Long-lived Sterile Neutrinos at `Belle II` in Effective Field Theory

in collaboration with Guanghui Zhou, Zeren Simon Wang,
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based on 2111.04403

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Motivation

BSM Long-Lived Particles

- SM has proven succesful, but incomplete
  ↪ neutrino oscillations , dark matter
  ↪ strong CP problem, hierarchy problem
- BSM particles can be long-lived
  ↪ heavy mediators
  ↪ weak couplings
  ↪ small phase space
- Displaced vertex signature

An Effective Description

Sterile Neutrinos in νSMEFT

- Extending the SM with n right-handed gauge-singlet neutrinos ν_R

$$\mathcal{L} \quad = \quad \mathcal{L}_{\rm SM} - \left[\frac{1}{2}\bar{\nu}_R^c\,\overline{M}_R\nu_R + \bar{L}\tilde{H}Y_\nu\nu_R + \text{h.c.}\right]$$

- Additional BSM effects in EFT

$$\mathcal{L}^{(5)}_{\nu_L} = \epsilon_{kl}\epsilon_{mn}(L_k^T\,C_L^{(5)}\,CL_m)H_lH_n\,, \qquad \mathcal{L}^{(5)}_{\nu_R} = -\bar{\nu}_R^c\,C_R^{(5)}\nu_R H^\dagger H\,.$$

Class 1	ψ^2H^3	**Class 4**	ψ^4
$\mathcal{O}_{L\nu H}$	$(\bar{L}\nu_R)\tilde{H}(H^\dagger H)$	$\mathcal{O}_{du\nu e}$	$(\bar{d}_R\gamma^\mu u_R)(\bar{\nu}_R\gamma_\mu e)$
Class 2	ψ^2H^2D	$\mathcal{O}_{Qu\nu L}$	$(\bar{Q}u_R)(\bar{\nu}_R L)$
$\mathcal{O}_{H\nu e}$	$(\bar{\nu}_R\gamma^\mu e_R)(\tilde{H}^\dagger iD_\mu H)$	$\mathcal{O}_{L\nu Qd}$	$(\bar{L}\nu_R)\epsilon(\bar{Q}d_R)$
Class 3	ψ^2HF	$\mathcal{O}_{LdQ\nu}$	$(\bar{L}d_R)\epsilon(\bar{Q}\nu_R)$
$\mathcal{O}_{\nu W}$	$(\bar{L}\sigma_{\mu\nu}\nu_R)\tau^I\tilde{H}W^{I\mu\nu}$	$\mathcal{O}_{L\nu Le}$	$(\bar{L}\nu_R)\epsilon(\bar{L}e_R)$
$\mathcal{O}_{\nu B}$	$(\bar{L}\sigma_{\mu\nu}\nu_R)\tilde{H}B^{\mu\nu}$		

Table: Dimension-six operators involving one sterile neutrino field ν_R. [Yi Liao , Xiao-Dong Ma, 2016 arXiv:1612.04527]

An Effective Description

Sterile Neutrinos in νSMEFT

- After EWSB

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \left[\frac{1}{2}\bar{\nu}_L^c M_L \nu_L + \frac{1}{2}\bar{\nu}_R^c M_R \nu_R + \bar{\nu}_L M_D \nu_R + \text{h.c.}\right] + \mathcal{L}^{(6)}_{CC} + \mathcal{L}^{(6)}_{NC} \,,$$

- Rotating to the neutrino mass basis

$$\mathcal{L}_m = -\frac{1}{2}\bar{N}^c M_\nu N + \text{h.c.}\,, \qquad \text{with } M_\nu = \begin{pmatrix} M_L & M_D^* \\ M_D^\dagger & M_R^\dagger \end{pmatrix} \text{ and } N = \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} ,$$

$$U^T M_\nu U = m_\nu \equiv \text{diag}(m_1, \ldots, m_{3+n})\,, \qquad \nu_\alpha = U_{\alpha i}\nu_i$$

- With this general framework, several scenarios can be investigated (see also talk from Giovanna Cottin, 3.25 pm Friday) [de Vries, et. al 2021 arXiv:2010.07305], [Cottin, et. al 2021 arXiv:2105.13851], [Beltrán, et. al 2021 arXiv:2110.15096]

