Neutrino Physics

陆锦标 Kam-Biu Luk

Tsinghua University

and

University of California, Berkeley

and

Lawrence Berkeley National Laboratory

Lecture 4, 7 June, 2007

Outline

- General principle of production
  - radioactive sources
  - particle decays
- Artificial sources
  - neutrino beams
  - nuclear reactor
- Natural sources
  - Active galactic nucleus
  - Supernova
  - Atmosphere
  - Sun

Production Of Electron Neutrinos

1. Low-energy $\bar{\nu}_e$ and ν_e (pure sources):

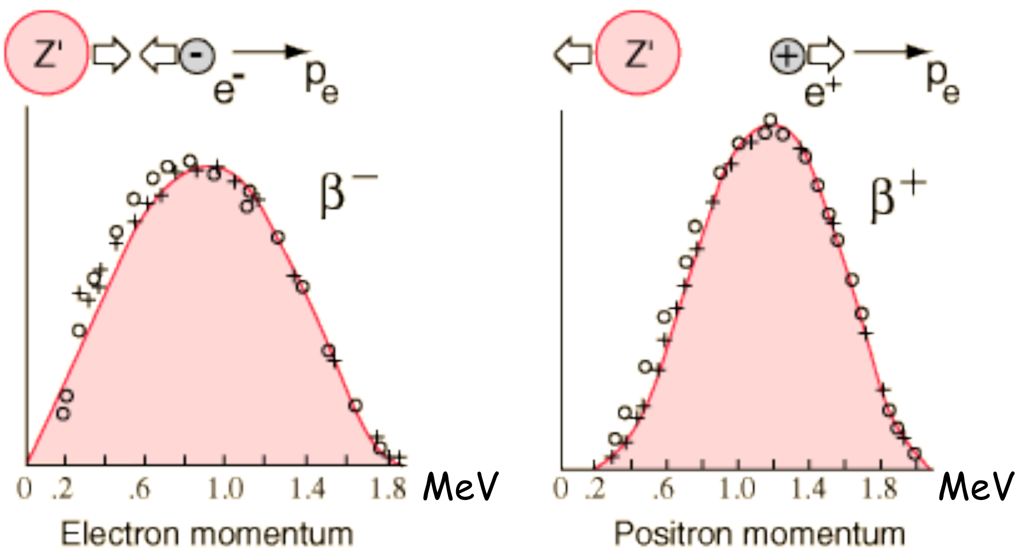
$$^{A}_{Z}N \rightarrow {}^{A}_{Z+1}N + e^- + \bar{\nu}_e$$

$$^{A}_{Z}N \rightarrow {}^{A}_{Z-1}N + e^+ + \nu_e$$

For example,

$$^{64}Cu \rightarrow {}^{64}Zn + e^- + \bar{\nu}_e$$

$$^{64}Cu \rightarrow {}^{64}Ni + e^+ + \nu_e$$



Momentum spectra from the beta decay of ^{64}Cu

The beta distribution is:

$$N(p) = Cp^2[Q - E_e + m_e]F(Z', p)$$

- C: constant
- $[Q - E_e + m_e]$: Energy released in the decay
- $F(Z', p)$: Fermi function: Coulomb interaction between daughters

Need to convert from the beta spectrum to obtain the distribution of the neutrino

Production of Electron Neutrinos

1. 'High'-energy $\bar{\nu}_e$ and ν_e (pure sources):

   (a) From pion decays:

$$\pi^- \to e^- + \bar{\nu}_e \qquad \text{branching ratio} = 1.23 \times 10^{-4}$$
$$\pi^+ \to e^+ + \nu_e$$

In the rest frame of π, the total energy of the neutrino is:

$$E_\nu = \frac{M_\pi^2 + m_\nu^2 - m_e^2}{2M_\pi} = \frac{M_\pi^2 - m_e^2}{2M_\pi} \approx \frac{(140)^2 - (0.5)^2}{2(140)} MeV \approx 70\, MeV$$

   (b) From kaon decays:

$$K^- \to e^- + \bar{\nu}_e \qquad \text{branching ratio} = 1.55 \times 10^{-5}$$
$$K^+ \to e^+ + \nu_e$$

Total energy of neutrino: $E_\nu = \frac{M_K^2 - m_e^2}{2M_K} \approx \frac{M_K}{2} MeV \approx 247\, MeV$

$$K^- \to \pi^0 + e^- + \bar{\nu}_e \qquad \text{branching ratio} = 0.0487$$
$$K^+ \to \pi^0 + e^+ + \nu_e$$

But these are all rare to too rare !!

