The effective nucleon axial mass approach and quasielastic neutrino event rates in the Near Detector of NOνA

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Outline

- The nucleon axial mass:
  - the problem
  - the solution concept
- The NOνA experiment:
  - physical goals
  - some details
- QES event rates in the Near Detector of NOνA
- Conclusions

QES of neutrino on the nucleon

QES section:

$$d\sigma = \frac{G_F^2 M}{16\pi^2 (kp)} \left(1 + \frac{Q^2}{M_W^2}\right)^{-2} L^{\alpha\beta} W_{\alpha\beta} \frac{d^3 \vec{k}'}{2k_0'}.$$

Lepton tensor:

$$L^{\alpha\beta}(k,k') = \begin{cases} j^\alpha(k,k') j^{*\beta}(k,k') & \text{for } \nu; \\ \bar{j}^\alpha(k,k') \bar{j}^{*\beta}(k,k') & \text{for } \bar{\nu}. \end{cases}$$

Weak lepton currents:

$$j^\alpha(k,k') = \bar{u}(k')\gamma^\alpha \frac{1-\gamma_5}{2} u(k), \qquad \bar{j}^\alpha(k,k') = \bar{v}(k)\gamma^\alpha \frac{1-\gamma_5}{2} v(k').$$

Hadron tensor:

$$W_{\alpha\beta}(p,q) = \frac{1}{4} \int J_\alpha(p,p') J_\beta^*(p,p') \delta^4(k' + p' - k - p) \frac{d^3 \vec{p}'}{2p_0'}.$$

Weak form factors of the nucleon

Weak hadron current is given by

$$J_\alpha(p,p') = V_{ud}^{\mathrm{CKM}} \bar{u}_p(p') \Gamma_\alpha(p,q) u_n(p).$$

Basis expansion of $\Gamma_\alpha(p,q)$ comes to

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

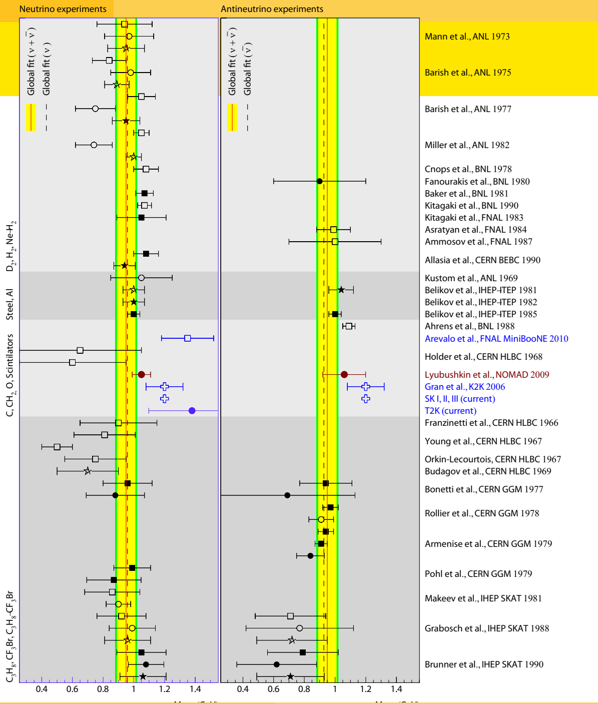
Standard dipole parametrization of the axial form factor is

$$F_A(Q^2) = g_A \left(1 + \frac{Q^2}{{M_A}^2}\right)^{-2}, \qquad g_A = -1.2695.$$

PCAC gives the formula for pseudoscalar form factor:

$$F_P(Q^2) = \frac{2M^2}{m_\pi^2 + Q^2} F_A(Q^2).$$

World survey of M_A



The current best-fit value:
$M_A = 0.95 \pm 0.06$ GeV[1].

The bands:
1σ and 2σ st. deviations.

[1] Kuzmin, Lyubushkin & Naumov, 2008;
Kuzmin & Naumov, in preparation.

