What do we need to do to determine neutrino fluxes to +- 10^{-3} at a Neutrino Factory?

source: M. Apollonio et al,
OSCILLATION PHYSICS WITH A NEUTRINO FACTORY
arXiv:hep-ph/0210192 v1 13 Oct 2002
+ ISS report
→+ recent work by Marco Apollonio (NUFACT10)
→ and IDR report

why?

In the high intensity scenario

- the event rates in the far detector are above 10^{6}/yr/100kton

➔precision measurement of the mixing angle and mass differences.

ESPECIALLY NOW THAT $\sin^2 2\theta_{13}$ seems to be large, systematics are crucial

2. the event rates in the near detectors are at the level of 10^{7}/yr/kg (depends on position of detector)

➔ precision measurements of total cross-sections

➔ structure functions

➔ SM tests etc…

CP Asymmetries may be only a few percent, systematics must be much better than %. Try to do as well as possible, ***there will be physics in every bit of precision.***

Neutrino fluxes $\mu^+ \to e^+ \nu_e \nu_\mu$

ν_μ/ν_e ratio reversed by switching μ^+/μ^-
$\nu_e\, \nu_\mu$ spectra are different
No high energy tail.

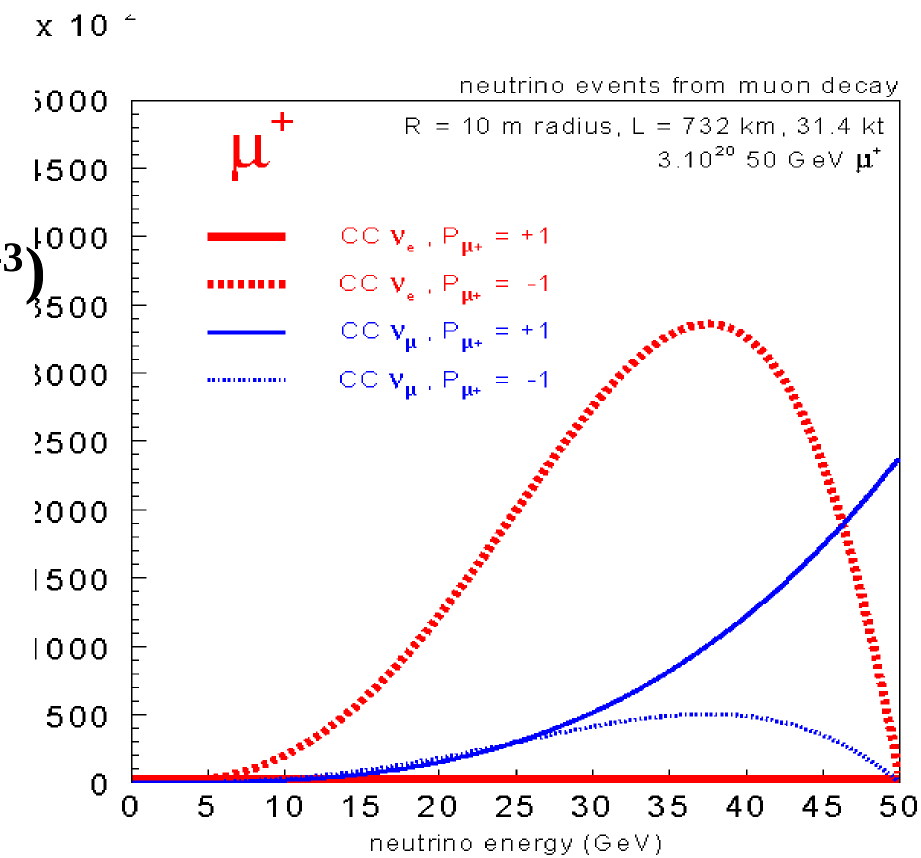
Very well known flux (aim is 10^{-3})

- absolute flux measured from muon current
or by $\nu_\mu\, e^- \to \mu^-\, \nu_e$ in near expt. IMD

-- in triangle or race-track ring,
muon polarization precesses and averages out

for 'free':
-- $E\&\sigma_E$ calibration from muon spin precession
IMPORTANT: Event rate scales as E^3!

-- angular divergence: significant effect if $\theta > 0.1/\gamma$,
to be monitored.



μ polarization controls ν_e flux:

μ^+ -X> ν_e in forward direction

System where one stores a beam of decaying particles

Neutrino Factory,

⇨potential for excellent neutrino flux control

Main parameters to MONITOR

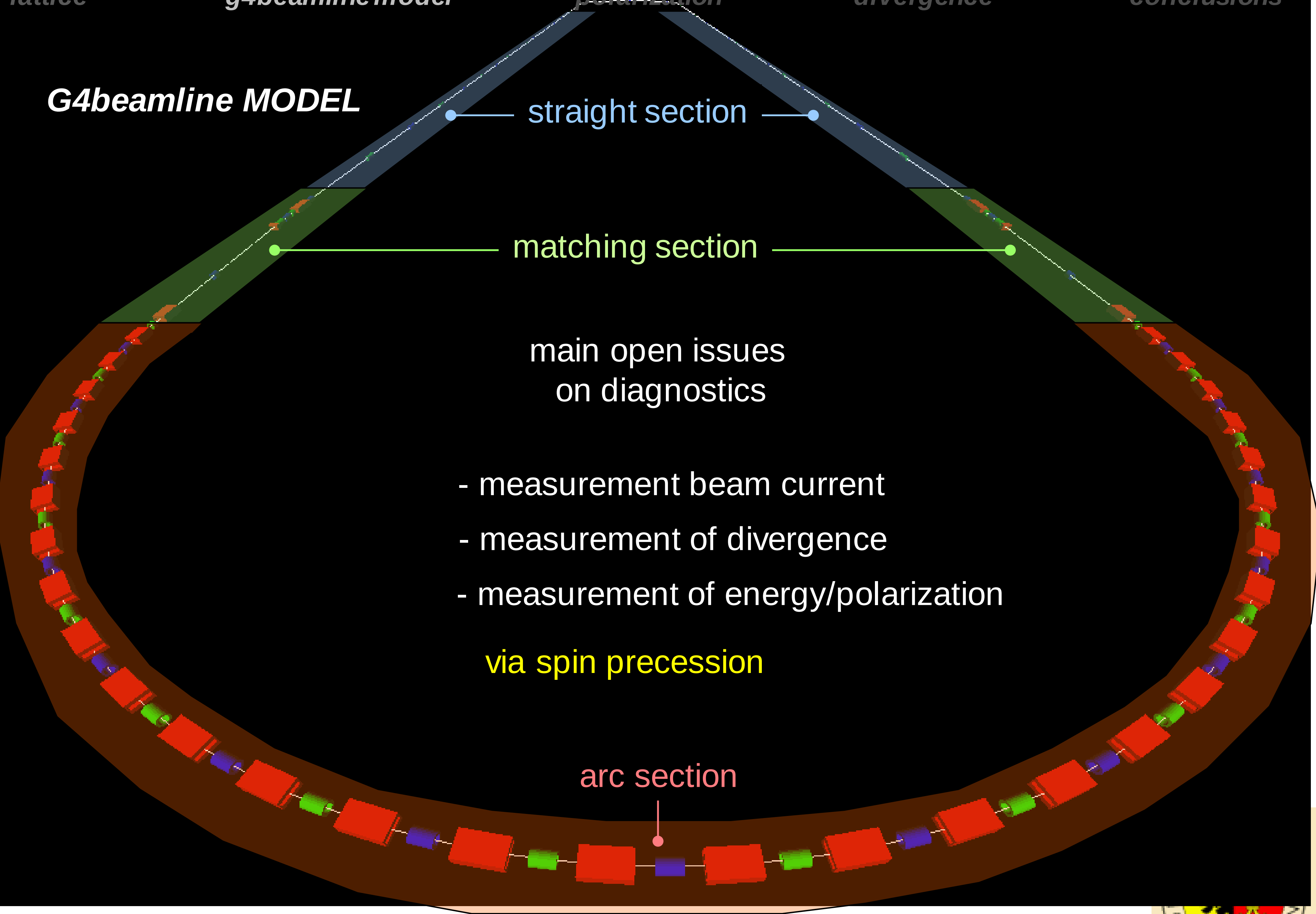
1. Total number of muons circulating in the ring,
2. muon beam polarisation, OK
3. muon beam energy and energy spread, OK
4. muon beam angle and angular divergence.
5. Theory of μ decay, including radiative effects OK

MUCH work has been taking place in IDS-NF on some aspects

-- Marco Apollonio has implemented polarimeter in NUFACT ring!
With ~ 3×105 electrons per turn reaching the device and 50 turns sampled, we expect a statistical precision of
0.2% on the central muon energy and 4% on the energy spread
for each machine fill.
with 50 fills of the ring per second, the statistical uncertainties on the flux will be negligible. The systematic uncertainties are also expected to be small.

-- Tsenov et al have verified inverse muon decay IMD as capable to provide a fixed candle (equiv. to Bhabha scattering in lepton collider.

G4beamline MODEL



main open issues
on diagnostics

- measurement beam current
- measurement of divergence
- measurement of energy/polarization

