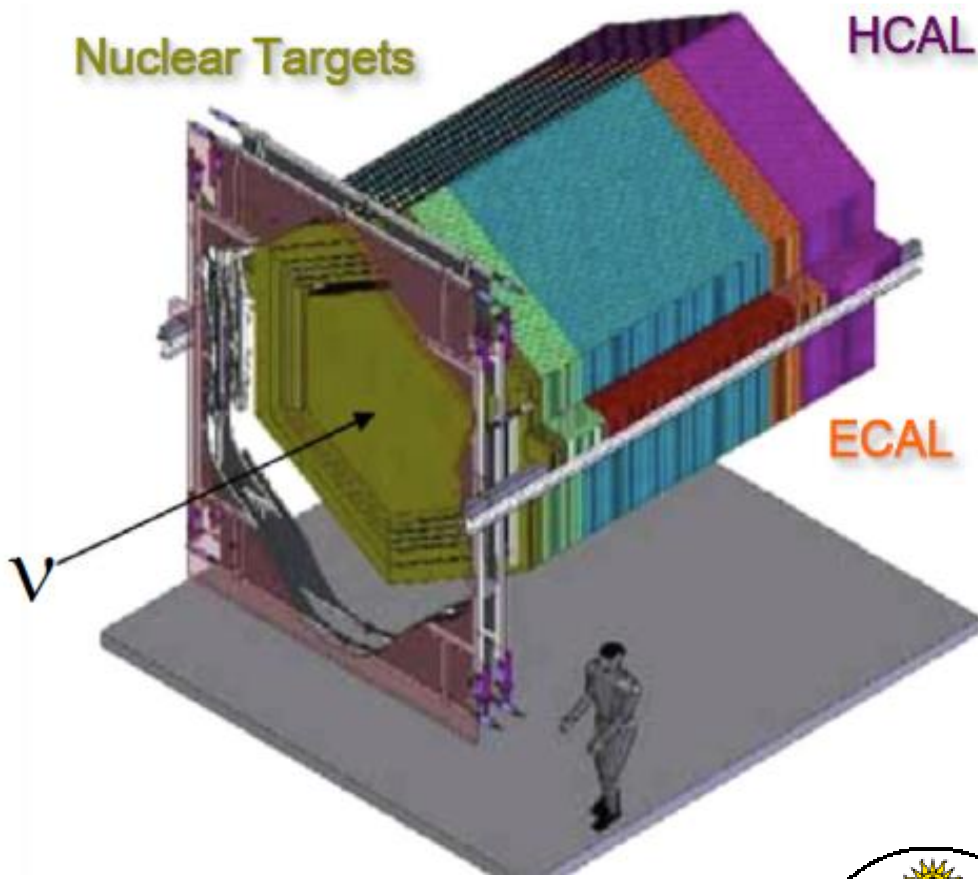
MINERνA Cross Sections



what is MINERνA ?

why MINERνA ?

ν beam and ν flux

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

nuclear effects

NuFACT2017
Uppsala
26 Sept. 2017

Alessandro Bravar
Université de Genève
for the Minerνa Collaboration

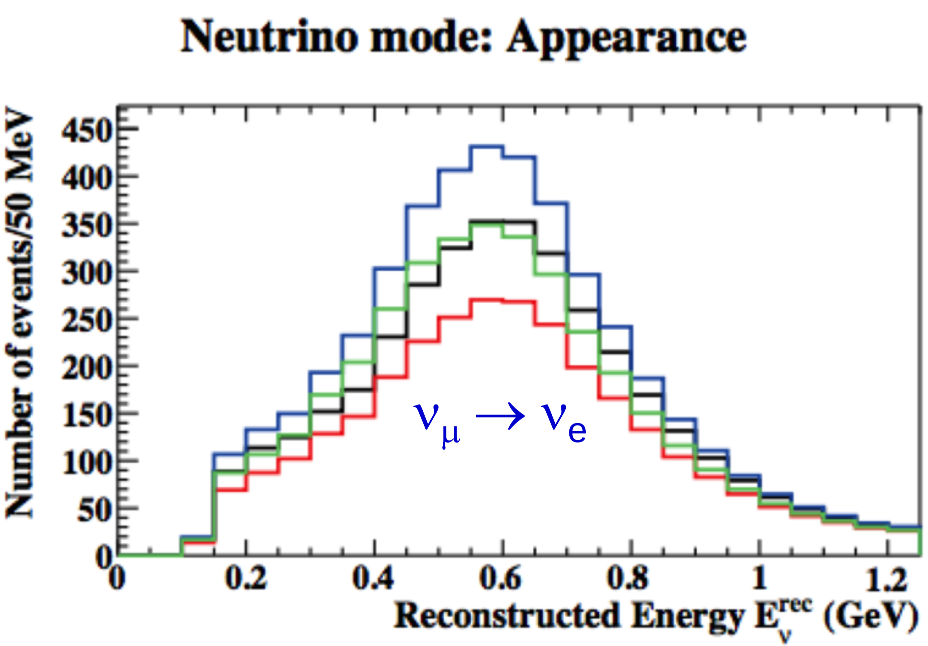
Neutrino Oscillation Measurements

Ambitious plans for new oscillation experiments: expect 1000's of events

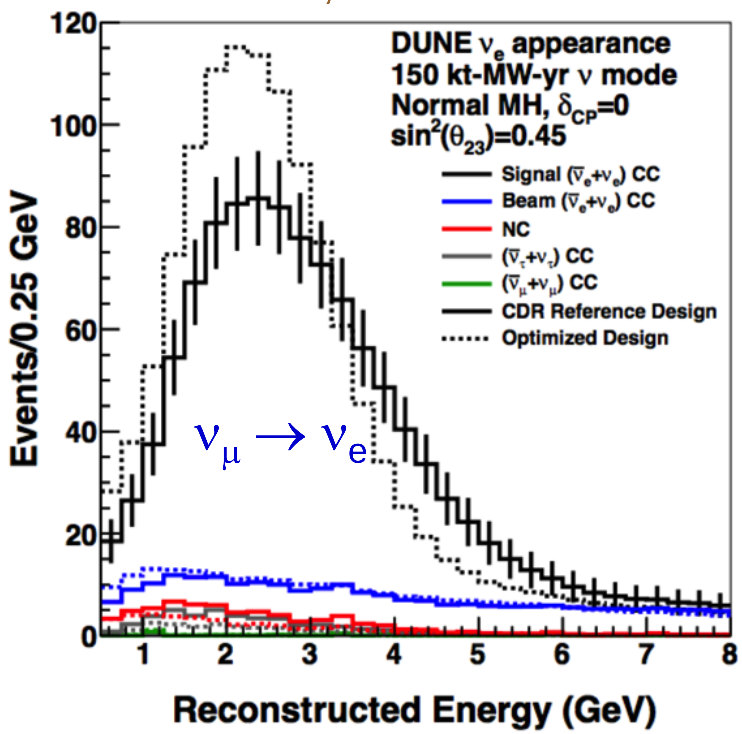
- Because of "large" mixing angles, will be looking for small differences in oscillation probabilities between neutrino and antineutrino mode
- Neutrino Energy is a big part of extracting oscillation parameters
- How a neutrino's energy shows up in a detector is an important effect both for Water-Cherenkov and "fully active" detectors:

in general E_{rec} not equal E_ν

Hyper-K, arXiv:1412.04673



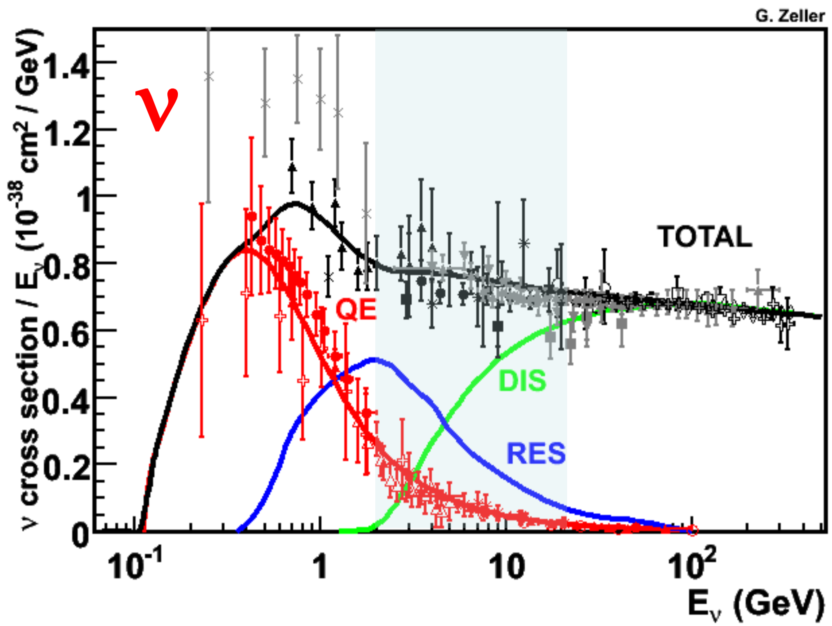
DUNE, arXiv:1512.06148

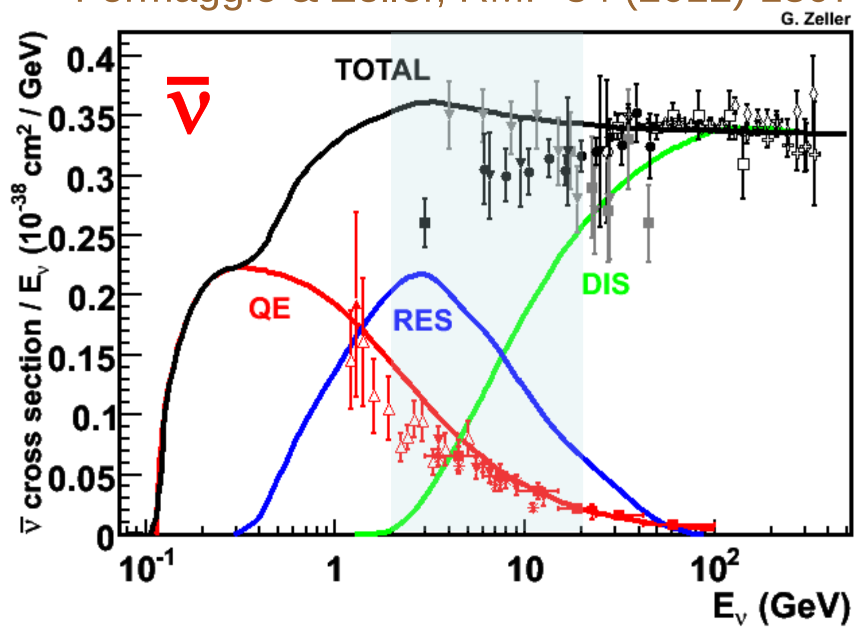


ν $\times$-sections

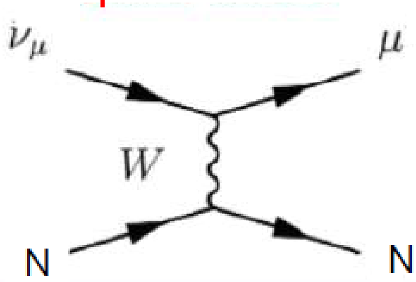
MINERνA measures ν – N interactions in the transition region from exclusive states to DIS

