Neutral Currents and Tests of 3-neutrino Unitarity in Long-Baseline Exeriments

Steve Geer

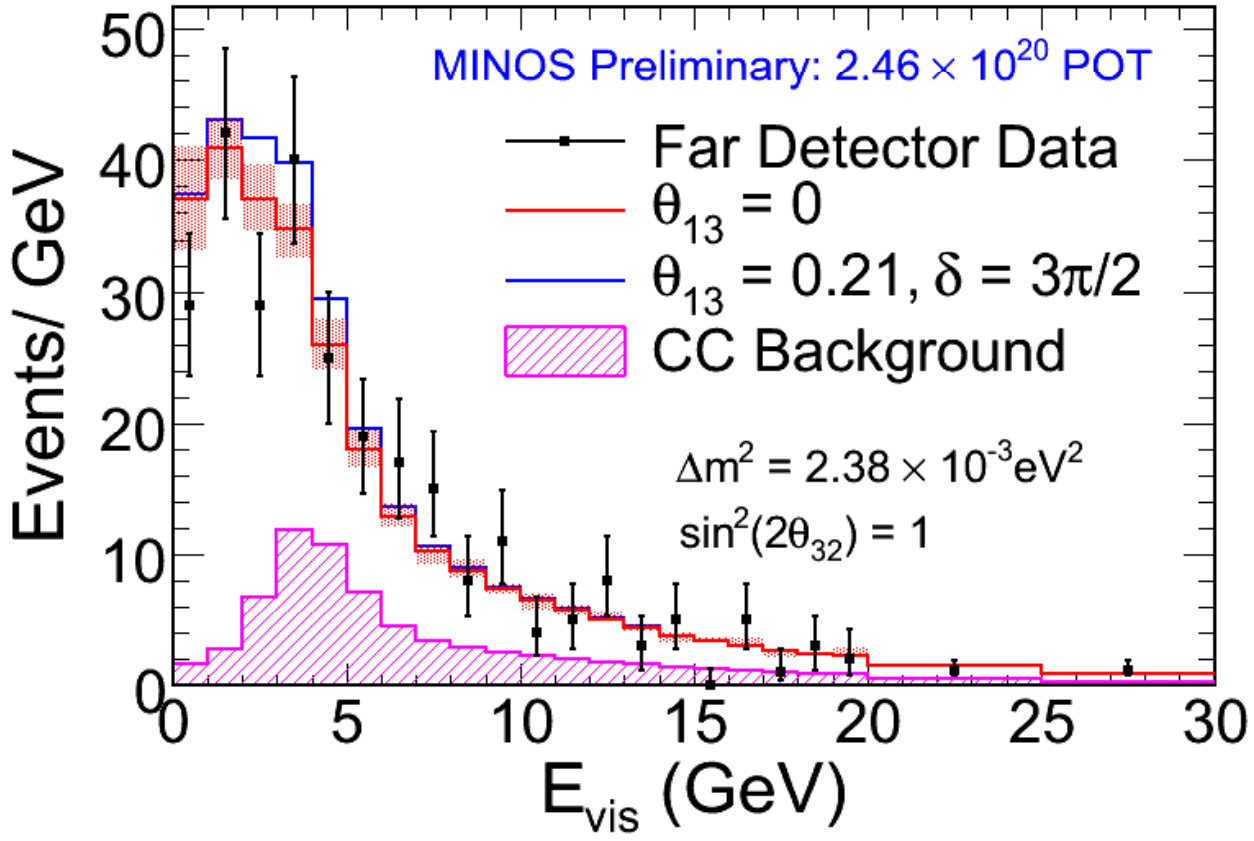
Barger, Geer, Whisnant, New J. Phys. 6 (2004) 135.

