The Higgs Symposium

Higgs boson mass and the scale of new physics

Mikhail Shaposhnikov
July 4, 2012, Higgs at ATLAS and CMS

ATLAS

CMS

Edinburgh, January 10, 2013 – p. 2
July 4, 2012, Higgs at ATLAS and CMS

ATLAS 2011 - 2012

\[ m_H = 126.0 \text{ GeV} \]

\[
\begin{align*}
W, Z, H & \to bb \\
H & \to \tau\tau \\
H & \to WW^{(*)} \to l\nu l\nu \\
H & \to gg \\
H & \to ZZ^{(*)} \to 4l \\
\text{Combined} &
\end{align*}
\]

Signal strength (\( \mu \))

\[
\begin{align*}
\mu &= 1.4 \pm 0.3 \\
\end{align*}
\]
According to CMS,

\[ M_H = 125.8 \pm 0.4\text{(stat)} \pm 0.5\text{(syst)} \text{ GeV,} \]

According to ATLAS,

\[ M_H = 126.0 \pm 0.4\text{(stat)} \pm 0.4\text{(syst)} \text{ GeV.} \]

\[ M_H = 125.2 \pm 0.3\text{(stat)} \pm 0.6\text{(syst)} \text{ GeV.} \]
According to CMS,

\[ M_H = 125.8 \pm 0.4 \text{(stat)} \pm 0.5 \text{(syst)} \text{ GeV}, \]

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\[ M_H = 126.0 \pm 0.4 \text{(stat)} \pm 0.4 \text{(syst)} \text{ GeV}. \]

\[ M_H = 125.2 \pm 0.3 \text{(stat)} \pm 0.6 \text{(syst)} \text{ GeV}. \]

Suppose that this is indeed the Higgs boson of the SM. What does it mean for high energy physics?
There is no new energy scale between the Fermi and Planck scales.

Electroweak scale is determined by Planck physics.

New physics responsible for dark matter, baryon asymmetry of the universe and neutrino masses is hidden below the Fermi scale.
What did we know about the Higgs boson mass before its discovery?

Higgs mass from asymptotically safe SM+gravity

New physics between the Fermi and Planck scales?

Higgs mass from inflation

New physics below the Fermi scale

Conclusions
Self-consistency of the SM

Within the SM the mass of the Higgs boson is an arbitrary parameter which can have any value (if all other parameters are fixed) from

\[ m_{\text{meta}} \simeq 111 \text{ GeV} \] (metastability bound)

to

\[ m_{\text{Landau}} \simeq 1 \text{ TeV} \] (triviality bound)
L. Maiani, G. Parisi and R. Petronzio ’77; Lindner ’85; T. Hambye and K. Riesselmann ’96;...

The Higgs boson self-coupling has a Landau pole at some energy determined by the Higgs mass. For $M_H \approx m_{\text{Landau}} \approx 1 \text{ TeV}$ the position of this pole is close to the electroweak scale.

Higgs mass $1 \text{ TeV} \approx M_1 > M_2 > M_3 \approx 175 \text{ GeV}$
Triviality bound

If $m_H < m_{\text{max}} \sim 175$ GeV the Landau pole appears at energies higher than the Planck scale $E > M_P$.

LHC: The Standard Model is weakly coupled all the way up to the Planck scale
Metastability bound

Krasnikov ’78, Hung ’79; Politzer and Wolfram ’79; Altarelli and Isidori ’94; Casas, Espinosa and Quiros ’94,’96;...; Ellis, Espinosa, Giudice, Hoecker, Riotto ’09;...

The life-time of our vacuum is smaller than the age of the Universe if \( m_H < m_{\text{meta}} \), with \( m_{\text{meta}} \approx 111 \text{ GeV} \) Espinosa, Giudice, Riotto ’07
If the Higgs mass happened to be smaller than $m_{\text{meta}} \sim 111$ GeV, we would be forced to conclude that there must be some new physics beyond the SM, which stabilizes the SM vacuum.

However, already since LEP we know that $m_H > m_{\text{meta}}$ so that new physics is not needed from this point of view.