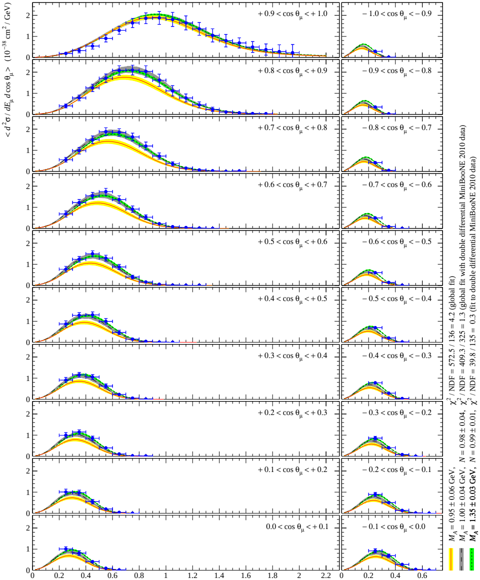
MiniBooNE

The flux-weighted double differential cross sections for the $\nu_\mu n \to \mu^- p$ reaction.

The MiniBooNE result[1]:
$M_A = 1.35 \pm 0.17\,\text{GeV}$.

The gray bands are calculated by using the nuclear model of Martini *et al.*[2].

Does the RFG model[3] work at low energies?



[1] Aguilar-Arevalo *et al.* (The MiniBooNE Collaboration), 2010.

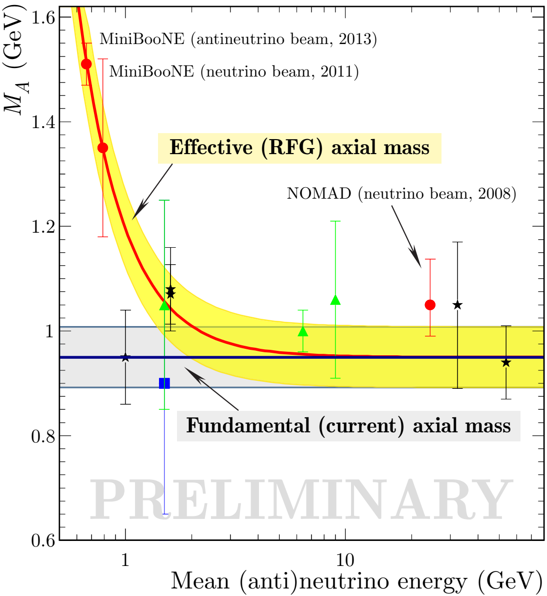
[2] Martini, Ericson & Chanfray, 2011.

Effective (RFG) and current M_A

We do not have properly working nuclear model for all energy ranges!

There is some dependence on E_ν in experimental values of M_A extracted with the RFG model.

So, we can fit experimental data to get $M_A^{\text{eff}}(E_\nu)$ using which will compensate nuclear effects.



Effective (RFG) and current M_A

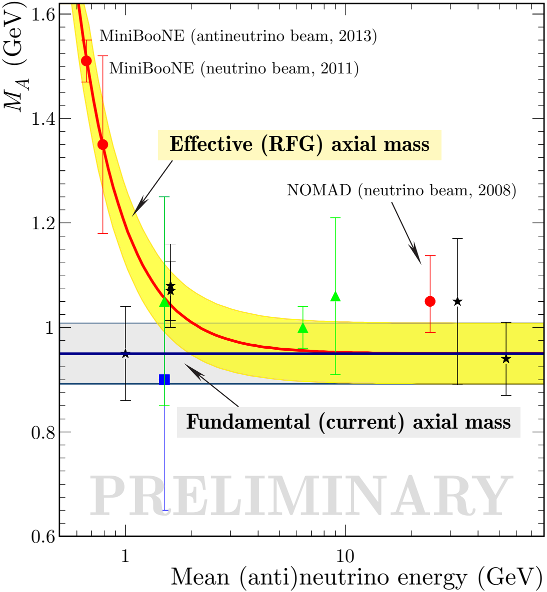
$$M_A^{\text{eff}} = M_0 \left(1 + \left(\frac{E_0}{E_\nu}\right)^{a_0}\right),$$

$$M_0 = 0.964 \pm 0.044 \text{ GeV},$$

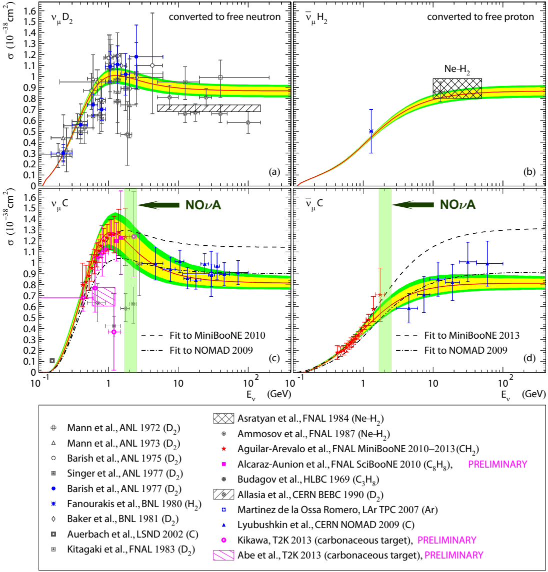
$$E_0 = 0.356 \pm 0.076 \text{ GeV},$$

$$a_0 = 0.846 \pm 0.220.$$

Only MininBooNE data are used to fit the M_A^{eff} curve. Only selected experimental points are shown.



