Search for heavy neutrinos in the ND280 near detector of the T2K experiment

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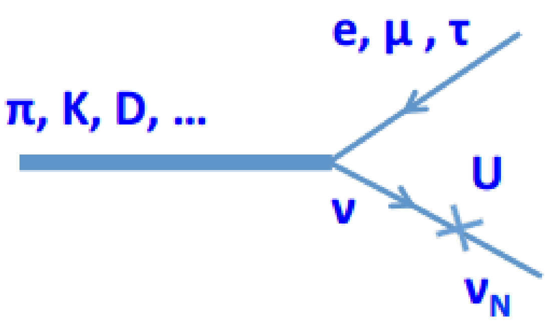
Heavy neutral leptons

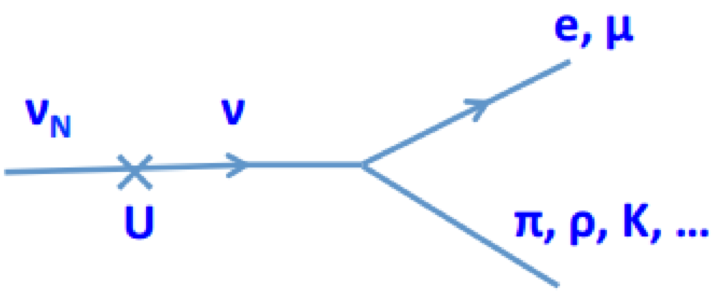
- Heavy Neutral Leptons (HNL) or heavy sterile neutrinos proposed to solve some problems of the Standard Model (SM) (i.e. νMSM arXiv:050.3065)
- Explain neutrino masses, baryon asymmetry, dark matter

- Different mass regions:
  - $10^9 \div 10^{14}$ GeV: GUT scales, Baryon asymmetry generation
  - $10^2 \div 10^3$ GeV: can study at LHC energy scales
  - $10^{-3} \div 10^2$ GeV: masses of already known leptons and quarks **This region studied in current work**
  - $\sim$ eV: neutrino oscillation anomalies

How to find HNL

- Mixing between HNL and active neutrinos leads to:
  - their production in decays of heavy mesons
  - HNL decays into SM particles



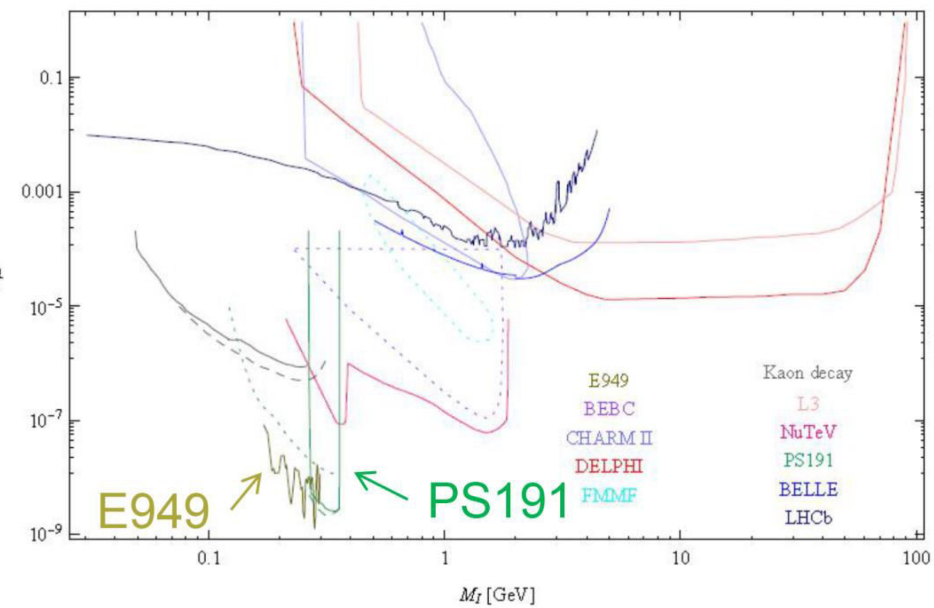


- Two ways for experimental search:
  - direct measurement of meson decays:
    e.g. modified kinematics w.r.t. SM decays with $m_\vartheta = 0$
    - signal $\sim |U|^2$
  - search for decay products of HNLs originating in intense beam of "ordinary" neutrinos → T2K ND280 corresponds to this case
    - signal $\sim |U|^4$

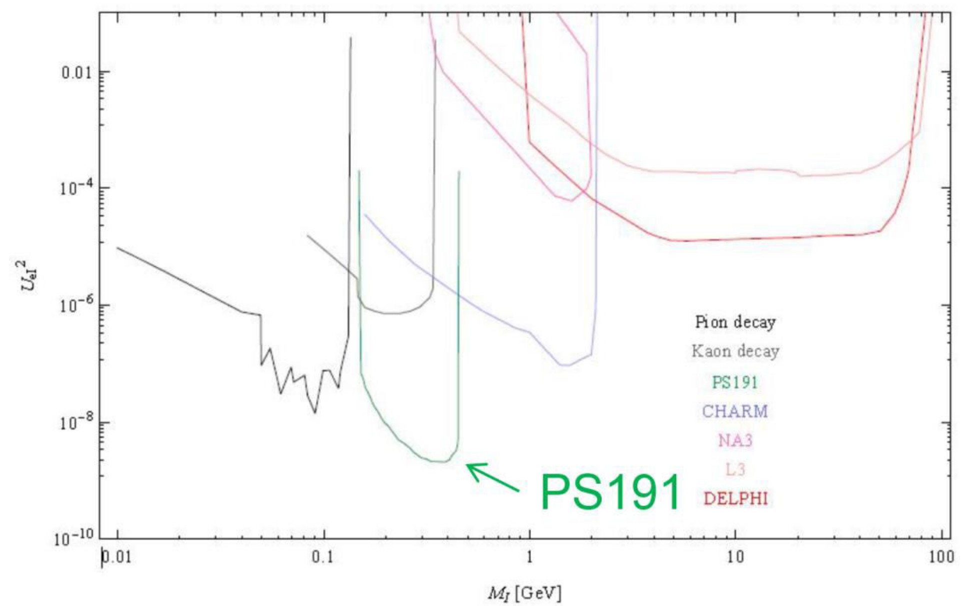
Previous constraints

- Interested in region $100\ MeV < M_{HNL} < 500\ MeV$
- Best current limits:
  - PS191 (CERN experiment, 1980-s)
  - E949 (BNL, 2015)
- Some hints that that T2K experiment can improve limits

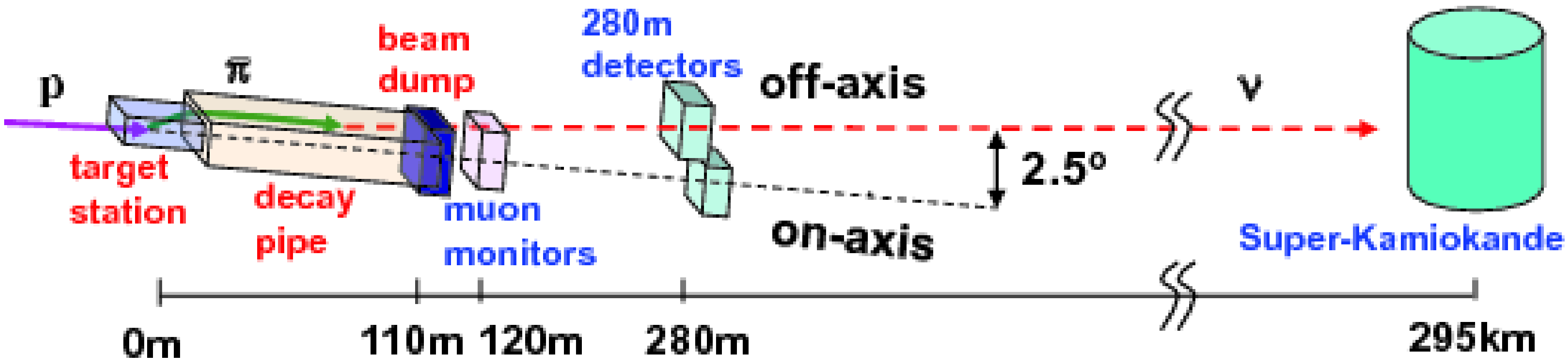
$|U_\mu|^2$



$|U_e|^2$

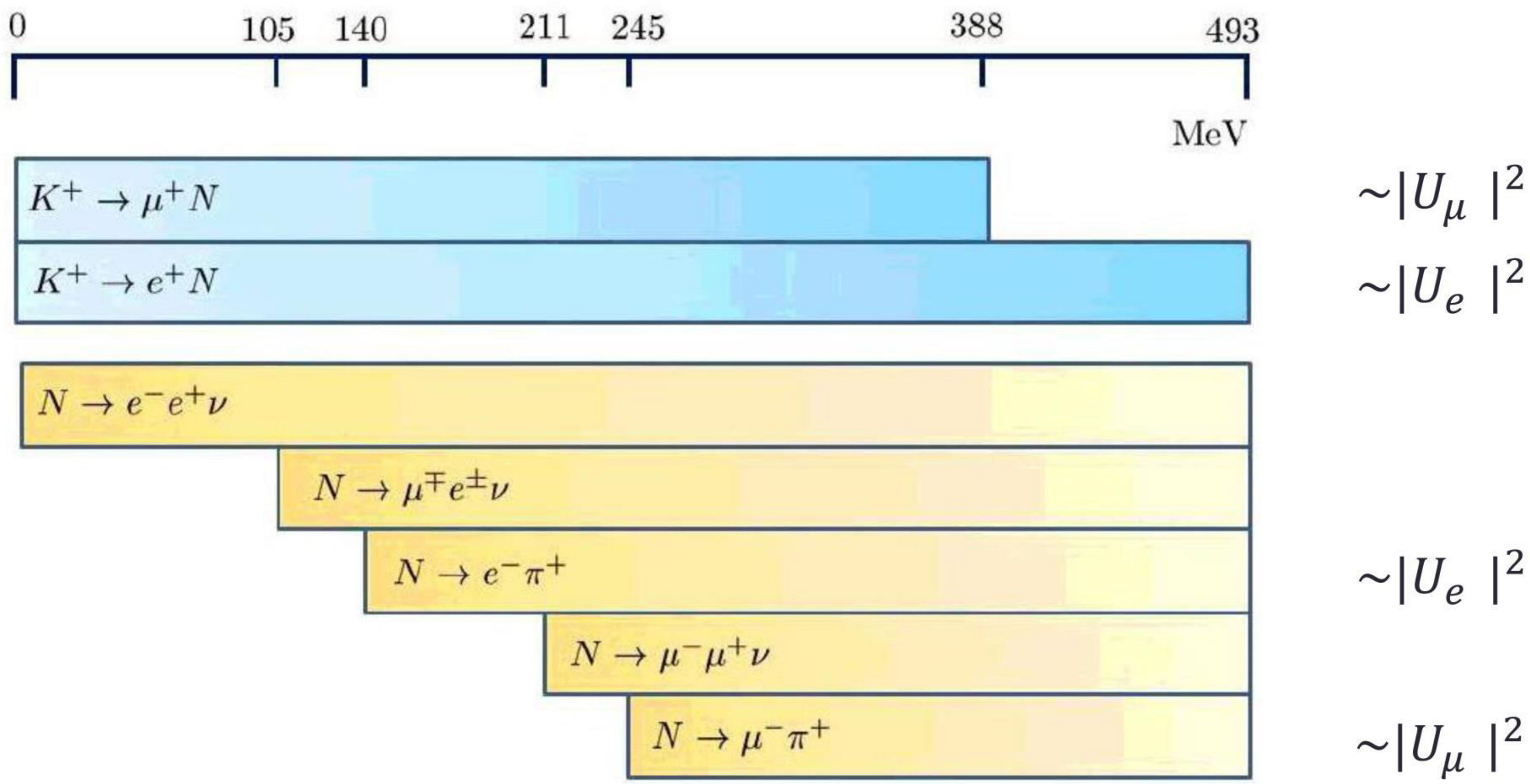


T2K experiment



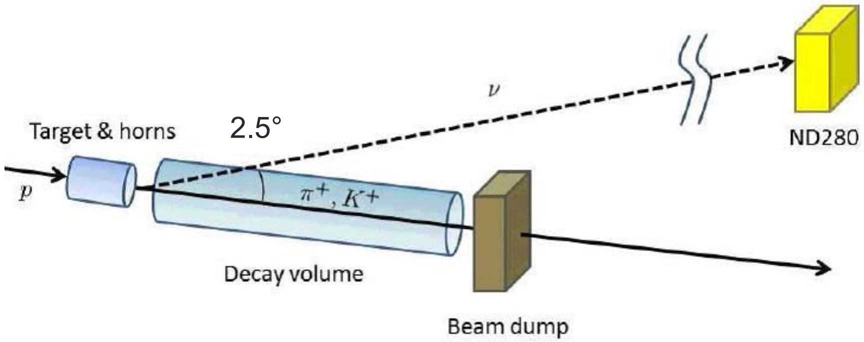
- The T2K (Tokai-to-Kamioka) accelerator long-baseline neutrino oscillation experiment
- Study (anti-)neutrino oscillations $\nu_\mu \rightarrow \nu_e, \nu_\mu \rightarrow \nu_\mu,$
- Neutrino and antineutrino beam from mesons' decays (π, K)

