

From a Neutrino Factory to Carlsbad



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Science Facility*

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<http://puhep1.princeton.edu/~mcdonald/nufact/>

The Opportunity for a Neutrino Factory

- Recent evidence for neutrino mass and oscillation among neutrino types is literally a gift from the heavens.
- Systematic exploration of the physics of massive neutrino is possible using accelerator sources of neutrinos and large underground detectors separated by long baselines.
- The WIPP underground science facility is well sized and well located to host a large detector for neutrinos from a neutrino factory.

The neutrino detector must be able to distinguish the sign of the muon from the reaction $\nu + N \rightarrow \mu + X$.

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 (that don't decay), 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

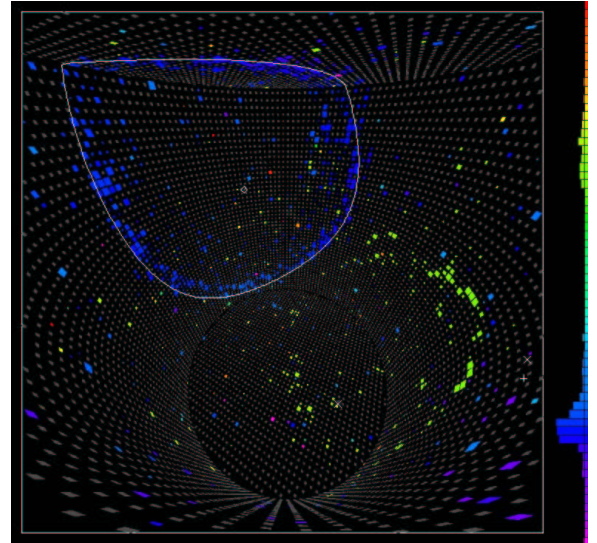
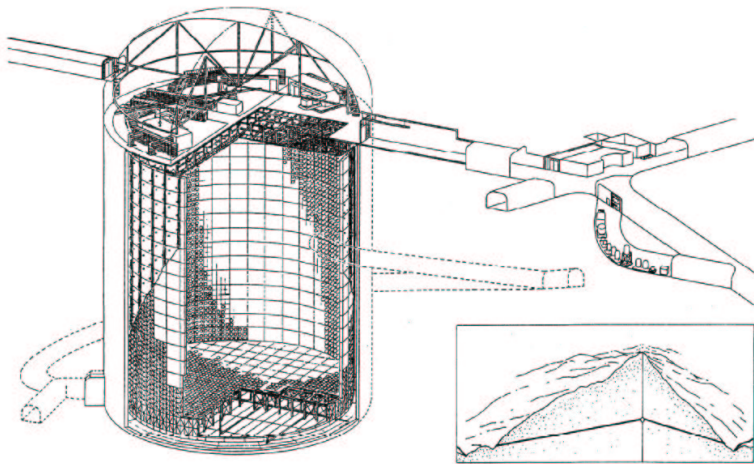
$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 [\text{eV}^2] L [\text{km}]}{E [\text{GeV}]} \right).$$

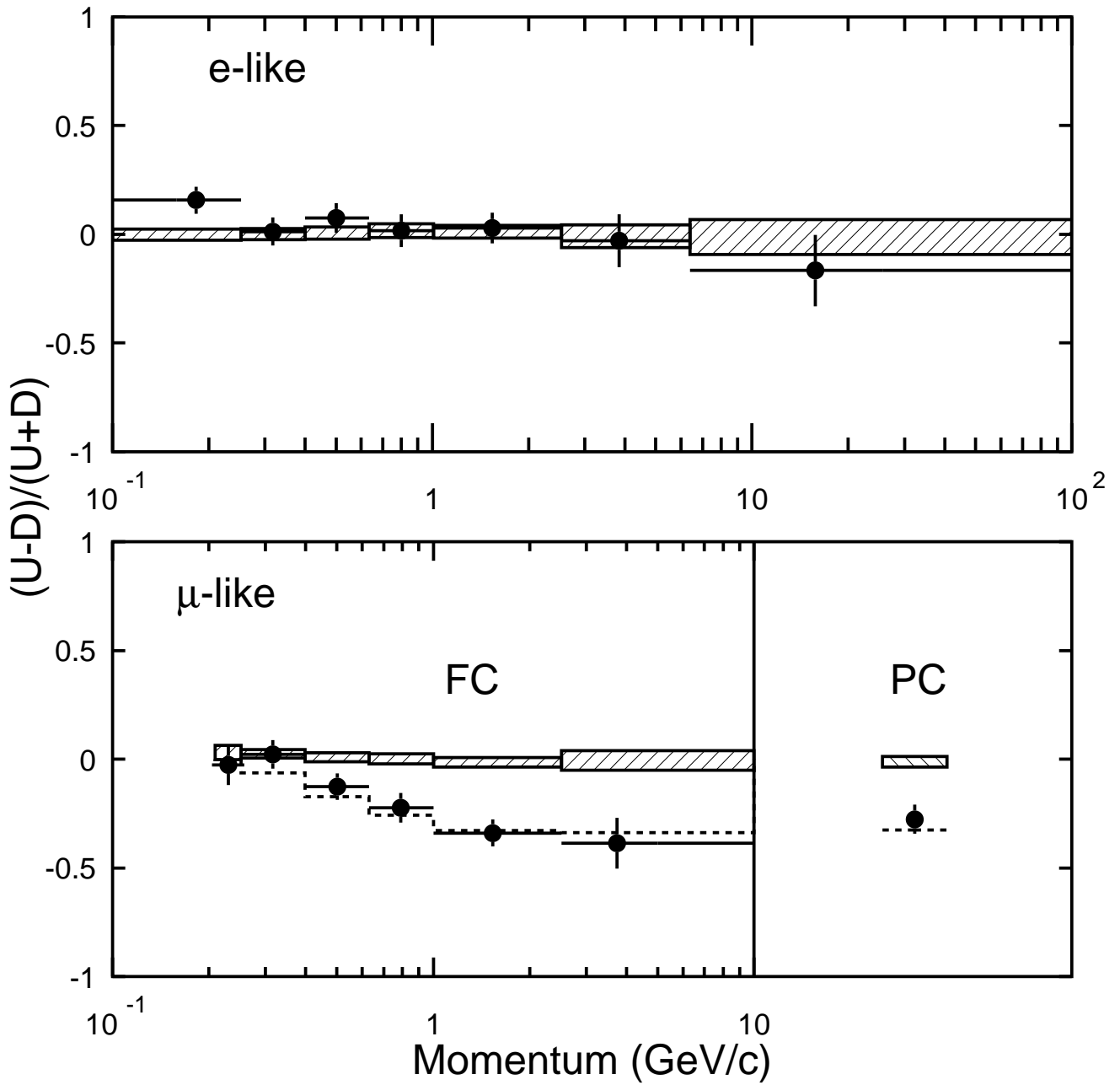
The probability that ν_a does not disappear is

