Search for heavy neutrinos with the T2K near detector

A. Izmaylov[1,3], **M. Lamoureux**[2], S. Suvorov[2,3] for the T2K collaboration

[1]IFIC, Valencia, Spain ; [2]IRFU, CEA, France ; [3]INR, Moscow, Russia

(mathieu.lamoureux@cea.fr)

Heavy neutrinos

Motivation

- ➢ In the Standard Model, neutrinos are left-handed (ν_L) and massless, while oscillations imply small but non-zero masses ⇒ need to go beyond the SM.
- ➢ A minimal way is to introduce 3 right-handed neutrino singlets ν_R and to use both Dirac and Majorana mass terms:

$$\mathcal{L}^{D+M} = -\frac{1}{2}\left(\overline{\nu_L}\ \overline{\nu_R^c}\right)\underbrace{\begin{pmatrix} 0 & m_D \\ m_D^T & m_R \end{pmatrix}}_{\mathcal{M}}\begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + \text{h.c.}$$

Heavy neutrinos and their mixings

$\mathcal{M}$ is diagonalized under the assumption $\theta \equiv m_D m_R^{-1} \ll 1$:

3 interaction eigenstates ($\nu_{e,\mu,\tau}$) — 3 light mass eigenstates (m_i) — 3 heavy mass eigenstates (M_I)

$$\nu_\alpha = V_{\alpha i}\,\nu_i + \theta_{\alpha I}\,N_I$$

PMNS matrix ($V_{\alpha i}$) — heavy neutrinos mixings ($\theta_{\alpha I}$)

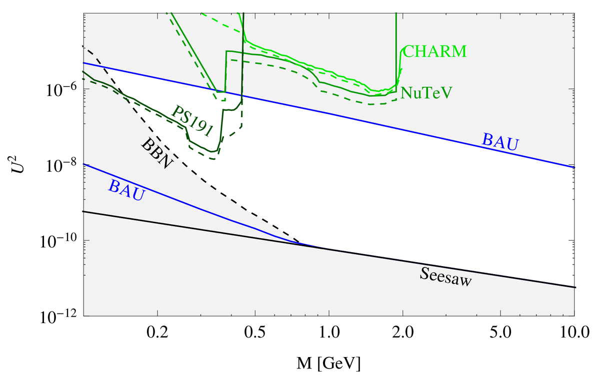
$|V_{\alpha i}| = \mathcal{O}(1)$

$|\theta_{\alpha I}| \equiv U_{\alpha I} = \mathcal{O}\left(\sqrt{\frac{m_\nu}{M_N}}\right)$

