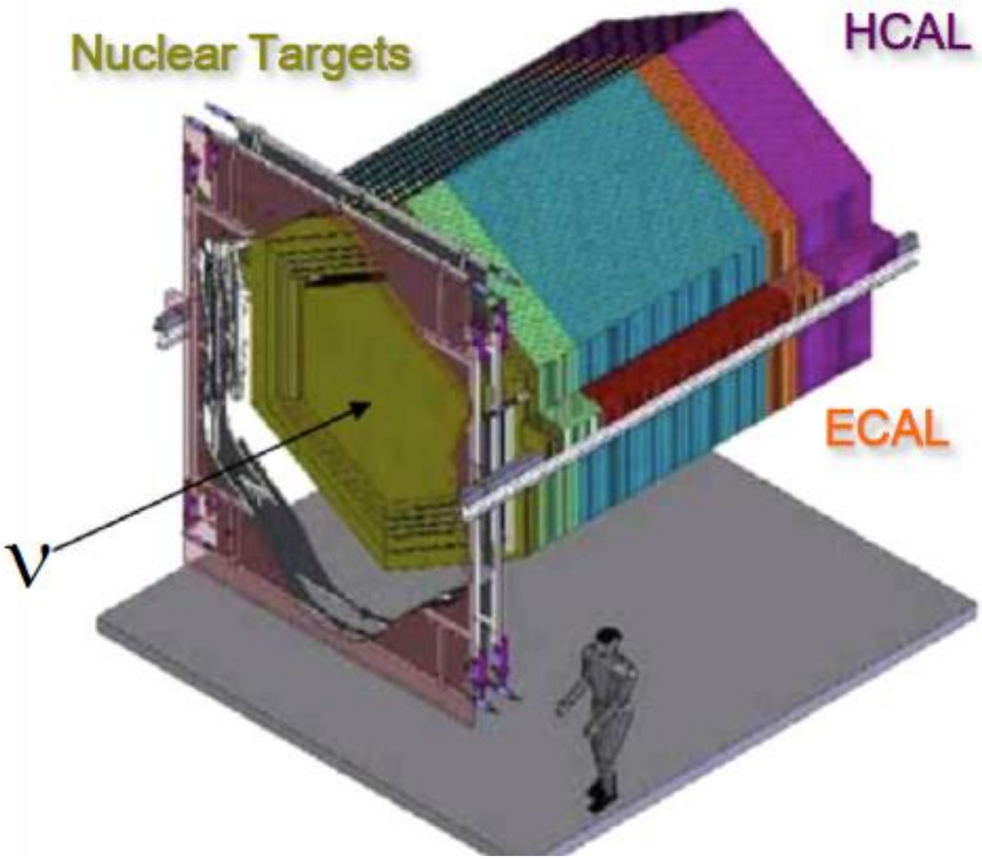
Neutrino-Nucleus Interactions Measurements at MINERνA



What is Minerνa ?

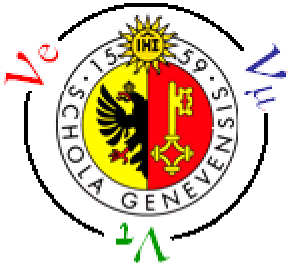
Why Minerνa ?

ν beam and ν flux

ν / $\overline{\nu}$ inclusive x-sections

Single pion production

Alessandro Bravar
Université de Genève
for the Minerνa Collaboration



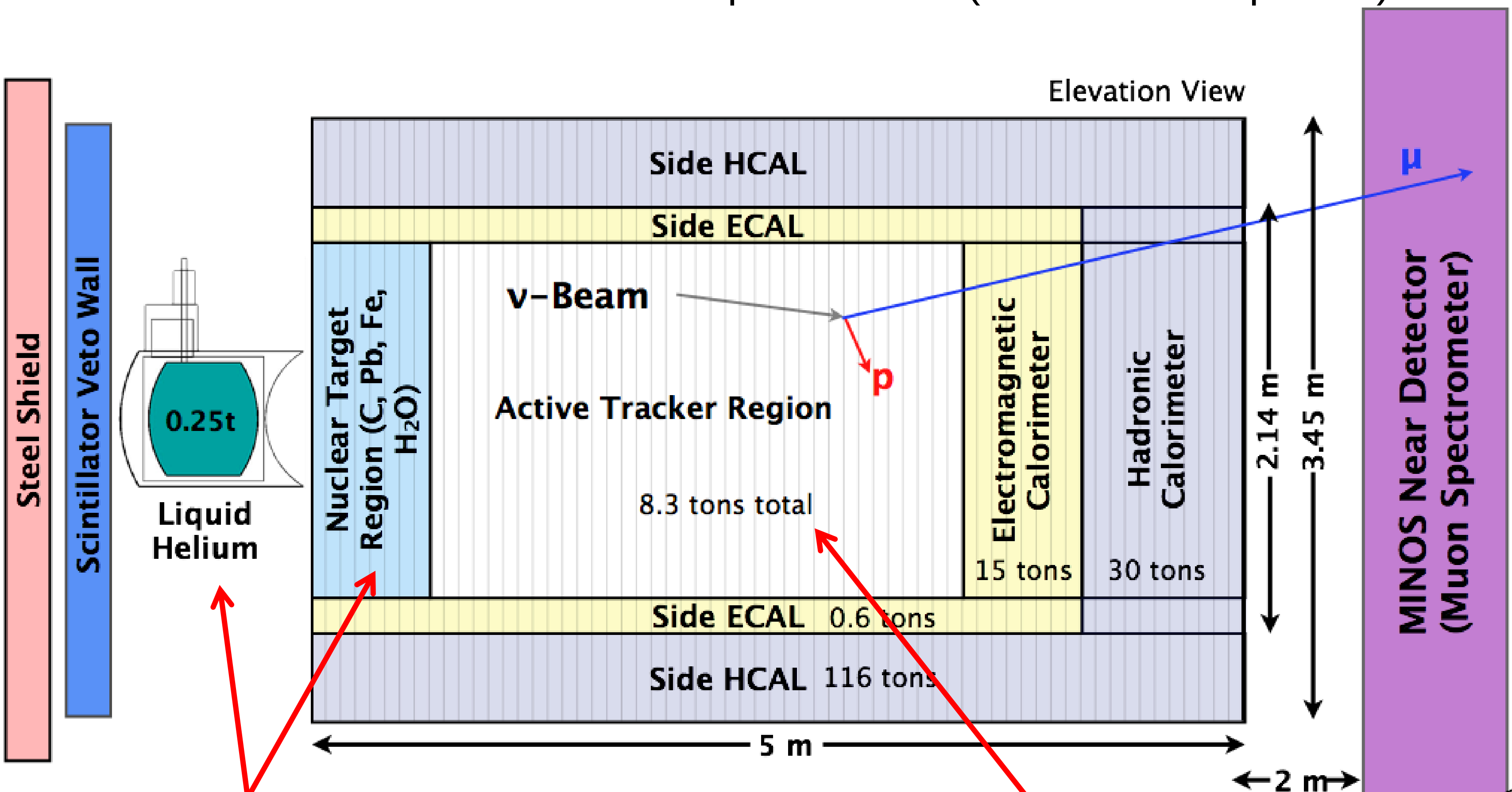
EPS 2015
Wien, July 23rd '15

The MINERνA Detector

MINERνA, NIM A743 (2014) 130

120 plastic fine-grained scintillator modules stacked along the beam direction for tracking and calorimetry (~32k readout channels with MAPMTs)

MINOS Near Detector serves as muon spectrometer (limits the acceptance)



nuclear targets: He, C, H_2O, Fe, Pb

fully active scintillator tracker (x/v and x/u modules)

Why MINERνA ?

