Measurements of Quasi-Elastic Interactions in the NOMAD Experiment

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"Neutrino-Nucleus Interactions for Next Generation Neutrino Oscillation Experiments"

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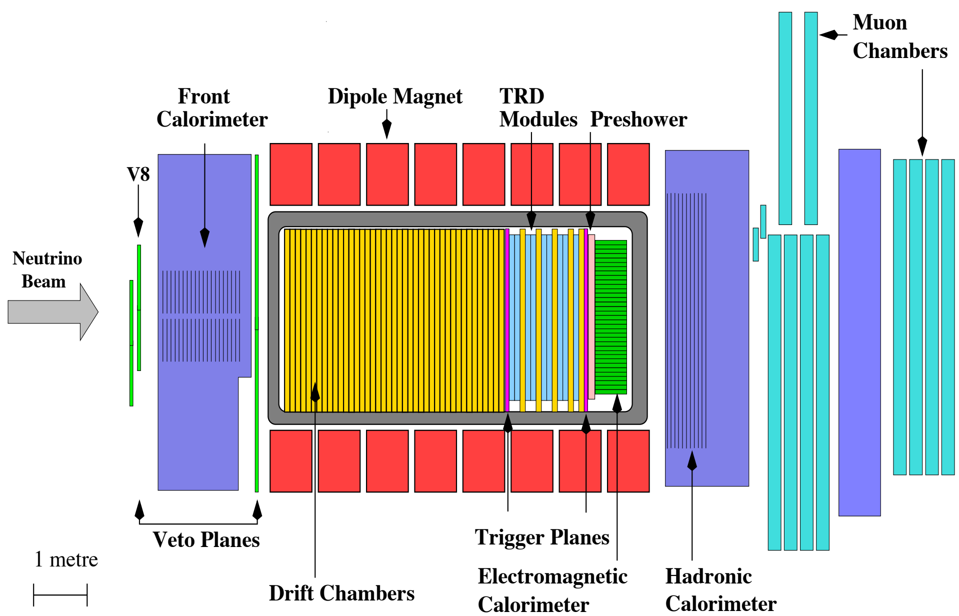
THE NOMAD DETECTOR

- **Low-density magnetic spectrometer**
  $B = 0.4$ **T**, $\rho \sim 0.1$ **g/cm**^{3}, $X_0 \sim 5\ m$

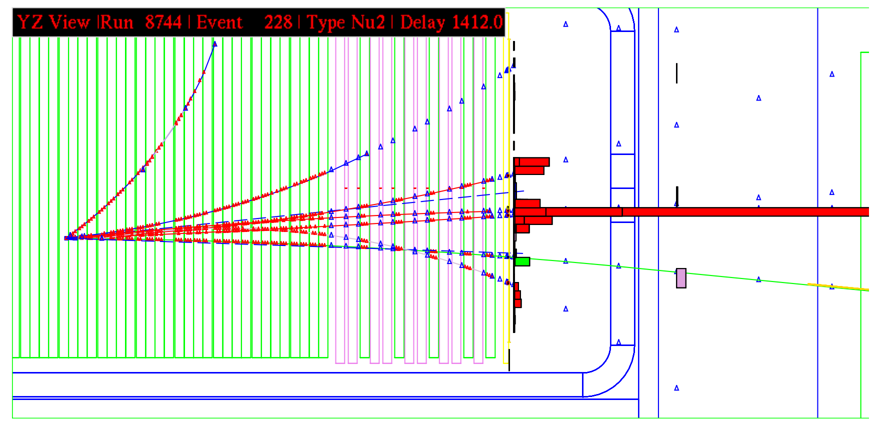
  I *high resolution tracking*
  $\Longrightarrow$ *mom. resolution ∼3.5% (p<10*GeV/c*)*;

  II *fine-grained calorimeter*
  $\Longrightarrow$ $\sigma(E)/E = 3.2\%/\sqrt{E[\mathrm{GeV}]} \oplus 1\%$;

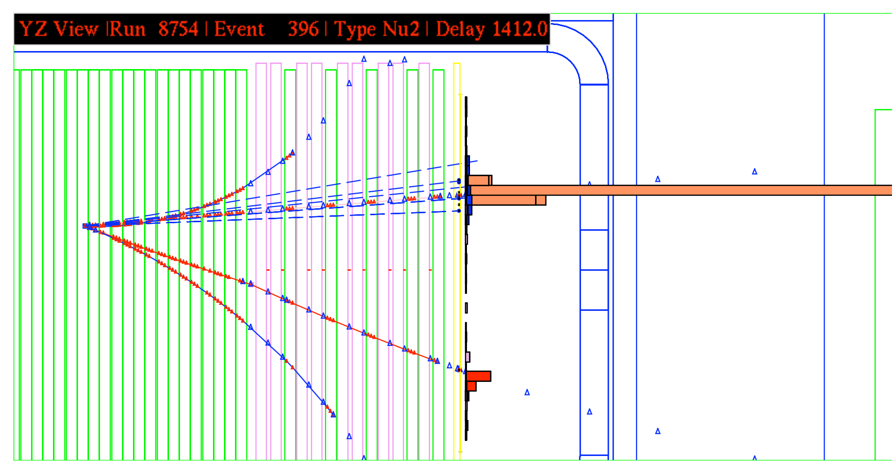
  III *excellent lepton identification*
  & charge measurement
  $\Longrightarrow$ *can detect* $\nu_\mu, \nu_e, \bar{\nu}_\mu, \bar{\nu}_e$ **CC**.



