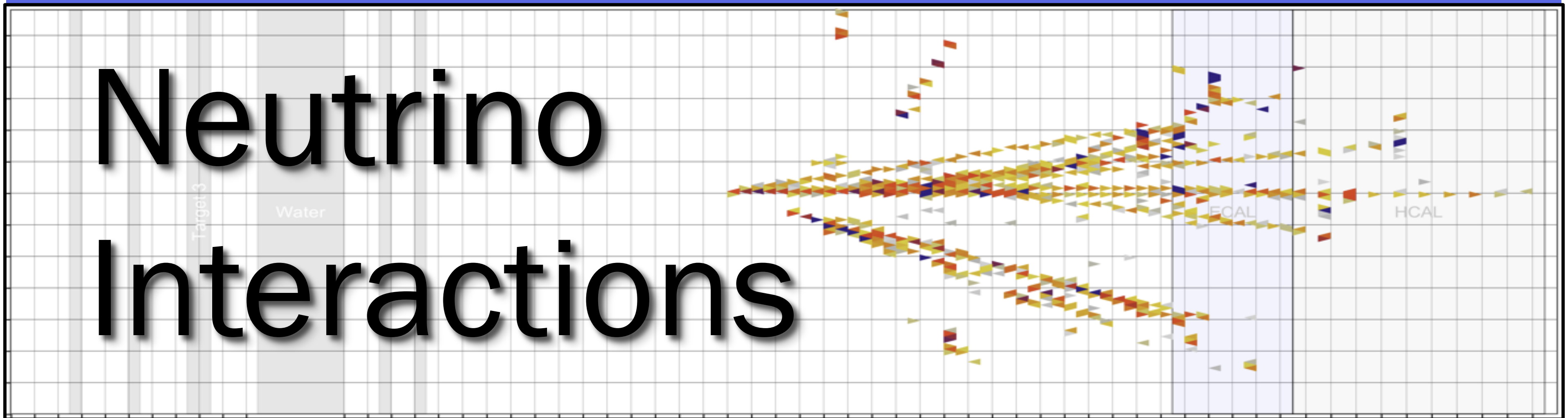
Neutrino Interactions



Fundamental Physics at the Intensity Frontier

November 30 – December 2, 2011

Rockville, MD

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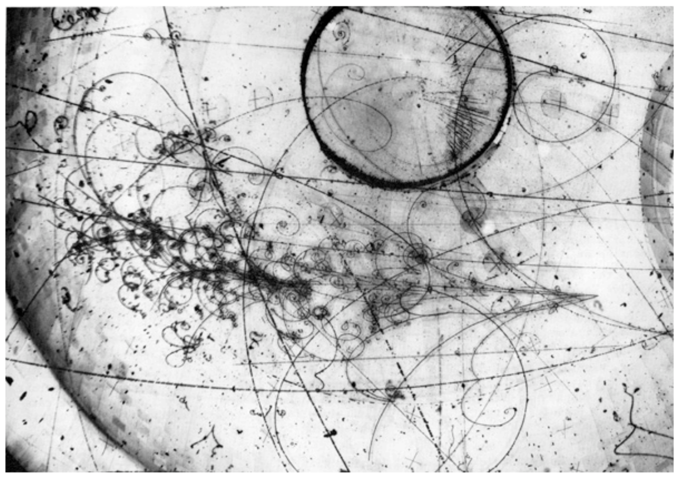
Fermi National Accelerator Laboratory

Fermilab

U.S. DEPARTMENT OF ENERGY | Office of Science

Introduction

- Physicists have been scattering neutrinos off nuclei for decades!
- So why are we still doing this!?!
- A few of the reasons…

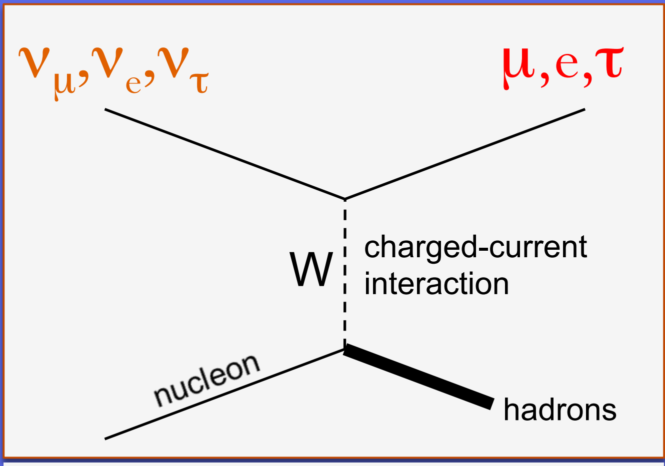


1. The discovery of neutrino oscillations in the past 15 years has put a new emphasis on understanding neutrino interactions around 1 GeV
2. Availability of modern, very intense neutrino sources provides an excellent opportunity to revisit the physics
3. Like any measurement, new data and higher statistics explorations can sometimes reveal previously hidden subtleties

Physics of GeV ν Interactions

- What physics are we after in making measurements of neutrino scattering in the $E_\nu \geq 1$ GeV region?
  - We need improved models of what happens when neutrinos interact on a nucleus (particularly in the 1 GeV region - not as simple as we thought)
    - Direct impact for interpreting neutrino oscillation data in the future
  - Neutrinos provide a pure weak force probe of nucleon structure and the nuclear environment
    - Contribute to our knowledge of nuclear physics, complimentary to wealth of available electron scattering data
    - Provide constraints for proton collider measurements (nucleon PDFs)

