Neutrino upscattering to HNLs as an explanation of MB LEE

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Jaime Hoefken Zink

In collaboration with A. Abdullahi, M. Hostert, D. Massaro, S. Pascoli

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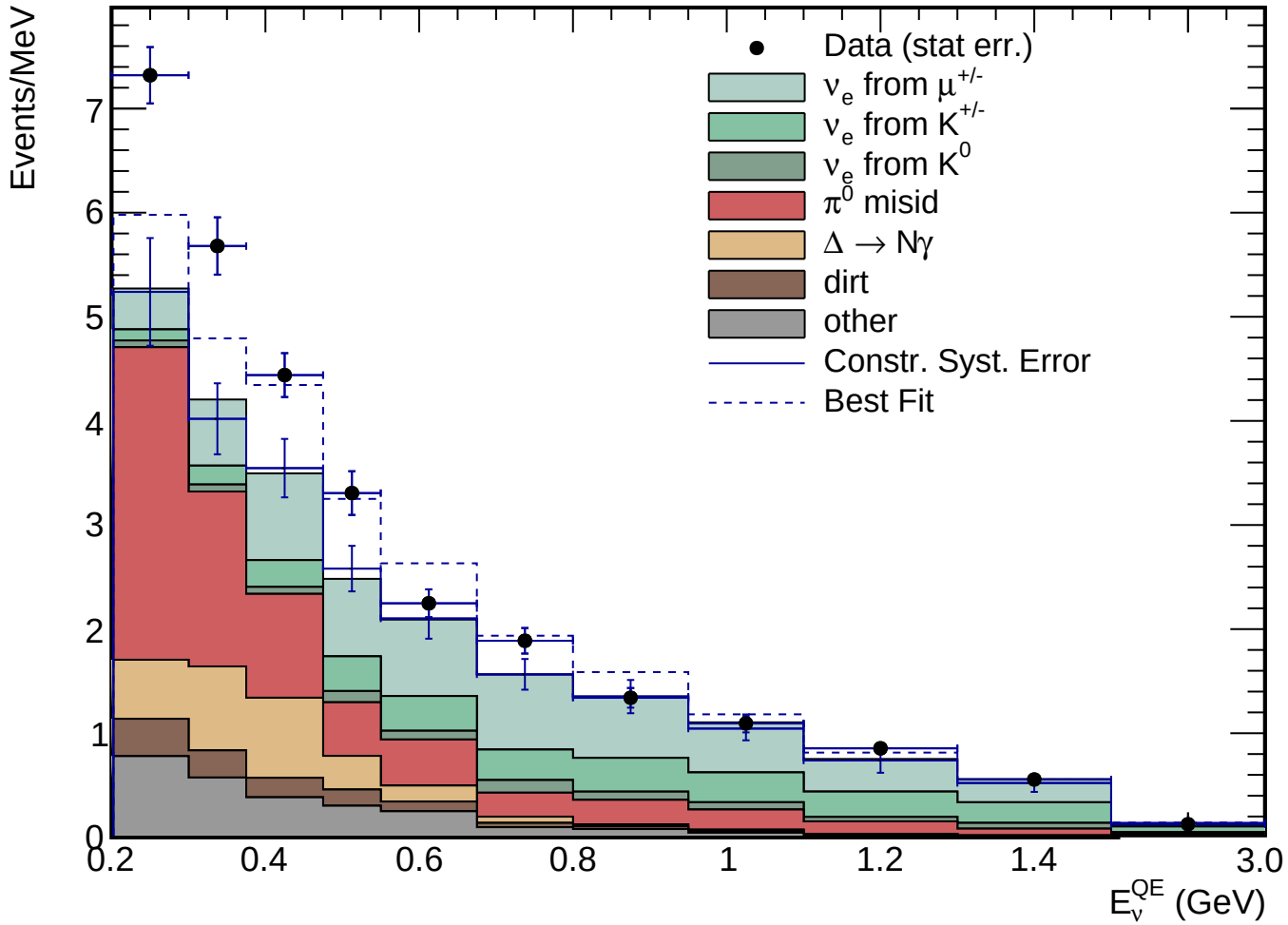
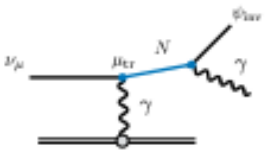
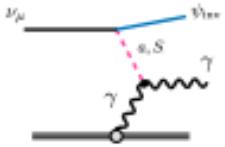
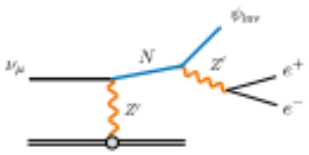
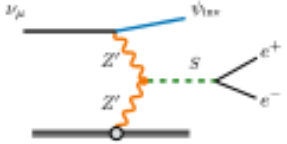
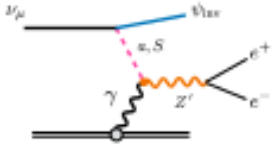
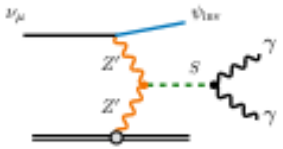
Anomaly: MiniBooNE Low Energy Excess