Formaggio & Zeller, RMP 84 (2012) 1307

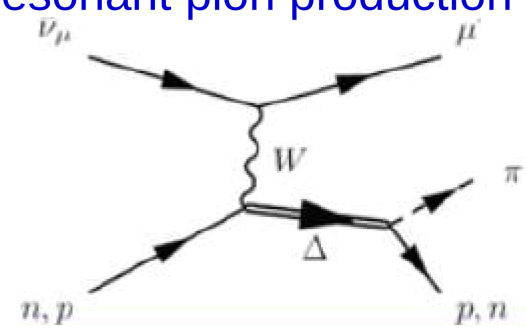




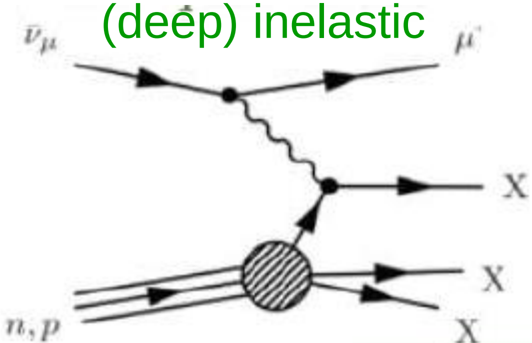
quasi-elastic



resonant pion production



(deep) inelastic

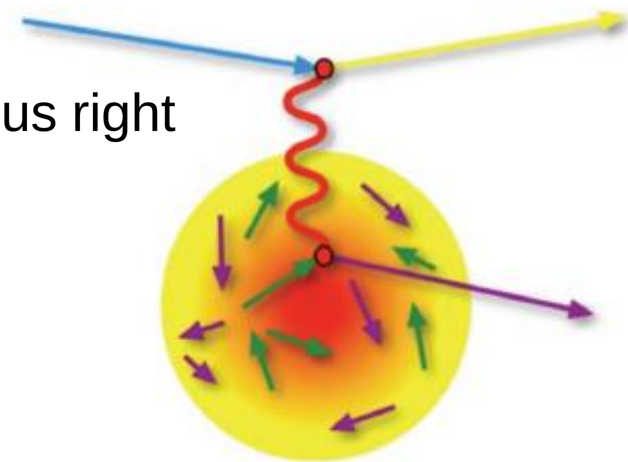


elastic

inelastic

increasing E$_\nu$, Q^2

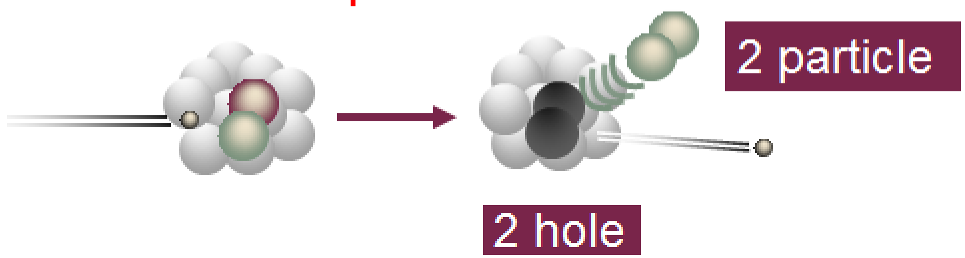
Don't Forget the Nucleus!



The nucleus is a complicated object …

First you have to get the nucleons inside the nucleus right

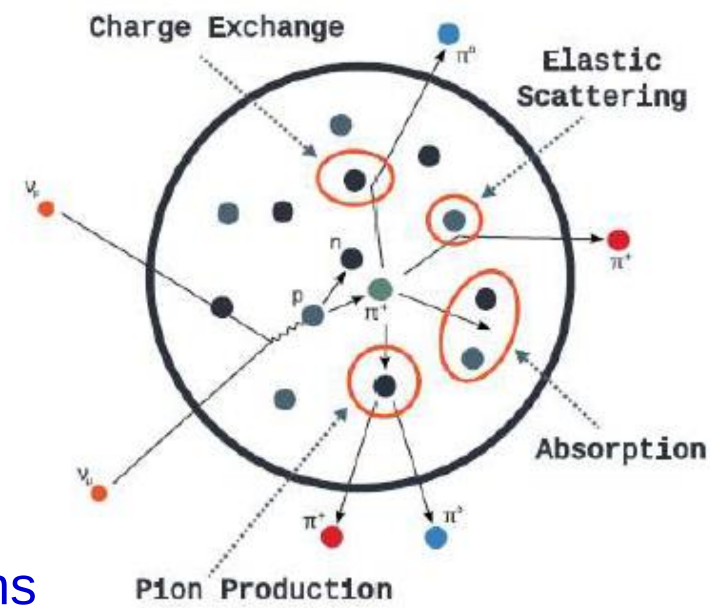
- Fermi motion
- short range correlations and
- medium range correlations
  - scatters off a pair of correlated nucleons – 2p2h effect



- long range correlations – RPA effect

Then you have to get right how created particles work their way out throug the nucleus

- final state interactions



big source of uncertainties in neutrino interactions

Minerνa tries to provide information on all these effects

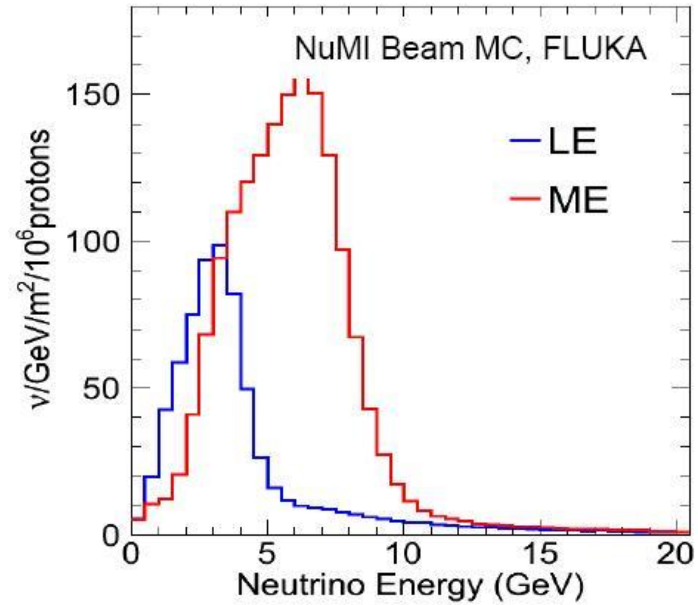
MINERνA's "Input"

existing data (~1 – 20 GeV) still not fully understood

- low statistics samples
- large uncertainties on neutrino flux

oscillation analyses need detailed understanding of ν_μ , ν_e , $\bar{\nu}_\mu$, $\bar{\nu}_e$ x-sections

- Broad Range of Neutrino Energies
  - this gives a broad range of interaction channels
  - able to measure ν_μ and ν_e



- Capable detector
  - fully active
  - low thresholds, good particle identification

- High intensity Neutrino Beam
  - provides high statistics, but…
  - need good flux constraints too

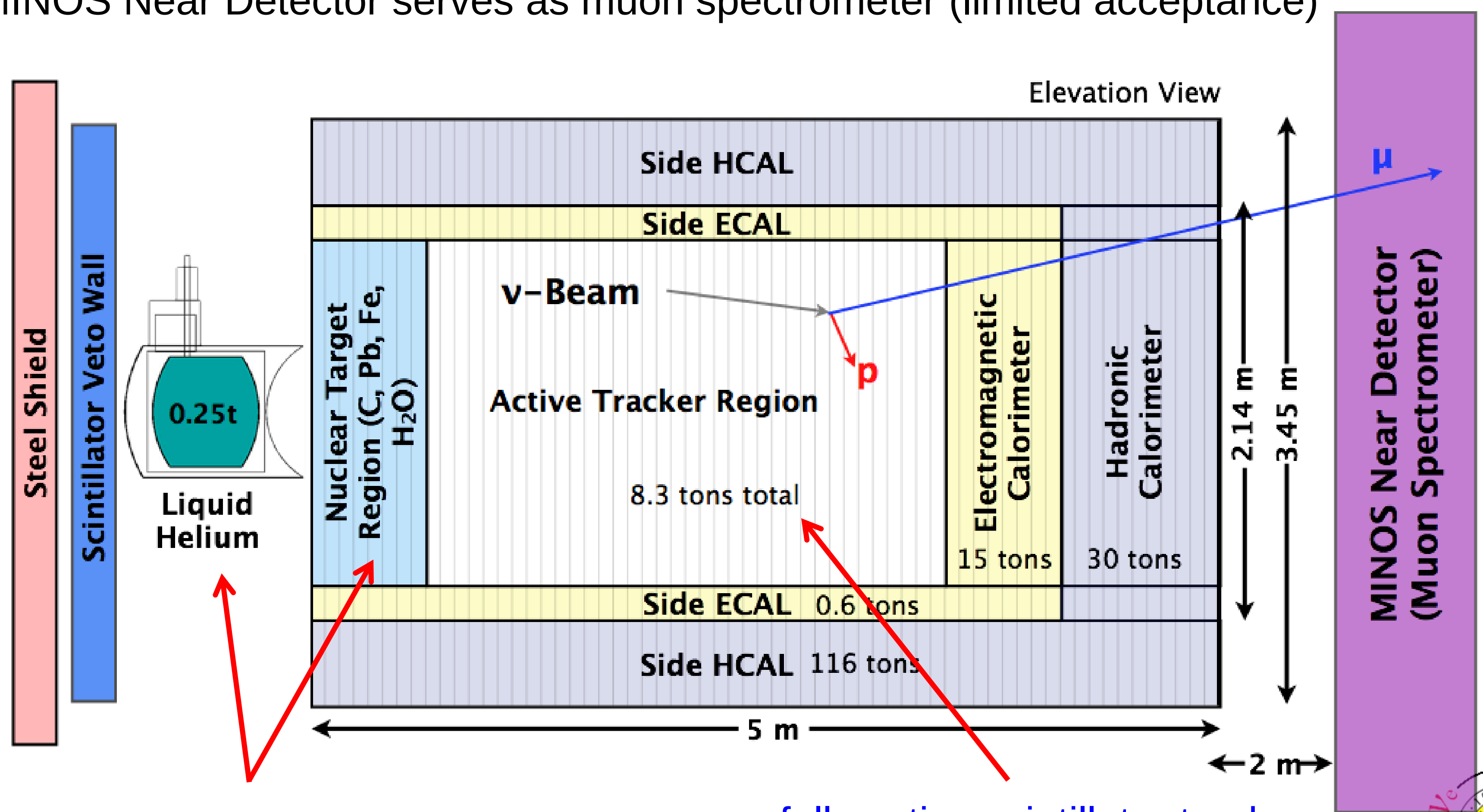
- Broad Range of Target Nuclei
  - to constrain both the nucleon-level processes and the role of the nucleus

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)

