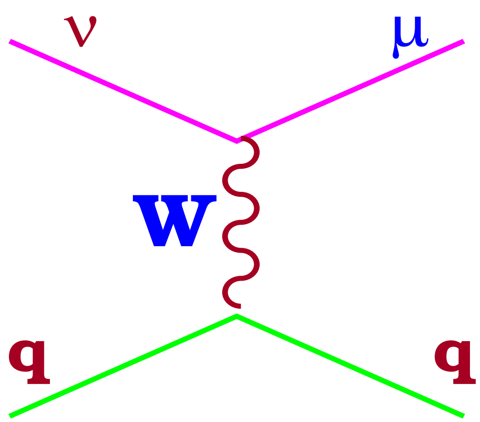
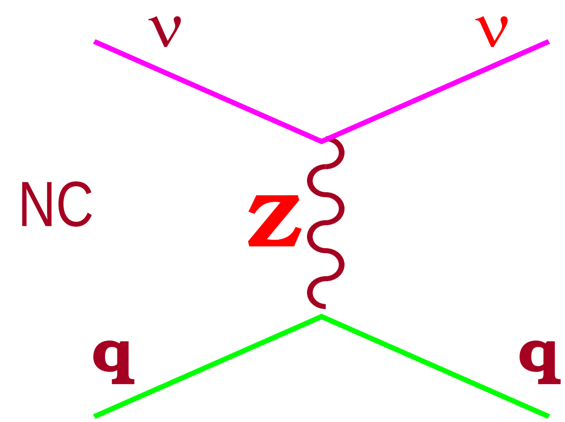
PHYS 5326 – Lecture #2

Wednesday, Jan. 24, 2007
Dr. Jae Yu

1. Sources of Neutrinos
2. How is neutrino beam produced?
3. Physics with neutrino experiments
4. Characteristics of accelerator based neutrino experiments
5. Neutrino-Nucleon DIS
6. ν-N DIS Formalism

Neutrino Cross Sections





$$coupling \propto I^{(3)}_{weak}$$

$$coupling \propto I^{(3)}_{weak} - Q_{EM} \sin^2 \theta_W$$

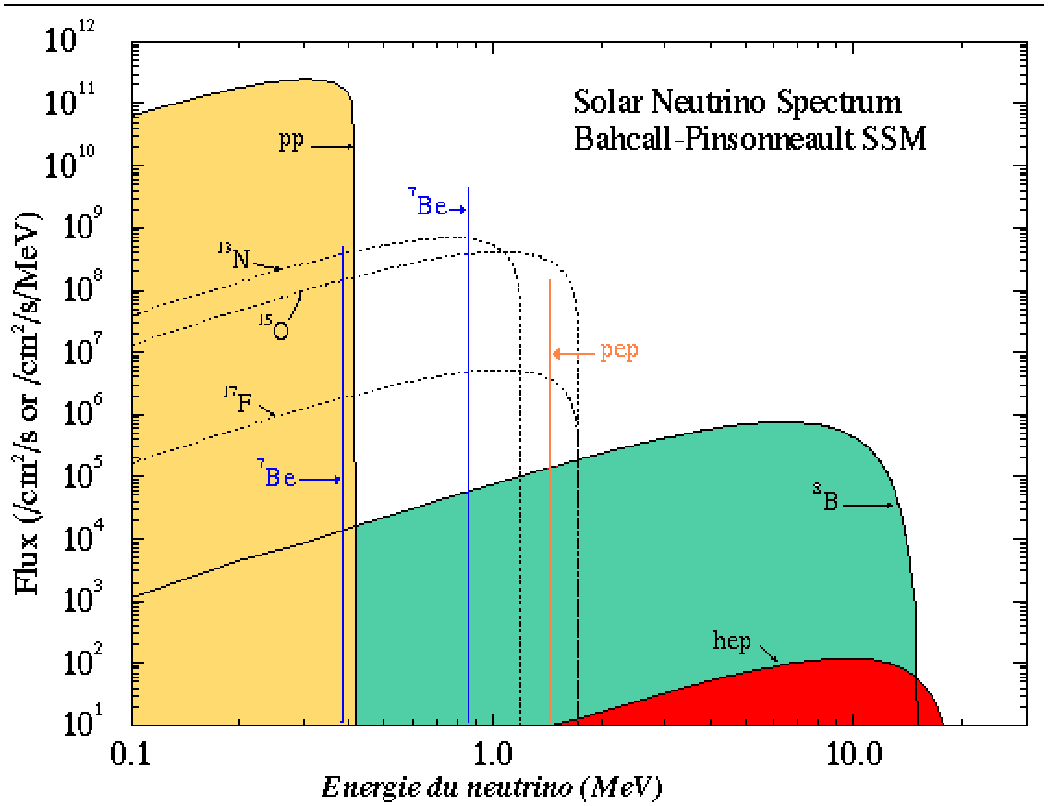
$$\frac{d^2\sigma}{dxdy} = \frac{2G_F ME}{\pi}\left[\left(1 - y - \frac{Mxy}{2E}\right)F_2\left(x,Q^2\right) + \frac{y^2}{2} 2xF_1\left(x,Q^2\right) \pm y\left(1 - \frac{y}{2}\right)xF_3\left(x,Q^2\right)\right]$$

$$\sigma_{\nu N} / E_\nu \approx 0.68 \times 10^{-38}\ \mathrm{cm}^2 / \mathrm{GeV}$$

$$\sigma_{\bar{\nu} N} / E_\nu \approx 0.35 \times 10^{-38}\ \mathrm{cm}^2 / \mathrm{GeV}$$

