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

Neutrino Oscillation MAgnetic Detector

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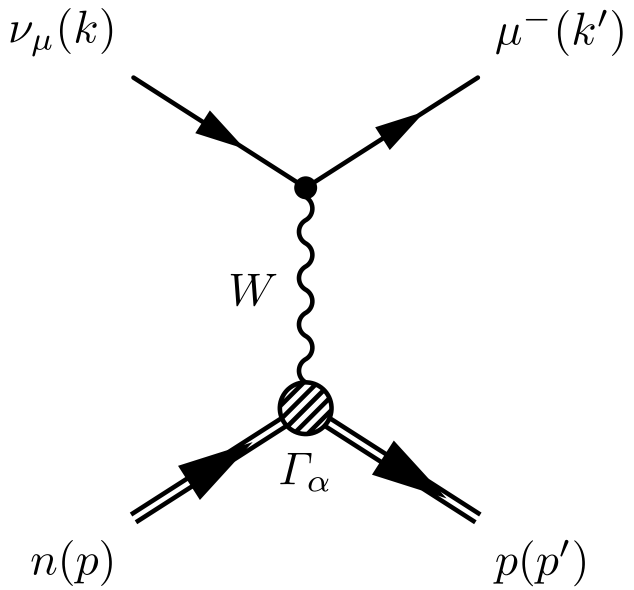


The most general form of the electroweak $N_{in} \to N_{out}$ transition current is given by [a]

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

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 $F_i\left(Q^2\right)$ in the vertex function Γ_α are in general complex.

The most general restrictions to the form factors:

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

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

Electromagnetic form factors

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

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

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

- Simple dipole parametrization:

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

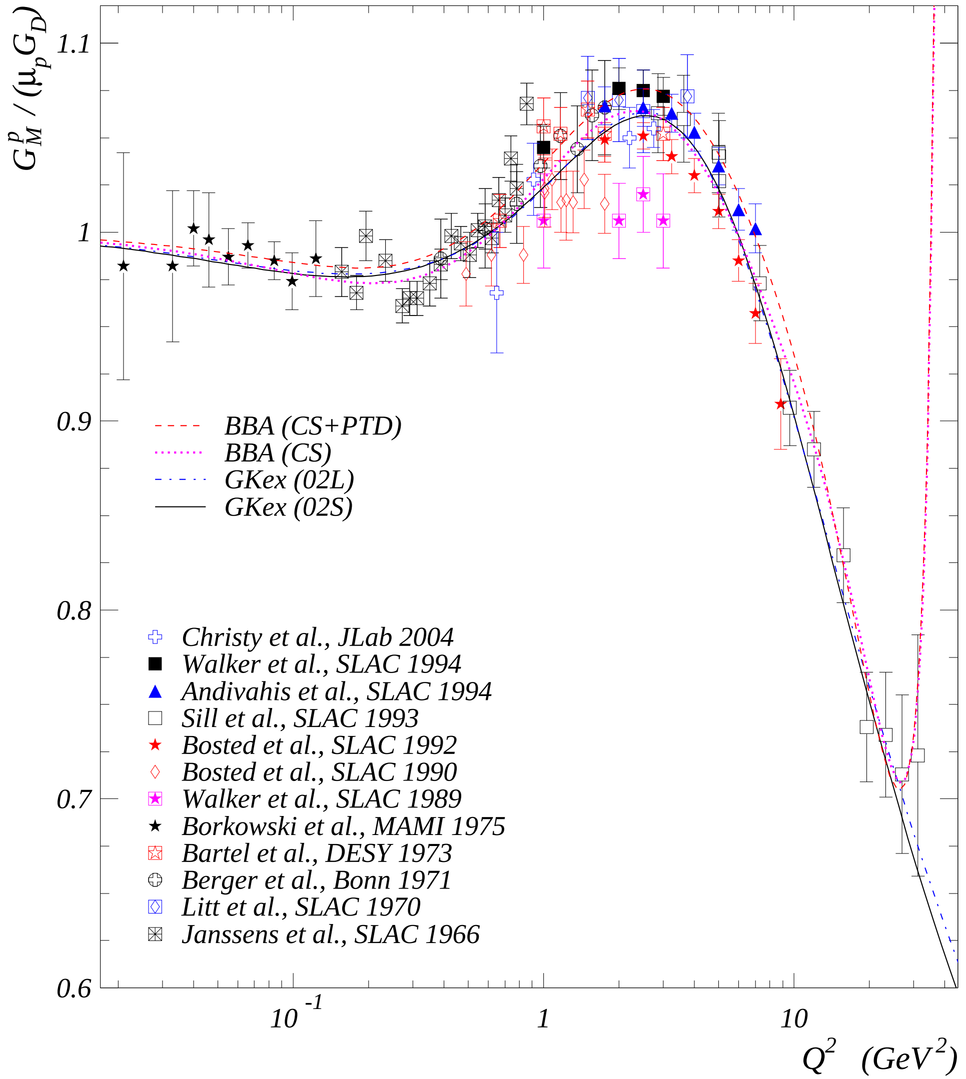
- Gari–Krüempelmann (GK) model[a] extended and fine-tuned by Lomon[b] to match current experimental data. Specifically, as the "reference model", we explore the so-called GKex(02S) which fits the modern and consistent older data well and meets the requirements of dispersion relations and of QCD at low and high 4-momentum transfer.
- Global fit by Budd *et al.*,[c] (BBA model) to the data from Rosenbluth analysis of elastic ep cross section measurements and those from the polarization transfer techniques.

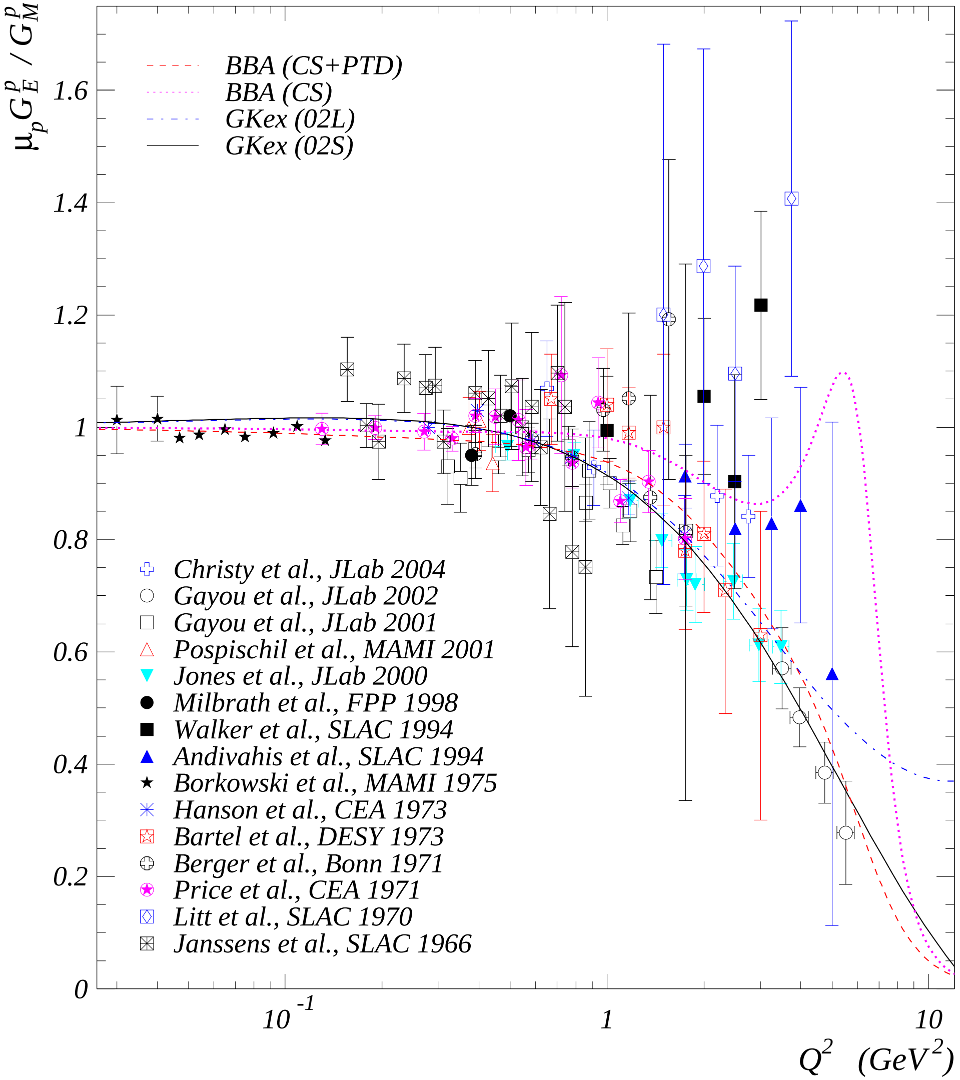
[a] M. F. Gari and W. Krüempelmann, "The electric neutron form factor and the strange quark content of the nucleon," Phys. Lett. B **274** (1992) 159-162; erratum – *ibid*. **282** (1992) 483-484.

[b] 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].

[c] 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.).

