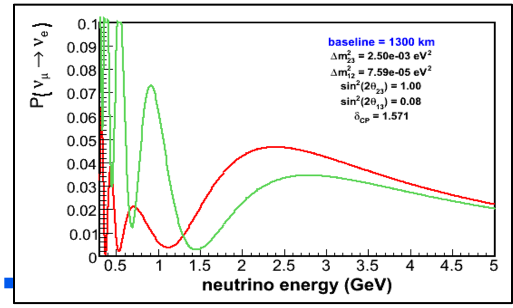
Brief Overview of the Interplay of Neutrino Nucleus Cross Sections and Nuclear Effects

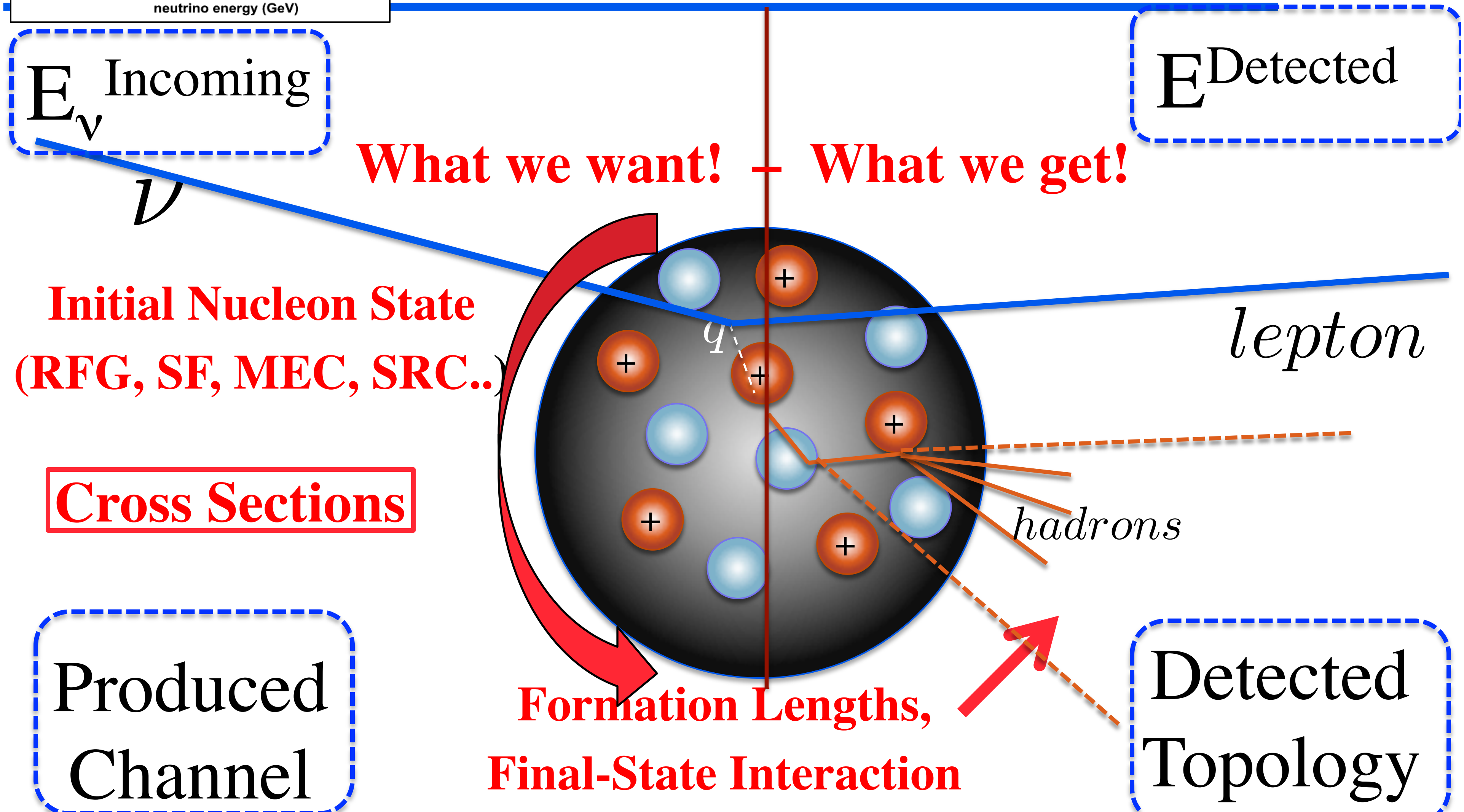
With thanks to Dave Schmitz and Masashi Yokoyama for use of figures.

Jorge G. Morfín
Fermilab

WIN 2013 – Natal, Brasil



Physics of GeV ν-N Interactions



What do we observe in our detectors?

Further implications for Oscillation Experiments

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

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

Could certainly use Brasilian Nuclear Theorists here!!

What do we observe in our detectors?

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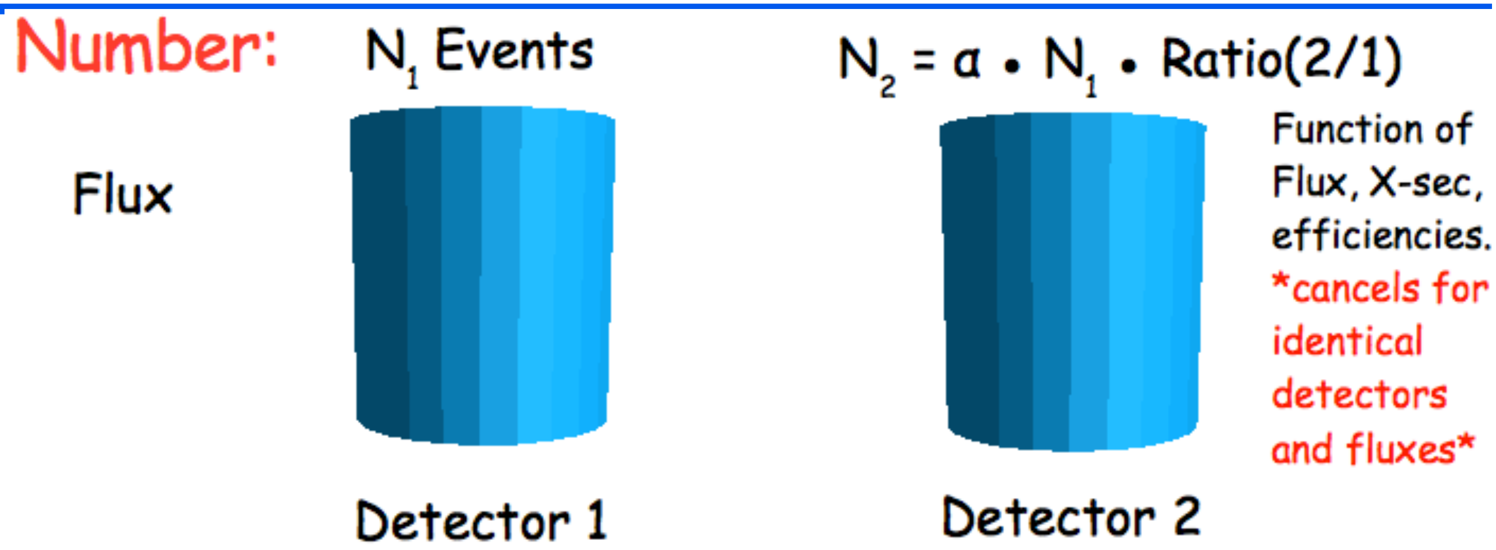
- The events we observe in our detectors are convolutions of:

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

  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 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. **However, the ND results give us an excellent starting point for calculating the difference.**

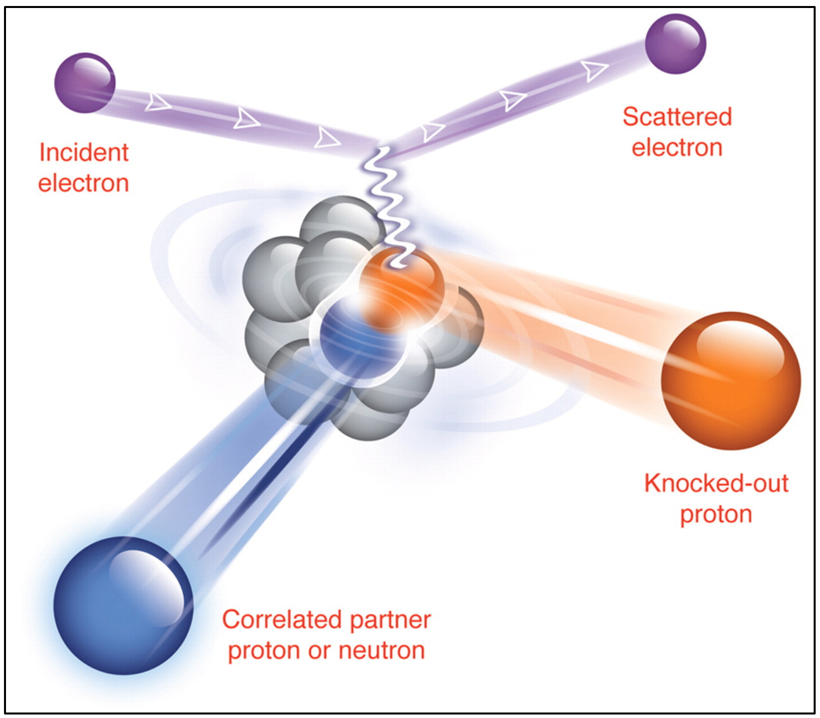
The Danger of Depending on Near and Far Detectors to Cancel Systematic Effects!.



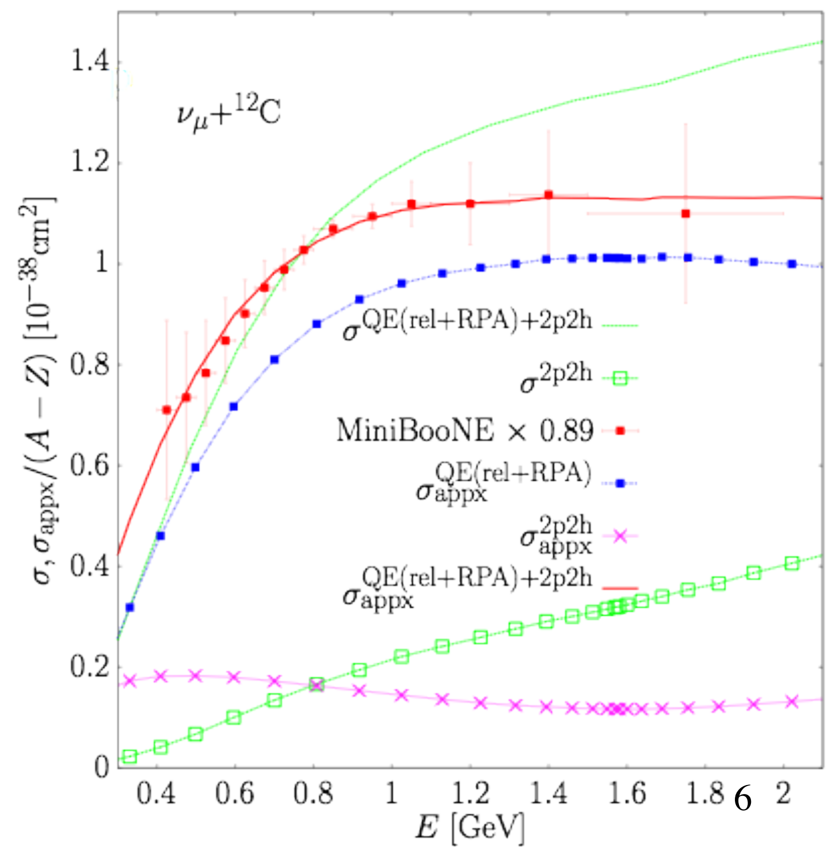
- We use a detector near to the beam to measure the number and energy spectra of the produced neutrinos. Then we predict how many we should see in a far detector based on what we measured and the divergence of the beam.
- Due to geometry and oscillations, the neutrino spectra at the far detector is (considerably) different than at the near detector.
- Therefore the convolution of energy-dependent flux, energy-dependent cross sections and energy-dependent nuclear effects will be different at near and far detectors. **SYSTEMATIC EFFECTS DO NOT SIMPLY CANCEL!**

Nucleon-nucleon Correlations

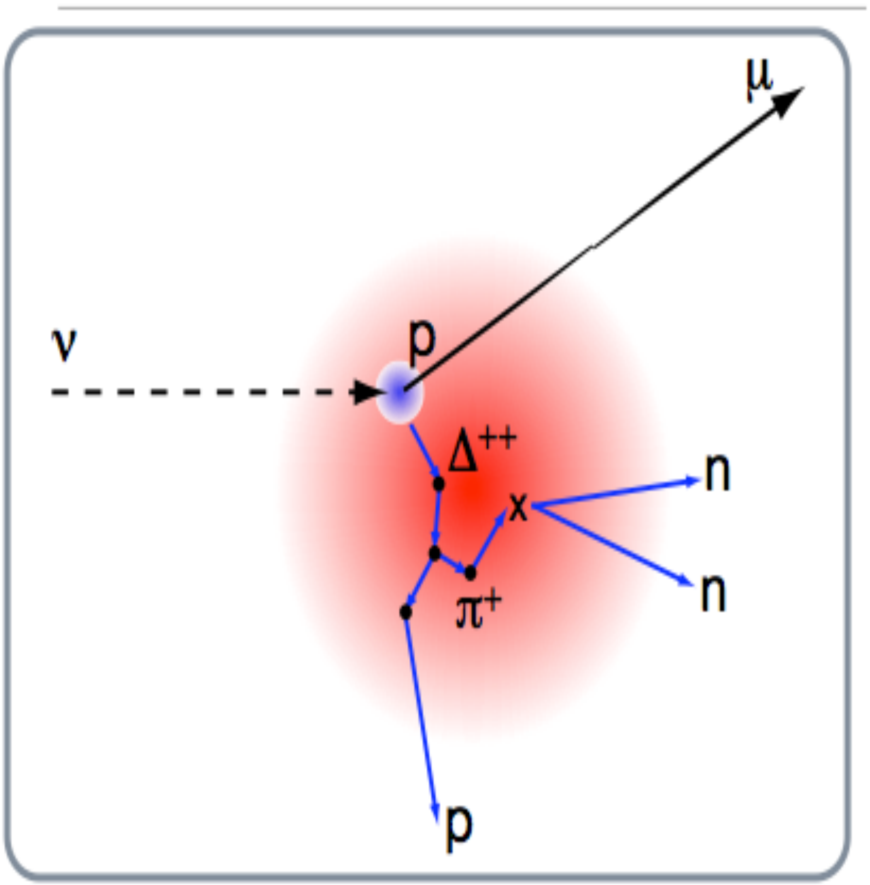
- Electron scattering
  - Fit to electron data described by Arie Bodek talk coming up next. About a 20% effect. Only vector current contribution!



- Neutrino Scattering
  - J. Nieves et al. – the serious problem of miscalculating E_ν when using QE hypothesis.



Nuclear Effects Masking the Initial Production State and, most likely, the Incoming Neutrino Energy



- Consider the example of Delta production at left.
- Delta scatters before it decays
- Pion from Delta decay is absorbed releasing two neurons that may/may-not be detected
- Proton from delta decay scatters and comes out of the nucleus.
- Final state observed is μ + p that makes this a fine candidate for QE production. We've probably also lost measurable energy.

Cross Sections and Nuclear Effects: a Significant Sources of Uncertainty for Oscillation Parameter Measurements.

Particularly for Future High-statistics Studies

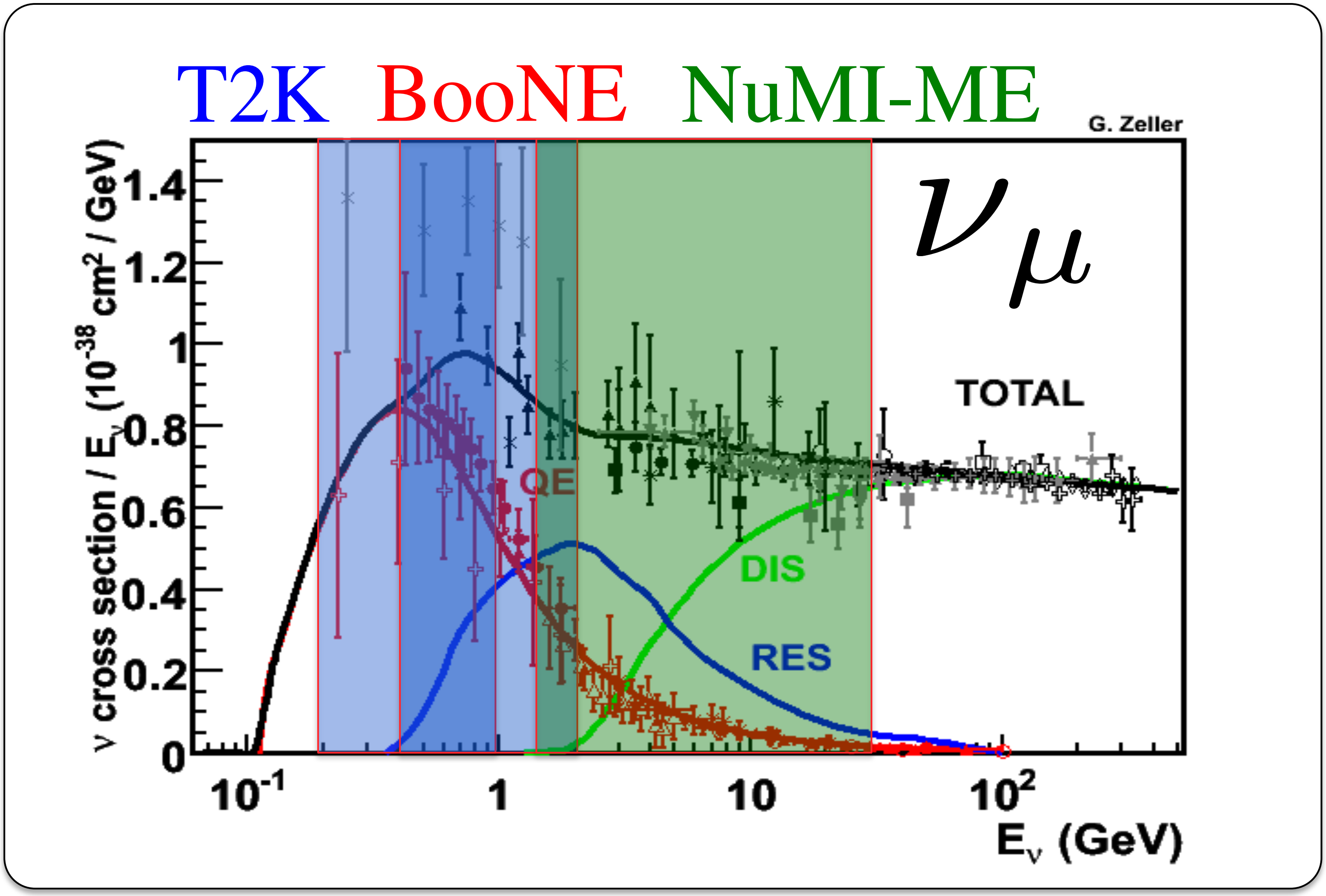
Systematic uncertainties on T2K ν_μ-disappearance analysis.

TABLE II. Systematic uncertainties on the predicted number of SK selected events without oscillations and for oscillations with $\sin^2(2\theta_{23}) = 1.0$ and $|\Delta m^2_{32}| = 2.4 \times 10^{-3}$ eV^2.

