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Neutrino Interactions

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International Neutrino Summer School 2018

May 28 2018

Outline

- History and Introduction
- Neutrino beam
- Neutrino interactions and neutrino cross sections
- Ingredients to compute cross sections
  - Flux

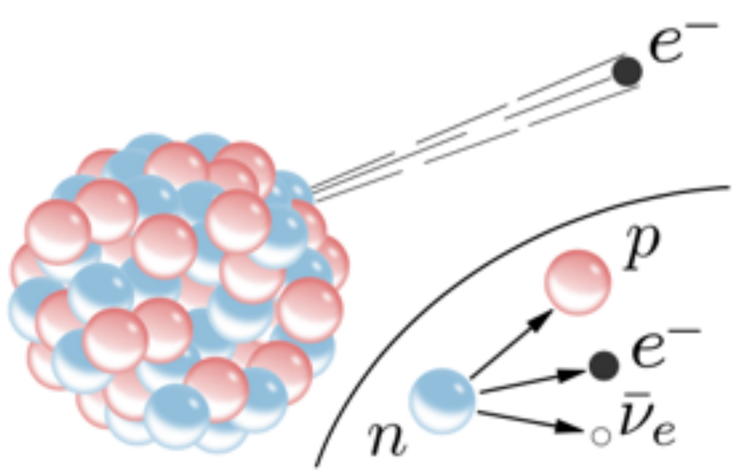
How did we discover neutrinos?

- Radioactivity: Nucleus emits particle due to nuclear instability
- While studying the beta decay, the energy did not seem to be conserved in beta decay?
  - We know energy is always conserved
  - Energy can neither be created nor destroyed only can be transformed into a different form
- In 1930, Pauli postulated the neutrino

Dear Radioactive Ladies and Gentlemen,

I have done a terrible thing.

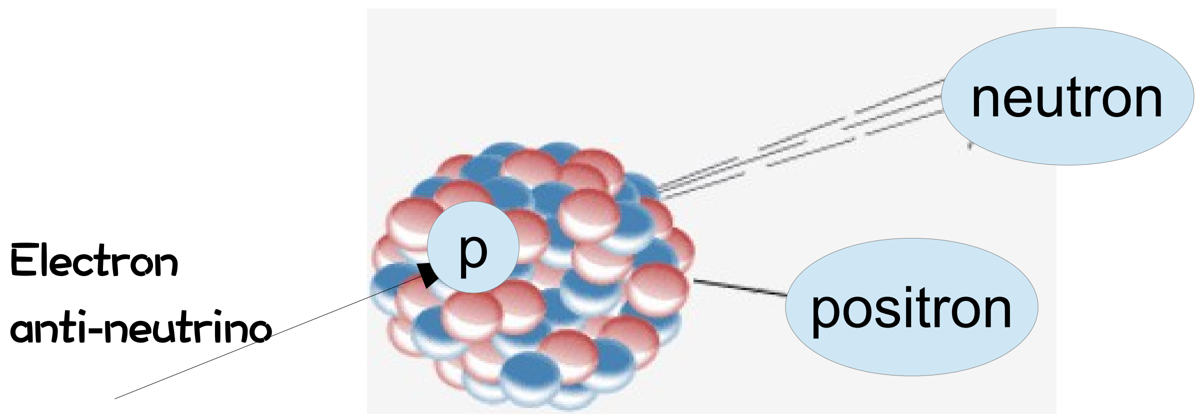
I have postulated a particle that cannot be detected



The Discovery of Anti-Neutrino (1956)

- Artificially produced neutrinos from nuclear reactors
  - Emits around 10 trillion anti-neutrinos per cm^2/s
- Inverse Beta decay

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

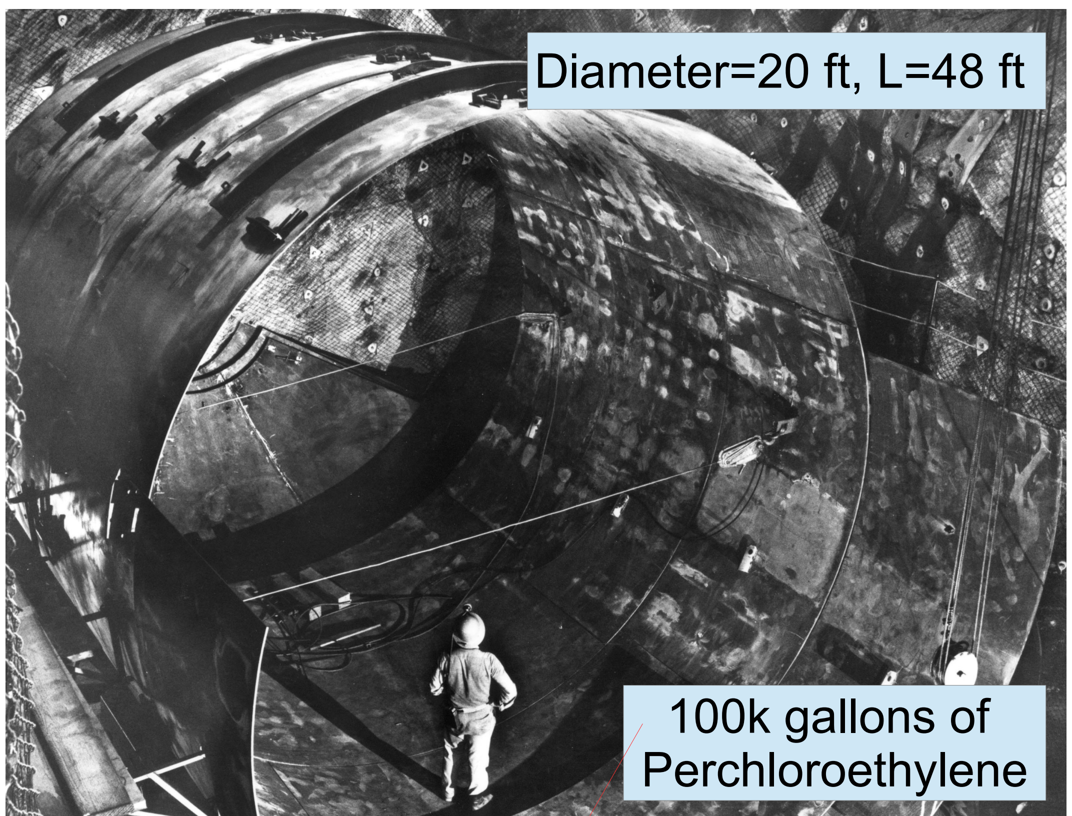


1995 Nobel Prize

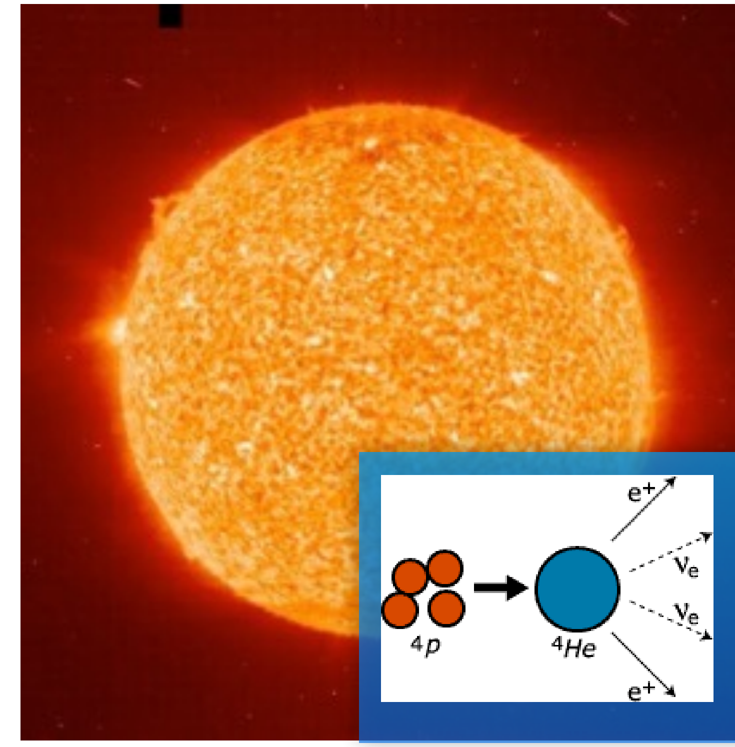
The Solar Neutrino Problem (1968)

- Nuclear reactions in the core of the sun produce ν_e
- In 1968, Ray Davis's HomeStake experiment measured the ν_e that arrives at earth using a huge tank of cleaning fluid

solar neutrino+chlorine atom->electron+argon atom



Cleaning fluid

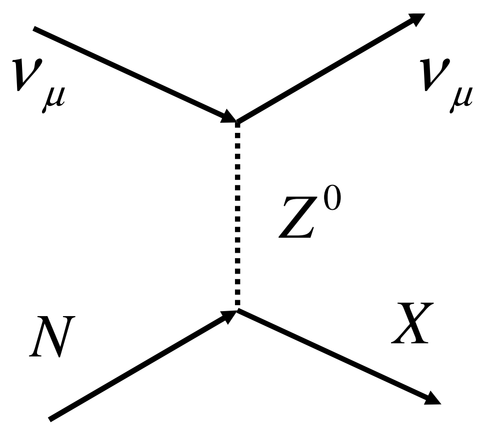


2002 Nobel Prize

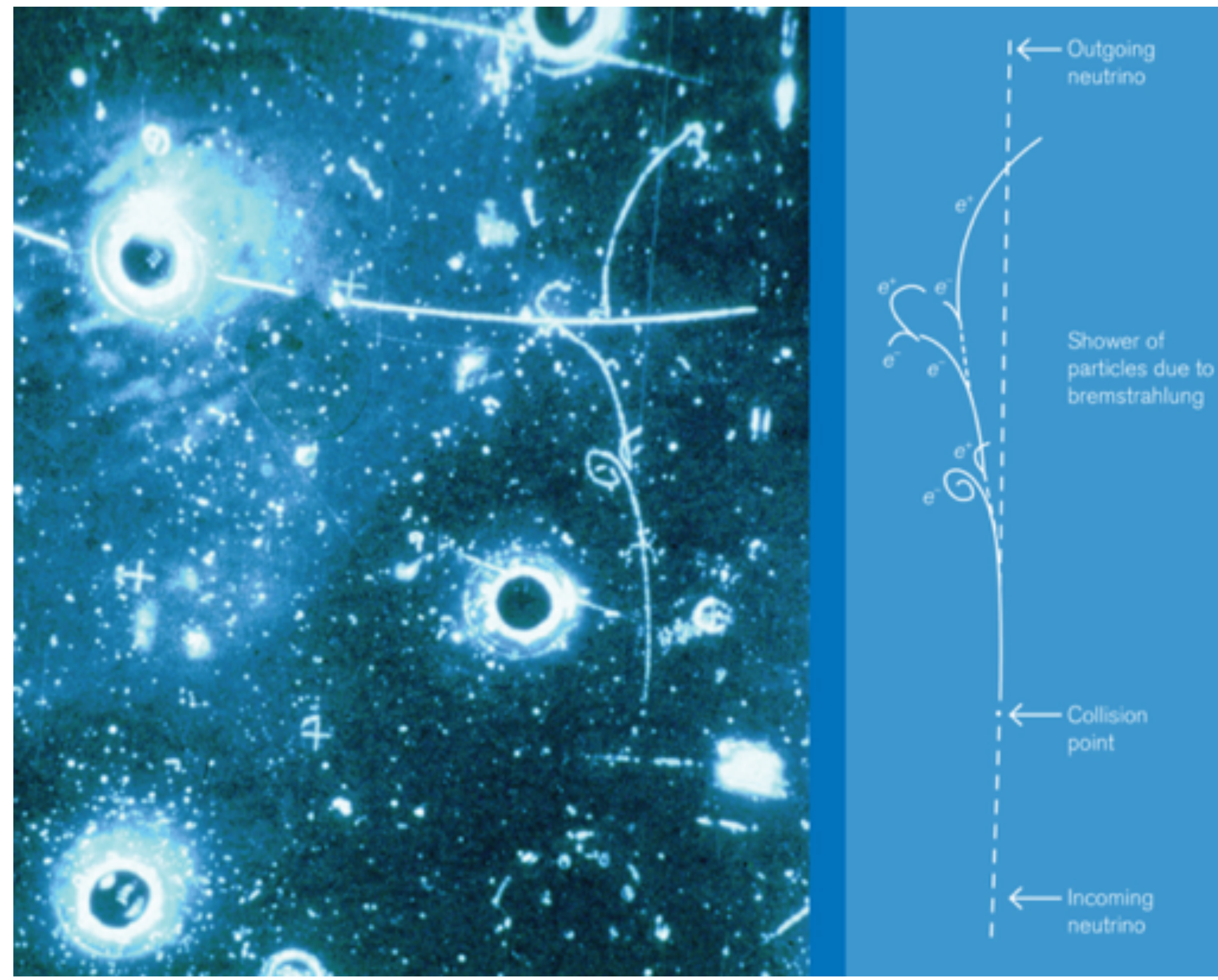
- Davis published the first results indicating that only 1/3 of the neutrinos were observed, i.e. the solar neutrino problem

Another Interaction Neutral Current

- In 1973 first example of NC observed at Gargamelle bubble chamber filled with freon
  - 700,000 pictures!



$$\nu_\mu + N \rightarrow \nu_\mu + X$$

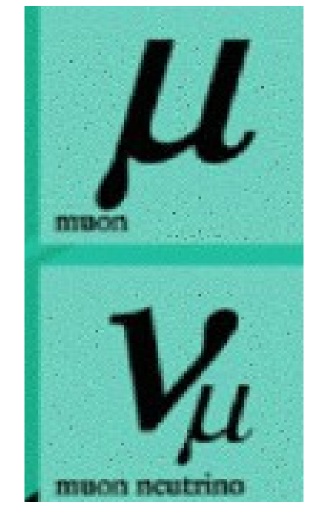


Other Neutrino Flavors

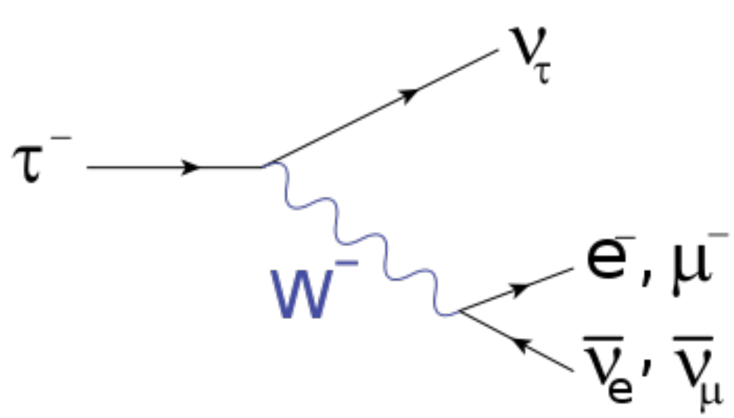
- In 1988 the muon neutrino was discovered at Nacional de Brookhaven lab
  - The first accelerator neutrino beam (5GeV protons on Be target)

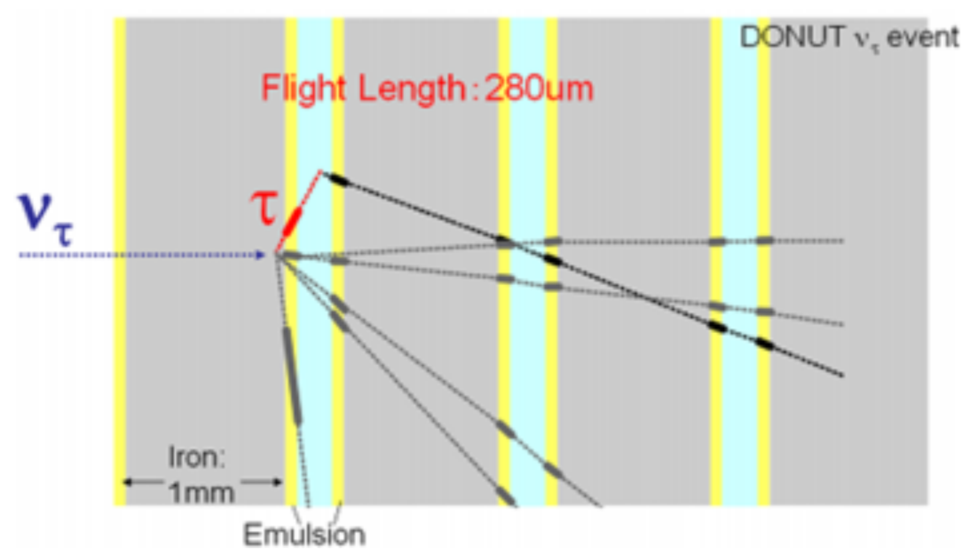
$\pi^+ \rightarrow \mu^+ \nu_\mu$

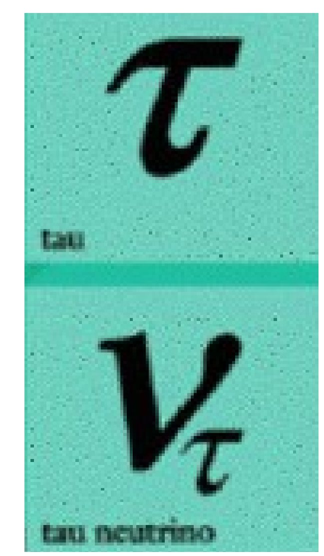




- In 2000, the third neutrino (tau neutrino) was discovered at DONUT (Fermilab).



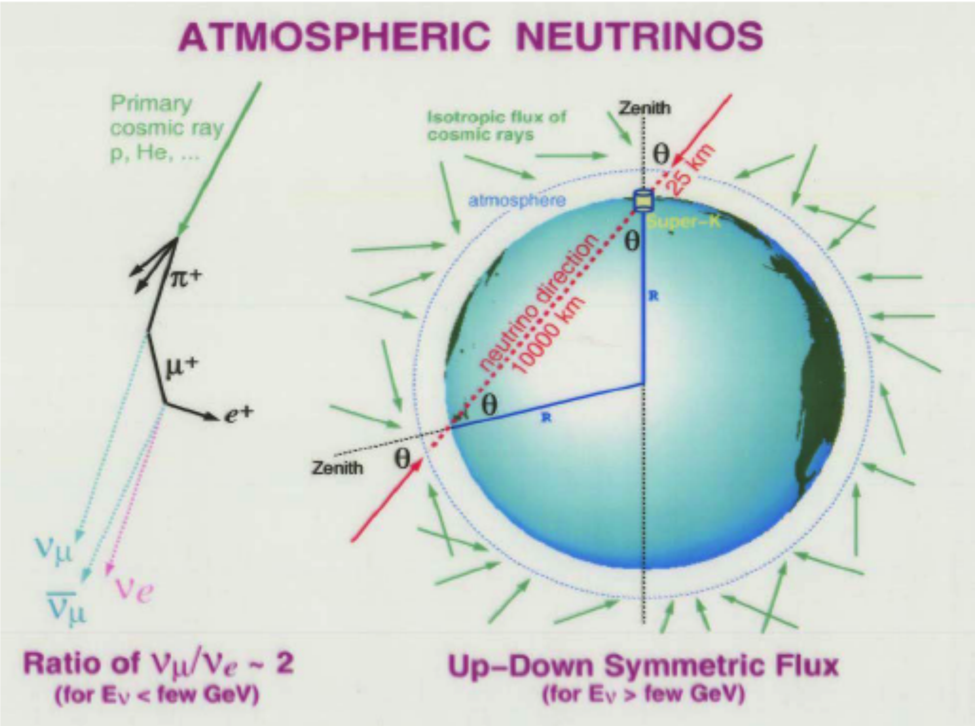


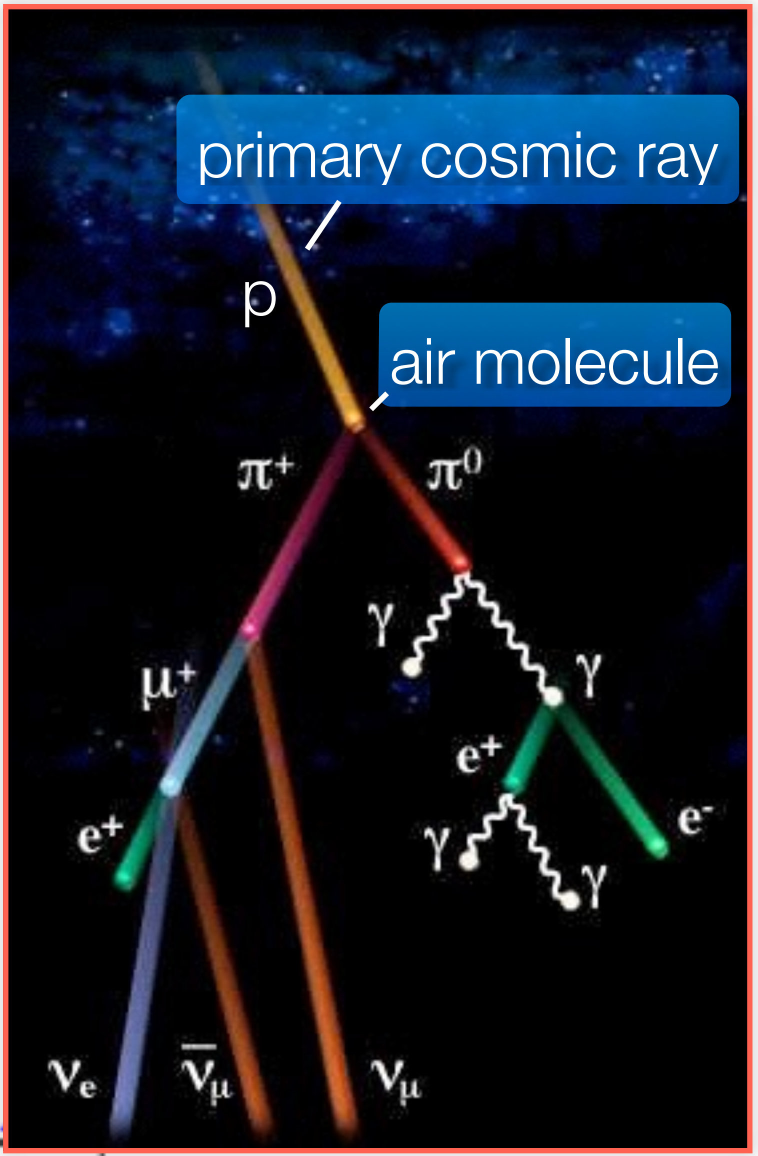


The Atmospheric Neutrino Anomaly

- Cosmic rays hit the earth isotropically
- People expected:

$$\frac{\Phi_{\nu_\mu}(Up)}{\Phi_{\nu_\mu}(Down)} = 1$$

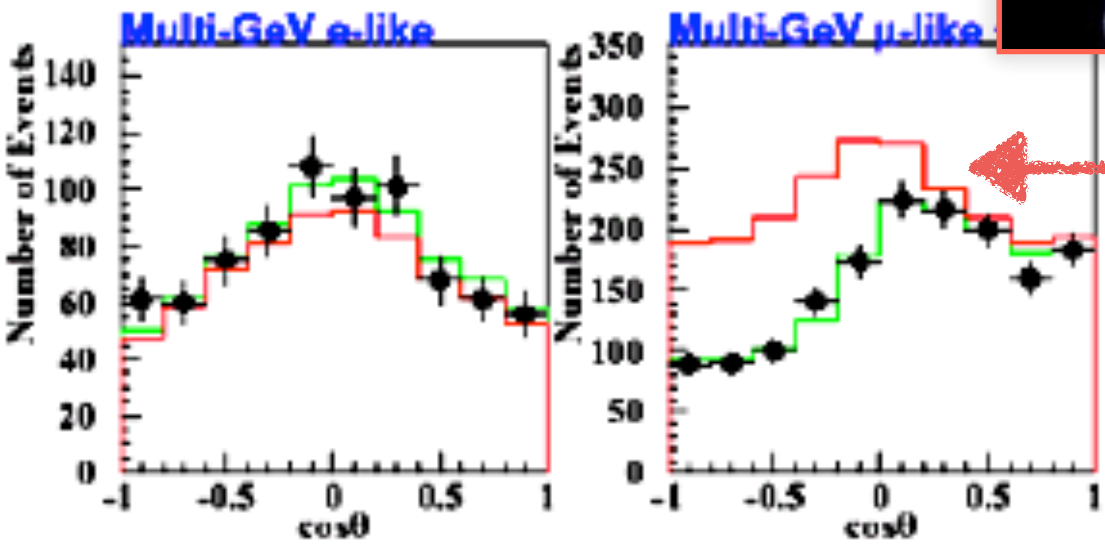




- However, Super-Kamiokande found

$$\frac{\Phi_{\nu_\mu}(Up)}{\Phi_{\nu_\mu}(Down)} = 0.54 \pm 0.04$$

- In 1998 Super-Kamionkande announces the discovery of neutrino oscillation



Upward-going muon neutrinos depleted

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Standard Model Neutrino Interactions

- Lagrangian for electroweak interactions:

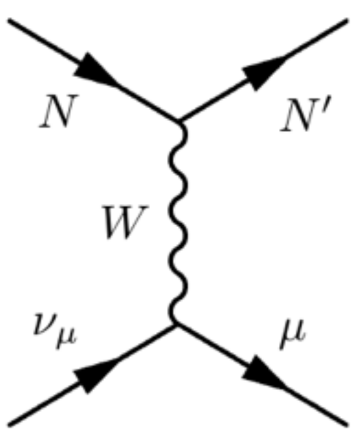
$$L_{\text{int}} = i\frac{g}{\sqrt{2}}\left[j_\mu^{(+)}W^\mu + j_\mu^{(-)}W^{\mu+}\right] + i\left[g\cos\theta_W\, j_\mu^{(3)} - g'\sin\theta_W\, j_\mu^{(Y/2)}\right]Z^\mu +$$
$$+ i\left[g\sin\theta_W\, j_\mu^{(3)} + g'\cos\theta_W\, j_\mu^{(Y/2)}\right]A^\mu$$

- First term: charged current interactions (W^+,W^- exchange)
- Second term: neutral current interactions (Z^0 exchange)
- Third term: electromagnetic interactions (photon exchange)

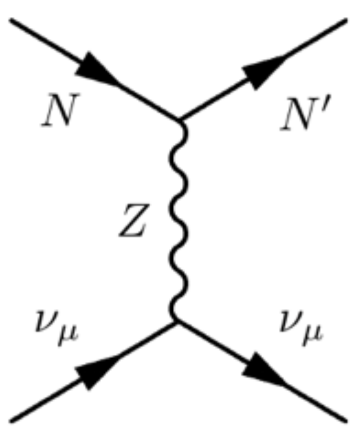
- Electron charge: $e = g\sin\theta_W = g'\cos\theta_W$

