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A Large Magnetic Detector for the Neutrino Factory

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whith

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Overview

1. Physical motivation
2. Detector simulation
3. The Beam
4. Signal and backgrounds
5. Kinematical analysis
6. Study of the muon-beam momentum
7. Study of both polarities
8. Dependence on the smearing

8½. Charge identification

9. Conclusions

Wrong sign muons

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

$\bar{\nu}_\mu + N \longrightarrow \boxed{\mu^+} + X$ right sign muon	$\bar{\nu}_\mu$ CC	BACKGROUNDS
$\bar{\nu}_\mu + N \longrightarrow \bar{\nu}_\mu + X$	$\bar{\nu}_\mu$ NC	
$\nu_e + N \longrightarrow \boxed{e^-} + X$	ν_e CC	
$\nu_e + N \longrightarrow \nu_e + X$	ν_e NC	
$\nu_e \overset{osc}{\sim} \nu_\mu$		
$\nu_\mu + N \longrightarrow \boxed{\mu^-} + X$ wrong sign muon	ν_μ CC	SIGNAL

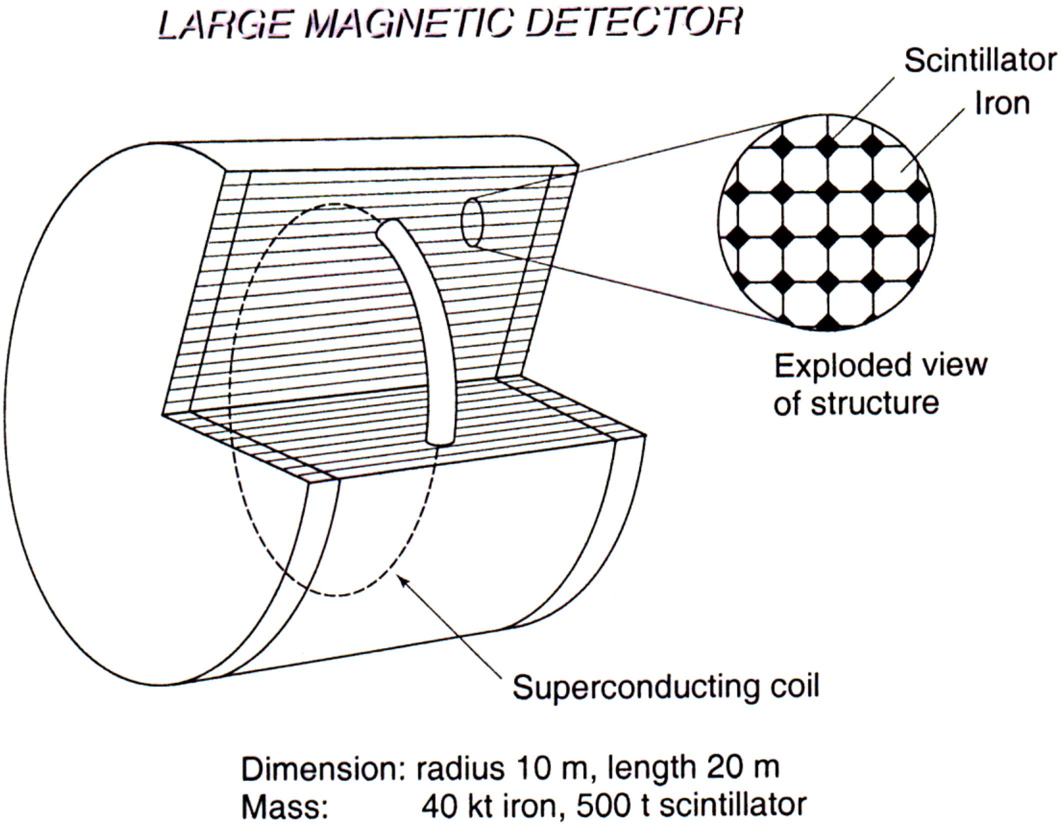
Having a very pure neutrino beam

$50\ \%\ \bar{\nu}_\mu$ $\qquad$ $50\ \%\ \nu_e$

the neutrino oscillation search is very clear

The detector

- We need large mass ⟹ 40 Kton
- Reasonable muon identification
- Good charge identification ⟹ 1 tesla magnetic field
- Reasonable hadronic shower resolution
- Reasonable angular resolution ⟹ Reasonable granularity



