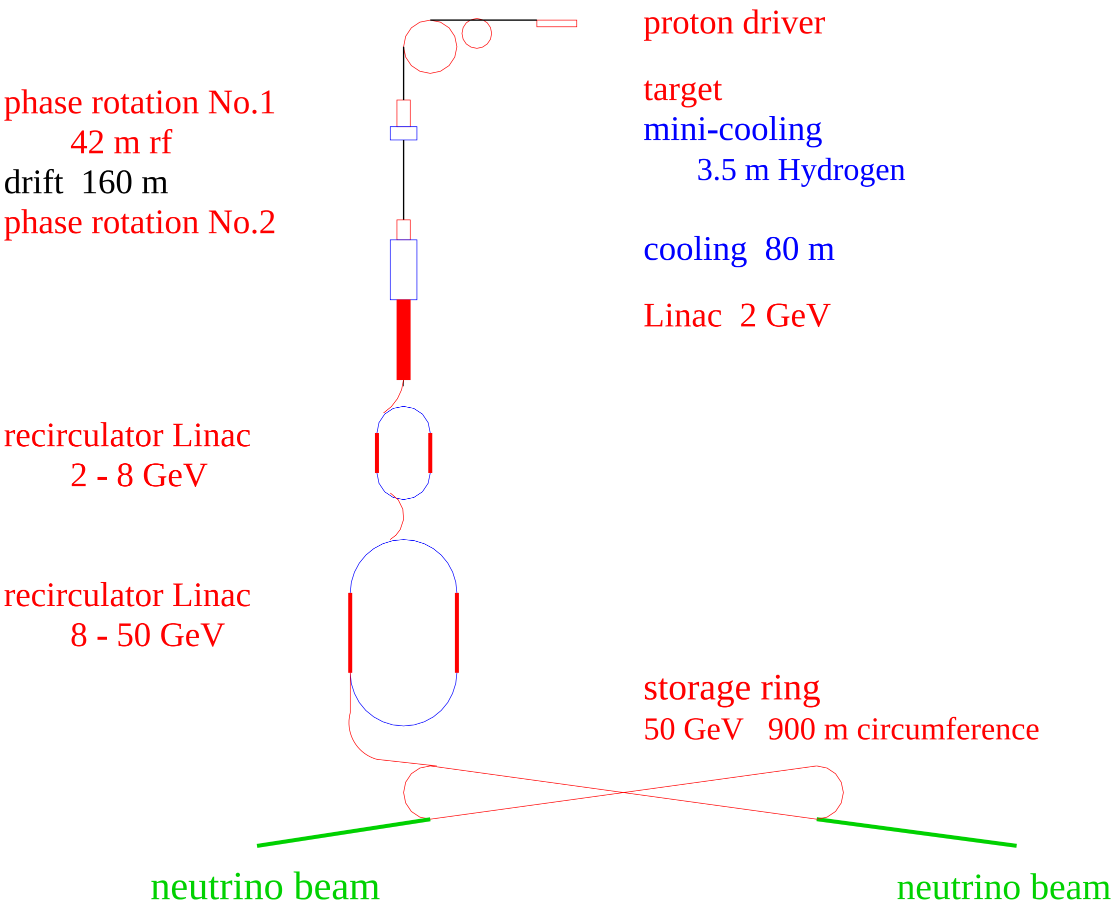
Physics Opportunities with Muon Beams: Neutrino Factories and Muon Colliders



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Presented at the 5th International Conference on

Physics Potential and Development of $\mu^+\mu^-$ Colliders

San Francisco, December 15, 1999

http://puhep1.princeton.edu/~mcdonald/mumu/nufact/

The Y2K Problem for Particle Physics

- Can elementary particle physics prosper for a 2nd century with laboratory experiments based on innovative particle sources?
- Can a full range of new phenomena 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 ....
- Will our investment in future accelerators result in 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**.

