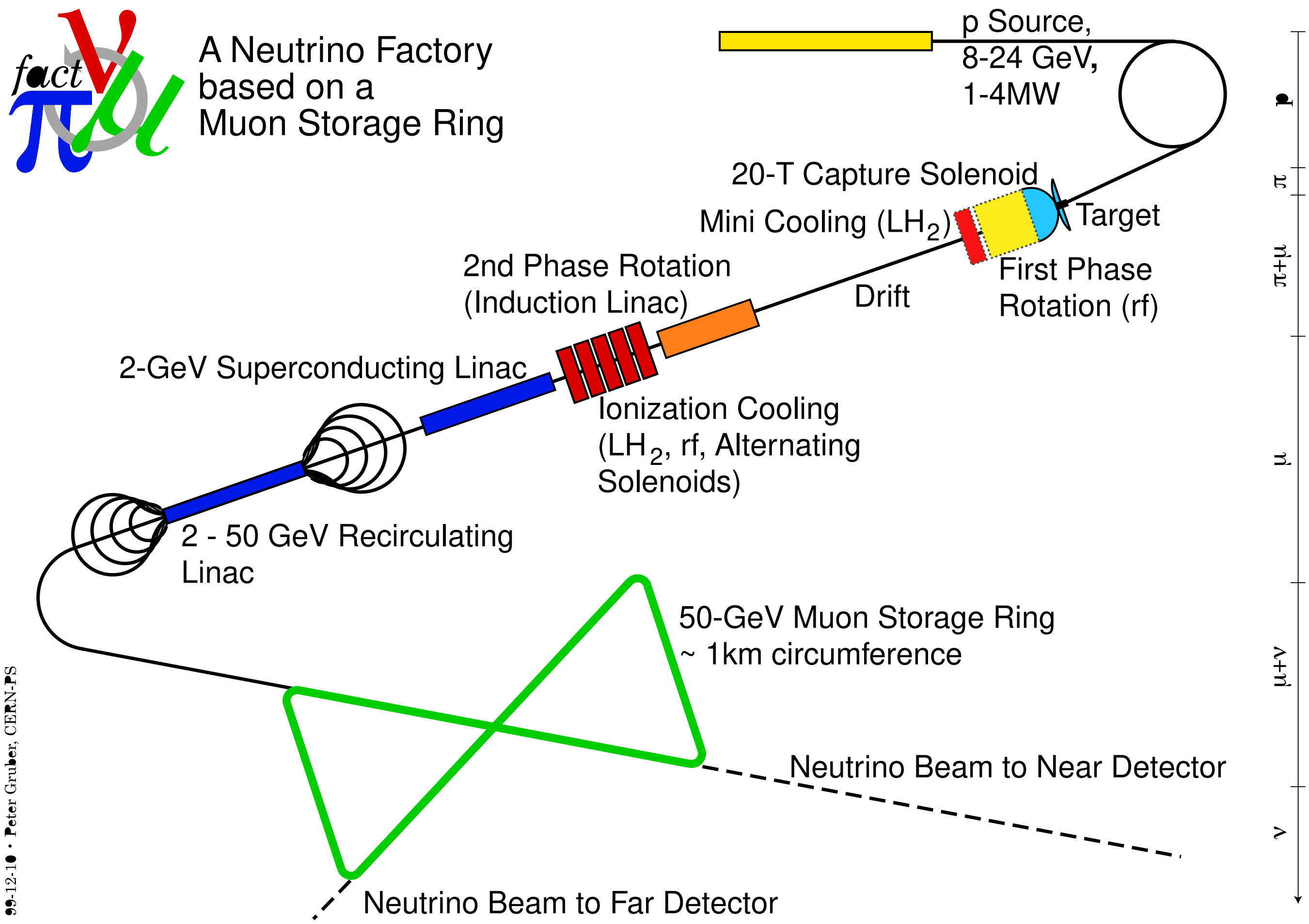
Physics Opportunities with Muon Beams:

Neutrino Factories and Muon Colliders



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A New Opportunity for a New Millenium

- Elementary particle physics can prosper for a 2nd century with laboratory experiments based on innovative particle sources.
- A full range of new phenomena can be investigated:
  - Neutrino mass $\Rightarrow$ a 2nd 3×3 (or larger?) mixing matrix.
  - Precision studies of Higgs bosons.
  - A rich supersymmetric sector (with manifestations of higher dimensions).
  - ... And more ....
- For this we need accelerators with a more cost-effective technology, that is capable of extension to 10's of TeV of constituent center-of-mass energy.

The Solution...

- Accelerator facilities based on muon storage rings: **Neutrino Factories** and **Muon Colliders**.

Why Muons?

- Muons are heavy leptons.
  - $\Rightarrow$ Very little initial state radiation (beamstrahlung).
  - $\Rightarrow$ Precision initial state with full-energy coupling to gauge bosons.
  - $\Rightarrow$ Enhanced coupling to Higgs boson(s).
  - $\Rightarrow$ Can store muons in rings.
  - $\Rightarrow$ Lower cost of acceleration.
- But muons decay.
  - $\Rightarrow$ Secondary neutrino beams.
  - $\Rightarrow$ Must cool and accelerate the muons quickly.

What is a Muon Collider?

