Overview of Neutrino Experiments and Facilities

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Workshop on Intersections of Nuclear Physics with Neutrinos and Electrons

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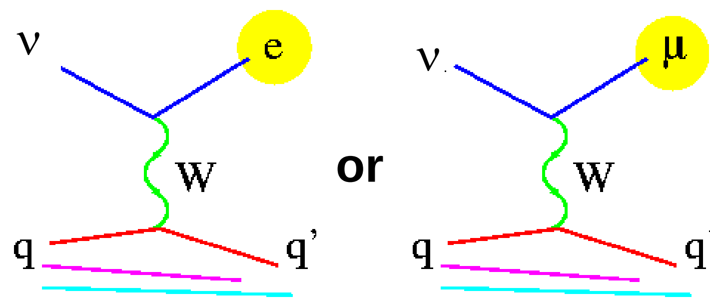
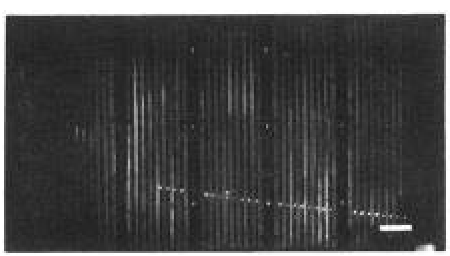
Outline

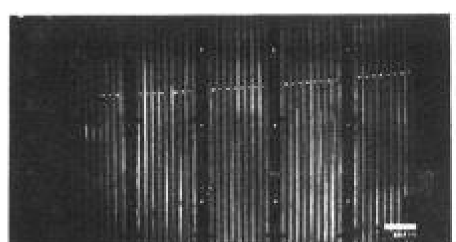
- Brief History of Neutrino Beams and Experiments
- What you can and cannot measure with neutrino scattering events
- What beamlines and detectors are currently (or soon to be) in operation

1st Neutrino Beam Experiment



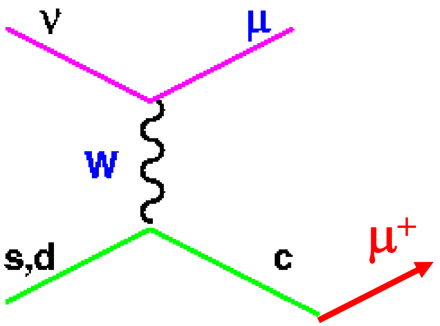
- 1960: Used to determine neutrinos have lepton flavor like muon and electron Nobel citation: "for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon-neutrino"



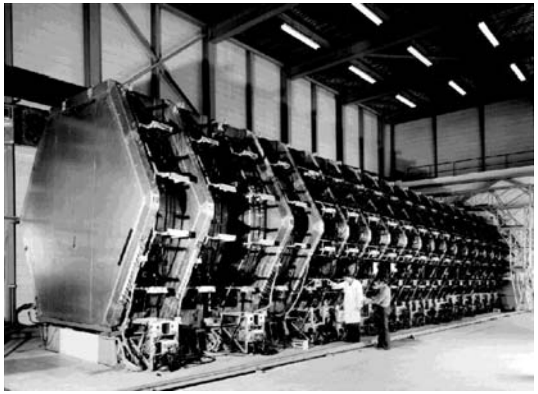


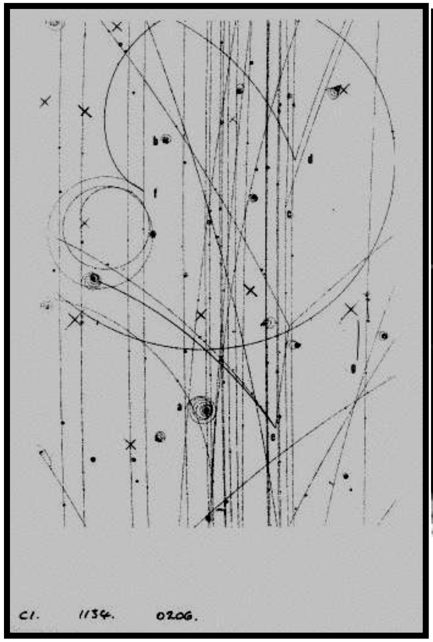
- If $\mu^+\to e^+\nu\bar{\nu}$, why not $\mu^+\to e^+\gamma$?
- 5BeV protons on Be Target (3.5×10^{17} of them)
- $\pi^+\to\mu^+\nu_\mu$
- 21m decay region
- 13.5m Fe Shield, 1 Ton Detector
- 34 single-μ events
- 5 background
- NO e-like events!
- PRL: 1960, NP: 1988
- Lederman, Swartz, Steinberger Brookhaven Nat'l Lab

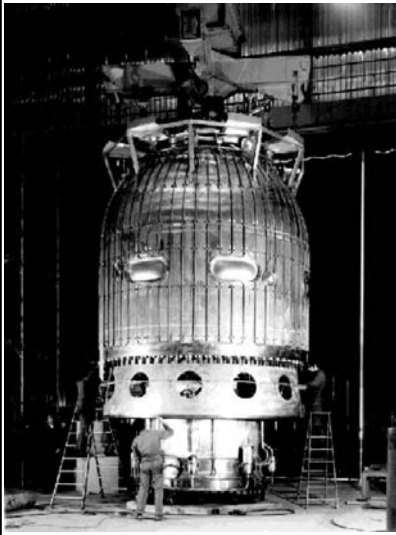
Neutrino Experiments



- Beamline Progression: Add focusing horns
- Detector Progression: look at more than just "is there a muon or not"
- Sixties and Seventies: Measurements of nucleon structure
  - CDHS, CHARM, CHARMII, BEBC



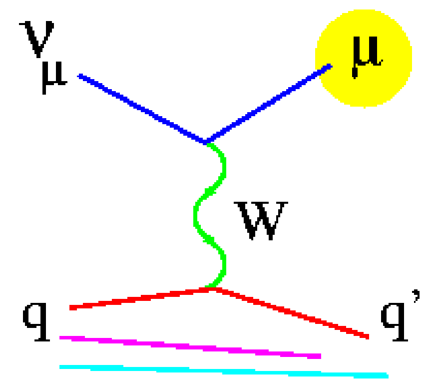




Trying to see what else gets produced with neutrinos…Resonances Kaons, Di-muons (evidence of charm)

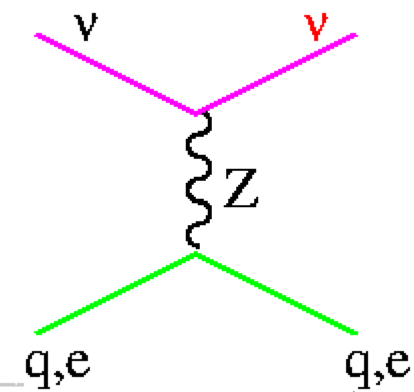
What is and isn't measured in ν Scattering: Charged Currents

- Outgoing Lepton
  - Momentum (p_μ)
  - Charge (maybe: determines if ν or νbar)
  - Flavor
  - Angle
- Other outgoing particles:
  - Total visible energy
  - If Particle Identification: could add rest masses too
- What is known *a priori*: ν direction

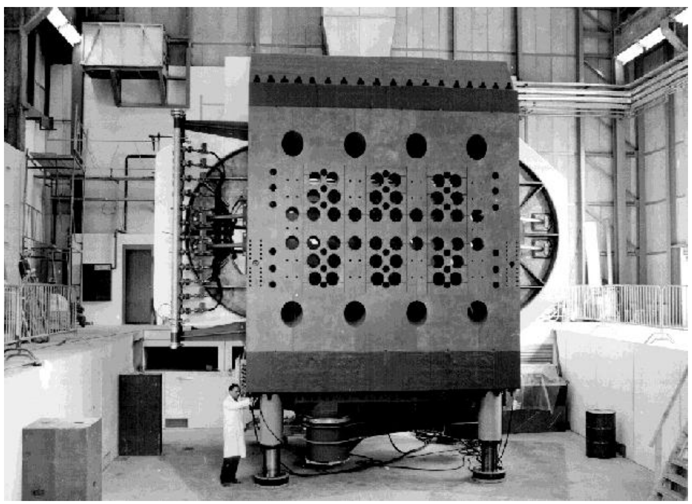


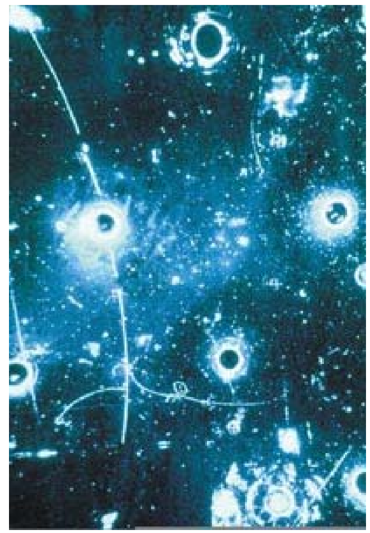
$$E_\nu = p_\mu + E_{\rm had} \,,$$
$$y = \frac{E_{\rm had}}{E_\nu} \,,$$
$$Q^2 = 4 E_\nu p_\mu \sin^2(\frac{\theta_\mu}{2})$$
$$x = \frac{Q^2}{2 M_{\rm N} E_{\rm had}} \,,$$