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

A Sketch of Current Data

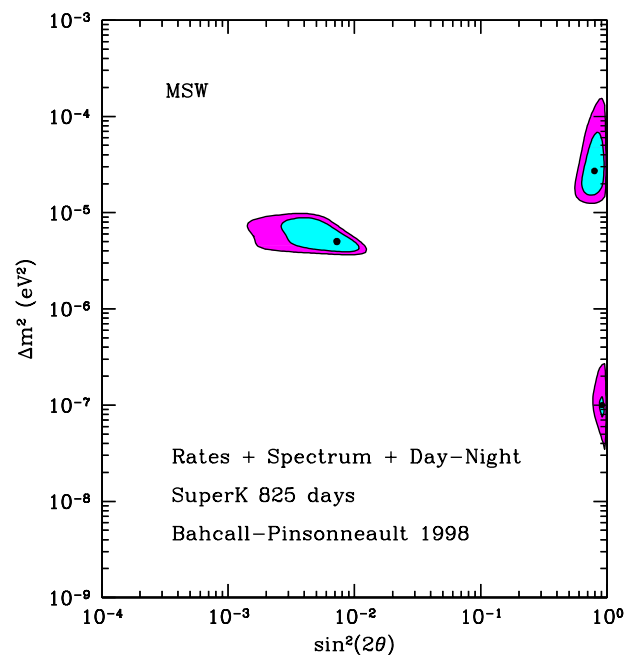
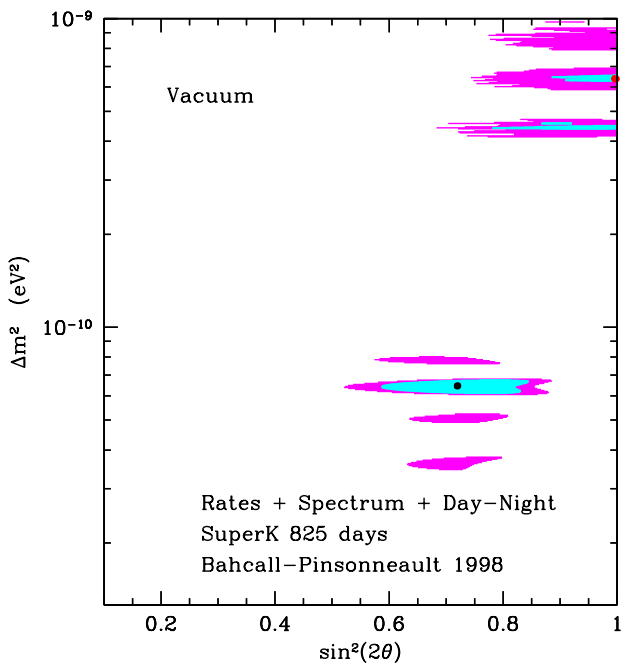
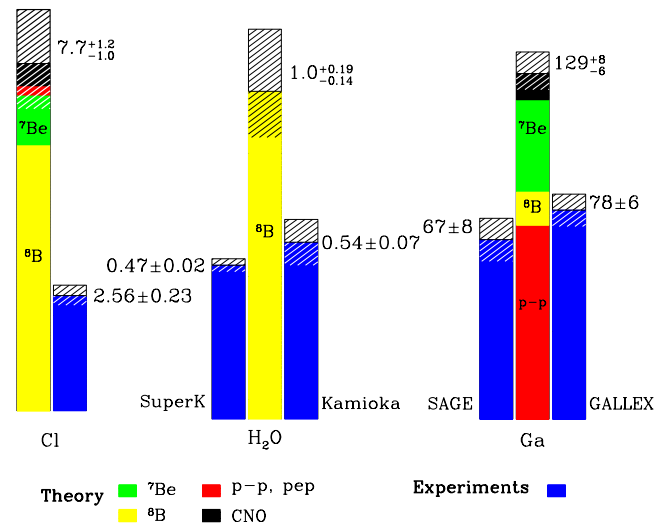
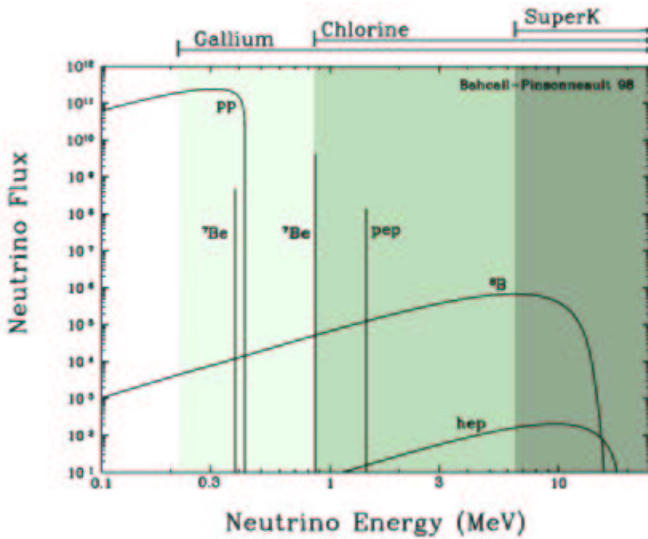
- The **Atmospheric Neutrino “Anomaly”** suggests that GeV ν_μ 's (from $p+N_2 \rightarrow \pi \rightarrow \mu\nu_\mu$) disappear while traversing the Earth's diameter, $\Rightarrow \Delta m^2 \approx 10^{-3} \text{ (eV)}^2$ for $\sin^2 2\theta \approx 1$. (Kamiokande, IMB, Soudan-2, MACRO, Super-Kamiokande)



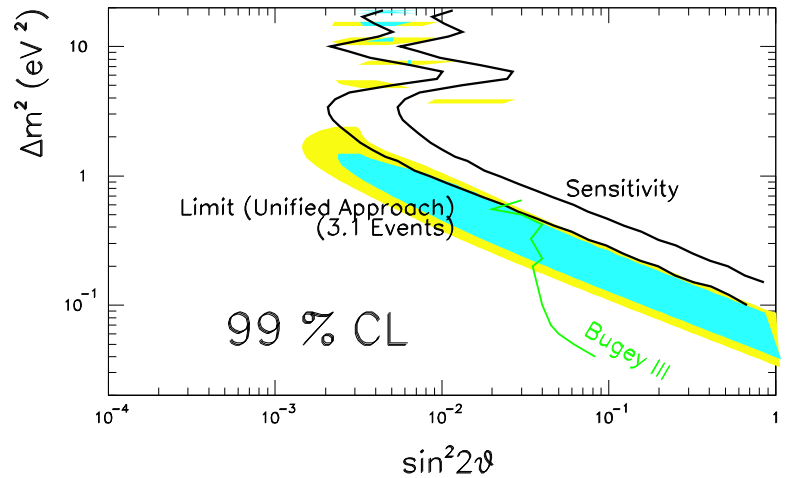
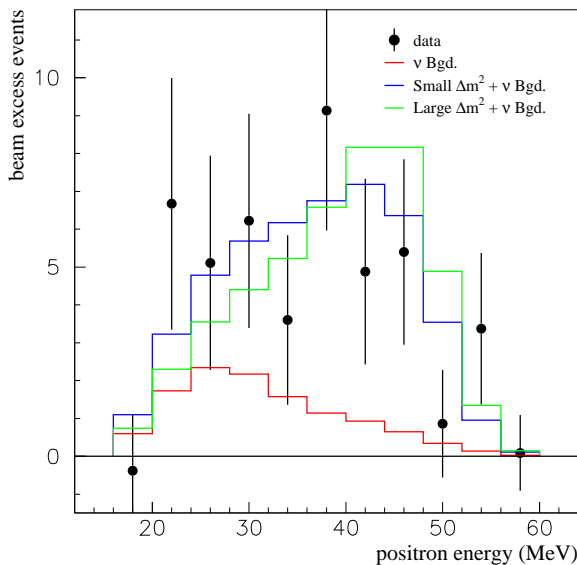
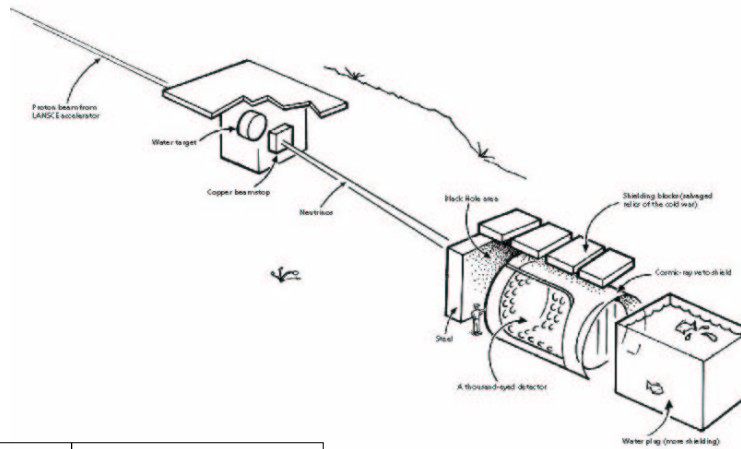


- The **Solar Neutrino “Deficit”** suggests that MeV ν_e 's disappear between the center of the Sun and the Earth.
 $\Rightarrow \Delta m^2 \approx 10^{-10} \text{ (eV)}^2$ for $\sin^2 2\theta \approx 1$, if vacuum oscillations.
 (Homestake, Super-Kamiokande, GALLEX, SAGE)

Total Rates: Standard Model vs. Experiment
 Bahcall–Pinsonneault 98



- The **LSND Experiment** suggests that 30-MeV $\bar{\nu}_\mu$'s (from $p + \text{H}_2\text{O} \rightarrow \pi^- \rightarrow \mu^- \bar{\nu}_\mu$) appear as $\bar{\nu}_e$'s after 30 m. $\Rightarrow \Delta m^2 \approx 1 \text{ (eV)}^2$, but reactor data requires $\sin^2 2\theta \lesssim 0.03$.



