# Search for heavy neutrinos with the T2K near detector ND280

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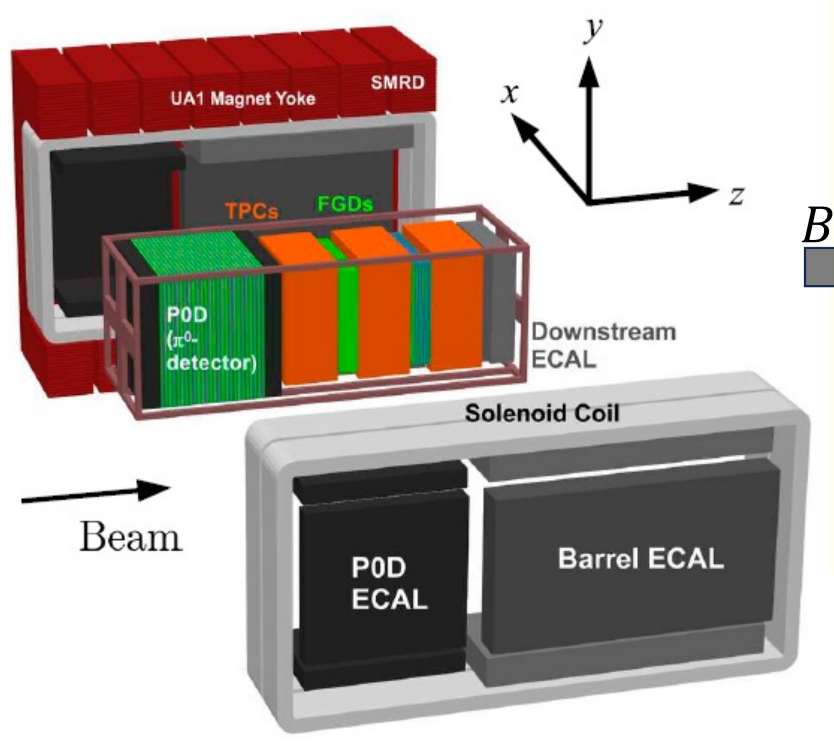
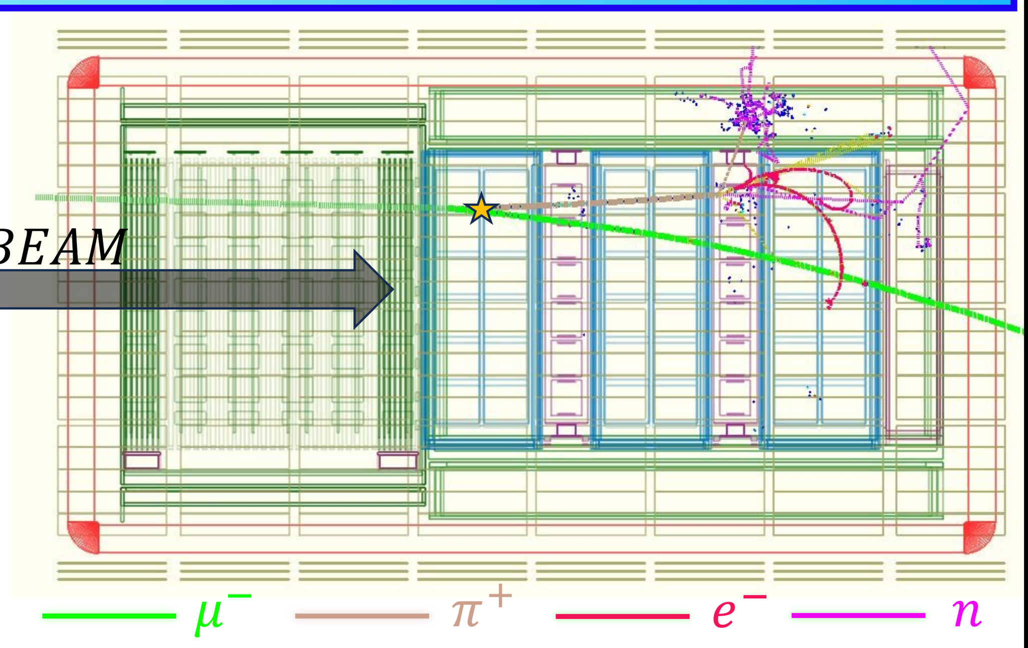
## Motivation

Update of the “Search for Heavy Neutral Leptons (HNLs) in T2K” analysis [1]:

- Including $\pi^\pm$ decays to HNLs (in [1] only $K^\pm$ decays);
- Including additional HNLs decay channels;
- Updated tracking & signal and backgrounds selection methods;