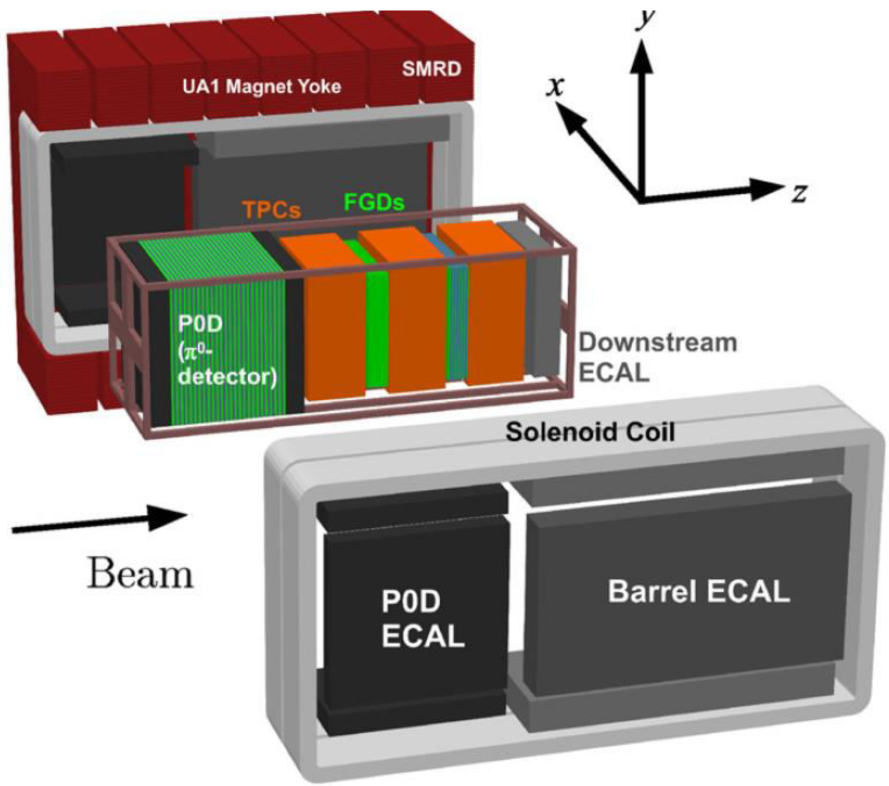
HNL in kaon decays



- Other reactions: $N \to \gamma\nu$, $N \to \nu\pi^0$, $N \to 3\nu$.
- We study products of HNL decay with ND280:
  Number of events $\sim |U|^4$

T2K near detector ND280





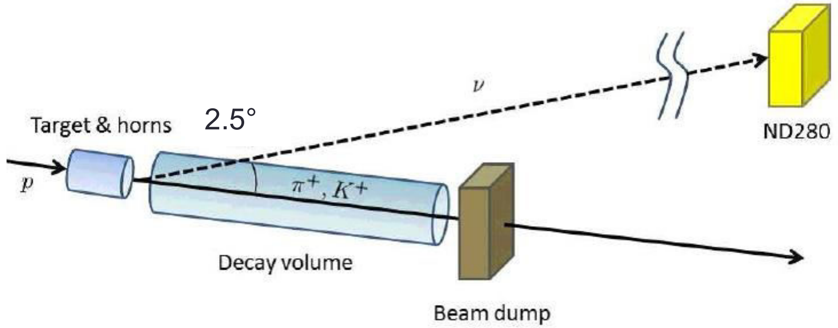
- Off-axis detector at 280 meters from target station
- Contains:
    - 3 Time Projection Chambers (TPC)
    - 2 Fine Grained Detectors (FGD)
    - Electromagnetic Calorimeter (ECal)
    - Side Muon Range Detector (SMRD)
    - UA1 magnet
- Optimized for tracking and PID at 1GeV

Analysis plan

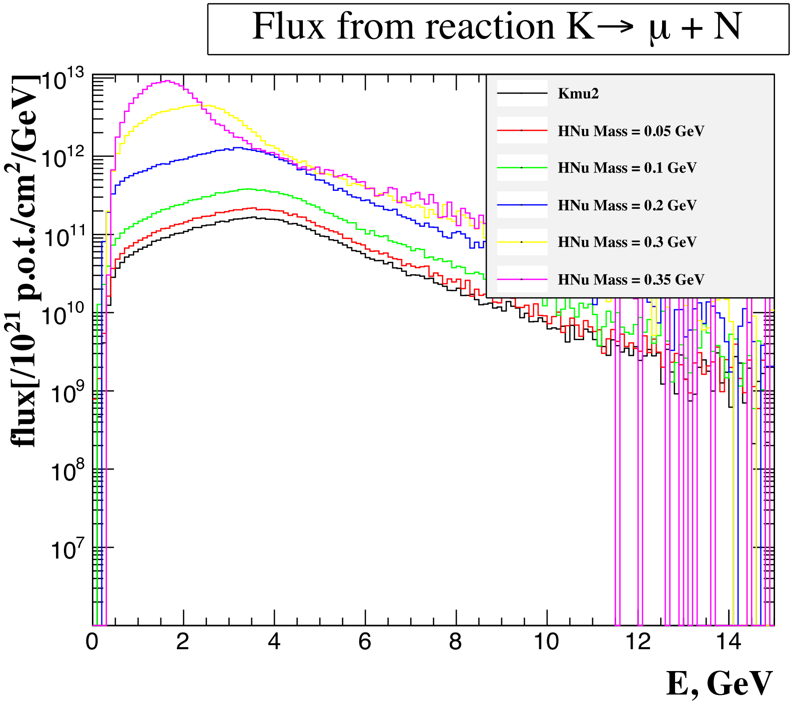
- Active neutrino interactions → main background for HNL search
- Look for decay in TPC filled with Ar → reduce the impact from active neutrino interactions

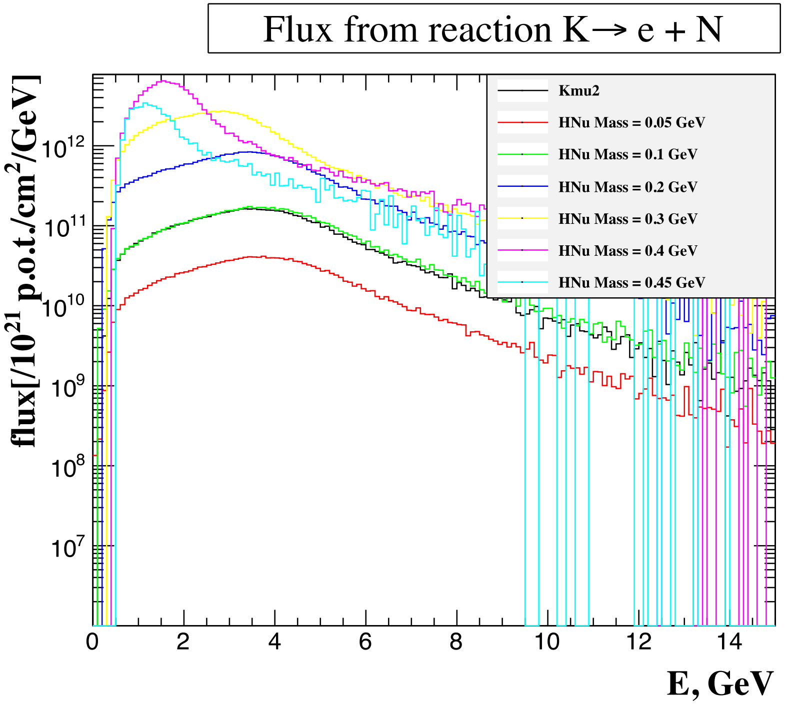
- Background: gas interactions and reconstruction failures
  - poor knowledge of Ar cross-section at ~1 GeV
- Optimize cuts to eliminate background
- “Zero signal strategy” – assume all observed events are BG and put C.L. limits on mixing elements

HNL flux simulation



- Use flux from $K\mu2$ $(K \rightarrow \mu\nu)$
- Reweight $K\mu2$ flux for HNL:
  - Massive lepton kinematic
  - HNL branching ratio $\Gamma(K \rightarrow lN) = \rho(M_{HNL})\Gamma(K \rightarrow l\nu)|U|^2$

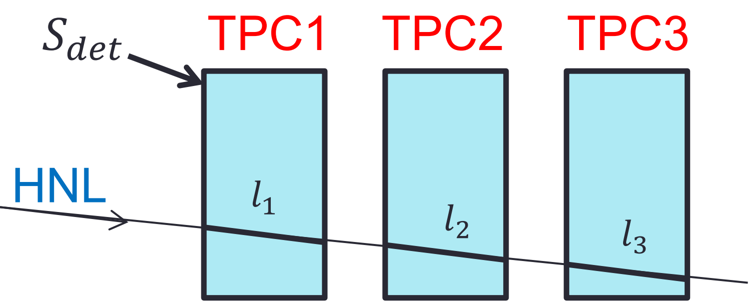




HNL decay in ND280

- Number of signal events estimated from:
  - HNL flux – $\varphi(\mathrm{HNL}/10^{21}\mathrm{p.o.t/cm^2})$
  - detector front area - S_{det}
  - probability of HNL decay inside TPC - P_{decay}^{TPC}
  - decay mode branching ratio - Br_{mode}

$$\mathrm{N_{events}} = \varphi(\mathrm{HNL}/10^{21}\mathrm{p.o.t/cm^2}) \cdot S_{det} \cdot P_{decay}^{TPC} \cdot Br_{mode}$$



$$l_{TPC} = l_1 + l_2 + l_3$$

assume HNL life time

$\boldsymbol{\tau \gg 1\mu s}$ mean free path $\Lambda = c\beta\gamma\tau \gg 280m$

From cosmology (BBN) $\tau < 0.1s$

Finally:

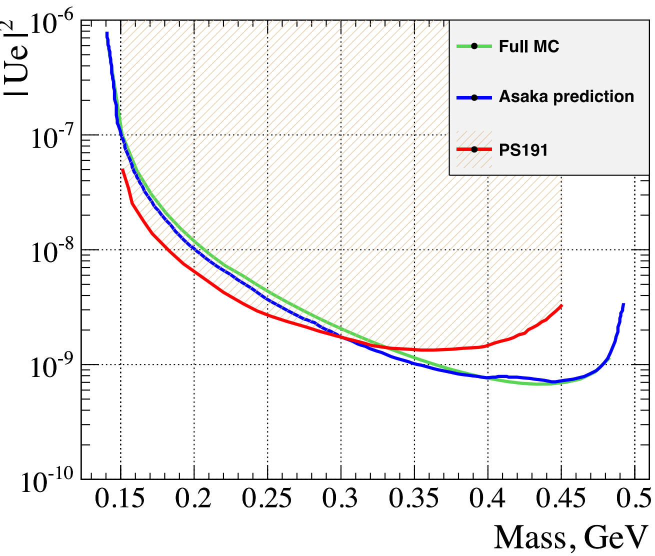
$$\mathrm{N_{events}} = \varphi(\mathrm{HNL}/10^{21}\mathrm{p.o.t/cm^2}) \cdot S_{det} \cdot \frac{l_{TPC}}{c\beta\gamma} \cdot \Gamma_{mode}$$

Expected sensetivity

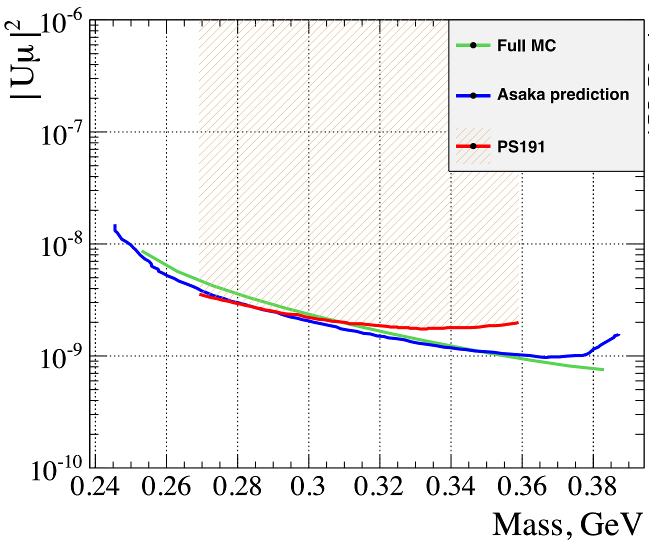
$$|U|^2_{limit} = \sqrt{\frac{U_{C.L.}}{N_{events}}}$$, no BG → $U_{C.L.} = 2.44$ (Feldman Cousins)

- PS191 limits
- Asaka et al prediction (arXiv:1212.1062) (“theoretical estimation”)
- Full MC simulation
- Assume 10^{21} POT, no background, 100% efficiency, 90% C.L.