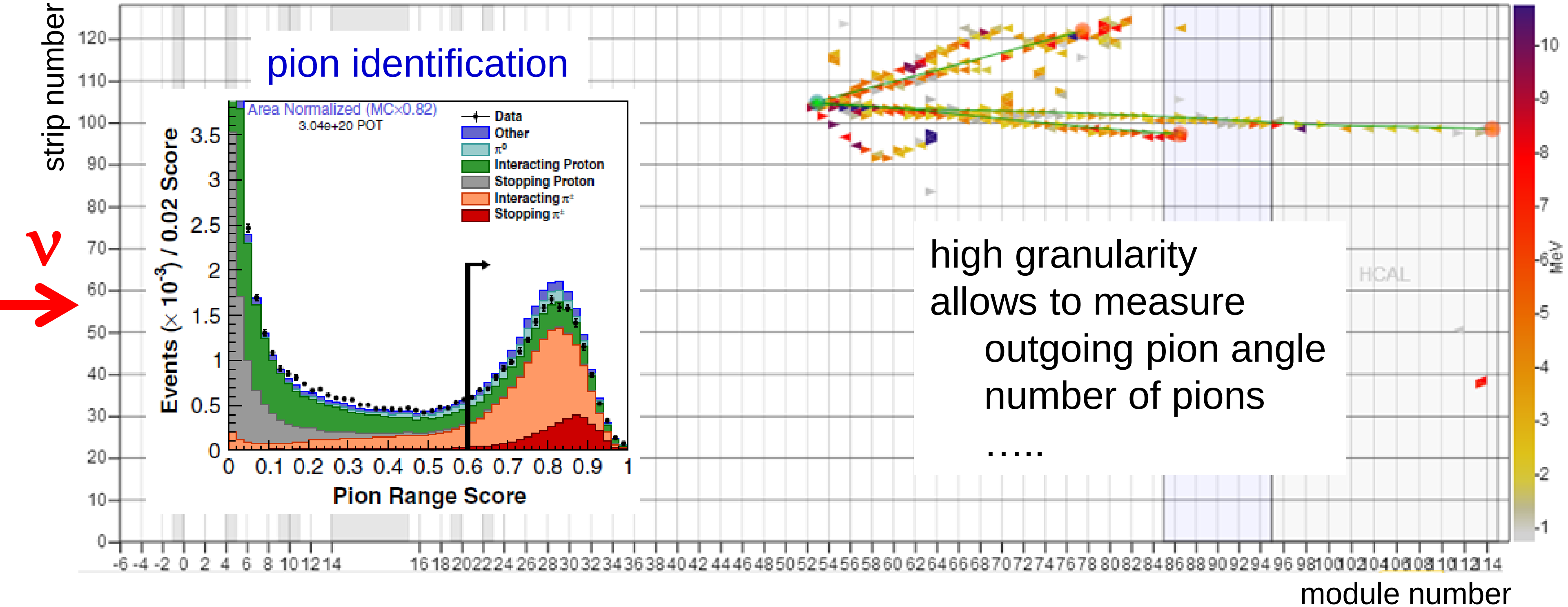
MINOS Near Detector serves as muon spectrometer (limited acceptance)



nuclear targets: He, C, $H_2$0, Fe, Pb in the same neutrino beam

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

MINERνA Event Display



Identification of outgoing muon track

Vertex activity

Identification of charged particles (p, $\pi^\pm$, K, e^-) and π^0, γ

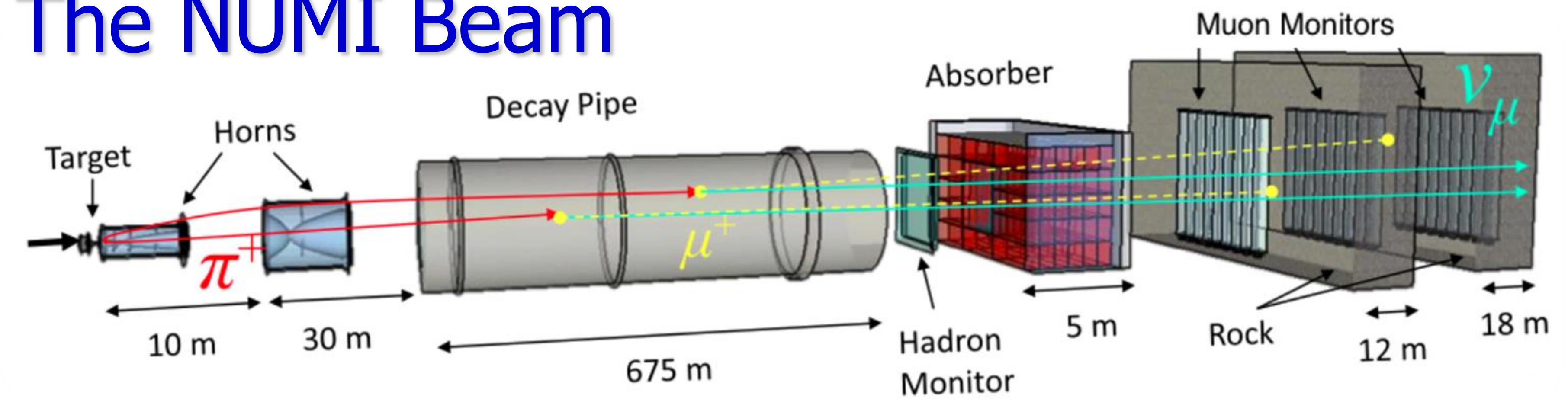
Calorimetric reconstruction of recoil energy

$$\boxed{\text{calorimetric } E_{\text{recoil}} = \alpha \times \sum_i c_i E_i}$$

$$\boxed{E_\nu = E_\mu + E_{\text{hadronic}}}$$

More selective identification of events

The NUMI Beam



NuMI (Neutrinos at the Main Injector)

- 120 GeV protons from Main Injector
- 2 focusing horns
- 675m long decay region
- beam power ~650 kW

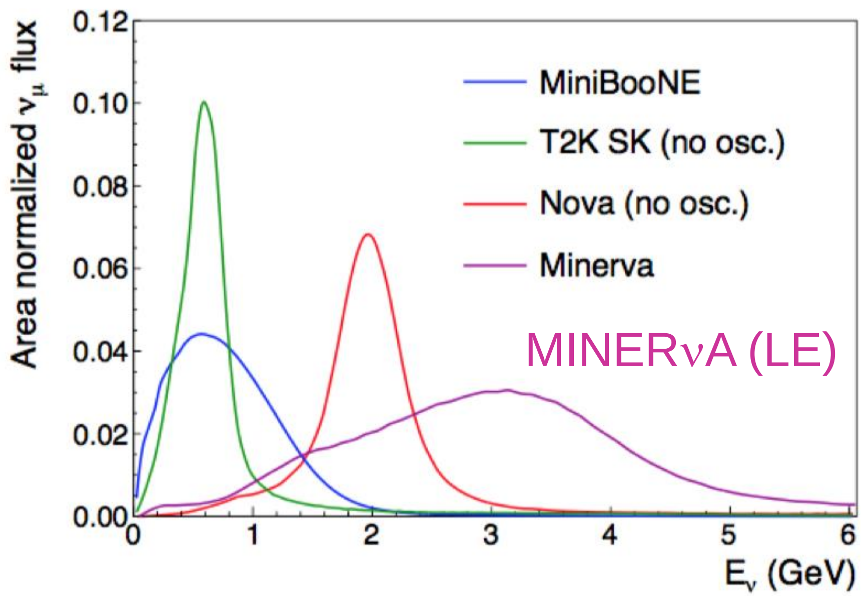
By changing beamline configuration one can modify the ν spectrum:

LE (peak ~3 GeV) → ME (peak ~6 GeV)

LE data taking completed in 2012 (ν and $\bar{\nu}$)

since 2013 running in ME mode,

now in $\bar{\nu}$ mode



MINERνA can see processes relevant for ν oscillation experiments from T2K to ICECUBE

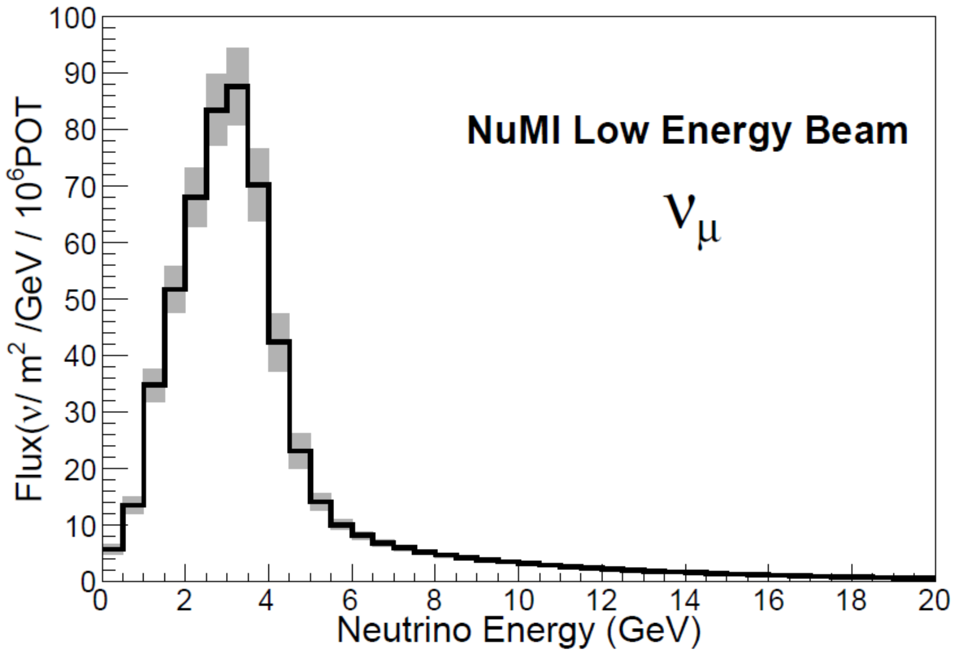
Low Energy ν Flux and Uncertainties

Extensive revision of the NuMI beamline simulation

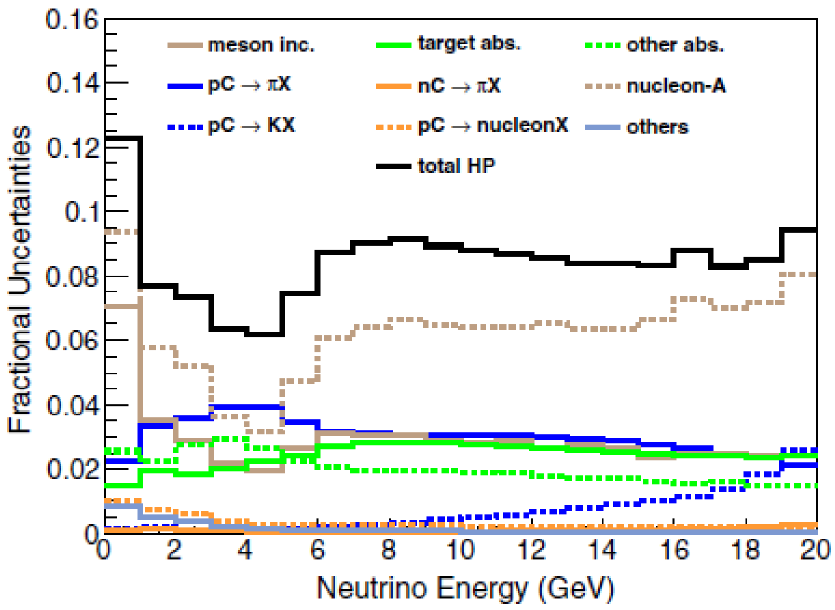
Aliaga et al., PRD94 (2016) 092005

Flux determination

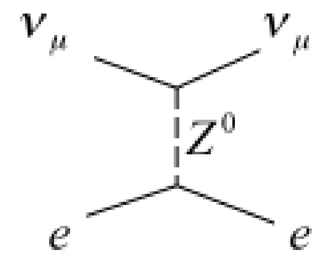
- external hadron production data
- ν – e elastic scattering
- low–ν extrapolation
- special runs (vary beam configuration)



hadro-production uncertainties



Flux from ν-e Elastic Scattering

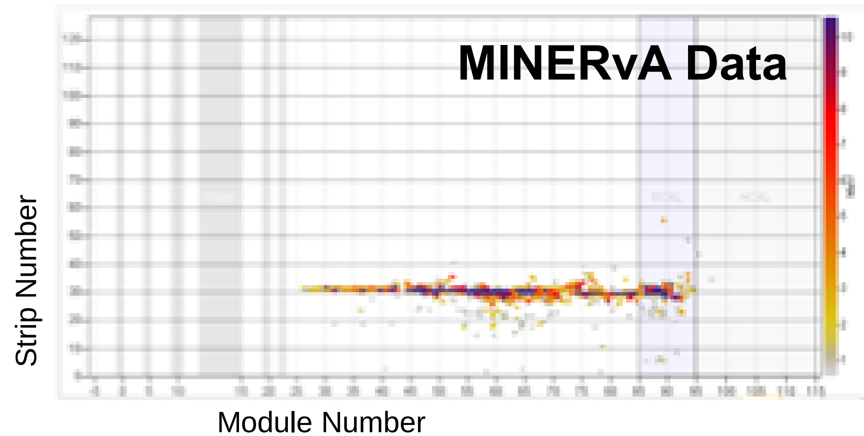


Signal is a single electron moving in beam direction

- Purely electro-weak process
- x-section is smaller than nucleus scattering
  - by ~2000
- 123 ±17(stat) ±9(syst) events

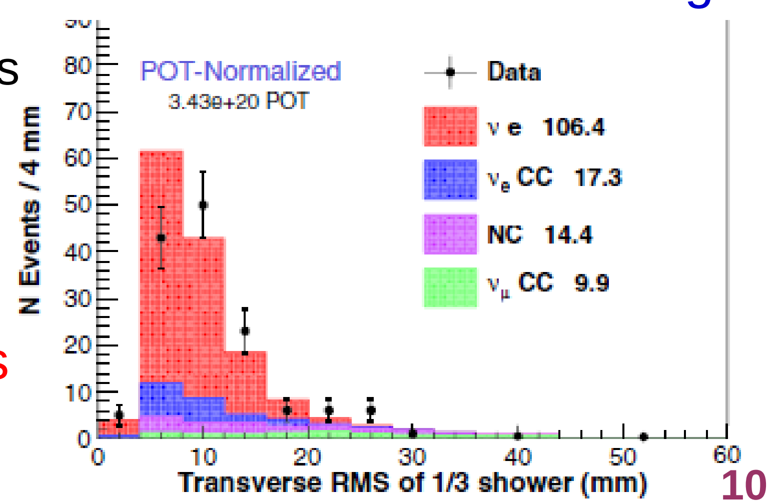
Independent *in situ* flux constraint

- Important proof of principle for future experiments
- Statistically limited in the MINERvA LE sample (~8% error)
- Results are consistent with new flux calculations
- Results are consistent with the *a priori* flux (~2%) and with the low ν flux



Park et al., PRD 93 (2016) 112007

in situ νe elastic scattering



3 independent methods yield consistent results

Further confidence in flux!