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

MINERνA is studying neutrino interactions with unprecedented detail
on many nuclei – He, C, CH_2, H_2O, Fe, Pb

in the transition region from exclusive states to DIS (E_ν ~1 – 20 GeV)
(no systematic study of ν – N scattering attempted so far)

- ν / $\bar{\nu}$ scattering data (~1 – 20 GeV) don't fit in a coherent picture
- need detailed understanding of ν and $\bar{\nu}$ cross sections
- critical for model-building
- measure nuclear effects on inclusive and exclusive final states

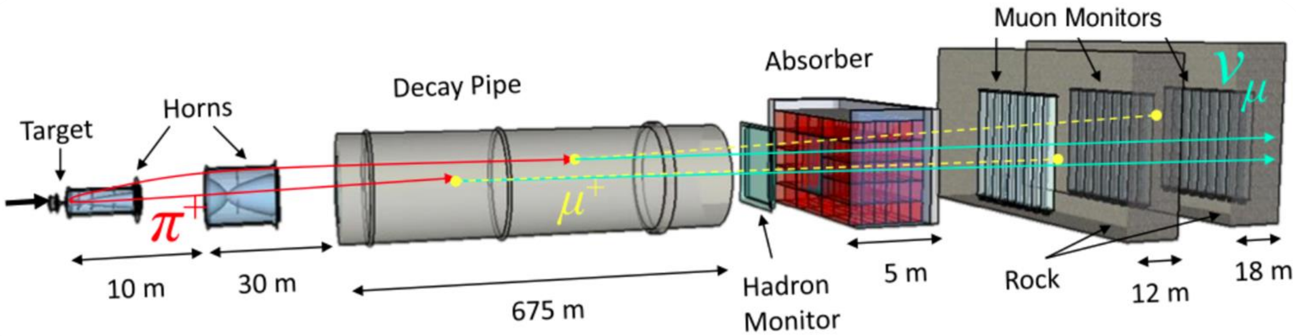
Low Energy (LE) Beam goals:

- measure exclusive channel cross sections and dynamics on various nuclei
- relevant to precision neutrino oscillation experiments
  - all experiments use dense nuclear targets (CH_2, H_20, Ar, Fe, …)
  - $\rightarrow$ nuclear effects modify event kinematics ($\rightarrow$ extraction of oscillation parameters)

Medium Energy (ME) Beam goals:

- measure parton densities modifications in nuclei
- study high energy background to ν oscillation experiments

The NUMI Beam (Fermilab)

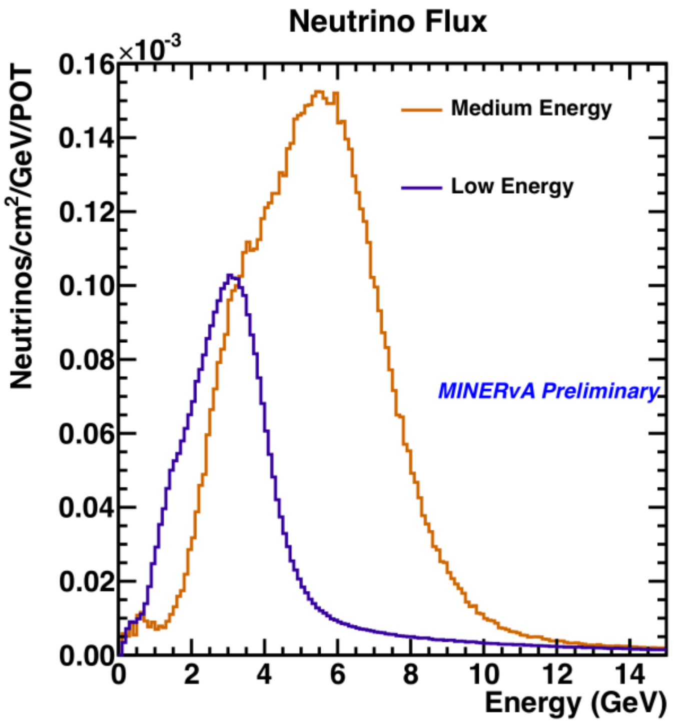


NuMI (Neutrinos at the Main Injector)

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

By moving the production target w.r.t. 1st horn and changing the distance between the horns one can modify the ν spectrum:

- LE (peak ~3 GeV) $\rightarrow$ ME (peak ~6 GeV)

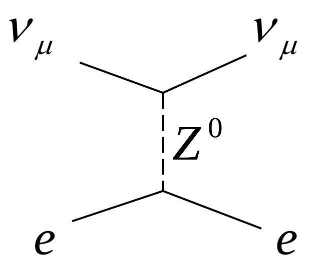


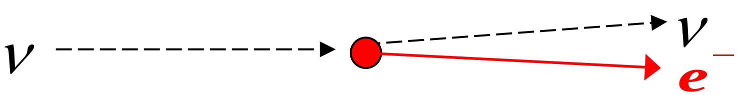
Flux determination

- external hadron production data
- ν – e elastic scattering
- low–ν extrapolation
- muon monitor data
- special runs (vary beam parameters)

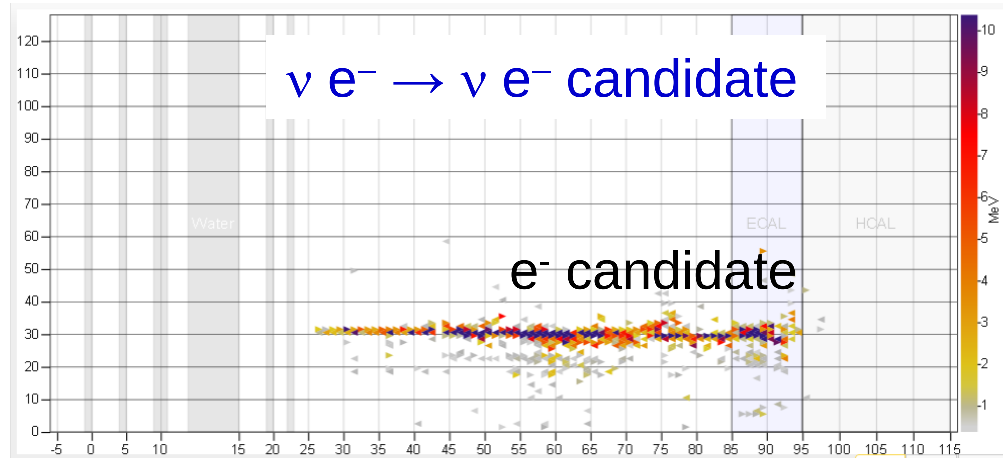
ν – e elastic scattering

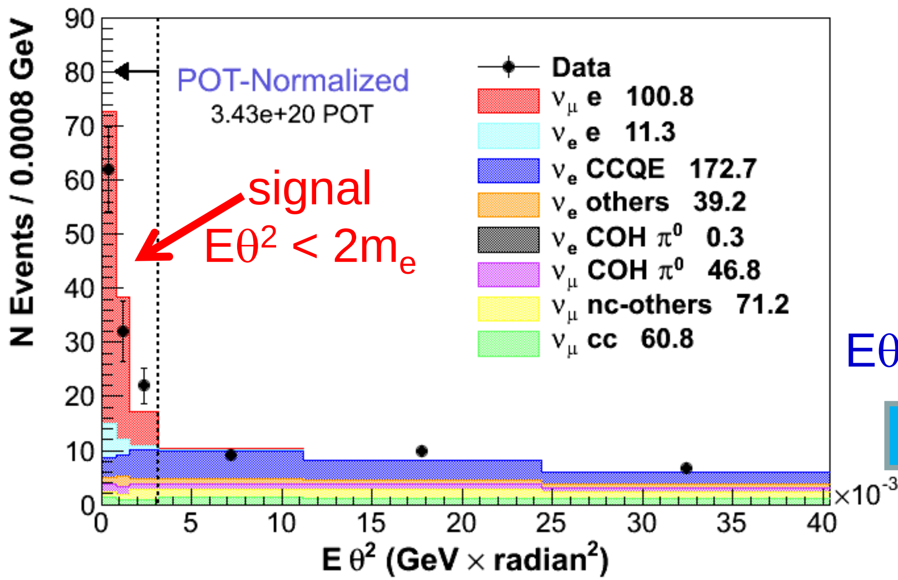
neutrino – electron elastic scattering is the only "standard candle" in neutrino scattering (in situ flux measurement)

