New Physics Beyond the Standard Model

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Outline

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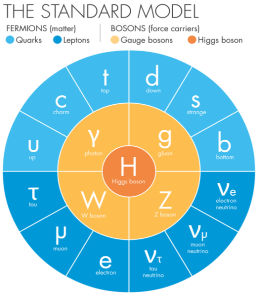
Why New Physics Beyond the Standard Model?

- The SM describes the interactions between quarks, leptons and the force carriers very successfully.



But!

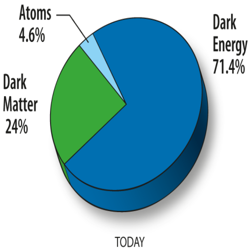
THERE ARE PROBLEMS

? No dark matter (DM) candidate in the SM.

? Neutrinos are massless.

? Anomalies

- In 1933, Zwicky noticed that the mass of luminous matter in the Coma cluster is much smaller than its total mass.

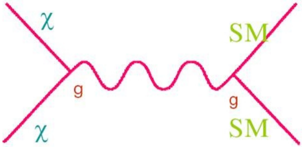


- In 1970, the existence of DM be considered, as the explanation for the anomalous rotation curves of spiral galaxies.

- **DM candidate must be non-baryonic, with the following properties:**
  1. **Stable**
  2. **Electrically neutral, no color**
  3. **Weakly interacting massive particle (WIMP)**
  4. **Relic abundance compatible to observation**

- **DM candidate must satisfy the direct/indirect detection results and the LHC search.**

- **DM was in thermal equilibrium with the SM particles in the early Universe, and decoupled when they were non-relativistic.**

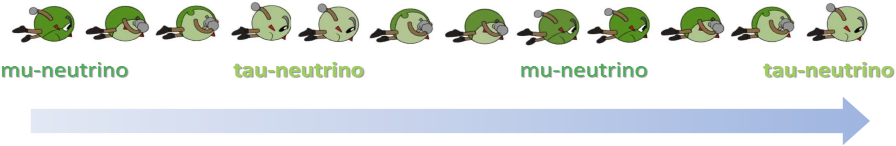


- **DM freezes out due to the expansion of Universe. The relic density today**

$$\Omega_\chi \approx \frac{7 \times 10^{-27} cm^3\, s^{-1}}{\langle \sigma_{ann} v \rangle}$$

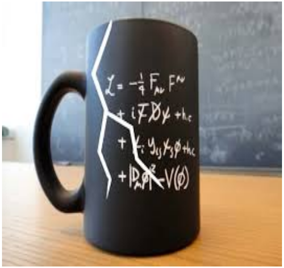
- **What are neutrinos? Neutrinos:**
  1. **are fundamental particles like electrons and quarks, but without electric charge,**
  2. **can easily pass through even the Earth, but can interact with matter very rarely,**
  3. **have 3 types: electron-neutrinos (ν_e), muon-neutrinos (ν_μ) and tau-neutrinos (ν_τ),**
  4. **have been assumed to have no mass.**

- **If neutrinos have mass, neutrinos change their type from one type to the other.**



- **The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass."**


The SM can not explain a number of phenomena such as the presence of DM, non-zero neutrino masses and further anomalies.



WE NEED!

NEW PHYSICS BEYOND THE STANDARD MODEL

To address (at least one of) these issues, one may need to extend the SM gauge group and/or its particle content and go to physics BSM as follows:

1. Gauge group extension: BLSM(IS), $U(1)'$ models, etc.
2. Particle content extension: 2HDMs, 2HDM with singlet scalar, etc.
3. SUSY models: MSSM, NMSSM, BLSSM, etc.

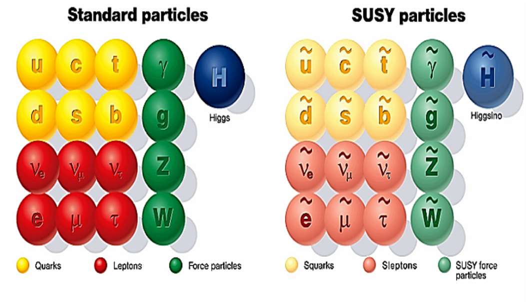
SUSY

- **Supersymmetric models are promising candidates for unified theory beyond the SM (BSM).**
- **SUSY is a symmetry between bosons and fermions.**
- **Even if SUSY has no rule in low energy particle physics, it remains an essential tool for any extension of the SM at high energy scales.**

Minimal Supersymmetric Standard Model (MSSM)

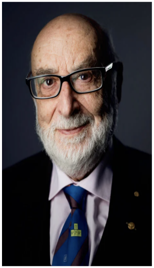
- **The most simple supersymmetric extension of the SM is known as the MSSM.**

$$W = Y_u Q_L U_L^c H_2 + Y_d Q_L D_L^c H_1 + Y_e L_L E_L^c H_1 + \mu H_1 H_2.$$



- **A new symmetry, $R_P = (-1)^{3B+L+2S}$, is introduced.**
- **Accordingly, SUSY particles are produced or destroyed only in pair. Hence, the Lightest Supersymmetric Particle (LSP) is stable, a possible candidate for DM.**

- The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter Higgs "for the theoretical discovery of Higgs mechanism that explains the origin of mass of particles, and which recently was confirmed through the discovery of Higgs boson, by the ATLAS and CMS experiments at CERN's LHC."



