NuFact Oscillation Working Group

CERN, 8 May 2000

Conventional beam vs neutrino factory

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Proceedings
νFad 99

Neutrino beams: μ decay vs π decay

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Abstract

We propose a preliminary comparison, in terms of general features, yields and event rates, of neutrino factories based on muon decay and conventional neutrino beams based on pion decay. The comparison focuses on high energy neutrinos, with average energy of 10 Gev or more.

Most emphasis is given to beams designed for modern searches of long baseline neutrino oscillations. Performance for conventional short baseline neutrino experimentation is also considered.

In both type of facilities, yields and event rates increase steeply with the average energy of the neutrino parents. At equal energy of the parent, ν_μ rates about 100 times larger and ν_e rates more than 10000 times larger appear accesible to neutrino factories. This large additional yield of high energy ν_e, that can be separated by lepton number (charge) recognition in the neutrino detector, is possibly the most important new feature of neutrino factories. A much wider and complete range of physics goals, including study of the full leptonic mixing matrix and possibly of CP violation, can be addressed.

Decay of a measurable rate of muons provides a much better known and controllable neutrino flux, free of the hadronic uncertainties on the number and distribution of parent hadrons that affect conventional neutrino beams. This is likely to be one of the major advantages of neutrino factories. In addition, they can provide beams more flexible, tunable, and orientable and a more effective production of neutrinos per unit consumption of energy.

Because a much shorter shielding is required, short baseline neutrino detectors will be able to profit of much more intense and collimated beams. Sofisticated devices of small dimensions will be able to replace the traditional large coarse grain detectors.

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1 Introduction

Neutrino factories based on muon decay are the subject of this workshop. My task is to collect here a number of qualitative and quantitative arguments

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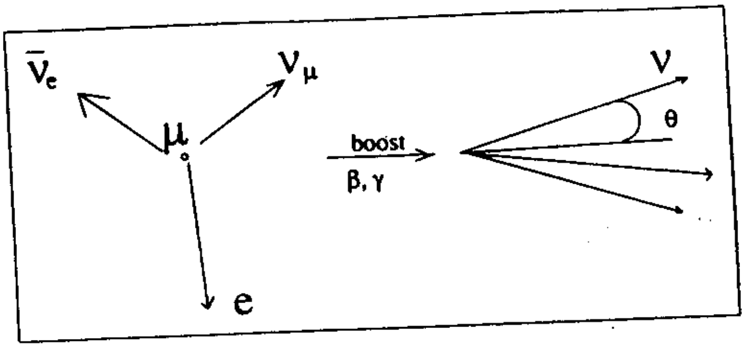

Fig. 5. Muon decay.

the smallness of the solid angle covered by the neutrino detector, most of the flux will come from pions of higher energy and line of flight parallel (or made parallel by the focusing system) to the central (proton) beam axis.

The flux of neutrinos through the neutrino detector described above can now be simply calculated for a beam where N_π pions, with γ factor γ_π, decay. At very large L, only neutrinos emitted with θ angles very close to 0 and therefore with $y = 0.427$ will be relevant. The detector surface element being $dS = 2\pi L^2 d\cos\theta$, one gets, for large γ_π ,

$$d^2N_\nu/(dSdy)(\theta = 0) = N_\pi \gamma_\pi^2 \delta(y - 42.7\%)/(\pi L^2) \qquad (4)$$

π decay
2-body

4.2 muon decay

Muon decay is a three body decay of a spin 1/2 particle (fig 5).

In the very forward direction, however, one obtains the same sharply peaked angular distribution of neutrinos (with forward value growing as γ^2 and width shrinking as $1/\gamma^2$). Similarly the flux of neutrinos in a detector centered on the axis of the muon storage ring straigth section and placed at a very large distance L from the region of muon decays, can be simply calculated for a straigth section where N_μ muons, with γ factor γ_μ, decay. At very large L, one gets, for large γ_μ,

$$d^2N_\nu/(dSdy)(\theta = 0) = N_\mu \gamma_\mu^2 F_\nu(y)/(\pi L^2) \qquad (5)$$

μ decay
3-body

The only difference with respect to pions is that the y distributions $F_\nu(y)$ are not δ functions (at 42.7% of the parent momentum), but real distributions over the full y range. They are different for the ν_μ ($\bar{\nu}_\mu$) and $\bar{\nu}_e$ (ν_e) produced in μ^- (μ^+) decays and are shown in fig. 6. The ν_μ ($\bar{\nu}_\mu$) distribution is harder in the average ($< y >= 0.7$) than the $\bar{\nu}_e$ (ν_e) distribution ($< y >= 0.6$). We have assumed here that we are dealing with unpolarized muons.