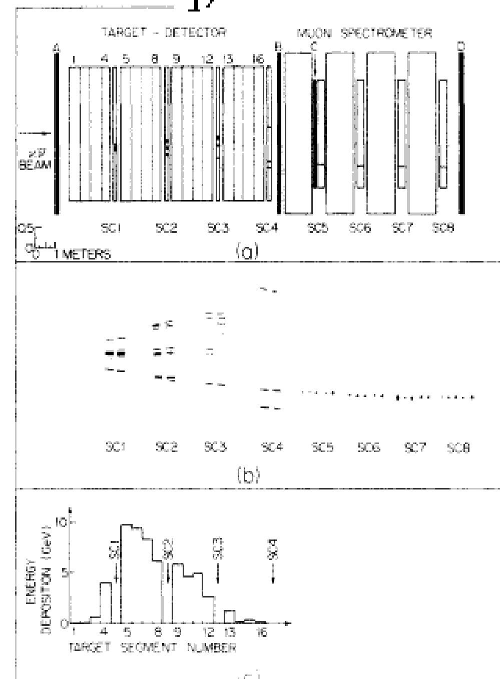
Neutral Currents with Neutrinos



- 1973: Neutral Currents first seen!
  - Gargamelle at CERN, E1A at Fermilab





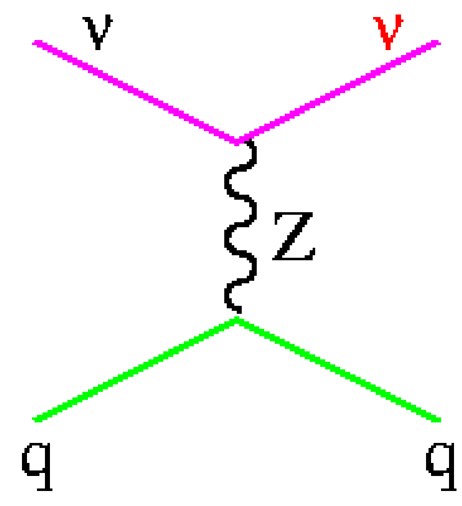


- 1980: Higher energy beams: higher Q^2, more events, better precision on $\sin^2\theta_W$
  - CHARM, CCFR

$$R^{\nu(\overline{\nu})} = \frac{\sigma_{NC}^{\nu(\overline{\nu})}}{\sigma_{CC}^{\nu(\overline{\nu})}} = \rho^2 \left(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W \left(1 + \frac{\sigma_{CC}^{\overline{\nu}(\nu)}}{\sigma_{CC}^{\nu(\overline{\nu})}} \right) \right)$$

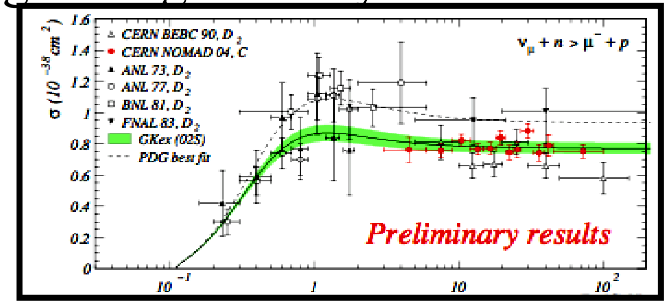
What is and isn't measured in ν Scattering: Neutral Currents

- Outgoing Lepton
  - Momentum (p_μ)
  - Charge (maybe: determines if ν or νbar)
  - Flavor
  - Angle
- Other outgoing particles:
  - Total visible energy
  - If PID: could add rest masses too
- What is known *a priori*: ν direction
- And if you have really pure beams of only one charge of pion, can know if it's a neutrino vs antineutrino...



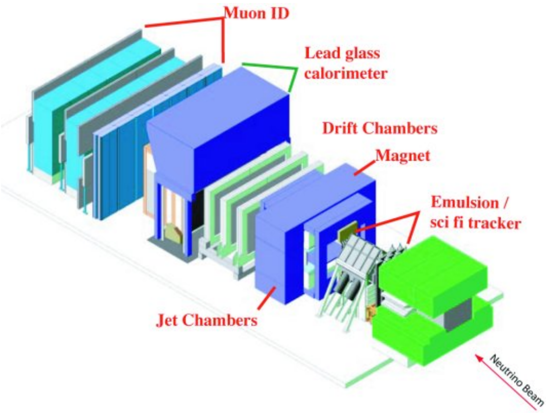
Neutrinos in the Nineties

- Searches for ν oscillations at short distances, high energies: maybe ν matrix is like quark matrix…
  - CHORUS, NOMAD
  - Structure functions and cross sections
  - R. Petti, NOMAD Nuint05, ^{12}C target

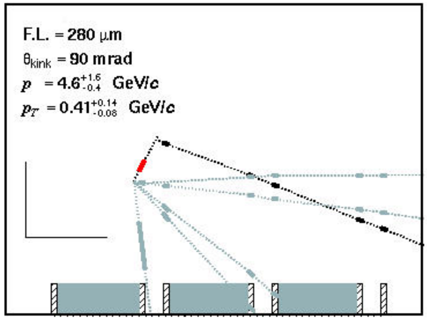


- 1996-7: NuTeV: High intenstiy sign-selected beam: pure neutrino or antineutrino beam for $\sin^2\theta_W$

$$R^- = \frac{\sigma^\nu_{NC} - \sigma^{\overline{\nu}}_{NC}}{\sigma^\nu_{CC} - \sigma^{\overline{\nu}}_{CC}} = \frac{R^\nu - rR^{\overline{\nu}}}{1-r}$$
$$= \rho^2 \left(\frac{1}{2} - \sin^2\theta_W\right)$$

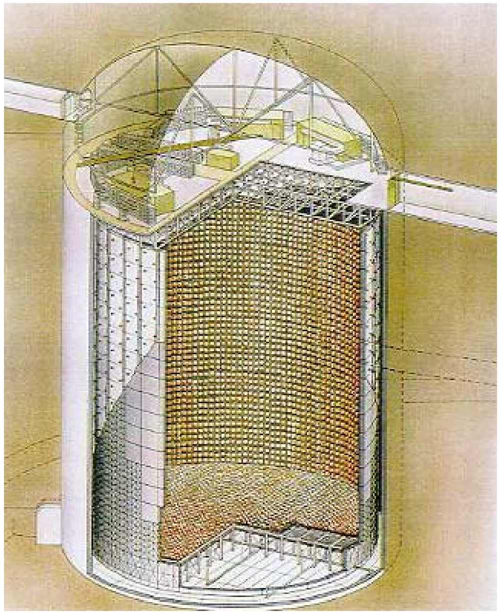


- 1996-7: DONUT: search for ν_τ measurement, last unseen fermion

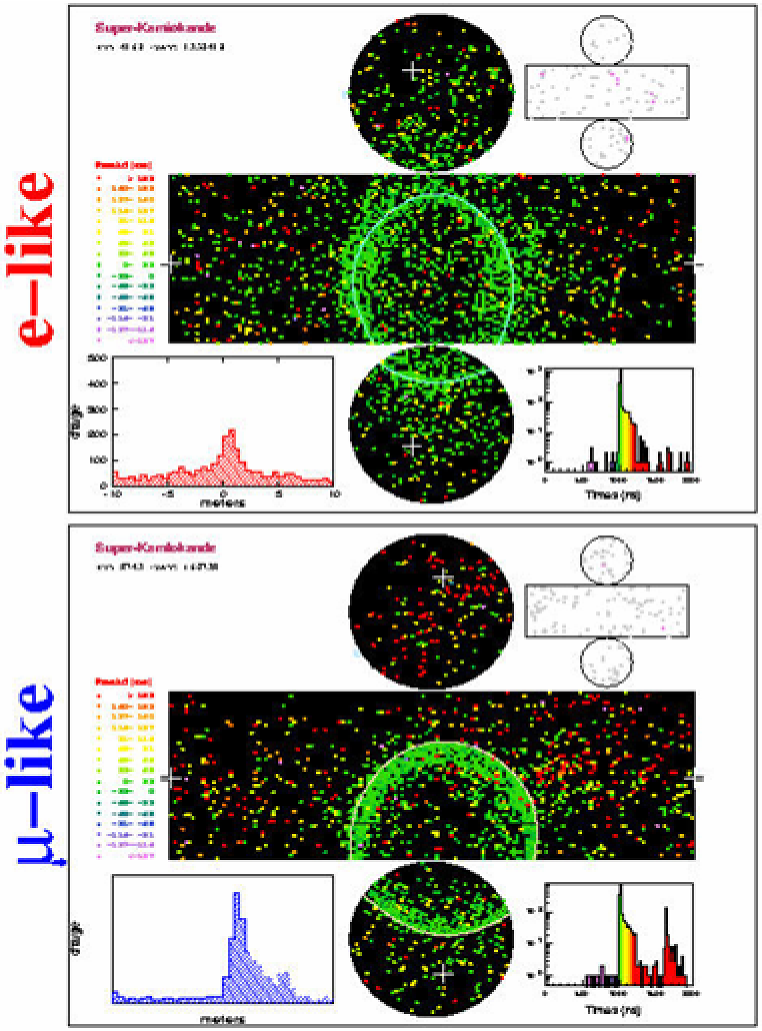


New Direction for ν Experiments

- 1998: "Smoking Gun Evidence" for Neutrino Oscillations in Atmospheric neutrinos
- 300km/GeV becomes an interesting place to look
- Water Cerenkov detector takes center stage