Sources of Neutrinos: Solar Neutrinos

- Nuclear Fusion inside stars with the primary (85%) reaction $p + p \rightarrow {}^{2}H + e^{+} + \nu_e$
- Energy spectra



Sources of Neutrinos:Atm and other

- High energy cosmic-ray (He, p, n, etc) interactions in the atmosphere
  - Cosmic ray interacts with air molecules $He + p \rightarrow \pi, \mathrm{K}$
  - Secondary mesons decay $\pi^{(\pm)} \rightarrow \mu^{(\pm)} + \nu_\mu (\bar{\nu}_\mu)$
  - Muons decay again in 2.6μs $\mu \rightarrow e + \nu_\mu + \nu_e$
- Neutrinos from the Big Bang (relic neutrinos)
- Neutrinos from star explosions
- Neutrinos from natural background, resulting from radioactive decays of nucleus
- Neutrinos from nuclear reactors in power plants

Physics With Neutrinos

- Investigation of weak interaction regime
  - Only interact via weak interaction ➔ This is why neutrinos are used to observe NC interactions
  - Measurement of weak mixing angle
    - Measurement of coupling strength $e=g\sin\theta_W$
    - Test for new mediators, such as heavy neutral IVBs
    - Measurement of SM ρ parameter
    - Indirect measurement of M_W: $\sin^2\theta_W=\rho(1-M_W^2/M_Z^2)$
- Measurement of proton structure functions
- Measurement of neutrino oscillations

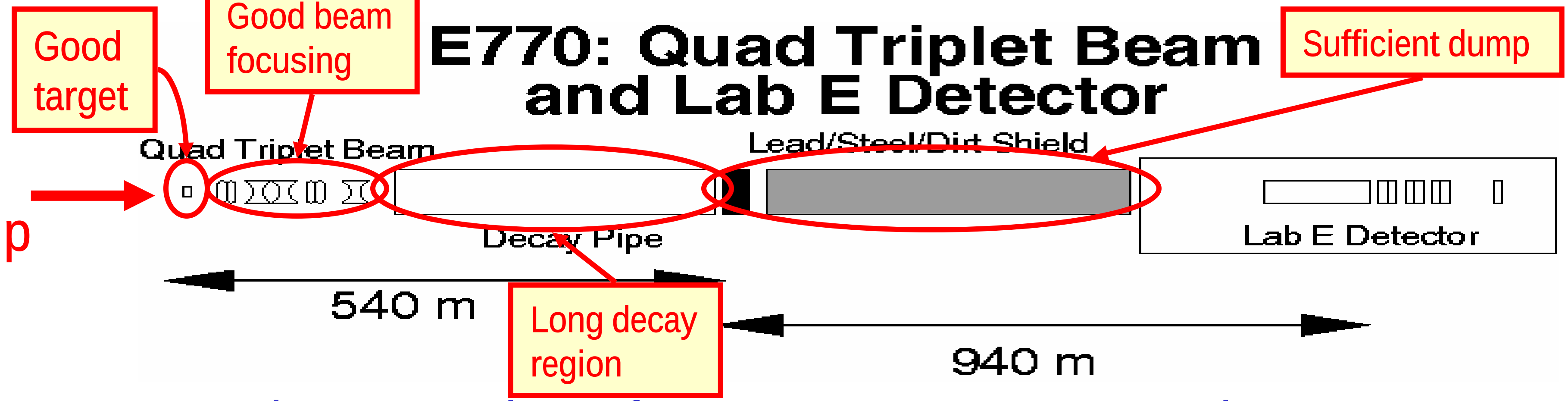
Neutrino Experiments

- What are the difficulties in neutrino experiments?
  - Neutrino cross sections are small ~$10^{-38} E_\nu$
  - Neutrinos interact very weakly w/ matter
- To increase statistics
  - Increase number of neutrinos
    - Natural or reactor sources will not give you control of beam intensity
    - Need man-made neutrino beams
  - Increase neutrino energy
  - Increase thickness of material to interact with neutrinos → Detectors with dense material
- Beam can be made so that it is enriched with a specific flavors of neutrinos, such as ν_τs.
  - How does one do this?

