Sterile neutrino searches at the T2K experiment

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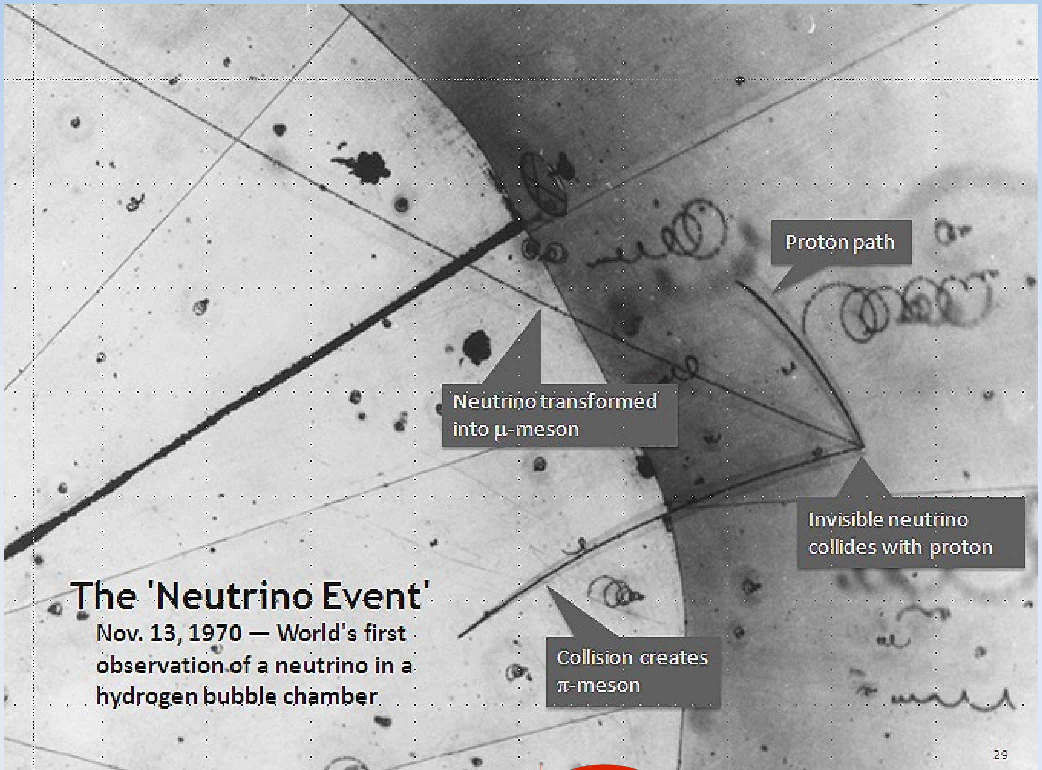
IFAE Pizza Seminar – February 26th 2014

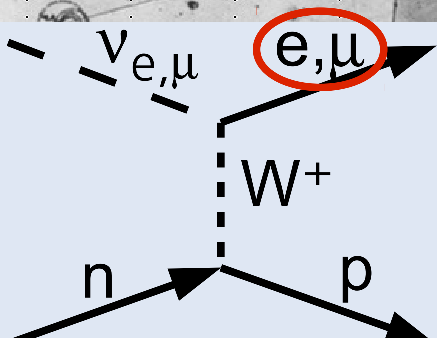
Outline

- Introduction to the neutrino oscillations
- Experimental hints to sterile neutrinos
- The T2K experiment and the near detector
- The ν_e selection at the near detector
- Results for the $\nu_e \rightarrow \nu_s$ channel (ν_e disappearance)

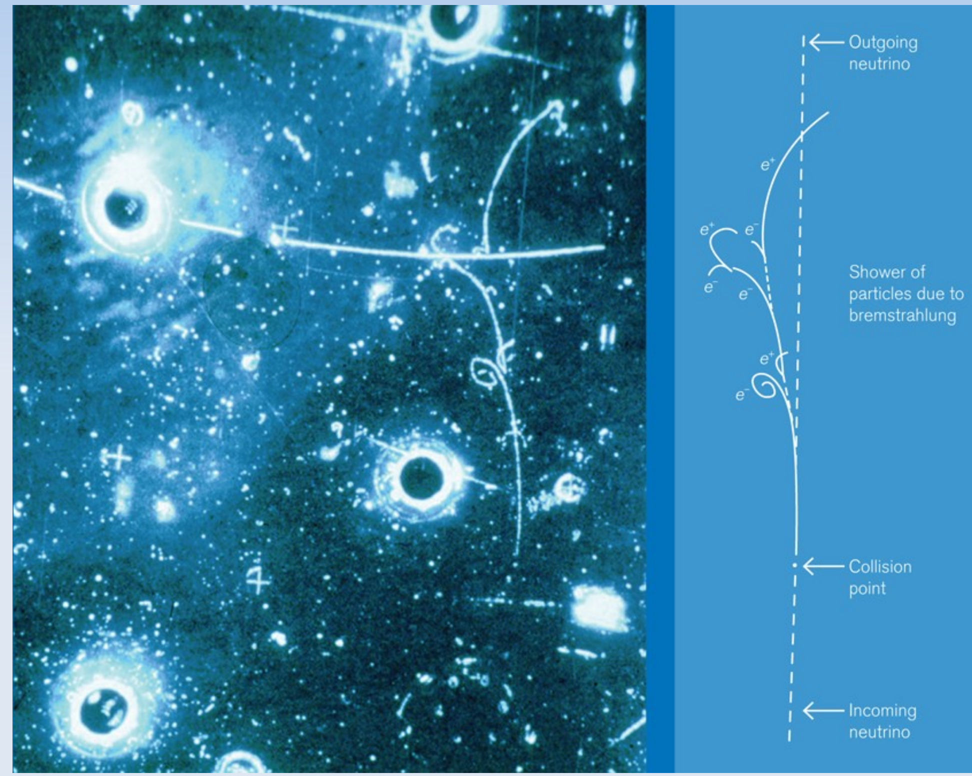
Neutrino facts: they exist!