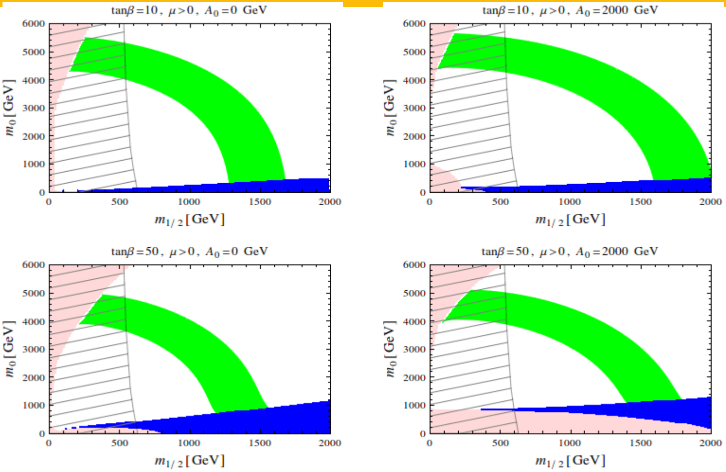
- In the MSSM, the mass of the lightest Higgs state can be approximated, at the one-loop level, as

$$m_h^2 \leq M_Z^2 + \frac{3g^2}{16\pi^2 M_W^2} \frac{m_t^4}{\sin^2\beta} \log\left(\frac{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}{m_t^4}\right).$$

- MSSM predicts an upper bound for the Higgs mass: $m_h \lesssim 130$ GeV, which was consistent with the measured value of Higgs mass ($\simeq$ 125 GeV) at the LHC.

- This mass of lightest Higgs boson implies that the SUSY particles are quite heavy. This may justify the negative searches for SUSY at the current LHC runs.

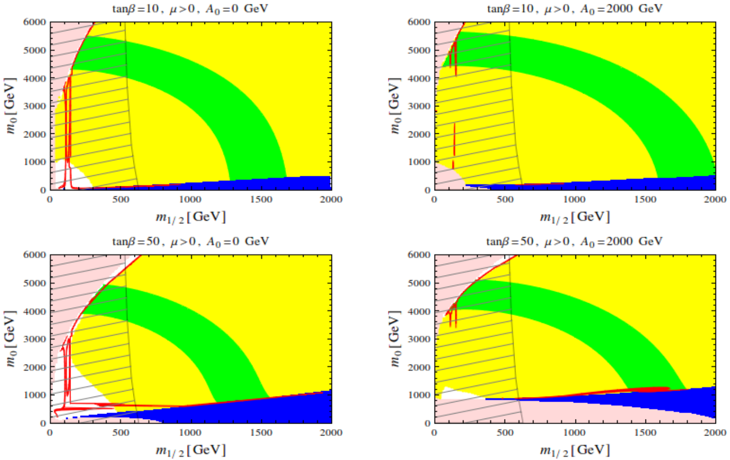
MSSM After the LHC Runs †



Green region indicates for $124 \lesssim m_h \lesssim 126$ GeV**. Blue region is excluded because the lightest neutralino is not the LSP. Pink regions are excluded due to the absence of radiative electroweak symmetry breaking** $(\mu^2 < 0)$**. Gray shadow denotes the excluded area because of** $m_{\tilde{g}} < 1.5$ TeV**.**

† W. Abdallah and S. Khalil, AHEP **2016**, 5687463 (2016).