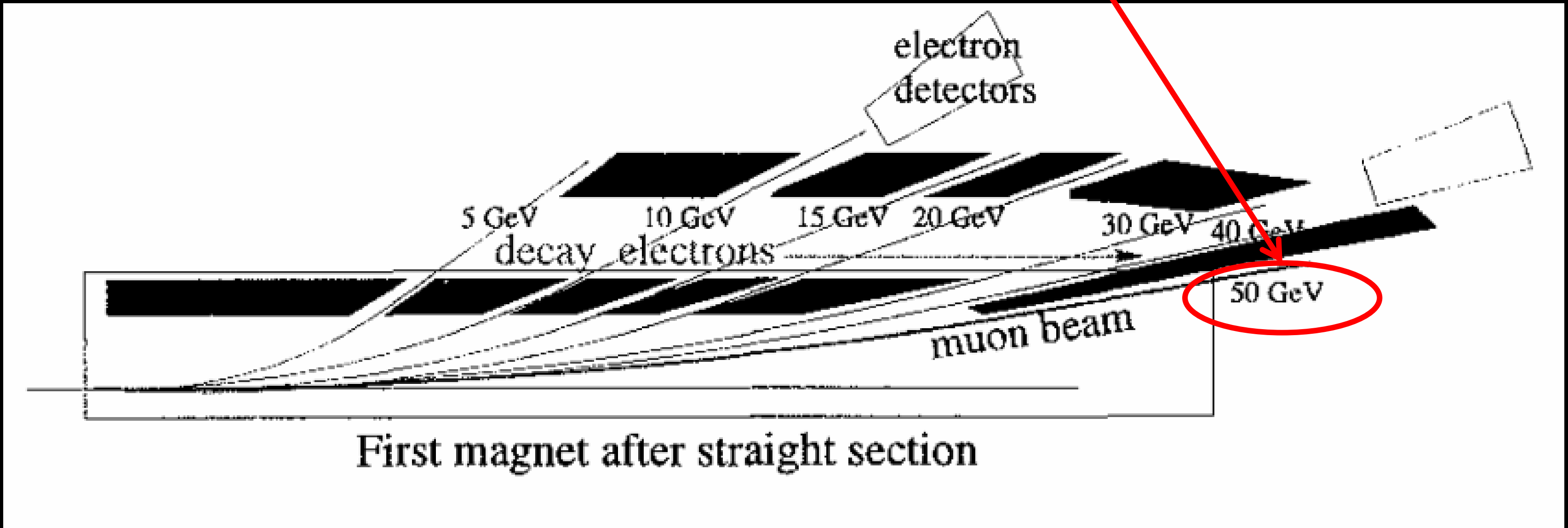
via spin precession

This is somewhat ideal ... we need to collect the electrons!

How do we turn it into a *realistic device* for our case?

suggested [Blondel – ECFA 99-197(1999)] to use the *first bending magnet* after the decay straight section to SELECT electron energy bins: what does that mean today with a realistic lattice (25 GeV)?

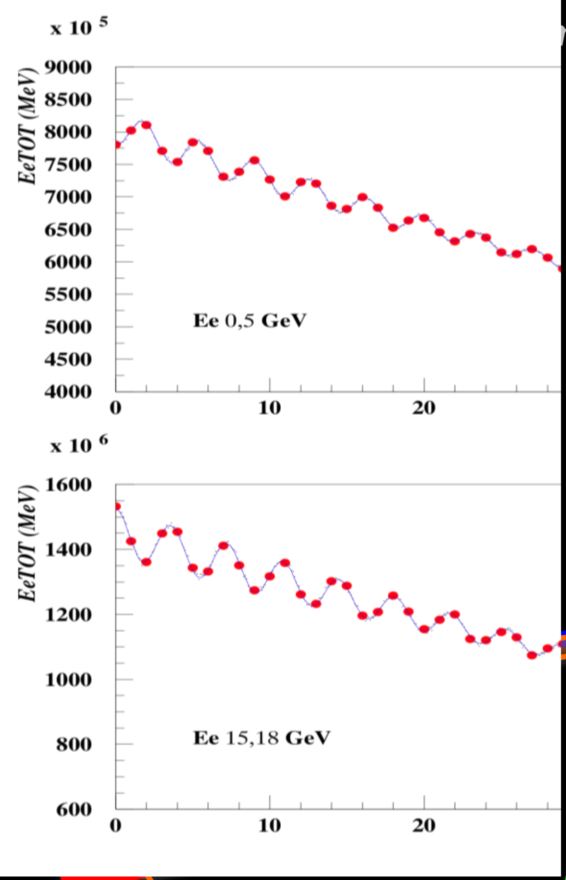
In fact electron is emitted ~parallel to μ (due to the high γ)