ν_μ Charged Current



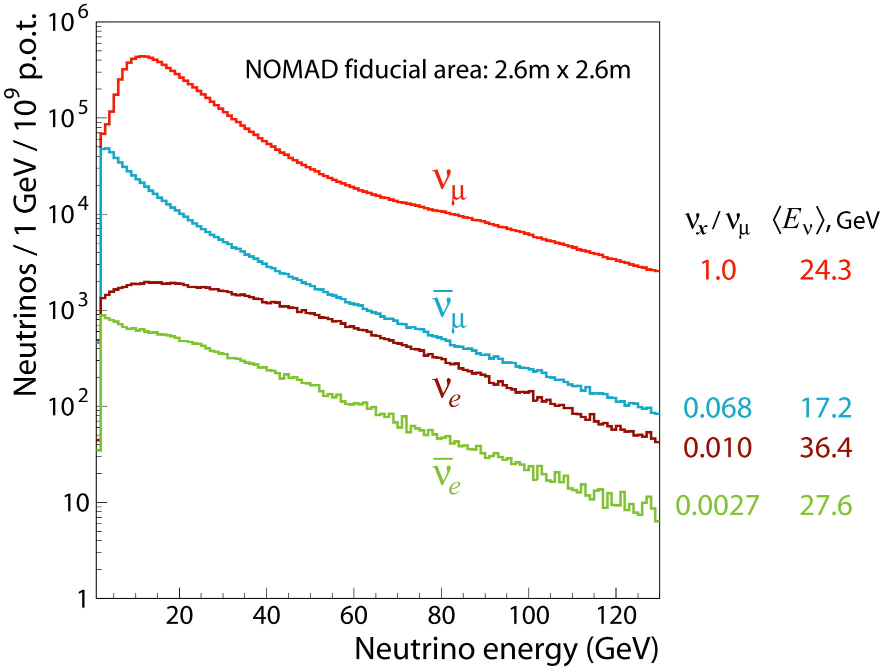
$\bar{\nu}_e$ Charged Current

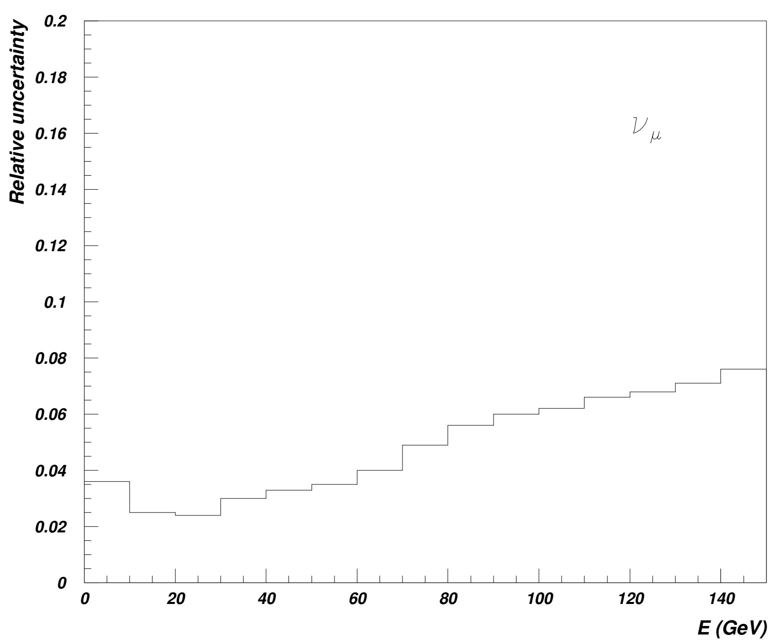


DETERMINATION OF (ANTI)NEUTRINO FLUXES

- *Detailed calculations developed for $\nu_\mu \to \nu_e$ appearance search (LSND at high Δm^2):*
  - *FLUKA+GEANT3 description of primary target, beam focusing elements and secondary particle propagation along beam line*
  - *Constraints on K/π vs. p from dedicated SPY/NA56 hadroproduction experiment (p on Be target at 450 GeV)*
- *Validation of ν and $\bar{\nu}$ fluxes from comparison with different CC spectra in NOMAD:*
  - *Standard/reversed horn polarity (focusing);*
  - *Horn / Reflectors switched off*
- *Normalization of absolute flux ν_μ flux to world average DIS cross-section $\sigma(E)/E$ in the range 40 GeV $< E_\nu <$ 150 GeV ($\sim$ 2.1% precision)*

  $\Longrightarrow$ *Need only extrapolation of relative flux below 40 GeV*





MONTE CARLO SIMULATION

- *Quasi-Elastic (QE) neutrino scattering:*
  - *Based upon the Smith-Monitz approach*
  - *Vector form factors F_V and F_M parameterized following the well-known GKex(05) form*
  - *Axial form factor with the dipole parameterization $F_A(Q^2) = F_A(0)\left[1 + Q^2/M_A^2\right]^{-2}$*
- *Single pion production via intermediate resonance state*
  - *Based upon the Rein-Sehgal (RS) model*
  - *Set of 18 baryon resonances with masses below 2 GeV as in RS with parameters updated from PDG*
- *Deep Inelastic Scattering (DIS)*
  - *Primary interaction with modified LEPTO 6.1*
  - *Hadronization and decays with JETSET 7.4*
  - *Structure functions re-weighted with LO GRV 98 Bodek-Yang (BY), as well as with full NNLO calculation Alekhin, Kulagin and P. (AKP)*
- *Benhar-Fantoni parameterization of momentum distribution $n(k)$ in nucleus*
- *Final State Interactions (FSI) modeled with the DPMJET package based on the concept of the formation zone intra-nuclear cascade*
- *Cross-check signal and background efficiencies with NUANCE and GENIE event generators interfaced with the NOMAD detector simulation and reconstruction*

