Measurements of The Neutrino Flux Using Fine-Grained Tracker

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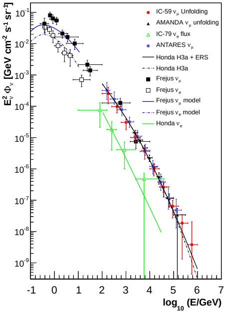
Outline

The Neutrino Fluxes

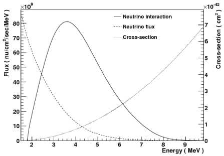
$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & 0 & S_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta_{\mathrm{CP}}} & 0 & C_{13} \end{pmatrix} \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric + Accelerator | Reactor + Accelerator | Reactor + Solar

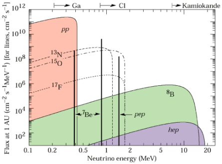
Atmospheric ($\times$)



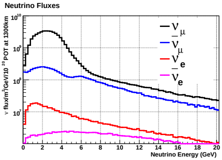
Reactor ($\times$)



Solar ($\times$)



Accelerator ($\surd$)



Flux uncertainty dominates the cross section measurements

"Measurement of Muon Neutrino Quasi-Elastic Scattering on a Hydrocarbon Target at E_ν ~3.5 GeV", MINERνA, PRL 111, 022502 (2013).

Q^2_{QE} (GeV^2)	I	II	III	IV	V	VI	Total
0.0 − 0.025	0.06	0.04	0.02	0.04	0.09	0.03	0.13
0.025 − 0.05	0.06	0.03	0.02	0.03	0.09	0.02	0.12
0.05 − 0.1	0.06	0.03	0.02	0.03	0.09	0.02	0.12
0.1 − 0.2	0.06	0.03	0.03	0.02	0.09	0.02	0.11
0.2 − 0.4	0.05	0.02	0.03	0.03	0.09	0.01	0.11
0.4 − 0.8	0.05	0.03	0.04	0.04	0.09	0.01	0.13
0.8 − 1.2	0.08	0.07	0.07	0.15	0.09	0.02	0.22
1.2 − 2.0	0.12	0.07	0.07	0.16	0.09	0.02	0.24

"Measurement of Muon Antineutrino Quasi-Elastic Scattering on a Hydrocarbon Target at E_ν ~3.5 GeV", MINERνA, PRL 111, 022501 (2013).

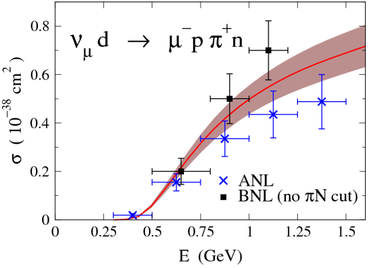
Q^2_{QE} (GeV^2)	I	II	III	IV	V	VI	Total
0.0 − 0.025	0.05	0.04	0.00	0.02	0.11	0.02	0.13
0.025 − 0.05	0.05	0.04	0.01	0.01	0.11	0.02	0.13
0.05 − 0.1	0.05	0.04	0.01	0.01	0.11	0.01	0.13
0.1 − 0.2	0.04	0.04	0.01	0.01	0.11	0.01	0.12
0.2 − 0.4	0.03	0.06	0.01	0.02	0.11	0.01	0.13
0.4 − 0.8	0.05	0.07	0.02	0.03	0.11	0.01	0.15
0.8 − 1.2	0.11	0.11	0.02	0.02	0.11	0.02	0.20
1.2 − 2.0	0.13	0.15	0.04	0.04	0.12	0.02	0.23

"Measurement of the ν_μ charged current quasi-elastic cross-section on carbon with the T2K on-axis neutrino beam", arXiv/hep-ex:1503.07452.