LHC: SM is a consistent effective theory all the way up to the Planck scale!
Higgs boson mass predictions

Though the Higgs mass cannot be predicted within the Standard Model, embedding it into larger context may fix $M_H$.

Compilation of 81 predictions, Thomas Schücker (as of November 2, 2010)
Higgs boson mass predictions

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- The highest number of predictions by one person (Gogoladze): 12
Higgs boson mass predictions

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- The most precise prediction: $m_H = 161.8033989$ by El Naschie
- The highest number of predictions by one person (Gogoladze): 12
- No predictions in intervals:
  
  $600 - 739, 781 - 1800, 2000 - 10^{18} \text{ GeV}$
Bayesian approach

(As of November 2, 2010)

Bayesian “prediction” : $m_H \simeq 140$ GeV
Extract from M.S., Wetterich ’09:

“Asymptotic safety of gravity and the Higgs boson mass”

“... This results in $M_H = m_{\text{crit}} = 126$ GeV, with only a few GeV uncertainty...”

Also, the same value is a critical point for Higgs inflation

Bezrukov, M.S., ’09
Higgs mass from asymptotically safe gravity
What if gravity is asymptotically safe?

Asymptotic safety = existence of non-Gaussian UV fixed point for gravity Weinberg ’79. Though the theory is non-renormalizable, it is predictive and self-consistent.

Possible consequence: SM + Gravity is a final theory
To be true: all the couplings of the SM must be asymptotically safe or asymptotically free

Problem for:

- U(1) gauge coupling \( g_1 \), \( \mu \frac{dg_1}{d\mu} = \beta_{1}^{\text{SM}} = \frac{41}{96\pi^2} g_1^3 \)
- Scalar self-coupling \( \lambda \), \( \mu \frac{d\lambda}{d\mu} = \beta_{\lambda}^{\text{SM}} = \)
  \[
  = \frac{1}{16\pi^2} \left[ (24\lambda + 12h^2 - 9(g_2^2 + \frac{1}{3}g_1^2))\lambda - 6h^4 + \frac{9}{8}g_2^4 + \frac{3}{8}g_1^4 + \frac{3}{4}g_2^2g_1^2 \right]
  \]
- Fermion Yukawa couplings, t-quark in particular \( h \), \( \mu \frac{dh}{d\mu} = \beta_{h}^{\text{SM}} = \)
  \[
  = \frac{h}{16\pi^2} \left[ \frac{9}{2}h^2 - 8g_3^2 - \frac{9}{4}g_2^2 - \frac{17}{12}g_1^2 \right]
  \]

Landau pole behaviour
Gravity contribution to RG running

Let $x_j$ is a SM coupling. Gravity contribution to RG:

$$\mu \frac{dx_j}{d\mu} = \beta_j^{\text{SM}} + \beta_j^{\text{grav}}.$$

On dimensional grounds

$$\beta_j^{\text{grav}} = \frac{a_j}{8\pi} \frac{\mu^2}{M_P^2(\mu)} x_j.$$

where

$$M_P^2(\mu) = M_P^2 + 2\xi_0 \mu^2,$$

with $M_P = (8\pi G_N)^{-1/2} = 2.4 \times 10^{18}$ GeV, $\xi_0 \approx 0.024$ from a numerical solution of FRGE.
Computations of $a_j$ are ambiguous and controversial

Robinson and Wilczek ’05, Pietykowski ’06, Toms ’07&’08, Ebert, Plefka and Rodigast ’07, Narain and Percacci ’09, Daum, Harst and Reuter ’09, Zanusso et al ’09, Folkerts, Litim and Pawlowski ’11, Ellis, Mavromatos ’12 ...

