# How accurately do we estimate the (anti)neutrino NCE and CCQE cross sections?

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# Outline

1. Axial mass determination
2. Selected theoretical estimates of multinucleon contribution to the (anti)neutrino cross sections
3. Review of the available NCE and CCQE data
4. Uncertainty of the (anti)neutrino cross sections for carbon
5. Summary

# Axial mass

# Axial mass

The axial form factor is typically parametrized as

$$F_A \propto 1/(1+Q^2/M_A^2)^2,$$

with the cutoff parameter $M_A$ called the axial mass.

The axial mass may be determined from charged-pion electroproduction or from neutrino scattering.

# Axial mass

The sizable contribution of $F_A$ to the cross section allows the $M_A$ determination from

- the absolute value of the cross section
- shape analysis of (some) distribution of events

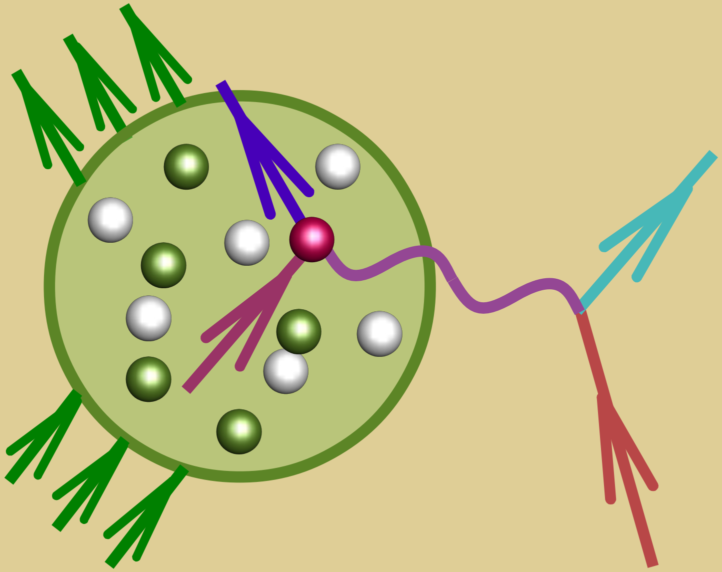
The two methods are equivalent for free nucleons.

For nuclear targets, this may not be the case without the accurate description of nuclear effects.

# Nuclear effects in the simplest case: impulse approximation (IA) regime

When the momentum transfer |**q**| is high enough, the nucleus may be treated as a collection of individual nucleons, as the probe's spatial resolution is ~1/|**q**|.

Then the scattering involves predominantly a single nucleon, and the remaining ones act as a spectator system.



# Nuclear effects in the IA

In the **IA regime**, nuclear effects have much larger influence on the **normalization** of the differential cross section than on its **shape**.

Example: NCE (or CCQE) scattering at the MiniBooNE kinematics. Then the SF and RFG approaches yield $d\sigma/dQ^2$ such that

- their shapes differ by **< 2.5%** for $0.13<Q^2<2$ GeV$^2$
- their absolute values differ by **13%**.

Stronger model dependence

# Nuclear effects in the IA

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Example: NCE (or CCQE) scattering at the MiniBooNE kinematics. Then the SF and RFG approaches yield $d\sigma/dQ^2$ such that

- their shapes differ by **< 2.5%** –
- their absolute

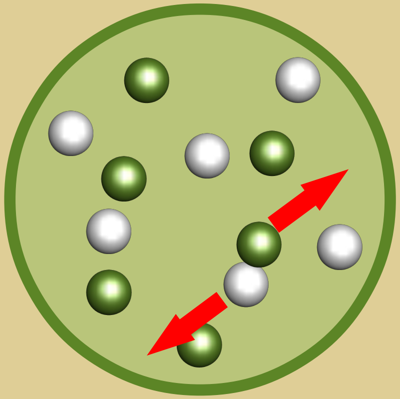
MiniBooNE: similar $M_A$

NOMAD: 1.05 (RFG) vs. 1.17 – 1.23 (SF)

# Nuclear effects in the IA

The main source of the difference between the two models are **short-range correlations (SRC)**, accounted for in the SF approach.

SCR create NN (typically np) pairs with high relative momentum, moving ~20% of nucleons from low-binding shell-model states to high binding states.



# Nuclear effects beyond the IA

The effects beyond the IA (multinucleon reaction mechanisms) affect both the shape of the differential cross section and its absolute value.

What is very important, in a broad kinematical range of MiniBooNE, these effects may be accounted for by using an effective value of $M_A$.

Nieves *et al.*, PLB **707**, 72 (2012)

# Low-$Q^2_{rec}$ region

For $Q^2_{rec} \lesssim 0.2$ GeV$^2$, the cross section is not well understood:

R. Gran *et al*. (K2K), PRD **74**, 052002 (2006);

K. Hiraide *et al*. (SciBooNE), PRD **78**, 112004 (2008);

Aguilar-Arevalo *et al*. (MiniBooNE), PRL **100**, 032301 (2008);

M. Dorman (MINOS), AIP Conf. Proc. **1189**, 133 (2009)

# Low-$Q^2_{rec}$ region

This issue is related to the breakdown of the IA for $|q| \lesssim 450$ MeV.

At this kinematics, multinucleon effects in the interaction vertex and in the final state become important.

AMA, Proc. Sci. NUFACT08, 118 (2008);

AMA, O. Benhar, and N. Farina, PRD **82**, 013002 (2010);

AMA and O. Benhar, PRC **83**, 054616 (2011)

# Axial mass from shape analysis

- $1.144 \pm 0.077$ GeV for $^{12}C$,
  C. Mariani (K2K), AIP Conf. Proc. **981**, 247 (2008)
- $1.23 \pm 0.20$ GeV for $^{12}C$, $\langle E \rangle = 0.8$ GeV,
  Aguilar-Arevalo *et al*. (MiniBooNE),PRL **100**, 032301 (2008)
- $1.07 \pm 0.06$(stat)$\pm 0.07$(syst) GeV for $^{12}C$,$\langle E \rangle = 25.9$ GeV
  V.Lyubushkin *et al.* (NOMAD), EPJ C **63**, 355 (2009)
- $1.35 \pm 0.17$ GeV for $^{12}C$, $\langle E \rangle = 0.8$ GeV,
  Aguilar-Arevalo *et al*. (MiniBooNE), PRD **81**, 092005 (2010)
- $1.20 \pm 0.12$ GeV for $^{16}O$, $\langle E \rangle = 1.3$ GeV,
  R. Gran *et al.* (K2K), PRD **74**, 052002 (2006)
- $1.19^{+0.09}_{-0.10}$(fit)$^{+0.12}_{-0.14}$(syst) GeV for $^{56}Fe$, all $Q^2$, peak at 3 GeV
  M. Dorman (MINOS), AIP Conf. Proc. **1189**, 133 (2009)

# Axial mass determination

- The $M_A$ extraction from the absolute x-section shows **stronger model dependence** than the shape analysis
- The shape analysis yields an effective axial mass when multinucleon processes are not modeled accurately
- The cross section uncertainties increase in the low-$Q^2$ region

