Fine-Grained Tracker as a Near Detector for LBNE

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Outline

A High-Resolution Fine Grained Tracker as a ND for LBNE(F)

Physics Sensitivity Studies
- Measure Absolute and Relative Flux using ND
- QE and Resonance Processes
- Constrain Nuclear Effects

An Example of Precision Measurements
- Electroweak Contant

Outlook

Goals of the ND in Long-Baseline Neutrino Facility

- 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/μ/proton/π/K ID

  ⇒ 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.

Quantify the Neutrino Source Using ND

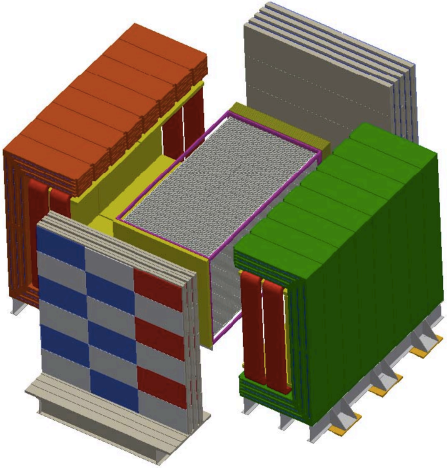
- Precision measurement of all 4 neutrino species
  - $\overset{(-)}{\nu}_{\mu} \to \mu^{\pm}$ as a function of E_{ν} – FD/ND (E_{ν})
  - $\overset{(-)}{\nu}_{e} \to e^{\pm}$ as a function of E_{ν} – FD/ND (E_{ν}) [1]
- These considerations imply the following requirements
  - Magnetized tracker to ID 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

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

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

- ~ 3.5 m $\times$ 3.5 m $\times$ 7 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

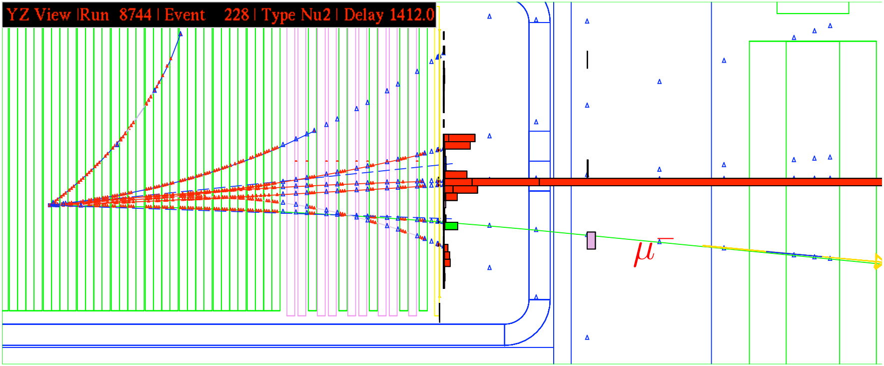


- Trasition Radiation : $e^{\pm}$
- dE/dx : $\pi^{\pm}$, $K^{\pm}$ and proton
- Magnet : + .vs. -
- MuID : μ

  $\Rightarrow$ Absolute flux measurement

A ν_μ CC candidate in NOMAD

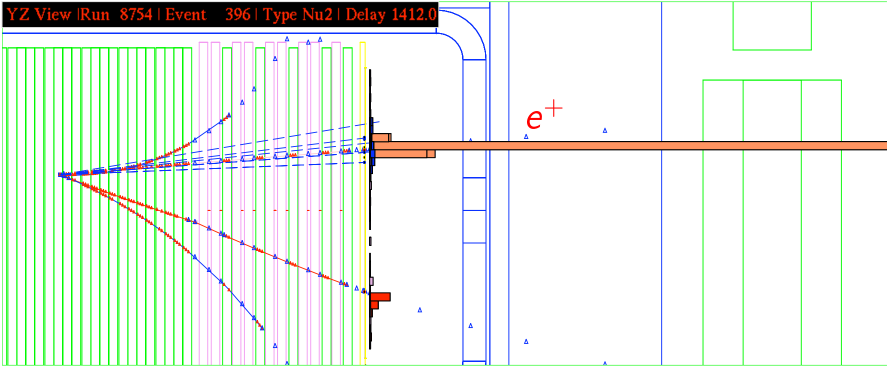
FGT will have $\sim \times$ 10 higher granularity



- Observations
    - Hadrons are tracks, enabling the momentum vector measurement
    - μ is kinematically separated from hadron-vector $\Rightarrow$ miss p_T measurement

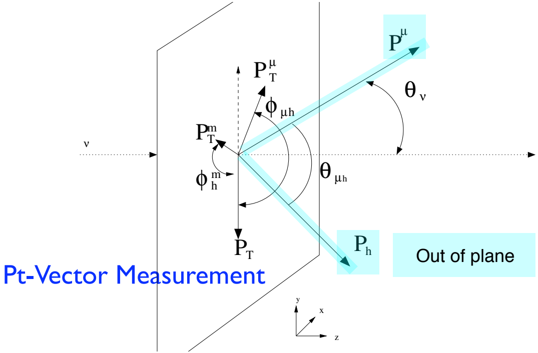
A $\bar{\nu}_e$ CC candidate in NOMAD

Most difficult to measure among the 4 neutrino species



- Conclusions
  - μ from ν_μ and e from ν_e interactions are tracks : determined with very high precision
  - Universality equivalence : $\mu \leftrightarrow \nu_\mu \Leftrightarrow e \leftrightarrow \nu_e$

