Muon facilities: from Neutrino to Higgs Factories

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Outline: A three step scenario

1. Neutrino Factory (2010-2020?)
   - Precision neutrino oscillation physics
2. Precision muon colliders (2020-2030)
   - Precision study of the Higgs sector
3. A very High Energy muon collider (2030 and beyond)
   - New Physics beyond LHC energies

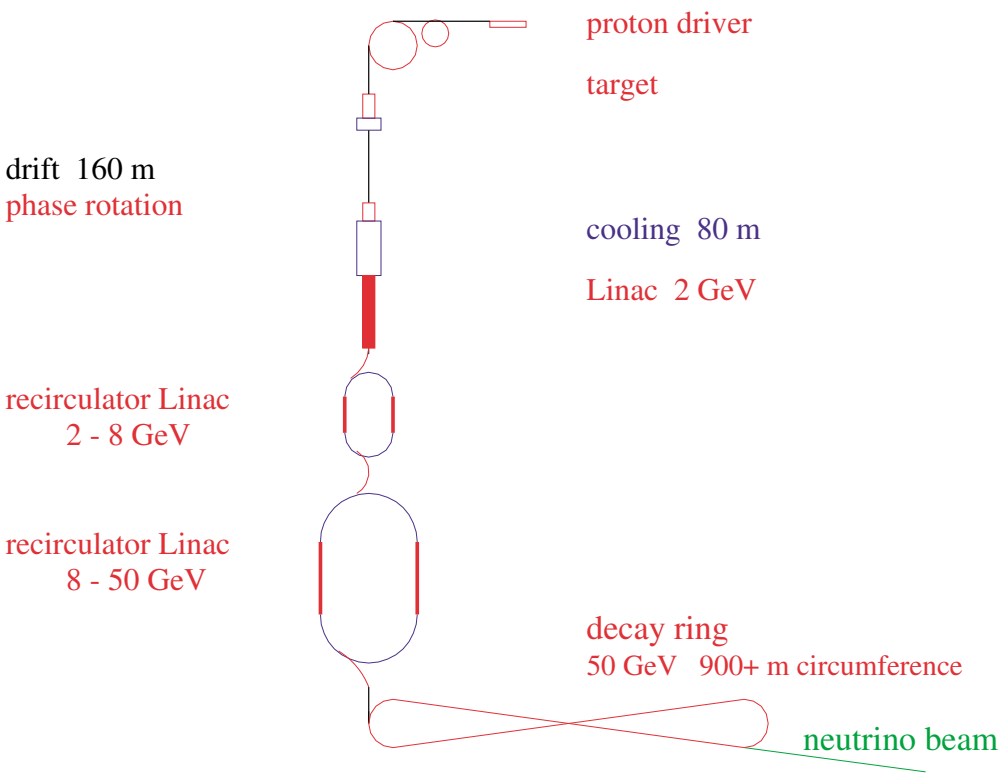
Step 1: The Neutrino Factory

- Recipe to make a Neutrino Factory

1. Hit a nuclear target with an intense proton beam
2. Allow the produced pions to decay
3. Cool the resulting muon beam
4. Accelerate the muons to the maximum energy possible
5. Store the accelerated muons in a storange ring with long straight sections (pointing in different directions)

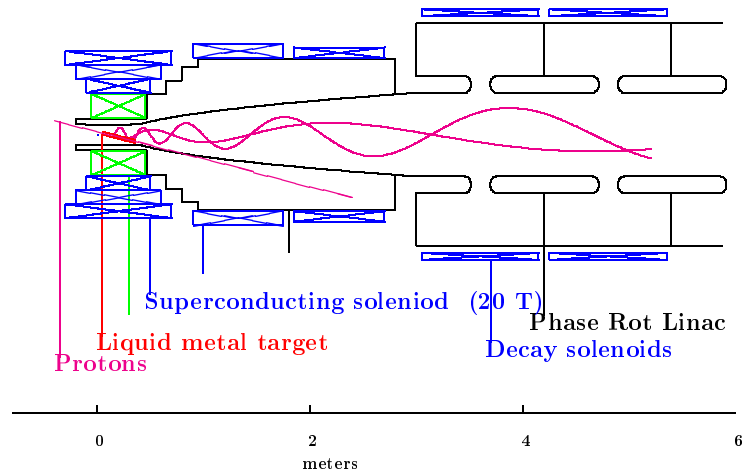
- Goal (physics) $\Longrightarrow$ $10^{21} - 10^{22} \mu$'s per year
- Maximize number of produced pions
  - Very intense proton driver
  - Very heavy material target
  - Very efficient pion capture scheme
- Minimize looses due to beam emittance
  - Phase Rotation
  - Ionization Cooling

The Neutrino Factory



Pion Production

- If $10^{21}\mu$'s per year required
  - at least $10^{22}\pi$'s per year must be produced
  - assuming optimistically 10 % efficiency after π decay & μ cooling, acceleration and storage
- How do you produce a $10^{22}\pi$'s per year?
  1. Locate Heavy (Hg) Thick (24 cm) Target inside a solenoid magnet
  2. Solenoid has very intense (20 T) magnetic field
  3. And very large $r \sim 10\ cm$ acceptance
  4. After solenoid install RF cavities to accelerate selected phase space pions and a decay channel



Proton Beam Power

- Pion rate depends on proton Beam Power

$$\Pi = \frac{N}{t} E \; = proton\ current \times energy$$

- N = # protons per pulse (CERN-PS =10^{13})
- t = accelerator repetition rate (CERN-PS =0.5 Hz)
- E = proton energy (CERN-PS =20 GeV)

$$\Pi = 10^{13}\ ppp \times 0,5 Hz \times 20\ GeV = 10^{14}\ p\ GeV/s = 0.016\ MW$$

- Thus in one year ($10^7\ s$) $\Longrightarrow$ CERN-PS $\Pi = 10^{21}\ p\ GeV$

Pion Yields

- Pion Yield per proton · GeV

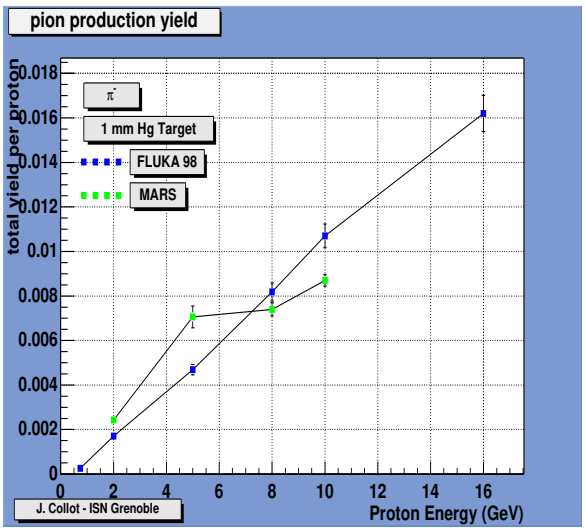
$$\pi/p \cdot GeV = \xi_\pi L(1 - e^{-L/\Lambda} \int_0^{P_t} dp_t \int_{y_1}^{y_2} \frac{\partial^2 N_\pi}{\partial p_t \partial y} dy$$

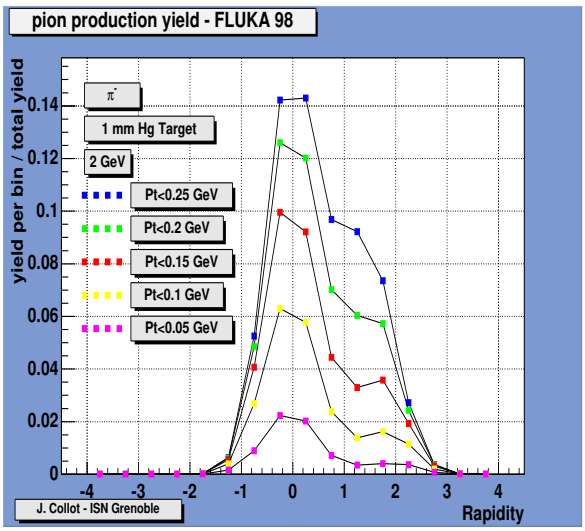
- $\xi_\pi \Longrightarrow$ pion yield per proton · GeV and unit length
  - $2 \times 10^{-3} \pi/p\, mm^{-1}$ for 2 GeV protons in Hg
- $L \Longrightarrow$ target length
  - 24 cm = 2Λ
- $(1 - e^{-L/\Lambda}) \Longrightarrow$ absortion due to reinteraction
  - $(1 - e^{-2}) = 0.86$
- $\int_0^{P_t} dp_t \int_{y_1}^{y_2} \frac{\partial^2 N_\pi}{\partial p_t \partial y} dy \Longrightarrow$ acceptance on $p_t \times y$
  - (10% for $p_t < 220\ MeV, 1 < y < 1.5$)

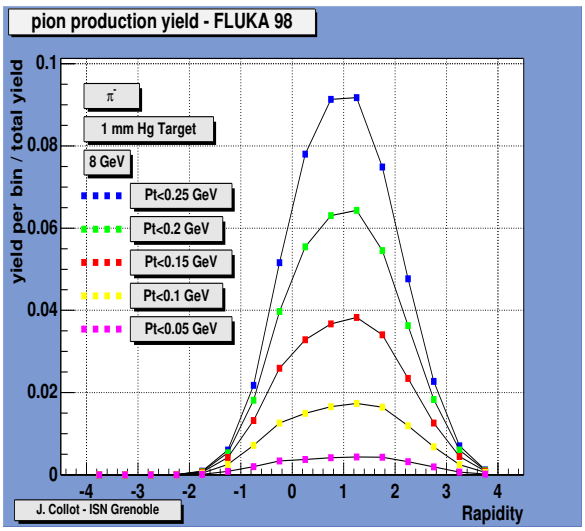
$$\pi/p \cdot GeV = 2\ 10^{-3} \times 24\ 10^{1} \times 9\ 10^{-1} \times 10^{-1} = 0.04$$