Low-ν Method

Charged-current scattering with low hadronic recoil energy ν (sub-set of all events) is flat as a function of E_ν

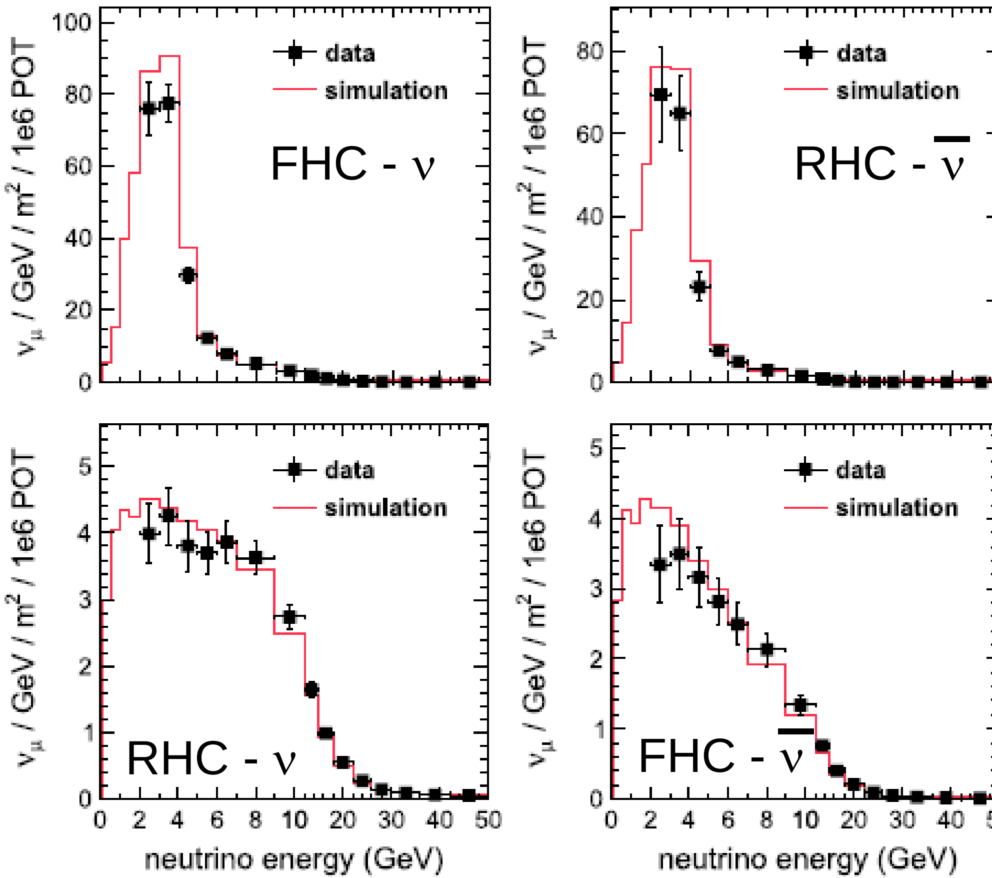
$$\frac{d\sigma}{d\nu} = A\left(1 + \frac{B}{A}\frac{\nu}{E_\nu} - \frac{C}{A}\frac{\nu^2}{2E_\nu^2}\right)$$

where A, B, and C depends on integrals overs structure functions

Gives a measurement of the flux shape

Flux is normalized so that the extracted inclusive cross section matches an external measurement at high neutrino energy

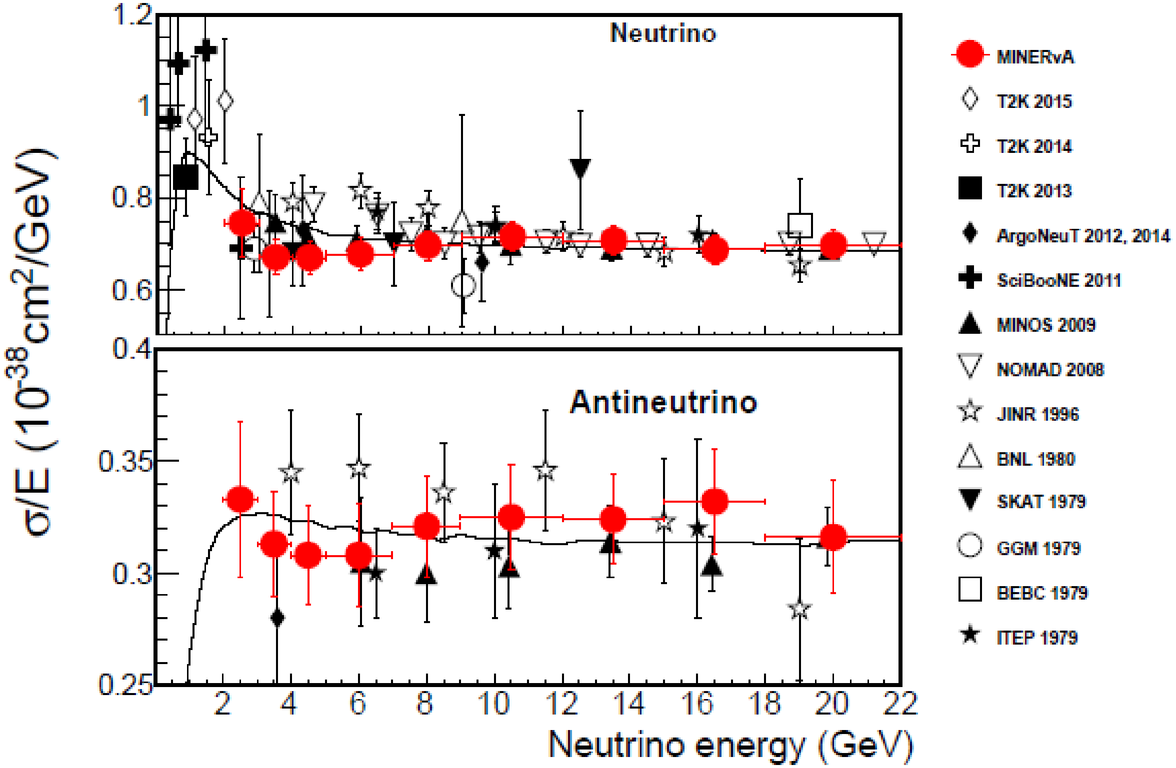
Devan et al., PRD94 (2016) 112007

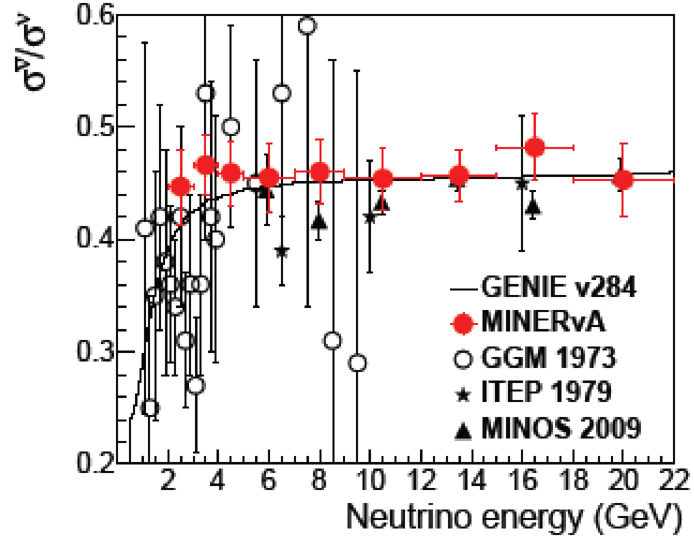


low ν-flux compared to flux simulations

ν and $\bar{\nu}$ CC Interaction $\times$-sections

Ren et al., PRD95 (2017) 072099

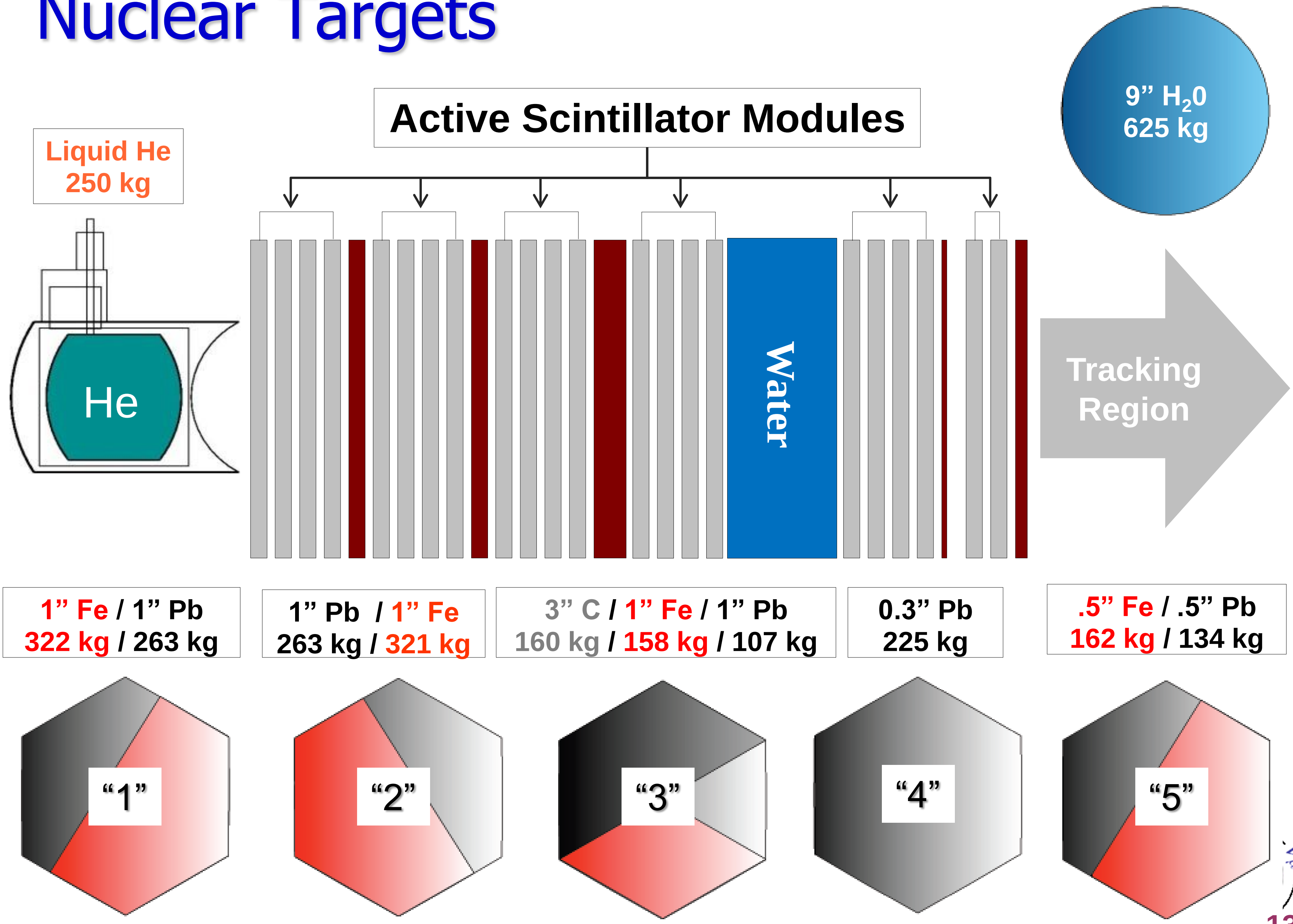




reference curve shows the prediction of GENIE 2.8.4

GENIE and NuWro generators slightly overestimate the measured CC cross sections at low E_ν