$\sim 10^{-5}$ for $M_N \sim$ GeV and $m_\nu \sim 0.1$ eV

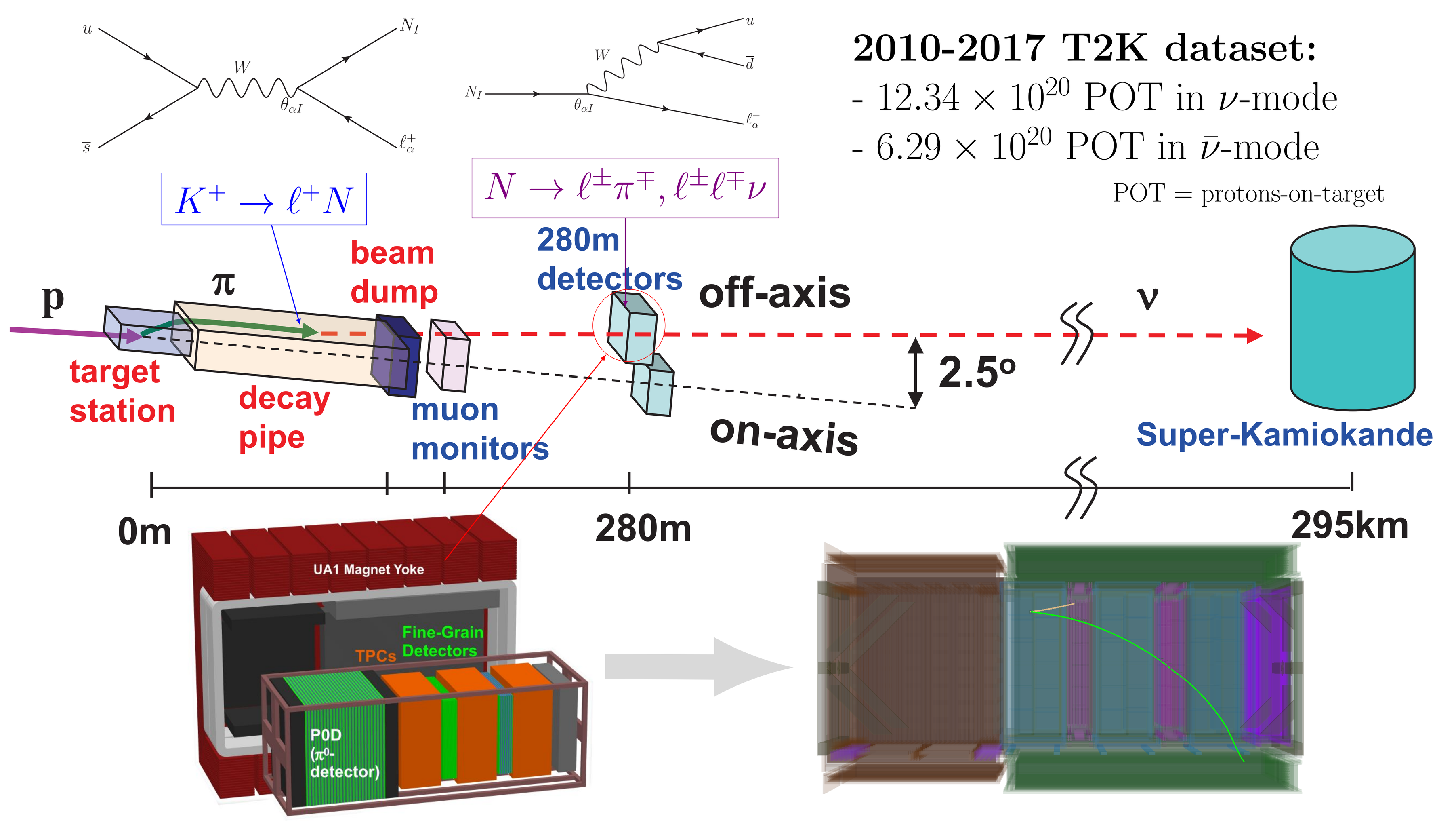
Heavy neutrinos below the electroweak scale

- ➢ If $M_N \sim 0.1 - 100$ GeV, they can generate **baryogenesis** via leptogenesis.
- ➢ For instance, the νMSM model contains two heavy neutrinos $N_{2,3}$ with: $M_2 \simeq M_3 = 0.1 - 100$ GeV.



Review: *The Phenomenology of Right Handed Neutrinos*, M. Drewes
νMSM first introduced by T. Asaka& M. Shaposhnikov (arXiv:0503065)

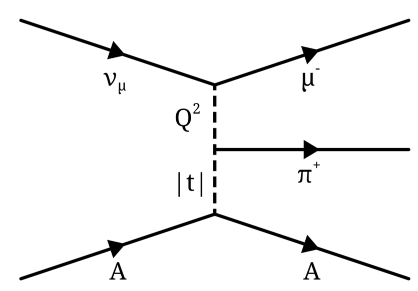
T2K (Tokai to Kamioka) experiment†



2010-2017 T2K dataset:
- 12.34×10^{20} POT in ν-mode
- 6.29×10^{20} POT in $\bar{\nu}$-mode

