# Muon-derived neutrino beams

"UK Muon Collider Working Group"**

- Background
- Current designs
- Accelerator R&D required
- Physics possibilities: neutrino oscillations
  deep inelastic scattering
  stopped muons
- Conclusions

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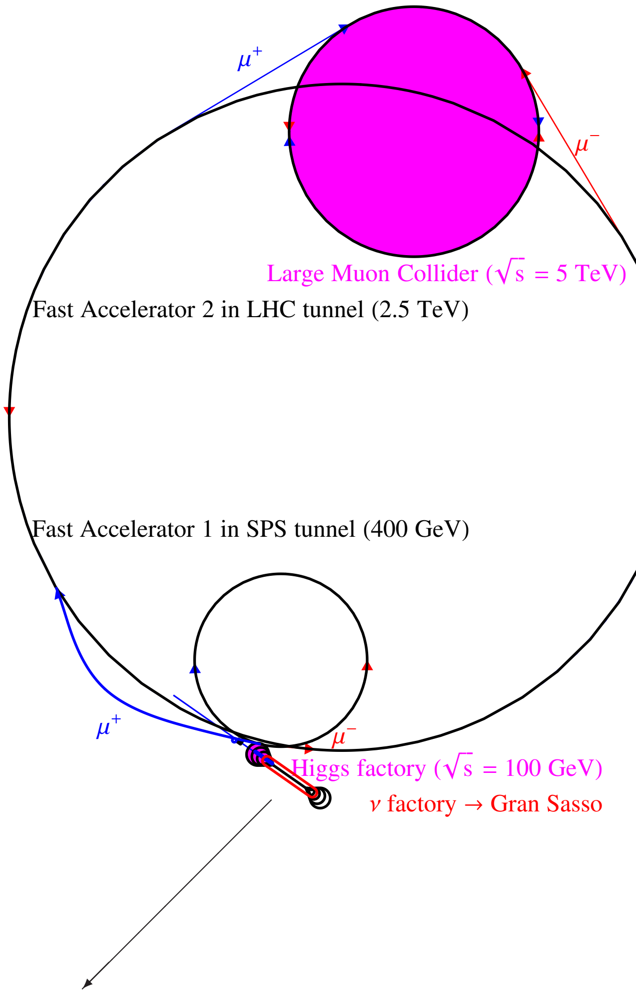
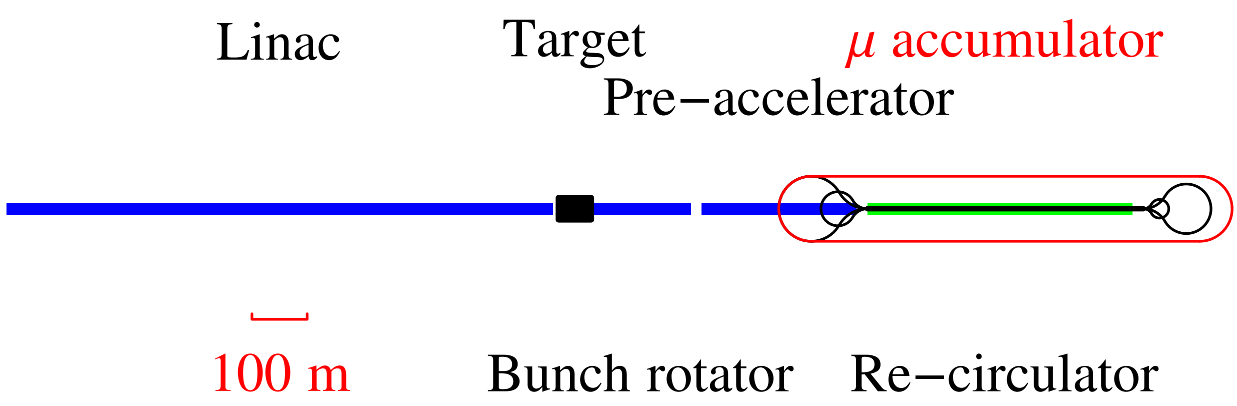
# A brief history of muon colliders

