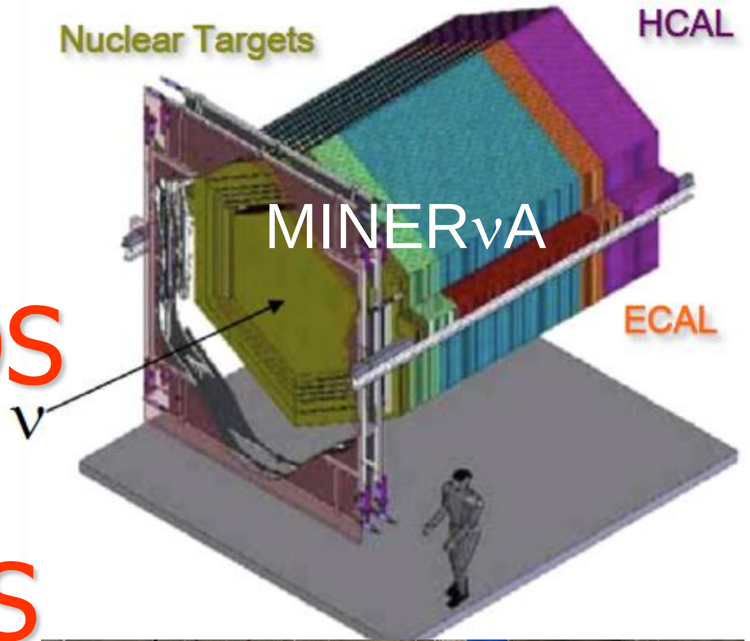
NEUTRINOS
&
NUCLEONS
&
NUCLEI

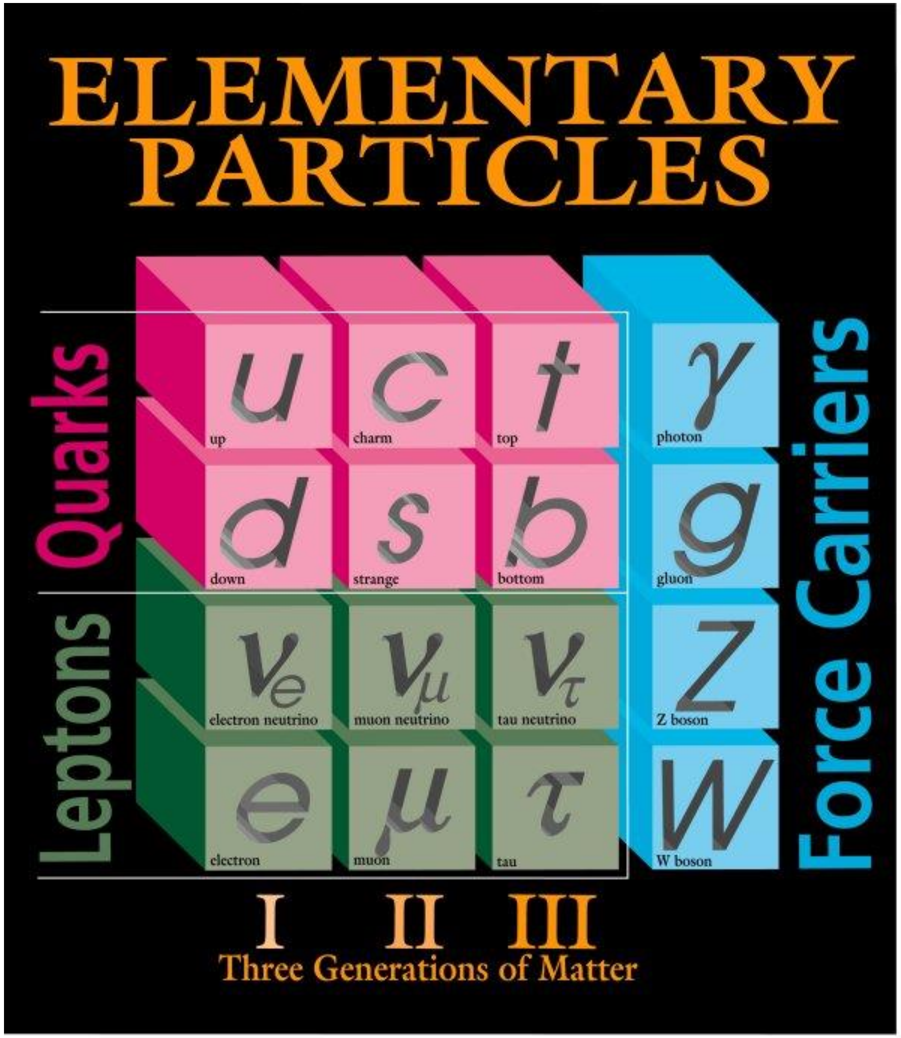


(An Experimental Overview)

EINN 2013
Paphos
November 2nd '13

Alessandro Bravar

Neutrinos In the “Current” Standard Model



Fermilab 95-759

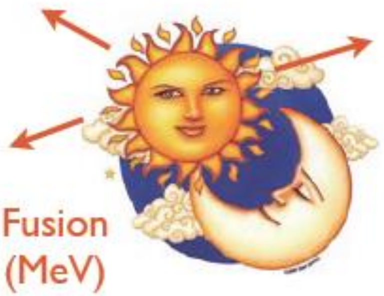
Standard Model :

using 19 parameters the SM predicts the interactions of electroweak and strong forces, the properties of 12 fermions, and 12 bosons carrying the force

neutrinos :

- 3 types (flavors)
- lefthanded
- only neutral fermions
  - interact only weakly
- all have equal (weak) interactions
- assumed massless in the SM

But Where They Are ?

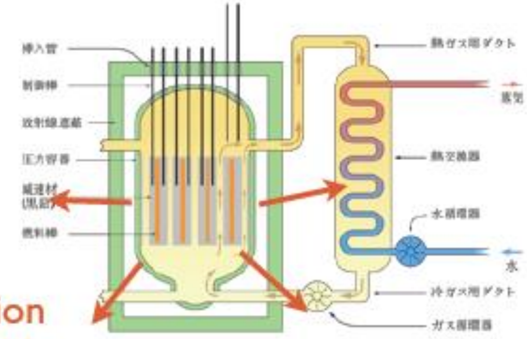


Fusion
(MeV)

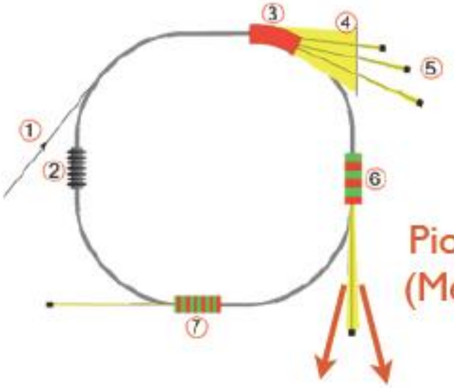
Pion decay
(MeV-EeV)

Beta decay
(^{40}K)
(MeV)

Neutrinos are naturally produced in the Sun, the atmosphere, earth, our bodies, …



Fission
(MeV)



Pion decay
(MeV-GeV)

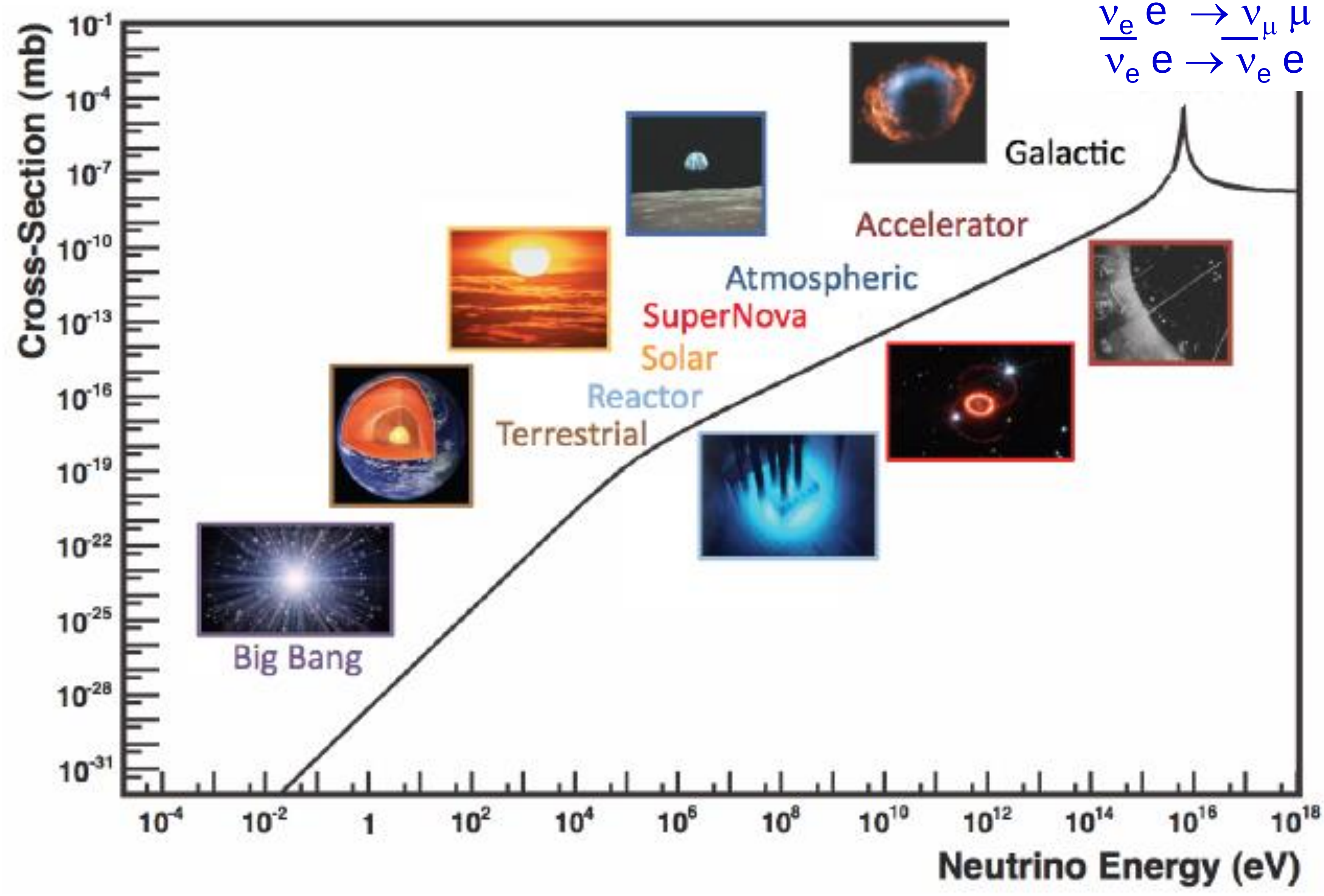
They can be also “fabricated” in nuclear reactors or by accelerators, …

Neutrino Sources

Glashow resonance

$\bar{\nu}_e\, e \to \bar{\nu}_\mu\, \mu$

$\bar{\nu}_e\, e \to \bar{\nu}_e\, e$



Neutrino Physics Situation

Especially since 1998, neutrino physics has made great progress

- discovery of oscillation (ν_μ disappearance) in atmospheric ν by SK (1998)
  confirmation in accelerator ν_μ beam by K2K (2004) / MINOS (2006)
- ν_e disappearance ($\rightarrow \nu_\mu/\nu_\tau$)
  established by solar neutrino measurements by SNO / SK (2002)
  confirmation in reactor ν by KamLAND (2004)
- ν_e appearance $\nu_\mu \rightarrow \nu_e$ by T2K (2.5 σ in 2011 and 7.5 σ in 2013)
  $\theta_{13} \neq 0$ by DayaBay (2012)
  confirmed 3 flavor mixing picture of neutrinos

Surprises (= Mysteries) are

- neutrino has really finite (but small) mass:
  first evidence of deviations from Standard Model
- neutrino has finite (but big) flavor mixing (unlike quarks)
  lepton flavor is violated

Neutrino Oscillation

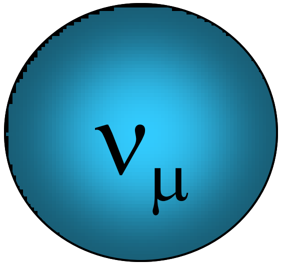
- ν oscillations are a quantum mechanical effect
- neutrino flavor eigenstates (e, μ, τ)
  are different from mass eigenstates (1, 2, 3)

$$\boxed{\nu_\alpha = \sum_{i=1,2,3} U_{\alpha i}\, \nu_i}$$

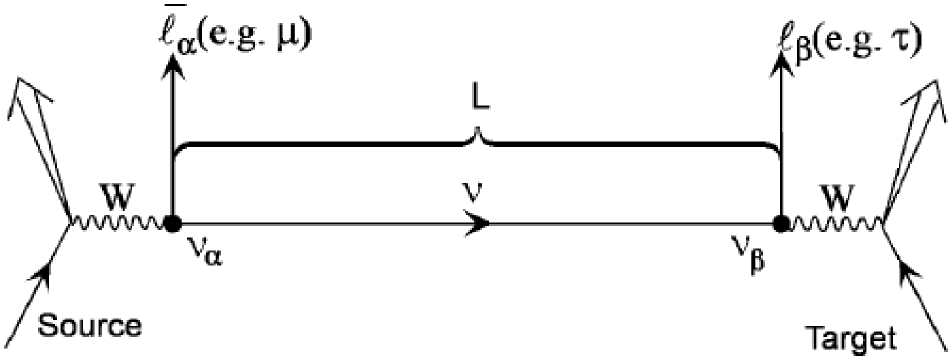
- propagation in time (& space) described by the free Hamiltonian

➔ neutrino oscillations: probability of observing a given ν flavor will vary with time (flavor changes to other flavor in flight)

- only occur when neutrinos have finite mass and mix



Mu neutrino

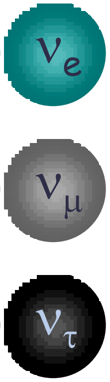


Tau neutrino

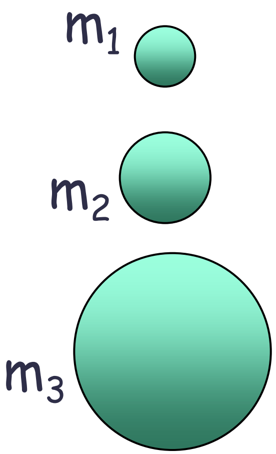
3 Flavor Mixing of Neutrinos

Flavor eigenstates

Mass eigenstates



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Pontecorvo-Maki-Nakagawa-Sakata Matrix (CKM matrix in lepton sector)

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha/2} & 0 \\ 0 & 0 & e^{-i\beta/2} \end{pmatrix}$$

$\theta_{23} = 45^0 \pm 6^0$
SuperK (atm. ν)
K2K / Minos
T2K

$\theta_{13} \sim 9.1^0 \pm 0.6^0$
Daya Bay
Reno
T2K

$\theta_{12} \sim 33.6^0 \pm 1.0^0$
solar ν
KamLAND
future solar ν exp.

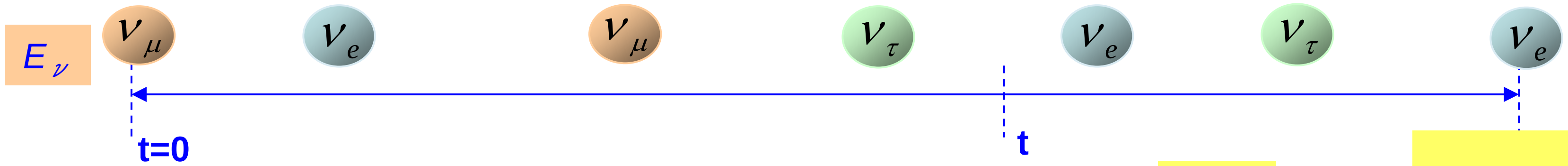
neutrinoless double beta decay

6 independent parameters govern oscillation

θ_{12}, θ_{23}, θ_{13}, δ_{cp}, Δm_{12}^2, Δm_{23}^2, Δm_{13}^2

Neutrinos Oscillations In Time Evolution

(three flavor oscillations)



$$\left|\nu_\alpha(t=0)\right\rangle = \sum_i U_{\alpha\,\mathrm{i}}\left|\nu_i\right\rangle \dashrightarrow \left|\nu_\alpha(t)\right\rangle = \sum_i U_{\alpha\,\mathrm{i}}\, e^{-iE_i t}\left|\nu_i\right\rangle$$

$$E_i = p + \frac{m_i^2}{2p}$$

$$P_{\alpha\to\beta} = \left|\left\langle \nu_\beta(t)\middle|\nu_\alpha(t=0)\right\rangle\right|^2 = \sum_i \left|U_{\alpha\ i}\ U_{\beta\ i}\right|^2 + \sum_{i\neq j} U_{\alpha\ i}\ U^*_{\beta\ \mathrm{i}}\ U^*_{\alpha\ \mathrm{i}}\ U_{\beta\ i}\ \mathrm{e}^{-i(E_i - E_j)\,t}$$

$$P_{\mu\to e} = 4C_{13}{}^2 S_{13}{}^2 S_{23}{}^2 \sin^2\frac{\Delta m_{31}^2 L}{4E}\left(1+\frac{2a}{\Delta m_{31}^2}\left(1-2S_{13}^2\right)\right)$$

leading, θ_{13} driven

$$+8C_{13}{}^2 S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23})\cos\frac{\Delta m_{32}^2 L}{4E}\sin\frac{\Delta m_{31}^2 L}{4E}\sin\frac{\Delta m_{21}^2 L}{4E}$$

CPC

$$-8C_{13}{}^2 C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin\frac{\Delta m_{32}^2 L}{4E}\sin\frac{\Delta m_{31}^2 L}{4E}\sin\frac{\Delta m_{21}^2 L}{4E}$$

CPV

$$+4S_{12}{}^2 C_{13}{}^2 (C_{12}{}^2 C_{23}{}^2 + S_{12}{}^2 S_{23}{}^2 S_{13}{}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta)\sin^2\frac{\Delta m_{21}^2 L}{4E}$$

solar

$$-8C_{13}{}^2 S_{13}{}^2 S_{23}{}^2 (1-2S_{13}{}^2)\frac{aL}{4E}\cos\frac{\Delta m_{32}^2 L}{4E}\sin\frac{\Delta m_{31}^2 L}{4E}$$

matter effect

Two flavor Oscillation in Vacuum

(to make it simple)

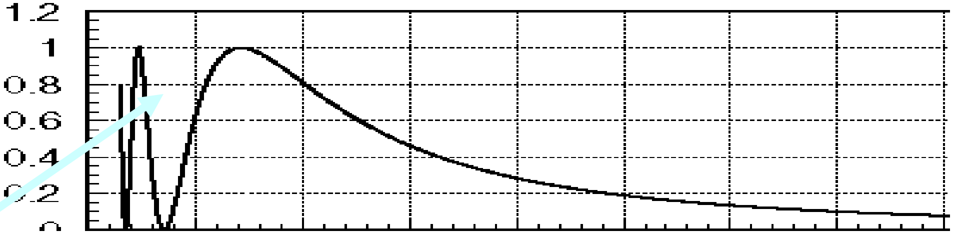
For two flavors, ν_α and ν_β,
the mixing matrix reduced to

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

then the oscillation probability $P(\nu_\alpha \to \nu_\beta)$ is given by

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \ \sin^2\left(\frac{(E_i - E_j)t}{2}\right)$$

Making the approximation $E_i = p + \dfrac{m_i^2}{2p}$



(and including the factors h and c)

the oscillation probability becomes

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \cdot \sin^2\left(1.27 \ \frac{\mathrm{L\,[km]}}{E\,\mathrm{[GeV]}} \Delta\mathrm{m}^2\,[\mathrm{eV}^2]\right)$$

maximum oscillation amplitude

L : distance ν - source

E : ν -energy at t = 0 (source)

oscillation frequency

Present Knowledge

$$\Delta m^2_{12} = 7.58^{+0.22}_{-0.26} \times 10^{-5} eV^2$$

$$|\Delta m^2_{23}| = 2.35^{+0.12}_{-0.09} \times 10^{-3} eV^2$$

$$\sin^2\theta_{12} = 0.306^{+0.018}_{-0.015}$$

atmo.

$$\sin^2\theta_{23} = 0.42^{+0.08}_{-0.03}$$

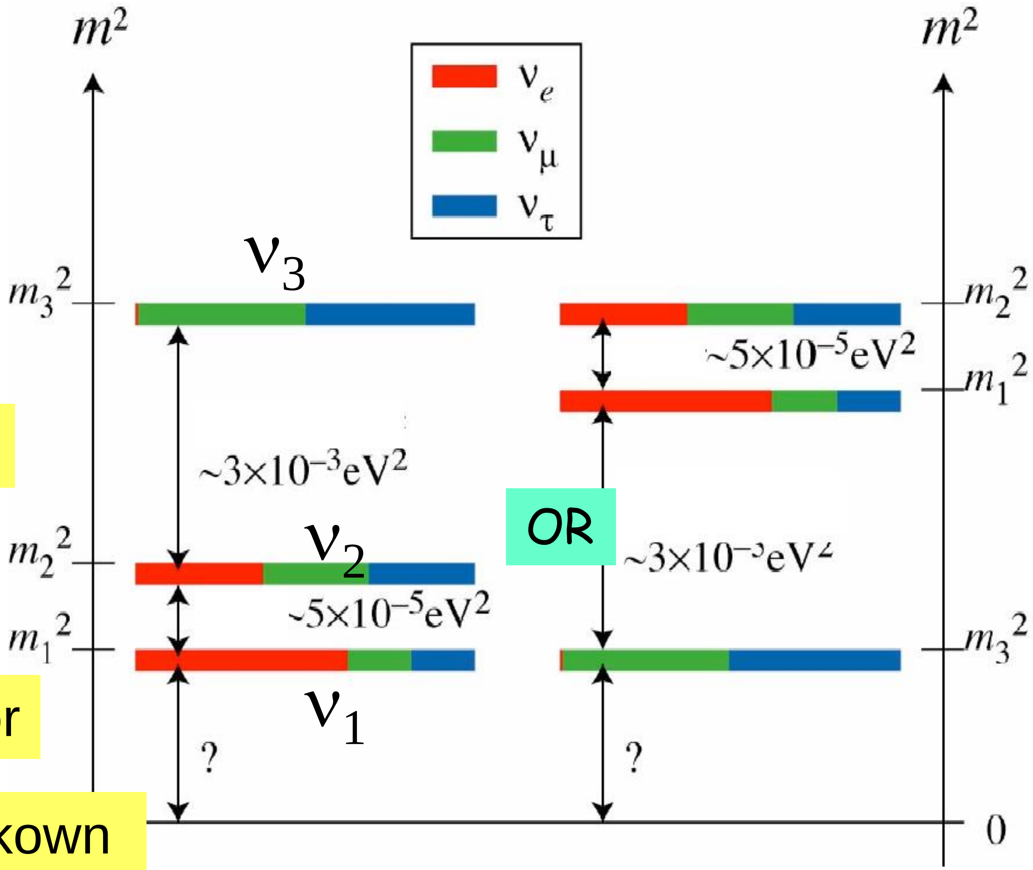
solar

$$\sin^2\theta_{13} = 0.021^{+0.07}_{-0.08}$$

reactor

$$\delta_{CP} \in [0^\circ, 360^\circ]$$

δ_{CP} unkown



which ? both ordering allowed by data

NEUTRINOS

$$U_{MNSP} \sim \begin{pmatrix} 0.8 & 0.5 & 0.14 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

QUARKS

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

ν_μ

big difference w.r.t. CKM matrix

Today's Questions In Neutrino Physics

- Mass hierarchy

  we do not know if the neutrino ν_1 (contains more ν_e) is the lightest one or not

  ➔ Long baseline accelerator neutrino experiments

- Is CP symmetry violated ?

  help solve origin of matter-antimatter asymmetry in universe (leptogenesis)

  ➔ Long baseline accelerator neutrino experiments

- Absolute neutrino mass

  ➔Tritium beta decay spectrum

  ➔neutrino-less double beta decay

- Existence of sterile neutrinos

- Neutrino is Dirac ? or Majorana ?