# Theoretical cross sections

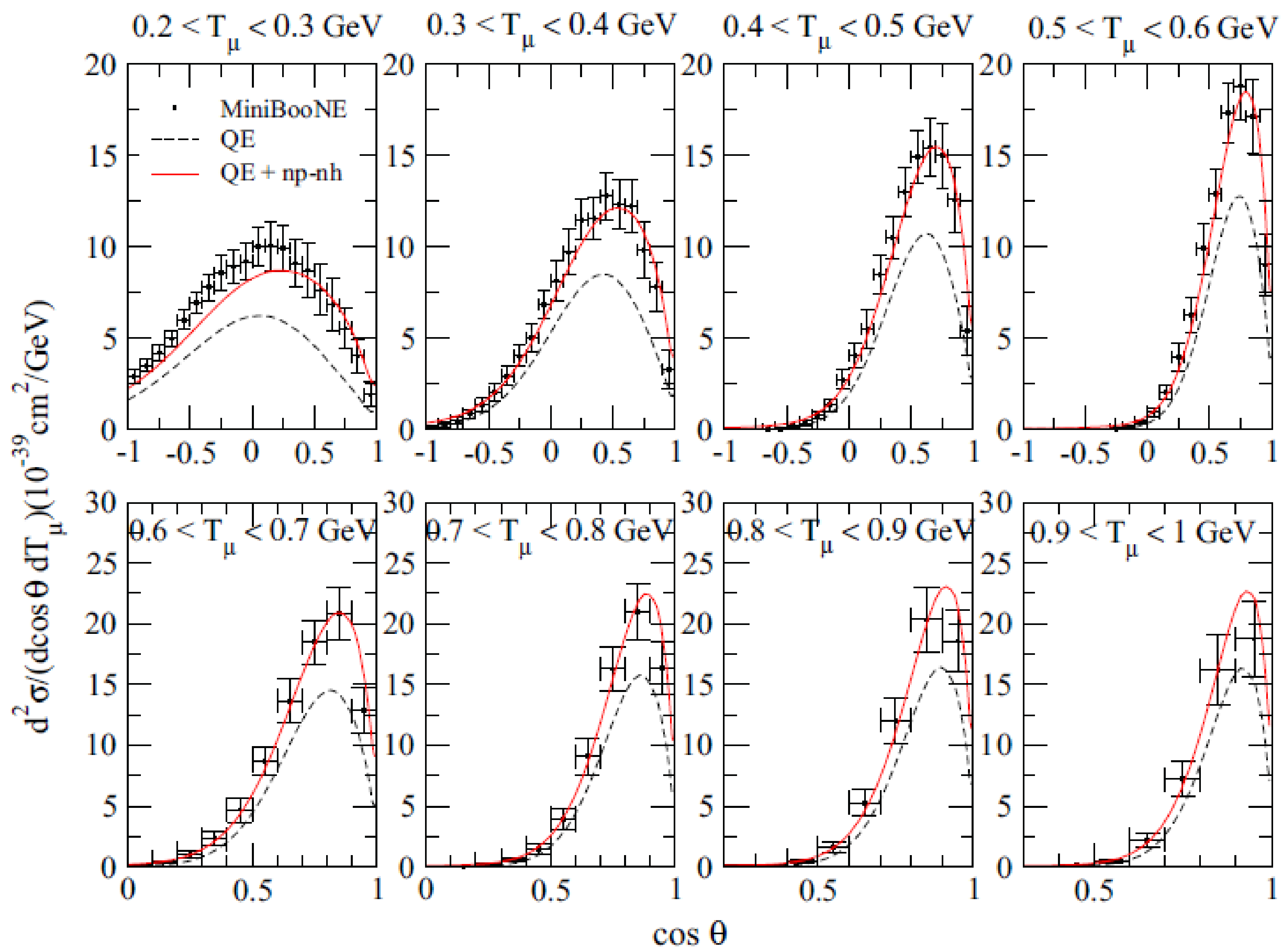
# Martini *et al.*

- PRC **80**, 065501 (2009); PRC **81**, 045502 (2010); PRC **84**, 055502 (2011); based on the approach of Marteau [EPJ A 5, 183 (1999)]; 2p2h processes from Alberico at al. [Annals Phys. **154**, 356 (1984)] ; 3p3h contribution from Oset & Salcedo [NPA **468**, 631 (1987)]

- RPA effects, 2p2h and 3p3h reaction mechanisms

- Very good agreement with the $d\sigma/d\cos\theta \, dT_\mu$ extracted from MiniBooNE

# Martini *et al.*

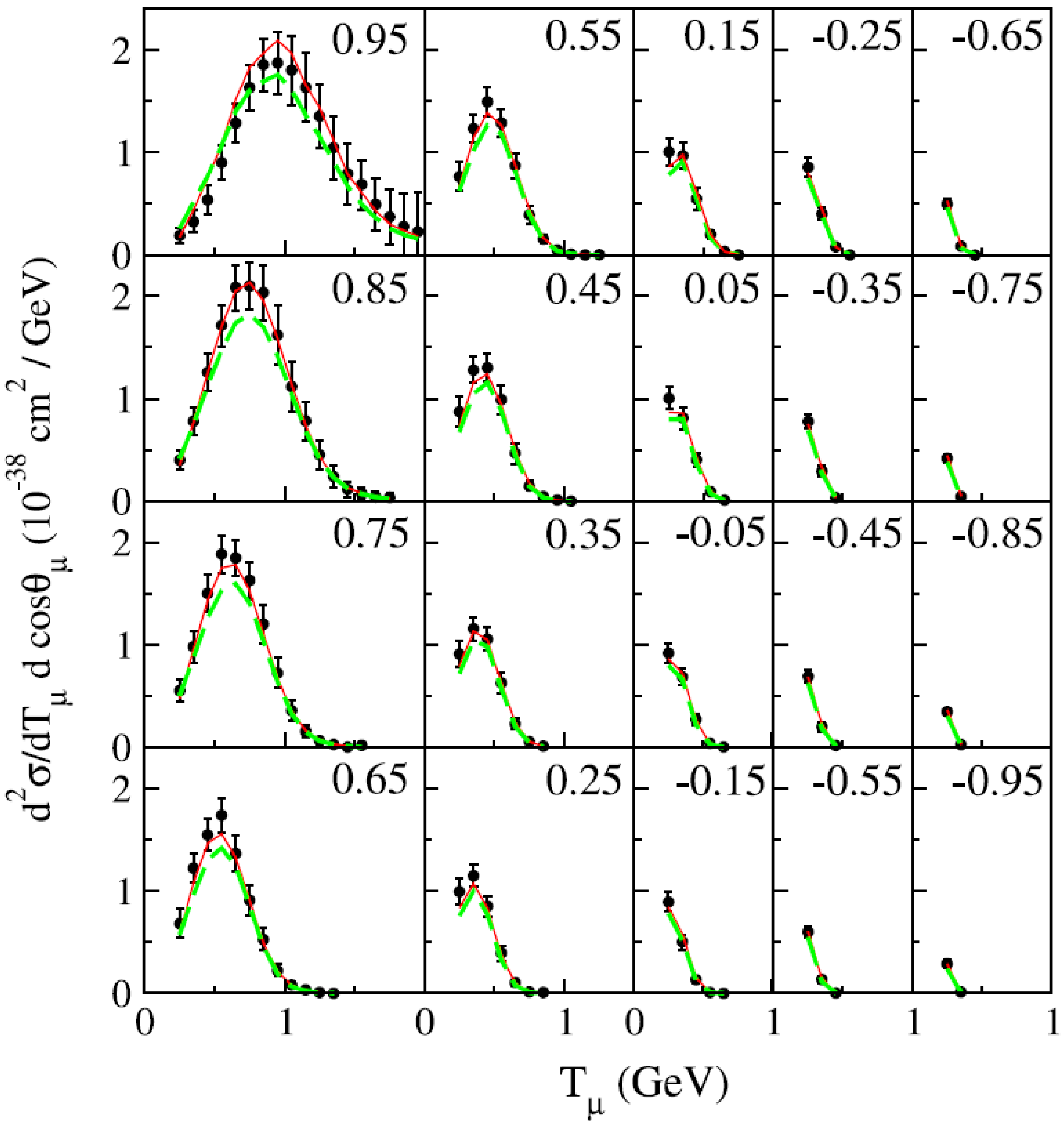


# Nieves *et al.*

- PRC **83**, 045501 (2011); PLB **707**, 72 (2012)
- Effective interaction determined from data for photon, electron, and pion scattering off nuclei, **no free parameters**
- RPA effects, including Δ-hole degrees of freedom and explicit π and ρ meson exchanges in the vector-isovector channel of NN interaction
- The shape of dσ/dcosθ d$T_\mu$ from MiniBooNE described very accurately. The normalization underestimated by 9% for $M_A$ = 1.077 GeV (20.5% for $M_A$ = 1.007 GeV)

