Signatures of a sterile neutrino in B and D Decays.

Alakabha Datta

University of Mississippi

June 4, 2024

BEACH 2024

Collaborators: Hongkai Liu, Jacky Kumar, Lopamudra Mukherjee, Danny Marfatia: arXiv: 2310:15136; PRD, 2010.12109, 2103.04441 JHEP

Introduction

I will mainly focus on framework to explore sterile neutrino in various decays (B, D, K).

- One or more right handed (RH) neutrinos appear in many well motivated extensions of the SM and they have been invoked to explain many phenomena like neutrino masses, dark matter, portal to new physics etc.
- Sterile neutrinos are motivated to explain tiny neutrino masses. Seesaw mechanism (Majorana)

$$\mathcal{L} = (\bar{\nu}_L^c, \bar{\nu}_R) \begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} + h.c.,$$

$$m_\nu \approx -m_D M_N^{-1} m_D^T \quad m_n \approx M_N$$

The neutrinos are Majorana and the heavy sterile neutrino can be produced or decay through mixing with the SM active neutrino: Example in Meson decays $M_1 \to M_2 \ell \bar{\nu} \to M_2 \ell \bar{N}$

Majorana versus Dirac

- Seesaw mechanism (Dirac) Example is Mirror world Models (9503481, 2212.00737)

- The model is $G_{SM} \times G_M$:
  1. $\psi = (\nu_L, e_L)^T, e_R$ are doublet and singlet in G_{SM} and singlets in G_M, $\psi' = (\nu_R, e'_R)^T, e'_L$ are doublet and singlets in G_M and singlets in G_{SM}.
  2. The sterile neutrino $N = (N_L, N_R)^T$ are singlets under both gauge groups and $\nu = (\nu_L, \nu_R)$ is the light Dirac neutrino.
  3. Mixing comes from $\psi H N_R$ in G_{SM} and $\psi' H' N_L$ in G_M.

- $$\mathcal{L} = (\bar{\nu}_R, \bar{N}_R) \begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix} \begin{pmatrix} \nu_L \\ N_L \end{pmatrix} + h.c.,$$

Outline

- Sterile neutrino interaction with SM: Different Mechanisms.
- New interactions of the sterile neutrino - Heavy Mediators.
- Some examples, $\bar{B} \to D^* \mu^- \bar{\nu}_\mu, \bar{B} \to D^{*+} \tau^- \bar{\nu}_\tau, B^+ \to K^+ + \mathrm{inv}.$
- New interactions of the sterile neutrino: light mediator, e.g. $B^+ \to K^+ + \mathrm{inv}$, MiniBooNE, and$g-2$.
- Conclusions.

Outline

- Sterile neutrino interaction with SM: Different Mechanisms.
- New interactions of the sterile neutrino - Heavy Mediators.
- Some examples, $\bar{B} \to D^* \mu^- \bar{\nu}_\mu, \bar{B} \to D^{*+} \tau^- \bar{\nu}_\tau, B^+ \to K^+ + \mathrm{inv}$.
- New interactions of the sterile neutrino: light mediator, e.g. $B^+ \to K^+ + \mathrm{inv}$, MiniBooNE, and$g-2$.
- Conclusions.

Outline

- Sterile neutrino interaction with SM: Different Mechanisms.
- New interactions of the sterile neutrino - Heavy Mediators.
- Some examples, $\bar{B} \to D^* \mu^- \bar{\nu}_\mu, \bar{B} \to D^{*+} \tau^- \bar{\nu}_\tau, B^+ \to K^+ + \mathrm{inv}$.
- New interactions of the sterile neutrino: light mediator, e.g. $B^+ \to K^+ + \mathrm{inv}$, MiniBooNE, and$g - 2$.
- Conclusions.

Outline

- Sterile neutrino interaction with SM: Different Mechanisms.
- New interactions of the sterile neutrino - Heavy Mediators.
- Some examples, $\bar{B} \to D^* \mu^- \bar{\nu}_\mu, \bar{B} \to D^{*+} \tau^- \bar{\nu}_\tau, B^+ \to K^+ + \mathrm{inv}$.
- New interactions of the sterile neutrino: light mediator, e.g. $B^+ \to K^+ + \mathrm{inv}$, MiniBooNE, and$g-2$.
- Conclusions.

Outline

- Sterile neutrino interaction with SM: Different Mechanisms.
- New interactions of the sterile neutrino - Heavy Mediators.
- Some examples, $\bar{B} \to D^* \mu^- \bar{\nu}_\mu, \bar{B} \to D^{*+} \tau^- \bar{\nu}_\tau, B^+ \to K^+ + \text{inv}$.
- New interactions of the sterile neutrino: light mediator, e.g. $B^+ \to K^+ + \text{inv}$, MiniBooNE, and$g - 2$.
- Conclusions.

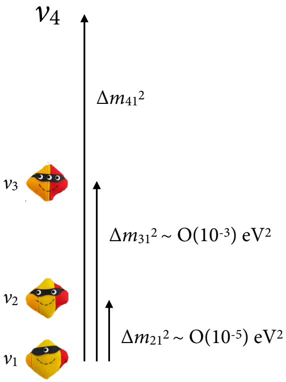
3+1 Neutrino Mixing

- Simplest model is to add a single new neutrino mass state with correct mass difference.