Source	$\delta N^{exp}_{SK}/N^{exp}_{SK}$ (%, no osc)	$\delta N^{exp}_{SK}/N^{exp}_{SK}$ (%, with osc)
SK CCQE efficiency	±3.4	±3.4
SK CC non-QE efficiency	±3.3	±6.5
SK NC efficiency	±2.0	±7.2
ND280 efficiency	+5.5 -5.3	+5.5 -5.3
ND280 event rate	±2.6	±2.6
Flux normalization (SK/ND280)	±7.3	±4.8
CCQE cross section	±4.1	±2.5
CC1π/CCQE cross section	+2.2 -1.9	+0.4 -0.5
Other CC/CCQE cross section	+5.3 -4.7	+4.1 -3.6
NC/CCQE cross section	±0.8	±0.9
Final-state interactions	±3.2	±5.9
Total	+13.3 -13.0	+15.0 -14.8

arXiv:1201.1386 **[hep-ex]**

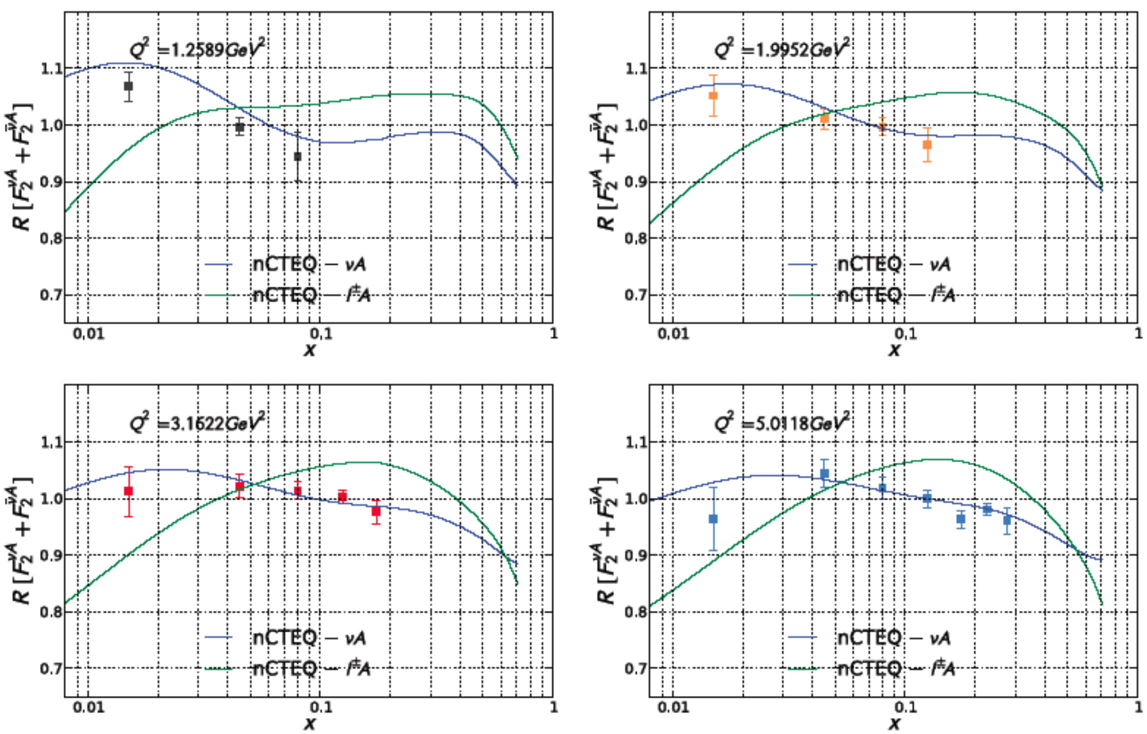
Review of Status of Cross Sections with Emphasis on Nuclear Effects

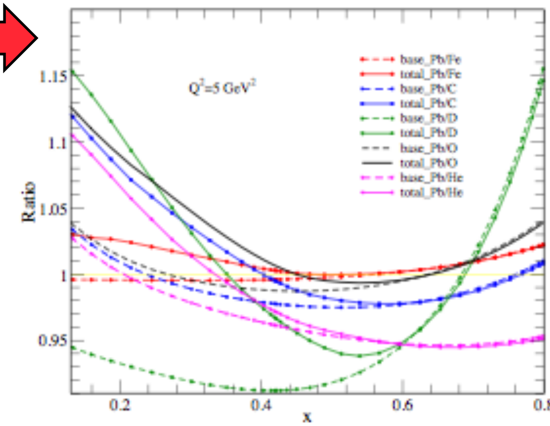


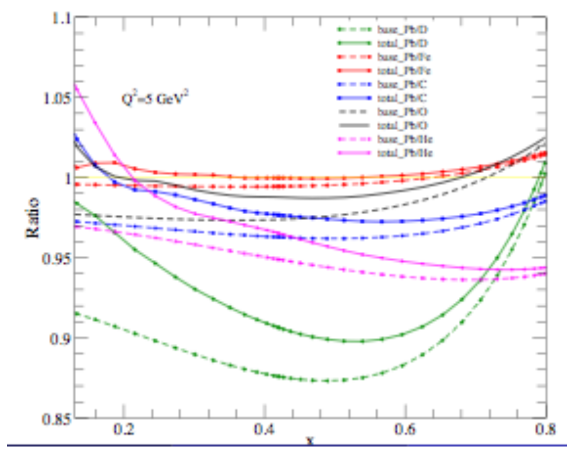
Review of Status of Cross Sections with Emphasis on Nuclear Effects

DIS (MINERvA in the ME beam will revive this study)

- nCTEQ study indicating that the x-dependent nuclear effects for neutrino could be different than those of e/μ interactions. One expt., one A - need MINERvA!
- Latest work by Athar, Haider, Simo and Vicente Vacas looking theoretically at this effect. Ratio of Pb/A for F_2 and xF_3 predicted.

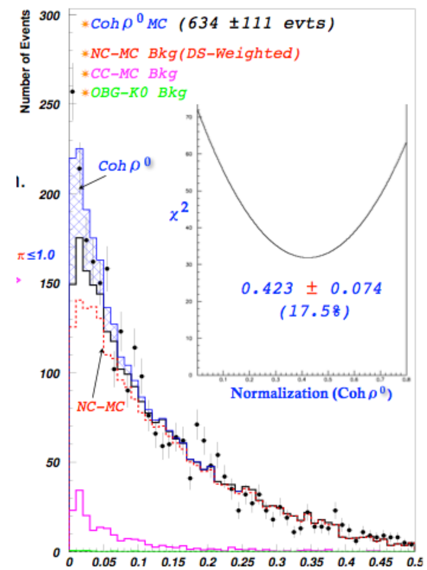


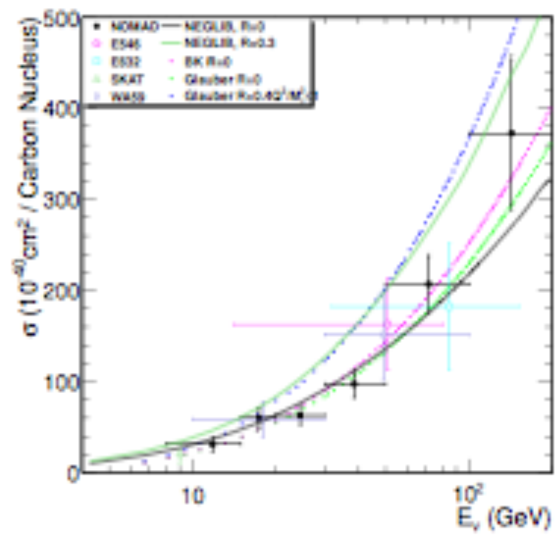




Meson Production

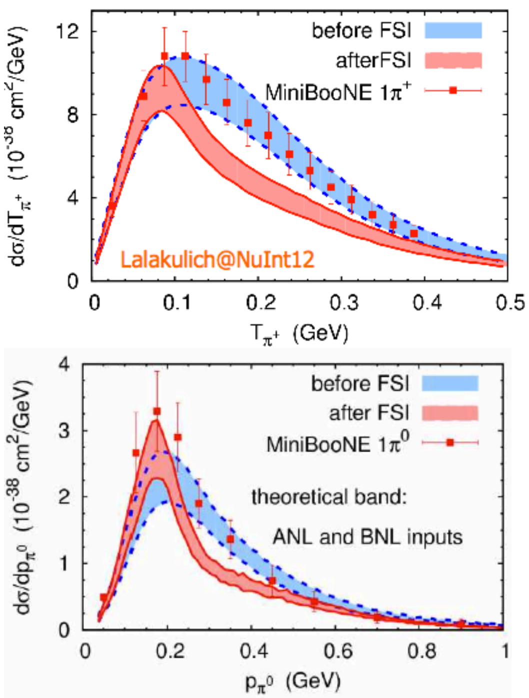
- Meson Production –
  - MINERvA Coherent and Resonant pion production: see Joel Mousseau's talk this session.
  - NOMAD NC coherent ρ^0 production. **FIRST observation of ρ^0 production (611 ± 110 ± 95 events.** Rate with respect to CC is **(4.41 ± 1.0) x 10^{-4}. No Nuclear Effects Allowed!** **Hongyue Duyang NuFact13**
  - NOMAD CC coherent ρ^+ production. Large sample of 4319 ± 307 ± 168. Rate with respect to CC events **(3.00 ± .24) x 10^{-3}. coherent ρ^0 / ρ^+ = 0.147 ± 0.036 consistent with CVC plus VMD.** **Xinchun Tian - NuFact13**





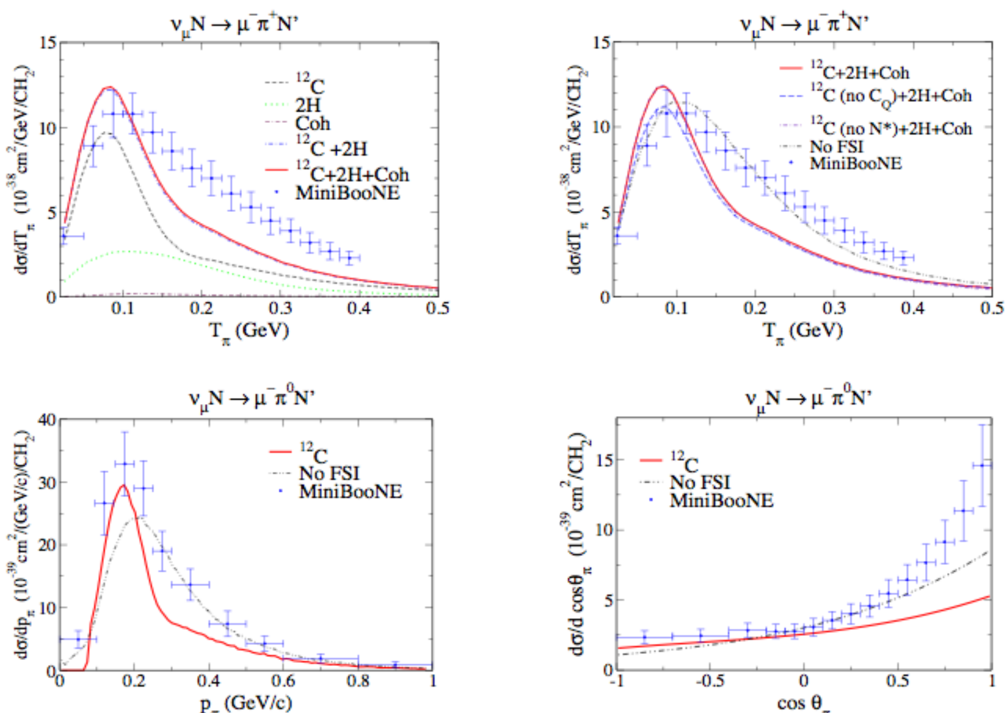
Meson Production – Theory vs Measurement

- Hernandez, Nieves & Vicente Vacas – MiniBooNE Pion Production
  Curve with NO FINAL STATE INTERACTIONS **FITS BEST!**



Lalakulich@NuInt12

Incoherent pion production in nuclei. CC Results



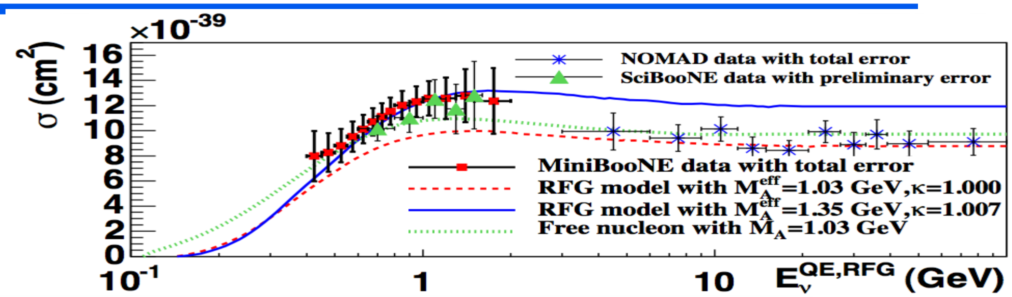
Nufact13. Beijing, August-2013 – p. 20

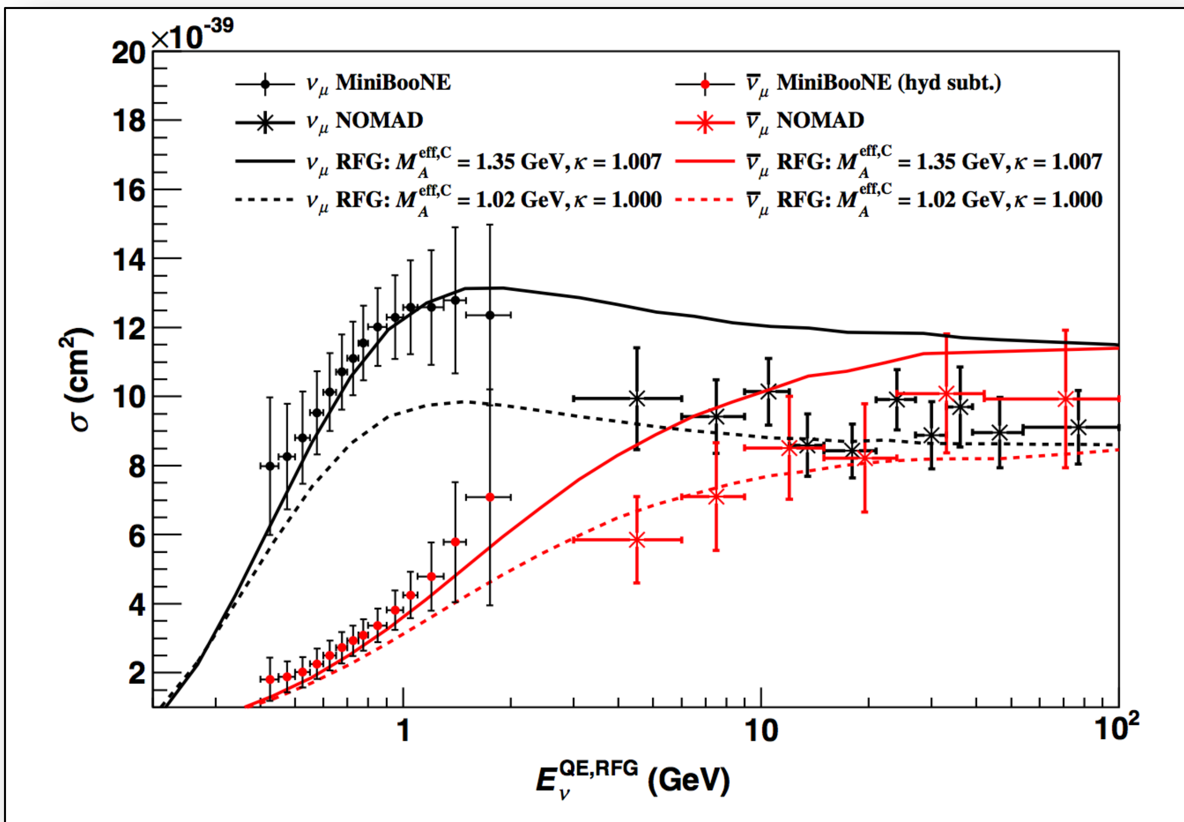
OUCH!
What's going on?

Review of Status of Cross Sections with Emphasis on Nuclear Effects

Charged Current Quasi Elastic Scattering

- The start of a very interesting journey!

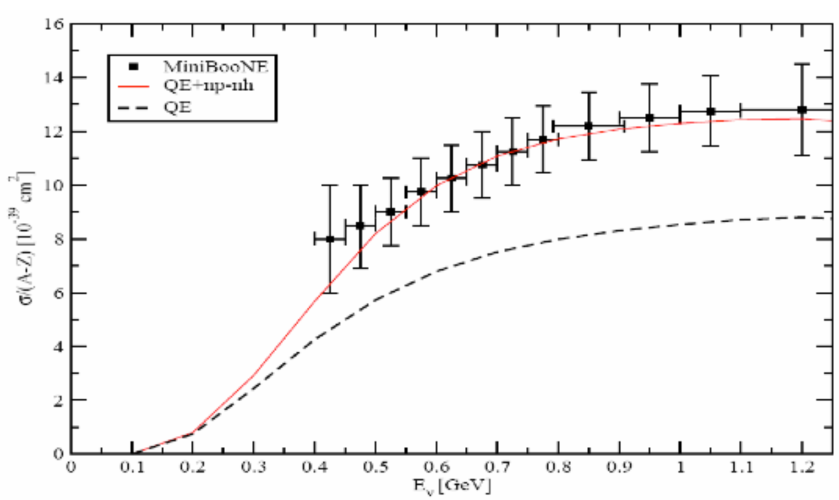


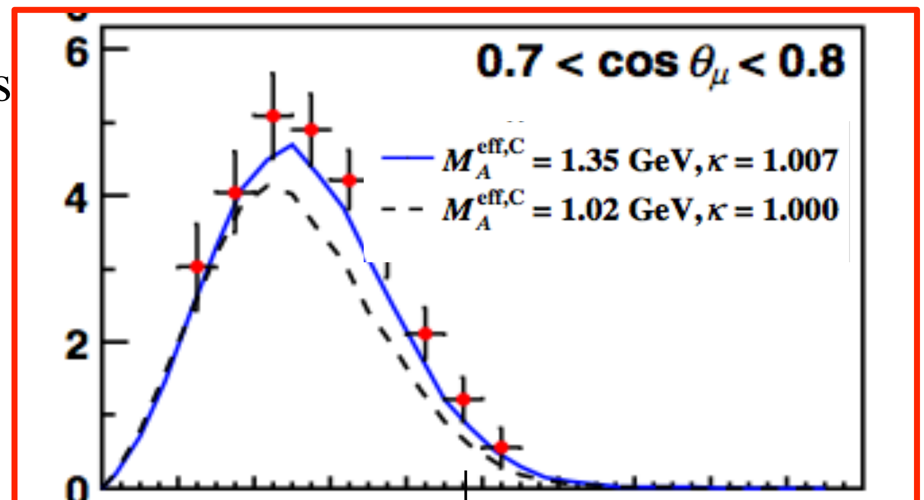


Review of Status of Cross Sections with Emphasis on Nuclear Effects

Latest MiniBooNE Results (PRD 88, 032001 (2013))

- First Measurement of the Muon Antineutrino Double-Differential Charged-Current QE Cross Section.
  - "It is clear ( ) that the RFG model assuming $M_A \sim 1$ GeV does not adequately describe these data in shape or in normalization."
  - "Consistent with other recent CCQE measurements on nuclear material, a significant enhancement in the normalization that grows with decreasing muon scattering angle is observed compared to the expectation with M_A=1.0 GeV."
  - E_ν results described by adding ≈ 20% scattering off nucleon pairs in nucleus





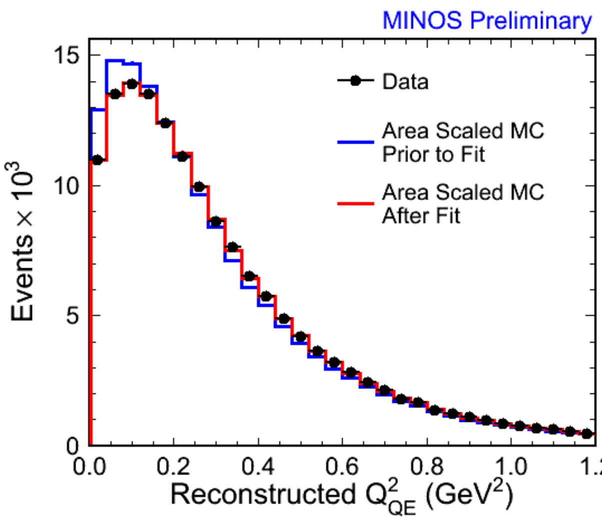
T_μ = 1 GeV

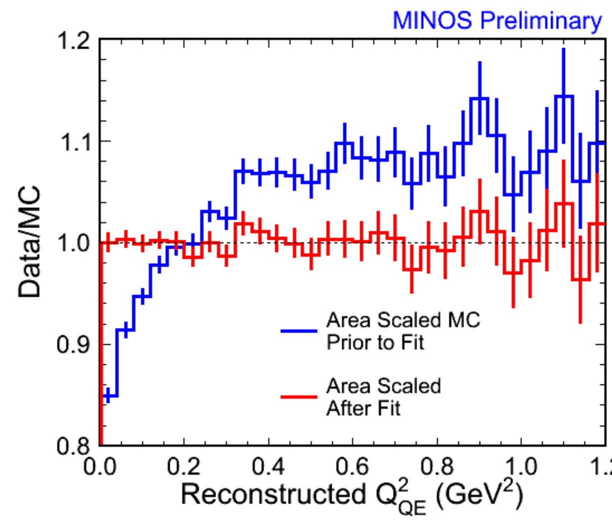
Review of Status of Cross Sections with Emphasis on Nuclear Effects

MINOS (Nick Graf – NuFact13)

- MINOS observes an deficit of low Q^2 RES events compared to our MC and has developed a data driven re-weighting function to better describe this region.
- MINOS reports results for an effective axial vector mass for quasi-elastic interactions on iron in the range $1 < E_\nu < 8$ GeV with 189, 000 candidates..