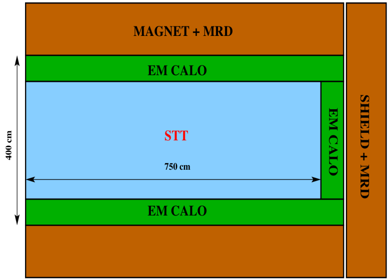
Kinematics in High Resolution FGT



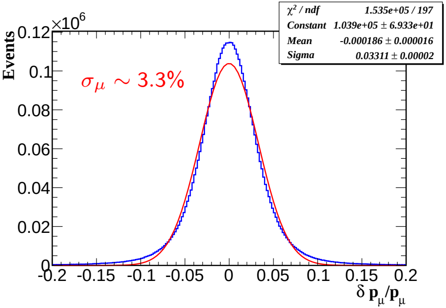
- $e^{\pm}$: transition radiation
- "h" : vector sum of hadronic tracks

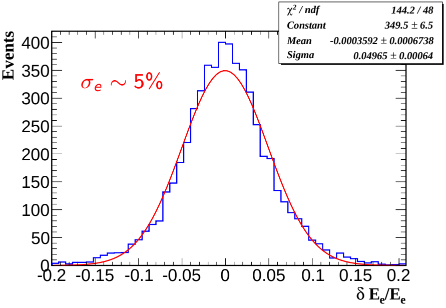
The reconstruction of the detailed event kinematics from individual tracks and neutral clusters is a powerful tool to identify NC and CC topologies.

FGT Performance



Radiator (Target) Mass	7 tons
Other Nuclear Target Mass	1–2 tons
Vertex Resolution	0.1 mm
Angular Resolution	2 mrad
E_e Resolution	$6\%/\sqrt{E}$ (4% at 3 GeV)
E_μ Resolution	3.5%
$\nu_\mu/\bar{\nu}_\mu$ ID	Yes
$\nu_e/\bar{\nu}_e$ ID	Yes
π^- .vs. π^+ ID	Yes
π^+ .vs. *proton* .vs. K^+	Yes
NCπ^0/CCe Rejection	0.1%
NCγ/CCe Rejection	0.2%
CCμ/CCe Rejection	0.01%





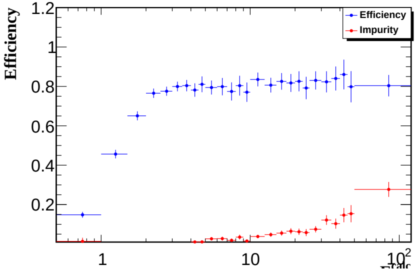
Absolute Flux: Neutrino electron NC/CC scattering [2]

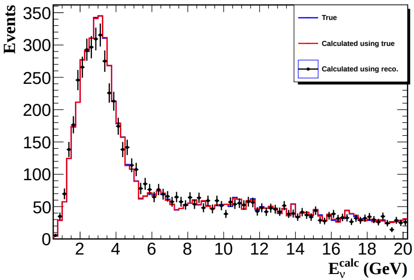
- Cross section is extremely small, but well known
- Assuming 1.2 MW beam power, 5 tons ND fiducial mass, 5 years neutrino running
  - 10 k $\nu e^- \to \nu e^-$ events, 78 k $\nu_\mu e$, 1.7 k $\bar{\nu}_\mu$, 1 k $\overset{(-)}{\nu}_e e$
  - 5.4 k $\sigma(\nu_\mu e^- \to \mu^- \nu_e)$ events
- Clean determination of neutrino flux at low energy (NC) and high energy (IMD)

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

Absolute Flux: ν-e NC Scattering

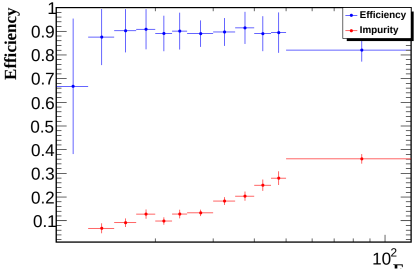
- Signal
  - Single, forward e^-
  - Efficiency $\sim 73\%$
- Background
  - ν_e CCQE & NC (charge-symmetric)
  - Benign, constrained by "e^+" analysis
- Total neutrino energy
  - High resolution tracker allows the reconstruction of E_ν from (E_e, θ_e)
- Absolute flux : $\sim 2\%$ precision in $0.5 \leq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

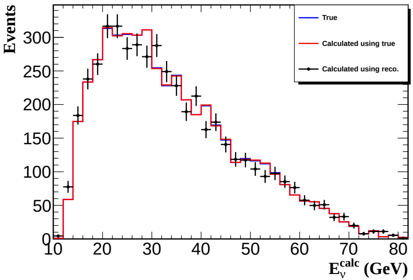




Absolute Flux: ν-e CC Scattering (IMD)

- 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 $(E_\mu,\ \theta_\mu)$
- Absolute flux : $\sim$ 2.5% precision in 15$\leq$ E_ν $\leq$ 50 GeV range.