Neutrinos only couple to W and Z^0

Charged Current (CC) interactions via a W-boson

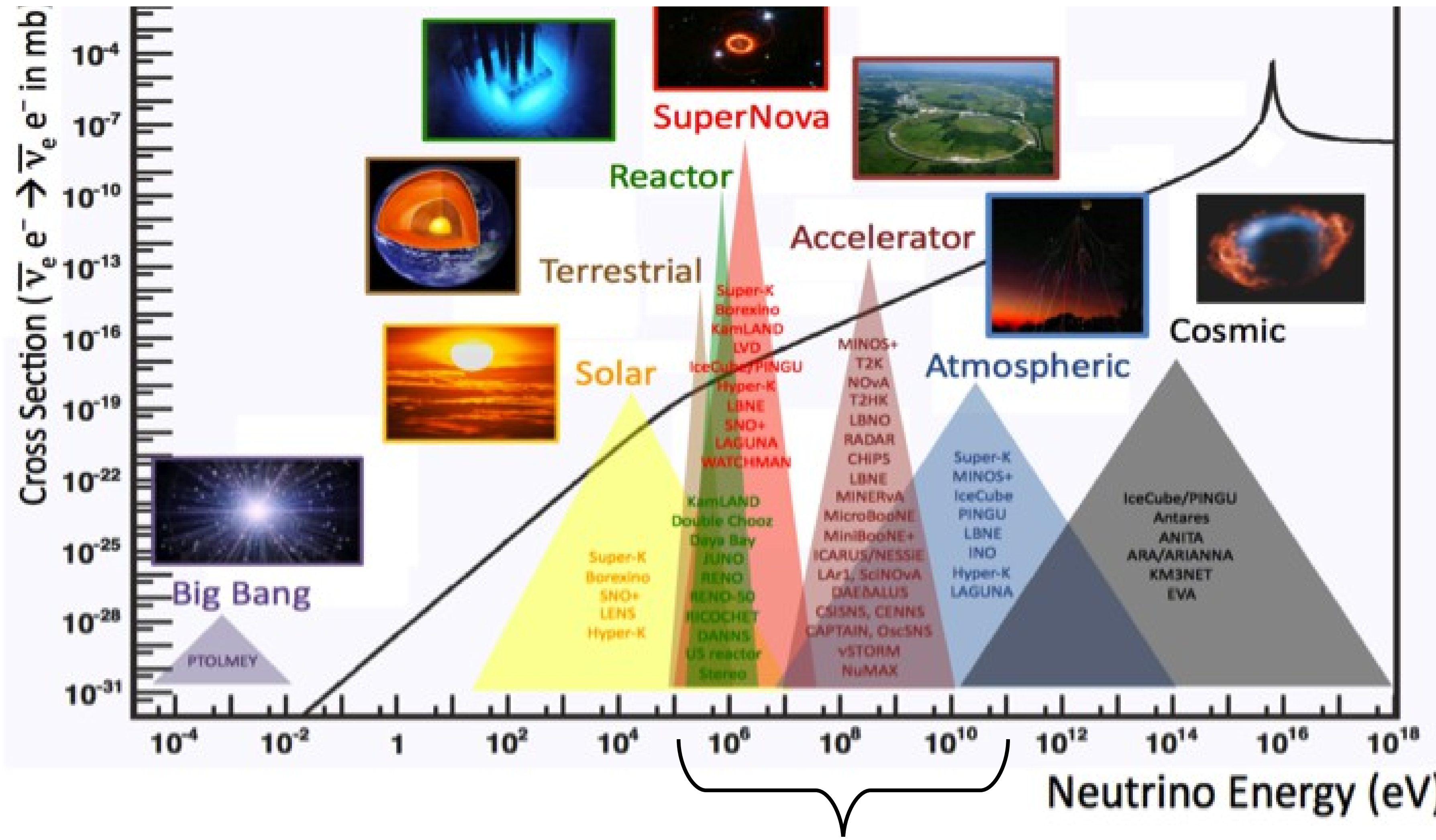


Neutral Current (NC) interactions via a Z-boson



Different Neutrino Sources

- Different neutrino sources determine the range of energies



- Few GeV energy range neutrinos are very important for accelerator neutrino oscillations
- Reviewing a few neutrino interactions relevant to neutrino oscillation at the few GeV region

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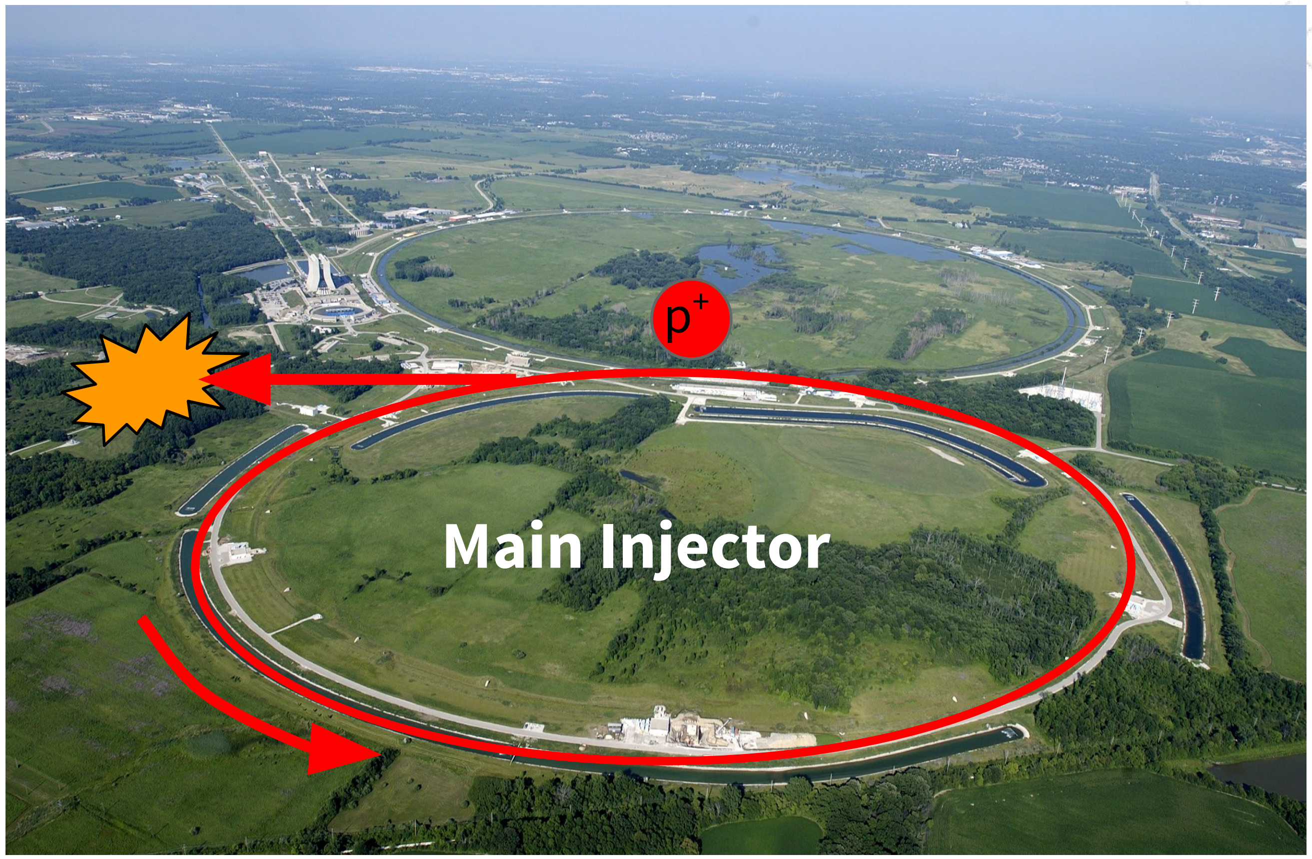
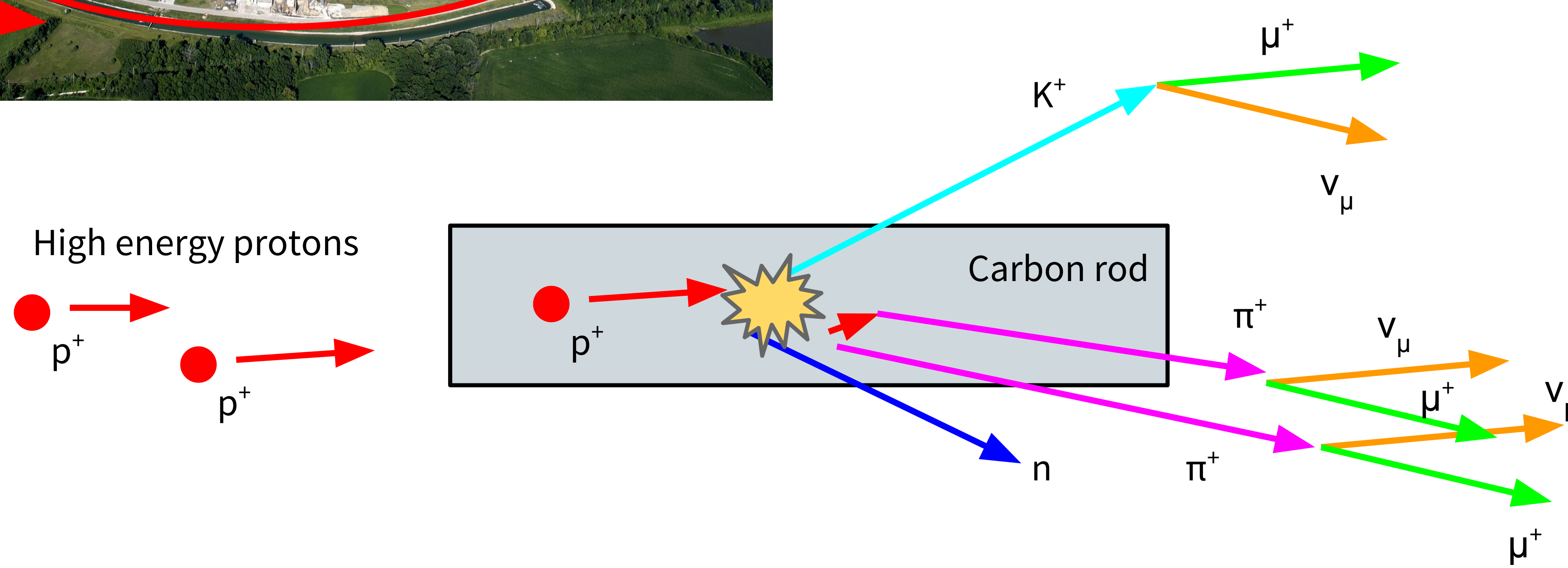
How to make a neutrino beam

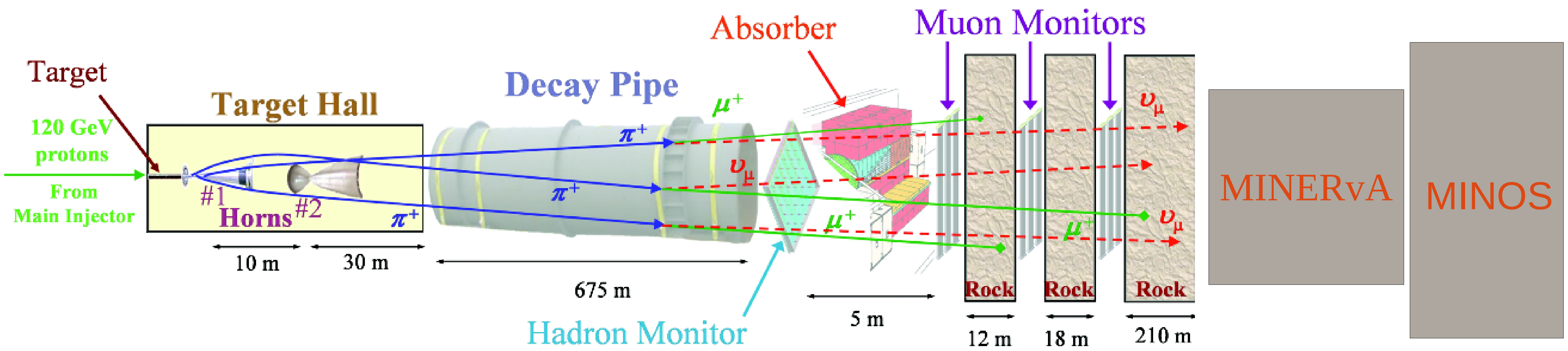


- Protons hit carbon
- Charged pions are produced
- Pions decay to neutrinos



Neutrinos From Accelerators

- A beam of protons interact with a target and produce pions and kaons



- Focusing system (2 horns, with current, emitting B field)
- Decay region (large pipe, filled with helium)
- Monitors and absorbers
- Neutrino beam produces mainly ν_μ and a small component of ν_e

Addressing the Remaining Questions

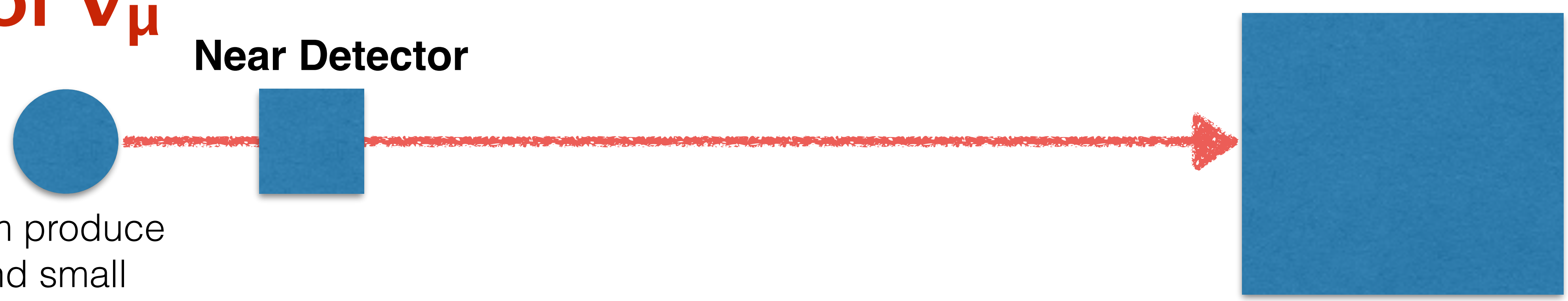
- Is there CP violation in the lepton sector $P[\nu_\mu \rightarrow \nu_e] \neq P[\overline{\nu}_\mu \rightarrow \overline{\nu}_e]$?
- What is the mass hierarchy? (sign of Δm^2_{32})

Far Detector

Beam of ν_μ

Near Detector

Source



Neutrino beam produce mainly ν_μ and small component of ν_e

Signal: ν_e

$\phi \times \sigma \times$ **Nuclear Effects**

$\phi' \times \sigma \times$ **Nuclear Effects** $\times P_{\nu_\mu \rightarrow \nu_e}$

Nuclear model

- Use simulations to extrapolate from near detector to far detector $\sigma_{\nu\mu} \longrightarrow \sigma_{\nu e}$
- We definitely need a nuclear model to convert from produced to detected energy spectra and topologies in the near and the far detectors
- This illustrates the significance of precise knowledge of neutrino interactions physics needed for oscillation studies

Long-baseline Experiments: What can we learn?

- Use a high intensity beam of neutrinos from Fermilab
- Construct detectors at far locations: MINOS+ at 735 Km (ended data-taking), NOvA at 810 km (taking data) and DUNE at 1300 km (in design)

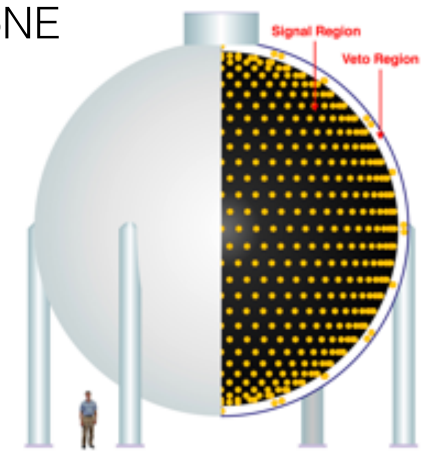
$$P[\nu_\mu \to \nu_e] \neq P[\overline{\nu}_\mu \to \overline{\nu}_e] \ ?$$

also, T2K in Asia

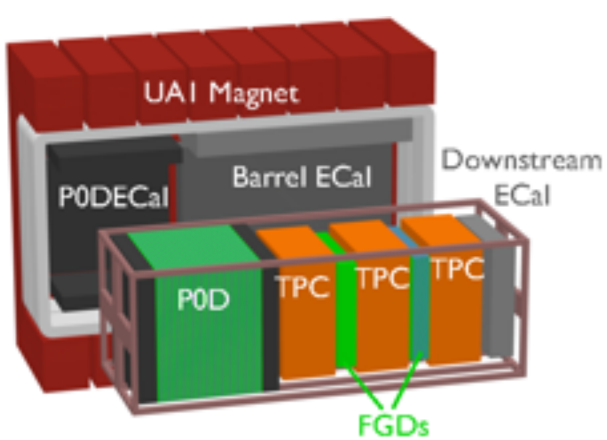
Cross Section Experiments

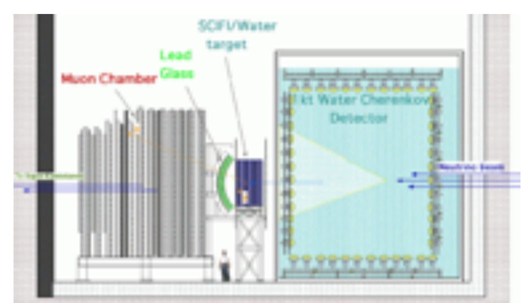
- Modern neutrino experiments using neutrino from accelerators
  - Different detector technologies and targets:
    - Oxygen, carbon, iron, liquid argon, helium, lead..
  - Different neutrino beams
- Common goal for all the experiments:
  - Study neutrino interactions

MiniBooNE



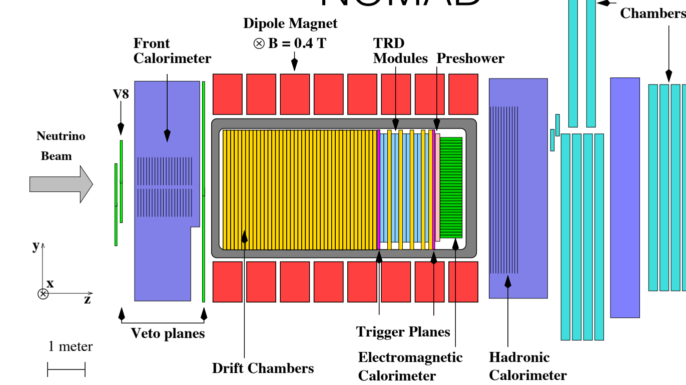
T2K





K2K

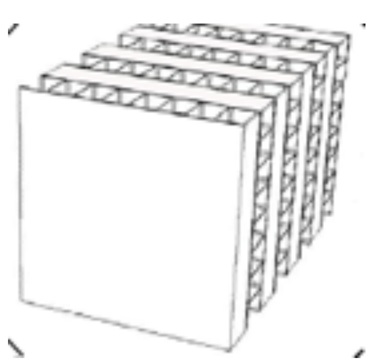
NOMAD



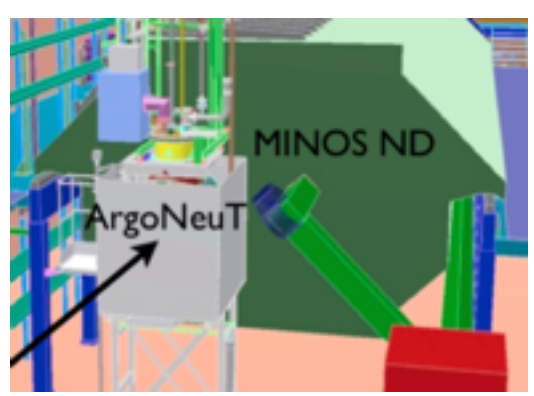
Argonut

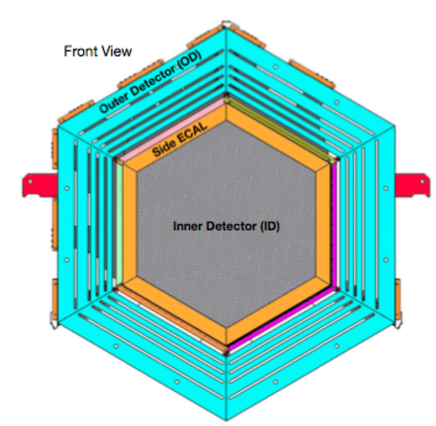
Minerva

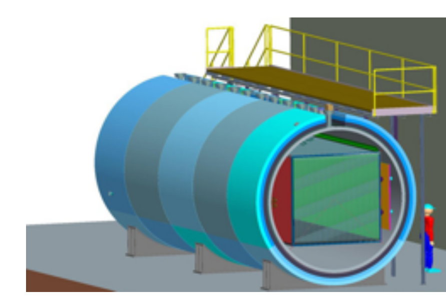
MicroBooNE



NOvA

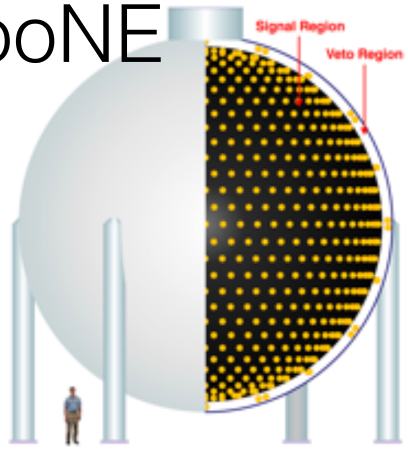


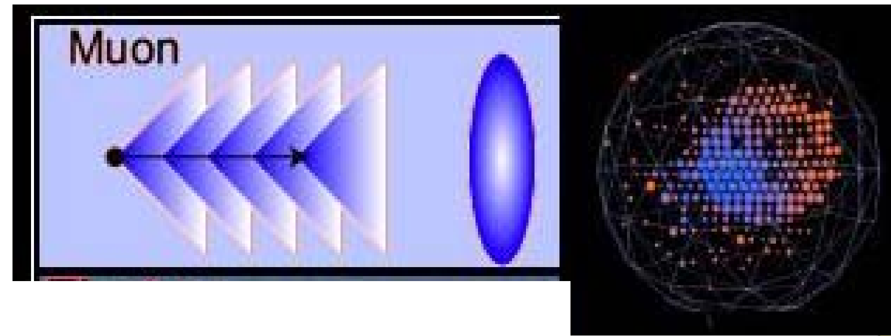




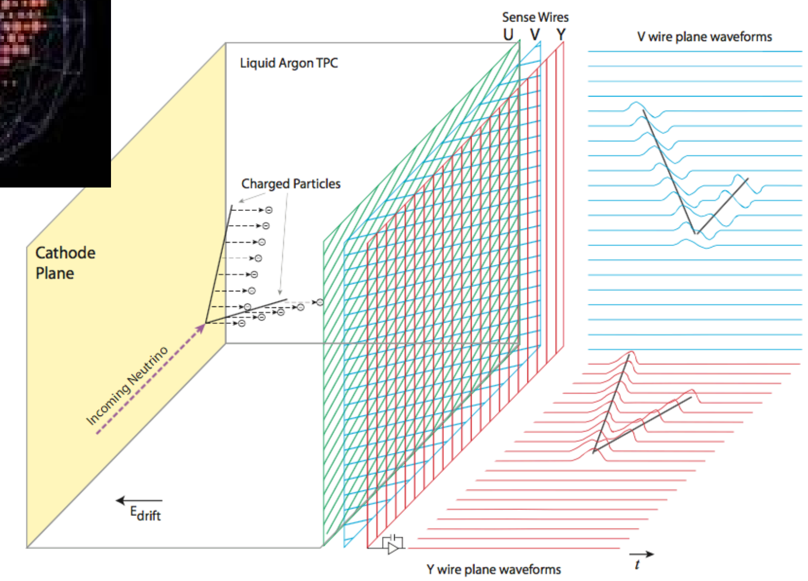
Examples of Different Detector Technologies