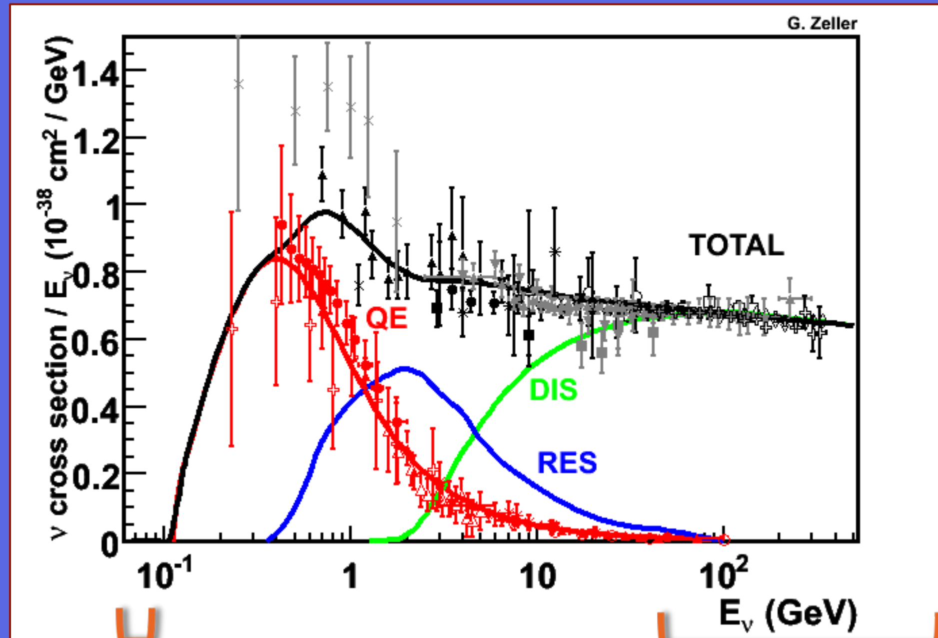
ν Cross Section Landscape



Quasi-Elastic, no pions

Nucleon Resonances, pions

Deep Inelastic Scattering



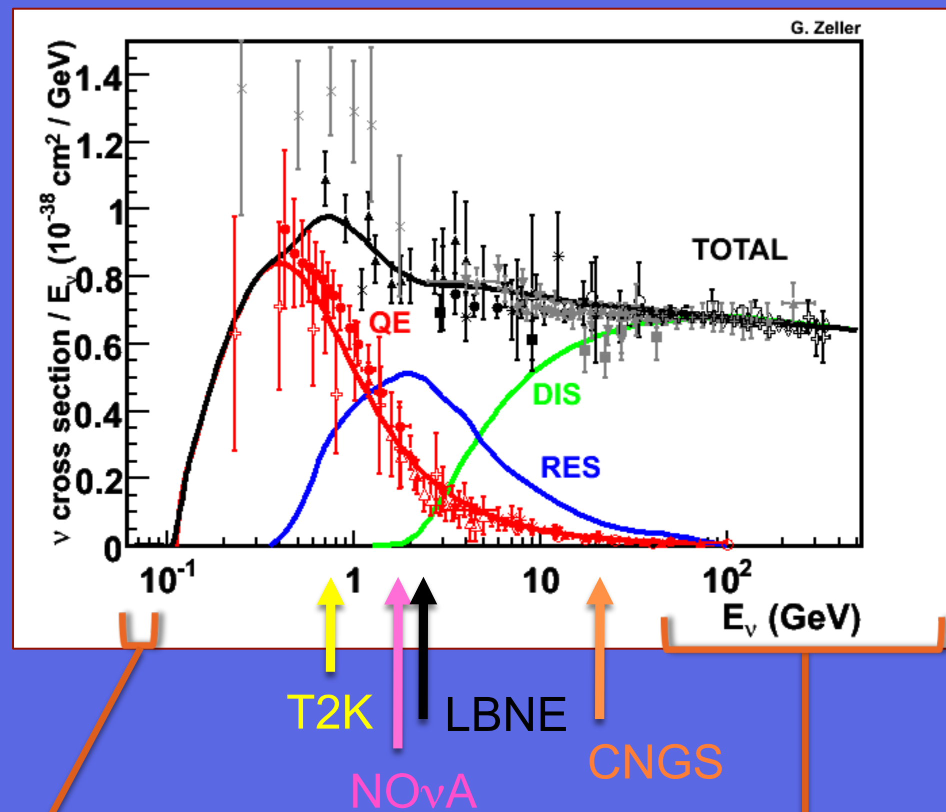
only CC cross sections shown

At low energies
Inverse Beta Decay
cross-section known to ~1%

At high energies
Deep Inelastic Scattering
cross section known to ~3%

GeV Neutrino Cross Sections

- Future long-baseline experiments addressing θ_{13}, mass hierarchy, and CP violation operate in the rather complex region at intermediate energies
- Large uncertainties, 20-40%
- Nuclear effects & final state interactions (FSI) are very important



At low energies

Inverse Beta Decay

cross-section known to ~1%

At high energies

Deep Inelastic Scattering

cross section known to ~3%

Input to Oscillation Searches

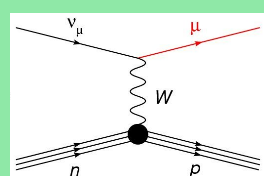
- The measured signal in a super beam, long-baseline neutrino experiment is a complicated convolution of:
  - energy-dependent, flavor-dependent neutrino fluxes + oscillations
  - energy-dependent, nu/antinu-dependent ν-N cross sections
  - energy-dependent, nu/antinu-dependent nuclear effects + FSI
  - kinematic-dependent, flavor-dependent detector response

Neutrino Beam Fluxes

$\nu_\mu \quad \bar{\nu}_\mu$

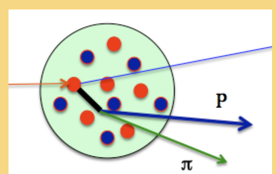
$\nu_e \quad \bar{\nu}_e$

ν-*N* Interactions



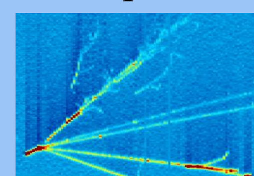
CC/NC $\nu, \bar{\nu}$

Final State Interactions



$\nu, \bar{\nu}$

Detector Response



PID, E_{vis}

Analysis Methods

Account for oscillations. Leverage Near Detector data.

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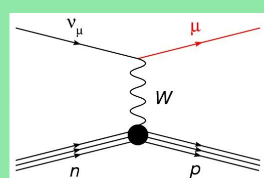
Neutrino Beam Fluxes

ν_μ $\bar{\nu}_\mu$

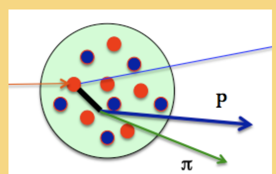
ν_e $\bar{\nu}_e$

ν-*N* Interactions



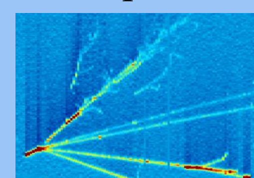
CC/NC $\nu, \bar{\nu}$

Final State Interactions



$\nu, \bar{\nu}$

Detector Response



PID, E_{vis}

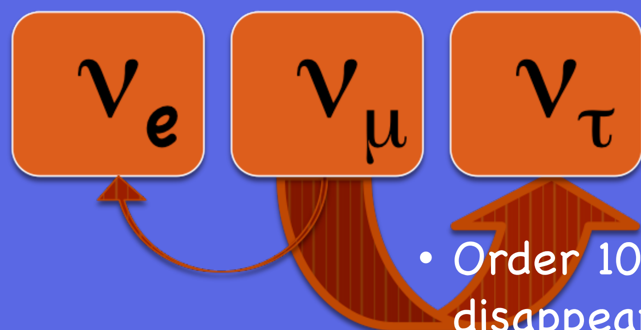
Analysis Methods

Account for oscillations. Leverage Near Detector data.

Input to Oscillation Searches

- Why the search for θ_{13}, neutrino mass hierarchy, and CP violation represents a paradigm shift in long-baseline neutrino oscillation experiments*

*and these issues suddenly matter a lot more



- Order 100% muon neutrino disappearance in muon neutrino beam
- Dominant effect simple two neutrino oscillation formalism
- Signal is CC ν_μ interactions virtually without background
- The near detector/far detector ν_μ spectrum distortion is the signal

Input to Oscillation Searches

- Why the search for θ_{13}, neutrino mass hierarchy, and CP violation represents a paradigm shift in long-baseline neutrino oscillation experiments*

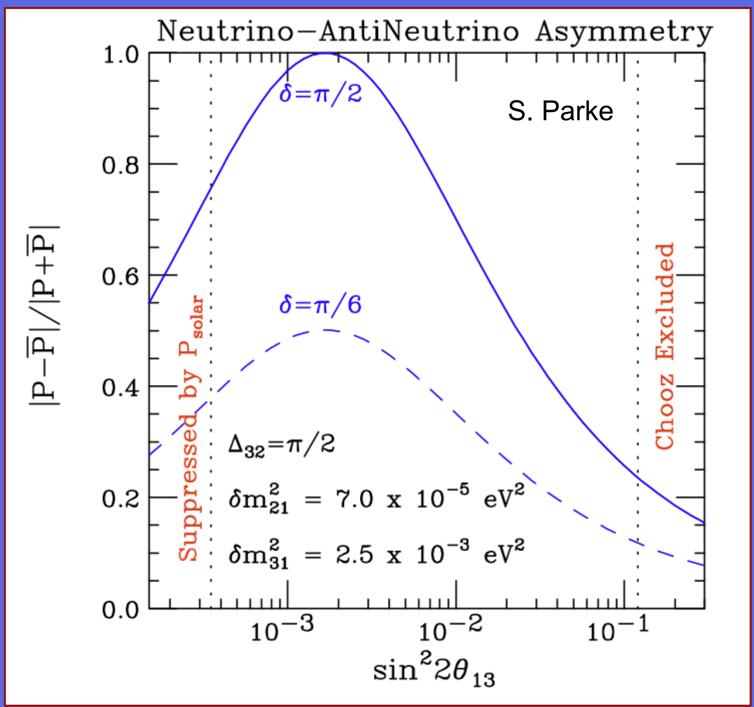
*and these issues suddenly matter a lot more

- Order 1% electron neutrino appearance in muon neutrino beam
- Oscillation has lots of structure from tangled effects (mass order, CP phase)
- Signal is CC ν_e interactions over a large ν_μ NC background
- The near detector/far detector ν_μ spectrum distortion causes the background rates to change radically

- Order 100% muon neutrino disappearance in muon neutrino beam
- Dominant effect simple two neutrino oscillation formalism
- Signal is CC ν_μ interactions virtually without background
- The near detector/far detector ν_μ spectrum distortion is the signal

Input to Oscillation Searches

- We've all been hoping for large θ_{13}, but may not help with ~~CP~~
- Discovery of ~~CP~~ will require tight control of systematics
  - Comparing oscillations measured in different beams with very different spectra and different backgrounds (different systematics)



- Need a detailed understanding of absolute effects, but especially any neutrino / antineutrino differences

  different fluxes ($\sigma \approx$7-25%)

