A sterile neutrino in the B and MiniBooNE anomalies.

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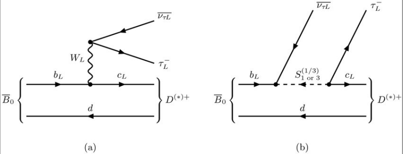
Introduction

- For some time now there have been anomalies in B decays.
- These are in semileptonic $b \to c\tau\bar{\nu}_\tau$ transitions: $R_{D^{(*)}}$ puzzle : CC processes.
- These are in semileptonic $b \to s\ell^+\ell^-(l = \mu, e)$ transitions. BR of $b \to s\mu^+\mu^-$ modes are lower and also deviation in P_5' angular observable. Could be long distance QCD effects.
- The semileptonic $B^+ \to K^+\nu\bar{\nu}$ transitions was observed with enhanced rate by Belle 2 .
- There are puzzles in non-leptonic decays: ($b \to s\bar{q}q$) (see for e.g. 1709.07142, 2311.18011).

Simultaneous Explanations

- Some of the anomalies may have a common solution or share common elements.
- NC $b \to s\ell^+\ell^-(l = \mu, e)$ and $b \to s\bar{q}q$ anomalies may be related. NC and $b \to s\ell^+\ell^-(l = \mu, e)$ and CC $b \to c\tau\bar{\nu_\tau}$ may be related(SMEFT).
- The semileptonic $b \to c\tau\bar{\nu_\tau}$ transitions and $B^+ \to K^+\nu\bar{\nu}$ involve invisible final state and so might share a common element- a sterile neutrino.
- A sterile neutrino appears in solution to neutrino anomalies and so it is interesting to connect it to the B anomalies.

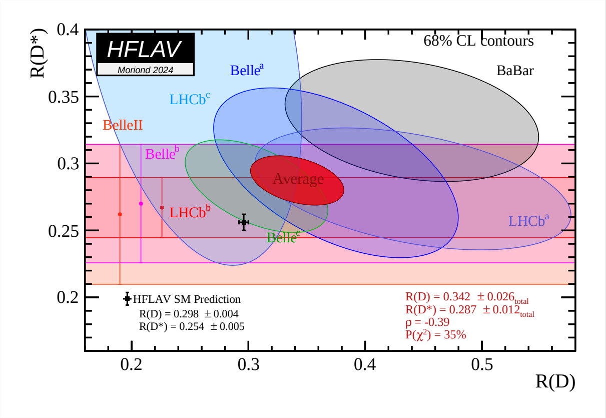
$R(D) - R(D^*)$ puzzle



$$A_{SM} = \frac{G_F}{\sqrt{2}} V_{cb} \left[\langle D^{(*)}(p') | \bar{c}\gamma^\mu (1-\gamma_5) b | \bar{B}(p) \rangle \right] \bar{\tau}\gamma_\mu (1-\gamma_5)\nu_\tau$$

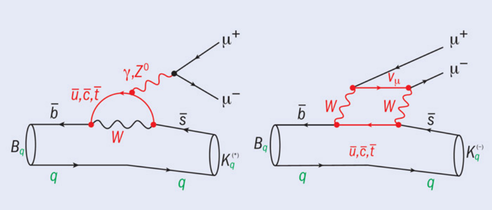
$$R(D) \equiv \frac{\mathcal{B}(\bar{B} \to D^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^+ \ell^- \bar{\nu}_\ell)} \qquad R(D^*) \equiv \frac{\mathcal{B}(\bar{B} \to D^{*+} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{*+} \ell^- \bar{\nu}_\ell)}.$$

Experiments: $R(D) - R(D^*)$ puzzle



Including correlations, one finds that the deviation is at the level of 3.31σ from the SM prediction.

