Consistent analysis of NCE and CCQE scattering off carbon

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Outline

❶ Introduction

- Motivation: the NOMAD-MiniBooNE difference
- Description of the approach

❷ NCE and CCQE (anti)neutrino scattering

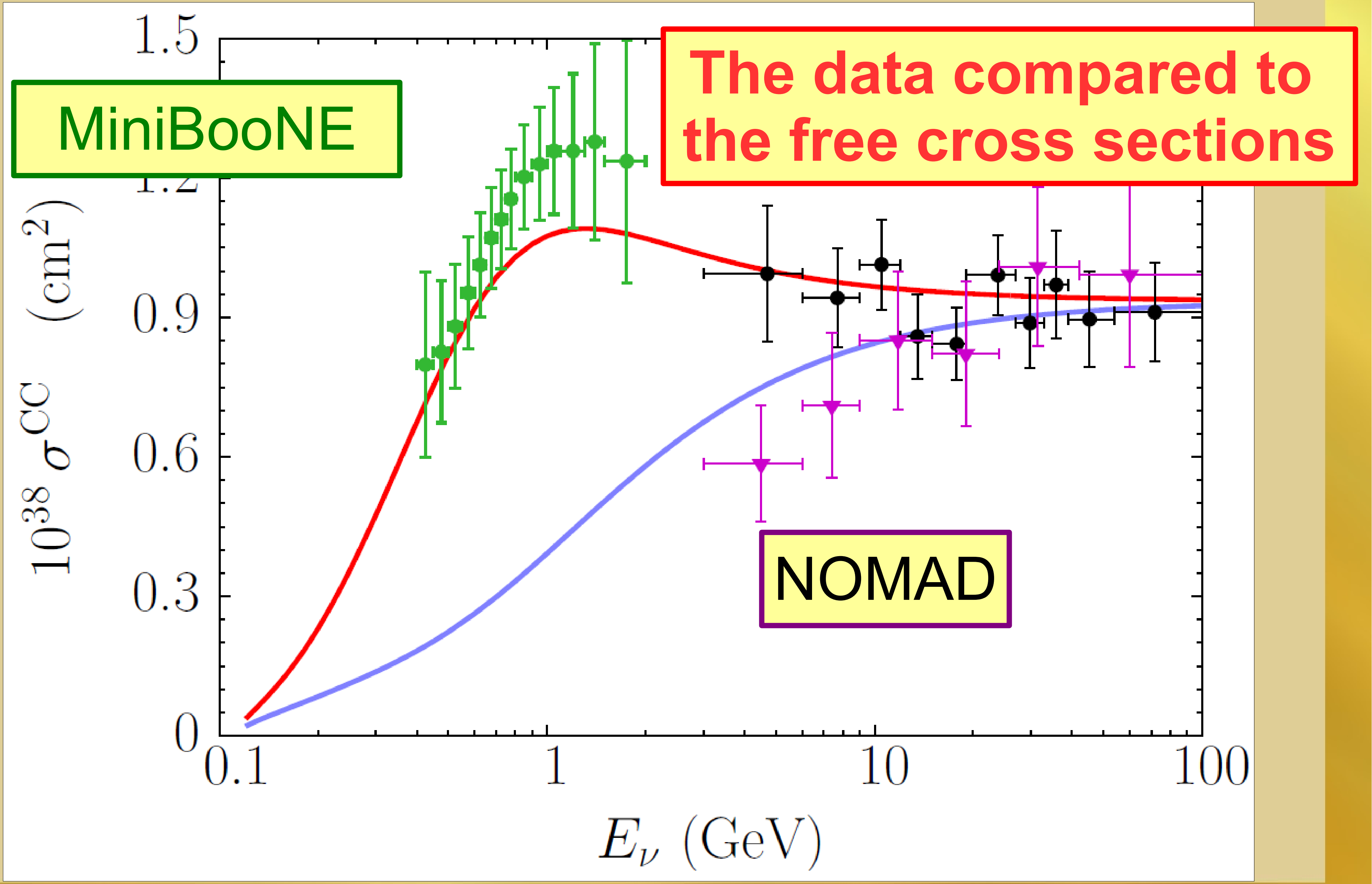
- NOMAD, Lyubushkin *et al.*, EPJ C **63**, 355 (2009)
- BNL E734, Ahrens *et al.*, PRD **35**, 785 (1987)
- MiniBooNE, Aguilar-Arevalo et al., PRD **81**, 092005 (2010), PRD **82**, 092005 (2010)

❸ What are the features of the NOMAD-MiniBooNE difference?

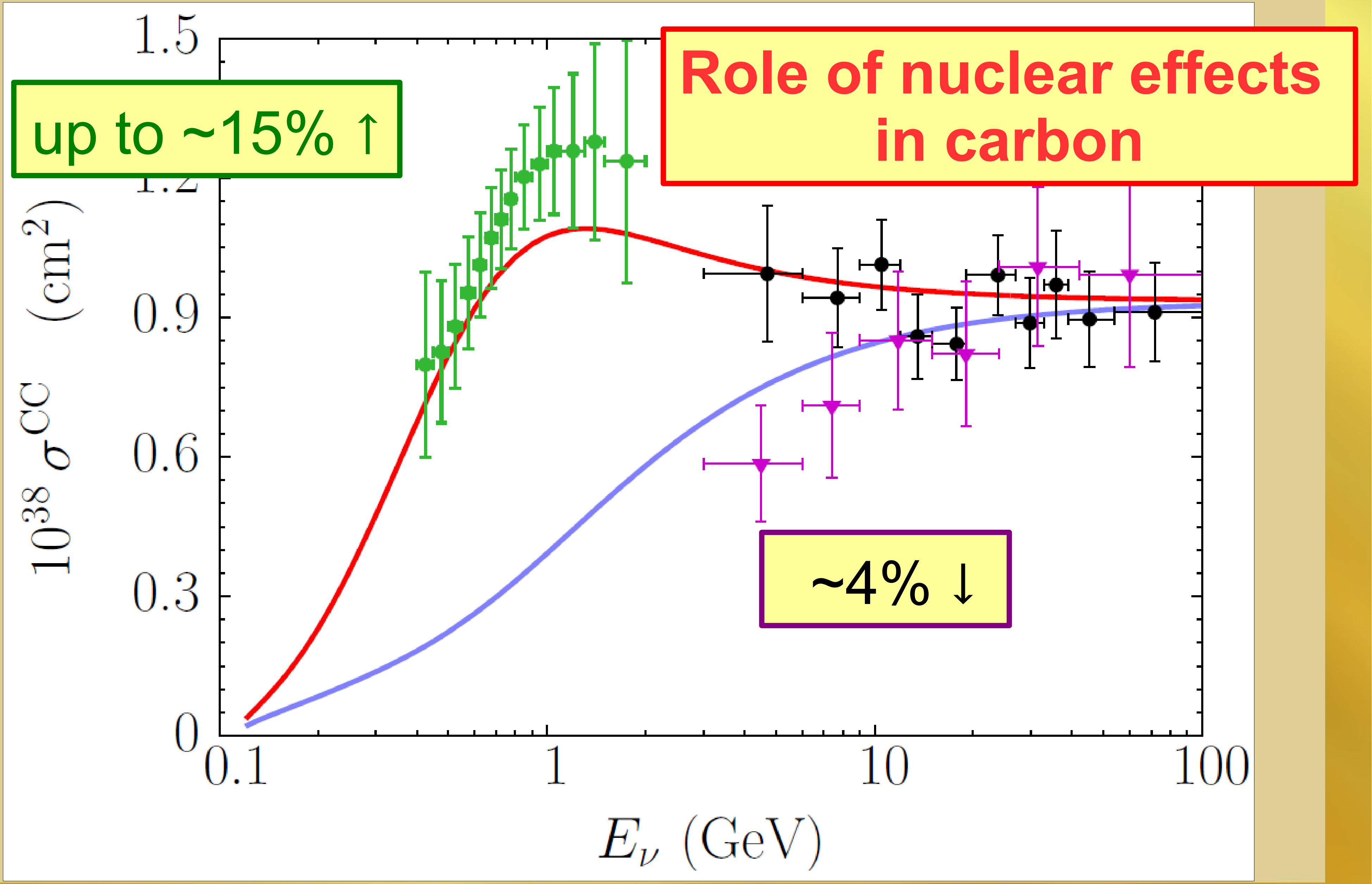
❹ Summary

Motivation

Available CCQE data



Available CCQE data



Available CCQE neutrino data

MiniBooNE

- Cherenkov detector
- CCQE = no pions observed
- 146 070 events (193 709 events) in neutrino mode
- flux from MC simulation, involving extrapolation to the target 35 times thicker
- average energy of **788 MeV**

NOMAD

- drift-chamber detector
- CCQE = muon only or muon + proton of kin. energy > 47 MeV
- 14 021 events in neutrino mode
- normalization from the total inclusive CC cross section and from inverse muon decay
- average energy of **25.9 GeV** (CCQE events only)

Do the two kinematics differ significantly?