POT = protons-on-target

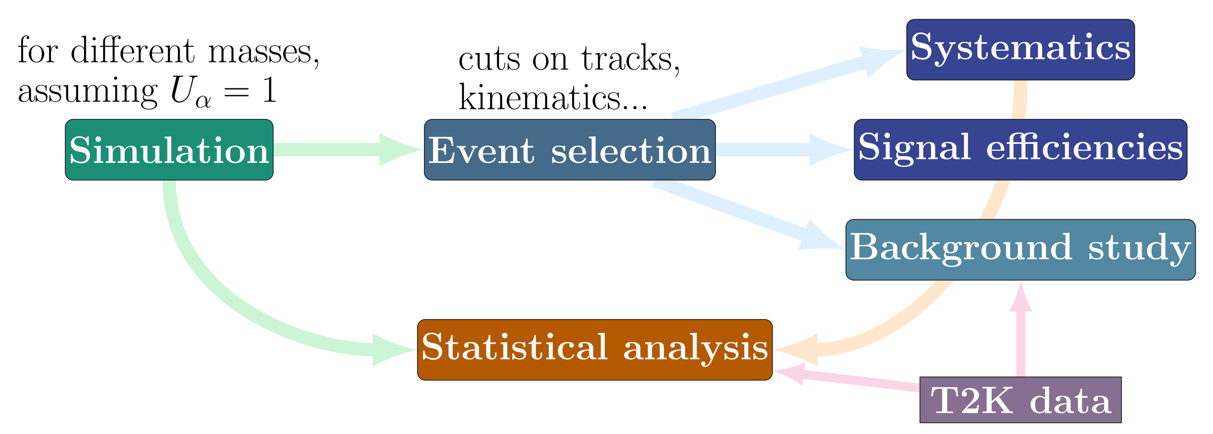
- ➢ Heavy neutrinos can be produced in $K^\pm$ decays ($M_N < 493$ MeV) along standard ν beam.
- ➢ They can be detected in ND280, through their semi-leptonic or leptonic decays.
- ➢ Background comes from interactions of active ν, e.g. coherent pion production $\nu_\mu + \text{A} \to \mu^- + \text{A} + \pi^+$.
- ➢ We search for decays in gas-filled TPCs to improve signal-over-background ratio ($\propto 1/\text{density}$).