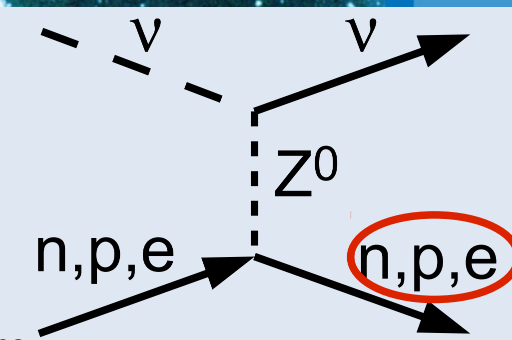
1970 Charged Current





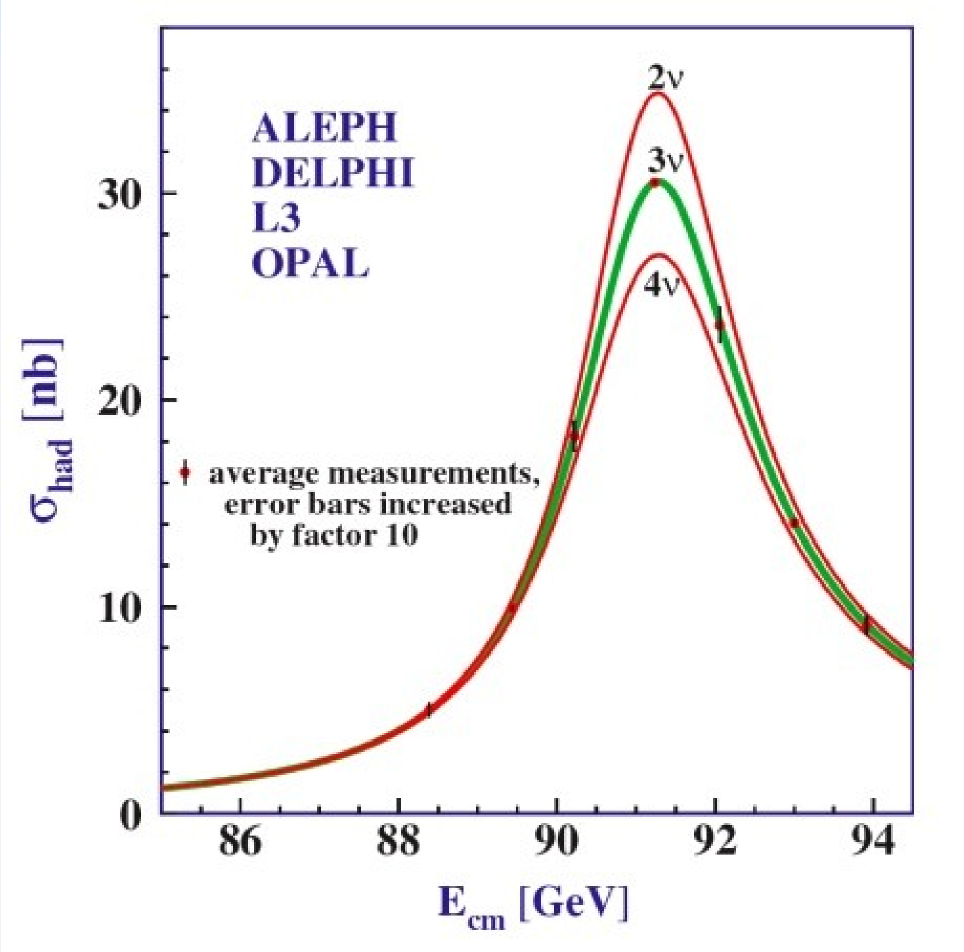
1972 Neutral Current





Neutrino facts: 3 flavours

Three neutrino flavour < $m_Z/2$



ν_e

ν_μ

ν_τ

Neutrino facts: they oscillate

- Neutrinos can change their flavour due to mixing

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}.$$

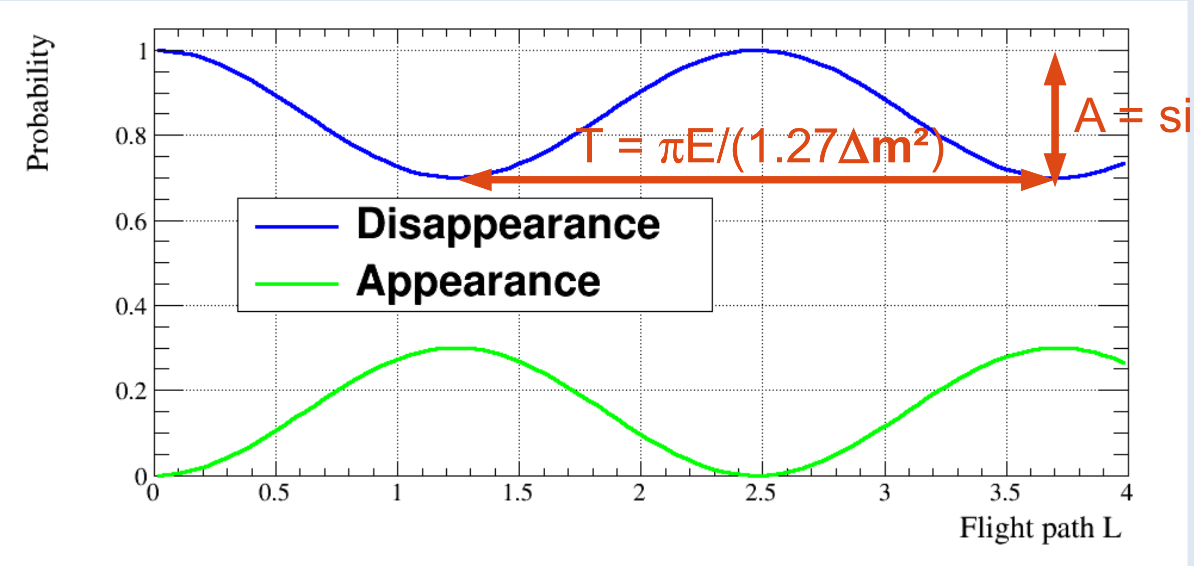
Weak eigenstates (Flavours)

PMNS Matrix

Mass eigenstates

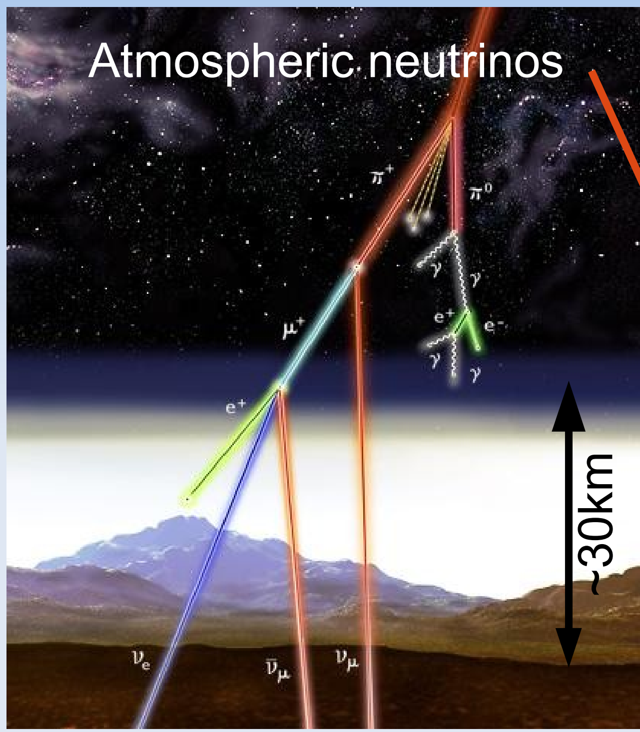
- Two neutrino approximation

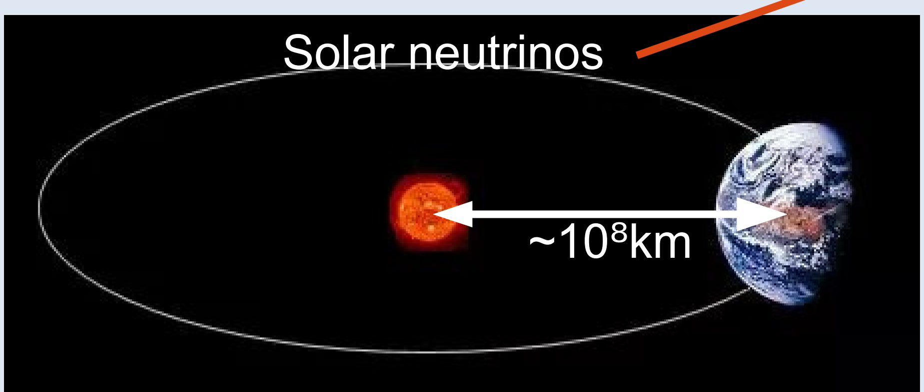
$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu(t) \rangle|^2 = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2[\mathrm{eV}^2]L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$

