Understanding the MiniBooNE and the muon $g - 2$ anomalies with a light $Z'$ and a second Higgs doublet

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MiniBooNE (MB) is a short-baseline accelerator-based neutrino experiment.

Schematic representation of MB:

- MB looked for an *electron like* signal in the final states.
  \[ \nu_\mu \text{ beam } \text{ and } \nu_\mu + A \rightarrow e^- + X \]
- Detector can’t distinguish the signal from \( e^- , e^+ , \gamma \) or collimated \( e^- e^+ \) pair.
An excess of *electron-like* events over the expected background was observed.

Excess events are distributed over all possible directions.
One of the possible solutions of this excess could be the neutrino oscillation driven by an eV scale sterile neutrino.

Two flavor case:

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu
\end{pmatrix}
= \begin{pmatrix}
\cos \theta & -\sin \theta \\
\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix}
\]

\[
P_{\mu e} = \sin^2 \theta \sin^2 \frac{1.27 \Delta m^2 L \text{(meter)}}{E \text{(MeV)}}
\]

\[
\Delta m^2 |_{\text{solar}} \sim 10^{-5} \text{ eV}^2 \text{ and } \Delta m^2 |_{\text{atm}} \sim 10^{-3} \text{ eV}^2, \quad P_{\mu e} \rightarrow \text{very small}.
\]

We need \(\Delta m^2 \sim 1 \text{ eV}^2\) to explain the observed excess.

Leptonic mixing matrix in the presence of sterile neutrino:

\[
U^{3+1} = O(\theta_{34}, \delta_{34}) O(\theta_{24}, \delta_{24}) O(\theta_{14}) O(\theta_{23}) O(\theta_{13}, \delta_{13}) O(\theta_{12})
\]
Constraint on sterile parameters:

Solution to MB excess via light sterile neutrino does not fit very well in the global picture.
Some general constraints

MB beam dump run:

- If events scale as POT, as in DM production and scattering, then 35.5 excess events expected.
- However, only 6 events seen, whereas the expected background was 8.8.

Conclusion: Excess disappears when neutrino flux is suppressed, and is thus linked to neutrinos.
The proposed model:

The SM is extended by a second Higgs doublet, and either i) a $U(1)_{B-3L_{\tau}}$ gauge boson, coupled to baryons and the $\tau$ sector or ii) a $U(1)_B$ gauge boson coupled to baryon number alone with gauge coupling $g_B$. In both cases the coupling to the incoming muon neutrinos is indirectly generated via mixing with the dark neutrino $\nu_d$.

The SM Lagrangian is extended by the following terms to obtain $\mathcal{L}_{tot}$, the full Lagrangian of the extended theory,

$$\mathcal{L}_{tot} \supset -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \bar{\nu}_d \gamma^\mu (i \partial_\mu + g_d Z'_\mu) \nu_d + \mathcal{L}_q + \mathcal{L}_f - \mathcal{L}_Y^f - V + \mathcal{L}_{S^{K_{in}}} + \mathcal{L}_m,$$

where

$$\mathcal{L}_q = \sum_q \frac{1}{3} g_B \bar{q} \gamma^\mu Z'_\mu q, \quad \mathcal{L}_f = \sum_f g_B q_f \bar{f} \gamma^\mu Z'_\mu f,$$

$$\mathcal{L}_Y^f = \sqrt{2} \left[ (Y^u_{ij} \tilde{\phi}_h + \tilde{Y}^u_{ij} \phi_H) \bar{Q}^i_L u^i_R + (Y^d_{ij} \phi_h + \tilde{Y}^d_{ij} \phi_H) \bar{Q}^i_L d^i_R + (Y^e_{ij} \phi_h + \tilde{Y}^e_{ij} \phi_H) \bar{L}^i_L e^i_R \right] + h.c. \right].$$

$$V = \phi_h^\dagger \phi_h \left( \frac{\lambda_1}{2} \phi_h^\dagger \phi_h + \lambda_3 \phi_{H}^\dagger \phi_H + \mu_1 \right) + \phi_{H}^\dagger \phi_H \left( \frac{\lambda_2}{2} \phi_{H}^\dagger \phi_H + \mu_2 \right) + \lambda_4 (\phi_h^\dagger \phi_H)(\phi_H^\dagger \phi_h)$$

$$+ \left\{ \left( \frac{\lambda_5}{2} \phi_h^\dagger \phi_H + \lambda_6 \phi_h^\dagger \phi_h + \lambda_7 \phi_{H}^\dagger \phi_H + \lambda'_5 \phi_{h'}^\dagger \phi_{h'} - \mu_{12} \right) \phi_h^\dagger \phi_H + h.c. \right\}$$

$$+ \phi_{h'}^\dagger \phi_{h'} (\lambda'_2 \phi_{h'}^\dagger \phi_{h'} + \lambda'_3 \phi_h^\dagger \phi_h + \lambda'_4 \phi_{H}^\dagger \phi_H + \mu'),$$