Dimension: radius 10 m, length 20 m
Mass: 40 kt iron, 500 t scintillator

Geant Simulation

- Simulate ν interactions with LEPTO (tuned to NOMAD data)
- Let Geant handle propagation of particles
  - Multiple scattering
  - Decays
  - Nuclear interactions
- Stop particles when they undergo a nuclear interaction. Then add they energy to a total hadronic momentum (E_{had}, θ_{had})
- Follow a track (π, K) until it interacts or decays. Then follow decay product if it is a muon
- Record a hit every time a muon croses a scientillator plane (N_{hits})

Smearing

Smearing of muon momentum resolution and hadronic resolutions following MINOS proposal

Update

- We have [redacted] updated the previous analysis
- With more statistics
  1. 10^7 $\overline{\nu}_\mu$CC
  2. 10^7 $\overline{\nu}_\mu$NC
  3. 10^7 ν_eCC

1. Golden measurements at a Neutrino Factory
2. A large Magnetic Detector for the Neutrino Factory

NuFact '99 proceedings.

- With different smearing
  1. Previous ~~analisys~~ analysis (MINOS fine grain)

$$\delta\theta_{had} = \frac{9.0}{\sqrt{E}} + \frac{25.0}{E}$$

  2. This ~~analisys~~ analysis (MINOS proposal, more conservative!!)

$$\delta\theta_{had} = \frac{16.67}{\sqrt{E}} + \frac{12.15}{E}$$

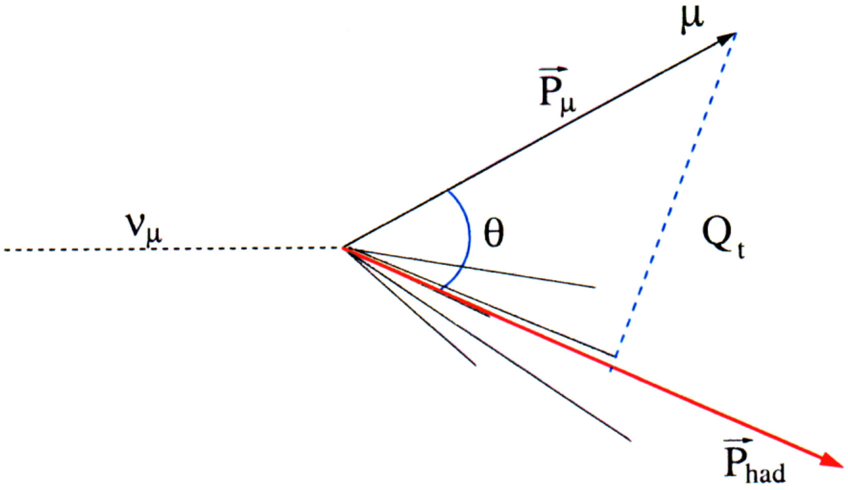
- With both polarities (stored μ^+ and μ^-)

Physical variables

The detector provides information about:
$\vec{P}_\mu$,E_{had}, and θ_{had}.

The most simple analisys we can think on is based in two variables:

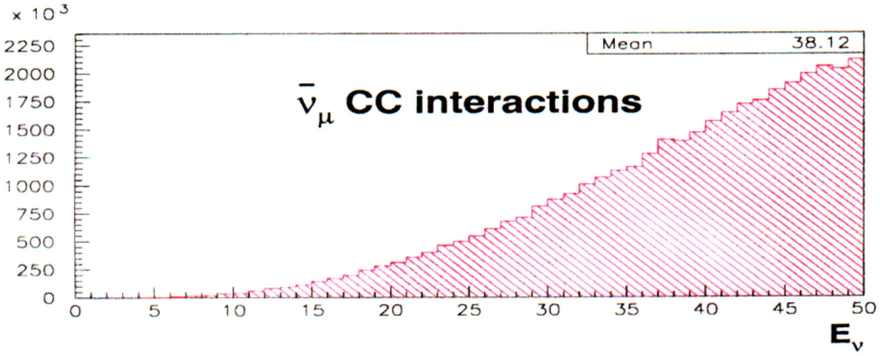
- The momentum of the muon P_μ
- Q_t

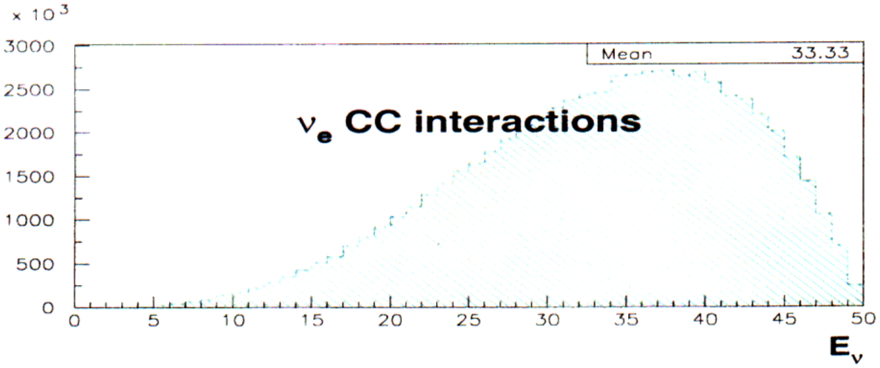


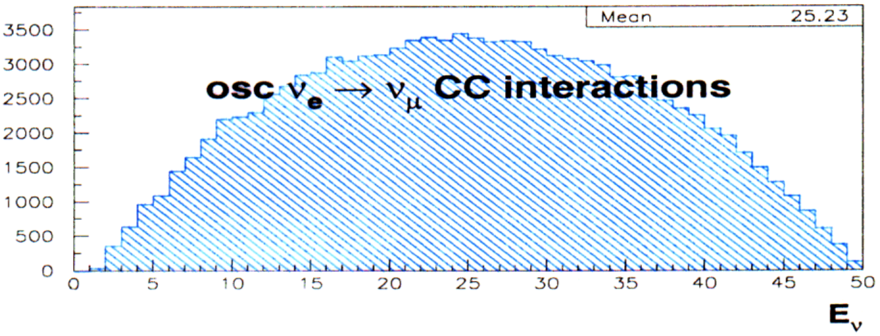
$$Q_t = P_\mu \sin\theta$$

The Beam

- Intensity: 10^{21} useful μ^+ (5 years × 2 × 10^{20} μ^+)



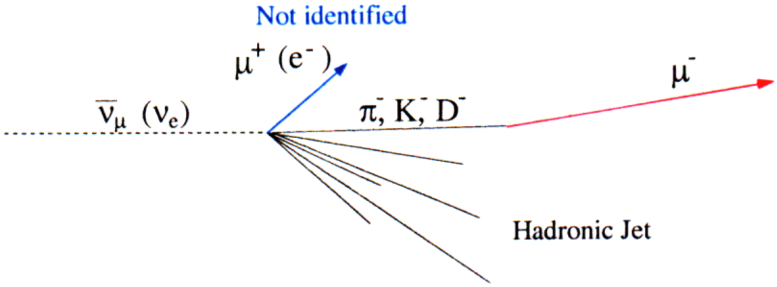




Potencial Backgrounds

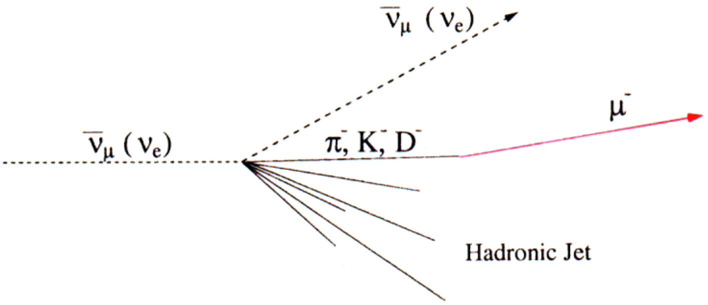
Charged currents ($\overline{\nu}_\mu$+ ν_eCC)

- ν_eCC : We assume the worst case in which there is not electron identification. Then $\pi^-, K^-, D^- \longrightarrow \mu^-$ decay.
- $\overline{\nu}_\mu$CC : The μ^+ is not recontructed. Then some particle of the hadronic jet decays into a μ^-.