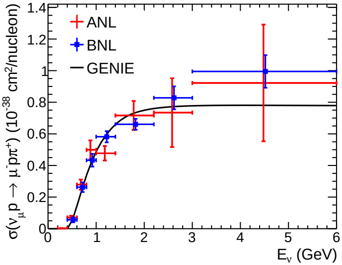
Item	High energy region	Low energy region
Neutrino flux	−11.01% + 13.61%	−13.57% + 17.04%
M_A^{QE}	−0.89% + 2.25%	−0.08% + 0.39%
M_A^{RES}	−0.92% + 1.31%	−0.82% + 1.10%
CC1π normalization (E_ν <2.5 GeV)	−0.55% + 0.50%	−3.71% + 3.59%
CC1π normalization (E_ν >2.5 GeV)	−2.69% + 2.69%	−1.88% + 1.83%
CC coherent π normalization	−1.40% + 1.38%	−1.73% + 1.71%
CC other E_ν shape	−0.86% + 0.85%	−0.11% + 0.09%
NC1π^0 normalization	−0.65% + 0.65%	−0.40% + 0.40%
NC coherent π normalization	−0.10% + 0.10%	−0.09% + 0.09%
NC1$\pi^\pm$ normalization	−0.47% + 0.47%	−0.46% + 0.45%
NC other normalization	−0.33% + 0.31%	−0.75% + 0.74%
π-less Δ decay	−0.54% + 2.10%	−1.60% + 3.34%
Spectral function	−2.01% + 0.00%	−0.00% + 1.21%
Fermi momentum	−1.67% + 2.22%	−3.71% + 4.43%
Binding energy	−0.44% + 0.65%	−1.24% + 1.42%
Pion absorption	−0.20% + 0.81%	−0.80% + 1.20%
Pion charge exchange (low energy)	−0.15% + 0.18%	−0.22% + 0.28%
Pion charge exchange (high energy)	−0.11% + 0.13%	−0.11% + 0.11%
Pion QE scattering (low energy)	−0.66% + 0.71%	−0.84% + 0.79%
Pion QE scattering (high energy)	−0.04% + 0.03%	−0.09% + 0.09%
Pion inelastic scattering	−0.05% + 0.04%	−0.29% + 0.25%
Nucleon elastic scattering	−0.25% + 0.21%	−0.29% + 0.21%
Nucleon single π production	−0.15% + 0.11%	−0.60% + 0.51%
Nucleon two π production	−0.57% + 0.42%	−0.01% + 0.01%
Target mass	±0.31%	±0.38%
MPPC dark noise	±0.03%	±0.08%
Hit efficiency	±0.84%	±0.41%
Light yield	±1.47%	±2.22%
Event pileup	±0.02%	±0.06%
Beam-induced external background	±0.00%	±0.00%
Cosmic-ray background	±0.00%	±0.01%
2D track reconstruction	±0.67%	±0.81%
Track matching	±0.45%	±1.13%
3D tracking	±0.21%	±0.15%
Vertexing	±0.30%	±0.43%
Timing cut	±0.00%	±0.00%
Veto cut	±0.82%	±0.64%
Fiducial volume cut	±1.55%	±0.84%
Secondary interaction	±2.45%	±2.37%
Total	−12.44% + 15.06%	−15.49% + 19.04%

ANL-BNL Puzzle

"Single π production in neutrino-necleus scattering", PRD 87, 113009 (2013).

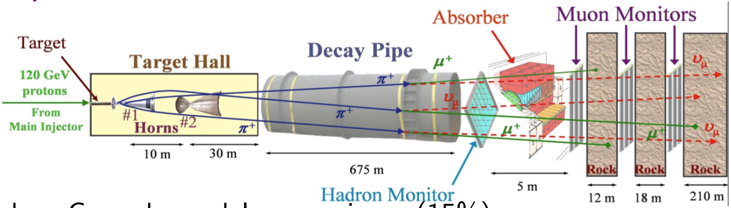


"Reanalysis of bubble chamber measurements of muon-neutrino induced single pion production", arXiv/hep-ex:1503.07452.



- The long standing ANL-BNL pion production cross section disagree $\sim$25%
- Reanalysis shows that this may be due to a flux normalization problem in BNL (See also K. M. Graczyk, *et al.*, PRD 80 093001 (2009))

How to produce and constrain the neutrino flux[1]



- Hadron Cascade model comparisons (15%)
  - Geant4 vs FLUKA
  - FTFP vs QGSP vs BERT ...
- External measurements (6-10%)
  - NA49 pC @ 158 GeV, MIPP pC @ 120 GeV
- In-situ measurements
  - Secondary muon fluxes (15-30%)
  - Absolute flux: Neutrino-electron NC/CC scattering
  - Relative flux: Low-ν
- Tests with modified beamline geometries
  - Moving target relative to horn ($<$7%)
  - Turning off the horn ...