Where We Are Coming From

- (1956) O'Neill: proposes ionization cooling; realizes it won't work for e or p; proposes electron cooling (with Spitzer).
- (1960) Melissinos: proposes a muon storage ring.
- (1966) Budker: develops electron cooling for protons.
- (1968) Tikhonin: first known mention of $\mu^+\mu^-$ collisions.
- (1969-71) Budker, Skrinsky: Development of idea of a muon collider with storage rings.
- (1970) Ado, Balbekov: revival of idea of ionization cooling.
- (1972) Van der Meer: proposes stochastic cooling.
- (1979) Neuffer: proposes muon collider as a Z^0 factory.
- (1980) Cline, Neuffer: muon storage ring as neutrino source.
- (1987) Neuffer: proposes muon collider as a Higgs factory.
- (1993) Mikhailichenko, Zolotorev: optical stochastic cooling.
- (1994) Palmer: proposes high performance source and cooling channel for a muon collider.

What is a Muon Collider?

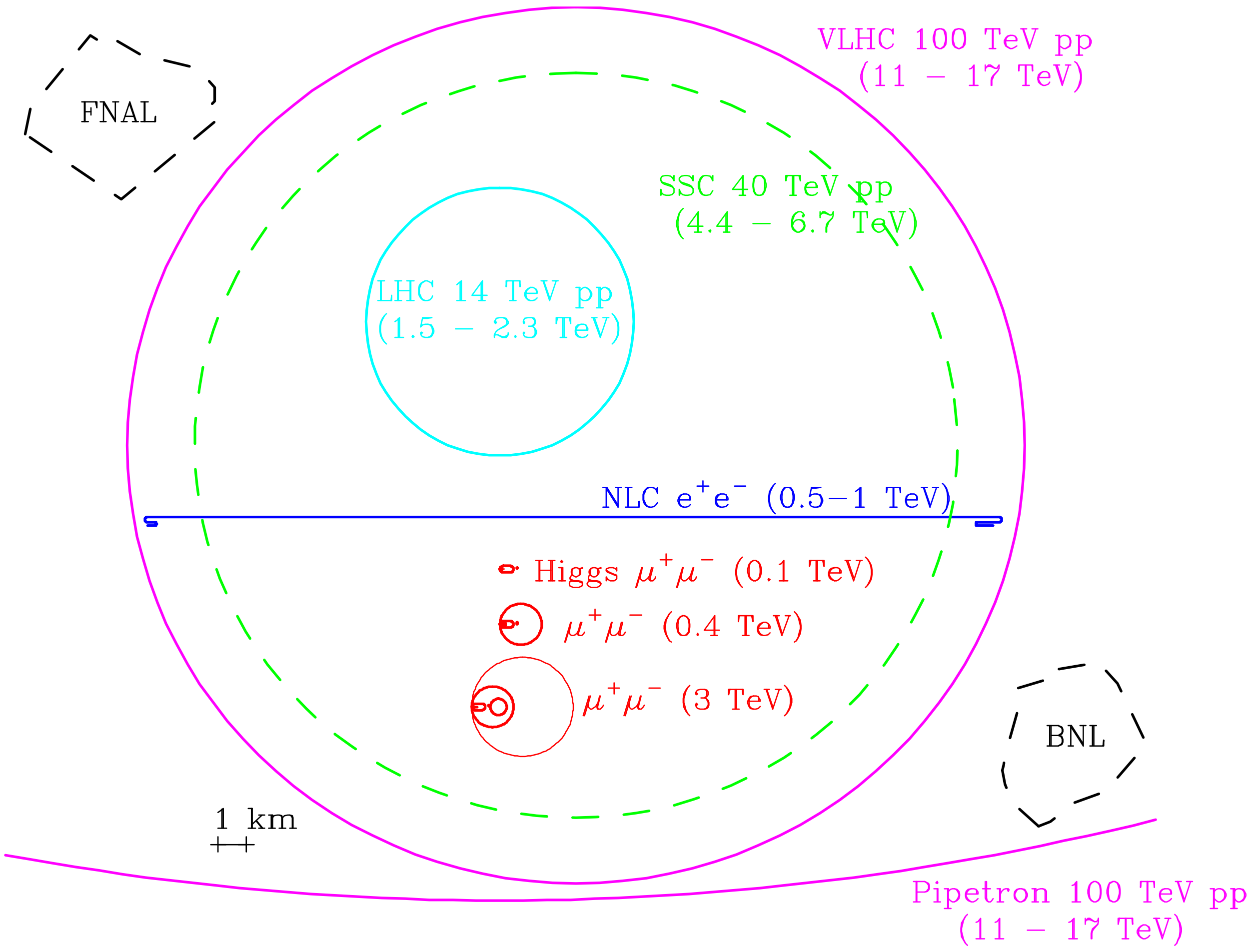
An accelerator complex in which

- 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 ≈ 1000 turns at any energy.
- Intense neutrino beams (and spallation neutron beams) are available as byproducts.