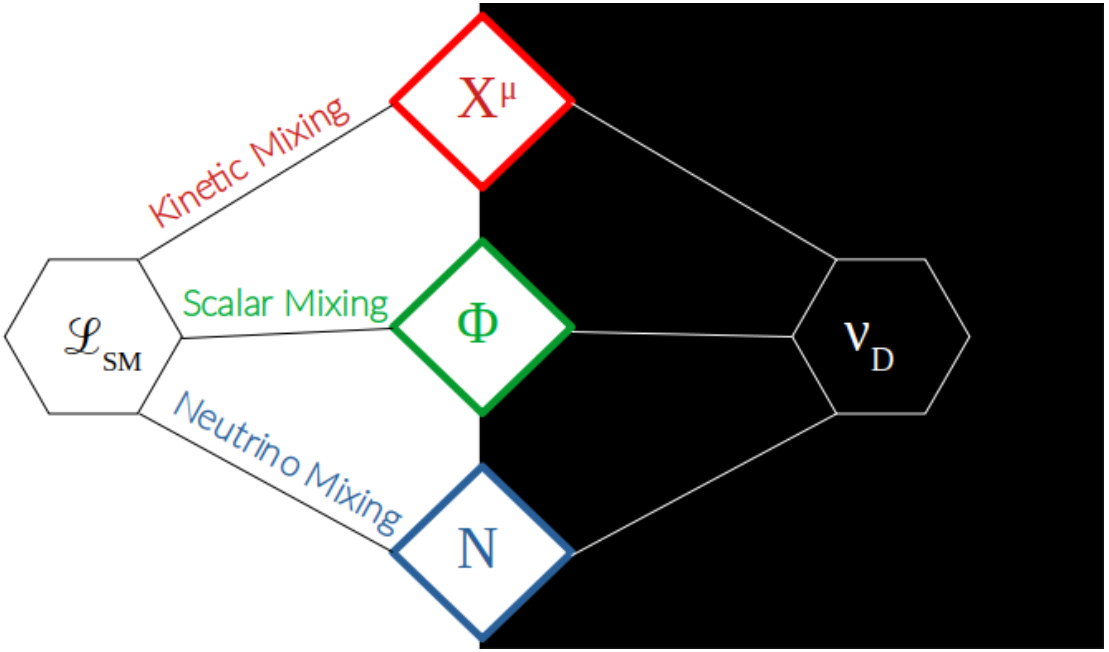
$560.6 \pm 119.6 (77.4 \pm 28.5)$ in $\nu(\bar{\nu})$ mode: $\mathbf{4.8\sigma}$

Anomaly: possible solutions

Topology	Model	Diagram	Signal
single γ	Transition magnetic moment		$N \to \nu\gamma$
	neutrino-induced inverse-Primakoff scattering		$a^* + A \to \gamma A$
e^+e^-	upscattering to N		$N \to \psi_{\rm inv} e^+ e^-$
	bremsstrahlung of light Z'		$N^* \to \nu(Z' \to e^+e^-)$
	neutrino-induced Z' fusion		$Z'^* Z'^* \to (S \to e^+e^-)$
	neutrino-induced inverse-Primakoff scattering to Z'		$S^* \gamma^* \to (Z' \to e^+e^-)$
$\gamma\gamma$	neutrino-induced Z' fusion		$Z'^* Z'^* \to (S \to e^+e^-)$

Dark Photon Model

Portals



Dark photon model:

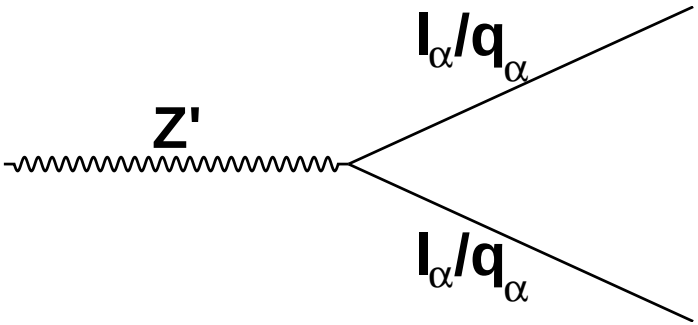
1. $U(1)_{\text{dark}}$ extension
2. dark Higgs singlet
3. ν_S and ν_D

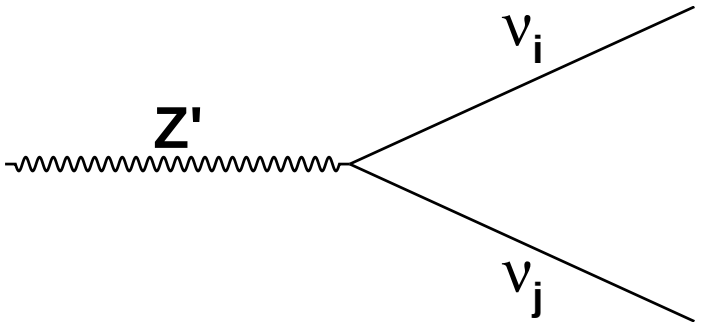
Dark Photon Model

Lagrangian

$$\begin{aligned}\mathscr{L} =& \mathscr{L}_{\mathrm{SM}} + \overline{\nu}_D i \not{D}^x \nu_D \\ &+ (D^x_\mu \Phi)^\dagger (D^{x\mu}\Phi) - V(\Phi, H) \\ &- \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\sin\chi}{2} B_{\mu\nu} X^{\mu\nu} \\ &+ \overline{N} i \not{\partial} N - [y^\alpha_\nu (\overline{L}_\alpha \cdot \widetilde{H}) N^C + \frac{\mu'}{2} \overline{N} N^C + y_N \overline{N} \nu^C_D \Phi + \mathrm{h.c.}]\end{aligned}$$

$$\mathscr{L} \subset \epsilon e Z'_\mu J^\mu_{\mathrm{EM}} + g_D U_{Di} U^*_{Dj} Z'_\mu \left(i \overline{\nu}_i \not{\partial} \nu_j \right) \qquad (1)$$