NC FCNC: $b \to s\mu^+\mu^-$ and $b \to s\nu\bar{\nu}$ - SM



$$H_{\rm eff}(b \to s\ell\bar{\ell}) = -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb} V_{ts}^* \left[C_9\, (\bar{s}_L \gamma^\mu b_L)\, (\bar{\ell}\gamma_\mu \ell) + C_{10}\, (\bar{s}_L \gamma^\mu b_L)\, (\bar{\ell}\gamma_\mu \gamma^5 \ell)\right] ,$$

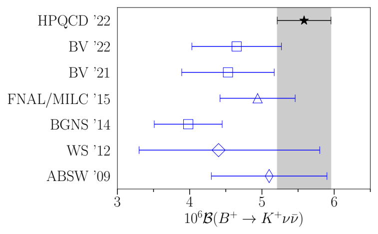
$$H_{\rm eff}(b \to s\nu\bar{\nu}) = -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb} V_{ts}^*\, C_L\, (\bar{s}_L \gamma^\mu b_L)\, (\bar{\nu}\gamma_\mu (1-\gamma^5)\nu) ,$$

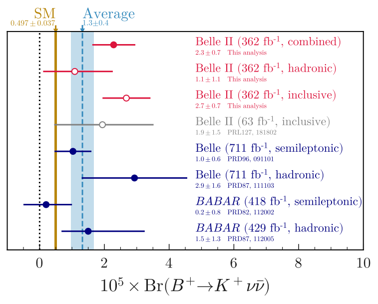
$$H_{\rm eff}(b \to s\gamma^*) = C_7\, \frac{e}{16\pi^2} [\bar{s}\sigma_{\mu\nu}(m_s P_L + m_b P_R) b]\, F^{\mu\nu}$$

$B^+ \to K^+\nu\bar{\nu}$ Anomaly

$$M_{\rm SM}(B \to K^{(*)}\nu\bar{\nu}) \;=\; -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb} V_{ts}^{*}\, C_L \,\langle K^{(*)}|\bar{s}_L\gamma^\mu b_L|B\rangle \bar{\nu}\gamma_\mu(1-\gamma^5)\nu$$

Same Form Factors. From lattice:arXiv: 2207.13371, HPQCD





A sterile neutrino may be involved in $b \to c\tau\bar{\nu_\tau}$ and $B^+ \to K^+\nu\bar{\nu}$. How do the sterile neutrino couple to SM particles?

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 muon $g-2$.
- Conclusions.

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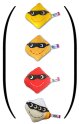
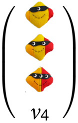
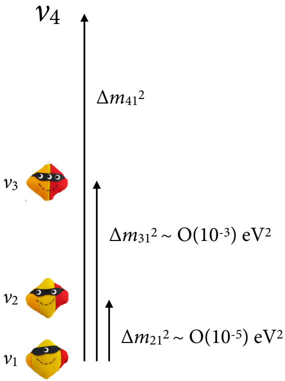
3+1 Neutrino Mixing

- Simplest model is to add a single new neutrino mass state with correct mass difference.
- PMNS mixing matrix increases from 3x3 to 4x4.



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





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 (νSMEFT).

- 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- e.g. arXiv: 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	$(\bar{3},1)_{1/3}$	$z_u(\bar{U}_R^c \ell_R) S_1 + z_d(\bar{d}_R^c N_R) S_1 + z_Q(\bar{Q}_L^c \epsilon L_L) S_1$

CC B Decays Effective Operators

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

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

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

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

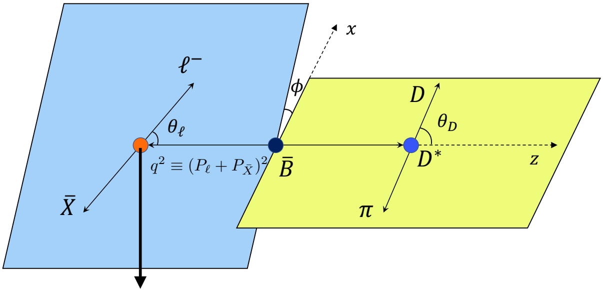
6

A sterile neutrino can solve the $R(D) - R(D^*)$ puzzle. (1211.0348, 1704.06659,1711.09525, 1804.04135,1804.04642, 1810.06597, 1811.04496 ....). The NP adds incoherently with SM and enhances rate.