- Concept has been around for a while: Tinlot (1960), Tikhonin (1968), Budker(1969), Skrinsky (1971) and Neuffer (1979).
- Recent enthusiasm results from the realisation that high intensity beams can be produced by ionisation cooling: Skrinsky and Parkhomchuk (1981)
- Also, realised high intensity $\mu' s \Longrightarrow$ high intensity $\nu_\mu$ and $\overline{\nu_e}$
- Design work has been underway in the States since 1992 leading to the formation of the Muon Collider Collaboration in 1997 ($>$ 100 physicists, including 3 CERN accelerator physicists)
- In Europe, a prospective study group was formed by ECFA/CERN in 1998. This consists of 3 working groups:
  - Neutrino physics - convener Bruno Autin, 66 members
  - Precision muon colliders - convener Alain Blondel, 24 members
  - High energy frontier - convener John Ellis, 37 members
- European proposal is to build in these three stages, with the $\nu$-factory being ready $<$ 2010(??)

# Possible layout in the CERN scheme

- Complete muon complex makes use of (some) existing infrastructure.
- Neutrino beam points at LNGS.




- Scales: proton linac $\sim$ 1km, decay distance $\sim$ 50m, bunch rotator $\sim$ 100m, pre-accelerator $\sim$ 300m and muon linac $\sim$ 500m

# Accelerator R&D required

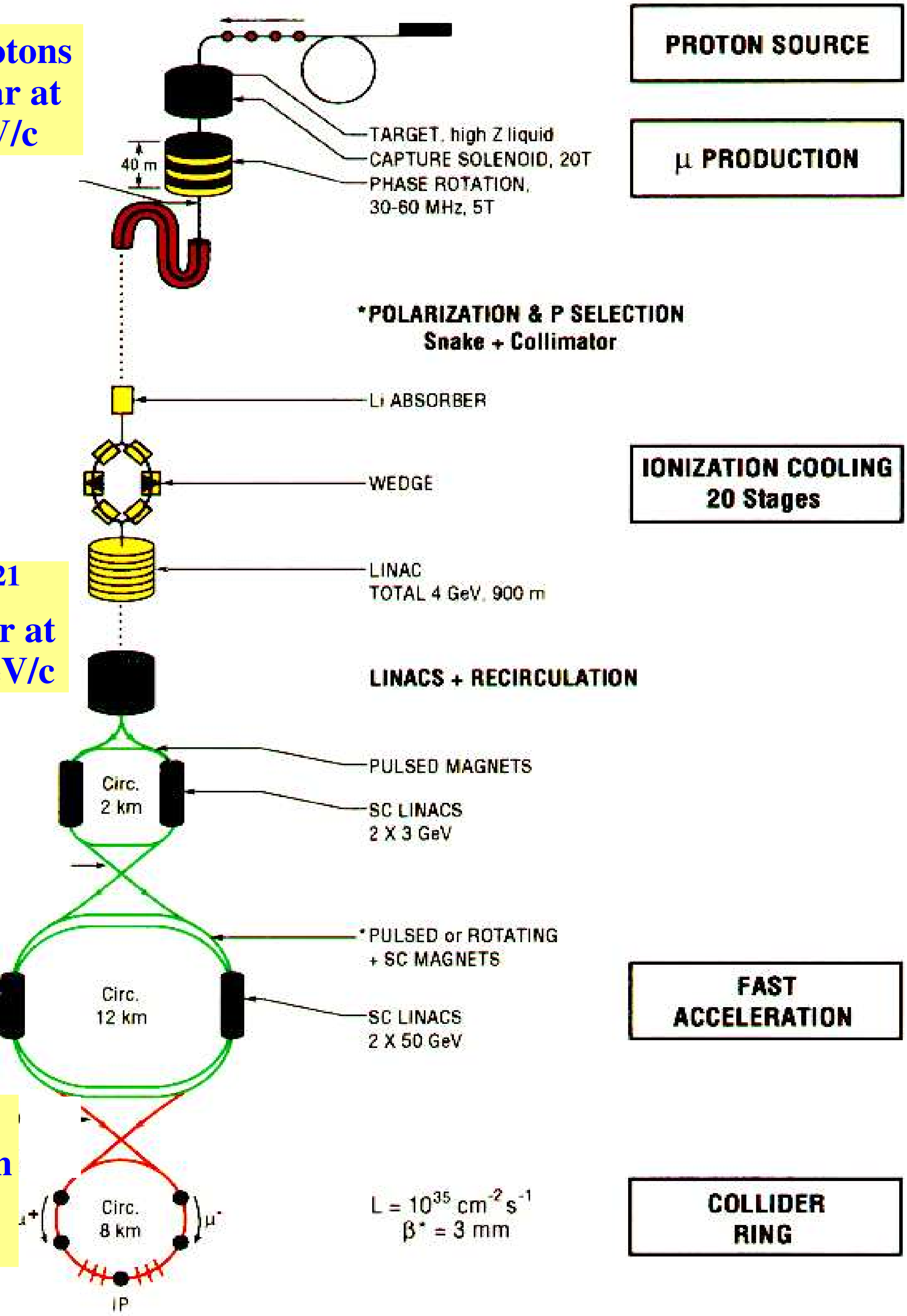
- Proton linac : Designed for high intensity, with CW operation using LEP superconducting rf cavities
  $\longrightarrow$ bunches are 24 ps long, separated by 3 ns (1 m)
  $\longrightarrow$ maximum current 10 mA, i.e. $6 \times 10^{16}$ protons/s
  $\longrightarrow$ 20 MW at 2 GeV
- Target : Has to withstand proton intensity over a long period
  $\longrightarrow$ physical shock, heating and radioactivity
  $\Longrightarrow$ major R&D project
- $\pi$ capture : Very important for muon intensity
  $\longrightarrow$ assume $\pi$ current $\sim$ 1% p current
  $\Longrightarrow$ also major R&D project
- Muon storage ring : At 20 GeV, $\mu$ decay time $=$ 440 $\mu$s
  revolution time $=$ 3.5 $\mu$s $\Rightarrow$ accumulation
  $\longrightarrow$ "ample room for ingenuity"

