Neutrino as a Dark Matter Candidate

in a Leptophobic Z' Model

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Exclusive $B \to M\nu\bar{\nu}$ $(M = \pi, K, \rho, K^*)$ Decays

- We investigate $B \to M\nu\bar{\nu}$ $(M = \pi, K, \rho, K^*)$ decays in the leptophobic Z′ model as a possible candidate of new physics in the EW penguin sector.

SM

$$H_{\rm eff}(b \to q\nu_{\rm SM}\bar{\nu}_{\rm SM}) = \frac{G_F\alpha}{2\pi\sqrt{2}} V_{tb}V^*_{tq}C^{\nu}_{10}\bar{q}\gamma^{\mu}(1-\gamma^5)b\bar{\nu}\gamma_{\mu}(1-\gamma^5)\nu,$$

  - C^{ν}_{10}, dominated by the short-distance dynamics with top quark exchange, has the theoretical uncertainty only due to the error of top quark mass

- In order to cancel the uncertainties from the hadronic form factors, we can take ratios

$$\frac{\mathcal{B}(B^{\pm} \to \pi^{\pm}\nu\bar{\nu})}{\mathcal{B}(B^{\pm} \to \pi^{0}e^{\pm}\nu)} \qquad \frac{\mathcal{B}(B^{\pm} \to \rho^{\pm}\nu\bar{\nu})}{\mathcal{B}(B^{\pm} \to \rho^{0}e^{\pm}\nu)} \qquad \frac{\mathcal{B}(B^{\pm} \to K^{*\pm}\nu\bar{\nu})}{\mathcal{B}(B^{\pm} \to \rho^{0}e^{\pm}\nu)}$$

- Additional right-handed neutrinos(ν^c, s^c) can contribute to the missing energy signal in $B \to M + \not{E}$ Decays

$$\mathcal{B}(B \to M\nu\bar{\nu}) = \mathcal{B}(B \to M\nu_{\rm SM}\bar{\nu}_{\rm SM}) + \mathcal{B}(B \to M\nu_R\bar{\nu}_R).$$

where ν_R could be a candidate of Dark matter

Experimental bounds

Table B.1 Expected BRs in the SM and experimental bounds (90% C.L.) in units of 10^{-6}.

mode	BRs in the SM	Experimental bounds **(present)**	**2005**
$B \to K \nu \bar{\nu}$	$5.31^{+1.11}_{-1.03}$	$<$ 14 [83]	$<$ 36
$B \to \pi \nu \bar{\nu}$	$0.22^{+0.27}_{-0.17}$	$<$ 100 [84]	$<$ 100
$B \to K^* \nu \bar{\nu}$	$11.15^{+3.05}_{-2.70}$	$<$ 140 [83]	-
$B \to \rho \nu \bar{\nu}$	$0.49^{+0.61}_{-0.38}$	$<$ 150 [83]	-

[83] K. F. Chen *et al.* [BELLE Collaboration], Phys. Rev. Lett. **99**, 221802 (2007) [arXiv:0707.0138 [hep-ex]].

[84] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **94**, 101801 (2005) [arXiv:hep-ex/0411061].

LEPTOPHOBIC Z′ MODEL

✓ Extra neutral U(1) gauge boson, Z′
- has been considered one of the extensions of the SM
- motivated by
  String-inspired GUTs (J.L.Hewett, T.G.Rizzo, M.Cvetic, P.Langacker, etc)
  Dynamical symmetry breaking models (G.Buchalla, G.Burdman, etc)
  Extra dimension models (M.Masip, A.Pomarol)
  Little higgs models (N.Arkani-Hamed, A.G.Cohen, T.Han, etc) , ….