  ➔ neutrino-less double beta decay

Unraveling full nature of neutrino could provide breakthrough
to approach our goals in particle physics

How Do We Make an Oscillation Experiment

1. measure ν spectrum at near detector before oscillations

2. make prediction at far detector assuming no oscillations

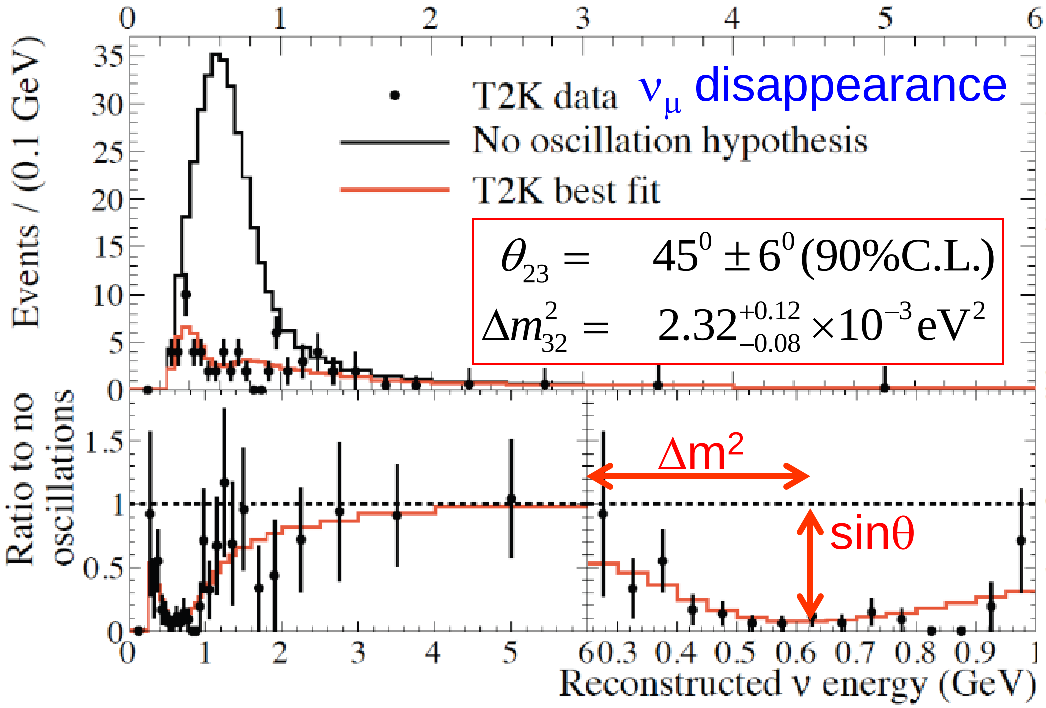
$$\Phi_{FD}^{\exp} = P_{OSC}\cdot R_{F/N}\cdot \Phi_{ND}^{obs} \Leftrightarrow \#\mathrm{ev}_{FD}\left(E_\nu\right) = P_{OSC}\left(E_\nu\right)\cdot \#\mathrm{ev}_{ND}\left(E_\nu\right)\cdot R_{F/N}\cdot \frac{\sigma_{FD}\left(E_\nu\right)}{\sigma_{ND}\left(E_\nu\right)}\cdot \frac{eff_{ND}}{eff_{FD}}$$

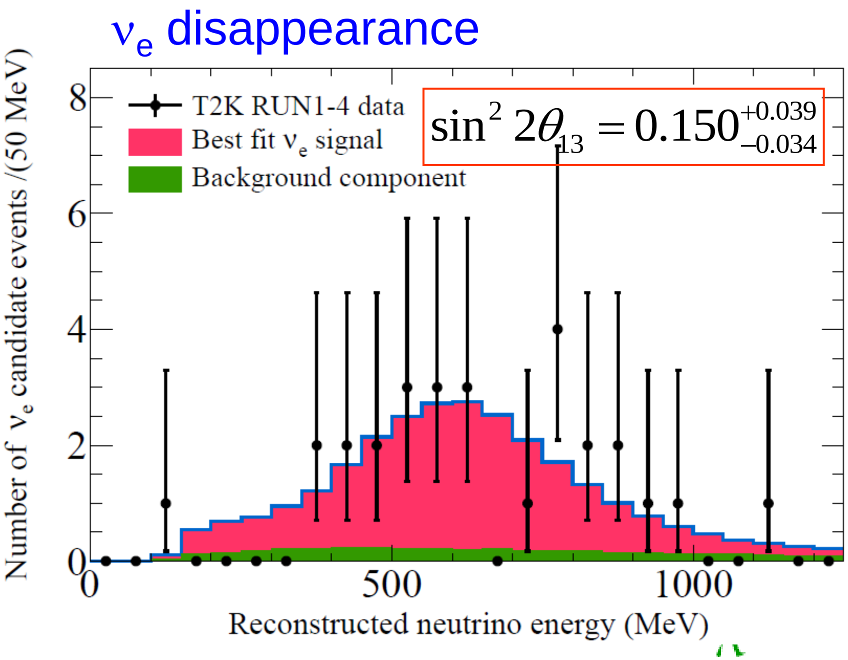
3. compare measured ν spectrum at far detector with predictions (2)

   deviations ? ⇒ oscillations

4. extract oscillation parameters

does not cancel ☹
because different spectra !





Why Neutrino Cross–Sections ?

existing ν scattering data (~1 – 20 GeV) poorly understood

mainly (old) bubble chamber data
low statistics samples
large uncertainties on ν flux

need detailed understanding of ν_μ and anti-ν_μ cross sections

ν oscillation

precision neutrino oscillation measurements
all experiments use dense nuclear targets (CH, H_20, Ar, Fe, …)
→ additional complications whose impact needs to be understood
backgrounds (i.e. NC π^0's)

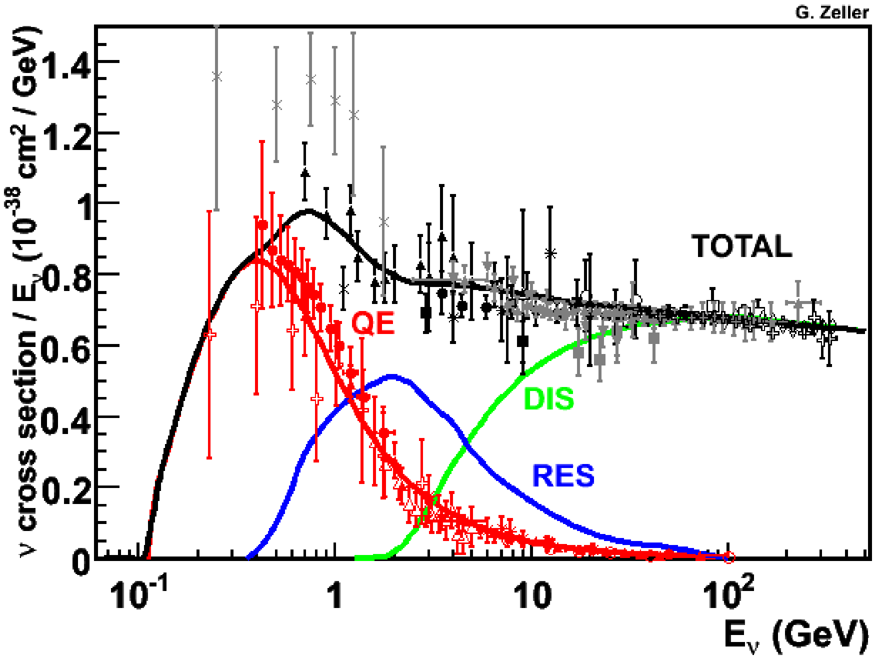
neutrinos – weak probe of nuclear (low E) and hadronic (high E) structure

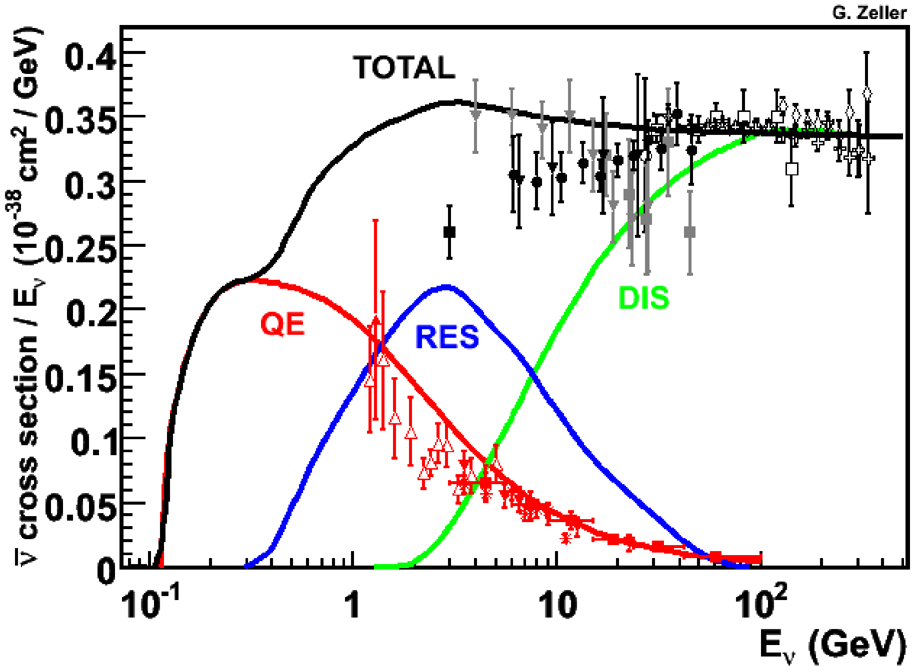
elastic : axial form factors of the nucleon

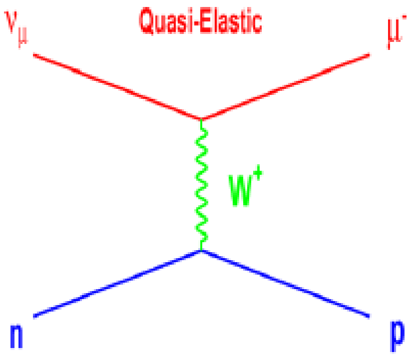
inclusive : quark structure of the nucleon (parton distribution functions)
nucleons are confined in nuclei and are not free
→ expect deviations from ν – *free* nucleon (p or n) interactions
→ quark densities modifications in nuclei (EMC effect)

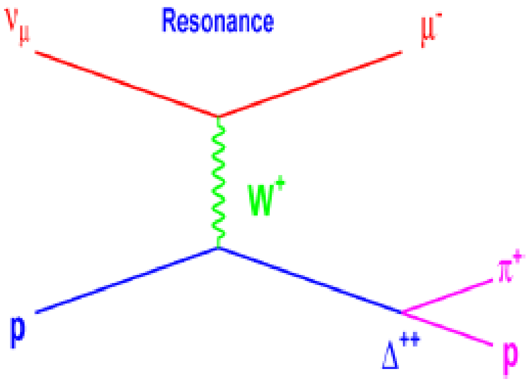
(today we have very high intensity neutrino beams that allow us to study all this)

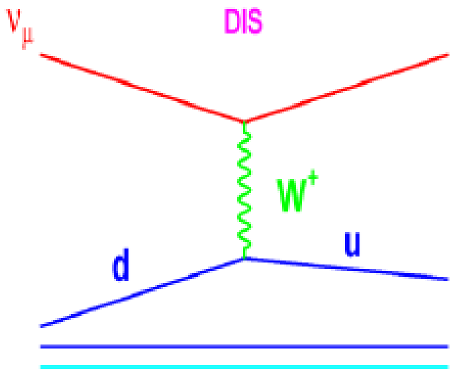
ν ×-sections


G. Zeller
ν cross section / E_ν (10^{-38} cm^2 / GeV)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^{-1}
1
10
10^2
E_ν (GeV)
TOTAL
QE
DIS
RES

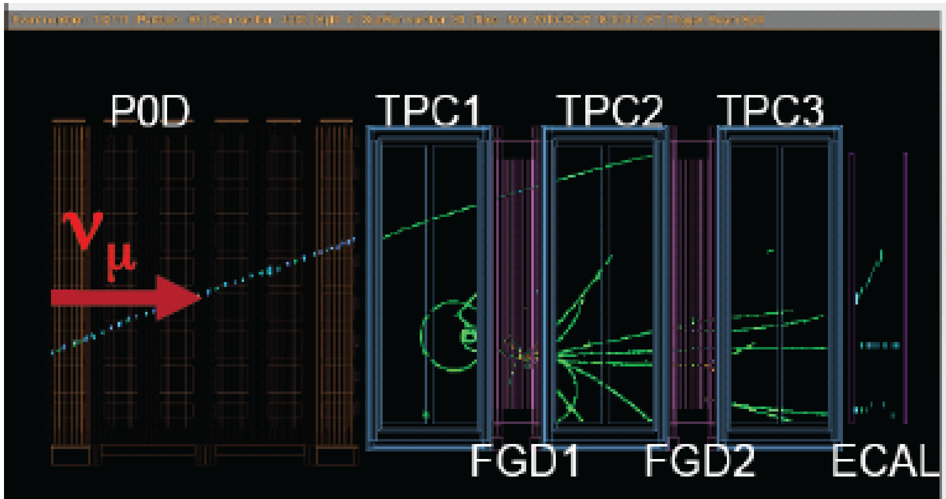

G. Zeller
$\bar{\nu}$ cross section / E_ν (10^{-38} cm^2 / GeV)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
10^{-1}
1
10
10^2
E_ν (GeV)
TOTAL
QE
RES
DIS


ν_μ
Quasi-Elastic
μ^-
W^+
n
p

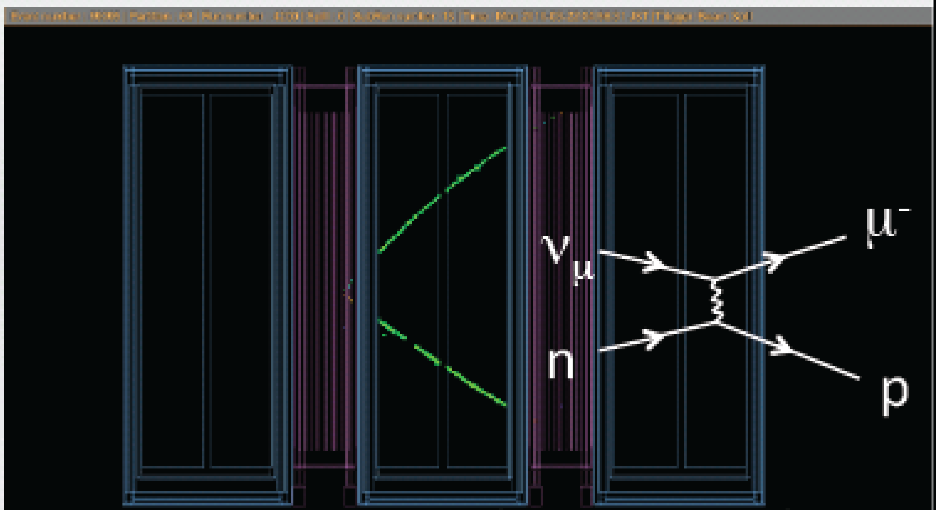

ν_μ
Resonance
μ^-
W^+
p
π^+
Δ^{++}
p


ν_μ
DIS
μ^-
W^+
d
u

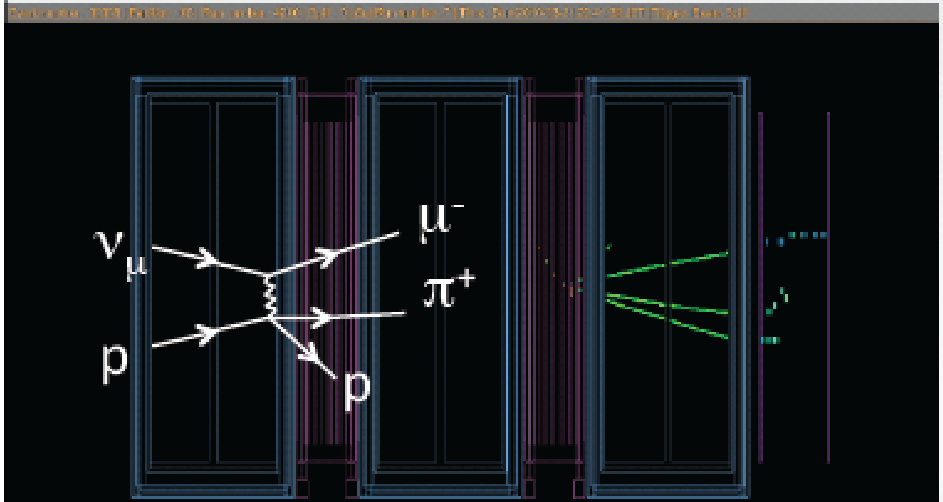
T2K ND280 Off-Axis Event Gallery



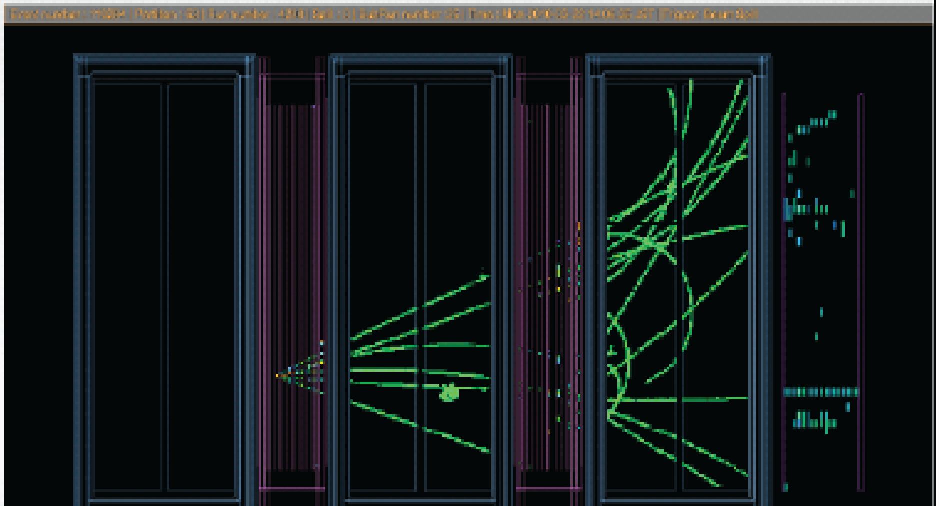
sand muon + DIS candidate



quasi-elastic candidate



single pion candidate



DIS candidate

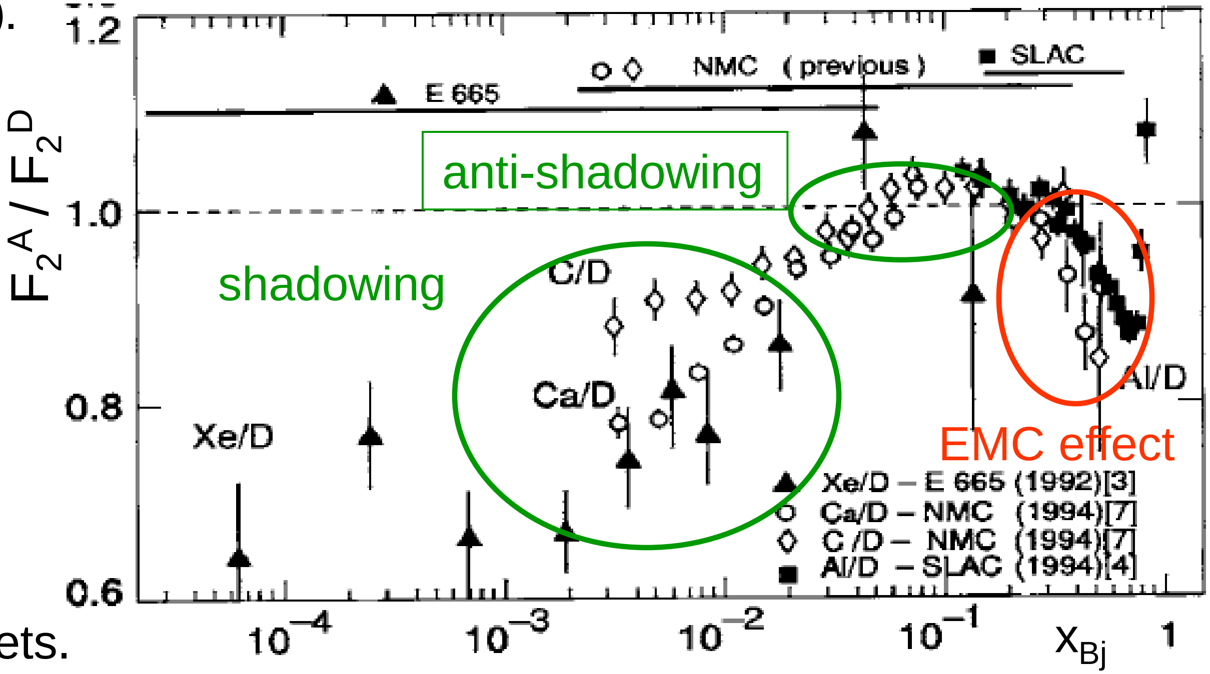
Probing Nucleon Structure

Charged lepton scattering data show that quark distributions are modified in nucleons confined (bound) in a nucleus:
PDFs of a nucleon within a nucleus are different from PDFs of a free nucleon.