CC B decays with Effective Operators

Even though no deviation in BR there can be striking signatures in angular distributions. Note large statistics in CC decays with a BR of a few percent.

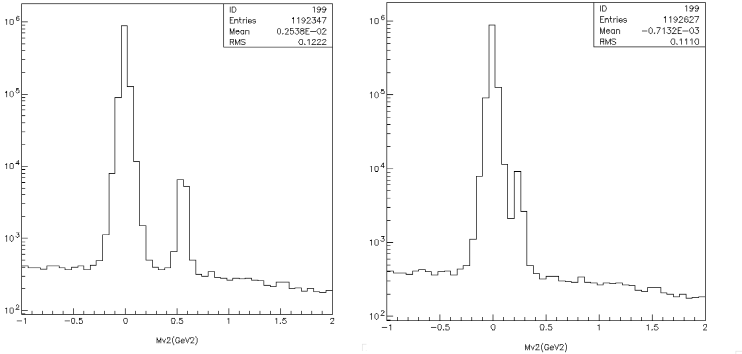
N production from B meson decay $\bar{B} \to D^{(*)} \ell \bar{X}$



$$\cdot\, L \equiv L\,(q^2, m_\ell, m_N, \theta_\ell, \phi)$$

Signature of N in B 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

Signature of N in B 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

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

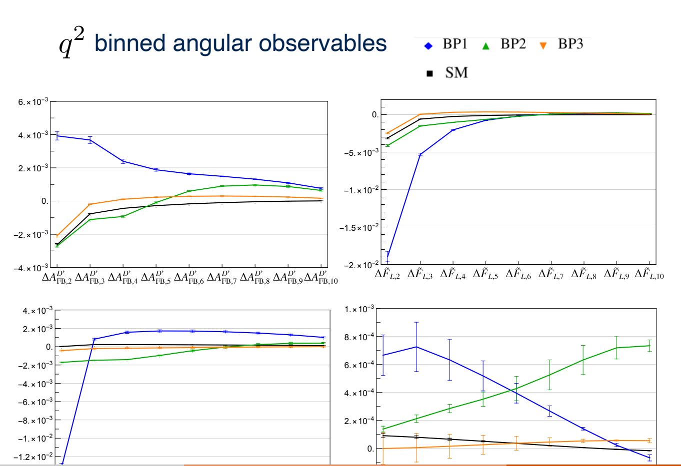
$$\tilde{F}_L(q^2) = \frac{1}{3} - \frac{8}{9}\frac{2\mathcal{I}_{2s}(q^2) + \mathcal{I}_{2c}(q^2)}{\Gamma_f^{D^*}(q^2)}$$

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

10

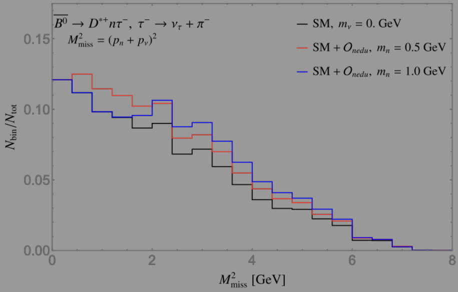
Signature of N in B at Belle 2: e-Print: 2204.01818.

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 $R^{\tau/\ell}_{D^{(*)}} \equiv \frac{\mathcal{B}(\bar{B}\to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}\to D^{(*)}\ell^-\bar{\nu}_\ell)}$ ($\ell = e, \mu$)
- 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 $\tau \to \pi\nu_\tau$.

Sterile neutrino in $B^+ \to K^+ + \mathrm{inv}$

- 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.

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: arXiv: 2310.15136

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

A dark Higgs, S , mixes with a general extended unspecified Higgs sector (see: arXiv:1606.04943, 1908.08625, 2001.06522) and couples to a sterile neutrino state.