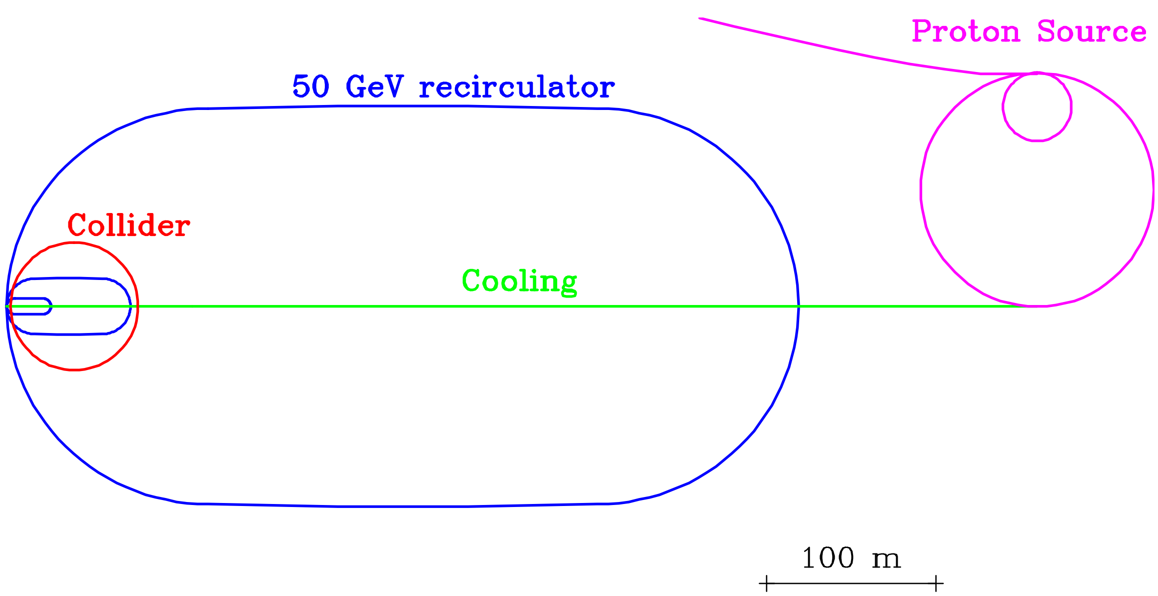
Muons decay: $\mu \to e\nu \qquad \Rightarrow$

- 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:



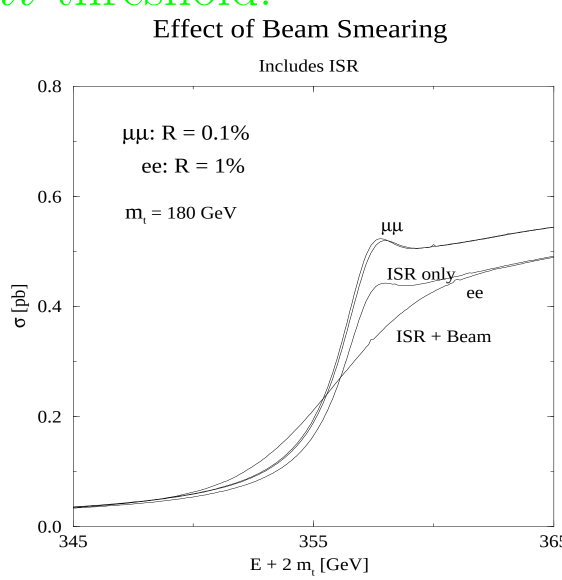
The Case for a Muon Collider

- 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^-.