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

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

- 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_0 method [3]

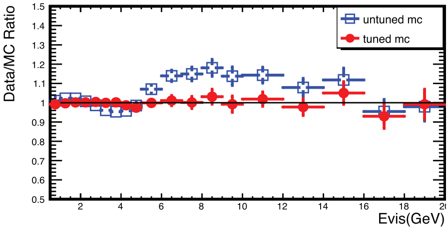
- Relative ν_μ, $\bar{\nu}_\mu$ flux .vs. energy from low-ν_0 method

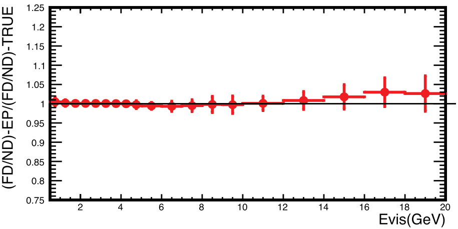
$$N(E_\nu, E_{\mathrm{Had}} < \nu_0) = k\Phi(E_\nu) f(\frac{\nu_0}{E_\nu}) \tag{1}$$

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

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

- Study relative ν_μ, $\bar{\nu}_\mu$ fluxes in LBNF with $E_{\mathrm{Had}} < \nu_0$ =0.5 GeV
  - Use standalone sim. with LBNF 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
- Overall uncertainty on FD/ND flux ratio ~1-2%





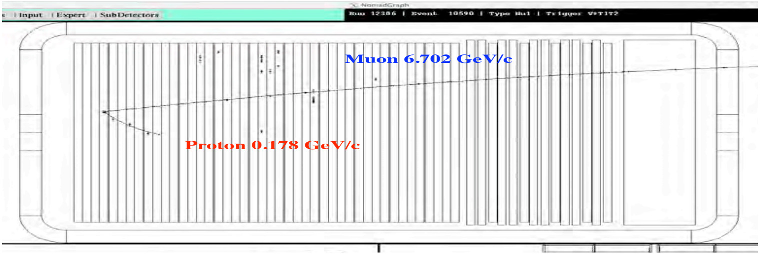
[3] S. R. Mishra, World Sci., 84 (1990), Ed. D. Geesman.

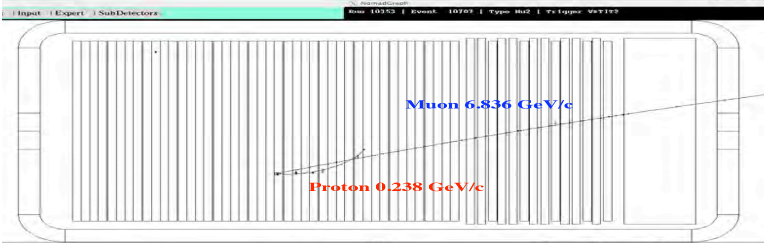
Absolute and Relative Flux in LBNF using ND – Summary

- 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

QE Candidates in NOMAD

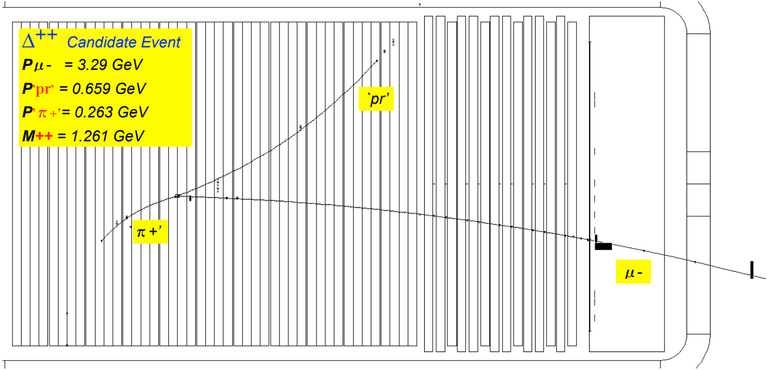
FGT will have $\sim \times$ 10 higher granularity





Resonance Candidates in NOMAD (See H. Y. Duyang's talk on Friday)

FGT will have $\sim \times$ 10 higher granularity



Efficiency as a function of E_{vis}

- CCQE 2-track: average signal eff. is 48% with 19% background
- CCQE 1-track: average signal eff. is 23% with 6% background
- CCRes 3-track: average signal eff. is 33% with 23% background