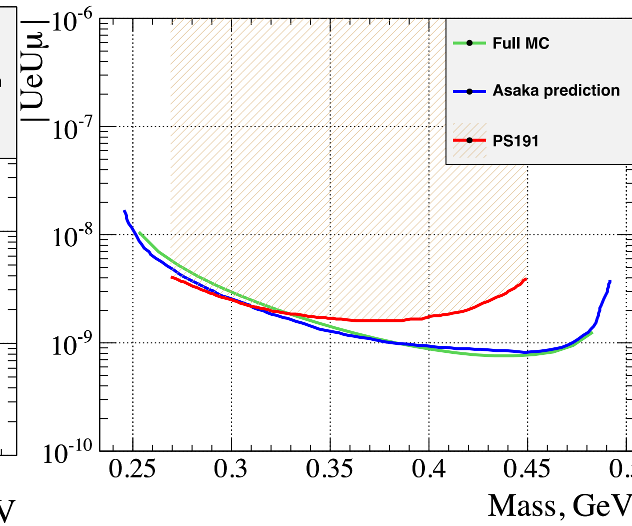
$|Ue|^2$



$|U\mu|^2$



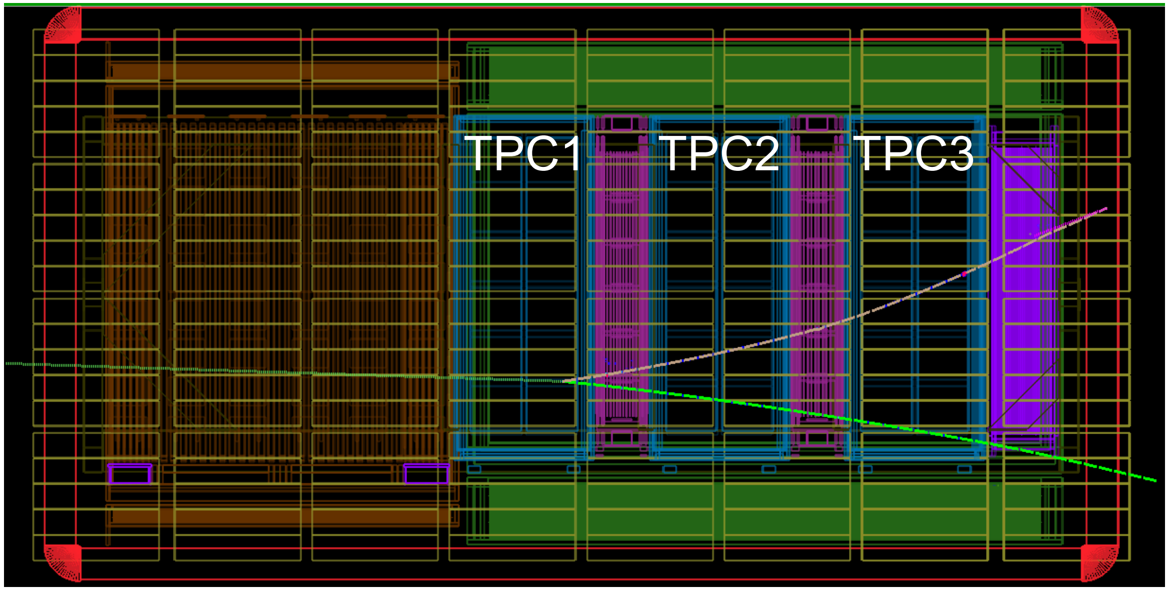
$|UeU\mu|$



HNL Selection

- Recon two-tracks' vertex in TPC FV, good quality,
- Tracks of opposite charge
- PID: $e\pi$ or $\mu\pi$
- Invariant mass cut $250 \div 700\ MeV$ for $\mu\pi$ and $140 \div 700\ MeV$ for eπ
- At least one track use vertex TPC
- No other activity in vertex TPC
- No activity in upstream detectors
- Kinematics cuts: tracks opening angle, HNL candidate polar angle.

Example of signal event simulation. HNL decay in TPC1.

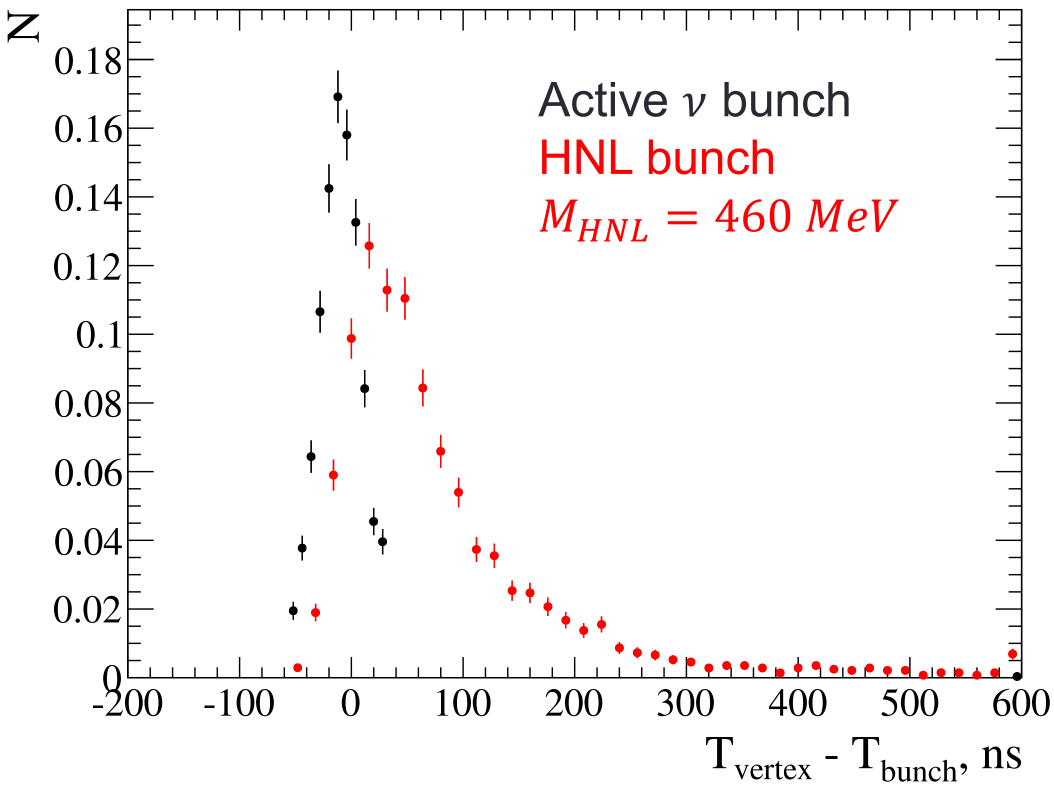


HNL Time of Flight

- T2K beam 8 bunches $\sigma \sim 19\ ns$
- Massive HNL → $dT = \frac{d}{c}\left(\frac{1}{\beta} - 1\right)$

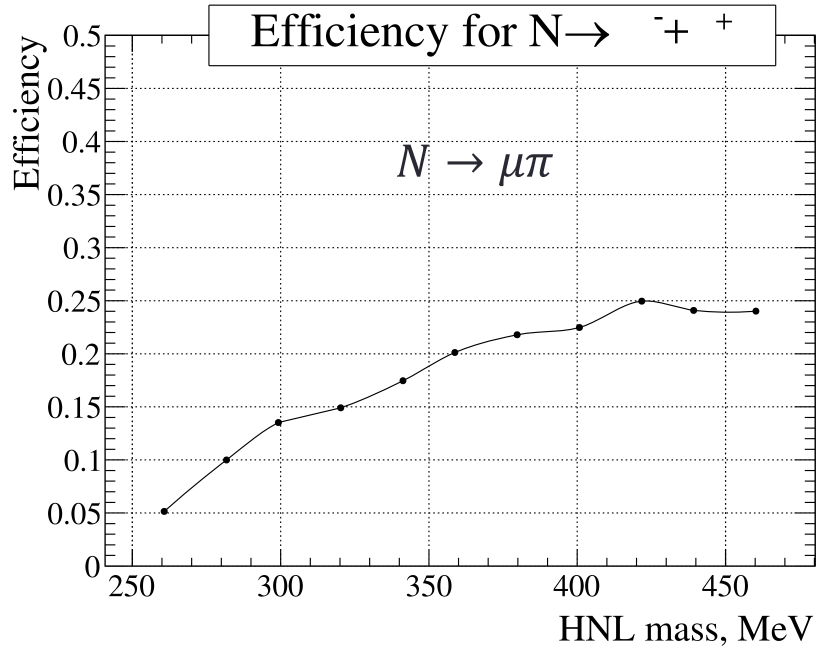
$$d \approx 280\ m$$

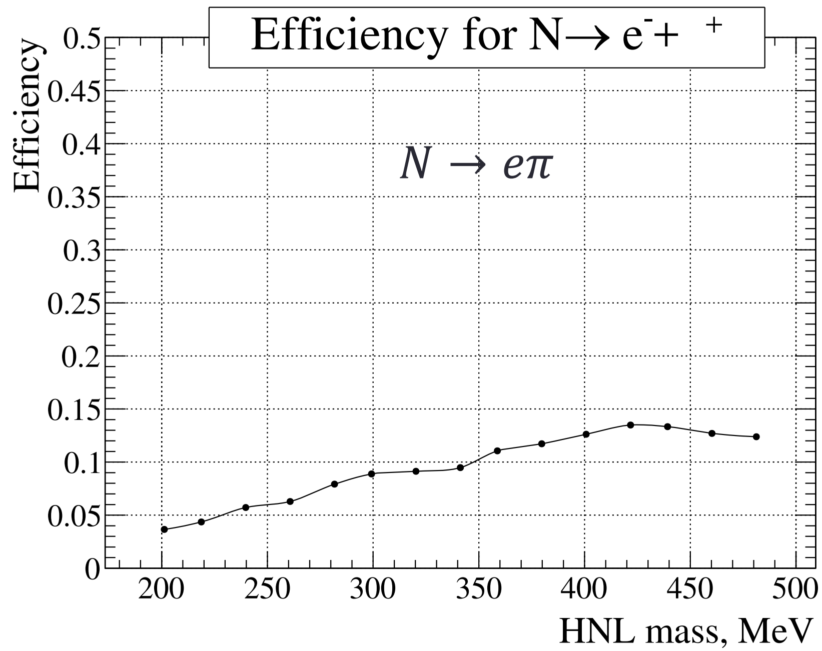
Time cut:
$-100ns < T_{vertex} - T_{bunch} < 300ns$
limited by electronic gates