Dark Photon Model

Neutrino Mixing

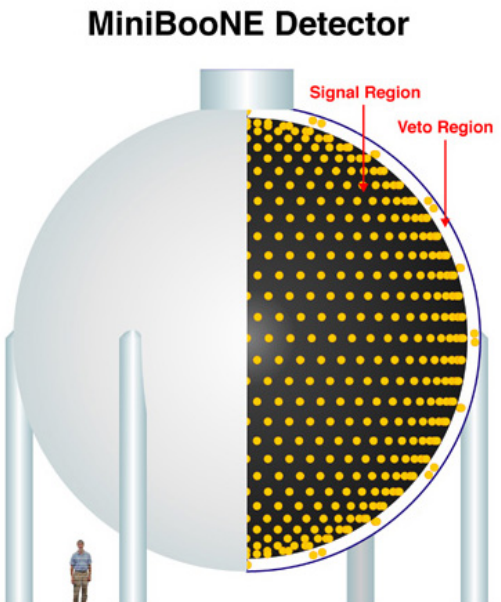
$$\mathscr{L}^{\nu}_{\text{mass}} = -\frac{1}{2}\begin{pmatrix}\overline{\nu_\alpha} & \overline{N} & \overline{\nu_D}\end{pmatrix}\begin{pmatrix}0_{3\times3} & m_D^{\mathrm{T}} & 0\\ m_D & \mu' & \Lambda^{\mathrm{T}}\\ 0 & \Lambda & 0\end{pmatrix}\begin{pmatrix}\nu_\alpha\\ N^C\\ \nu_D^C\end{pmatrix} \tag{2}$$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ N^C\\ \nu_D^C\end{pmatrix} \xRightarrow[\text{mass basis}]{\text{From flavor to}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\\ N_4\\ N_5\end{pmatrix}$$

Dark Photon Model

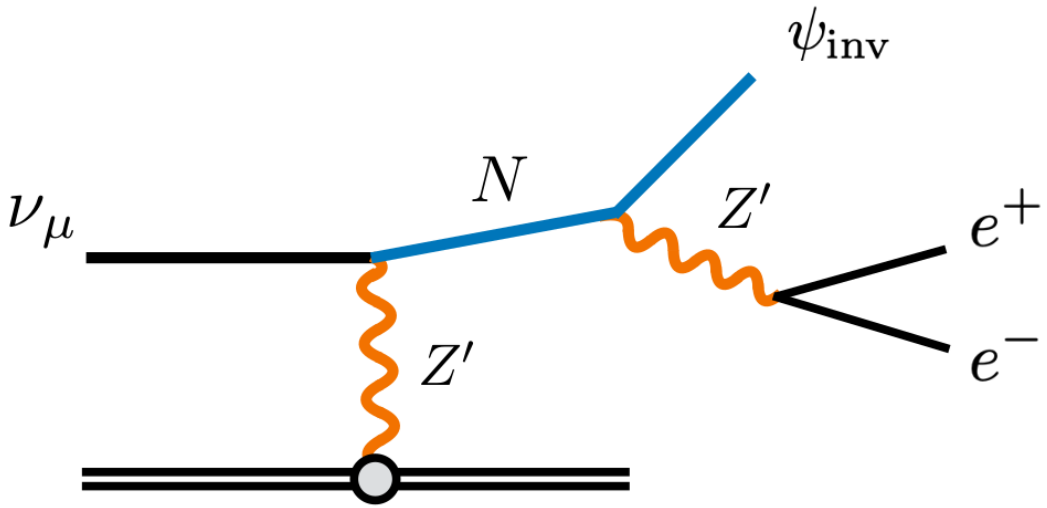
MiniBooNE detector

- **Material**: pure mineral oil (CH_2) in spherical shape (radius: 6.1 m)
- **Baseline**: 541 m
- **Mean** energy: 800 MeV
- **Beam**: ν_μ, $\bar{\nu}_\mu$ (mainly), from BNB
- **Peaks**: 600 MeV (ν_μ), 400 MeV ($\bar{\nu}_\mu$)
- **Detection**: Cherenkov, PMTs