The EMC effect (valence region) does not shows a strong A dependence for F_2^A / F_2^D

Nuclear effects in neutrino scattering are not well established, and have not been measured directly : experimental results to date have all involved one target material per experiment (Fe or Pb or …).

A / D Ratio (e / μ DIS)



ν probes same quark flavors as charged leptons but with different “weights”

→ expect different shape

→ expect different behavior ?

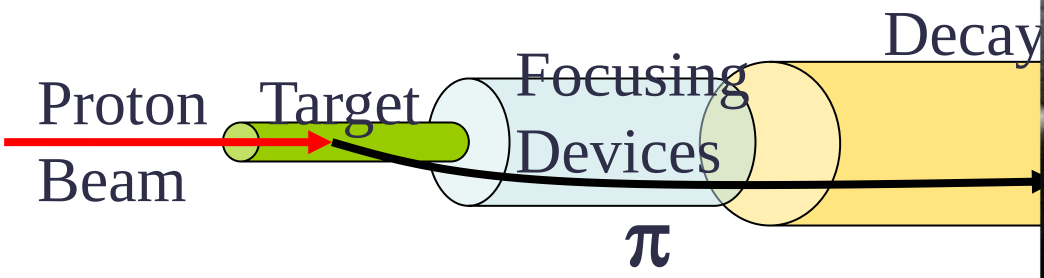
→ x → 1 ?

→ is shadowing the same ?

Should be studied using D targets.

How To Make a ν_μ Beam

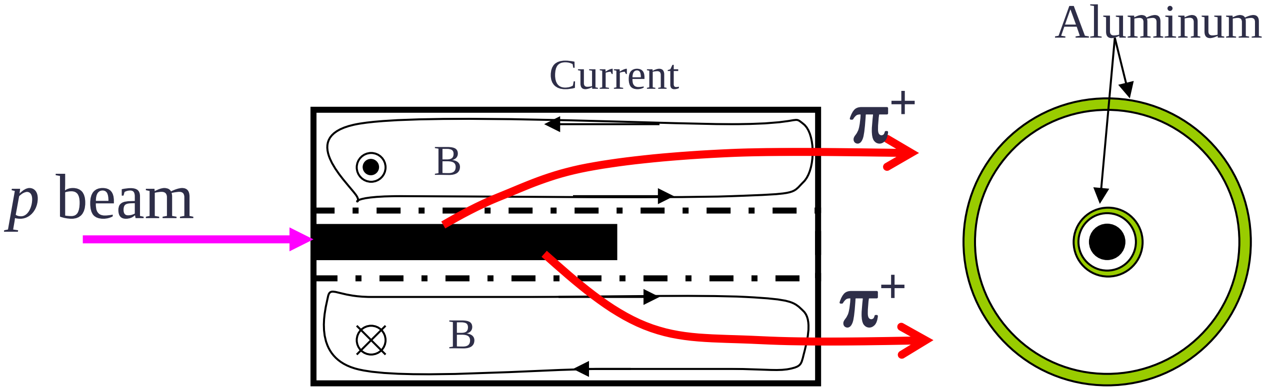
(conventional horn focused beam)



Simon van der Meer
(1925~2011)

Beam Dump

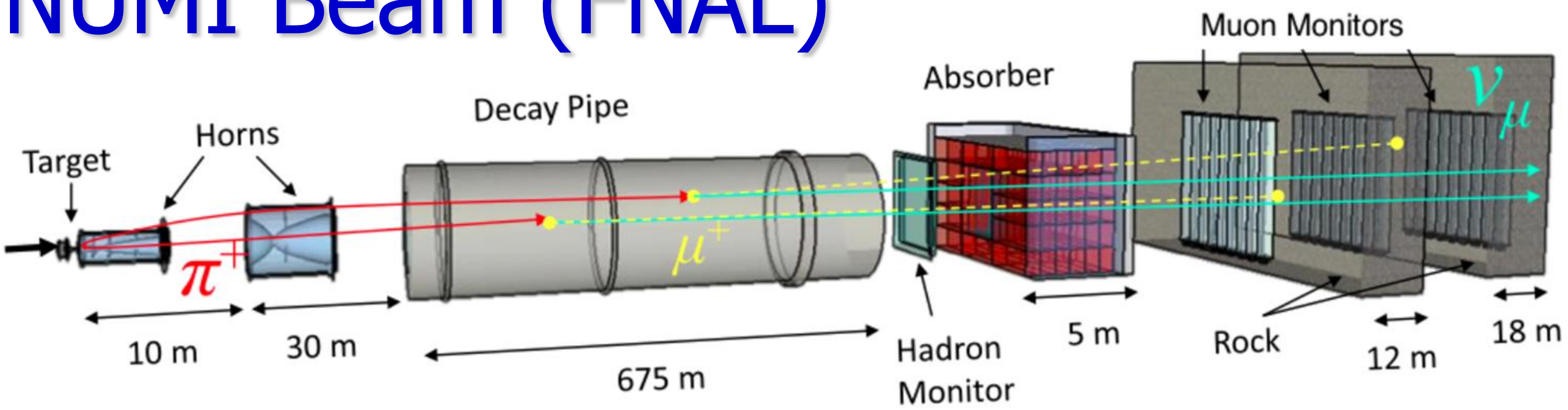
Focusing device: Electromagnetic Horn



$B = 4.3\,T\,,\ r = 15\,mm,\ I = 320kA$

- pure ν_μ beam ($\gtrsim$99%)
- ν_e ($\lesssim$1%) from $\pi \rightarrow \mu \rightarrow e$ chain and K decays (K_{e3})
- $\nu_\mu / \overline{\nu}_\mu$ can be switched by flipping polarity of Horns

The NUMI Beam (FNAL)



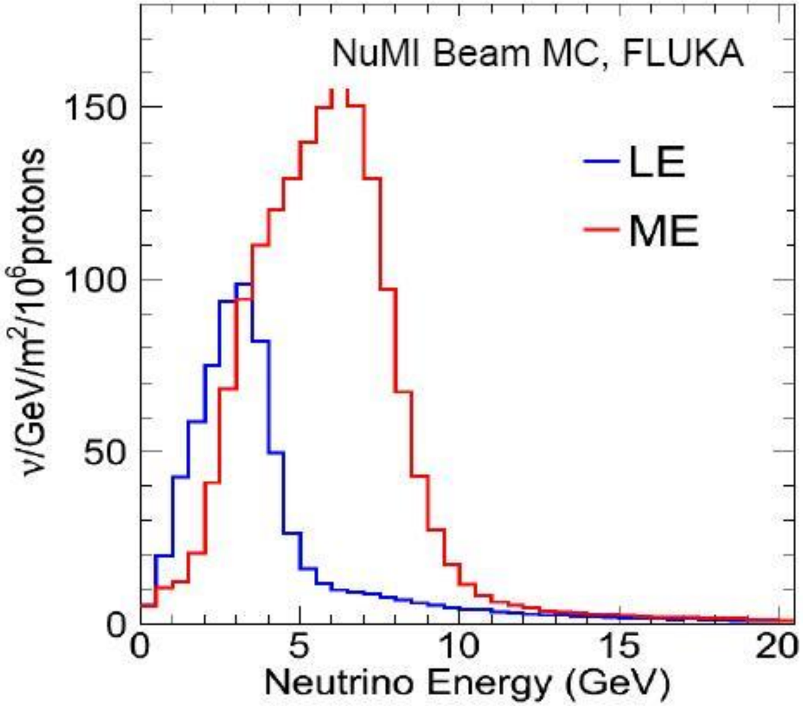
NuMI (Neutrinos at the Main Injector)

- 120 GeV protons from Main Injector, ~ 300 - 350 kW
- 90 cm graphite target
- 675 m decay tunnel

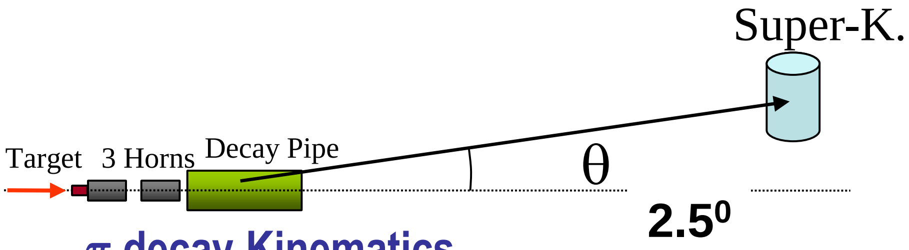
By moving the production target w.r.t. 1st horn and the distance between horn 1 and horn 2 one can modify the ν spectrum:
LE (peak ~3 GeV) → ME (peak ~6 GeV)

Flux determination

- muon monitor data
- special runs (vary beam parameters)
- ν_μ – electron scattering
- low–ν method
- external hadron production data



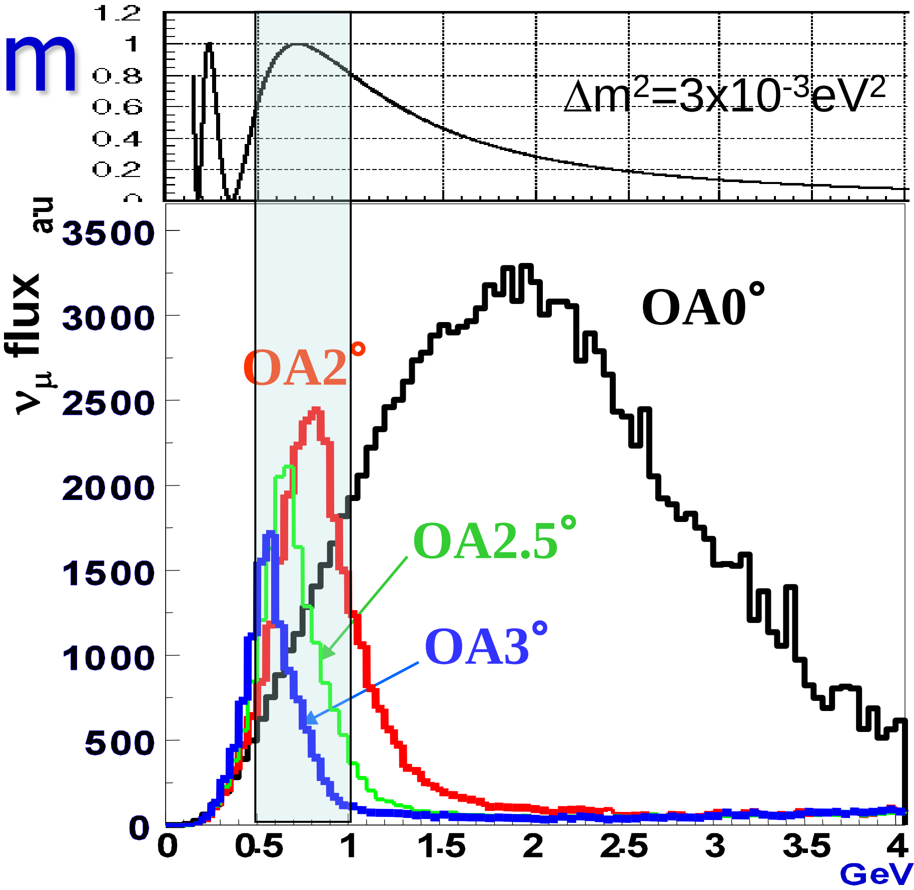
The Off-Axis T2K ν Beam

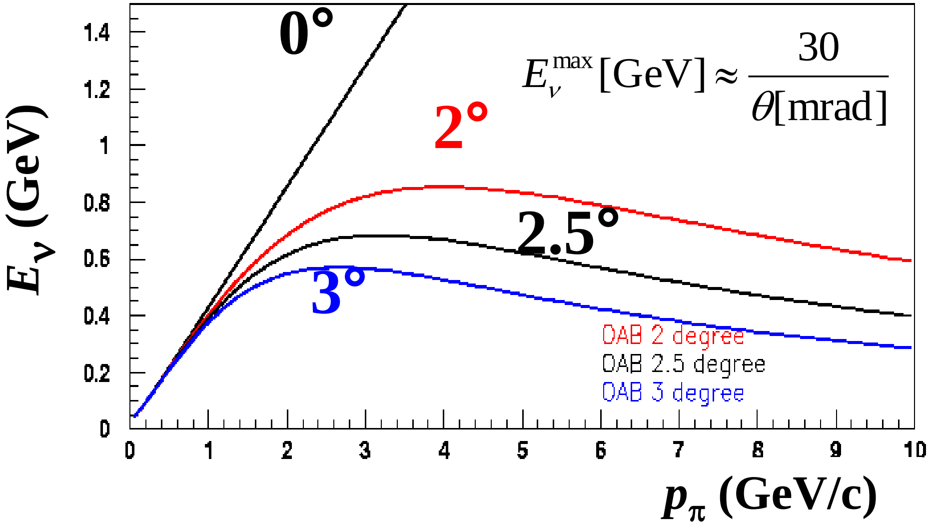


π decay Kinematics

Very narrow energy spectrum
(almost monochromatic beam)

Neutrino beam energy “tuned” to oscillation maximum

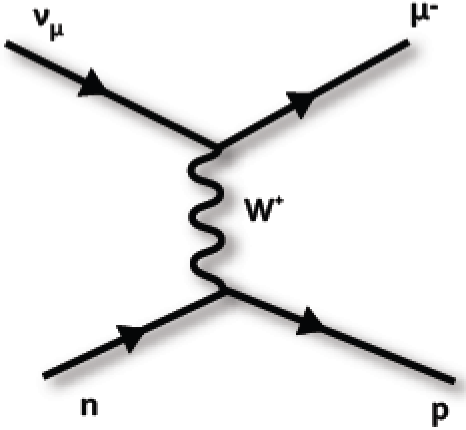




neutrino energy E_ν almost independent of parent pion energy

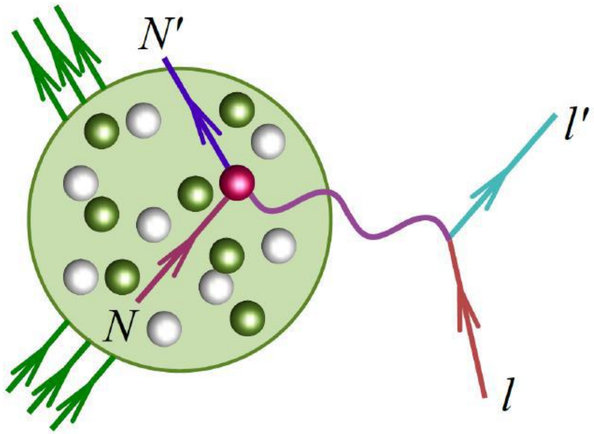
horn focusing cancels partially the p_T dependence of the parent pion

Quasi-Elastic Scattering



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

$$Q_{QE}^2 = -m_\mu^2 + 2E_\nu^{QE}\left(E_\mu - \sqrt{E_\mu^2 - m_\mu^2}\cos \vartheta_\mu\right)$$

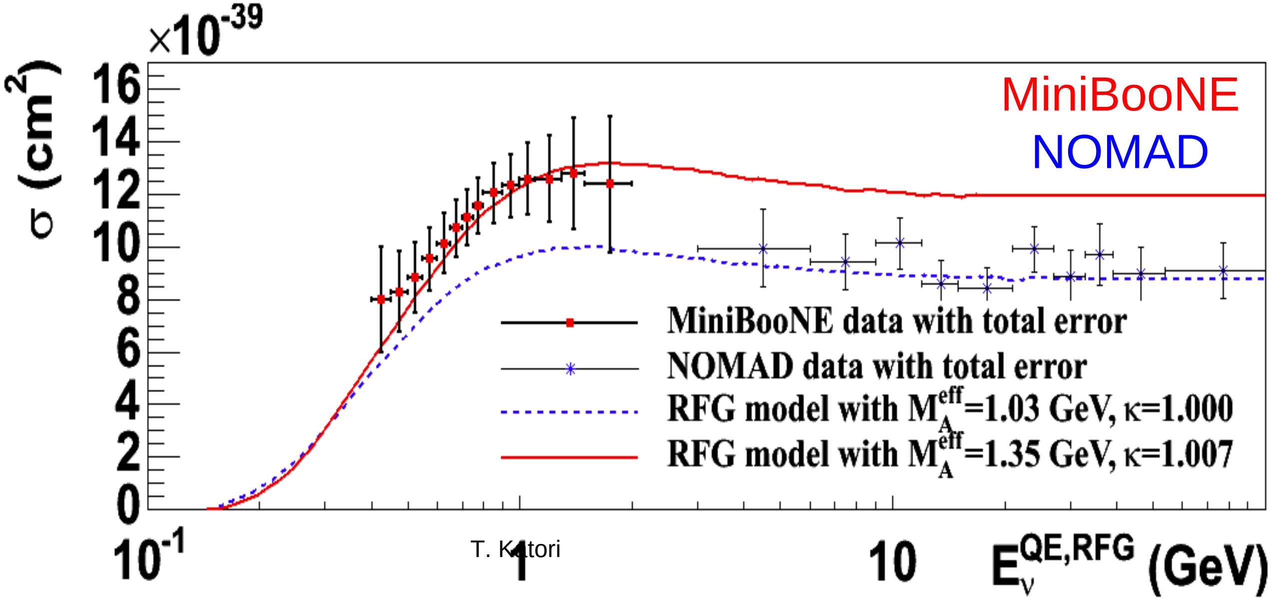


$E_{REC} = E_{TRUE}$?

$Q_{REC} = Q_{TRUE}$?

ν CCQE scattering

- considered a possible standard candle for ν oscillation experiments ($E\nu \sim 1$ GeV)
    - E_ν and Q^2 can be determined from outgoing μ energy and angle



T. Katori

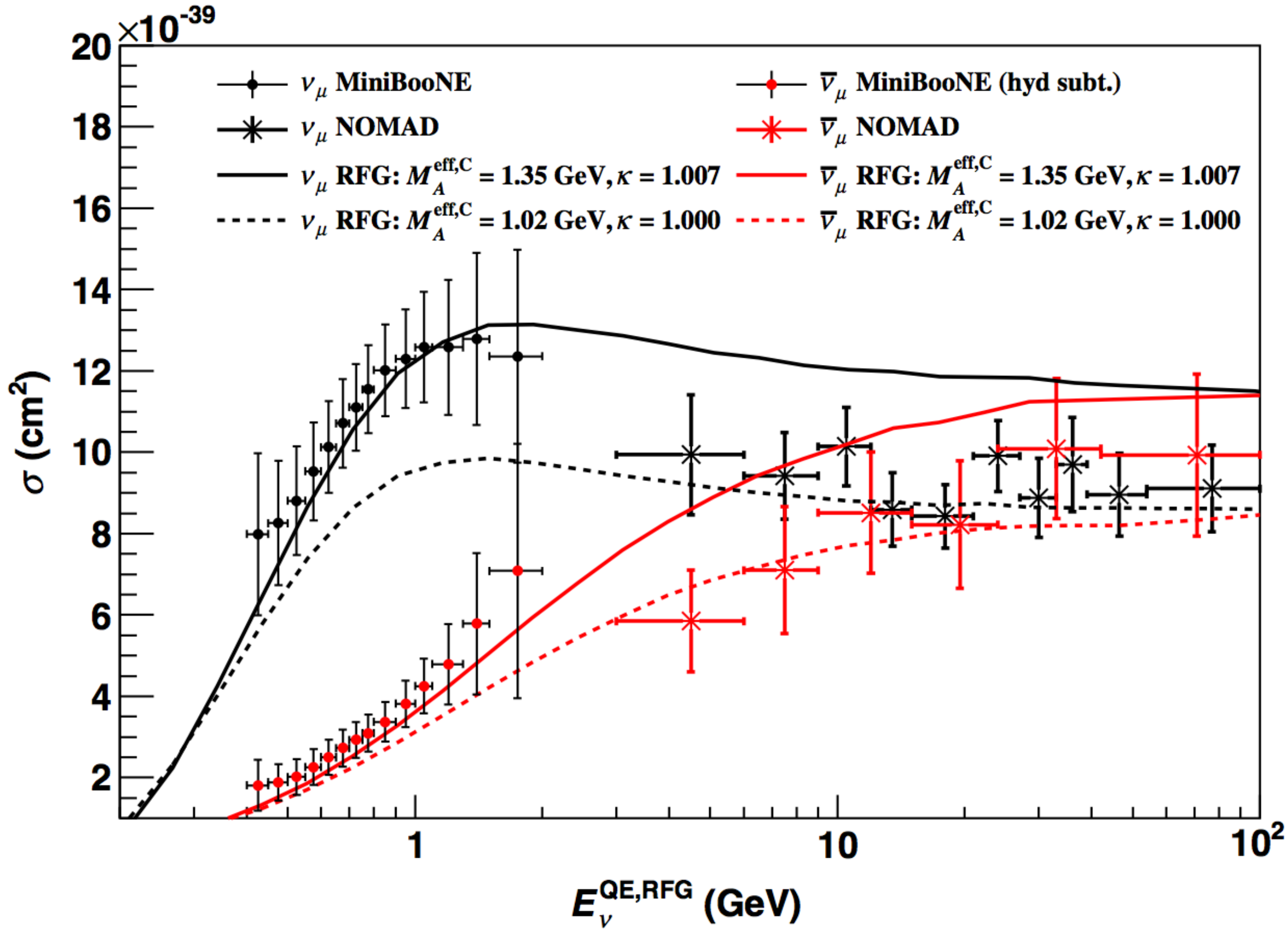
Relativistic Fermi Gas model +
axial form factors

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

- ~30% discrepancy in the QE x-section measurements between recent exp.
    - identification of QE events (purity, backgrounds, …)
    - reconstructed E_ν energy
    - axial mass M_A
    - nuclear effects, FSI, two body currents (MEC), …

tension between datasets and RFG model : increase M_A in the axial FF ?

And If Experiments “Do Not Agree” ?