# 2 x 2 TeV Muon Collider Schematic

$10^{22}$ protons per year at 8 GeV/c

$2 \times 10^{21}$ muons/yr at ~100 MeV/c

~$2 \times 10^{12}$ muons/bunch x 4 bunches x 15 Hz



# Physics possibilities I: $\nu$ oscillations

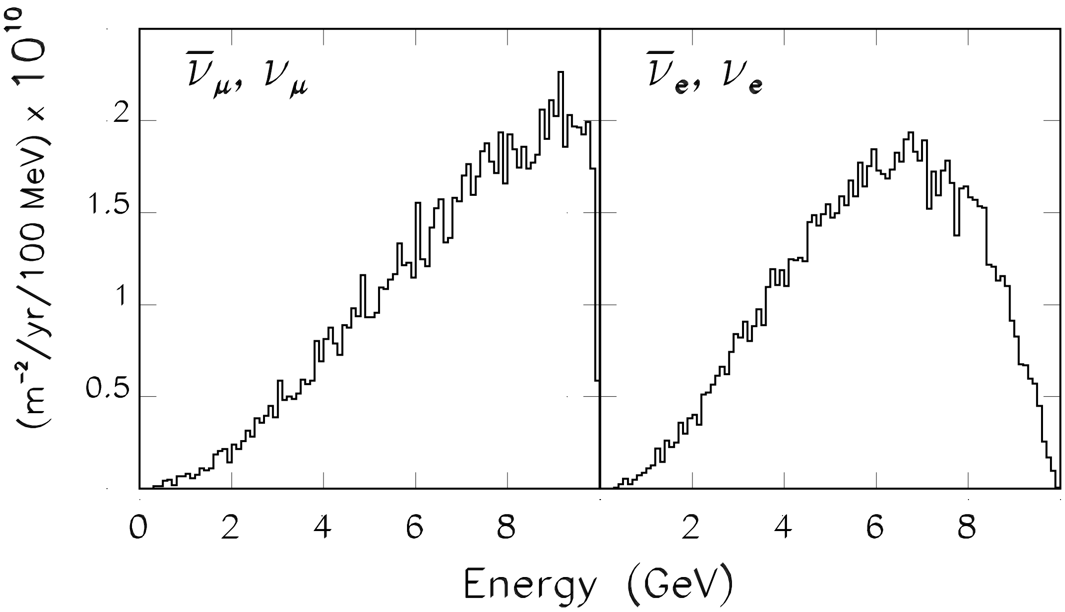
Advantages of $\mu$-decays over $\pi$-decays:

- The decay is:

$$\mu^- \to e^- \nu_\mu \bar{\nu}_e$$

  For stored $\mu^-$ ($\mu^+$): pure beam of equal numbers of $\nu_\mu$ ($\bar{\nu}_\mu$) and $\bar{\nu}_e$ ($\nu_e$).