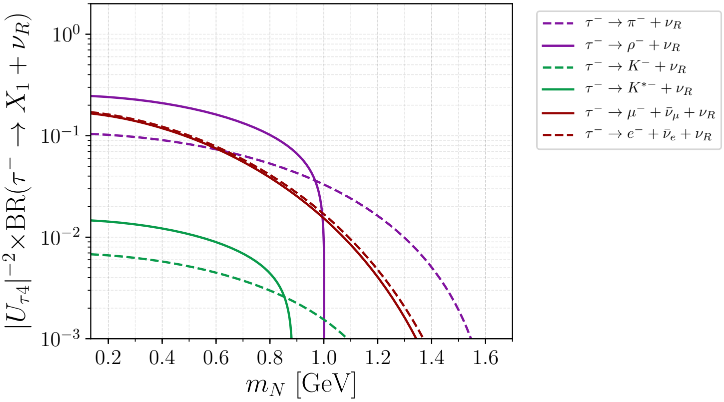
Simulation Procedure for rare τ decays

- We consider a single sterile neutrino ($n = 1$) at **Belle II**
  $\hookrightarrow$ τ-pair production, expecting 4.6×10^{10} pairs
- Fiducial volume with $10\,\text{cm} < r < 80\,\text{cm}$ and $-40\,\text{cm} < z < 120\,\text{cm}$
- Perform Monte-Carlo simulations with `Pythia8.245` to obtain overall event selection efficiencies ϵ [Dey, et. al 2021 arXiv:2012.00438], [Dib, et. al 2021 arXiv:1908.09719]
- Expected signal event number

$$N_S = 2 \cdot N_{\tau\bar{\tau}} \cdot \text{BR}(\tau \to 1\text{ prong}) \cdot \text{BR}(\tau \to \nu_R + X_1) \cdot \text{BR}(\nu_R \to \text{visible}) \cdot \epsilon\,,$$

Minimal Scenario

Only active-sterile mixing $U_{\tau 4}$



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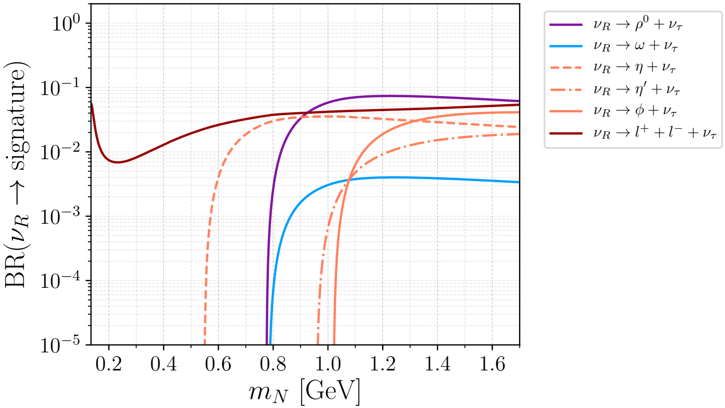
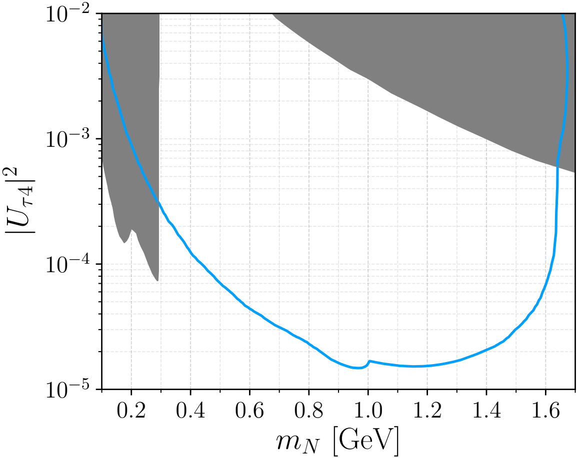


Minimal Scenario - Results

3-event isocurves (95% C.L. exclusion limit)

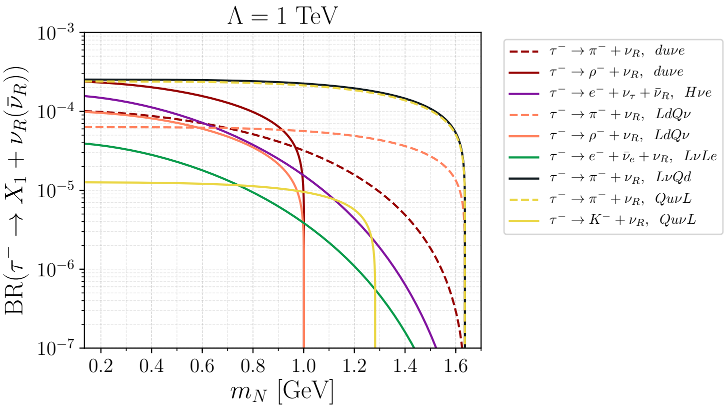
[Dib, et. al 2021
arXiv:1908.09719]