[1] Deborah Harris, CETUP 2014, South Dakota

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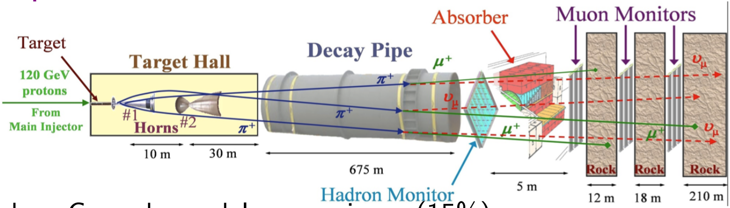

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DUNE and LBNF

With a wideband neutrino beam produced by a proton beam with power of 1.2 MW, this exposure implies a far detector with fiducal mass of more than 40 kilotons (kt) of liquid argon (LAr) and a suitable **near detector**.

Recommendation 12: In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.

For a long-baseline oscillation experiment, based on the science Drivers and what is practically achievable in a major step forward, we set as the goal a mean sensitivity to CP violation[2] of better than 3σ (corresponding to 99.8% confidence level for a detected signal) over more than 75% of the range of possible values of the unknown CP-violating phase δ_{CP}. By current estimates, this goal corresponds to an exposure of 600 kt*MW*yr assuming systematic uncertainties of 1% and 5% for the signal and background, respectively. With a wideband neutrino beam produced by a proton beam with power of 1.2 MW, this exposure implies a far detector with fiducal mass of more than 40 kilotons (kt) of liquid argon (LAr) and a suitable near detector. **The minimum requirements to proceed are the identified capability to reach an exposure of at least 120 kt*MW*yr by the 2035 timeframe, the far detector situated underground with cavern space for expansion to at least 40 kt LAr fiducial volume, and 1.2 MW beam power upgradable to multi-megawatt power. The experiment should have the demonstrated capability to search for supernova (SN) bursts and for proton decay, providing a significant improvement in discovery sensitivity over current searches for the proton lifetime.**

Goals of the ND in DUNE

- Constrain the systematic uncertainties in the oscillation measurements/searches
  - Neutrino source : content and spectra of all 4 species, ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$
  - Precise prediction of FD/ND CC spectra for all 4 species and of NC
  - Energy scale of neutrino and antineutrino
  - Background : $\pi^{0,\pm}$ in NC and CC; $e/\mu/$proton$/\pi/K$ ID

  $\Rightarrow$ Measure the 4-momenta of particles in neutrino interactions providing an "Event-Generator Measurement" for the FD
- A generational advance in the precision neutrino physics
  - Cross sections: QE, Resonance, Coherent and DIS
  - Neutrino-nucleus interactions and nucleon structure
  - Electroweak and isospin physics
- Search for New Physics at short-baseline
  - Short-baseline oscillations, include constraining of the background for FD signal
  - Light Dark Matter, Universality, and right-handed currents, etc.

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Quantify the Neutrino Source Using ND

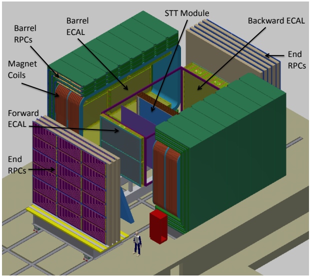
- Precision measurement of all 4 neutrino species
  - $\overset{(-)}{\nu}_\mu \rightarrow \mu^\pm$ as a function of E_ν – FD/ND (E_ν)
  - $\overset{(-)}{\nu}_e \rightarrow e^\pm$ as a function of E_ν – FD/ND (E_ν) [2]
- These considerations imply the following requirements
  - Magnetized tracker to ID positive from negative particle – $B \sim 0.4$ T
  - Low density medium to track $e^\pm$ – $\rho \sim 0.1$ g/cm^3
    - Momentum vectors of hadrons: $\pi^{\pm,0}$, $K^{\pm,0}$ and proton
  - Large statistics – $\sim 10^8$ neutrino interactions

The proposed FGT builds upon the NOMAD experience

[2] $\frac{\nu_e}{\nu_e+\bar{\nu}_e} \sim 1$ in neutrino mode .vs. $\frac{\bar{\nu}_e}{\nu_e+\bar{\nu}_e} \sim 0.5$ in antineutrino mode

