Two-Higgs doublet solution to the LSND, MiniBooNE and muon $g-2$ anomalies

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(work with W.Abdallah and R. Gandhi)

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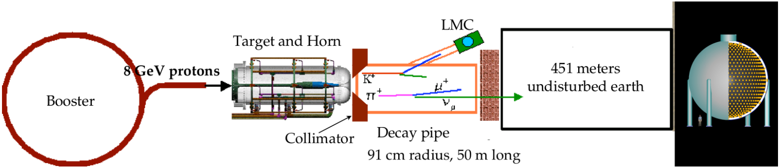
Anomalies 2021, IITH

Outline of Talk

- LSND and MiniBooNE (MB) excesses
- Present constraints on light sterile neutrino
- Decay of heavy sterile neutrino as a solution
- Constraints on our model
- Conclusions

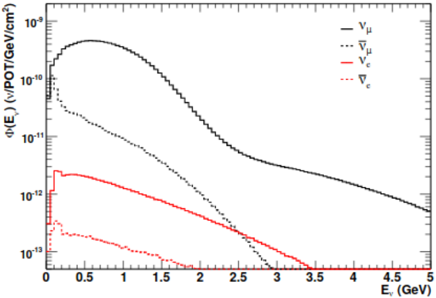
LSND and MB excess

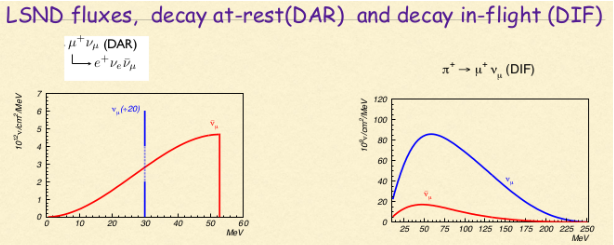
- LSND and MB are two short-baseline neutrino experiments.
- Schematic representation of MB :



- LSND : proton energy 800 MeV and base-line $\sim$ 30 meters.
- Detectors can't distinguish the signals from e^-, e^+, and γ.

MB and LSND fluxes:





- MB looked for an *electron like* signal in the final states.

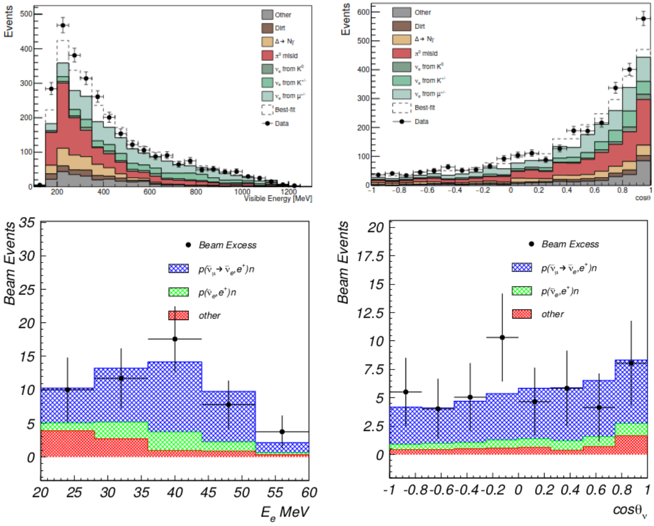
$$\nu_\mu \text{ beam} \quad \text{and} \quad \nu_\mu + \mathrm{A} \to \mathrm{e}^- + \mathrm{X}$$

- LSND signal looks like an inverse β-decay.

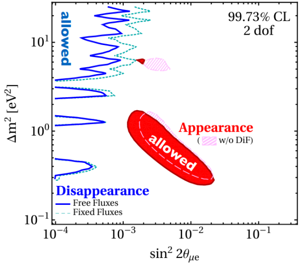
$$\bar{\nu}_\mu \quad \text{beam} \quad \text{and} \quad \bar{\nu}_\mathrm{e} + \mathrm{p} \to \mathrm{e}^+ + \mathrm{n}$$

and n is captured by the free hydrogen in the detector. This produces a unique signature of 2.2 MeV gamma in the detector.

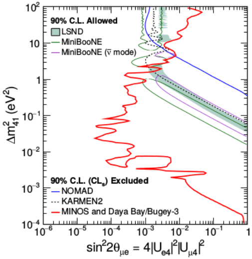
MB and LSND events



- An excess of *electron (positron) like* events over the expected background was observed.



