Quasi-sterile neutrinos at long-baseline oscillation experiments

Bogdan Dobrescu

Fermilab, Theoretical Physics Department

Long-baseline neutrino experiments can search for various new particles.

This talk: a theory that predicts unusual signals in the far detector.

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New gauge symmetry acting on quarks only: $U(1)_B$
charges proportional to baryon number

Fields	spin	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	$U(1)_B$
$q_L^i = (u_L^i,\ d_L^i)^\top$	1/2	3	2	$+1/6$	$+1/3$
u_R^i , d_R^i	1/2	3	1	$+2/3$, $-1/3$	$+1/3$

Theoretical requirements:

- $U(1)_B$ must be spontaneously broken.

  Simple choice: a new scalar field ϕ acquires a VEV.

- All $U(1)_B$ gauge anomalies must cancel.

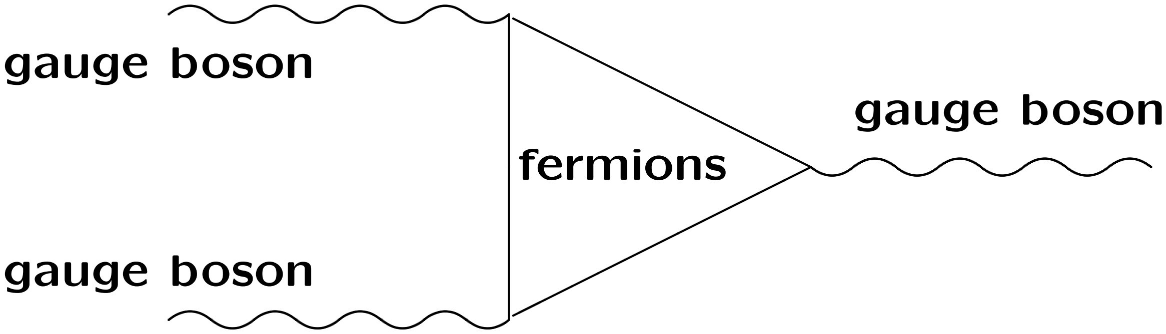
  $\Rightarrow$ Some new fermions ("anomalons") must be vectorlike with respect to $SU(3)_c \times SU(2)_W \times U(1)_Y$, and chiral with respect to the new gauge group.

Gauge anomaly cancellation

W. Bardeen, 1969, ...

Gauge symmetries may be broken by quantum effects.

Cure: sums over fermion triangle diagrams must vanish.



Standard Model – anomalies cancel within each fermion generation:

$[SU(3)_c]^2U(1)_Y$: $\quad 2(1/6)+(-2/3)+(1/3)=0$

$[SU(2)_W]^2U(1)_Y$: $\quad 3(1/6)+(-1/2)=0$

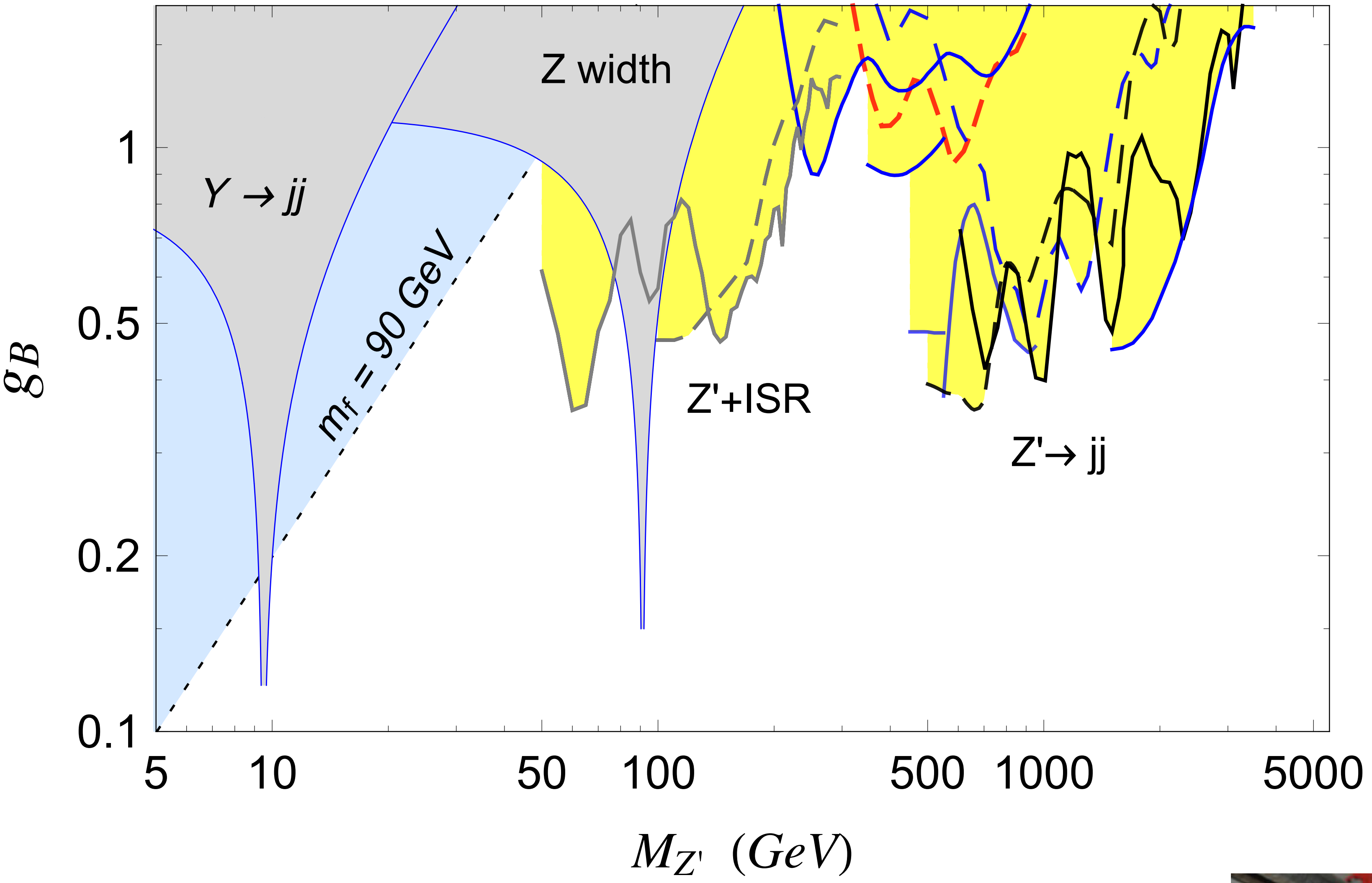
$[U(1)_Y]^3$: $\quad 3\left[2(1/6)^3+(-2/3)^3+(1/3)^3\right]+2(-1/2)^3+(-1)^3=0$

... $\qquad (u_L, d_L) \qquad u_R \qquad d_R \qquad (\nu_L, e_L) \qquad e_R$

A complete, renormalizable model:

Fields	spin	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	$U(1)_B$
$q_L^i = (u_L^i,\ d_L^i)^\top$	1/2	3	2	$+1/6$	$+1/3$
u_R^i , d_R^i	1/2	3	1	$+2/3$, $-1/3$	$+1/3$
$L_L = (L_L^N,\ L_L^E)^\top$	1/2	1	2	$-1/2$	$-3/2$
$L_R = (L_R^N,\ L_R^E)^\top$	1/2	1	2	$-1/2$	$+3/2$
E_L	1/2	1	1	-1	$+3/2$
E_R	1/2	1	1	-1	$-3/2$
N_L	1/2	1	1	0	$+3/2$
N_{*R}	1/2	1	1	0	$-3/2$
N_{0R}	1/2	1	1	0	0
ϕ	0	1	1	0	$+3$
ϕ'	0	1	1	0	$+3/2$

“Baryonic” Z'_B: same coupling (g_B) to all six quark flavors.



$$\mathcal{L}_q = \frac{g_B}{2} Z'_\mu \sum_q \left(\frac{1}{3} \overline{q}_L \gamma^\mu q_L + \frac{1}{3} \overline{q}_R \gamma^\mu q_R \right)$$

with Felix Yu:
update to 1306.2629

Limits on anomalon masses impose the constraint on g_B at low mass B.A. Dobrescu, C. Frugiuele, 1404.3947

Yukawa interactions of neutral fermions:

$$-\left(\lambda_N \langle\phi\rangle\,\overline{N}_{*R} + \lambda'_N \langle\phi'\rangle\,\overline{N}_{0R}\right) N_L + \mathrm{H.c.}$$

This leads to a Dirac mass for a fermion N with

$$N_R \equiv N_{*R}\cos\alpha + N_{0R}\sin\alpha$$

The state orthogonal to N_R,

$$\nu_R \equiv -N_{*R}\sin\alpha + N_{0R}\cos\alpha$$

remains a massless Weyl fermion.

This is a “quasi-sterile” neutrino because its interactions are mediated only by the Z'_B boson.