Detector and Beam Requirements

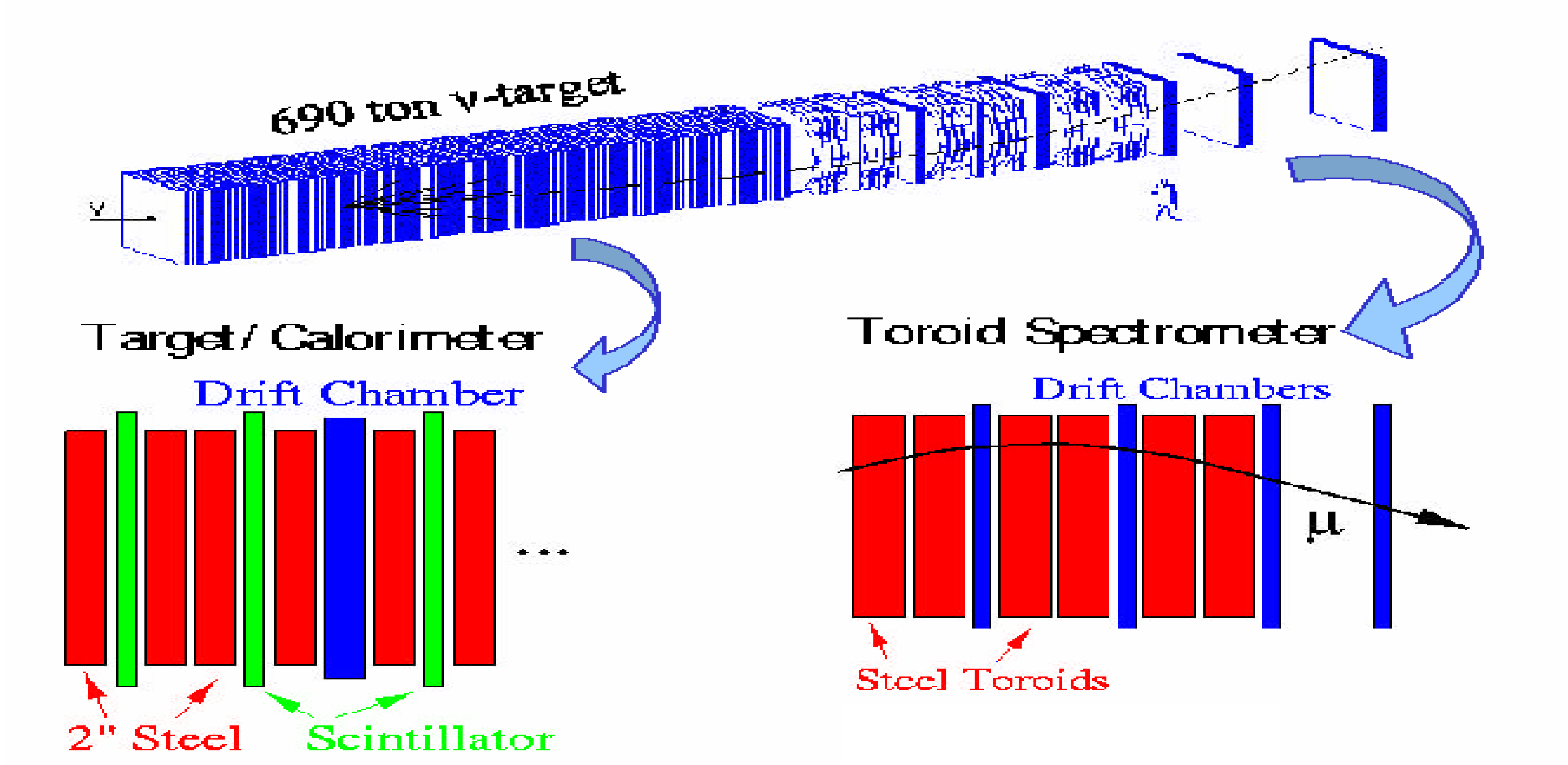
- Beam and apparatus need to be determined by physics needs
- For weak mixing angle & structure function
  - Need large statistics ➔ Accelerator based experiment with dense detector (target) needed
    - Good focusing of the secondary hadrons from the primary beam target
  - Wider energy range of neutrinos
  - Ability to distinguish CC and NC interactions
    - Tracks of leptons from CC interactions for PID
    - Precise momentum measurement of leptons
    - Precise measurement of hadronic shower energy
    - Finer longitudinal segmentation
    - Cosmic-ray veto

Conventional Neutrino Beam



- Use large number of protons on target to produce many secondary hadrons (π, K, D, etc)
- Let π and K decay in-flight for ν_μ beam
  - $\pi \rightarrow \mu + \nu_\mu$ (99.99%), $K \rightarrow \mu + \nu_\mu$ (63.5%)
  - Other flavors of neutrinos are harder to make
- Let the beam go through thick shield and dirt to filter out μ and remaining hadrons, except for ν
  - Dominated by ν_μ

A Typical Neutrino Detector: NuTeV



- Calorimeter
  - 168 FE plates & 690tons
  - 84 Liquid Scintillator
  - 42 Drift chambers interspersed
- Solid Iron Toroid
  - Measures Muon momentum
  - $\Delta p/p \sim 10\%$

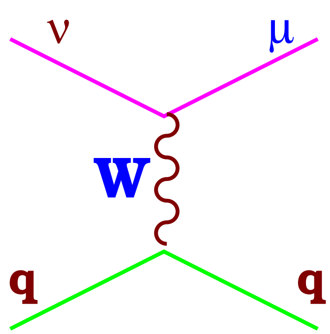
Continuous test beam for in-situ calibration