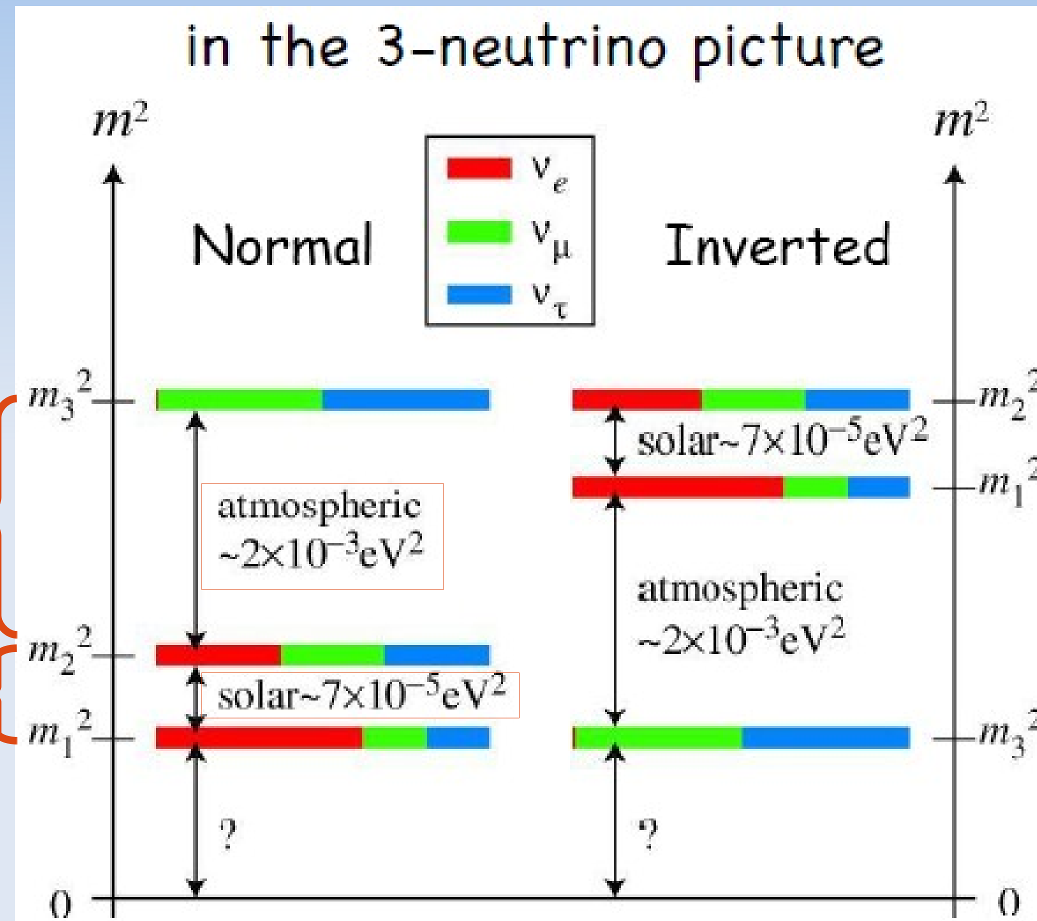


L = Distance travelled by the ν
E = ν energy

Standard 3 neutrino oscillations



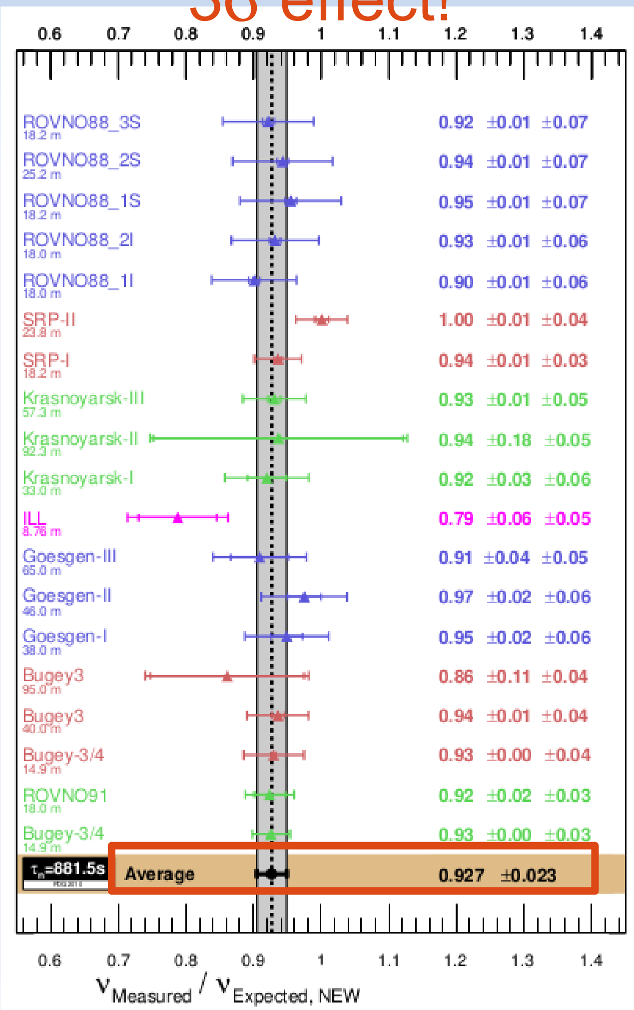


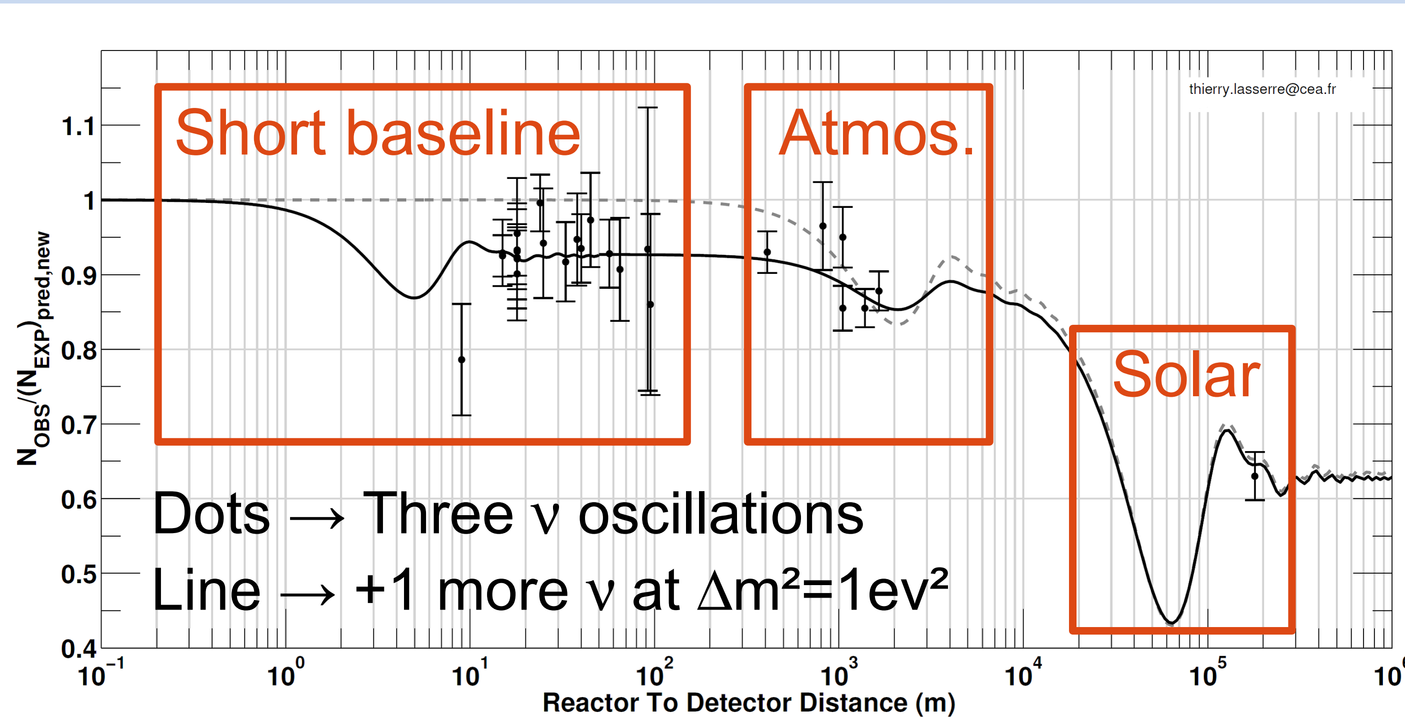


The reactor neutrino anomaly (2010)

- A depletion from the expectation of ν_e events is observed in the nuclear reactors

3σ effect!





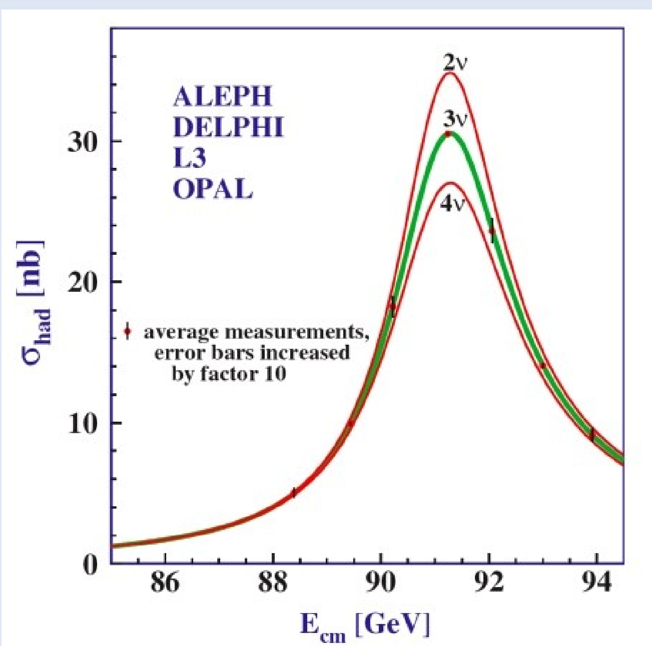
Some more anomalies...

