# Neutrino – Nucleus Scattering Physics with nuSTORM

## What can a dedicated nuSTORM neutrino-nucleus scattering physics program deliver?

ν

**Jorge G. Morfín**
**Fermilab**

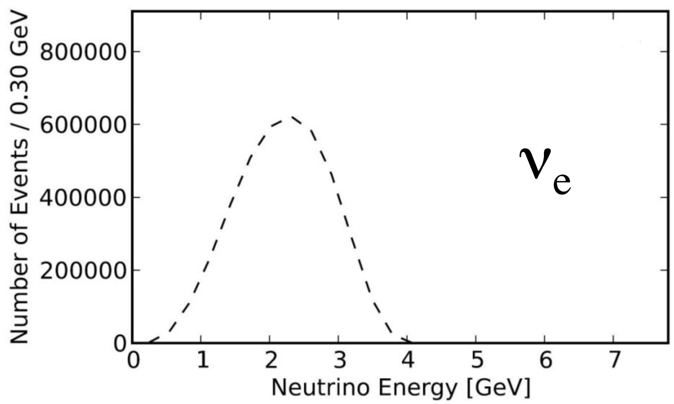
nuSTORM Workshop – Fermilab, November 2013

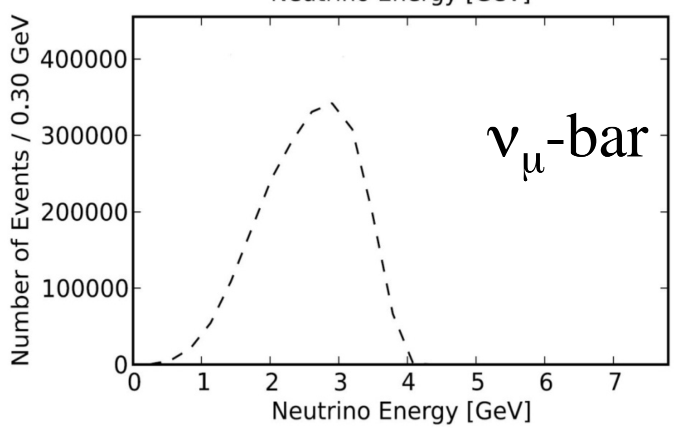
# The nuSTORM Neutrino Beam: The **Advantages**

$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$ $\mu^- \rightarrow \nu_\mu + \bar{\nu}_e + e^-$

Mitchell YU

- The νSTORM beam will provide a very well-known **($\delta\,\phi(E) \leq 1\%$)** beam of ν and $\bar{\nu}$. Intensity of $\nu_\mu$ good not great for 10 ton detector.
- A high-intensity source of **$\nu_e$ events** for experiments.




3.8 GeV $\mu^+$ stored, 226m straight, flux at 50m

$\mu^+$

| Channel | $N_{evts}$ |
|---|---|
| $\bar{\nu}_\mu$ NC | 844,793 |
| $\nu_e$ NC | 1,387,698 |
| $\bar{\nu}_\mu$ CC | 2,145,632 |
| $\nu_e$ CC | 3,960,421 |

$\mu^-$

| Channel | $N_{evts}$ |
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| $\bar{\nu}_e$ NC | 709,576 |
| $\nu_\mu$ NC | 1,584,003 |
| $\bar{\nu}_e$ CC | 1,784,099 |
| $\nu_\mu$ CC | 4,626,480 |

event rates per 1E21 POT -
100 tons at 50m

# nuSTORM Event Rates

- A beam of 700 kW yields order 6x$10^{20}$ POT/year. The 1100 kW for LBNE could yield close to $10^{21}$ POT/year (depends on E of LBNE proton beam). **WE DON'T GET ALL THE PROTONS!**

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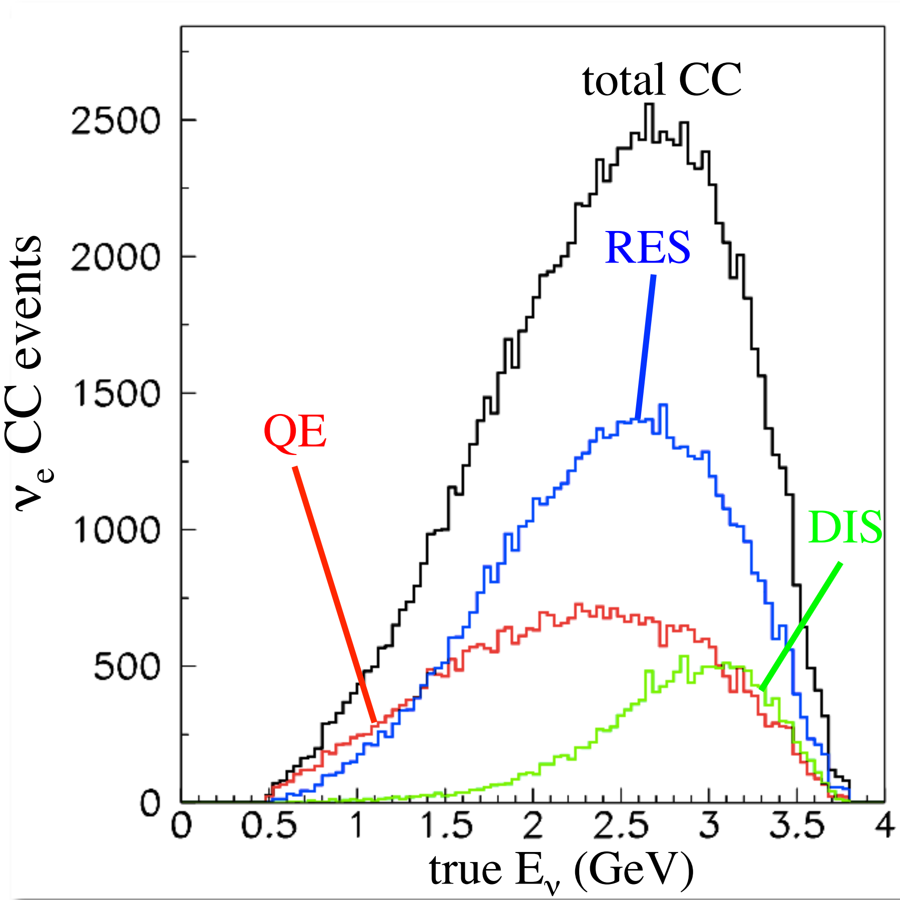
- It would be preferable to have a near detector of order 30-50 ton fiducial volume.

# ν **Produced** Events in a nuSTORM Near Detector

- ν produced by 3.8 GeV $\mu^+$ beam.




**out of the CC modes:**

* 56% resonant
* 32% QE
* 12% DIS

- For $\bar{\nu}$ sample, 52% resonant, 40% QE, 8% DIS)

# Why is Neutrino Nucleus Scattering Important?

## What do we observe in our detectors?

- The events we observe in our detectors are convolutions of:

$$Y_{\text{c-like}}(E) \propto \phi(E' \geq E) \otimes \sigma_{c,d,e..}(E' \geq E) \otimes Nuc_{c,d,e..\rightarrow c}(E' \geq E)$$

- $\phi(E)$ is the energy dependent neutrino flux that enters the detector. Currently, with traditional meson-decay-source neutrino beams, $\phi(E)$ ≈10% absolute and ≈ 7% energy bin-to-bin accuracy. **Significant contribution to systematics.**
- $\sigma_{c,d,e..}(E' \geq E)$ is the measured or the Monte Carlo (model) energy dependent neutrino cross section off a **nucleon within a nucleus.**
- $Nuc_{c,d,e..\rightarrow c}(E' \geq E)$ **– Nuclear Effects**
  - **Nuclear Effects** – a migration matrix that mixes produced/observed channels and energy
  - In general the interaction of a neutrino with energy E' creating initial channel d,e… can appear in our detector as energy E and channel c.
  - Particularly **fierce bias** when using the **QE hypothesis** to calculate E and $Q^2$!
- $Y_{\text{c-like}}(E)$ is the event energy and channel / topology of the event observed in the detector. Appears to be channel c but may not have been channel c at interaction.

# What do we observe in our detectors?

## Further implications for Oscillation Experiments

- The events we observe in our detectors are convolutions of:

  $Y_{c\text{-like}}(E)\ \alpha\ \phi(E' \geq E) \otimes \sigma_{c,d,e..}(E' \geq E) \otimes Nuc_{c,d,e..\rightarrow c}(E' \geq E)$

  effective $\sigma_c^A(E)$

- Experimentally, the convolution of initial cross section and nuclear effects are combined into an effective cross section $\sigma_c^A(E)$ that **depends on incoming neutrino energy spectrum and nuclear effects that populate the yield $Y_c^A(E)$.**
- This implies, for example, effective $\sigma_{\pi+}^C$ (1 GeV) measured in the Booster beam **will be different** than the same effective $\sigma_{\pi+}^C$ (1 GeV) observed in the higher energy NuMI beam due to, for example, more feed down from multi-pi events. **Can not simply plug in effective $\sigma_{\pi+}^A$ from experiments in a different beam.**
- In a two-detector LBL oscillation experiment, neutrino flux entering the FD is different than the neutrino flux at the ND due to geometry and oscillations. The $\sigma_c^A$ (E) effective that should be applied to expectations (Monte Carlo) at FD is NOT the same as that which we would measure at the ND. **The ND results give us an excellent starting point for calculating the difference.**

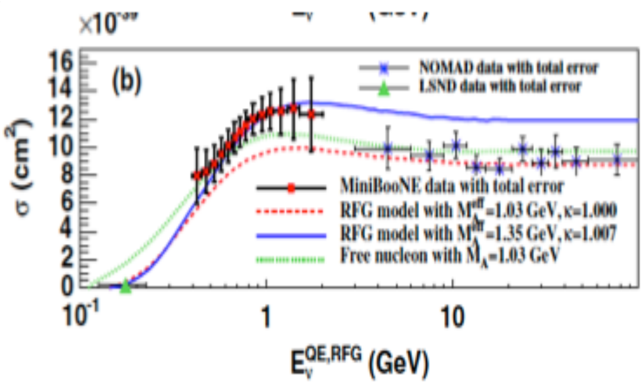
# How do we address this $\nu_\mu$ scattering problem? What could a nuSTORM Scattering analysis add?

- Use the unique qualities of the nuSTORM beam meaning the fantastic knowledge of absolute and relative flux. And we can vary the energy distribution of this well-known beam.
- Combine with a **high-resolution near detector with multiple nuclear targets** to provide detailed studies of the final states including the vertex multiplicities and energy flow..
- **nuSTORM, providing a beam with knowledge of the flux to ≤ 1%, to such a near detector would provide an outstanding neutrino-nucleus scattering experiment addressing both electroweak and nuclear physics questions. It would allow us to measure, for example, $\sigma_{\pi+}{}^{A}$ (E) for multiple A and various E.**

# QE History
## Very important for nuSTORM

- problem of low $Q^2$

- problem of axial mass




- $M_A$ provides a convenient tool to describe exp. data in shape & normalization with Fermi Gas

Have they got the flux wrong? nuSTORM could tell us? Distinction between Fermi Gas and Spectral Functions? With accurate $d\phi / dE$ – maybe nuSTORM could help.