Many works get for gauge couplings a universal value

$\lambda_1 = \lambda_2 = \lambda_3 < 0$: U(1) gauge coupling get asymptotically free in asymptotically safe gravity

$\lambda_\lambda \sim 2.6 > 0$ according to Percacci and Narain ’03 for scalar theory coupled to gravity

$\lambda_q > 0$ ?? The case $\lambda_q > 0$ is not phenomenologically acceptable - only massless fermions are admitted
Suppose that indeed \( a_1 < 0, \ a_h < 0, \ a_\lambda > 0 \), what is found in a number of computations. Then the Higgs mass is predicted to be coming from solution of equation

\[
\lambda(M_P) = 0
\]

with uncertainty of few hundreds of MeV. Simultaneously, it is required that \( \beta_\lambda(M_P) \ll 1 \).
Computation of $M_H$

Definition: “$\overline{MS}$ benchmark Higgs mass $M_{crit}$" is defined from equations

$$\lambda(\mu_0) = 0, \quad \beta^\text{SM}_\lambda(\mu_0) = 0$$

together with parameter $\mu_0$, assuming that all parameters of the SM, except the Higgs mass, are fixed.
Most recent computation of $M_{\text{crit}}$ (Bezrukov et al, May 13, 2012), incorporating $O(\alpha\alpha_s)$ two-loop matching and 3-loop running of coupling constants (Chetyrkin, Zoller, May 13, 2012)

$$m_{\text{crit}} = [129.0 + \frac{m_t - 172.9}{1.1} \times 2.2 - \frac{\alpha_s - 0.1184}{0.0007} \times 0.56] \text{ GeV},$$

Theoretical uncertainties: $\pm 1.2$ GeV (different sources are summed quadratically) or $\pm 2.3$ GeV (different sources are summed linearly).

Effect of contributions $\propto y_t^4, y_t^2\lambda^2, \lambda^4$ (Degrassi et al., May 29, 2012): shift of the Higgs mass by $100 - 200$ MeV. Quadratic theoretical uncertainty is reduced to $\sim 0.8$ GeV.
Higgs mass $M_h=124.7$ GeV

Higgs mass $M_h=125.3$ GeV

Higgs mass $M_h=126$ GeV

Higgs mass $M_h=126.6$ GeV
To decrease uncertainty: (the LHC accuracy can be as small as 200 MeV!)

- Compute remaining two-loop $\mathcal{O}(\alpha^2)$ corrections to pole - $\overline{MS}$ matching for the Higgs mass and top masses. Theoretical uncertainty can reduced to $\sim 0.5$ GeV, due to irremovable non-perturbative contribution $\sim \Lambda_{QCD}$ to top quark mass.

- Measure better t-quark mass (present error in $m_H$ due to this uncertainty is $\sim 4$ GeV at $2\sigma$ level): construct t-quark factory – $e^+e^-$ or $\mu^+\mu^-$ linear collider with energy $\sim 200 \times 200$ GeV. The same conclusion - Alekhin et al, ’12

- Measure better $\alpha_s$ (present error in $m_H$ due to this uncertainty is $\sim 1$ GeV at $2\sigma$ level)
Behaviour of the Higgs self-coupling

Higgs mass $M_h=124$ GeV

Higgs mass $M_h=125$ GeV

Higgs mass $M_h=126$ GeV

Higgs mass $M_h=127$ GeV

Scale $\mu$, GeV
New Physics between the Fermi and Planck scales?
From two equations

\[ \lambda(\mu_0) = 0, \quad \beta^{\text{SM}}_\lambda(\mu_0) = 0 \]

one can determine not only the Higgs mass, but also the scale \( \mu_0 \).

\( \mu_0 \) determined by the EW physics gives the Planck scale, \( \mu_0 \approx M_P \)!
Numerical coincidence?

Fermi scale is determined by the Planck scale (or vice versa)?

This relation is generically spoiled if new physics exists between the Fermi and Planck scales.

Argument in favour of absence of new physics scales between Fermi and Planck.
Higgs mass and inflation
non-minimal coupling of Higgs field to gravity

\[ \Delta S = \int d^4x \sqrt{-g} \left\{ -\frac{\xi h^2}{2} R \right\} \]

Feynman, Brans, Dicke,...

Consider large Higgs fields \( h \).

- Gravity strength: \( M_P^{\text{eff}} = \sqrt{M_P^2 + \xi h^2} \propto h \)
- All particle masses are \( \propto h \)

For \( h > \frac{M_P}{\xi} \) (classical) physics is the same (\( M_W / M_P^{\text{eff}} \) does not depend on \( h \))!

