Low energy Superbeams, Beta beams and the Neutrino Factory.

Leslie Camilleri
CERN

Neutrino 2006
Santa Fe, 18th June 2006

What's needed next?

- **What is the value of θ_{13} ?**

  Plans for several experiments using reactors, accelerators, etc…

- **What is the mass the mass hierarchy ?**

  Some of these experiments, especially if extended through the use of upgraded accelerators, could begin to address this.

- **Any CP violation in the neutrino sector?**

  A new neutrino facility (a neutrino factory or a beta-beam complex) would be the only way to address this problem.

Compare $\nu_\mu \leftarrow\rightarrow \nu_e$ to $\bar{\nu}_\mu \leftarrow\rightarrow \bar{\nu}_e$ oscillations
At the Atmospheric $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2

⇓

CP violation, (and θ_{13} , mass hierarchy)

Outline of talk.

- Low energy Superbeam (SPL at CERN). **E_ν ~ 350 MeV**
- Beta-beams. **E_ν ~ 500 MeV**
- Neutrino Factory. **E_ν ~ 10 GeV**
- R&D on targets (MERIT) and muon cooling (MICE, MUCOOL).

Acknowledgments

- Beta Beams: Mats Lindroos, Mauro Mezzetto, J-E. Campagne.

- Neutrino Factories.

Alain Blondel,

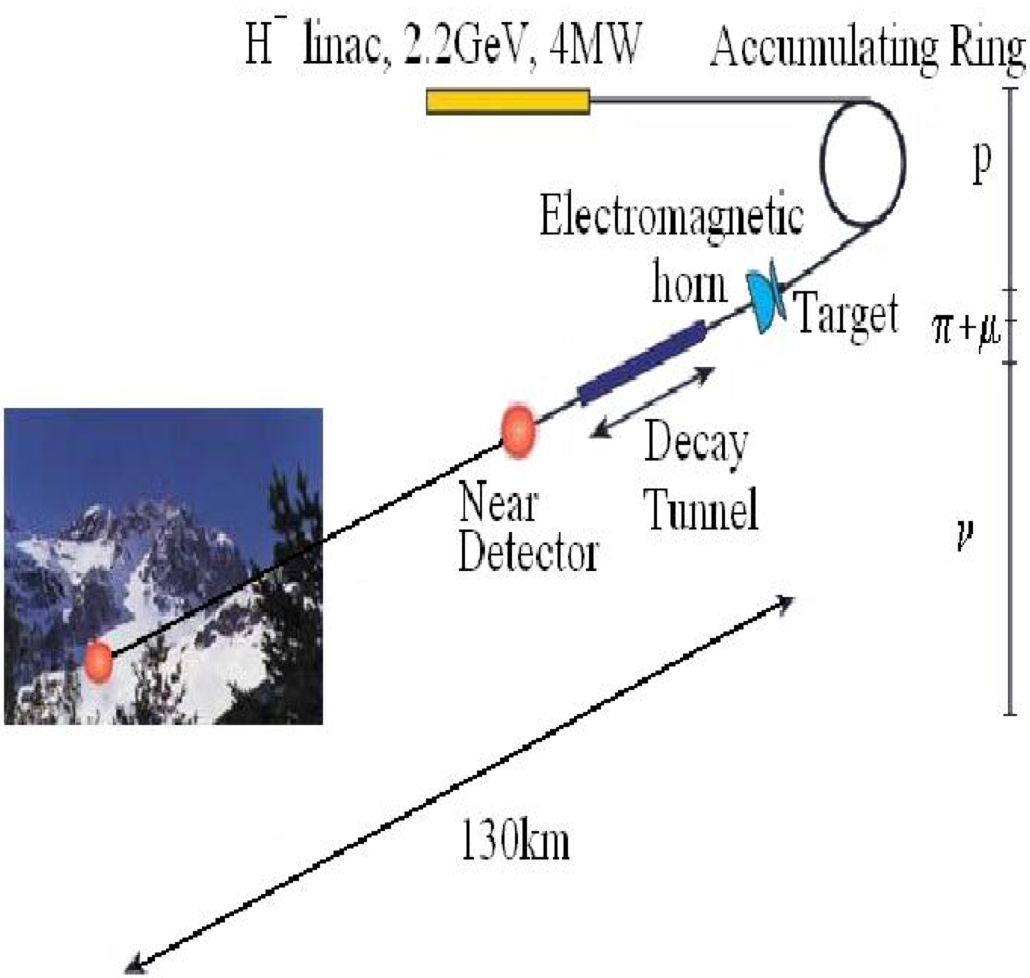
Talks based on April 2006 International Scoping Study meeting at RAL.

Presentations by:

- Bob Palmer on machine
- Paul Soler on Detectors
- Yori Nagashima on Physics

Superconducting Proton Linac: ν_μ beam.

Classic accelerator ν_μ beam. Intrinsic ν_e component results in a background.



- Power : **4 MW**
- Kin. Ener. : **Up to 5 GeV.**
- Shorten pulse length. (Reduce atmospheric ν's contam.)
- Target: **Liquid Mercury Jet** to cope with stress due to high flux.
- Focusing: **Horn and Reflector**
- Detector: New lab in **Fréjus** tunnel
- (Safety gallery approved April 2006: **opportunity**)
- Distance: **130km**
- Neutrino energy to be at oscillation maximum for $\Delta m_{23}^2 = 2.5 \times 10^{-3}\ eV^2$ **260 MeV → 350 MeV more sensitive**

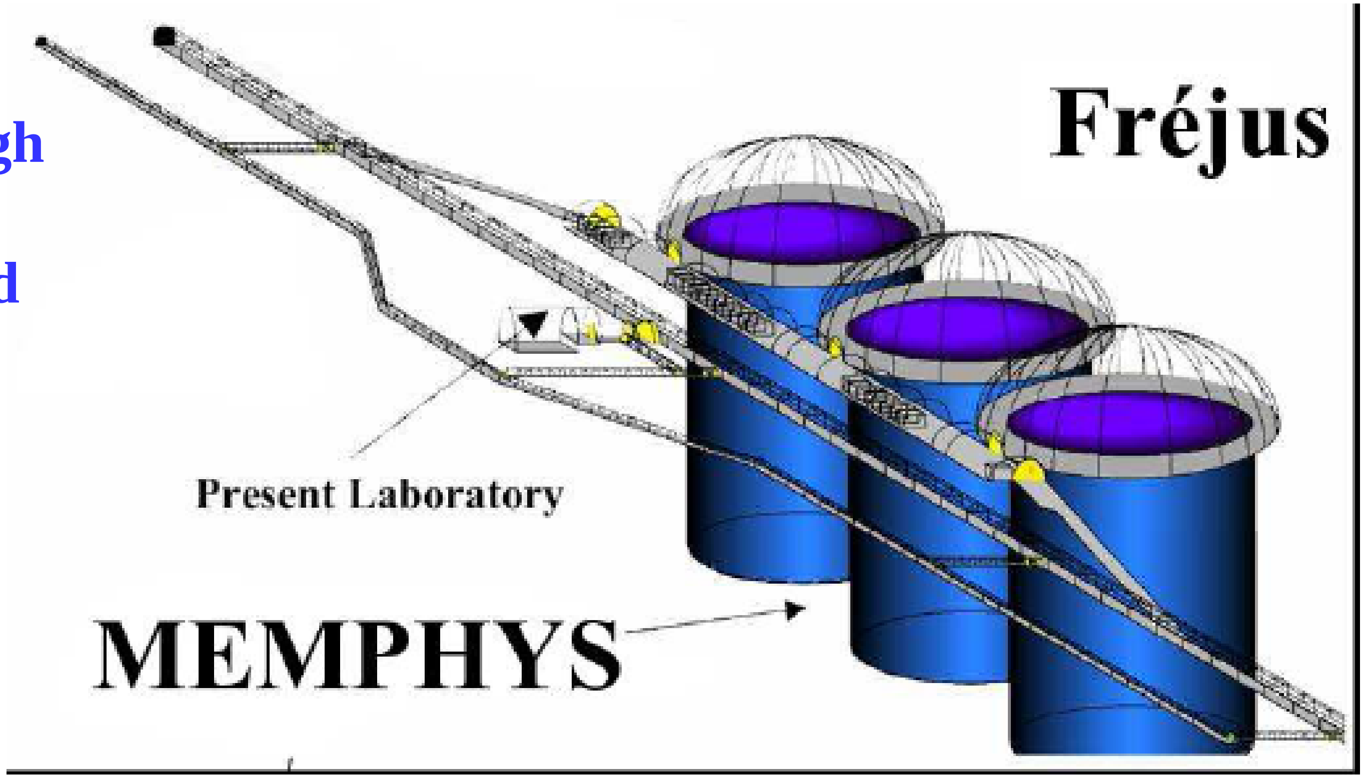
Near detector also needed, as in all schemes.

