Sterile neutrinos beyond LSND at NF

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Collaborators: Walter Winter, Davide Meloni,
Many thanks to members in the IDS-NF collaboration.

Outline

1. Motivations
   - Sterile neutrinos
   - Recent progress at IDS-NF
2. Sensitivities at NF
   - Sterile neutrinos with arbitrary masses
   - Sterile neutrinos with particular masses
3. Summary

Outline

What is the sterile neutrino?

- No SM interactions but massive
- Not absolute ghost
  1. Gravitational interactions
  2. New NSIs beyond SM
  3. Neutrino oscillations: $\nu_e\,,\nu_\mu\,,\nu_\tau \longrightarrow \nu_s$.
- Observables
  1. Gravitational signals: Extremely hard!
  2. Disappearance of active neutrinos $\nu_e\,,\nu_\mu\,,\nu_\tau$
  3. Indirect evidence from a global analysis of neutrino oscillation data
  4. Any others?

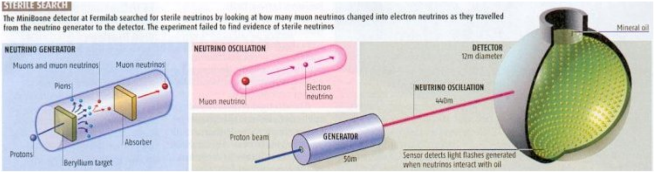
The simple analysis of neutrino oscillation

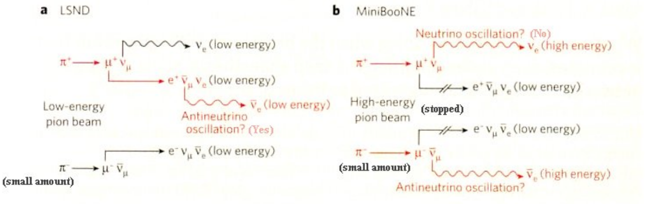
- Standard oscillation pictures with $\mathcal{J}_{ij}^{\alpha\beta} \equiv U_{\alpha i} U_{\alpha j}^* U_{\beta i}^* U_{\beta j}$:
  $\mathcal{P}_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i<j} \mathrm{Re}(\mathcal{J}_{ij}^{\alpha\beta}) \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right) + 2\sum_{i<j} \mathrm{Im}(\mathcal{J}_{ij}^{\alpha\beta}) \sin\left(\frac{\Delta m_{ij}^2 L}{2E}\right)$
- For 3+1 & $\Delta m_{41}^2 \gg \Delta m_{31}^2$, $\mathcal{P}_{e\mu} \approx 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$
- Focus on $\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right) \Longrightarrow L_{\mathrm{osc}} = 2.47\frac{E[\mathrm{GeV}]}{\Delta m^2[\mathrm{eV}^2]}\mathrm{km}$.
  If $E \sim$ GeV and $L \sim$ km $\Longrightarrow$ discovery reach of Δm^2 at eV^2.
- LSND: $\bar{\nu}_\mu \to \bar{\nu}_e$ $E \sim 30$ MeV and $L \sim 30$ m
  MiniBooNE: $\nu_\mu \to \nu_e \& \bar{\nu}_\mu \to \bar{\nu}_e$ $E \sim 500$ MeV and $L \sim 500$ m

Why do we need sterile neutrinos?

Are there any sterile neutrinos in Nature?

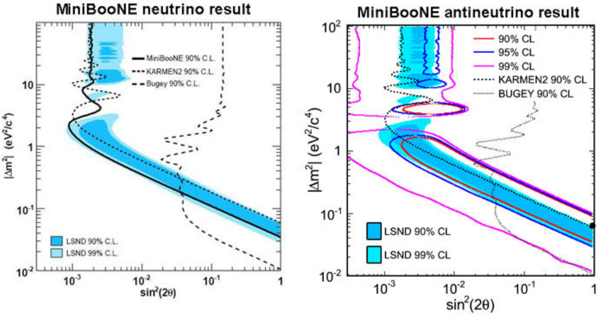
LSND v.s **MiniBooNE**





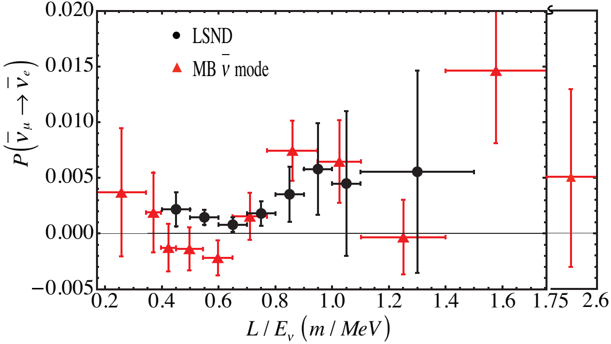
ref: www-boone.fnal.gov/

Anomaly?



ref: www-boone.fnal.gov/

Point at sterile neutrinos!