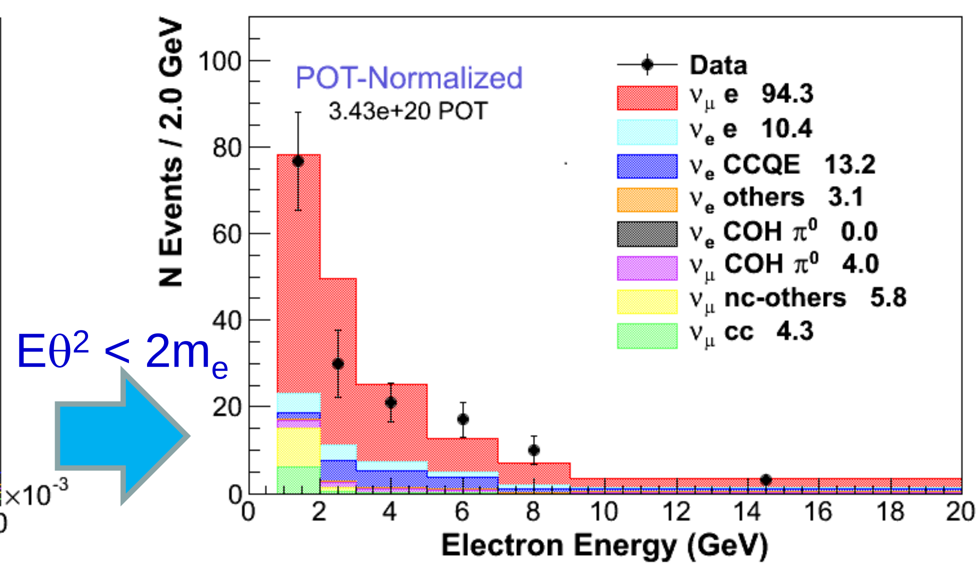




very forward single electron final state



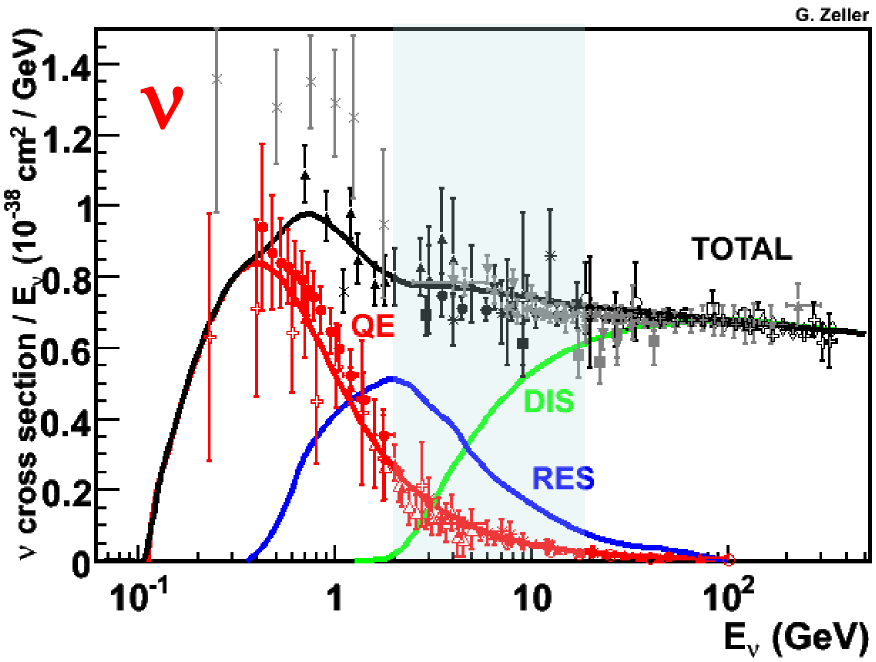


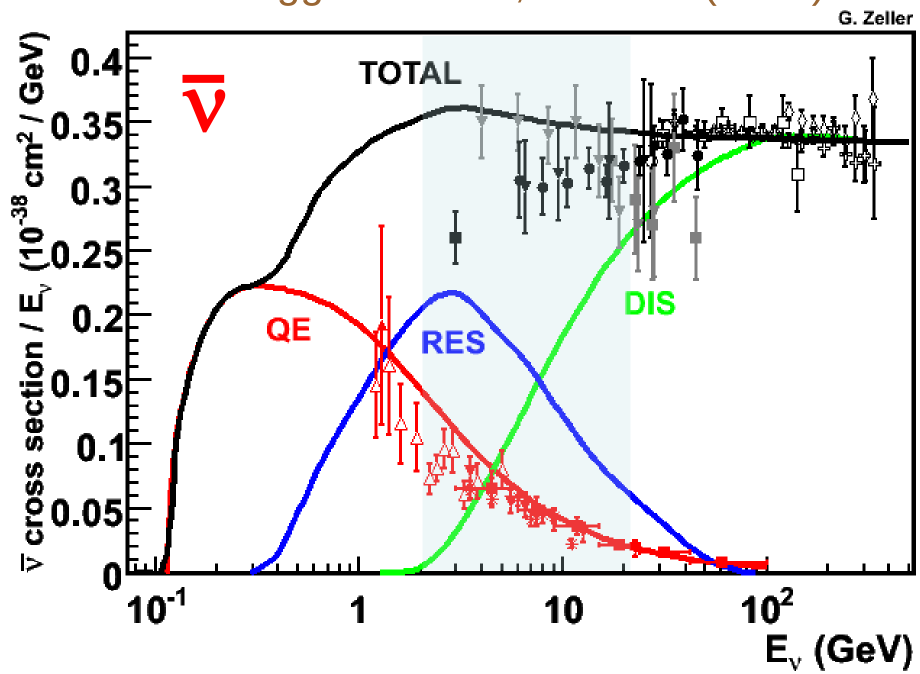


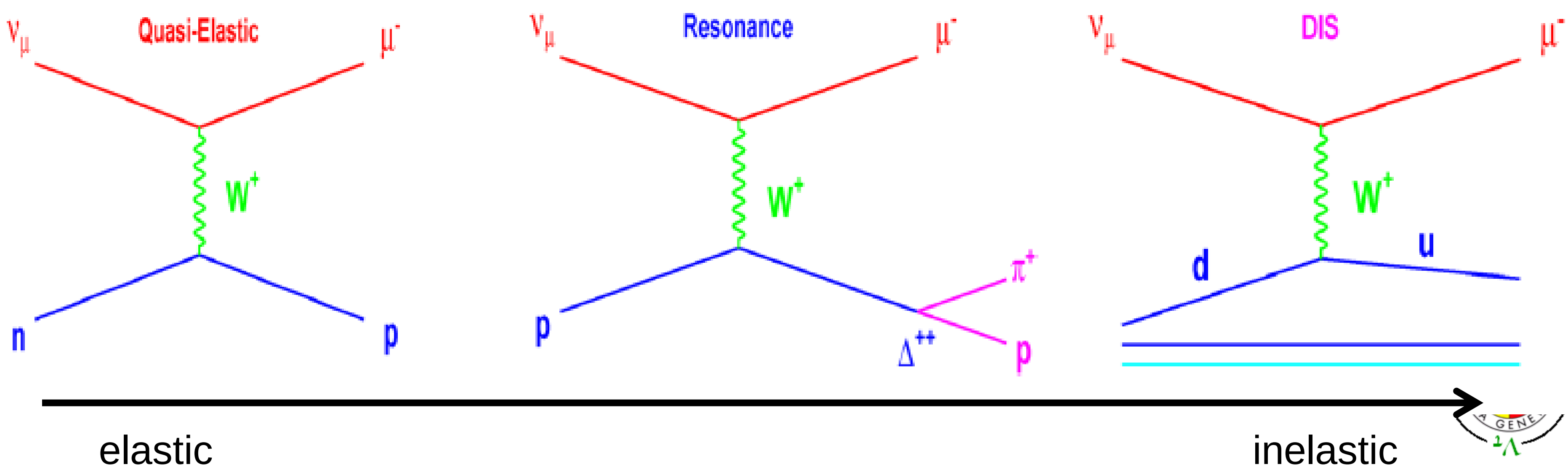
~100 events in LE sample → 10% flux constraint (expect 5% precision in ME)