MEMPHYS at Fréjus

Up to 5 shafts possible
Each 57m diam., 57m high

For most studies assumed
3 x 145 ktons.
Water Cerenkov

Depth: 4800 m.w.e



Per shaft: 81,000 12” PMT’s → 80 M€ including electronics (65M$)
+80 M€ for civil engineering. (65M$)

Standard scenario:
mix neutrino and antineutrino running

- 3.5 and 4.5 GeV proton beam
- 260 and 350 MeV options

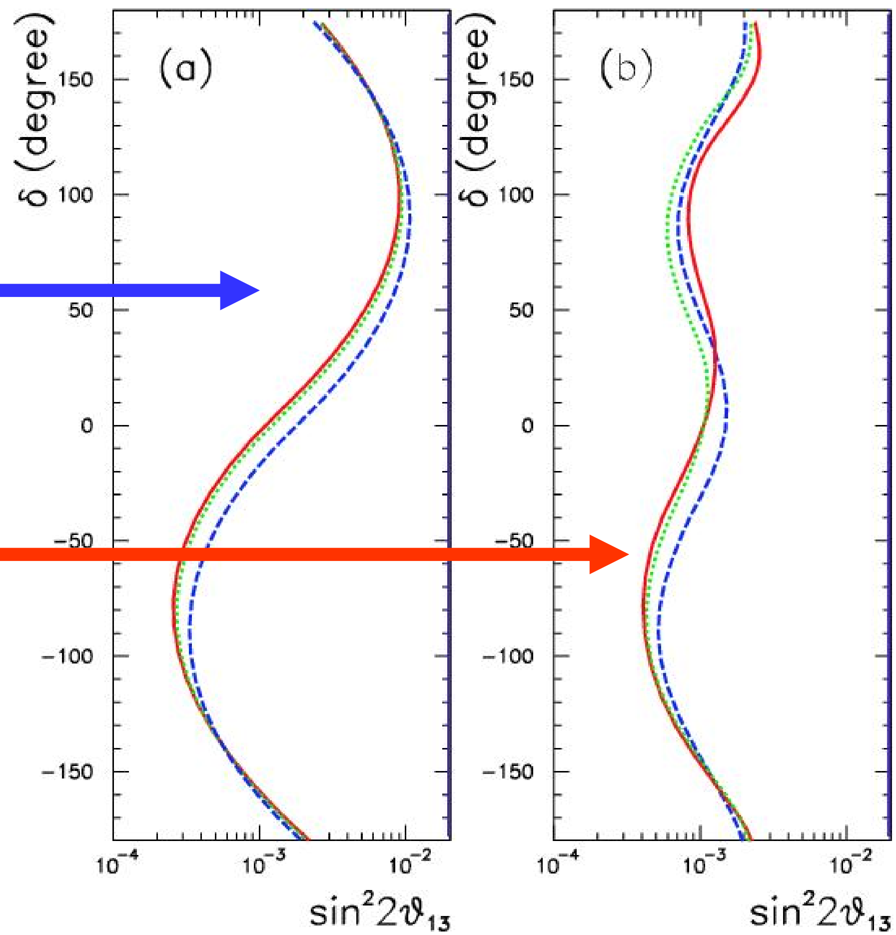
- 5 years of ν running.

- 2 years of ν running and

  8 years of $\bar{\nu}$ running

The curves flatten

90% CL Limit on $\sin^2 2\theta_{13}$ → **about 0.001.**



Beta beams

- Idea introduced by Piero Zucchelli.
- Accelerate radioactive ions decaying via

  β^+ (^{18}Ne) or β^- (^{6}He).
- Because of Lorentz boost, the decay electron neutrinos or antineutrinos will be focused forward into a narrow beam.
- Look for: Appearance of $\bar{\nu}_\mu$ or ν_μ using CC interactions → μ^+ **or** μ^-
- Advantages:
- “Clean” beams with no intrinsic ν_μ component.
- Energy of beam tunable through acceleration of ions.

Eurisol : Nuclear Physics facility using Radioactive Ions (ISOLDE type).
Conceptual design study financed by European Union .
Synergy with beta-beams

Includes beta-beam studies

Study to be completed by 2010

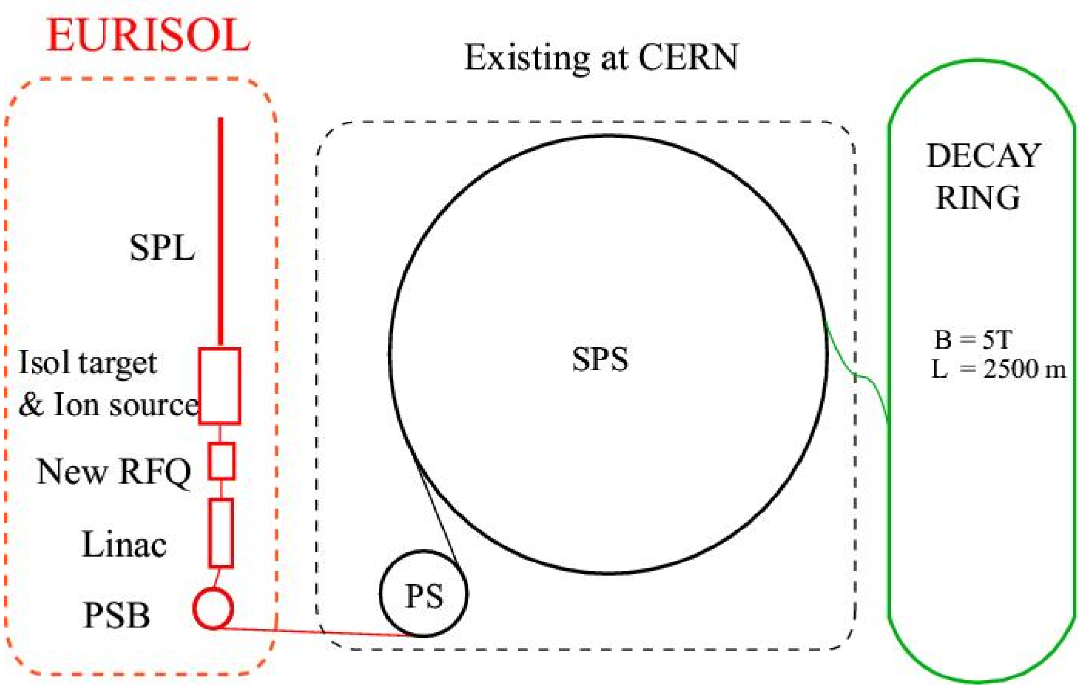
Beta beams

- Accelerate protons in SPL
- Impinge on appropriate source.
- Bunch resulting ions (atmospheric **ν's** !)
- Accelerate ions in PS and SPS.
- Store in decay ring. 8 bunches.
- $^{6}He \rightarrow {}^{6}Li + e^{-} + \nu_e$
- $^{18}Ne \rightarrow {}^{18}F + e^{+} + \bar{\nu}_e$ ← Production rate Still 20 times too low.Potential solution in sight

Stored together if $\gamma(^{18}Ne) = 1.67\ \gamma(^{6}He)$.

But could also be stored separately

Detector: Same as for SPL (Frejus)



Very attractive because:

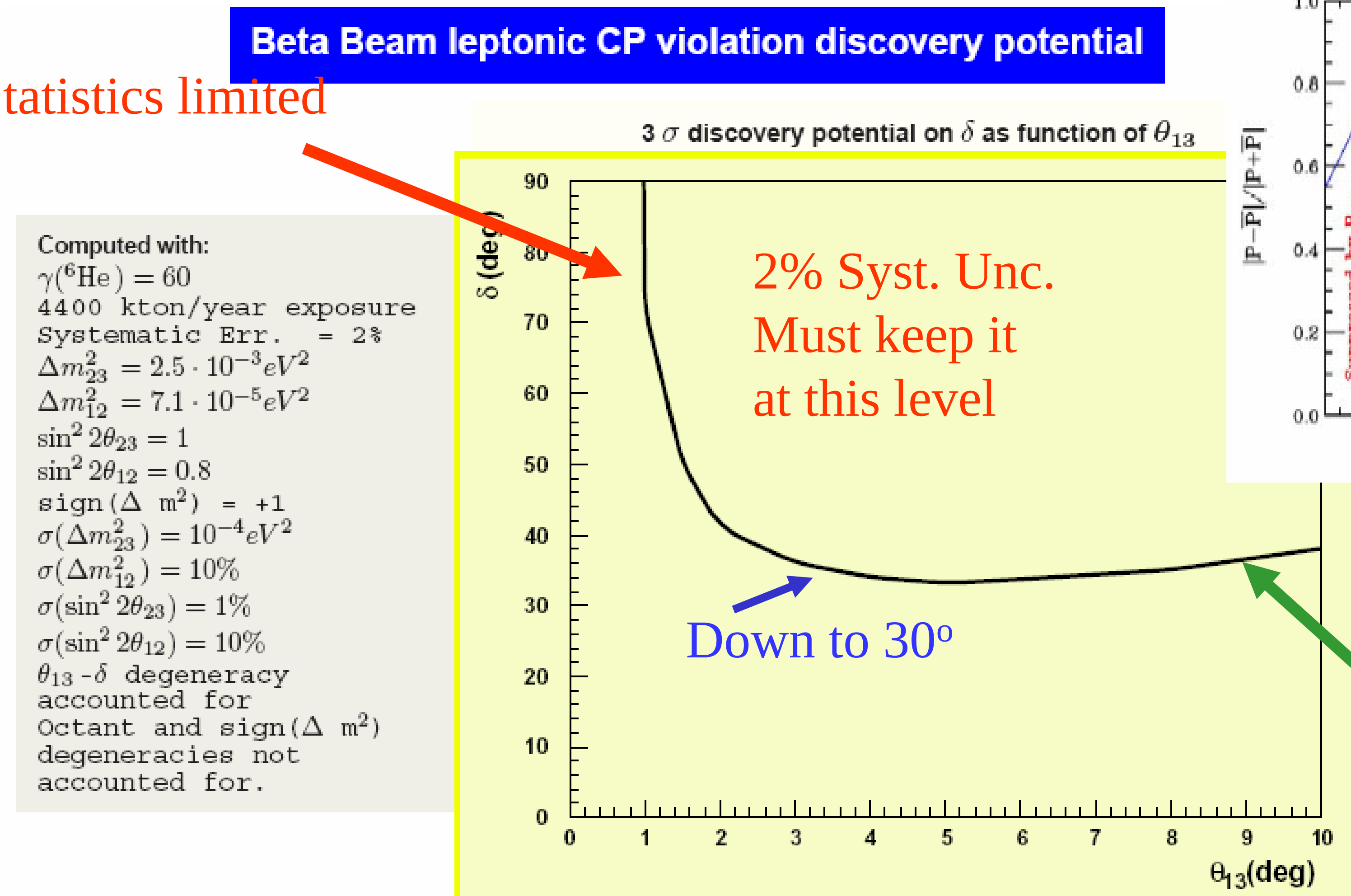
- Front end → Eurisol
- PS and SPS exist.

