The New Minimal Standard Model

HOOMAN DAVOUDIASL (IAS)

Based on :

H. D., R. Kitano, T. Li, and H. Murayama,

hep-ph/0405097.

The Minimal Standard Model (MSM) has been a great success of the 20th century physics. Classical General Relativity and the MSM together have accurately described nearly all observed phenomena in our universe, based on a Lagrangian with only 19 independent parameters:

$$\mathcal{L}^{GR}_{MSM} = \mathcal{L}_{MSM} + \bar{M}_P^2 R \quad ; \quad \bar{M}_P = 2.4 \times 10^{18}\ GeV.$$

$\mathcal{L}^{GR}_{MSM}$ is invariant under the gauge group $G_{MSM} = SU(3)_C \times SU(2)_L \times U(1)_Y$, has 3 generations of quarks and leptons plus one scalar Higgs doublet H : $\langle H \rangle = v \neq 0 \Rightarrow SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$.

The MSM was constructed to explain the observed experimental data, with a minimal number of degrees of freedom, and did not address purely theoretical or aesthetic issues, like quantum gravity or the hierarchy problem.

Until recently, most proposed extensions of the MSM could only be motivated by such considerations without urgent experimental clues. However, all of these proposals have been shown to suffer from serious phenomenological problems, such as excessive FCNC's, CP̸, proton decay, cosmological relics, --- .

However, over the last several years, we have witnessed important experimental discoveries that provide a solid foundation ($>5\sigma$) for extending the MSM. These are:

* Dark Matter: Compelling evidence for a non-baryonic matter component. Spergel et al., Ast. J. Suppl. 148, 175 (2003).

* Dark Energy: Concordance of evidence from CMB anisotropy, galaxy clusters, high-redshift Type IA SN.

Verde et al., Mon. Not. Roy. Astron. Soc. 335, 432 (2002).
Perlmutter et al., Astrophys. J. 517, 565 (1999).
Riess et al., Astron. J. 116, 1009 (1998).

* Atmospheric and solar ν oscillations, supported by reactor $\bar{\nu}$ data → ν masses and mixings.

Fukuda et al., Phys. Rev. Lett. 81, 1562 (1998).
Ahmed et al., nucl-ex/0309004.
Eguchi et al., Phys. Rev. Lett. 92, 071301 (2004).

* Cosmic baryon asymmetry, unexplained by MSM.
* Nearly scale-invariant, adiabatic, Gaussian density fluctuations → Inflation (not strictly proven, but compelling). Komatsu et al., Astrophys. J. Suppl. 148, 119 (2003).

Following the MSM, we adopt the principle of "minimal degrees of freedom" to write down the most general Lorentz-invariant, renormalizable, 4-d QFT, to describe all current data. The result is the

New Minimal Standard Model (NMSM).

* Dark Matter: Real Klein-Gordon field S, singlet under G_{MSM}. Stability → Symmetry under Z_2.

$$\mathcal{L}_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{k}{2} |H|^2 S^2 - \frac{h}{4!} S^4 .$$

We show S is still a viable candidate (correct abundance, lack of detection so far, ...). Burgess et al., Nucl. Phys. B 619, 709 (2001).

* Dark Energy: Cosmological Constant.

$\mathcal{L}_\Lambda = \Lambda^4$; $\Lambda = 2.3 \times 10^{-3}$ eV.

* ν masses and bi-large mixings:

$\Delta m^2_{atm} \approx 2.5 \times 10^{-3}$ eV^2 , $\Delta m^2_{sol} \approx 7 \times 10^{-5}$ eV^2.

$(L\tilde{H})^2/\bar{M}_P$, $\tilde{H} = i\sigma_2 H^*$, gives $m_\nu \lesssim 10^{-5}$ eV , too small!

Currently, we only need 2 massive ν's.

m_ν: Dirac or Majorana from minimality alone.

Introduce 2 right-handed ν's : N_α , $\alpha = 1, 2$.

* Baryon asymmetry:

Cannot be explained by initial conditions, if we accept the inflationary paradigm. Given N_α, leptogenesis $\rightarrow \Delta B \neq 0$. Minimality favors the see-saw generated Majorana masses.

Decays of N_α coupled with EW anomaly (sphalerons)

$\rightarrow \Delta B \neq 0$. We have:

$$\mathcal{L}_N = \bar{N}_\alpha \, i\not\partial N_\alpha - \left(\frac{M_\alpha}{2} N_\alpha N_\alpha + h_\nu^{\alpha i} N_\alpha L_i \tilde{H} + \text{c.c.}\right).$$

$\mathcal{L}_N$ has 11 real parameters, enough to accommodate current light-ν data with 7 real parameters [2 masses, 3 mixing angles, 2 phases (Dirac or Majorana)].