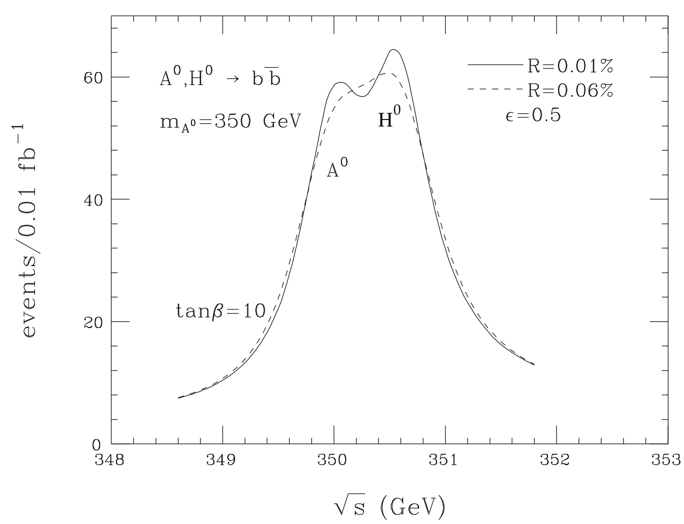
  Muon polarization $\approx 25\%$,

  $\Rightarrow$ Can determine E_{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.

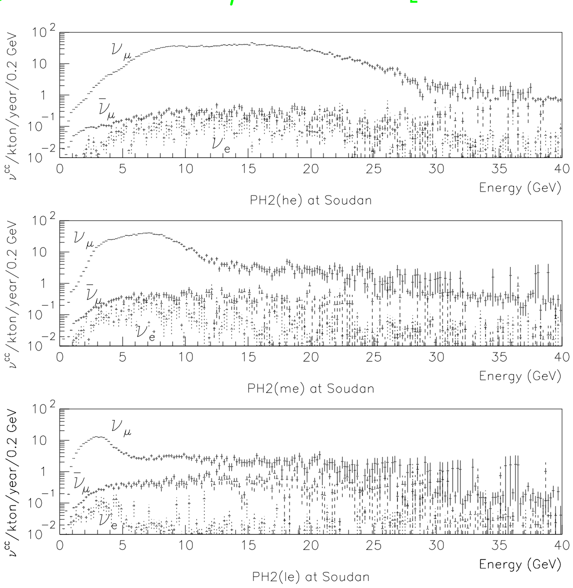
  Add rings to 3 TeV later.

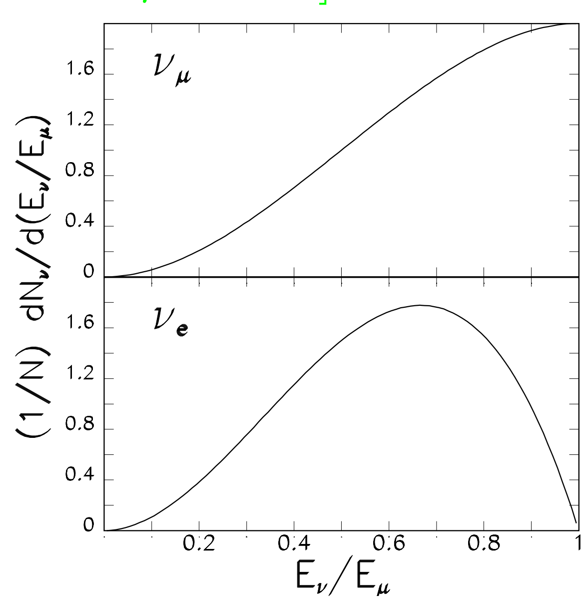
The Opportunity for a Neutrino Factory

- 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.
- Higher (per proton beam power), and better characterized, neutrino fluxes of both ν_μ and ν_e are obtained from μ decay.

  Collect low-energy μ's from π decay, accelerate the μ's to the desired energy, and store in a ring while they decay via

  $\mu^- \to e^-\nu_\mu\overline{\nu}_e$. [Of course, can use μ^+ also.]