HNL Selection Efficiency

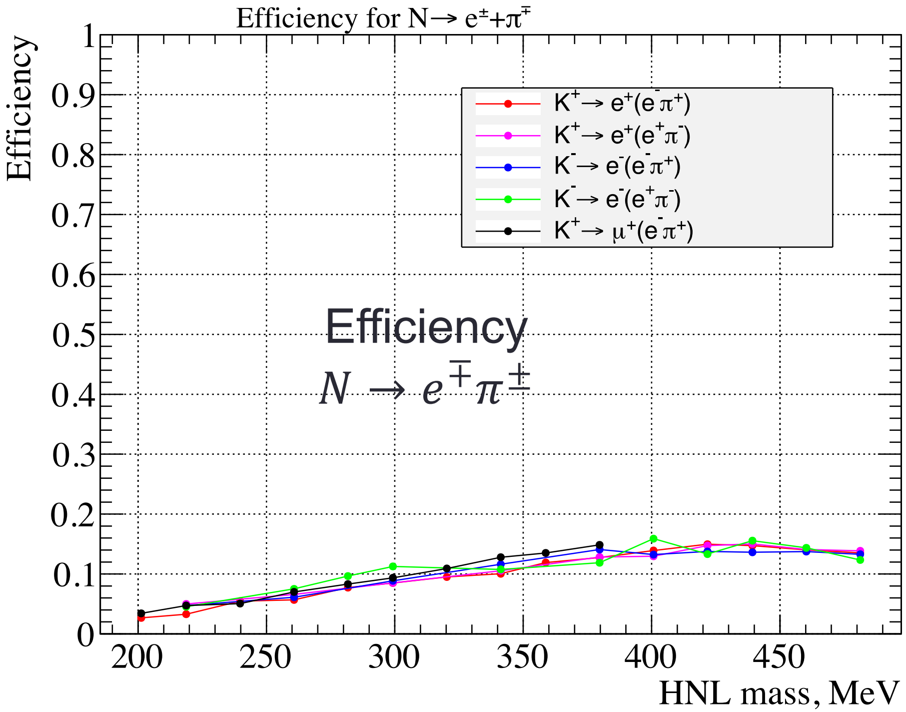
- Limited by detector design:
  - Low efficiency at TPC edges
  - Pion interactions
  - Small relative angle between tracks → TPC tracking limitations

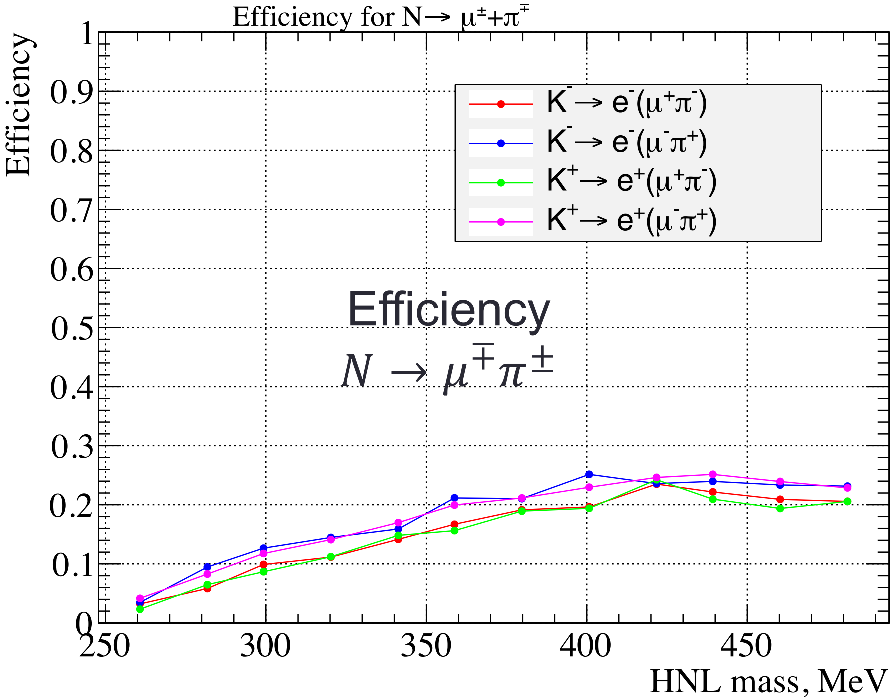




Charge conjugated modes

- T2K collects data with different horn polarity $(6.2\nu + 2\bar{\nu})10^{20}POT)$
- Assume Majorana cases of HNL, look for both $K^{\pm} \to l^{\pm}N,\ N \to l^{\mp}\pi^{\pm}$ → increase statistic for analyse





MC background study

- Use MC to estimate BG. Checks with
  - GENIE $(2.27 \cdot 10^{21}\ POT)$
  - NEUT $(6.5 \cdot 10^{21}\ POT)$

MC estimation at data statistics
For $(6.2\nu + 2\overline{\nu})10^{20} POT$
2010-1015 ND280

$\mu\pi$	3.34
$e\pi$	2.83

- NEUT $10^{21}\ POT$ equivalent

1. $\mu\pi$ mode 4.6
2. $e\pi$ mode 3.23

- GENIE

1. $\mu\pi$ mode 4
2. $e\pi$ mode 1.76

- NEUT $\overline{\nu}$

1. $\mu\pi$ mode 3.4
2. $e\pi$ mode 1.3

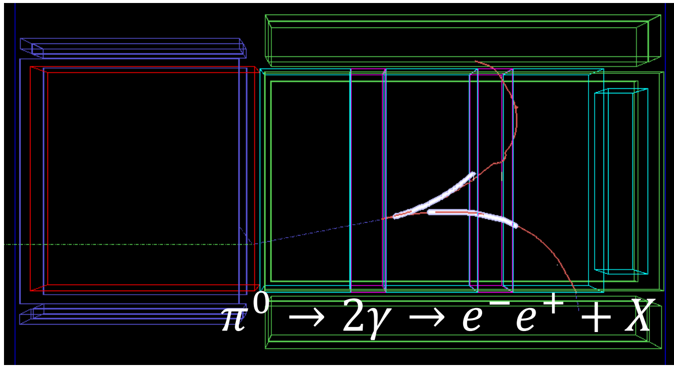
MC background study with NEUT

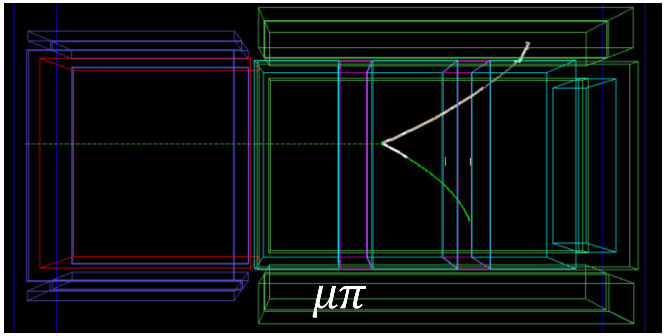
- BG origin for $\mu\pi$ mode:

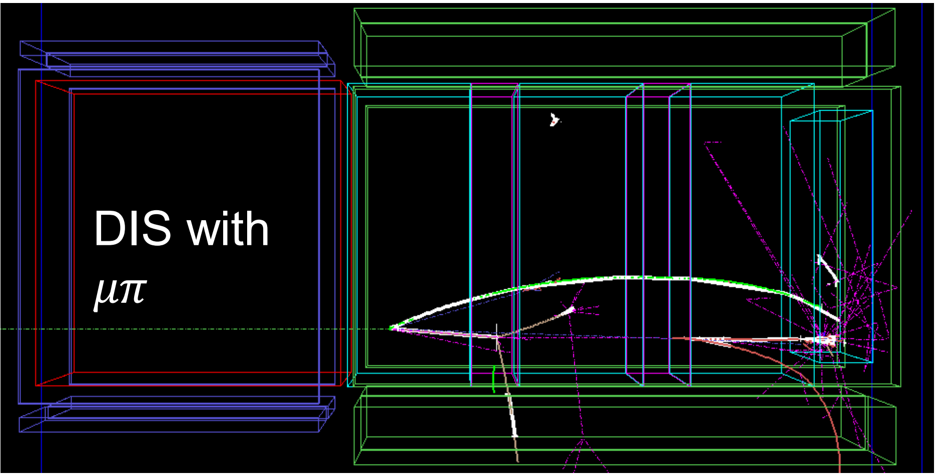
1. $\mu\pi$ 41%
2. $\mu\pi + X$ 23%
3. $\mu p + (X)$ 7.7%
4. $\pi^-\pi^+ + X$ 2.6%
5. $\eta \rightarrow \pi^+\pi^-\pi^0$ 2.6%
6. $\Lambda \rightarrow \pi^- p + X$ 2.6%
7. $K^0 S \rightarrow \pi^+\pi^-$ 5.2%
8. $K^0 L \rightarrow \mu\pi + X$ 2.6%
9. $\delta - ray$ spoils μ track 10.3%

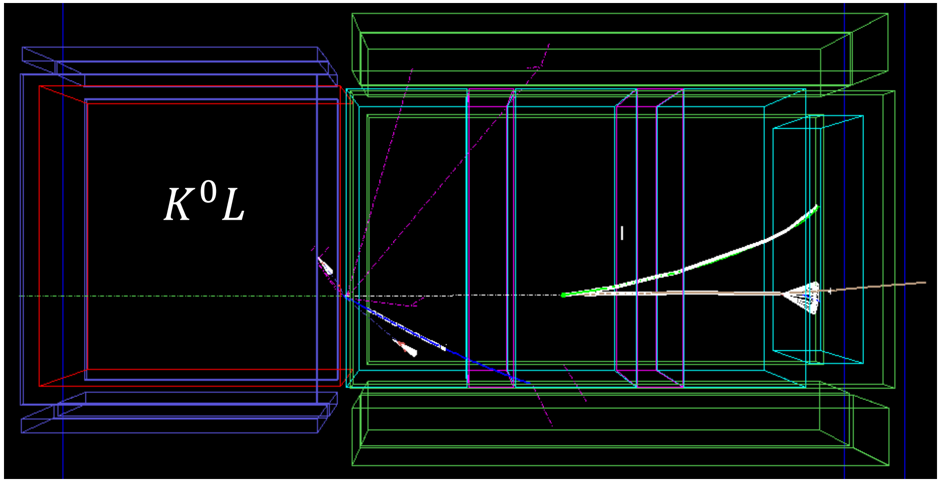
- BG origin for $e\pi$ mode:

1. $\pi^0 \rightarrow 2\gamma \rightarrow e^- e^+ + X$ 46%
2. $\delta - ray\ from\ \mu$ 14%
3. $\mu\pi$ 14%
4. $\delta - ray$ spoils μ track 26%









Systematics

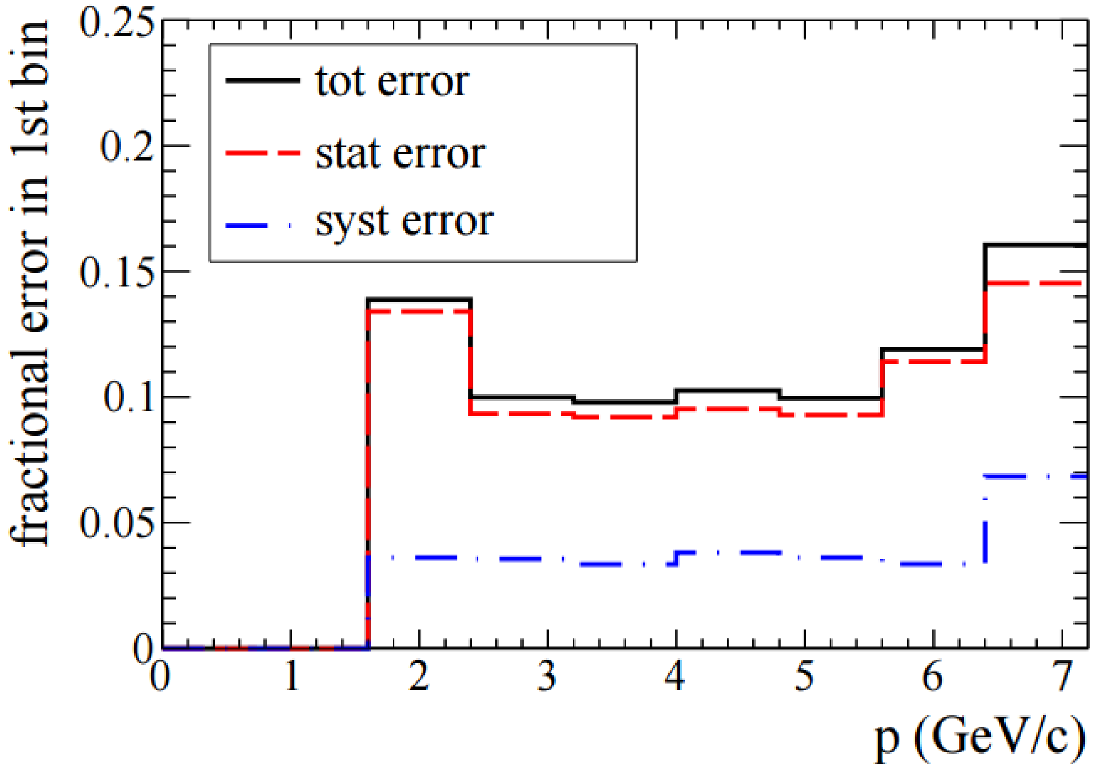
- Predicted events in ND280:

$$\mathrm{N_{events}} = \varphi(\mathrm{HNL}) \cdot \frac{V_{TPC}}{c\beta\gamma} \cdot \Gamma_{decay} \cdot Eff_{det}$$

