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

NOMAD

ν_μ ν_τ

Neutrino Oscillation MAgnetic Detector

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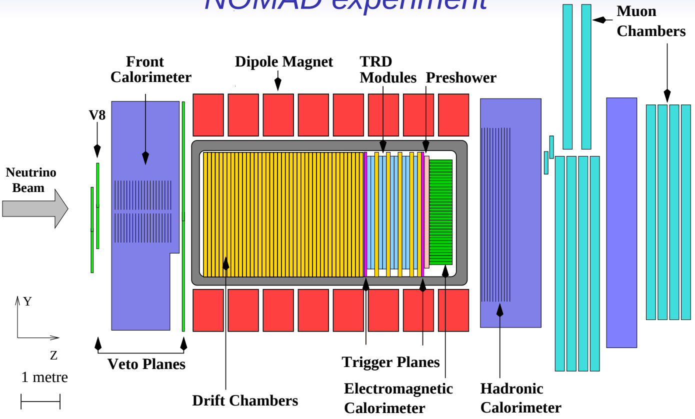
Outline

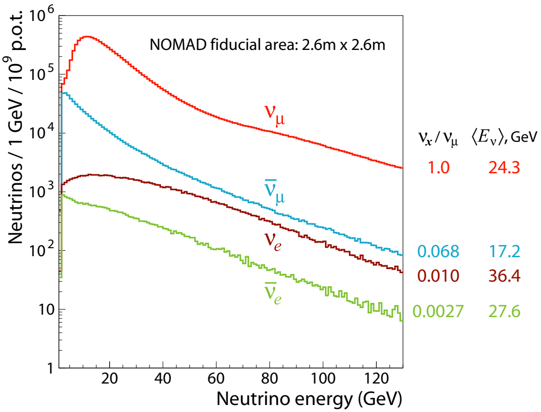
- Description of the NOMAD detector
- MC simulation and nuclear reinteraction (FSI) effects
- Selection of quasi-elastic events in NOMAD:
  topology and kinematic criteria
- The QEL cross section the axial mass M_A measurement
- Our *results* and *conclusions*

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 $\dfrac{\sigma(E)}{E} = (1.04 \pm 0.01)\% + \dfrac{(3.22 \pm 0.07)\%}{\sqrt{E\ (\text{GeV})}}$
- Muon Chambers for $\mu^{\pm}$ identification: efficiency $\approx 97\%$ ($p_{\mu} > 5$ GeV/c)
- Hadronic Calorimeter for n and K_L^0 veto

