Resonance Interaction Measurement in NOMAD

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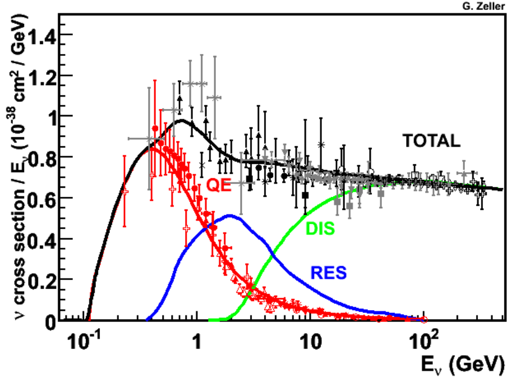
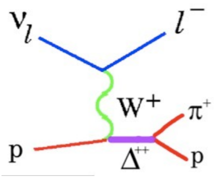
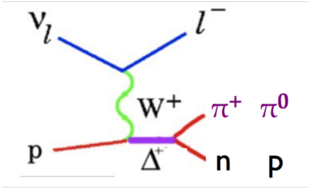
Introduction



- Resonance (RES) is an important channel for the next generation long-baseline neutrino experiments in few-GeV energy region.
- Unfortunately also the least measured.

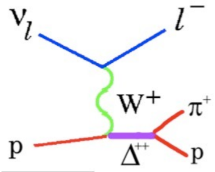
Resonance Interaction

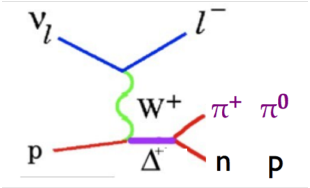




- A neutrino inelastically scatters off target nucleon, with a short term resonant state of the excited target nucleon created (N^*, Δ) which decay into a nucleon and a single pion.
  - $\nu_\mu + p \longrightarrow \mu^- + \Delta^{++} \longrightarrow \mu^- + p + \pi^+$
  - $\nu_\mu + n \longrightarrow \mu^- + \Delta^+ \longrightarrow \mu^- + n + \pi^+$
  - $\nu_\mu + n \longrightarrow \mu^- + \Delta^+ \longrightarrow \mu^- + p + \pi^0$
- Described by Rein-Seghal (RS) model.
  - 3-quark system in relativistic harmonic oscillator potential.
  - All resonance states with $W < 2$ GeV.
  - A non-interfering background with isospin 1/2.

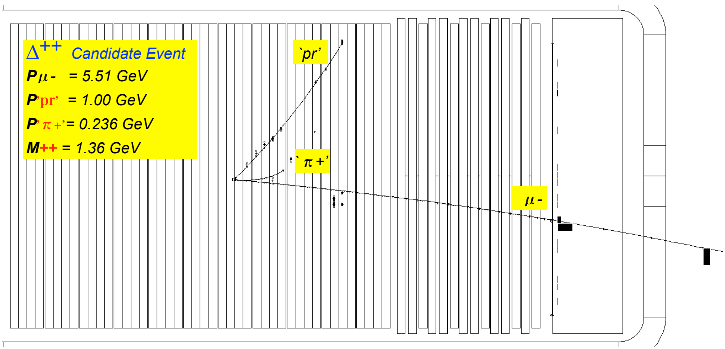
Resonance In a Fine Grained Tracker





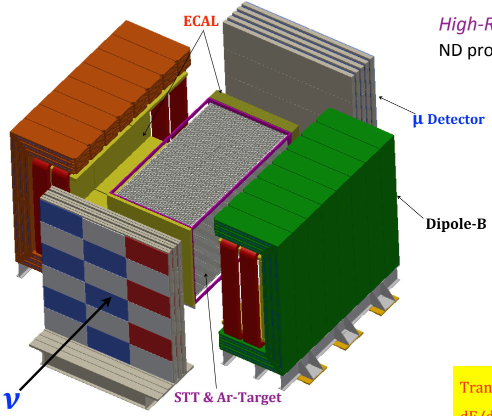
- Focus on 2 topologies:
  - 3-track : $\nu_\mu + p \longrightarrow \mu + p + \pi^+$.
  - 2-track: $\nu_\mu + p \longrightarrow \mu + p + \pi^0$, $\nu_\mu + p \longrightarrow \mu + n + \pi^+$.
- Measurement of resonance cross-section.
- Constraint on nuclear effects.