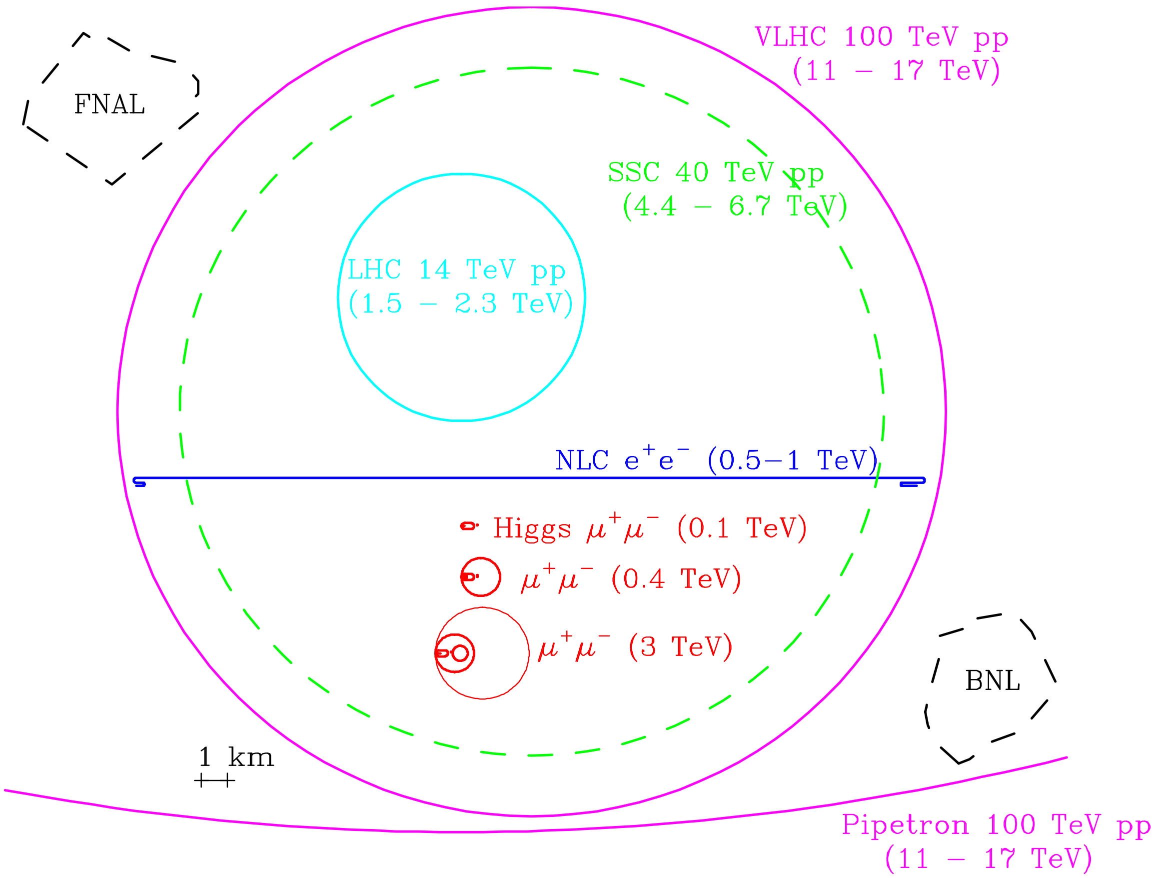
An accelerator complex in which

- Muons (both μ^+ and μ^-) are collected from pion decay following a pN interaction.
- Muon phase volume is reduced by 10^6 by ionization cooling.
- The cooled muons are accelerated and then stored in a ring.
- $\mu^+\mu^-$ collisions are observed over the useful muon life of $\approx$ 1000 turns at any energy.
- Intense neutrino beams (and spallation neutron beams) are available as byproducts.

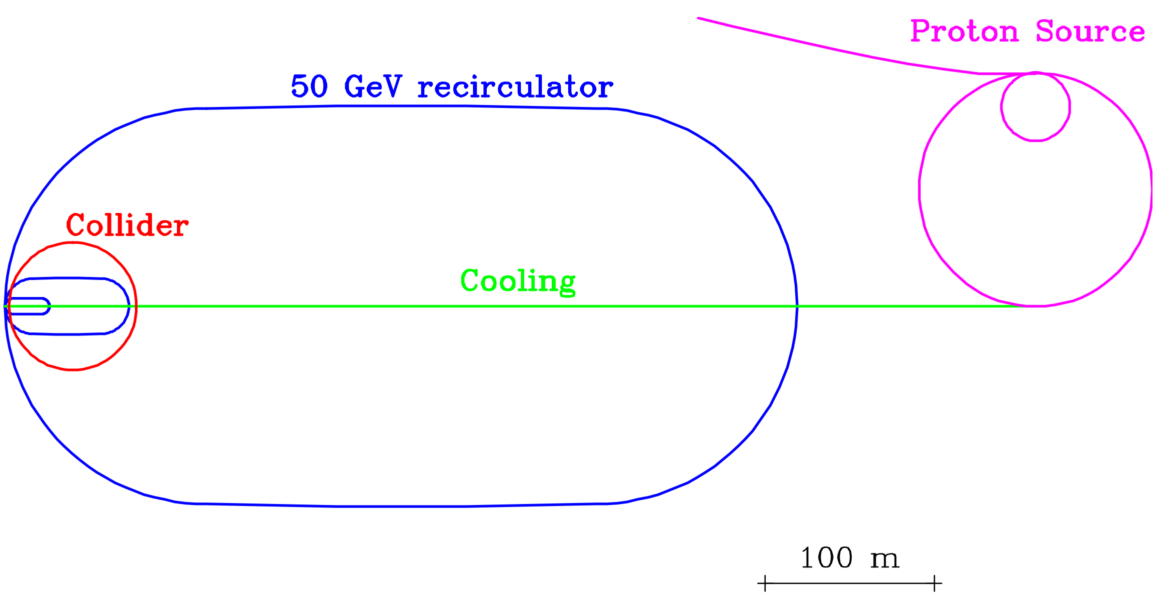
Muons decay: $\mu \rightarrow e\nu \qquad \Rightarrow$

- Must cool muons quickly (stochastic cooling won't do).
- Detector backgrounds at LHC level.
- Potential personnel hazard from ν interactions.

Footprints



A First Muon Collider to study light-Higgs production:



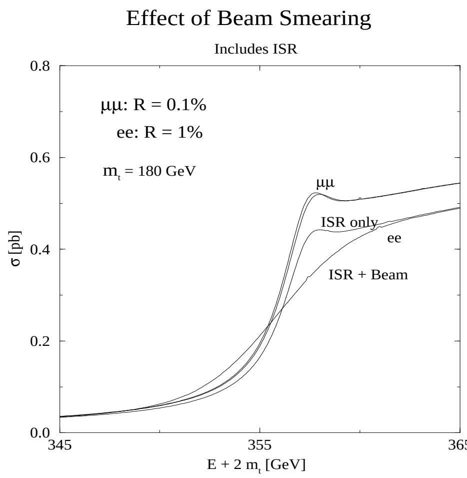
The Case for a Muon Collider

- More affordable than an e^+e^- collider at the TeV (LHC) scale.
- More affordable than either a hadron or an e^+e^- collider for (effective) energies beyond the LHC.
- Precision initial state superior even to e^+e^-.

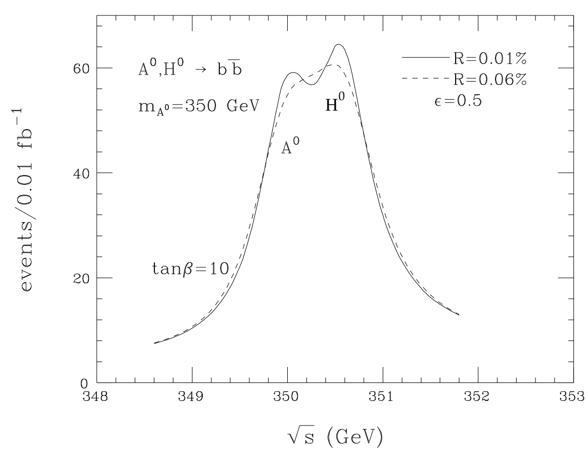
  Muon polarization $\approx$ 25%,

  $\Rightarrow$ Can determine $E_{\rm beam}$ to 10^{-5} via $g-2$ spin precession.

