Anomalous Tau Neutrino Appearance in Short-Baseline Neutrino Experiments

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arXiv:2304.02031.

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Why single out the taus?

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$$P_{\mu\to\tau} = \sin^2(2\theta_{23})\,\sin^2\left[1.267\frac{\left(\frac{\Delta m^2_{23}}{\mathrm{eV}^2}\right)\;\left(\frac{L}{\mathrm{km}}\right)}{E/\mathrm{GeV}}\right]$$

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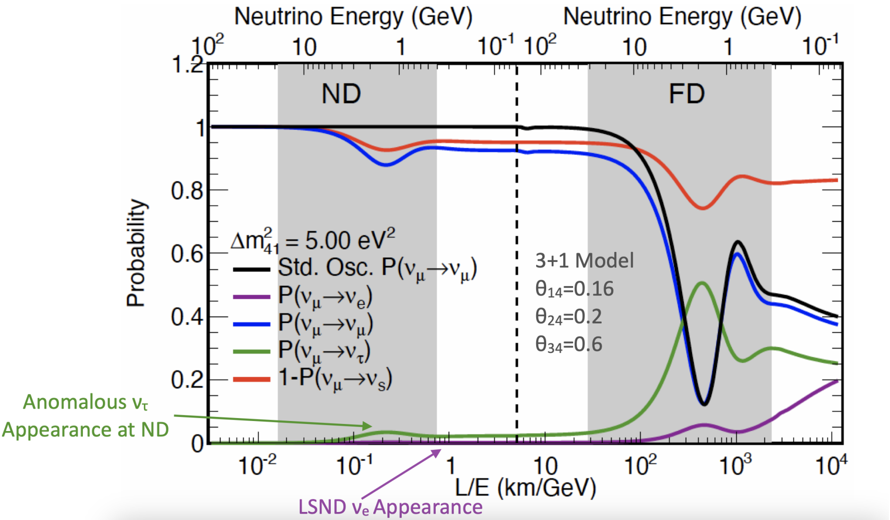
- Production rate of D_s mesons is too small to give enough ν_τ events (from $D_s \to \tau\nu_\tau$).
- Therefore, appearance of ν_τ events at SBN is *anomalous*.
- A 'smoking gun' signature of new physics (modulo background issues).

Popular mechanism: Sterile neutrinos



[from Alex Sousa's talk at NuTools Workshop (Dec 2022)]

Larger (smaller) Δm^2_{41} corresponds to ND (FD)-dominated signal.

see also de Gouvêa, Kelly, Stenico, Pasquini, 1904.07265 (PRD '19)

A new mechanism for anomalous tau production

$$\boxed{\pi^\pm/K^\pm \to \ell^\pm \overset{(-)}{\nu}_\ell\, V \quad \text{with} \;\; V \to \nu_\tau \bar{\nu}_\tau}$$

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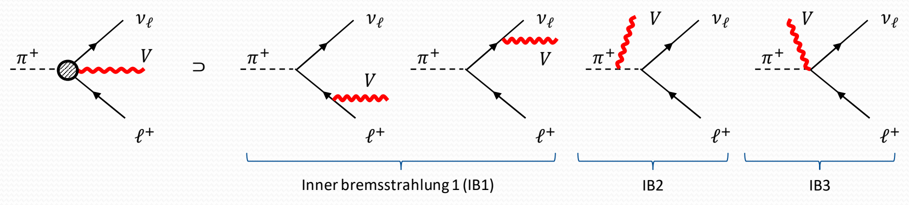

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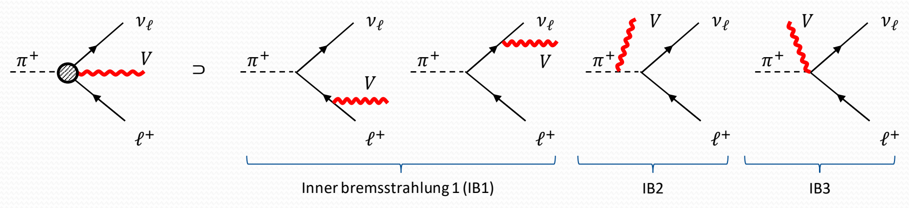

