Figures of Merit for the Physics Performance of DUNE ND

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EVALUATION OF ND OPTIONS

- ✦ *Impact on the sensitivity to oscillation parameters can be evaluated with available fitters, e.g. VALOR and TF studies focused at CP violation (see talk by E. Worcester for a more complete picture)*

- ✦ *Beam and detector related performance can be quantified in terms of specific quantities (e.g. pile-up, energy and space resolutions, particle ID, etc.) as outlined by B. Rebel in January (AnalysisOutput package)*

- ✦ *The physics performance of ND can be quantified in terms of the sensitivity to a set of key physics measurements, which are crucial to achieve the primary DUNE scientific requirements for oscillation analyses*

- ✦ *Considerable efforts made within the NDWG to discuss and define a minimal set of key measurements to be used as figures of merit for the ND physics performance*

  $\Longrightarrow$ *General consensus on 5 main physics topics to be addressed by ND options*

- *According to DUNE requirements ND measurements shall be sufficiently precise and accurate that the LBL oscillation analysis capability be limited by the statistics of the planned exposure and the systematic uncertainties of the far detector.*

- *Taking into account oscillations we expect roughly 10,000* ν_μ *CC and 1,000* ν_e *CC events in the FD, which implies predictions extrapolated from ND measurements should achieve an accuracy at the level of a few percent in the relevant energy bins*

- *Sensitivity studies from FD analyses indicate that a normalization uncertainty on the appearance sample of* $\leq 2\%$ *is required for CPV/precision measurements (see talk by E. Worcester for details)*

I. $\nu(\bar{\nu})$-e NC ELASTIC SCATTERING

✦ *Most important measurement, need to collect the highest statistics possible:*

- *Measurement of absolute flux;*
- *Calibration of the absolute neutrino energy scale (statistics permitting).*

✦ *Event selection:*

- *Signal efficiency;*
- *Backgrounds;*
- *Statistical and systematic uncertainties.*

✦ *Availability of control samples to constrain/calibrate backgrounds and efficiencies*

$\Longrightarrow$ *Can NOT rely upon simulations, especially for tails of distributions*

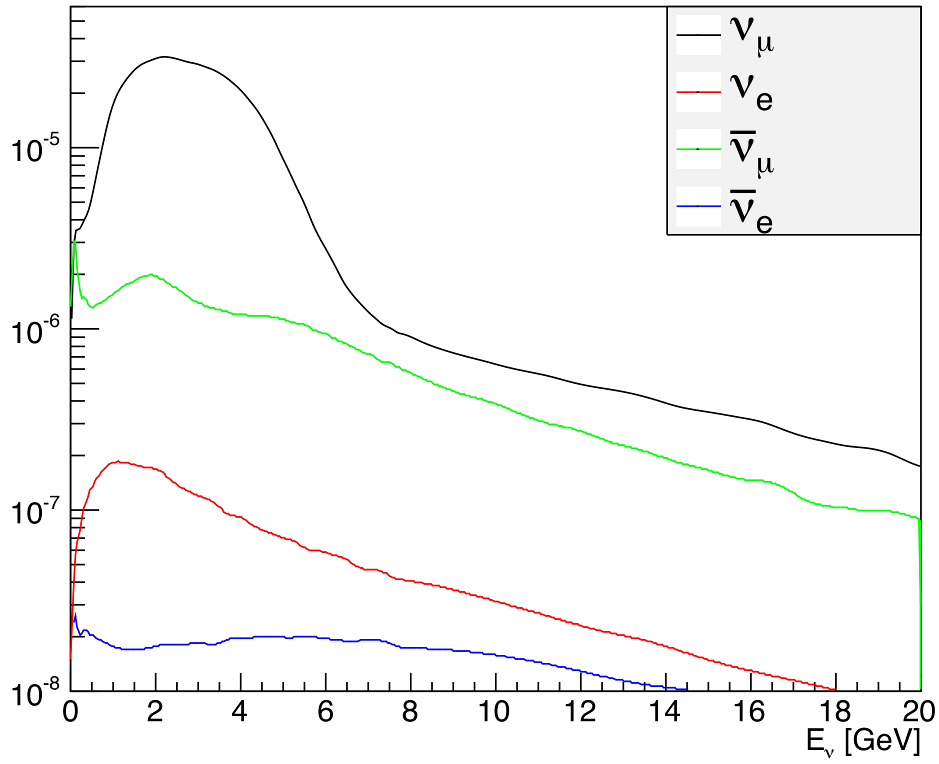
✦ *Need to deconvolute flavor content since ν–e NC is flavor blind:*

