Search for heavy neutrinos using T2K near detector ND280

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Physics motivation

New physics beyond SM:

- $m_\nu \neq 0$
- Baryon asymmetry of the Universe
- Dark Matter

νMSM-model [1,2]:

- 3 right-handed neutrinos $N_I, I = \{1,2,3\}$
- ν & N_I – Majorana particles
- $m_{N_1} \sim keV$ could be dark matter
- $m_{N_{2,3}} \sim MeV - GeV$ could generate baryogenesis

Left-handed flavor eigenstates as combination of light (ν_i) and heavy (N_I) mass eigenstates:

$$\nu_\alpha = \sum_{i=1}^{3} V_{\alpha i}^{PMNS} \nu_i + \sum_{I=1}^{n} \Theta_{\alpha I} N_I \ \ (\alpha = e, \mu, \tau;\ i = 1,2,3;\ \ I = 1,2,3)$$

- Assuming $M_2 \sim M_3 \equiv M_N$, $|U_\alpha|^2 = \sum_{I=\{2,3\}} |\Theta_{\alpha I}|^2$

Heavy Neutral Leptons (HNLs) or heavy neutrinos

HNL search methods:

Study meson decay ($H^\pm \to l_\alpha^\pm N$) kinematics

↓

Used in E949, NA62, etc.

↓

Sensitive to U_α^2

Search for ***HNL*** decays in a detector, study ***daughter kinematics***

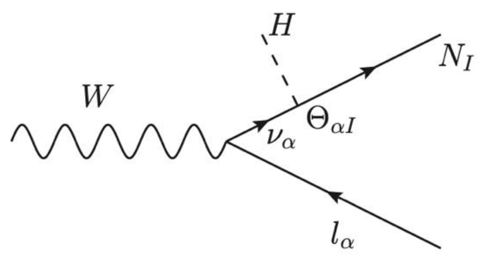
↓

CERN-PS-191; ***can probe in neutrino experiments***

↓

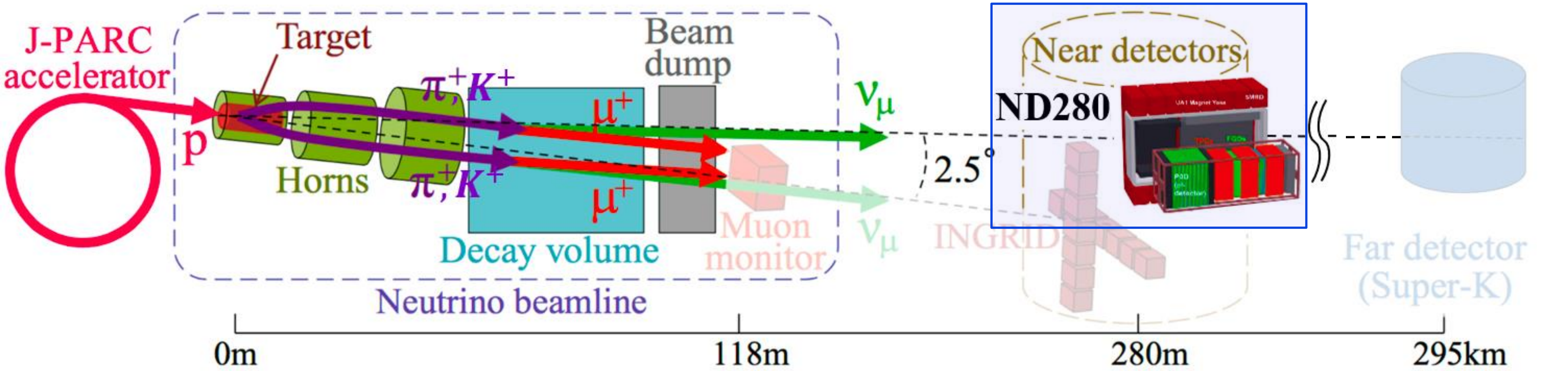
Sensitive to $\boldsymbol{U_\alpha^2 U_\beta^2}$

Feynman representation of HNL contributions

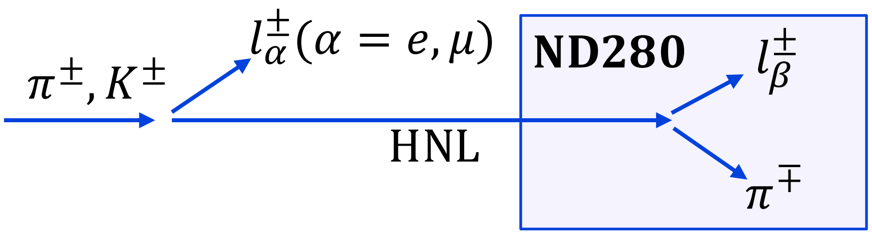


1. T. Asaka, M. Shaposhnikov. "The nuMSM, dark matter and baryon asymmetry of the universe". In: Phys. Lett. B620 (2005), pp. 17–26
2. T. Asaka, S. Blanchet, M. Shaposhnikov. "The nuMSM, dark matter and neutrino masses". In: Phys. Lett. B631 (2005), pp. 151–156.

T2K experiment

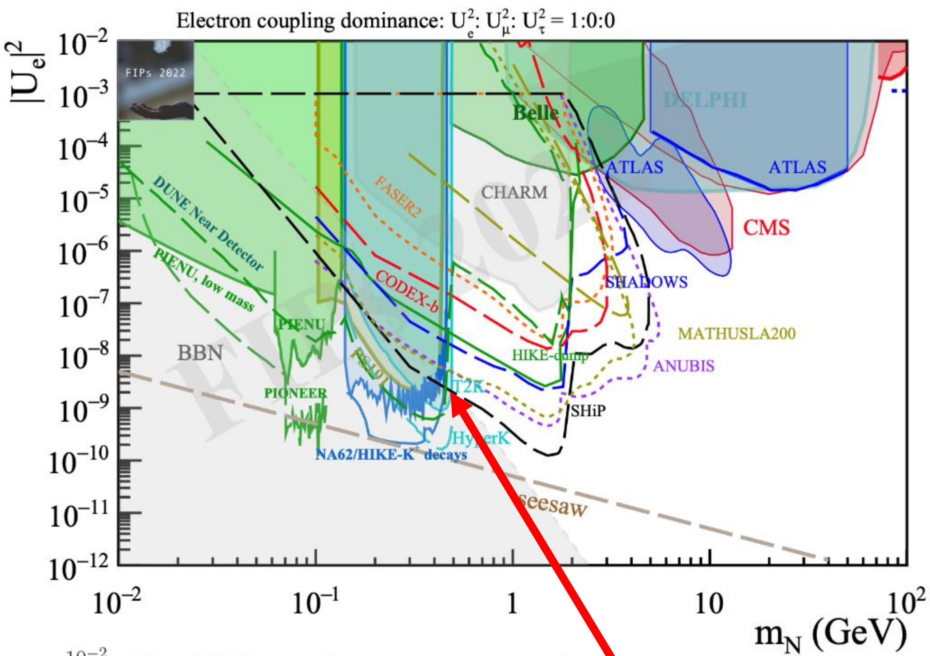


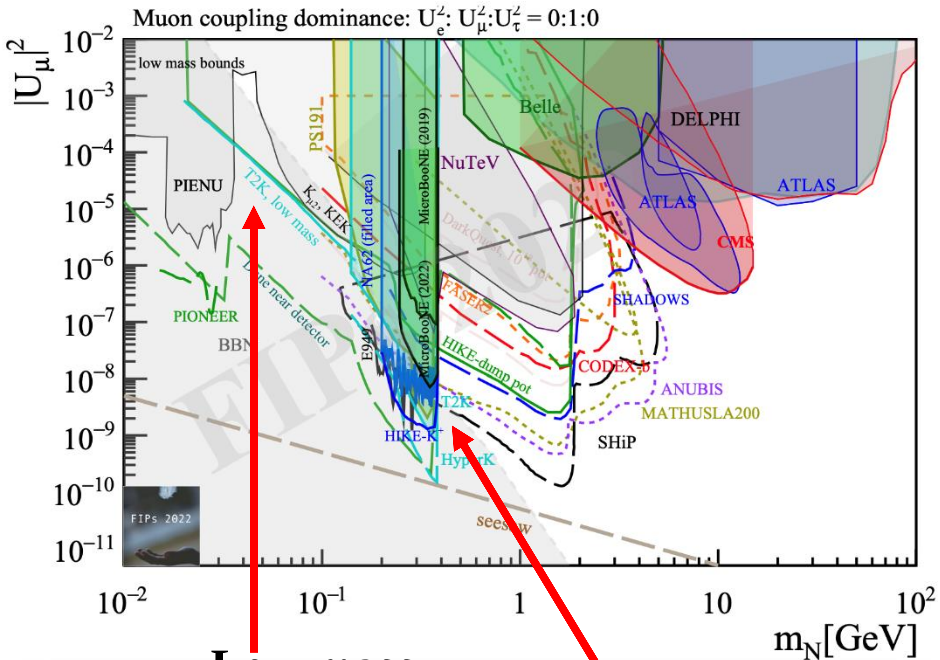
- Tokai-to-Kamioka (T2K) [3] – long-baseline neutrino experiment in Japan
  Main goal – study ν oscillations, search for lepton CP violation.
- Accelerator experiment based on 30 GeV proton beam @ J-PARC
- Neutrino beam from π and K mesons decays
- π and K mesons focused with magnetic horns for $\nu_\mu(\overline{\nu_\mu})$ - enhanced beam.
- Probe HNLs with T2K ND280:



3. K. Abe et al. (T2K), Nucl. Instrum. Meth. A659, 106 (2011), arXiv:1106.1238 [physics.ins-det].

Current constraints on mixing elements





T2K results (2019)