- The atmospheric neutrino anomaly + the solar neutrino deficit (if both correct) require at least 3 massive neutrinos.
- If LSND is correct as well, need 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

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix},$$

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: $\Delta m_{12}^2 = \Delta m^2(\text{solar})$ and $\Delta m_{23}^2 = \Delta m^2(\text{atmospheric})$.
- [$J_{CP} = s_{12}s_{23}s_{31}c_{12}c_{23}c_{31}^2s_\delta = \text{Jarlskog invariant.}$]

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.

Matter Effects

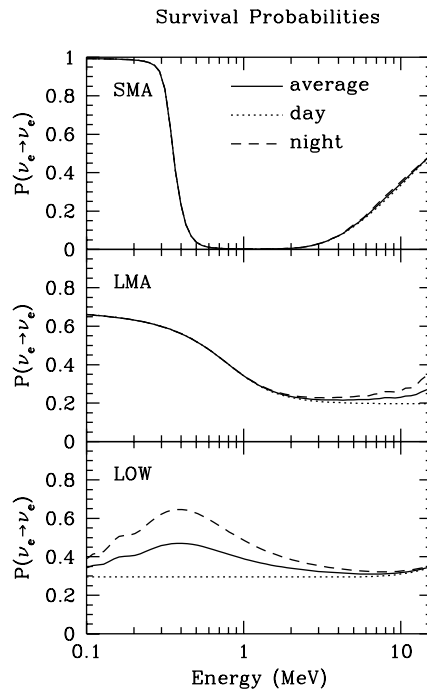
ν_e 's can interact with electrons via both W and Z^0 exchanges, but other neutrinos can only interact with e 's via Z^0 exchange.

$$\Rightarrow \sin^2 2\theta_{\text{matter}} = \frac{\sin^2 2\theta_{\text{vac}}}{\sin^2 2\theta_{\text{vac}} + (\cos 2\theta_{\text{vac}} - A)^2},$$

where $A = 2\sqrt{2}G_F N_e E / \Delta m^2$ depends on sign of Δm^2 .

At the “resonance”, $\cos 2\theta_{\text{vac}} = A$, $\sin^2 2\theta_{\text{matter}} = 1$ even if $\sin^2 2\theta_{\text{vac}}$ is small (Wolfenstein, 1978, Mikheyev, Smirnov, 1986).

\Rightarrow 3 MSW solutions to the solar neutrino problem:



In all of these MSW solutions, $\Delta m_{\text{solar}}^2 = \Delta m_{12}^2 > 0$.

Too Many Solutions

There are 8 scenarios suggested by present data:

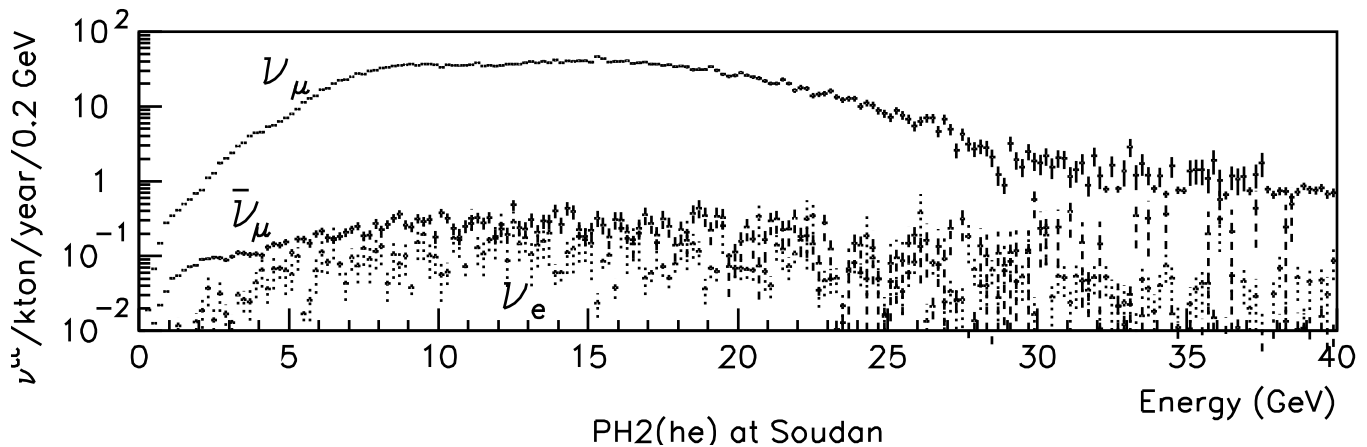
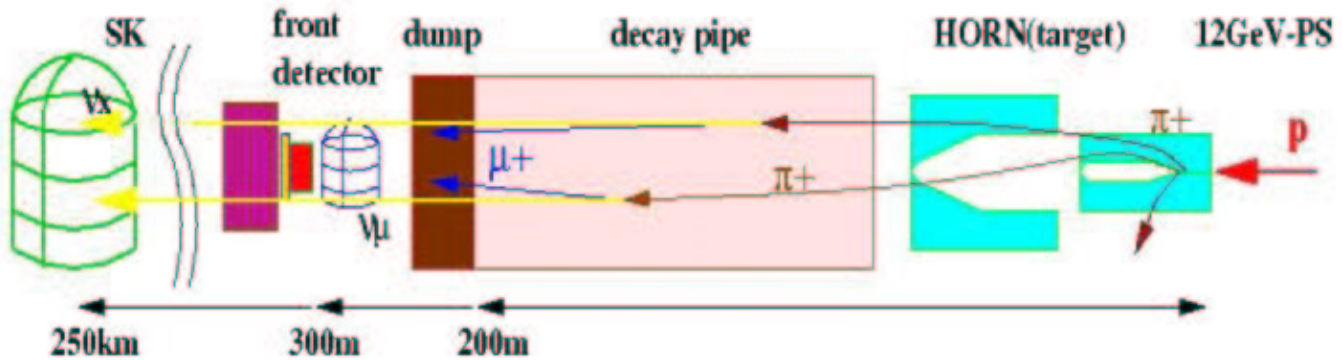
- Either 3 or 4 massive neutrinos.
- Four solutions to the solar neutrino problem:
 1. Vacuum oscillation (VO, or “Just So”) solution;
 $\Delta m_{12}^2 \approx (0.5 - 5.0) \times 10^{-10} \text{ eV}^2, \sin^2 2\theta_{12} \approx (0.7 - 1.0).$
 2. Low MSW solution;
 $\Delta m_{12}^2 \approx (0.5 - 2.0) \times 10^{-7} \text{ eV}^2, \sin^2 2\theta_{12} \approx (0.9 - 1.0).$
 3. Small mixing angle (SMA) MSW solution;
 $\Delta m_{12}^2 \approx (4.0 - 9.0) \times 10^{-6} \text{ eV}^2, \sin^2 2\theta_{12} \approx (0.001 - 0.01).$
 4. Large mixing angle (LMA) MSW solution;
 $\Delta m_{12}^2 \approx (0.2 - 2.0) \times 10^{-4} \text{ eV}^2, \sin^2 \theta_{12} \approx (0.65 - 0.96).$
- Atmospheric neutrino data $\Rightarrow \Delta m_{23}^2 \approx (3 - 5) \times 10^{-4} \text{ eV}^2,$
 $\sin^2 \theta_{12} > 0.8.$
- θ_{13} very poorly known ($\sin^2 2\theta_{13} \lesssim 0.2$).
- δ completely unknown.