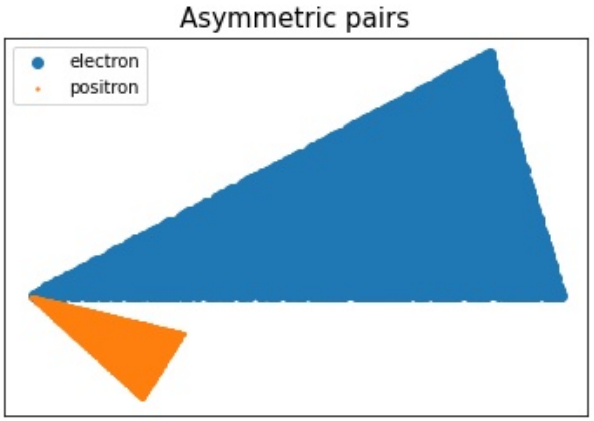


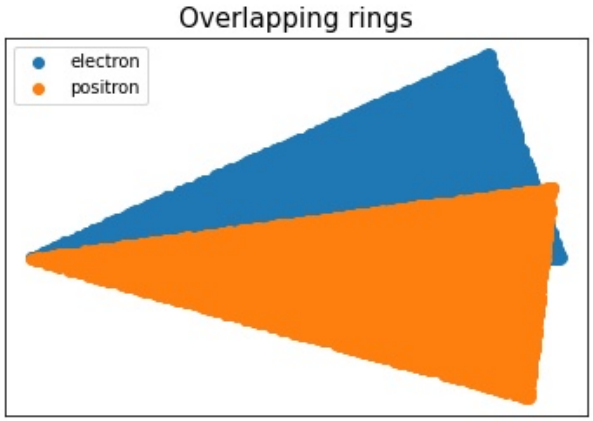
Dark Photon Model

Misreconstruction at MiniBooNE



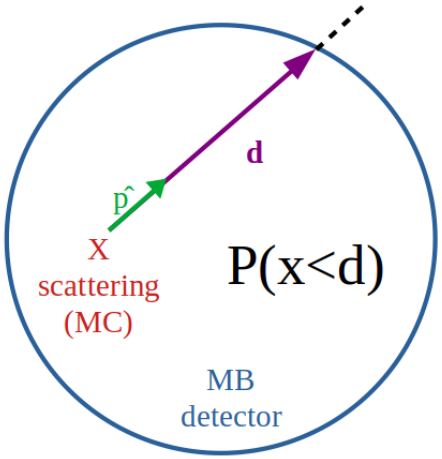
Condition: $< 13^\circ$ or $E_\nu < 0.03$ GeV