- *Use CC Inverse Muon Decay $\nu_\mu e \to \mu^- \bar{\nu}_e$ ($\bar{\nu}_e e \to \mu^- \bar{\nu}_\mu$) at $E_\nu > 11$ GeV, NOT sensitive to $\bar{\nu}_\mu$*
- *Use ratio of coherent π^+/π^- to constrain/monitor the $\nu_\mu/\bar{\nu}_\mu$ ratio in each beam mode*

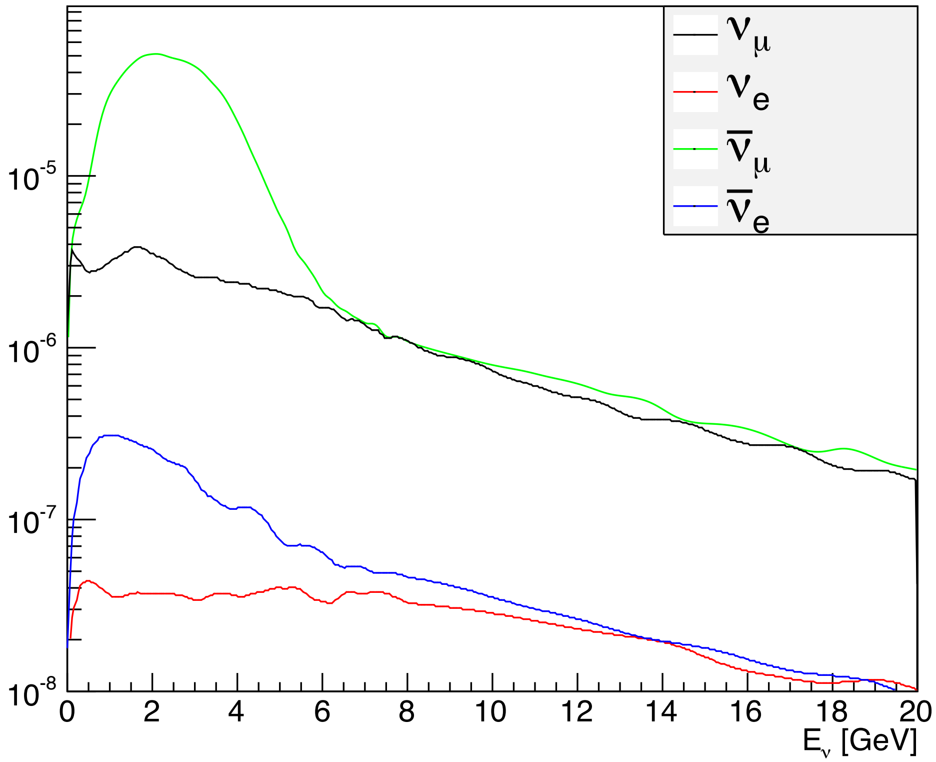
✦ *Need to constrain beam divergence for accurate energy reconstruction:*

- *Use coherent $\pi^\pm$ to measure distribution of beam divergence;*
- *Exploit beam geometry by performing measurements in different radial & longitudinal bins/locations.*

Neutrino beam (FHC)



Anti-neutrino beam (RHC)



Energy Range	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
0.5-5.0 GeV	0.907	0.085	0.006	0.001
5.0-10 GeV	0.624	0.345	0.022	0.009
$>$ 10 GeV	0.624	0.332	0.026	0.017

II. RELATIVE $\nu_\mu(\bar{\nu}_\mu)$ FLUX VS. ENERGY

✦ *Two measurements aspects to be considered:*

- *Measurement of the relative bin-to-bin $\nu_\mu(\bar{\nu}_\mu)$ flux vs. energy in ND;*
- *Extrapolation of flux spectra to FD/ND(E) ratio.*

✦ *Methods, statistical & systematic uncertainties, robustness against simulations*