QES cross section analysis



Total QES $\nu_\mu n$ & $\overline{\nu}_\mu p$ cross sections measured in experiments with deuterium, hydrogen & carbon/propane targets.[1]

[1] Kuzmin & Naumov, in preparation.

NuMI Off-axis ν_e Appearance (NOνA) experiment

The NOνA experiment goals:

- neutrino mass hierarchy investigation
- θ_{13} measurement in ν_e appearance mode
- constraining of δ_{CP}
- θ_{23} rectification
- precise measurement of $|\Delta m^2_{32}|$
- other physics:
  - neutrino cross section measurement

NOνA

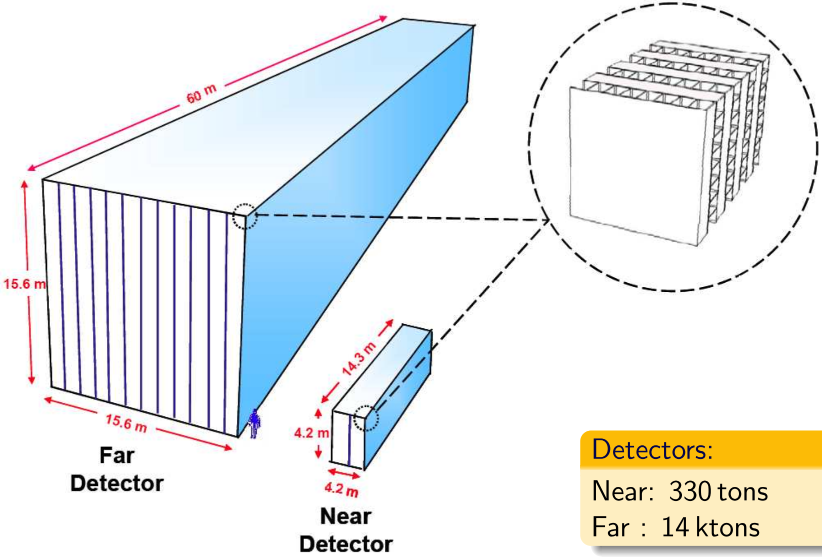
810 km baseline

14 mrad off-axis

$E_\nu \sim 2$ GeV

3 years ν, 3 years $\bar{\nu}$

NOνA detectors

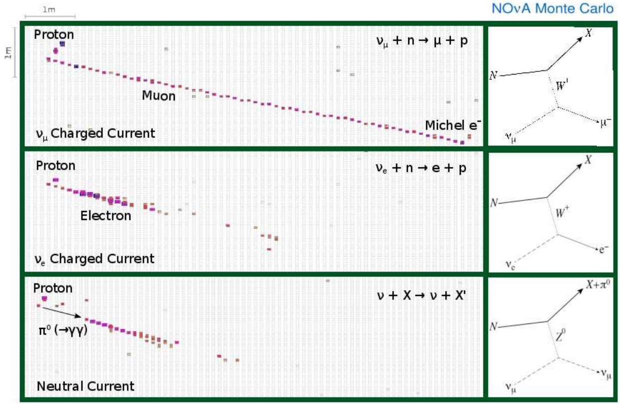


Detectors:

Near: 330 tons

Far : 14 ktons

NOνA event topology



ν_μ CC

- long well-defined μ-track
- short p-track with large energy deposition at the end

ν_e CC

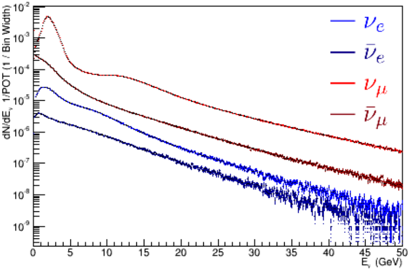
- single EM shower
- characteristic development of EM shower

