Physics with Near Detectors at a Neutrino Factory

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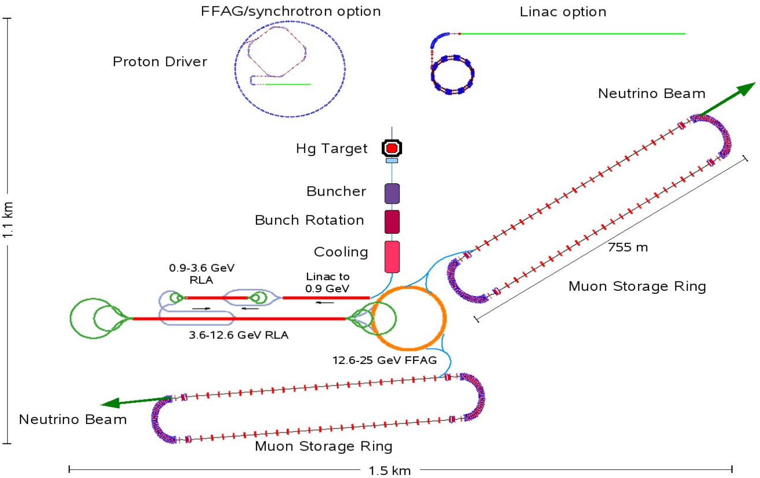
J. Tang and W. Winter, arXiv:0903.3039 [hep-ph].

Outline

1. Introduction
2. Definition and spectra of Near Detectors (NDs)
   - Neutrino fluxes
   - Arrangements of NDs
3. Simulations
   - Systematics treatment
   - Simulation results
4. Conclusion

IDS-NF setup


FFAG/synchrotron option
Linac option
Proton Driver
Neutrino Beam
Hg Target
Buncher
Bunch Rotation
Cooling
0.9-3.6 GeV
RLA
Linac to
0.9 GeV
755 m
Muon Storage Ring
3.6-12.6 GeV RLA
12.6-25 GeV FFAG
Neutrino Beam
Muon Storage Ring
1.1 km
1.5 km

Questions from IDS-NF

- Study of the potential of near detectors to cancel systematical errors.
- Study of the characteristics of the near detectors, such as technology, number, *etc*.
- Study of the use of the near detectors for searches of new physics.

reference: https://www.ids-nf.org/

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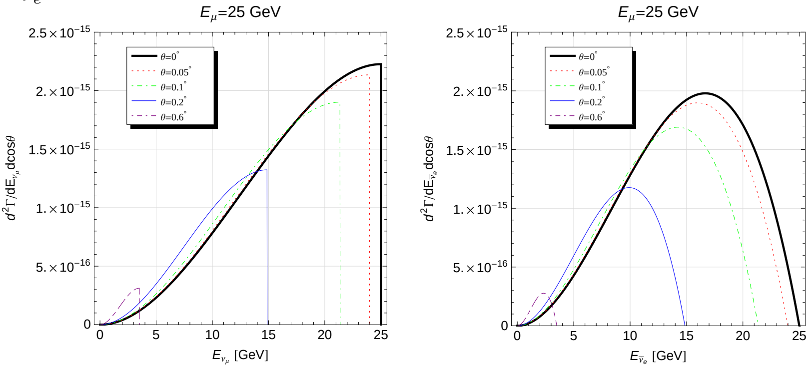
Differential spectra

S.Geer, hep-ph/9712290 V.Barger et al. hep-ph/9906487

$$\frac{d^2\Gamma}{dE_{\nu_\mu}\, d\cos\theta} = \frac{G_F^2 m_\mu}{24\pi^3}\gamma(1-\beta\cos\theta)E_{\nu_\mu}^2\left[3m_\mu - 4\gamma E_{\nu_\mu}(1-\beta\cos\theta)\right],$$

$$\frac{d^2\Gamma}{dE_{\nu_e}\, d\cos\theta} = \frac{G_F^2 m_\mu}{4\pi^3}\gamma(1-\beta\cos\theta)E_{\nu_e}^2\left[m_\mu - 2\gamma E_{\nu_e}(1-\beta\cos\theta)\right].$$



Angular dependence

Beam divergence

$$\frac{1}{\Gamma_0}\int_0^{\hat{\theta}} \frac{d\Gamma}{d\cos\theta}\sin\theta d\theta = \wedge \qquad \text{with} \quad \Gamma_0 = \frac{G_F^2 m_\mu^5}{192\pi^3}\,.$$

It's useful to define Near Detectors (NDs) which covers the whole flux of the beam.