6 Classes of Experiments at a Neutrino Factory

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

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

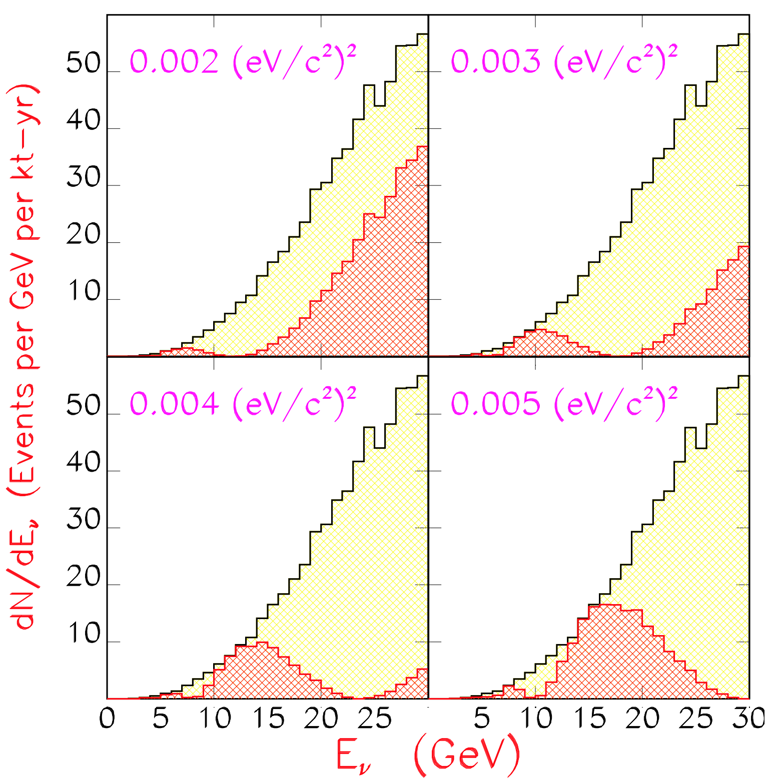
$$\nu_\mu \to \nu_\tau \to \tau^- \quad \text{(appearance)}, \tag{3}$$

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

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

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

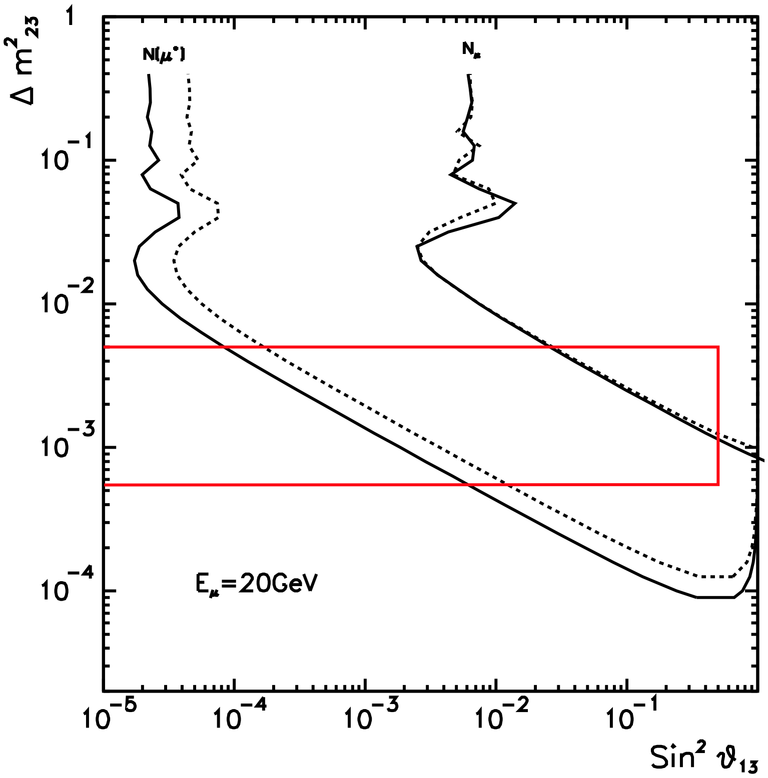
$\nu_\mu \to \nu_\mu \to \mu^-$ Disappearance



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

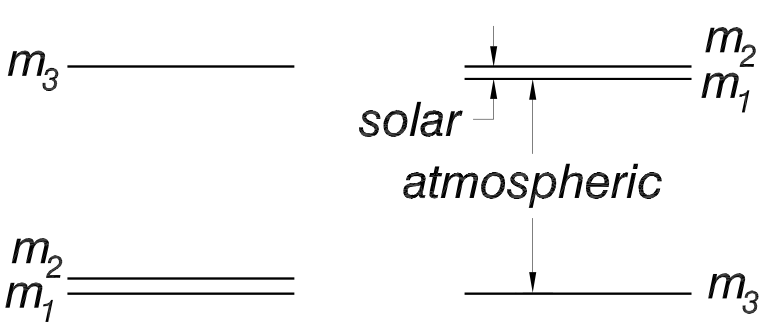
Δm^2_{23} (eV^2)	Events (per 10 kt-yr)
0.002	2800
0.003	1200
0.004	900
0.005	1700
No Osc.	6200

