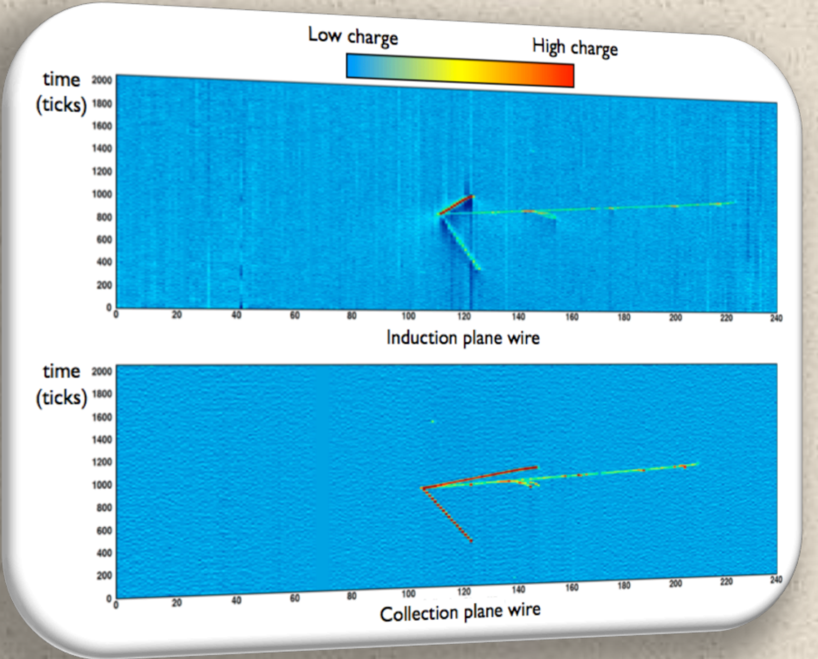
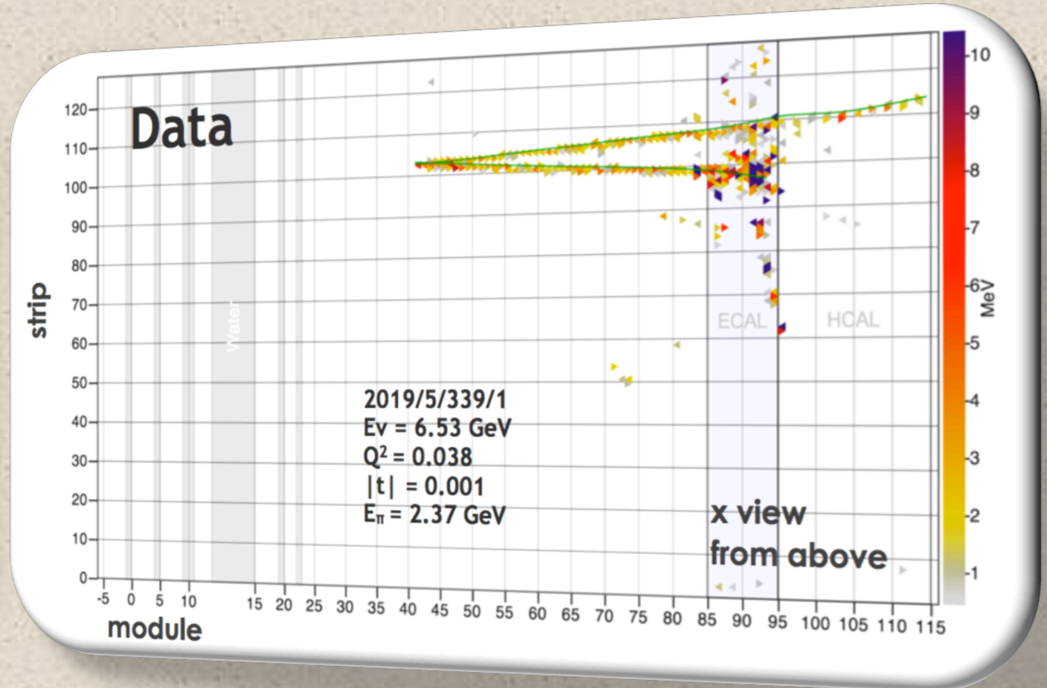
Experimental Overview of Neutrino-Nucleus Scattering





ν_μ CC candidate in ArgoNeuT

ν_μ CC candidate in MINERvA

NuFact 2013: International Workshop on Neutrino Factories, Super Beams and Beta Beams

23 August 2013, IHEP, Beijing, China

David Schmitz, University of Chicago

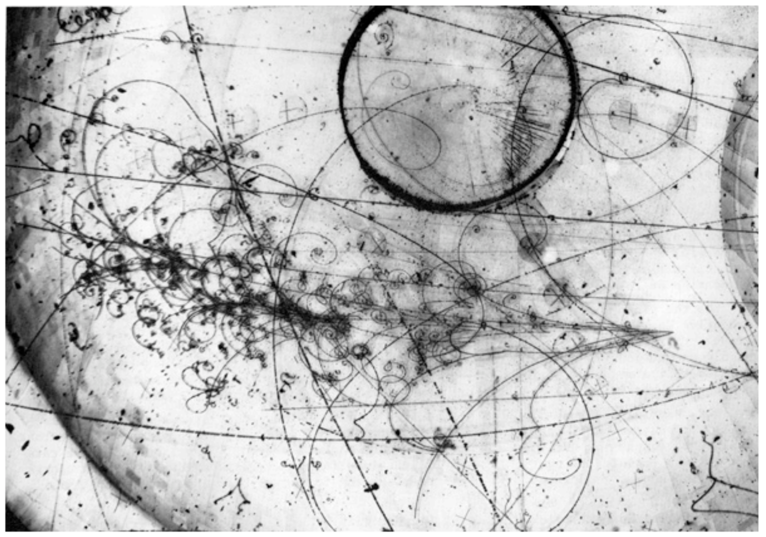
Outline

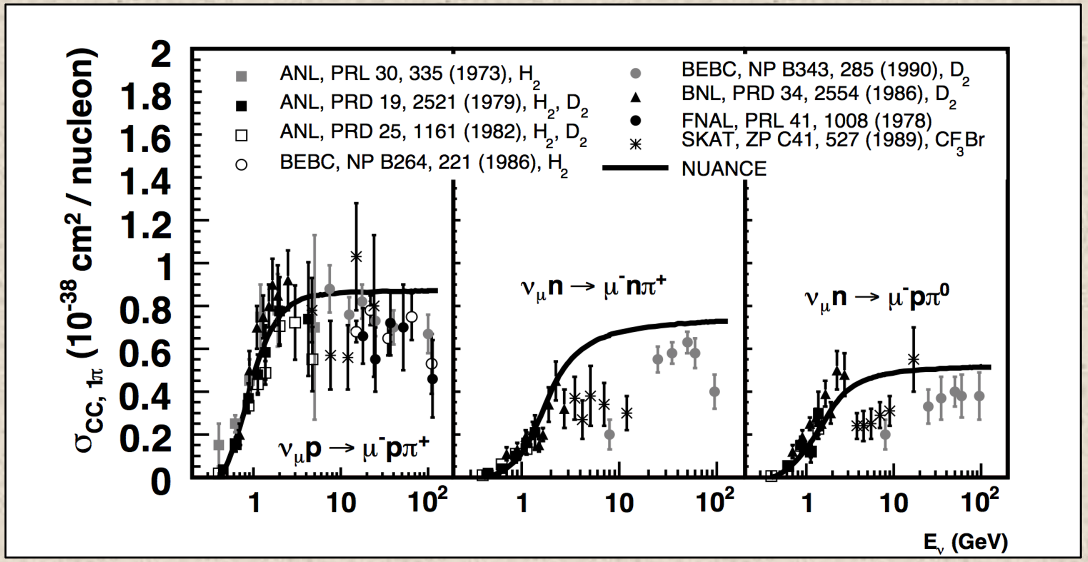
- Why do we need to measure neutrino-nucleus scattering?
- Recent measurements from:
  - MiniBooNE
  - MINERvA
  - ArgoNeuT
  - T2K
- Future possibilities

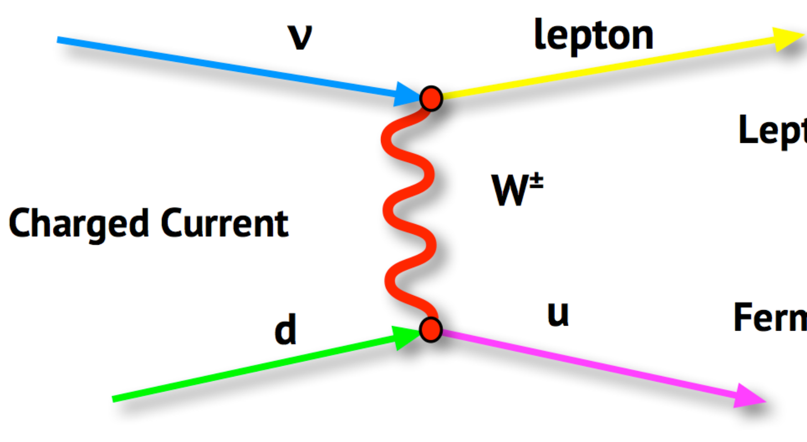
First, a Question

Physicists have been scattering neutrinos off nuclei and studying what happens for decades

Why are we still doing this!?!

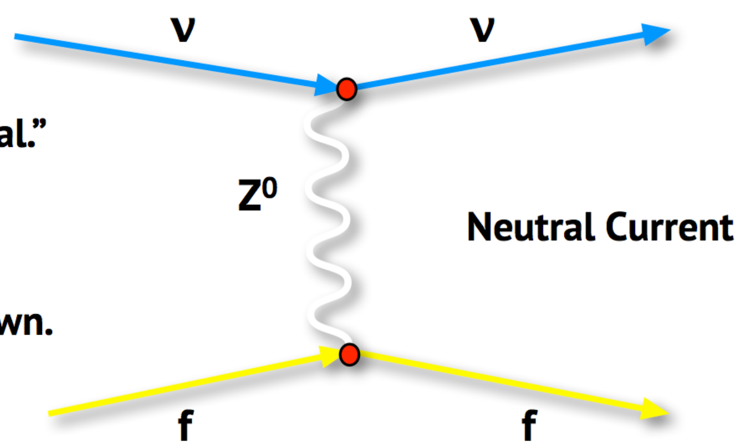


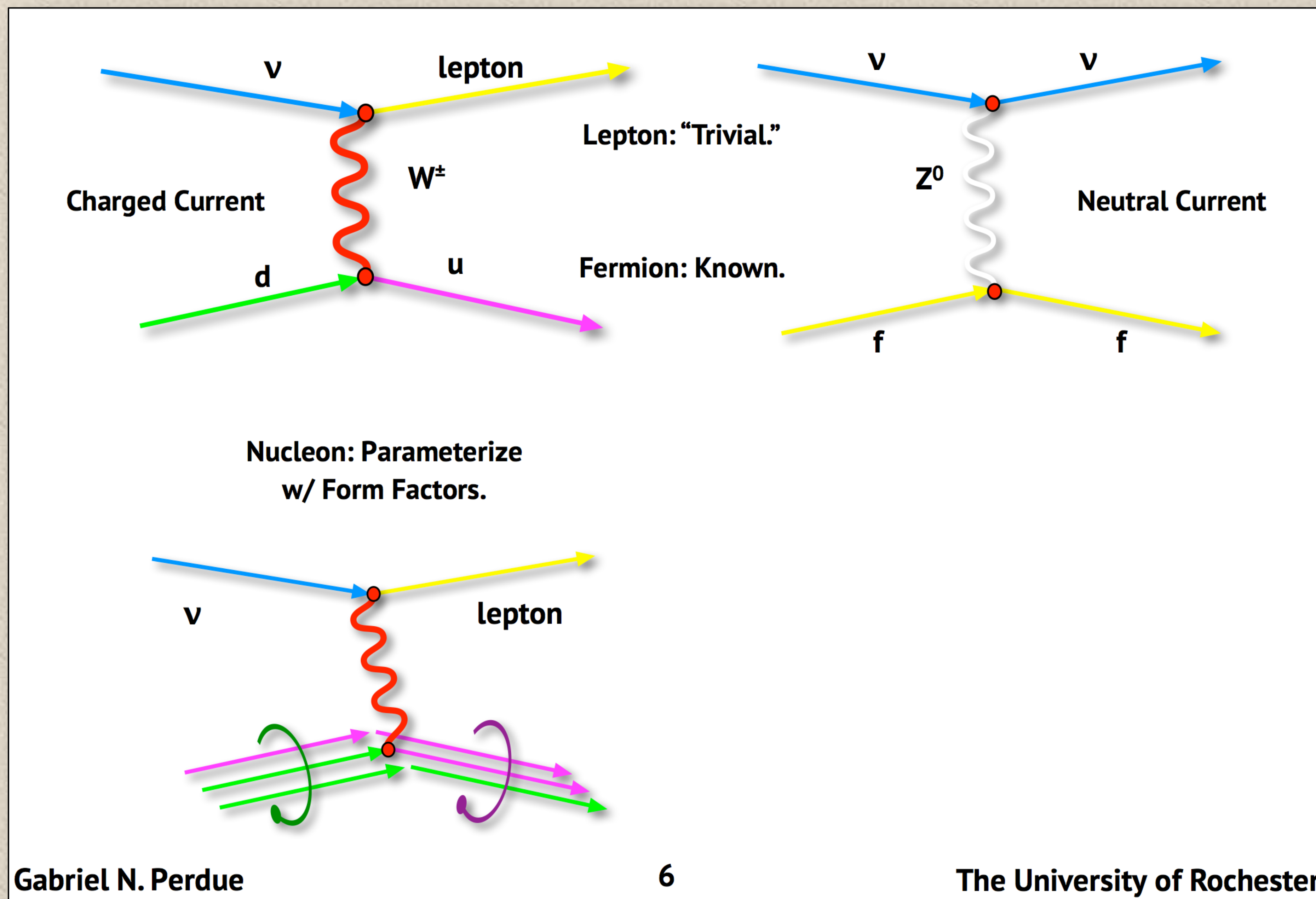


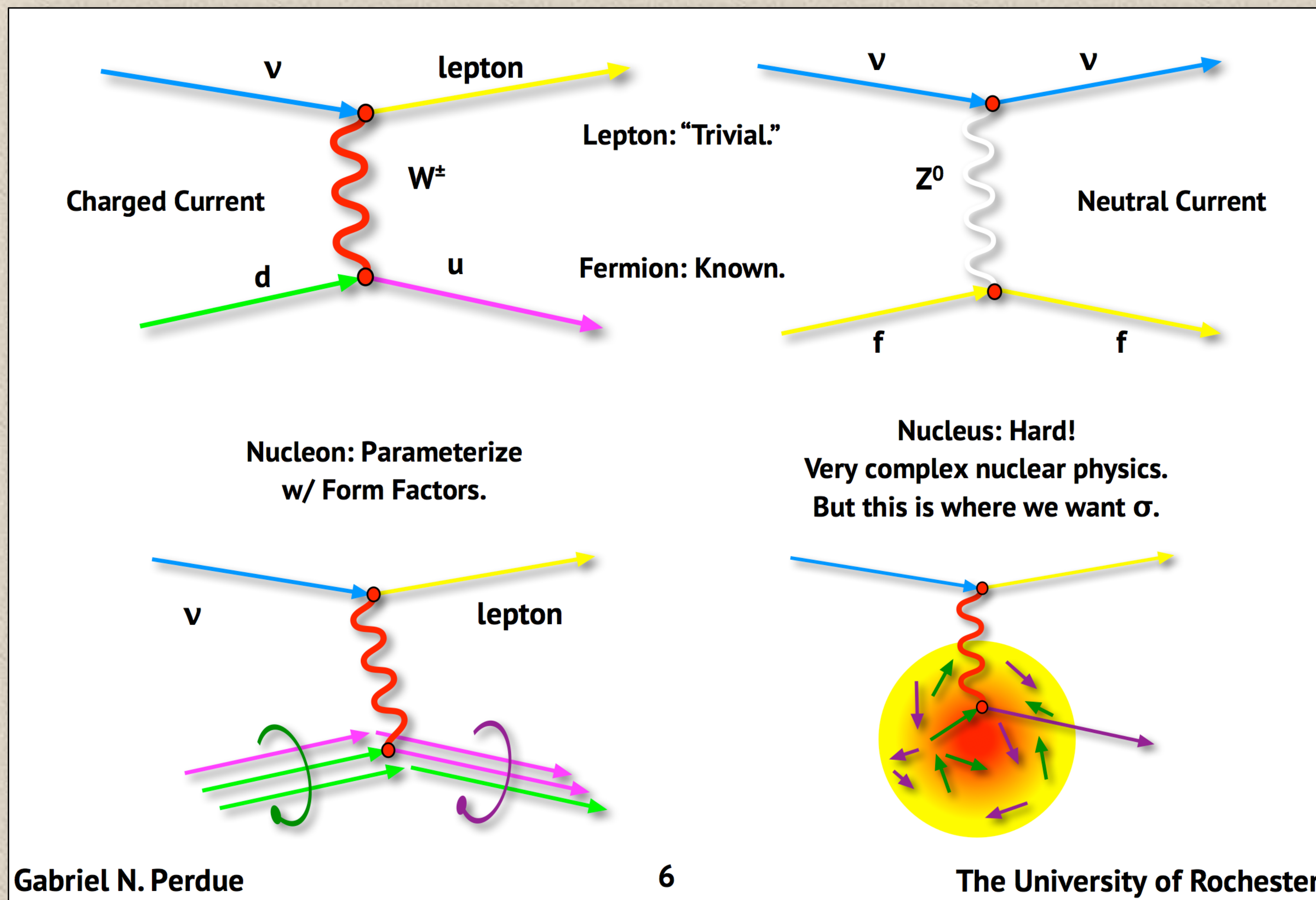


Lepton: "Trivial."

Fermion: Known.




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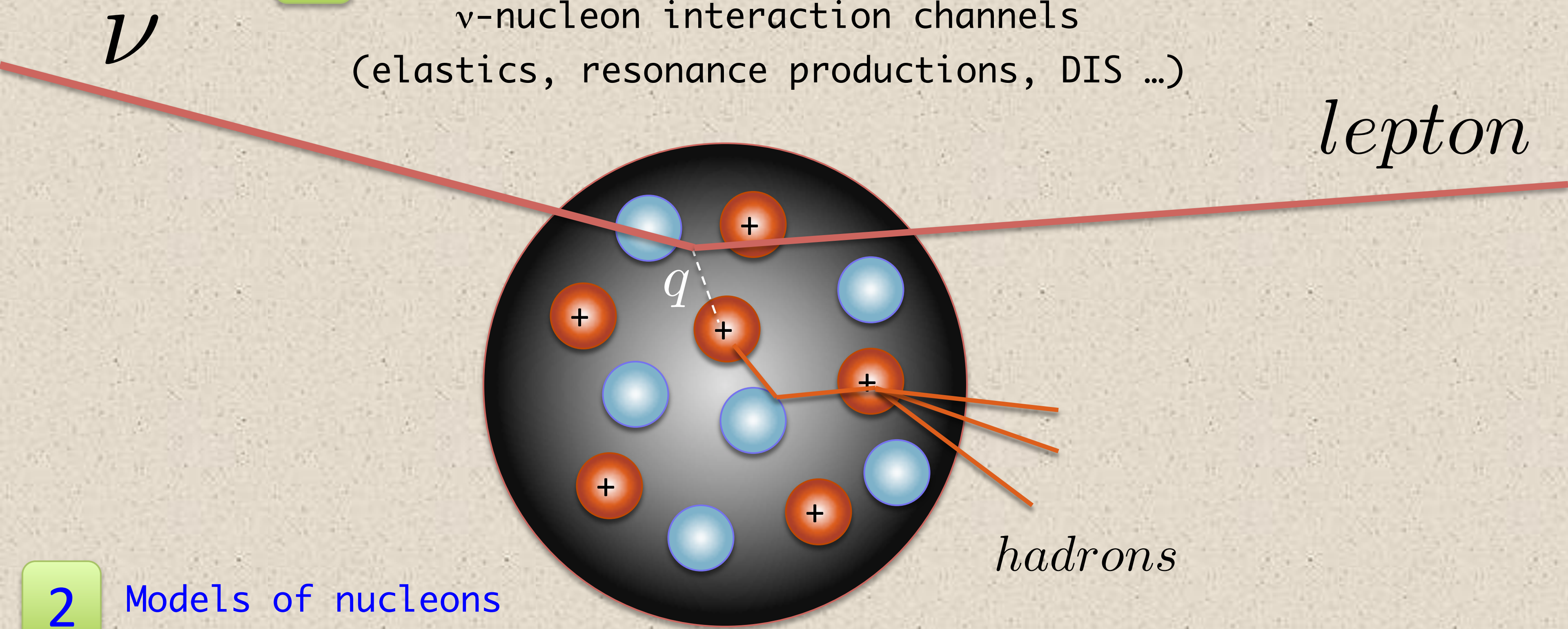
Neutral Current
f
f
Nucleon: Parameterize
w/ Form Factors.
Nucleus: Hard!
Very complex nuclear physics.
But this is where we want σ.
ν
lepton
Gabriel N. Perdue
6
The University of Rochester

Physics of GeV ν-N Interactions

1 Cross section models for all exclusive ν-nucleon interaction channels (elastics, resonance productions, DIS …)



2 Models of nucleons within the nucleus (Relativist Fermi Gas, spectral functions, nucleon correlations, …)

3 Final state interaction models which alter the hadronic final state (rescattering, absorption, charge exchange, …)

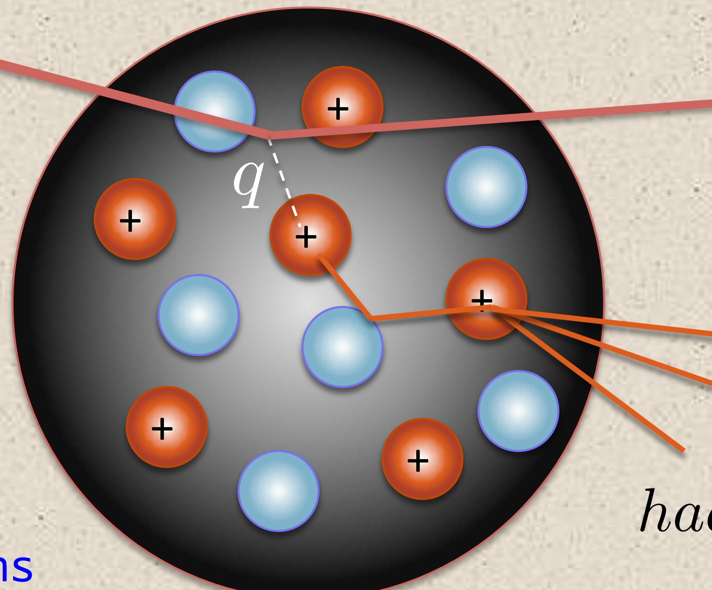
Physics of GeV ν-N Interactions

1 Cross section models for all exclusive ν-nucleon interaction channels (elastics, resonance productions, DIS …)

ν

lepton

E_{ν}^{true}



$E_{visible}$

hadrons

2 Models of nucleons within the nucleus (Relativist Fermi Gas, spectral functions, nucleon correlations, …)

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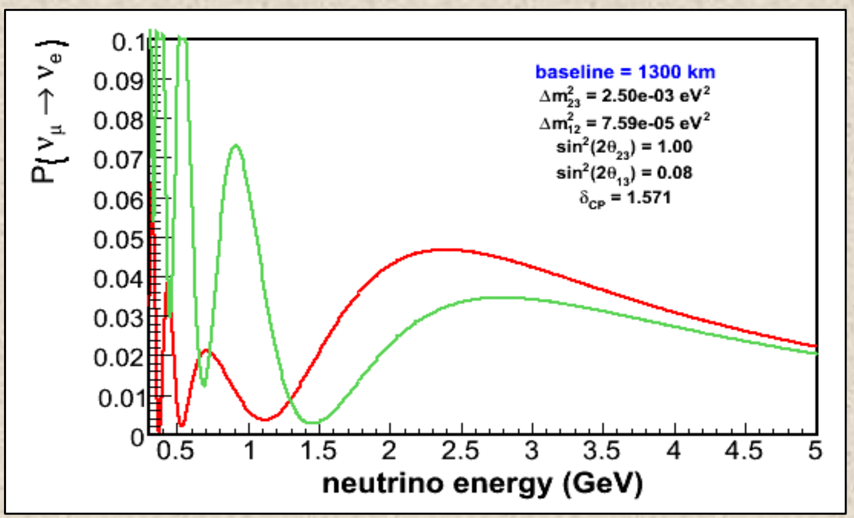
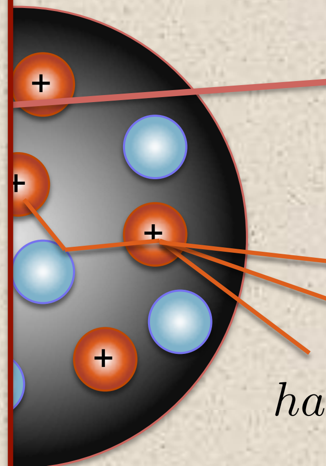
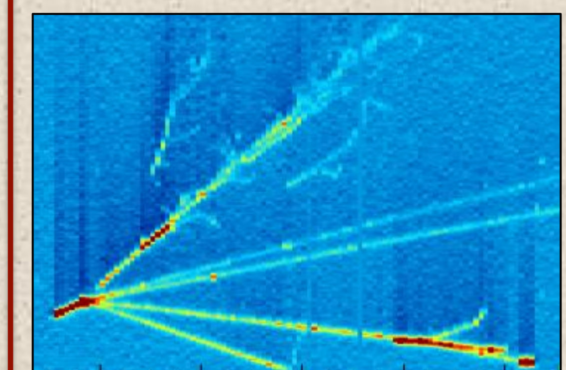
Physics of GeV ν-N Interactions