MiniBooNE

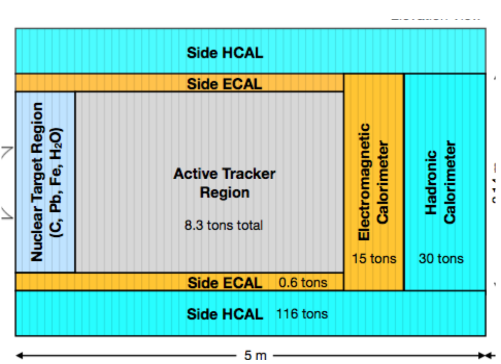


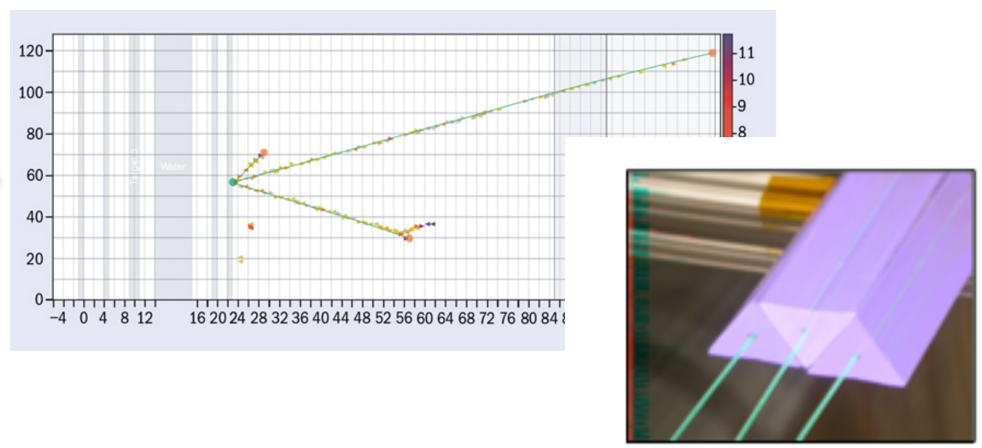


MicroBooNE

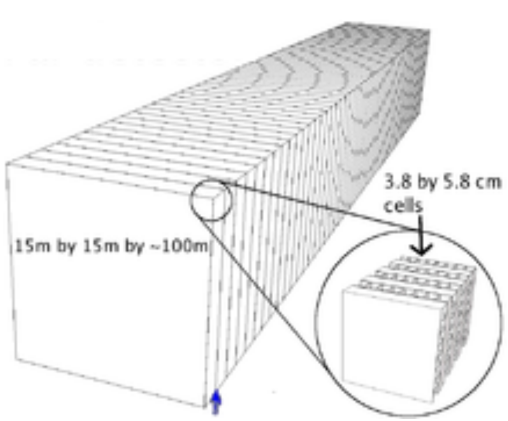


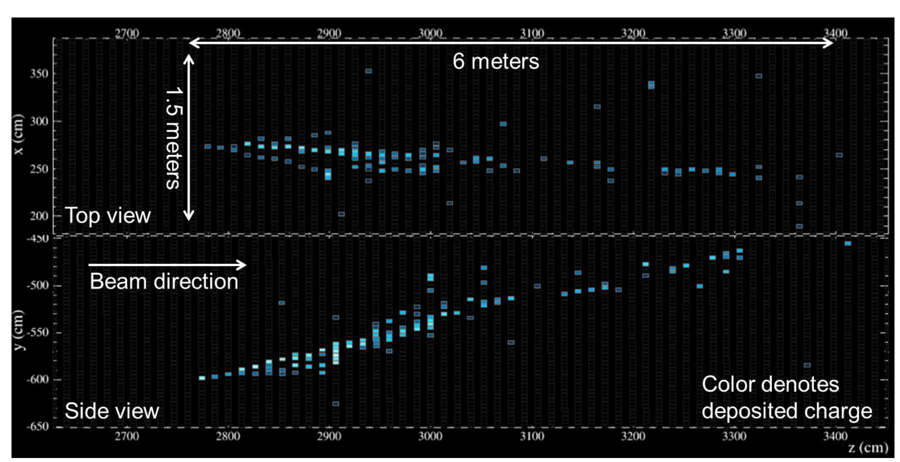
MINERvA

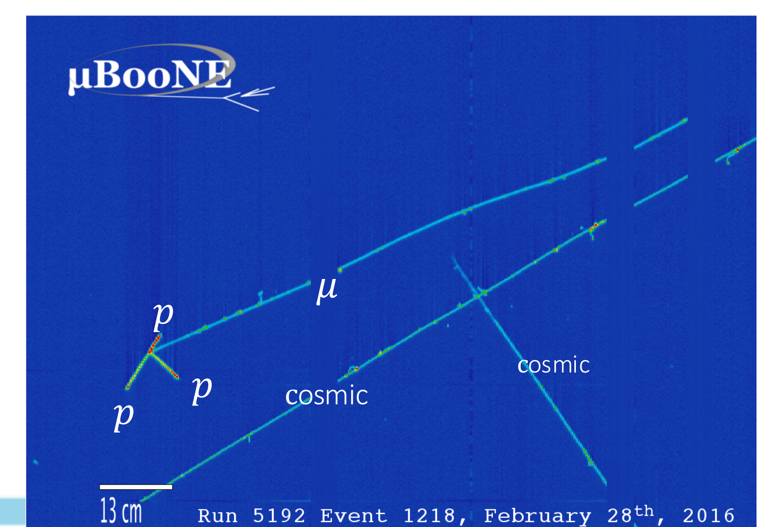




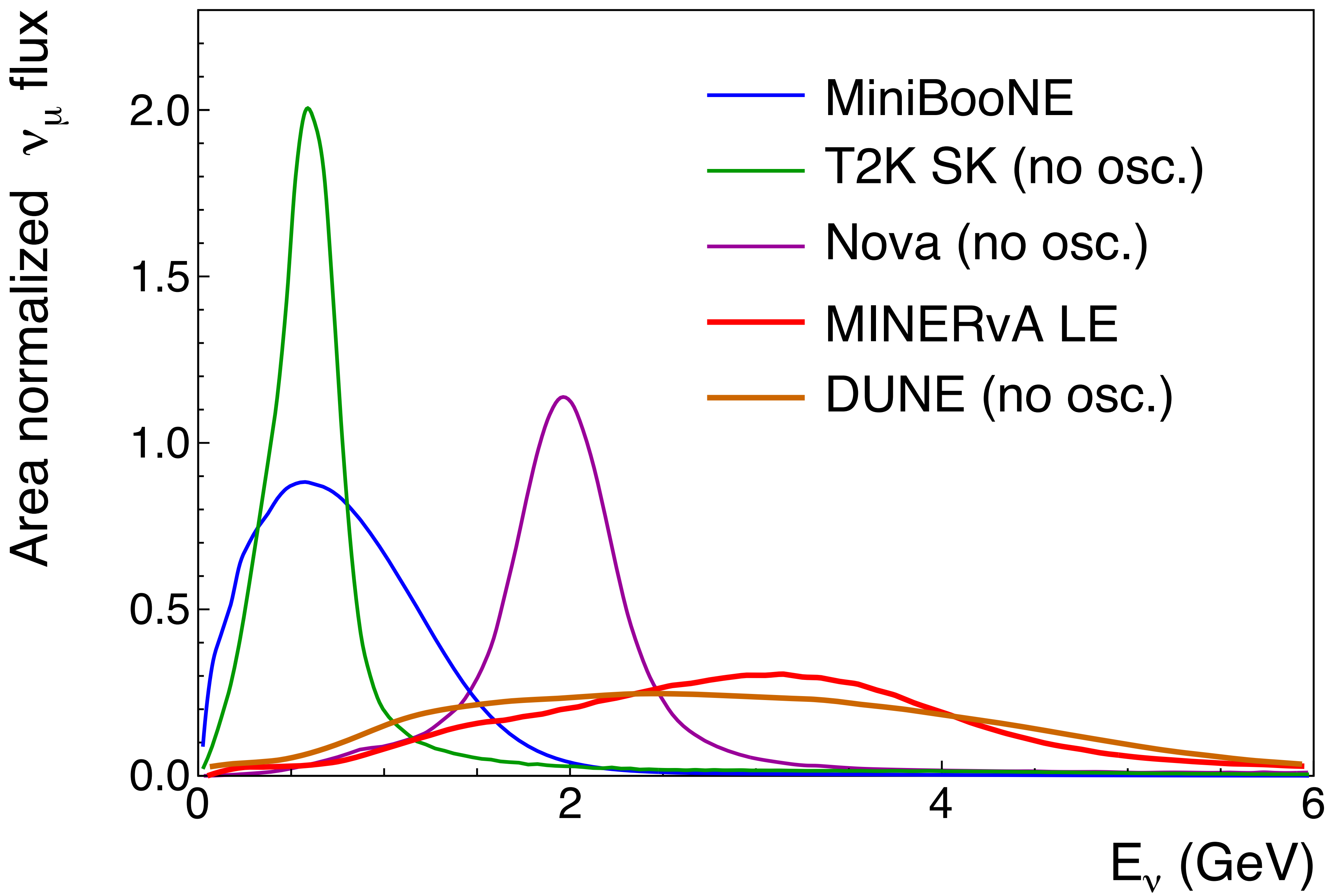
NOvA







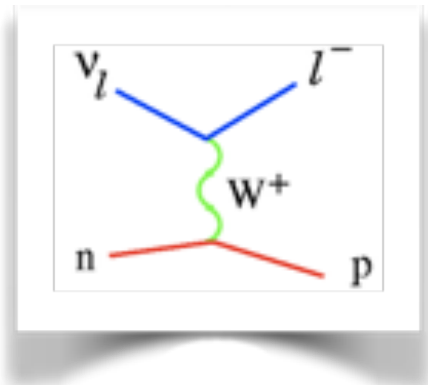
Neutrino Energies for Different Experiments



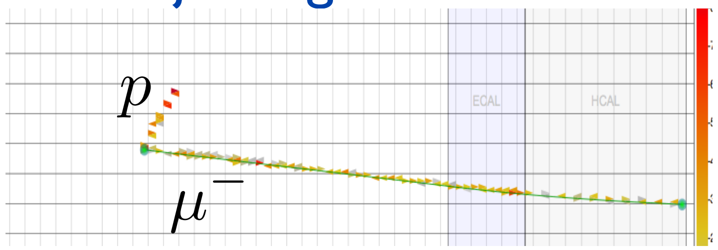
Plot courtesy of Phil Rodrigues

Charged Current Interactions

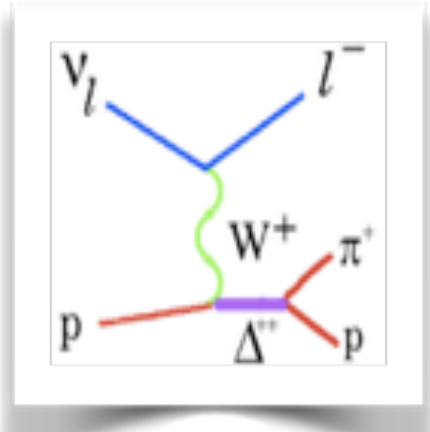
Quasi-elastic scattering (QE)



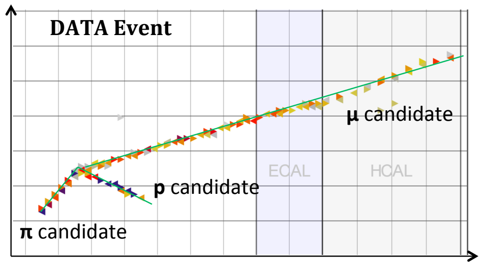
The neutrino scatters elastically off the nucleon ejecting a nucleon from the target



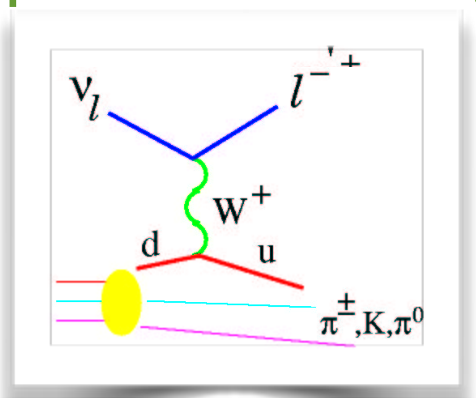
Resonance production (RES)



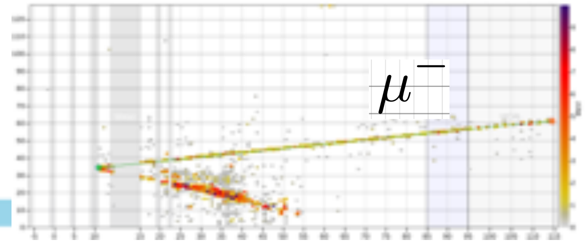
The neutrino can excite the target nucleon to a resonance state



Deep Inelastic scattering (DIS)

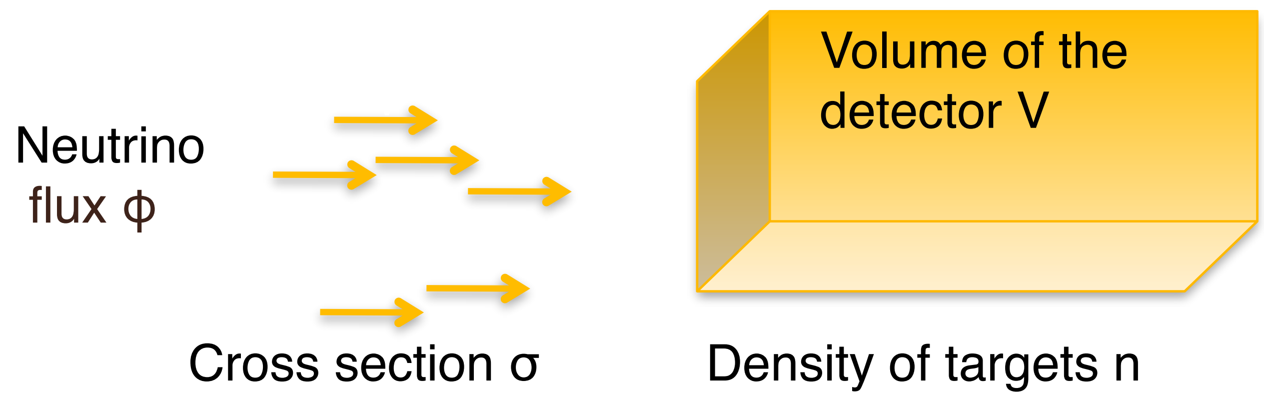


The neutrino scatters off a quark in the nucleon producing a hadronic system in the final state



Neutrino Cross Section

- What is the cross section?
  - A measure of the probability of an interaction occurring



Number of interactions per second

Cross Section $$\sigma = \frac{N}{\phi T \epsilon}$$ Number of interactions that occurred

Total flux of incident neutrinos per unit area

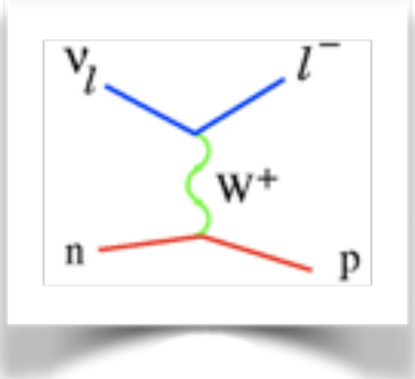
Number of targets

Neutrinos interact only by week force, at 1 GeV $$\sigma(\nu N) \sim 10^{-38} cm^2 \longrightarrow$$ tiny

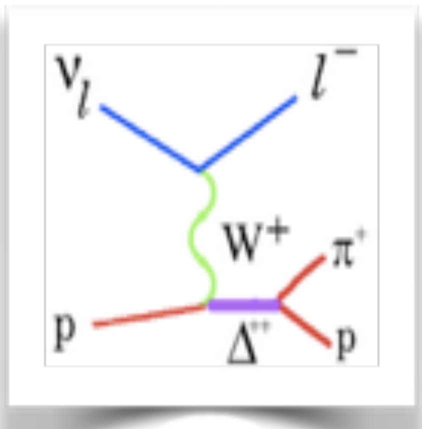
compare with $$\sigma(pp) \sim 10^{-26} cm^2$$

Charged Current Interactions

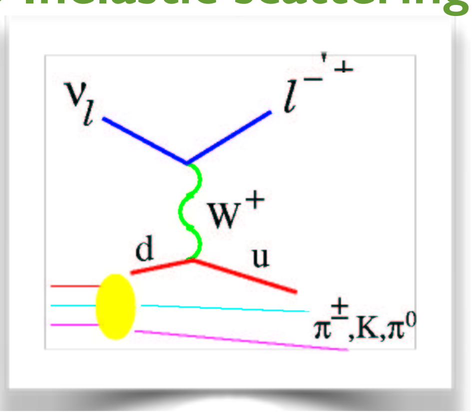
Quasi-elastic scattering (QE)

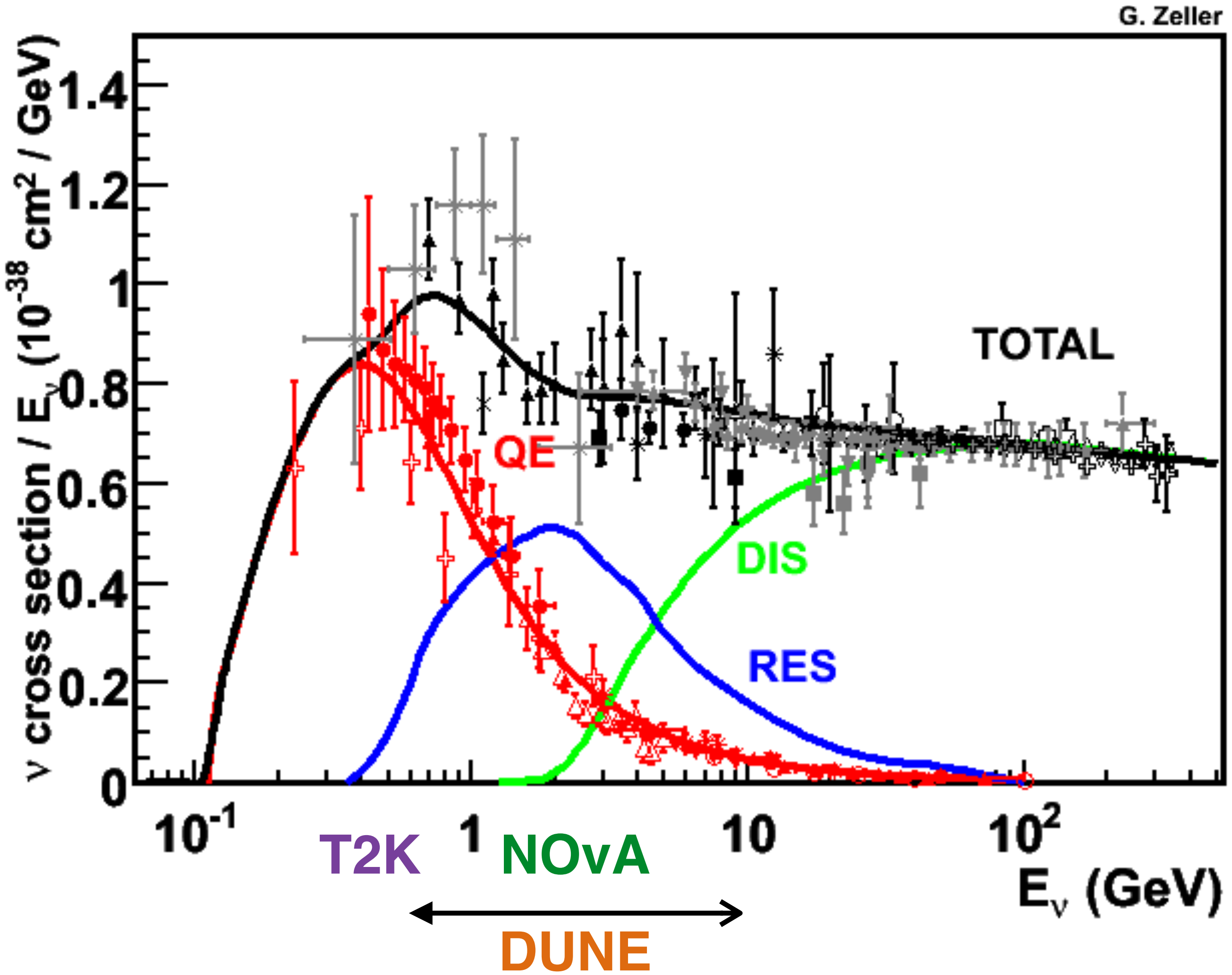


Resonance production (RES)



Deep Inelastic scattering (DIS)





J.A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)

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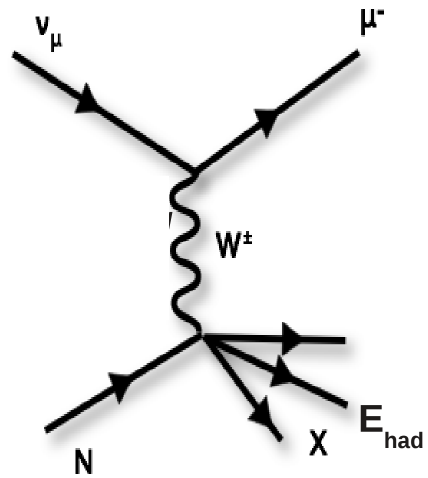
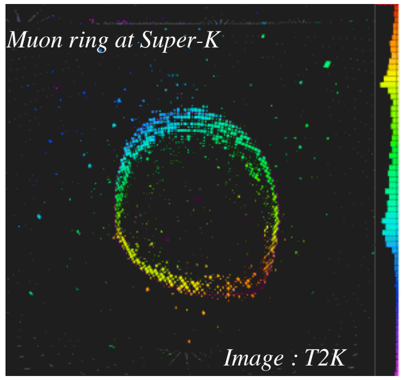
In More Detail

- Oscillation probability depends on neutrino energy E_ν
- We need to reconstruct the neutrino energy precisely



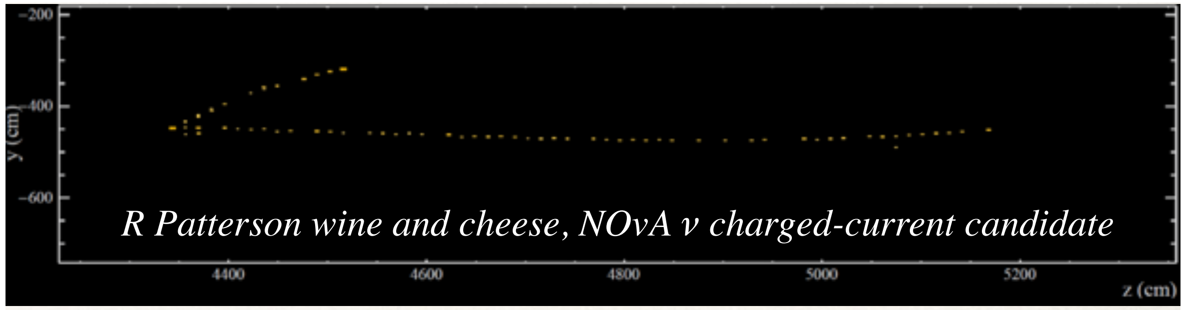
$$P(\nu_\alpha \to \nu_\beta) \approx 1 - \sin^2 2\theta \sin^2(\frac{\Delta m^2 L}{E_\nu})$$

- Neutrino energy reconstruction is obtained using the final state particles
  - Cherenkov experiments use muon information



$$E_{QE} = \frac{m_n^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

  - Fully active experiments reconstruct the energy using: $E_\nu = E_{lepton} + hadron$



- Nuclear effects modify the kinematics of the particles and the reconstruction of the neutrino energy

Cross Section is one of the largest systematics

PRL 116, 181801 (2016) PHYSICAL REVIEW LETTERS week ending 6 MAY 2016

Measurement of Muon Antineutrino Oscillations with an Accelerator-Produced Off-Axis Beam

Cross section is one of the largest systematic uncertainties for oscillation experiments like T2K as an example

TABLE IV. Percentage change in the number of one-ring μ-like events before the oscillation fit from 1σ systematic parameter variations, assuming the oscillation parameters listed in Table III and that the antineutrino and neutrino oscillation parameters are identical.

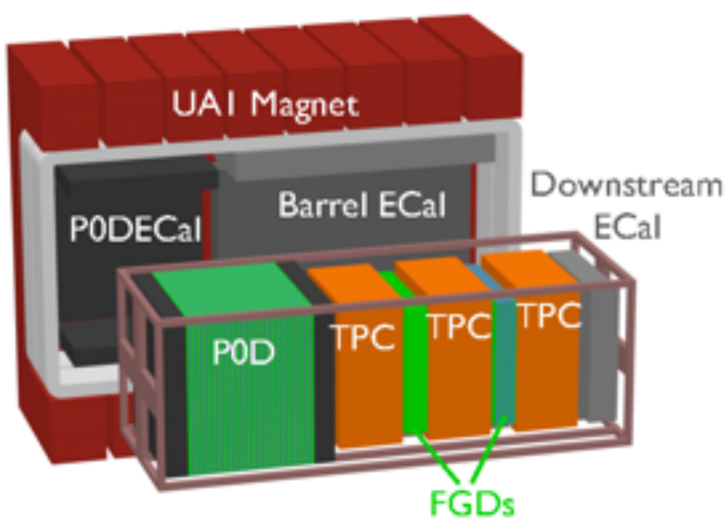
Source of uncertainty (number of parameters)	$\delta n_{\mathrm{SK}}^{\mathrm{exp}}/n_{\mathrm{SK}}^{\mathrm{exp}}$ (%)
ND280-unconstrained cross section (6)	10.0
Flux and ND280-constrained cross section (31)	3.4
Super-Kamiokande detector systematics (6)	3.8
Pion FSI and reinteractions (6)	2.1
Total (49)	11.6

T2K's uncertainties, from PRL 116, 181801 (2016)

Another reason Why We Need to Understand Nuclear Effects

- Plus if the near and far detector are made of different materials, we need to worry about A dependence of nuclear effects
- For example, T2K uses near detector carbon measurements even though the far detector is made of water

T2K Near Detector

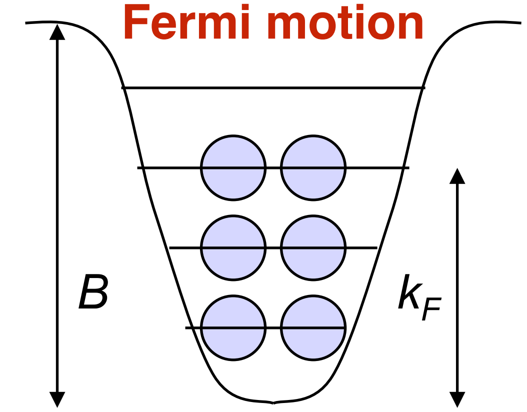


T2K Far Detector

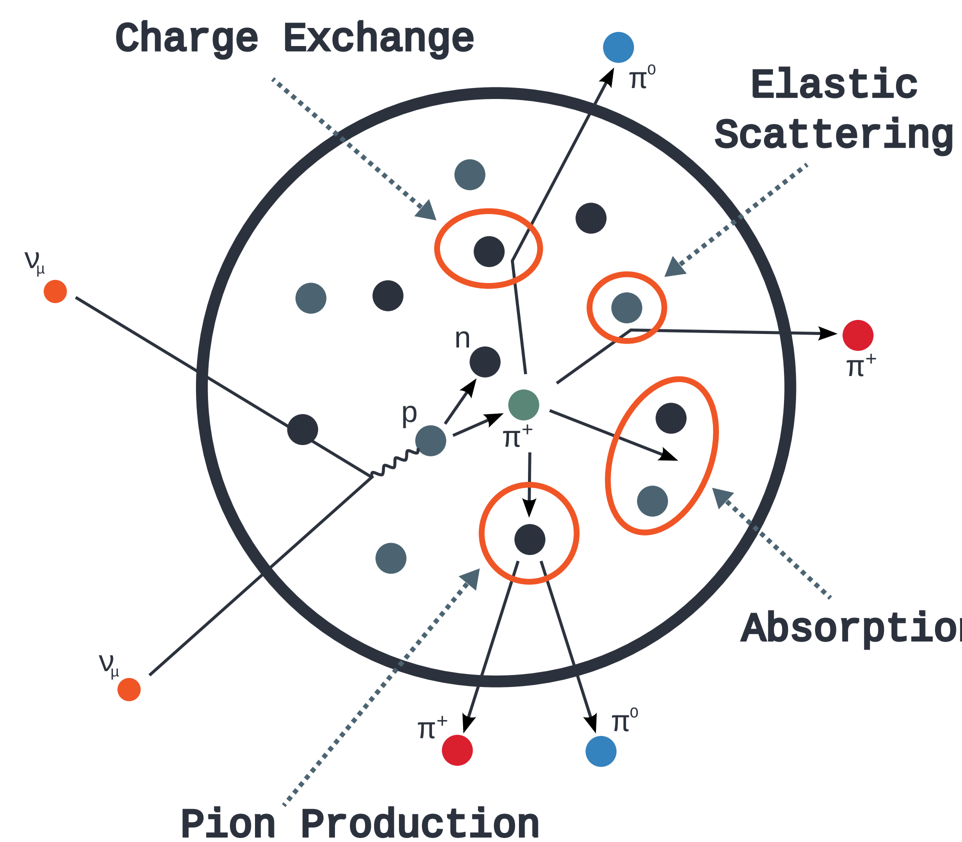
Nuclear Effects

- Fermi motion: In a nucleus, the target nucleon has a momentum. Modeled as Fermi gas that fills up all available state until some Fermi momentum
- Pauli blocking: Pauli exclusion principle ensures that states cannot occupy states that are already filled
- Multi nucleon interactions
- Final state interactions

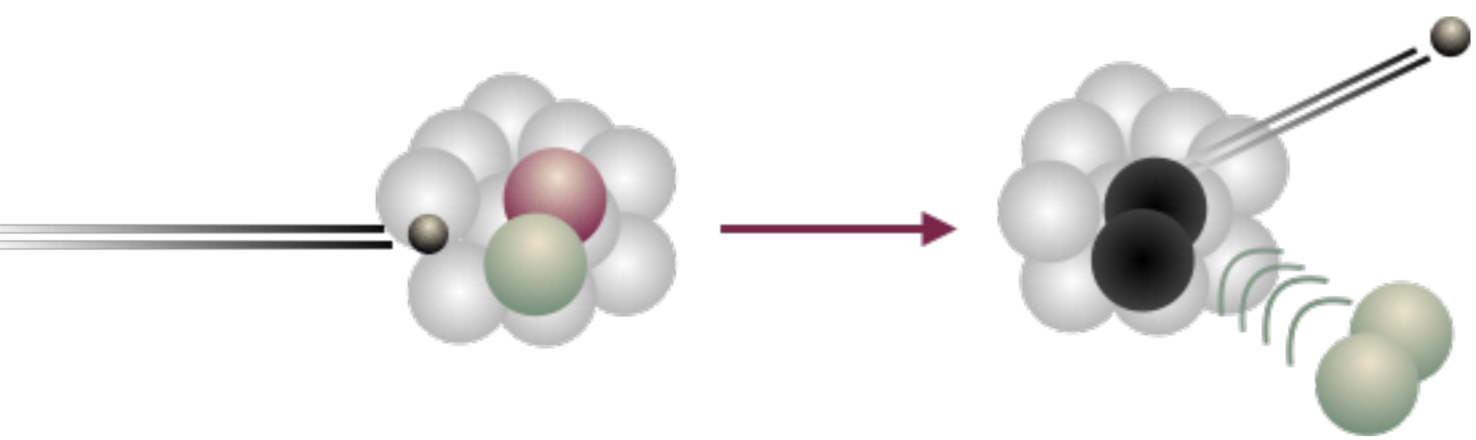
Fermi motion



Final State Interactions (FSI)

