Search for Heavy Neutrinos with the T2K near detector

PHENIICS Fest

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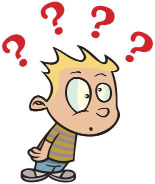

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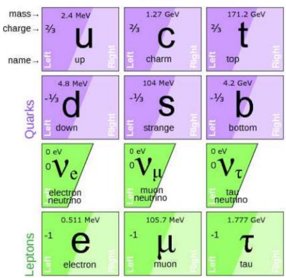
Why? (Theory)

Neutrinos



Standard Model

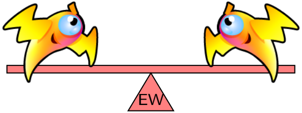
- Neutrinos come in three flavours: ν_e, ν_μ, ν_τ
- They are left-handed (right-handed neutrinos have never been observed)
- Neutrinos are **massless**

Neutrino oscillations

- Neutrinos change flavours between production and detection.
- Two-flavours oscillations: $\text{Prob}(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$
- $\Delta m^2 \neq 0 \Rightarrow$ Neutrinos are **massive**

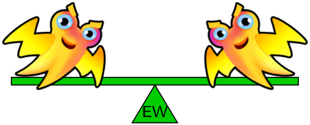
Why neutrinos are massless in the Standard Model?

left-handed electron right-handed electron



$m_e = 0.5$ MeV

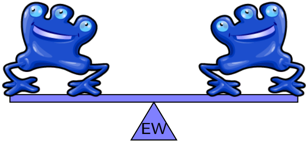
left-handed muon right-handed muon



$m_\mu = 140$ MeV

. . .

left-handed top right-handed top



$m_t = 173$ GeV

left-handed neutrino

neutrino is alone

$\Rightarrow m_\nu = 0$

~~right-handed neutrino~~

$$\boxed{\mathcal{L} = m\overline{\Psi}_L\Psi_R + m\overline{\Psi}_R\Psi_L}$$ (Dirac mass term)

Right-handed partner for the neutrino

- Introduction of right-handed neutrinos

left-handed neutrino

weak int.
+ gravitation

right-handed neutrino

gravitation only

- When you write the whole theory, you end up with:
  - 3 light neutrinos ($m \sim 0.1$ eV) $\Rightarrow$ the ones we know
  - 3 heavy neutrinos ($m_N =$ keV, MeV, GeV, ... ?) that interact through weak interaction with a penalty factor U_α=mixing between light and heavy neutrinos $\Rightarrow$ new particles !

Why is it interesting?

We can choose heavy neutrino mass and mixing U_α to solve other issues.

Example: νMSM by Asaka and Shaposhnikov (2005), 3 new states:

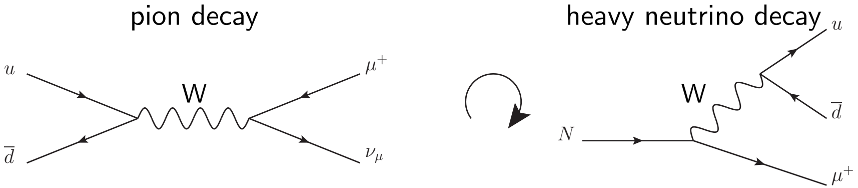
- N_1 with $M_1 \sim \mathcal{O}(\text{keV}) \Rightarrow$ candidate for warm dark matter
- $N_{2,3}$ with $M_{2,3} \sim \mathcal{O}(\text{GeV}) \Rightarrow$ explains matter-antimatter asymmetry

We can look for new physics with current experiments by putting limits in $m_N - U_\alpha^2$ plane ($U_\alpha^2 \lesssim 10^{-8}$ from past exp.)

How can we see heavy neutrinos?

- It behaves like a neutrino
- The kinematic is different, because of different mass
- We add an additional factor U_α^2 each time we put an heavy neutrino instead of a standard neutrino ν_α $(\alpha = e, \mu, \tau)$

- $K^+ \to e^+\nu_e \Longrightarrow K^+ \to e^+ N$ if $m_N < m_K - m_e$ with mixing U_e^2
- $\pi^+ \to \mu^+\nu_\mu \Longrightarrow N \to \pi^-\mu^+$ if $m_N > m_\pi - m_\mu$ with mixing U_μ^2
- $Z \to \nu N$, $N \to \mu^+ e^- \nu$, $N \to 3\nu$, $N \to \gamma\nu$...