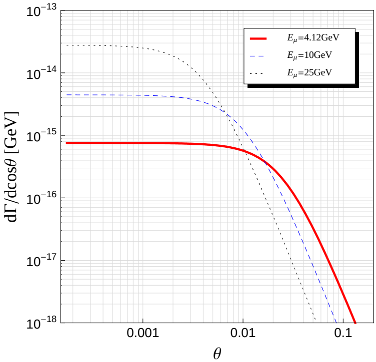
Beam opening angle

$$\frac{d\Gamma}{d\cos\theta}|_{\theta=\tilde{\theta}} = \wedge\cdot\frac{d\Gamma}{d\cos\theta}|_{\theta=0}\,,$$

which quantifies the angle over which the flux stays almost constant. It's useful to define NDs similar to Far Detectors (FDs).

Angular dependence

	Beam divergence $\hat{\theta}$		Beam opening angle $\tilde{\theta}$	
	$\wedge = 0.90$	$\wedge = 0.99$	$\wedge = 0.90$	$\wedge = 0.99$
$E_\mu = 25\,\mathrm{GeV}$	0.0127	0.0420	0.000983	0.000300
$E_\mu = 4.12\,\mathrm{GeV}$	0.0769	0.2538	0.005966	0.001821



$$D \simeq 2 \times L \times \theta$$

L: The distance between the production and detection point.
D: The diameter of spectra.
θ: The angular dependence of spectra.

Outline

Definitions of NDs

ND limit

The neutrino beam divergence is smaller than the detector diameter for the farthest decay point of the decay straight, so that the full flux (integrated over the angle) is seen by the detector from any decay point in the straight.

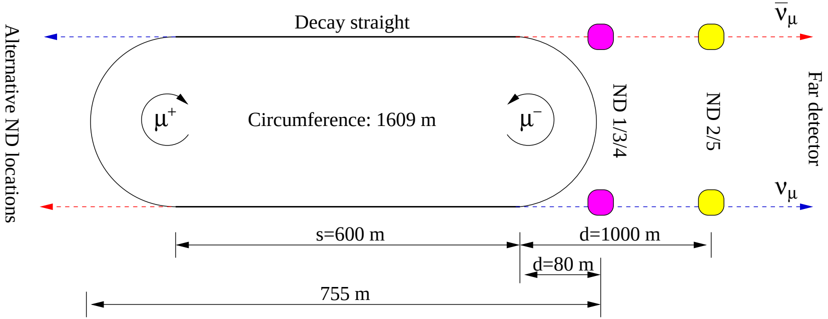
FD limit

The beam diameter given by the opening angle is of the order of the detector diameter at the nearest decay point, so that the whole detector is located in neutrino space like a far detector.

$$\frac{d^2\Gamma}{dE_{\nu_\alpha}\, d\cos\theta}(\cos\theta) \simeq \frac{d^2\Gamma}{dE_{\nu_\alpha}\, d\cos\theta}\Big|_{\theta=0}\,, \quad L \gg s \quad (\text{Size of source})$$

Definitions of NDs

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



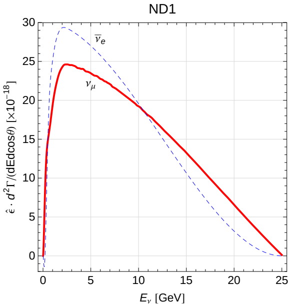
Assumptions

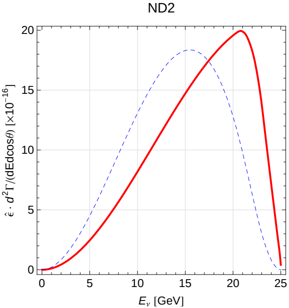
- The only purpose of the near detectors is the ν_μ (from μ^- decays) and the $\bar{\nu}_\mu$ (from μ^+ decays) event rate measurement using the inclusive charged current cross sections.
- We do not measure the ν_e and $\bar{\nu}_e$ event rates, since we do not need the corresponding cross sections in the neutrino factory far detector.
- We use the same characteristics as in the far detectors, such as energy resolution and binning, for the sake of simplicity.
- We do not extrapolate the backgrounds from the near to the far detector, but instead use relatively large background uncertainties uncorrelated among all channels.
- We assume the fiducial volume to be cylindrical and no **CID** in the detections.