✓ Leptophobic Z′ can come from the string-inspired GUTs (E_6 or Flipped SU(5))
- does not couple to SM leptons
- introduced to explain the R_b-R_c puzzle at LEP and anomalous high-E_T jet cross section at CDF

Leptophobic Z' *in* E_6 (& Flipped) *GUTs*

- ✓ comes from heterotic superstring ($E_8 \to SU(3) \times E_6$)
- ✓ was the natural anomaly free choice for a GUT group after SO(10)
- ✓ could have several intermediate mass breaking scales

- ✓ Maximal breakings of E6 : $\begin{cases} 1. & SO(10)\times U(1) \\ 2. & [SU(3)]^3 \\ 3. & SU(2)\times SU(6) \end{cases}$

If we consider the following breaking chain

$$\begin{aligned} E_6 &\to SO(10) \times U(1)_\psi \\ &\to SU(5) \times U(1)_\chi \times U(1)_\psi \\ &\to SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)' \end{aligned}$$

U(1)′ can be a linear combination of

1. two U(1)s $[U(1)' = U(1)_\psi \sin\theta - U(1)_\chi \cos\theta,\ \textit{Flipped } SU(5)]$
2. three U(1)s [ambiguity of embeddings, $\textit{Flipped } SU(5) + Ma$]

$$E_6 \to SO(10) \times U(1)_\psi$$
$$\to SU(5) \times U(1)_\chi \times U(1)_\psi$$
$$\to SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$$

✓ directly SU(5) → SM : SU(5) (Geogri-Glashow)

- $SU(5)_{GG}$: $F = (10, \frac{1}{2}) = \{Q, u^c, e^c\}$ $\quad \bar{f} = (\bar{5}, -\frac{3}{2}) = \{L, d^c\}$ $\quad l^c = (1, \frac{5}{2}) = \{\nu^c\}$
- $U(1)' = U(1)_\psi \sin\theta - U(1)_\chi \cos\theta$

✓ SU(5)XU(1)$_\chi$ → SM : Flipped SU(5) (S.M.Barr,1982)
Flipped SU(5) is a different breaking pattern of SO(10)

- Flipped $SU(5)$: $F = (10, \frac{1}{2}) = \{Q, d^c, \nu^c\}$ $\quad \bar{f} = (\bar{5}, -\frac{3}{2}) = \{L, u^c\}$ $\quad l^c = (1, \frac{5}{2}) = \{e^c\}$
- $Y/2 = \alpha\, U(1)_{SU(5)} + \beta\, U(1)_\chi \qquad (\alpha = \beta = -1/5)$

Leptophobic Z′ does not couple to multiplet(f) and singlet(ℓ^c)

There is an ambiguity in the assignment of the various fields

Table 2.1. Charges of fermions contained in the **27** representation of E_6 within the conventional particle embedding [1].

$SO(10)$	$SU(5)$	Particles	$SU(3)_c$	$Y/2$	$2\sqrt{10}Q_\chi$	$2\sqrt{6}Q_\psi$
16	**10**	$Q=(u,d)^T$	**3**	1/6	−1	1
		u^c	$\bar{\mathbf{3}}$	−2/3	−1	1
		e^c	**1**	1	−1	1
	$\bar{\mathbf{5}}$	$L=(\nu,e)^T$	**1**	−1/2	3	1
		d^c	$\bar{\mathbf{3}}$	1/3	3	1
	1	ν^c	**1**	0	−5	1
10	$\bar{\mathbf{5}}$	$H=(N,E)^T$	**1**	−1/2	−2	−2
		h^c	$\bar{\mathbf{3}}$	1/3	−2	−2
	5	$H^c=(N^c,E^c)^T$	**1**	1/2	2	−2
		h	**3**	−1/3	2	−2
1	**1**	S^c	**1**	0	0	4

1) $Q_{\varphi,\chi}$ of the fields (L,d^c,ν^c) can be interchanged with those of (H,h^c,S^c)

2) The pairs (u^c,e^c) and (d^c,ν^c) are interchanged : Flpped SU(5)

3) We can consider the interchange of both (1) and (2) simutaneously

Leptophobic Z' in stringy flipped $SU(5)$

(J.L Lopez, D.V. Nanopoulos, and K.J.Yuan (NPB399,654(1993))

- *Gauge group* : $\underbrace{\mathrm{SU}(5)\times\mathrm{U}(1)}_{observable}\times\underbrace{\mathrm{SO}(10)\times\mathrm{SU}(4)}_{hidden}\times\underbrace{\mathrm{U}(1)^5}_{U(1)'}$

In addition to its own beauty this scenario has the following phenomenologically interesting features:

- The new Z' coupling is generation dependent and can generate FCNC processes.
- The FCNC couplings allow large CP violation.
- It violates the isospin symmetry in the right-handed up- and down-quarks.
- The new gauge boson interaction maximally violates the parity in the up-quark sector.