- PMNS mixing matrix increases from 3x3 to 4x4.

$$= \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

ν_4



Effective Interactions of the sterile neutrino

- Sterile neutrinos might have new interactions via the exchange of light or heavy mediators(Higgs, Vector Bosons, Leptoquarks). Heavy mediators can be integrated out to get an effective theory:SMNEFT.

- To lowest order in SMNEFT, the dimension-six B and L conserving SMNEFT Lagrangian is

$$L_{\mathsf{SMNEFT}} \supset L_{\mathrm{SM}} + \bar{n}\partial\!\!\!/ n + \sum_i \mathcal{C}_i \mathcal{O}_i \,,$$

where $\mathcal{C}_i$ are the WCs with the scale of new physics absorbed in them, The 16 baryon and lepton number conserving ($\Delta B = \Delta L = 0$) operators involving the field n in SMNEFT are shown in next slide.

Effective Operators

Construct dim 6 operators with the sterile neutrino.

SMNEFT = SMEFT + N

16 new SMNEFT operators at dimension-six $\Delta B = \Delta L = 0$

$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$		$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$	
$\mathcal{O}_{nd}$	$(\bar{n}_p\gamma_\mu n_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{qn}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{n}_s\gamma^\mu n_t)$	$\mathcal{O}_{\ell n\ell e}$	$(\bar{\ell}_p^j n_r)\epsilon_{jk}(\bar{\ell}_s^k e_t)$
$\mathcal{O}_{nu}$	$(\bar{n}_p\gamma_\mu n_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{\ell n}$	$(\bar{\ell}_p\gamma_\mu \ell_r)(\bar{n}_s\gamma^\mu n_t)$	$\mathcal{O}_{\ell nqd}^{(1)}$	$(\bar{\ell}_p^j n_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$\mathcal{O}_{ne}$	$(\bar{n}_p\gamma_\mu n_r)(\bar{e}_s\gamma^\mu e_t)$			$\mathcal{O}_{\ell nqd}^{(3)}$	$(\bar{\ell}_p^j \sigma_{\mu\nu} n_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} d_t)$
$\mathcal{O}_{nn}$	$(\bar{n}_p\gamma_\mu n_r)(\bar{n}_s\gamma^\mu n_t)$			$\mathcal{O}_{\ell nuq}$	$(\bar{\ell}_p^j n_r)(\bar{u}_s q_t^j)$
$\mathcal{O}_{nedu}$	$(\bar{n}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu u_t)$				
$\psi^2\phi^3$		$\psi^2\phi^2 D$		$\psi^2 X\phi$	
$\mathcal{O}_{n\phi}$	$(\phi^\dagger\phi)(\bar{l}_p n_r\tilde{\phi})$	$\mathcal{O}_{\phi n}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{n}_p\gamma^\mu n_r)$	$\mathcal{O}_{nW}$	$(\bar{\ell}_p\sigma^{\mu\nu} n_r)\tau^I\tilde{\phi}W_{\mu\nu}^I$
		$\mathcal{O}_{\phi ne}$	$i(\tilde{\phi}^\dagger D_\mu \phi)(\bar{n}_p\gamma^\mu e_r)$	$\mathcal{O}_{nB}$	$(\bar{\ell}_p\sigma^{\mu\nu} n_r)\tilde{\phi}B_{\mu\nu}$

UV models- archiV: 1807.04753

mediator WCs	irrep	$\delta\mathcal{L}_{\text{int}}$
W'_μ	$(1,1)_1$	$g'\left(c_q \bar{u}_R\gamma_\mu d_R + c_N \bar{\ell}_R\gamma_\mu N_R\right)W'^\mu$
Φ	$(1,2)_{1/2}$	$y_u \bar{u}_R Q_L \epsilon\Phi + y_d \bar{d}_R Q_L \Phi^\dagger + y_N \bar{N}_R L_L \epsilon\Phi$
U_1^μ	$(3,1)_{2/3}$	$\left(\alpha_{LQ}\bar{L}_L\gamma_\mu Q_L + \alpha_{\ell d}\bar{\ell}_R\gamma_\mu d_R\right)U_1^{\mu\dagger} + \alpha_{uN}\left(\bar{u}_R\gamma_\mu N_R\right)U_1^\mu$
$\tilde{R}_2$	$(3,2)_{1/6}$	$\alpha_{Ld}\left(\bar{L}_L d_R\right)\epsilon\tilde{R}_2^\dagger + \alpha_{QN}\left(\bar{Q}_L N_R\right)\tilde{R}_2$
S_1	$(\bar{3},1)_{1/3}$	$z_u(\bar{U}_R^c \ell_R)S_1 + z_d(\bar{d}_R^c N_R)S_1 + z_Q(\bar{Q}_L^c \epsilon L_L)S_1$

Production and Decay

- N can be produced from semileptonic decays of B, D, K, π at various experiments such as Belle 2, LHCb, FASER, DUNE ND.
- N can be Dirac or Majorana with different signatures. Depending on the N mass dominant contributions come from different mesons.
- N can be invisible or decay as $N \to \ell^+ \ell^- \nu$ through mixing or effective operators.
- The angular distribution of the decay products can reveal the Majorana or Dirac nature of N.

