Proposed search for a ν_τ-mixing heavy neutrino

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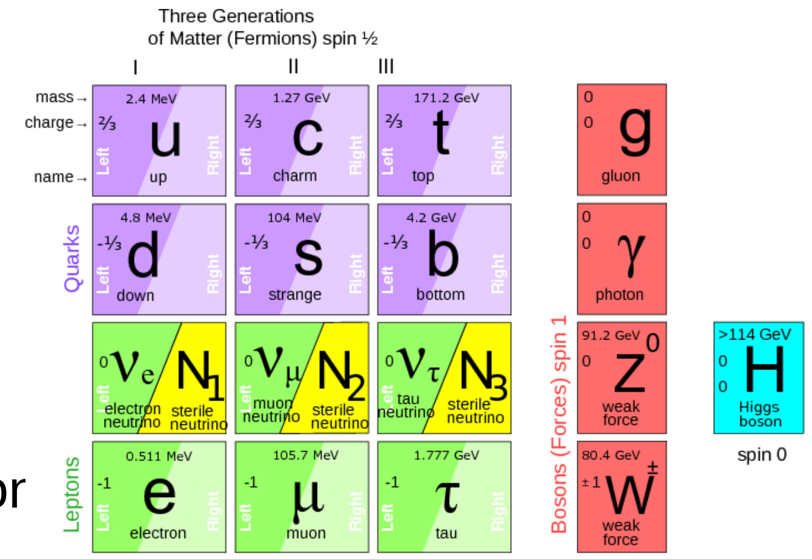
Heavy Neutral Leptons (N)

- 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 compor 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: $N \leftrightarrow \nu_{SM}$
- 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: $pp \rightarrow N l^{\pm}$

$M_N < M_{Z,W}$

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

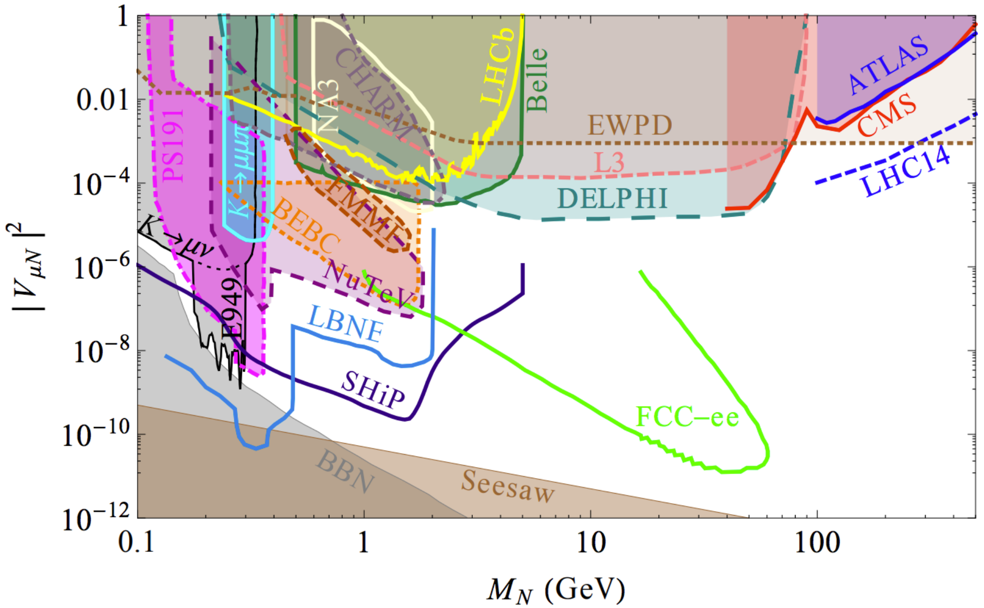
Z. Phys. C 74, 57 (1997) Erratum: [Z. Phys. C 75, 580 (1997)]

