NO-VE Venice July 24-26, 2001

What kind of ν beam ?

A. Guglielmi
INFN - Padova

1. ν oscillations
2. ν beams @ accelerators
3. ν - factory
4. superbeams

conclusions

1. ν oscillations

Atmospheric & solar data ⟶ 3 ν mixing

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

V : 3 x 3 mixing matrix, 6 parameters

2 mass differences Δm_{12}^2, Δm_{23}^2

3 mixing angles θ_{12} θ_{23} θ_{13}

1 CP phase δ $\quad (\Delta m_{ij}^2 = m_i^2 - m_j^2)$

ν oscillation data (2 state mixing)

$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \cdot \sin^2 \left(1.27 \frac{\Delta m^2 (eV^2)\, L\,(Km)}{E_\nu\ (GeV)} \right)$$

today:

- atmosph. ν : $\nu_\mu \to \nu_\tau$

  $|\Delta m_{23}^2| \sim 1.5 \div 5 \cdot 10^{-3} eV^2$, $\sin^2 2\theta_{23} \sim 1$

- solar ν : $\nu_e \to \nu_\mu$

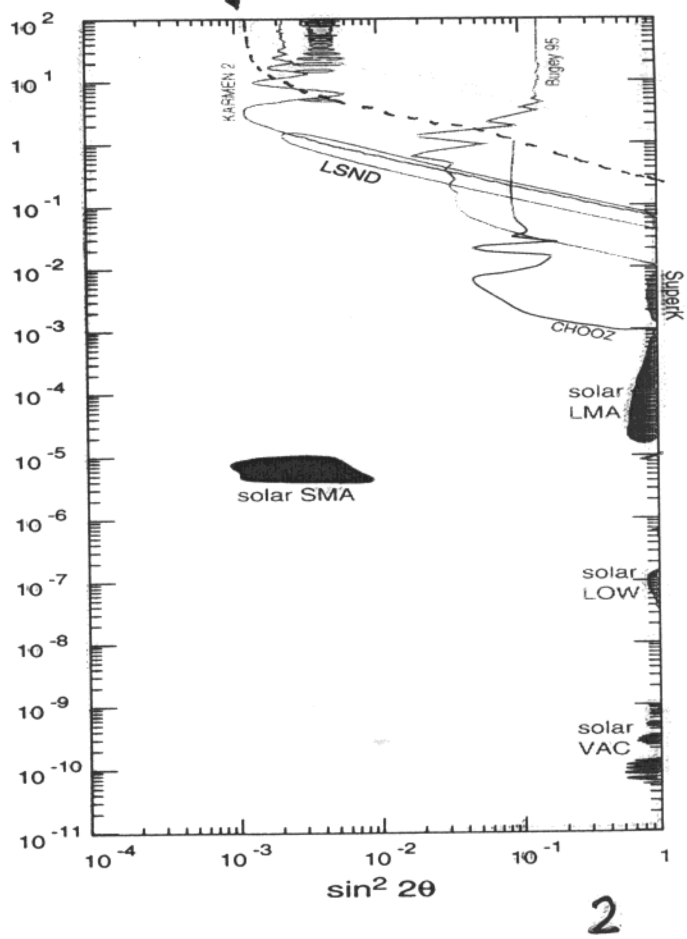
  $|\Delta m_{12}^2| \sim 10^{-5} \div 10^{-4} eV^2$, SMA or LMA

  $\sim 10^{-7}$, max. mixing

- CHOOZ : $\sin^2 2\theta_{13} \lesssim 0.05$

- all 3 Known νs partecipate in the oscillations

NOMAD $\nu_\mu - \nu_e$ NEW!



- in the limit $|\Delta m^2_{23}| \gg |\Delta m^2_{12}|$

solar & atmosph. ν oscillations largely decoupled:

$$P(\nu_e \to \nu_\mu) = \sin^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{\Delta m^2_{23} \cdot L}{4 E_\nu}\right)$$

$$P(\nu_e \to \nu_\tau) = \cos^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{\Delta m^2_{23} \cdot L}{4 E_\nu}\right)$$

$$P(\nu_\mu \to \nu_\tau) = \cos^4\theta_{13} \cdot \sin^2 2\theta_{23} \cdot \sin^2\left(\frac{\Delta m^2_{23} \cdot L}{4 E_\nu}\right)$$

in this approx., very good for SMA o LOW,

ν oscillations are described by only θ_{13}, θ_{23}, Δm^2_{23}

in LMA scenario (Δm^2_{12}) $\Rightarrow$ all 6 parameters:

$$P(\nu_e \to \nu_\mu) = \sin^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin\left(\frac{\Delta m^2_{23} \cdot L}{4 E_\nu}\right)$$
$$+ \cos^2\theta_{23} \cdot \sin^2 2\theta_{12} \cdot \sin^2\left(\frac{\Delta m^2_{12} \cdot L}{4 E_\nu}\right)$$
$$+ \tilde{J} \cdot \cos\left(\delta - \frac{\Delta m^2_{23} \cdot L}{4 E_\nu}\right) \cdot \frac{\Delta m^2_{12} \cdot L}{4 E_\nu} \cdot \sin\left(\frac{\Delta m^2_{23} \cdot L}{4 E_\nu}\right)$$

where

$$\tilde{J} = \cos\theta_{13} \cdot \sin 2\theta_{12} \cdot \sin 2\theta_{23} \cdot \sin 2\theta_{13}$$

- if LSND confirmed, the situation ... more complex...

near future: what will we know in 10 years?

- oscillation pattern $\nu_\alpha \to \nu_\beta$, ν_β appearance ?
  - solar/reactor exp.: SNO, Borexino, KamLAND, ICARUS, GNO...
  - accelerator exp.: K2K, MINOS, OPERA, ICARUS, MiniBooNE

- if ν oscillation confirmed:
  - SMA or LMA ? $10 \div 20\%$ accuracy on θ_{12}, Δm_{12}^2
  - $|\Delta m_{23}^2|$, $\sin^2 2\theta_{23}$ at 10% level
  - $\sin^2 2\theta_{13}$ explored down $\sim 10^{-2}$

remaining questions:

1. θ_{13} : link solar $\leftrightarrow$ atmosph. ν ?
2. sign of Δm_{23}^2: ν - mass spectrum ?
3. CP δ ?

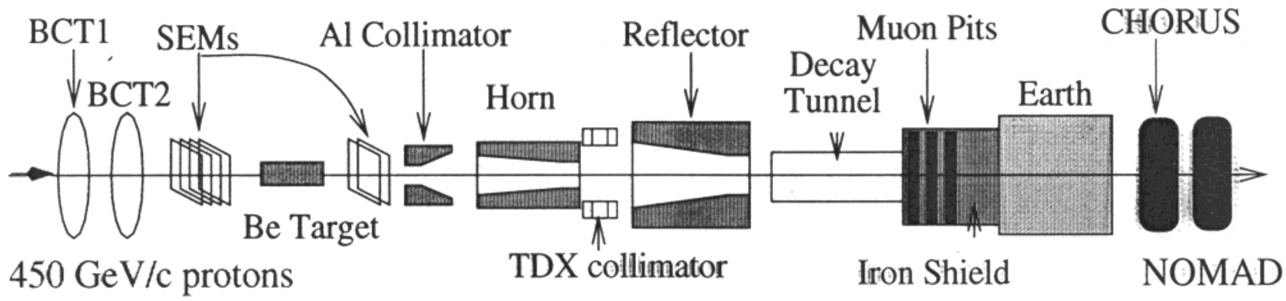
future: $\rightsquigarrow$ small coupling & mass differences:

$\Rightarrow$ increase ν intensity & L/E
more than a factor 10 !!!