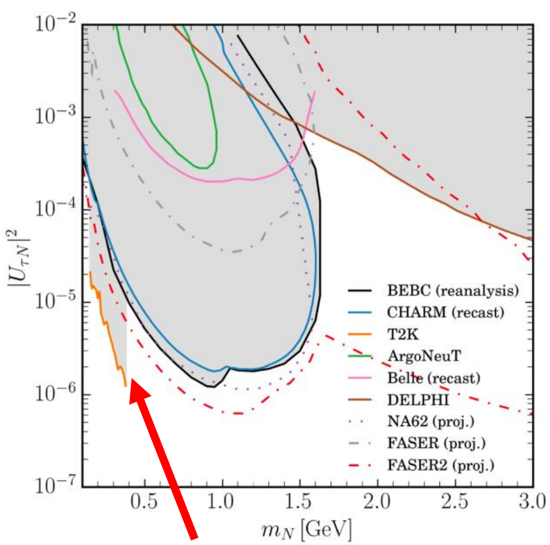
Low mass projections

T2K results (2019)

Current bounds and future projections for 90% CL limits [4]

Filled colored areas - bounds set by experimental collaborations

- T2K limits ***still competitive***



T2K results (2019)

Example:

Meson decay: $K^+ \to e^+ N_I,\ BR\sim|\Theta_{eI}|^2$

HNL decay: $N_I \to \mu^\pm \pi^\mp,\ BR\sim|\Theta_{\mu I}|^2$

Sensitive to $U_e^2 U_\mu^2$

4. Antel, C., Battaglieri, M., Beacham, J. et al. Feebly-interacting particles: FIPs 2022 Workshop Report. Eur. Phys. J. C **83**, 1122 (2023)

Motivation for new analysis

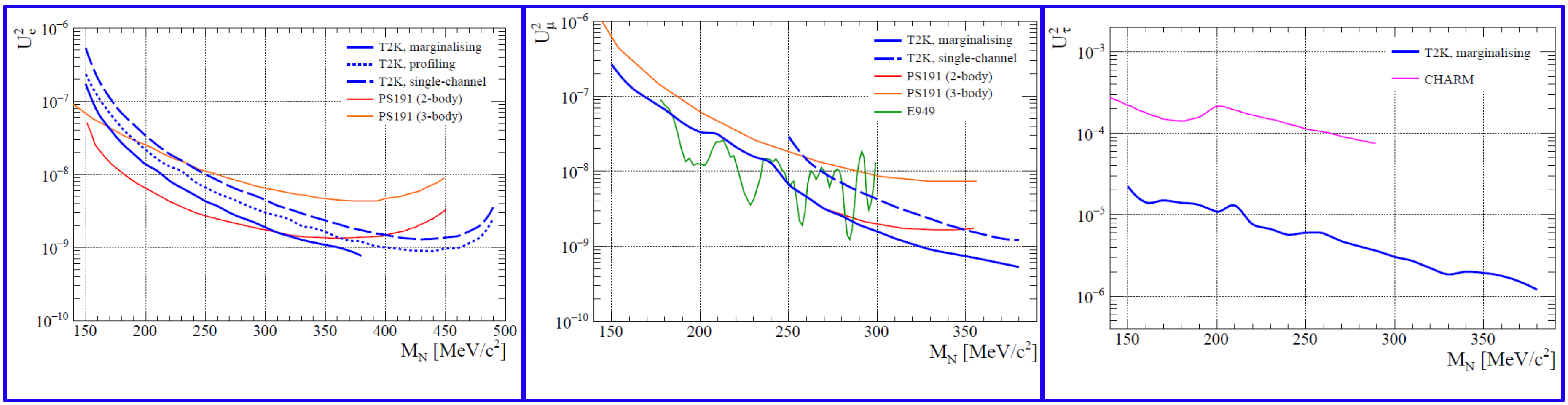
<u>Search for HNL ***in 2019***</u> [5]:

- $K^{\pm} \rightarrow l_{\alpha}^{\pm} N \;\; (\alpha = e, \mu)$
- K^{+} in ν-mode and K^{-} in $\bar{\nu}$-mode

<u>***New*** search for HNL</u>:

- $H^{\pm} \rightarrow l_{\alpha}^{\pm} N \;\; (\boldsymbol{H = K, \pi};\;\; \alpha = e, \mu)$
- $\boldsymbol{H^{\pm}}$ $(\boldsymbol{H = K, \pi})$ in ν and $\bar{\nu}$ beam modes
- ***Updated*** tracking, signal and background
- ***Additional statistics*** available

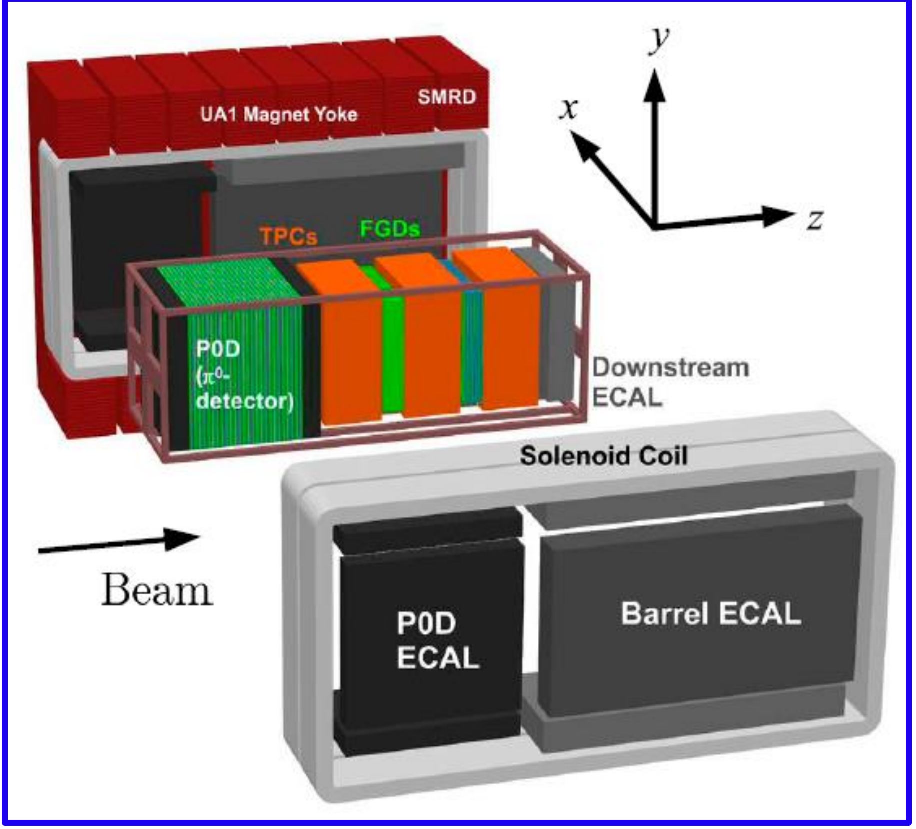
T2K results obtained in 2019 [5]

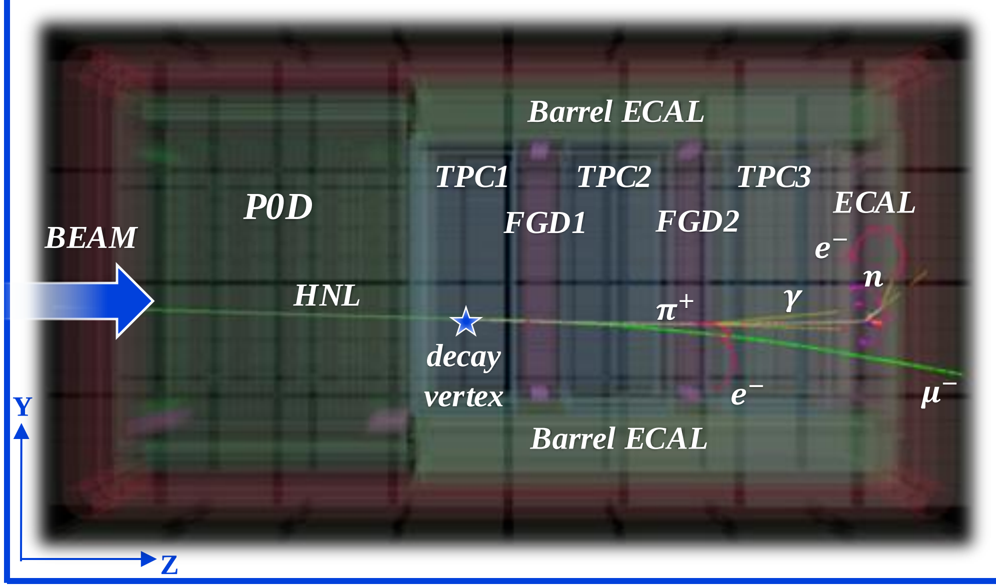


90% upper limits on $|U_{\alpha}|$ as function of M_{HNL}

5. Abe, Koji, et al. Physical Review D, 100.5 (2019): 052006

ND280 and HNL typical event





Example of simulated HNL decay in ND280

- UA1 magnet – dipole magnetic field 0.2 T
- P0D – π^0 detector
- ECAL – Electromagnetic Calorimeter

- **TPCs – Gaseous-Argon Time Projection Chambers**
- FGDs – Fine Grained plastic-scintillator Detectors
- SMRD – Side Muon Range Detector,

  scintillator plates inside magnet yokes

TPC Fiducial Volume: no walls, no cathode
Margin of 59 mm upstream and 150 mm downstream