$t\bar{t}$ threshold:



Nearly degenerate A^0 and H^0:



- Initial machine could produce light Higgs via s-channel:

  Higgs coupling to μ is $(m_\mu/m_e)^2 \approx 40,000\times$ that to e.

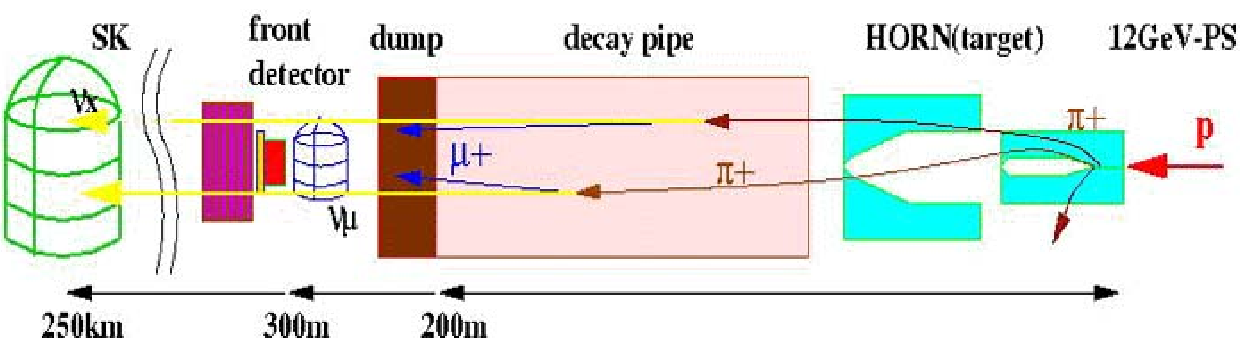
  Beam energy resolution at a muon collider $< 10^{-5}$,

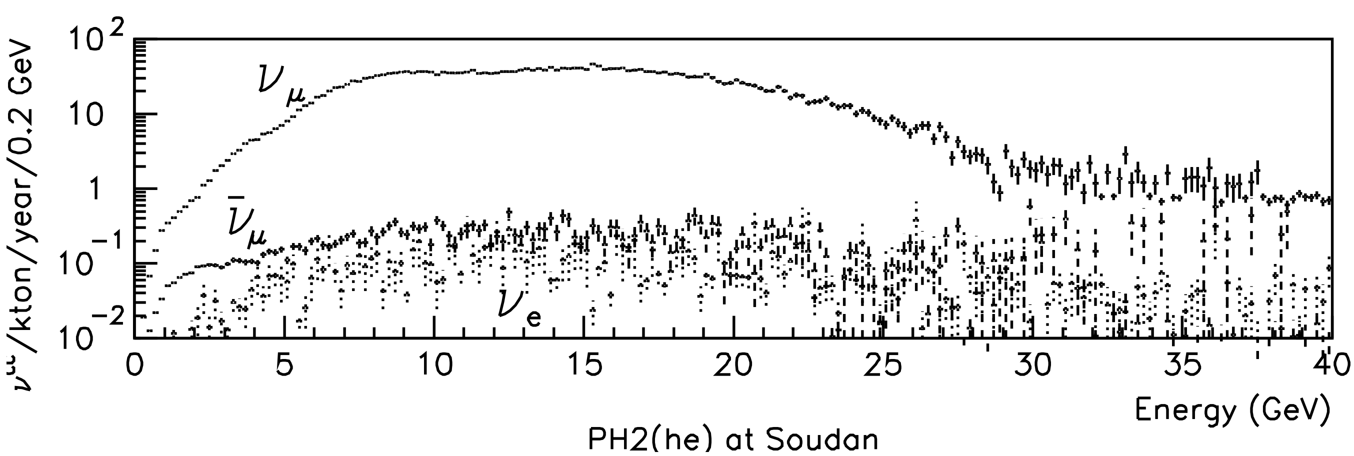
  $\Rightarrow$ Measure Higgs width.

  Add rings to 3 TeV later.

The Opportunity for a Neutrino Factory

- Many of the neutrino oscillation solutions permit study of the couplings between 2, 3, and 4 neutrinos in accelerator based experiments.
- More neutrinos are needed!
- Present neutrino beams come from $\pi, K \to \mu\nu_\mu$ with small admixtures of $\overline{\nu}_\mu$ and ν_e from μ and $K \to 3\pi$ decays.