ν ×-sections

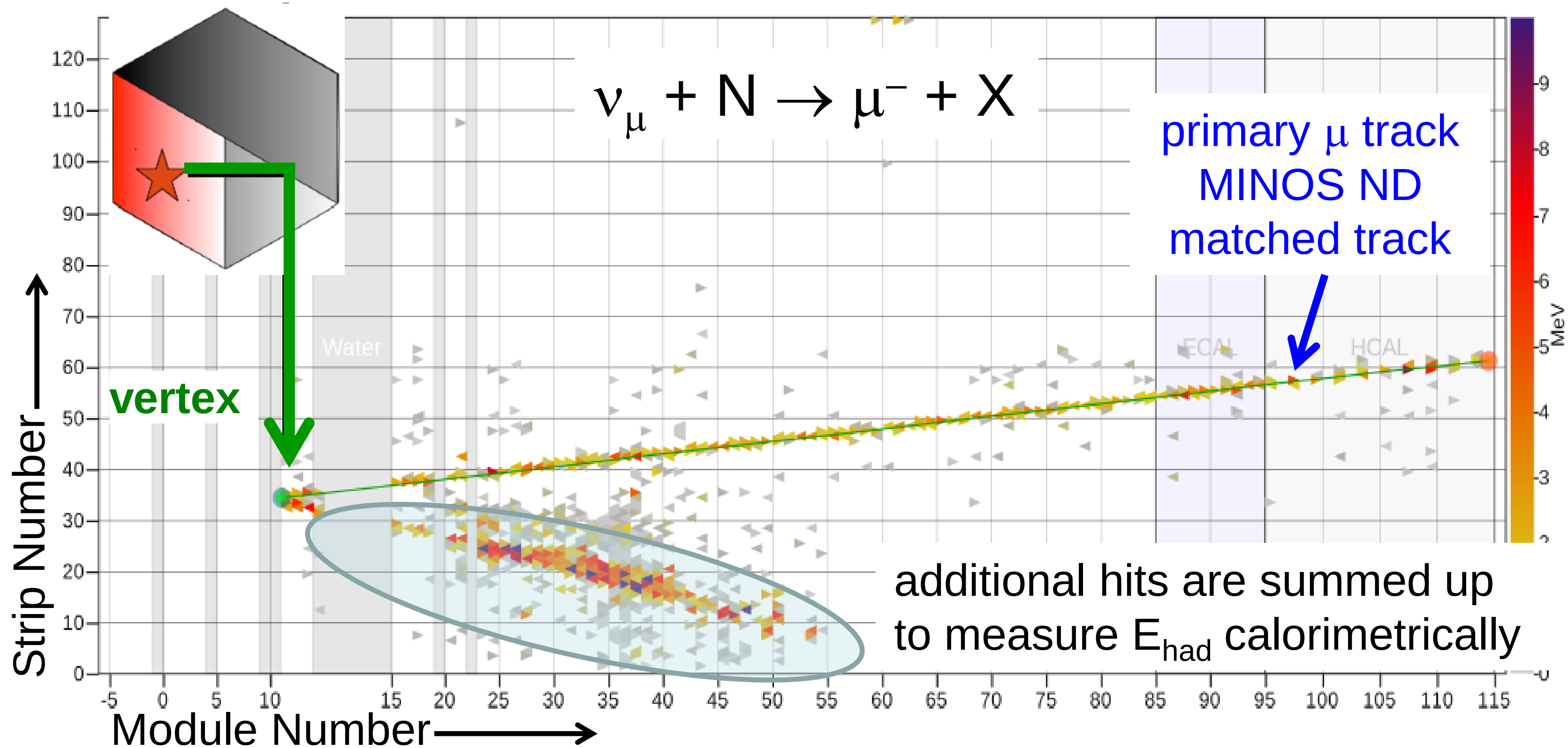
Formaggio & Zaller, RMP 84 (2012) 1307







An Event from a “Nuclear Target”



Event selection criteria:

single muon track in MINERνA, well reconstructed and matched into MINOS ND

“standard cuts”: $2 < E_\nu < 20$ GeV & $\theta_\mu < 17^0$ (MINOS ND acceptance)

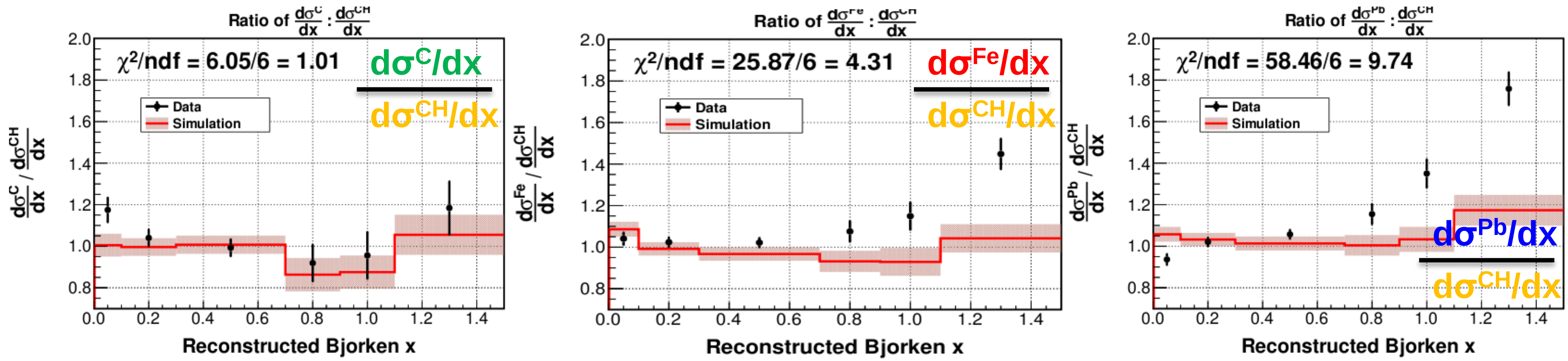
CH_2: reconstructed vertex inside fiducial tracker region

nuclear targets: z position of vertex consistent with nuclear target

recoil energy E_{REC} reconstructed calorimetrically

⇒ incoming neutrino energy E_ν: $E_\nu = E_\mu + E_{REC}$

Inclusive Cross Section Ratios – $d\sigma$ / dx_{Bj}



Tice, PRL 112 (2014) 231801

Reconstructed *x* (no correction for detector smearing)

Taking ratios removes uncertainties due to the neutrino flux, acceptance, …

At low x, *x* < 0.1, observe a *deficit* that increases with the size of the nucleus
(possibly additional nuclear shadowing in ν scattering, study more directly in DIS)

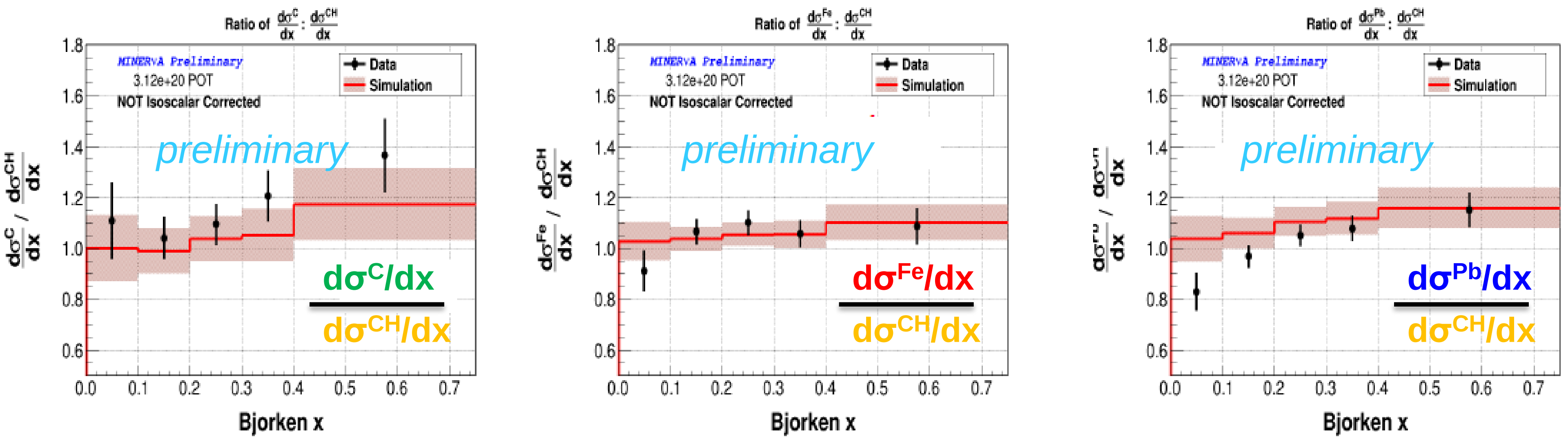
At high x, x > 0.7, observe an *excess* that grows with the size of the nucleus
(events are dominated by CCQE and resonances)

These effects are not reproduced by current neutrino interaction models

GENIE assumes an x dependent effect from charged lepton scattering on nuclei
but ν sensitive to xF_3 and also to the axial part of F_2

When studied as a function of E_ν:
no evidence of tension between MINERνA data and GENIE 2.6.2 simulations

DIS Cross Section Ratios – dσ / dx_{Bj}



Select DIS sample by requiring $Q^2 > 1$ GeV^2 and $W > 2$ GeV
(these cuts remove the quasi-elastic and resonant background)

x dependent ratios directly translates to *x* dependent nuclear effects
(interpret data at partonic level)
cannot reach the high-*x* with current beam energy (LE data sample)

MINERνA data suggests additional nuclear shadowing in the lowest *x* bin
($\langle x \rangle = 0.07$, $\langle Q^2 \rangle = 2$ GeV^2)