HNL search in ND280

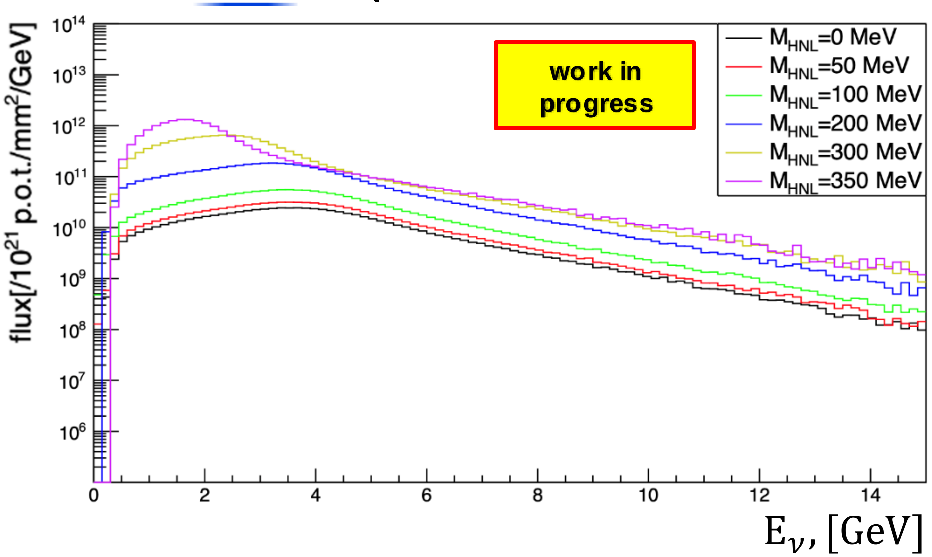
- ***Events in TPC gas*** to reduce background from ν interactions
- Study decays: $H^{\pm} \to l_{\alpha}^{\pm} N \ \ (H = K, \pi; \ \ \alpha = e, \mu)$

$$N \to \mu^{\pm}\pi^{\mp}, N \to e^{\pm}\pi^{\mp}, N \to e^{+}e^{-}\nu, N \to \mu^{+}\mu^{-}\nu, \mathrm{N} \to \mathrm{e}^{\pm}\mu^{\mp}\nu$$

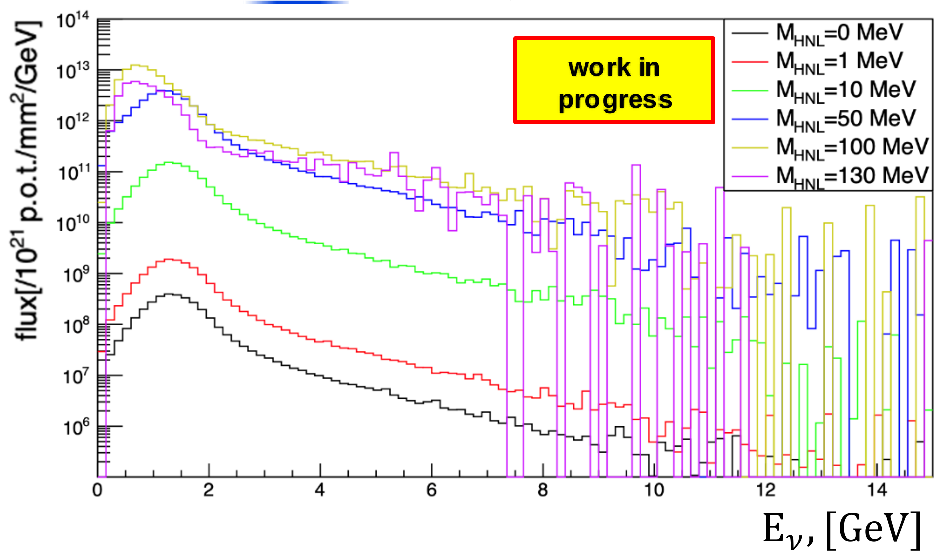
- Signal topology: 2 close opposite charged tracks starting in same TPC fiducial volume
- Applying veto, PID and kinematic selection criteria

HNL flux at ND280 front plane

$K^{+} \to \mu^{+}N, \nu$-beam mode

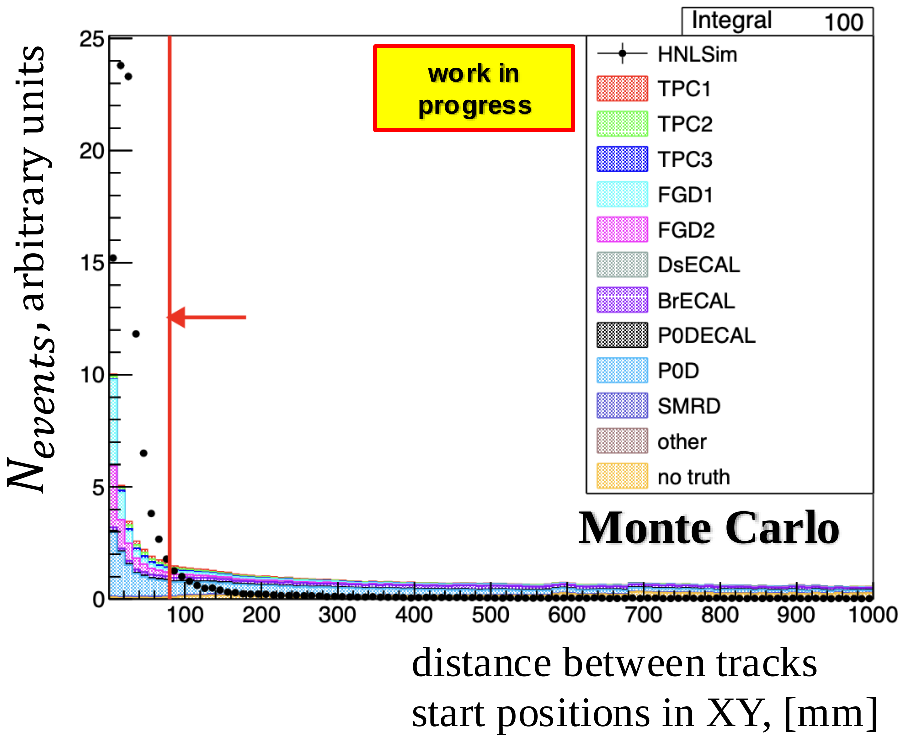


$\pi^{+} \to e^{+}N, \nu$-beam mode



assume $|U_e| = |U_\mu| = 1$

Selection criteria examples

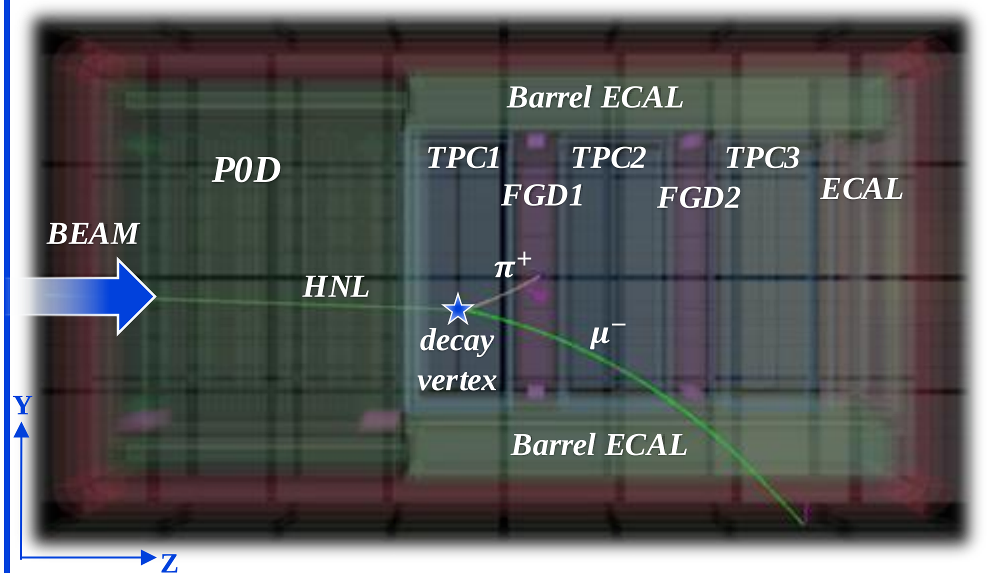


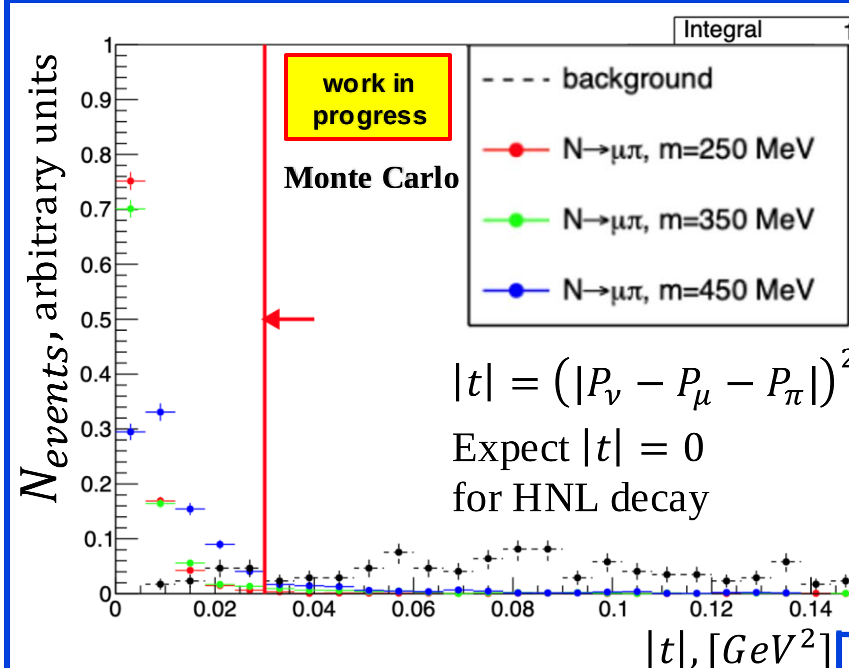
- Starting positions < 80 mm in XY plane

- Reconstructed vertex in TPC Fiducial Volume

Monte Carlo simulation:

- ➢ Background – **colored** histogram
- ➢ Signal – **black** dots



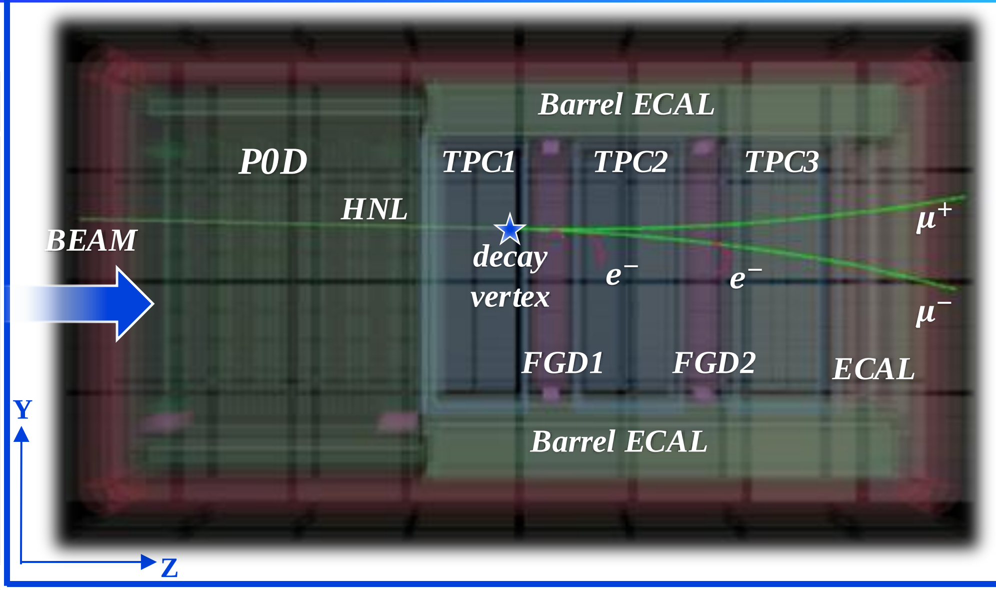


Systematics

- **Detector systematics:**

HNL decay mode	$N \to e^- \pi^+$	$N \to \mu^- \mu^+ \nu$	$N \to e^- e^+ \nu$	$N \to e^- \mu^+ \nu$
M_N, MeV	250	350	105	130
B field distortion	0.27%	0.27%	0.09%	0.09%
Momentum scale	0.06%	0.03%	0.04%	0.14%
Momentum resolution	0.45%	0.34%	0.49%	0.28%
TPC PID	0.92%	0.75%	1.41%	0.9%
ECal EM resolution	-	0.78%	-	-
ECal EM scale	-	0.42%	-	-
Position resolution	0.14%	0.22%	0.94%	0.12%
Parent decay	0.03%	-	-	0.02%
Charge identification efficiency	0.11%	0.04%	0.1%	0.03%
TPC cluster efficiency	0.0005%	0.00057%	0.00034%	0.00079%
TPC track efficiency	0.38%	0.16%	0.23%	0.35%
TPC-FGD match efficiency	0.04%	0.02%	0.03%	0.03%
Pion secondary interactions	2.21%	-	-	-
TPC-ECAL match efficiency	-	1.26%	-	-
ECAL PID	-	3.96%	-	-
All	2.49%	4.34%	1.79%	1.03%

preliminary



- **Flux systematics (*preliminary*):**

20% for $K^{\pm}$ and 10% for $\pi^{\pm}$ [6]

ECAL used only for $N \to \mu^+ \mu^- \nu$

ECAL related:

- TPC-ECAL match efficiency
- ECAL PID
- EM Energy resolution and scale

TPC related:

- Magnetic field distortions
- Momentum resolution and scale
- TPC PID
- Charge confusion
- Cluster efficiency
- Track efficiency
- TPC-FGD match efficiency
- Pion Secondary Interactions

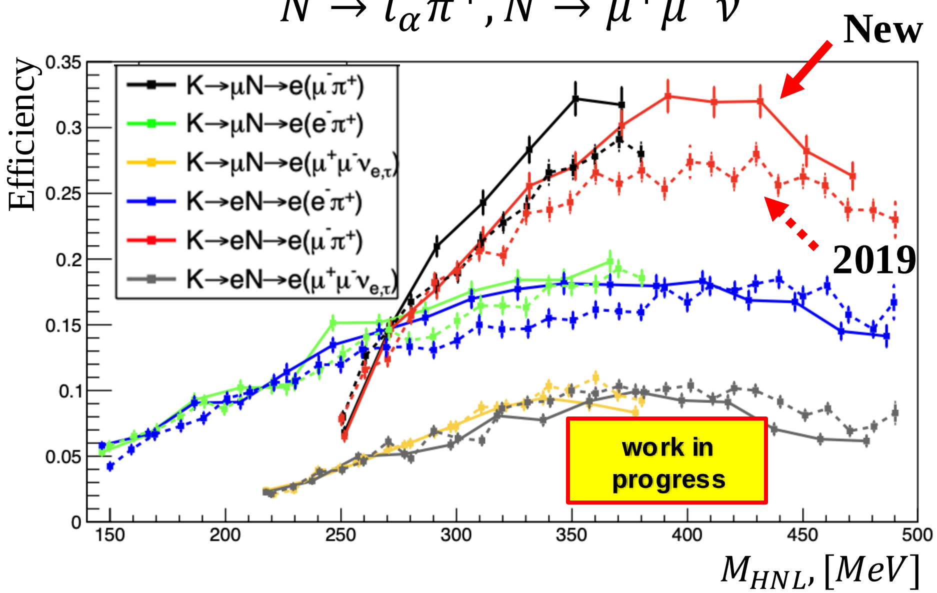
Specific for the analysis:

- Position resolution
- Parent decay

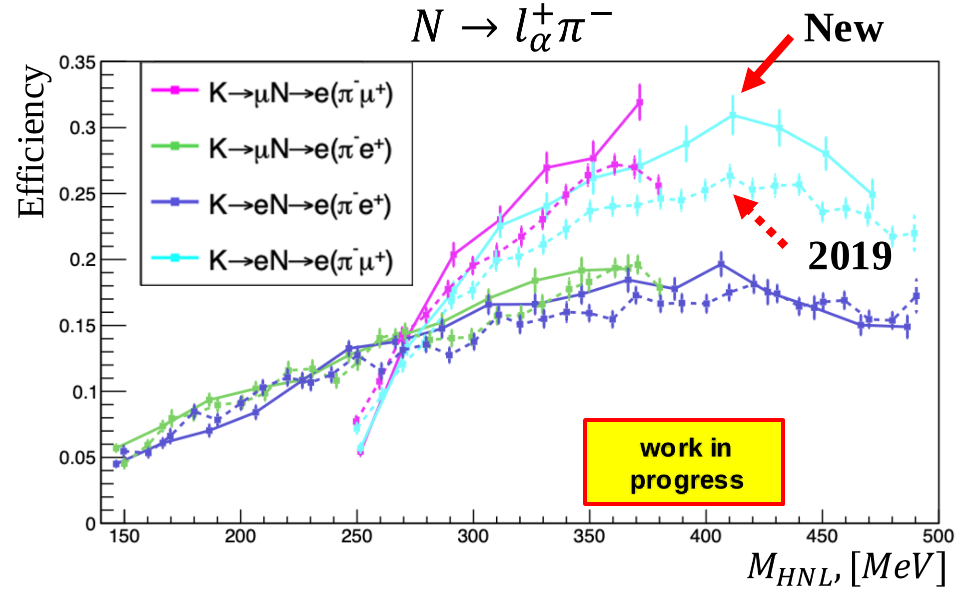
6. K. Abe, et. al. "Improved constraints on neutrino mixing from the T2K experiment with 3.13×10^{21} protons on target". Physical review D 103, 112008 (2021)

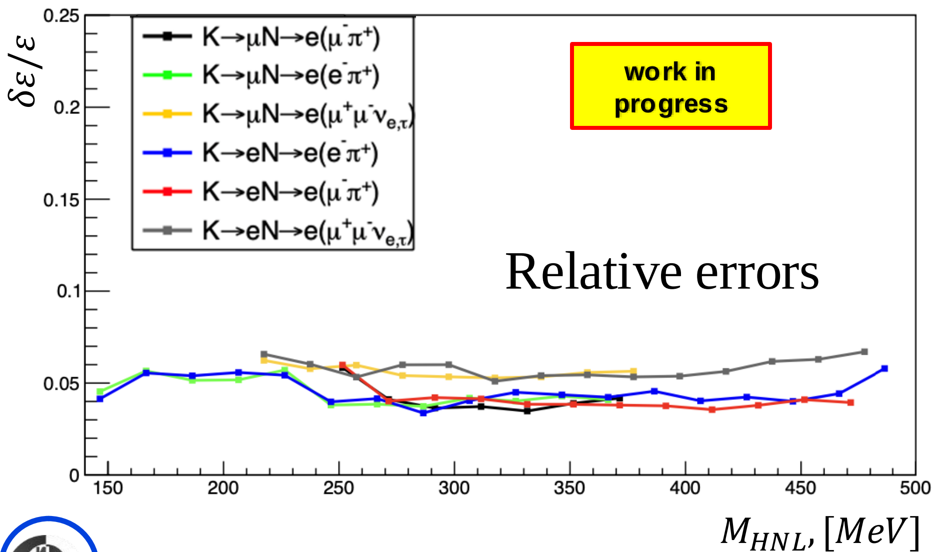
Efficiency: new analysis (solid lines) vs 2019 [5] (dashed)