## ND280 detector (2010-2022 configuration)




Typical event, HNL decay in TPC: $N \to \pi^+\mu^-$

- UA1 magnet – dipole magnetic field 0.2 T
- P0D – $\pi^0$ detector;
- **TPCs – Gaseous-Argon Time Projection Chambers;**
- FGDs – Fine Grained plastic-scintillator Detectors;
- ECAL – Electromagnetic Calorimeter;
- SMRD – Side Muon Range Detector, scintillator plates inside magnet yokes

## Analysis strategy

- Events in TPC gas considered. Significantly reduced background from light neutrino interactions.
- Source of HNLs ($N$): meson ($M^\pm = K^\pm, \pi^\pm$) decays: $M^\pm \to l_\alpha^\pm N$ ($\alpha = \mu, e$)
- $\nu_\alpha = \sum_{i=1}^{3} V_{\alpha i}^{PMNS}\nu_i + \sum_{I=1}^{n}\Theta_{\alpha I}N_I$ ($\alpha = e, \mu, \tau$)
- $M^\pm \to l_\alpha^\pm N_I,\ BR \sim |\Theta_{\alpha I}|^2$, HNL decays: e.g. $N_I \to l_\beta^\pm \pi^\mp,\ BR \sim |\Theta_{\beta I}|^2$
- Experiment is sensitive to $U_\alpha^2 U_\beta^2$, where $|U_\alpha|^2 = \sum_{I=\{2,3\}}|\Theta_{\alpha I}|^2$
- Start from standard $\nu$ flux and apply event-by-event weighting, kinematics modification to account for HNL
- HNL decays simulated at random points along trajectories in TPCs
- Required 2 opposite charge tracks in TPC, further kinematic cuts: invariant mass, angle between 2 tracks, incoming HNL polar angle; veto activity in upstream detectors
- Systematic uncertainties: signal flux prediction ($\approx$ 15%), detector systematics (example: TPC tracking, PID, angle resolution; overall effect $\approx$ 5%)

## Background sources

Dominant contribution is light $\nu$ interactions in TPC gas:

$$\nu_\mu + Ar \to \mu^- + \pi^+ + Ar$$

Two control samples to constrain background with data measurements:

- Signal-like events with inverted kinematic cut on polar angle to constrain resonant pion production, quasi-elastic processes on argon;
- Interactions in TPC dead material to constrain photon conversions;

Background estimation done with the NEUT Monte-Carlo generator [2]

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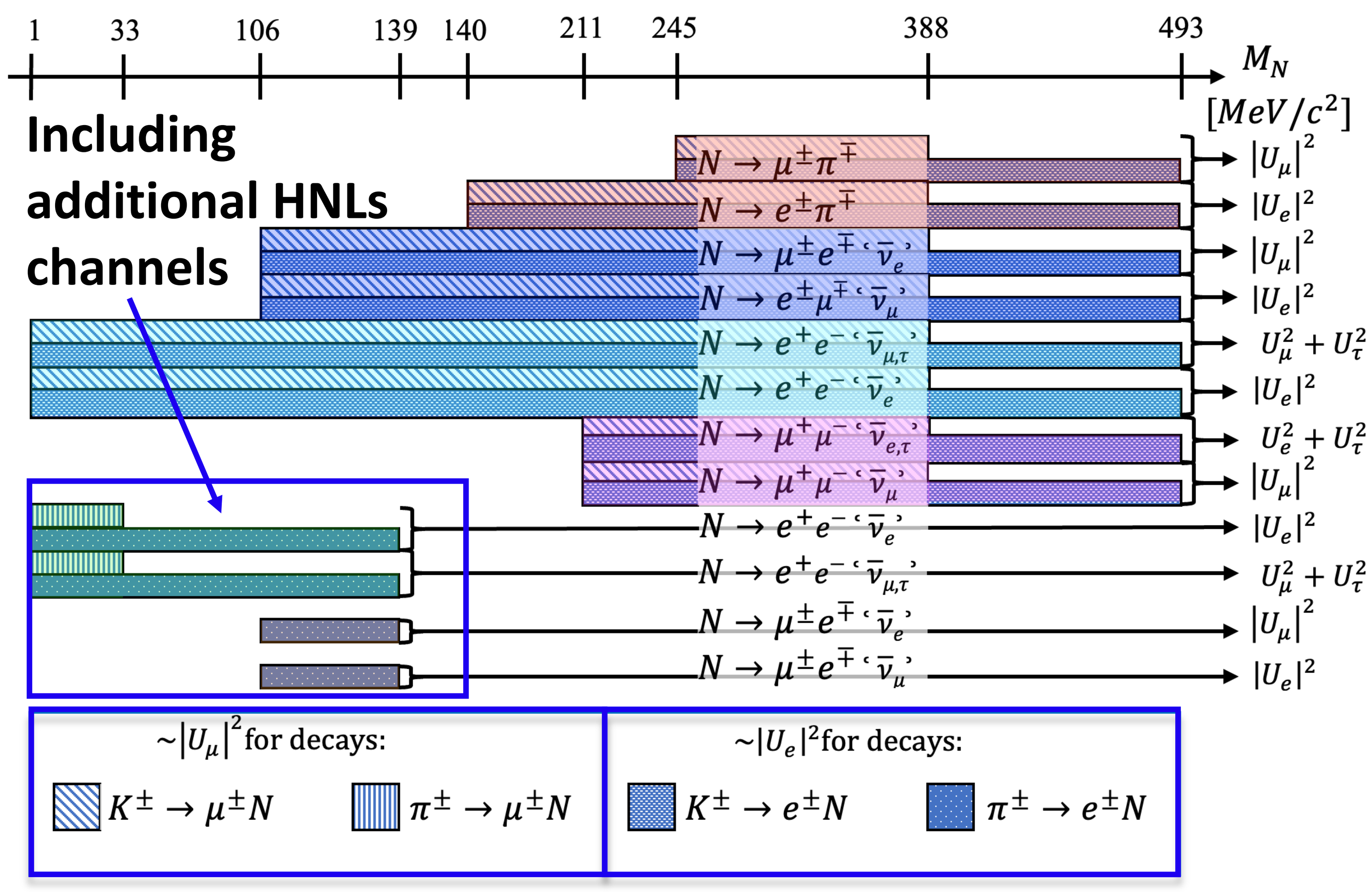