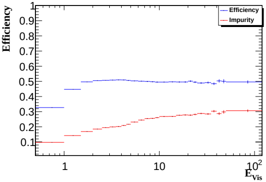


Figure: CCQE 2-track

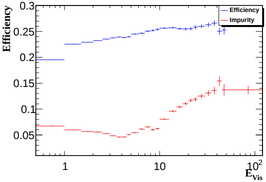


Figure: CCQE 1-track

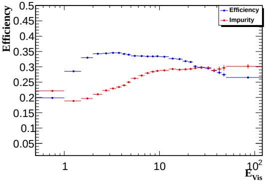
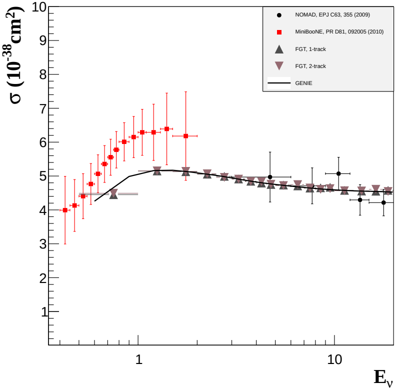
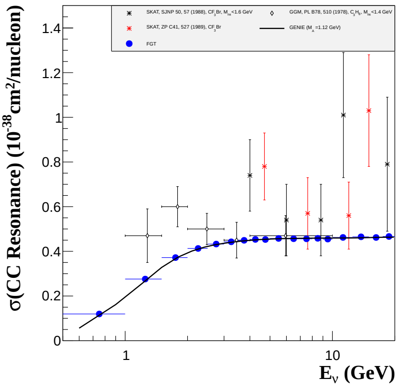


Figure: CCRes 3-track

Cross section





Constraining Nuclear Effects using QE and Resonance Processes

- Energy scale using 2-track QE
- Energy scale using 3-track Resonance
- FSI using 2- .vs. 1-track QE cross section
- Backward-going π/proton momentum in Resonance

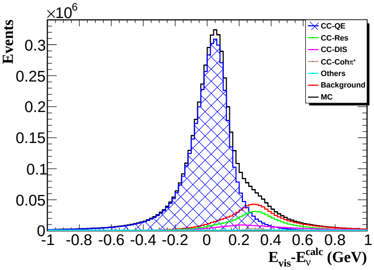
Compare $E_{\rm vis} - E_\nu^{\rm calc}$ using CCQE 2-track

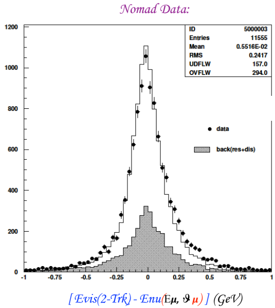
- Nuclear effects: initial state pair wise correlations & final state interactions

$$E_{\rm vis} = E_\mu + E_{\rm had}, \tag{3}$$

$$E_\nu^{\rm calc} = \frac{2(M_n - E_B)E_\mu - (E_B^2 - 2M_nE_B + m_\mu^2 + \delta M^2)}{2[(M_n - E_B) - E_\mu + p_\mu \cos\theta_\mu]}, \tag{4}$$

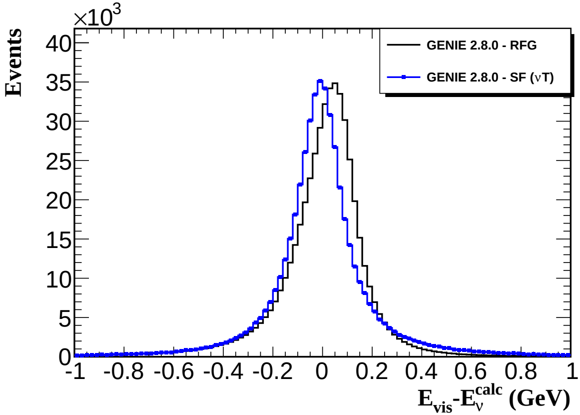
$$\delta M^2 = M_n^2 - M_p^2. \tag{5}$$





Compare $E_{\rm vis} - E_\nu^{\rm calc}$ using CCQE 2-track with different Nuclear Models

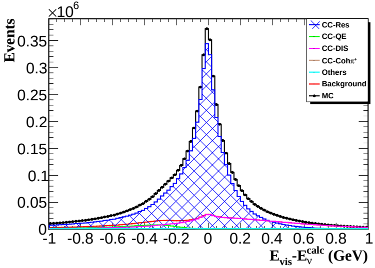
- GENIE 2.8.0: RFG (Bodek-Ritchie); Q^2 selection is not affected by the initial nucleons's kinematics
- GENIE 2.8.0 + SF (νT): Realistic Nuclear Spectral Functions; Q^2 selection takes into account the dependence of the initial interaction vertex on both energy and momentum of the struck nucleon



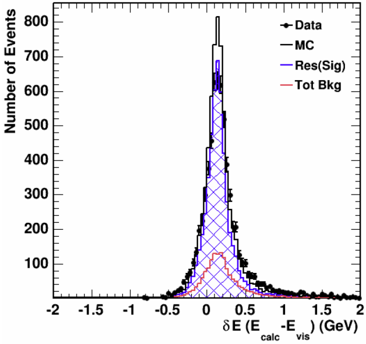
Compare $E_{\rm vis} - E_\nu^{\rm calc}$ using CCRes 3-track [4]

$$E_{\rm vis} = E_\mu + E_{\rm had}, \qquad (6)$$

$$E_\nu = \frac{m_\mu^2 + m_\pi^2 - 2m_N(E_\mu + E_\pi) + 2p_\mu \cdot p_\pi}{2(E_\mu + E_\pi - |\mathbf{P}_\mu|\cos\theta_\mu - |\mathbf{P}_\pi|\cos\theta_\pi - m_N)} \qquad (7)$$