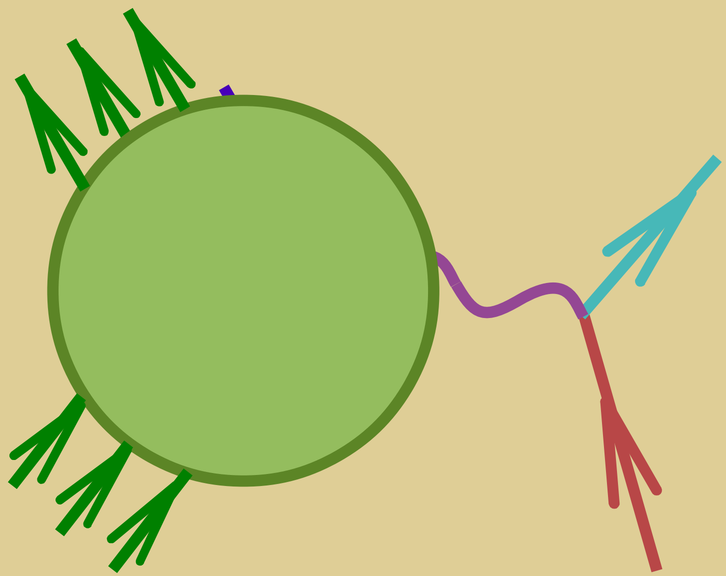
For a neutrino energy of **100 GeV**, **89.8 (97.5)%** of the CCQE cross section comes from the momentum transfer range allowed for neutrino of **E = 1 (2) GeV**.

Therefore, in the context of CCQE interactions, the NOMAD and MiniBooNE experiments probe a similar region of the (ω, $|\mathbf{q}|$) plane.

Approach

Impulse approximation (IA)

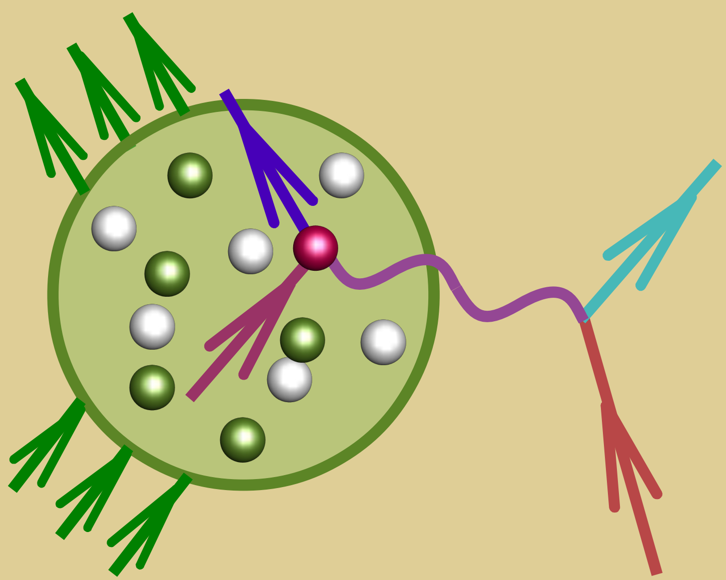
Assumption: the dominant process of neutrino-nucleus interaction is scattering off a single nucleon, the remaining nucleons act as a spectator system.



Impulse approximation (IA)

Assumption: the dominant process of neutrino-nucleus interaction is scattering off a single nucleon, the remaining nucleons act as a spectator system.

It is valid when the momentum transfer $|\mathbf{q}|$ is high enough, as the probe's spatial resolution is $\sim 1/|\mathbf{q}|$.



Impulse approximation (IA)

In the IA regime, the neutrino-nucleus cross section is equal to the **elementary off-shell cross section** for neutrino scattering off a moving nucleon **averaged over the momentum and energy distribution of nucleons**.

This distribution is called **the spectral function (SF)**.

For neutral current elastic (NCE) interaction,

$$\frac{d\sigma_{\nu A}^{\mathrm{NC}}}{dQ^2} = \sum_{N=p,\,n} \int d^3p\, dE\, P_{\mathrm{hole}}^{N}(\mathbf{p}, E)\, \frac{d\sigma_{\nu N}^{\mathrm{NC}}}{dQ^2}$$

Spectral function (SF)

The realistic SFs of various nuclei have been obtained by Benhar *et al*. [NPA 579, 493 (1994)] in the local-density approximation, combining

- the shell structure from the Saclay *(e,e')* data
- the correlation contribution from theoretical calculations for uniform nuclear matter at different densities

Spectral function (SF)

In short, in the carbon nucleus

- ~80% of nucleons occupy the *s* and *p* shells
- ~20% of nucleons are deeply bound due to strong short-range correlations creating NN pairs of high relative momentum
  (2-nucleon final states in the absence of reinteractions)

Effects beyond the IA

In scattering off bound nucleons, the effective M_A=1.23 GeV is applied to account for multinucleon reaction mechanisms (*e.g.* involving MEC).

This method seems to be justified in the kinematical setup of MiniBooNE by the results of Nieves *et al.* [PLB **707**, 72 (2012)] for the double diff. cross section.

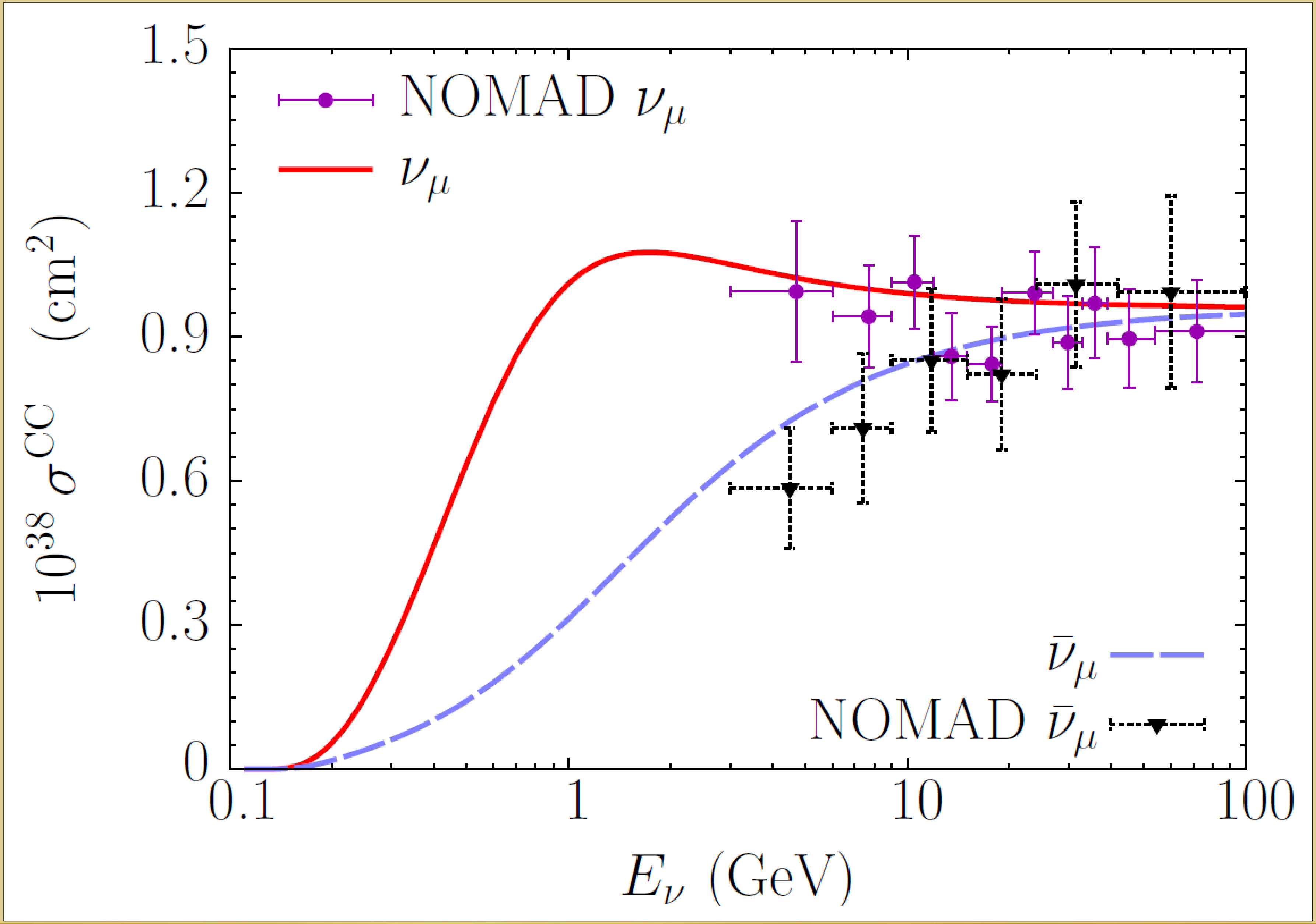
The value of M_A is motivated by the result of the MiniBooNE Collaboration, obtained from the first shape analysis of the Q^2 distribution of the largest statistics of CCQE events collected to date [PRL 100, 032301 (2008)].