δ sensitivity for γ = 60,100

E_ν= (3 MeV) x γ = 200 – 500 MeV

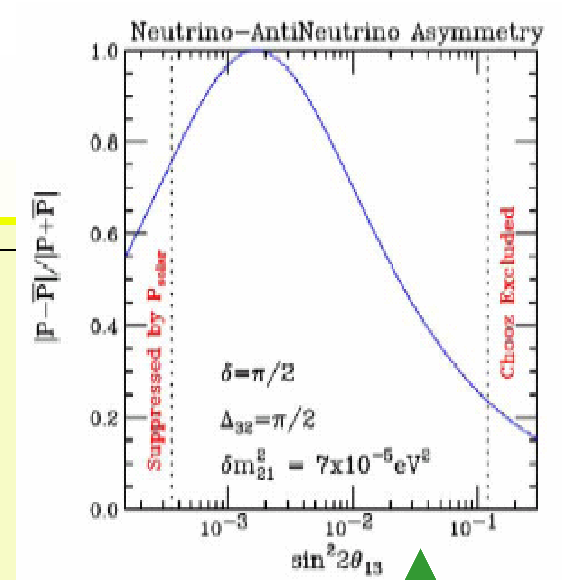
M. Mezzetto SPSC Villars

Statistics limited



2% Syst. Unc.
Must keep it
at this level

Down to 30º



CP violation Asymmetry decreases with increasing θ_{13}

2.9 x 10^{18} ^{6}He ions and 1.2 x 10^{18} ^{18}Ne ions per year decaying in straight sections

Optimize to higher energies

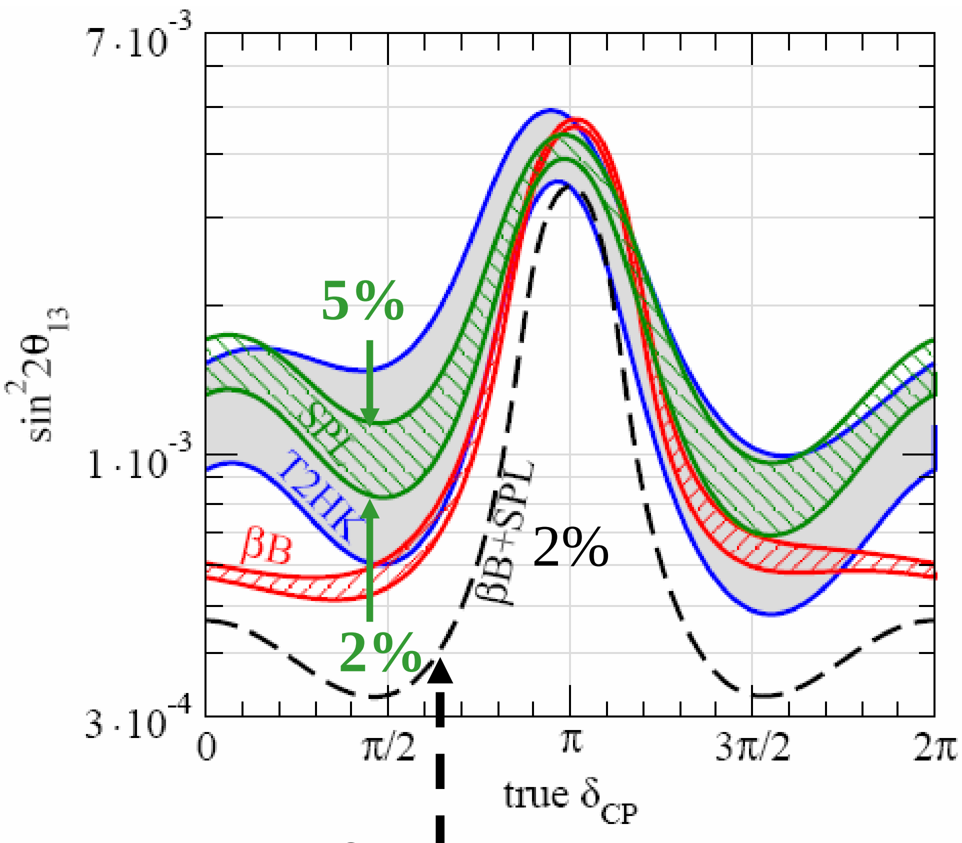
hep/ph/0503021 and M. Mezetto.

- Store ions separately.
- Optimize γ for a detector at Fréjus (**130km**). **γ (60,100) → γ (100-120,100-120)**
- **Minimum δ for which CP violation can be observed at 3σ goes down to 15^{o}.**

SPL, βbeam (γ=100), SPL+βbeam comparisons

- Mass: Each detector: 440 ktons ,
- Running time: SPL: 2 yrs ν + 8 yrs $\bar{\nu}$. Beta-beam: 5 yrs + 5 yrs.
- Systematics: 2% - 5%.

3σ discovery potential for $\sin^2 2\theta_{13}$



J-E. Campagne et al hep/ph0603172 v1

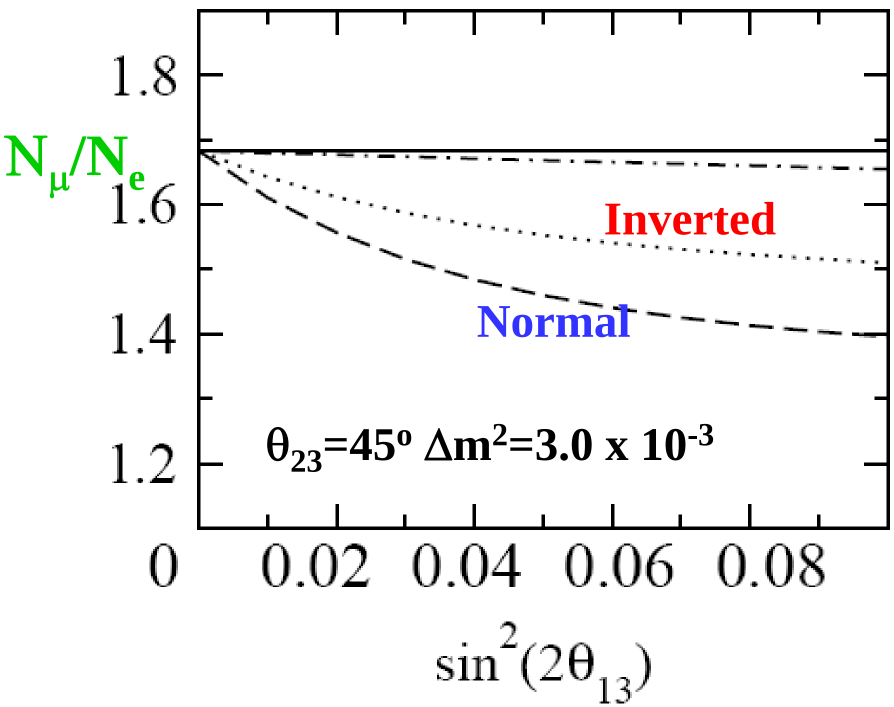
Combining β beam and SPL, in same detector
Improves sensitivity

Can the Mass Hierarchy be determined with SPL or β beams?