3-Track Event In A FGT



- 3-track topology: $\nu_\mu + p \longrightarrow \mu + p + \pi^+$.
- Event from NOMAD data.
- LBNE FGT will have $10\times$ more hits.

LBNE Fine-Grained-Tracker ND (See Xinchun's Talk Monday)



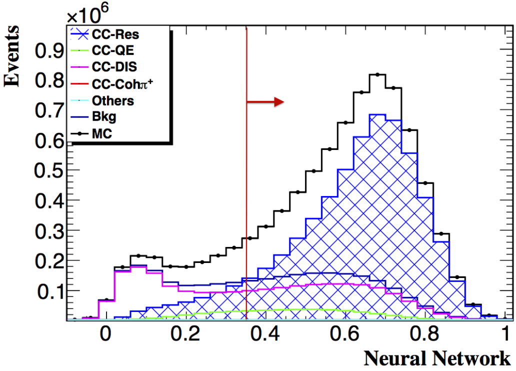
High-Resolution Fine Grain Tracker:
ND proposed by the *LBNE-India Group*

- ~3.5m x 3.5m x 7m STT ($\rho \simeq 0.1 gm/cm^3$)
- 4π-ECAL in a Dipole-B-Field (0.4T)
- 4π-μ-Detector (RPC) in Dipole and Downstream
- Pressurized Ar-target (≃x5 FD-Stat) ⇛ *LAr-FD*

Transition Radiation ↠ $e^{+/-}$ ID ⇒ γ
dE/dx ↠ Proton, $\pi^{+/-}$, $K^{+/-}$
Magnet/Muon Detector ↠ $\mu^{+/-}$ $e^{+/-}$
(⇒ ***Absolute Flux measurement***)

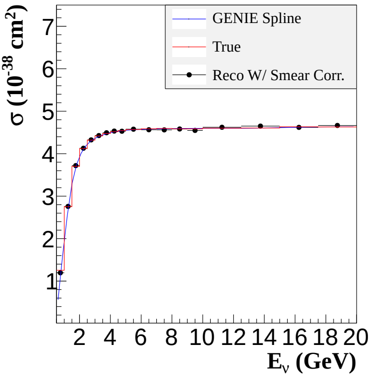
Resonance Analysis in FGT

- Select muon.
- Select 3-track $\mu^- p\pi^+$ (or 2-track) topology.
- Pre-selection cuts (missing-p_T, Hadron-momentum vector) to reduce background.
- Multivariate NN analysis.

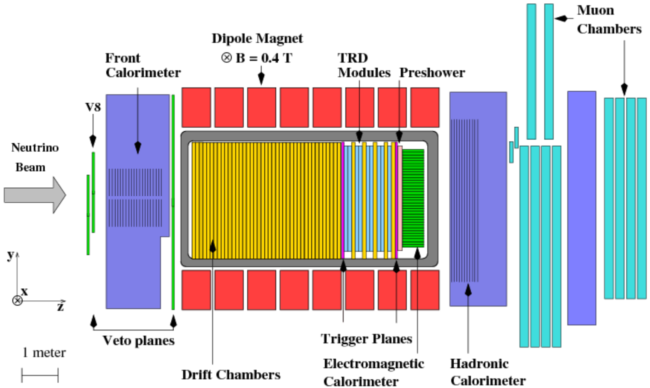


Resonance Study in FGT

- The primary goal of the resonance study is cross-section measurement.
- Additional Studies:
    - Learning Background characteristics
    - Constraining the Energy-scale of the Neutrino
    - Constraining Nuclear Effects
- Apply these tools, and check ideas, on data from NOMAD,
- Finally apply to LBNE-FGT