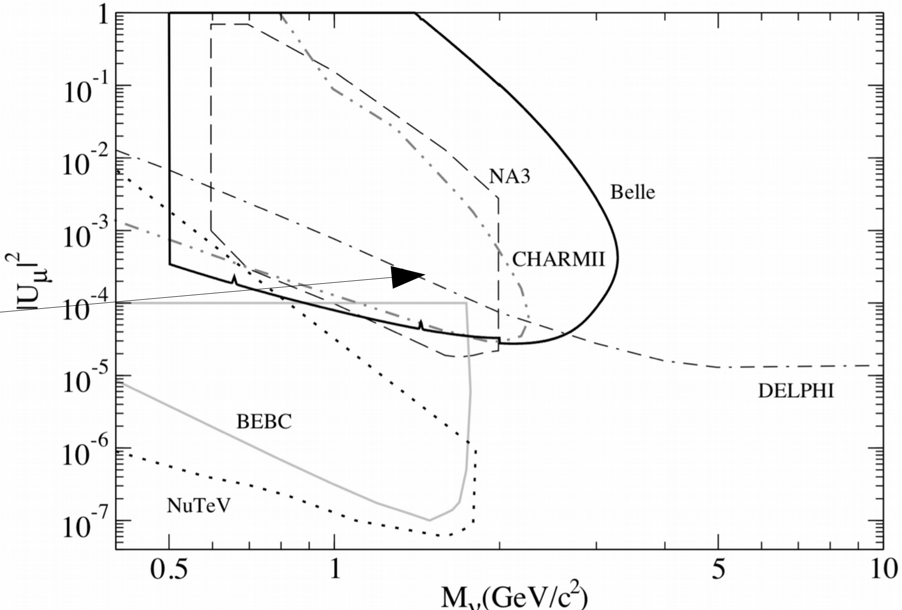
- ATLAS/CMS ($W^{\pm} \rightarrow N l^{\pm}$)

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

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

arXiv:1502.06541





- 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
- Might explain $R(D^{(*)})$ discrepancy: $R(D^{(*)}) = \frac{Br(B \rightarrow D^{(*)} \tau N)}{Br(B \rightarrow D^{(*)} l N)} = \frac{|U_{\tau N}|^2}{|U_{lN}|^2}$