High Reso. Fine-Grain Tracker (Proposed by the Indian & US Groups)

- $\sim$ 3.5 m $\times$ 3.5 m $\times$ 6.4 m STT ($\rho \simeq 0.1$ g/cm^3)
- 4π ECAL in a dipole magnetic field ($B = 0.4$ T)
- 4π MuID (RPC) in dipole and up/downstream
- Pressurized Ar target $\simeq \times 10$ FD statistics

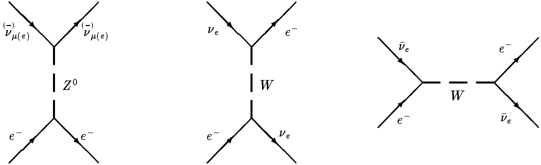


- Trasition Radiation : $e^{\pm}$
- dE/dx : $\pi^{\pm}$, $K^{\pm}$ and proton
- Magnet : + .vs. -
- MuID : μ

  $\Rightarrow$ Absolute flux measurement

Performance Metric	FGT
Straw Tube Detector Volume	3.5m x 3.5m x 6.4m
Straw Tube Detector Mass	8 tonnes
Vertex Resolution	0.1 mm
Angular Resolution	2 mrad
E_e Resolution	5%
E_μ Resolution	5%
$\nu_\mu/\bar{\nu}_\mu$ ID	Yes
$\nu_e/\bar{\nu}_e$ ID	Yes
NCπ^0/CCe Rejection	0.1%
NCγ/CCe Rejection	0.2%
CCμ/CCe Rejection	0.01%

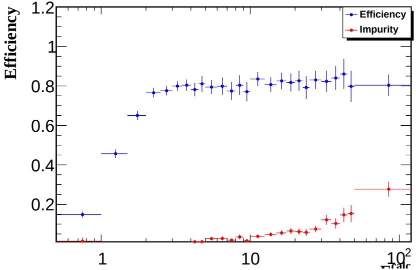
$\nu e^- \to \nu e^-$ (W. Marciano and Z. Parsa, arXiV: hep-ph/0403168)

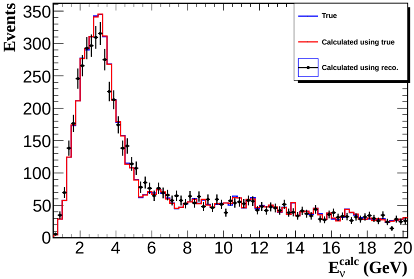


- Cross section is extremely small, but well known
  - $\sigma(\nu_{\mu,\tau} e \to \nu_{\mu,\tau} e) = \frac{G_\mu^2 m_e E_\nu}{2\pi}[1 - 4\sin^2\theta_W + \frac{16}{3}\sin^4\theta_W]$
  - $\sigma(\bar{\nu}_{\mu,\tau} e \to \bar{\nu}_{\mu,\tau} e) = \frac{G_\mu^2 m_e E_\nu}{2\pi}[\frac{1}{3} - \frac{4}{3}\sin^2\theta_W + \frac{16}{3}\sin^4\theta_W]$
  - $\sigma(\nu_e e \to \nu_e e) = \frac{G_\mu^2 m_e E_\nu}{2\pi}[1 + 4\sin^2\theta_W + \frac{16}{3}\sin^4\theta_W]$
  - $\sigma(\bar{\nu}_e e \to \bar{\nu}_e e) = \frac{G_\mu^2 m_e E_\nu}{2\pi}[\frac{1}{3} + \frac{4}{3}\sin^2\theta_W + \frac{16}{3}\sin^4\theta_W]$
- $\sigma(\nu_{\mu,\tau} e){:}\sigma(\bar{\nu}_{\mu,\tau} e){:}\sigma(\nu_e e){:}\sigma(\bar{\nu}_e e) = 1{:}0.854{:}6.077{:}2.547$
- Assuming 1.2 MW beam power, 5 tons ND fiducial mass, 5 years neutrino running
  - 10.5 k $\nu e^- \to \nu e^-$ events, 7.8 k $\nu_\mu e$, 1.7 k $\bar{\nu}_\mu$, 1 k $\overset{(-)}{\nu}_e e$
- A clean determination of the neutrino flux at low energy

Absolute Flux: $\nu e^- \rightarrow \nu e^-$

- Signal
  - Single, forward e^-
  - Efficiency $\sim$ 73%
- Background
  - ν_e CCQE & NC (charge-symmetric)
  - Benign, constrained by "e^+" analysis
- Total neutrino energy
  - High resolution tracker allows the reconstruction of E_ν from (E_e, θ_e)
- Absolute flux : $\sim$ 2% precision in 0.5$\leq E_\nu \leq$ 10 GeV range.