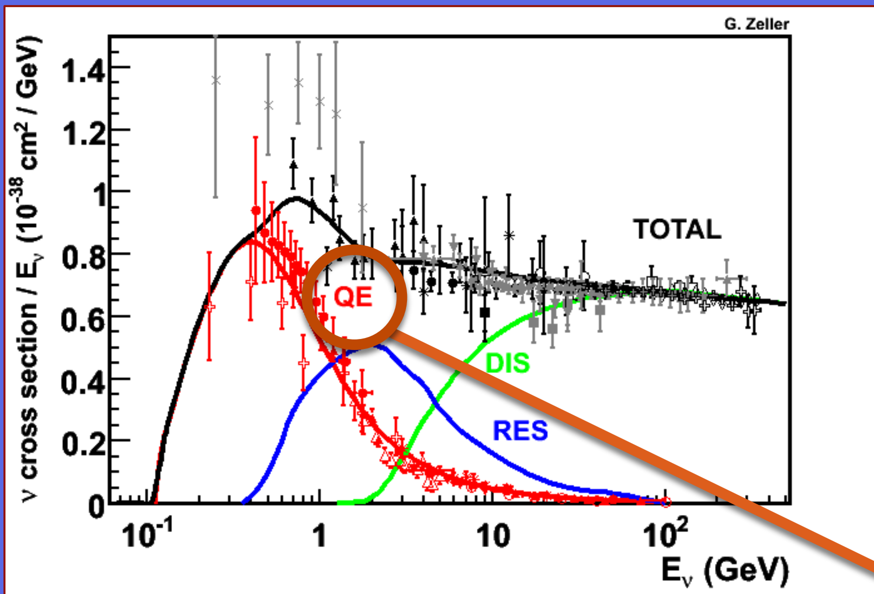
  different cross sections ($\sigma \approx$20-50%)

  different nuclear effects ($\sigma \approx$20-50%)

  different backgrounds

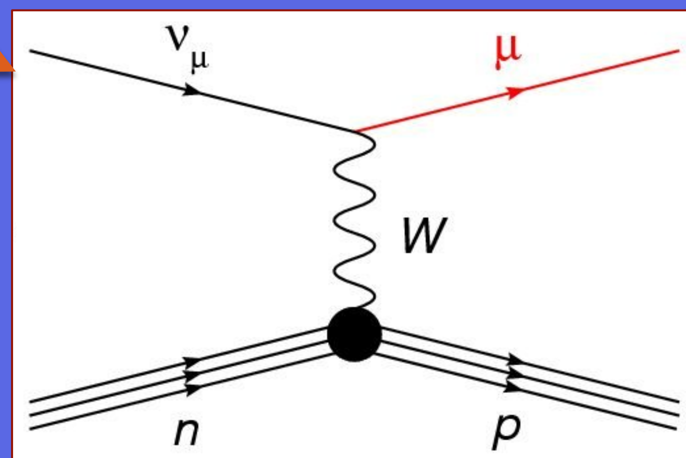
  different E_ν -> $E_{visible}$

Example: ν Quasi-Elastic Scattering



- Quasi-Elastic channel
- Largest fraction of σ < 1 GeV
- Often largest contribution to oscillation signal samples

$$\nu_\ell + n \rightarrow \ell^- + p$$



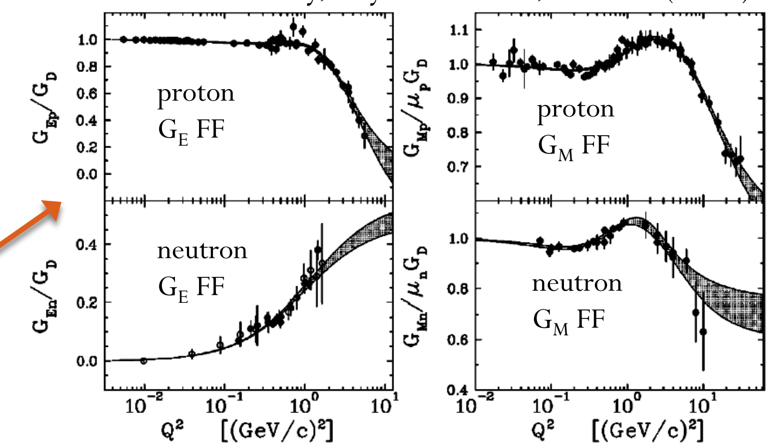
- Lepton gives you neutrino Flavor ID
- Determine neutrino energy from lepton kinematics alone

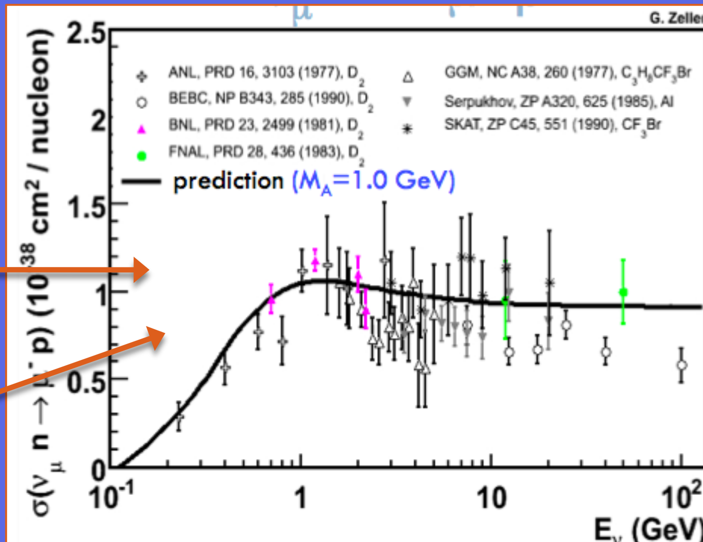
So, clearly, important to understand QE scattering

Example: ν Quasi-Elastic Scattering

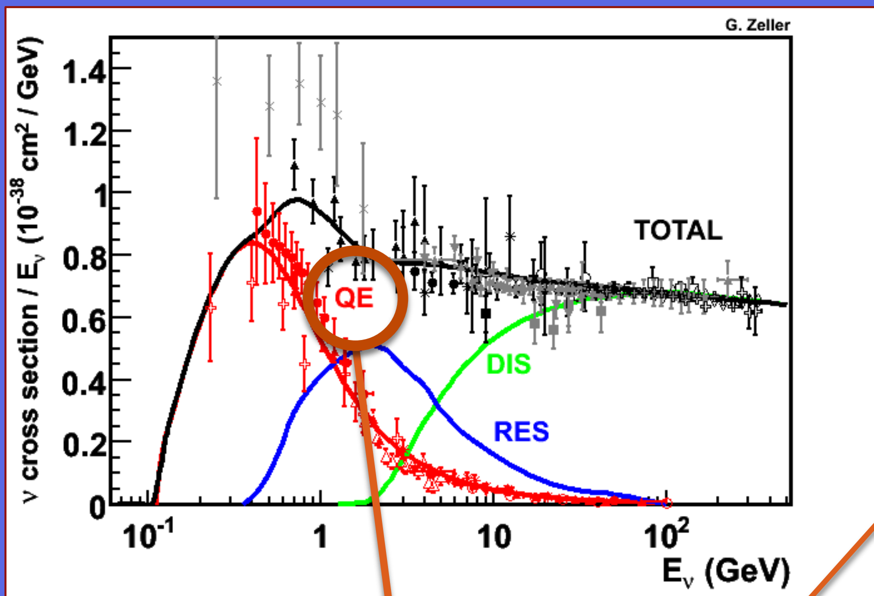
- With first measurements, basic strategy was straightforward:
  - Start with model of cross section with vector and axial-vector components
  - Vector Form Factors well known from precise electron scattering data
  - Target nucleus modeled as Relativistic Fermi Gas (RFG) of independent nucleons
  - Assume dipole form for Axial-Vector Form Factor, and determine axial mass from neutrino data
  - Early ν scattering data mostly on light targets (D_2), with low intensity beams

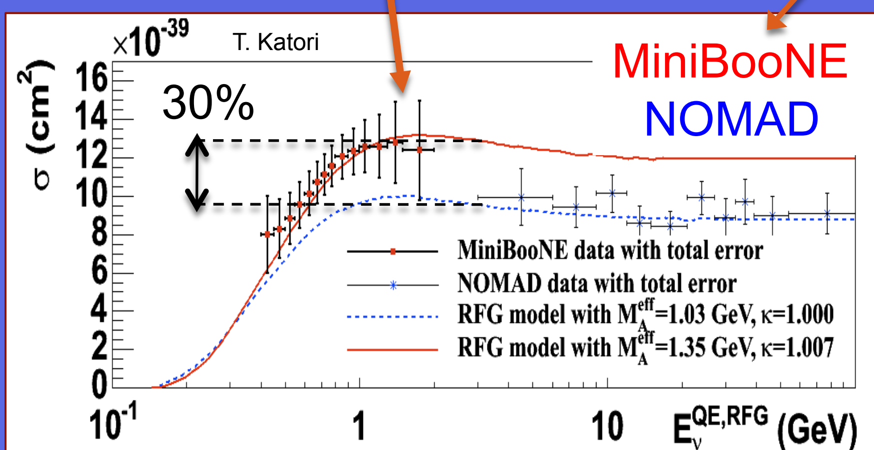
Kelly, Phys. Rev. **C70**, 068202 (2004)