In EMC region ($0.3 < x < 0.7$) good agreement between data and models
(GENIE assumes an *x* dependent effect from charged lepton scattering on nuclei)

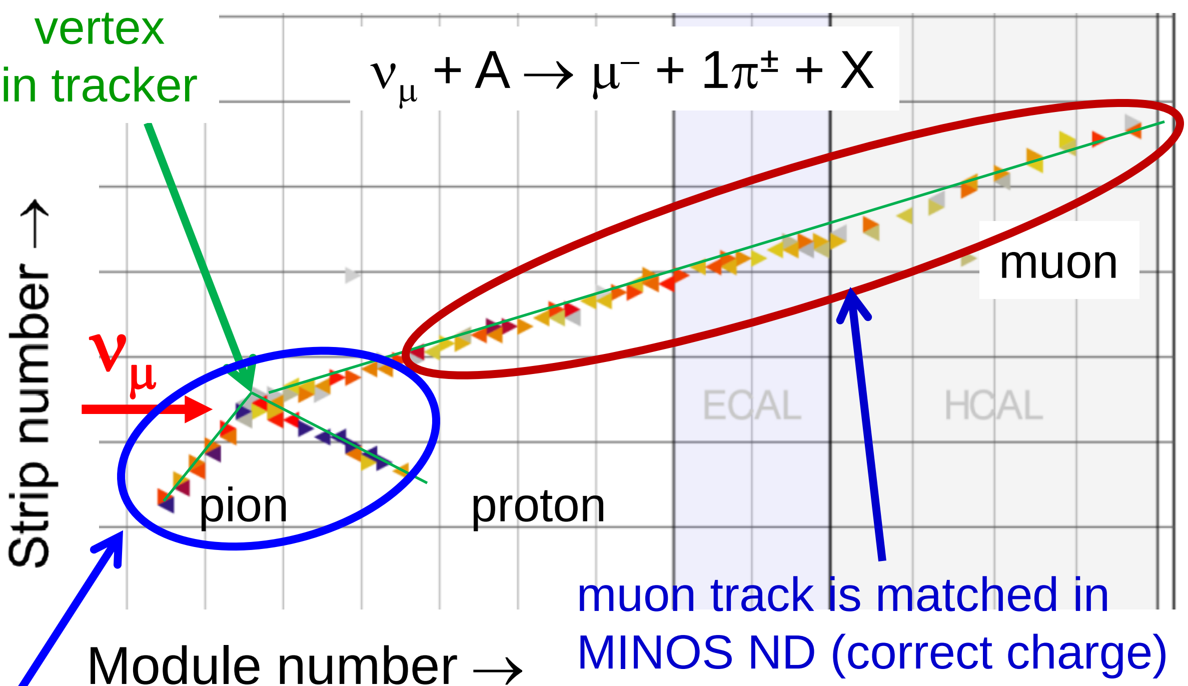
Single Pion Production

Recent single pion production data show tension with models

Proceeds mainly through a resonant channel (Δ^{++} or Δ^0)
Two ways to look at pion production

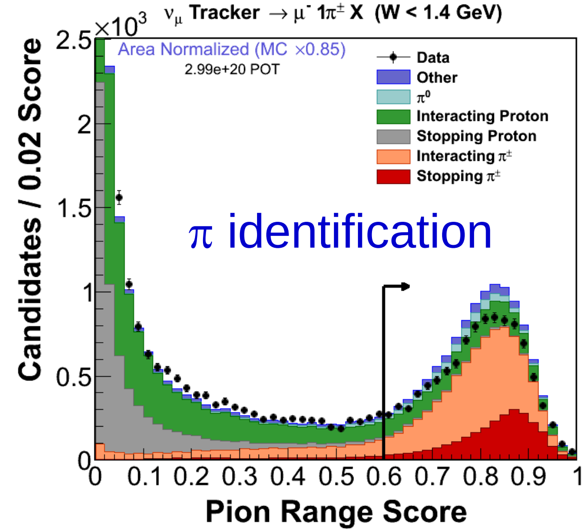
π^+ production by ν, π^0 production by anti-ν

Determine strength and nature of final state interactions using pion kinematics

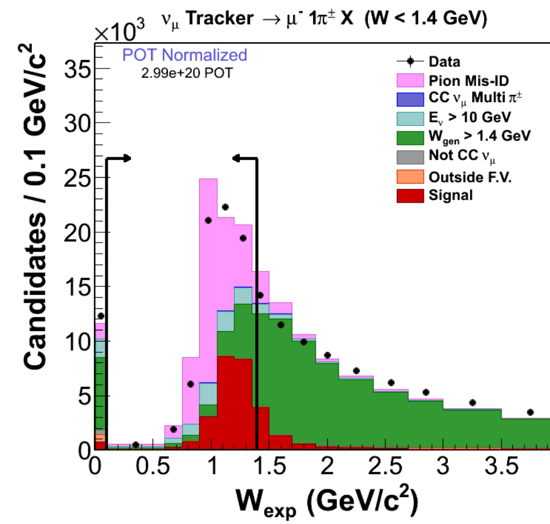


muon track is matched in MINOS ND (correct charge)

1-2 non-muon tracks at the primary vertex, but only 1 π



avoid high multiplicity
require W <1.4 GeV



Single Charged Pion Production Results

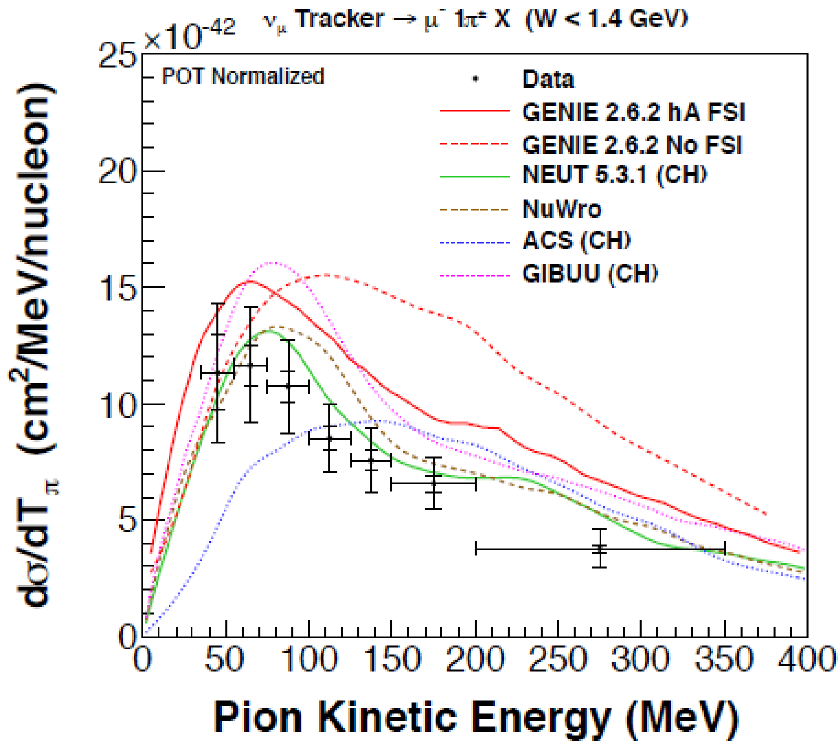
$$\nu_\mu + A \rightarrow \mu^- + 1\pi^\pm + X$$

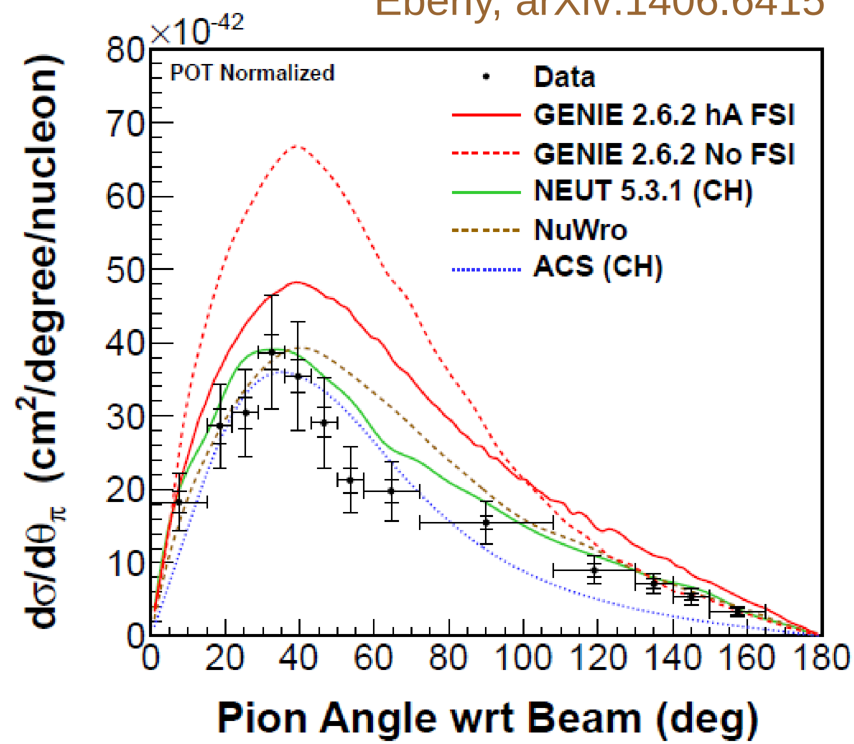
MINERνA data strongly prefers models with final state interactions
(shape equally described by all calculations with modern FSI, i.e. π rescattering)