The Next Generation of Neutrino Experiments

- Short baseline accelerator experiments (miniBoone, ORLAND, CERN) will likely clarify the LSND result.
- Super-Kamiokande + new long baseline accelerator experiments (K2K, Minos, NGS) will firm up measurements of θ_{23} and Δm_{23}^2 , but will provide little information on θ_{13} and δ .
- New solar neutrino experiments (BOREXino, SNO, HELLAZ, HERON,) will explore different portions of the energy spectrum, and clarify possible pathlength-dependent effects. SNO should provide independent confirmation of neutrino oscillations via comparison of reactions
 $\nu + {}^2\text{H} \rightarrow p + p + e$ and $\nu + {}^2\text{H} \rightarrow p + n + \nu$.
- Each of these experiments studies oscillations of only a single pair of neutrinos.
- The continued search for the neutrinoless double-beta decay ${}^{78}\text{Ge} \rightarrow {}^{78}\text{Se} + 2e^-$ will improve the mass limits on Majorana neutrinos to perhaps as low as 0.01 eV (GENIUS).

The Opportunity for a Neutrino Factory

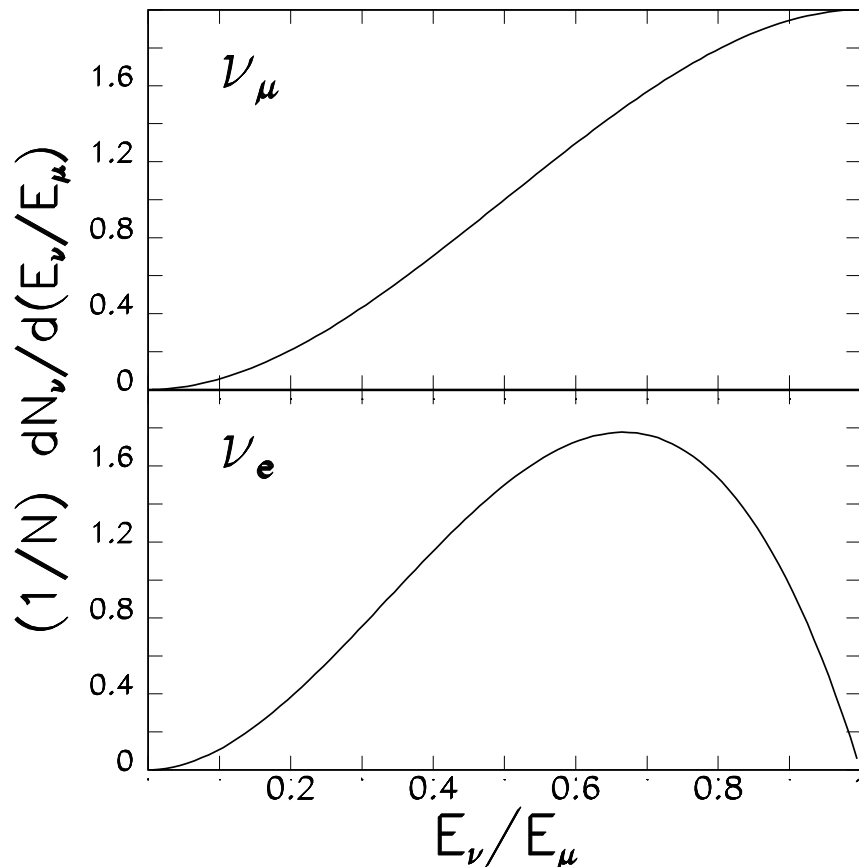
- Many of the neutrino oscillation solutions permit study of the couplings between 2, 3, and 4 neutrinos in accelerator based experiments.
- More neutrinos are needed!
- Present neutrino beams come from $\pi, K \rightarrow \mu\nu_\mu$ with small admixtures of $\bar{\nu}_\mu$ and ν_e from μ and $K \rightarrow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

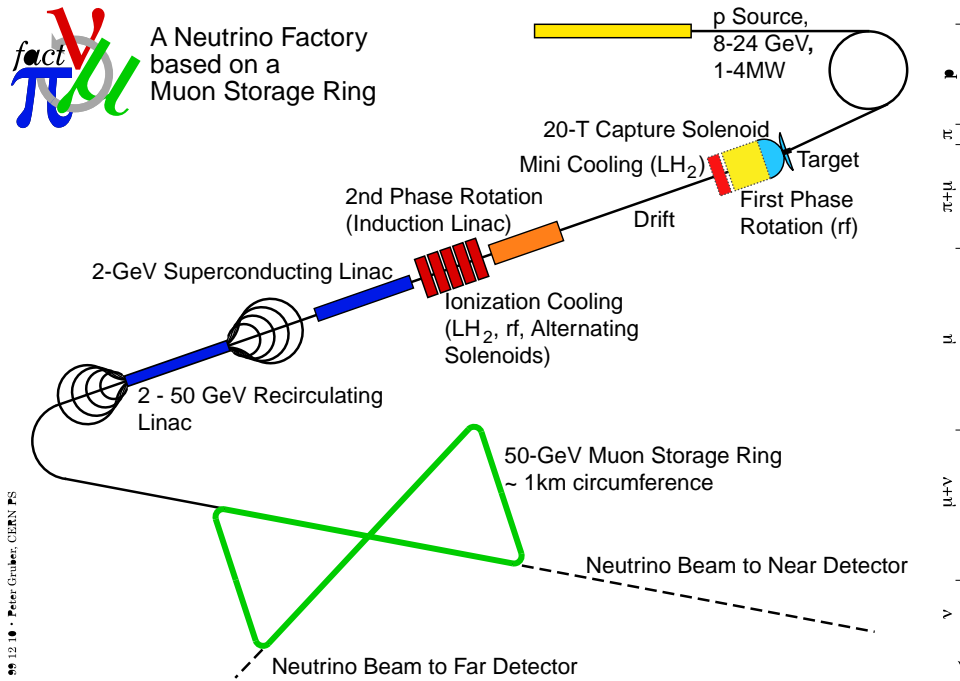


- Cleaner spectra and comparable fluxes of ν_e and ν_μ desirable.

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





6 Classes of Experiments at a Neutrino Factory

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

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

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

$$\bar{\nu}_e \rightarrow \bar{\nu}_e \rightarrow e^{+} \quad (\text{disappearance}), \quad (4)$$

$$\bar{\nu}_e \rightarrow \bar{\nu}_{\mu} \rightarrow \mu^{+} \quad (\text{appearance}), \quad (5)$$

$$\bar{\nu}_e \rightarrow \bar{\nu}_{\tau} \rightarrow \tau^{+} \quad (\text{appearance}). \quad (6)$$

[Plus 6 corresponding processes for $\bar{\nu}_{\mu}$ from μ^{+} decay.]

Processes (2) and (5) are easiest to detect, via the final state μ .

Process (5) is noteworthy for having a “wrong-sign” μ .

Processes (3) and (6) with a final state τ require μ 's of 10's of GeV.

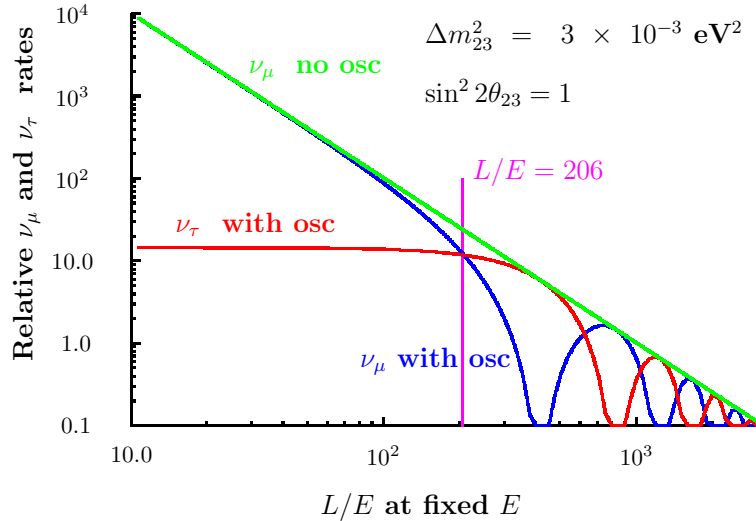
Processes (1) and (4) with a final state electron are difficult to distinguish.

Magnetic detectors of 10's of kilotons will be required, with fine segmentation if τ 's are to be measured.