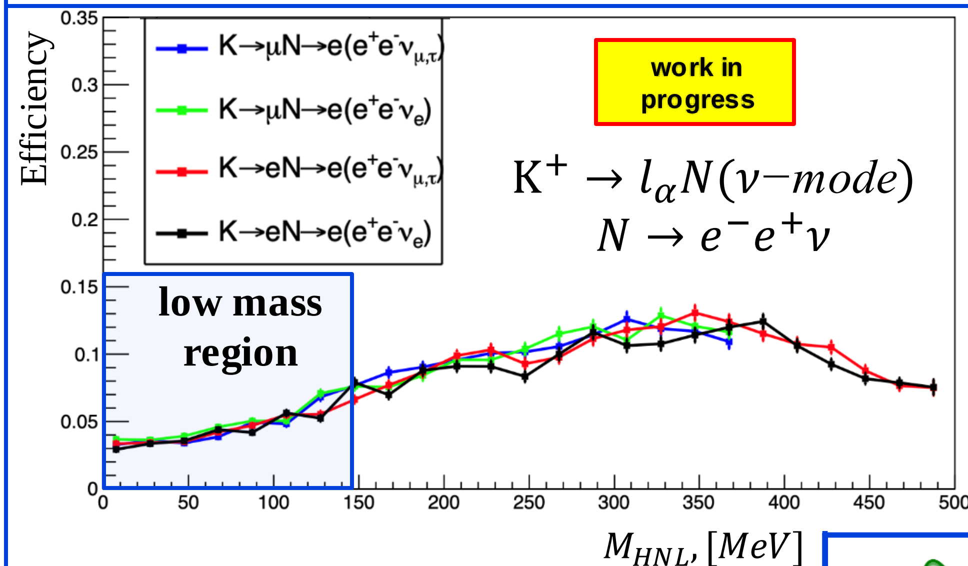
$$K^+ \to l_\alpha^+ N(\nu\text{-mode})$$
$$N \to l_\alpha^- \pi^+, N \to \mu^+\mu^-\nu$$



$$K^+ \to l_\alpha^+ N(\nu\text{-mode})$$
$$N \to l_\alpha^+ \pi^-$$







Background

Dominant contribution (for N $\rightarrow \mu^{\pm}\pi^{\mp}$ and N $\rightarrow \mu^{+}\mu^{-}$) is

neutrino-induced coherent pion production on argon nuclei in TPC gas:

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

- Light neutrino interactions estimation with NEUT Monte-Carlo generator [7]
- Constraints with real data via control samples
- Control samples:

1. Inverted polar angle → resonant π production, quasi-elastic processes on Ar
2. Events in TPC dead material → γ conversions

Expected background *in 2019* analysis [5]

Mode	Ch.	Expected background	Uncertainties total
neutrino	$\mu^{\pm}\pi^{\mp}$	1.543	0.516
	$e^{-}\pi^{+}$	0.376	0.259
	$e^{+}\pi^{-}$	0.328	0.250
	$\mu^{+}\mu^{-}$	0.216	0.133
	$e^{+}e^{-}$	0.563	0.233
anti-neutrino	$\mu^{\pm}\pi^{\mp}$	0.384	0.202
	$e^{-}\pi^{+}$	0.018	0.020
	$e^{+}\pi^{-}$	0.219	0.243
	$\mu^{+}\mu^{-}$	0.038	0.040
	$e^{+}e^{-}$	0.015	0.016

Total exposure (protons-on-target): 12.34×10^{20} in ν-mode, 6.29×10^{20} in $\bar{\nu}$-mode

7. Hayato, Y., Pickering, L., et. al. “The NEUT neutrino interaction simulation program library”. Eur. Phys. J. Spec. Top. 230, 4469–4481 (2021)

Conclusion

New search for heavy neutrinos in T2K ND280 ***in progress***:

- In 2019 T2K set still competitive limits in mass range $140 < m_N < 493\ MeV$

- New analysis based on **updated tracking** and extended to **low masses** $m_N < 140\ MeV$

Current status:

For $\pi^{\pm}$, $K^{\pm}$ decays to HNLs in ν- and $\bar{\nu}$-beam modes:

- **Selection criteria** reviewed
- Signal **efficiencies increased**
- Preliminary estimation of **systematics**

In progress:

- Background studies and constraints
- Updates to statistical framework

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Author is grateful for the contribution given by Yu. Kudenko and T2K collaboration members.

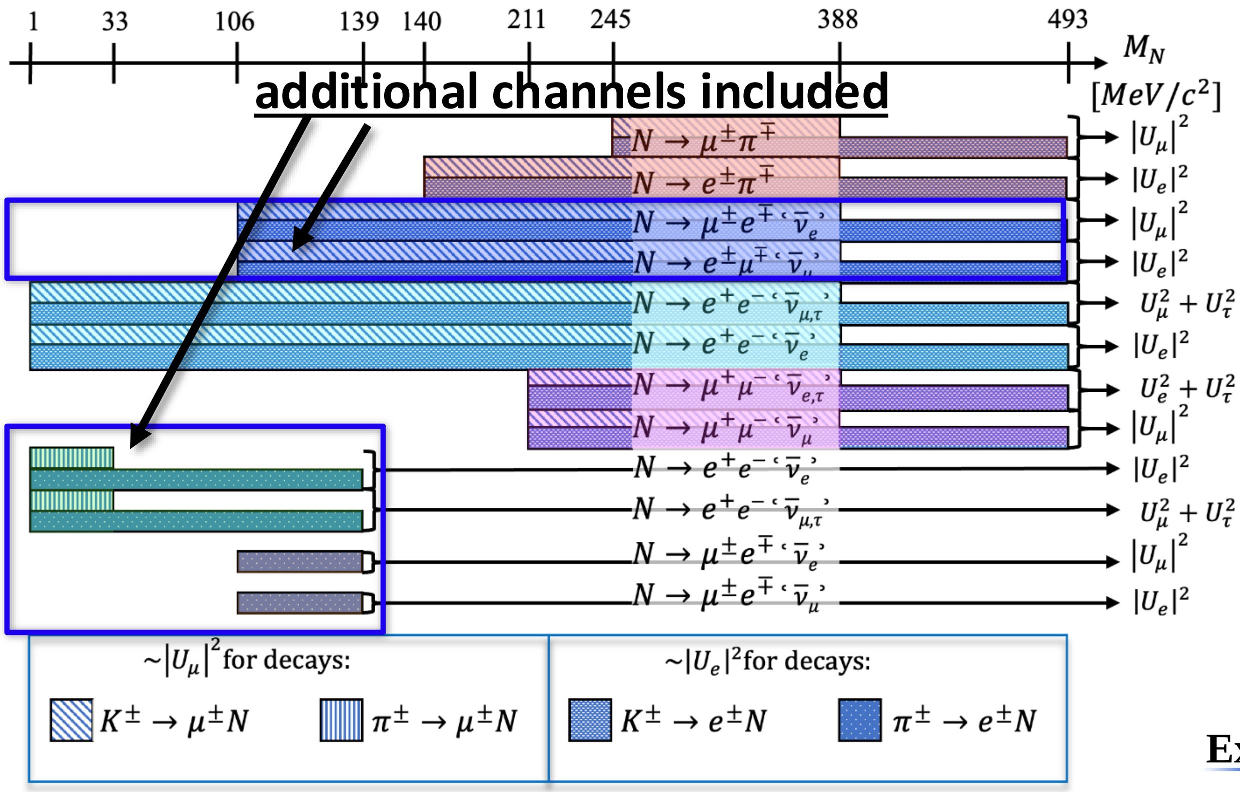
THANK YOU
FOR ATTENTION!

BACKUP

Heavy neutrino decays

HNLs decay through charged or neutral current.

Considered decay modes:



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).

- Assuming $M_2 \sim M_3 \equiv M_N$, hence experiment sensitive to $|U_\alpha|^2 = \sum_{I=\{2,3\}} |\Theta_{\alpha I}|^2$
- Look for heavy neutrino decay after their production, study kinematics of daughter particles. Sensitive to $U_\alpha^2 U_\beta^2$

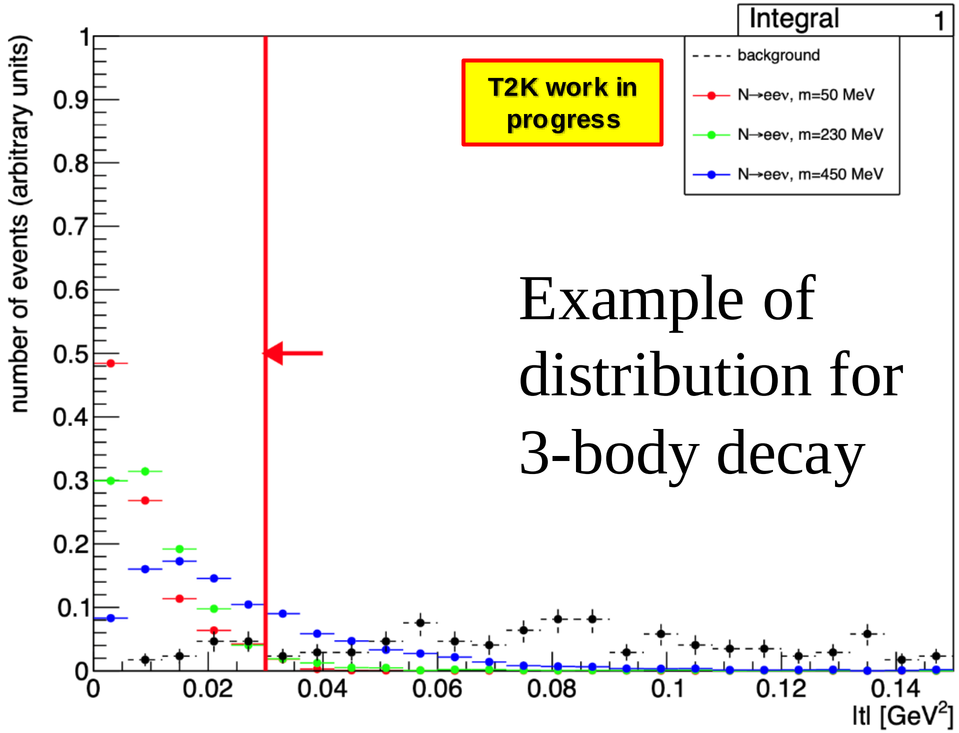
Example:

meson decays $H^\pm \to l_\alpha^\pm N_I,\ BR \sim |\Theta_{\alpha I}|^2$

HNL decays: $N_I \to l_\beta^\pm \pi^\mp,\ BR \sim |\Theta_{\beta I}|^2$

Experiment is sensitive to $U_\alpha^2 U_\beta^2$, where $|U_\alpha|^2 = \sum_{I=\{2,3\}} |\Theta_{\alpha I}|^2$

