Neutrino – Nucleus Scattering Physics with nuSTORM

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

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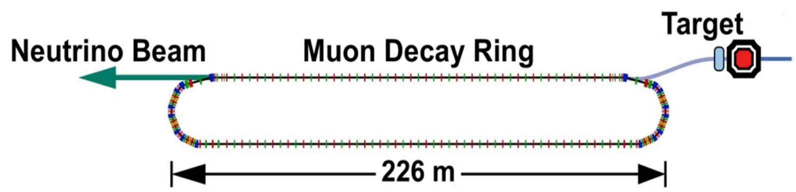
NuFact 2013
IHEP-Beijing
August 2013

What is nuSTORM?

Neutrinos from Stored Muons – Alan Bross Presentation on Saturday

- High-Precision ν interaction physics program.
- **ν_e and $\overline{\nu}_e$ cross-section measurements.**
- Address the large Δm^2 oscillation regime, make a major contribution to the study of sterile neutrinos.
  - Either allow for precision study (in many channels), if they exist in this regime.
  - Or greatly expand the dis-allowed region.

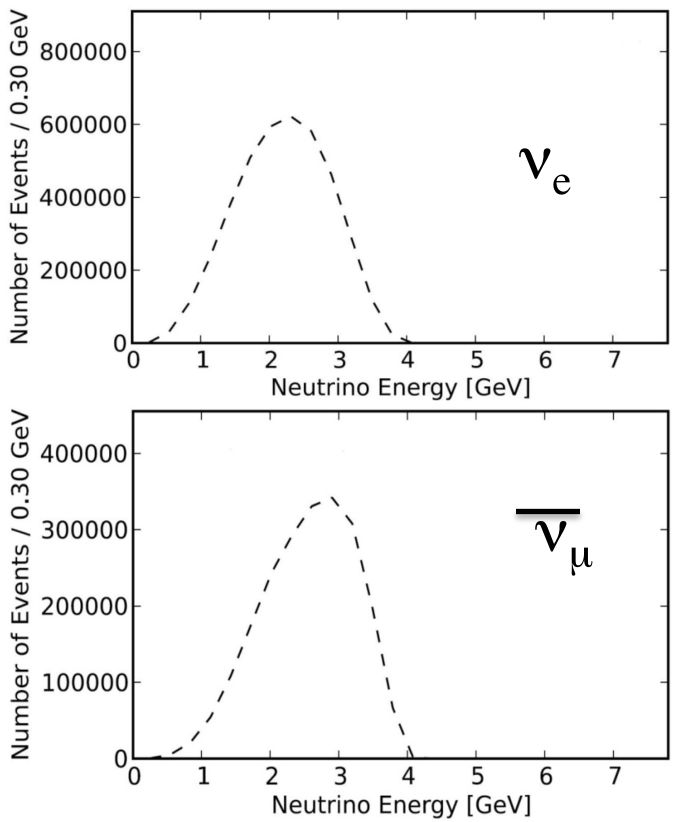


- Provide a technology test demonstration (μ decay ring) and μ beam diagnostics test bed.
- Provide a precisely understood ν beam for detector studies.
- **Change the conception of the neutrino factory.**

The nuSTORM Neutrino Beam

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

- nuSTORM will provide a **very well-known ($\delta\,\phi(E) \leq 1\%$)** beam of ν and $\bar{\nu}$.
- nuSTORM will provide a **high-intensity source of ν_e events!**



3.8 GeV μ^+ stored, 175m straight, flux at 50m

μ^+

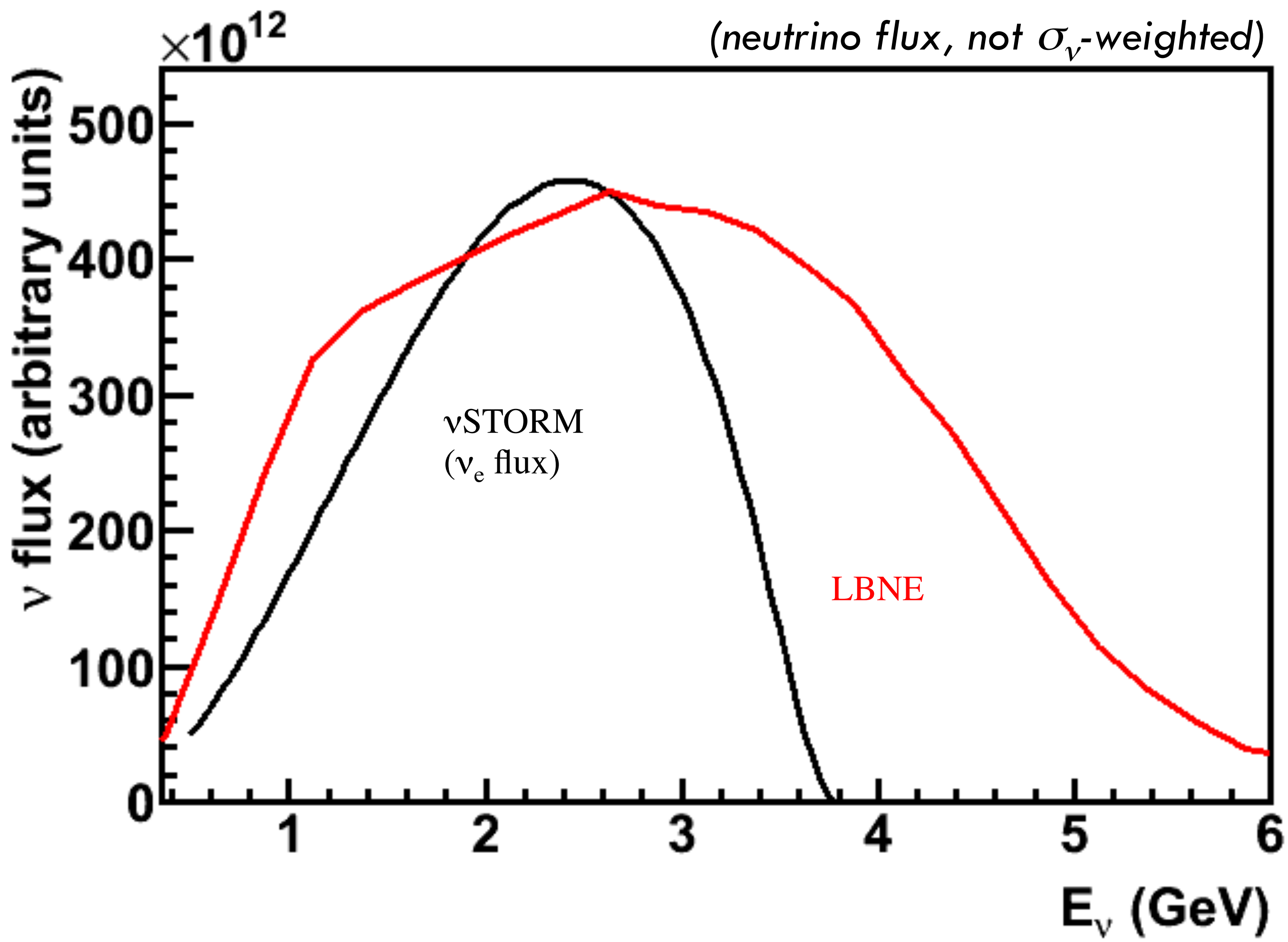
Channel	N_{evts}
$\bar{\nu}_\mu$ NC	844,793
ν_e NC	1,387,698
$\bar{\nu}_\mu$ CC	2,145,632
ν_e CC	3,960,421

μ^-

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

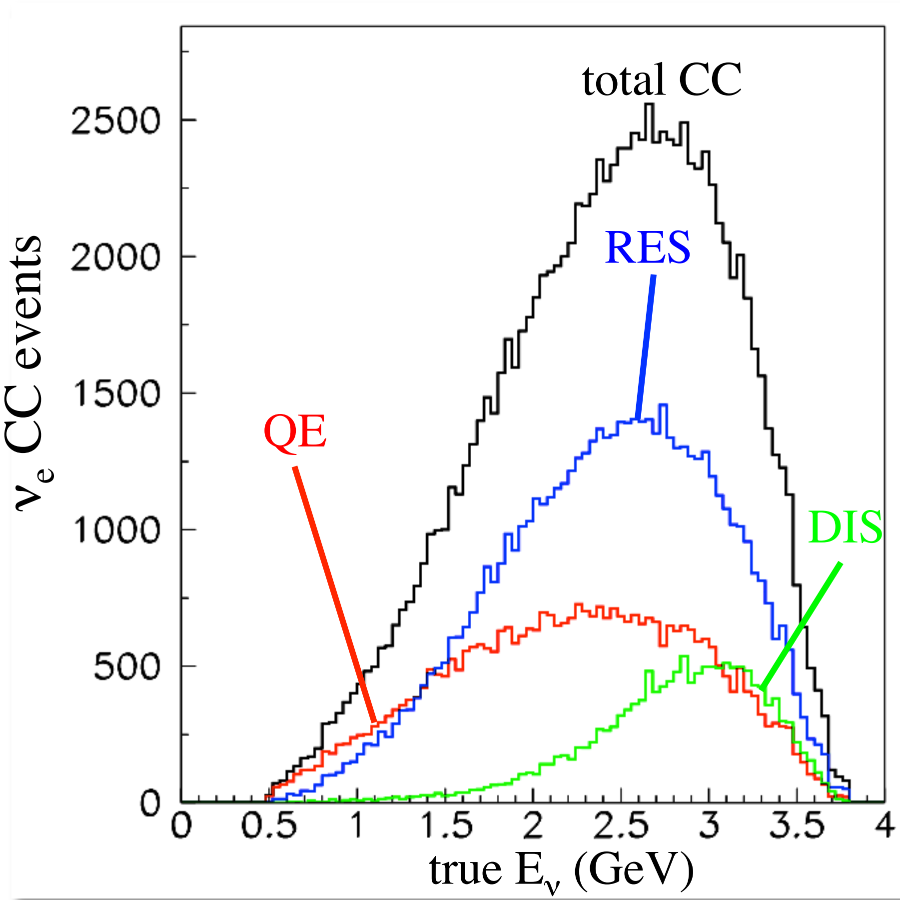
event rates per 1E21 POT -
100 tons at 50m

