Study of Quasi-Elastic muon (anti)neutrino interactions in the NOMAD experiment

Neutrino Oscillation MAgnetic Detector

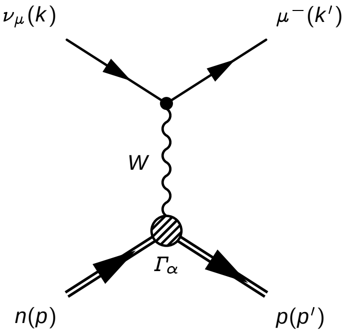
Vladimir Lyubushkin[1] and Boris Popov[1,2]

[1] *Joint Institute for Nuclear Research, DLNP, Dubna*
[2] *LPNHE, Univ. of Paris VI and VII, Paris*

Outline

- Phenomenology of $\nu_\mu\, n \to \mu^-\, p$ and $\bar{\nu}_\mu\, p \to \mu^+\, n$ processes
- Review of existing experimental data:
  total cross-sections and the axial form-factor of the nucleon
- Description of the NOMAD detector
- MC simulation and nuclear reinteraction (FSI) effects
- Selection of quasi-elastic events in NOMAD:
  topology and kinematic criteria
- The QEL cross section the axial mass M_A measurement
- Our *results* and *conclusions*

Phenomenology of Quasi-Elastic Neurino Scattering



The most general form of the electroweak $N_{in} \to N_{out}$ transition current is given by [1]

$$J_\alpha = \langle N_{out}; p' | \widehat{J}_\alpha | N_{in}; p \rangle = \bar{u}_p(p') \Gamma_\alpha u_n(p)$$

Here p and p' are the 4-momenta of the target nucleon N_{in} and final baryon N_{out} respectively. The the vertex 4-vector is

$$\Gamma_\alpha = \gamma_\alpha F_1 + i\sigma_{\alpha\beta} \frac{q^\beta}{2M} F_2 + \frac{q_\alpha}{M} F_S + \\ + \left(\gamma_\alpha F_A + \frac{p_\alpha + p'_\alpha}{M} F_T + \frac{q_\alpha}{M} F_P \right) \gamma_5$$

The six form factors $F_i(Q^2)$ in the vertex function Γ_α are in general complex.

The most general restrictions to the form factors:

1. T invariance $\Rightarrow$ $\text{Im}\,(F_V, F_M, F_A, F_P, F_S, F_T) = 0$
2. C invariance $\Rightarrow$ $\text{Im}\,(F_V, F_M, F_A, F_P) = 0$ and $\text{Re}\,(F_S, F_T) = 0$
3. no SCC $\Rightarrow$ $F_S = F_T = 0$ ($\equiv$ T invariance + C invariance)
4. $\partial_\alpha V^\alpha = 0$ (CVC) $\Rightarrow$ $F_S = 0$

[1] *C. H. Llewellyn Smith, "Neutrino reactions at accelerator energies," Phys. Rept.* **3** *C (1972) 261–379.*

Electromagnetic form factors of nucleon

We have investigated several models for the nucleon electromagnetic Sachs form factors

$$G_E(Q^2) = F_1(Q^2) - \frac{Q^2}{4M_i^2} F_2(Q^2) \quad \text{and} \quad G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$$

where $F_1(Q^2)$ and $F_2(Q^2)$ are the Dirac and Pauli form factors, respectively.

- Simple dipole parametrization:

$$G_E(Q^2) = G_M(Q^2)/(\mu_p - \mu_n) = G_D(Q^2) = (1 + Q^2/0.71)^{-2}$$

- Gari–Krüempelmann (GK) model[1] extended and fine-tuned by Lomon[2] to match current experimental data. Specifically, as the "reference model", we explore the so-called GKex(05) which fits the modern and consistent older data well and meets the requirements of dispersion relations and of QCD at low and high 4-momentum transfer.
- Global fit by Budd *et al.*,[3] (BBA model) to the data from Rosenbluth analysis of elastic *ep* cross section measurements and those from the polarization transfer techniques.

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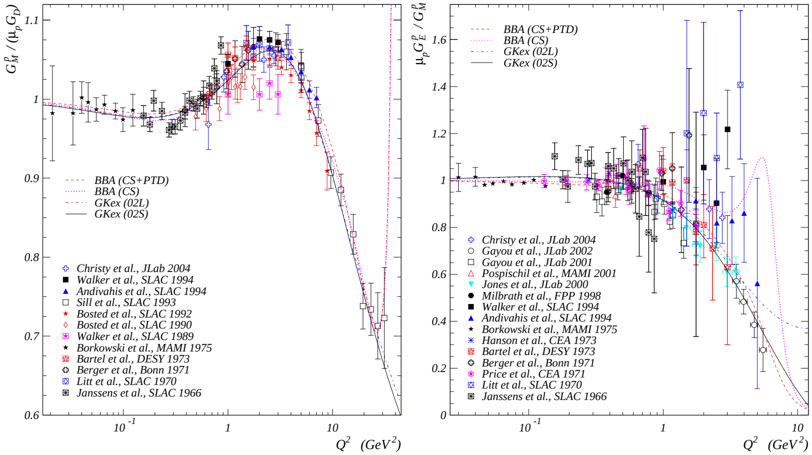
[1] *M. F. Gari and W. Krüempelmann, "The electric neutron form factor and the strange quark content of the nucleon," Phys. Lett. B* **274** *(1992) 159-162; erratum – ibid.* **282** *(1992) 483-484.*

[2] *E. L. Lomon, "Effect of recent R_p and R_n measurements on extended Gari–Krüempelmann model fits to nucleon electromagnetic form factors," Phys. Rev. C* **66** *(2002) 045501 [nucl-th/0203081].*