NOMAD Experiment

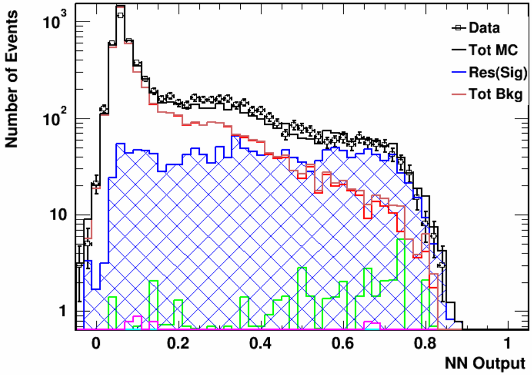


- The Neutrino Oscillation MAgnetic Detector (NOMAD, WA-96) was designed to search for ν_μ to ν_τ appearing from oscillations in the CERN SPS wide band neutrino beam.
- Accumulated 2M ν-Interactions leading to precision measurements of several processes.
- Precisely measurement of all four neutrinos interaction types.

Monte Carlo Simulation

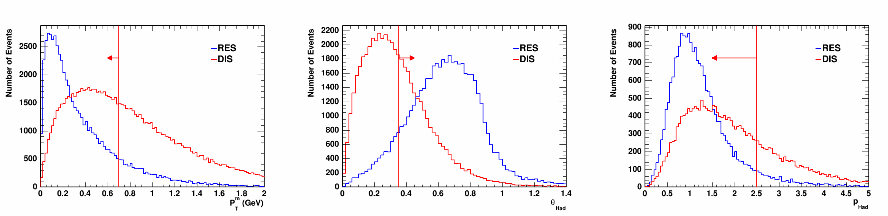
- Use GENIE as event generator.
- A Geant program built for detector response.
- All major neutrino interaction modes simulated.
- Default
  axial mass $MA = 1.12 GeV$,
  vector mass $MV = 0.84 GeV$.
- All types of interactions simulated:
  - Resonance: 50k.
  - CC-DIS: 1.36M.
  - QE: 37K.
  - Coherent: 10k.

Control Sample ($\mu^- p\pi^-$)



- The 3-Track ($\mu^- p\pi^-$) is dominated by DIS.
- The Genie MC reasonably well reproduces the kinematics.
- The shape of the NN output well reproduces data in signal region (NNo>0.4).
- Background well controlled.

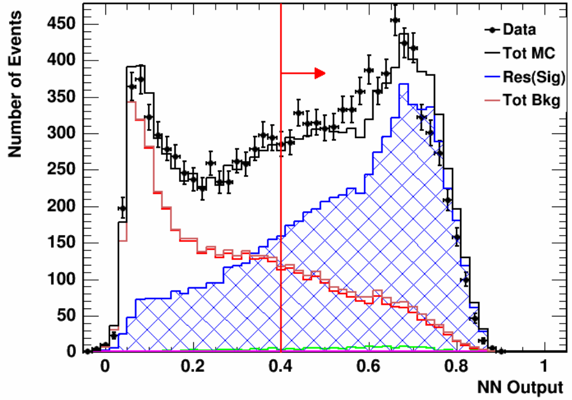
3-Track ($\mu^- p \pi^+$) Analysis: Pre-selection



- Select 3-track events in fiducial volume (one muon track + two positive hadron tracks)
- Selection cuts to reduce backgrounds: Missing $P_t < 0.7 GeV$, $\theta_{had} > 0.35$, $P_{had} < 2.5$.
- Background is dominated by DIS.
- Events selected are taken into neural network analysis.

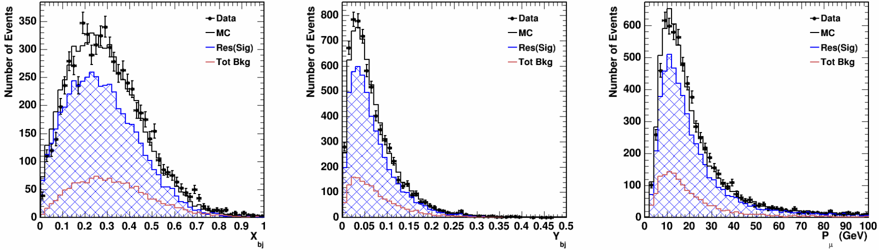
Cuts	QE	RES	CCDIS	NCDIS	COH	TOT-Bac	MC	Data
Events Selected	449.0	6999.2	12367.2	0.2	6.4	12822.8	19822.0	11992.0