- problem of np-nh (more complex nuclear effects: SRC + MEC)

- However there is an alternative path involving a more sophisticated nuclear models. MEC implies extra tracks and energy at vertex, nuSTORM could help. **Time to retire impulse approximation with RFG!**

# The nuSTORM Neutrino Beam

$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$    $\mu^- \rightarrow \nu_\mu + \bar{\nu}_e + e^-$

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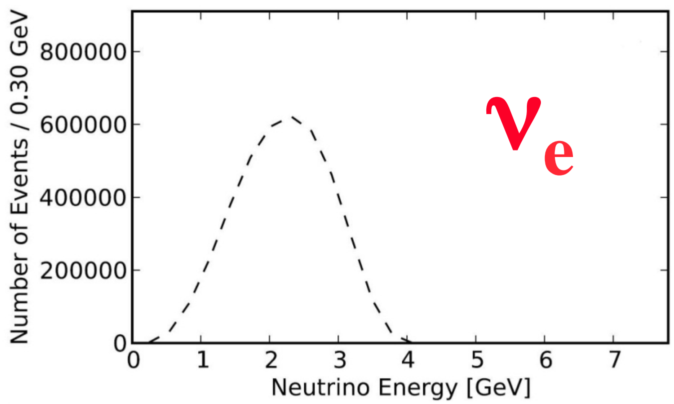
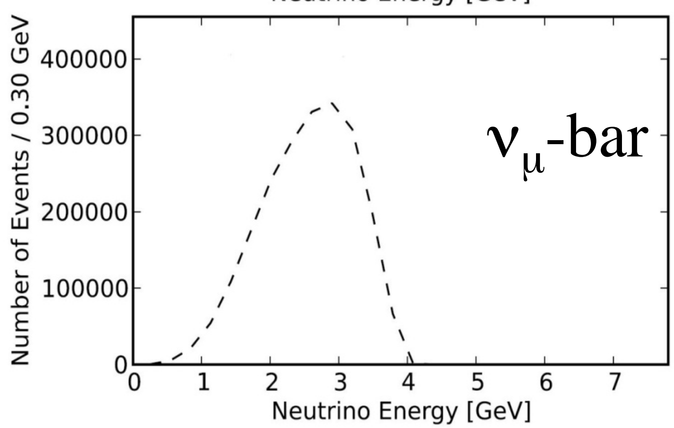
- **A high-intensity source of $\nu_e$ events for experiments.**

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event rates per 1E21 POT -
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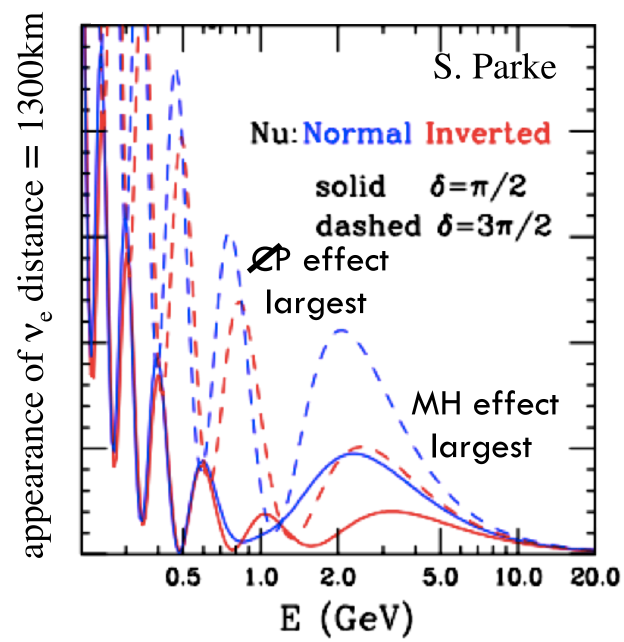
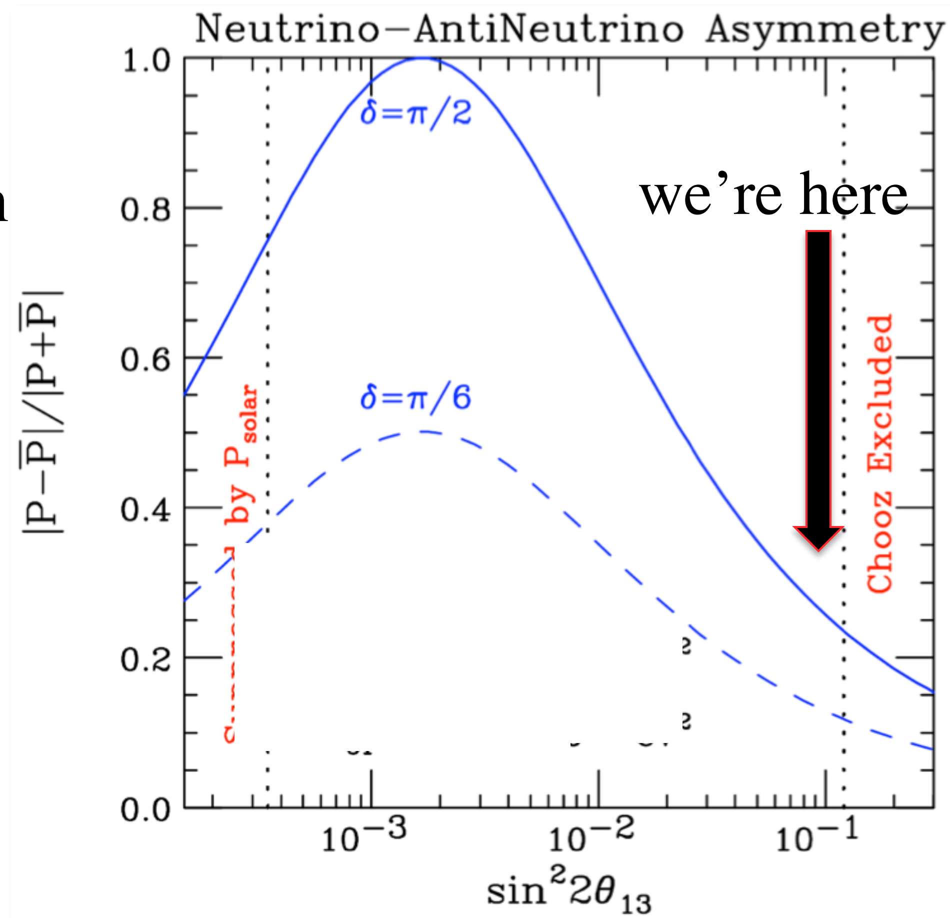
# Why are $\nu_e$ Cross Sections Important?

- $\nu_e$ A – scattering results are interesting on their own.
- Recent determination of large $\theta_{13}$ has opened up possibilities of
  - Determining $\nu$ mass ordering.
  - Searching for CP-violation in the $\nu$ sector.
- To be sensitive to these effects, current/near-future long-baseline experiments will be looking for $\nu_\mu$ to $\nu_e$ and $\bar{\nu}_\mu$ to $\bar{\nu}_e$ oscillations over a range of energies.
- These will no longer be only "counting" experiments but rather will depend on observing distortions in the far detectors neutrino energy spectrum in **both neutrino and anti-neutrino samples**.



# Why are $\nu_e$ and $\overline{\nu}_e$ Cross Sections Important?

- Large $\theta_{13}$ means we could have reasonable statistics.
- However, as the now-well-known plot at right suggests, the asymmetry between $\nu$ and $\overline{\nu}$ will be small and the goal of constraining the range of $\delta$ will demand minimal systematic errors.
- One of these systematics will be our knowledge of $\nu_e$ and $\overline{\nu}_e$ cross sections in the relevant energy range.

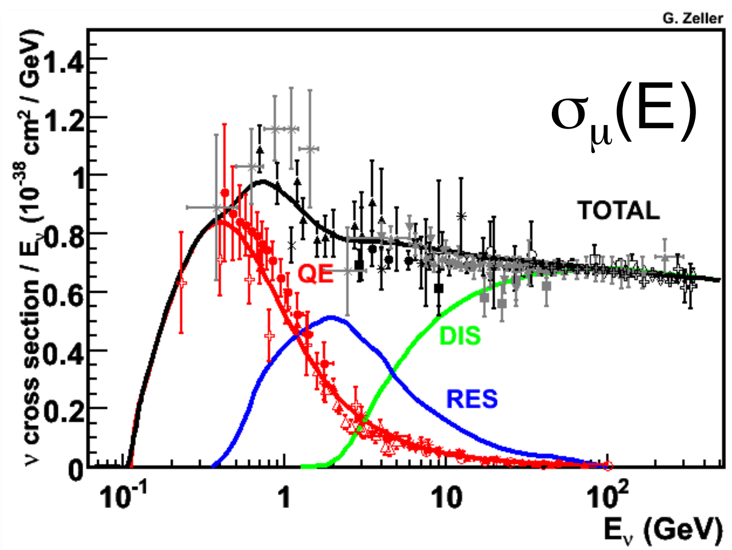


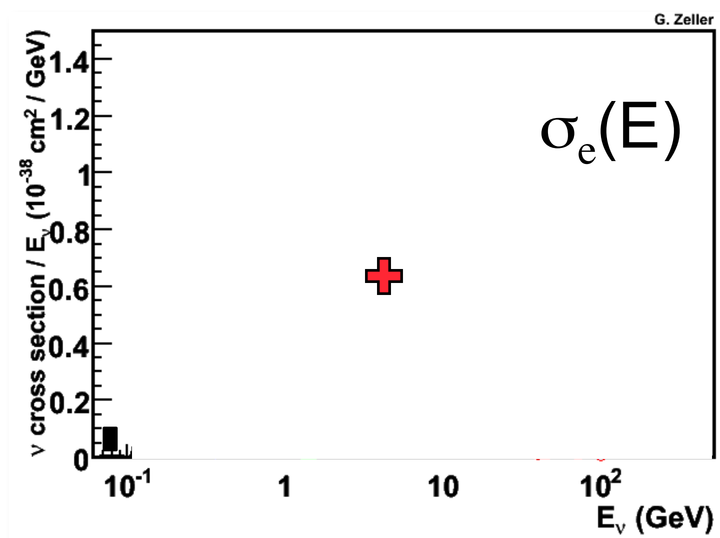

(not including matter effects & backgrounds)

(S. Parke)

# How well do we know $\nu_e$ cross sections?

- **WE DON'T!** Need to measure the $\sigma_{\nu e}(E)$ of multiple channels to fully predict a spectrum at a far detector for LBL experiments.




- **We infer them from $\sigma_{\nu\mu}(E)$ results. The validity of this inference directly impacts the uncertainty of the measurements.**

# One (+ ONE) to add to the collection…of one

Gargamelle: Nucl. Phys. B **133**: 205 (1978)

- Gargamelle experiment published with around 200 electron and 60 positron events.
- Error bars on the order of 30%.

**TOTAL CROSS SECTIONS FOR $\nu_e$ AND $\bar{\nu}_e$ INTERACTIONS AND SEARCH FOR NEUTRINO OSCILLATIONS AND DECAY**

*Gargamelle Collaboration*

J. BLIETSCHAU, H. DEDEN, F.J. HASERT, W. KRENZ, D. LANSKE, J. MORFIN, M. POHL, K. SCHULTZE, H. SCHUMACHER, H. WEERTS and L.C. WELCH

*III. Physikalisches Institut der Technischen Hochschule, Aachen, Germany*

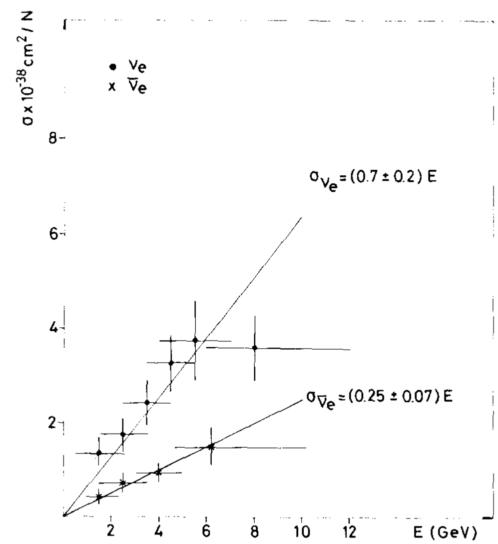



Fig. 2. Neutrino and antineutrino cross sections as a function of energy.