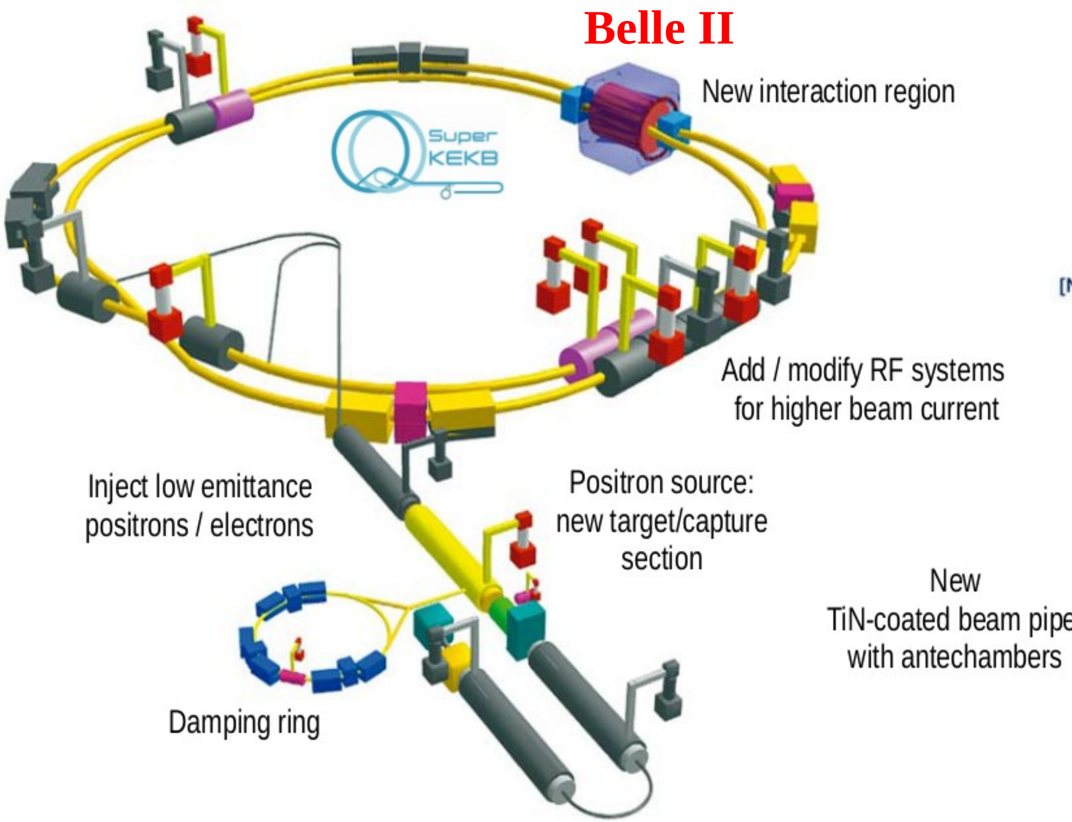
arXiv:1702.04335

Direct Searches of HNL in tau Decays at B-factories

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

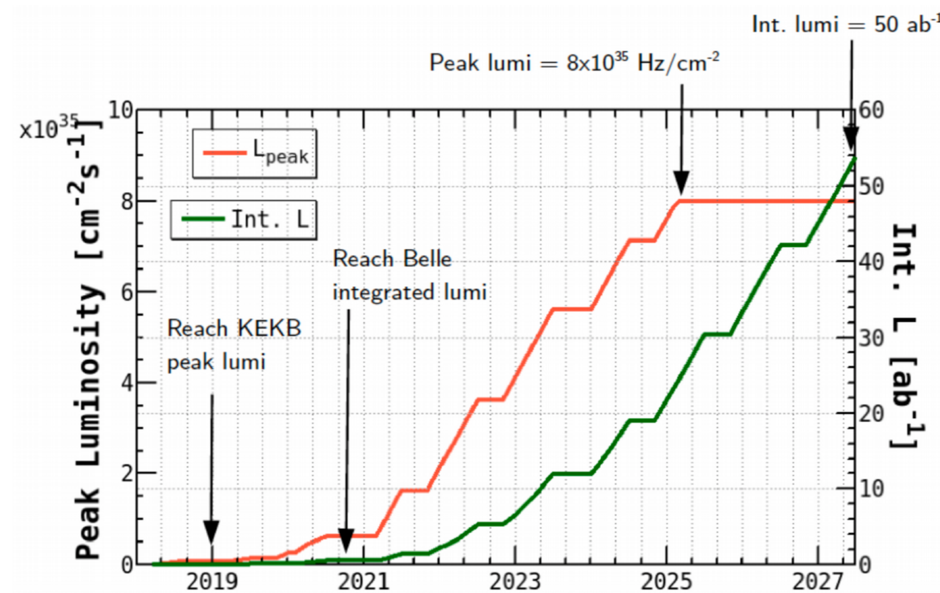
- Best place to search for τ decay is B-factories
- $\sigma(e^+e^- \to \tau^+\tau^-)$ ~0.9 nb.
- Belle: $N(e^+e^- \to \tau^+\tau^-) = 8.8 \times 10^8$
- BaBar: $N(e^+e^- \to \tau^+\tau^-) = 4.6 \times 10^8$
- Belle II with 50 ab^{-1} : $N(e^+e^- \to \tau^+\tau^-) = 4.6 \times 10^{10}$ by 2027.

SuperKEKB and Belle II



x40 higher instantaneous luminosity than Belle:

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

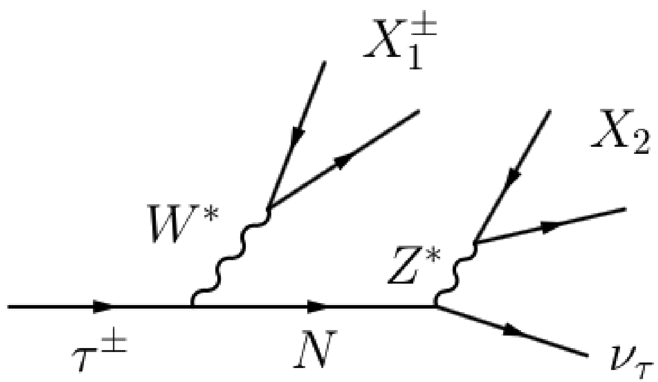


Belle II detector components needed for this search

- 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: 50 ab^{-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(NC) decay $N \rightarrow \nu_\tau X_2$, mediated by the Z*
- Sensitivity for $|U_{\tau N}|$ from: $N = N_\tau \times B(\tau \rightarrow X_1 N) \times B(N \rightarrow \nu_\tau X_2) \times a \times \epsilon$



