# Futures in Accelerator-Based Physics

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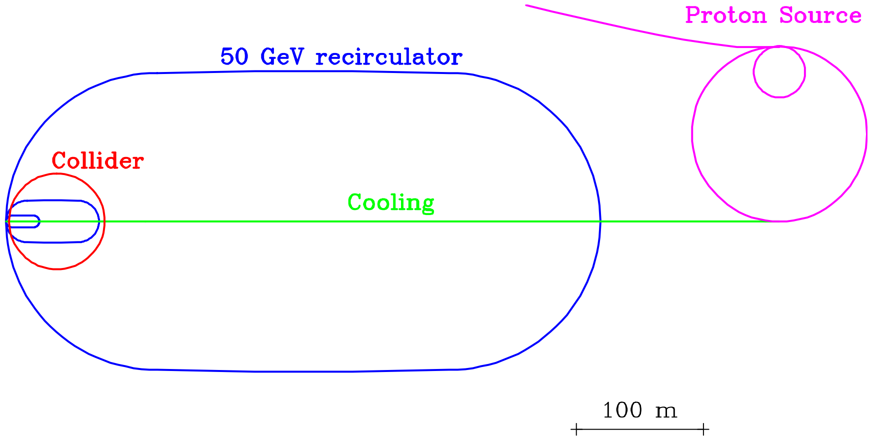
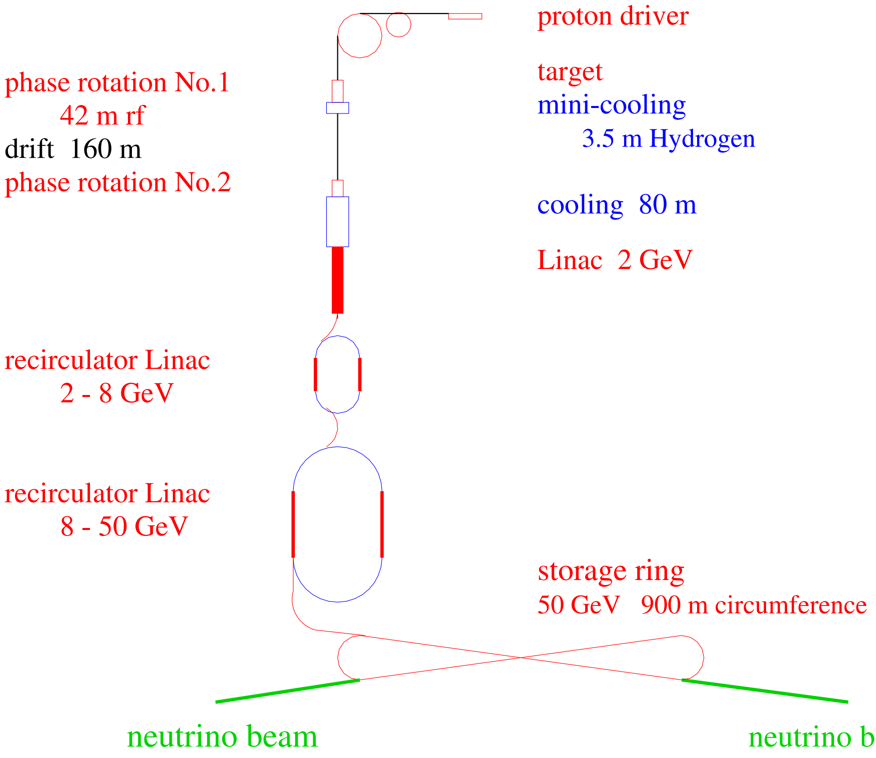
**May 21, 2004**

`http://puhep1.princeton.edu/ mcdonald/accel/`





# From the Cathode Ray Tube to a Muon Collider

**1897 Braun: Cathode ray tube ($\sim 20$ keV, ....television sets).**

**1930 Cockcroft & Walton, Van de Graaff, Wideroe: Linear accelerators to $\sim$ 1 MeV.**

**1930 Lawrence: Cyclotron = first circular accelerator, $\sim 10$ MeV.**

**1940 Kerst: Betatron = circular induction accelerator, $\sim 10$ MeV.**

**1945 McMillan, Veksler: Synchrotron = circular ring accelerator, $\sim 1$ GeV.**

**1950 Christofilos: Alternating gradient focusing, $\Rightarrow$ synchrotrons to 10 GeV.**

**1955 Kerst: Proton colliding rings (first built as electron rings).**

**1956 Wigner: Liouville's theorem applies to particle beams.**

**1956 O'Neill: Ionization cooling for storage rings.**

**1960 Melissinos: Muon storage ring.**

**1962 Milburn: Laser-electron Compton backscattered photon beam.**

**1966 Budker: Electron cooling.**

**1968 Van der Meer: Stochastic cooling of antiproton rings.**

**1968-69 Tikhonin, Budker: Muon colliding rings with ionization cooling.**

**1993 Mikhailichenko, Zolotorev: Optical stochastic cooling.**

# Nicholas Christofilos

ΜΕΛΕΤΩΝ ΣΥΓΓΡΑΜΜΑΤΑ

ΗΝ ΑΥΤΟΔΙΔΑΚΤΟΣ ΑΤΟΜΙΚΟΣ ΕΠΙΣΤΗΜΩΝ ΕΦΕΥΡΕ

ΜΕΘΟΔΟΝ ΜΕΤΑΤΡΟΠΗΣ ΤΗΣ ΕΝΕΡΓΕΙΑΣ ΕΙΣ ΥΛΗΝ

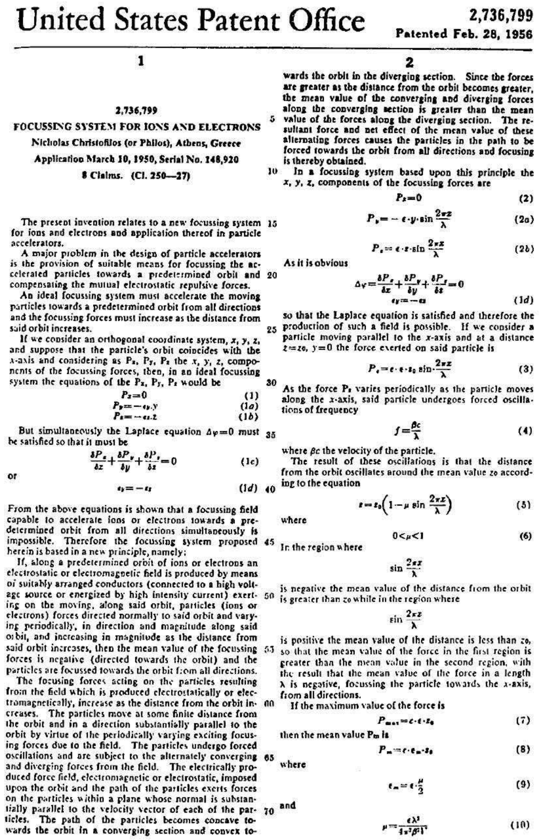
[illegible]

ΠΟΦΟΙΤΟΣ ΤΟΥ ΕΘΝΙΚΟΥ ΠΟΛΥΤΕΧΝΕΙΟΥ

Developed the concept of alternating gradient focusing (inverted pendulum stability) in 1950 while working as an elevator operator.

Later invented the induction linac.

Pioneered studies of electromagnetic pulses and aurorae producing by high altitude explosions of nuclear bombs.



United States Patent Office

2,736,799

Patented Feb. 28, 1956

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2,736,799

FOCUSSING SYSTEM FOR IONS AND ELECTRONS

Nicholas Christofilos (or Philos), Athens, Greece

Application March 10, 1950, Serial No. 148,920

8 Claims. (Cl. 250—27)

The present invention relates to a new focussing system for ions and electrons and application thereof in particle accelerators.

A major problem in the design of particle accelerators is the provision of suitable means for focussing the accelerated particles towards a predetermined orbit and compensating the mutual electrostatic repulsive forces.

An ideal focussing system must accelerate the moving particles towards a predetermined orbit from all directions and the focussing forces must increase as the distance from said orbit increases.

If we consider an orthogonal coordinate system, $x, y, z$, and suppose that the particle's orbit coincides with the $x$-axis and considering as $P_x$, $P_y$, $P_z$ the $x, y, z$, components of the focussing forces, then, in an ideal focussing system the equations of the $P_x$, $P_y$, $P_z$ would be

$$P_x=0 \quad (1)$$

$$P_y=-\epsilon_y.y \quad (1a)$$

$$P_z=-\epsilon_z.z \quad (1b)$$

But simultaneously the Laplace equation $\Delta\varphi=0$ must be satisfied so that it must be

$$\frac{\delta P_x}{\delta x}+\frac{\delta P_y}{\delta y}+\frac{\delta P_z}{\delta z}=0 \quad (1c)$$

or

$$\epsilon_y=-\epsilon_z \quad (1d)$$

From the above equations is shown that a focussing field capable to accelerate ions or electrons towards a predetermined orbit from all directions simultaneously is impossible. Therefore the focussing system proposed herein is based in a new principle, namely:

If, along a predetermined orbit of ions or electrons an electrostatic or electromagnetic field is produced by means of suitably arranged conductors (connected to a high voltage source or energized by high intensity current) exerting on the moving, along said orbit, particles (ions or electrons) forces directed normally to said orbit and varying periodically, in direction and magnitude along said orbit, and increasing in magnitude as the distance from said orbit increases, then the mean value of the focussing forces is negative (directed towards the orbit) and the particles are focussed towards the orbit from all directions.

The focusing forces acting on the particles resulting from the field which is produced electrostatically or electromagnetically, increase as the distance from the orbit increases. The particles move at some finite distance from the orbit and in a direction substantially parallel to the orbit by virtue of the periodically varying exciting focusing forces due to the field. The particles undergo forced oscillations and are subject to the alternately converging and diverging forces from the field. The electrically produced force field, electromagnetic or electrostatic, imposed upon the orbit and the path of the particles exerts forces on the particles within a plane whose normal is substantially parallel to the velocity vector of each of the particles. The path of the particles becomes concave towards the orbit in a converging section and convex towards the orbit in the diverging section. Since the forces are greater as the distance from the orbit becomes greater, the mean value of the converging and diverging forces along the converging section is greater than the mean value of the forces along the diverging section. The resultant force and net effect of the mean value of these alternating forces causes the particles in the path to be forced towards the orbit from all directions and focusing is thereby obtained.

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In a focussing system based upon this principle the $x, y, z$, components of the focussing forces are

$$P_x=0 \quad (2)$$

$$P_y=-\epsilon\cdot y\cdot\sin\frac{2\pi x}{\lambda} \quad (2a)$$

$$P_z=\epsilon\cdot z\cdot\sin\frac{2\pi x}{\lambda} \quad (2b)$$

As it is obvious

$$\Delta\varphi=\frac{\delta P_x}{\delta x}+\frac{\delta P_y}{\delta y}+\frac{\delta P_z}{\delta z}=0$$

$$\epsilon_y=-\epsilon_z \quad (1d)$$

so that the Laplace equation is satisfied and therefore the production of such a field is possible. If we consider a particle moving parallel to the $x$-axis and at a distance $z=z_0$, $y=0$ the force exerted on said particle is

$$P_z=e\cdot\epsilon\cdot z_0\sin\cdot\frac{2\pi x}{\lambda} \quad (3)$$

As the force $P_z$ varies periodically as the particle moves along the $x$-axis, said particle undergoes forced oscillations of frequency

$$f=\frac{\beta c}{\lambda} \quad (4)$$

where $\beta c$ the velocity of the particle.

