Proposed search for a ν_τ-mixing heavy neutrino

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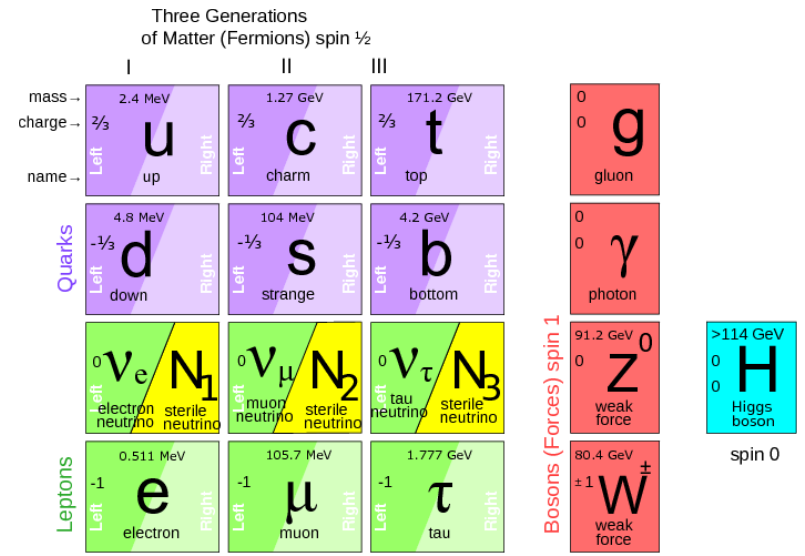
Heavy Neutral Leptons (N)



- Neutrino oscillation opened a new window in the search for new physics.
- Neutrino masses can be incorporated to SM by introducing RH (Majorana) neutrinos
- Being neutral under the SM, they can have Majorana mass term
- N is mostly the RH neutrino, but small LH component allow it to interact with SM particles
- N in GeV scale as allows to solve some of the outstanding problems of the SM.
    - **Origin of the SM neutrino masses (seesaw mechanism)**
    - **non-baryonic darkmatter**
    - **baryogenesis**

arXiv:hep-ph/0503065

- N are sterile: Interacts with ν_{SM} through mixing: N ↔ ν_{SM}
- Long lifetime of N: due to small M_N and small mixing

Status of Direct Searches of HNL

Explored regions of M_N by different experiments

$M_N > M_Z$

- Direct searches @LHC: $pp \rightarrow Nl^{\pm}$

$M_N < M_{Z,W}$

- DELPHI ($Z^0 \rightarrow \nu N$)

Z. Phys. C 74, 57 (1997) Erratum: [Z. Phys. C 75, 580 (1997)]

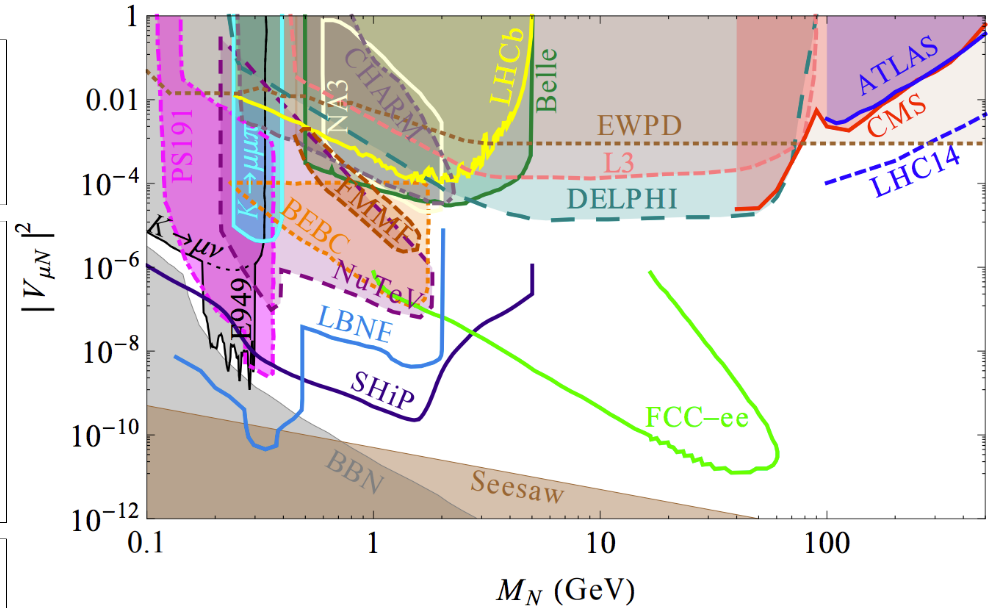
- ATLAS/CMS ($W^{\pm} \rightarrow Nl^{\pm}$)