Selection criteria examples



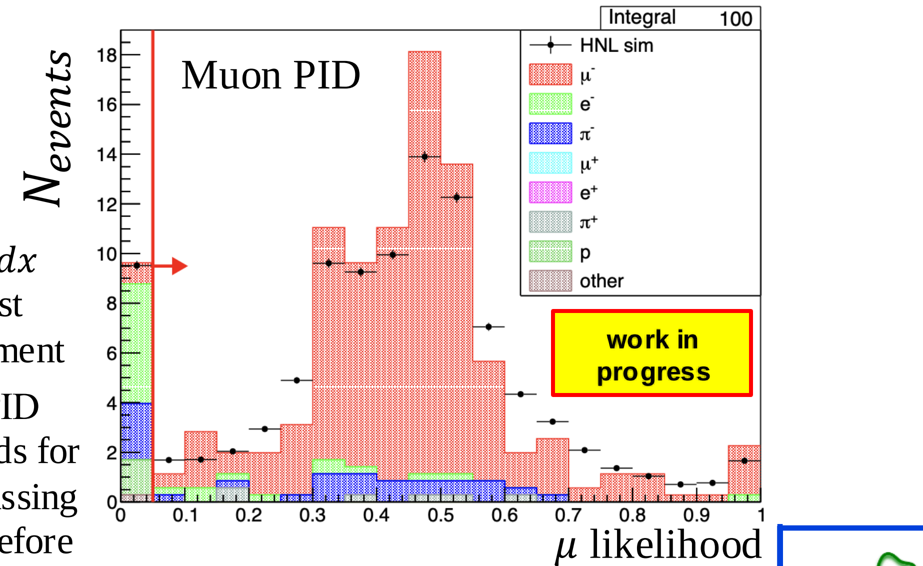
Example of kinematic cut:
4-momentum transfer

$$|t| = \left(|P_\nu - P_\mu - P_\pi|\right)^2$$

For HNL decay expect $|t| = 0$
as there no nucleus involved

Use dE/dx for longest TPC segment

Tracks' PID likelihoods for events passing all cuts before



Simulation strategy

- Start from standard ν flux, apply event-by-event weighting, kinematics modification:
    1. $m_\nu \neq m_N$, hence change kinematics of parent meson decay
    2. BR($K \rightarrow l_\alpha \nu_\alpha$) changed to BR($K \rightarrow l_\alpha N$) assuming $U_\alpha = 1$
- ***Events in TPC gas fiducial volume*** to reduce background from ν interactions
- HNL decays simulated randomly along trajectories in TPCs

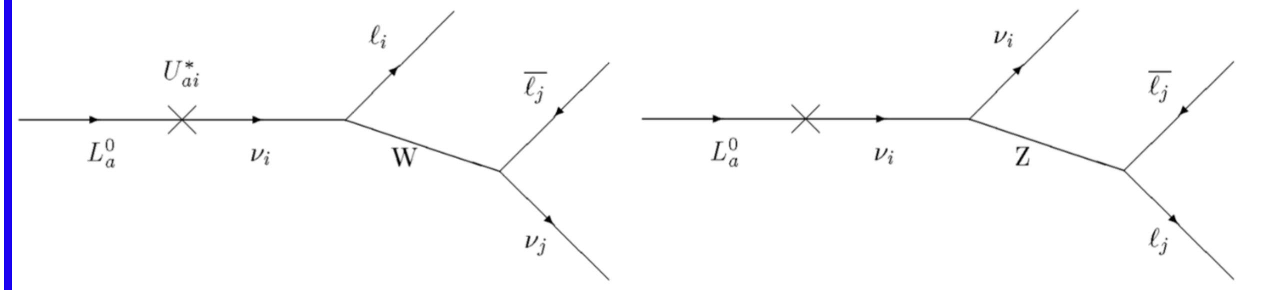
Fiducial Volume in TPCs:

	TPC 1	TPC 2	TPC 3
X	$[-870; -20]$ or $[20; 870]$		
Y	$[-930; 1030]$		
Z	$[-725; -162]$	$[634; 1197]$	$[1993; 2556]$

Unused Ar	$[-870, -20], [20, 870]$	$[-930, 1030]$	$[-784, -725]$	$[575, 634]$	$[1934, 1993]$

Constraints on $|U_\tau|$

$N \to \mu^+\mu^-\nu_\mu$ (NC, CC) and $N \to \mu^+\mu^-\nu_{e,\tau}$ (NC) modes:



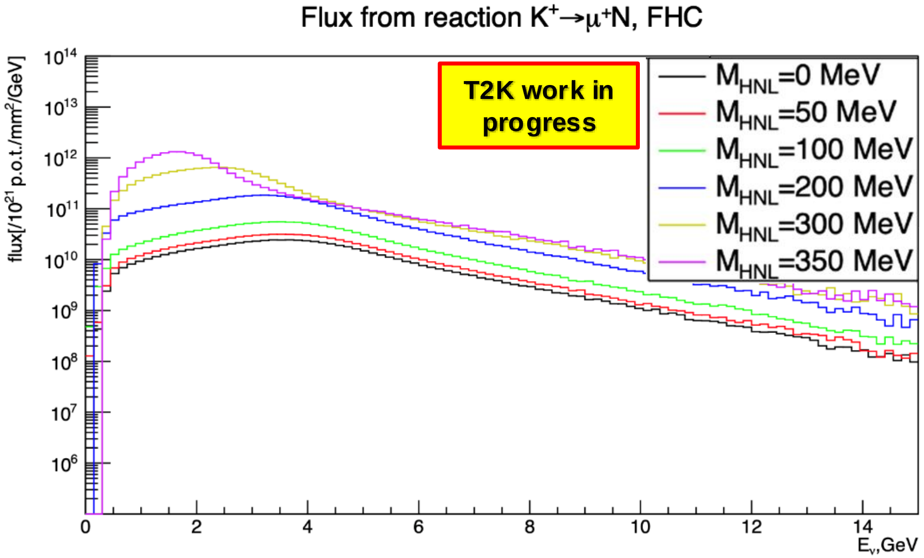
Feynman diagrams for HNL decay $N \to \mu\mu\nu$ via CC (left) an NC (right)

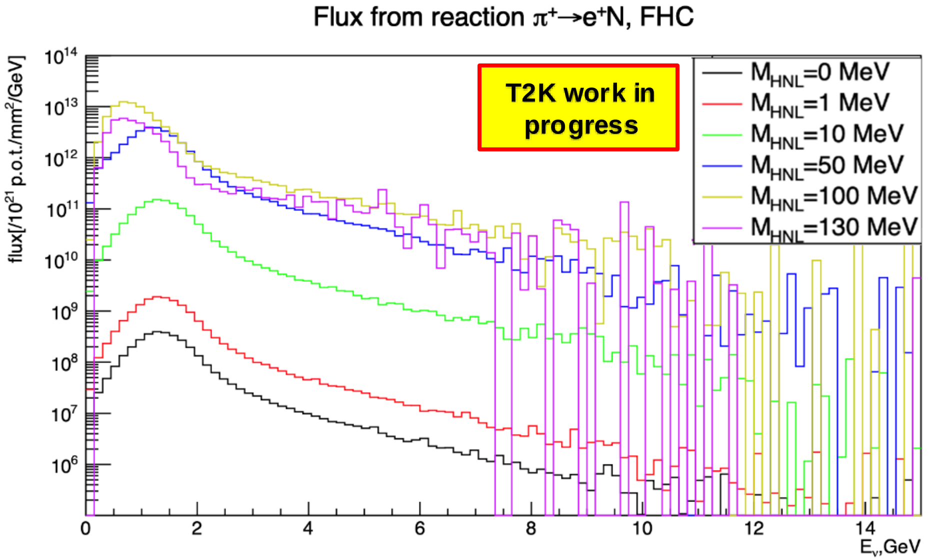
With NC any type of active neutrino can be produced $(\nu_e, \nu_\mu, \nu_\tau) \to$ sensitive to $|U_\tau|$,

e.g. $K \to eN, N \to \mu^+\mu^-\nu_{e,\tau}$ sensitive to $(U_e)^2(U_e^2 + U_\tau^2)$

Antel, C., Battaglieri, M., Beacham, J. *et al*. Feebly-interacting particles: FIPs 2022 Workshop Report. *Eur. Phys. J. C* **83**, 1122 (2023)