EFT Scenarios

Turn on one particular flavour configuration, $\mathcal{O}_{Qu\nu L}^{11\nu_R 3}$, assume $C_{Qu\nu L} \sim 1/\Lambda^2$

$$\tau^- \to \nu_R + (\pi^-, K^-), \qquad \nu_R \to \nu_\tau + (\pi^0, \eta, \eta'),$$



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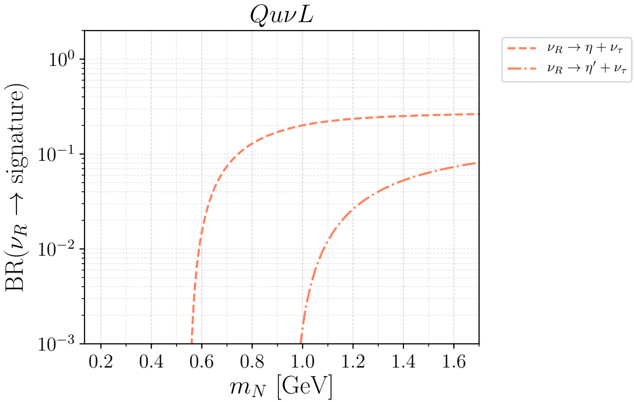

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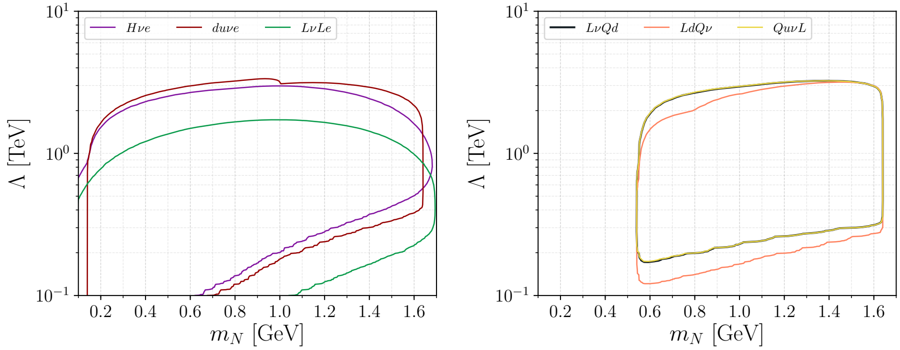

Conclusion

- We investigated rare tau decays at **Belle II** in the framework of νSMEFT
- For a minimal scenario our results are in agreement with the literature
- For EFT scenarios, new physics scales up to 3 TeV can be probed

Thank you!

Back-Up Slides

$\tau^- \to \nu_R\,(\bar\nu_R) + X_1$ & $\nu_R \to X_2$	X_1	X_2
Minimal scenario	$\pi^-, \rho^-, K^-, K^{*-}$, $e^- + \bar\nu_e\,, \mu^- + \bar\nu_\mu$	$(\pi^0, \rho^0, \eta, \eta', \omega, \phi$, $\bar\nu_e + \nu_e\,, \bar\nu_\mu + \nu_\mu\,, \bar\nu_\tau + \nu_\tau$, $e^- + e^+\,, \mu^- + \mu^+) + \nu_\tau$
Scenario $\mathcal{O}_{L\nu Qd}^{3\nu_R 11}$	π^-	$(\pi^0\,, \eta\,, \eta'\,, K^0) + \nu_\tau$
Scenario $\mathcal{O}_{Qu\nu L}^{11\nu_R 3}$	$\pi^-\,, K^-$	$(\pi^0\,, \eta\,, \eta') + \nu_\tau$
Scenario $\mathcal{O}_{H\nu e}^{\nu_R 1}$	$e^- + \nu_\tau\,(+\bar\nu_R)$	$(\,\pi^+, \rho^+, K^+, K^{*+}$, $e^+ + \nu_e\,, \mu^+ + \nu_\mu) + e^-$
Scenario $\mathcal{O}_{du\nu e}^{11\nu_R 3}$ & $\mathcal{O}_{du\nu e}^{11\nu_R 1}$	$\pi^-\,, \rho^-$	$(\pi^+\,, \rho^+) + e^-$
Scenario $\mathcal{O}_{L\nu Le}^{1\nu_R 31}$	$e^- + \bar\nu_e$	$e^- + \nu_\tau + e^+$
Scenario $\mathcal{O}_{LdQ\nu}^{311\nu_R}$	$\pi^-\,, \rho^-$	$(\pi^0\,, \rho^0\,, \omega\,, \eta\,, \eta'\,, K^0\,, K^{*0}) + \nu_\tau$

Table: All possible production, X_1, and decay, X_2, modes of a sterile neutrino ν_R at Belle II. The charge conjugate modes are implied.