Simulation and Fitting

DarkNews



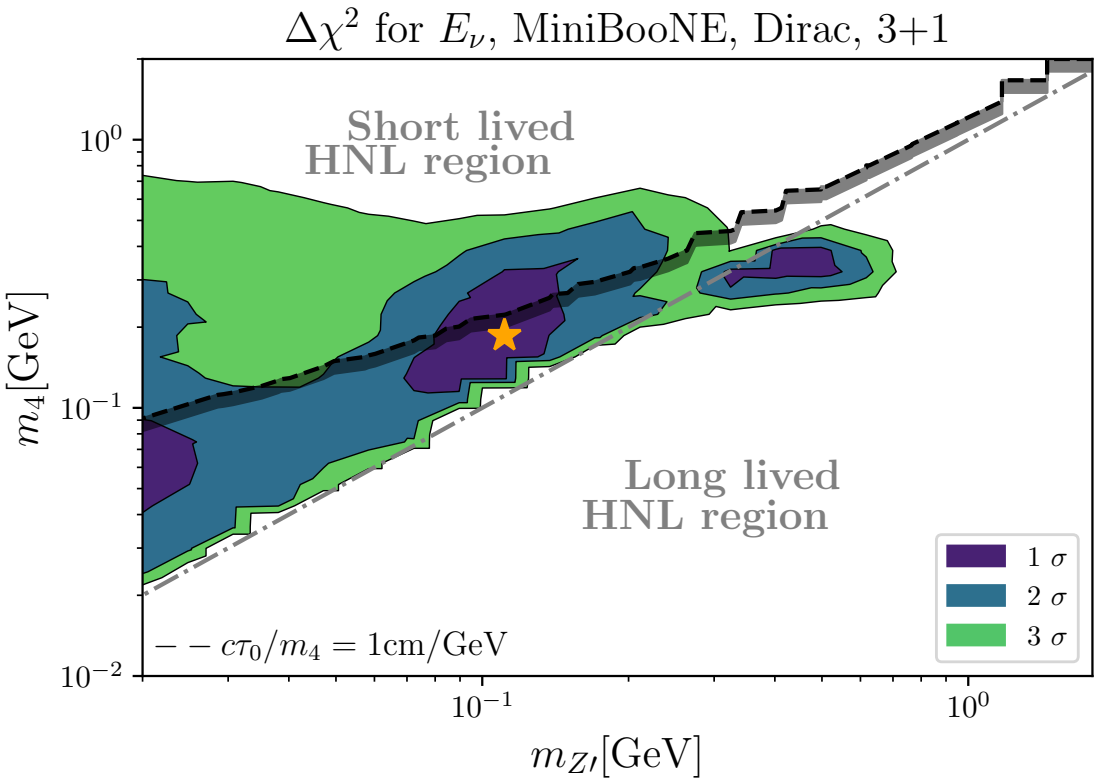
$$-2 \ln L =$$

$$\sum_{i,j} (D_i - P_i) M_{ij}^{-1} (D_j - P_j)$$

$$+ \ln \det M$$

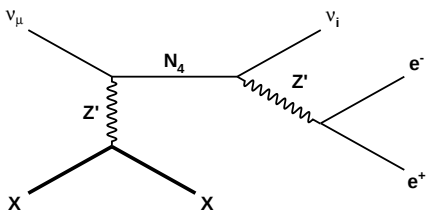
Results

3+1



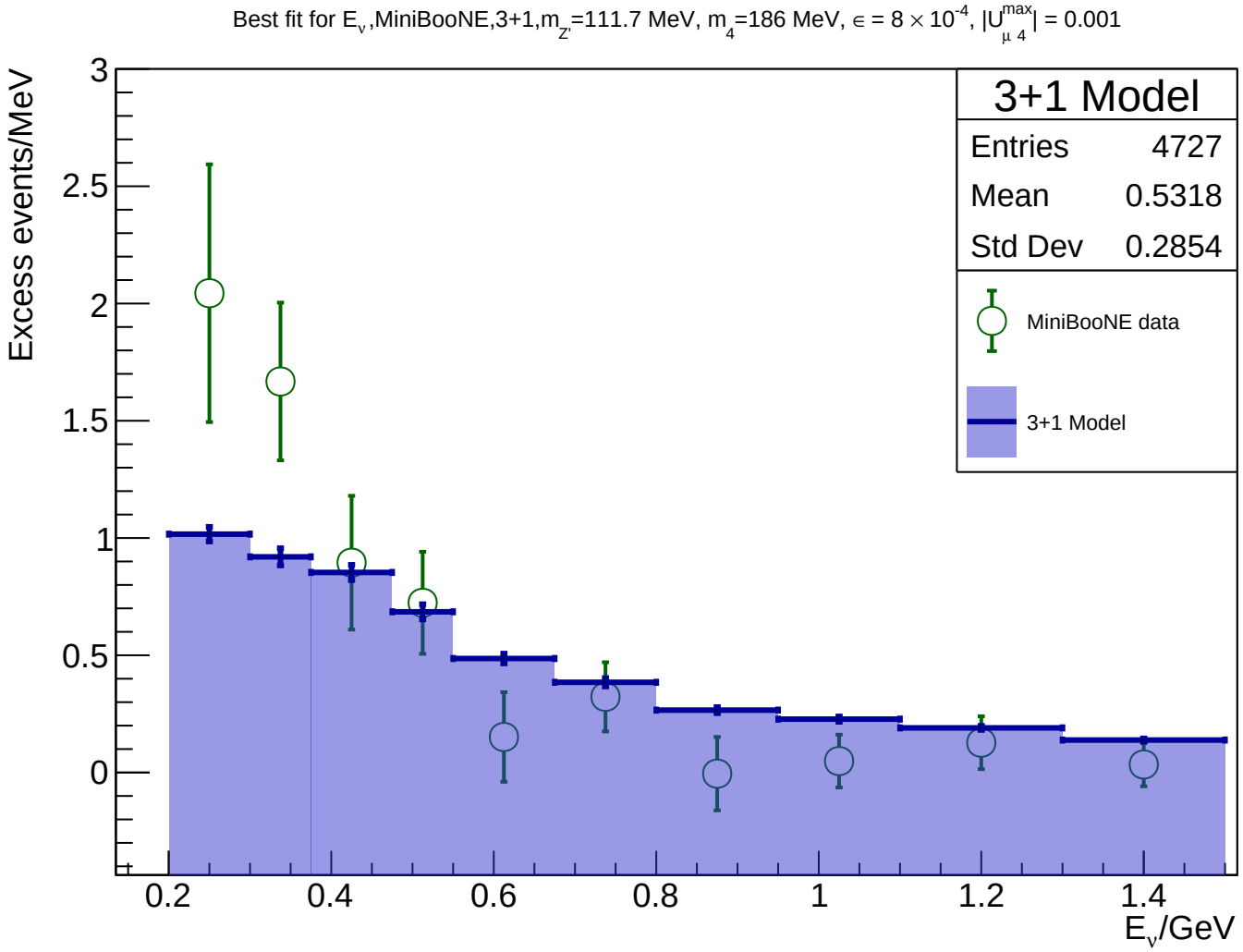
Best Fit: $m_{Z'}$=111.7MeV, m_4=186MeV,