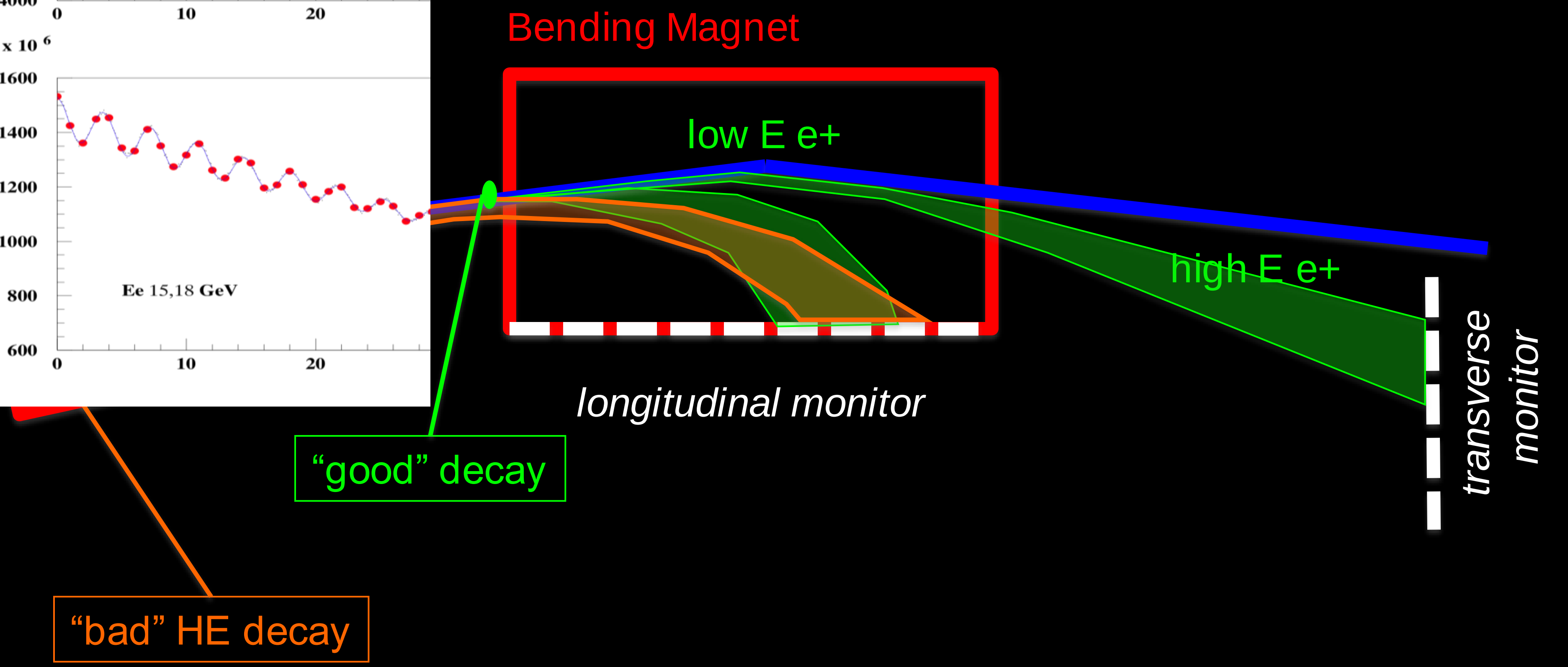


The spectral power of the 1st magnet depends on its *FIELD* and *LENGTH*

A *G4Beamline simulation* used to determine downstream electron distributions

Device location and Naming Convention





Absolute number of muons in the ring: maybe the most difficult?

Total beam current: Beam Current Transformer

-- difficulties:

1. presence of decay electrons in the ring?

Keil CERN-NUFACT Note 54 (2000), showed that the electrons are swept in the arcs and destroyed. Since the lifetime is 200 turns, the maximum fraction of electrons is 0.3/200 = 1.6 10^{-3} at the ***end*** *of a straight section, much less at the entrance of it.*

NOT really a problem!

→ Monitor should be placed at entrance of straight section

2. absolute calibration? 10^{-3} difficult, impossible?

3. the most practical way to cross-normalize μ^+ vs μ^- fluxes

alternative: count the electrons or photons at the exit of a straight.

this has a nice feature of counting the decays

the acceptance of the monitor (see polarimeter later) is tricky

A

More on BCT:

-- absolute calibration is performed by injecting calibrated pulses

-- noise can be an issue for slow pulses

-- really need ratio of mu+ to mu-…

investigated LHC who care about currents for luminosity prediction:

Strategy for 2011

BCT DC will remain our main source of absolute calibration in 2011. We will push their performance as much as we can with the current hardware and we reasonably think to be able to **push their absolute scale uncertainty below 1%** .

systematic error on μ^+/μ^- is dependent on this number, since there is no absolute calibration signal for the μ^+ decay

The number of bunches is not an issue, rather a help!

Absolute normalisation (ctd)

-- Near detector will measure product of flux X cross-section for individual channels

-- better: $\nu_\mu\, e^- \rightarrow \mu^-\, \nu_e$ in a dedicated near detector. IMD