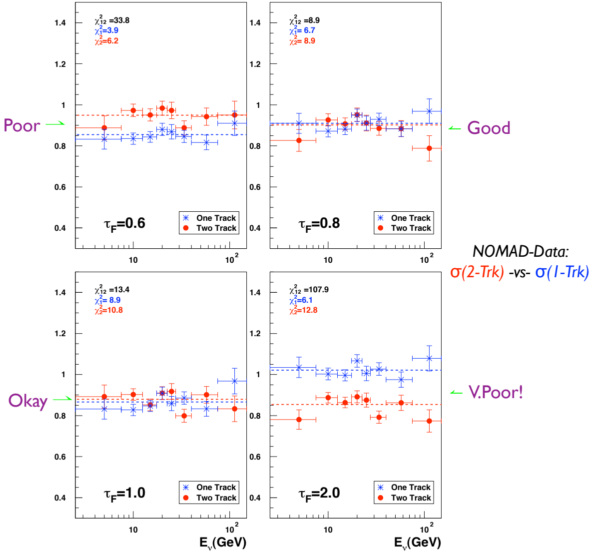


Nomad Data:

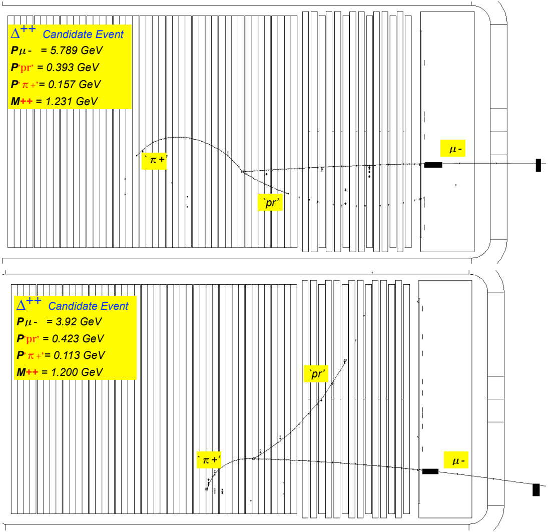


[4] See Duyang's talk for details

Compare CCQE 1- .vs. 2-track x-sections - NOMAD Data



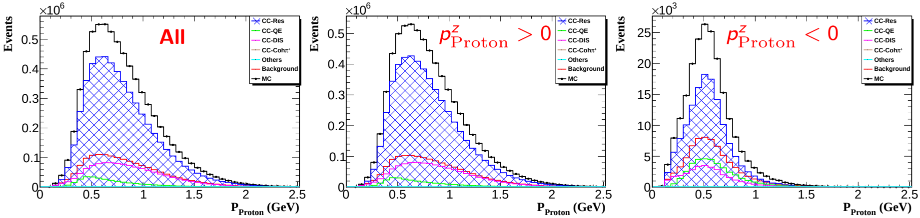
Backward going particle in CCRes 3-track [5]