Practicality of nuSTORM Neutrino Spectrum



ν_e Event Fractions in a νSTORM Near Detector

- ν_e produced by 3.8 GeV μ^+ beam.



out of the CC modes:

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

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

ν-Nucleus Interaction Physics with nuSTORM

A partial sampling

- ν_e and $\bar{\nu}_e$ cross-section measurements
  - A UNIQUE contribution from nuSTORM
  - Essentially no existing data
- π^0 production in ν interactions
  - Coherent and quasi-exclusive single π^0 production
- Charged π & K production
  - Coherent and quasi-exclusive single π^+ production
- Multi-nucleon final states
- ν-e scattering
- ν-Nucleon neutral current scattering
  - Measurement of NC to CC ratio
- Charged and neutral current processes
  - Measurement of ν_e induced resonance production
- Nuclear effects
- Semi-exclusive & exclusive processes
  - Measurement of K_s^0, Λ & Λ-bar production
- New physics & exotic processes
  - Test of ν_μ - ν_e universality
  - Heavy ν
  - eV-scale pseudo-scalar penetrating particles

Combined with the right detector, opportunity for detailed studies of the hadronic vertex.

Why is Neutrino Nucleus Scattering Important?

What do we observe in our (neutrino oscillation) experiment detectors?

- The events we observe in our detectors are convolutions of:
  $Y_{c\text{-like}}(E) \propto \phi(E' \geq E) \otimes \sigma_{c,d,e..}(E' \geq E) \otimes Nuc_{c,d,e..\rightarrow c}(E' \geq E)$

- $\phi(E)$ is the energy dependent neutrino flux that enters the detector. Currently, with traditional meson-decay-source neutrino beams, $\phi(E) \approx 10\%$ absolute and $\approx 7\%$ 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!

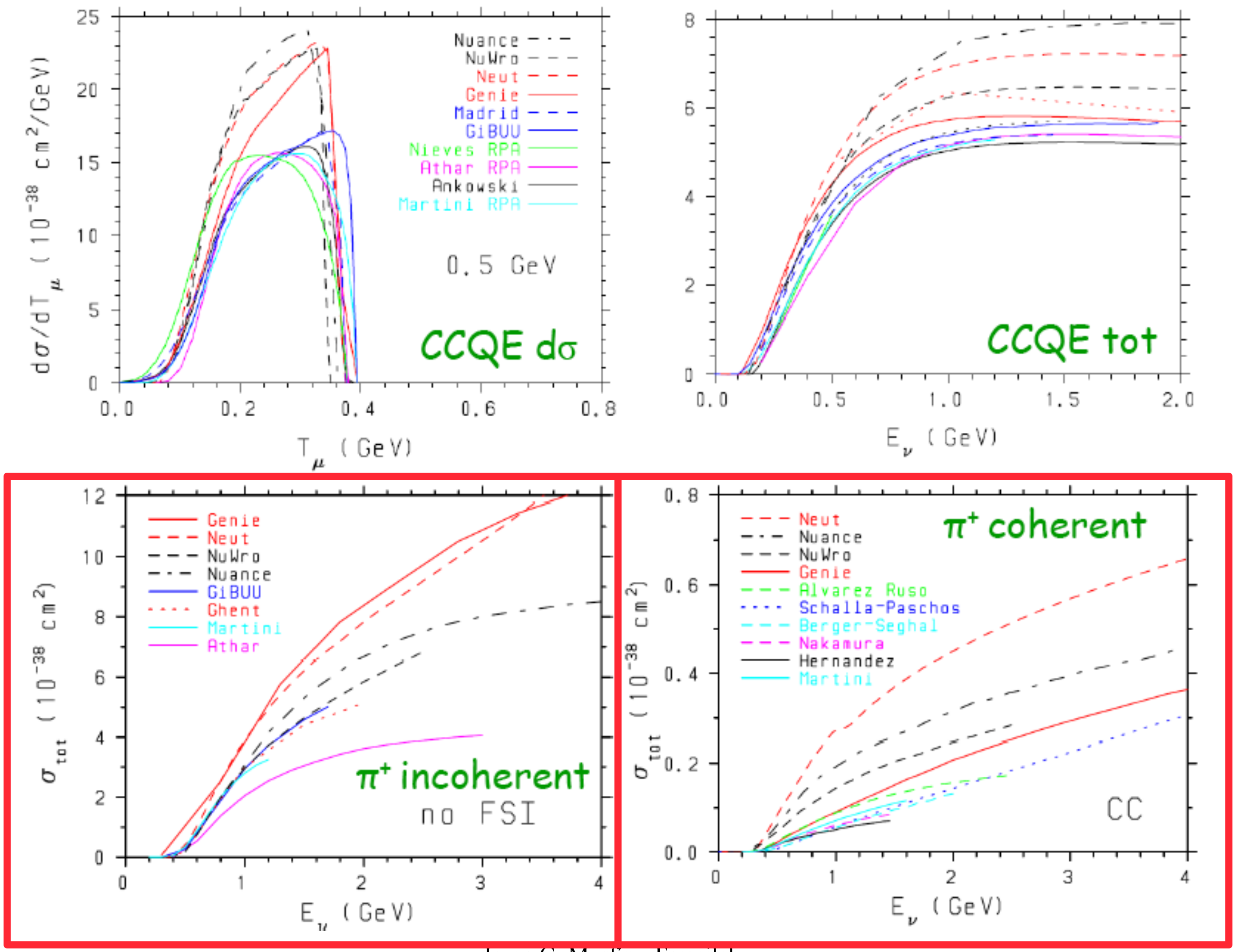
- $Y_{c\text{-like}}(E)$ is the event energy and channel / topology of the event observed in the detector. Appears to be channel c but may not have been channel c at interaction.

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

- 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 ⓧ π-charge-exchange/ absorption probabilities and nuclear density uncertainties.
- **Systematics associated with each of these effects.**
- Event Generators – like GENIE – try to include all these effects.

How well off are we with ν_μ 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.

What do we observe in our detectors?