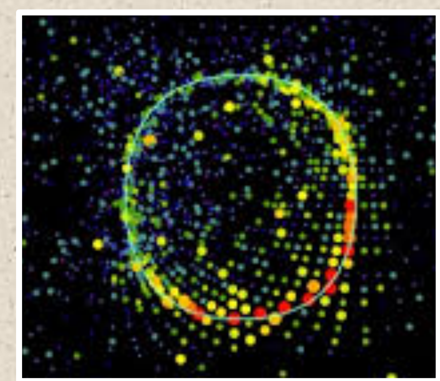
$$E_\nu^{true}$$





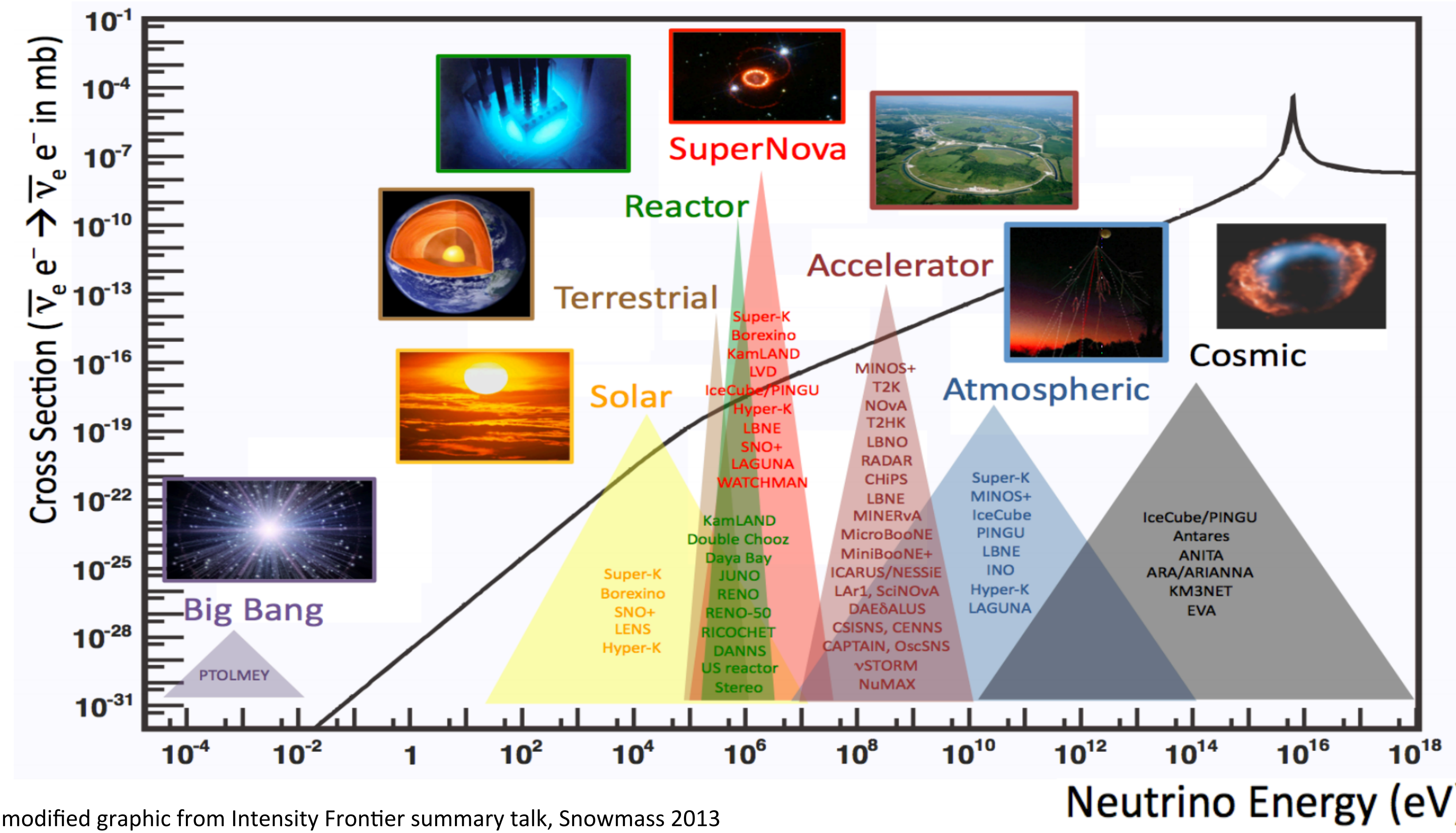
$$E_{visible}$$





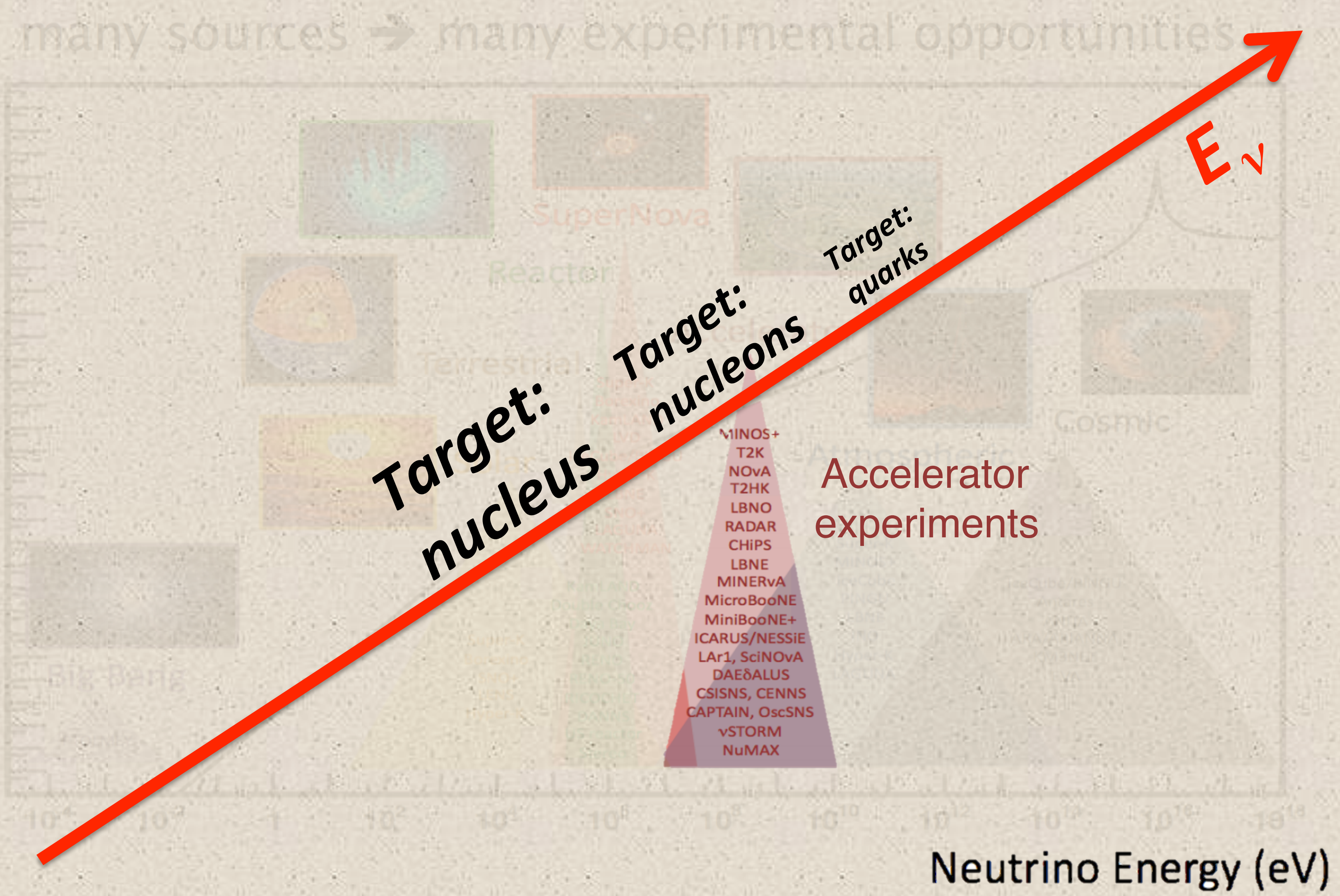
Neutrino Sources

many sources → many experimental opportunities

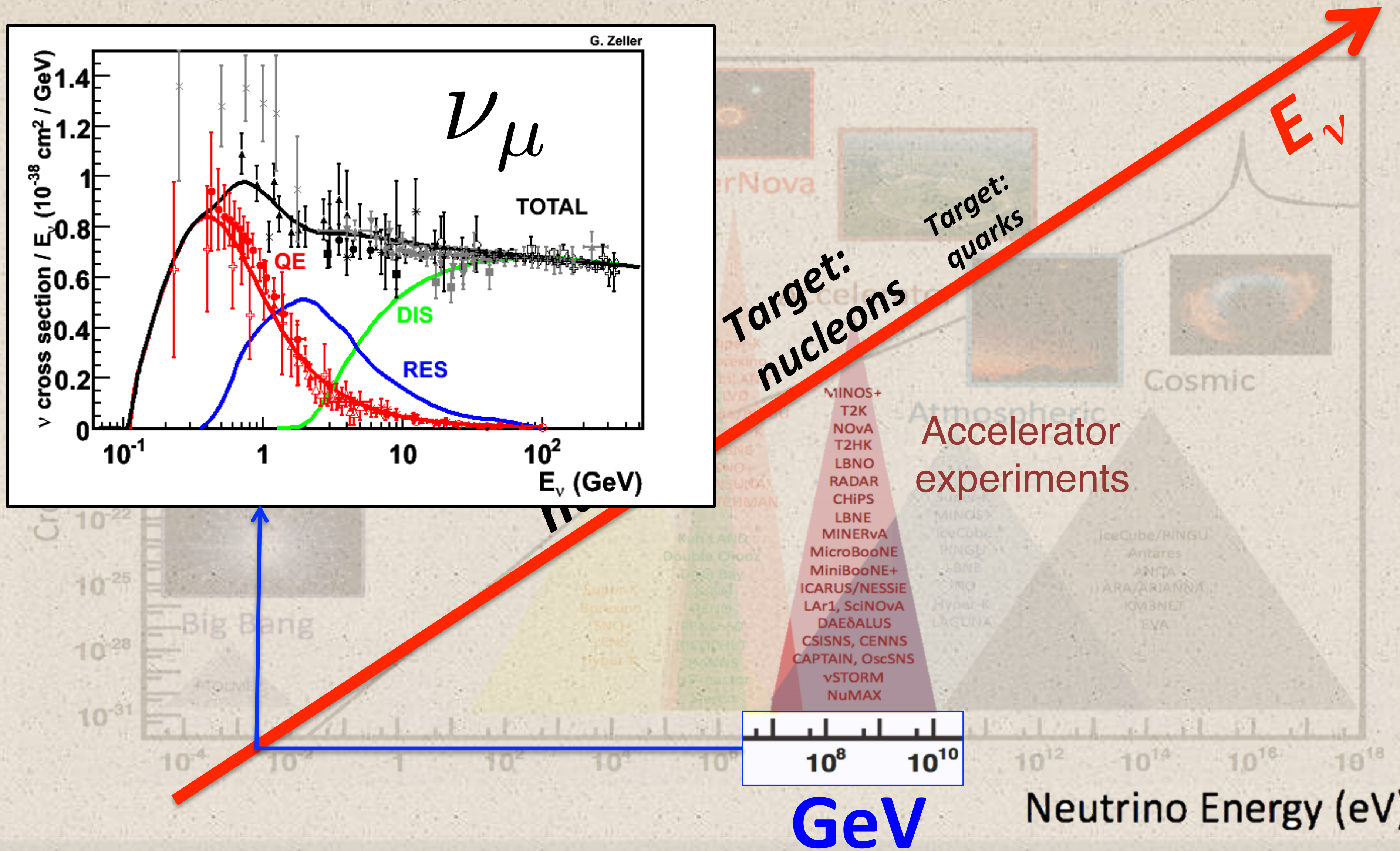


modified graphic from Intensity Frontier summary talk, Snowmass 2013
original from J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84, 1307-1341, 2012

Neutrino Targets



QE — charged-current quasi-elastic: $\nu n \to \ell^- p \quad \bar{\nu} p \to \ell^+ n$
RES — excite a nucleon resonance, decays to pions & nucleons
DIS — scatter off quarks instead of nucleon, high multiplicity



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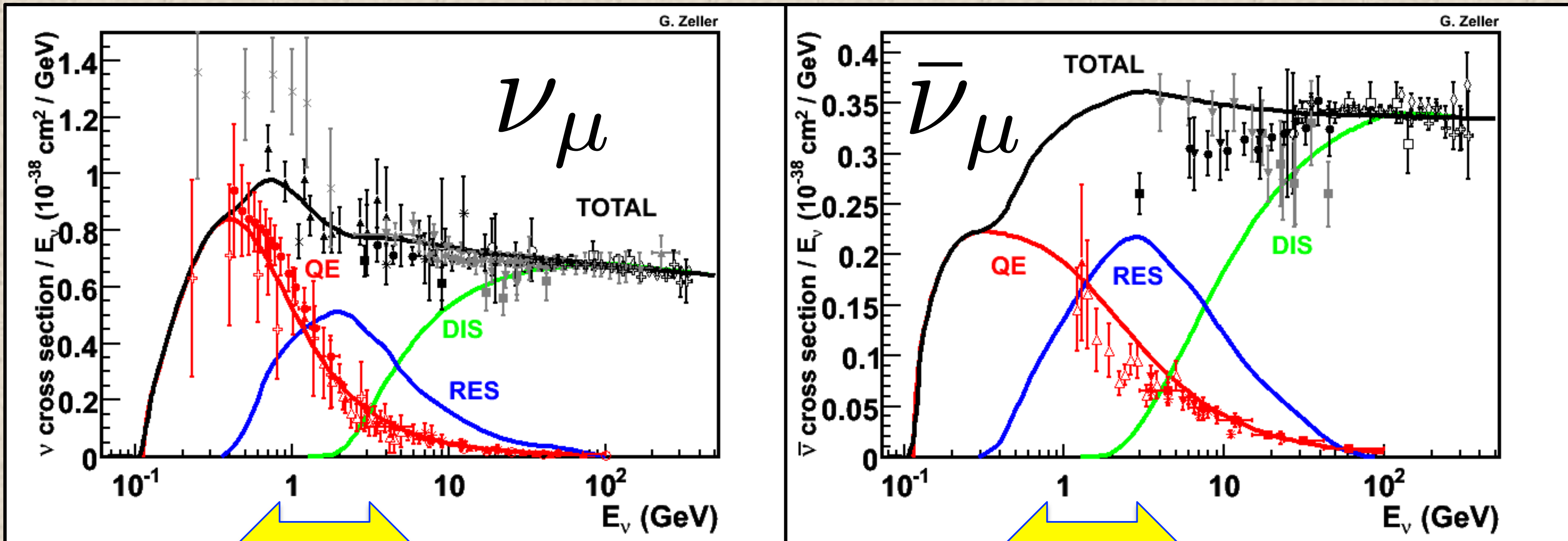
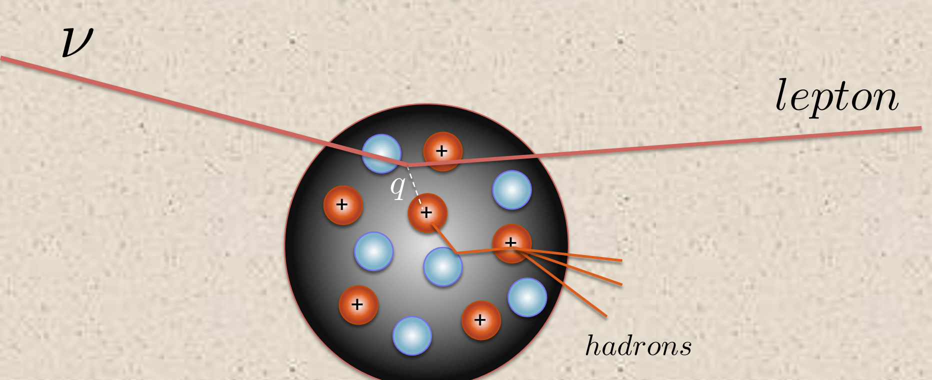




Accelerator-based experiments carried out in a sweet spot of maximally complicated nuclear effects in neutrino interactions!

For more quantitative look at impact, see Pilar Coloma's talk later in this session

In Summary: Nuclear Physics Meets Neutrino Physics

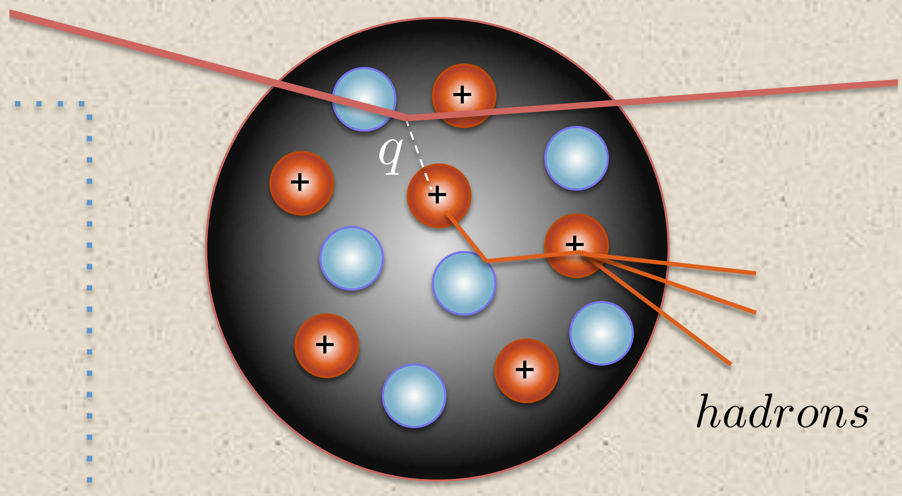
In Summary: Nuclear Physics Meets Neutrino Physics

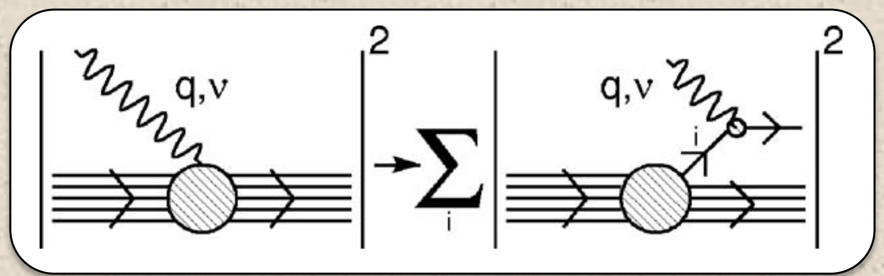
The results I will highlight today are steps toward understanding how the nuclear environment alters the models of neutrino scattering we have been using for decades.

CC inclusive, CC quasi-elastic, studies of final state nucleons

Relativistic Fermi Gas For Nucleus

- Nuclear model in neutrino scattering event generators same since 1970s
- In the *Impulse Approximation*, scatter off <u>independent</u> single nucleons incoherently summed over all nucleons in the nucleus





NEUTRINO REACTIONS ON NUCLEAR TARGETS ‡

R. A. SMITH ‡‡ and E. J. MONIZ ‡‡‡

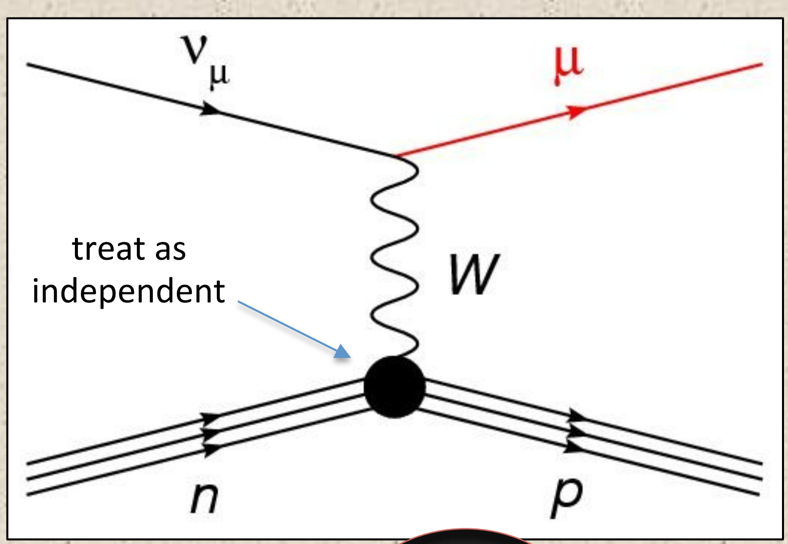
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305

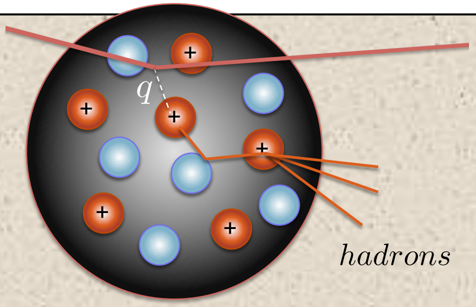
with energies lowered from free particle energies by an average nuclear potential. Although this choice of wave functions corresponds to a nucleus without detailed structure, the dominant features of the nuclear cross section are consistently represented.

Smith, R. A., and E. J. Moniz, 1972, Nucl. Phys. B43, 605.