- **Combining the LHC and astrophysics constraints almost rule out the MSSM.**



- **At low** $\tan\beta$**, red regions of co-annihilation between** χ **and lightest** $\tilde{l}$ **are excluded by the Higgs & gluino mass constraints.**
- **At large** $\tan\beta$**, red regions with a possible resonance due to** $M_A \simeq 2m_\chi$ **are allowed:** $0.09 < \Omega h^2 < 0.14$

TeV Scale $B-L$ Extension of the SM with Type I Seesaw

- **The $B-L$ extension of the SM is based on the gauge group**

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

- **In this model, the following particles are added:**

  1. **Three right-handed neutrinos, $N_R^i,\ i=1,2,3$.**
  2. **An extra gauge boson Z' and an extra SM singlet scalar.**

After $U(1)_{B-L}$ and EW symmetry breaking, the mass matrix of the neutrinos is

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}, \quad \text{where} \quad m_D = \frac{1}{\sqrt{2}} Y_\nu v, \qquad M_R = \frac{1}{\sqrt{2}} Y_N v'$$

The digitalization of the mass matrix leads to the light and heavy neutrinos masses, respectively:

$$m_{\nu_\ell} \simeq -m_D M_R^{-1} m_D^T, \quad m_{\nu_H} \simeq M_R.$$

A simple solution to the LSND, MiniBooNE and muon $g-2$ anomalies‡

- **In addition to accelerator/collider physics, two categories of long-standing anomalous results which have large statistical significance are:**

  1. **excesses in electron-like events in short baseline neutrino experiments, in particular, the LSND and MB excesses,**
  2. **observed discrepancy in the muon anomalous magnetic moment value, $(g-2)_\mu$.**

In collaboration with Raj Gandhi (HRI, India) and Samiran Roy (INFN, Italy)

‡Waleed Abdallah, Raj Gandhi, Samiran Roy, Phys. Rev. D **104** (2021).

Two-Higgs Doublet Model with a singlet scalar

- **In this model, the SM particle content has been extended by**
  1. **a second Higgs doublet, ϕ_H, in addition to the SM one, ϕ_h,**
  2. **a singlet real scalar, $\phi_{h'}$,**
  3. **three singlet neutrinos, ν_{R_i}.**

- **In the Higgs basis $(\phi_h, \phi_H, \phi_{h'})$ the relevant Lagrangian is as follows.**

$$\mathcal{L} = \sqrt{2}\Big[(X^u_{ij}\tilde{\phi}_h + \bar{X}^u_{ij}\tilde{\phi}_H)\bar{Q}^i_L u^j_R + (X^d_{ij}\phi_h + \bar{X}^d_{ij}\phi_H)\bar{Q}^i_L d^j_R + (X^e_{ij}\phi_h + \bar{X}^e_{ij}\phi_H)\bar{L}^i_L e^j_R$$
$$+ \quad (X^\nu_{ij}\tilde{\phi}_h + \bar{X}^\nu_{ij}\tilde{\phi}_H)\bar{L}^i_L \nu_{R_j} + \frac{1}{\sqrt{8}} m_{ij}\bar{\nu}^c_{R_i}\nu_{R_j} + \lambda^N_{ij}\bar{\nu}^c_{R_i}\phi_{h'}\nu_{R_j} + h.c.\Big]. \qquad (1)$$

- **The fermion masses, m_f, receive contributions only from X^f_{ij}, since $\langle\phi_h\rangle = v \simeq 246\,\text{GeV}$ while $\langle\phi_H\rangle = 0 = \langle\phi_{h'}\rangle$. Consequently, $\bar{X}^f$ are non-diagonal matrices and independent of X^f.**

The interactions: LSND, MB and $(g-2)_\mu$

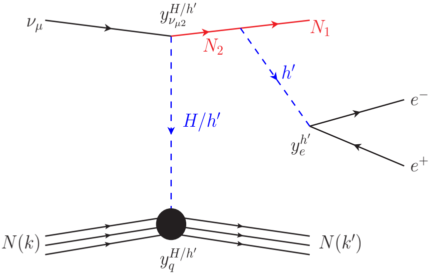
- **After rotation, respectively, the coupling strengths of the scalars h, h', H (mass eigenstates) with fermions are**

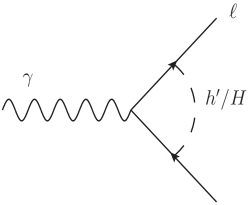
$$y_f^h = \frac{m_f}{v}, \quad y_f^{h'} = y^f\, s_\delta, \quad y_f^H = y^f\, c_\delta, \tag{2}$$

where $s_\delta \equiv \sin\delta$, $c_\delta \equiv \cos\delta$ and δ is the scalar mixing angle between the mass and gauge eigenstates.