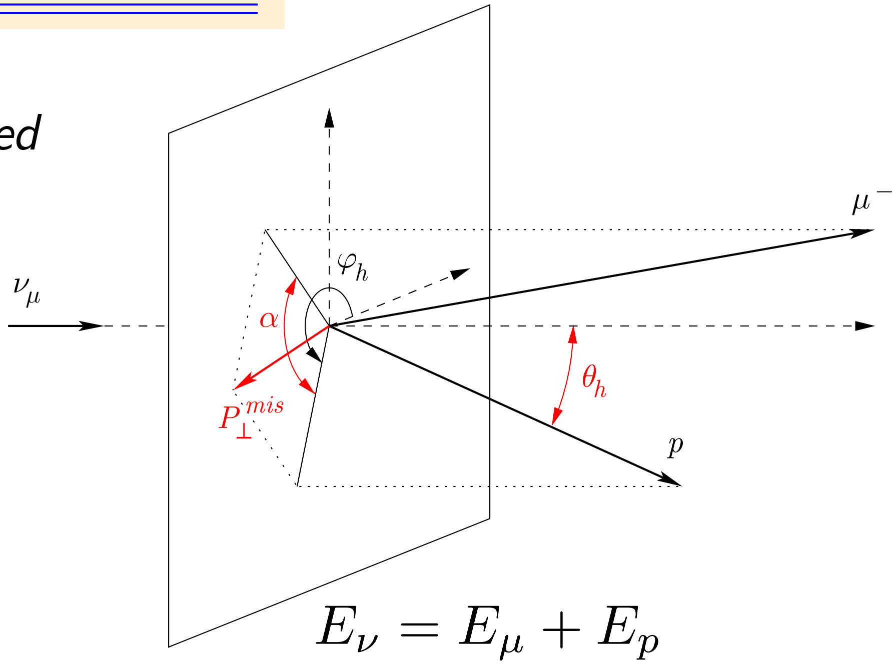
SELECTION OF QE EVENTS: 2-TRK SAMPLE

- ✦ *Topologies classified based on # of reconstructed tracks with* $N_{\rm HITS} \geq 7 \longrightarrow L \sim 18$ *cm*
  - *1 track sample* (μ) $\Longrightarrow$ *complementary (control)*
  - *2 track sample* ($\mu + p$) $\Longrightarrow$ *golden sample*
  - *3 track sample etc.*
- ✦ *Muon ID and* $0 \leq \phi_\mu \leq \pi$
- ✦ *Proton ID with momentum-range relations*
- ✦ *Pre-selection cuts:*
  - *Angle in transverse plane* $0.8 \leq \alpha/\pi \leq 1$
  - *Missing transverse momentum* $P_\perp^{\rm miss} \leq 0.8$ *GeV/c*
  - *Proton angle with beam* $0.2 \leq \theta_h/\pi \leq 0.5$
- ✦ *Energy range* $3 \leq E_\nu \leq 100$ *GeV*
- ✦ *Kinematic selection with 3D likelihood function:*

$$\mathcal{L} = [p_\perp^{\rm miss}, \alpha, \theta_h]$$

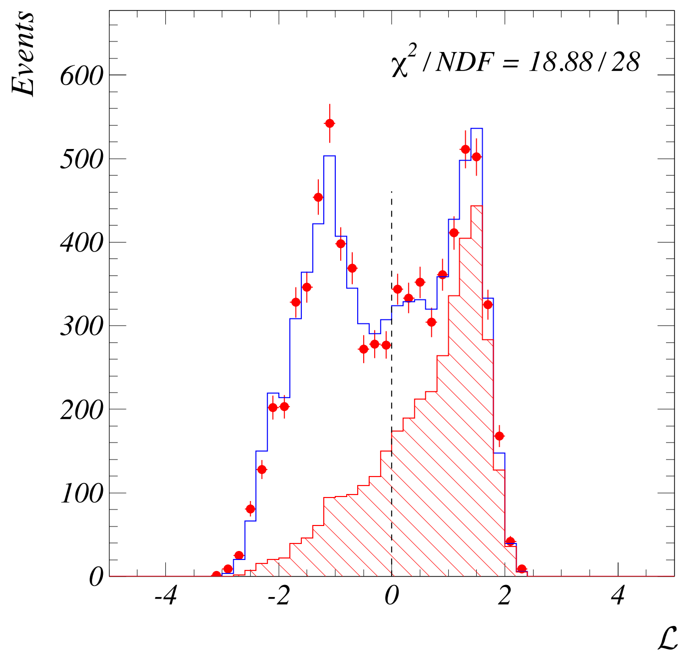
with discriminant $\ln\lambda = \ln \mathcal{L}_{\rm QE}/\mathcal{L}_{\rm RES}$

$\Longrightarrow$ *Selected 3663 QE candidates in data with* $\varepsilon_{\rm QE} = 13\%$ *and purity of 74%.*