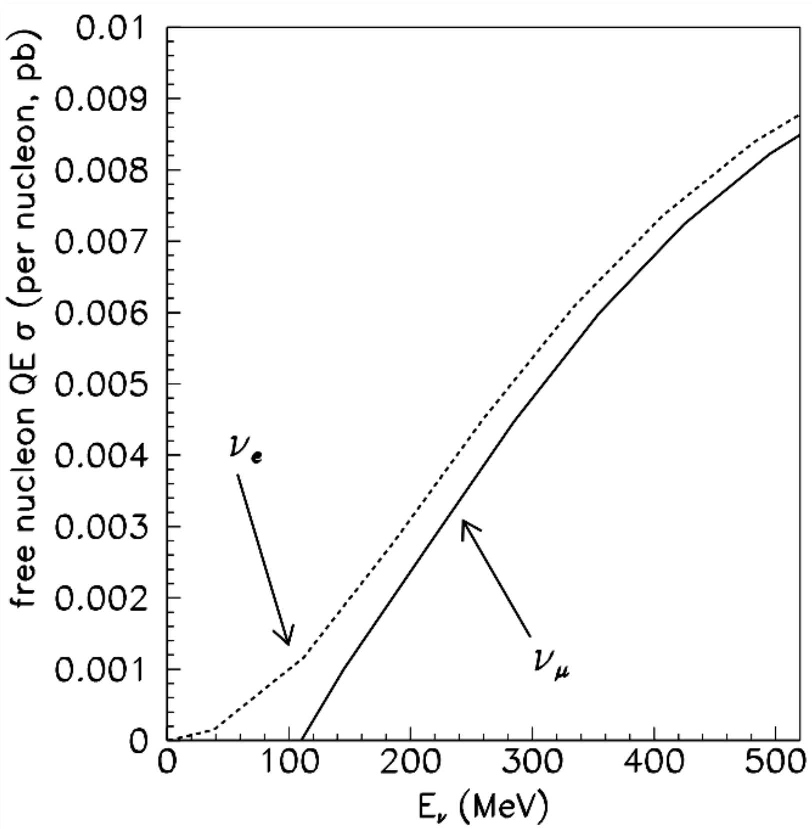
- MINERvA will have a sample of 65k $\nu_e$ CC events; 2.5k $\nu_e$ CCQE-like produced events in LE beam. In the ME beam probably factor of 5 higher statistics. Will be systematics limited → FLUX.

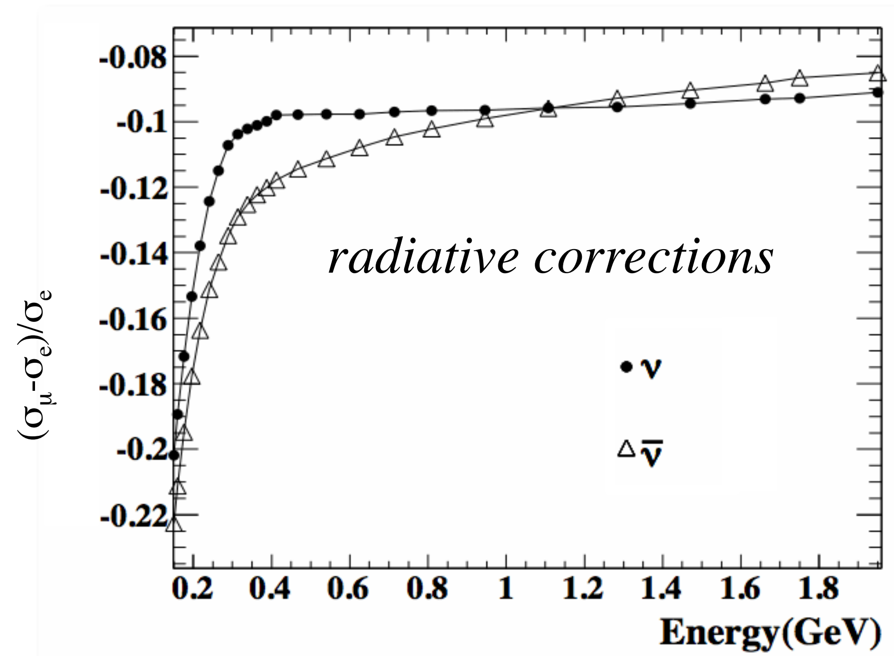
- **Until then, we infer them from $\sigma_{\nu\mu}(E)$ results. The validity of this inference directly impacts the uncertainty of measurements.**

# What are the Differences $\sigma_{\nu\mu}(E)$ and $\sigma_{\nu e}(E)$? Quasi-elastic Scattering

Day-McFarland study: Phys.Rev. D86 (2012) 053003

- QE scattering dominates at low energies (2nd oscillation maxima)
- Sources of possible differences and uncertainties - obvious:
  - Kinematic limits from μ / e mass difference.
  - Radiative Corrections. This may be an overestimate. Need full calculation.




*(M. Day, K. McFarland, arXiv:1206.6745)*

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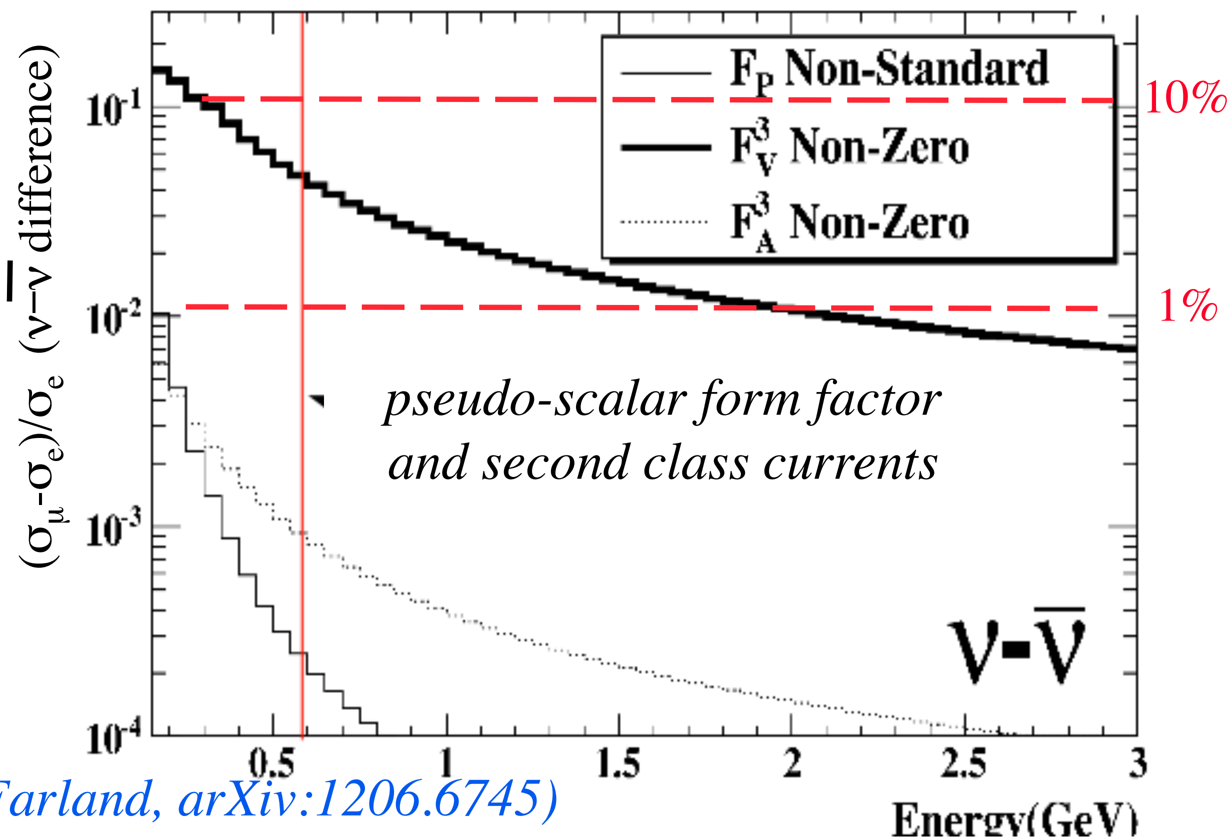
- Sources of possible differences: form factor uncertainties entering through lepton mass alterations - much more subtle:
  - Form factor contributions – both Axial and Pseudoscalar
  - Second class current contributions to vector and axial-vector form factors
- Possible contribution to CP uncertainties: effect on the FF could be different for $\nu$ and $\bar{\nu}$

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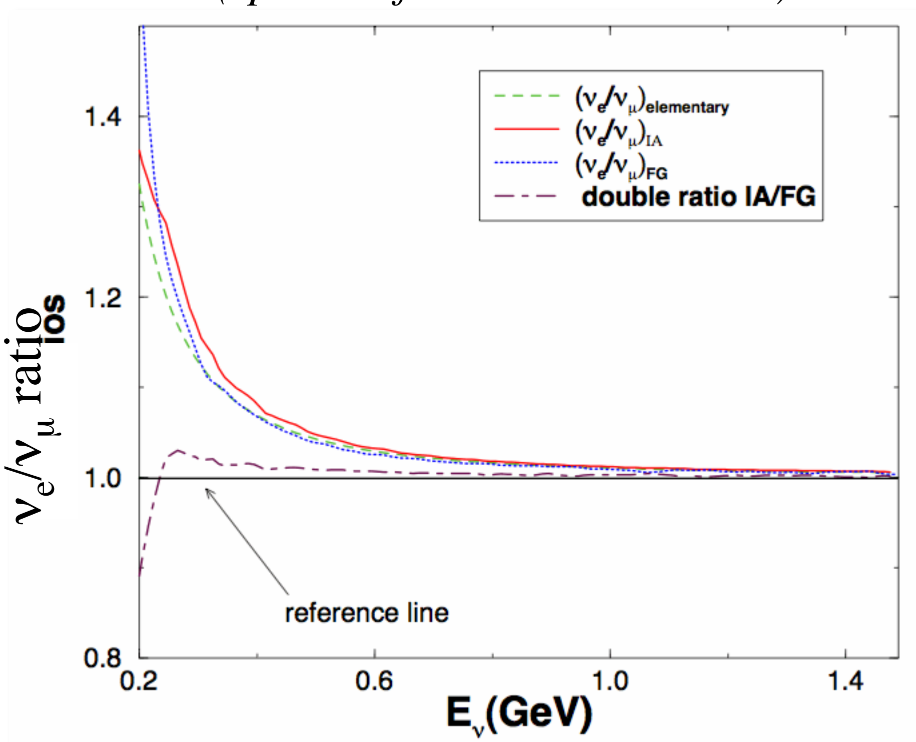
# What are the Differences? Mainly QE Scattering