Sampled fluxes of NDs

ND limit
(Beam smaller than detector)
$\Downarrow$

FD limit
(Spectra similar to FD)
$\Downarrow$





Geometric effects provide the efficiency ratio: $\varepsilon(E,L) = \frac{A_{\text{eff}}}{A_{\text{Det}}}$, and the averaged efficiency ratio: $\hat{\varepsilon}(E) \equiv \frac{L_{\text{eff}}^2}{s} \int_d^{d+s} \frac{\varepsilon(L,E)}{L^2} dL$, $L_{\text{eff}} = \sqrt{d(d+s)}$.

Outline

IDS-NF setup

Initial IDS-NF baseline set-up:

- $E_\nu = 25$ GeV;
- Combine with $L \approx 4000$ km and the magic baseline $L \approx 7500$ km.
- Their energy resolution can be assumed to be $55\%/\sqrt{E_\nu}$.
- Their systematic uncertainties on the size of the signal and background samples correspond to 2.5% and 20%, respectively.

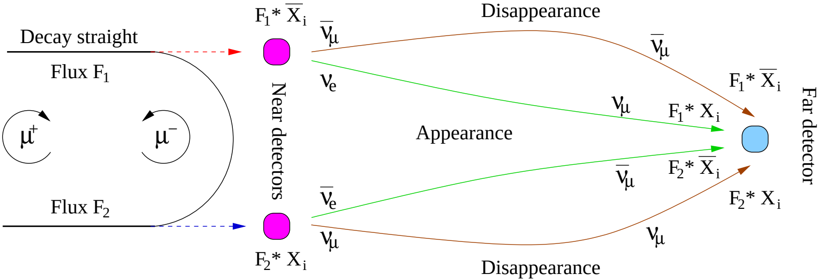
Refined systematics treatment

Flux normalization errors, fully uncorrelated among the different polarities $+$, $-$ and storage rings $S1$, $S2$, but fully correlated among all bins and all channels operated with the same beam.

Cross section errors for the inclusive charged current cross sections, fully correlated among all signal and background channels measuring ν_μ or $\bar{\nu}_\mu$, but fully uncorrelated among all bins.

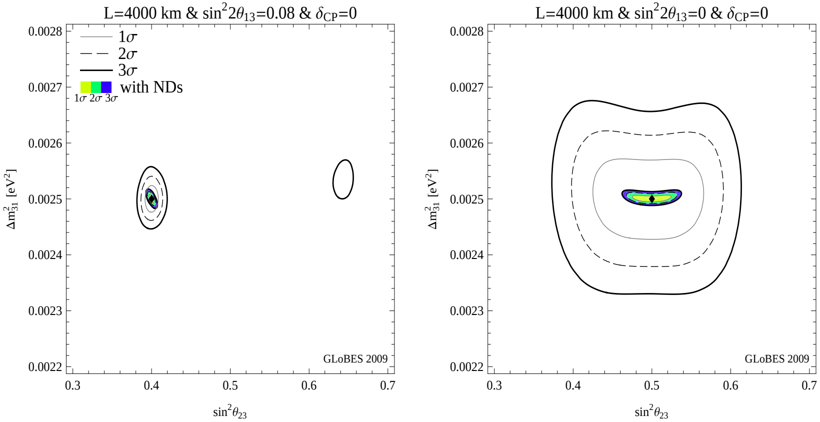
Background normalization errors, fully correlated among all bins, but fully uncorrelated among all channels, polarities, and detectors. We assume a 20% error each, just as in the IDS-NF baseline setup.

Refined systematics treatment



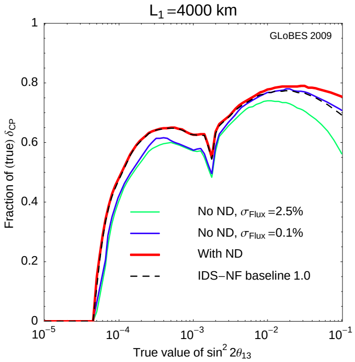
Outline

Measurements of atmospheric parameters



Degeneracy appears if θ_{23} is not located in the maximal case.

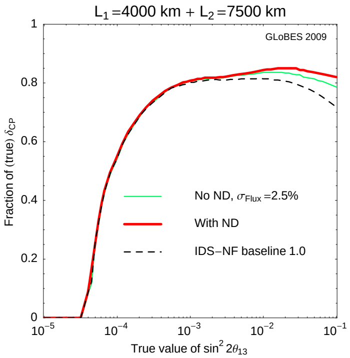
Measurements of CP violation



remarks:

- An improved flux knowledge only helps for large θ_{13} in the absence of the near detectors.
- A better matter density knowledge of 0.5% (compared to 2%) slightly improves the measurement in all cases for large θ_{13}.
- No improvement from better known fluxes.