	M_A^{QE} (GeV)	E_μ Scale	M_A^{RES} (GeV)
Principal: $0 < Q^2 < 1.2$	$1.21 {}^{+0.18}_{-0.10}$	$0.996 {}^{+0.007}_{-0.015}$	$1.10 {}^{+0.15}_{-0.16}$

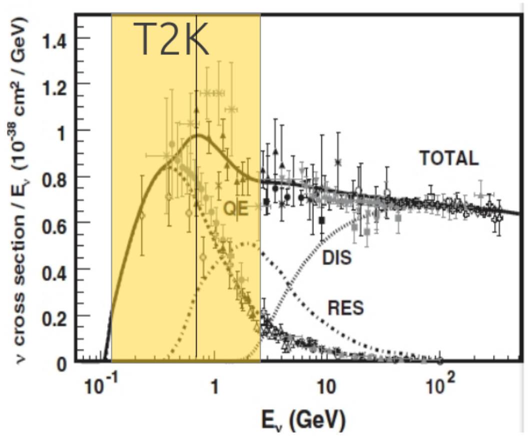


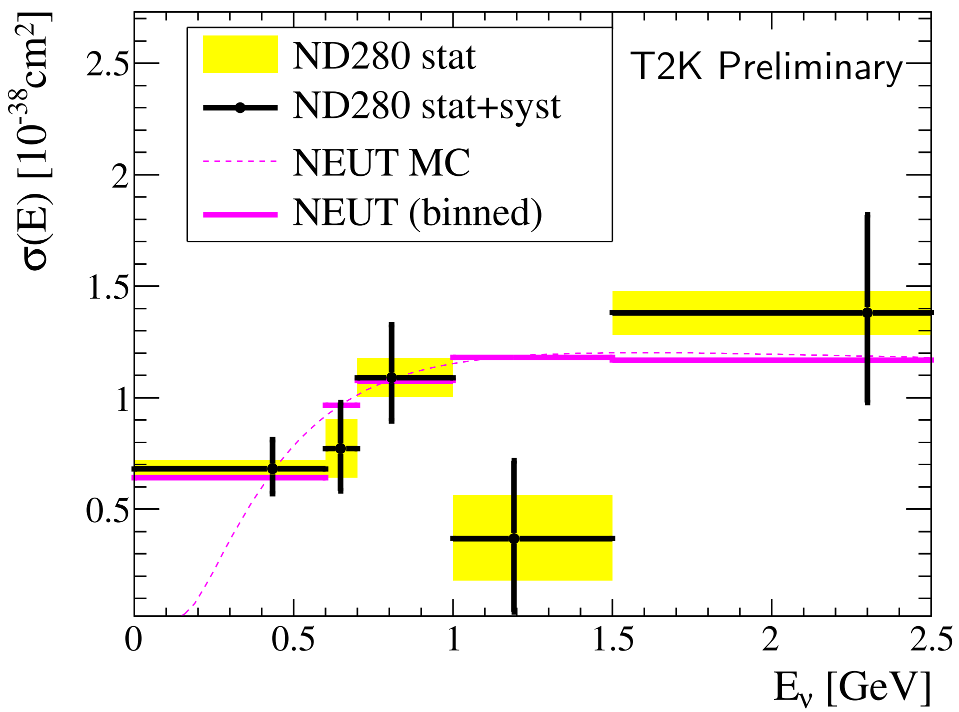


Review of Status of Cross Sections with Emphasis on Nuclear Effects

T2K (D. Hadley, NuFact13)

Measurement of the CCQE Cross Section Based on 2.7×10^{20} POT





A χ^2 test comparing the fitted result with the nominal NEUT model, with $M_A^{QE} = 1.2\mathrm{GeV}$, gives a p-value of 17% indicating agreement between the data and the cross section model.

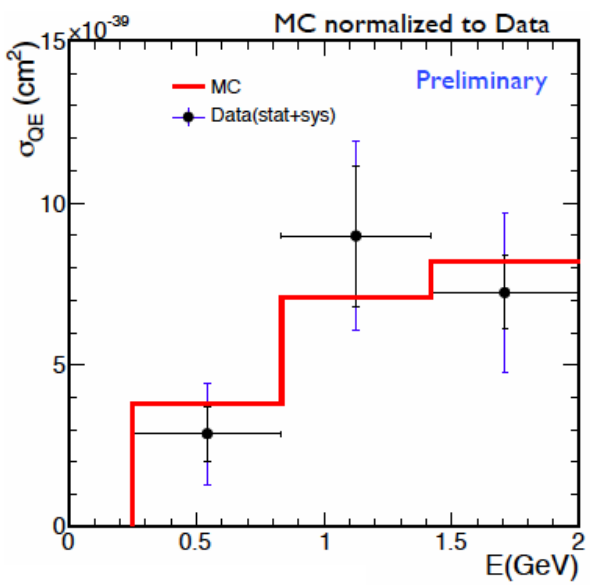
Review of Status of Cross Sections with Emphasis on Nuclear Effects

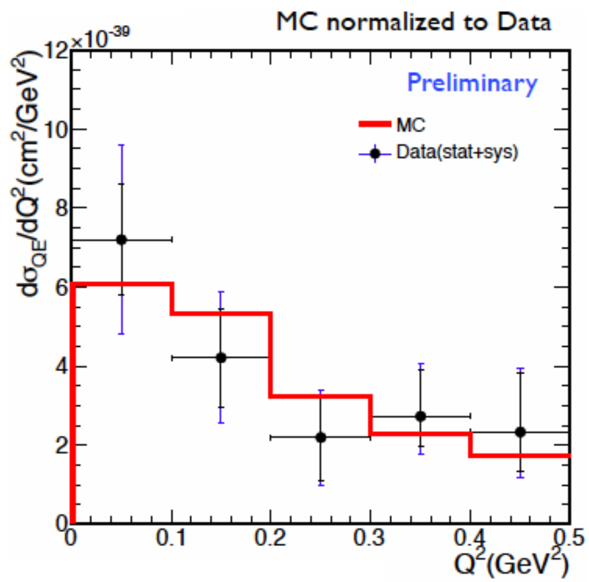
NOvA – NDOS (J. Paley-NuFact13)

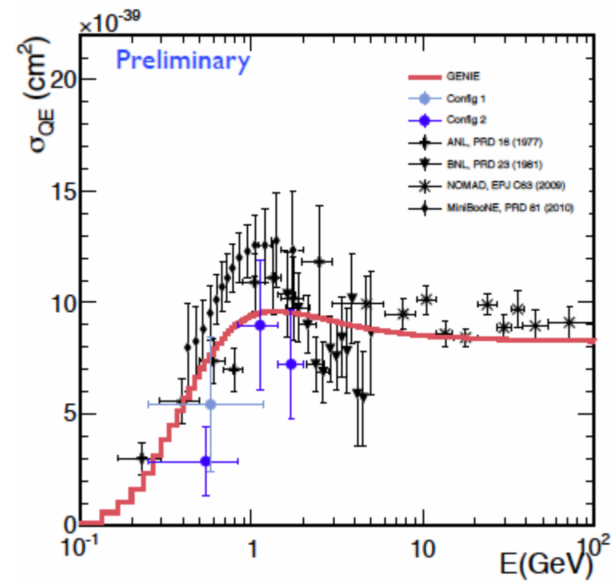
Measurement of ν_μ CC *QE* Cross-Section in NDOS (Minerba Betancourt, first NOvA Ph.D.!)

Partially instrumented surface prototype detector:

- 106 mrad off-axis from NuMI beam
- collected ~1.7x10^{20} POT
- sensitive to kaon production off target





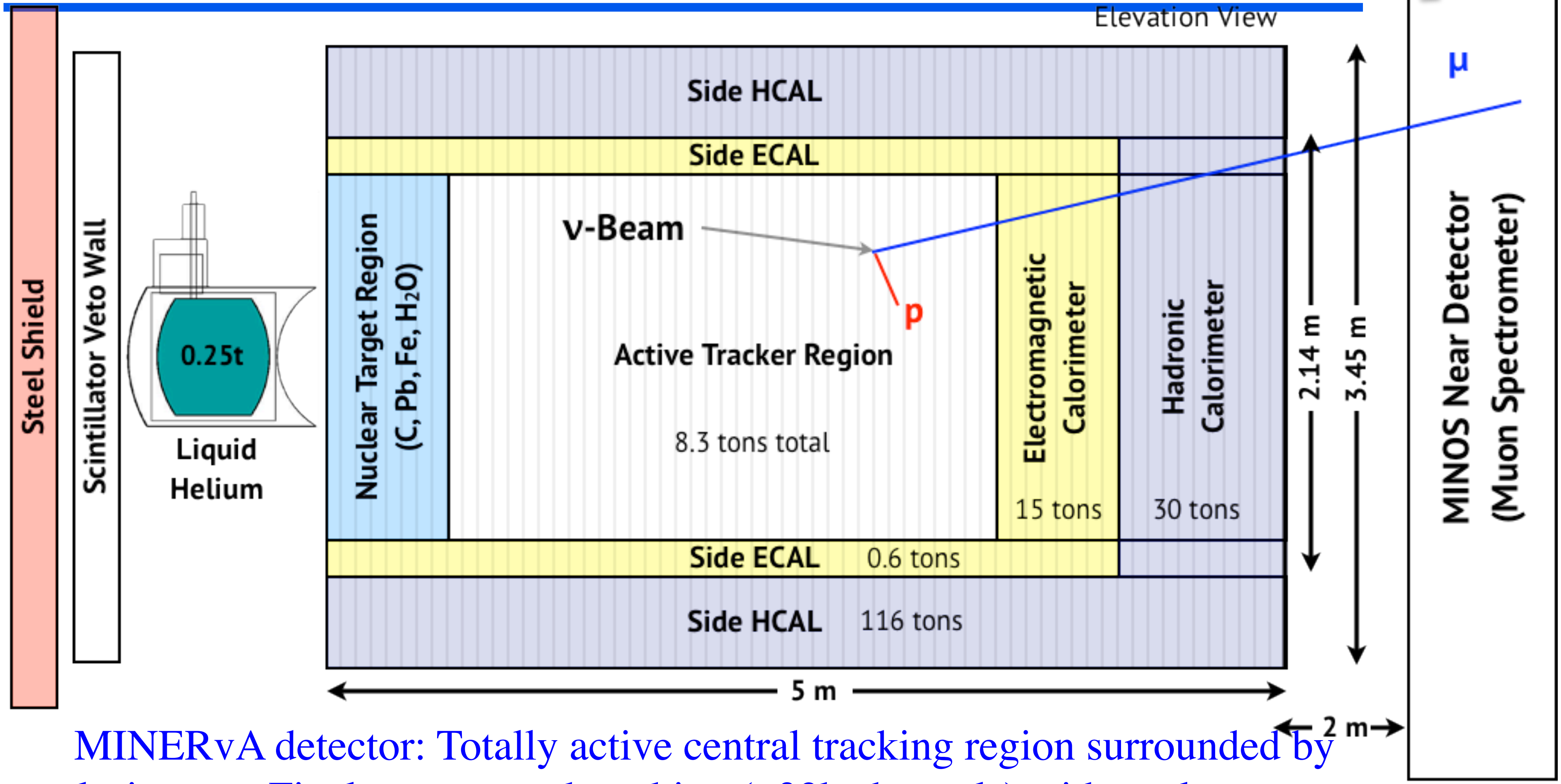


Distributions are unfolded (reco → true), efficiency corrections applied. MC distributions above are normalized to Data.

The MINERνA CCQE Analysis

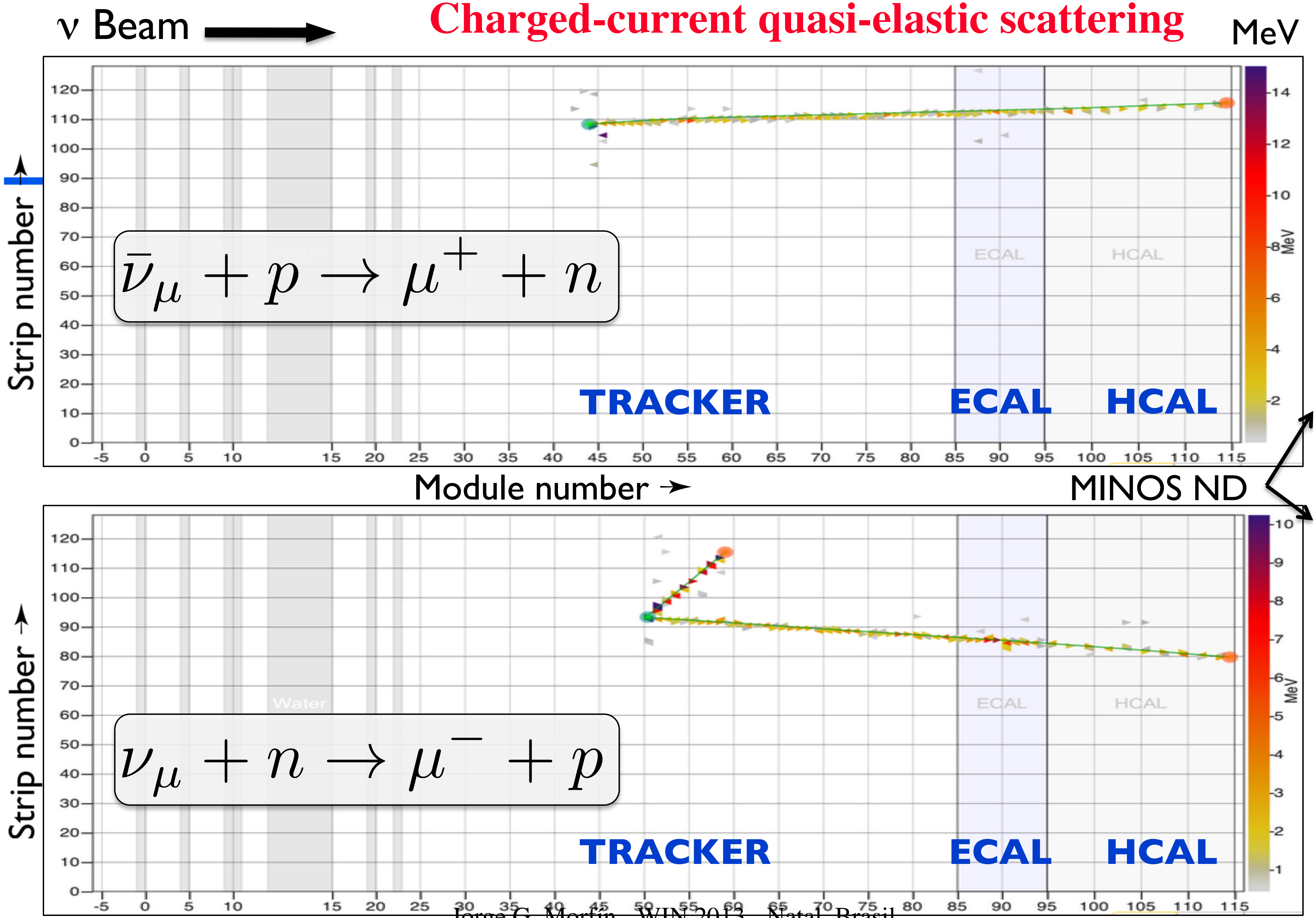
slides based on D. Schmitz – NuFact13

MINOS ND serves as muon spectrometer

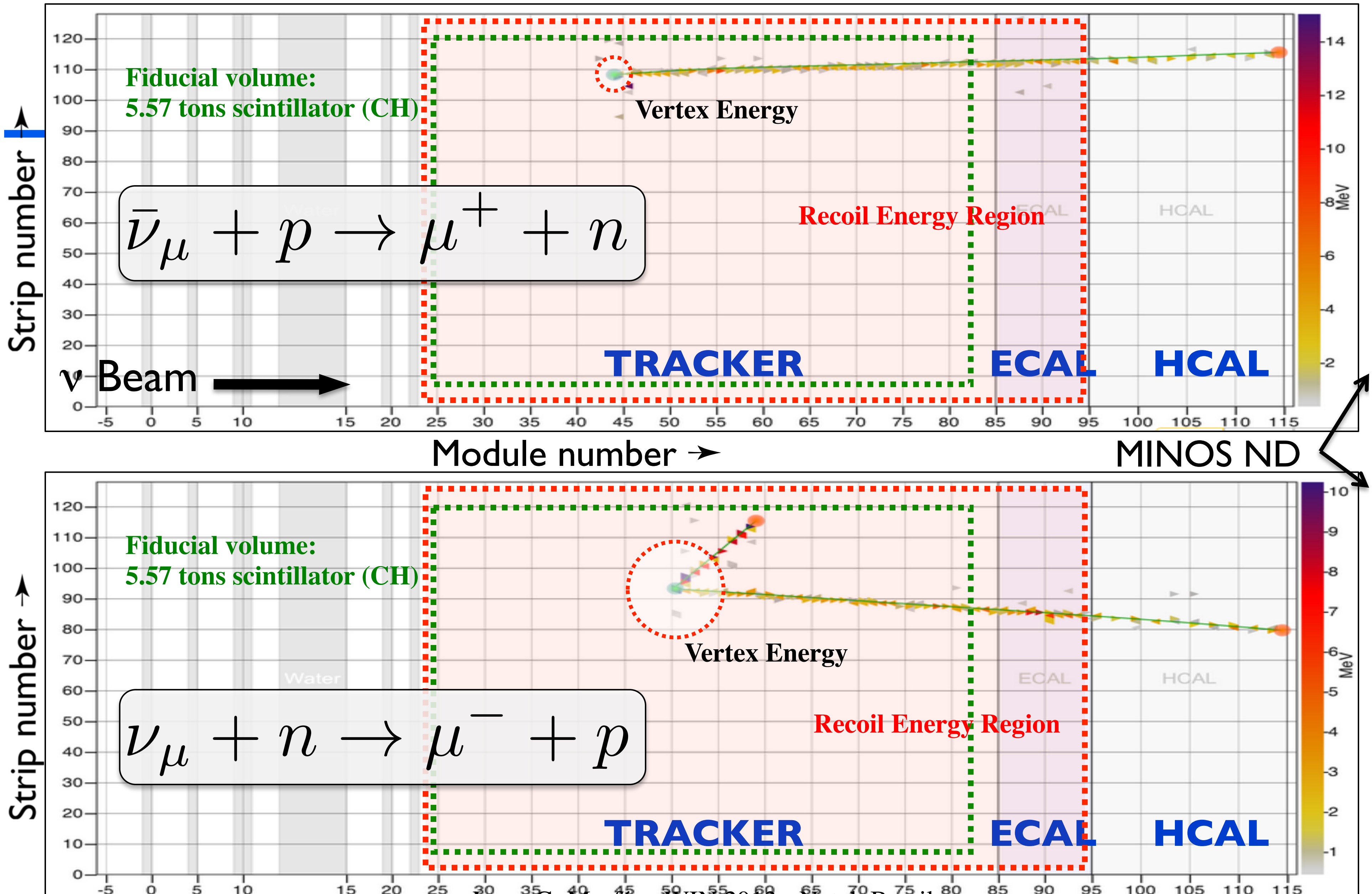


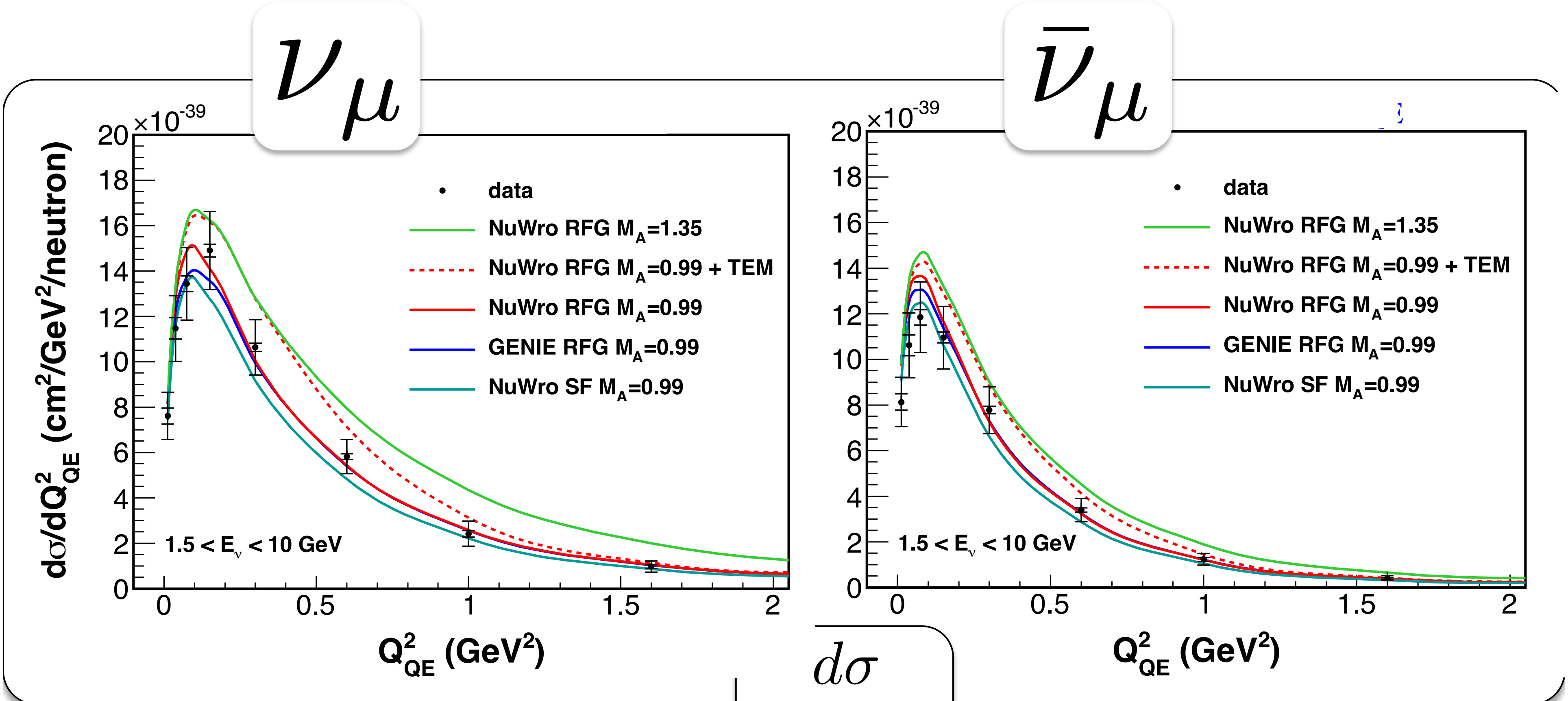
MINERνA detector: Totally active central tracking region surrounded by calorimetry. Finely segmented tracking (~32k channels) with nuclear targets (C,CH,Fe,Pb,He,H_2O) upstream.