Charged current pion production significantly lower than expected

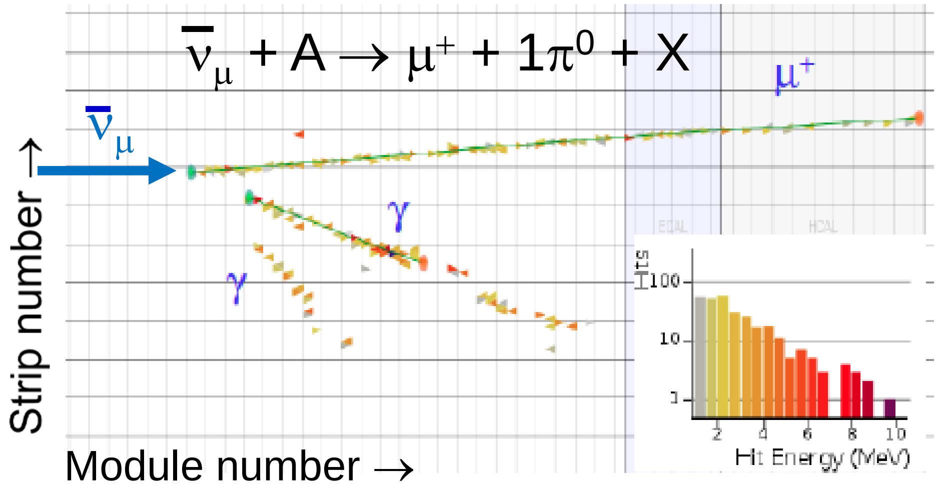
Important to characterize FSI effects for better understanding