- Very short baselines gallium experiments sees ν_e disappearance
- LSND experiment sees $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ at short baseline
- MiniBooNE experiment sees $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ (but $\nu_e \rightarrow \nu_\mu$ doesn't)

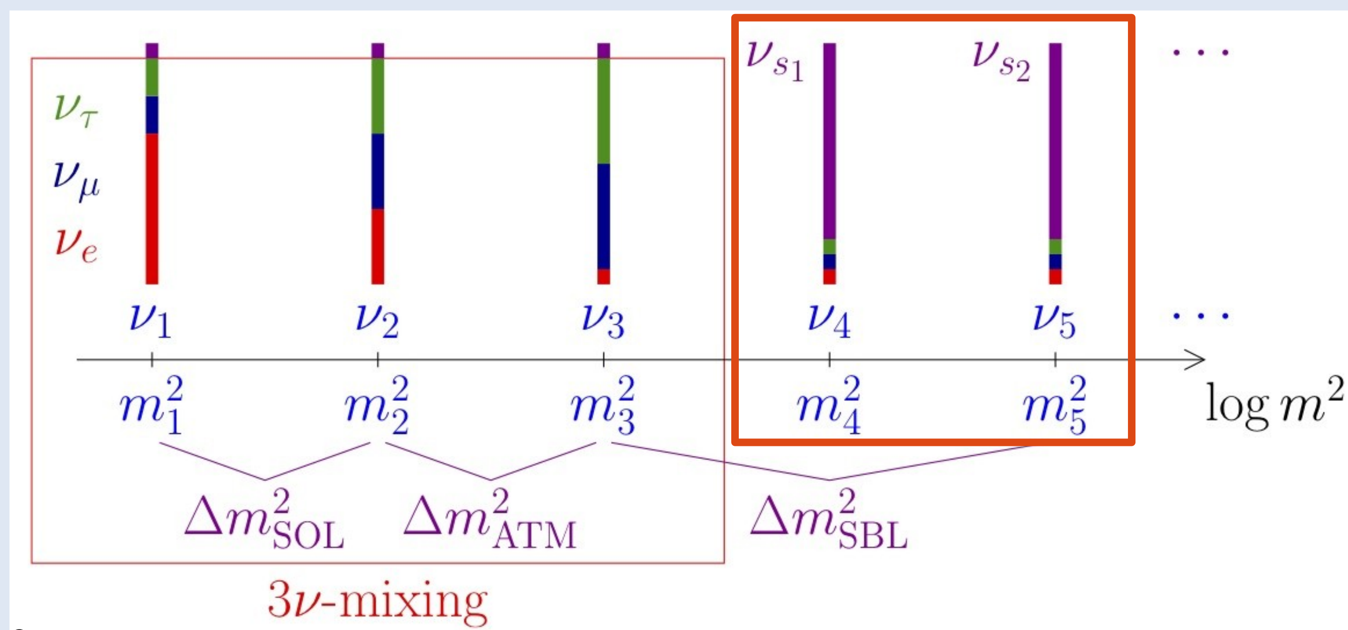
- Very puzzling field!

Why sterile neutrinos?

- There are some anomalies seen at short baseline
- To explain it in the picture of the ν oscillations we need a new mass state with large Δm^2
- It does not interact weakly → Sterile neutrinos



Only three flavour coupled to Z^0



3+1 model

- Simplest model with only one sterile neutrino

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}.$$

U_{e4} $U_{\mu4}$ $U_{\tau4}$

$[\nu_s]$ U_{s1} U_{s2} U_{s3} U_{s4} $[\nu_4]$

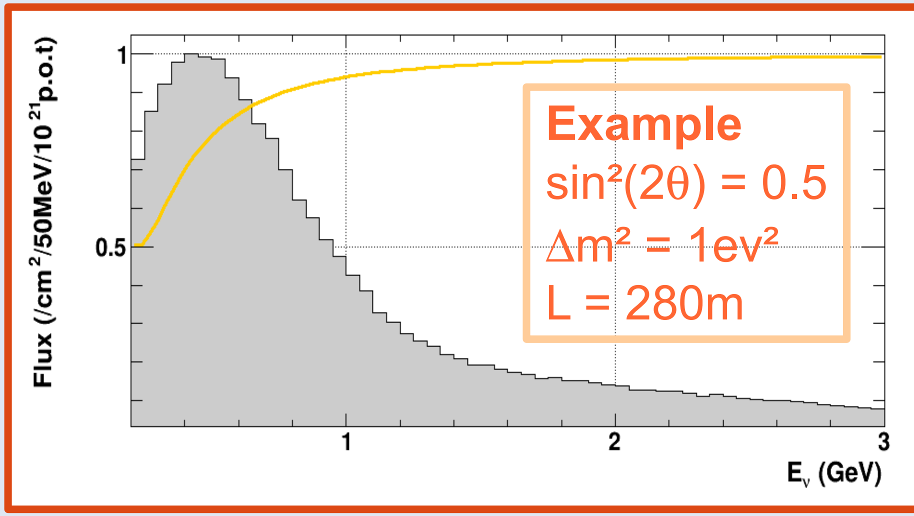
- Two neutrinos approximation works well
- Three possible channels:

$$P(\nu_e \to \nu_e) = 1 - 4|U_{e4}|^2(1 - |U_{e4}|)\sin^2\left(1.27\,\Delta m^2_{41}\frac{L}{E}\right)$$

$\sin^2(2\theta_{ee})$

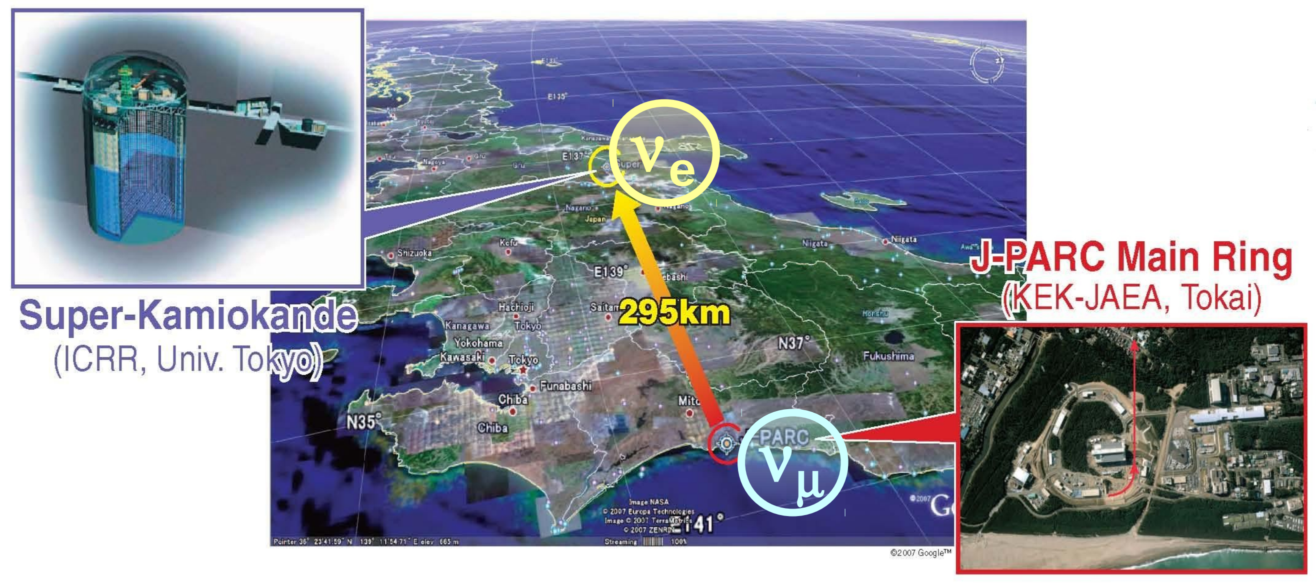
$$P(\nu_\mu \to \nu_\mu) = 1 - 4|U_{\mu4}|^2(1 - |U_{\mu4}|)\sin^2\left(1.27\,\Delta m^2_{41}\frac{L}{E}\right)$$

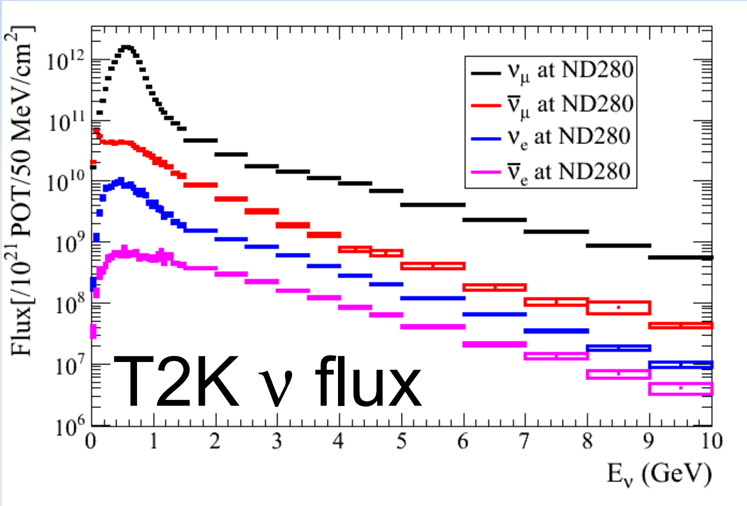
$$P(\nu_\mu \to \nu_e) = P(\nu_e \to \nu_\mu) = 4|U_{e4}|^2|U_{\mu4}|^2\left(1.27\,\Delta m^2_{41}\frac{L}{E}\right)$$

