

Search for heavy neutral lepton at Belle

Dmitri Liventsev (Wayne State University)

HEP journal club, University of Hawaii May 7, 2024

Standard model



• The Standard model reins since mid-1970s.

Standard Model of Elementary Particles



Experimental foundation



- Long history of experimental study
 - Discovery of *CP*-violation in *B*-decays by Belle and BABAR in 2001,
 - Discovery of Higgs boson by CMS and ATLAS in 2012.
- The Standard Model describes most of the known processes really well.
- However, there are indications that the SM is not complete:
 - Hints in particle physics (*e.g.* $R(D^{(*)})$, but no single definitive deviation from SM);
 - Anomalous muon magnetic moment;
 - Neutrino oscillations;
 - Baryon asymmetry, dark matter;
 - Too many parameters, hierarchy problem.
- There should be something beyond the SM New Physics (NP).

What we know about neutrinos



- There are three neutrino types in the SM: v_e , v_{μ} , v_{τ} .
- Neutrino is a fermion, massless left-handed neutral lepton.
 - Masses of fermions in the SM are generated by coupling of the Higgs boson to left- and right-handed components of the particle.
 - There is no right-handed neutrino in the SM thus neutrinos should be strictly massless; however, oscillations show that neutrinos have masses.
 - lowever, oscillations show that neutrinos have masses.
 - One right-handed neutrino gives mass to one left-handed neutrino.
 - We need at least two.
- Lepton flavor is conserved
 - Oscillations show that lepton flavor is not conserved.

Dirac and Majorana masses



• If there are right-handed neutrinos, Dirac mass term is possible

$$\mathcal{L}^D = -Y^{\nu}_{\alpha\beta}\bar{L}^{\alpha}H\nu^{\beta}_R + h.c.$$

After electro-weak symmetry breaking

$$\mathcal{L}^D = -\frac{v}{\sqrt{2}} Y^\nu \bar{\nu}_L \nu_R + h.c. = -m_D \bar{\nu}_L \nu_R + h.c.$$

But for right-handed neutrino one more mass term is possible

$$\mathcal{L}^M = -\frac{1}{2}m_M\bar{\nu}_R^c\nu_R + h.c.$$

• There are several mass terms, which may be rewritten in a matrix form

$$\begin{pmatrix} \bar{\nu}_L \bar{\nu}_R \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & m_M \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R^c \end{pmatrix}$$

$$m_L = m_D^2/m_M$$

• After diagonalization if $m_M \gg m_D$ we get two masses,

 $m_R = m_M$

Hawaii U. - May 7, 2024

Standard Standard Model



- We need right handed neutrino in the model?
 - Also known as sterile neutrino, heavy neutrino or heavy neutral lepton (HNL).



SM with right-handed neutrinos



For example, vMSM: SM + 3 right-handed neutrinos (2 heavy, 1 light)
 ⇒ every left particle gets its right-handed counterpart.



Asaka, Blanchet, Shaposhnikov, Phys. Lett. B 631 (2005) 151

Heavy neutrinos and NP

Belle II

vMSM explains

- Neutrino masses and oscillations:
 - Enough parameters to describe any oscillation pattern;
- Dark matter:
 - Heavy neutrinos are not stable; yet the lightest one (>10 keV) lives long enough to be quasi-stable;
- Baryon asymmetry:
 - vMSM satisfy Sakharov conditions.
- Everything may be achieved with the same set of parameters.
- HNLs also appear in many models beyond the SM: SUSY, GUT etc.
- There are other ways to give mass to neutrinos (*e.g.* modify Higgs).



- Sterile:
 - No strong interaction (it is lepton),
 - No weak interaction (it is right-handed),
 - No electromagnetic interaction (it is neutral).

The only way to interact is to mix with (usual) left-handed neutrino:

$$v_{\alpha} = \sum U_{\alpha i} v_i, \; \alpha = e, \; \mu, \; \tau, \; ..., \; i = 1, \, 2, \, 3, \, 4, \; ...,$$

 α – flavor eigenstates, *i* – mass eigenstates.