†NIM, A 659 (2011) pp.106-135

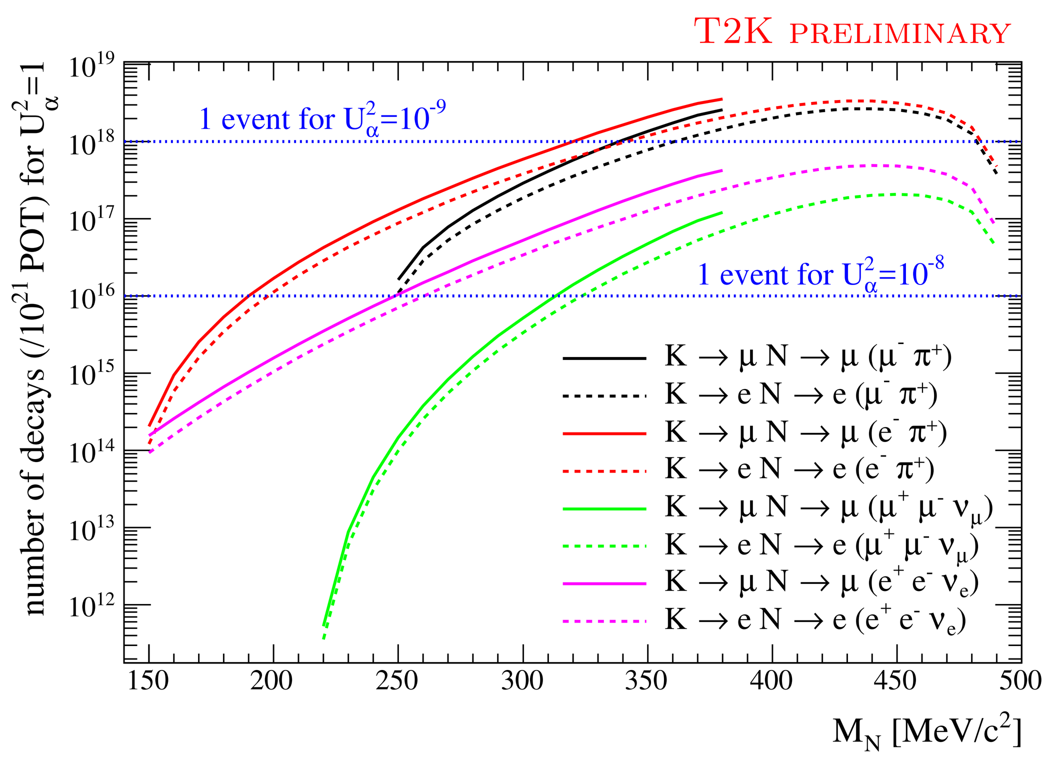
Analysis method and results

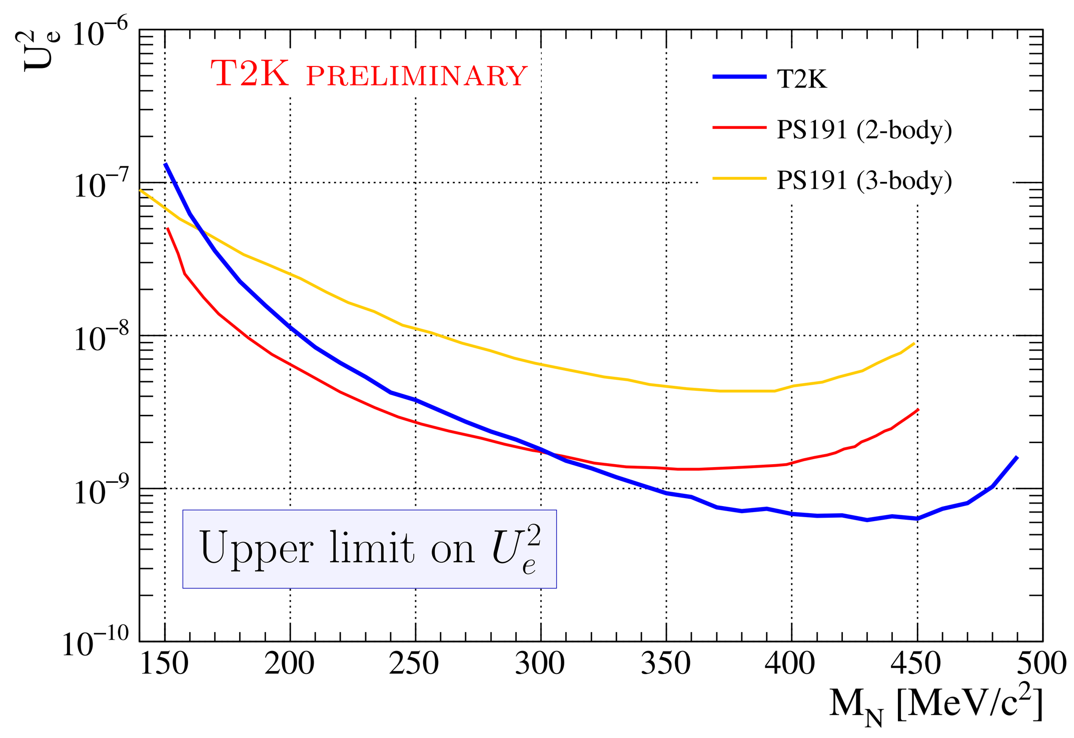
NO EVENTS OBSERVED IN THE SIGNAL REGIONS