Sufficient CP in leptogenesis $\Rightarrow M_\alpha > 10^{10}$ GeV.

Endoh et al., Phys. Rev. Lett. 89, 231601 (2002).

Barger et al., Phys. Lett. B 583, 173 (2004).

* Inflation: To explain observed structure, velocity field, and CMB anisotropy. Real Klein-Gordon field φ:

$$\mathcal{L}_\varphi = \frac{1}{2}\partial_\mu\varphi\,\partial^\mu\varphi - \frac{1}{2}m^2\varphi^2 - \frac{\mu}{3!}\varphi^3 - \frac{\kappa}{4!}\varphi^4 ,$$

(linear term absorbed by a shift).

$\varphi > M_P \Rightarrow$ Chaotic inflation. Current data prefer the φ^2-term with $m \simeq 1.8\times10^{13}$ GeV, $\mu \lesssim 10^6$ GeV, $\kappa \lesssim 10^{-14}$.

Other renormalizable couplings:

$$V_{RH} = \mu_1\varphi\,|H|^2 + \mu_2\varphi S^2 + \kappa_H\varphi^2|H|^2 + \kappa_S\varphi^2 S^2 + \left(y_N^{\alpha\beta}\varphi N_\alpha N_\beta + \text{c.c.}\right).$$

Thermal leptogenesis $\Rightarrow T_{RH} > M_\alpha \Rightarrow T_{RH} \gtrsim 10^{10}$ GeV.

$\Rightarrow \mu_{1,2} \gtrsim 10^9$ GeV or $y_N^{\alpha\beta} \gtrsim 10^{-4}$.

These do not spoil the flatness of the φ potential if $\kappa_{H,S} \lesssim 10^{-6}$.

$$\mathcal{L}_{NMSM} = \mathcal{L}^{GR}_{MSM} + \mathcal{L}_{S} + \mathcal{L}_{\Lambda} + \mathcal{L}_{N} + \mathcal{L}_{\varphi} - V_{RH}.$$

NMSM valid up to M_P. All higher dimensional operators suppressed by M_P. ⇒ No excessive FC effects, CP, proton decay, deviation from EW precision data.

Constraints on the NMSM

Stability and triviality bounds. 1-loop gauge and top Yukawa couplings same as in the MSM.

