Fine-Grained Tracking Detectors for Neutrino Physics: Part II

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Outline

- Motivations
- Demonstration of reconstruction capability
  - Coherent neutral pion production in NOMAD
- Demonstration of distinguishing nuclear models
  - Minerva quasi-elastic scattering results
    - Anti-neutrinos
    - Neutrinos
- Demonstration of finding important phenomena
  - Minerva measurement of ratios of charged-current cross-sections on carbon, iron, lead and polystyrene
- Conclusions

Motivations

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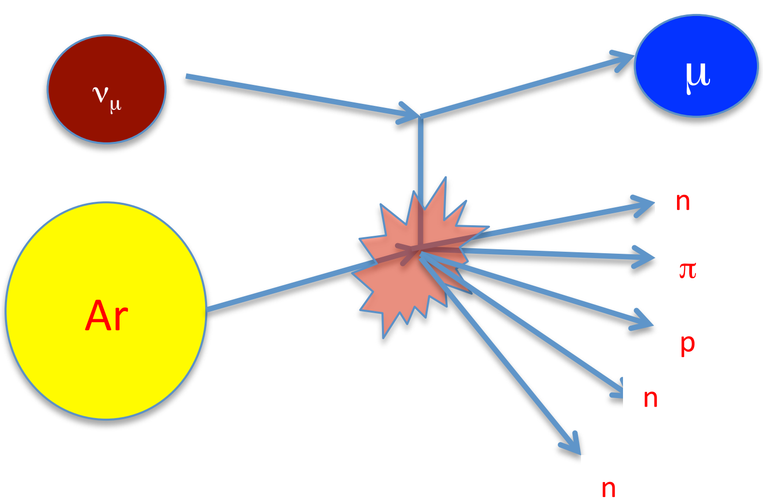
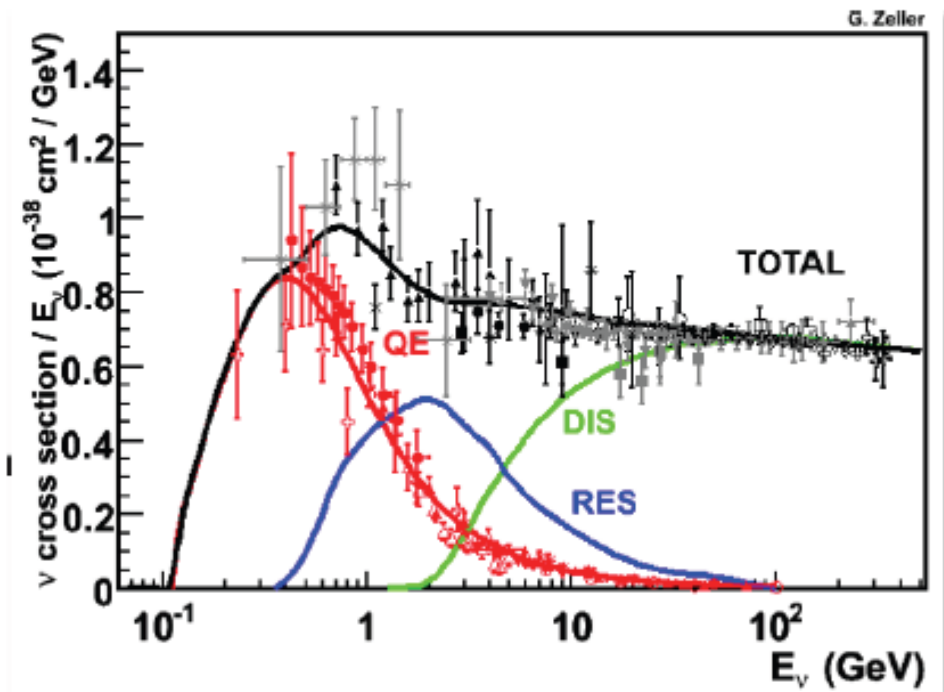
- Neutrino oscillation experiments require us to get this right.

LBNE Physics Challenges – medium-energy neutrinos

- LBNE does long-baseline physics in resonance regime (1st Oscillation Maximum at ~2.4 GeV) and resonance/DIS cross-over regime
- Atmospheric neutrinos are measured in the same neutrino energy regime
- Neutrino oscillation phenomena depend on mixing angles, masses, matter densities, distance from production to measurement point, neutrino flavor and neutrino energy
- Critical to understand the correlation between true and reconstructed neutrino energy

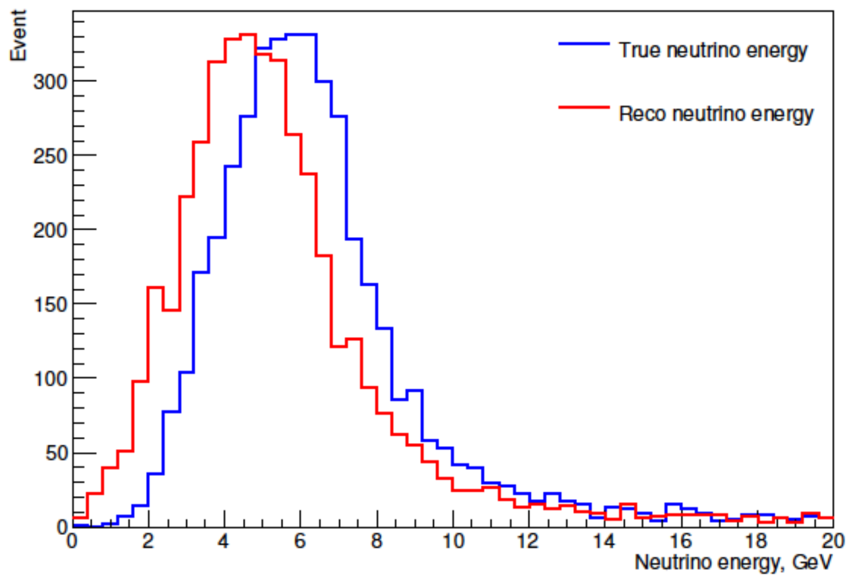


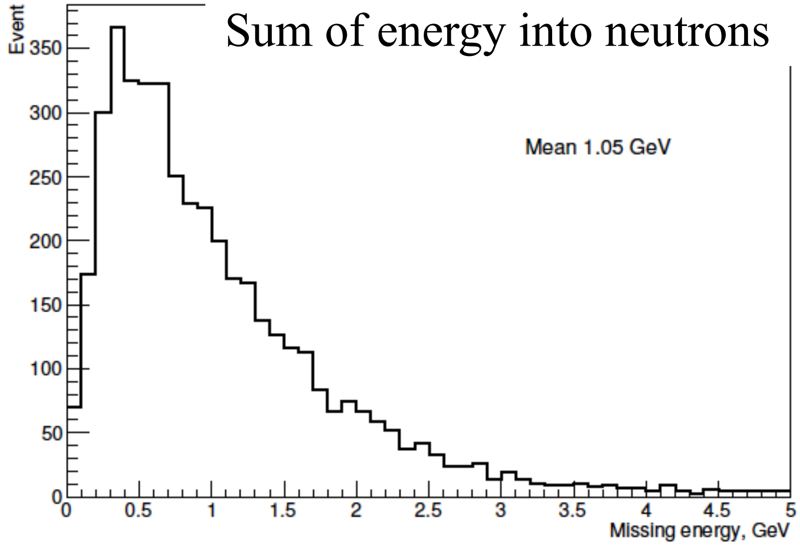
Let's think about neutrons for a moment.



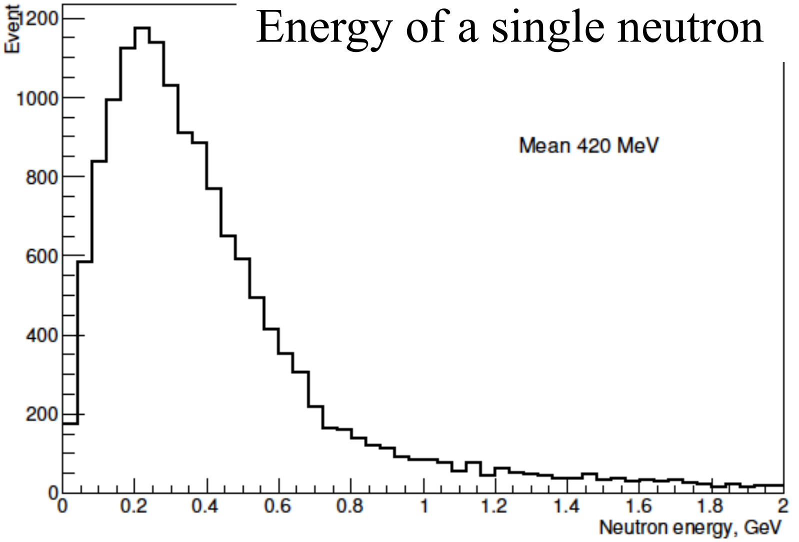
NuMI Medium Energy Tune

- Neutrons can carry away significant energy
- Uncertainties also large





Sum of energy into neutrons

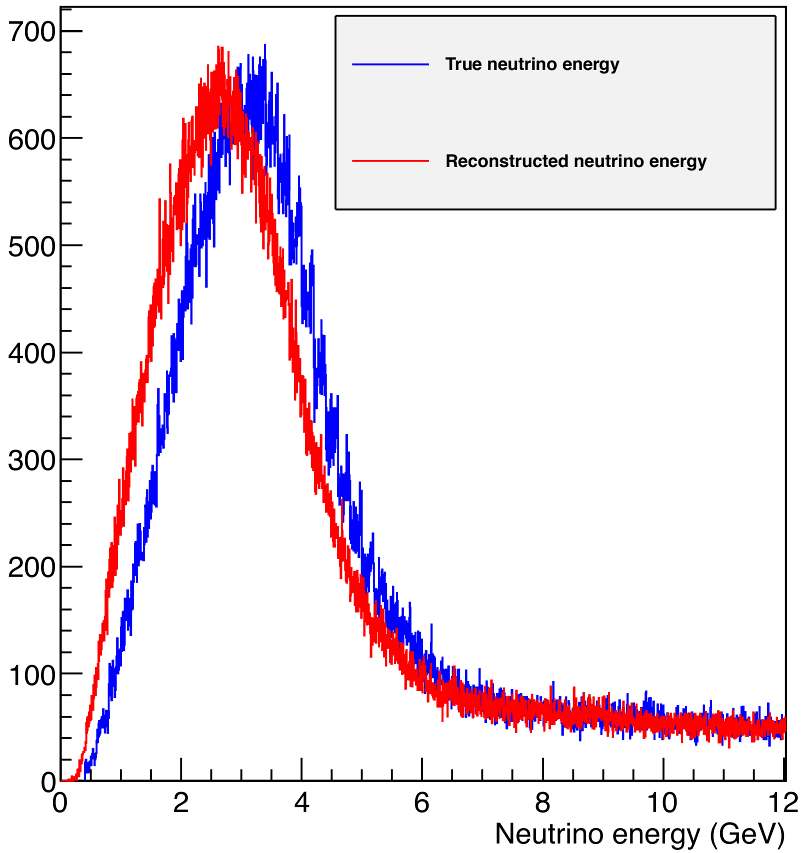


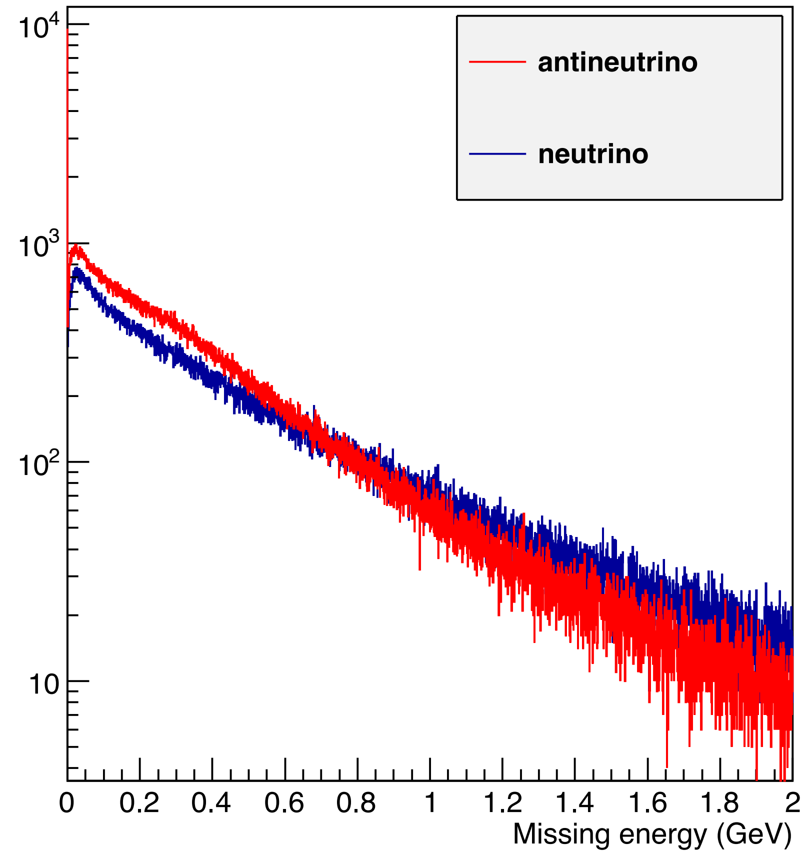
Energy of a single neutron

Simulation by Qiuguang Liu

LBNE Beam

Missing neutrons for LBNE. Neutrino – Anti-neutrino differences.

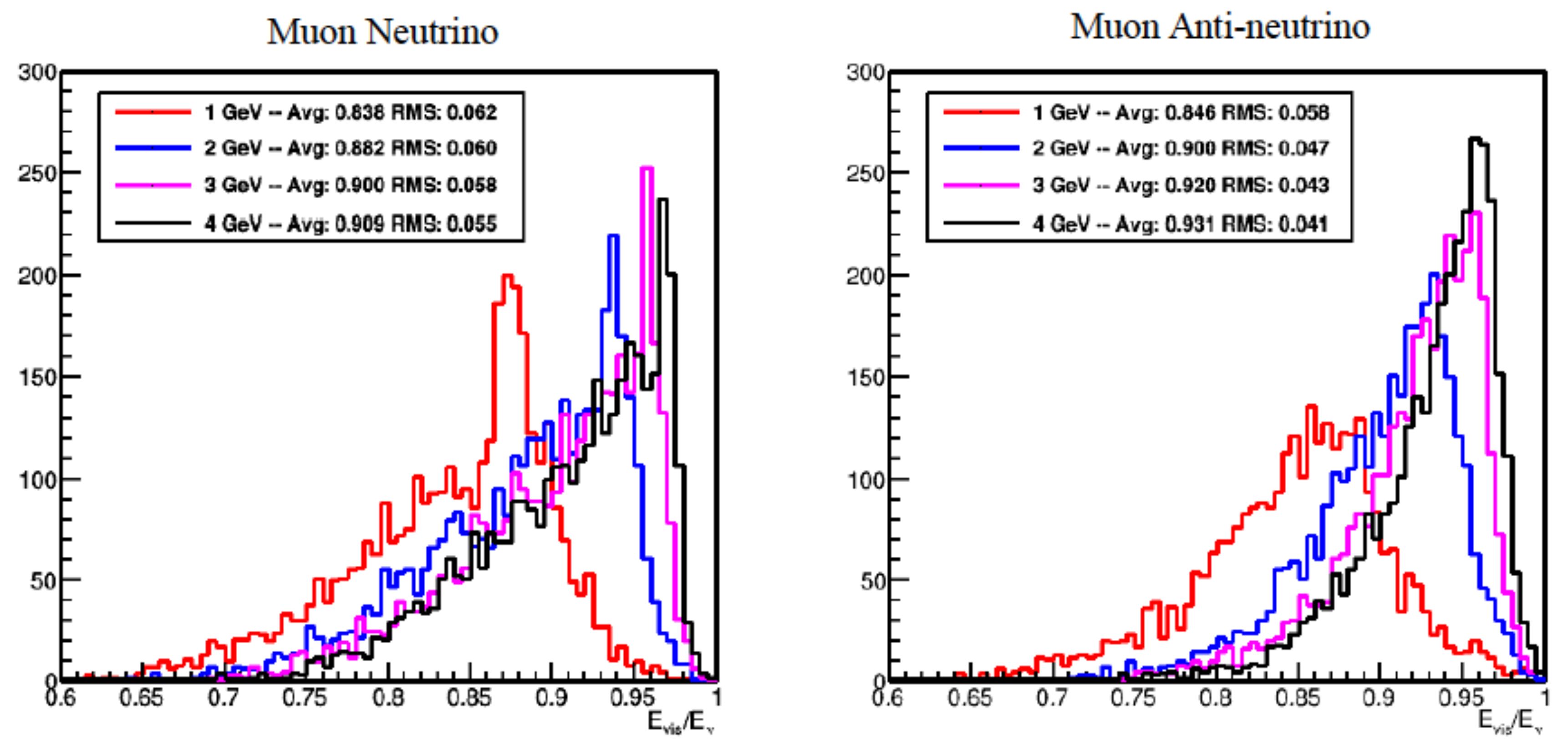




Simulation by Elena Guardincerri

Fraction of neutrino energy that is visible

Can't we simply measure the energy calorimetrically? No!



- Fraction is different for neutrinos and anti-neutrinos

- Clark McGrew at the Santa Fe LBNE Scientific Workshop (http://public.lanl.gov/friedland/LBNEApril2014/)

Long-Baseline Neutrino Oscillation Experiments

- We need to understand what we are doing.
- Measurements in fine-grained trackers can help us make headway.