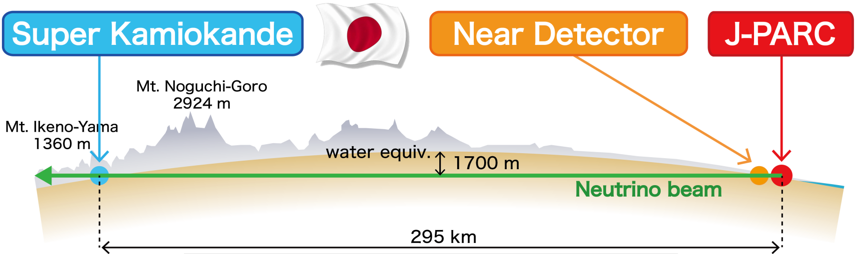
pion decay

heavy neutrino decay

Where? (Experiment)

The T2K experiment

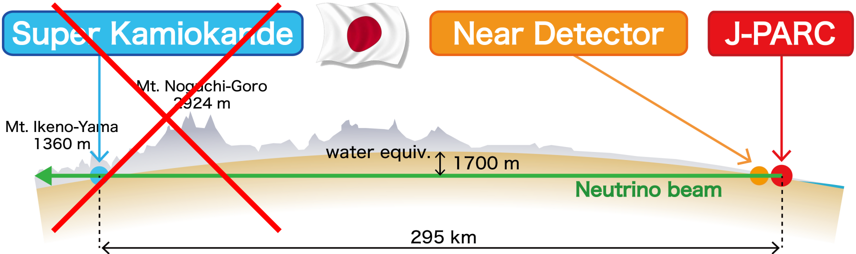
Neutrino oscillation experiment in Japan, running since 2010



$$\pi^+/K^+ \to \mu^+\nu_\mu \text{ and } \nu_\mu A \to \mu^- A' + X$$

- At J-PARC, 30 GeV proton beam is sent on a graphite target
- It produces kaons/pions that decays to neutrinos
- They propagate up to far detector (295 km) and are detected through their interaction with nucleus

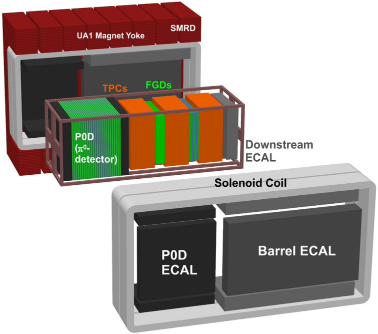
The T2K experiment



$$\boxed{K^+ \to l_\alpha^+ N \text{ and } N \to l_\beta^\pm \pi^\mp}$$

- At J-PARC, 30 GeV proton beam is sent on a graphite target
- It produces kaons that decays to heavy neutrinos ($\# \propto U_\alpha^2$)
- They decay within a few kilometers and can be detected through their decay in the near detector
- Number of decays is proportional to $U_\alpha^2 U_\beta^2$
- Heavy neutrino mass should be: $m_\pi < m_N < m_K$

The near detector ND280



- **Initial goal:** detect standard neutrino interaction on nuclei
- **Target:** carbon scintillators + water modules
- **Tracking:** using Argon gas Time Projection Chambers

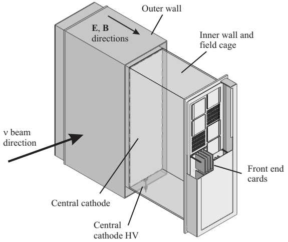
Heavy neutrino search

- Signal: $N \to \mu\pi$ or $N \to e\pi \Rightarrow \boxed{\# \text{ of events} \propto \text{volume}}$
- Background: $\nu_\mu A \to \mu^- A' + X \Rightarrow \boxed{\# \text{ of events} \propto \text{mass}}$

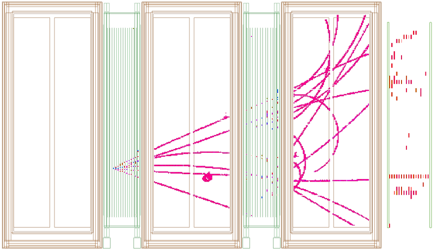
$\boxed{S/B \propto 1/\text{density}}$ $\Rightarrow$ light materials are an excellent lab for the search!