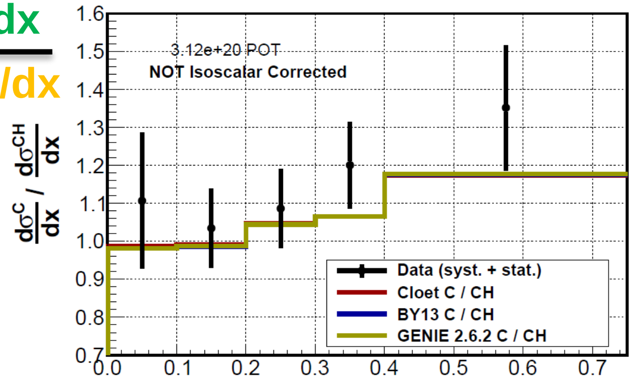
Nuclear Targets



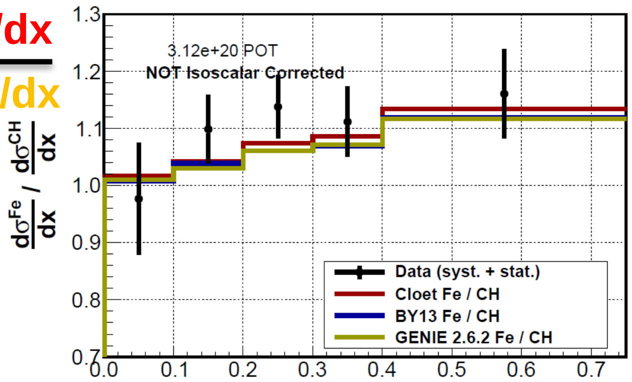
DIS Cross Section Ratios – $d\sigma / dx_{Bj}$

Mousseau et al., PRD93 (2016) 071101

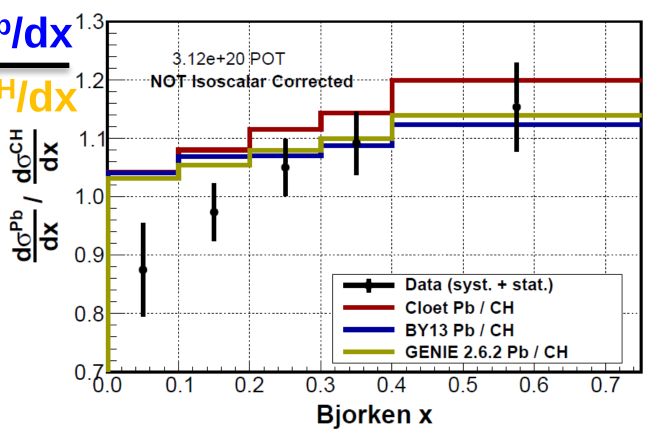
$\frac{d\sigma^{C}/dx}{d\sigma^{CH}/dx}$



$\frac{d\sigma^{Fe}/dx}{d\sigma^{CH}/dx}$



$\frac{d\sigma^{Pb}/dx}{d\sigma^{CH}/dx}$



DIS selections

- $Q^2 > 1$ GeV^2
- $W > 2.0$ GeV
- 5 GeV < E_ν < 50 GeV (HE tail of LE beam)

Unfolded x (detector smearing)
Not corrected for n excess (isosclar correction)

"Simulation" based on nuclear effects observed with electromagnetic probes

Observe no neutrino energy dependent nuclear effect

In EMC region ($0.3 < x < 0.7$) agreement between data and models

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

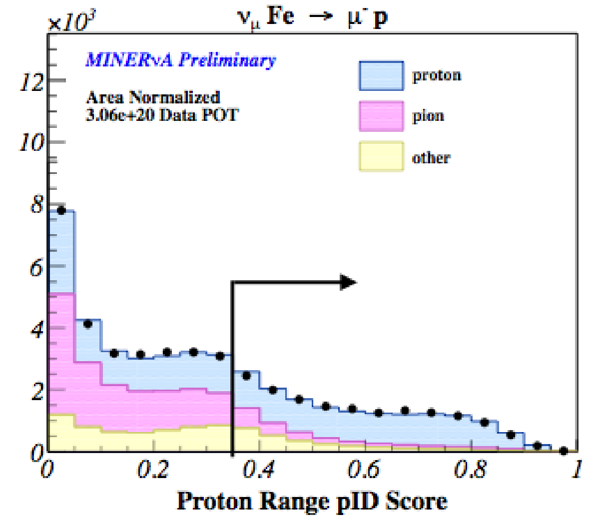
CCQE-like on Nuclear Targets

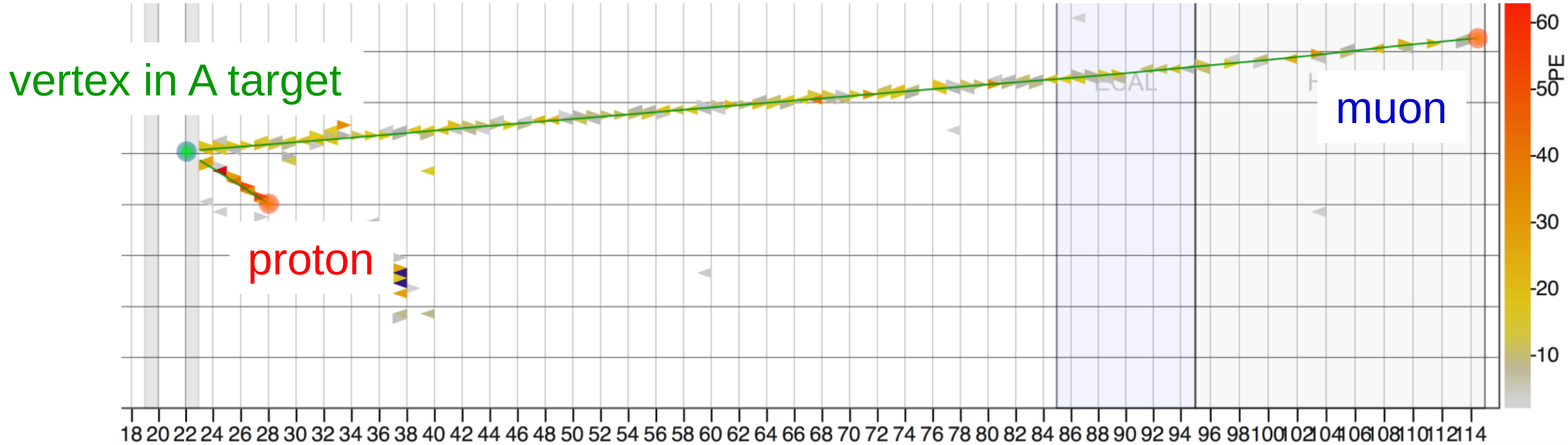
see also C. Patrick's talk on Friday

Study nuclear effects (A-dependence) mainly from FSI

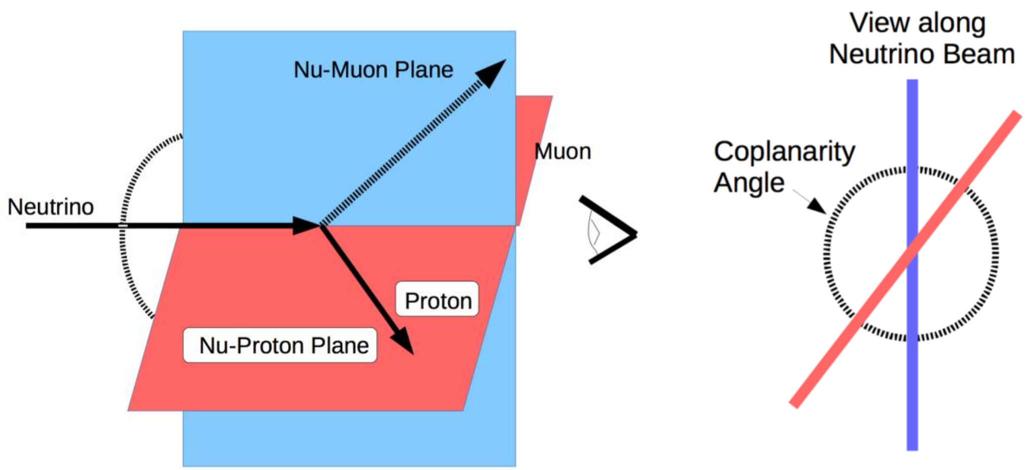
Event selections:

- At least two tracks
- Reconstructed vertex is in the "nuclear" target
- One muon
- Select events with a proton candidate, p > 450 MeV/*c*
- No pions
- Dominant background from resonance production (30%) an DIS (10%) (tune the background while keeping the signal constant)