***See Juan's talk on Friday***

# Nieves *et al.*



0.95
0.55
0.15
-0.25
-0.65
0.85
0.45
0.05
-0.35
-0.75
0.75
0.35
-0.05
-0.45
-0.85
0.65
0.25
-0.15
-0.55
-0.95
d²σ/dT_μ d cosθ_μ (10⁻³⁸ cm² / GeV)
T_μ (GeV)

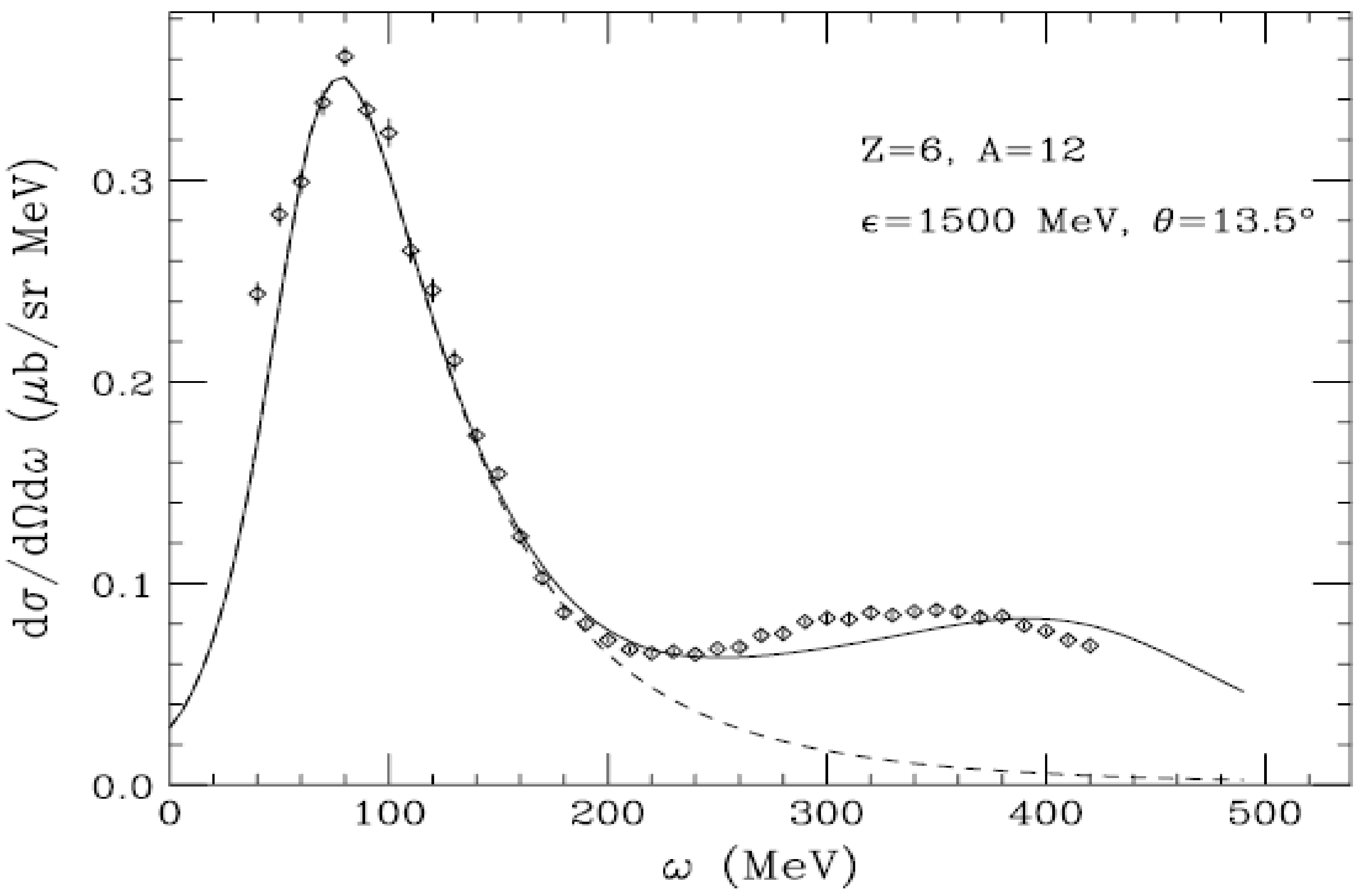
# Superscaling approach of Amaro *et al.*

- PRC **71**, 015501 (2005); PRD **84**, 033004 (2011); PRL **108**, 152501 (2012)
- Universal scaling functions (longitudinal and transverse) allow obtaining the neutrino and electron cross sections