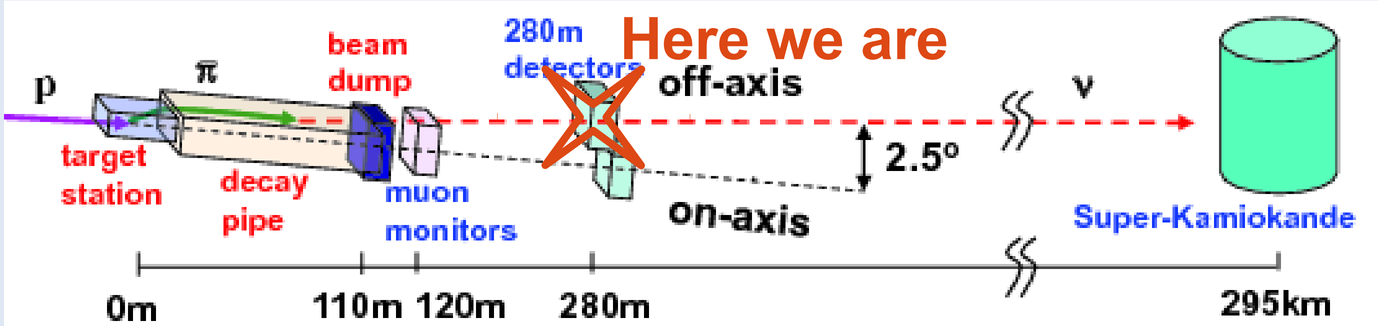


The T2K experiment

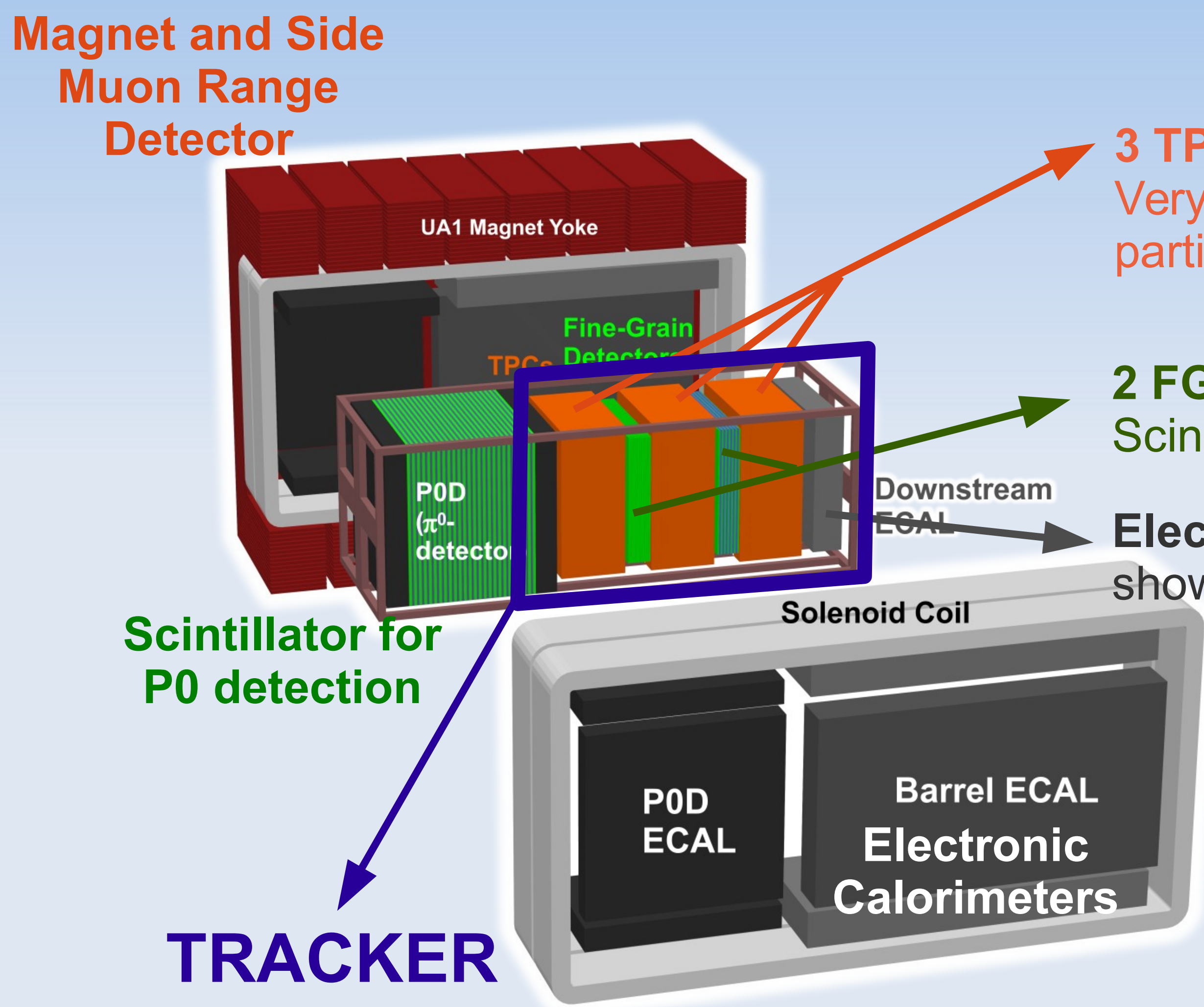
- Provides a ν_μ and ν_e beam
- Detector placed at 280m → Short baseline experiment







The near detector: ND280



3 TPCs (Time Projection Chambers): Very good particle identification and particle tracking

2 FGDs (Fine Grained Detectors): Scintillator detectors and active target

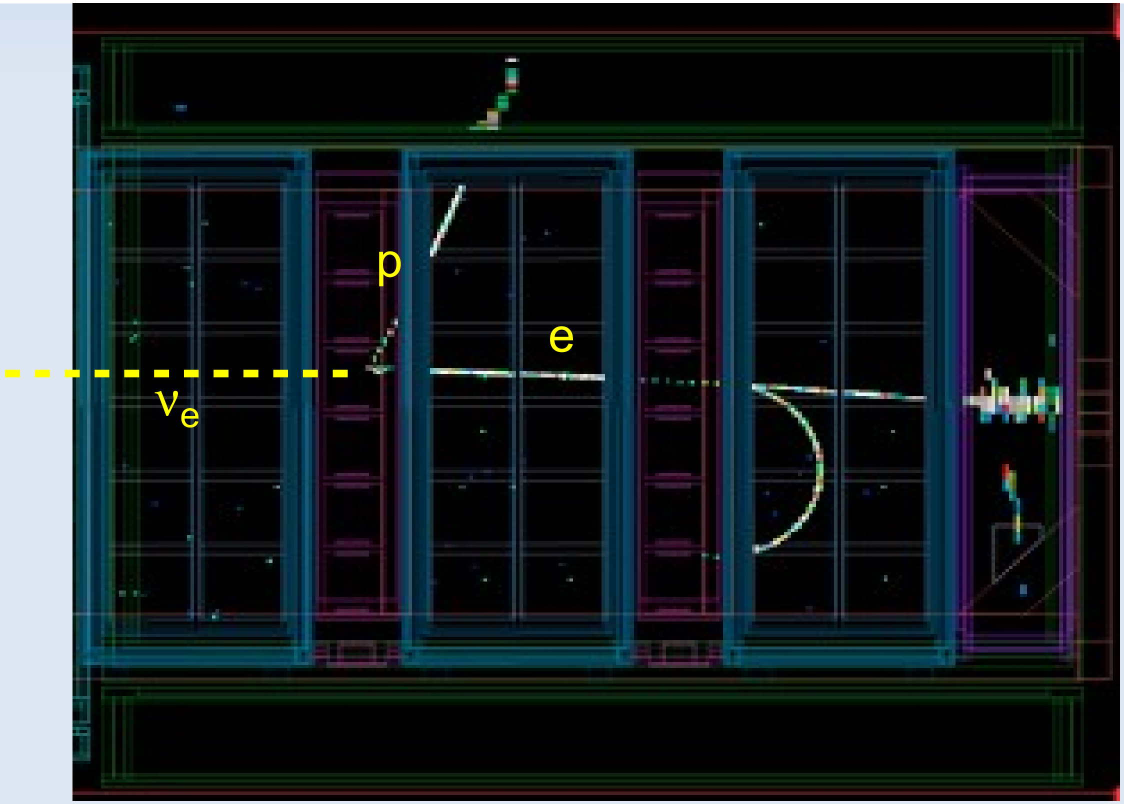
Electronic Calorimeter: Distinguish showers and tracks