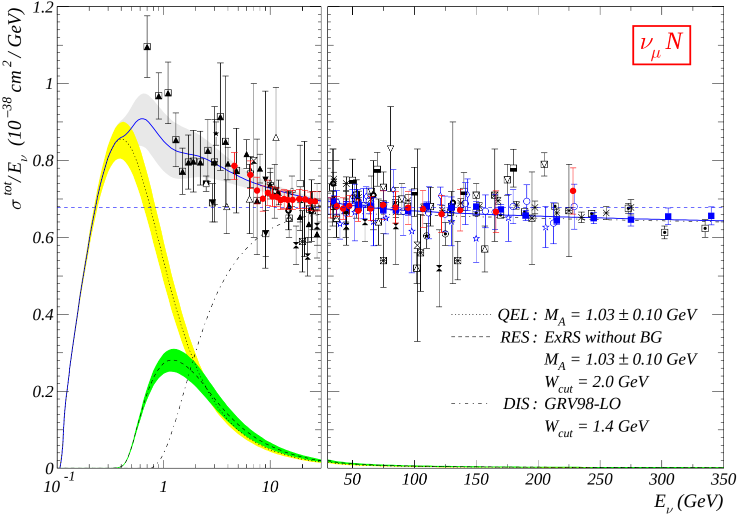
Neutrino fluxes at NOMAD experiment



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

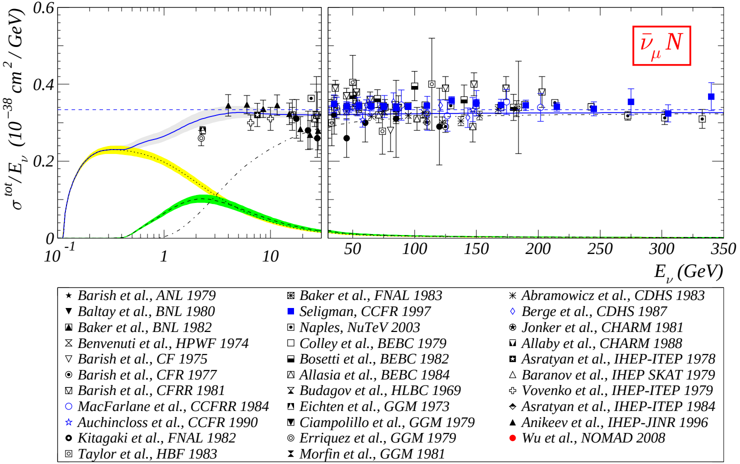
Mode	Neutrino	Antineutrino
QEL	0.430	0.393
RES	0.575	0.430
DIS	15.954	4.834

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.

Monte Carlo simulation

✓ Quasi-elastic neutrino scattering

- based on the Smith-Moniz approach
- the vector form-factors F_V and F_M are supposed to be well known (the GKex(05) parametrization)
- the axial form-factor has the dipole form $F_A(Q^2) = F_A(0)[1 + Q^2/M_A^2]^{-2}$

✓ Single pion production via intermediate resonance state

- based on Rein–Sehgal model
- 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

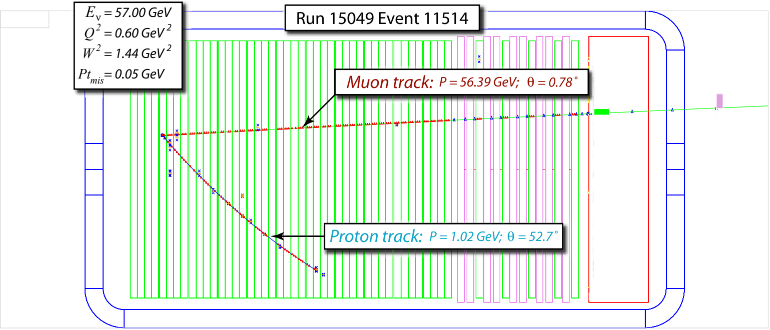
- modelled with the help of modified LEPTO 6.1 package
- production of all *zoo* of hadrons is simulated with help of JETSET 7.4
- structure functions are calculated for LO GRV 98 pdf according A. Bodek prescriptions

✓ Coherent pion production

✓ Final State Interactions: Intra-nuclear cascade

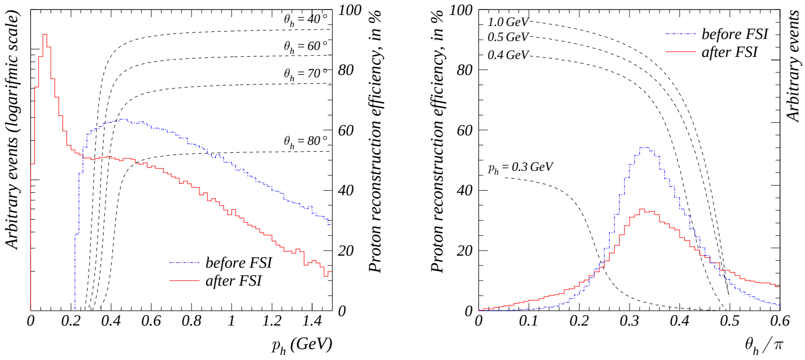
- modelled with the help of DPMJET package, based on the Formation Zone Intranuclear Cascade model
- using the NUANCE event generator for a cross-check