- $\mu$ momentum is well defined $\Rightarrow$ perfectly calculable $\nu_\mu$ and $\bar{\nu}_e$ momentum




- $\mu$ momentum is tunable to experimental requirements
- $\nu$ intensity precisely calculated from $\mu$ current
- With $E_\mu = 20$ GeV and a 10 kT detector at Gran Sasso:

  $\Longrightarrow 2.2 \times 10^5 \mu^-$ and $9.6 \times 10^4 e^+$ cc events per year

# Introduction to $\nu$ oscillations

For 2-fold mixing, e.g. $\nu_\mu \longrightarrow \nu_\tau$, the oscillation probability is given by

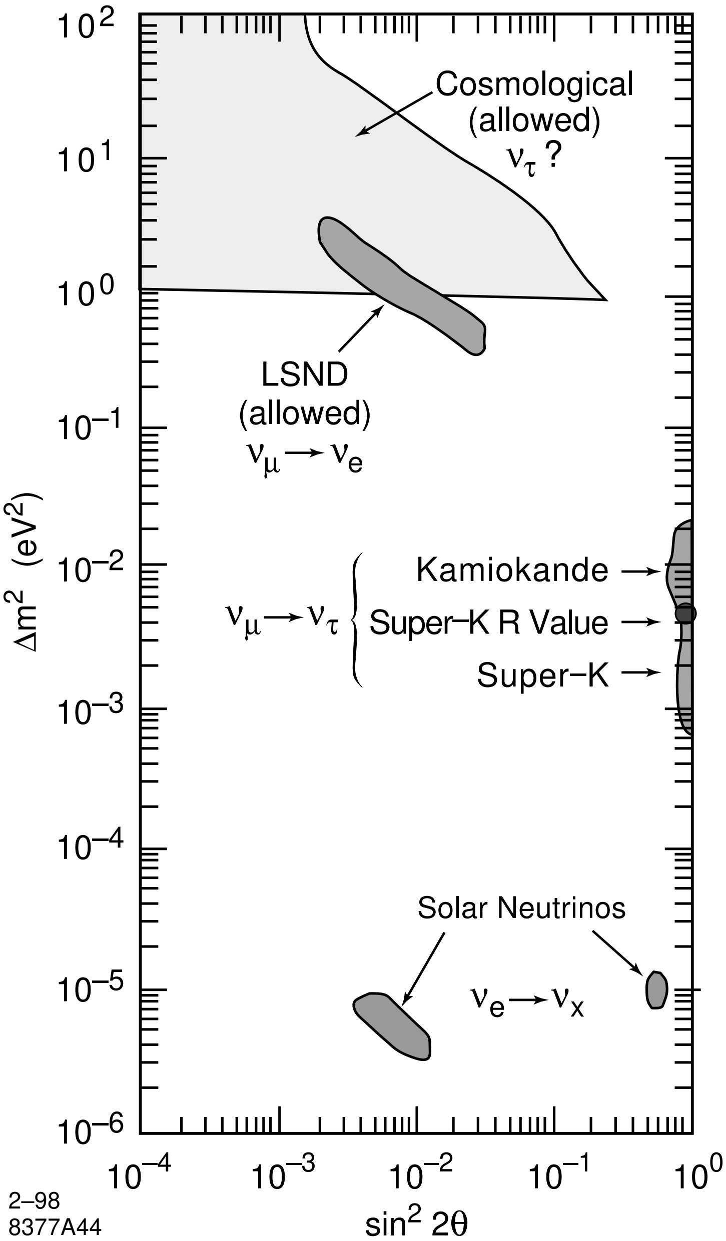
$$P(\nu_\mu \longrightarrow \nu_\tau) = \sin^2(2\theta)\sin^2(\frac{\kappa\Delta m^2 L}{E_\nu})$$

