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Heavy Neutrino Search in accelerator-based experiments

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Heavy (sterile) neutrinos

The particles which mix with the ordinary neutrinos, having the same quantum-numbers

$$\nu_\alpha = U_{\alpha i}\,\nu_i + \Theta_\alpha N$$

Weak eigenstates

$\alpha = e, \mu, \tau$

``PMNS'' matirx

Mass eigenstates

$i = 1, 2, 3$

Active-sterile mixing parameter

$\Theta_\alpha \ll 1$

The sterile neutrinos often appear in extensions of the standard model

``Light'' sterile neutrinos

Besides (usual) super heavy scenarios, lighter masses are also interesting in phenomenology

● eV sterile neutrino $\Rightarrow$ modified neutrino oscillation

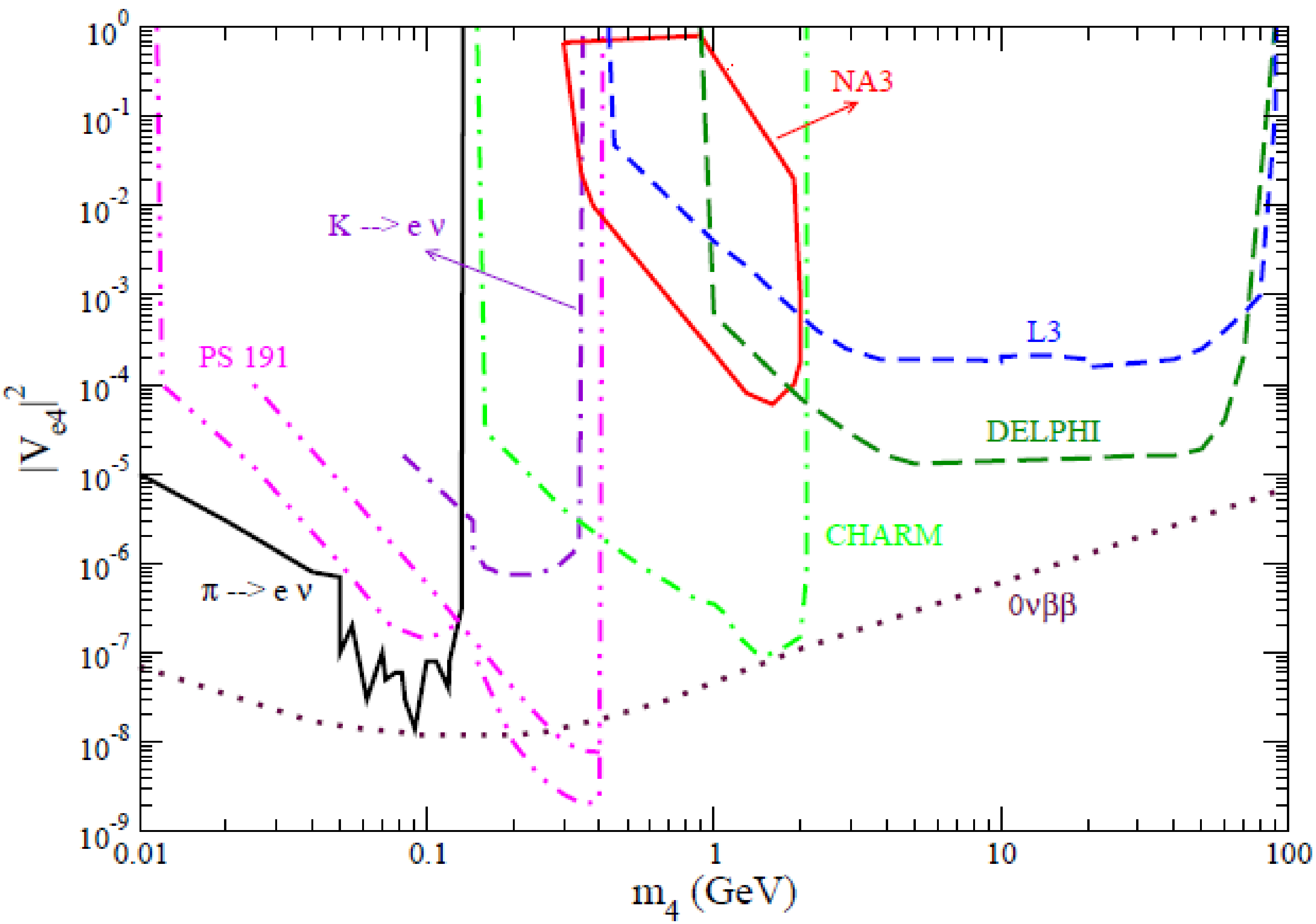
● keV sterile neutrino $\Rightarrow$ a viable dark matter candidate
[Dodelson,Widrow,1994; Shi,Fuller,1999; Dolgov,Hansen,2002;….]

●pulsar kick
[Kusenko,Segre,1997; Fuller,Kusenko,Mocioiu,Pascoli,2003; …]

●baryon asymmetry, νMSM
[Akhmedov,Rubakov,Smirnov,1998; Asaka,Blanchet,Shaposhnikov,2005;….]