In the mass eigenstates the interactions of Z' gauge boson with the quarks can be written as

$$\mathcal{L} = -\frac{g_2}{\cos\theta_W}\delta Z'_\mu\left(\overline{u}\gamma^\mu P_L\left[V_L^u\hat{c}V_L^{u\dagger}\right]u + \overline{d}\gamma^\mu P_L\left[V_L^d\hat{c}V_L^{d\dagger}\right]d + \overline{d}\gamma^\mu P_R\left[V_R^d\hat{c}V_R^{d\dagger}\right]d\right),$$

where δ parameterizes the size of the new gauge coupling relative to the SM coupling and is expected to be of $\mathcal{O}(1)$. The $\hat{c} = \mathrm{diag}(c_1, c_2, c_3)$ represent the generation-dependent $\mathrm{U}(1)'$ quantum numbers

We introduce complex parameters, L and R,

$$\left[V_L^d\hat{c}V_L^{d\dagger}\right]_{23} \equiv \frac{1}{2}L_{sb}^{Z'}, \quad \left[V_R^d\hat{c}V_R^{d\dagger}\right]_{23} \equiv \frac{1}{2}R_{sb}^{Z'}.$$

$$c_L^u \equiv \left[V_L^u\hat{c}V_L^{u\dagger}\right]_{11}, \quad c_L^d \equiv \left[V_L^d\hat{c}V_L^{d\dagger}\right]_{11}, \quad c_R^d \equiv \left[V_R^d\hat{c}V_R^{d\dagger}\right]_{11}.$$

Neutral – Current Interaction

$$\mathcal{L}_{\mathrm{FCNC}}^{Z'} = -\frac{g_2}{2\cos\theta_W}\left[L_{sb}^{Z'}\overline{s}_L\gamma_\mu b_L Z'^\mu + R_{sb}^{Z'}\overline{s}_R\gamma_\mu b_R Z'^\mu\right] + h.c,$$

For R-handed neutrinos

$$\mathcal{L}(Z'\overline{\nu}_R\nu_R) = -\frac{g}{\cos\theta_W}\delta\; Z'^\mu\left[\overline{\nu}\; c_R^d P_R \nu\right],$$

$|R_{qb}^{Z'}|$

BF×10^6	89M$_{B\bar{B}}$ (BaBar)	275M$_{B\bar{B}}$ (Belle)
B($B \to K \nu\nu$)	< 52	<36
B($B \to \pi\nu\nu$)	< 100	