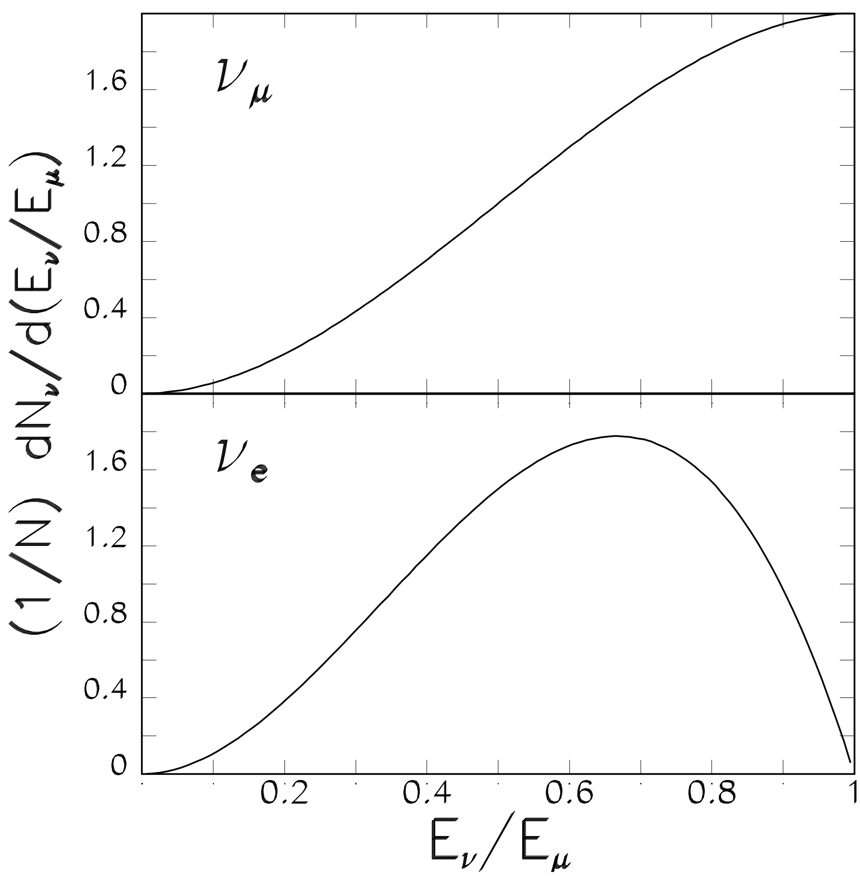




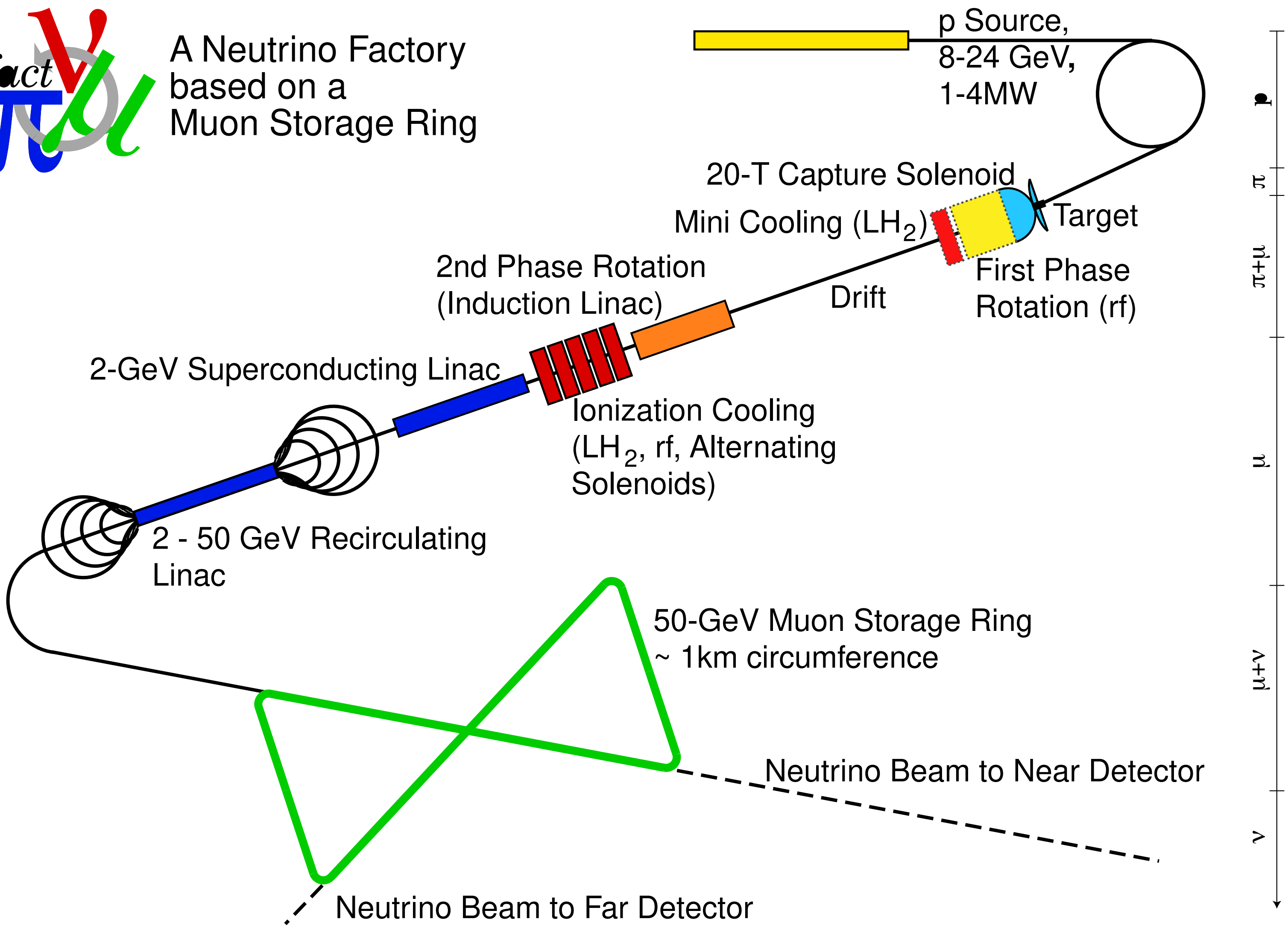
- Cleaner spectra and comparable fluxes of ν_e and ν_μ desirable.

A Neutrino Factory based on a Muon Storage Ring

- Higher (per proton beam power) and better characterized neutrino fluxes are obtained from μ decay.
- Collect low-energy μ's from π decay,
  Cool the muon bunch,
  Accelerate the μ's to the desired energy,
  Store them in a ring while they decay via $\mu^- \to e^- \nu_\mu \overline{\nu}_e$.
  [Of course, can use μ^+ also.]



A Neutrino Factory based on a Muon Storage Ring



Oscillations of Massive Neutrinos

Neutrinos could have a small mass (Pauli, Fermi, Majorana, 1930's).

Massive neutrinos can mix (Pontecorvo, 1957).

In the example of only two massive neutrinos, with mass eigenstates ν_1 and ν_2 with mass difference Δm and mixing angle θ, the flavor eigenstates ν_a and ν_b are related by

$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}.$$

The probability that a neutrino of flavor ν_a and energy E appears as flavor ν_b after traversing distance L in vacuum is

$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 [\mathrm{eV}^2]\ L[\mathrm{km}]}{E[\mathrm{GeV}]} \right).$$

The probability that ν_a does not disappear is

$$P(\nu_a \to \nu_a) = \cos^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 [\mathrm{eV}^2]\ L[\mathrm{km}]}{E[\mathrm{GeV}]} \right).$$

A Sketch of Current Data

1. The "anomaly" of atmospheric neutrinos suggests that GeV ν_μ's disappear while traversing the Earth's diameter.
   $\Rightarrow \Delta m^2 \approx 10^{-3}$ (eV)^2 for $\sin^2 2\theta \approx 1$.
   (Kamiokande, IMB, Soudan-2, MACRO, Super-Kamiokande)
2. The solar neutrino "deficit" suggests that MeV ν_e's disappear between the center of the Sun and the Earth.
   $\Rightarrow \Delta m^2 \approx 10^{-10}$ (eV)^2 for $\sin^2 2\theta \approx 1$, if vacuum oscillations.
   (Homestake, GALLEX, SAGE)
3. The LSND experiment at Los Alamos suggests that 30-MeV $\overline{\nu}_\mu$'s appears as $\overline{\nu}_e$'s after 30 m.
   $\Rightarrow \Delta m^2 \approx 1$ (eV)^2, but reactor data requires $\sin^2 2\theta \lesssim 0.03$.