F_ν

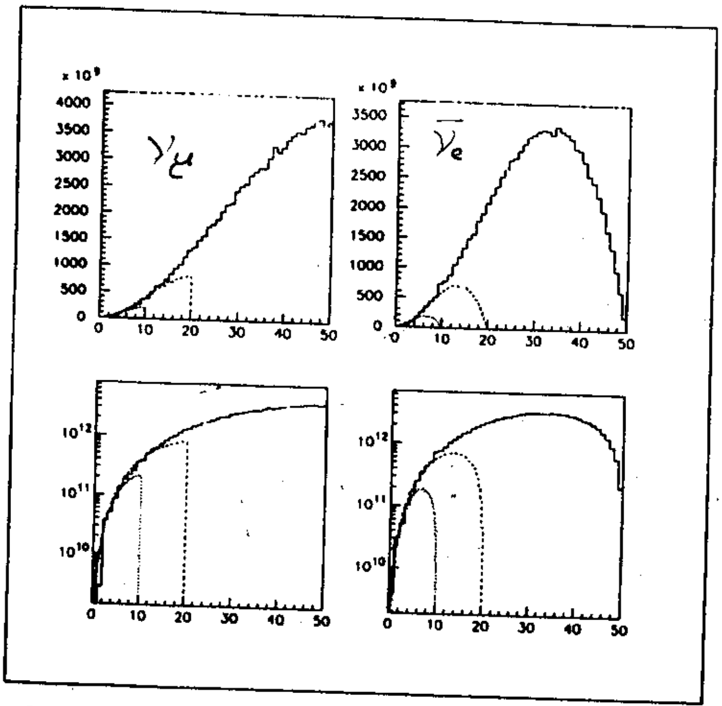

Fig. 8. Energy distribution of ν_μ (left) and ν_e (right), in linear (top) and log (bottom) scale, from an ideal μ^+ beam of 10, 20 and 50 Gev/c momentum.

that the ν flux at low energy stays unchanged and additional flux at higher energies is gained when the muon momentum grows. One is thus lead to the conclusion that as much energy as possible should be provided to the muons in their final acceleration. This is the best use one can make of them after the difficult tasks of collection and phase space reduction will have been painfully mastered.

- comparison of the two types of neutrino facilities should take in account that the performance of both depends strongly on the energy of the parents.

The claim that the highest parent momentum should be sought is however only one of the aspects. Apart from the fact that on physics ground a lower energy may be sometime desirable, neutrino yield per unit time is influenced also by the number of parent decays that one is capable to induce per unit time.

In general, for both type of neutrino sources, the forward flux from N_{decay} decays of parents with γ factor γ_{decay} is

$$d^2N_\nu/(dSdy)(\theta=0) = N_{decay}\gamma^2_{decay}F_\nu(y)/(\pi L^2) \qquad (6)$$

π and μ !

N_{decay} is the number of decays of neutrino parents that any given facility is capable to provide. It multiplies a kinematical and geometrical factor that depends on the particular decay being considered only via the $F_\nu(y)$ function

$$N_{CC} = N_{decay} \frac{E^3_{decay}}{m^2} \langle y \rangle \frac{1}{\pi L^2} \sigma_0 N_{TARGETS}$$

$\langle y \rangle = 42.7\%$ $\pi \to \nu_\mu$
70% $\mu \to \nu_\mu$
60% $\mu \to \bar{\nu}_e$

F_ν relevant for N_{cc}
$\langle y \rangle E_{decay}$

basic conclusions
at νFact99

$\phi \sim N_{decays} E^2_{decay}$

for both π and μ

! comparison must be done at same Energy of decay parents !

