STERILE NEUTRINOS FROM TAU DECAYS AT B FACTORIES

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Motivation

- Neutrino oscillations $\Rightarrow$ at least two neutrinos have mass.
- Right handed neutrinos (SM singlets) allow to include neutrino masses.
- We consider the generic form of seesaw models, where the SM neutrinos are mainly the light fields ν_i with small admixtures of the extra fields N_j:

$$\nu_\ell = \sum_{i=1}^{3} U_{\ell i}\nu_i + \sum_j V_{\ell N_j} N_j. \qquad (1)$$

- The relation between masses and mixings depends on the specific seesaw model.
- We consider m_N and $V_{\ell N}$ as independent parameters.

Motivation (cont.)

- For $m_N \sim \mathcal{O}(\text{GeV})$, the most stringent constraints are on $|V_{eN}|$ and $|V_{\mu N}|$. (e.g., meson decays.)
- There are weaker bounds on $|V_{\tau N}|$ from Z decays. (DELPHI: $e^+e^- \to Z \to N\nu_\ell$)
- We focus on the scenario where $|V_{\tau N}| \gg |V_{eN}|, |V_{\mu N}|$

Heavy Neutrino Production

- $e^+e^- \to \tau^+\tau^-$ ($\sqrt{s} = 10.58$ GeV)
  - BABAR: $N_{\tau\tau} \approx 4.6 \times 10^8$.
  - Belle: $N_{\tau\tau} \approx 8.8 \times 10^8$.
  - Belle-II: scheduled to collect $N_{\tau\tau} \approx 4.6 \times 10^{10}$ by 2027.
- We study heavy neutrinos produced in tau decays:

$$\tau \to N + X_1 \; (\propto |V_{N\tau}|^2) \tag{2}$$

- We explore the mass range 300 MeV $\lesssim m_N \lesssim 1.7$ GeV.
- N lifetime:

$$\tau_N \sim G_F^{-2} |V_{\tau N}|^{-2} \, m_N^{-5}$$

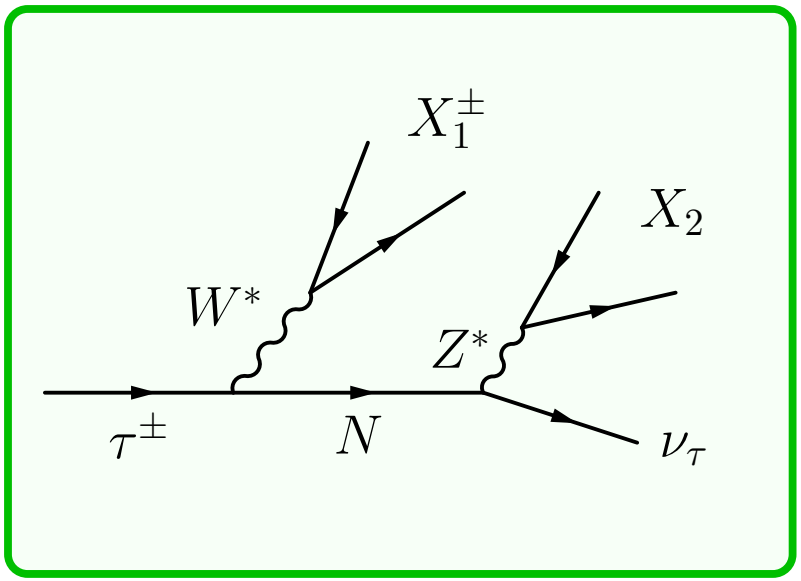
long-lived for small m_N

Heavy Neutrino Decay

- N decays through its mixing with ν_τ:

$$N \to X_2 \nu_\tau$$

- The complete decay chain:



- We focus on the case where
  - $X_1^\pm = \pi^\pm, \pi^\pm\pi^0$
  - $X_2 = e^+e^-, \mu^+\mu^-$