Charged-current quasi-elastic scattering



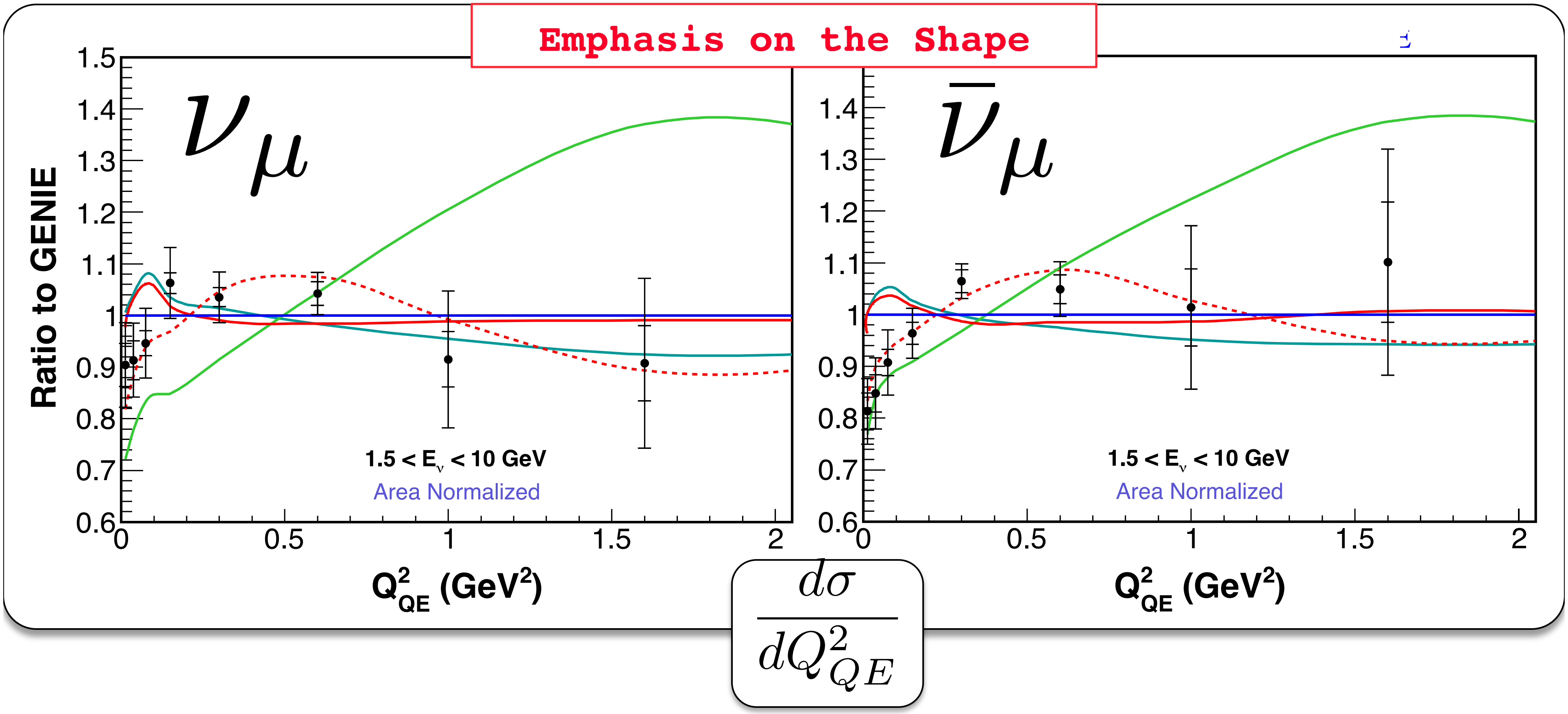
Charged-current quasi-elastic scattering analysis





$$\frac{d\sigma}{dQ^2_{QE}}$$

	Events	Efficiency	Purity
Neutrinos	29,620	47%	49%
Antineutrinos	16,467	54%	77%



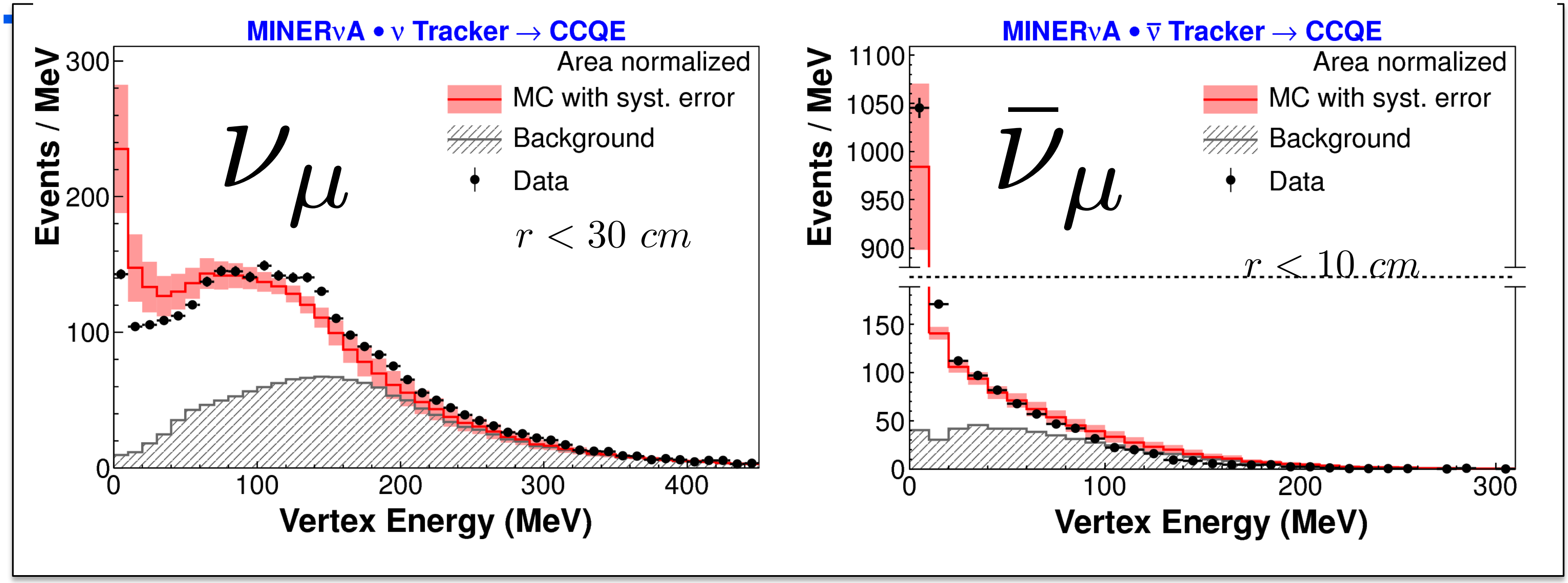
GENIE — independent nucleons in a mean field (M_A = 0.99 GeV)

M_A = 1.35 GeV — best fit to MiniBooNE data

Spectral Function — improved nucleon momentum-energy relation

TEM ··········· empirical model based on electron scattering data to account for nucleon-nucleon correlations. A, Bodek next talk.

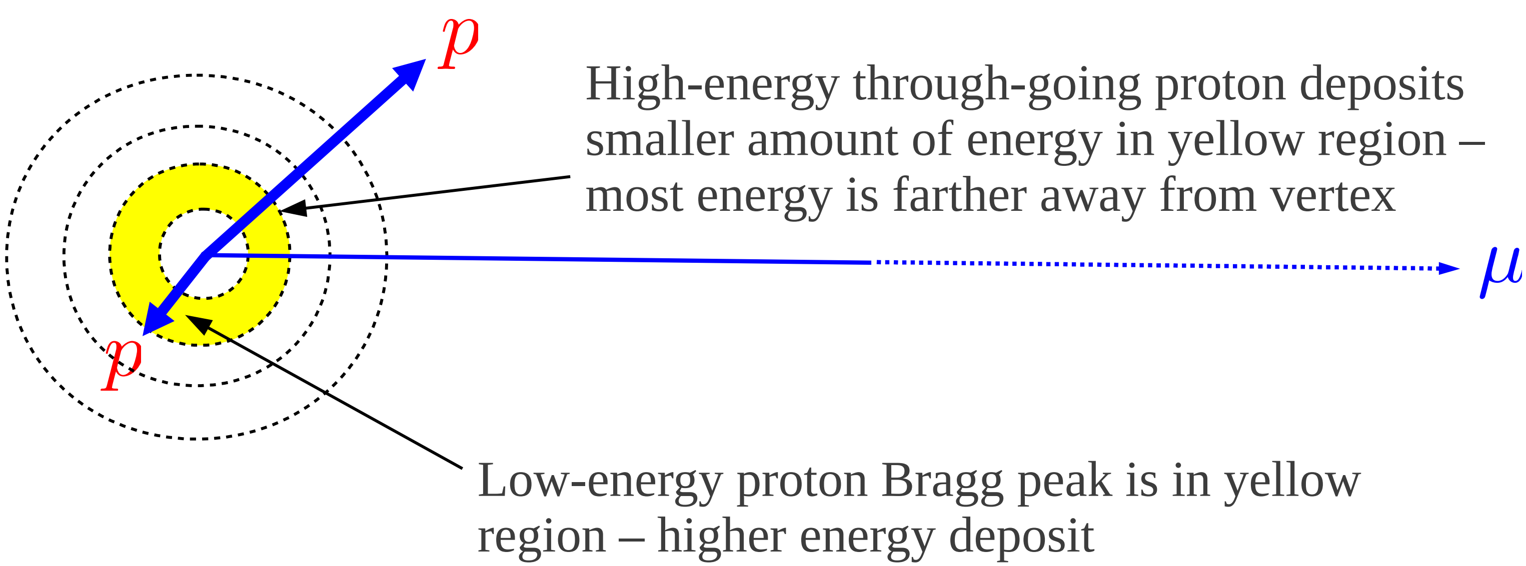
Vertex Energy



- A harder spectrum of vertex energy is observed in neutrinos.
- All systematics considered, including energy scale errors on charged hadrons and FSI model uncertainties.
- At this point, we make the ***working assumption*** that the additional vertex energy per event in data is ***due to protons***

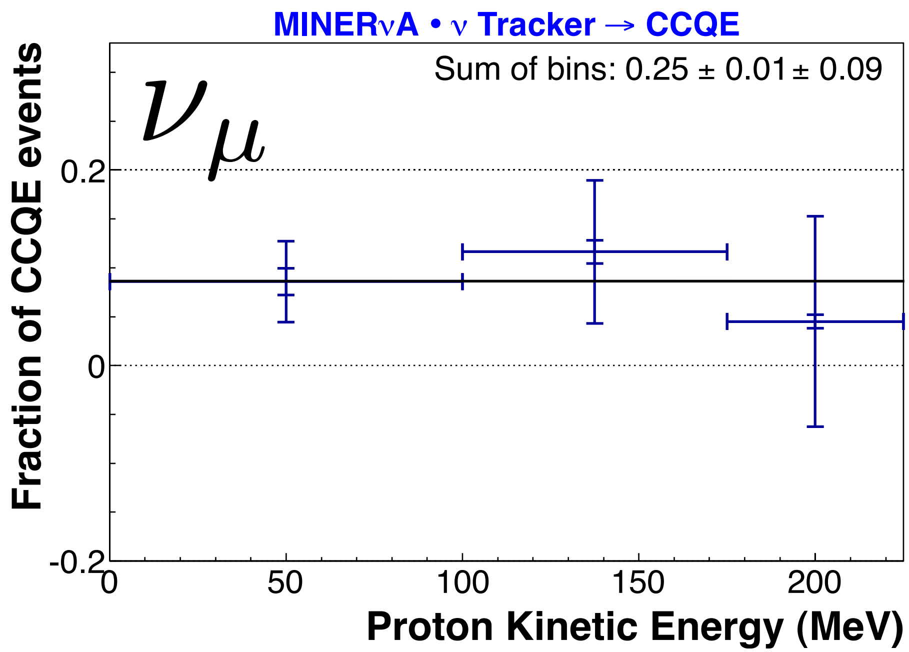
Vertex Energy

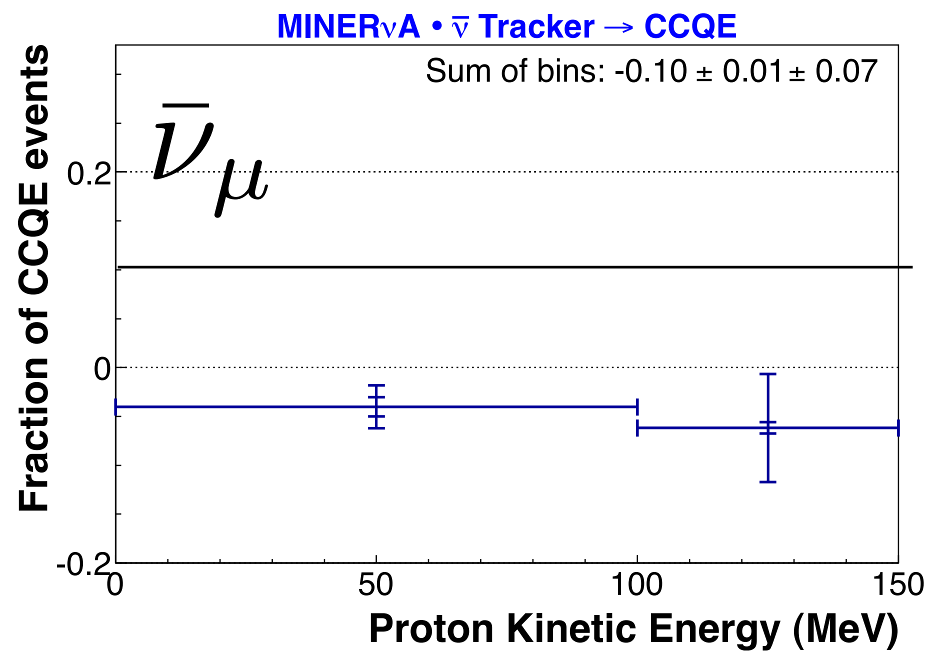
- Examine annular rings around the reconstructed vertex
  - Out to 10 cm for antineutrino (~120 MeV proton)
  - Out to 30 cm for neutrino (~225 MeV proton)



Note: to add visible energy to an inner annulus you must ***add a charged hadron***, not just increase energy of an existing one

Vertex Energy





The fit wants to add an additional low-energy proton (KE < 225 MeV) to **(25 ± 9)% of QE events to** improve agreements with data

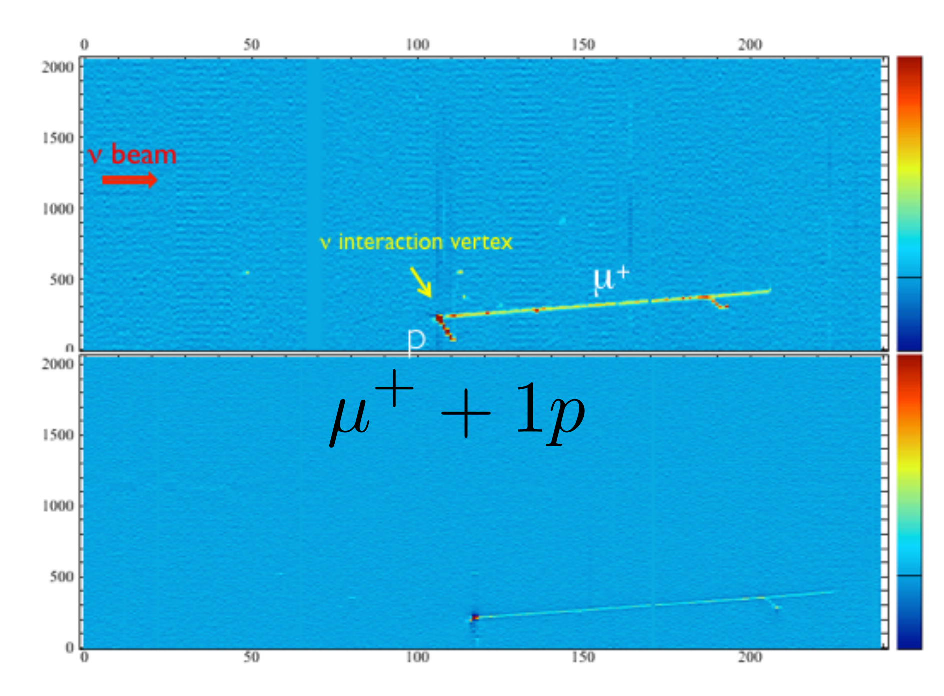
No such additional proton is required for antineutrinos. Slight reduction if anything. **(-10 ± 7)% of QE events**

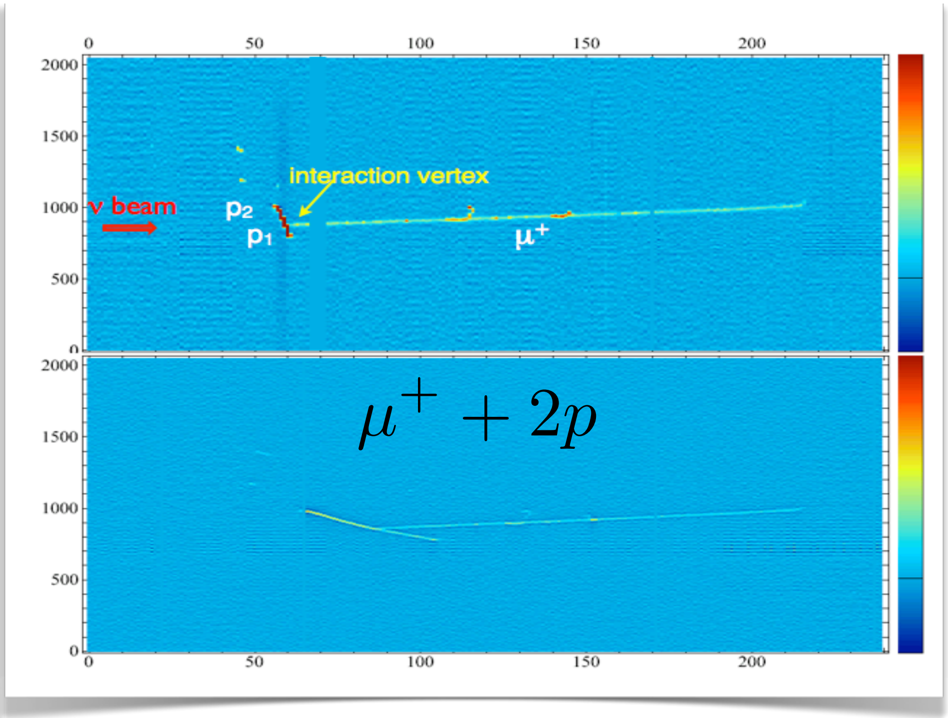
Where are we?