	NuMI	CNGS	νFact
E_ν	~10 GeV	~17 GeV	
E_{decay}	~ 24 GeV	~40 GeV	20 GeV
$N_{decays/yr}$		$7.2\ 10^{18}$	$7.2\ 10^{20}$

⇒ **factor 100** + **energy factor!**

$\wr$

somewhat high

.... thou not outrageous

N.B. ① $(\gamma_\mu)^2/(\gamma_\pi)^2 = \left(\frac{m_\pi}{m_\mu}\right)^2 = 1.78$ at same E_{parent}

② $\langle Y_{\mu\to\nu_\mu}\rangle = 70\% = 1.63 \cdot 42.7\%$

$\langle Y_{\mu\to\bar{\nu}_e}\rangle = 60\%$

Additional arguments at νFact99

$\underline{\underline{\nu_e}}$!! + sign selection of μ's

.... CKM, $\cancel{CP}$, matter effects

control of source (flux, spectra ...

minimal uncertainties

can do w/o near detector

even "disappearance"

flexibility, tunability, orientability

VLBL

$\underline{\underline{2}}$ far locations

"no" shielding .... small, very intense

SBL stations

.... "jewel" detector physics

e: Thu, 24 Feb 2000 09:20:39 +0100 (MET)
om: Friedrich DYDAK <Friedrich.Dydak@cern.ch>
: Vittorio PALLADINO <vittorio.palladino@na.infn.it>
oject: Re: High-intensity conventional neutrino beam (fwd)

ar Vittorio:

eresting reading, isn't it? I am sending this to you, to underline what portance is given to the themes which you are treating in your written ntributions to Lyon'99, and what further importance it will have in nterey.

ncerely, Friedrich

: You MUST submit your two contributions, even if brief.

-------- Forwarded message ----------
te: Wed, 23 Feb 2000 16:13:29 -0800
om: Burton Richter <BRichter@SLAC.Stanford.EDU>
: Friedrich DYDAK <Friedrich.Dydak@cern.ch>
: Alain Blondel <Alain.Blondel@cern.ch>,
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Yoshitaka KUNO <yoshitaka.kuno@kek.jp>
ıbject: Re: High-intensity conventional neutrino beam

ear Friedrich:

think you under-rate the difficulties of using a mixed muon-electron eutrino source and over-rate the difficulties of using a more conventional ource. We are not really going to know much more about electron-neutrino roperties until the KamLAND and MiniBOONE experiments are done. From what ? e know from the solar neutrino problem, it will take a very sophisticated etector to untangle electron and muon-neutrino interactions with the mixed eutrinos originating in a high-energy muon storage ring.

lectron and neutrino backgrounds in muon-neutrino beams produced onventionally (either horn focused, or monochromatic) are typically below ne per cent. It should be easier to make a definitive determination of ıon neutrino properties and mixing from those beams if they can be made ntense enough and clean enough. I don't have enough information on what ind of conventional beams you can create to answer my own question. I till think it would be quite interesting to hear from someone who has done he necessary work.

egards,

urt

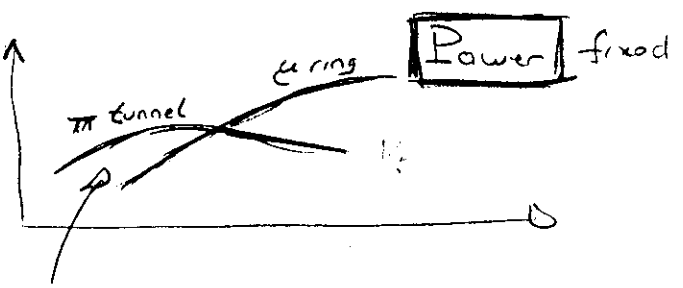
t 09:20 AM 02/16/2000 +0100, Friedrich DYDAK wrote:
On Tue, 15 Feb 2000, Burton Richter wrote:
>
> I mentioned in my earlier message that for the lower energies a
> conventional neutrino source may well be competitive and faster to build.