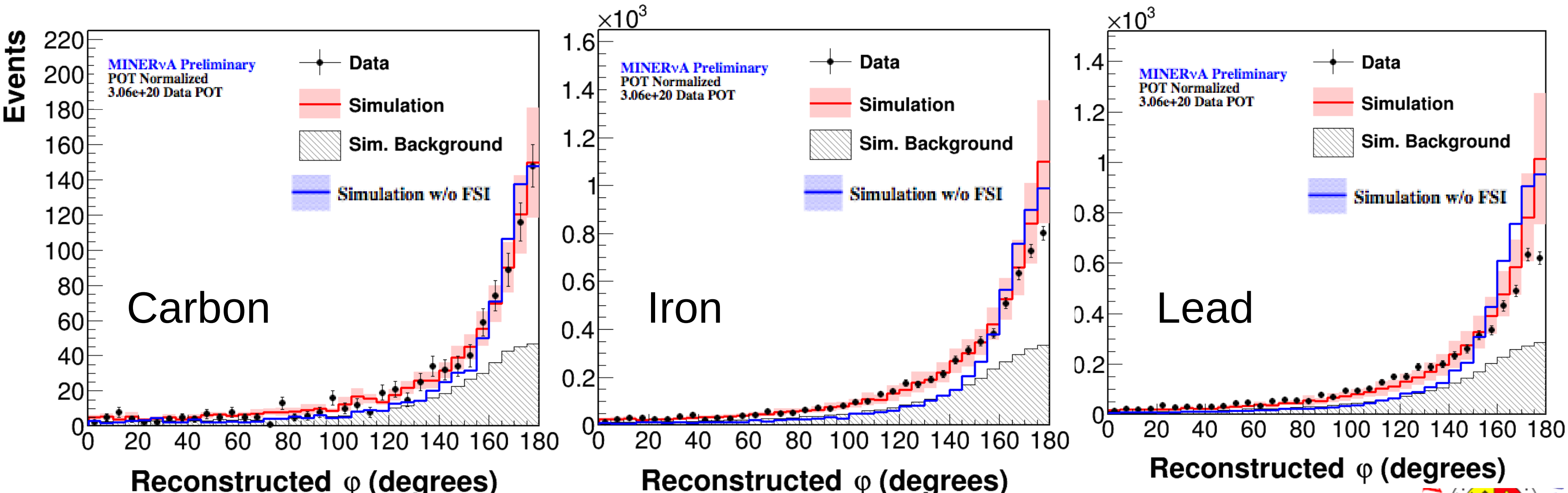
CCQE Event Coplanarity on C, Fe, Pb



ϕ: Coplanarity

180º for proton at rest
and 2-body interaction
and no final state interactions

Betancourt et al., PRL119 (2017) 082001



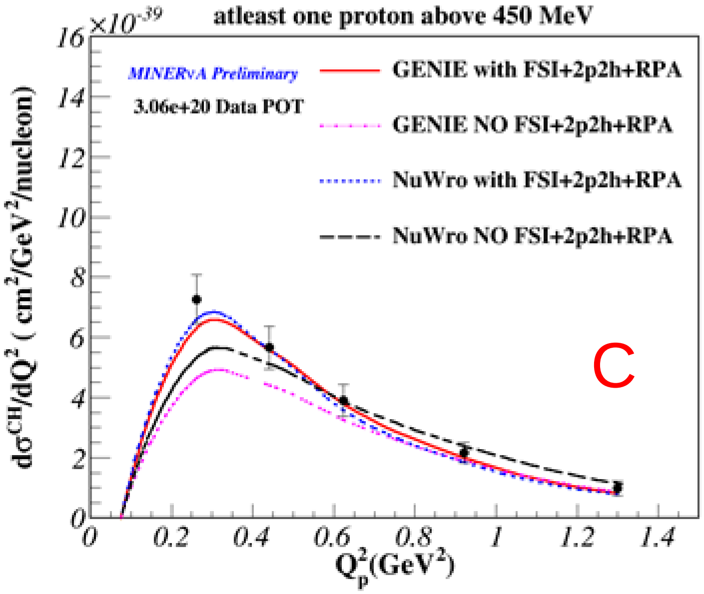
Data/MC discrepancy increases with A

CCQE Cross Sections on C, Fe, Pb

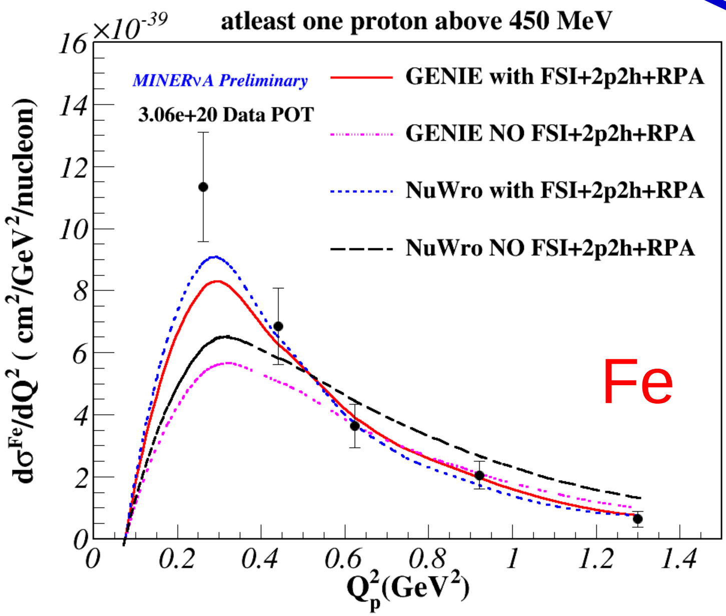
Just because a model gets carbon right does not imply that it gets higher A right

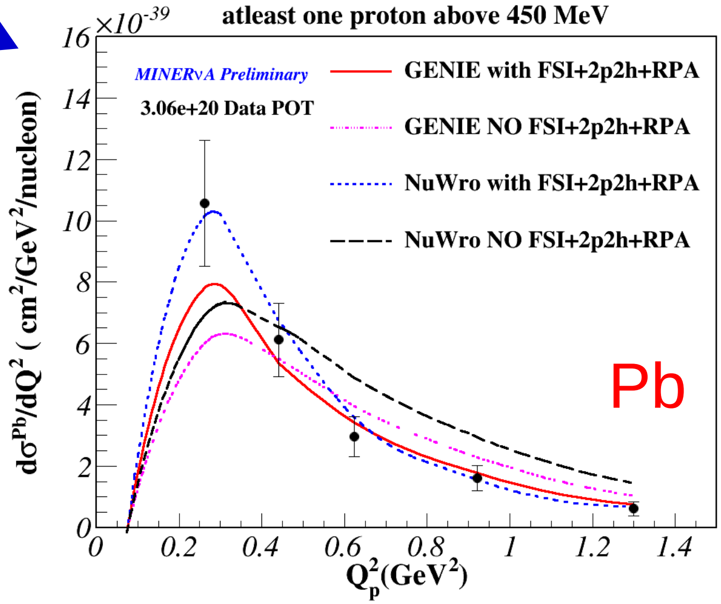
Need to get nuclear effects of primary int. AND final state Interactions correct

Lead data prefers A dependence in NuWro model



Betancourt et al., PRL119 (2017) 082001





Q^2 from the leading proton in the event

A New Way to Study CCQE Interactions

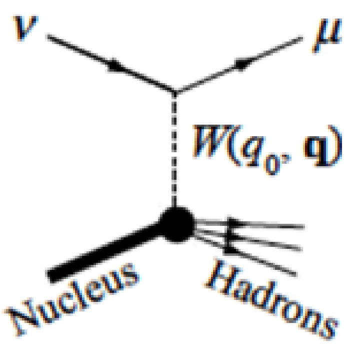
Look at inclusive scattering in 2 kinematic dimensions

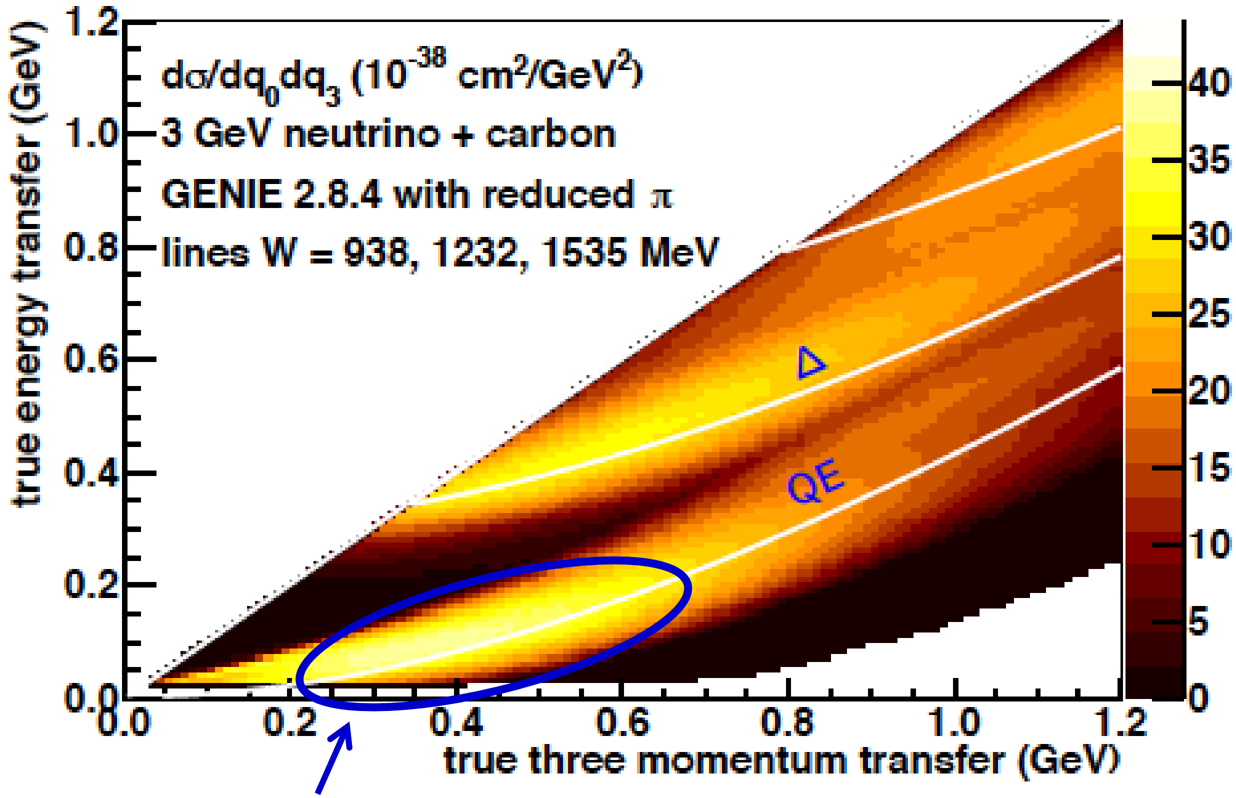
Separate Q^2 into energy transfer q_0 and 3-momentum transfer q_3

(do not cut on the recoil but look at the low recoil in an inclusive sample)

bands in the q_0 – $\mathbf{q}_3$ plot show different scattering channels

(dσ / dQ^2 integrates across the “bands” hiding the details)





N(1535)

Δ Resonance

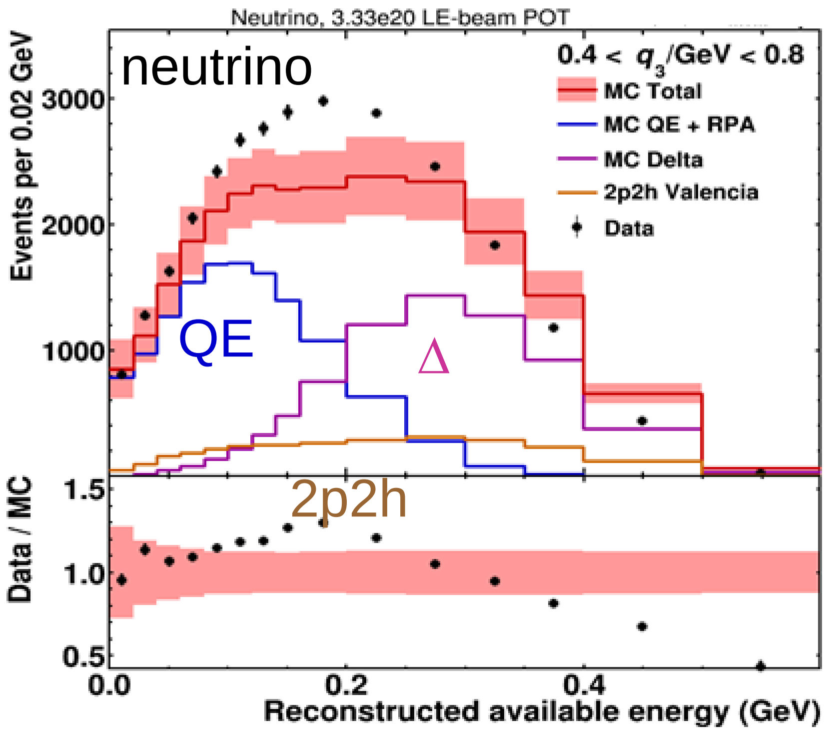
quasi-elastic

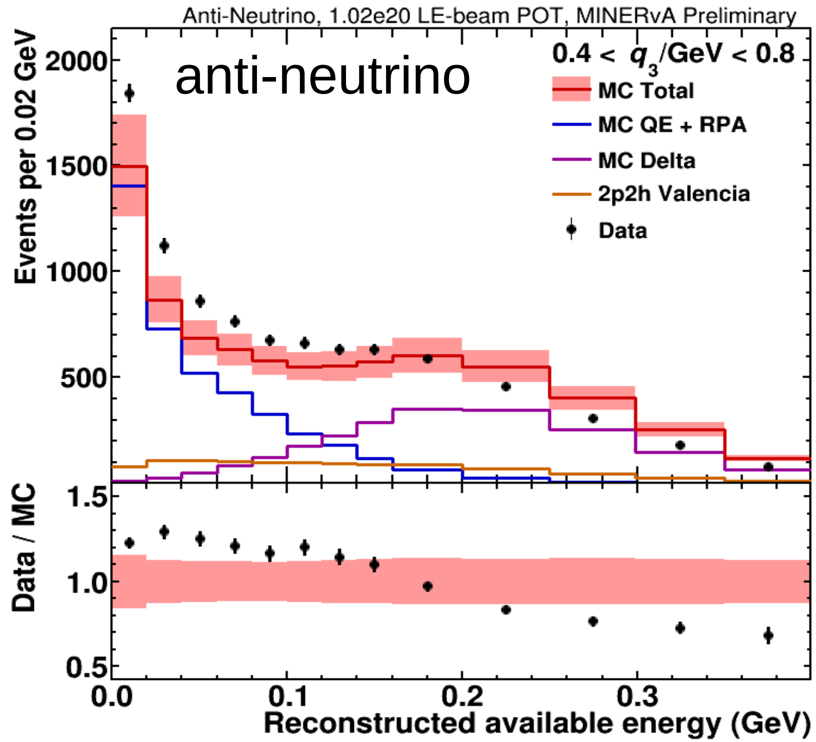
models of scattering off two nucleons
tend to increase the cross-section in this area