The result of these oscillations is that the distance from the orbit oscillates around the mean value $z_0$ according to the equation

$$z=z_0\left(1-\mu\sin\frac{2\pi x}{\lambda}\right) \quad (5)$$

where

$$0<\mu<1 \quad (6)$$

In the region where

$$\sin\frac{2\pi x}{\lambda}$$

is negative the mean value of the distance from the orbit is greater than $z_0$ while in the region where

$$\sin\frac{2\pi x}{\lambda}$$

is positive the mean value of the distance is less than $z_0$, so that the mean value of the force in the first region is greater than the mean value in the second region, with the result that the mean value of the force in a length $\lambda$ is negative, focussing the particle towards the $x$-axis, from all directions.

If the maximum value of the force is

$$P_{max}=e\cdot\epsilon\cdot z_0 \quad (7)$$

then the mean value $P_m$ is

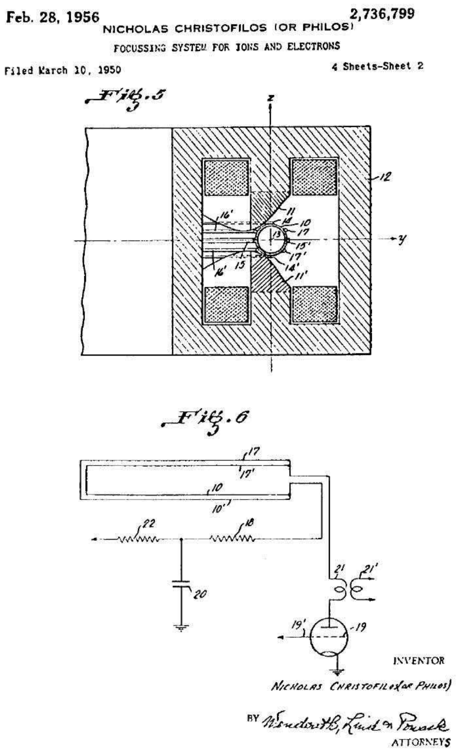
$$P_m=e\cdot\epsilon_m\cdot z_0 \quad (8)$$

where

$$\epsilon_m=\epsilon\cdot\frac{\mu}{2} \quad (9)$$

and

$$\mu=\frac{\epsilon\lambda^2}{4\pi^2\beta^2 V} \quad (10)$$



Feb. 28, 1956

NICHOLAS CHRISTOFILOS (OR PHILOS)

2,736,799

FOCUSSING SYSTEM FOR IONS AND ELECTRONS

Filed March 10, 1950

4 Sheets-Sheet 2

Fig. 5

Fig. 6

INVENTOR

NICHOLAS CHRISTOFILOS (OR PHILOS)

BY Wenderoth, Lind & Ponack

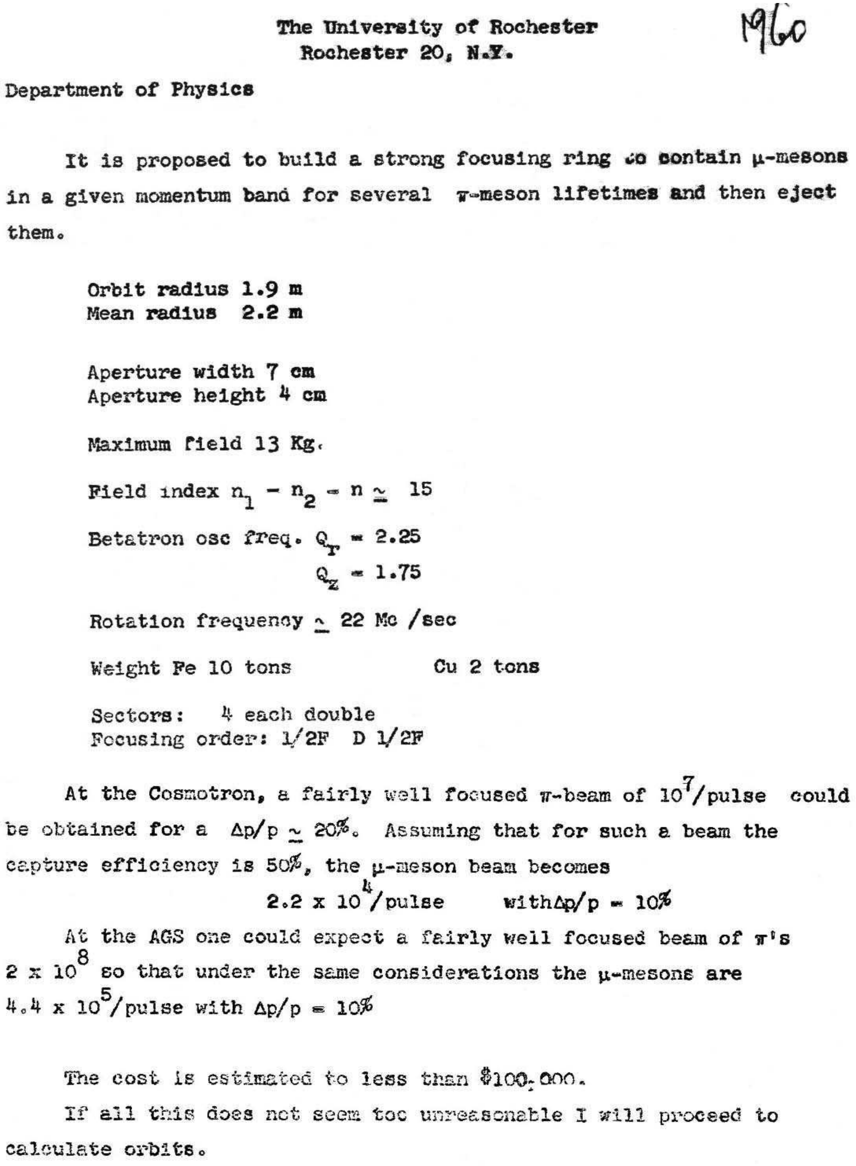
ATTORNEYS

Tribute by A.C. Melissinos: http://puhep1.princeton.edu/~mcdonald/accel/christofilos.pdf

# Adrian Melissinos

**1960: First proposal for a muon storage ring. Later implemented for studies of $g-2$ of the muon.**

**1997: Production of positrons in nonlinear light-by-light scattering (with KTM).**
**"Sparking the Vacuum".**



1960

The University of Rochester
Rochester 20, N.Y.

Department of Physics

It is proposed to build a strong focusing ring to contain μ-mesons in a given momentum band for several π-meson lifetimes and then eject them.

Orbit radius 1.9 m
Mean radius 2.2 m

Aperture width 7 cm
Aperture height 4 cm

Maximum field 13 Kg.

Field index $n_1 - n_2 = n \simeq 15$

Betatron osc freq. $Q_r = 2.25$
$Q_z = 1.75$

Rotation frequency ≃ 22 Mc /sec

Weight Fe 10 tons     Cu 2 tons

Sectors: 4 each double
Focusing order: 1/2F D 1/2F

At the Cosmotron, a fairly well focused π-beam of $10^7$/pulse could be obtained for a $\Delta p/p \simeq 20\%$. Assuming that for such a beam the capture efficiency is 50%, the μ-meson beam becomes

$2.2 \times 10^4$/pulse   with $\Delta p/p = 10\%$

At the AGS one could expect a fairly well focused beam of π's $2 \times 10^8$ so that under the same considerations the μ-mesons are $4.4 \times 10^5$/pulse with $\Delta p/p = 10\%$

The cost is estimated to less than $100,000.

If all this does not seem too unreasonable I will proceed to calculate orbits.

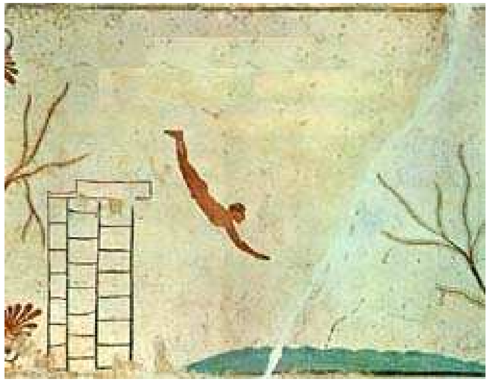
**Tribute by KTM: http://puhep1.princeton.edu/˜mcdonald/adrianfest/adrianfesttrans.pdf**

# The Sandal-Making Poet of Athens

“Take away the Glories and the Honors
The granite palaces of this vain world
And only give me the smile of Pain
The tear of Joy and I will erect
A thousand palaces in me in which to live.”
–Stavros Melissinos,

Known among sandal-makers as “The Poet”
(and among poets as “the Sandal-Maker”).
89 Pondrossou Street in Monastiraki, Athens

# Melissos of Samos



Student of Parmenides.
Admiral of Samian navy, defeated Pericles 441 BC.
“Nor is anything empty. For what is empty is nothing.
What is nothing cannot be.”
“Accordingly, being was not generated, nor will it be destroyed;
So it always was and always will be.”

## Why Muons?

- **A muon is a heavy electron.**
  **⇒ Fundamental interest in the properties of the muon and of its decays.**
- **Muons live 2.2 $\mu$s when at rest.**
  **⇒ Muons of any energy live ≈ 1,000 turns in a 2-T magnetic field.**
  **⇒ Can use rings to accelerate, store and collide muons.**

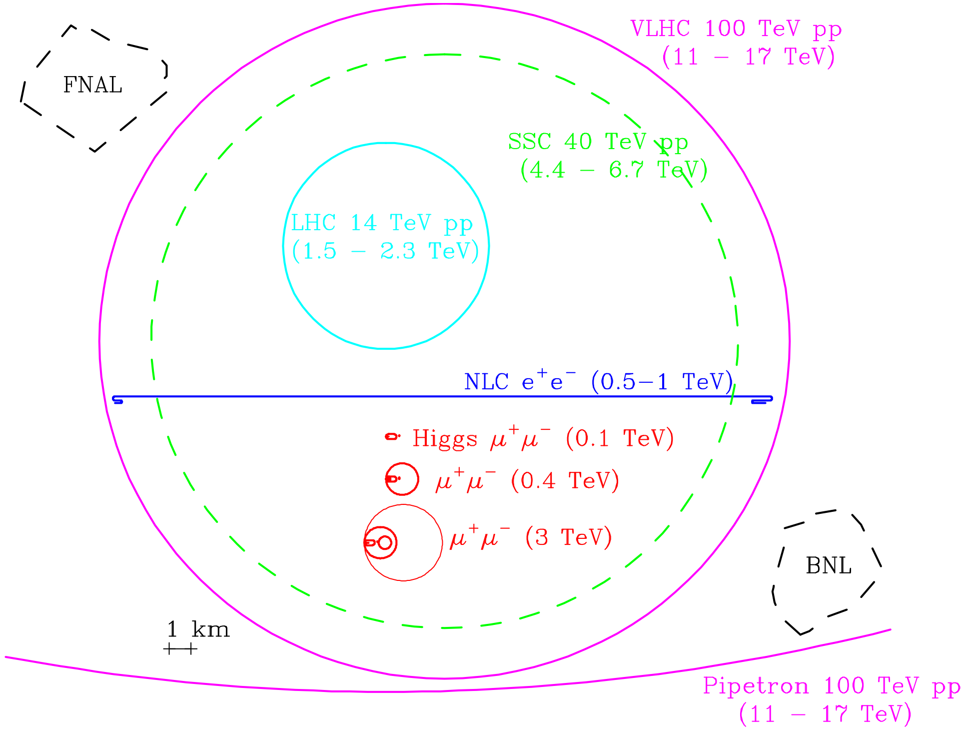
## Why Now?