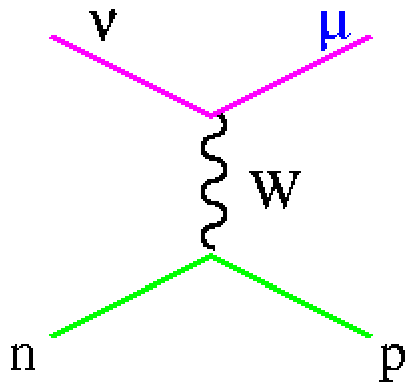


- 1993: LSND signal seen, implying 1km/GeV is another signal region

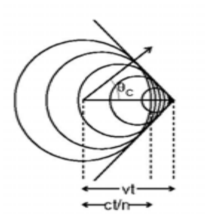


What is and isn't measured in ν Scattering: Water Cerenkov Detectors

- Outgoing Lepton
  - Momentum (p_μ)
  - Flavor
  - Angle
- Other outgoing particles
  - Only if momentum above Cerenkov threshold
- What is known *a priori*: ν direction



If you assume Quasi-Elastic Event:



$$p_{threshold} = \frac{m}{\sqrt{n^2 - 1}}$$

$$n(water) = 1.33 - 1.36$$

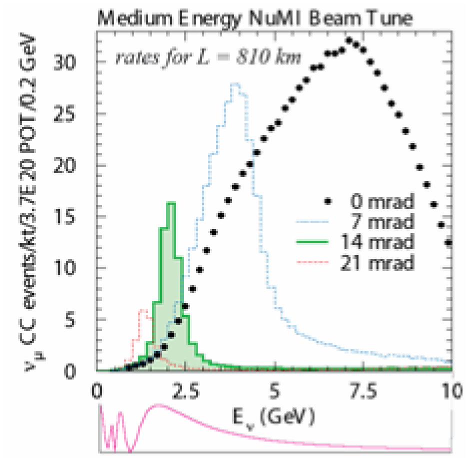
particle	Momentum Threshold
e	0.66MeV
μ	140MeV
π	180MeV
K	640MeV
p	1.2GeV

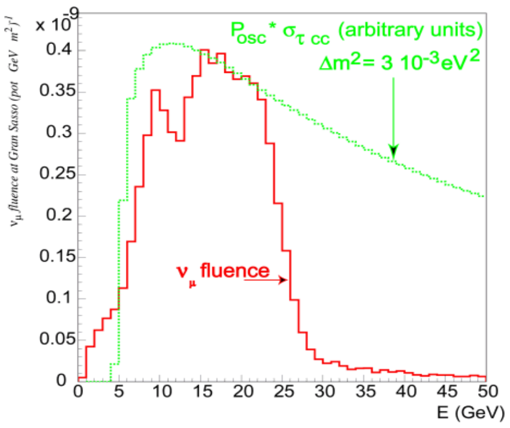
$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

$$Q^2 = 4E_\nu p_\mu \sin^2\left(\frac{\theta_\mu}{2}\right)$$

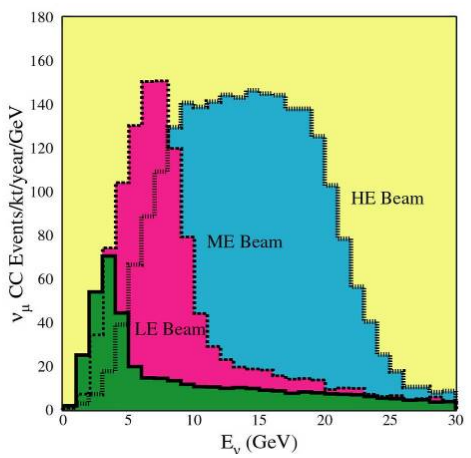
Sea Change in Neutrino Experiments

- Now: Lower and Lower Energies
  - K2K, MINOS: ν_μ disappearance over 250,735km
  - OPERA: $\nu_\mu \rightarrow \nu_\tau$ over 732km
  - MiniBooNE: $\nu_\mu \rightarrow \nu_e$ over 1km
  - T2K, NOvA: $\nu_\mu \rightarrow \nu_e$ over 295, 810km