Existence of effective flat direction, necessary for successful inflation.
Formalism: go from Jordan frame to Einstein frame with the use of conformal transformation:

\[ \hat{g}_{\mu\nu} = \Omega^2 g_{\mu\nu} , \quad \Omega^2 = 1 + \frac{\xi h^2}{M_P^2} \]

Potential in Einstein frame
Inflaton potential and observations

If inflaton potential is known one can make predictions and compare them with observations.

- \( \delta T / T \) at the WMAP normalization scale \( \sim 500 \) Mpc

- The value of spectral index \( n_s \) of scalar density perturbations

\[
\left\langle \frac{\delta T(x)}{T} \frac{\delta T(y)}{T} \right\rangle \propto \int \frac{d^3 k}{k^3} e^{i k(x-y)} k^{n_s - 1}
\]

- The amplitude of tensor perturbations \( r = \frac{\delta \rho_s}{\delta \rho_t} \)

These numbers can be extracted from WMAP observations of cosmic microwave background. Higgs inflation: one new parameter, \( \xi \rightarrow \) two predictions.
CMB parameters—spectrum and tensor modes

![Graph showing the parameters of CMB (Cosmic Microwave Background) spectrum and tensor modes with various models and their corresponding regions in the parameter space. The graph includes data from WMAP5 and various theoretical models such as $\lambda\phi^4$, $m^2\phi^2$, N-flation $m^2\phi^2$, SM+$\xi h^2R$, and HZ. The parameter space is marked with different colored regions, each representing a different model or parameter set.]
Radiative corrections to inflationary potential: Higgs inflation works only for $\lambda(M_P/\sqrt{\xi}) > 0$ (Bezrukov, MS). Numerically, $M_H > M_{\text{crit}} - 200$ MeV. The equality leads to the minimal value of non-minimal coupling, $\xi \simeq 700$, what extends the region of weak coupling of the theory.

\[ M_H > M_{\text{crit}} \]

\[ M_H < M_{\text{crit}} \]
New Physics below the Fermi scale
SM + Gravity and no new physics?

The most conservative hypothesis: we have Standard Model + Gravity and nothing else.

Ruled out by:

- Observations of neutrino oscillations (in the SM neutrinos are massless and do not oscillate)
- Evidence for Dark Matter (SM does not have particle physics candidate for DM)
- No antimatter in the Universe in amounts comparable with matter (baryon asymmetry of the Universe is too small in the SM)
the SM

Three Generations of Matter (Fermions) spin $\frac{1}{2}$

<table>
<thead>
<tr>
<th>I</th>
<th>II</th>
<th>III</th>
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<tbody>
<tr>
<td>mass</td>
<td>charge</td>
<td>name</td>
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<tr>
<td>$\frac{2}{3}$</td>
<td>$\frac{2}{3}$</td>
<td>$\frac{2}{3}$</td>
</tr>
<tr>
<td>$2.4$ MeV</td>
<td>$1.27$ GeV</td>
<td>$171.2$ GeV</td>
</tr>
<tr>
<td>$d$ down</td>
<td>$c$ charm</td>
<td>$t$ top</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quarks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>Right</td>
<td></td>
</tr>
<tr>
<td>$4.8$ MeV</td>
<td>$104$ MeV</td>
<td>$4.2$ GeV</td>
</tr>
<tr>
<td>$\frac{-1}{3}$</td>
<td>$\frac{-1}{3}$</td>
<td>$\frac{-1}{3}$</td>
</tr>
<tr>
<td>$\nu_e$ electron neutrino</td>
<td>$\nu_\mu$ muon neutrino</td>
<td>$\nu_\tau$ tau neutrino</td>
</tr>
<tr>
<td>Leptons</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>Right</td>
<td></td>
</tr>
<tr>
<td>$0.511$ MeV</td>
<td>$105.7$ MeV</td>
<td>$1.777$ GeV</td>
</tr>
<tr>
<td>$-1$</td>
<td>$-1$</td>
<td>$-1$</td>
</tr>
<tr>
<td>$e$ electron</td>
<td>$\mu$ muon</td>
<td>$\tau$ tau</td>
</tr>
<tr>
<td>Bosons (Forces) spin 1</td>
<td></td>
<td></td>
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<tr>
<td>$0$</td>
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<td></td>
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</tr>
<tr>
<td>$91.2$ GeV</td>
<td></td>
<td>$&gt;114$ GeV</td>
</tr>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma$ photon</td>
<td></td>
<td>$H$ Higgs boson</td>
</tr>
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<tr>
<td>spin 0</td>
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</table>