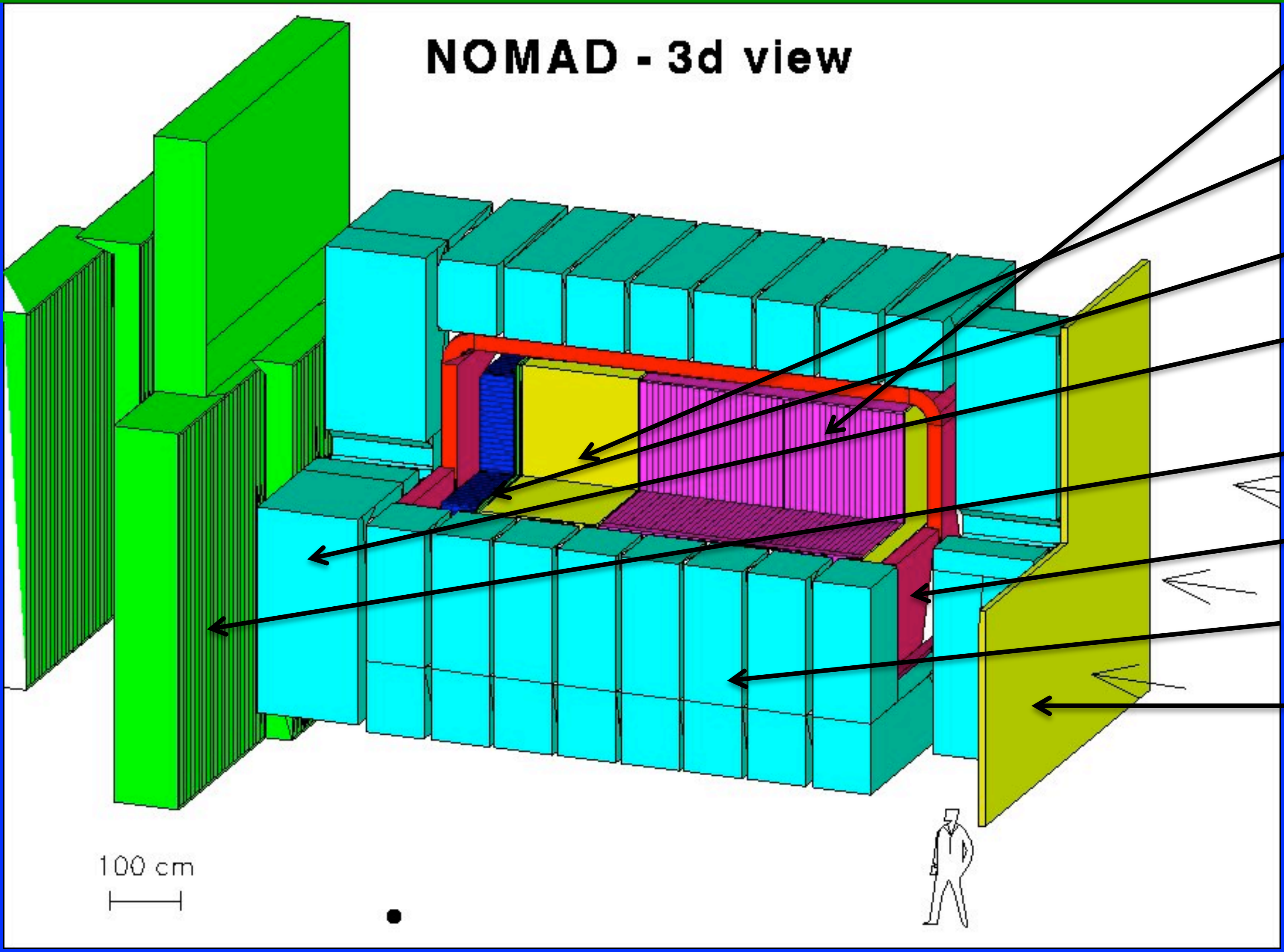
NOMAD Coherent Neutral Pions

Coherent Neutral Pion Production in NOMAD

$$\nu + \mathcal{A} \rightarrow \nu + \mathcal{A} + \pi^0$$

- Target mass: 2.7 tons
- Composition: Carbon (64%), Oxygen (22%), Nitrogen (6%) and Hydrogen (5%) – effective atomic number A=12.8 (similar to carbon)
- Over 1.7 Million neutrino interactions recorded in the fiducial volume
- Beam energies 1 to 300 GeV – average of 24.8 GeV

Examples of detectors - NOMAD



Drift planes

Transition radiation detectors

E&M calorimeter

Hadronic calorimeter

Muon detectors

Magnet

Magnet Return

Veto plane

NOMAD Detector

- Density in the drift region 0.1 g/cm^3
- Average material encountered ~ 0.5 radiation length
- Predominantly muon neutrino beam
- Neutral pions decay to 2 gammas
- Gammas can convert in the drift chamber region or calorimeters

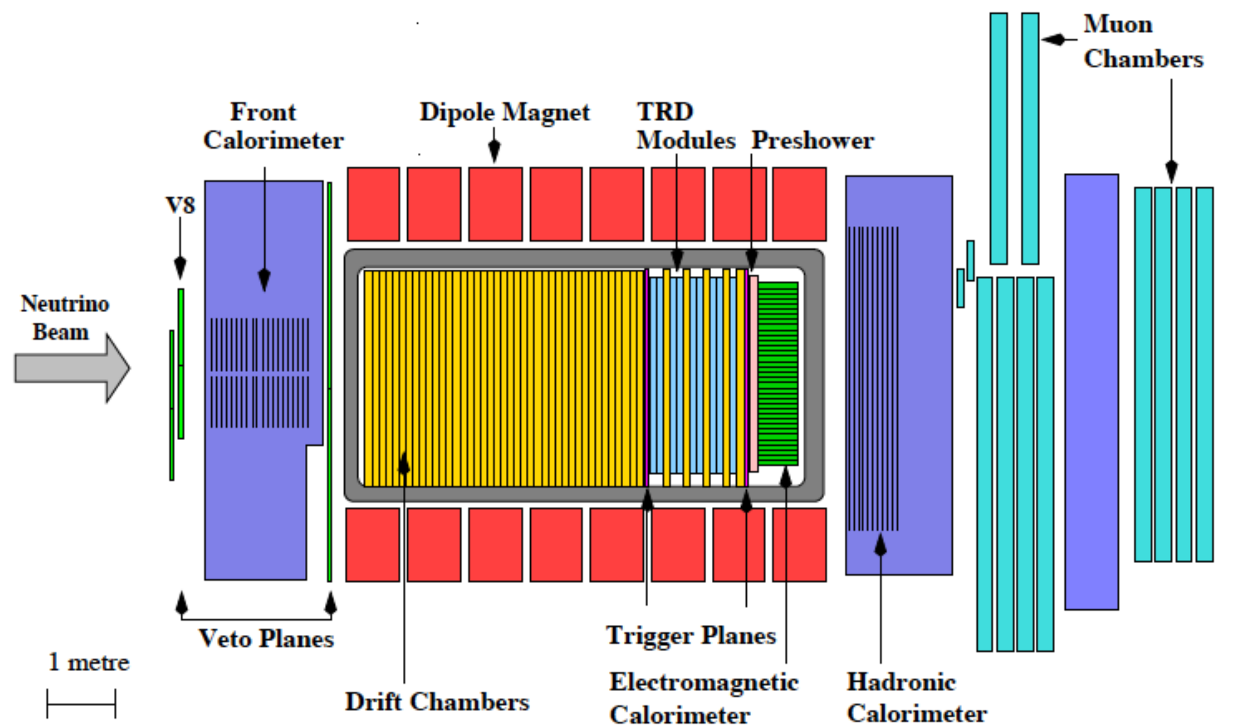
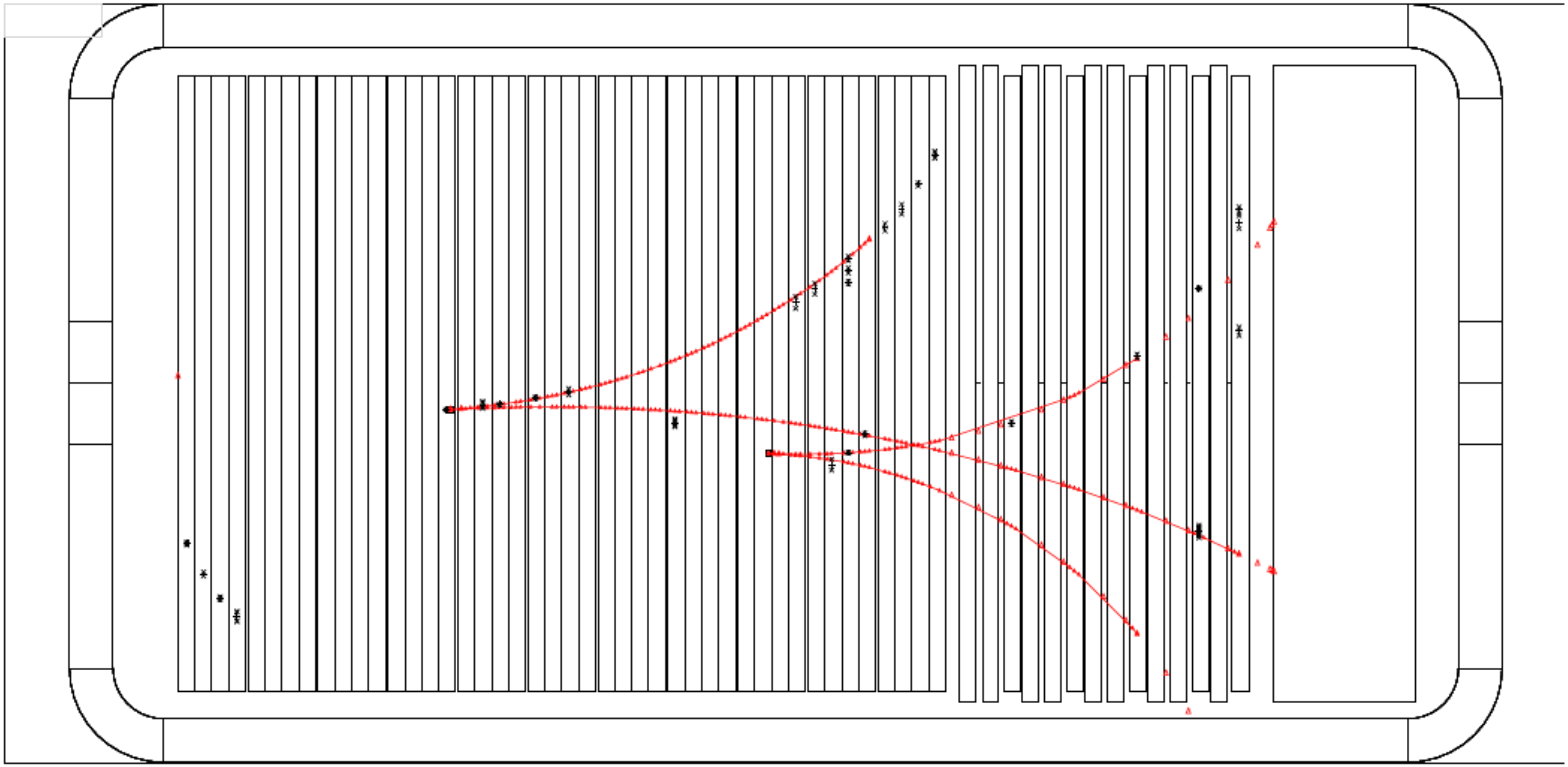


Fig. 1. Side view of the NOMAD detector.

- Event signature: 2 gamma-rays and nothing else
- This analysis requires both gammas to convert in the drift chamber region

Event display of a typical candidate



Reconstructed neutral pion momentum not written in the paper, but …

Salient Distributions

- Left plot: Summed gamma-ray energy
- Right plot: Transverse momentum distribution

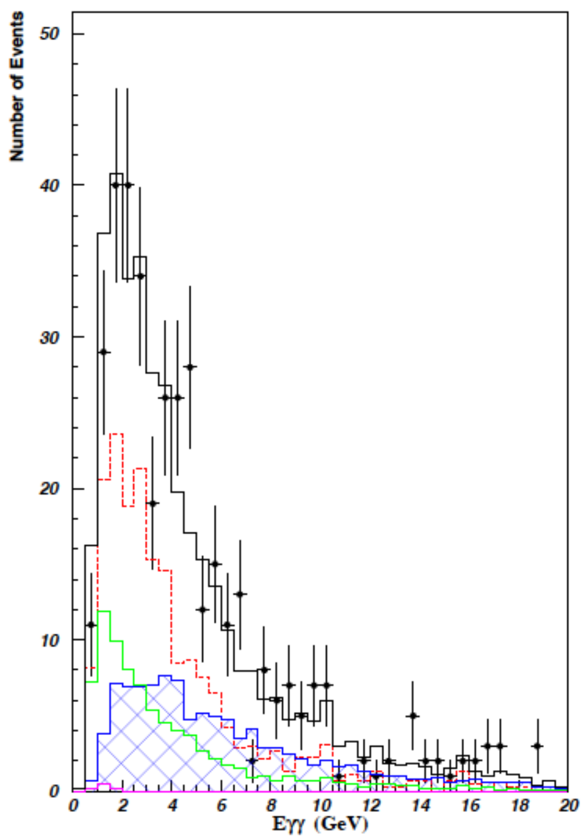


Fig. 4. Comparison of the $E_{\gamma\gamma}$, defined as $E_{\gamma 1} + E_{\gamma 2}$, between data (symbol) and MC (Cohπ^0 in hatched blue, OGB in dot-dash green, NCDIS in dotted red, total in solid histograms).

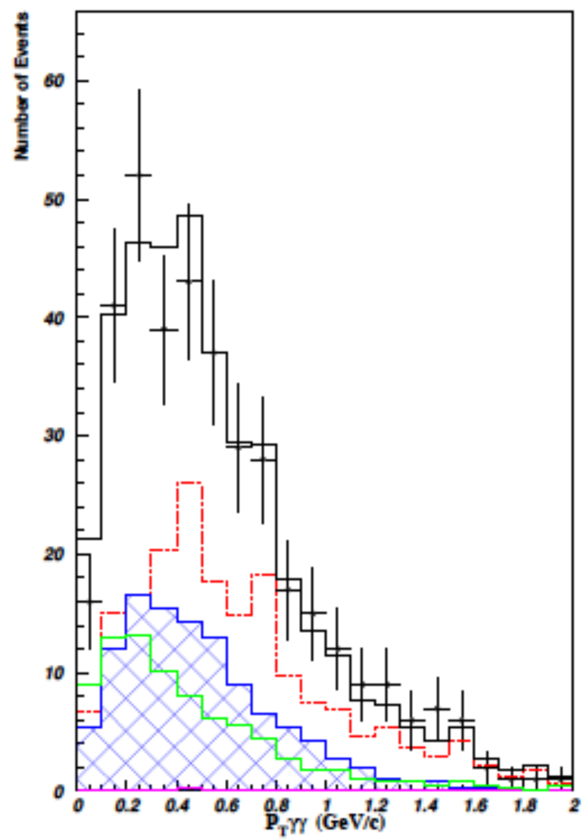


Fig. 5. Data and MC Comparison of the $P_{T_{\gamma\gamma}}$ Distribution.

- Blue hatched region: Coherent neutral pion simulation
- Dot-dash green: Entering background
- Dotted red: Neutral current background
- Solid: Sum total of the simulation
- Points: data

NOMAD Coherent Neutral Pion Results

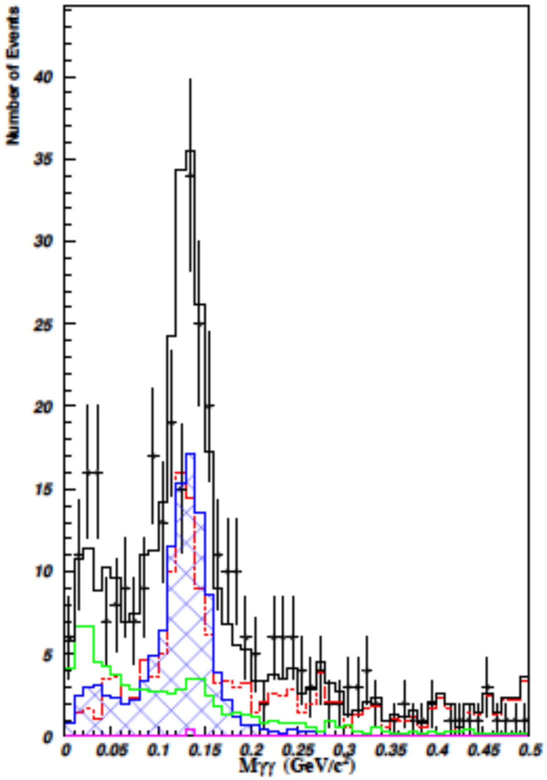


Fig. 6. Data and MC Comparison of the $M_{\gamma\gamma}$ Distribution.

- Extracted observed signal:

$$110.9 \pm 12.5$$

- Efficiency: 2.27%
- After correction for non muon neutrinos:

$$4630 \pm 522(stat) \pm 426(syst)$$

$$\frac{\sigma(\nu\mathcal{A} \to \nu\mathcal{A}\pi^0)}{\sigma(\nu_\mu\mathcal{A} \to \mu^- X)} = [3.21 \pm 0.36(stat) \pm 0.29(syst)] \times 10^{-3}$$

Results II

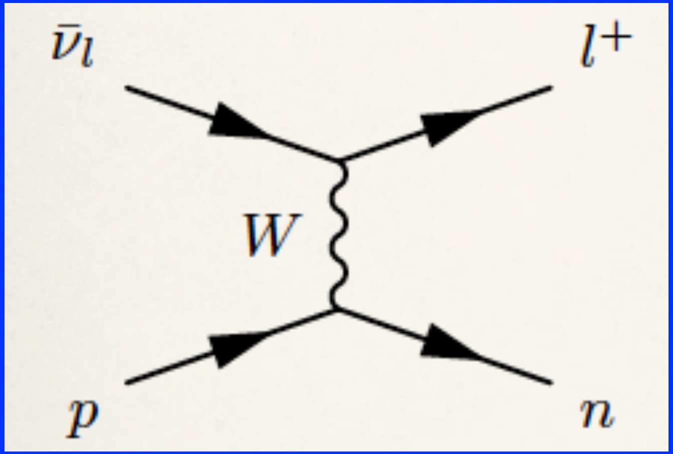
- Comparison with other experiments and final cross-section result – consistent with Rein-Sehgal model

Experiment	$\mathcal{N}$ucleus	Avg-E_ν GeV	$\sigma(Coh\pi^0)$ $10^{-40} cm^2/\mathcal{N}ucleus$	Cohπ^0 /ν_μ-CC 10^{-3}
Aachen-Padova [2]	27	2	(29 ± 10)	
Gargamelle [3]	30	2	(31 ± 20)	
CHARM [4]	20	30	(96 ± 42)	
SKAT [5]	30	7	(79 ± 28)	(4.3 ± 1.5)
15' BC [6]	20	20		(0.20 ± 0.04)
NOMAD	12.8	24.8	(72.6 ± 10.6)	(3.21 ± 0.46)

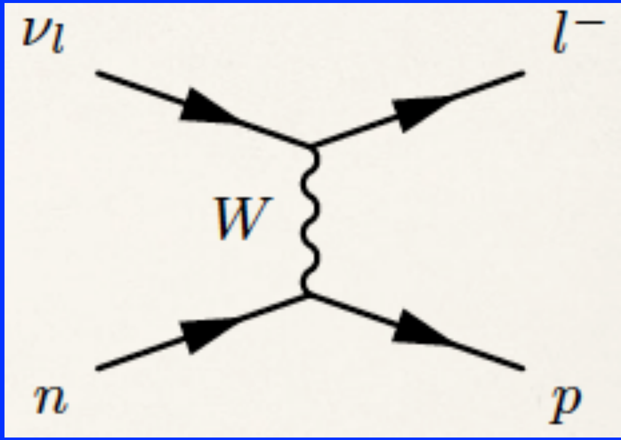
$$\sigma(\nu\mathcal{A} \rightarrow \nu\mathcal{A}\pi^0) = [72.6 \pm 8.1(stat) \pm 6.9(syst)] \times 10^{-40} cm^2/nucleus$$

Minerva Quasi-elastic Cross-sections

Quasi-elastic Scattering Assumptions



From Cheryl Patrick's 2013 EPS talk



- Simple process with no pions in the final state
- On free nucleons, if we know the direction of the neutrino, the free nucleon mass, and the muon mass, the kinematics are completely constrained by momentum and direction of the muon