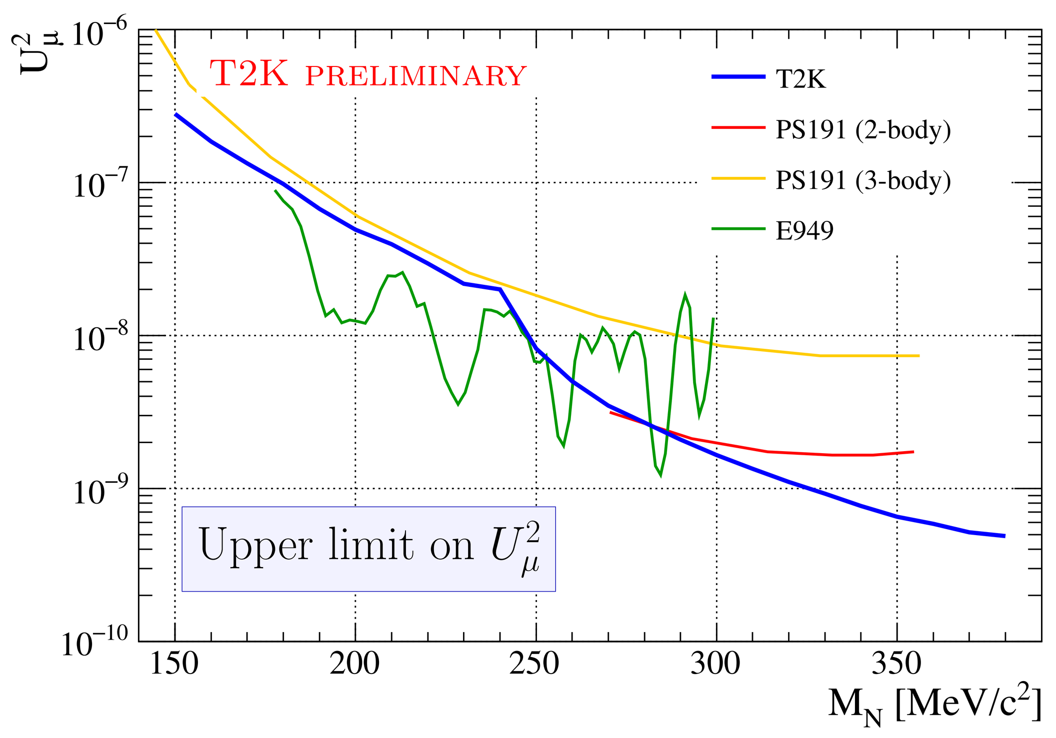


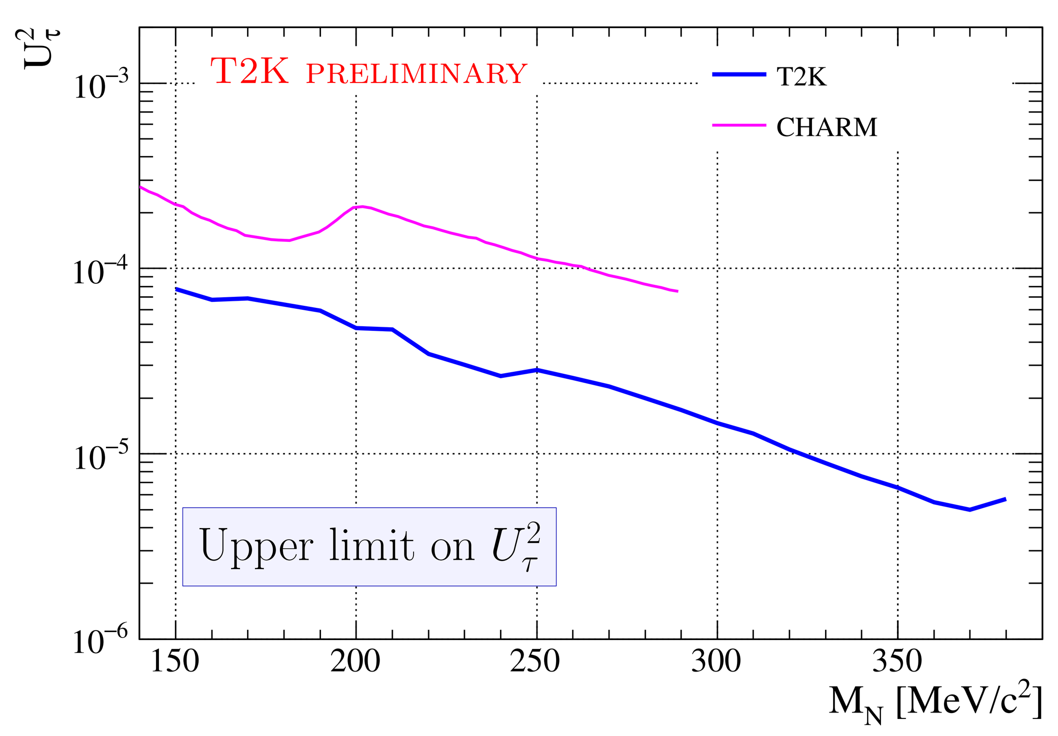
Heavy neutrino flux simulation

Use of T2K official kaon flux predictions