Hawaii U. - May 7, 2024



- Located in KEK, Tsukuba, Japan
- KEKB is an asymmetric-energy e^+e^- collider 3.5 GeV × 8.0 GeV, $c\bar{c}, q\bar{q}, \ell\ell \leftarrow e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}, \ \mathcal{C}_{peak} = 21 \text{ nb}^{-1}\text{s}^{-1}$

Detector functionality



Tracking

- Charged particles create ionization track in SVD and CDC.
- Charge
 - Due to magnetic field tracks bend.
- Particle identification
 - Combined information from CDC (*dE/dx*), TOF and ACC identifies type of a charged particle.
- Neutrals
 - Photons and π^o are detected in ECL, their energy is measured.
- KLM
 - Identification of long-living muons and K_L .

Hawaii U. - May 7, 2024

B-factories



- BaBar: PEP-II e^+e^- collider, SLAC, USA, 1999–2008.
- Belle: KEKB e^+e^- collider, KEK, Tsukuba, Japan, 1999–2010.
- Combined BaBar and Belle luminosity is ~1.5 ab^{-1} (1.25*10° $B\overline{B}$ pairs).
- Main focus: *CP*-violation (published in 2001)
 - Also B-decays, CKM parameters, charmonium(-like) states,

charm- and τ -physics etc.

- 500+ publications from BaBar,
 500+ from Belle.
- But still no definitive observation of the New physics (NP)!
- Upgraded the detector after 2010.

Belle II experiment started running in 2016.



Quest for high luminosity

KEKB

SuperKEKB

Belle II

- We need a lot of events to search for New physics
- There are two ways to increase luminosity:
 - Increase beam currents
 - Decrease beam size
- SuperKEKB uses

 2x increase in currents
 and "nano-beams"
- 40x luminosity
- Beam energy changed to reduce beam background





Belle II detector



Belle II is built on basis of Belle

Main structure and

magnet reused;

- ECL and KLM mostly reused;
- Vertex detector,
 drift chamber,
 PID, partially KLM
 upgraded;



Belle II Detector

KL and muon detector: Resistive Plate Counter (barrel) Scintillator + WLSF + MPPC (end-caps)

Particle Identification

• All electronics replaced.

EM Calorimeter:

CsI(TI), waveform sampling (barrel)

waveform sampling (end-caps)

How to find heavy neutrino?



- Search for HNL wherever conventional neutrinos appear.
- For fast decaying neutrino, use usual way: combine tracks from the vicinity of the interaction point (IP), look for a peak.
 - Fast decay means large U_{α} , which means large production would be seen.
- Slow decaying neutrino escapes detector, look for missing mass.
 - No need to reconstruct neutrino decay;
 - Needs reconstruction of the rest of event. For tagging *B* full reconstruction efficiency is $\sim 10^{-3}$, plus signal *B* reconstruction.
- Relatively slow decaying neutrino which decays far from the IP, but still in the detector.
 - Needs reconstruction of the neutrino decay (additional U_{α});
 - Topic of this talk.

Heavy neutrino in B decays



- We search for $B \rightarrow \ell_p v_h(X)$, $v_h \rightarrow \ell \pi$ decays, where $\ell = e, \mu, M(v_h) = M(\ell \pi)$.
- Physical background:
 - Decays with similar topology, followed by particle misidentification:
 - $K_{S,L} \to \pi^+ \pi^-, \ \gamma \to e^+ e^- \text{ etc},$
 - Remnants of multi-body decays,
 - Interactions with matter,
- Combinatorial background.
- Distant ℓh vertex ($c\tau \sim 20$ m for $M(v_h) = 1 \text{ GeV}/c^2$, $|U_{\alpha}|^2 < 10^{-4}$).



Existing experimental limits



- From cosmological and baryogenesis considerations and existing experimental data for any heavy neutrino:
 - for M_N < M(K) nontrivial experimental limits exist;</p>
 - $M(K) < M_N < M(B)$ is possible to study at Belle (II), experimental limits exist;
 - $M_N > 20 \text{ GeV}/c^2$ is cosmologically unfavored.



Hawaii U. - May 7, 2024

Inclusive vs exclusive reconstruction

Larger distance to v_h vertex r_{vtx} and $M(v_h)$ means smaller background level. Up to ~3 GeV/ c^2 contribution of $B \rightarrow D^{(*)}\ell v_h$ is dominant. For small $M(v_h)$ we use tighter requirements and consider only $B \rightarrow D^{(*)}\ell v_h$ decays. For higher masses we consider inclusive v_h production.