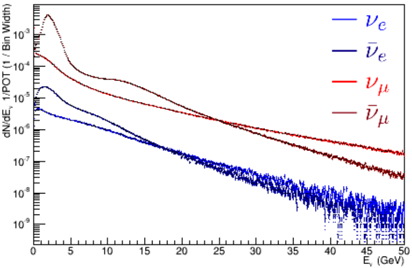
NC with π^0 final state

- multiple displaced EM showers
- possible gaps near event vertex

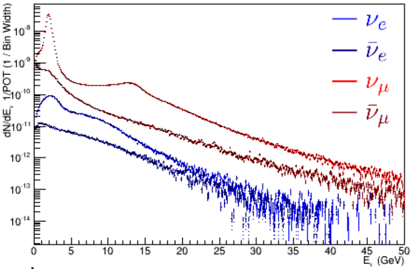
Fluxes

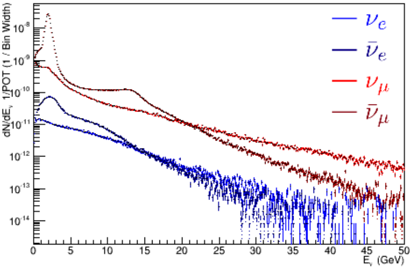
ND:





FD:

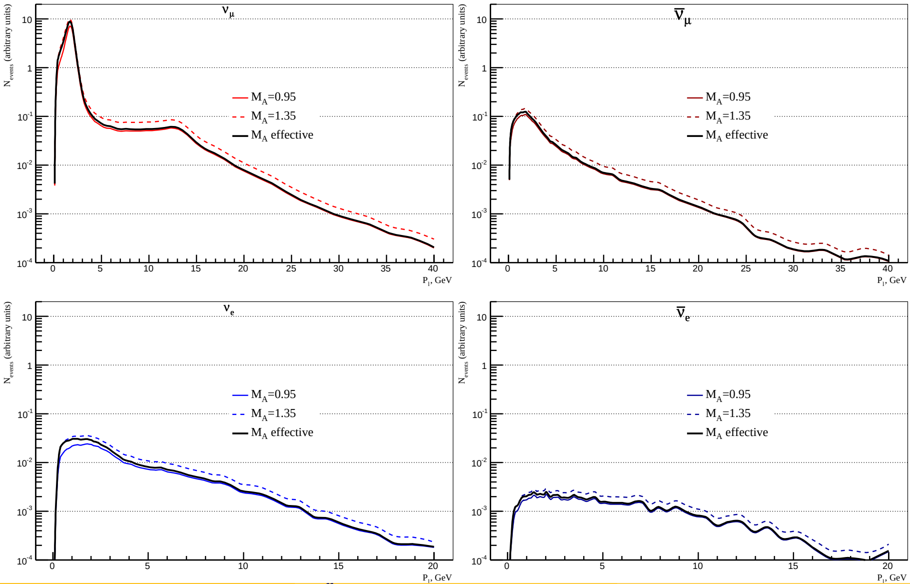




ν mode

$\bar{\nu}$ mode

QES event rates in the Near Detector (ν mode)



Conclusions

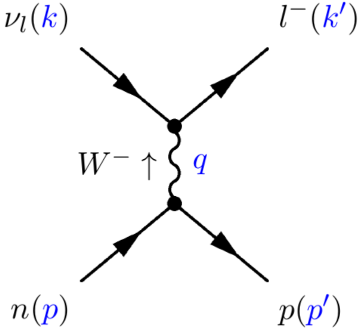
- The M_A value essentially affects the predicted count rates.
- The effect should be taken into account.
- Using the effective axial mass instead of the constant values like:
  - 1.35 GeV (MiniBooNE)[1] or 1.39 GeV (T2K)[2]
  - 1.05 GeV (NOMAD)[3]

  should improve the validity of the mixing parameter values.
- The estimations presented herein are preliminary.

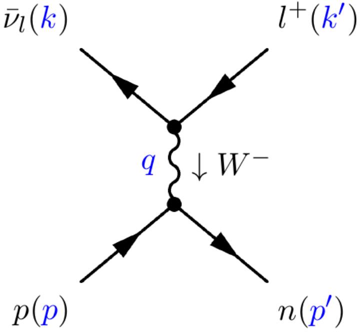
[1] Aguilar-Arevalo *et al.* (The MiniBooNE Collaboration), 2010.
[2] Hadley (The T2K Collaboration), 2013.
[3] Lyubushkin (NOMAD Collaboration), 2009.

THANK YOU!

