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MEC in MB NCEL data analysis

- Neutrino-nucleon elastic scattering
- Meson Exchange Currents (MEC)
- MiniBooNE (MB) data
- NuWro based analysis of the MB data

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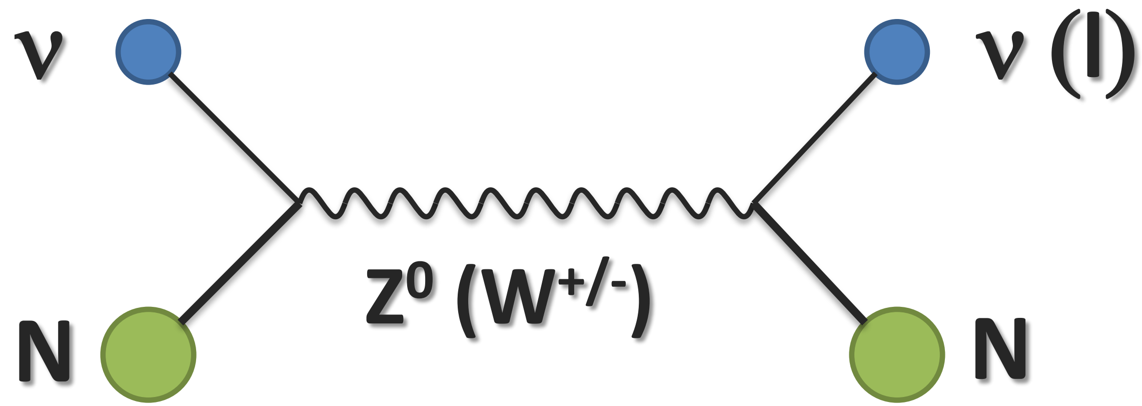
Elastic scattering off nucleon



Scattering amplitude:

$$i\mathcal{M}^{(1)}_{cc,nc} \approx -i f_{cc,nc} \frac{G_F}{\sqrt{2}} j_\mu h^\mu_{cc,nc}$$

Fermi constant

lepton current

hadron current

$$f_{nc} = 1$$
$$f_{cc} = \cos\theta_C$$

Lepton current

$$j_\mu = \bar{u}(k')\gamma^\mu(1-\gamma_5)u(k)$$

initial and final lepton fields

Hadron current

$$h^\mu_{cc,nc}(q) = \overline{u}(p')\Gamma^\mu_{cc,nc}(q)u(p)$$

initial and final hadron fields

Γ^μ needs the phenomenological input!

Hadronic vertex for CC

$$\Gamma^{\mu}_{cc}(q) = \gamma^{\mu} F_1^V(Q^2) + \frac{i\sigma^{\mu\nu} q_\nu}{2M} F_2^V(Q^2) - \gamma_\mu \gamma_5 G_A(Q^2) - q^\mu \gamma_5 \frac{F_P(Q^2)}{2M}$$

vector form factors

CVC *(Conserved Vector Current)*

$$F^V_{1,2}(Q^2) = F^p_{1,2}(Q^2) - F^n_{1,2}(Q^2)$$

electromagnetic form factors known from the electron scattering data

axial form factor

$$g_A = 1.2673$$

$$G_A(Q^2) = \frac{g_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$

axial mass

pseudoscalar form factor

PCAC *(Partially Conserved Axial Current)*

$$F_P(Q^2) = \frac{4M^2}{m_\pi^2 + Q^2} G_A(Q^2)$$

Hadronic vertex for NC

$$\Gamma^{\mu}_{NC,p(n)} = \gamma^{\mu} F_1^{NC,p(n)} + \frac{i\sigma^{\mu\nu} q_\nu}{2M} \gamma^{\mu} F_2^{NC,p(n)} - \gamma^{\mu}\gamma_5 G_A^{NC,p(n)}$$

$$F_{1,2}^{NC,p(n)}(Q^2) \;=\; \pm\frac{1}{2}\left\{F^p_{1,2}(Q^2) - F^n_{1,2}(Q^2)\right\} - 2\sin^2\theta_W F_{1,2}^{p(n)}(Q^2) - \frac{1}{2} F^s_{1,2}(Q^2)$$

strange form factor = 0

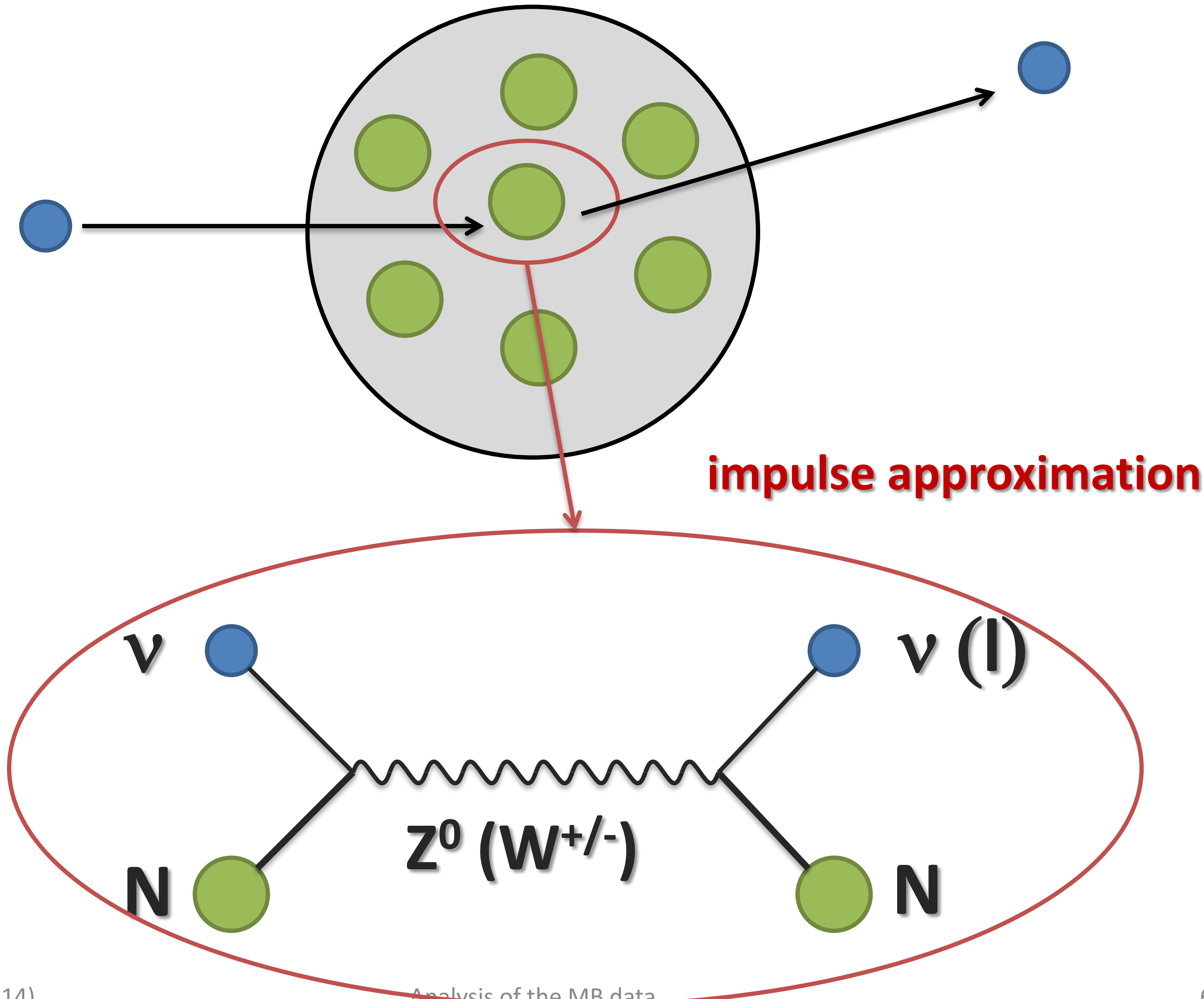
$$G_A^{NC,p(n)}(Q^2) \;=\; \pm\frac{1}{2} G_A(Q^2) - \frac{1}{2} G_A^s(Q^2)$$