2. ν beams @ accelerators

high energy accelerators provide ν_μ beams by the decay of π, Ks produced by high energy protons on light targets

i.e. WANF @ CERN SPS



- 450 GeV/c protons on Be rods, $\phi = 3$ mm, 3×10^{13} pot/14.4s

- + (−) mesons focussed (defocussed) by magnetic horns to CHORUS, NOMAD detectors, $L = 840$m

$$\Rightarrow \quad 0.95 \cdot 10^{-2} \, \nu_\mu / pot / 6.8 m^2 \quad E_{\nu_\mu} \sim 24.3 \text{ GeV}$$

$$\frac{\bar{\nu}_\mu}{\nu_\mu} \sim 6.9\% \quad \frac{\nu_e}{\nu_\mu} \sim 1\% \quad \frac{\bar{\nu}_e}{\nu_\mu} \sim 0.26\%$$

- high resolution & granularity of NOMAD detector

  ⇒ study of ν beam with unprecedent accuracy ($1.3 \cdot 10^6 \, \nu_\mu CC$

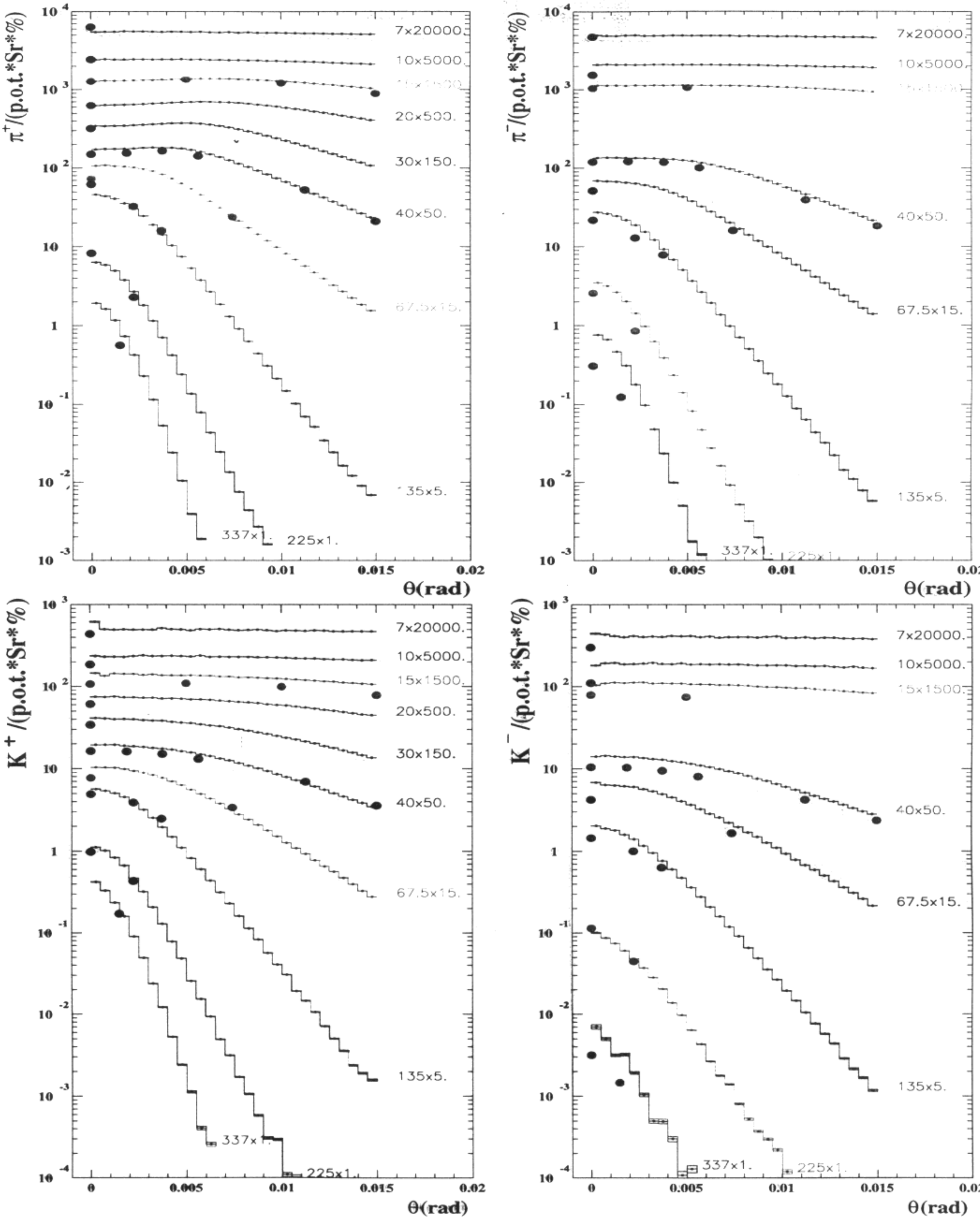
  ↳ benchmark for conventional ν beams!

  CNGS, K2K, NUMI ...

to predict ν beam intensity, spectrum & composition:

- precise description of π, K yields by 450 GeV/c protons on Be ($K/\pi \Leftrightarrow \nu_e/\nu_\mu$!)
  - experimental data on π, K, p by 400, 450 GeV/c protons on Be { Atherton et al. (198 / SPY Collab (1999
  - MC hadronic generators: Fluka, 20% of accuracy K^0_L ?
    ↳ <u>limit to sensitivity!</u>
- accurate description of the focussing system
- accurate description of primary proton spot: tails of protons missing the target will interact in the downstream material → ~30% of $\bar{\nu}_\mu$, $\bar{\nu}_e$ (minor components from defocussed π^-, K^-, ...)
- accurate description of particle propagation in the material of the beam line (reinteractions...)

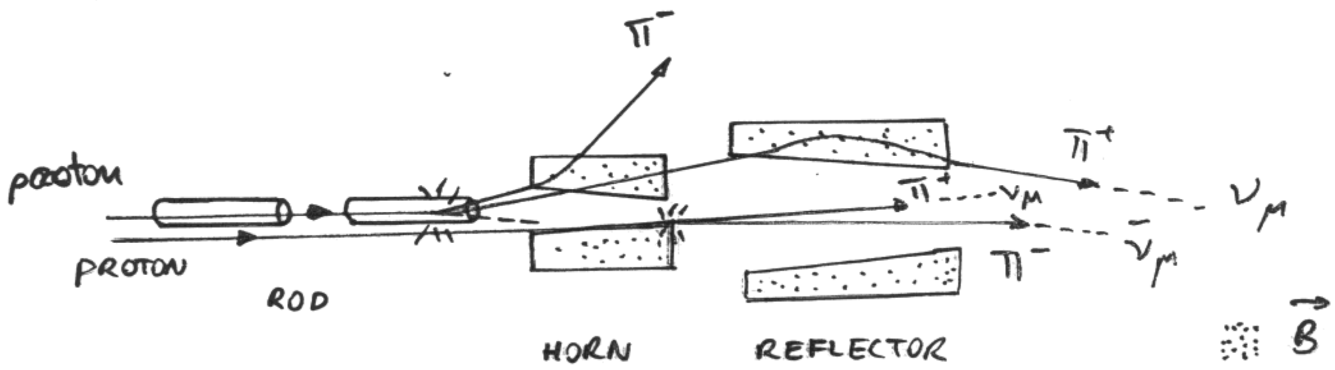
⇒ Simulation of a real ν beam is ~ complicated cascade of physical processes and not just a calculation of π, K production where mesons decay in a vacuum tunnel...