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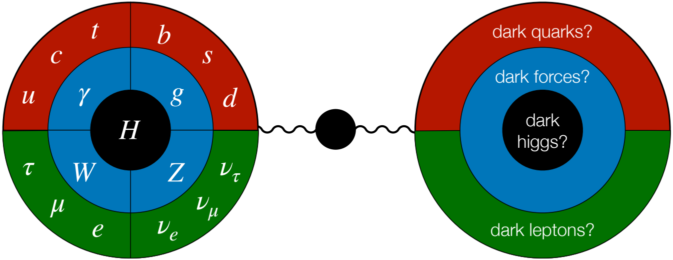
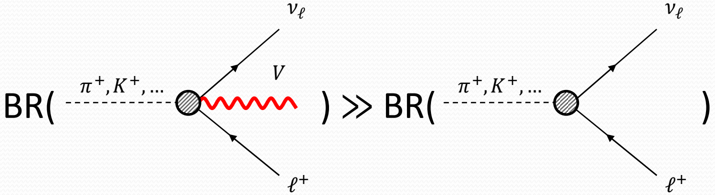
Motivation: V can serve as a portal to the dark sector

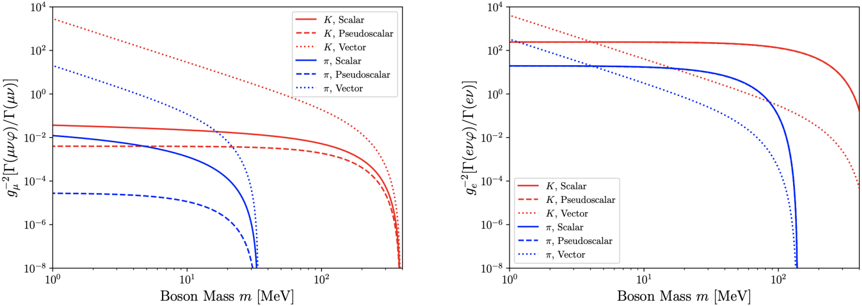


Why charged meson decay is important?

1. Large BR enhancement for 3-body decays.

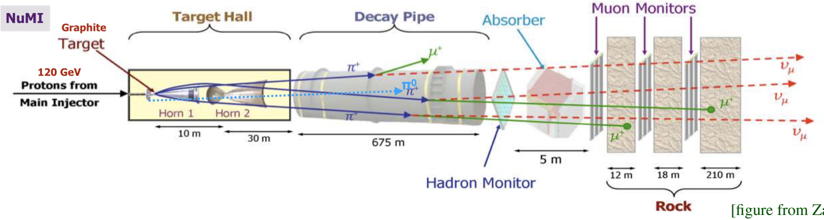


(assuming an $\mathcal{O}(1)$ dark-sector coupling for purposes of comparison)



Dutta, Kim, Thompson, Thornton, Van de Water, 2110.11944 (PRL '22)

2. Focusing of charged mesons can be used to enhance the BSM signal at ND.



[figure from Zarko Pavlovic]

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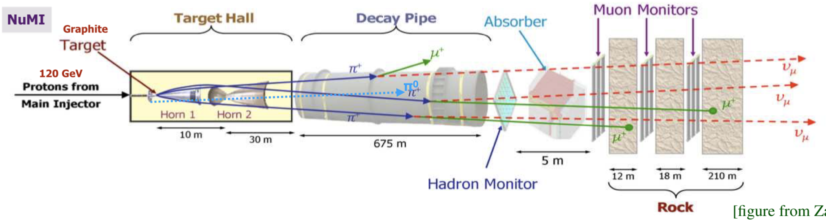