Example: ν Quasi-Elastic Scattering

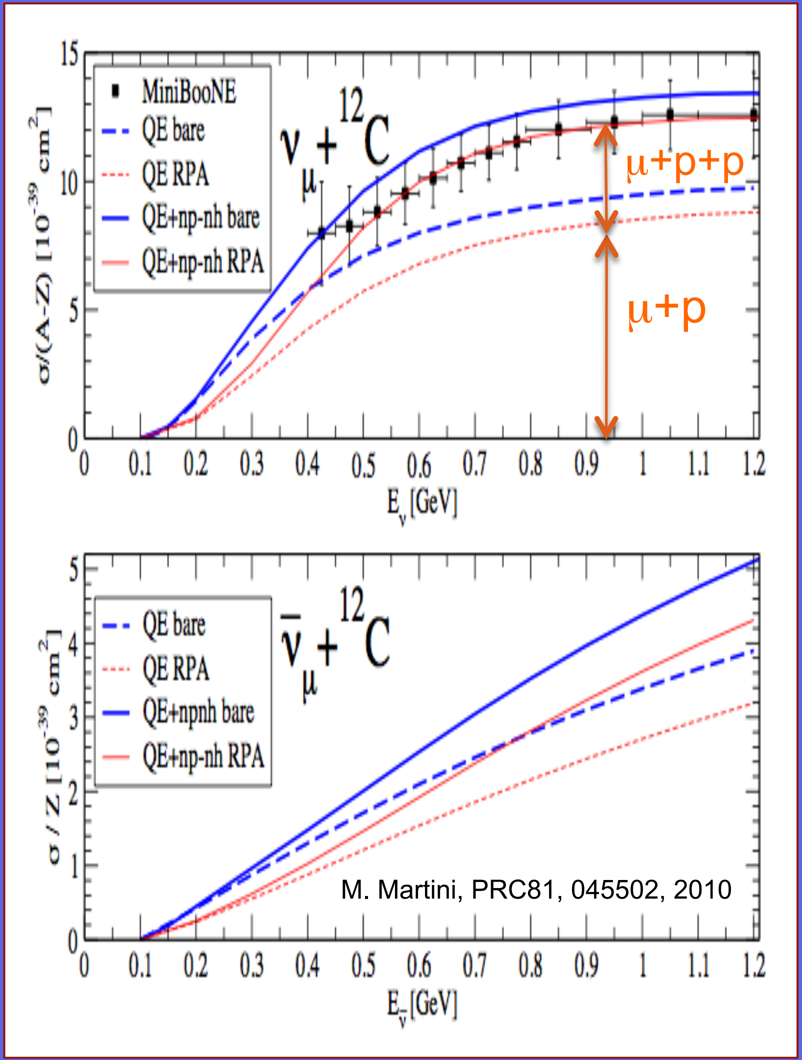




- But with modern, high statistics data on heavier targets (carbon), one finds tension with models that needs to be resolved
- For example, how to explain the low-energy / high-energy discrepancy seen in measurements of quasi-elastics by different experiments
- Very active area of study by both theory & experiment to understand and properly model

- QE just an example: many other important channels to understand

Nuclear Effects



- Quite a few models have become available to explain the excess QE cross section reported by MiniBooNE at ~1 GeV

- For example, discrepancy may be tied to nuclear dynamic effects

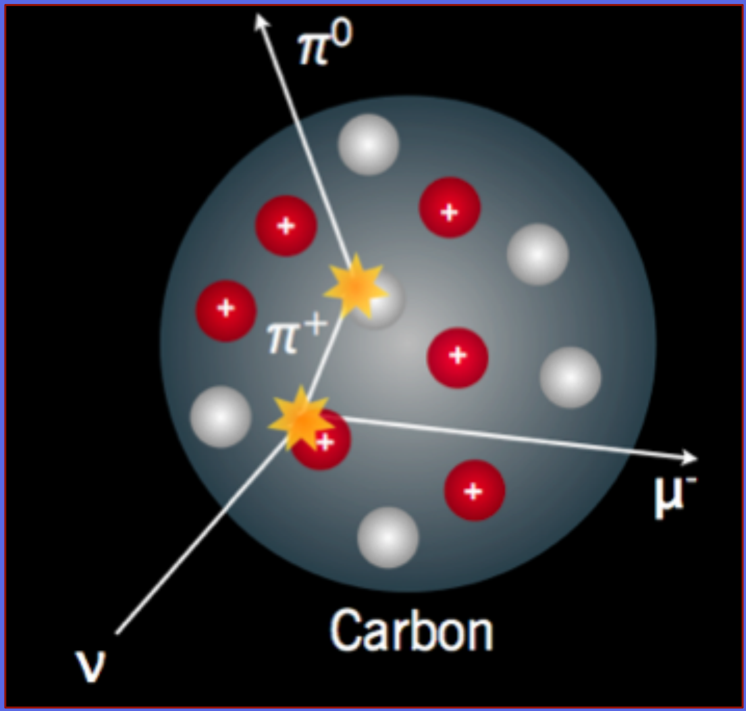
  Ex. multi-nucleon correlations that create an enhancement in the "quasi-elastic" cross section (no pions – μ, μ+p, μ+p+p, …)

- Important to resolve this and get it right in neutrino event generator MCs

- Models often predict different effects for neutrinos and antineutrinos

Final State Interactions

- Have come to realize importance of final state interactions (FSI) in this energy range as well
  (more nuclear effects!)
- Once produced, hadrons have to actually make it out of the target nucleus
  - nucleon rescattering
  - π absorption
  - π charge exchange
- Distortions are large (>20%) and predictions can vary

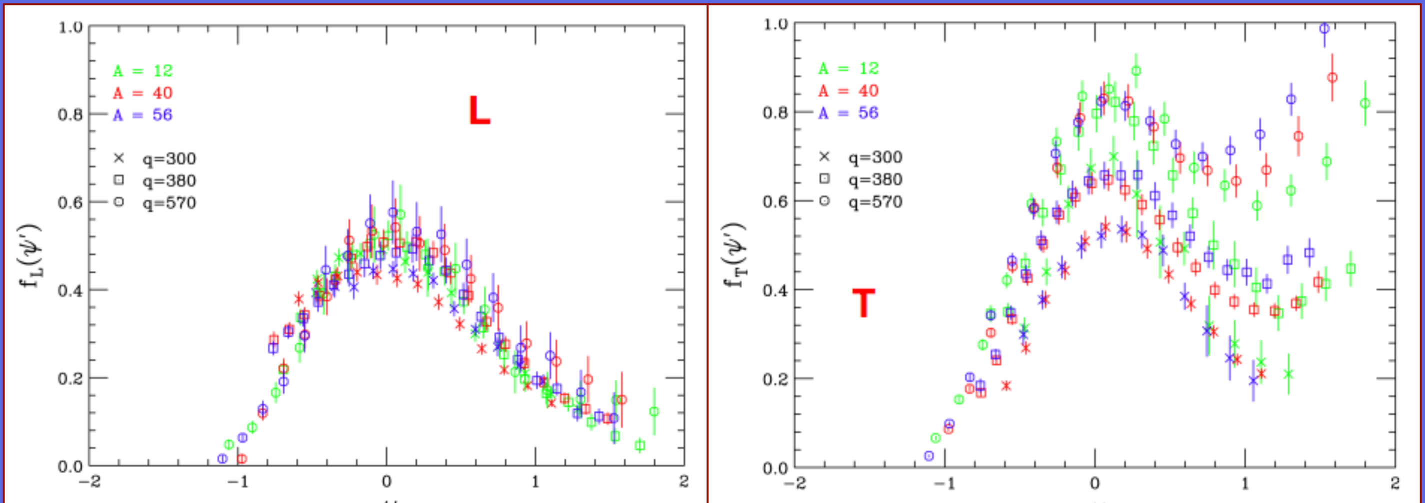


signals ←→ backgrounds

ν/e⁻ Scattering

- Briefly hinted earlier at a connection between ν/e scattering (used to get vector part of the QE cross section)
- More than QE. Available e-A scattering data is high statistics, not to mention you know the kinematics of the incident lepton!
- Any complete model of these interactions should be able to reproduce effects seen in both charged and neutral lepton scattering data