View of tipical QEL candidate event in NOMAD detector



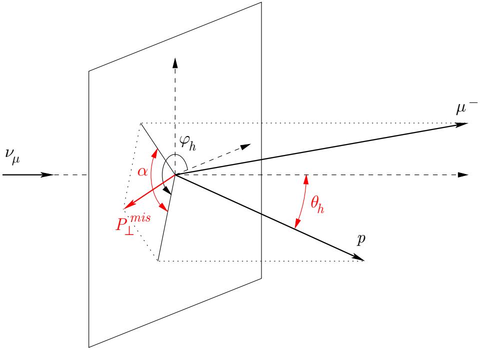
Typical examples of data events identified as $\nu_\mu n \to \mu^- p$ (run 15049 event 11514). Long track is identified as negatively charged muon, short track is associated with proton.

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.

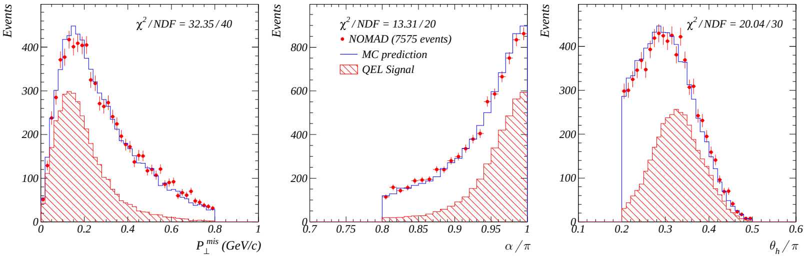
Signal identification procedure: $\nu_\mu n \to \mu^- p$ QEL scattering



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

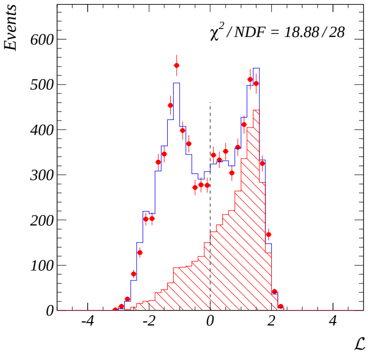
- proton identification: momentum – range relations,
- angle α between the transverse components of the charged primary tracks: $0.8 \leqslant \alpha/\pi \leqslant 1$,
- missing transverse momentum $P_\perp^{mis} \leqslant 0.8$ GeV,
- angle θ_h between the proton momentum and the z axis: $0.2 \leqslant \theta_h/\pi \leqslant 0.5$,
- 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:

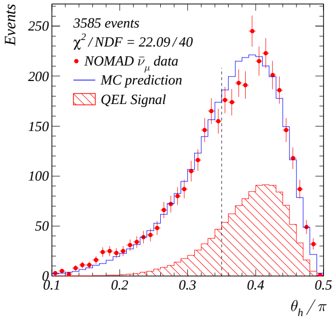
$$\mathcal{L} = \ln \frac{P(\vec{\ell}\,|QEL)}{P(\vec{\ell}\,|RES)}$$

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: $0.2 \leqslant \theta_h/\pi \leqslant 0.5$

QEL cross section measurement: normalization to DIS

$$\langle\sigma_{qel}\rangle = \langle\sigma_0\rangle \frac{N_{qel}}{N_0} \quad \Rightarrow \quad \langle\sigma_{qel}\rangle = \frac{1}{\varepsilon_{qel}} \left[N_{dat} \frac{\Phi_0 \langle\sigma_0\rangle}{N_0} - \langle\sigma_{dis}\rangle\, \varepsilon_{dis} - \langle\sigma_{res}\rangle\, \varepsilon_{res} \right]$$

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. Bodek et al., arXiv:hep-ex/0203009, hep-ex/0210024]
- (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. Bodek et al., arXiv:hep-ex/0203009, hep-ex/0210024]
- (3) the total visible energy in the event $40 \leqslant E_\nu \leqslant 200$ GeV [PDG value for σ_{tot} slope]