strange axial form factor

$$G_A^s(Q^2) = \frac{g_A^s}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$

to be obtained from the experiment

Elastic scattering off nucleus



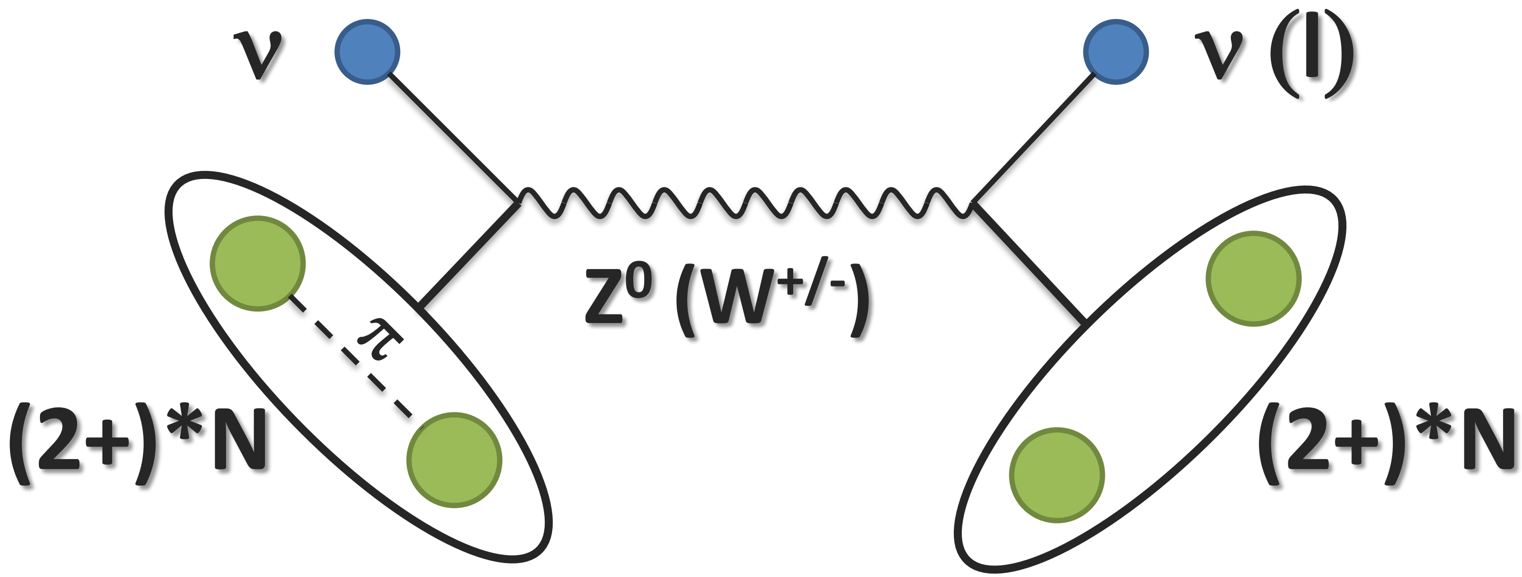
Axial mass measurements

x -> y (peak in x, tail to y)

Experiment	Target	<E_ν> [GeV]	M_A [GeV]	Reference
ANL	D	0.5 -> 6	**1.00** +/- 0.05	PRD 26, 537 (1982)
FNAL	D	27	**1.05** +0.12/-0.16	PRD 28, 436 (1983)
BNL	D	1.6	**1.07** +0.040/-0.045	PRD 42, 1331 (1990)
BNL	Fe	0.5 -> 6	**1.05** +/- 0.2	PRL 22, 1014 (1969)
CERN	CF_3Br	0.5 -> 6	**0.94** +/- 0.17	PRD 16, 3103 (1977)
BNL	HC, Al (?)	0.5 -> 6	**1.06** +/- 0.05	PRD 35, 785 (1987)
SKAT	CF_3Br	9.0	**1.04** +/- 0.05 +/- 0.14	ZPhysC 45, 551 (1990)
NOMAD	C	24	**1.05** +/- 0.02 +/- 0.06	EurPhJC 63, 355 (2009)
K2K	H_2O	1.3	**1.20** +/- 0.12	PRD 74, 052002 (2006)
MINOS	Fe	10 -> 30	**1.26** +/- 0.17	AIPCon 1189, 133 (2009)
MiniBooNE	CH_2	0.81	**1.35** +/- 0.17	PRD81, 013005 (2010)

MEC was not included in the analysis.

Meson Exchange Currents



There are 3 models implemented in NuWro:

- IFIC group model (Nieves et al.) for CC
- Lyon group model (Marteau et al.) for CC
- **Transverse Enhancement (TE) model (Bodek et al.) for CC i NC**

Transverse Enhancement model

The MEC contribution is introduced by a modification of the vector magnetic form factors:

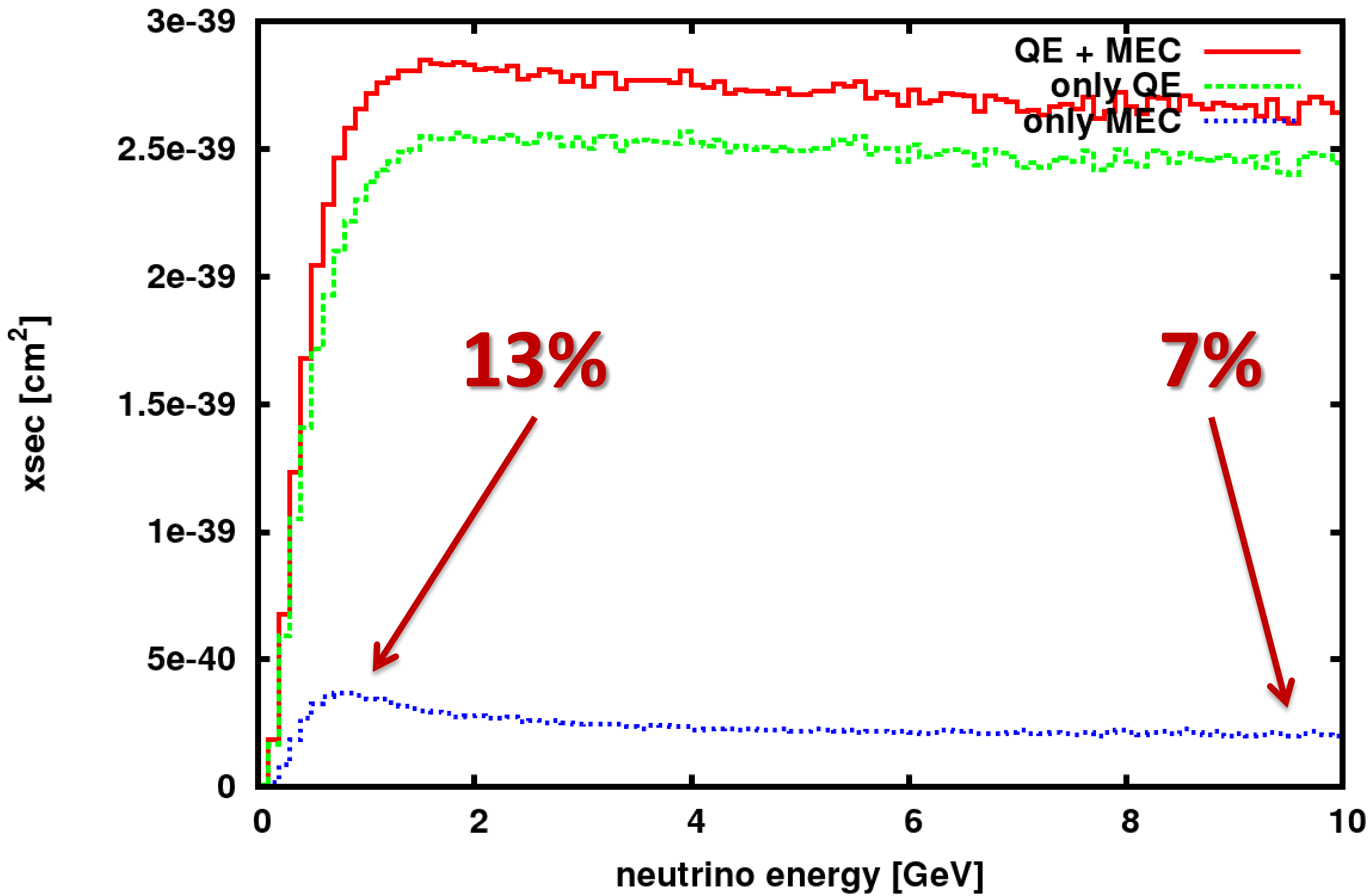
$$G_M^{p,n} \rightarrow \tilde{G}_M^{p,n} = \sqrt{1 + AQ^2 \exp\left(-\frac{Q^2}{B}\right)} G_M^{p,n}(Q^2)$$

$A = 6\ \mathrm{GeV}^{-2}$ and $B = 0.34\ \mathrm{GeV}^2$ **are set from the electron scattering data.**

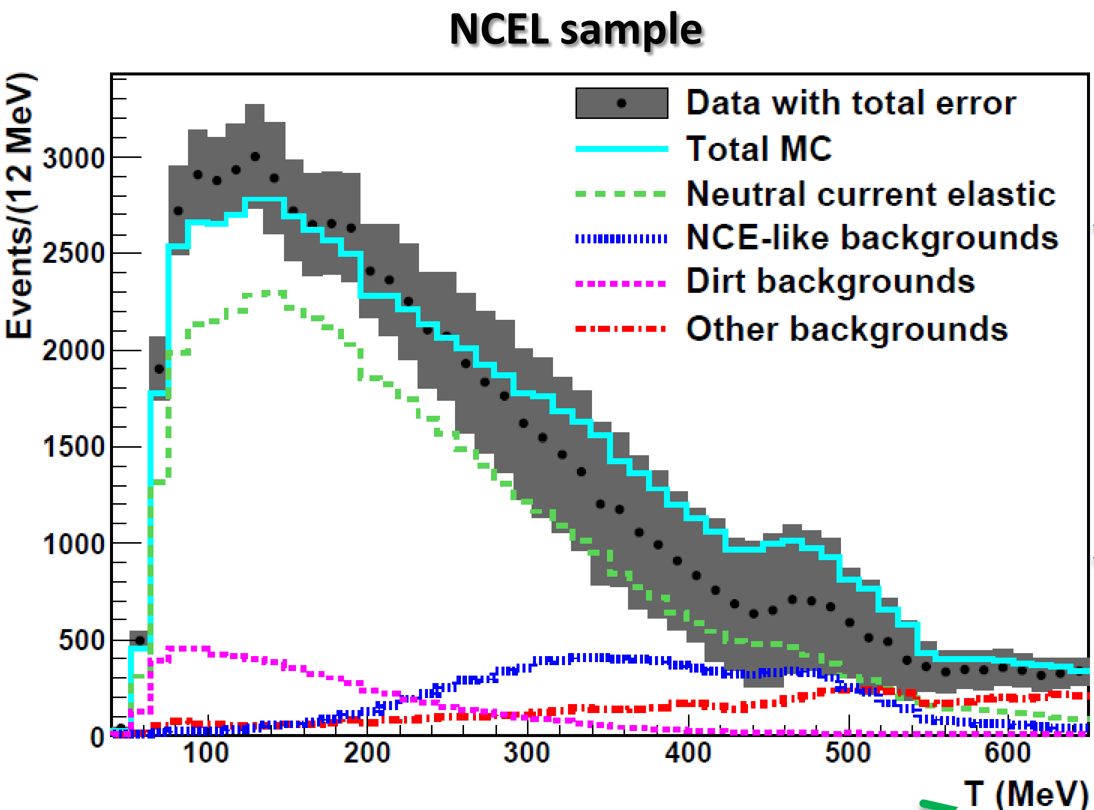
The MEC cross section is calculated from the difference:

$$\frac{d^2\sigma^{\mathrm{MEC}}}{dq d\omega} \equiv \frac{d^2\sigma^{\mathrm{NCE}}}{dq d\omega}(\tilde{G}_M^{p,n}) - \frac{d^2\sigma^{\mathrm{NCE}}}{dq d\omega}(G_M^{p,n})$$

Cross section per nucleon (NC elastic and MEC)



MiniBooNE data (PRD 82, 092005 (2010))



Events with no charged lepton in a final state

Only protons are visible (neutrons are seen as an effect of secondary interactions)