Time Projection Chambers

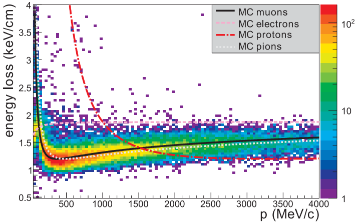
Particles ionize the gas



Curvature ∝ momentum



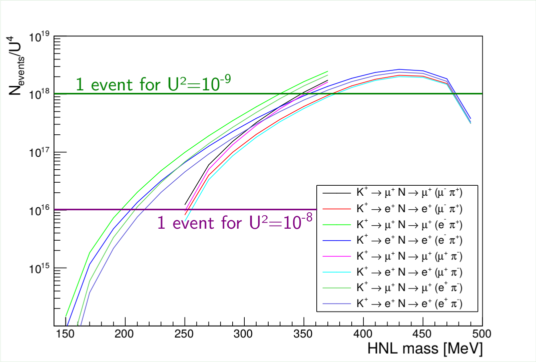
Energy loss → Identification



9 cubic meters of gas

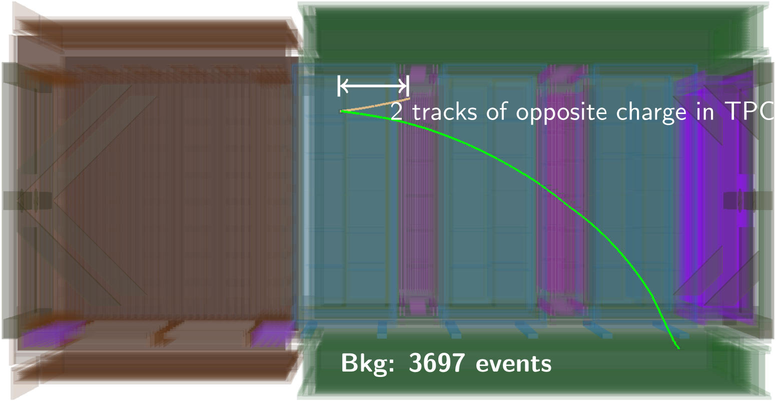
How? (Analysis)

Analysis strategy



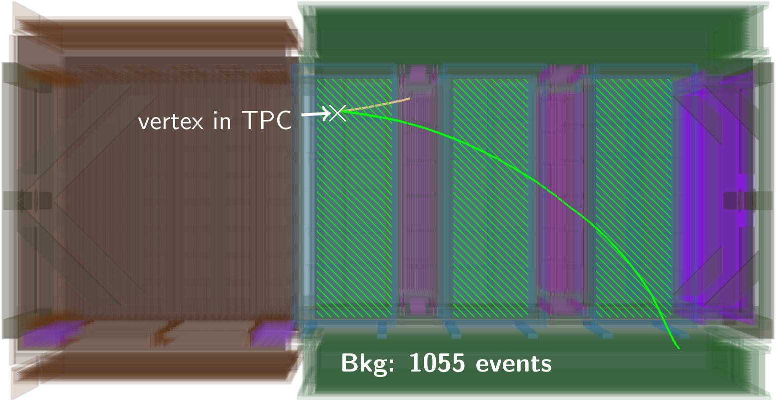
- simulation of heavy neutrino signal for different possible m_N
- selection of the signal based on the simulation
- background study
- study of systematic uncertainties for
  - signal (detector effects, flux...)
  - background (theory, flux...)
- sensitivity analysis

Selection



- Two opposite charge tracks
- Good quality tracks
- Reconstructed vertex in TPC
- No other activity before
- Particle identification
- Correct kinematics