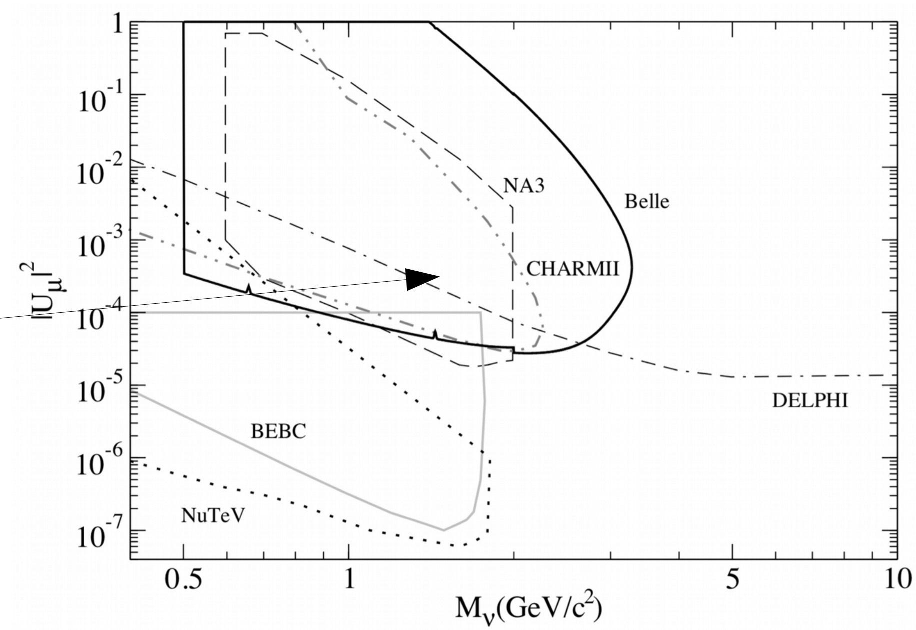
$M_N < M_{B,D,K}$

- Belle, LHCb, beam-dump, NA62 etc.

- All the above experiments provide tight limits on $|U_{eN}|$ and $|U_{\mu N}|$
- Limits on $|U_{\tau N}|$ is much weaker: which motivates $|U_{\tau N}| >> |U_{eN}|, |U_{\mu N}|$
- Experimentally challenging
- $|U_{\tau N}|$ was constrained only by DELPHI