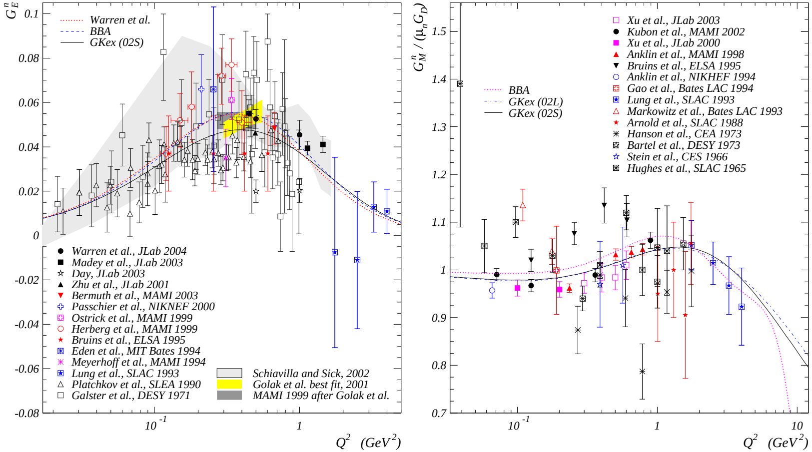
[3] *H. Budd, A. Bodek, and J. Arrington, "Modeling quasi-elastic form factors for electron and neutrino scattering," hep-ex/0308005, to be published in Nucl. Phys. B (Proc. Suppl.).*

Proton electromagnetic form factors



Normalized magnetic form factor and ratio of electric and magnetic form factors of the proton. BBA: Budd-Bodek-Arrington [hep-ex/0308005] global fit to the data from Rosenbluth analysis of elastic *ep* cross section measurements and those from the polarization transfer techniques. GKex: extended Gari–Krüempelmann model after Lomon [PRC **66** (2002) 045501].

Neutron electromagnetic form factors



Electric and normalized magnetic form factors of the neutron. Together with the BBA and GKex fits (see previous slide), the recent fit by Warren *et al.* [PRL **92** (2004) 042301] is also shown. The filled areas represent some theoretical extractions from different data subsets.

Axial and pseudoscalar form factors

The customary parametrizations for the axial and pseudoscalar form factors

$$F_A(Q^2) = F_A(0)\left(1+\frac{Q^2}{M_A^2}\right)^{-n} \quad \text{with} \quad n = \begin{cases} 2 & \text{– “dipole”} \\ 1 & \text{– “monopole”} \end{cases}$$

$$F_P(Q^2) = \frac{2M^2}{m_\pi^2 + Q^2} F_A(Q^2) \quad \text{(PCAC)} \quad \text{and} \quad F_A(0) = g_A = -1.2695 \pm 0.0029$$

The pseudoscalar contribution is important for τ production.[4] *Note that the “standard” expression for the F_P is at most a (doubtful) parametrization inspired by the PCAC hypothesis (+ pion pole dominance near $Q^2 = 0$).*

The experiments on QE and pion electroproduction permit very wide spread of M_A:

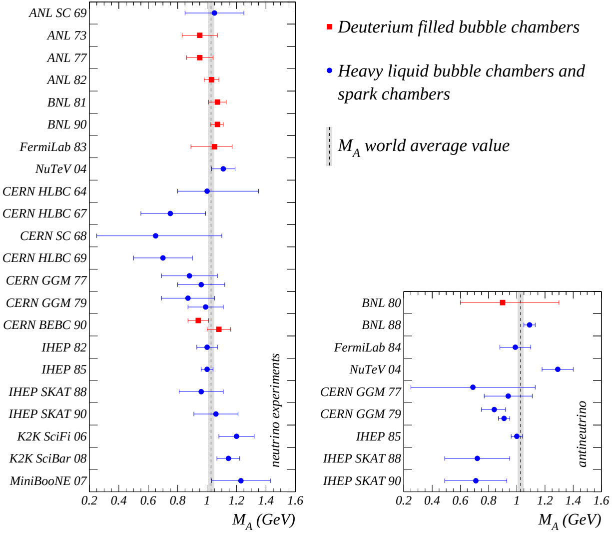
from roughly 0.7 to 1.2 GeV/c^2 for dipole F_A,

from roughly 0.6 to 0.8 GeV/c^2 for monopole F_A.

However the monopole parametrization seems to be obsolete.

[4] *K. Hagiwara, K. Mawatari and H. Yokoya, “Pseudoscalar form factors in tau-neutrino nucleon scattering,” hep-ph/0403076; see also poster by H. Yokoya in this workshop.*

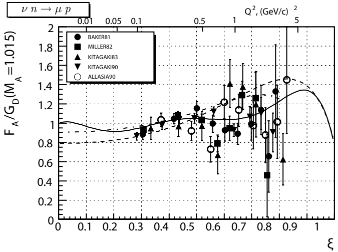
Axial mass from neutrino scattering experiments

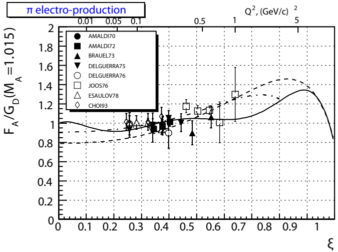


Axial mass average value $M_A = 1.026 \pm 0.021$ GeV was borrowed from review by V. Bernard *et al.* [5]

[5] *V. Bernard, L. Elouadrhiri and Ulf-G. Meißner, "Axial structure of the nucleon," J. Phys. G* **28** *(2002) R1–R35 [hep-ph/0107088].*

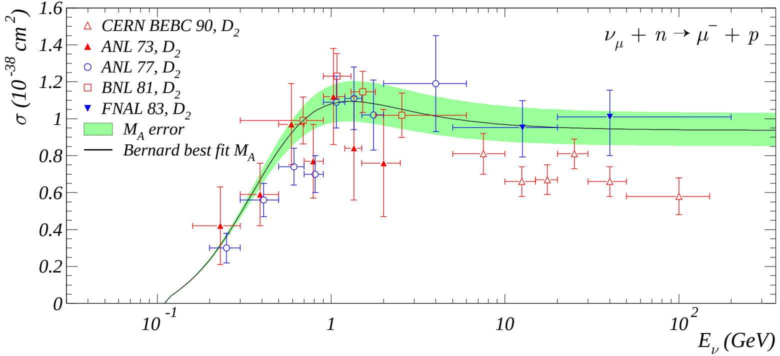
Axial form factor: Q^2 dependence





Axial form factor of the nucleon F_A, re-extracted from *neutrino-deuterium* (left) and *pion electro-production* (right) data. Taken from A. Bodek et al, ArXiV: hep-ex/0709.3538.v1