NCE vs. CCQE

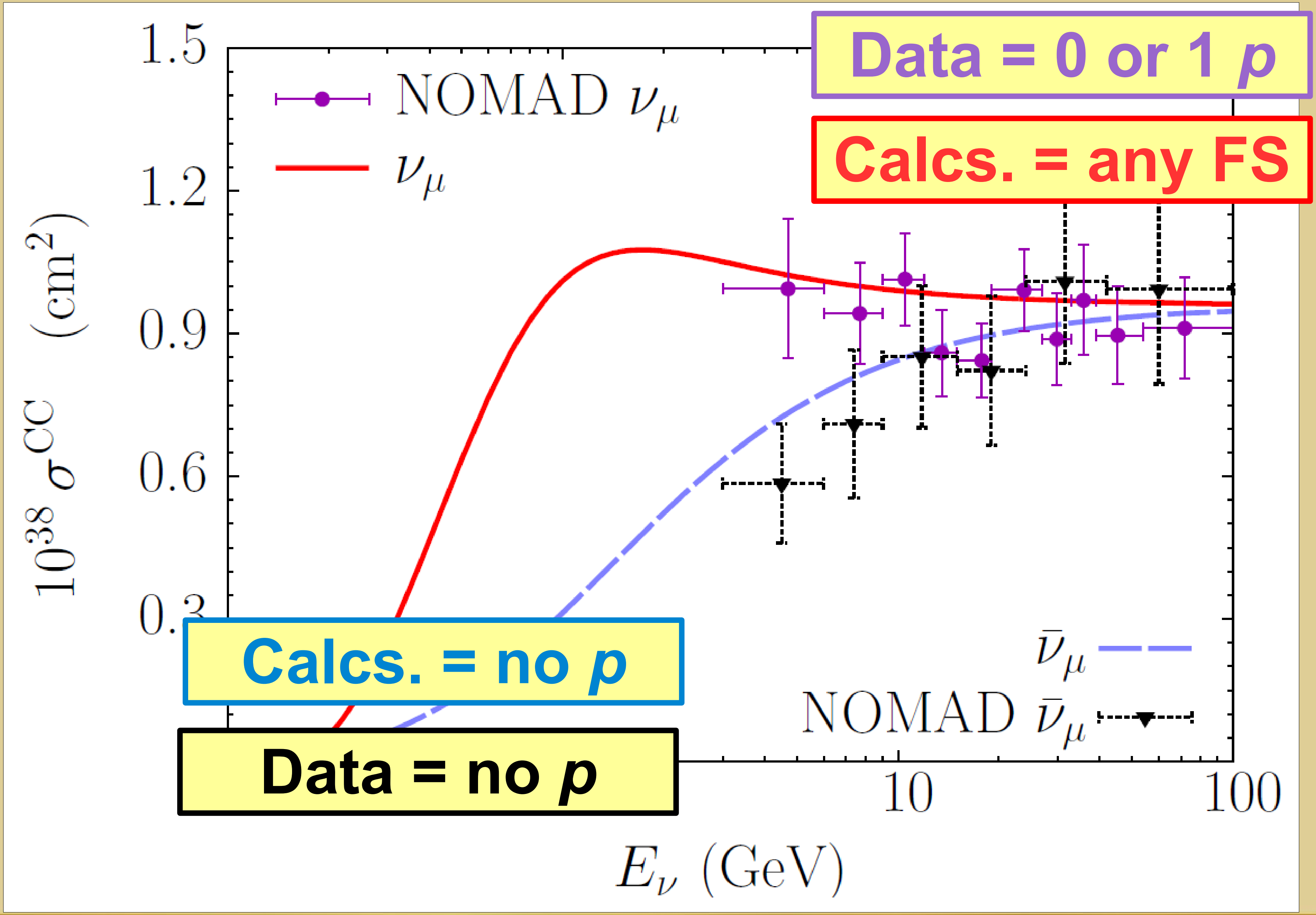
NCE	CCQE
both n's and p's contribute	only νn and $\bar{\nu} p$
G_F	$G_F \cos\theta_C$
$E_{k'} = \lvert\mathbf{k}'\rvert$	$E_{k'} = \sqrt{m'^2 + \mathbf{k}'^2}$
$\mathcal{F}_i^N = \pm\frac{1}{2}(F_i^p - F_i^n) - 2\sin^2\theta_W F_i^N$	$F_i = F_i^p - F_i^n$
$\mathcal{F}_A^N = \frac{1}{2}(F_A^s \pm F_A) = \frac{1}{2}\frac{\Delta s \pm g_A}{(1 - q^2/M_A^2)^2}$	$F_A = \frac{g_A}{(1 - q^2/M_A^2)^2}$

NOMAD

Comparison to the NOMAD data



Comparison to the NOMAD data



Comparison to the NOMAD data

- Good agreement between the results and the data

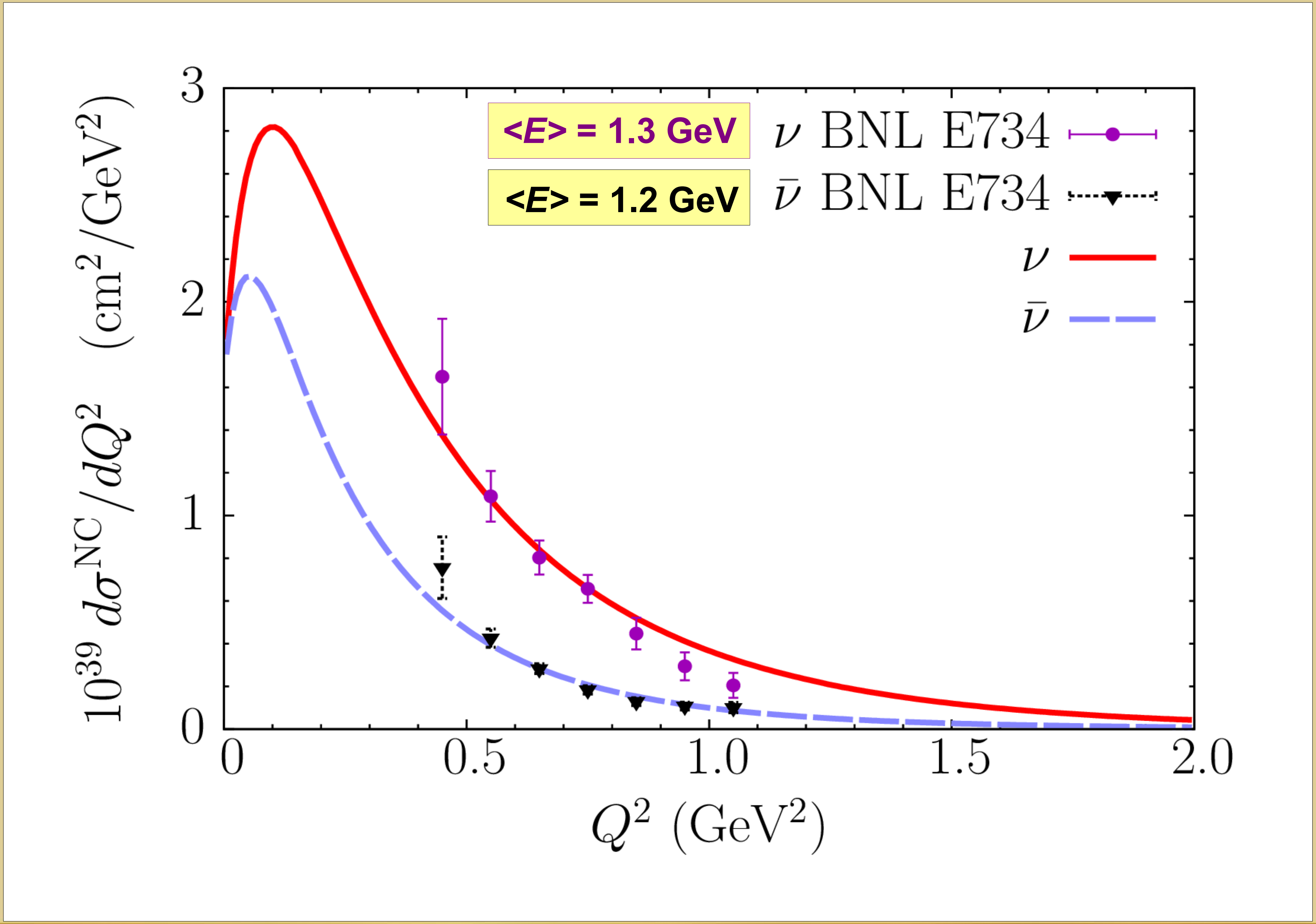
- The SF results higher by ~6% than the NOMAD best fit, to be compared to the ~8% (~11%) systematic uncertainty of the ν ($\bar{\nu}$) data