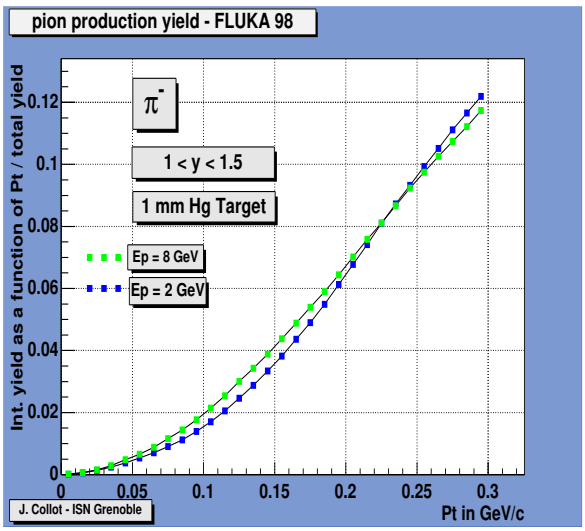
- Needed $10^{21} \mu \rightarrow 10^{22} \pi \rightarrow 2.5\ 10^{23} p \cdot GeV$ on target in one year $\Longrightarrow$ 250 times the PS power

Pion Yields


pion production yield
total yield per proton
π⁻
1 mm Hg Target
FLUKA 98
MARS
J. Collot - ISN Grenoble
Proton Energy (GeV)


pion production yield - FLUKA 98
yield per bin / total yield
π⁻
1 mm Hg Target
2 GeV
Pt<0.25 GeV
Pt<0.2 GeV
Pt<0.15 GeV
Pt<0.1 GeV
Pt<0.05 GeV
J. Collot - ISN Grenoble
Rapidity


pion production yield - FLUKA 98
yield per bin / total yield
π⁻
1 mm Hg Target
8 GeV
Pt<0.25 GeV
Pt<0.2 GeV
Pt<0.15 GeV
Pt<0.1 GeV
Pt<0.05 GeV
J. Collot - ISN Grenoble
Rapidity


pion production yield - FLUKA 98
Int. yield as a function of Pt / total yield
π⁻
1 < y < 1.5
1 mm Hg Target
Ep = 8 GeV
Ep = 2 GeV
J. Collot - ISN Grenoble
Pt in GeV/c

Phase Rotation & Cooling

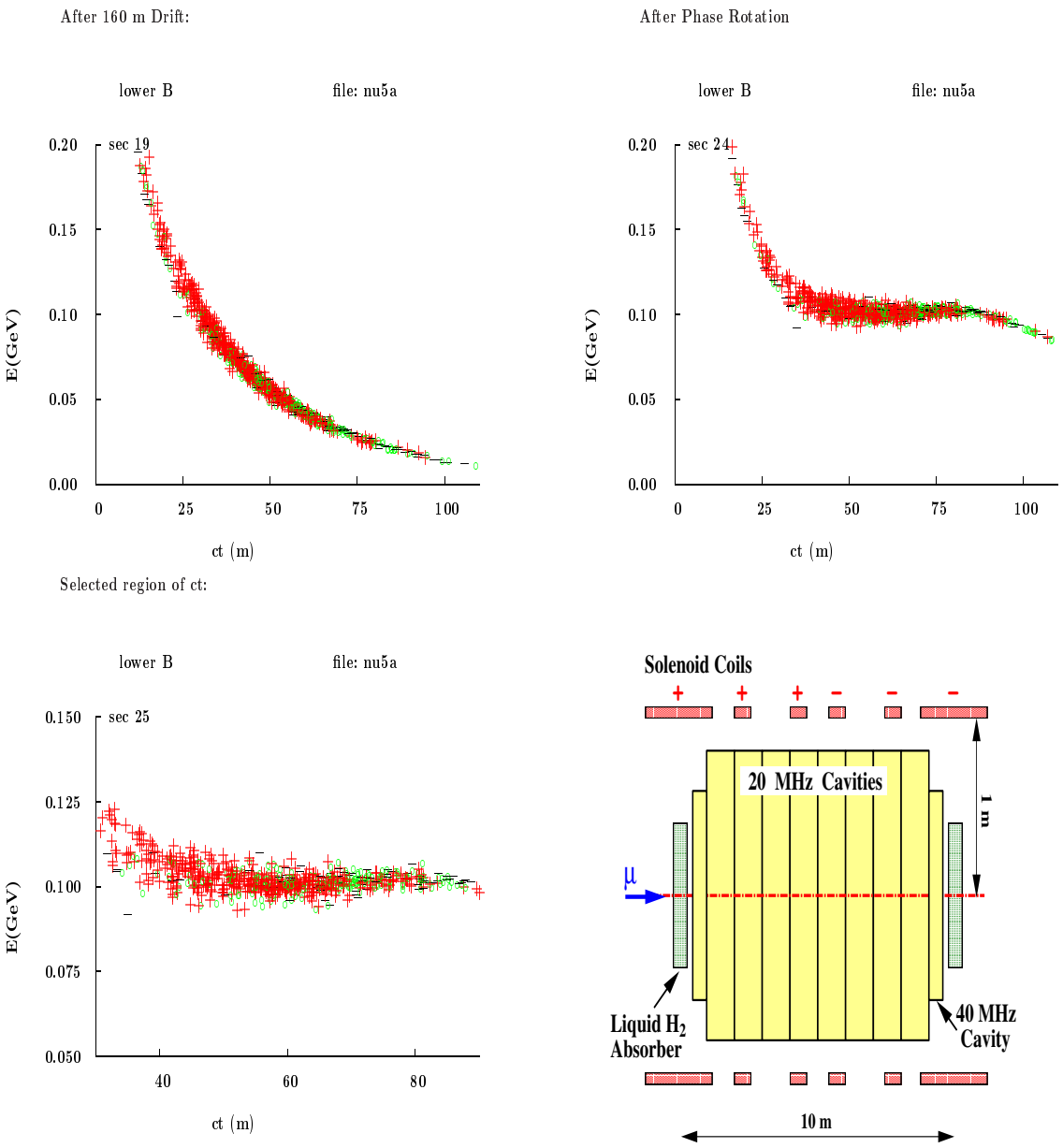


Fig. 2. Schematic of a 10 m long cooling cell. Fifteen cells are required for the cooling scheme discussed in the text.

Neutrino Oscillations

Atmospheric $\oplus$ Solar data require three ν mixing

$$\Delta m^2_{atmos} \equiv \Delta m^2_{23} \quad \gg \quad \Delta m^2_{solar} \equiv \Delta m^2_{12}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = V_{CKM} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$V_{CKM} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Oscillation experiments are in principle sensitive to the mass differences: $\Delta m^2_{12}, \Delta m^2_{23}$, the three mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$ and the CP-odd phase δ.

If $\theta_{13} = 0 \Longrightarrow$atmospheric and solar oscillations become 2 independent two–family mixings:

- Atmospheric data determine Δm^2_{23} and $\sin^2 2\theta_{13}$:

$\Delta m^2_{23} = \mathcal{O}(10^{-3}\ \text{eV}^2)$	$\sin^2 2\theta_{23} \sim 1$

- Solar data determine Δm^2_{12} and $\sin^2 2\theta_{12}$:

LMA-MSW	$\Delta m^2_{12} \sim \mathcal{O}(10^{-5}\text{-}10^{-4})\ \text{eV}^2$	$\sin^2 2\theta_{12} \sim 1$
SMA-MSW	$\Delta m^2_{12} \sim \mathcal{O}(10^{-6})\ \text{eV}^2$	$\sin^2 2\theta_{12} \sim 10^{-3}$
VO	$\Delta m^2_{12} \sim \mathcal{O}(10^{-10})\ \text{eV}^2$	$\sin^2 2\theta_{12} \sim 1$

The complementary information from Reactor experiments (Chooz) indicate

$$\sin\theta_{13} < 5 \times 10^{-2}$$

What will be known at the time of NuF ?

Evidence of oscillations confirmed and further constrained by ongoing and planned experiments:

- Solar and Reactors: θ_{12}, Δm^2_{12}

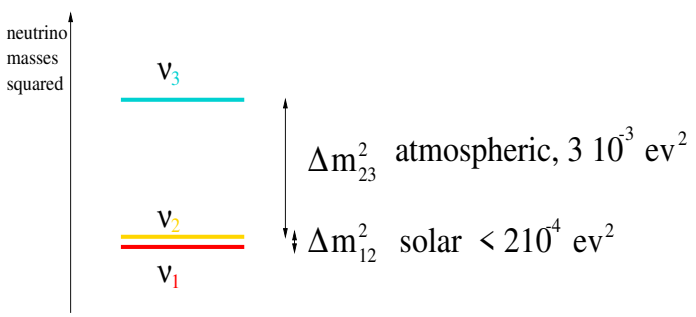
  $\rightarrow$ SuperK, Borexino, SNO, KAMLAND

- Atmospheric LBL accelerator experiments: θ_{23}, $|\Delta m^2_{23}|$

  $\rightarrow$ K2K, MINOS, OPERA, ICANOE, MiniBoone

Need for more precise ν experiments (Neutrino Factory) to measure

- The angle θ_{13}: bridge between the atmospheric and solar neutrino realms
- The sign of $\Delta m^2_{23} \Longrightarrow$pattern of neutrino spectrum:



- The CP-odd phase $\delta \Longrightarrow$Leptonic CP-violation !