- The first two results require at least 3 massive neutrinos.
- All results together require at least 4 massive neutrinos.
- The measured width of the Z^0 boson (LEP) $\Rightarrow$ only 3 Standard Model neutrinos. A 4th massive neutrino must be "sterile".

Mixing of Three Neutrinos

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

where $c_{12} = \cos\theta_{12}$, *etc.* (Maki, Nakagawa, Sakata, 1962).

Three massive neutrinos $\Rightarrow$ six independent parameters:

- Three mixing angles: θ_{12}, θ_{13}, θ_{23},
- A phase δ related to CP violation,
- Two differences of the squares of the neutrino masses.
  Ex: $\Delta m^2_{12} = \Delta m^2(\text{solar})$ and $\Delta m^2_{23} = \Delta m^2(\text{atmospheric})$.

Measurement of these parameters is a primary goal of experimental neutrino physics.

If four massive neutrinos, then 6 mixing angles, 3 phases, 3 independent squares of mass differences.

6 Classes of Experiments at a Neutrino Factory

$$\nu_\mu \to \nu_e \to e^- \qquad \text{(appearance)}, \tag{1}$$

$$\nu_\mu \to \nu_\mu \to \mu^- \qquad \text{(disappearance)}, \tag{2}$$

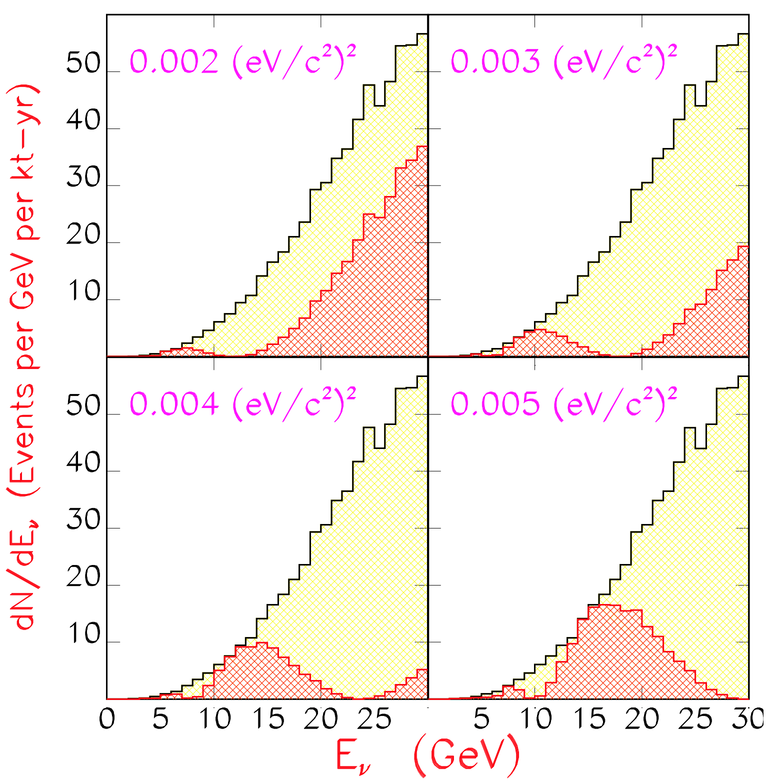
$$\nu_\mu \to \nu_\tau \to \tau^- \qquad \text{(appearance)}, \tag{3}$$

$$\overline{\nu}_e \to \overline{\nu}_e \to e^+ \qquad \text{(disappearance)}, \tag{4}$$

$$\overline{\nu}_e \to \overline{\nu}_\mu \to \mu^+ \qquad \text{(appearance)}, \tag{5}$$

$$\overline{\nu}_e \to \overline{\nu}_\tau \to \tau^+ \qquad \text{(appearance)}. \tag{6}$$

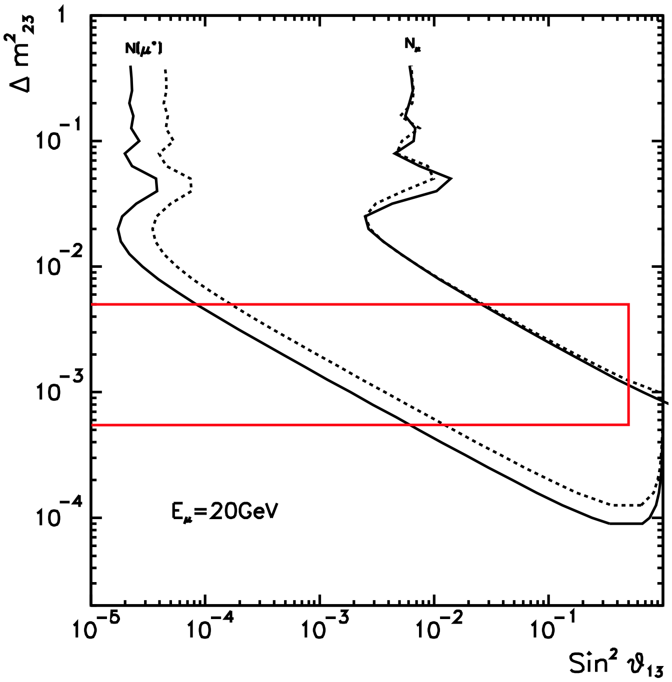
$\nu_\mu \to \nu_\mu \to \mu^-$ Disappearance



$E_\mu = 30$ GeV,
2×10^{20} μ decays,
$L = 7000$ km,
$\sin^2 2\theta_{23} = 1$.