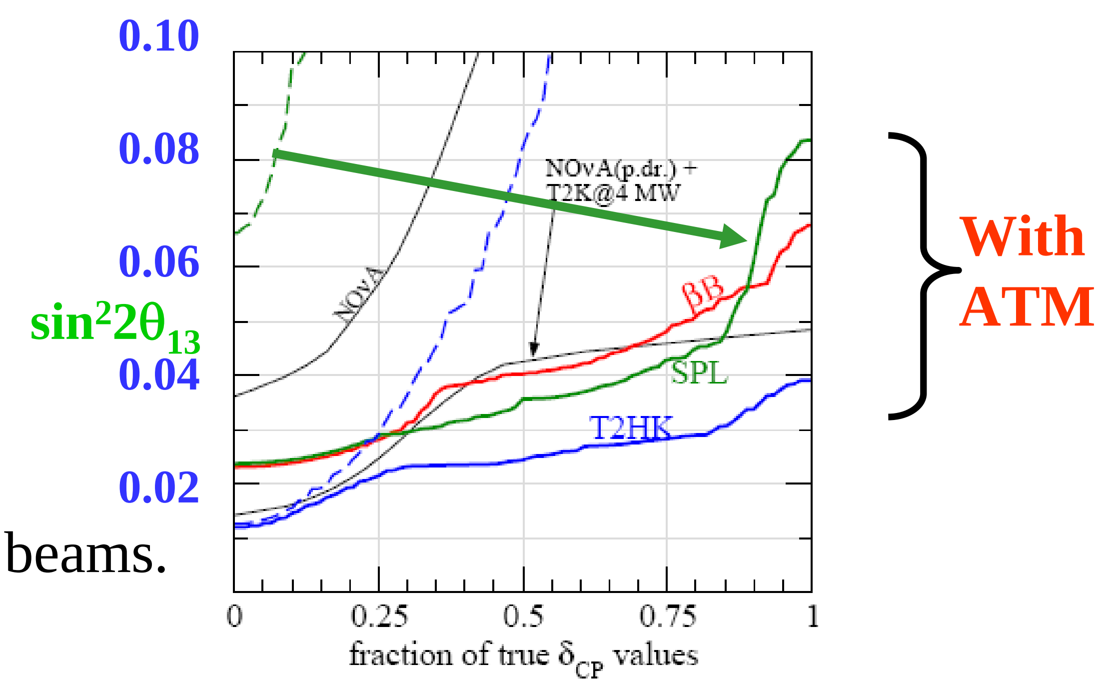
hep-ph/0305152
hep-ph/0603172

Too short a baseline, but…..

Multi-GeV (2-10 GeV)Atmospheric neutrinos (ATM) going through the core of the Earth (cos θ: 0.4-1.0) are particularly affected by Matter effects And are therefore sensitive to the Mass hierarchy.



Improves the fraction of δ_{CP} over which the mass hierarchy can be determined at 2 σ



Use ATM observed in MEMPHYS, HK in conjunction with SPL, beta and T2HK beams. Makes up for small matter effects due to short baseline of β beams.

Neutrino Factory

Being studied in context of International (Really is!) Scoping Study

Report by August 2006 → Basis for Conceptual Design Study → 2010

Store muons, look for $\nu_e \rightarrow \nu_\mu$ oscillations using ν's from their decay

$$\mu^+ \rightarrow e^+ \; \bar{\nu}_\mu \; \nu_e$$

interact giving μ^+

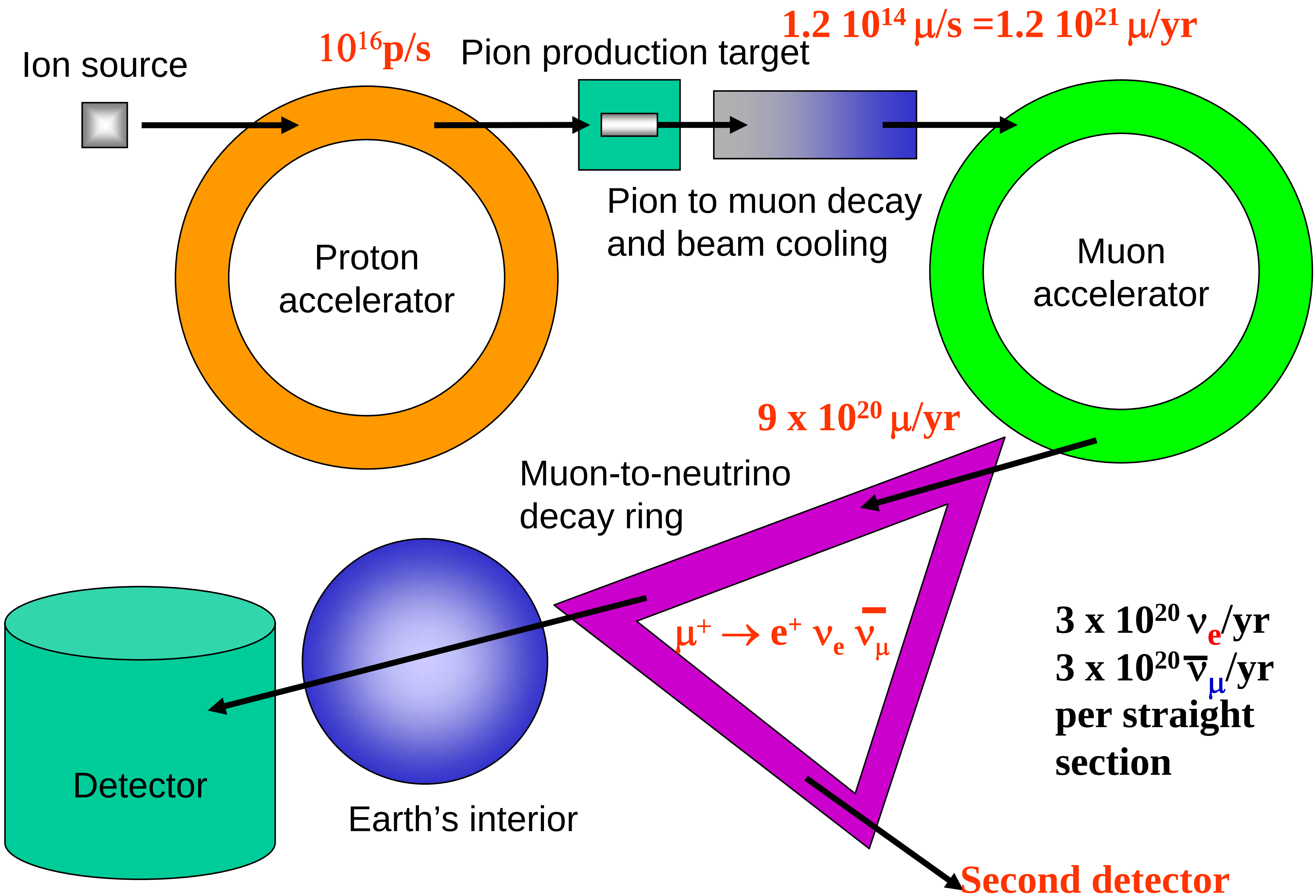
oscillate $\nu_e \rightarrow \nu_\mu$ interact giving μ^- WRONG SIGN MUON → **Golden channel**

Need to measure μ charge → Magnetic detector

Other channels:

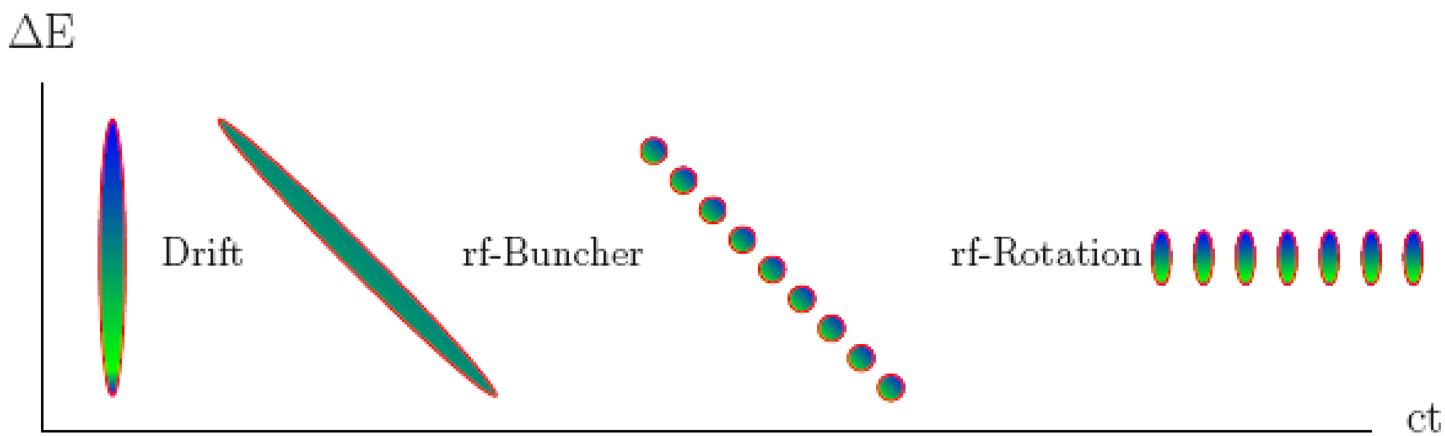
- **Platinum channel: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ T violation.**
- **Silver channel: $\nu_e \rightarrow \nu_\tau$ Resolve ambiguities.**

Simplified Neutrino Factory



Cooling

- **Longitudinal Cooling. → Phase rotation Neuffer scheme.**
  Capture multibunches in very high freq. RF.
  Rotate with RF frequency decreasing along tunnel



- **Transverse Cooling. Ionization. dE/dx + RF.**

Preliminary conclusions reached at April ISS meeting

Summary

- RF Frequency: Baseline is 201 MHz
- Phase Rotation: Baseline is Neuffer bunched beam rotation
- Phase Rotation: Baseline RMS bunch length $\approx$ 2 ns
- Amount of Cooling: Baseline is 50 m
- Target: Baseline is Liquid Mercury instead of solid
- Pion Collection: 20 T Solenoid instead of horn
- Repetition Rate: $\approx$ 50 (Hz)
- Proton bunch structure: $\approx$ 4 bunches spaced by $\approx$16 μsec
- Proton energy: 5-15 (GeV)
- Final acceleration: No decision yet
- Storage Ring: Choice is site dependent

Allows simultaneous collection of μ^+ and μ^-. Bunches separated by 400 ns → distinguish them through timing.