meant to be illustrative - data on many nuclei across range of energy transfers



B. Donnelly, Fermilab seminar, 2011

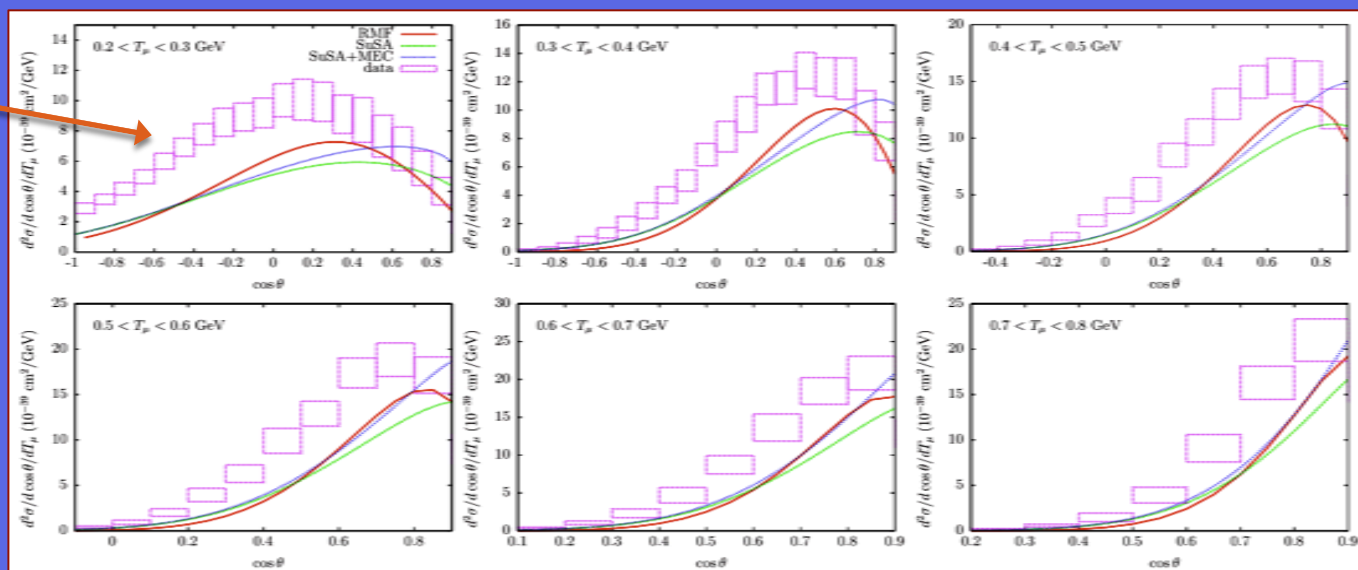
Differential Cross Sections

- Very important to go beyond exclusive channel cross sections vs. E_ν only and map out **differential cross sections** vs. lepton and hadron kinematics in the final state
- Historically, have not had the statistics to do this until now
- Will provide a **much more complete test of cross section and final state interaction models**

J.E. Amaro et. al. PRD84, 033004, 2011

an example using MiniBooNE QE data

$d\sigma/d\cos\theta_\mu$ in bins of T_μ



ν Scattering Experiments

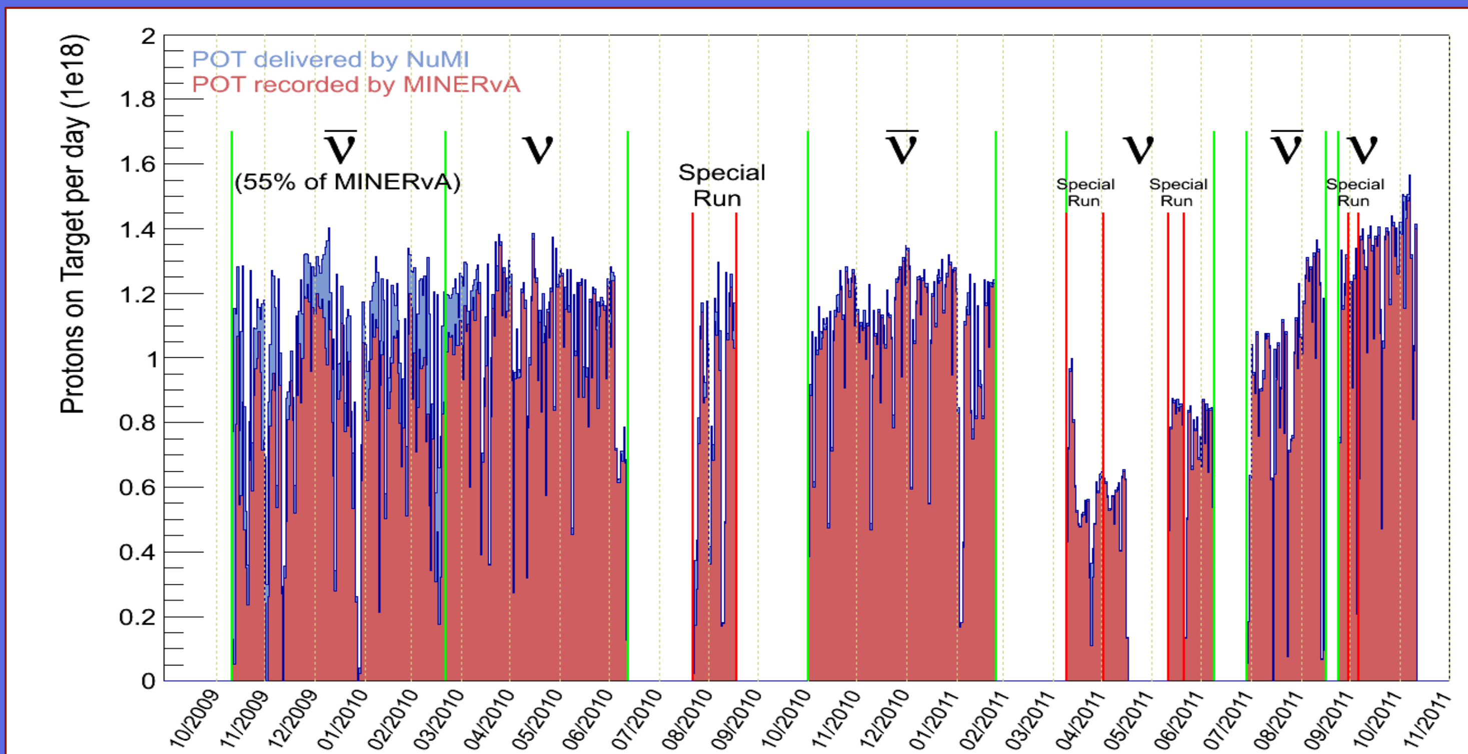
- Lots of experiments have contributed to understanding GeV cross sections in recent years:
  - Short-baseline oscillation experiments like MiniBooNE and NOMAD
  - Long-baseline oscillation near detectors like K2K, MINOS and T2K
  - Dedicated experiments like SciBooNE

Basics of MINERνA

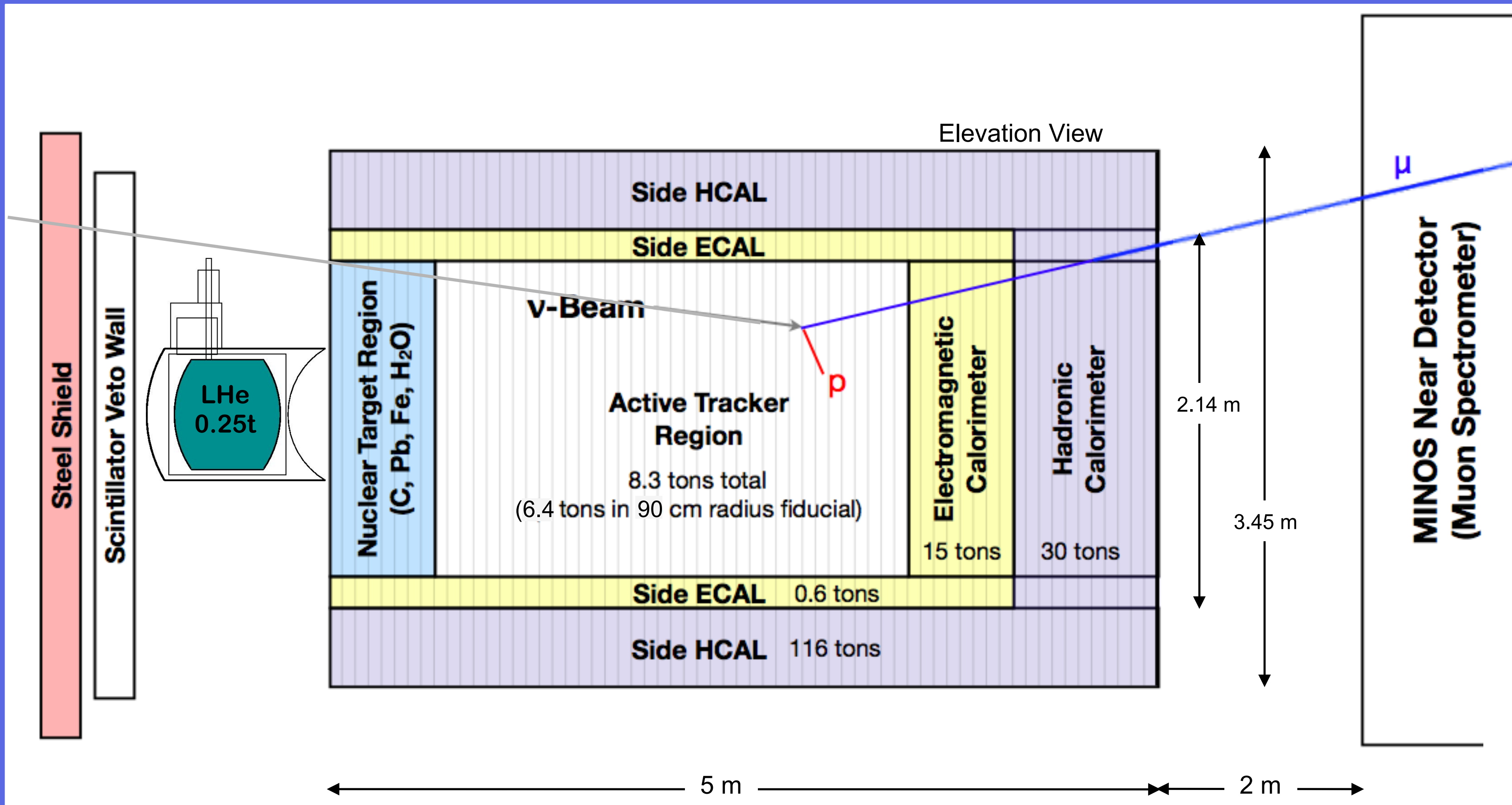
- MINERνA was designed specifically to advance our knowledge of neutrino cross sections and nuclear physics
- The only currently running dedicated ν scattering experiment
- Makes use of the existing high-intensity NuMI beam and MINOS Near Detector at Fermilab ($E_\nu \approx$ 1-20 GeV)
- Detector is finely-segmented, fully-active scintillator core surrounded by electromagnetic and hadronic calorimetry
- Range of nuclear targets (He, C, H_2O, Fe, Pb) in the same detector and same neutrino flux for measuring A dependence and untangling nuclear effects in neutrino scattering