arXiv:1502.06541



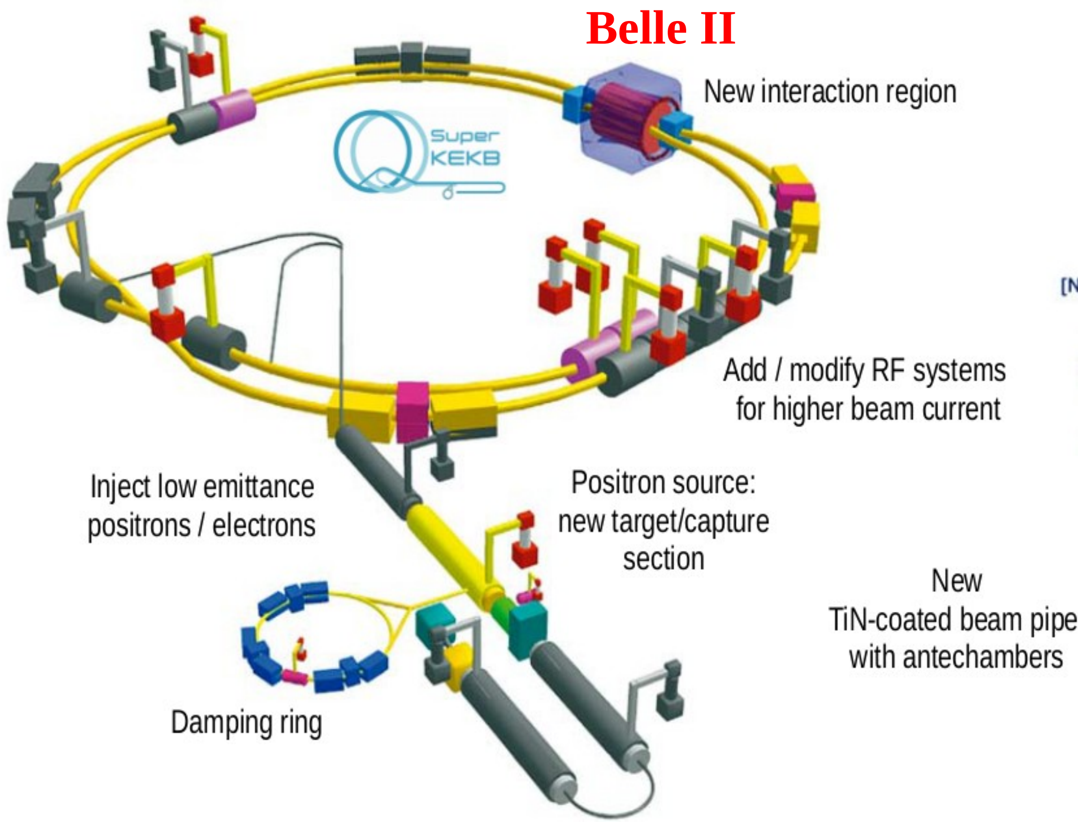


Direct Searches of HNL in tau Decays at B-factories

Proposed search of N-mixing with τ at B-factories with $M_N < M_\tau$

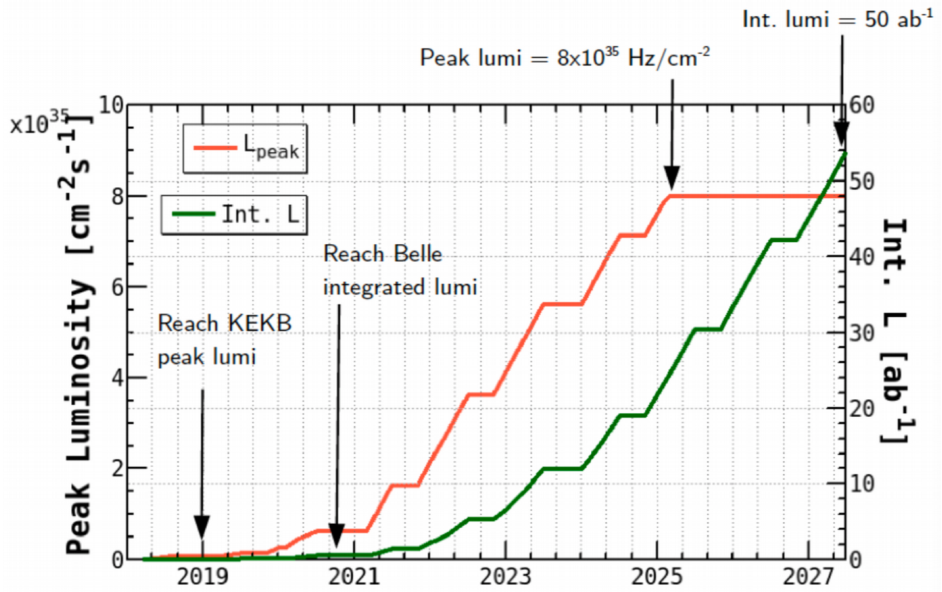
- Best place to search for τ decay is B-factories
- $\sigma(e^+e^- \to \tau^+\tau^-)$ ~0.9 nb.
- Belle: $N(e^+e^- \to \tau^+\tau^-) = 8.8 \times 10^8$
- BaBar: $N(e^+e^- \to \tau^+\tau^-) = 4.6 \times 10^8$
- Belle II with 50 ab^{-1} : $N(e^+e^- \to \tau^+\tau^-) = 4.6 \times 10^{10}$ by 2027.