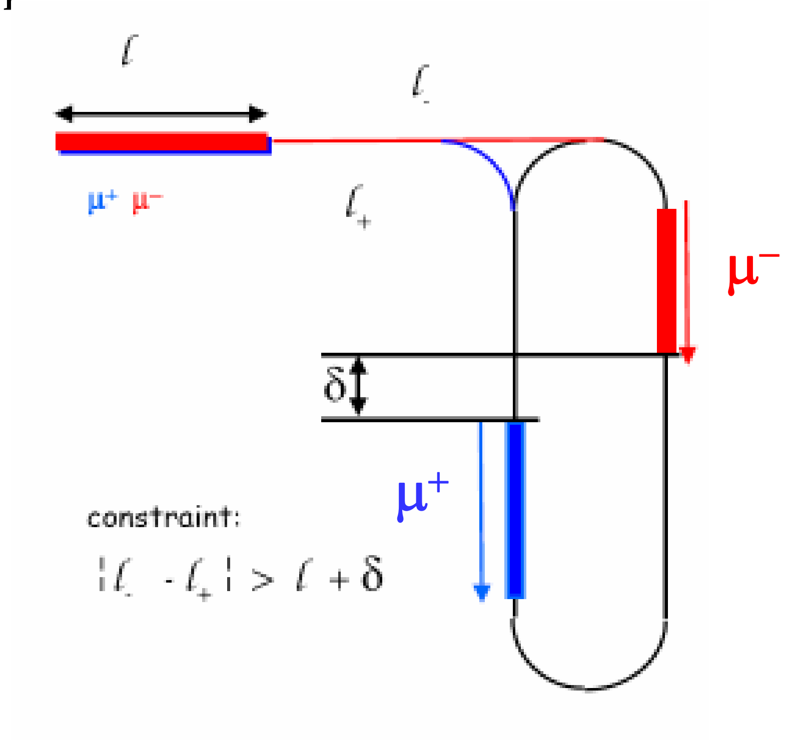
10^{21} ($\mu^+ + \mu^-$) decays per year
Half per straight section

Storage Ring Geometry

- **Race Track**

One ring can supply one detector

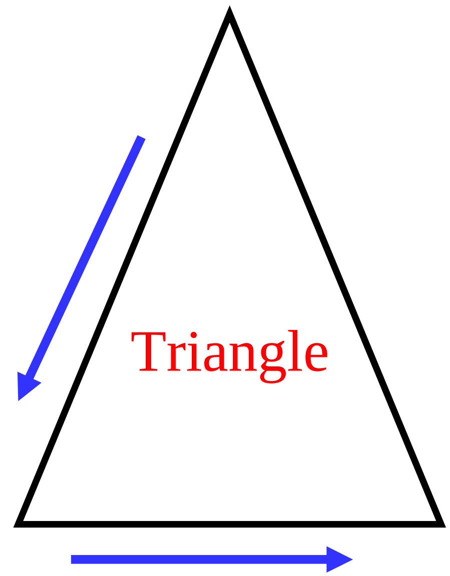
With both signs stored in opposite directions and separated by timing gaps.



If **two** detectors are active at once in two directions need **two** rings.

- **Triangle**

One ring can supply same sign to two detectors at different locations using two arms of the triangle.



If **both** signs are needed at once need **two** rings, again separating the two signs by timing.

Baseline → Mass hierarchy

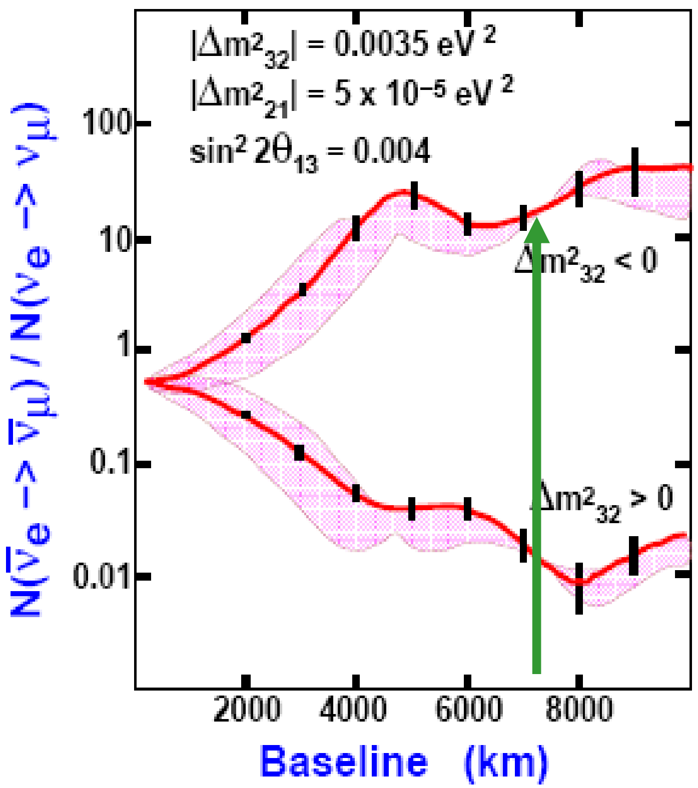
Introducing matter effects, at the first oscillation maximum:

$P(\nu_\mu - \nu_e)_{mat} = [1 \pm (2E/E_R)]\, P(\nu_\mu - \nu_e)_{vac}$ +- depends on the mass hierarchy.

with $E_R = [12\ \mathrm{GeV}][\Delta m^2_{32}/(2.5\times10^{-3})][2.8\ \mathrm{gm.cm^{-3}}/\rho] \sim$ **12 GeV**

Matter effects **grow** with energy.

The higher the energy, the longer the baseline needed to be at oscillation maximum.



- The difference between the two hierarchies grows with distance.
- At 7000 km the CP phase has no influence. (width of pink band shrinks to zero)

Magic distance

Long distance: Must understand earth density to understand matter effects.

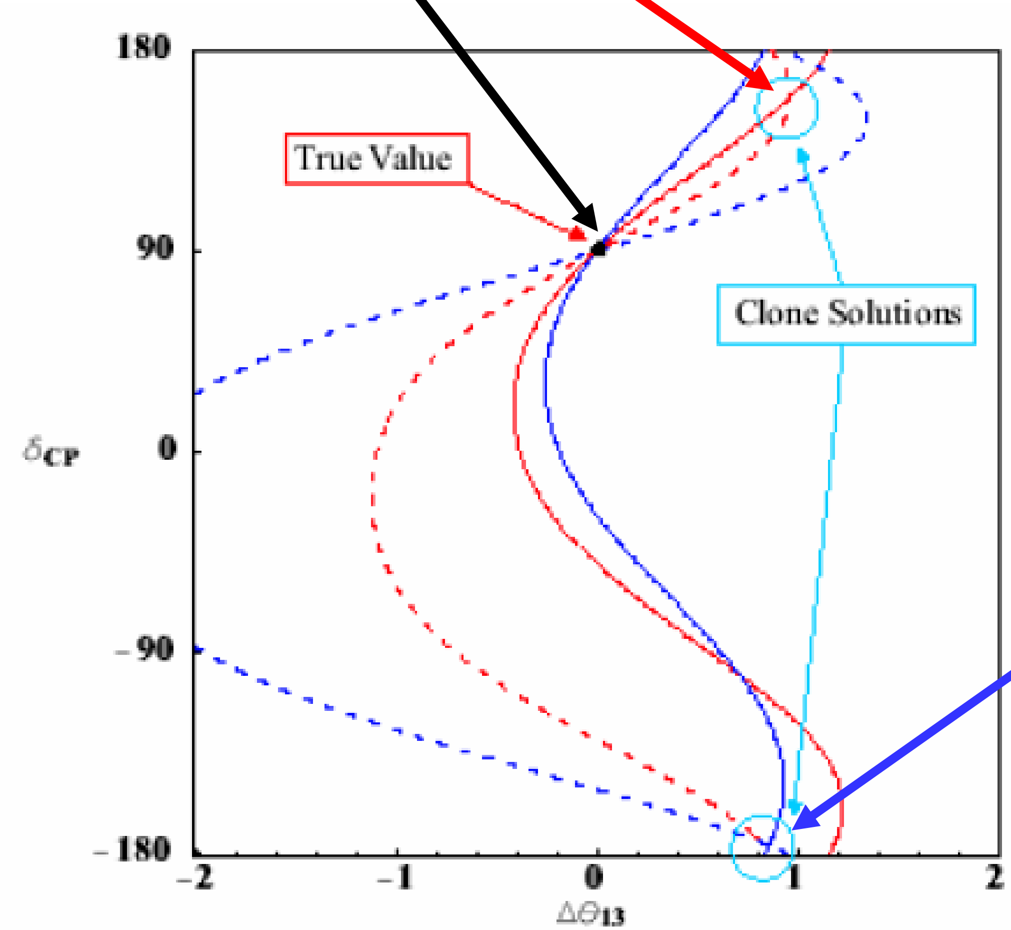
Can probably estimate density to ~ 2%.