Relativistic Fermi Gas For Nucleus

- For quasi-elastic scattering, 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 blind to the hadronic final state





neutrino energy

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

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

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

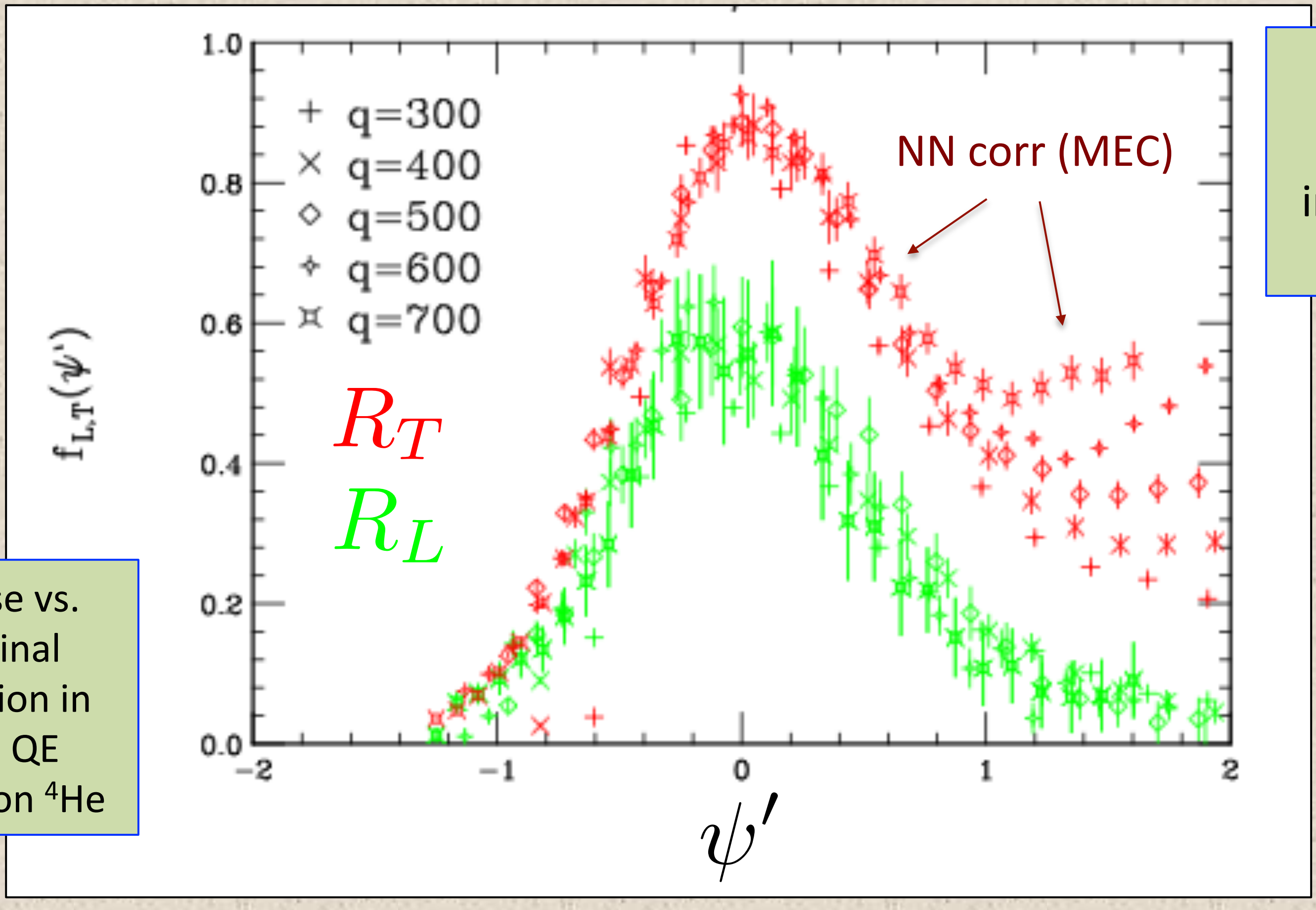
But Is It Good Enough?

- Both theory and experimental hints tell us that it is not
- Nucleon-nucleon interactions and 2-body currents are ignored
  - RPA effects ('nucleus as a whole') expected to suppress rate at low Q^2
  - NN correlations such as ***meson exchange currents (MEC)*** which may enhance part of the cross section significantly
    - Correlated nucleon(s) may be ejected when partner is scattered by a probe
    - This change on the hadronic side of the interaction impacts the kinematics and spoils your neutrino energy estimation
  - For A ≥ 12 ***short range correlations (SRC)*** affect ~20% of nucleons
    - These can lead to nucleon momentum well above the Fermi sea cutoff
    - Again, multi-nucleon emission and impacted energy reconstruction are consequences

See Jan Sobczyk's theory summary coming up next

Transverse and Longitudinal Strength

- Impact of correlations seen in *electron scattering* data



$R_L = R_T$ for RFG of independent nucleons!

Transverse vs. longitudinal cross-section in electron QE scattering on ^{4}He

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

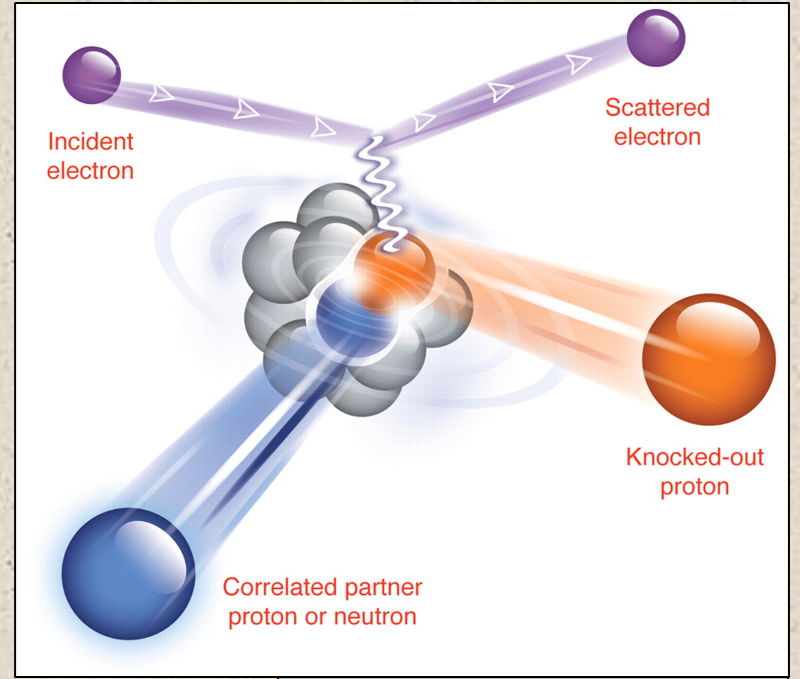
$$\psi' = \frac{\sqrt{\omega^2 + 2M\omega} - q}{k_F}$$

ω = energy transfer to nucleus

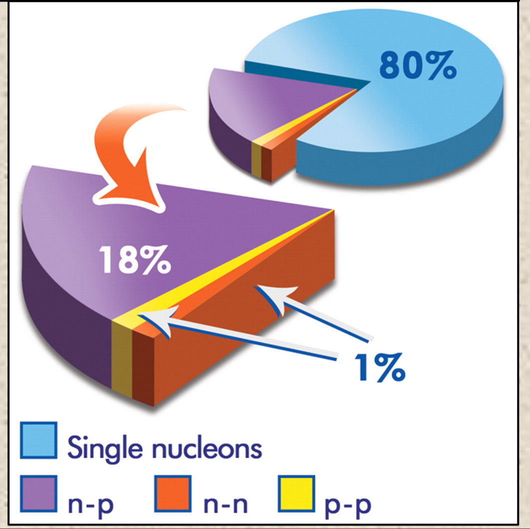
q = 3-momentum transfer to nucleus

Short Range NN Correlations

- Electron scattering
  - Measurements on ^{12}C indicate 20% correlated nucleons with mostly **np** pairs in the initial state
- Neutrino scattering
  - Implies final states in neutrino scattering of **nn in antineutrino** and **pp in neutrino** CC scattering
  - For other forms of correlation, final state depends on model
  - Of course, strongly coupled to Final State Interactions when interpreting neutrino scattering data



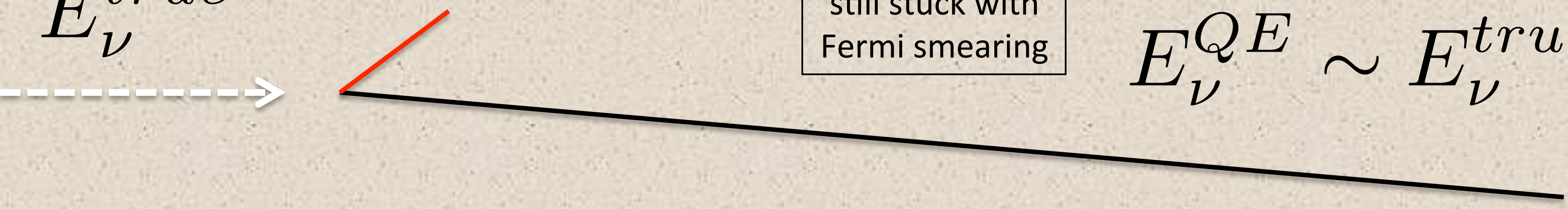
R. Subedi et al., Science 320, 1476 (2008)



Kinematic

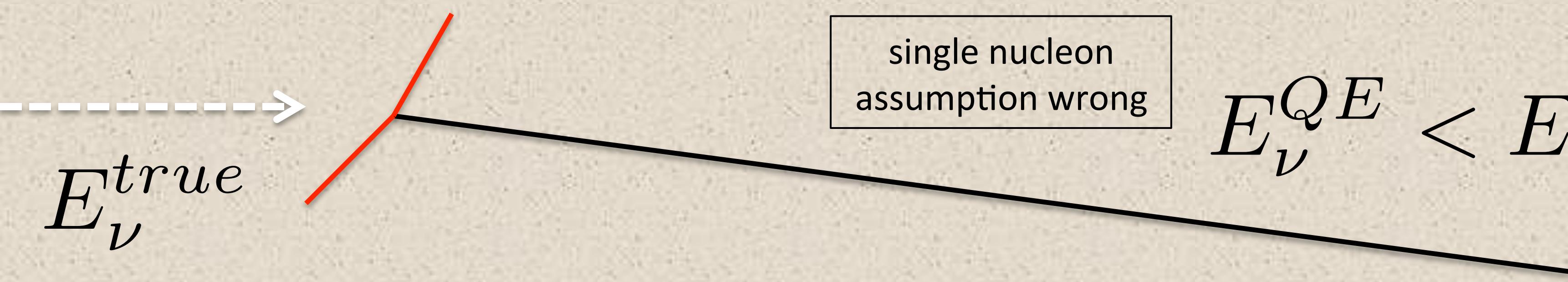
$$E_\nu^{QE} = \frac{2\,(M_n - E_B)\,E_\ell - \left[(M_n - E_B)^2 + m_\ell^2 - M_p^2\right]}{2\,[M_n - E_B - E_\ell + p_\ell \cos(\theta_\ell)]}$$

E_ν^{true}



still stuck with Fermi smearing

$$E_\nu^{QE} \sim E_\nu^{true}$$



E_ν^{true}

single nucleon assumption wrong

$$E_\nu^{QE} < E_\nu^{true}$$

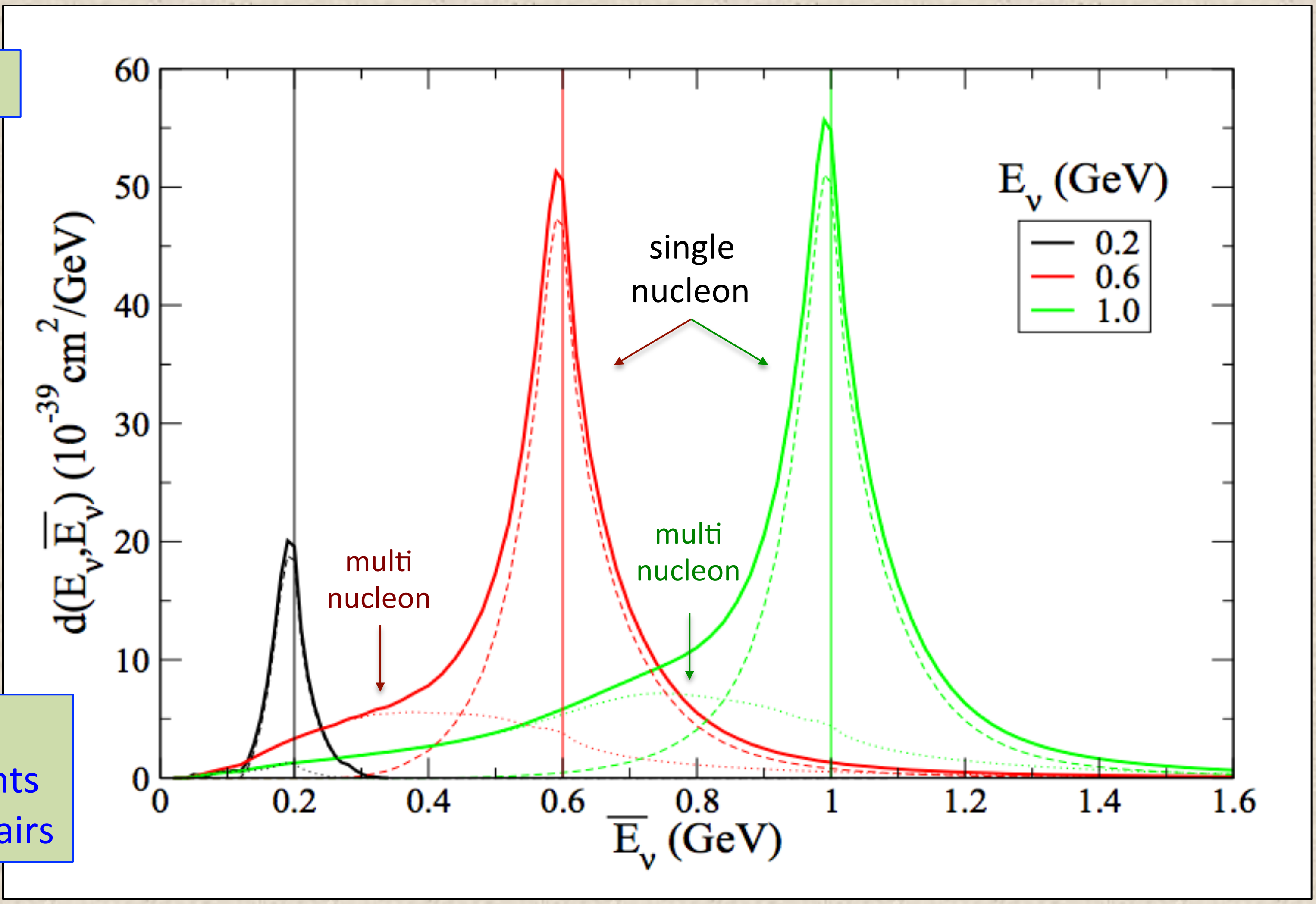
Calorimetric

$$E_\mu + E_{visible}^{had} \leq E_\nu^{true}$$

invisible component

Impact For Neutrino Experiments

Kinematic



Recall, up to
20-30% of events
off correlated pairs

Martini et al. arXiv:1211.1523

Also: J. Sobczyk arXiv:1201.3673,
Lalakulich et al. arXiv:1208.3678,
Nieves et al. arXiv:1204:5404

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

New Results in 2013

- **MiniBooNE:** antineutrino charged-current quasi-elastic differential cross sections on carbon

  PRD 88, 032001 (2013)

- **MINERvA:** neutrino and antineutrino charged-current quasi-elastic $d\sigma/dQ^2$ on carbon

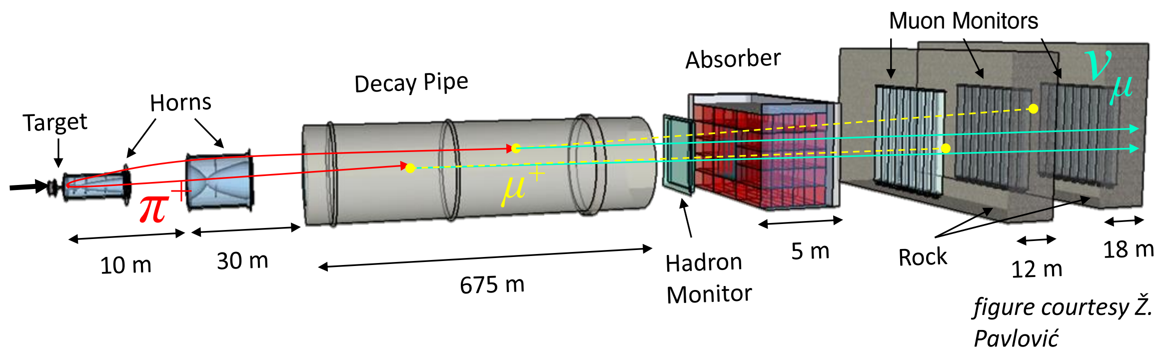
  PRL 111, 022501 (2013)
  PRL 111, 022502 (2013)

- **ArgoNeuT:** detailed studies of proton multiplicities in charged-current interactions on argon

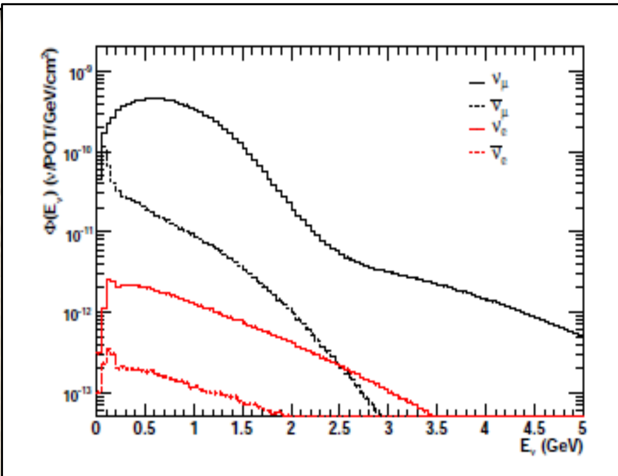
  PRL 108, 161802 (2012)
  + preliminary proton data

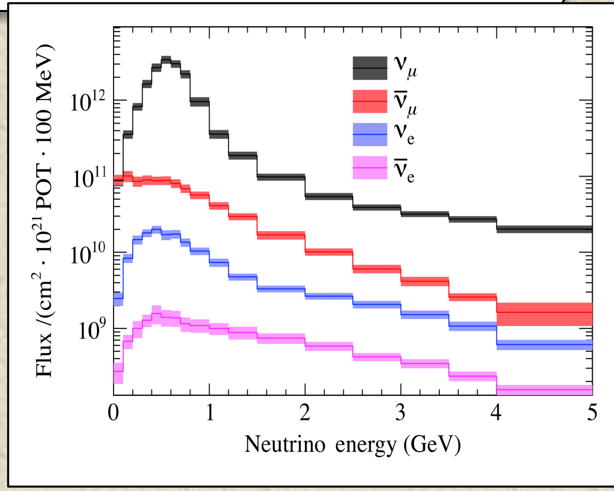
- **T2K ND280:** neutrino charged-current inclusive differential cross sections on carbon

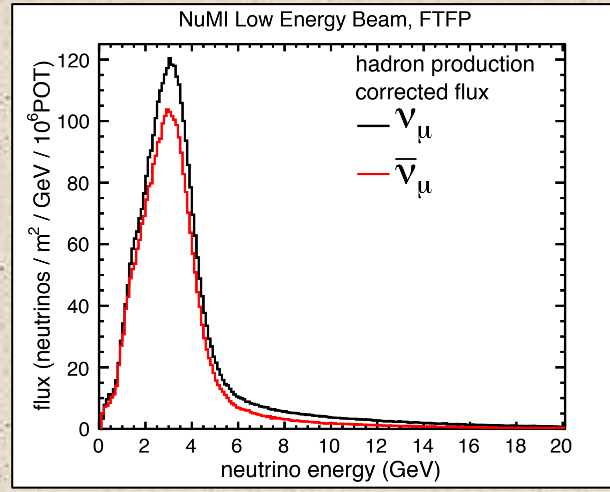
  PRD 87, 092003 (2013)



Flux predictions a tough problem for all super beam facilities. Heroic progress, really.

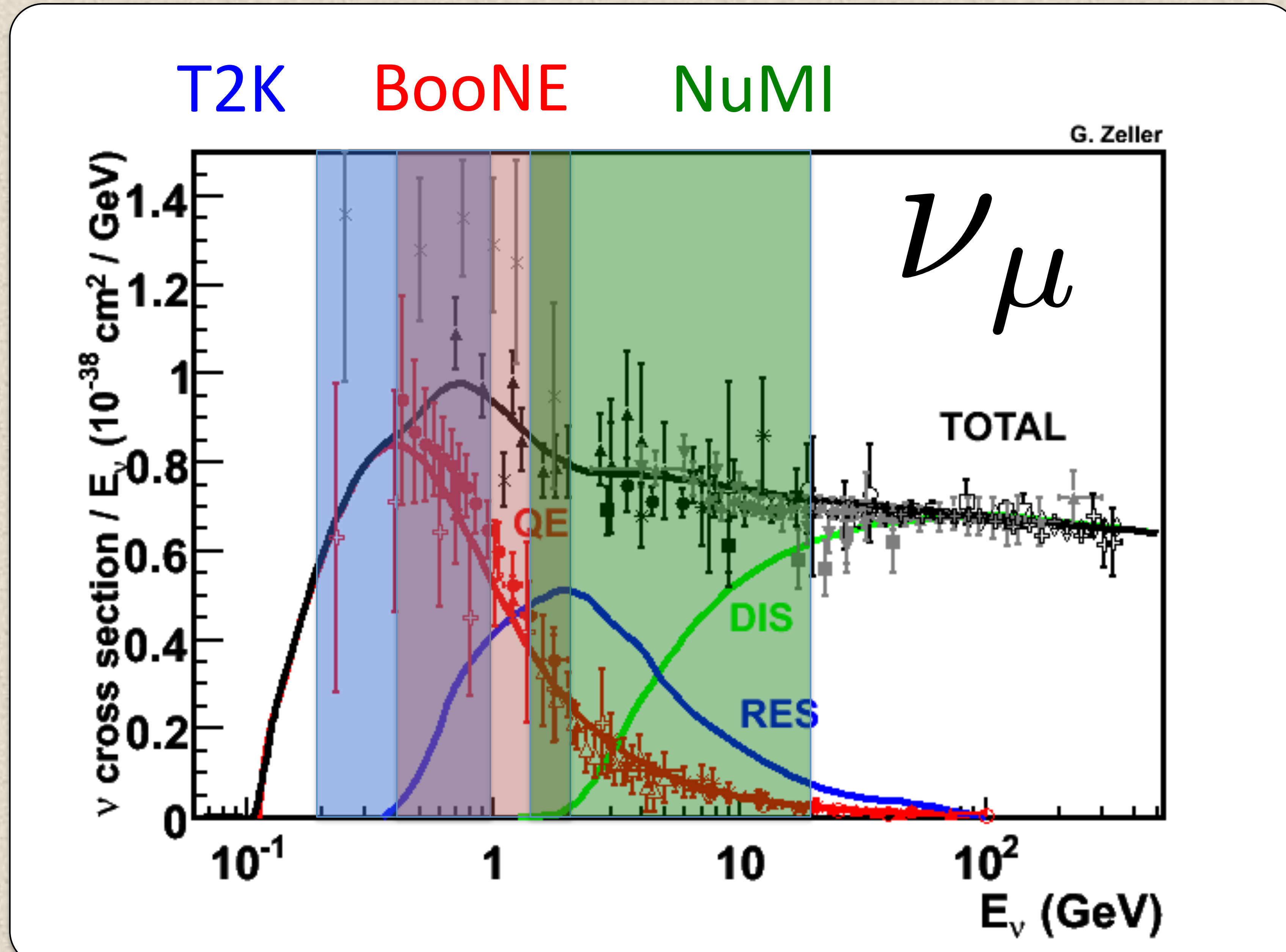






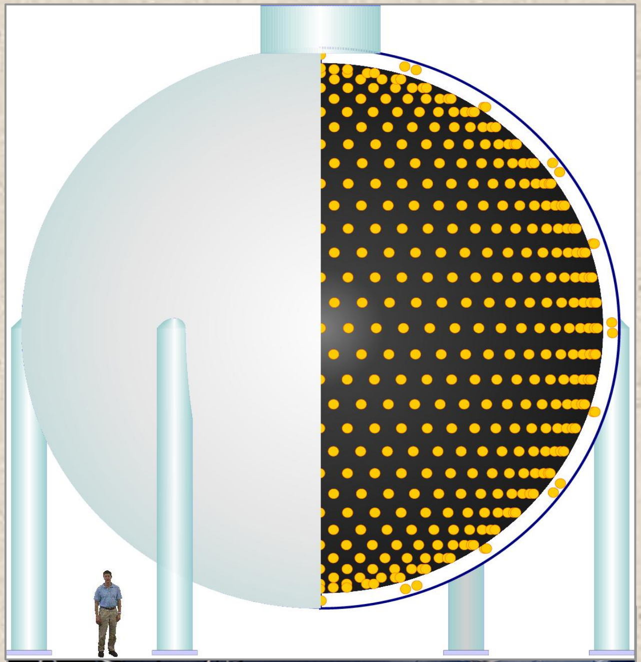
BooNE	T2K	NuMI
8 GeV p+beryllium	30 GeV p+carbon	120 GeV p+carbon
HARP π prod.	NA61 π/K/p prod.	NA49 158 GeV p prod.
2nd interactions < 10%	2nd interactions ~ 35%	2nd interaction > 40%
		configurable beamline
≥ 9% uncertainty	**10-15% uncertainty**	**10-15% uncertainty**