• To select semileptonic decays $B \rightarrow D^{(*)}\ell v_h$ we calculate mass of unreconstructed part ($X = D^{(*)}$, recoil mass):

and require $1.4 < M(X) < 2.4 \text{ GeV}/c^2$

Background distribution





Signal vs background MC





Phys. Rev. D. 87, 071102 (2013)



Selection criteria summary



Phys. Rev. D. 87, 071102 (2013)

- Strict lepton ID on ℓ_p , ℓ , lepton veto on h;
- Heavy lepton vertex geometrical quality:
 - Tracks approach to the interaction point,
 - Distance between tracks at decay point,
 - Angle between the momentum vector and decay vertex vector of the heavy neutrino candidate

in dependence on SVD hits of the neutrino daughter tracks;

- Distance from *l*h vertex to associated hits in SVD or CDC;
- Constraint on χ^2 of the vertices fits;
- Constraint on recoil mass M(X) and proton veto on h in the "small mass" region $(M(v_h) < 2\text{GeV}/c^2)$.

Selection criteria application



Phys. Rev. D. 87, 071102 (2013)

How selection criteria affect number of events for generic and signal MC.

$$\mathcal{L}_{MC} = 3\mathcal{L}_{data}$$



Efficiency



Phys. Rev. D. 87, 071102 (2013)

- Efficiency depends on mass $M(v_h)$ and decay radius r_{vtx} of HNL;
- Signal MC with different mass hypotheses and production modes used to create $\varepsilon(r_{vtx}, M(v_h))$.



Upper limit calculation



Phys. Rev. D. 87, 071102 (2013)

The number of neutrinos detected in the Belle detector is

$$n(\nu_h) = 2N_{BB} \ \mathcal{B}(B \to \nu_h) \ \Gamma(\nu_h \to \ell \pi) \frac{m}{p} \int \exp\left(-\frac{m\Gamma R}{p}\right) \varepsilon(R) dR$$

where N_{BB} is a number of *BB* pairs, \mathcal{B} is the branching fraction of v_h production, Γ is the width of v_h decay, *m* and *p* are v_h mass and momentum, $\varepsilon(R)$ is the reconstruction efficiency.

- \mathcal{B} and Γ depend on $|U_{\alpha}|^2$
- Since Γ and, therefore, v_h flight length, change a lot in 0.5-5.0GeV/c², we can not ignore the exponent and have to numerically solve the equation for the variable |U_α|²



Upper limit on $|U|^2$



Phys. Rev. D. 87, 071102 (2013)

- Couplings $|U_e|^2$, $|U_{\mu}|^2$ and $|U_eU_{\mu}|$ are defined from $ee\pi$, $\mu\mu\pi$ and $e\mu\pi + \mu e\pi$ modes, respectively.
- For high *|U|²* flight length of the neutrino becomes too short and such events are rejected by selection criteria.

Only a few isolated events found in agreement with MC expectation



If we do not take into account flight length, we get result shown by dashed line.



Heavy neutrino search comparison

• Search for HNL at Belle gives competitive result.

Shuve, Peskin, Phys. Rev. D 94, 113007 (2016)



Dmitri Liventsev (WSU) - HNL at Belle

Belle II

Heavy neutrino search comparison

• If compared with all experiments, not so impressive.

• May help to fill the gap between other experiments.



Belle II

Heavy neutrino search at Belle II



• If we assume similar zero background at Belle II (probably, too optimistic), upper limit improves as $\mathcal{L}^{-1/2}$



Heavy neutrino in τ decays



- At ~10.58 GeV cross-section of $\tau\tau$ production (0.919nb) is comparable to that of $B\overline{B}$ production (1.05nb).
- Background sources, analysis strategy similar to v_h search in *B* decays.
- Search for $\tau \to \pi_p v_h$, $v_h \to \ell \pi$ decays, where $\ell = e, \mu, M(v_h) = M(\ell \pi)$.
- Since τ is fully reconstructed, can use
 - Energy difference $\Delta E = E_{\pi\pi\ell} E_{CM}$,
 - Invariant mass $M(\pi_p \pi \ell)$.



Existing experimental limits



• $|U_{\tau}|^2$ is less populated compared to $|U_e|^2$, $|U_{\mu}|^2$.