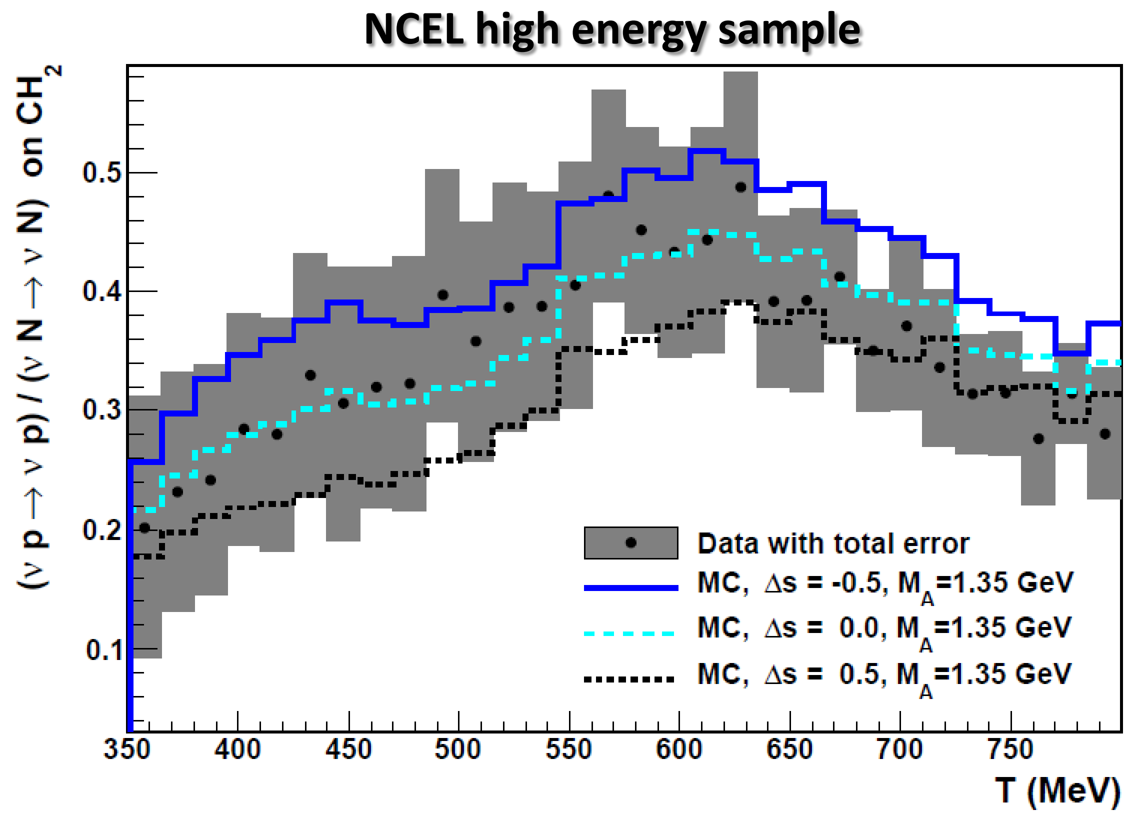
Sum of kinetic energies of all nucleons as seen in the detector

Measured axial mass = 1.39 +/- 0.11 GeV for $g_s^A = 0$

MiniBooNE data (PRD 82, 092005 (2010))

Measured strange quark contribution to the form factors (for MA = 1.35 GeV):

$g_A^s = 0.08 +/- 0.26$



" νp -> νp " = events with proton above Cherenkov treshold and $\theta > 60^0$

one can assume that those are events on proton without reinteractions

Unfolding procedure

- MB data are presented as a function of recontructed kinetic energy (ν)
- theory predicts distributions in true kinetic energy (μ)
- unfolding procedure translate μ ←→ ν

response matrix

$$\nu_j^{MC} = \sum_i R_{ij}^{(1)}\mu_i^{(1)} + \sum_i R_{ij}^{(2)}\mu_i^{(2)} + \sum_i R_{ij}^{(3)}\mu_i^{(3)} + \sum_i R_{ij}^{(4)}\mu_i^{(4)} + \sum_i R_{ij}^{(5)}\mu_i^{(5)} + \nu_j^{BKG}$$

dirt and other backgrounds

Potential signals:

1. scattering on hydrogen
2. scattering on proton w/o FSI
3. scattering on proton with FSI
4. scattering on neutron
5. NCE-like background (π production + absorption)

There is no MEC in MB analysis!

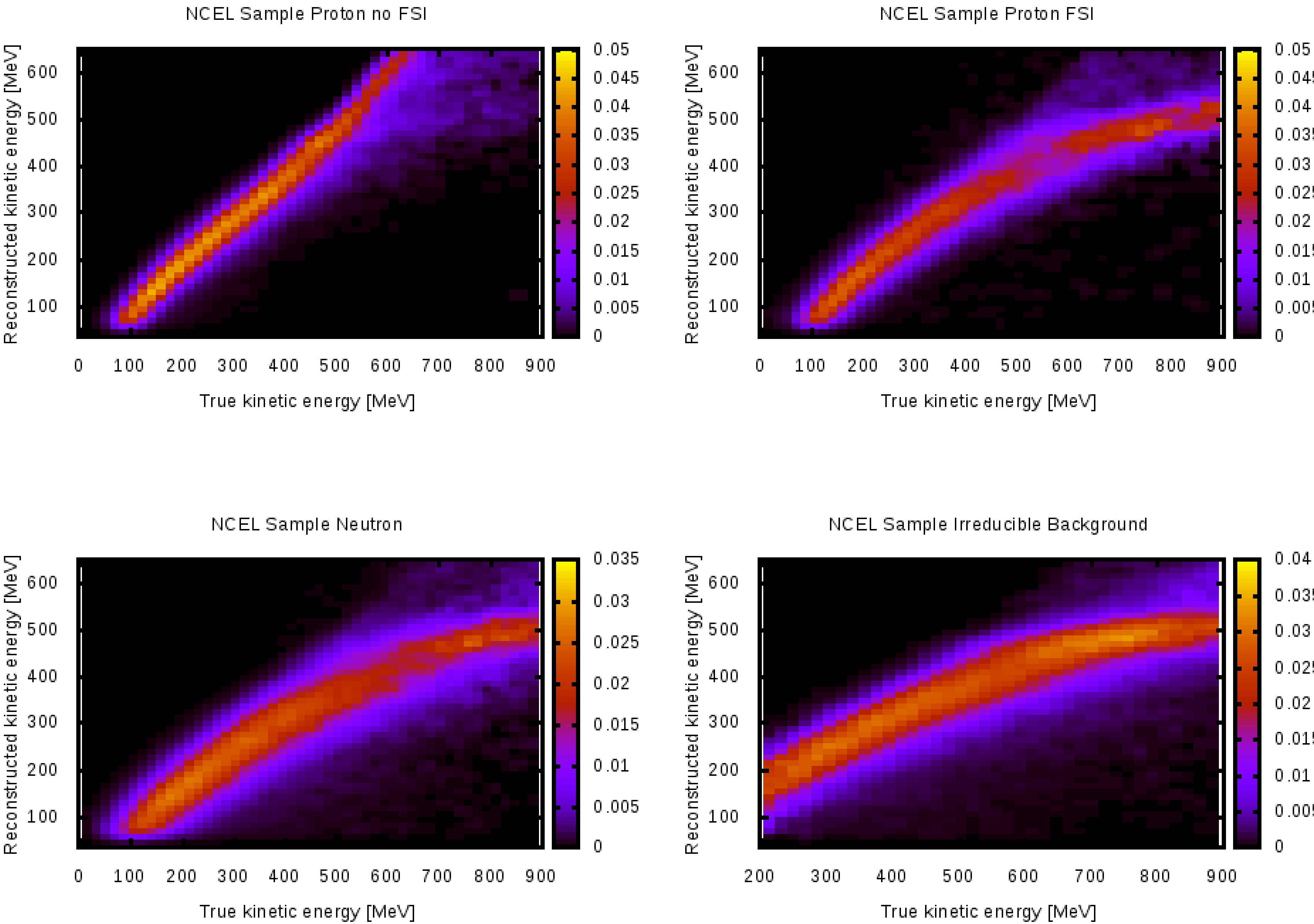
Reponse matrices

- five 51x51 matrices for NCEL sample
  - for true kinetic energy: 50 bins from 0 to 900 MeV