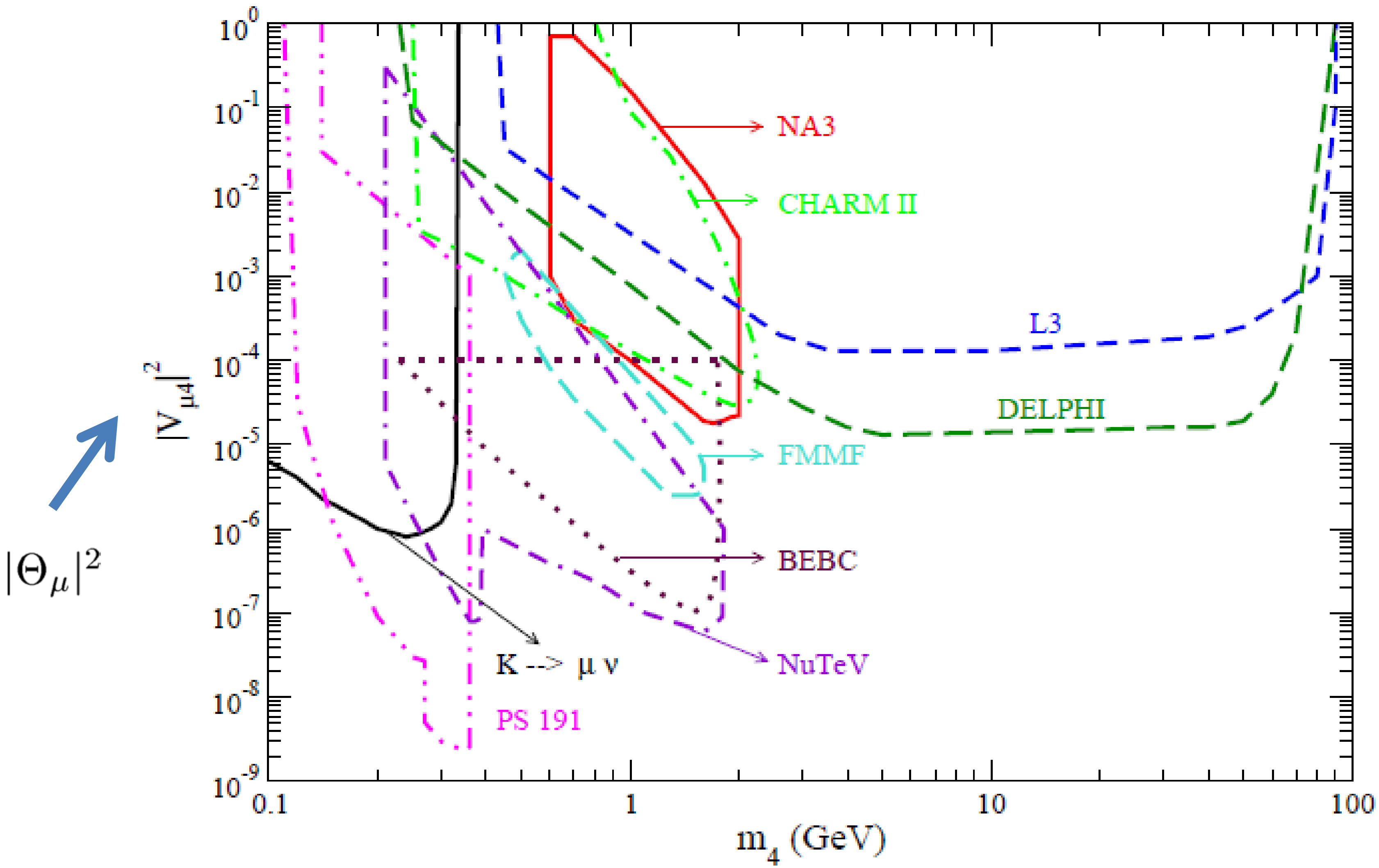
●TeV , EW precision
[Akhmedov, Kartavtsev, Lindner, Michaels, Smirnov,2013]

Experimental constraints on the mass and mixing



$|\Theta_e|^2$

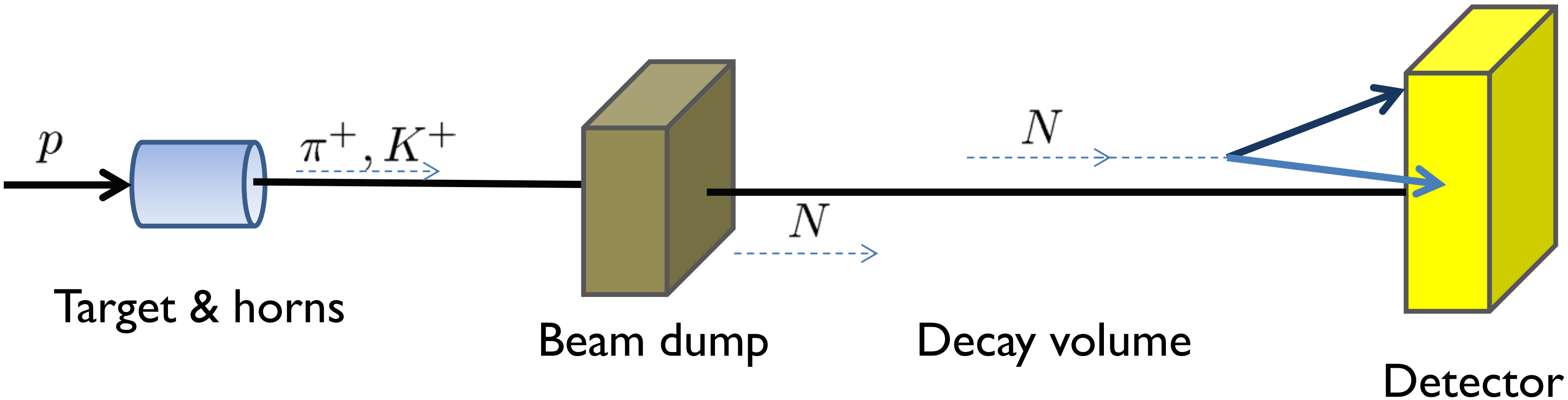
[Atre,Han,Pascoli,Zhan,'09]