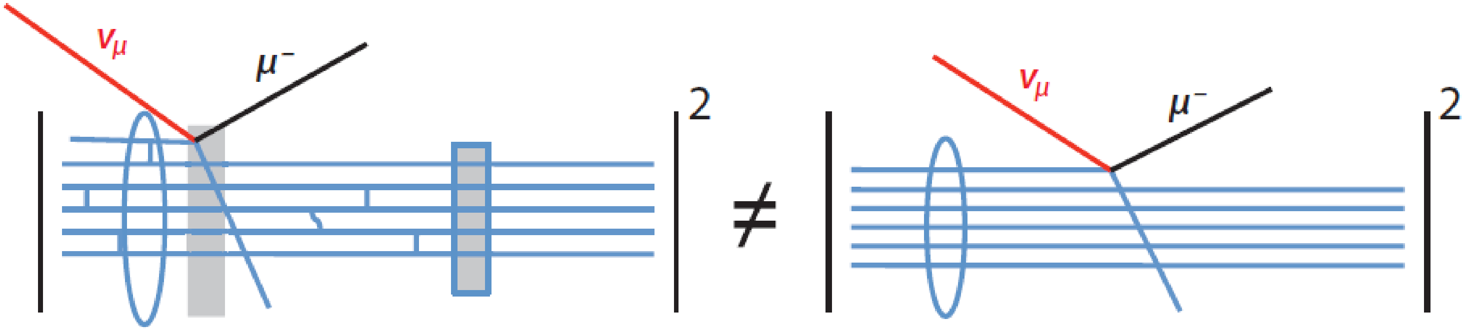


NOMAD data consistent with “standard” QE prediction (with $M_A = 1.0$ GeV)

MiniBooNE data is well above “standard” QE prediction (+30%)
(increasing $M_A \to 1.35$ can reproduce σ)

And If Experiments “Do Not Agree” ?

or how neutrino physicists discovered nuclear physics

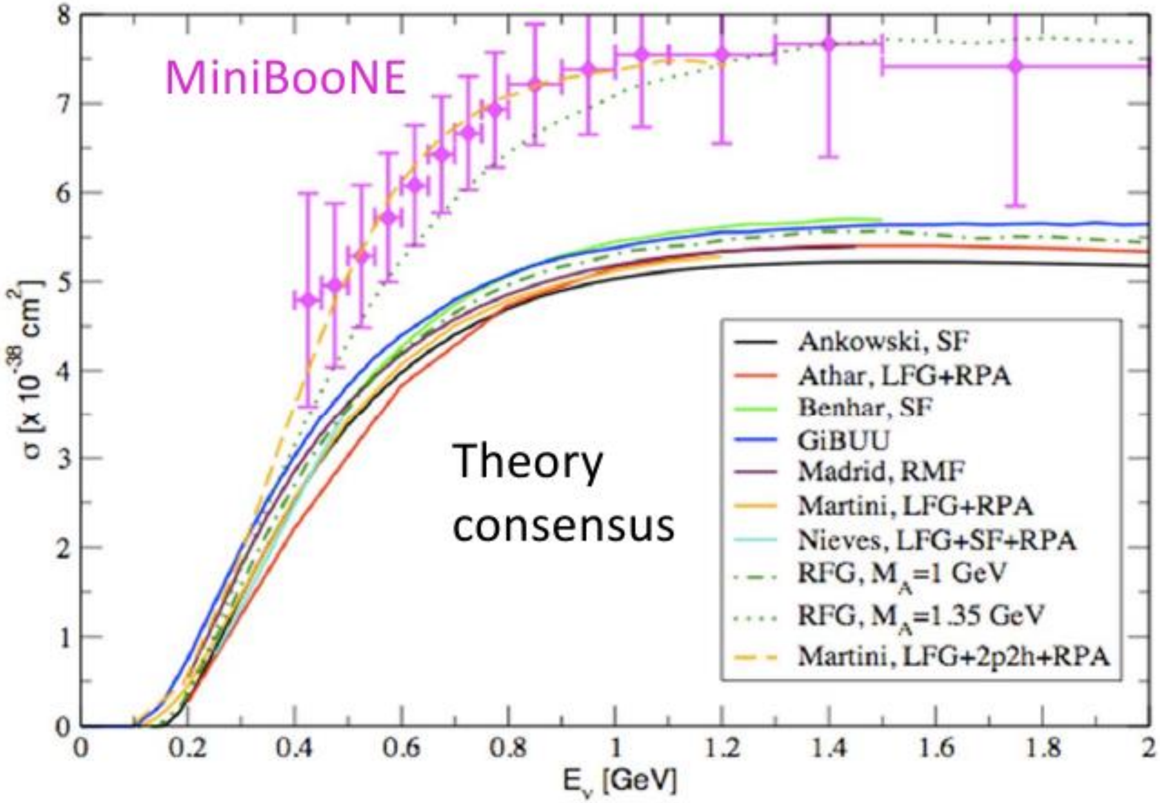


recognize that
nucleons are not free
in a nucleus

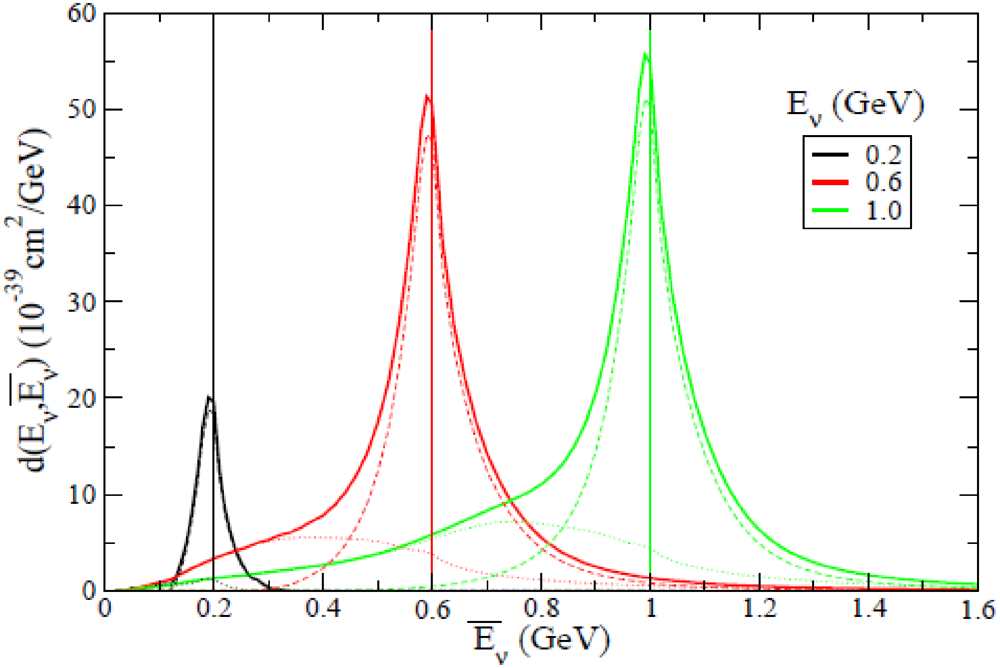
(the RFG model does
not work)

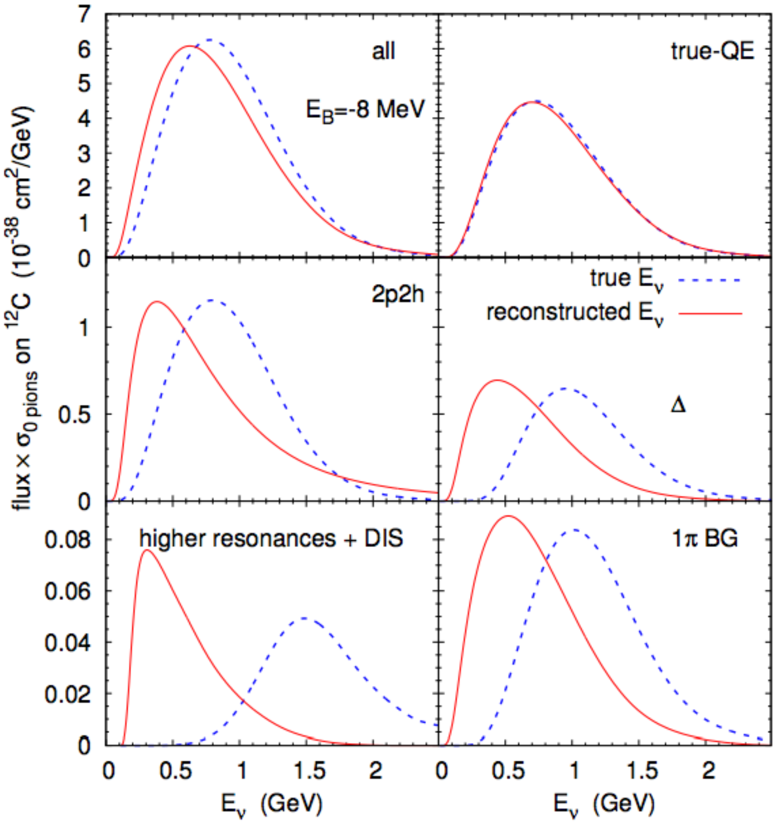
many models and authors
including nuclear effects :
- correlations (SRC)
- two body currents (MEC)
- *2p2h*
- TEM
- FSI

$\Rightarrow M_A \sim 1$ GeV



What About E_ν ?





input E_ν ~ Dirac δ

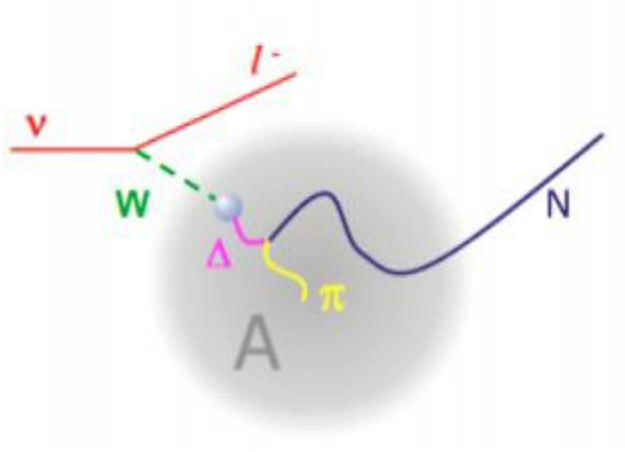
effects of

1) single nucleon

(RFG smearing)

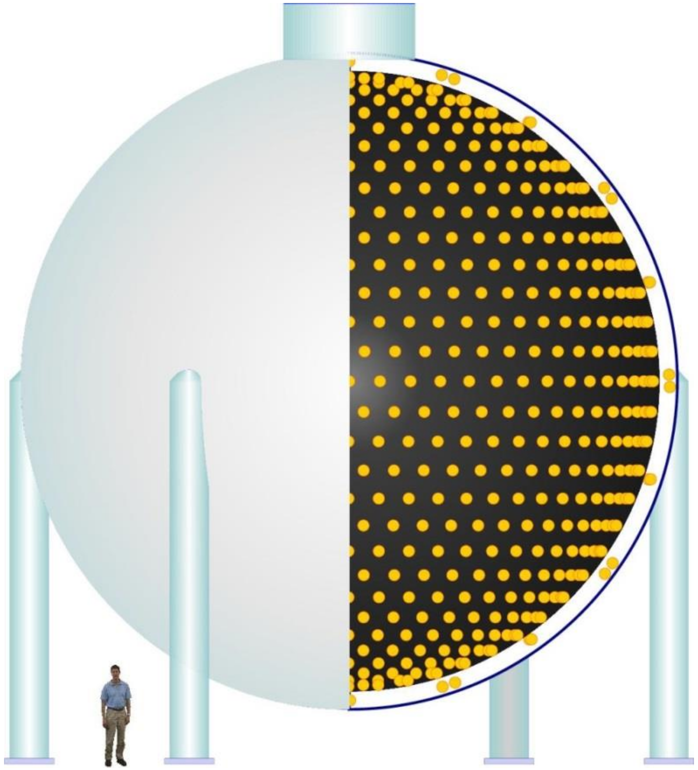
2) multi nucleon scattering

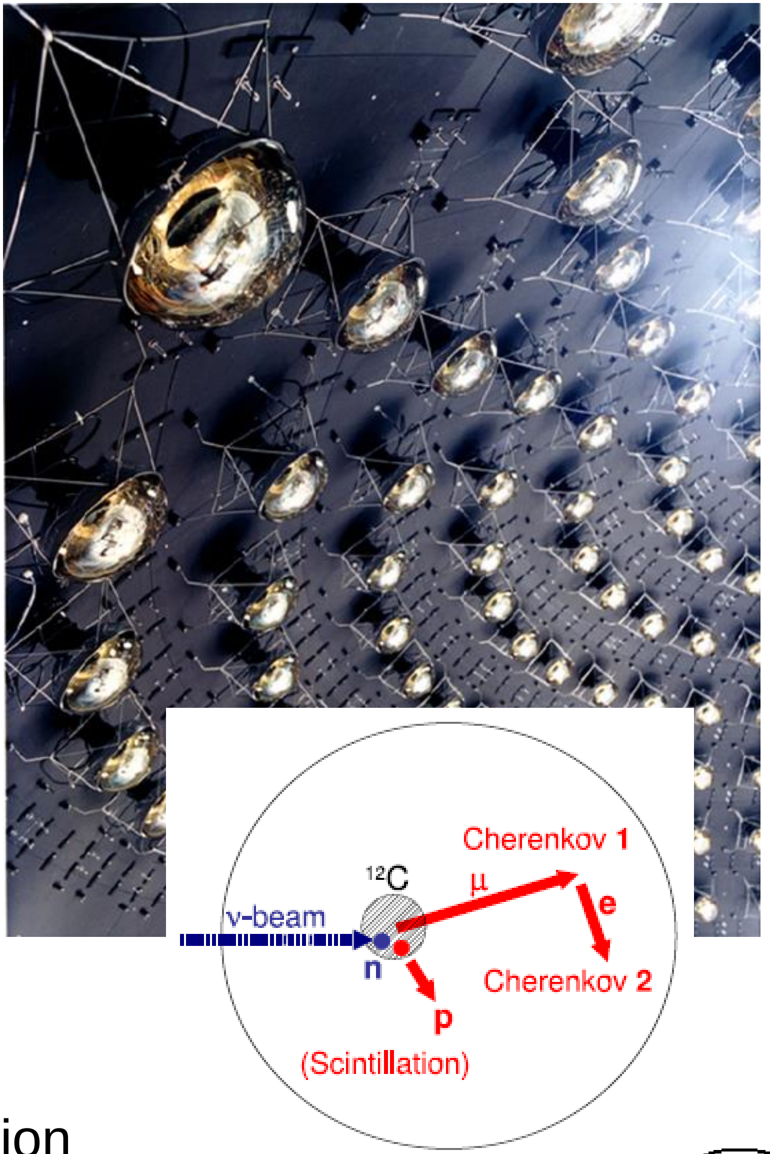
(20 -30% of events off correlated pairs)



$$E_\nu^{QE} \neq E_{REC}^{QE} = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + \left|p_\mu\right| \cos\vartheta_\mu}$$

MiniBooNE @ FNAL





Liquid Scintillator CH_2 target

4π detector, complete angular coverage

Good lepton reconstruction & pion rejection

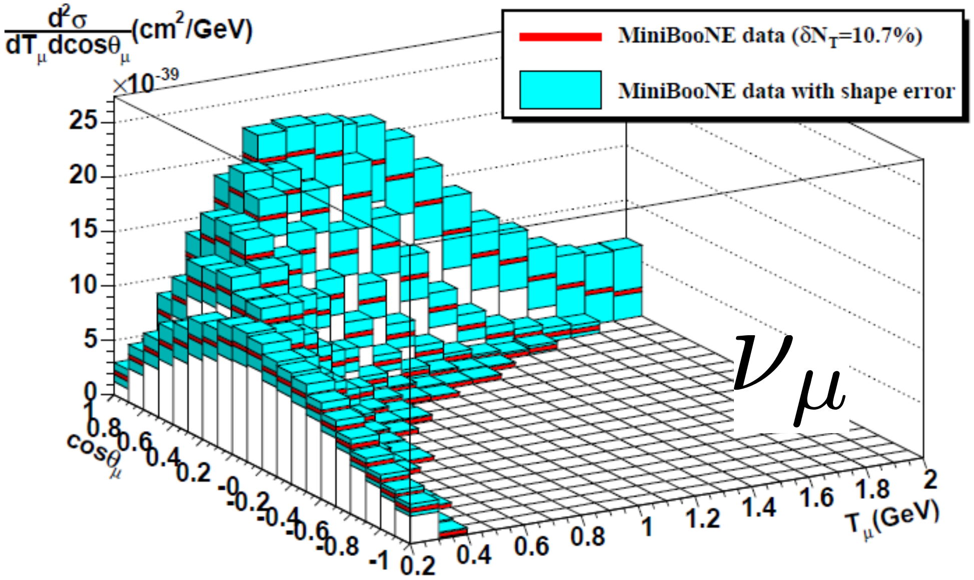
Essentially blind to details of the nucleon final state in CC events

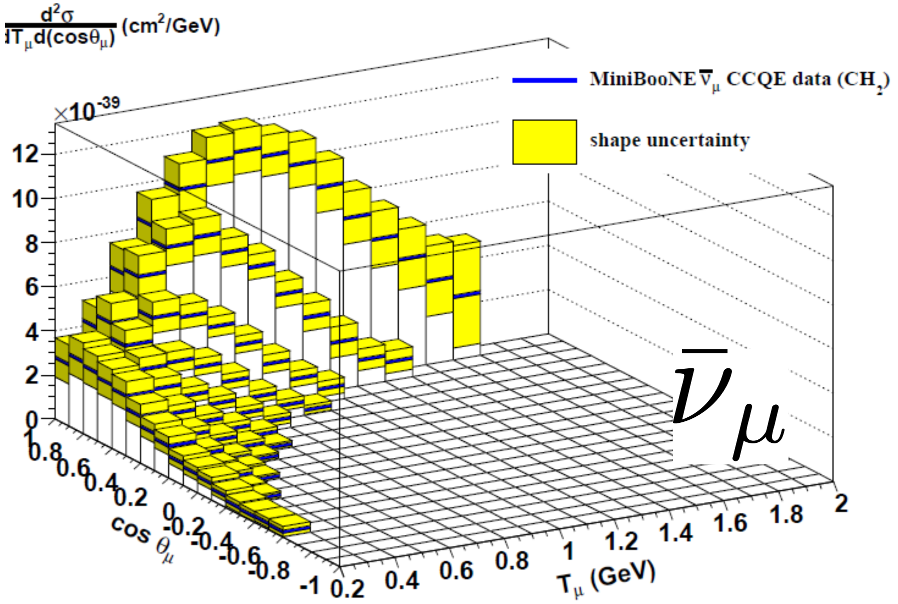
Detect both scintillating light and Cherenkov light

ν / anti-ν CCQE ×-Sections $d^2\sigma/dT_\mu d\cos\theta_\mu$

flux averaged doubly differential cross sections $$\frac{d^2\sigma}{dT_\mu d(\cos\theta_\mu)}$$

largely model independent measurement of muon kinematics



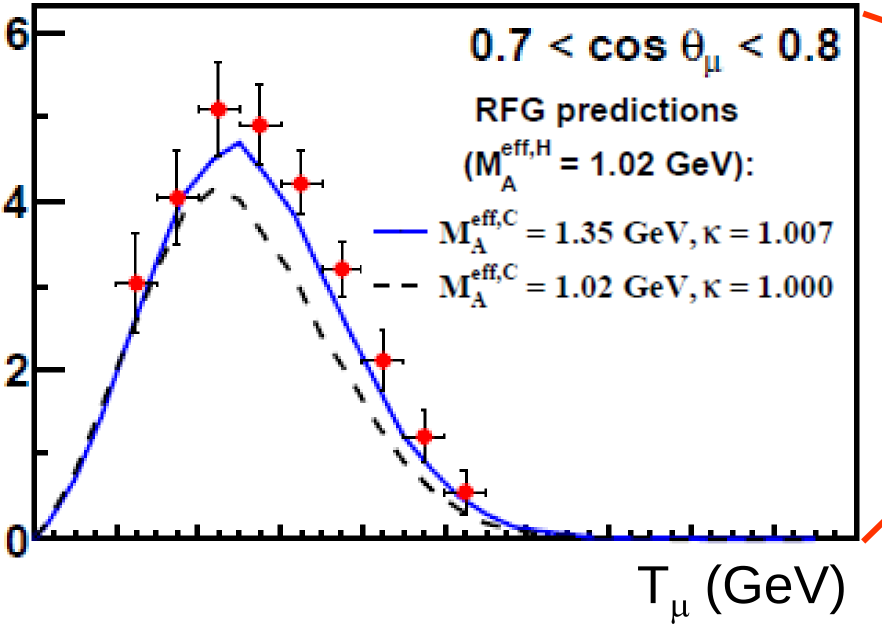


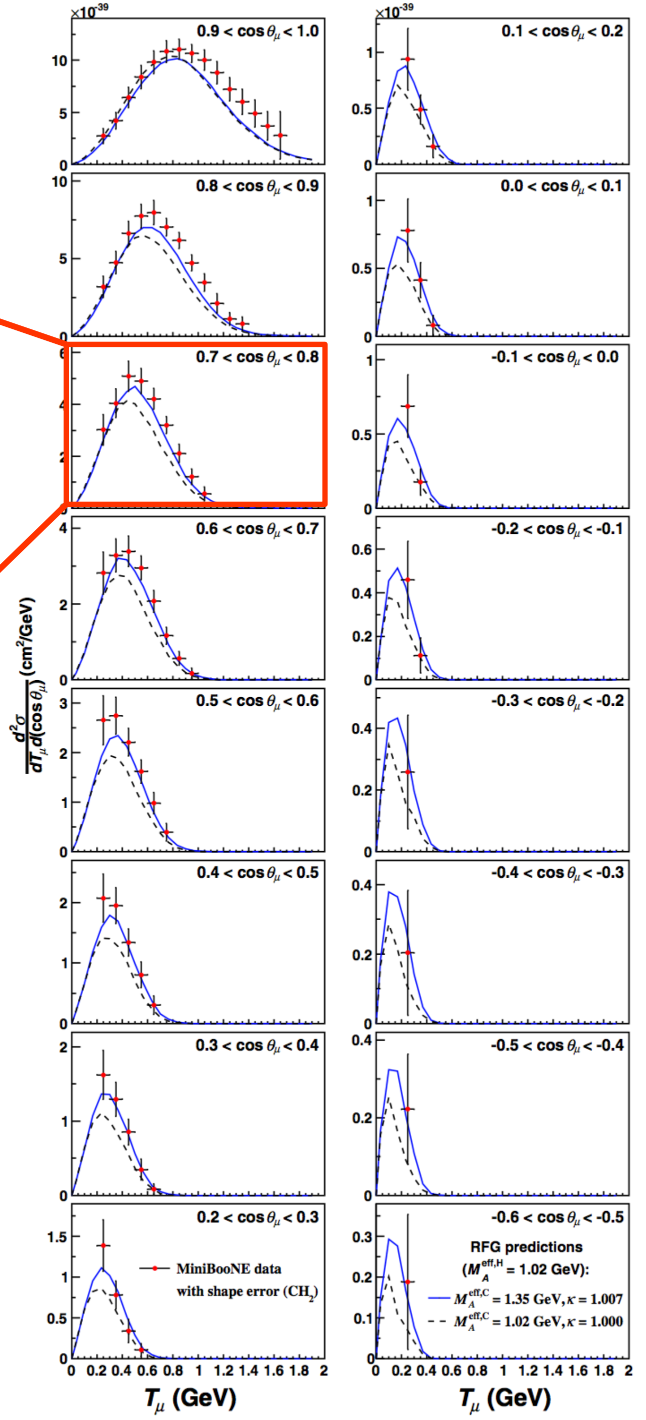
Older experimental data is consistent with dipole axial FF and M_A = 1.015 GeV.