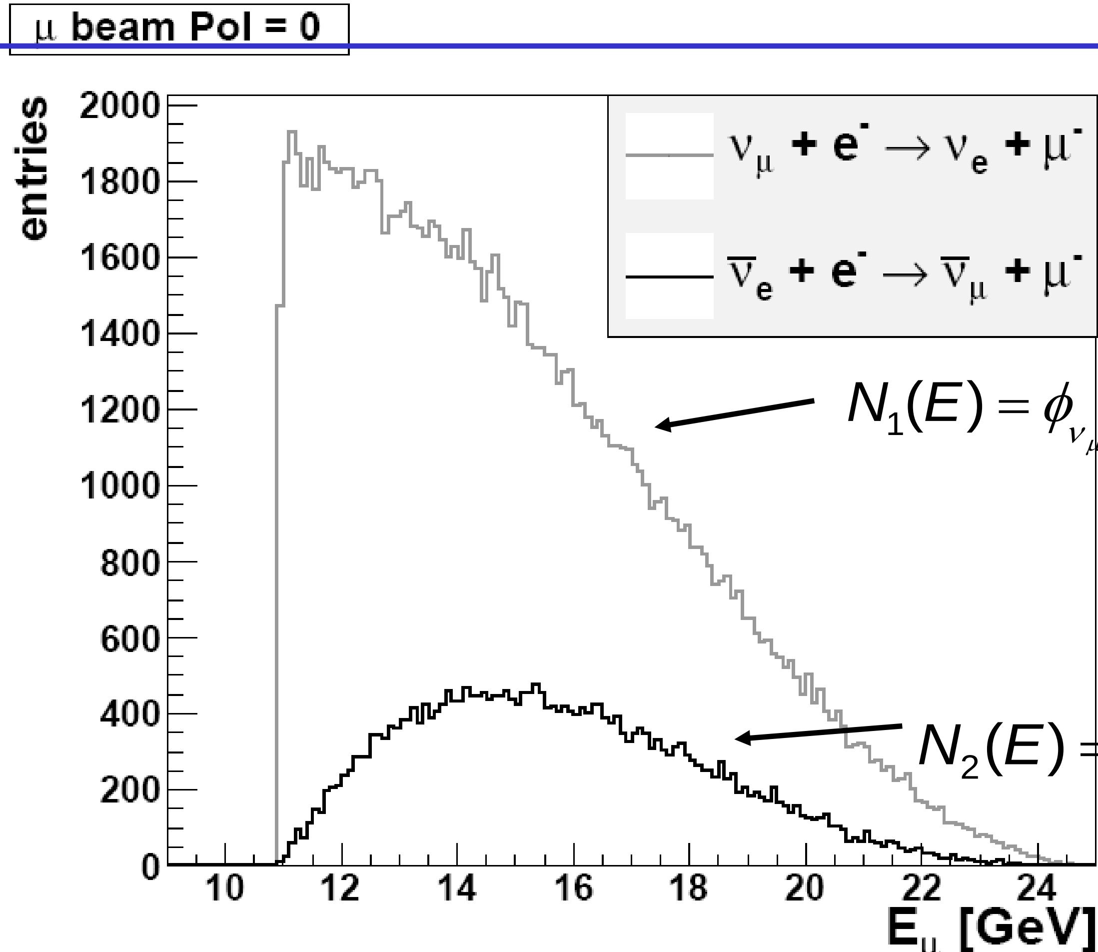
this study has been described by R. Tsenov et al in the IDR report – can do better than 1% (statistical) on fraction of exposure.

→ numbers to be consistent with far detector for a given exposure.
Increase volume of detector if needed to reach absolute normalization to 10^{-3}

This only works for neutrinos above threshold of 10.6 GeV
– what is the constrainton the flux at oscillation maximum
(e.g. 4.5 GeV for Pyhasalmi)
This only works for the μ^- beam. What about the μ^+ beam?

Inverse Muon Decay

- Charged current processes:



$$N_1(E) = \phi_{\nu_\mu e^-}(E)\sigma^{CC}_{\nu_\mu e^-}(E)$$

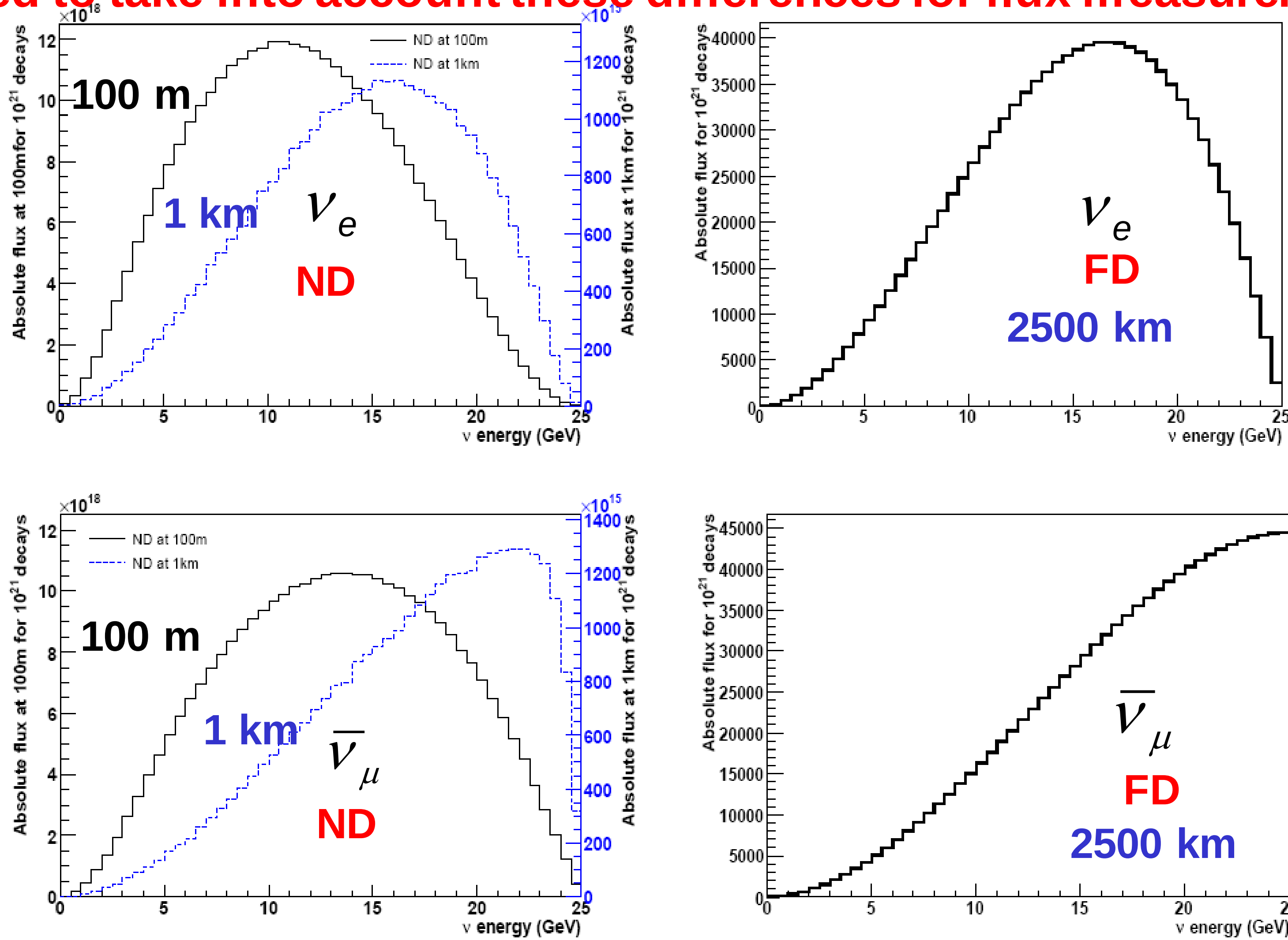
$$N_2(E) = \phi_{\overline{\nu}_e e^-}(E)\sigma^{CC}_{\overline{\nu}_e e^-}(E)$$

But this calibration depends on fraction of flux situated above 10 GeV

Spectra at Near Detector

- Near Detector sees a line source (600 m long decay straight)
- Far Detector sees a point source

Need to take into account these differences for flux measurement



Alain Blond

Angular divergence

If the muons have transverse momentum comparable to that of muon decay (50 MeV) the neutrino beam will be seriously degraded

this corresponds to $\sigma(\theta) = 0.5\ m_{\mu}\ /E_{\mu}$ ➔

for the effect of uncertainty on beam divergence to affect the flux error by less than a few 10^{-3} beam, divergence must be very small.

I. Papadopoulos has calculated the effect.

we have tried to discuss a low pressure Cerenkov or a permanent OTR detector situated in the beam.
Number of issues related to high muon rate
– 10^{14} muons/second x 200 passages / muon.

keep searching.