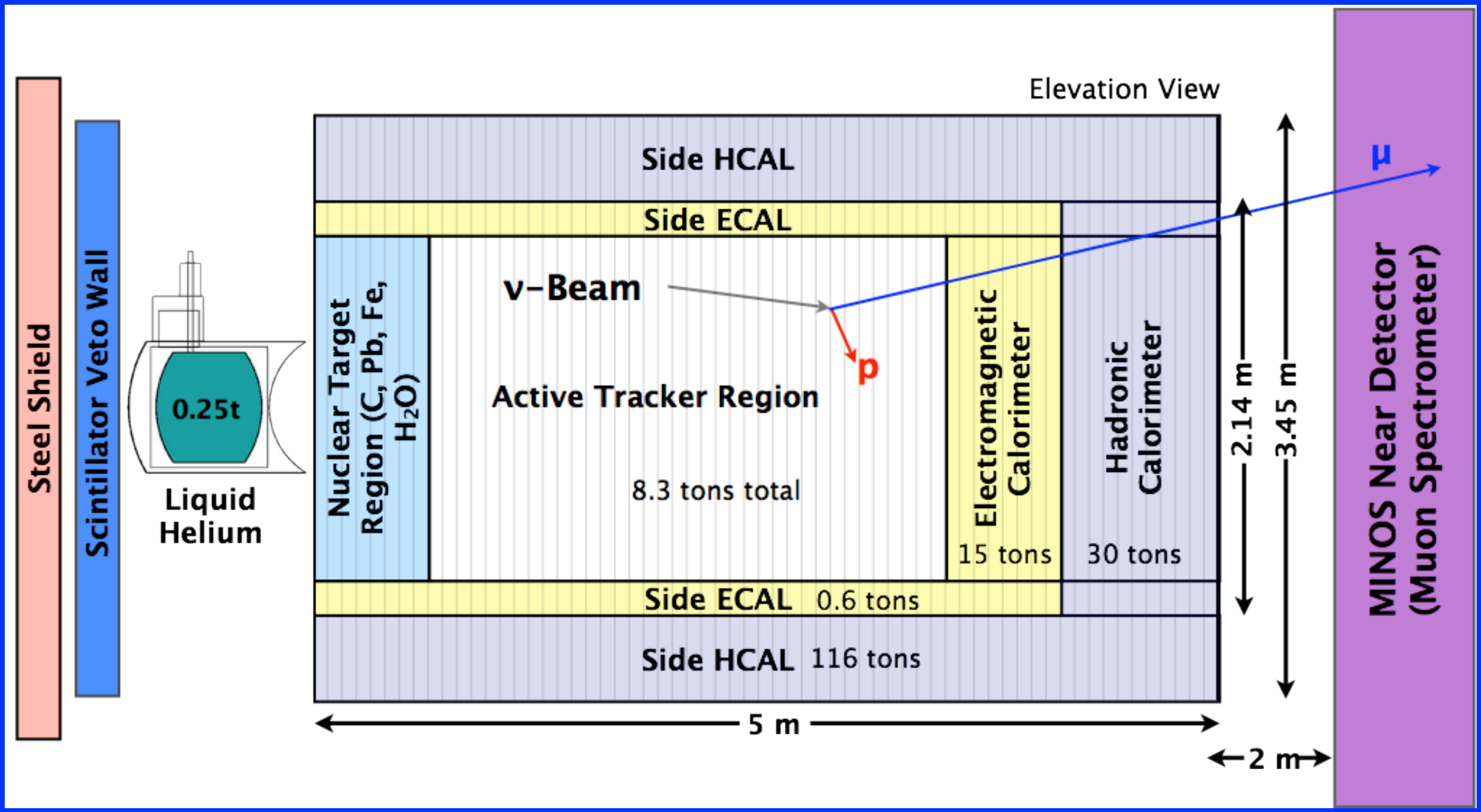
Quasi-elastic Scattering Assumptions

- In an nucleus, there is binding energy, Fermi motion, short-range correlations that impact the final state kinematics
- Fermi motion smears the kinematics
- Short-range correlations more complicated
- With binding energy:

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

$$Q_{QE}^2 = 2E_\nu^{QE}(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2,$$

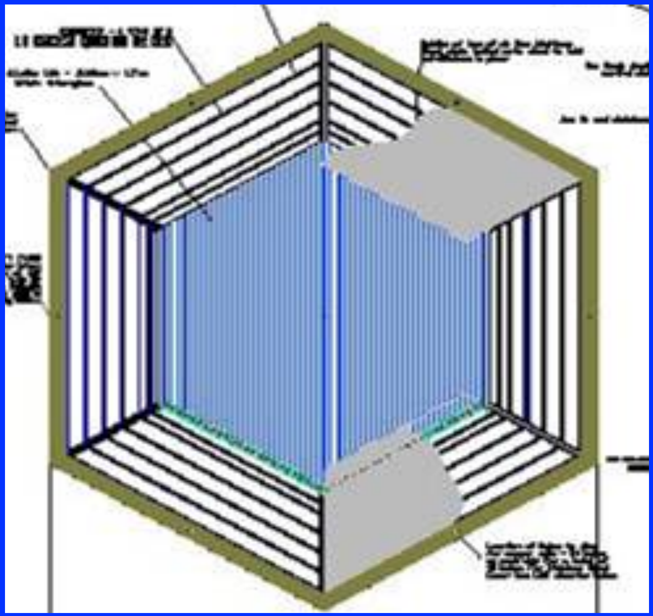
Examples of detectors – Minerva

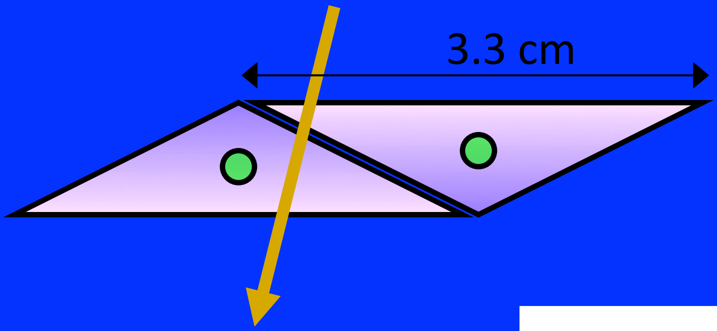


- 120 modules for tracking and calorimetry
- Magnetized MINOS near detector for downstream muon tracking/sign selection

From: Brian Tice

Examples of detectors – Minerva active target modules





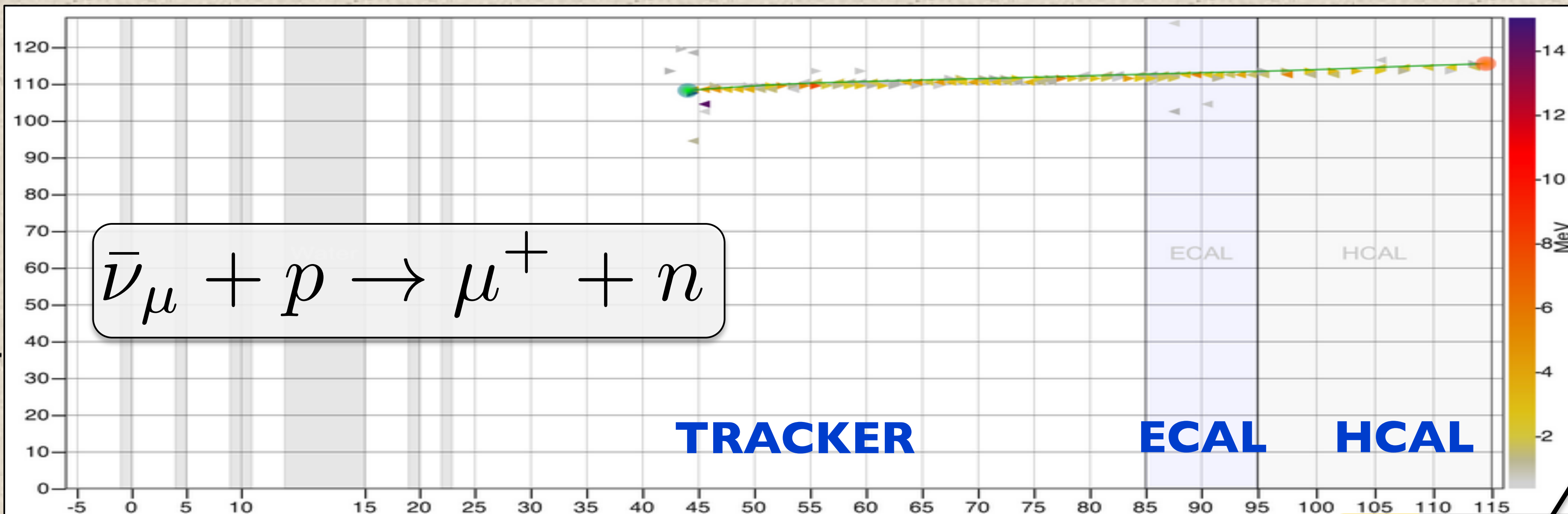
From: Jorge Morfin

- Inner detector: active scintillator strip tracker – triangular extrusions using charge sharing rotated by 60 degrees for stereo views
- Lead pieces on outer 15cm of active target for side electromagnetic calorimeter
- Outer frame provides side hadronic calorimeter/muon identifier

charged-current quasi-elastic scattering

ν Beam →

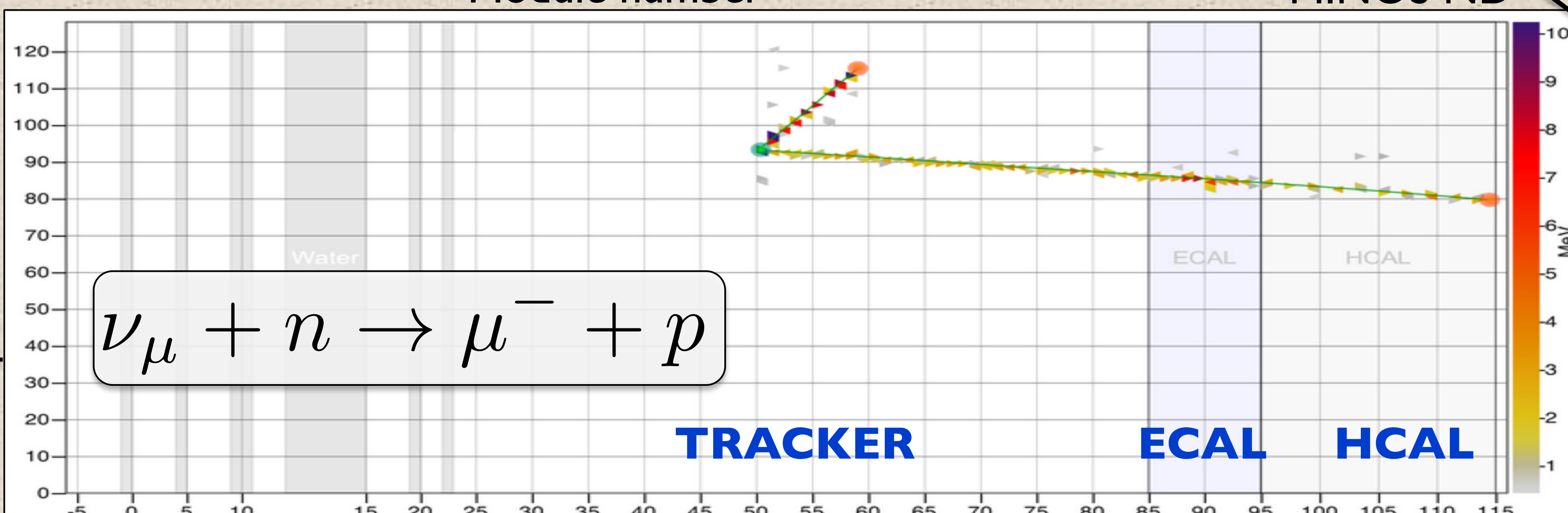
MeV



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

Module number →

MINOS ND

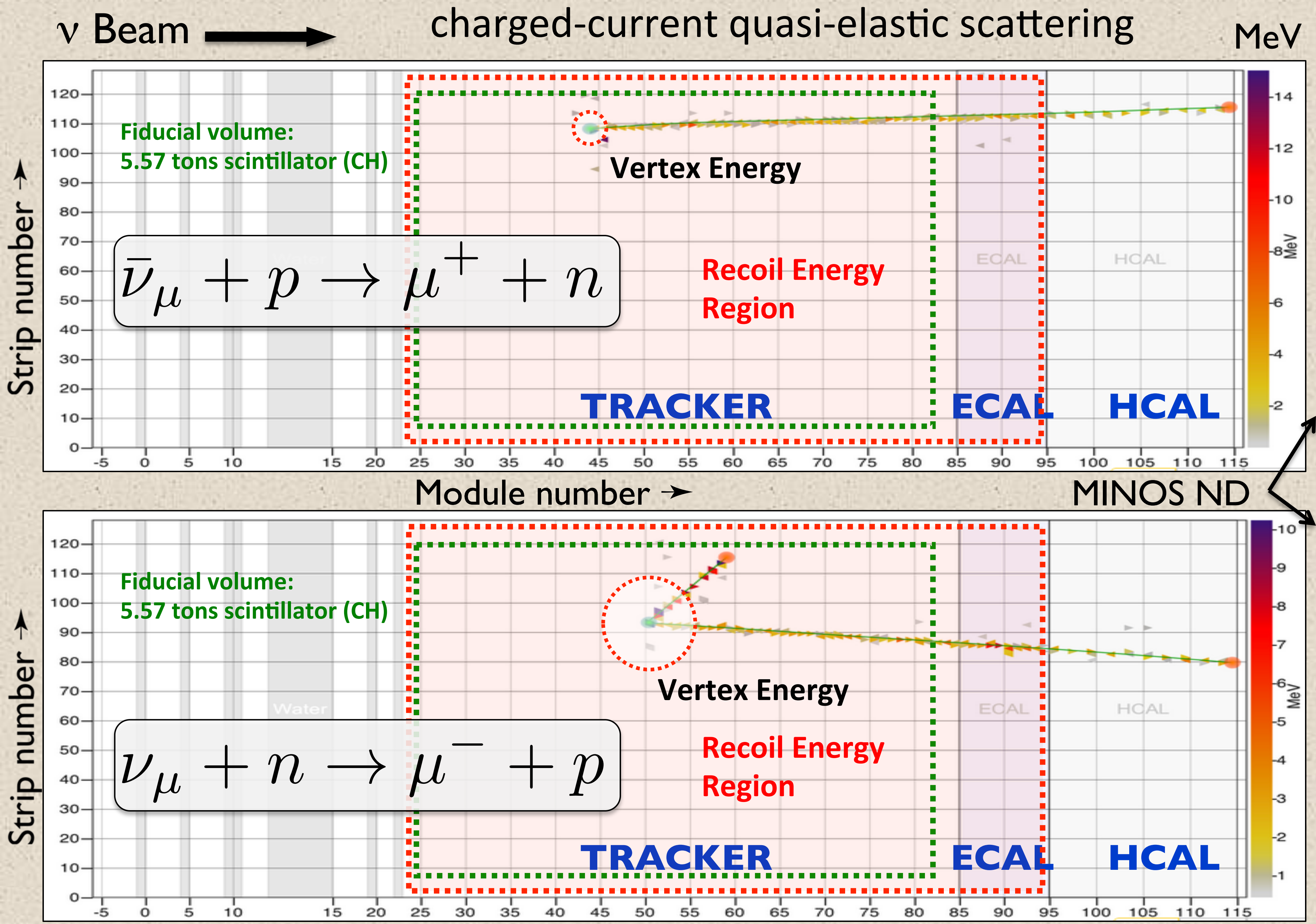


$$\nu_\mu + n \rightarrow \mu^- + p$$

Event Selection Criteria

- Look for muon from the 5.57 ton fiducial volume in the tracker region of the detector that is also measured downstream in MINOS (17 degree angular acceptance). Muon charge should be positive for anti-neutrinos and negative for neutrinos
- Define a region close to the vertex that is ``blacked out" where one or more nucleons might interact. This ``vertex energy region" is not used in the event selection.
  - Neutrino sample: 30cm around vertex
    - proton kinetic energy 225 MeV
    - pion kinetic energy 100 MeV
  - Antineutrino sample: 10cm around vertex
    - proton kinetic energy 120 MeV
    - pion kinetic energy 65 MeV
- Remainder of the tracker is the ``recoil energy region." If the interaction produced a pion (or if there are multiple neutrino interactions in the beam bunch), expect signal. Reject events with significant activity in this region.

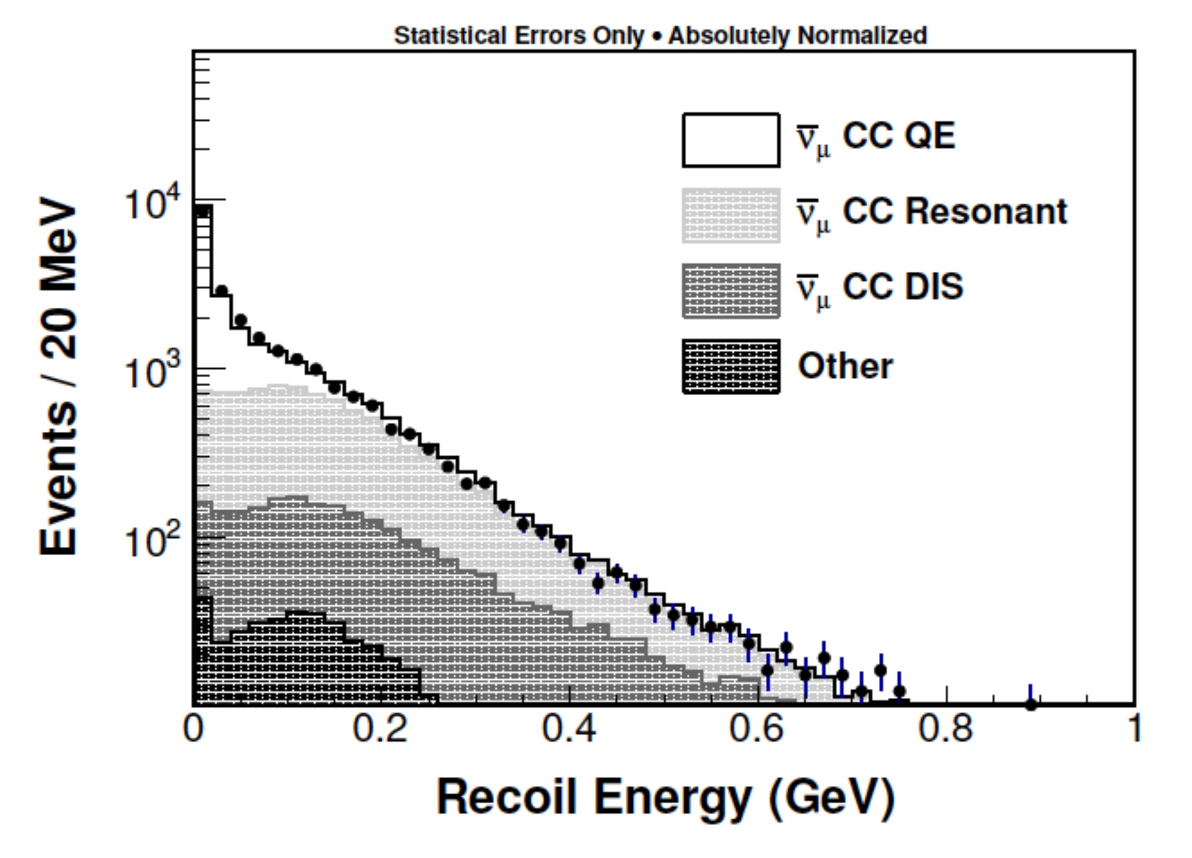
charged-current quasi-elastic scattering



