Unitarity Tests using Neutral Currents

K. Whisnant
Argonne
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with V. Barger, S. Geer

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Primary goal: Promote discussion on NC

1. Introduction

- Expect 3 light active
- 3-ν unitarity violated if $\nu_a \to \nu_s$
- NC can measure $1 - P(\nu_a \to \nu_s)$
- Major sources of error:

  Event mis-identification

  Normalization uncertainty
  (NC cross section, flux renormalization)

For an initial ν_μ beam

N_μ^0 = # of CC μ interactions in detector (no osc.)

σ_x = cross section for interaction type X ($x = e, \mu, \tau, NC$)

ζ_{xy} = Probability that interaction type x is identified in detector as type y
(ζ_{xx} = efficiency for type x)

$P_{xy} = P(\nu_x \to \nu_y)$

Number of events of type y is

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

Then

$$R_{NC} = 1 - P_{\mu s} + P_{\mu\mu} f_{\mu,NC} + P_{\mu e} f_{e,NC} + P_{\mu\tau} f_{\tau,NC}$$

$$R_{\mu} = (1 - P_{\mu s}) f_{NC,\mu} + P_{\mu\mu} + P_{\mu e} f_{e,\mu} + P_{\mu\tau} f_{\tau,\mu}$$

$$R_{e} = (1 - P_{\mu s}) f_{NC,e} + P_{\mu\mu} f_{\mu,e} + P_{\mu e} + P_{\mu\tau} f_{\tau,e}$$

where

$$f_{x,y} \equiv \frac{\sigma_x \, \xi_{xy}}{\sigma_y \, \xi_{yy}}$$

normalized mis-identification factor

$f_{x,y}$ determined using NEUGEN simulation

Different analysis for above/below τ threshold

2. Below τ threshold (K2K / JPARC)

- $f_{\tau,x} = 0$, $P_{\mu\tau}$ terms drop out
- Measure $R_\mu, R_e, R_{NC} \Rightarrow$ determine $P_{\mu\mu}, P_{\mu e}, 1-P_{\mu s}$
- For small $P_{\mu e}$

$$\simeq 1 \quad \frac{R_{NC} \quad R_\mu f_{\mu,NC}}{1 \quad f_{\mu,NC} f_{NC,\mu}}$$

- Figure of Merit

$$FOM = \frac{P_{\mu s}}{\delta P_{\mu s}} \simeq \frac{1 - f_{\mu,NC} f_{NC,\mu} - R_{NC} + R_\mu f_{\mu,NC}}{\sqrt{(\delta R_{NC})^2 + f_{\mu,NC}^2 (\delta R_\mu)^2}}$$

$$\delta R_x = R_x \sqrt{\frac{1}{N_x} + \epsilon_x^2}$$

$$\epsilon_x \equiv \delta N_x^0 / N_x^0 \quad \text{(cross section, flux norm.)}$$

- Perfect detector $(f_{x,y} = 0)$

$$FOM = \frac{P_{\mu s}}{\sqrt{(1-P_{\mu s}) \frac{1}{\zeta_{NC,NC} N_{NC}^0} + (1-P_{\mu s})^2 \epsilon_{NC}^2}}$$

K2K/JPARC experiments

- Simple model for detector response

$E_{rms} > 100$ MeV

$$\frac{\Delta E_{rms}}{E} = .005 + \frac{.025}{\sqrt{E}} \quad \text{for } e$$

$$\frac{\Delta p_{rms}}{p} = .03 \quad \text{for } \mu,$$

- Use NEUGEN to simulate ν interactions (4×10^5 events)

μ CC : single μ-like ring

e CC : single e-like ring

NC : two e-like rings (from $\pi^0 \to \gamma\gamma$)