- $\varphi(\mathrm{HNL})$ - HNL flux, affected by kaon flux systematics
  V_{TPC} - fiducial volume of TPC
  Γ_{decay} - HNL decay width for current mode
- Eff_{det} - detector efficiency,
  affected by detector systematics

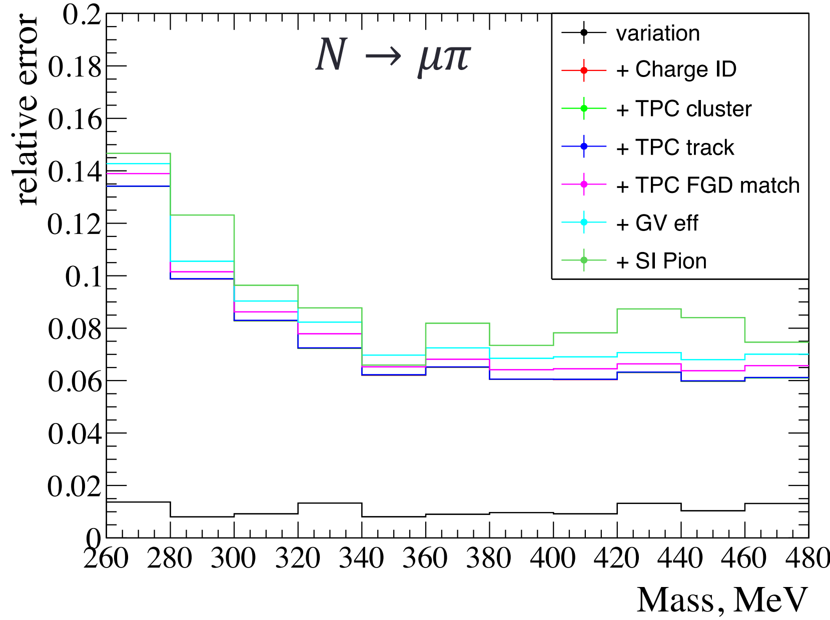
Flux systematics

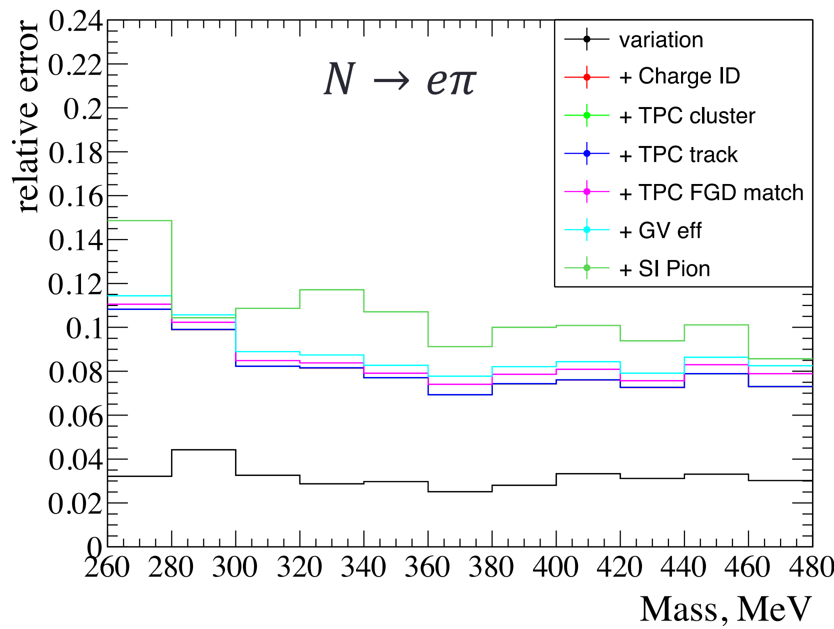
- Largest impact from K^+ multiplicity measurements (NA61)
  - also affects from focusing, target position etc.
- Expect uncertainties $\lesssim$30%



Detector systematics

	$\mu\pi$	$e\pi$
Variation-Like		
Distortions of magnetic field	0.17%	0.13%
TPC momentum scale	0.1%	0.1%
TPC momentum resolution	0.99%	0.74%
TPC dE/dx particle ID	0.43%	1.67%
Efficiency-like		
TPC cluster efficiency	<<1%	<<1%
TPC tracking efficiency	0.3%	3%
TPC charge ID efficiency	5.95%	6.22%
TPC-FGD matching efficiency	0.69%	0.82%
Pion secondary interactions	2.67%	2.43%
Global Vertexing	0.87%	0.79%
Total	**7.48%**	**8.11%**





$|U|^2$ limits with ND280

- MC efficiency, background, systematics → $|U|^2$ limits
- $(6.2\nu + 2\bar{\nu})10^{20} POT$ statistics (2010-2015 ND280 data)
- $|U|^2$ limits estimated from observed events (Feldman Cousins):

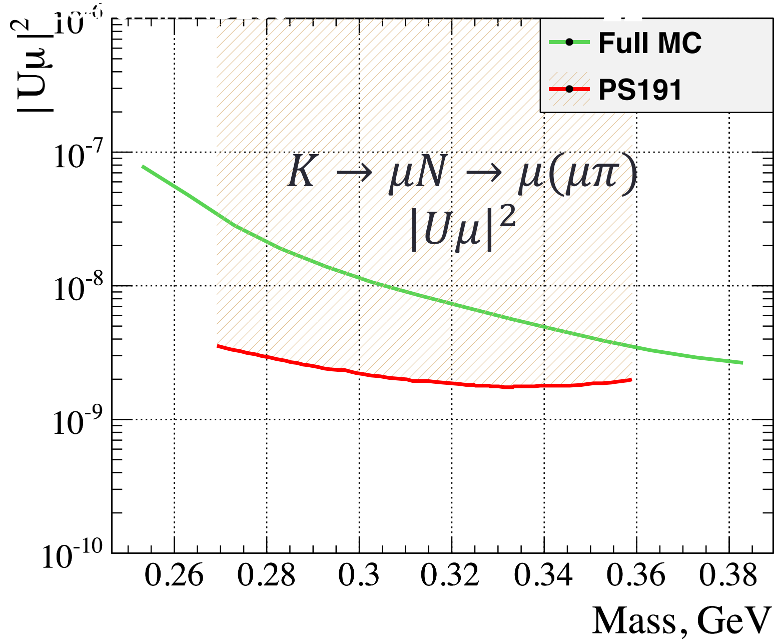
$$U = U_n \left(1 + E\frac{\sigma^2}{2}\right)\left(1 + \left(E\frac{\sigma}{2}\right)^2\right)$$

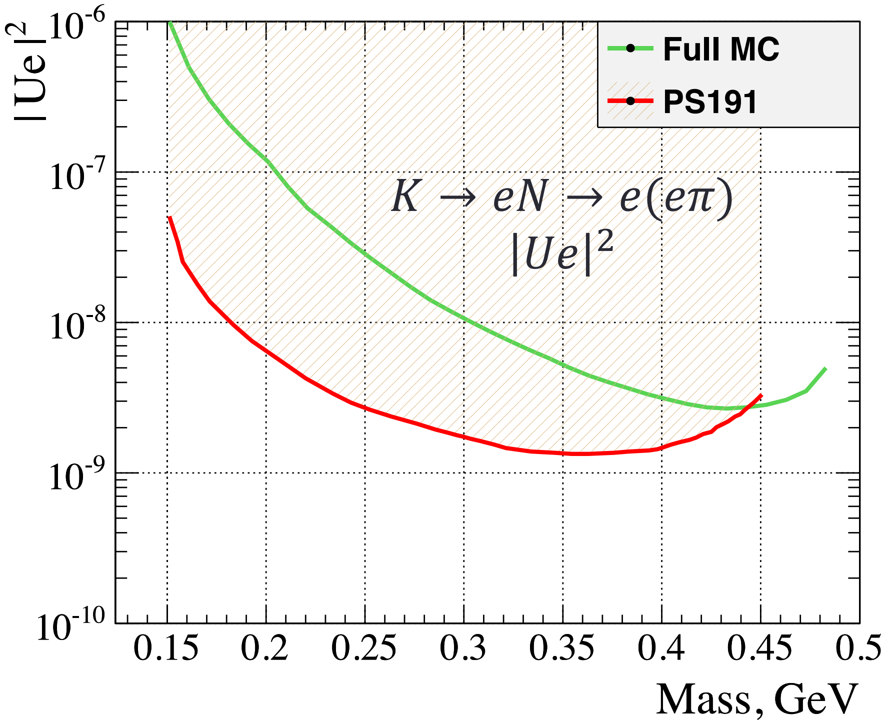
where k_n is CL limit for observed n events (no syst),
$E = k_n - n$,
σ - acceptance RMS

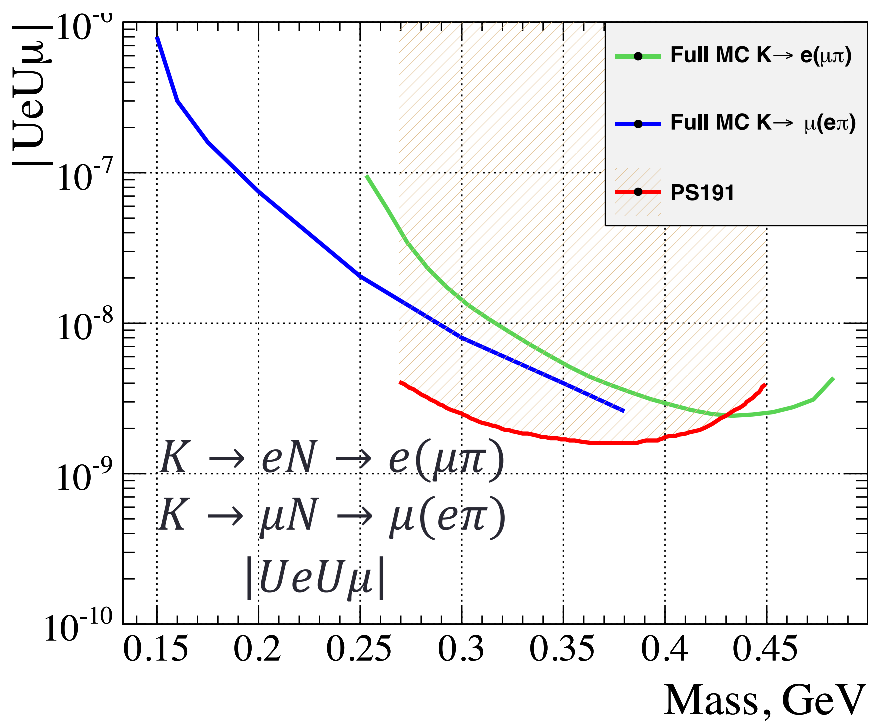
$|U|^2$ limits based on MC

- Red - previous PS191 limit, scaled to HNL Majorana nature
  Green – 90% CL ND280 estimation

$(6.2\nu + 2\bar{\nu})10^{20}POT$ statistics
(2010-2015 ND280 data)







Conclusion

- MC study of HNL production and decays in ND280
- Developed HNL selection→ study efficiency and BG with MC
- Studied detector systematics
- $|U|^2$ expected limits estimated with MC
- Ready for data analysis