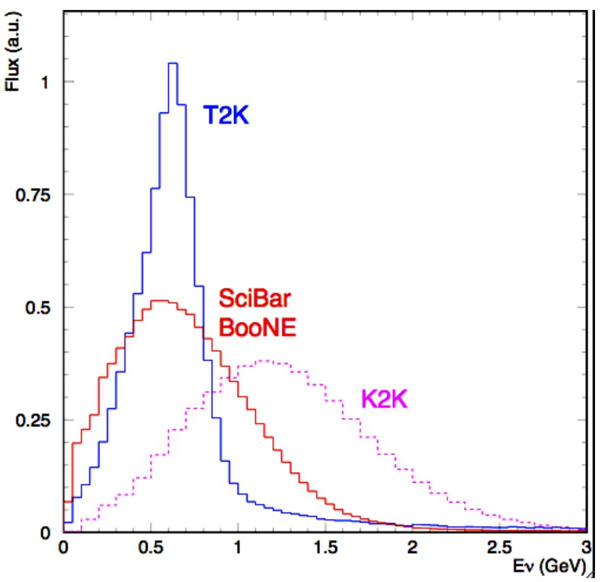




Opera

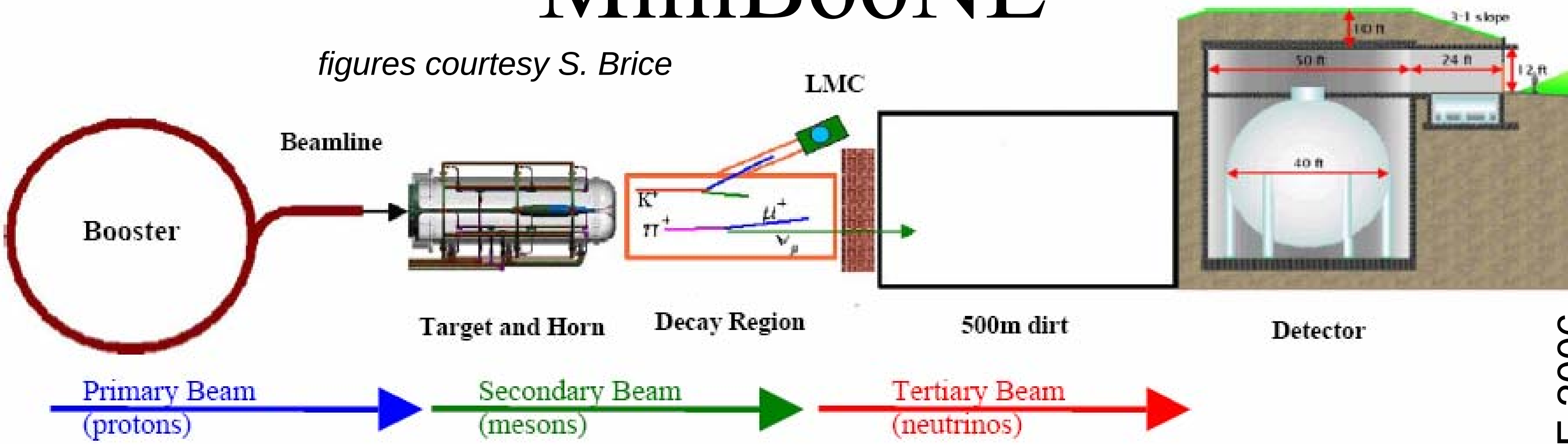


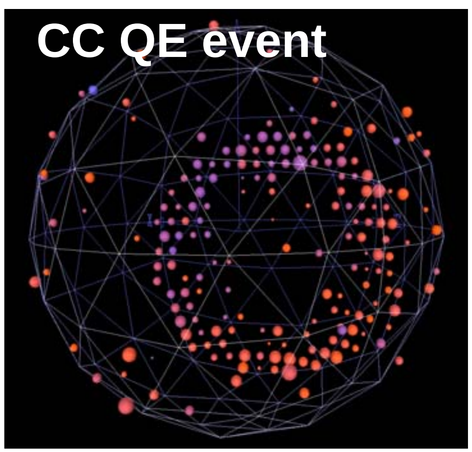
MINOS

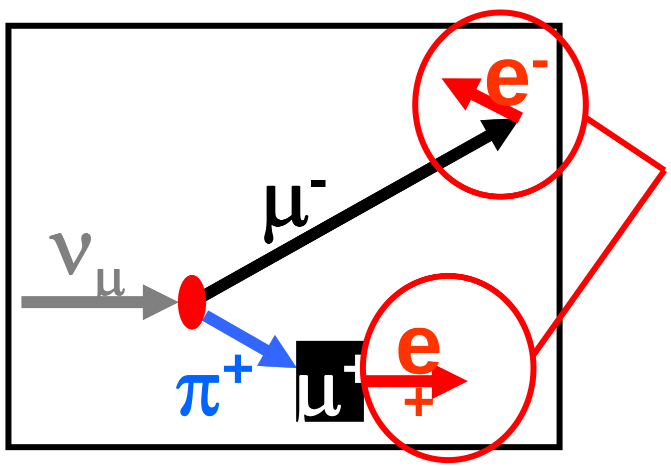


MiniBooNE

figures courtesy S. Brice







- New kinematic "trick"
  - events with 2 decay electrons
  - unique, results in 84% purity

Plots courtesy G.Zeller, NOVE 2006

MINOS

Goal: precise ν_μ disappearance measurement

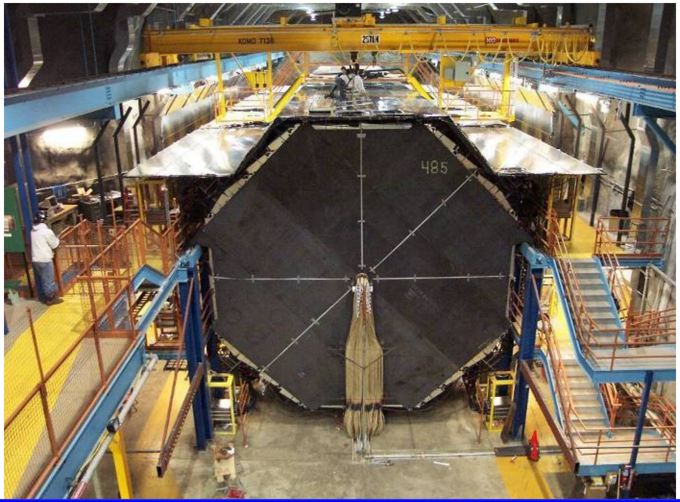
Gives $\boldsymbol{\delta m^2_{23}}$

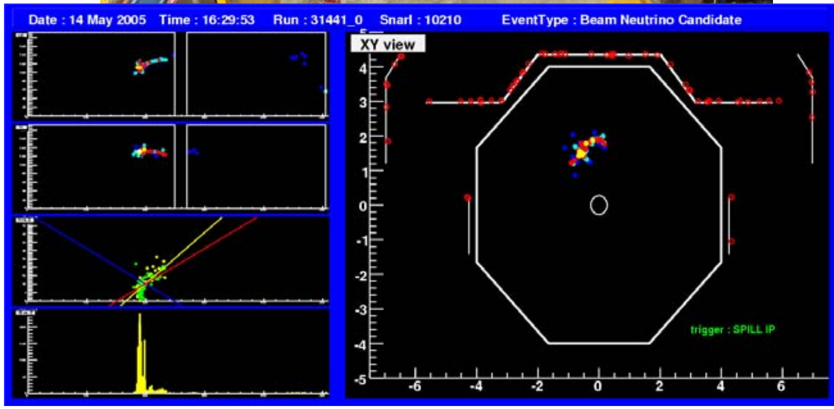
735km baseline

5.4kton Far Det.

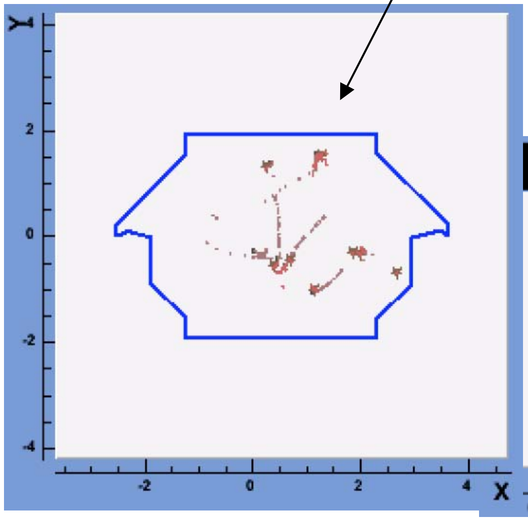
1 kton Near Det.

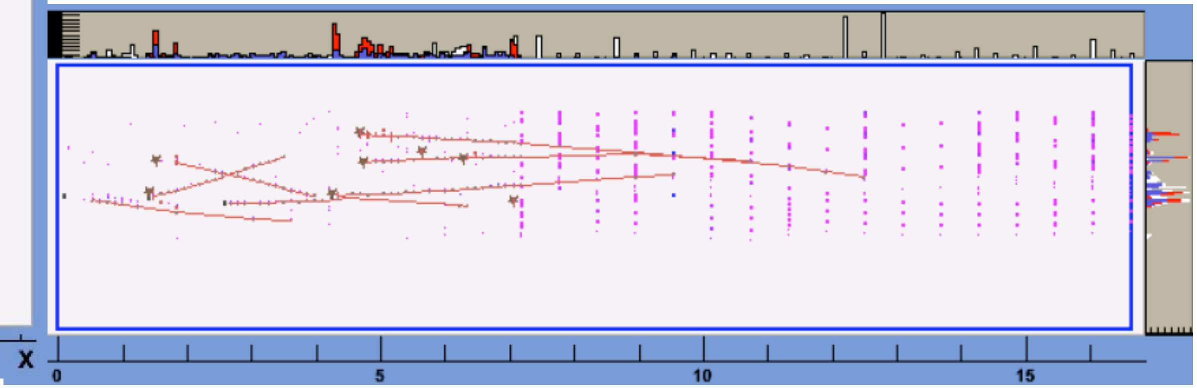
Running since early 2005





Near Detector:
Events in 10μsec!