Data Sample

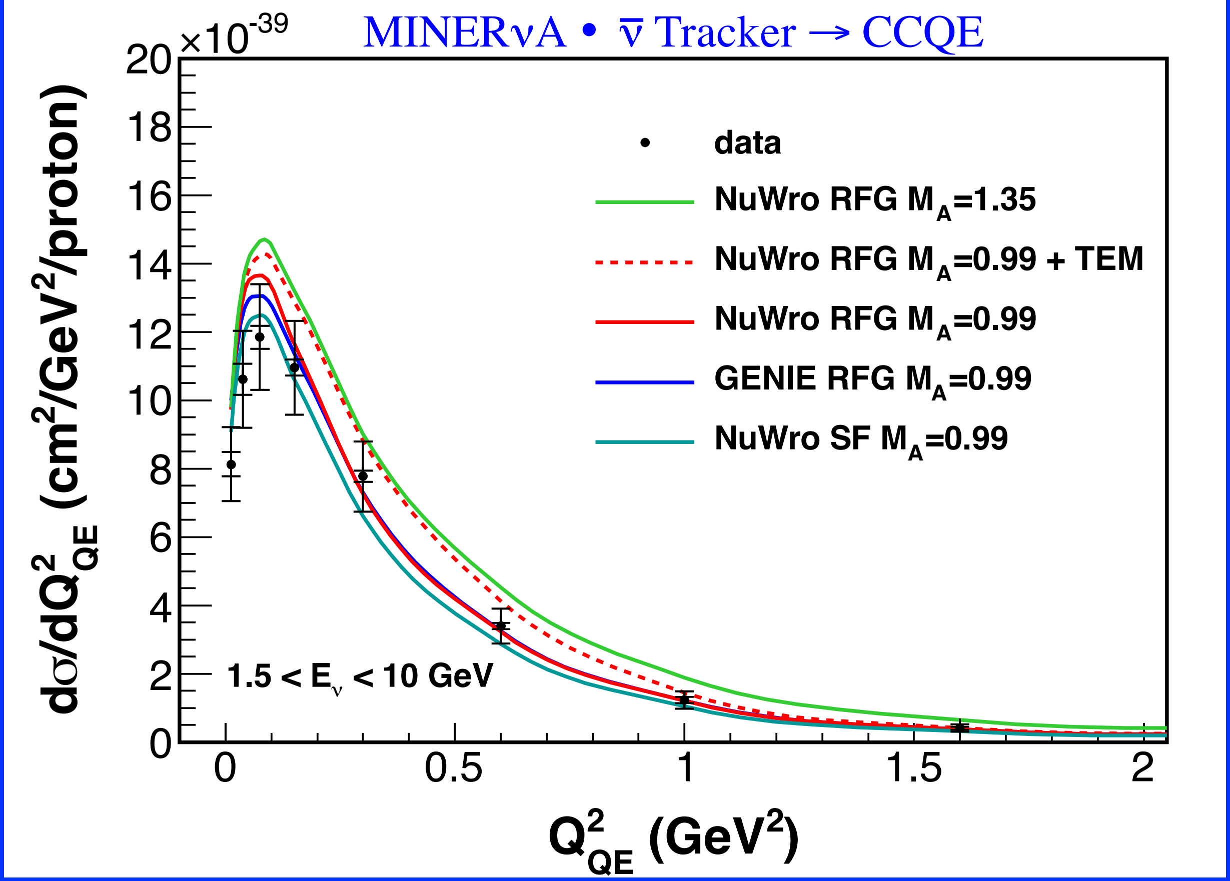
- Anti-neutrinos: NuMI low-energy anti-neutrino tune, November 2010-February 2011
  1.014×10^{20} protons on target
- Neutrinos: NuMI low-energy neutrino tune, March-July 2010
  9.42×10^{19} protons on target

Anti-neutrino recoil energy spectrum



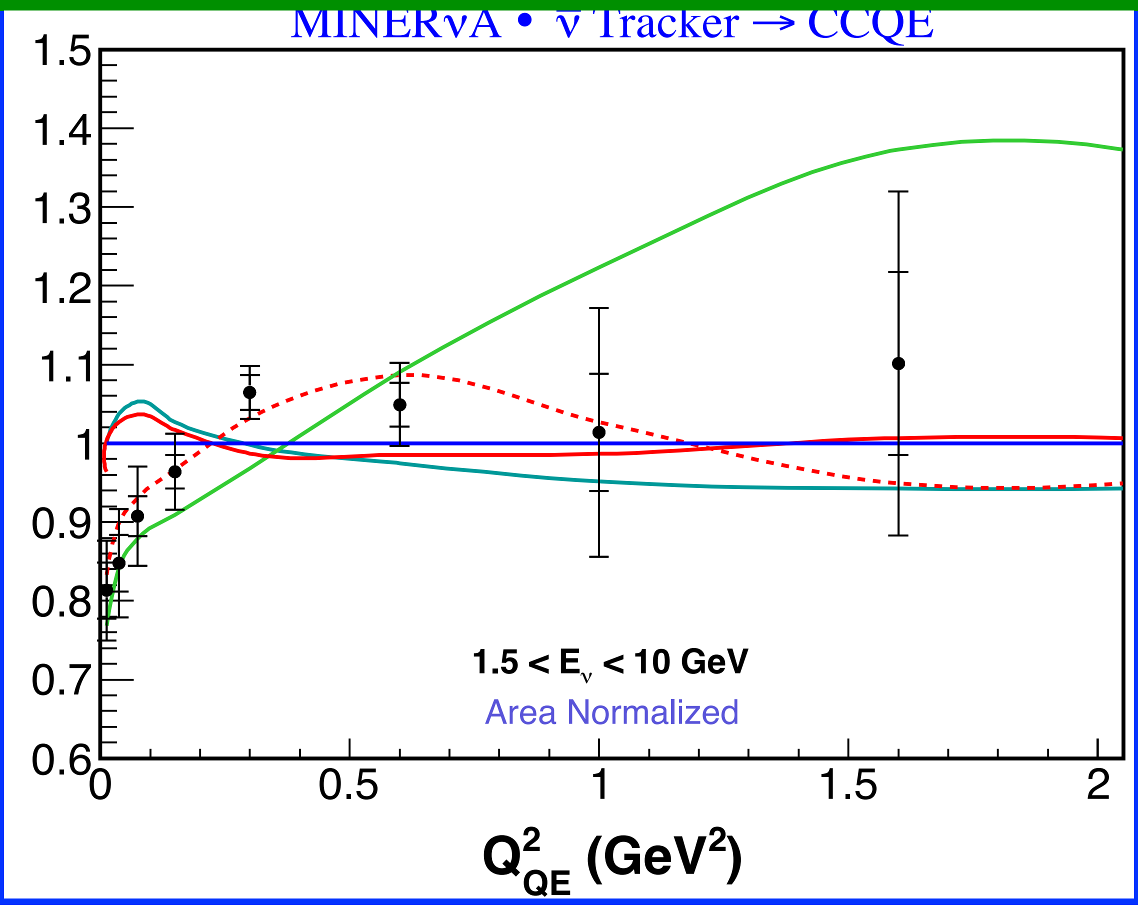
- Expect low recoil energy for quasi-elastic sample
- Inelastic events should have more energy deposited away from the vertex

Anti-neutrino differential cross-section



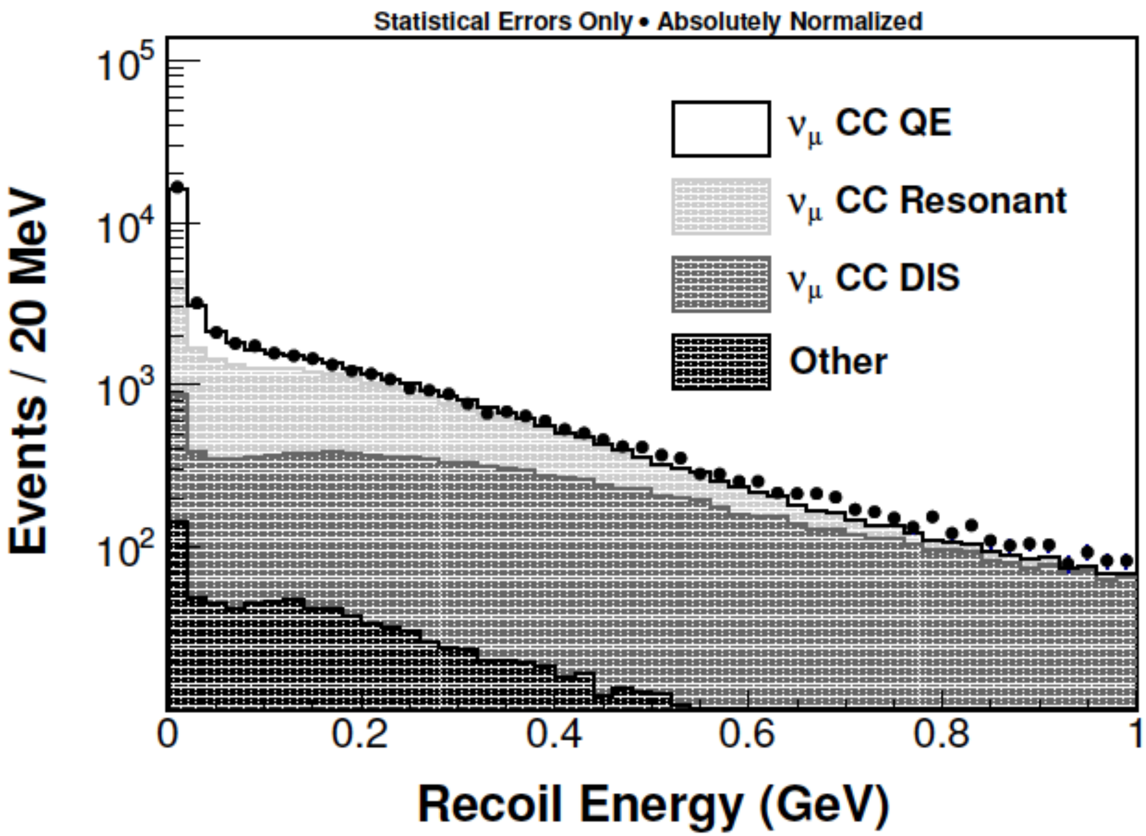
- 16,467 anti-neutrino events, 54% efficiency, 77% purity
- Compare absolute predictions to several different models

Shape comparison



- Normalize predictions to compare shape to several different models containing different microphysics.
- Minerva can distinguish between models!

Neutrino recoil energy spectrum



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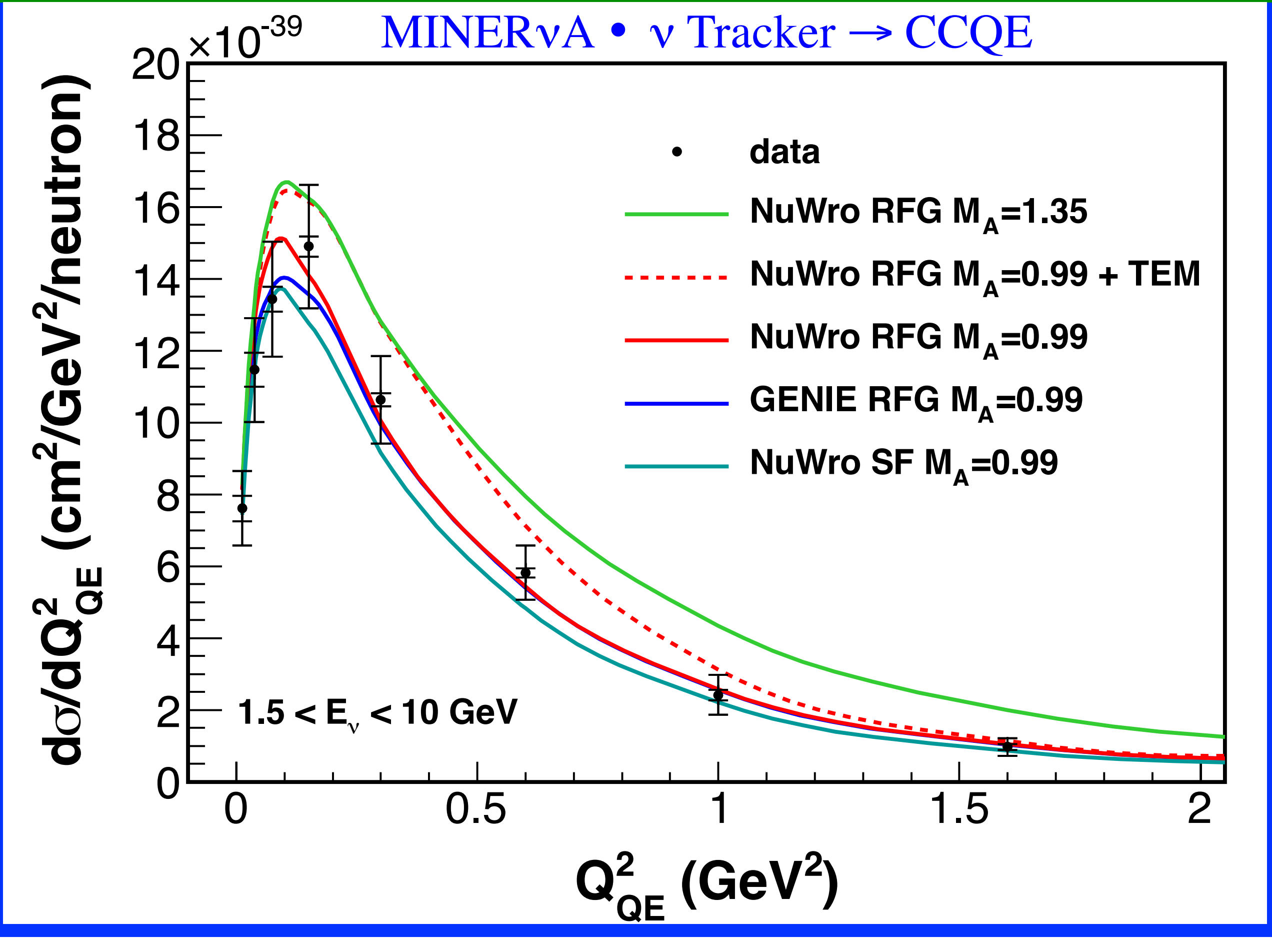
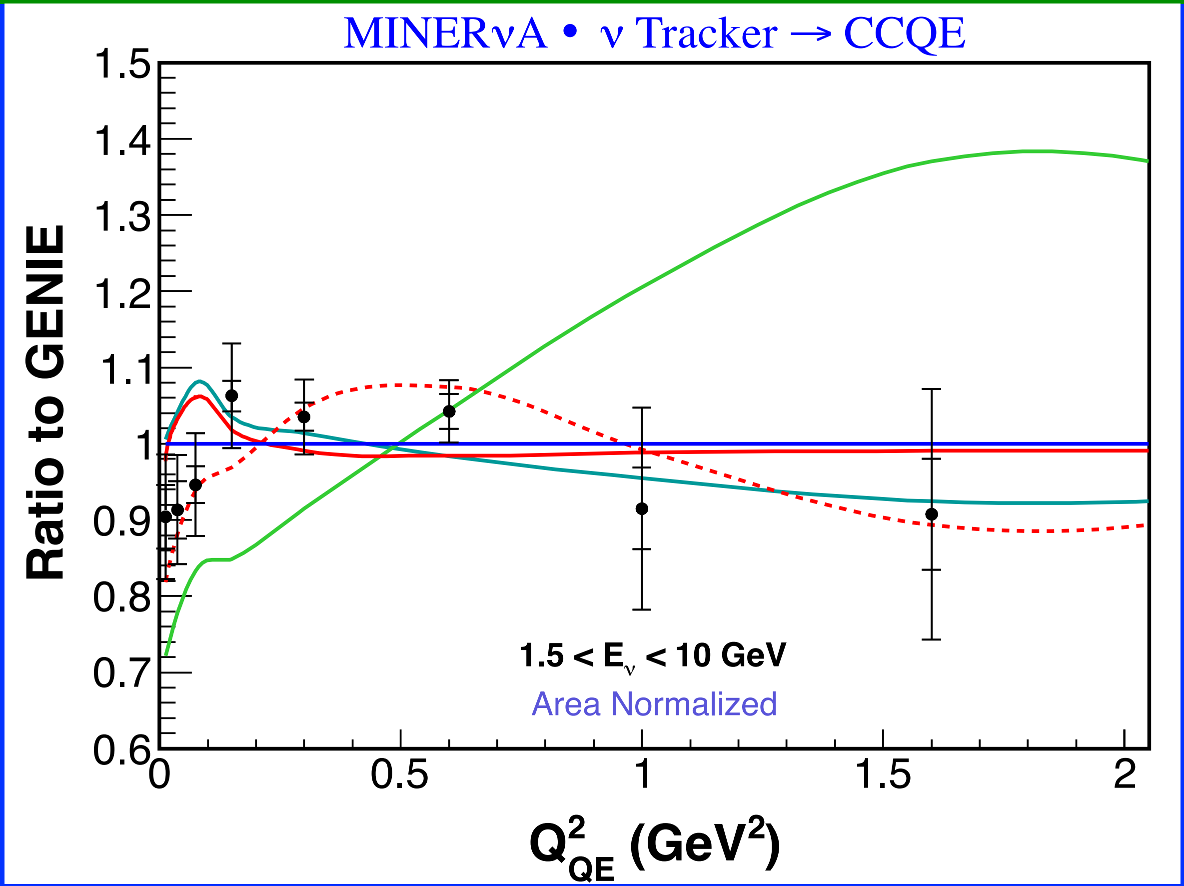
Neutrino differential cross-section



- 29,620 neutrino events, 47% efficiency, 49% purity
- Compare absolute predictions to several different models

Shape comparison



- Normalize predictions to compare shape to several different models containing different microphysics
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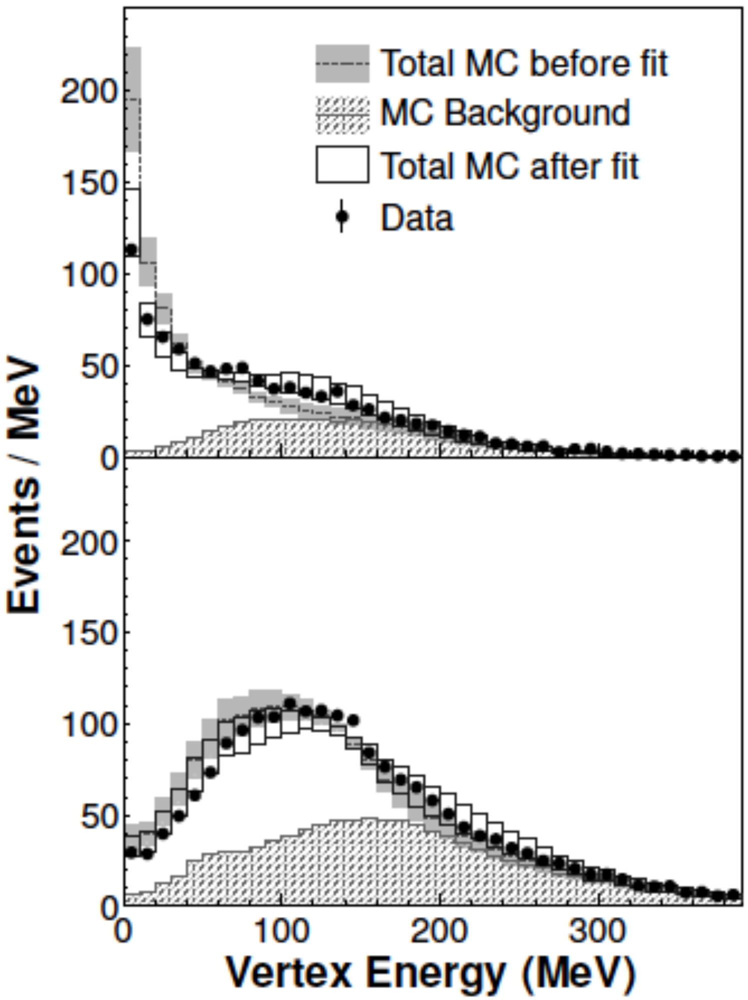
Vertex energy in neutrino mode



- Left upper: $Q^2 < 0.2$ GeV^2/c^2
- Left lower: $Q^2 > 0.2$ GeV^2/c^2
- Minerva uses vertex energy distributions to ask the question, ``additional protons possible''?
- Prefer additional proton of < 225 MeV K.E. in 25% of sample
- Evidence for short-range correlations in neutrino data?