$$E_\nu = E_\mu + E_p$$

$$Q^2 = 2E_\nu\left(E_\mu - P_\mu \cos\theta_\mu\right) - m_\mu^2$$



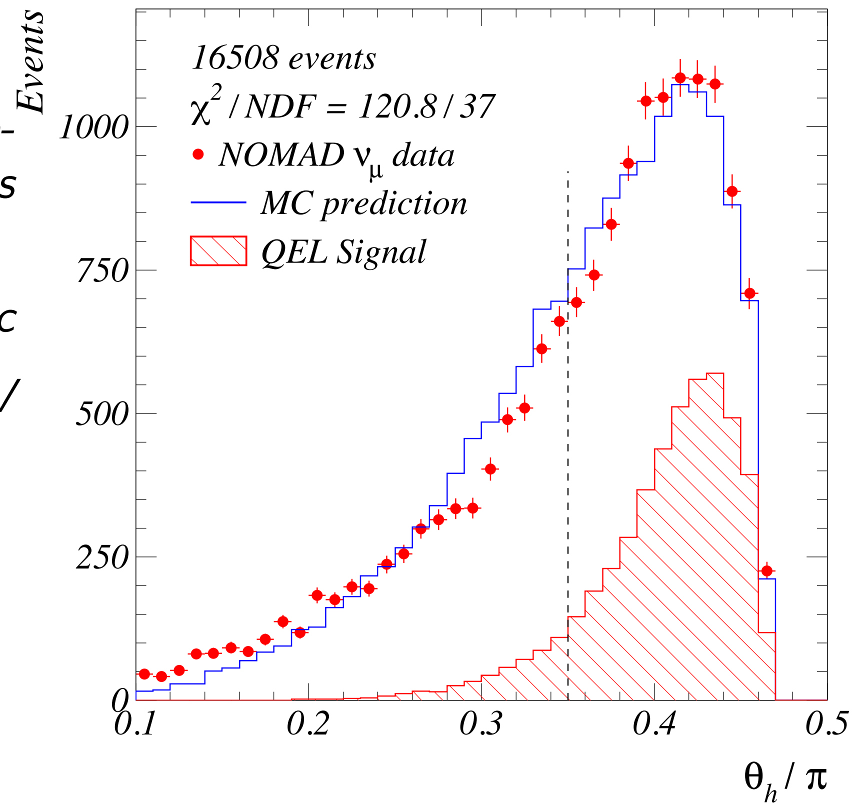
SELECTION OF QE EVENTS: 1-TRK SAMPLE

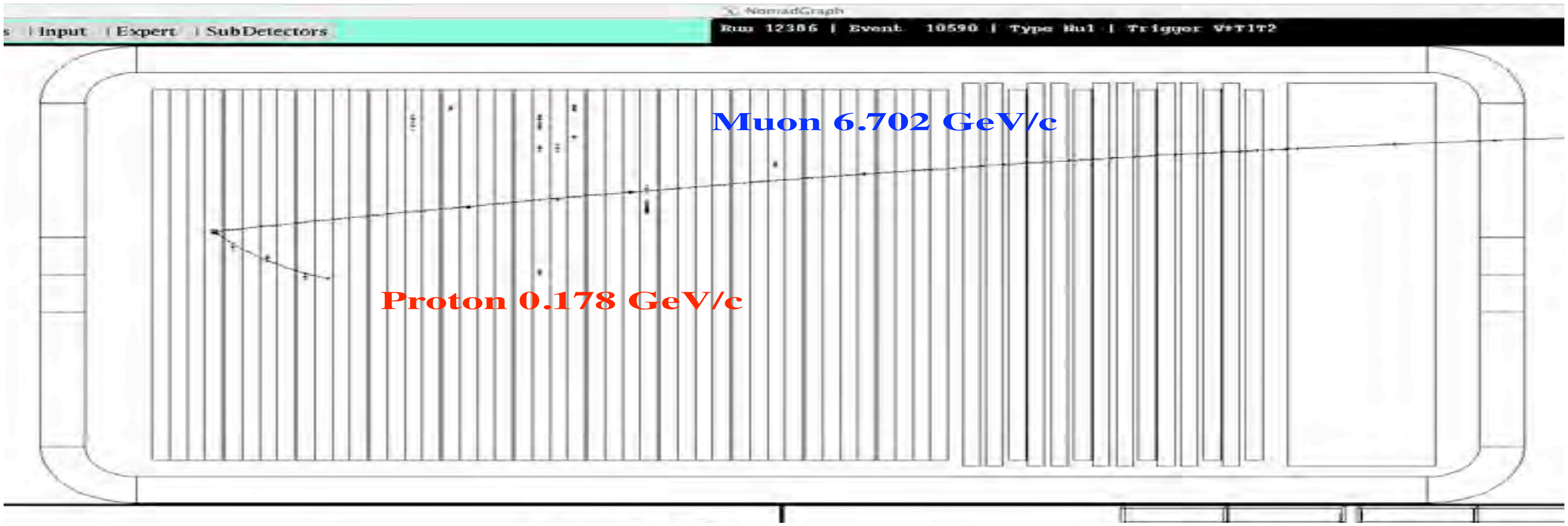
- *Only one reconstructed track with # of hits $N_{\mathrm{HITS}} \geq 7 \longrightarrow L \sim 18$ cm*
  - *Tighter fiducial volume cut than 2-trk sample*
  - *No reconstructed track segments other than the muon*
- *Muon ID and $0 \leq \phi_\mu \leq 2\pi$*
- *Calculate neutrino energy E_ν and missing kinematic variables (θ_h etc.) assuming QE kinematics with nucleon at rest*
- *Transverse momentum of muon $P_\mu^{\mathrm{T}} > 0.2$ GeV/c*
- *Calculated energy (QE) range $3 \leq E_\nu \leq 100$ GeV*
- *Muon emission angle $\theta_\mu/\pi \leq 0.1$*
- *Calculated proton angle $0.35 \leq \theta_h/\pi \leq 0.5$*

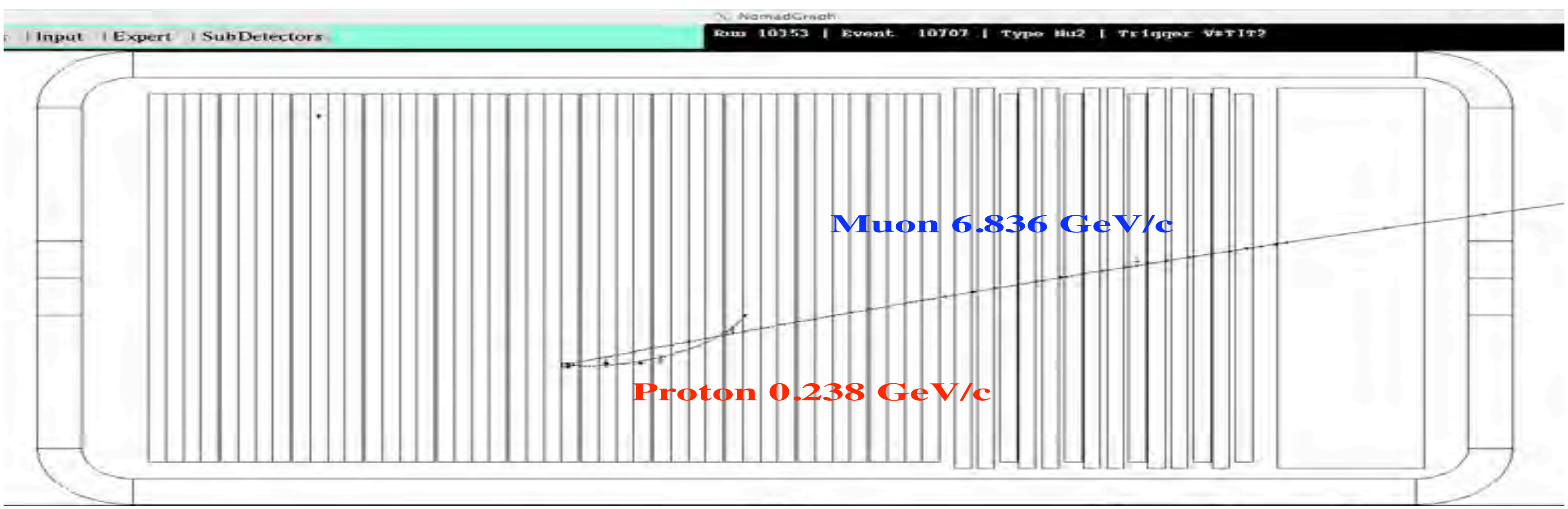
$\Longrightarrow$ *Selected 10358 QE candidates in data with $\varepsilon_{\mathrm{QE}} = 21\%$ and purity of 50%.*