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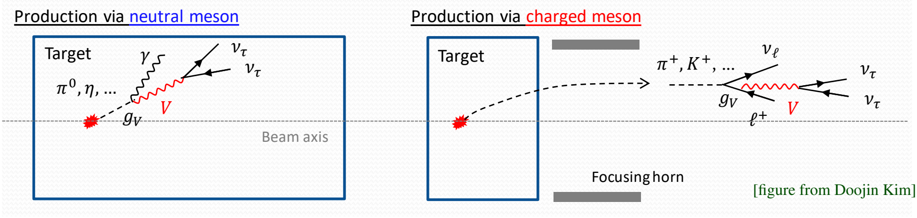
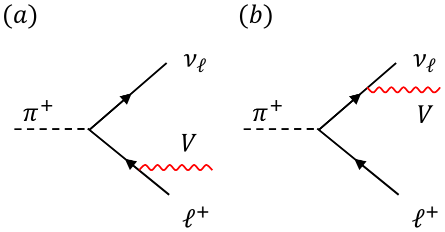


[figure from Doojin Kim]

3. Dominant (only) production channel for leptophilic dark-sector mediators.



- Otherwise difficult to search (e.g. by dark matter direct detection experiments).
- There exist several models for leptophilic $U(1)$. See e.g. He, Joshi, Lew, Volkas (PRD '91); Araki, Heeck, Kubo (1203.4951); Farzan, Heeck (1607.07616); Farzan, Tortola (1710.09360); Chauhan, Xu (2012.09980); Chauhan, BD, Xu (2204.11876) (and references therein).

$$\mathcal{L}_{\rm int} \supset \sum_f g_V x_f V_\mu \bar{f} \gamma^\mu f \,.$$

We consider three cases for the vector mediator (to illustrate the effect of ν_τ appearance):

1. Neutrinophilic: $x_f = 1$ for $f = \nu_e, \nu_\mu, \nu_\tau$, and $x_f = 0$ otherwise.
2. $B - L$: $x_f = 1/3$ for $f =$ quarks, and $x_f = -1$ for $f =$ leptons.
3. $B - 3L_\tau$: $x_f = 1/3$ for $f =$ quarks, $x_f = -1$ for $f = \tau, \nu_\tau$ and $x_f = 0$ for e, μ, ν_e, ν_μ.

Take the appropriate BR($V \to \nu_\tau \bar{\nu}_\tau$) in each case.

	DUNE ND-LAr [2002.02967]	ICARUS-NuMI [1312.7252]
Beam energy	120 GeV	120 GeV
Dist. to dump	204 m	715 m
Dist. to detector	575 m	800 m
Detector angle	On axis	$\sim 6^\circ$ off-axis
Active volume $(w \times h \times l)$ [m^3]	$3 \times 4 \times 5$	$2.96 \times 3.2 \times 18$ ($\times$ 2 modules)
POT	2×10^{22}	10^{22}
Run-time	$\sim$ 20 years	$\sim$ 10 years

Unknown form factors

- For a massive V coupling to quarks, unknown form factors in the hadronic current:

$$\begin{aligned} T^{\mu\rho} &= c_1 g^{\mu\rho} + c_2 (p_\ell + p_\nu)^\mu p_V^\rho + c_3 (p_\ell + p_\nu)^\rho p_V^\mu \\ &+ c_4 (p_\ell + p_\nu)^\mu (p_\ell + p_\nu)^\rho + c_5 p_V^\mu p_V^\rho \\ &+ F_V \epsilon^{\mu\rho\lambda\sigma} (p_\ell + p_\nu)_\lambda p_{V,\sigma} \,. \end{aligned}$$

- Unlike massless case, where using Ward identities yields [Khodjamirian, Wyler, hep-ph/0111249]

$$\begin{aligned} c_1 + c_2 (p_\ell + p_\nu) \cdot p_V &= f_{\mathfrak{m}} \,, \\ c_4 (p_\ell + p_\nu) \cdot p_V &= f_{\mathfrak{m}} \,. \end{aligned}$$

- We choose two benchmark cases for illustration:

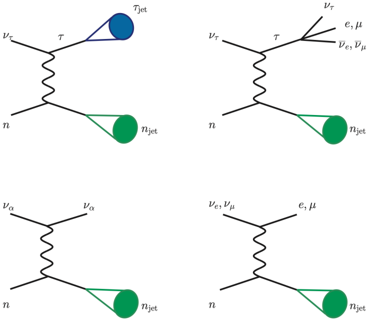
$$\begin{aligned} \text{I}: &\qquad c_1 = 0.1\ \text{GeV},\ c_2 = c_4 = 10\ \text{GeV}^{-1}, \\ \text{II}: &\qquad c_1 = 10^2\ \text{GeV},\ c_2 = c_4 = 10^4\ \text{GeV}^{-1}. \end{aligned}$$

- F_V should be inferred from $\pi^+ \to e^+ \nu_e \gamma$ data [Bryman, Depommier, Leroy (Phy. Rep. '82); Donoghue, Golowich, Holstein (OUP '14)].
- Should not blindly use the photon form factors, as sometimes done in the literature [e.g. Chiang, Tseng, 1612.06985 (PLB '17)].

Background

- In real life, tau identification efficiency is not 100%.
- Neutrino energy threshold of 3.4 GeV.
- ν_τ events limited by statistics.
- Any mis-ID (from NC/CC) would cause backgrounds.
- But not so bad at FD.

[Machado, Schulz, Turner, 2007.00015 (PRD '20)]



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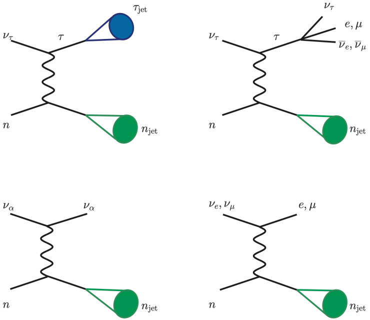

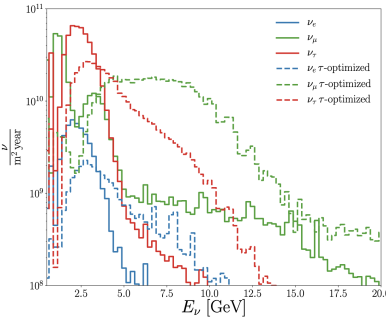

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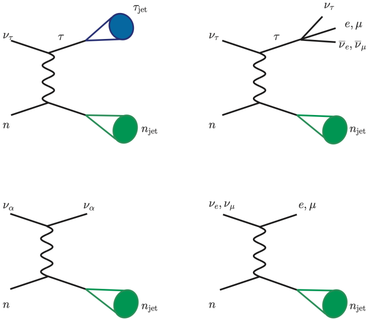
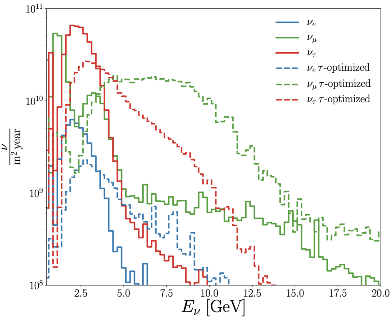
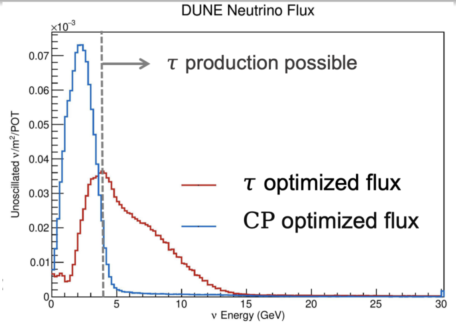




Mode	beam	charge id	N_{sig}	N_{bg}	$S/\sqrt{B}$
τ_{had}	nominal	✓	79	565	3.3
τ_{had}	nominal	✗	83	731	3.1
τ_{had}	tau-optimized	✓	433	2411	8.8
τ_{had}	tau-optimized	✗	439	3077	7.9
τ_e	tau-optimized	✗	63	33	11.0
τ_e	nominal	✗	13	32	2.3