New data also described with dipole axial FF but require M_A = 1.35 GeV

Old resonance scattering data (e.g. via Δ^{++} production) M_A ~ 1.3 GeV

anti-ν $d^2\sigma/dT_\mu d\cos\theta_\mu$





It is clear that the RFG model assuming M_A ~ 1 GeV does not adequately describe these data in shape or in normalization.

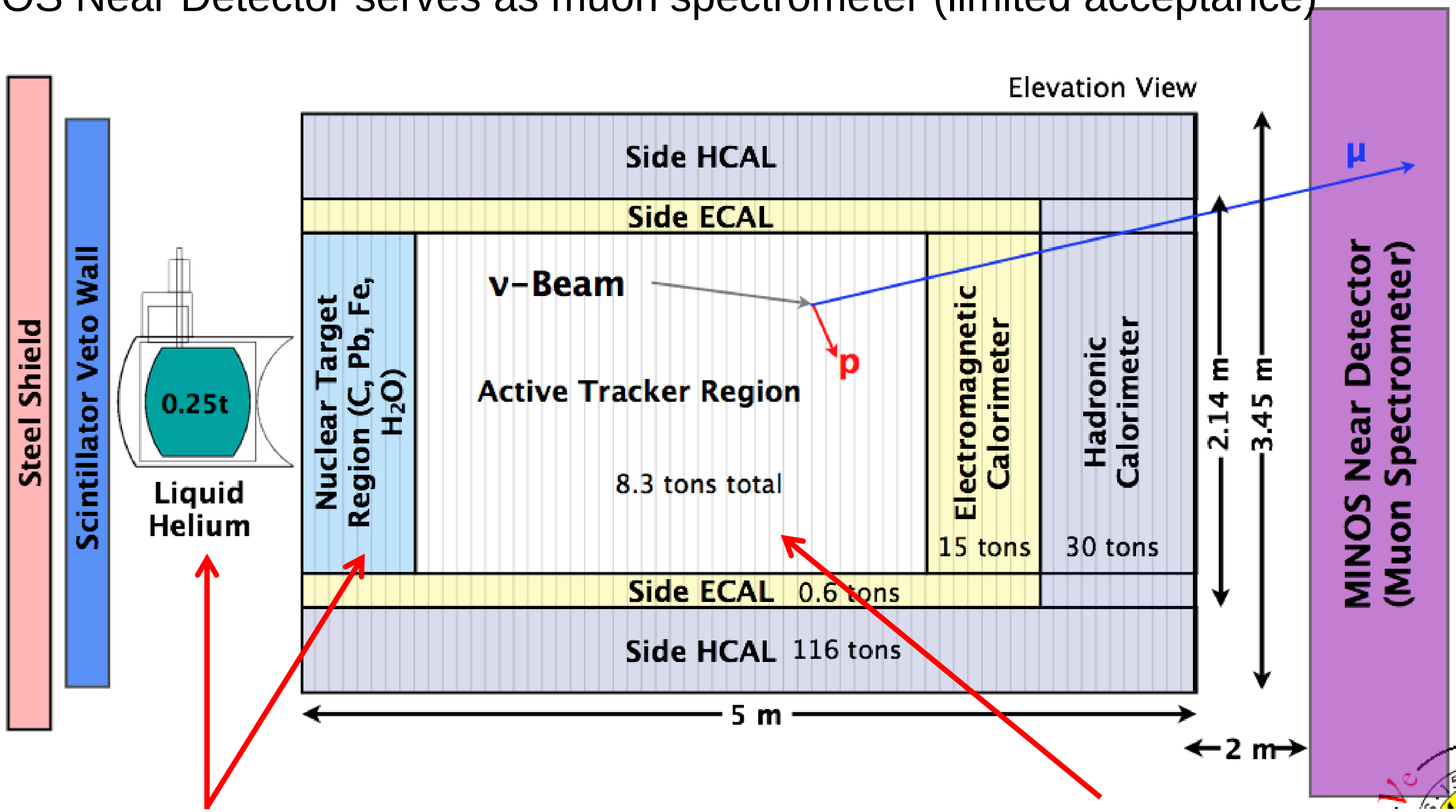
PRD 88, 032001 (2013)

The MINERνA Detector

120 plastic scintillator modules for tracking and calorimetry (~32k readout channels)

Construction completed in Spring 2010. He and $H_2$0 targets added in 2011

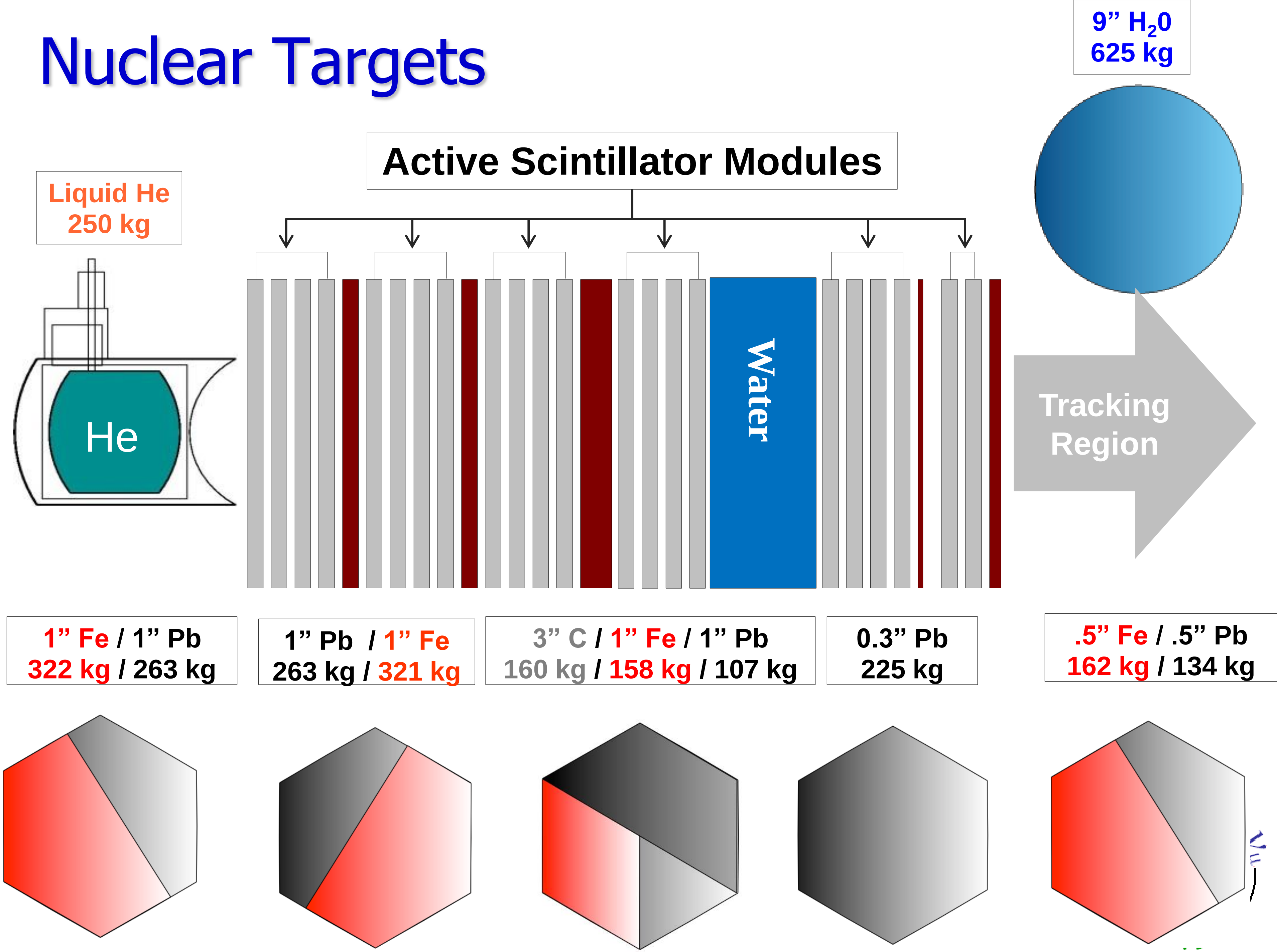
MINOS Near Detector serves as muon spectrometer (limited acceptance)



nuclear targets: He, C, $H_2$0, Fe, Pb

fully active scintillator tracker

Nuclear Targets



Active Scintillator Modules

Liquid He
250 kg

He

Water

Tracking Region

9” H_20
625 kg

1” Fe / 1” Pb
322 kg / 263 kg

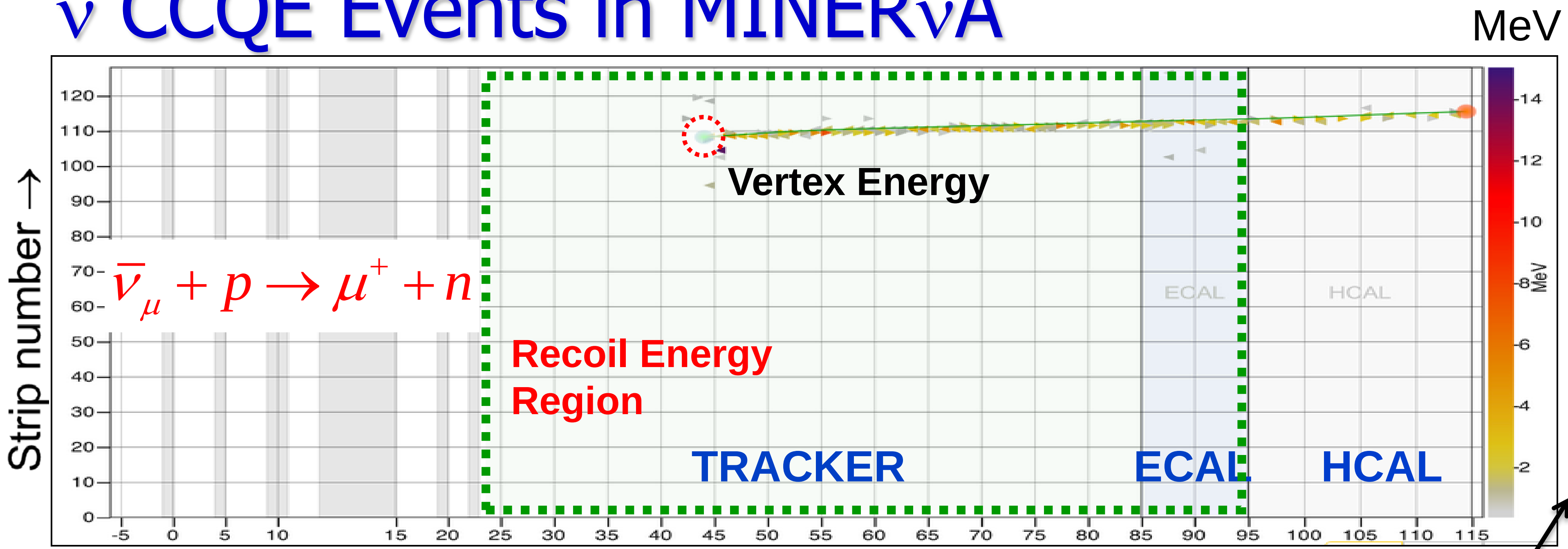
1” Pb / 1” Fe
263 kg / 321 kg

3” C / 1” Fe / 1” Pb
160 kg / 158 kg / 107 kg

0.3” Pb
225 kg

.5” Fe / .5” Pb
162 kg / 134 kg

ν CCQE Events in MINERνA

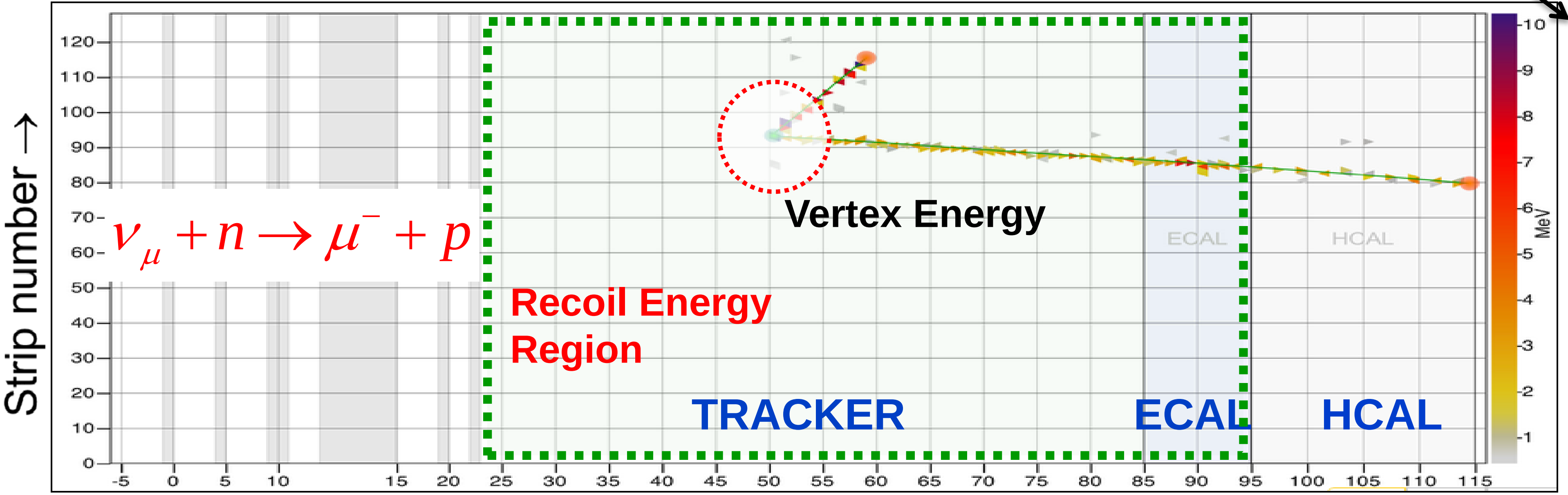


$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

ν Beam

Module number →

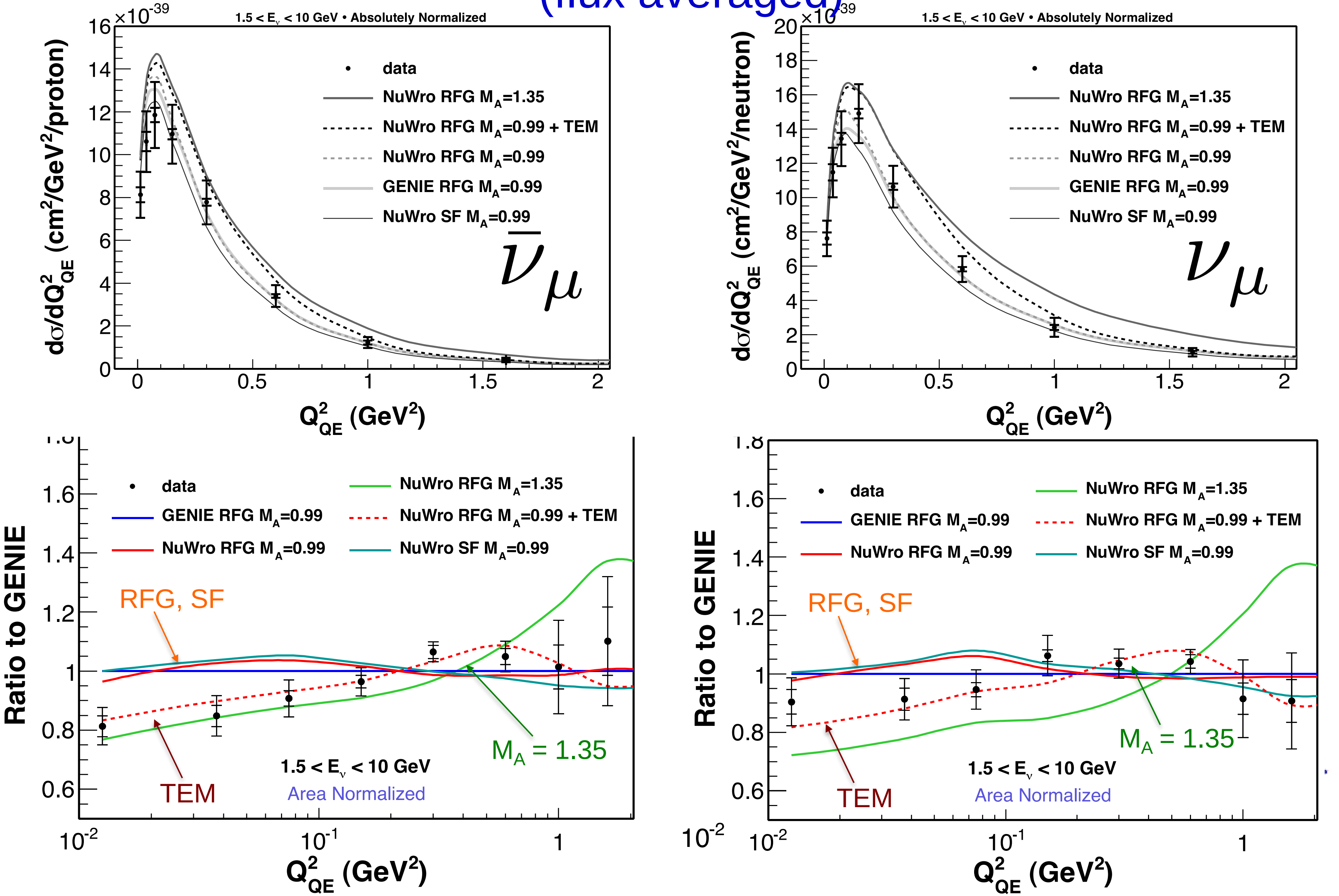
MINOS ND



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

anti-ν / ν CCQE ×-Sections dσ/dQ²

(flux averaged)

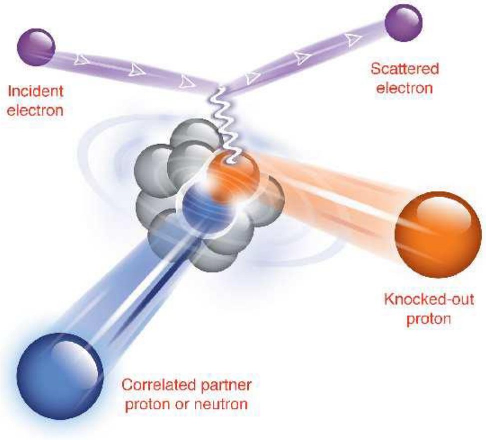


Conclusions CCQE

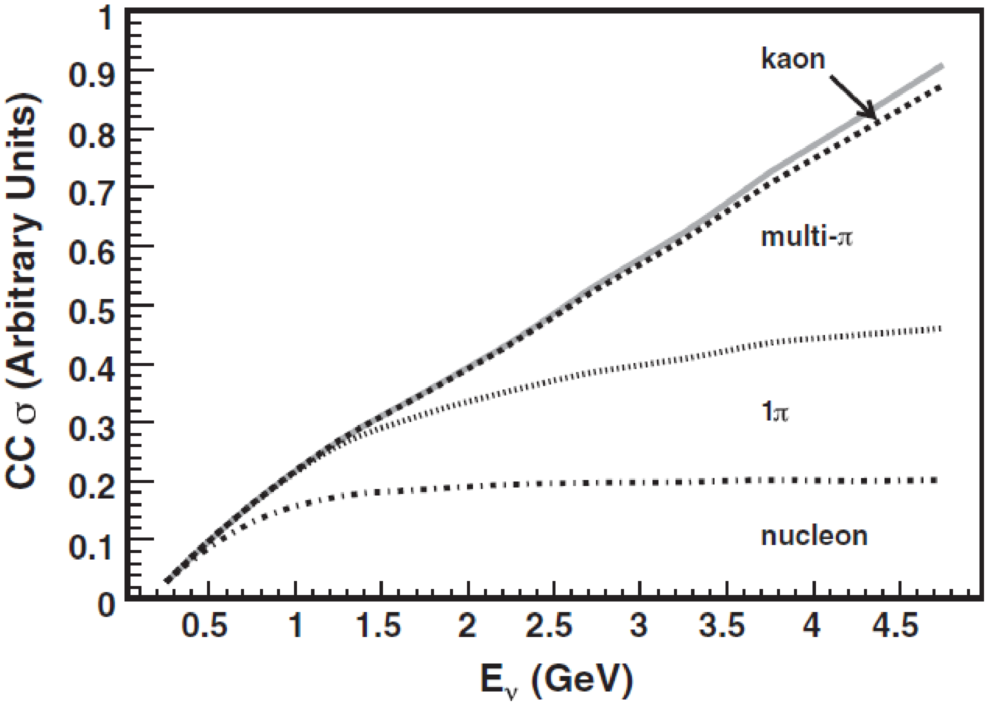
Recent CCQE measurements on nuclear materials are consistent :
a significant enhancement in the normalization
that grows with decreasing muon scattering angle
is observed compared to the expectation with $M_A = 1.0$ GeV.
1) a significant enhancement (+ 30%) in the normalization
2) a significant deficit of events is observed at low Q^2 ($Q^2 < 0.1$ GeV^2)
3) a significant excess of events is observed at larger Q^2 ($Q^2 > 0.3$ GeV^2)