Selection



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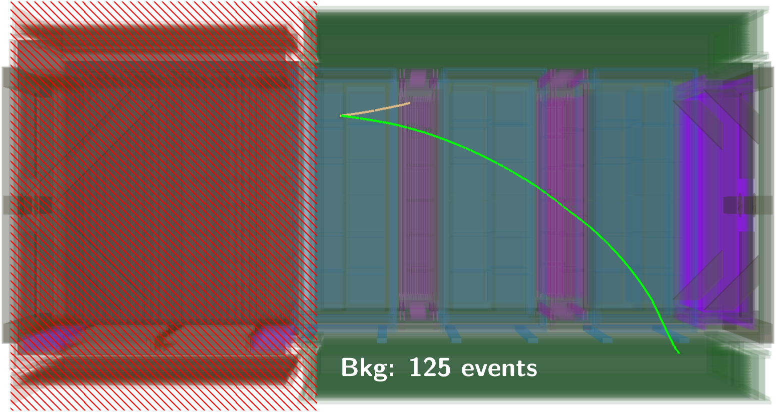

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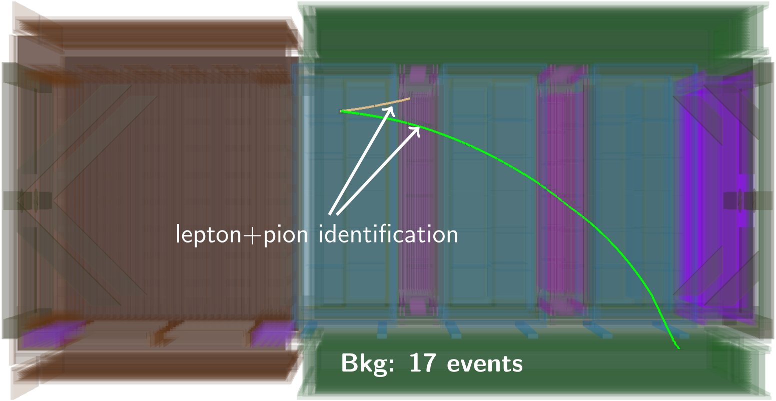

- Two opposite charge tracks
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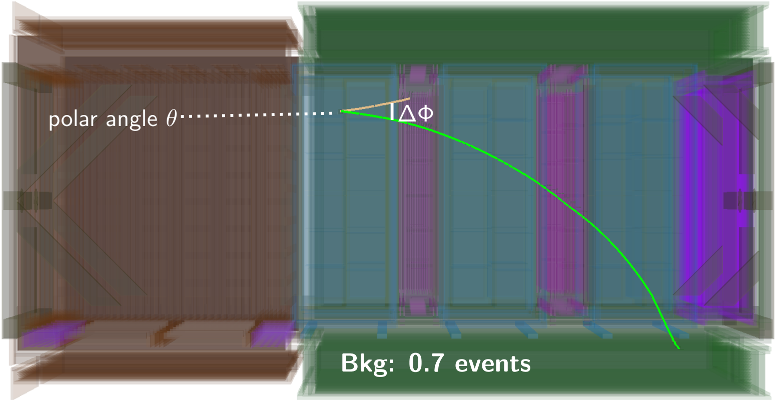
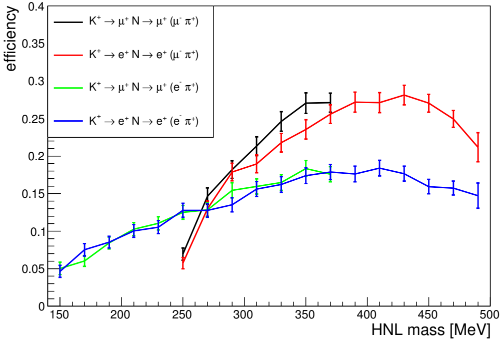


Bkg: 0.7 events

- Two opposite charge tracks
- Good quality tracks
- Reconstructed vertex in TPC
- No other activity before
- Particle identification
- Correct kinematics

Efficiency



Conclusions

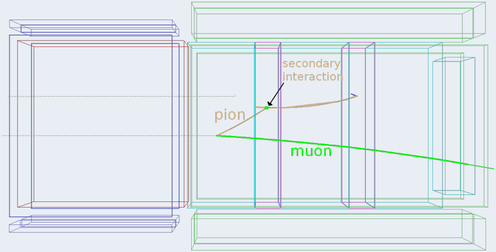
- Selection is more efficient for higher masses
- Lower efficiency when asking for an electron

$\Rightarrow$ to be taken into account in the analysis

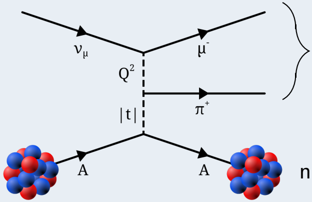
Remaining background

Less than 1 event expected for all 6 years of T2K data)

Example: Coherent pion production on Argon



- exactly like signal
- not precisely known



muon and pion share all the energy

nucleus remains unchanged ($|t|$ small)

Source of systematics

Signal

- statistical error on efficiency
- detector response: momentum/position resolution, PID discrepancy between data and MC...
- flux: beam intensity, kaon production...