- Simulation results for K2K/JPARC-like experiments

$S_{NC,NC} = 0.39$ $\quad f_{\mu,NC} = .07$ $\quad f_{e,NC} = .05$

$S_{\mu,\mu} = 0.52$ $\quad f_{NC,\mu} = .09$ $\quad f_{e,\mu} = .001$

$S_{e,e} = 0.50$ $\quad f_{NC,e} = .003$ $\quad f_{\mu,e} = .0004$

all $\leq$

Define 3σ sensitivity: $P_{\mu s}^{3\sigma} = 3\,\delta P_{\mu s}$

$$\frac{3\left(\delta R_{NC}/R_{NC}\right)}{1+3\left(\delta R_{NC}/R_{NC}\right)} \leq P_{\mu s}^{3\sigma} \lesssim \frac{3\left(1+f_{\mu,NC}\right)\left(\delta R_{NC}/R_{NC}\right)}{1+3\left(1+f_{\mu,NC}\right)\left(\delta R_{NC}/R_{NC}\right)}$$

perfect detector
$f_{x,y}=0$

$\nu_\mu \not\to \nu_\tau, \nu_e$

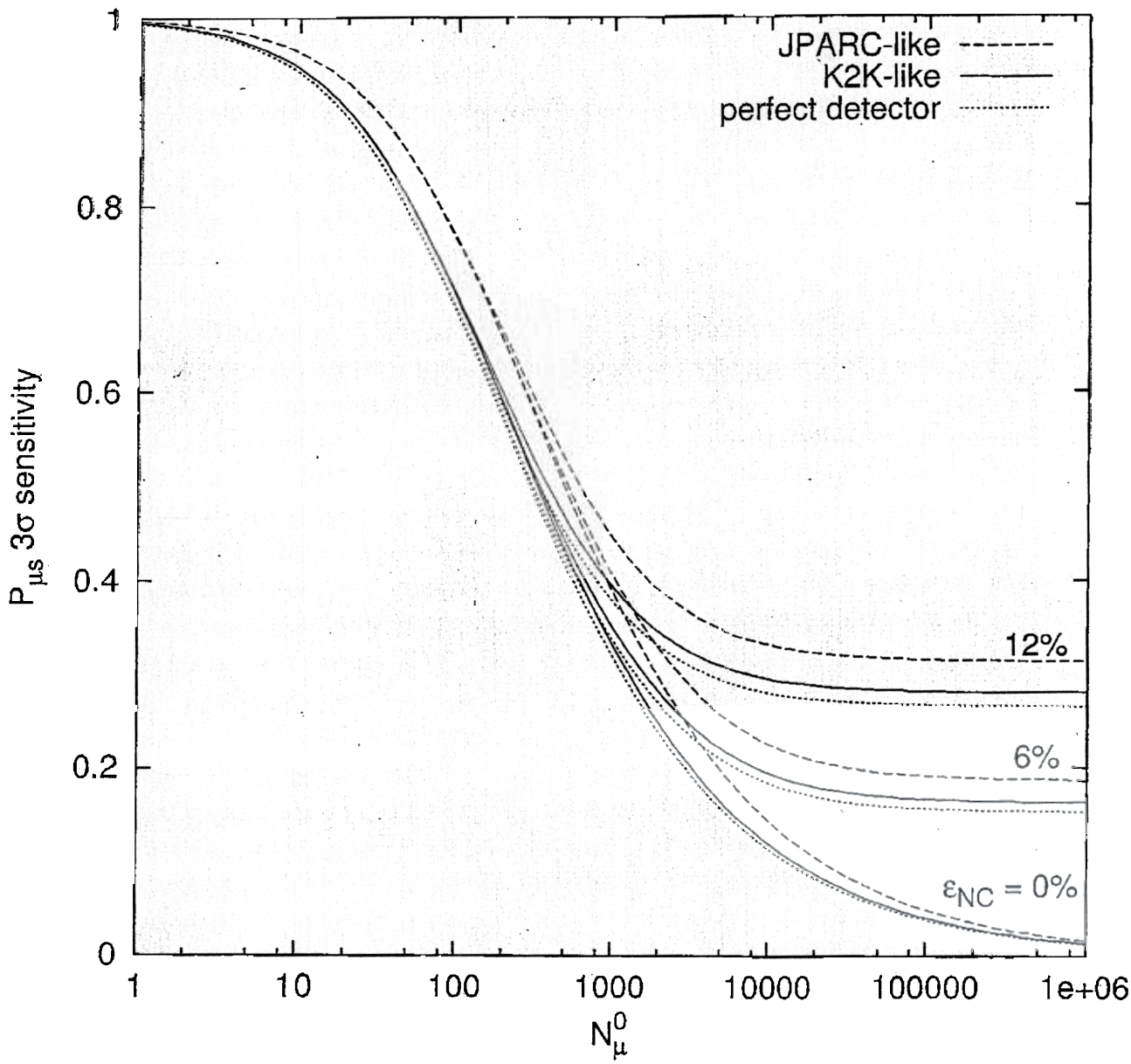
$\Rightarrow$ $f_{\mu,NC}$ most critical K2K : .07