Eberly, arXiv:1406.6415

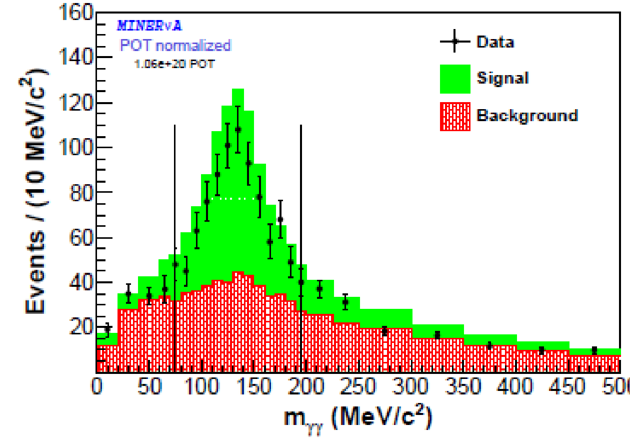




Single π^0 Production $\bar{\nu}_\mu + A \rightarrow \mu^+ + 1\pi^0 + A$



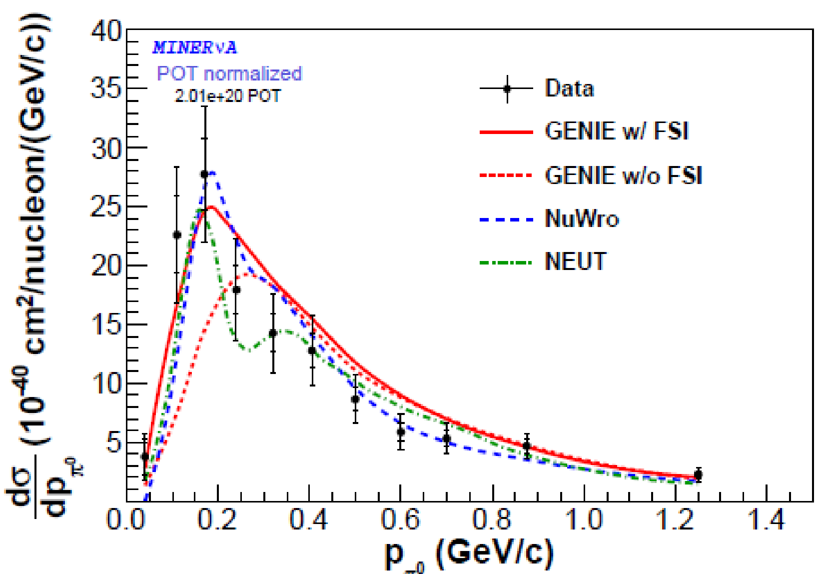
invariant $\gamma\gamma$ mass

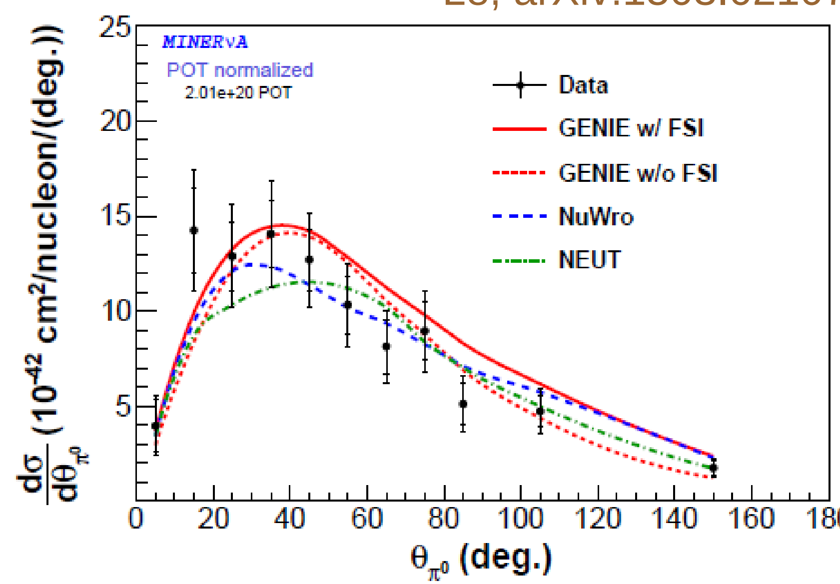


Acceptable agreement with most event generators

Data is in better agreement when final state interactions are included

Le, arXiv:1503.02107

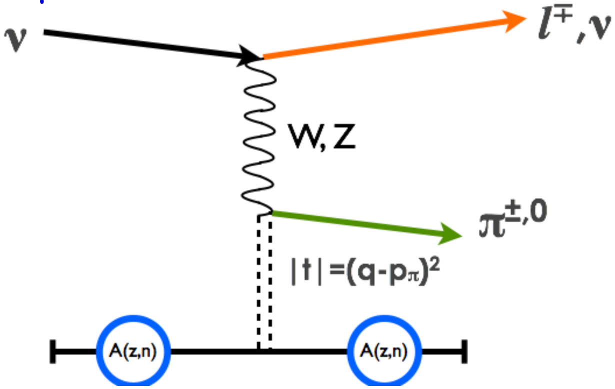


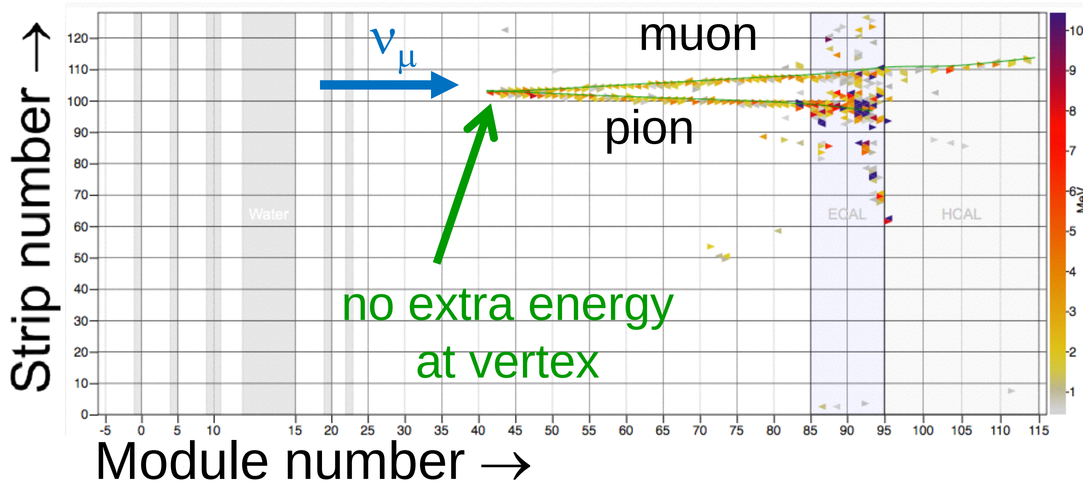


Coherent Pion Production

Higuera, PRL 113 (2014) 261802

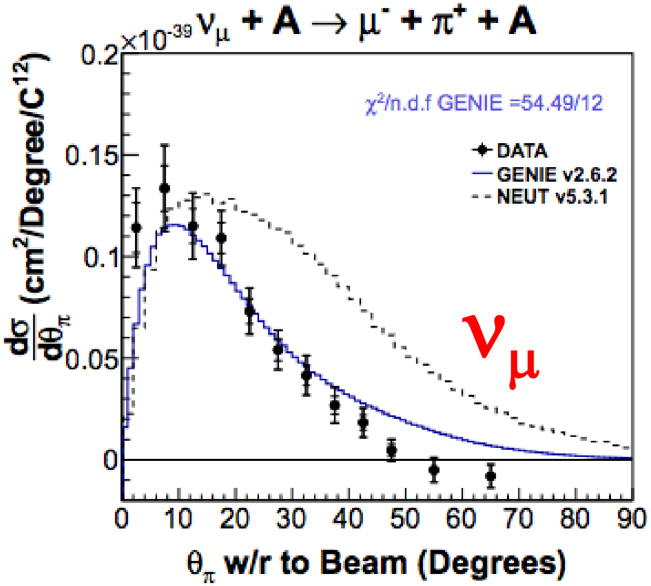
$\nu_\mu + A \rightarrow \mu^- + \pi^+ + A$

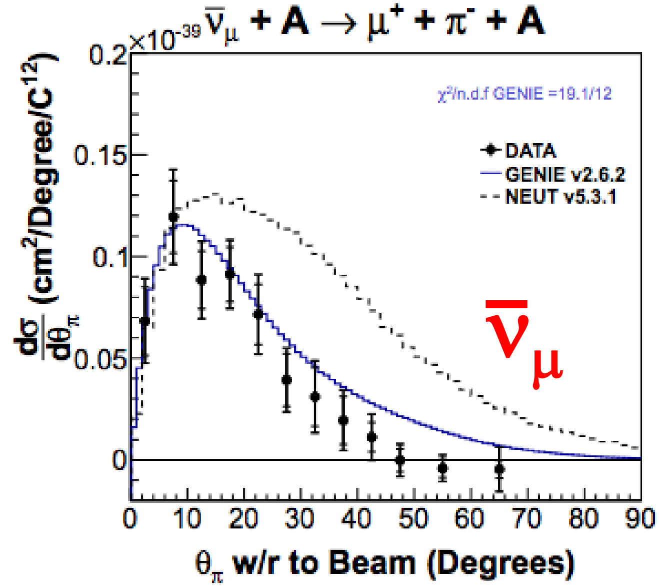




MINERνA sees clear evidence of coherent pion production for ν and $\bar{\nu}$ at E_ν ~3.5 GeV

MINERνA coherent pion kinematics disfavor current models.





Conclusions

MINERνA studies neutrino – nucleus interactions in the 1 – 20 GeV region over the transition region from exclusive states to DIS

MINERνA pion production data is being used by ν oscillation experiments to improve their predictions for their far detectors and reduce systematic errors

Still lots of Low Energy data for analysis

- Electron neutrino CCQE
- Kaon production
- Exclusive channels nuclear target ratios
- Double differential CCQE cross sections

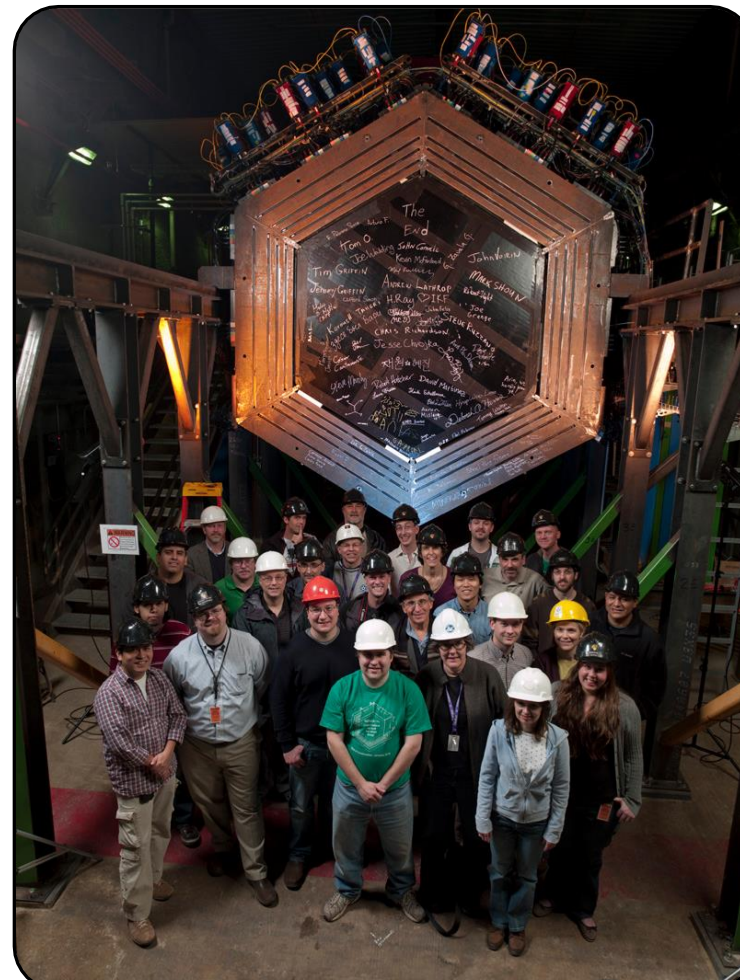
Learning how to make neutrino flux measurements in situ via ν – e el. scattering

Data taking with a "Medium Energy" ν beam started in fall 2013

- E_ν peak ~6 GeV
- already more POT than LE data taking
- new possibilities:
  - the higher neutrino beam allows access to the DIS region and quark dist.s
  - increased statistics gives nuclear target ratios for all interactions

The MINERνA Collaboration

~65 collaborators (from nucl. and part. physics)
~20 institutions



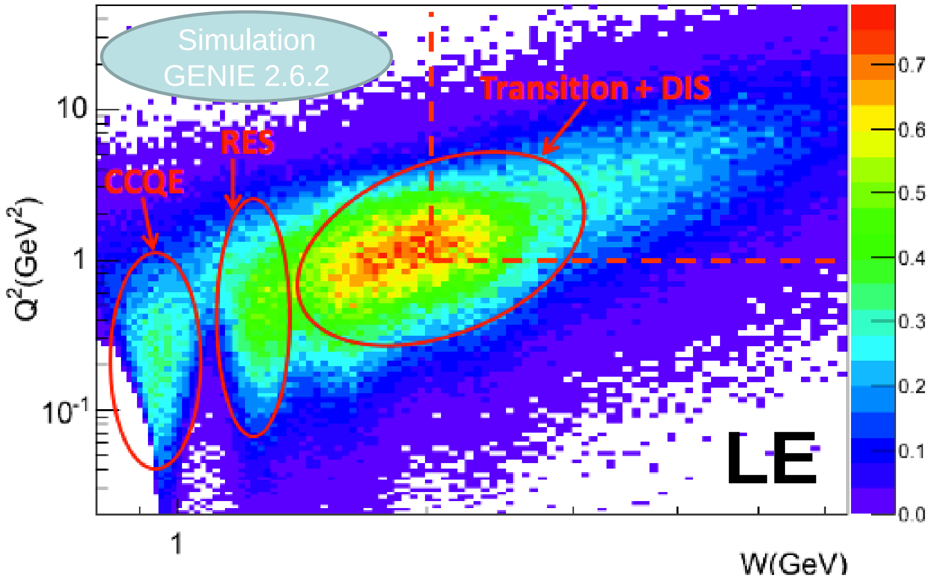
Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
UC Irvine, Irvine, CA
University of Chicago, Chicago, IL
Fermi National Accelerator Laboratory, Batavia, IL
University of Florida, Gainsville, IL
Université de Genève, Genève, Switzerland
Universidad de Guanajuato, Ganajuato, Mexico
Hampton University, Hampton, VA
Mass. Col. Lib. Arts, North Adams, MA
University of Minnesota-Duluth, Duluth, MN
Northwestern University, Evanston, IL
Oregon State University, Portland, OR
Otterbein College, Westerville, OH
University of Pittsburgh, Pittsburgh, PA
Pontificia Universidad Católica del Perú, Lima, Peru
University of Rochester, Rochester, NY
Rutgers University, Piscataway, NJ
Universidad Técnica Federico Santa María, Valparaiso, Chile
Tufts University; Medford, MA
Universidad Nacional de Ingeniería, Lima, Peru
College of William & Mary, Williamsburg, VA