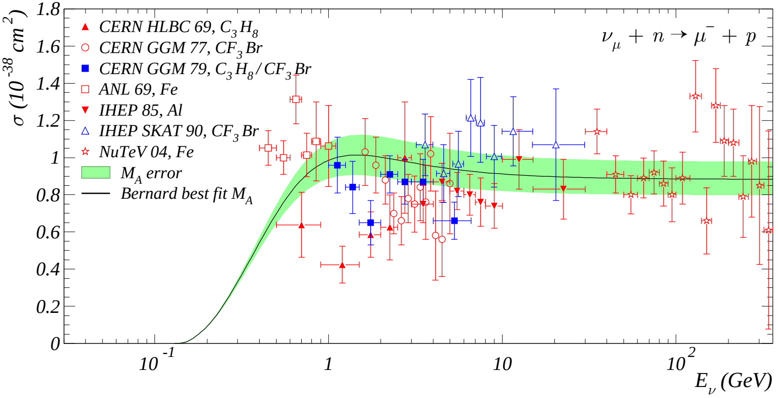
Total QE $\nu_\mu n$ cross section from deuterium filled bubble chambers



The total cross-section of $\nu_\mu n \to \mu^- p$ process extracted from $\nu_\mu D$ scattering data. The solid curve corresponds to the world average value of axial mass $M_A = 1.03$ GeV while the shaded area shows a ± 0.1 GeV error band. Points correspond to available experimental data from ANL (Argonne 12-foot BC), BNL (Brookhaven 7-foot BC), FNAL (FermiLab 15-foot BC), CERN (BEBC, Big European Bubble Chamber).

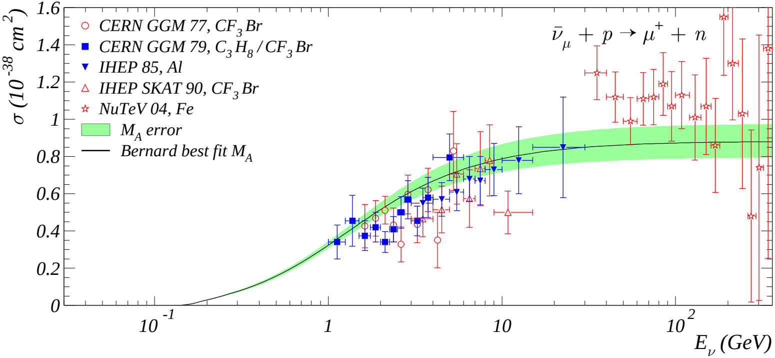
Corrections for nuclear effects have been made by the authors of the experiments.

Total QE $\nu_\mu n$ cross section measured on heavy nuclei target



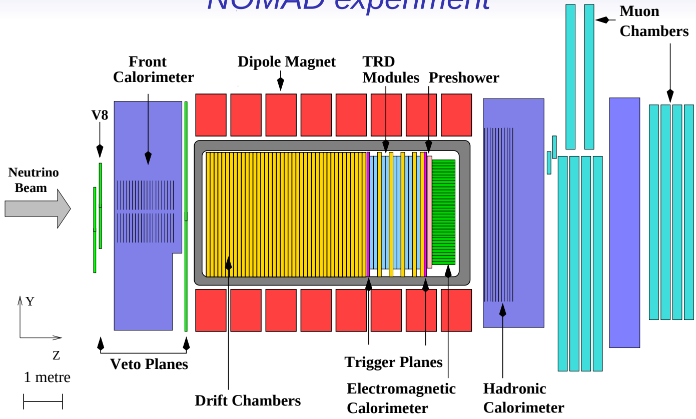
The total cross-section of $\nu_\mu n \to \mu^- p$ process extracted from the data on ν_μ scattering off heavy nuclei. *Nuclear effects are included into calculations* according to the relativistic Fermi gas model by Smith and Moniz for Carbon with binding energy $E_b = 25.6$ MeV and Fermi momentum $P_F = 221$ MeV; the axial mass value is $M_A = 1.03 \pm 0.1$ GeV. Points correspond to available experimental data from ANL (Spark-chamber), NuTeV (FermiLab), CERN (Heavy Liquid Bubble Chamber, Gargamelle BC), IHEP (Spark-chamber and SCAT BC).

Total QE cross $\bar{\nu}_\mu p$ cross section from heavy nuclei target



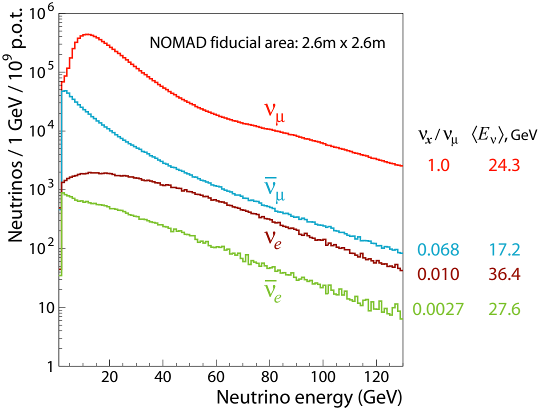
The total cross-section of $\bar{\nu}_\mu p \rightarrow \mu^+ n$ process extracted from the data on $\bar{\nu}_\mu$ scattering off heavy nuclei. *Nuclear effects are included into calculations* according to the relativistic Fermi gas model by Smith and Moni for Carbon; the axial mass value is $M_A = 1.03 \pm 0.1$ GeV. Points correspond to available experimental data from NuTeV, CERN (Gargamelle BC), IHEP (Spark-chamber and SCAT BC).