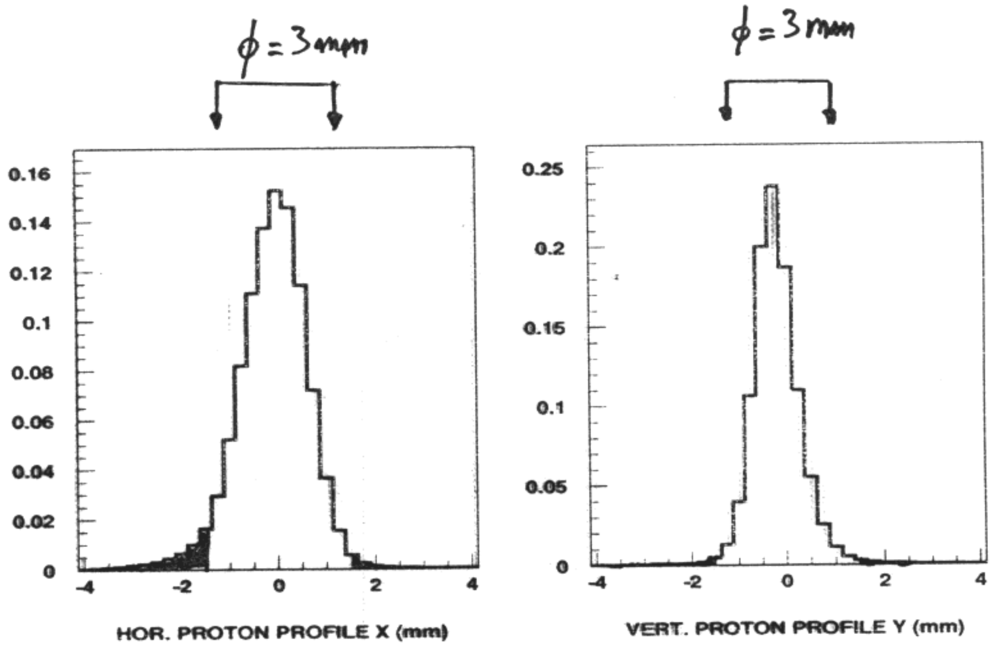


• SPY/Atherton (rescaled) data

—— FLUKA predictions : accuracy ~20% !
(the best hadronic generator)

450 GeV/c protons on 100 mm Be target



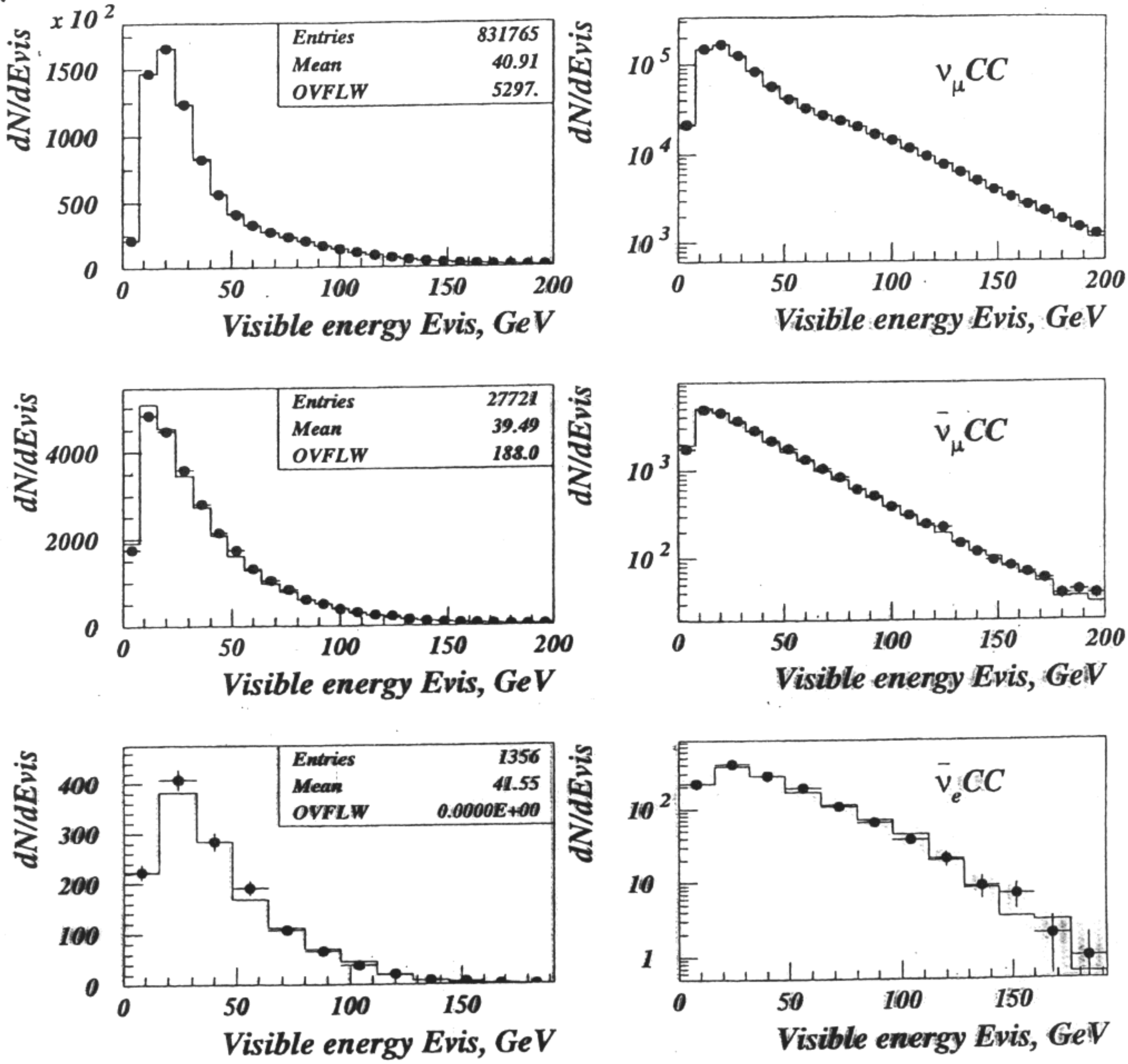


Knowlegde { p beam profiles / stability in the accelerator
material in the beam line

is critical for $\bar{\nu}_\mu$, $\bar{\nu}_e$ fluxes!

NOMAD final results

State of the Art!