In 140 MeV < M < 500 MeV, PS191(1984) has placed the strongest bound

PS191

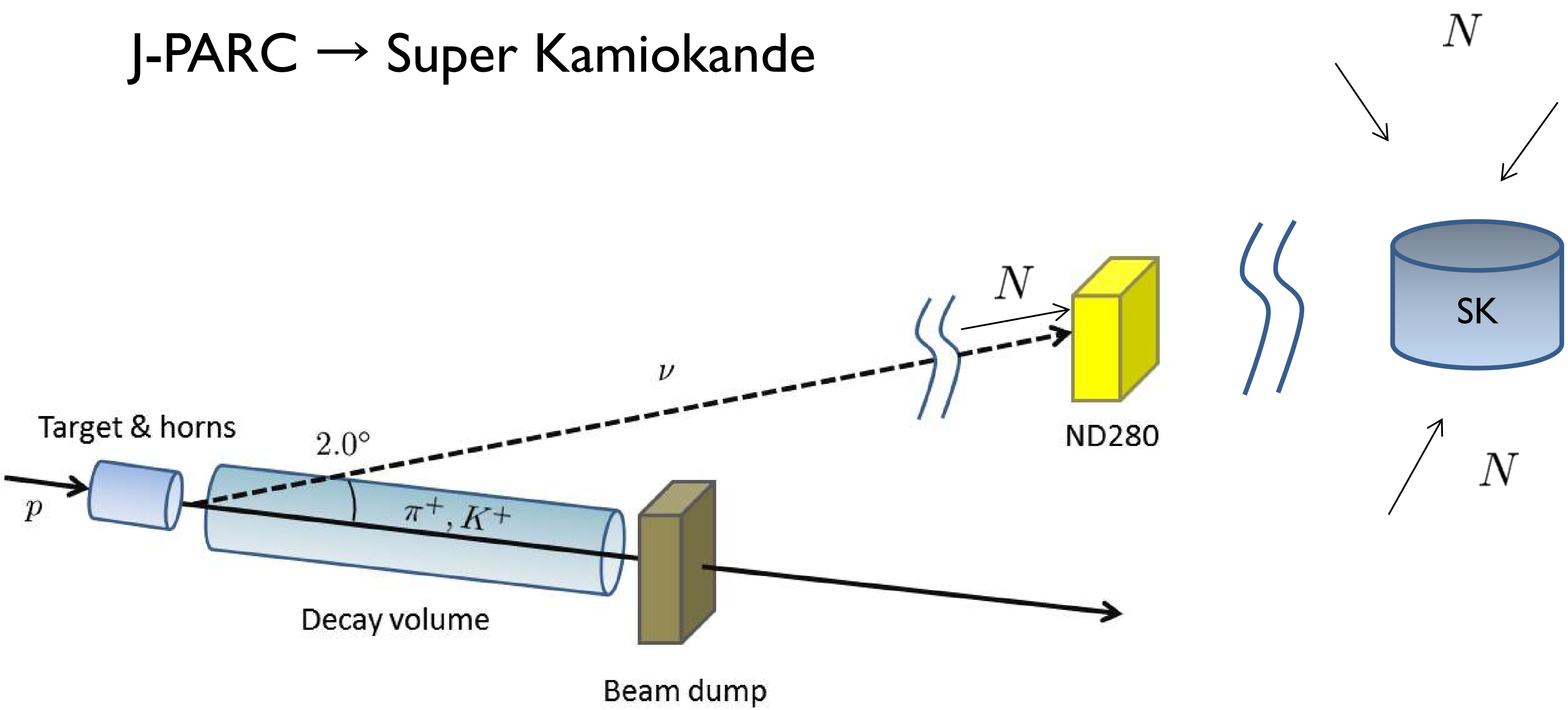
PS191 : beam dump experiment



	PS191	T2K	MINOS	MiniBooNE	SciBooNE
POT	0.86×10^{19}	10^{21}	10^{21}	10^{21}	10^{21}
$(\text{Distance})^{-2}$	$(128\,\text{m})^{-2}$	$(280\,\text{m})^{-2}$	$(1\,\text{km})^{-2}$	$(541\,\text{m})^{-2}$	$(100\,\text{m})^{-2}$
Volume	$216\,\text{m}^3$	$88\,\text{m}^3$	$303\,\text{m}^3$	$524\,\text{m}^3$	$15.3\,\text{m}^3$
Events	1	9.9	2.7	15.8	13.5