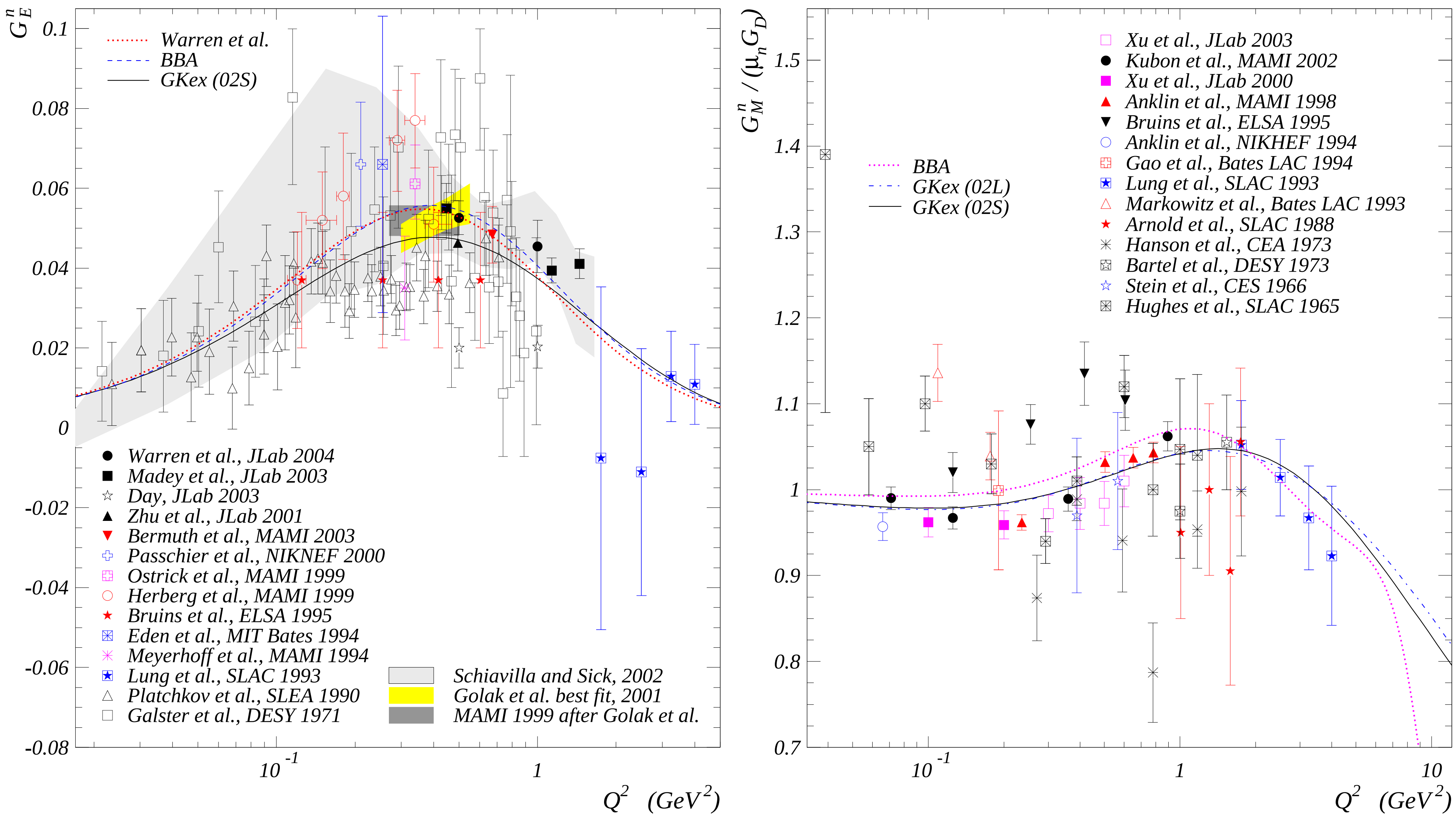
Proton electromagnetic form factors





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 are

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

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

The pseudoscalar contribution is important for τ production.[a] 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:

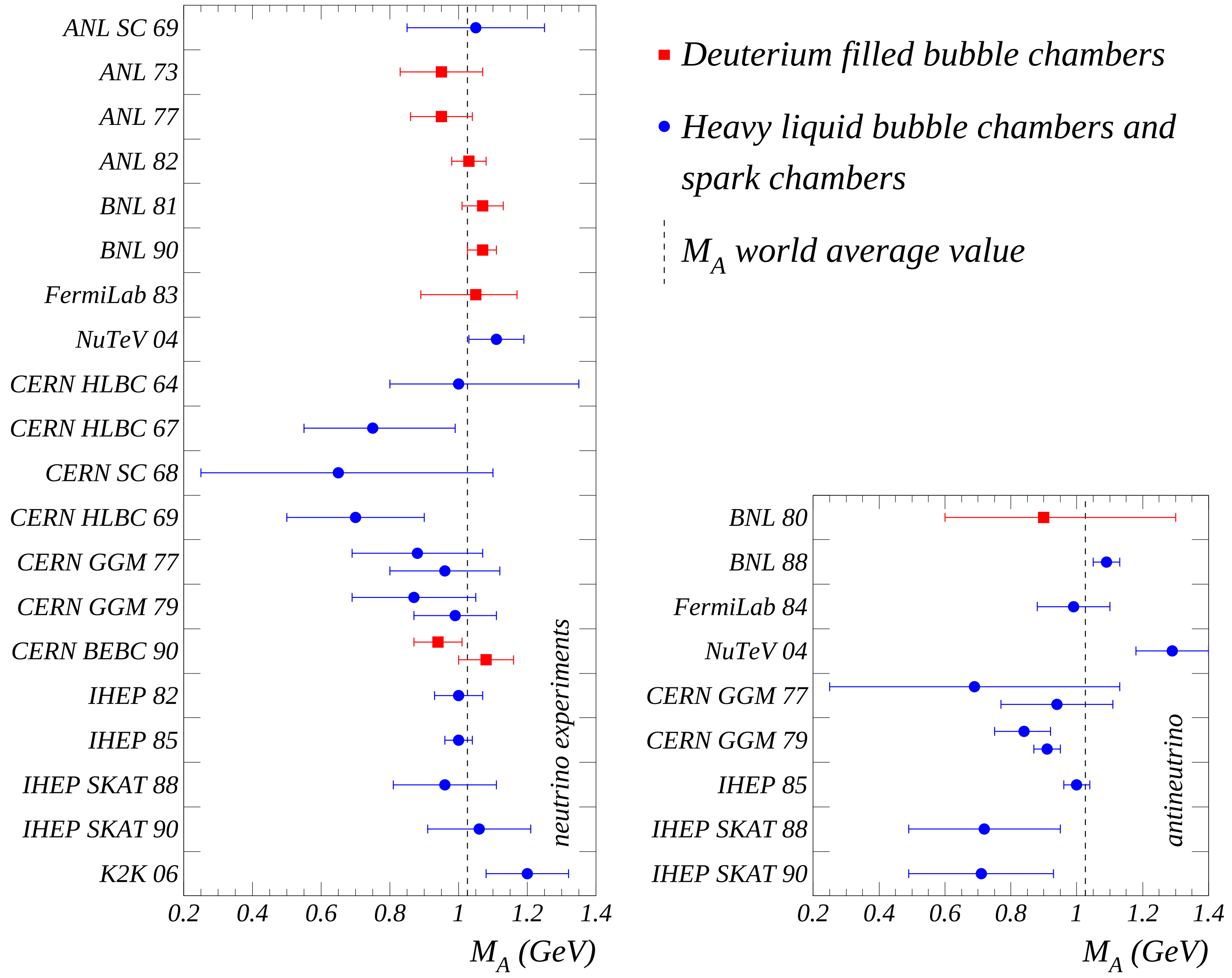
from roughly 0.7 to 1.2 GeV/c^2 for dipole F_A,

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

However the monopole parametrization seems to be obsolete.

[a] 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 form factor from neutrino scattering experiments



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

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

- *NEUTRINO QEL scattering*

  ✓ We analyse $9.17 \times 10^5\ \nu_\mu\ CC$ events and identify 11965 *QEL* candidates with about 41% background contamination from the *DIS* (20%) and *RES* (21%) events. Total efficiency of *QEL* selection is about 55%.

  ✓ The measured $\nu_\mu n \to \mu^- p$ cross section and corresponding axial mass value:

$$\sigma^{\nu}_{qel} = [0.93 \pm 0.02(stat) \pm 0.05(syst)] \cdot 10^{-38}\ \mathrm{cm}^2$$
$$M_A = [1.06 \pm 0.02(stat) \pm 0.06(syst)] \cdot \mathrm{GeV}$$