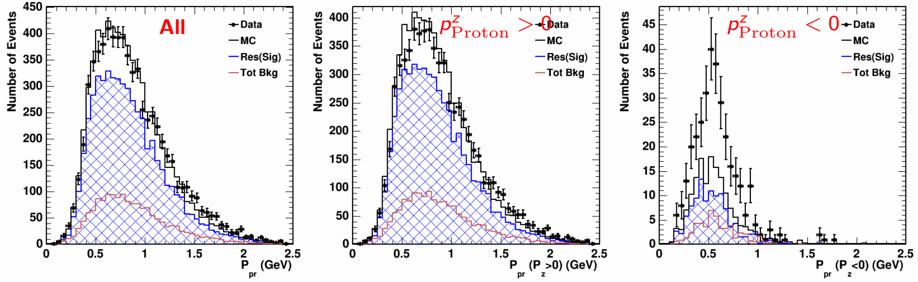
[5] See Duyang's talk for details

p_{Pr} in Res 3-track: top: GENIE & bottom: NOMAD Data

GENIE: 97.4% of the Proton is forward going

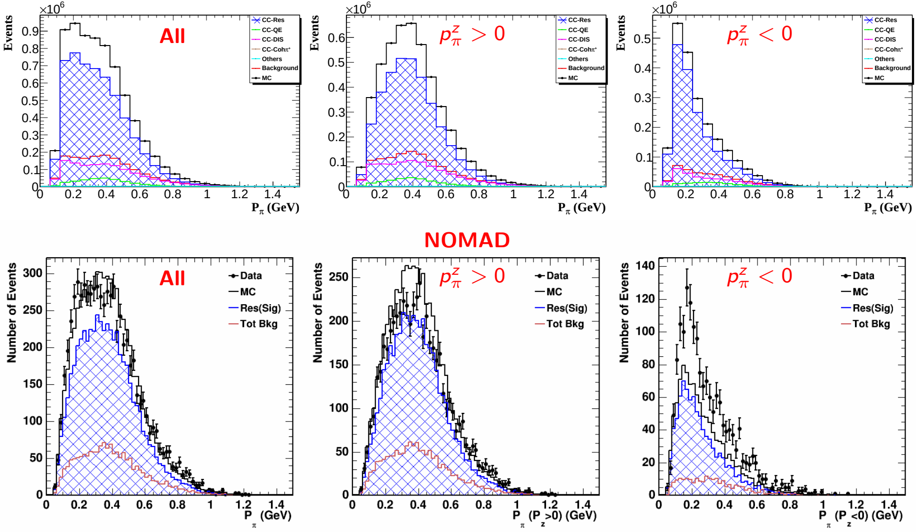


NOMAD

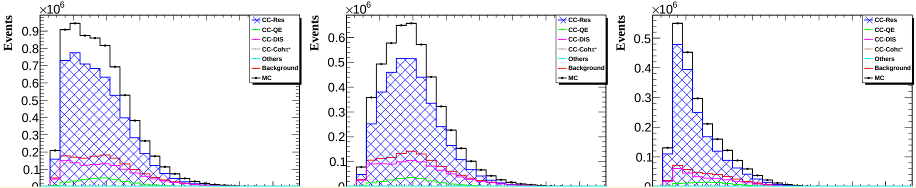


p_π in Res 3-track: top: GENIE & bottom: NOMAD Data

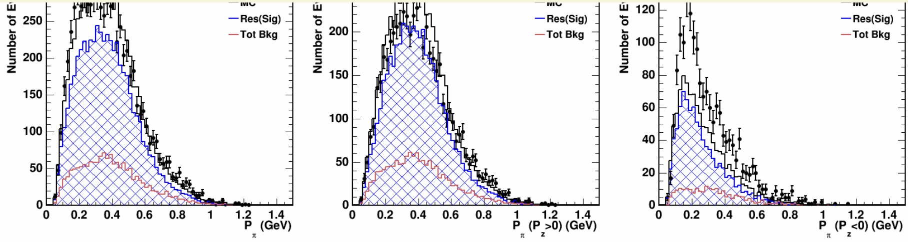
GENIE: 67.3% of the π is forward going



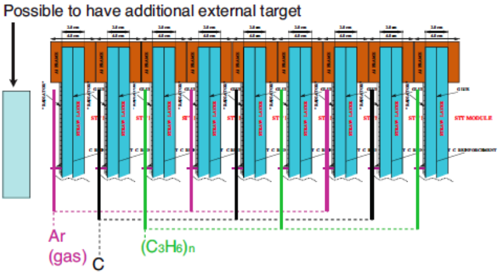
p_π in Res 3-track: top: GENIE & bottom: NOMAD Data



Backward-going particles are an excellent probe to constrain nuclear effects, both Fermi-motion (2-particle correlation) and FSI

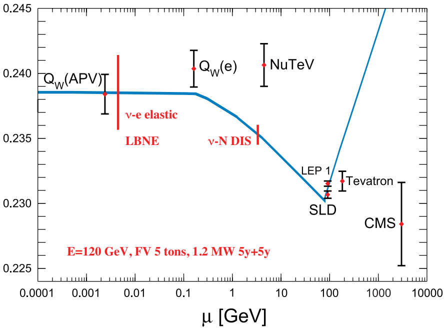


Neutrino-Nuclear Interactions



- Main target polypropylene $(C_3H_6)_n$ foils in radiators
- Multiple nuclear targets in STT: $(C_3H_6)_n$ radiators, Ar gas ($\times$10 statistics of FD), H_2O, D_2O, Ca, Fe, Pb
- Excellent vertex resolution ($\sim 100\ \mu$m) and angular resolution ~ 1 mrad allow clean separation of different nuclear targets

$\sin\theta_W^2$ measurement



- Default 1.2 MW beam with 5 year ν + 5 year $\bar{\nu}$ data taking is sufficienct to achieve competitive electroweak measurements with LBNF ND
  - The measurement of $\sin\theta_W^2$ with ν-N DIS can reach a precision of $\sim$0.35%
  - The measurement of $\sin\theta_W^2$ with ν-e elastic scattering can reach a precision of $\sim$1%

Conclusion

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

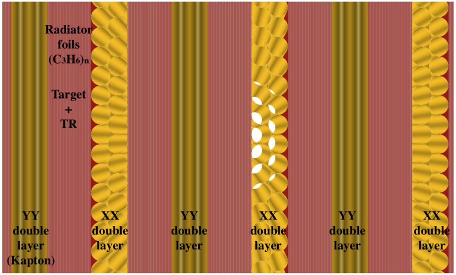
- Determination of the relative abundance and of the energy spectrum of the four neutrino species in LBNF beam: ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$
  - Extrapolation to FD and predictions of FD/ND(E_ν) fluxes to $\sim 1\%$
- Determination of the absolute ν_μ and $\bar{\nu}_\mu$ fluxes to $\sim 2\%$ for oscillation measurements
- Measure cross sections and exclusive topologies of NC and CC interactions
- Calibration of the absolute neutrino energy scale in ν-Ar and $\bar{\nu}$-Ar interactions
- Quantify asymmetries between ν and $\bar{\nu}$ (energy scale, flux, interactions) for δ_{CP}

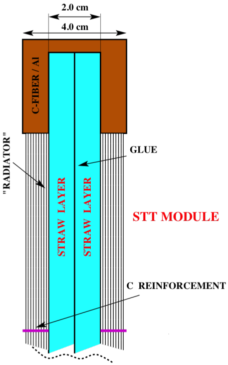
A generational advance in precision measurement and searches will produce over 120 topics providing a rich program

Backups

Straw Tube Tracker (Panjab Univ.)