Schematic of production and decay modes included in analysis for HNL with $M_N < 493\ MeV/c^2$. Bars show allowed kinematic regions for each decay mode with the corresponding mixing element(s).

## Statistical analysis

All HNL production and decay modes are considered simultaneously.
For channel $A$ the contribution of mode $i$ is characterized by:

- expected number of decays $\Phi_i$ assuming $U_e^2 = U_\mu^2 = U_\tau^2 = 1$
- selection efficiency of decays in current channel, $\varepsilon_{A,i}$
- actual values of $U_{e,\mu,\tau}^2$ via the factor $f_i = U_\alpha^2 \sum U_{\beta_j}^2$

$\alpha, \beta_j \in \{e, \mu, \tau\}$, $\alpha$ – flavor in HNL production, $\beta_j$ – flavors in HNL decay

Expected number of events $N_A$ in channel $A$ (with background $B_A$):

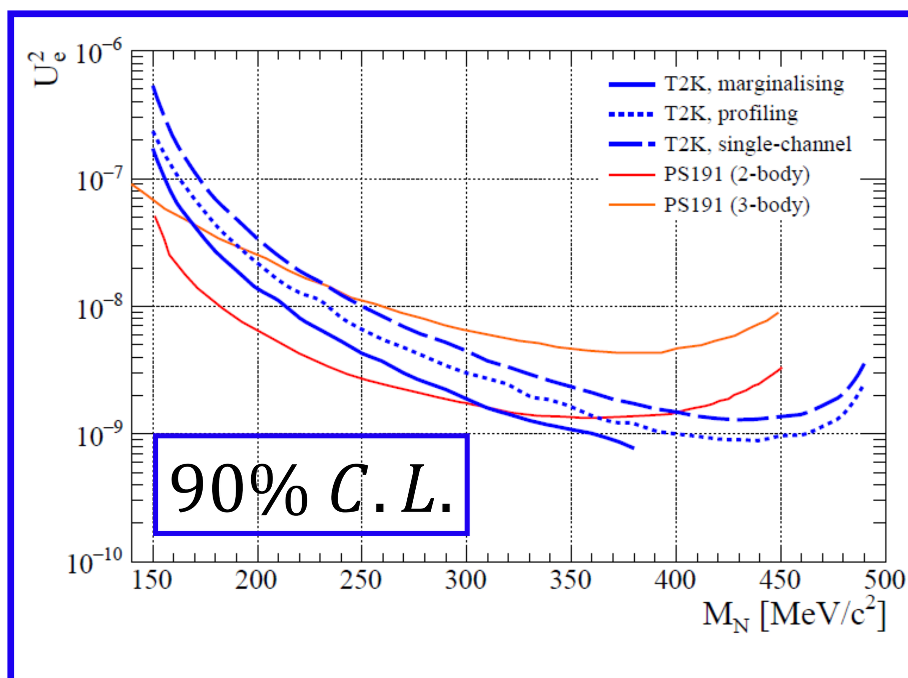
$$N_A = B_A + \sum_i \varepsilon_{A,i} \times f_i(U_e^2, U_\mu^2, U_\tau^2) \times \Phi_i$$