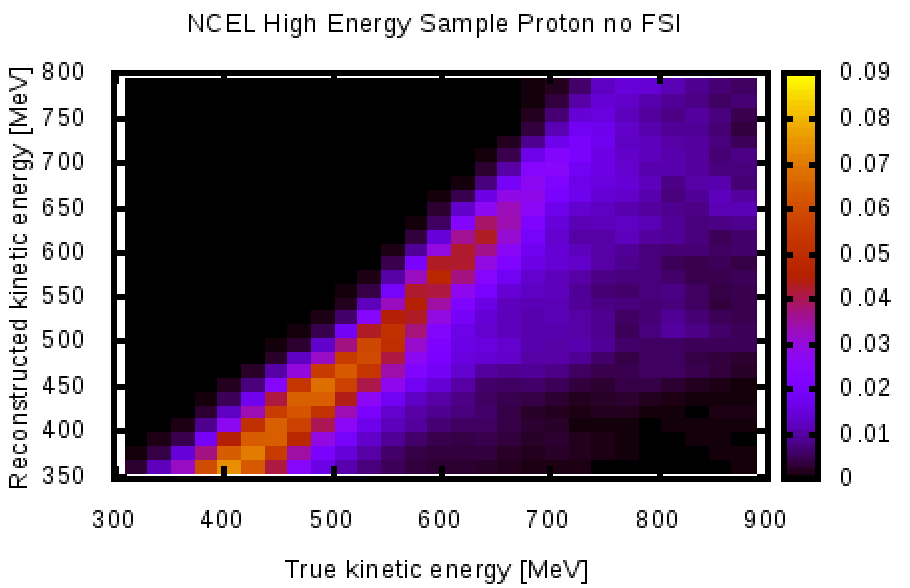
    + one overflow
  - for recontructed kinetic energy: 51 bins from 40 to 650 MeV
- ten 30x30 matrices for NCEL high energy sample

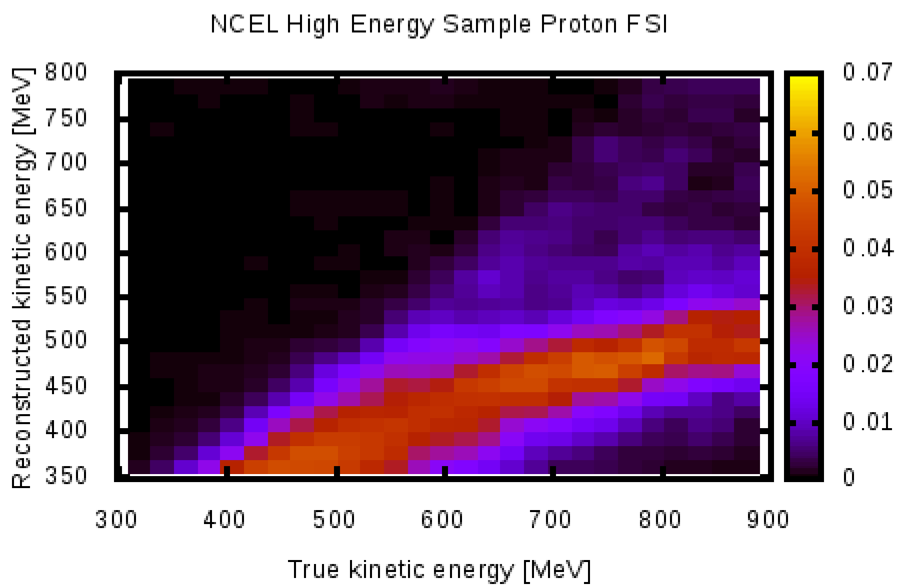
  (5 for numerator and 5 for denominator)
  - for true kinetic energy: 28 bins from 300 to 900 MeV

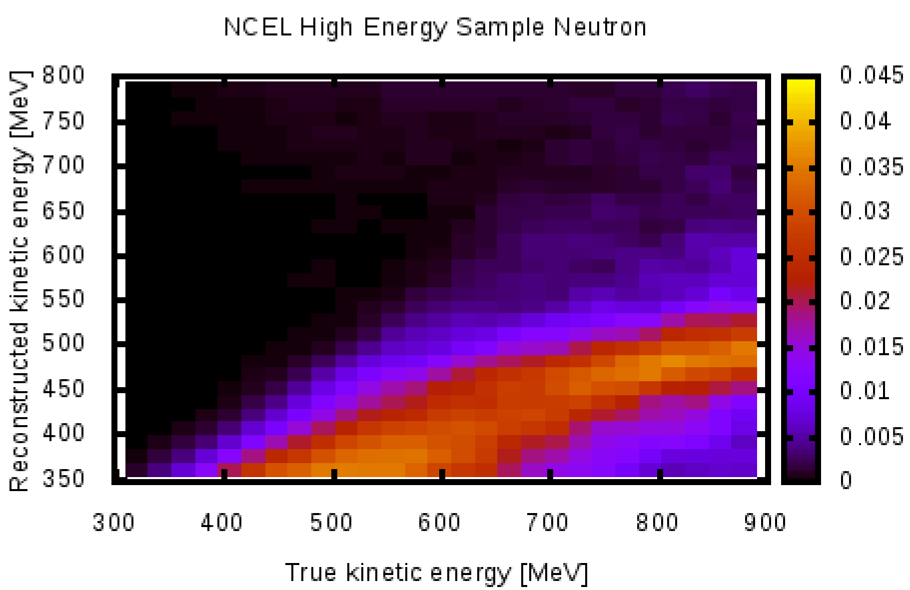
    + one overflow and one underflow
  - for reconstructed kinetic energy: 30 bins od 350 to 800 MeV
- each column is normalized to the efficiency