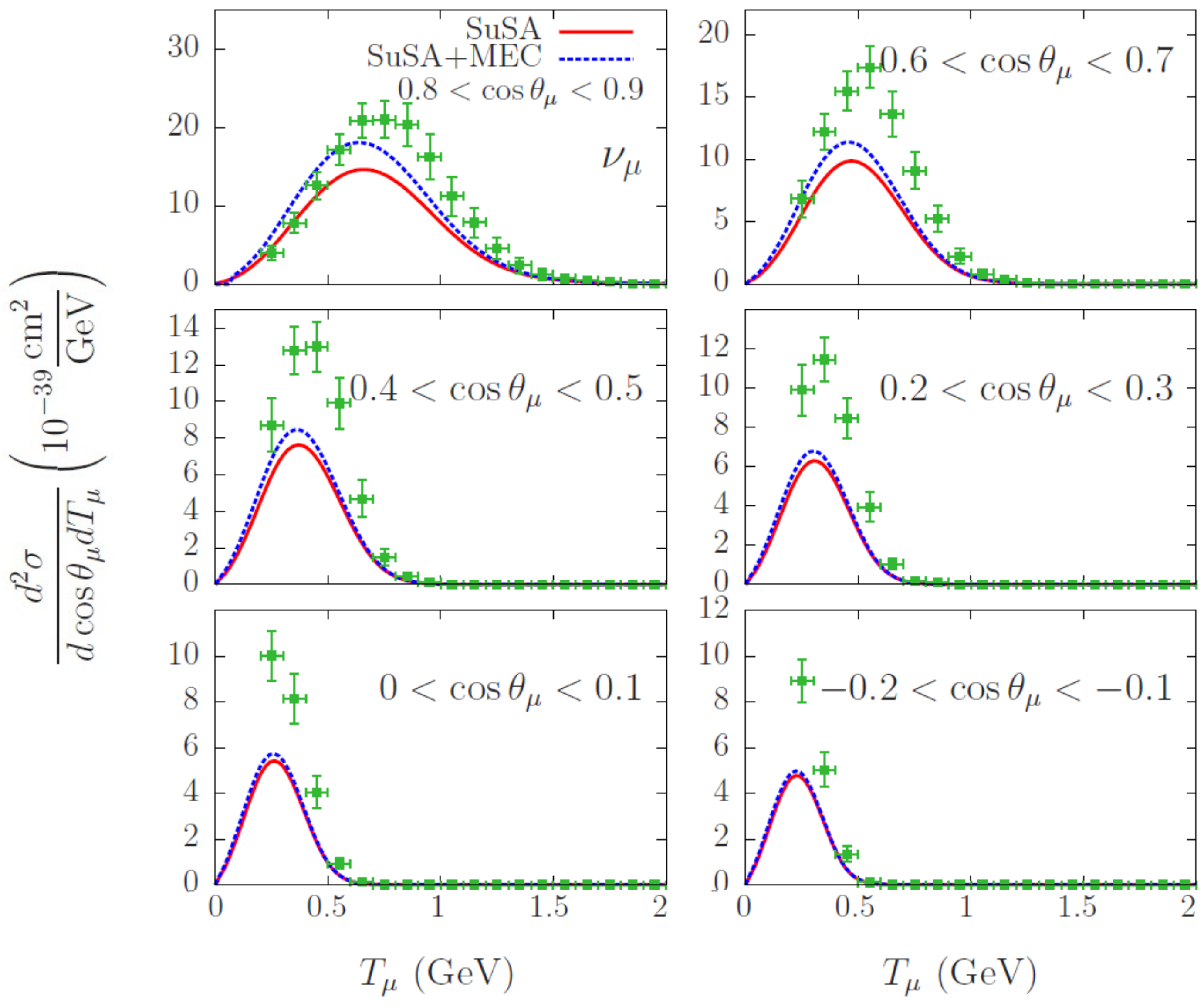
***See Maria's talk on Friday***

- Successful description of the C(e,e') cross section in the region of the QE peak, dip (at some kinematics), and Δ production
- Underestimates the MiniBooNE CCQE cross section

# Superscaling approach of Amaro *et al.*



# Superscaling approach of Amaro *et al.*



# Antineutrino

- Martini *et al*.: minor role of the 2p2h mechanisms in antineutrino scattering

- Nieves *et al*.: the relative contribution of the 2p2h mechnisms similar for neutrino and antineutrino

- Amaro *et al*.: major role of the 2p2h mechanisms in antineutrino scattering (when only the vector part of 2p2h MEC is accounted for)

# Antineutrino

- Experimental evidence from the NOMAD experiment:

$M_A = 1.05 \pm 0.06$ from the $\nu_\mu$ sample

$M_A = 1.06 \pm 0.14$ from the $\bar{\nu}_\mu$ sample

Within the uncertainties, the result is consistent with the role of nuclear effects in neutrino and antineutrino interactions being similar.

# Experimental cross sections

# BNL Experiment 734

- PRL **56**, 1107 (1986); PRL **56**, 1883(E) (1986), PRD **34**, 75 (1986) [flux]; PRD **35**, 785 (1987)
- Scintillator detector, 79% of the target protons bound in carbon and aluminum, 21% of free *p*'s
- Fluxes determination involved fitting to the CCQE event sample, <*E*> = 1.3 (1.2) GeV for the $\nu p$ ($\bar{\nu} p$) beam
- The differential cross section for NCE $\nu p$ ( $\bar{\nu} p$ ) scattering was extracted from 1686 (1821) event candidates [951 (776) events after bkgd subtraction]

# NOMAD

- NIM A **481**, 339 (2002) [detector]; EPJ C **63**, 355 (2009)
- Scintillator detector, 64% of C, 22% of O, 6% of N, 5% of H, 3% of others
- Fluxes determined from a large sample of DIS events and from inverse $\mu$ decay events, $\nu_\mu e \rightarrow \mu \nu_e$, for CCQE $\nu_\mu$ ( $\bar{\nu}_\mu$ ) events <*E*> = 25.9 (17.6) GeV
- The total cross sections for CCQE $\nu_\mu$ ( $\bar{\nu}_\mu$ ) scattering were obtained from 14 021 (2237) events. The 1-track (2-track) events compose ~74% (~26%) of the $\nu_\mu$ sample

# MiniBooNE

- PRL **100**, 032301 (2008) [CCQE]; PRD **79**, 072002 (2009) [flux]; PRD **81**, 092005 (2010) [CCQE], PRD **82**, 092005 (2010) [NCE]
- Cherenkov detector with mineral oil, $CH_2$
- Fluxes determined from the Monte Carlo simulation extrapolating the HARP *p*-Be data
- Reported cross sections:

$d\sigma/dQ^2_{rec}$ for NCE and CCQE $\nu_\mu$ scattering

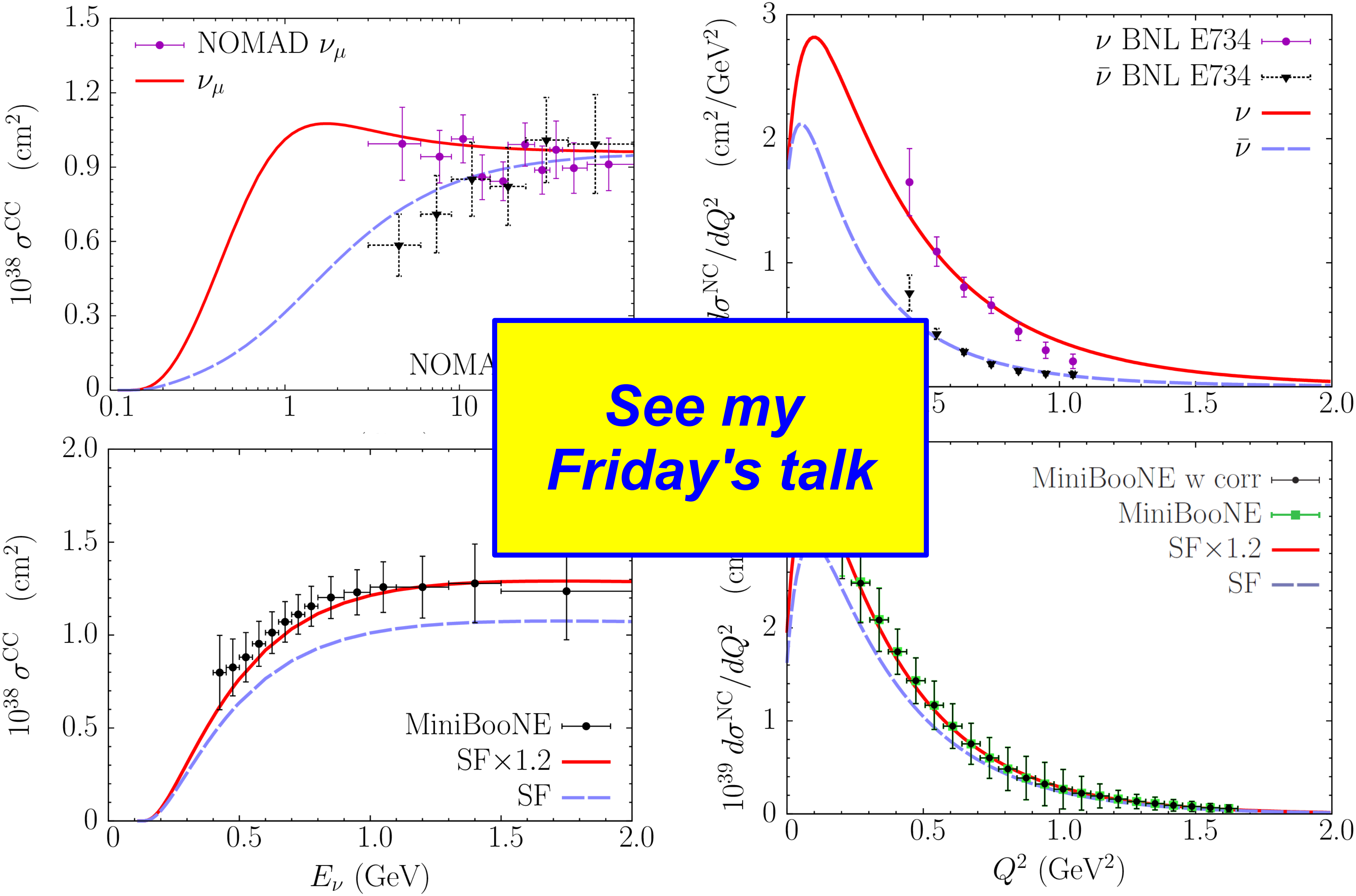
$d^2\sigma/d\cos\theta\, dT_\mu$ for CCQE $\nu_\mu$ scattering