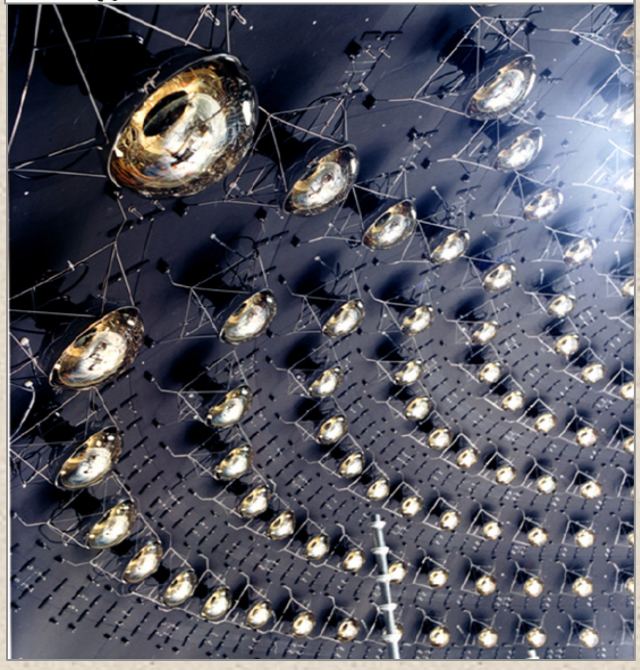
See WG2 talks from A. Korzenev (NA61), J. Paley (MIPP)


T2K
BooNE
NuMI
G. Zeller
ν_μ
ν cross section / E$_\nu$ (10^{-38} cm^2 / GeV)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
TOTAL
QE
DIS
RES
10^{-1}
1
10
10^2
E$_\nu$ (GeV)

BooNE BOOSTER NEUTRINO EXPERIMENT

- CH_2 target
- 4π detector, complete angular coverage
- Good lepton reconstruction & pion rejection
- Essentially blind to details of the nucleon final state in CC events





BooNE
BOOSTER NEUTRINO EXPERIMENT

- MiniBooNE has been a prolific producer of neutrino-carbon cross section measurements in the ≤1 GeV region
  - CCQE MA – PRL 100, 032301 (2008)
  - NC π^0 – PL B664, 41 (2008)
  - CC π^+/QE – PRL 103, 081801 (2009)
  - NC π^0 – PRD 81, 013005 (2010)
  - QE – PRD 81, 092005 (2010)
  - NC elastic – PRD 82, 092005 (2010)
  - CC π^0 – PRD 83, 052009 (2011)
  - CC π^+ – PRD 83, 052007 (2011)
  - **Antineutrino QE – PRD 88, 032001 (2013)**
  - **CC inclusive and antineutrino NC elastic coming soon**

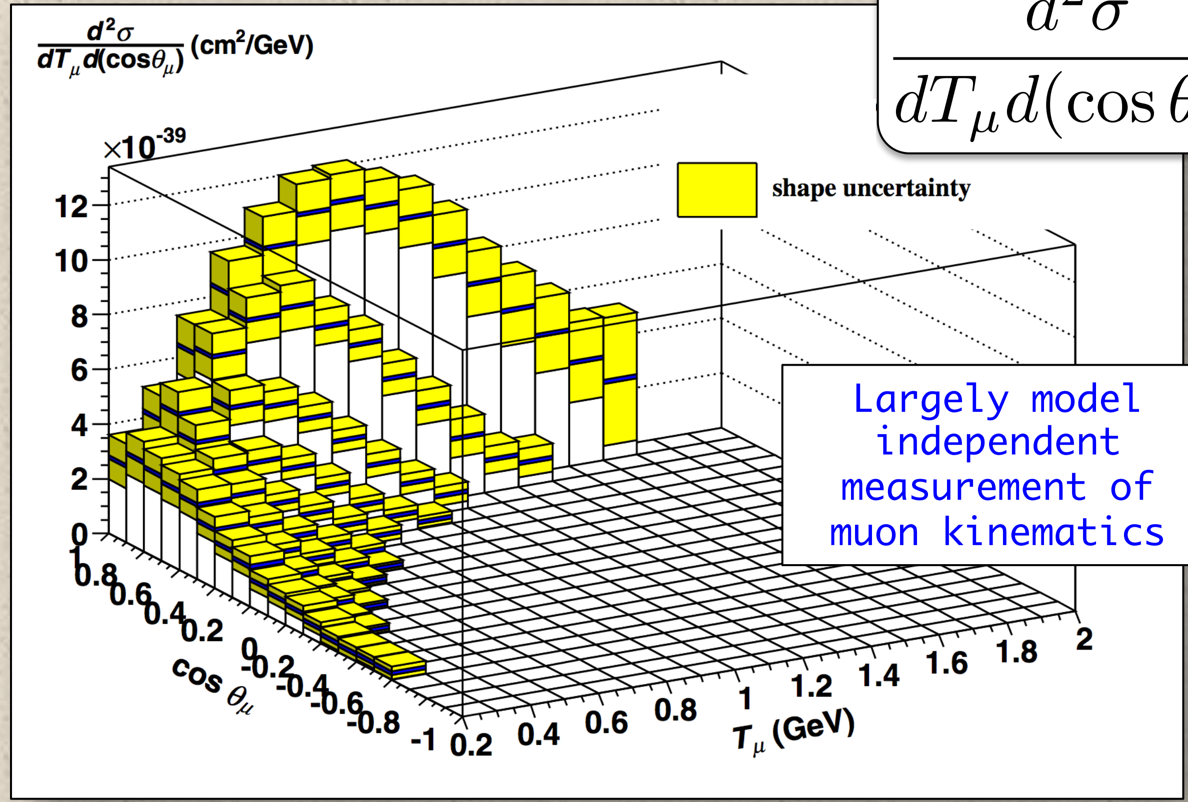
Several examples of first measurements of differential cross sections

See Zarko Pavlovic's talk from WG2 on Tuesday

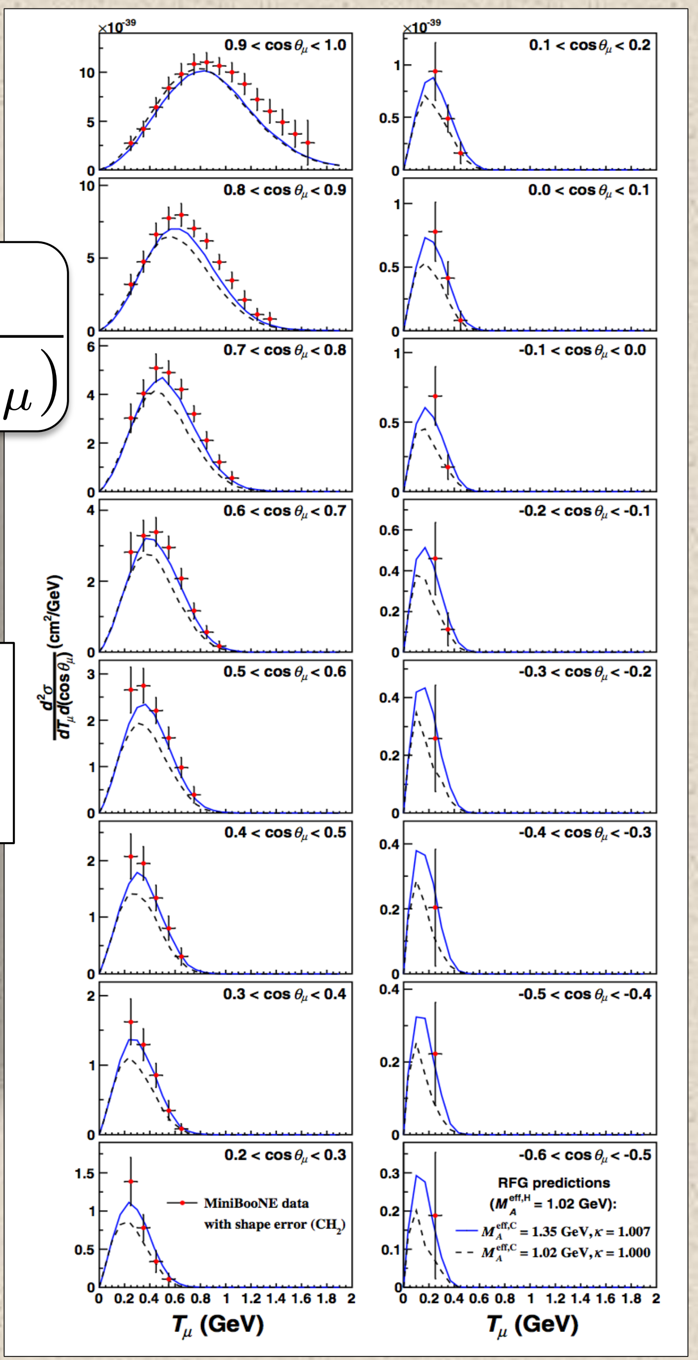
First Measurement of the Muon Antineutrino Double-Differential Charged-Current Quasielastic Cross Section

PRD 88, 032001 (2013)

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



Largely model independent measurement of muon kinematics



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

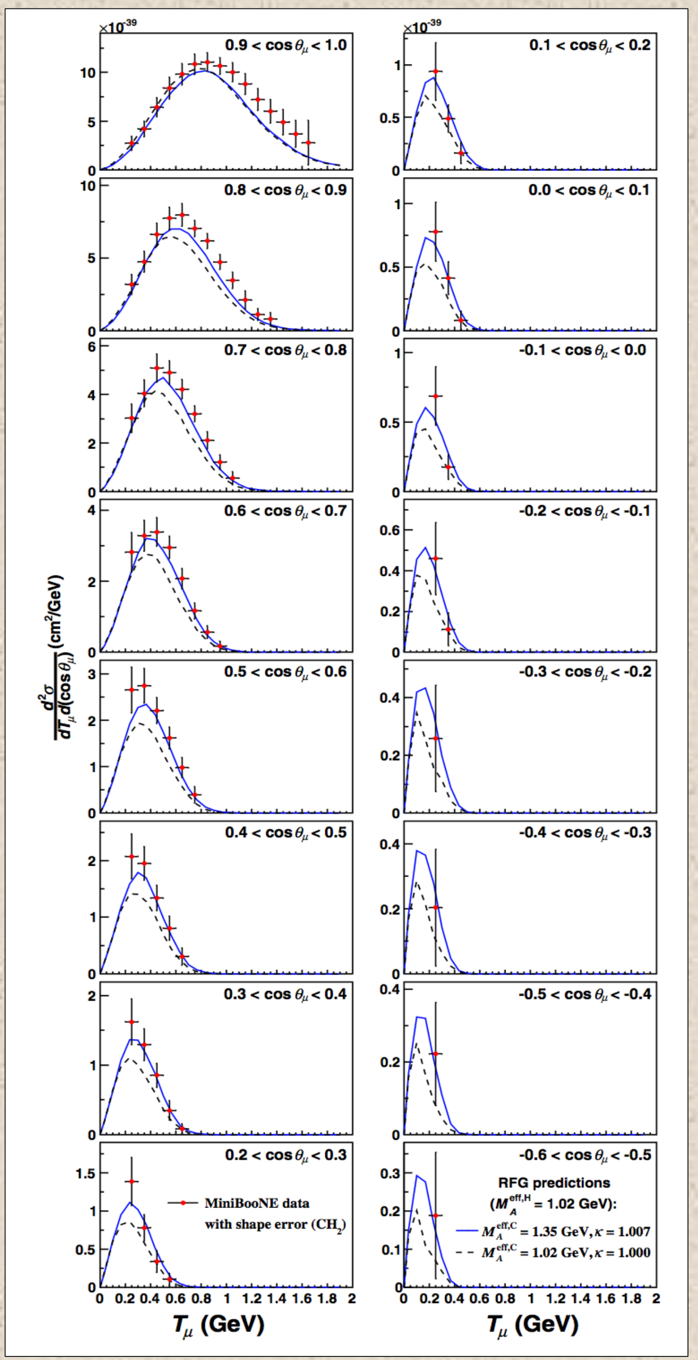
BooNE
BOOSTER NEUTRINO EXPERIMENT

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

PRD 88, 032001 (2013)

- Strong conclusions about the RFG model:
  - "It is clear in Fig. 9 [right] that the RFG model assuming M_A ~ 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."

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

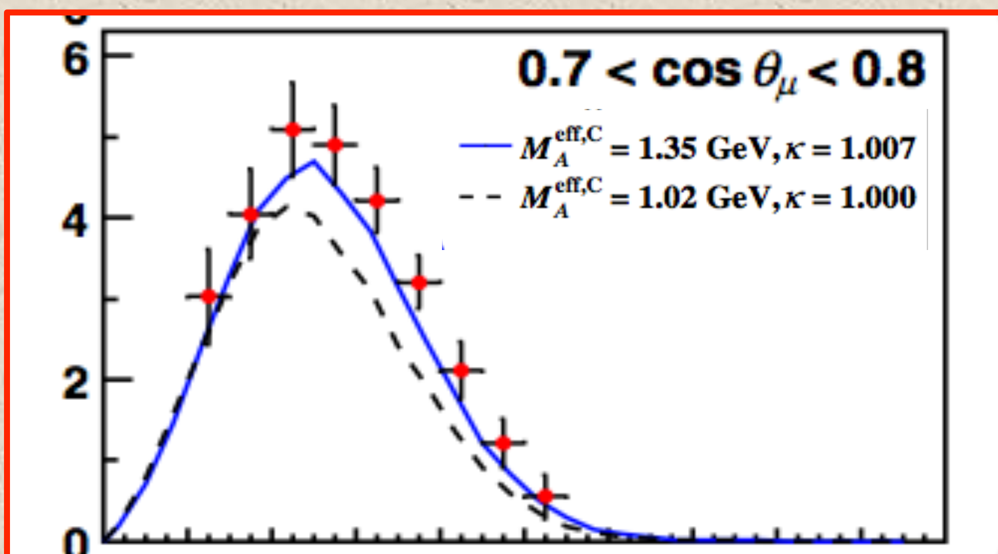


BooNE
BOOSTER NEUTRINO EXPERIMENT

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

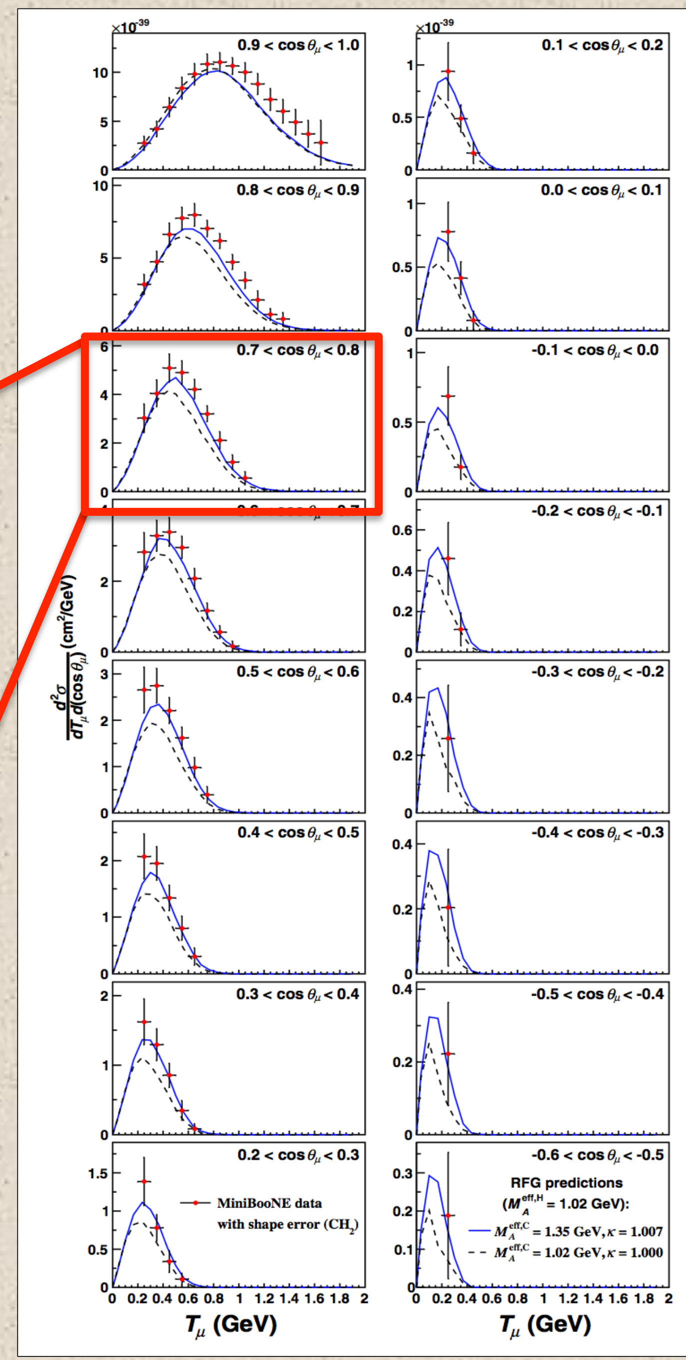
PRD 88, 032001 (2013)

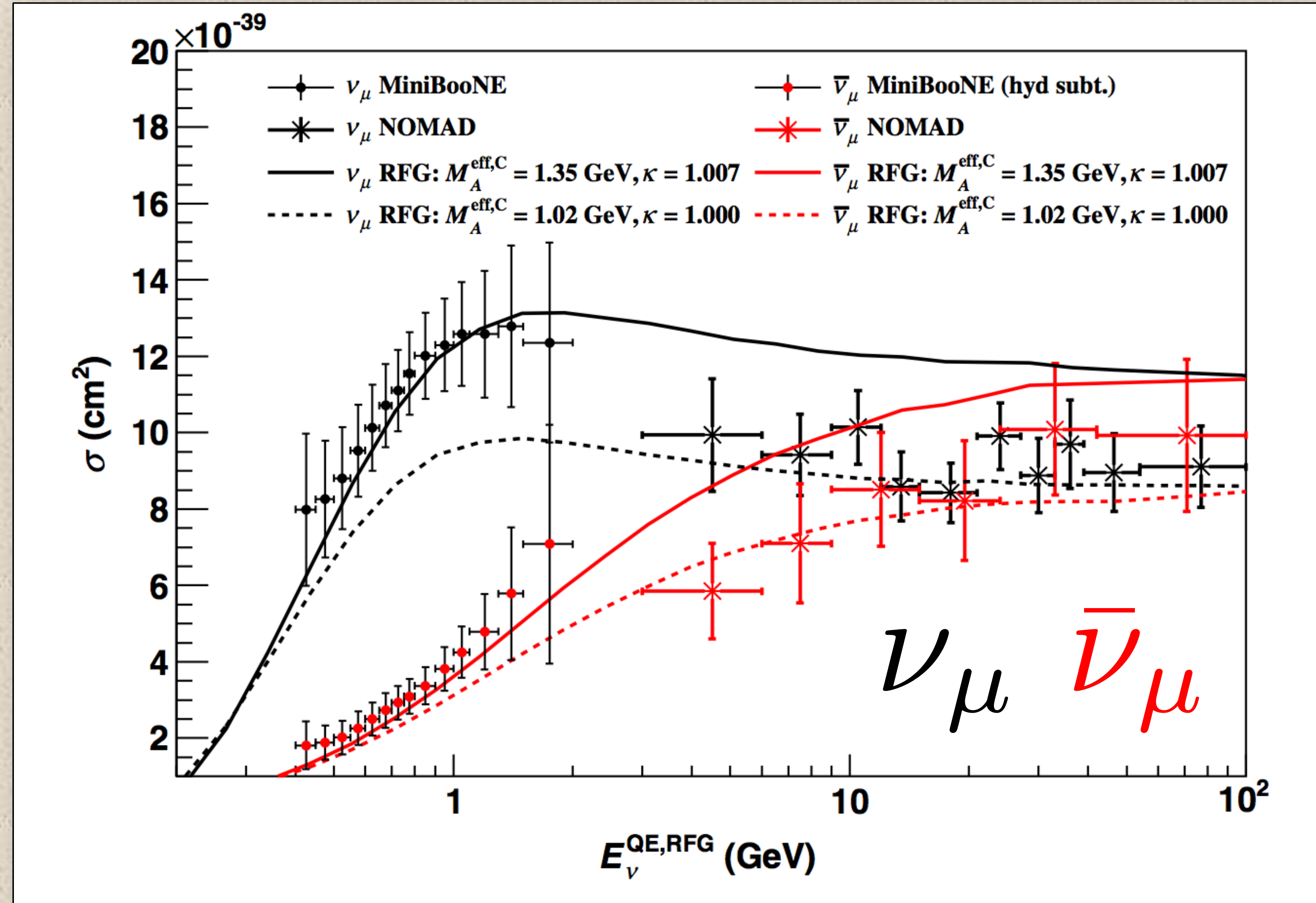
- Strong conclusions about the RFG model:



expectation with M_A = 1.0 GeV.”