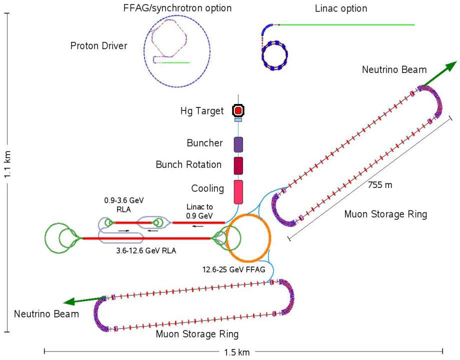
ref: 1007.1150 [hep-ex] by MiniBooNE Collaboration
Other explanations: CPT violations· · ·

Outline

IDS-NF

Initial IDS-NF set-up ($E = 25$ GeV, $L_1 \approx 4000$ km and $L_2 \approx 7500$ km).
Wrong-sign muon events at NF:

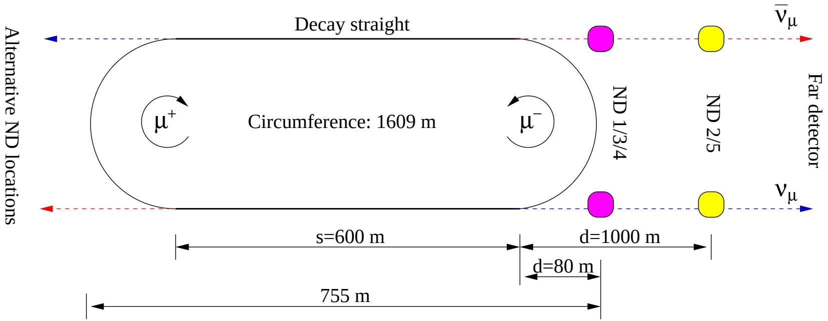
$$\Gamma(\boxed{\mu^+} \to e^+\bar{\nu}_\mu\nu_e) \times P_{\nu_e\to\nu_\mu} \times \sigma(\nu_\mu N \to \boxed{\mu^-} X)$$



ref: www.ids-nf.org/wiki

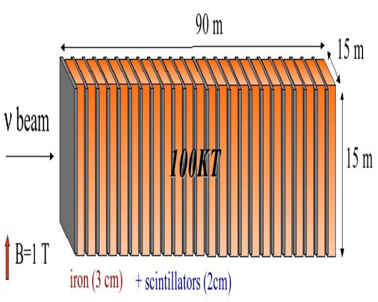
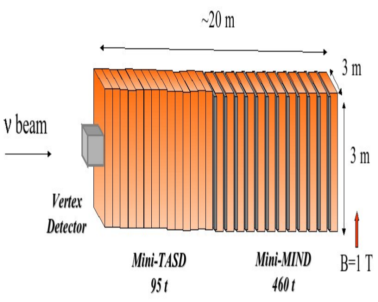
ND at the NF

Parameter	ND1	ND2	ND3	ND4	ND5
Diameter D	17 m	4 m	4 m	0.32 m	6.8 m
Distance d	80 m	1000 m	80 m	80 m	1000 m
Mass	450 t	25 t	25 t	0.2 t	2000 t



ref: Phys.Rev.D80:053001 JT,W.Winter

Detectors

Magetized Iron Detector(MIND)	A hybrid Near Detector(ND-Hybrid)
	

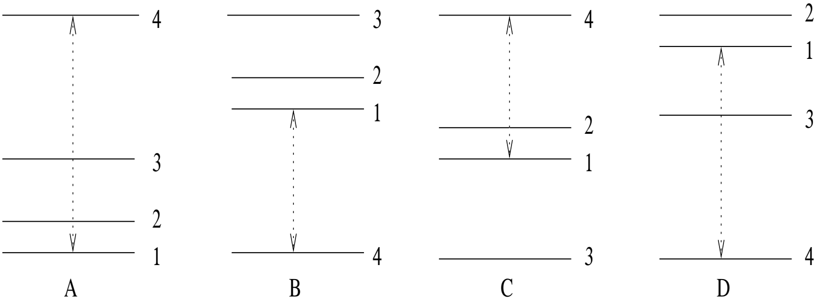
ref: Detector R&D @The 6th plenary meeting of IDS-NF by P. Soler.