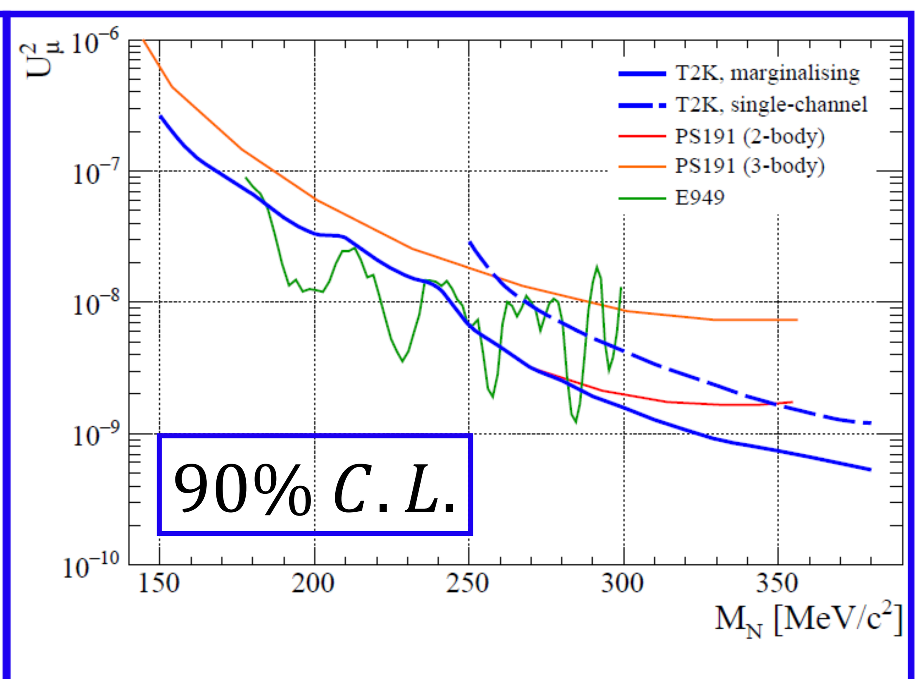
Bayesian approach. Likelihood for observed number of events $n_A^{obs}$

$$L = \prod_A Poisson\ (n_A^{obs}, N_A)$$

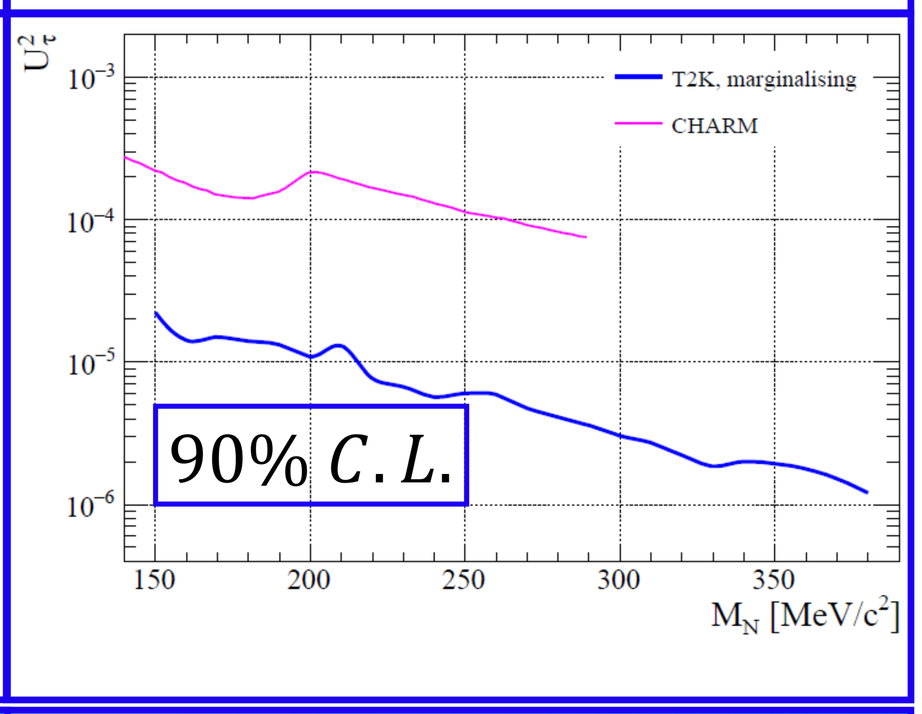
PyMC Markov Chain method used for integration.
90% domains are defined by profiling/marginalizing over other mixing elements.

## Results (of the original analysis [1])




90% upper limits on mixing elements as a function of HNL mass.
Blue dashed lines – single-channel approach (one single HNL production and decay mode considered at a time)
Blue solid lines – after marginalization over other mixing elements.
Top left plot: blue dotted line – profiling used ($U_\mu^2 = U_\tau^2 = 0$).
Limits compared to PS191 [3], E949 [4], CHARM [5]. Results still competitive [6]




## References

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