- $m_\mu = 205 m_e$
  **⇒ Initial state radiation suppressed in $\mu^+\mu^-$ collisions.**
  **⇒ Precision leptonic initial states up to 100 TeV.**
- **Muon decay, $\mu \to \nu_\mu e \overline{\nu}_e$, provides well-known fluxes of $\nu_\mu$, $\overline{\nu}_e$ ($\overline{\nu}_\mu$, $\nu_e$) in equal amounts.**
  **⇒ Neutrino factory.**

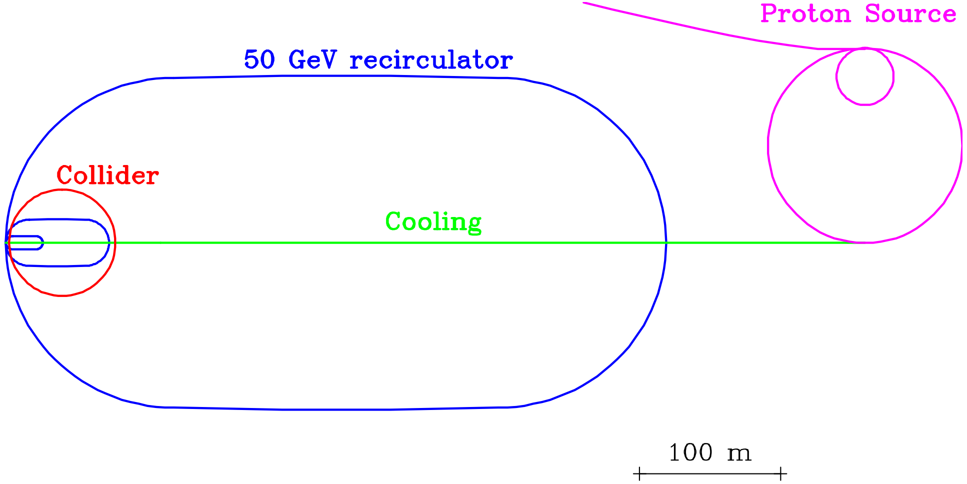
# What is a Muon Collider?

An accelerator complex in which

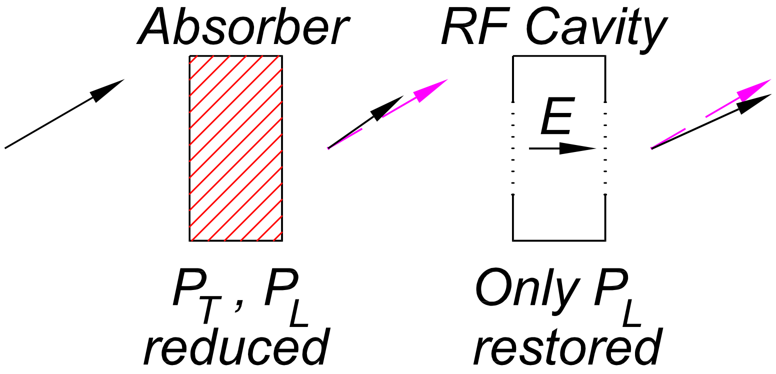
- Muons (both $\mu^+$ and $\mu^-$) are collected from pion decay following a $pN$ interaction.
- Muon phase volume is reduced by $10^6$ by ionization cooling.
- The cooled muons are accelerated and then stored in a ring.
- $\mu^+\mu^-$ collisions are observed over the useful muon life of $\approx 1000$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



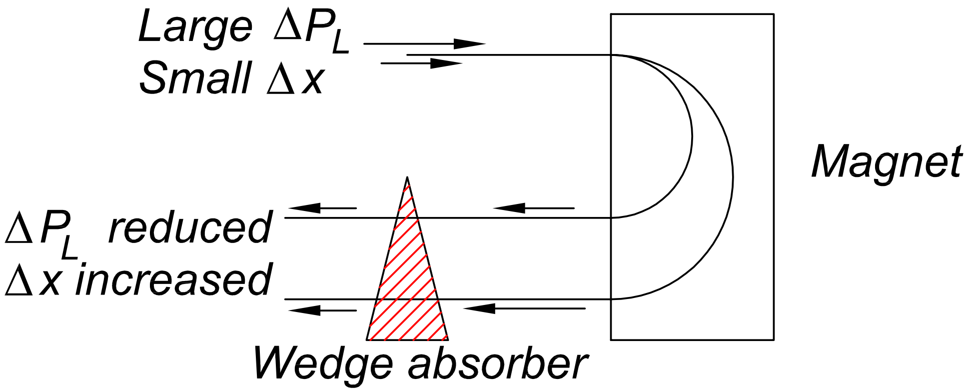
A First Muon Collider to study a light-Higgs



# Fast Ionization Cooling of Muon Beams



- $dE/dx$ loss cools both $P_T$ and $P_L$.
- Multiple scattering heats $P_T$, straggling heats $P_L$.
- With low-$Z$ absorber can have net cooling of $P_T$, but $P_L$ is heated.



- A magnet + wedge absorber can exchange transverse and longitudinal phase space.
- Then cool transversely again....

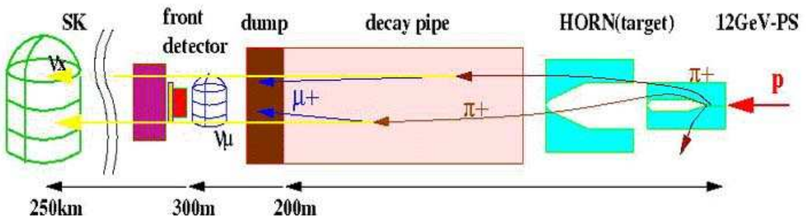
An affordable implementation of fast ionization cooling is the major R&D challenge for a muon collider.

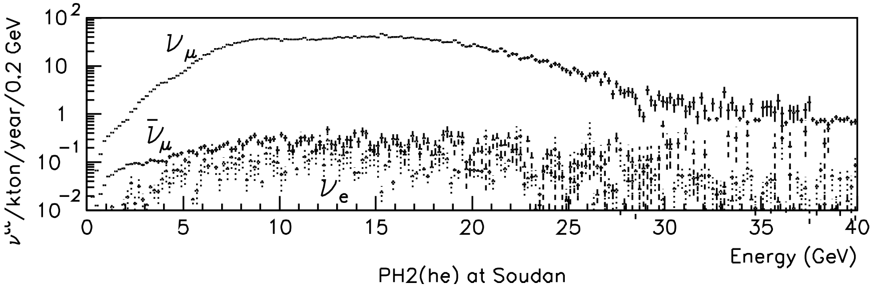
The Neutrino Factory and Muon Collider Collaboration:

http://www.cap.bnl.gov/mumu/mu_home_page.html

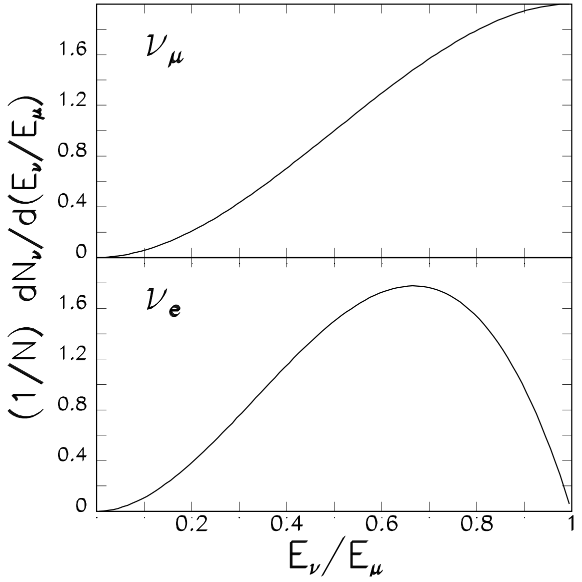
# A Neutrino Factory Based on a Muon Storage Ring

- 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 $\overline{\nu}_\mu$ and $\nu_e$ from $\mu$ and $K \rightarrow 3\pi$ decays.