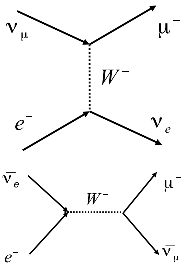
Inverse Muon Decay [3]

$$\frac{d\sigma(\nu_l e \to l \nu_e)}{dy} = \frac{G_\mu^2}{\pi}(2m_e E_\nu - (m_l^2 - m_e^2)) \quad (1)$$

$$\frac{d\sigma(\bar{\nu}_e e \to l \bar{\nu}_l)}{dy} = \frac{G_\mu^2}{\pi}(2m_e E_\nu (1-y)^2 - (m_l^2 - m_e^2)(1-y)) \quad (2)$$

$$y = \frac{E_l - \frac{m_l^2 + m_e^2}{2m_e}}{E_\nu} \quad (3)$$

$$0 \leq y \leq y_{\max} = 1 - \frac{m_l^2}{2m_e E_\nu + m_e^2} \quad (4)$$

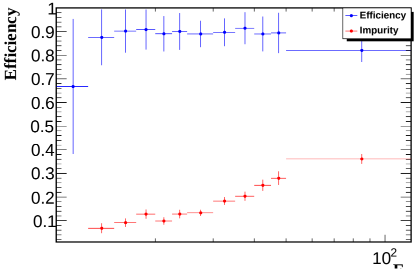


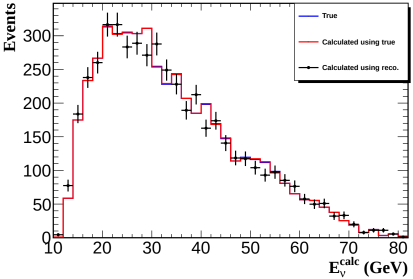
- Cross section is extremely small, but well known
  - $\sigma(\nu_\mu e^- \to \mu^- \nu_e) \simeq 3\sigma(\bar{\nu}_\mu e^- \to \mu^- \bar{\nu}_\mu) \simeq \frac{2G_\mu^2 m_e E_\nu}{\pi} \simeq 1.5 \times 10^{-41}\ (E_\nu/\mathrm{GeV})\ \mathrm{cm}^2$
- Threshold $E_\nu \geq \frac{m_l^2 - m_e^2}{2m_e} \simeq 10.9$ GeV
- 5.4k $\sigma(\nu_\mu e^- \to \mu^- \nu_e)$ events assuming 1.2 MW beam power, 5 tons ND fiducial mass, 5 years neutrino running
- A clean determination of the neutrino flux at higher energy

[3] W. Marciano and Z. Parsa, arXiV: hep-ph/0403168

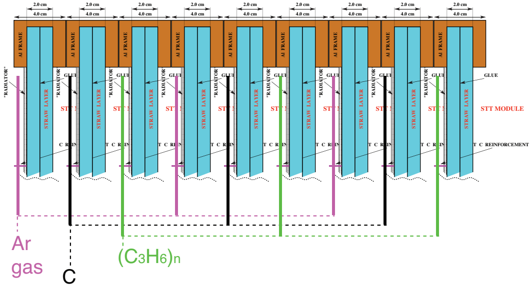
Absolute Flux: ν-e CC Scattering (IMD)

- Signal
  - Single, forward μ^-
  - Efficiency $\sim$ 91%
- Background
  - $\sim$ 20%, dominated by CCQE 1-track
  - Constrained by 2-track ν_μ-CC analysis after removing the "proton"
- Total neutrino energy
  - High resolution tracker allows the reconstruction of E_ν from (E_μ, θ_μ)
- Absolute flux : $\sim$ 2.5% precision in 15$\leq E_\nu \leq$ 50 GeV range.