where

$$\phi_h = \begin{pmatrix} H^1_1 \\ \frac{\nu + H^0_1 + i G^0_1}{\sqrt{2}} \end{pmatrix}, \quad \phi_H = \begin{pmatrix} H^2_2 \\ \frac{H^0_2 + i A^0_2}{\sqrt{2}} \end{pmatrix}, \quad \phi_{h'} = \frac{\nu' + H^0_3 + i G^0_3}{\sqrt{2}},$$

$$H = \cos \delta H^0_2 - \sin \delta H^0_3 \text{ and } h' = \sin \delta H^0_2 + \cos \delta H^0_3.$$
The scalar kinetic term $L_S^{\text{Kin}}$ can be written as

$$L_S^{\text{Kin}} = \sum_{\mathcal{H}} (D_{\mu}^{\mathcal{H}} \phi_{\mathcal{H}}) \bar{D}^{\mathcal{H}}_{\mu} \phi_{\mathcal{H}} \supset \frac{1}{2} g_d^2 \left( v' + H_3^0 \right)^2 Z'_{\mu} Z'_{\mu}.$$  \hspace{1cm} (8)

The interaction term in the mass basis:

$$L_{\text{int}} = -g_d \sum_{i,j=1}^{4} U_{di}^* U_{dj} \bar{\nu}_i \gamma_{\mu} \left( 1 - \gamma_5 \right) \frac{1}{2} \nu_j Z'_{\mu}.$$  \hspace{1cm} (9)

| $m_{\nu_{4}}$ (MeV) | $m_{Z'}$ (MeV) | $m_{h'}$ (MeV) | $m_{H}$ (MeV) | $|U_{\nu_{4}}|^2$ | $g_B$ | $g_d$ | $\sin \delta$ | $y_{\nu_{4}(\mu)} = y_{e(\mu)} \sin \delta$ | $y_{e(\mu)} = y_{e(\mu)} \cos \delta$ | $|y_{e}\bar{y}_{\mu}|$ |
|-----------------|----------------|----------------|---------------|----------------|------|-------|-------------|-----------------|-----------------|----------------|
| 50              | 800            | 23             | 106           | $2.6 \times 10^{-5}$ | $3 \times 10^{-4}$ | 2.85  | 0.28  | $0.45(1.8) \times 10^{-4}$ | $1.5(6.0) \times 10^{-4}$ | $5.6 \times 10^{-7}$ |
The total differential cross section, for the target in MB, i.e., CH$_2$, is given by

\[
\left( \frac{d\sigma}{dE_{h'}} \right)_{CH_2} = 14 \times \left( \frac{d\sigma}{dE_{h'}} \right)_{\text{incoherent}} + 144 \times \exp(2b(k' - k)^2) \left( \frac{d\sigma}{dE_{h'}} \right)_{\text{coherent}}.
\]  

(10)
There is a long-standing discrepancy between the experimental value and theoretical prediction of the anomalous magnetic moment of muon, $a_\mu = (g_\mu - 2)/2$.

$$\Delta a_\mu = a_\mu^{\text{meas}} - a_\mu^{\text{theory}} = (2.74 \pm 0.73) \times 10^{-9}$$

The one-loop contribution of a scalar $\phi$ to the muon anomalous magnetic moment is given by

$$\Delta a_\mu = \frac{(y_{\mu}^{\phi})^2}{8\pi^2} \int_0^1 dx \frac{(1-x)^2(1+x)}{(1-x)^2 + x r_\phi^2},$$

where $r_\phi = m_\phi/m_\mu$, and $\phi = h', H$. $y_{\mu}^{\phi}$ is the coupling strength of the scalar $\phi$ with the muon.
Discussion of some important constraints:

- **Constraints on** $m_{Z'}$ **and** $g_{B-3L\tau}$ (or $g_B$):

  ![Graph showing constraints on $m_{Z'}$ and $g_{B-3L\tau}$](image1.png)

- **Contributions to NC $\nu$–nucleon scattering**:

  ![Graph showing contributions to NC $\nu$–nucleon scattering](image2.png)

- **IceCube and DeepCore are a possible laboratory for new particles which are produced via deep inelastic scattering. Hence, $h'$ should decay promptly so that there are no double bang events at these detectors.**
Evidence for anomalous signals at short-baseline neutrino experiments increased over time.

Explanation of MB excess via light sterile neutrino does not fit very well in the global picture.

Our proposed model could provide a non-oscillatory, new physics explanation for MB.

Two of the three CP even scalars in the model are relatively light \((m_{h'} = 23 \text{ MeV} \text{ and } m_H = 106 \text{ MeV})\) and participate in the interaction that generates the excesses in MB, as well as contribute to the value of muon \(g - 2\).
Thank you for your attention