Neutrino Beams from μ decays

Neutrino beams from μ decays have several advantages over conventional beams (e.g. CERN-SPS) from $\pi^{\pm}, K^{\pm}, K_L$ decays:

- Contain only two ν flavours with opposite C:

$$
\begin{aligned}
\mu^- \rightarrow e^- \;\; \nu_\mu \;\; \bar{\nu}_e \,; & \\
\bar{\nu}_e \rightarrow \bar{\nu}_e \rightarrow e^+ \;\; & \text{disappearance}, \\
\bar{\nu}_e \rightarrow \bar{\nu}_\mu \rightarrow \mu^+ \;\; & \underline{\text{appearance}}, \\
\bar{\nu}_e \rightarrow \bar{\nu}_\tau \rightarrow \tau^+ \;\; & \underline{\text{appearance}} \;\; (\tau^+ \rightarrow \mu^+ ;\; e^+) \,, \\
\nu_\mu \rightarrow \nu_\mu \rightarrow \mu^- \;\; & \text{disappearance}, \\
\nu_\mu \rightarrow \nu_e \rightarrow e^- \;\; & \underline{\text{appearance}}, \\
\nu_\mu \rightarrow \nu_\tau \rightarrow \tau^- \;\; & \underline{\text{appearance}} \;\; (\tau^- \rightarrow \mu^- ; \; e^-)
\end{aligned}
$$

- The fluxes are well known:

$$\frac{dN_{\nu_\mu,\bar{\nu}_\mu}}{dy\,dS}\,|_{\theta\simeq 0}\simeq \frac{E_\mu^2\,n_\mu}{\pi\,m_\mu^2\,L^2}\,2\,y^2\,(3-2y)\Theta(y)\,\Theta(1-y)$$

$$\frac{dN_{\nu_e,\bar{\nu}_e}}{dy\,dS}\,|_{\theta\simeq 0}\simeq \frac{E_\mu^2\,n_\mu}{\pi\,m_\mu^2\,L^2}\,12\,y^2\,(1-y)\,\Theta(y)\,\Theta(1-y)$$

  with $y \equiv E_\nu/E_\mu$.

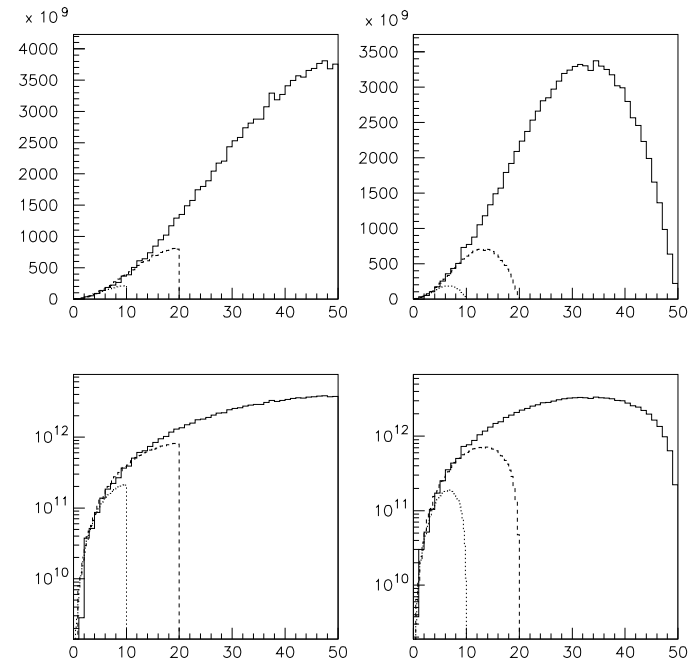
- Fluxes grow like E_ν^2:

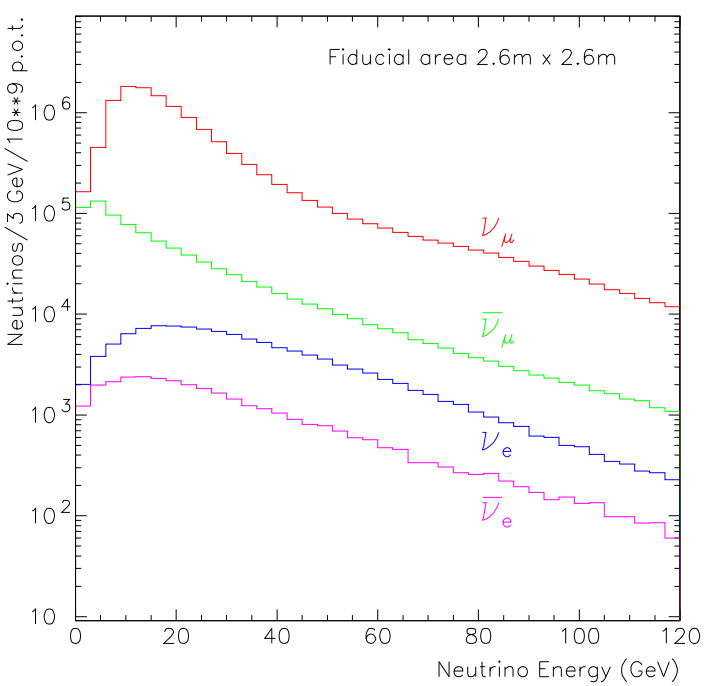
$$N_{CC} \sim Flux \times \sigma_\nu \sim \frac{E_\nu^3}{L^2}$$

$$N_{osc} \sim Flux \times \sigma_\nu \times P_{osc} \sim \frac{E_\nu^3}{L^2}\sin^2\frac{L}{E_\nu} \sim E_\nu$$

- Number of oscillated events increase linearly with the beam energy !
- Optimal beam energy is as large as possible: consesus to reach $E_\mu = 50GeV$

Neutrino Fluxes



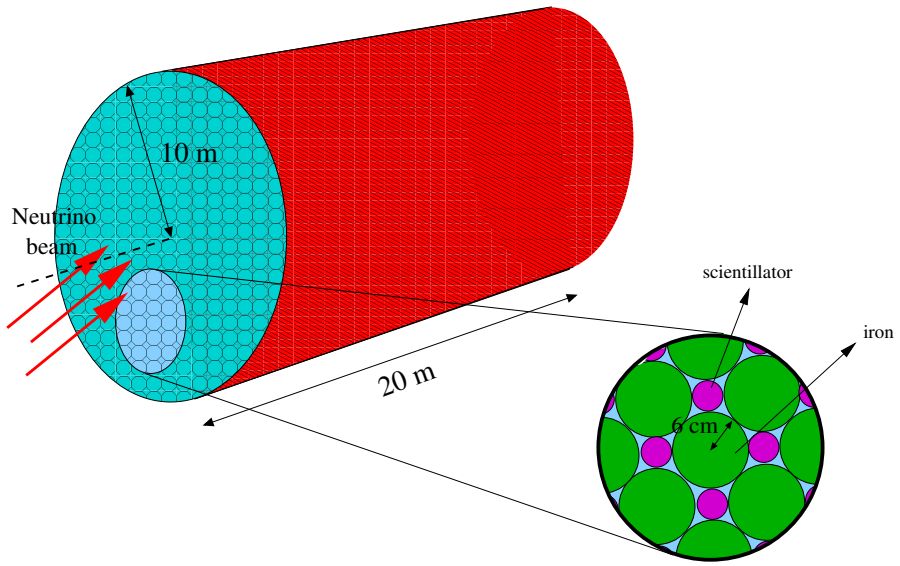


Experimental Signatures

- Appearance of wrong sign muons: $\nu_e \rightarrow \nu_\mu$
  - Most sensitive to the precision parameters: θ_{13} , δ, sign of Δm^2_{23}
  - Requires a detector able to measure final muon charge $\Longrightarrow$ Very Massive Magnetized Calorimeter
- Appearance of taus: $\nu_\mu \rightarrow \nu_\tau$ and $\bar{\nu}_e \rightarrow \bar{\nu}_\tau$
  - $\nu_\mu \rightarrow \nu_\tau$ most sensitive to θ_{23} and Δm^2_{23}
  - $\nu_e \rightarrow \nu_\tau$ most sensitive to precision parameters, but not competitive with wrong sign muon signals (τ detectors cannot be very massive).
  - It is hard to measure the charge of the τ.
- Disappearance of right sign muons: $\nu_\mu \rightarrow \nu_\mu$
  - Most sensitive to θ_{23} , Δm^2_{23}
  - Very Massive Calorimeter ideal for the measurement $\Longrightarrow$ competitive with τ appearance measurements

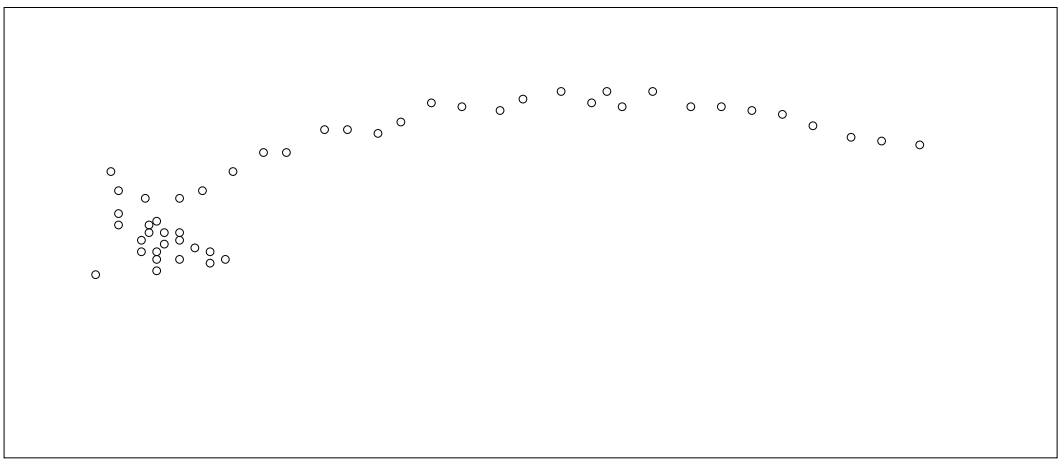
Large Magnetized Calorimeter

- Cylindrical symmetry. $R = 10m, L = 20m$
- $6cm$ thick iron rods intersped with $2cm$ thick scintillators longitudinally segmented
- $40Kton$ fiducial mass
- 1 Tesla magnetic field
- Hadronic shower energy and angular resolution "a la Minos"



Detection of neutrino interactions in a LMC

- ν_μ Charged Currents
  - $\mu \Longrightarrow$ Penetrating long track 10 m long or more
  - hadronic shower $\Longrightarrow$ about 1 m.
- ν_μ Neutral Currents
  - Only a hadronic shower
- ν_e Charged current
  - $e \Longrightarrow$ electromagnetic shower: most of the time not disentangled from hadronic shower
  - a ν_e CC event looks similar to a NC