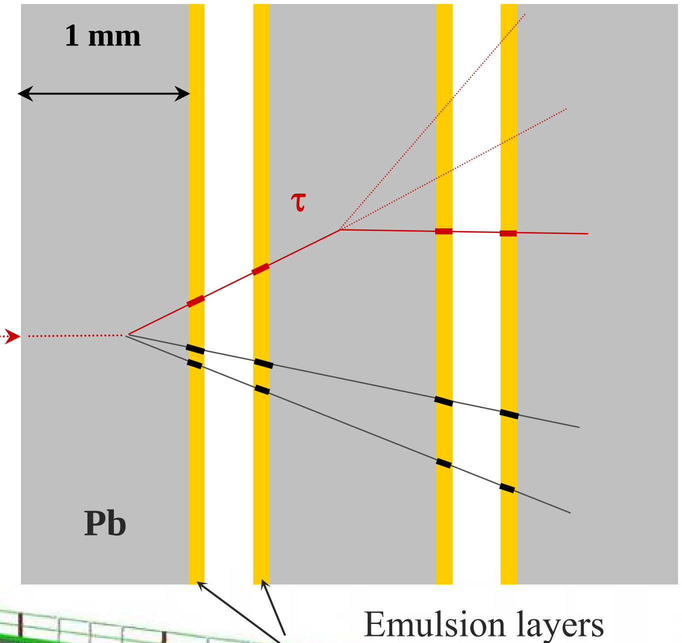


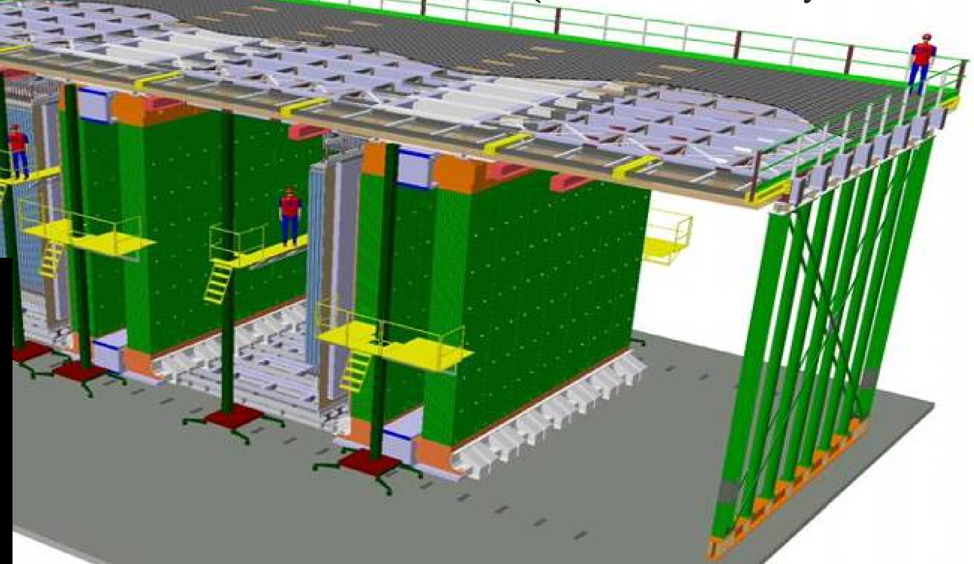
OPERA

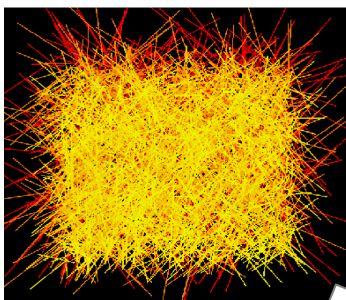
Goal: ν_τ appearance

- handfuls of ν_τ events/yr
- Thousands of other CC events/year, but scanning takes time
- No near detector

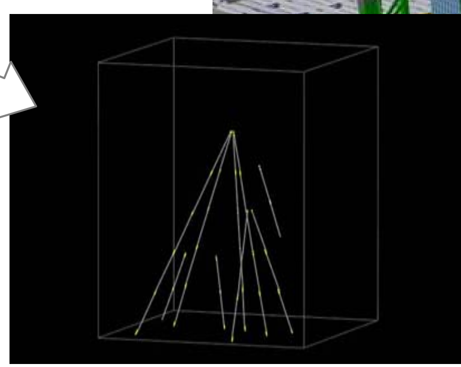
1.8kTon







Vertex reconstruction

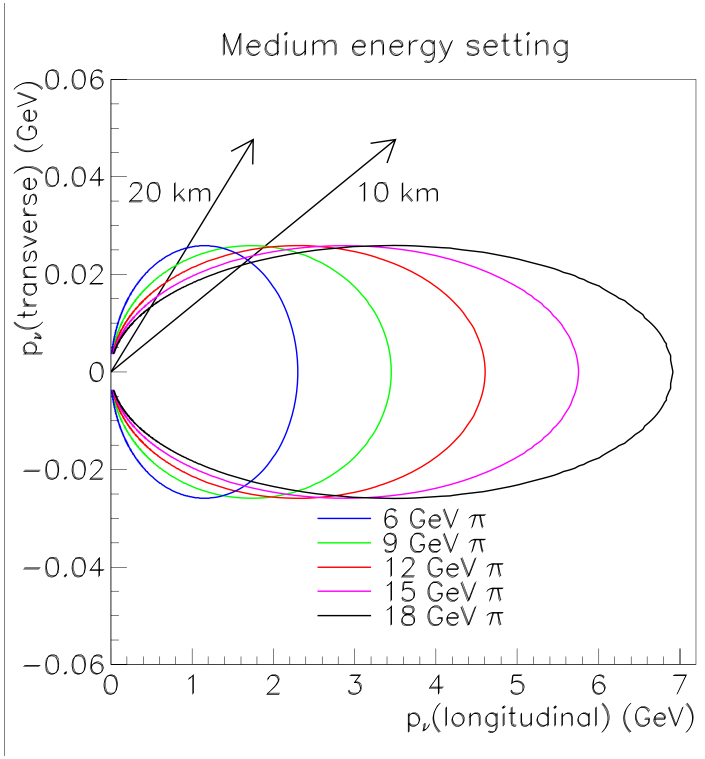


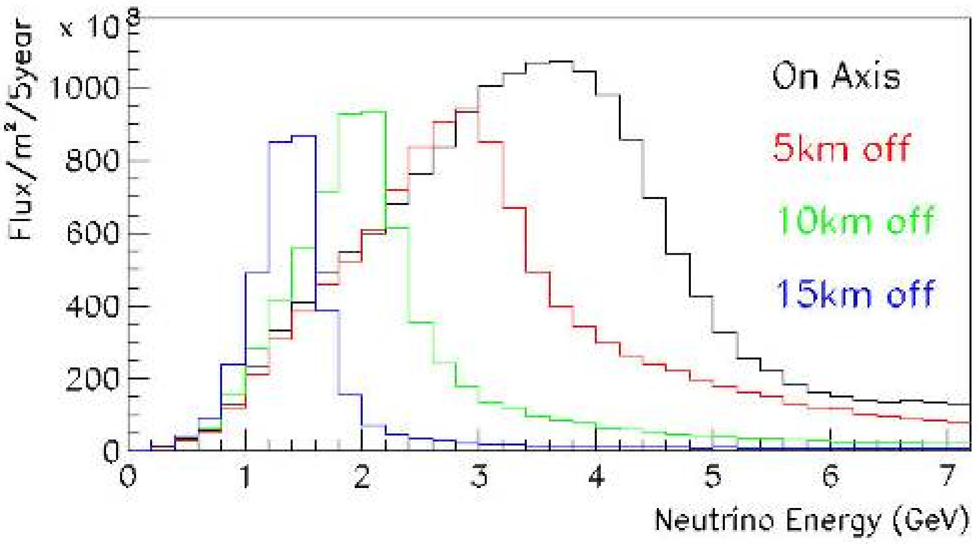
Track segments found in 8 consecutive plates

figures courtesy D. Autiero

Off Axis Strategy

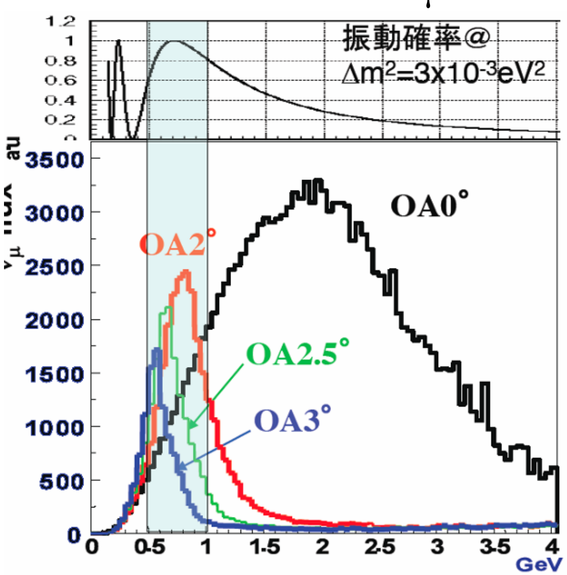
- Trick used by T2K, NOvA (first proposed by BNL)
  - Fewer total number of neutrino events
  - More at one narrow region of energy
  - For ν_μ to ν_e oscillation searches, backgrounds spread over broad energies

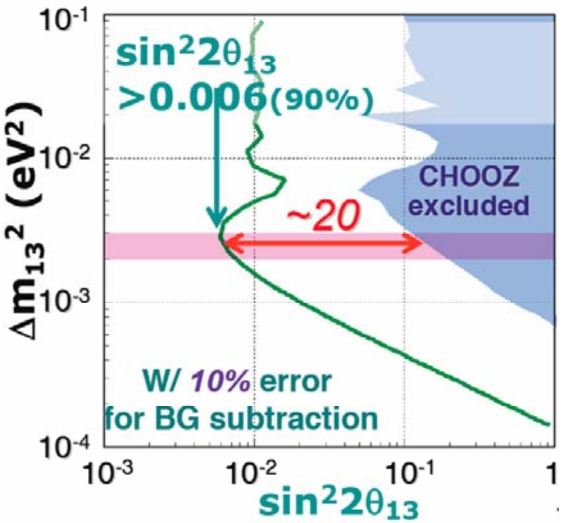


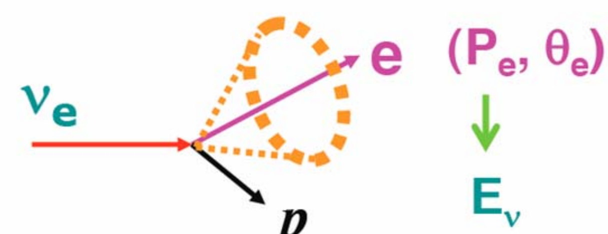


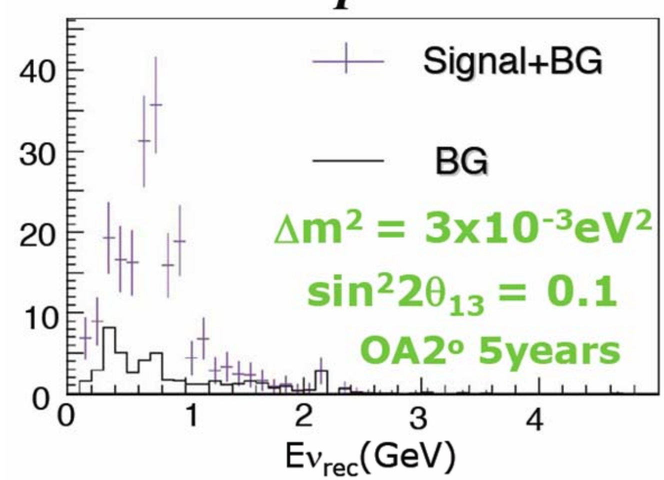
T2K

- Tunable off-axis beam from J-PARC to Super-K detector
  - beam and ν_μ backgrounds are kept below 1% for ν_e signal
  - ~2200 ν_μ events/yr (w/o osc.)