- data

$\lceil$ MC - Fluka tuned to SPY/Atherton data
$\nu_\mu CC$ MC normalized to the data

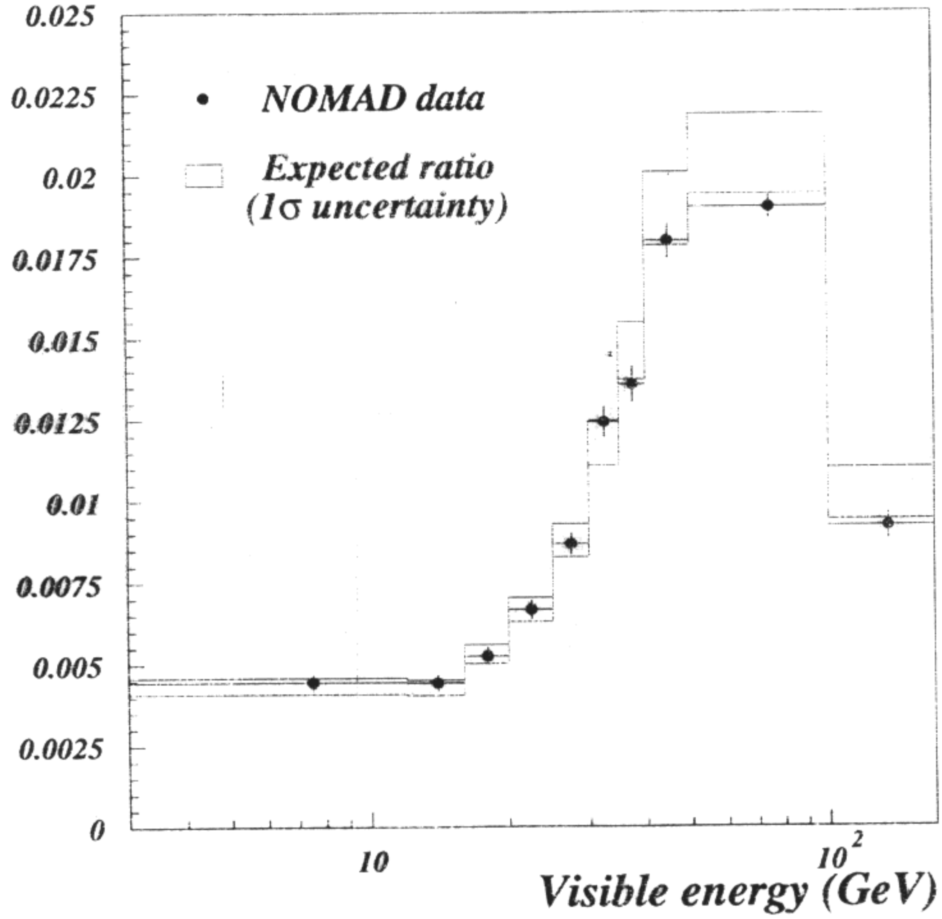
- agreement MC - ν_{cc} / data @ few % level (shape)

- systematics on $\nu_e/\nu_\mu \sim 5\%$ (beam)

Preliminary Results

- Bin-to-bin systematic errors: 5-8%
(mainly due to uncertainties in π^+, K^+ and K_L^0 yields)
- Overall (normalization) uncertainty: 2%

$R_{e\mu}$ ratio as a function of neutrino energy:



Data are analysed in 10 energy and 3 radial bins:

- χ^2 in the absence of oscillations: 19.7 / 29 d.o.f.
- $\chi^2_{\min}$ with oscillation hypothesis: 18.6 / 27 d.o.f.

No evidence for oscillations

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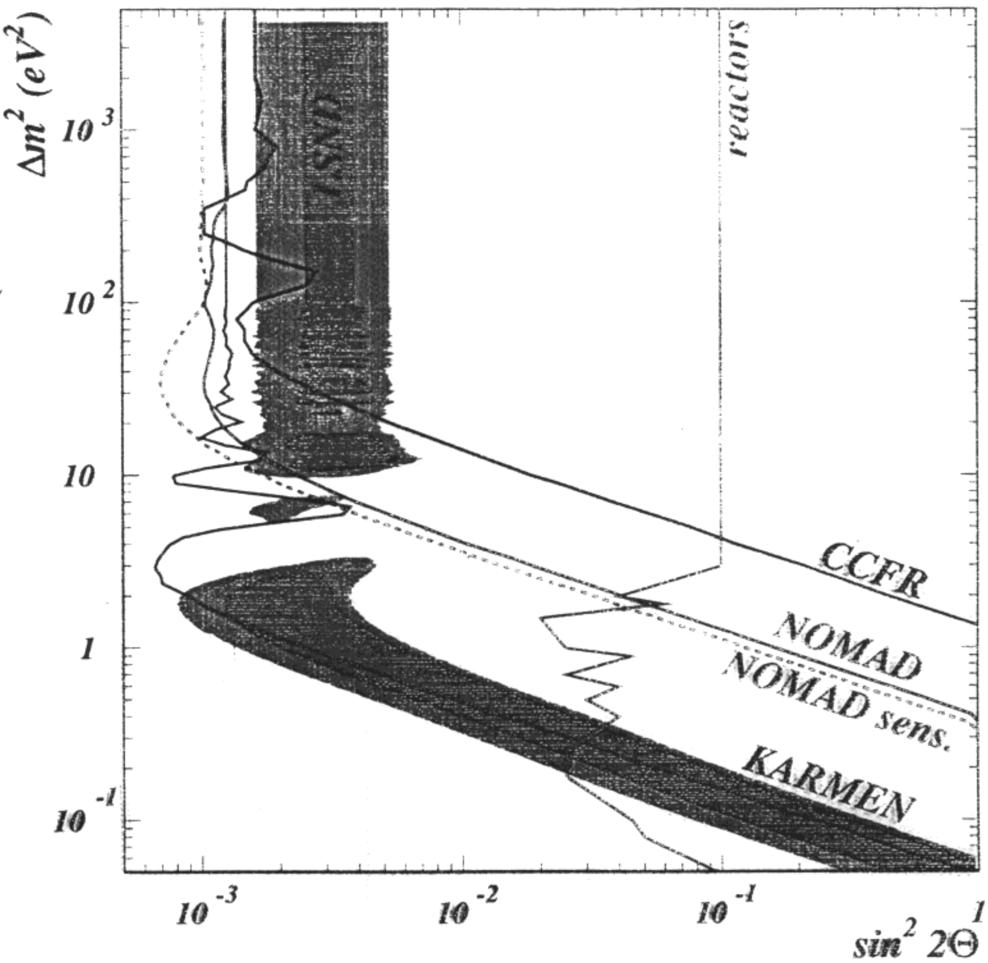
Exclusion Region (Preliminary)

(full NOMAD data sample)



At large Δm^2: $\sin^2 2\theta < 1.2 \times 10^{-3}$ @ 90% C.L.

(Feldman-Cousins method)

- Exclude high Δm^2 region of oscillation parameters from LSND down to $\sim$ 10 eV^2
- NOMAD is not sensitive to low Δm^2 LSND solutions (limited by beam energy and source–detector distance)

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Conventional ν beams @ accelerators

from π, K decay:

- not pure ν_μ (ν_e) beams
- caveat of hadronic cross-section, particle transport which limit the sensitivity

– small coupling & Δm_{ij}^2 –

more intense, more collimated, better defined ν beams than the conventional-ones !!!

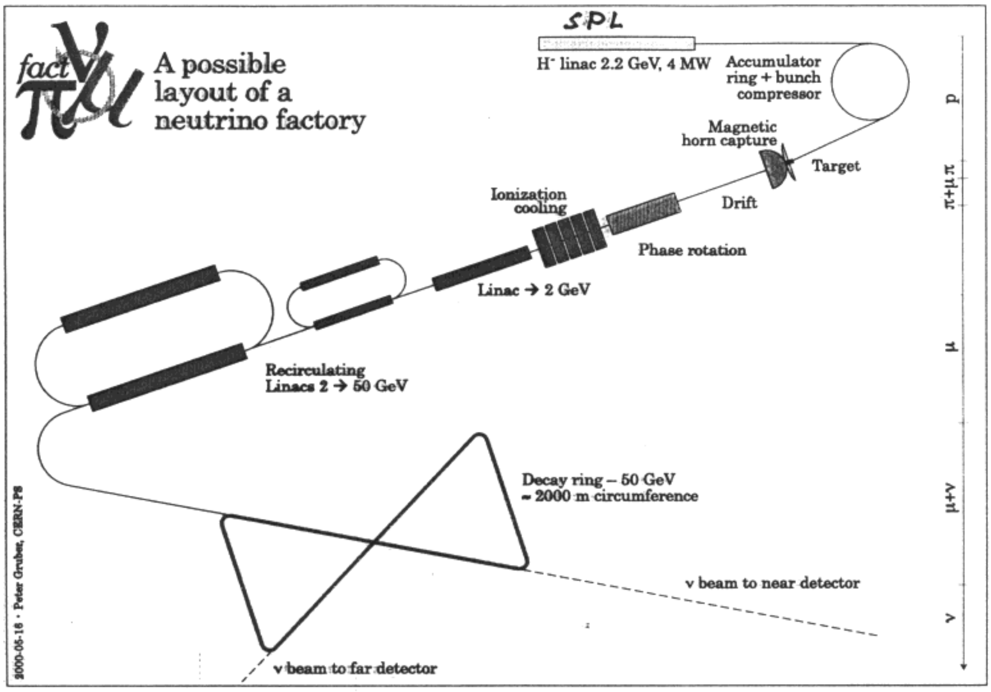
super beam

β - beam

ν- factory !