>> The higher the neutrino energy required, the more advantage there is for
>> the muon ring source. Could we get a talk on the potential of conventional
>> horn focused beams vs muon storage rings as a function of energy for the
>> same proton source power?
>>
>
>Dear Burt:
>
>I certainly agree that a conventional horn-focused neutrino beam is easier
>and faster to build, and that it would have a comparable beam intensity
>compared to what one gets from an associated muon storage ring.
>
>But the beam quality is very different as you know well. HERE you have
>essentially muon-neutrinos with a typical 5 - 10 % uncertainty in
>everything, with badly known backgrounds of electron-neutrinos and
>anti-neutrinos of either flavour. THERE you have well-determined
>muon-neutrinos and electron-neutrinos of equal strength, with no
>background. It is in the first instance the intense electron-neutrinos
>which make the neutrino factory superior.
>
>Why? The physics challenge is the determination if the mass-sign of
>Delta_m squared, and of the CKM elements of the neutrino mixing matrix, up
>to and including CP violation. Remaining with muon-neutrino beams alone
>does not bring us much further, so why bother with yet another round of
>conventional horn-focused neutrino beams? To attack Theta_13 and the CP
>violation phase, we need electron-neutrino beams.
>
>This said, I hasten to add that I have of course nothing against a talk
>which either agrees or disagrees with this opinion of mine, with a view to
>putting the arguments on the table.
>
>Sincerely, Friedrich
>
>

~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Professor Burton Richter
Director Emeritus
Stanford Linear Accelerator Center
Tel: 650/926-2601
Fax: 650/926-4500

→ talk on the potential of

present on
April 10 or
May 8



how powerful

is this true?
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

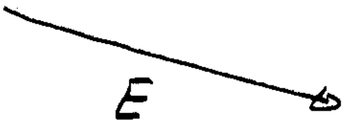
energy dependence

	$\langle E_\nu \rangle$ (Gev)	$\langle E_\pi \rangle$ (Gev)	$\frac{N_{\pi\,decay}}{pot}$	$\frac{1}{\pi L^2}$	$(\langle E_\pi \rangle / m_\pi)^2$
S SBL→LBL x 5!	1.5	3.5	.1	$6\ 10^{-13}\,m^2$ at 732 Km	$6.3\ 10^2$
uMI	10	24	.13		$2.7\ 10^4$
NGS	17	40	.15		$8.3\ 10^4$

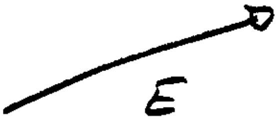
↑ will document it better

…. about energy independent

decay



acceptance



$$1 - e^{-L/\gamma c \tau} \lesssim \frac{L}{\gamma c \tau}$$

p_T ~ constant

p_L grows

…. will include

arguments and numbers

νFact

use PJK

0.004 $\mu/p/$Gev

in the ring!

4 MW $\Rightarrow$ 2.5 10^{16} Gev/s

10^{14} μ/sec

10^{21} μ/yr

(1 yr ~ 10^{7}s)

for E_{μ} = 3.5 Gev

24 Gev

40 Gev

50 Gev

↳ 82 Gev π give
same $\langle E_{\nu} \rangle = 35$

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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NEUTRINO FACTORY NOTE 09

A Cost-Effective Design for a Neutrino Factory

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C. Johnson and E. Keil
CERN, Geneva, Switzerland

Abstract

The design of a neutrino factory based on a muon storage ring draws upon several tried and tested technologies, upon existing design work for other accelerator projects, e.g. neutron spallation sources, but it also depends on the development of technical solutions to certain specific requirements. These include the efficient capture of muons in a large volume of phase space, some reduction in overall phase space volume by ionization cooling, fast acceleration to the desired energy to avoid unacceptable decay losses and storage in a decay ring optimised for its purpose as a neutrino source. There is no obvious single combination of machines to achieve this aim. Here we present a scenario which relies to a large extent upon known technologies together with a relatively unambitious mix of new schemes. Some will be tried and tested during design and construction. Others during the early operational phase of the facility leading to a staged upgrade path – a well-proven strategy in the development of accelerator complexes.