JPARC :

NC cross section uncertainty

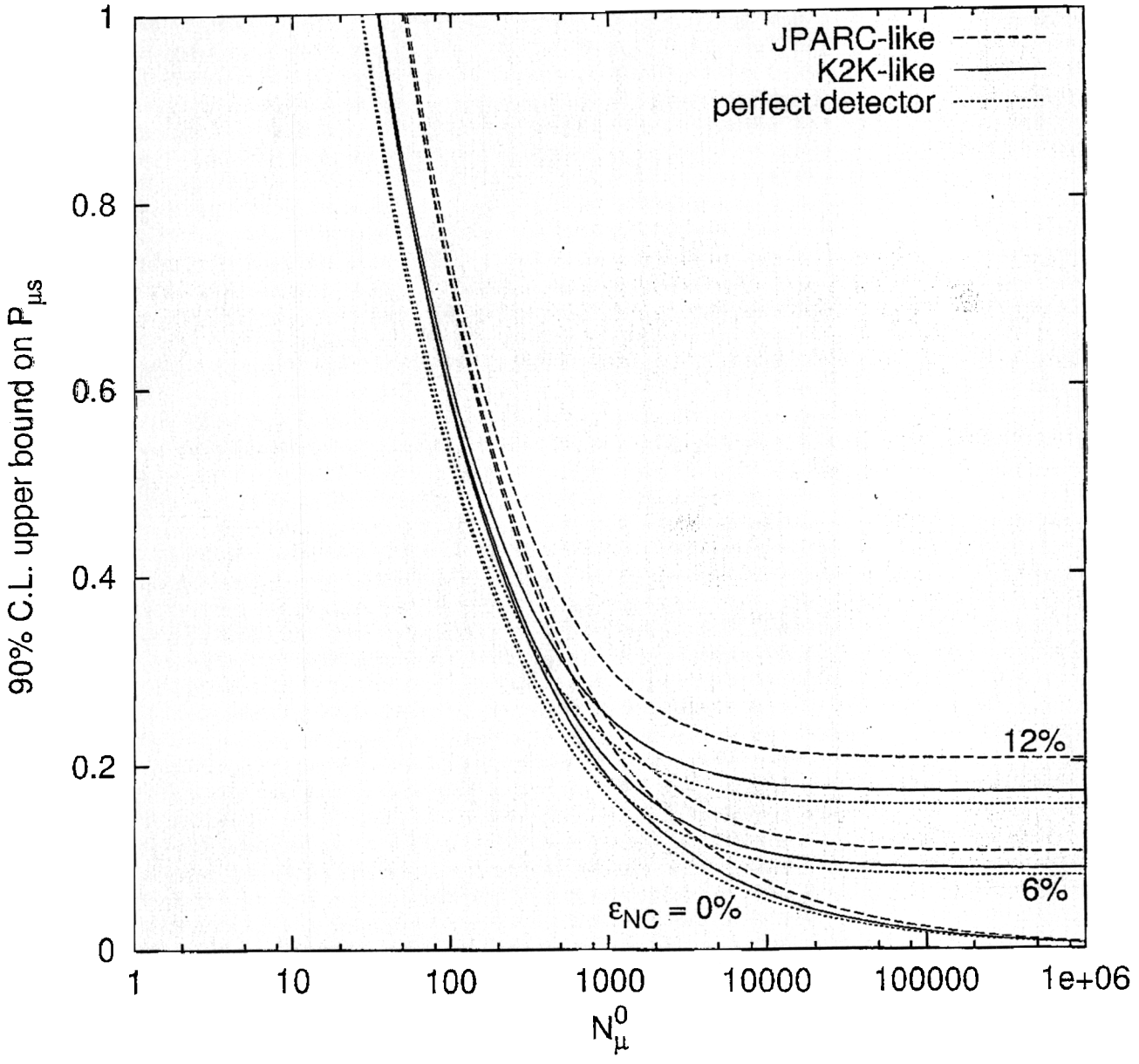
Now: $\epsilon_{NC} \sim 0.12$

Future: $\epsilon_{NC} \sim 0.06$?