Introduction

- In addition to measureing oscillation parameters, it is important to test the 3-flavor mixing framework.
- The NC event rate measures the total flux of active neutrinos. Hence the anticipated far detector NC event sample will be depleted if there are transitions to sterile neutrinos
- To understand prospects observing/limiting the sterile neutrino transition probability $P_{\mu s}$ using NC measurements we must account for:
  - statistics
  - normalization uncertainties (Flux, spectrum & cross-section)
  - detector efficiencies
  - event-type mis-identification

Current Example: MINOS

- Far detector NC prediction based on near detector measurements → look for deficit



Measured NC Spectrum in Far Dectector

arXiv:0807.2424
3 Oct 2008

Observations

- Present sensitivity based on O(100) NC events is limited by statistics, and is sensitive to $P_{\mu s}$ > few $\times$ 10%

- NC events selected with 90% efficiency & 60% purity.

- In the future expect superbeam experiments will provide very large NC event samples, and it seems likely that the systematic uncertainties will limit the ultimate sensitivity to $P_{\mu s}$.

In a Perfect World

- Pure ν_μ beam with well known flux and spectrum, perfect detector, no cross-section uncertainties.
- Use NC & CC event rates integrated over spectra (N_{NC}, N_μ, N_e, N_τ) $\rightarrow$ oscillation probabilities

$$N_{NC} = N_\mu^0 (1 - P_s)\ \sigma_{NC} / \sigma_\mu$$

$$N_\mu = N_\mu^0 P_{\mu\mu}$$

$$N_e = N_\mu^0 P_{\mu e}\ \sigma_e / \sigma_\mu$$

$$N_\tau = N_\mu^0 P_{\mu\tau}\ \sigma_\tau / \sigma_\mu$$

DEFINE

N_μ^0 Predicted number of ν_μ CC interactions with no oscillations

$P_{xy} \equiv P(\nu_x \rightarrow \nu_y)$

σ_{NC} NC cross-section

σ_x CC cross-sections

With a Less Perfect Detector

$$N_{NC} = \frac{N_\mu^0}{\sigma_\mu}\left[(1-P_s)\,\sigma_{NC}\xi_{NC,NC} + \sum_{x=e,\mu,\tau} P_{\mu x}\sigma_x\xi_{x,NC}\right]$$

$$N_\mu = \frac{N_\mu^0}{\sigma_\mu}\left[(1-P_s)\,\sigma_{NC}\xi_{NC,\mu} + \sum_{x=e,\mu,\tau} P_{\mu x}\sigma_x\xi_{x,\mu}\right]$$

$$N_e = \frac{N_\mu^0}{\sigma_\mu}\left[(1-P_s)\,\sigma_{NC}\xi_{NC,e} + \sum_{x=e,\mu,\tau} P_{\mu x}\sigma_x\xi_{x,e}\right]$$

$$N_\tau = \frac{N_\mu^0}{\sigma_\mu}\left[(1-P_s)\,\sigma_{NC}\xi_{NC,\tau} + \sum_{x=e,\mu,\tau} P_{\mu x}\sigma_x\xi_{x,\tau}\right]$$

- Define:

$\xi_{x,x}$ Probability that event of type x correctly identified

$\xi_{x,y}$ Probability event of type x mis-identified as event of type y

- Solutions for $P_{\mu s}$, including a statistical analysis to obtain significance $P_{\mu s}/\delta(P_{\mu s})$, given in New J. Phys. 6 (2004) 135 for some limiting cases.

A few definitions

- Normalized mis-id factor $f_{xy} \equiv \xi_{xy}\sigma_x / \xi_{yy}\sigma_y$

  (= no. wrong / no. right)

- Normalized NC rate $R_{NC} \equiv \dfrac{N_{NC}}{\xi_{NC,NC} N^0_{NC}}$

- Normalized CC rate $R_{\mu} \equiv \dfrac{N_{\mu}}{\xi_{\mu,\mu} N^0_{\mu}}$

No. observed divided by No. expected if nothing interesting is happening

- Systematic uncertainty on fluxes & σ_{NC} $\varepsilon_{NC} \equiv \delta N^0_{NC} / N^0_{NC}$

Aside: Analytical expressions for $P_{\mu s}$ / $\delta P_{\mu s}$

Consider simplest case: Below ν_τ CC threshold, & ignore ν_e CC interactions (for other cases →New J. Phys 6 (2004)135):