ν_μ CCQE Data in the $(q_0 - q_3)$ Plane

Rodrigues et al., PRL116 (2016) 071802

Gran, NuINT17





$$E_{\text{avail}} = \sum \text{p and } \pi^{\pm} \text{ K.E.} + \text{total energy of all other particles except n}$$

Adding in RPA (a charge screening nuclear effect) and 2p2h (correlations) processes improves agreement in some regions

The 2p2h contribution in the Valencia model is not quite enough

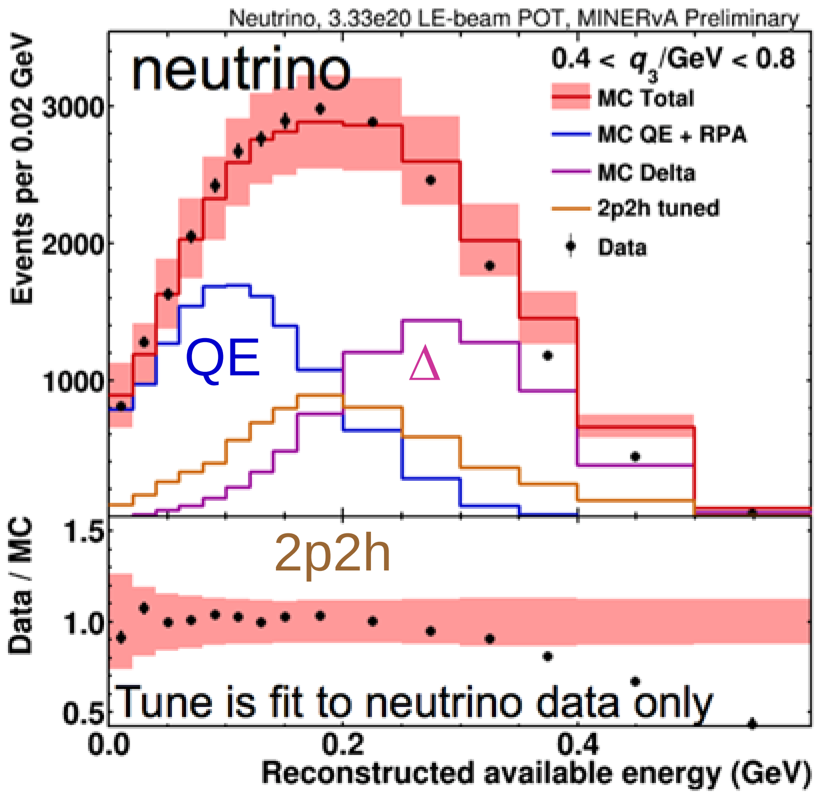
Excess observed in similar kinematic region as in antineutrino CCQE

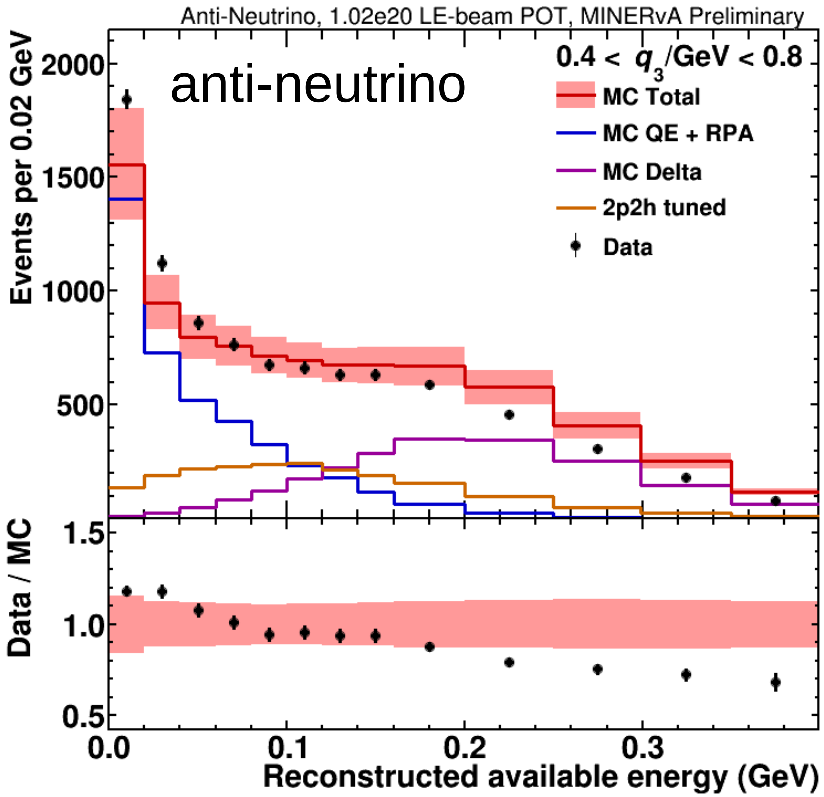
The Low Energy Recoil Fit

Weighting up the 2p2h events with a 2D Gaussian weight in true (q_0, q_3)

This tune designed to empirically "fill in" the dip region not whole kinematic range (does not scale true QE or resonant production)

Adds ~50% overall, but x2 in dip region



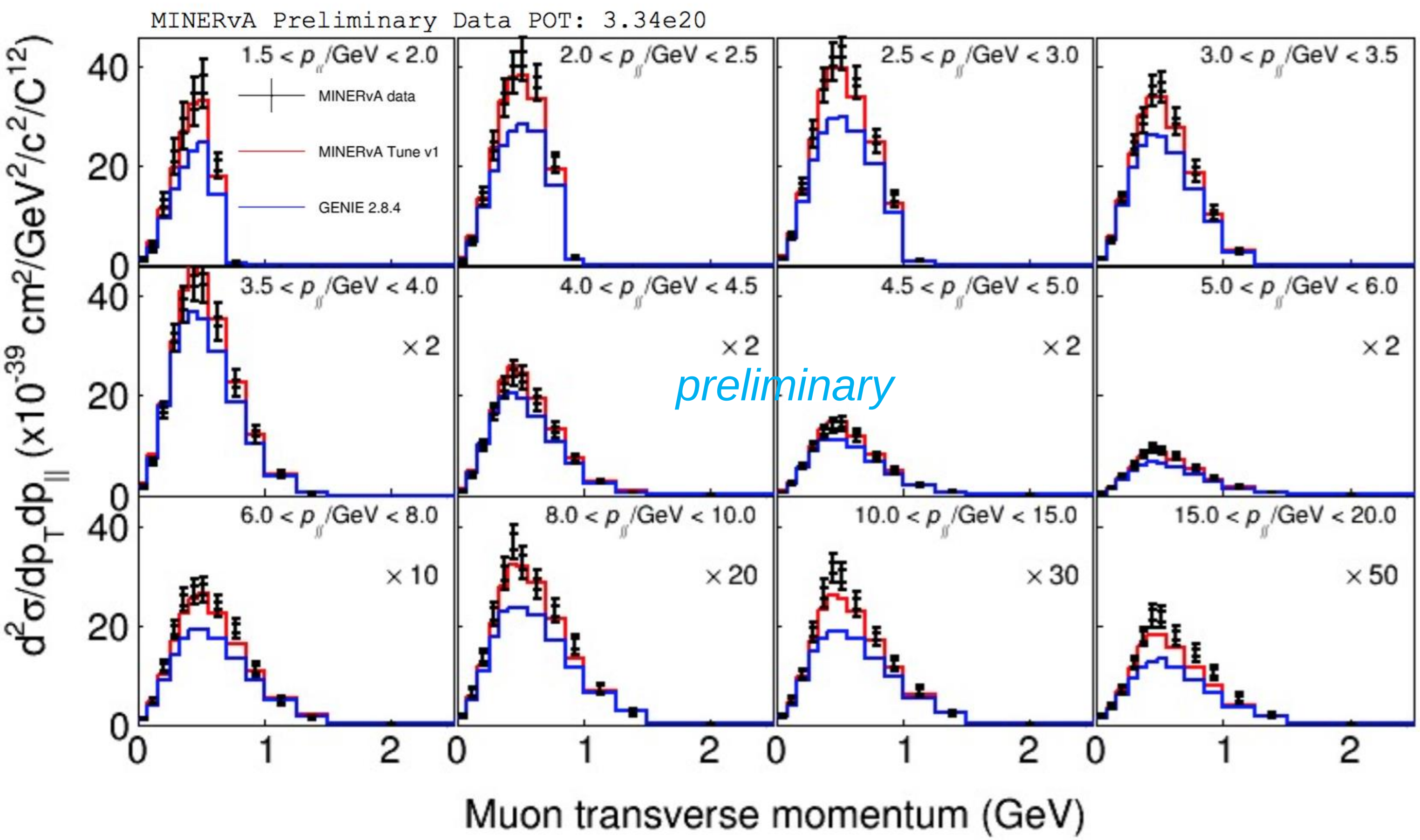


⇒ modified simulation which represents inclusive data quite well
but does this new model have any predictive power?