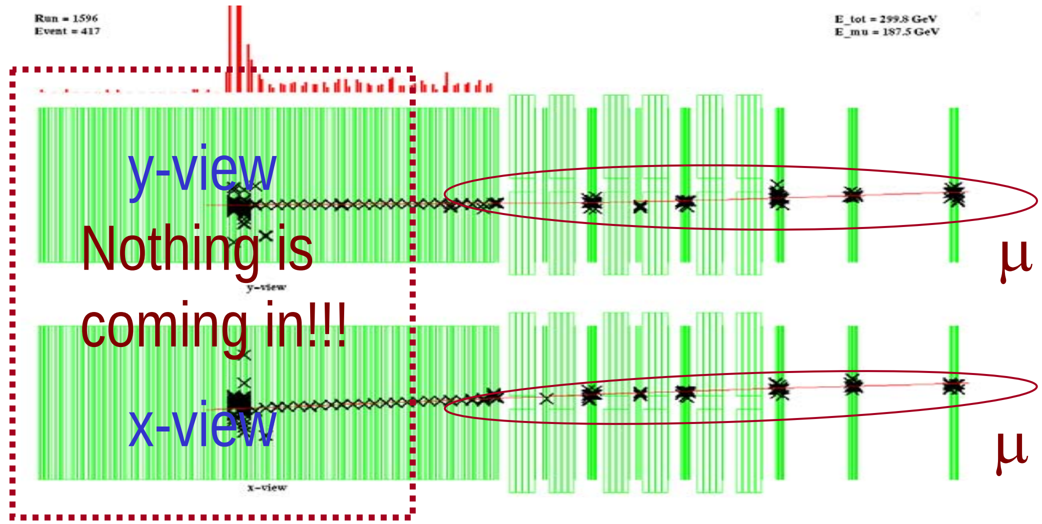
The NuTeV Detector

A picture from 1998. The detector has been dismantled to make room for other experiments, such as DØ, CMS and ILC

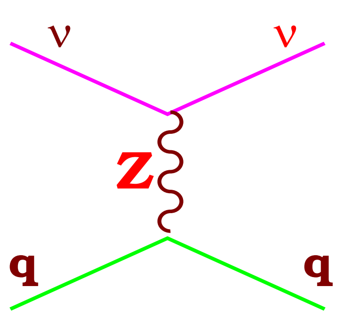
How Do Neutrino Events Look?