Map at Great Wall

Future Neutrino-Nucleus Scattering Experiments

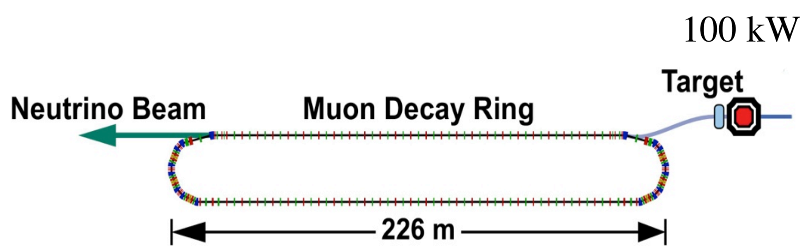
- LAr TPC's: (ArgoNeuT) Liquid argon time projection chambers offer an opportunity for a detailed study of neutrino-nucleus scattering
- ArgoNeuT detector exposed to NuMI beam
  - 0.085e20 POT neutrino mode
  - 1.2e20 POT antineutrino mode





Future Precision ν-Nucleus Scattering Experiments
nuSTORM - Neutrinos from Stored Muons

- **High-Precision ν interaction physics program.**
- **ν_e and $\bar{\nu}_e$ 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.

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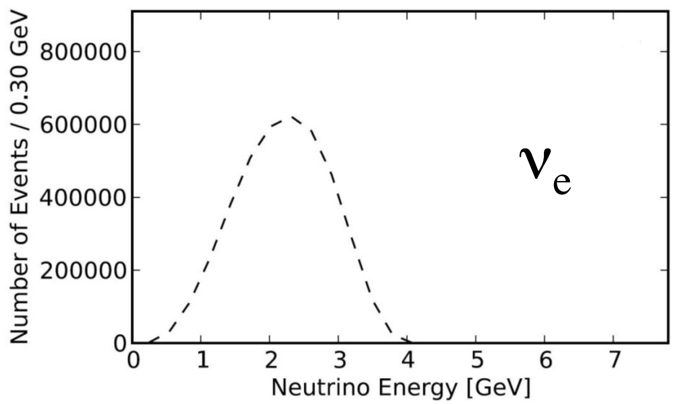
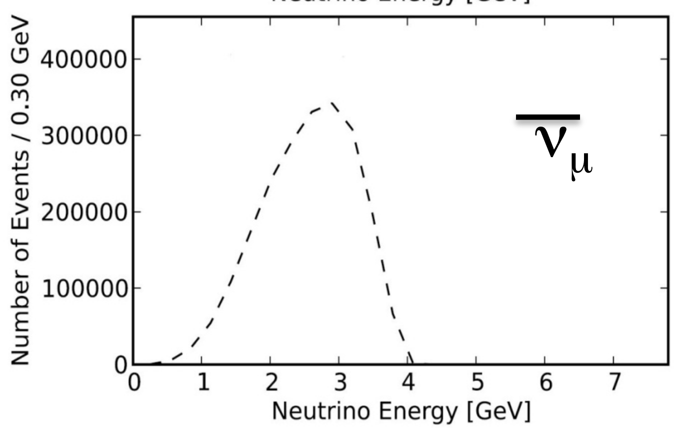
The nuSTORM Neutrino Beam

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

- 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^+

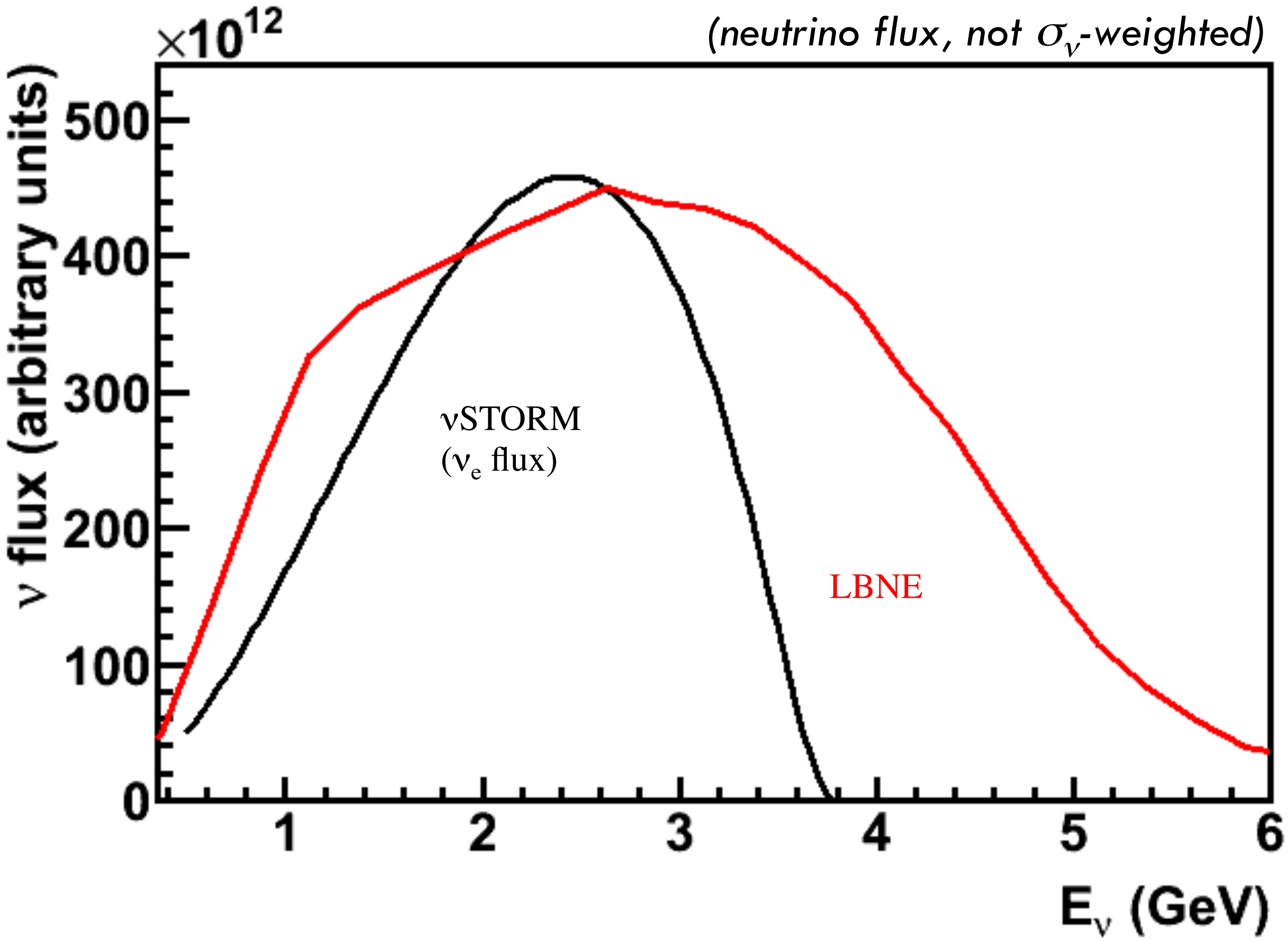
Channel	N_{evts}
$\bar{\nu}_\mu$ NC	844,793
ν_e NC	1,387,698
$\bar{\nu}_\mu$ CC	2,145,632
ν_e CC	3,960,421

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

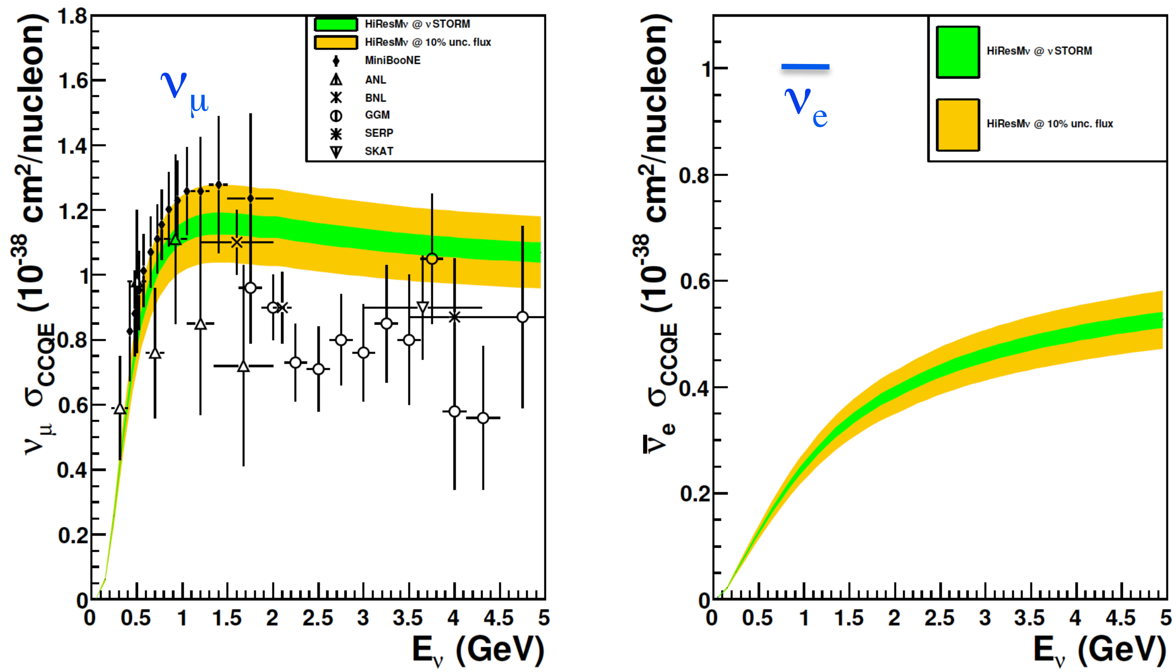


Scattering Measurements with nuSTORM + Near Detector

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

Ed Santos – Imperial College

HIRESMν − systematics



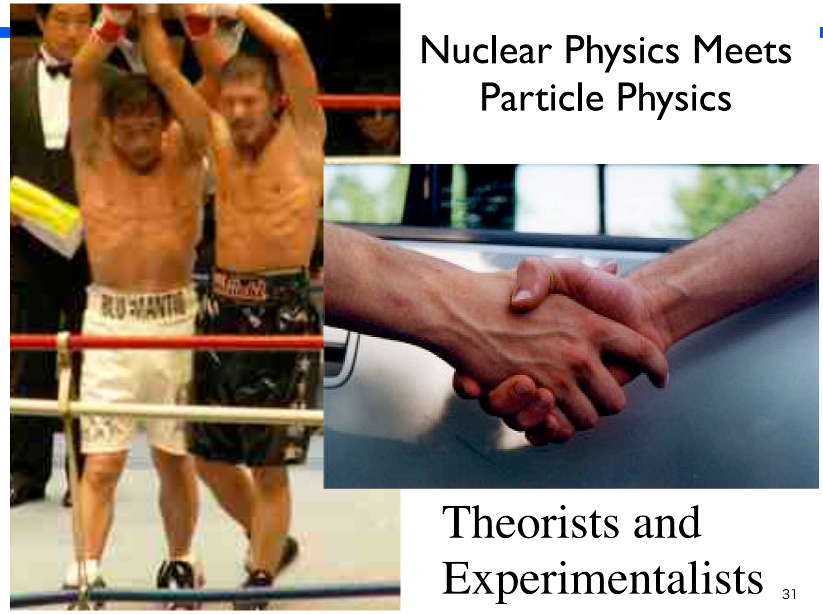
Forming a separate nuSTORM Neutrino Scattering Collaboration. Interested?

In Summary: Nuclear Physics Meets Neutrino Physics

Dave Schmitz – NuFact13

Conclude with NuSTEC Concept

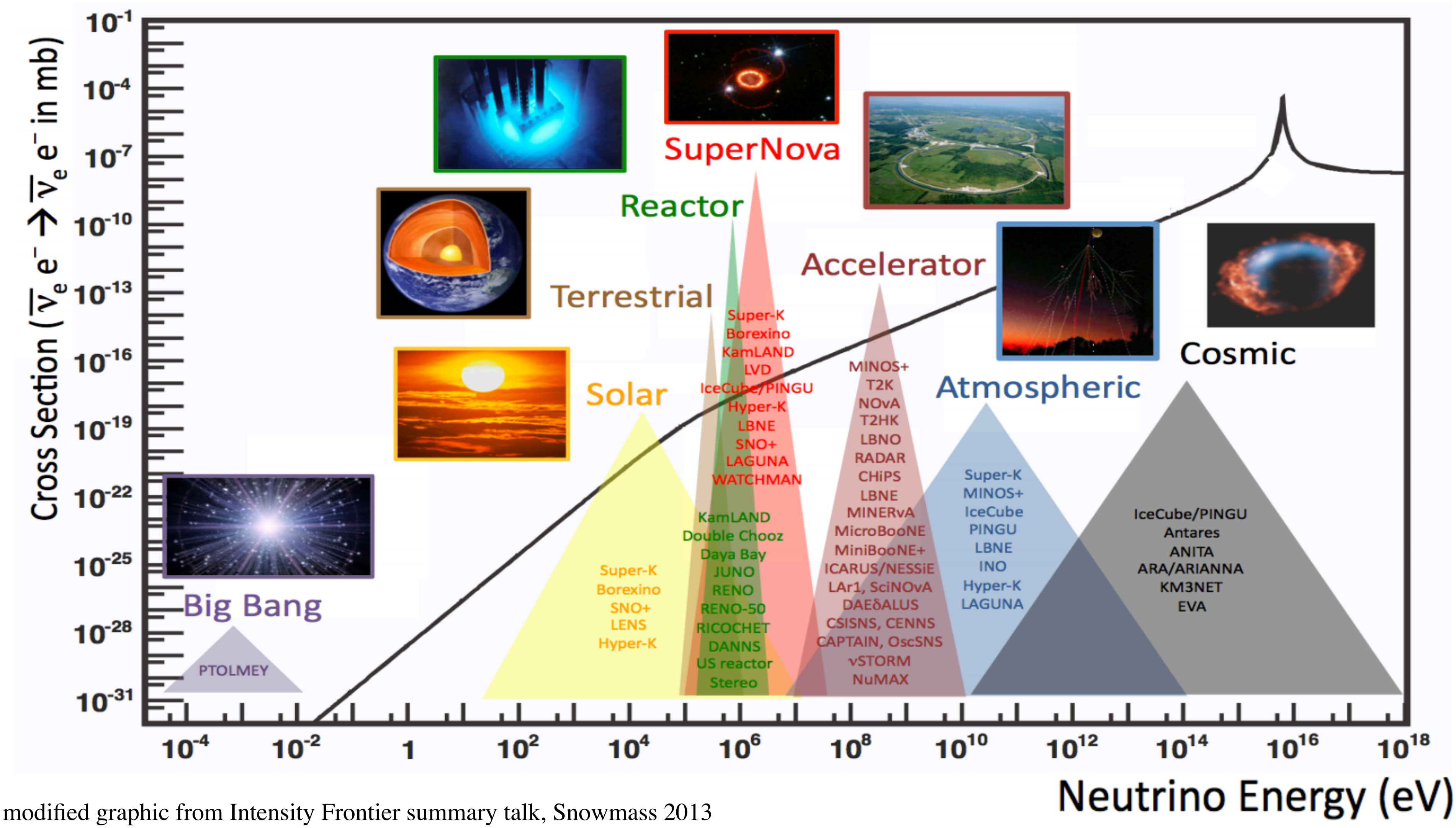
Neutrino Scattering Theorist Experimentalist Collaboration



- CTEQ-like collaboration of experimentalists and theorists nuclear and HEP working together on:
  - Joint theoreticalexperimental neutrino scattering physics studies that, among many things, could lead to improvements of Monte Carlo generators.
  - Based on the challenges and progress of the physics studies, organizing workshops that bring the community together to discuss a particular issue.
  - A Neutrino Scattering Physics School aimed at advanced doctoral students and beginning postDocs.

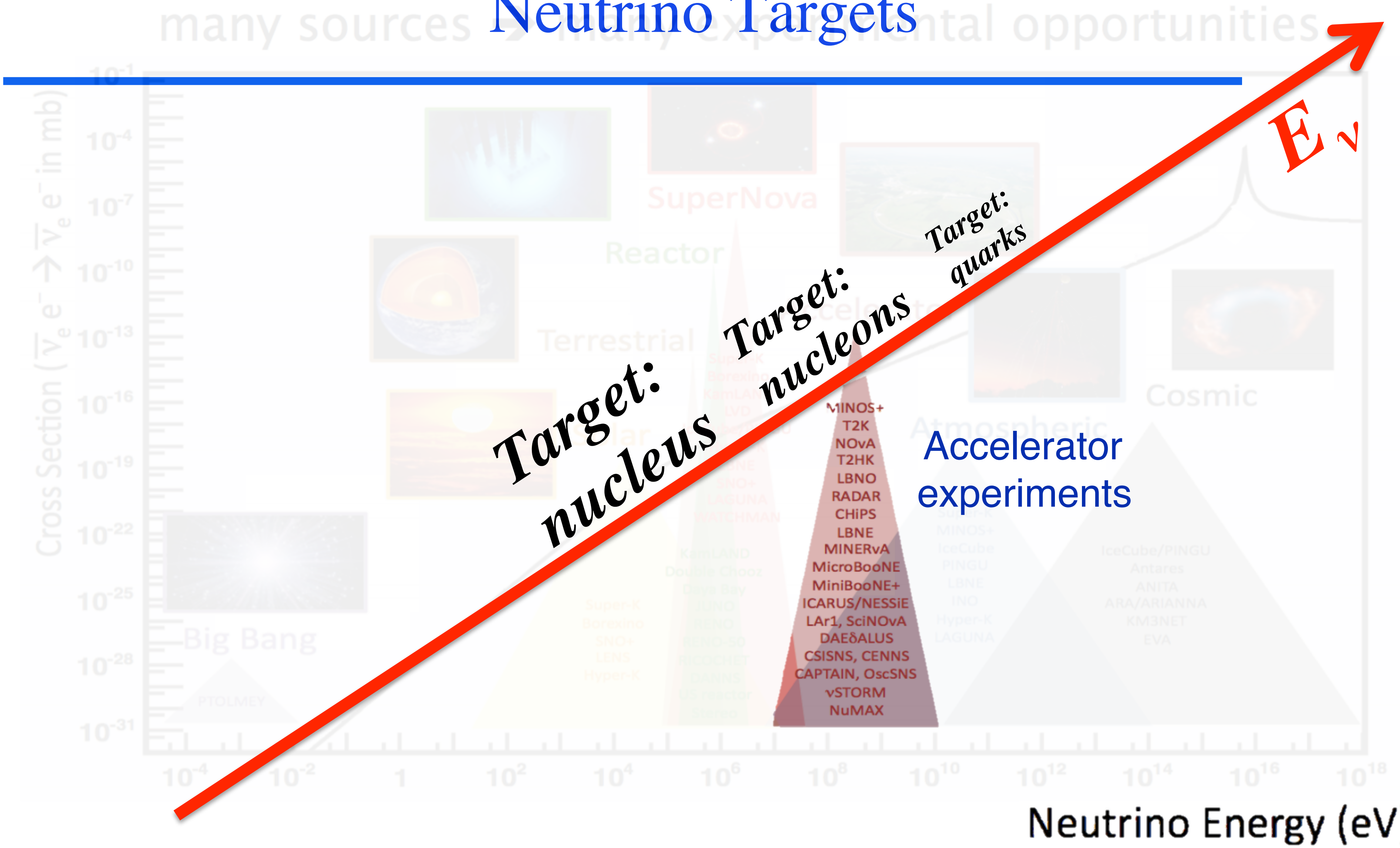
End

many sources → many experimental opportunities



modified graphic from Intensity Frontier summary talk, Snowmass 2013
original from J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84, 1307-1341, 2012

Neutrino Targets

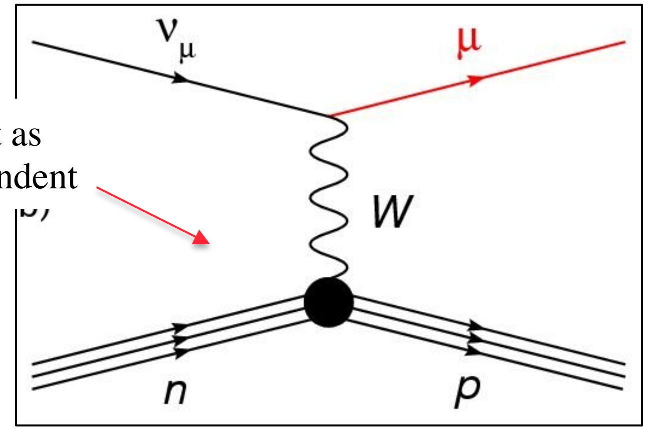


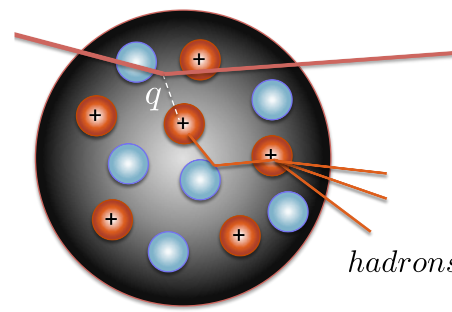
Relativistic Fermi Gas For Nucleus

- For <u>quasi-elastic scattering</u>, if we further assume the ***nucleon is at rest***, we can determine E_ν and Q^2 from lepton kinematics only ("2-body interaction")