Wrong Sign Muons

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

$$\bar{\nu}_\mu + N \longrightarrow \mu^+ + X \qquad \text{CC}$$

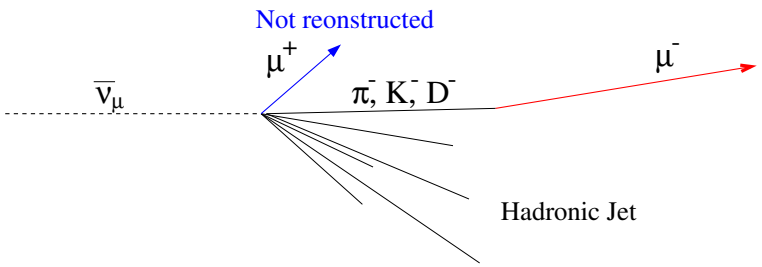
right sign muon

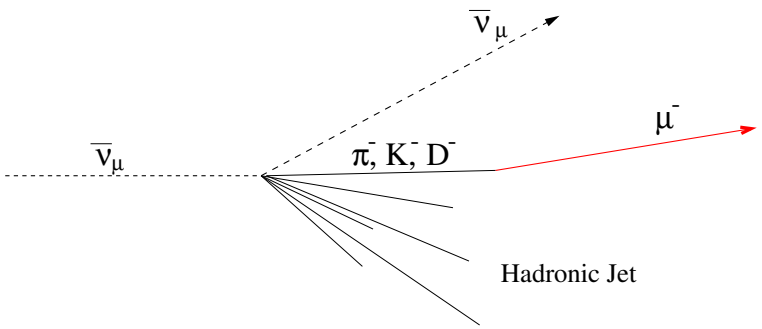
$$\bar{\nu}_\mu + N \longrightarrow \bar{\nu}_\mu + X \qquad \text{NC}$$

$$\nu_e \overset{\text{osc}}{\sim} \nu_\mu$$

$$\nu_\mu + N \longrightarrow \mu^- + X \qquad \text{SIGNAL}$$

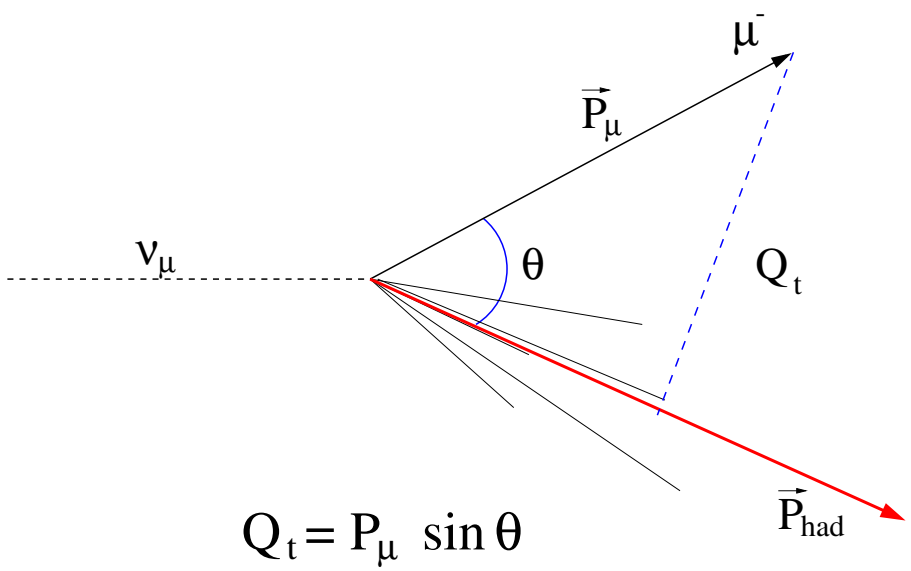
wrong sign muon





Analysis

- The detector provides information about:
  - The momentum of the μ (fit or dE/dx) $\Longrightarrow \vec{P}_\mu$
  - The energy and direction of the hadron shower (calorimetry) $\Longrightarrow$ E_{had}, θ_{had}
- Analysis performed in terms of two variables:
  - The magnitude momentum of the muon $\Longrightarrow |\vec{P}_\mu|$
  - The isolation of $\vec{P}_\mu$ from the hadronic vector: $\Longrightarrow Q_t$



Wrong Sign Muon Search Analysis

- Signal and potential backgrounds in a 40 kT detector for 10^{21} useful μ^+ decays

Base line (km)	$\overline{\nu}_\mu$ CC	ν_e CC	$\overline{\nu}_\mu + \nu_e$ NC	ν_μ(signal)
734	3.5×10^7	5.9×10^7	3.1×10^7	1.1×10^5
3500	1.2×10^6	2.4×10^6	1.2×10^6	1.0×10^5
7332	1.2×10^5	5.1×10^5	2.1×10^5	3.8×10^4

- Signal efficiency and fractional backgrounds cutting at $P_\mu > 7.5$ GeV, $Q_t > 1.0$ GeV

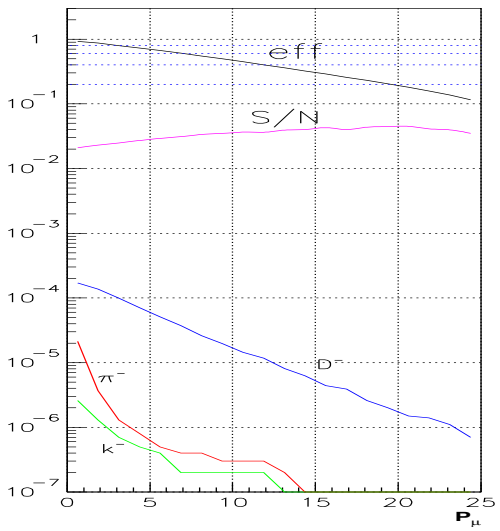
$\overline{\nu}_\mu$ CC	ν_e CC	$\overline{\nu}_\mu + \nu_e$NC	ν_μ(signal)
1.0×10^{-7}	5.0×10^{-7}	1.0×10^{-6}	3×10^{-1}

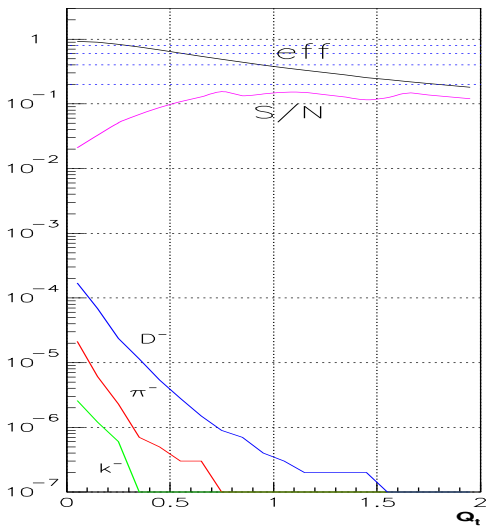
- Events surviving the cuts

Base line (km)	$\overline{\nu}_\mu$ CC	ν_e CC	$\overline{\nu}_\mu + \nu_e$NC	ν_μ(signal)
734	3.5	30	31	3.3×10^4
3500	~ 0.1	1.2	1.2	3×10^4
7332	< 0.1	< 0.2	< 0.2	1.3×10^4

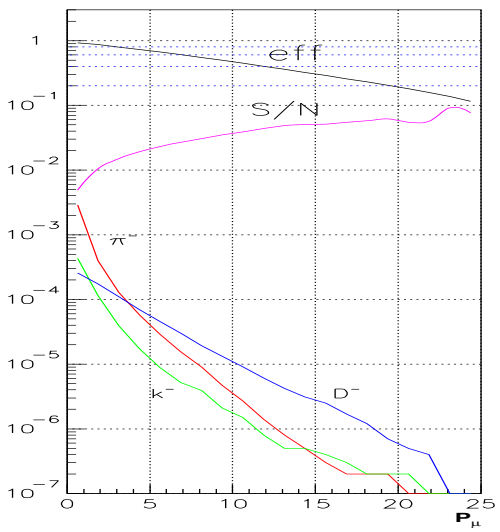
Signal and backgrounds for $\overline{\nu}_\mu$ CC and NC events

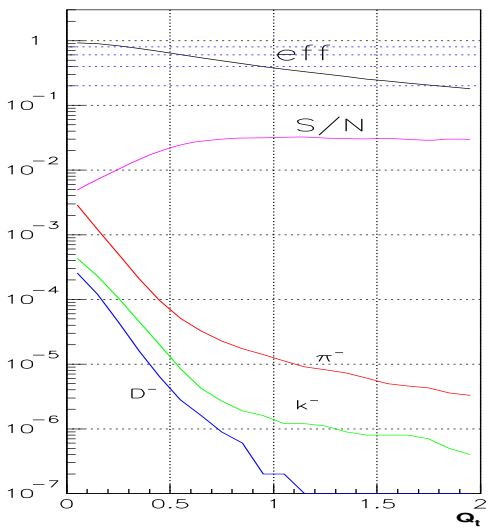
$\overline{\nu}_\mu$ Charged Currents





$\overline{\nu}_\mu$ Neutral Currents





SMA-MSW (or VO) Scenario

The solar mass difference $\Delta m^2_{12} \leq \mathcal{O}(10^{-6}\ \mathrm{eV}^2)$ is negligible at terrestrial distances: oscillation probabilities become independent of Δm^2_{12}, θ_{12} and the CP-odd phase.

In vacuum the probabilities are the same for ν's and $\bar{\nu}$'s:

$$
\begin{aligned}
P(\nu_e \to \nu_\mu) &= \sin^2(\theta_{23})\ \sin^2(2\theta_{13})\ \sin^2\left(\frac{\Delta_{23}\, L}{2}\right) \\
P(\nu_e \to \nu_\tau) &= \cos^2(\theta_{23})\ \sin^2(2\theta_{13})\ \sin^2\left(\frac{\Delta_{23}\, L}{2}\right) \\
P(\nu_\mu \to \nu_\tau) &= \cos^4(\theta_{13})\ \sin^2(2\theta_{23})\ \sin^2\left(\frac{\Delta_{23}\, L}{2}\right)
\end{aligned}
$$

where

$$\Delta_{ij} \equiv \frac{\Delta m^2_{ij}}{2E_\nu}$$

There is access to the sign of Δm^2_{23} nor to leptonic CP-violation.