JPARC-like
K2K-like
perfect detector
12%
6%
ε_{NC} = 0%
$P_{\mu s}$ 3σ sensitivity
N_μ^0
0
0.2
0.4
0.6
0.8
1
1
10
100
1000
10000
100000
1e+06

For null result

(assume standard 3-ν osc. parameters)



Sensitivity nearly independent of:

- Signal definition
- $P_{\mu e}$ (since $f_{e,NC}$, $P_{\mu e} \leq 0.1$)
- Exact nature of high-energy tail
- E_{vis} cut

Ultimate limit for 3σ sensitivity (for high statistics)

$$P_{\mu s}^{3\sigma} = \frac{3\,\epsilon_{NC}}{1 + 3\,\epsilon_{NC}}$$

Summary

- Water Cerenkov detectors at low E do well
- Reducing ϵ_{NC} most important

3. Above τ threshold

- $1-P_{\mu s}$, $P_{\mu\mu}$, $P_{\mu e}$, $P_{\mu\tau}$ all contribute
- Measure R_μ, R_e, R_{NC} (or R_μ, R_τ, R_{NC})
- Use $P_{\mu\tau} = 1 - P_{\mu s} - P_{\mu e}$ $P_{\mu\mu}$ (or $P_{\mu e} = 1 - P_{\mu s} - P_{\mu\mu} - P_{\mu\tau}$)

Preliminary studies show:

Large $f_{\mu,NC}$ and $f_{\tau,NC}$ for MINOS-like detector

$f_{\tau,NC}$ very sensitive to high-energy tail of ν spectrum

Large $f_{\tau,NC}$ for Liquid Argon detector with simple cuts

4. Neutrino Factory

- Disadvantage

  Can't measure a channels separately

  $\nu_\mu + \nu_e$ beam

  6 measurements: $\mu^-, \mu^+, \tau^-, \tau^+, e^- + e^+$, NC+NC

  Bad news! 8 unknowns $P_{\mu e}, P_{\mu\mu}, P_{\mu\tau}, 1-P_{\mu s}$

  $\bar{P}_{ee}, \bar{P}_{e\mu}, \bar{P}_{e\tau}, 1-\bar{P}_{es}$

  Good news! 2 conditions $P_{\mu e} + P_{\mu\mu} + P_{\mu\tau} = 1 - P_{\mu s}$

  $\bar{P}_{ee} + \bar{P}_{e\mu} + \bar{P}_{e\tau} = 1 - \bar{P}_{es}$

  $\Rightarrow$ sufficient to determine all probabilities

  be overcome in principle

- Advantages

  Large flux – approach high statistics limit even for long L

  Higher E – DIS NC cross section less uncertain

5 Other dea (need furth r study)

R = tt NC m. r)

D t ed ν fit l k fo co stencies

Mea ure $P_{\mu\mu}$ P_{μ} $P_{\mu\tau}$

U: n rgy nfor ation

strong energy d p d nce of $f_{x,y}$

L k fo n y d pend t q t s

$$\frac{P_{\mu s}}{1 \; P_{\mu}} = \underbrace{n\,\theta_{\tau}\cos\theta_{2\tau}}_{n\,\alpha} \quad n \quad m \quad \varphi$$

$P_{\mu\mu} \to 0$ on p k f o eimin tes $f_{\mu,NC}$ effect

B l w τ thre hold ⇒ ν go d detector performance

Above τ thresho d ⇒ $P_{\mu\tau}$ xima $f_{\tau,NC}$ mpo tany

Use tt ff t fo v ry g L t d t gu sh

$\nu_\mu \to \nu_\tau$ from $\nu_\mu \to \nu_s$ (k Supe K tm s ν an ysis)

teri ffect at lit de live − G_F kn n

U rtai ity n matt den ty

SUMMARY

- Use NC to measure $1 - P_{\mu s} \Rightarrow P_{\mu s}$
- Event mis-ID scrambles signal (especially $f_{x,NC}$)
- Water Cerenkov detectors at low E do well
- Uncertainty in NC cross section at low E sets ultimate limit

  Need $\epsilon_{NC} \sim 2\text{-}3\%$ to push $P_{\mu s}^{3\sigma}$ down to 5 10%
- No single "golden" measurement

  Multipronged approach best