Further implications for Oscillation Experiments

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

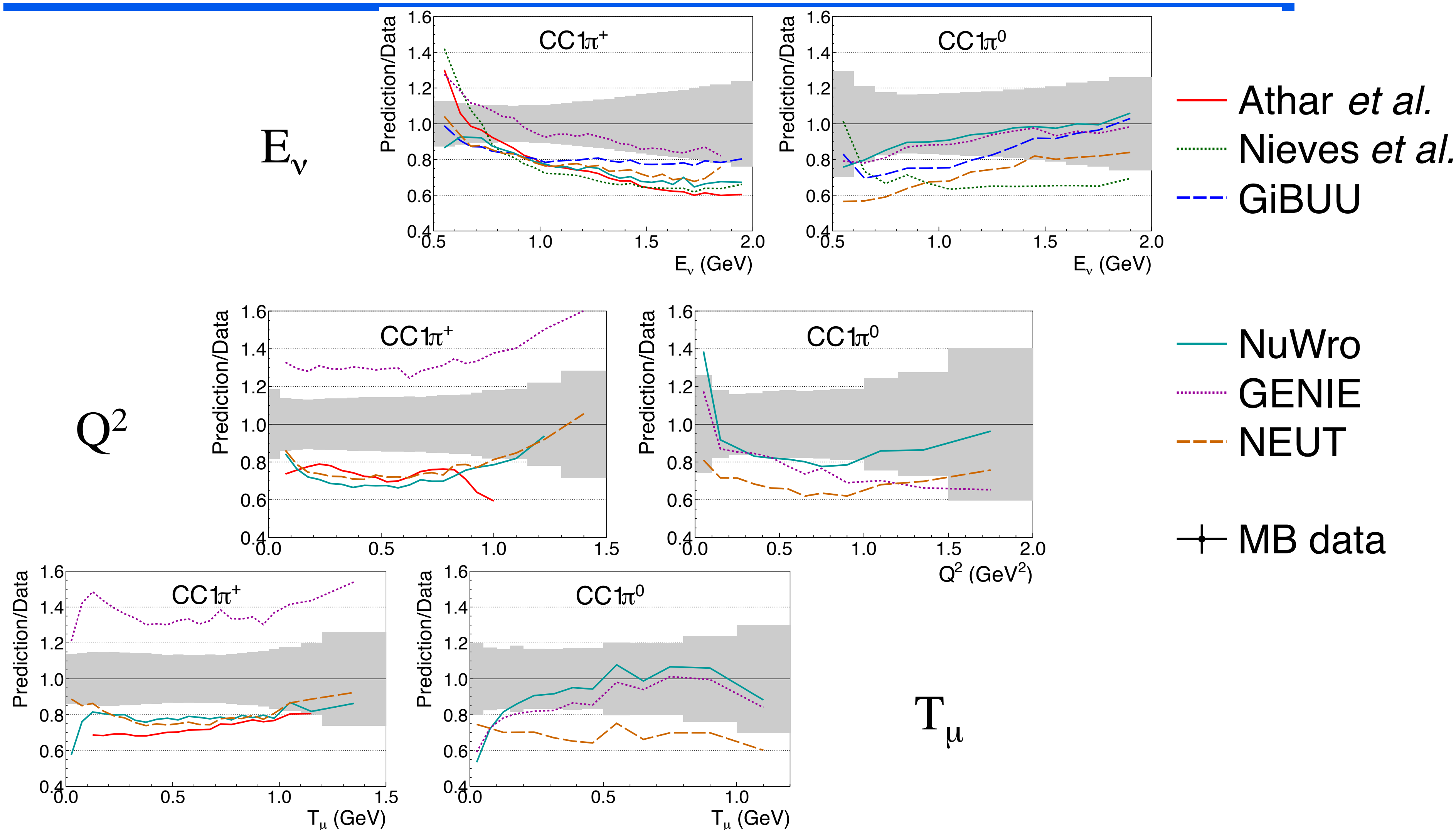
  $Y_{c\text{-like}}(E) \;\alpha\; \phi(E' \geq E) \otimes \sigma_{c,d,e..}(E' \geq E) \otimes Nuc_{c,d,e..\rightarrow c}(E' \geq E)$

  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 $Y_c^A(E)$.**
- 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 σ_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.**
- What would be ideal is a measurement of the nuclear effects migration matrix. Since we can't isolate that from cross section and flux, the next best measurement would be a **measurement of the effective σ_c^A(E) for different well-measured incoming neutrino spectra.**

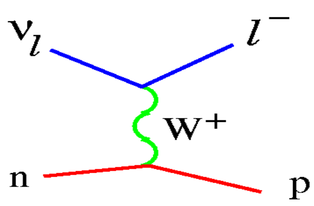
How well off are we with ν_μ Cross sections: Ratios: Prediction/MiniBooNE Data – NuInt12

NuInt12 – Phil Rodrigues



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

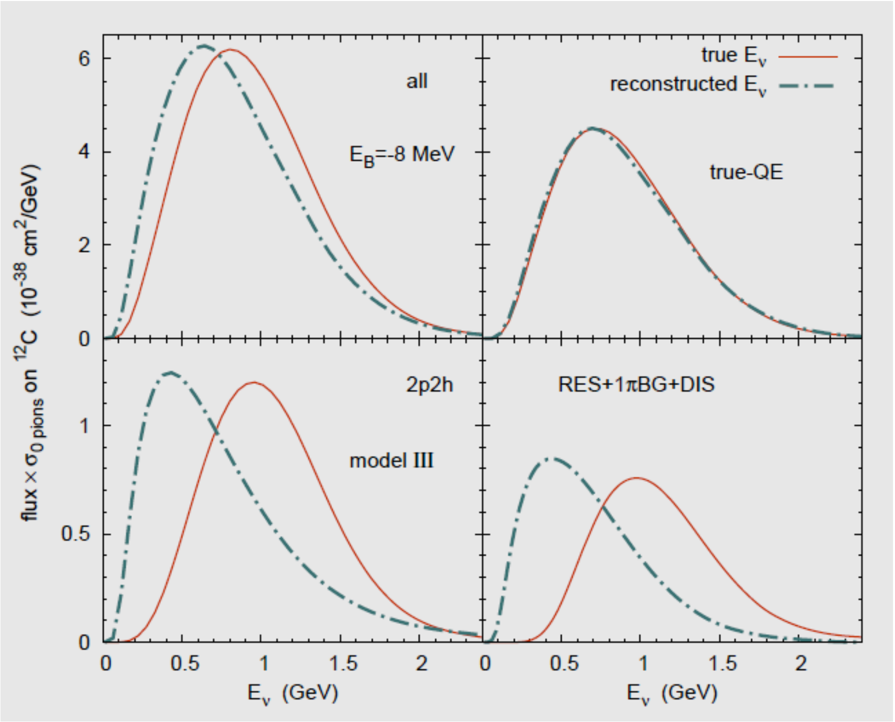
- In pure QE scattering on a nucleon at rest, the outgoing lepton can determine the neutrino energy:



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

However, not on nuclei.

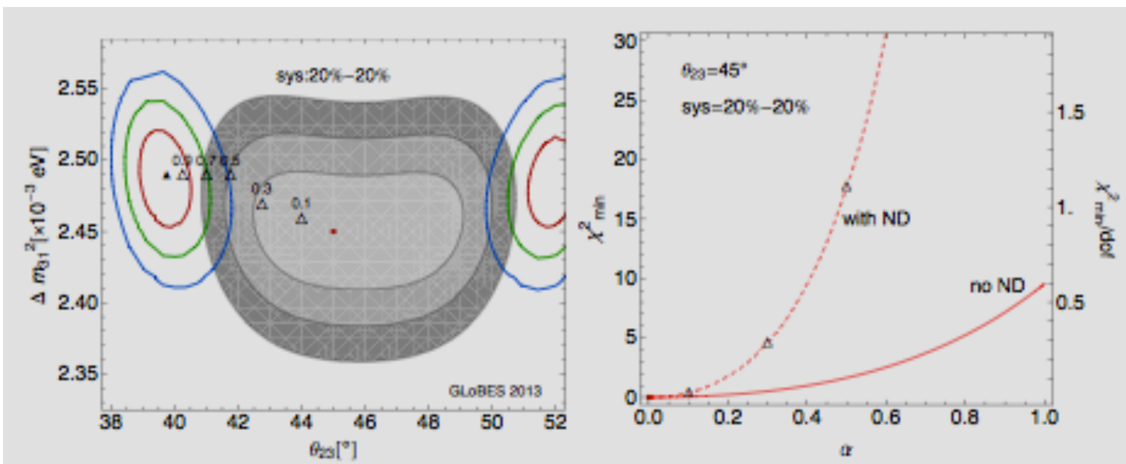
Reconstructed energy is shifted to lower values for all processes other than true QE off nucleon at rest



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_ν is reconstructed from the observed muon which gives a lower E_ν 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!**



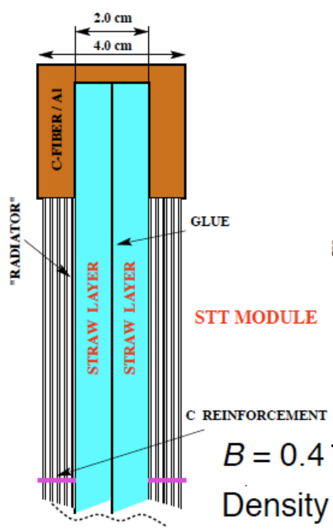
Advantage Number One of nuSTORM

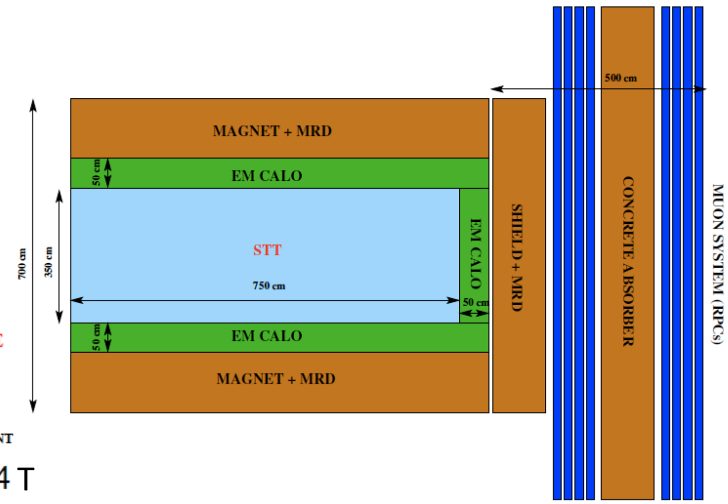
The nuSTORM beam will provide a very well-known ($\delta\ \phi(E) \approx 1\%$) beam of ν and $\bar{\nu}$.