Notes:

- 2 parameters: $\sin^2(2\theta)$ and $\Delta m^2$
- Oscillation depends on $L/E_\nu$

Three experimental indications of $\nu$ oscillations:

- Atmospheric neutrinos, in particular SuperKamiokande. Interpreted as $\nu_\mu \longrightarrow \nu_\tau$ (CHOOZ and $\nu_e$ zenith angle distribution).
- Solar neutrino deficit, from various experiments. Interpreted as $\nu_e \longrightarrow \nu_x$.
- LSND: claim to have seen $\overline{\nu}_\mu \longrightarrow \overline{\nu}_e$.



# Introduction to $\nu$ oscillations 2

More generally, for 3-fold mixing, we have a 3X3 mixing matrix, e.g.

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

With this, the $\nu_\mu \longrightarrow \nu_\tau$ transition probability becomes

$$P(\nu_\mu \longrightarrow \nu_\tau) = \cos^4(\theta_{13}) \sin^2(2\theta_{23}) \sin^2\left(\frac{\kappa \Delta m_{23}^2 L}{E_\nu}\right)$$

and there are 6 parameters to be measured: 4 angles and 2 mass differences, e.g. $\theta_{12}, \theta_{23}, \theta_{13}, \delta, \Delta m_{12}$ and $\Delta m_{23}$.

- Oscillation channels available:

$$\mu^- \longrightarrow e^- \; \nu_\mu \; \bar{\nu}_e$$

| | |
|---|---|
| $\bar{\nu}_e \longrightarrow \bar{\nu}_e \longrightarrow e^+$ | disappearance |
| $\bar{\nu}_e \longrightarrow \bar{\nu}_\mu \longrightarrow \mu^+$ | appearance |
| $\bar{\nu}_e \longrightarrow \bar{\nu}_\tau \longrightarrow \tau^+$ | appearance |
| $\nu_\mu \longrightarrow \nu_\mu \longrightarrow \mu^-$ | disappearance |
| $\nu_\mu \longrightarrow \nu_e \longrightarrow e^-$ | appearance |
| $\nu_\mu \longrightarrow \nu_\tau \longrightarrow \tau^-$ | appearance |