Scaling Laws for Rates at a Neutrino Factory

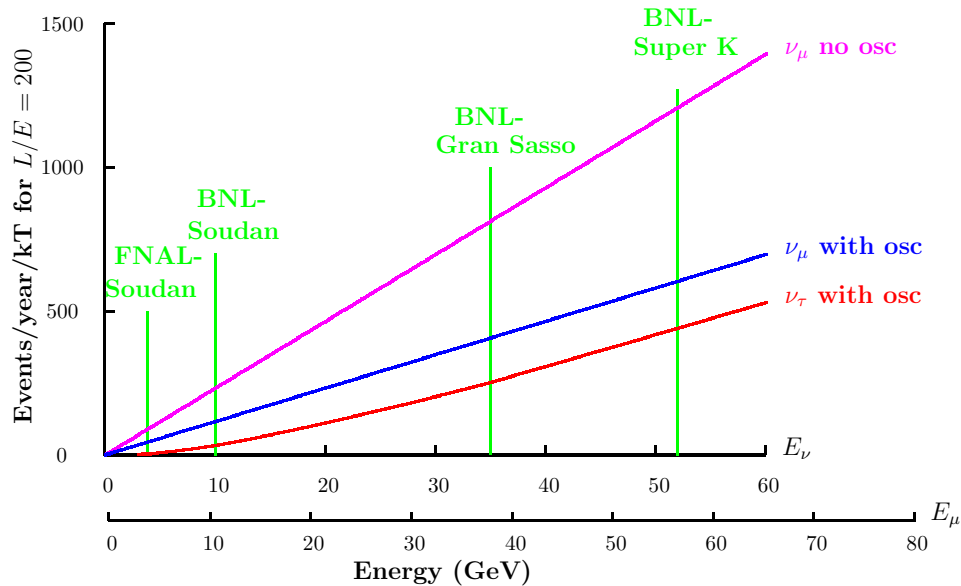
$$\sigma_\nu \propto E; \quad I_\nu \propto 1/(\theta)^2 \propto (E/L)^2; \quad \text{Rate} \propto I_\nu \sigma_\nu \propto E^3/L^2.$$

$$\Rightarrow \text{Rate} \propto E^3 \text{ at fixed } L, \quad \text{Rate} \propto 1/L^2 \text{ at fixed } E.$$



Neutrino oscillation probability varies with L/E ,

$$\Rightarrow \text{Rate} \propto E \text{ for fixed } L/E.$$



τ appearance suppressed at low energy. Larger $E \Rightarrow$ larger L .

The Rates are High at a Neutrino Factory

Charged current event rates per kton-yr.

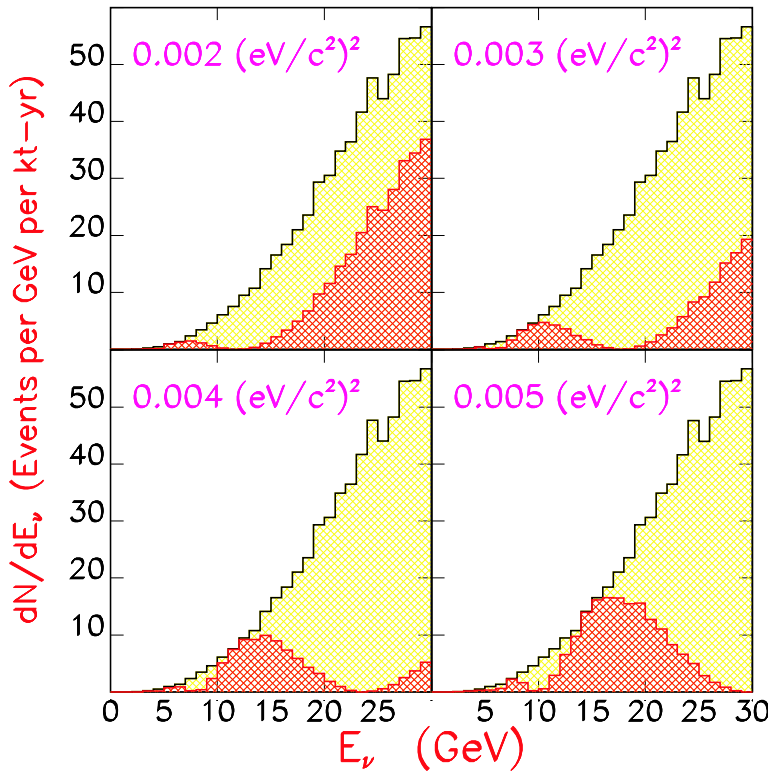
$(L = 732 \text{ km})$	ν_μ	$\bar{\nu}_e$
Neutrino Factory	$(2 \times 10^{20} \nu_\mu/\text{yr})$	
10 GeV	2200	1300
20 GeV	18,000	11,000
50 GeV	2.9×10^5	1.8×10^5
250 GeV	3.6×10^7	2.3×10^7
MINOS (WBB)		
Low energy	460	1.3
Medium energy	1440	0.9
High energy	3200	0.9

Even a low-energy neutrino factory has high rates of electron neutrino interactions.

A neutrino factory with $E_\mu \gtrsim 20 \text{ GeV}$ is competitive for muon neutrino interactions.

$\nu_\mu \rightarrow \nu_\mu \rightarrow \mu^-$ Disappearance

$E_\mu = 30$ GeV,
 2×10^{20} μ decays,
 $L = 7000$ km,
 $\sin^2 2\theta_{23} = 1$.
 (hep-ph/9906487)



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

$\nu_\mu \rightarrow \nu_\tau \rightarrow \tau^-$ Appearance

Δm_{23}^2 (eV^2)	Events (per 10 kton-yr)
0.002	1200
0.003	1900
0.004	2000
0.005	1800

For conditions as above.

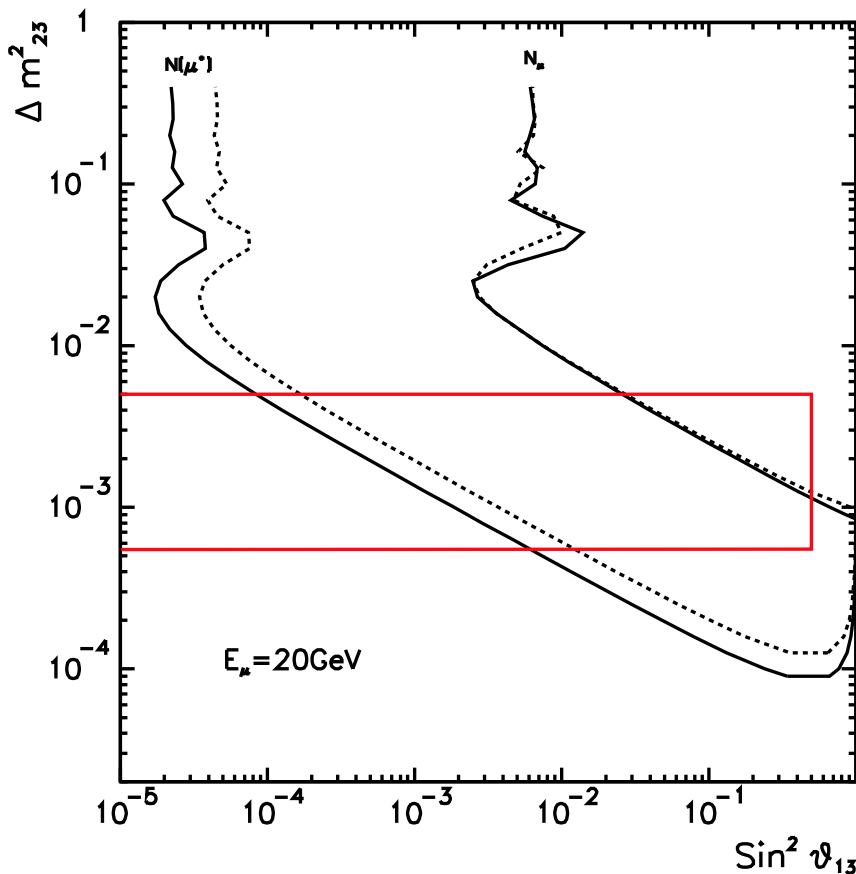
Measuring θ_{13}

Many ways:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \frac{1.27 \Delta m_{23}^2 L}{E_\nu},$$