  - Technique used by many oscillation experiments, particularly when <u>blind to the hadronic final state</u>

treat as independent





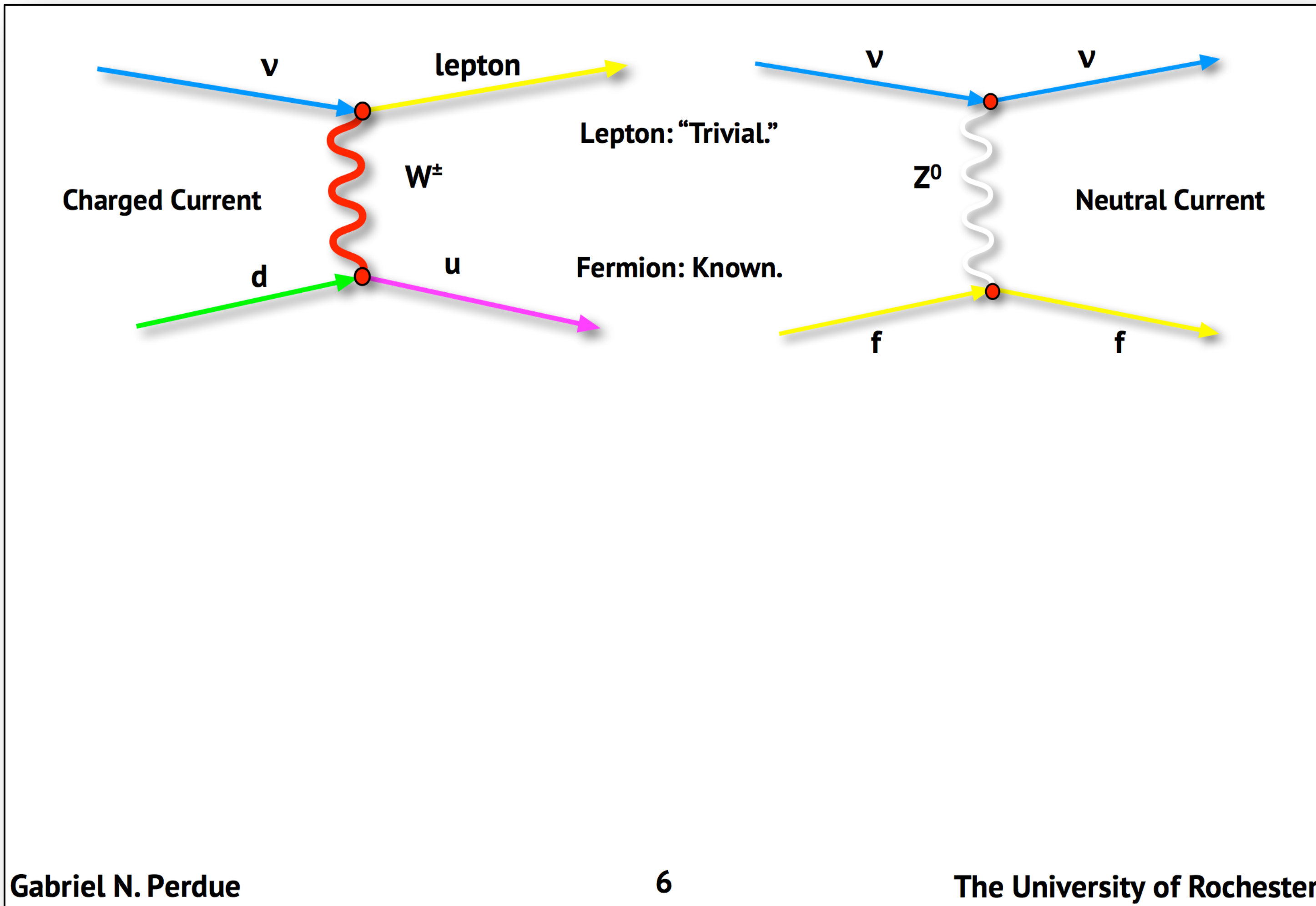
neutrino energy

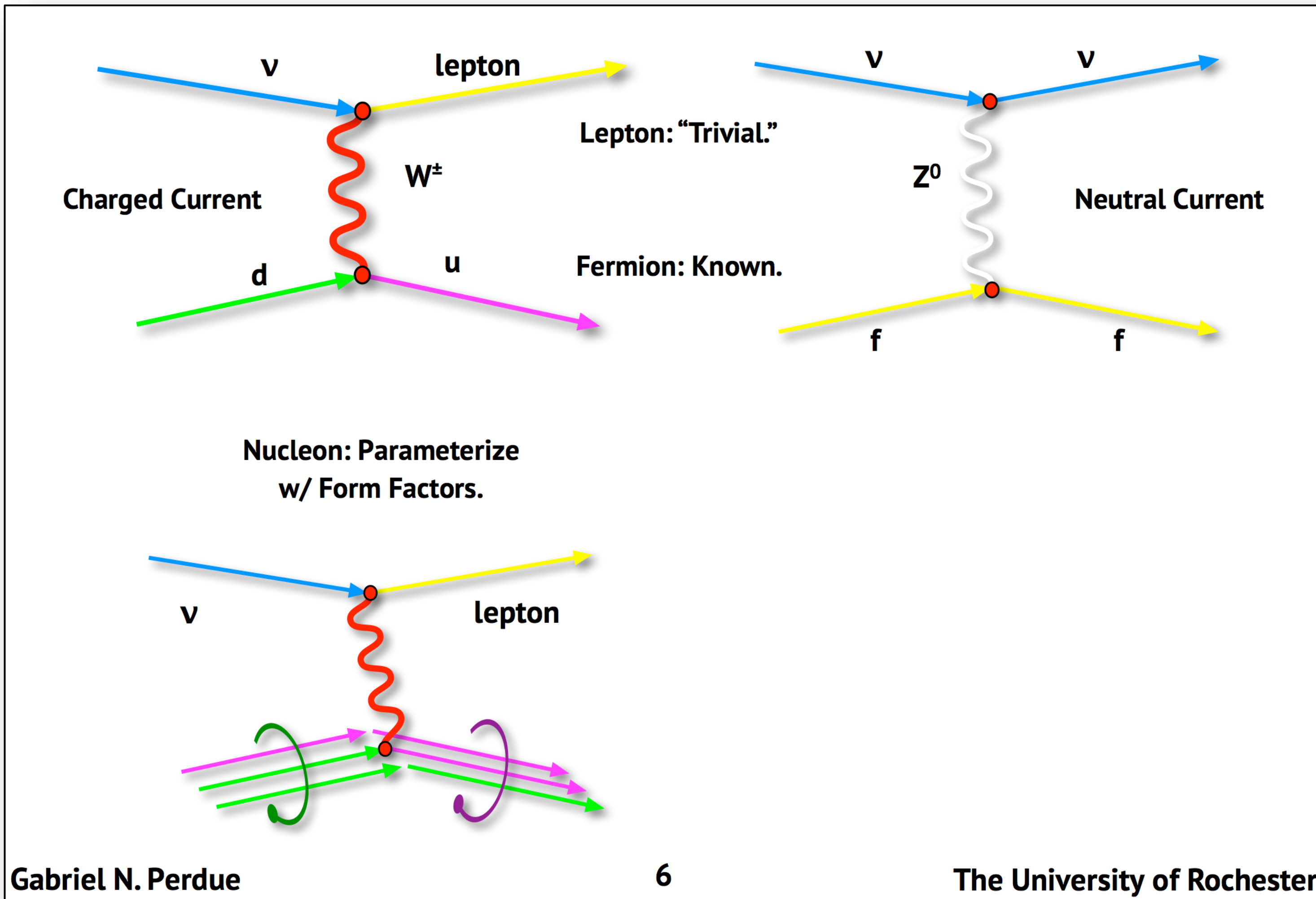
$$E_\nu^{QE} = \frac{2\left(M_n - E_B\right) E_\ell - \left[\left(M_n - E_B\right)^2 + m_\ell^2 - M_p^2\right]}{2\left[M_n - E_B - E_\ell + p_\ell \cos(\theta_\ell)\right]}$$

$$Q^2_{QE} = -m_\ell^2 + 2E_\nu^{QE}\left(E_\ell - \sqrt{E_\ell^2 - m_\ell^2}\cos(\theta_\ell)\right)$$

4-momentum transferred

M_n = neutron mass
M_p = proton mass
E_B = separation energy
m_ℓ = lepton mass
E_ℓ, θ_ℓ = lepton energy and angle


ν
lepton
ν
ν
Lepton: "Trivial."
W±
Z0
Charged Current
Neutral Current
d
u
Fermion: Known.
f
f
Gabriel N. Perdue
6
The University of Rochester



ν
lepton
Lepton: "Trivial."
W±
Charged Current
d
u
Fermion: Known.
ν
ν
Z0
Neutral Current
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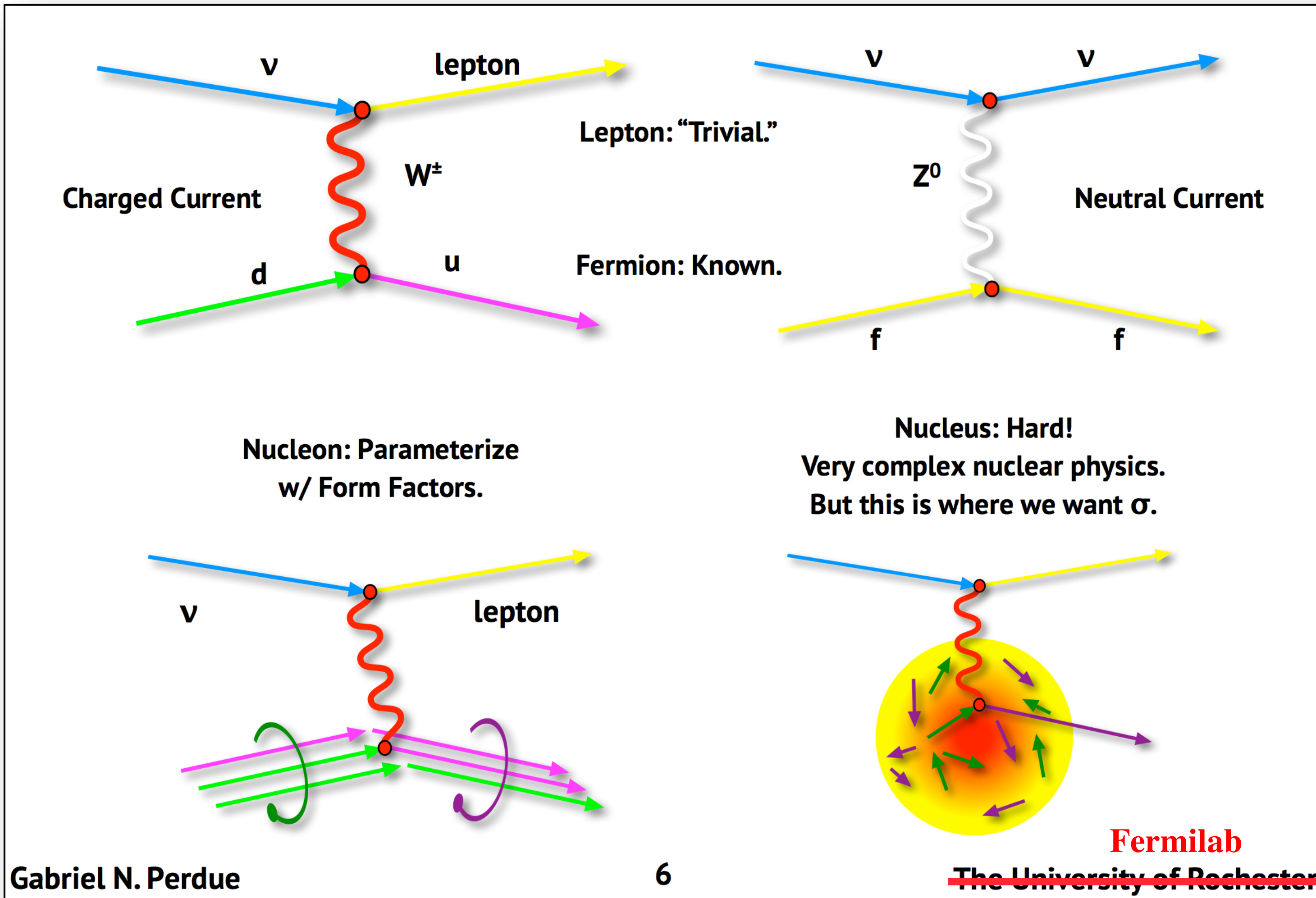
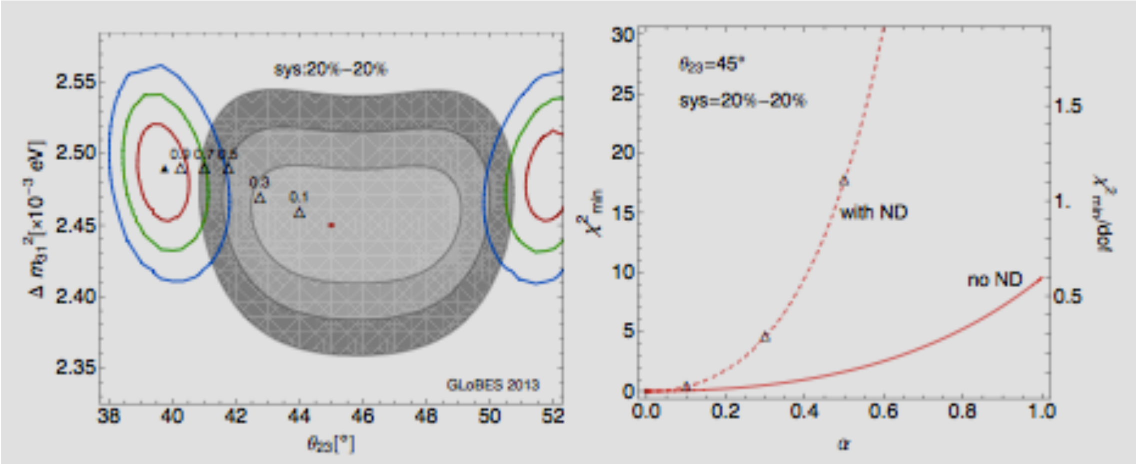
f
Nucleon: Parameterize
w/ Form Factors.
ν
lepton
Gabriel N. Perdue
6
The University of Rochester


ν
lepton
Lepton: “Trivial.”
W±
Charged Current
d
u
Fermion: Known.
ν
ν
Z0
Neutral Current
f
f
Nucleon: Parameterize
w/ Form Factors.
Nucleus: Hard!
Very complex nuclear physics.
But this is where we want σ.
ν
lepton
Fermilab
The University of Rochester
Gabriel N. Perdue
6

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!**



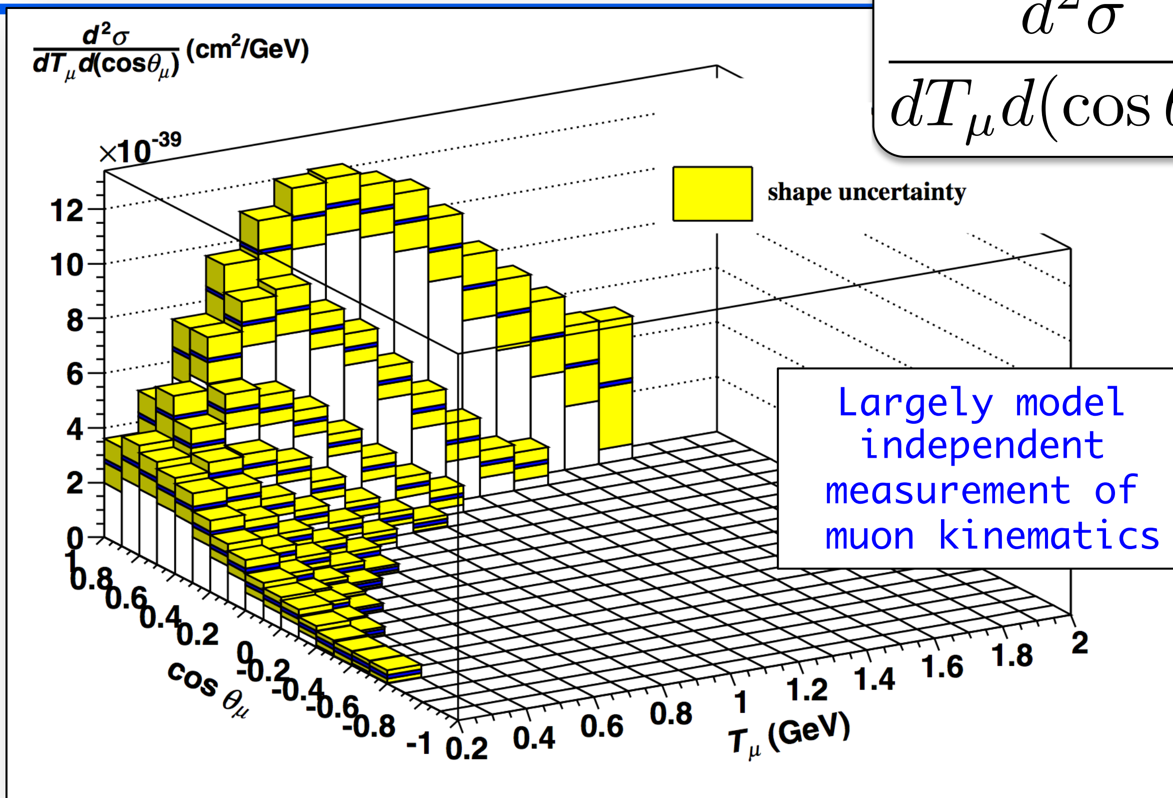
Elements of a ν-N Program

1. Span of neutrino energies (~100 MeV to 10 GeV)
   - With minimized flux uncertainties (spectrum and normalization)
2. Range of nuclear targets
3. High resolution detectors
   - Good resolution of leptonic and hadronic sides of the final state
4. Differential cross sections ➔ statistics
   - Required to untangle underlying physics and validate models
5. Close collaboration with theoretical community
   - » Much of this physics is at the cross roads of particle and nuclear
   - » **Improvement of event generators is key to utilizing in osc. experiments**

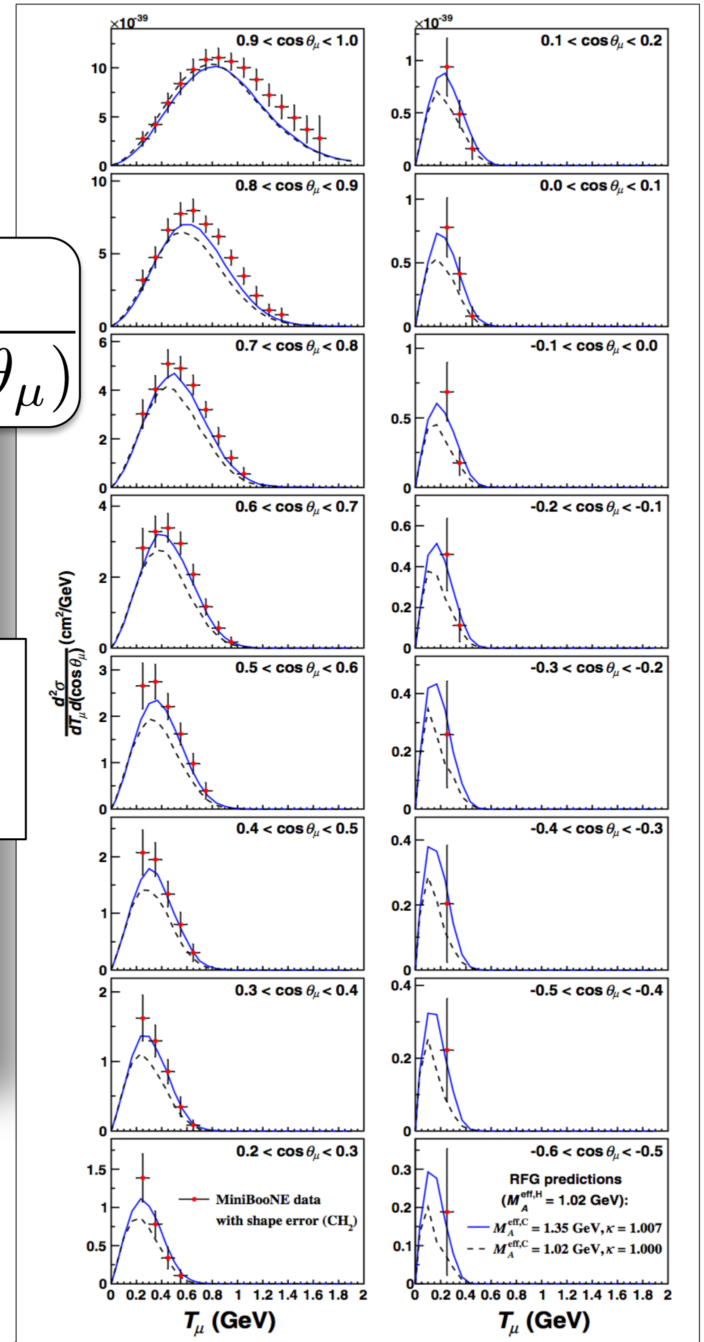
First Measurement of the Muon Antineutrino Double-Differential Charged-Current Quasielastic Cross Section