B and D decays at Belle 2

For $\bar{B} \to D^{*+}\ell^-\bar{\nu}_\ell$, N can be produced through mixing or effective operators. Mixing will alter just the SM operator.

N production operator

- We assume N can talk to B quark and is at sub GeV scale
- N can be produced via B meson decay

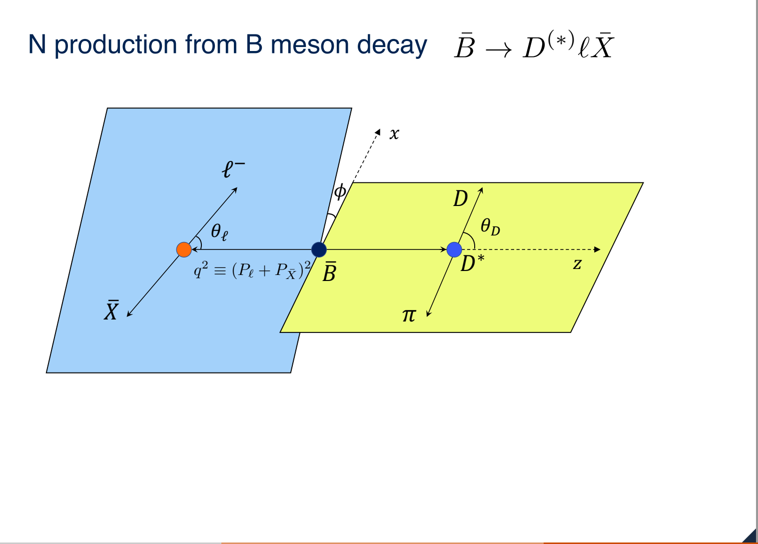
$$-\mathcal{L}_{\text{eff}} = \frac{4G_F V_{cb}}{\sqrt{2}}\Big(O^V_{LL} + \sum_{\substack{X=S,V,T \\ \alpha,\beta=L,R}} C^X_{\alpha\beta}\, O^X_{\alpha\beta}\Big)$$

$$\begin{aligned}
O^V_{\alpha\beta} &\equiv (\bar{c}\gamma^\mu P_\alpha b)(\bar{\ell}\gamma^\mu P_\beta \nu)\,, \\
O^S_{\alpha\beta} &\equiv (\bar{c}P_\alpha b)(\bar{\ell}P_\beta \nu)\,, \\
O^T_{\alpha\beta} &\equiv \delta_{\alpha\beta}(\bar{c}\sigma^{\mu\nu}P_\alpha b)(\bar{\ell}\sigma_{\mu\nu}P_\beta \nu)\,.
\end{aligned}$$

$$\begin{aligned}
\mathcal{O}_{nedu} &\to O^V_{RR} \\
\mathcal{O}_{\ell nuq} &\to O^S_{LR} \\
\mathcal{O}^{(1)}_{\ell nqd} &\to O^S_{RR} \\
\mathcal{O}^{(3)}_{\ell nqd} &\to O^T_{RR}
\end{aligned}$$

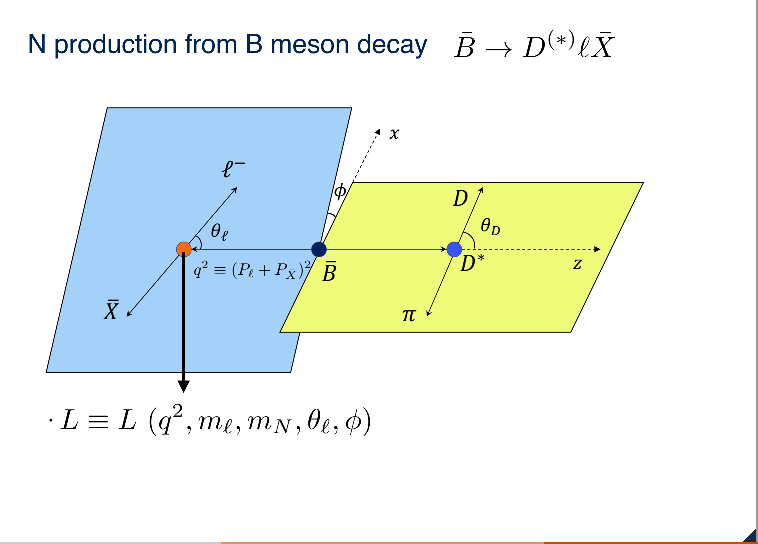
B and D decays at Belle 2

For $\bar{B} \to D^{*+}\ell^-\bar{\nu}_\ell$, N can be produced through mixing or effective operators. Mixing will alter just the SM operator.