Outline

Parametrization and mass schemes

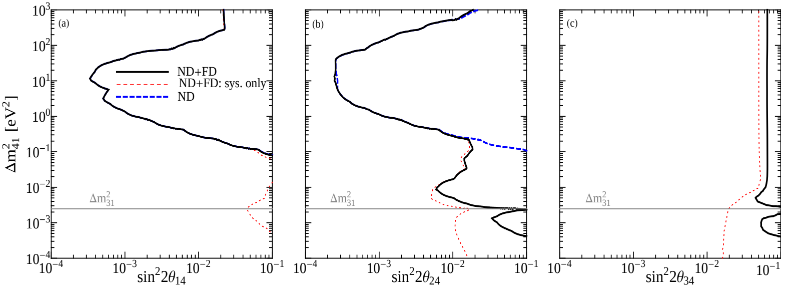
Our parametrization explicitly reads

$$U = R_{34}(\theta_{34},\, 0)\; R_{24}(\theta_{24},\, 0)\; R_{14}(\theta_{14},\, 0)\; R_{23}(\theta_{23},\, \delta_3)\; R_{13}(\theta_{13},\, \delta_2)\; R_{12}(\theta_{12},\, \delta_1)$$

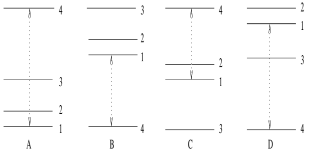


Systematic analysis of mass ordering A

Δm^2_{41} [eV^2]	$\sin^2 2\theta_{14}$	$\sin^2 2\theta_{24}$	$\sin^2 2\theta_{34}$	$\theta_{14}[^\circ]$	$\theta_{24}[^\circ]$	$\theta_{34}[^\circ]$
0.001	0.403	0.029	0.042	19.7	4.9	5.9
0.01	0.224	0.004	0.044	14.1	1.9	6.1
0.1	0.054	0.013	0.047	6.7	3.3	6.3
1	0.001	0.0009	0.047	0.9	0.8	6.3
10	0.0002	0.0002	0.047	0.5	0.5	6.3
100	0.0043	0.0006	0.047	1.9	0.7	6.3
1000	0.0168	0.015	0.047	3.7	3.5	6.3



Generalized exclusion limits

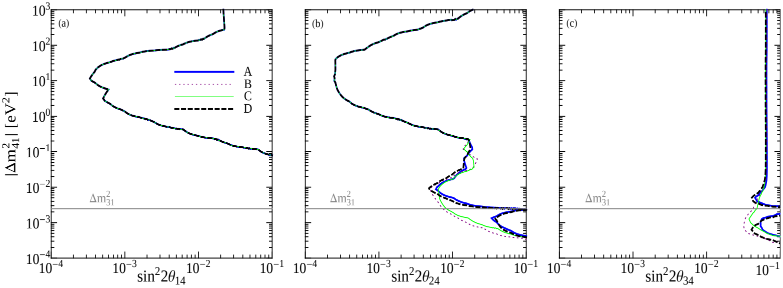


Osc. Probabilities at ND:

$$\mathcal{P}_{e\mu} = \mathcal{P}_{\mu e} = 4c_{14}^2 s_{14}^2 s_{24}^2 \sin^2(\Delta_{41})$$

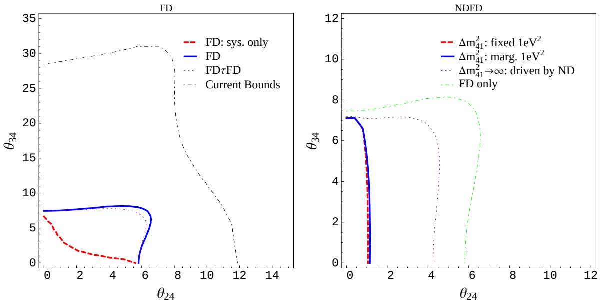
$$\mathcal{P}_{ee} = 1 - \sin^2(2\theta_{14}) \sin^2(\Delta_{41})$$

$$\mathcal{P}_{\mu\mu} = 1 - c_{14}^2 s_{24}^2 \left[3 + 2c_{14}^2 \cos(2\theta_{24}) - \cos(2\theta_{14})\right]$$