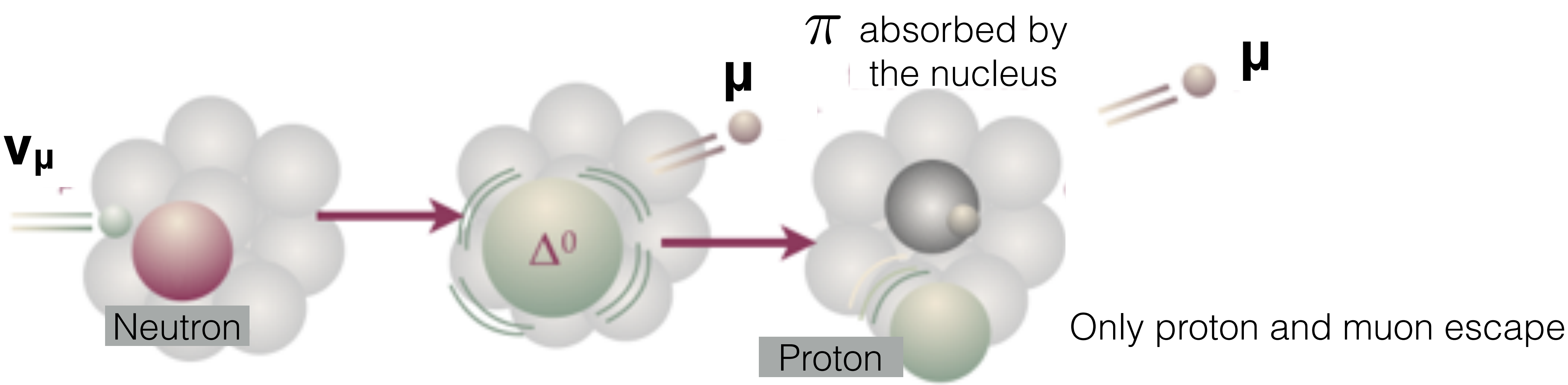


Multi nucleon interactions



Example of Nuclear Effects (Final State Interaction)

- Final state interaction (FSI):
  - Due to final state interactions, particles can interact with nucleons and pions can be absorbed before exiting the nucleus and other nucleons get knocked out

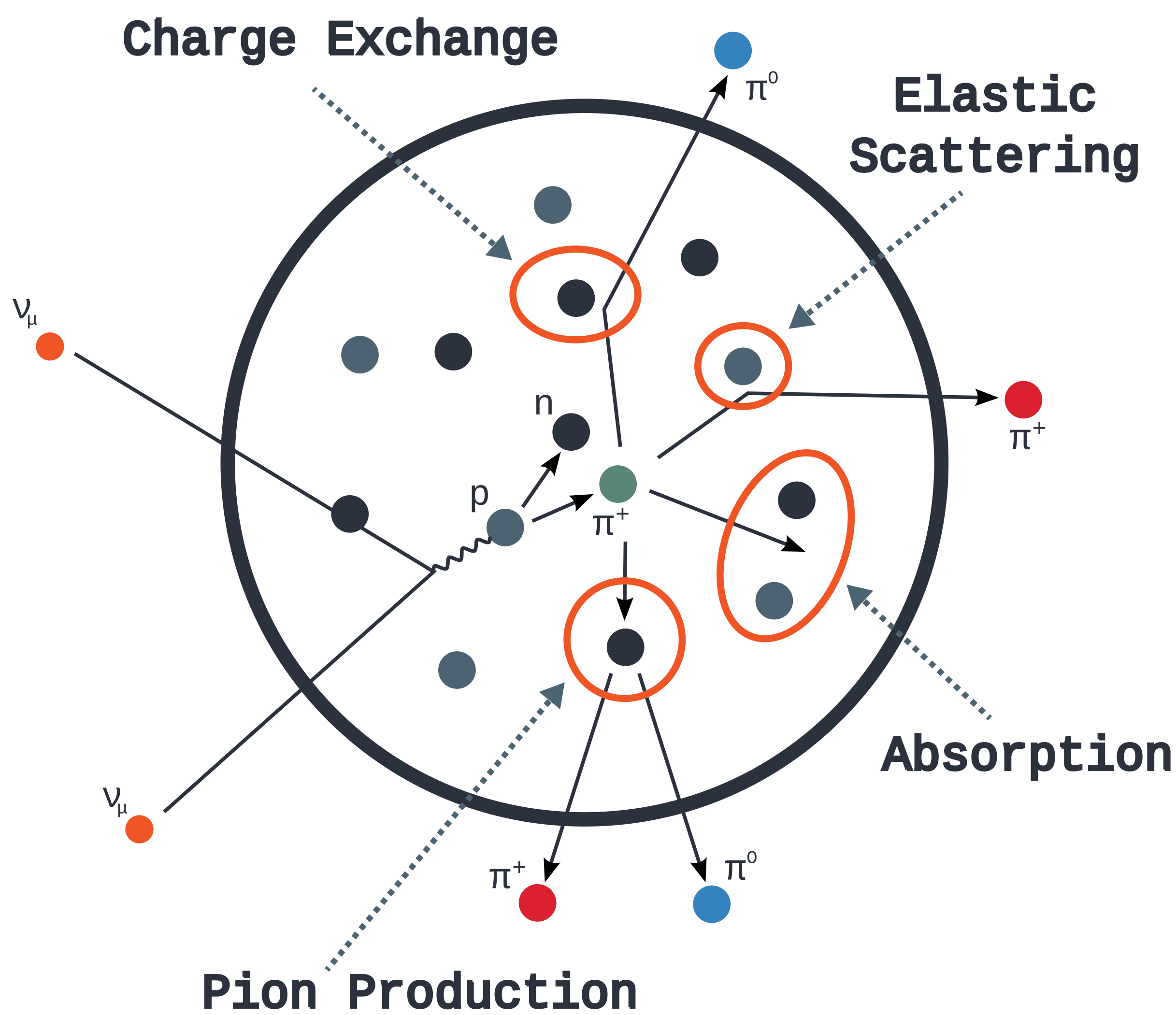


Start as a RES interaction, the pion is absorbed and the interaction looks QE like in our detector

- Nuclear effects modify the true/reco neutrino energy relationship and final-state particle kinematics
- Pion absorption is twice as big in Argon as it is in Carbon!

Example of Nuclear Effects (Final State Interactions)

- Nuclear effects modify the true/reco neutrino energy relationship and final-state particle kinematics



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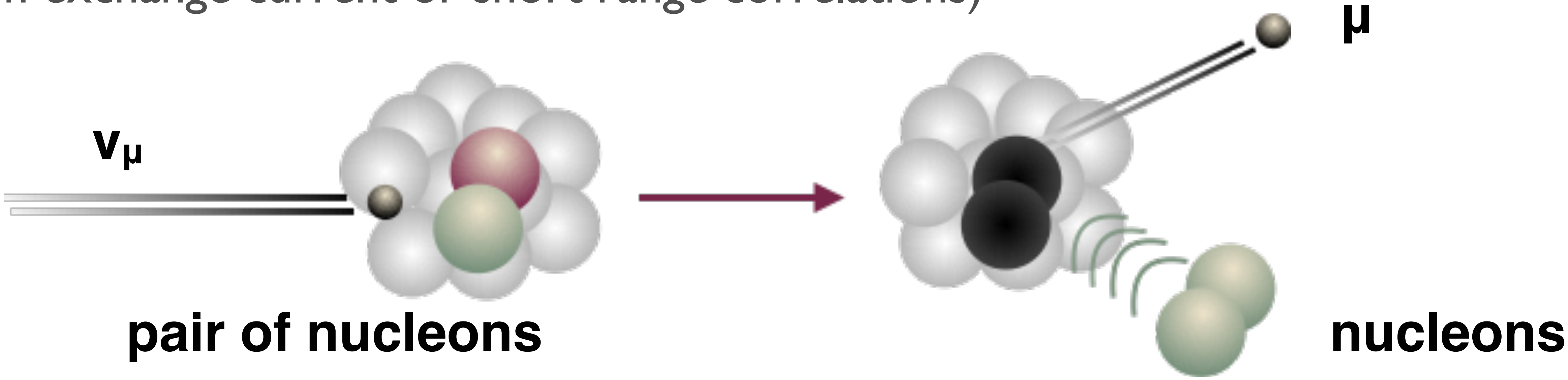
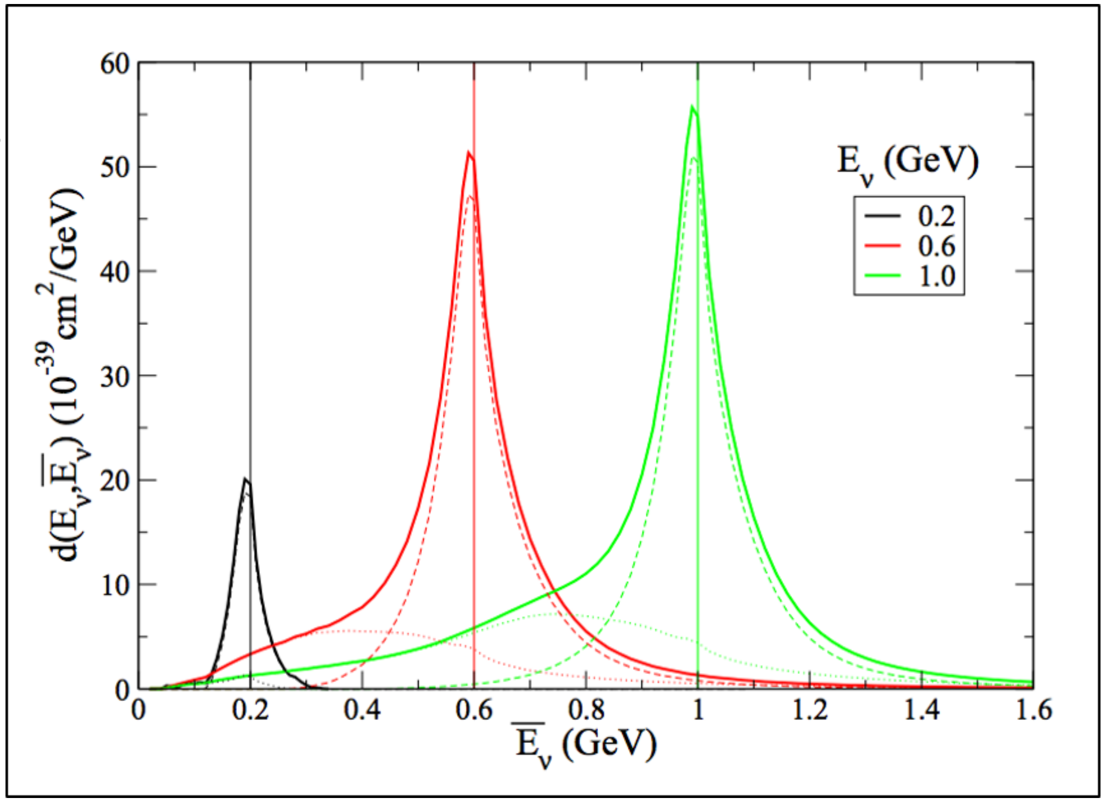
Example of Nuclear Effects (multi-nucleon interaction)[2p2h]

- Nuclear effects modify the neutrino energy, for example multi-nucleon interactions (Meson exchange current or short range correlations)

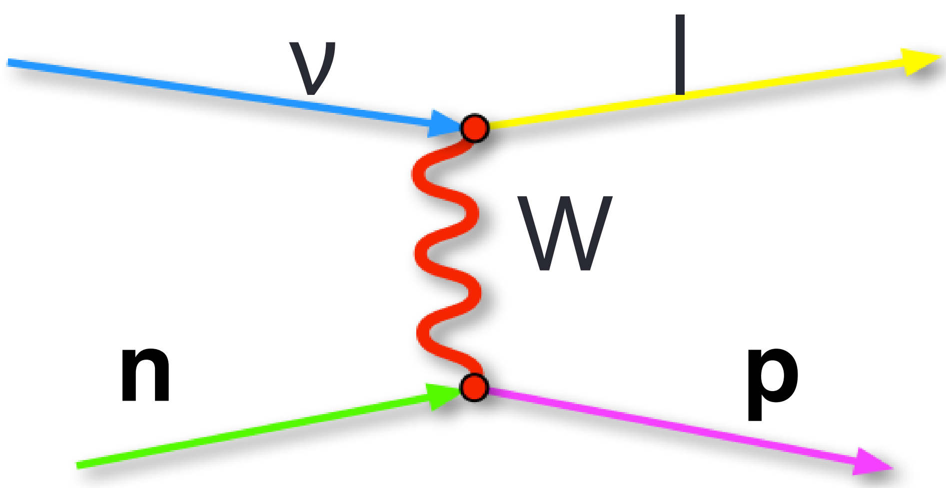


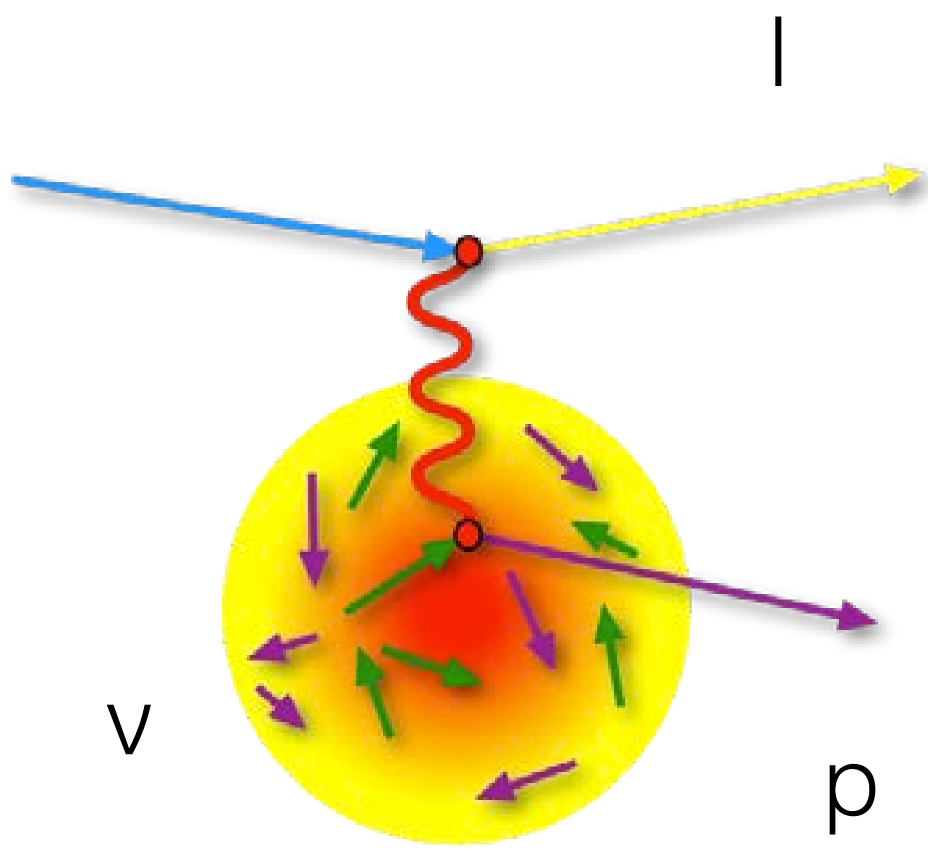
- The resulting di-nucleon pair undergoes final state interaction and produce low energy protons and neutrons which we do not detect well
- Multi-nucleon processes smear the reconstructed neutrino energy
- Solid lines: multi nucleon contributions
- Dashed lines: genuine CCQE events



Martini et al. arXiv:1211.1523

Neutrino Interactions



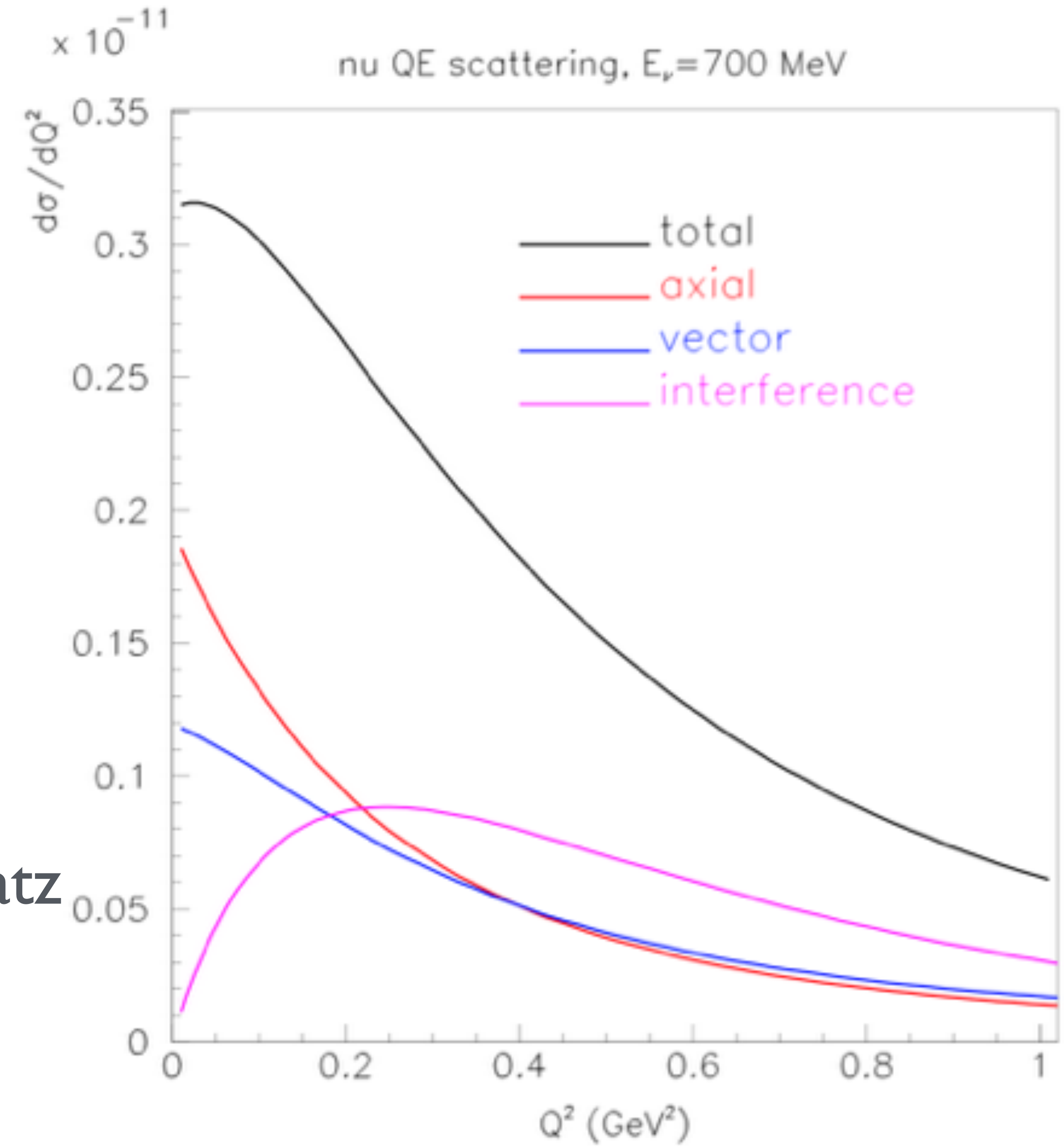


- We do not know:
  - Initial state bound nucleon momenta
  - Bound nucleon cross section
  - Multi-nucleon correlated states
  - Final state interactions
- Several challenges from the theoretical model side and experimental side to understand neutrino interactions

Quasi-Elastic Scattering (CCQE)

- The Quasi-elastic process gives the largest contribution for the signal in many oscillation experiments
- We use a free nucleon CCQE formalism to determine the cross section

$$\frac{d\sigma}{dq^2} \propto (F_1, F_2, F_A)$$



- Depend on the form factors F_1, F_2 and the axial form factor FA
- The vector form factors F_1, F_2 are known from electron-nucleon scattering
- The axial form factor is described using an ansatz

$$F_A(Q^2) = \frac{F_A(0)}{(1 - \frac{q^2}{M_A^2})^2}$$

- FA(0) is constrained from neutron beta decay and M_A is the axial mass

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Axial Form Factor

- The dipole axial form factor ansatz:

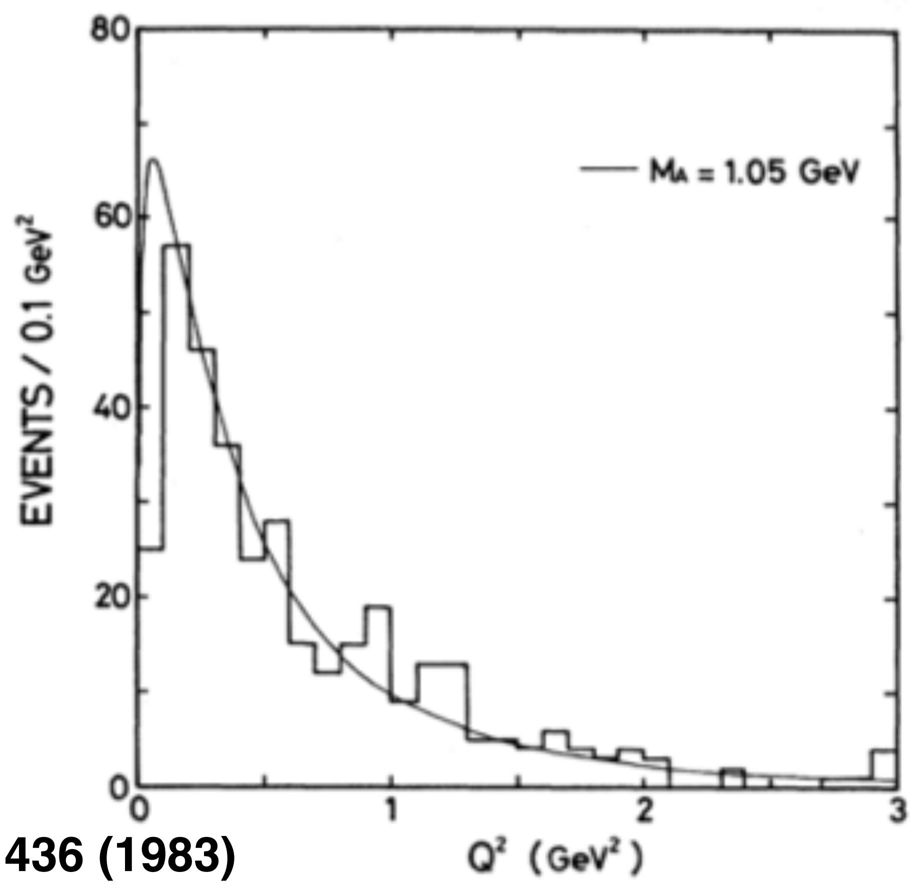
$$F_A(Q^2) = \frac{F_A(0)}{(1 - \frac{q^2}{M_A^2})^2}$$

- Experiments with deuterium targets have employed this anzatz, obtaining a world average M_A

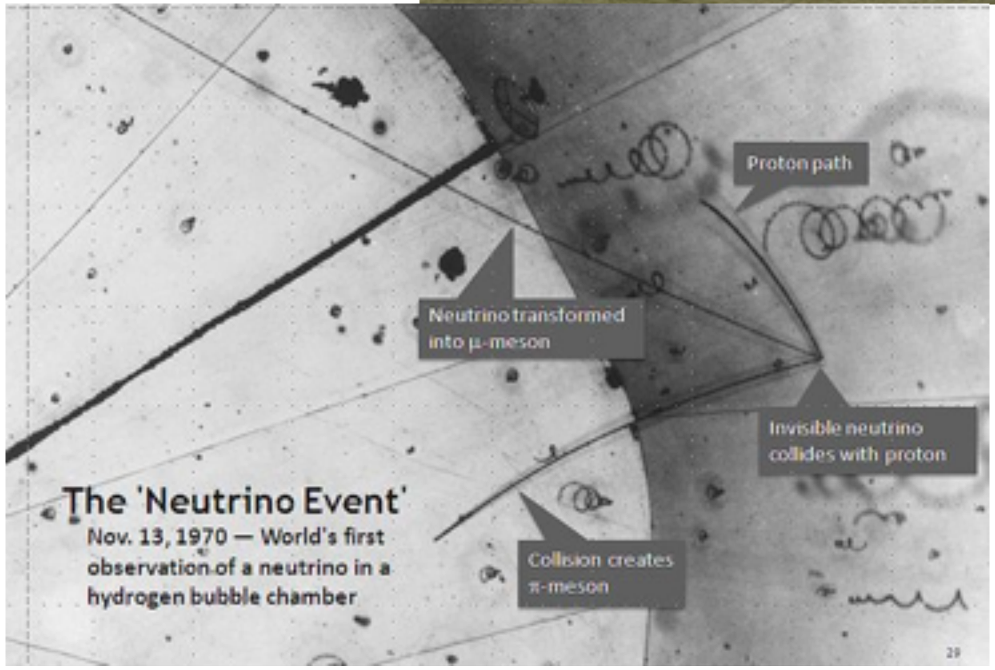
$$M_A = 1.014 \pm 0.014 GeV$$

Eur. Phys. J. C 53, 349 (2008)

Bubble chamber experiment at Fermilab



Kitagaki, PRD 28, 436 (1983)

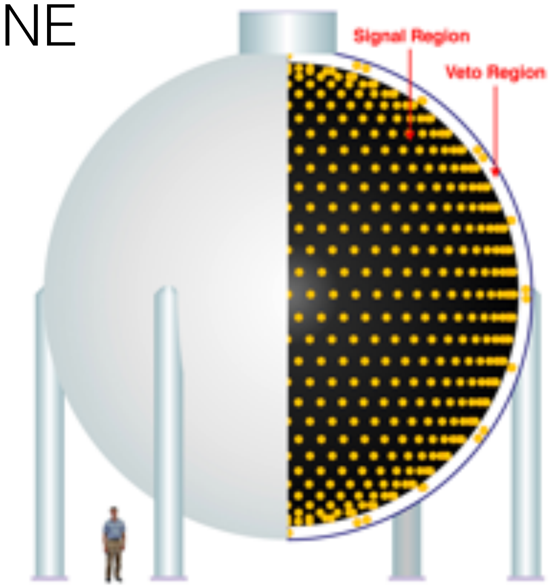


Axial Form Factor

- The dipole axial form factor ansatz:

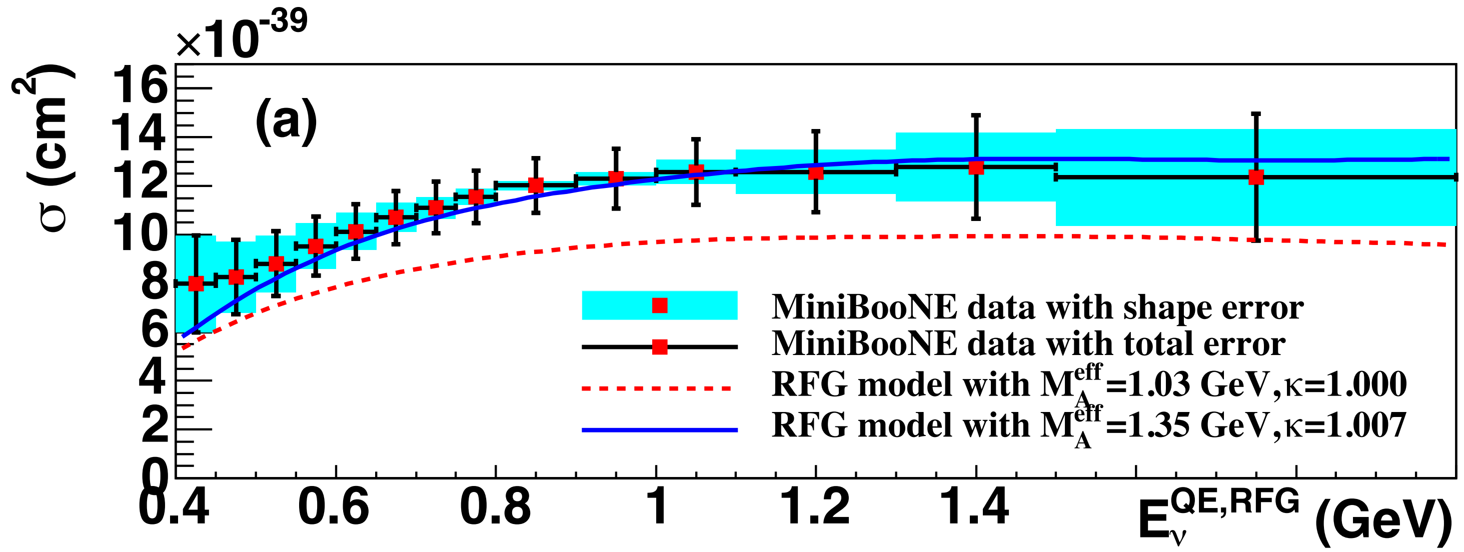
$$F_A(Q^2) = \frac{F_A(0)}{(1-\frac{q^2}{M_A^2})^2}$$

MiniBooNE



- Modern experiments using heavy targets, like carbon from MiniBooNE reported a higher axial mass

$$M_A = 1.35 \pm 0.17 GeV$$



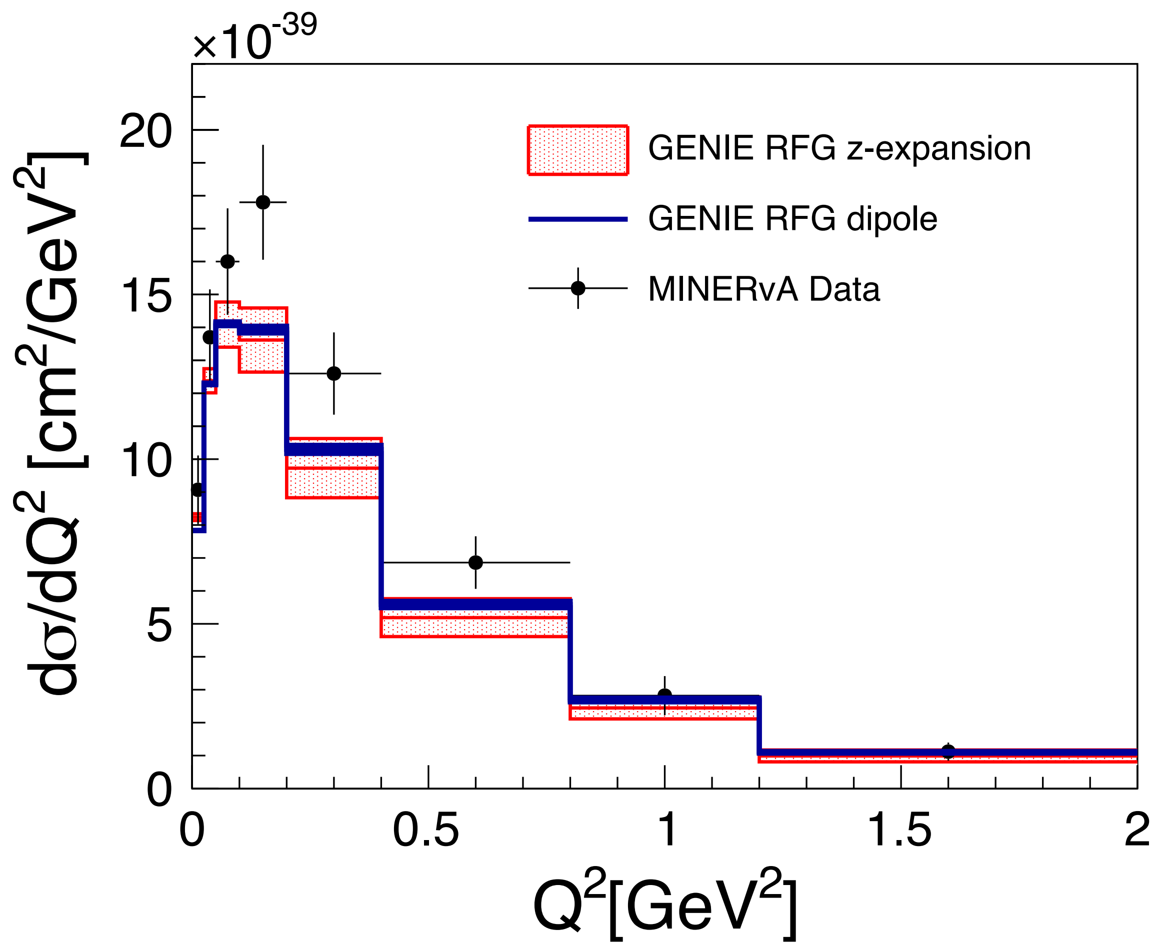
- Other experiments such as K2K, SciBar and MINOS find similar higher axial mass compared with the world average
- **This high mA is an effective parameter that we expect represents multi-nucleons effects, and not directly the form factor itself**

Axial Form Factor

- A model independent description of the axial form factor called z-expansion is derived in Phys. Rev. D84 (2011)
- The form factor can be expressed as a power series of a new variable z

$$F_A(q^2) = \sum_{k=0}^{k_{\max}} a_k z(q^2)^k$$

- where the expansion coefficients a_k are dimensionless numbers representing nucleon structure information
- Derived from first principles of QCD
- Extensively used in meson decay

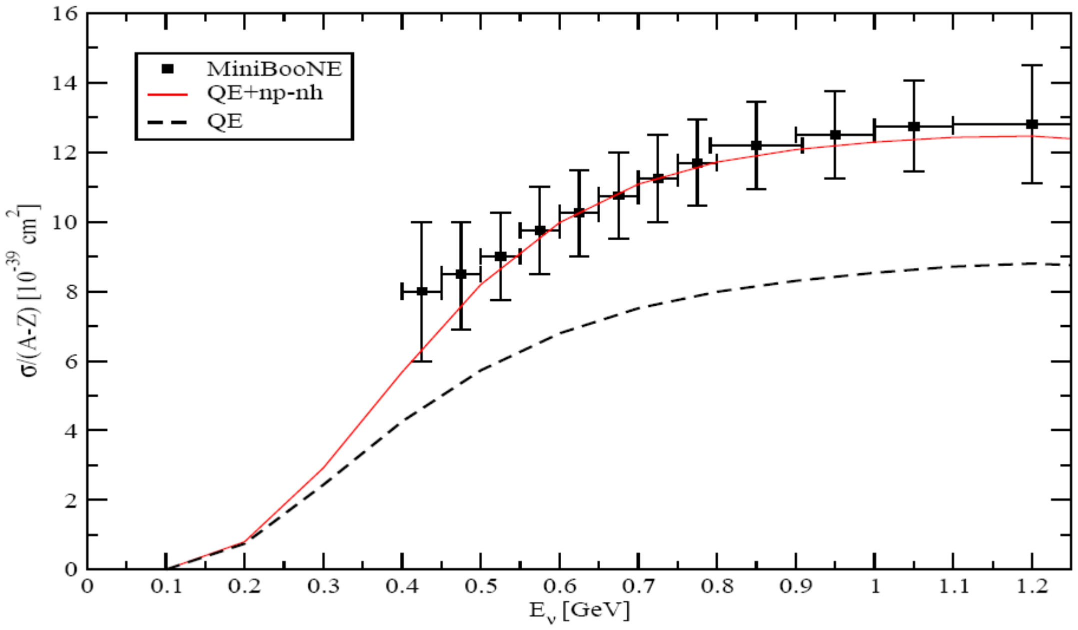


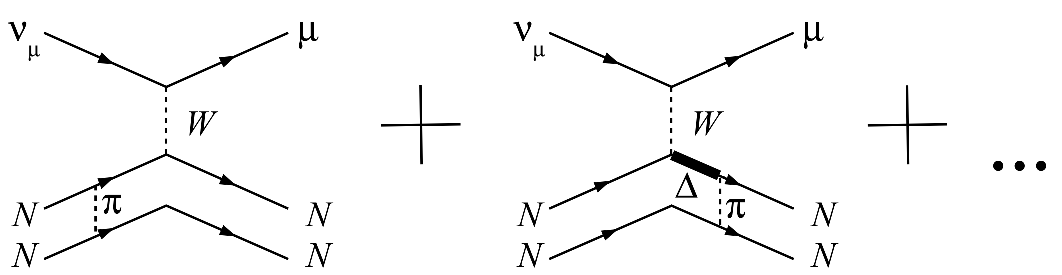
Phys.Rev. D93 (2016) no.11, 113015

Including multi nucleon Interactions (2p2h)

- Inclusion of the multi nucleon emission channel (np-nn) gives better agreement with data

Model compared to MiniBooNE data



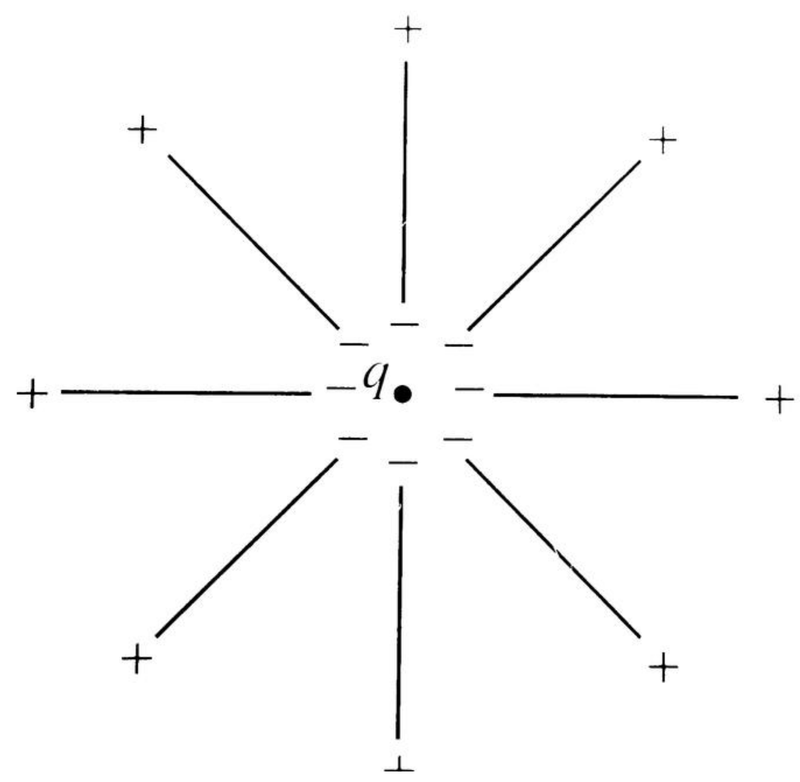


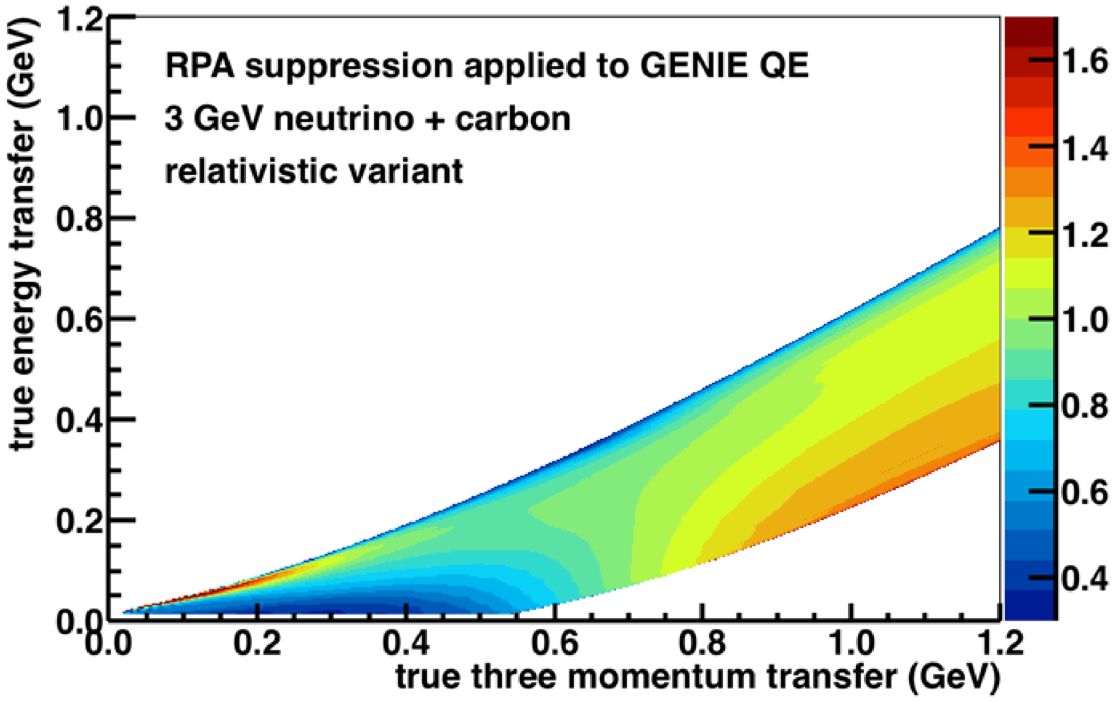
M. Martini, M. Ericson, G. Chanfray, J. Marteau Phys. Rev. C 80 065501 (2009)

- Several theoretical predictions, one of the most use is from the Valencia group for QE-like 2p2h, arXiv:1601.02038, PRC 70, 055503 (2004), PRC 83, 045501 (2011)

Including Random Phase Approximation (RPA)

- Analogous to screening of electric charge in a dielectric
- For neutrino scattering in a nucleus, imagine the W as having a weak charge and polarizing the nuclear medium
- Calculated using Random phase approximation (RPA), PRC 70, 055503 (2004)
- Suppress cross sections at low four momentum transfer Q^2

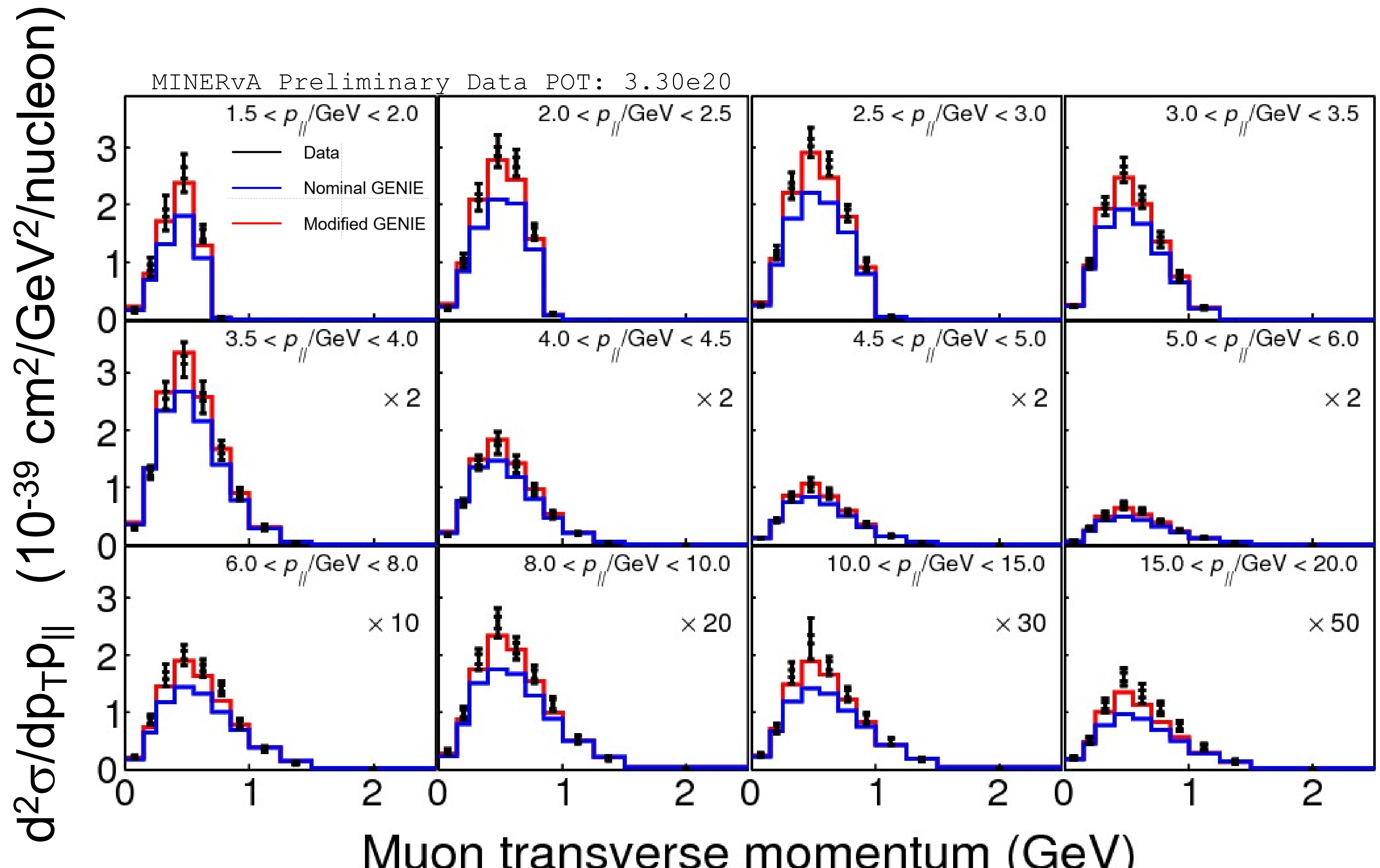




Double Differential Cross Section (Neutrinos)

- Muon longitudinal P_{Z_μ} and transverse momentum P_{T_μ} are measurable quantities

$$\frac{d^2\sigma}{dP_{T_\mu}dP_{Z_\mu}}$$



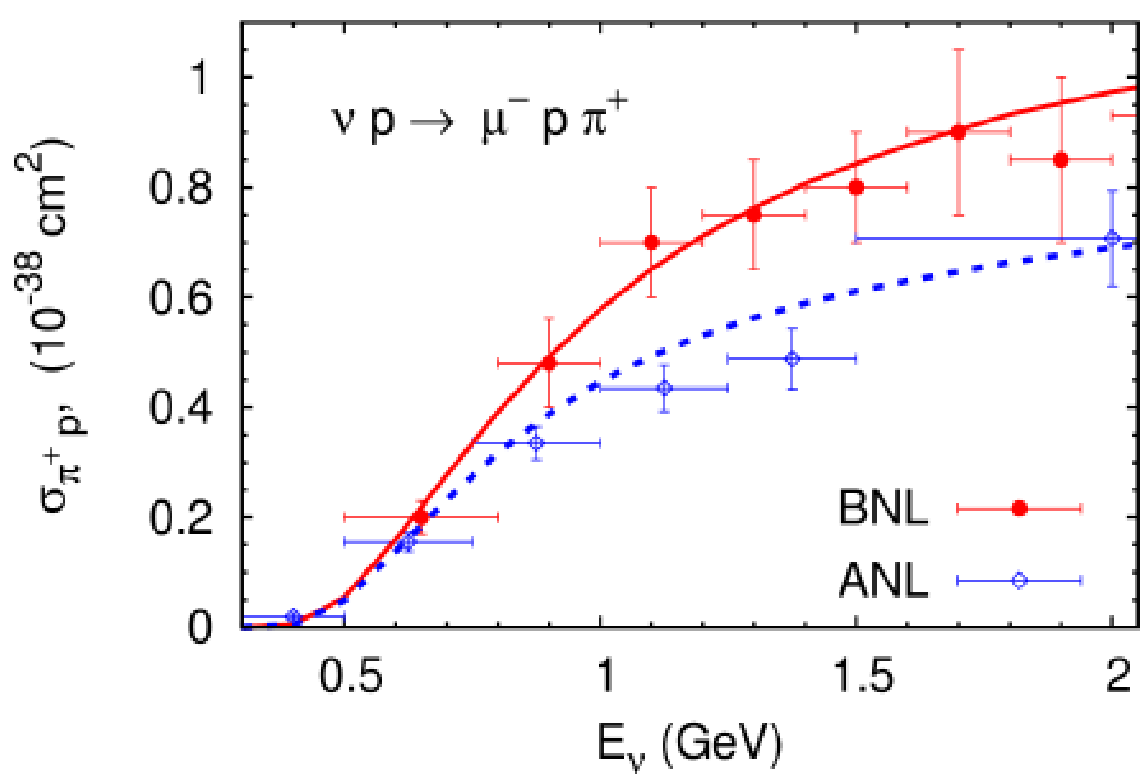
Fermilab Wine and Cheese Seminar, March 3rd 2017
Daniel Ruterbories

Modified GENIE contains new nuclear models (RPA+2p2h)

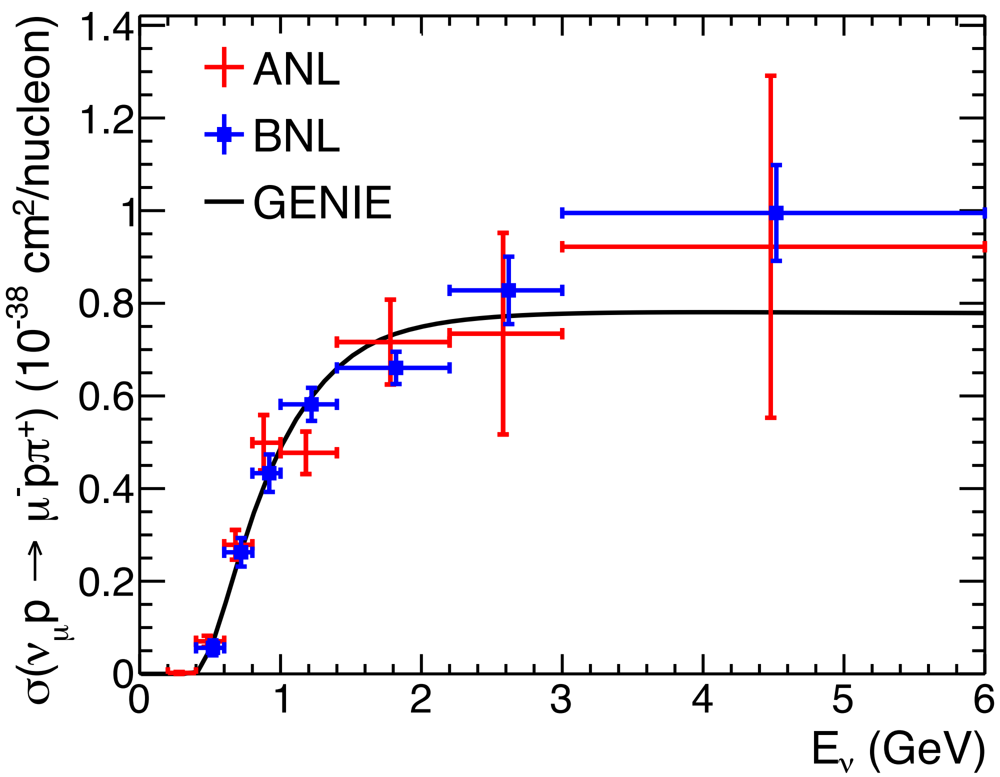
Resonance Production

- Next important channel for neutrino oscillation and increasing the W toward the QCD list
- Most experiments use the Rein-Sehgal model for resonance production
  - More recent models by M. Athat, Salamanca-Valencia, M. Pascos

Old bubble chamber deuterium data



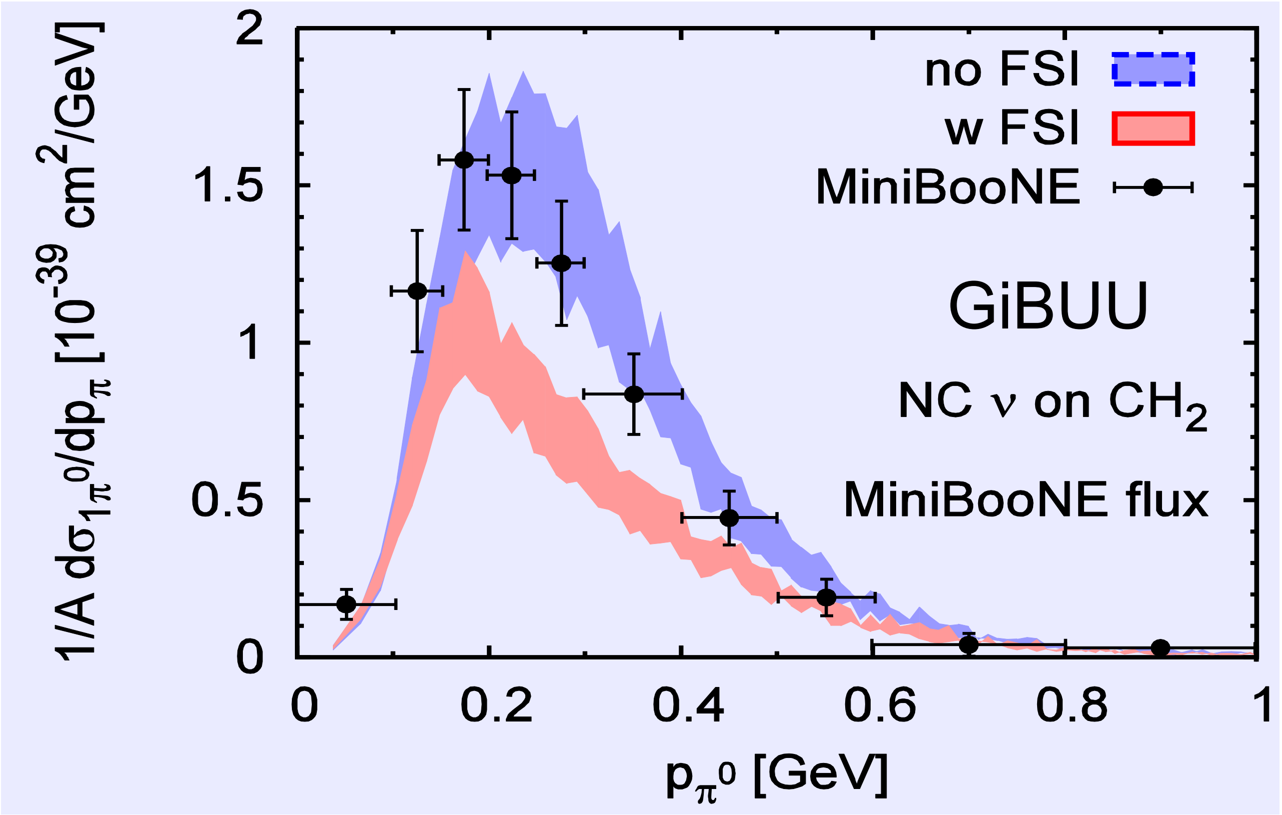
Recent reanalysis of deuterium data finds consistency between ANL and BNL