MINERνA Physics Run

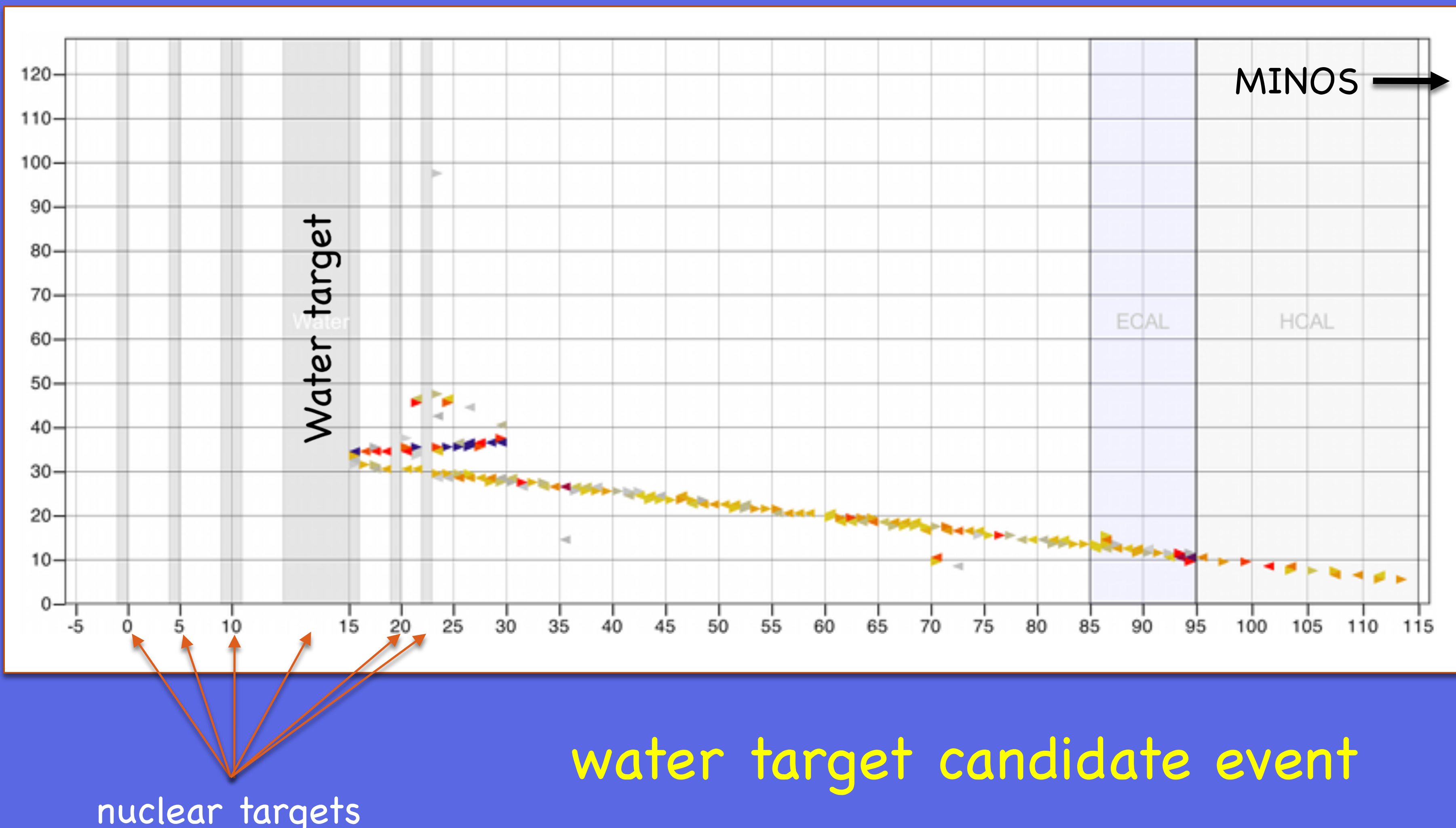
- Neutrino and antineutrino exposures over past 2 years
- Presently completing an effort to calibrate and reconstruct full data set for analysis