PRD 88, 032001 (2013)

$$\frac{d^2\sigma}{dT_\mu d(\cos\theta_\mu)}$$



Largely model independent measurement of muon kinematics

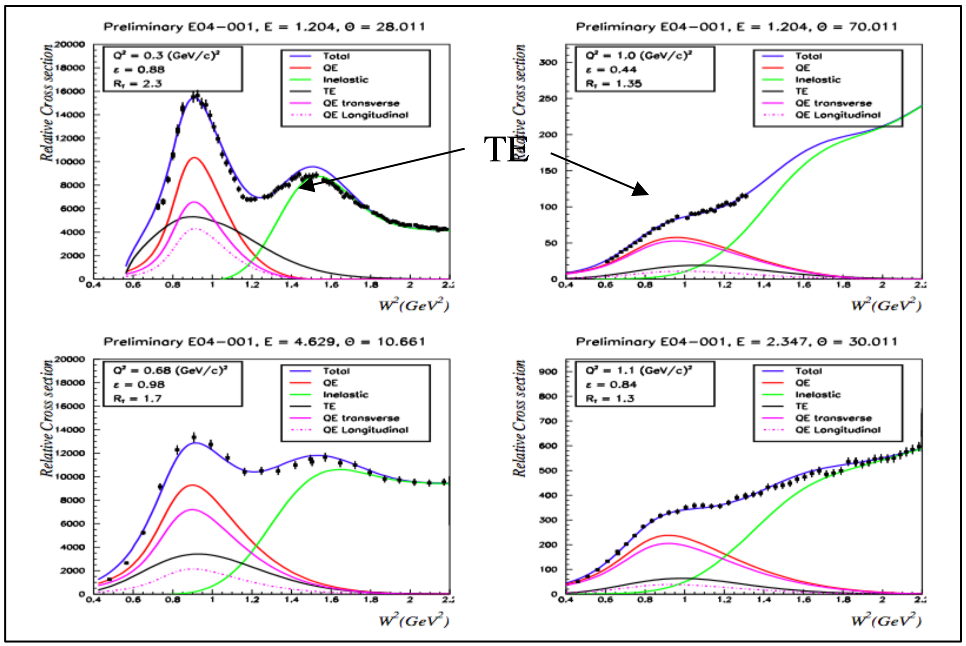


$$\bar{\nu}_\mu + p \rightarrow \mu^+ + nucleons$$

BooNE
BOOSTER NEUTRINO EXPERIMENT

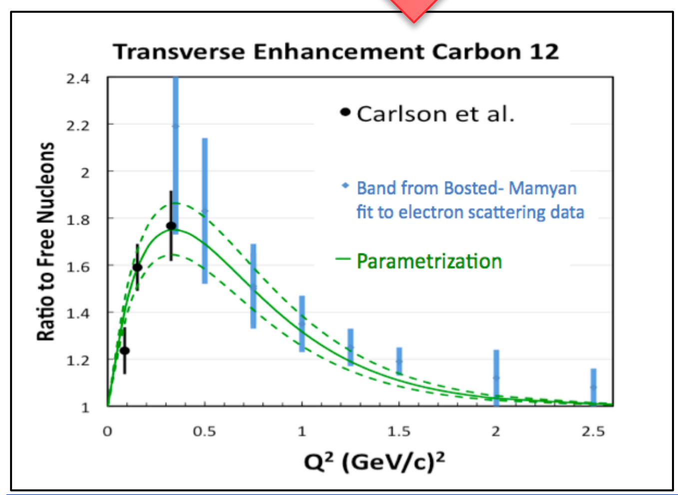
Transverse Enhancement Model

Bodek, Budd, Christy, Eur. Phys. J. C 71:1726 (2011), arXiv:1106.0340

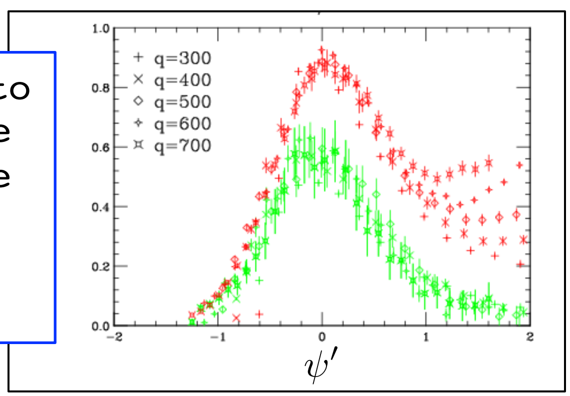


Fits in Q^2 bins

$$R_T = \frac{QE_{transverse} + TE}{QE_{transverse}}$$



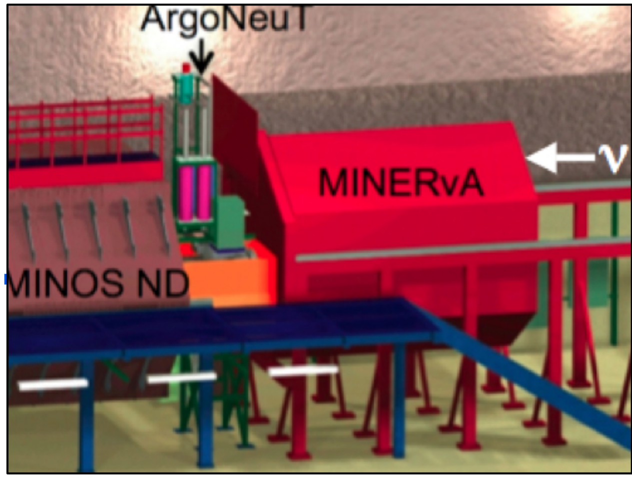
An attempt to parameterize this feature we saw in electron scattering



J. Carlson, et al., PRC 65, 024002 (2002)

$$G_M^p(Q^2)$$
$$G_M^n(Q^2)$$

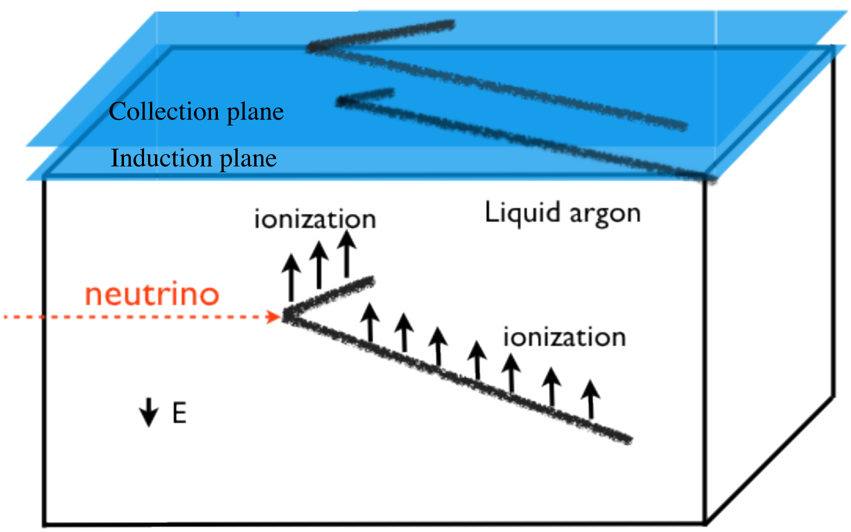
Applied as modifications of the ***magnetic form factors for bound nucleons***

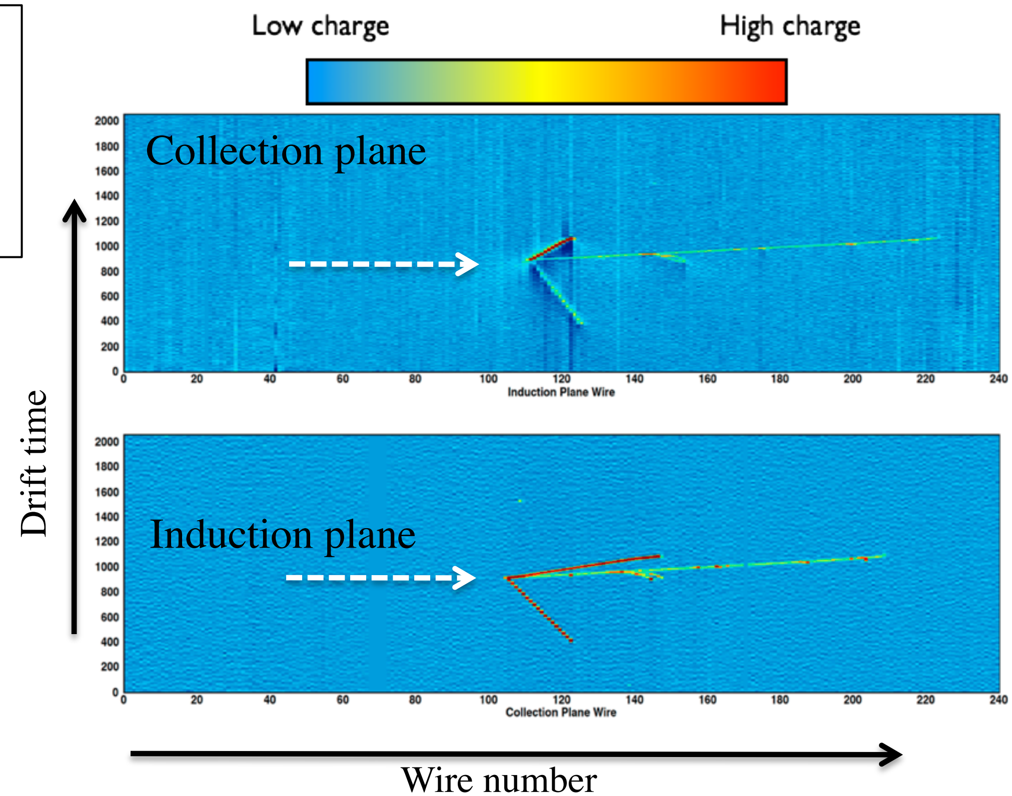


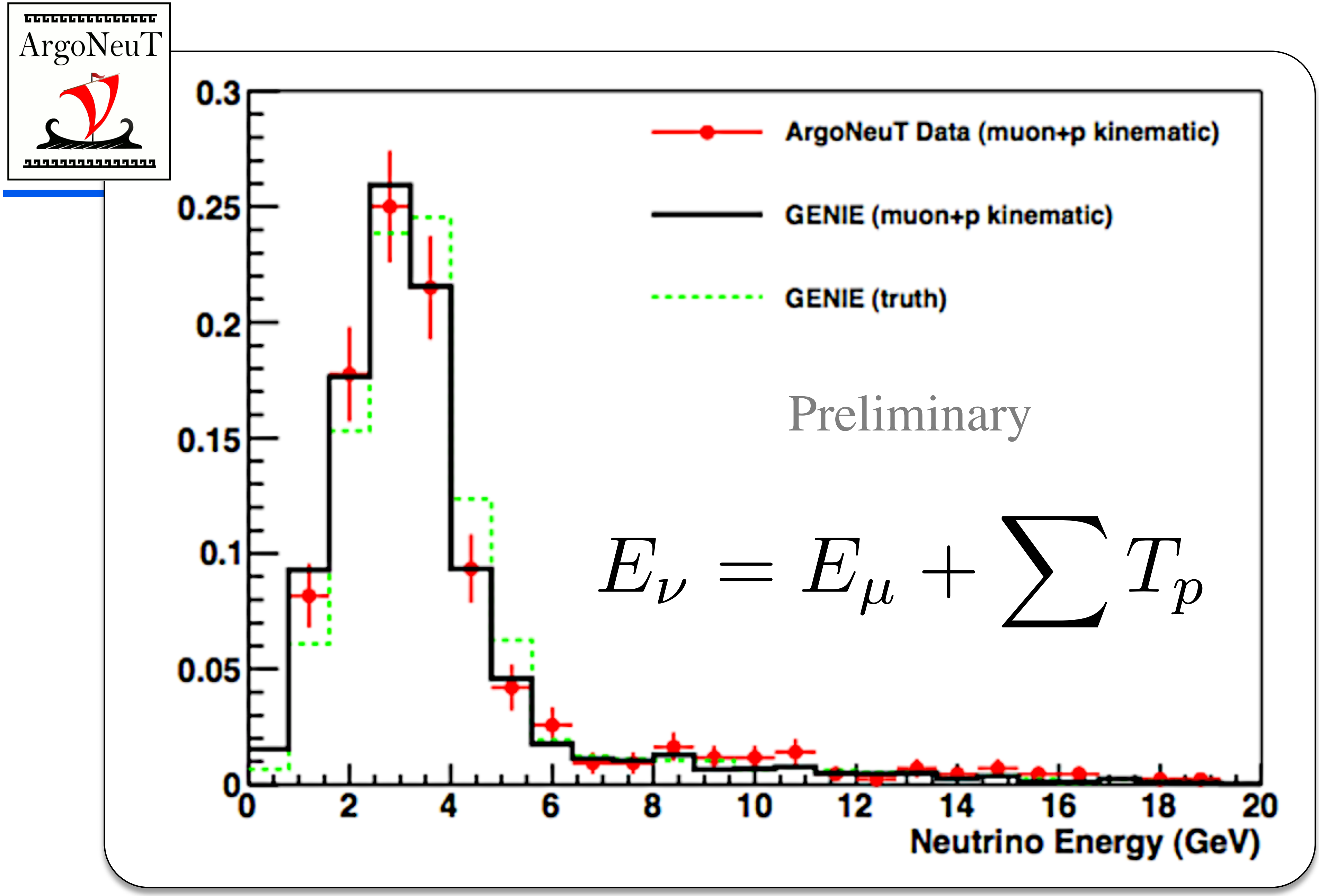
- Liquid argon time projection chambers offer a great opportunity for neutrino physics, including detailed study of neutrino-nucleus scattering
- ArgoNeuT detector exposed to NuMI beam
  - 0.085e20 POT neutrino mode
  - 1.2e20 POT antineutrino mode

ArgoNeuT

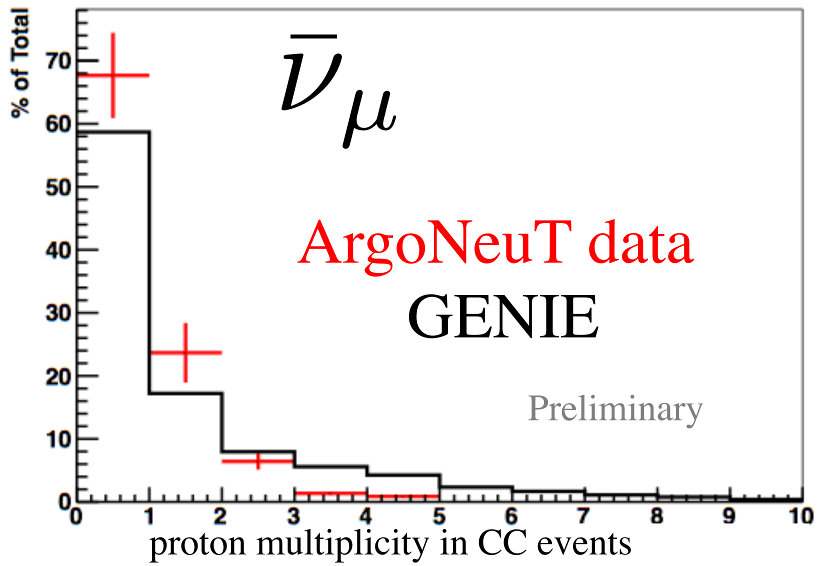
TPC Volume: 175 L
Wire Pitch: 4 mm
Max Drift: 0.5 m (330 μs)
Electric Field: 500 V/m



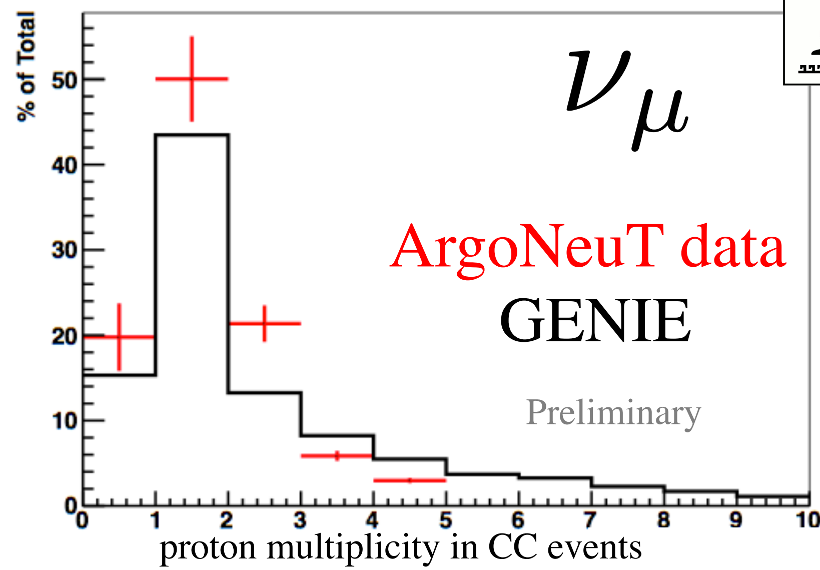


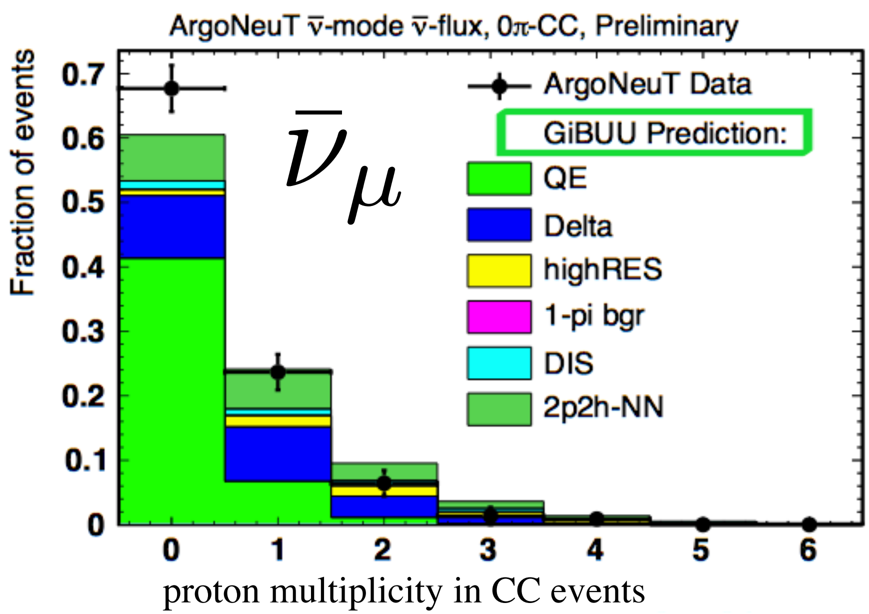

ArgoNeuT
0.3
0.25
0.2
0.15
0.1
0.05
0
0 2 4 6 8 10 12 14 16 18 20
Neutrino Energy (GeV)
ArgoNeuT Data (muon+p kinematic)
GENIE (muon+p kinematic)
GENIE (truth)
Preliminary
$E_\nu = E_\mu + \sum T_p$