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



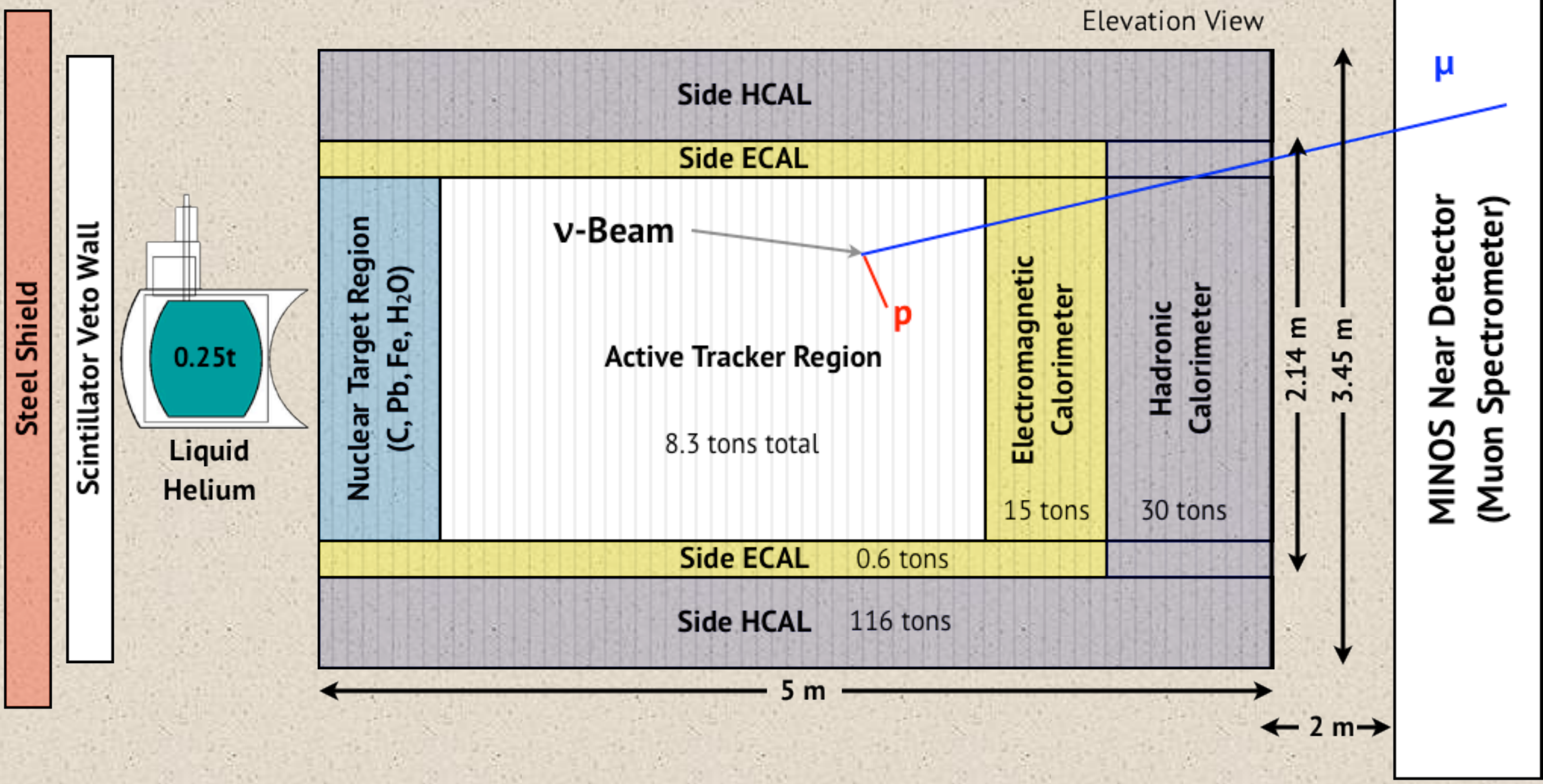


×10^-39
20
18
16
14
12
10
8
6
4
2
σ (cm²)
1
10
10²
$E_\nu^{QE,RFG}$ (GeV)
ν_μ MiniBooNE
$\bar{\nu}_\mu$ MiniBooNE (hyd subt.)
ν_μ NOMAD
$\bar{\nu}_\mu$ NOMAD
ν_μ RFG: $M_A^{eff,C}$ = 1.35 GeV, κ = 1.007
$\bar{\nu}_\mu$ RFG: $M_A^{eff,C}$ = 1.35 GeV, κ = 1.007
ν_μ RFG: $M_A^{eff,C}$ = 1.02 GeV, κ = 1.000
$\bar{\nu}_\mu$ RFG: $M_A^{eff,C}$ = 1.02 GeV, κ = 1.000
ν_μ
$\bar{\nu}_\mu$

MINERvA

See WG2 talks from C. Marshall, A. Higuera, A. Bravar

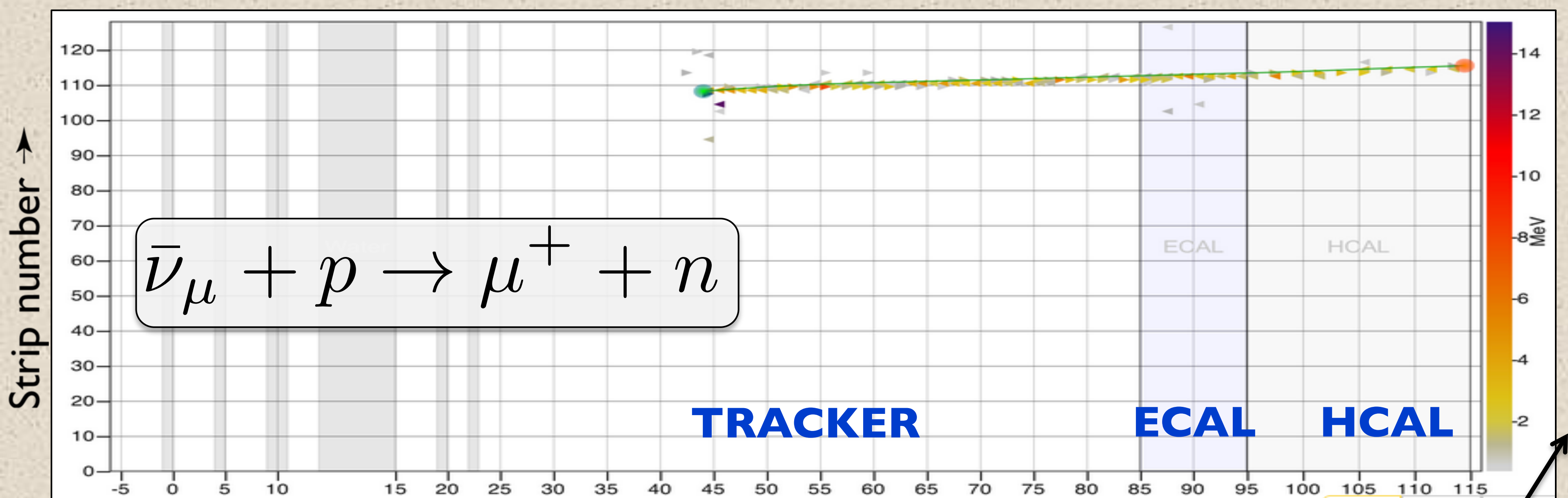
MINOS ND serves as muon spectrometer



MINERvA detector comprised of 120 modules of varying composition stacked along the beam direction. Finely segmented tracking (~32k channels) with nuclear targets (C,CH,Fe,Pb,He,H_2O)

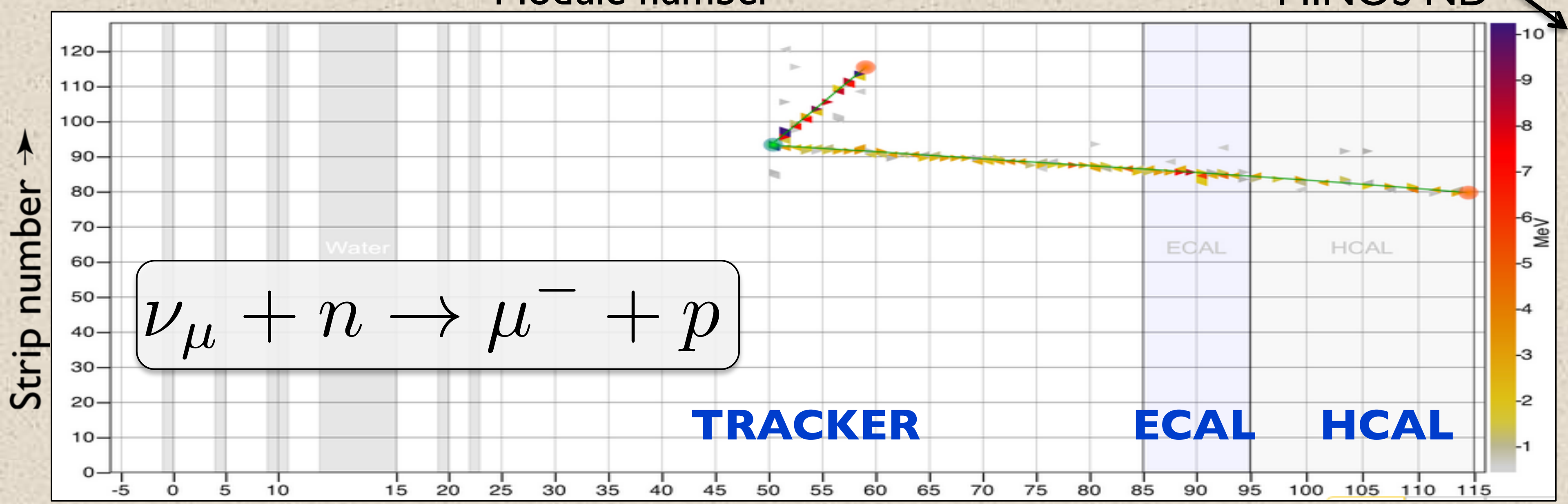
ν Beam →

charged-current quasi-elastic scattering



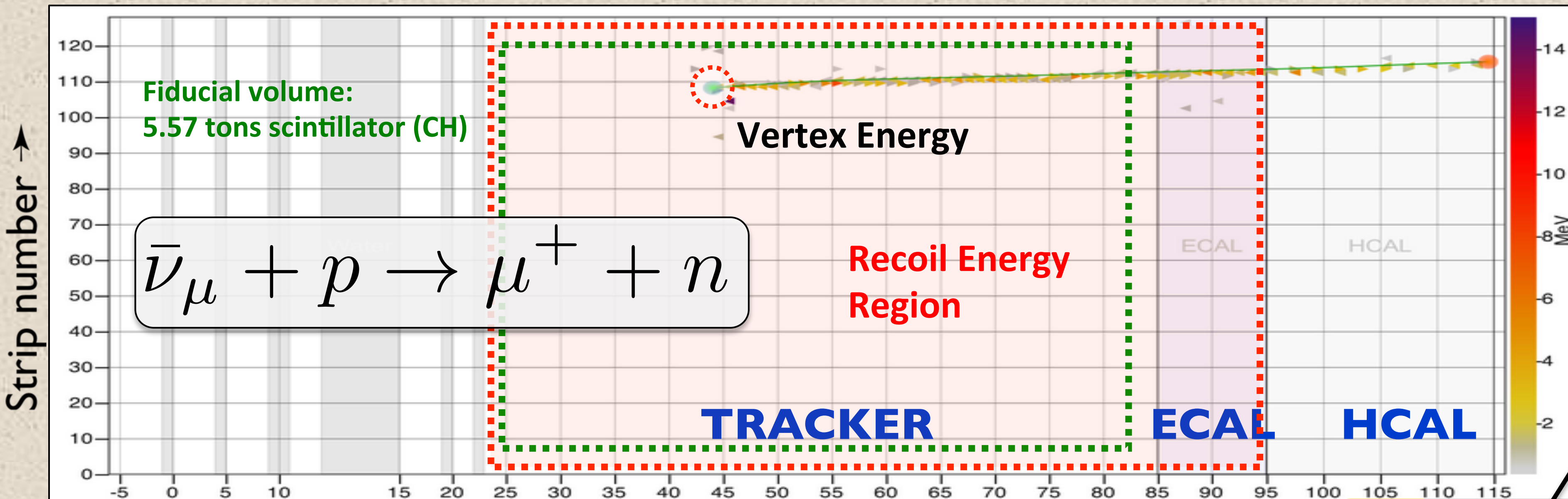
Module number →

MINOS ND

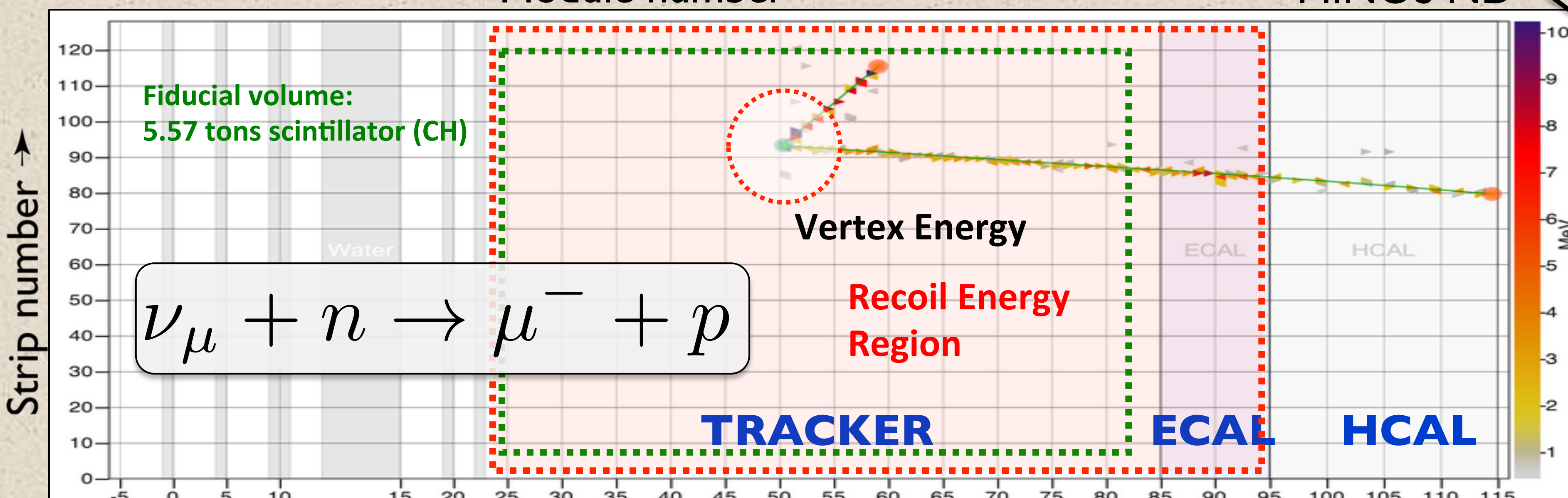


charged-current quasi-elastic scattering

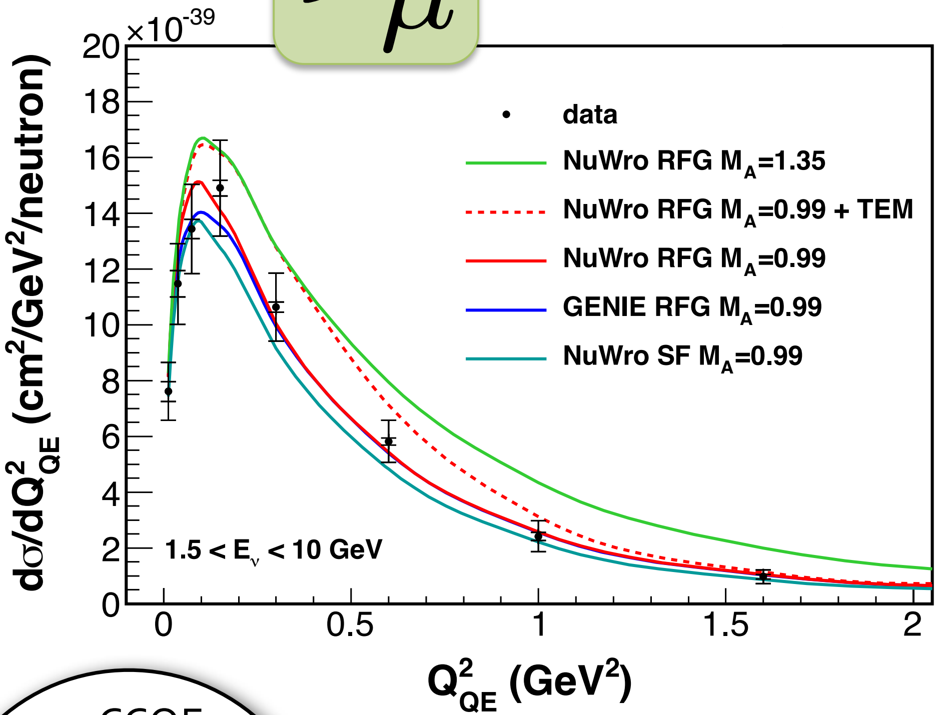
ν Beam → MeV

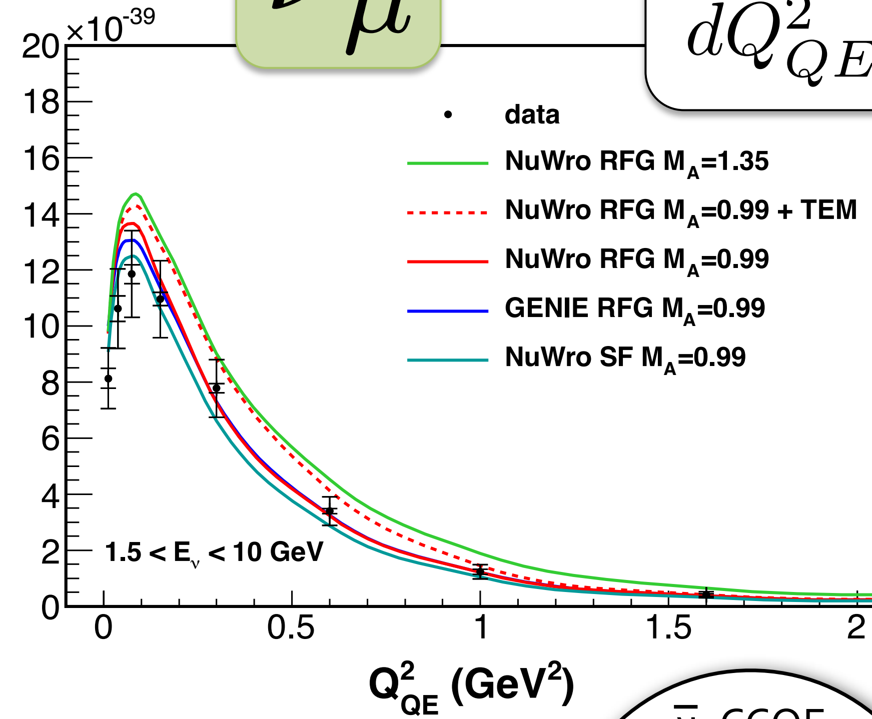


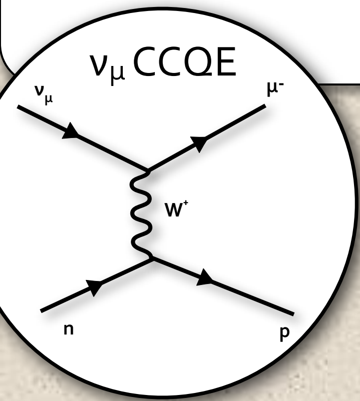
Module number → MINOS ND



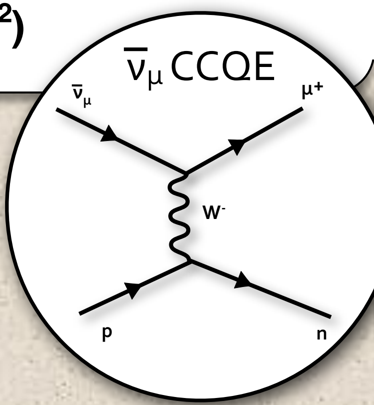
ν_μ $\bar{\nu}_\mu$ $\frac{d\sigma}{dQ^2_{QE}}$







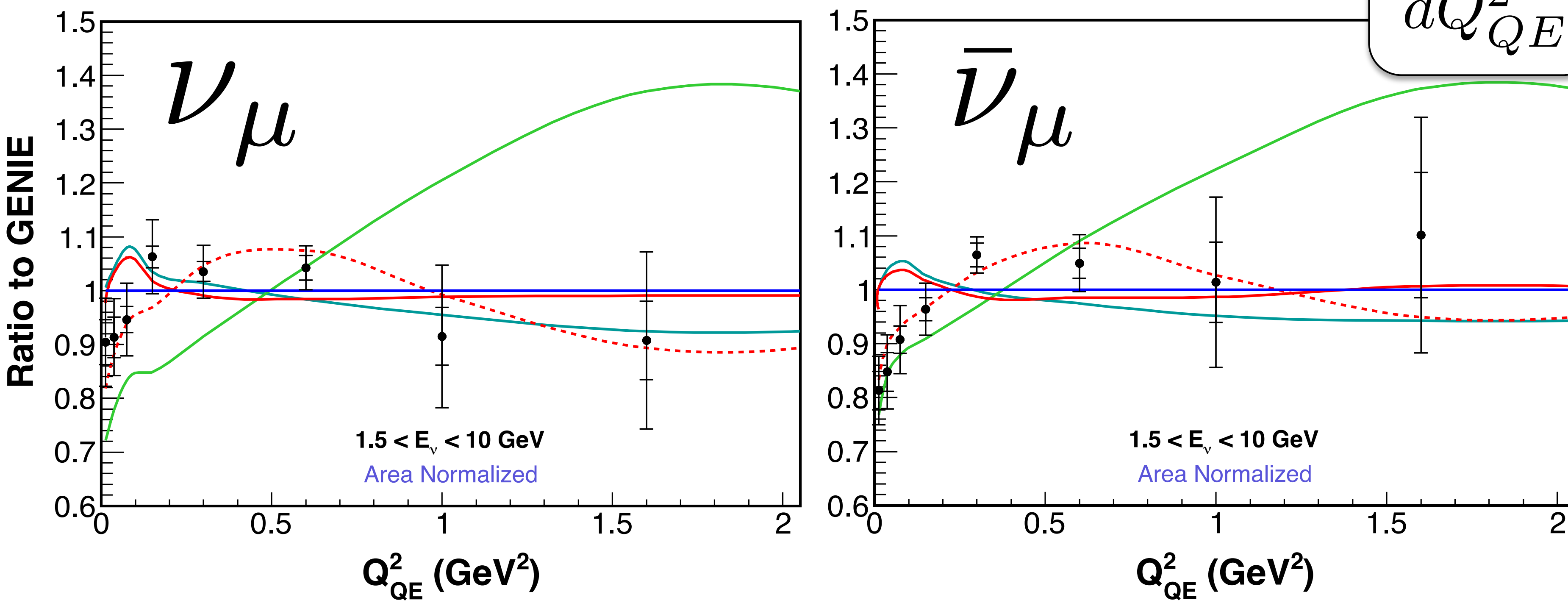
	Events	Efficiency	Purity
Neutrinos	29,620	47%	49%
Antineutrinos	16,467	54%	77%



MINERvA

Emphasize Shape: Normalize each prediction and the measured cross section to GENIE prediction and form ratio

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



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

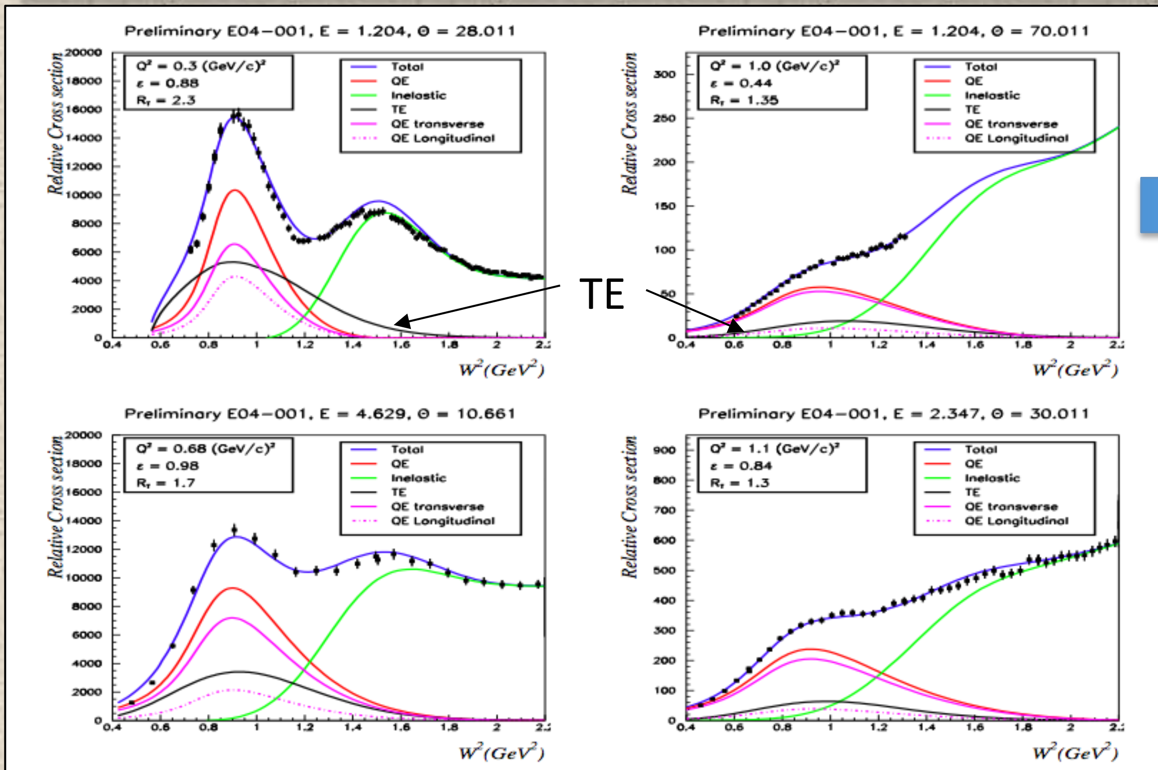
M_A = 1.35 GeV —— best fit to MiniBooNE data