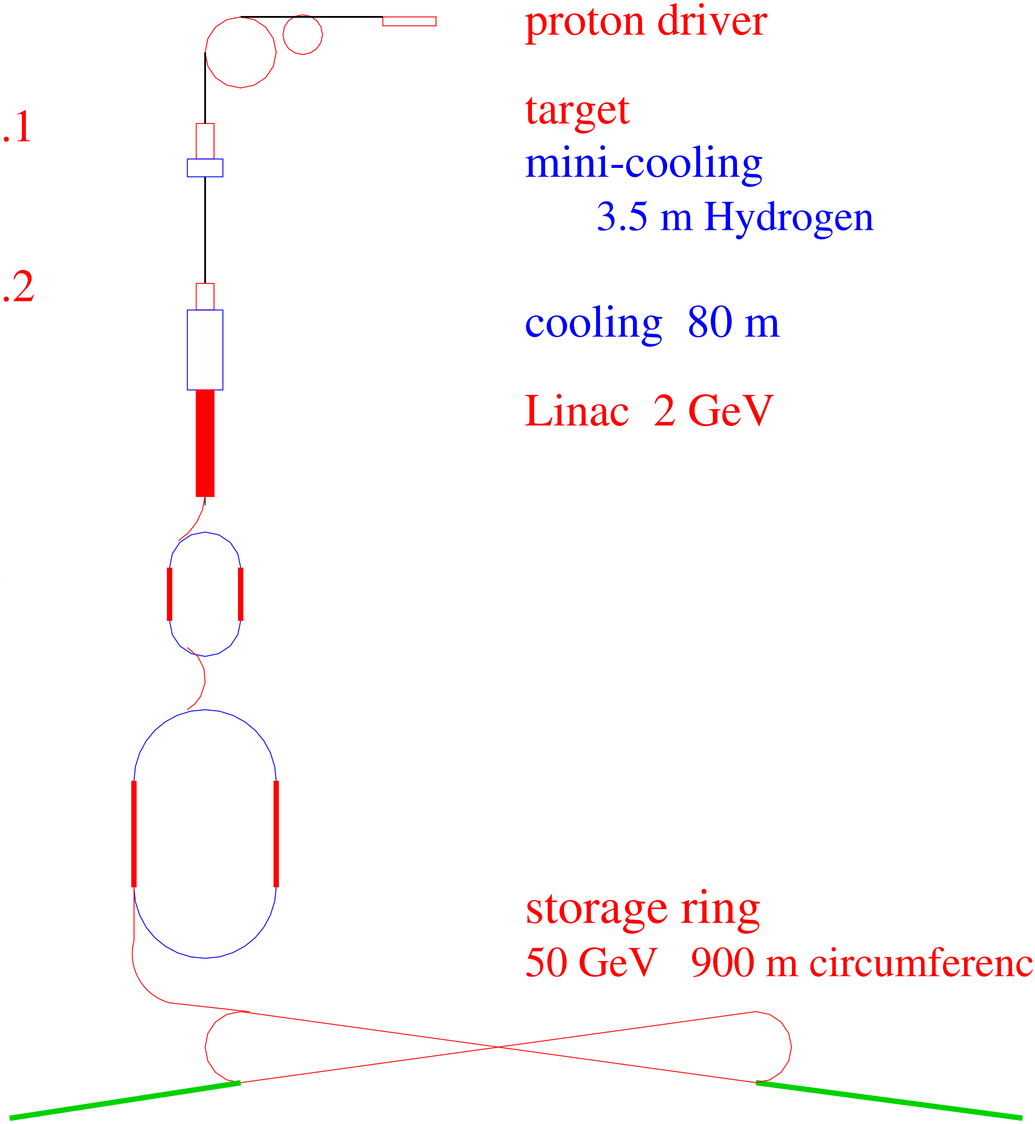




- Higher (per proton beam power) and better characterized neutrino fluxes are obtained from $\mu$ decay.
- Collect low-energy $\mu$'s from $\pi$ decay,
  Cool the muon bunch,
  Accelerate the $\mu$'s to the desired energy,
  Store them in a ring while they decay via $\mu^- \rightarrow e^-\nu_\mu\overline{\nu}_e$.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



# A Neutrino Factory Based on a Muon Storage Ring



proton driver

target

mini-cooling

3.5 m Hydrogen

phase rotation No.1

42 m rf

drift 160 m

phase rotation No.2

cooling 80 m

Linac 2 GeV

recirculator Linac

2 - 8 GeV

recirculator Linac

8 - 50 GeV

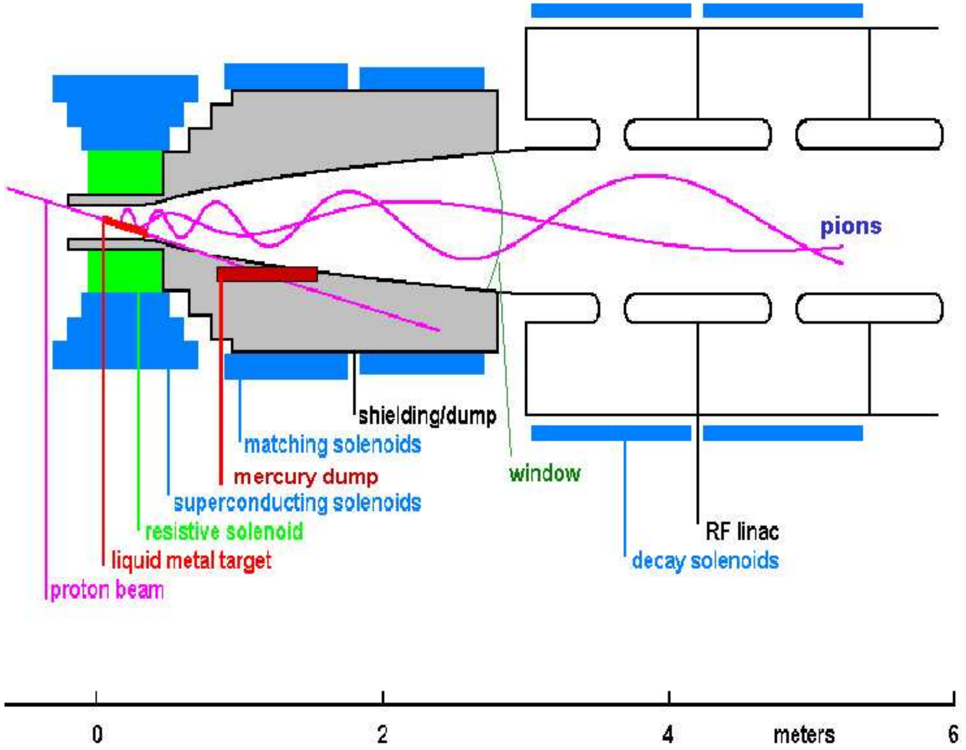
storage ring

50 GeV 900 m circumference

neutrino beam

neutrino beam

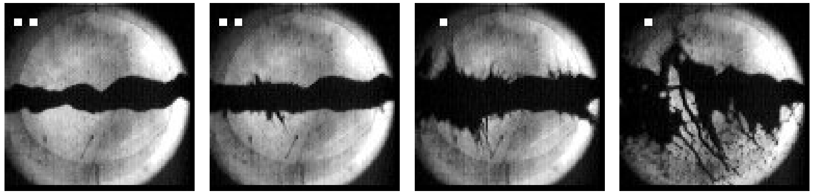
# Multimawatt Target for a Muon Collider/Neutrino Factory



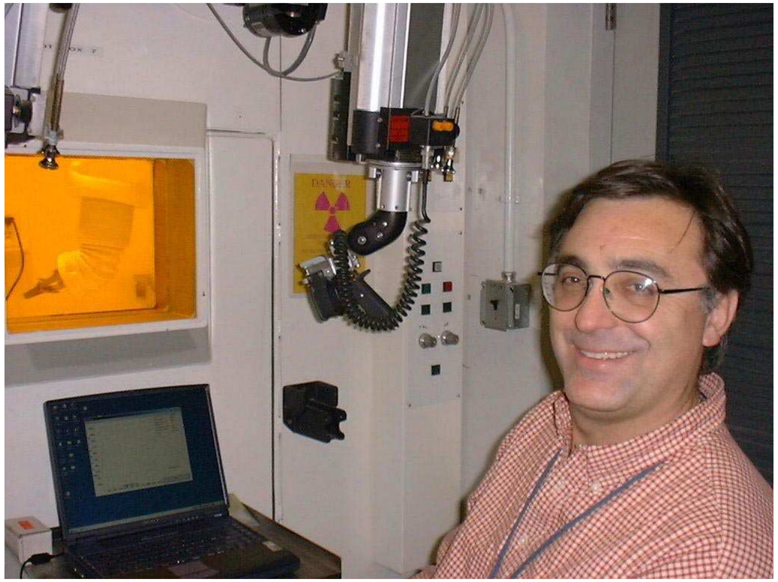
Use a free mercury jet as target for a 4-MW proton beam to produce $\pi$'s, $\mu$'s and $\nu$'s.

Capture the charged $\pi$'s in a 20-T solenoid magnet.

## Targetry R&D:



Mercury jet dispersed by a proton beam.



Nick Simos performing solid target studies in a BNL hot cell.

# Can Study CP Violation of Neutrinos at $L/E = (2n+1)500$ km/GeV

[Marciano, hep-ph/0108181, Diwan *et al.*, hep-ph/0303081]

The $n$th maximum of $\nu_2$-$\nu_3$ oscillations occurs at $L/E \approx (2n+1)400$ km/GeV.

The CP asymmetry grows with distance:

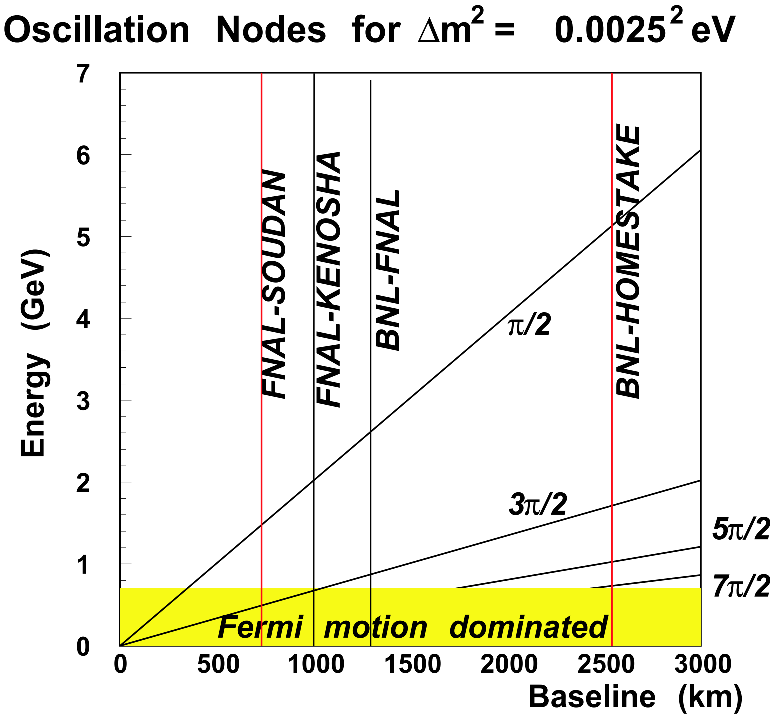
$$A = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \approx \frac{2 s_{12} c_{12} c_{23} \sin\delta}{s_{23} s_{13}} \left(\frac{\Delta m^2_{12}}{\Delta m^2_{23}}\right) \frac{\Delta m^2_{23} L}{4 E_\nu}$$

$$\Rightarrow \frac{\delta A}{A} \approx \frac{1}{A\sqrt{N}} \propto \frac{E_\nu}{L\sqrt{N}} \approx \text{ independent of } L \text{ at fixed } E_\nu.$$

$N_\text{events} \propto 1/L^2$,
$\Rightarrow$ Hard to make other measurements at large $L$.

Low $E_\nu$ favorable for CP violation measurements.

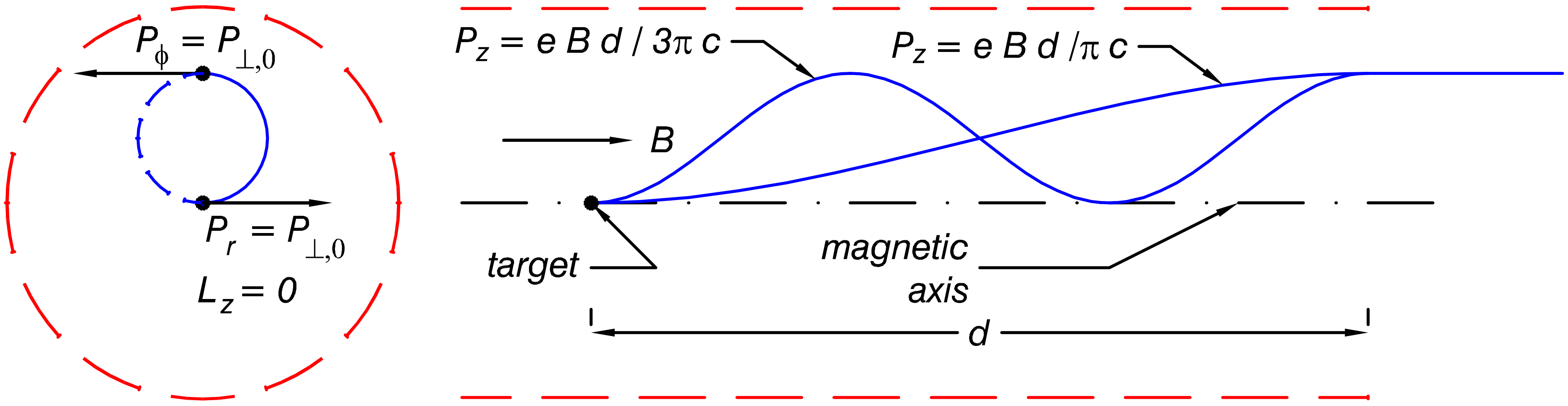
If (still) need to disentangle matter effects from CP asymmetries, use the $n = 0$ and 1 oscillation maxima with $E_1$ as low as possible,
Ex: FNAL-Kenosha (986 km),
BNL-FNAL (1286 km).