δ=0, no matter effects

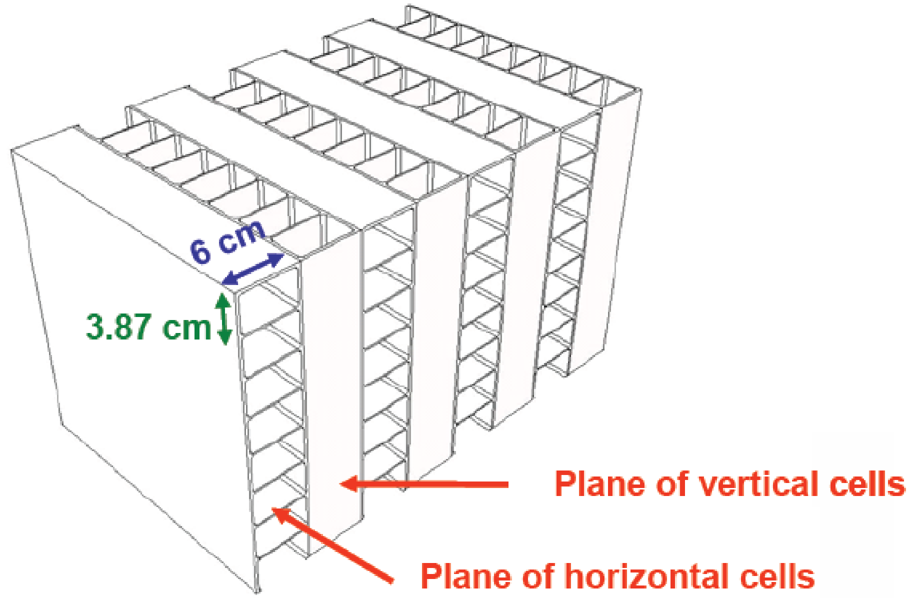
figures courtesy T. Kobayashi

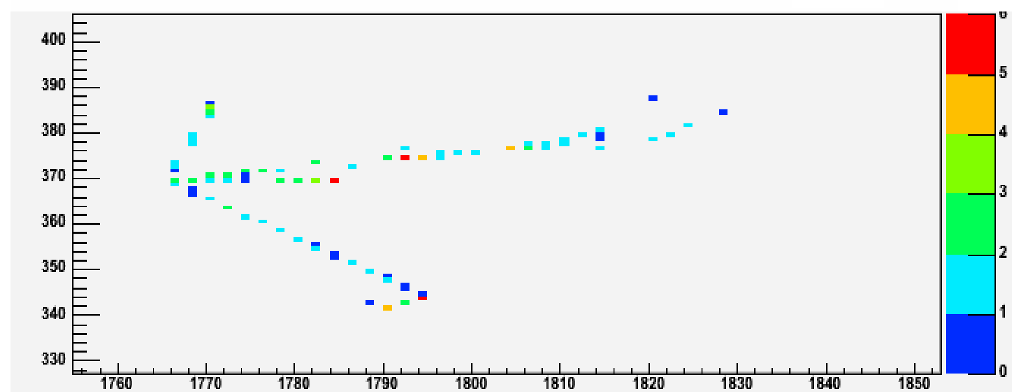
NOνA

- Use Existing NuMI beamline
- Build new 30kTon Scintillator Detector
- 810km baseline--compromise between reach in θ_{13} and matter effects
- Near detector: similar granularity, off-axis

Goal:
ν_e appearance
In ν_μ beam

figures courtesy J. Cooper

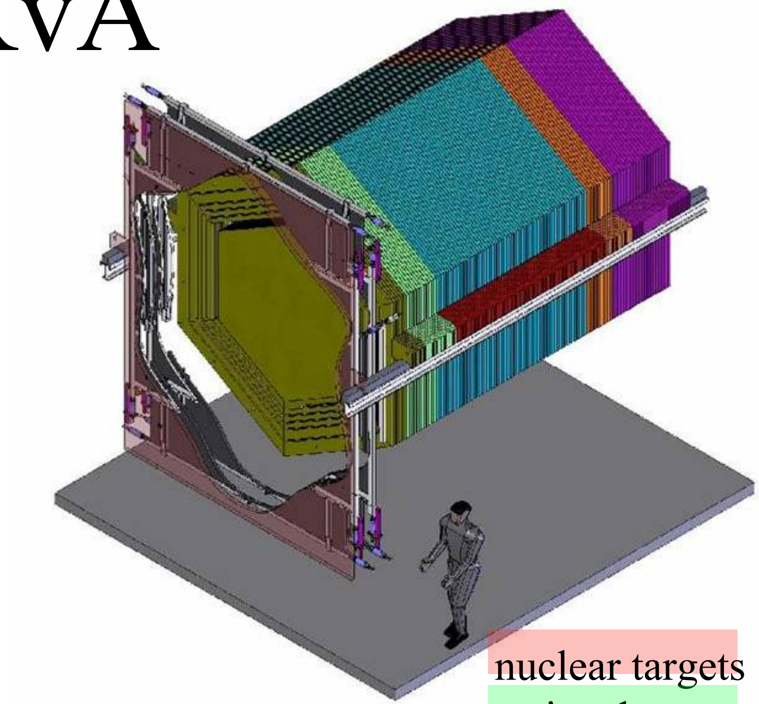




ν_e+A→p π^+ π^- e^-

MINERνA

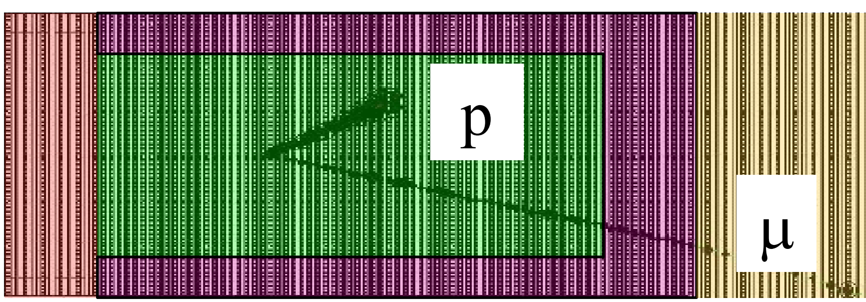
- Dedicated Neutrino Interaction Experiment!
- Fine-grained scintillator detector
- Surrounded by Calorimetry
- Nuclear targets upstream
- Focus on exclusive final state reconstruction and energy containment
- Right in front of MINOS near detector (muon spectrometer)
- To run in NuMI Beamline (Fermilab)