$\overline{\nu}_\mu$ – antineutrino mode run

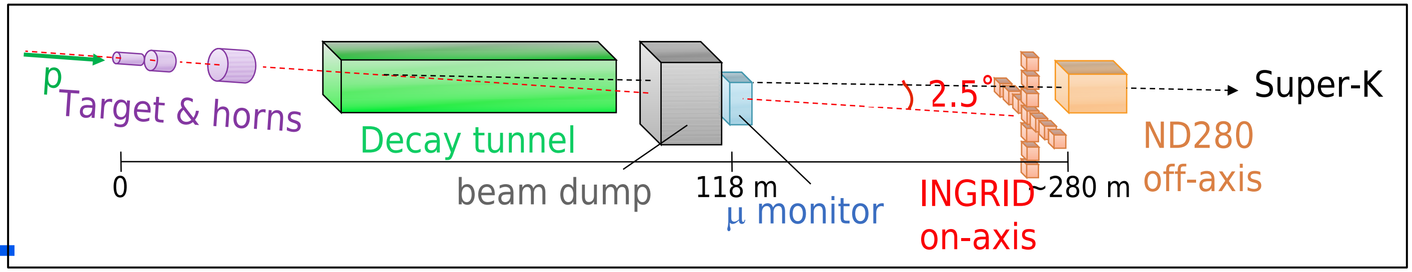


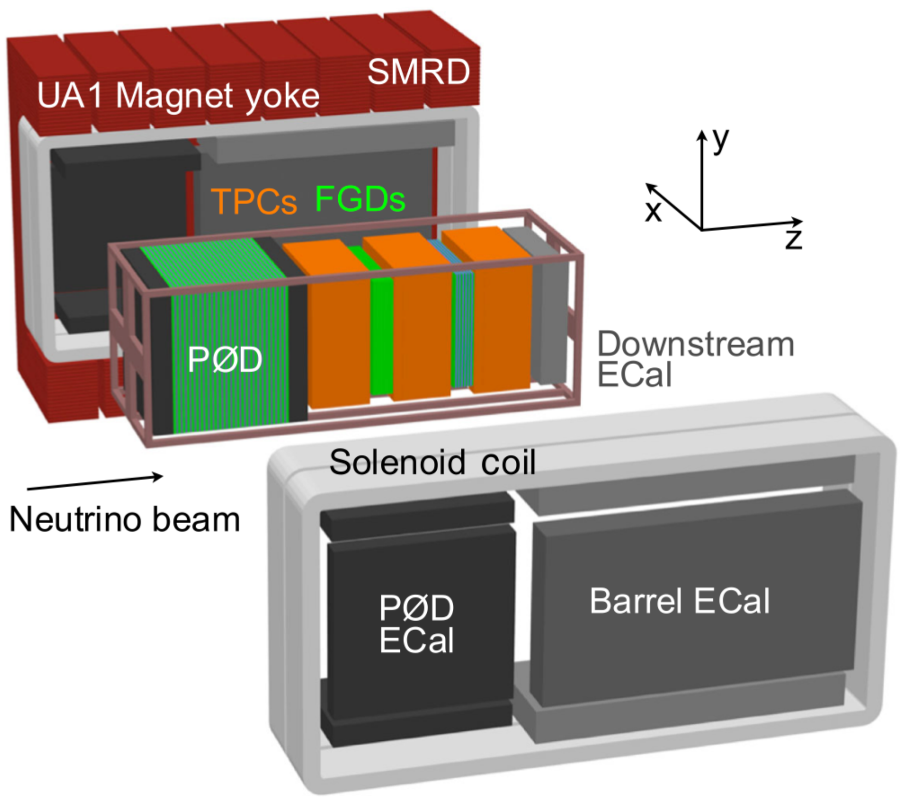
ν_μ – antineutrino mode run

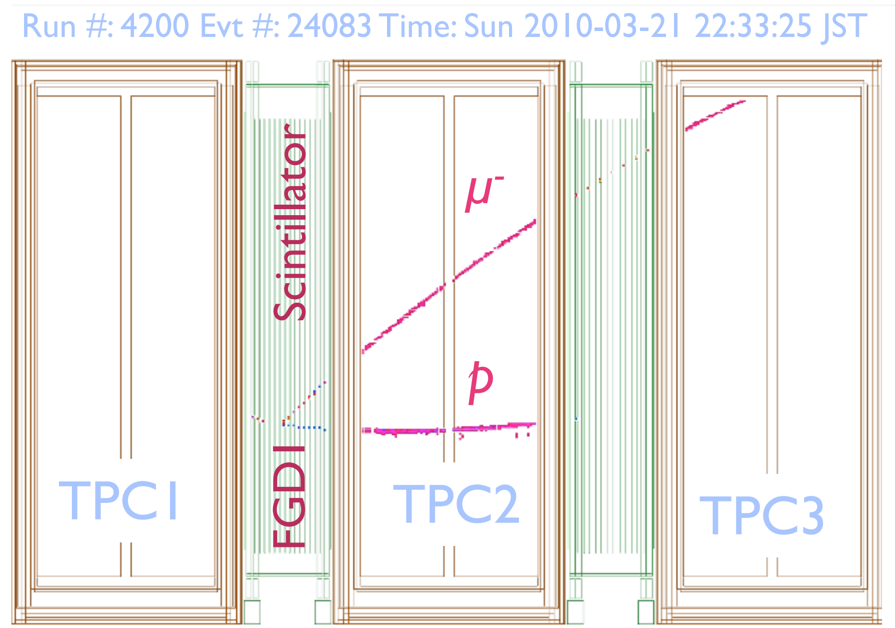




Low threshold allows model independent reconstruction of complete final state for detailed testing of models



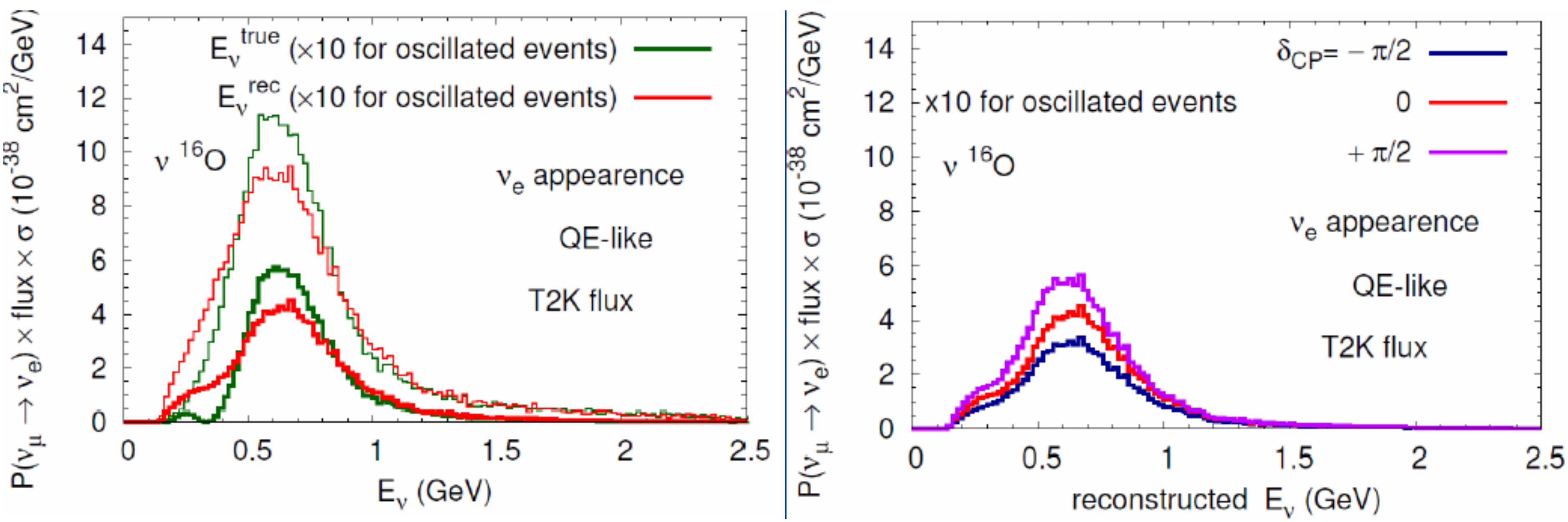


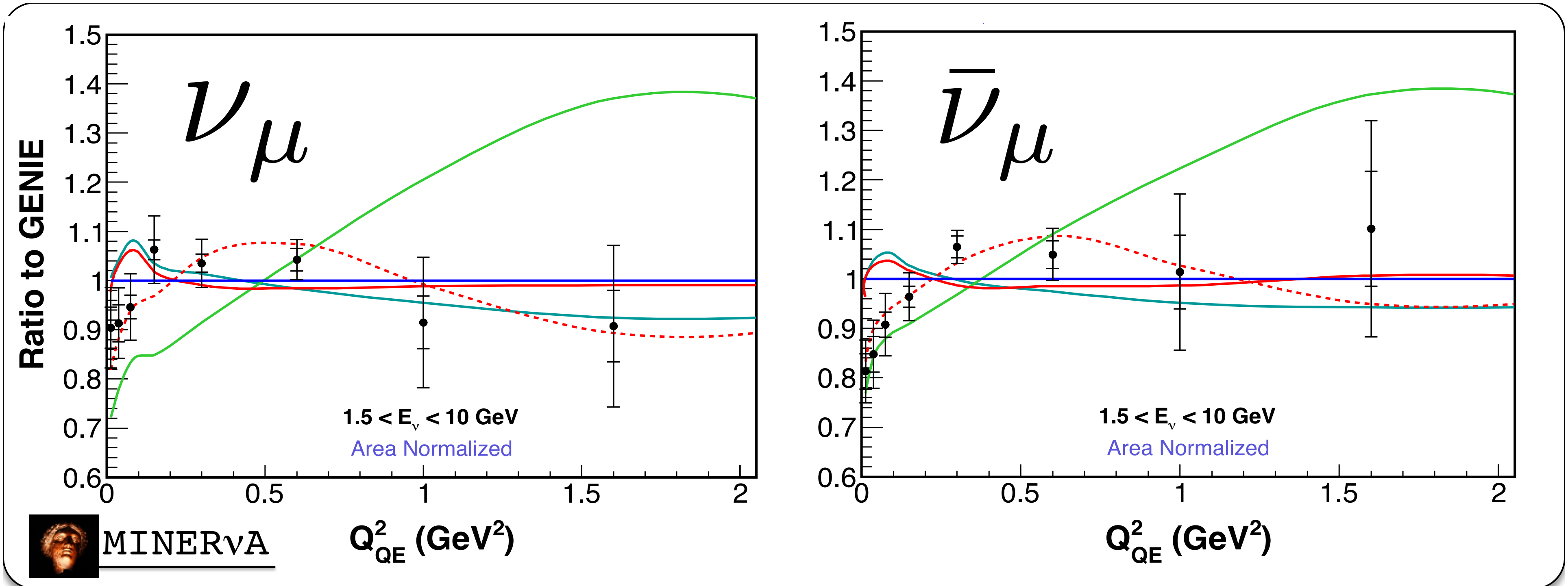


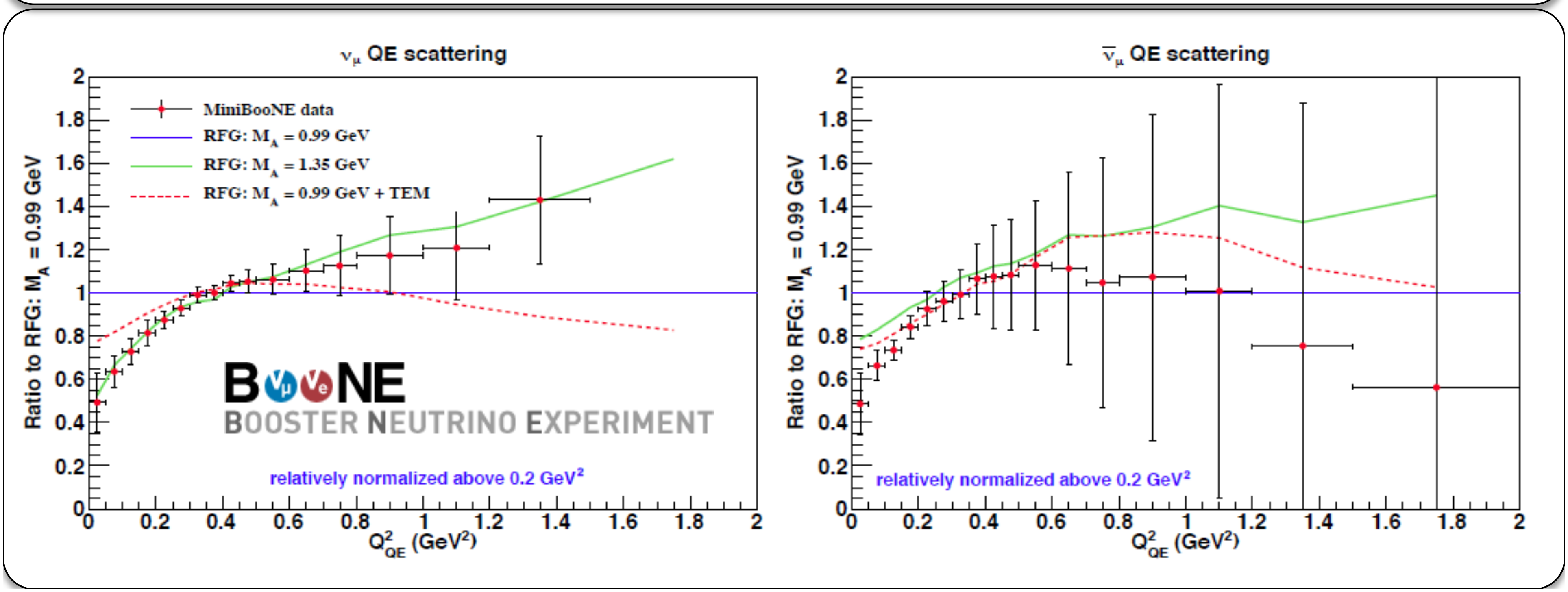
CCQE event candidate in the tracker region of the near detector. Muon reconstructed angle 40° and reconstructed momentum: 566 MeV/c

Nuclear Effects and Oscillation Measurements

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




Ratio to GENIE
ν_μ
$\bar{\nu}_\mu$
1.5 < E$_\nu$ < 10 GeV
Area Normalized
Q$^2_{QE}$ (GeV^2)
MINERvA


ν_μ QE scattering
$\bar{\nu}_\mu$ QE scattering
MiniBooNE data
RFG: M$_A$ = 0.99 GeV
RFG: M$_A$ = 1.35 GeV
RFG: M$_A$ = 0.99 GeV + TEM
Ratio to RFG: M$_A$ = 0.99 GeV
BooNE
BOOSTER NEUTRINO EXPERIMENT
relatively normalized above 0.2 GeV^2
Q$^2_{QE}$ (GeV^2)

Why is Neutrino Nucleus Scattering Important?

What do we observe in our detectors?

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

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

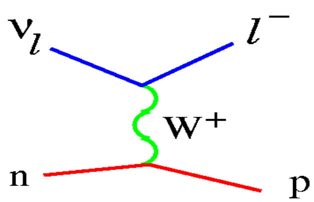
- $\phi(E)$ is the energy dependent neutrino flux that enters the detector. Currently, with traditional meson-decay-source neutrino beams, $\phi(E)$ ≈10% absolute and ≈ 7% energy bin-to-bin accuracy. **Significant contribution to systematics.**
- $\sigma_{c,d,e..}(E' \geq E)$ is the measured or the Monte 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!
- **$Y_{c\text{-like}}(E)$** 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.

Jorge G. Morfin - Fermilab

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

J. Sobczyk arXiv:1201.3673, - O. Lalakulich et al. arXiv:1208.3678, - J. Nieves et al. arXiv:1204:5404 – M. Martini et al. arXiv:1211.1523

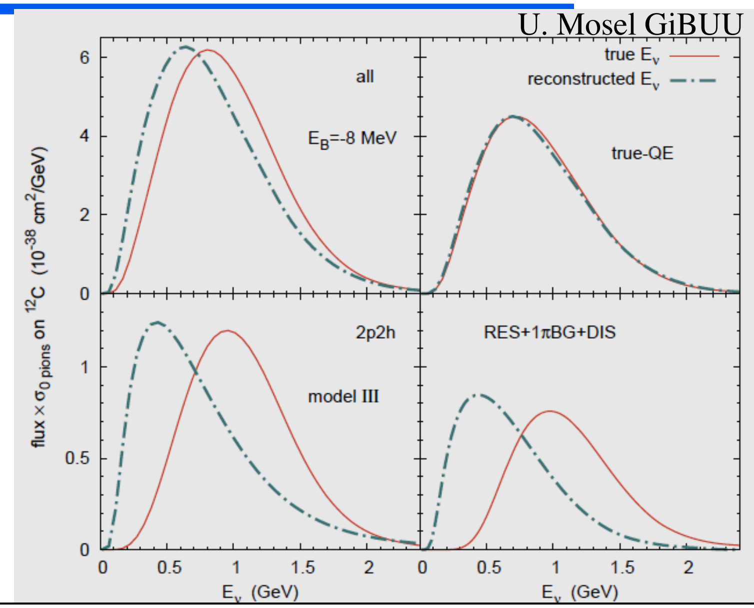
- In pure QE scattering on a nucleon at rest, the outgoing lepton can determine the neutrino energy:

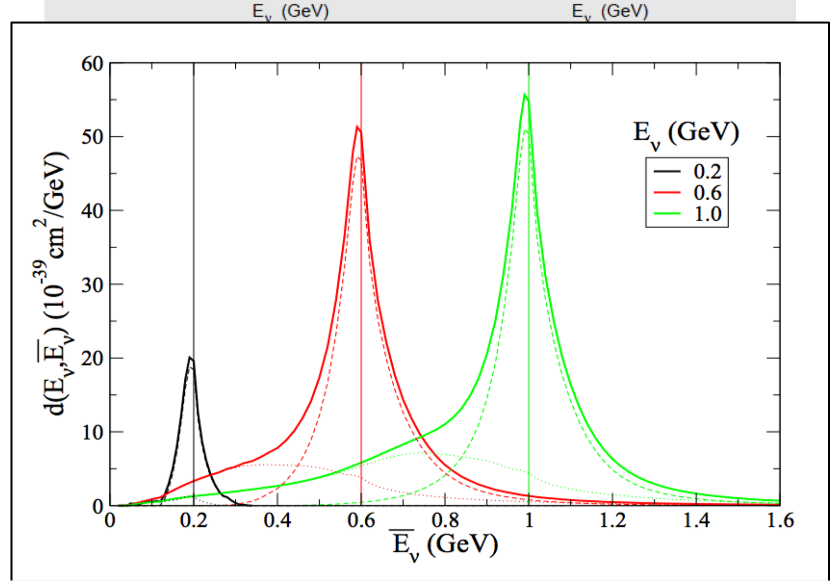


$$E_\nu = \frac{2 M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

However, not on nuclei.

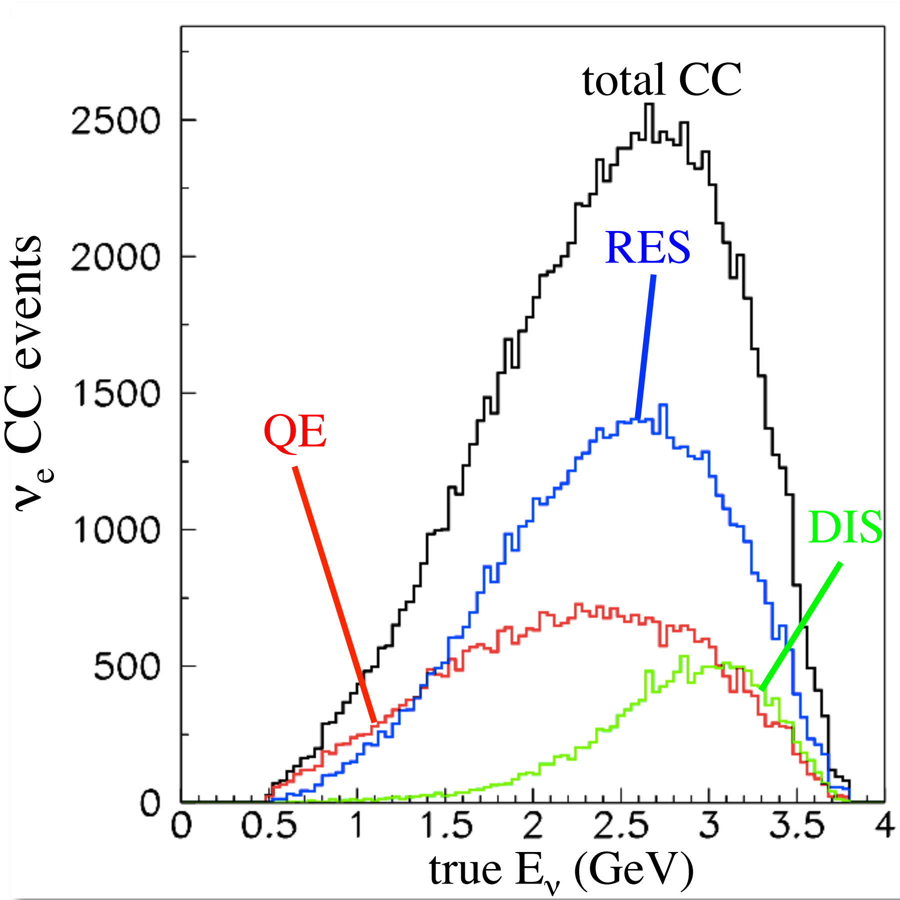
Reconstructed energy is shifted to lower values for all processes other than true QE off nucleon at rest





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