The scalar sector: $t \equiv \ln \mu$, y: Top Yukawa

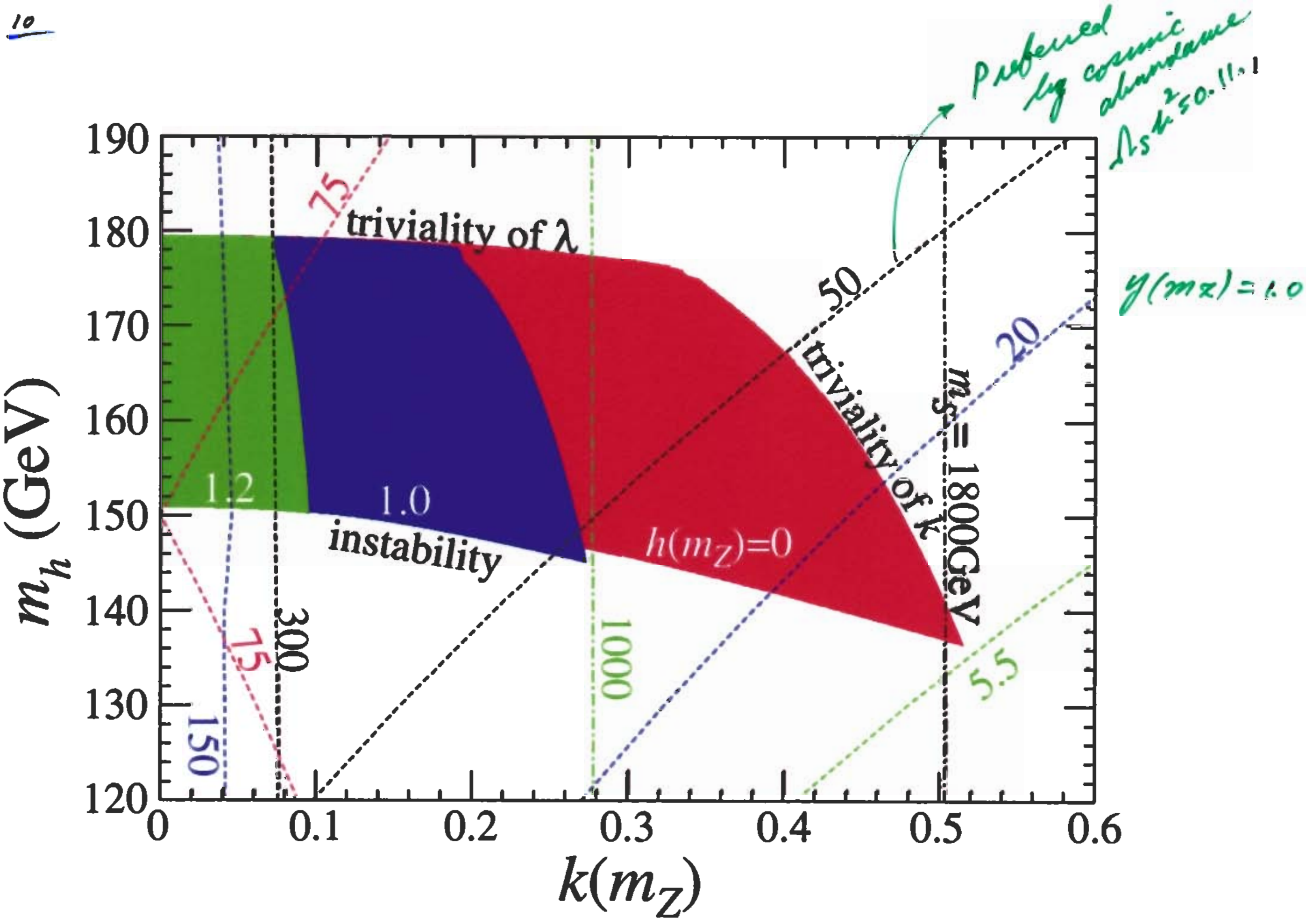
$$(4\pi)^2 \frac{d\lambda}{dt} = 12\lambda^2 + 12\lambda y^2 - 12 y^4 - 3\lambda(g'^2 + 3g^2) + \frac{3}{4}\left[2g^4 + (g'^2 + g^2)^2\right] + k^2$$

$$(4\pi)^2 \frac{dk}{dt} = k\left[4k + 6\lambda + h + 6y^2 - \frac{3}{2}(g'^2 + 3g^2)\right]$$

$$(4\pi)^2 \frac{dh}{dt} = 3h^2 + 12k^2$$

Stability below M_P: $\lambda, k, h > 0$.

Triviality below M_P: $\lambda, k, h < 10$.



$h(m_Z) = 0, 1.0, 1.2$, region disappears for $h(m_Z) > 1.3$.