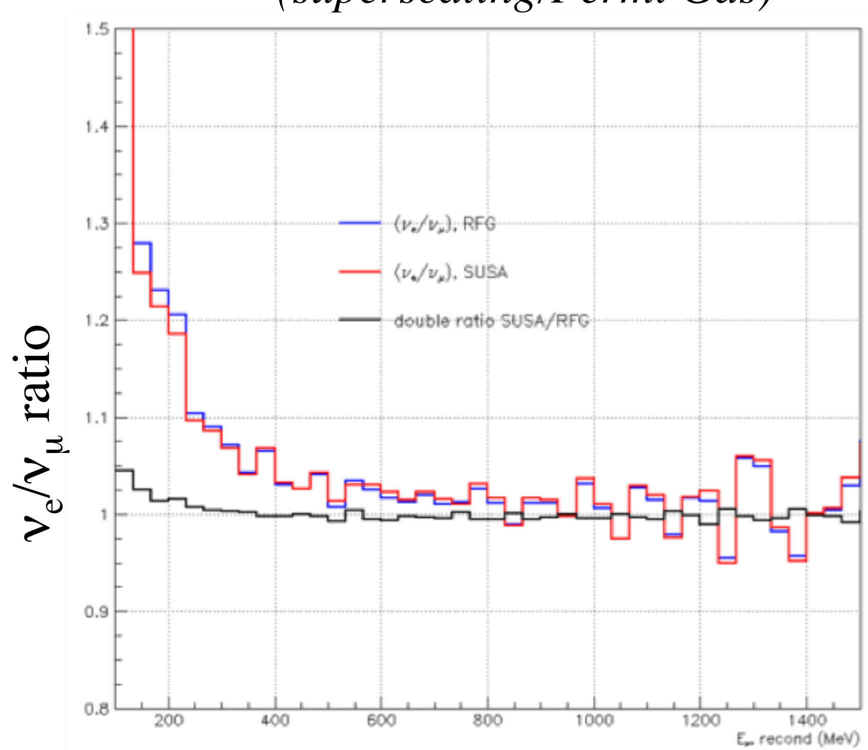
## Due to Nuclear Effects

- For standard models, ≤ 5% differences on $\nu_e/\nu_\mu$ ratio E < 200 MeV

*(spectral function/Fermi Gas)*



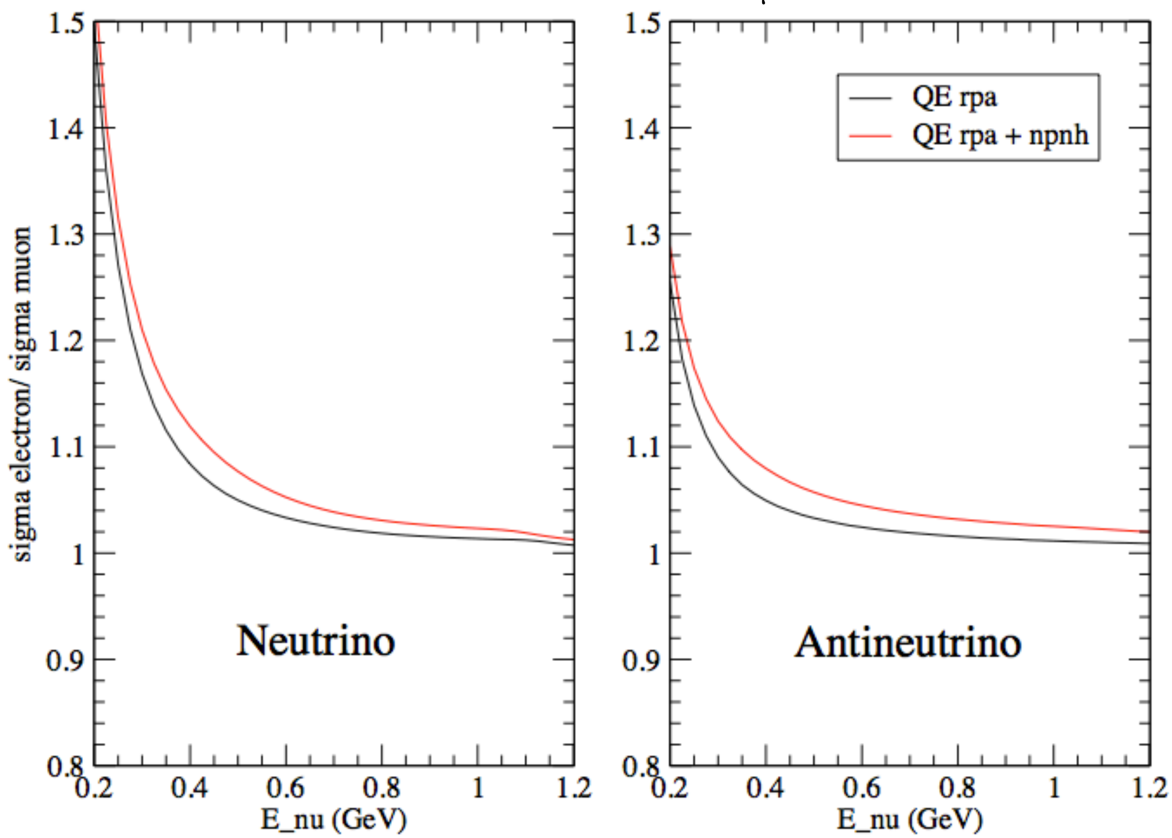

*(superscaling/Fermi Gas)*



# What are the Differences? Mainly QE Scattering

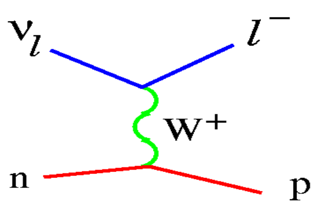
## Meson-exchange Current Contributions – Marco Martini

- Hadronic part (nuclear response functions) is the same for $\nu_e$ or $\nu_\mu$ cross section.
- However, the lepton tensor changes → the relative weight of the nuclear responses in the several channels may change.
- The double ratio suggests the effect on the $\nu_e/\nu_\mu$ cross section ratio is ≤ 5% (S. Zeller)



# Nuclear Effects can Change the Energy Reconstruction for "QE" Events

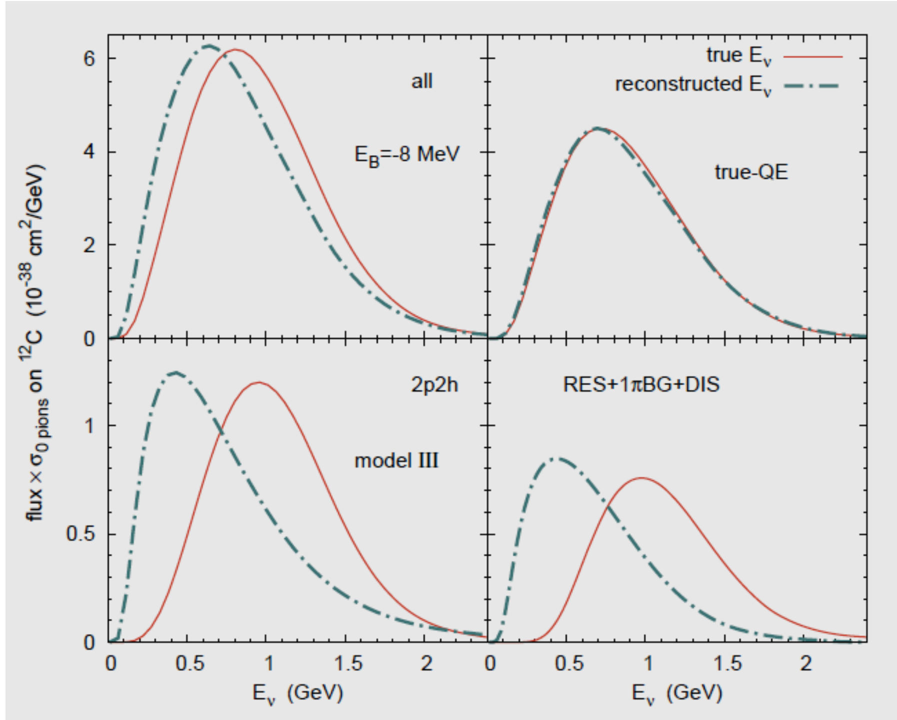
- In pure QE scattering on a nucleon at rest, the outgoing lepton can determine the neutrino energy:




$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

**However, not on nuclei.**

Reconstructed energy is shifted to lower values for all processes other than true QE off nucleon at rest

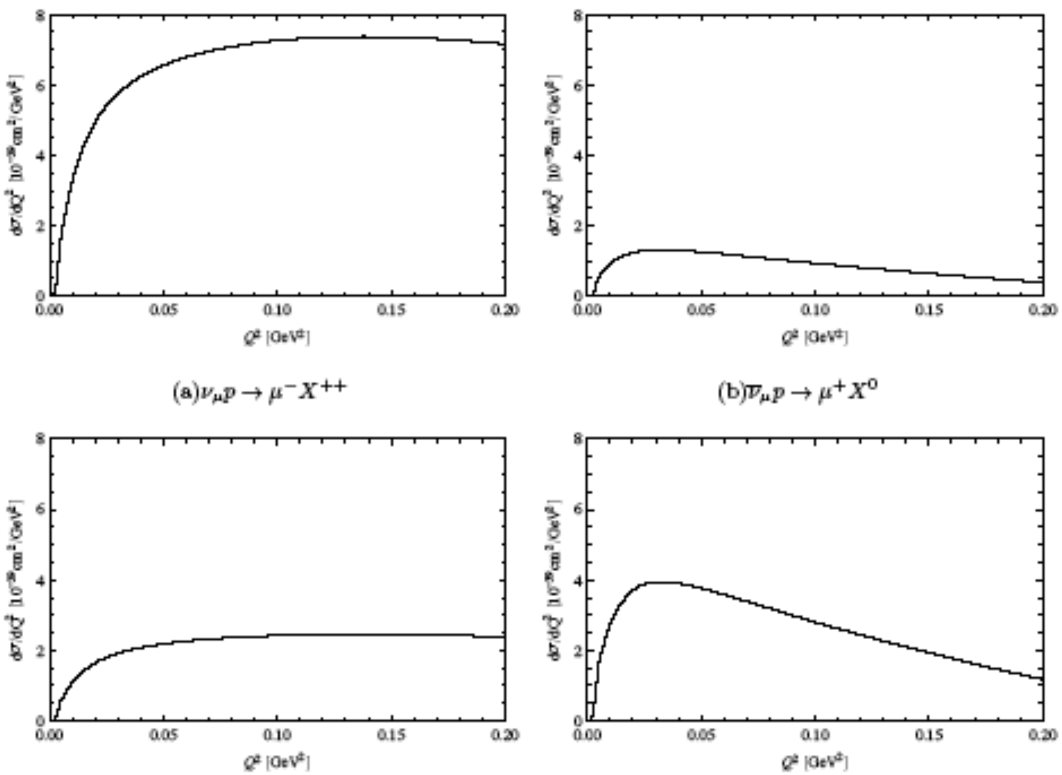



U. Mosel GiBUU

# What are the Differences? Δ Production

## Paschos – Schalla: arXiv:1209.4219

- Manny and his student have investigated $\nu_\mu$ and $\overline{\nu}_\mu$ differences in Δ production in the low-Q ($Q^2 \approx m_\pi^2$ ) region where PCAC dominates the axial contribution.
- At E = 1-2 GeV, V part and V/A interference same size → cancel for $\overline{\nu}$
- Use the Adler-Nussinov-Paschos model for nuclear corrections.



(a) $\nu_\mu p \to \mu^- X^{++}$

(b) $\overline{\nu}_\mu p \to \mu^+ X^0$

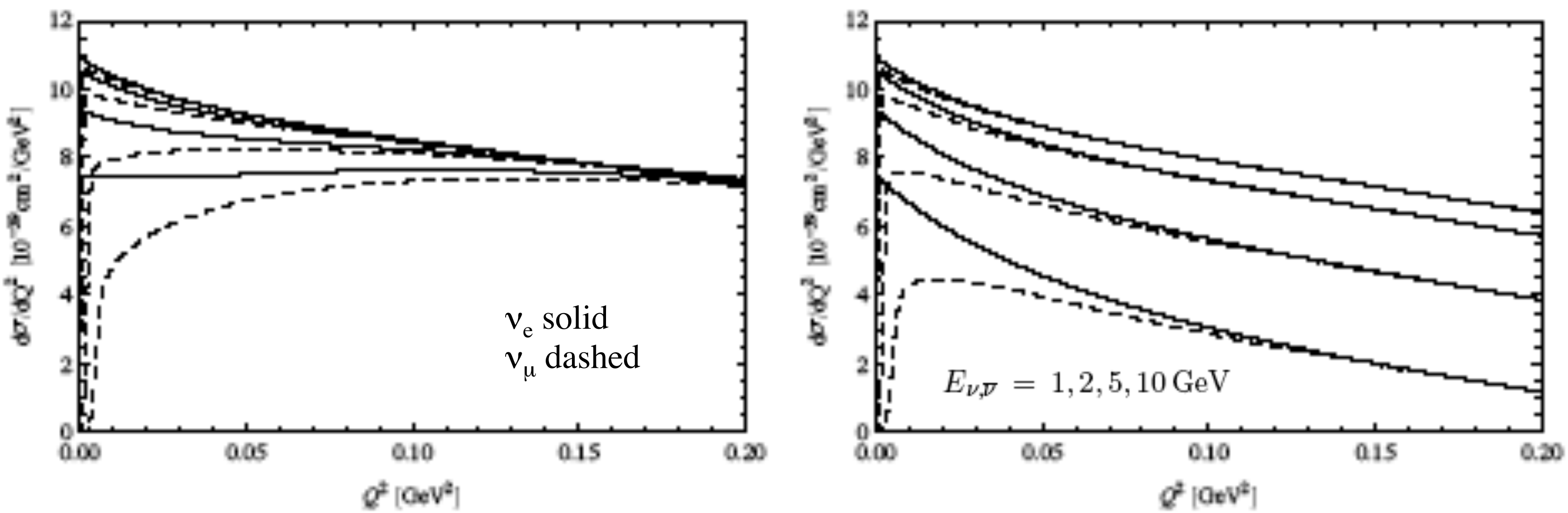
(c) $\nu_\mu n \to \mu^- X^+$

(d) $\overline{\nu}_\mu n \to \mu^+ X^-$

# What are the Differences? Δ Production

## Paschos – Schalla: arXiv:1209.4219

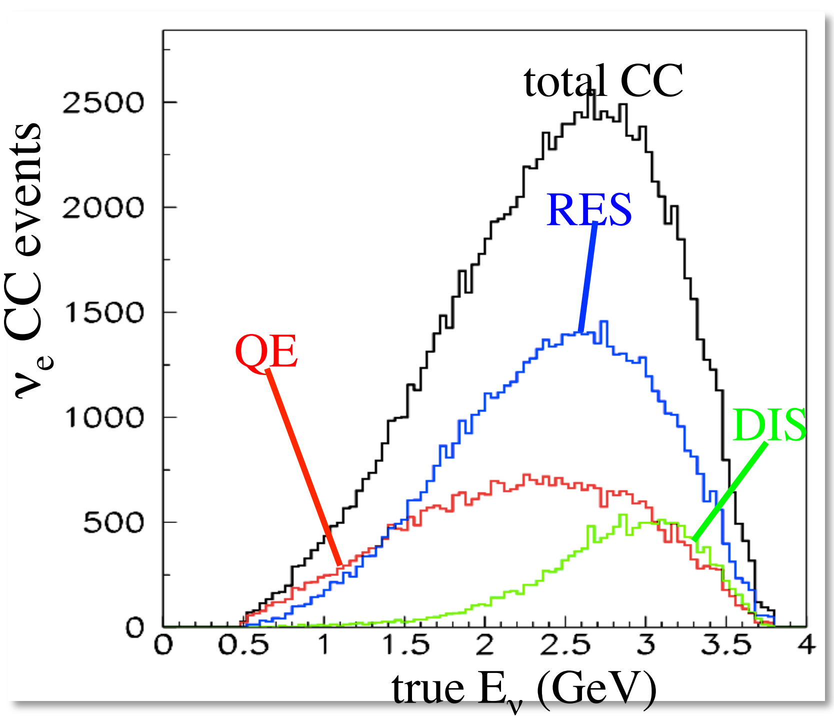
- Paschos-Schalla predicts the following differences in cross sections where only the lepton mass term contributions are shown and any differences in form factors are not yet included.