3: ν - factory : ν from μ - decay νF @ CERN

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



- 2.2 GeV/c protons from SPL (4 MW) → Accumulator
- πs produced in thin target (Hg)
  captured by Magnetic Horn → Drift space
- μs cooled/accelerated by a linac up to 2 GeV/c
- μs accelerated up to 50 GeV/c by Recirculating Linacs
- μs injected in the μ-accumulator
  deliver in the straight sections ν_s to experiments

SPL : $1.1 \cdot 10^{16}$ p/s $\rightsquigarrow$ 10^{23} p/year

$0.3 \cdot 10^{21}$ μ decay/year ($\rightsquigarrow \nu$)

Several advantages of νF over conventional ν sources:

- decay is $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$

  $\Rightarrow$ pure beam of equal number of $\bar{\nu}_\mu$, ν_e ($2\nu/\mu$-decay!)

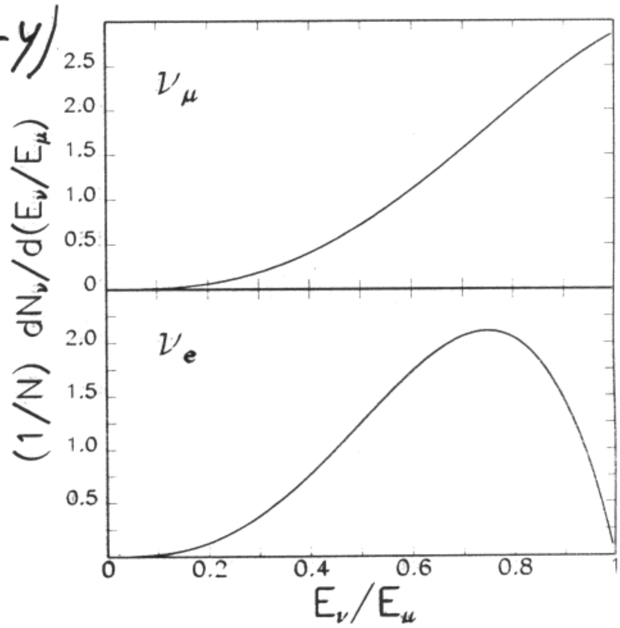
- μ momentum is well defined

  $\Rightarrow$ perfectly calculable E_ν-spectra and ϕs

$$\left.\frac{d^2 N_{\nu_\mu,\bar{\nu}_\mu}}{dy\, ds}\right|_{\theta\simeq 0} \simeq \frac{E_\mu^2}{\pi m_\mu^2 L^2} \cdot 2y^2 \cdot (3-2y) \cdot \theta(y)\, \theta(1-y)$$

$$\left.\frac{d^2 N_{\nu_e,\bar{\nu}_e}}{dy\, ds}\right|_{\theta\simeq 0} \simeq \frac{E_\mu^2}{\pi m_\mu^2 L^2} \cdot 12y^2 (1-y) \cdot \theta(y) \cdot \theta(1-y)$$

ds: detector area $\quad y = E_\nu / E_\mu$



- ϕ_ν grows like E_ν^2

  (conventional ν beam $\phi_\nu \propto E_\nu$)

$$N_{cc} \sim \phi_\nu \cdot \sigma_\nu \sim \frac{E_\nu^3}{L^2}$$

$$N_{osc} \sim \phi_\nu \cdot \sigma_\nu \cdot P \simeq \frac{E_\nu^3}{L^2} \cdot \sin^2 \frac{L}{E_\nu} \sim E_\nu$$

$\Rightarrow$ optimal beam energy as large as possible: $E_\mu = 50$ GeV

- pure ν beam: sensitivity to oscillations increases linearly with statistics

$$P(\bar{\nu}_\mu - \bar{\nu}_e) \propto \frac{1}{N_{\mu^+}}$$

conventional ν beams: sensitivity $\propto$ square root of statistics

$$P(\nu_\mu - \nu_e) \propto \frac{\sqrt{N_{e^-}}}{N_{\mu^-}} = \frac{\sqrt{f}}{\sqrt{N_{\mu^-}}} \qquad f = \frac{\nu_e}{\nu_\mu} : \text{ beam contam}$$

- extimed ν-flux intensity: more $\times$ 100 w.r.t. conventional bea

$E_\mu = 50$ GeV , $0.3 \cdot 10^{21}$ μ-decay/year

$\bar{\nu}_\mu$ cc/KT/year $\simeq 0.3 \cdot 10^6$ } at 732 Km
ν_e cc/KT/year $\simeq 0.5 \cdot 10^6$

cfr CNGS: $2.4 \cdot 10^3$ ν_μ cc/KT/year
20 ν_e cc/KT/year

- extimed ν angular divergence $\times$ 1/5 w.r.t. conventional beau

$\Rightarrow$ VLBL, $L \sim 3000$ Km, 7000 Km, $E_\nu \sim 30$ GeV !!!

- ν intensity precisely determined from μ-current ($\lesssim 1\%$

- ν à la carte: μ-momentum tunable to experimental requirements!

νF: very intense, pure, collimated, well defined ν beams

short-baseline
medium-baseline
long-baseline
very long-baseline $\frac{L}{E} \gtrsim 10^3$ Km/GeV

$\Rightarrow$ $\simeq$ full Δm^2 exploration

νF: available oscillation channels $(\mu^+ \to e^+ \bar{\nu}_\mu \nu_e)$

$\nu_e - \nu_\mu$ appearance, wrong-sign muons, μ^-
$\bar{\nu}_\mu - \bar{\nu}_e$ " " " electrons, e^+

$\nu_e - \nu_x$ disappearance, E spectrum, NC/CC
$\bar{\nu}_\mu - \nu_x$ " " "

$\nu_e - \nu_\tau$ appearance, τ^- events
$\bar{\nu}_\mu - \bar{\nu}_\tau$ " τ^+ events