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_\tau) = \sin^2 2\theta_{13} \cos^2 \theta_{23} \sin^2 \frac{1.27 \Delta m_{23}^2 L}{E_\nu},$$

$$P(\nu_\mu \rightarrow \nu_\tau) = \cos^4 \theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{1.27 \Delta m_{23}^2 L}{E_\nu}.$$



10 kton detector,

$E_\mu = 20$ GeV,

2×10^{20} μ decays,

$L = 732$ km,

$\sin^2 2\theta_{23} = 1$,

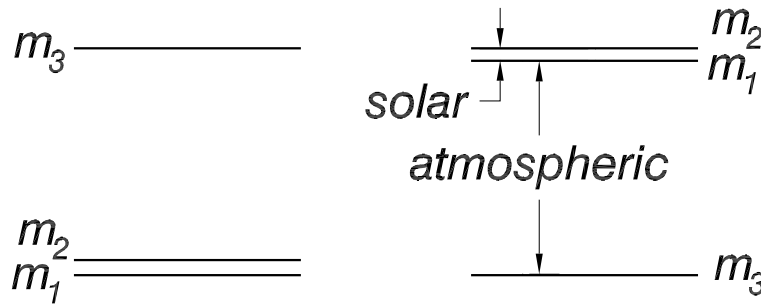
Left: $\bar{\nu}_e \rightarrow \bar{\nu}_\mu \rightarrow \mu^+$,

Right: $\nu_\mu \rightarrow \nu_\mu \rightarrow \mu^-$,

Box = presently allowed.

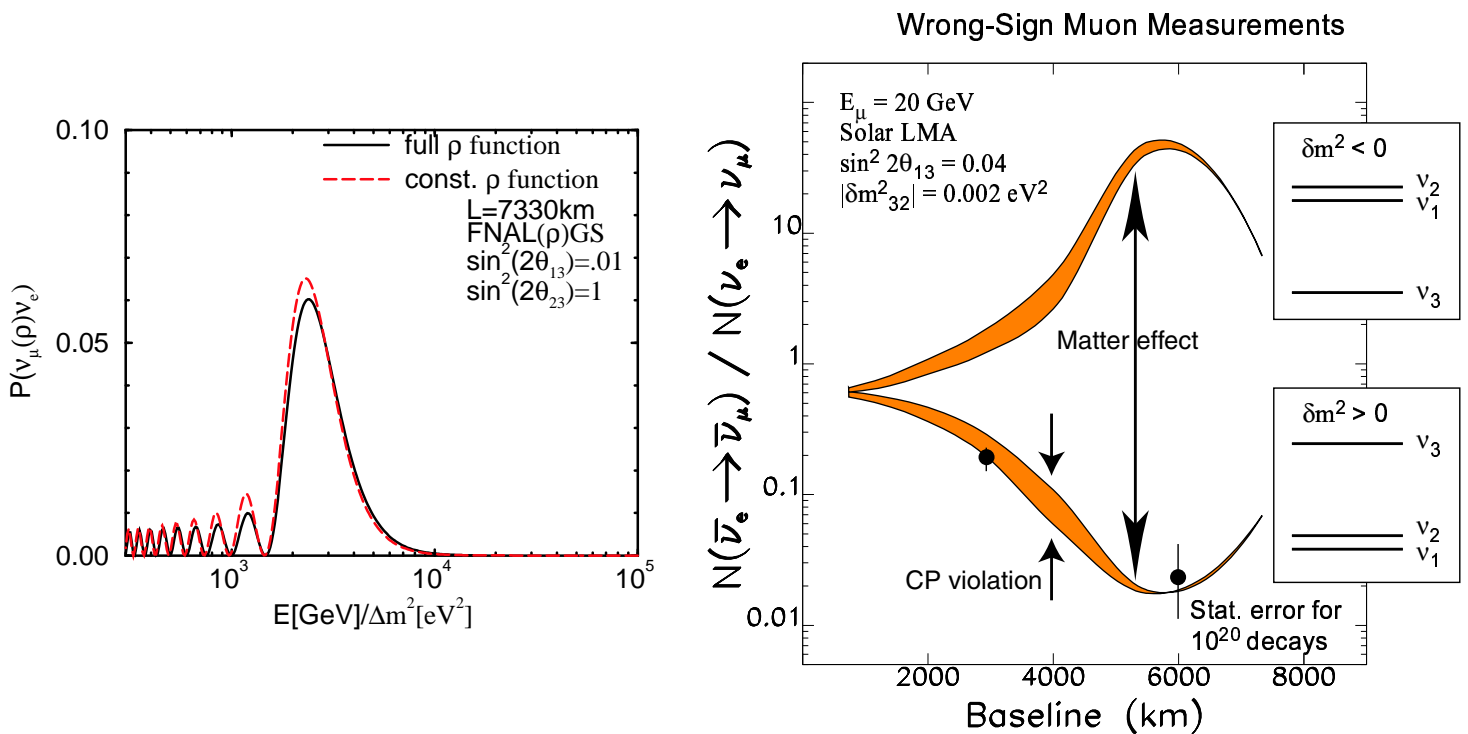
(hep-ph/9811390).

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



The matter-effect resonance depends on the sign of Δm_{23}^2 (p. 8).

Crisper to observe $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ appearance than ν_μ disappearance.



Baseline of 5000-7000 km needed to build up the matter effect for measurement of Δm_{23}^2 .

[Measurement of CP violation more favorable at 3000 km.]

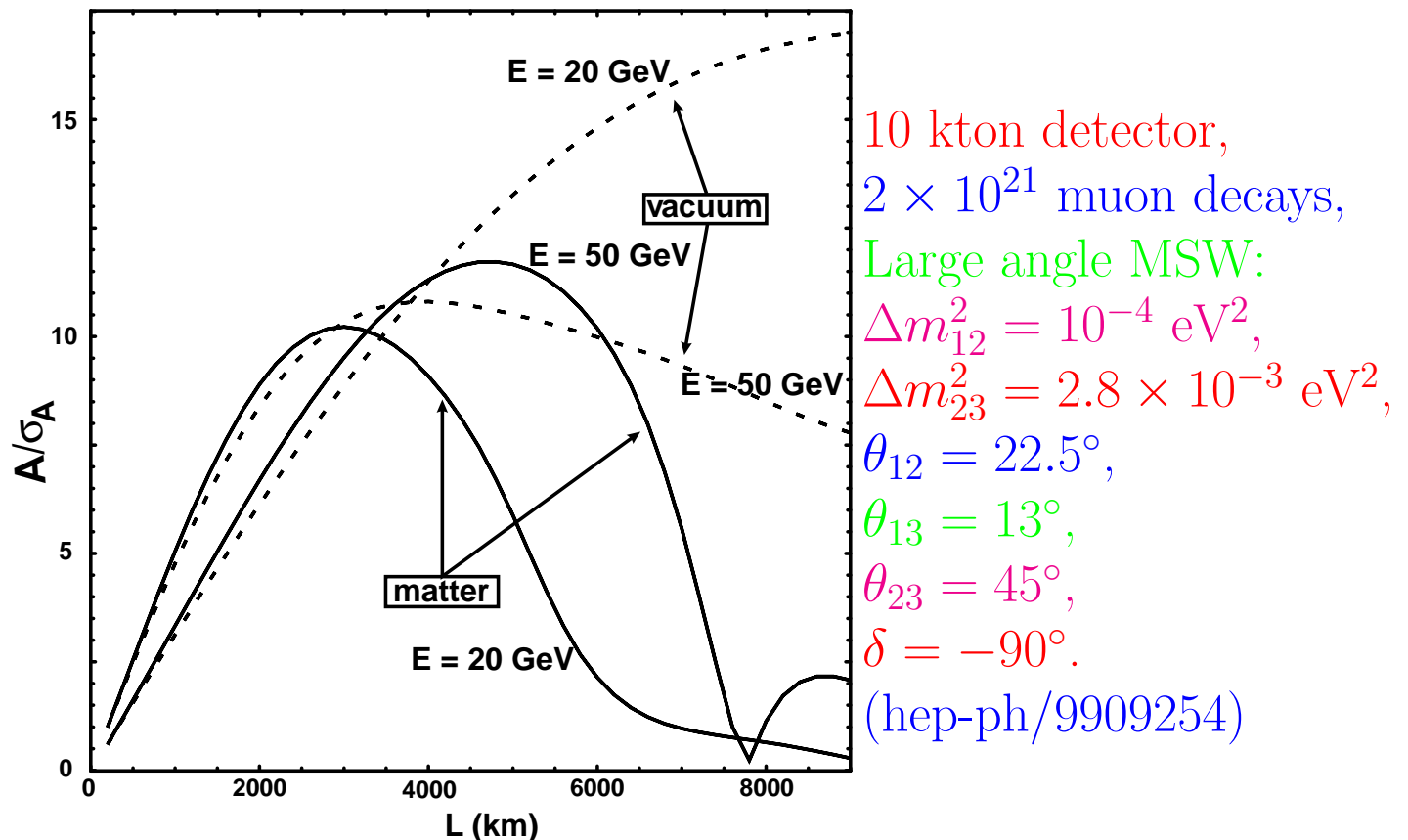
Measuring δ via CP Violation

The phase δ is accessible to terrestrial experiment in the large mixing angle (LMA) solution to the solar neutrino problem (or if there are 4 massive neutrinos).