QES of neutrino on the nucleon



$$\nu_l + n \to l^- + p$$



$$\bar{\nu}_l + p \to l^+ + n$$

$$Q^2 = -q^2$$

Electroweak form factors of the nucleon

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

C and T invariance of the hadron current $\Rightarrow$

$$\text{scalar } F_S = \text{tensor } F_T = 0.$$

Dirac and Pauli electromagnetic form factors:

$$F_V = \frac{G_E + x' G_M}{1 + x'}, \quad F_M = \frac{G_M - G_E}{1 + x'} \quad \text{where } x' = \frac{Q^2}{4M^2}.$$

Sachs form factors:

$$G_E = G_E^p - G_E^n, \quad G_M = G_M^p - G_M^n,$$

BBBA(2007) model is used for $G_E^{p,n}$ & $G_M^{p,n}$.

Martini *et al.* model

Martini *et al.* model incorporates relativistic corrections in the nuclear response functions and includes the multinucleon component of the "particle-hole" (2p-2h and 3p-3h contributions) processes. The model describes parameters of the "particle-hole" force which governs the collective aspect of the nuclear response via the random phase approximation. In the case of the MiniBooNE experiment multinucleon ejection is not distinguishable from single-nucleon production. The quasielastic cross section thus defined contains a certain proportion of 2p-2h and 3p-3h excitations. This proportion is large for neutrinos, which may be the interpretation of the increase in the axial cutoff mass needed to describe the data in the relativistic Fermi gas.[1]

[1] Martini, Ericson & Chanfray, 2011.

RFG model

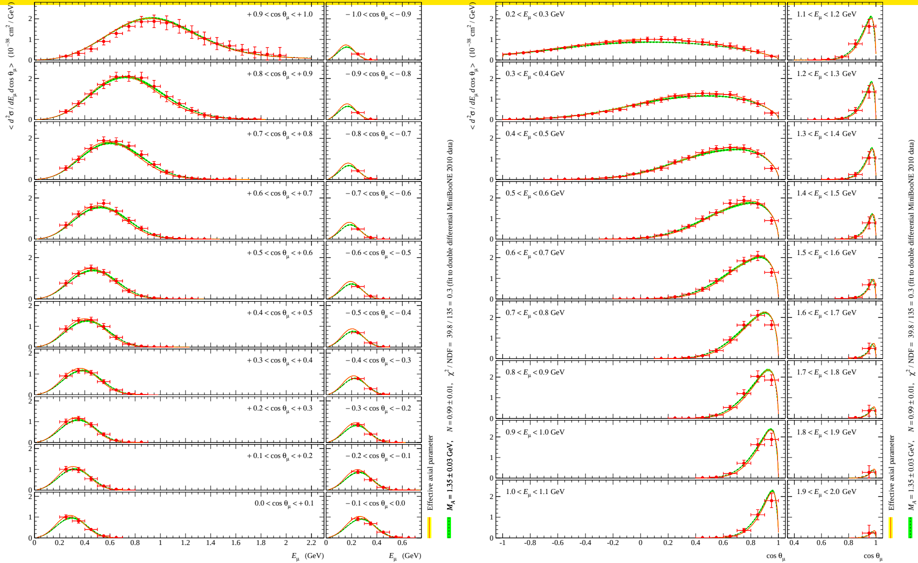
$$d\sigma^b = \frac{G_F^2 M_t}{16\pi^2(kp)} \left(1 + \frac{Q^2}{M_W^2}\right)^{-2} L^{\alpha\beta} T_{\alpha\beta} \frac{d^3\vec{k}'}{2k_0'}$$

$$T_{\alpha\beta}(p_{\rm lab}, q) = \int f(\vec{p}, \vec{q}) W_{\alpha\beta}(p, q) d\vec{p}$$

$$f(\vec{p}, \vec{q}) = {v_{\rm rel}}^{-1} \bar{n}_i(\vec{p})[1 - n_f(\vec{p'})]$$