NOMAD experiment



- Drift Chambers (target and momentum measurement) — Position resolution $< 200\ \mu$m (small angle tracks); Momentum resolution $\sim 3.5\%$ ($p < 10$ GeV/c)
- Transition Radiation Detector for $e^{\pm}$ identification: π rejection $\sim 10^3$ for electron efficiency $\geqslant 90\%$
- Lead glass Electromagnetic Calorimeter $\frac{\sigma(E)}{E} = (1.04 \pm 0.01)\% + \frac{(3.22 \pm 0.07)\%}{\sqrt{E\ (\mathrm{GeV})}}$
- Muon Chambers for $\mu^{\pm}$ identification: efficiency $\approx 97\%$ ($p_{\mu} > 5$ GeV/c)
- Hadronic Calorimeter for n and K_L^0 veto

Neutrino fluxes at NOMAD experiment

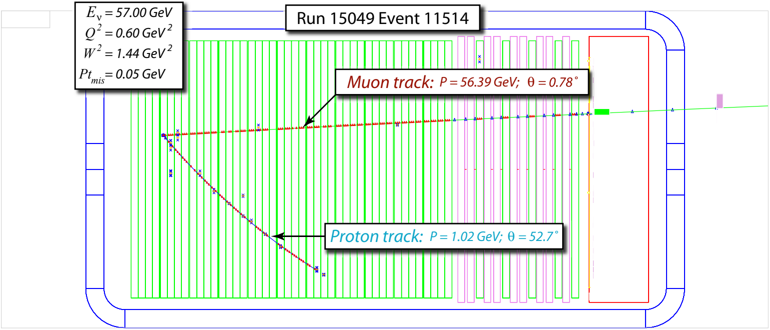


$$\langle \sigma_i \rangle = \int \sigma_i(E_\nu)\Phi(E_\nu)dE_\nu$$

Mode	Neutrino	Antineutrino
QEL	0.430	0.393
RES	0.575	0.430
DIS	15.954	4.834

[1] *P. Astier et al. [NOMAD Collaboration], "Prediction of neutrino fluxes in the NOMAD experiment," Nucl. Instrum. Meth. A* **515**, *800 (2003) [arXiv:hep-ex/0306022].*

View of tipical QEL candidate event in NOMAD detector



Typical examples of data events identified as $\nu_\mu n \to \mu^- p$ (run 15049 event 11514). Long track is identified as negatively charged muon, short track is associated with proton.

Monte Carlo simulation

- *Quasi-elastic neutrino scattering*
  - based on the Llewellyn Smith's formalism [6]
  - Pauli blocking for outgoing nucleon and impact of nuclear reinteractions in nucley are taken into account
- *Single pion production via intermediate resonance state*
  - based on Rein–Sehgal model [7]
  - set of 18th baryon resonances with masses below 2 GeV as in RS but with all relevant parameters updated according to the most recent PDG
  - factors which were estimated in RS numerically are corrected by using the new data and a more accurate integration algorithm
- *Deep inelastic scattering*
  - modelled with the help of modified LEPTO 6.1 package [8]
  - production of all *zoo* of hadrons is simulated with help of JETSET 7.4 [9]
  - specific nuclear effects (such as nuclear shadowing, pion excess and off-shell corrections to bound nucleon structure functions) are described in the unique theoretical framework, proposed recently by S. Kulagin and R. Petti [10]

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6 *C. H. Llewellyn Smith, "Neutrino reactions at accelerator energies," Phys. Rept.* **3** *C (1972) 261–379.*

7 *D. Rein and L. Sehgal, "Neutrino excitation of baryon resonances and single pion production," Annals Phys.* **133** *(1981) 79–153*

8 *G. Ingelman, LEPTO version 6.1, "The Lund Monte Carlo for Deep Inelastic Lepton-Nucleon Scattering," TSL-ISV-92-0065 (1992); see also G. Ingelman, A. Edin, J. Rathsman, LEPTO version 6.5, Comp. Phys. Comm.* **101** *(1997) 108, [hep-ph/9605286]*

9 *T. Sjöstrand, "PYTHIA 5.7 and JETSET 7.4: physics and manual," LU-TP-95-20 (1995), [hep-ph/9508391]*

10 *S. Kulagin, R. Petti, "Global study of nuclear structure functions," Nucl. Phys. A* **765** *(2006) 126, [hep-ph/0412425]*

Final State Interactions: Intra-nuclear cascade

The simulation of the re-interaction between particles, produced at the primary neutrino collision off the target nucleon, and the residual nucleus has been done wth the help of DPMJET package [11] according to the Formation Zone Intranuclear Cascade model. Secondaries from this first collision are followed along straight trajectories and may also induce in turn intranuclear cascade processes if they reach the end of their formation zone inside the target, otherwise they leave the nucleus without interaction.

There are two important parameters in DPMJet:

- *Formation time* τ_0 controls the development of the intranuclear cascade. With increasing τ_0 the number of cascade generations and the number of low-energy particles will be reduced. Its default value is $\tau_0 = 2.0$.
- *Correction factor* α^F_{mod}. Inside DPMJet the momenta of the spectator nucleons are sampled from the zero temperature Fermi-distribution. However, the nuclear surface effects and the interaction between nucleons result in the reduction of the Fermi momentum. Its default value is $\alpha^F_{mod} = 0.6$.

At the end of intranuclear cascade the residual nucleus is supposed to go through some de-excitation mechanisms. As a result, it can disassembled into two or more fragments, emit photons, nucleons or light particles (like d, α, $^3\mathrm{H}$, $^3\mathrm{He}$).

As a cross-check we compare our MC simulation for QEL process with predictions of NUANCE event generator. [12] The program uses a model of the final state interaction in the nucleus originally developed for the IMB experiment. Hadrons are tracked through the nucleus in 0.2 fm steps, treating the nucleus as an isoscalar sphere of nuclear matter with radially-dependent density and Fermi momentum.