CP violation:

$$A_{\text{CP}} = \frac{P(\nu_e \rightarrow \nu_\mu) - P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)}{P(\nu_e \rightarrow \nu_\mu) + P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)} \approx \left| \frac{2\sin\delta}{\sin 2\theta_{13}} \sin \frac{1.27\Delta m_{12}^2 L}{E} \right|,$$

assuming $\sin^2 2\theta_{12} \approx \sin^2 2\theta_{23} \approx 1$ (LMA).



Matter effects dominate the asymmetry for $L > 1000$ km.

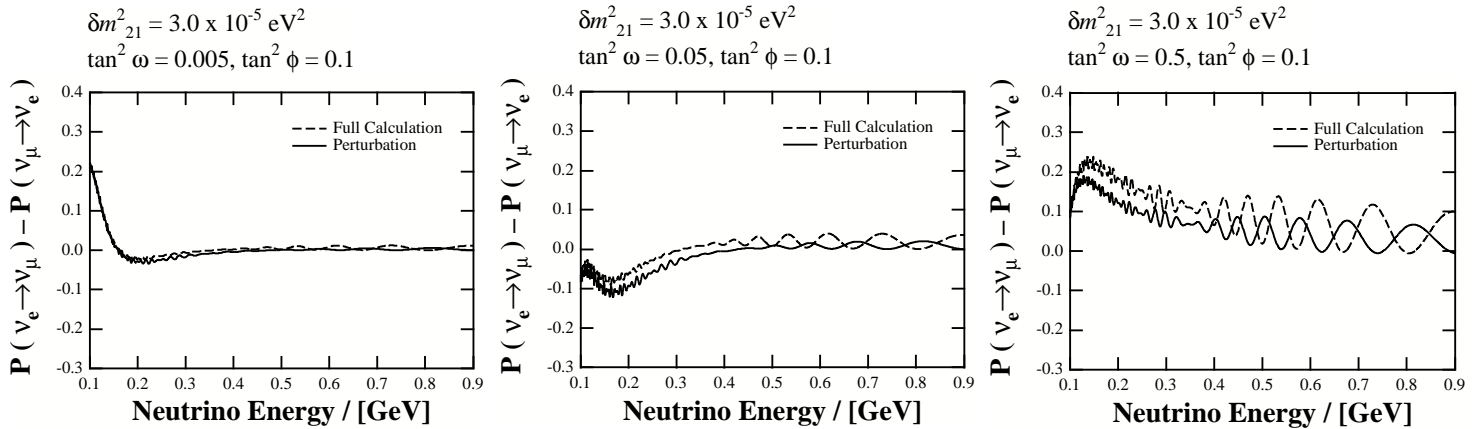
Measuring δ via T Violation

If the small mixing angle (SMA) solutions holds, may still be able to measure δ via T violation:

$$P(\nu_e \rightarrow \nu_\mu) - P(\nu_\mu \rightarrow \nu_e) = 4J_{\text{CP}} \sin \frac{1.27\Delta m_{12}^2 L}{E} \sin \frac{1.27\Delta m_{13}^2 L}{E} \sin \frac{1.27\Delta m_{23}^2 L}{E},$$

$$8J_{\text{CP}} = \cos \theta_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin \delta = \text{Jarlskog invariant.}$$

Matter effects could make $\sin 2\theta_{12}$ resonate for $E \approx 100$ MeV and $L \approx 10,000$ km (hep-ph/9911258).

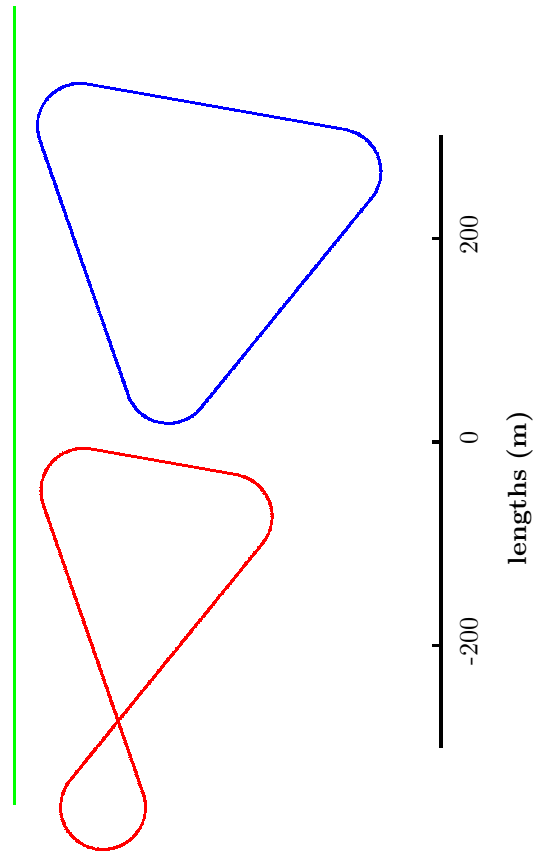


However, not easy to measure $\nu_\mu \rightarrow \nu_e \rightarrow e^-$ (appearance) against background of $\bar{\nu}_e \rightarrow \bar{\nu}_e \rightarrow e^+$ in a large, massive detector in which the electrons shower immediately. [Rates low also.]

A Neutrino Factory is a Global Facility

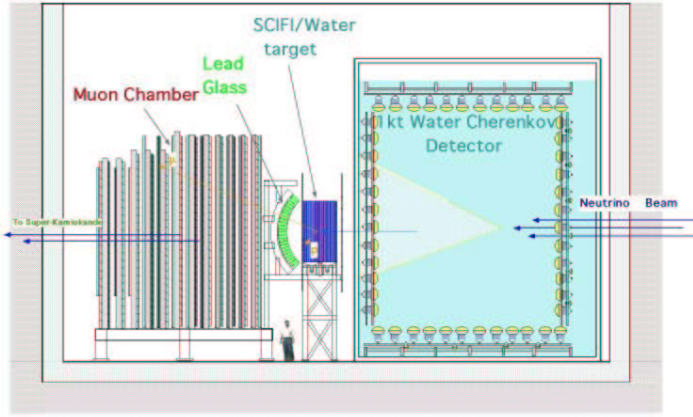


- Host lab with the muon storage ring and near detector.
- Could have two larger detectors located elsewhere, possibly one on the same, and the second on another continent.
- For this, the muon storage ring needs 3 straight sections, and would not lie in a horizontal plane.