Edinburgh, January 10, 2013 – p. 37
Right-handed neutrinos. What else?
the SM

Three Generations of Matter (Fermions) spin $\frac{1}{2}$

- **Quarks**:
  - Mass: $\frac{2}{3}$, Charge: $\frac{2}{3}$, Name: $u$, Mass: $2.4$ MeV, Charge: $\frac{2}{3}$, Name: $c$, Mass: $1.27$ GeV, Charge: $\frac{2}{3}$, Name: $t$, Mass: $171.2$ GeV
  - Mass: $-\frac{1}{3}$, Charge: $-\frac{1}{3}$, Name: $d$, Mass: $4.8$ MeV
  - Mass: $-\frac{1}{3}$, Charge: $-\frac{1}{3}$, Name: $s$, Mass: $104$ MeV
  - Mass: $-\frac{1}{3}$, Charge: $-\frac{1}{3}$, Name: $b$, Mass: $4.2$ GeV

- **Leptons**:
  - Mass: $0$ eV, Charge: $0$, Name: $e$, Mass: $0.511$ MeV
  - Mass: $0$ eV, Charge: $0$, Name: $\mu$, Mass: $105.7$ MeV
  - Mass: $0$ eV, Charge: $0$, Name: $\tau$, Mass: $1.777$ GeV

- **Bosons (Forces)**:
  - Mass: $91.2$ GeV, Charge: $0$, Name: $Z$, Spin: $0$
  - Mass: $80.4$ GeV, Charge: $\pm 1$, Name: $W$, Spin: $1$
  - Mass: $>114$ GeV, Charge: $0$, Name: $H$, Spin: $0$
the $\nu$MSM

Three Generations of Matter (Fermions) spin $\frac{1}{2}$

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<td>2.4 MeV</td>
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<td>$\frac{2}{3}$</td>
<td>$\frac{2}{3}$</td>
</tr>
</tbody>
</table>

Quarks

- $d$: down, 4.8 MeV, $-\frac{1}{3}$
- $s$: strange, 104 MeV, $-\frac{1}{3}$
- $b$: bottom, 4.2 GeV, $-\frac{1}{3}$

Leptons

- $e$: electron, 0.511 MeV, $-1$
- $\mu$: muon, 105.7 MeV, $-1$
- $\tau$: tau, 1.777 GeV, $-1$

Bosons (Forces) spin 1

- $Z^0$: weak force, 91.2 GeV
- $W^\pm$: weak force, 80.4 GeV

Higgs boson

$>114$ GeV

Edinburgh, January 10, 2013 – p. 40
The less conservative hypothesis: there are no intermediate energy scales between the Fermi scale $100 \text{ GeV}$ and the Planck scale $10^{18} \text{ GeV}$.

Role of $N_1$ with mass in keV region: dark matter

Role of $N_2$, $N_3$ with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe, all due to the Higgs boson.
Constraints on DM sterile neutrino $N_1$

- **Stability.** $N_1$ must have a lifetime larger than that of the Universe.

- **Production.** $N_1$ are created in the early Universe in reactions $l\bar{l} \rightarrow \nu N_1$, $q\bar{q} \rightarrow \nu N_1$ etc. We should get correct DM abundance.

- **Structure formation.** If $N_1$ is too light it may have considerable free streaming length and erase fluctuations on small scales. This can be checked by the study of Lyman-$\alpha$ forest spectra of distant quasars and structure of dwarf galaxies.