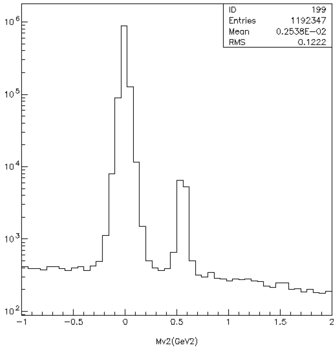
B and D decays at Belle 2

For $\bar{B} \to D^{*+}\ell^- \bar{\nu}_\ell$, N can be produced through mixing or effective operators. Mixing will alter just the SM operator.

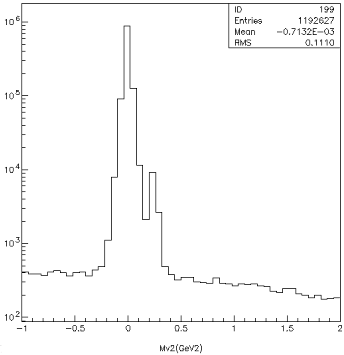


B and D decays at Belle 2

For $\bar{B} \to D^{*+}\ell^-\bar{\nu}_\ell$, N can be produced through mixing or effective operators. Mixing will alter just the SM operator.



Mhv=0.75 GeV
5% SM d*lv
Phase space



Mhv=0.50 GeV
5% d*lv
Phase space

B and D decays

For $\bar{B} \to D^{*+}\ell^-\bar{\nu}_\ell$, N can be produced through mixing or effective operators. Mixing will alter just the SM operator.

$$\bar{B} \to D^*(\to D\pi)\ell\bar{X}$$

Four-body decay

$$\frac{8\pi}{3}\frac{d^4\Gamma_{D^*}}{dq^2 d\cos\theta_\ell d\cos\theta_D d\phi} = (\mathcal{I}_{1s} + \mathcal{I}_{2s}\cos 2\theta_\ell + \mathcal{I}_{6s}\cos\theta_\ell)\sin^2\theta_D$$
$$+ (\mathcal{I}_{1c} + \mathcal{I}_{2c}\cos 2\theta_\ell + \mathcal{I}_{6c}\cos\theta_\ell)\cos^2\theta_D$$
$$+ (\mathcal{I}_3\cos 2\phi + \mathcal{I}_9\sin 2\phi)\sin^2\theta_D\sin^2\theta_\ell$$
$$+ (\mathcal{I}_4\cos\phi + \mathcal{I}_8\sin\phi)\sin 2\theta_D\sin 2\theta_\ell$$
$$+ (\mathcal{I}_5\cos\phi + \mathcal{I}_7\sin\phi)\sin 2\theta_D\sin\theta_\ell\,,$$

Angular functions

$$A_{FB}^{D^*}(q^2) = -\frac{\mathcal{I}_{6s}(q^2) + \frac{1}{2}\mathcal{I}_{6c}(q^2)}{\Gamma_f^{D^*}(q^2)} \qquad F_L(q^2) = \frac{\mathcal{I}_{1c}(q^2) - \frac{1}{3}\mathcal{I}_{2c}(q^2)}{\Gamma_f^{D^*}(q^2)}$$

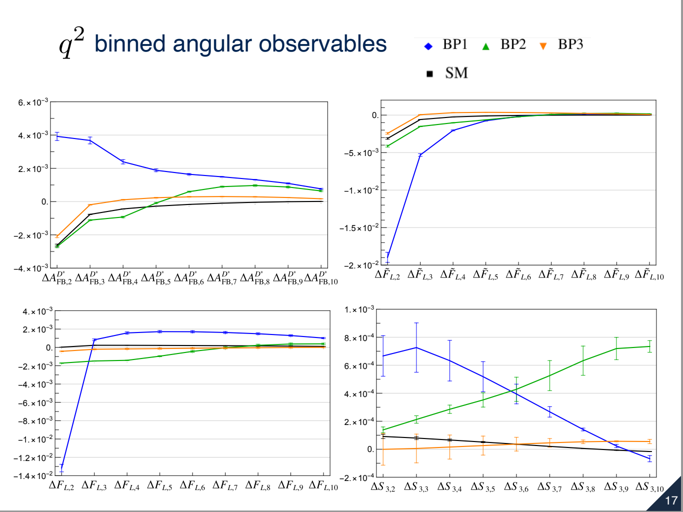
$$\tilde{F}_L(q^2) = \frac{1}{3} - \frac{8}{9}\frac{2\mathcal{I}_{2s}(q^2) + \mathcal{I}_{2c}(q^2)}{\Gamma_f^{D^*}(q^2)}$$

$$S_i(q^2) = \frac{\mathcal{I}_i(q^2)}{\Gamma_f^{D^*}(q^2)}\,, \quad i = \{3,4,5,7,8,9\}$$

10

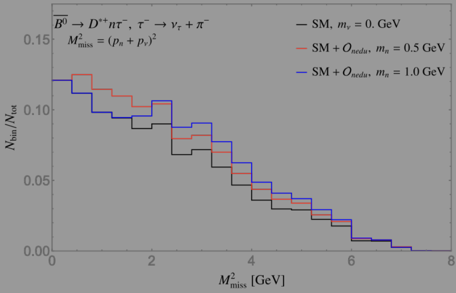
B and D decays at Belle 2

For $\bar{B} \to D^{*+}\ell^-\bar{\nu}_\ell$, N can be produced through mixing or effective operators. Mixing will alter just the SM operator.