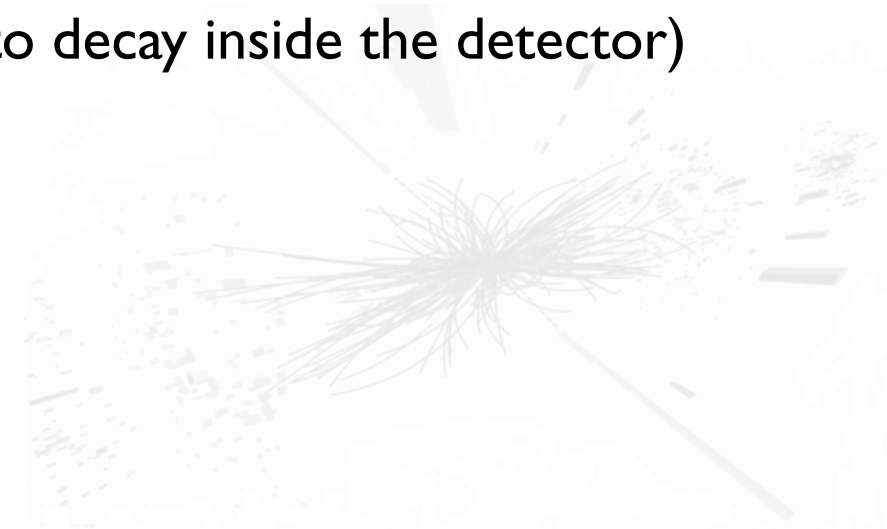
($X_1 = \ell\nu$ and $X_2 = \pi^+\pi^-$ could also be included.)

Signal Events

- The number of observed events is

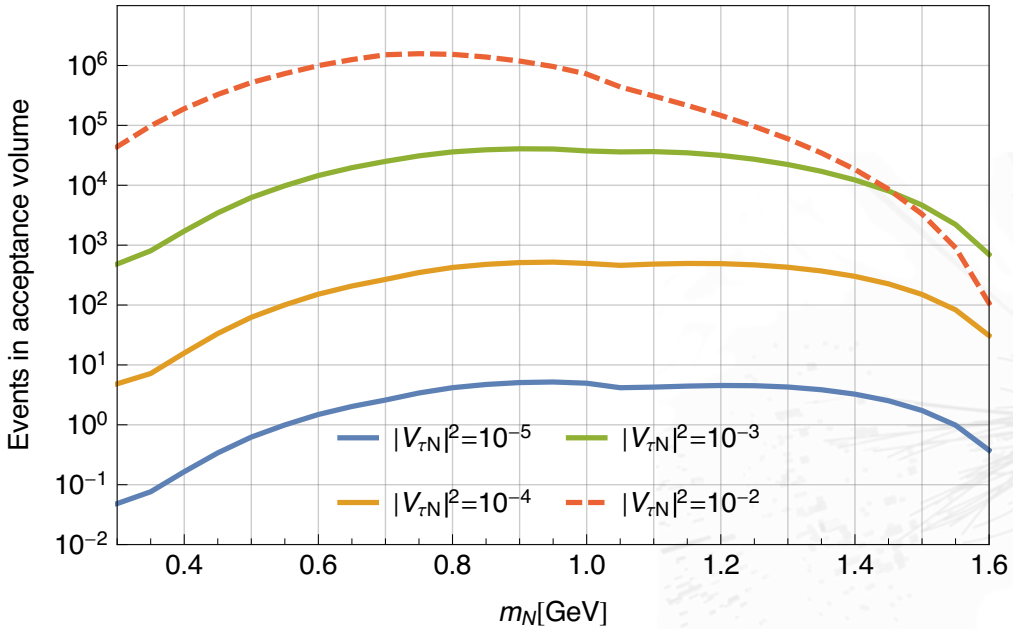
$$\mathcal{N} = 2\mathcal{N}_{\tau\tau} \times \mathcal{B}(\tau \to X_1 N) \times \mathcal{B}(N \to \nu_\tau X_2) \times a \times \epsilon, \quad \textbf{(3)}$$

  where
  - $N_{\tau\tau}$: total number of tau-lepton pairs produced
  - a: acceptance (probability for N to decay inside the detector)
  - ϵ: reconstruction efficiency