If L is large the neutrinos will have to cross the crust or even the mantle of the Earth:

- ν_e and $\bar{\nu}_e$ interact with electrons in the Earth via charged-current elastic scattering inducing "effective masses"

$$\mu = \pm 2\sqrt{2} E_\nu \, G_F \, n_e$$

(n_e is the electron number density)

- For $E_\mu = 50$ GeV: $|\mu| \sim |\Delta m^2_{23}| \Longrightarrow$ Matter effects are important at long distances ($L \gg 1000$ Km):

$$P_{\nu_e \nu_\mu (\bar{\nu}_e \bar{\nu}_\mu)} \simeq \sin(\theta_{23})^2 \, \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{B_\mp} \right)^2 \, \sin^2 \left(\frac{B_\mp \, L}{2} \right) \, ,$$

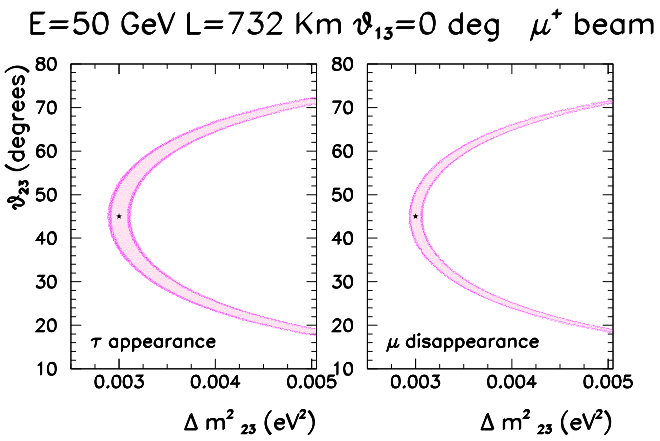
where

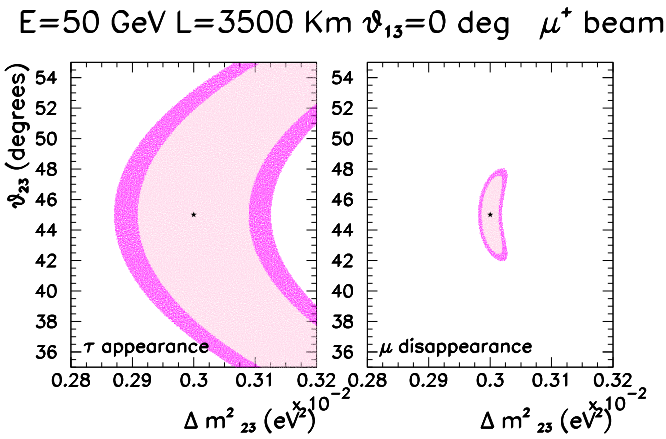
$$B_\mp \equiv \sqrt{\left[\Delta_{13} \, \cos 2\theta_{13} \mp A \right]^2 + \left[\Delta_{13} \, \sin 2\theta_{13} \right]^2} \, .$$

- Matter effects induce a CP-odd asymmetry: $P_{\nu_e \nu_\mu} \neq P_{\bar{\nu}_e \bar{\nu}_\mu}$
- There is sensitivity to sign of Δm^2_{23}: a change in this sign is equivalent to $P_{\nu_e \nu_\mu} \leftrightarrow P_{\bar{\nu}_e \bar{\nu}_\mu}$

Measurement of Δm^2_{23}, θ_{23}

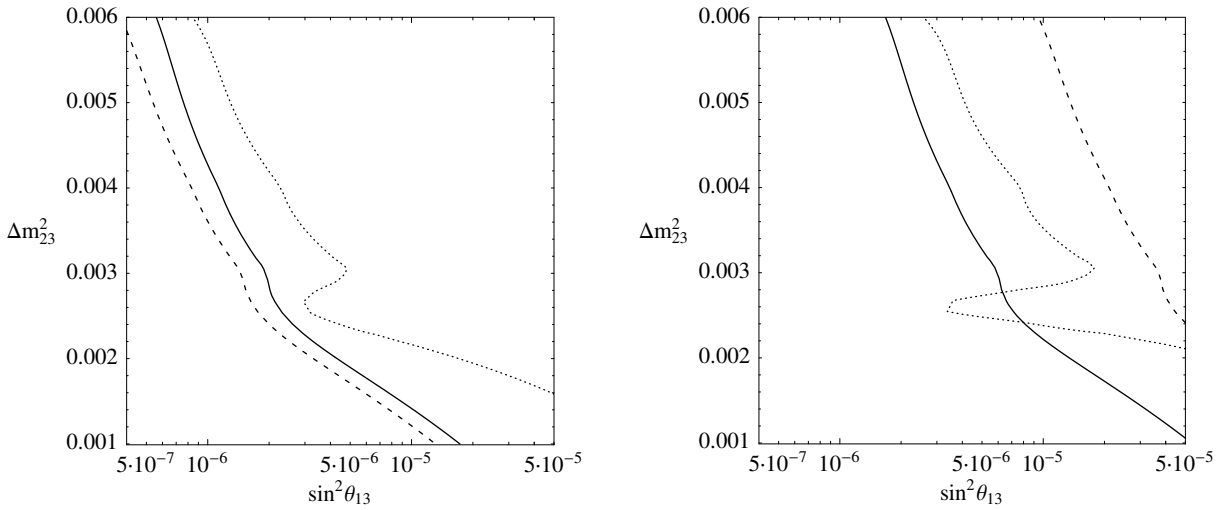
- Tau Appearance
  - Small detector mass $\Longrightarrow$ reduced statistics but sensitivity $\propto 1/N$
  - Serious backgrounds (Charm)
- Muons disappearance
  - Large detector mass $\Longrightarrow$ large statistics but sensitivity $\propto 1/\sqrt{N}$
  - Backgrounds irrelevant





Measurement of θ_{13}

- Best sensitivity obtained from wrong sign muon search: $\nu_e \rightarrow \nu_\mu$



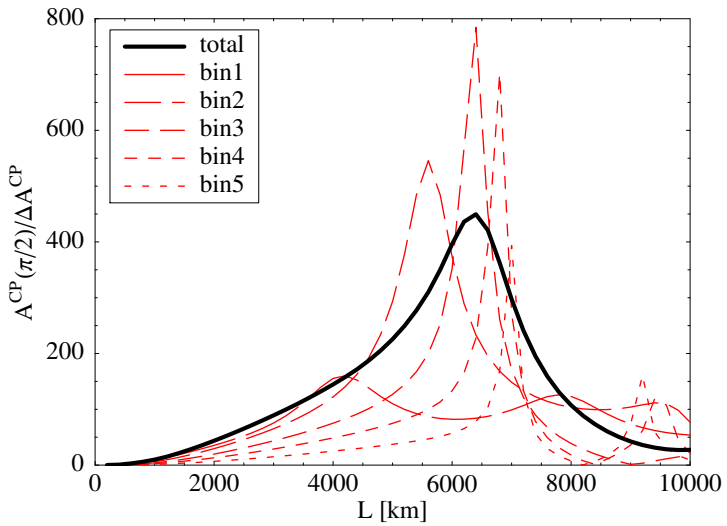
- Present limits can be improved by more than 3 orders of magnitude!

Measurement of the sign of Δm^2_{23}

Oscillation probability in matter depends on the sign of Δm^2_{13}: a change on this sign is equivalent to a CP transformation.

$\rightarrow$ The sensitivity to the sign is thus equivalent to the sensitivity to the CP-odd asymmetry in wrong sign muon signals obtained by running in the two polarities of the μ beam:

$$\bar{A}^{CP}_{e\mu} = \frac{\{N[\mu^-]/N_o[e^-]\}_+ - \{N[\mu^+]/N_o[e^+]\}_-}{\{N[\mu^-]/N_o[e^-]\}_+ + \{N[\mu^+]/N_o[e^+]\}_-}$$



- The optimal sensitivity is found at $O(7000)$ Km but the sign can be measured at already at $O(3000)$ Km.

SMA-MW (or VO) Scenario

- No access to CP violation
- Very precise measurement or stringent limit on θ_{13} through wrong sign muon appearance
  - Best sensitivity at $L \sim 3500$ Km (no backgrounds)
- Etablish unambiguously the sign of Δm^2_{23} by measuring the CP-asymmetry induced by matter
  - Best sensitivity at very large distances but very good already at $L \sim 3500$ Km
  - No sensitivity at $O(700)$ Km
- Very Precise measurement of θ_{23} , Δm^2_{23} through muon disappearance
  - Best sensitivity at $L \sim 3500$ Km
- Conclusion
  - One Base line may be enough (~ 3500 Km)
  - One detector may be enough (Large Magnetized Calorimeter)

LMA-MSW Scenario

The effects of Δm^2_{12} are not negligible over terrestrial distances, given the high intensity of the neutrino factory.

- In vacuum a good approximation for the $\nu_e \to \nu_\mu$ probability is:

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s^2_{23}\,\sin^2 2\theta_{13}\,\sin^2\left(\frac{\Delta_{13}\,L}{2}\right) + c^2_{23}\,\sin^2 2\theta_{12}\,\sin^2\left(\frac{\Delta_{12}\,L}{2}\right) + \tilde{J}\,\cos\left(\pm\delta - \frac{\Delta_{13}\,L}{2}\right)\,\frac{\Delta_{12}\,L}{2}\sin\left(\frac{\Delta_{13}\,L}{2}\right)$$

$$\tilde{J} \equiv c_{13}\,\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}$$

- Including matter effects:

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s^2_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{\tilde{B}_\mp}\right)^2\sin^2\left(\frac{\tilde{B}_\mp\,L}{2}\right) + c^2_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2\sin^2\left(\frac{A\,L}{2}\right) + \tilde{J}\,\frac{\Delta_{12}}{A}\,\frac{\Delta_{13}}{\tilde{B}_\mp}\,\sin\left(\frac{AL}{2}\right)\,\sin\left(\frac{\tilde{B}_\mp L}{2}\right)\,\cos\left(\pm\delta - \frac{\Delta_{13}\,L}{2}\right)$$

with

$$\tilde{B}_\mp \equiv |A \mp \Delta_{13}|$$

Measurement of the CP-odd phase

In the LMA-MSW solar scenario the $\nu_e \to \nu_\mu$ probability depends on δ but also on θ_{13}: can they be measured simultaneously ?