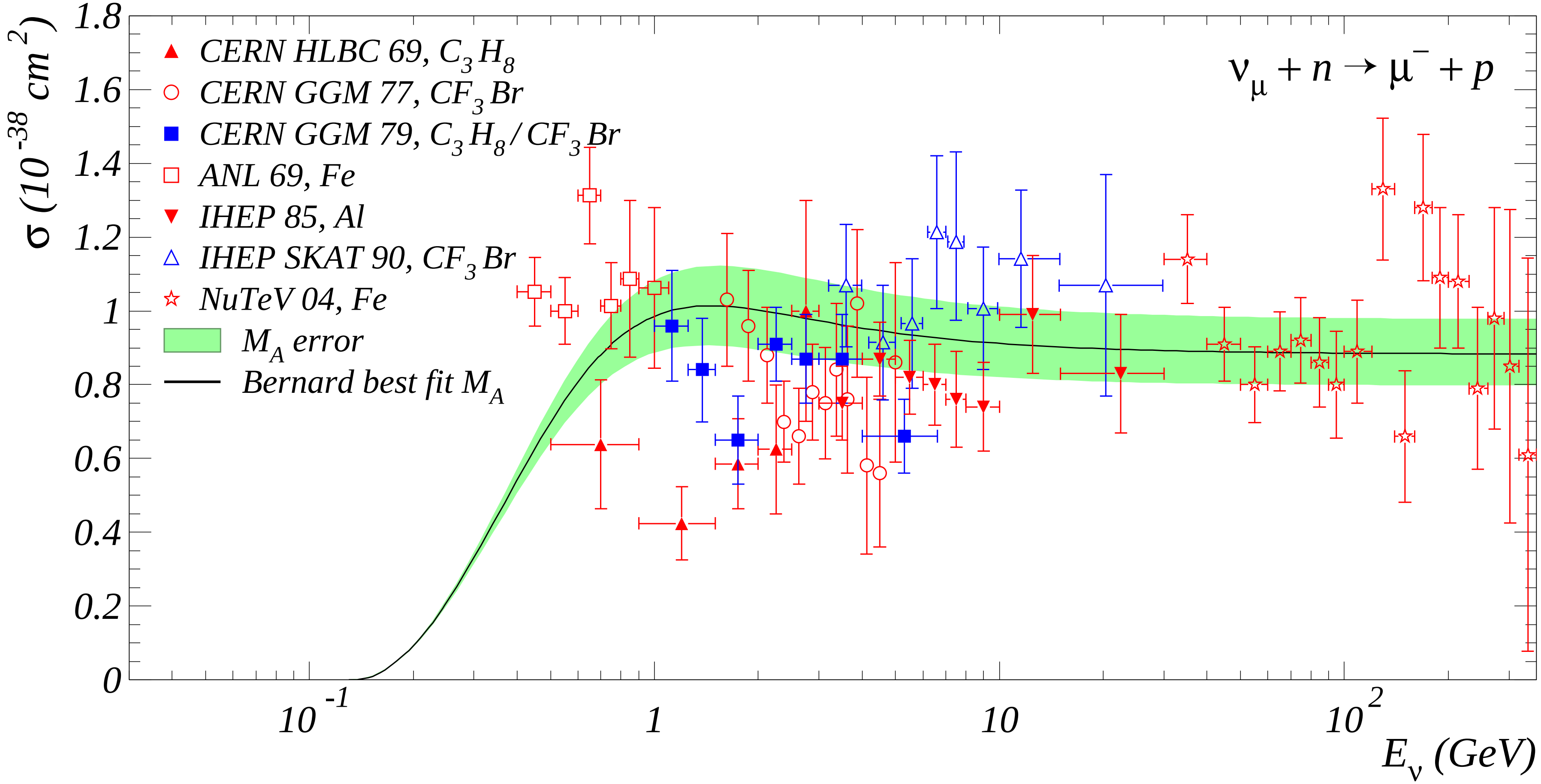
- *ANTINEUTRINO QEL scattering*

  ✓ We analyse $3.47 \times 10^4\ \bar{\nu}_\mu\ CC$ events and identify 1641 *QEL* candidates with about 60% background contamination from the *DIS* (24%) and *RES* (36%) events. Total efficiency of *QEL* selection is about 42%.

  ✓ The measured $\bar{\nu}_\mu p \to \mu^+ n$ cross section and corresponding axial mass value:

$$\sigma^{\bar{\nu}}_{qel} = [0.72 \pm 0.05(stat) \pm 0.08(syst)] \cdot 10^{-38}\ \mathrm{cm}^2$$
$$M_A = [0.98 \pm 0.08(stat) \pm 0.14(syst)] \cdot \mathrm{GeV}$$

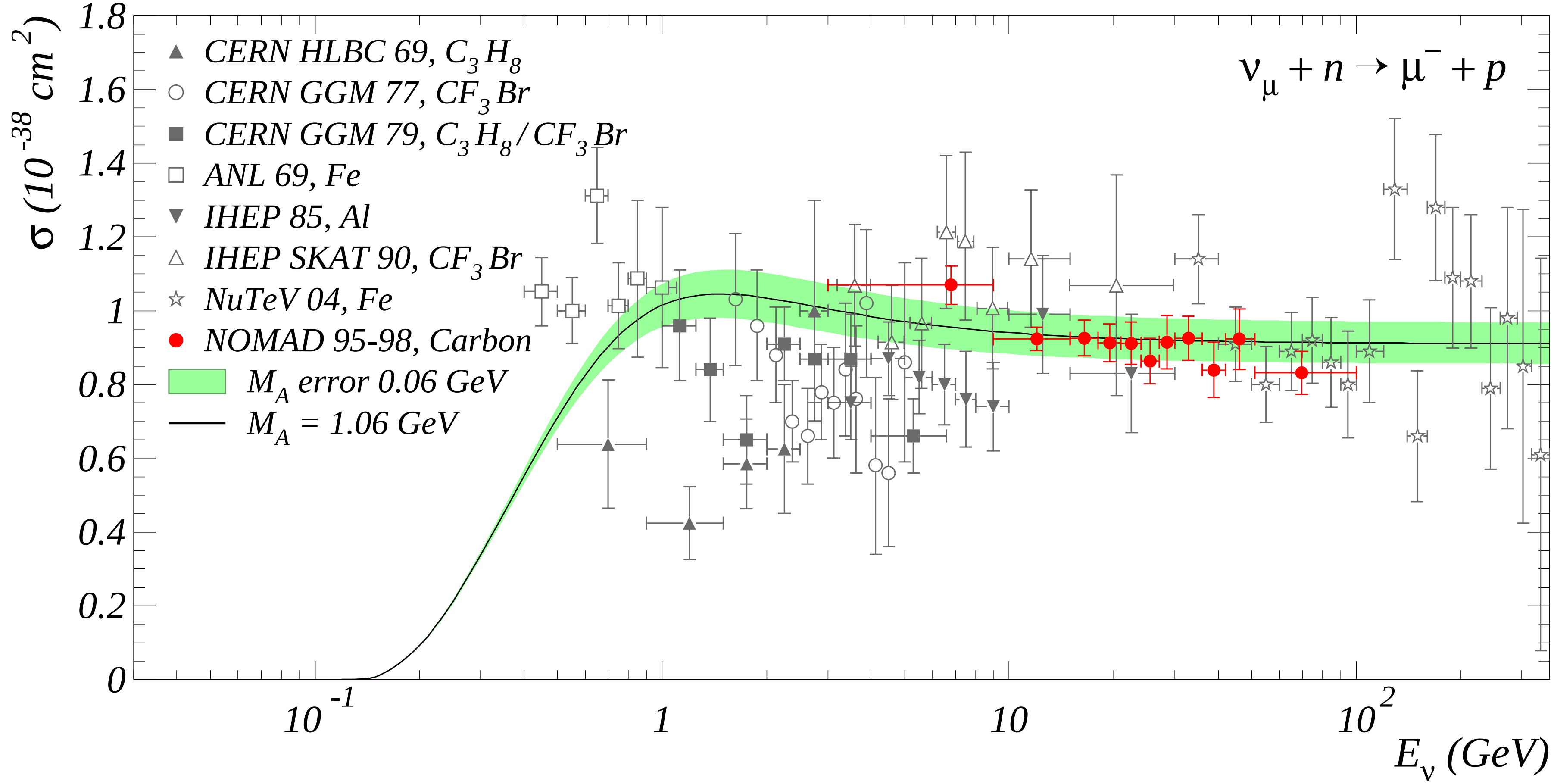
Total QE $\nu_\mu n$ cross section measured on heavy nuclei target



Total QE cross $\nu_\mu n$ cross section extracted from the data on ν_μ scattering off heavy nuclei. Nuclear effects are included into calculations according to the standard relativistic Fermi gas model.[a] The theoretical band corresponds to variations of $M_A = 1.03 \pm 0.10$ GeV.