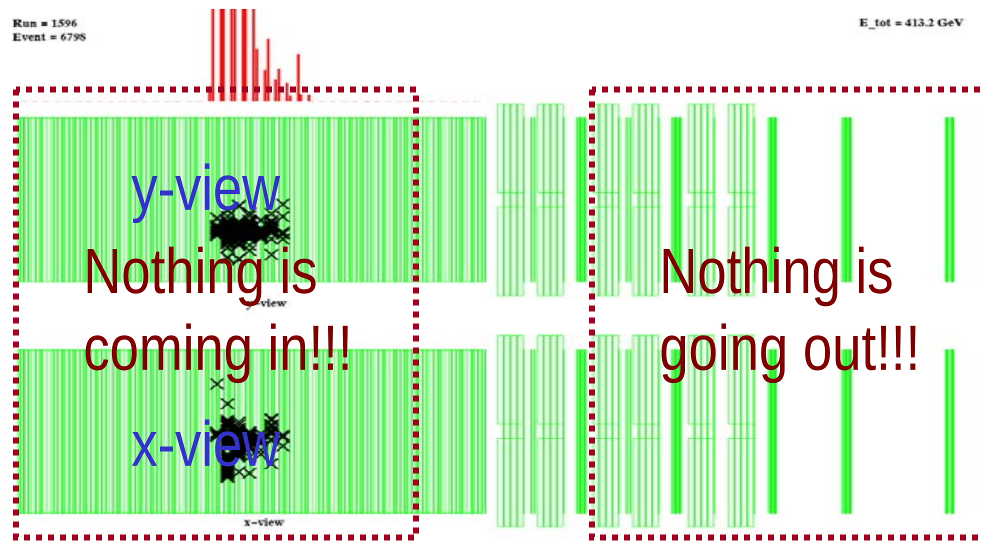
Charged Current Events





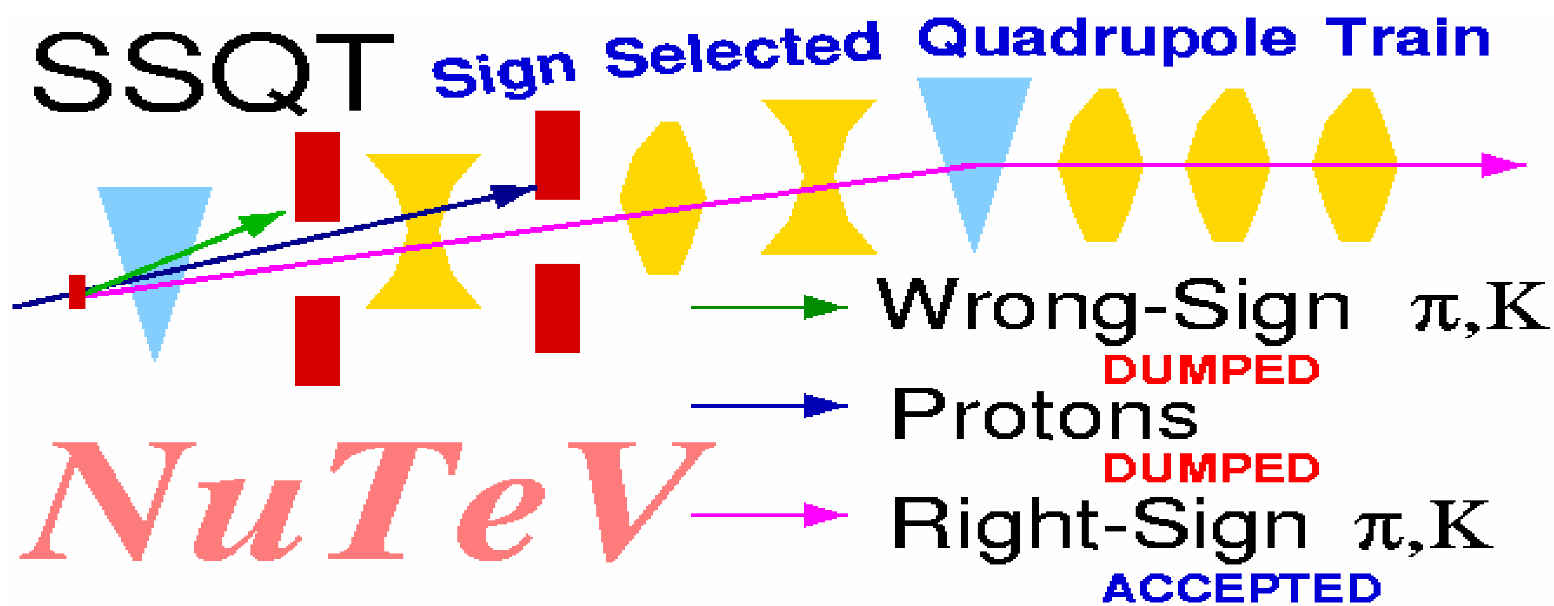
Neutral Current Events



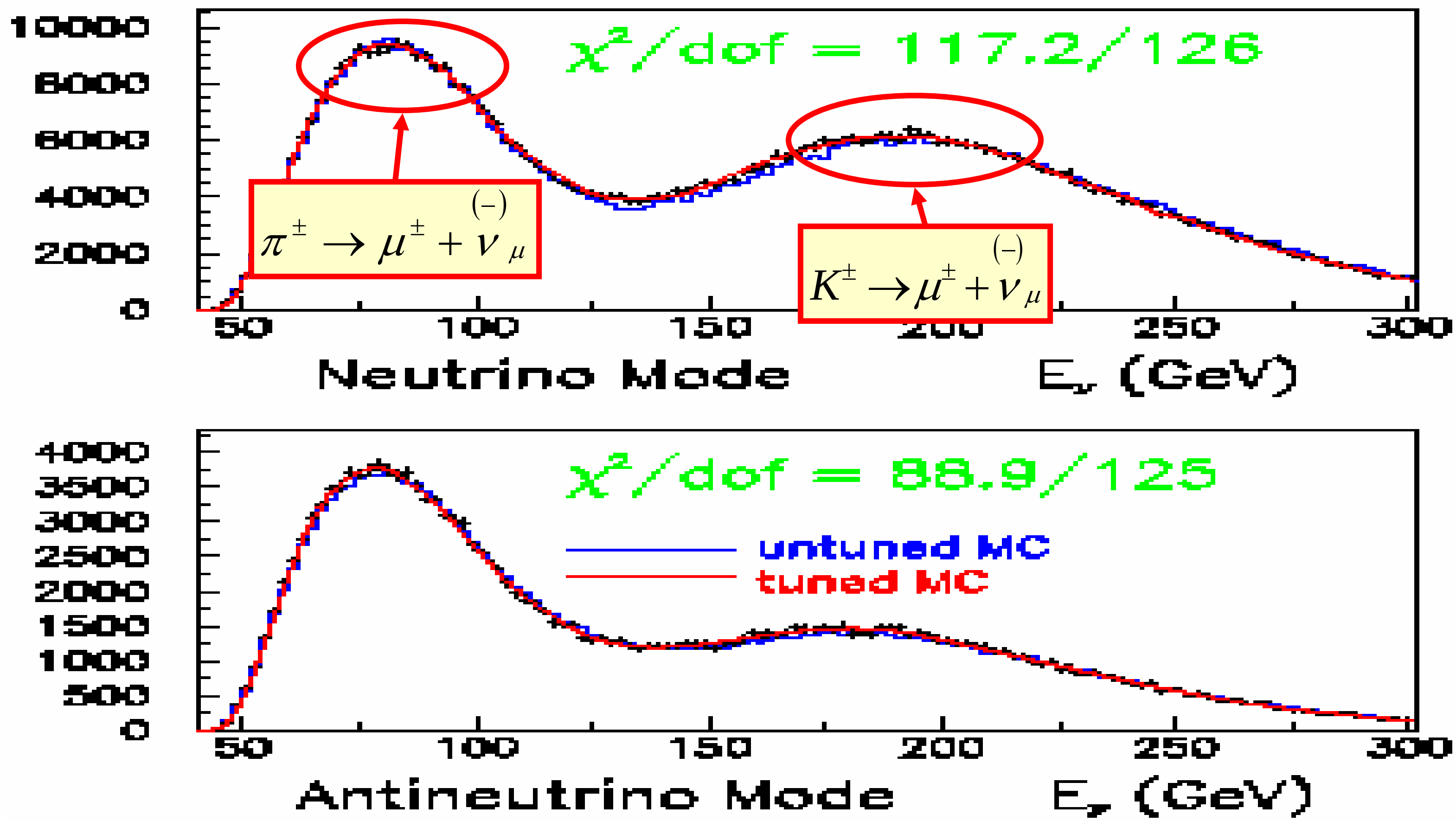


How can we select sign of neutrinos?