Geneva, Switzerland

November 25, 1999

Supported by US Department of Energy contract DE-AC02-98CH10886

Acceleration

min E for full sc cells 7.5 GeV min E for 1/4 sc cells 1.8 GeV

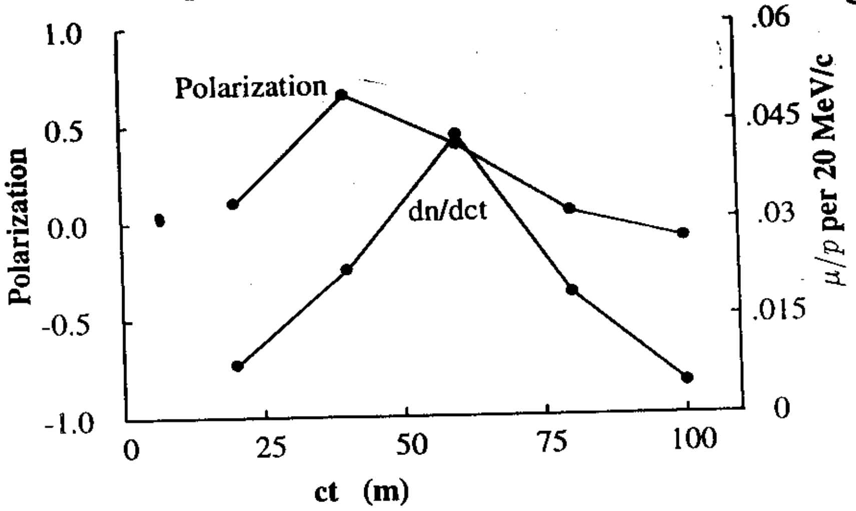
		Lin 1	Lin 2	Recirc 1	Recirc 2
p	GeV/c	.1-.7	.7-2.0	2-8.2	8.2-30
freq	MHz	175	350	350	350
Grad	MV/m	15	10	10	10
Δ p	GeV/c	.6	1.3	1.5	5.5
n		1	1	4	4