• If the f_{ij} are small we can ignore terms $O(f^2)$, and obtain:

$$\frac{P_{\mu s}}{\delta P_{\mu s}} \approx \frac{1 - R_{NC} + f_{\mu,NC} R_\mu}{\delta R_{NC}}$$

Significance of deviation of $P_{\mu s}$ from zero

• In the limiting case where normalization uncertainties dominate (over event mis-identification):

$$\frac{P_{\mu s}}{\delta P_{\mu s}} \approx \frac{P_{\mu s}}{\sqrt{(1 - P_{\mu s})/(\xi_{NC,NC} N^0_{NC}) + (1 - P_{\mu s})^2 \varepsilon^2_{NC}}}$$

Detector Simulations

- Need efficiency and mis-id factors:
  - Consider several "toy experiments"
    → integrate over parametrized beam spectra
    → use parametrized detector responses
  - Use NEUGEN to simulate neutrino interactions
  - Define NC & CC event samples using various simple selection criteria matched to candidate detector technologies (e.g. water cherenkov, iron-scintillator)

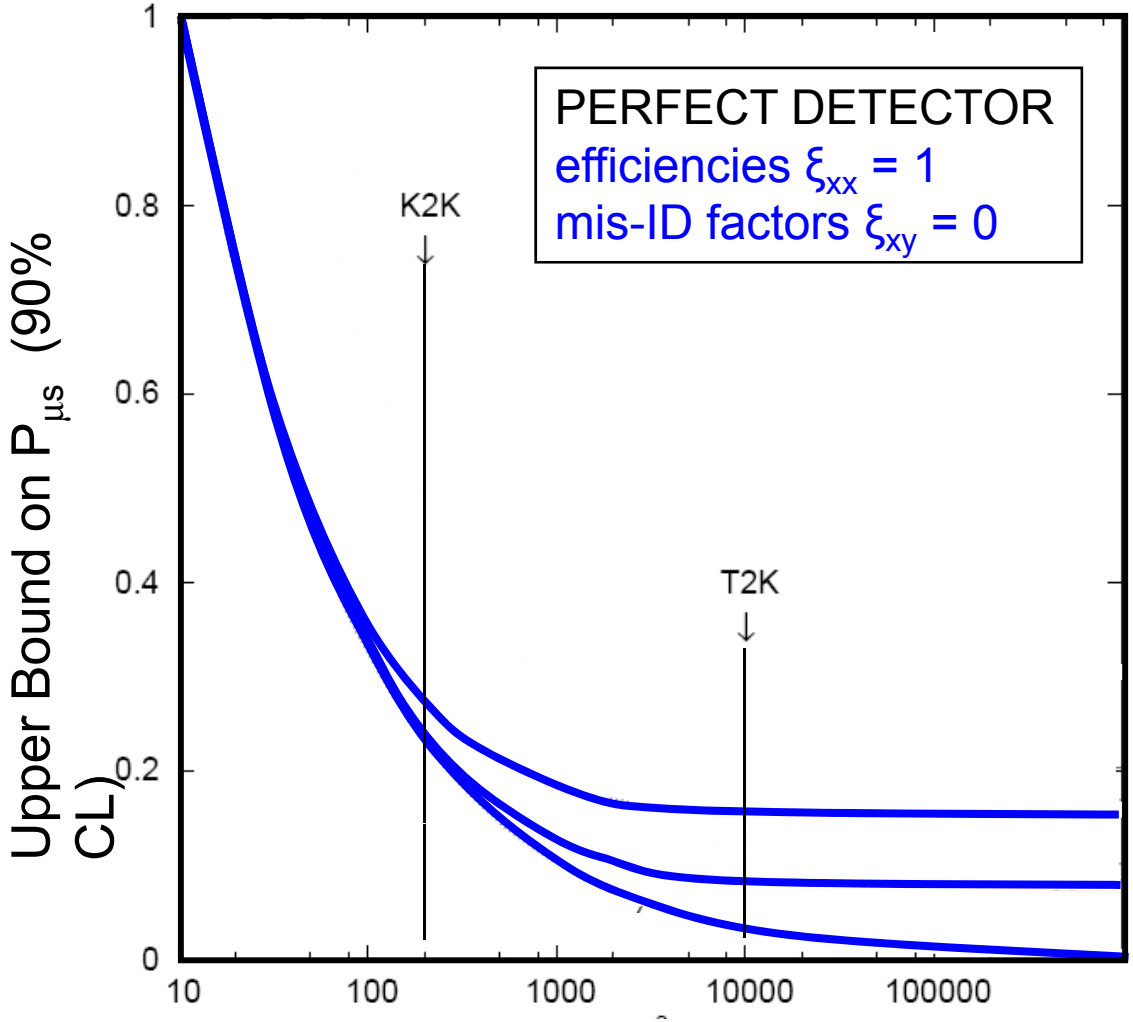
Toy Results for ξ_{xx} and $f_{xy} \equiv \xi_{xy}\sigma_x / \xi_{yy}\sigma_y$