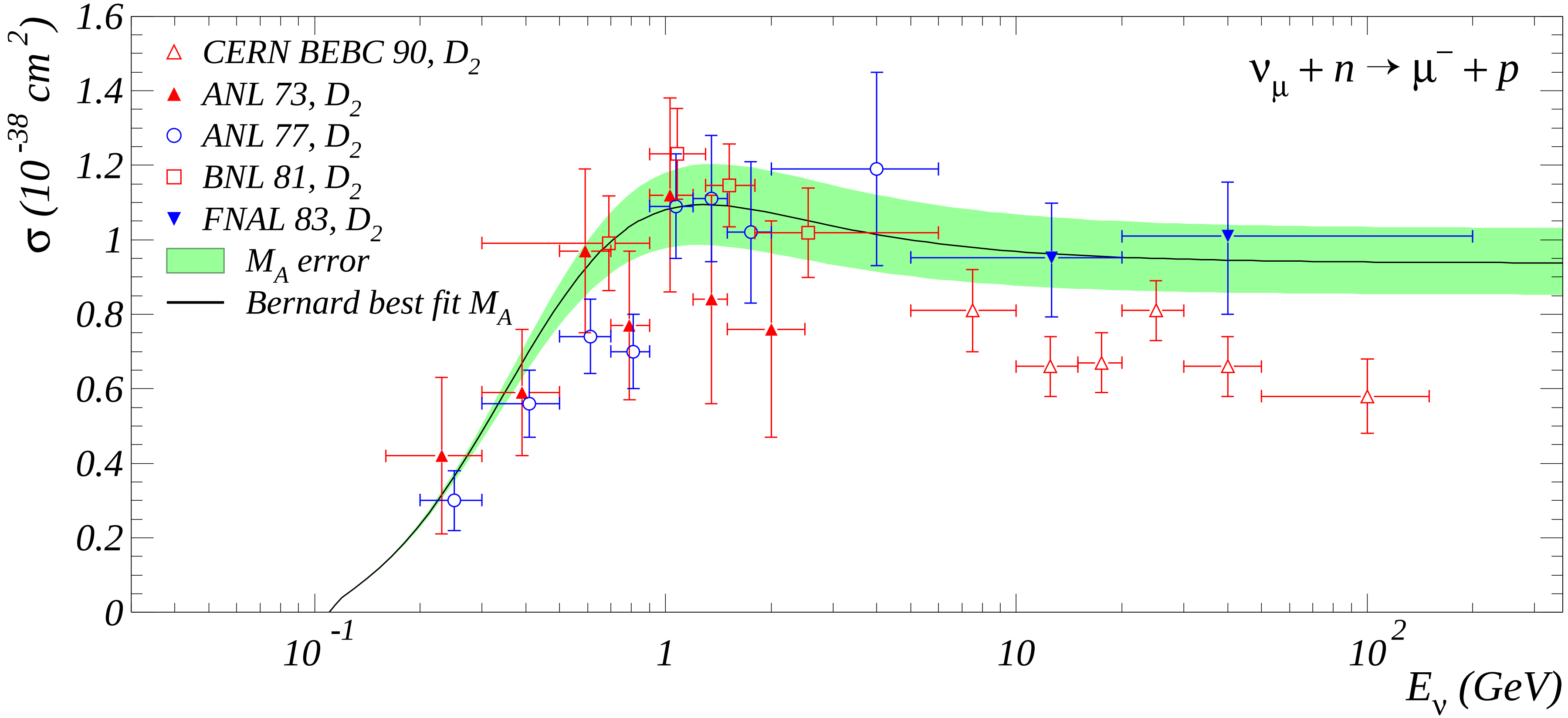
[a] R. A. Smith and E. J. Moniz, "Neutrino reactions on nuclear targets," Nucl. Phys. B **43** (1972) 605–622; erratum – *ibid*. **101** (1975) 547.

NOMAD results in comparison with previous experimental data



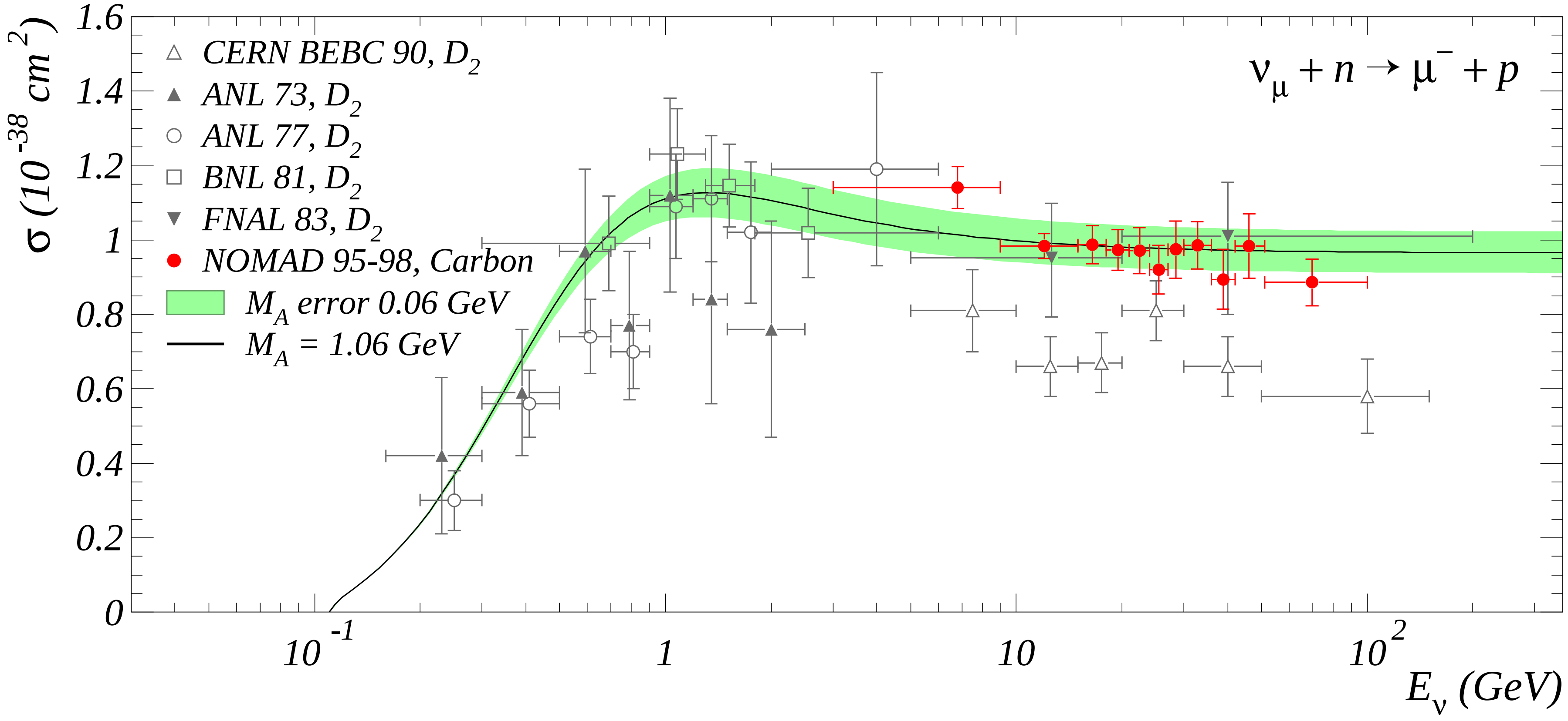
Comparison with previous experimental data extracted from the data on ν_μ scattering off heavy nuclei. The solid line and error band corresponds to the M_A value obtained in the NOMAD experiment. Nuclear effects are included into calculations according to the standard relativistic Fermi gas model. The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

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



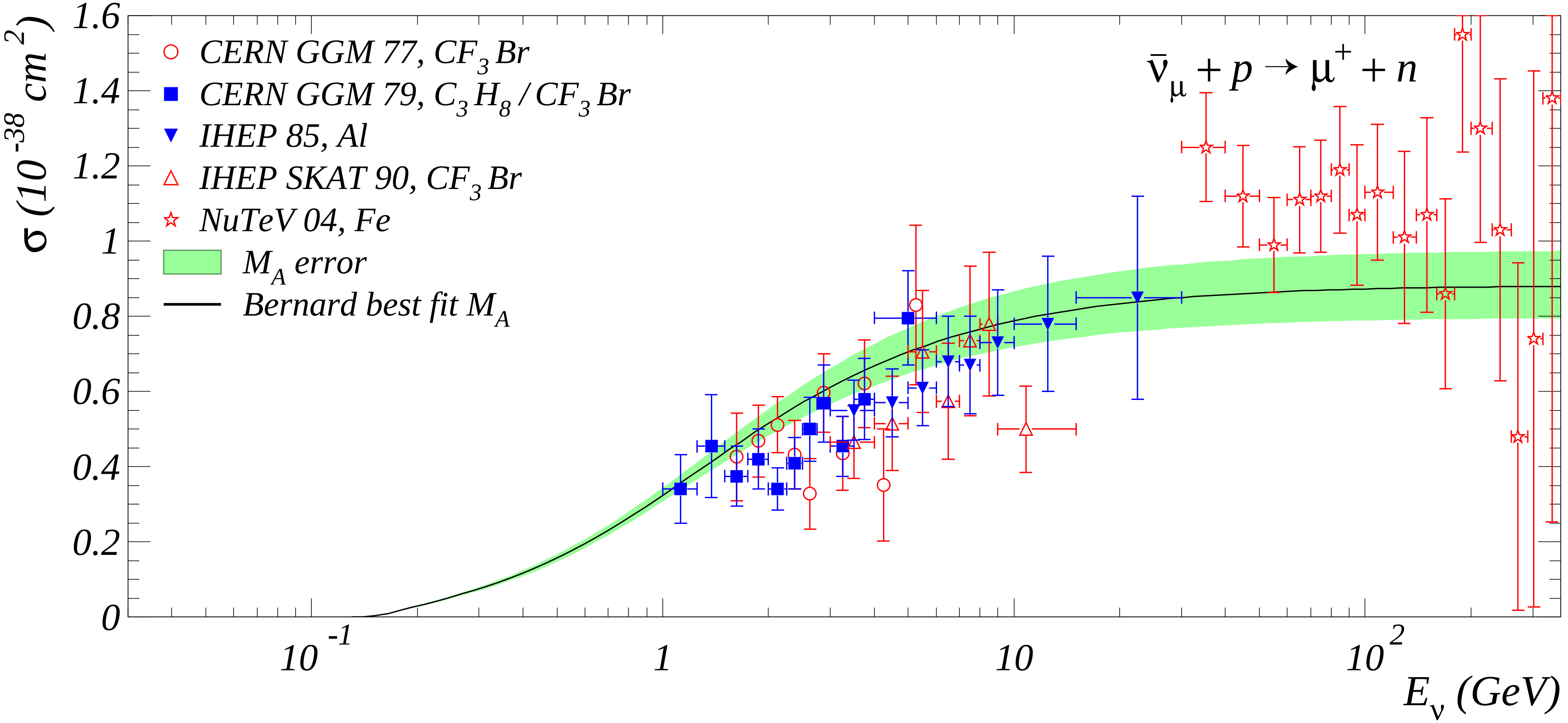
Total QE $\nu_\mu n$ cross section extracted from $\nu_\mu D$ scattering data. All the data are corrected to nuclear effects. The theoretical band corresponds to variations of $M_A = 1.03 \pm 0.10$ GeV.