Oscillation Nodes for $\Delta m^2 =$ 0.0025$^2$ eV

# Narrowband Beam via Solenoid Focusing

(physics/0312022)



- **Point-to-parallel focusing occurs for $P_\pi = eBd/(2n+1)\pi c$.**
- **⇒ Narrowband neutrino beam with multiple peaks at**

$$E_\nu \approx \frac{4}{9}\frac{eBd}{(2n+1)2\pi c}.$$

- **⇒ Can study several neutrino oscillation peaks at once, at**

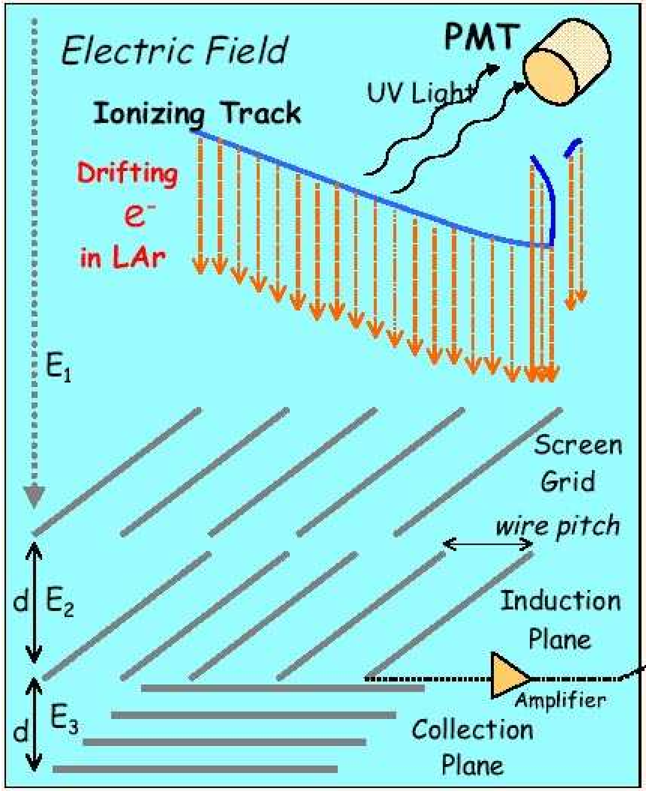
$$\frac{1.27 M_{23}^2[\mathbf{eV}^2]\ L[\mathbf{km}]}{E_\nu[\mathbf{GeV}]} = \frac{(2n+1)\pi}{2}.$$

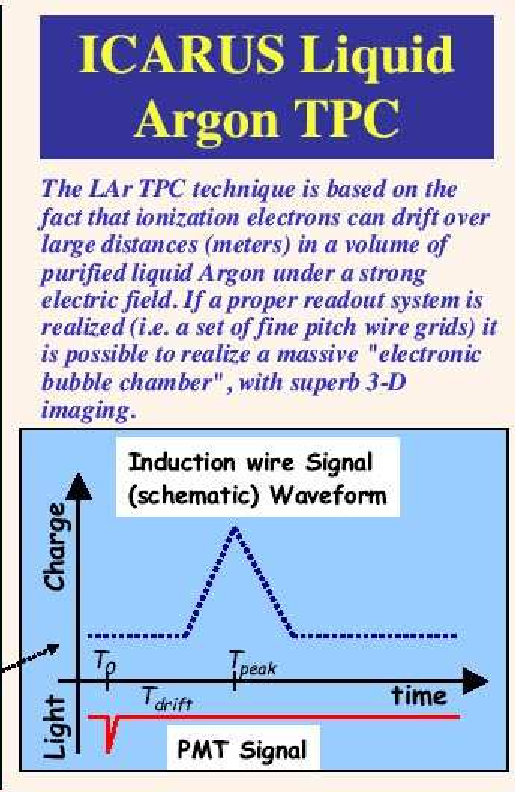
- **Get both $\nu$ and $\bar\nu$ at the same time (while $\nu_e$ and $\bar\nu_e$ suppressed),**
  **⇒ Must use detector that can identify sign of $\mu$ and $e$,**
  **⇒ Magnetized liquid argon TPC.**

# Liquid Argon TPC Overview

- A liquid argon time-projection chamber is a total-absorption tracking calorimeter = An electronic bubble chamber.
- It's efficiency for detection of $\nu_e$ appearance events will be greater than 90% for GeV energies.
  (This is $\gtrsim 3$ times the efficiency of low-$Z$ sampling detectors.)
- A large ($> 10$ kton) liquid argon TPC, if in a single cryostat, will cost very nearly the same as a low-$Z$ sampling detector of the same mass.
  (There is highly competitive industry support for production, purification and storage of large quantities of liquid argon.
  Liquid scintillator costs 2.5 times as much as liquid argon, per unit mass.)
- The hardware of a liquid argon TPC is in a mature state, and readily scalable to large masses.
- More in need of further development is the software
  – in the style of bubble chambers.
  (Human scanning of event displays if necessary.)

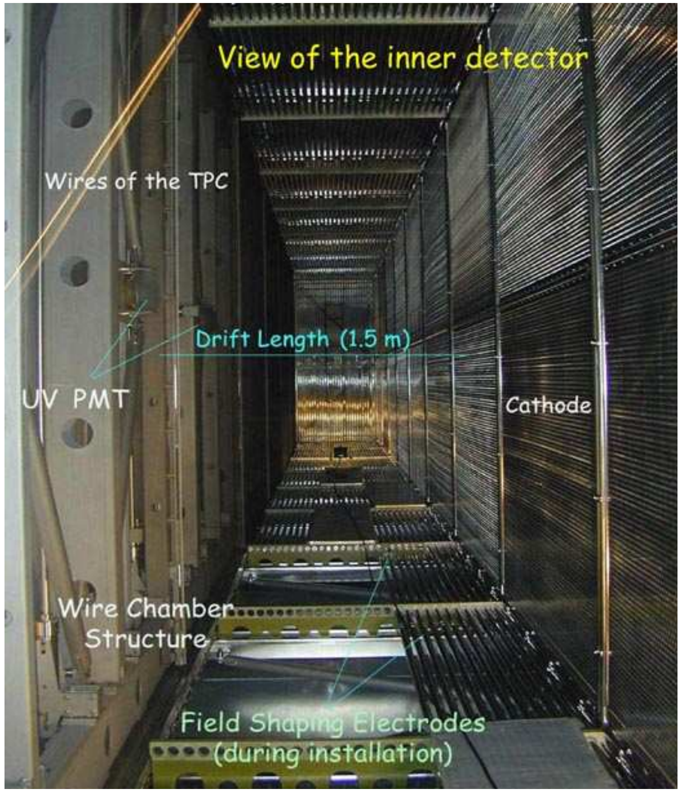
# ICARUS Liquid Argon TPC





**ICARUS Liquid Argon TPC**

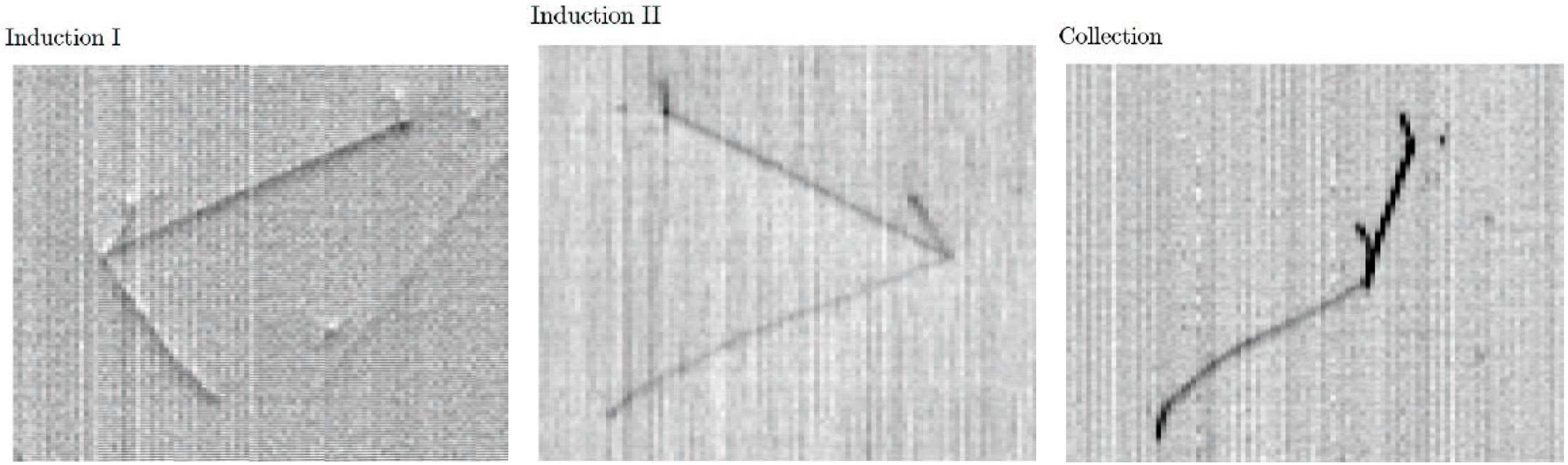
*The LAr TPC technique is based on the fact that ionization electrons can drift over large distances (meters) in a volume of purified liquid Argon under a strong electric field. If a proper readout system is realized (i.e. a set of fine pitch wire grids) it is possible to realize a massive "electronic bubble chamber", with superb 3-D imaging.*



**Liquid argon time projection chamber conceived by C. Rubbia (1977).**

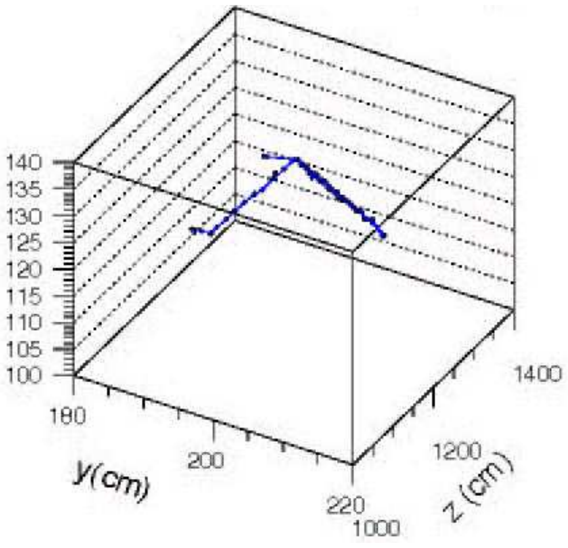
**Largest implementation to date is the ICARUS T600 (600 ton) module,
on the surface in Pavia, Italy.
http://www.aquila.infn.it/icarus/**