Measurements of CP violation



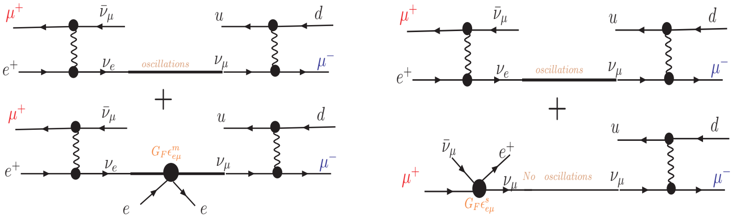
remarks:

- Our systematics treatment (including near detectors) leads to a better sensitivity than the IDS-NF systematics.
- A two-baseline neutrino factory hardly benefits from the near detectors.

Non-Standard Interactions (NSIs)

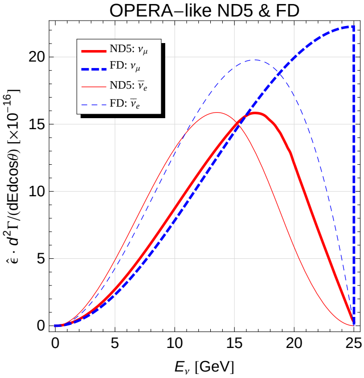
Such flavor violation interactions with neutrinos as $\nu_\alpha f \to \nu_\beta f$, $l_\alpha^- \to \nu_\beta e^- \bar{\nu}_e, \cdots$

$$\mathrm{L}_{\mathsf{eff}} = 2\sqrt{2}\, G_F\, (\epsilon^{L/R})^{\alpha\gamma}_{\beta\delta}\ \left(\bar{\nu}^\beta \gamma^\rho \mathrm{P}_L \nu_\alpha\right)\ \left(\bar{\ell}^\delta \gamma^\rho \mathrm{P}_{L/R} \ell_\gamma\right)$$



Sensitivities of NSIs

$$\mathrm{L}_{\text{eff}} = 2\sqrt{2}\, G_F\, (\epsilon^{L/R})^{\alpha\gamma}_{\beta\delta}\ \left(\bar{\nu}^{\beta}\gamma^{\rho}\mathrm{P}_L\nu_{\alpha}\right)\ \left(\bar{\ell}^{\delta}\gamma^{\rho}\mathrm{P}_{L/R}\ell_{\gamma}\right)$$



$$|\nu^s_\alpha\rangle = |\nu_\alpha\rangle + \textstyle\sum_\beta \epsilon^s_{\alpha\beta}|\nu_\beta\rangle$$

with $\epsilon^s_{\mu\beta} = (\epsilon^L)^{e\mu}_{\beta e}$;

$$\epsilon^m_{\beta\alpha} = \epsilon^{m,L}_{\beta\alpha} + \epsilon^{m,R}_{\beta\alpha}$$

with $\epsilon^{m,L/R}_{\beta\alpha} = (\epsilon^{L/R})^{\alpha e}_{\beta e}$

	Without ν_τ ND5	With ν_τ ND5
$\lvert\epsilon^s_{e\tau}\rvert$	0.004	0.0007
$\lvert\epsilon^s_{\mu\tau}\rvert$	0.4	0.0006
$\lvert\epsilon^m_{e\tau}\rvert$	0.004	0.004
$\lvert\epsilon^m_{\mu\tau}\rvert$	0.02	0.02

J. Kopp, T. Ota and W. Winter, [arXiv:0804.2261 [hep-ph]].

Summary

- Near detector fluxes in terms of the geometry of the neutrino source and the detector are discussed;
- We introduce the refined systematics treatment which includes cross section errors, flux errors, and background uncertainties;
- Two NDs at a neutrino factory are mandatory for the leading atmospheric parameters with only one long baseline, while the results hardly depend on which of ND1 to ND4 is chosen.
- For such a long baseline as 4000 km, NDs provide slightly improvements of CP violation measurements at large θ_{13}.
- It's robust to use IDS-NF two baseline setup for CP violation measurements. But the refined systematics treatment is more realistic.
- Sensitivities of NSIs at source can be obtained up to 10^{-4} in terms of the OPERA-like ND5.

Thank you!

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Efficiency ratio