Acceptance

- To estimate the acceptance signal events were generated with `EvtGen`.
- Acceptance volume: 10 cm $< r <$ 80 cm, -40 cm $< z <$ 120 cm.
- Number of sterile neutrino decays inside the acceptance volume given $N_{\tau\tau} = 4.6 \times 10^{10}$ at Belle II:



Event Selection and Backgrounds

- The cut $|\vec{r}| > 10$ cm rejects prompt tracks and most bakground from K_S decays.
- The events are required to have only four tracks. (This rejects $e^+e^- \to B\bar{B}$ and $e^+e^- \to q\bar{q}$ events, which have high track multiplicity.)
- Additional non-$\tau\tau$ events can be reduced by exploiting the back-to-back production of the tau leptons. (e.g., in the CM, $\cos\theta_{X_1X_2,\tau} < -0.5$.)
- After applying the previous cuts, the main background comes from

$$\tau^\pm \to \pi^\pm K_L \nu_\tau,\ K_L \to \pi\mu\nu,$$

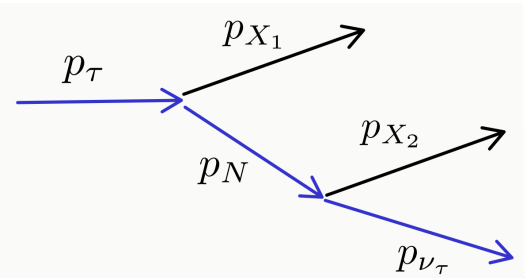
  where the displaced π is misidentified as a muon.
- The expected yield of the K_L background is 17 events per ab^{-1} (850 events in the entire Belle II event sample).

Further Background Suppression

(Exploit constraints from signal hypothesis)