(a) $\nu_\ell p \to \ell^- \Delta^{++}$ (b) $\bar{\nu}_\ell n \to \ell^+ \Delta^-$

# Can we Actually MEASURE these Differences in the 0.5 – 6 GeV region

- Need to measure the $\sigma_e(E)$ of multiple channels to predict spectrum at the far detector.
  - Want an intense source of $\nu_e$ events.
  - Would like to know the flux of $\nu_e$ (and $\nu_\mu$, by the way) to order 1%.

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event rates per 1E21 POT - 100 tons at 50m

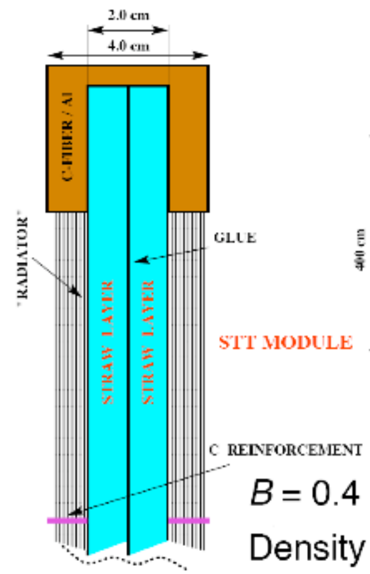
# nuSTORM Near Detector(s)

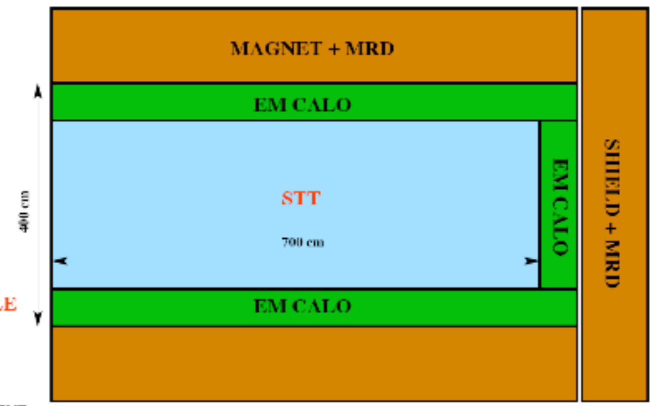
Etam MESSOMO

## 1) HighRes -

High Resolution Straw-tube.
transtion radiation
Magnetized Detector

Considered now by LBNE




$B = 0.4$ T.

Density = 0.1 g/cm3, 85% in the radiator foils.

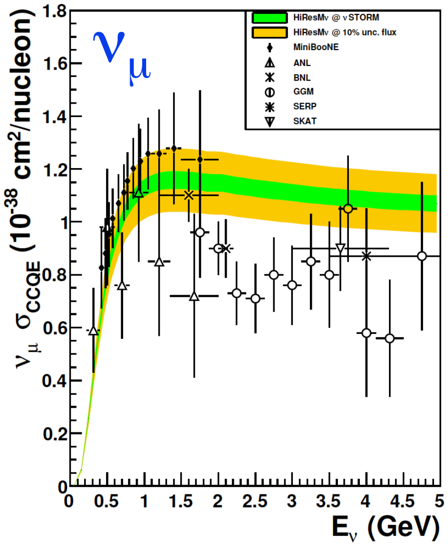
Transition Radiation → Electron ID ⇒ γ (w. Kinematics)
dE/dx → Proton, π, K ID
Magnet/Muon Detector → μ

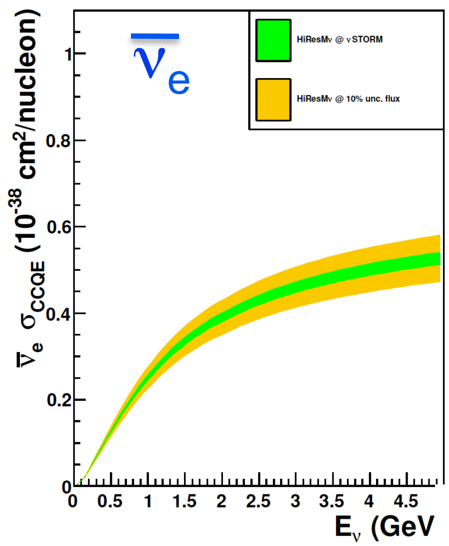
2) A 1-2 ton fiducial liquid hydrogen/deuterium track sensitive target upstream of HiRes. This could be a "bubble chamber".

# Scattering Measurements with nuSTORM + Near Detector

**nuSTORM provides a well-known ($\delta\,\phi(E) \approx 1\%$) beam of $\nu$ and $\bar{\nu}$.**

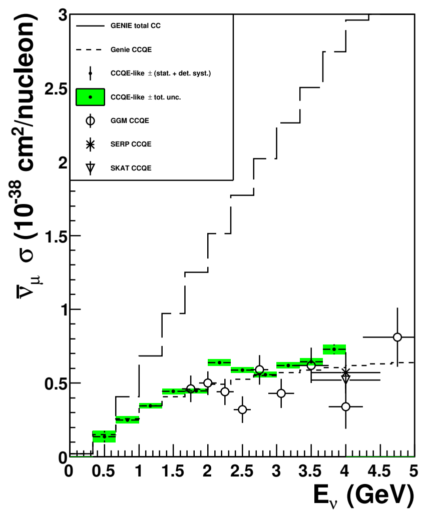
Ed Santos – Imperial College

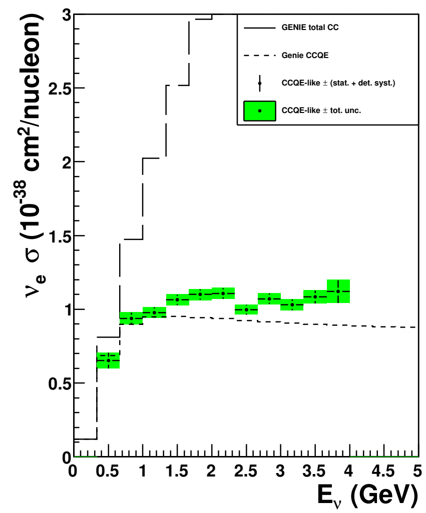



HIRESMν − systematics only

Total errors:
μBooNE LAr



# Conclusions: What does nuSTORM bring to Neutrino-nucleus Interaction Physics?

- Obvious benefit in measuring $\nu_e$ events.
- Use vastly improved nuSTORM neutrino flux uncertainty to measure neutrino cross sections and nuclear effects!
- There are many physics topics important in their own right and essential for precision neutrino oscillation experiments that will be awaiting the results of a high-resolution detector in the accurate nuSTORM flux!
- However, this is not the nuSTORM experiment that was approved.

  Adding at least a precision near detector and perhaps a H/D target.
- **This calls for a new collaboration using the nuSTORM facility. First meeting/workshop to establish this collaboration in November.**

# BACKUP

# What are the Differences $\sigma_{\nu\mu}(E)$ and $\sigma_{\nu e}(E)$? Quasi-elastic Scattering

Day-McFarland study: Phys.Rev. D86 (2012) 053003

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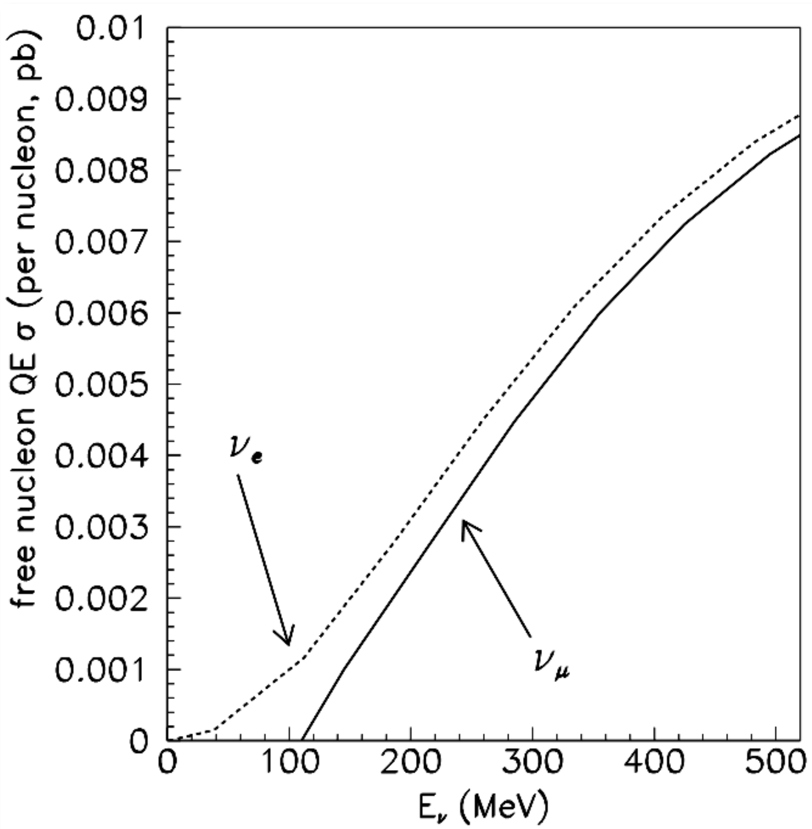
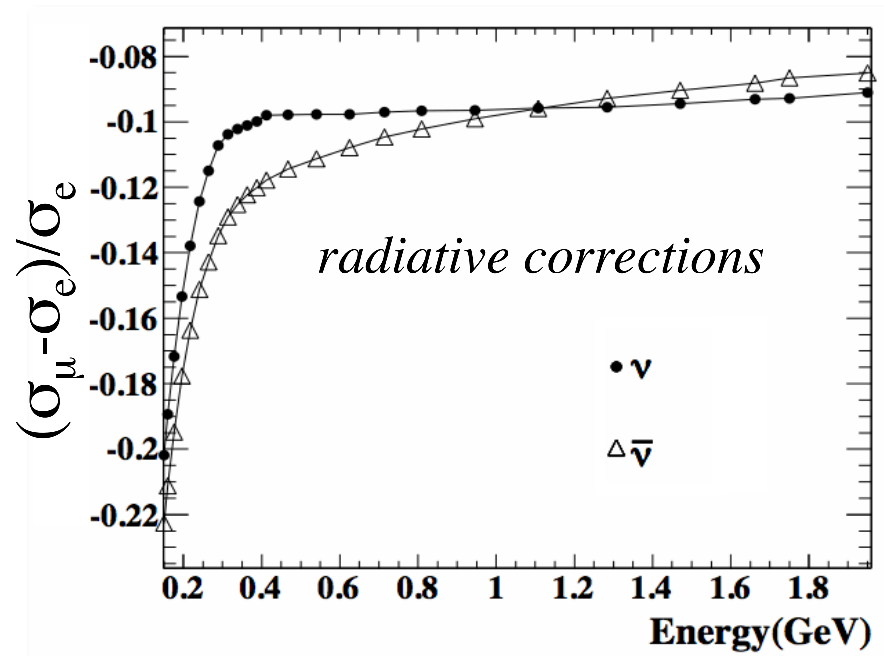
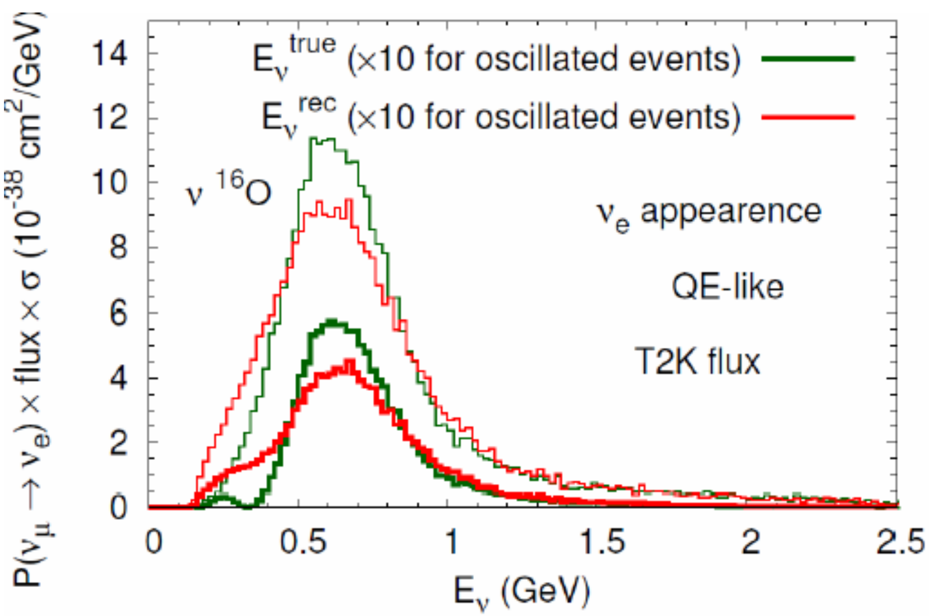