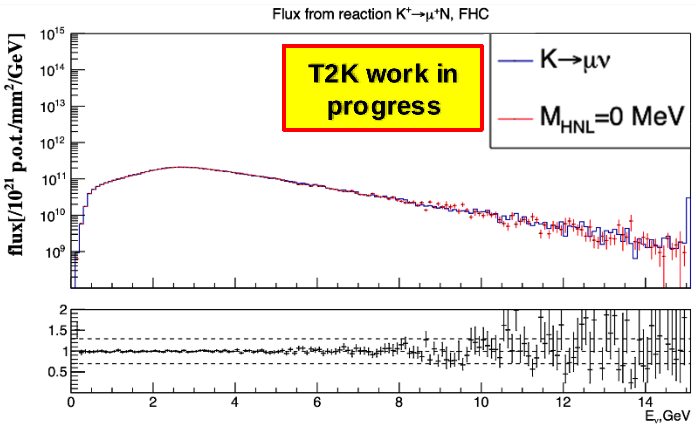
Heavy neutrino flux

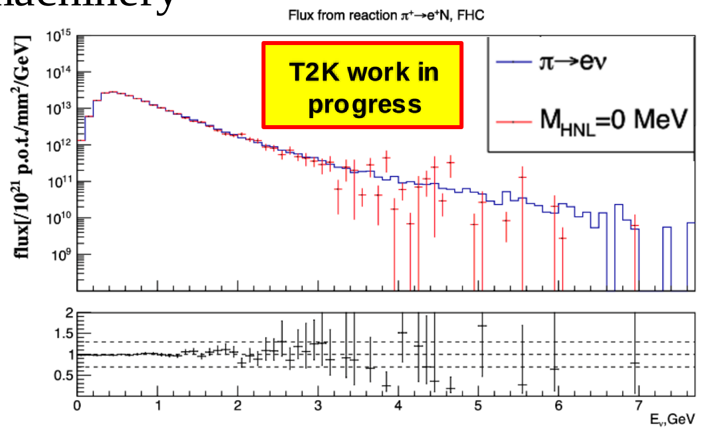




HNL flux at ND280 front plane for $K^+ \to \mu^+ N$ and $\pi^+ \to e^+ N$ modes for different HNL masses assuming $|U_e| = |U_\mu| = 1$

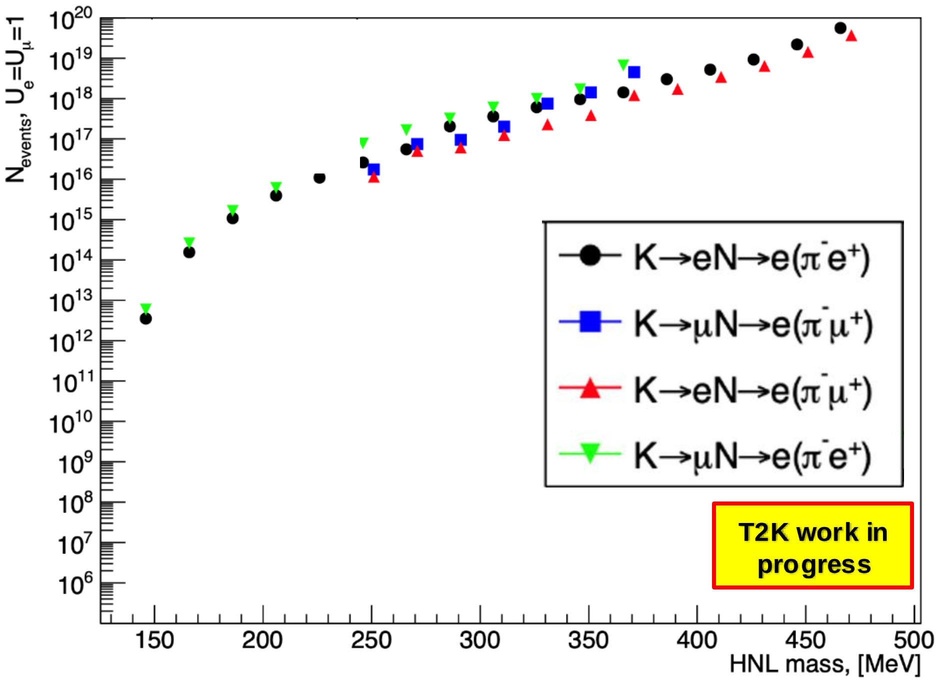
Cross check of weighting machinery

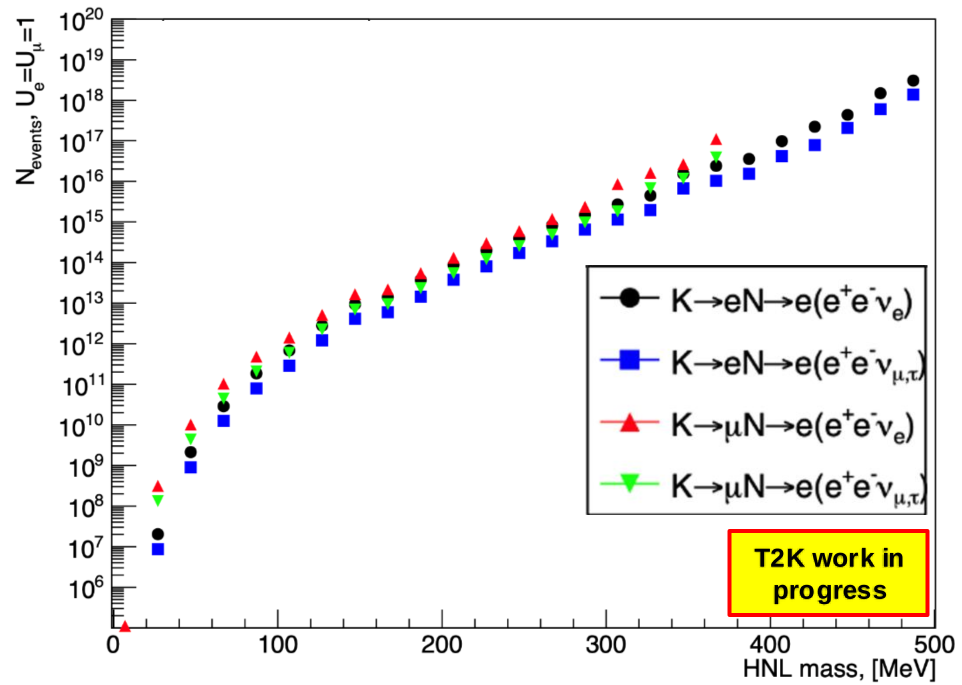




Comparison of HNL spectra for $M_{HNL} = 0\ MeV$ with active neutrino spectrum from $K^+ \to \mu^+ \nu$ and $\pi^+ \to e^+ \nu$ decays (assuming $|U_e| = |U_\mu| = 1$)

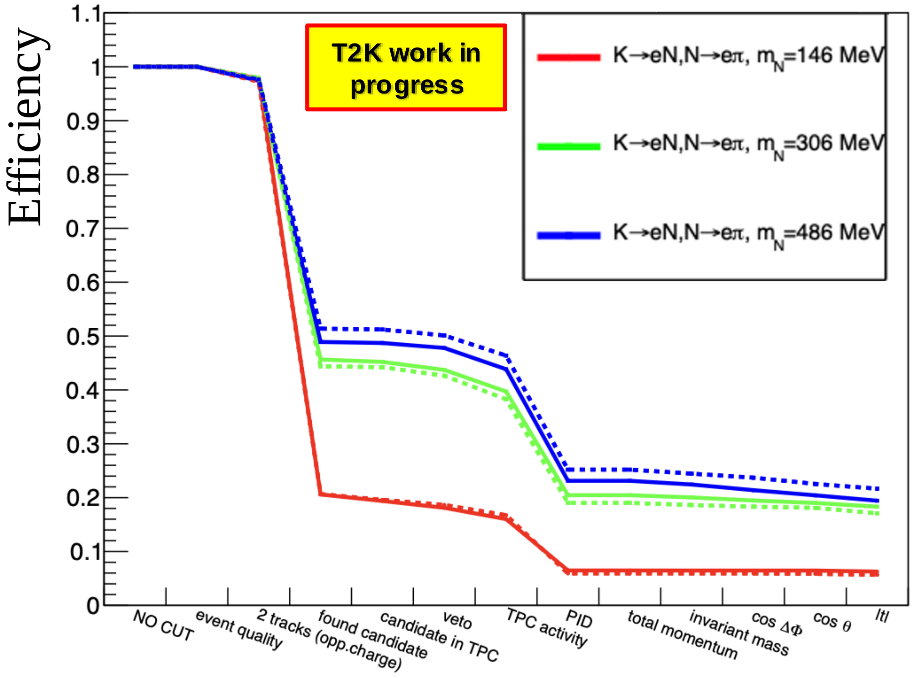
Number of decays in TPCs



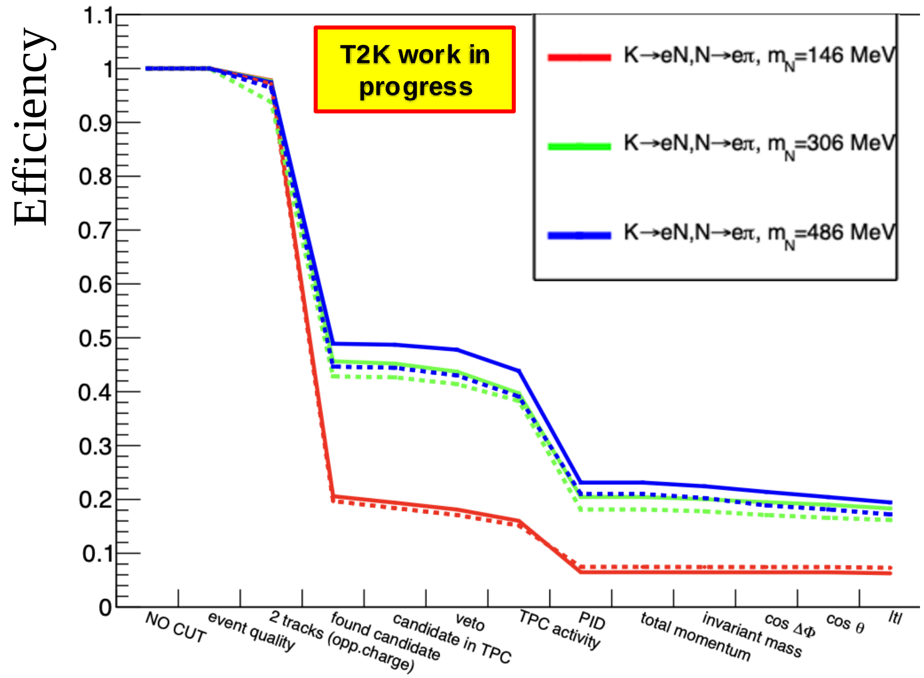


Number of decays in the TPCs for different production and decay modes as a function of heavy neutrino mass. It is given for FHC K^+ decay assuming $|U_e| = |U_\mu| = 1$ and scaled to 10^{21} POT