NOMAD results in comparison with previous experimental data



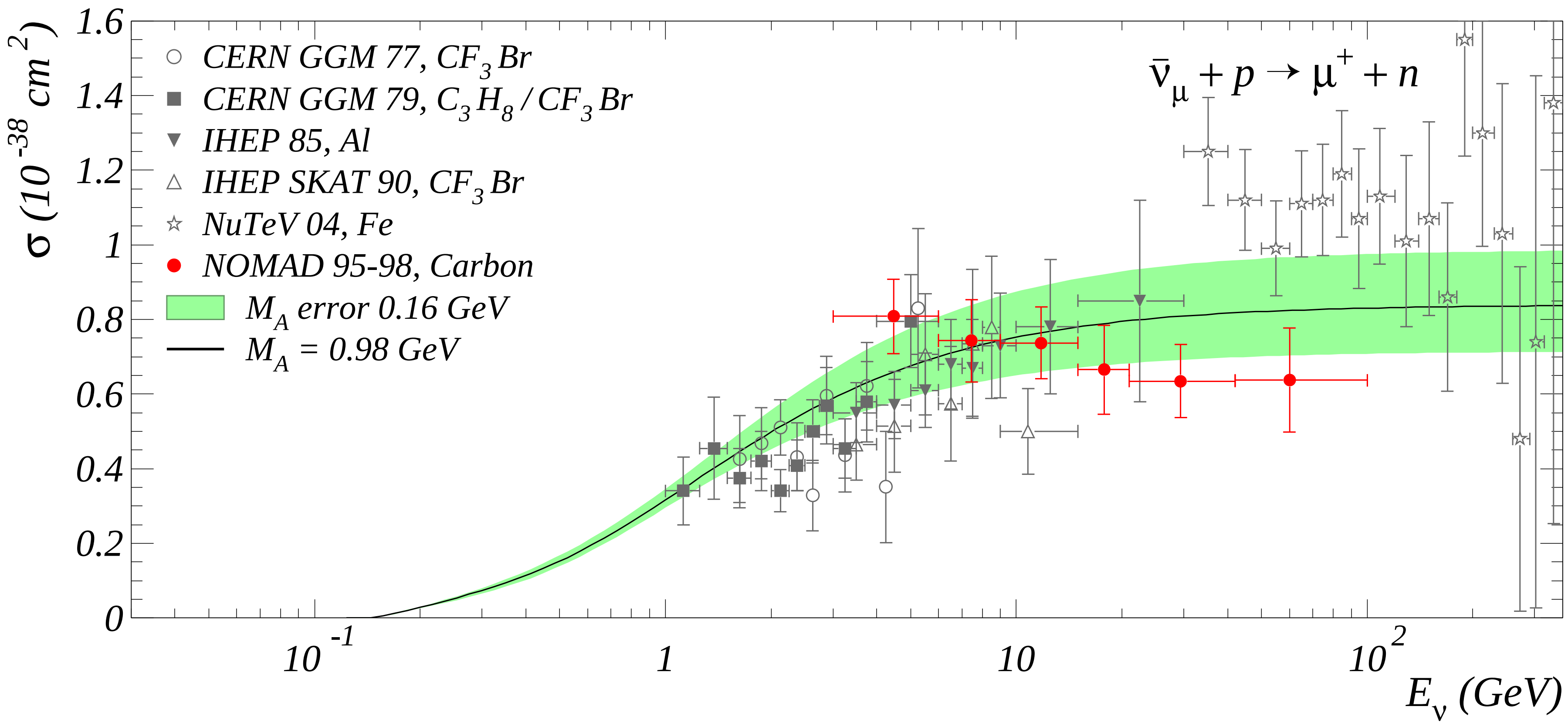
Comparison with previous experimental data from deuterium filled bubble chambers. The solid line and error band corresponds to the M_A value obtained in the NOMAD experiment. All experimental data are corrected to nuclear effects.

Total QE cross $\overline{\nu}_\mu p$ cross section measured on heavy nuclei target



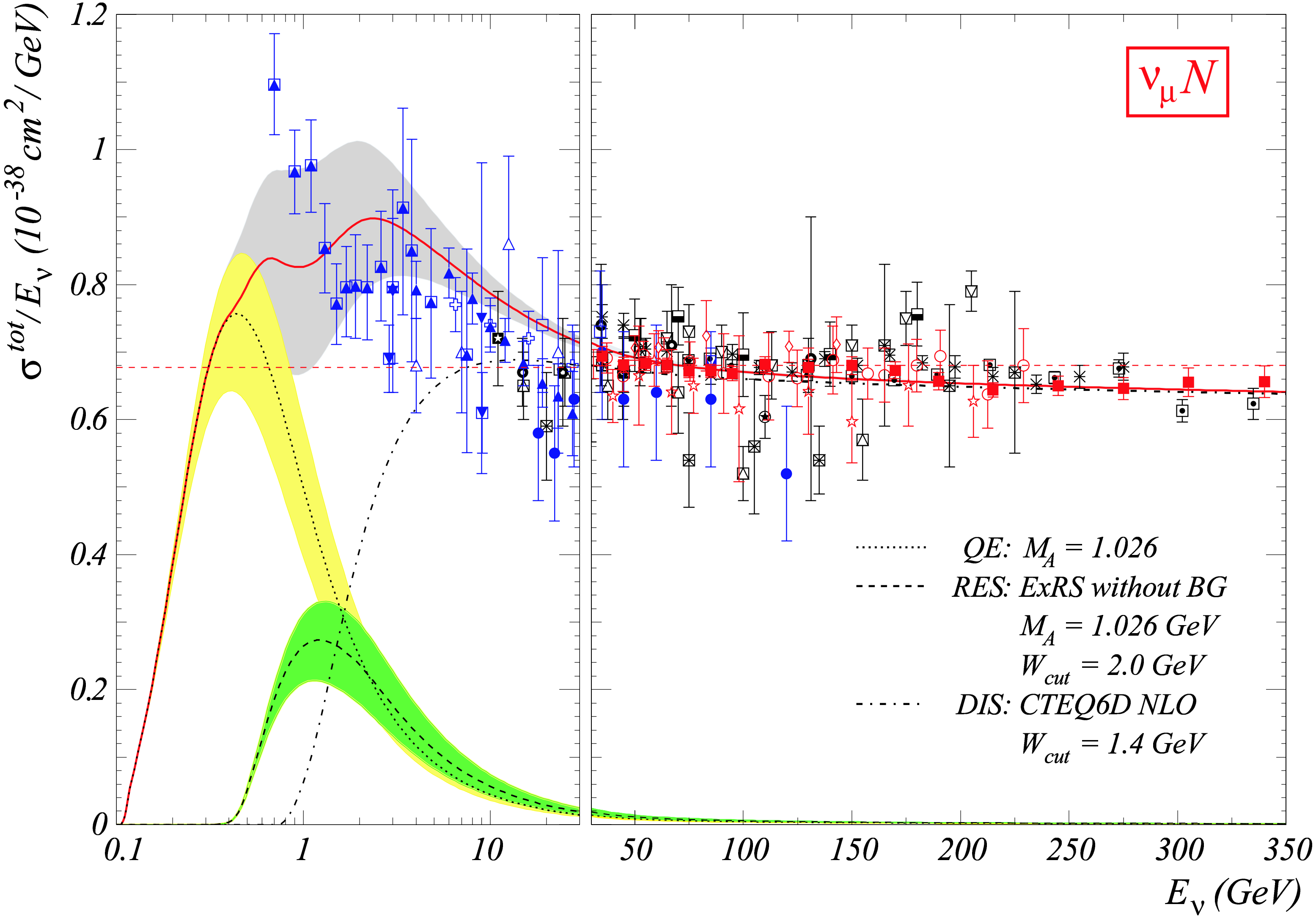
Total QE cross $\overline{\nu}_\mu p$ cross section extracted from the data on $\overline{\nu}_\mu$ scattering off heavy nuclei. Nuclear effects are included into calculations according to the relativistic Fermi gas model by Smith and Moniz (see previous slide for the reference). The theoretical band corresponds to variations of $M_A = 1.03 \pm 0.10$ GeV.