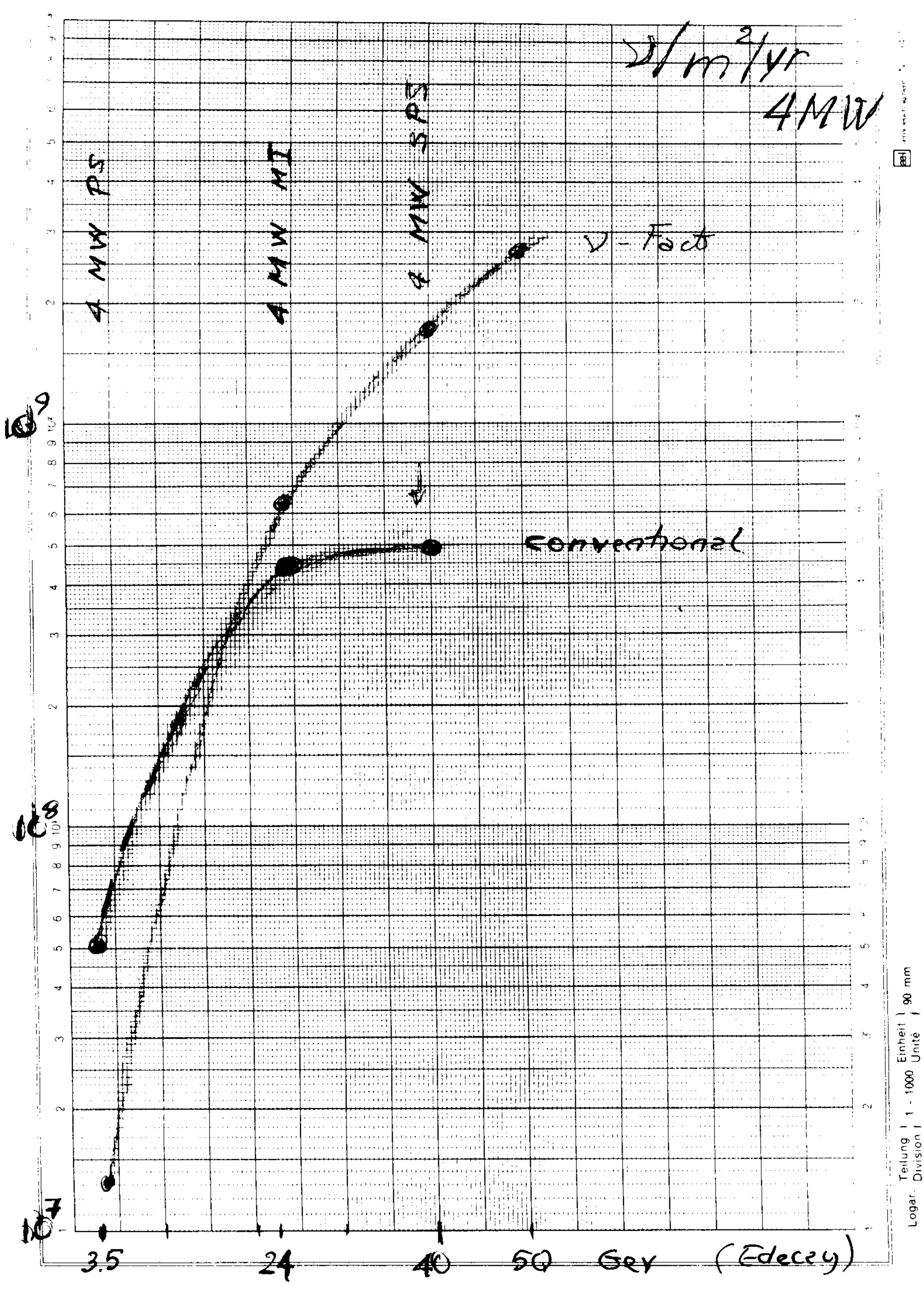
Muon Budget

	Factor	μ/24 GeV proton
Muons after Match (below 1 GeV)		0.66
Muons after Phase Rotation #1 (selected)	0.45	0.3
Muons after Phase Rotation #2 (selected)	0.7	0.21
Muons after RF Capture	0.7	0.15
Muons after Cooling	0.9	0.13
Muons after Acceleration	0.7	0.092

.004
μ/GeV/p

Polarization vs. position along the bunch train




ν/m²/yr
4MW
4 MW PS
4 MW MI
4 MW SPS
ν-Fact
conventional
10^9
10^8
10^7
3.5
24
40
50
GeV
(Edecay)
Logar. Teilung | Division | 1 - 1000 Einheit | Unité | 90 mm

BEAM PARAMETERS

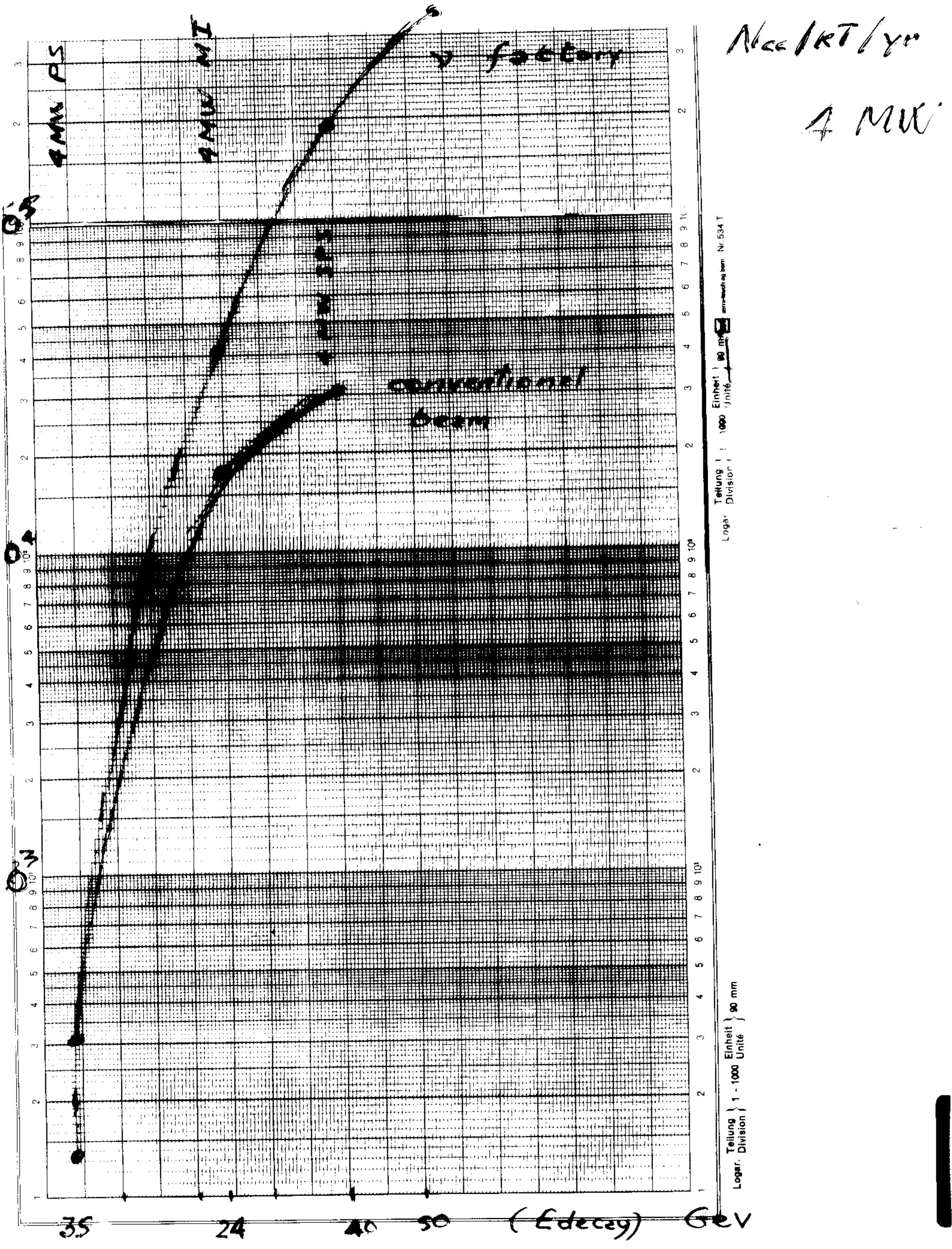
Conventional Neutrino beam vs Neutrino Factory beam