$\sigma(E)$ for CCQE $\nu_\mu$ scattering

# Uncertainty estimate

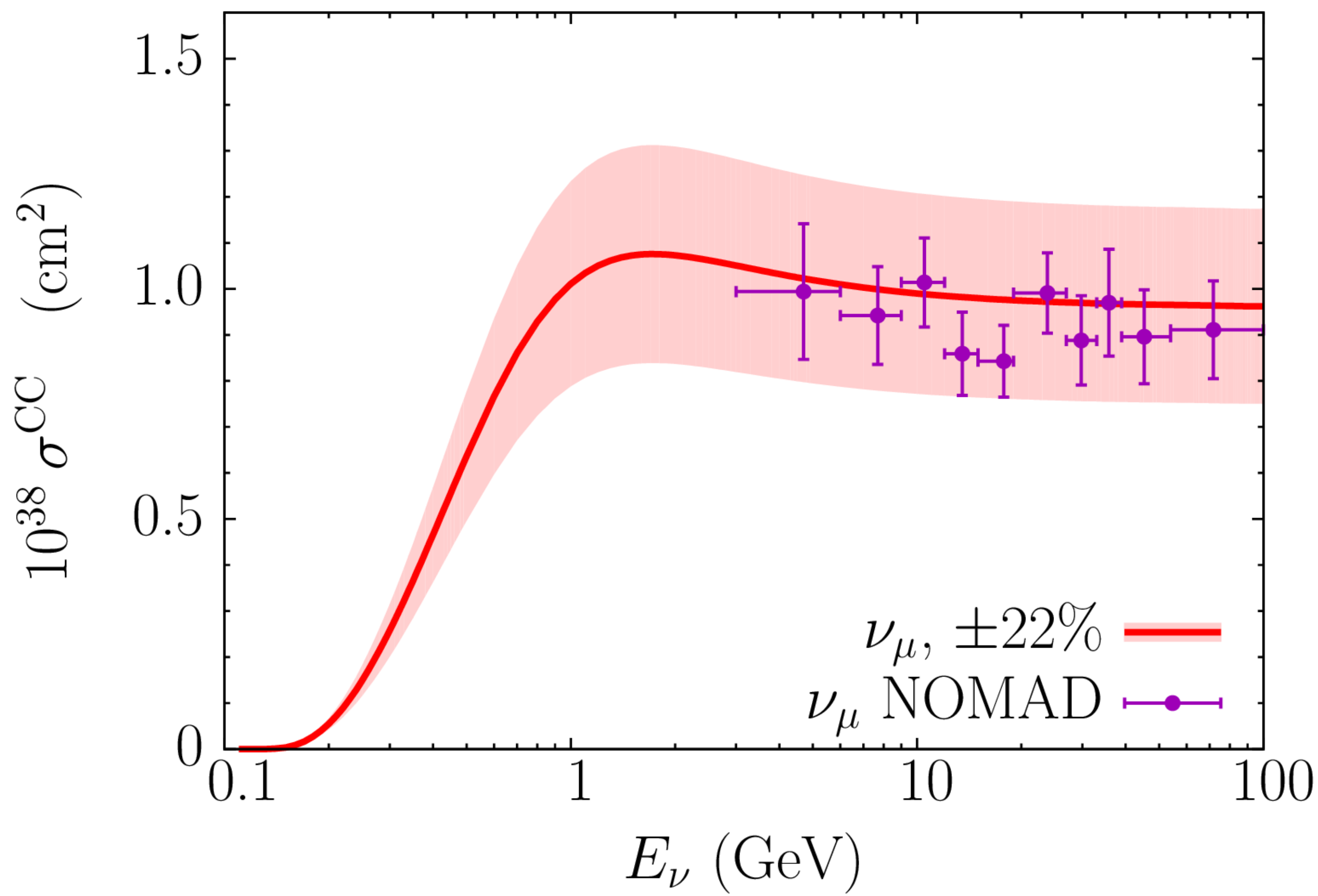
# Advertisement

**Spectral function, $M_A$ = 1.23 GeV**



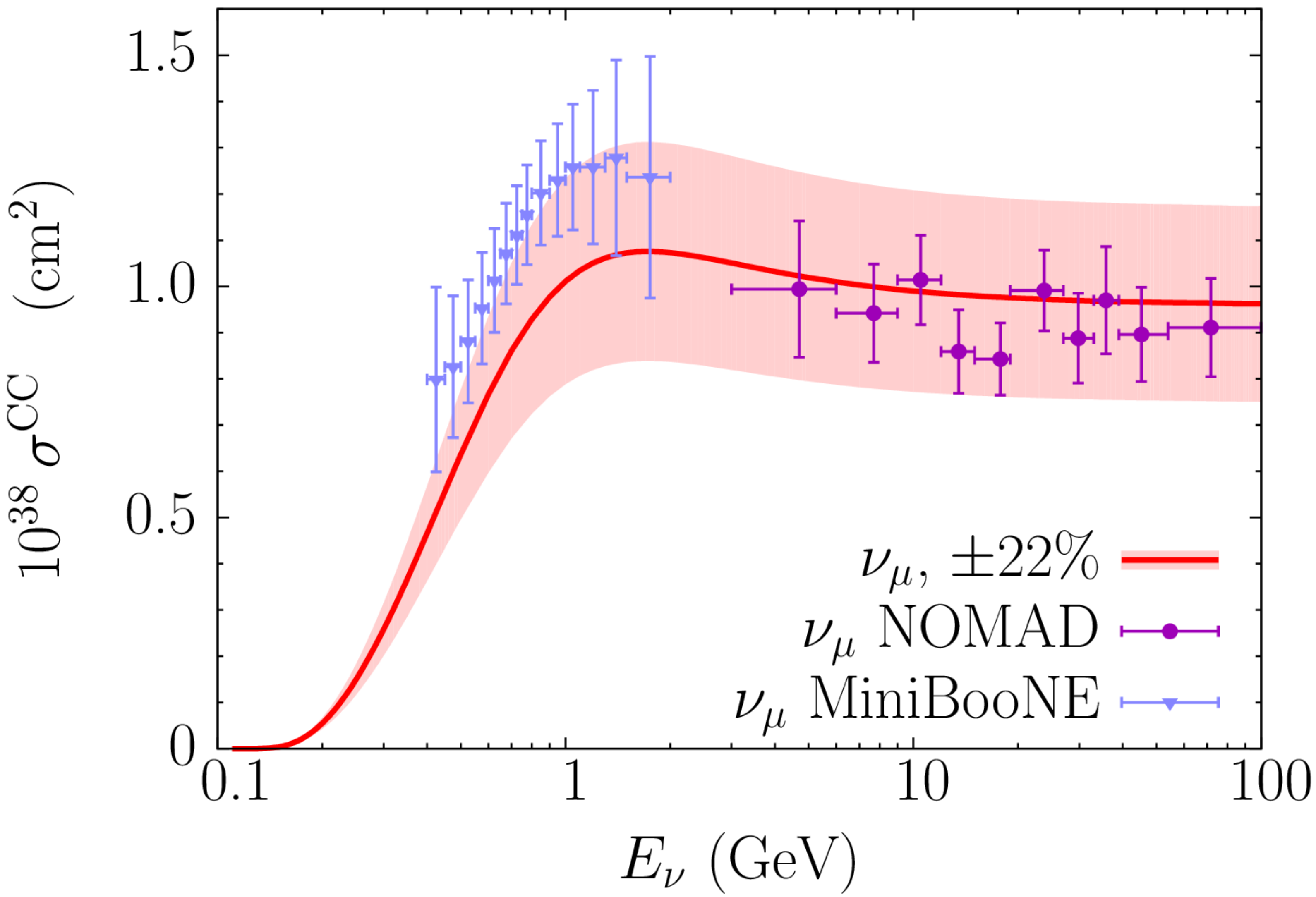