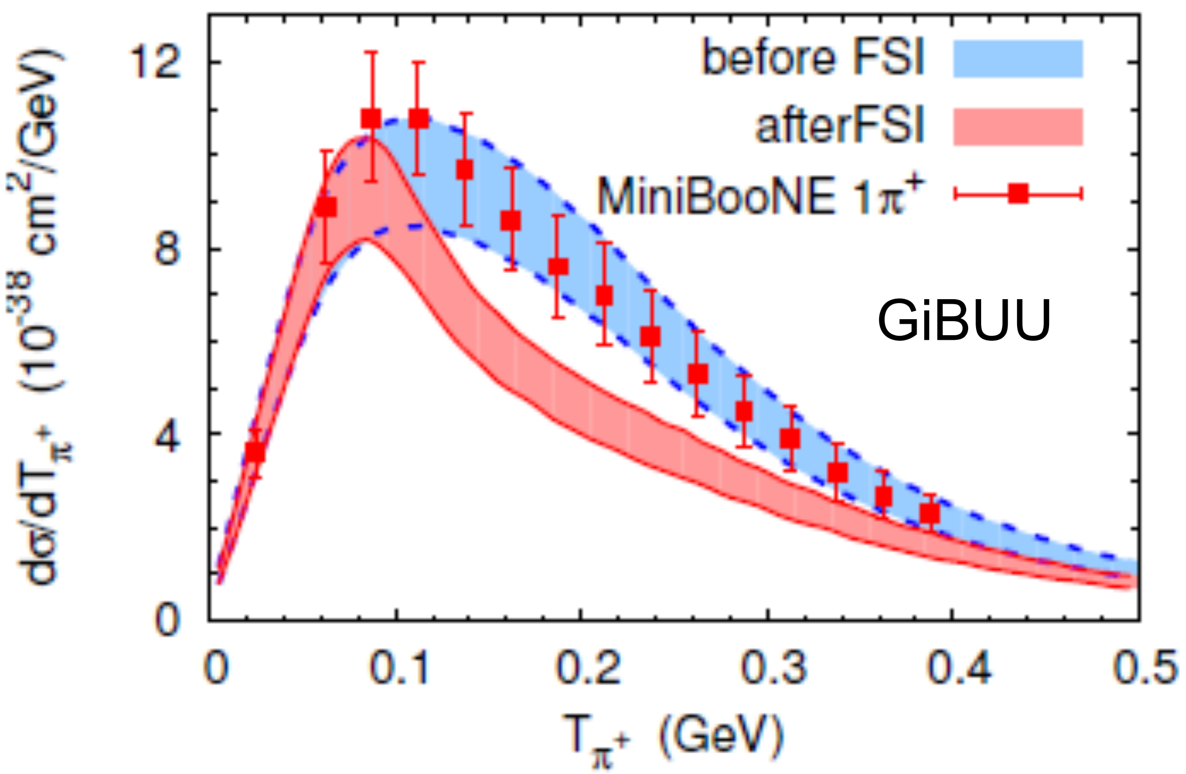


Callum Wilkinson, et al., Phys. Rev. C70(2004) 055503

Comparison of π^0 and $\pi^\pm$ Models with Data from MiniBooNE

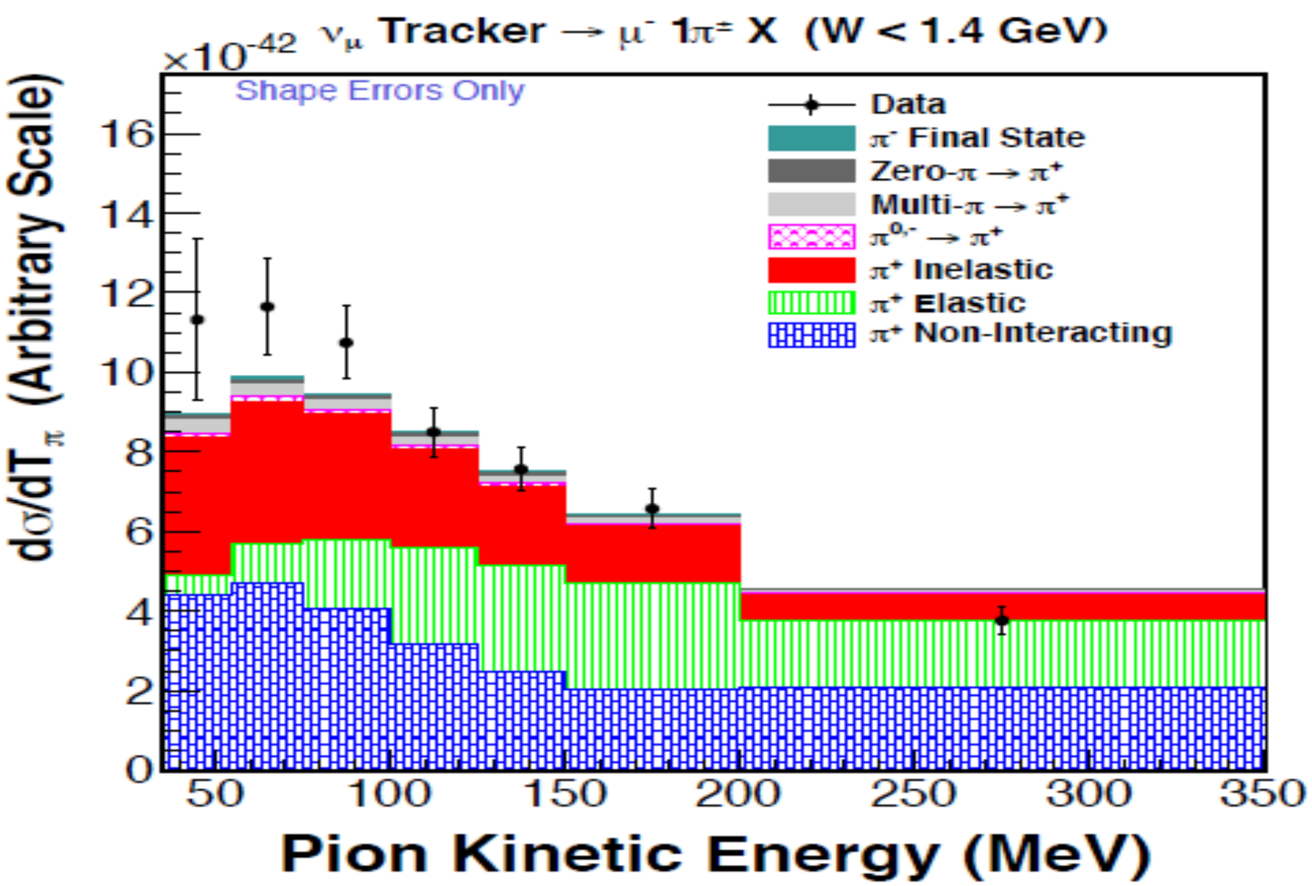
- Data is compared against a theoretical model (GIBUU)
- Data prefers GIBBU with no FSI for both π^0 and $\pi^\pm$



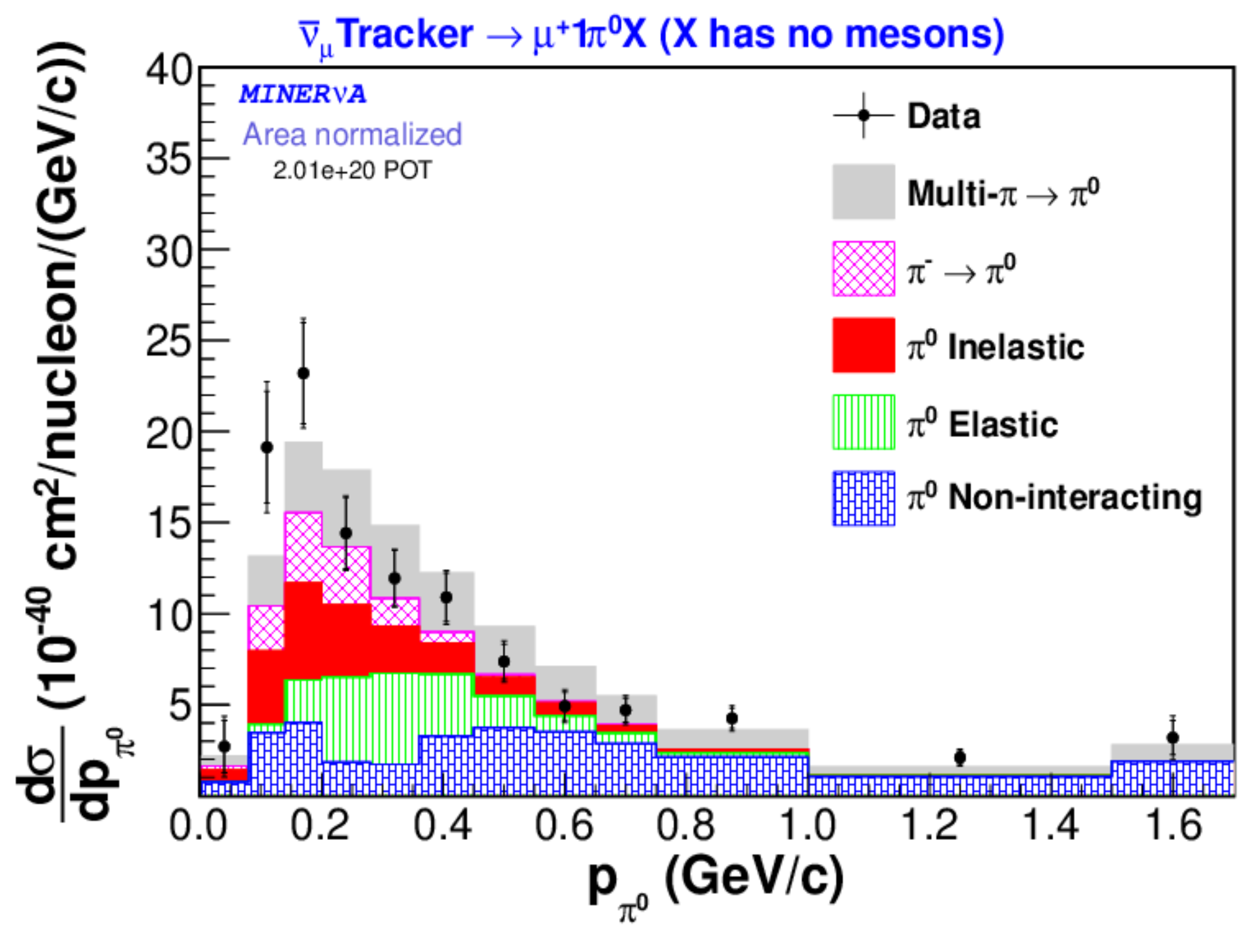


Pion Production and Final State Interactions

- MINERvA has measured pion π^+ and π^0 production
- Both prefer slightly softer pions than GENIE's final state cascade model predicts



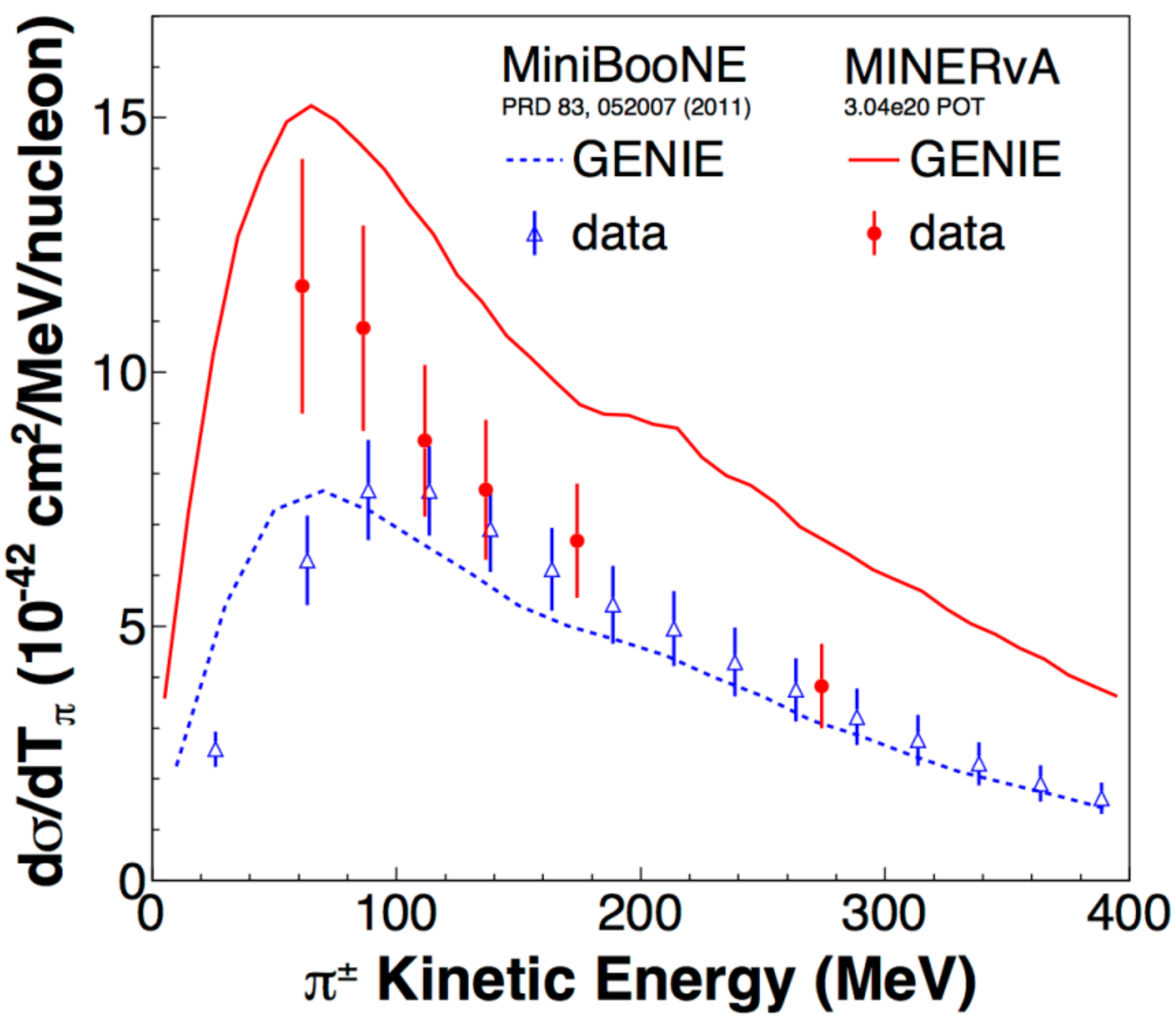
Phys.Rev. D92, 092008 (2015)



Phys. Lett B749 (2015) 130

Comparing MINERvA and MiniBooNE measurements

- No models describe all data sets well
  - MiniBooNE <E>~1 GeV: best theory models (GIBUU) strongly disagree in shape
  - MINERvA <E>=4 GeV: Event generator has shape but not magnitude



Neutrino Deep-Inelastic Scattering

- Deep inelastic neutrino-nucleon scattering reactions have large q2 ($q^2 >> m^2_N$, $E_\nu >> m_N$)

$$\nu_l(p) + N \rightarrow l^-(p') + X$$

- Quark-Pardon model valid due to asymptotic freedom of QCD, which makes quarks behave as free point-like particles

- Using Mandelstam variables in DIS

Bjorken Variables
(0<x<1, 0<y<1)

$$s = (p + p_N)^2 \approx 2ME_\nu = 2ME$$

$$Q^2 = -q^2 = -(p + p')^2 = 4EE' \sin^2 \frac{\theta}{2}$$

$$W^2 = E_X{}^2 - p_X{}^2 = -Q^2 + 2M\nu + M^2$$

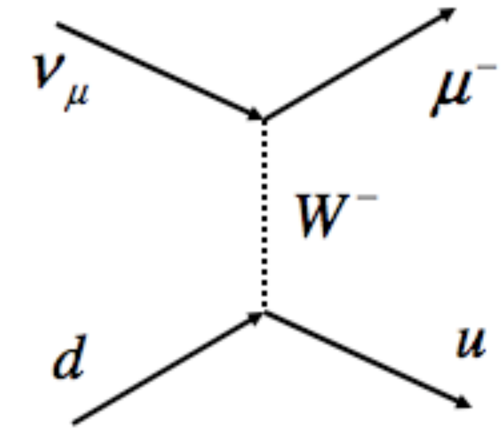
$$\nu = \frac{q \cdot p_N}{M} = E - E'$$

$$x = \frac{-q^2}{2q \cdot p_N} = \frac{Q^2}{2M\nu}$$

$$y = \frac{q \cdot p_N}{p \cdot p_N} = \frac{\nu}{E} = \frac{Q^2}{2MEx}$$

Neutrino Deep Inelastic Scattering

- Scattering off protons



$$\frac{d\sigma_{CC}(\nu_\mu p)}{dxdy} = \frac{G_F{}^2 ME}{\pi} 2x\left\{\left[d(x)+s(x)\right]+\left[\bar{u}(x)+\bar{c}(x)\right](1-y)^2\right\}$$

$$\frac{d\sigma_{CC}(\bar{\nu}_\mu p)}{dxdy} = \frac{G_F{}^2 ME}{\pi} 2x\left\{\left[u(x)+c(x)\right](1-y)^2+\left[\bar{d}(x)+\bar{s}(x)\right]\right\}$$

- Structure functions

$$F_2^{\nu p}(x) = 2x\left[d(x)+\bar{u}(x)+s(x)+\bar{c}(x)\right]$$
$$xF_3^{\nu p}(x) = 2x\left[d(x)-\bar{u}(x)+s(x)-\bar{c}(x)\right]$$
$$F_2^{\bar{\nu} p}(x) = 2x\left[u(x)+c(x)+\bar{d}(x)+\bar{s}(x)\right]$$
$$xF_3^{\bar{\nu} p}(x) = 2x\left[u(x)+c(x)-\bar{d}(x)-\bar{s}(x)\right]$$

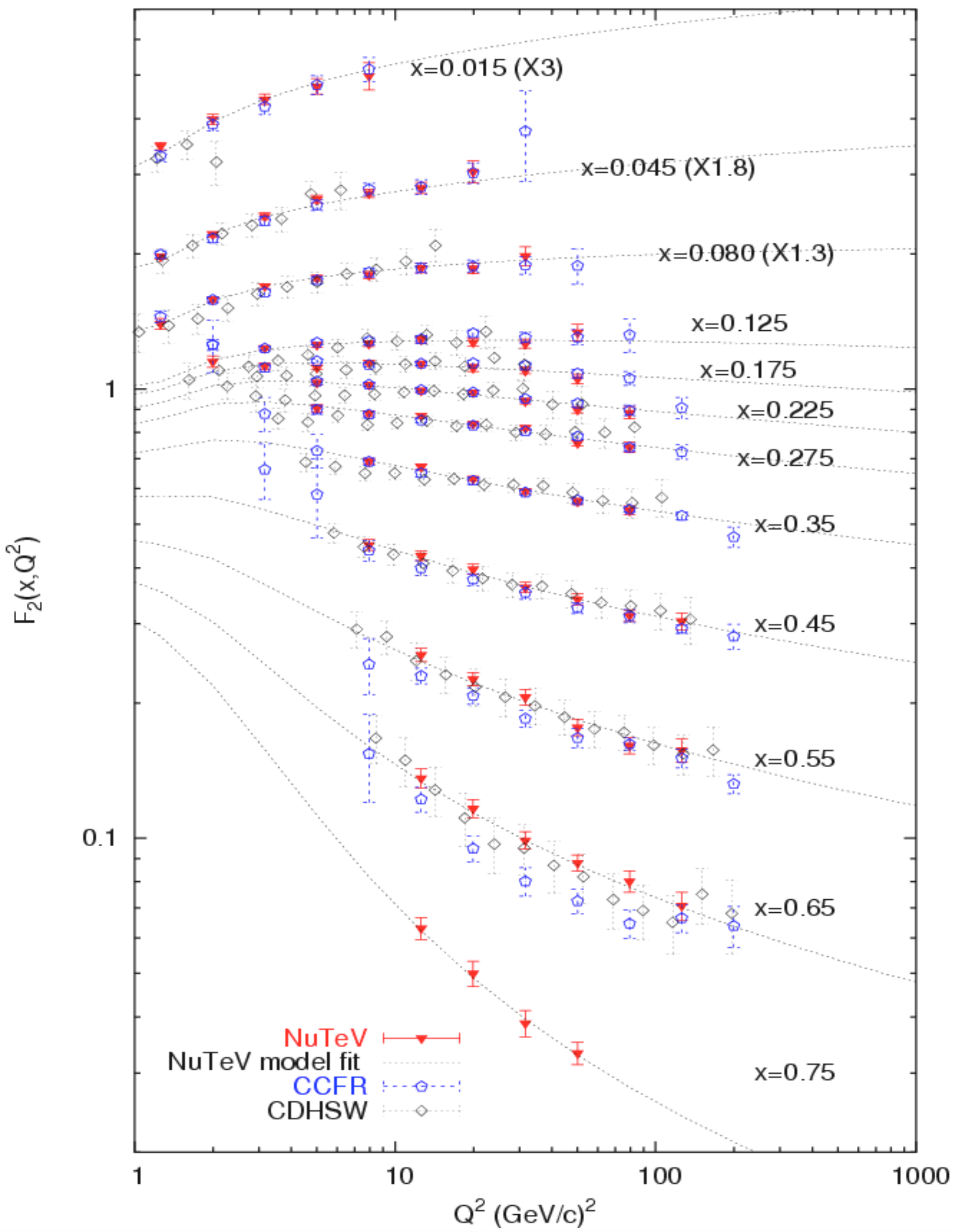
- Neutron (isospin symmetry)

$$F_2^{\nu n}(x) = 2x\left[u(x)+\bar{d}(x)+s(x)+\bar{c}(x)\right]$$
$$xF_3^{\nu n}(x) = 2x\left[u(x)-\bar{d}(x)+s(x)-\bar{c}(x)\right]$$

DIS Scattering Data

- NuTeV experiment at Fermilab studied DIS scattering
- NuTeV collected over 3 million event 20 GeV<E<400 GeV

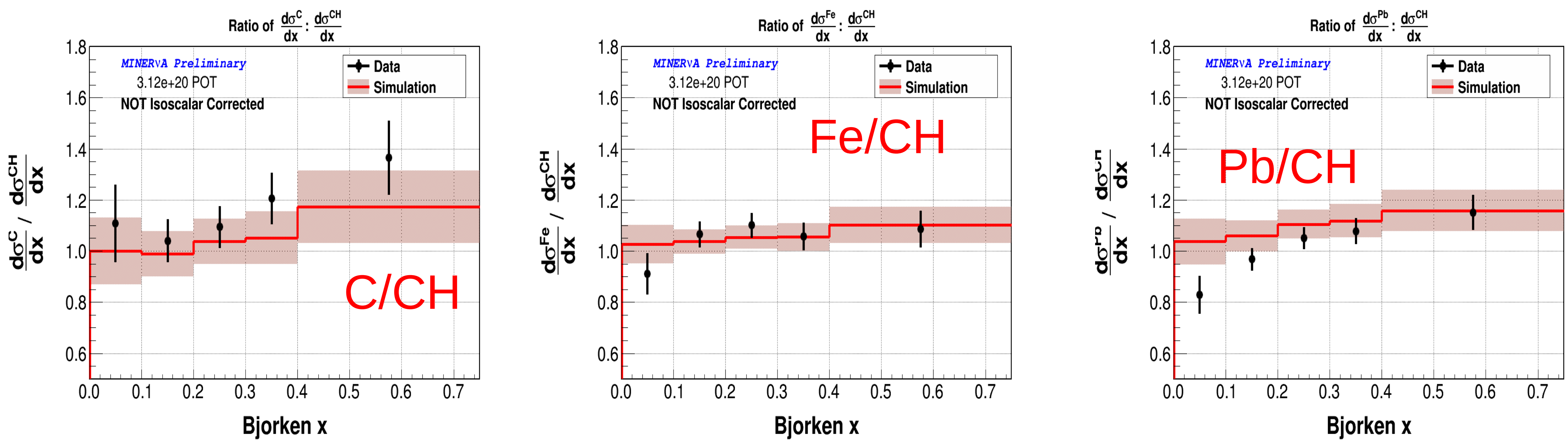
F2 measurement on Iron



- Data agrees with charge lepton data for x<0.5
- NuTeV F2 and xF3 agrees with theory for medium x
  - At low x different Q2 dependence
  - At high x (x>0.6) NuTeV is systematically higher

Deep Inelastic From MINERvA

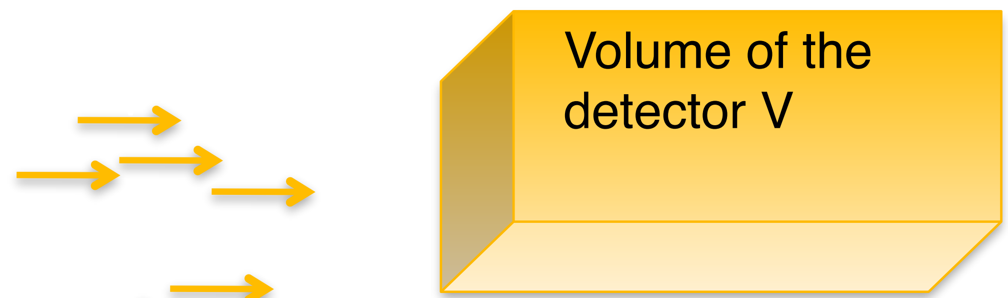
- MINERvA produced deep inelastic ratios from nuclear targets to study x dependent nuclear effects
- We have a x range from the low x shadowing region through the EMC region
- The simulation used in the analysis assumes the same x-dependent nuclear effects for C, Fe and Pb based on charged lepton scattering



- The data suggest additional nuclear shadowing in the lowest x bin (0<x<0.1) than predicted in lead, it is at a value of x and Q2 where shadowing is not normally found in charged lepton nucleus scattering
- In the MEC region (0.3<x<0.75), we see good agreement between data and simulation

Neutrino Cross Section

- Let’s concentrate on each of the ingredients to compute the cross section



Cross Section

$$\sigma = \frac{N}{\phi T \epsilon}$$

Number of interactions that occurred

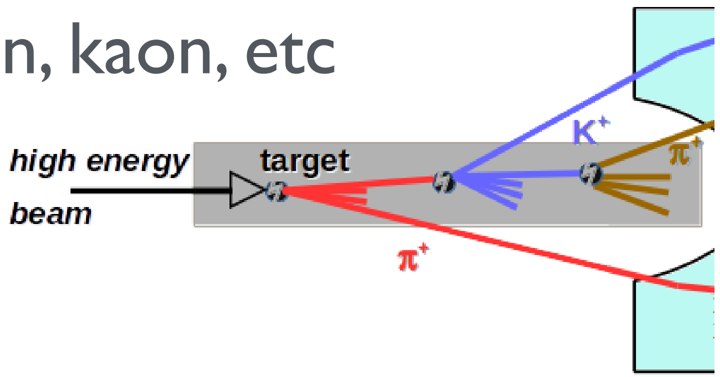
Total flux of incident neutrinos per unit area