- The events we observe in our detectors are convolutions of:
  $Y_{c\text{-like}}(E)\ \alpha\ \phi(E' \geq E) \otimes \sigma_{c,d,e..}(E' \geq E) \otimes Nuc_{c,d,e..\rightarrow c}(E' \geq E)$
- **$Y_{c\text{-like}}(E)$** is the event energy and channel / topology of the event observed in the detector. **The errors on the three components create a nasty, oozy morass!**
- nuSTORM takes one of these convoluted components $\phi(E' \geq E)$ essentially out of the equation: **a very well-known ($\delta\ \phi(E) < 1\%$) beam of ν and $\bar{\nu}$.**
- **With a variable incoming ν spectrum, nuSTORM can get a first measurement of the energy dependence of:**
  $$\sigma_c^A(E) = \sigma_{c,d,e..}(E' \geq E) \otimes Nuc_{c,d,e..\rightarrow c}(E' \geq E)$$
- 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 Near Detectors

- **HighRes - High Resolution Straw-tube Magnetized Detector.**





$B = 0.4$ T

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

Transition Radiation	↠ e-/e+ ID ⇒ γ (w. Kinematics)
dE/dx	↠ Proton, π+/-, K+/- ID
Magnet/Muon Detector	↠ μ+/-

⇒ *HiResMNu idea being developed within the LBNE collaboration*

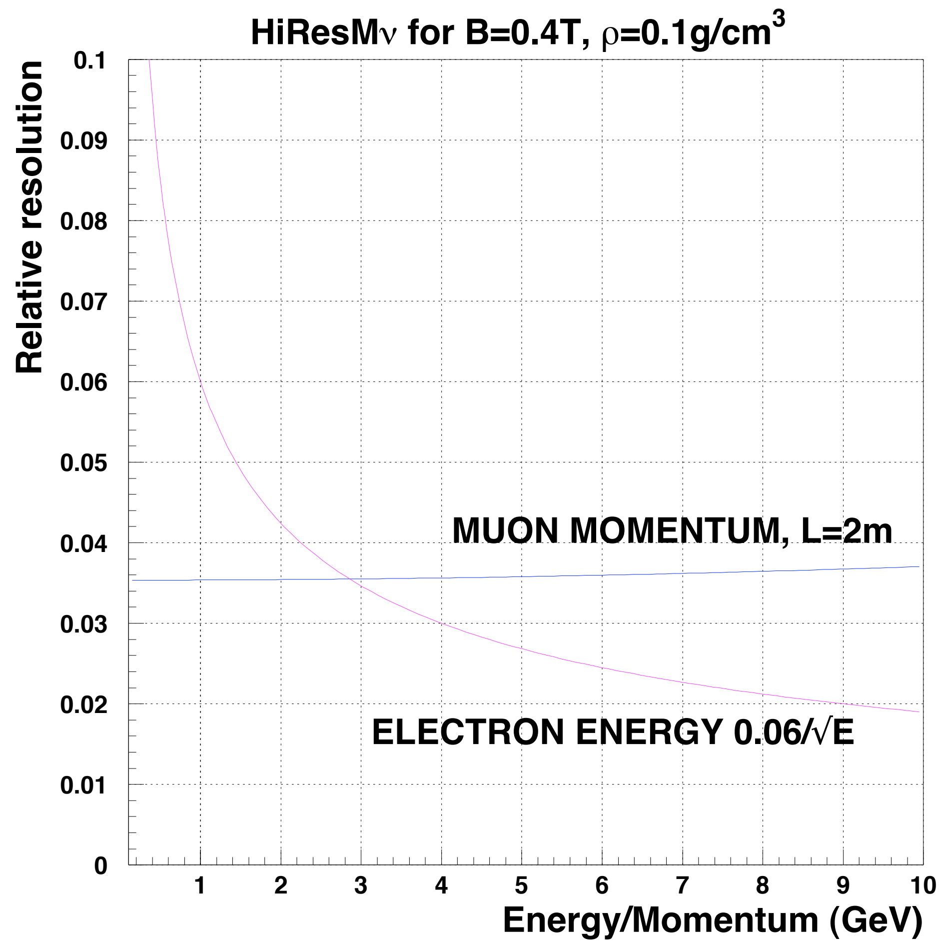
- **A 1-2 ton fiducial liquid hydrogen/deuterium track sensitive target upstream of HiRes for normalization. This could be a bubble chamber.**

Resolutions in HiResMν

- $\rho \simeq$ 0.1gm/cm^3
- Space point position $\simeq$ 200μ
- Time resolution $\simeq$ 1ns

- CC-Events Vertex: Δ(X,Y,Z) $\simeq$ *O*(100μ)
- Energy in Downstream-ECAL $\simeq$ 6%/√E
- μ-Angle resolution (~5 GeV) $\simeq$ *O*(1 mrad)

- μ-Energy resolution (~3 GeV) ~ 3.5%
- e-Energy resolution (~3 GeV) ~ 3.5%



Sensitivity Calculations:

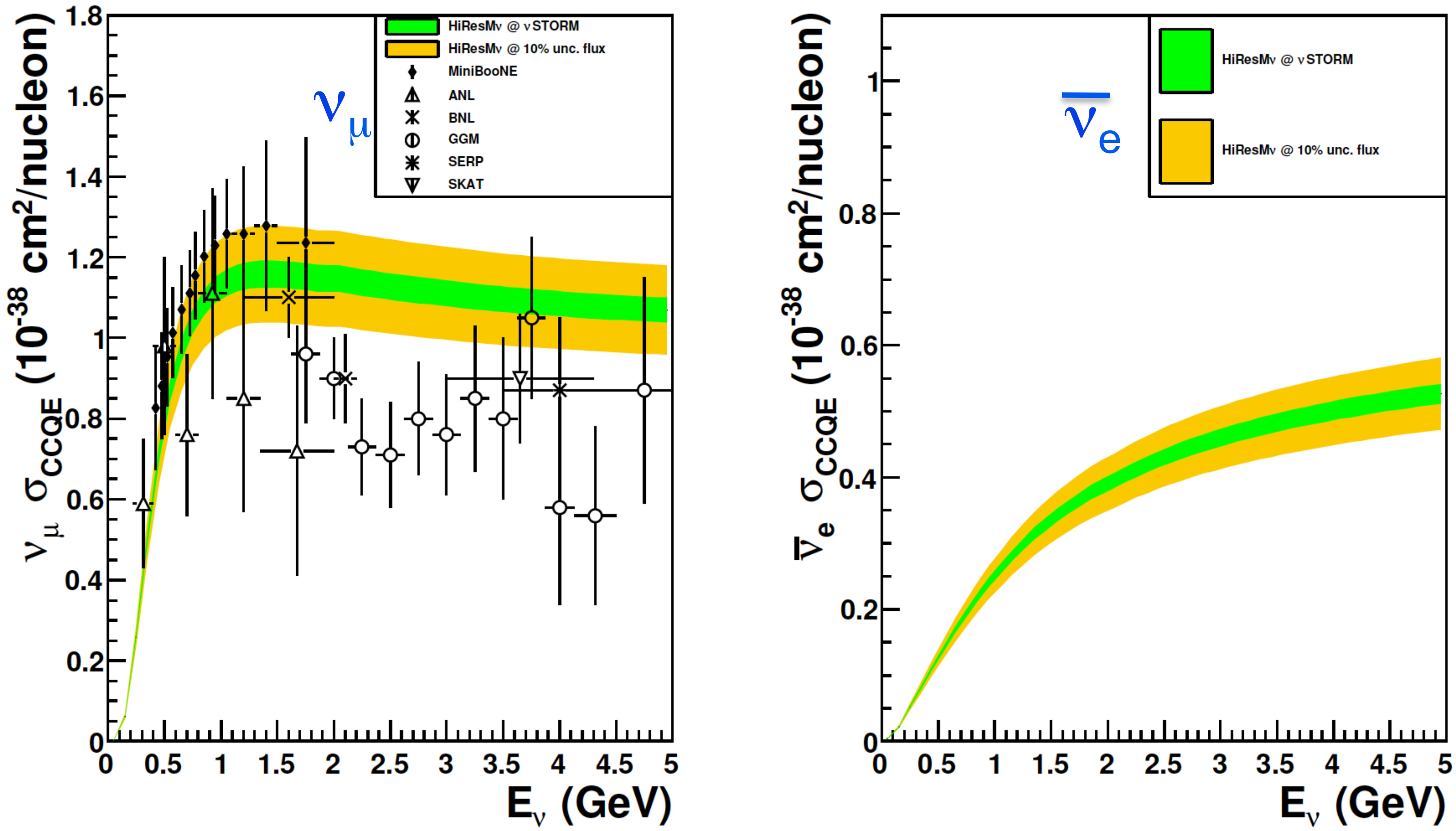
- We have used LBNE Flux: Flux from μ ➢ ν_e ν_μ will be cleaner/simpler
- Parametrized calculation
- Repeat with NOMAD configuration and checked against the Data and Geant-MC (Agree within 15%)