Able to improve previous limits in high mass region

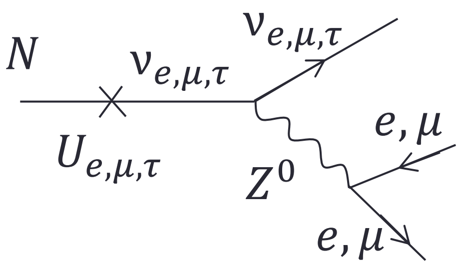
We are here

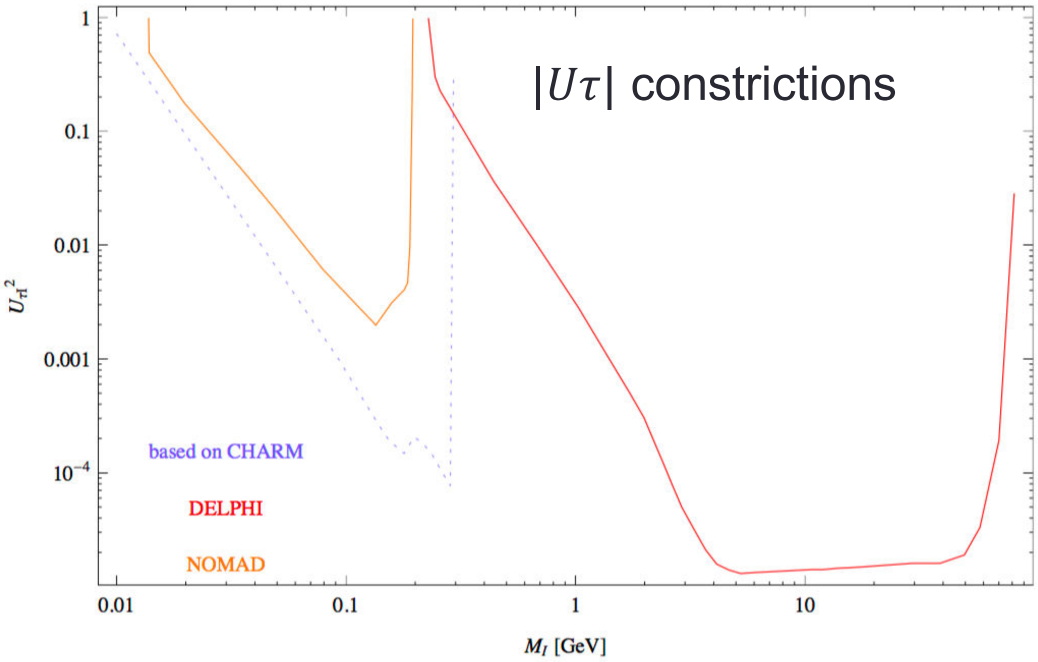
Signal samples generation ⇨ design Selection ⇨ Efficiency study ⇨ Background study ⇨ Systematics ⇨ Data

$|U\tau|$ limits

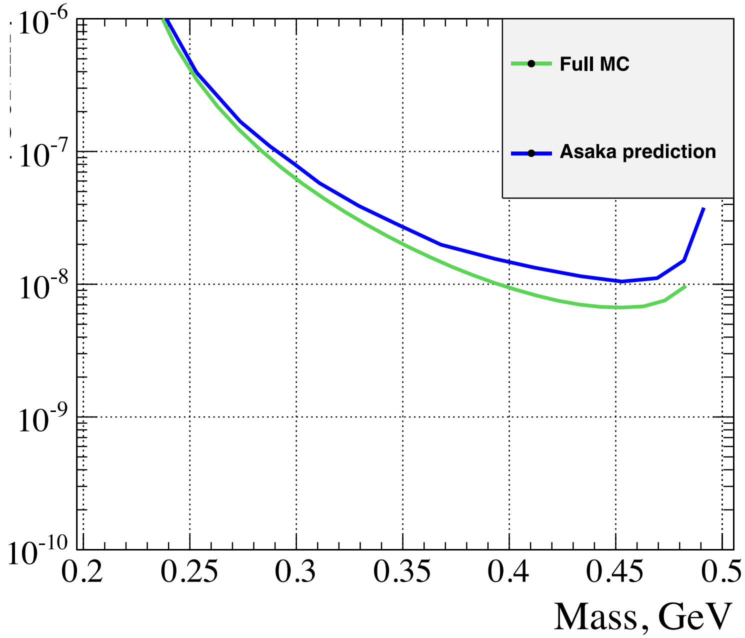
- $|U\tau|$ element is poor studied
- Reaction $N \rightarrow l^- l^+ \nu_{e,\tau}$ through NC provide study $|Ue|\sqrt{|Ue|^2 + |U\tau|^2}$,

assume $|U\mu| \ll |Ue|$





Expected sensitivity to $|Ue|\sqrt{|Ue|^2 + |U\tau|^2}$



BackUP

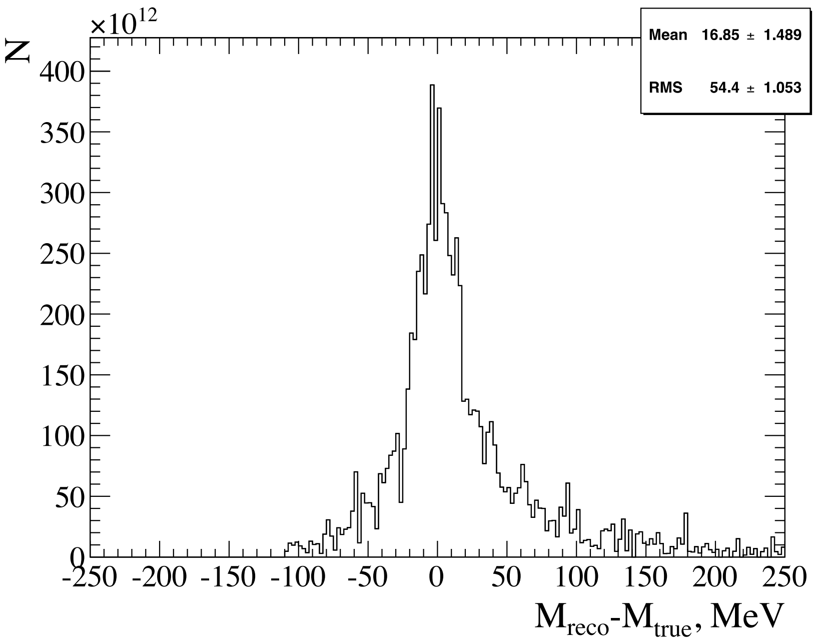
Pile up

- Possible pile up sources:
  - No activity in upstream detector
  - No activity in TPC with HNL candidate vertex

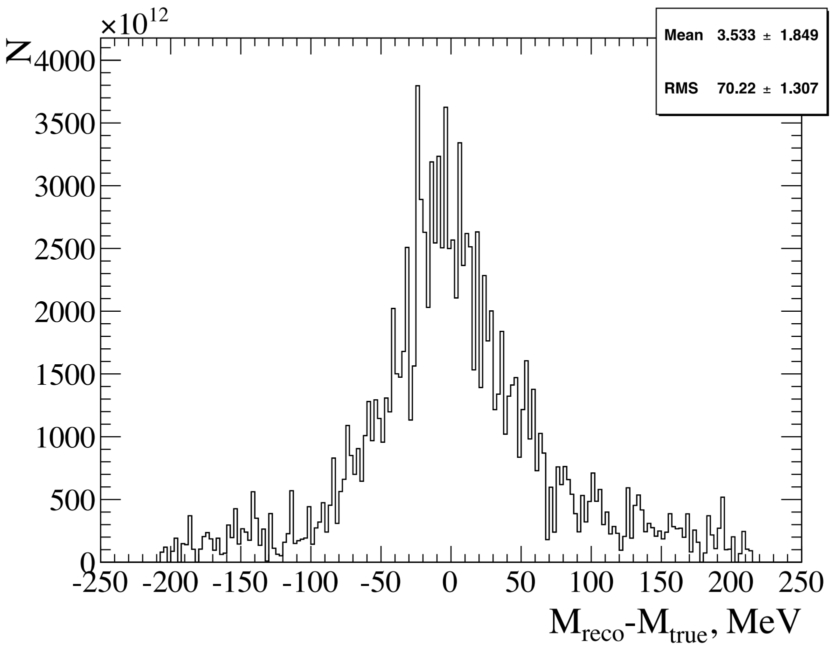
- Study real data for pile up value
- Chose the maximum pile up from all runs for each TPC
  - 3.3% TPC1
  - 3.2% TPC2
  - 2.8% TPC3