How many baselines?

Single baseline, say 3000km, ν and $\bar{\nu}$ together
Yields true value +clone: Not enough.

3000km
ν
$\bar{\nu}$

730km
ν
$\bar{\nu}$



Second baseline,
Say 730km,
Clone in different
position

2 baselines together resolve ambiguity

Usefulness of the silver channel: $\nu_e \rightarrow \nu_\tau$

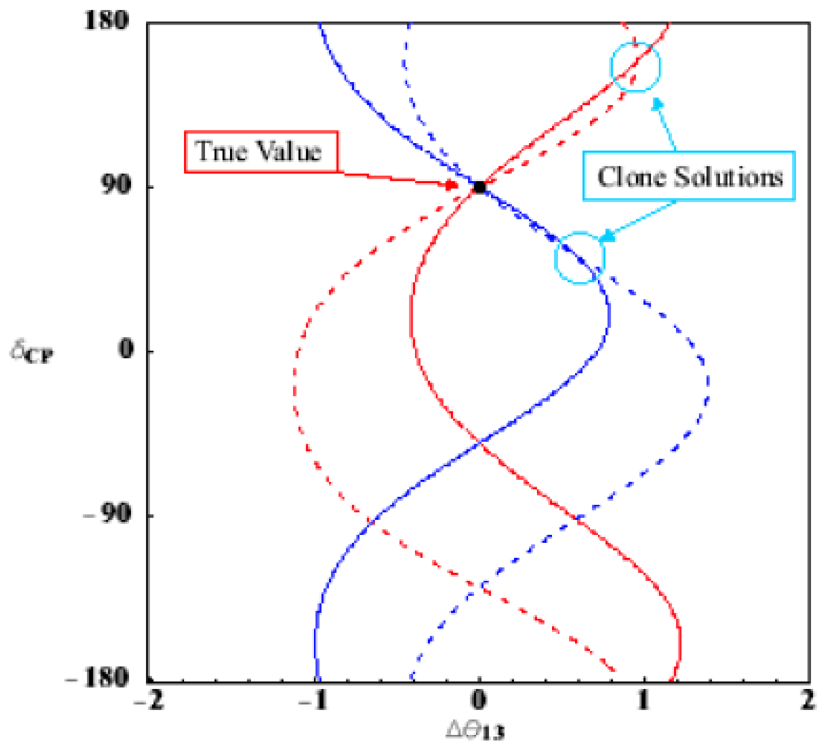
S. Rigolin, hep-ph/0407009 **D. Autiero et al. hep-ph/0305185**

$\nu_e \rightarrow \nu_\tau$ and $\nu_e \rightarrow \nu_\mu$ channels have "opposite" sign CP violation.

$\nu_e \rightarrow \nu_\mu$

— ν

- - - $\bar{\nu}$



$\nu_e \rightarrow \nu_\tau$

— ν

- - - $\bar{\nu}$

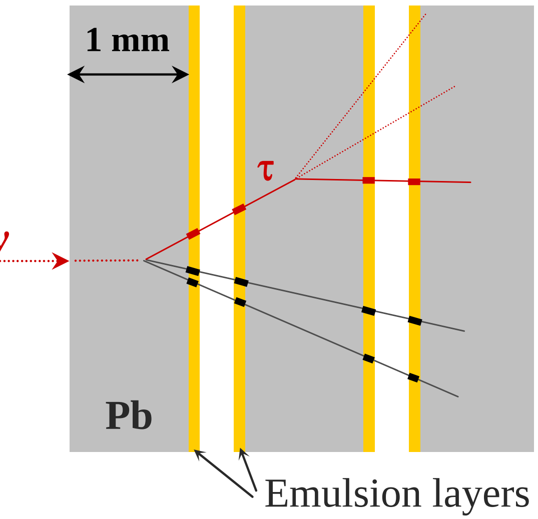
Clones for 2 reactions are also at different positions.

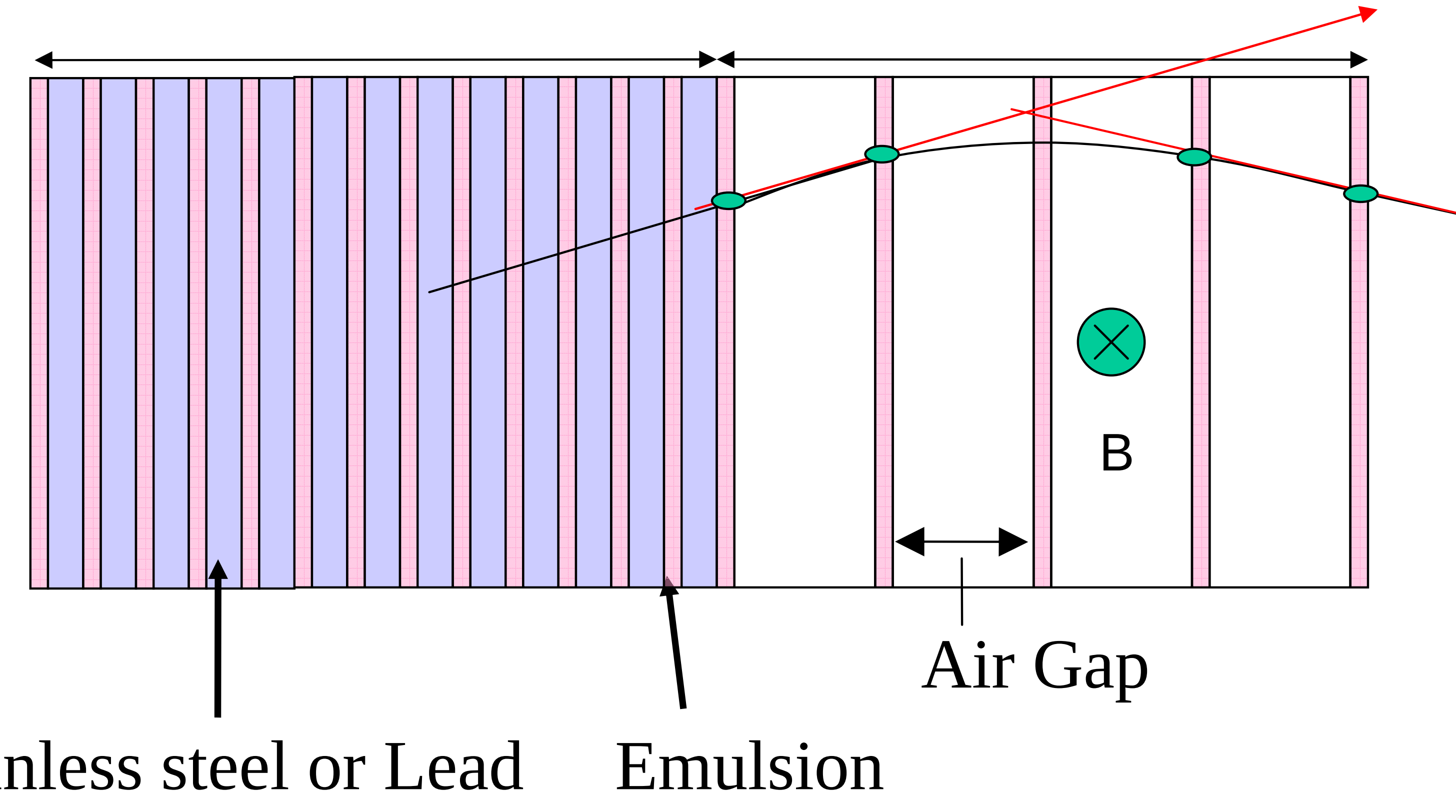
Alternative to 2 baselines

Needs fine grained detector for τ secondary vertex or kink:
DONUT/OPERA technology

DONUT/OPERA type target + Emulsion spectrometer

Must be placed in a magnet





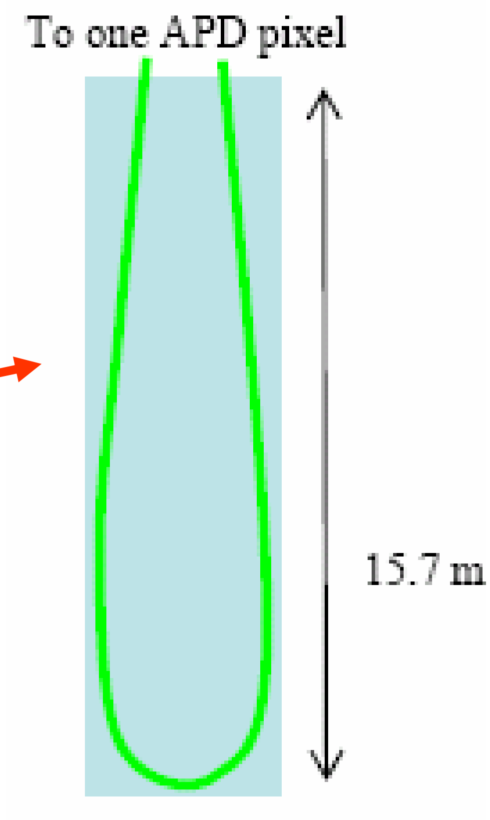
Can measure momentum of muons
and of some fraction of electrons
Identify τ using topology à la OPERA