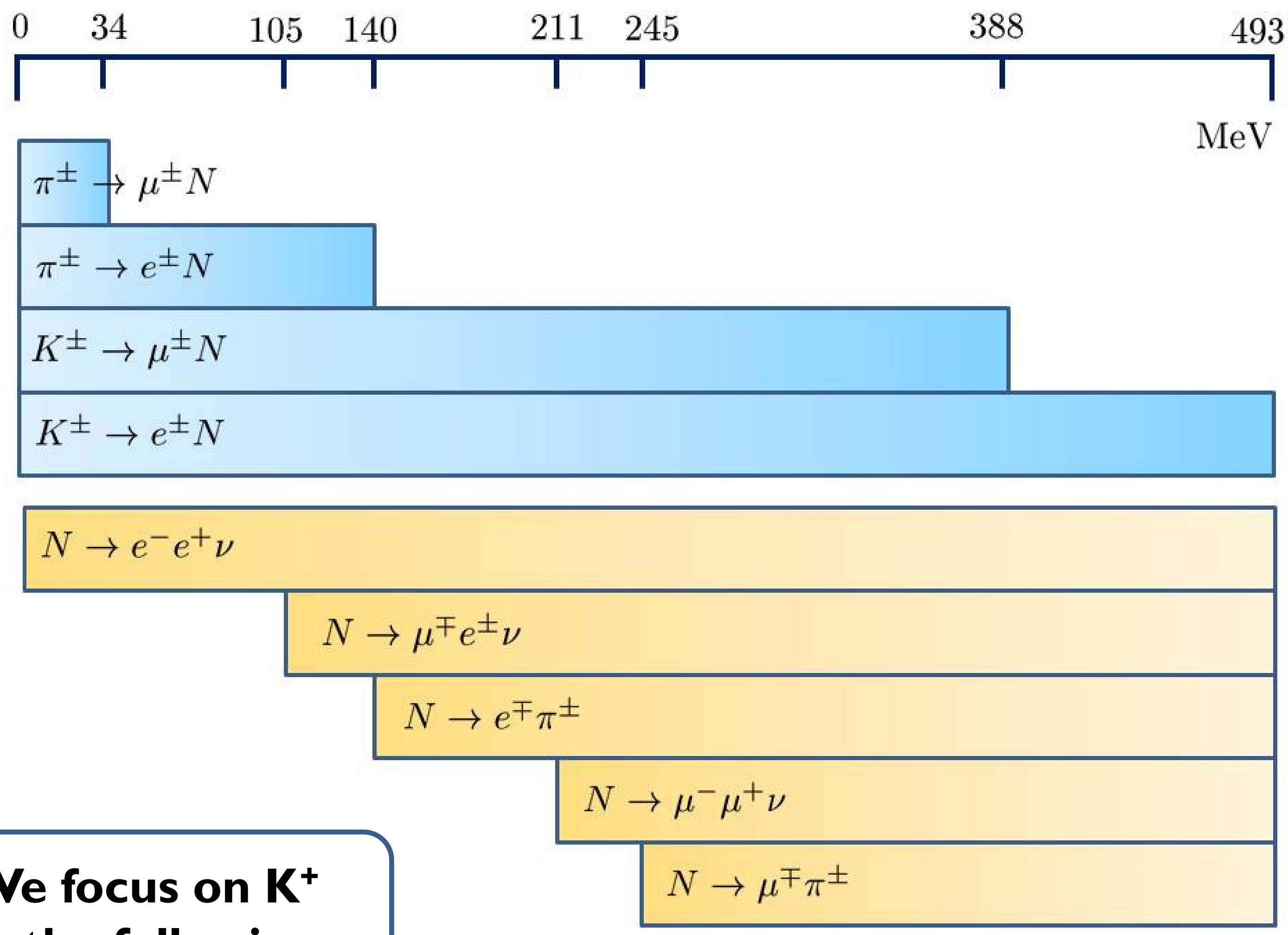
T2K

J-PARC → Super Kamiokande



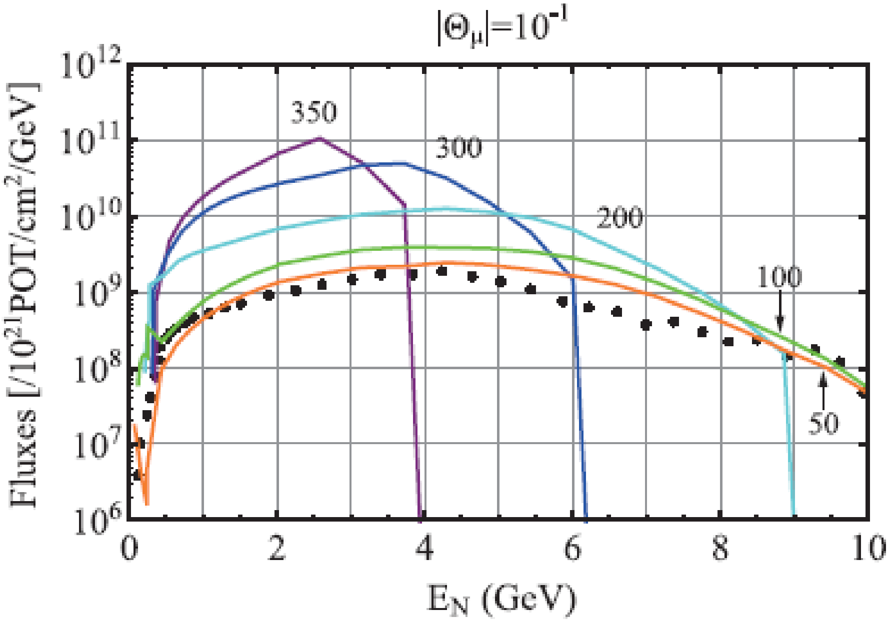
- Ep = 31 GeV
- off-axis ⇒ E = 0.6 GeV

Production and detection of N



We focus on K^+ in the following

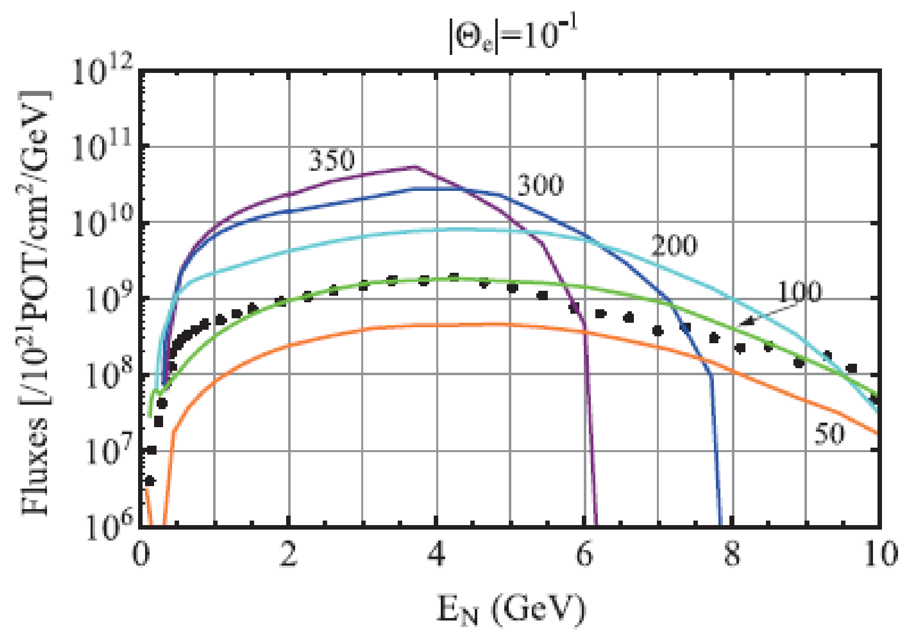
Flux of heavy neutrinos