3-Track Analysis: Neutral Network



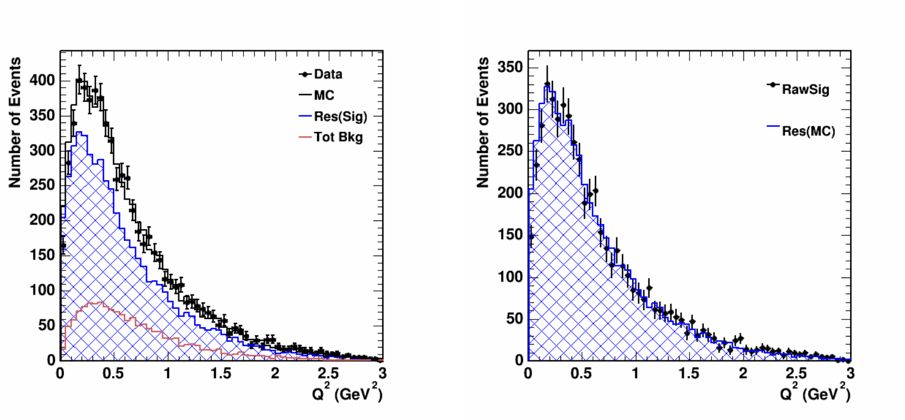
- Built NN with 9 inputs:
  p_{μ}^{x}, p_{μ}^{y}, p_{μ}^{z}, p_{Proton}^{x}, p_{Proton}^{y}, p_{Proton}^{z}, p_{π}^{x}, p_{π}^{y}, p_{π}^{z}.
- Compare kirnematic variables data vs MC.

Kinematics Comparison: MC vs Data (3-Track)



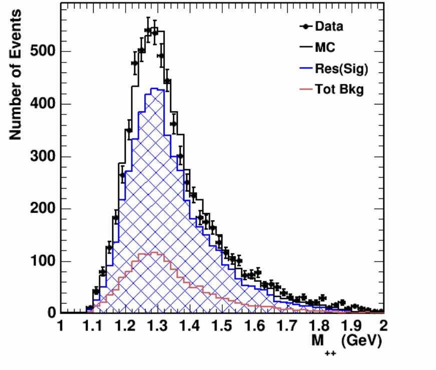
The kinematic variables are reasonably well described by MC.

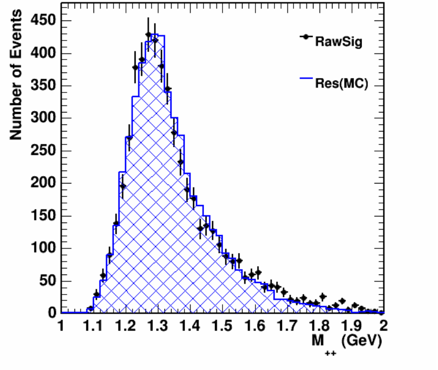
Q^2



- Q^2 is qualitatively consistent with the Genie prediction

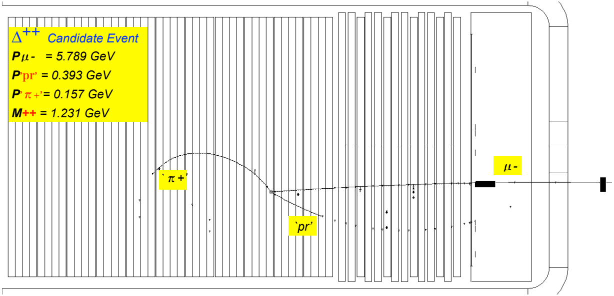
Invariant Mass





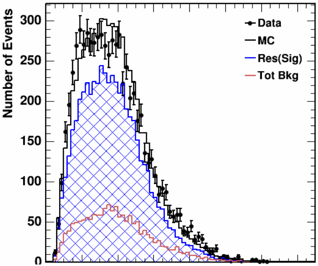
- Reconstruct invariant mass using 4-momentums of the 2 positive reconstructed tracks.
- M_{++} is qualitatively consistent with the Genie prediction