Production of Muon Neutrinos

2. 'High'-energy $\bar{\nu}_\mu$ and ν_μ (pure sources):

(a) From pion decays:

$\pi^- \to \mu^- + \bar{\nu}_\mu$ branching ratio = 1.

$\pi^+ \to \mu^+ + \nu_\mu$

In the rest frame of π, the energy of the neutrino is:

$$E_\nu = \frac{M_\pi^2 + m_\nu^2 - m_\mu^2}{2M_\pi} = \frac{M_\pi^2 - m_\mu^2}{2M_\pi} \approx \frac{(140)^2 - (106)^2}{2(140)} MeV \approx 30 MeV$$

(b) From kaon decays:

$K^- \to \mu^- + \bar{\nu}_\mu$ branching ratio = 0.634

$K^+ \to \mu^+ + \nu_\mu$

Total energy of neutrino: $$E_\nu = \frac{M_K^2 - m_\mu^2}{2M_K} \approx \frac{(494)^2 - (106)^2}{2(494)} MeV \approx 235 MeV$$

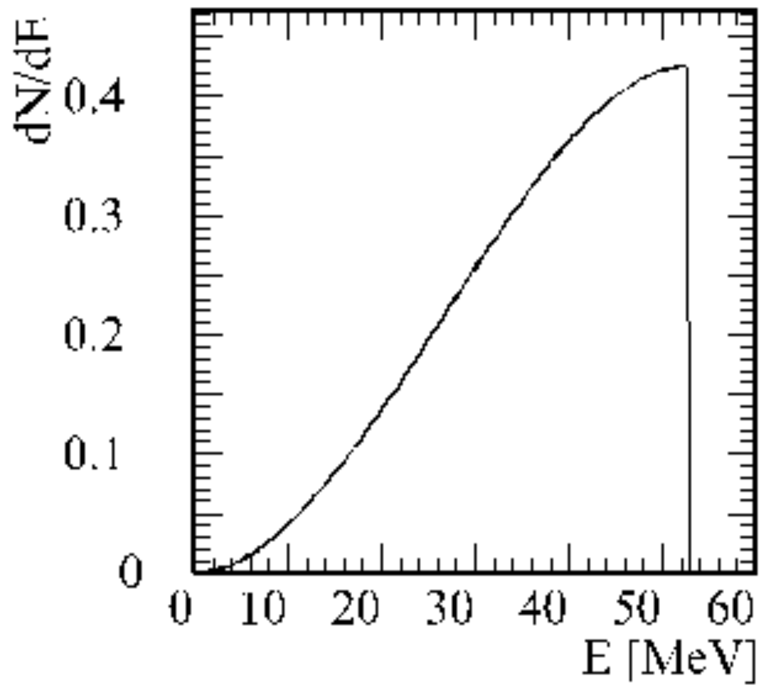
More On Neutrino Production

Typically from muon decay:

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \qquad \text{branching ratio = 1.}$$
$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$

which gives a mixture of electron and muon neutrinos

Energy of the (Michel) electron or positron



Production of Tau Neutrinos

3. Pure sources of $\bar{\nu}_\tau$ and ν_τ :

From charmed-strange meson decays:

$$D_s^- \rightarrow \tau^- + \bar{\nu}_\tau \qquad \text{branching ratio} = 0.064.$$

$$D_s^+ \rightarrow \tau^+ + \nu_\tau$$

The total energy of the neutrino is:

$$E_\nu = \frac{M_{D_S}^2 + m_\nu^2 - m_\tau^2}{2M_{D_S}} \approx \frac{(1968)^2 - (1777)^2}{2(1968)} MeV \approx 182 MeV$$

Another Source of Neutrinos

$$Z \to u + \bar{u}$$
$$\to d + \bar{d}$$
$$\to c + \bar{c}$$
$$\to s + \bar{s}$$
$$\to b + \bar{b}$$

$$Z \to e^- + e^+$$
$$\to \mu^- + \mu^+$$
$$\to \tau^- + \tau^+$$
$$\to \nu_e + \bar{\nu}_e$$
$$\to \nu_\mu + \bar{\nu}_\mu$$
$$\to \nu_\tau + \bar{\nu}_\tau$$