$K^+ \to \mu^+ N$ only

- Masses of 350,300,200,100,50 MeV
- Dots shows $|\Theta|^2 \times \nu_\mu$

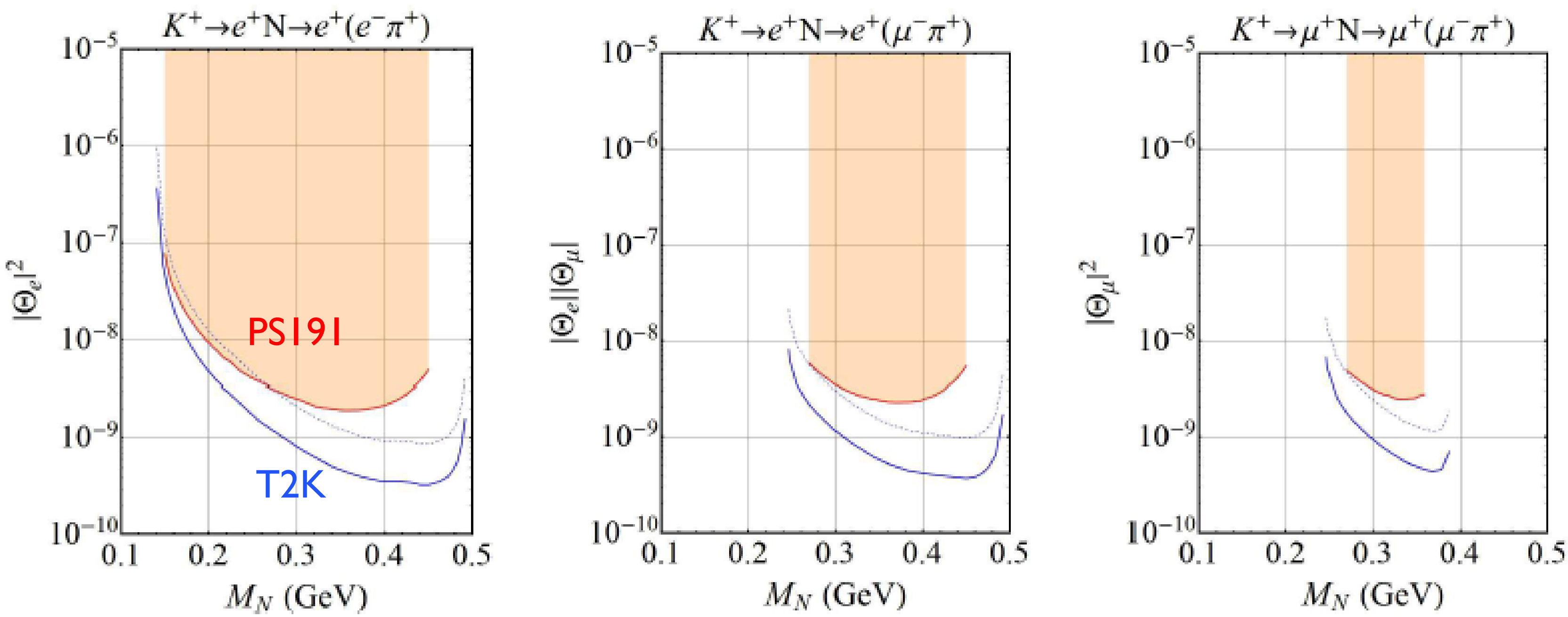
$K^+ \to e^+ N$ only



For larger masses, fluxes can be significantly larger than the naive expectation「$|\Theta|^2 \times \nu_\mu$」 at low energy