# Events from the ICARUS T300 Cosmic Ray Test

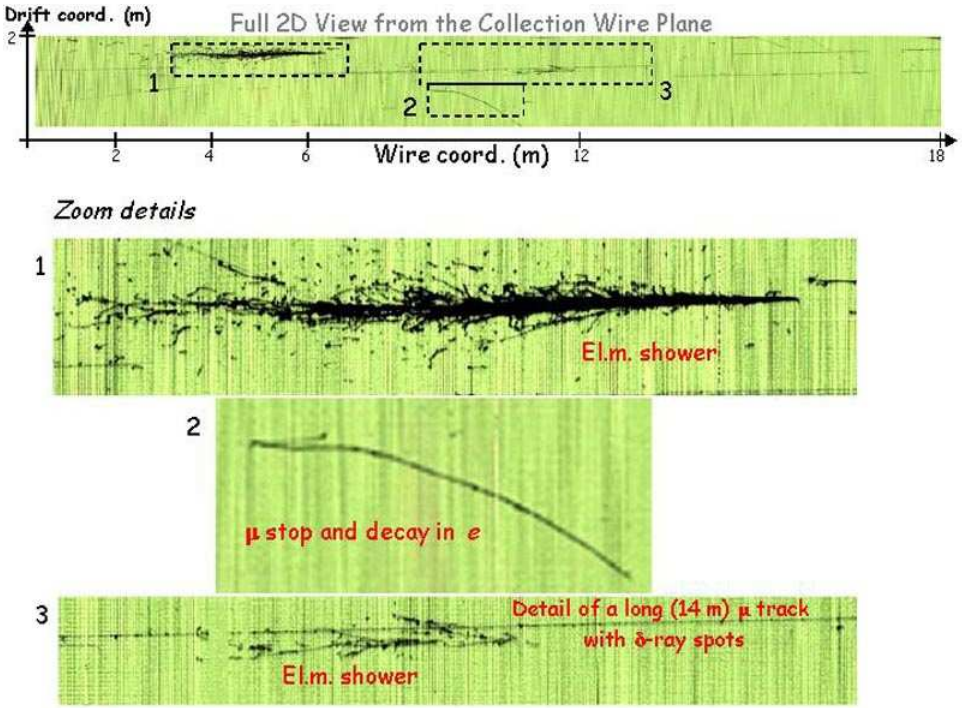


**Above: 3 views of a low-energy hadronic interaction.**

**Right: Computer reconstruction.**



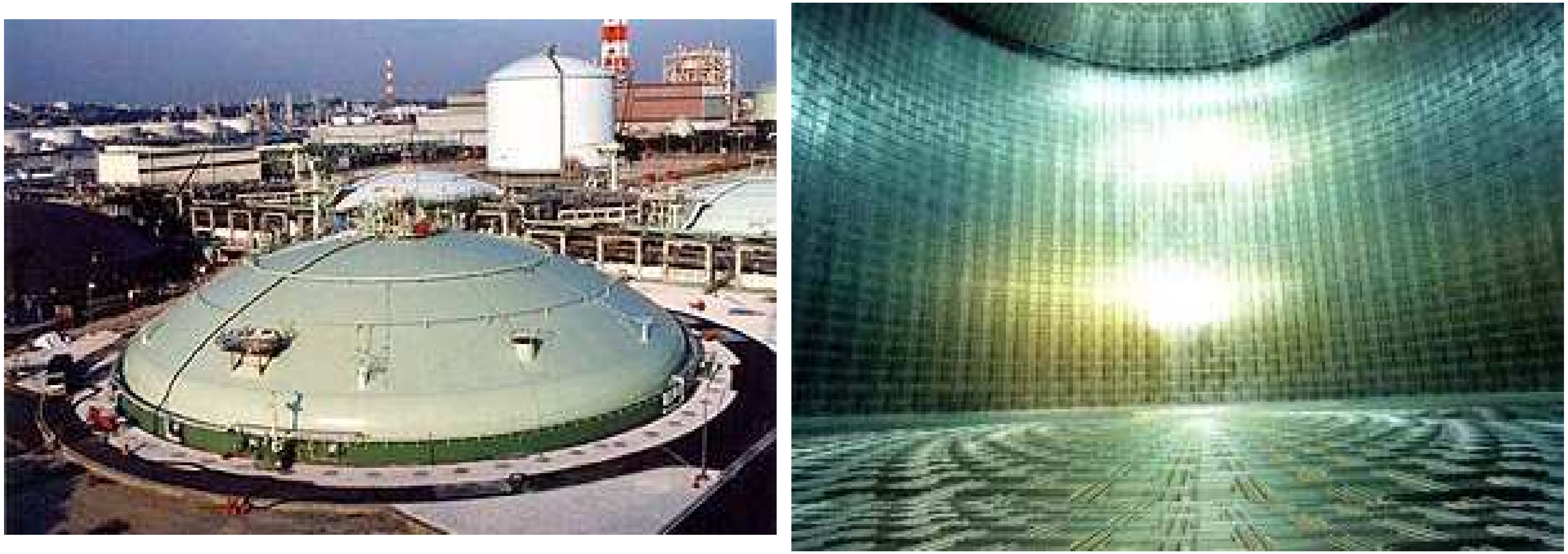
**Far right: Cosmic ray shower that includes a muon with a $\delta$-ray, a stopping muon, and an electromagnetic shower.**



# Liquid Argon TPC Properties

- 3D tracking + total-absorption calorimetry.
- Pixel size: 3 mm × 3 mm (wire planes) × 0.6 mm (via 400 ns time sampling).
- $\rho = 1.4$ g/cm$^3$, T = 89K at 1 atm., $X_0 = 14$ cm, $\lambda_{\rm int} = 80$ cm.
- A minimum ionizing particle yields 50,000 $e$/cm.
- Drift velocity of 1.5 m/msec at 500 V/cm $\Rightarrow$ 5 m drift in 3 msec.
- Diffusion coef. $D = 6$ cm$^2$/s $\Rightarrow \sigma = 1.3$ mm after 3 msec.
- Can have only 0.1 ppb of $O_2$ for a 5 m drift,
  $\Rightarrow$ Purify with Oxisorb.
- Liquid argon costs \$0.7M/kton – and is “stored” not “used”.

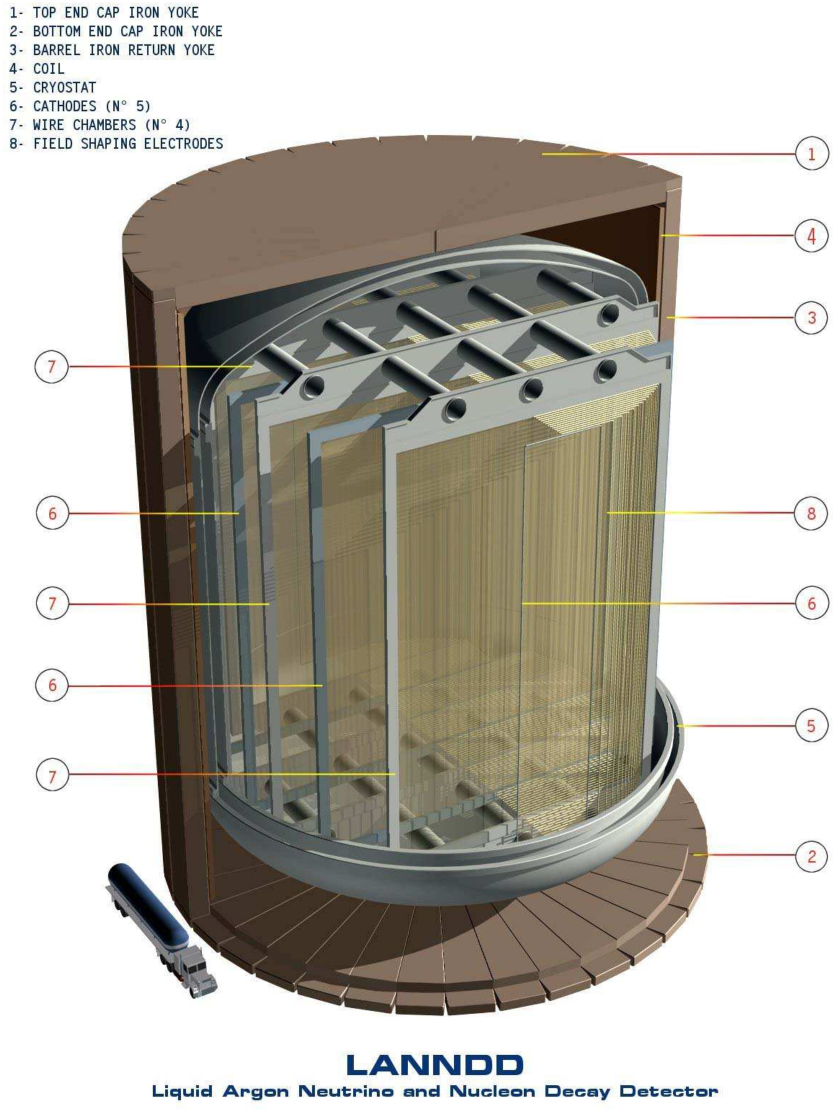
- **Large modules ($\gtrsim 100$ kton) can be built using technology of liquid methane storage. (Total cost of a 100-kton detector is estimated to be $200M.)**



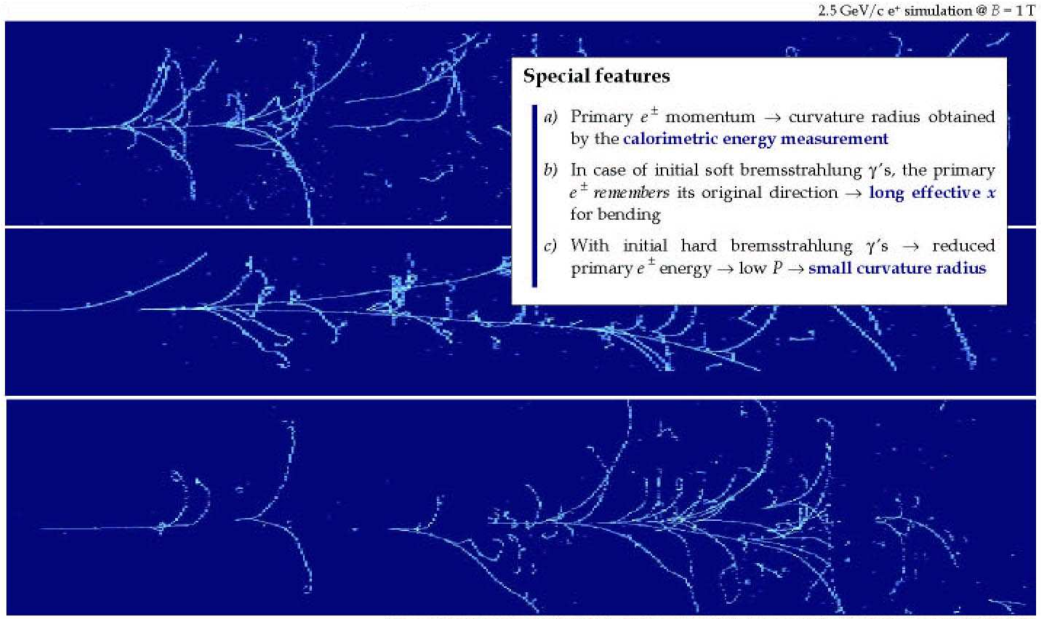
- **Detector is continously "live" and can be "self-triggered" using pipelined, zero-suppression electronics.**
- **Operates at the Earth's surface with near zero overlap of cosmic ray events.**
- **Detector is compatible with operation in a magnetic field.**