The RFG model assuming $M_A \sim 1$ GeV does not adequately describe these data in shape nor in normalization

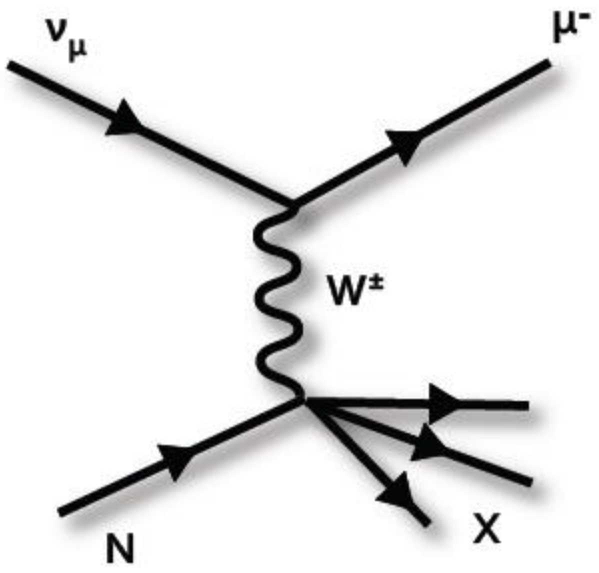
The interpretation of MINERνA data suggests that the resulting final-state pairs would be predominantly *pp* in neutrino scattering and *nn* in anti-neutrino scattering. (these results are consistent with the observation in quasi-elastic e – C scattering suggesting that multi-body final states are dominated by initial-state *np* pairs [JLab])



Inclusive Scattering



cross section build up: elastic + 1π +nπ + K + …
(“schematic”)

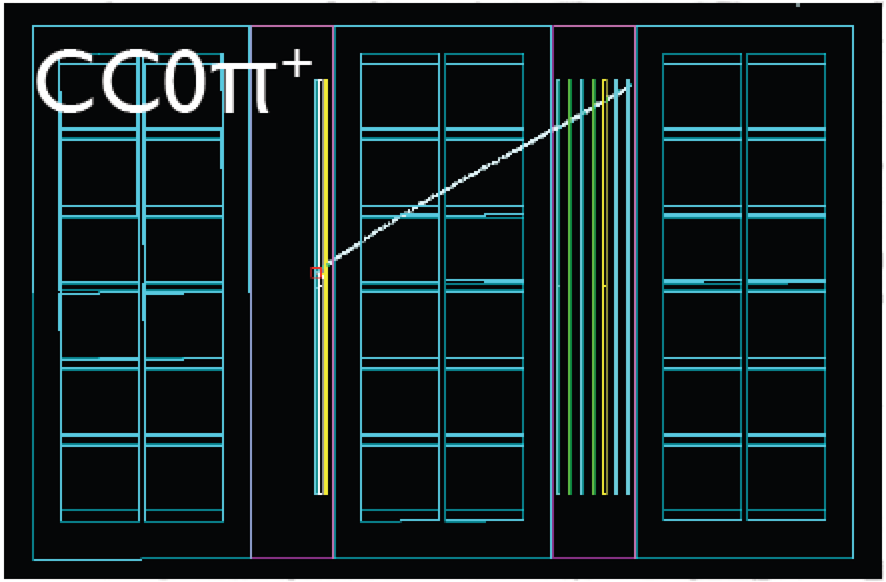


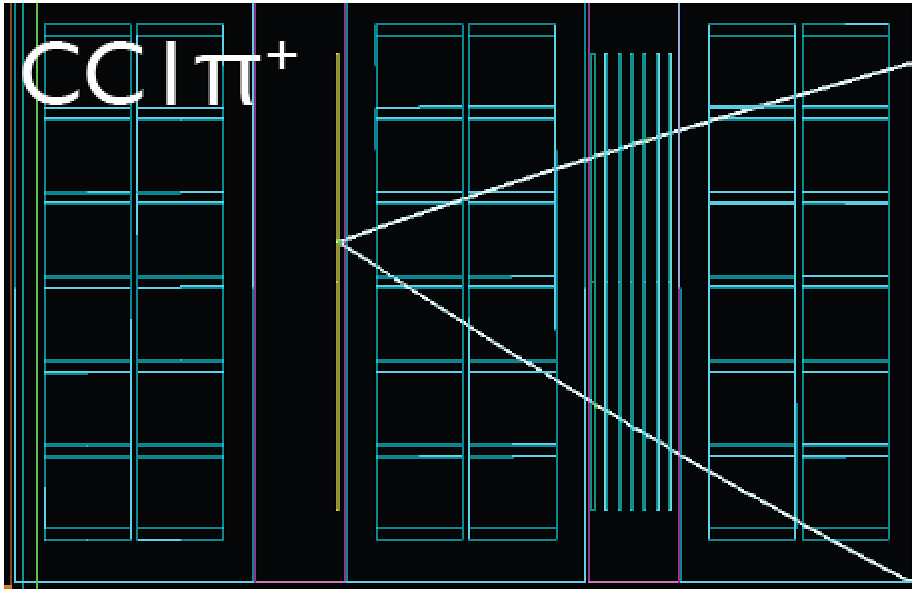
in principle ignore X

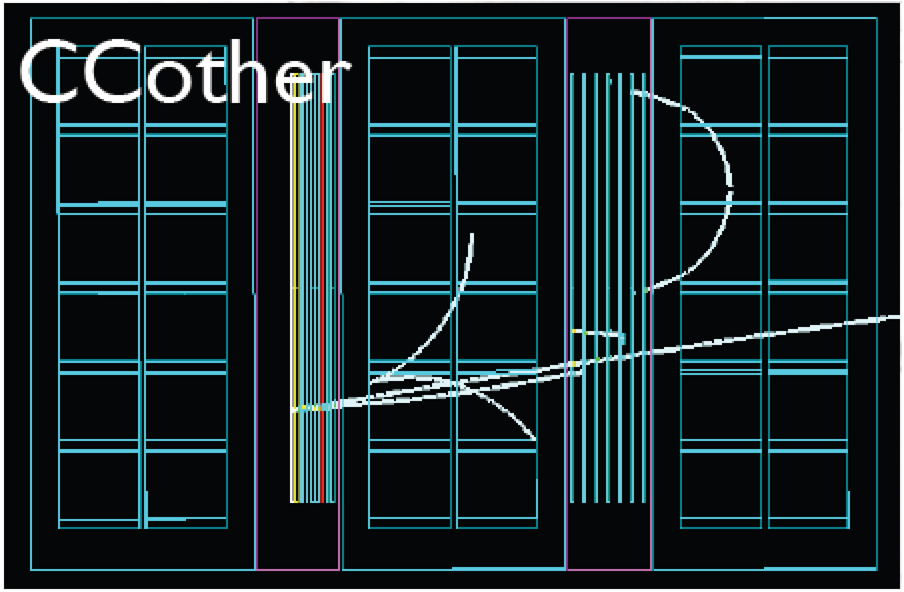
in reality need X
to reconstruct E_ν calorimetrically

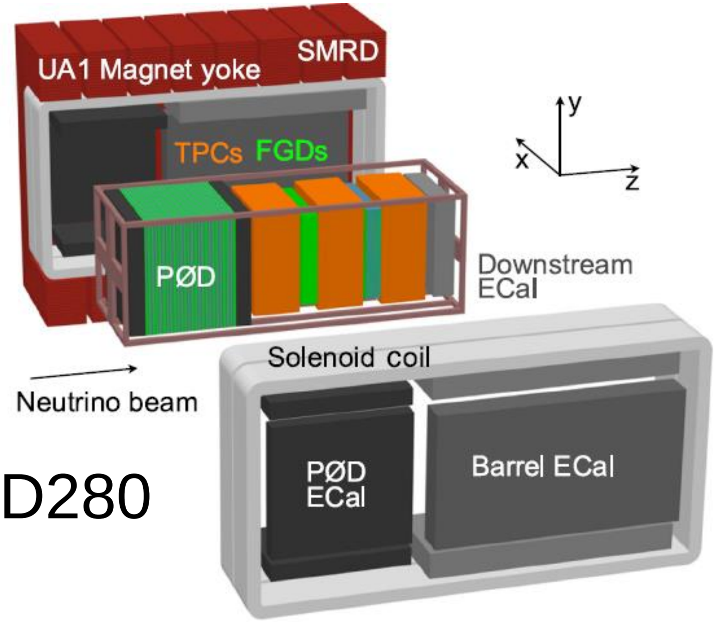
$$E_\nu = E_\mu + E_X$$

T2K CC Inclusive ν Scattering



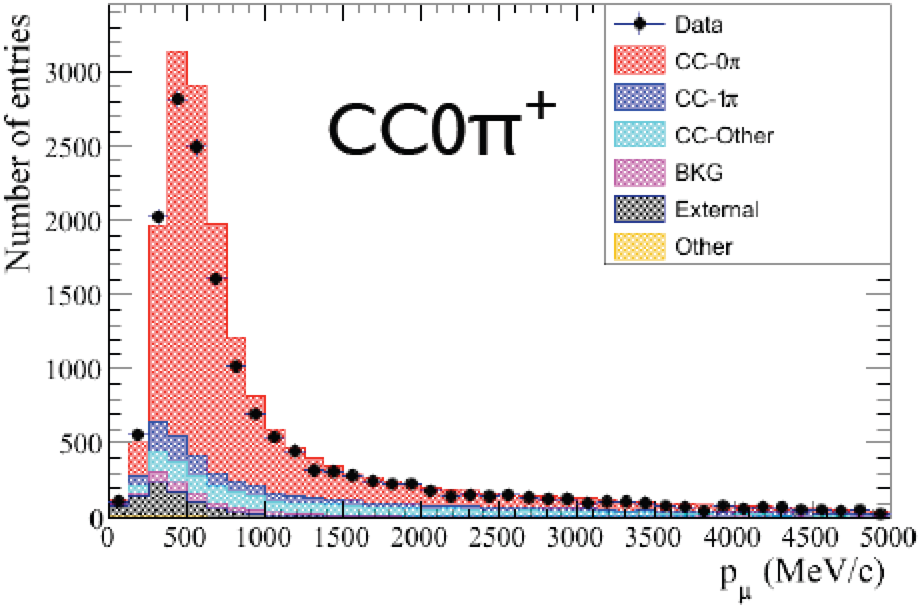


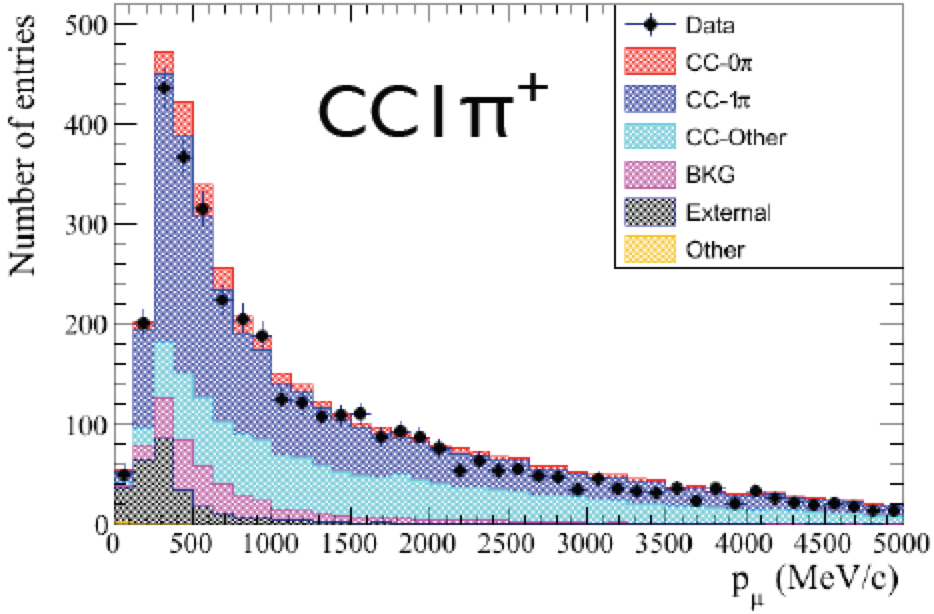


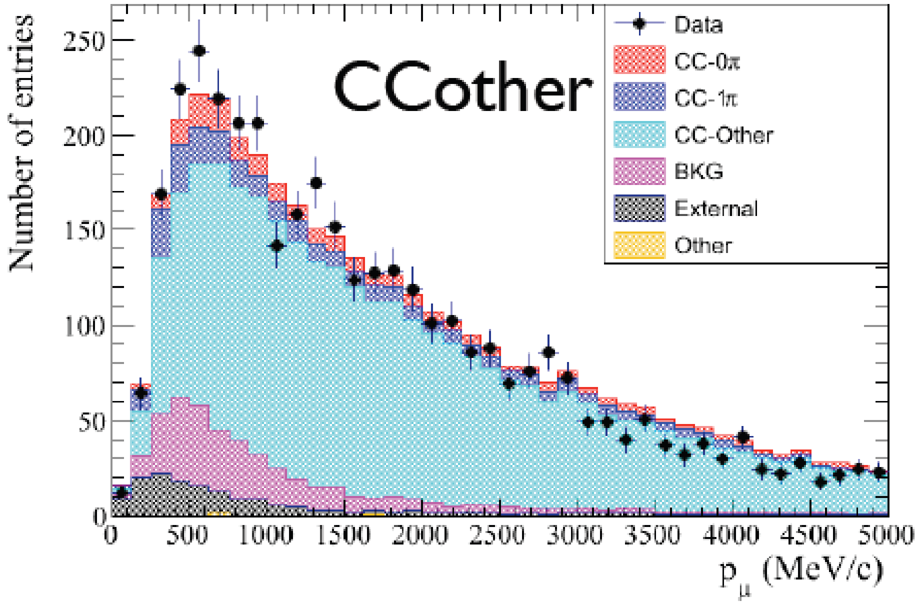


ND280

T2K Off-Axis ν_μ Analysis





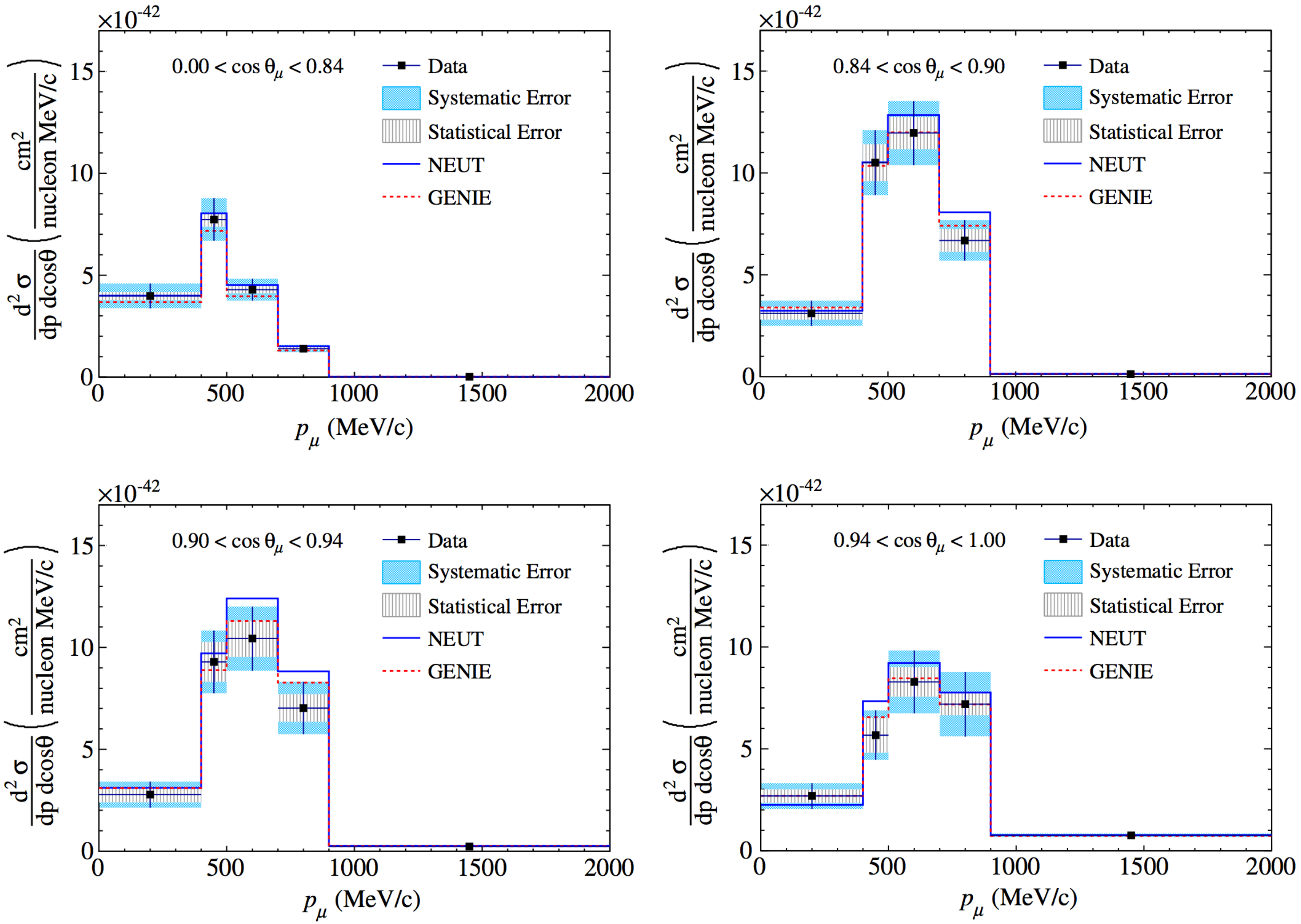


0.6 < E_ν < 2 GeV + tail

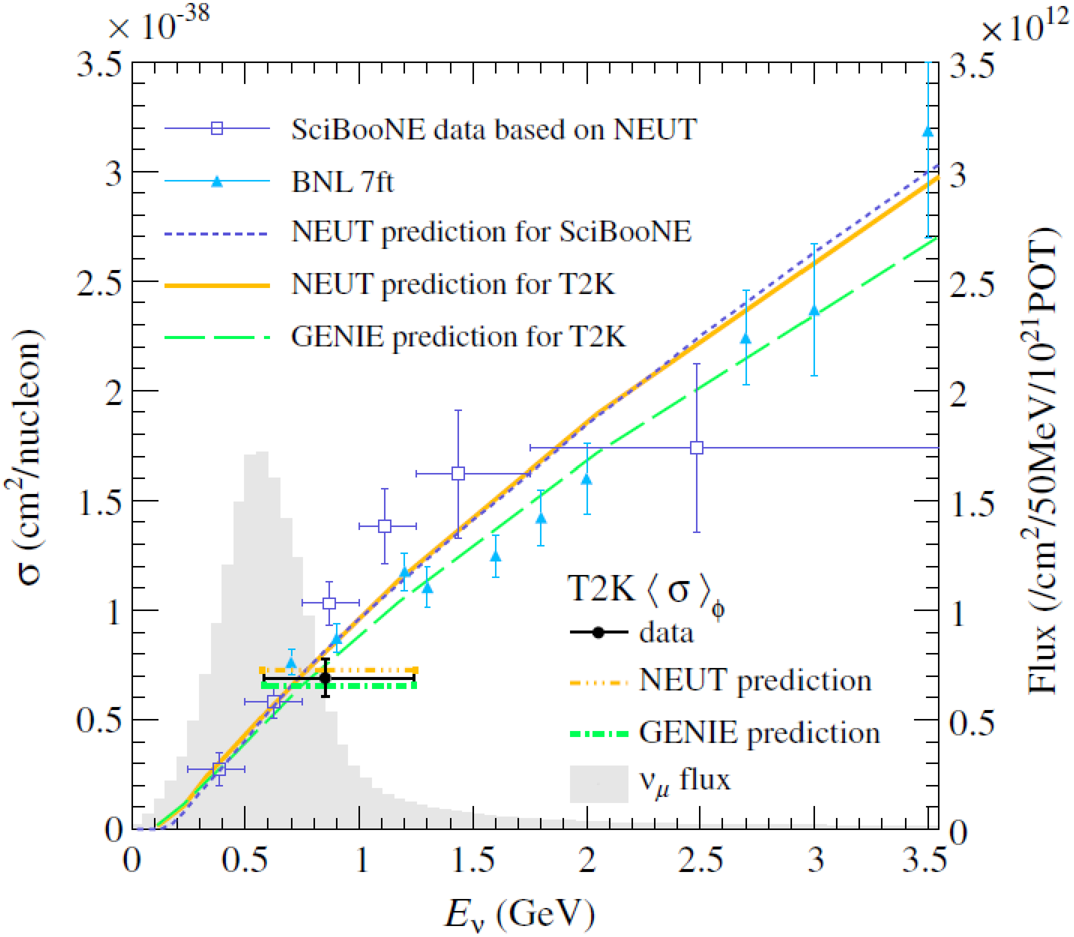
Off-Axis ND280 detector

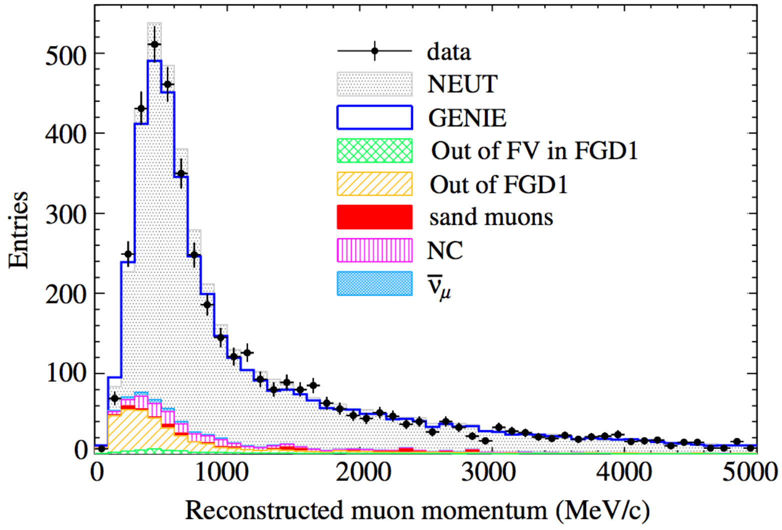
T2K CC Inclusive ν cross sections

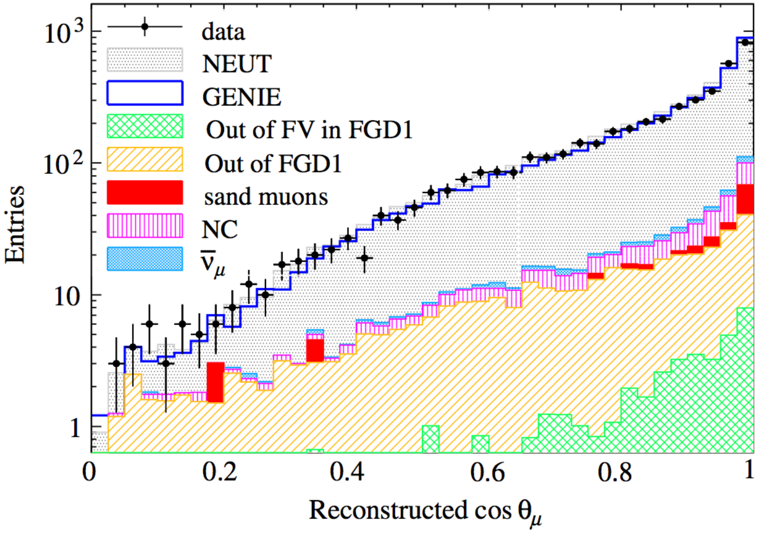
doubly differential flux averaged cross section $d^2\sigma / dp\, d\cos\theta$



