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

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# Outline

# Introduction

- **The SM has provided a reliable framework for both theoretical and experimental progress in particle physics.**

- **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, $(g-2)_\mu$.**

- **Assuming that these discrepancies are due to new physics, as opposed to ununderstood SM backgrounds or detector-specific effects, we show that the addition of a second Higgs doublet, acting as a portal to the dark sector, provides an understanding of all three discrepant results mentioned above.**

# Two-Higgs Doublet Model + a singlet scalar (dark sector)

- In this model, the SM particle content has been extended by
  1. a second Higgs doublet, $\phi_H$, in addition to the SM one, $\phi_h$,
  2. a singlet real scalar, $\phi_{h'}$,
  3. three singlet neutrinos, $\nu_{R_i}$.
- In the Higgs basis $(\phi_h, \phi_H, \phi_{h'})$ the relevant Lagrangian is as follows.

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

- 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 $X^f$. That is, the off-diagonal couplings of the additional scalars to quarks are free parameters and can be very tiny.
- All important bounds, notably from i) CHARM II and MINERvA, ii) the T2K near detector, ND280 and iii) NC $\nu$-nucleon scattering at high energies are respected by our model.

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

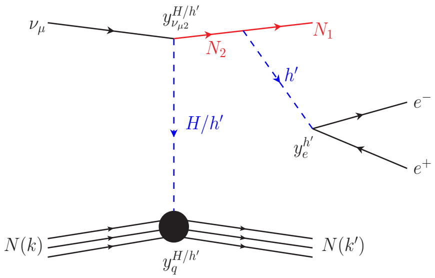
- **After rotation, respectively, the coupling strengths of the scalars $h, h', H$ (mass eigenstates) with fermions are**

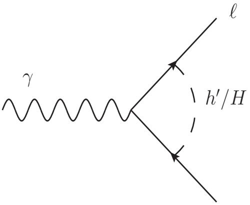
$$y_f^h = \frac{m_f}{v}, \quad y_f^{h'} = y^f\, s_\delta, \quad y_f^H = y^f\, c_\delta, \tag{2}$$

**where $s_\delta \equiv \sin\delta$, $c_\delta \equiv \cos\delta$ and $\delta$ 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**

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

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

$$\left[\frac{d\sigma}{dE_{N_2}}\right]_{\mathrm{CH}_2} = \Big[\underbrace{(8F_p+6F_n)}_{\textbf{incoherent}} + \underbrace{(6F_p+6F_n)^2 e^{-2b|q^2|}}_{\textbf{coherent}}\Big] \frac{d\sigma}{dE_{N_2}}. \quad (4)$$

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

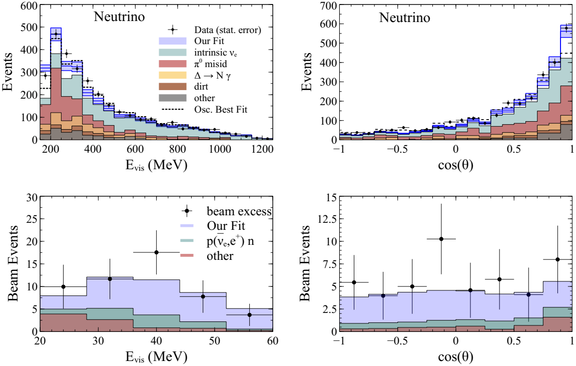
$$\mathrm{N}_{\mathrm{events}} = \eta \int dE_\nu \, dE_{N_2} \frac{d\Phi^\nu}{dE_\nu} \frac{d\sigma}{dE_{N_2}} \times \mathrm{BR}(N_2 \to N_1 h'), \quad (5)$$

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

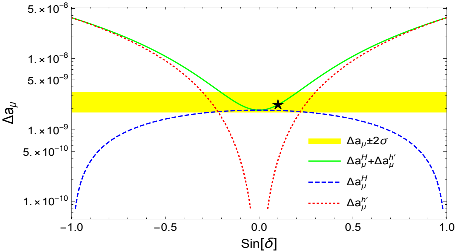
| $m_{N_1}$ | $m_{N_2}$ | $m_{N_3}$ | $y_u^{h'(H)} \times 10^6$ | $y_{e(\mu)}^{h'} \times 10^4$ | $y_{e(\mu)}^{H} \times 10^4$ |
|---|---|---|---|---|---|
| 85 MeV | 130 MeV | 10 GeV | 0.8(8) | 0.23(1.6) | 2.29(15.9) |
| $m_{h'}$ | $m_H$ | $\sin\delta$ | $y_d^{h'(H)} \times 10^6$ | $y_{\nu_{i2}}^{h'(H)} \times 10^3$ | $\lambda_{12}^n \times 10^2$ |
| 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 $\Delta a_\mu$. The $H$ contribution $\Delta a_\mu^H$ is significantly larger, with the $h'$ contribution being 17% of the total.**



Several points are relevant to understanding the results obtained.

1. **All LSND events in our scenario stem from the high energy part of their DIF flux, which is kinematically capable of producing the $N_2$ ($m_{N_2} \simeq 130$ MeV). The $\nu_\mu$ beam interacts in the detector via**

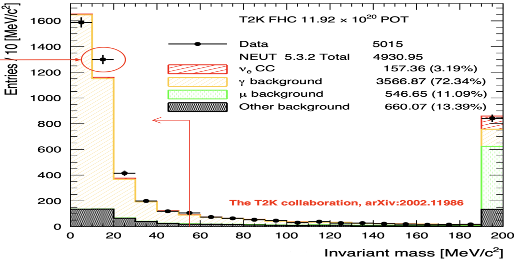
$$\nu_\mu \, \mathrm{CH}_2 \to n\, N_2\, X \to n\, N_1\, h'\, X \to N_1\, \gamma\, e^+ e^-\, X.$$

2. **Both $H$ and $h'$ act as mediators and contribute to the total cross section. The contribution of $h'$ is much smaller ($\sim 10\%$) than that of $H$, since $\sin\delta \simeq 0.1$. However, this plays an important role in producing the correct angular distribution in MB. In particular, $h'$ is responsible for a coherent contribution which helps sufficiently populate the first ($i.e.$ most forward) bin.**

3. **As a consequence of the heavy particle production ($N_2$) necessary, our model would not give any signal in KARMEN, which has a narrow-band DIF flux that peaks at $\sim 30$ MeV, hence making it compatible with their null result.**

# 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.**
- **Of the sub-GeV scalars in our model, $H$ can be searched for in Belle-II and $h'$ in HPS.**
- **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*