- The correlated contribution (6% for |p| > 300 MeV) would explain the difference for ν's but not for $\bar{\nu}$'s

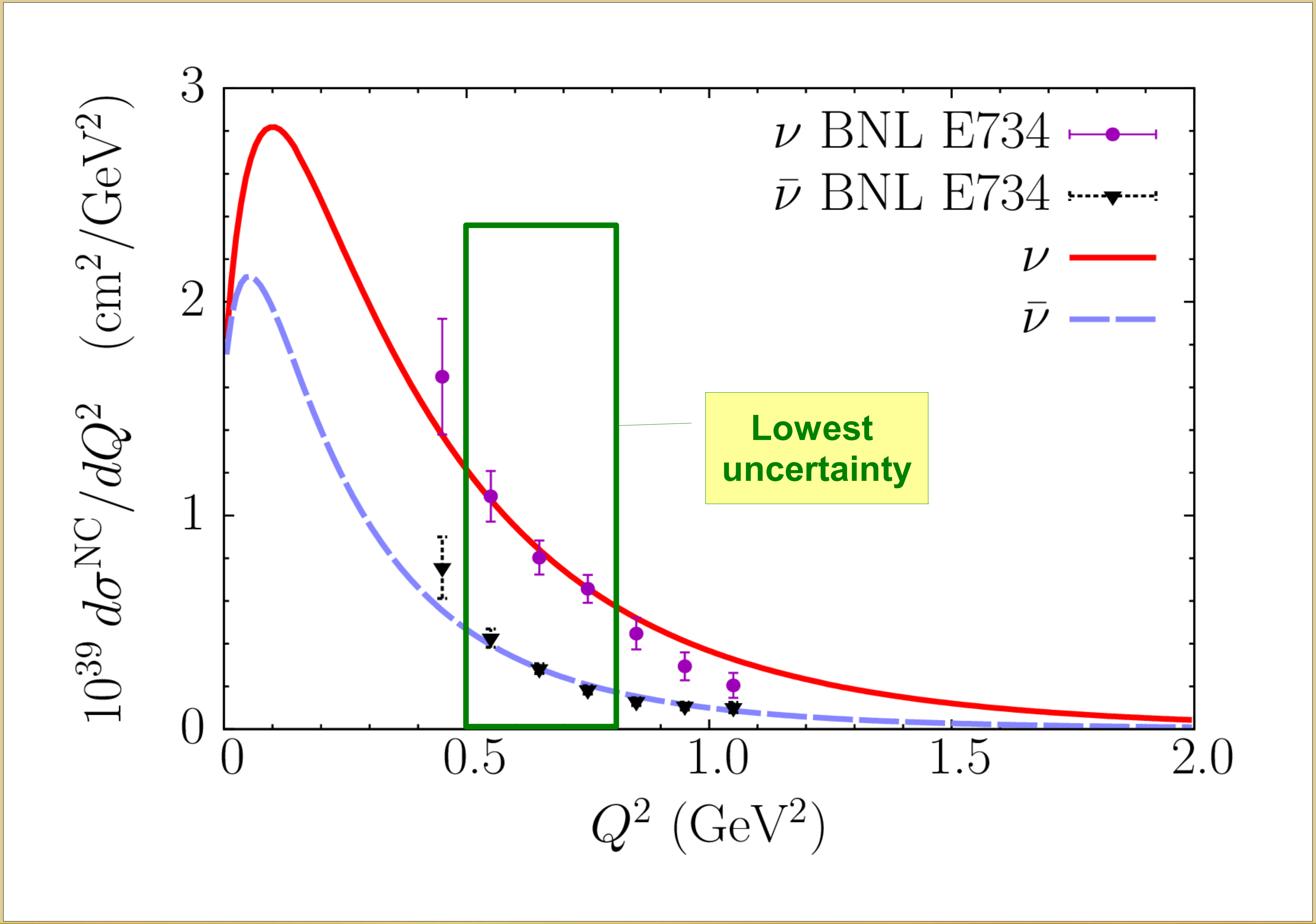
- The difference may be related to the overestimated cross section in the low-Q^2 region

BNL E734

NCE cross sections from BNL E734



NCE cross sections from BNL E734



NCE cross sections from BNL E734

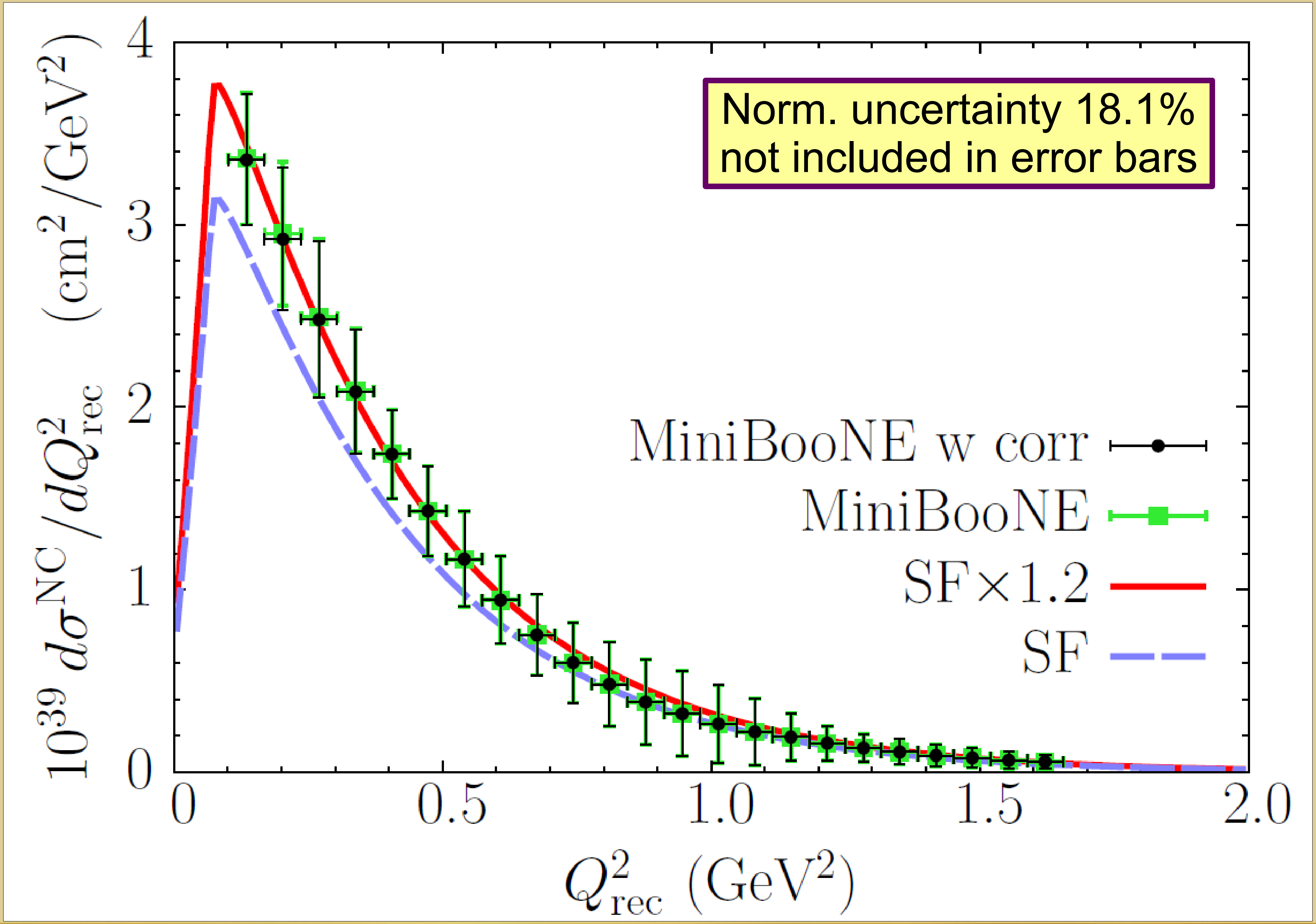
- Overall agreement with the data is **fairly good**