Experiment	j (channel)	Signal	ζ_{jj}	$f_{NC,j}$	$f_{\mu,j}$	$f_{e,j}$	$f_{\tau,j}$
K2K-like	NC	two e-like, no μ-like	0.391	–	0.068	0.052	–
(basic)	μ	one μ-like, no e-like	0.520	0.087	–	0.0007	–
	e	one e-like, no μ-like	0.497	0.003	0.0004	–	–
K2K-like	NC	even e-like, no μ-like	0.437	–	0.078	0.060	–
(aggressive)	μ	even e-like, ≥ 1 μ-like	0.989	0.086	–	0.003	–
	e	odd e-like	0.993	0.002	0.005	–	–
K2K-like	NC	even e-like, no μ-like	0.494	–	0.081	0.011	–
(Gaussian	μ	even e-like, ≥ 1 μ-like	0.994	0.073	–	0.0007	–
beam)	e	odd e-like	0.999	0.0003	0.0004	–	–
T2K-like	NC	even e-like, no μ-like	0.420	–	0.25	0.006	–
(Gaussian	μ	even e-like, ≥ 1 μ-like	0.988	0.036	–	0.0014	–
beam)	e	odd e-like	0.944	0.00002	0.00001	–	–
MINOS-like	NC	no $\mu > 1$ GeV	1.000	–	0.903	–	0.429
$P_{\mu e} = 0$	μ	any $\mu > 1$ GeV	0.749	0	–	–	0
MINOS-like	NC	no e, μ, or γ	0.520	–	1.067	0.005	0.347
$P_{\mu e} \neq 0$	μ	any $\mu > 1$ GeV	0.749	0	–	0	0
	e	no $\mu > 1$ GeV, ≥ 1 e or γ	0.999	0.125	0.090	–	0.064