Back-Up Slides

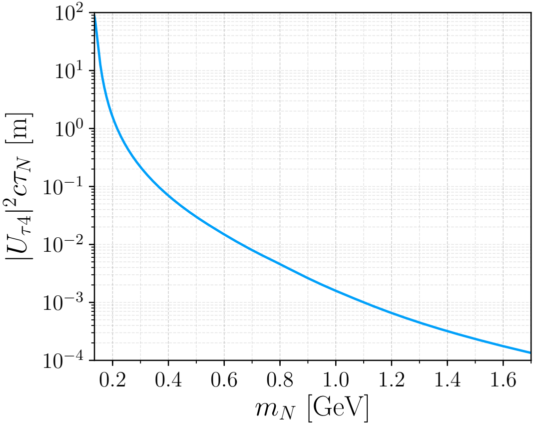

Figure: Proper decay length of the sterile neutrino times $|U_{\tau 4}|^2$ in the minimal scenario.

Back-Up Slides

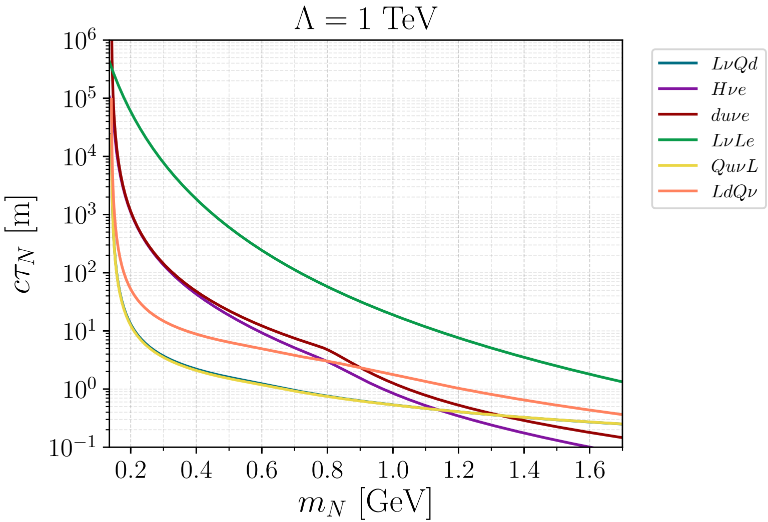

Figure: Proper decay lengths of the sterile neutrino in various EFT scenarios for $\Lambda = 1$ TeV.

Back-Up Slides

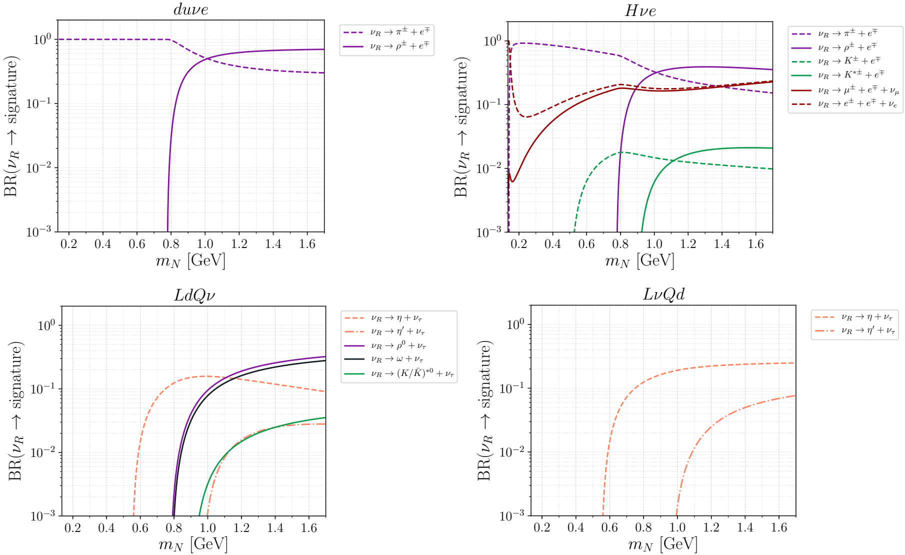

Figure: Branching ratios of visible decay modes for the sterile neutrino in νSMEFT scenarios.