Background

- statistical error on background
- knowledge of background
- flux

Source of systematics

Signal

- statistical error on efficiency $\Rightarrow \delta\varepsilon = \sqrt{\frac{\varepsilon(1-\varepsilon)}{N}}$
- detector response: momentum/position resolution, PID discrepancy between data and MC... $\Rightarrow$ variance of toy experiments
- flux: beam intensity, kaon production... $\Rightarrow$ throwing flux randomly

Background

- statistical error on background $\Rightarrow \delta B = \sqrt{B}$
- knowledge of background $\Rightarrow$ checked using control samples
- flux $\Rightarrow$ 10% normalization uncertainty

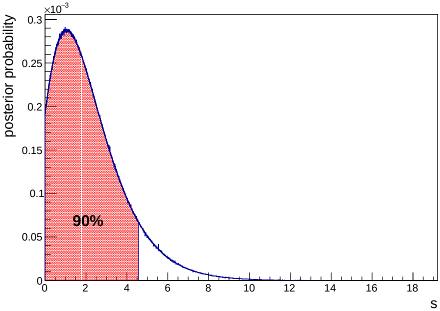
Sensitivity

Conversion of all information (efficiency, background, uncertainties) to a limit on mixings U_α, using a Bayesian posterior probability

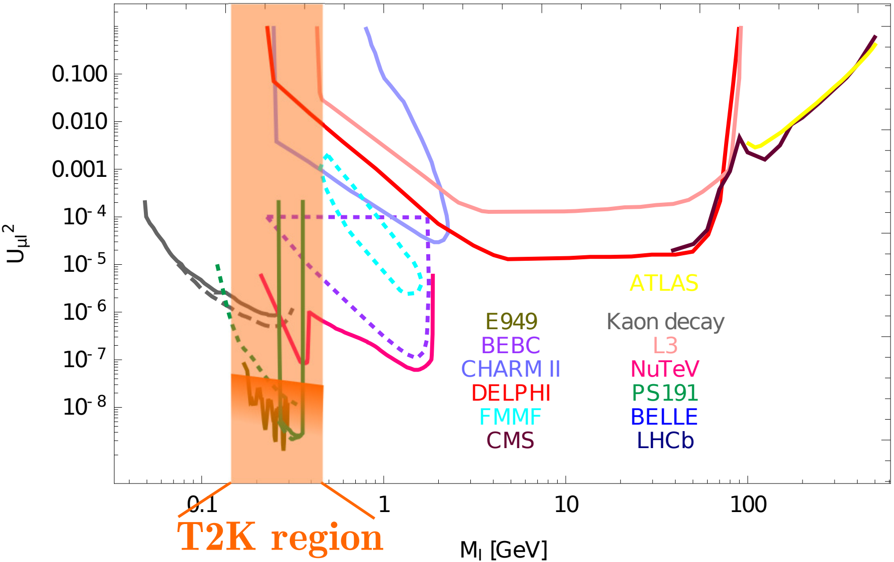
$$p(s|n) \propto \int_0^\infty db \int_0^\infty d\eta \; \underbrace{\frac{(s\eta+b)^n}{n!} e^{-s\eta-b}}_{\text{likelihood}} \; \underbrace{\pi_S(\eta)\pi_B(b)}_{\text{priors}}$$

We define an upper limit s_{up} at 90% by:

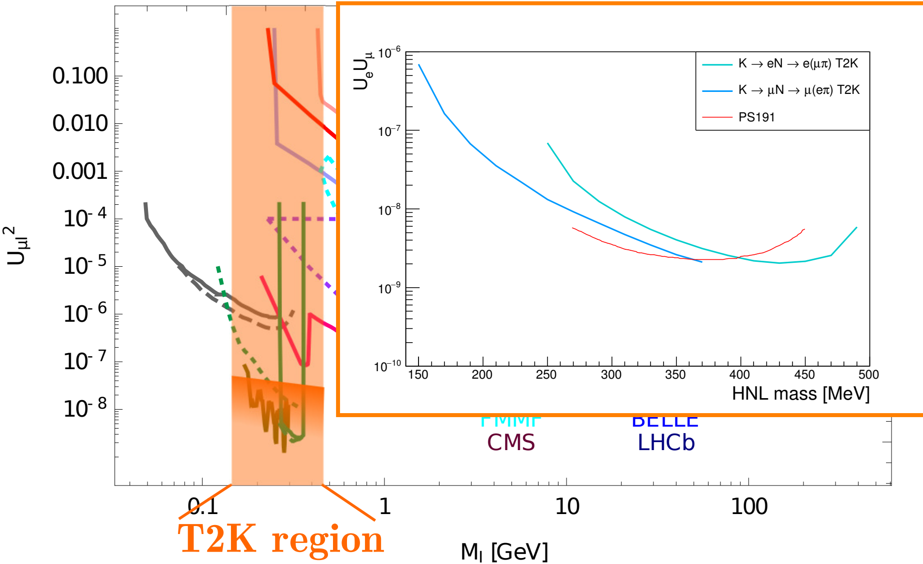
$$\int_0^{s_{up}} p(s|n) ds = 0.90$$



Sensitivity



Sensitivity



Summary

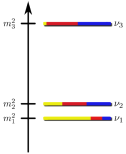
Standard model

$+$

$3\ \nu_R$

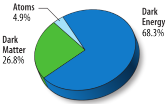
$=$

$m_\nu \neq 0$



Matter-antimatter asymmetry

Dark matter



- T2K can look for heavy neutrinos with $140 < m < 500$ MeV
- Simulation + complete study have been done.
- Background is reduced to less than 1 event in current data.
- Limits on mixing between active and heavy neutrinos U_α can be put.

Backups

Right-handed partner for the neutrino

Introduction of ν_R singlet

Simple case with one ν_L and one ν_R:

$$\text{mass term} = \frac{1}{2}(\overline{\nu_L}\ \overline{\nu_R^c}) \begin{pmatrix} 0 & A \\ \underset{\text{Dirac term}}{A} & \underset{\text{Majorana term}}{B} \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

left-handed neutrino

weak int.
+ gravitation

right-handed neutrino

gravitation only

- Dirac term: as for charged fermions
- Majorana term: additional term allowed as neutrinos are neutral

Right-handed partner for the neutrino

Introduction of ν_R singlet

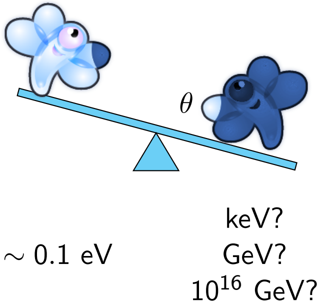
Simple case with one ν_L and one ν_R:

$$\text{mass term} = \frac{1}{2}(\overline{\nu_L}\ \overline{\nu_R^c}) \begin{pmatrix} 0 & A \\ A & B \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

Dirac term Majorana term

If $\theta \equiv A/B \ll 1$ (seesaw condition), the matrix has two mass eigenstates:

- one mainly left (active) with mass $\boxed{m \simeq \theta^2 B}$
- one mainly right (sterile) + a fraction θ of left (active) with mass $\boxed{M \simeq B}$



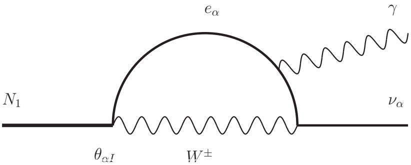
Matter-antimatter asymmetry with neutrinos at GeV-scale