- Chirality suppression (enhancement)
- Phase space effect

Expected sensitivities from the two-body modes



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

- Red solid curve PS191(90%CL)
- Blue solid curve 90%CL limit when zero signal is observed with zero background
- Blue dotted curve V = 9 m^3 (Full volume is 61.25 m^3) ⇒ next slide

Comments about the backgrounds

Interactions of the active neutrinos

$$\nu_\mu + n \to \mu^- + \pi^+ + n \qquad (\mathrm{CC} - n\pi^+)$$

$$\nu_\mu + {}^{16}\mathrm{O} \to \mu^- + \pi^+ + {}^{16}\mathrm{O} \qquad (\mathrm{CC} - \mathrm{coherent}\ \pi^+)$$

∼7300 events/10^{21} POT/ton

[Karlen'05]

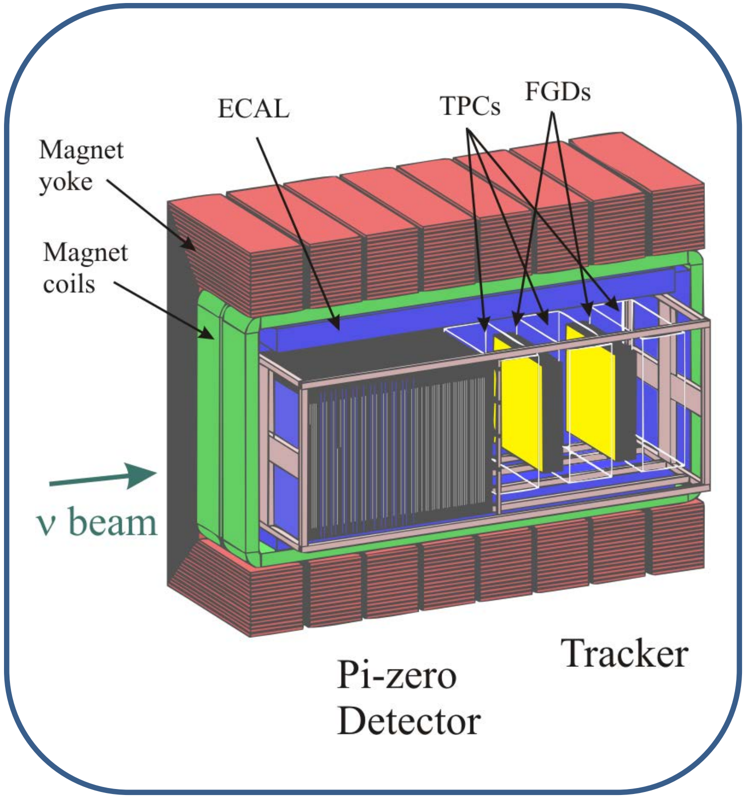
- Invariant mass distribution of μ- and π+ momenta

⇒ Signals peak at the heavy neutrino mass
It would be nice if the background distribution is mild(?)

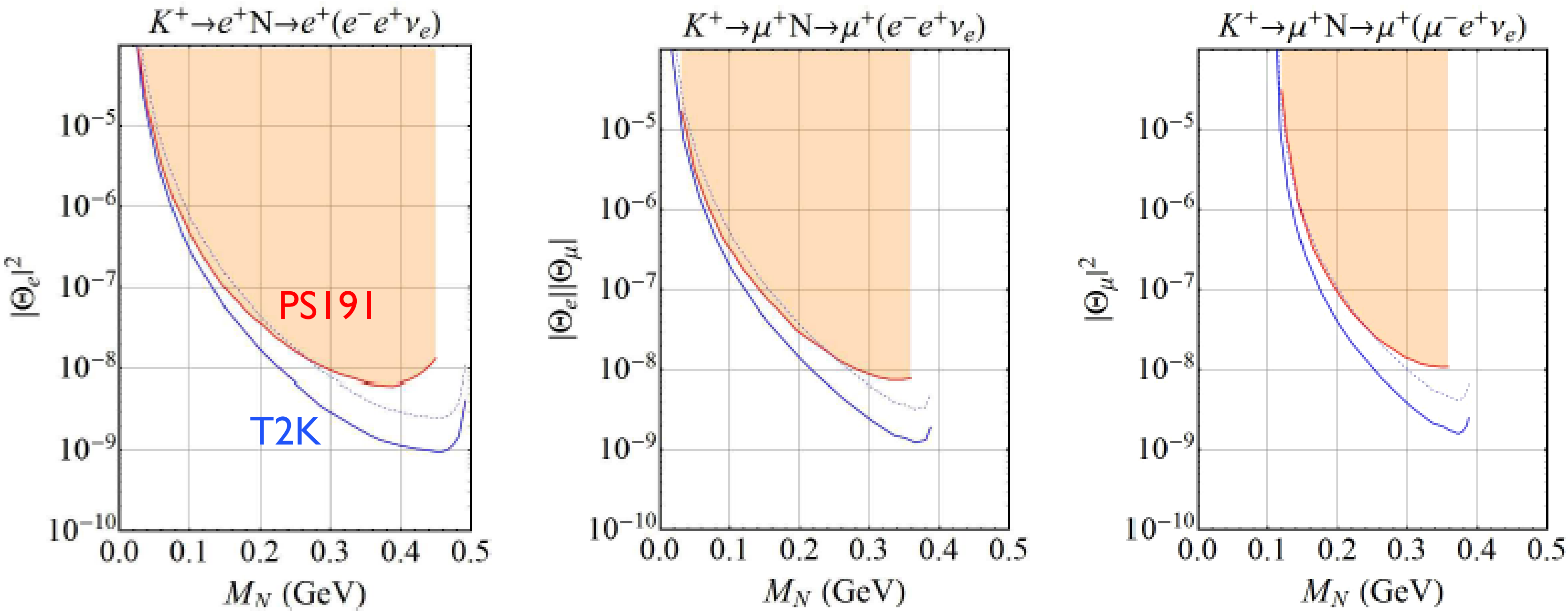
- The backgounds can be suppressed if we restricts the events happened in TPC volume filled in Argon gas