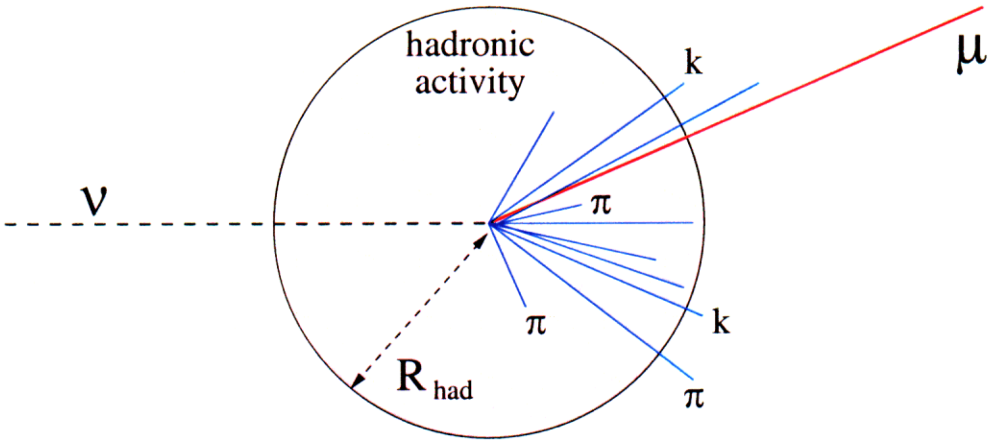
Neutral currents ($\overline{\nu}_\mu$+ ν_eNC)

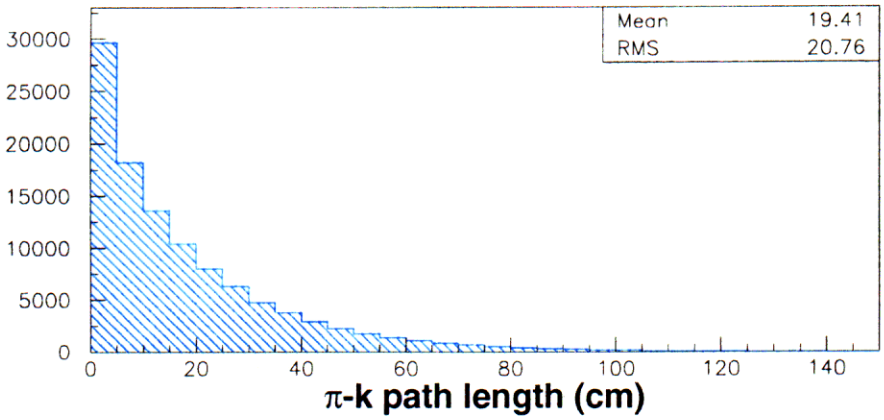
- $\pi^-, K^-, D^- \longrightarrow \mu^-$ decay



Muon identification

- We have to ensure that the distance traveled by the muon is sufficient to know its charge
- We have to be outside the region of hadronic activity