✦ *Relative bin-to-bin $\nu_\mu(\bar{\nu}_\mu)$ flux from low-ν method:*

$$N(E_\nu,\ E_{\rm Had} < \nu_0) \propto \Phi(E_\nu) f_c(\tfrac{\nu_0}{E_\nu}) \qquad f_c \to 1 \text{ for } \nu_0 \to 0$$

✦ *Measurement of CC spectra of $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$ constrains parent mesons:*

$$\begin{aligned}
\nu_\mu &\equiv \pi^+ \oplus K^+ \\
\bar{\nu}_\mu &\equiv \pi^- \oplus K^- \\
\nu_e &\equiv \mu^+(\pi^+ \to \nu_\mu) \oplus K^+(\to \nu_\mu) \oplus K_L^0 \\
\bar{\nu}_e &\equiv \mu^-(\pi^- \to \bar{\nu}_\mu) \oplus K^-(\to \bar{\nu}_\mu) \oplus K_L^0
\end{aligned}$$

- *Beam simulations expect uncertainties $< 2\%$ on FD/ND but need IN-SITU measurement;*
- *Fit ND $\nu_\mu, \bar{\nu}_\mu$ ($\nu_e, \bar{\nu}_e$) spectra in 4-5 (x,y) radial bins;*

$\Longrightarrow$ *Need good reconstruction & identification of all 4 neutrino species.*

III. INCLUSIVE $\nu_e(\bar{\nu}_e)$ CC

✦ *Need precise measurement of ν_e/ν_μ and $\bar{\nu}_e/\bar{\nu}_\mu$ ratios since in FD simultaneous fit to $\nu_\mu(\bar{\nu}_\mu)$ disapperance and $\nu_e(\bar{\nu}_e)$ appearance*

✦ *Event selection:*

- *Signal efficiency;*
- *Backgrounds;*
- *Statistical and systematic uncertainties.*

✦ *Availability of control samples to constrain/calibrate backgrounds and efficiencies*

✦ *Measurement of ν_e AND $\bar{\nu}_e$ provides redundancy to check predictions:*

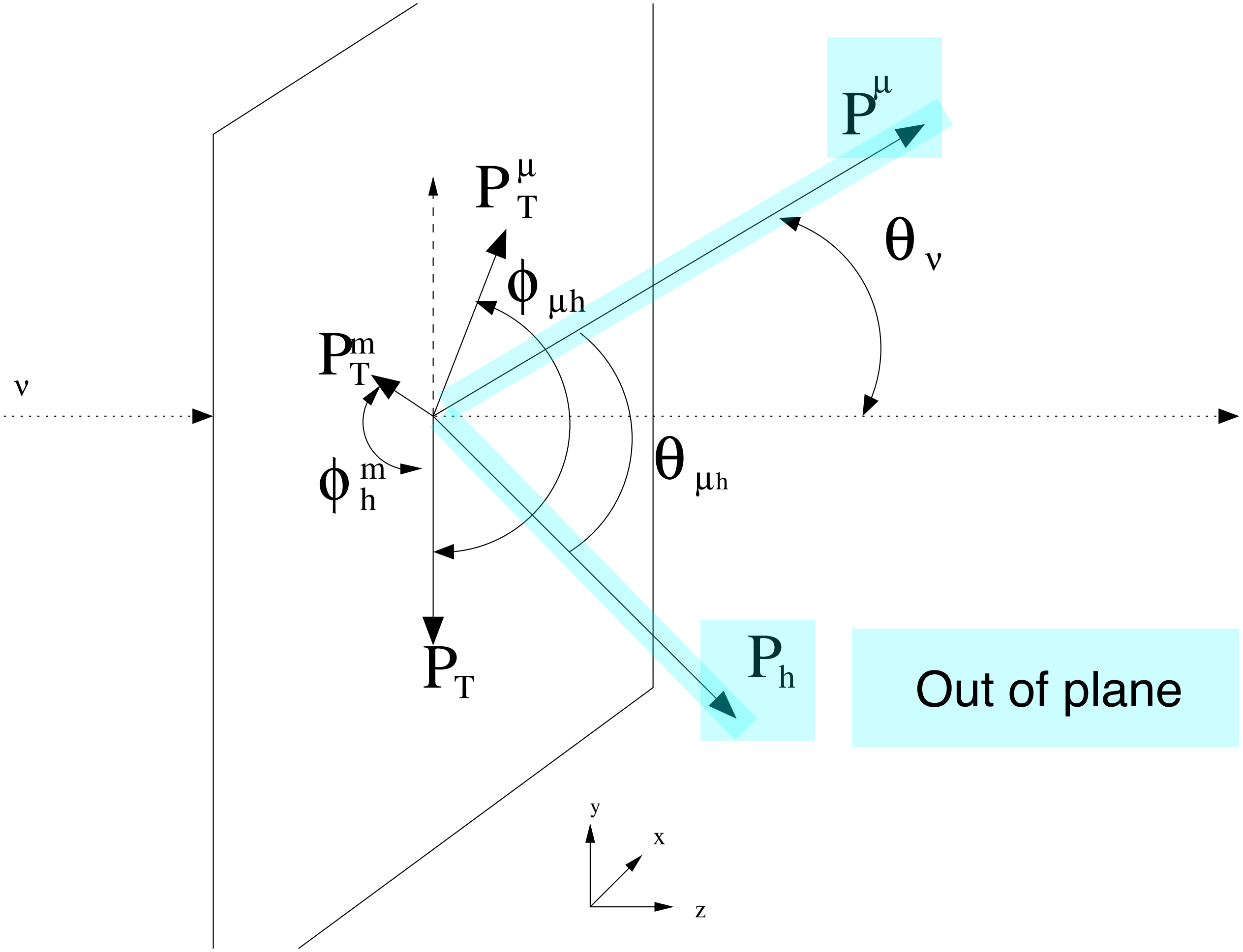
$$\begin{aligned} \nu_e &\equiv \mu^+(\pi^+ \rightarrow \nu_\mu) \oplus K^+(\rightarrow \nu_\mu) \oplus K^0_L \\ \bar{\nu}_e &\equiv \mu^-(\pi^- \rightarrow \bar{\nu}_\mu) \oplus K^-(\rightarrow \bar{\nu}_\mu) \oplus K^0_L \end{aligned}$$