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

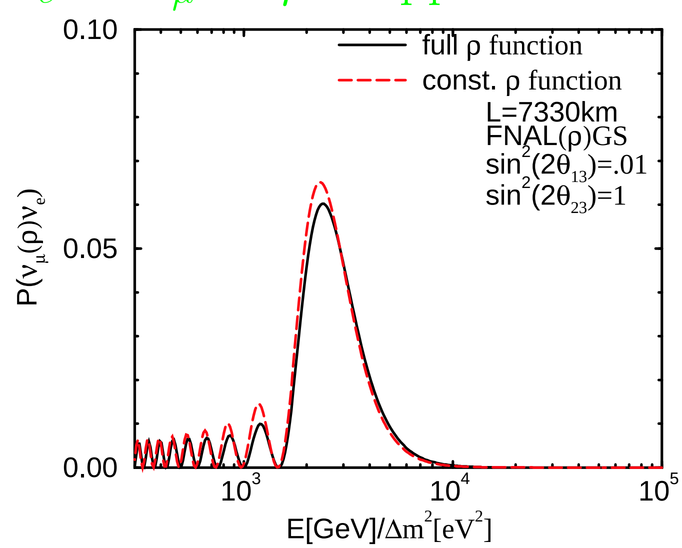


10 kton detector,
$E_\mu = 20$ GeV,
2×10^{20} μ decays,
$L = 732$ km,
$\sin^2 2\theta_{23} = 1$,
Left: $\overline{\nu}_e \to \overline{\nu}_\mu \to \mu^+$,
Right: $\nu_\mu \to \nu_\mu \to \mu^-$,
Box = presently allowed.

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



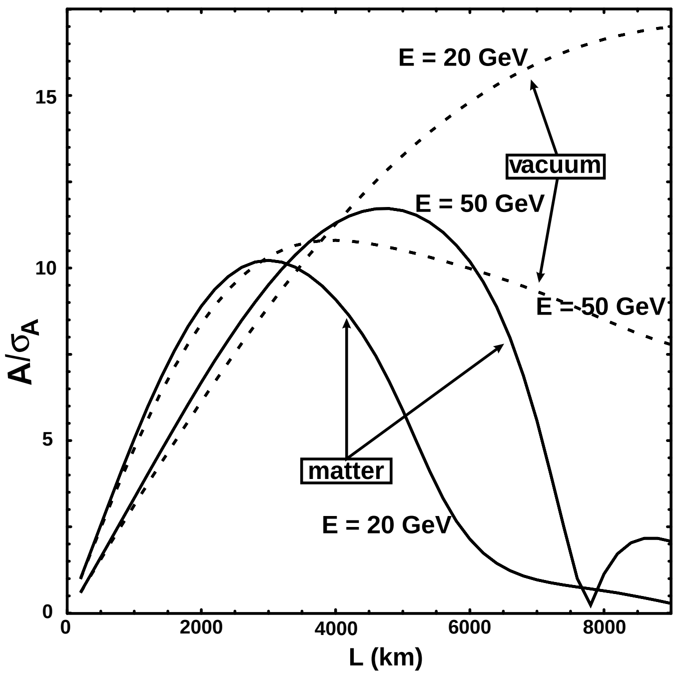
$\overline{\nu}_e \to \overline{\nu}_\mu \to \mu^+$ Appearance