- Neutrinos are electrically neutral
- Need to select the charge of the secondary hadrons from the proton interaction on target
- NuTeV experiment at Fermilab used a string of magnets called SSQT (Sign Selected Quadrupole Train)



Neutrino Flux from NuTeV



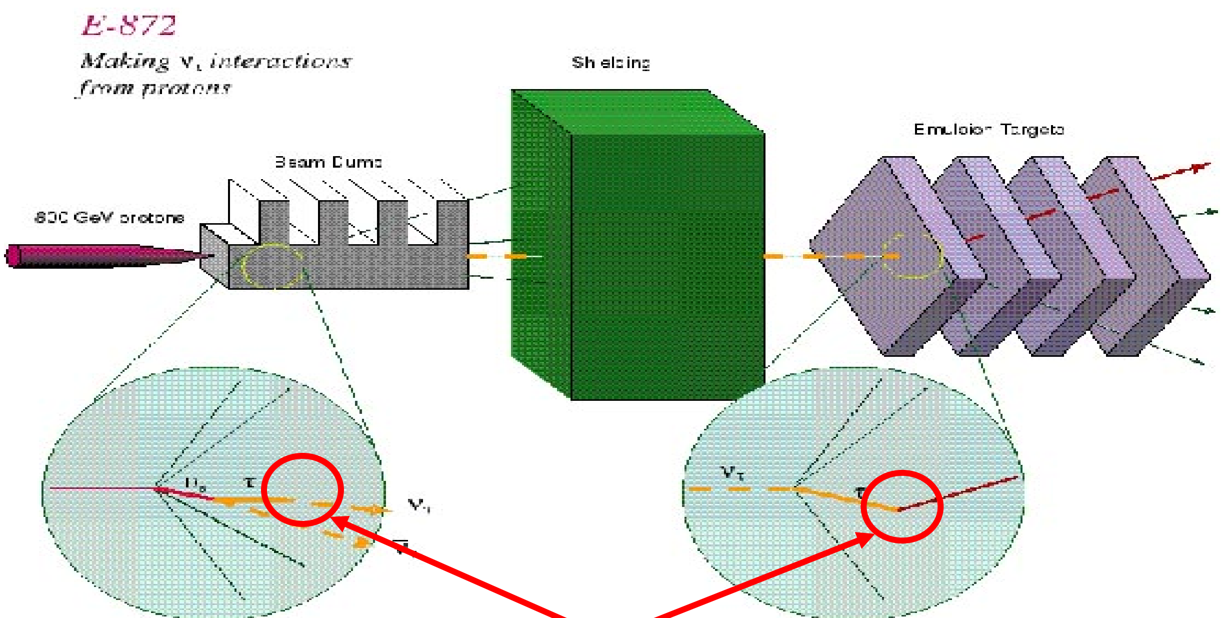
Two distinct peaks depending on the sources of neutrinos