Scattering Measurements with nuSTORM + Near Detector

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

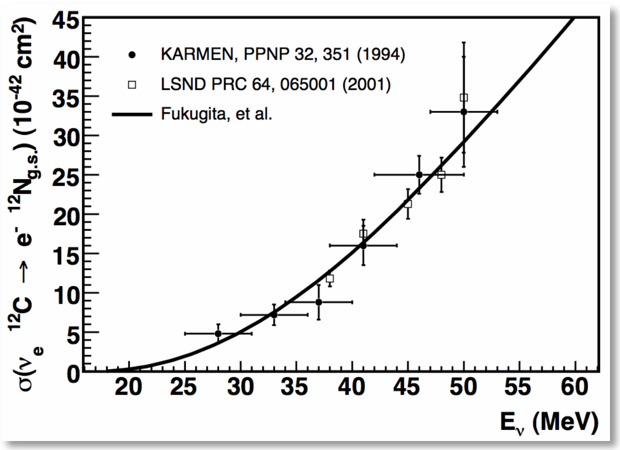
Ed Santos – Imperial College

HIRESMν − systematics



Advantage Number 2 of nuSTORM
How well do we know cross sections: ν_e vs. ν_μ ?
Existing ν_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 π/μ 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 σ reflects the upper limit of most existing measurements, E $\leq$ 50 MeV.

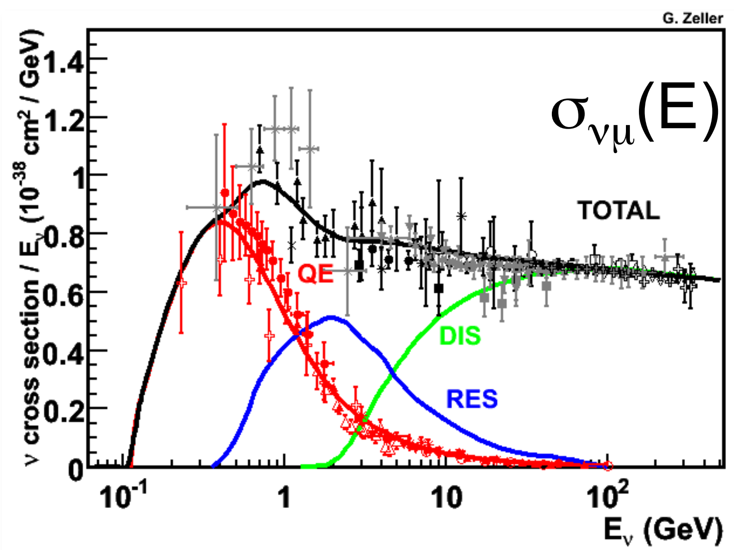


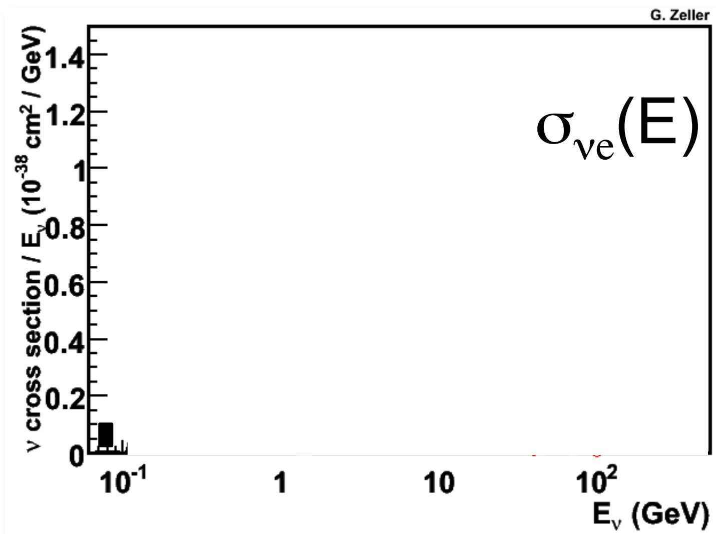
$\nu_e\ ^{12}C \rightarrow e^-\ ^{12}N_{g.s.}$

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

Where Are We with High-energy ν_e Cross Sections?

- **NOWHERE!** Need to measure the $\sigma_{\nu e}(E)$ of multiple channels to fully predict a spectrum at a far detector for LBL experiments.



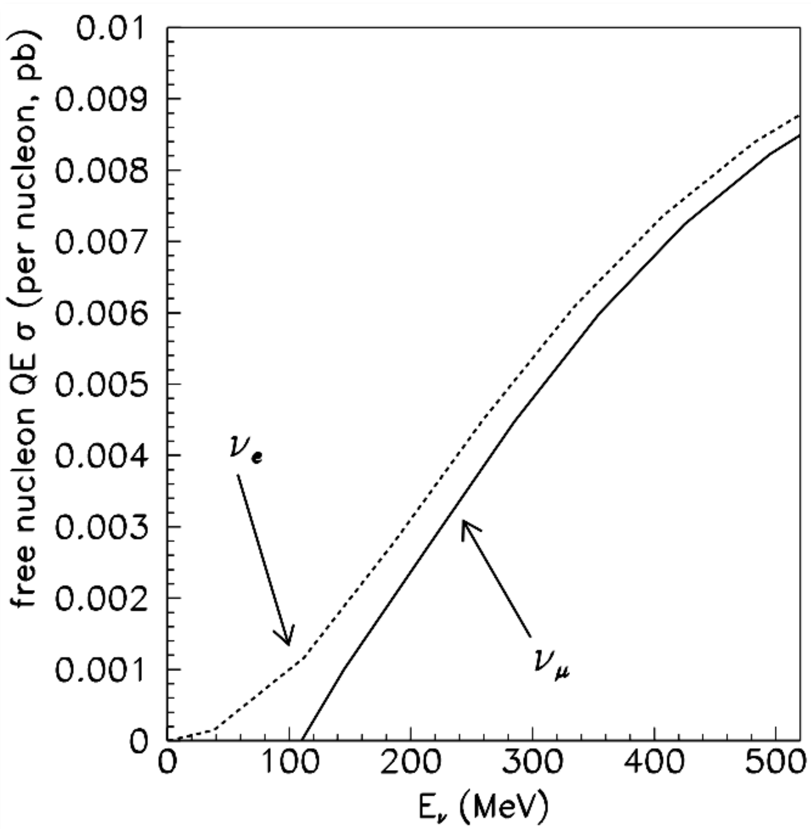


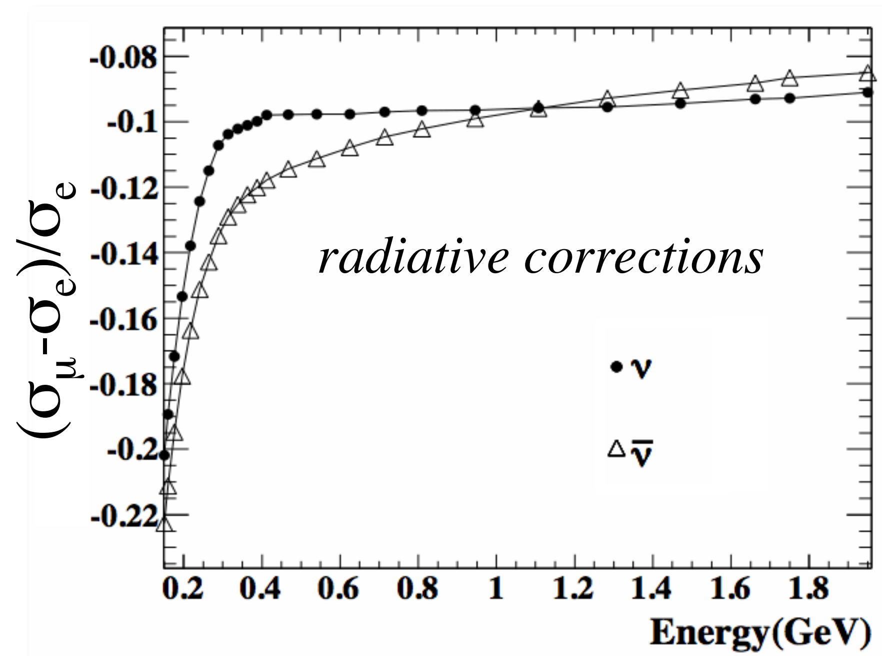
- **We infer them from $\sigma_{\nu\mu}(E)$ results. The validity of this inference directly impacts the uncertainty of the measurements.**

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 overestimated. Need full calculation**.