[see also Thomas Kosc's PhD Thesis, 2021 (Lyon)]

More difficult at Near Detector



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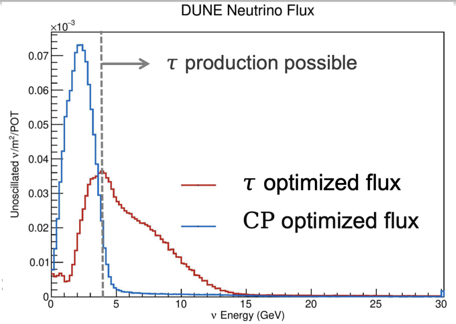

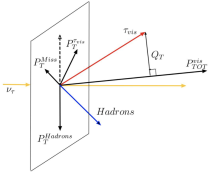

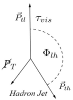

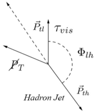

Background interaction products in the transverse plane

ν_τ CC interaction products in the transverse plane

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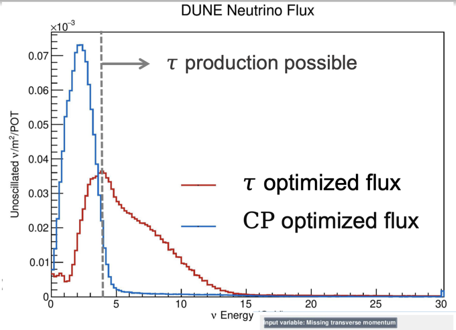

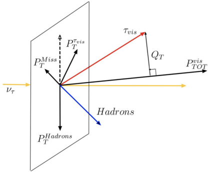

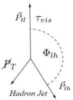

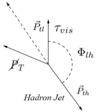

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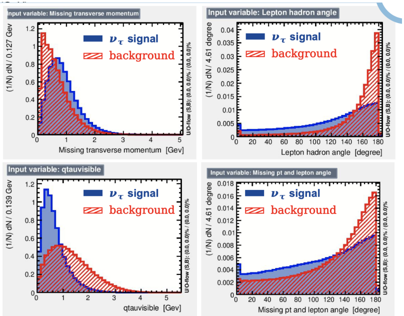

[from Miriama Rajaoalisoa's talk at NuTau 2021]

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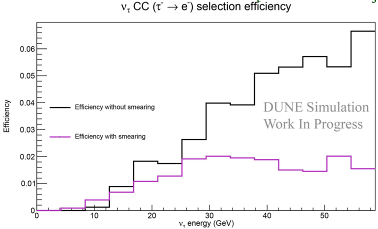

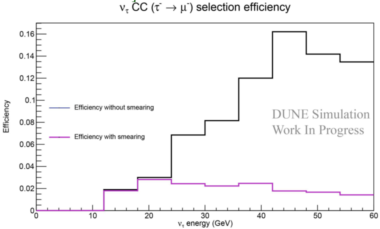

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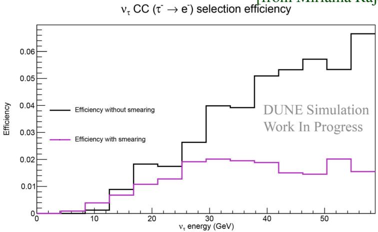