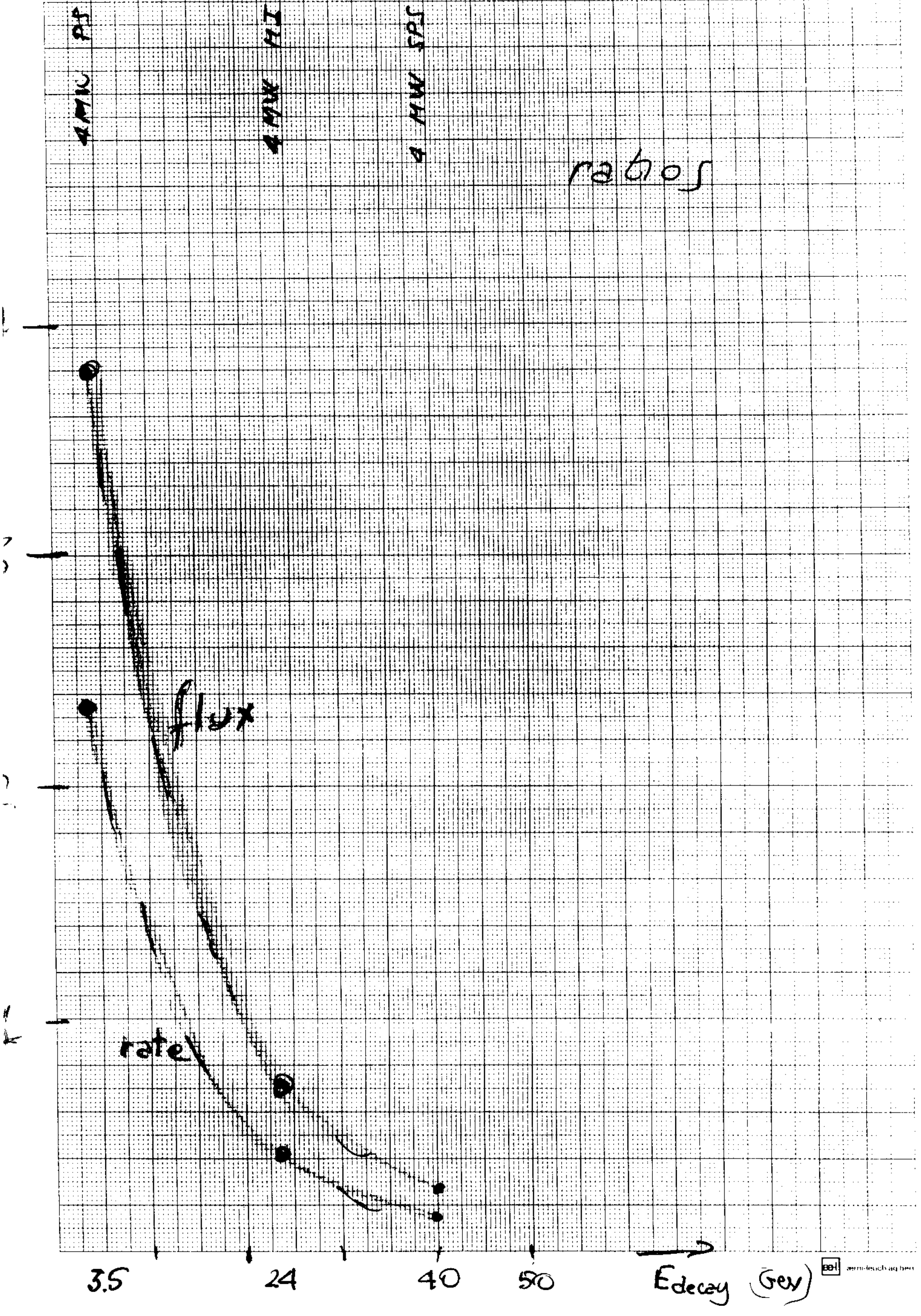
	Conventional	Neutrino Factory
parents	π^+, K^+ or π^-, K^-	μ^- or μ^+
ν_μ beam	ν_μ	$\nu_\mu : \bar{\nu}_e = 1 : 1$
background	$\sim 2\%$ of $\bar{\nu}_\mu$, $\sim 1\%$ of ν_e	none
$\bar{\nu}_\mu$ beam	$\bar{\nu}_\mu$	$\bar{\nu}_\mu : \nu_e = 1 : 1$
background	$\sim 6\%$ of ν_μ, $\sim 0.5\%$ of $\bar{\nu}_e$	none
variation of average energy	limited	free within factor of ~ 3
uncertainty of ν energy spectrum	$\pm 10\%$	$< 1\%$
uncertainty of ν radial spectrum	$\pm 10\%$	$< 1\%$
uncertainty of absolute ν flux	$\pm 10\%$	$< 1\%$
ν flux per year at 730 km (ν_μ per cm^2)	3×10^7 (optim. NGS) (4.5×10^{19} 400 GeV pot)	3×10^9 (10^{21} injected 50 GeV μ)