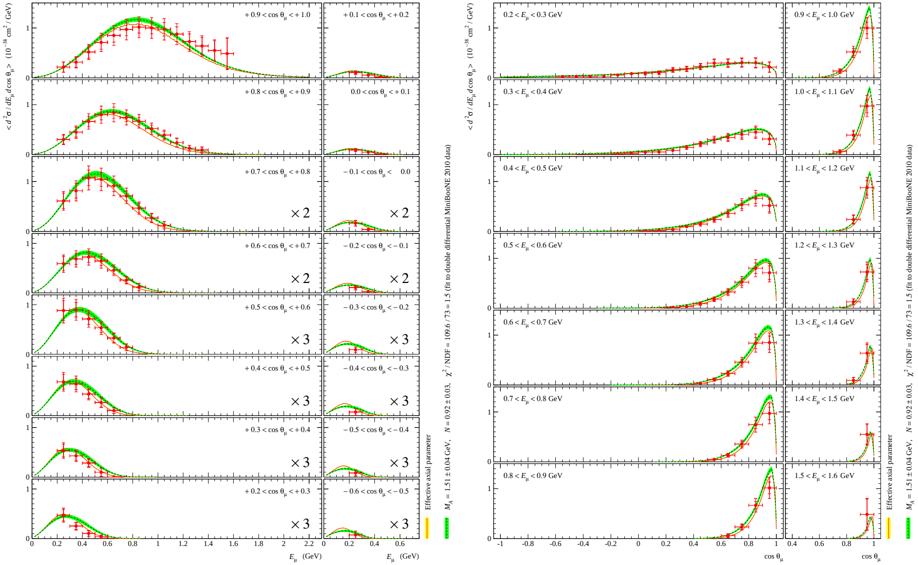
$$v_{\rm rel} = \frac{(kp)}{M_t E_\nu}$$

MiniBooNE ν



The red curves with the yellow bands are calculated by using $M_A^{\rm eff}$.

MiniBooNE $\bar{\nu}$



Neutrino oscillation theory

$$P_{\alpha\beta}(E_\nu, L) = \sum_{ij} V_{\alpha i} V_{\beta j} (V_{\alpha j} V_{\beta i})^* \exp\left(2\pi i \frac{L}{L_{ij}}\right)$$

$$L_{ij} = \frac{4\pi E_\nu}{\Delta m^2_{ij}}$$

$$V = O_{23}\Gamma_D O_{13}\Gamma_D^\dagger O_{12}\Gamma_M$$

$$\Gamma_D = \mathrm{diag}(1, 1, e^{i\delta}), \quad \Gamma_M = \mathrm{diag}(e^{i\phi_1}, e^{i\phi_2}, 1)$$

$$O_{12} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad O_{13} = \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}, \quad O_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij}, \quad c_{ij} = \cos\theta_{ij}$$

Event rates

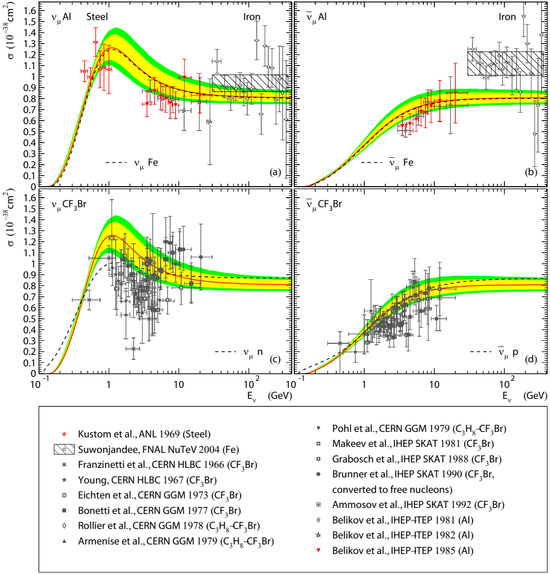
Flux of leptons l generated by QES of neutrino on one atom of ${}^{Z}_{A}\mathrm{El}$ per second:

$$\frac{dN_l^{\mathrm{El}}}{dp_l} = \begin{cases} \int \frac{d\sigma_{\bar{\nu}_l}}{dp_l}\bar{\nu}_l(E_\nu)dE_\nu, & \text{if } \mathrm{El} = \mathrm{H}; \\ \int \left(Z\frac{d\sigma^{\mathrm{El}}_{\nu_l}}{dp_l}\nu_l(E_\nu) + (A-Z)\frac{d\sigma^{\mathrm{El}}_{\bar{\nu}_l}}{dp_l}\bar{\nu}_l(E_\nu) \right) dE_\nu, & \text{if } \mathrm{El} \neq \mathrm{H}, \end{cases}$$

on one gramm $\mathrm{El}^1_{n_1}\mathrm{El}^2_{n_2}\dots\mathrm{El}^m_{n_m}$ per second:

$$\frac{dN_l}{dp_l} = \frac{N_A}{\mu}\sum n_k \frac{dN_l^{\mathrm{El}^k}}{dp_l}.$$