Observations

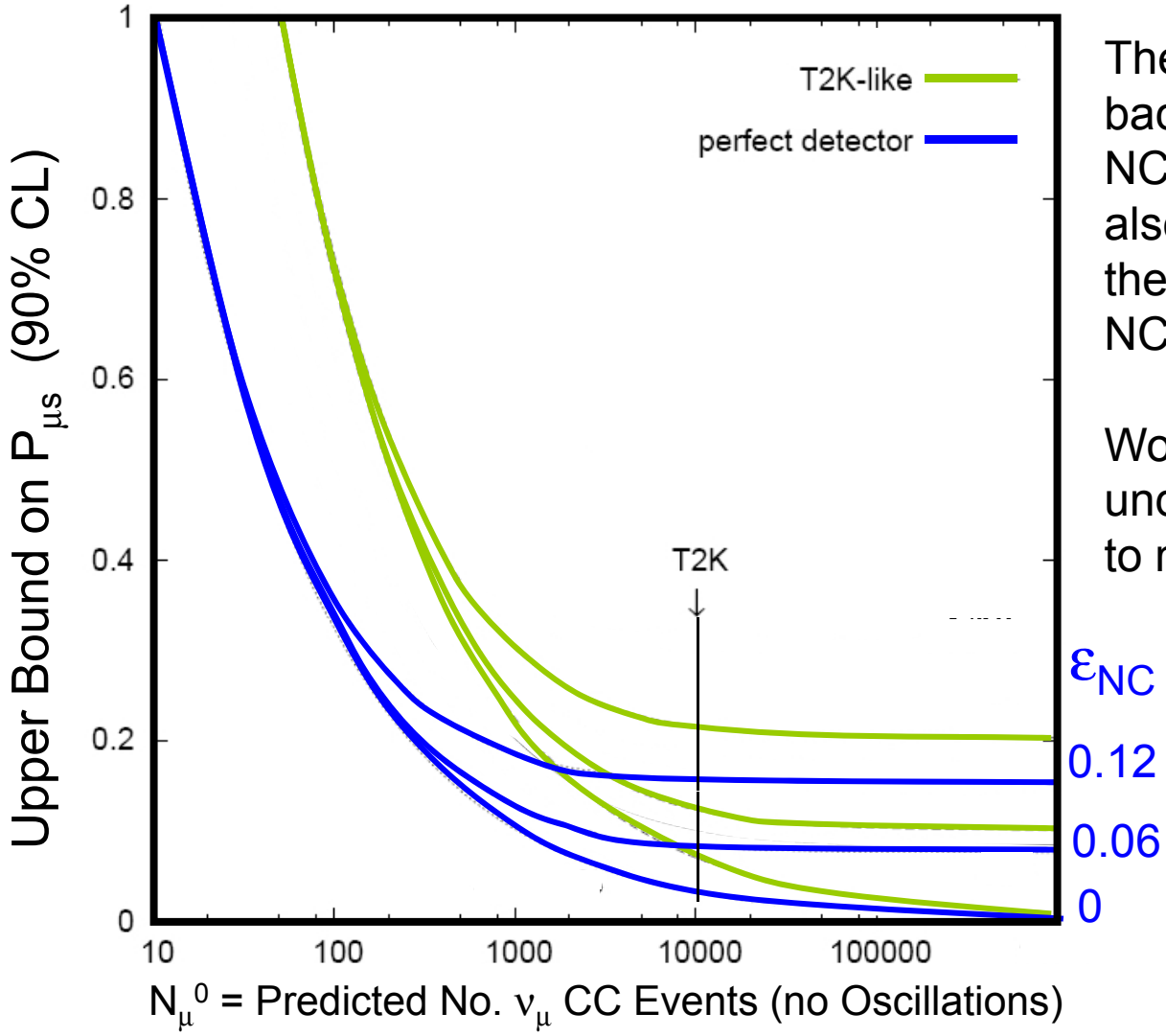
- K2K-Like experiment:
  - All $f_{i,j} < 0.1$, hence impact of mis-id small compared to statistical uncertainties
- T2K-Like experiment:
  - $f_{NC,NC} \sim 0.5$
  - $f_{\mu,NC} \sim 0.25 \rightarrow$ suggests cannot neglect mis-id
- MINOS-Like experiment:
  - $f_{NC,NC} \sim 1 \rightarrow$ good NC event efficiency
  - $f_{\mu,NC} \sim 1 \rightarrow$ cannot neglect if stats large
  - Simulated f's consistent with present MINOS analysis (better than we have a right to expect)

NC Cross-Section Uncertainty



Sensitivity of the next generation of experiments will be limited by normalization uncertainties unless they can be reduced below a few % → Additional motivation for experiments like Minerva