$\bar{B} \to D^{*+}\tau^-\bar{\nu}_\tau$ in Effective Theories.

- Note presence of n might explain the $R^{\tau/\ell}_{D^{(*)}} \equiv \frac{\mathcal{B}(\bar{B}\to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}\to D^{(*)}\ell^-\bar{\nu}_\ell)}$ ($\ell = e, \mu$) Ex: 1804.04135,1804.04642
- In $\bar{B} \to D^{*+}\tau^-\bar{\nu}_\tau$ there are additional signals in missing energy.



$B \to D^*\tau X$ where $X = \nu, n$ with $\tau \to \pi\nu_\tau$.

ν_4 in Effective Theories $B^+ \to K^+ + \mathrm{inv}$

- For $d_i \to d_j + \mathrm{inv} \to d_j \bar{n} n$ - one can study in an effective field theory-νSMEFT or SMNEFT:

$$(\bar{n}_p \gamma_\mu n_r)(\bar{d}_s \gamma^\mu d_t), (\bar{q}_p \gamma_\mu q_r)(\bar{n}_s \gamma^\mu n_t), (\bar{\ell}^j_p \sigma_{\mu\nu} n_r)\epsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} d_t)$$

$$(\bar{\ell}^j_p n_r)\epsilon_{jk}(\bar{q}^k_s d_t)$$

- With the $B^+ \to K^+ + \mathrm{inv}$ measurement and other $B \to K^* + \mathrm{inv}$ bounds scalar operators are preferred (arXiv: 2309.02940).Unique signatures in the distributions.

- But RGE effects can generate operators like $\bar{\nu}\sigma_{\mu\nu} n F^{\mu\nu}$ which can contribute to neutrino scattering.

N interactions with light mediator

- The sterile neutrino can couple to a light mediator like a dark vector boson or a dark Higgs.
- Through mixing there are new production and decay mechanisms. Eg :$N \to \nu X$, where X is a light state which can decay to SM particles.
- Different signatures and can lead to neutrino NSI.

A specific example - Dark Higgs and sterile neutrino.

Motivated by the recent excess observed by Belle 2 in $B \to K + \mathrm{inv.}$

A dark Higgs, S , mixes with a general extended unspecified Higgs sector and couples to a sterile neutrino state.

$$\mathcal{L}_S \supset \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - \eta_d \sum_{f=d,\ell} \frac{m_f}{v}\bar{f}fS$$
$$- \sum_{f=u,c,t} \eta_f \frac{m_f}{v}\bar{f}fS - g_D S\bar{\nu}_D\nu_D - \frac{1}{4}\kappa S F_{\mu\nu}F^{\mu\nu} , \quad (1)$$

The sterile neutrino ν_D and the light neutrino mix and are taken to be Dirac fermion.

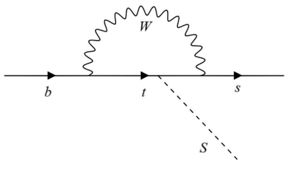
$$\nu_{\alpha(L,R)} = \sum_{i=1}^{4} U_{\alpha i}^{(L,R)} \nu_{i(L,R)} , \quad (\alpha = e, \mu, \tau, D) , \quad (2)$$

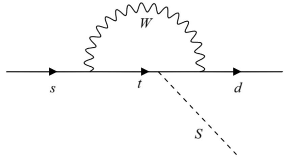
$(U^L = U^R \equiv U)$. Here, we assume $U_{e4} \approx U_{\tau 4} \approx 0$

Model specifics.

- The scalar has a mass $m_S = 100 - 150$ MeV and the sterile neutrino has a mass $\sim 400 - 500$ MeV.
- Both S and sterile neutrino are short lived.
- The mixing of the S in the down sector is universal but not in the up sector.
- The production of S($B \to KS, K \to \pi S$) and its decay ($S \to e^+e^-, \gamma\gamma, \bar{\nu}\nu$).
- The production of ν_D(from mixing with light neutrino) and its decay ($\nu_D \to \nu_\mu S \to \nu_\mu e^+e^-, \nu_\mu\gamma\gamma, \nu_\mu\bar{\nu_\mu}\nu_\mu$).

$B \to KS$ and $K \to \pi S$





$$\mathcal{L}_{FCNC} = g_{bs}\bar{s}P_R bS + g_{sd}\bar{d}P_R sS,$$

$$g_{bs} \approx \frac{3\sqrt{2}G_F}{16\pi^2}\frac{m_t^2 m_b}{v}\eta_t V_{tb}V_{ts}^*$$

and

$$g_{sd} \approx \frac{3\sqrt{2}G_F}{16\pi^2}\frac{m_t^2 m_s}{v}V_{ts}V_{td}^*\left(\eta_t + \eta_c\frac{m_c^2}{m_t^2}\frac{V_{cs}V_{cd}^*}{V_{ts}V_{td}^*}\right)$$

- $\frac{V_{cs}V_{cd}^*}{V_{ts}V_{td}^*} \sim \lambda^{-4}$, λ is the Cabibbo angle..
- η_t can be fixed to accommodate the new measurement of $B \to K + \mathrm{inv}$.