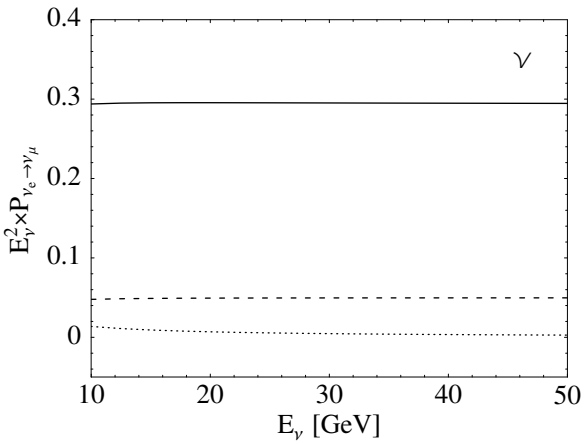
- For $\theta_{13} \geq 1^\circ$, the dominant contributions in the $\nu_e \to \nu_\mu$ transition are:

$$
\begin{aligned}
P_1 &\equiv s^2_{23} \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{\tilde{B}_\mp}\right)^2 \sin^2\left(\frac{\tilde{B}_\mp L}{2}\right), \\
P_2 &\equiv \tilde{J}\,\frac{\Delta_{12}}{A}\frac{\Delta_{13}}{\tilde{B}_\mp} \cos\delta \cos\left(\frac{\Delta_{13} L}{2}\right) \sin\left(\frac{A L}{2}\right) \sin\left(\frac{\tilde{B}_\mp L}{2}\right), \\
P_3 &\equiv \pm\tilde{J}\,\frac{\Delta_{12}}{A}\frac{\Delta_{13}}{\tilde{B}_\mp} \sin\delta \sin\left(\frac{\Delta_{13} L}{2}\right) \sin\left(\frac{A L}{2}\right) \sin\left(\frac{\tilde{B}_\mp L}{2}\right)
\end{aligned}
$$

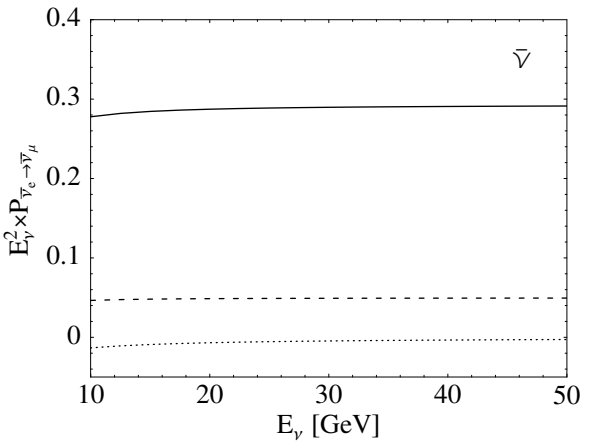
- The term in $\cos\delta$ is more significant at short distances while the term in $\sin\delta$ is more significat at large distances.
- However, the sensitivity through $\cos\delta$ is fake, because at short distances, the terms P_1 and P_2 cannot be disentangled $\Longrightarrow$ there is a strong correlation between θ_{13} and δ and δ is not measurable.
- At longer baselines $O(3000)$Km, the energy dependence of the different terms and the comparison of the two beam polarities permits disentangling θ_{13} and δ.

Significance of δ and θ_{13} Terms

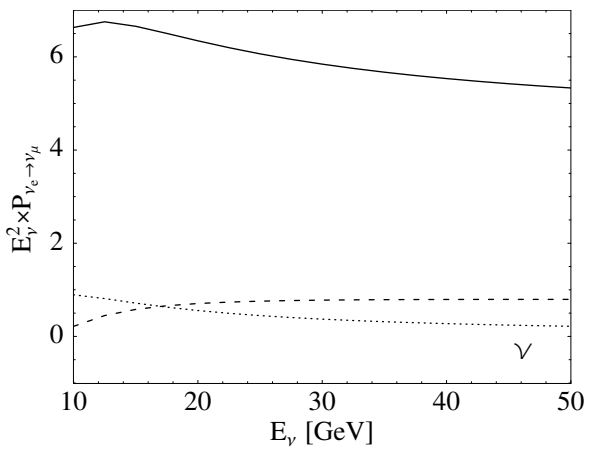
- Parameters corresponding to the LMA-MSW solution:
  - $\Delta m^2_{23} = 2.8 \times 10^{-3}$ eV^2, $\Delta m^2_{12} = 1 \times 10^{-4}$ eV^2
  - $\theta_{12} = 22.5^\circ, \theta_{23} = 45^\circ$ and $\theta_{13} = 8^\circ$



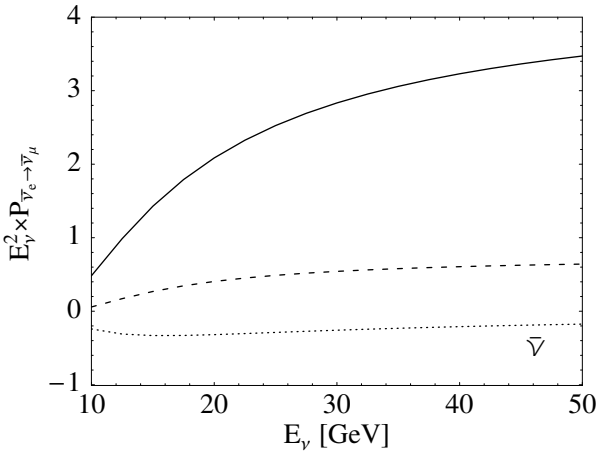
(a)



(b)

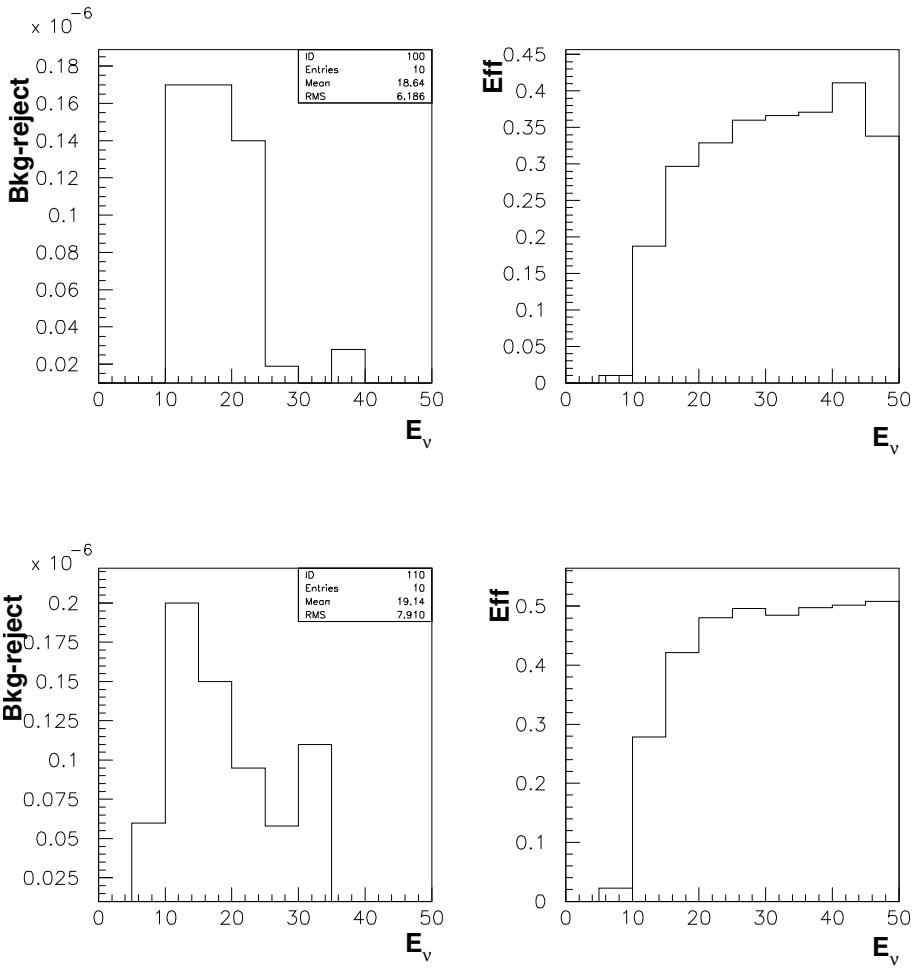


(a)

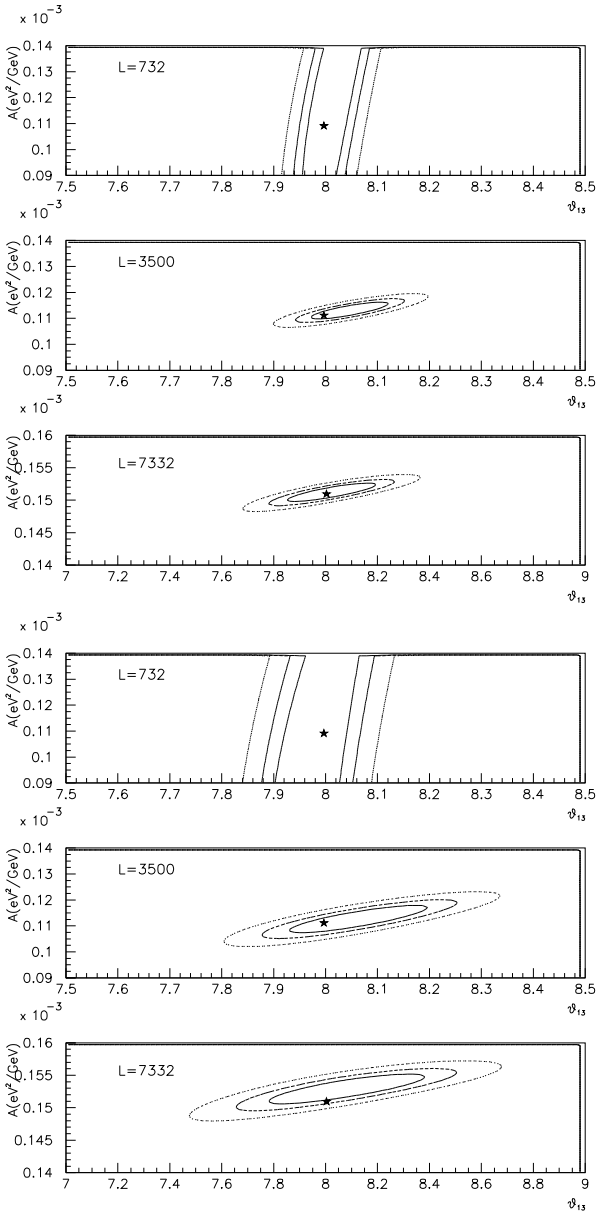


(b)