- *Direct measurement of $\nu_e(\bar{\nu}_e)$ CC spectra;*
- *In-situ validation of predictions from fitted parent meson distributions.*

IV. π^0 PRODUCTION IN NC & IN CC

- ✦ *Measure the background for the $\nu_e(\bar{\nu}_e)$ apperance in the FD*
- ✦ *Event selection:*
  - *Reconstruction, identification and efficiency (E_π, θ_π);*
  - *Backgrounds;*
  - *Statistical and systematic uncertainties.*
- ✦ *Availability of control samples to constrain/calibrate backgrounds and efficiencies*
- ✦ *Event-by-event NC/CC separation using event kinematics:*
  - *Momentum balance in transverse plane (missing p_T);*
  - *Kinematic tagging of most likely leading CC lepton;*
  - *Multivariate analysis (likelihood function) of complete event kinematics for NC/CC separation.*

  $\Longrightarrow$ *Verify performance at low energies and define appropriate data control samples*
- ✦ *More detailed measurements of π^0 production as a function of kinematic variables (e.g. x_F, z, p_T, etc.) in CC*



Out of plane

V. NUCLEAR EFFECTS

- ✦ *Important to calibrate/understand the (anti)neutrino energy scale in FD*

- ✦ *Two aspects to be addressed:*
  - *Quantify effects on cross-sections in ND and predict event rates on ^{40}Ar in FD;*
  - *Unfold the FD measurements to determine the actual $\nu\&\bar{\nu}$ spectra in FD.*

- ✦ *Unfolding nuclear smearing requires in-situ calibration of (anti)neutrino energy scale:*
  - *Physics smearing related to nuclear modification of cross-sections (ISI) and topologies (FSI);*
  - *Detector smearing related to event reconstruction.*