Kopp et al. 10.1007/JHEP08(2018)010

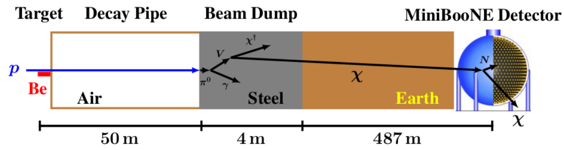


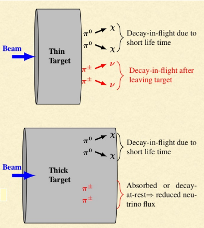
Daya Bay + MINOS Collaboration 1607.01177

- Solution to the LSND and MB anomalies via light sterile neutrino does not fit very well in the global picture.
- Recent results of MicroBooNE also disfavor the light sterile neutrino hypothesis. (arXiv : 2110.14065)

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 were seen, when expected background was 8.8.

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

The proposed model:

We consider two Higgs doublet model (2HDM) with a dark singlet scalar $\phi_{h'}$. In addition, three right-handed neutrinos help to generate neutrino masses via the seesaw mechanism and participate in the interaction which gives the signal in MB and LSND.

$$
\begin{aligned}
V = & |\phi_h|^2 \left(\frac{\lambda_1}{2} |\phi_h|^2 + \lambda_3 |\phi_H|^2 + \mu_1 \right) \\
& + |\phi_H|^2 \left(\frac{\lambda_2}{2} |\phi_H|^2 + \mu_2 \right) + \lambda_4 (\phi_h^\dagger \phi_H)(\phi_H^\dagger \phi_h) \\
& + \phi_{h'}^2 \left(\lambda_2' \phi_{h'}^2 + \lambda_3' |\phi_h|^2 + \lambda_4' |\phi_H|^2 + m' \phi_{h'} + \mu' \right) \\
& + \Big[\phi_h^\dagger \phi_H \Big(\frac{\lambda_5}{2} \phi_h^\dagger \phi_H + \lambda_6 |\phi_h|^2 + \lambda_7 |\phi_H|^2 + \lambda_5' \phi_{h'}^2 - \mu_{12} \Big) \\
& + \phi_{h'} (m_1 |\phi_h|^2 + m_2 |\phi_H|^2 + m_{12} \phi_h^\dagger \phi_H) + h.c. \Big]
\end{aligned}
$$

where

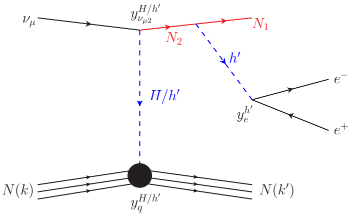
$$
\begin{aligned}
\phi_h &= \begin{pmatrix} H_1^+ \\ \frac{v + H_1^0 + iG^0}{\sqrt{2}} \end{pmatrix}, \\
\phi_H &= \begin{pmatrix} H_2^+ \\ \frac{H_2^0 + iA^0}{\sqrt{2}} \end{pmatrix} \\
\phi_{h'} &= H_3^0 / \sqrt{2}
\end{aligned}
$$

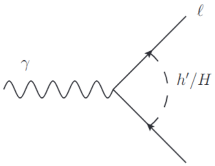
In the Higgs basis the relevant Lagrangian $\mathcal{L}$ can be written as

$$
\begin{aligned}
\mathcal{L} = \sqrt{2} \Big[& (X_{ij}^u \tilde{\phi}_h + \bar{X}_{ij}^u \tilde{\phi}_H) \bar{Q}_L^i u_R^j + (X_{ij}^d \phi_h + \bar{X}_{ij}^d \phi_H) \bar{Q}_L^i d_R^j \\
+ & (X_{ij}^e \phi_h + \bar{X}_{ij}^e \phi_H) \bar{L}_L^i e_R^j + (X_{ij}^\nu \tilde{\phi}_h + \bar{X}_{ij}^\nu \tilde{\phi}_H) \bar{L}_L^i \nu_{R_j} \\
+ & \frac{1}{\sqrt{8}} m_{ij} \bar{\nu}_{R_i}^c \nu_{R_j} + \lambda_{ij}^N \bar{\nu}_{R_i}^c \phi_{h'} \nu_{R_j} + h.c. \Big]
\end{aligned}
$$

Neutrino interactions:

$$\mathcal{L}_{\nu}^{\rm int} \simeq y^{\phi}_{\nu_{ij}} \bar{\nu}_i N_j \phi + (\lambda^{h'}_{N_{ij}} h' + \lambda^{H}_{N_{ij}} H) \bar{N}_i N_j + h.c. \quad (1)$$