Efficiency vs selection criteria applied one-by-one

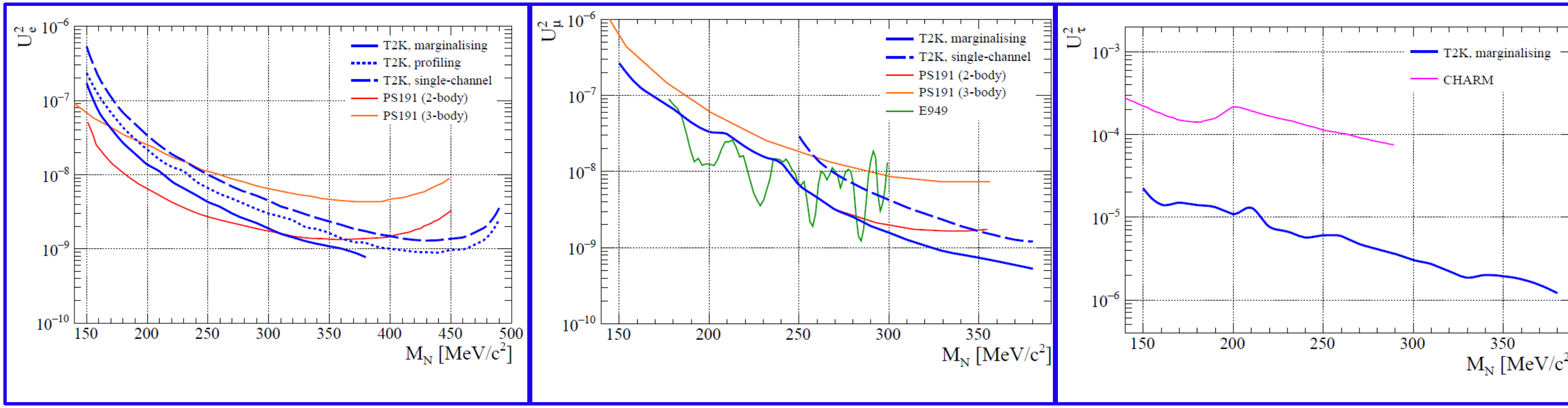


K^+, FHC (**solid**)
vs
K^-, RHC (**dashed**)



FHC, K^+ (**solid**)
vs
FHC, K^- (**dashed**)

2019 results



90% upper limits on mixing elements as a function of HNL mass.
“Combined” and “single-channel” approaches.

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, E949, CHARM. Figures taken from [*].

*Abe, Koji, et al. Physical Review D, 100.5 (2019): 052006

Expected sensitivity

U_α limits can be set with two approaches:

1. "Single-channel": each HNL production & decay mode independently

   For example, $\mu^\pm\pi^\mp$ channel can constrain:
   - U_μ^2 considering only $K^\pm \to \mu^\pm N, N \to \mu^\pm\pi^\mp$
   - or $U_e \times U_\mu$ considering only $K^\pm \to e^\pm N, N \to \mu^\pm\pi^\mp$

2. "Combined": all HNL production & decay modes simultaneously
   - limits on U_α $(\alpha = e, \mu, \tau)$ without assumptions about U_α hierarchy

Example:

- Using $N \to \mu\mu\nu$ mode, we can put a limit on $U_e\sqrt{U_e^2 + U_\tau^2}$ with assumption $U_\mu \ll U_e$, where contribution comes only from $K \to eN, N \to \mu^+\mu^-\nu_{e,\tau}$

- With "combined" approach we can put limits on each individual U_α $(\alpha = e, \mu, \tau)$ without assumptions about U_α hierarchy

Expected sensitivity

"Combined" approach:
For channel A the contribution of mode i is characterized by:

- expected number of decays Φ_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 $f_i = U_\alpha^2 \sum U_{\beta_j}^2$

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

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

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

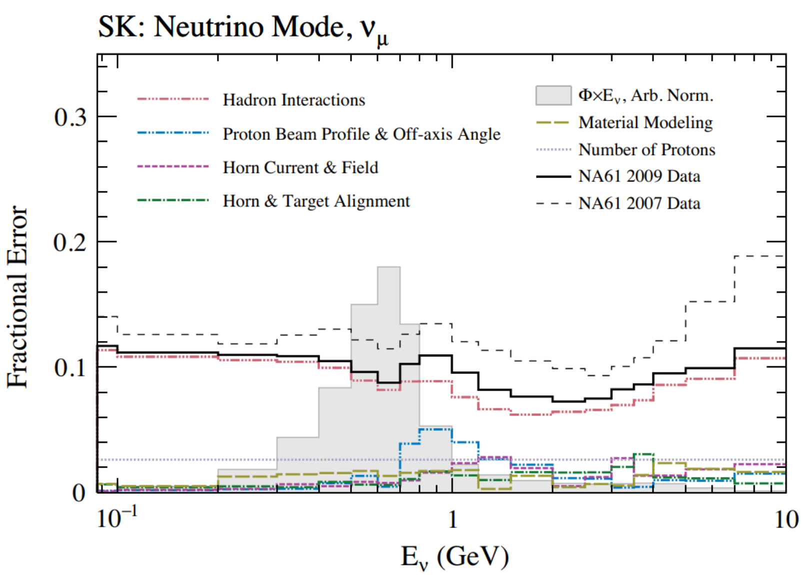
Bayesian approach. Likelihood for observed number of events n_A^{obs}

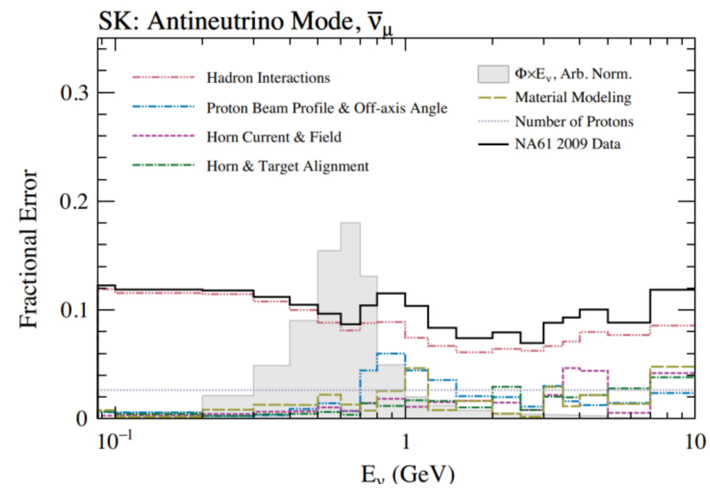
$$L = \prod_A Poisson\,(n_A^{obs}, N_A)$$

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

Flux systematics:

20% for $K^{\pm}$ and 10% for $\pi^{\pm}$ [*] **preliminary estimation!**





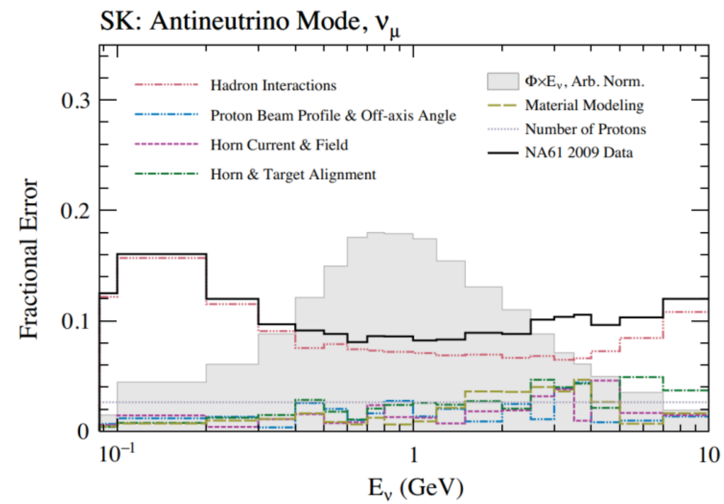


FIG. 2. The fractional systematic uncertainty on the ν_μ flux at SK in FHC mode (top), on the right-sign $\bar{\nu}_\mu$ flux at SK in RHC mode (middle), and on the wrong-sign ν_μ flux at SK in RHC mode (bottom). The solid black line shows the current total fractional uncertainty (NA61/SHINE 2009 data), while the dashed black line in the top panel shows the fractional uncertainty from an earlier flux prediction (NA61/SHINE 2007 data).

*K. Abe, et. al. "Improved constraints on neutrino mixing from the T2K experiment with 3.13 × 10^{21} protons on target". Physical review D 103, 112008 (2021)

Selection criteria

- Required 2 close opposite charge tracks in TPC with extrapolated vertex in TPC Fiducial Volume

- Veto cuts: no activity in detector upstream to TPC where decay occurred (e.g. FGD1 for TPC2)

- No additional good quality tracks in the TPC

- Analysis branches: $\mu^{\pm}\pi^{\mp}$, $e^{-}\pi^{+}$, $e^{+}\pi^{-}$, $\mu^{+}\mu^{-}$, $e^{+}e^{-}$

- PID cuts: use TPC dE/dx to build corresponding PID likelihoods (e.g. $\mathcal{L}_{\mu}, \mathcal{L}_{\pi}, \mathcal{L}_{e}$)
- For $N \rightarrow \mu\mu\nu$ use ECAL PID

- Kinematic cuts:
  - total HNL momentum
  - angle between HNL daughter tracks
  - invariant mass
  - polar angle (between HNL direction and Z-axis)
  - 4-momentum transfer $|t| \equiv \left(P_{\nu} - P_{\mu} - P_{\pi}\right)^{2}$