Absolute Flux: $\bar{\nu}_\mu$ Proton QE Scattering



- Signal
  - Single μ^+ obtained after subtraction: $(C_3H_6)_n$ [Radiator] - C [Graphite]
  - Collect $(1.0 \pm 0.0045) \times 10^6$ (subtracted) $\bar{\nu}$-H events ($\sim 25\%$ QE)
  - Collect $(3.3 \pm 0.0090) \times 10^6$ (subtracted) ν-H events ($\sim 0\%$ QE)
- Background
  - Dominated by $\bar{\nu}_\mu$-CC
- Systematic Handle (ancillary, in situ measurement of the background)
  - Conduct the analysis on multi-track $\overset{(-)}{\nu}_\mu$-CC to check the target location
- Estimate a $\sim 3\%$ precision in $0.5 \leq E_\nu \leq 20$ GeV

Relative Flux: Low-ν method (S. R. Mishra, World Sci., 84 (1990), Ed. D. Geesman.)

- Low-ν ($E_{\mathrm{had}} = E_\nu - E_\mu$): low energy transfer to the hadronic system
- Relative ν_μ, $\bar{\nu}_\mu$ flux .vs. energy from low-ν method

$$N(E_\nu, E_{\mathrm{Had}} < \nu_0) = k\Phi(E_\nu) f_c(\frac{\nu_0}{E_\nu}) \tag{5}$$

  - The correction factor $f_c(\frac{\nu_0}{E_\nu}) \to 1$ for $\nu_0 \to 0$

$$f(\frac{\nu_0}{E_\nu}) = 1 + (\frac{\nu_0}{E_\nu})\frac{\mathcal{B}}{\mathcal{A}} + (\frac{\nu_0}{E_\nu})^2 \frac{\mathcal{C}}{2\mathcal{A}} + \ldots\ldots \tag{6}$$

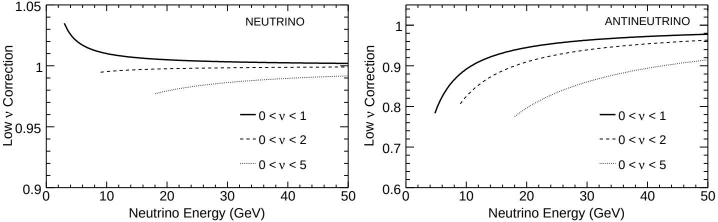
  where $\mathcal{A} = G_F^2 M/\pi \int_0^1 \mathcal{F}_2(x)dx$, $\mathcal{B} = -G_F^2 M/\pi \int_0^1 (\mathcal{F}_2(x) \mp \mathcal{F}_3(x))dx$,
  $\mathcal{C} = \mathcal{B} - G_F^2 M/\pi \int_0^1 \mathcal{F}_2(x)[(1 + 2Mx/\nu)/(1 + \mathcal{R}(x, Q^2)) - Mx/\nu - 1]dx$.
- In practice use MC to calculate the correction factor normalized at high neutrino energy E_ν

$$f_c(E_\nu) = \frac{\sigma(E_\nu, E_{\mathrm{Had}} < \nu_0)}{\sigma(E_\nu \to \infty, E_{\mathrm{Had}} < \nu_0)} \tag{7}$$

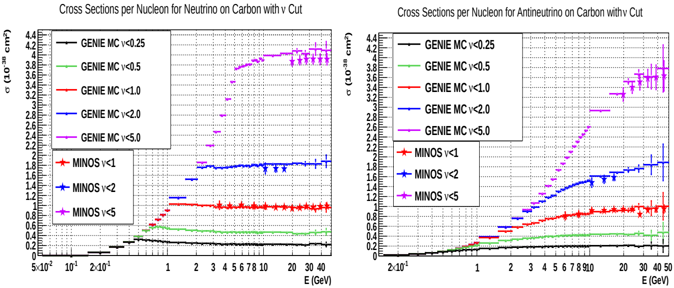
  where denominator is evaluated at the highest energy accessible in spectrum
  - Need precise muon energy scale and good resolution at low-ν values because a larger fraction of the E_ν per event is carried by the muon
  - Reliable flux predictions for $E \geq 2\nu_0$
    - DUNE spectra require $\nu_0 = 0.25 - 0.5$ GeV

The correction factor $f_c(E_\nu)$

MINOS, PRD 81, 072002 (2010)