$$E_\nu = \frac{M E_\mu - m_\mu^2/2}{M - E_\mu + P_\mu \cos\theta_\mu}$$

$$Q^2 = 2M\left(E_\nu - E_\mu\right)$$




Input
Expert
SubDetectors
NomadGraph
Run 12386 | Event 10590
Muon 6.702 GeV/c
Proton 0.178 GeV/c


Input
Expert
SubDetectors
NomadGraph
Run 10353 | Event 10707
Muon 6.836 GeV/c
Proton 0.238 GeV/c

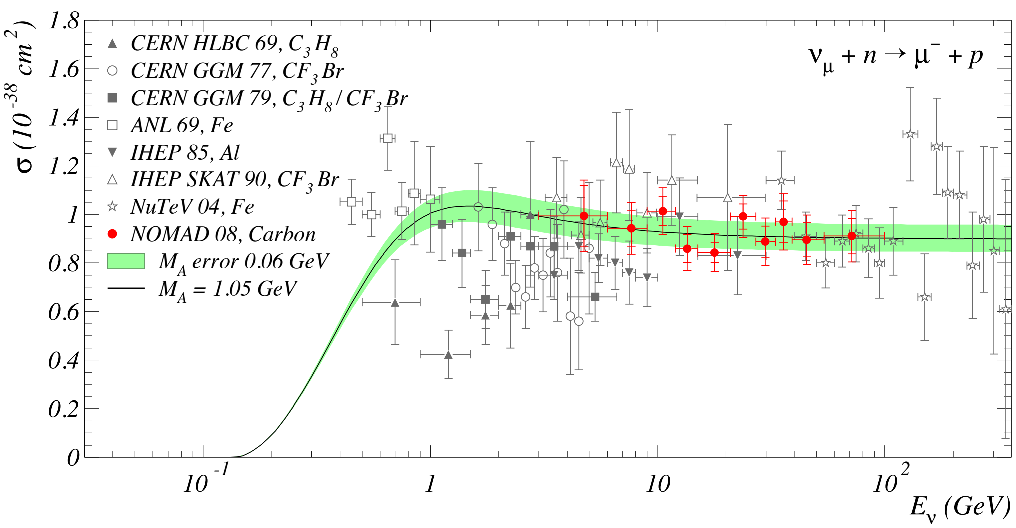
PUBLISHED NOMAD MEASUREMENT (2009)

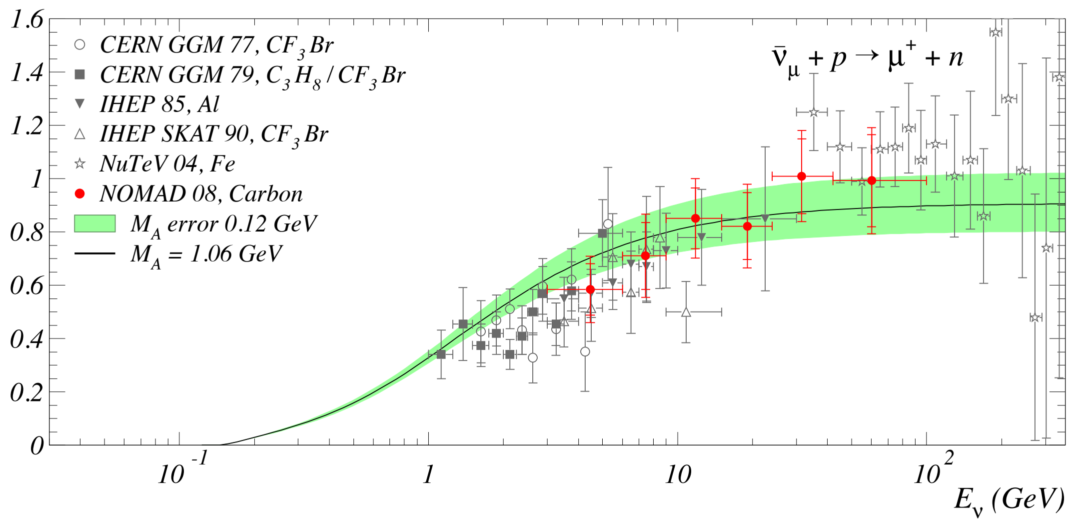
- *Overall ν_μ CC QE candidates selected in data 14021 (1-trk + 2-trk) with total QE selection efficiency $\varepsilon_{\mathrm{QE}} = 34\%$ and purity of about 50%*
- *Overall $\bar{\nu}_\mu$ CC QE candidates selected in data 2237 (1-trk) with total QE selection efficiency $\varepsilon_{\mathrm{QE}} = 64\%$ and purity of about 38%*
- *Measurement of total QE cross-sections:*

$$\sigma^{\nu}_{\mathrm{QE}} = [0.92 \pm 0.02(stat.) \pm 0.06(syst.)] \times 10^{-38} cm^2$$
$$\sigma^{\bar{\nu}}_{\mathrm{QE}} = [0.81 \pm 0.05(stat.) \pm 0.08(syst.)] \times 10^{-38} cm^2$$

- *Determination of the effective axial mass M_A from fit to $\sigma(E) \oplus d\sigma/dQ^2$:*

$$M_A(\nu) = [1.06 \pm 0.02(stat.) \pm 0.06(syst.)]\ GeV$$
$$M_A(\bar{\nu}) = [1.06 \pm 0.07(stat.) \pm 0.10(syst.)]\ GeV$$