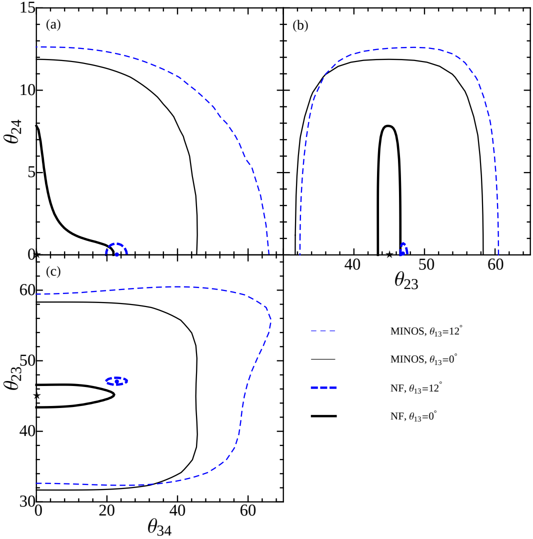
Outline

LSND-motivated Δm_{41}^2

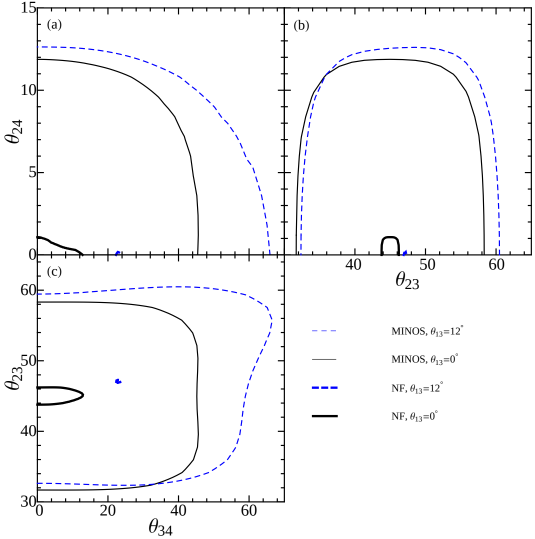


Bounds from ref: 0812.3703

FD4000 km@NF v.s MINOS



NDFD@NF v.s MINOS



Summary

- We invstigate sensitivities to sterile neutrinos with arbitrary masses at NF. Two mass regions are available:
  - one is LSND-type by ND;
  - the other one is close to atmospheric Δm^2_{31} by FD.
- Four mass schemes are allowed but have different $\sin^2 2\theta_{i4} - \Delta m^2_{41}$ dependence.
- For the special $\Delta m^2_{41} \sim \mathcal{O}(1)$ eV^2, we discuss whether τ detections are necessary or not. Meanwhile, we compare our results with those in MINOS. ND takes an important role in the game.

Vielen Dank!

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Osc. Probabilities at ND

$$\mathcal{P}_{e\mu} = \mathcal{P}_{\mu e} = 4c_{14}^2 s_{14}^2 s_{24}^2 \sin^2(\Delta_{41})$$
$$\mathcal{P}_{e\tau} = 4c_{14}^2 c_{24}^2 s_{14}^2 s_{34}^2 \sin^2(\Delta_{41})$$
$$\mathcal{P}_{es} = 4c_{14}^2 c_{24}^2 c_{34}^2 s_{14}^2 \sin^2(\Delta_{41})$$
$$\mathcal{P}_{ee} = 1 - \sin^2(2\theta_{14}) \sin^2(\Delta_{41})$$
$$\mathcal{P}_{\mu e} = 4c_{14}^2 s_{14}^2 s_{24}^2 \sin^2(\Delta_{41})$$
$$\mathcal{P}_{\mu\tau} = 4c_{14}^4 c_{24}^2 s_{24}^2 s_{34}^2 \sin^2(\Delta_{41})$$
$$\mathcal{P}_{\mu s} = 4c_{14}^4 c_{24}^2 c_{34}^2 s_{24}^2 \sin^2(\Delta_{41})$$
$$\mathcal{P}_{\mu\mu} = 1 - c_{14}^2 s_{24}^2 \left[3 + 2c_{14}^2 \cos(2\theta_{24}) - \cos(2\theta_{14})\right] \sin^2(\Delta_{41})$$