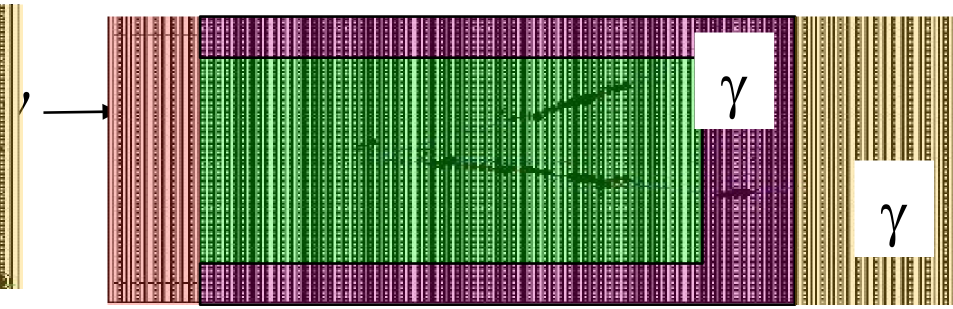
Figures courtesy K.McFarland

nuclear targets
active detector
ECAL
HCAL

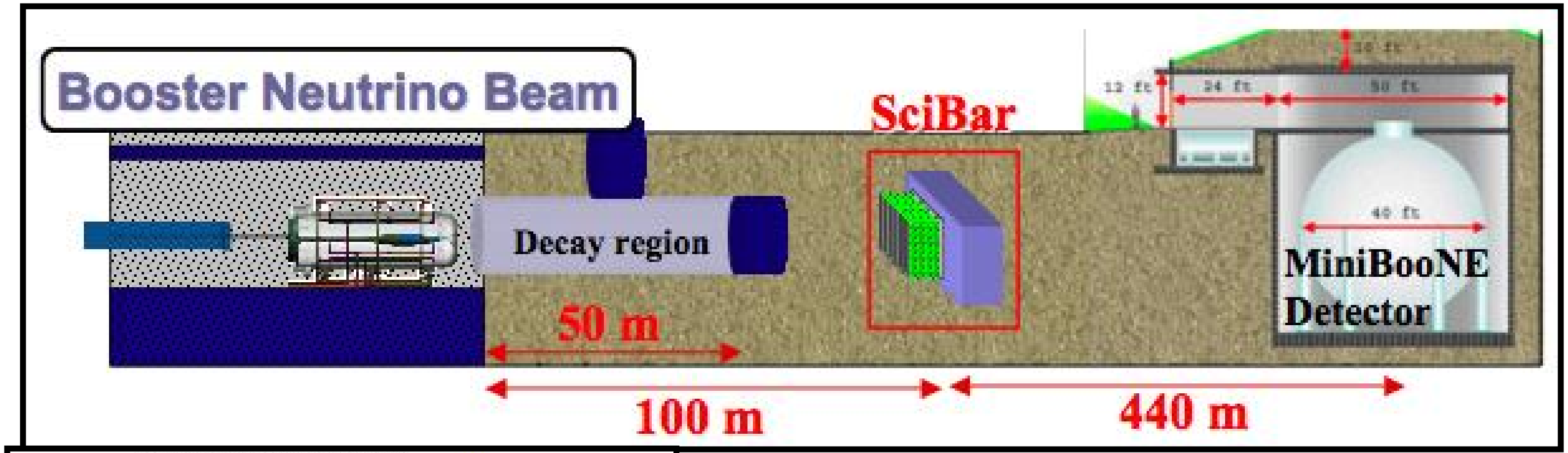
$\nu_\mu n \rightarrow \mu^- p$

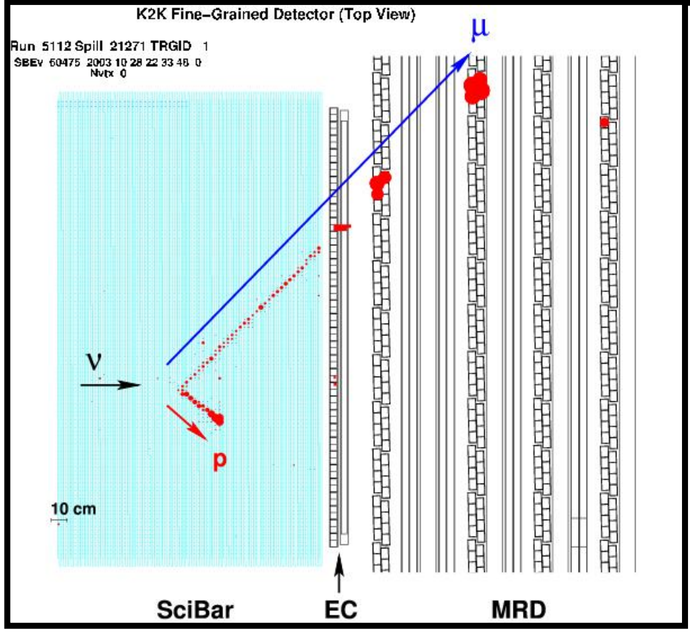


$\nu_\mu p \rightarrow \nu_\mu \pi^0 p$



SciBooNE

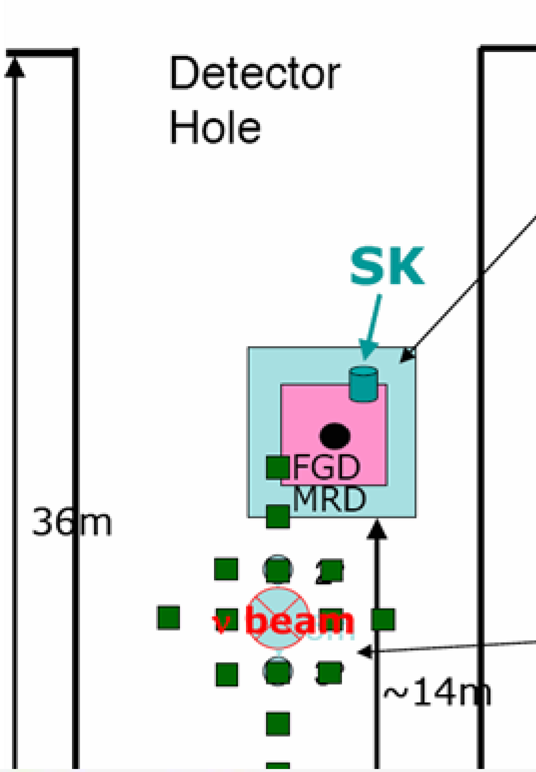




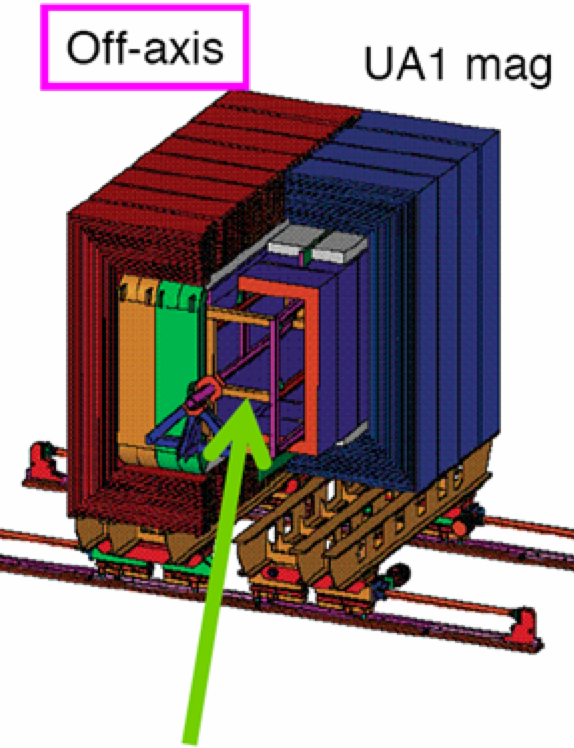
- Running parasitically in MiniBooNE beamline (Fermilab)
- Will see both ν and $\bar{\nu}$
- Fine grained Scintillator Detector
- Re-use SciBAR K2K near detectors
- Explore ~.5-1.5GeV region
- Help predict MiniBooNE events

Plots courtesy G.Zeller, NOVE 2006

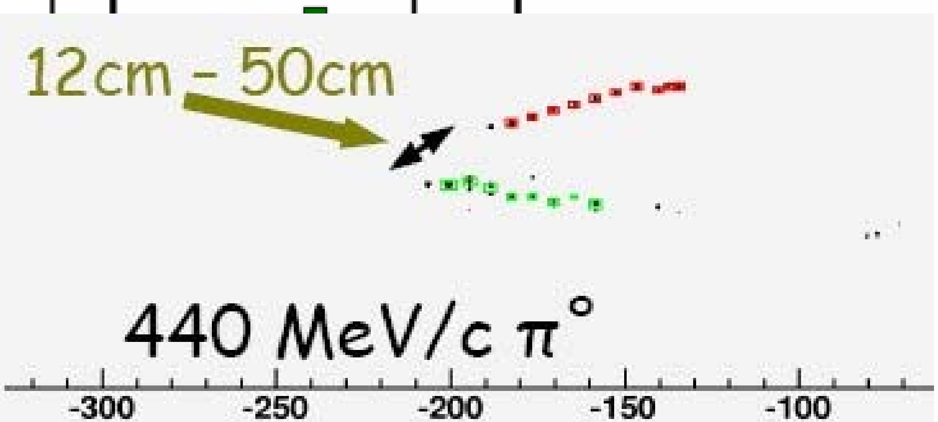
T2K Detectors at 280m



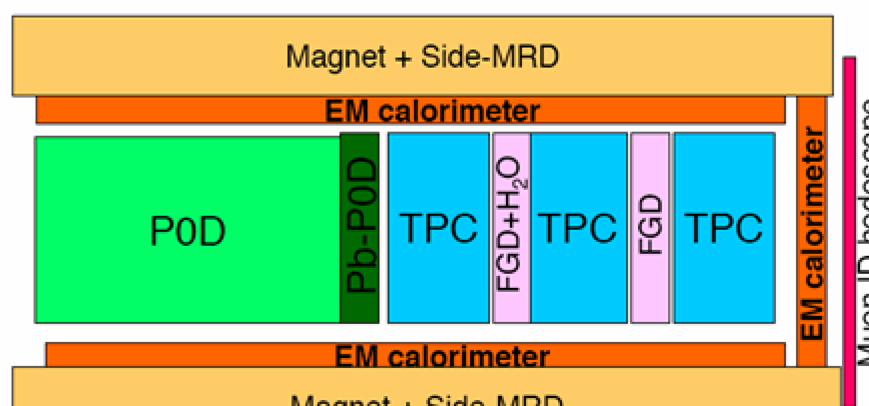
- Off-axis detector
  - ν spectrum
  - Cross sect.
  - ν_e contami.
  - UA1 mag, FGD, TPC, Ecal,..
- On axis detector
  - Monitor beam dir.
  - Grid layout