$K_L \to \pi^0 + \mathrm{inv}$ Bounds

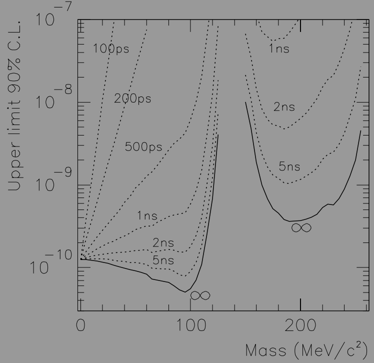
If kinematically allowed: $m_s + m_\pi \leq m_K$ then $K_L \to \pi^0 + \mathrm{inv}$ put bounds on η_c

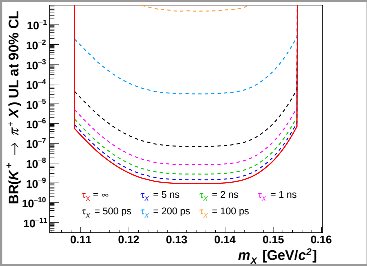
$$g_{sd} \approx \frac{3\sqrt{2}G_F}{16\pi^2}\frac{m_t^2 m_s}{v} V_{ts}V_{td}^* \left(\eta_t + \eta_c \frac{m_c^2}{m_t^2}\frac{V_{cs}V_{cd}^*}{V_{ts}V_{td}^*}\right)$$

- If $\eta_t \sim \eta_c$ then predicted $K_L \to \pi^0 + \mathrm{inv}$ violates the KOTO bound (KOTO - arXiv: 2012.07571).
- $K_L \to \pi^0 S$ is CP conserving and so rate $\sim Re[V_{ts}V_{td}^* \left(\eta_t + \eta_c \frac{m_c^2}{m_t^2}\frac{V_{cs}V_{cd}^*}{V_{ts}V_{td}^*}\right)]$ and cancellation is possible to satisfy KOTO bound.
- We find $\eta_t \sim 0.005$ and $|\eta_c| \sim 0.1$ for $\mathcal{B}[S \to \bar{\nu}\nu] \sim 1$.

$K^+ \to \pi^+ + \text{inv}$ Bounds

$K^+ \to \pi^+ + \text{inv}$ interpreted as $K^+ \to \pi^+ X$





Various experiments like E979 (arXiv:0903.0030), NA62(arXiv: 2010.07644) put bounds on the $\mathcal{BR}[K^+ \to \pi^+ X]$ for different lifetimes. We avoid these bounds as we have shorter lifetime.

The sterile neutrino

The sterile neutrino ν_D and the light neutrino are taken to be Dirac fermion.

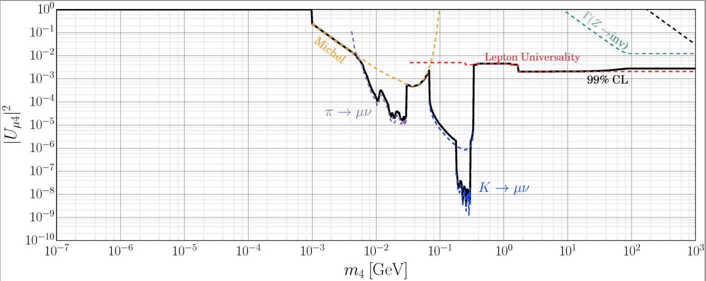
$$\nu_{\alpha(L,R)} = \sum_{i=1}^{4} U_{\alpha i}^{(L,R)} \nu_{i(L,R)} \; , \quad (\alpha = e, \mu, \tau, D) \, , \tag{3}$$

$(U^L = U^R \equiv U)$. Here, we assume $U_{e4} \approx U_{\tau 4} \approx 0$

- Several experiments including PS191, NuTeV, BEBC , FMMF, CHARM II, NA62, T2K and MicroBooNE have placed limits on U for long lived HNL.
- We avoid these bounds because both S and ν_D are short lived with lifetime less than 0.1 ps.

Bounds on $U_{\mu 4}$

Decay independent bounds: arXiv:1511.00683



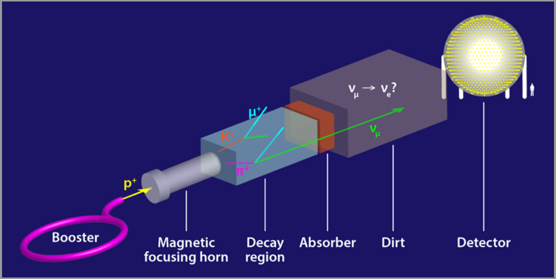
- arXiv:1802.02965(CMS) Upper limits at 95% limit for $|U_{e4}|^2$ and $|U_{\mu 4}|^2$ from $W \to \ell\nu_4, \nu_4 \to \ell e^+e^-\nu(100\%)$ between $1.2 \times 10^{-5} - 1.8$ for $m_{\nu 4}$ between 1 GeV- 1.2 TeV.
- Require m_{ν_4} around $400 - 500$ MeV with $U_{\mu 4} \sim 10^{-3}$ and so consistent with bounds.