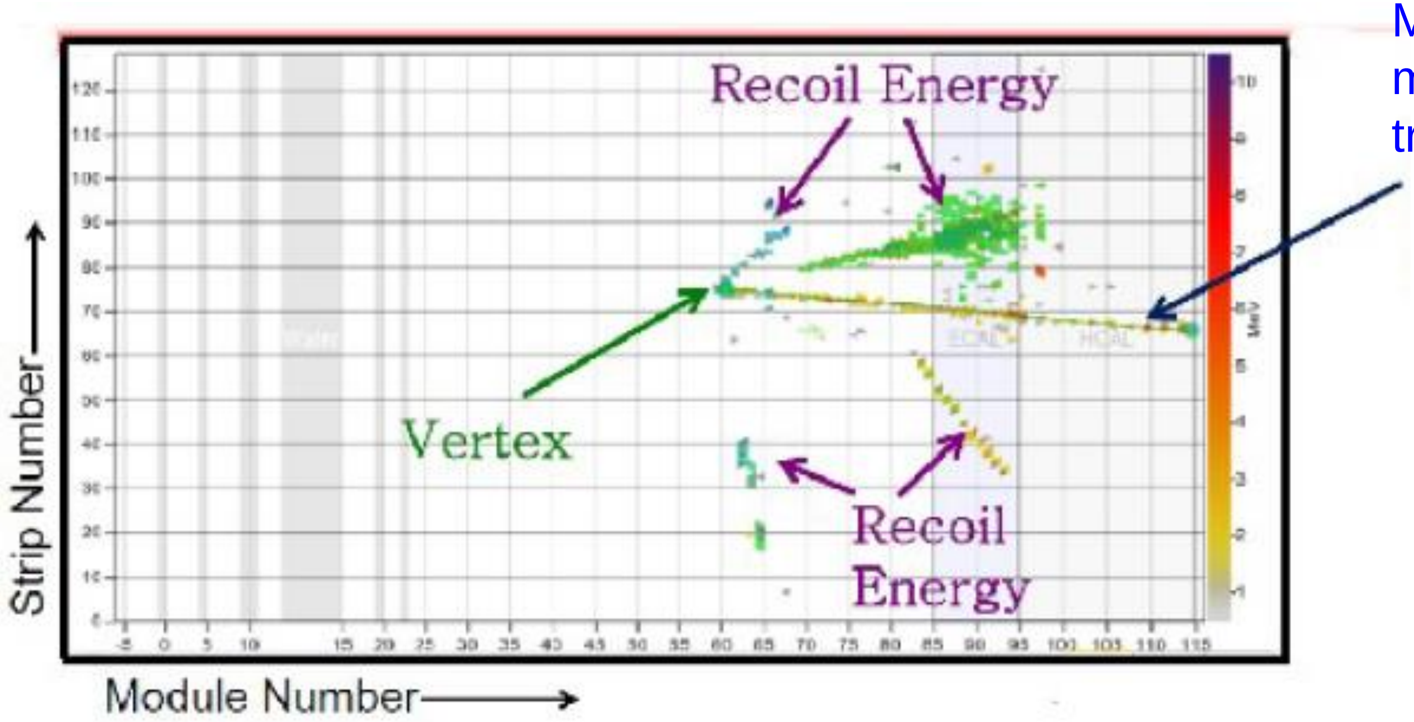
T2K CC Inclusive ν cross sections







Minerνa Inclusive ν ×–sections



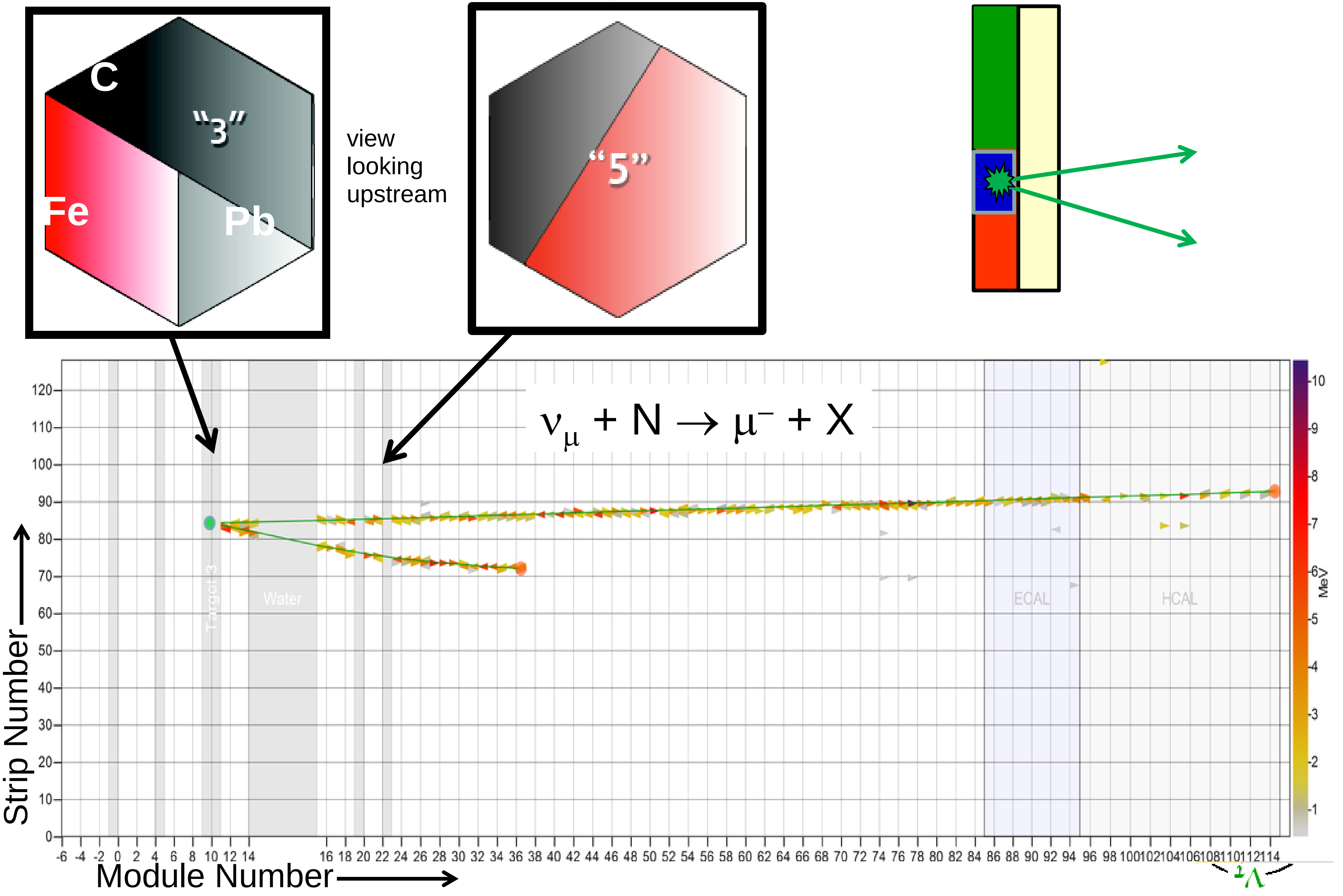
MINOS ND matched track

Event selection criteria:

- single muon track in MINERνA
- well reconstructed and matched into MINOS ND
- reconstructed vertex inside fiducial tracker region
- nuclear targets : z position consistent with nuclear target
- recoil energy E_{REC} reconstructed calorimetrically :

$$E_{\nu} = E_{\mu} + E_{REC}$$

An Event from Target 3



view looking upstream

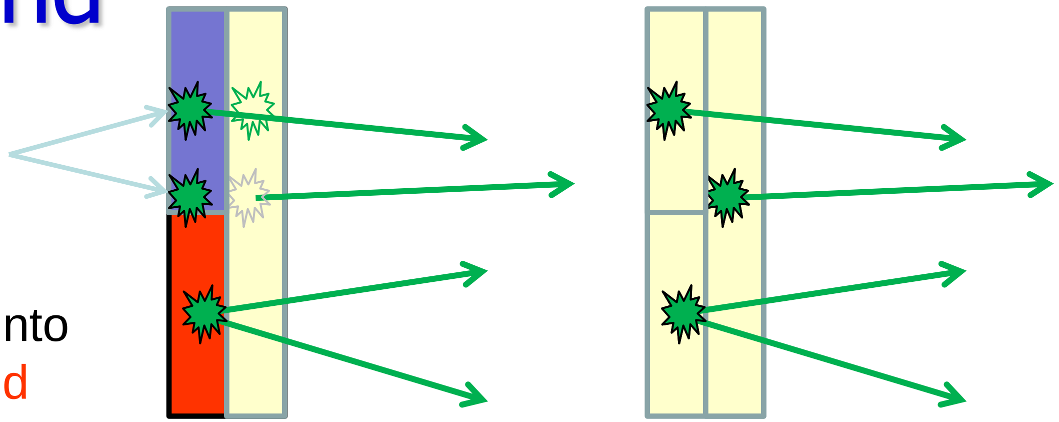
$$\nu_\mu + N \rightarrow \mu^- + X$$

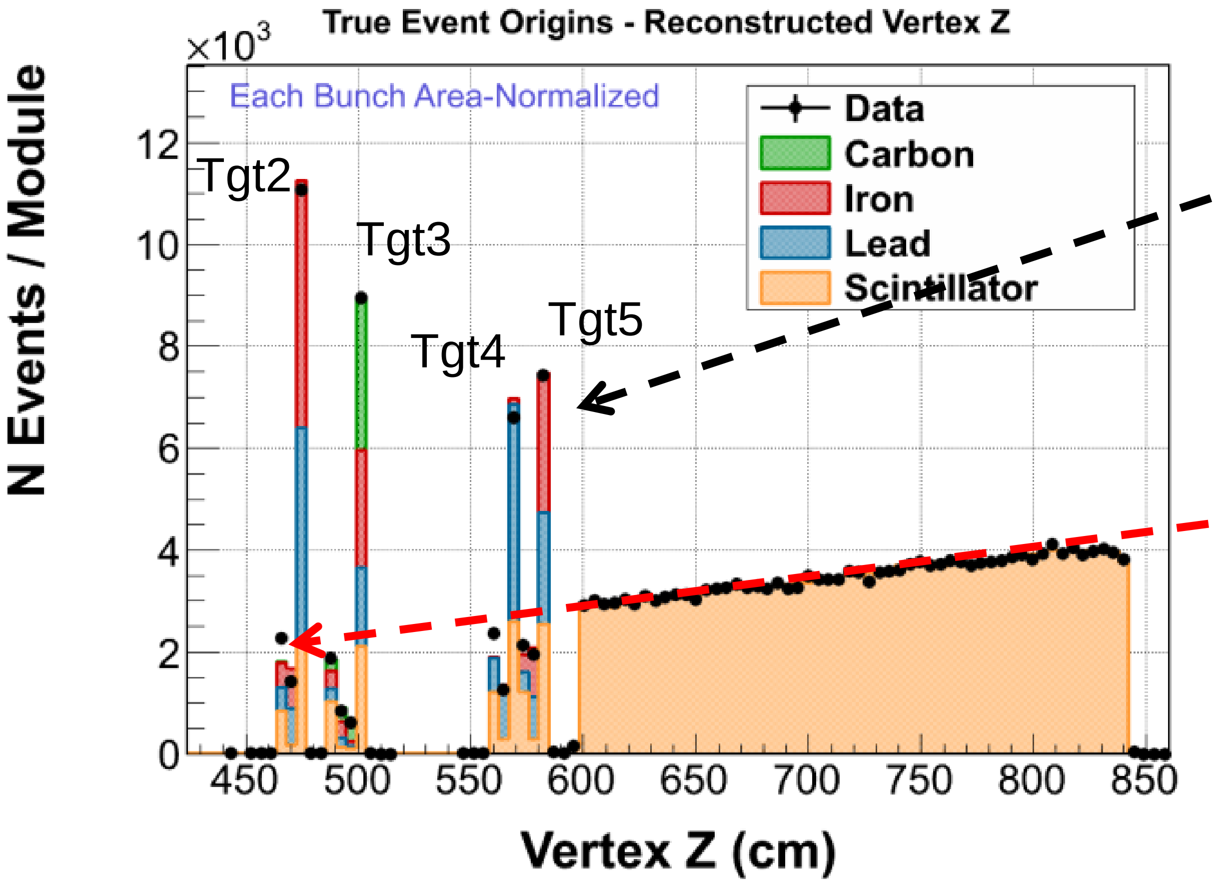
“Plastic” Background

Project the one track events to the passive target’s center in *z*

This is the best guess of the vertex

Scintillator events wrongly accepted into passive target sample are background



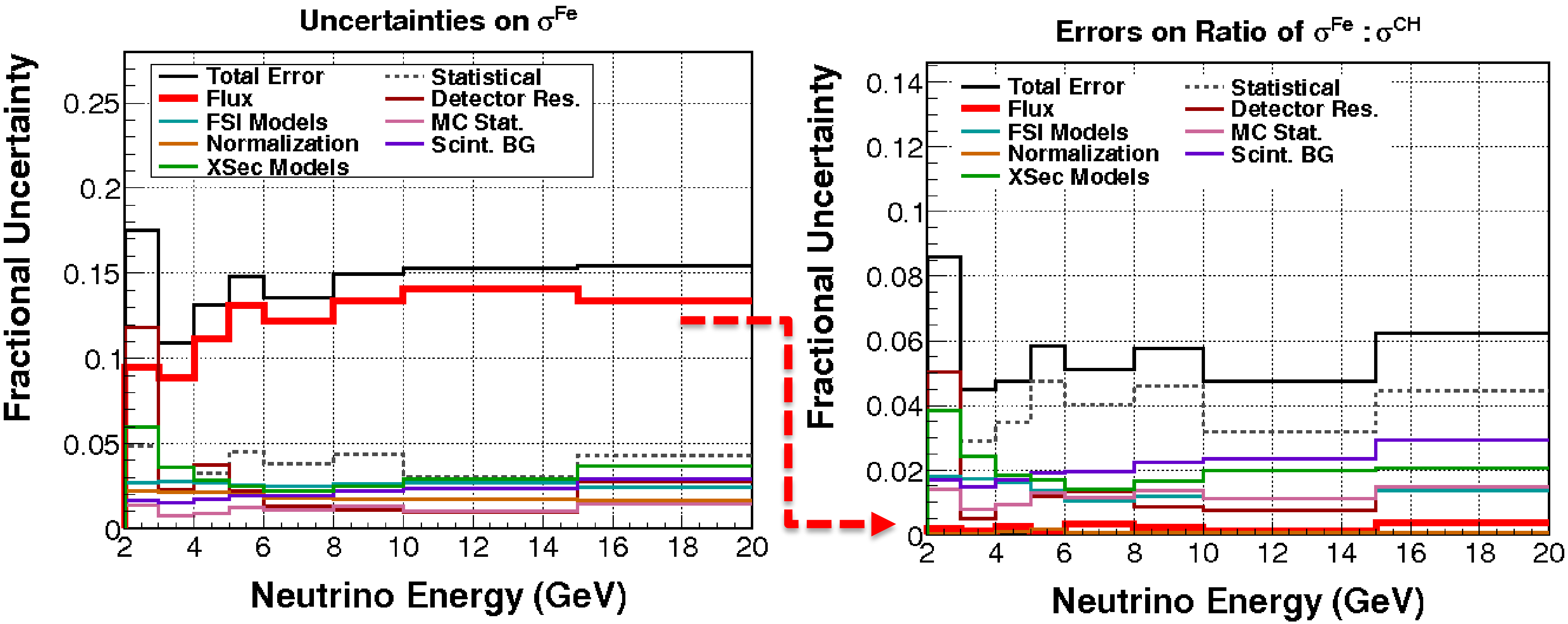


these peaks are at the location of the first module downstream of the passive targets

use events in the tracker modules to predict and subtract the plastic background

Errors on absolute cross sections

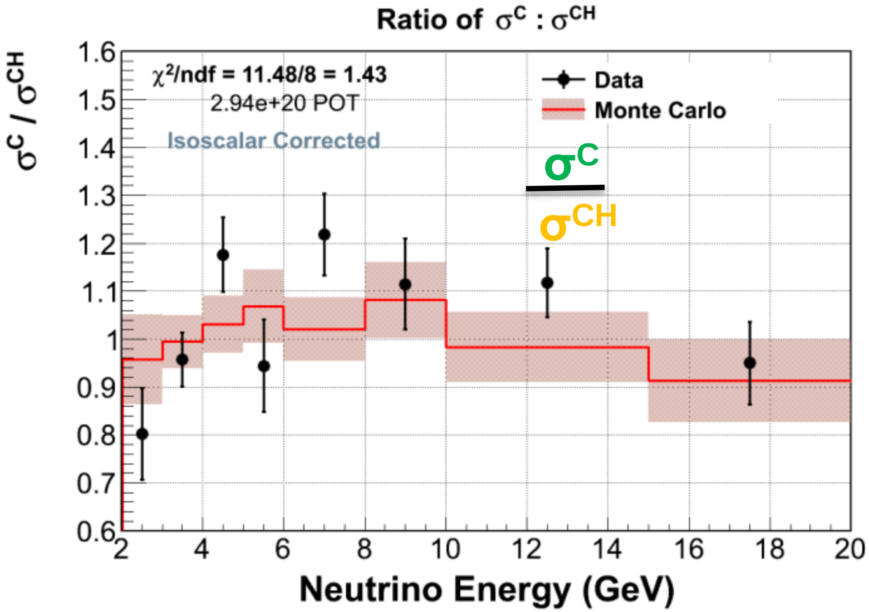
Errors on ratio of cross section

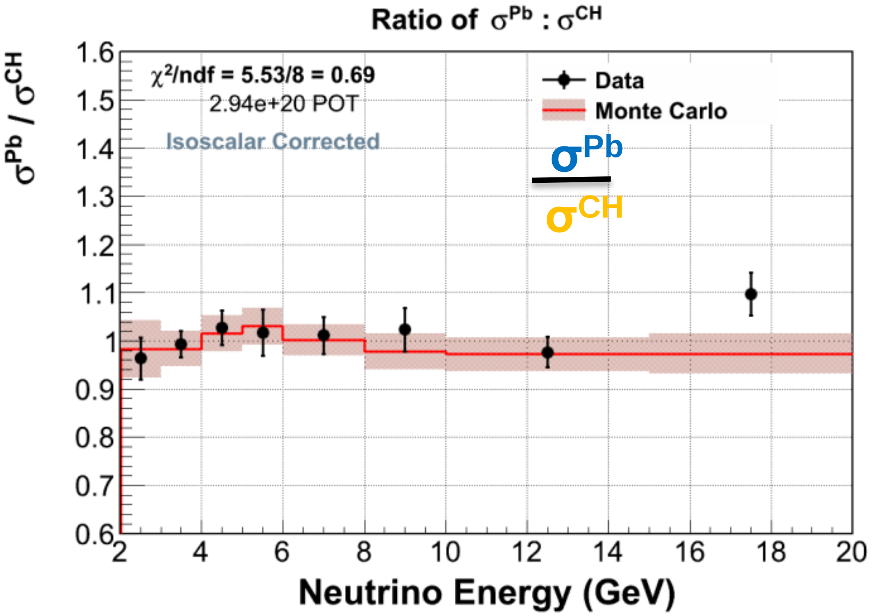


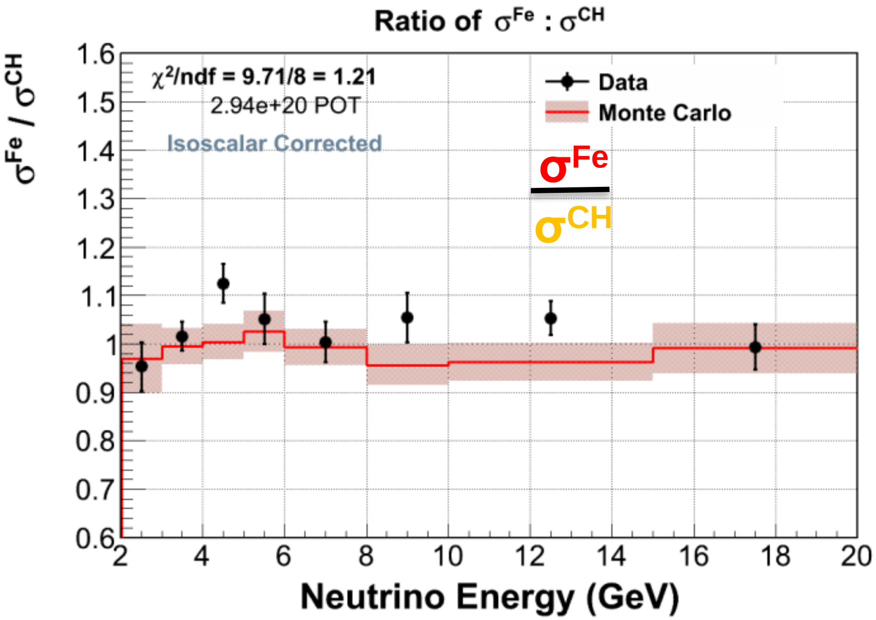
Taking ratios removes large uncertainties due to the neutrino flux

all targets in same beam
→ flux largely cancels
→ similar acceptance and reconstruction

