ^*	3 e, μ, τ	-	-	20.3	q* mass 1.6 TeV
Other	Type II Seesaw	1 e, μ	≥ 2	Yes	79.8	M_{Δ} mass 560 GeV
	LRSM Majorana	1 e, μ	2 J	-	36.1	N mass 870 GeV
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2, 3, 4 e, μ (SS)	-	-	36.1	H mass 870 GeV
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	3 e, μ, τ	-	-	20.3	H mass 800 GeV
	Multi-charged particles	-	-	-	36.1	multi-charged particle mass 1.22 TeV
	Magnetic monopoles	-	-	-	34.4	multi-charged particle mass 2.97 TeV

*Only a selection of the available mass limits on new states or phenomena is shown.

[†]Small-radius (large-radius) jets are denoted by the letter J (J_L).

Scales

Plank Mass $\sim 10^{19}$ GeV

Grand Unification scale $\sim 10^{15} - 10^{16}$ GeV ?

Neutrino physics (see-saw) scale $\sim 10^{12} - 10^{13}$ GeV ?

SM vacuum metastability scale $\sim 10^{10} - 10^{11}$ GeV ?

Some BSM models, some SUSY scenarios $\sim 10^3 - 10^4$ GeV ?

EW scale (v_{SM}) $\sim 10^2$ GeV

The SM Lagrangian $L_\Phi = D_\mu \Phi^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^4$

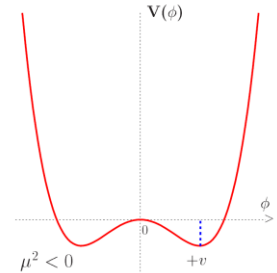
in terms of the fields:

$$W_\mu^\pm = (W_\mu^1 \mp iW_\mu^2) / \sqrt{2}$$

$$W_\mu^3 = Z_\mu \cos \theta_W + A_\mu \sin \theta_W$$

$$B_\mu = -Z_\mu \sin \theta_W + A_\mu \cos \theta_W$$

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$



The diagonal mass matrix -> physics states with definite masses

$$M_W = M_Z \cos \theta_W$$

$$L_H = \frac{1}{2} (\partial^\mu h) (\partial_\mu h) + \frac{M_h^2}{2} h^2 - \frac{M_h^2}{2v} h^3 - \frac{M_h^2}{8v^2} h^4 + \\ + (M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu) \left(1 + \frac{h}{v}\right)^2 - \sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right)$$

$$M_H^2 = 2\lambda v^2 = -2\mu^2$$

Why the mass parameter μ^2 is negative?

Simple model

$$\begin{aligned} L = & (D_\nu^{(1)} H_1)^\dagger (D^{(1)\nu} H_1) - \mu_1^2 H_1^\dagger H_1 - \lambda_1 (H_1^\dagger H_1)^2 \\ & + k_{12} (H_1^\dagger H_1) (H_2^\dagger H_2) \\ & + (D_\nu^{(2)} H_2)^\dagger (D^{(2)\nu} H_2) - \mu_2^2 H_2^\dagger H_2 - \lambda_2 (H_2^\dagger H_2)^2 \end{aligned}$$

Consider the case $\mu_1^2 = 0, \mu_2^2 = -|\mu_2^2| < 0$

Spontaneous symmetry breaking at the level 2 leads to appearing of the induced negative parameter

$$\mu_1'^2 = -k_{12} \cdot v_2^2/2 \quad (\text{for } k_{12} > 0)$$

Negative $\mu_1'^2$ leads to induced spontaneous symmetry breaking at the level 1

Quadratic form: $2\lambda_1 v_1^2 \widetilde{h_1}^2 - 2k_{12} v_1 v_2 \widetilde{h_1} \widetilde{h_2} + 2\lambda_2 v_2^2 \widetilde{h_2}^2$