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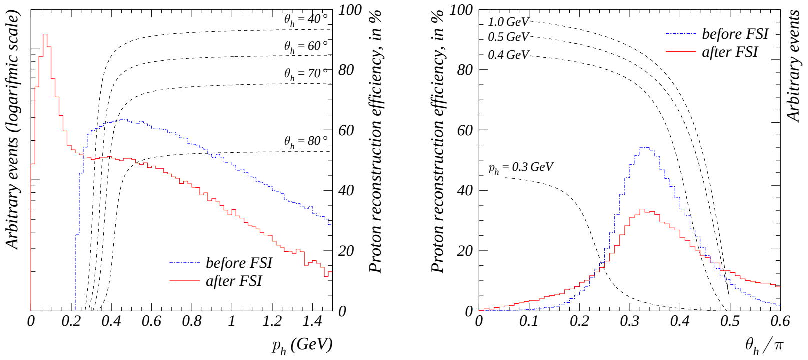
[11] *J. Ranft,"DPMJET version II.5: Sampling of hadron hadron, hadron nucleus and nucleus nucleus interactions at accelerator and cosmic ray energies according to the two-component dual parton model: Code manual," arXiv:hep-ph/9911232.*

[12] *D. Casper, "The nuance neutrino physics simulation, and the future," Nucl. Phys. Proc. Suppl.* **112**, *161 (2002) [arXiv:hep-ph/0208030].*

Intranuclear cascade and proton track reconstruction probability



Distribution of leading proton momentum p_h and emission angle θ_h before (dash-dotted line) and after (solid line) intra-nuclear cascade. Dashed lines show the reconstruction probability of proton track.

QEL cross section measurement: normalization to DIS

$$\langle \sigma_{qel} \rangle = \langle \sigma_0 \rangle \frac{N_{qel}}{N_0} \quad \Rightarrow \quad \langle \sigma_{qel} \rangle = \frac{1}{\varepsilon_{qel}} \left[\langle \sigma_0 \rangle \frac{N_{dat}}{N_0} - \langle \sigma_{dis} \rangle \, \varepsilon_{dis} - \langle \sigma_{res} \rangle \, \varepsilon_{res} \right]$$

Selection of *DIS* events:

- the primary vertex should be in the chosen fiducial volume
- at least two charged tracks at the primary vertex, one of them should be identified as a muon
- (1) the total visible energy in the event $1 \leqslant E_\nu \leqslant 300$ GeV and the reconstructed hardonic mass squared $W \geqslant 1.4$ GeV [a]
- (2) the total visible energy in the event $40 \leqslant E_\nu \leqslant 200$ GeV and the reconstructed hardonic mass squared $W \geqslant 1.4$ GeV [a]
- (3) the total visible energy in the event $40 \leqslant E_\nu \leqslant 200$ GeV [b]

Mode	ν_μ CC		$\bar{\nu}_\mu$ CC	
	$\langle \sigma_0 \rangle$	N_0	$\langle \sigma_0 \rangle$	N_0
(1)	15.954	968340	4.834	24497
(2)	6.154	370842	2.114	10100
(3)	6.317	380045	2.304	10893

12a *A. Bodek and U. K. Yang, "Modeling deep inelastic cross sections in the few GeV region," Nucl. Phys. B (Proc. Suppl.)* **112** *(2002) 70–76 [arXiv:hep-ex/0203009]; A. Bodek and U. K. Yang, "Higher twist, ξ_W scaling, and effective LO PDFs for lepton scattering in the few GeV region," J. Phys. G* **29** *(2003) 1899–1906 [arXiv:hep-ex/0210024].*

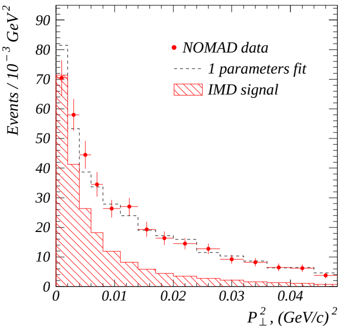
12b *S. Eidelman* et al. *(Particle Data Group), Phys. Lett. B* **592** *(2004) 1–1109*

QEL cross section measurement: normalization to IMD

Inverse muon decay (IMD) $\nu_\mu e^- \to \mu^- \nu_e$ is a purely leptonic process, which is well known both on theoretical and experimental grounds. Its cross-section in the Born approximation is:

$$\sigma_{imd}(E_\nu) = \sigma_{as} E_\nu \left(1 - \frac{m_\mu^2}{2m_e E_\nu}\right)^2, \quad \text{where} \quad \sigma_{as} = \frac{2m_e G_F^2}{\pi} = 1.723 \times 10^{-41}\ \text{cm}^2/\text{GeV}$$

$\langle\sigma_{imd}\rangle = 1.017 \times 10^{-40}\ \text{cm}^2$ and measured number of events $N_0 = 496.6 \pm 32.5$

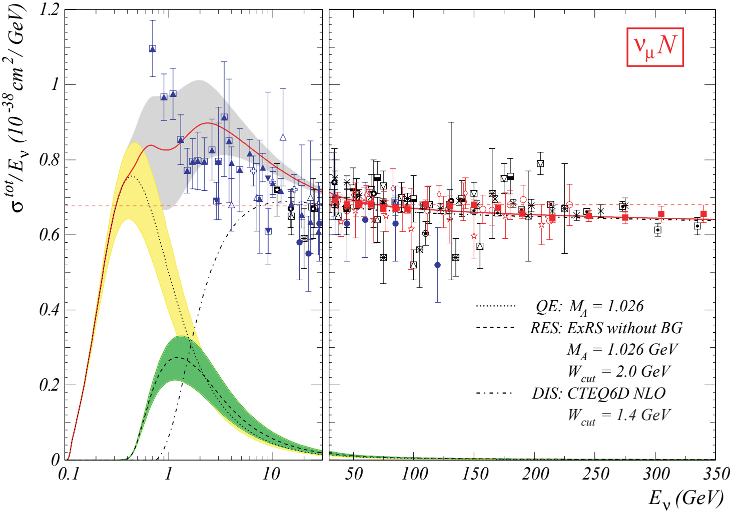


- there is only one negatively charged track in the events; it should be identified as a muon
- there are no veto chamber hits in the vicinity of the intersection point of the extrapolated muon track and the first drift chamber (quality cut, the same as for 1-track events from the QEL sample)
- the muon energy is above the threshold:

$$E_\mu \geqslant \frac{m_\mu^2 + m_e^2}{2m_e} = 10.93\ \text{GeV}$$

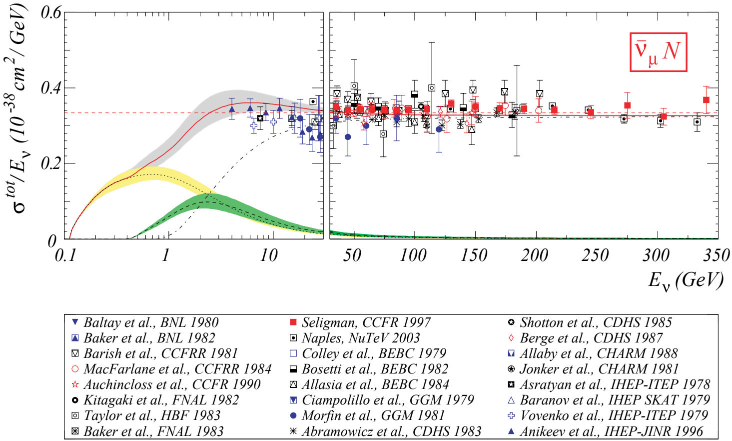
- the transverse momentum $p_\perp$ of the muon produced in IMD event is very limited by kinematics: $p_\perp^2 \leqslant 2m_e E_\mu$

The total ν_μ CC cross section: mixture of QEL, RES and DIS contributions



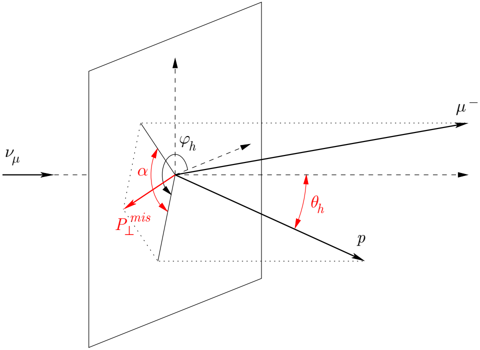
σ^{tot}/E_ν, for the muon neutrino charged-current total cross section as function of neutrino energy. The straight line is the average value $(0.677 \pm 0.014) \times 10^{-38}$ cm^2/GeV.

The total $\bar{\nu}_\mu$ CC cross section: mixture of QEL, RES and DIS contributions



σ^{tot}/E_ν, for the muon antineutrino charged-current total cross section as function of neutrino energy. The straight line is the average value $(0.334 \pm 0.008) \times 10^{-38}$ cm^2/GeV.

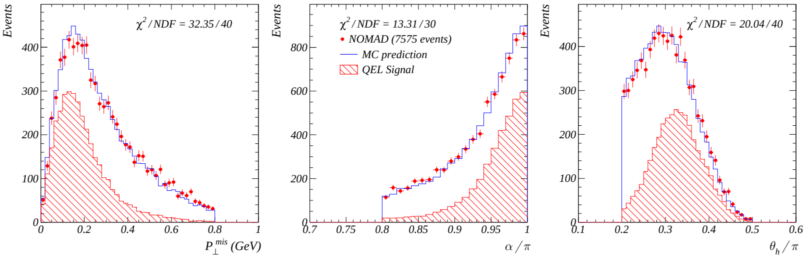
Signal identification procedure: $\nu_\mu n \to \mu^- p$ *QEL scattering*



- $E_\mu = \left(P_\mu^2 + m_\mu^2\right)^{1/2}, P_\mu = |\vec{k}\,'|$
- $E_\nu = P_\mu \cos\theta_\mu + P_h \cos\theta_h$
- $Q^2 = 2E_\nu(E_\mu - P_\mu \cos\theta_\mu) - m_\ell^2$

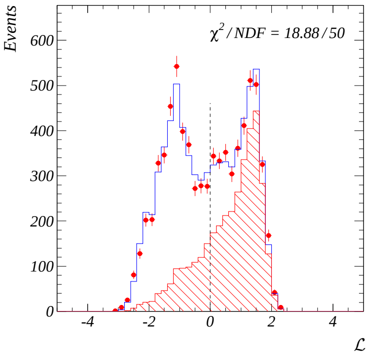
- proton identification: momentum – range relations,
- angle α between the transverse components of the charged primary tracks: $0.8 \leqslant \alpha/\pi \leqslant 1$,
- missing transverse momentum $P_\perp^{mis} \leqslant 0.8$ GeV,
- angle θ_h between the proton momentum and the z axis: $0.2 \leqslant \theta_h/\pi \leqslant 0.5$,
- Likelihood ratio $\mathcal{L}(\alpha, P_\perp^{mis}, \theta_{pr}) \geqslant 0$.

Likelihood variables in simulated events and experimental data



Missing transverse momentum $P_\perp^{mis}$, angle α between the transverse components of the charged primary tracks and angle θ_h between the proton momentum and z axis. Comparison of expected and experimental data distributions.

