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 unitariry of VV->VV (V: W,Z) amplitudes: $\left|\mathrm{Re}(a_l)\right| \leq \frac{1}{2}$

Either light Higgs $M_H \lesssim 710\ \mathrm{GeV}$

or

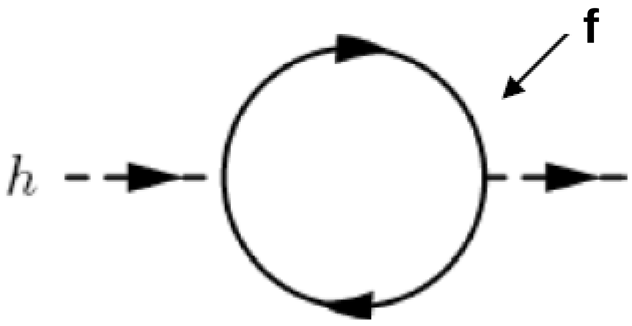
New Physics at $\sqrt{s} \lesssim 1.2\ \mathrm{TeV}$

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 contaning new particle



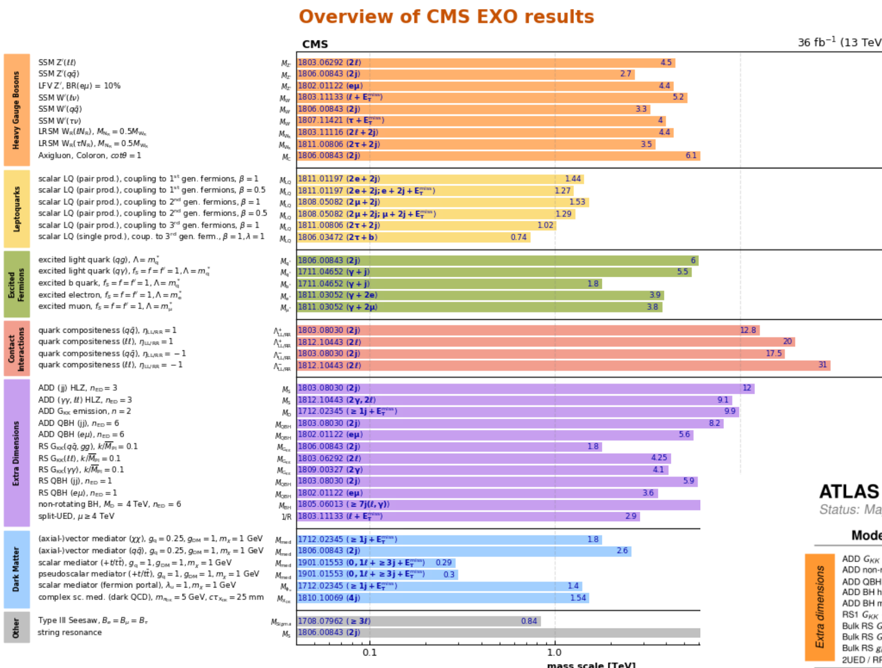
$$|M^2_H(\Lambda) - M^2_H(v)| \sim 3/(8\pi^2)\, y_f^2\, M_f^2 \ln(\Lambda^2/v^2) + \ldots$$