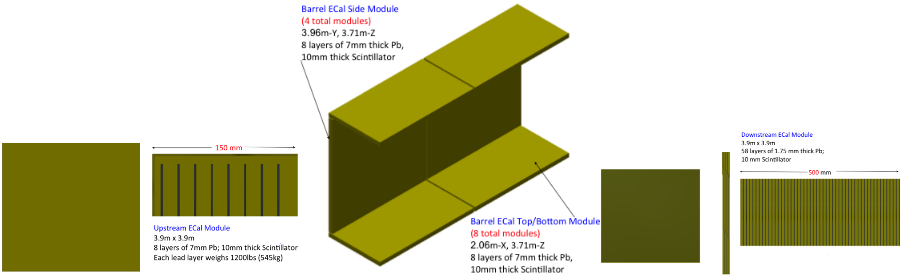
Geant4 schematic of STT with Radiator

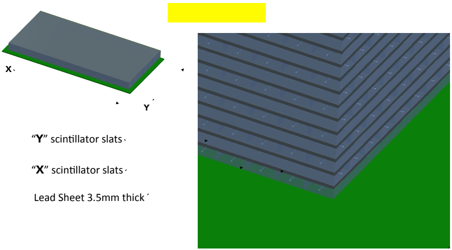




- Straw inner diameter: 9.530 ± 0.005 mm
- Operate with 70%/30% Xe/CO_2 gas mixture
- Raidator/target thickness ~ 20 mm with 75 $(C_3H_6)_n$ foils (40 μm) for transition radiation and tulle spacers
- Straws arranged in double layers glued together inserted with C-fiber/Al composite frames
- 166 modules arranged by alternating vertical and horizontal orientation with total length of 7 m
- Mass of the active target dominated by the radiators (82.6% of the total mass) can be tuned to achieve desired events and momentum resolution

Electromagnetic Calorimeter (IIT, Guwahati & Delhi Univ.)

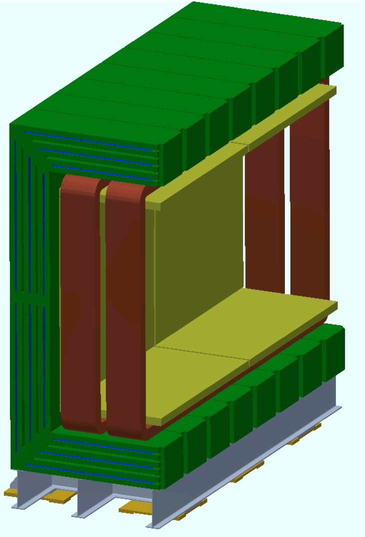




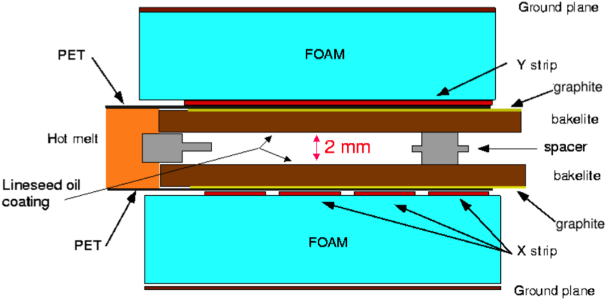
- Leadscintillator based on the T2K-ECAL, embedded inside the 0.4 T dipole magnet
- 58 layers of alternating horizontal/vertical scintillator strips per 1.75 mm Pb along the z-direction
- Plastic Scintillator bars: 4 m $\times$ 2.5 cm $\times$ 1.0 cm, 160 bars/layer, 9,280 bars in total
- Two sided readout

Magnet (Bhabha Atomic Research Center)

- 4.5 m × 4.5 m × 8 m inner dimensions
- 2.4 MW, 60 cm thick steel
- 0.4 T magnetic field
- <2% magnetic field variation over inner volumne



MuID - RPC (Variable Energy Cyclotron Center)



- Muon Range Detector - identify muons at low momenta exiting the sides of the detetor
    - 32 RPC planes interspersed between 20 cm thick layers of steel
- External Muon Identifier - identify high energy forward muons

Z position Radiography – NOMAD Tracker

Resolution of FGT will be much better

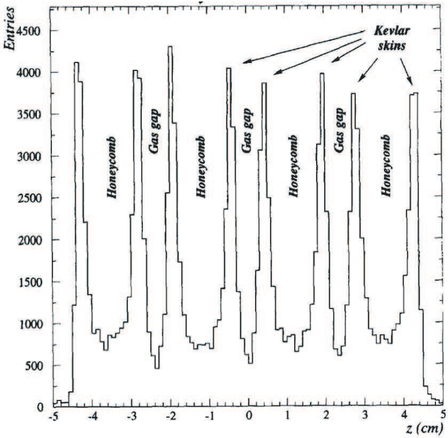


Figure: A neutrino radiograph of the NOMAD drift chambers shows the internal structure of the tracking volume. It illustrates the high resolution of the z-postion of the vertex.