Mass eigenstates after diagonalizing the mass matrix

$$\begin{pmatrix} 2\lambda_1 v_1^2 & -k_{12} v_1 v_2 \\ -k_{12} v_1 v_2 & 2\lambda_2 v_2^2 \end{pmatrix} \text{ with } v_1 = \sqrt{\frac{k_{12}}{2\lambda_1}} v_2, \quad v_2 = \sqrt{\frac{4\lambda_1 |\mu_2^2|}{4\lambda_1 \lambda_2 - k_{12}^2}}$$

$$m_{1,2}^2 = \left[\lambda_2 + \frac{k_{12}}{2} \mp \lambda_2 \sqrt{\left(1 - \frac{k_{12}}{2\lambda_2}\right)^2 + \frac{k_{12}}{2\lambda_1} \frac{k_{12}^2}{\lambda_2^2}} \right] v_2^2$$

For the case $\frac{k_{12}}{\lambda_1}, \frac{k_{12}}{\lambda_2} \ll 1$

$$m_2^2 = 2\lambda_2 v_2^2, \quad m_1^2 = k_{12} v_2^2$$

$$\Rightarrow \mathbf{m_1^2 \ll m_2^2}$$

The model

$$\begin{aligned} L = & (D_\nu^{(1)} H_1)^\dagger (D^{(1)\nu} H_1) - \mu_1^2 H_1^\dagger H_1 - \lambda_1 (H_1^\dagger H_1)^2 \quad (1) \\ & + L_{Fields(1)} + k_{12} (H_1^\dagger H_1) (H_2^\dagger H_2) \\ & + (D_\nu^{(2)} H_2)^\dagger (D^{(2)\nu} H_2) - \mu_2^2 H_2^\dagger H_2 - \lambda_2 (H_2^\dagger H_2)^2 \\ & + L_{Fields(2)} + k_{23} (H_2^\dagger H_2) (H_3^\dagger H_3) \\ & \dots \\ & + (D_\nu^{(N-1)} H_{N-1})^\dagger (D^{(N-1)\nu} H_{N-1}) - \mu_{N-1}^2 H_{N-1}^\dagger H_{N-1} \\ & \quad - \lambda_{N-1} (H_{N-1}^\dagger H_{N-1})^2 \\ & + L_{Fields(N-1)} + k_{N-1,N} (H_{N-1}^\dagger H_{N-1}) (H_N^\dagger H_N) \\ & + (D_\nu^{(N)} H_N)^\dagger (D^{(N)\nu} H_N) - \mu_N^2 H_N^\dagger H_N - \lambda_N (H_N^\dagger H_N)^2 \\ & \quad + L_{Fields(N)}, \end{aligned}$$