- HNL production: through decays of $\tau \rightarrow X_1 \nu_\tau$ (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: $N \rightarrow \nu_\tau X_2$ (X_2 restricted to $\mu^+\mu^-$, e^+e^-)
- NC is used only to make V0
- Hadronic X_2 avoided here since it requires correct accounting of the fragmentation.. It could be used in the final analysis
- Long lifetime of N: $c\tau_N \propto |U_{N\tau}|^{-2} m_N^{-5}$

Background Suppression

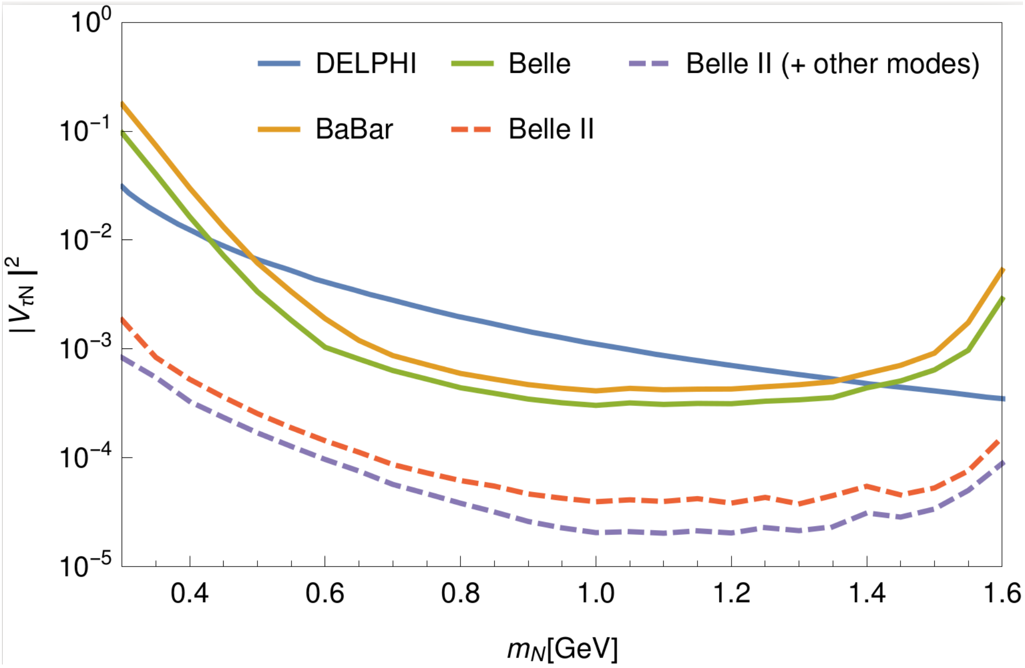
Decay processes	σ[nb]
$e^+e^- \to B^+B^-$	0.525
$e^+e^- \to B^0\bar{B}^0$	0.525
$e^+e^- \to u\bar{u}$	1.61
$e^+e^- \to d\bar{d}$	0.4
$e^+e^- \to s\bar{s}$	0.38
$e^+e^- \to c\bar{c}$	1.3
$e^+e^- \to \tau\bar{\tau}$	0.9

- We expect continuum and $B\bar{B}$ backgrounds should be zero by using event topology, and continuum suppression criteria.
- Based on other B-factory τ analyses, we expect non-ττ background to be negligible after applying standard cuts on the number of tracks, no extra photons, and event topology.
- Based on other displaced-vertex analyses (e.g. arXiv: 1301.1105), we expect the background to be further suppressed
- Final background suppression and extraction of signal yield can be done in terms of the M_N, the measurement of which is discussed in next slide.

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)
  - 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 $m_2 \approx m_N$ (detector resolution should be added)
- Background events are spread out uniformly throughout the (m_1 , m_2) plane.
- With final data: Determine signal yield from fit (m1,m2) to sum of signal + background distribution.

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



- Result obtained assuming that the background can be reduced to 0. We are working on estimating the background, but we expect it to be low based on the strong background-rejection capabilities of the displaced vertex and m_1-m_2 selection.
- 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 our large samples of $e^+ e^- \rightarrow \tau^+ \tau^-$ events
- 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.
- Belle II simulation results are under review by collaboration. Soon be available for public
- The study was performed in collaboration with Claudio Dib, Juan Carlos Helo, Nicolás Neill, Jilberto Zamora Saá.

THANK YOU!