- **Better description** of the lower-uncertainty antineutrino data

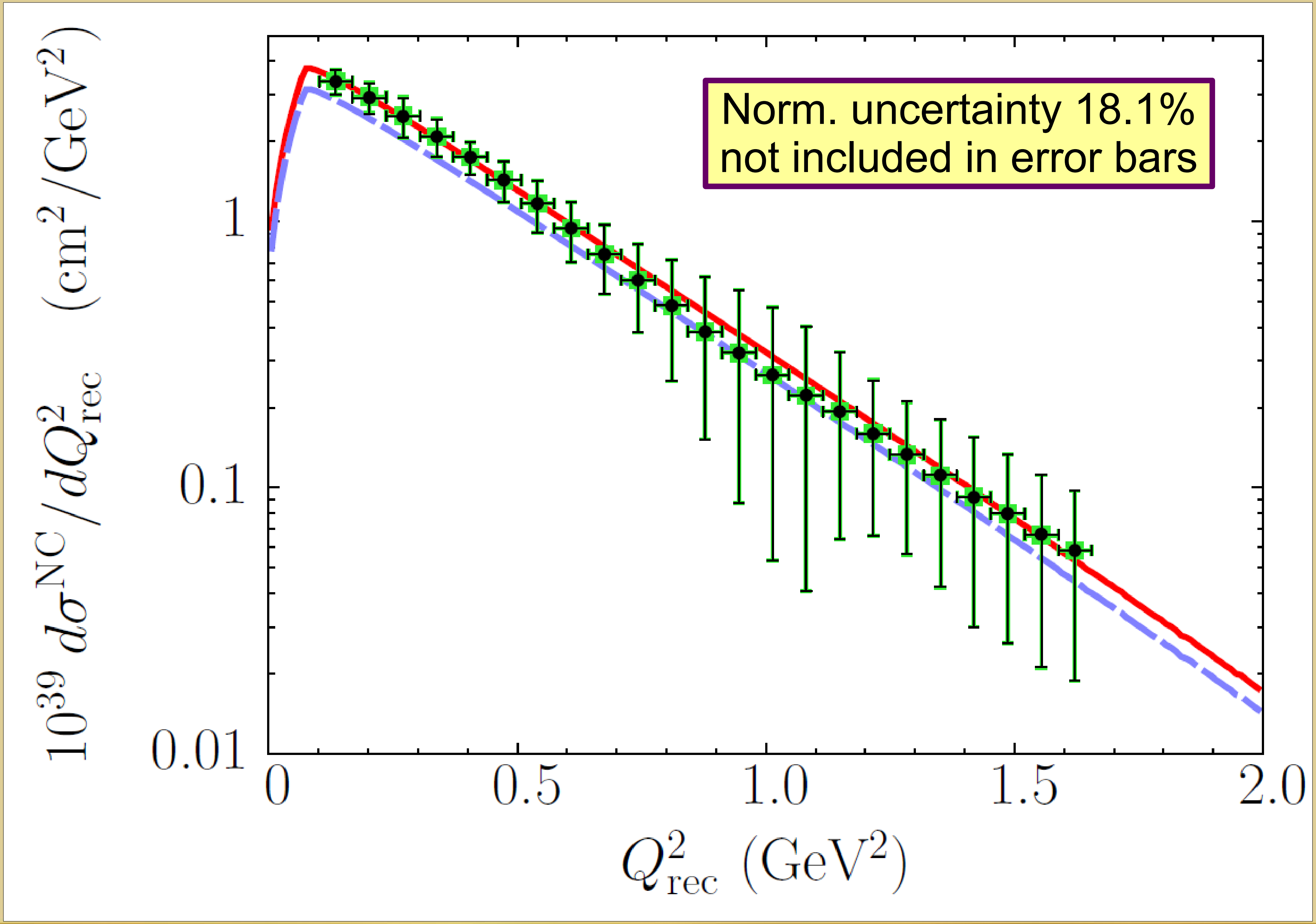
- For the neutrino case, the agreement **improves** in the lowest uncertainty region, $0.5 \leq Q^2 \leq 0.8$ GeV^2