MINERνA Detector

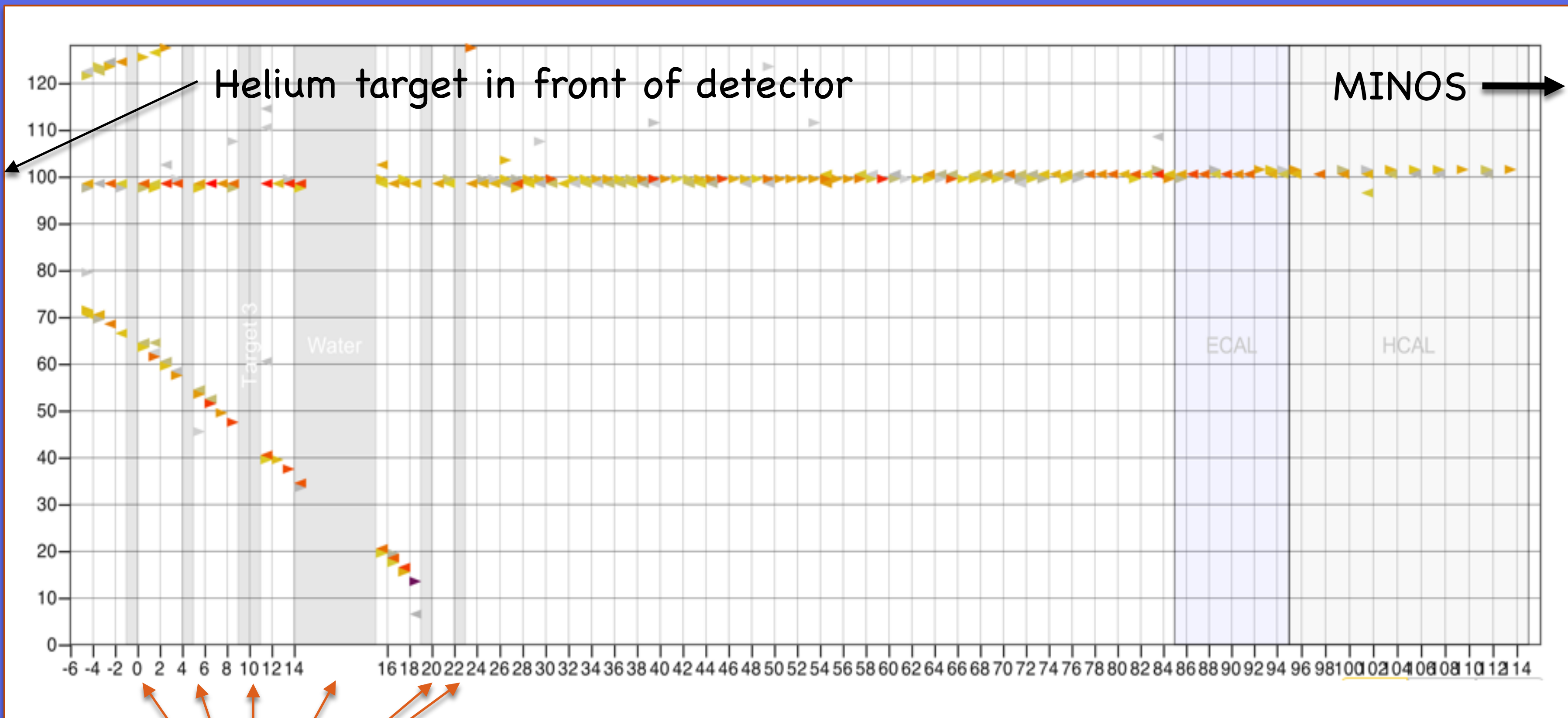


MINERνA Events



water target candidate event

MINERvA Events

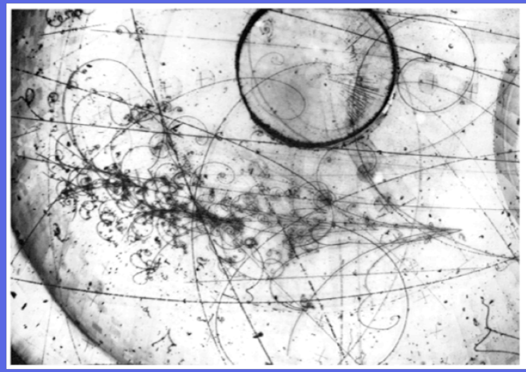


nuclear targets

helium target candidate event

ν – Hydrogen / Deuterium

- Speaking of helium, modern high-intensity neutrino beams provide an excellent opportunity to revisit "nuclear effects free" ν-H, ν-D_2 scattering at high statistics (no data since bubble chambers)
- Precise flavor and sea/valence separations of nucleon parton distributions possible
- MINERνA has submitted an LOI to fill their helium tank with hydrogen and deuterium
- But MINERνA tank is not instrumented, miss activity near the vertex



- Ideal detector would be to truly "return to our roots" with something like a bubble chamber detector + muon tracking

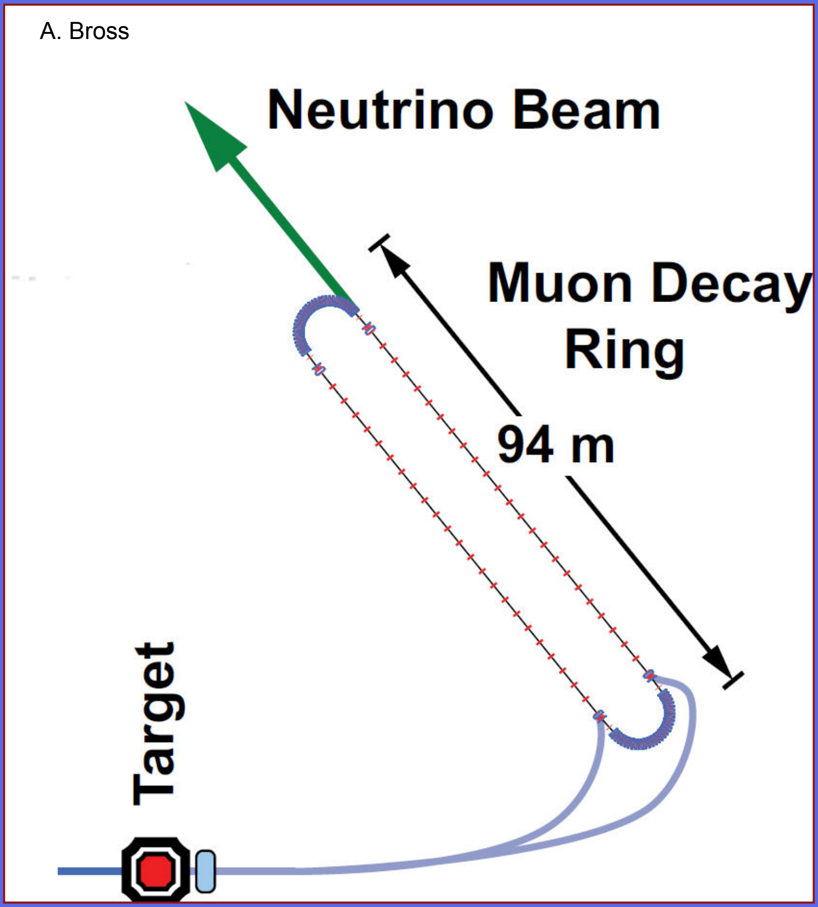
Beyond MINERνA?

- The question was asked last evening, "Will we need neutrino scattering measurements beyond MINERνA for CP measurement?"
- There is important data on the horizon to complement MINERνA measurements with data on other targets and at lower E_ν
  - T2K near detectors, MicroBooNE
- Right kinds of near detectors at future SB complexes would surely enjoy extremely high event rates
- Key ingredient to any good cross section measurement – flux!
  - MINERνA is working hard to fully exploit neutrino data taken in special beam configurations as well as existing external hadron production data
  - Assembling proposal now to make dedicated hadron measurements at NA61
    - IMO, all modern super beam experiments should just do this

Cross sections to 1%?

- If needed, the ultimate solution may be something like the "mini neutrino factory" proposed by A. Bross
  - A. Blondel's talk yesterday

- Measure absolute muon and electron neutrino cross sections to 1%?



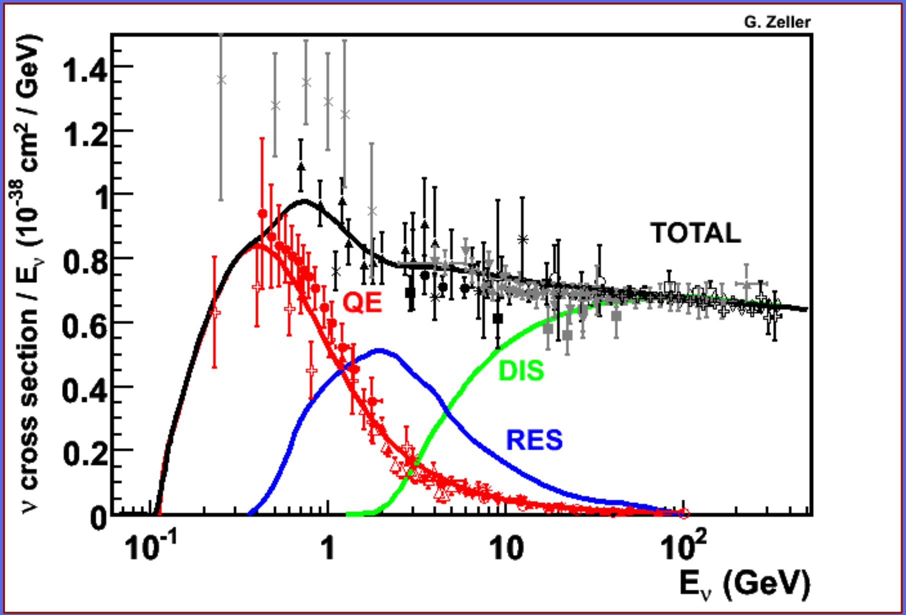
Summary

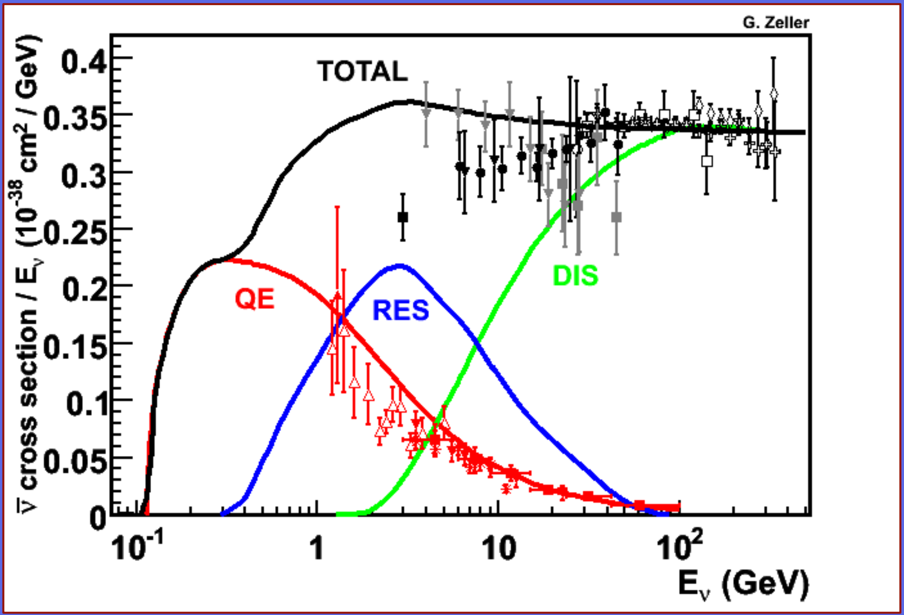
- ν-A scattering is a rich field at the boundary of high-energy and nuclear physics, weak and strong interactions
- Lots of compelling questions, majority of Ph.D.'s in the field probably still neutrino scattering related measurements (even on oscillation experiments)
- While low and high-energy cross sections are well known, the GeV energy region relevant for LBL oscillation experiments is complicated and more crudely understood
- Critically important to know ν cross sections and the impacts of nuclear effects for interpreting LBL $\overset{(-)}{\nu}_\mu$ -> $\overset{(-)}{\nu}_e$ oscillation data.