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

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

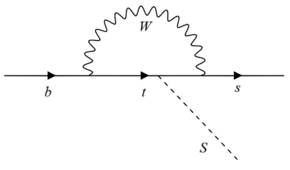
$$\nu_{\alpha(L,R)} = \sum_{i=1}^{4} U_{\alpha i}^{(L,R)} \nu_{i(L,R)} \,, \quad (\alpha = e, \mu, \tau, D)\,, \quad (2)$$

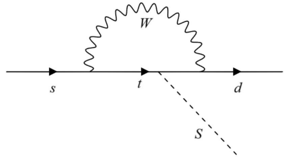
$(U^L = U^R \equiv U)$. Here, we assume $U_{e4} \approx U_{\tau 4} \approx 0$

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 $B \to K + \text{inv}$.

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

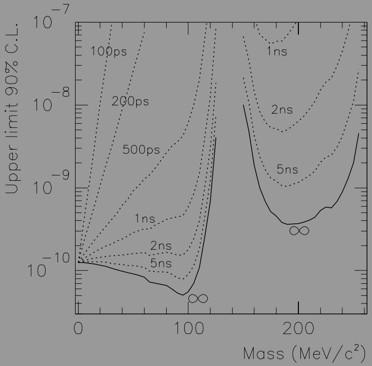
If kinematically allowed: $m_s + m_\pi \leq m_K$ then $K_L \to \pi^0 + \mathrm{inv}$ put bounds on η_c

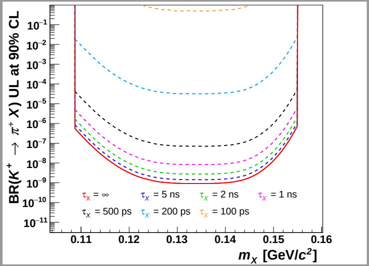
$$g_{sd} \approx \frac{3\sqrt{2}G_F}{16\pi^2}\frac{m_t^2 m_s}{v} V_{ts}V_{td}^* \left(\eta_t + \eta_c \frac{m_c^2}{m_t^2}\frac{V_{cs}V_{cd}^*}{V_{ts}V_{td}^*}\right)$$

- $K_L \to \pi^0 S$ 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 can choose η_t and η_c to explain $B \to K + \mathrm{inv}$ and satisfy the KOTO bound $\mathcal{B}[S \to \bar{\nu}\nu] \sim 1$.

$K^+ \to \pi^+ + \text{inv}$ 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: Mixing Constraints

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

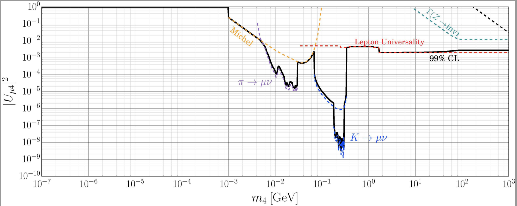
$$\nu_{\alpha(L,R)} = \sum_{i=1}^{4} U_{\alpha i}^{(L,R)} \nu_{i(L,R)} \ , \quad (\alpha = e, \mu, \tau, D) \, , \tag{3}$$

$(U^L = U^R \equiv U)$. 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 $U_{\mu 4}$

Bounds: arXiv:1511.00683



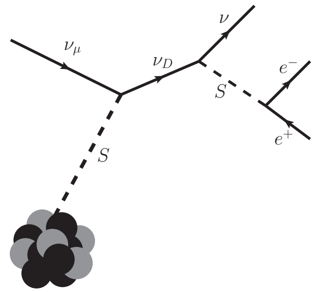
- arXiv:1802.02965(CMS) Upper limits at 95% limit for $|U_{e4}|^2$ and $|U_{\mu 4}|^2$ from $W \to \ell N, N \to \ell e^+ e^- \nu (100\%)$ between $1.2 \times 10^{-5} - 1.8$ for m_N between 1 GeV - 1.2 TeV.
- Require m_{ν_4} around $400 - 500$ MeV with $U_{\mu 4} \sim 10^{-3}$ and so consistent with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