# LANNDD – 100 kton Liquid Argon Neutrino and Nucleon Decay Detector

## (astro-ph/0105442, Nucl. Instr. and Meth. A503, 136 (2003))



F. Sergiampietri-August 2000


2.5 GeV/c $e^+$ simulation @ $B = 1$ T

**Special features**

- *a)* Primary $e^\pm$ momentum → curvature radius obtained by the **calorimetric energy measurement**
- *b)* In case of initial soft bremsstrahlung $\gamma$'s, the primary $e^\pm$ *remembers* its original direction → **long effective $x$** for bending
- *c)* With initial hard bremsstrahlung $\gamma$'s → reduced primary $e^\pm$ energy → low $P$ → **small curvature radius**

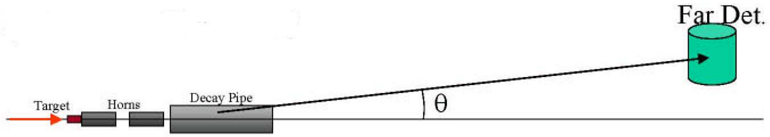
A. Bueno, M. Campanelli, A. Rubbia, *IX International Workshop on "Neutrino Telescopes"*, VENICE, 2001

**Can resolve sign of electron up to $\approx 2.5$ GeV in a 0.5-T magnetic field.**

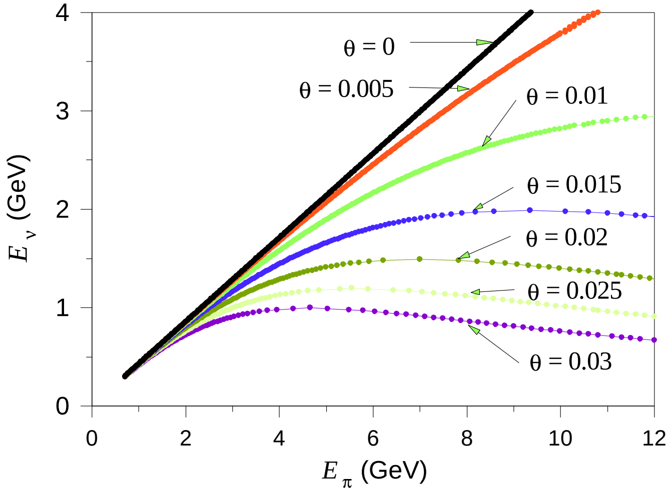
**Max drift length of 5 m (limited by $O_2$ purity), ⇒ Several drift cells.**

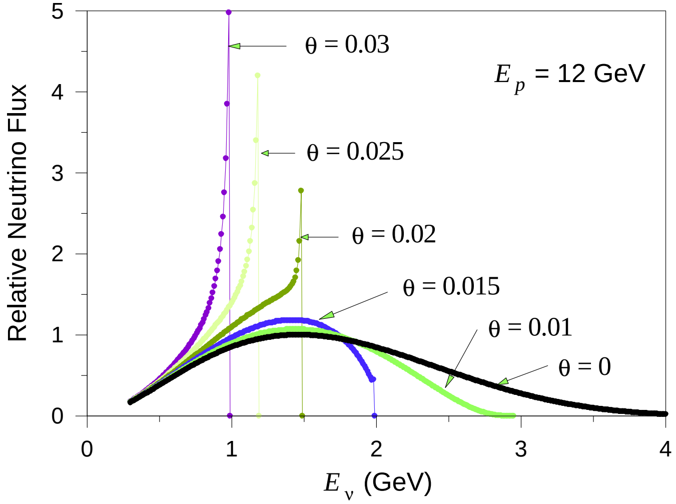
# Before a Neutrino Factory, a Neutrino Superbeam

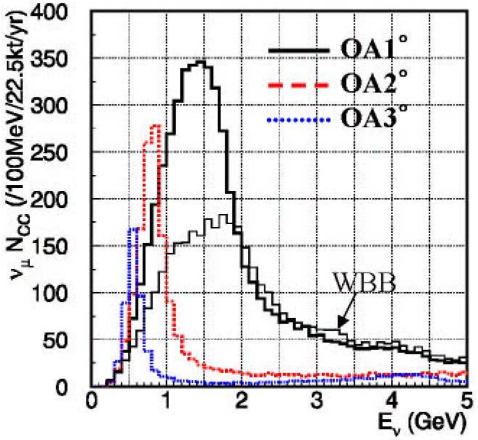
**Use an Off-Axis Neutrino Beam (BNL E-889).**