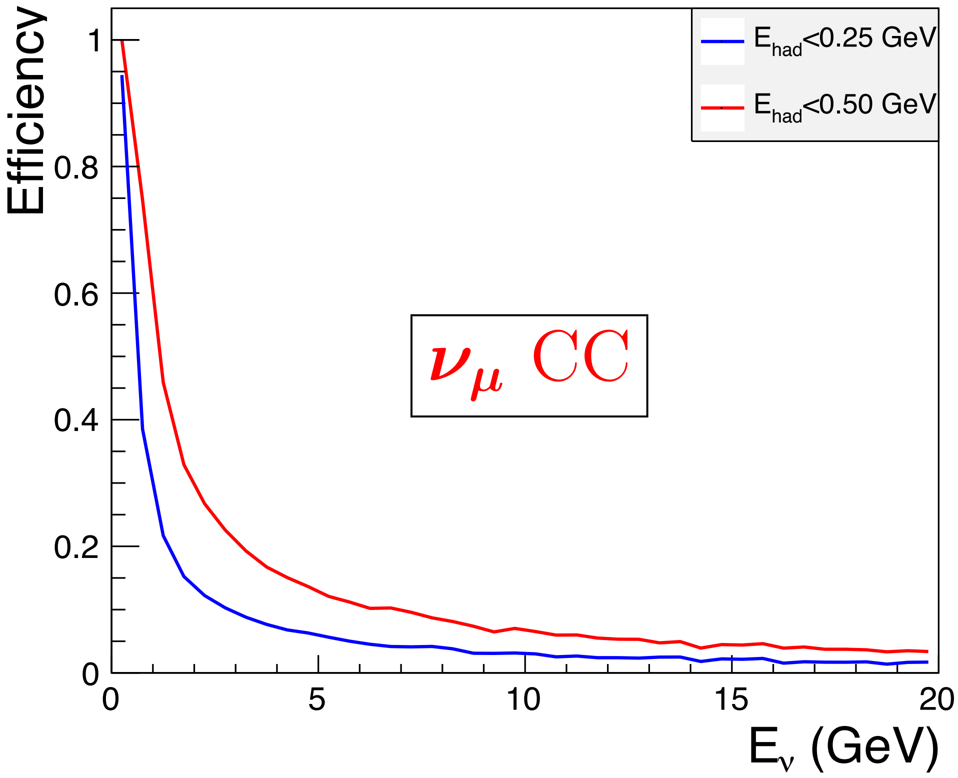
- ✦ *Physics smearing can be addressed by measurements w/o nuclear effects and validated with dedicated in-situ nuclear target suite including ^{40}Ar:*
  - *Energy spectrum determination from ν–e NC elastic scattering (statistics permitting);*
  - *Measurements on free nucleon (proton).*

- ✦ *Detector smearing requires LAr detector and a way to mimic effects of FD readout (combination of test beam and in-situ measurements)*