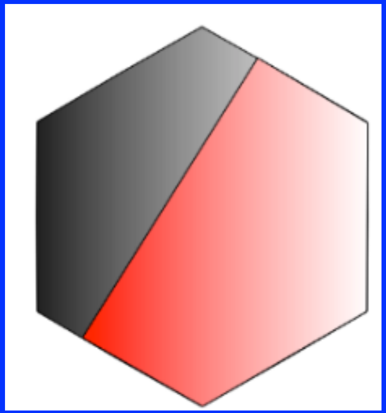
Minerva CC Cross-section Ratios

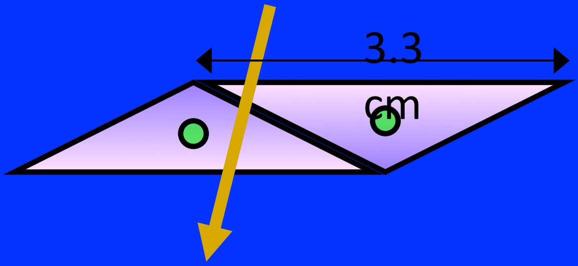
Cross-section ratios important

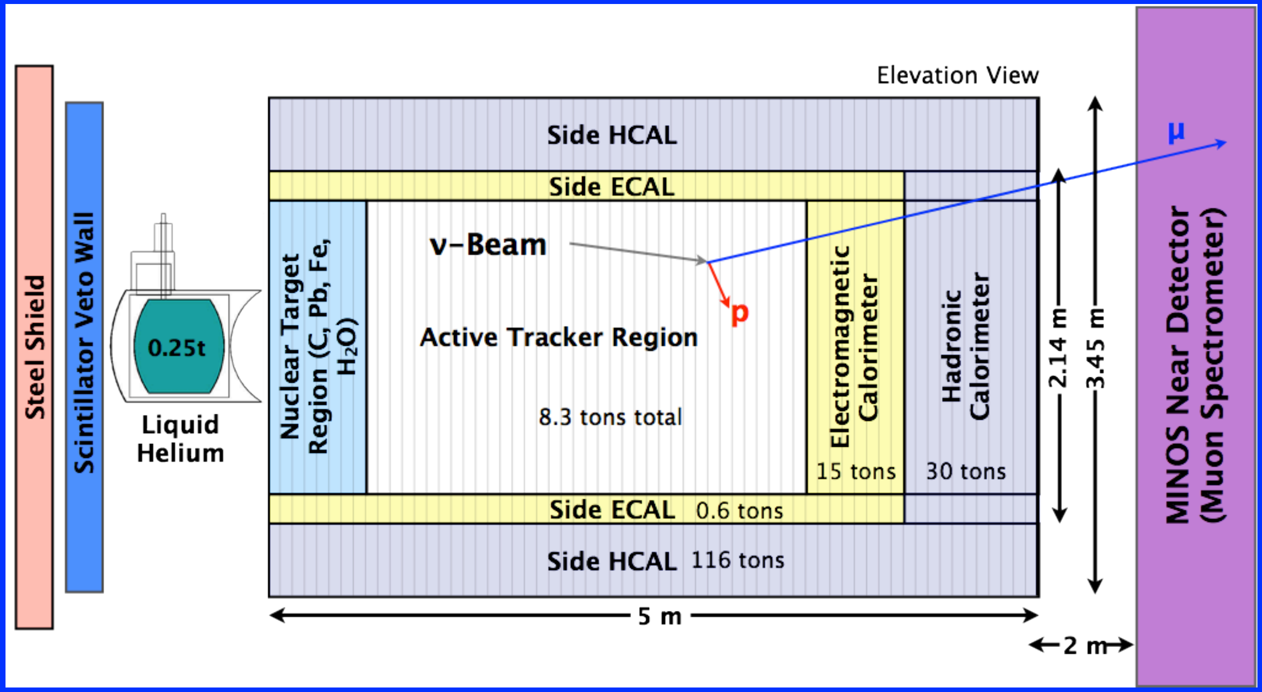
- Cross-section ratios of different nuclei can constrain models of the impact of the nucleus
- Important demonstration of the validity of a model
- Crucial for planning future experiments that have a large nucleus like argon

Minerva nuclear targets

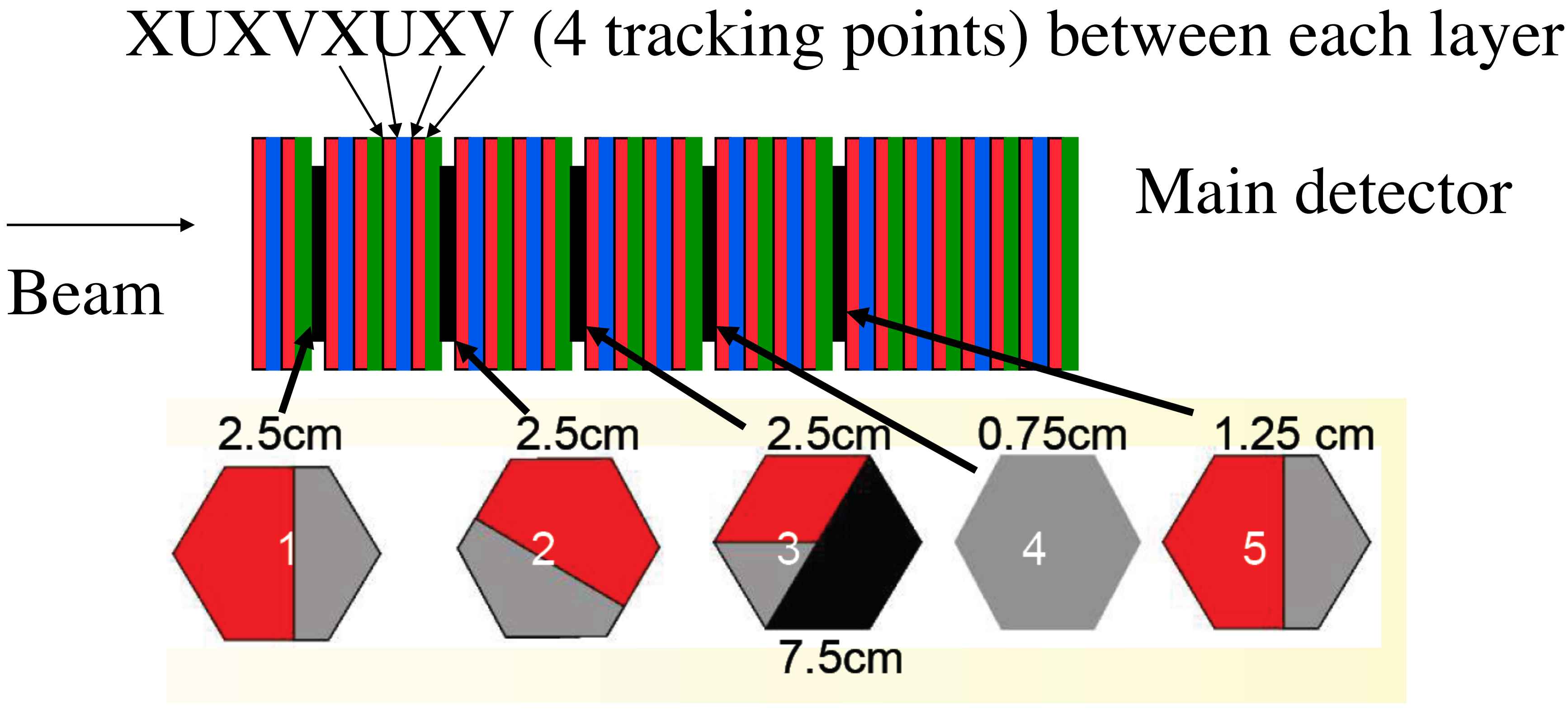
- Nuclear target region of Minerva allows us to look at cross-section ratios
- Begin with inclusive charged-current cross-sections
- In the future, such comparisons with specific topologies will be very interesting







Solid Nuclear Target Region



Carbon, Iron, Lead – mixed elements in layers to give similar systematics

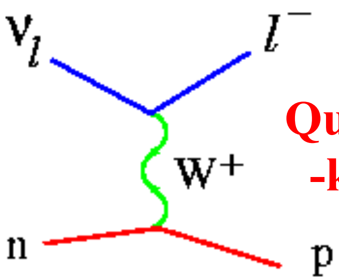
From: Jorge Morfin

Data Sample

- Data from March 2010 to April 2012
- NuMI low energy tune – peak at 3.5 GeV
- 95% muon neutrinos at peak energy

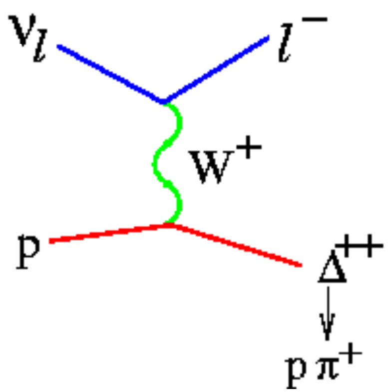
  2.94×10^{20} protons on target
- 5953 events on carbon, 19,024 on iron, 23,967 on lead, 189,168 on CH

Inclusive Neutrino Cross Sections

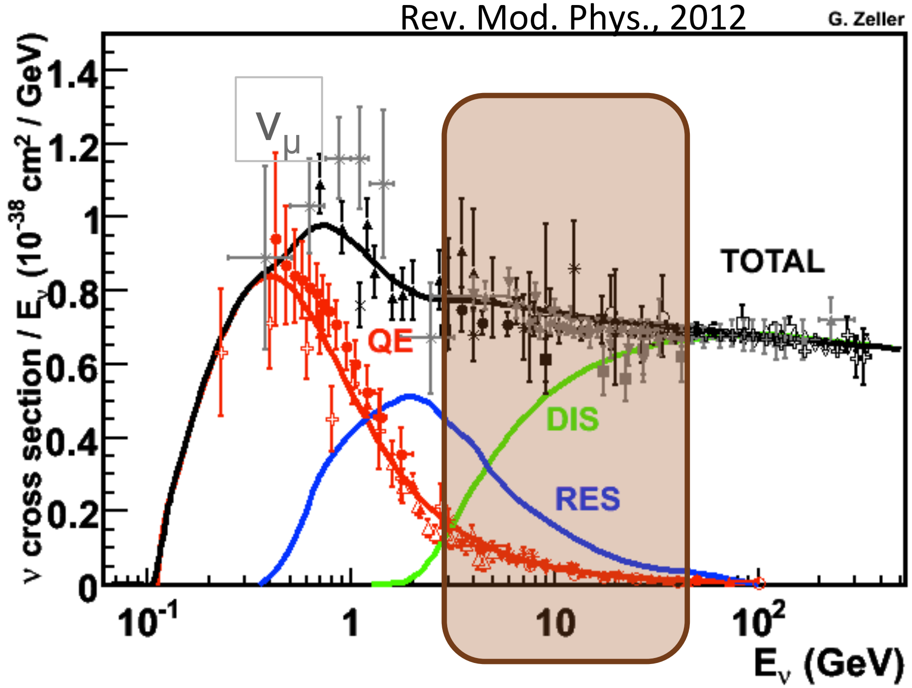


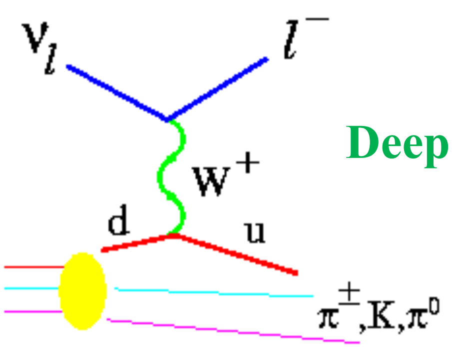
Quasi-Elastic (CCQE)
-knock out nucleon-

Resonance Production (Res)
-excite nucleon-



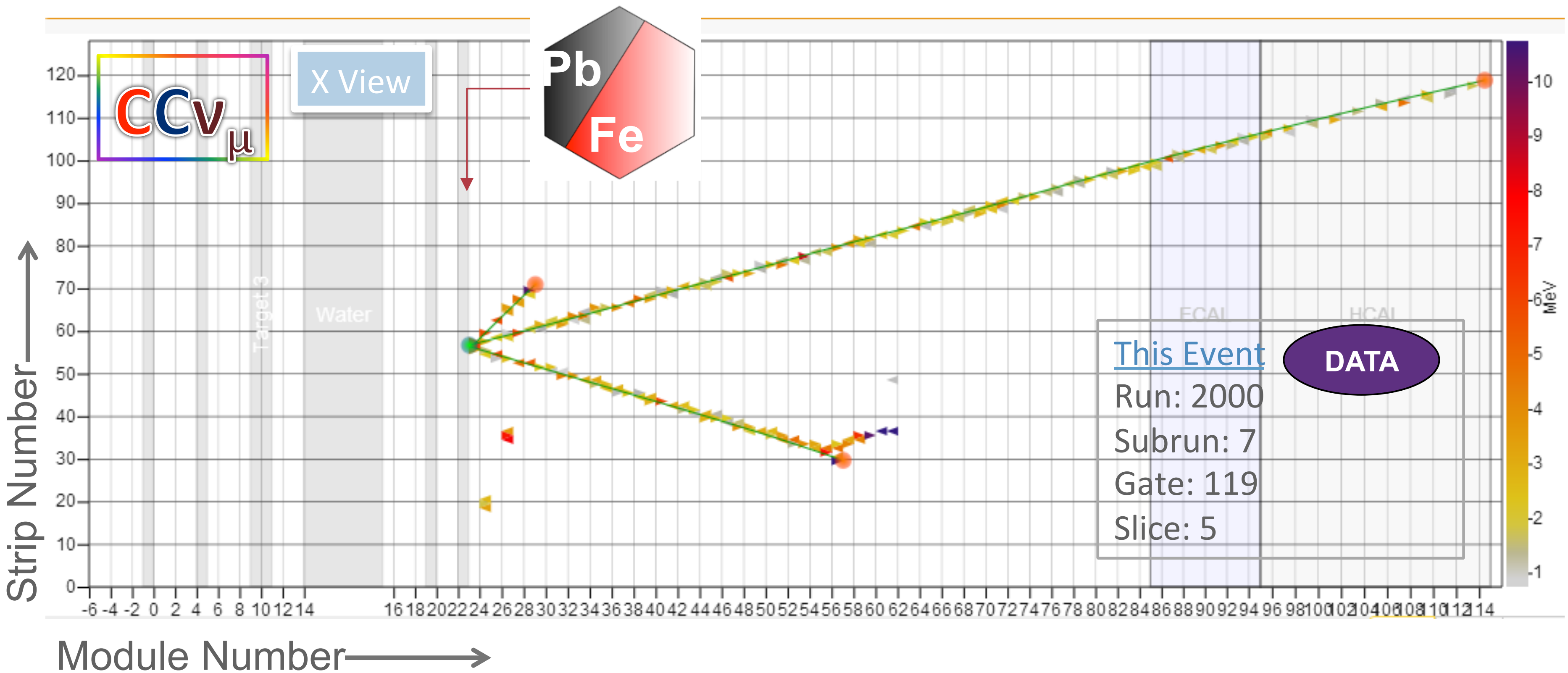
J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys., 2012





Deep Inelastic Scattering (DIS)
-destroy nucleon-

Event Selection



Event Topology

Muon must be matched to a momentum- and charge-analyzed track in MINOS ND

Interaction Material

Vertex must be in passive nuclear target or adjacent scintillator plane

Event Reconstruction

Hadronic Energy

Sum of non-muon visible energy.

Weight for passive material traversed.

$$\nu = E_{recoil} = \alpha \times \sum_{i}^{hits} \frac{E_i}{f_i}$$

Muon Energy

From range or curvature in MINOS.

Add energy lost in MINERvA.

Muon Angle

Fitted track slopes at vertex.

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

Unfold neutrino energy distributions

Use simulation of detector smearing

$$x = \frac{Q^2}{2M\nu}$$

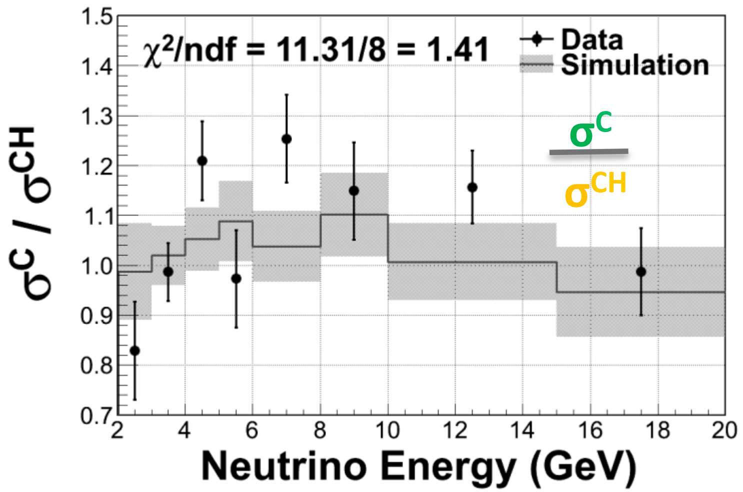
Do not unfold x distributions

Large migration among x bins

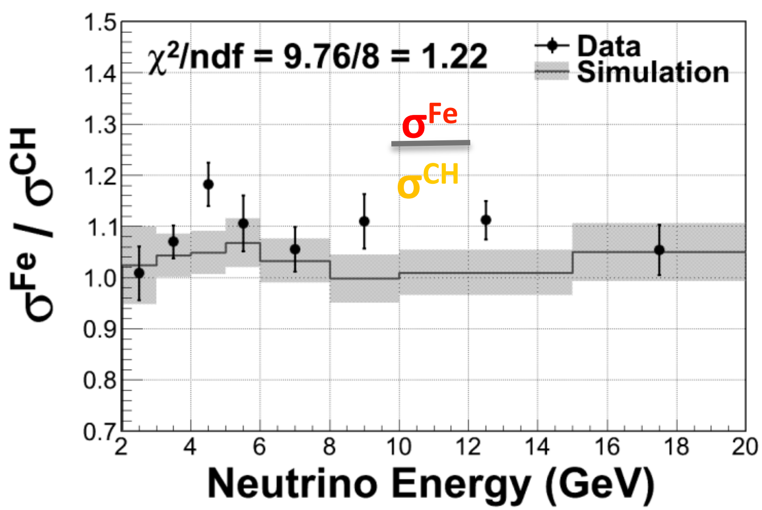
Avoid systematic effects

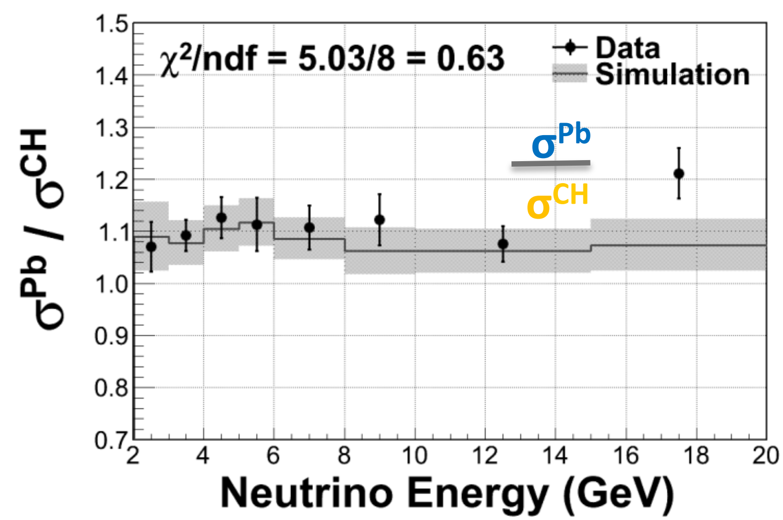
$$Q^2 = 2E_\nu \left(E_\mu - p_\mu cos\left(\theta_\mu\right)\right)$$