Mode			ν_μ CC			$\bar{\nu}_\mu$ CC
	$\Phi_0\langle\sigma_0\rangle$	N_0	$\Phi_0\langle\sigma_0\rangle/N_0$	$\Phi_0\langle\sigma_0\rangle$	N_0	$\Phi_0\langle\sigma_0\rangle/N_0$
(1)	16.643	792162	2.101	4.876	16807	29.012
(2)	6.462	303791	2.127	2.133	7129	29.924
(3)	6.634	310617	2.136	2.332	7553	30.872

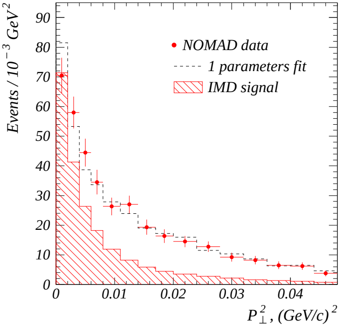
* the units used for $\Phi_0\langle\sigma_0\rangle$ are 10^{-38} cm^2 while for $\Phi_0\langle\sigma_0\rangle/N_0$ are 10^{-43} cm^2

QEL cross section measurement: normalization to IMD

Inverse muon decay (IMD) $\nu_\mu e^- \rightarrow \mu^- \nu_e$ 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:

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

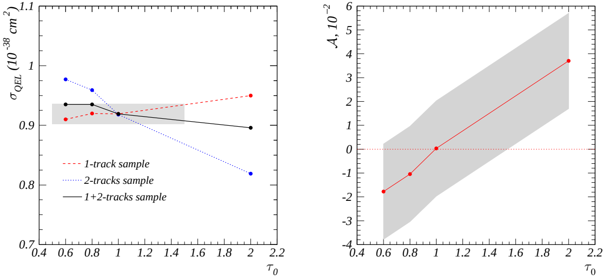
- the transverse momentum $p_\perp$ of the muon produced in IMD event is very limited by kinematics: $p_\perp^2 \leqslant 2m_e E_\mu$

Measured cross-section $\nu_\mu n \to \mu^- p$: dependence from FSI

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

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 $\alpha^F_{mod} = 0.6$.



$$\mathcal{A} = \frac{\sigma_1 - \sigma_2}{2(\sigma_1 + \sigma_2)}$$

where σ_1 and σ_2 - measured cross-section $\langle \sigma_{qel} \rangle$ for 1- and 2-track samples.

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	3.5	3.2	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	1.8	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	6.5	5.9	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:

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

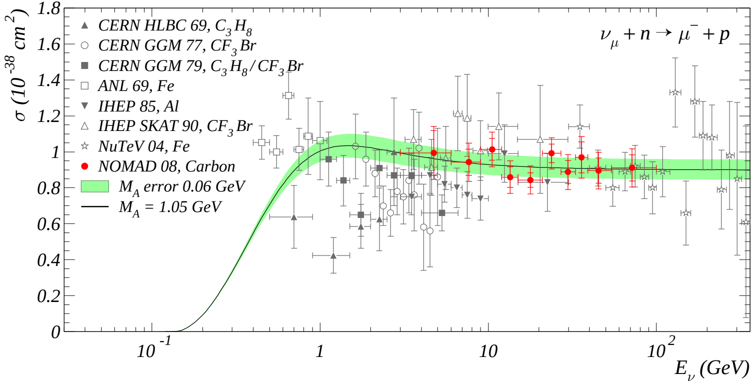
$$M_A = [1.05 \pm 0.02(stat) \pm 0.06(syst)]\ \text{GeV}$$

- *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:

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

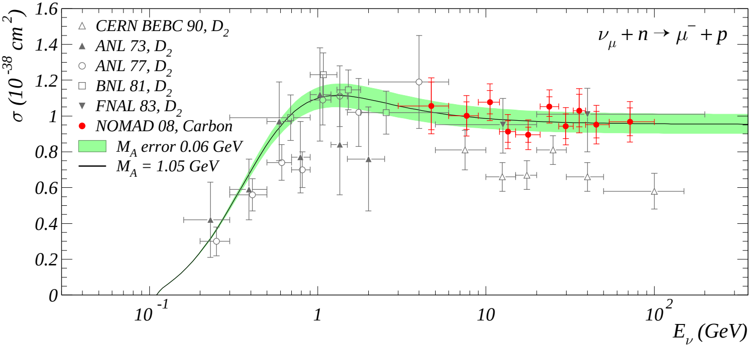
$$M_A = [1.06 \pm 0.07(stat) \pm 0.10(syst)]\ \text{GeV}$$