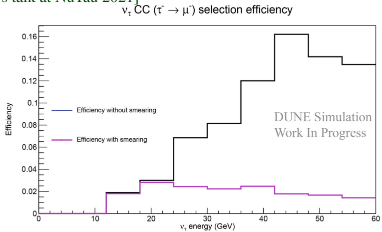

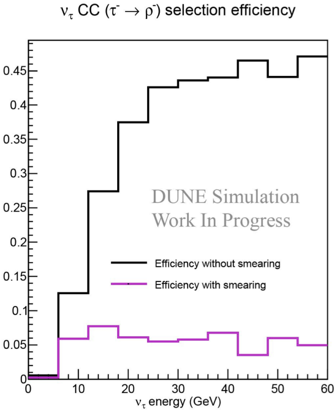

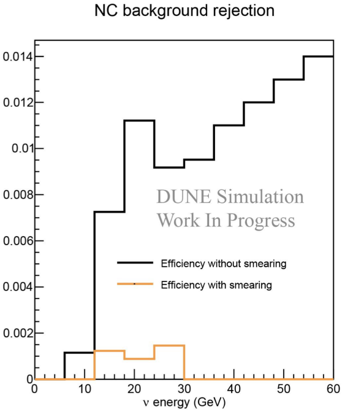

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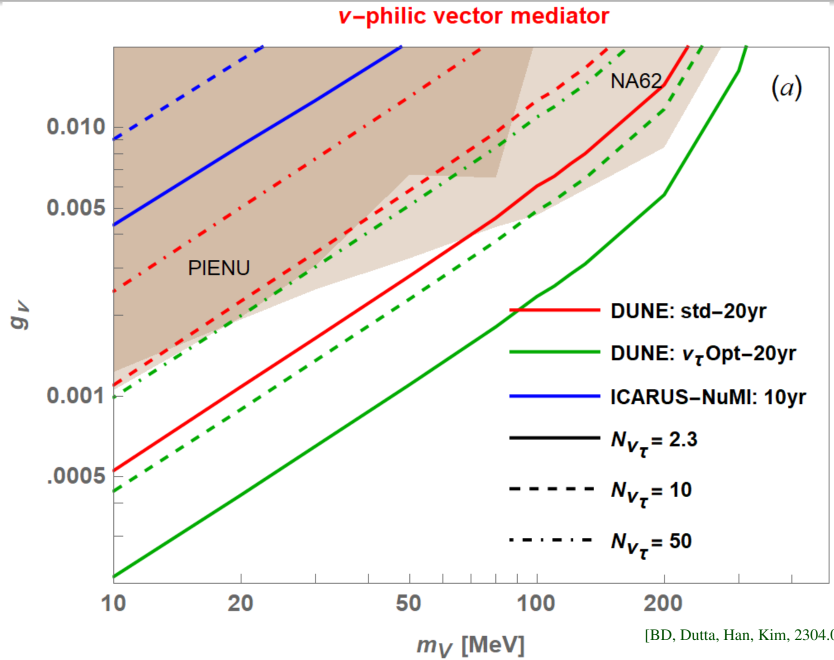

[BD, Dutta, Han, Kim, 2304.02031]

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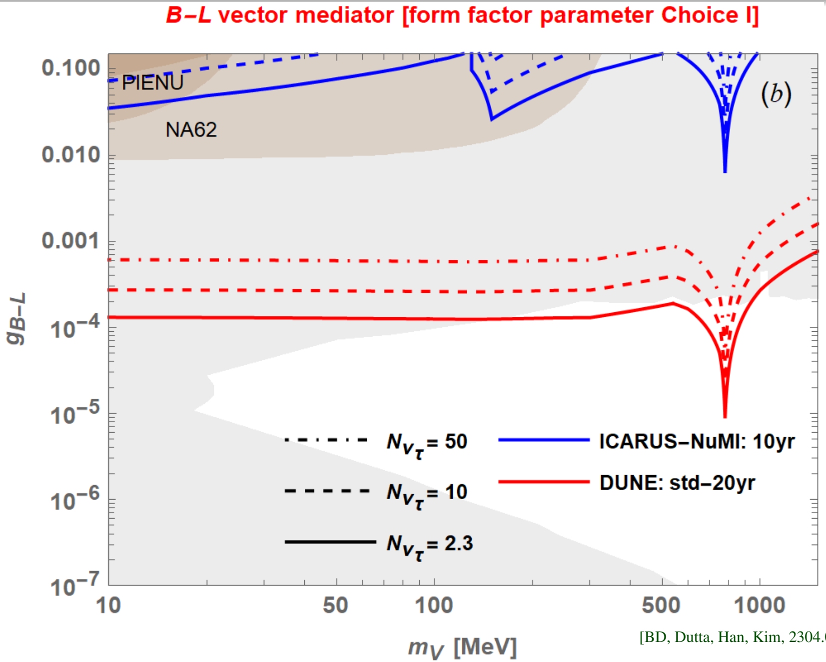