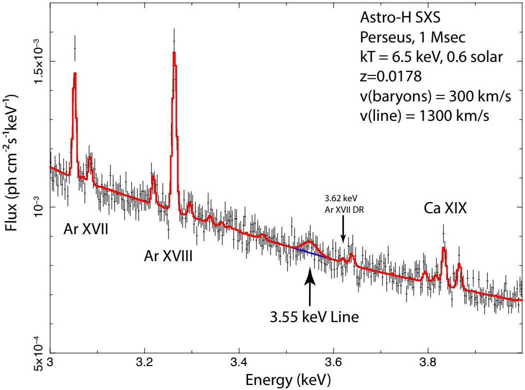
Baryogenesis via leptogenesis

- Singlet neutrinos are produced through their Yukawa coupling, equally split in $+1$ and -1 helicities, then $L_I = 0$ (conserves CP)
- Singlet neutrinos oscillate conserving $L_{\text{tot}} = L_{\text{active}} + \sum_{I=1}^{3} L_I = 0$, but $\Delta L_I \neq 0$ (violates CP)
- Singlet neutrinos communicate their asymmetries to active neutrinos $L_{\text{active}} \neq 0$ through active-sterile mixing
- $L_{\text{active}} \neq 0$ is converted to $B \neq 0$ by sphaleron process (that conserves only $B - L$ and not B,L individually)

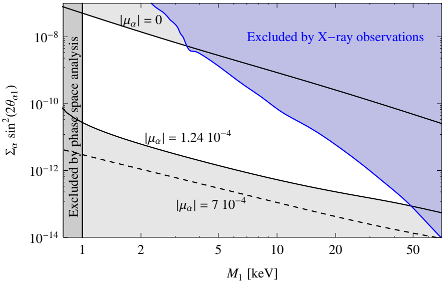
Requires two degenerate heavy neutrinos at GeV-scale, or three free heavy neutrinos

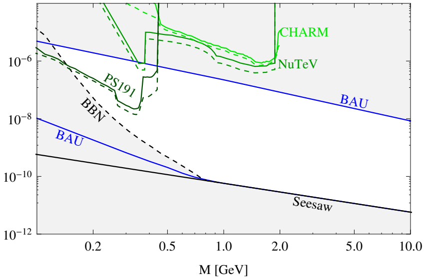
Dark matter candidate



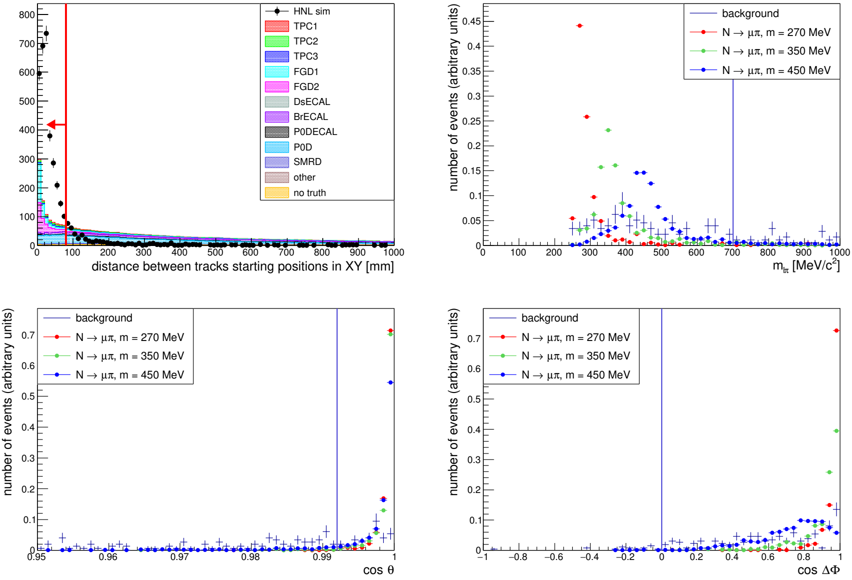


Exclusions from other experiments





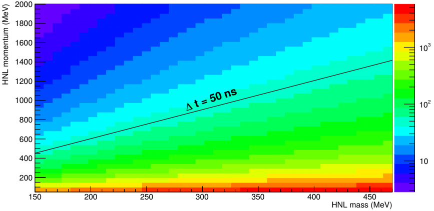
Cut variables

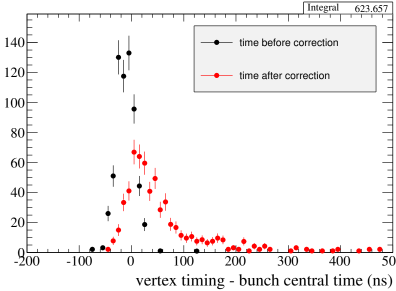


Time of Flight correction

As compared to standard neutrinos, heavy neutrinos need more time to reach ND280:

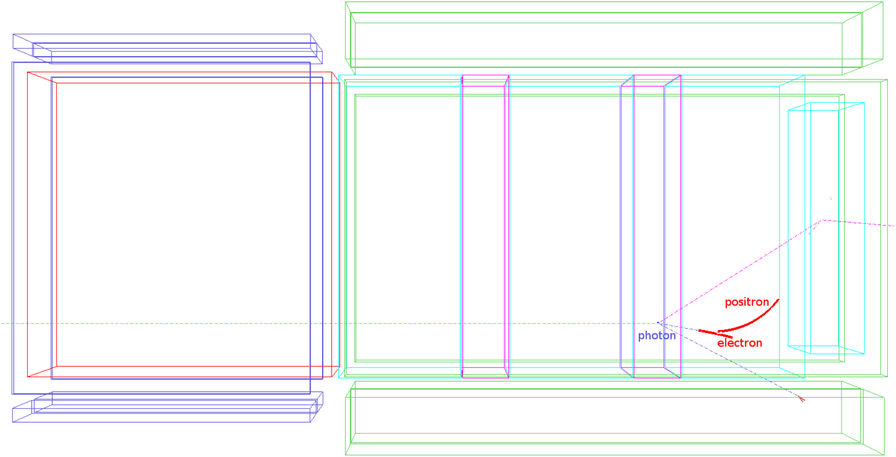
$$\Delta t = \frac{d}{c}\left(\frac{\sqrt{p^2 + m^2}}{p} - 1\right)$$





Background for electron channel

$\nu A \rightarrow X + \pi^0$, $\pi^0 \rightarrow \gamma\gamma$, $\gamma \rightarrow e^+e^-$, one misidentification



How to use the results?

What we have

- Expected number of events if $U = 1$ $(N_{\text{exp}} = N_{\text{sim}} \times \epsilon)$ with its error
- Expected number of background N_b with its error δN_b
- Measurement of a number of events n_{obs}

What we want to know

- have we observed new physics?
- signal $\in [s_{\text{down}}, s_{\text{up}}]$ at a given confidence level (e.g. 90%)
- a confidence interval for U_e^2, $U_e U_\mu$ and U_μ^2:

As $\# \propto U_\alpha^2 U_\beta^2$, in the channel $\{K^\pm \to l_\alpha^\pm N, N \to l_\beta^\pm \pi^\mp\}$:

$$(U_\alpha U_\beta) \in \left[\sqrt{\frac{s_{\text{down}}}{N_{\text{up}}(U=1)}}; \sqrt{\frac{s_{\text{max}}}{N_{\text{exp}}(U=1)}}\right]$$

Bayesian computation of an upper limit

- If background b and signal acceptance η are known, s follows:

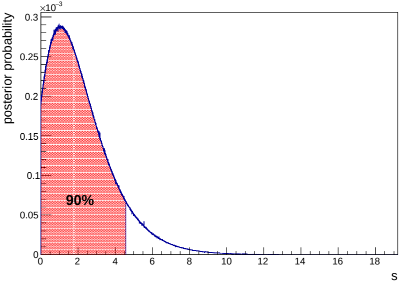
$$\mathcal{L}(s,\eta,b|n) = \frac{(s\eta+b)^n}{n!} e^{-s\eta-b} \qquad \textbf{(Likelihood)}$$

- b and η have a given distribution with standard deviation $\neq 0$, e.g.

$$\pi_B(b) = \frac{1}{\sqrt{2\pi}\sigma_B} e^{-(b-B)^2/(2\sigma_B^2)} \qquad \textbf{(Prior)}$$

- Then, s follows

$$p(s|n) \propto \int_0^\infty db \int_0^\infty d\eta \mathcal{L}(s,\eta,b|n)\pi_S(\eta)\pi_B(b) \qquad \textbf{(Posterior)}$$



From the posterior probability, we define an upper limit s_{up} at 90% by

$$\int_0^{s_{up}} p(s|n)ds = 0.90$$