SuperKEKB and Belle II



x40 higher instantaneous luminosity than Belle:

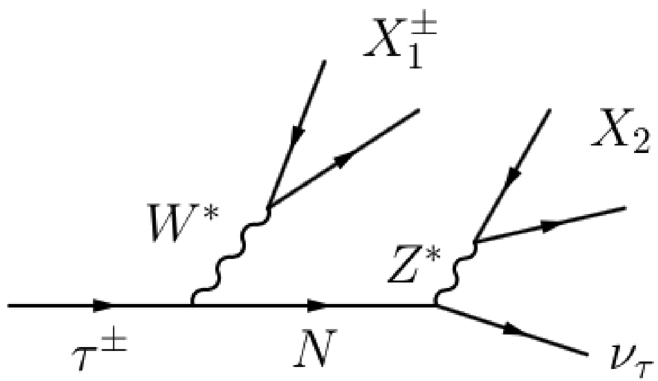
- ➔ Double beam current
- ➔ Major increase by small beam size "nano-beam" (vertical spot size ~50nm !!)



- With Belle II VXD: large improvement to vertex resolution w.r.t B-Factories
- IP resolution improved by PXD being at radius of 1.4 cm
- Increased tracking volume compared to Belle in both SVD and CDC ⇒ ~30%
- Improved PID with better K/π separation relative to Belle.
- Belle II by 2027: 50ab^{-1} data

Sensitivity study at Belle II

- Since $|U_{\tau N}| >> |U_{eN}|, |U_{\mu N}|$ and $m_N < m_\tau$, N must decay via the neutral-current decay $N \to \nu_\tau X_2$, mediated by the Z*
- Sensitivity for $|U_{\tau N}|$ from: $N = N_\tau \times B(\tau \to X_1 N) \times B(N \to \nu_\tau X_2) \times a \times \epsilon$



- HNL production: through decays of $\tau \to X_1 \nu_\tau$ (X_1 restricted here to $\pi^\pm, \pi^\pm \pi^0$) and ν_τ mixes with N with mixing $|U_{N\tau}|^2$
- HNL Decays: $N \to \nu_\tau X_2$ (X_2 restricted to $\mu^+\mu^-$, e^+e^-)
- Hadronic X_2 avoided due to fragmentation issues
- Using full GEANT4 simulation to study the B-factory sensitivity for the decay chain $\tau \to NX_1$, $N \to \nu_\tau X_2$.
- Long lifetime of N: $c\tau_N \propto |U_{N\tau}|^{-2} m_N^{-5}$

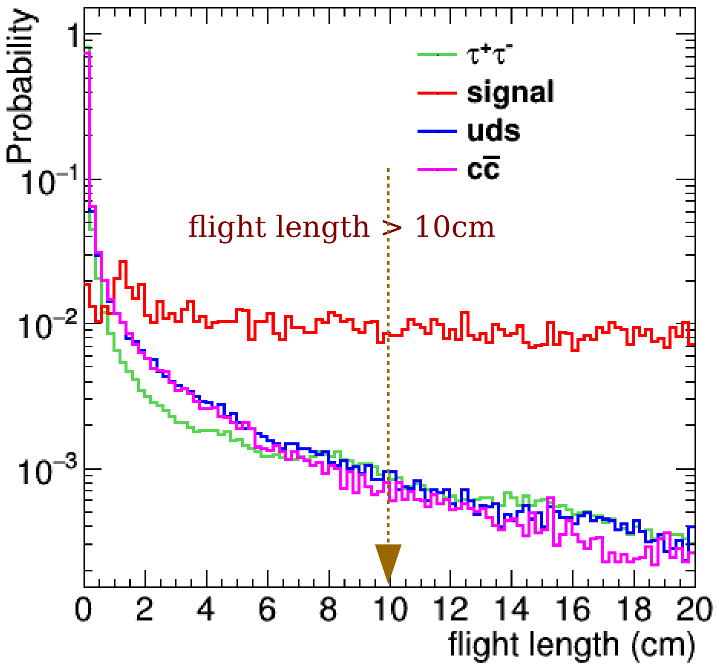
Background Suppression

- Background estimated using Belle II simulated samples
- A rough background suppression achieved by applying simple event-selection criteria:
- Given here for $\tau_{sig} \to \pi N$, $N \to \mu\mu\nu_\tau$, $\tau_{other} \to e\nu\nu$