MiniBooNE

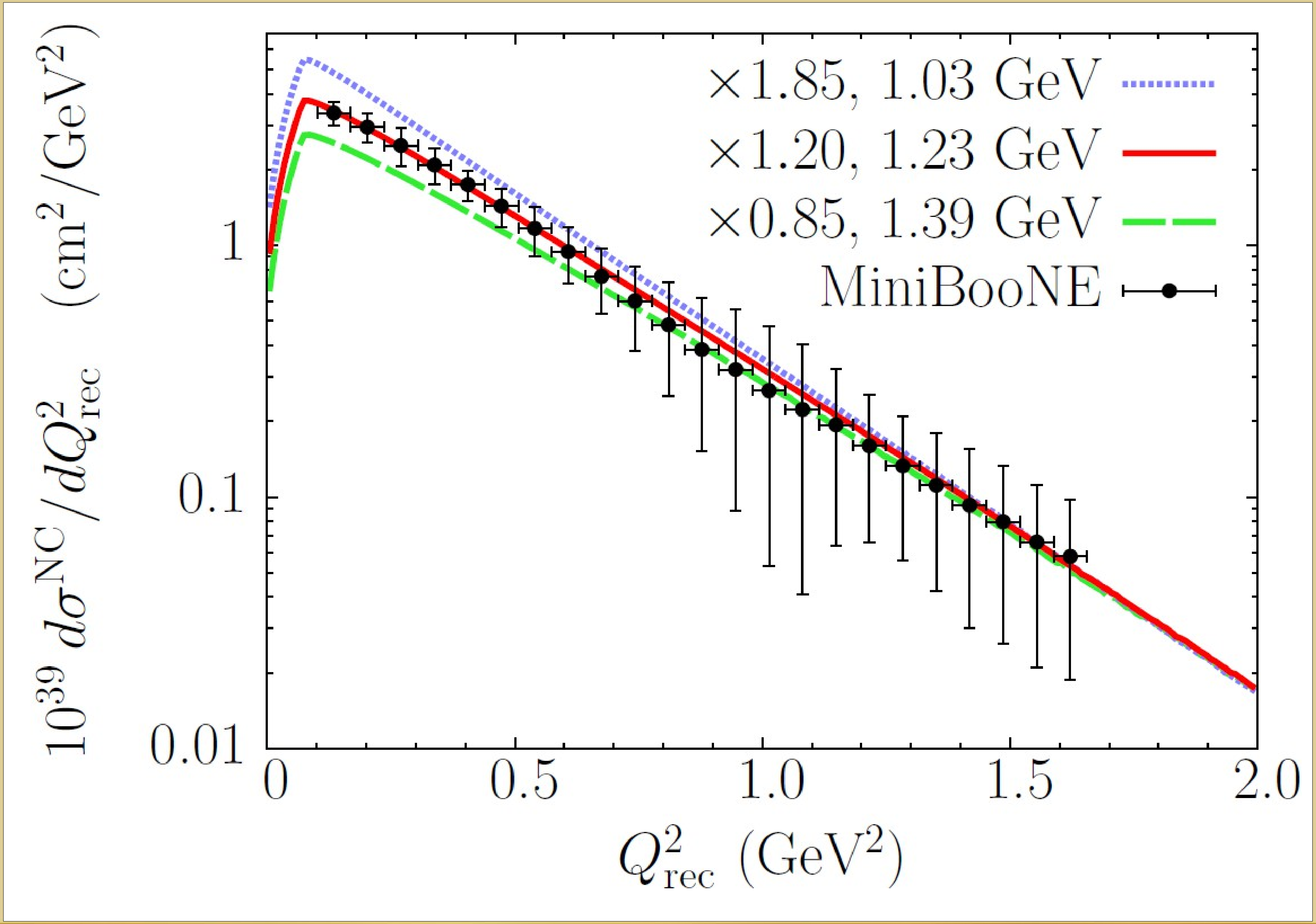
NCE cross section from MiniBooNE



NCE cross section from MiniBooNE



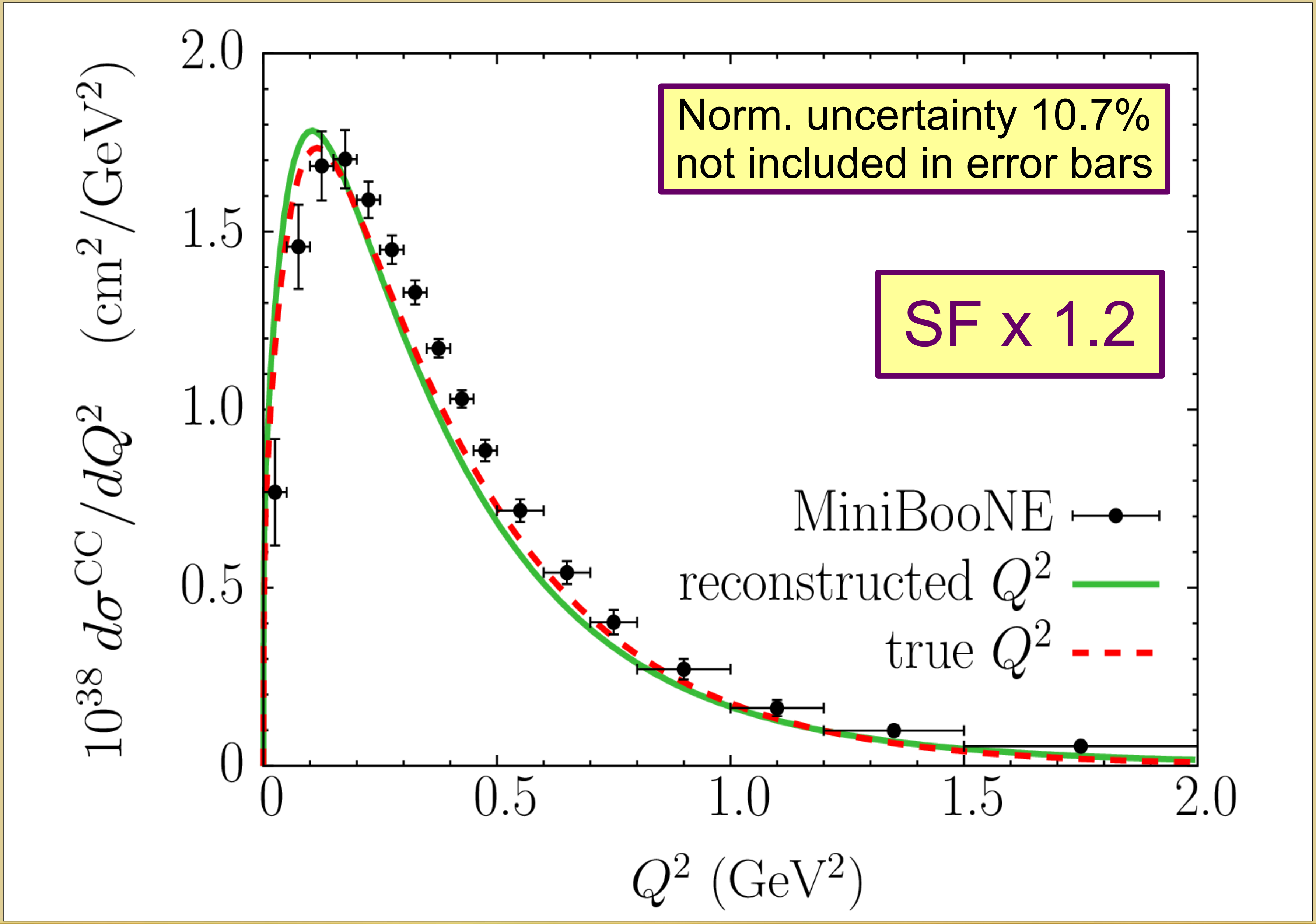
NCE cross section from MiniBooNE



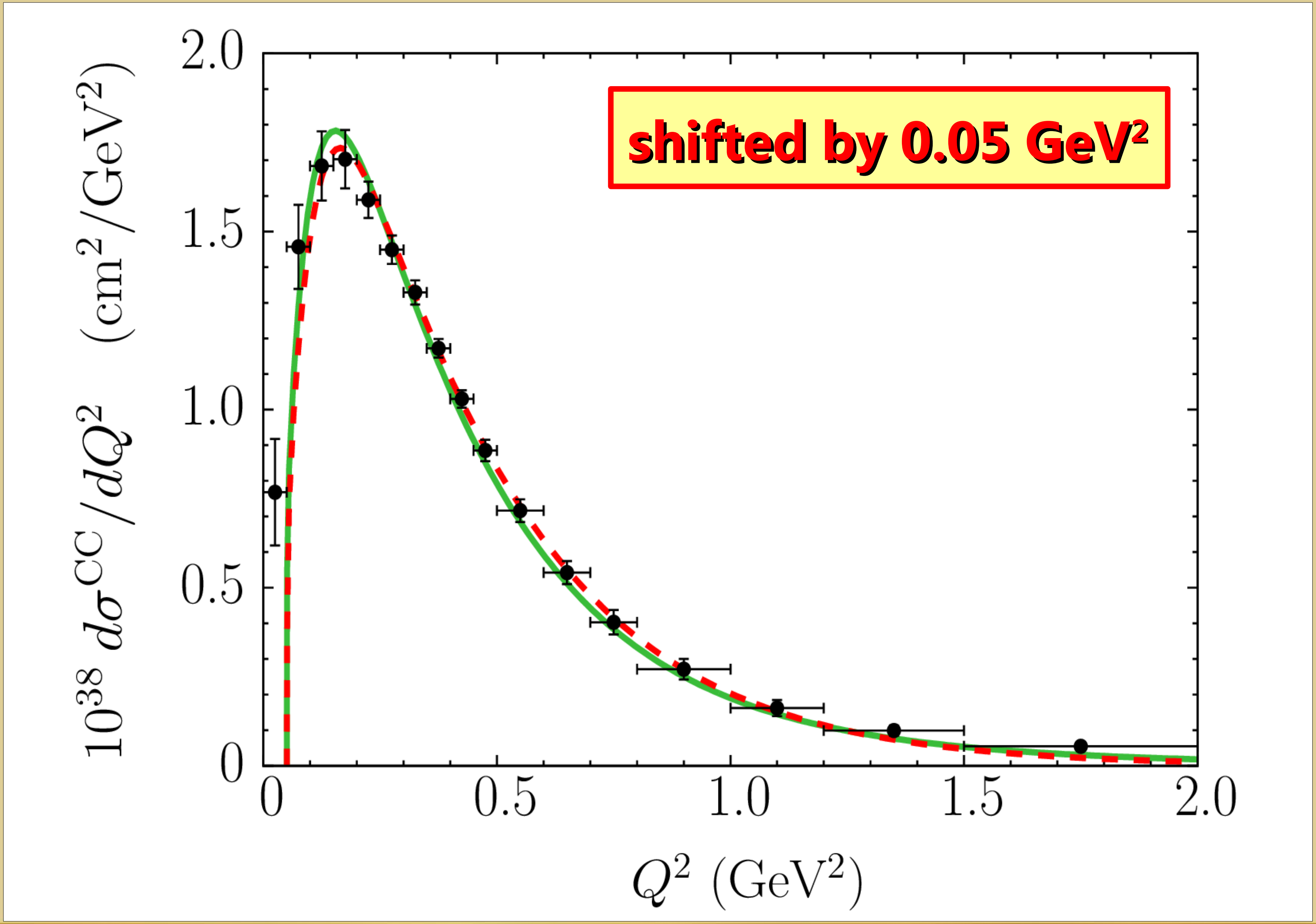
NCE cross section from MiniBooNE

- The calculations fail to reproduce the normalization by **20%** (compared to the norm. uncertainty 18.1%), consistent with the 1st shape analysis of CCQE events (data/MC = 1.21±0.24) .
- The shape reproduced **very well**. For $Q^2 \leq 0.64$ GeV^2, the differences are on average 1.6%. The largest deviations for $0.8 \leq Q^2 \leq 1.1$ GeV^2 remain well within the error bars.
- The slope of the cross section is not consistent with the axial mass very different from 1.23 GeV