NEW IMPROVED ANALYSIS

- *A new measurement of QE cross-sections in NOMAD has been completed and is expected to be published next year*
  - *Use complete kinematic range* $0 \leq \phi_\mu \leq 2\pi$ *and larger fiducial volume*
  - *More efficient kinematic selection (likelihood function and pre-selection)*
  - *Better understanding of reconstruction systematics*
  - *Calibration of backgrounds in control regions*

  $\Longrightarrow$ *Total 2-trk QE candidates selected* ~ 16800
  with efficiency $\varepsilon_{\rm QE} = 25\%$ *and purity of 57%*

  $\Longrightarrow$ *Total 1-trk QE candidates selected* ~ 18600
  with efficiency $\varepsilon_{\rm QE} = 29\%$ *and purity of 57%*

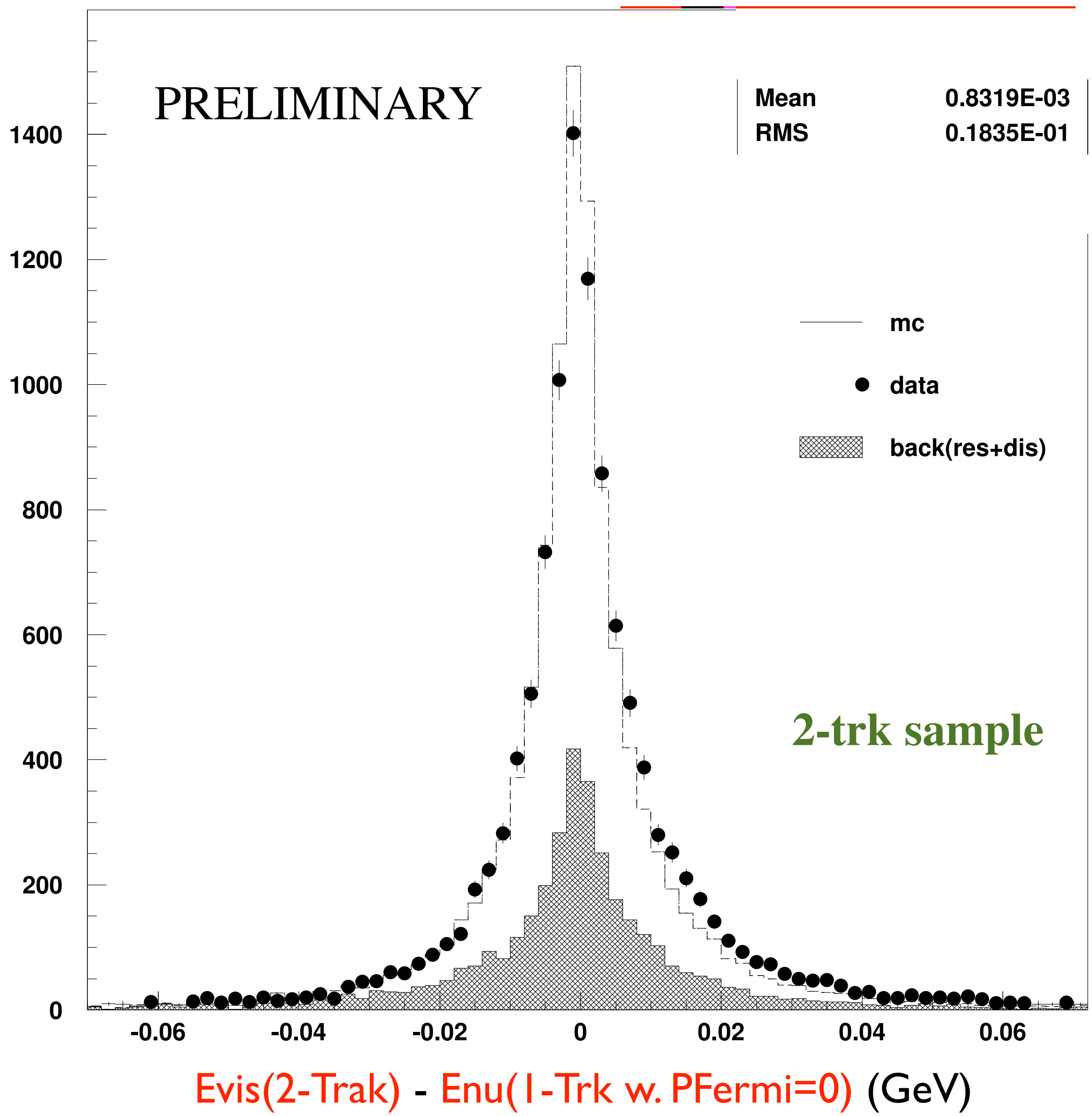
  $\Longrightarrow$ *High purity samples with tighter kinematic cuts*