Constraints

Observable	SM expectation	Measurement or constraint
$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})$	$(5.58 \pm 0.38) \times 10^{-6}$	$(2.40 \pm 0.67) \times 10^{-5}$
$\mathcal{B}(B^0 \to K^{*0} \nu\bar{\nu})$	$(9.2 \pm 1.0) \times 10^{-6}$	$< 1.8 \times 10^{-5}$
$\mathcal{B}(B^+ \to K^{*+} \nu\bar{\nu})$	$\mathcal{B}(B^0 \to K^{*0} \nu\bar{\nu}) \frac{\tau_{B^+}}{\tau_{B^0}}$	$< 4 \times 10^{-5}$
$\mathcal{B}(B^0 \to K^{*0} e^+ e^-)_{0.03-1\ \mathrm{GeV}}$	$(2.43^{+0.66}_{-0.47}) \times 10^{-7}$	$(3.1^{+0.9+0.2}_{-0.8-0.3} \pm 0.2) \times 10^{-7}$
$\mathcal{B}(B_s \to \gamma\gamma)$	5×10^{-7}	$< 3.1 \times 10^{-6}$
$\mathcal{B}(B_s \to \mu^+\mu^-)$	$(3.57 \pm 0.17) \times 10^{-9}$	$(3.52^{+0.32}_{-0.31}) \times 10^{-9}$
$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$	$(3.4 \pm 0.6) \times 10^{-11}$	$< 4.9 \times 10^{-9}$
$\mathcal{B}(K_L \to \pi^0 e^+ e^-)$	$(3.2^{+1.2}_{-0.8}) \times 10^{-11}$	$< 2.8 \times 10^{-10}$
$\mathcal{B}(K_L \to \pi^0 \gamma\gamma)$	-	$(1.273 \pm 0.033) \times 10^{-6}$
$\mathcal{B}(K_S \to \pi^0 \gamma\gamma)$	-	$(4.9 \pm 1.8) \times 10^{-8}$
$\mathcal{B}(K^+ \to \pi^+ \gamma\gamma)$	-	$(1.01 \pm 0.06) \times 10^{-6}$
$\mathcal{B}(K^\pm \to \mu^\pm \nu_\mu e^+ e^-)_{m_{e^+e^-} \geq 140\ \mathrm{MeV}}$	-	$(7.81 \pm 0.23) \times 10^{-8}$
ΔM_{B_s}	$(18.4^{+0.7}_{-1.2})\ \mathrm{ps}^{-1}$	$(17.765 \pm 0.006)\ \mathrm{ps}^{-1}$
ΔM_K	$(47 \pm 18) \times 10^8\ \mathrm{s}^{-1}$	$(52.93 \pm 0.09) \times 10^8\ \mathrm{s}^{-1}$
a_μ	$116591810(43) \times 10^{-11}$	$116592059(22) \times 10^{-11}$

Neutrino NSI - MiniBooNE Electron like events

- Model predicts new effect in neutrino scattering $\nu_\mu + Z \to \nu_4 + Z$ and ν_4 decay, $\nu_4 \to \nu_\mu S \to \nu_\mu + (e^+e^-, \gamma\gamma, \bar{\nu_\mu}\nu_\mu)$.
- Consider as explanation for the MiniBooNE Electron like events. arXiv: 2308.02543(for review).

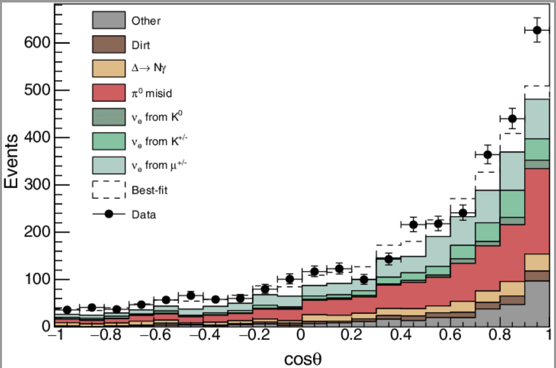


MiniBooNE Electron like events

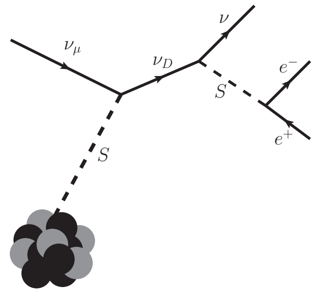
- There is an apparent $\nu_\mu \to \nu_e$ conversion of neutrinos and antineutrinos at short baselines in the MiniBooNE experiment and the Liquid Scintillator Neutrino Detector (LSND).
- The MiniBooNE, excess is characterized by electron-like events in the energy region between 200 MeV and 600 MeV and is coincident in time with the $\langle E_\nu \rangle \sim 0.8$ GeV neutrino beam. Considered a 4.8 σ significance.
- Many solutions, oscillatory(3+1 oscillations) and non-oscillatory- like additional new physics sources of e^+e^- or $\gamma\gamma$ pairs and we focus on the later
- MicroBooNE rules out some of the solutions but many solutions still unconstrained.