If the SM neutrinos acquire Majorana masses as usual from dimension-5 operators

$$\frac{c_{ij}}{M} H H \bar{\ell}_L^{ic} \ell_L^j \quad ,$$

then the dimension-5 operator

$$\frac{c_i'}{M} \phi' H \, \bar{\ell}_L^i N_{*R}$$

is also likely to be present. This leads to mixing between SM neutrinos and the ν_R and N fermions.

The mixing of the SM ν_μ with the massless ν_R is restricted by various measurements of neutrino properties: $\theta \lesssim O(0.2)$

For the future DUNE experiment, $L \approx 1300$ km and E_ν is typically in the 1–4 GeV range, so that $P(\nu_\mu \to \nu_R) \approx \theta^2 \sim O(10^{-2})$.

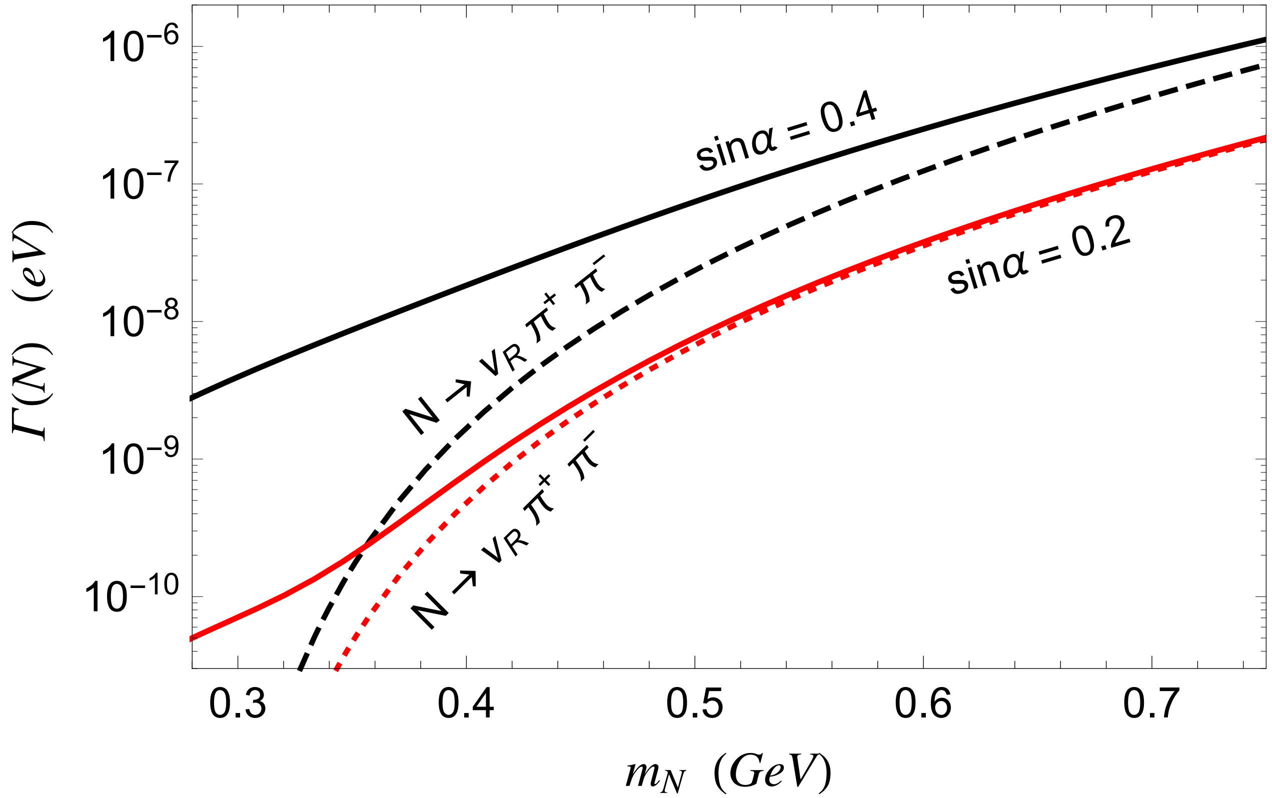
The quasi-sterile neutrino ν_R and the heavy Dirac state N have the following interactions with the Z'_B boson:

$$-\frac{3g_B}{4} Z'_{B\mu} \Big[-\sin\alpha\cos\alpha \left(\overline{N}_R \gamma^\mu \nu_R + \mathrm{H.c} \right) \\ + \sin^2\!\alpha\, \overline{\nu}_R \gamma^\mu \nu_R + \cos^2\!\alpha\, \overline{N}_R \gamma^\mu N_R \Big]$$

The first term here allows the up-scattering of ν_R in N_R, when the energy of the incoming neutrino is large enough.