- *Measurement of total QE cross-section* $\sigma(E)$*:*

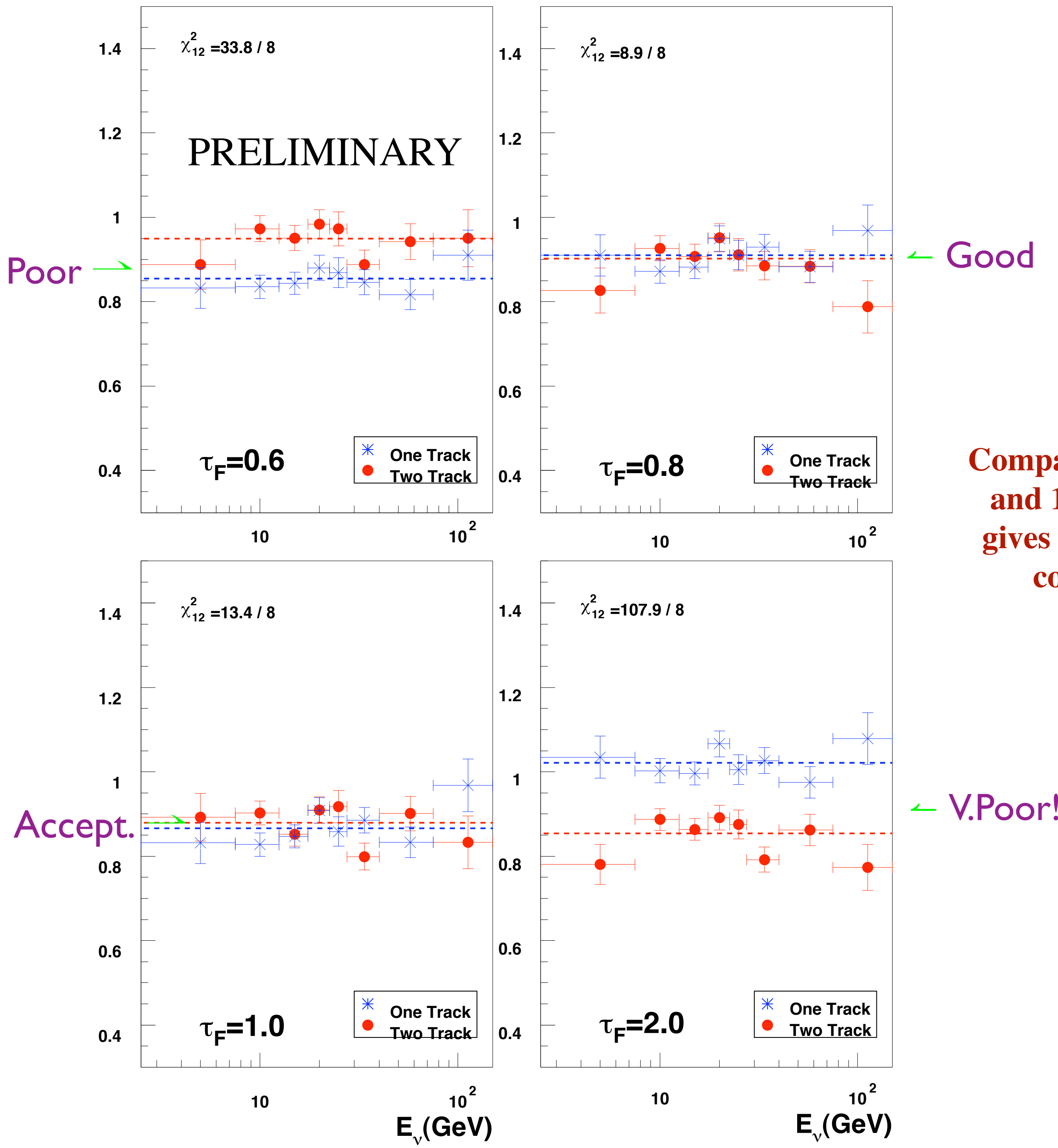
  $\sigma^{\nu}_{\rm QE} = [0.914 \pm 0.013(stat.) \pm 0.038(syst.)] \times 10^{-38} cm^2$ *avg. 1-trk + 2-trk*

- *Measurement of differential cross-section* $d\sigma/dQ^2$

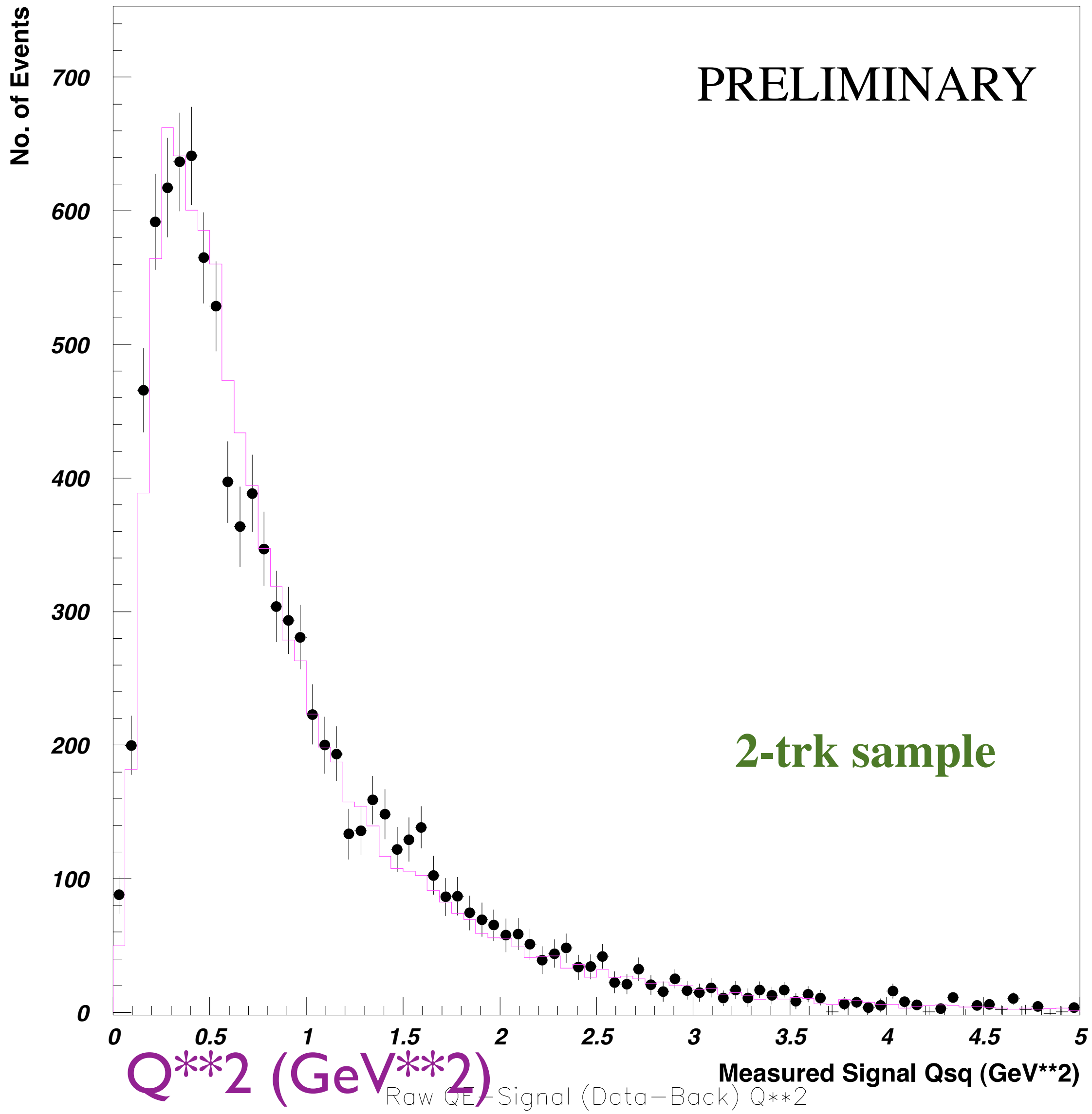
- *Model-independent study of nuclear effects and Final State Interactions (FSI) from comparison of 2-trk and 1-trk samples*