Energy Scale of Neutrino and Antineutrino

- Problem: simplest of interactions, *e.g.* QE, Resonance, are obfuscated by nuclear effects (2-particle correlation, FSI). Furthermore, these effects could affect the antineutrino differently from neutrino.
- The key is: the measurement of the hadron-vector
  - ν-QE: 2-track events
  - $\overset{(-)}{\nu}$-Resonance : 2/3-track events
  - Coherent $\pi^{\pm}$
    - With missing $p_t < 300$ MeV ($\sqrt{t} < 5$ MeV)
    - Identical topology in ν_μ .vs. $\bar{\nu}_\mu$ (to the first order little nuclear-effect)

Coherent π/ρ Production – Constraining Absolute Flux

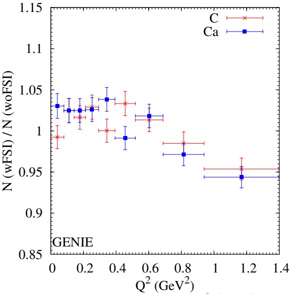
$$\nu_\mu + \mathcal{A} \rightarrow \mu^- \mathcal{A} + \pi^+(\rho^+)\ (CC) \tag{8}$$

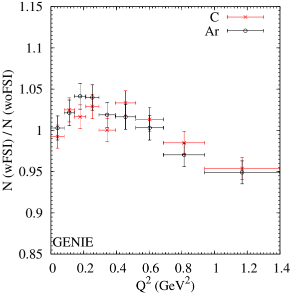
$$\nu_\mu + \mathcal{A} \rightarrow \nu_\mu \mathcal{A} + \pi^0(\rho^0)\ (NC) \tag{9}$$

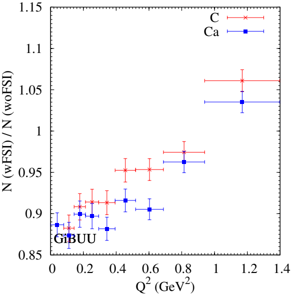
- Measure coherent ρ with $\sim 2\%$ precision
- Tie the neutrino measurement to photo-production and extract flux – to determine the absolute flux $\sim 5\%$ precision
  - Dominated by systematics in relating neutrino to electron (CVC)
- Critical measureables
  - $\pi^{0,\pm}$ momentum vectors
  - Veto additional particles : secondary tracks in STT and calorimeter
  - MuID : RPC

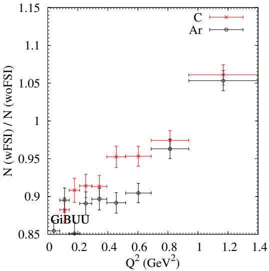
QE FSI Effects : C .vs. Ca .vs. Ar using GENIE & GiBUU

HRI with Carolina Group





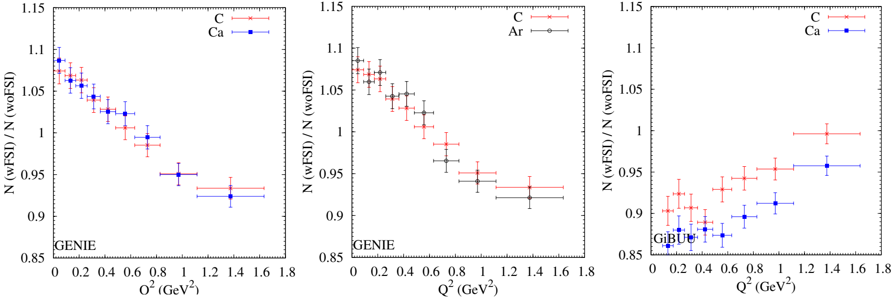


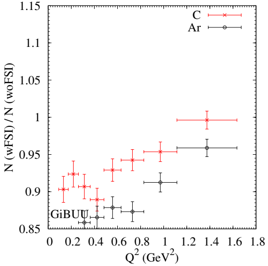


- FSI effects at $\pm \sim 10\%$
- Different in GENIE .vs. GiBUU
- Similar in Ca/C & Ar/C

Res FSI Effects : C .vs. Ca .vs. Ar using GENIE & GiBUU

HRI with Carolina Group





- FSI effects at $\pm \sim 10\%$
- Different in GENIE .vs. GiBUU
- Similar in Ca/C & Ar/C

Relative Flux: Low-ν_0 method

- Relative ν_μ, $\bar{\nu}_\mu$ flux .vs. energy from low-ν_0 method

$$N(E_\nu, E_{\mathrm{Had}} < \nu_0) = k\Phi(E_\nu) f(\frac{\nu_0}{E_\nu}) \quad (10)$$

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

$$f(\frac{\nu_0}{E_\nu}) = 1 + (\frac{\nu_0}{E_\nu})\frac{\mathcal{B}}{\mathcal{A}} + (\frac{\nu_0}{E_\nu})^2 \frac{\mathcal{C}}{2\mathcal{A}} + \ldots\ldots \quad (11)$$

  - In practice use MC to calculate the correction factor normalized at high E_ν

$$f(E_\nu) = \frac{\sigma(E_\nu, E_{\mathrm{Had}} < \nu_0)}{\sigma(E_\nu \to \infty, E_{\mathrm{Had}} < \nu_0)} \quad (12)$$

- Need precise muon energy scale and good resolution at low ν values
- Main systematic uncertainties
  - Muon (Hadronic) energy scale
  - Detector smearing and effects of ν_0 cut
  - Cross sections (anti)neutrino-nucleus (QE, Res, DIS) and FSI
  - Backgrounds and selection cuts