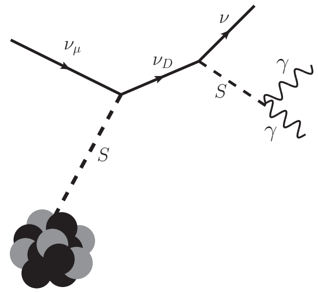
MiniBooNE- Distributions

MiniBooNE signal has a distinct angular distribution distribution.



MiniBooNE - S model





$$\mathcal{L}_{SN} = C_N \bar{\psi}_N \psi_N S\,,$$
$$C_N = ZC_p + (A-Z)C_n\,.$$

The proton and neutron couplings are related to the quark-scalar couplings by

$$C_p = \frac{m_p}{v}\left(\eta_c f_c^p + \eta_t f_t^p + \sum_d \eta_d f_d^p\right), \quad C_n = \frac{m_n}{v}\left(\eta_c f_c^n + \eta_t f_t^n + \sum_d \eta_d f_d^n\right)$$

MiniBooNE - S model

The proton and neutron couplings are related to the quark-scalar couplings by

$$C_p = \frac{m_p}{v}\left(\eta_c f_c^p + \eta_t f_t^p + \sum_d \eta_d f_d^p\right), \quad C_n = \frac{m_n}{v}\left(\eta_c f_c^n + \eta_t f_t^n + \sum_d \eta_d f_d^n\right)$$

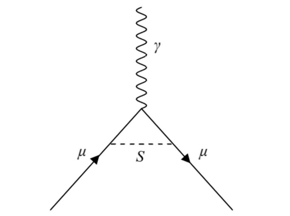
- η_t and η_c constrained from $B \to K + \mathrm{inv}$ and $K \to +\pi \mathrm{inv}$ decays.
- η_d determines coupling of S to electron pairs and so controls $B \to Ke^+e^-$ and $K \to \pi e^+ e^-$.
- So all terms in the coherent neutrino scattering are constrained from rare B and K decays.

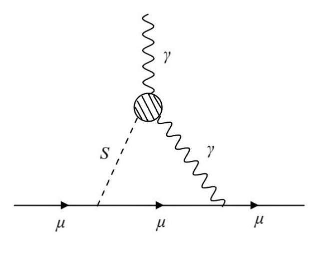
Predictions - S model

BP	$\mathcal{B}(S \to \gamma\gamma)$	$\mathcal{B}(S \to \nu\bar{\nu})$	$\mathcal{B}(S \to e^+e^-)$	$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$	$\mathcal{B}(B_s \to \nu\bar{\nu})$	$\mathcal{B}(B \to K^{(*)}\gamma\gamma)$
1	0.093	0.907	4.26×10^{-5}	1.71×10^{-9}	5.13×10^{-7}	1.3×10^{-6}
2	0.717	0.282	7.06×10^{-4}	3.61×10^{-11}	3.54×10^{-7}	3.7×10^{-5}
3	0.496	0.504	5.93×10^{-5}	9.02×10^{-10}	4.14×10^{-7}	1.7×10^{-5}
4	0.165	0.835	1.10×10^{-4}	1.73×10^{-9}	1.43×10^{-6}	2.65×10^{-6}
5	0.829	0.170	9.72×10^{-4}	2.04×10^{-10}	1.72×10^{-7}	6.8×10^{-5}
6	4.58×10^{-6}	0.999	7.10×10^{-4}	1.89×10^{-9}	1.01×10^{-6}	6.5×10^{-11}
7	3.95×10^{-4}	0.997	2.14×10^{-3}	2.84×10^{-9}	4.86×10^{-7}	7.6×10^{-9}

- $K_L \to \pi^0 + \text{inv}$ can be close to the KOTO bound.
- Resonance in $B \to K^{(*)}\gamma\gamma$ is the main prediction.
- The branching ratio of S to electron-positron pair is tiny and so $b \to s\ell^+\ell^-(B \to K^{(*)}\ell^+\ell^-)$ decays mostly SM.

a_μ, a_e constraints/predictions





Because of small S coupling to leptons the Barr-Zee diagram dominates .

$$\delta(g-2)_\ell^{S\gamma\gamma} \approx \frac{\eta_d}{4\pi^2}\frac{\kappa m_\ell^2}{v}\ln\frac{\Lambda}{m_S}\,, \qquad (4)$$

η_d and κ control the $S \to e^+e^-$ and $S \to \gamma\gamma$ rates.

Conclusions

- Sterile neutrino is a well motivated extension of the SM - neutrino masses, dark matter.
- The sterile neutrino can couple to SM via various mechanisms- mixing, new interactions with heavy and light mediators
- We discussed some examples of these interactions.
- Make other applications and signatures possible in different experiments.