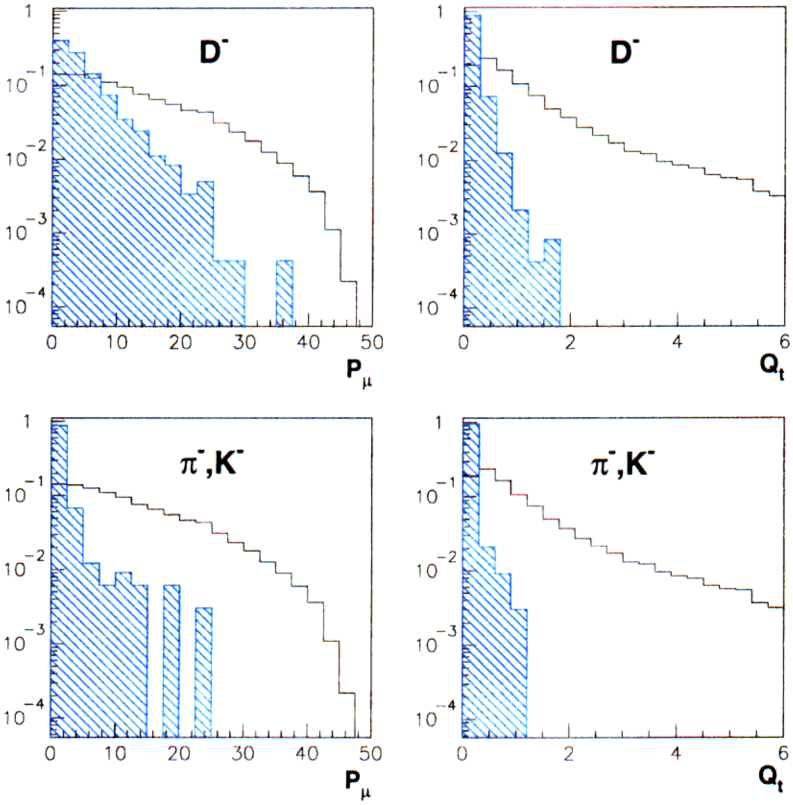


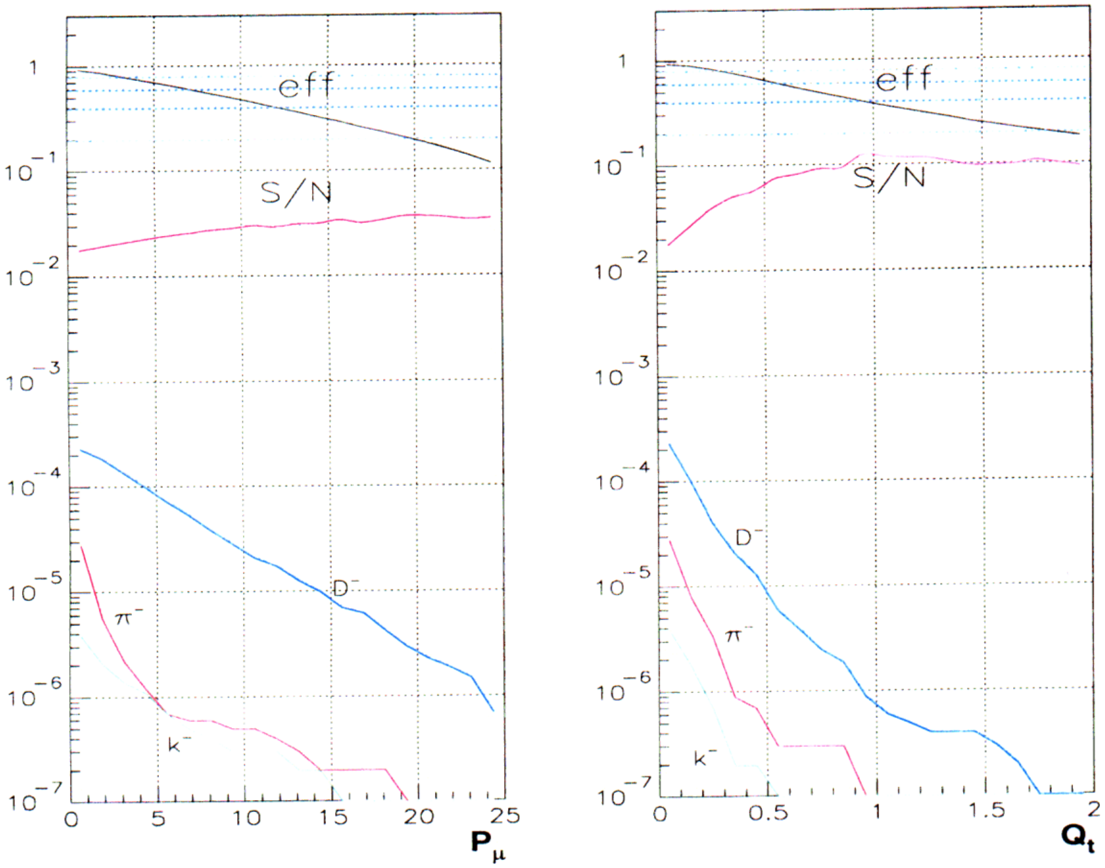


$$R_{had} = 75\,cm \longrightarrow 3\ \%\ \text{of hadronic activity}$$

$\overline{\nu}_{\mu}$CC background

- Study based in 10^7 $\overline{\nu}_{\mu}$CC events (50 Gev stored muons)
- π and K decays momentum spectra is very soft
- In the case of lost muon charm is quite hard (leading particle)