QES cross section analysis

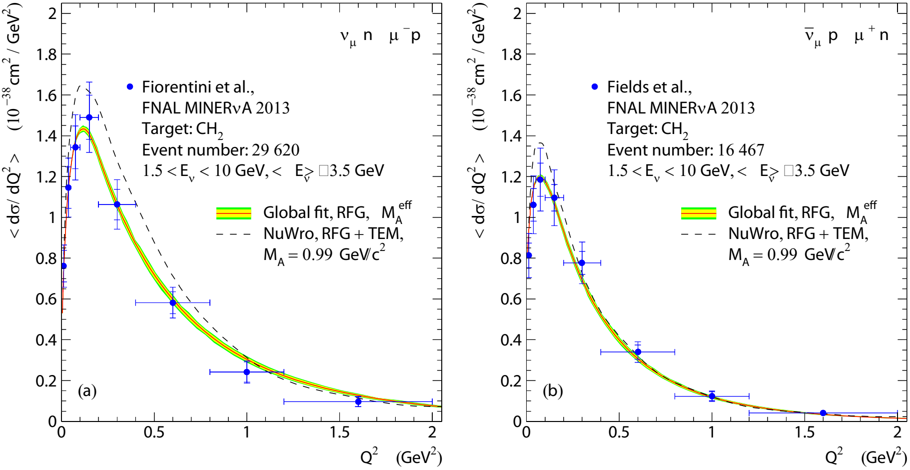


QES of $\nu_\mu n$ & $\overline{\nu}_\mu p$ on aluminium, iron/steel & freon targets.

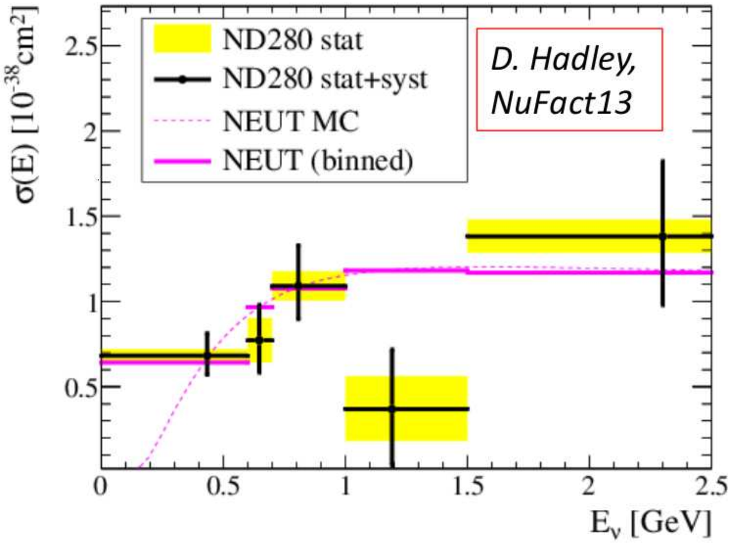
The gray points are excluded from the global fit being either superseded by newer experiments, or not satisfying selection criteria.[1]

[1] Kuzmin & Naumov, in preparation.