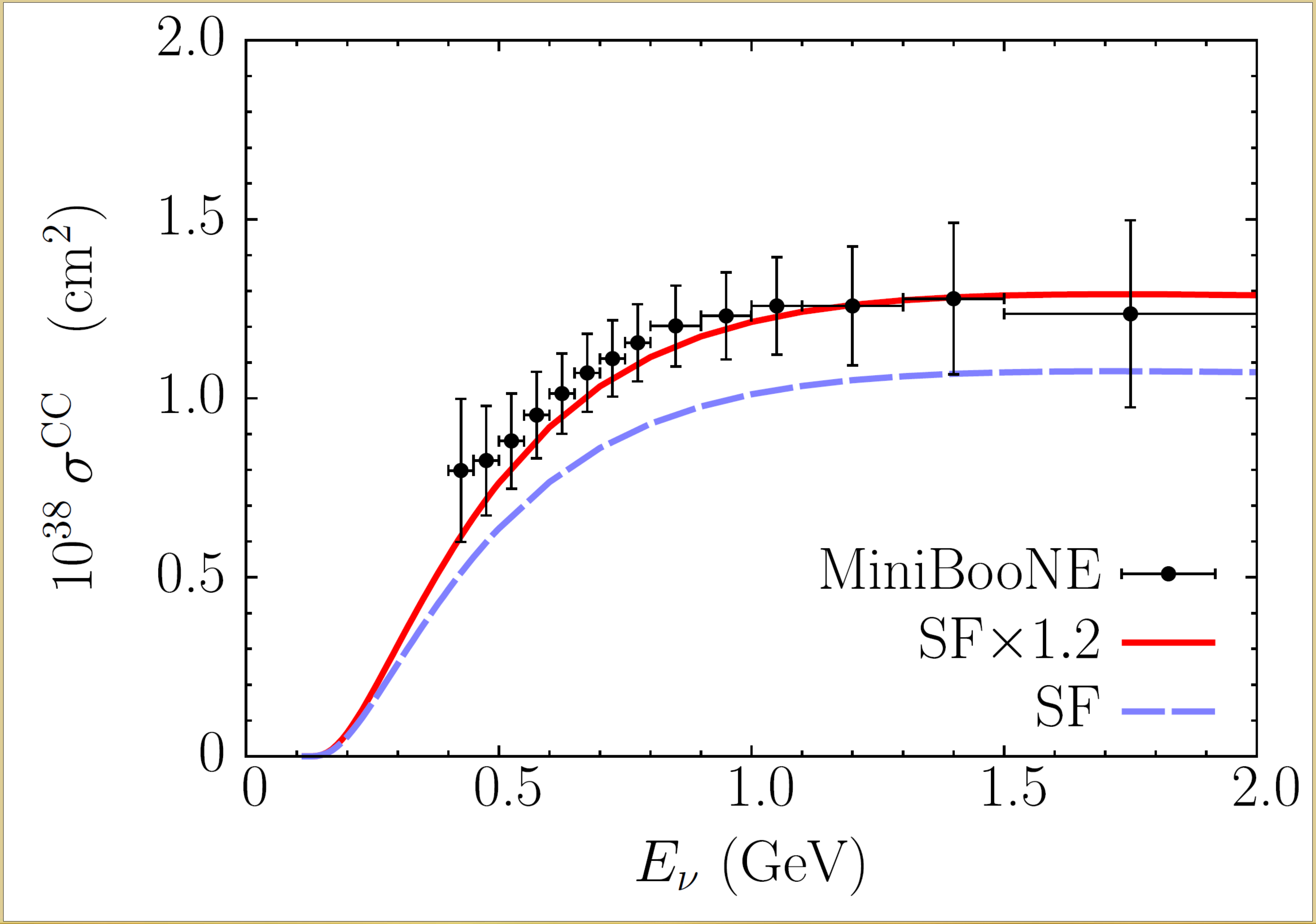
CCQE x section from MiniBooNE



CCQE x section from MiniBooNE



Total CCQE cross section



CCQE cross section from MiniBooNE

- The calculations correctly describe the NCE to CCQE cross sections ratio
- The CCQE result and the data seem to be shifted by +0.05 GeV^2 (the smallest bin size)
- The energy-dependence of the total cross section in a good agreement with the data
- The normalization consistently different by **20%**.

NOMAD-MiniBooNE difference

NOMAD-MiniBooNE difference

- CCQE are defined **differently** in both experiments
  - NOMAD: muon only or muon + proton ($T > 47$ MeV)
  - MiniBooNE: no pions detected

NOMAD-MiniBooNE difference

- In NOMAD, CCQE events may involve **any number of protons of $T < 47$ MeV each** and **any number of neutrons**. Such multinucleon final states seem to contribute equally to the 1- and 2-track events (73.9 and 26.1% of the sample, respectively) and independently of energy for $3 < E < 100$ GeV

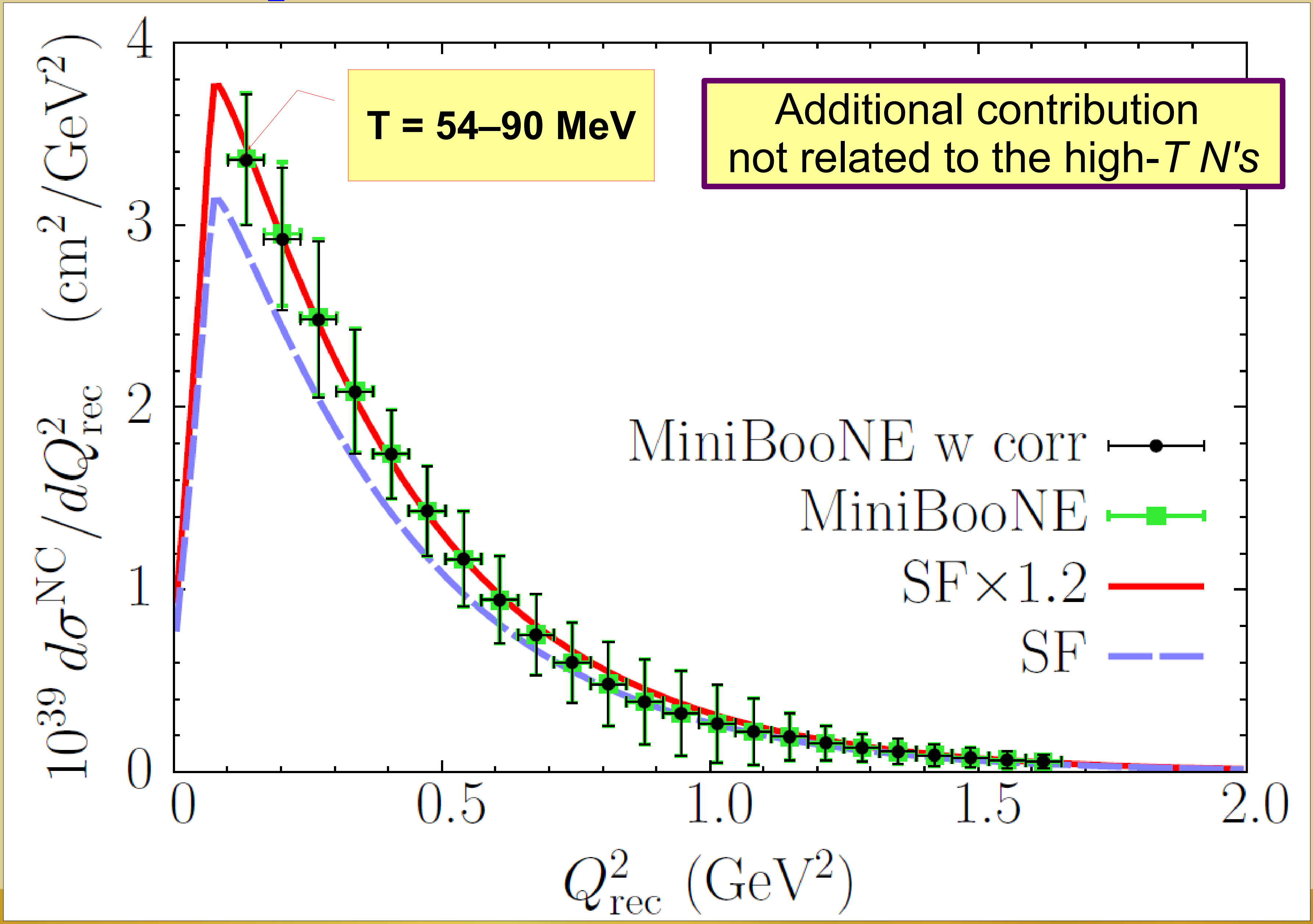
- In MiniBooNE, a broader class of multinucleon final states may, in principle, contribute to the CCQE data, such as those involving **at least two protons of $T > 2*47=94$ MeV in total**

Does the ~20% difference result from the multiproton events subtracted in NOMAD?