χ^2_{red}=1.255, $|U^{\max}_{\mu 4}|$=10^{-3}, ϵ=8×10^{-4}



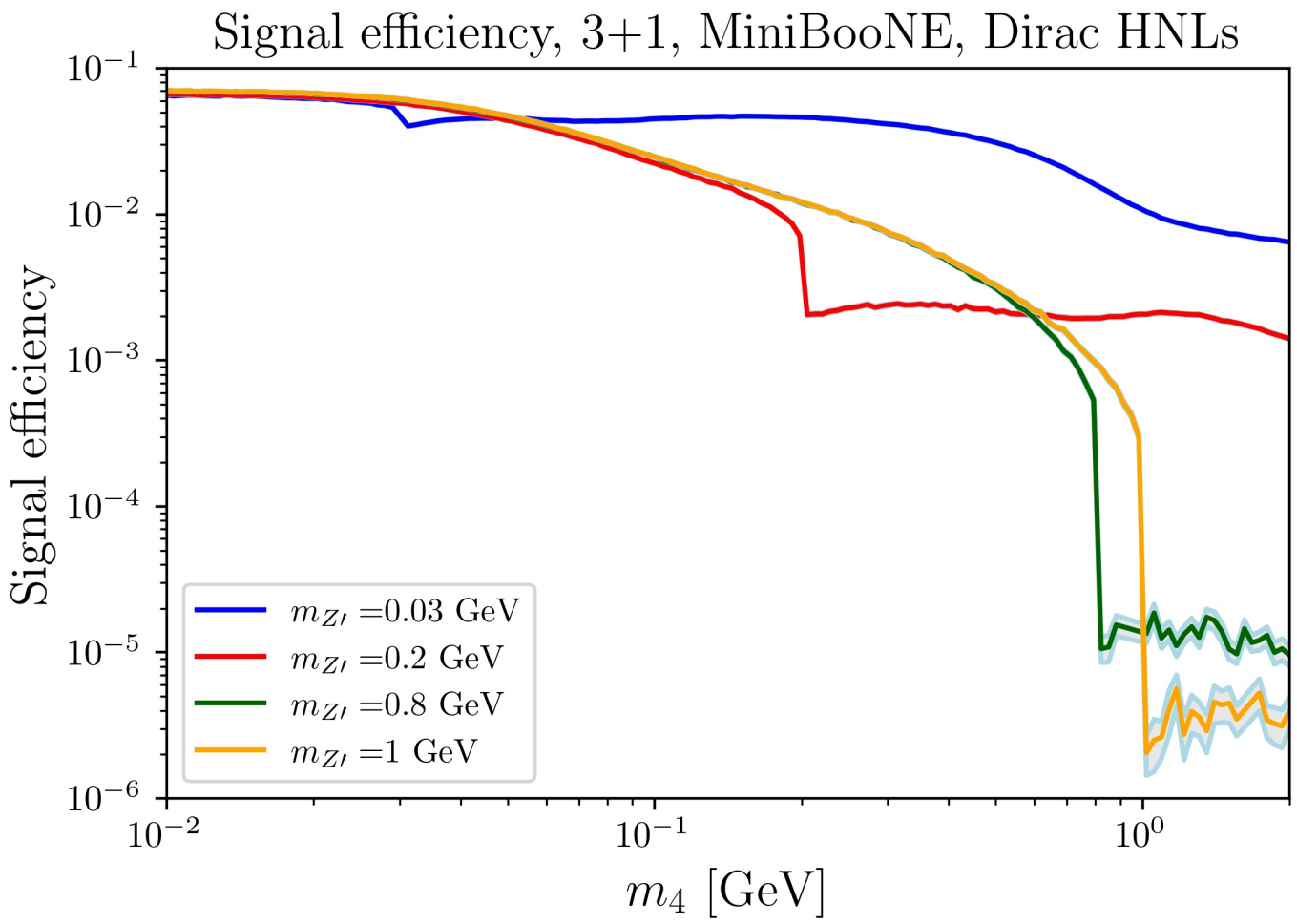
Results

3+1 best fit



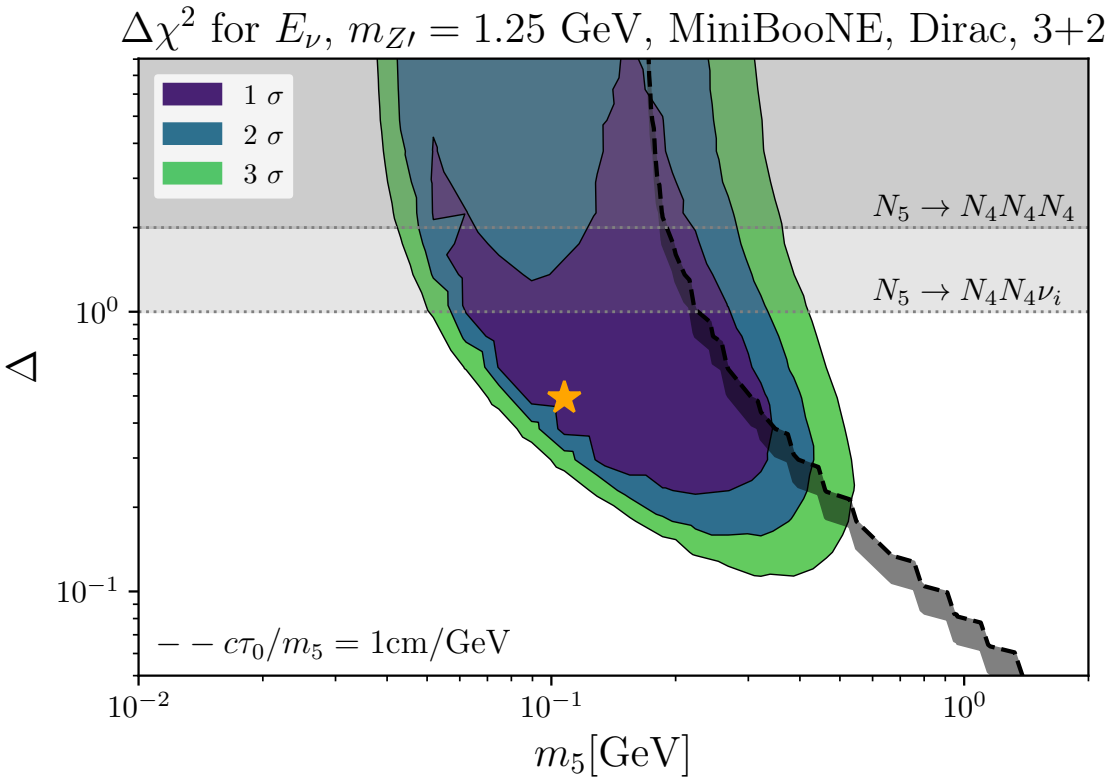
Results