NOMAD results in comparison with previous experimental data



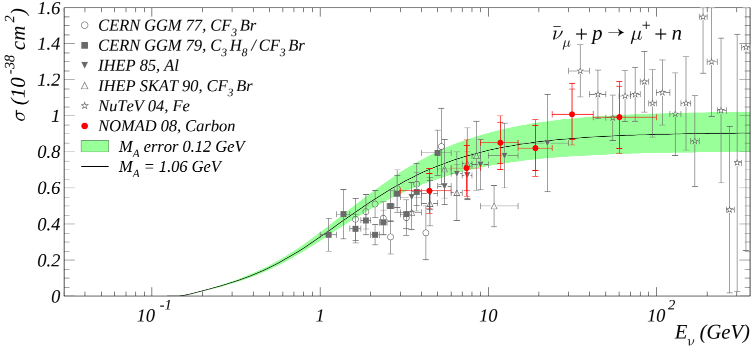
Comparison with previous experimental data extracted from the data on ν_μ scattering off heavy nuclei. The solid line and error band corresponds to the M_A value obtained in the NOMAD experiment. *Nuclear effects are included into calculations according to the standard relativistic Fermi gas model.*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

NOMAD results in comparison with previous experimental data



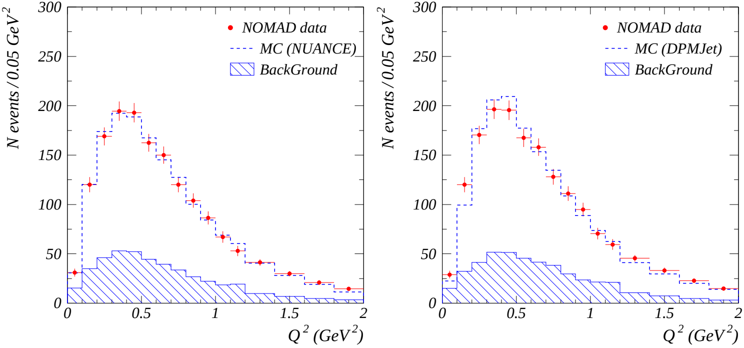
Comparison with previous experimental data from deuterium filled bubble chambers. The solid line and error band corresponds to the M_A value obtained in the NOMAD experiment. *All experimental data are corrected to nuclear effects.*

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.

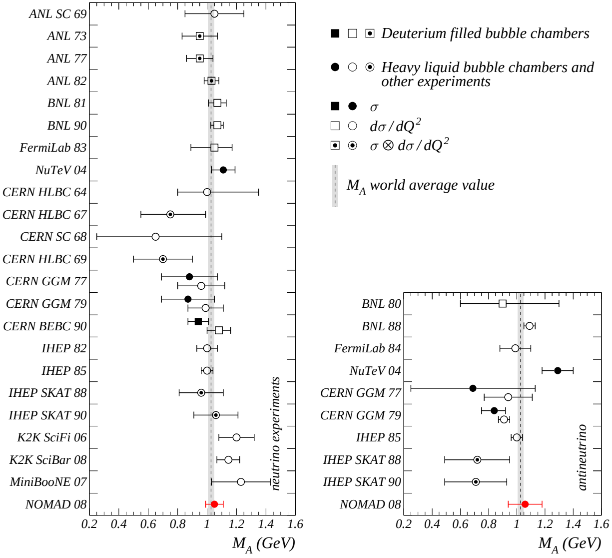
Axial mass M_A measurement from the Q^2 distribution



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

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

Axial mass: NOMAD and previous neutrino experiments



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.