At 280m the active ν oscillation are negligible

ν_e selection

Look for electrons with topology compatible with a CC interaction and reconstruct the ν energy

$$E_{Rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_e}{2(m_n - E_b - E_e + p_e \cos\theta_e)}$$



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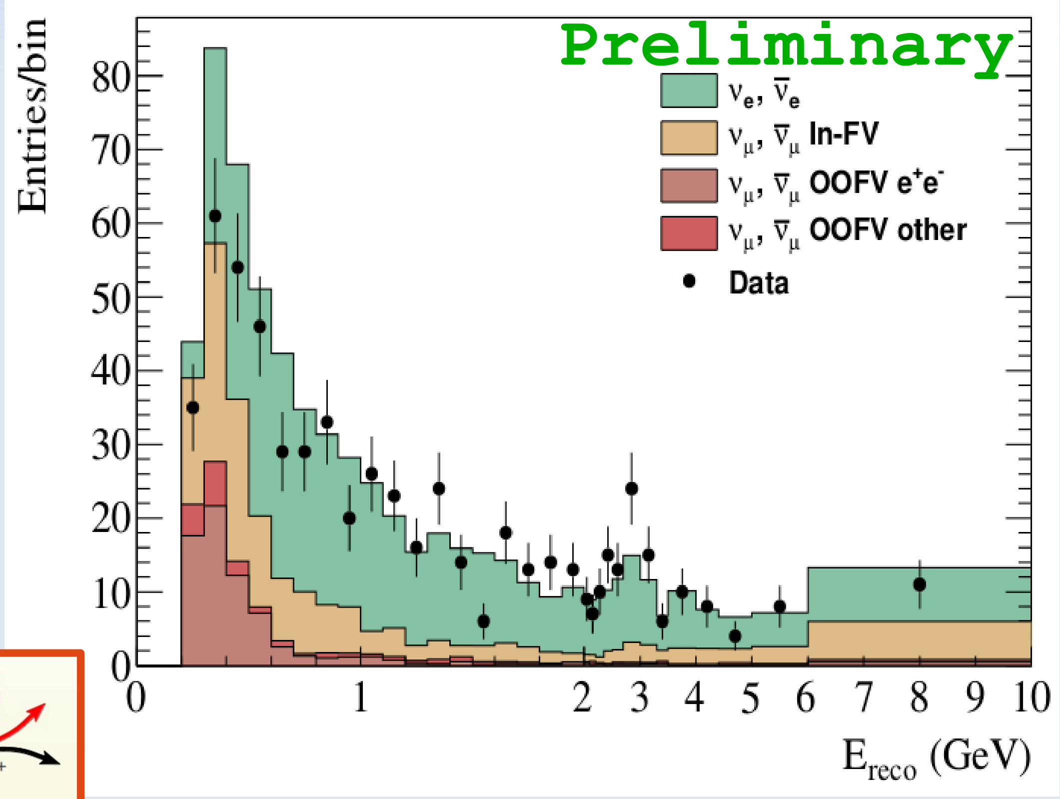
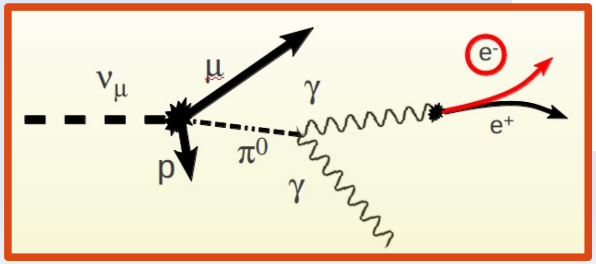


Background illustration



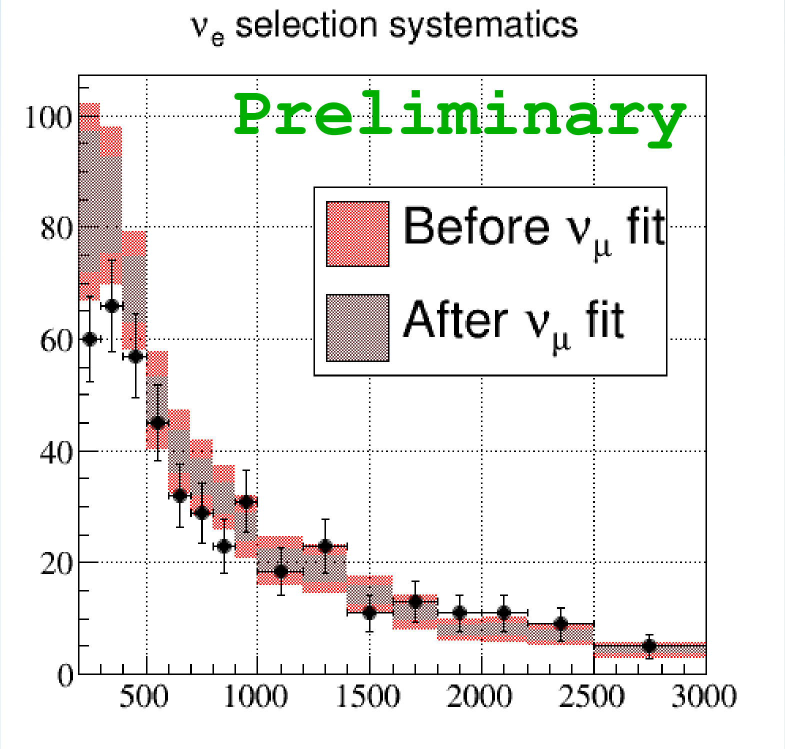
Flux and cross-section systematics

- ν_μ and ν_e flux are very correlated

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

  $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$

- ν_μ and ν_e cross-section are equivalent
- Constrain their systematics performing a fit for a ν_μ sample



ν_e selection

Looking for ν_e disappearance

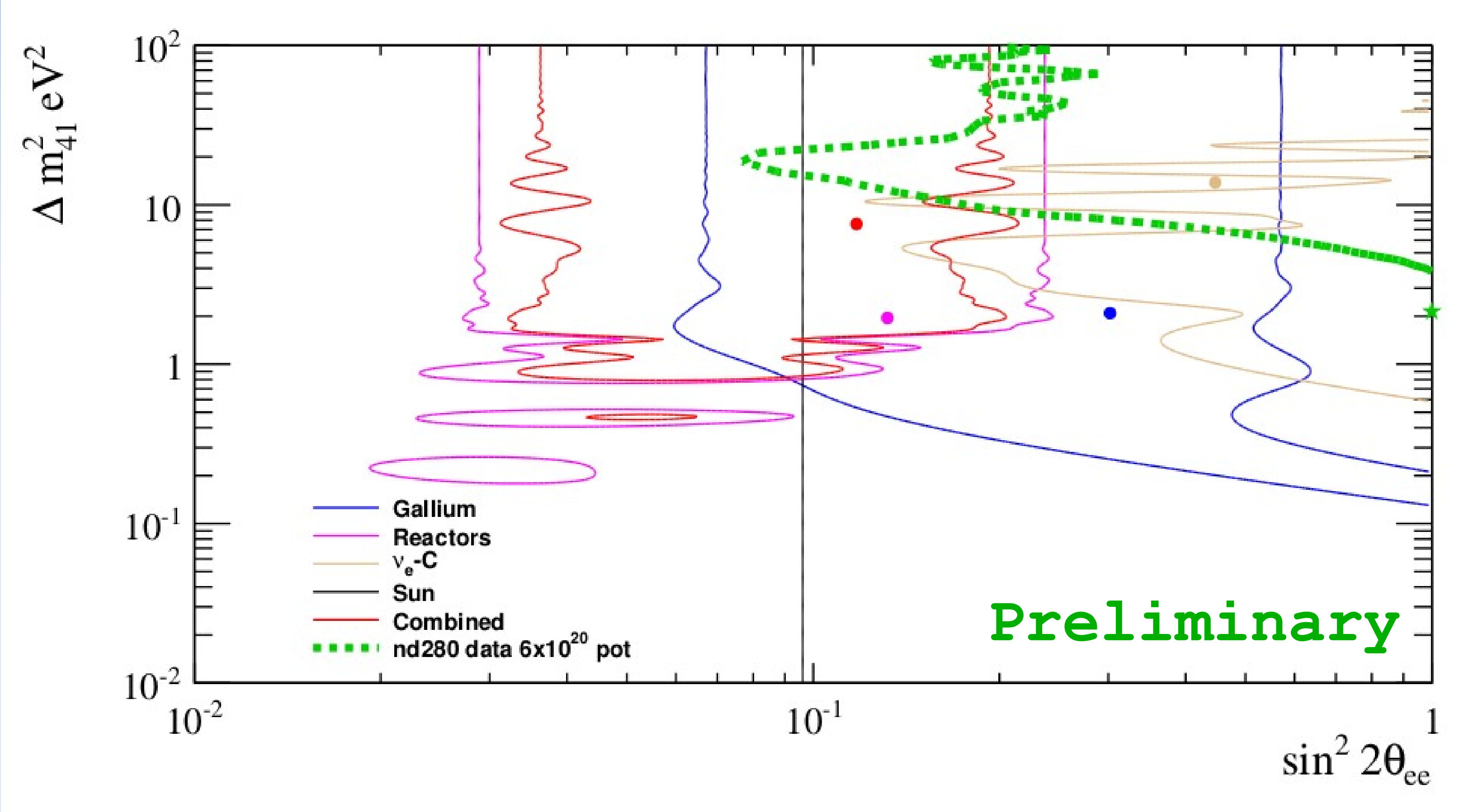
- Maximum likelihood fit with nuisance parameters