2005

Kνν sensitivity now <10X SM rate

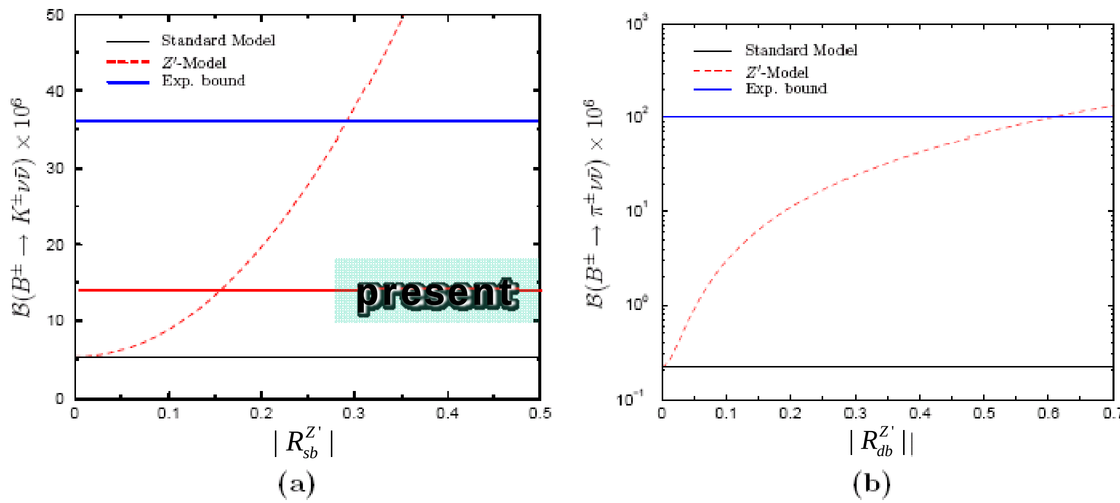


FIG. 1: Branching ratios for (a) $B^\pm \to K^\pm \nu\bar{\nu}$ and (b) $B^\pm \to \pi^\pm \nu\bar{\nu}$, where ν can be the ordinary SM neutrinos or right-handed neutrinos.

$$|R_{sb}^{Z'}| \leq 0.29, \quad |R_{db}^{Z'}| \leq 0.61,$$

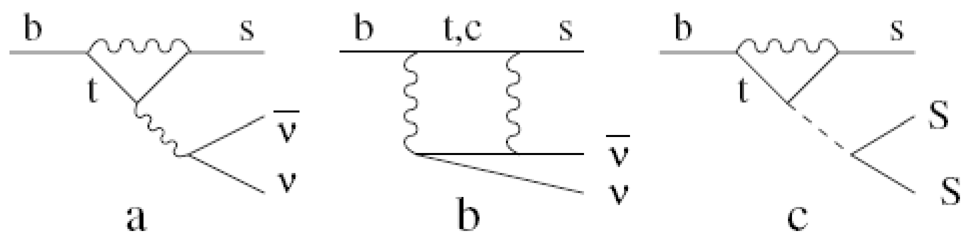
$$|R_{sb}^{Z'}| \leq 0.14$$

Dark Matter Particle Production in b→s Transition with Missing Energy

Chris Bird et al, PRL 93,201803(2004)

✓ B decays can be effective probe of dark matter near the lower edge of the Lee-Weinberg window. ($m_s \sim 2.6$ GeV)

✓ Pair production of WIMPs in the decays B→K(K*)SS can compete with the standard model mode B→K(K*)vvbar .



✓ the singlet scalar model(S) of dark matter

$$-\mathcal{L}_S = \frac{\lambda_S}{4} S^4 + \frac{m_0^2}{2} S^2 + \lambda S^2 H^\dagger H$$

$$= \frac{\lambda_S}{4} S^4 + \frac{1}{2}(m_0^2 + \lambda v_{EW}^2) S^2 + \lambda v_{EW} S^2 h + \frac{\lambda}{2} S^2 h^2,$$

$$m_S^2 = m_0^2 + \lambda v_{EW}^2$$

the physical mass of the scalar S can be small even if each term is on the order $\pm O(\upsilon^2_{EM})$

- ✓ More model-building possibilities open up if new particles, other than EW gauge bosons or Higgs fields, mediate the interaction between WIMPs and SM particles.

- ✓ The Higgs mass, m_h ,is heavy compared to m_s of interest, which means that in all processes such as annihilation, pair production, and elastic scattering of S particles, λ and m_h enter in the same combination, $\lambda^2 m_h^{-4}$