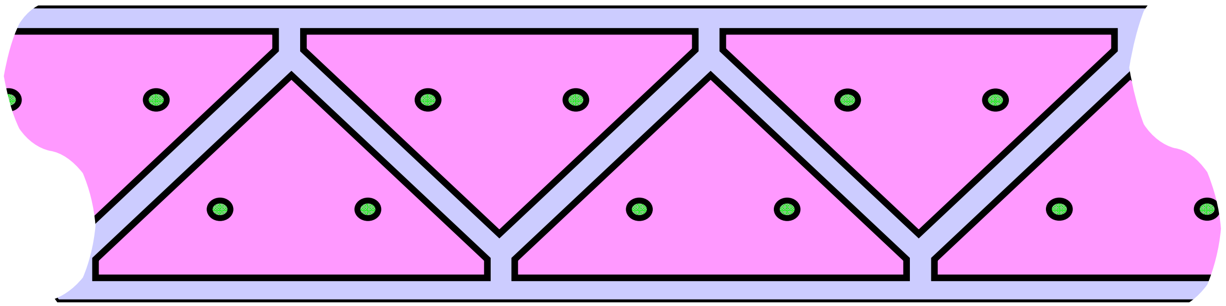
A Strawman Concept for a Nufact Magnetized Iron Tracker Detector

- 1 cm Iron sheets magnetized à la MINOS alternating with
- Planes of triangular

  4cm x 6 cm PVC tubes à la MINERVA.
- Filled with liquid scintillator
- Read by looped WLS fibres

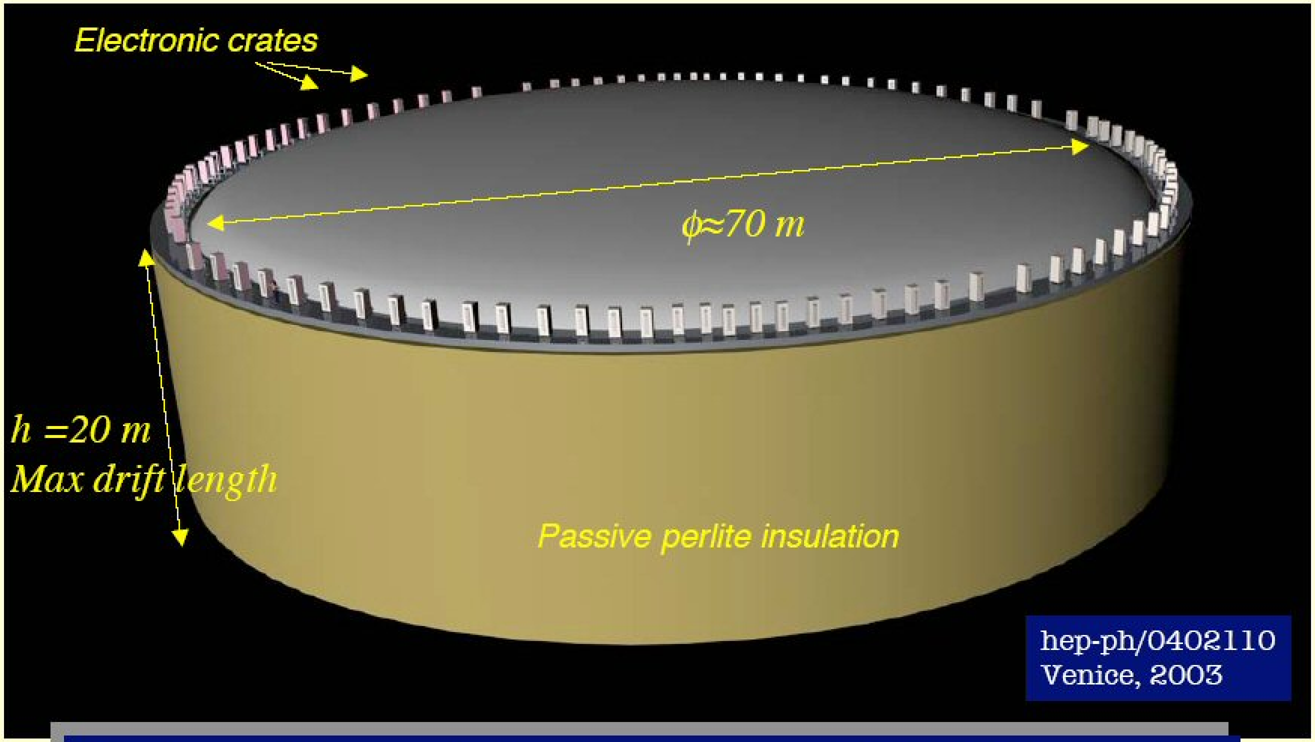
  connected to APD's à la NOvA





Giant Liquid Argon Charge Imaging Experiment

A 100 kton liquid Argon TPC detector



Single module cryo-tanker based on industrial LNG technology

A "general-purpose" detector for superbeams, beta-beams and neutrino factories with broad non-accelerator physics program (SN ν, p-decay, atm ν, …)

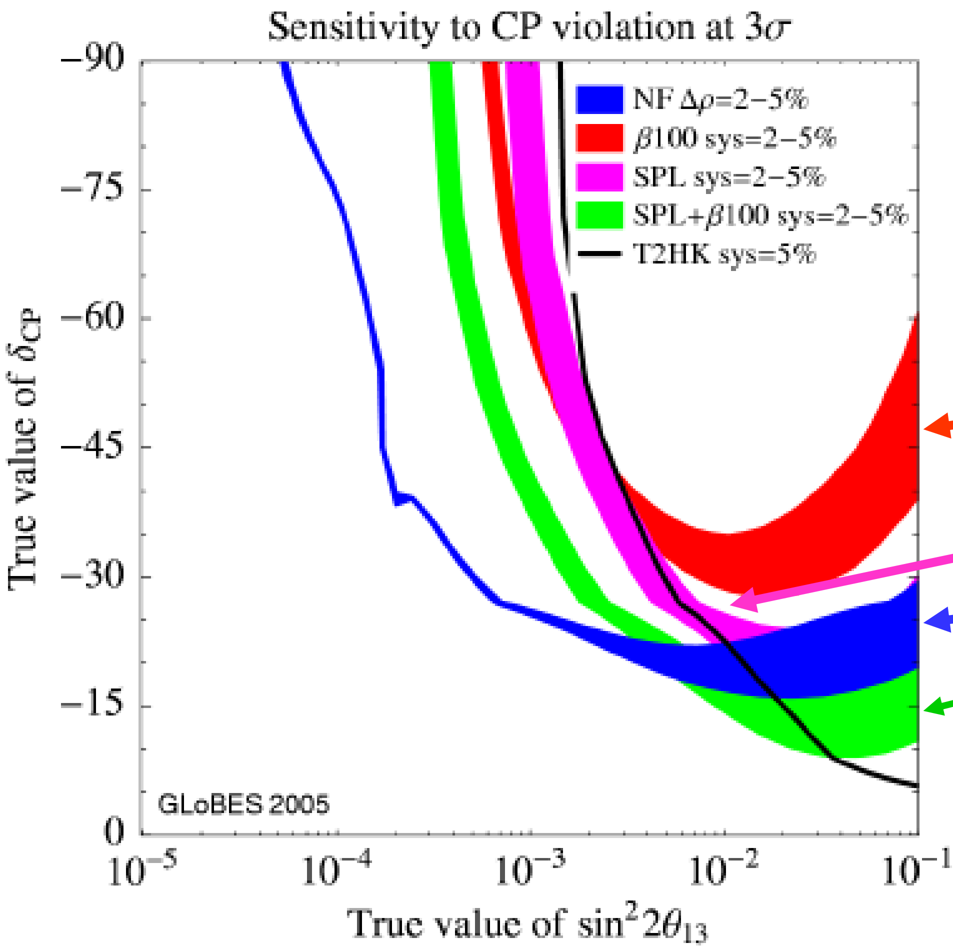
High efficiency Compared to Scintillators: x 2-3.

US-Europe Synergy ?

Impression was that magnet limited detector mass to 15 ktons.

A. Rubbia

Reach of beta-beams and ν Factory



Globes analysis shown for 1 quadrant
About the same for other 3 quadrants of CP phase.
Systematics: 2-5%. T2HK: 5%

β beams: γ = 100,100. Fréjus.

SPL

ν fact.: 7000km, 3000km

SPL + β beams 100,100

β-beams + SPL are more sensitive for $\sin^2 2\theta_{13} > 0.01$.
(needs confirmation: cuts used in analysis $E_\mu > 5$ GeV)

But below this value ν factory is more sensitive.

Comparison of beta-beam and ν factory

Beta-beam advantages.

- Synergy with Eurisol + existing PS,SPS (if at CERN)
- Clean ν_e and $\bar{\nu}_e$ beams.
- No need for analyzing magnet.
- Negligible matter effects.