Signal efficiency



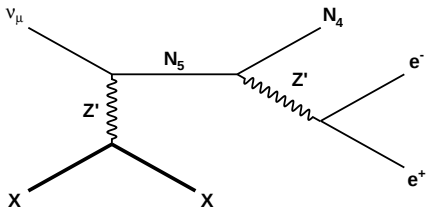
Results

3+2



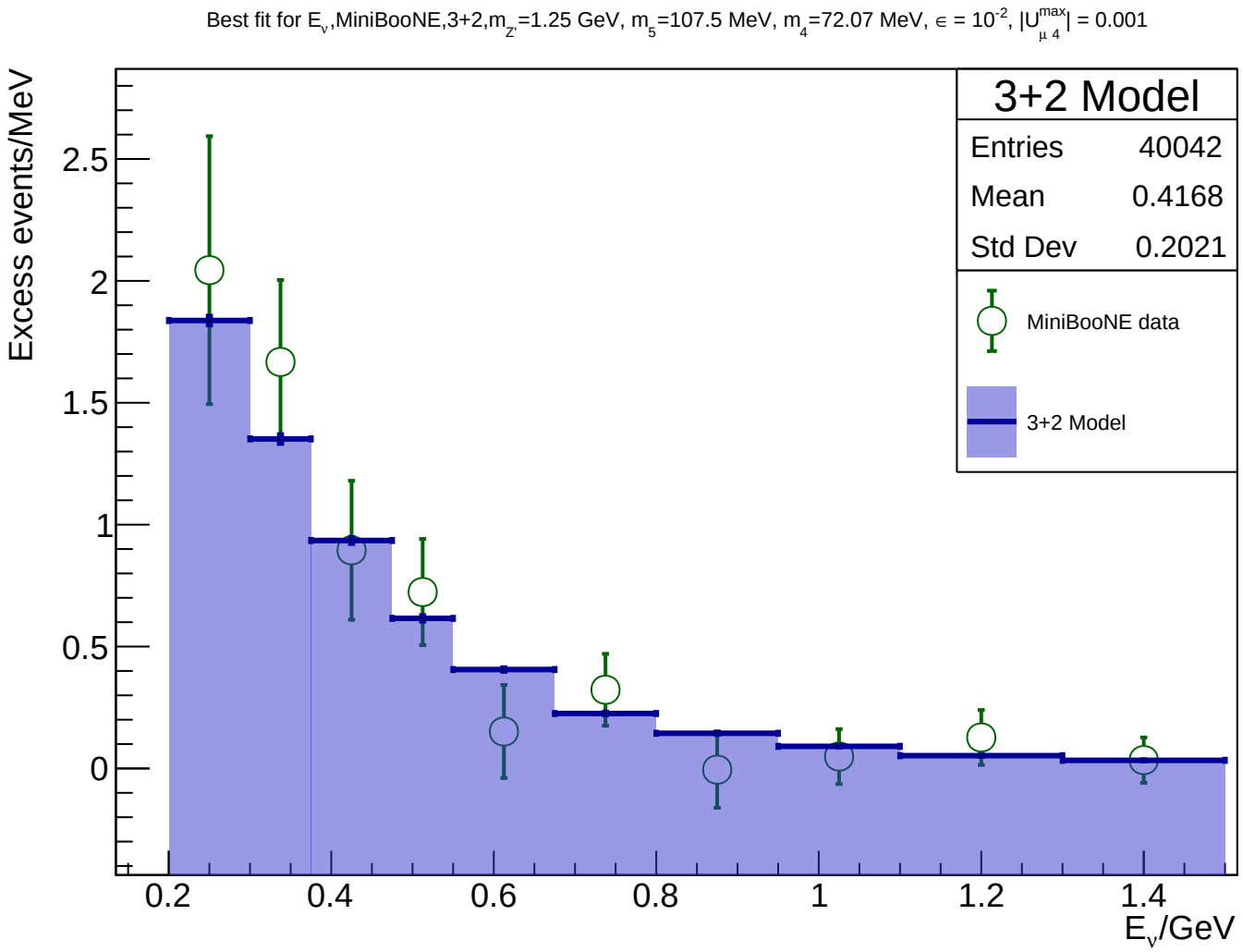
Best Fit: $m_{Z'}$=1.25GeV, m_5=107.5MeV, m_4=72.07MeV,