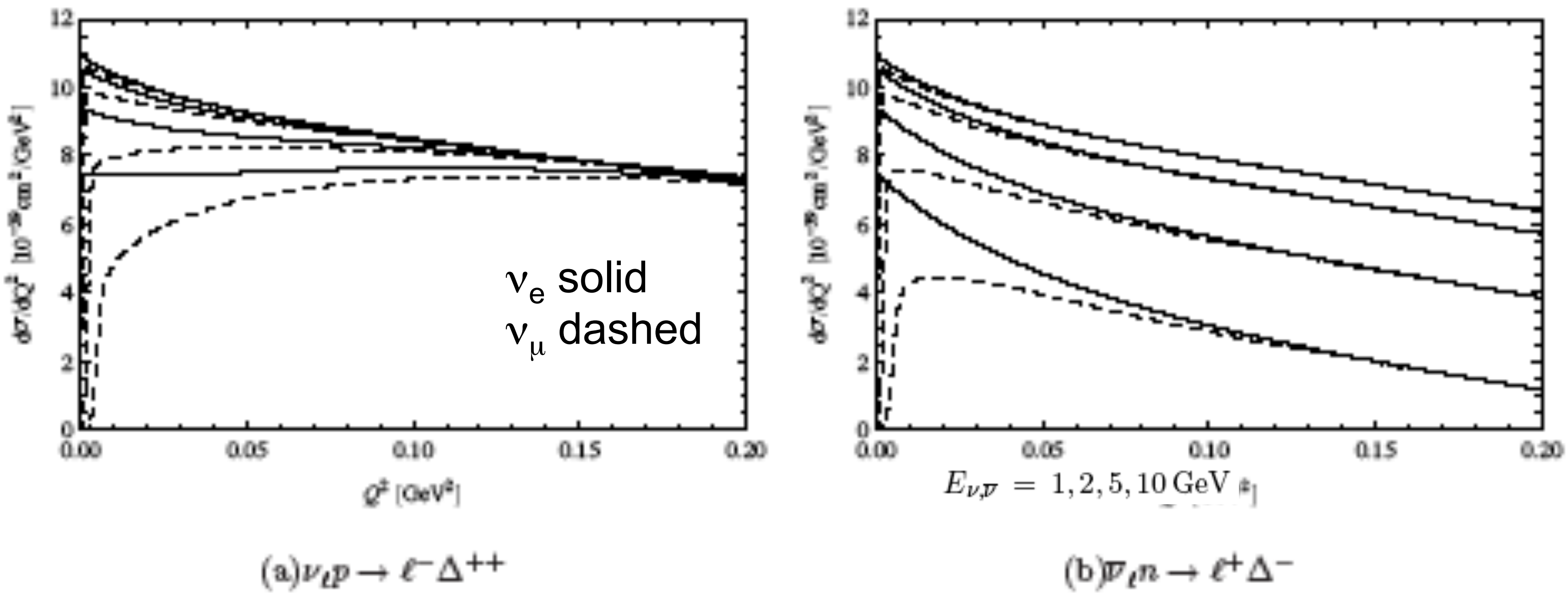


(M. Day, K. McFarland, arXiv:1206.6745)

What are the Differences? Δ Production

Paschos – Schalla: arXiv:1209.4219

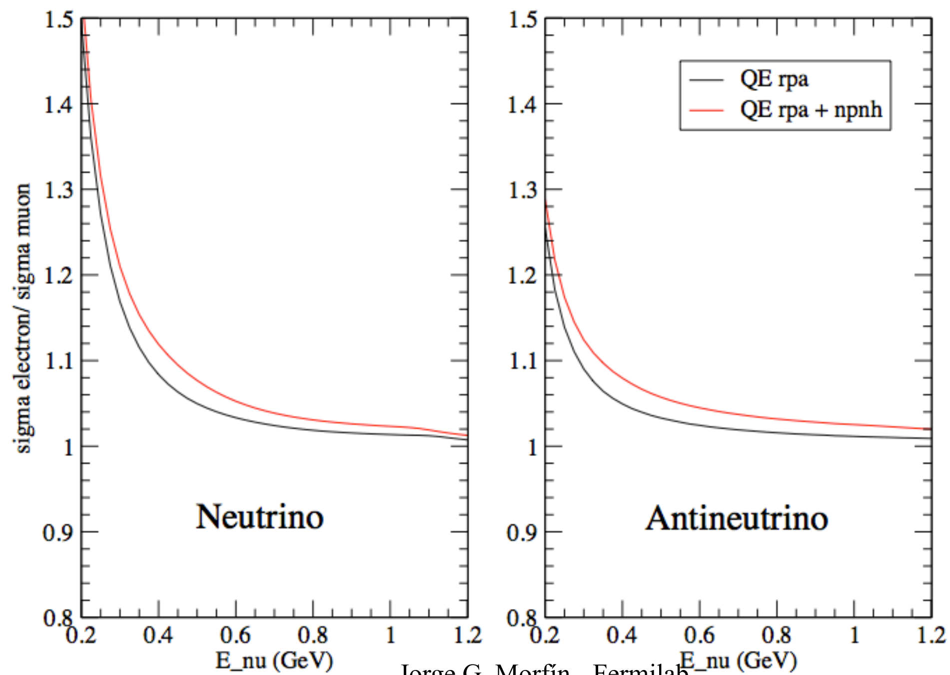
- Paschos-Schalla predicts the following differences in cross sections where only the lepton mass term contributions are shown and any differences in form factors are not yet included.



- We need to measure these ν_e cross sections. **nuSTORM sould do it.**

Differences between ν_e or ν_μ
Meson-exchange Current Contributions – Marco Martini

- Hadronic part (nuclear response functions) is the same for ν_e or ν_μ 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 ν_e/ν_μ cross section ratio is ≤ 5%
- **nuSTORM could measure this difference ν_e vs. ν_μ .**



What could a nuSTORM Scattering analysis add?

Provide significant input to knowledge of electro-weak physics.

- Use the unique qualities of the nuSTORM beam meaning the flux of ν_e and the fantastic knowledge of absolute and relative flux.
- Need an experiment that has a track sensitive H and D target (bubble chamber) upstream of a **high-resolution near detector with multiple nuclear targets** to provide detailed studies of the final states including the vertex (multiplicities and energy flow.
- However, this is not the same nuSTORM approved by the Fermilab PAC. This requires a high-resolution near detector and, preferably, a H/D Bubble Chamber.
- Now forming an independent nuSTORM **neutrino interaction collaboration** for the nuSTORM facility!

BACKUP

High Resolution Near Detector

- NOMAD-like resolution in HiRes detector allows to:
  - Measure absolute flux using ν - e elastic scattering –
  - Measure quasi-elastic scattering
  - NC vs CC events (NOMAD with 90% purity)
  - Coherent π^0
  - Comparison $\sin^2\theta_W$ from DIS and $\nu e \rightarrow \nu e$
  - 77 different physics topics!