Difference between measured 2-trk energy and calculated QE energy with nucleon at rest provides measurement of nuclear effects and FSI



Comparison between 2-trk and 1-trk cross-sections gives model-independent constraint on FSI



Good agreement with the Q^2 distribution in the 2-trk sample down to low values

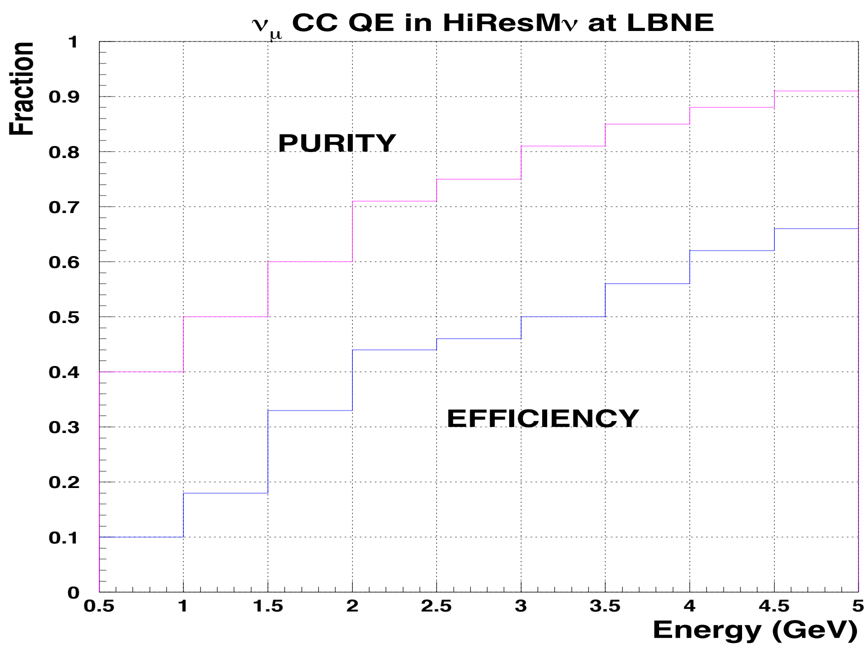
Characteristics of selected ν_μ QE events	NOMAD values
QE event selection	2-trk sample: 1 identified muon + 1 identified proton 1-trk sample: 1 identified muon without any other rec. trk
Nuclear target	64% C, 22% O, 6% N, 5% H, 1.7% Al
Neutrino flux range	$2.5 < E_\nu < 300$ GeV
Sign-selection?	yes
Muon angular range	$0^0 < \vert\theta_\mu\vert < 180^0$ track reconstruction $0^0 < \vert\theta_\mu\vert < 50^0$ acceptance muon ID
Muon energy range	$E_\mu > 2$ GeV for muon ID
Proton detection threshold	P ~ 200 MeV/c
How is E_ν determined?	i) Sum of muon E_μ + proton E_p from p fit in B field (0.4 T) ii) Comparison with E_ν from QE kinematics (from muon only) gives direct measurement of nuclear effects iii) Comparison of 2-trk vs. 1-trk gives measurement of FSI
How is Q^2 determined?	2-trk sample: $Q^2 = -m_\mu^2 + 2E_\nu (E_\mu - p_\mu \cos\theta_\mu)$ 1-trk sample: Q^2_{QE}
Monte Carlo generator	NOMAD generator (LEPTO/JETSET/DPMJET) checked with NUANCE *(tuned with NOMAD data, resonance Rein-Sehgal)*
QE measurements and associated publications	$\sigma(E_\nu)$: Eur.Phys. J. C 63 (2009) 355-381 $d\sigma/dQ^2$, nuclear effects and FSI in C (new analysis)

FUTURE QE MEASUREMENTS WITH LBNE ND

- *Next generation High-Resolution Near Detector (ND) for LBNE based upon the NOMAD concept:*
  - *Low density magnetic spectrometer:* $B = 0.4$ *T,* $\rho \sim 0.1$ *g/cm*^{3}*, target* $(C_3H_6)_n$
  - *Straw Tube Tracker with* $\times 12$ *higher granularity than NOMAD*
  - *Complete* 4π *coverage of calorimetry and muon ID*

  $\Longrightarrow$ *Improved* p *resolution and recontruction efficiency w.r.t. NOMAD*

- *Expect to collect* $\sim 10(5) \times 10^6$ $\nu(\bar{\nu})$ *QE events in 5y* ν + *5y* $\bar{\nu}$ *data taking with energy range* $0.5 \leq E_\nu \leq 20$ *GeV*



- *Protons easily identified by the large dE/dx in tracker & range*
- *New NOMAD QE analysis also used for sensitivity studies in LBNE ND*
  $\Longrightarrow$ *Same reconstruction & selection*
- *Use multi-dimensional likelihood functions incorporating the full event kinematics to reject DIS & Res backgrounds*
  $\Longrightarrow$ *On average* $\varepsilon = 52\%$ *and* $\eta = 82\%$ *for CC QE at LBNE (New NOMAD* $\varepsilon = 54\%$*,* $\eta = 57\%$*)*