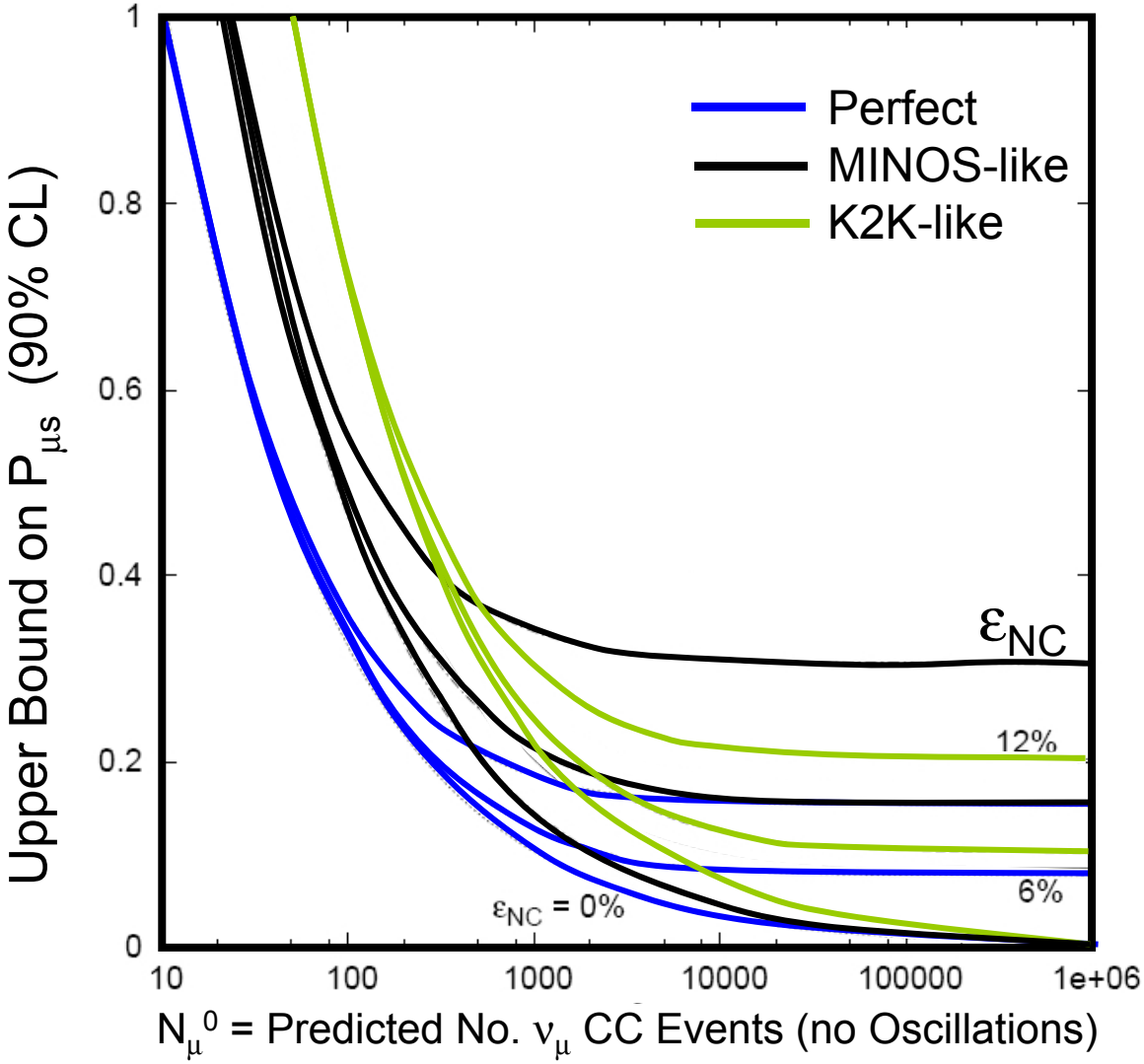
Efficiencies & Mis-ID: T2K-Like



The impact of ν_μ CC background in the NC sample seems also likely to limit the precision of the NC test.