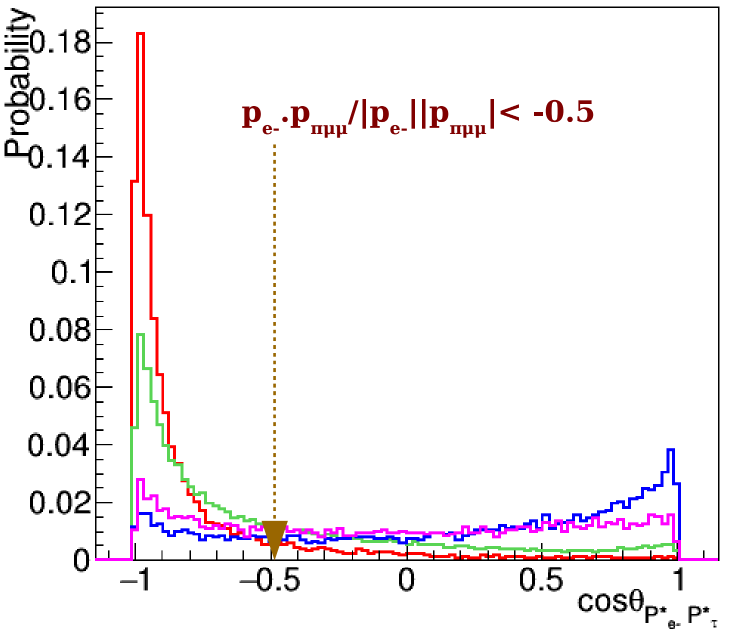
Decay processes	σ[nb]
$e^+e^- \to B^+B^-$	0.525
$e^+e^- \to B^0\bar{B}^0$	0.525
$e^+e^- \to u\bar{u}$	1.61
$e^+e^- \to d\bar{d}$	0.4
$e^+e^- \to s\bar{s}$	0.38
$e^+e^- \to c\bar{c}$	1.3
$e^+e^- \to \tau\bar{\tau}$	0.9

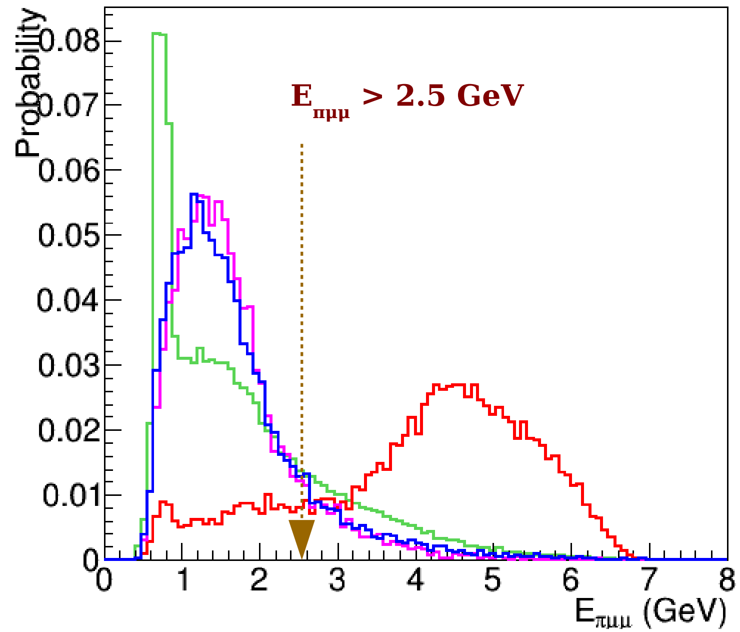
To remove backgrounds:

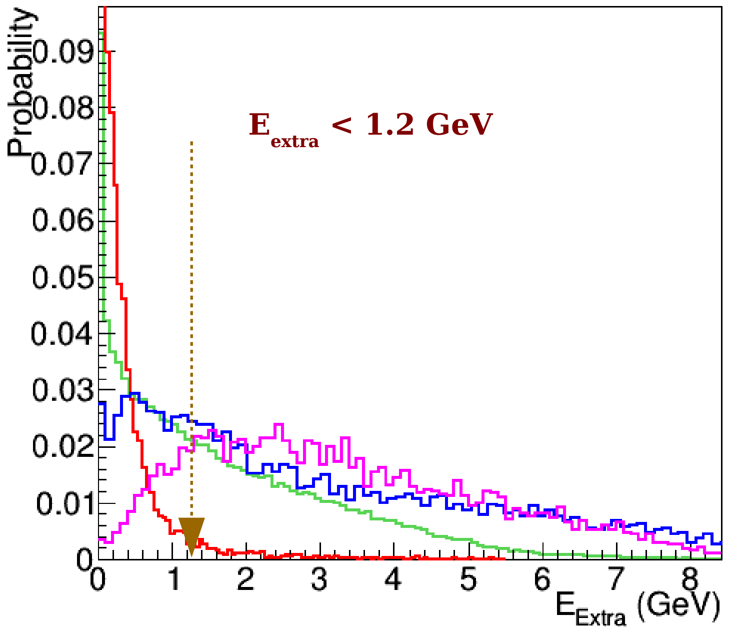
- Strict Particle-Identification requirement
- Tag side: 1-track, Signal side: 3-charged tracks
- Impact Parameter Cuts on $\pi^\pm$,$e^\pm$ in x-y plane and z-axis: $|d0| < 0.5$ cm, $|z0| < 2$cm
- Vertex probability cut for $N \to \mu\mu > 0$
- $M_{\pi\mu\mu} < M_\tau$
- Flight length of N > 10cm (rejects most background from KS decays and material interactions)
- Other discriminating variables summerized in next page:

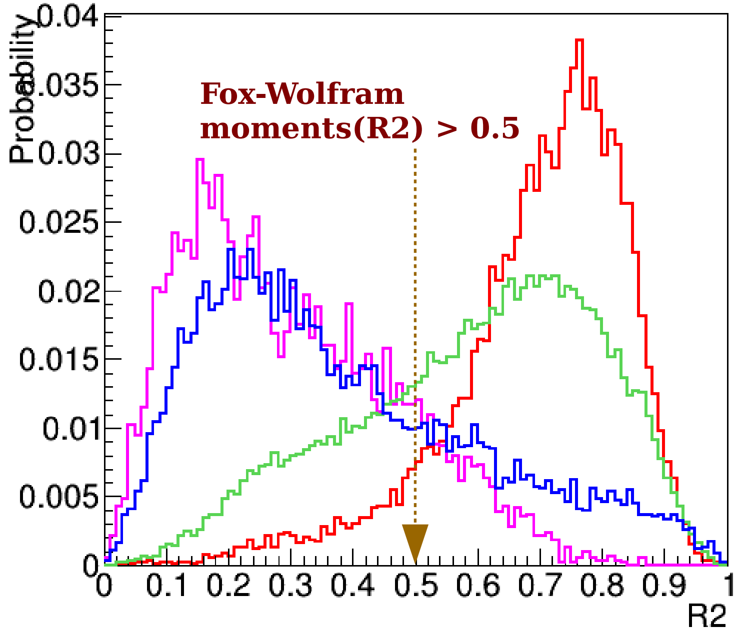


Few powerful shape variables



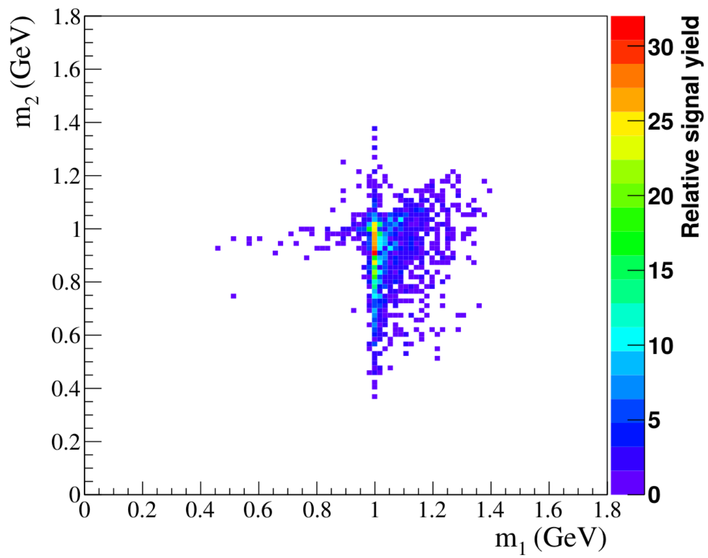






M_N reconstruction

- 12 unknowns: p^μ_ν , p^μ_N, and p^μ_τ
- 12 constraints: p_4 conservation in the τ and N decays (8 constraints), mass of τ and ν_τ (2 constraints), and the unit vector from the production point of the X_1 system to that of the X_2 system, which is the direction of the p_3 of N. The last constraint is large flight distance of the N
- Quadratic relation between E_N and P_N leads two solutions for M_N: m_1 and m_2.
- For signal, either $m_1 \approx m_N$ or $m_2 \approx m_N$
- Background events are spread out uniformly throughout the (m_1 , m_2) plane.
- Signal distribution obtained from simulated signals with particular values of m_N and $|V_{\tau N}|^2$ (lifetime τ_N).
- For each point in (m_N , $|V_{\tau N}|^2$) space, the fit gives the signal yield and the local signal significance.
- With final data: Determine signal yield from fit (m1,m2) to sum of signal + background distribution.