Figures from K.Nishikawa, NOVE 2006

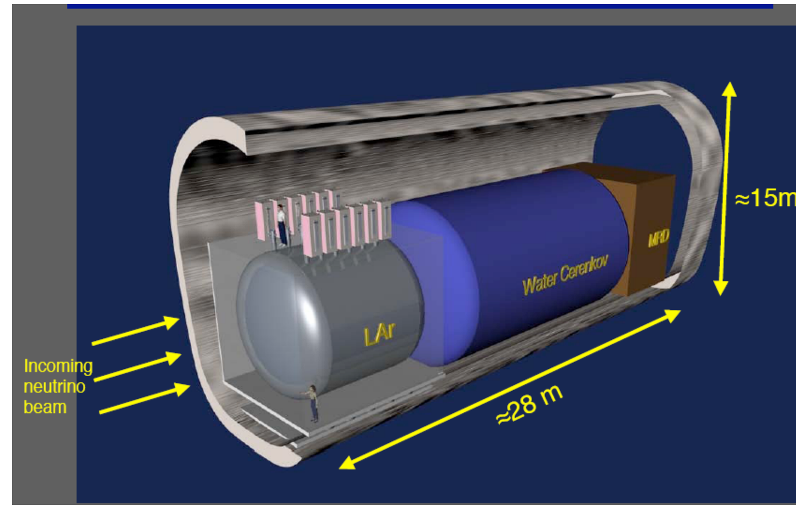


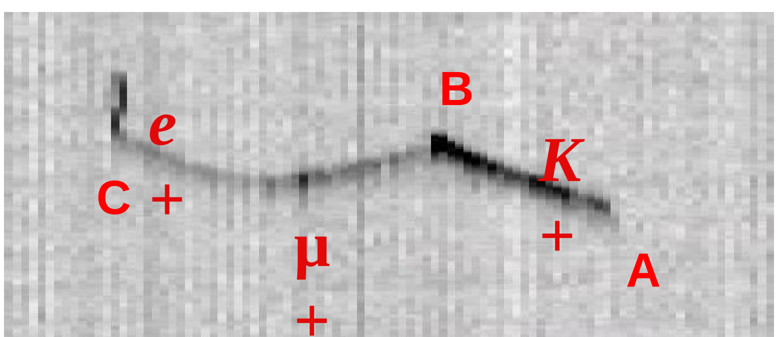
Event display courtesy K.McFarland



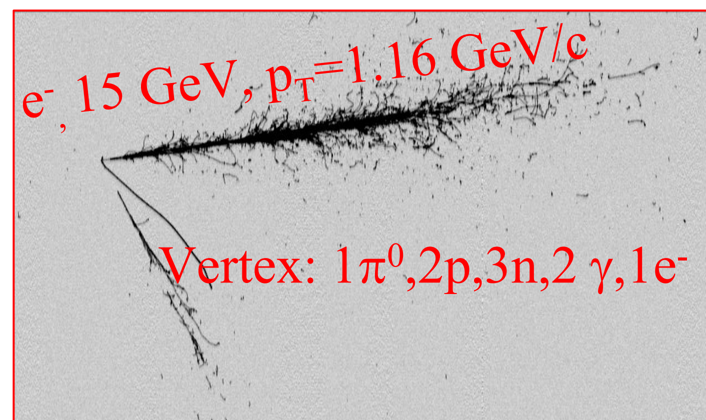
T2K Detectors at 2km

- Liquid Argon and Water Cerenkov
- Liquid Argon: electronic bubble chamber
  - Particle ID by dE/dx
  - Particle mometum by range
  - No magnetic field…



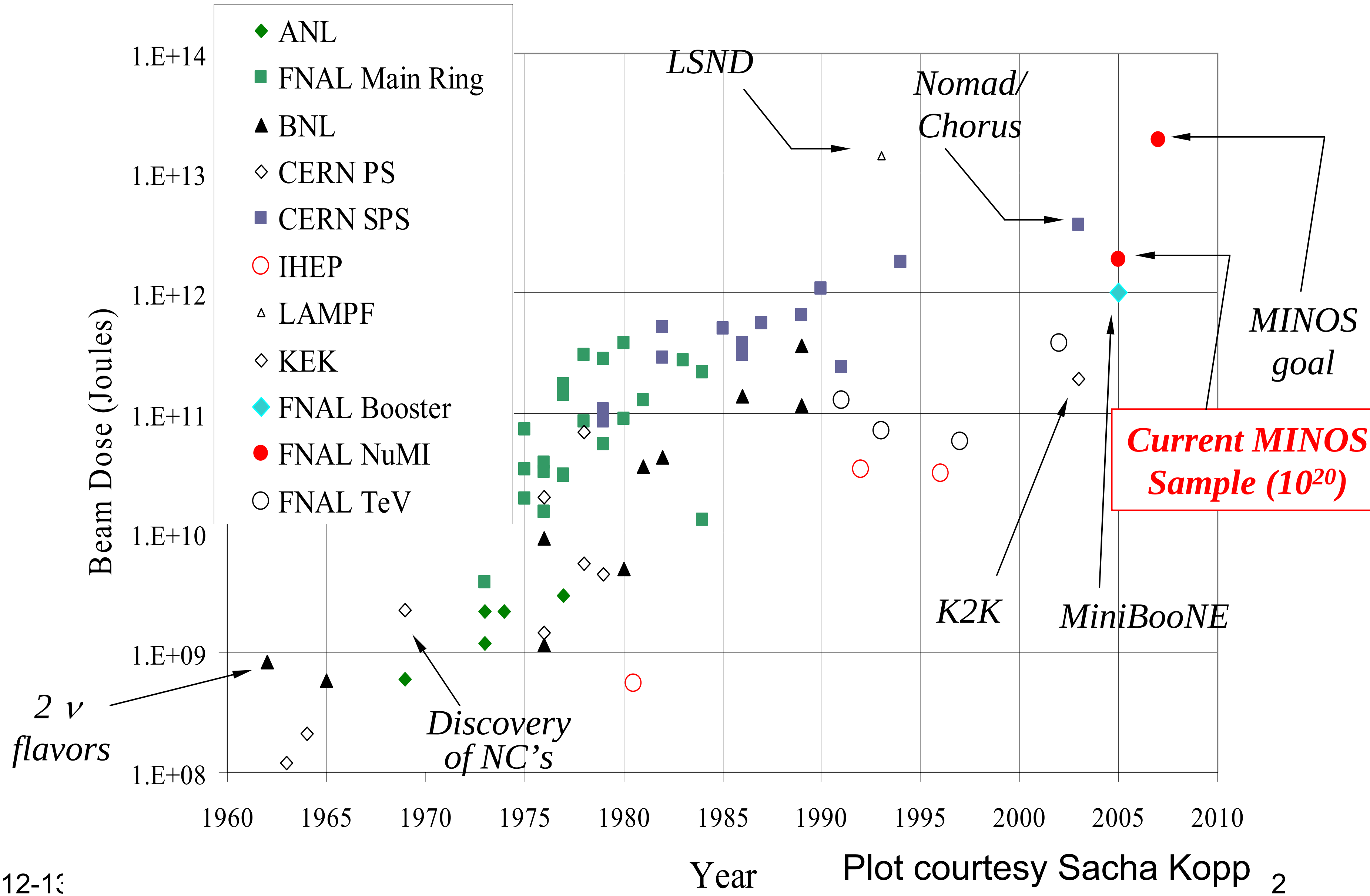


Courtesy André Rubbia



ν_e interaction, E_ν=17 GeV

Integrated proton power vs time…



Plot courtesy Sacha Kopp

Conclusions

- Neutrino Beamlines are getting more and more intense, but lower and lower energies.
- Neutrino detector physics is returning to its roots
  - Lower energy neutrinos needed for oscillation studies
  - Finer and finer grained detectors needed to see
    - $\nu_\mu \rightarrow \nu_\tau$
    - $\nu_\mu \rightarrow \nu_e$
- Many "tricks" up our sleeves
  - Changing beamline configurations in one run
  - Putting in several nuclear targets simultaneously
  - Measuring neutrino cross sections in these energy ranges precisely!
    - Taking advantage of really intense beamlines
    - use relatively light (very fine-grained) detectors