The effective Lagrangian for b→s transition

$$\mathcal{L}_{b\to s\not{E}} = \tfrac{1}{2} C_{DM} m_b \bar{s}_L b_R S^2 - C_\nu \bar{s}_L \gamma_\mu b_L \bar{\nu}\gamma_\mu \nu + (\text{H.c.}).$$

$$\begin{aligned}\text{Br}_{B^+\to K^+ + \not{E}} &= \text{Br}_{B^+\to K^+\nu\bar{\nu}} + \text{Br}_{B^+\to K^+ SS} \\ &\simeq 4\times 10^{-6} + 2.8\times 10^{-4}\kappa^2 F(m_S).\end{aligned}$$

$$\text{Br}_{B^+\to K^{+*} + \not{E}} \simeq 1.3\times 10^{-5} + 4.3\times 10^{-4}\kappa^2 F(m_S).$$

$$\kappa^2 \equiv \lambda^2 \left(\frac{100\ \text{GeV}}{m_h}\right)^4$$

$$F(m_S) = \int_{\hat{s}_{\min}}^{\hat{s}_{\max}} f_0(\hat{s})^2 I(\hat{s}, m_S) d\hat{s} \left[\int_{\hat{s}_{\min}}^{\hat{s}_{\max}} f_0(\hat{s})^2 I(\hat{s}, 0) d\hat{s}\right]^{-1}$$

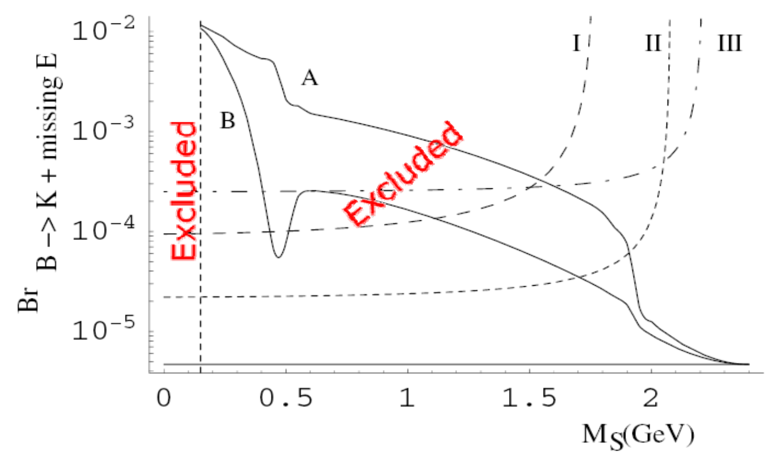
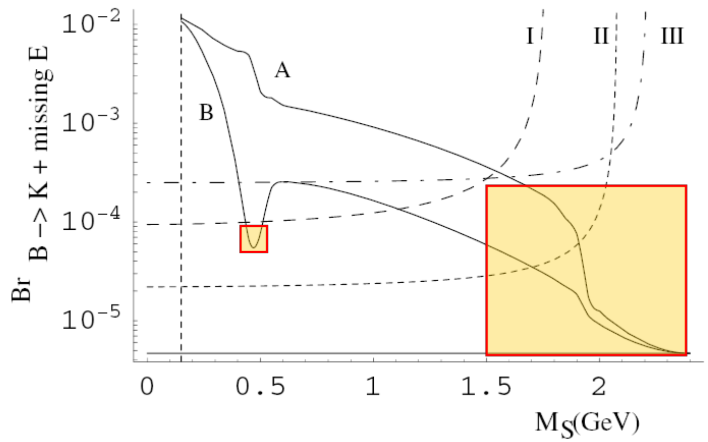


FIG. 2. Predicted branching ratios for the decay $B \to K +$ *missing energy*, with current limits from *BABAR* (*I*) [12], CLEO (*III*) [13], and expected results from *BABAR* (*II*). Parameter space above curves *I* and *III* is excluded. The horizontal line shows the SM $B \to K\nu\bar{\nu}$ signal. Parameter space to the left of the vertical dashed line is also excluded by $K^+ \to \pi^+ \not{E}$.



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In the interval 350 -650 MeV
the strangeness threshold opens up and annihilation into pions via the s-channel resonance becomes important.