The total branching ratio of neutrino pairs is:

$$Br(Z \to \nu + \bar{\nu}) \approx \frac{3}{3 \times 5 + 3 + 3} = 0.14$$

The energy of the neutrino is:

$$E_\nu = \frac{M_Z}{2} = 45.6 GeV$$

Produce Neutrino Beams With Accelerators

To produce a beam of neutrinos,

- Accelerate protons to high energy
- Guide the energetic protons to hit a target to produce mesons:

$$p + p \rightarrow p + n + K^{+} + K^{-} + \pi^{+} + \pi^{-} + \pi^{+} + \pi^{-} + \ldots$$

- Use a magnetic field to select either a positive or a negative secondary charged beam
- Collimate the selected charged mesons
- Allow the mesons to decay, in particular, the pions:

$$\pi^{-} \rightarrow \mu^{-} + \bar{\nu}_{\mu}$$

or

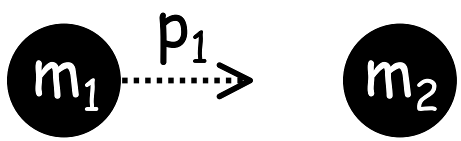
$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$

and absorb any unwanted hadrons at the end of the beamline

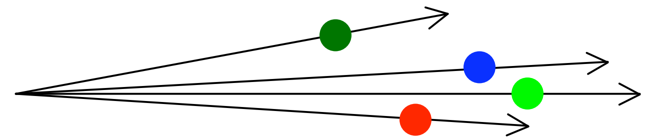
Particle Collision

- In the laboratory,

Before collision



After collision



The center-of-mass energy, $\sqrt{s}$, is:

$$s = m_1^2 + m_2^2 + 2m_2E_1$$

For a 800 GeV proton collides with a stationary proton:

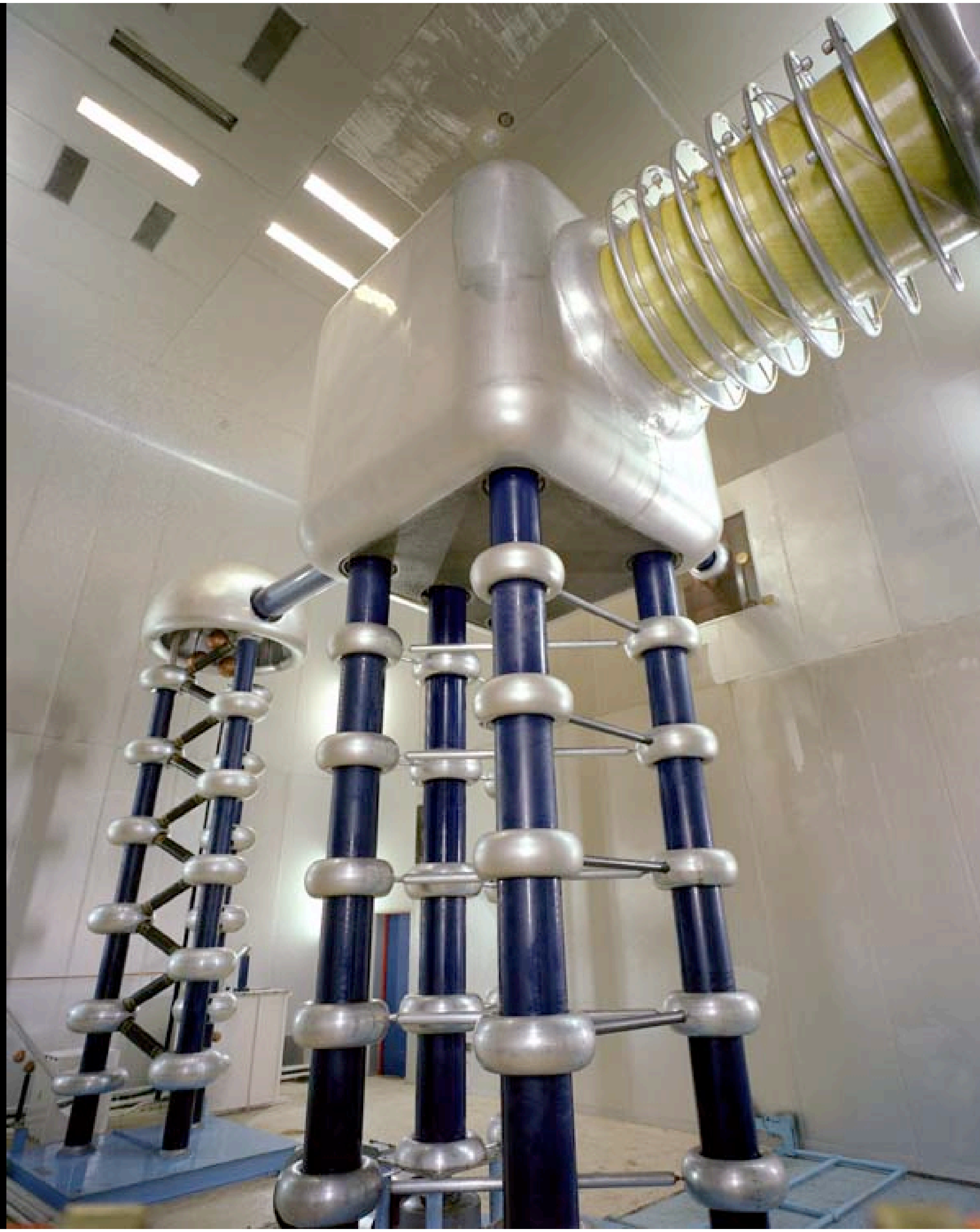
$$\sqrt{s} = 38.8GeV$$

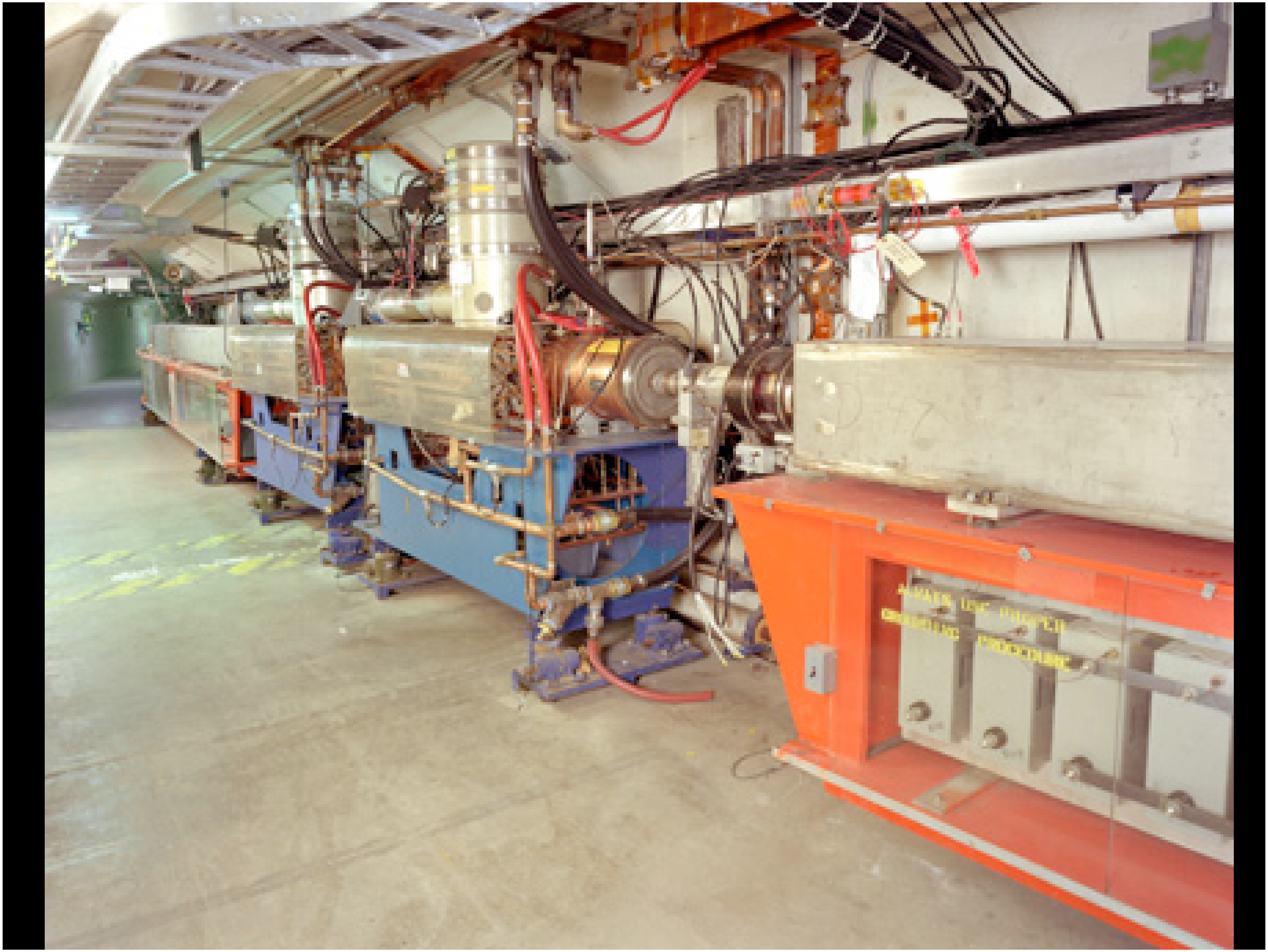
- In the center of mass, a particle with mass m and momentum p_{cm}, its momentum in the laboratory is:

$$p_{lab} = \gamma\beta E_{cm} + \gamma p_{cm}$$

where $\gamma\beta = \frac{p_1}{\sqrt{s}}$ *and* $\gamma = \frac{\sqrt{m_1^2 + p_1^2} + m_2}{\sqrt{s}}$

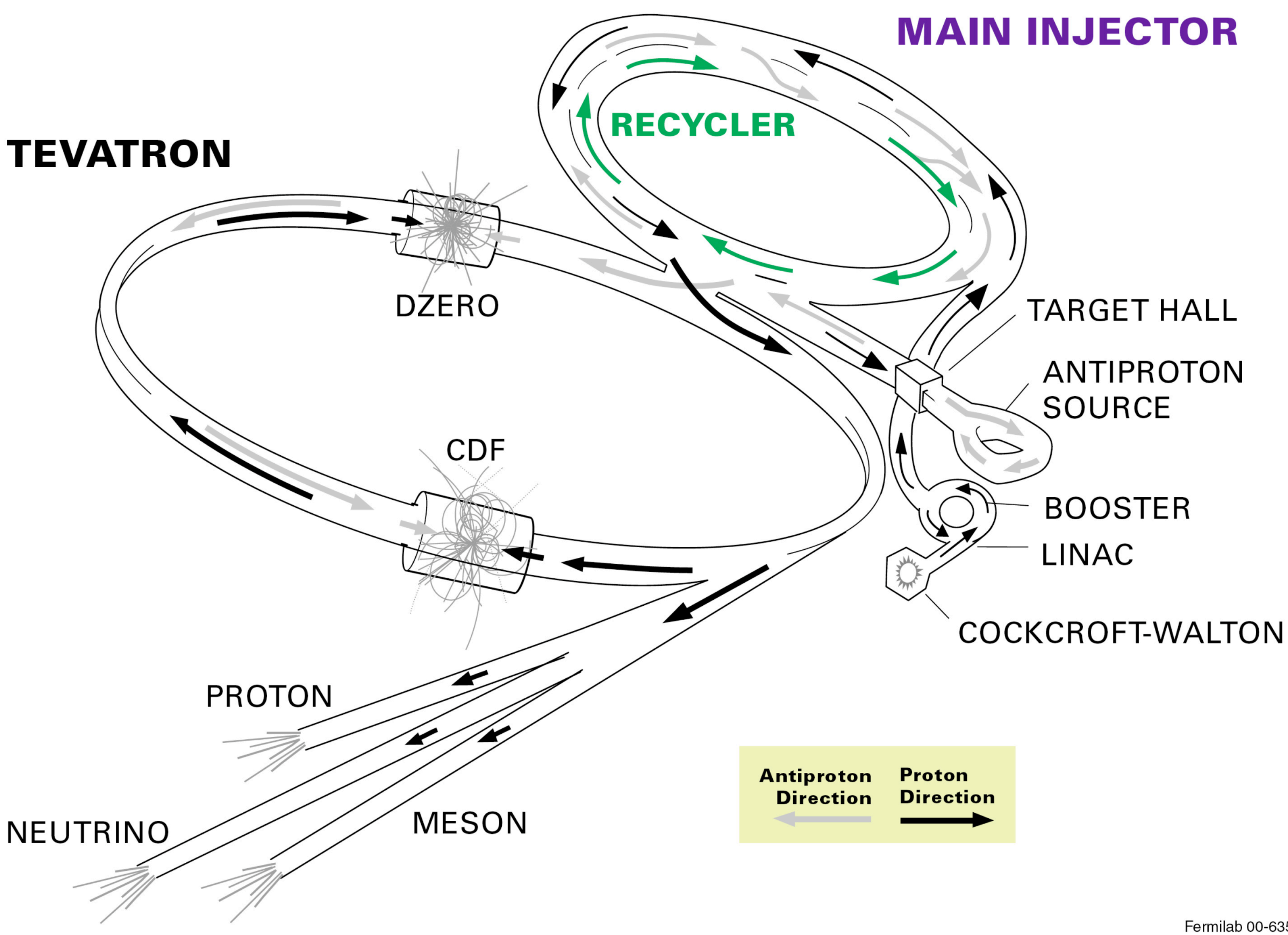
For m = 0.14 GeV and p_{cm} = 0, its momentum in the lab is about 3 GeV