Beta-beam disadvantages

- Low energy:
  - Cross sections not so well known,
  - Fermi motion
  - Atmospheric neutrinos background
- Silver channel energetically impossible
- Need of SPL:
  - Improve sensitivity
  - Measure ν_μ cross-sections

Comparison of beta-beam and ν factory II

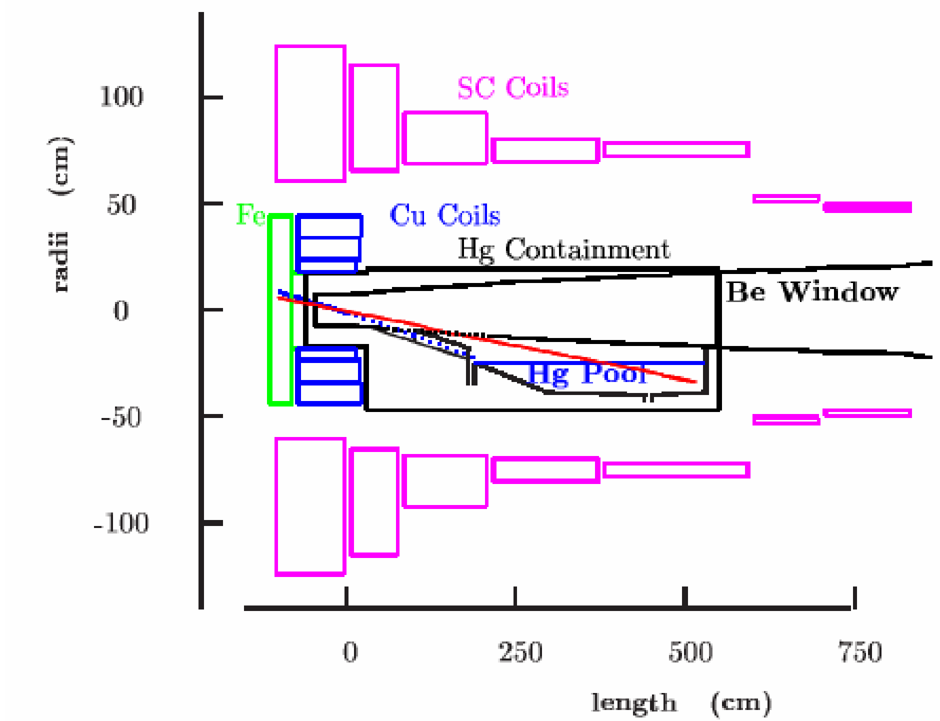
Advantages of Neutrino Factory

- Ultimate reach
- Presence of both ν_μ and ν_e in beam allows measurement of cross-sections in near detector
- Higher energies: better measured cross sections, no atmospheric neutrinos background

Disadvantages of Neutrino Factory.

- Technically more challenging
- Matter effects must be well understood.
- Need for a magnetic detector to separate signal from background

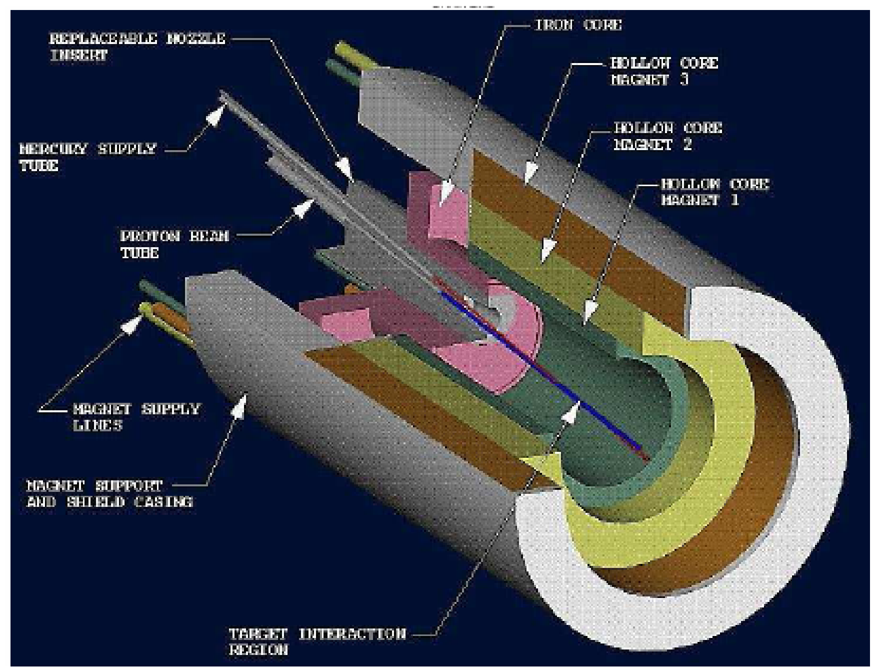
MERIT: Hg jet target tests at CERN PS



Test performed in magnetic field (15T)
To simulate actual conditions:
π collection solenoid

Proton intensity: 2 x 10^{13} protons/pulse at 24 GeV

1cm diameter jet at small angle(40 mrad) to beam to maximize overlap: 2 inter. lengths.

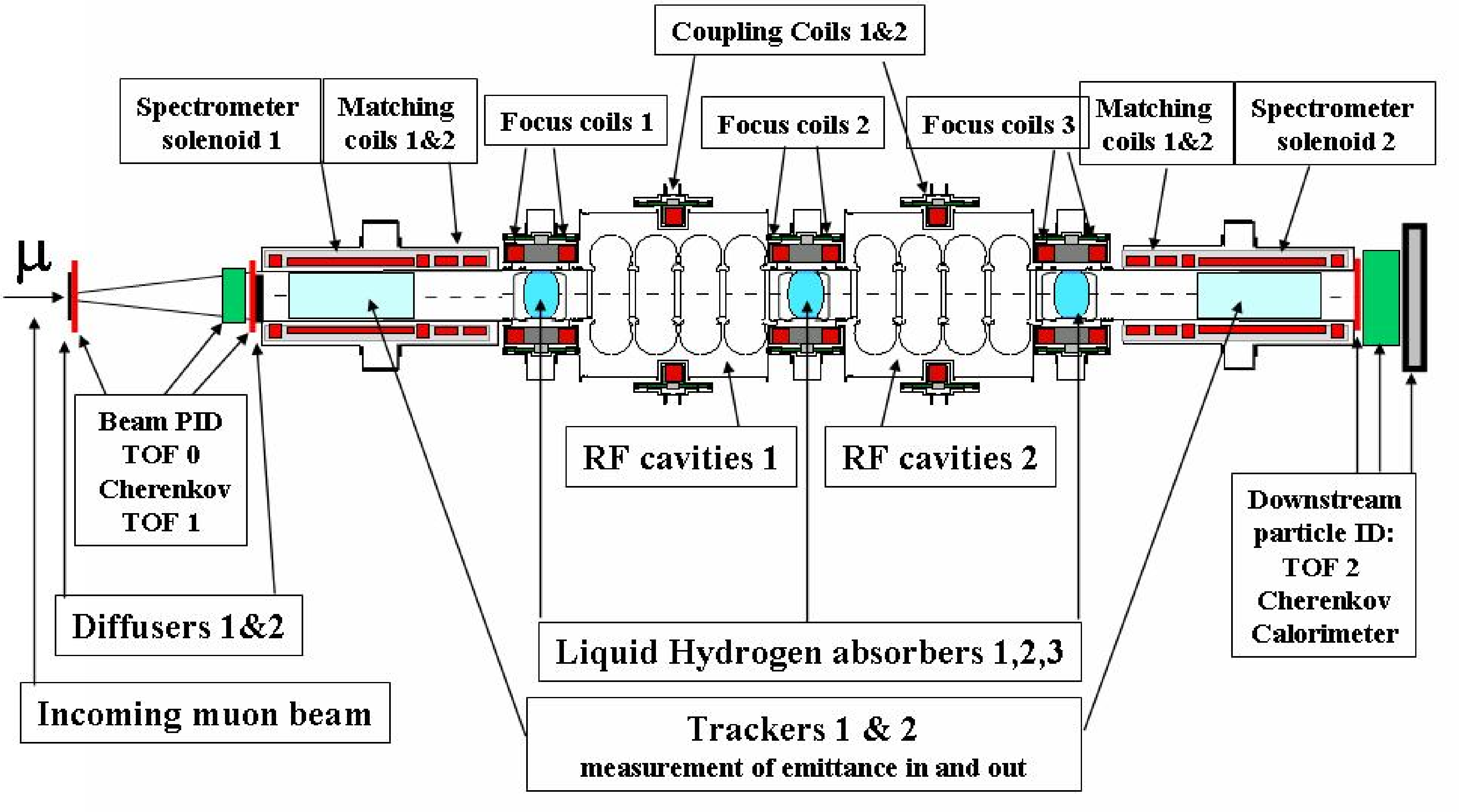


Aims: Proof of principle.
Jet dispersal.
Effect of field on jet flow and dispersal.

Scheduled to run in Spring 2007

MICE: Muon cooling experiment at RAL

Prove the feasibility of ionization cooling. Strong synergy with MUCOOL.



Start Spring 2007. Complete by 2009.

Time line

2010: A critical year in many ways.

- Possible ILC decision.
- CLIC possibilities.
- LHC results.
- Decision on LHC upgrades.
- Eurisol siting. CERN ?
- Possible first measurement of θ_{13}: MINOS, Double CHOOZ

It is essential to know which Neutrino Facility is favoured by that date.

Decision process and construction will take another 8-10years.

Its approval in this international context will be difficult.

But it’s definitely worth fighting for…!