NOMAD results in comparison with previous experimental data



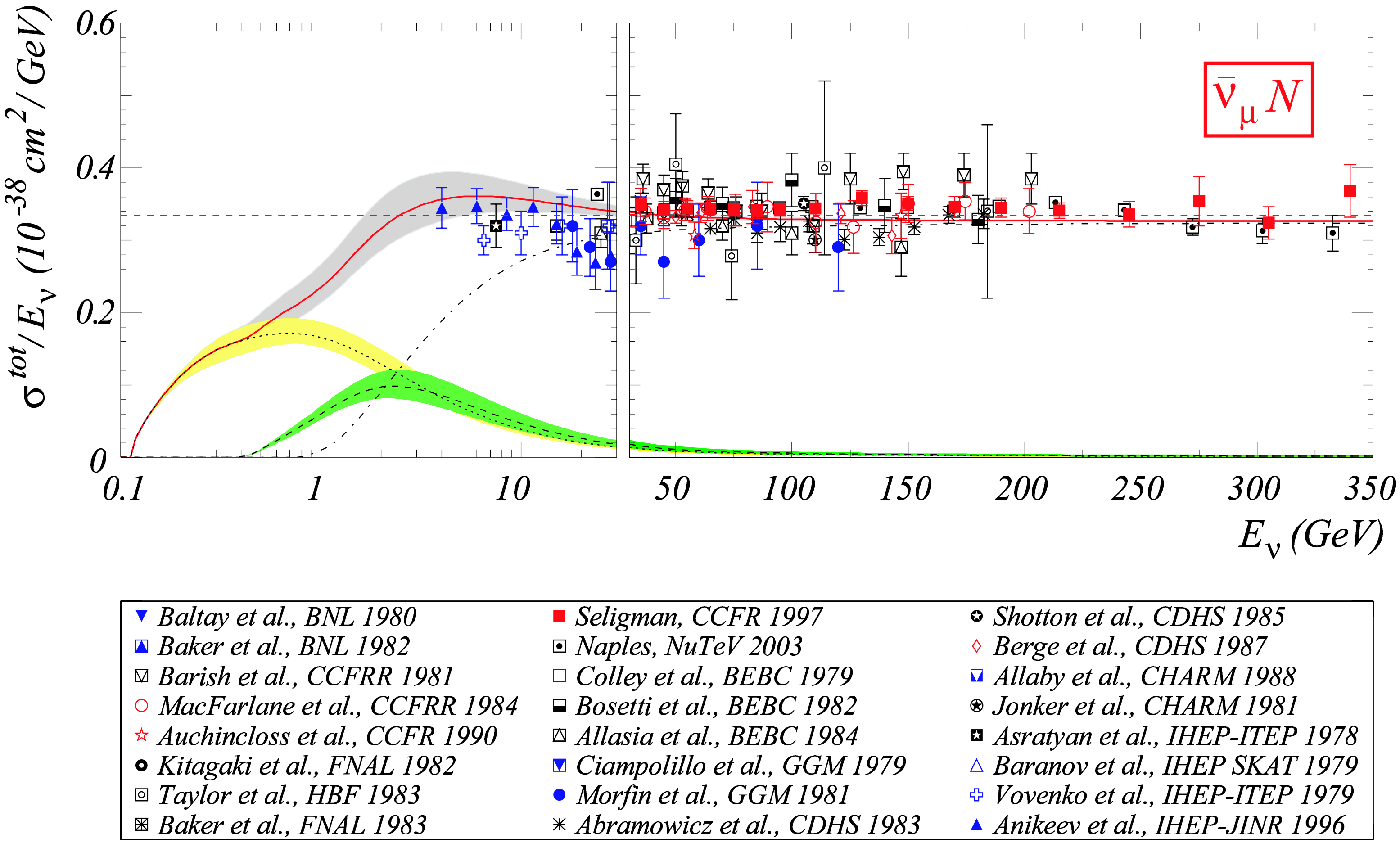
The total cross-section of $\bar{\nu}_\mu p \to \mu^+ n$ process extracted from the data on $\bar{\nu}_\mu$ scattering off heavy nuclei. Nuclear effects are included into calculations according to the standard relativistic Fermi gas model. Solid line and error band corresponds to the M_A value obtained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

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



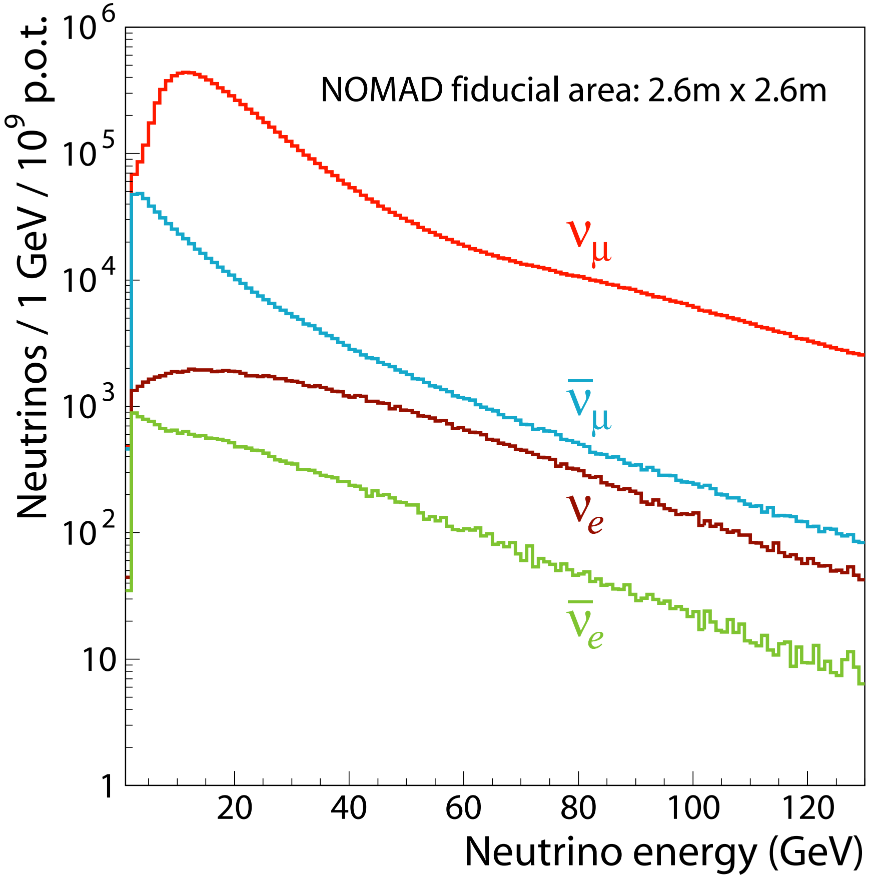
σ^{tot}/E_ν, for the muon neutrino charged-current total cross section as function of neutrino energy. The straight line is the average value $(0.677 \pm 0.014) \times 10^{-38}\,\mathrm{cm}^2/\mathrm{GeV}$.

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 $(0.334 \pm 0.008) \times 10^{-38}\,\mathrm{cm}^2/\mathrm{GeV}$.

Neutrino fluxes at NOMAD experiment



ν_x / ν_μ	$\langle E_\nu \rangle$, GeV
1.0	24.3
0.068	17.2
0.010	36.4
0.0027	27.6

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

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

[a] 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].

QEL cross section measurement: Normalization to Deep Inelastic Scattering

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

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	Neutrino		Antineutrino	
	$\langle\sigma_0\rangle$	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

[a] 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].

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

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

✓ reconstructed primary vertex in fiducial volume: $|X,Y| \leqslant 120\,\mathrm{cm}$, $5 \leqslant Z \leqslant 395\,\mathrm{cm}$,

✓ 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:

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

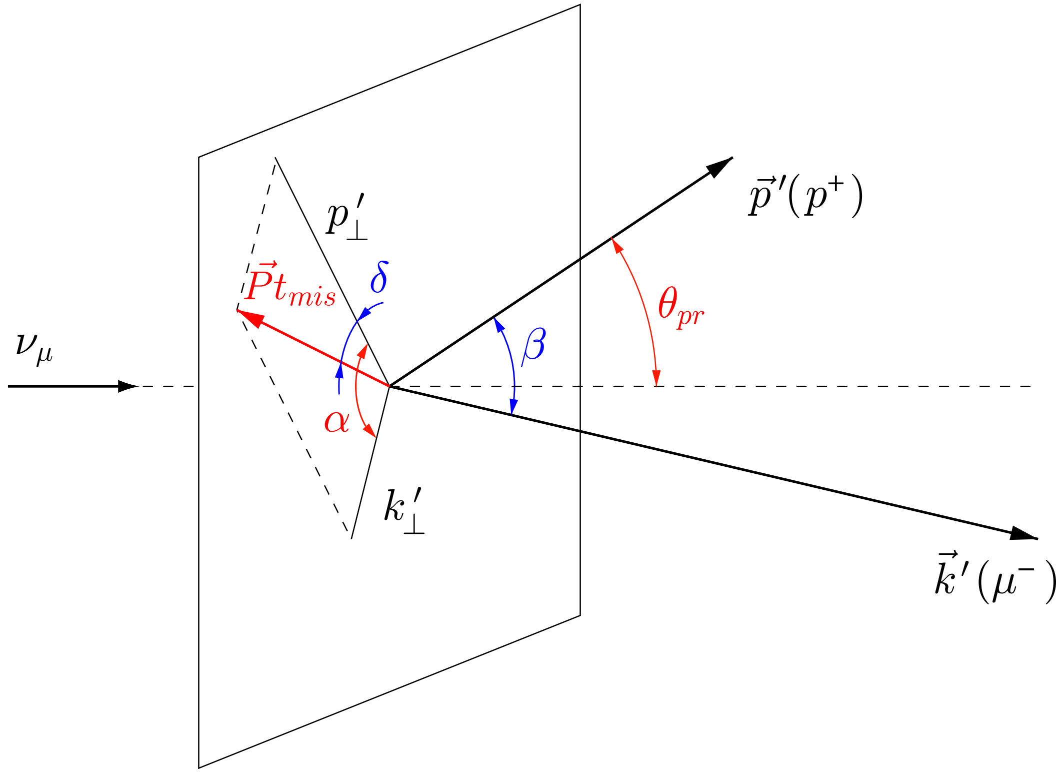
✓ reconstructed neutrino energy $3 \leqslant E_\nu \leqslant 100\ GeV$,