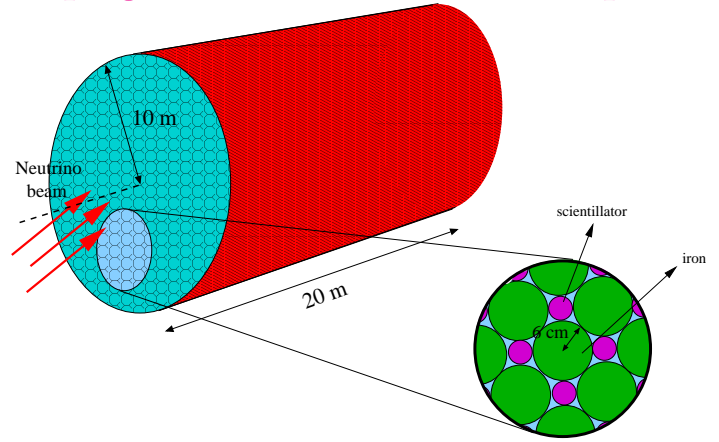


Large Underground Detectors

K2K:



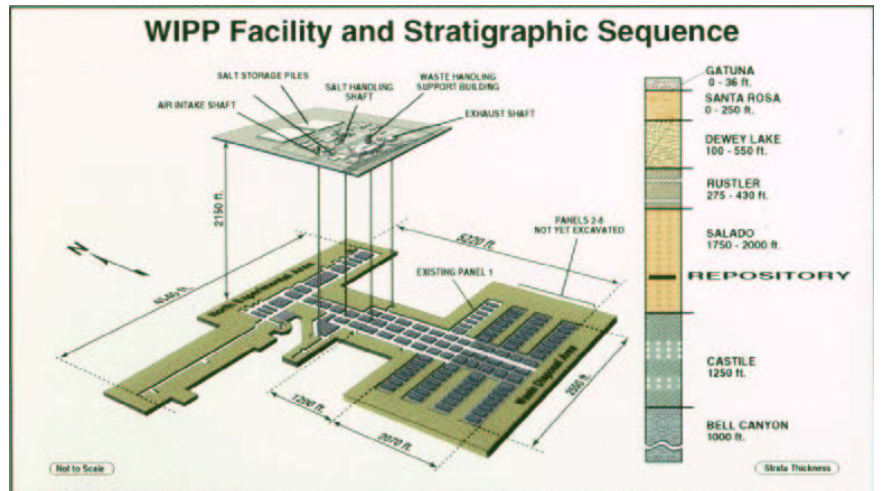
“Spaghetti” detector concept:



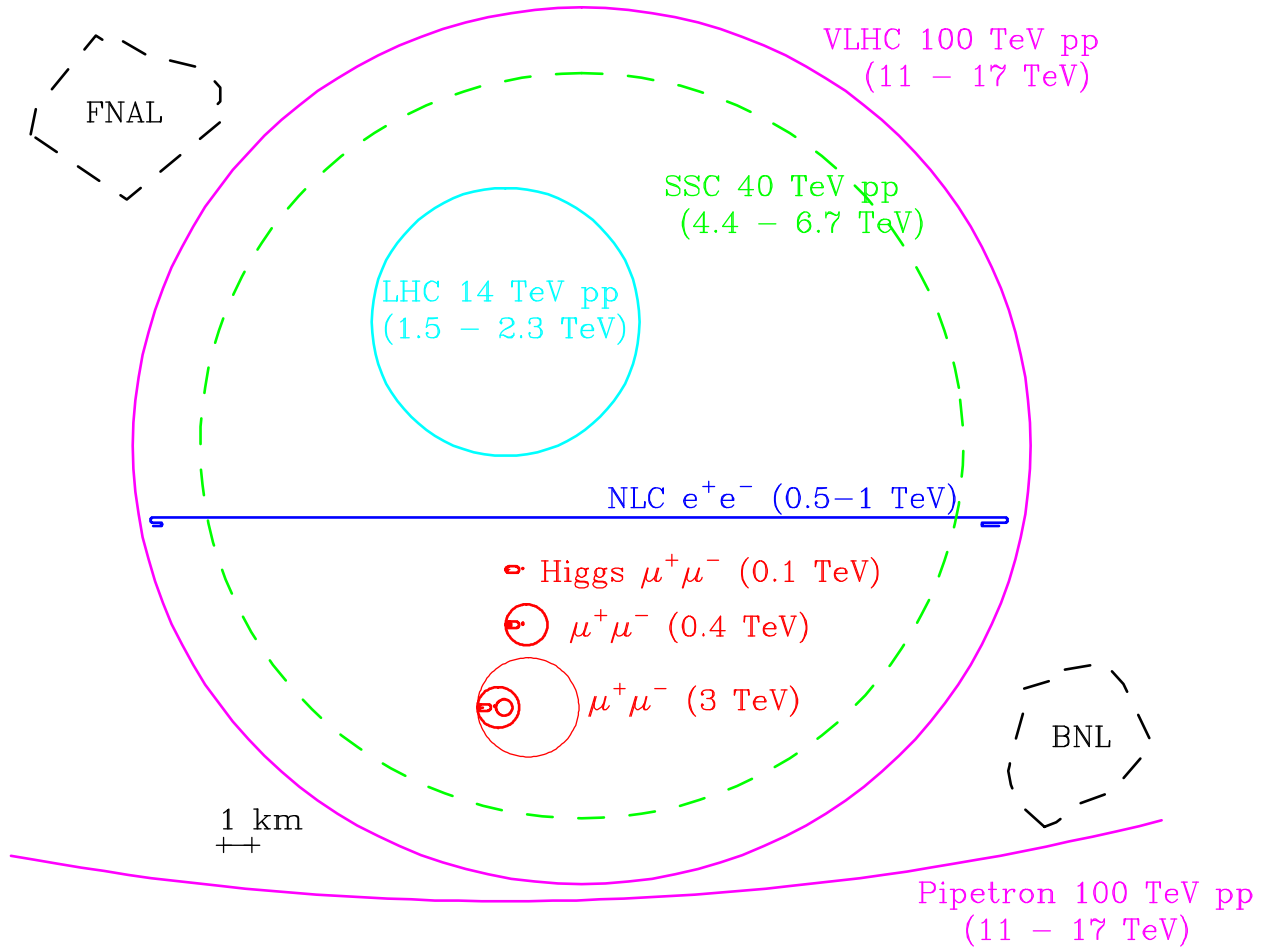
Gran Sasso in Italy:



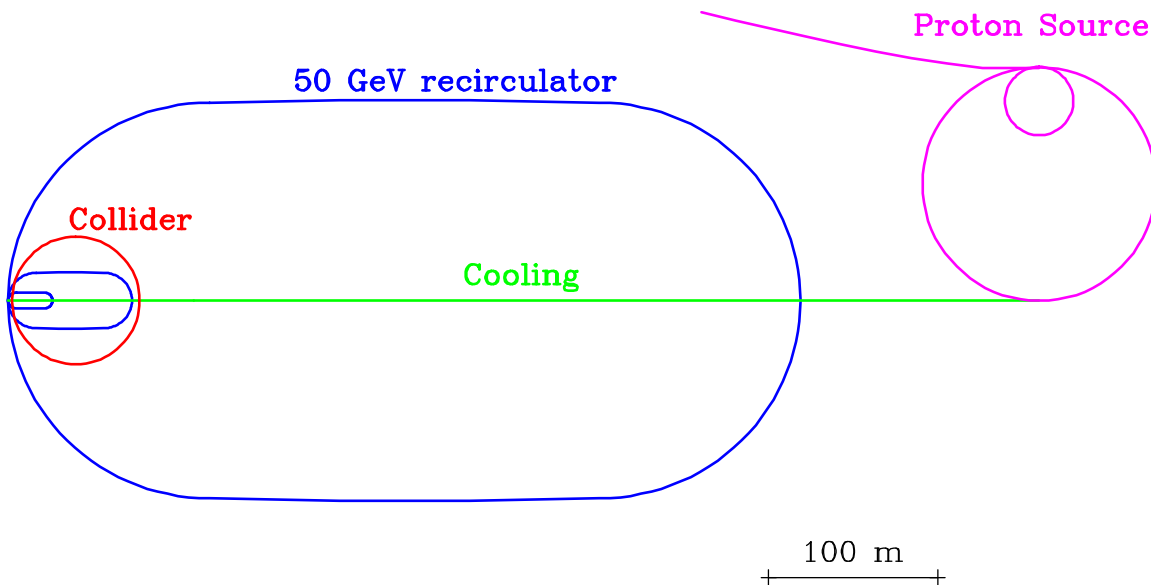
DOE WIPP facility in New Mexico:



A Neutrino Factory is a Step to a Muon Collider



A First Muon Collider to study light-Higgs production:



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 $E \gtrsim 30$ 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 $\nu_e \rightarrow e$ modes.