Total number of events after cuts: 1.62M ν & 350k $\bar{\nu}$

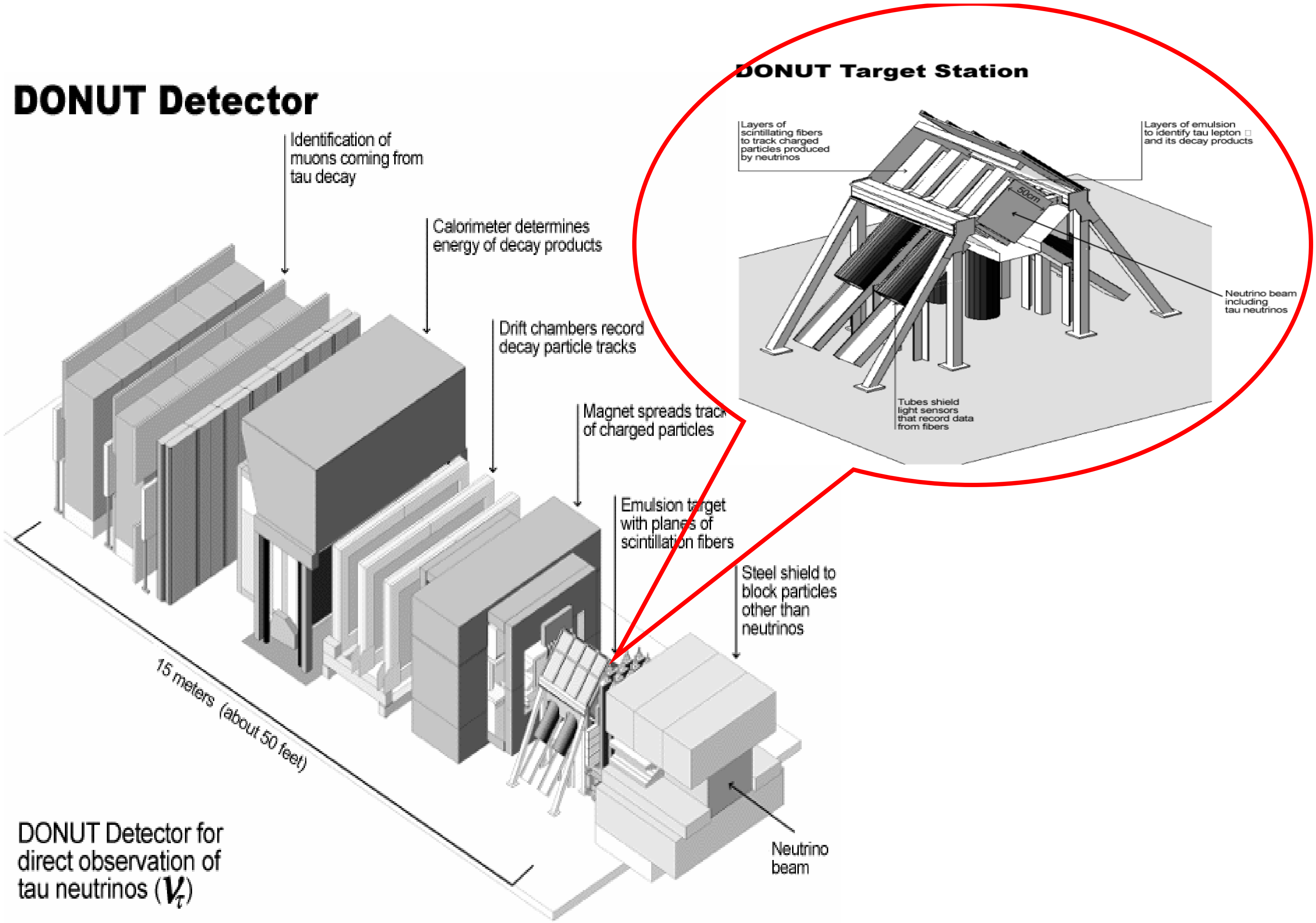
Neutrino Detector for ν_τ Observation

- Make an observation of ν_τ interaction with nucleon, producing τ in the target, decaying leptonically or hadronically
- Beam of ν_τ is produced using $D_S \rightarrow \tau + \nu_\tau$ (~7%), $\tau \rightarrow h + \nu_\tau + K_L^0$ (one-prong decay, 49.5%), $\mu\, \nu_\tau\, \nu_\mu$ (17%), $e\, \nu_\tau\, \nu_e$ (17%)
- Large number of protons on target (10^{17} PoT $\rightarrow 2\times10^{12}\ \nu_\tau /m^2$)
- Precise detector to observe the kinks of τ decays (emulsion)

FNAL E-872
DONUT (Direct Observation of NU Taus)

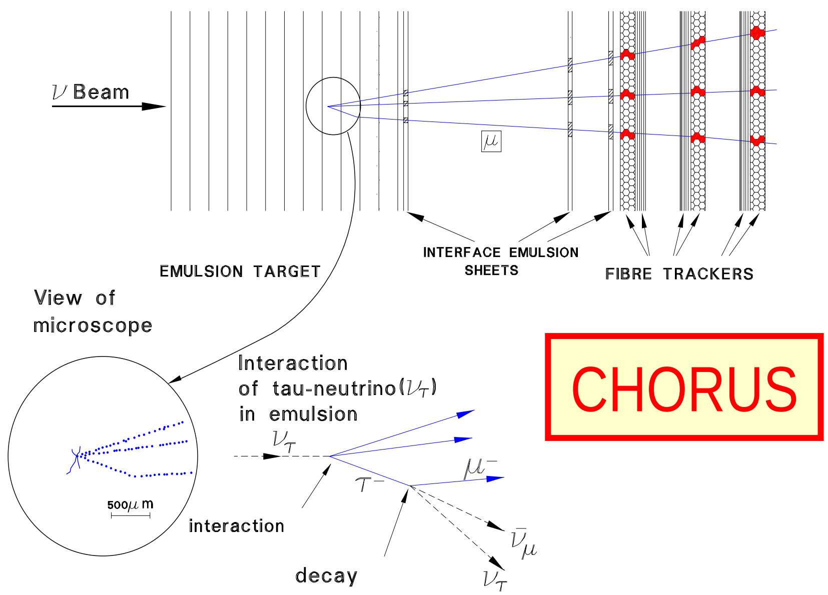


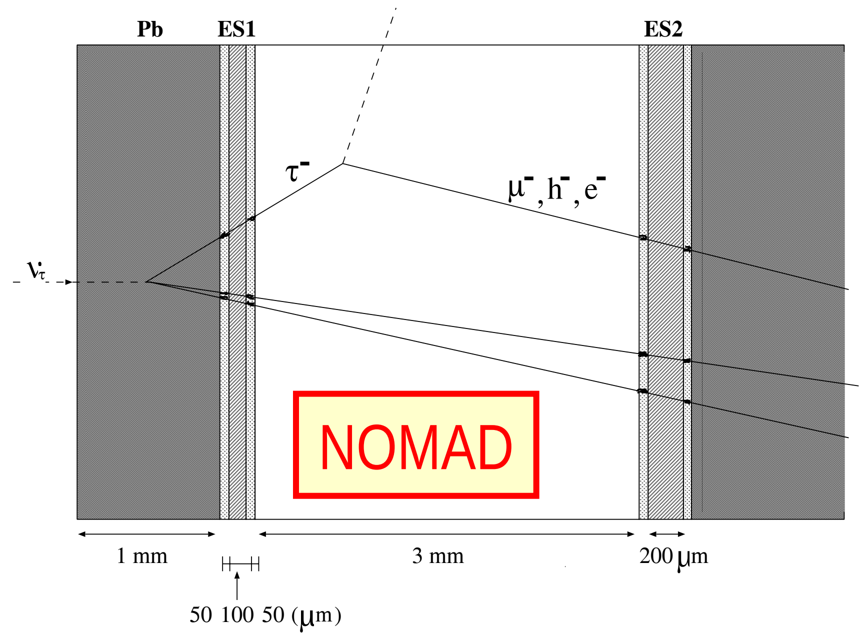
Classical signatures of τ decays


DONUT Detector
Identification of muons coming from tau decay
Calorimeter determines energy of decay products
Drift chambers record decay particle tracks
Magnet spreads tracks of charged particles
Emulsion target with planes of scintillation fibers
Steel shield to block particles other than neutrinos
Neutrino beam
15 meters (about 50 feet)
DONUT Detector for direct observation of tau neutrinos (ν_τ)
DONUT Target Station
Layers of scintillating fibers to track charged particles produced by neutrinos
Layers of emulsion to identify tau lepton and its decay products
50cm
Neutrino beam including tau neutrinos
Tubes shield light sensors that record data from fibers