✓ angle θ_μ between the muon momentum and the z axis: $\theta_\mu/\pi \leqslant 0.1$

✓ fake angle θ_{pr} between the proton momentum and the z axis: $0.2 \leqslant \theta_{pr}/\pi \leqslant 0.5$,

MC	M_A^{sim}	$\langle\sigma_{qel}\rangle$	$\delta_{stat}\langle\sigma_{qel}\rangle$	M_A^{rec}
a1	0.83	0.674	0.044	0.91
a3	1.03	0.715	0.047	0.98
a5	1.23	0.797	0.053	1.10

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



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

✓ proton identification: momentum – range relations,

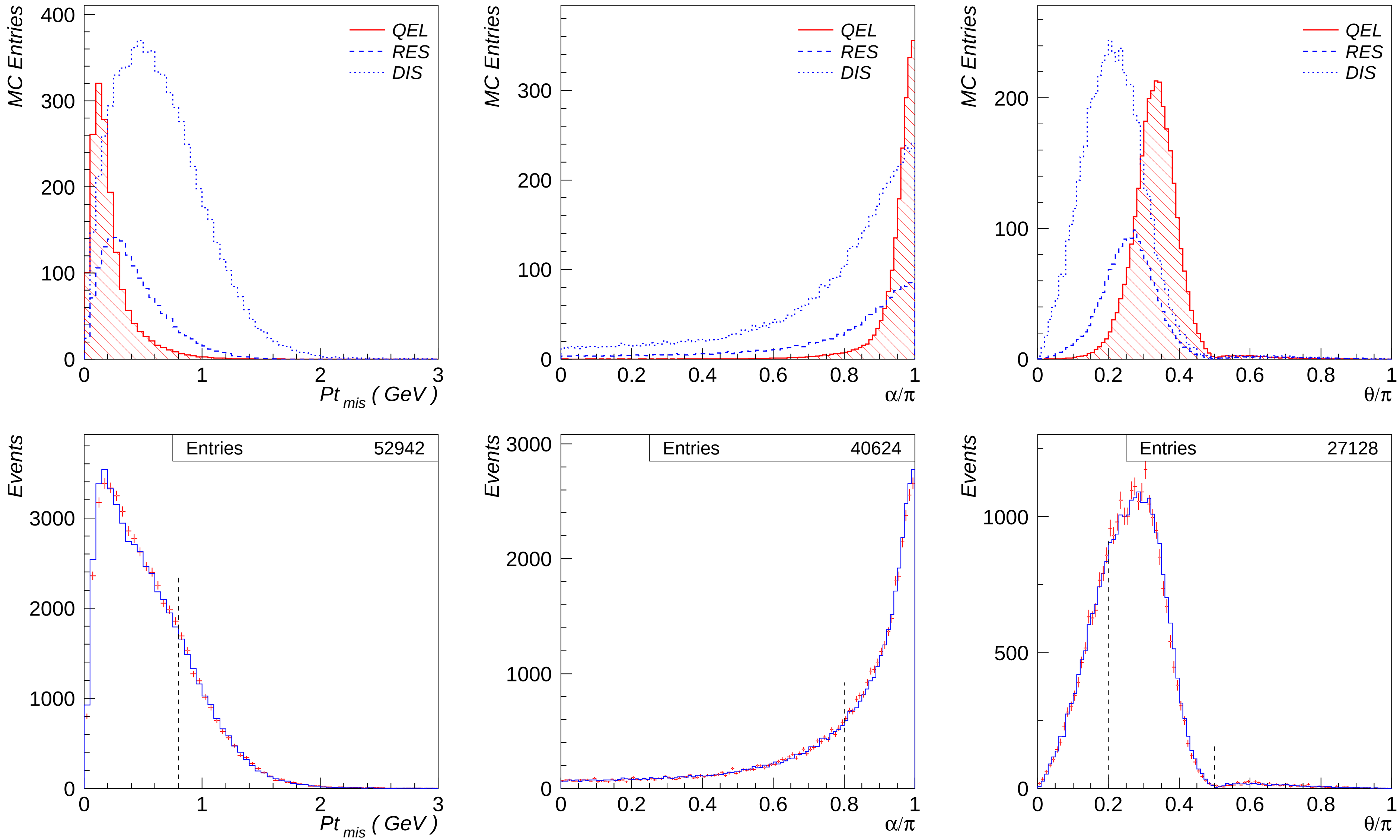
✓ angle α between the transverse components of the charged primary tracks: $0.8 \leqslant \alpha/\pi \leqslant 1$,

✓ missing transverse momentum $Pt_{mis} \leqslant 0.8$ GeV,

✓ angle θ_{pr} between the proton momentum and the z axis: $0.2 \leqslant \theta_{pr}/\pi \leqslant 0.5$,

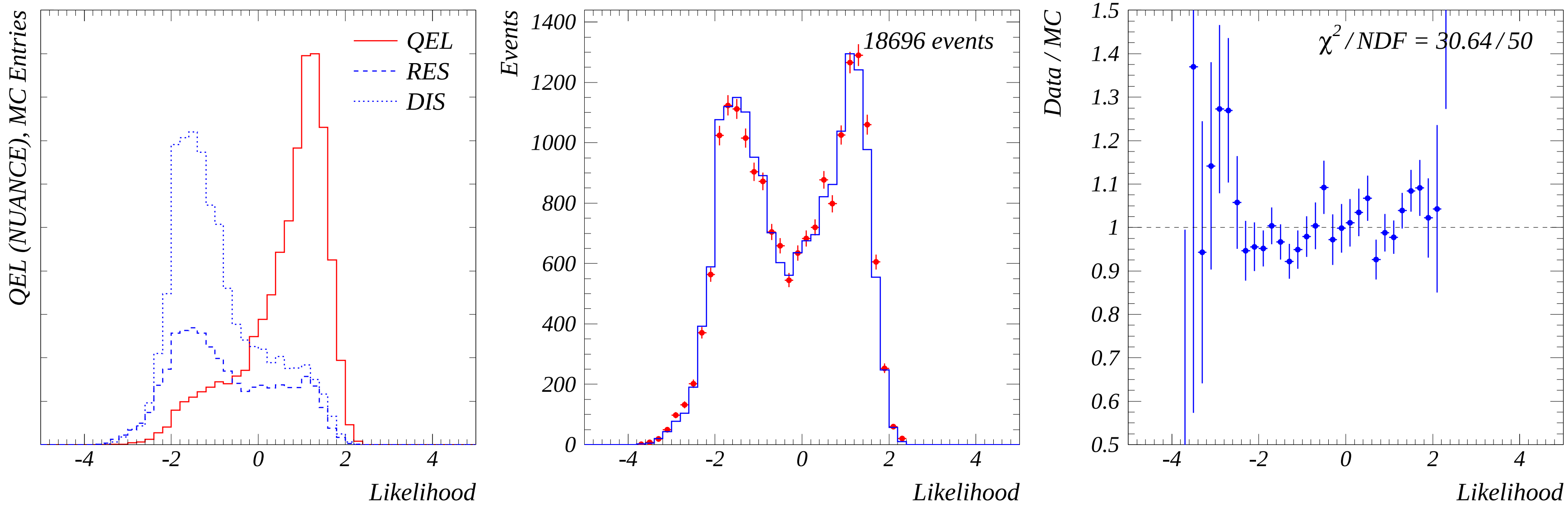
✓ Likelihood ratio $\mathcal{L}(\alpha, Pt_{mis}, \theta_{pr}) \geqslant 0$.

Likelihood variables in simulated events and experimental data



Missing transverse momentum Pt_{mis}, angle α between the transverse components of the charged primary tracks and angle θ_{pr} between the proton momentum and z axis. Distributions for simulated events of different modes (top). Comparison of expected and experimental data distributions (bottom).

Likelihood ratio



The set of variables $\vec{\ell} = \{Pt_{mis}, \theta_{pr}, \alpha\}$ 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 $\vec{\ell}$.

Nuclear effects: DPMJET

- *DPMJET samples hadron-hadron, hadron-nucleus, nucleus-nucleus interactions at high energies. DPMJET can also be applied to neutrino nucleus collisions. It also contains the code for the quasi elastic and deep inelastic neutrino-nucleon scattering.*

- *The generation of events for quasi-elastic neutrino nucleus collisions was done in the same way as in NEGQRC. The Fermi motion of the target nucleon was done according to Benhar parametrization.*

- *The nucleon generated by the QEL code can reinteract in DPMJET inside the nucleus according to the Formation Zone Intranuclear Cascade (FZIC) model, contained inside DPMJET. Secondaries from this first collision are followed along straight trajectories and may 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.*

- *If the excitation energy of the residual nucleus is higher than the separation energy, the additional low-energy nucleons and light fragments can be emitted. The nuclear evaporation module can not be obtained directly from the author of DPMJET. The permission to use the evaporation module from FLUKA has to be obtained from the authors of FLUKA.*

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.