Likelihood ratio



The set of variables $\vec{\ell} = \{P_\perp^{mis}, \theta_h, \alpha\}$ can be associated with some likelihood ratio:

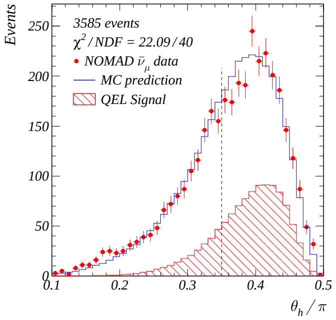
$$\mathcal{L} = \ln \frac{P(\vec{\ell}\,|QEL)}{P(\vec{\ell}\,|RES)}$$

where $P(\vec{\ell}\,|QEL)$ and $P(\vec{\ell}\,|RES)$ are the probabilites for the signal and background events to have kinematic variables $\vec{\ell}$.

Signal identification procedure: $\bar{\nu}_\mu p \to \mu^+ n$ QEL scattering

- reconstructed primary vertex in fiducial volume: $|X, Y| \leqslant 100$ cm, $5 \leqslant Z \leqslant 395$ cm
- only one charged track, originated from primary vertex, should be identified as the muon (here we do not take into account neutral tracks and charged tracks, which does not pass quality cuts: $P > 0.3$ GeV and $N_{hits} > 7$)
- reconstructed kinematical variables:

$$Q^2 = 2M(E_\nu - E_\mu) \quad \Rightarrow \quad E_\nu = \frac{ME_\mu - m_\mu^2/2}{M - E_\mu + P_\mu \cos\theta_\mu} = P_\mu \cos\theta_\mu + P_{pr} \cos\theta_{pr}$$



- reconstructed neutrino energy: $3 \leqslant E_\nu \leqslant 100$ GeV,
- muon emission angle θ_μ: $\theta_\mu/\pi \leqslant 0.1$
- fake angle θ_h between the proton momentum and the z axis: $0.2 \leqslant \theta_h/\pi \leqslant 0.5$

Systematic uncertainties in QEL cross section

- ✓ (1) QEL Identification procedure. The corresponding errors can be estimated by varying the selection criteria with in reasonable limits (likelihood $\mathcal{L} = -2 \div 1.2$ and $\theta_{pr}/\pi = 0.3 \div 0.4$)
- ✓ (2) Uncertainty in the DIS cross-section, used both for normalization and DIS background subtraction. Experimental errors are 2.0% for ν_μ and 2.5% for $\bar{\nu}_\mu$.
- ✓ (3) Uncertainty of the single pion production cross-section. We assume 10% error in $\langle\sigma_{res}\rangle$.
- ✓ (4) Nuclear reinteractions (Intranuclear cascade).
- ✓ (5) Shape of neutrino spectrum.
- ✓ (6) Neutral Current contribution.
- ✓ (7) Muon misidentification.
- ✓ (8) Coherent Diffractive Pion Production ($\nu_\mu + Z \to \mu^- + Z + \pi^+$)

Source	$\langle\sigma_{qel}\rangle_{\nu_\mu}$	M_A from $\langle\sigma_{qel}\rangle_{\nu_\mu}$	M_A from $d\sigma_\nu/dQ^2$	$\langle\sigma_{qel}\rangle_{\bar{\nu}_\mu}$	M_A from $\langle\sigma_{qel}\rangle_{\bar{\nu}_\mu}$
1	3.2	2.9	2.4	4.3	4.2
2	2.9	2.6	0.2	4.2	4.2
3	4.0	3.6	0.6	7.6	7.4
4	1.7	1.6	6.5	–	–
5	0.2	0.2	0.1	0.9	0.9
6	< 0.1	< 0.1	–	1.1	1.1
7	< 0.1	< 0.1	–	1.0	1.0
8	0.8	0.7	< 0.1	1.1	1.1
total	6.1	5.5	7.0	9.9	9.5

QEL cross section measurements in NOMAD

- *NEUTRINO QEL scattering*
  - ✓ We analyse 751.000 ν_μ CC events and identify 14021 *QEL* candidates with about 49.7% background contamination from the *DIS* (29.8%) and *RES* (19.9%) events. Total efficiency of *QEL* selection is about 34.6%.
  - ✓ The measured $\nu_\mu n \to \mu^- p$ cross section and corresponding axial mass value:

$$\sigma_{qel}^{\nu} = [0.92 \pm 0.02(stat) \pm 0.06(syst)] \cdot 10^{-38}\ \text{cm}^2$$

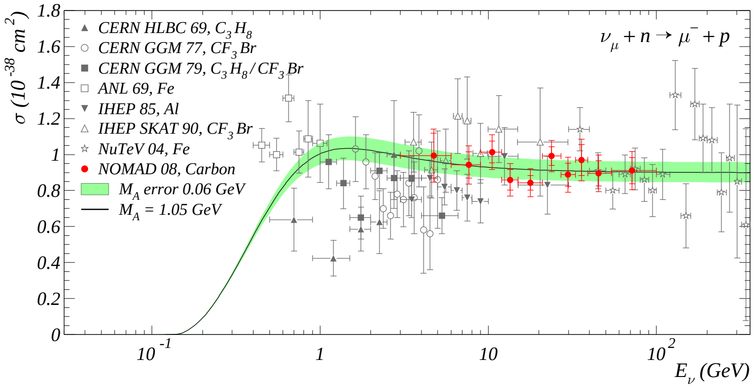
$$M_A = [1.05 \pm 0.02(stat) \pm 0.06(syst)]\ \text{GeV}$$

- *ANTINEUTRINO QEL scattering*
  - ✓ We analyse 23.000 $\bar{\nu}_\mu$ CC events and identify 2237 *QEL* candidates with about 62.0% background contamination from the *DIS* (33.5%) and *RES* (28.5%) events. Total efficiency of *QEL* selection is about 64.4%.
  - ✓ The measured $\bar{\nu}_\mu p \to \mu^+ n$ cross section and corresponding axial mass value:

$$\sigma_{qel}^{\bar{\nu}} = [0.81 \pm 0.05(stat) \pm 0.08(syst)] \cdot 10^{-38}\ \text{cm}^2$$