Number of targets

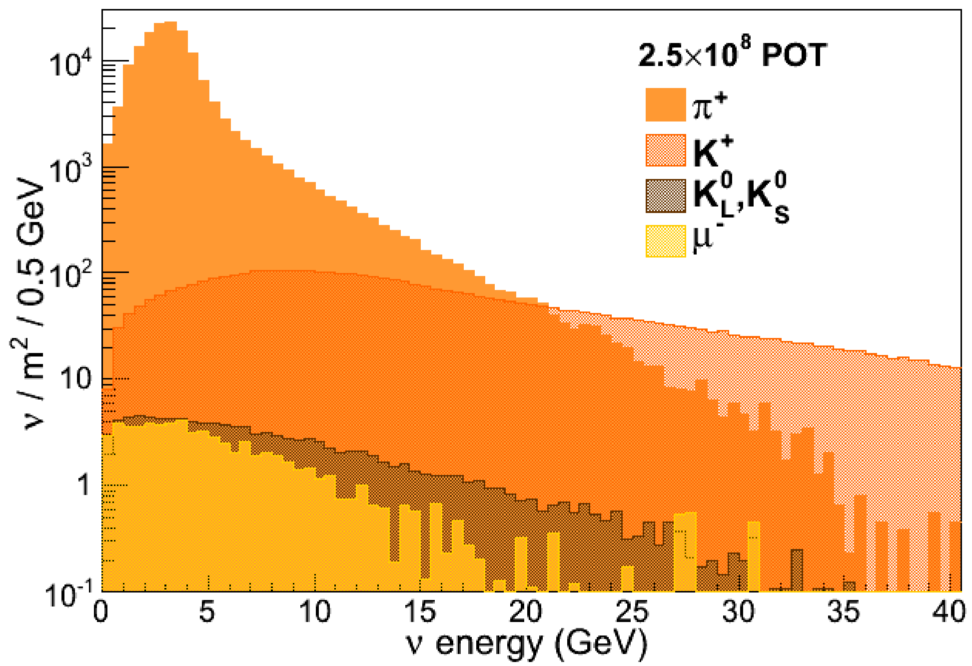
- Neutrino Flux
  - Considering the procedure from MINERvA experiment as an example

Hadronic Cascade in the Target

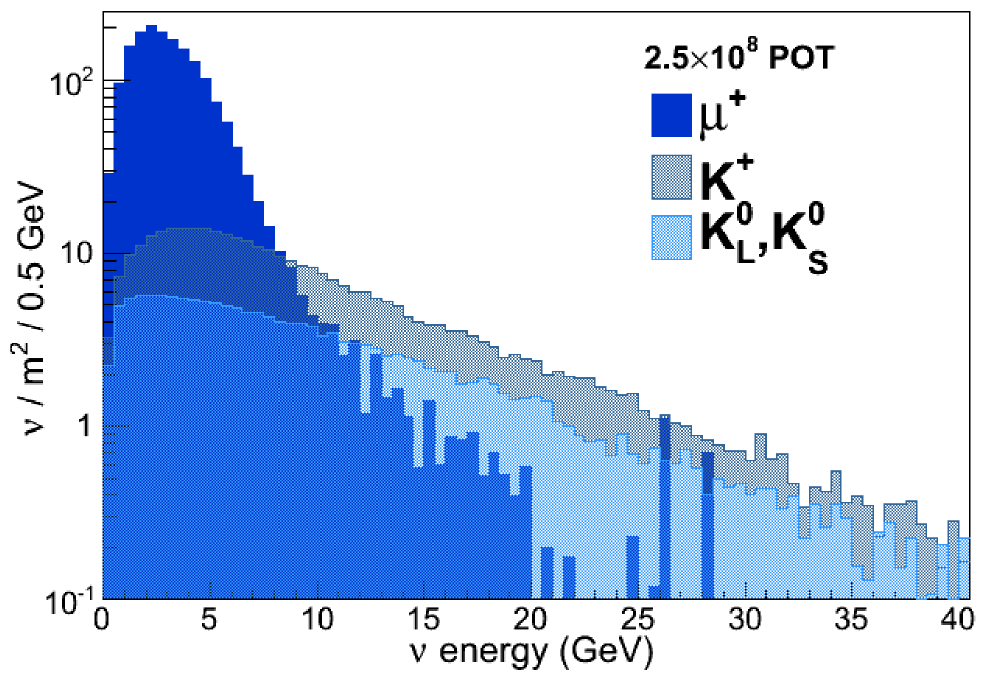
- The primary beam interactions in the target: proton on carbon
- Secondary and tertiary interactions in the target: proton, pion, kaon, etc
- Interaction outside of the target: proton, pion, kaon on aluminum, iron, helium, etc



Parents for muon neutrino



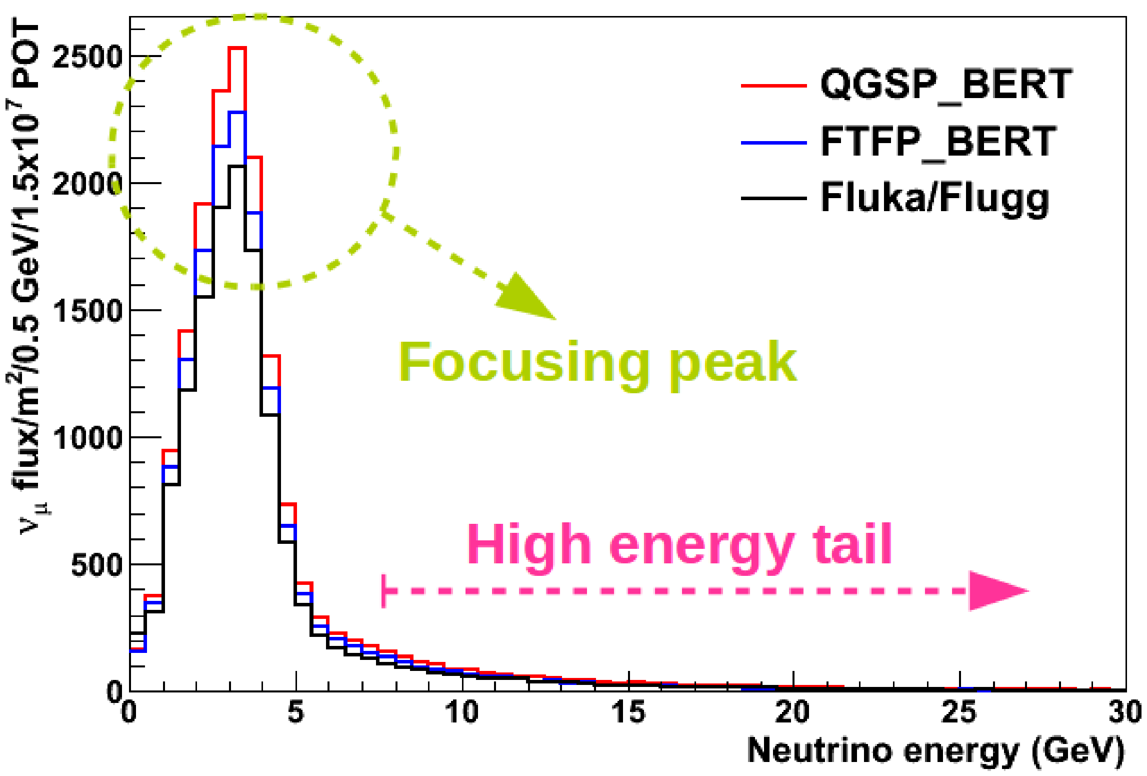
Parents for electron neutrino



Hadronic Cascade in the Target

- These interactions are non-perturbative QCD
- The simulation uses a model
  - MINERvA uses geant4.2.p03 and FTFP_BERT as hadronic model

Different Model predictions



- Big discrepancies between predictions from hadronic models

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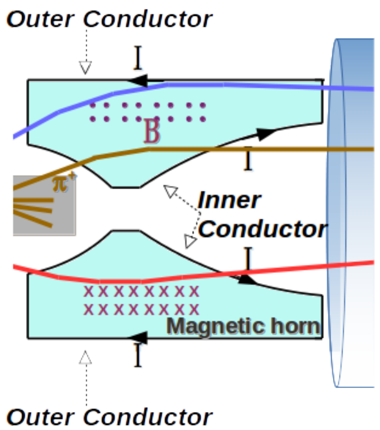
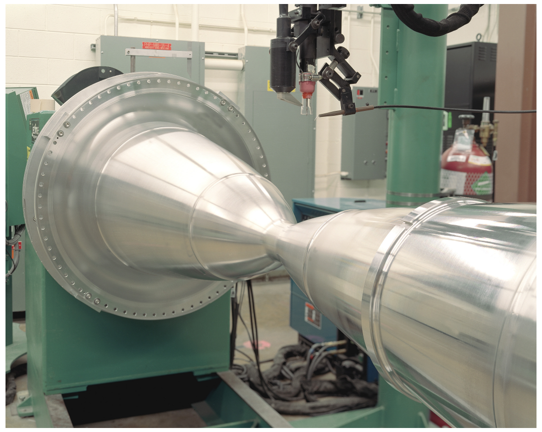
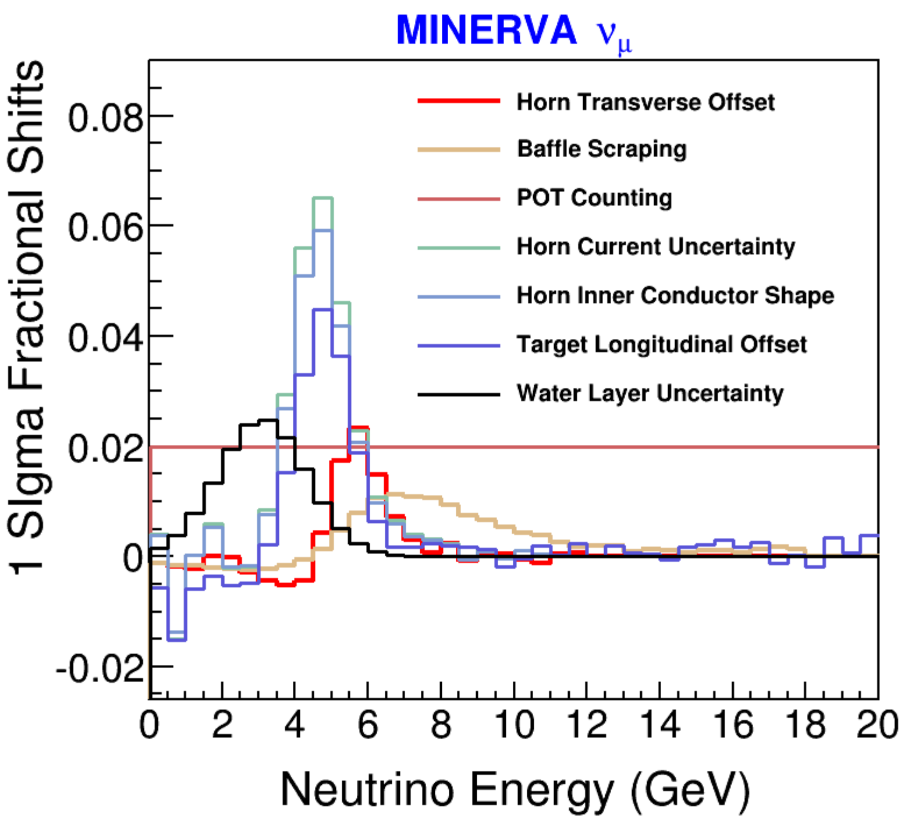
What are the sources for the Systematic Uncertainties?

- Focusing Uncertainties





A current is pulsed through two aluminum horns to create a toroidal magnetic field



- Hadronic interactions:
  - We need external data: Inelastic cross section of pion, kaon and all the particles that are part of the hadronic cascate

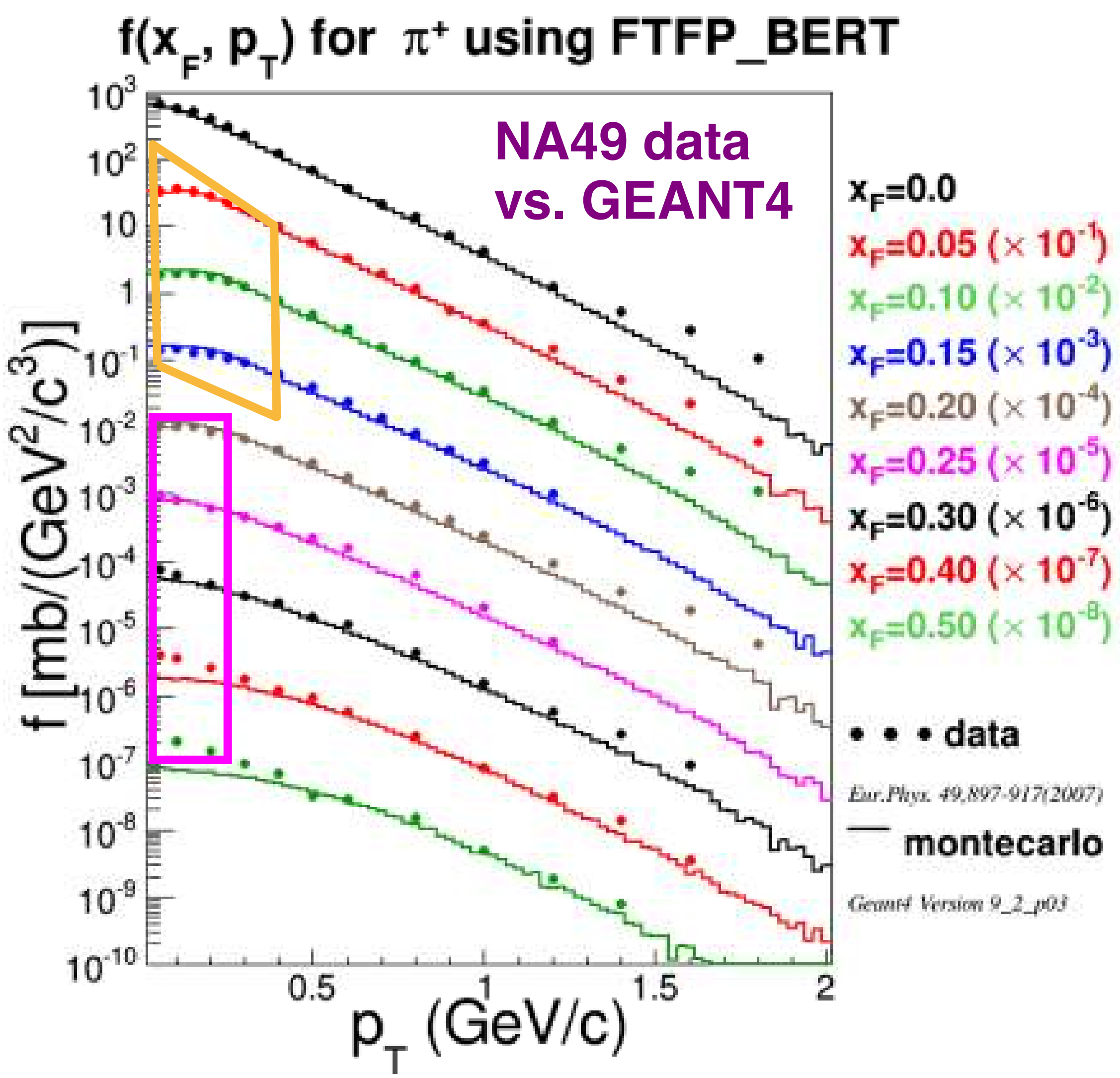
	Particle production	x_F	Reference
NA49 pC @158 GeV	$\pi^\pm$	<0.5	Eur.Phys.J. C49 (2007) 897
	$K^\pm$	<0.2	G. Tinti Ph.D. thesis
	p	<0.9	Eur.Phys.J. C73 (2013) 2364

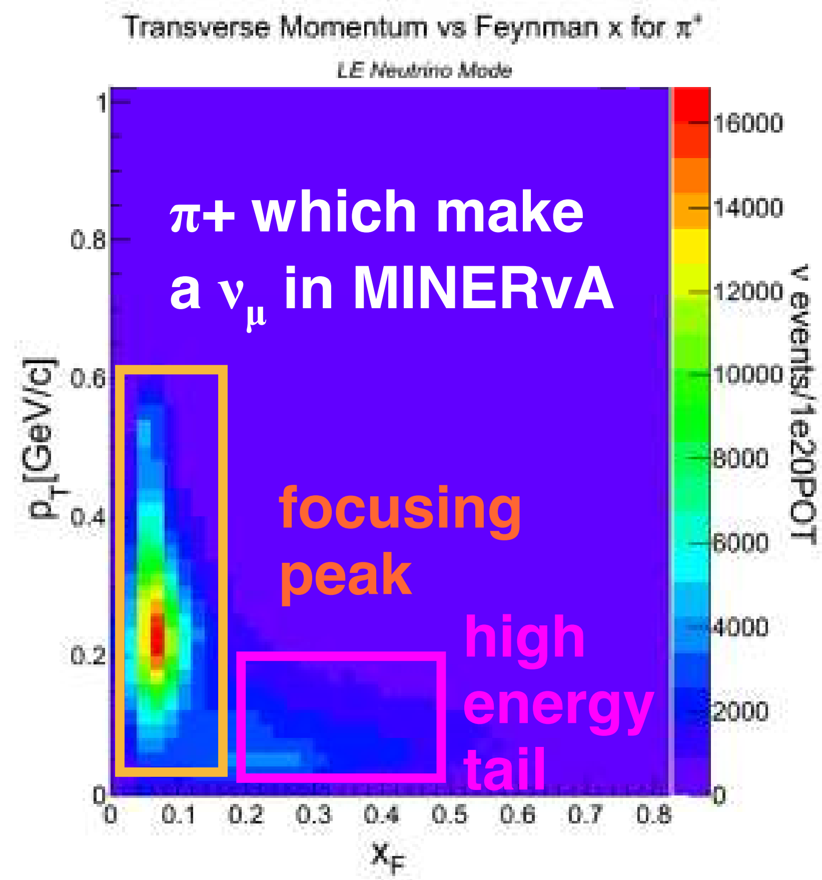
How do we use Data to Correct the simulations?

- A weight is applied to the ν based on its hadronic interaction history

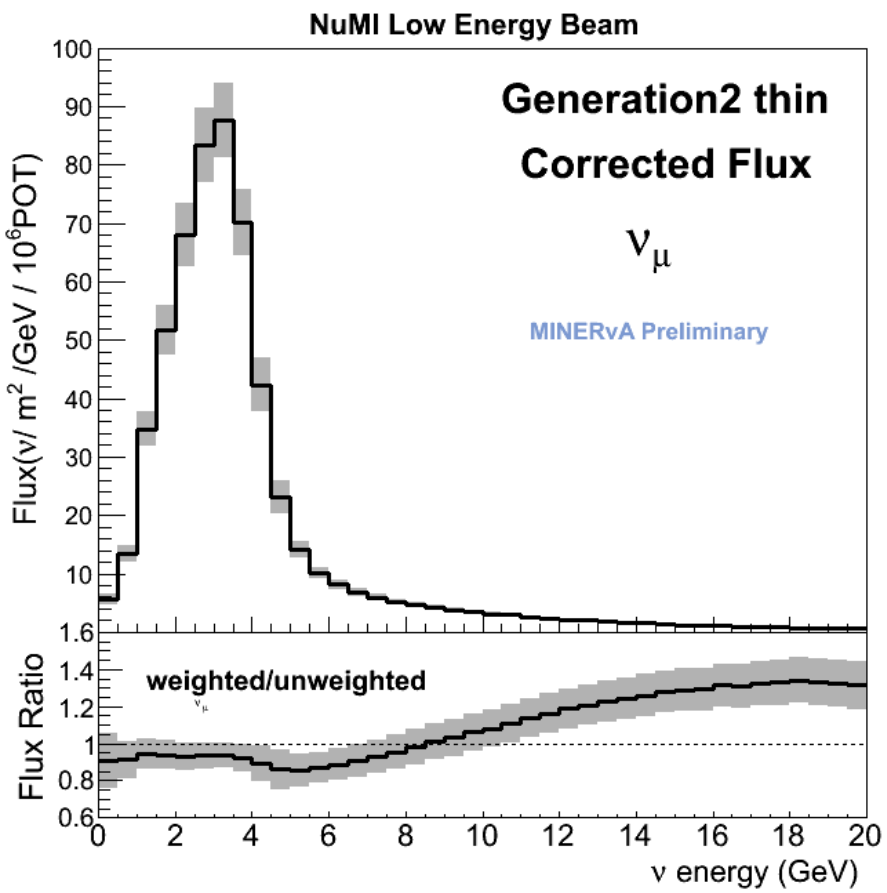
$$correction(x_F, p_T, E) = \frac{f_{Data}(x_F, p_T, E = 158GeV) \times scale(x_F, p_T, E)}{f_{MC}(x_F, p_T, E)}$$

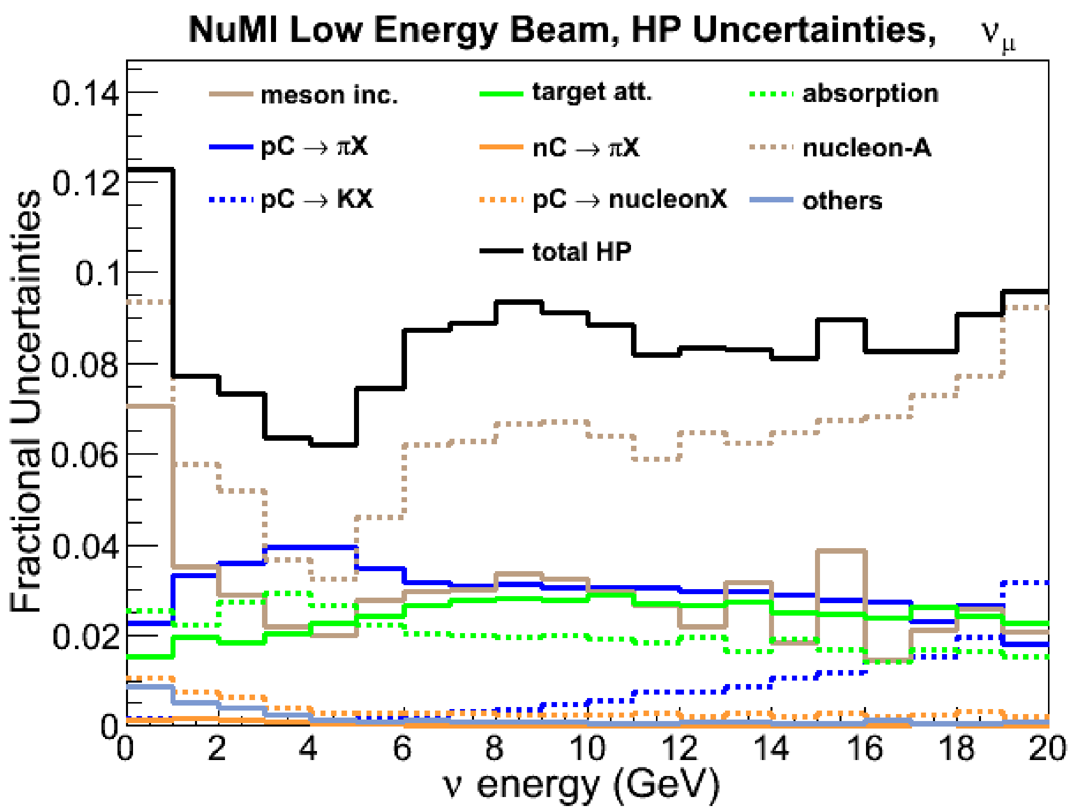
$f(x_F, p_T) = E\, d^3\sigma/dp^3$ = invariant production cross-section





Flux Prediction and Uncertainty





Low-ν Technique

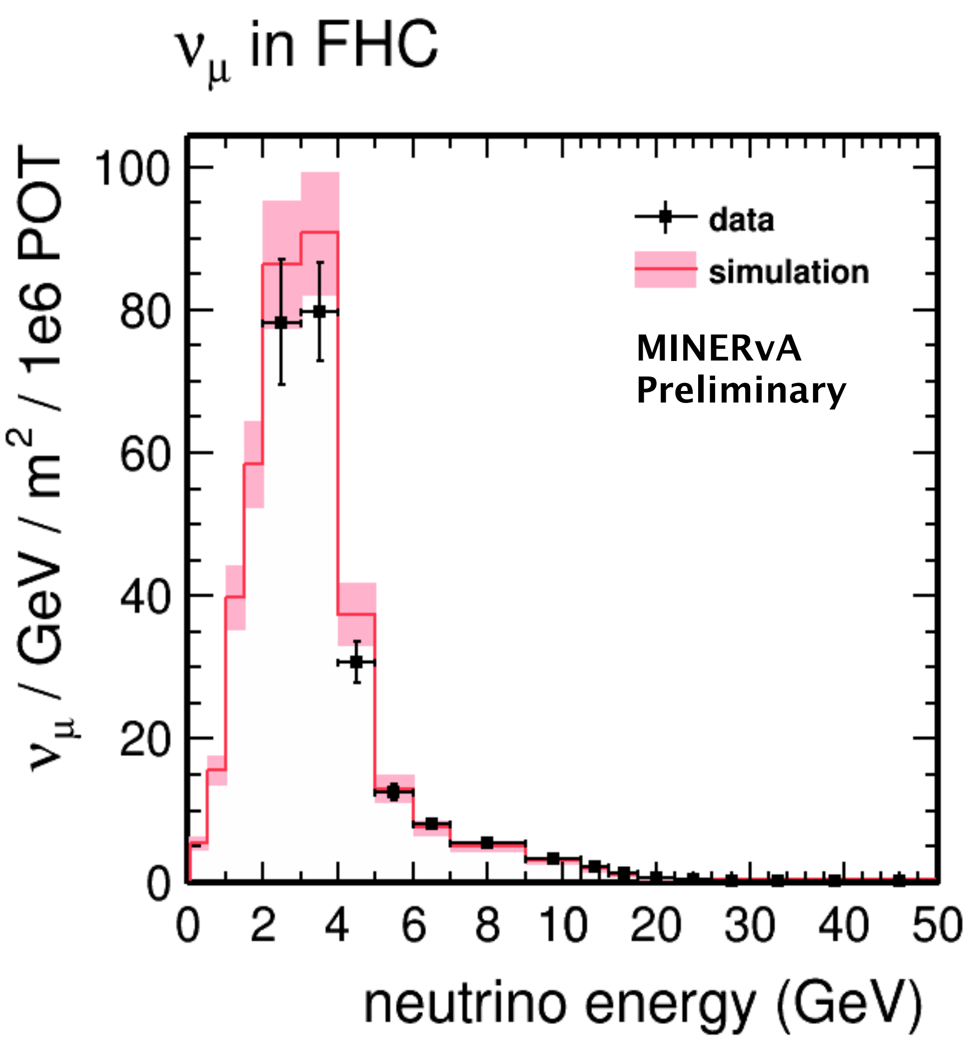
- Using charged-current scattering with lower hadronic recoil energy
- The ν is the energy transferred to the recoil system: $\nu = E(\text{neutrino}) - E_\mu$
- In the limit of small ν, the charged current cross section for neutrinos and antineutrinos is approximately constant