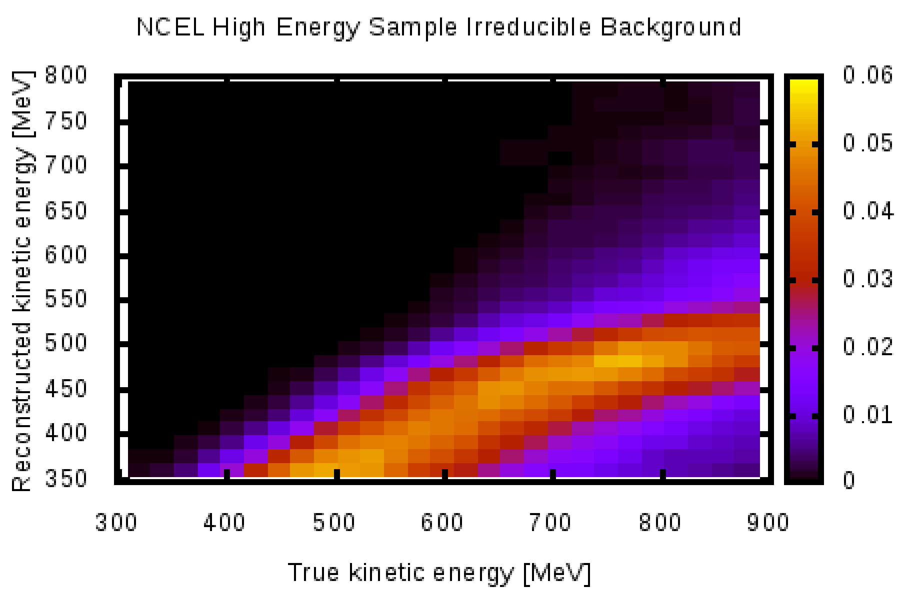


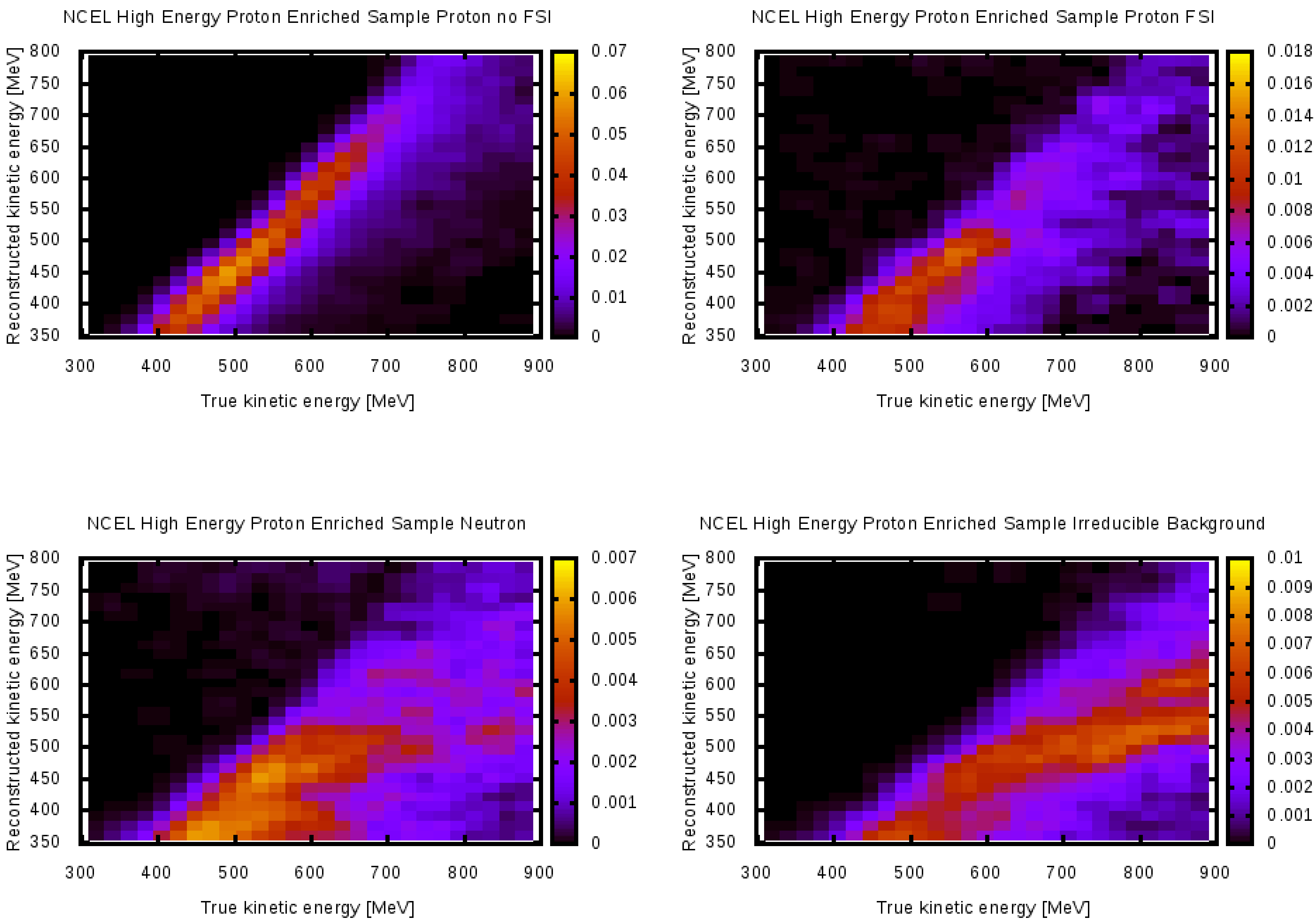
NCEL Sample Proton no FSI
NCEL Sample Proton FSI
NCEL Sample Neutron
NCEL Sample Irreducible Background
Reconstructed kinetic energy [MeV]
True kinetic energy [MeV]
100
200
300
400
500
600
700
800
900
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045
0.05


NCEL High Energy Sample Proton no FSI
Reconstructed kinetic energy [MeV]
True kinetic energy [MeV]
350
400
450
500
550
600
650
700
750
800
300
400
500
600
700
800
900
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09

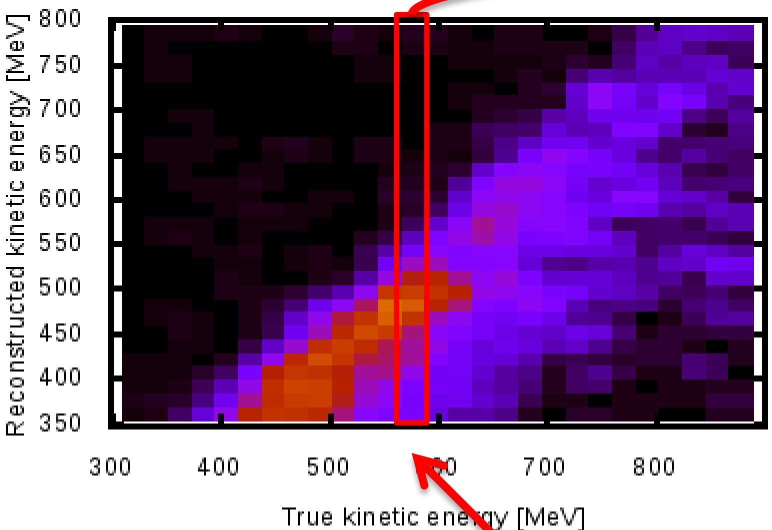

NCEL High Energy Sample Proton FSI
Reconstructed kinetic energy [MeV]
True kinetic energy [MeV]
350
400
450
500
550
600
650
700
750
800
300
400
500
600
700
800
900
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07