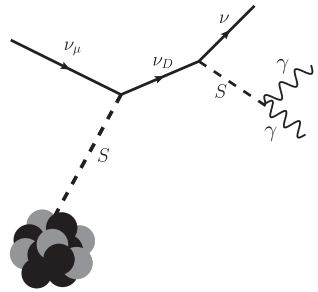
Constraints

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

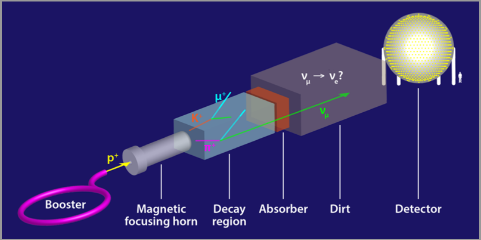
Neutrino NSI - MiniBooNE Electron like events

- 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

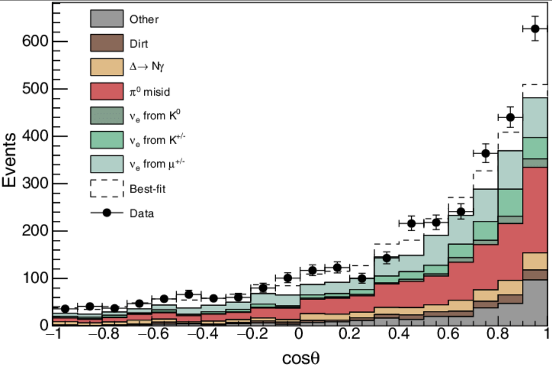


- There is an apparent $\nu_\mu \rightarrow \nu_e$ conversion of neutrinos and antineutrinos at short baselines in the MiniBooNE experiment and the Liquid Scintillator Neutrino Detector (LSND).

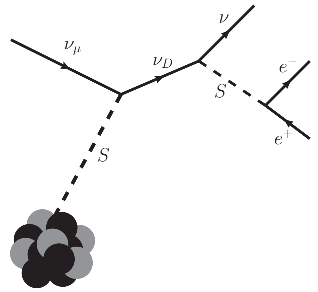
- Many solutions, oscillatory(3+1 oscillations) and non-oscillatory- like additional new physics sources of e^+e^- or $\gamma\gamma$ pairs and we focus on the later. MicroBooNE rules out some of the solutions but many solutions still unconstrained.

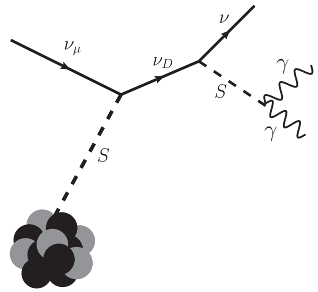
MiniBooNE - Distributions

MiniBooNE signal has a distinct angular distribution distribution.



MiniBooNE - S model





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

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

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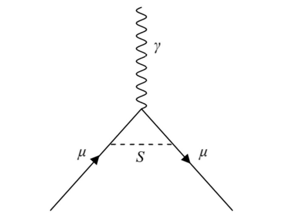
- η_t and η_c constrained from $B \to K + \mathrm{inv}$ and $K \to +\pi\mathrm{inv}$ decays.
- η_d determines coupling of S to electron pairs and so controls $B \to Ke^+e^-$ and $K \to \pi e^+e^-$.
- So all terms in the coherent neutrino scattering are constrained from rare B and K decays.

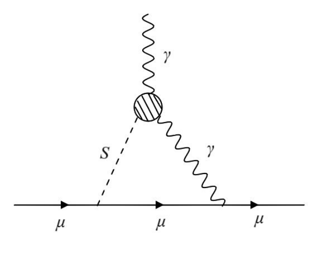
Predictions - S model

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}

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

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

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 how a sterile neutrino may be a common element in the $R(D) - R(D^*)$ and the $B^+ \to K^+ \mathrm{inv}$ anomalies with uniques signatures.