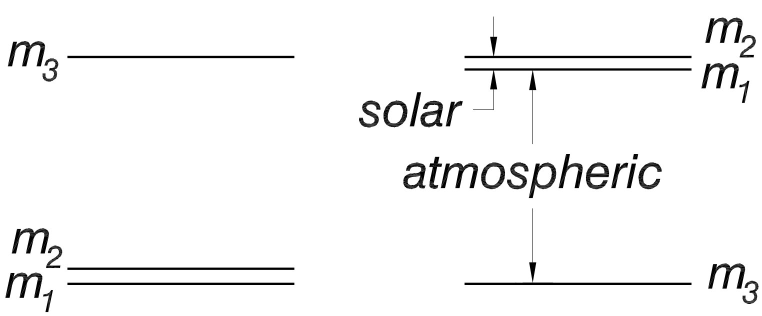
Δm^2_{23} (eV^2)	Events (per 10 kt-yr)
0.002	2800
0.003	1200
0.004	900
0.005	1700
No Osc.	6200

Measuring θ_{13} via $\overline{\nu}_e \to \overline{\nu}_\mu \to \mu^+$

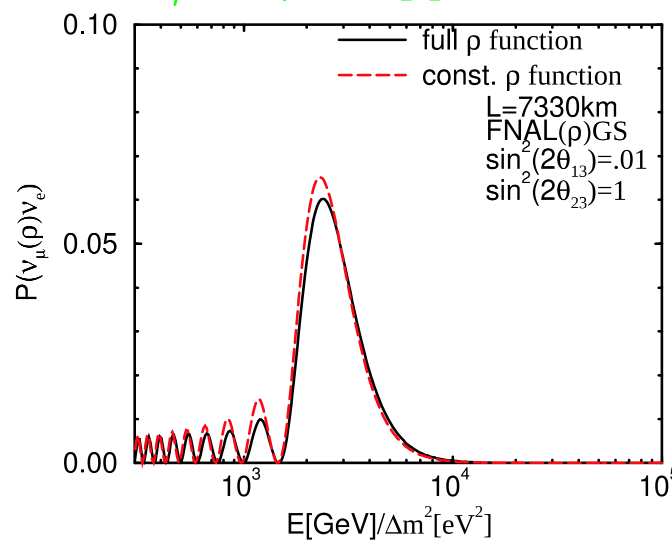


10 kton detector,
$E_\mu = 20$ GeV,
2×10^{20} μ decays,
$L = 732$ km,
$\sin^2 2\theta_{23} = 1$,
Left: $\overline{\nu}_e \to \overline{\nu}_\mu \to \mu^+$,
Right: $\nu_\mu \to \nu_\mu \to \mu^-$,
Box = presently allowed.

Measuring the Sign of Δm^2_{23} via Matter Effects



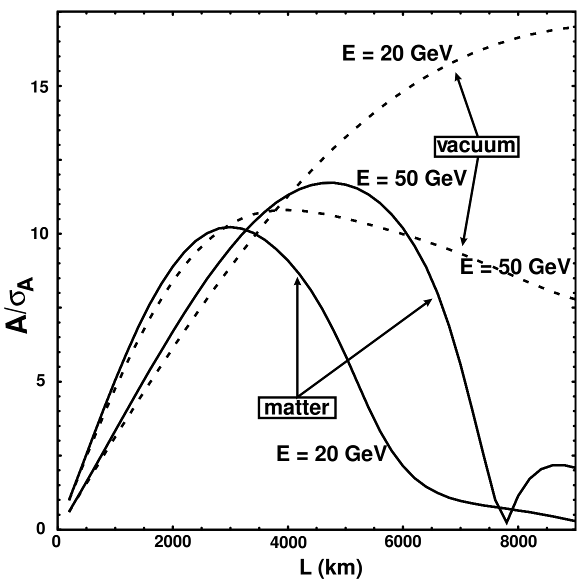
$\overline{\nu}_e \to \overline{\nu}_\mu \to \mu^+$ Appearance



The matter effect resonance depends on the sign of Δm^2.

Measuring δ via CP Violation in

$$P(\nu_e \to \nu_\mu) - P(\overline{\nu}_e \to \overline{\nu}_\mu)$$



10 kton detector,

2×10^{21} muon decays,

Large angle MSW:

$\Delta m^2_{12} = 10^{-4}\ \mathrm{eV}^2$,

$\Delta m^2_{23} = 2.8 \times 10^{-3}\ \mathrm{eV}^2$,

$\theta_{12} = 22.5°$,

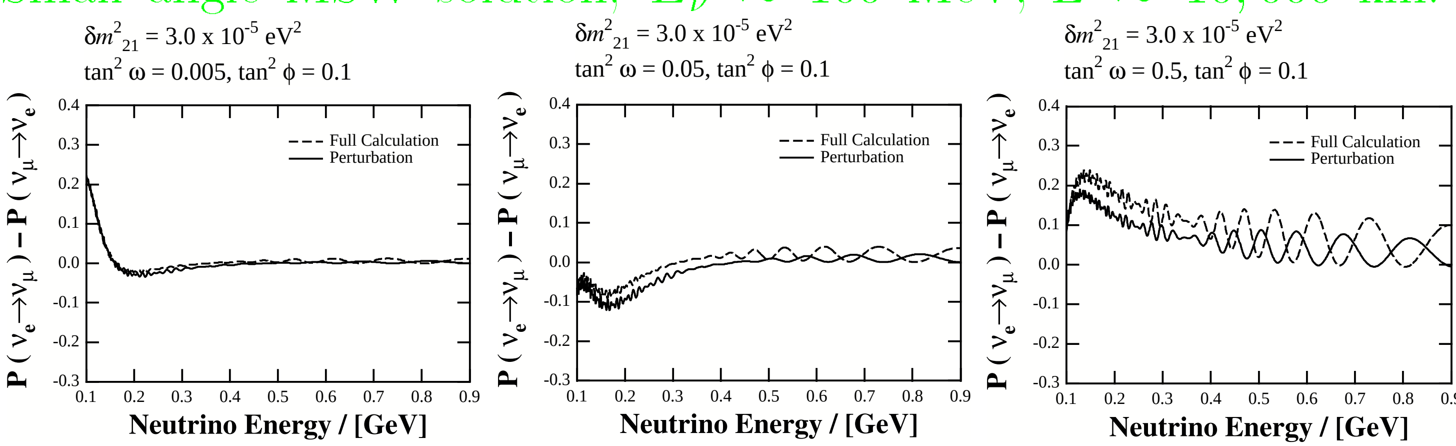
$\theta_{13} = 13°$,

$\theta_{23} = 45°$,

$\delta = -90°$.

Measuring δ via T Violation in $P(\nu_e \to \nu_\mu) - P(\nu_\mu \to \nu_e)$

Small angle MSW solution; $E_\nu \approx 100$ MeV, $L \approx 10,000$ km.