NCEL High Energy Sample Neutron
Reconstructed kinetic energy [MeV]
True kinetic energy [MeV]
350
400
450
500
550
600
650
700
750
800
300
400
500
600
700
800
900
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045


NCEL High Energy Sample Irreducible Background
Reconstructed kinetic energy [MeV]
True kinetic energy [MeV]
350
400
450
500
550
600
650
700
750
800
300
400
500
600
700
800
900
0
0.01
0.02
0.03
0.04
0.05
0.06


NCEL High Energy Proton Enriched Sample Proton no FSI
NCEL High Energy Proton Enriched Sample Proton FSI
NCEL High Energy Proton Enriched Sample Neutron
NCEL High Energy Proton Enriched Sample Irreducible Background
Reconstructed kinetic energy [MeV]
True kinetic energy [MeV]
300 400 500 600 700 800 900
350 400 450 500 550 600 650 700 750 800
0 0.01 0.02 0.03 0.04 0.05 0.06 0.07
0 0.002 0.004 0.006 0.008 0.01 0.012 0.014 0.016 0.018
0 0.001 0.002 0.003 0.004 0.005 0.006 0.007
0 0.001 0.002 0.003 0.004 0.005 0.006 0.007 0.008 0.009 0.01

Our unfolding procedure



Σ  = efficiency

for each event we count (μ) sum of kinetic energies of all nucleons

using distribution we decide what energy was visible in the detector

we decide if event was visible in the detector

Our unfolding procedure for MEC

- there was no MEC in MB analysis
- in MEC the interaction occurs on two nucleons
- we can not treat each nucleon separately

(single proton may not create enough PMT hits to be visible, but together they can)

- we count μ for all nucleons in final state

and use reponse matrix for signal:

  - on neutron, for events with two neutrons in final state
  - on proton with FSI, for other cases

Proton-enriched for MEC

- if there is a proton with $\theta > 60^0$, we translate its energy to reconstructed (as for proton w/o FSI signal) and check if it is above Cherenkov treshold to decide if the event gives contribution to the numerator of the ratio

Results

Following the MiniBooNE procedure we assume $g_A^s = 0$ and obtain (from the first observable):

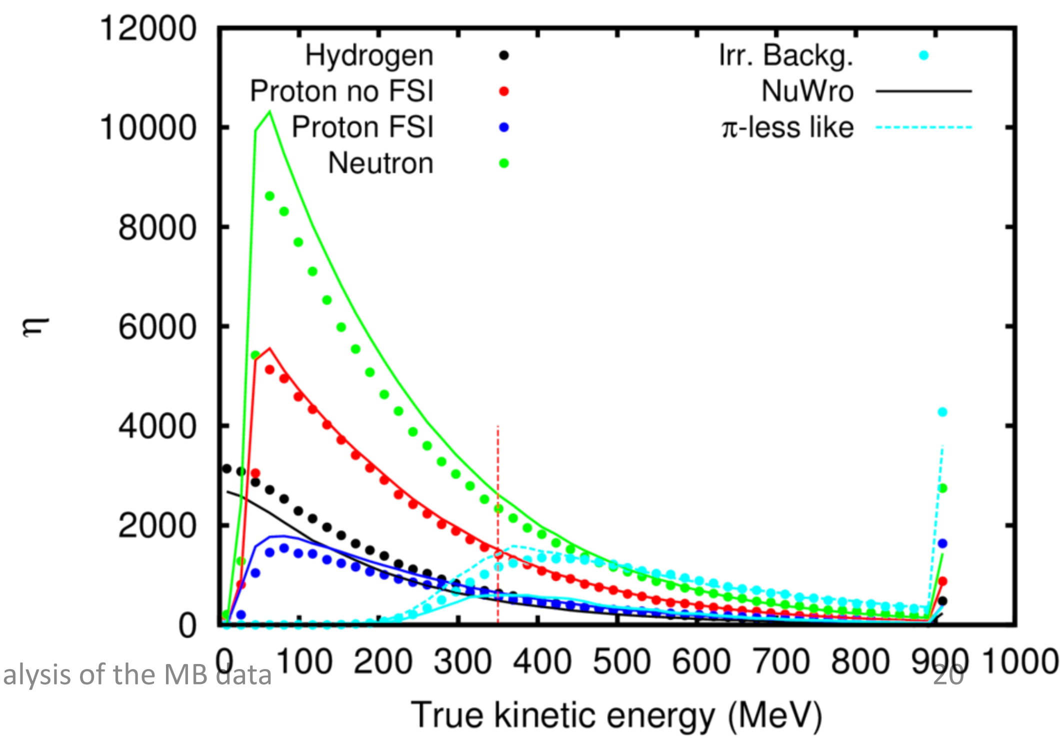
M_A = **1.47 +/- 0.10** GeV (MB result: M_A = **1.39 +/- 0.11** GeV)

Using the M_A = 1.47 GeV we extract the strangeness from the second observable with the result:

g_A^s = **0.24 +/- 0.46** (MB result: g_A^s = **0.08 +/- 0.26**)

The difference comes from π-less Δ decay present in NUANCE, but not in NuWro.

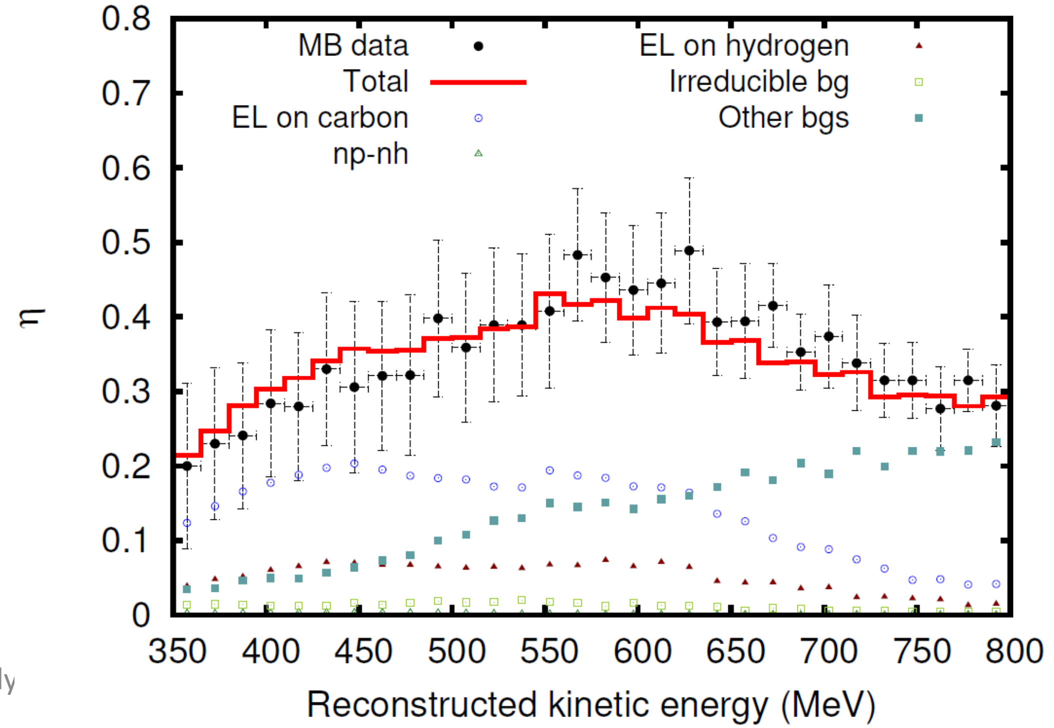
It would be double counting, as we are going to include MEC.