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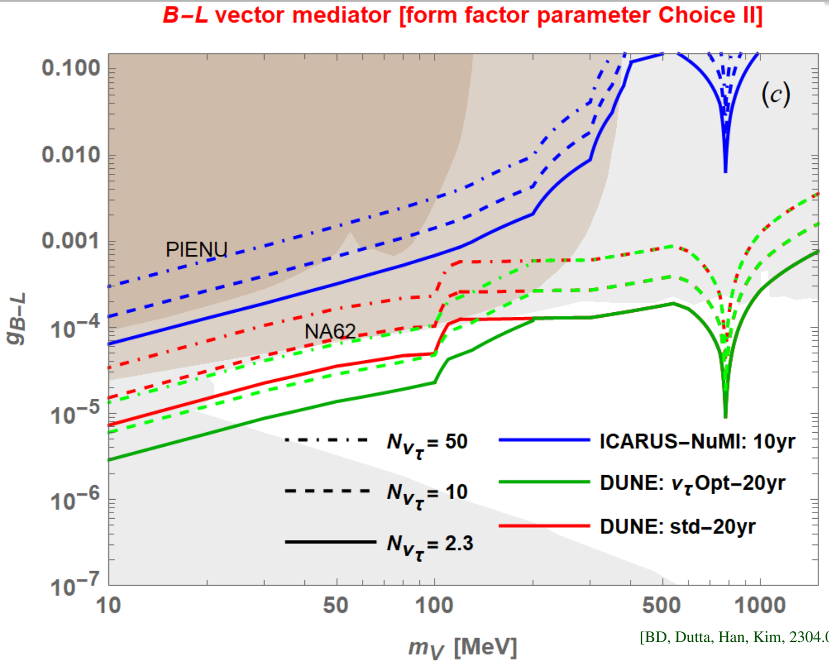

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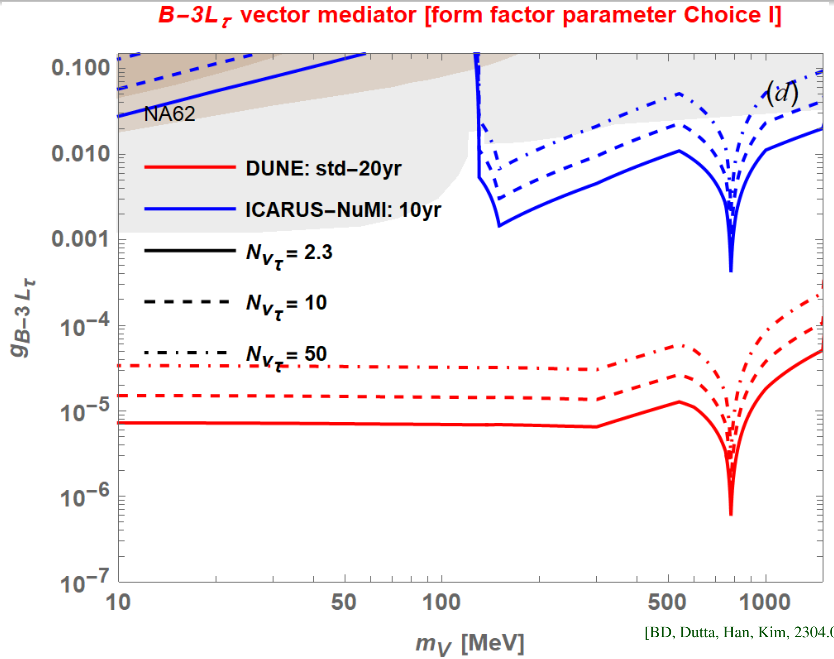

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- Charged meson decays provide an important BSM production channel for beam-focused SBN experiments.
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