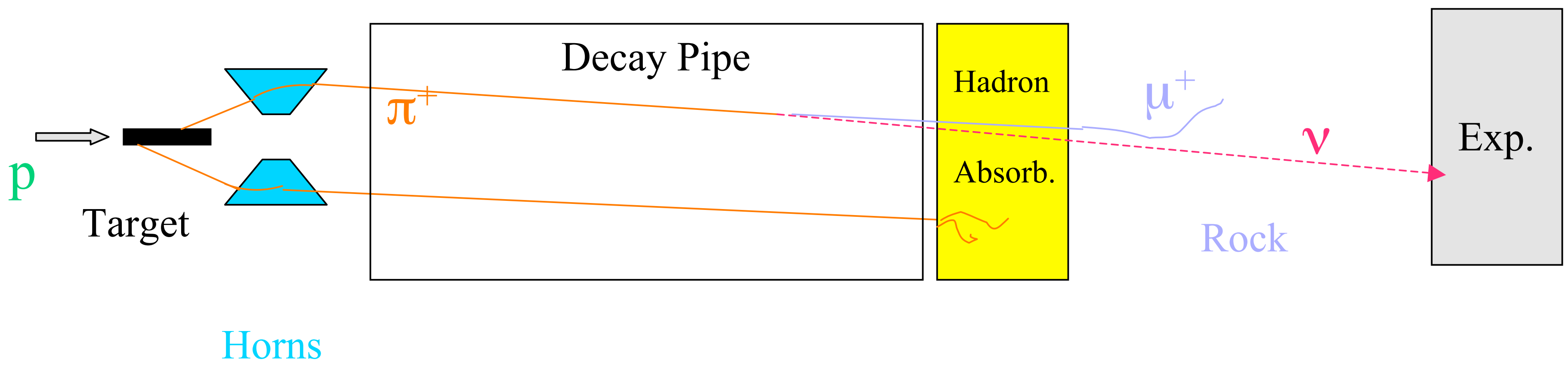


Fermilab Accelerator Complex

FERMILAB'S ACCELERATOR CHAIN

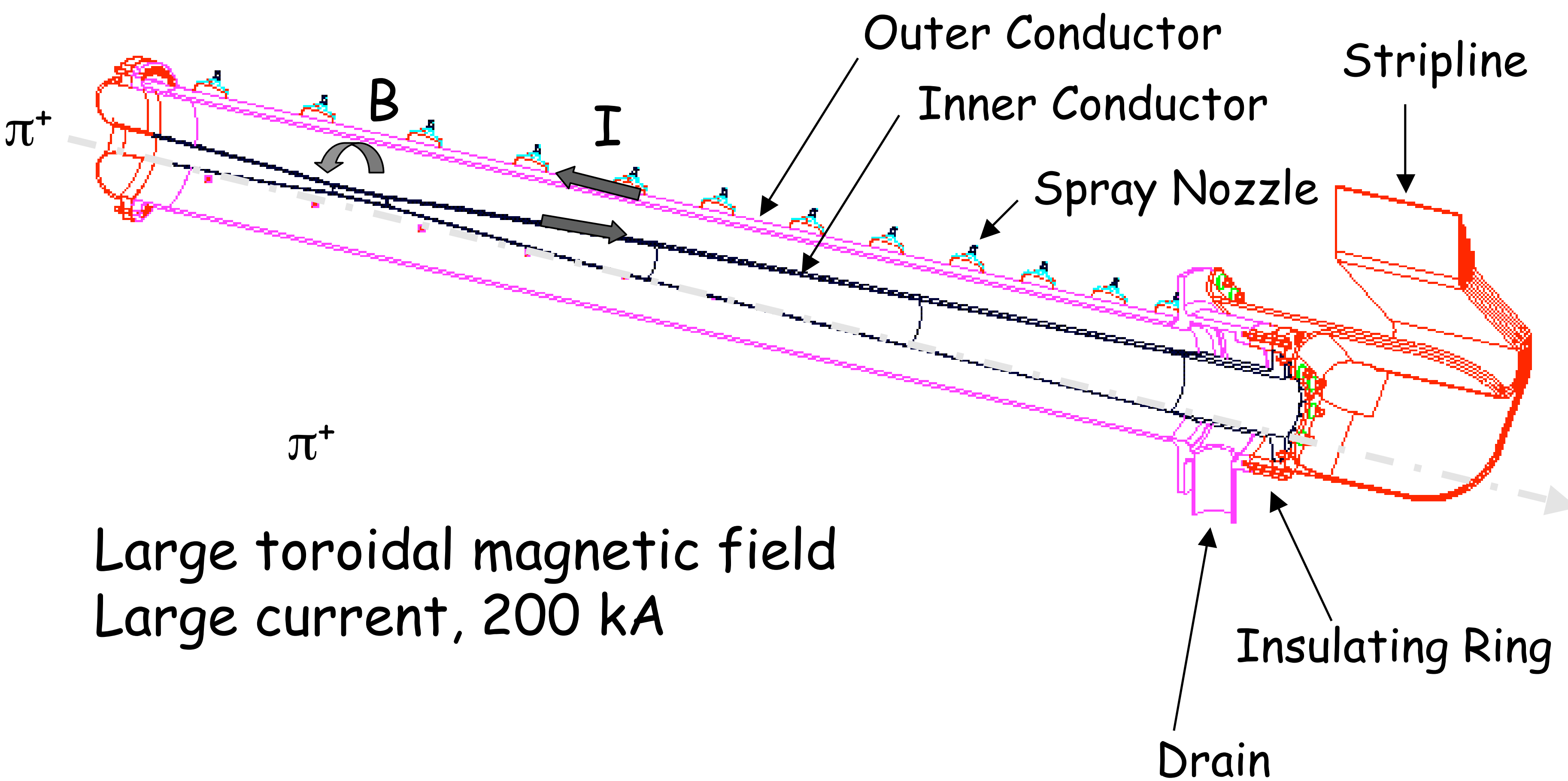


Creating A Neutrino Beam



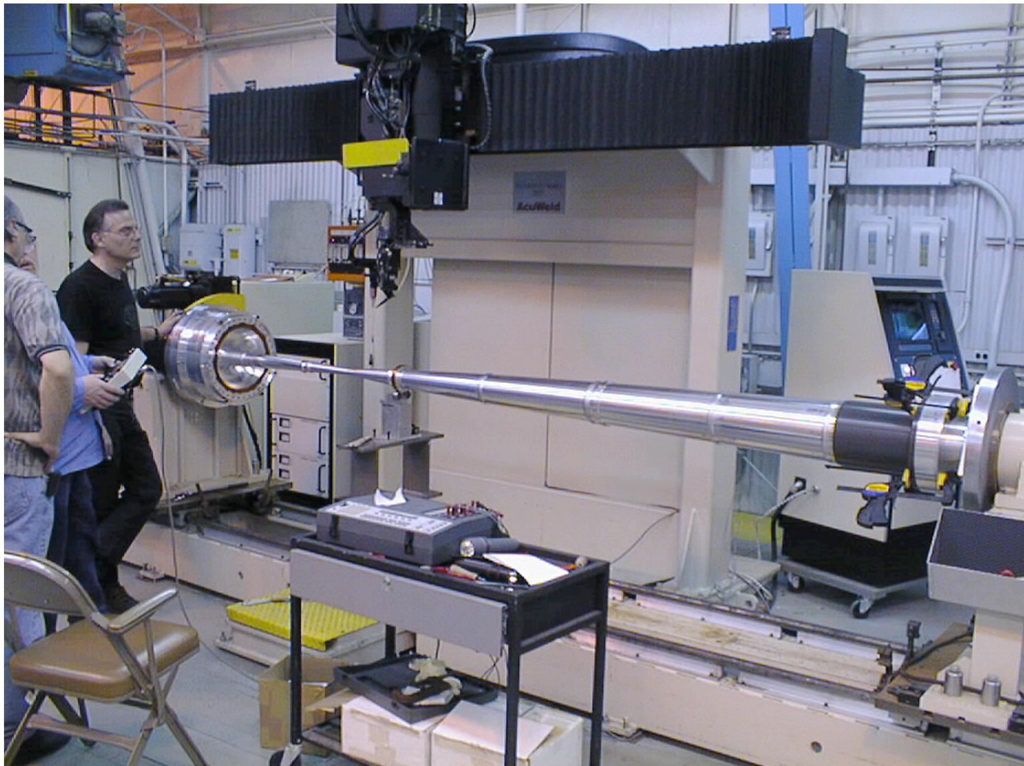
- 120 GeV protons from the Main Injector
- 4 x 10^{13} protons on target every 1.9 sec to give 3.7 x 10^{20} protons/yr
- Water cooled graphite target
- Flexible configuration of 2 parabolic magnetic horns
- 675-m-long, 1-m radius decay pipe
- Muon flux detectors for flux monitoring