Let us assume

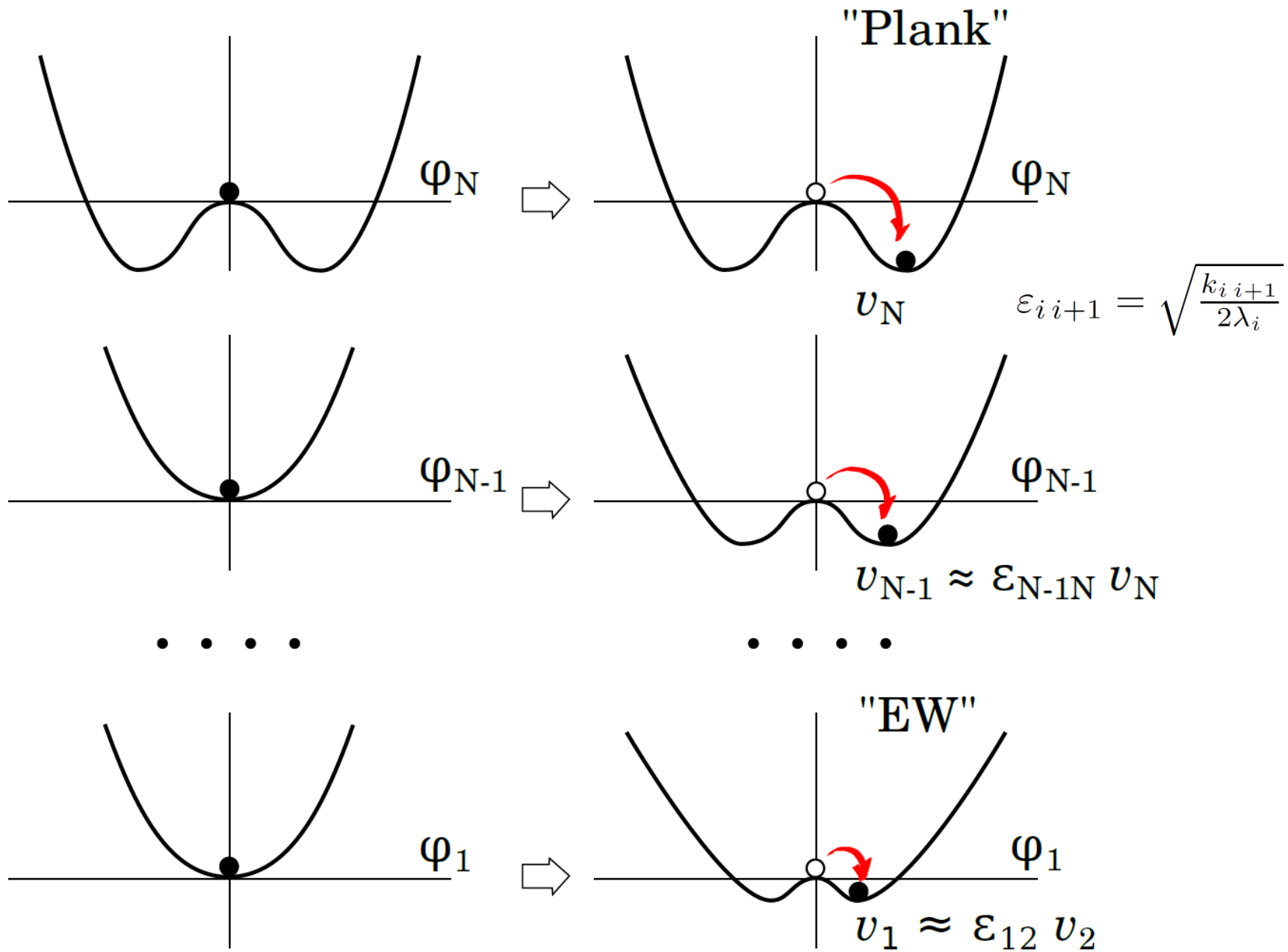
$$\mu_1^2 = \mu_2^2 = \dots = \mu_{N-1}^2 = 0$$

$$\mu_N^2 \neq 0 \quad \mu_N^2 = - | \mu_N^2 |$$

Small mixing parameters

$$\frac{k_{12}}{\lambda_1}, \frac{k_{12}}{\lambda_2}, \frac{k_{23}}{\lambda_2}, \frac{k_{23}}{\lambda_3}, \dots, \frac{k_{N-1N}}{\lambda_{N-1}}, \frac{k_{N-1N}}{\lambda_N} \ll 1$$

Spontaneous symmetry breaking chain



After spontaneous symmetry breaking at the level N

$$m_N^2 \simeq 2\lambda_N v_N^2$$

$$m_{N-1}^2 \simeq k_{N-1N} v_N^2 \simeq \frac{k_{N-1N}}{2\lambda_N} m_N^2$$

...

Induced spontaneous breaking chain leads to

$$v_1^2 \simeq \frac{k_{12}}{2\lambda_1} \frac{k_{23}}{2\lambda_2} \cdots \frac{k_{N-1N}}{2\lambda_{N-1}} v_N^2$$

$$m_1^2 \simeq \frac{k_{12}}{2\lambda_2} \frac{k_{23}}{2\lambda_3} \cdots \frac{k_{N-1N}}{2\lambda_N} m_N^2$$