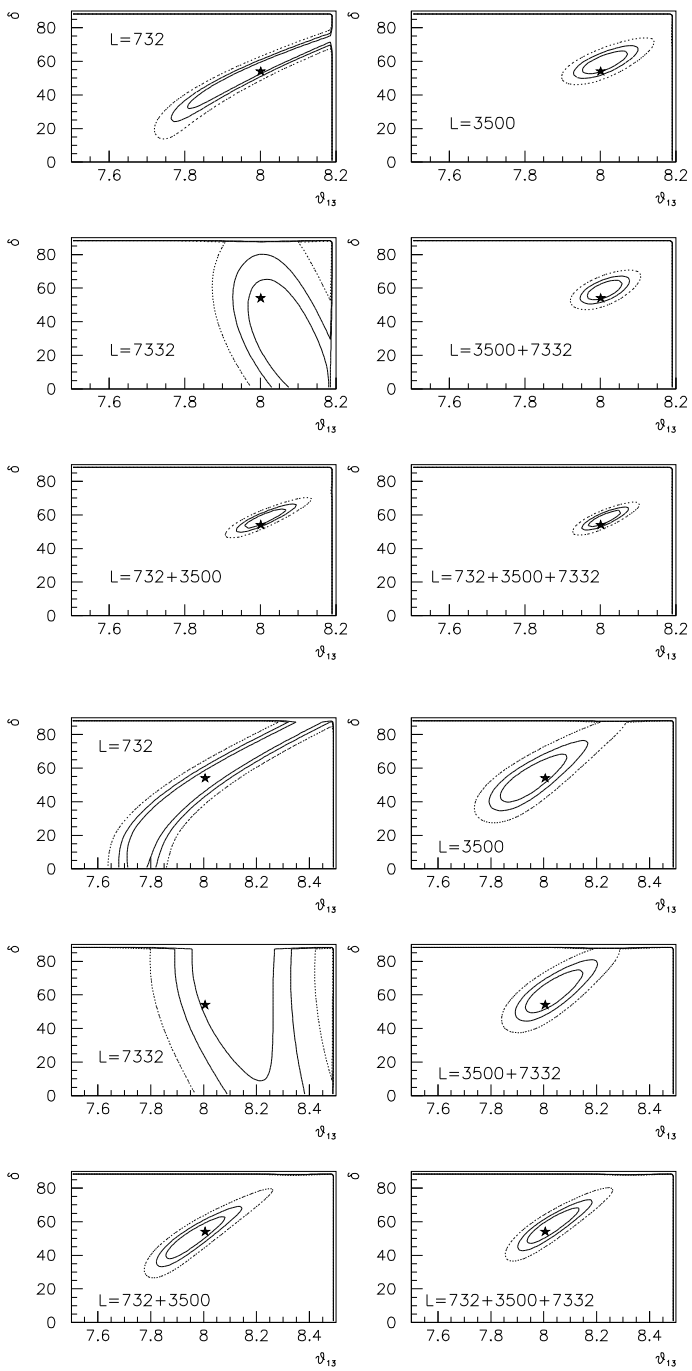
Dependence of the Signal and Backgrounds with Energy



Simultanous fits to θ_{13} and Matter

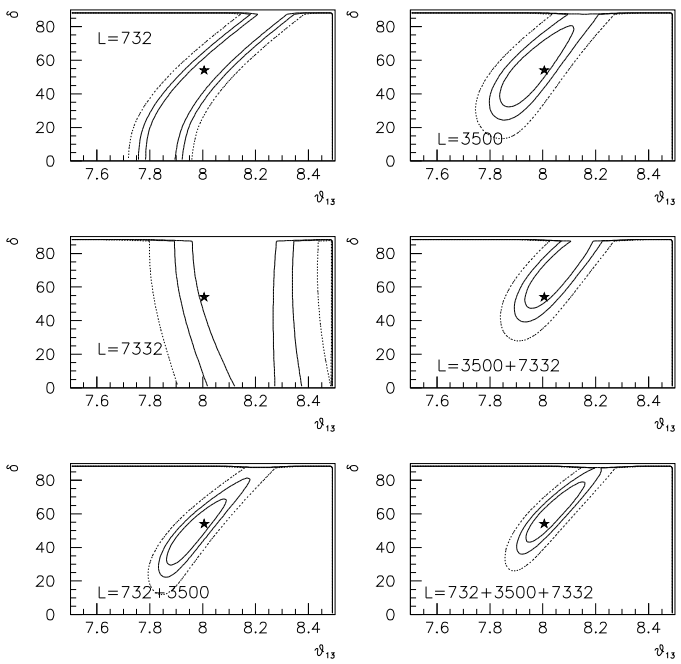


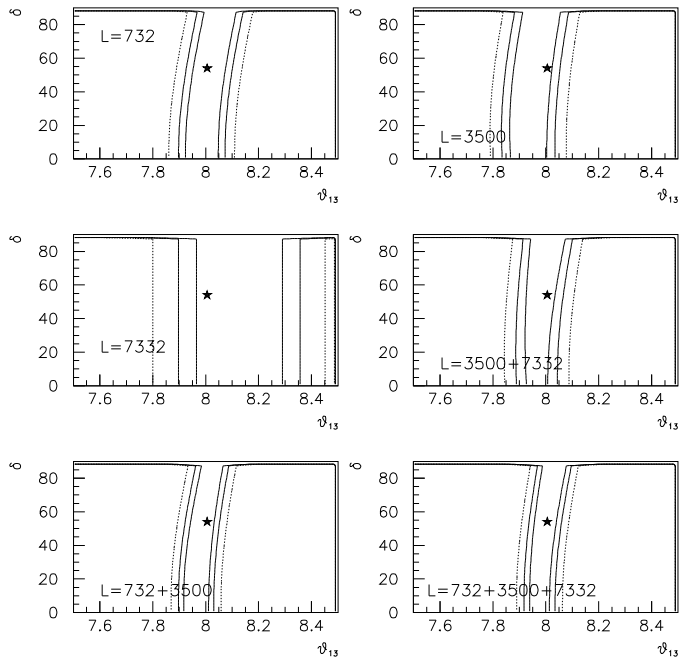
Simultanous fits to δ and θ_{13} (LMA)

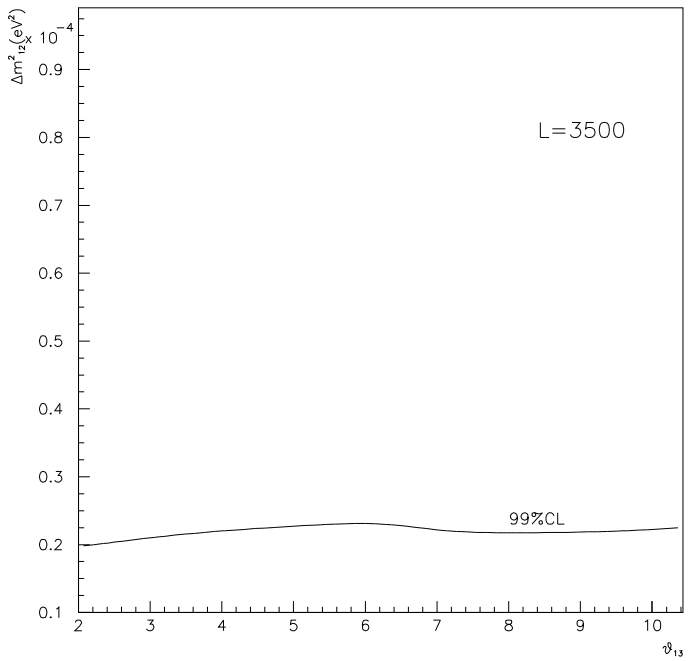


Dependence with Δm^2_{12}

- The sensitivity to CP-violation decreases linearly with Δm^2_{12}
  - At the central value of the LMA-MSW range $\Delta m^2_{12} = 5 \times 10^{-5}$ eV^2 $\Longrightarrow$ CP-violation can still be discovered
  - At the lower value allowed, $\Delta m^2_{12} = 1 \times 10^{-5}$ eV^2 $\Longrightarrow$ the sensitivity to CP-violation is lost with the experimental set-up considered
  - The minimum value of Δm^2_{12} for which a maximal CP-odd phase, $\delta = 90°$, can be distinguished at 99% CL from $\delta = 0°$ is $\Delta m^2_{12} > 2 \times 10^{-5}$ eV^2, with very small dependence on θ_{13}