Backward-Going Pions and Protons

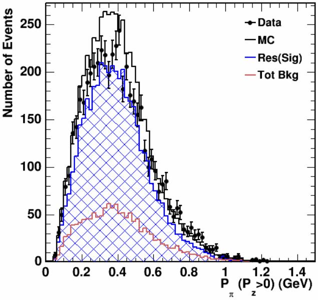


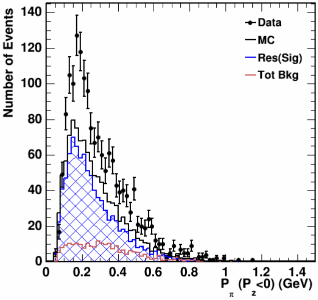
- Pion momentum are most sensitive to nuclear effects.
- Backward going ($p_z < 0$) pion and proton of special interest

Pion Momentum: Forward and Backward

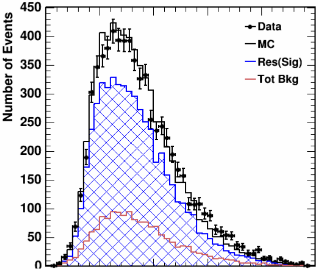


Backward-going pions are not well described by Genie.

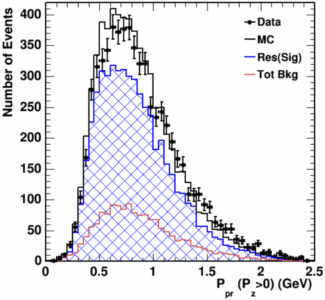


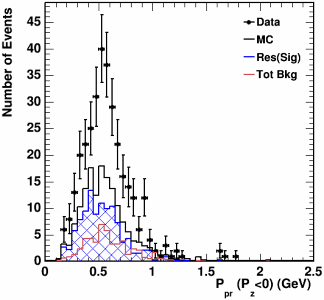


Proton Momentum: Forward and Backward

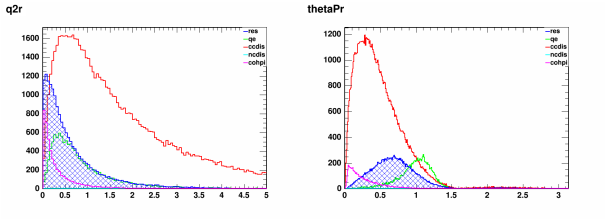


- Backward-going protons are not well described by Genie.





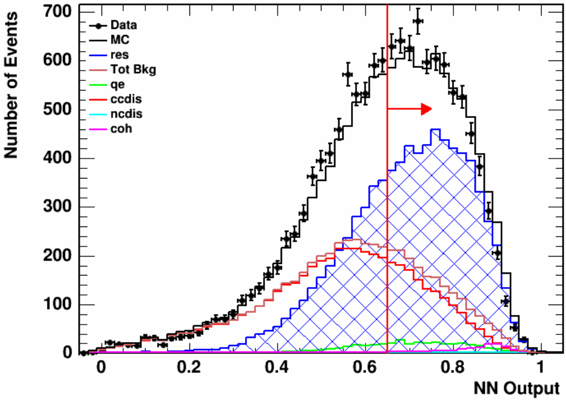
2-Track Sample



- Independent 2-track sample:
  one muon track + one positive hadron tracks.
- Pre-selection cuts to reduce backgrounds:
  $0.35 < \theta^{\mu}_{Had} < 1.0$, $Q^2 < 1GeV$.
- Events selected are taken into neural network analysis.