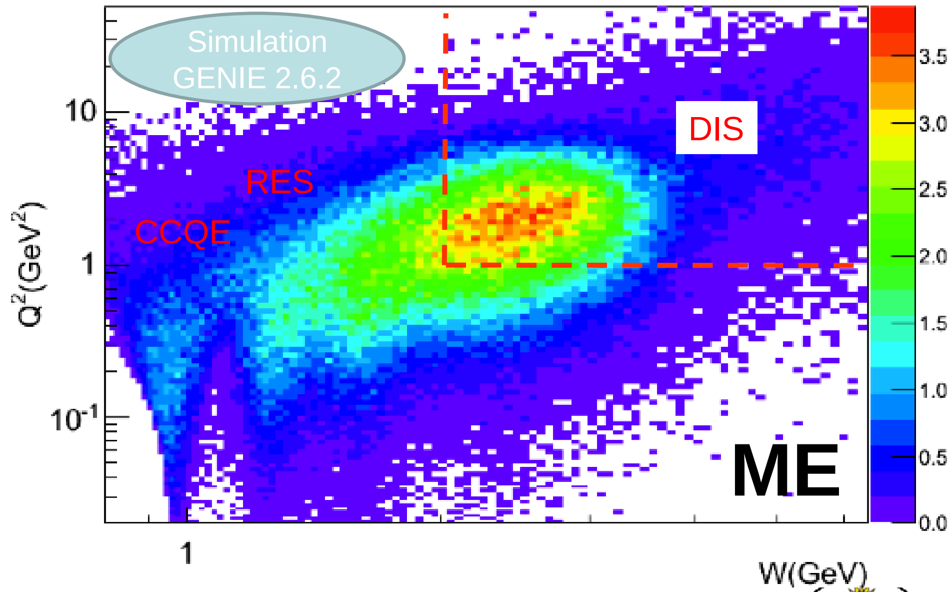
W – Q^2 Regions in LE and ME Beams

Hadronic Invariant Mass (W) range and Q^2 both shift up

kinematical distributions from GENIE v2.6.2 simulation
events shown have muon tracked in MINOS
LE $\rightarrow$ ME: observe shift to lower *x*, fewer quasi-elastic and resonance events

z axis : 10^3 events / 3 x 10^3 kg of C / 5e20 POT





CCQE with Observed Proton

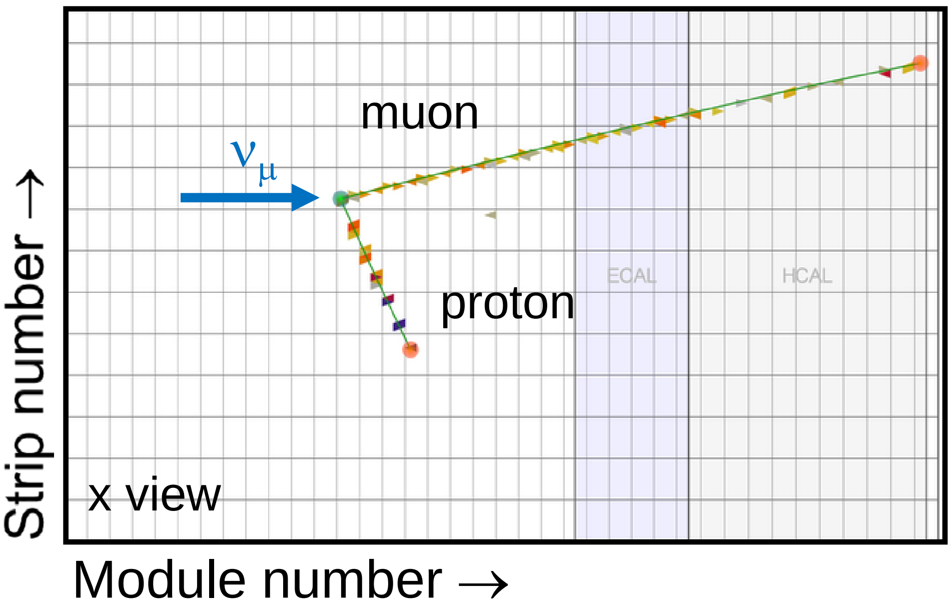
Use the muon and proton kinematics to study the nuclear effects and FSI

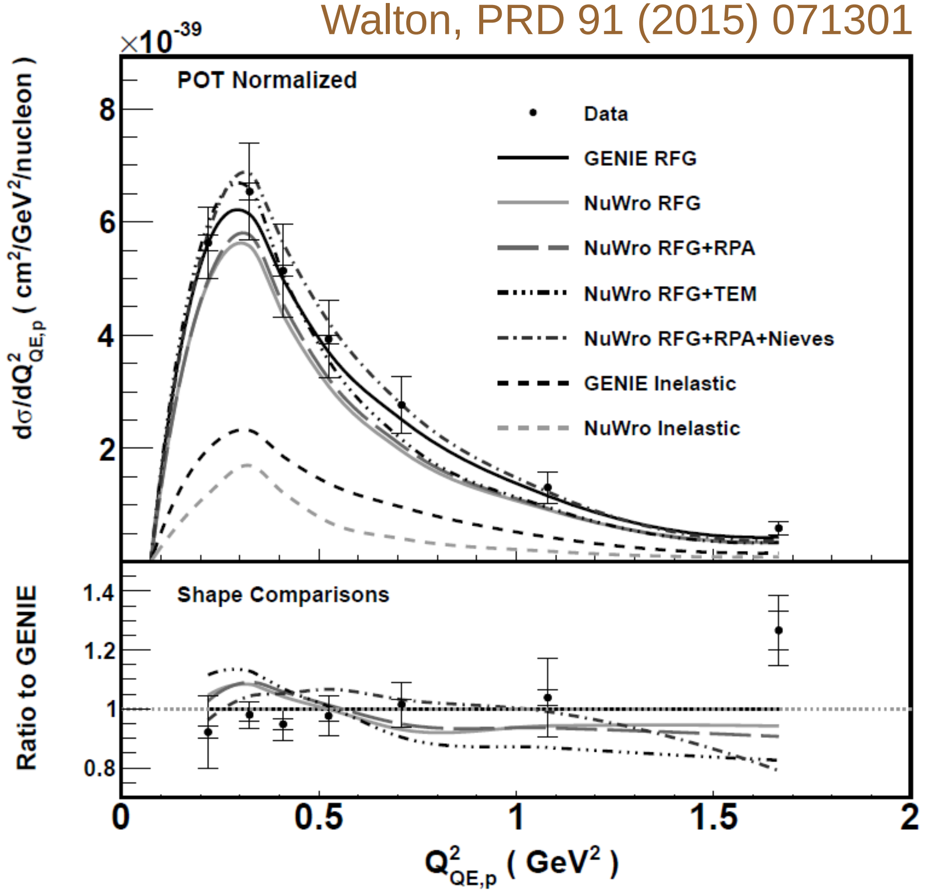
Reconstruct both the muon and proton tracks (no other track in event)

Event kinematics (Q^2 !) reconstructed using the proton track only

Signal defined as "CCQE-like" event: quasi-elastic and inelastic w/o pions components

Walton, PRD 91 (2015) 071301





best model for μ kinematics (RFG + TEM) is not the same as the one that best describes the protons (standard RFG)