~ 100 N fermions may be produced inside DUNE.

Total decay width, $\Gamma(N)$, of the N fermion (solid lines) and partial width for the $N \to \nu_R \pi^+\pi^-$ decay (dashed lines):

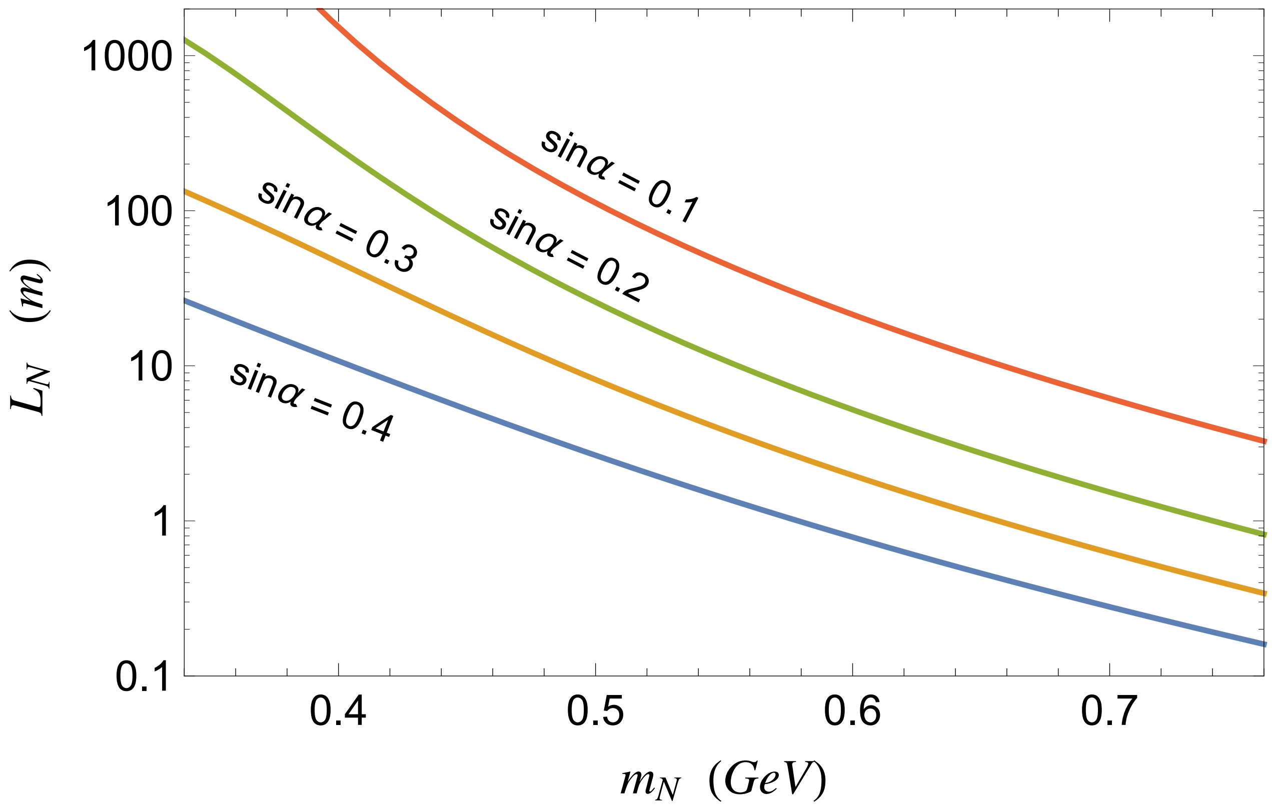


The difference between the total width and the $N \to \nu_R \pi^+\pi^-$ width is due to the invisible $N \to 3\nu_R$ decay.

Parameters used here are $M_{Z'} = 50$ GeV, $g_B = 0.5$.

Decay length of the N fermion in the rest frame, L_N, is proportional to $M_{Z'}/g_B$,

For $M_{Z'} = 50$ GeV, and $g_B = 0.5$:



Conclusions

- Quasi-sterile neutrinos have interactions only through nonstandard bosons.

- A quasi-sterile neutrino may be produced in long-baseline neutrino oscillation experiments.

- Interaction of a quasi-sterile neutrino ν_R with a Z' boson and a new fermion N of GeV-scale mass may lead to N production in the far detector.

- $N \to \pi^+\pi^-\nu_R$ decay would give a spectacular signal.

DUNE will probe the laws of nature in a new regime → many searches for new particles will be possible.