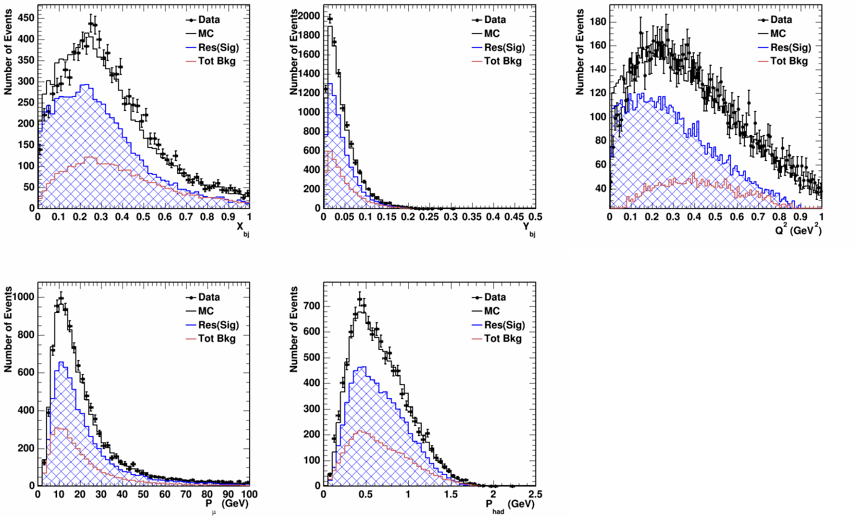
Cuts	QE	RES	CCDIS	NCDIS	COH	TOT-Bac	MC	Data
Event Selected	2042.5	9730.9	17084.5	0.7	1572.0	20699.8	30430.7	15817.0

2-Track Analysis



- Built Neural Network with 9 input variables: p^x_μ, p^y_μ, p^z_μ, p^x_{Had}, p^y_{Had}, p^z_{Had}, x_{bj}, y_{bj}, Q^2.
- Compare kinematic variables by data vs MC.

Kinematics Comparison: MC vs Data (2-Track)

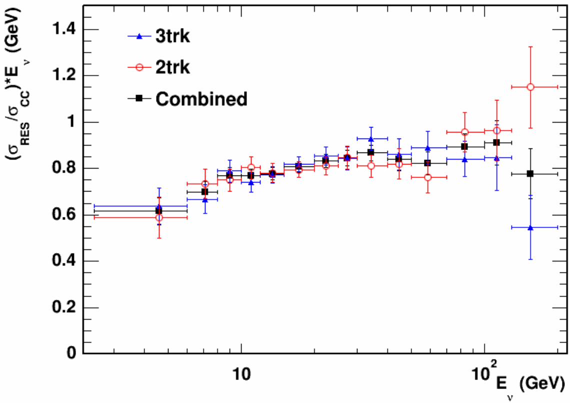


- x_{Bj}, and hence Q^2, poorly described by MC.
- y_{Bj}, p_μ, p_{Had} comparisons are satisfactory.

Combined Analysis

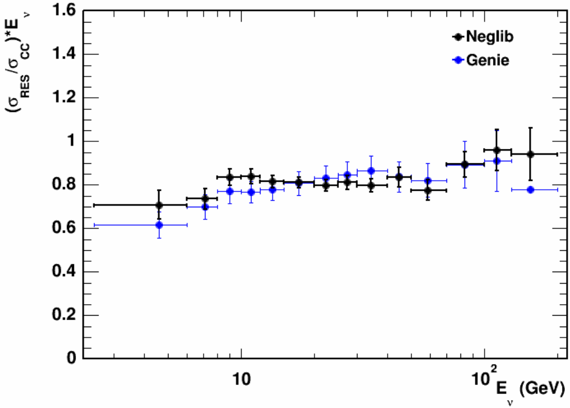
- Combine statistically independent 3-track and 2-track samples.
- The combined sample is less prone to systematic uncertainty.
- Corrected Signal events:
  - 3-Track: $48,364 \pm 938$
  - 2-Track: $47,386 \pm 1075$
  - Combined: $47,942 \pm 207$
- The two topologies give consistent results.

Resonance Ratio to Inclusive-CC



- $R_{RES} = \sigma_{RES}/\sigma_{CC} \times E_\nu$
- 3-Track: $R_{RES} = 0.838 \pm 0.017 GeV$
- 2-Track: $R_{RES} = 0.822 \pm 0.019 GeV$
- Combined: $R_{RES} = 0.831 \pm 0.012 GeV$

Resonance Analysis (3-Track + 2-Track) with NEGLIB



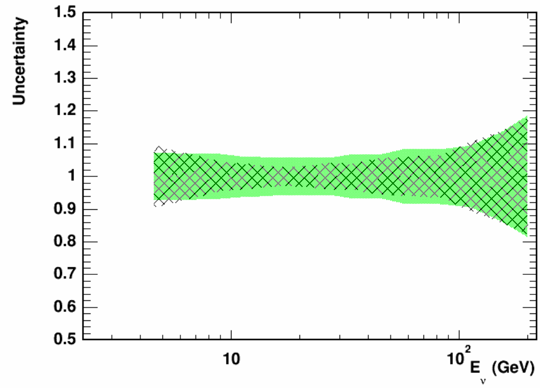
- Analysis conducted with NEGLIB MC (NOMAD's default event generator).
- A significantly different, and older, generator than Genie
- Measured resonance completely consistent between the two MC.