$$-2\ln\mathcal{L}_T(\sin^2 2\theta, \Delta m^2; \vec{f}) = -2\ln\mathcal{L}_{\nu_e} - 2\ln\mathcal{L}_{\gamma} + (\vec{f}-\vec{f}_0)^T V^{-1}(\vec{f}-\vec{f}_0)$$

- Likelihood for ν_e and γ selections
- Penalty term accounting on the systematic uncertainties
  - f, f_0 → Nuisance parameters and central values
  - V → Covariance matrix of the systematic uncertainties

Results

Preliminary results for 5.9x10^{20} protons on target (~10% of goal)



Best fit → $\sin^2(2\theta_{ee}) = 1.00 \pm 0.92$, $\Delta m_{41}^2 = 2.14 \pm 0.61$ ev²

We validate the null hypothesis within the 95% CL

Conclusions

- Sterile neutrino field is very active and there are a lot of future projects been built and operated
- Some anomalies supporting the sterile models, but much data compatible with standard oscillations
- ND280 at T2K is sensitive to the light sterile neutrino oscillations at $\Delta m^2 > 1ev^2$
- T2K data is compatible with the null hypothesis at 95%CL

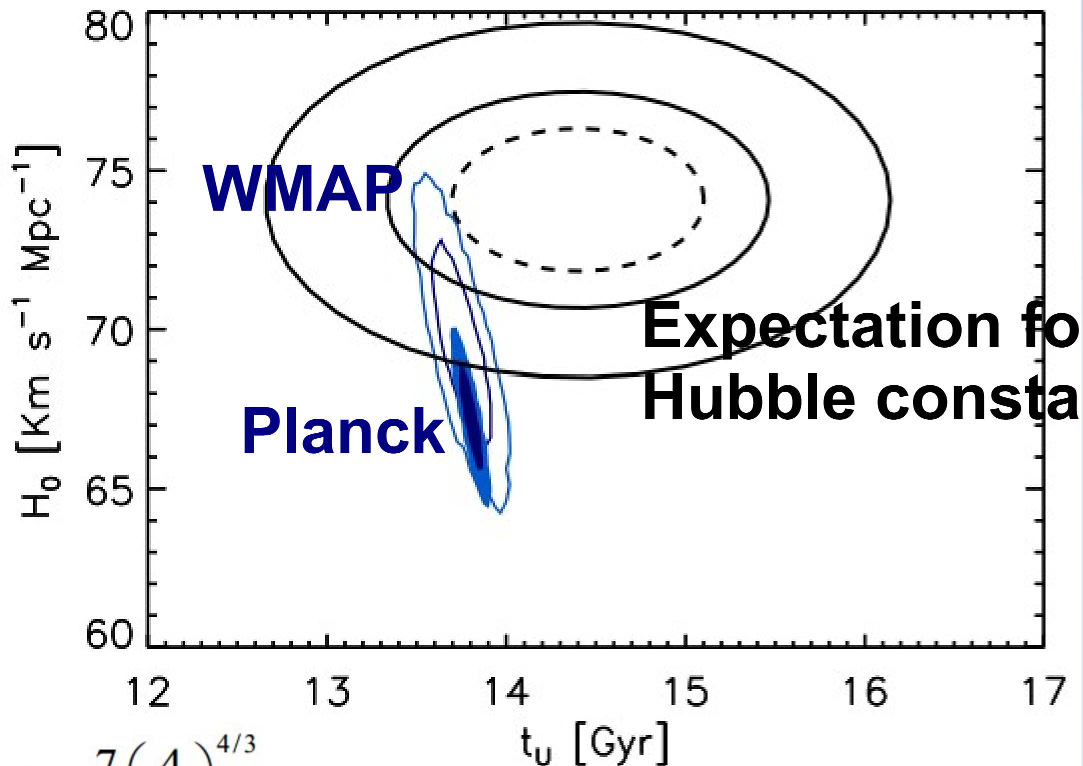
Thanks for your attention!

Backup

Systematic uncertainties

Systematic	Prior value	Prior error	nd280 fit	# of parameters
ν_μ-flux	$\sim$ 0.9-1.00	$\sim$ 0.07-0.9	Post BANFF	11
ν_e-flux	$\sim$ 0.9-1.01	$\sim$ 0.06-0.10	Post BANFF	7
$\bar{\nu}_\mu$-flux	$\sim$ 0.98-1.01	$\sim$ 0.09-0.14	Post BANFF	5
$\bar{\nu}_e$-flux	$\sim$ 0.9-1.0	$\sim$ 0.07-0.16	Post BANFF	2
M_A^{QE}[GeV]	1.01	0.06	Post BANFF	1
M_A^{RES}[GeV]	0.80	0.052	Post BANFF	1
CC Other Shape [GeV]	0.26	0.28	Post BANFF	1
Spectral Function ($^{12}C\&^{16}O$)	0.28	0.13	Post BANFF	1
P_F ($^{12}C\&^{16}O$)[MeVc^{-1}]	1.24	0.05	Post BANFF	1
E_b ($^{12}C\&^{16}O$)[MeVc^{-1}]	1.16	0.22	Post BANFF	1
W shape [MeV]	1	0.52	Pre BANFF	1
π-less Δ decay	-0.03	0.09	Post BANFF	1
CCQE (E_1,E_2,E_3)	0.96,0.89,0.89	0.08,0.10,0.12	Post BANFF	3
CC1π (E_1,E_2)	1.22,1.12	0.16,0.17	Post BANFF	2
NC1π^0	1.10	0.25	Post BANFF	1
NC Other	1.34	0.22	Post BANFF	1
CC Coherent	0.45	0.16	Post BANFF	1
$\sigma_{\nu_{eCC}}/\sigma_{\nu_{\mu CC}}$	1	0.03	Pre BANFF	1
$\sigma_{\bar{\nu}}/\sigma_{\nu}$	1	0.4	Pre BANFF	1
Out-FV e^+/e^-	1	0.3	Pre BANFF	1
Out-FV Other	1	0.3	Pre BANFF	1
Detector-like	1	$\sim$ 0.06-0.36	Pre BANFF	10
Total				55

Planck latest results



$$\Omega_\nu h^2 = \frac{7}{4}\left(\frac{4}{11}\right)^{4/3} N_{eff}^{\nu} \Omega_\gamma h^2$$