- **The Lagrangian specifying neutrino interactions with the scalars h', H is given by**

$$\mathcal{L}_\nu^{\rm int} \simeq y^\phi_{\nu_{ij}} \bar{\nu}_i N_j\, \phi + \lambda^n_{ij}(\, c_\delta\, h' - \, s_\delta\, H)\bar{N}_i N_j + h.c., \quad \text{where} \quad y^{h'}_{\nu_{ij}} = y^\nu_{ij}\, s_\delta, \quad y^H_{\nu_{ij}} = y^\nu_{ij}\, c_\delta.$$





$$\Delta a_\mu = \sum_{\phi = h', H} \frac{(y^\phi_\mu)^2}{8\pi^2} \int_0^1 dx \frac{(1-x)^2(1+x)}{(1-x)^2 + x\,(m_\phi/m_\mu)^2}$$

- **The effective coupling (F_N) of either scalar to a nucleon (N) can be written as**

$$\frac{F_N}{M_N} = \sum_{q=u,d} f^N_{T_q} \frac{f_q}{m_q}. \tag{3}$$

- **The total differential cross section, for the target in MB, *i.e.*, CH_2, is given by**

$$\left[\frac{d\sigma}{dE_{N_2}}\right]_{\mathrm{CH_2}} = \Big[\underbrace{(8F_p + 6F_n)}_{\text{incoherent}} + \underbrace{(6F_p + 6F_n)^2 e^{-2b|q^2|}}_{\text{coherent}}\Big] \frac{d\sigma}{dE_{N_2}}. \tag{4}$$

- **The number of events is given by**

$$\mathrm{N_{events}} = \eta \int dE_\nu \, dE_{N_2} \frac{d\Phi^\nu}{dE_\nu} \frac{d\sigma}{dE_{N_2}} \times \mathrm{BR}(N_2 \to N_1 h'), \tag{5}$$

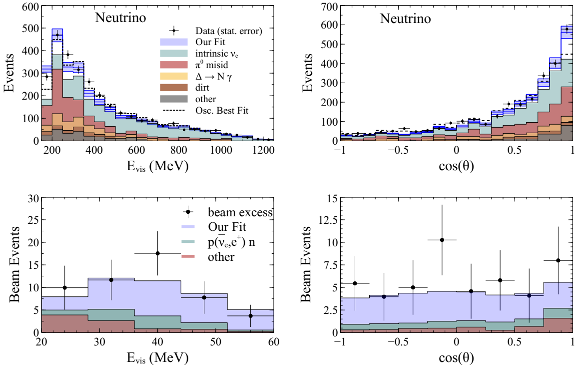
with $E_{h'} \in [E_{h'}, E_{h'} + \Delta E_{h'}]$ and Φ^ν is the incoming muon neutrino flux. η contains all detector related information like efficiencies, POT etc.

m_{N_1}	m_{N_2}	m_{N_3}	$y_u^{h'(H)} \times 10^6$	$y_{e(\mu)}^{h'} \times 10^4$	$y_{e(\mu)}^{H} \times 10^4$
85 MeV	130 MeV	10 GeV	0.8(8)	0.23(1.6)	2.29(15.9)

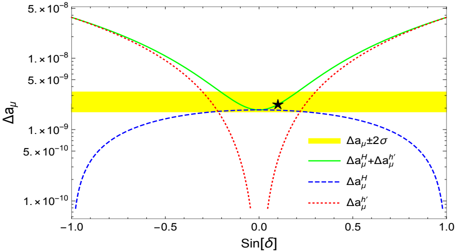
$m_{h'}$	m_H	$\sin\delta$	$y_d^{h'(H)} \times 10^6$	$y_{\nu_{12}}^{h'(H)} \times 10^3$	$\lambda_{12}^n \times 10^2$
17 MeV	750 MeV	0.1	0.8(8)	1.25(12.4)	7.5

Explaining the LSND, MB and $(g-2)_\mu$ anomalies

- **It is clearly seen that very good fits to the data are obtained for both the energy and the angular distributions. In MB, we have assumed a 15% systematic uncertainty (the blue bands in the plots).**



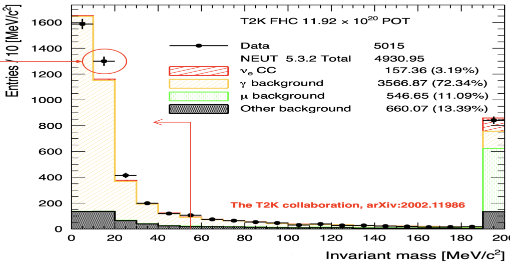
- **Both h' and H contribute to Δa_μ. The H contribution Δa_μ^H is significantly larger, with the h' contribution being 17% of the total.**



Conclusion

- **A common, non-oscillation, new physics explanation exists for both LSND and MB.**
- **In such an explanation, the second Higgs doublet allows us to obtain a portal to the dark sector and comfortably account for the observed value of the muon $g-2$.**
- **Three singlet neutrinos allow for generating neutrino masses via a Type I seesaw mechanism, with two of them participating in the interaction of LSND and MB.**

- **For h', there is an existing/interesting experimental hint which is a significant excess in the $10-20$ MeV invariant mass-bin of electron-like FGD1-TPC pairs detected by the T2K ND280 detector.**



Thank you