Cross Section Ratios – E_ν


Ratio of $\sigma^{C} : \sigma^{CH}$

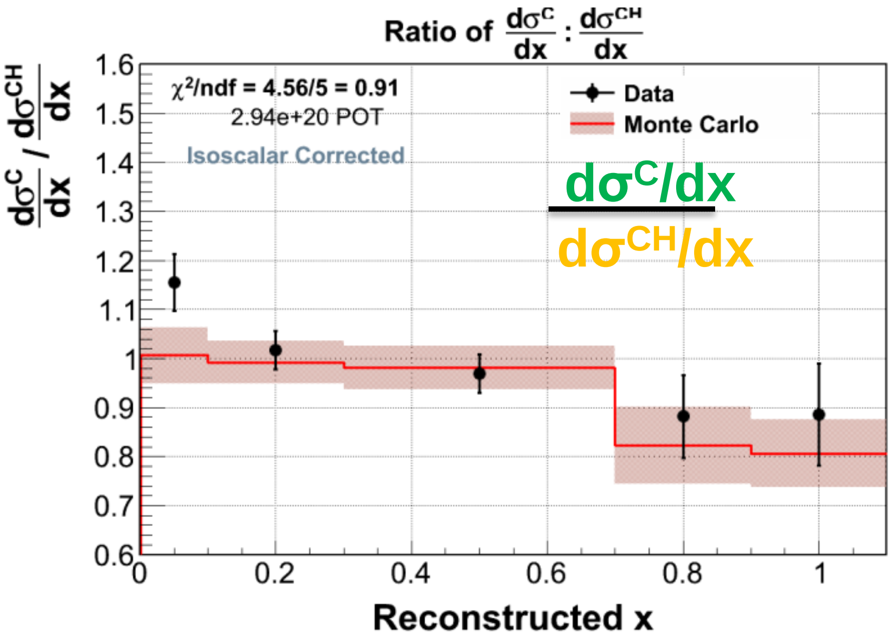

Ratio of $\sigma^{Pb} : \sigma^{CH}$

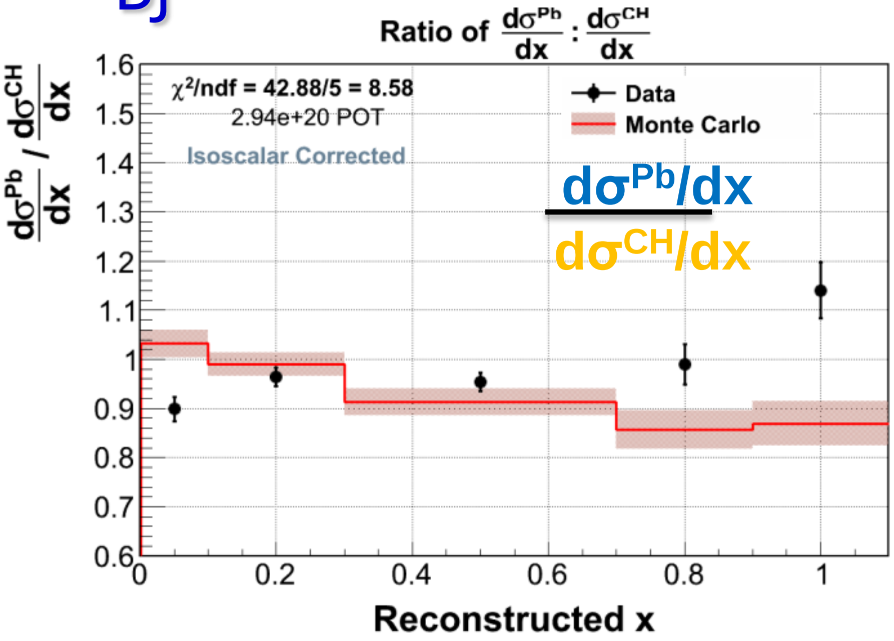

Ratio of $\sigma^{Fe} : \sigma^{CH}$

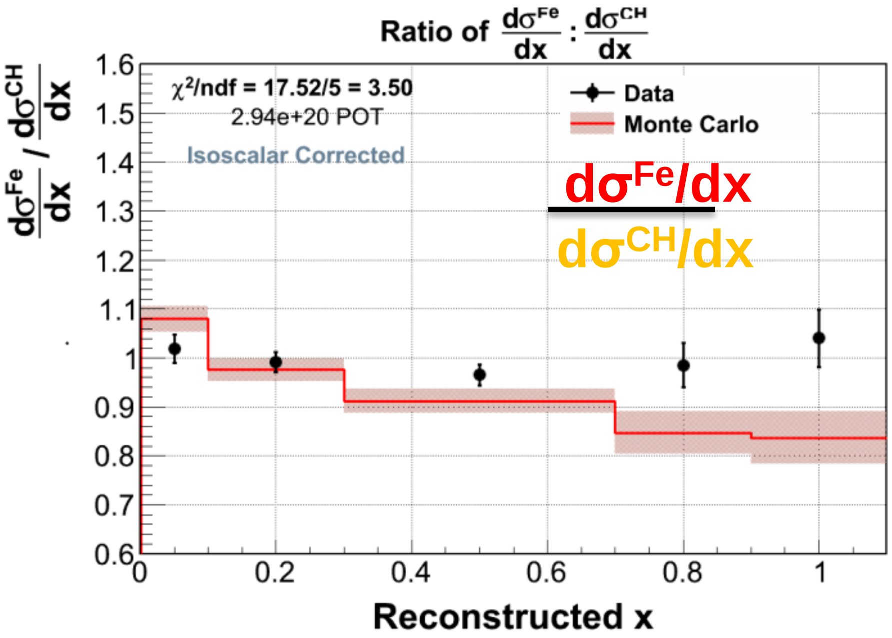
“standard” MINERνA kinematical cuts
2 < neutrino energy < 20 GeV
0 < muon angle < 17 deg

No evidence of tension between MINERνA data and GENIE 2.6.2 event generator

Cross Section Ratios – x_{Bj}





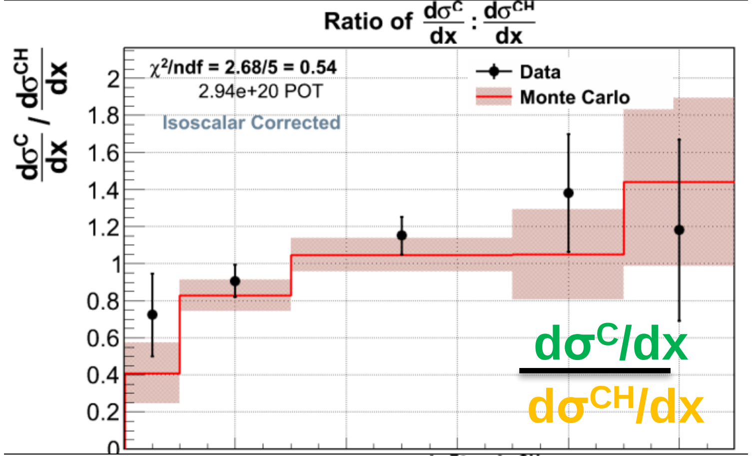


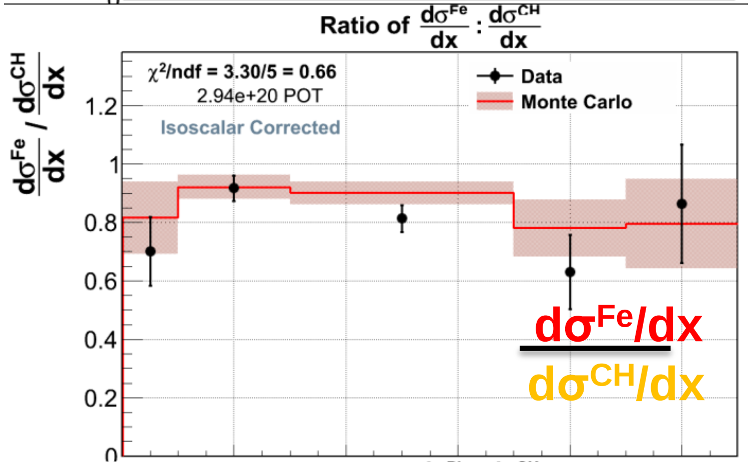
Observe an **excess** at 0.7 < x that grows with the size of the nucleus

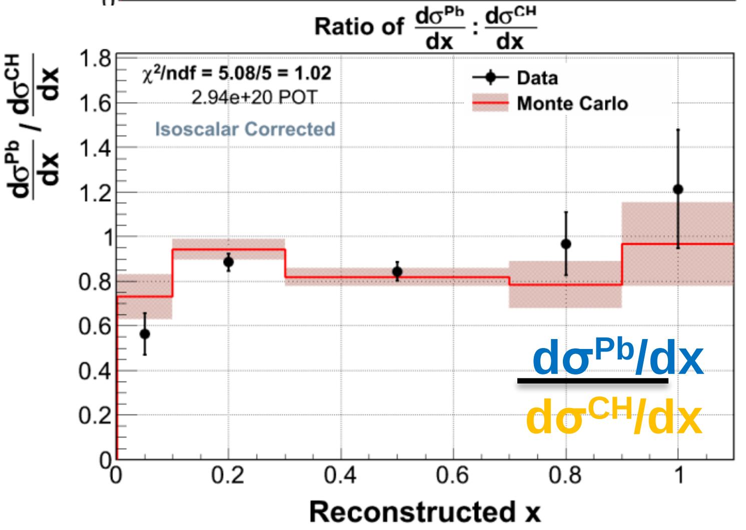
Observe a **deficit** for x < 0.1 that increases with the size of the nucleus

These effects are not modeled in event generator (GENIE)

⇒ remove elastic-like events

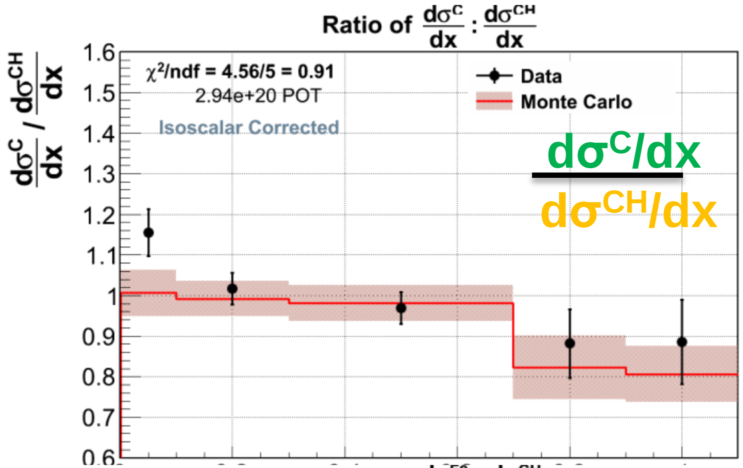


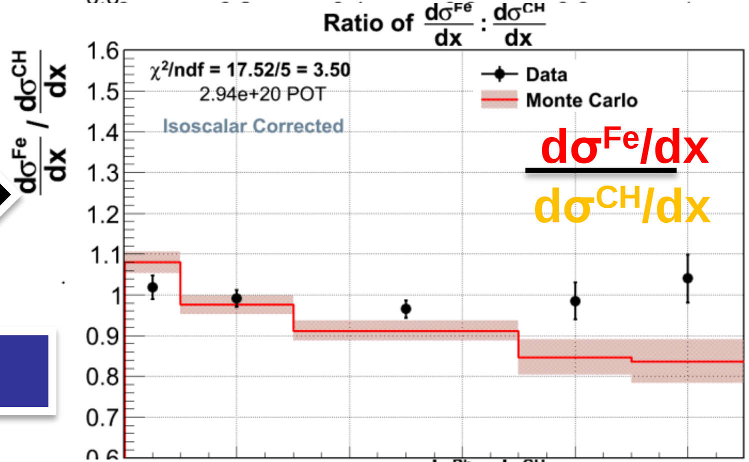


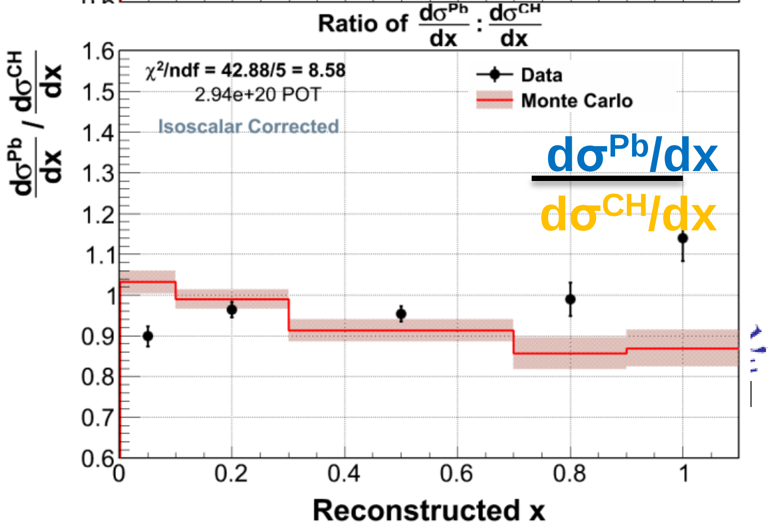


Inclusive

Inelastic







Nuclear Modification Simulation in MINERνA

“standard” GENIE model

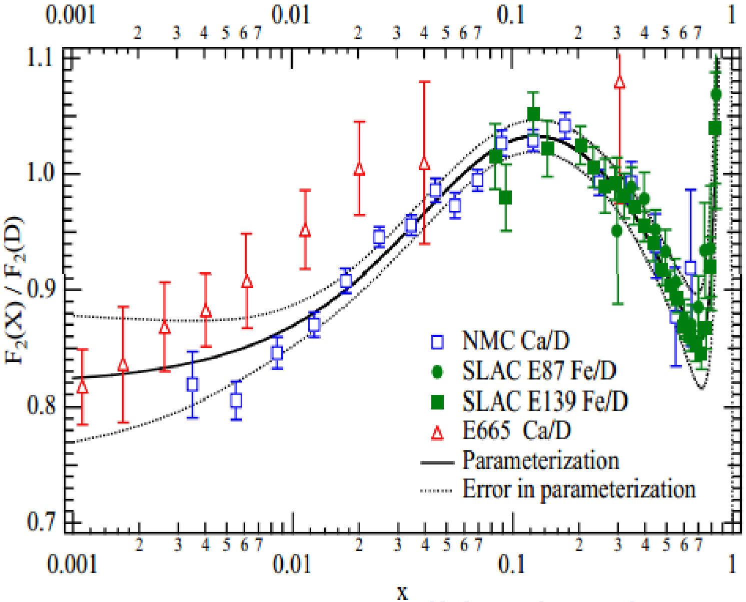
Bodek-Yang Model (2003)

arXiv:hep-ex/0308007

Fit to charged lepton data

All nuclei has same modification

All treated as isoscalar iron



Nuclear modification fit
for iron to deuterium ratio

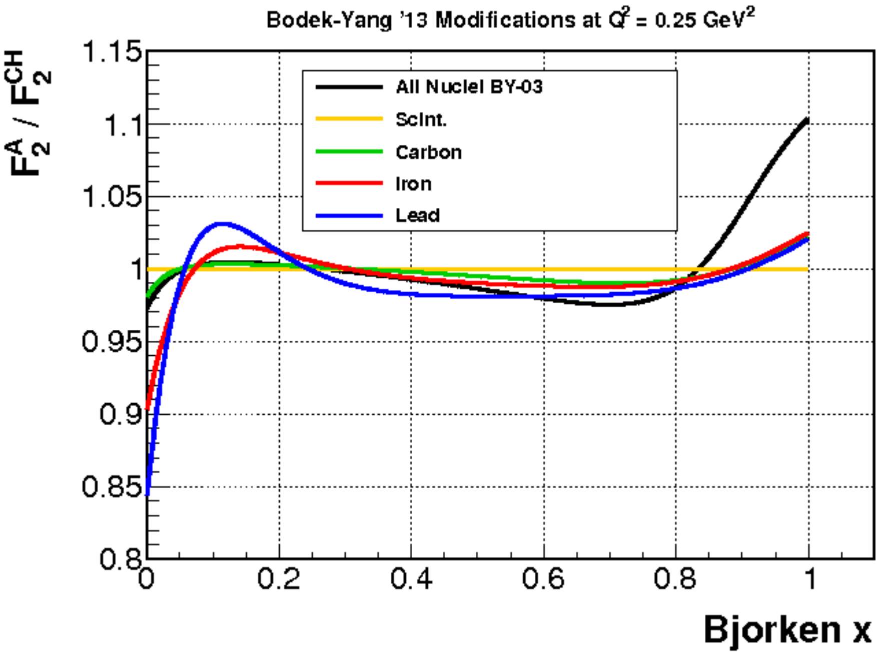
MINERνA models

Bodek-Yang Model (2013)

arXiv:hep-ph/1011.6592

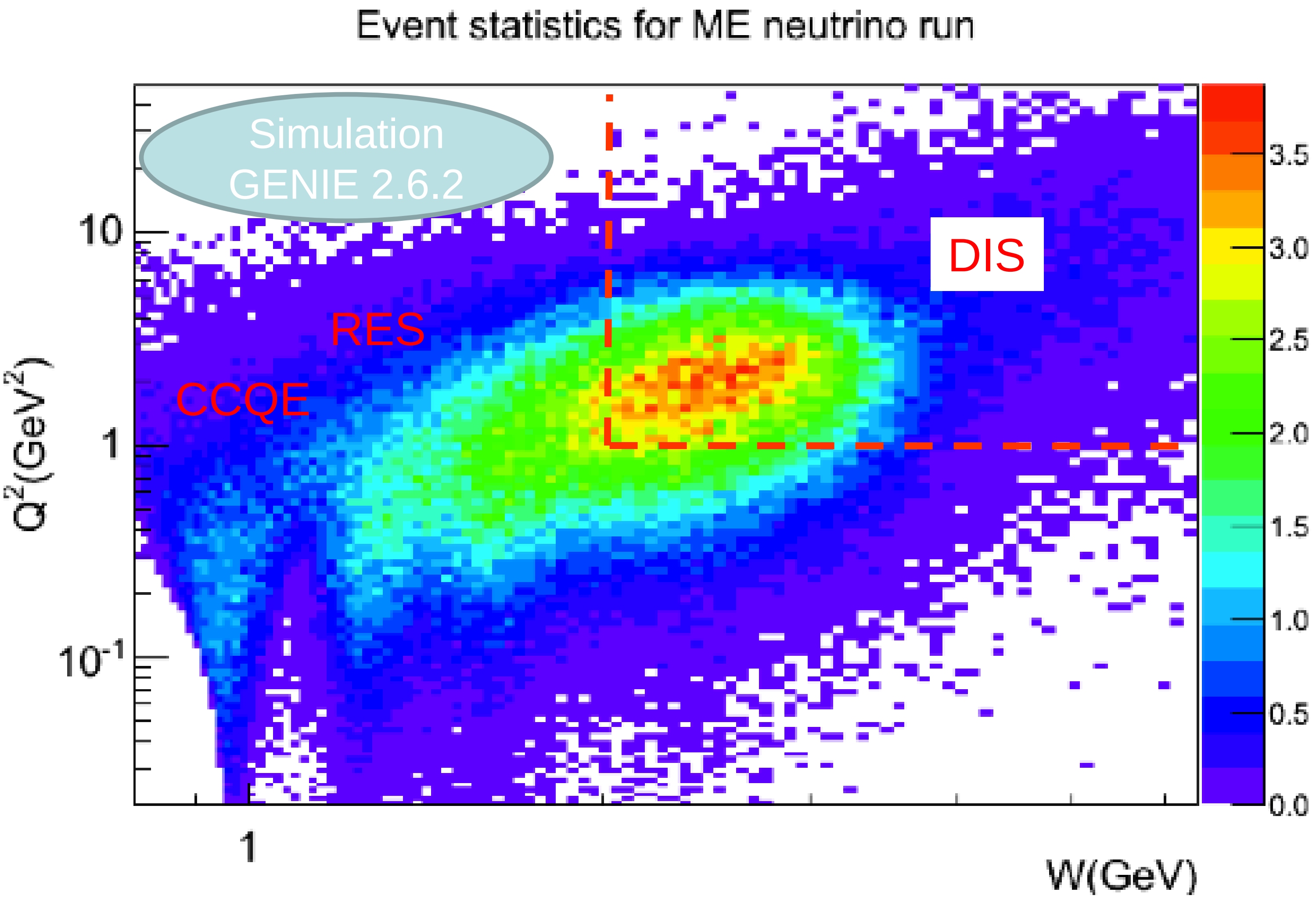
Very similar to widely used E139 fit

Specific fits for **C**, **Fe**, **Pb** on **CH**



W–Q^2 “acceptance” ME (2013–18)

z axis : 10^3 events / 3 x 10^3 kg of C / 6e20POT



kinematical distribution from GENIE 2.6.2 event generator with Minerνa “standard” cuts (E_μ > 2 GeV, θ_μ > 17^0)

Conclusion Inclusive

Finally we have sufficiently intense neutrino beams to study in detail nucleon and nuclear structure

First precise direct measurements of nuclear-dependence of neutrino cross sections in the few GeV regime

Good agreement with simulation as a function of E_ν

Deficit increases with A for $x_{Bj} < 0.1$ (Pb < Fe < C)
Excess increases with A for $x_{Bj} > 0.7$ (Pb > Fe > C)
both effects are not modeled in event generators

Enhanced statistics (>10x) in higher energy, intensity NOvA-era beam
higher energy → lower x_{Bj} reach
much more DIS → extract structure functions

Outlook

Neutrino Physics is entering an era of precision measurements

Precise knowledge and detailed understanding of ν – A cross sections required (sys. oscill. < 1-2% for CPV !)
(neutrino interaction simulation models rarely handle nuclear modifications correctly)

Today we have very high intensity neutrino beams that allow us to study ν – nucleon and ν – nucleus interactions in detail

Expect several, new ν – A cross section measurements in the 1 – 20 GeV region in the next years

Neutral Currents $\rightarrow \Delta s$
(first understand nuclear effects, however times are mature for a dedicated experiment using (liquid) H and D targets)