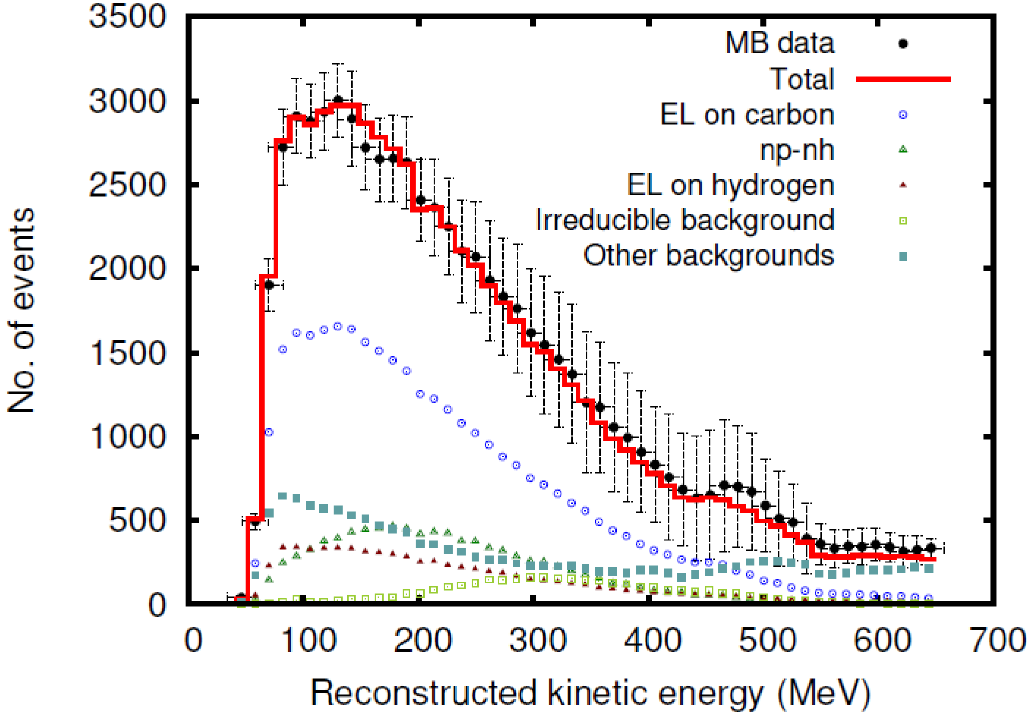
The ratio

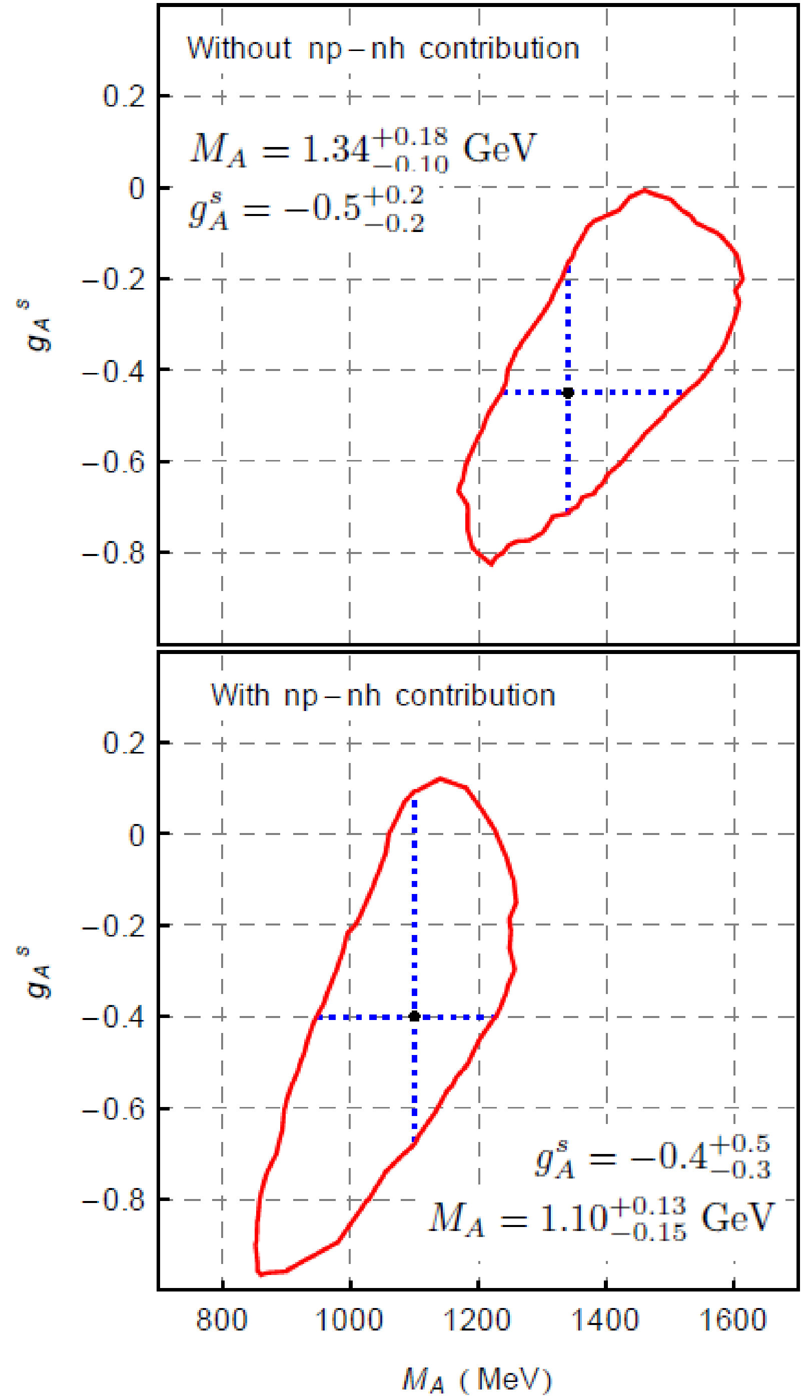
In a further part of the analysis we decide to not look at the ratio:

- It is very sensitive to other backgrounds.
- In this energy range there is quite large contribution from irreducible background.
- Using toy models based on TE model, but with modified distribution of energy transfer (based on Nieved model), we checked that the ratio it is very sensitive on that.



Two parameters fit





Summary

- including the MEC in the MB data analysis lead to axial mass value consistent with older measurements

- the ratio is very sensitive on the strange quark contribution to the from factors, however, it is also very sensitive to the background and dynamics model of MEC

- further investigation of neutral current would be very interesting and could discriminate between the models of MEC