∼80 events/10^{21} POT

- ν_e is smaller than ν_μ two orders of magnitude
$N \to e^- \pi^+$ is promising



Three-body modes



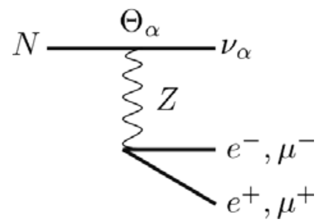
$N \to e^- e^+ \nu$ $N \to e^- e^+ \nu$ $N \to \mu^- e^+ \nu$

- N → e-e+ν π^0decay may be a serious background. Not promising compared to others
- N → μ-e+ν ν_μ CC -> D semi-leptonic decay , but this is rare since T2K uses off-axis beam
- N → μ-μ+ν is also promising

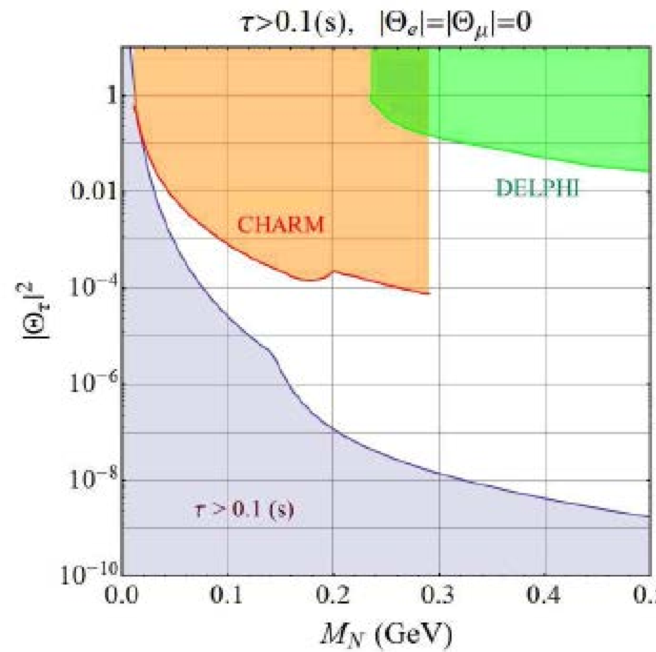
＊σ of the charm production is 1%（4%）of total @5GeV（15GeV）