PS191: Phys. Lett. **166B** (1986) 479
E949: Phys. Rev. D **91** (2015) 052001
CHARM: Phys. Lett. **550B** (2002) 1-2

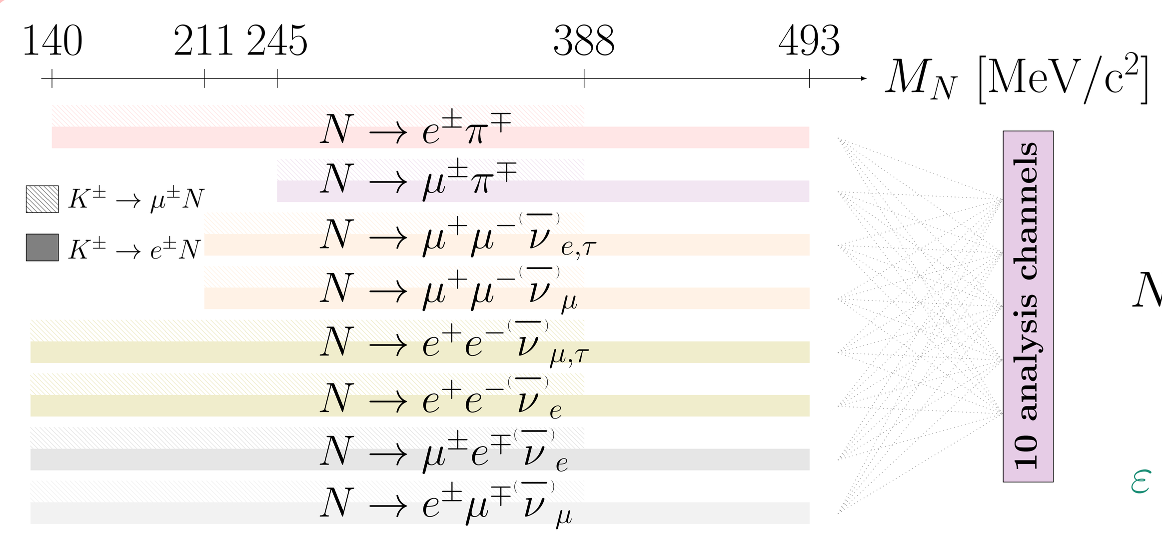
90% C.L.