The mixing matrix has the following form:

$$\begin{pmatrix} x_{11} & x_{12} & 0 & 0 & 0 & \dots & 0 \\ x_{21} & x_{22} & x_{23} & 0 & 0 & \dots & 0 \\ 0 & x_{32} & x_{33} & x_{34} & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & 0 & x_{N-2N-1} & x_{N-1N-1} & x_{N-1N} \\ 0 & 0 & 0 & \dots & 0 & x_{NN-1} & x_{NN} \end{pmatrix}$$

where $x_{11} = 2\lambda_1 v_1^2$, $x_{12} = x_{21} = -k_{12} v_1 v_2$,
 $x_{22} = \lambda_2 v_2^2$, $x_{23} = x_{32} = -k_{23} v_2 v_3$,
 $x_{33} = 2\lambda_3 v_3^2$, $x_{34} = x_{43} = -k_{34} v_3 v_4$,
 $x_{N-1N-1} = 2\lambda_{N-1} v_{N-1}^2$, $x_{N-2N-1} = x_{N-1N-2} = -k_{N-2N-1} v_{N-2} v_{N-1}$,
 $x_{NN} = 2\lambda_N v_N^2$, $x_{N-1N} = x_{NN-1} = -k_{N-1N} v_{N-1} v_N$.

Such NN matrix can be diagonalized using the product of rotation matrices that sequentially lead to a diagonal form of the 22 matrix blocks:

$$\begin{pmatrix} \cos\theta_1 & \sin\theta_1 & 0 & 0 & 0 & \dots & 0 \\ -\sin\theta_1 & \cos\theta_1 & 0 & 0 & \dots & 0 & \\ 0 & 0 & 1 & 0 & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & \dots & 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & \dots & 0 \\ 0 & \cos\theta_2 & \sin\theta_2 & 0 & 0 & \dots & 0 \\ 0 & -\sin\theta_2 & \cos\theta_2 & 0 & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & \dots & 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & \dots & 0 \\ 0 & 1 & 0 & 0 & 0 & \dots & 0 \\ 0 & 0 & 1 & 0 & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & 0 & 0 & \cos\theta_N & \sin\theta_N \\ 0 & 0 & 0 & \dots & 0 & -\sin\theta_N & \cos\theta_N \end{pmatrix}$$

The correction to the mass squared of the scalar h_1 from the loop contribution of the scalar h_i is proportional to

$$m_i^2 \cdot \log(m_i^2/m_1^2)$$

After the diagonalization the interaction vertex of the scalars h_1 and h_i contains the coupling constant being proportional to the product of mixing parameter and therefore

$$\frac{k_{12}}{2\lambda_2} \dots \frac{k_{i-1i}}{2\lambda_N} \cdot m_i^2 \cdot \log(m_i^2/m_1^2) \simeq m_1^2 \cdot \log(m_i^2/m_1^2).$$

The little hierarchy problem does not show up

Concluding remarks

In proposed Toy Model negative μ^2 at “our scale” is induced as a result of spontaneous symmetry breaking at some higher scales.

The hierarchy problem might be resolved due to a product of a number of small mixing parameters.

The construction is rather interesting mathematically

However, in order to be more realistic one has to address many questions:

- Loop corrections and renormgroup evolution ?**
- Collider phenomenology, unique observational signals ?**
- Cosmological implications ?**
(more degrees of freedom, changes in evolution ...)
Do the symmetry breakings in the chain happen simultaneously or at different temperatures?
- Examples addressing the Dark Matter issues ?**

Scalar Portals for DM: 0702143, 0011335, 0509209, 0701035, 1106.3097, 1211.1014, 1502.01361, 1501.02234, 1701.08134, 1903.03616, 2010.09718, 2103.17064...

DM constrains

1. Theoretical constraints:

The perturbative unitarity of VV \rightarrow hh scattering amplitudes

2. Thermal relic abundance:

DM relic density by numerically solving the Boltzmann equation at each parameter point. $\Omega_{\text{DM}} h^2 = 0.1188 \pm 0.0010$

3. Higgs invisible decays:

$$\Gamma_{\text{inv}}^h \leq 0.19 \Gamma_{\text{total}}^h$$

4. Indirect DM detection via gamma rays:

Fermi-LAT data

5. Direct DM detection:

XENON1T 2018, LUX 2016, PandaX 2016 and 2017, CDMSlite, CRESSTII, PICO-60 and DarkSide-50 data

6. DM capture and annihilation in the Sun:

likelihoods from the 79-string IceCube searches for high-energy neutrinos from DM annihilation in the Sun

Implemented in the GAMBIT software.

Thank you !

Back up slides