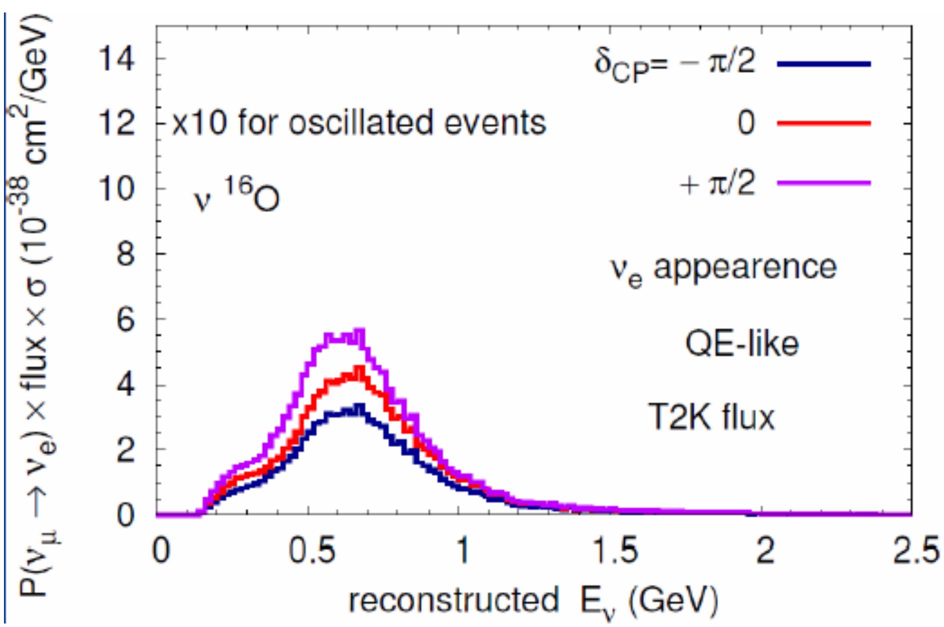




*(M. Day, K. McFarland, arXiv:1206.6745)*

# Nuclear Effects and Oscillation Measurements

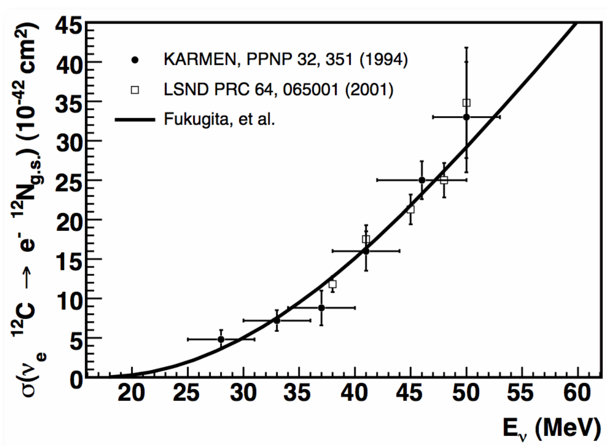
Ulrich Mosel using his Giessen Boltzmann-Uehling-Uhlenbeck (GiBUU) Transport Model looking at T2K



# How well do we know cross sections: $\nu_e$ vs. $\nu_\mu$? Existing $\nu_e$ Cross Section Data

- What do we know about $\sigma_{\nu e}(E)$? Mostly **very** low energy results.
  - Reactor neutrinos studying Inverse Beta Decay
  - Solar neutrino off deuterium (SNO)
  - Stopping $\pi/\mu$ decay neutrinos off higher A targets
  - See Formaggio and Zeller **Rev. Mod. Phys. 84, 1307–1341 (2012).**
- One of few measurements of spectral shape of $\sigma$ reflects the upper limit of most existing measurements, $E \leq 50$ MeV.




$\nu_e\,{}^{12}C \rightarrow e^-\,{}^{12}N_{g.s.}$

*(Formaggio & Zeller, Rev. Mod. Phys. 2012)*

# Addressing the lack of $F_2$ **Neutrino** Nuclear Effects Analyses

**Nuclear PDFs from neutrino deep inelastic scattering**

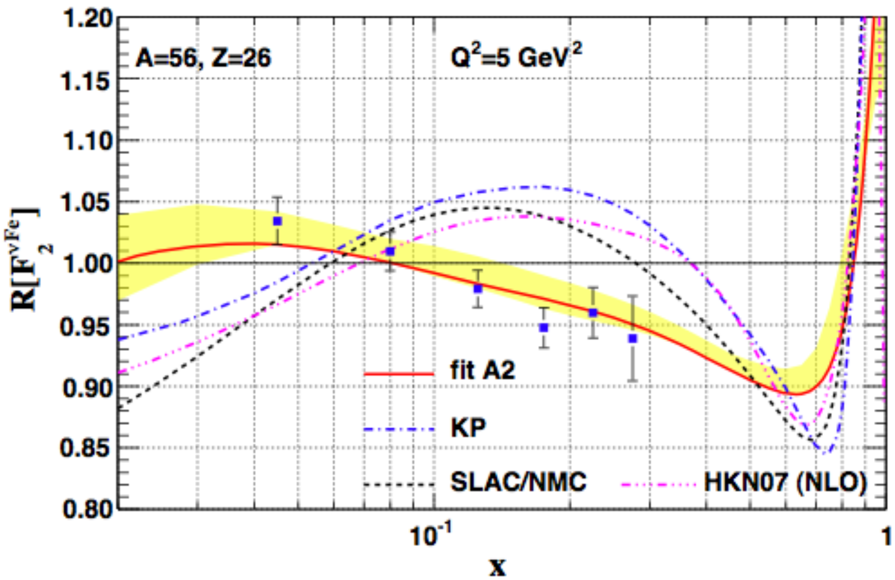
**nCTEQ**
**K. Kovarik (Karlsruhe) I. Schienbein (LPSC-Grenoble),**
**J-Y. Yu (SMU), C. Keppel (Hampton/JeffersonLab)**
**J.G.M. (Fermilab), F. Olness (SMU), J.F. Owens (Florida State U)**

Also analyses by:
K. Eskola, V. Kolhinen and C. Salgado
and
D. de Florian, R. Sassot, P. Zurita and M. Stratmann

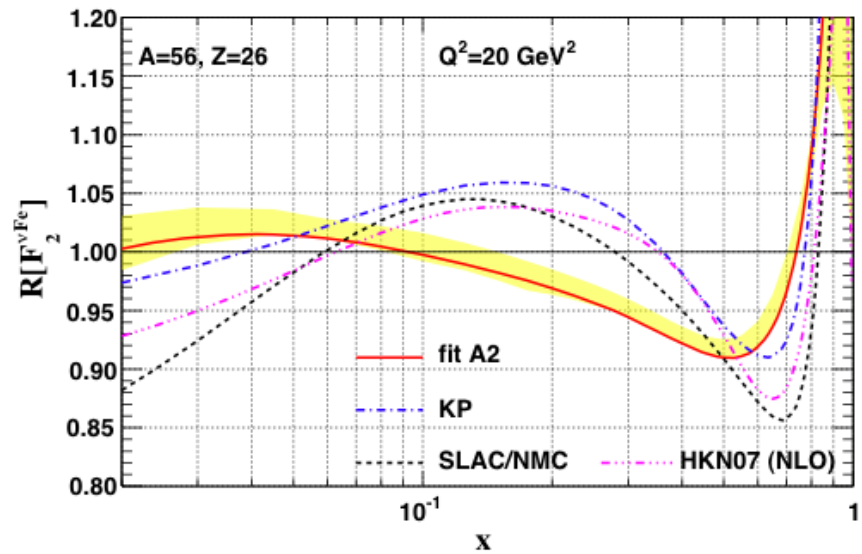
# Significant Implications for Oscillation Experiments

- Can not simply plug in effective $\sigma_{\pi+}^{A}$ from experiments in a significantly different beam.
- In a two-detector LBL oscillation experiment the neutrino flux entering the far detector is altered from the neutrino flux at the near detector due to geometry and oscillations.
- The $\sigma_{c}^{A}(E)$ effective that should be applied to expectations (Monte Carlo) at the far detector is NOT the same as that which we would measure at the near detector. **However, the near detector results give us an excellent starting point for calculating the difference.**
- **The convoluted $\phi(E' \geq E)$ ⓧ $\sigma(E)$ ⓧ Nuc($E' \geq E$) systematics need to be correctly incorporated in determining the systematics of oscillation parameter measurements. Who is addressing this important consideration now?**

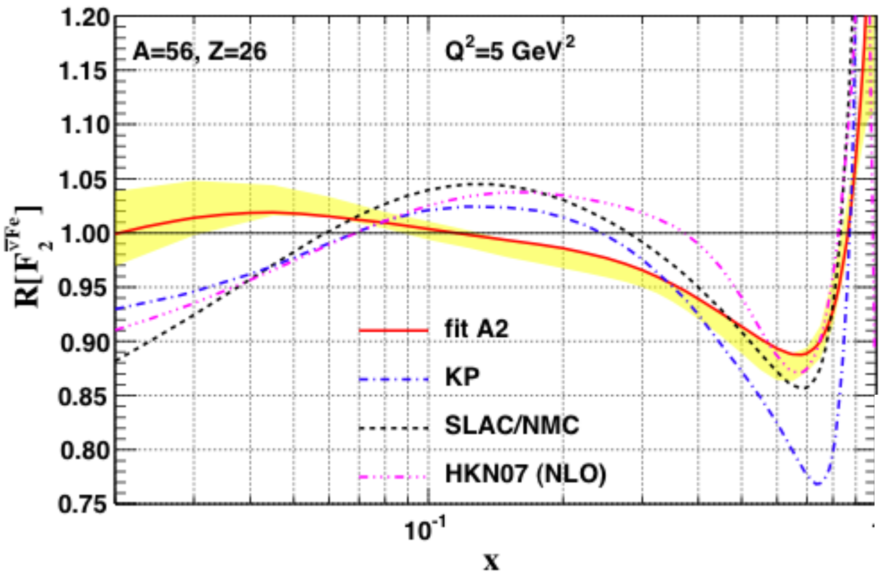
# $F_2$ Structure Function Ratios: ν-Iron