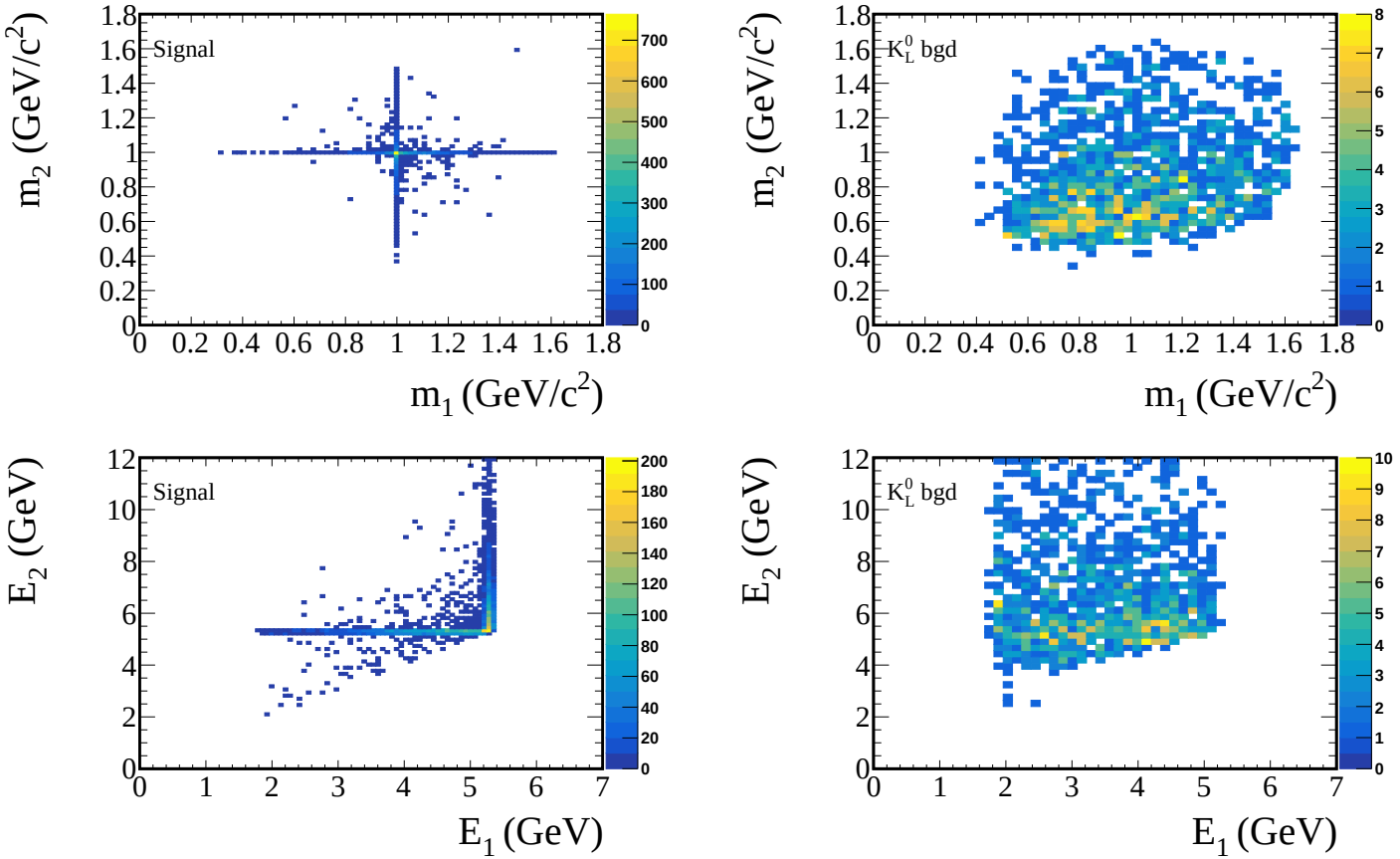
- $\tau \to X_1 N$, $N \to X_2 \nu_\tau$ not fully reconstructed due to ν_τ.
- However, it is possible to use the kinematical constraints on the decay chain to determine the 4-momenta of all particles up to a twofold ambiguity.

  - 12 unknowns (p_τ, p_N, p_{ν_τ})
  - 12 constraints:
    - 8 from momentum conservation in each vertex.
    - 2 from m_τ and m_{ν_τ} ($p_\tau^2 = m_\tau^2$, $p_{\nu_\tau}^2 = 0$).
    - 2 from the direction of $\vec{p}_N$.



- 2-fold ambiguity from quadratic eq. $\Rightarrow$ 2 solutions for m_N and E_τ.