Invariant mass resolution

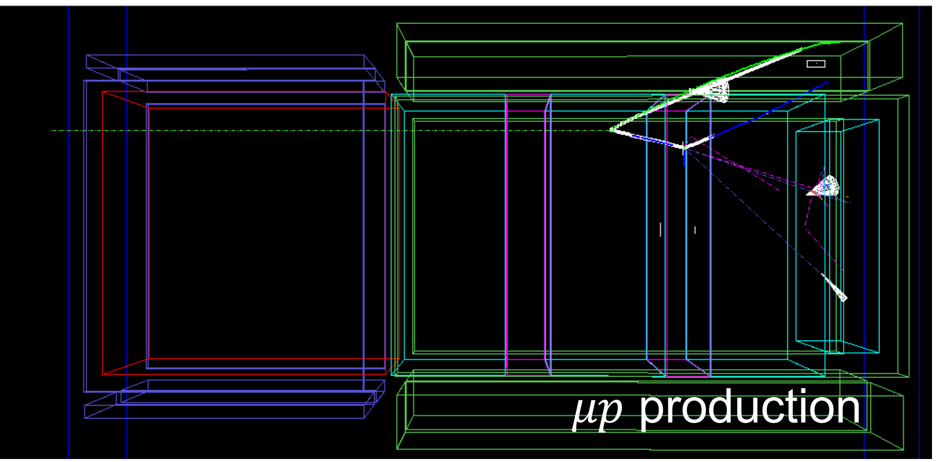
$M = 0.36GeV$

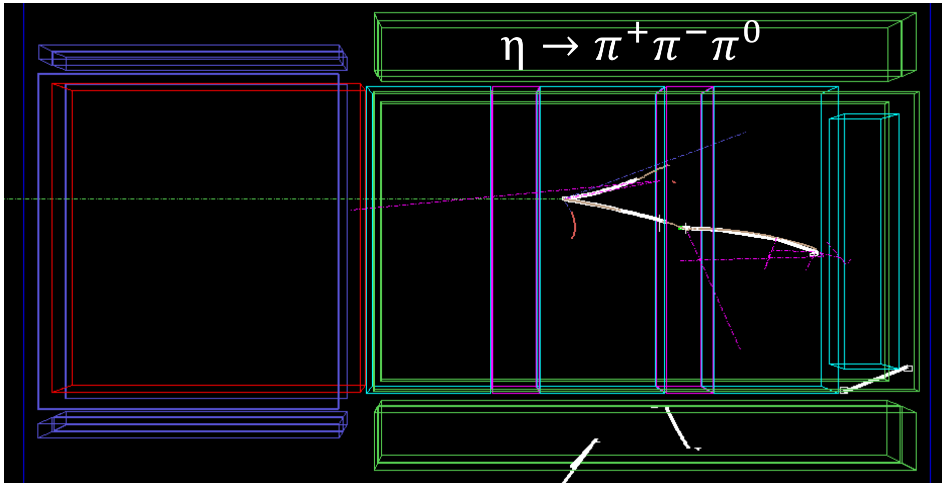


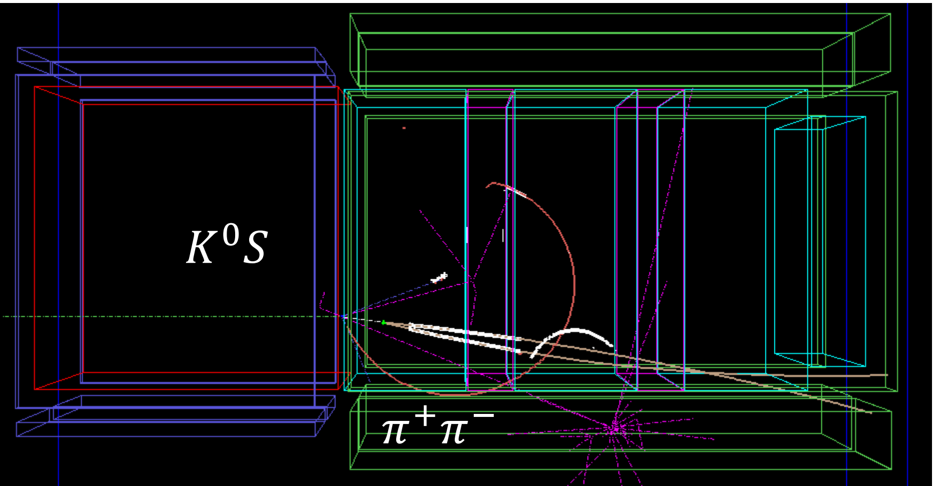
$M = 0.46GeV$

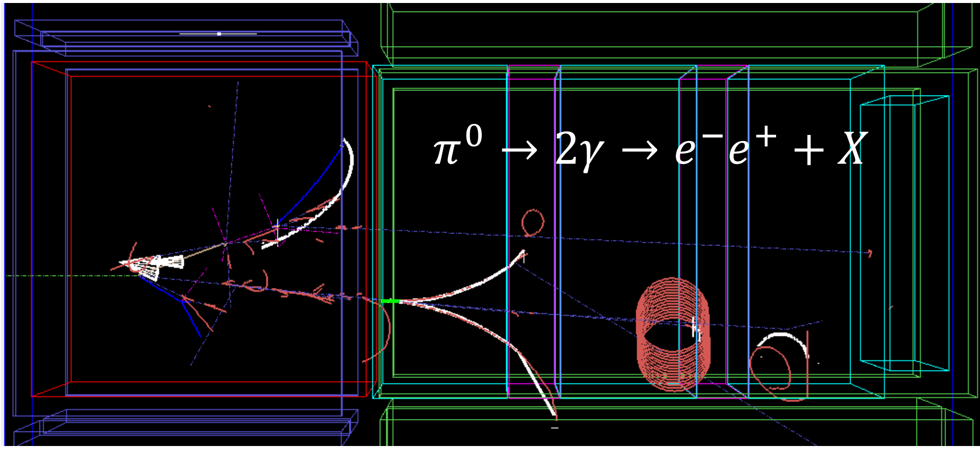


BG


μp production

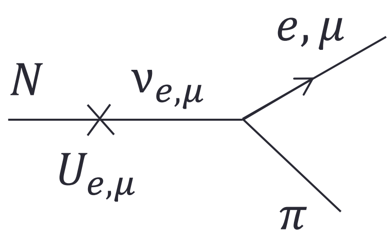

$\eta \rightarrow \pi^+\pi^-\pi^0$


K^0S
$\pi^+\pi^-$


$\pi^0 \rightarrow 2\gamma \rightarrow e^-e^+ + X$

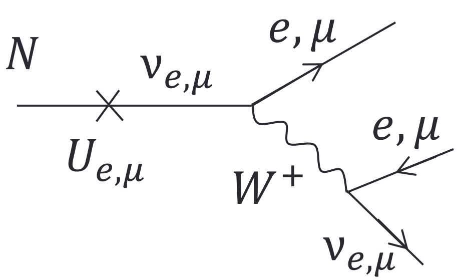
HNL decay

2-body decay:

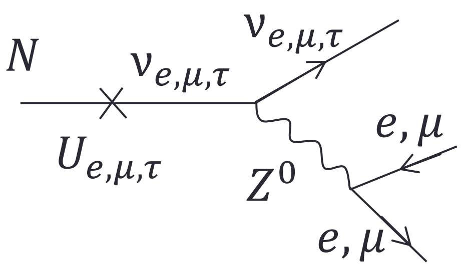


$$N \to e^- \pi^+$$
$$N \to \mu^- \pi^+$$

3-body decay:



$$N \to \mu^{\mp} e^{\pm} \nu_{e,\mu}$$
$$N \to l^- l^+ \nu_l$$

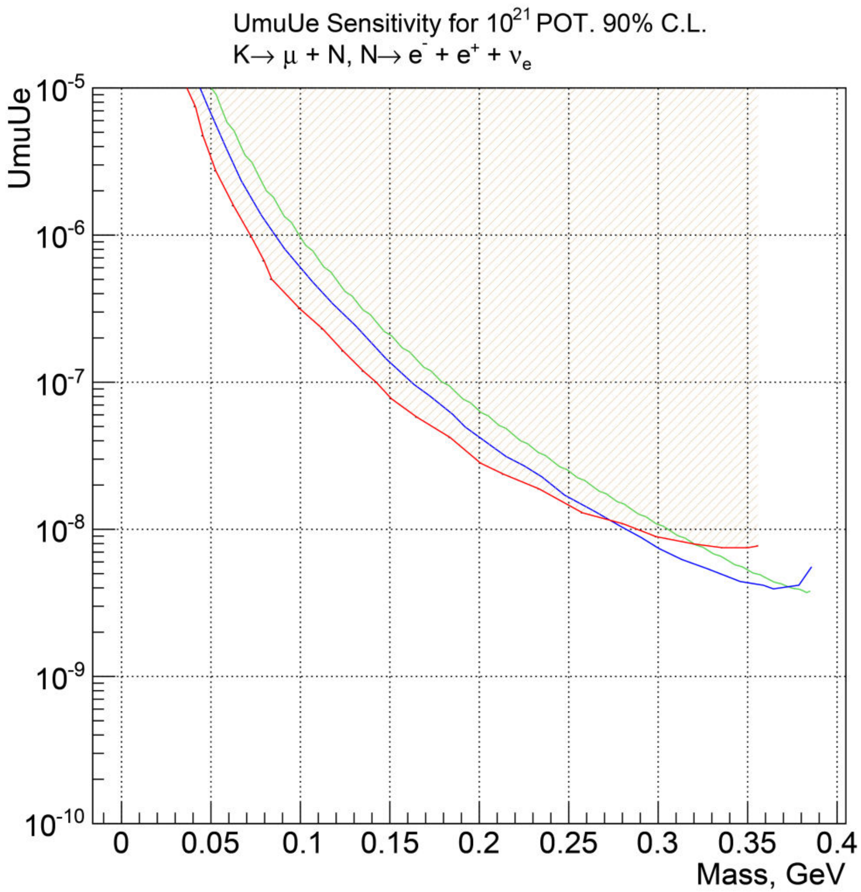


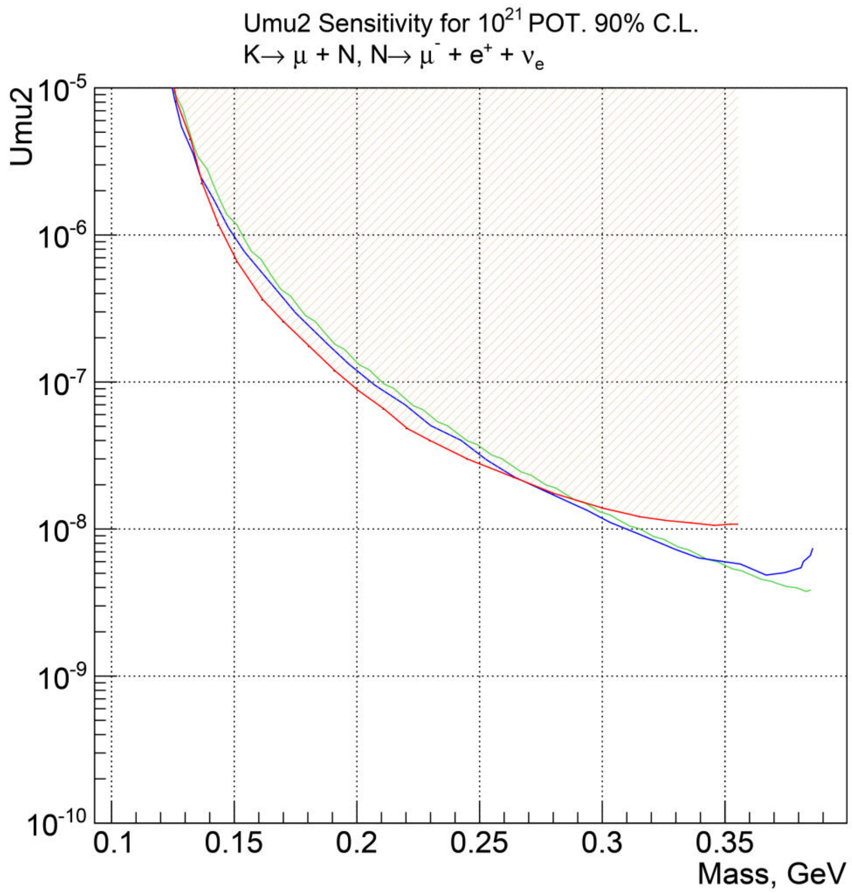
NC

$$N \to l^- l^+ \nu_{e,\mu,\tau}$$

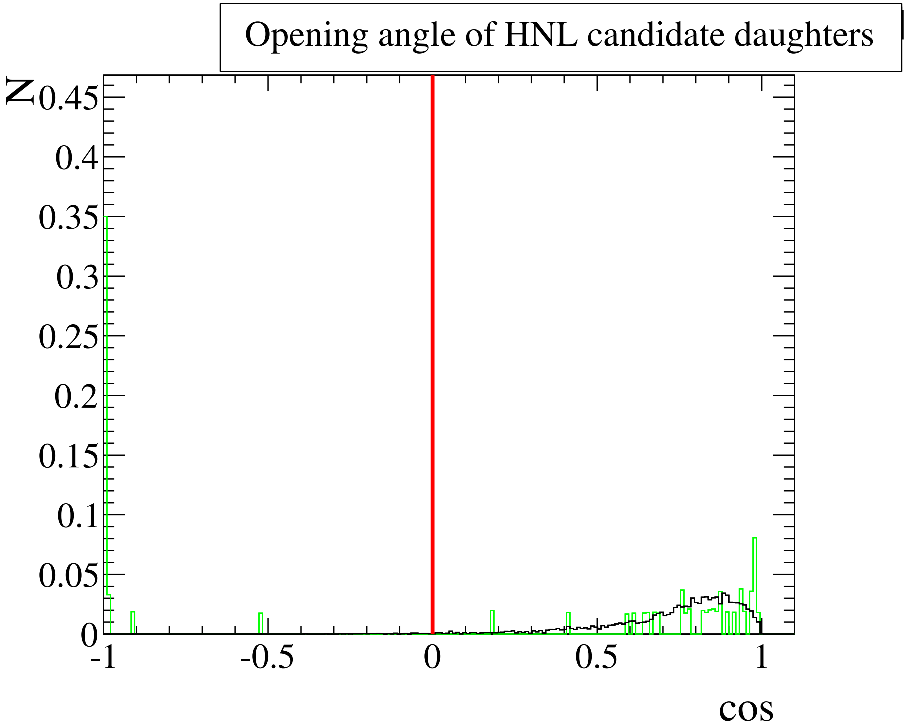
3-body mods

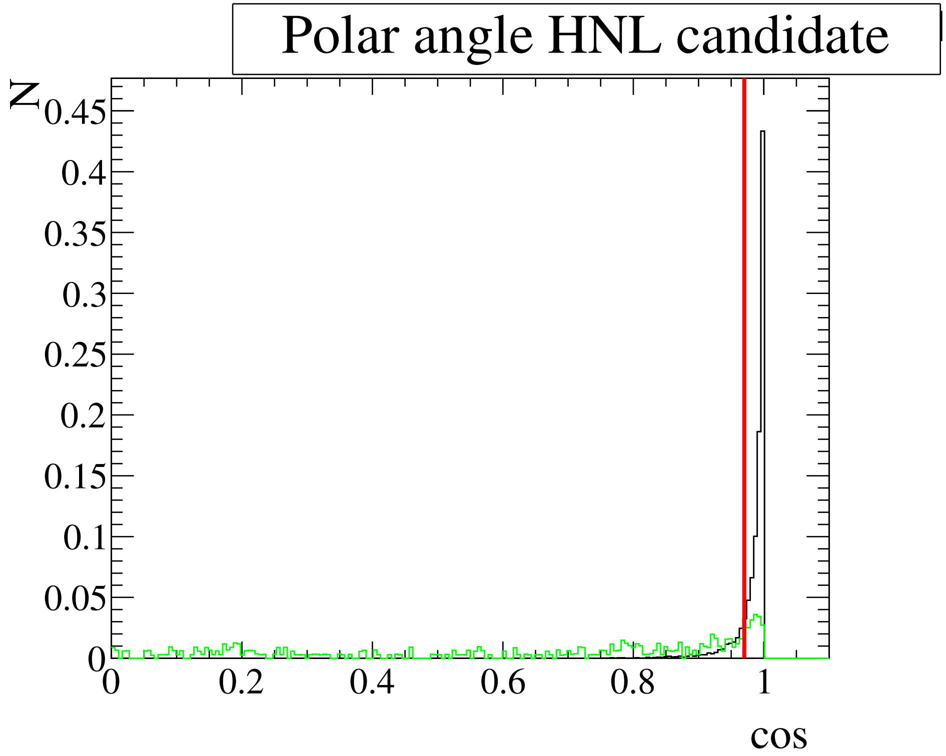
Assume 10^{21} POT, no background, 100% efficiency, 90% C.L