- *Nuance is a software tool for simulating neutrino interactions and related processes. It can be used for modelling charged/neutral current neutrino scattering off nuclear targets in rather wide spectrum of energies. It includes the quasi-elastic and deep-inelastic neutrino scattering, single-pion production via intermediate resonance state, coherent/diffractive pion production, inverse muon decay and other reactions.*

- *The modelling of the quasi elastic neutrino scattering was done in the framework of the relativistic Fermi gas model of Smith and Moniz, for the target nucleon the zero temperature Fermi momentum distribution was used.*

- *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. After ejection of a nucleon recoiling from a neutrino interaction, de-excitation and/or break-up of the residual nucleus can result in emission of one or two few-MeV along with possible evaporation of low-energy nucleons.*

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

Intranuclear cascade in DPMJET and NUANCE

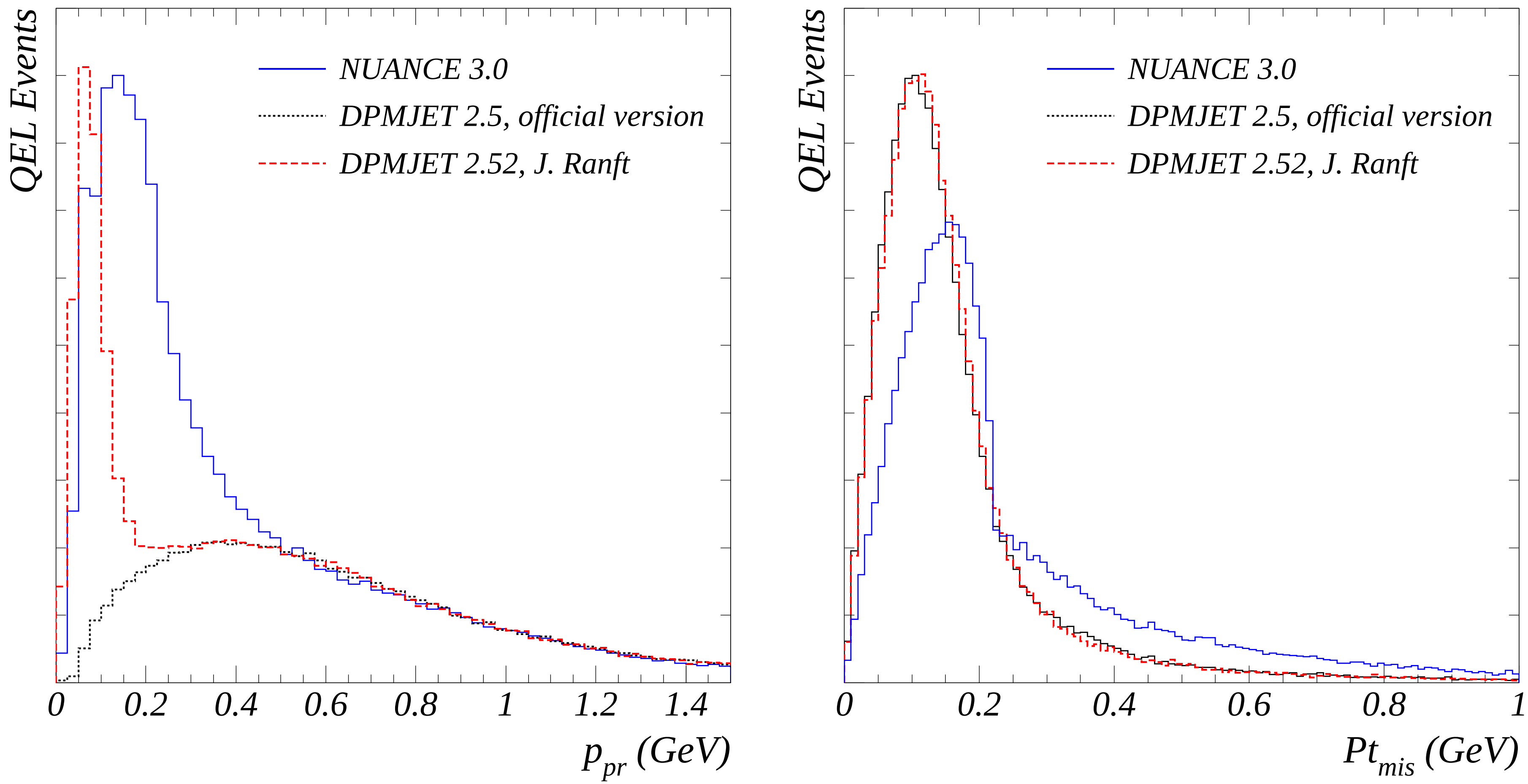
Simulation of the quasi-elastic ν_μ scattering on Carbon ($E_\nu = 10\, GeV$) in different MC generators: DPMJET 2.5 (taken from official web page [1], contains no nuclear evaporation module), DPMJET 2.52 (obtained directly from Johannes Ranft [2]) and NUANCE 3.0 [3]. Average multiplicities for proton , neutron, charged and neutral pions, photons (except from π^0 decay) are shown. The de-excitation gamma energy $\langle E_\gamma \rangle$ and the total transverse momentum of all charged particles in the final state $\langle P_\perp^{mis} \rangle$ are given in MeV. P_2 is the probability to obtain a clean two body final state (just muon plus one proton, photons are not taken into account).

MC generator	$\langle N_n \rangle$	$\langle N_p \rangle$	$\langle N_{\pi^\pm} \rangle$	$\langle N_{\pi^0} \rangle$	$\langle N_\gamma \rangle$	$\langle E_\gamma \rangle$	$\langle P_\perp^{mis} \rangle$	P_2
hep-ph/9801426	$\langle N_{n+p} \rangle = 1.49$		0.016	–	0.790	2.1	175	0.274
DPMJET 2.5, official	0.113	0.968	0.015	0.012	0.000	0.0	170	0.801
DPMJET 2.52, J. Ranft	0.139	1.367	0.017	0.011	0.715	2.1	169	0.676
NUANCE 3.0	0.760	1.808	0.042	0.031	0.688	5.7	265	0.385

1 *http://siwaps.physik.uni-siegen.de/kolloquium/dpmjet/*

2 *Johannes Ranft <ran@mail.cern.ch>*

3 *http://nuint.ps.uci.edu/nuance/*



Protons momentum distribution (left), and the total transverse momentum of all charged particles in the final state $\langle P_{\perp}^{mis} \rangle$ (right). 100000 QEL events with $E(\nu_\mu) = 10\, GeV$.

QEL ν_μ Cross Section measurement: various nuclear models

			Single track events			Two tracks events			Total sum		
MC	τ_0	M_A^{sim}	$\langle\sigma_{qel}\rangle$	$\delta\langle\sigma_{qel}\rangle$	M_A^{rec}	$\langle\sigma_{qel}\rangle$	$\delta\langle\sigma_{qel}\rangle$	M_A^{rec}	$\langle\sigma_{qel}\rangle$	$\delta\langle\sigma_{qel}\rangle$	M_A^{rec}
n7	-	1.03	0.947	0.023	1.08	0.938	0.022	1.07	0.943	0.016	1.07
m4	0.60	0.83	0.877	0.021	1.00	0.971	0.023	1.10	0.914	0.016	1.04
m5	1.00	0.83	0.889	0.022	1.02	0.917	0.022	1.04	0.901	0.016	1.03
m6	2.00	0.83	0.900	0.022	1.03	0.812	0.020	0.93	0.861	0.015	0.98
m7	0.60	1.03	0.942	0.023	1.07	0.935	0.023	1.06	0.939	0.017	1.07
l2	0.80	1.03	0.939	0.023	1.07	0.915	0.022	1.04	0.929	0.016	1.06
m8	1.00	1.03	0.957	0.023	1.09	0.873	0.021	1.00	0.920	0.016	1.05
m9	2.00	1.03	0.956	0.023	1.09	0.786	0.019	0.90	0.876	0.016	1.00
k5	0.60	1.23	1.066	0.026	1.19	0.887	0.021	1.01	0.983	0.018	1.11
k6	0.80	1.23	1.072	0.026	1.20	0.864	0.021	0.99	0.973	0.017	1.10
k7	1.00	1.23	1.064	0.026	1.19	0.845	0.020	0.97	0.959	0.017	1.09
k8	2.00	1.23	1.086	0.027	1.21	0.743	0.018	0.84	0.909	0.016	1.04

Systematic uncertainties in QEL cross section

✓ (1) Uncertainty of the single pion production cross-section. We assume 10% error in $\langle\sigma_{res}\rangle$

✓ (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) QEL Identification procedure. The corresponding errors can be estimated by varying the selection criteria with in reasonable limits (likelihood $\mathcal{L} = 0 \pm 0.4$ and $\theta_{pr}/\pi = 0.4 \pm 0.04$ for single track events)

✓ (4) Nuclear effects (Intranuclear cascade)

	Neutrino			Antineutrino		
	$\langle\sigma_{qel}\rangle$	$\delta_{stat}\langle\sigma_{qel}\rangle$	$\delta_{syst}\langle\sigma_{qel}\rangle$	$\langle\sigma_{qel}\rangle$	$\delta_{stat}\langle\sigma_{qel}\rangle$	$\delta_{syst}\langle\sigma_{qel}\rangle$
	0.929	0.016	0.053	0.715	0.047	0.082
(1)			0.032			0.063
(2)			0.025			0.034
(3)			0.017			0.040
(4)			$\sim$ 0.030			–

Conclusion

✓ We performed the most up to date accurate measurement of the $\nu_\mu n \to \mu^- p$ cross-section on bounded nucleon. Cross section and corresponding axial mass of the dipole parametrization of the axial form-factor results have the best statistical precision with comparable systematic uncertainties. Obtained results are found to be in good agreement with ones obtained in the previous bubble chamber experiments.