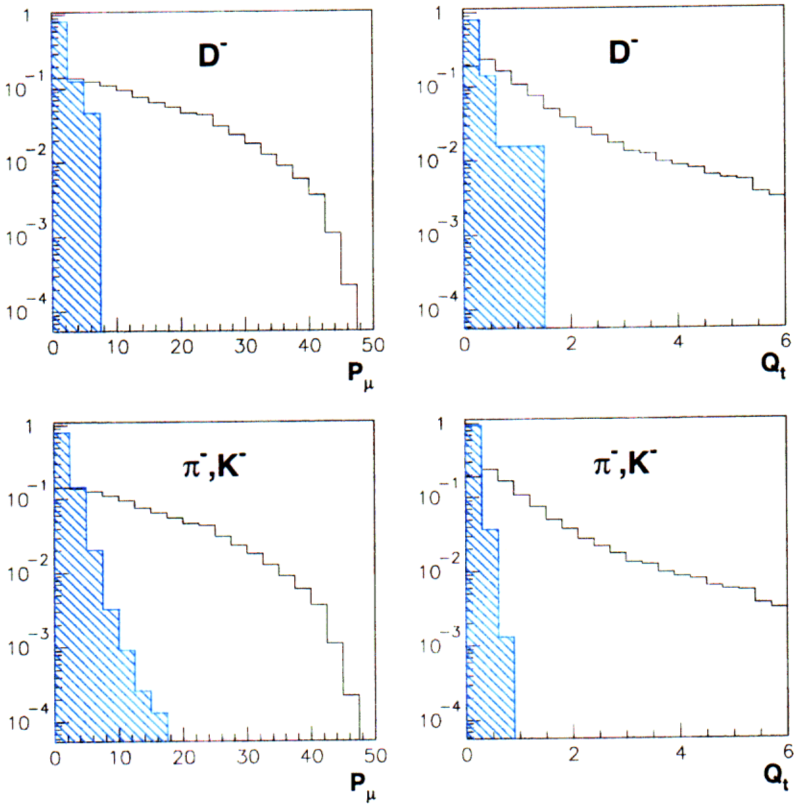


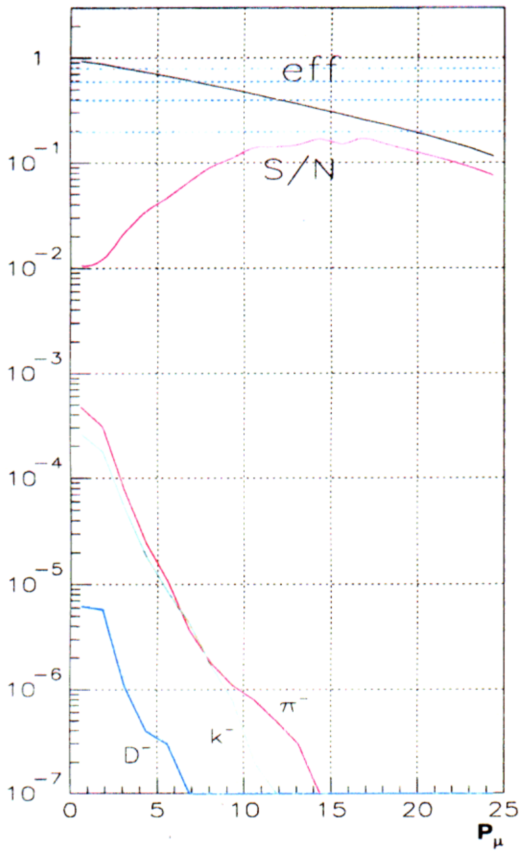


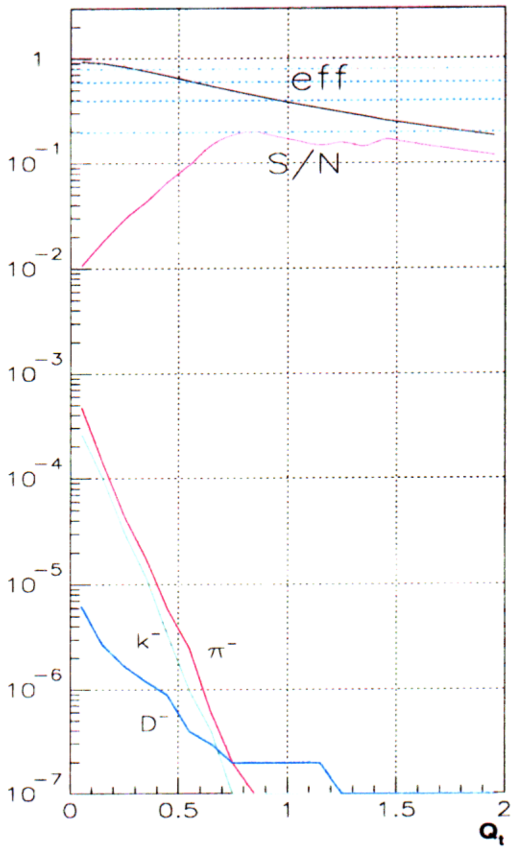
- Q_t is a good help for charm background rejection
- However a combined cut $P_\mu - Q_t$ gives better efficiency
- Less than 10^{-6} seems achievable at 30% efficiency