About Θτ

Θτ does not appear in production,
but appear in detection via NC



Θτ does not appear π and K decay,
so the bouds are weaker than Θe and Θμ



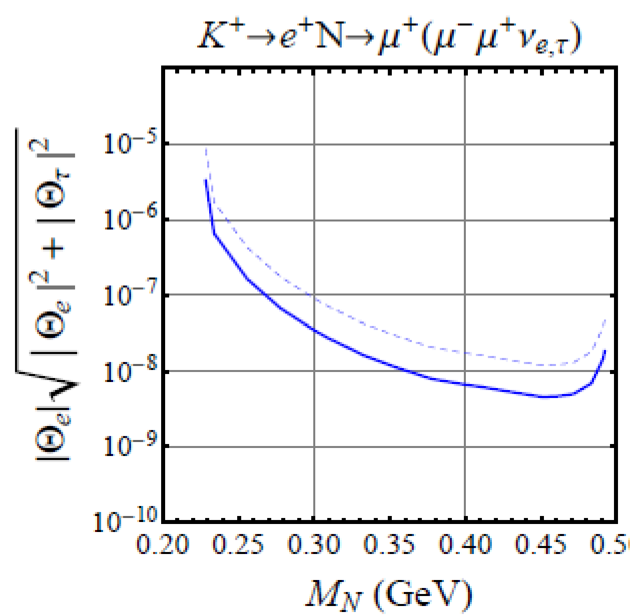
For example…

$|\Theta_e|, |\Theta_\tau| \gg |\Theta_\mu|$ and $M_N > 211\,\mathrm{MeV}$

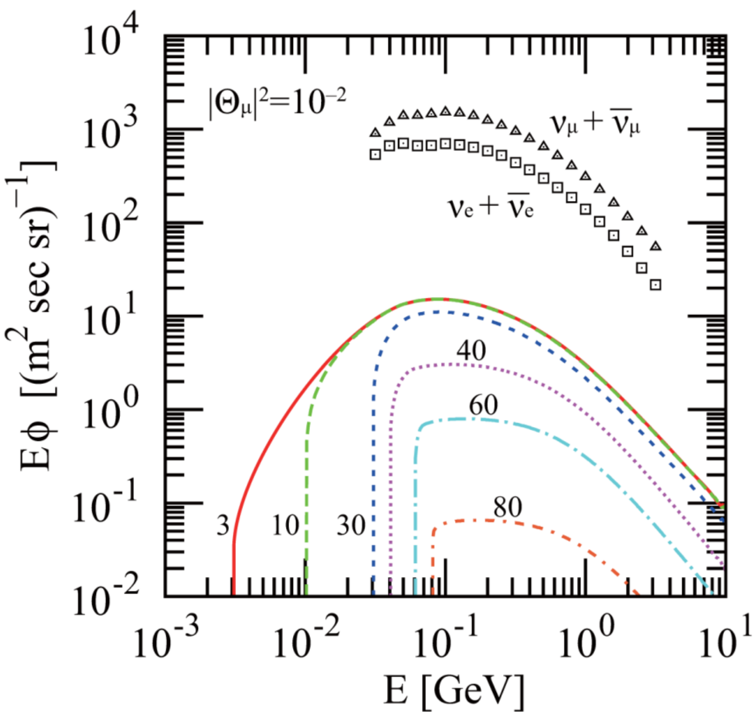
$\Rightarrow \quad |\Theta_e|\sqrt{|\Theta_e|^2 + |\Theta_\tau|^2}$ can be probed

e.g., 300 MeV < M_N < 400 MeV → $|\Theta_e|^{-4.5}, |\Theta_\tau|^{-2.5}$

⇒ Both N → μ-μ+ν and N → e-π+ are observable

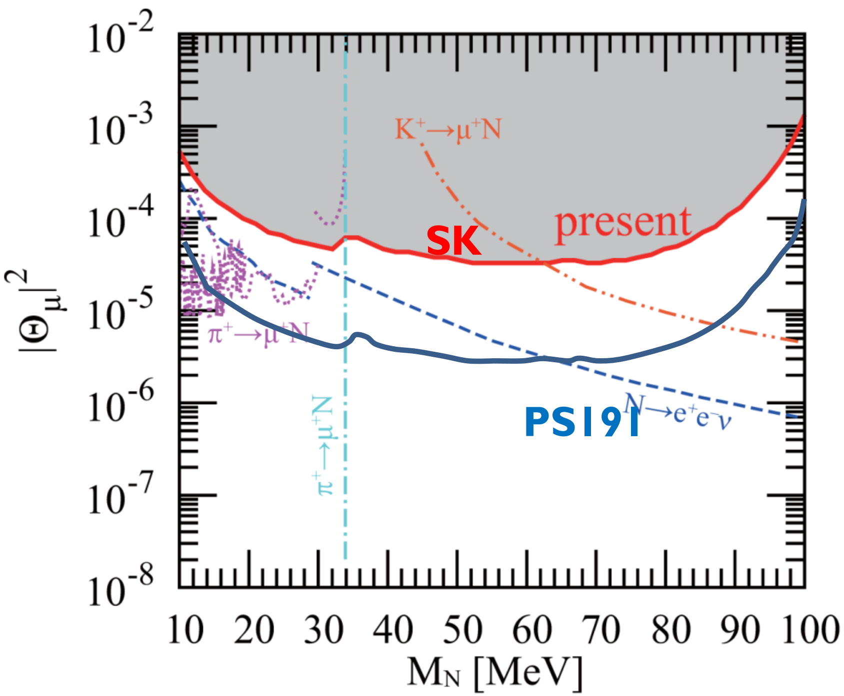


Production in the atmosphere



The main production processes

$$\pi^\pm \to \mu^\pm N$$
$$\mu^\pm \to e^\pm \nu_e(\bar{\nu}_e) N$$



Signal:

$$N \to e^+ e^- \nu$$

in the Super-Kamiokande

Summary

We have explored the detectability of the heavy neutrinos of 1MeV - 500MeV at the T2K experimet

- T2K can do better than PS191(In particular $N \rightarrow e^- \pi^+$)
- In the flux of the heavy neutrinos from Kaon decay, the mass effect is very important (when M_N > 100 MeV). $\Phi_N \neq |\Theta|^2 \Phi_\nu$
- S/N ratio can be enhanced by selecting the events in the TPC volume

Decay events at the detector

$$\text{Events} \simeq \int_{M_N}^{\infty} dE_N \; \phi_N(E_N) \, \frac{V}{\lambda},$$

ND280 volume

Decay length for

To compare T2K and PS191, we assume

- N is Dirac
- Neglect NC contribution in 3-body decay of N
- In the production of N, Either K+ → μ+N or K+ → e+N dominates the other

About the lifetime and the total decay length

$$\Gamma(N \to e^-\pi^+) = \frac{|\Theta_e|^2}{16\pi} G_F^2 |V_{ud}|^2 f_\pi^2 M_N^3 \left(1 - \frac{m_\pi^2}{M_N^2}\right)^2$$

$$\tau = \frac{\hbar}{\Gamma} \simeq 5.3 \times 10^{-10} \, |\Theta_e|^{-2} \left(\frac{0.3\,\mathrm{GeV}}{M_N}\right)^3 \left(1 - \frac{m_\pi^2}{M_N^2}\right)^{-2} \quad \mathrm{(s)}$$