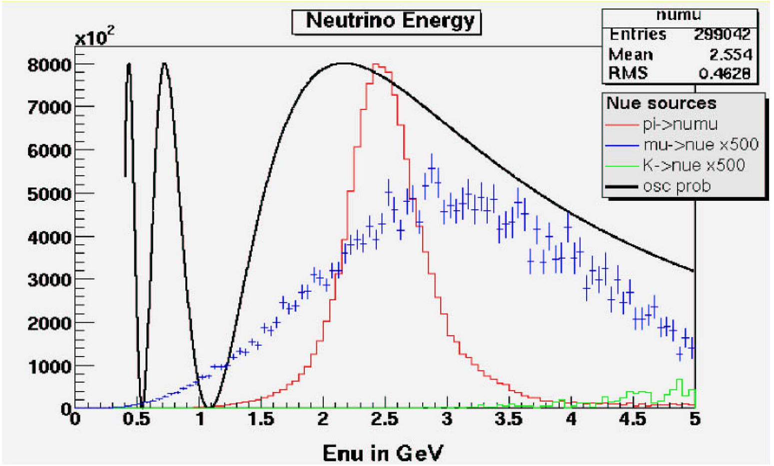


**$\pi \to \mu\nu$ decay kinematics has a Jacobian peak: $\theta \approx 2^\circ$ / GeV. (Sternheimer, 1955)**





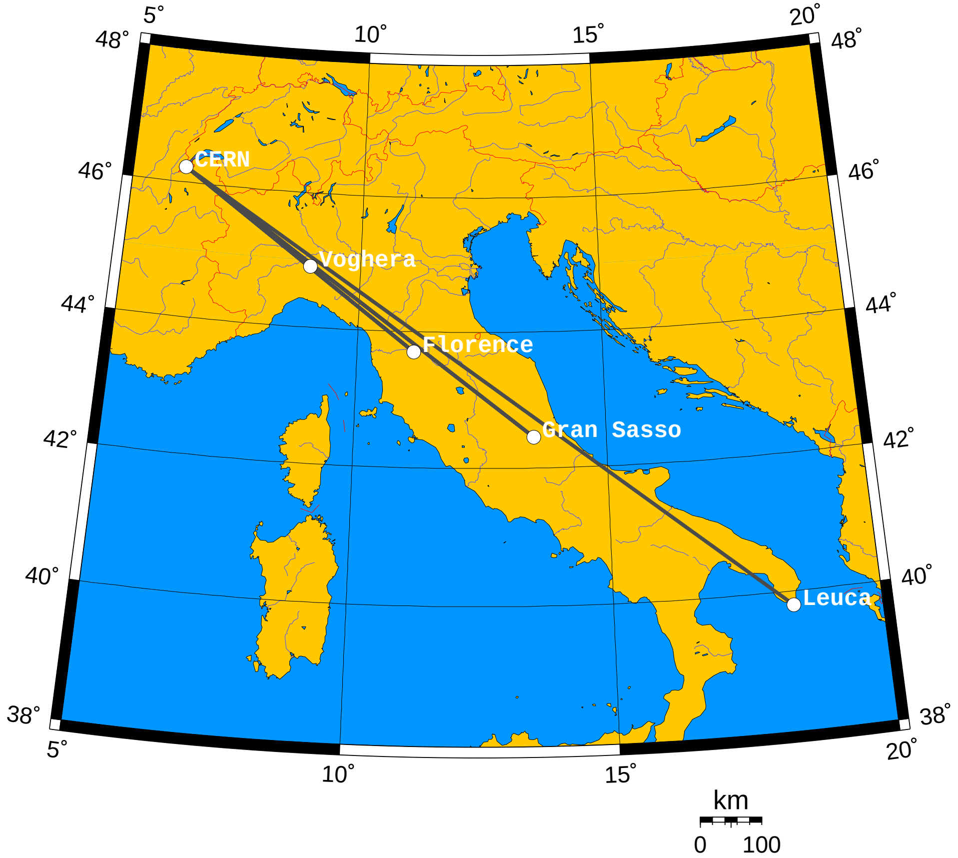




**J2K (Kobayashi)** **NUMI (Wojcicki)**

# Off-Axis Neutrino Beams from CERN

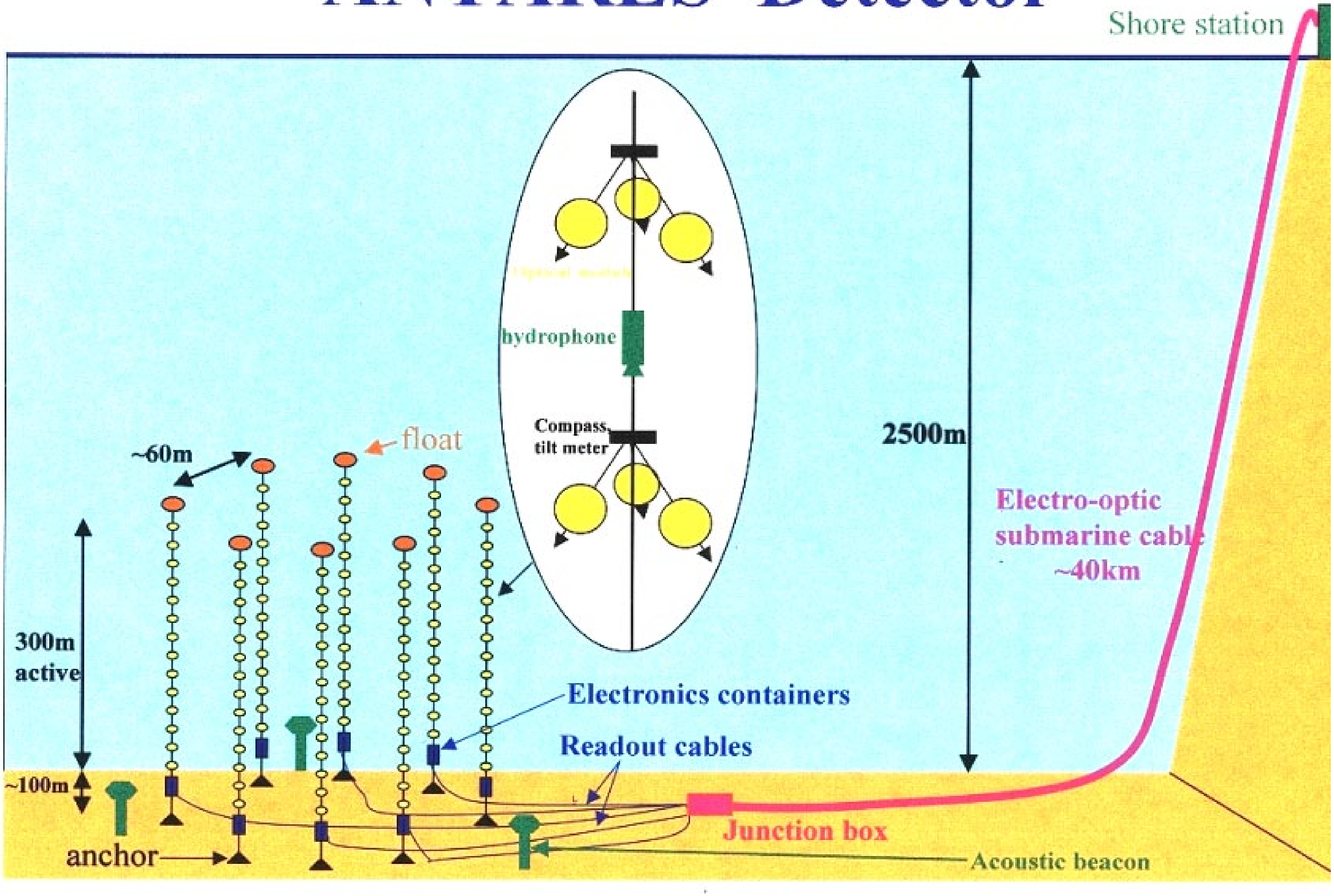
| Site | Distance to CERN (km) | Lat. | Long. | $\angle_{\text{CERN}}$ to Leuca |
|---|---|---|---|---|
| Voghera | 270 | 44.9° | 8.95° | 4.4° |
| Florence | 490 | 43.7° | 11.15° | 3.9° |
| Gran Sasso | 730 | 42.45° | 13.57° | 2.5° |
| Leuca | 1225 | 39.8° | 18.35° | – |



**Could also use converted LNG tanker in the Gulf of Taranto:**

ANTARES
NEMO
Corse
Sardaigne
Sicile
Palerme
Rome
Naples
Venise
Bassin médio adriatique
Bassin sud-adriatique
Bassin ionien
Plateau
Malte
Iles Ioniennes
Péloponnèse
Athènes
Thessalonique
Cyclades
Bassin de Candie
Crète
Arc crétois
Rhodes
Izmir
Istanbul
Thrace
Balkans
Rhodope
Alpes dinariques
Alpes de Transylvanie
Danube
Cône du Danube
Bassin
G. d'Odessa
Tunis
Annaba
Sfax
Golfe de Gabès
Mer Méditerranée
Ride
Bassin du Levant

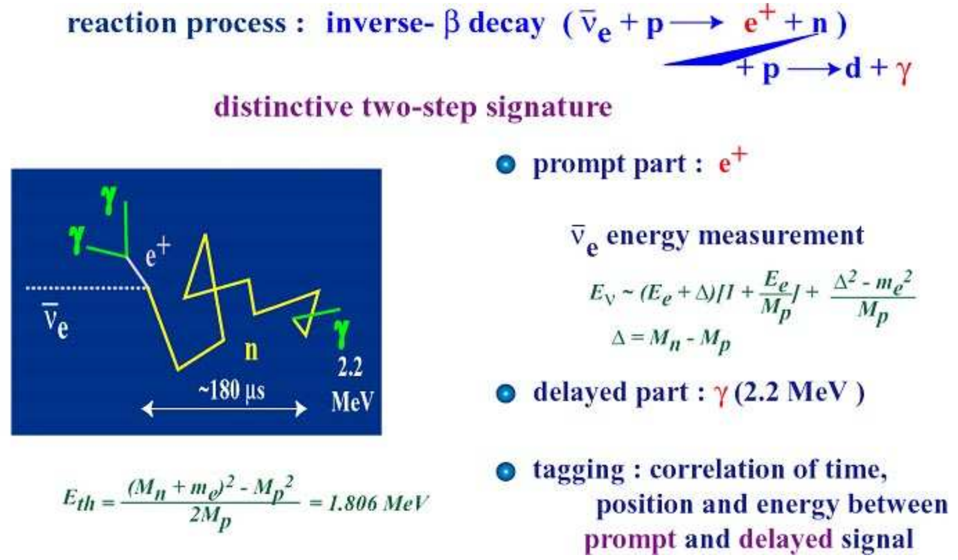
# ANTARES Detector



# Neutrinos and Arms Control Workshop, U. Hawaii, 5-7 February 2004

Goal: Detect Reactors from Whole Earth.

Need $\approx 1$ gigaton detector = 1 km$^3$, with $\approx 1$ MeV sensitivity.



**reaction process : inverse- β decay** ($\bar{\nu}_e + p \longrightarrow e^+ + n$)

$+ p \longrightarrow d + \gamma$

**distinctive two-step signature**

- **prompt part :** $e^+$

  **$\bar{\nu}_e$ energy measurement**

  $$E_\nu \sim (E_e + \Delta)[1 + \frac{E_e}{M_p}] + \frac{\Delta^2 - m_e^2}{M_p}$$

  $$\Delta = M_n - M_p$$

- **delayed part :** $\gamma$ (2.2 MeV )

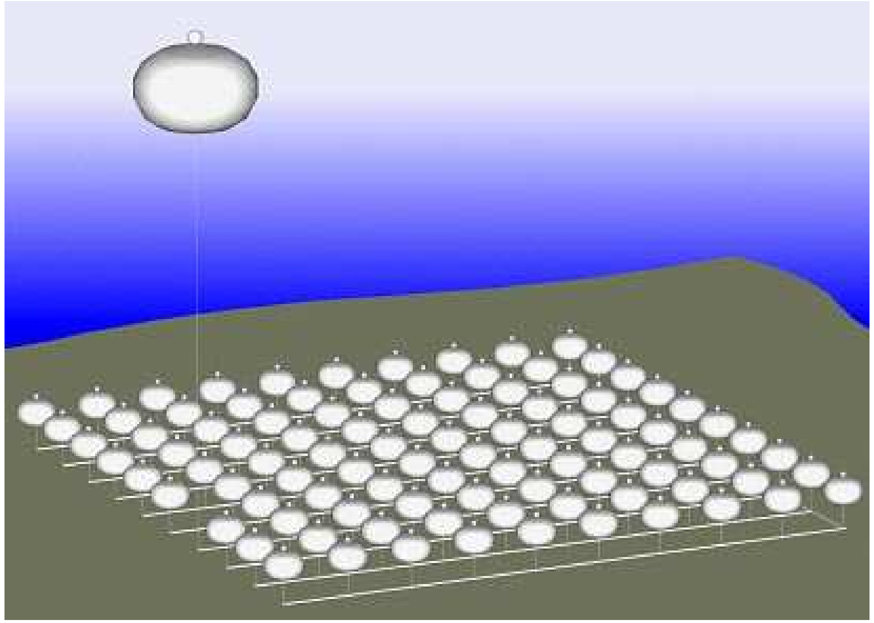
- **tagging : correlation of time, position and energy between prompt and delayed signal**

$$E_{th} = \frac{(M_n + m_e)^2 - M_p^2}{2M_p} = 1.806 \text{ MeV}$$

(J. Learned, U. Hawaii)

http://www.phys.hawaii.edu/˜jgl/nacw/agenda.html

- 100 modules @ $10^7$ ton each.
- Balloons with radius 134 m.
- Flexible bag with photodetector and electronics on inner wall, pressure tolerant.
- Slightly buoyant, haul up for service. Anchoring forces $< 30$ tons
- Get water from Antarctic? Reverse osmosis?



# Destruction of Nuclear Bombs Using Ultra-High Energy Neutrino Beam

— dedicated to Professor Masatoshi Koshiba —

Hirotaka Sugawara* Hiroyuki Hagura† Toshiya Sanami‡

### Abstract

We discuss the possibility of utilizing the ultra-high energy neutrino beam ($\simeq$ 1000 TeV) to detect and destroy the nuclear bombs wherever they are and whoever possess them.

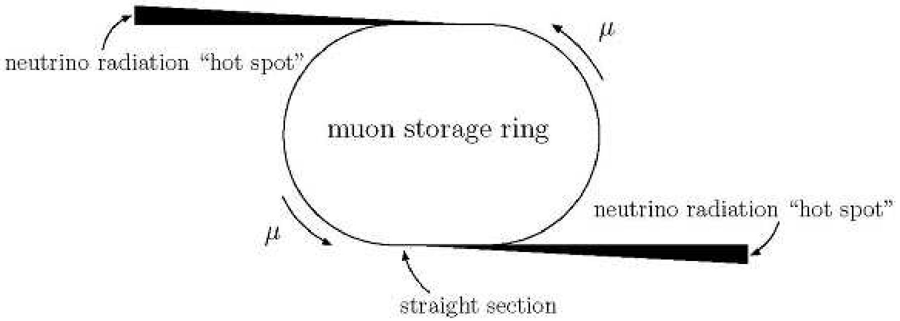


Figure 1: *Neutrino radiation from a race track shaped muon storage ring. The decay of muons will produce the neutrino radiation emanating out tangentially everywhere from the ring. In particular, the straight sections in the ring will cause radiation "hot spots" where all of the decays line up into a pencil beam.*

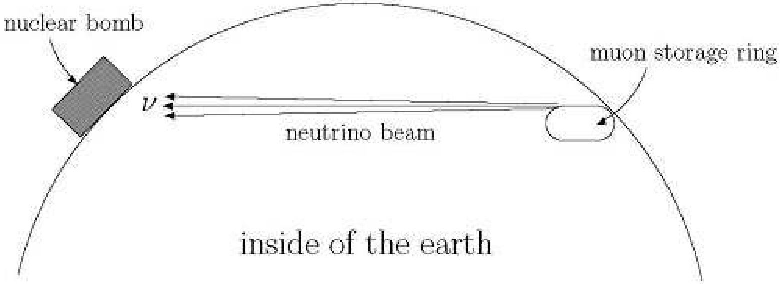


Figure 2: *Neutrino beam is aimed at the nuclear bomb that is placed on the opposite side of the earth. The beam is emitted downstream from one of the straight sections of the muon storage ring (see fig. 1), and reaches the bomb after passing through the inside of the earth.*