MC simulation





- Unusual kinematic point for $\tau \tau$;
- Many events with displaced vertex (*i.e.* conversion).
- Different normalizations: from fits, from luminosity. Normalization from fit is shown.
 - Don't use MC for quantitative background estimation.
- Due to low multiplicity of $\tau\tau$ events, should take into account trigger and skim (data subset) efficiency.





Selection criteria summary



General

- Trigger and skim requirements (MC);
- No extra tracks on signal side,
 1 or 3 tracks on tagging side, zero net charge;
- Elliptic ΔE vs $M(\pi \pi \ell)$ requirement (correlated);
- Prompt $\pi_p: |dr| < 0.5$ cm; |dz| < 3 cm;
- Particle ID
 - Strict lepton ID on ℓ , electron veto on π_p ;
- Vertex quality
 - Tracks approach to the interaction point (*dr*),
 - Distance between tracks at decay point (z_{dist}) ,
 - Angle between the momentum vector and decay vertex vector of the heavy neutrino candidate (φ)

in dependence on SVD hits of the neutrino daughter tracks.

Dmitri Liventsev (WSU) - HNL at Belle



Reconstruction efficiency



- Efficiency depends on mass $M(v_h)$ and decay radius r_{vtx} of HNL;
- Signal MC with different mass hypotheses used to create $\varepsilon(r_{vtx}, M(v_h))$.



Vertex requirements: data vs MC



Phys. Rev. Lett. 131 211802 (2023)

- Reconstructed $D^{*-} \rightarrow D^- \pi^0$, $D^- \rightarrow K_S \pi^-$;
- Applied vertex quality requirrements to K_s ;
- Drop at ~10cm is due to *dr* vertex requirement.



MC results



Phys. Rev. Lett. 131 211802 (2023)

- Successfully suppressed background to a few isolated events.
- Main source of background is $\gamma \rightarrow e^+e^-$ conversion in $\pi\pi e$ and $K_s \rightarrow \pi^+\pi^-$ in $\pi\pi\mu$.
- Enriched background samples (with reversed particle ID) used to construct peaking background functions for data fit by smoothing.
- *K_s* region is excluded
 0.464 0.494 GeV/*c*², ~ ±2σ,
 shown by dashed lines.



Signal shown by red curve

Data results



Phys. Rev. Lett. 131 211802 (2023)

- NHL mass varied between $m_{\ell} + m_{\pi}$ and m_{τ} .
- NHL resolution fixed from signal MC.
- Background described by MC functions plus constants.
- MC used to determine shape of background, normalizations free in fit.
- Number of events in data exceeds expectation, shape matches MC well.
- No signal with > 3σ significance observed.



Filled histograms are for candidates with opposite-charge τ and ℓ , open histograms are for candidates with same-charge combinations. Curves are the fits with the signal yield fixed at zero.

Signal region



- We can check signal region in ΔE and $M(\pi_p \pi \ell)$.
- No signal is seen.



Realistic model



- Define $U^2 = U_e^2 + U_\mu^2 + U_\tau^2$,
- Define $x_{\alpha} = U_{\alpha}^2/U^2$,
- Use full corpus of neutrino oscillation data to determine allowed x_{α} .
- Two heavy states with close masses:
 - HNL oscillations occur,
 - Two extreme cases: "Dirac-like limit" and "Majorana-like limit".
- Four "benchmark" cases:
 - Normal hierarchy vs inverted hierarchy,
 - "Dirac-like limit" vs "Majorana-like limit".



Tastet, Ruchayskiy, Timiryasov, J. High Energ. Phys. 12 (2021) 182

Orange and red stars show benchmark points

Results



- Upper limits at 95% CL on $|U|^2$.
- Upper (lower) plot is for normal (inverted) hierarchy.
- The solid (dashed) curve shows result in "Majorana-like limit" ("Dirac-like limit").
- Excluded area is above curves.



Comparison with existing limits



- Using x_{τ} recalculate our result (normal hierarchy, Majorana) to $|U_{\tau}|^2$.
- Our result fills the gap between other experiments.



Conclusions



- Neutrino oscillations definitively show that neutrinos have masses.
- The easiest way to introduce neutrino mass is to add right-handed neutrinos to the SM.
- Using Belle data we searched for heavy neutrino in *B* and τ decays.
- No signal was found in any case, upper limits were set.
- Belle II will continue the search for heavy neutrino.
 - More data;
 - Better efficiency;
 - Combine *B* and τ results.