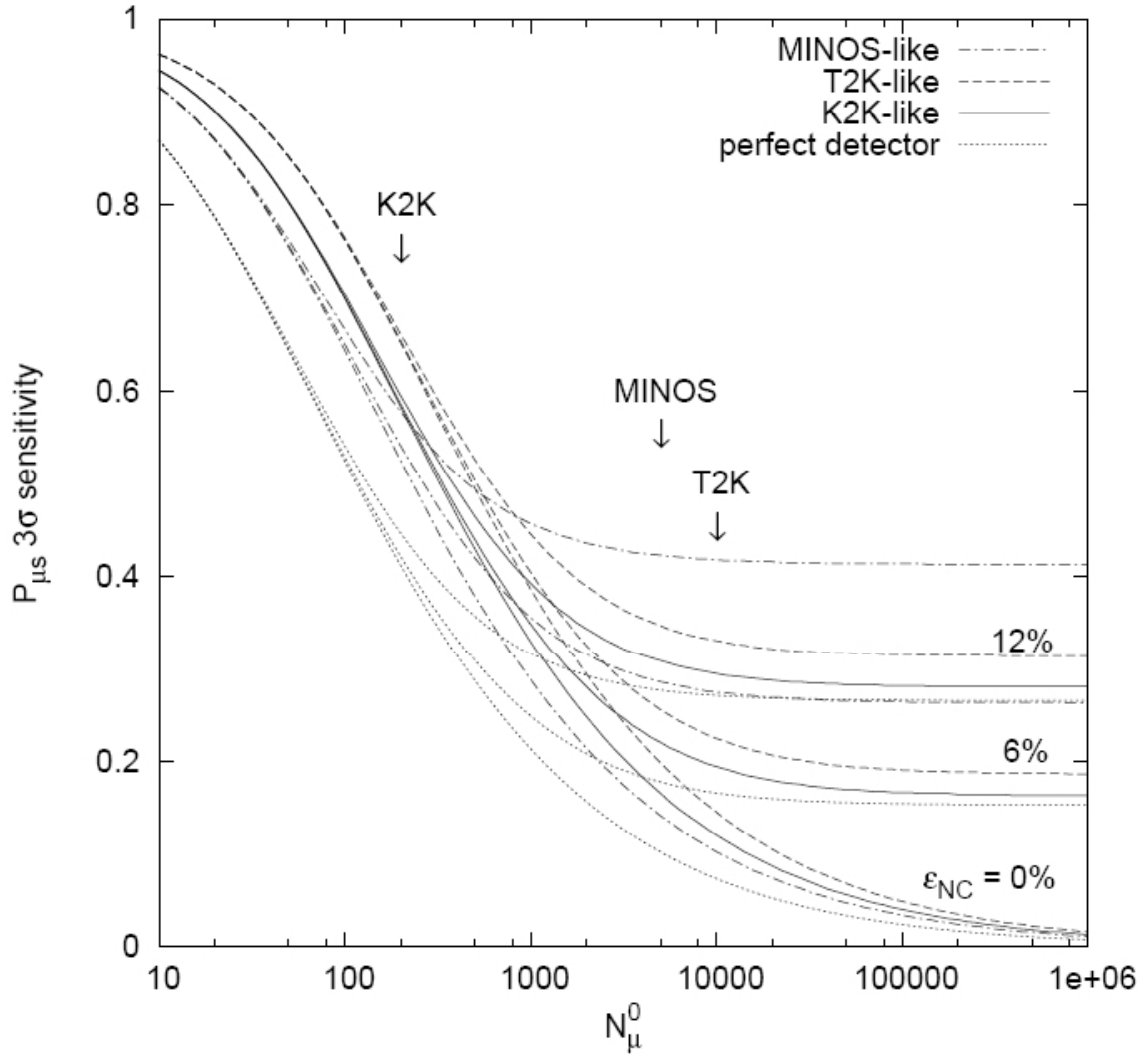
Worthwhile understanding how to minimize $f_{\mu,NC}$

Efficiencies & Mis-ID: MINOS-like



MINOS-like detector does better at low statistics (higher efficiency) but worse at high statistics (larger mis-id).

3σ Discovery Sensitivity



Summary

- Sensitivity to $P_{\mu s}$ below O(0.1) will require progress on background suppression & knowledge of normalizations (cross-sections & fluxes) $\rightarrow$ motivation for experiments like Minerva.

- If the sensitivity is ultimately limited by normalization-type uncertainties ε_{NC} the sensitivity to $P_{\mu s}$ can be understood analytically. For example, at 3σ, sensitivity $\rightarrow 3\varepsilon_{NC}/(1+3\varepsilon_{NC})$.

- To achieve few-percent-level 3σ sensitivity on $P_{\mu s}$ is likely to require (i) percent-level knowledge of fluxes and cross-sections, (ii) minimizing $f_{\mu,NC}$