Magnetic Horns



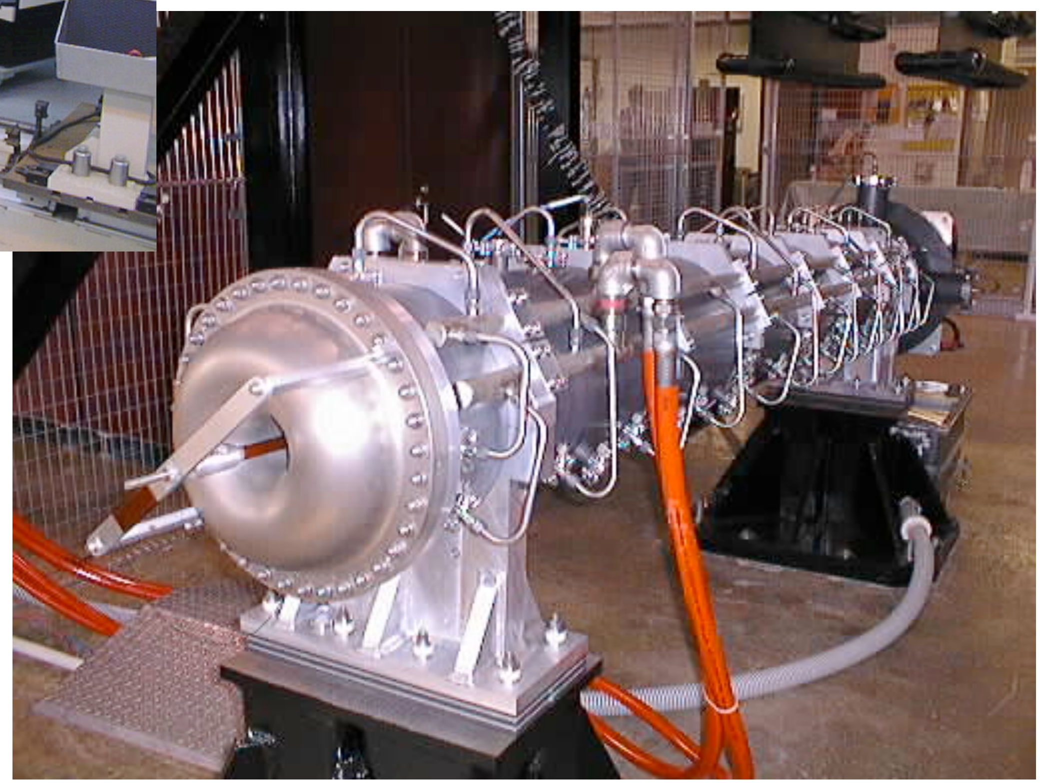
Large toroidal magnetic field
Large current, 200 kA

Magnetic Horns



Welding inner conductor

Assembled for testing



Decay 'Pipe' (Tunnel)

Absorber (Beam Dump)

Energy Spectrum of Neutrino Beam