- HNL mass with 2-fold ambiguity (smeared with detector resolution)
- 17 background events/ab^{-1}, mostly $\tau^+\tau^-$, before cutting on m1 vs m2

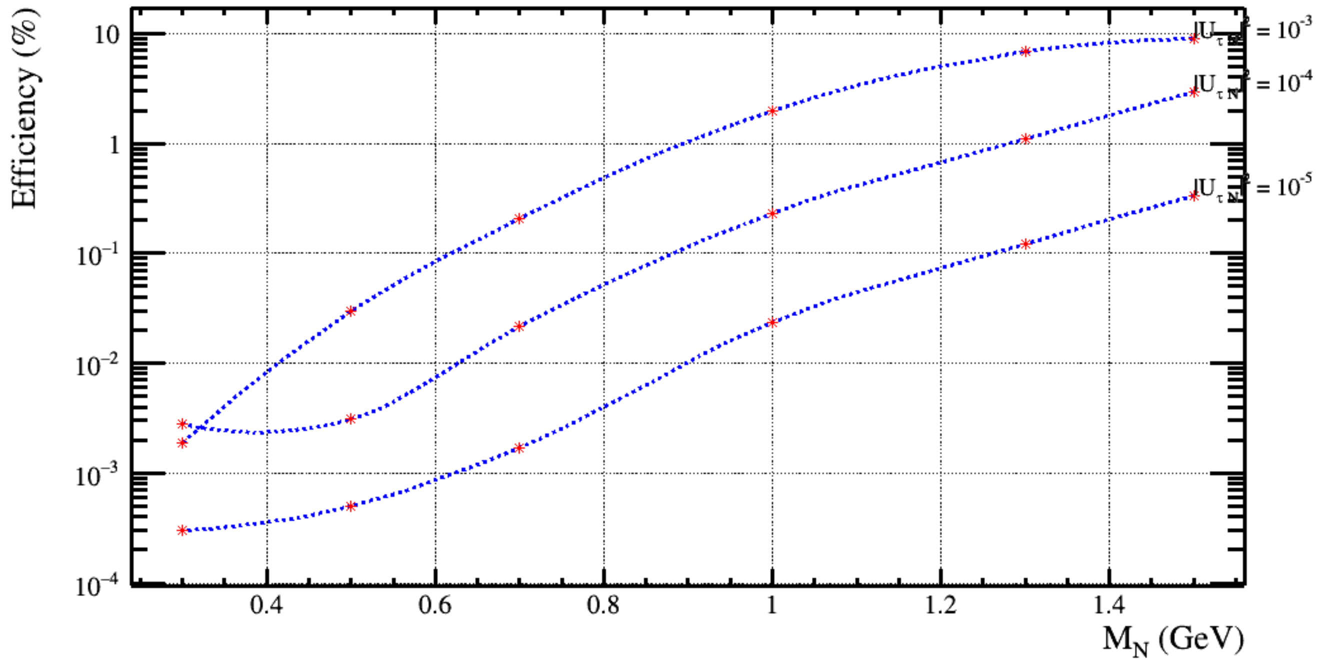
Efficiency vs M_N

Example: $|U_{N\tau}|^2 = 10^{-4}$, m_N = 1 GeV

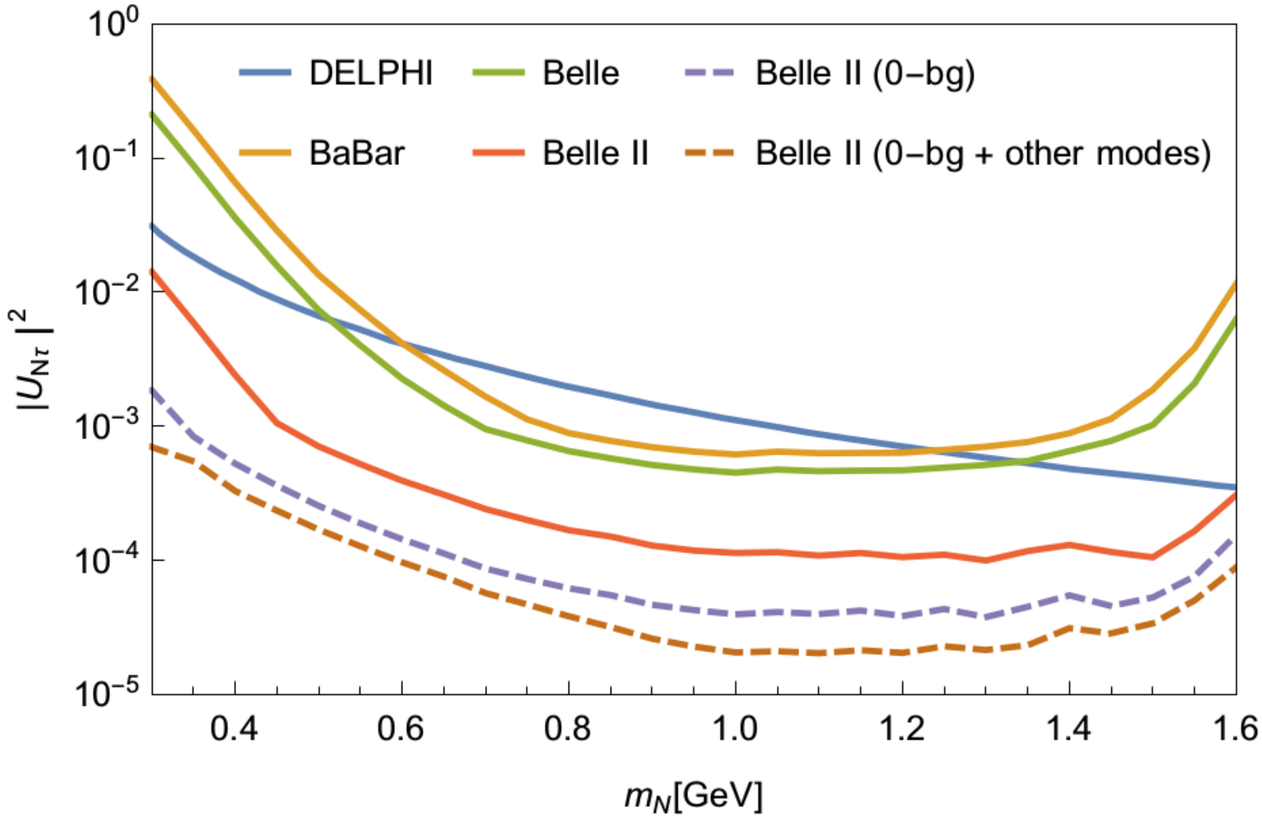
$\Rightarrow c\tau_N$ = 15.4 meter

$c\tau_N \propto |U_{N\tau}|^{-2} m^{-5}_N$

- Larger $c\tau_N$ → smaller reconstruction efficiency (a×ε)
- a×ε estimated at the Belle II experiment for various M_N and for various values of $|U_{\tau N}|^2$
- The efficiency plot below is with signal τ decay: $\tau \to \pi N$, $N \to \mu\mu\nu_\tau$, other τ decay: $\tau \to e\nu\nu$



Expected Limit on $|U_{N\tau}|$ from B-factories



- N decay occurs inside Belle II tracking volume of r = 1.2 m
- **Future Improvement:**
  Decays occurring inside the muon system, covering r = 2.5 m, can increase the sensitivity to lower values of $|U_{N\tau}|^2$ .This requires dedicated muon-system tracking

Conclusion

- We propose a new search for a sterile neutrino N that mixes predominantly with the ν_τ and that has mass $m_N < m_\tau$.
- The current best limits, obtained by DELPHI experiment, can be improved upon by current and future B-factories.
- Belle II can have best sensitivity to LLP search in τ decays by making use of their large samples of $e^+ e^- \to \tau^+ \tau^-$ events
- We use full GEANT4 simulation to study the B-factory sensitivity for the decay chain $\tau \to NX_1$, $N \to \nu_\tau X_2$.
- Our method exploits the long lifetime of N to greatly suppress background. In addition, kinematic and vertex-based constraints are used to further suppress backgrounds
- Paper: Dib, Helo, Nayak, Neill, Soffer, Zamora-Saa in preparation

THANK YOU!