**See my Friday's talk**

# Tot. CCQE $\nu_\mu$ cross section, NOMAD

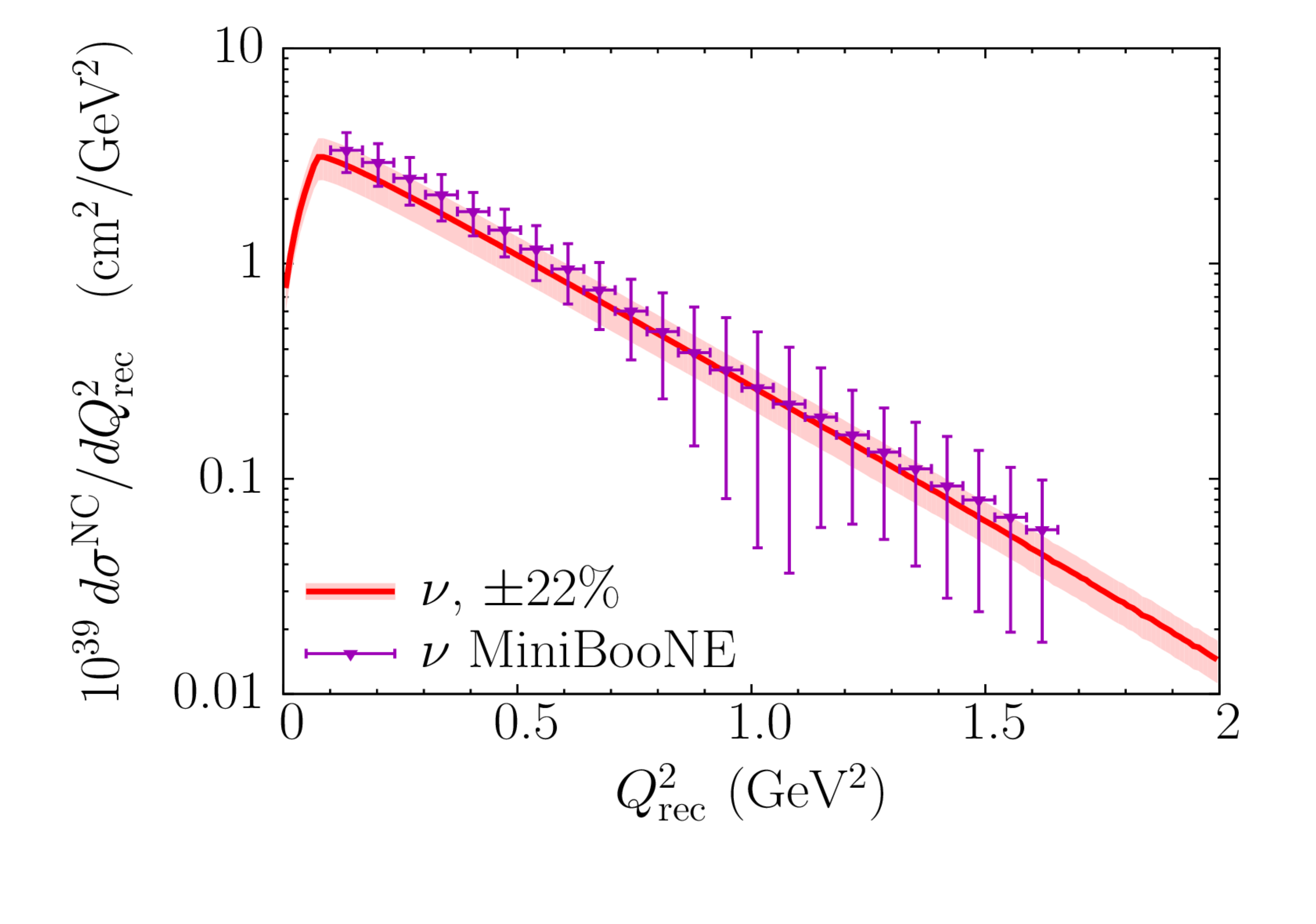



Uncertainty bands cover the points&errors

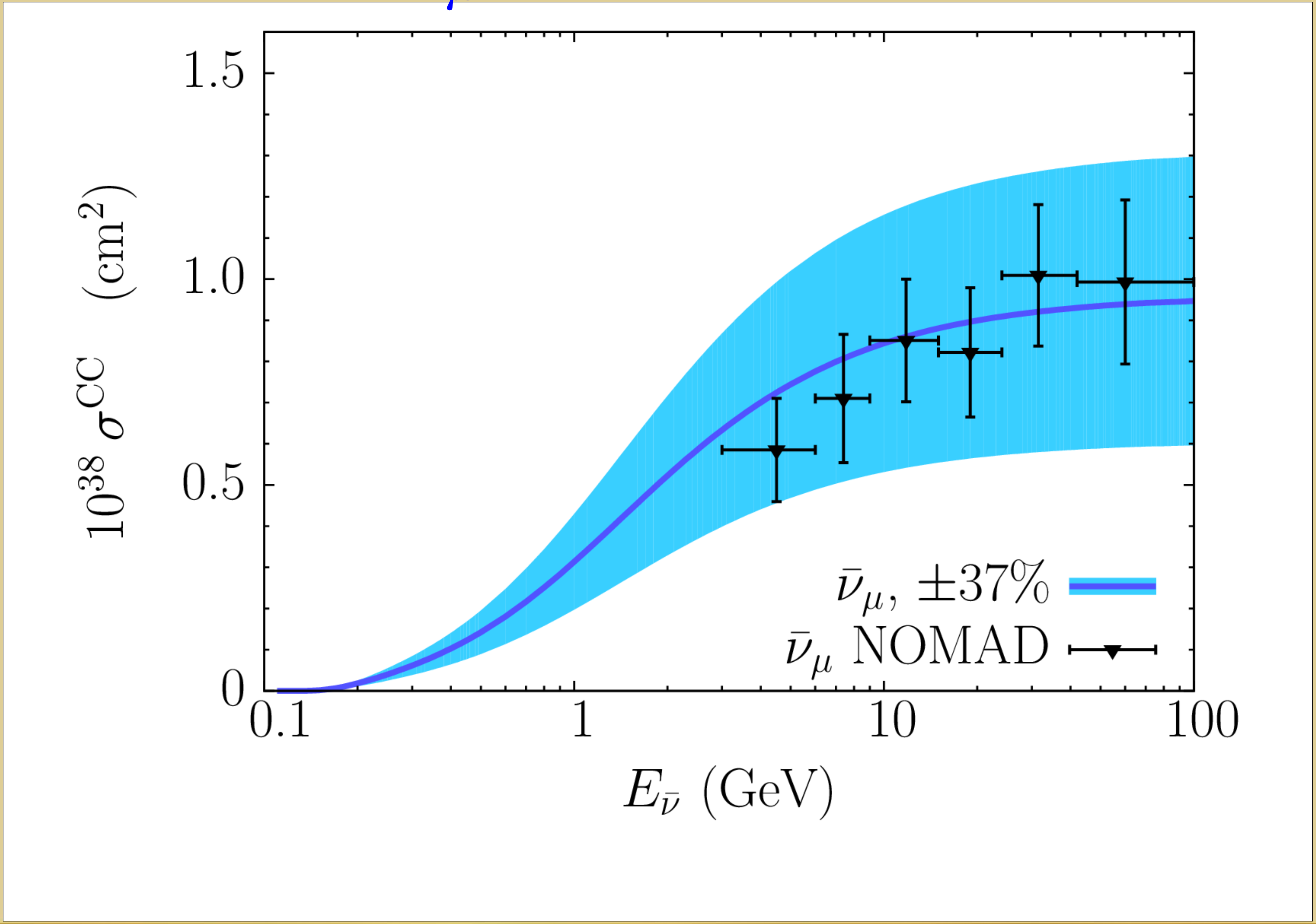