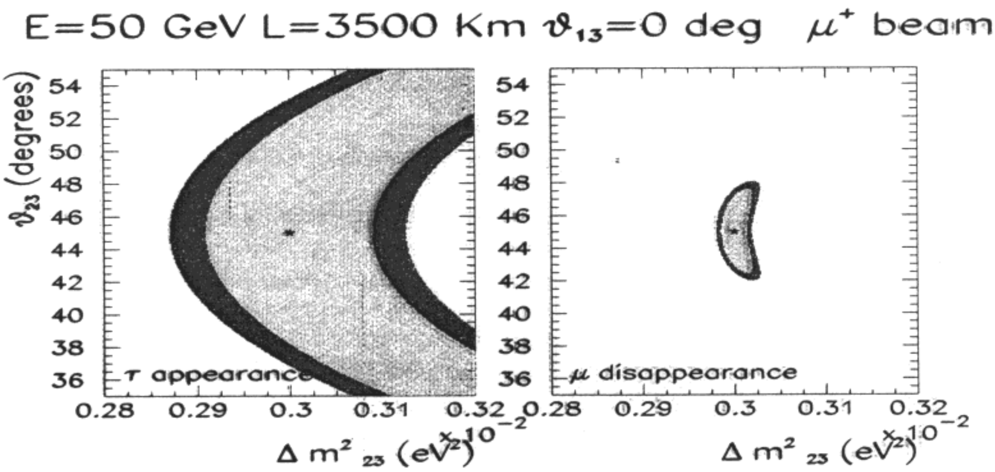
$\rightarrow$ charge identification is mandatory!!!

measurement of θ_{23} & $|\Delta m^2_{23}|$ $(\bar{\nu}_\mu \to \bar{\nu}_\tau)$

$\bar{\nu}_\mu$ - disappearance basic measurement @ νF (μ^+ identif.)

backgr., only $\bar{\nu}_\mu \to \bar{\nu}_\tau$
$\hookrightarrow \tau^+$
$\hookrightarrow \mu^+$

$\bar{\nu}_\tau$ - appearance but... backgr. from charm



$\Rightarrow$ θ_{23}, $|\Delta m^2_{23}|$ within 1% down $\sim 10^{-4}\,eV^2$!

40 kt, $\vec{B}$ detector à la MINOS for 10^{21} useful μ-decays
$E_\mu = 50$ GeV, $L = 3500$ km

measurement of θ_{13} ($\nu_e \rightarrow \nu_\mu$)

ν_μ - appearance

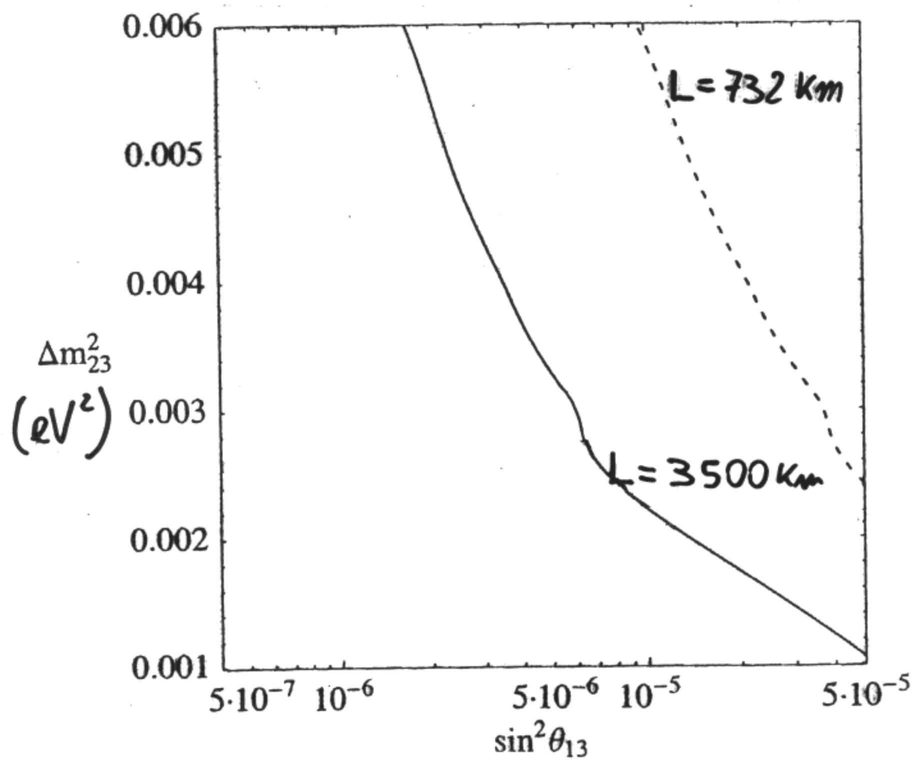
- basic measurement @ νF !
- search for "wrong sign" μ^-

  θ_{13} measured with $\Delta\theta \sim 0.1°$ down to $1°$

  with 40 KT, $\vec{B}$ detector

- S.K. region well covered:

  asymptotic sensitivity: more × 3 order of magnitude w.r.t. present limit



- if LMA scenario

  θ_{13} correlated to δ

measurement of the sign of Δm^2_{23}

LBL, VLBL $\Rightarrow$ ν propagate inside the Earth $\Rightarrow$ MSW effect

if $\Delta m^2 \gtrsim A = 2\sqrt{2}\, G_F\, n_e\, E_\nu$ (matter mass term)

oscillation probability depends on sign of Δm^2_{13} (~~Δm^2_{12}~~)

$$\Delta m^2_{32} \longrightarrow -\Delta m^2_{32} \iff P_{\nu_e \to \nu_\mu} \to P_{\bar{\nu}_e \to \bar{\nu}_\mu}$$

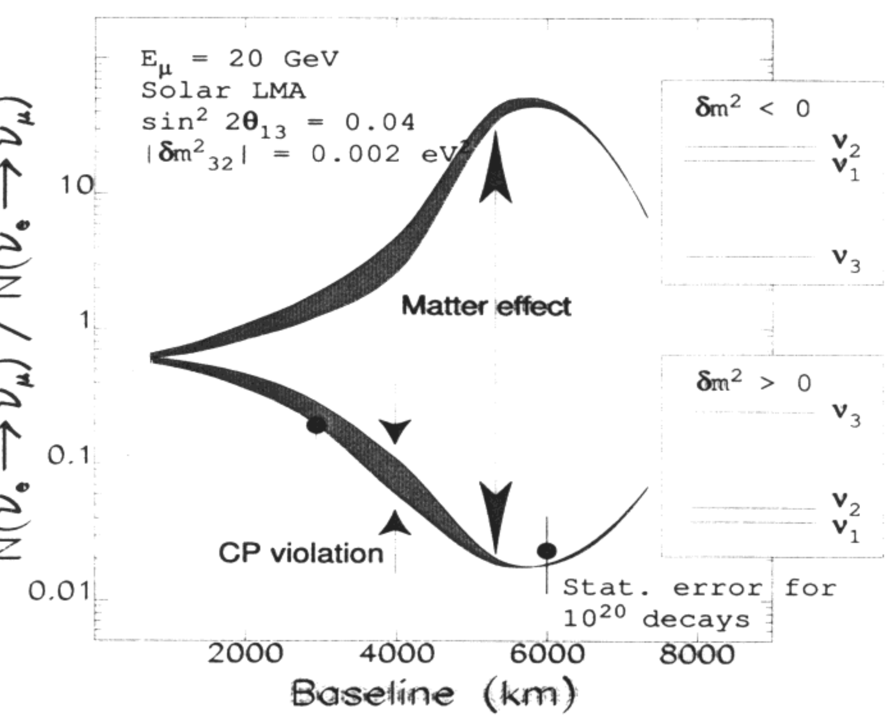
($A \to -A$ in the oscill. probability)

for: $\Delta m^2_{32} > 0$ $\quad P(\nu_e \to \nu_\mu)$ enhanced, $P(\bar{\nu}_e \to \bar{\nu}_\mu)$ suppressed

$\Delta m^2_{32} < 0$ $\quad$ " suppressed, $\quad$ " enhanced

$\Rightarrow$ <u>with both μ^+, μ^- beams:</u>

Wrong-Sign Muon Measurements



$L \sim 3500$ Km

40 KT, $\vec{B}$ detector

sign (Δm^2_{23}) determina.