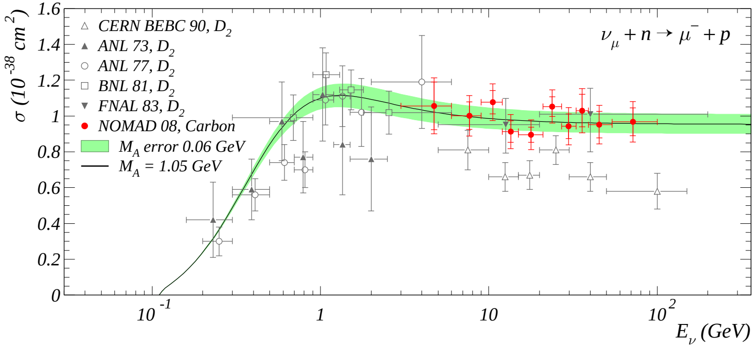
$$M_A = [1.06 \pm 0.07(stat) \pm 0.10(syst)]\ \text{GeV}$$

NOMAD results in comparison with previous experimental data



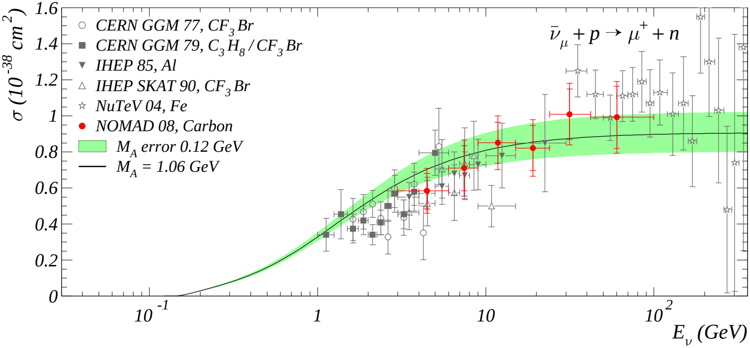
Comparison with previous experimental data extracted from the data on ν_μ scattering off heavy nuclei. The solid line and error band corresponds to the M_A value obtained in the NOMAD experiment. *Nuclear effects are included into calculations according to the standard relativistic Fermi gas model.* The theoretical band corresponds to both statistical and systematical uncertainties.

NOMAD results in comparison with previous experimental data



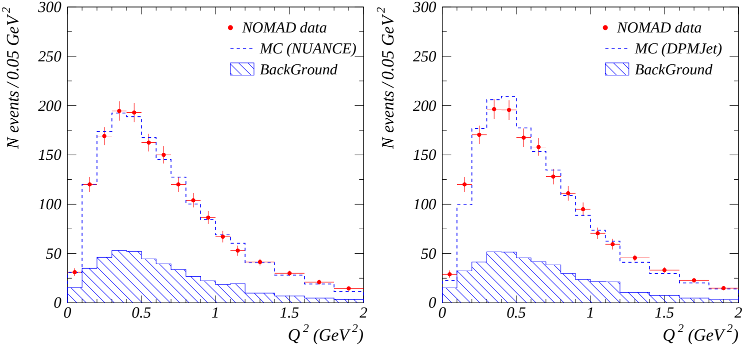
Comparison with previous experimental data from deuterium filled bubble chambers. The solid line and error band corresponds to the M_A value obtained in the NOMAD experiment. *All experimental data are corrected to nuclear effects.*

NOMAD results in comparison with previous experimental data



The total cross-section of $\bar{\nu}_\mu p \to \mu^+ n$ process extracted from the data on $\bar{\nu}_\mu$ scattering off heavy nuclei. *Nuclear effects are included into calculations according to the standard relativistic Fermi gas model.* Solid line and error band corresponds to the M_A value obtained in the NOMAD experiment.

Axial mass M_A measurement from the Q^2 distribution



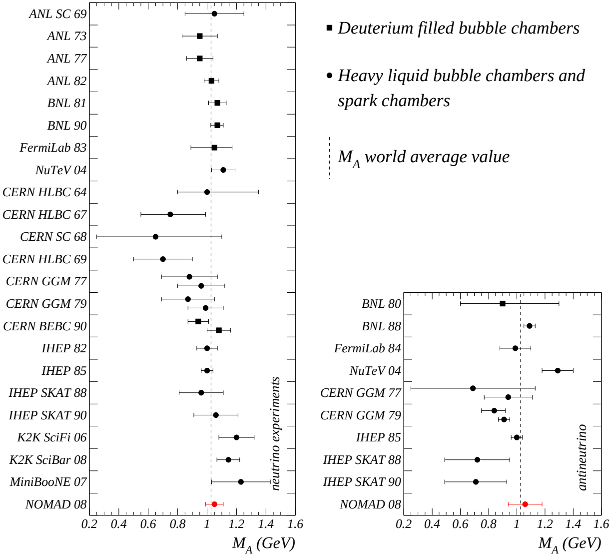
Q^2 distribution in identified QEL events in MC and experimental data: comparison between DPMJet and NUANCE generators.

$$M_A = 1.07 \pm 0.05 \text{ GeV}$$

Conclusion

- ✓ We performed the most up to date accurate measurement of the $\nu_\mu n \to \mu^- p$ cross-section on bound nucleon. Cross section, measured for the combined 1-track and 2-track samples, has the best statistical precision with comparable systematic uncertainties, since in this case obtained results are almost insensitive to the FSI effects.
- ✓ The axial mass parameter M_A was extracted from the measured quasi-elastic neutrino cross-section. The corresponding result is $M_A = 1.05 \pm 0.02(stat) \pm 0.06(syst)$ GeV. It is consistent with the axial mass values recalculated from the antineutrino cross-section and extracted from the pure Q^2 shape analysis of the high purity sample of ν_μ quasi-elastic 2-track events.
- ✓ Obtained results are found to be in good agreement with ones obtained in the previous bubble chamber experiments, but they do not M_A measurements published recently by the K2K and MiniBooNE collaborations, which reported somewhat larger values, which are however compatible with our results within their large errors.

Axial mass: NOMAD and previous neutrino experiments



BACKUP SLIDES