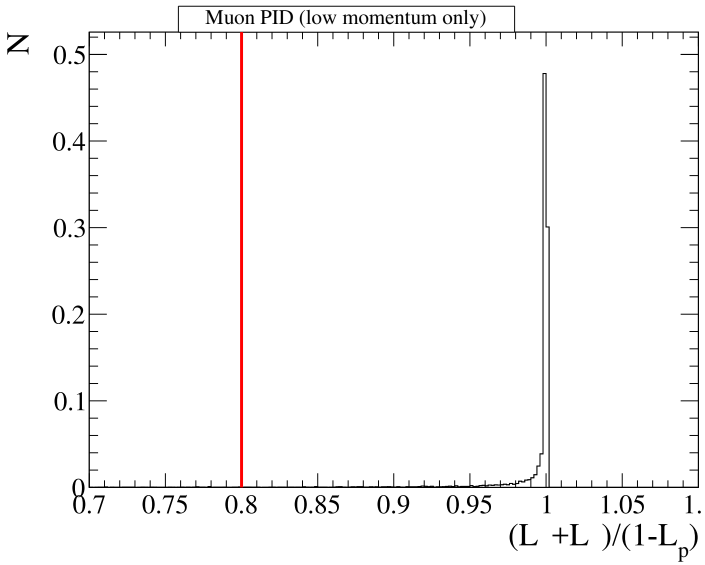


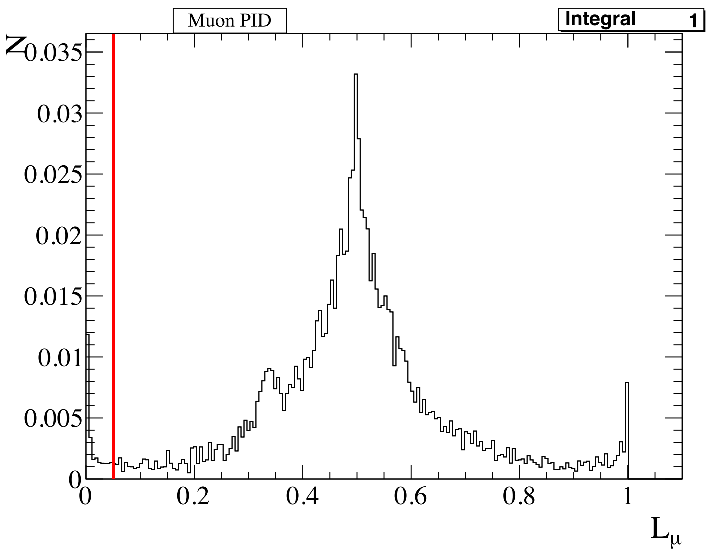
Angle cuts

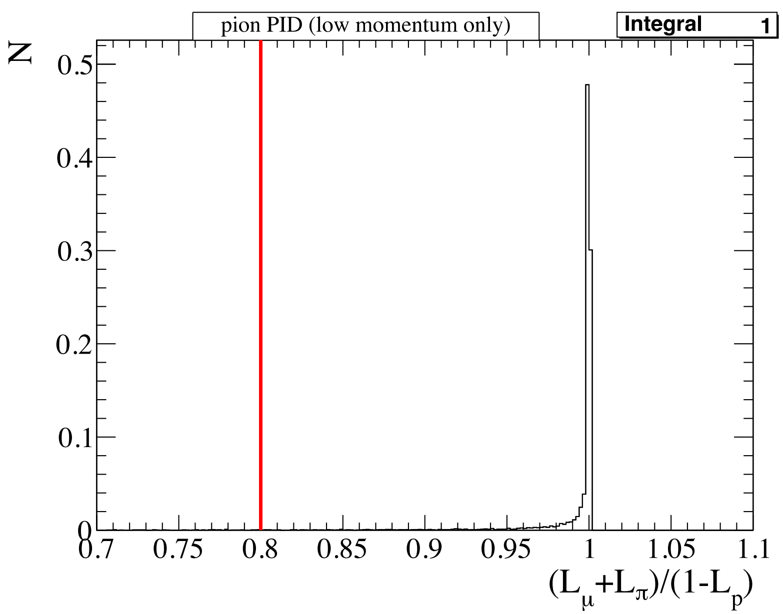

Opening angle of HNL candidate daughters
N
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-1
-0.5
0
0.5
1
cos

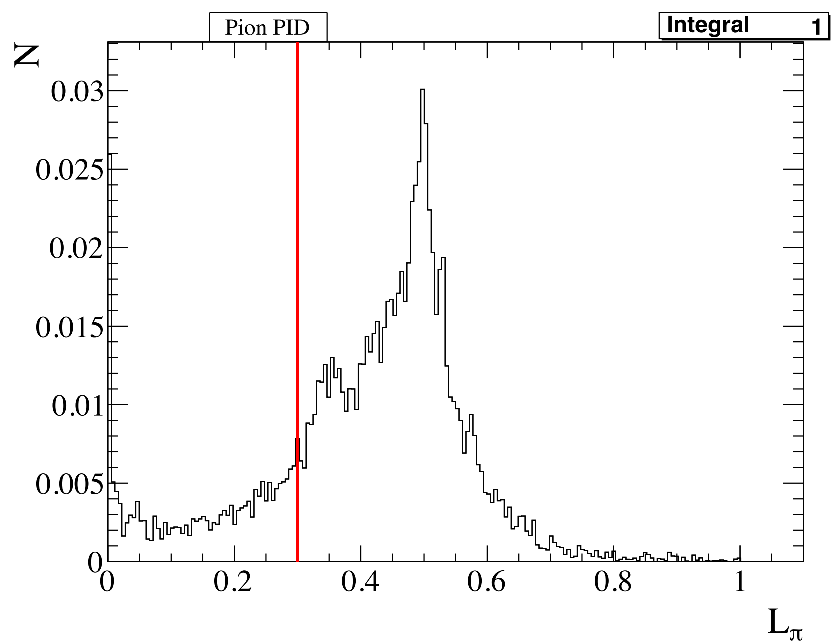

Polar angle HNL candidate
N
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.2
0.4
0.6
0.8
1
cos

PID cuts

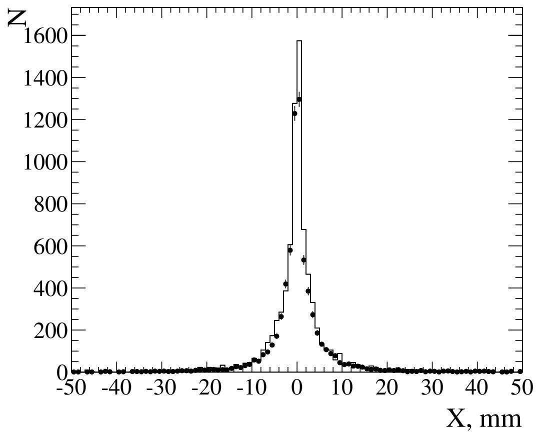

Muon PID (low momentum only)
N
(L +L)/(1-L_p)

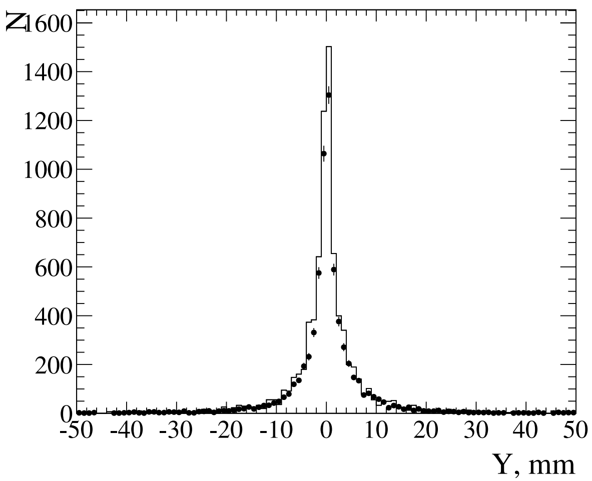

Muon PID
Integral 1
N
L_μ

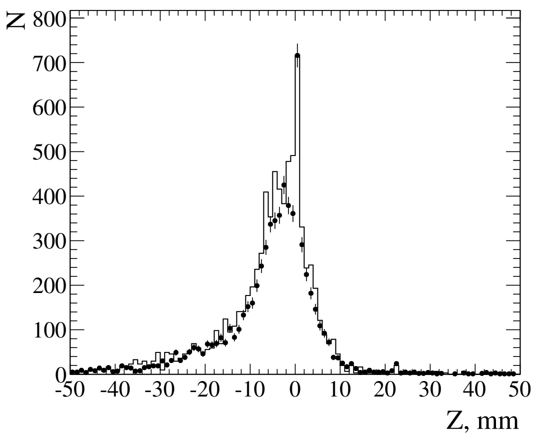

pion PID (low momentum only)
Integral 1
N
(L_μ+L_π)/(1-L_p)

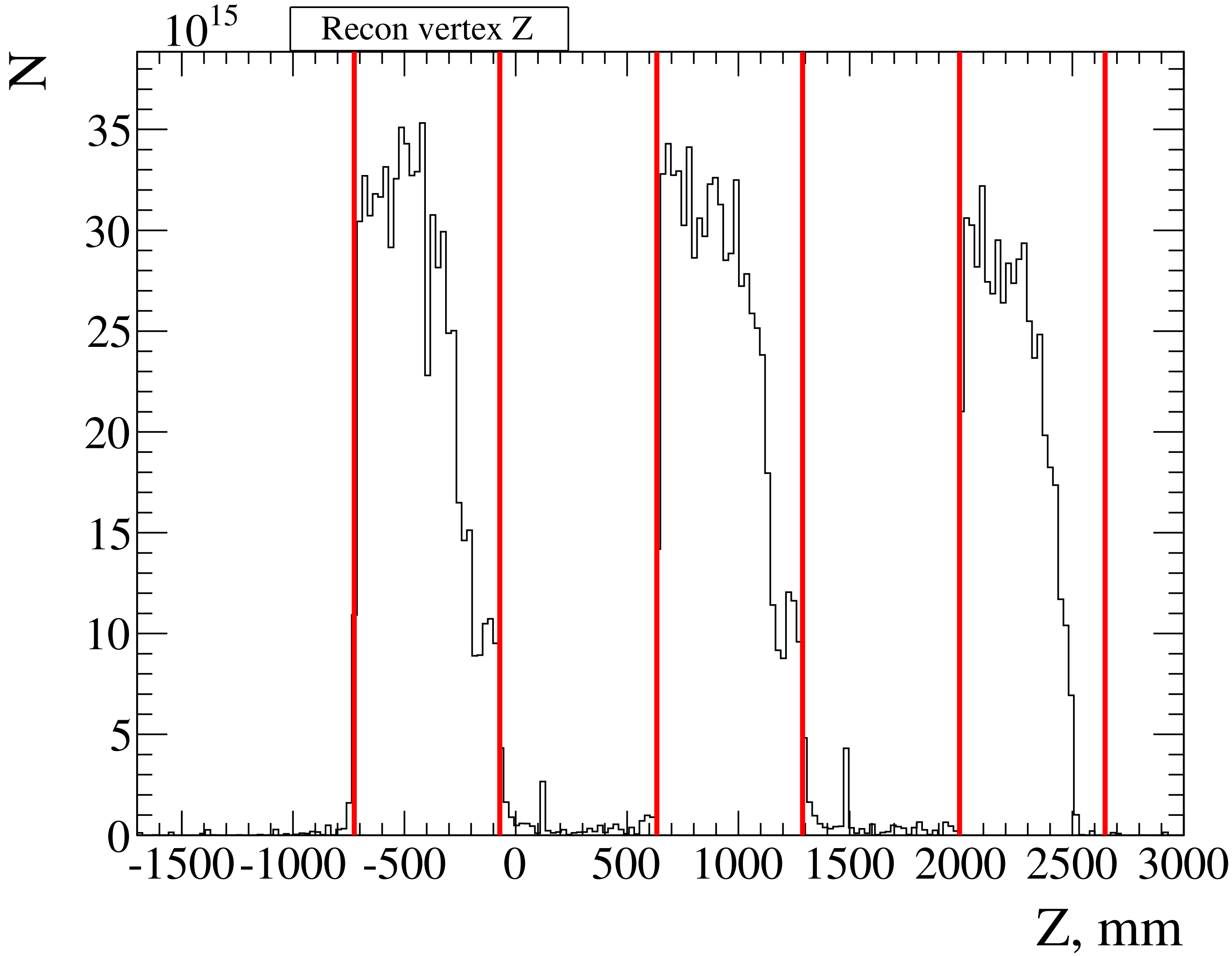

Pion PID
Integral 1
N
L_π

Vertex spatial reconstruction resolution









Recon vertex Z
10^{15}
N
0
5
10
15
20
25
30
35
-1500
-1000
-500
0
500
1000
1500
2000
2500
3000
Z, mm