Neutrino Energy



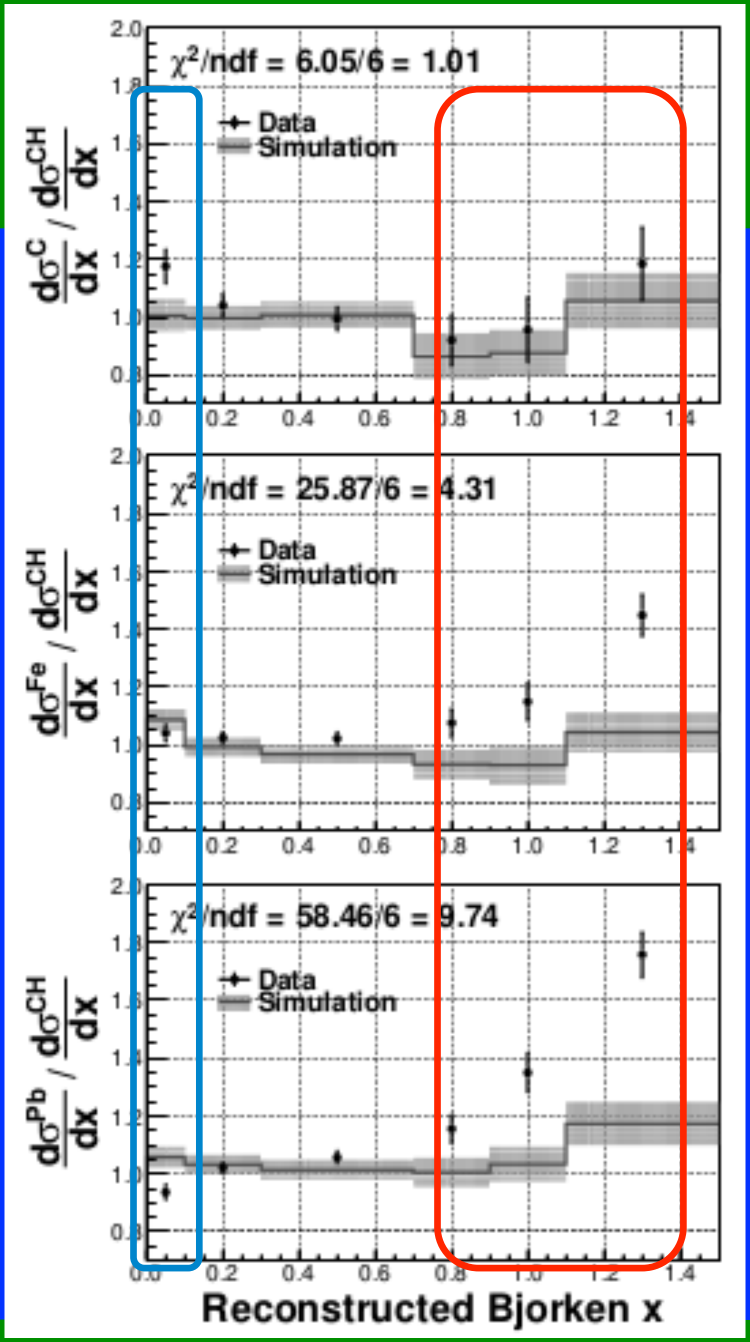
- No evidence of tension between our data and simulation here
  - Good news for oscillation experiments so far…





Results

- Discrepancies between data and simulation at both low and high x – both discrepancies increase as a function of A
- Low x due to insufficient shadowing in the simulation
- High x (dominated by quasi-elastic)

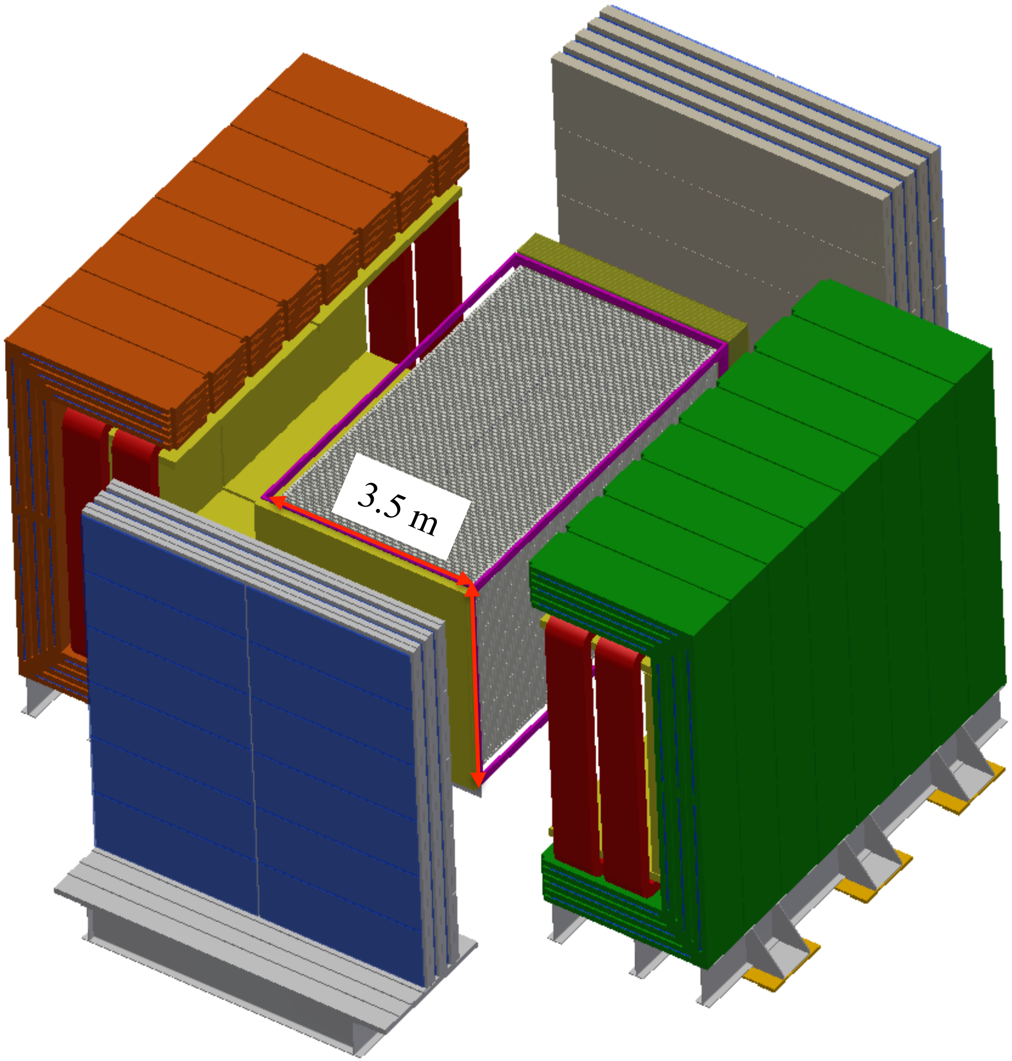


Conclusions

- Fine-grained trackers allow us to make precision neutrino measurements – even in broad-band neutrino beams
- The measurements can distinguish between models and even find new effects with statistical significance
- It is crucial for us to continue a program of measurements and incorporate these programs into neutrino oscillation experiments at the near site

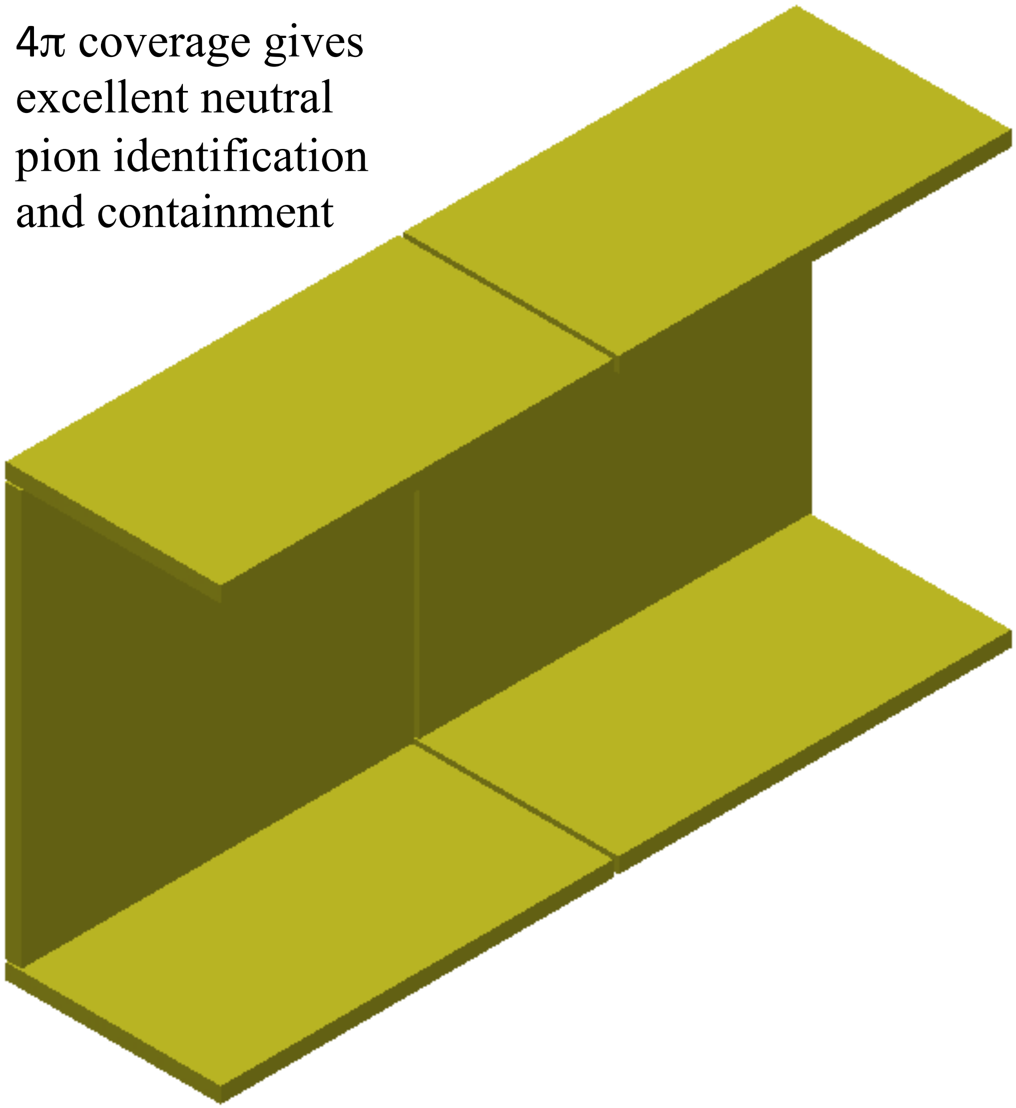
LBNE Near Neutrino Detector

- High precision straw-tube tracker with embedded high-pressure argon gas targets
- 4π electromagnetic calorimeter and muon identification systems
- Large-aperture dipole magnet
- Philosophy
  - make high-precision, high-statistics measurements of neutrino interactions with argon (far detector nucleus)
  - measure inclusive and exclusive cross-sections to build and constrain models to predict the event signatures at the far site *and correlate them with the true neutrino energy*
  - make detailed studies of electron (and muon) neutrinos and anti-neutrinos separately



Electromagnetic Calorimeter

4π coverage gives excellent neutral pion identification and containment



ECal designed to identify electrons and photons – critical for measuring neutral pion background

Sandwich of lead and plastic scintillator

Downstream ECal has 58 layers of 1.75mm lead with scintillator bars of 2.5cmx0.5cm profile (4m long)

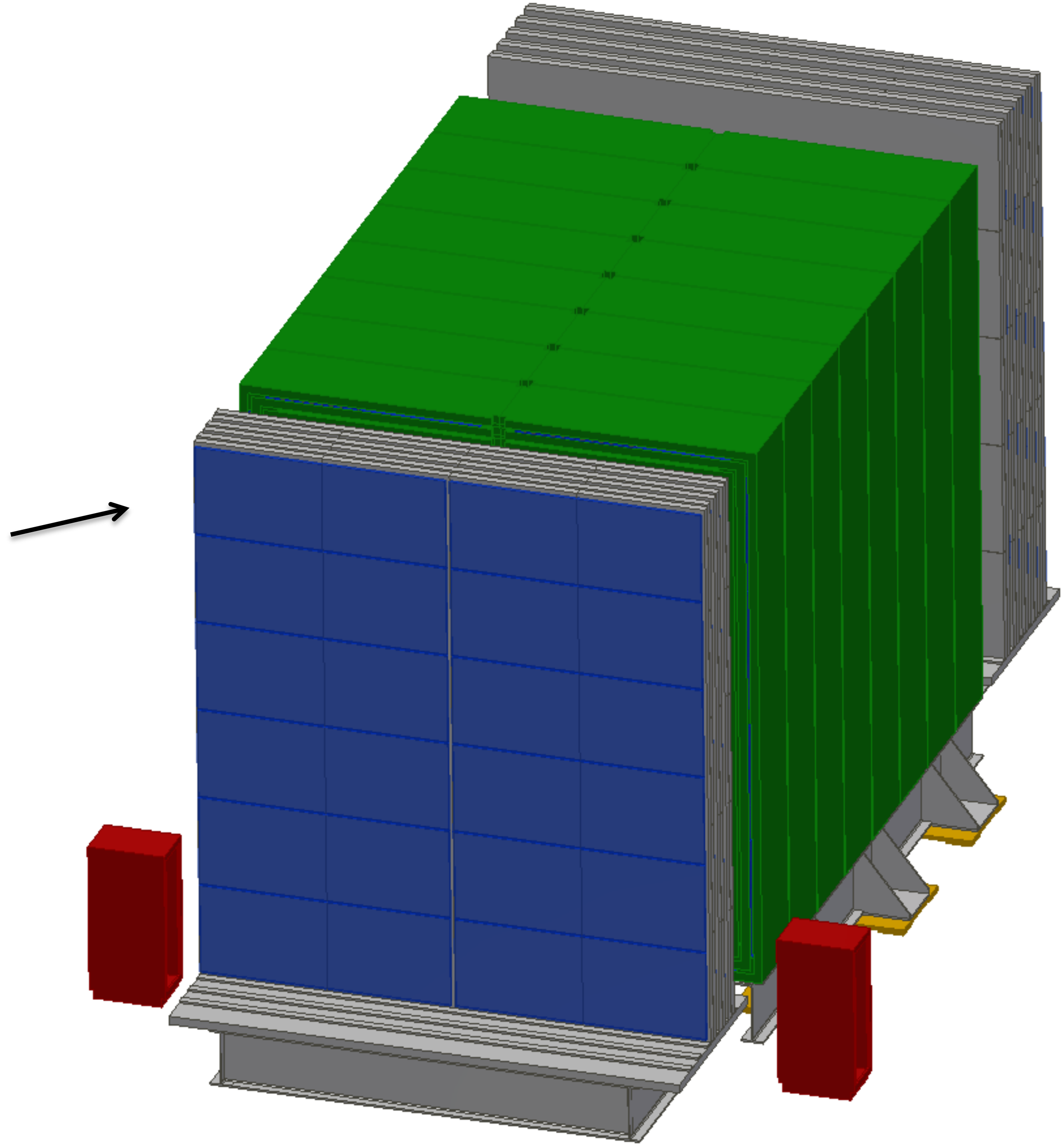
The Barrel ECal (shown at left) and Upstream ECal have 3.5mm of lead

Total lead mass is 110 tons, scintillator mass is 35 tons

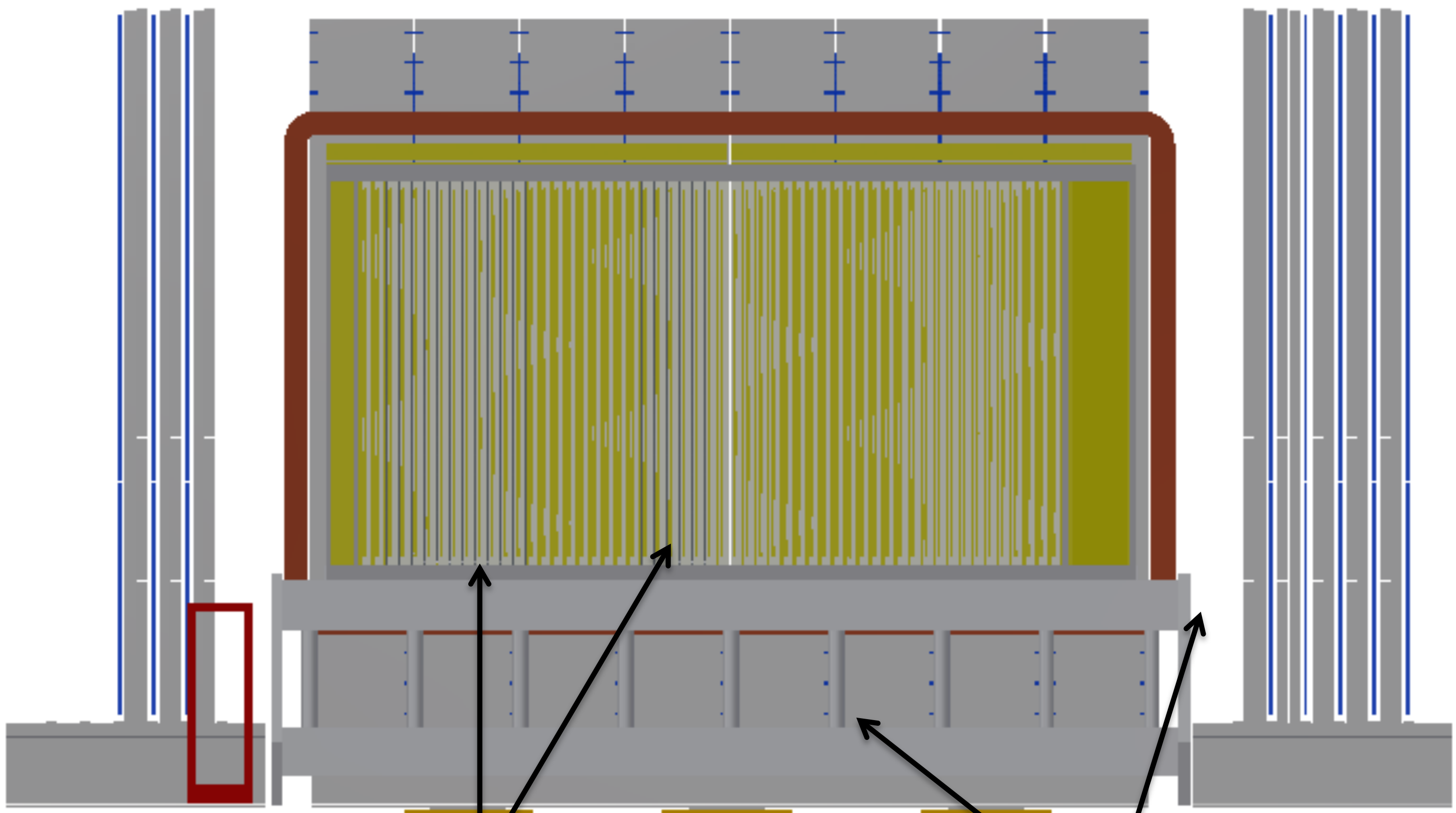
External Muon Identifier

Steel interleaved with Resistive Plate Chambers

Identifies muons – separates muons and charged hadron (e.g. pions)



LBNE Near Neutrino Detector



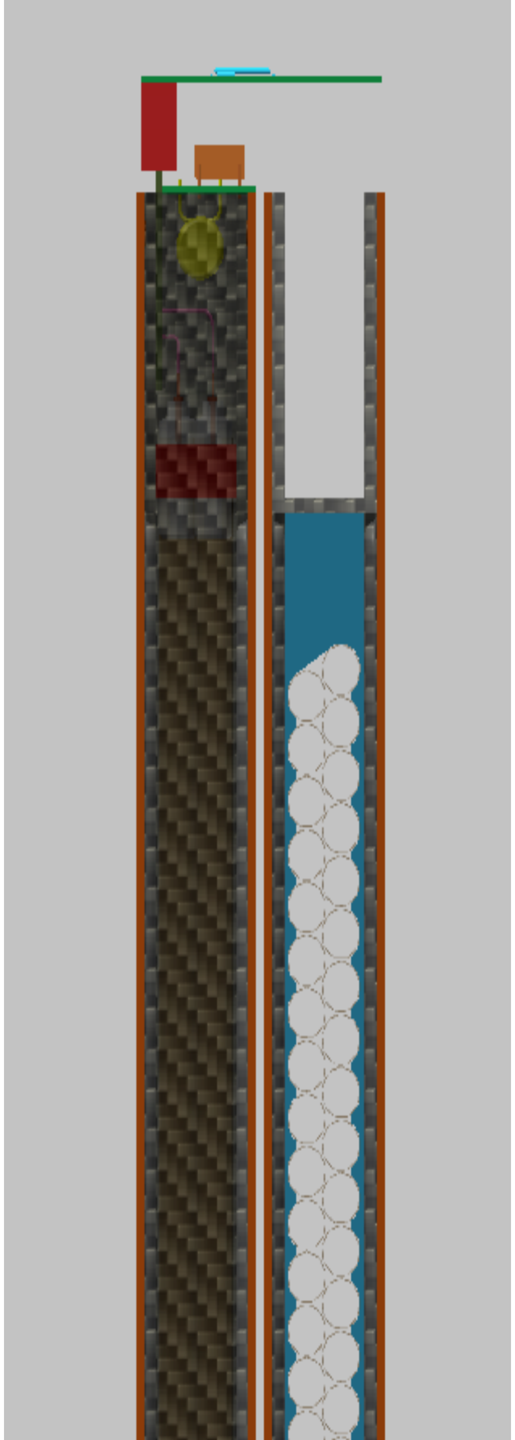
Transition Radiation Detector
Radiator foils, argon gas targets, other nuclear targets