Neutrino Detectors for $\nu_\mu \rightarrow \nu_\tau$ Oscillation

- Measure $\nu_\mu \rightarrow \nu_\tau$ oscillation, by observing ν_τ appearing at the detector far away from the source of the beam
- Beam of high flux ν_μ is produced using π, K decays $\rightarrow$ Use a magnet called horn to focus more hadrons
- Neutrino energies must be high enough to produce ν_τ

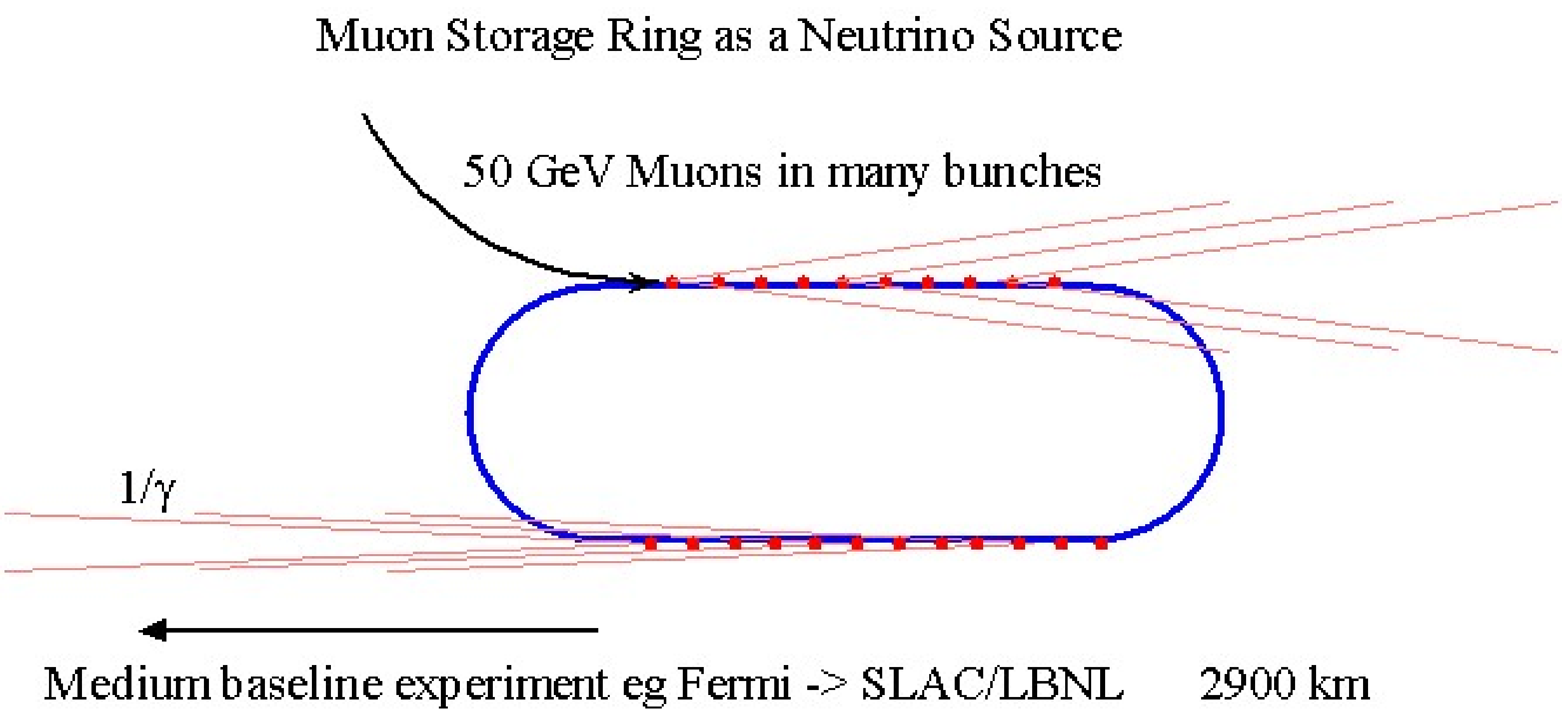




Source of Cleaner Neutrino Beam

Muon storage ring can generate 10^6 times higher flux and well understood, high purity neutrino beam ➔ significant reduction in statistical uncertainty

But ν_e and ν_μ from muon decays are in the beam at all times ➔ Deadly for traditional heavy target detectors



Homework Assignments

- Compute the fraction of 200GeV π that decay in a 540m decay pipe and the probability of μ, resulting from π decays, surviving in the shield, assuming 940m dirt shield
  - Due: Wed., Jan. 31