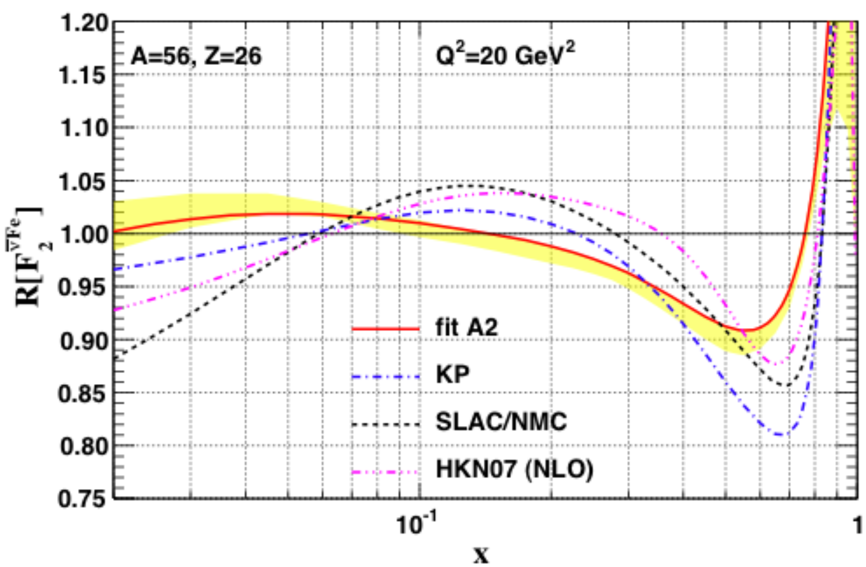

$$\frac{F_2(\nu + Fe)}{F_2(\nu + [n+p])}$$



# $F_2$ Structure Function Ratios: $\bar{\nu}$-Iron

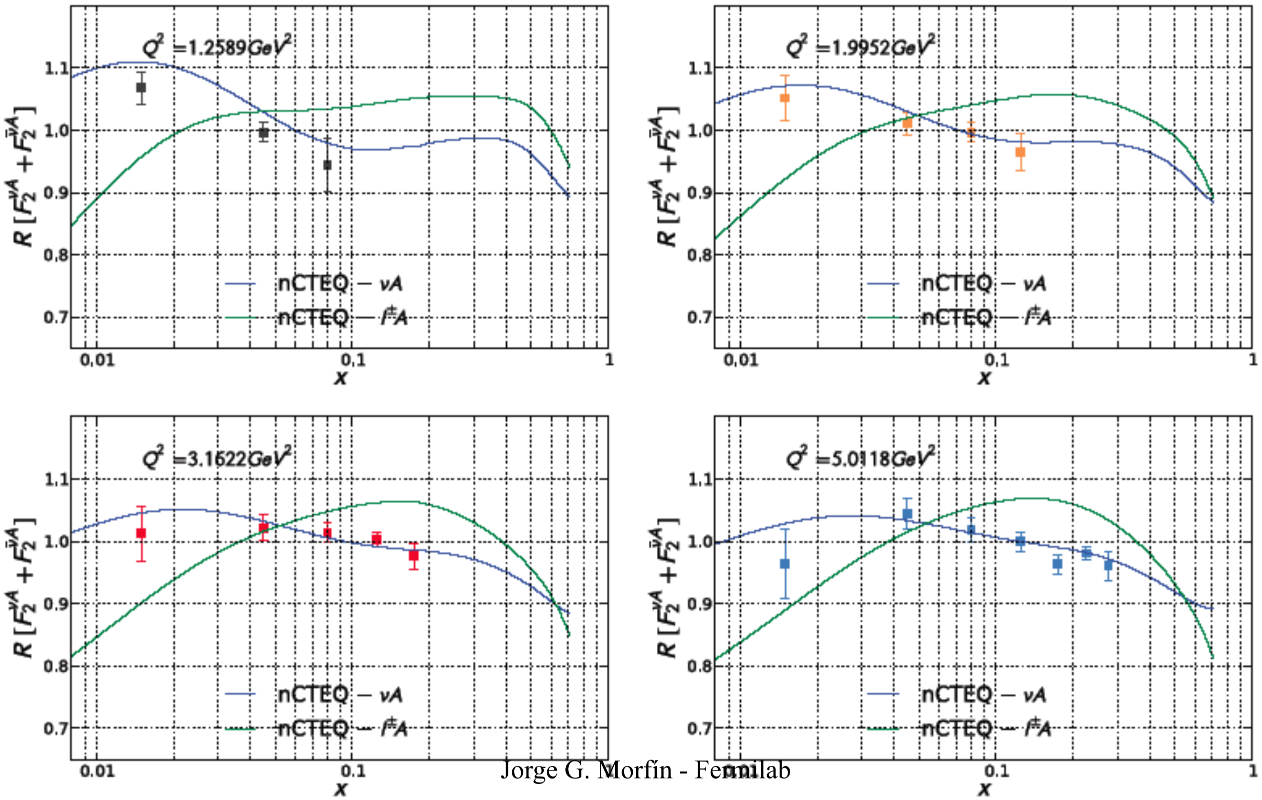



$$\frac{F_2(\nu + Fe)}{F_2(\nu + [n+p])}$$



# A More-Detailed Look at Differences

- NLO QCD calculation of $\frac{F_2^{\nu A} + F_2^{\bar{\nu} A}}{2}$ in the ACOT-VFN scheme
  - charge lepton fit undershoots low-x data & overshoots mid-x data
  - low-$Q^2$ and low-x data cause tension with the shadowing observed in charged lepton data



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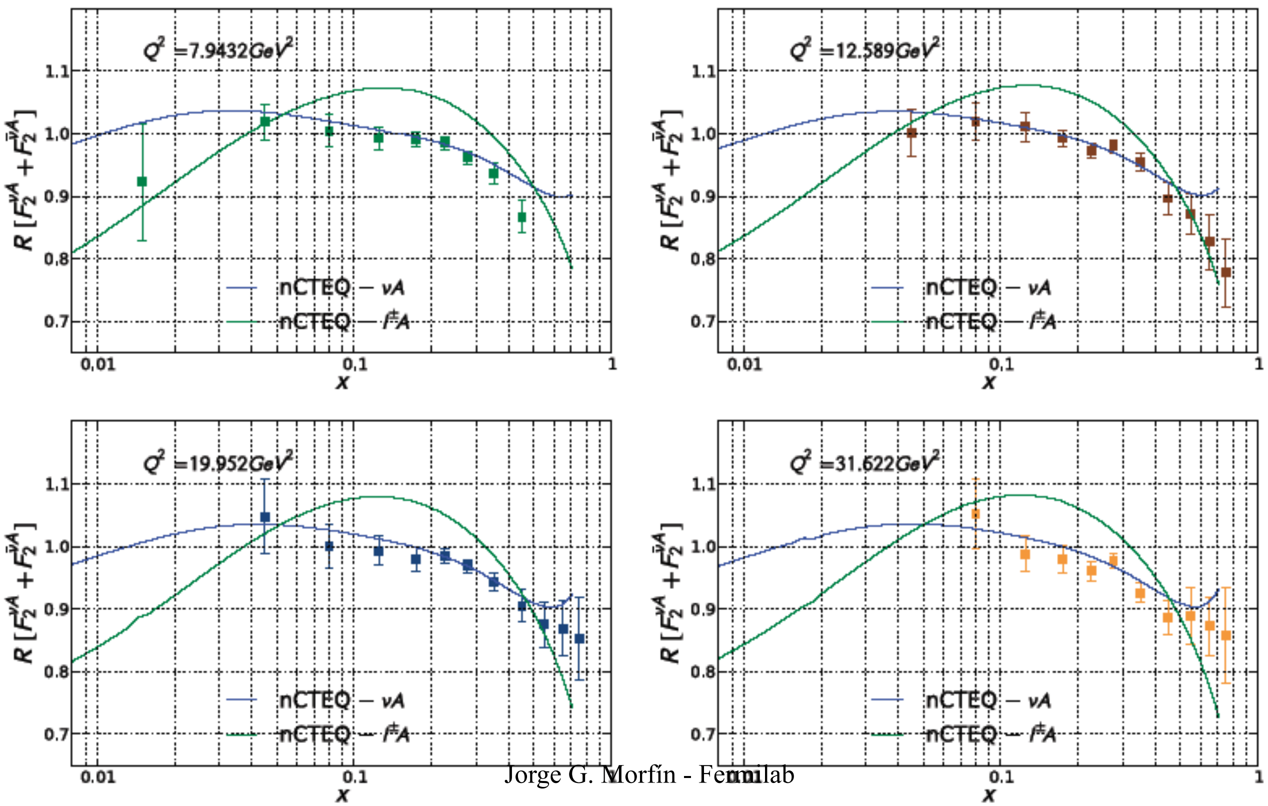


# What are these Nuclear Effects **$Nuc_{c,d,e..\rightarrow c}$ (E' ≥ E)** in Neutrino Nucleus Interactions? (Partial List)

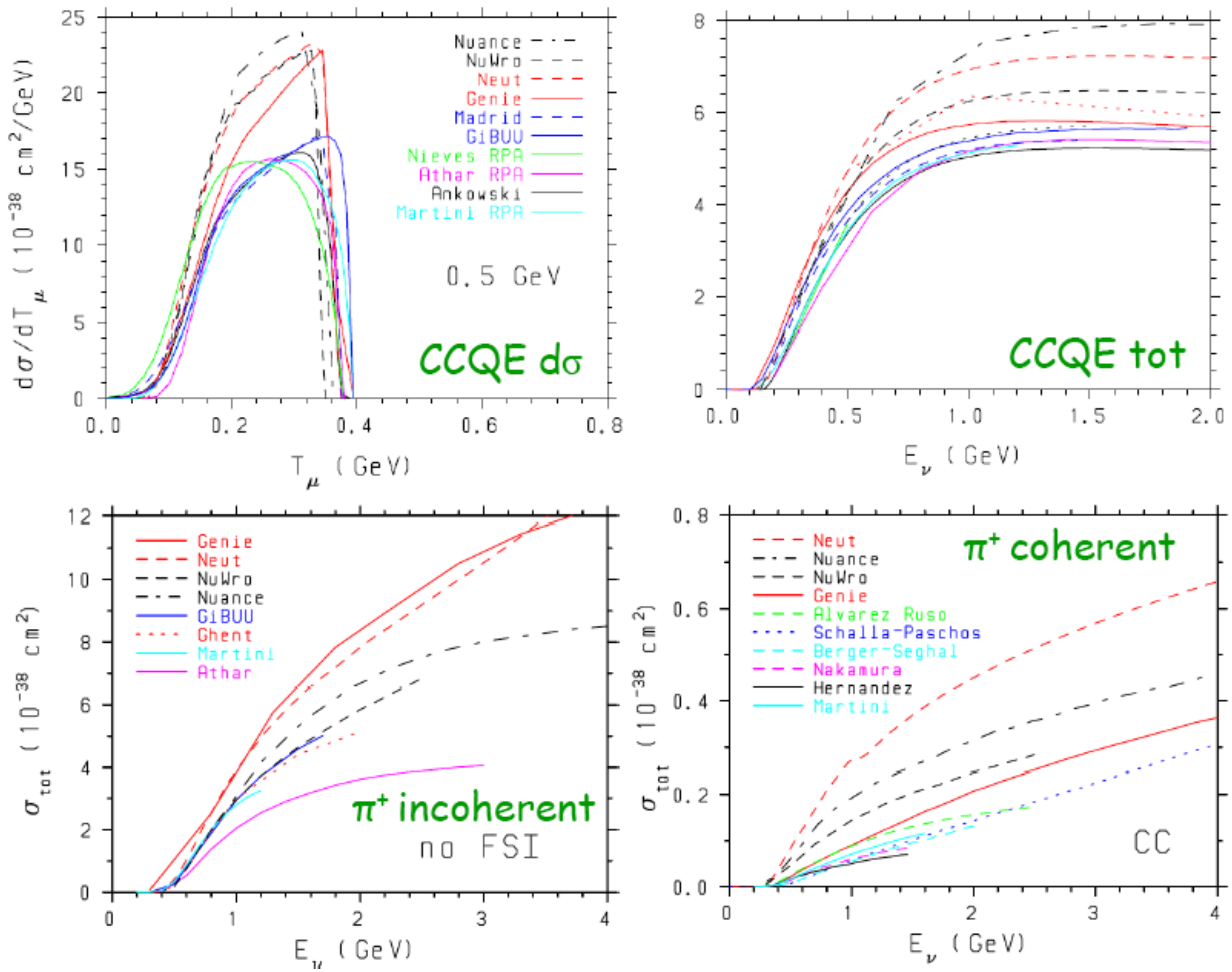
- Target nucleon in motion – classical Fermi gas model or the superior spectral functions (Benhar et al.)
- Multi-nucleon initial states: Short-range correlations, meson exchange currents.
- Form factors, structure functions, resonance widths, parton distribution functions and, consequently, cross sections are modified within the nuclear environment. (Butkevich / Kulagin, Tsushima et al., Kovarik et al.)
- Produced topologies are modified by final-state interactions modifying topologies and possibly reducing **detected** energy and **increasing** wrong-sign background.
  - Convolution of $\delta\sigma(n\pi)$ ⓧ formation zone uncertainties ⓧ $\pi$-charge-exchange/ absorption probabilities and nuclear density uncertainties.
- **Systematics associated with each of these effects.**

  - Monte Carlos – like GENIE – try to include all these effects.