Lots to do!

Backups…

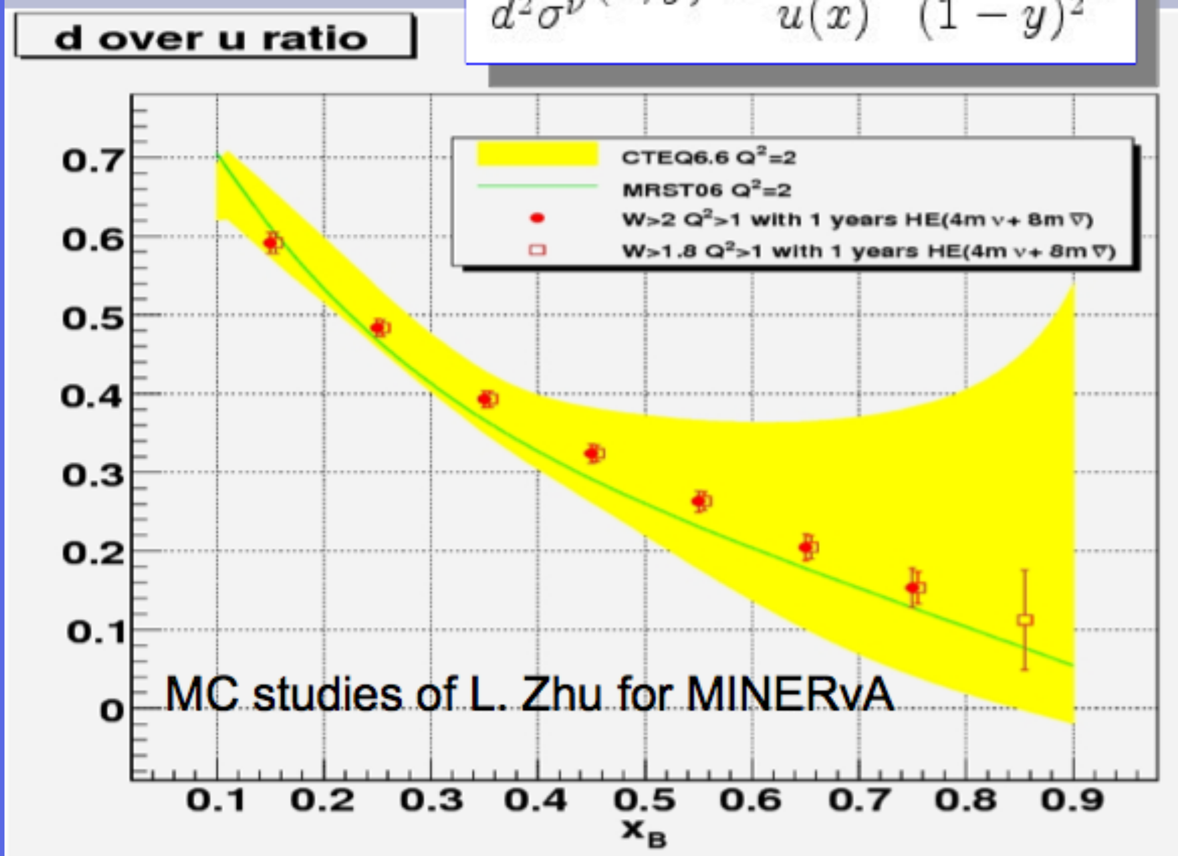
$\nu/\bar{\nu}$ Cross Sections





Nucleon Quark Content

$$\frac{d^2\sigma^{\nu}}{d^2\sigma^{\bar{\nu}}}(x,y) \sim \frac{d(x)}{u(x)} \cdot \frac{1}{(1-y)^2}.$$



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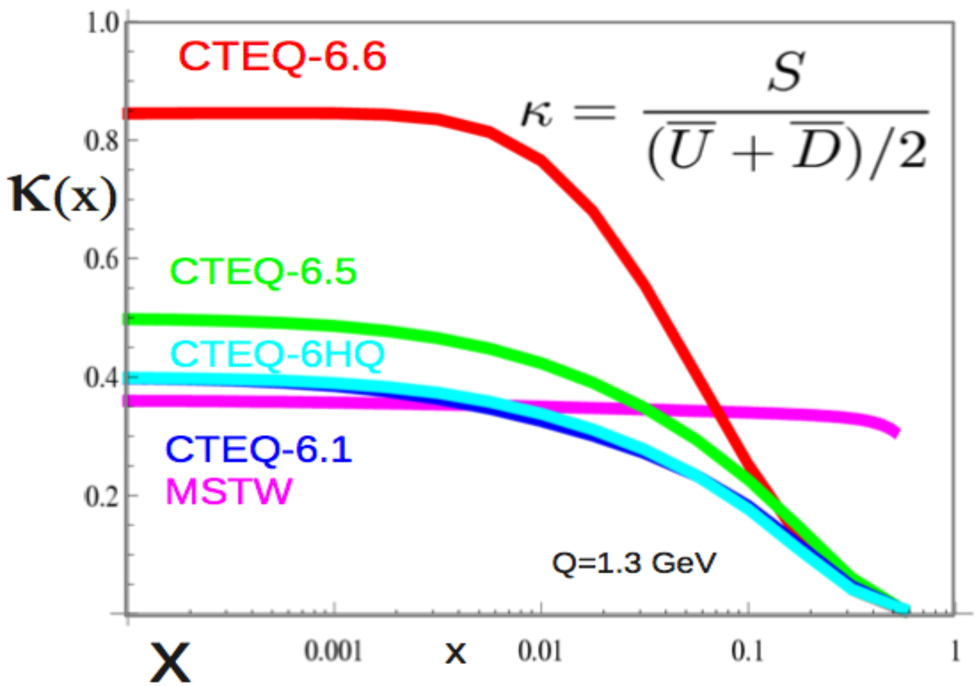
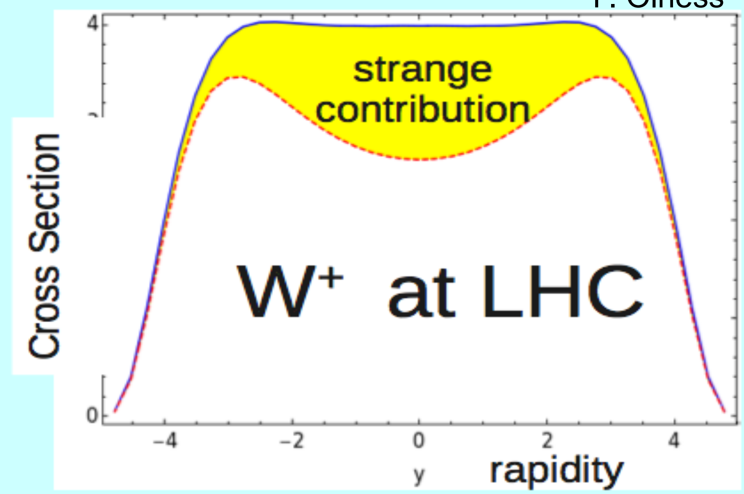


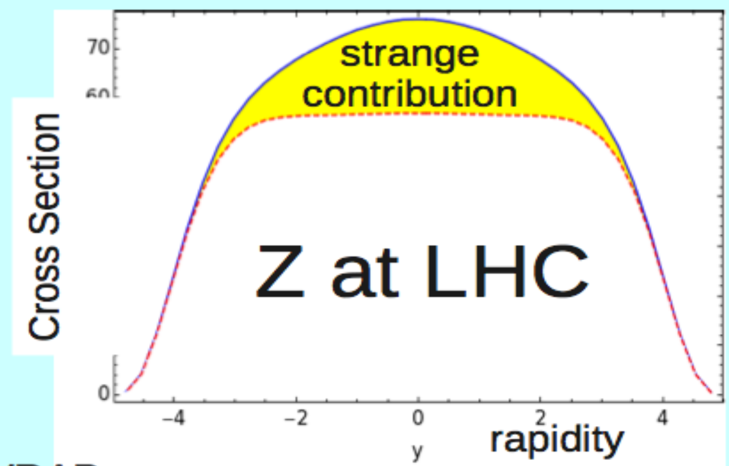
CTEQ6.5+ … no nu-DIS

PDF Uncertainties will feed into LHC "Benchmark" processes

Comparison with new NNPDF sets: Les Houches 2009

F. Olness





VRAP Code

Anastasiou, Dixon, Melnikov, Petriello, Phys.Rev.D69:094008,2004.