T2K puts the most stringent limits in the $300 < M_N < 493$ MeV/c² region

Statistical method:
- ✔ **Combined likelihood:** $\mathcal{L}(\{n_A^{\text{obs}}\}; U_\alpha^2) = \prod_A \text{Poisson}(n_A^{\text{obs}}, N_A)$
- ✔ **Priors:** multivariate gaussian priors for flux and efficiency parameters, log-normal prior for background parameters, and flat prior for U_e^2, U_μ^2, U_τ^2.
- ✔ **Posterior probability:** $p = \int d\varepsilon d\Phi dB \times \mathcal{L} \times \pi(\varepsilon)\pi(\Phi)\pi(B)\pi(\{U_\alpha^2\})$

Selection

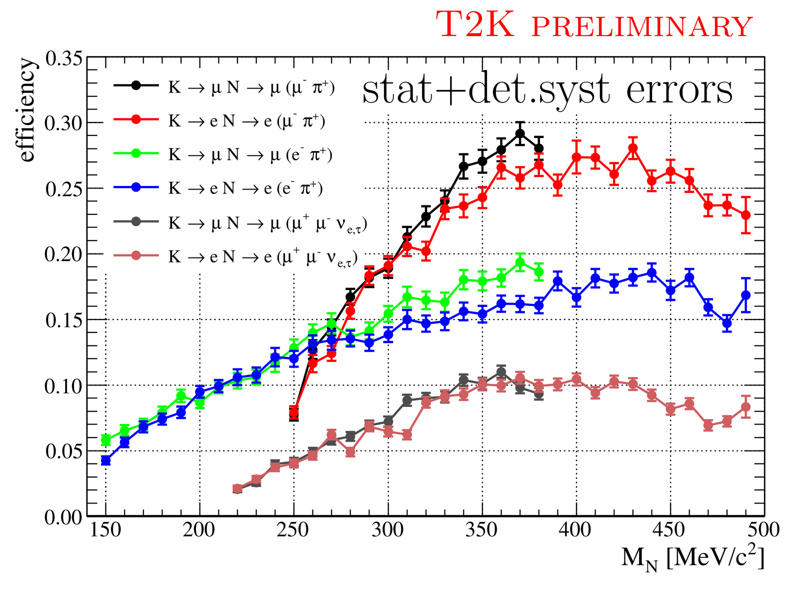
- ✂ Two oppositely charged tracks starting in TPC
- ✂ Particle identification using dE/dx in gas
- ✂ Veto: no other tracks upstream/in TPC
- ✂ Kinematics cuts: angle between tracks, invariant mass. . .



$$N_{\text{channel }A} = B_A + \sum_{\text{modes }i} \Phi_i\,\varepsilon_i\,U^4_{\text{eff},i}$$

expected background (B_A); selection efficiency (ε_i); expected signal for $\varepsilon = U_e^2 = U_\mu^2 = U_\tau^2 = 1$ (Φ_i); mixing parameters ($U^4_{\text{eff},i}$)

Efficiencies and systematics



Systematics:
- ➢ detector resolution
- ➢ performance of the reconstruction
- ➢ pion modelling in the detector media
- ➢ kaon flux prediction (constrained by NA61)

⇒ 5% (det) + 15% flux

Background study

Expected number of background events

Channel	ν-mode	$\bar{\nu}$-mode
$\mu^\pm\pi^\mp$	1.54 ± 0.52	0.38 ± 0.20
$e^-\pi^+$	0.38 ± 0.27	0.02 ± 0.02
$e^+\pi^-$	0.33 ± 0.25	0.22 ± 0.26
$\mu^+\mu^-$	0.22 ± 0.13	0.04 ± 0.04
e^+e^-	0.56 ± 0.24	0.02 ± 0.02

- ➢ Background estimated with NEUT 5.3.2 generator.
- ➢ Background constrained with control regions in data.
- ➢ $\mu^\pm\pi^\mp$ main background is coherent pion production.
- ➢ Sub-leading contaminations:
  - ➢ other types of ν-interactions in the gas
  - ➢ interactions outside the TPCs (e.g. γ conversions)