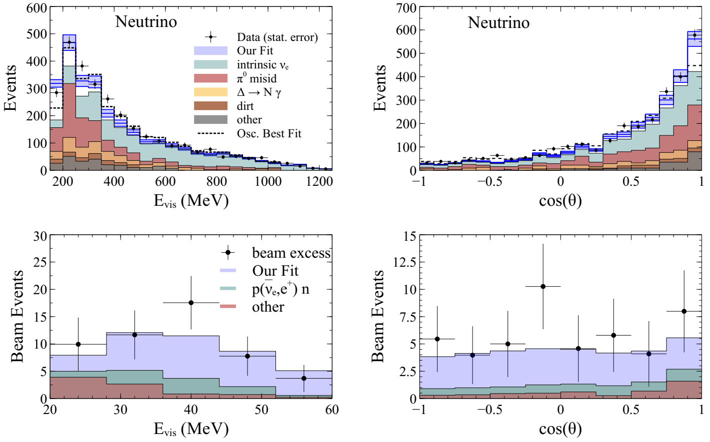


m_{N_1}	m_{N_2}	m_{N_3}	$y_u^{h'(H)}\times 10^6$	$y_{e(\mu)}^{h'}\times 10^4$	$y_{e(\mu)}^{H}\times 10^4$
85 MeV	130 MeV	10 GeV	0.8(8)	0.23(1.6)	2.29(15.9)

$m_{h'}$	m_H	$\sin\delta$	$y_d^{h'(H)}\times 10^6$	$y_{\nu_{i2}}^{h'(H)}\times 10^3$	$\lambda_{N_{12}}^{h'(H)}\times 10^3$
17 MeV	750 MeV	0.1	0.8(8)	1.25(12.4)	74.6(−7.5)

TABLE I: Benchmark point used for event generation in LSND, MB and for calculating the muon $g-2$.

Results:


Neutrino
Data (stat. error)
Our Fit
intrinsic ν_e
π^0 misid
$\Delta \rightarrow N \gamma$
dirt
other
Osc. Best Fit
Events
E_{vis} (MeV)
Neutrino
Events
$\cos(\theta)$
beam excess
Our Fit
$p(\bar{\nu}_e,e^+)\,n$
other
Beam Events
E_{vis} (MeV)
Beam Events
$\cos(\theta)$

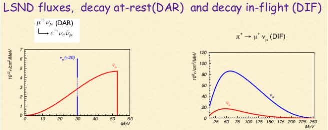
Discussion of some relevant points:

- All LSND events in our scenario stem from the high energy part of the DIF flux, which is kinematically capable of producing N_2 ($m_{N_2} = 130$ MeV).

$$\nu_\mu \mathrm{CH_2} \rightarrow \mathrm{nN_2X} \rightarrow \mathrm{nN_1h'X} \rightarrow \mathrm{N1\gamma e^+e^-X}$$

- The masses of N_2 and N_1 are important factors in obtaining both the correct number and the correct distributions of events in the detectors.

- KARMEN, a smaller experiment similar to LSND did not observe any excess. N_2 will not be produced as the high energy DIF flux of KARMEN is very small.



Discussion of some important constraints :

CHARM II and MINERνA constrain the proposed model by the $\nu_\mu - e$ scattering data.

$\nu_\mu \, A \rightarrow N_2 \, A$ coherent cross section becomes relevant. N_2 will decay and produce an electron-like signal in these detectors, and potentially conflict with measured $\nu - e$ data.

$\nu_\mu \, A \rightarrow N_2 \, A$ coherent cross section remains below the 1% of $\nu - e$ cross section in our model.

IceCube provides constraints on our model via the searches of double bang events. The decay time of N_2 (leading to e^+e^- pair) is short enough, to escape the detection at this detector. The distances traveled even at very high energies are much less smaller than the resolution necessary to signal a double bang events, $\sim$ 1 m in DeepCore, and $\sim$ a few hundred meters in IceCube.

Conclusions

- Evidence for anomalous signals at low-energy, and short-baseline neutrino experiments in particular, increased over time.
- Our proposed model could provide a common, non-oscillation, new physics explanation for both LSND and MB. It also explains the anomalous magnetic moment of muon.
- Our model does not conflict with the recent results of MicroBooNE.

Thank you for your attention