- **X-rays.** $N_1$ decays radiatively, $N_1 \rightarrow \gamma \nu$, producing a narrow line which can be detected by X-ray telescopes (such as Chandra or XMM-Newton). This line has not been seen yet.
Important: DM sterile neutrino production requires the presence of large, $\Delta L/L > 2 \times 10^{-3}$ lepton asymmetry at temperature $T \sim 100$ MeV. It can only be produced in the $\nu$MSM.
**Constraints on BAU sterile neutrinos $N_{2,3}$**

Baryon asymmetry generation: CP-violation in neutrino sector+singlet fermion oscillations+sphalerons

- **BAU generation** requires out of equilibrium: mixing angle of $N_{2,3}$ to active neutrinos cannot be too large

- **Neutrino masses.** Mixing angle of $N_{2,3}$ to active neutrinos cannot be too small

- **BBN.** Decays of $N_{2,3}$ must not spoil Big Bang Nucleosynthesis

- **Experiment.** $N_{2,3}$ have not been seen yet
Constraints on $U^2$ coming from the baryon asymmetry of the Universe, from the see-saw formula, from the big bang nucleosynthesis and experimental searches. Left panel - normal hierarchy, right panel - inverted hierarchy. Canetti et al.
Crucial tests and experiments
Experiments, which will be done anyway

- Crucial experimental test - the LHC. The $\nu$MSM prediction - no deviations from the SM (Perhaps, LHCb upgrade to search for N?)

- WIMP searches: no WIMPS in the $\nu$MSM

- Unitarity of PMNS neutrino mixing matrix: $\theta_{13}, \theta_{23} - \pi/4$, type of neutrino mass hierarchy, Dirac CP-violating phase

- Absolute neutrino mass. The $\nu$MSM prediction: $m_1 \lesssim 10^{-5}$ eV (from DM). Then $m_2 \approx 5 \times 10^{-2}$ eV, $m_3 \approx 9 \times 10^{-3}$ eV or $m_{2,3} \approx 5 \times 10^{-2}$ eV.
  (Double $\beta$ decay, Bezrukov)

Normal hierarchy: $1.3$ meV < $m_{\beta\beta}$ < $3.4$ meV
Inverted hierarchy: $13$ meV < $m_{\beta\beta}$ < $50$ meV

- Crucial cosmological test - precise measurements of cosmological parameters $n_s$, $r$, $\Delta n_s \approx 0.004$
New dedicated experiments
Construction of t-quark factory – $e^+e^-$ or $\mu^+\mu^-$ linear collider with energy $\simeq 200 \times 200$ GeV.

Precise measurement of top and Higgs masses, to elucidate the relation between the electroweak and Planck scales.
X-ray telescopes similar to *Chandra* or *XMM-Newton* but with better energy resolution: narrow X-ray line from decay $N_e \rightarrow \nu \gamma$

One needs:

- Improvement of spectral resolution up to the natural line width $(\Delta E/E \sim 10^{-3})$.
- $\text{FoV} \sim 1^\circ$ (size of a dwarf galaxies).
- Wide energy scan, from $\mathcal{O}(100) \text{ eV}$ to $\mathcal{O}(50) \text{ keV}$. 
Search for $N_2$, $N_3$

Challenge - from baryon asymmetry: $\theta^2 \lesssim 5 \times 10^{-7} \left( \frac{\text{GeV}}{M} \right)$ CERN

SPS is the best existing machine to uncover new physics below the electroweak scale. For $l \sim 100$ m detector.

Gorbunov, MS
Sketch of the proposed section detector of several kilometer total length; each standard section of length $l_{\parallel} \sim 100\,\text{m}$, height $5\,\text{m}$ and width $l_{\perp} \sim 5\,\text{m}$ may operate independently.
Conclusions
LHC experiments provide a strong evidence that the SM is a self-consistent effective theory all the way up to the Planck scale.

The case of $M_H = M_{crit}$ is very peculiar: if this is indeed the case, this is a strong indication for the absence of new energy scales between the Fermi and Planck scales.

The new physics responsible for neutrino masses, dark matter and baryon asymmetry of the Universe can be below the Fermi scale and associated with extension of the SM by 3 Majorana fermions with masses in keV - GeV region.

There are plenty of experiments which can confirm or reject the minimal model.