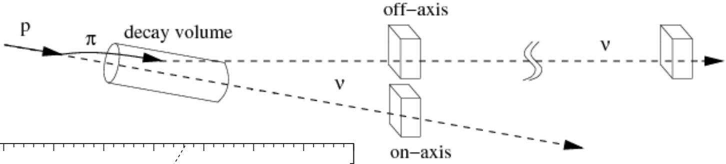
QES cross section in Minerva

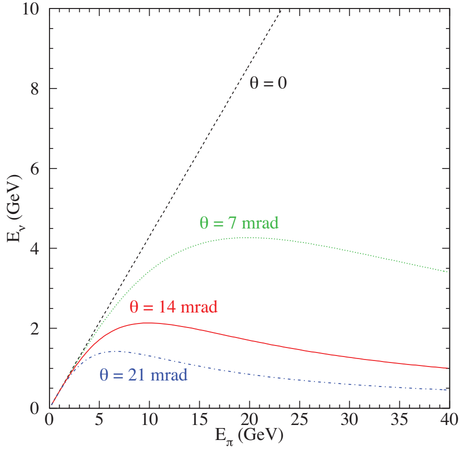


QES cross section in T2K



Off-axis experiment idea



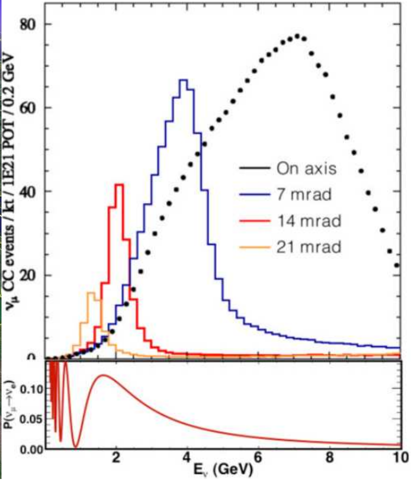


$$\pi^{\pm} \to \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu)$$

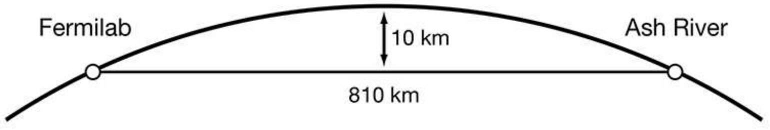
$$\frac{dE_\nu}{dE_\pi} = \left(1 - \frac{m_\mu^2}{m_\pi^2}\right) \frac{1 - \gamma^2\theta^2}{(1 + \gamma^2\theta^2)^2}$$

NuMI Off-axis ν_e Appearance (NOνA) experiment

$$\theta = 14 \text{ mrad} \Rightarrow E_\nu \sim 2 \text{ GeV} \Rightarrow L = 810 \text{ km}$$



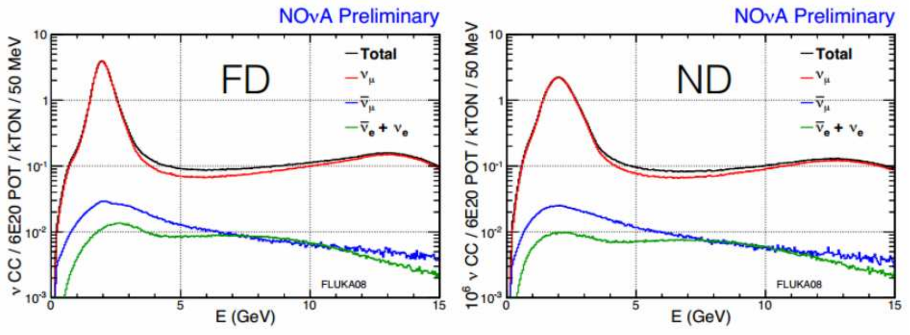
Far detector



ND: $3.9 \times 3.9 \times 14.3$ m^3, 330 tons; FD: $15.7 \times 15.7 \times 63$ m^3, 14 ktons

ν_{mu}CC

ν mode:

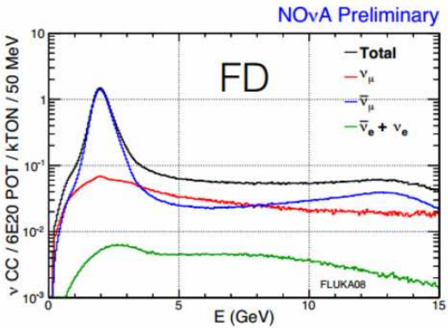


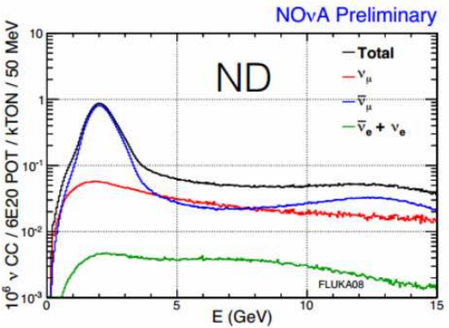
	[1,3]GeV	[0,120]Gev
Total	63.5	103.8
Numu	62.1	97.6
Anti-Numu	1.0	3.9
Nue+Anti-Nue	0.4	2.3

x10⁶	[1,3]GeV	[0,120]Gev
Total	53.9	95.0
Numu	52.6	89.5
Anti-Numu	0.9	3.5
Nue+Anti-Nue	0.4	2.0

$\bar{\nu}_{mu}$CC

$\bar{\nu}$ mode:





	[1,3]GeV	[0,120]Gev
Total	25.1	46.7
Numu	2.4	13.2
Anti-Numu	22.5	32.2
Nue+Anti-Nue	0.2	1.3

$\times 10^6$	[1,3]GeV	[0,120]Gev
Total	21.4	42.3
Numu	2.1	11.9
Anti-Numu	19.1	29.3
Nue+Anti-Nue	0.2	1.1

QES event rates in the Near Detector (ν mode)