- The additional ~20% contribution to the MiniBooNE CCQE data **lacks apparent dependence on energy** for $0.4 < E < 2$ GeV, so it should be recorded also in the NOMAD detector.

- However, the NOMAD Collaboration has not reported a sizable contribution of multinucleon background events

Does the ~20% difference result from the multiproton events subtracted in NOMAD?



Does the ~20% difference result from the multiproton events subtracted in NOMAD?

- The MiniBooNE data show no evidence for nuclear effects being different in NCE and CCQE scattering, so **nucleon kinematics in CCQE interaction may be deduced from the NCE result**

- In the MiniBooNE NCE data, the additional strength is **not** limited to the $T > 94$ MeV ($Q^2 > 0.177$ GeV^2) region, but it yields ~20% of the cross section over the whole considered range $50 < T < 650$ MeV (no bumps = no new channels)

Does the ~20% difference result from the multiproton events subtracted in NOMAD?

The MiniBooNE NCE and CCQE data suggest that

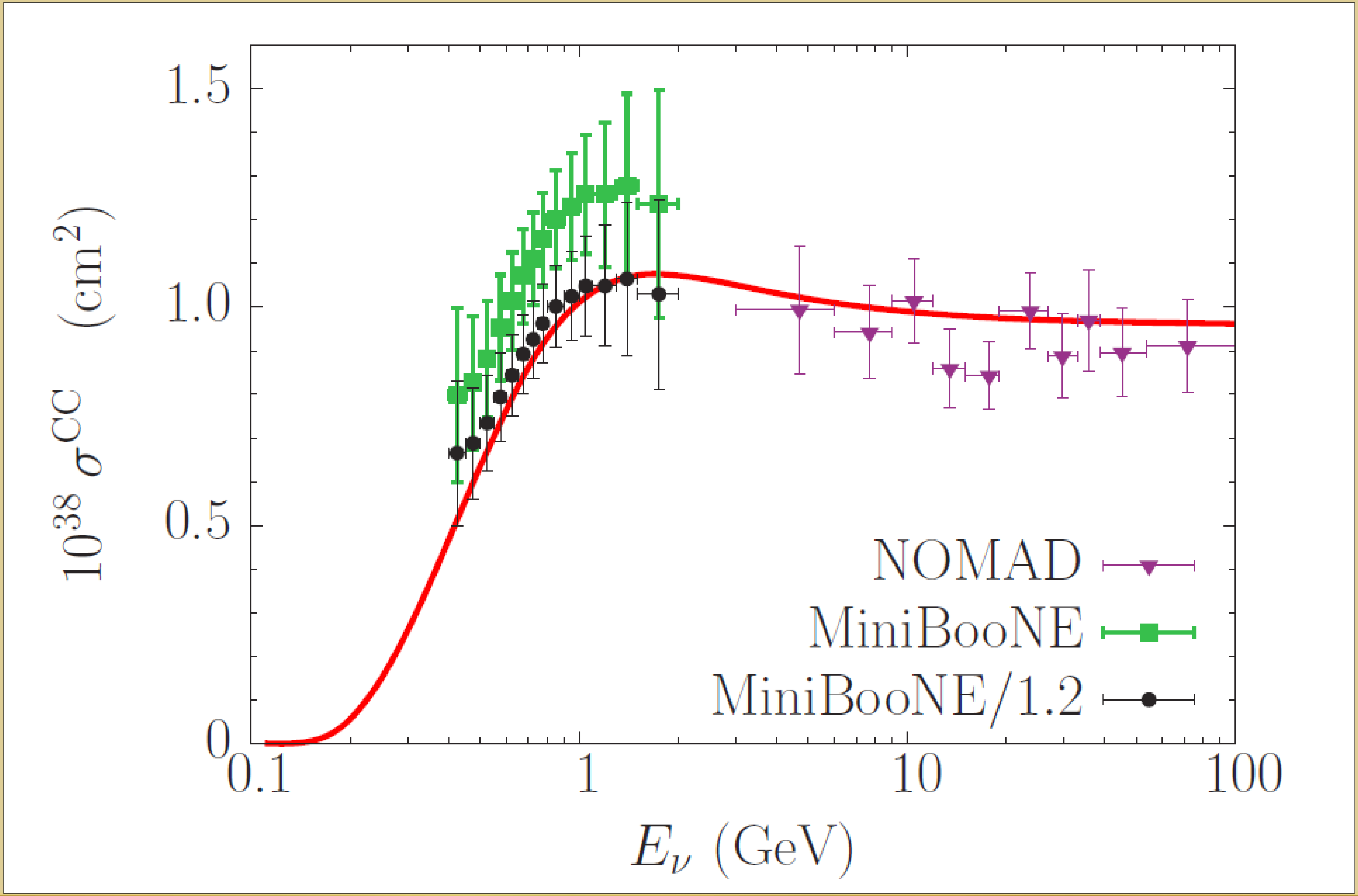
- all the multinucleon channels are open at $T = 50$ MeV and do not show energy dependence for $E > 0.4$ GeV, contributing also to the NOMAD data
- the NOMAD-MiniBooNE difference is not related to the multiproton events of $T > 94$ MeV
- the **same nuclear effects** contribute to the MiniBooNE and NOMAD results

Other channels

The ratio data/MC is (kappa ~1.02, M_A=1.23 GeV)

- 1.21 ± 0.24 for CCQE, MiniBooNE
- 1.23 for CC charged pion production, MiniBooNE
- 1.58 ± 0.05(stat) ± 0.26(syst) for CC neutral pion production, MiniBooNE
- 1.29 ± 0.02(fit) ± 0.03(efficiency&purity) for the **inclusive** CC cross section, SciBooNE

Does the ~20% difference result from the multiproton events subtracted in NOMAD?



Summary

❶ **Fairly good description of the BNL E734 data, good agreement with NOMAD**

❷ **The shape of the NCE MiniBooNE data described very accurately, similar results for CCQE. The normalization consistently off by 20%.**

❸ **In the MiniBooNE NCE data, I find no evidence for multinucleon contributions different than those in the NOMAD data.**

❹ **The NOMAD-MiniBooNE difference likely to be related to the flux uncertainty in MiniBoooNE.**

Back-up slides

NCE cross sections from BNL E734

- The fluxes determined from the CCQE cross sections (Llewellyn-Smith + corrections for Fermi motion and Pauli blocking)
- At $0.15 \leq Q^2 \leq 1.15$ GeV^2 the SF result (1.23 GeV) varies 9.1 times, differing by **less than 10%** from the free cross section (1.03 GeV); the corrections should diminish the difference
- Therefore, the agreement between the results and the data **does not seem to be accidental**

PRD **81**, 092005 (2012)

II. MINIBOONE EXPERIMENT

A. Neutrino beamline and flux

The Booster Neutrino Beamline (BNB) consists of three major components as shown in Fig. 1: a primary proton beam, a secondary meson beam, and a tertiary neutrino beam. Protons are accelerated to 8 GeV kinetic energy in the Fermilab Booster synchrotron and then fast-extracted in 1.6 μs "spills" to the BNB. These primary protons impinge on a 1.75 interaction-length beryllium target centered in a magnetic focusing horn. The secondary mesons

HARP data. The HARP data used was that from a thin (5% interaction length) beryllium target run [20]. While that