SF —— improved nucleon momentum-energy relation

TEM - - - - empirical model based on electron scattering data

MINERvA

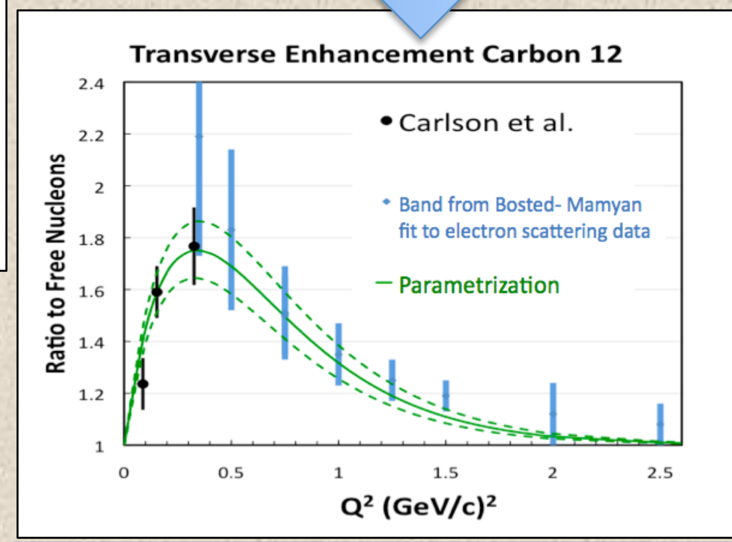
Transverse Enhancement Model



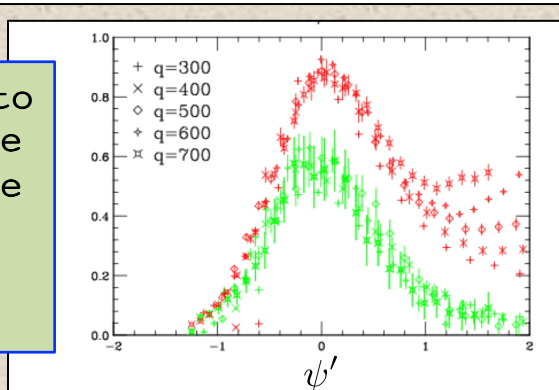
Bodek, Budd, Christy, Eur. Phys. J. C 71:1726 (2011), arXiv:1106.0340

Fits in Q^2 bins

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



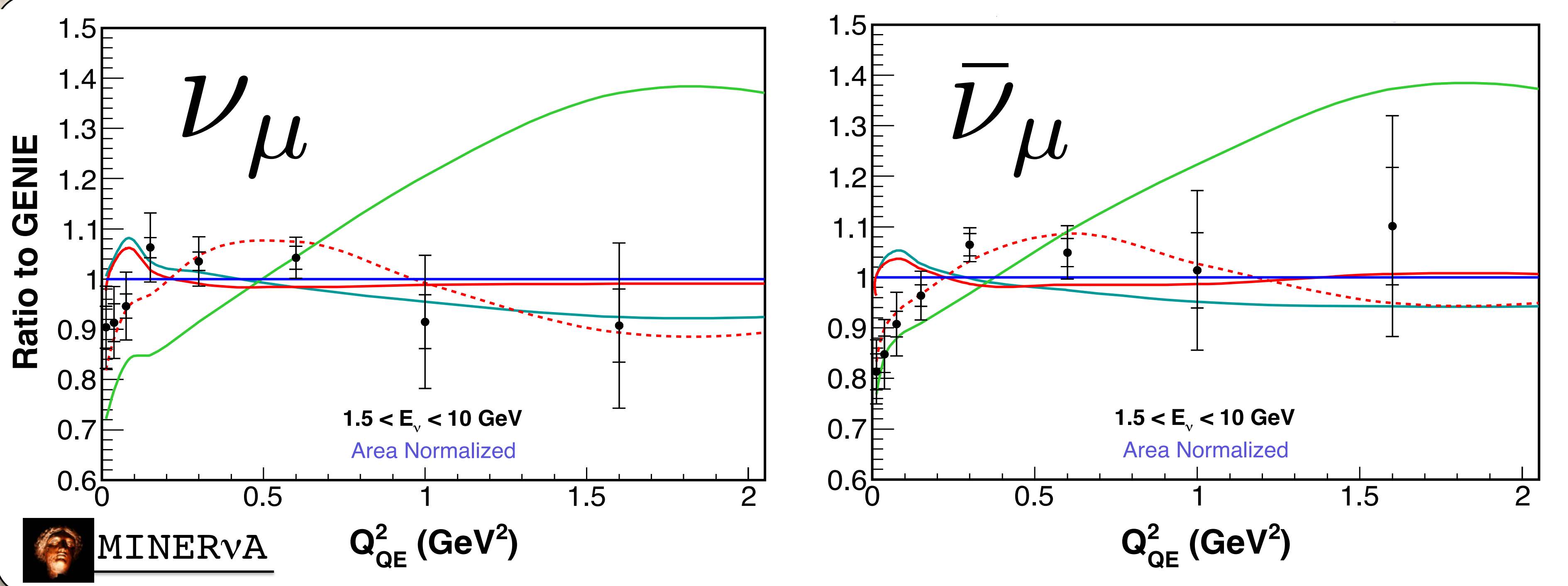
An attempt to parameterize this feature we saw in electron scattering



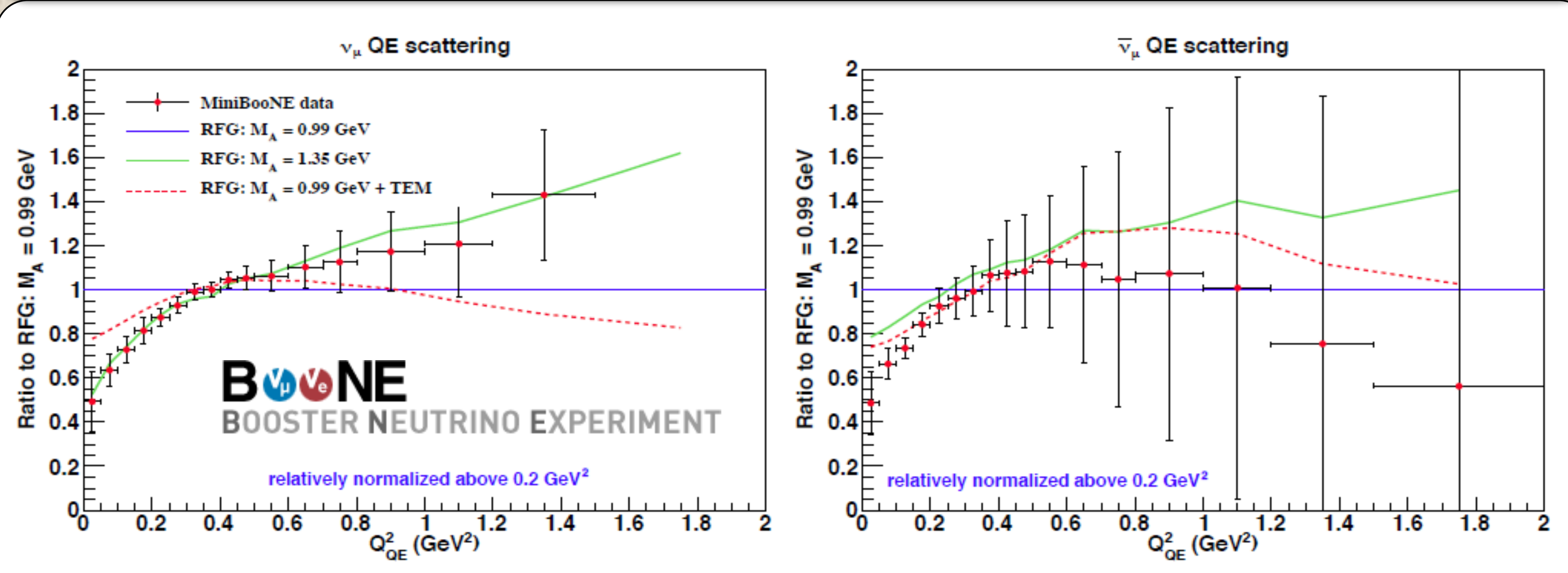
J. Carlson, et al., PRC 65, 024002 (2002)

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

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

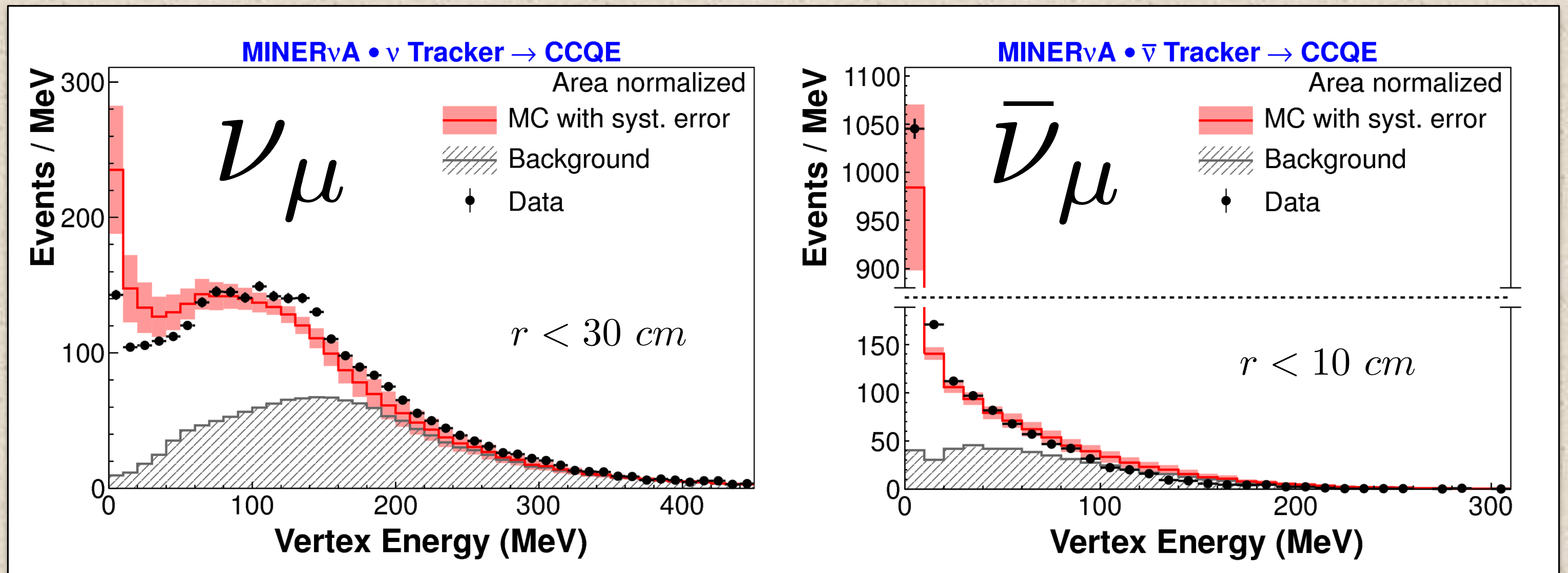


Ratio to GENIE
ν_μ
$\bar{\nu}_\mu$
1.5 < E_ν < 10 GeV
Area Normalized
1.5 < E_ν < 10 GeV
Area Normalized
Q^2_{QE} (GeV^2)
Q^2_{QE} (GeV^2)
MINERνA



ν_μ 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)
$\bar{\nu}_\mu$ QE scattering
Ratio to RFG: M_A = 0.99 GeV
relatively normalized above 0.2 GeV^2
Q^2_{QE} (GeV^2)

Vertex Energy



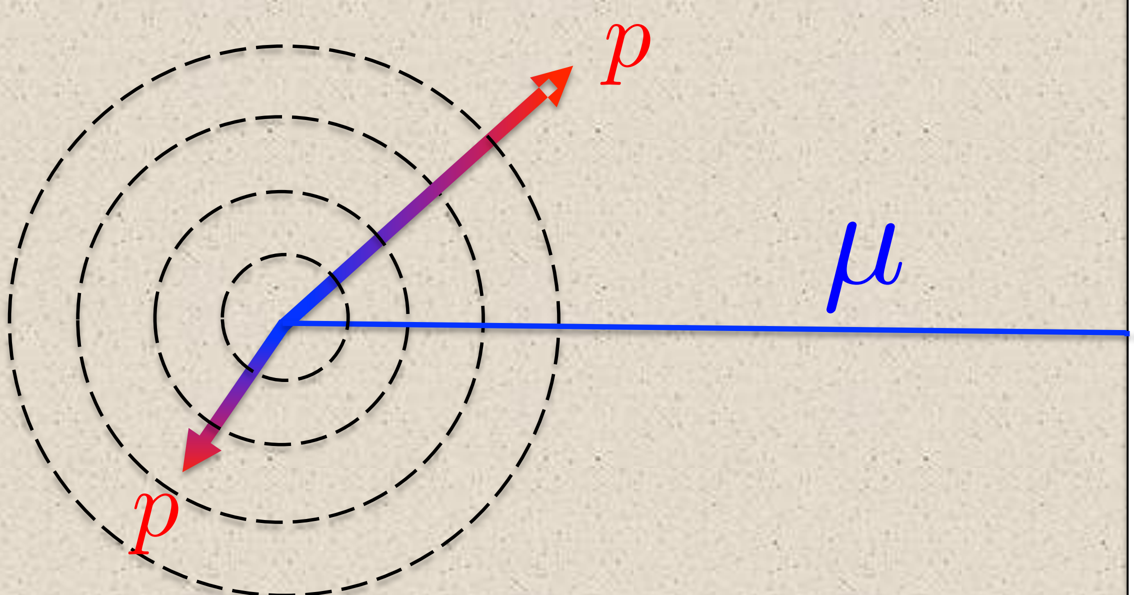
- A harder spectrum of vertex energy is observed in neutrinos
- All systematics considered, including energy scale errors on charged hadrons and FSI model uncertainties
- At this point, we make the *working assumption* that the additional vertex energy per event in data is *due to protons*

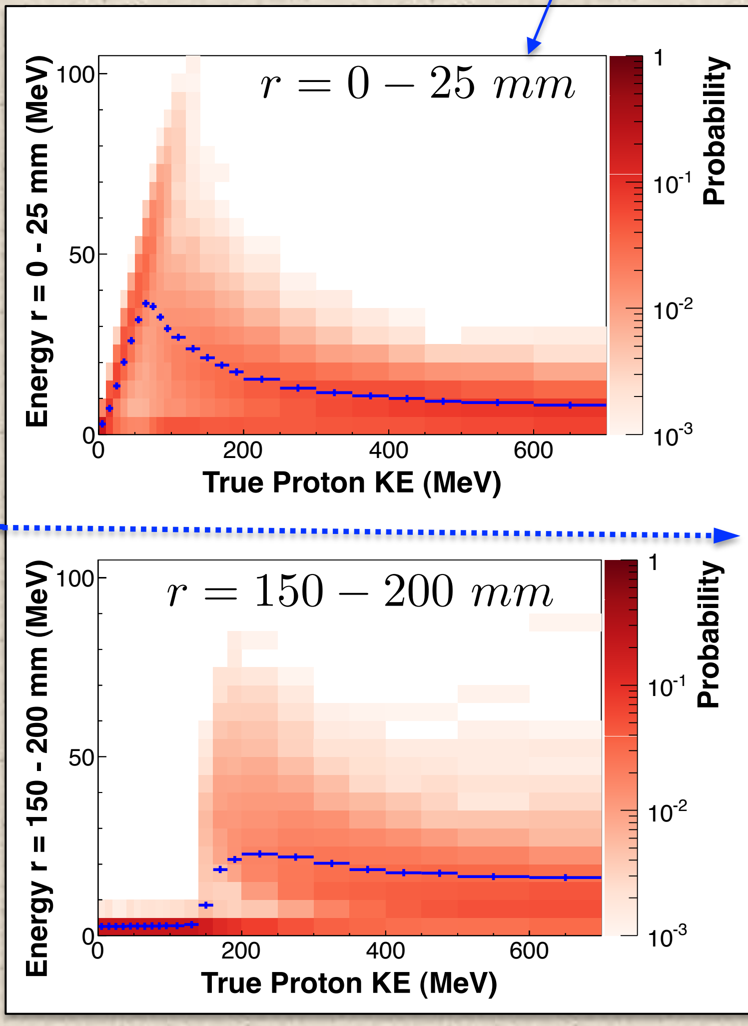
MINERvA

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)

E_{vis} in that annulus vs. true KE_{proton}

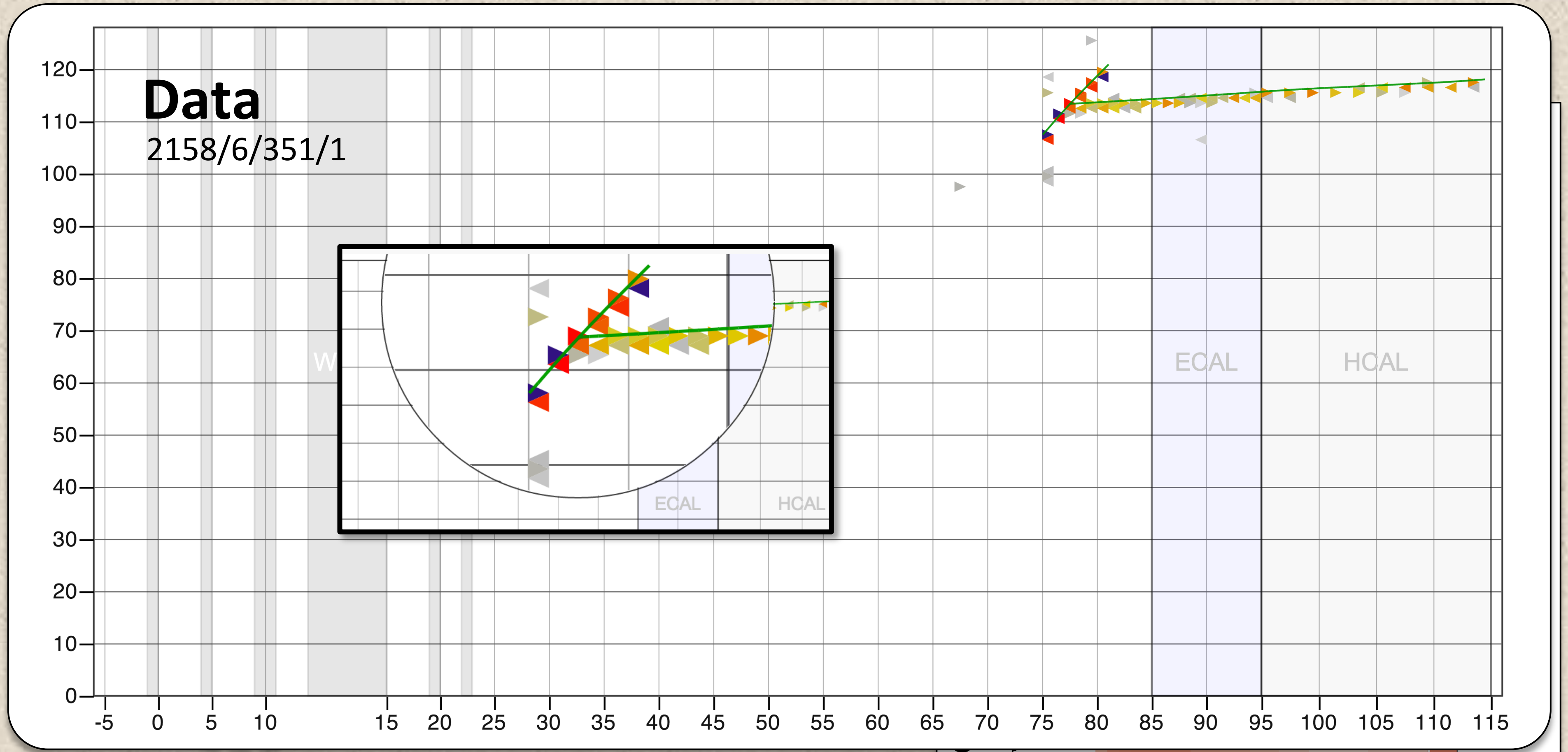


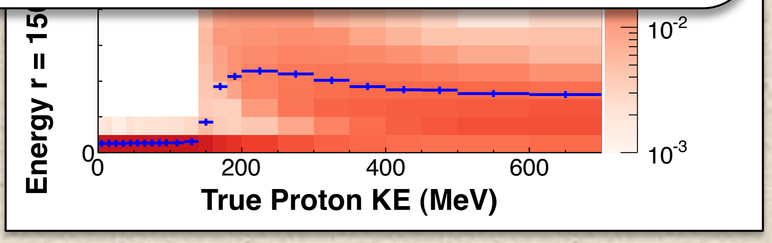


Note: to add visible energy to an inner annulus you must ***add a charged hadron***, not just increase energy of an existing one

MINERvA

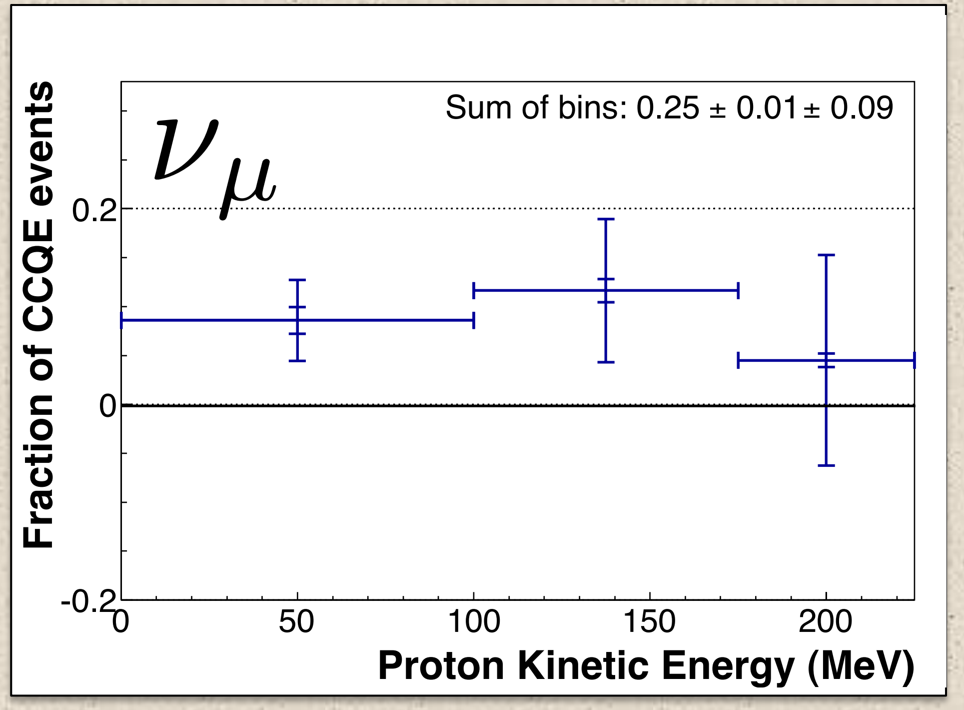
Vertex Energy

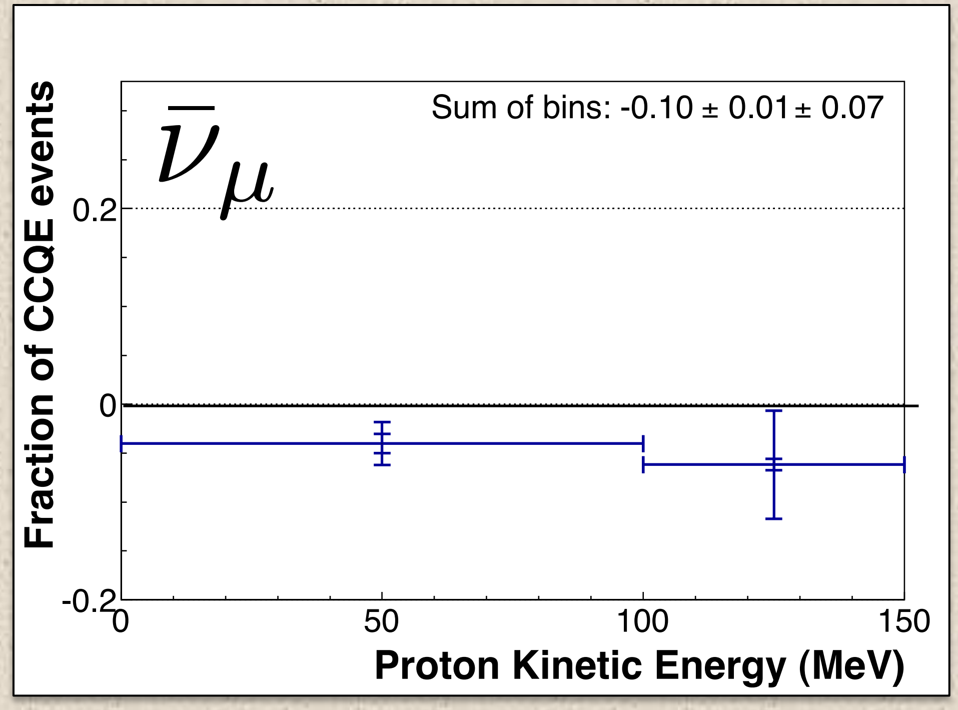




Note: to add visible energy to an inner annulus you must ***add a charged hadron***, not just increase energy of an existing one