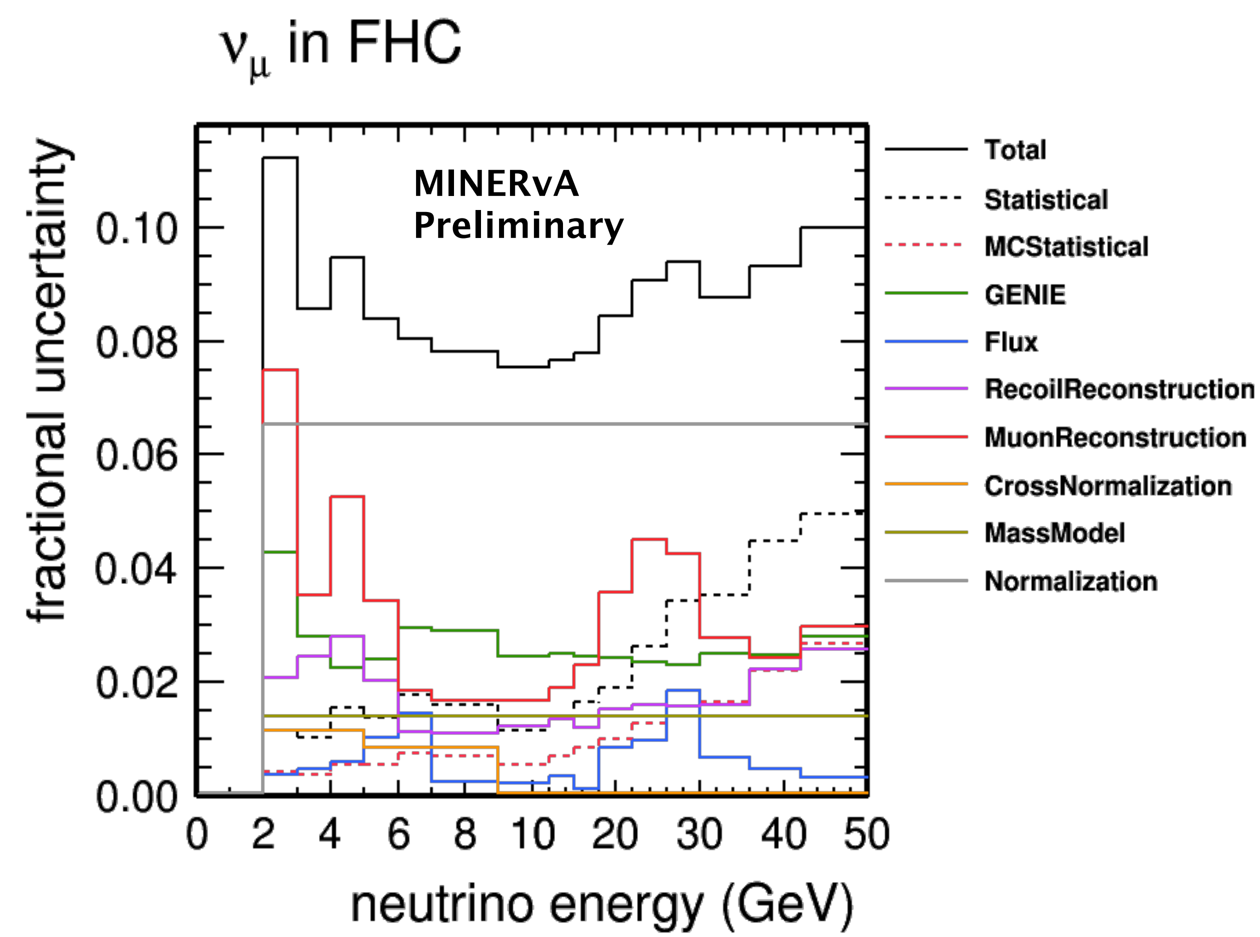
$$\frac{d\sigma}{d\nu} = A\left(1 + \frac{B}{A}\frac{\nu}{E} - \frac{C}{A}\frac{\nu^2}{E^2}\right)$$

- As $\nu/E \to 0$ $\quad \frac{d\sigma}{d\nu} \to A$
- A measurement of the low-ν interaction rate as a function of neutrino energy is equivalent to a measurement of the shape of the neutrino flux
- Technique used in different experiments
  - In 2006 NuTeV experiment used 5- 20GeV low-ν cut (M.Tzanov at al. Phys. Rev. D74 012008)
  - in 2010 MINOS experiment used 3- 50GeV low-ν cut (P.Adamson et al.) Phys. Rev. D 81, 072002

Low-Nu Technique

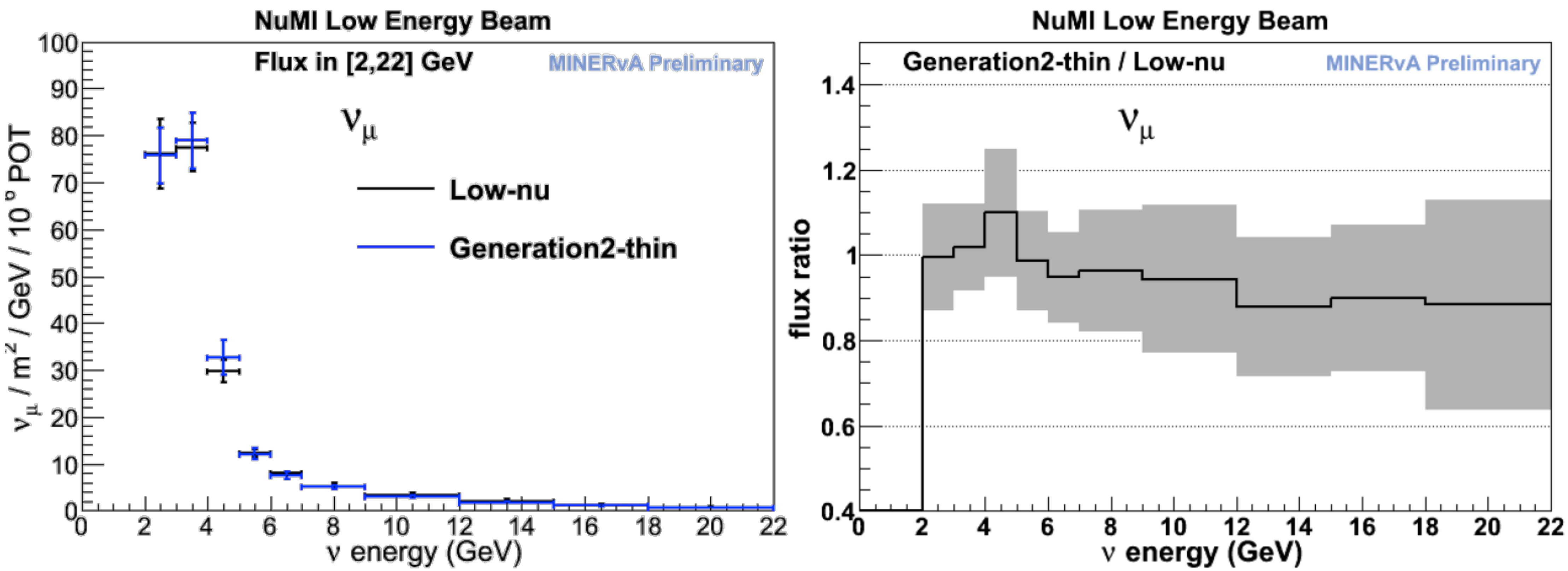
- Neutrino flux from the low-ν method





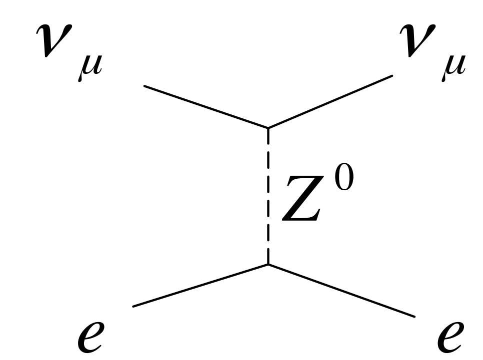
Constrained flux vs Low-nu

- Comparing with the flux constrained with hadron production data



Flux Constraint using Neutrino-Electron Scattering

- Well understood electroweak process



$$\frac{d\sigma(\nu_\mu e^- \to \nu_\mu e^-)}{dy} = \frac{G_F^{\,2} m_e E_\nu}{2\pi}\left[\left(\frac{1}{2} - \sin^2\theta_W\right)^2 + \sin^4\theta_W (1-y)^2\right]$$

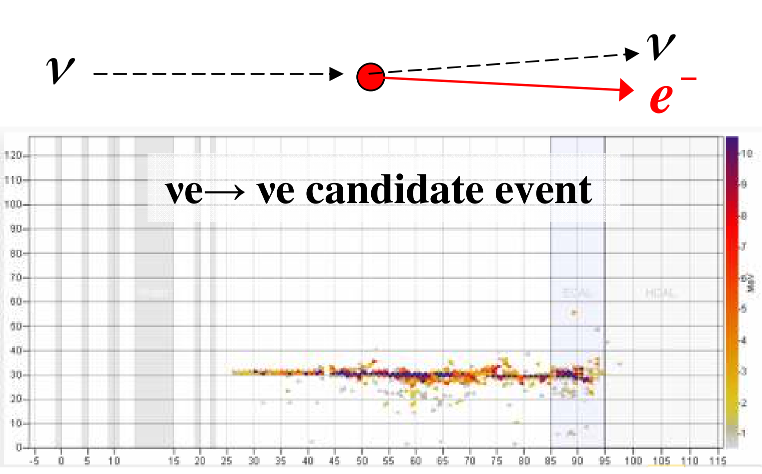
G_F and θ_W: well-known electroweak parameters

$$y = \frac{(\text{electron KE})}{(\text{neutrino energy})}$$

$$\nu_\mu + e^- \to \nu_\mu + e^-$$

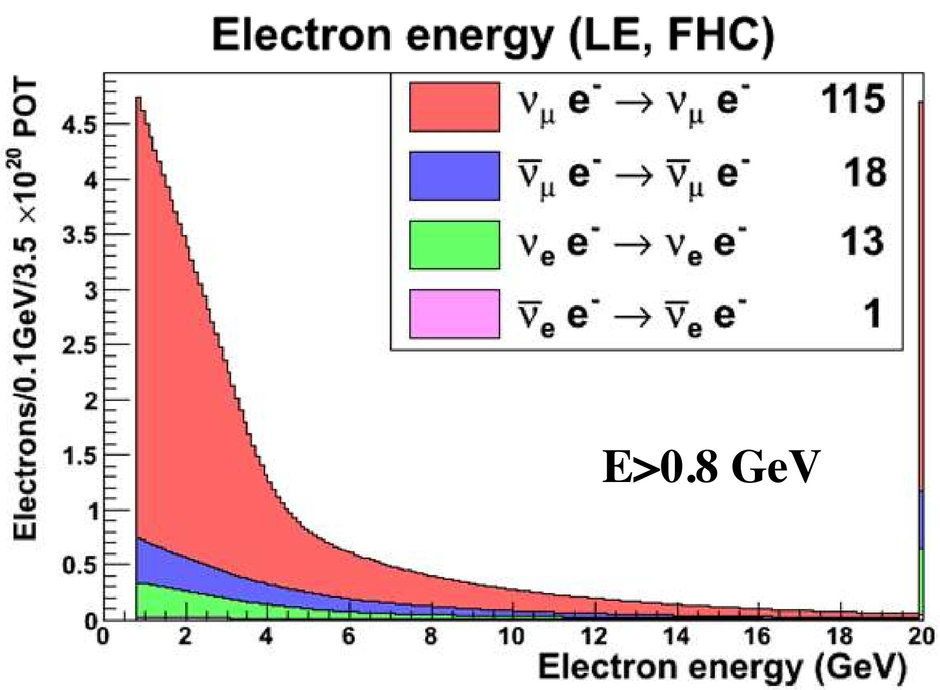
$$\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-$$

- Very small cross section (~1/2000 of nu-nucleon scattering)
- Very forward electron final state
  - Good angular forward electron final state
- Signal in MINERvA is a single electron moving in the beam direction



Signal and Backgrounds (Neutrino-Electron Scattering) at MINERvA

- Signal is a mixture of $\nu_\mu e^-, \bar{\nu}_\mu e^-, \nu_e e^-$ and $\bar{\nu}_e e^-$

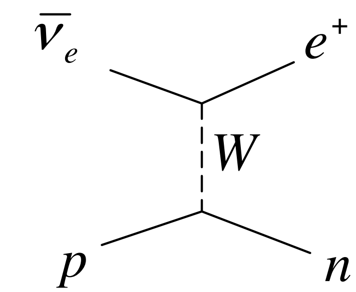


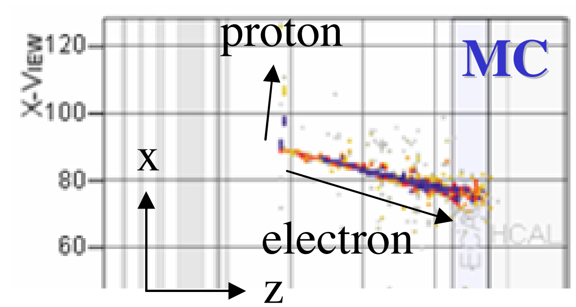
- We cannot distinguish neutrino type

$$\nu_\mu e^- \text{ and } \bar{\nu}_\mu e^- : 91\%$$
$$\nu_e e^- \text{ and } \bar{\nu}_e e^- : 9\%$$

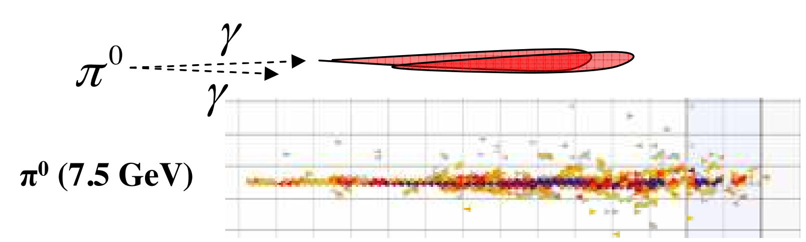
- Backgrounds

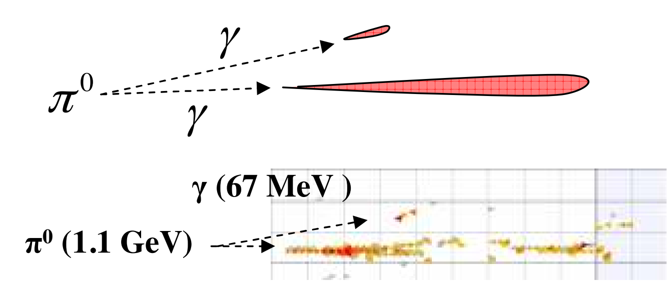
$$\nu_e + n \to e^- + p$$
$$\bar{\nu}_e + p \to e^+ + n$$





$$\nu_\mu A \to \nu_\mu A \pi^0 \quad \textbf{NC-coherent } \pi^0$$
$$\nu_\mu N \to \nu_\mu N \pi^0 \quad \textbf{NC-resonant } \pi^0$$





Event Selection

- Using Mandelstam variables

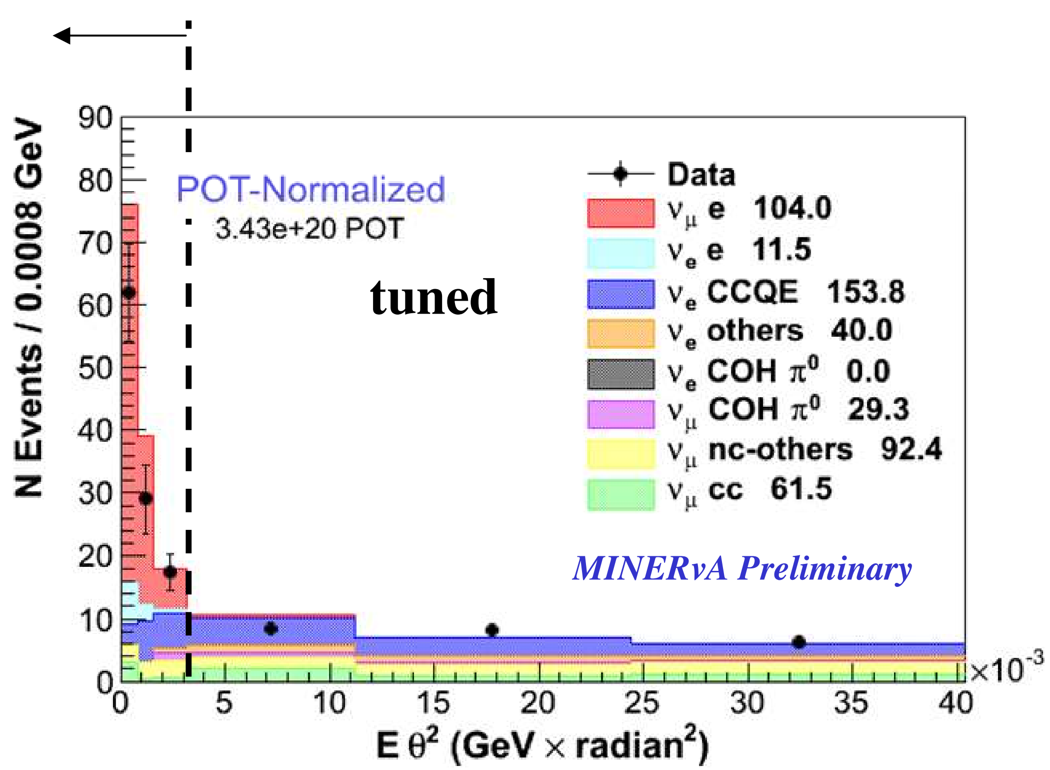
$$t = \frac{s}{2}\left(1-\cos\theta^*\right) \qquad y = -\frac{1}{2}\left(1-\cos\theta^*\right) \quad \text{in CM frame} \Longrightarrow t = -sy$$

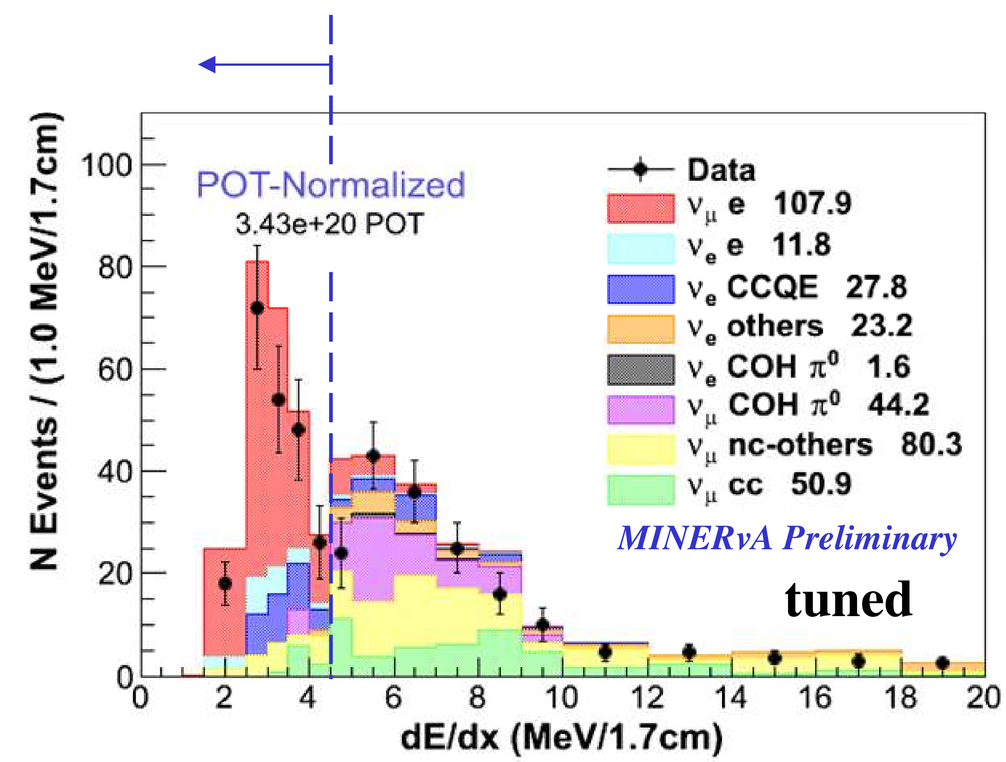
$$u = -2E_\nu E_e(1-\cos\theta) \quad \text{in lab frame}$$

$$\boxed{\begin{aligned} s + t &= -u \\ s(1-y) &= 2E_\nu E_e(1-\cos\theta) \\ 2m_e(1-y) &= E_e\theta^2 \end{aligned}}$$

$$\text{Since } 0 < y < 1, \qquad E_e\theta^2 < 2m_e$$

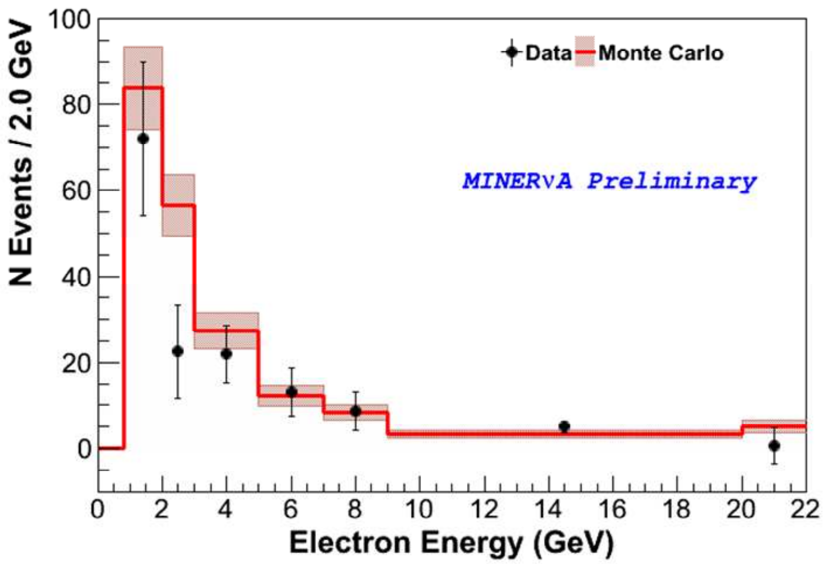
- Neutrino interaction does not always produce only single electron or single photon from π^0
- Non-single particle activity affects dE/dx





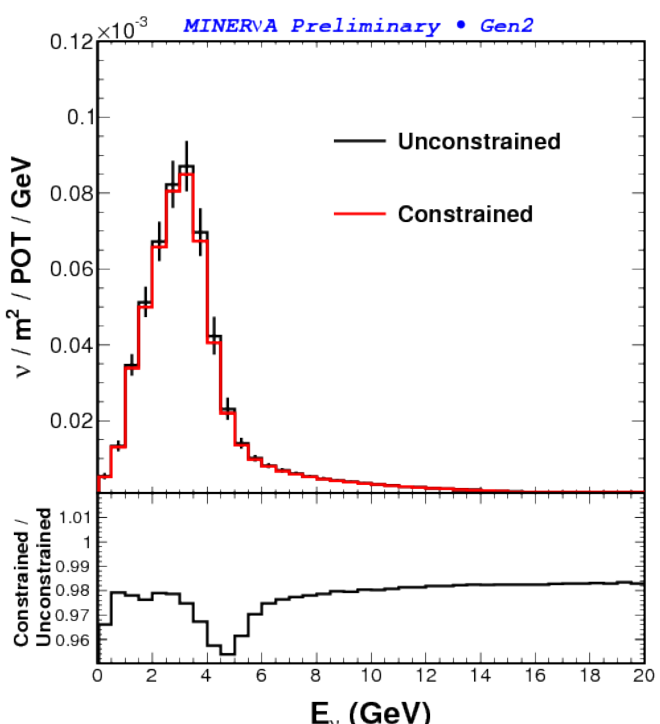
Results

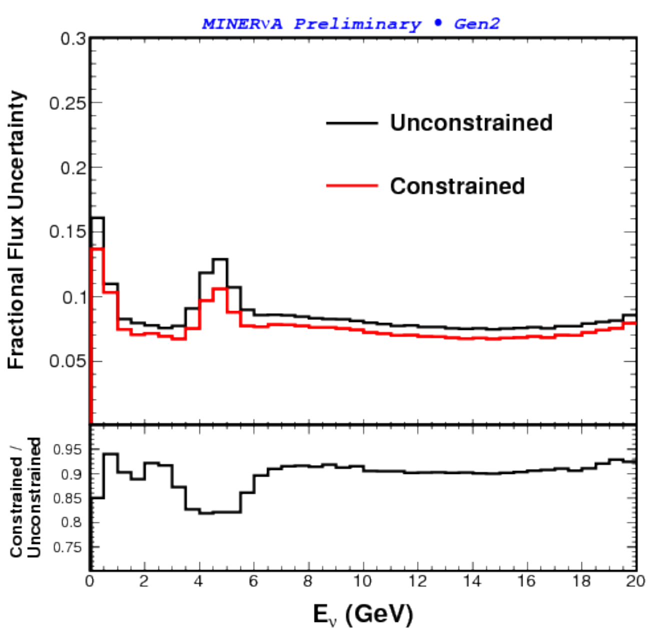
- Electron neutrino events after background subtraction and efficiency correction:



123.8 ± 17.0 (stat) ± 9.1 (sys)

- Using data the flux is constrained

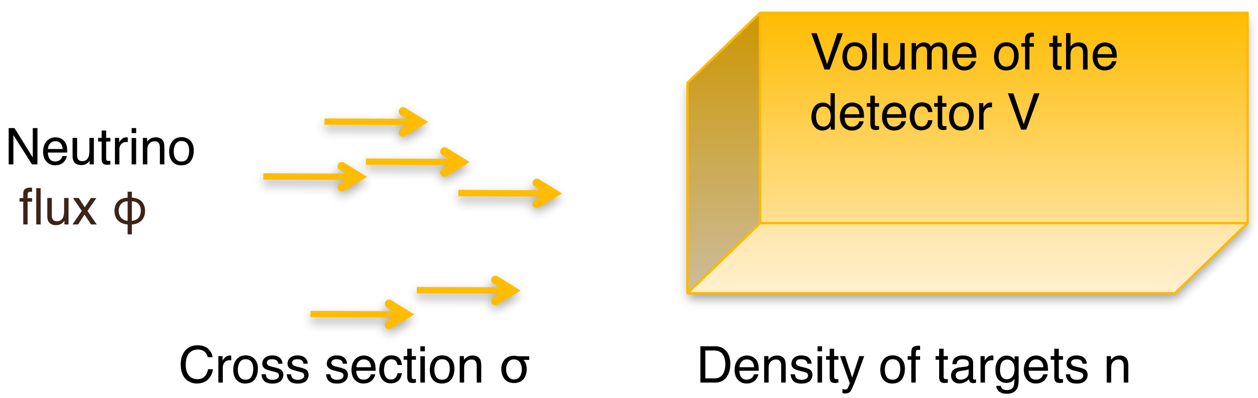




- The total uncertainty on the NuMi neutrino flux reduces from 9% to 6%

Neutrino Cross Section

- We reviewed some neutrino interactions and techniques to constraint the flux, tomorrow we will study in detail each step to compute the cross section



Number of interactions per second

$$\varphi\sigma nV$$

$$\sigma = \frac{N}{\phi T \epsilon}$$