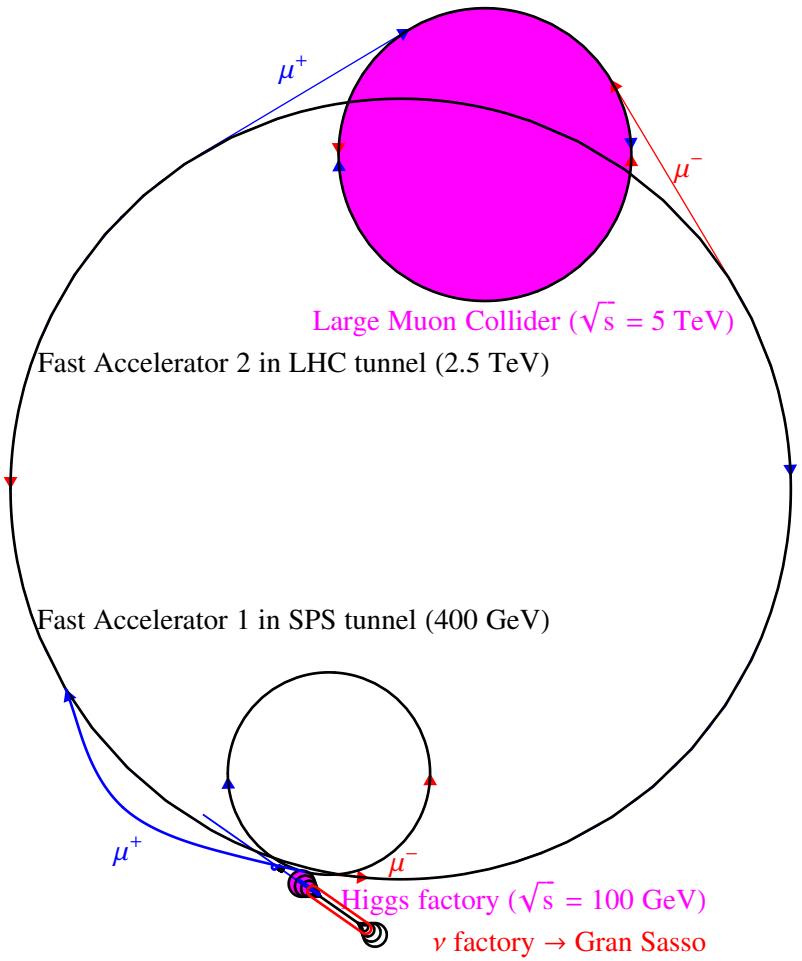



δ
L=732
L=3500
L=7332
L=3500+7332
L=732+3500
L=732+3500+7332
ϑ_{13}


$\Delta m^2_{12}(eV^2)$
10^{-4}
L=3500
99%CL
ϑ_{13}

The Muon Collider

- Next step $\Longrightarrow$ Inject the high intensitiy muon beams produced in the Neutrino Factory in Muon Colliders



$\mu^{\pm}$ Versus $e^{\pm}$ Colliders

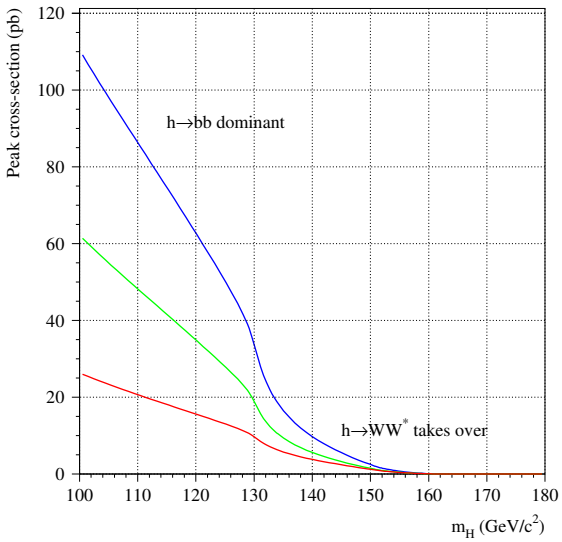
- Pros
  - Larger coupling to the Higgs Boson
  - Excellent energy definition (no bremms)
  - Very Precise beam energy measurement $\Longrightarrow$
    - Complete study of neutral Higgs resonances through line shape
    - Precision physics at WW & $t\bar{t}$ thresholds and/or discovery of new particles
- Cons
  - Luminosity smaller by a factor 10 than that foreseen for $e^{\pm}$ colliders due to larger emittance
  - Large detector backgrounds from muon decay products
  - Neutrino radiation increases rapidly with energy $\Longrightarrow$ can prevent the high energy frontier from being reached

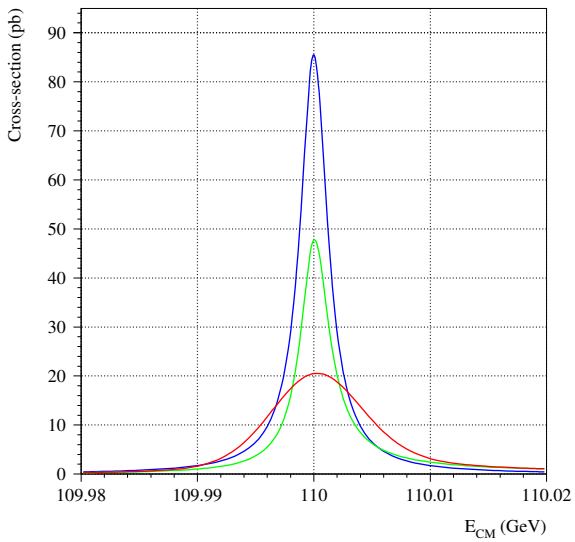
Precision Muon Colliders

Precision measurements at $\sqrt{s} = m_h$

- Energy scan across the ligther Higgs resonance
- Unrivaled accuracy if $m_h \lesssim 140\ GeV$

Higgs lineshape measurement $\Longrightarrow$ learn about the Higgs sector as much as about the Z





Beam Energy Calibration

Measuring Muon Spin Precession

- Muons are 100 % longitudinally polarized when produced and a longitudinal polarization $P_L \sim 20$ % can be preserved in the collider ring

- The spin of the muons then precesses with a frecuency:

$$\nu_0 = (g_\mu - 2)E_{beam}/2m_\mu$$

  e.g., for $\sqrt{s} = 110\ Gev,\ \nu_0 = 0.6069$

- If no energy spread $\Longrightarrow$ P_L oscillates with frecuency ν_0
- Energy Spread $\Longrightarrow$ P_L gets diluted at each turn T

$$P_L = P_0 \int_0^\infty \cos(2\pi\nu T) S(\nu) d\nu$$

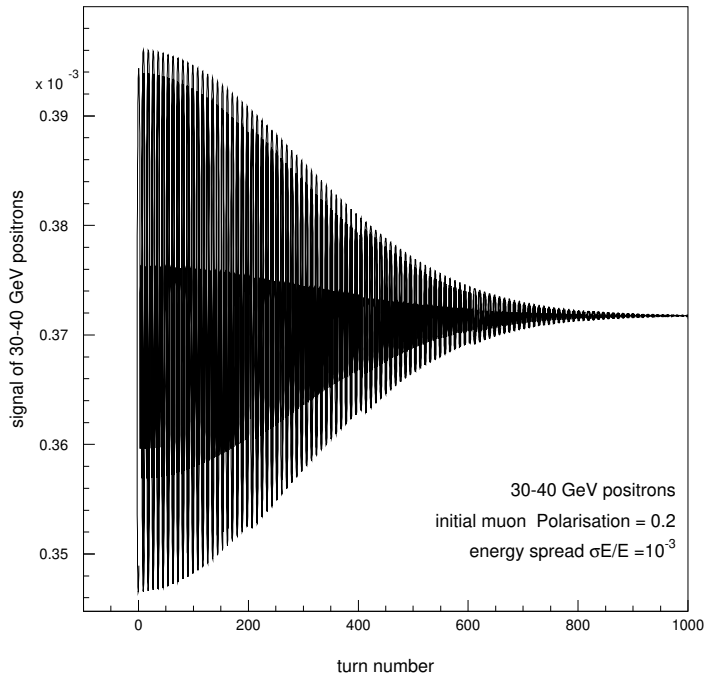
  P_L is the Fourier transform of the energy spectrum $S(\nu)$

- For a Gaussian energy distribution

$$P_L = P_0 \cos(2\pi\nu_0 T) \exp -\frac{1}{2}[2\pi\nu_0 T \frac{\delta E}{E}]^2$$

- The number of decay electrons $N_e(T)$ detected at each turn in a given energy range is proportional to P_L and therefore to the beam energy spectrum

$$N_e(T) \propto 1 + P_0 \cos(2\pi\nu_0 T) \exp -\frac{1}{2}[2\pi\nu_0 T \frac{\delta E}{E}]^2$$



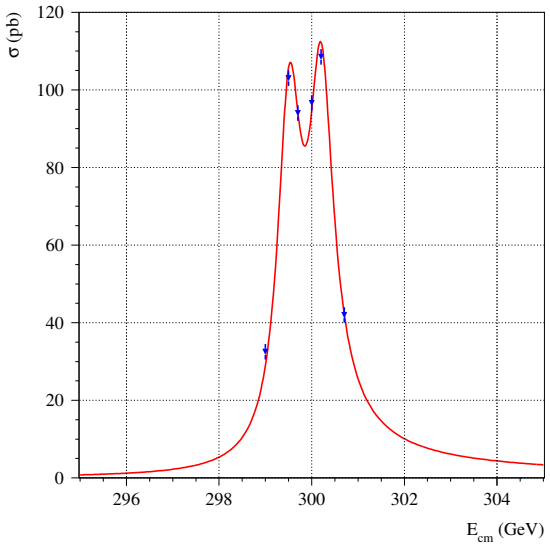
The High Energy Frontier

- A second Precision Muon Collider at $\sqrt{s} \sim m_A$ could perform an energy scan to determine the lineshape of the supersymmetric Higgs bosons A, H
- The decay channels of H and A are not identical because H is CP-even while A is CP-odd. For instance:

$$H \rightarrow W^+W^-, ZZ, hh$$

$$A \rightarrow Zh$$

- CP violation in the Higgs sector would lead to interference between the above decay modes



Conclusions

- Very Rich Physics Potential
  - Precision study of neutrino oscillations
  - Precision tests of SM and MSSM through Higgs line shape width and the peak cross section
  - Discovery of heavier Higgs bosons
  - Discovery of new physics at very high energy
- Numerous tecnical challenges
  - Proton drivers 10^3 or more intense than present ones
  - Ionization Cooling
  - Acceleration schemes, Final focus, Detector shielding
  - Neutrino radiation hazard may prevent the very high energy frontier (to multi TeV)