**GENIE needs improvements! GENIE group needs additional help from the community.**

# How well off are we with $\nu_\mu$ Cross sections: Range of Existing Model (MC) Predictions off C

NuInt09 – Steve Dytman



# Example Model Uncertainties

### *Cross Section Model Uncertainties*

| Uncertainty | 1 σ |
|---|---|
| $M_A$ (Elastic Scattering) | ± 25% |
| Eta (Elastic scattering) | ± 30% |
| $M_A$ (CCQE Scattering) | +25% −15% |
| CCQE Normalization | +20% −15% |
| CCQE Vector Form factor model | on/off |
| CC Resonance Normalization | ± 20% |
| $M_A$ (Resonance Production) | ± 20% |
| $M_V$ (Resonance Production) | ± 10% |
| 1pi production from $\nu p / \bar{\nu} n$ non-resonant interactions | ± 50% |
| 1pi production from $\nu n / \bar{\nu} p$ non-resonant interactions | ± 50% |
| 2pi production from $\nu p / \bar{\nu} n$ non-resonant interactions | ± 50% |
| 2pi production from $\nu n / \bar{\nu} p$ non-resonant interactions | ± 50% |
| Modify Pauli blocking (CCQE) at low $Q^2$ (change PB momentum threshold) | ± 30% |

### •*Intranuclear Rescattering Uncertainties*

| Uncertainty | 1 σ |
|---|---|
| Pion mean free path | ± 20% |
| Nucleon mean free path | ± 20% |
| Pion fates – absorption | ± 30% |
| Pion fates – charge exchange | ± 50% |
| Pion fates – Elastic | ± 10% |
| Pion fates – Inelastic | ± 40% |
| Pion fates – pion production | ± 20% |
| Nucleon fates – charge exchange | ± 50% |
| Nucleon fates – Elastic | ± 30% |
| Nucleon fates – Inelastic | ± 40% |
| Nucleon fates – absorption | ± 20% |
| Nucleon fates – pion production | ± 20% |
| AGKY hadronization model – $x_F$ distribution | ± 20% |
| Delta decay angular distribution | On/off |
| Resonance decay branching ratio to photon | ± 50% |

Hugh Gallagher

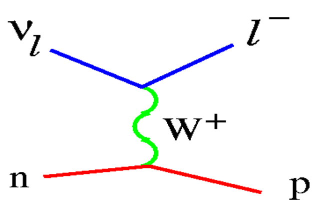
References: (1) www.genie-mc.org, (2) arXiv:0806.2119, (3) D. Bhattacharya, Ph. D Thesis (U. Pittsburgh) 2009.

# Have these experiments really measured $M_A$ ?

- Just as we have noted, we are observing an effective $\sigma_c^A(E)$ in our detectors…
  - What has been measured is a parameter $M_a^{eff}$
  - It depends on the use of RFGM or Spectral Functions.
  - It depends on the nucleus used and…
  - It depends on the incoming flux.
  - It also depends on number of initial nucleons involved
- Need nuSTORM with its accurate flux and series of nuclear targets with high-resolution detector(s).
- Also need at least a good model for pion production which, through FSI, is the main background for QE.
- (QE) measurements calculating E and $Q^2$ via the muon are in trouble!

# Nuclear Effects can Change the Energy Reconstruction for "QE" Events

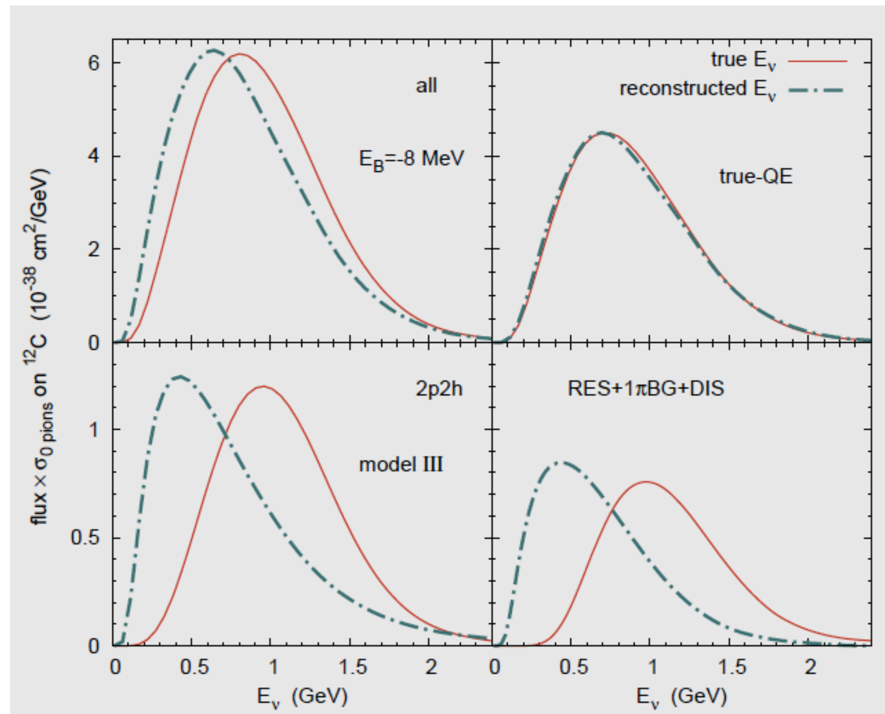
- In pure QE scattering on a nucleon at rest, the outgoing lepton can determine the neutrino energy:




$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

**However, not on nuclei.**

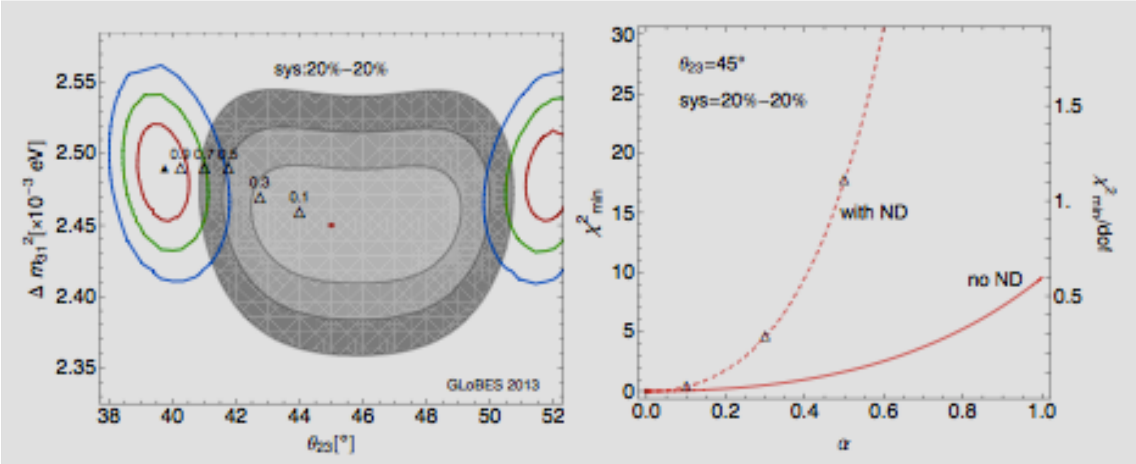
Reconstructed energy is shifted to lower values for all processes other than true QE off nucleon at rest




U. Mosel GiBUU

# Detailed Study by P. Coloma and P. Huber arXiv 1307.1243

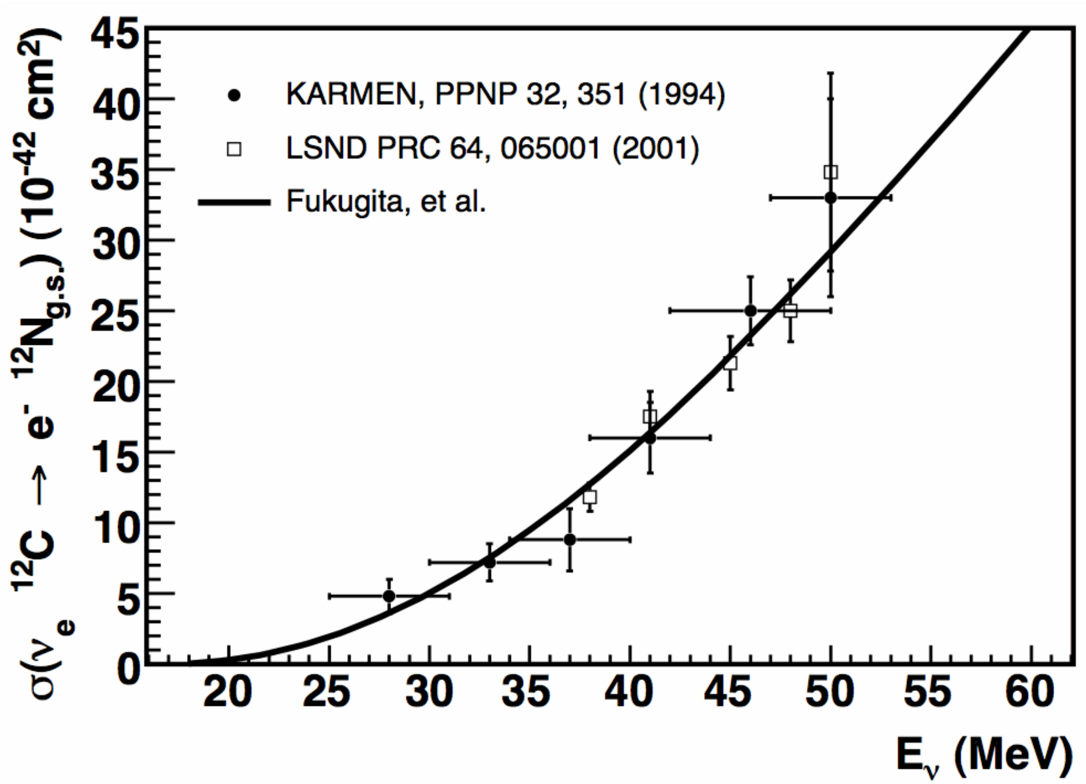
- Disappearance experiment using CC QE-**like** signal events. T2K – 5 years; 850 QE
- QE-**like** includes pion absorption and scattering off nucleon pairs. 1300 QE-**like**
- $E_\nu$ is reconstructed from the observed muon which gives a lower $E_\nu$ for non-QE.
- Give a quantitative estimate of this problem using: $N_i^{test}(\alpha) = \alpha \times N_i^{QE} + (1-\alpha) \times N_i^{QE-like}$
- $\alpha = 1$ implies completely ignore nuclear effects while $\alpha = 0$ implies you know/ model the nuclear effects completely.
- The importance of a near detector to help normalize the signal is obvious. However have not yet included different near and far incoming neutrino spectra.
- Even with ND, $\alpha = 0.3 \rightarrow 1\ \sigma$ bias in parameters! **Need accurate nuclear model!**



# Example of Existing Data: Carbon

$\nu_e \, ^{12}C \rightarrow e^- \, ^{12}N_{g.s.}$

- One of few measurements of spectral shape of σ reflects the upper limit of most existing measurements, E ≤ 50 MeV.




*(Formaggio & Zeller, Rev. Mod. Phys. 2012)*