0.01/γ

0.05/γ

0.2/γ

0.5/γ

lose 20% of flux

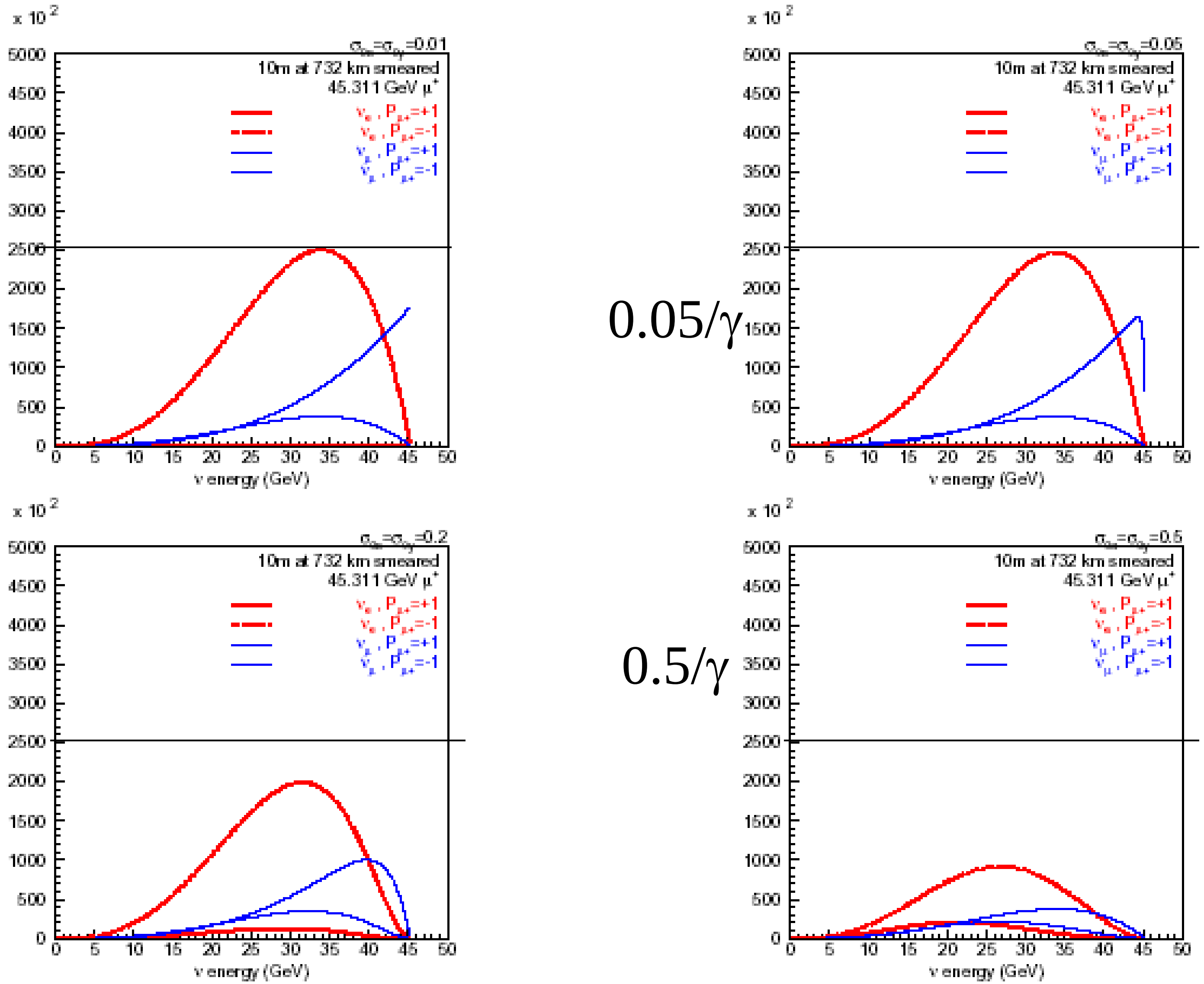
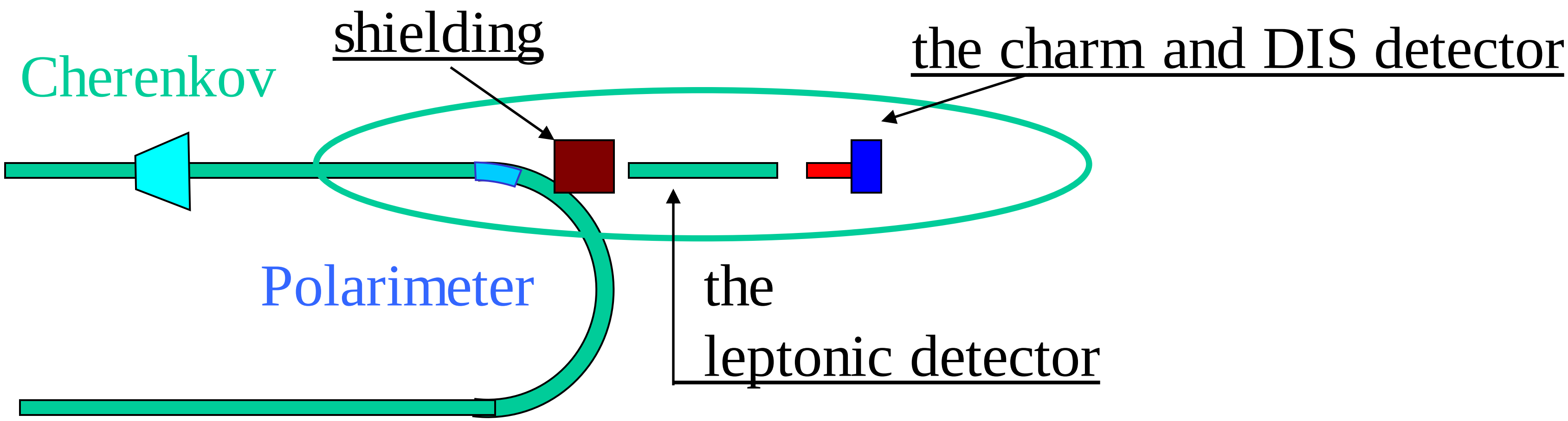


Fig. 34: *Neutrino event spectra for different beam divergences; Upper left:* $\sigma\theta_x = \sigma\theta_y = 0.01\ m_\mu/E_\mu$*; upper right:* $\sigma\theta_x = \sigma\theta_y = 0.05\ m_\mu/E_\mu$*; lower left:* $\sigma\theta_x = \sigma\theta_y = 0.2\ m_\mu/E_\mu$ *; lower right:* $\sigma\theta_x = \sigma\theta_y = 0.5\ m_\mu/E_\mu$*. It is clear that beam divergence results in a loss of events, and in a sizeable distortion of the spectra and of their*



storage ring

from the precision of this sketch, it can be concluded that a lot remains to be done.

for instance: is shielding necessary at all?