Systematic Uncertainties

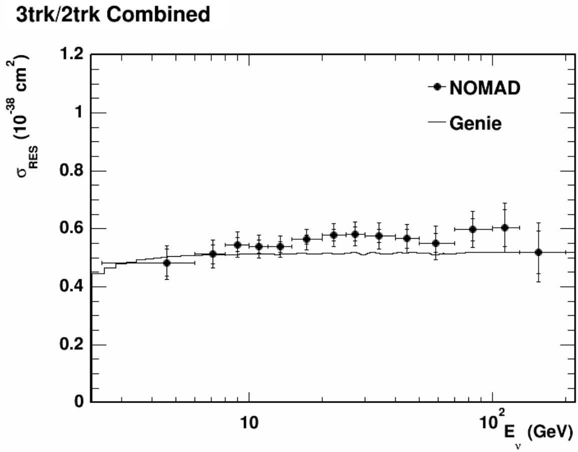
About a dozen sources of systematic errors are investigated:

- Event Selection (kinematic and NN cut): Vary the cuts by $\pm\sigma \longrightarrow \pm 1.2\%$
- MC modelling: $MV \pm 10\%$, $MA \pm 20\%$, $MFP \pm 20\% \longrightarrow \pm 3.2\%$
- Flux: $\pm 4.1\%$

Total systematic error: $\pm 5.3\%$

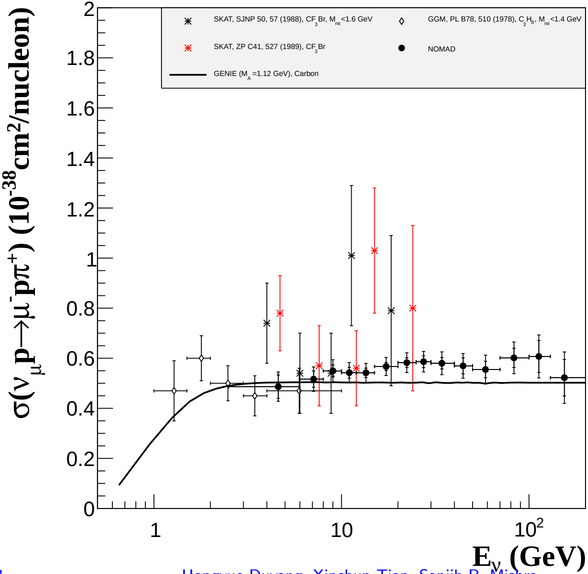


Resonance Cross Section



- NOMAD measurement is consistent with GENIE prediction.

Resonance cross section (C target)

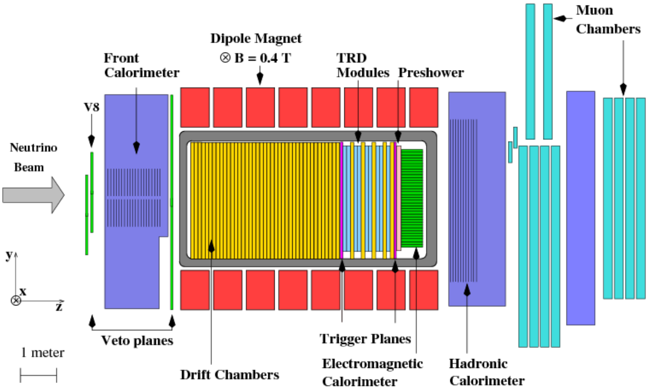


Summary

- Q^2, M_{++} are qualitatively consistent with the Genie prediction.
- Proton and Pion momenta distributions in reasonably well reproduced by Genie.
- The backward going particles are poorly described by the MC.
- NOMAD data provide the most precise Resonance cross-section in $2.5 GeV < E_\nu < 200 GeV$.
- An important benchmark to validate the LBNE FGT studies.