χ^2_{red}=0.91, $|U^{\max}_{\mu 5(4)}|=10^{-3}$, $\epsilon=10^{-2}$



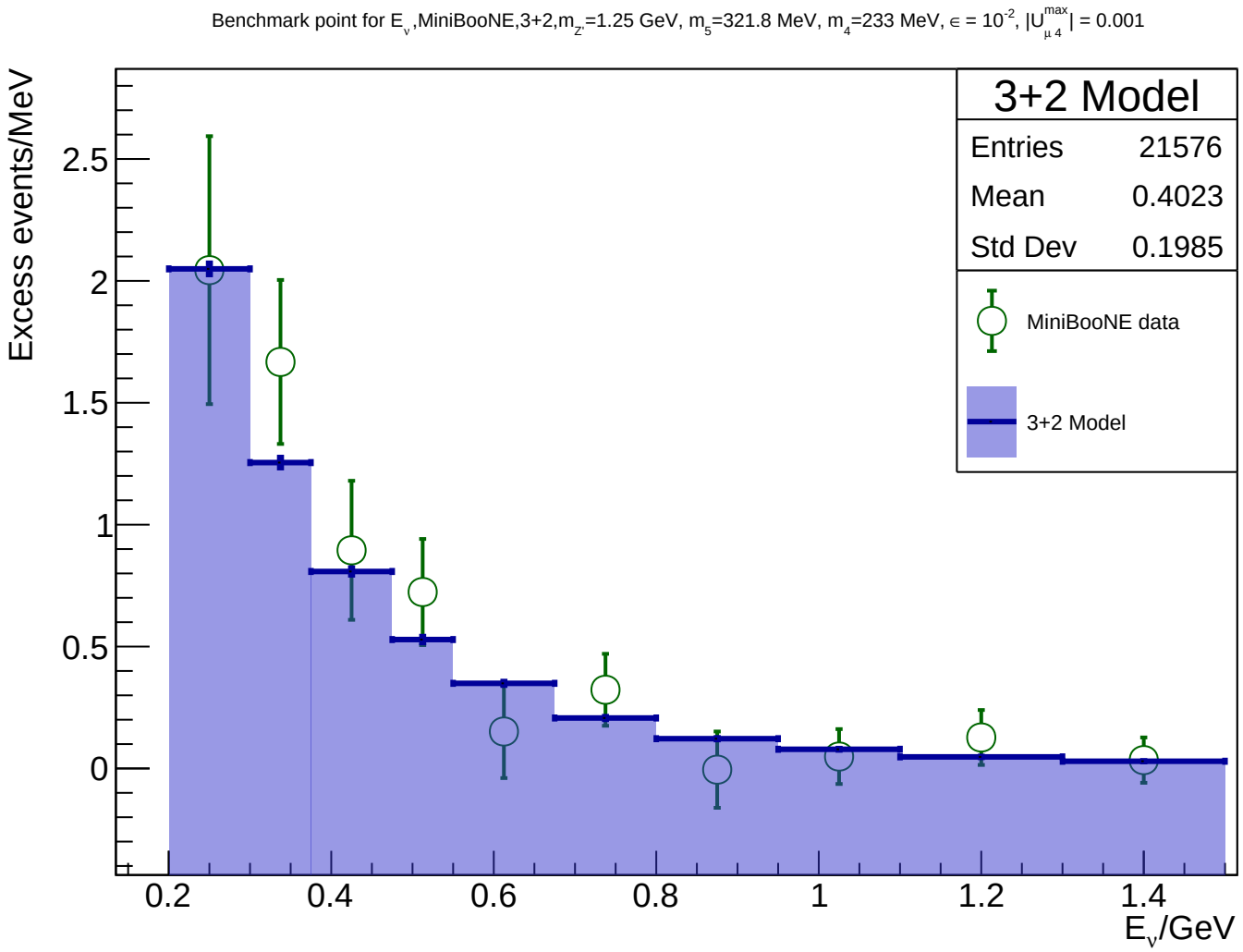
Results

3+2 best fit



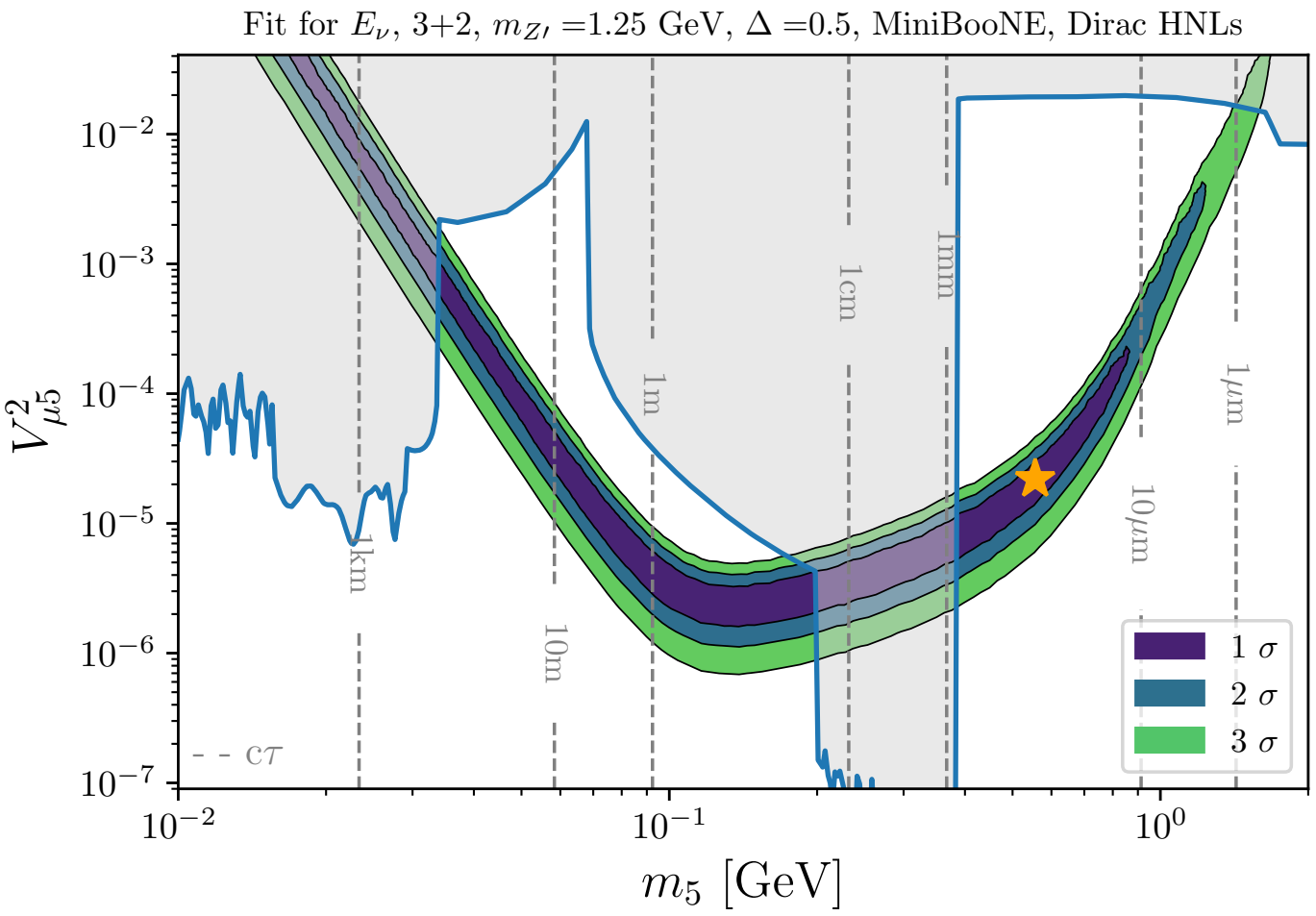
Results

3+2 benchmark point



Results

Couplings vs mass, 3+2



Summary

1. The 3+2 dark sector model can explain MB LEE in the off-shell decay regime of the HNL
2. It is a simple model with small number of parameters
3. The SBN program will be able to test it
4. It is not so constrained as other models, such as 3+1 DS

THANK YOU!

Limits for $U_{\mu N}$