Back to Exclusives – CCQE-like ν

Isolate only CCQE-like events:

cut on extra energy outside the vertex, subtract backgrounds, extract x-sections



D. Ruterbories, FNAL Seminar, 3/2017
publication in progress

The reweight from the inclusive neutrino fit gives improved agreement with the neutrino QE-like result

Back to Exclusives – CCQE-like $\bar{\nu}$

Isolate only CCQE-like events:

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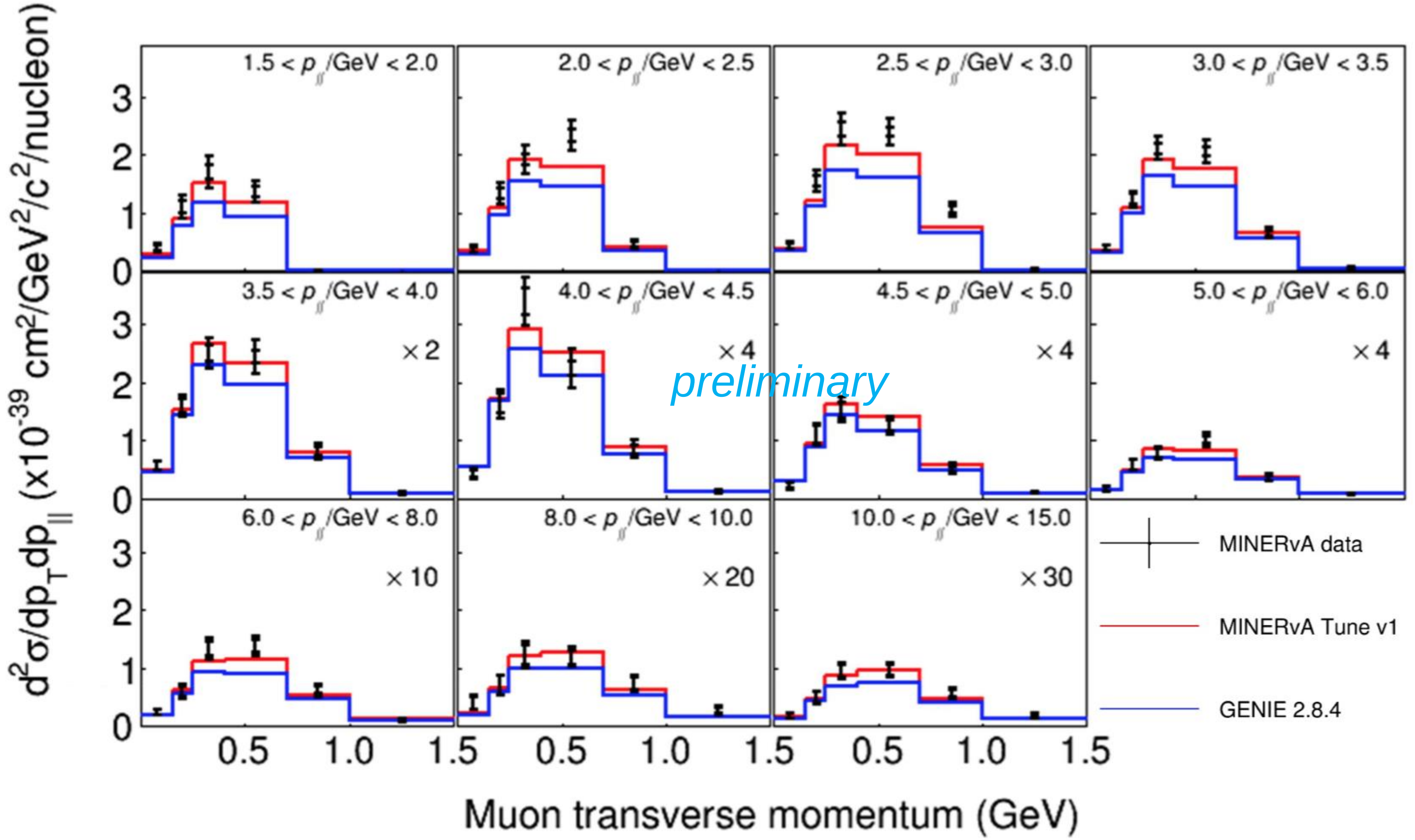


D. Ruterbories, FNAL Seminar, 3/2017
publication in progress

The reweight from the inclusive neutrino fit gives improved agreement with the anti-neutrino QE-like result
Extra strength coming at the right place in muon angle and momentum

Outlook

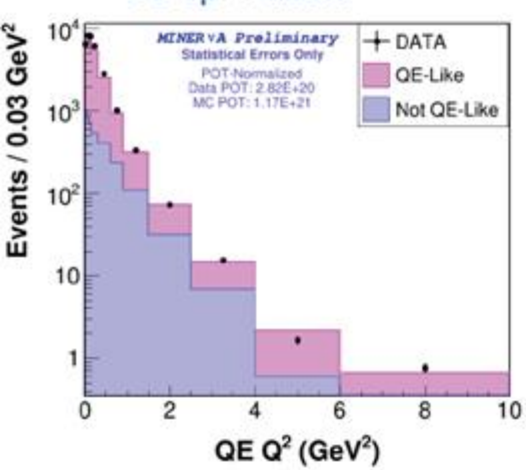
MINERνA provides measurements for a variety of neutrino induced processes over a broad energy range relevant to different ν oscillation experiments.
Today we saw only some results.
New first time measurements also on $\pi^{\pm}$, π^{0}, and K production.

see E. Valencia's talk from Monday

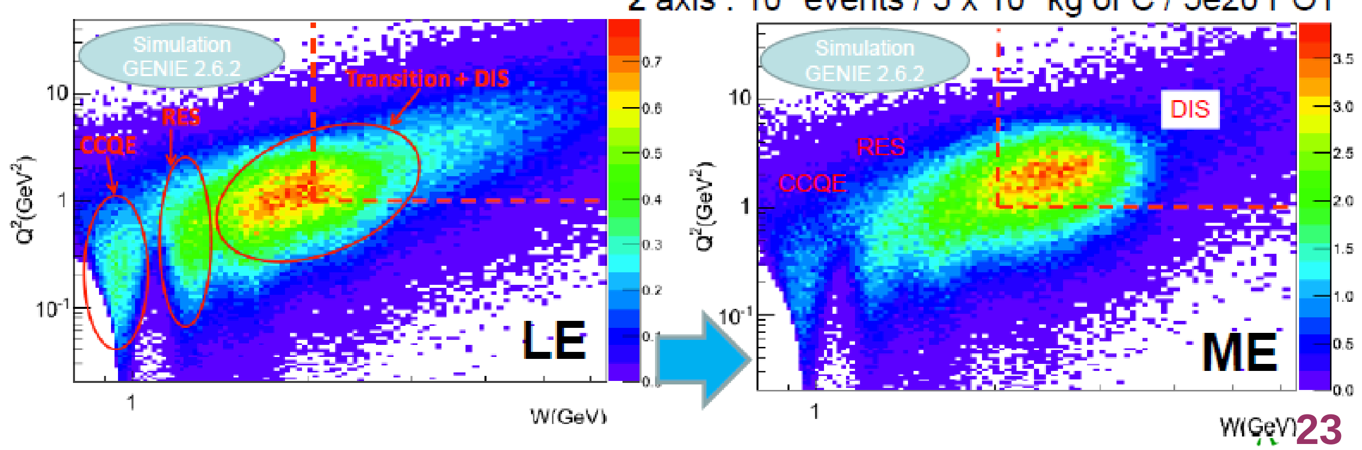
MINERνA data helps improve model descriptions.
Current models do not fully describe MINERνA data yet.
Able to differentiate between nuclear models – they favor a 2p2h component

Data taking with a "Medium Energy" ν beam started in fall 2013, switched to anti-neutrino mode this year.
Increased kinematic coverage, LE data able to reach $Q^2 \sim 2$ GeV^2

CC 0pi 1-track

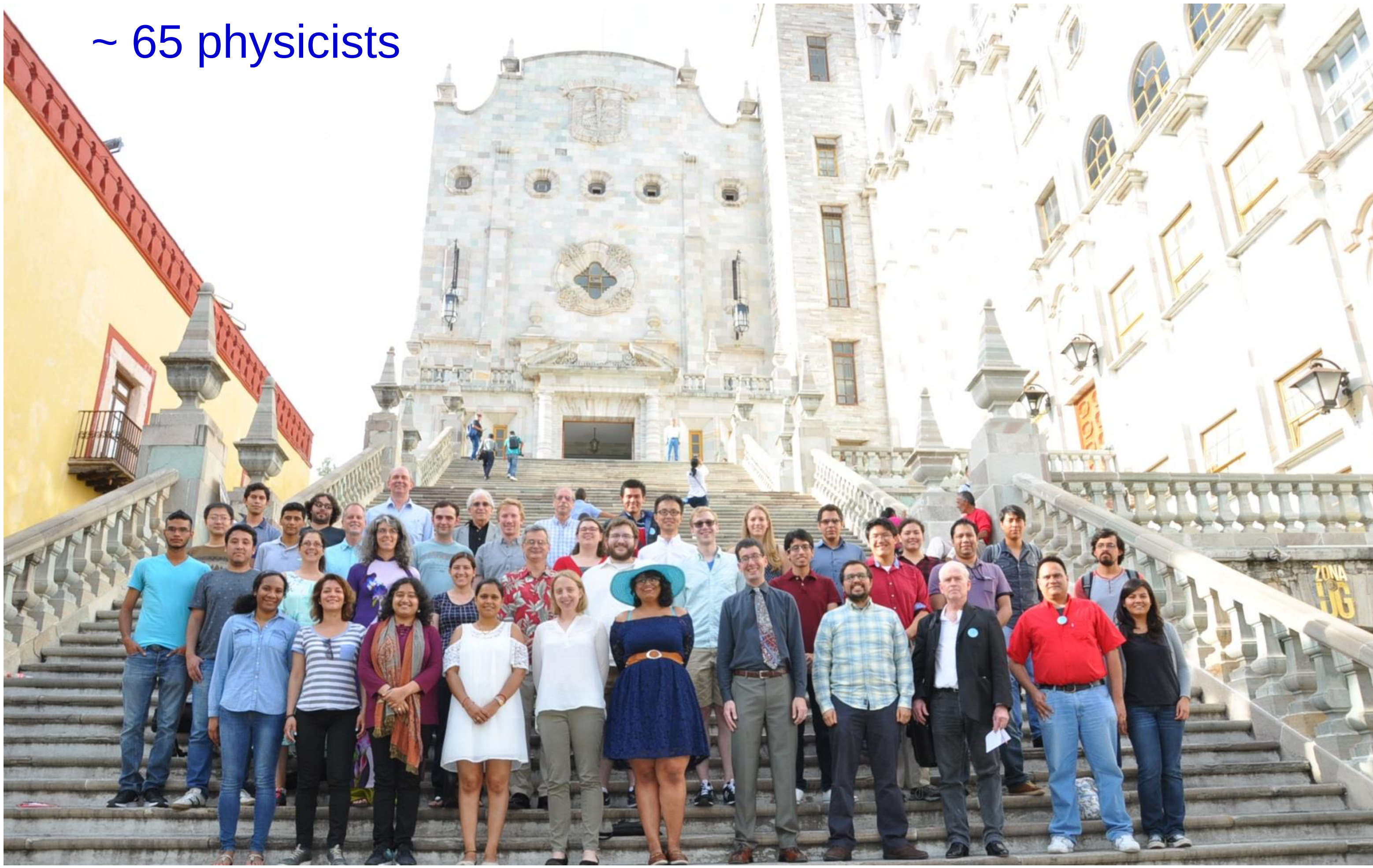


z axis : 10³ events / 3 x 10³ kg of C / 5e20 POT

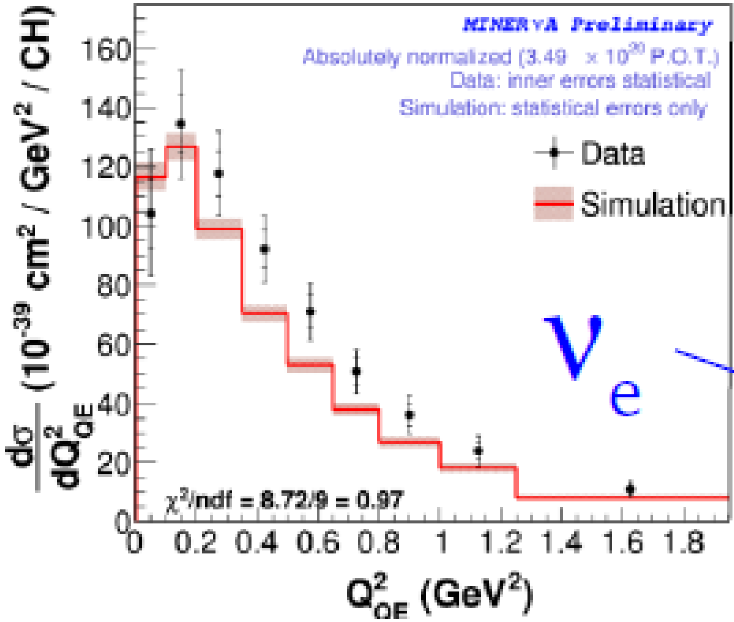


The MINERνA Collaboration

~ 65 physicists



ν_e VS. ν_μ



Wolcott et al., PRL116 (2016) 081802