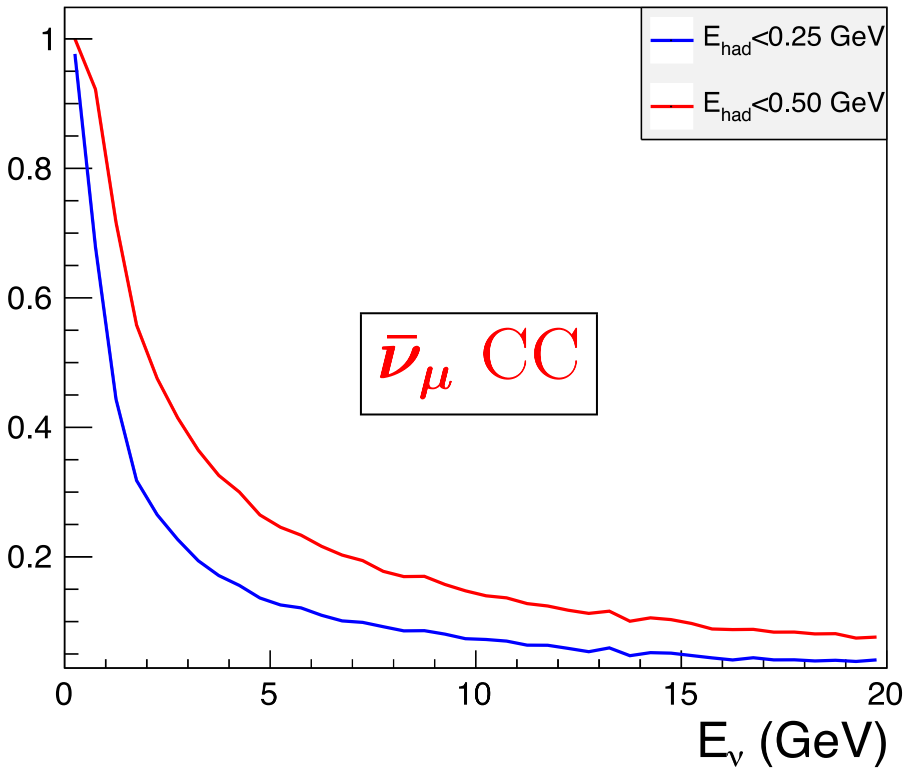
Backup slides

Relative efficiency of the cut $\boxed{\nu < \nu_0}$ *in DUNE ND*

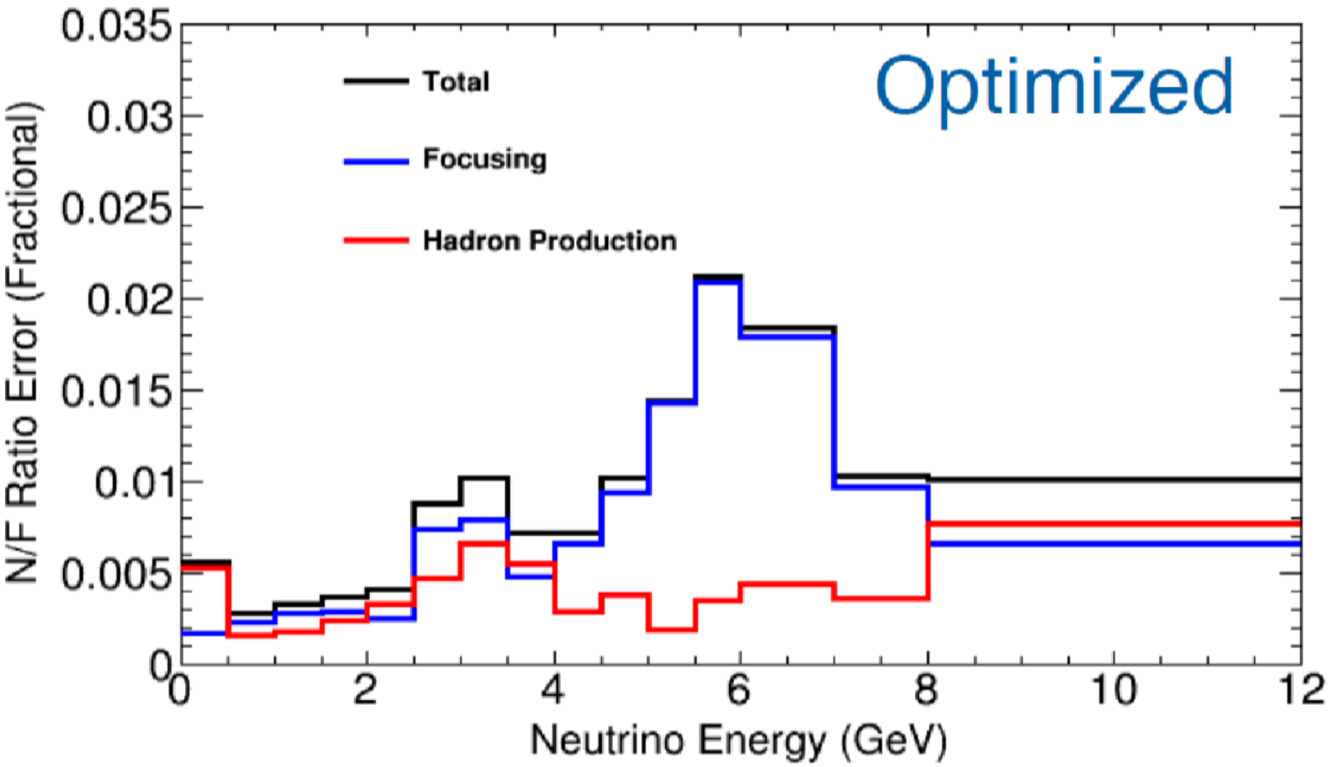
reconstruction efficiencies not included (typically $> 90\%$*)*



Cut	$\nu < 0.25$ *GeV*	$\nu < 0.50$ *GeV*
$\langle\varepsilon\rangle$	*9%*	*19%*



Cut	$\nu < 0.25$ *GeV*	$\nu < 0.50$ *GeV*
$\langle\varepsilon\rangle$	*11%*	*22%*


Optimized
Total
Focusing
Hadron Production
N/F Ratio Error (Fractional)
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
Neutrino Energy (GeV)
0
2
4
6
8
10
12