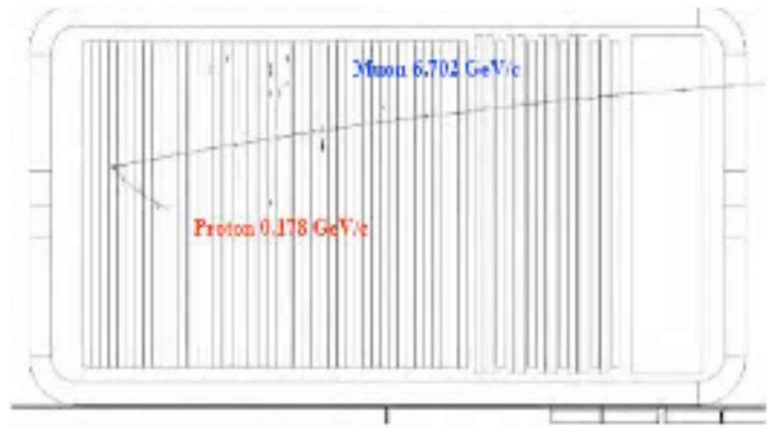
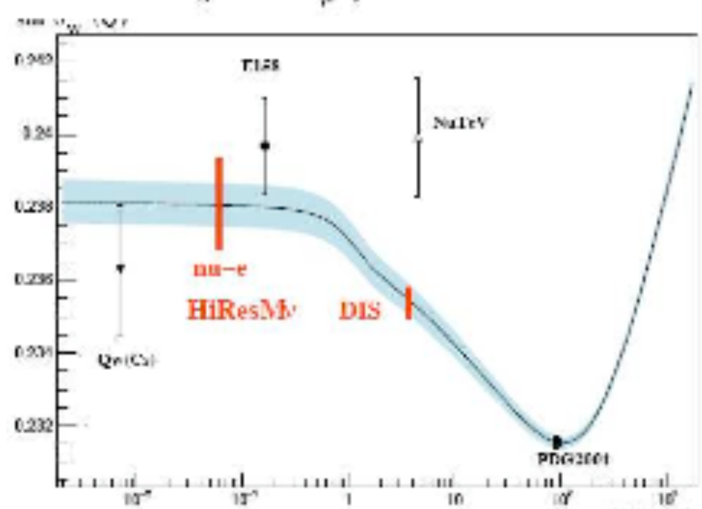
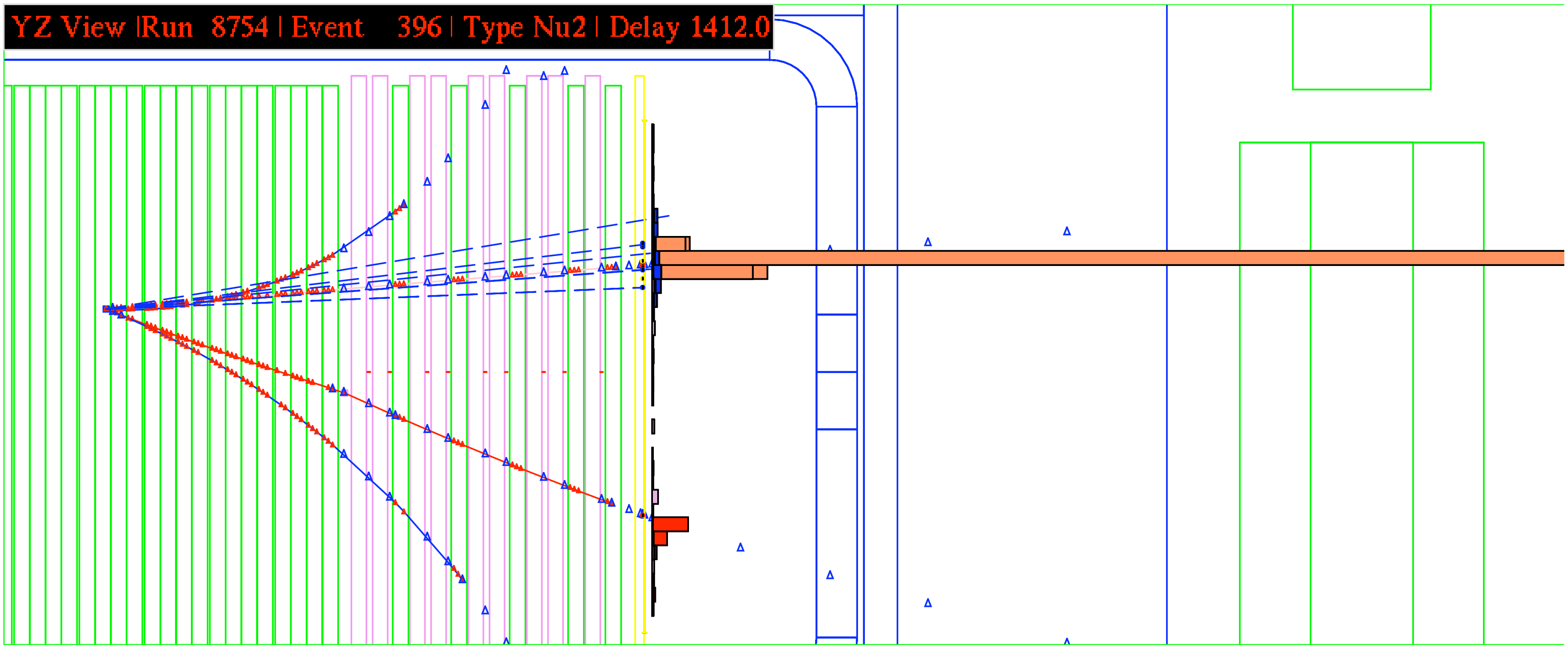


Figure 14: A ν_μ-QE candidate in NOMAD



A $\bar{\nu}_e$ CC candidate in NOMAD



- x12 higher sampling in HiResMnu
- x4π 12 calorimetric and μ converage

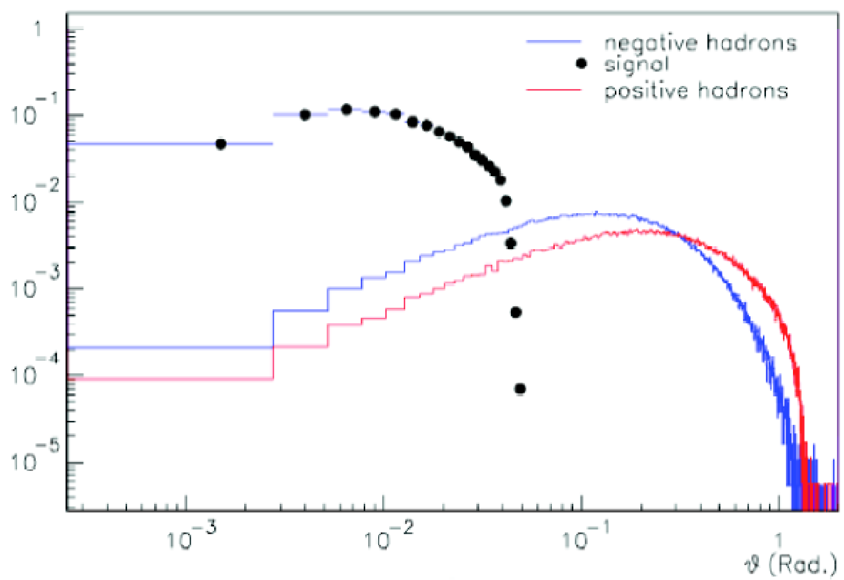
ν-e NC elastic scattering

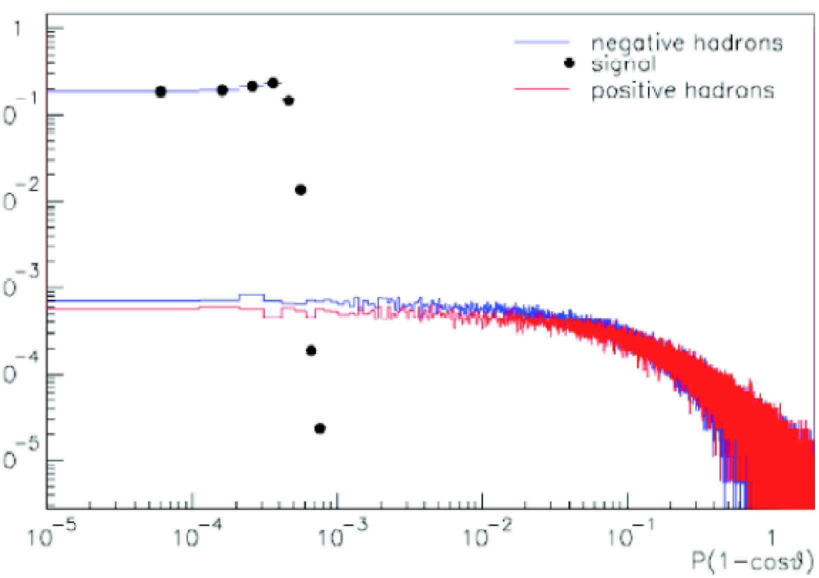
Mishra

$$\sigma(\nu_l e \to \nu_l e) = \frac{G_\mu^2 m_e E_\nu}{2\pi}\left[1 - 4\sin^2\theta_W + \frac{16}{3}\sin^4\theta_W\right]$$

$$\sigma(\bar{\nu}_l e \to \bar{\nu}_l e) = \frac{G_\mu^2 m_e E_\nu}{2\pi}\left[\frac{1}{3} - \frac{4}{3}\sin^2\theta_W + \frac{16}{3}\sin^4\theta_W\right]$$

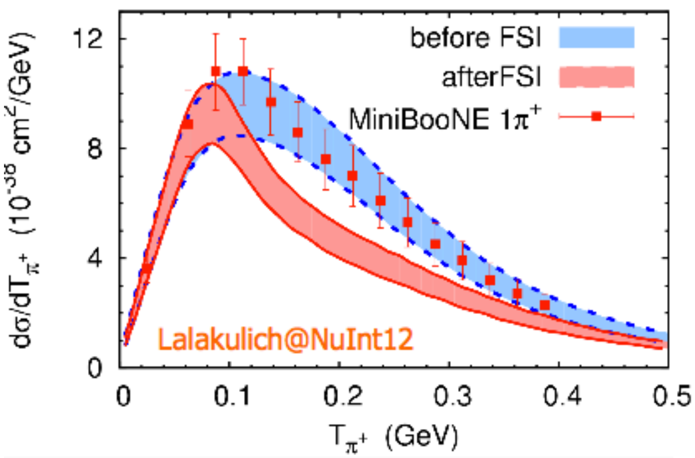
$$\sim 10^{-42}(E_\nu/\,\mathrm{GeV})\ cm^2$$