Average density ~ 0.1 g/cm^3

UA1-style dipole magnet – 0.4 T

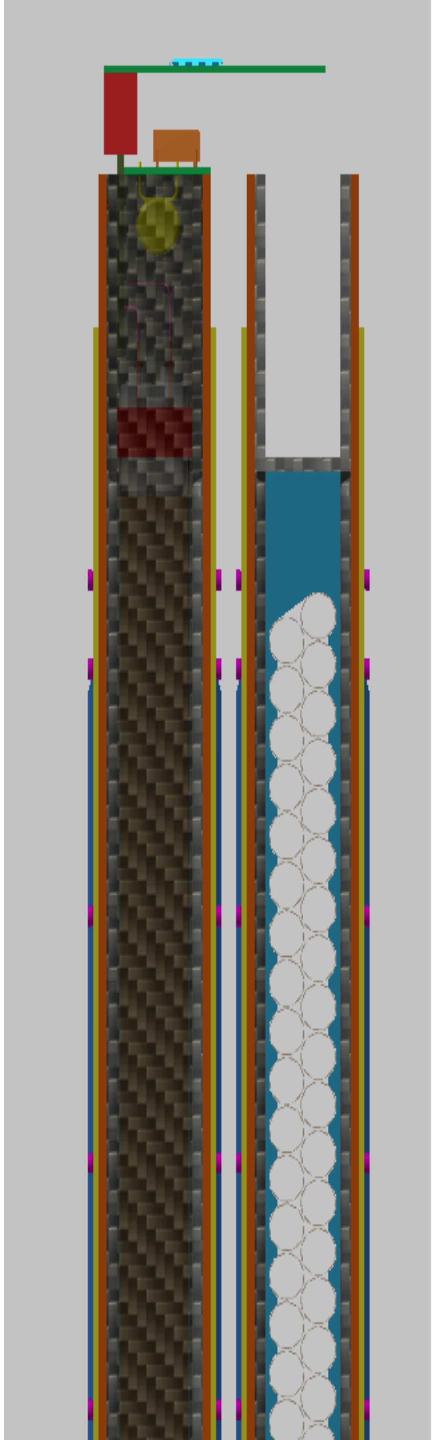
Muon identifier – also interleaved in magnet

Strawtube Tracker Module



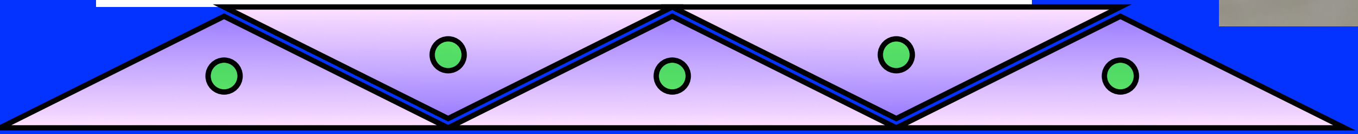
XX YY Module
62mm thick
leaving 18mm for
a nuclear target
module

TRD XX YY
Module
76mm thick



Basic Elements – Scintillator Bars

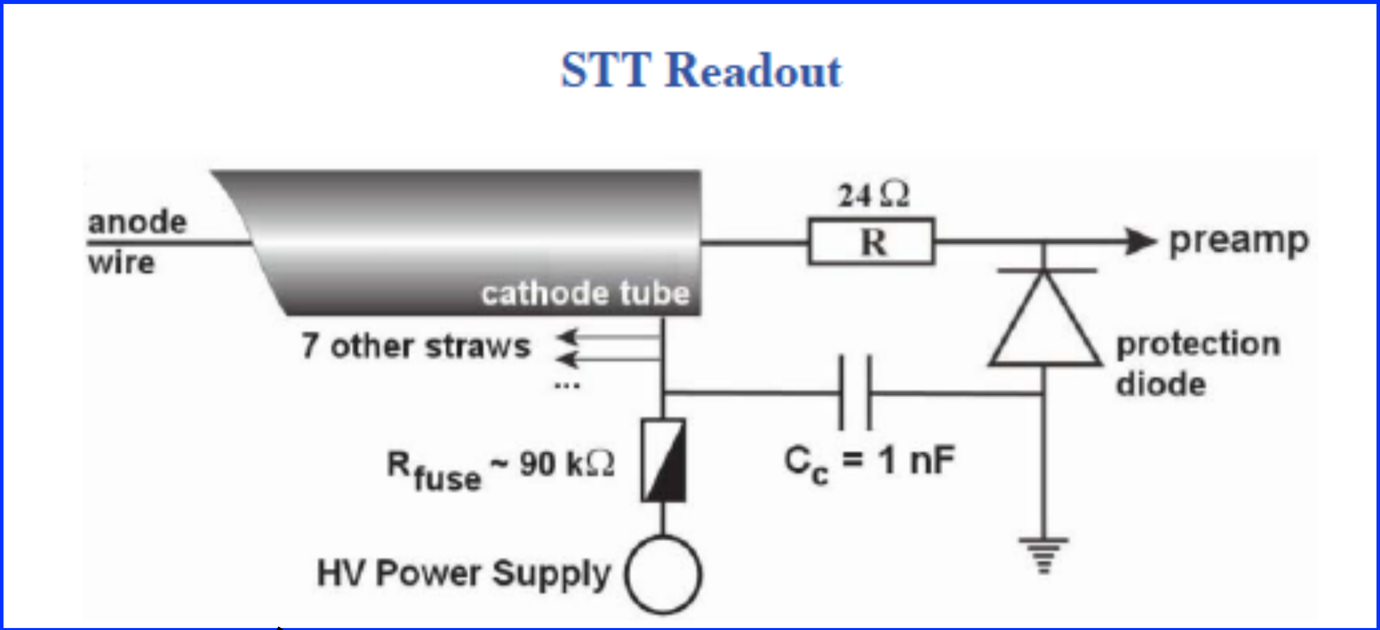
- Scintillation peaks at 420nm, cuts off at 400nm
- Collect scintillation light with wavelength shifting fiber – emission peak at 476 nm (green) – total internal reflection to end of bar
- Maximize collection efficiency with a reflector around the outside of the bar
- TO_2 reflecting material co-extruded with scintillator at FNAL
- Wavelength shifter attenuation length > 3m, so long bars are possible
- Versatile – used for tracking, ECal, Hcal
- Useful in moderate density applications

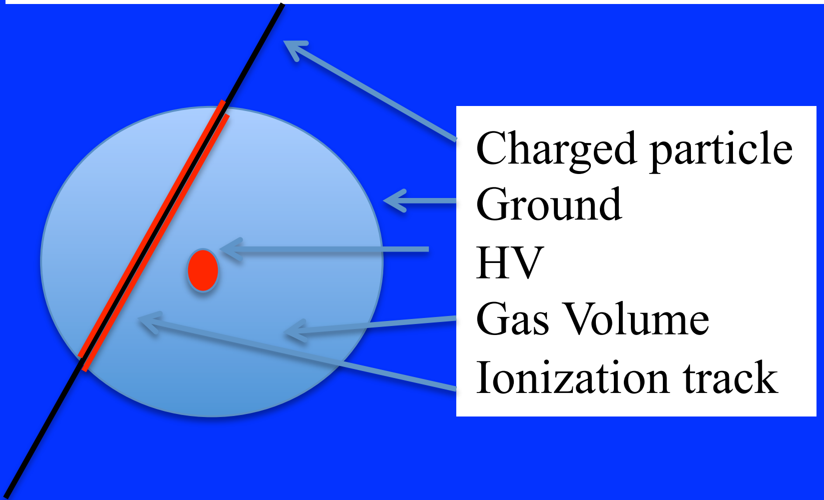


Basic Elements – Scintillator Bars

- Lab 5 at FNAL, polystyrene scintillator extrusion
- Co-extrusion with titanium dioxide successful, R&D on wavelength-shifting fiber co-extrusion

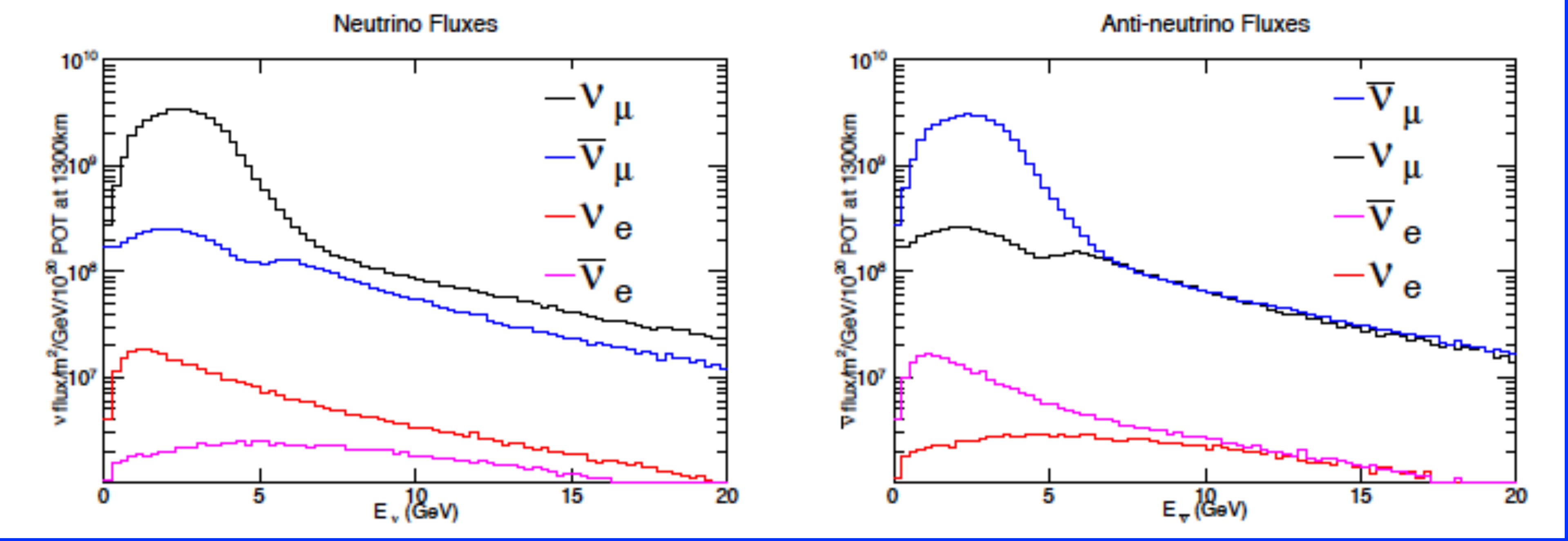
Basic Elements – Straw Tubes





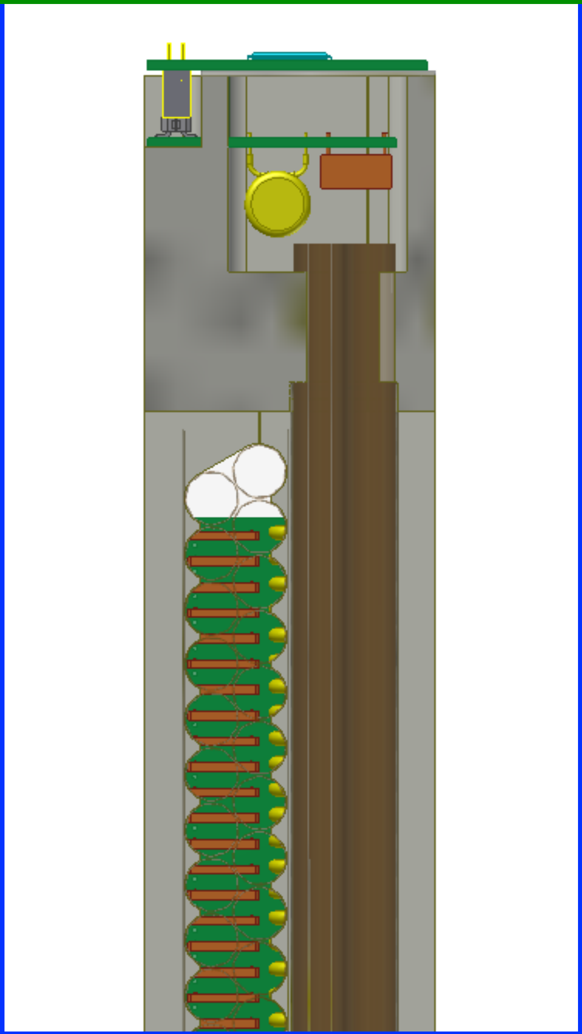
- Straws fabricated with conducting material (or coated with conducting material)
- Anode wire threaded through the straw (which can be a few meters in length)
- High electric field – especially near the anode results in electron multiplication
- Excellent response to charged particles
- Excellent in low-density applications

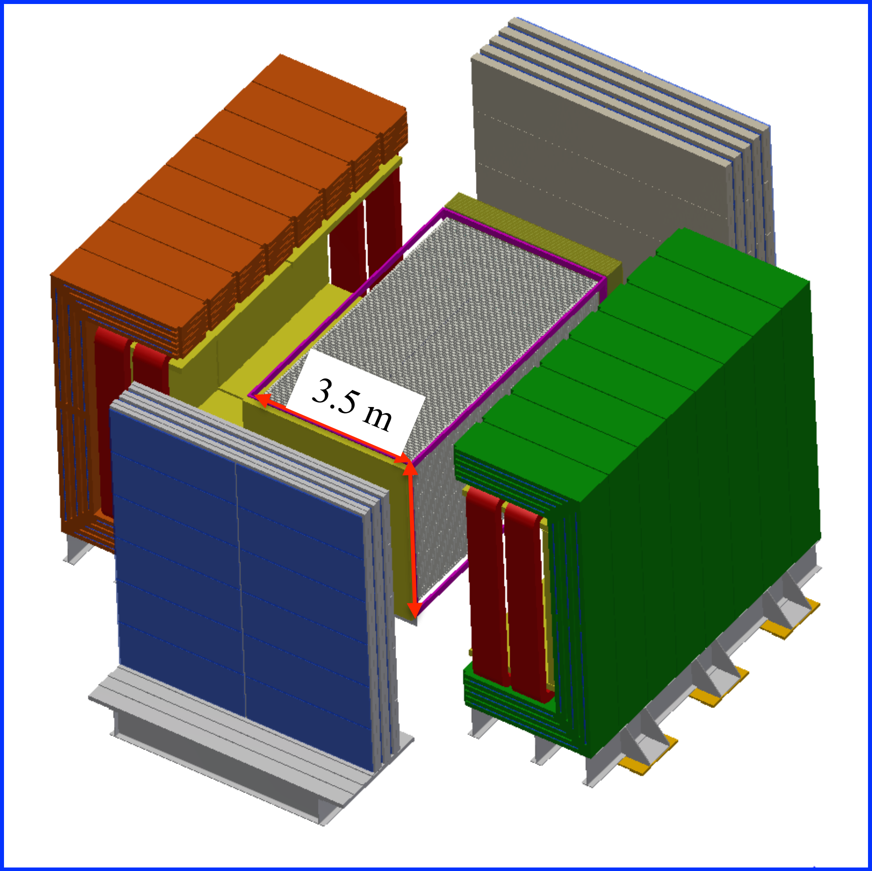
Characteristics of the Neutrino Beam



- Resultant Neutrino Beam (LBNE case)
- Neutrinos from few hundred MeV to 10's of GeV
- Predominantly muon (anti)neutrinos, but enough electron (anti)neutrinos to carry out studies in high-flux environments – it's a good thing, since LBL experiments are searching for electron neutrino appearance!

Tracking Detectors vs Monolithic Detectors

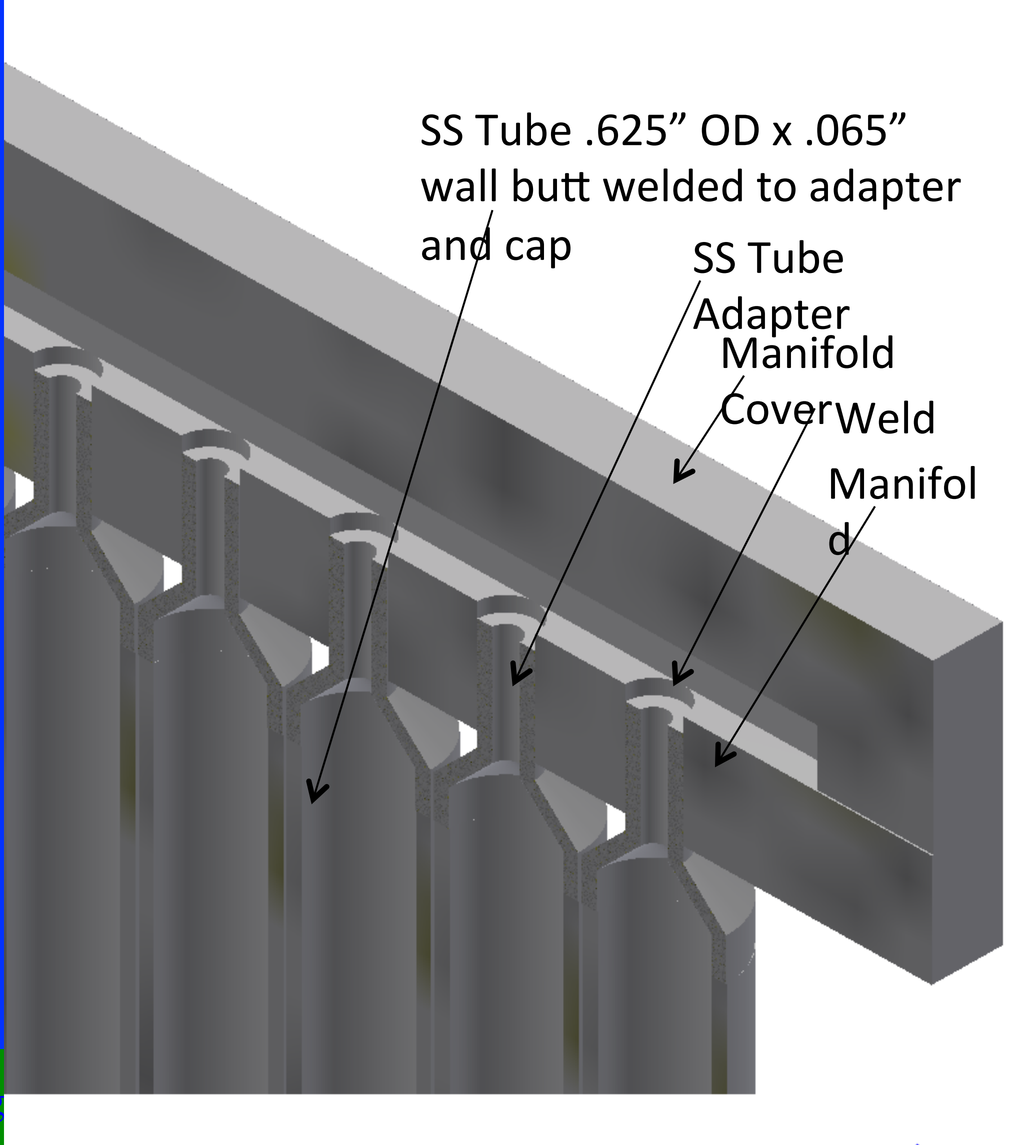




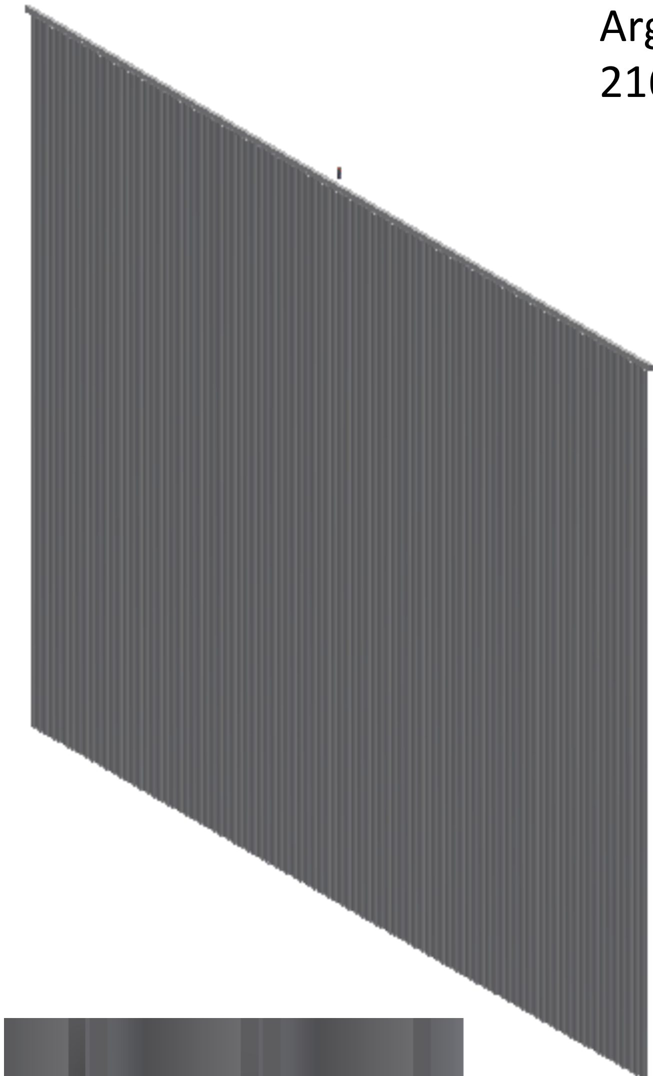
- Localization of particles by deploying many low-profile detector elements
- Detector elements throughout the volume
- Anisotropic distribution of elements
- Elements can be the target or targets can be separate from the elements