Model	Data	N_{eff}	Ref.
N_{eff}	W-5+BAO+SN+H_0	$4.13^{+0.87(+1.76)}_{-0.85(-1.63)}$	[346]
	W-5+LRG+H_0	$4.16^{+0.76(+1.60)}_{-0.77(-1.43)}$	[346]
	W-5+CMB+BAO+XLF+f_{gas}+H_0	$3.4^{+0.6}_{-0.5}$	[349]
	W-5+LRG+maxBCG+H_0	$3.77^{+0.67(+1.37)}_{-0.67(-1.24)}$	[346]
	W-7+BAO+H_0	$4.34^{+0.86}_{-0.88}$	[338]
	W-7+LRG+H_0	$4.25^{+0.76}_{-0.80}$	[338]
	W-7+ACT	5.3 ± 1.3	[343]
	W-7+ACT+BAO+H_0	4.56 ± 0.75	[343]
	W-7+SPT	3.85 ± 0.62	[344]
	W-7+SPT+BAO+H_0	3.85 ± 0.42	[344]
	W-7+ACT+SPT+LRG+H_0	$4.08^{(+0.71)}_{(-0.68)}$	[350]
	W-7+ACT+SPT+BAO+H_0	3.89 ± 0.41	[351]
$N_{eff}+f_\nu$	W-7+CMB+BAO+H_0	$4.47^{(+1.82)}_{(-1.74)}$	[352]
	W-7+CMB+LRG+H_0	$4.87^{(+1.86)}_{(-1.75)}$	[352]
$N_{eff}+\Omega_k$	W-7+BAO+H_0	4.61 ± 0.96	[351]
	W-7+ACT+SPT+BAO+H_0	4.03 ± 0.45	[352]
$N_{eff}+\Omega_k+f_\nu$	W-7+ACT+SPT+BAO+H_0	4.00 ± 0.43	[351]
$N_{eff}+f_\nu+w$	W-7+CMB+BAO+H_0	$3.68^{(+1.90)}_{(-1.84)}$	[352]
	W-7+CMB+LRG+H_0	$4.87^{(+2.02)}_{(-2.02)}$	[352]
$N_{eff}+\Omega_k+f_\nu+w$	W-7+CMB+BAO+SN+H_0	$4.2^{+1.10(+2.00)}_{-0.61(-1.14)}$	[353]
	W-7+CMB+LRG+SN+H_0	$4.3^{+1.40(+2.30)}_{-0.54(-1.09)}$	[353]

Tensions can be alleviated if 3.4>Neff>4.1

(True only for m_ν<10ev)

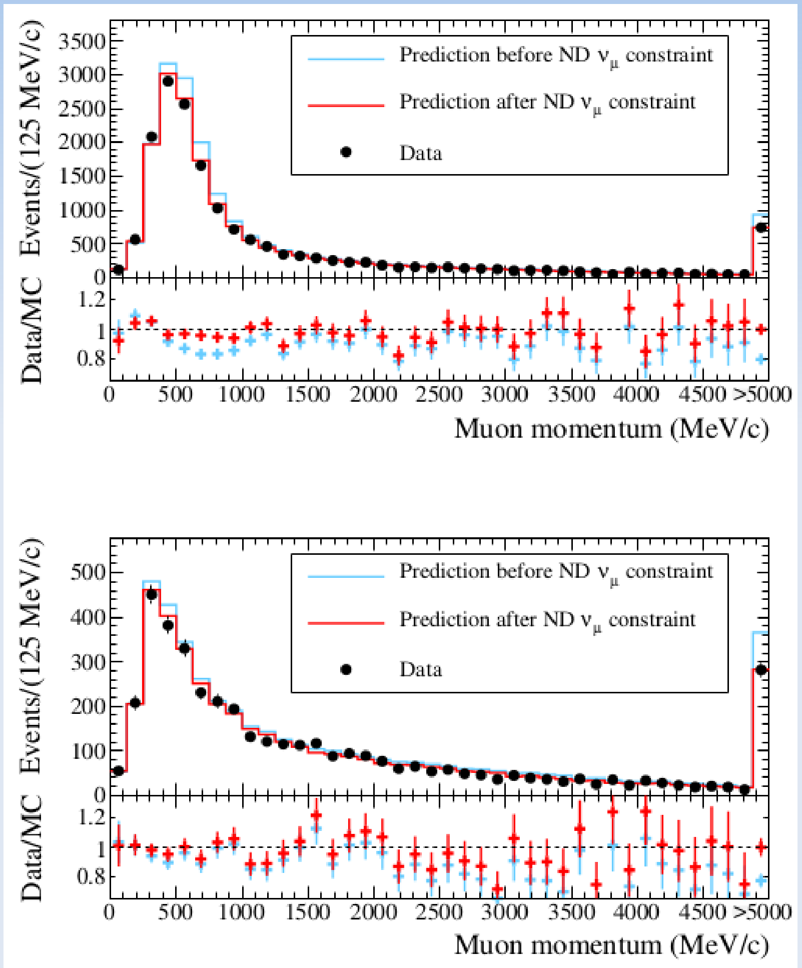
Systematic constrain

1) Look for ν_e interactions

2) Take a control sample of γ conversions

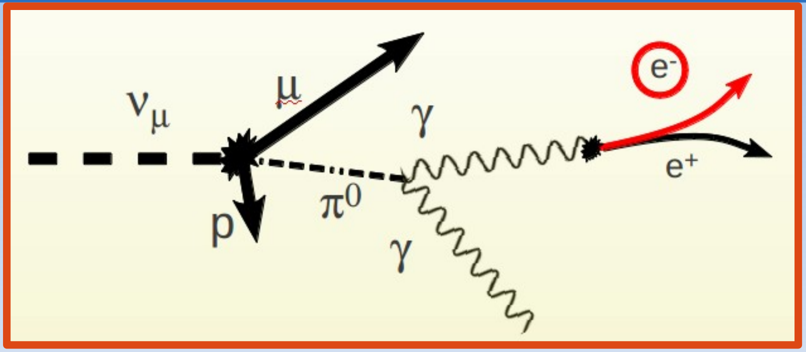
3) Constrain flux and cross-section systematics with ν_μ sample

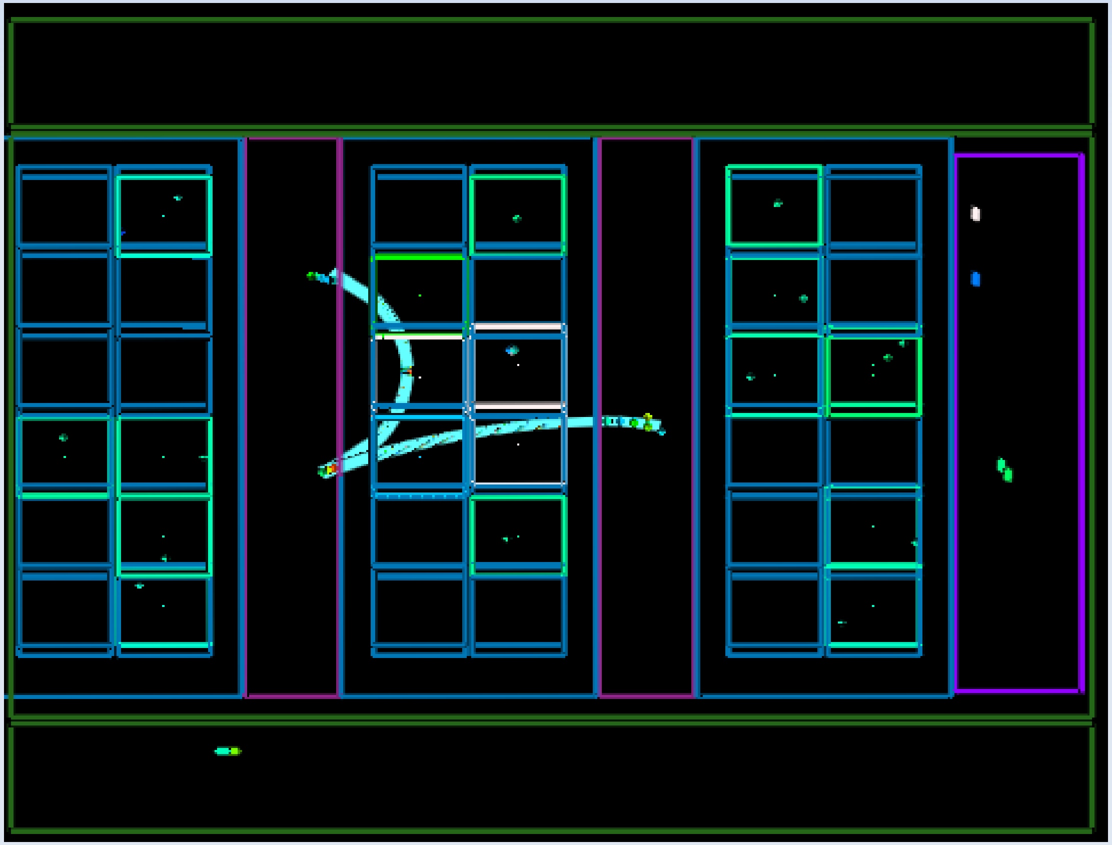
4) Search for any ν_e depletion using the maximum likelihood technique



γ background control sample

- Low energy part dominated by photon conversion
- e^+e^- pair selection → Enriched background sample





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