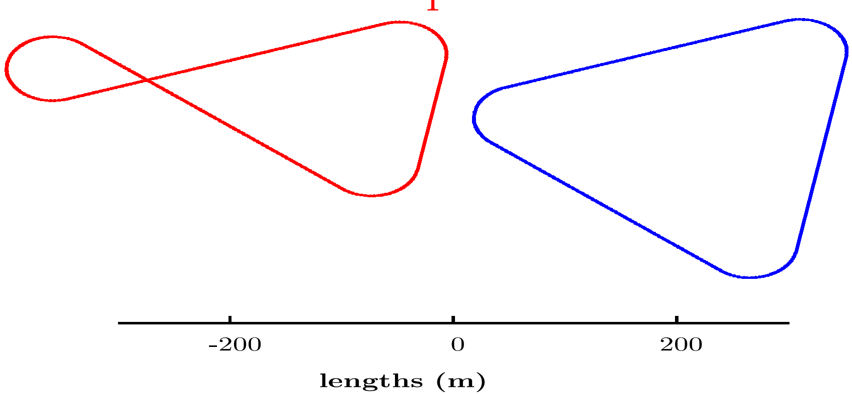


Modulate the muon polarization to modulate the relative rates of

$\nu_\mu \to \nu_e \to e^-$ and $\overline{\nu}_e \to \overline{\nu}_e \to e^+$.

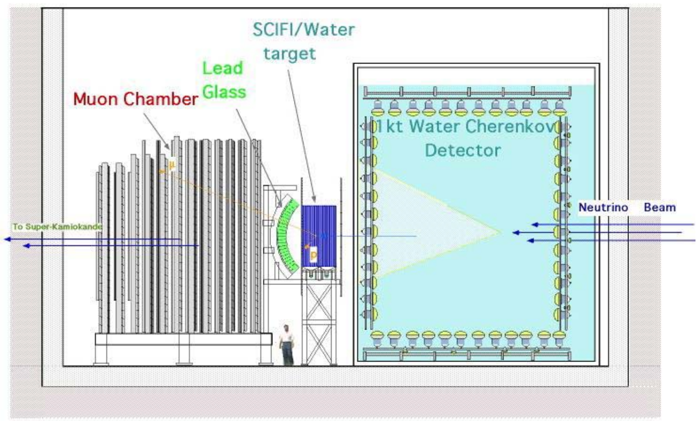
A Neutrino Factory is a Global Facility

- Host lab with the muon storage ring and near detector.
- Could have two larger detectors located elsewhere, possibly one on the same, and the second on another continent.
- For this, the muon storage ring needs 3 straight sections, and would not lie in a horizontal plane.

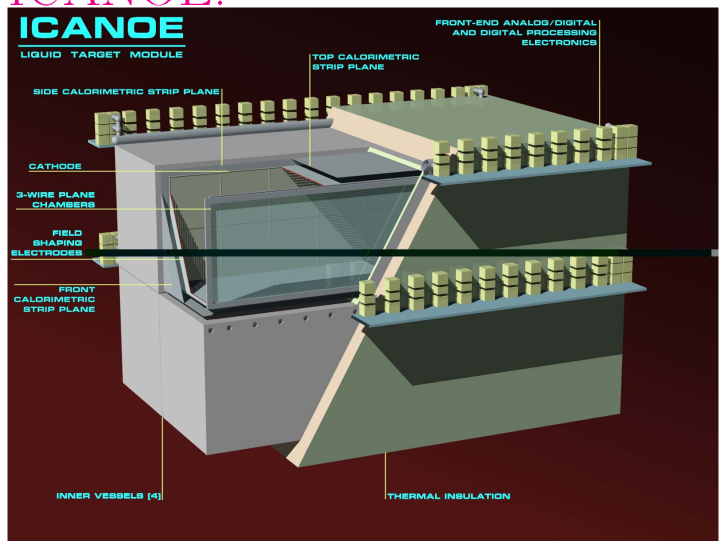


Large Underground Detectors

K2K:

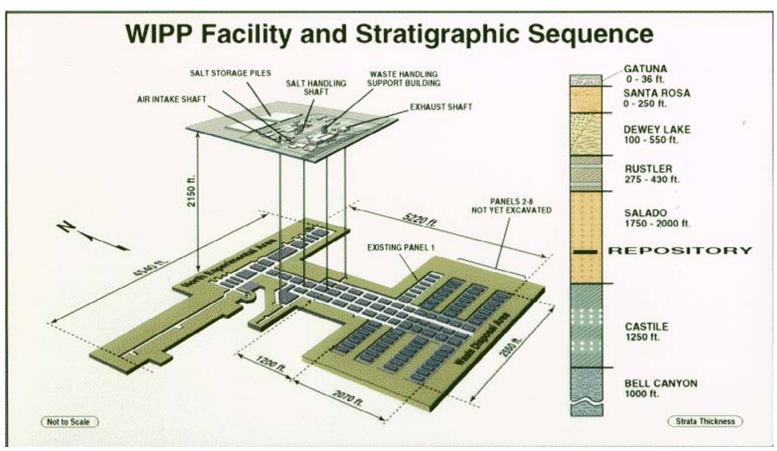


ICANOE:



Gran Sasso in Italy:

DOE nuclear waste facility in New Mexico:



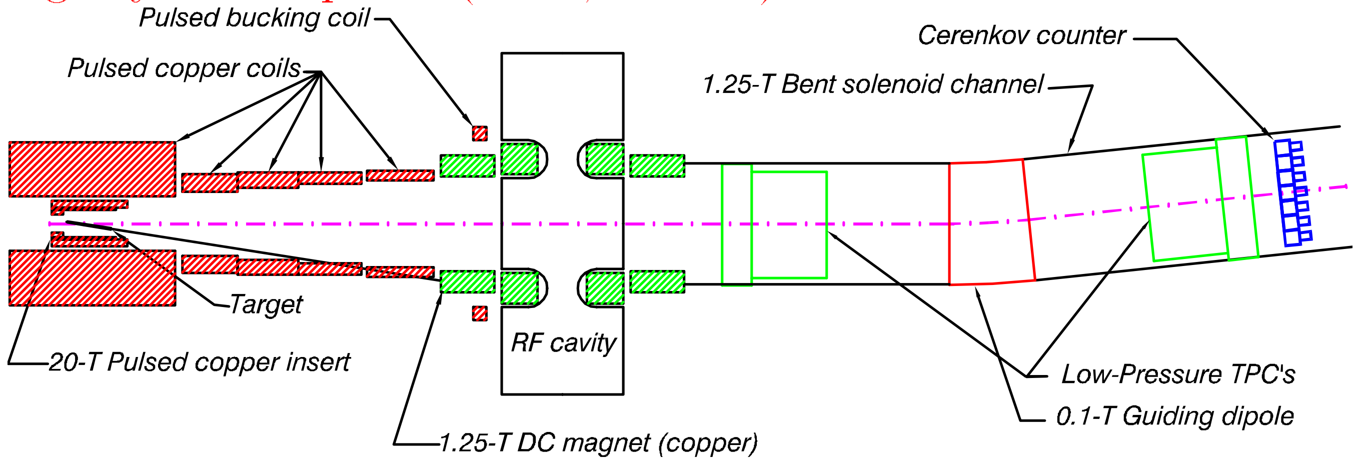
Physics Summary

- The physics program of a neutrino factory/muon collider is extremely diverse, and of scope to justify an international laboratory.