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

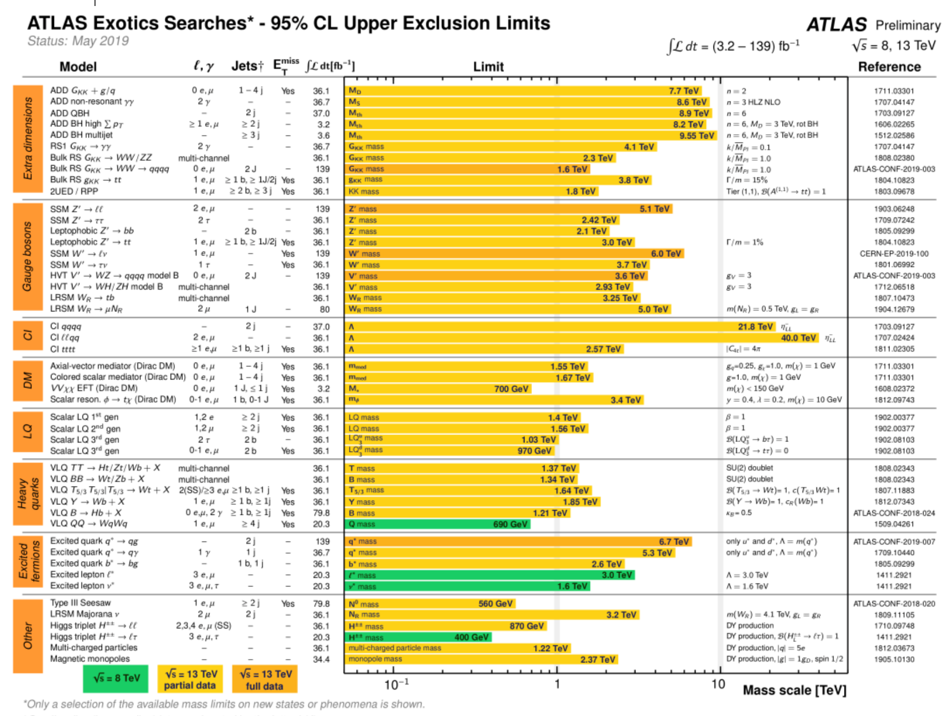
But a new fermion may have a very small coupling to the SM Higgs boson

No solid arguments for a new scale

Many limits already in TeV energy range



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).



Scales

Plank Mass ~ 10^{19} GeV

Grand Unification scale ~10^{15} - 10^{16} GeV ?

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

SM vacuum metastablity scale ~10^{10} - 10^{11} GeV ?

Some BSM models, some SUSY scenarios ~ 10^{3} - 10^{4} GeV ?

EW scale (v_{SM}) ~10^{2} GeV

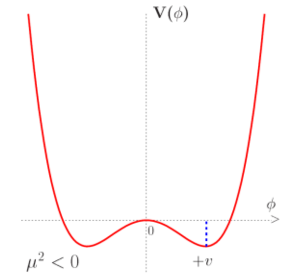
The SM Lagrangian $L_\Phi = D_\mu \Phi^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda(\Phi^\dagger\Phi)^4$

in terms of the fields: $W_\mu^\pm = (W_\mu^1 \mp i W_\mu^2)/\sqrt{2}$

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

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

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



The diagonal mass matrix -> physics states with definite masses

$M_W = M_Z \cos\theta_W$

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

$$\mathbf{M_H^2 = 2\lambda v^2 = -2\mu^2}$$

Why the mass parameter μ^2 is negative?

Simple model

$$L = (D_\nu^{(1)} H_1)^\dagger (D^{(1)\nu} H_1) - \mu_1^2 H_1^\dagger H_1 - \lambda_1 (H_1^\dagger H_1)^2$$

$$+ k_{12} (H_1^\dagger H_1)(H_2^\dagger H_2)$$

$$+ (D_\nu^{(2)} H_2)^\dagger (D^{(2)\nu} H_2) - \mu_2^2 H_2^\dagger H_2 - \lambda_2 (H_2^\dagger H_2)^2$$

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

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

$$\mu`_1^2 = -k_{12} \bullet v_2^2/2 \qquad \text{(for } k_{12} > 0)$$

Negative $\mu`_1^2$ leads to induced spontaneous symmetry breaking at the level 1