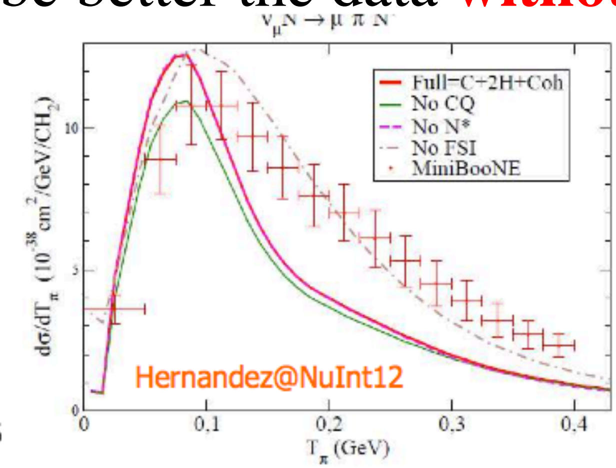


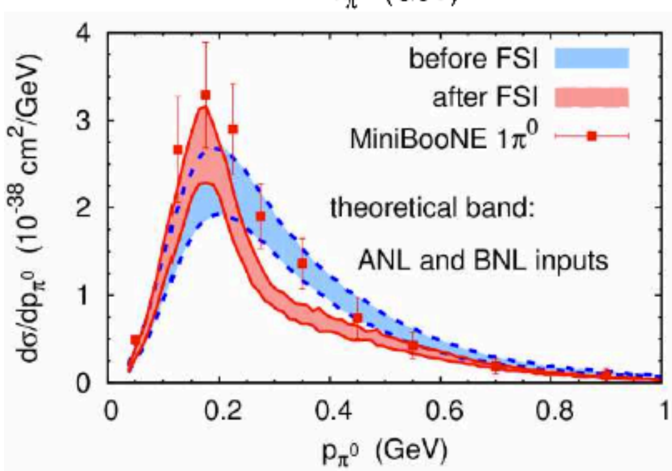


Pion Production Challenges

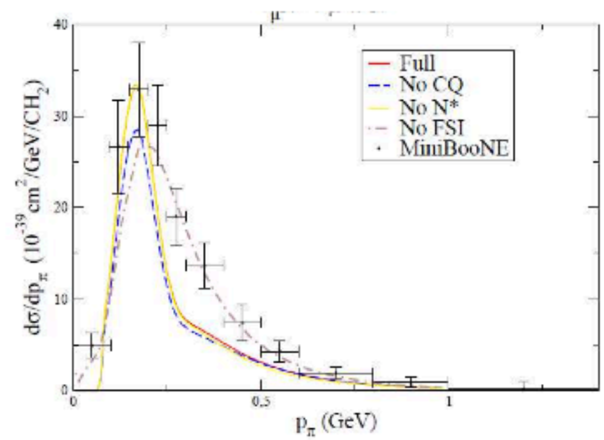
- State of the art calculations describe better the data **without FSI**







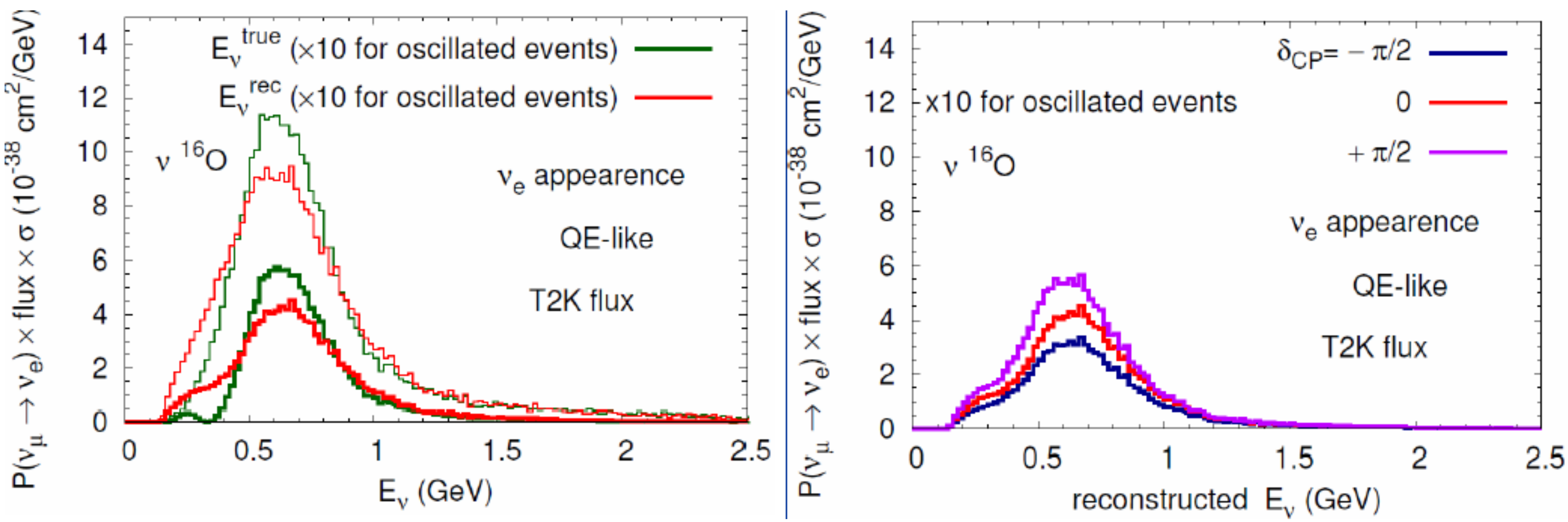
Lalakulich@NuInt12



Hernandez@NuInt12

Nuclear Effects and Oscillation Measurements

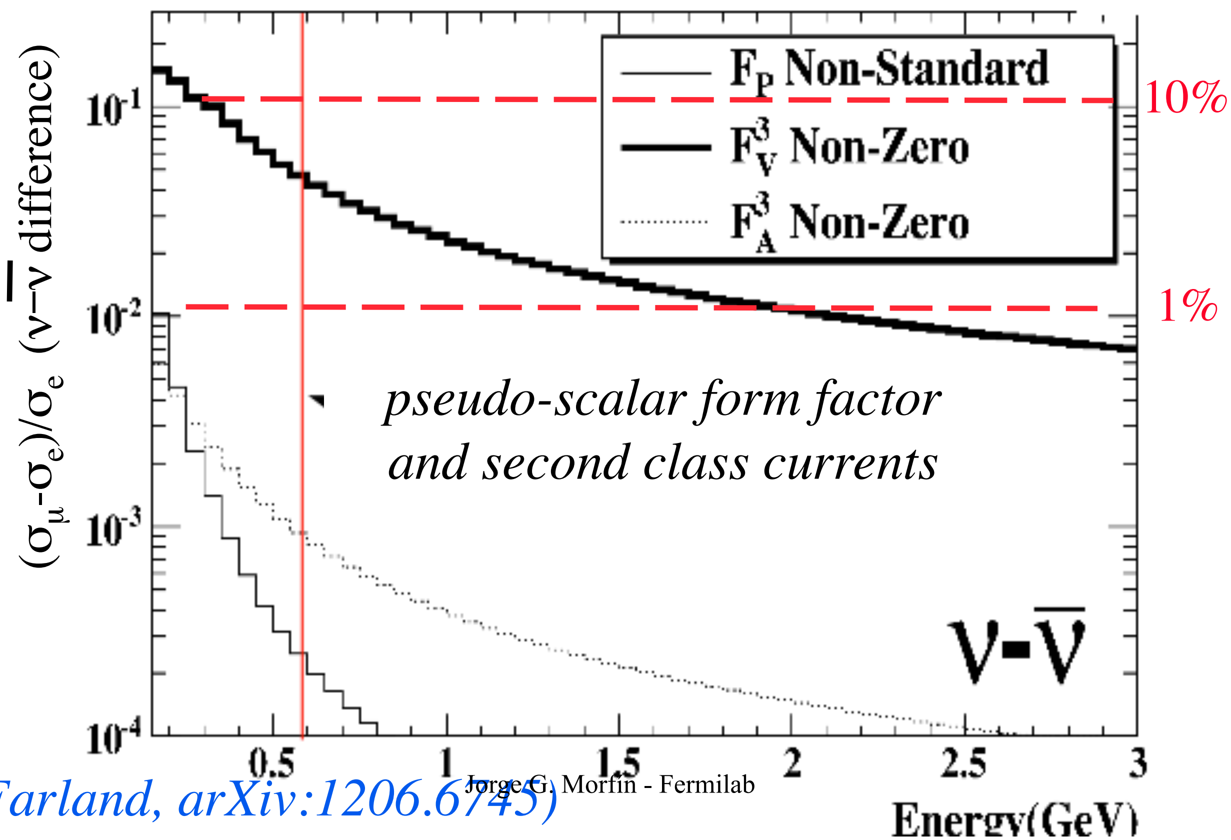
Ulrich Mosel using his Giessen Boltzmann-Uehling-Uhlenbeck (GiBUU) Transport Model looking at T2K



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

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

- 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 ν and $\bar{\nu}$



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What are the Differences? Δ Production

Paschos – Schalla: arXiv:1209.4219

- Manny and his student have investigated ν_μ 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.