NB I have never seen a convincing response to this question there is not much coming out of the muon beam pipe except PHOTONS (everything else is swept by magnetic field)

μ^- **DECAY MODES**		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$e^- \overline{\nu}_e \nu_\mu$		$\approx 100\%$		53
$e^- \overline{\nu}_e \nu_\mu \gamma$	[d]	(1.4 ± 0.4) %		53
$e^- \overline{\nu}_e \nu_\mu e^+ e^-$	[e]	$(3.4 \pm 0.4) \times 10^{-5}$		53

[d] This only includes events with the γ energy $>$ 10 MeV. Since the $e^- \overline{\nu}_e \nu_\mu$ and $e^- \overline{\nu}_e \nu_\mu \gamma$ modes cannot be clearly separated, we regard the latter mode as a subset of the former.

10 MeV in the center of mass → 5 GeV in lab!

$>10^{11}$ photons per straight section per second!

tentative conclusions

1. 50 X_0 = 28 cm of lead (to minimize neutrino interactions) is necessary to shield near detector (that is not 100m!)

2. photon spot contains information on beam properties

3. probably obscured by the beamline magnets
$1/\gamma$ * 200m = 1m…

4. can this be used to monitor possible variations in the divergence?

5. can the radial distribution of neutrino events across the near detector be used to monitor variations of the divergence?
(probably not in absolute terms since this implies assumption on $\sigma(E)$

6. ➔ still need to measure and monitor the beam divergence for absolute value!

Conclusions

Neutrino fluxes in the neutrino factory can be reliably predicted at 1% level. 10^{-3} level requires dedicated work.

➔study specifically the BCT for $\mu^+/\ \mu^-$ ratio and absolute normalization
➔study concept of using the photons present in muon decay as monitors of rate ratio and angular effects
➔continue search for practical means of continuous measurement of beam divergence.

This will involve work by near detector and storage ring designers together.

Conclusions I

Main parameters to MONITOR

1. Total number of muons circulating in the ring,
   Need to perform a study of dedicated BCT
   Fixed candle: purely leptonic CC process
2. muon beam polarisation, polarimeter OK OK
   ➔muon beam energy and energy spread,

3. muon beam angle and angular divergence.

+beam divergence monitors e.g. Cerenkov or OTR to resolve.
Radiative Photons perhaps for short time monitoring.

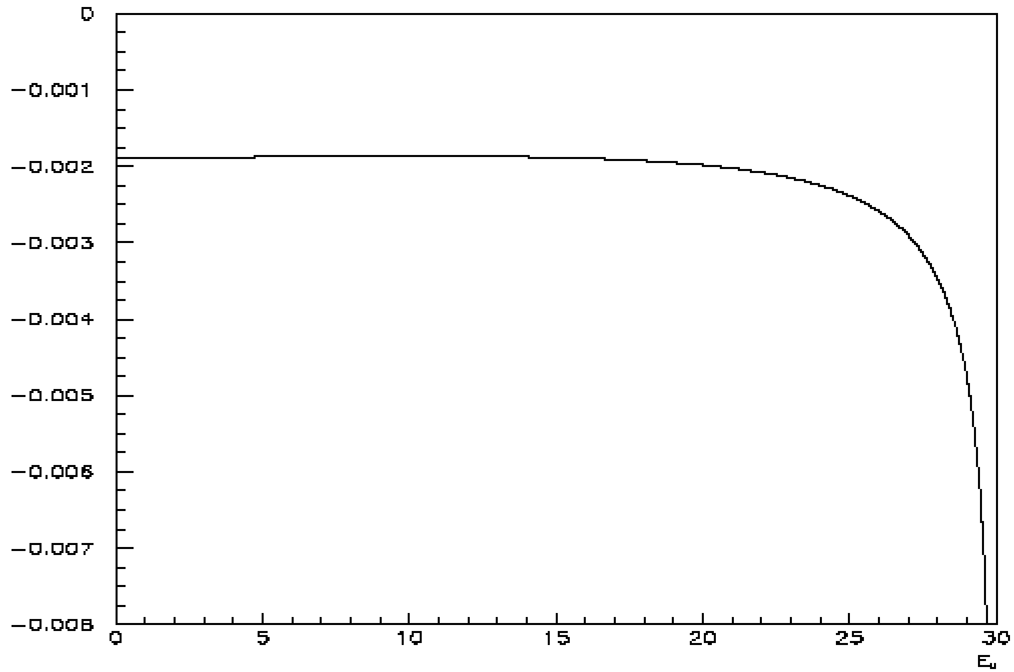
5. Theory of μ decay, including radiative effects OK

Need to integrate in the design neutrino flux monitoring to 10^{-3}.

+ quite a lot of work to do to design and simulate these diagnostics.

Radiative effects

Radiative effects
by Broncano & Mena



Ratio of 1st/0th order neutrino flux

Dominated by the presence of a photon in the final state, which reduces the energy of the neutrinos and thus the flux in forward direction.
(the total number of neutrinos emitted is constant of course)

Effect is –0.4% with a slight distortion of the end-point.
Error is small fraction thereof.