0612165, 0709.2750, 1103.2571, 1301.4224, 1306.2329 …

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

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

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

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

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

⇨ $m_1^2 \ll m_2^2$

The model

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

Let us assume

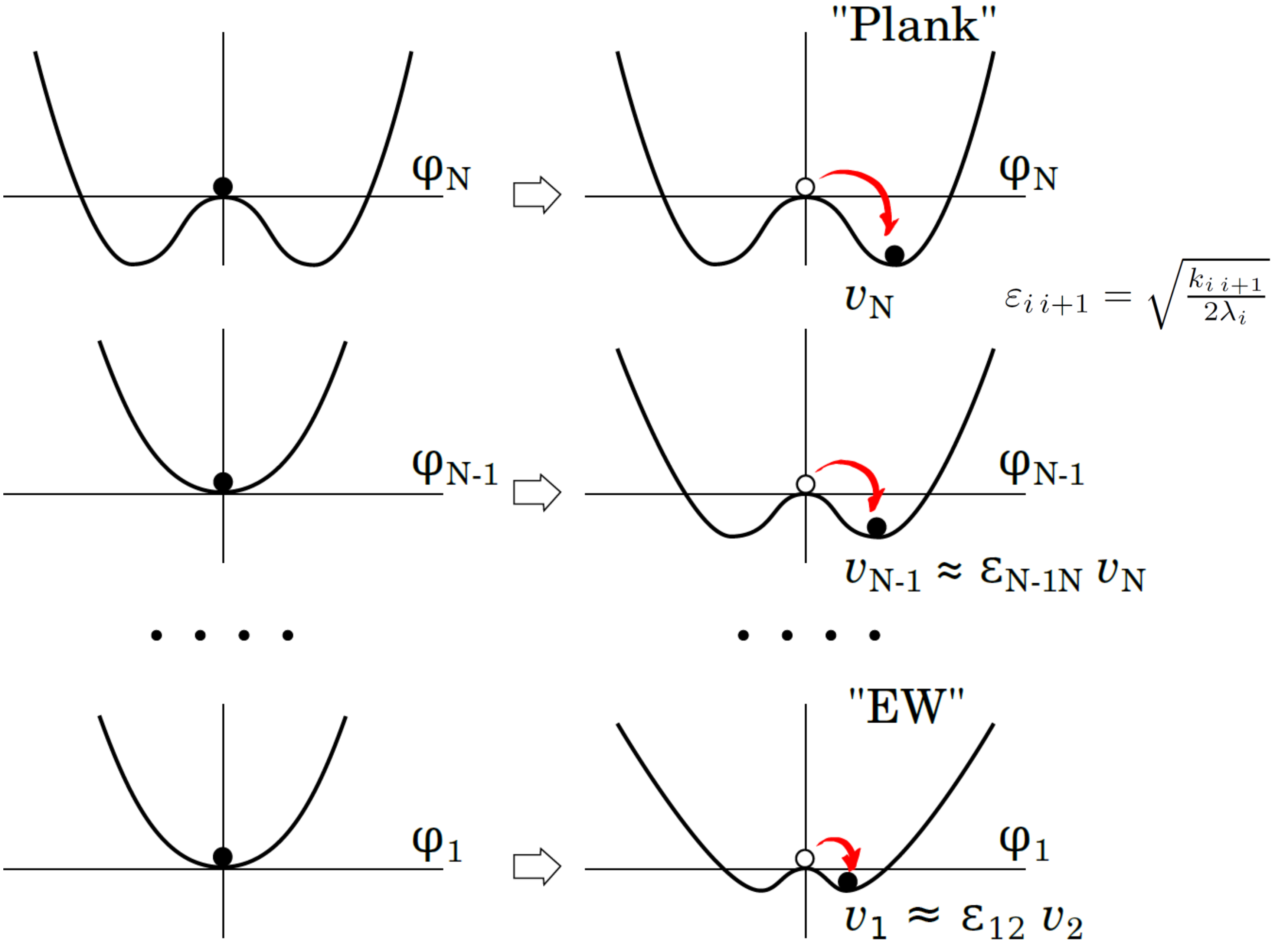
$$\mu_1^2 = \mu_2^2 = ... = \mu_{N-1}^2 = 0$$

$$\mu_N^2 \neq 0 \qquad \mu_N^2 = - \mid \mu_N^2 \mid$$

Small mixing parameters

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

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 h1 and hi contains the coupling constant being proportional to the product of mixing parameter and therefore

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

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 -> hh scattering amplitudes

2. Thermal relic abundance:

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

3. Higgs invisible decays:

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

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