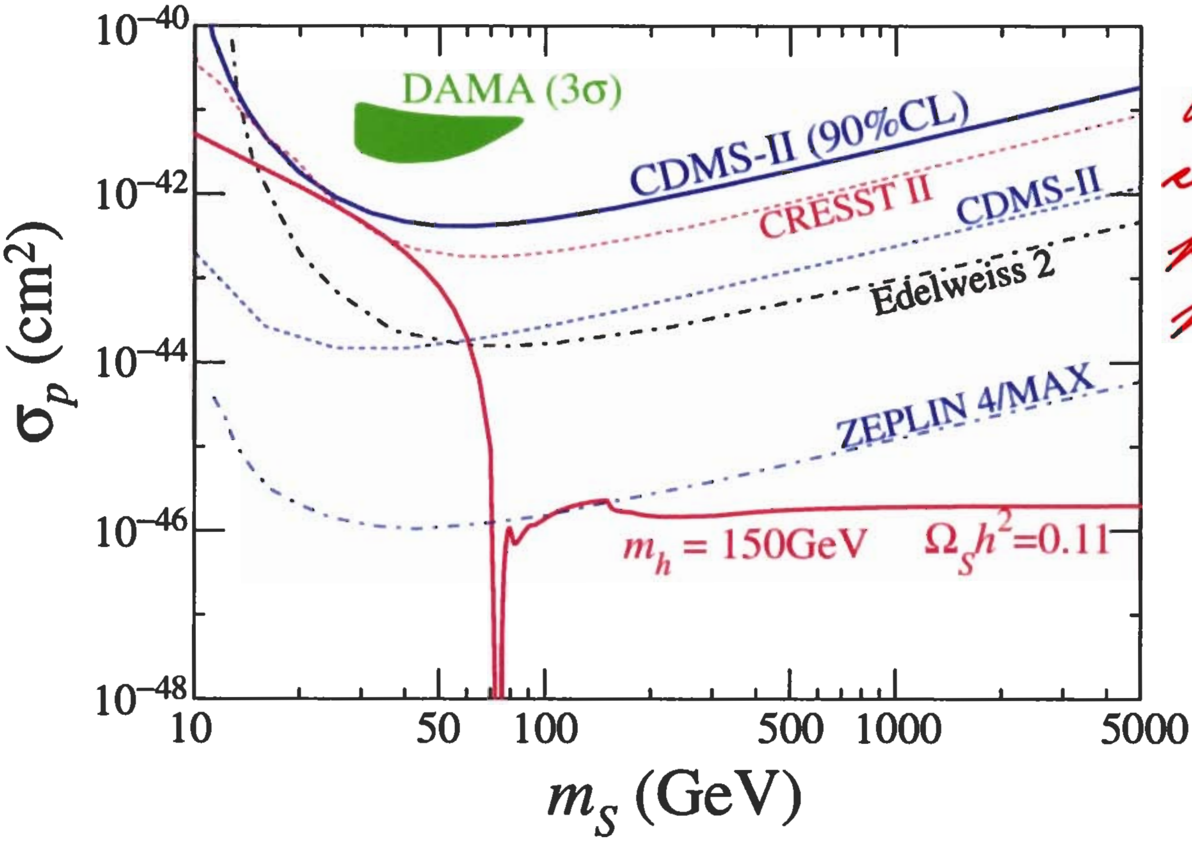
Prediction: $130\ \text{GeV} < m_h < 180\ \text{GeV}$, consistent with precision EW $m_h \lesssim 200$ GeV, while beyond LEP II reach.

$\sigma_{ann}^{(DM)} \propto k^2$ and depends on (m_S, m_h).

J. McDonald, Phys. Rev. D50, 3637 (1994).

We improved the abundance calculation using HDECAY and included the s-channel H-exchange in $SS \to HH$, left out by previous work. $\Omega_S h^2 = (\Omega_m - \Omega_b) h^2 = 0.11$.

Triviality and stability $\Rightarrow$ $5.5\ \text{GeV} < m_S < 1.8\ \text{TeV}$.



Underground search promising for $m_S \lesssim m_h/2$.

Observable Consequences of the NMSM

DM searches: Scattering of S on nuclei, dominated by H-exchange.
McDonald; Burgess et al.

For m_h = 150 GeV: NMSM consistent with CDMS-II, unable to explain controversial DAMA data.

Collider: Invisible decay $h \to SS$ at LHC or at LC.

For $m_S > m_h/2$ search very difficult

W-fusion: $qq \to qq\,SS + g(\gamma)$, tagged forward jets, large p_T $\oplus$ additional isolated jet (γ).

Inflation: φ^2 chaotic inflation spectral index 0.96.

May be confirmed by WMAP or Planck.

Tensor / Scalar = 0.16

$w = -1$ (Cosmological Constant).

Neutrinos: Majorana ν's $\Rightarrow$ ν-less double β-decay.

(One massless $\nu \rightarrow$ Signal possible for inverted hierarchy)

NMSM will need extension if:

Particles other than h and S at weak scale, DAMA is confirmed, signals such as $\mu \rightarrow e\gamma$, $\not{CP}$ beyond CKM and MNS phases, $\sin 2\beta(B \rightarrow \phi K_S) \neq \sin 2\beta(B \rightarrow \psi K_S)$, confirmation of LSND, $\Omega_{tot} \neq 1$, p-decay, ...

NMSM

- Extreme fine-tuning: 10^{-120} for $\mathcal{L}_\Lambda$ and $\left(\frac{m_h}{M_P}\right)^2 \sim 10^{-32}$, inflation; these are aesthetic issues.
- No explanation of fermion masses, $\theta_{QCD} \lesssim 10^{-10}$. $\mathbb{Z}_2$ is imposed by hand.
- However, it explains all known phenomena with only 6 new degrees of freedom (S, N_α, φ) and is free from phenomenological problems, providing a baseline.
- Future work: improving stability and triviality bounds to 2-loop level; studying collider search strategies for S when $m_S > m_h/2$; indirect DM search important for this mass region, since collider and direct searches are challenging; other possibilities for 1-field inflation.