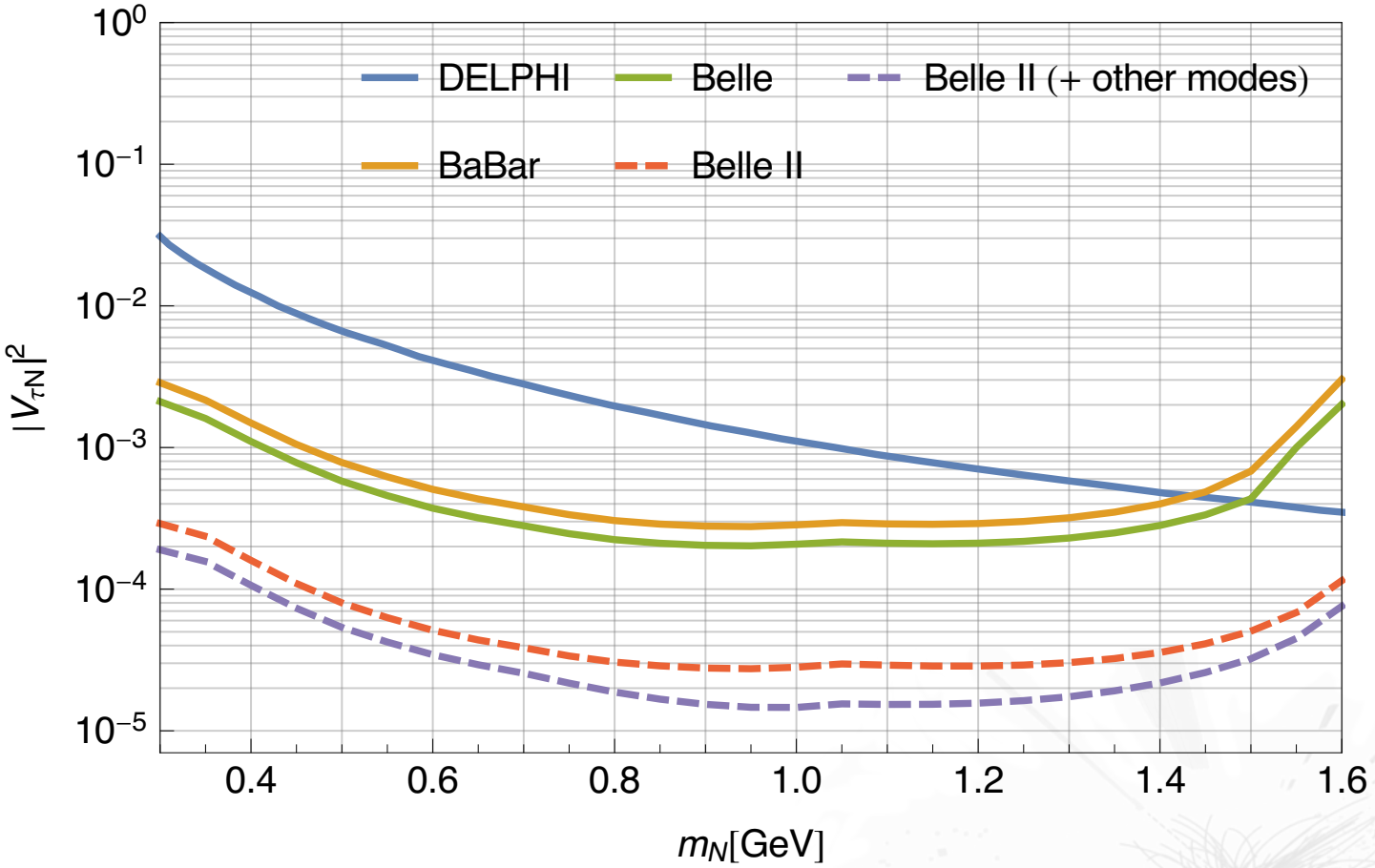
Application to K_L^0 Background



Distributions of the N mass solutions m_2 vs. m_1 (top plots) and of the τ c.m.-energy solutions E_2 vs. E_1 (bottom plots) for signal events generated with $m_N = 1$ GeV (left plots) and for K_L background events (right plots).

- For example, requiring either $E_1 > 5$ GeV or 5 GeV $< E_2 < 5.8$ GeV retains 75% of the signal while rejecting 75% of the background.

Current and Projected Bounds



Expected 95% confidence-level limits, obtainable from $\tau^- \to X_1 N$, $N \to X_2 \nu$ for $X_1 = \pi^-(\pi^0)$ and $X_2 = \ell^+\ell^-$. Also shown is the potential impact of adding the modes $X_1 = \ell\nu$ and $X_2 = \pi^+\pi^-$.

Summary and Conclusions

- We propose a new search for a sterile neutrino N with $m_N < m_\tau$ that mixes predominantly with ν_τ.
- We make use of the large samples of $e^+e^- \to \tau^+\tau^-$ events to produce the N via $\tau \to X_1 N$ decays.
- The method exploits the long lifetime N in this mass range to greatly suppress backgrounds.
- We proposed kinematic and vertex-based constraints to further suppress background and measure the N mass if signal is observed.
- The proposed search surpasses current best limit obtained by DELPHI.

Thank you!