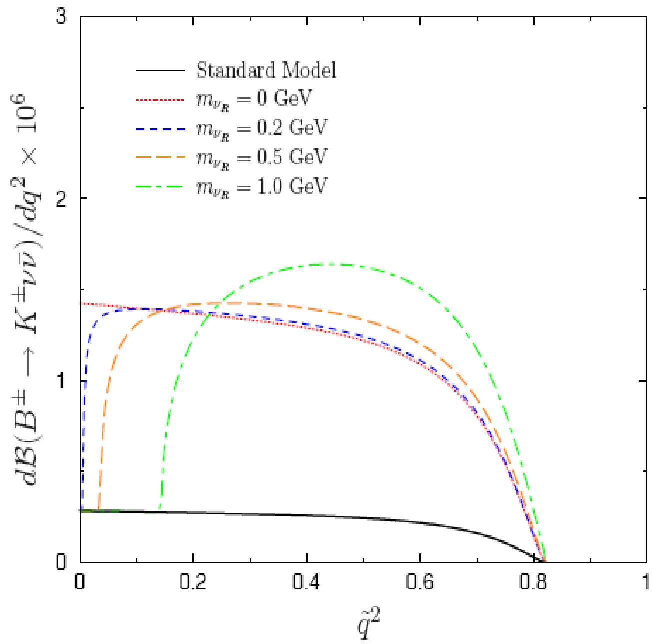
Above m_s = 1 GeV

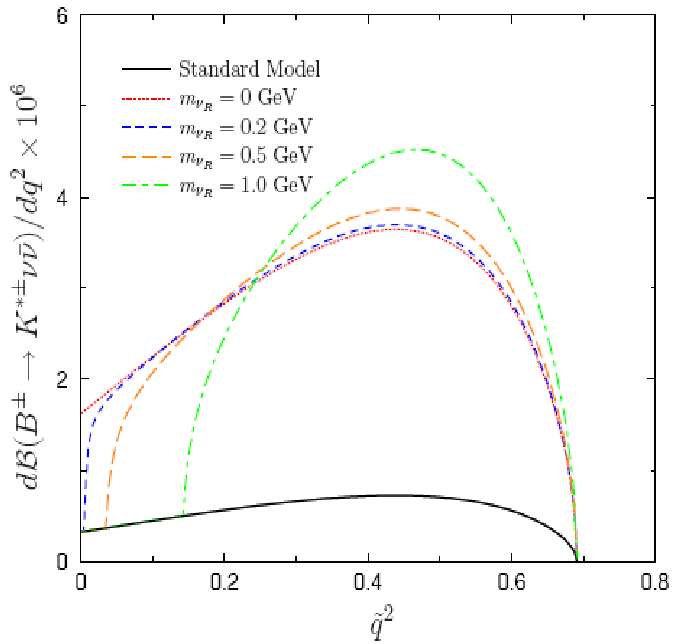
Curve B take into account the annihilation into hadrons mediated by α_s with the twofold enhancement suggested by charmonium decays

Curve A uses the perturbative formula

- *νMSM model* (T.Asaka and M. Shaposhnikov, PLB 620,17 (2005))
  - the extension of the SM by the ν_R with masses smaller than the EW scale
  - can explain simutaneously dark matter and baryon asymmetry of the universe and be consistent with the experiments on neutrino oscillations assuming that Majorana masses of ν_R are the order of the EW scale or below and Yukawa couplings are very small.

Exclusive $B \to K^{(*)}\nu\bar{\nu}$ Decays





- We normalized the integrated BRs such that the BRs in the leptophobic Z' model are 5 times larger than those in the SM
  - the sharp rise near the threshold point allows to increase the accuracy of the mass measurement of the lightest ν_R
  - Unfortunately, if its mass is lower than a few hundred MeV, it is very hard to find the difference from the masseless neutrino case