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

Measuring δ via CP Violation in

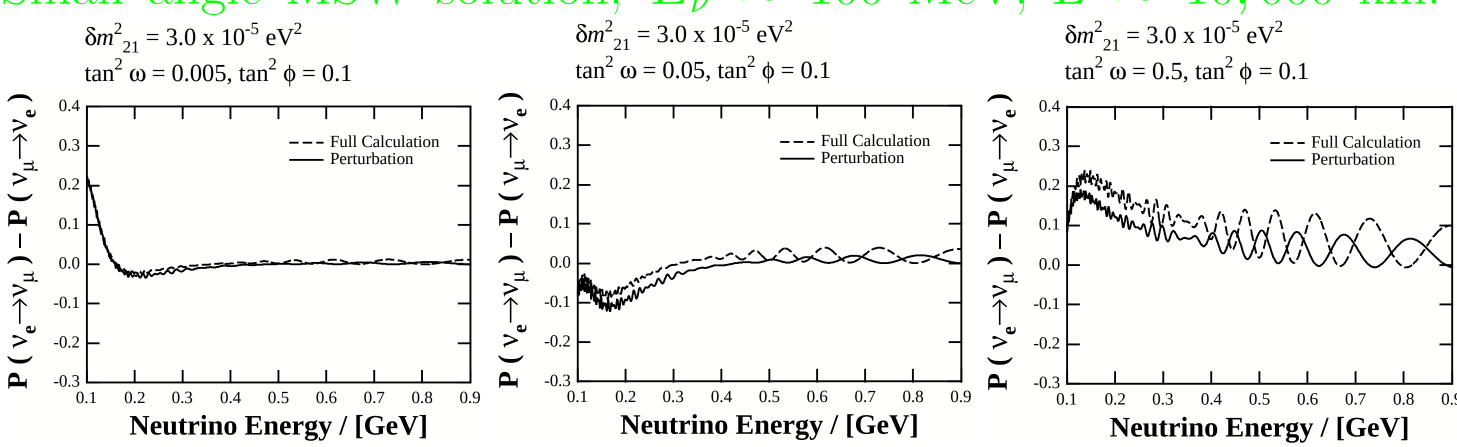
$$P(\nu_e \to \nu_\mu) - P(\overline{\nu}_e \to \overline{\nu}_\mu)$$



10 kton detector,
2×10^{21} muon decays,
Large angle MSW:
$\Delta m^2_{12} = 10^{-4}$ eV^2,
$\Delta m^2_{23} = 2.8 \times 10^{-3}$ 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.



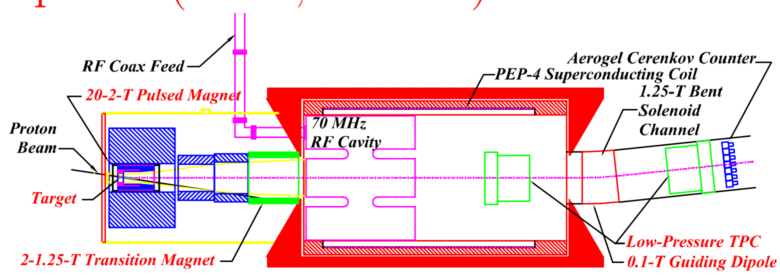
Modulate the muon polarization to modulate the relative rates of $\nu_\mu \to \nu_e \to e^-$ and $\overline{\nu}_e \to \overline{\nu}_e \to e^+$ (Blondel).

Physics Summary

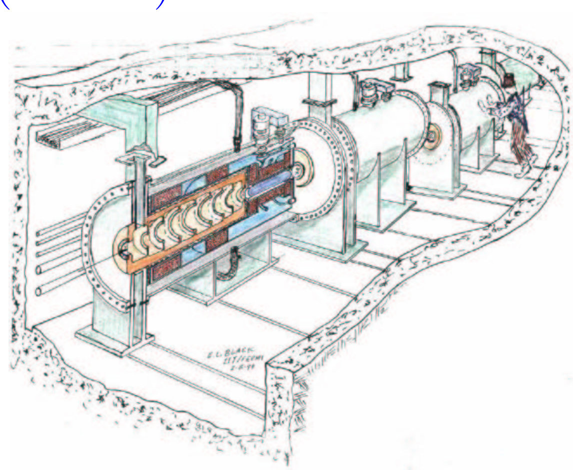
- The physics program of a neutrino factory/muon collider is extremely diverse, and of scope to justify an international laboratory.
- The first step is a neutrino factory capable of systematic exploration of neutrino oscillations.
  - With $\gtrsim 10^{20}$ ν's/year can go well beyond other existing 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).
- $\gtrsim 1$ Megawatt proton source (BNL, CERN, FNAL).
- Targetry and capture (BNL, CERN).



- Ionization cooling (FNAL).



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

with participation from many other labs and universities.