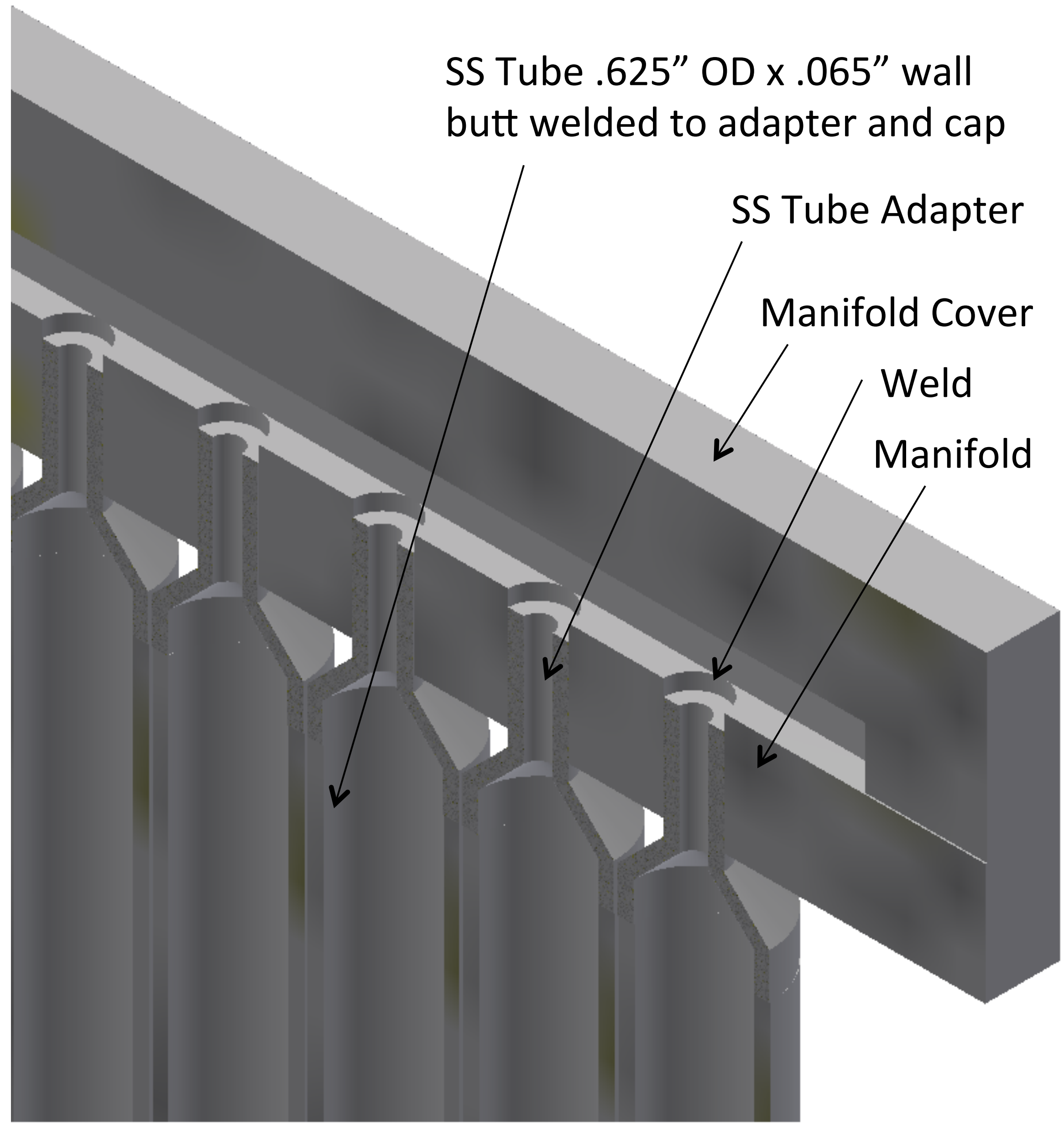
Gross Design Features – Nuclear Targets

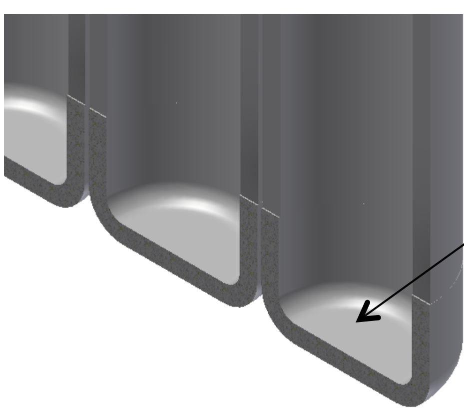
- Some materials require specialized target containment – gases, liquids
- In the case of liquid, liquid in, liquid out studies can be performed
- In the case of gas, can vary the pressure continuously to enable efficiency studies

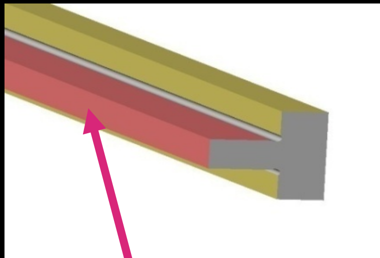


Argon Gas Target Assembly – SS Version
216 tu







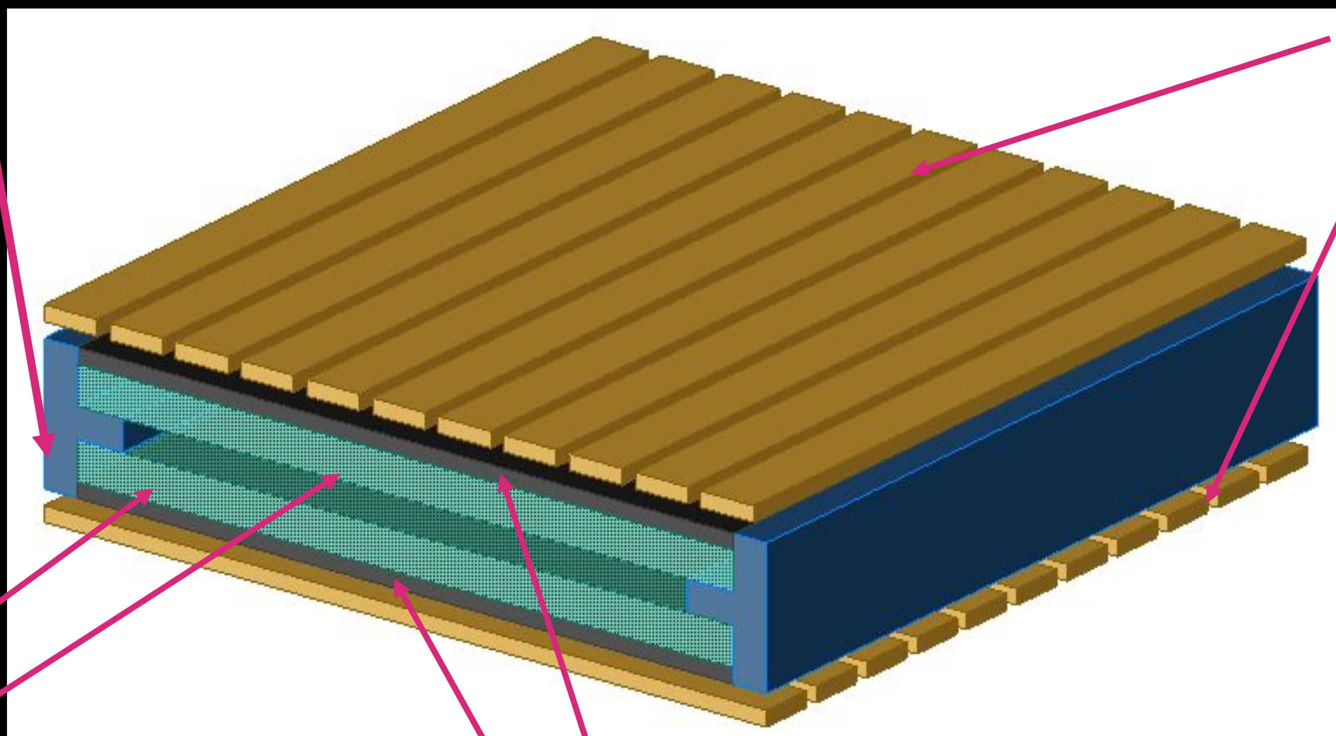


Construction of RPC

2 mm thick spacer

Two 2 mm thick float Glass
Separated by 2 mm spacer

Pickup strips



Glass plates

Resistive coating on the outer surfaces of glass

Basic Elements – Resistive Plate Chambers

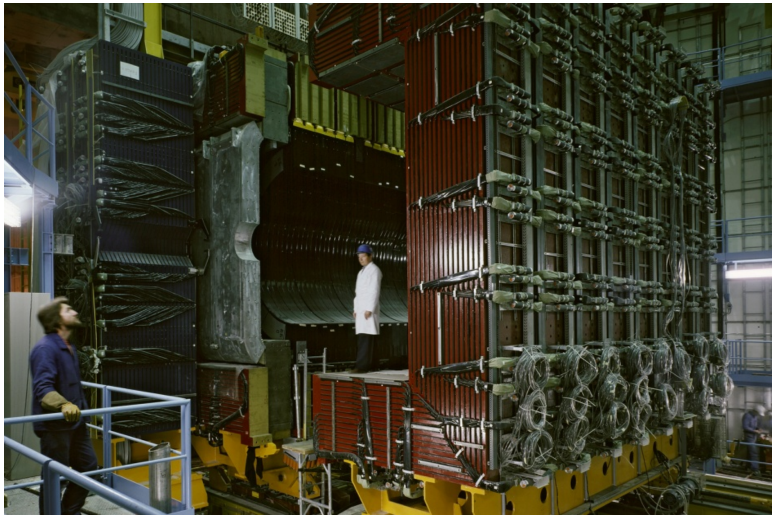
- RPCs can be built with glass or plastic (bakelite)
- Voltage drop across the plates (several kV)
- Spacers used to keep the plates separated (few mm thick)
- Charged particles induce a localized discharge
- Good timing resolution (25 ns)
- Enables inexpensive readout over a broad area

Examples of detectors - NOMAD

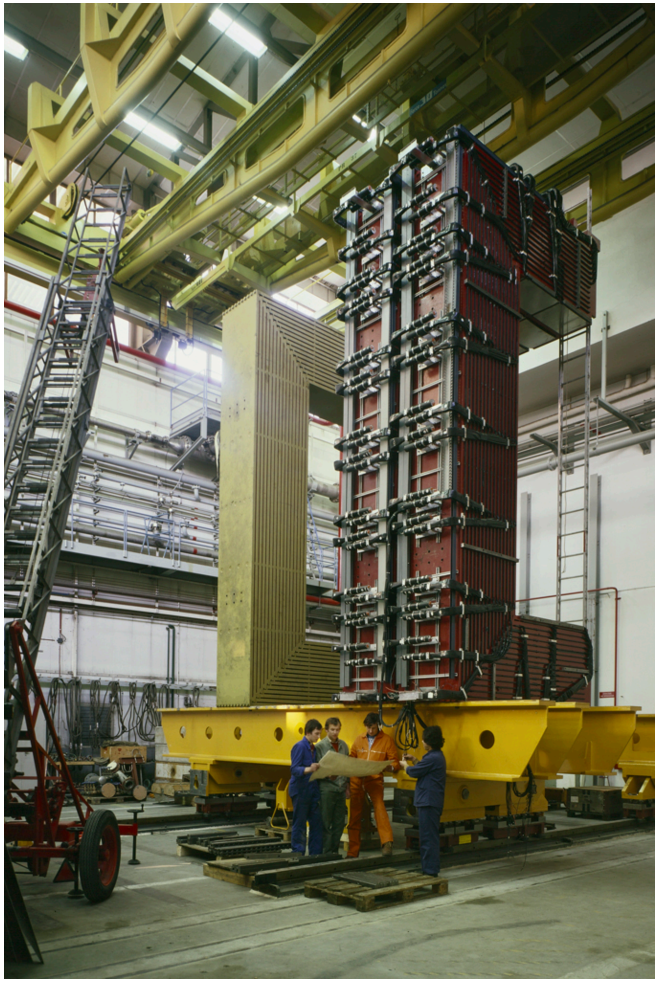
UA1 magnet at CERN:

Yoke material: EN S235JRG2, a European low Carbon steel

Yoke sections assembled, tested



Assembled magnet in hall



2 yoke sections on carriage, the total number of yoke sections is 16

UA1 magnet at CERN:

Essential to have a continuous magnetic circuit in steel yoke -

Assembled yoke sections on carriage in UA1 experimental hall at CERN. Total magnet weight 850. tons.

Data taking started in November, 1981.

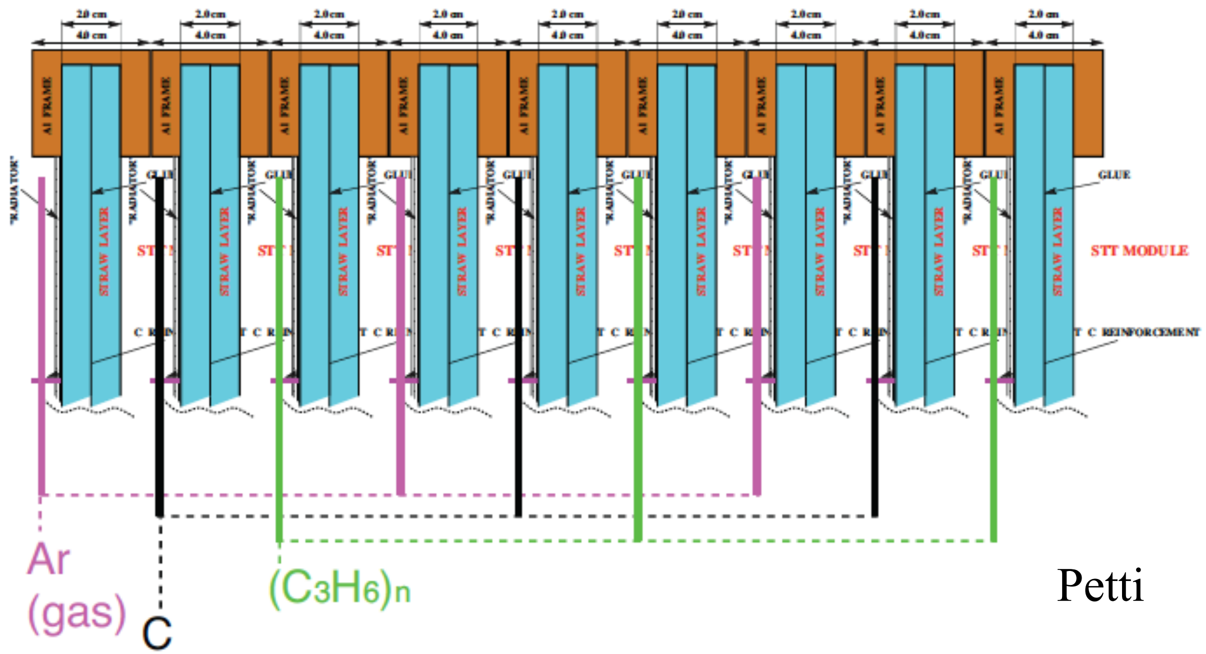
Operating properties: 10,000 amps, 576. V., resistance .0576Ω @ 40.^{o} C. Cooling water flow 50. liters/sec.

Original yoke costs – 2,000,000.00 *Euros* in 1978.

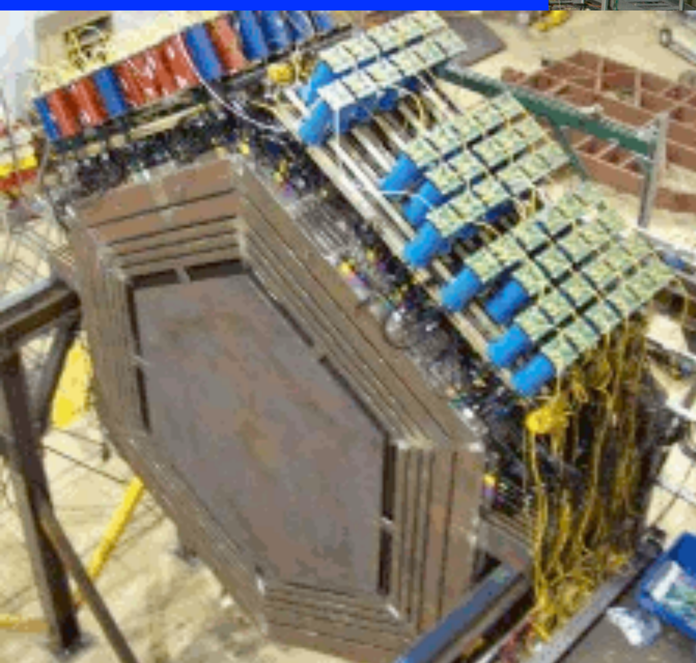
Sondheim

Gross Design Features – Nuclear Targets

- Geometry of typical fine-grained trackers such that planes of un-instrumented nuclear targets can be interspersed with tracking material
- This allows good possibilities for neutrino-nucleus interaction studies. Targets can even be swapped out.
- Care must be taken due to absorbed particles and side-going particles that will be missed.



Examples of detectors - Minerva



From Minerva website

Gross Design Features - Magnets

- Magnetic field useful for charge separation and momentum measurements
- Geometry of typical neutrino beams favors dipole configuration
- Low-density trackers (e.g. straw tubes) can do electron-positron separation
- Requires significant power – especially for cooling (few Mwatts)