Backup Slides

NOMAD Detector



- 2.7 ton, low average density ($0.1g/cm^3$).
- 44 Drift Chambers ($3 \times 3m^2$).
- TRD (Transition Radiation Detector), Preshower, ECal ⇒ Electron PID.
- Dipole magnetic field $B = 0.4T$. ⇒ High precision momentum measurement of positive/negative particles.

FGT vs NOMAD

NOMAD -vs- HiResFGT

✴ *Tracking Charged Particles* ⟹

✴ *Electron/Positron ID* ⟹

✴ *Calorimetry* ⟹

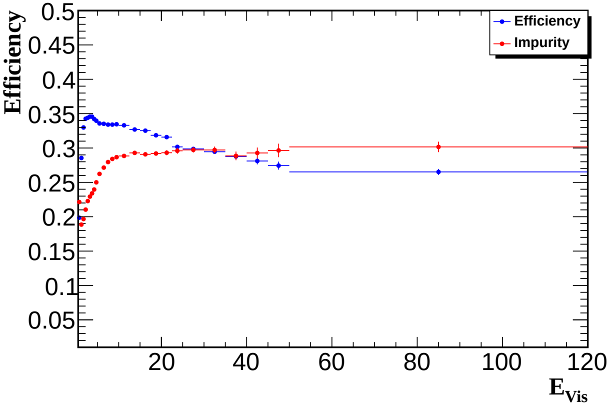
✴ *μ-ID* ⟹

✴ *Trigger* ⟹

Sub-Detector	NOMAD	HiResMnu	Improvement
Tracking		$\times$6 more hits in X-Y $\times$2 more hits along Z	$\times$2 higher QE-Proton Eff. $e^{\pm}$ down to 80 MeV γ-Conv. Reconstruction
TR: Electron-ID	Downstream	Continuous	$\simeq \times 3$ $e^{\pm}$-Eff
Calorimetry Segmentation	Downstream No Longitudinal Transverse	4π Coverage Fine Longitudinal Finer Transverse	Much better converage $e^{\pm}/\pi$ Separation Better miss-P_T Powerful 'Dirt'-Veto
E-shower Resolution	$3\%/\sqrt{E}$	$6\%/\sqrt{E}$	Poorer resolution
μ-ID	Downstream $P_\mu \geq 2.5$ GeV	4π Coverage	P_μ down to 0.3 GeV
Trigger	Downstream No Cal.Trigger	Continuous in STT Calorimetric Trigger	P down to 0.1 GeV $E \simeq 0.3$ GeV

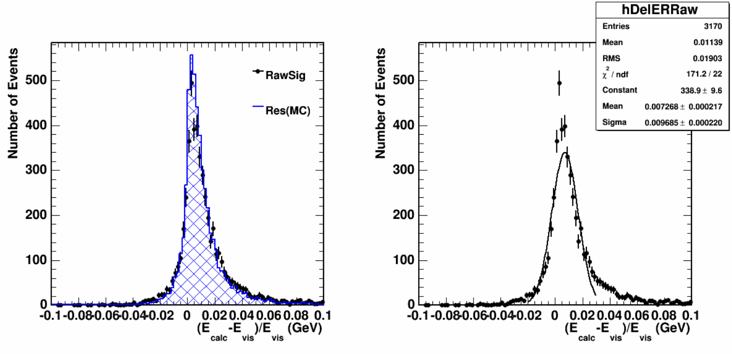
NOMAD versus HiResMnu

RES Sensitivity (Backup)



- The signal efficiency is ∼33%, and background is ∼23%.
- $FOM = signal/\sqrt{backgroud} = 0.69$.

Constraining Nuclear Effects using 3-track events (Backup)



- Constraints on nuclear effects such as Fermi Motion and final state interactions (FSI).
- Using muon and pion 4-momentums:

$$E_{\text{vis}} = E_\mu + E_{\text{had}}, \tag{1}$$

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