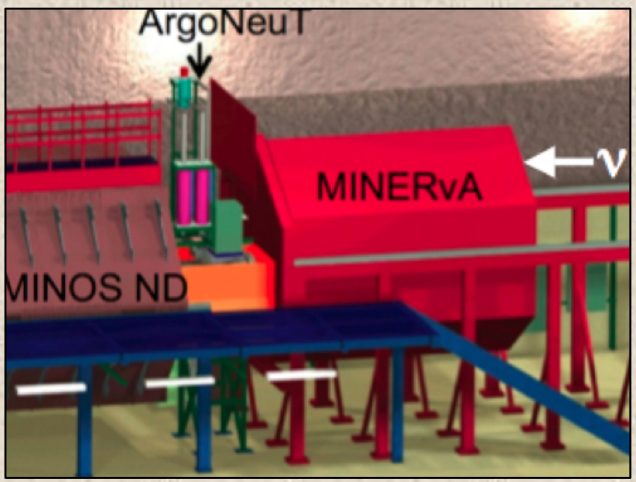
Vertex Energy





Find that adding an additional low-energy proton (KE < 225 MeV) to **(25 ± 9)% of QE events** improves agreements with data

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

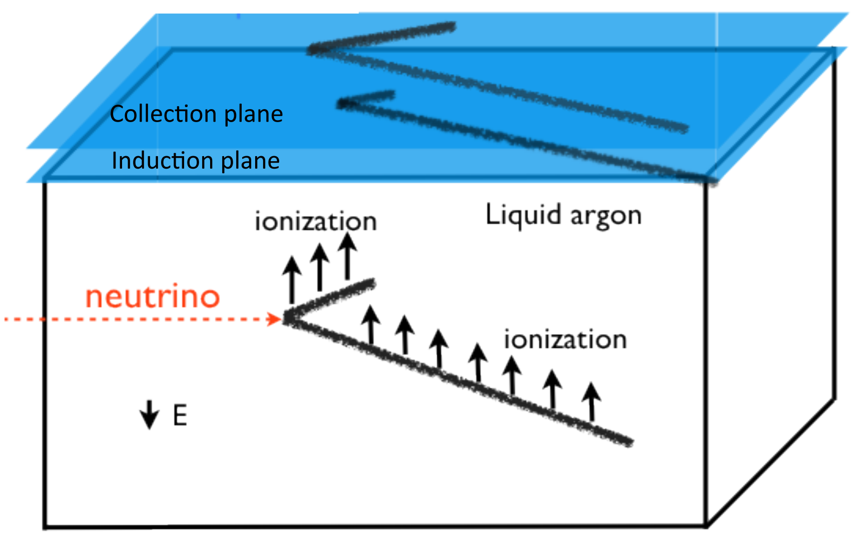


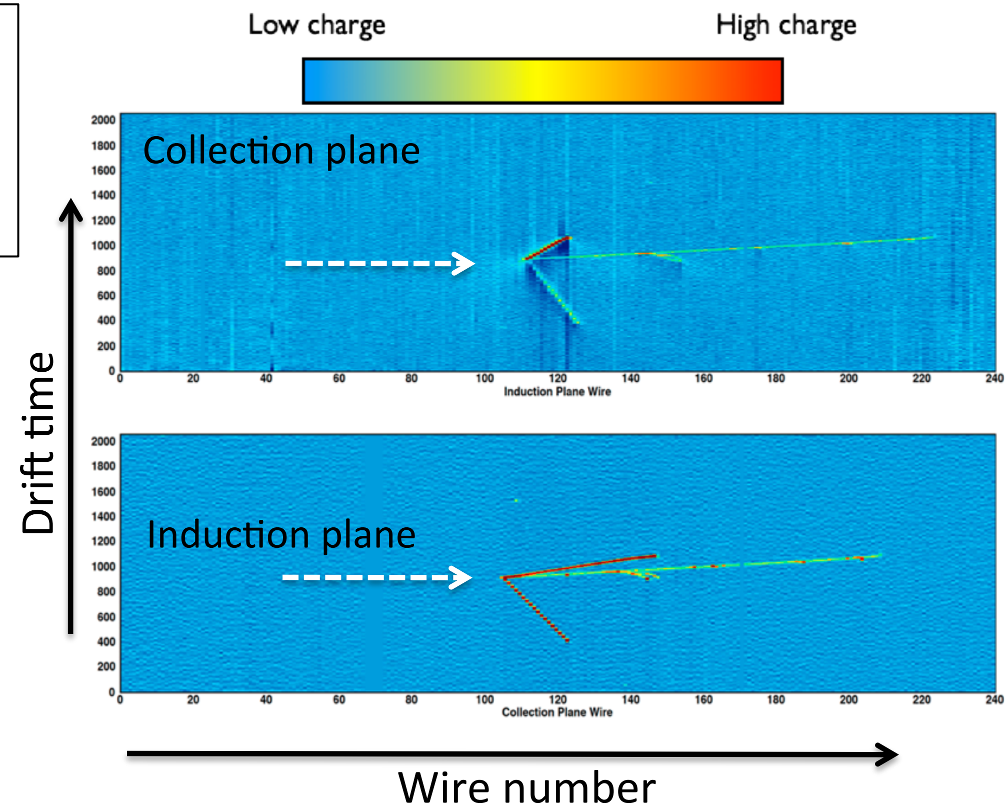
- Liquid argon time projection chambers offer a great opportunity for neutrino physics, including detailed study of neutrino-nucleus scattering
- ArgoNeuT detector exposed to NuMI beam
  - 0.085e20 POT neutrino mode
  - 1.2e20 POT antineutrino mode

See Tingjun Yang's talk from WG2 on Tuesday

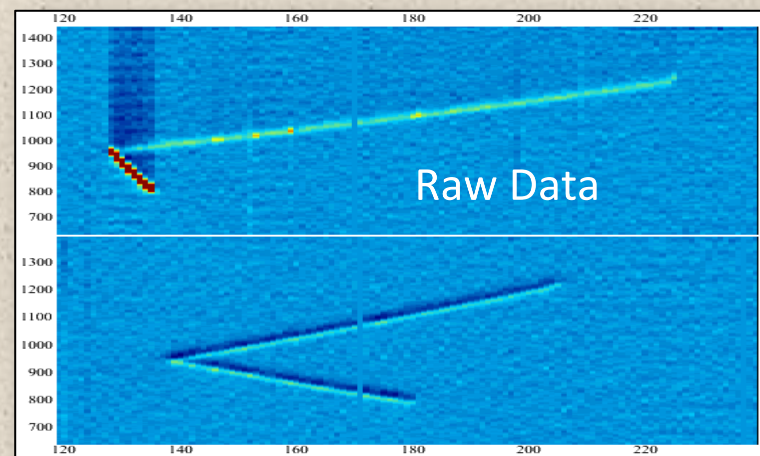
ArgoNeuT

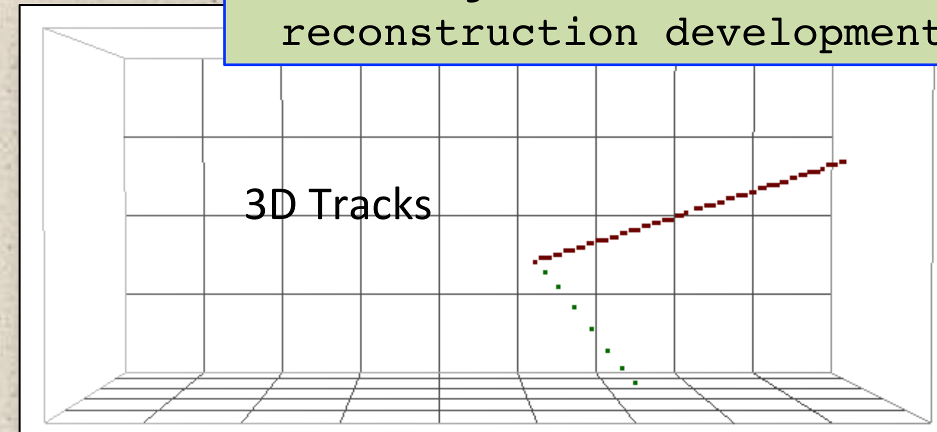
TPC Volume:	175 L
Wire Pitch:	4 mm
Max Drift:	0.5 m (330 μs)
Electric Field:	500 V/m

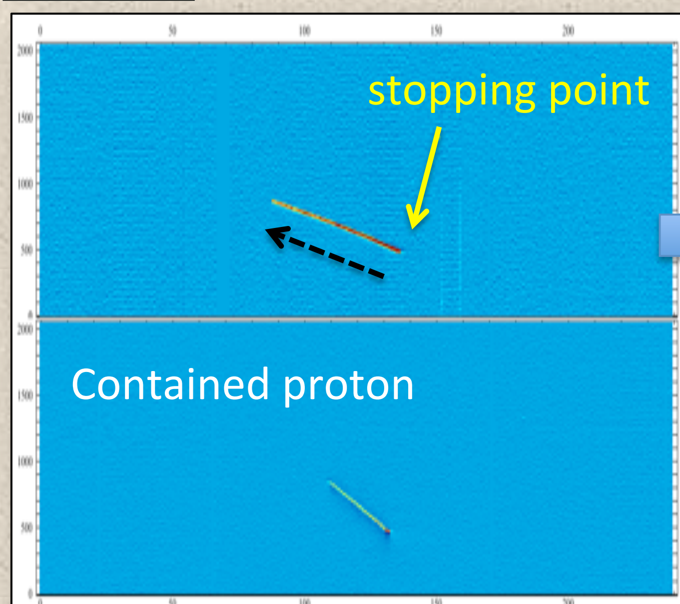


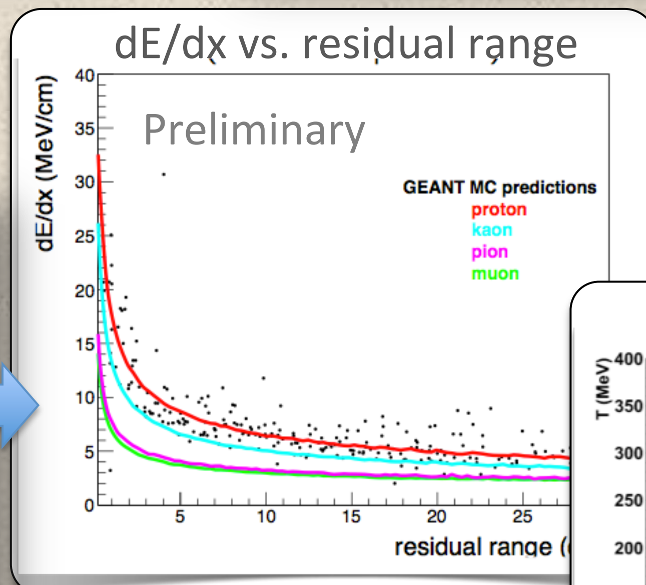


Providing test bed for event reconstruction development



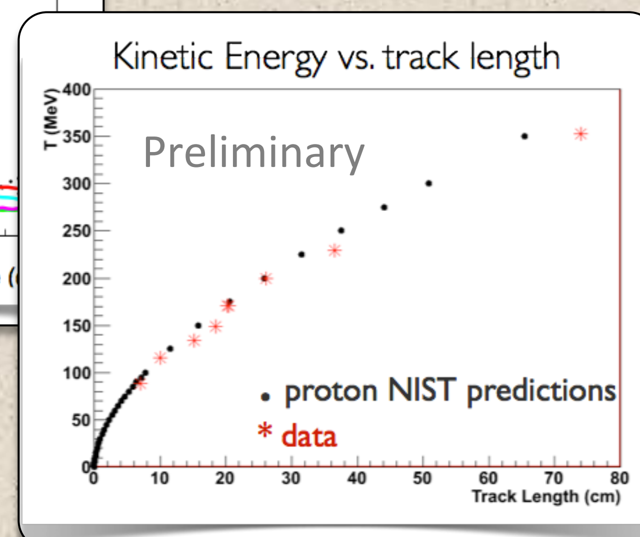


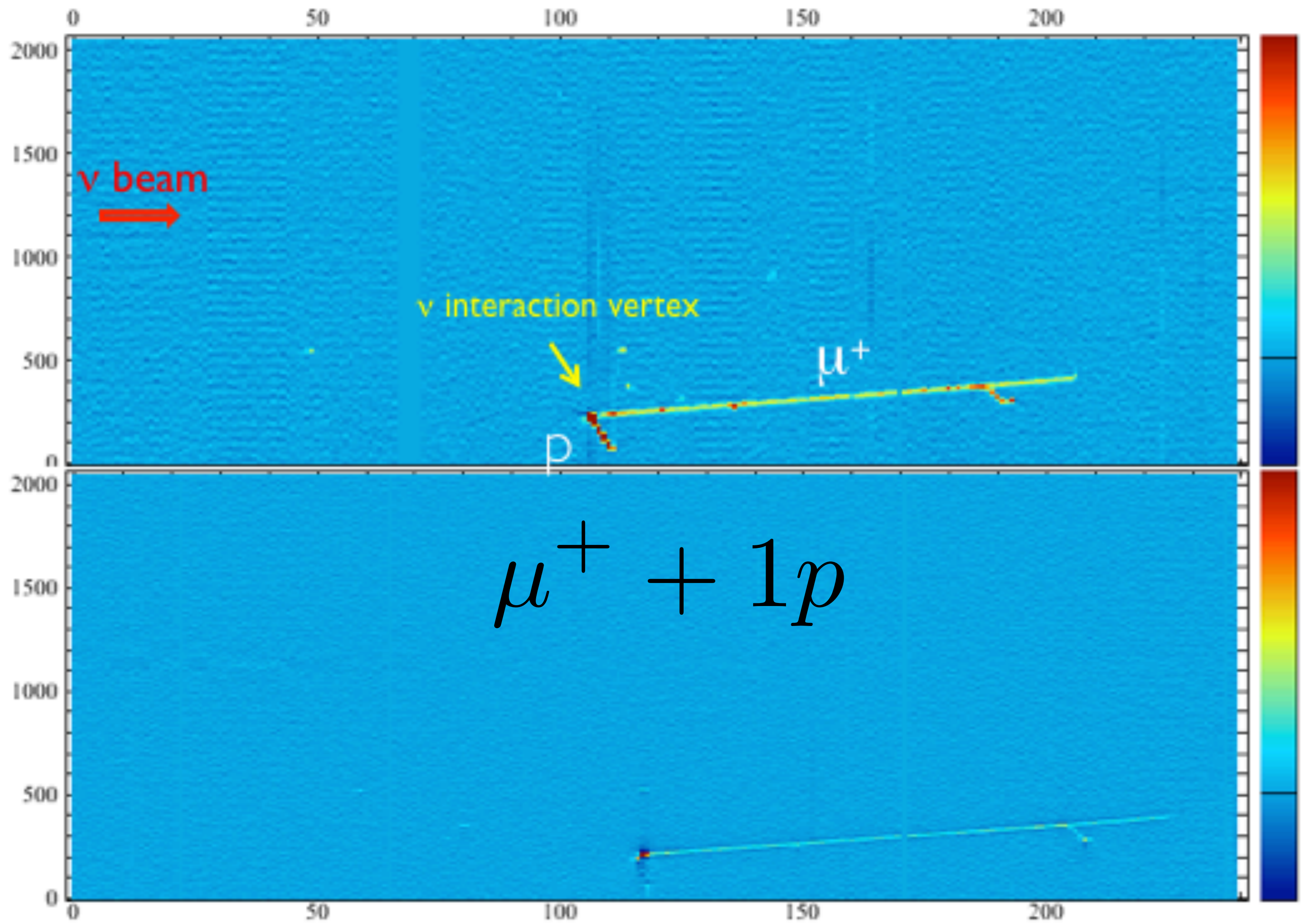




proton threshold:

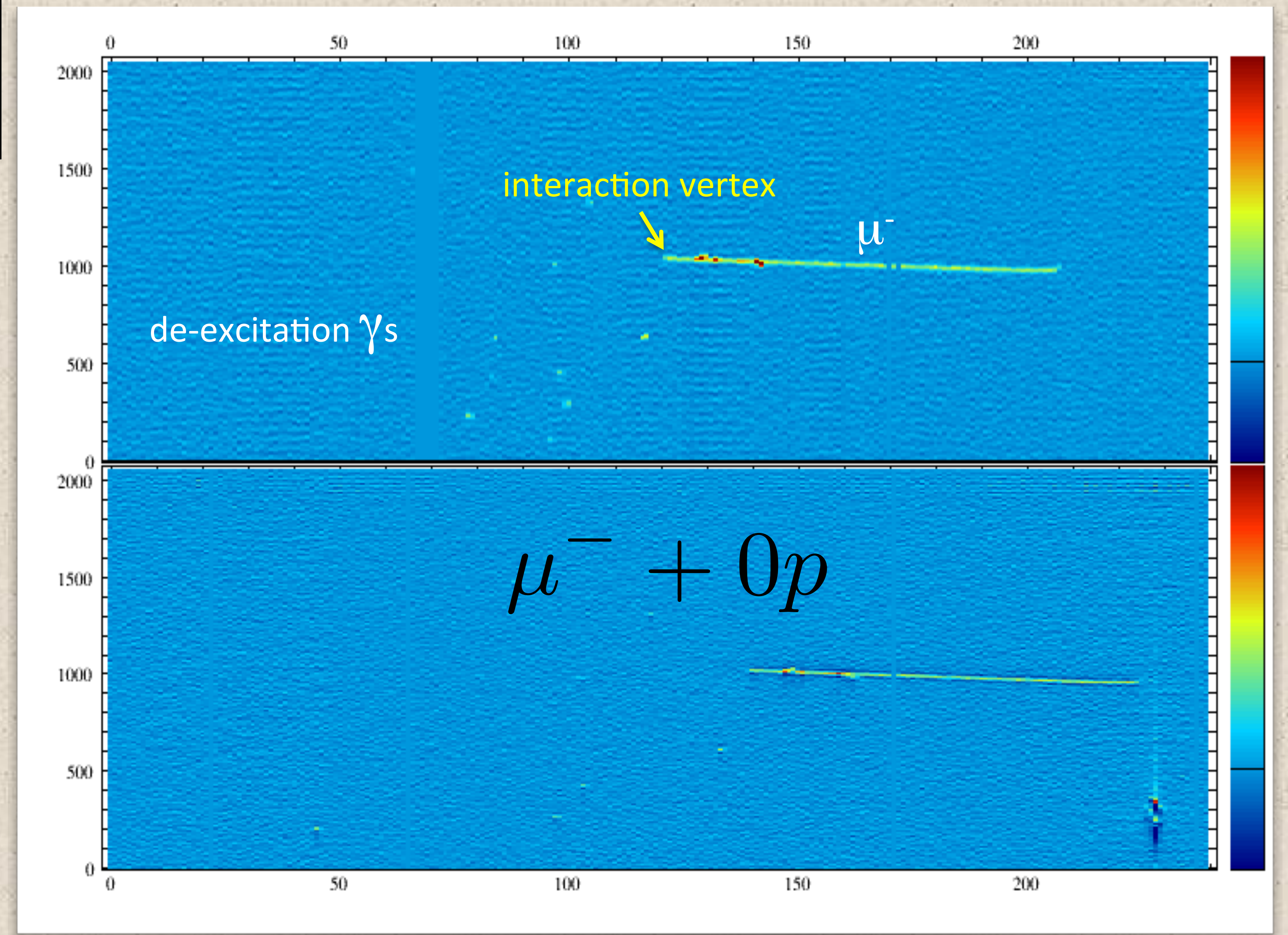
T_p > 21 MeV



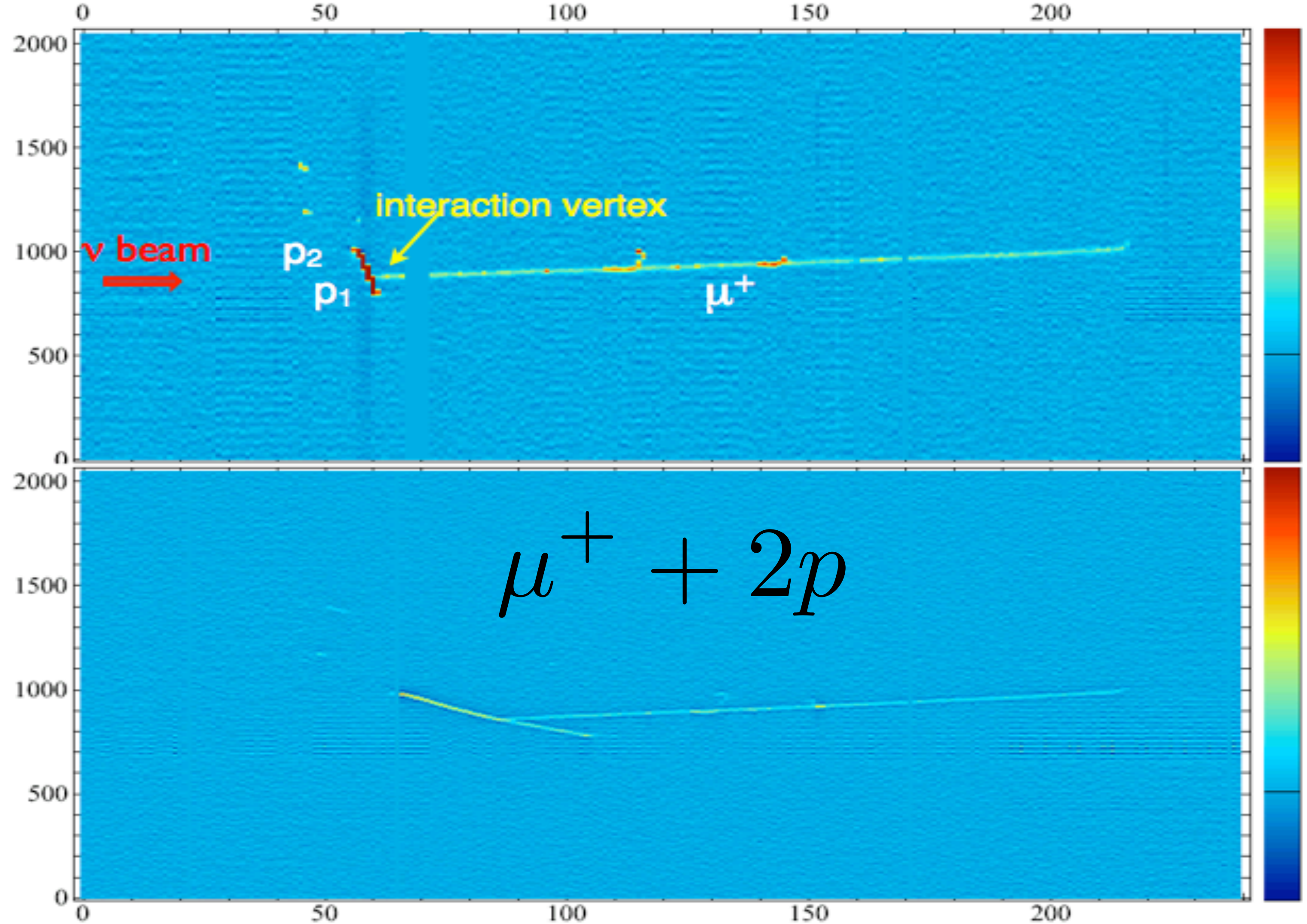


0
50
100
150
200
2000
1500
1000
500
0
ν beam
ν interaction vertex
μ+
p
$\mu^+ + 1p$