@ 99% C.L. for

$\theta_{13} \sim 1^\circ \div 10^\circ$

$|\Delta m_{23}|^2 \sim 1 \div 5 \cdot 10^{-3}\ eV^2$

CP : measurement of δ

- basic measurement @ νF with both μ^+, μ^- beams

$$A = \frac{P(\nu_e - \nu_\mu) - P(\bar{\nu}_e - \bar{\nu}_\mu)}{+} = \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin \delta \cdot \sin \frac{\Delta m_{12}^2 \cdot L}{4 E}$$

via "wrong-sign" μs.

- CP observable if LMA (favoured by most recent data)

- δ and θ_{13} to be determined simultaneosly in both μ^+, μ^- beams

↳ A vs. E, L to disentangle δ, θ_{13}

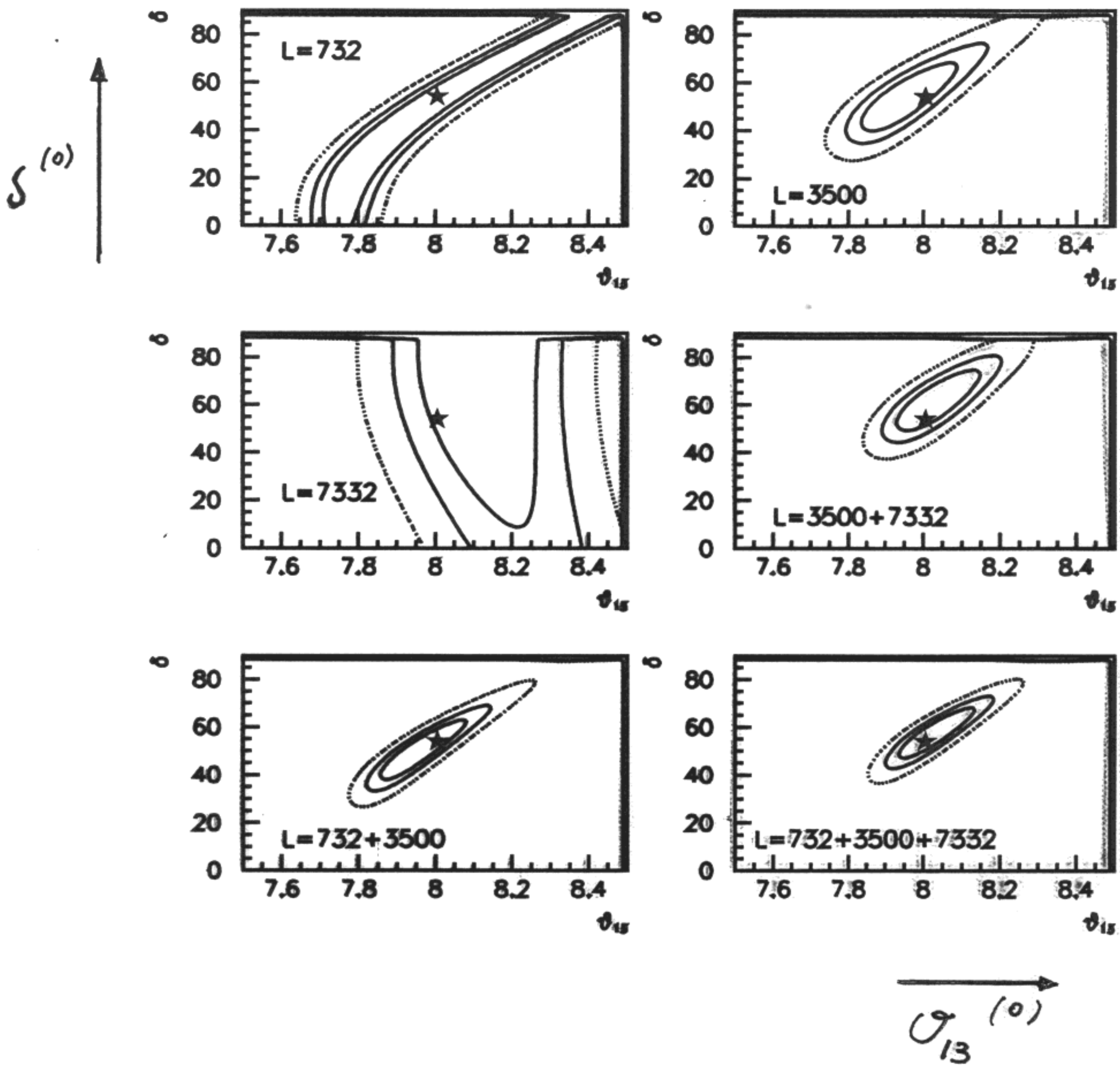
- matter effects => fake CP term which hides genuine CP

↳ careful choise of L

- sensitivity to CP decreases linearly with Δm_{12}^2

40 kt, $\vec{B}$ detector: for $|\Delta m_{12}^2| \geq 2 \cdot 10^{-5}$ eV^2 $\delta = \begin{cases} 0° \\ 90° \end{cases}$

well separated @ 99% C.L.



$\theta_{13} = 8^\circ$

$\delta = 45^\circ$

L = 732 k

3500 k

7332 k

40 KT, $\vec{B}$

detector

C.L. 68.5

90 %

99 %

two detectors:

"near" L = 732 Km

"far" = 3500 Km

⇒ νF: complete measurement of mixing matrix

CP measurement in the leptonic sector

fundamental impact on the ν physics !!!

4. super beams

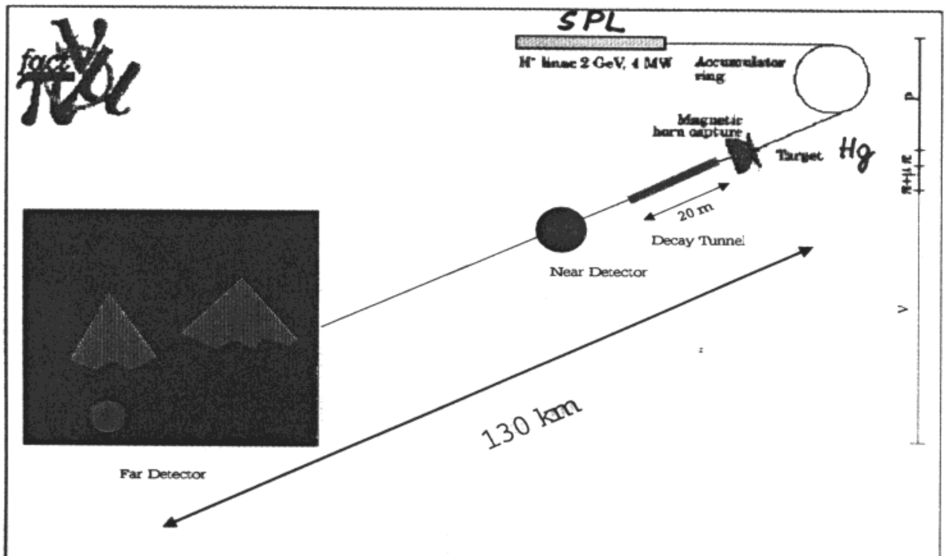
- CERN-MODANE high intensity, low energy ν_μ beam from π

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\quad \hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