# Total CCQE $\nu_\mu$ cross section



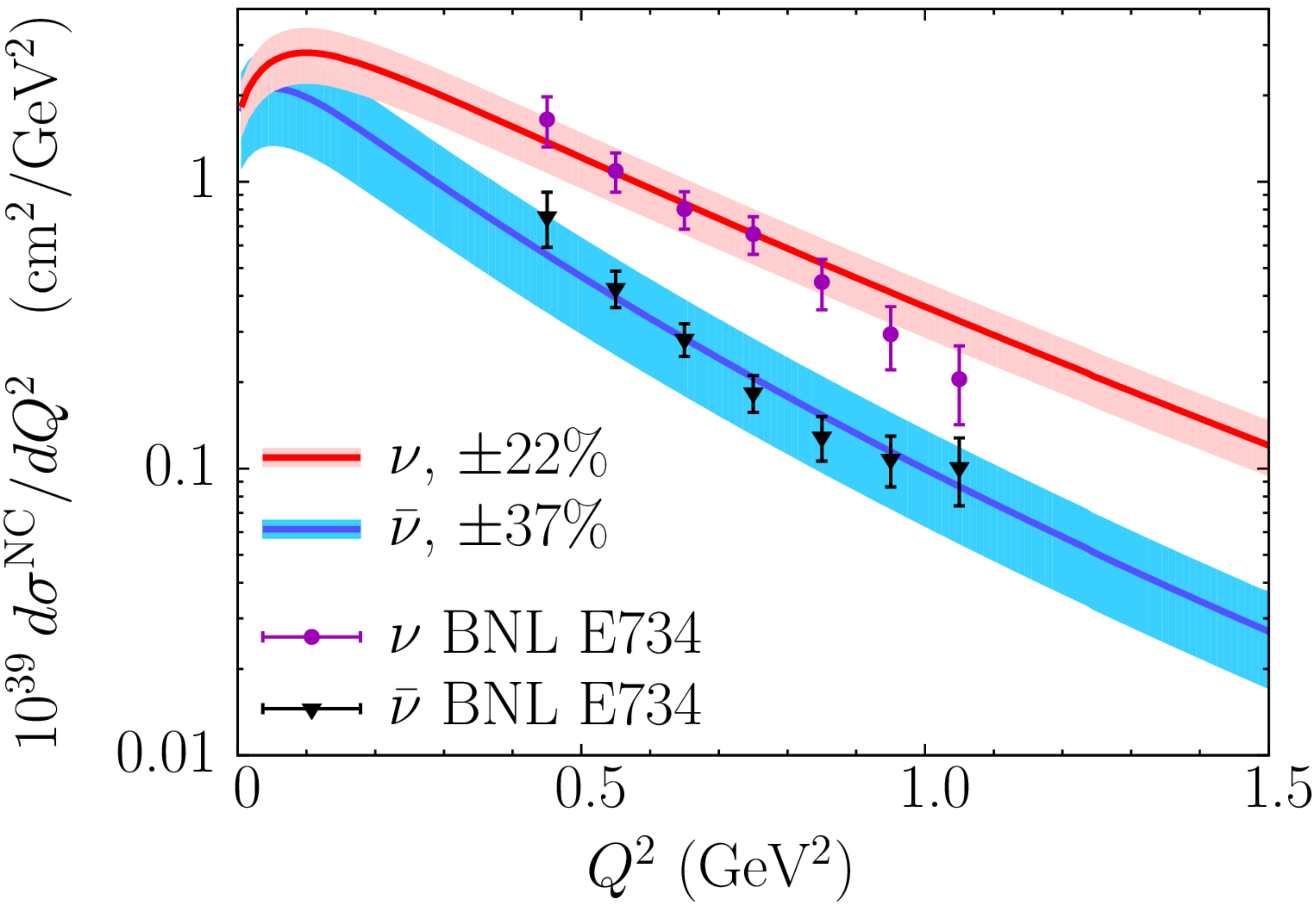
# Neutrino NCE x section, MiniBooNE



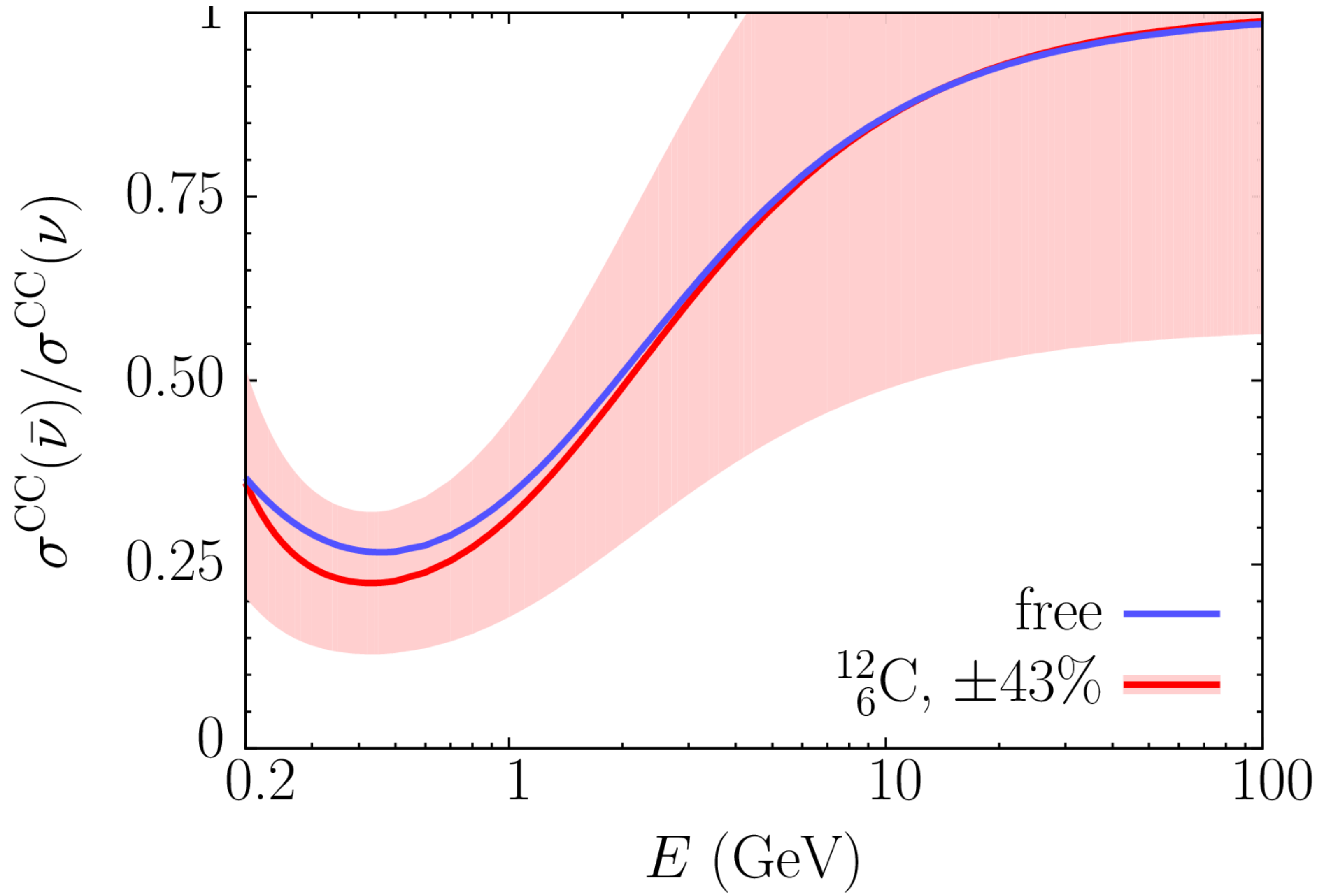
# Tot. CCQE $\bar{\nu}_\mu$ cross section, NOMAD