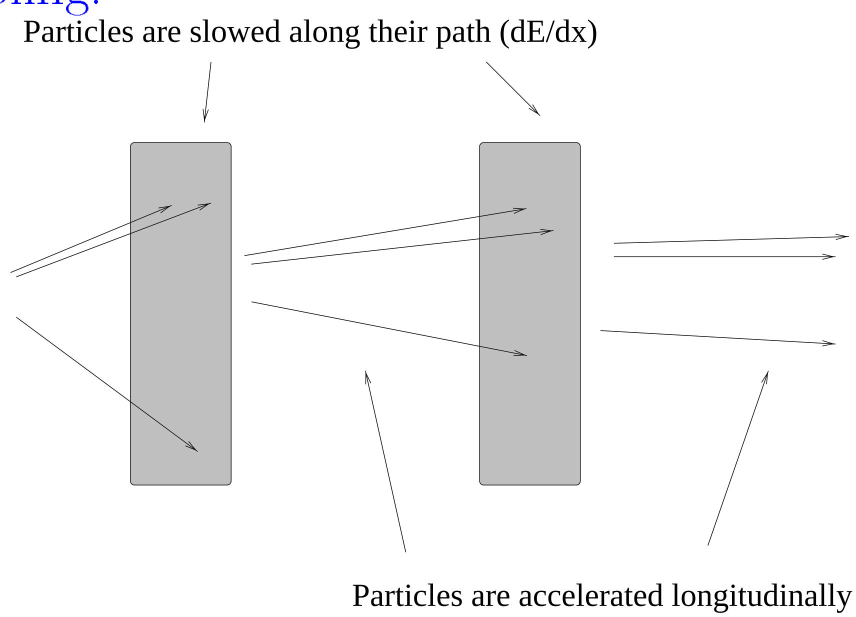
- The first step is a neutrino factory capable of systematic exploration of neutrino oscillations.
  - With $\gtrsim 10^{20}$ ν's/year can go well beyond other existing or planned accelerator experiments.
  - Beams with $E_{\nu_e} \lesssim 1$ GeV are already very interesting.
  - Higher energy is favored: Rate $\propto E$ at fixed L/E; ν_τ appearance practical only for $E \gtrsim 20$ GeV.
  - Detectors at multiple distances needed for broad coverage of parameter space $\Rightarrow$ triangle or "bowtie" storage rings.
  - CP and T violation accessible with $\gtrsim 10^{21}$ ν's/year.
  - Control of muon polarization extremely useful when studying $\nu_e \to e$ modes.

R&D To Make It Happen

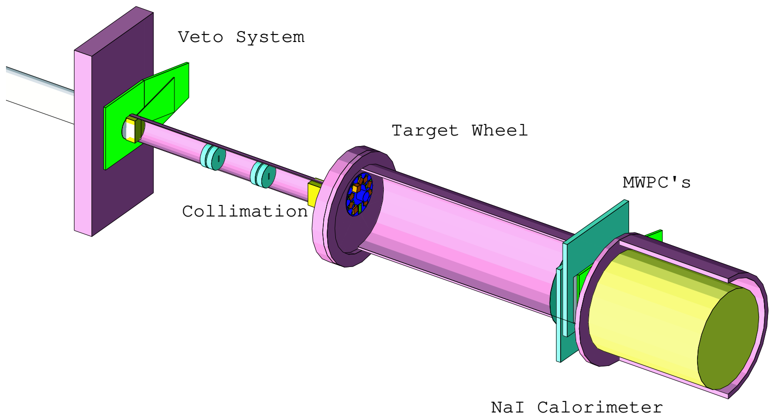
- Design (Neutrino Factory and Muon Collider Collaboration).
- 1-4 Megawatt proton source (BNL, CERN, FNAL, KEK).
- Targetry and capture (BNL, CERN).



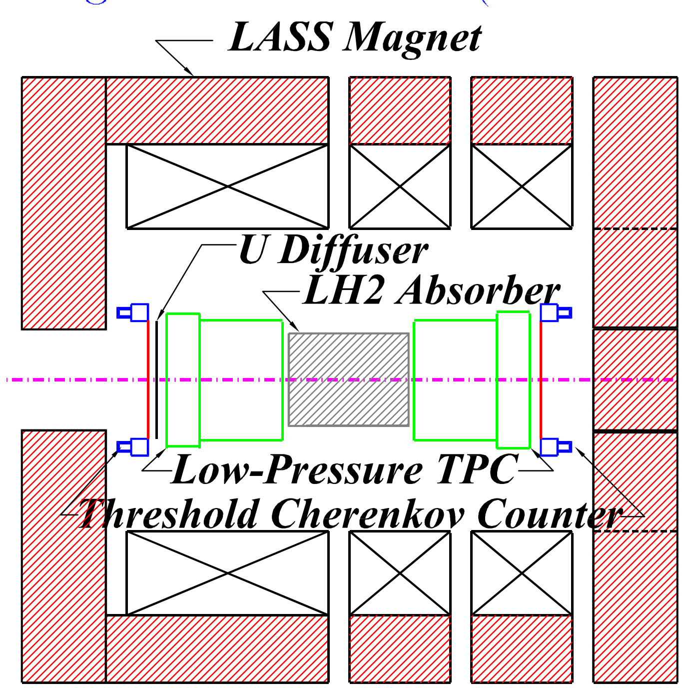
- Ionization cooling.



Muon Scattering Experiment (RAL, TRIUMF *et al.*):



An Initial Cooling Demonstration (BNL or TRIUMF):



- Induction linac (LBL).
- Recirculating linac (JLAB).
- Storage Ring (CERN, FNAL).

with participation from many other labs and universities.

R&D Schedule

- FY00: Feasibility study for a basic neutrino factory (5×10^{19} ν's/year).
- FY01: Feasibility study for more ambitious neutrino factory (2-4 $\times 10^{19}$ ν's/year).
  Neutrino Factory "book" for Snowmass '01.
- FY02-03: Continued R&D on accelerator design, targetry, cooling...
- FY04: Zeroeth Order Design Report.