$\phi_{\nu_\mu} = 1.7 \cdot 10^{14} \nu_\mu / 10^{23} \text{pot}/1a$

$E_{\nu_\mu} \sim 0.25\,\text{GeV}$

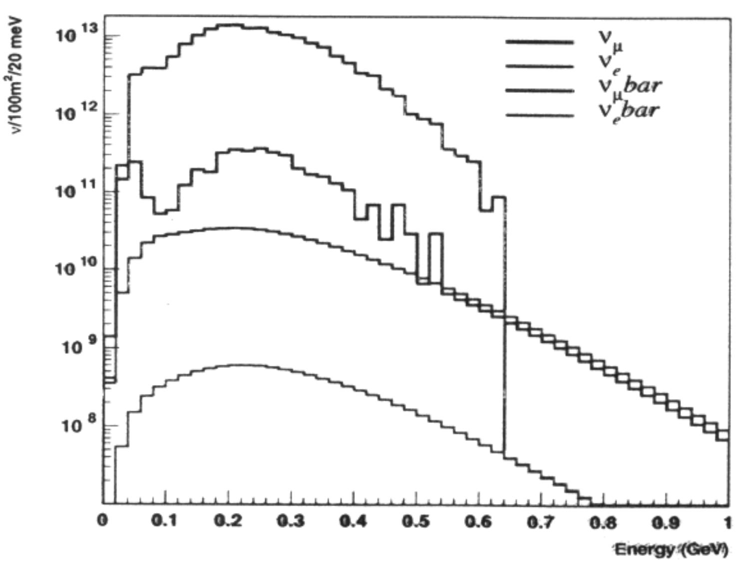
$L = 50\,\text{Km}$



Possible Low Energy Super Beam Layout

$P_{proton} = 2.2\,\text{GeV}$,

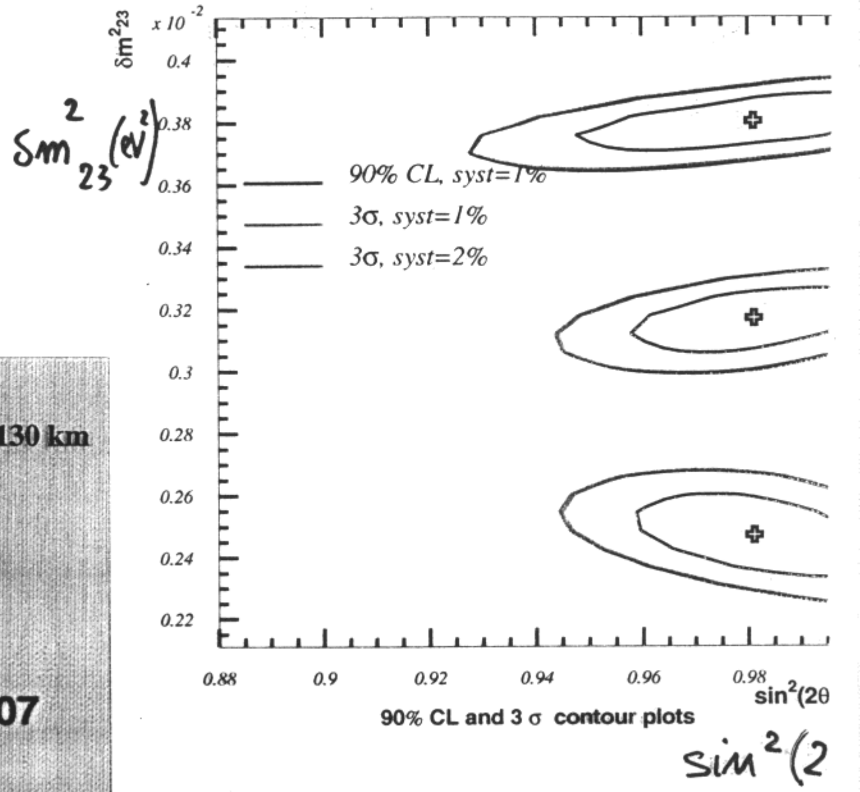
$I_{prot} > 10^{23}\,p/\text{yea}$

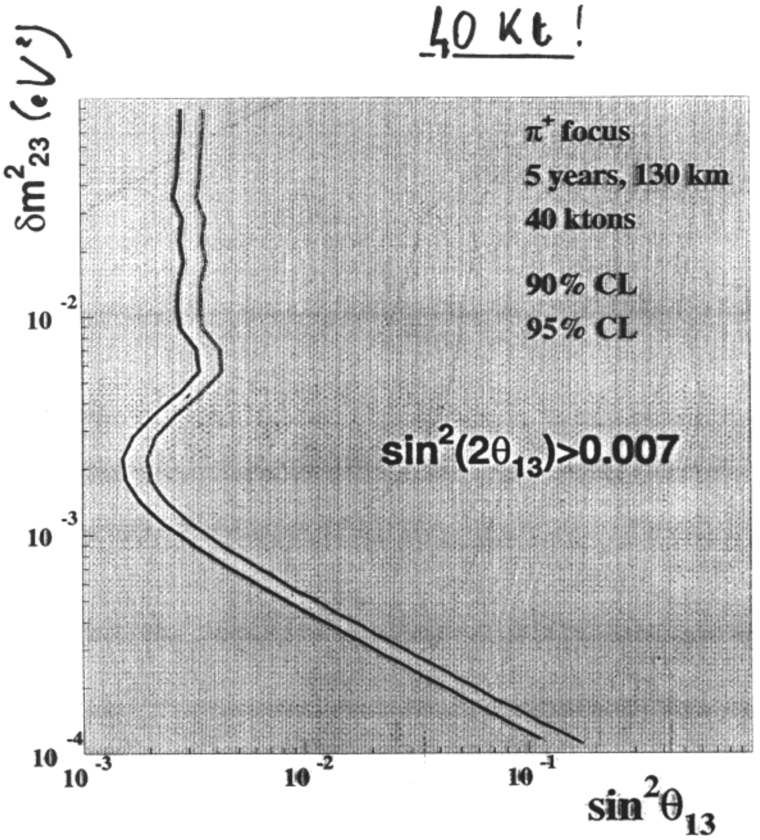


- ν_e production by K largely suppressed by threshold effects
  - ↳ ν_e from μ-decay ($\nu_e/\nu_\mu \sim 0.4\%$)
- close / far detectors: syst. error $\sim 2\%$

$\nu_\mu \rightarrow \nu_e$ appearance!

... expected sensitivity → 5 years! 40 Kt!





- $\sin^2(2\theta_{13}) > 0.007$
- $\sin^2(2\theta_{23})$, $|\Delta m^2_{23}|$ within $\sim 2\%$
- poor sensitivity to ~~CP~~, $\delta = 0°$ separated from $\delta = 90°$ in a small region of parameters ⇒ 400 Kt ?

- JHF project 50 GeV/c protons (PS), 0.77 MW (→ 4 MW)

  ~1 GeV ν_μ beam → S.K. L = 295 Km

  5000 ν_μ cc/year ... $3.3 \cdot 10^{14}$ p/3.4 s 10^{21} p/year

  but...a real conventional ν beam ... K/π ?

  sensitivity ≃ CERN-MODANE exp.

APPROUVED ~ 2007!

Conclusions

- conventional ν beams @ accelerators

  ⇝ will hopefully confirm ν oscillations

  – predicted 45 years ago by B. Pontecorvo –

  as a first signal of new phenomena

  beyond the Standard Model –

- νF based on μ-decay: the only way we know to produce a ν beam suitable for solve the ν oscillation puzzle and investigate ~~CP~~ in leptons !

- superbeams : only a first step toward νF ?

- A. O. B. ?