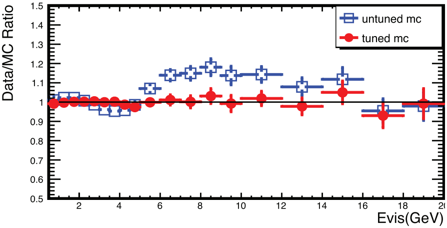


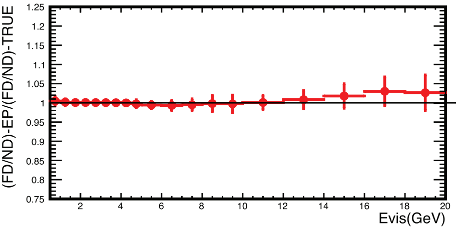
A. Bodek *et al.*, *EPJC 72, 1973 (2012)*



Relative Flux: Low-ν method@DUNE with FGT

- Study relative ν_μ, $\bar{\nu}_\mu$ fluxes in DUNE with $E_{\mathrm{Had}} < \nu_0 = 0.5$ GeV
  - Use standalone simulation with DUNE spectra and parameterized detector smearing
  - Perform empirical fits to modified ν_μ & $\bar{\nu}_\mu$ spectra in ND (fake data)
  - Extract modified fluxes and extrapolate to FD
- Considered several systematic uncertainties
  - Cross sections QE, Res, DIS
  - Variations in ν_0 correction
  - Muon and hadronic energy scales
- Overall uncertainty on FD/ND flux ratio ~1-2%





Absolute and Relative Flux in DUNE using ND

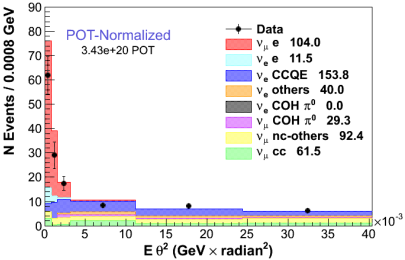
- Absolute flux
  - Leptonic channel
    - Neutrino electron NC scattering : expect a $\sim$ 2% precision in 0.5$\leq E_\nu \leq$ 10 GeV
    - Neutrino electron CC scattering : expect a $\sim$ 2.5% precision in $E_\nu \geq$ 11 GeV
  - 2^{nd} channel
    - $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$: estimate a $\sim$ 3% precision in 0.5$\leq E_\nu \leq$ 20 GeV
  - Coherent channel $(\nu_\mu + \mathcal{A} \rightarrow \nu_\mu + \mathcal{A} + \rho^0)$
- Relative flux
  - Low ν_0 method
    - $\overset{(-)}{\nu}_\mu + N \rightarrow \mu^\pm + X$: expect a FD/NC ratio at $\sim$1-2% precision in 0.5$\leq E_\nu \leq$50 GeV
  - Coherent π/ρ channel
    - $\overset{(-)}{\nu}_\mu \mathcal{A} \rightarrow \mu^\pm \pi^\mp (\rho^\mp) \mathcal{A}$: estimate a high precision in the $\bar{\nu}_\mu/\nu_\mu$ ratio in 0.5$\leq E_\nu \leq$50 GeV

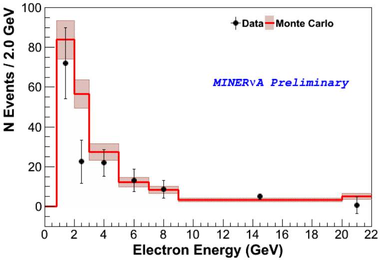
Conclusion

The ND complex, with a high resolution FGT, will:

- Determination of the relative abundance and of the energy spectrum of the four neutrino species in DUNE beam: ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$
    - Extrapolation to FD and predictions of FD/ND(E_ν) fluxes to $\sim 1\%$
- Determination of the absolute ν_μ and $\bar{\nu}_\mu$ fluxes to $\sim 2\%$ for oscillation measurements

MINERνA: $\nu e^- \to \nu e^-$ (Jaewon Park, FNAL W&C)





- ν-e scattering events after background subtraction and efficiency correction
  - 123.8±17.0 (stat.)±9.1 (syst)
  - Total uncertainty: 15%
- Projected precision in Medium Energy Era, a.k.a, NOνA era
  - Statistical uncertainty ∼2%
  - Total systematic uncertainty on this measurement ∼7%
  - Total uncertainty ∼7.3%