# Diff. NCE cross sections, BNL E734



# $\bar{\nu}_\mu$ to $\nu_\mu$ cross sections ratio



# Summary

1. The cross section uncertainties increase in the low $Q^2$ region due to multinucleon processes.

2. The available calculations of multinucleon contribution to the antineutrino cross section differ *qualitatively*.

3. The uncertainty of the neutrino (antineutrino)-carbon cross section is estimated to be 22% (37%). The cross sections ratio is then known with the 43% uncertainty.

# Back-up slides

# Low $Q^2$ contribution within the IA

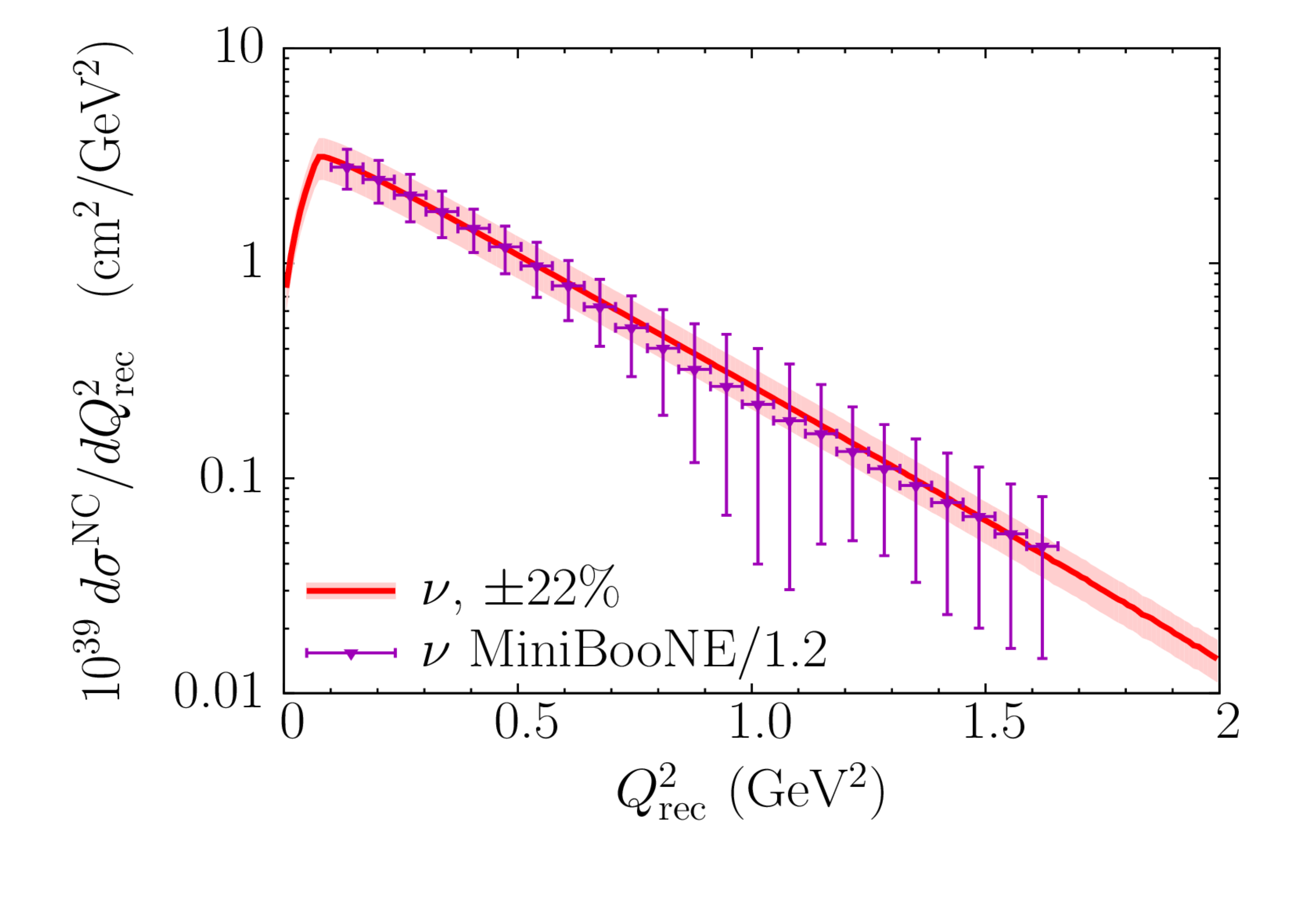
| | Neutrino energy (GeV) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 | 1.2 | 1.4 |
| $\lvert\mathbf{q}\rvert \leq 300$ MeV$/c$ | 97.2% | 18.9% | 11.9% | 10.1% | 9.4% | 9.1% | 9.0% |
| $\lvert\mathbf{q}\rvert \leq 400$ MeV$/c$ | 100.0% | 43.3% | 26.2% | 21.6% | 19.8% | 19.1% | 18.8% |

**Table 1:** Low-$\lvert\mathbf{q}\rvert$ contribution to the neutrino cross section.

| | Neutrino energy (GeV) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2.0 | 2.5 | 3.0 | 3.5 | 4.0 | 4.5 | 5.0 |
| $\lvert\mathbf{q}\rvert \leq 300$ MeV$/c$ | 9.1% | 9.2% | 9.3% | 9.3% | 9.4% | 9.4% | 9.5% |
| $\lvert\mathbf{q}\rvert \leq 400$ MeV$/c$ | 18.8% | 18.9% | 19.1% | 19.1% | 19.3% | 19.3% | 19.4% |

**Table 2:** Same as Table 1 but for higher neutrino energies.

# Neutrino NCE x section, MiniBooNE



# Total CCQE $\nu_\mu$ cross section