Exclusive $B \to \pi(\rho)\nu\bar{\nu}$ Decays

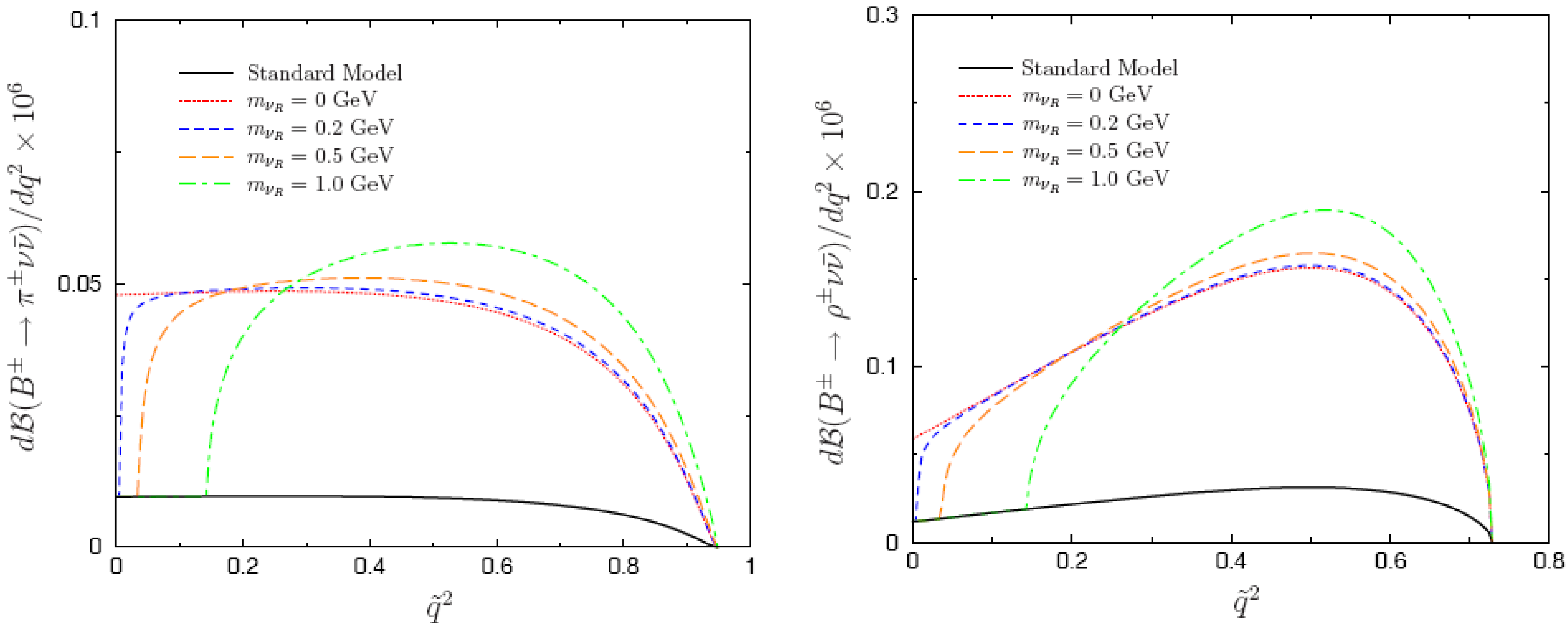


FIG. 3: Differential BRs as a function of the normalized momentum transfer square, $\tilde{q}^2 = q^2/M_B^2$, in units of 10^{-6}, for (a) $B^\pm \to K^\pm\nu\bar{\nu}$, (b) $B^\pm \to \pi^\pm\nu\bar{\nu}$, (c) $B^\pm \to K^{*\pm}\nu\bar{\nu}$, and (d) $B^\pm \to \rho^\pm\nu\bar{\nu}$. Here the decay rates in the leptophobic Z' model are normalized to be five times larger than those in the SM.

Conclusion

✓ The exclusive FCNC processes B→Mvvbar are very adequate to measure new physics in the leptophobic Z′ model with the R-handed neutrinos.

✓ This model could be quite important in the context of possibly large new physics scenario in the EW penguin sector.

✓ We show that ratios of BRs can reduce the large hadronic uncertainty from form factors.

✓ The differential BRs are very useful if the R-handed neutrinos have the sub-GeV masses

✓ We also note that the R-handed neutrinos could be accommodated with the nuMSM scenario