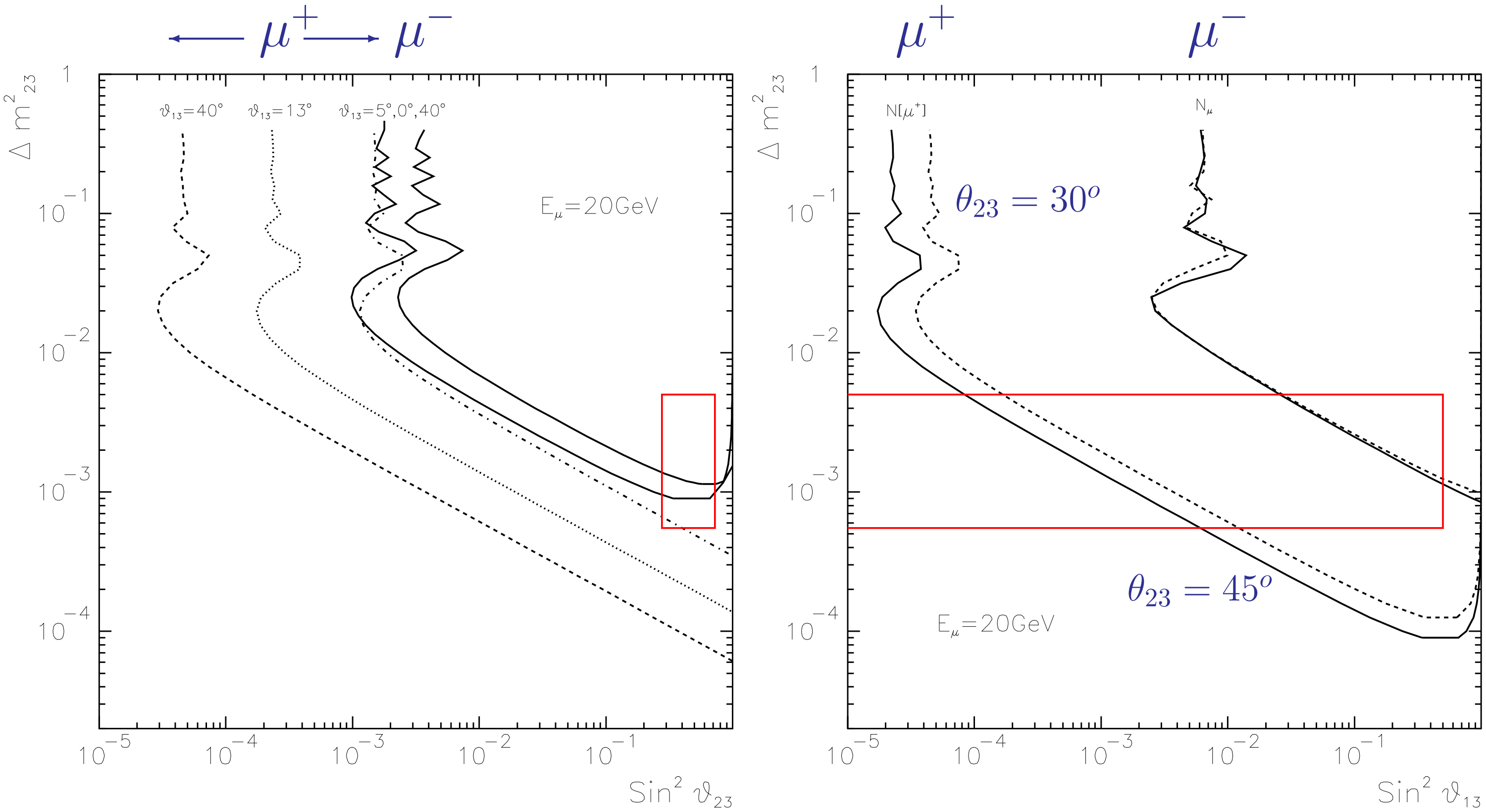
- NB for a $\mu^-$ beam:
  - the appearance of $\mu^+$ or $e^-$ $\Rightarrow$ oscillations
  - sign of $\tau$ distinguishes $\mu$ or $e$ oscillations

$\Longrightarrow$ charge identification is important

# Preliminary study of performance

- Uses $2 \times 10^{20}$ $\mu$-decays per year (pessimistic) at 20 GeV
- 10 kT detector at 732 km (CERN to Gran Sasso)
- 3-fold mixing framework, with parameter ranges from SuperK
- Assuming no background

Performance for $\mu^-$ disappearance and $\mu^+$ appearance




$\sim$ SuperK allowed region

# Preliminary study of performance

## Possibilities for CP violation

- Study uses CP-odd asymmetry:

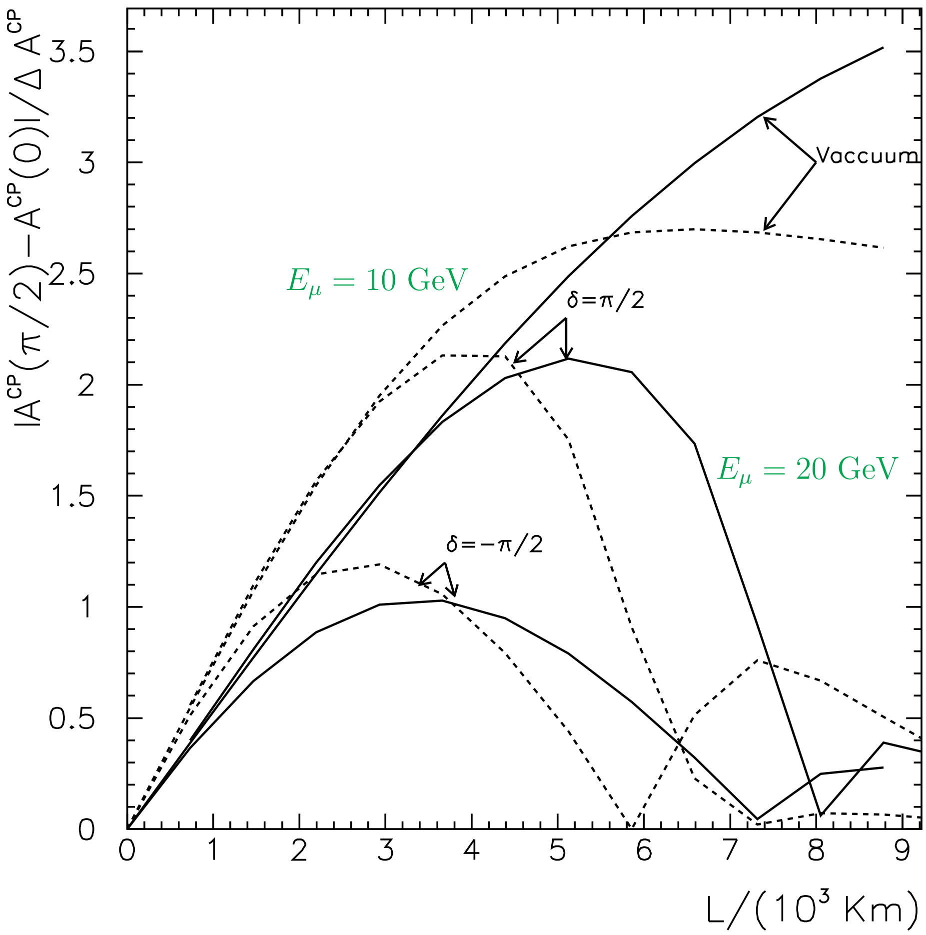
$$A_{e\mu}(\delta) = A_{e\mu}^{CP}(\delta) - A_{e\mu}^{CP}(0)$$

where the genuine CP asymmetry is

$$A_{e\mu}^{CP} = \frac{P(\nu_e \to \nu_\mu) - P(\overline{\nu_e} \to \overline{\nu_\mu})}{P(\nu_e \to \nu_\mu) + P(\overline{\nu_e} \to \overline{\nu_\mu})}$$

and $A_{e\mu}^{CP}(0)$ comes from the different interaction of $\nu_e$ and $\bar{\nu}_e$ in matter

- Setting $\delta = \pm 90^o$ (i.e. maximal) and other params in allowed ranges:



# Physics possibilities II: Deep inelastic scattering

- Detector placed close to the end of muon ring straight-section $\sim$ 1 km
- Studies used $E_\mu = 250$ GeV but most physics possible at 20-30 GeV
- After 1km, beam spot $<$ 1m radius $\Longrightarrow$ small detector required!
- Event rate in 10kg fiducial mass detector: $8 \times 10^5 \nu_\mu$ interactions per year
- Physics possibilities:
  - Precise measurement of $xF_3^N \Longrightarrow$ most accurate value for $\alpha_s$
  - $\sin^2\theta_W$ with precision equivalent to that of W mass
  - From charm decays, $V_{cd}$ could be measured to the same accuracy as $V_{us} \Longrightarrow$ tests unitarity of CKM matrix
  - High statistics deep-inelastic $\nu$ scattering from polarised targets possible. Combined with $\mu$ scattering, $\Longrightarrow$ test of the flavour SU(3) symmetry for 3 lightest quarks

# Physics possibilities III: Stopped muons

- Very high flux of low energy muons available after cooling
- Physics possibilities:
  - Search for lepton flavour violating decays: $\mu \rightarrow e\gamma$ and $\mu \rightarrow eee$
  - Search for flavour violating muon conversion: $\mu N \rightarrow eN$
  - Improved measurements of muon properties, e.g. lifetime, gyromagnetic anomaly $g_\mu - 2$, Michel parameters, EDM
  - Study of muonic atoms and muon capture

# Conclusions

- $\nu$-oscillations will (probably) be seen by near future long baseline experiments - Minos, CERN $\rightarrow$ Gran Sasso
- However, a $\nu$-factory will provide a second generation of $\nu$ experiments to make precise measurements of the oscillation parameters.

  $\Longrightarrow$ probably only way to do this
- Measuring the CP-violation angle looks difficult, but not impossible
- Many physics possibilities also available with
  - a near detector
  - stopped muons
- However, muon intensity very important (2.2$\mu$s lifetime)

  $\Longrightarrow$ Lots of accelerator R&D to do!!