$2\ 10^{20}$ μ's/year

$\downarrow$

10^{21} μ's/year


Ncc/kT/yr
4 MW
ν factory
4 MW PS
4 MW MI
4 MW SPS
conventional beam
10^5
10^4
10^3
3.5
24
40
50
(Edecay) GeV
Logar. Teilung / Division 1 - 1000 Einheit / Unité 90 mm
Nr. 534 T


4 MW PS
4 MW MI
4 MW SPS
ratios
flux
rate
3.5
24
40
50
Edecay (GeV)

still .... major technical questions . . .

) have assumed conventional ν beam

can *digest* high power (4 MW)

can it really?

— — — — — — —

WANF thin 3 mm ⌀ target

CNGS 4 mm

Be → C to stand 0.5 MW !

thin (⇒ fragile) to preserve high energy forward parents

can't defeat your purpose

higher E_π ⇒ higher E_{pot}

... acceleration takes longer

takes more power per pot

MI	120 GeV	1.9 sec	≈ 60 GeV/sec/pot
SPS	400 GeV	6 sec	

and ... of course ...

... major physics questions --

conventional ν beam cannot do

① $\nu_e \to \nu_\mu, \nu_\tau$ θ_{13}, CKM

② sign Δm^2

matter effects in general

③ $\cancel{CP}$ via Asym($\nu_e \to \nu_\mu$, $\bar{\nu}_e \to \bar{\nu}_\mu$)

We won't go very far

w/o ν_e's !

ANYWAY