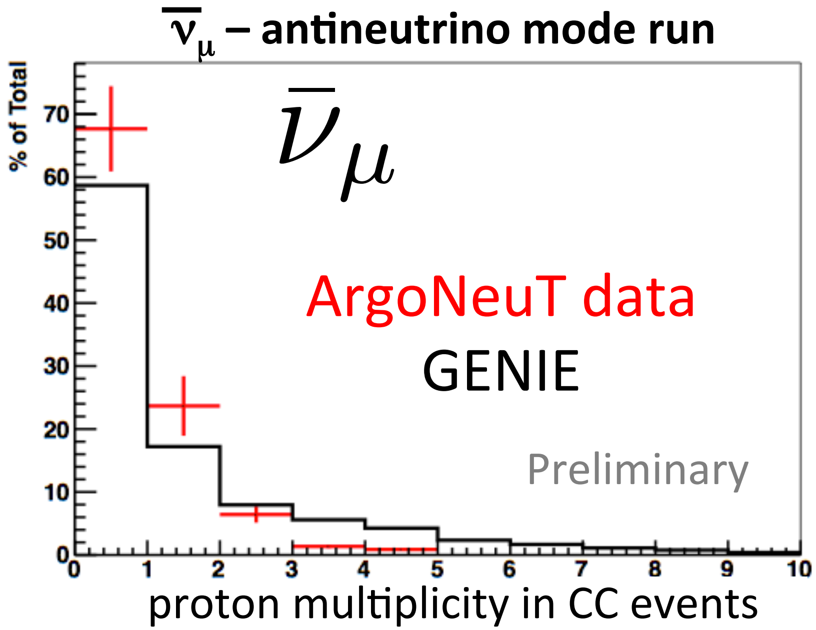
ArgoNeuT

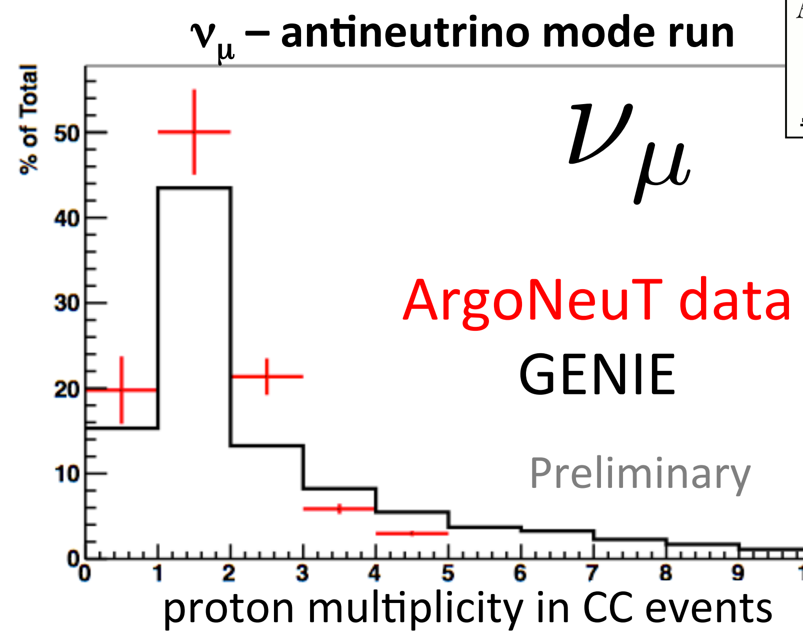


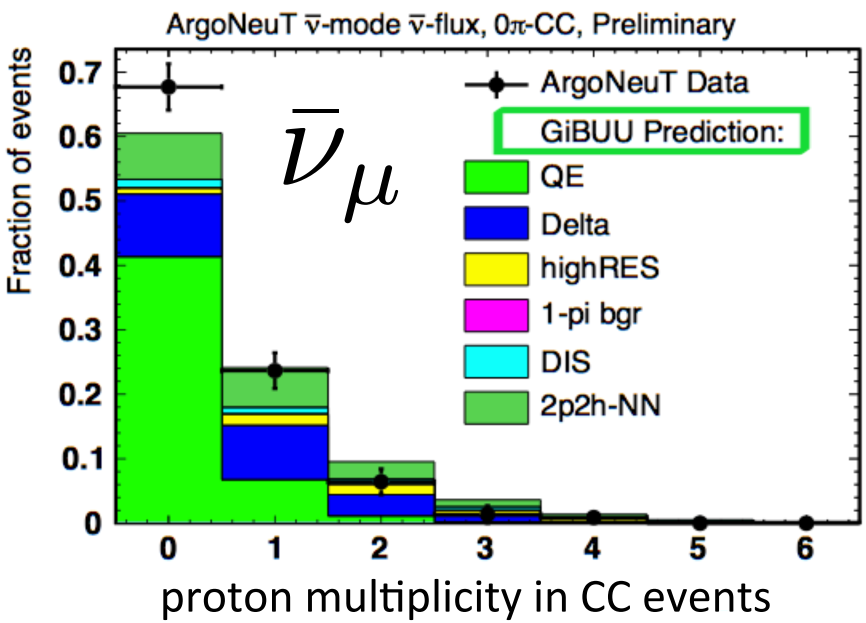
0
50
100
150
200
2000
1500
1000
500
0
interaction vertex
μ⁻
de-excitation γs
$\mu^- + 0p$



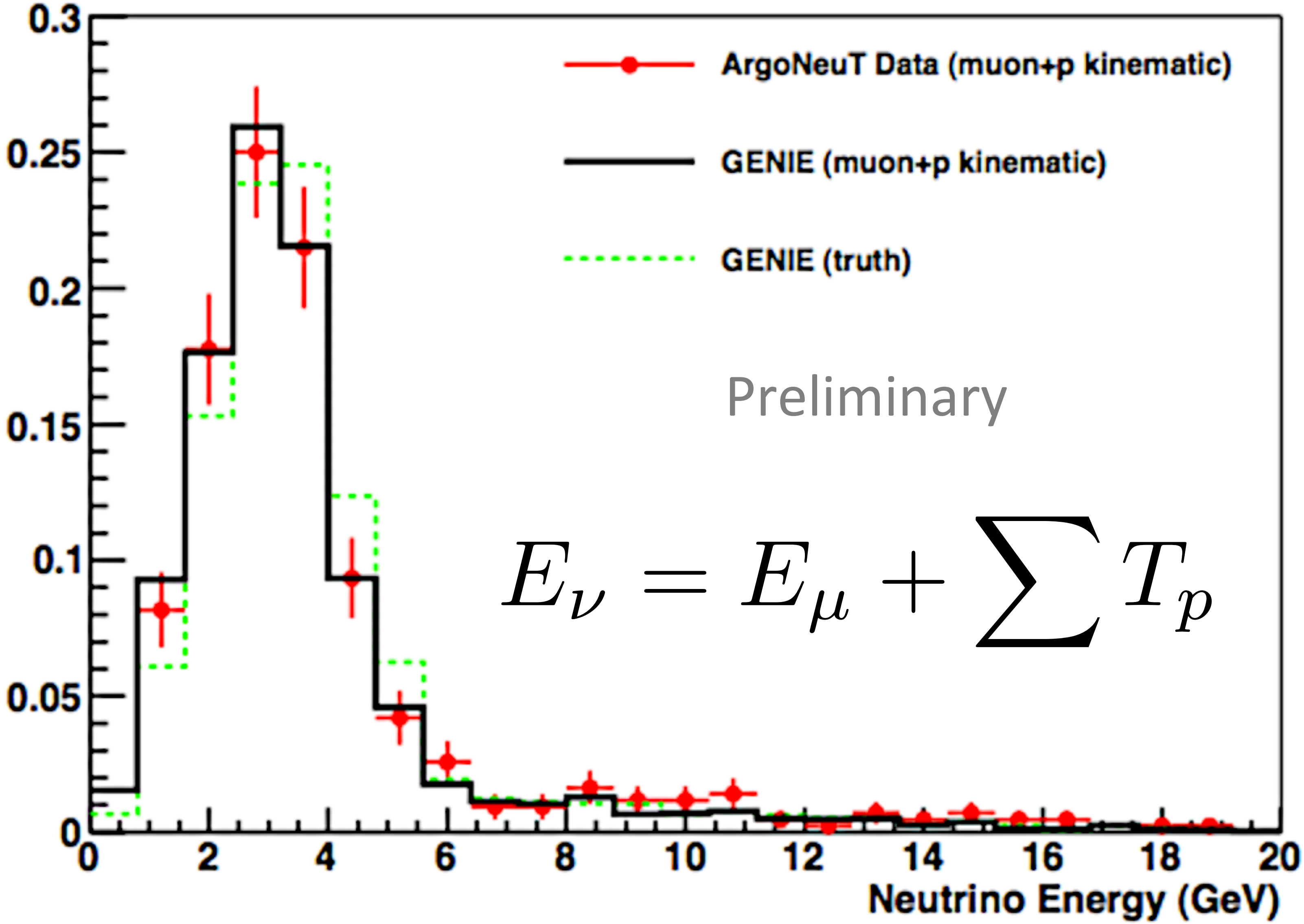
ν beam
p2
p1
interaction vertex
μ+
$\mu^+ + 2p$



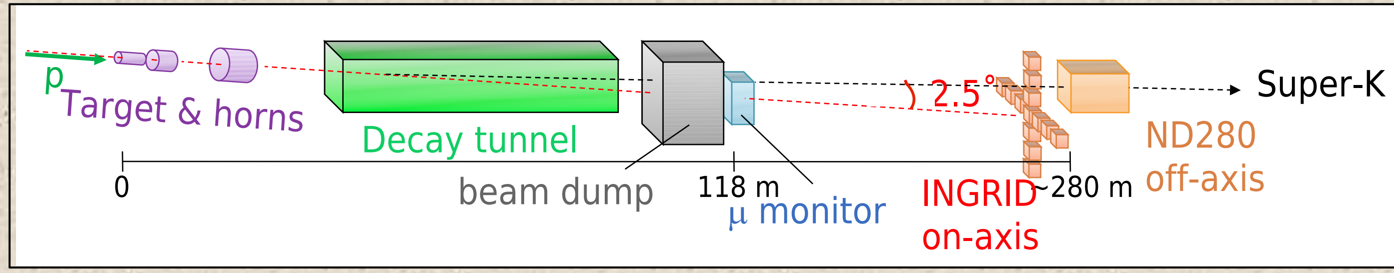


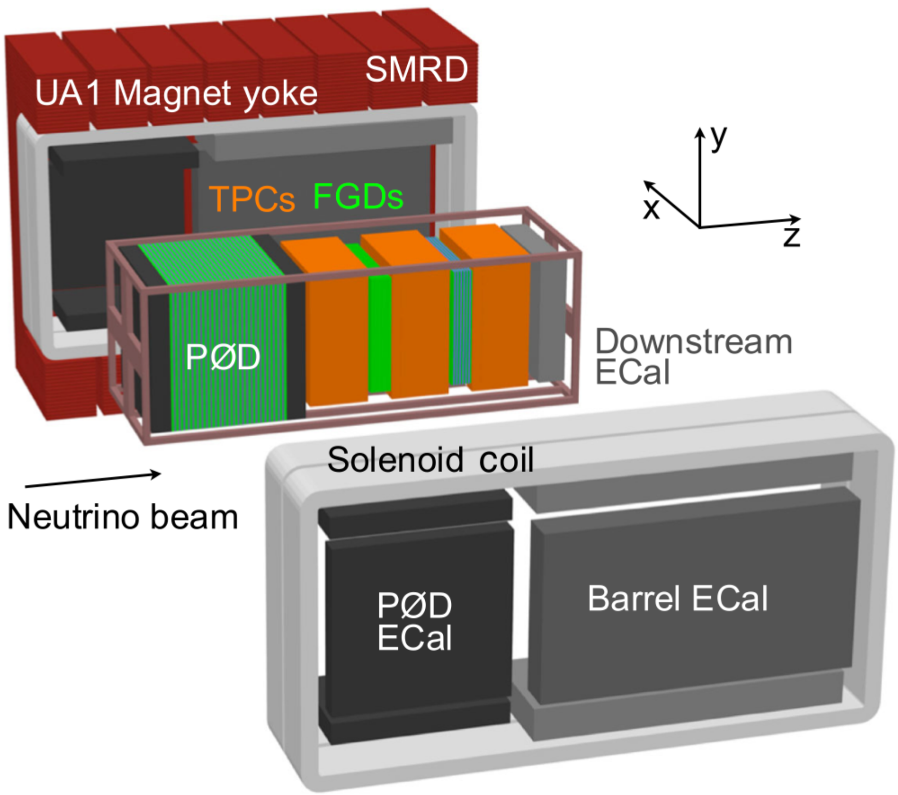


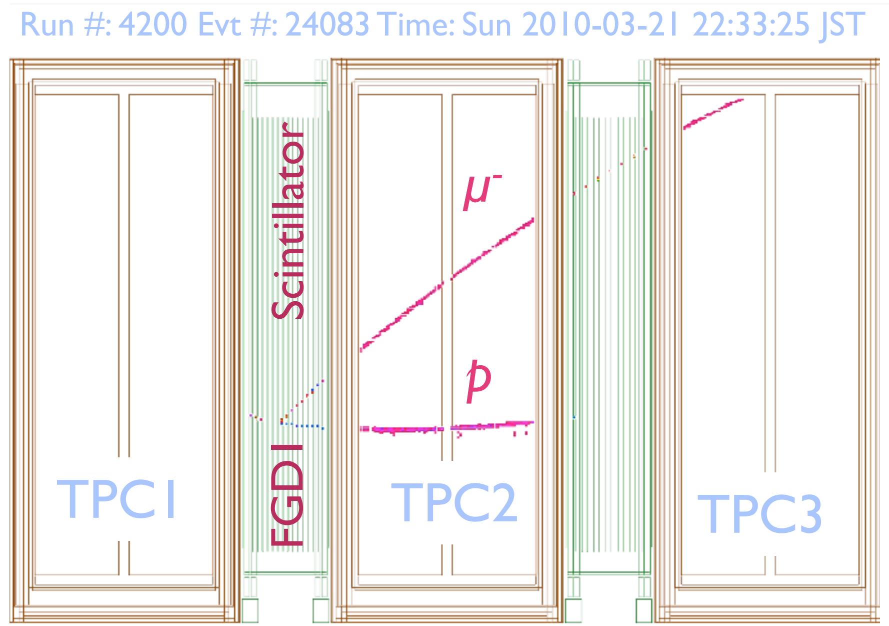
Low threshold allows model independent reconstruction of complete final state for detailed testing of models



$$E_\nu = E_\mu + \sum T_p$$



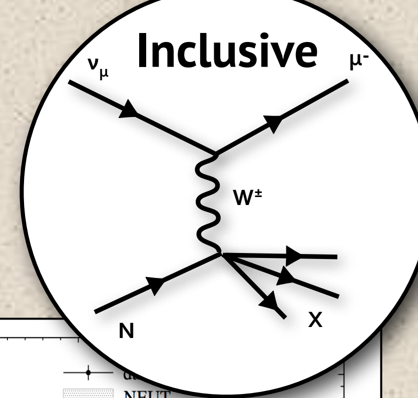


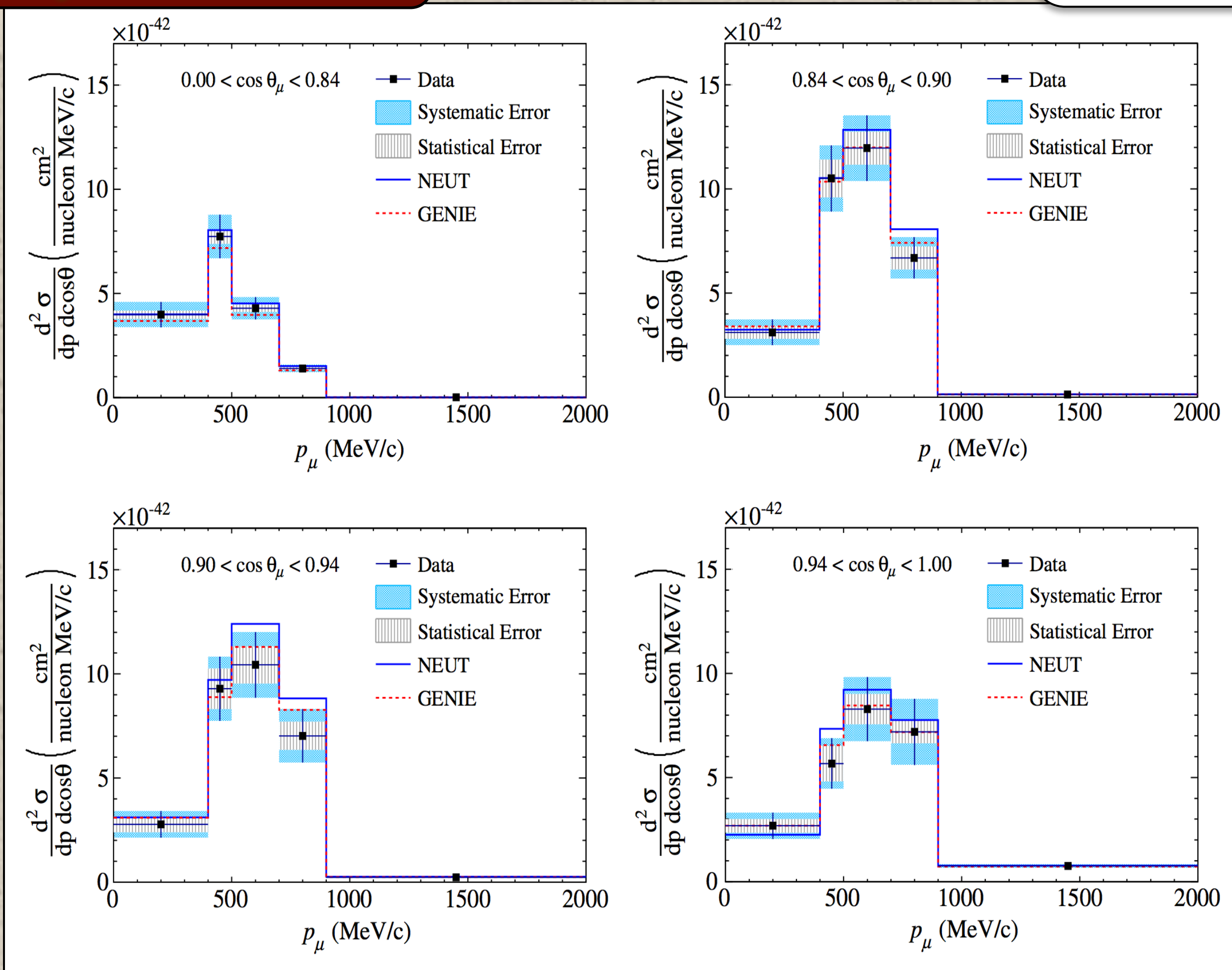


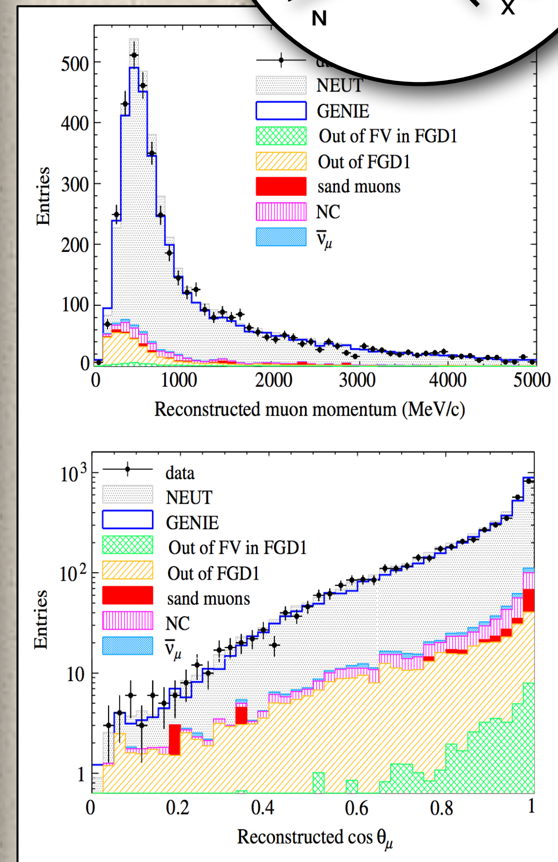
CCQE event candidate in the tracker region of the near detector. Muon reconstructed angle 40° and reconstructed momentum: 566 MeV/c

Differential cross sections very valuable!

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







CCQE and **NC elastic** measurements shown for first time here this week!

See WG2 talks from D. Hadley (CC), D. Ruterbories (NC)

Much More to Come

- MiniBooNE
  - CC inclusive cross sections
  - Antineutrino NC elastic
- MINERvA
  - More CCQE results
  - CC inclusive cross sections, comparisons between nuclear targets
  - Pion production processes (charged, neutral, coherent, resonant)
  - Electron scattering, electron neutrino CC interactions
- ArgoNeuT
  - Analysis of higher statistics antineutrino mode data (nu and nubar)
  - NC π^0, de-excitation g, pion production, electron events
- T2K
  - CCQE cross sections
  - NC channels

Future Possibilities

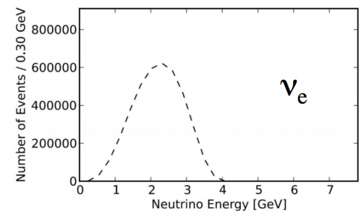
- The current generation of experiments will tell us a lot, but flux uncertainties in 5-10% range probably best we can do
- In some cases, analysis techniques used to reduce sensitivity to flux uncertainties

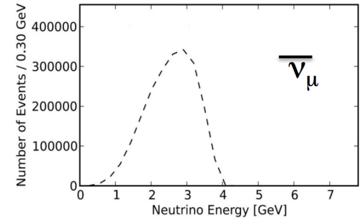
1. New sources would go a long way
   - nuSTORM $\delta\Phi(E) < 1\%$
   - Narrow band beams
2. Fine-grained, low-density detectors
   - The resolution and thresholds of LAr are fantastic, but we only measure on one pretty massive, non-isoscalar nucleus
   - Coupling trackable hydrogen/deuterium detector (bubble chamber) with well know ν_μ/ν_e fluxes represents the ideal complex for untangling cross sections and nuclear effects

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}	μ^- Channel	N_{evts}
$\bar{\nu}_\mu$ NC	844,793	$\bar{\nu}_e$ NC	709,576
ν_e NC	1,387,698	ν_μ NC	1,584,003
$\bar{\nu}_\mu$ CC	2,145,632	$\bar{\nu}_e$ CC	1,784,099
ν_e CC	3,960,421	ν_μ CC	4,626,480

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

Jorge G. Morfin - Fermilab 3

See WG2 talk from J. Morfin on Wednesday

Motivations Summary

- Precision matters (P. Huber's talk from Monday)
- Systematics are key (M. Mezzetto's talk from Monday)
  - Uncertainty in interaction and nuclear models often largest systematic on oscillation parameters measured through appearance. Are we even accounting for all the things we don't know in these models?
- Accelerator-based neutrino experiments performed in a very tricky region for neutrino-nucleus interactions
  - E_ν ~ 1 GeV off nuclear targets
  - Need to study both signal and background channels
  - Relationship between visible energy and the true neutrino energy has direct impact on extraction of oscillation parameters from data
- Be prepared…

Conclusions

- Busy times in neutrino interaction physics
  - Significant progress in past year from new experiments MINERvA, ArgoNeuT and T2K
  - Past year's results focused on inclusive samples and understanding nuclear effects in neutrino scattering (especially QE)
- Guaranteed to be continued progress by NuFact 2014. See you there!

End