ν_eCC background

- Study based in 10^7 ν_eCC events
- Assuming no electron identification !!
- π and K decays momentum spectra is even softer than for $\overline{\nu}_\mu$CC
- Charm is soft because it is not leading



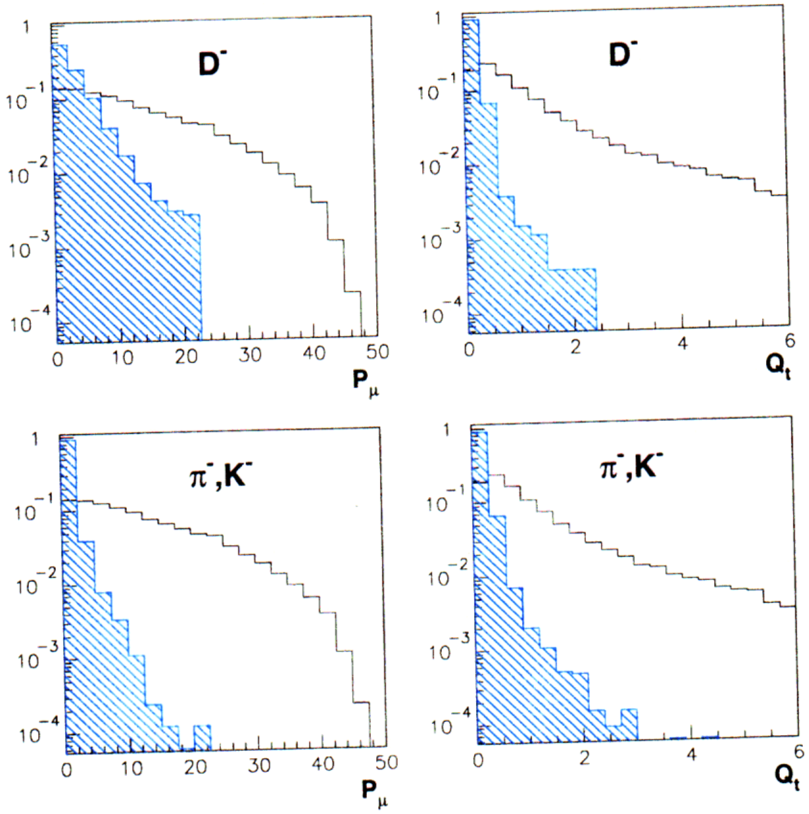


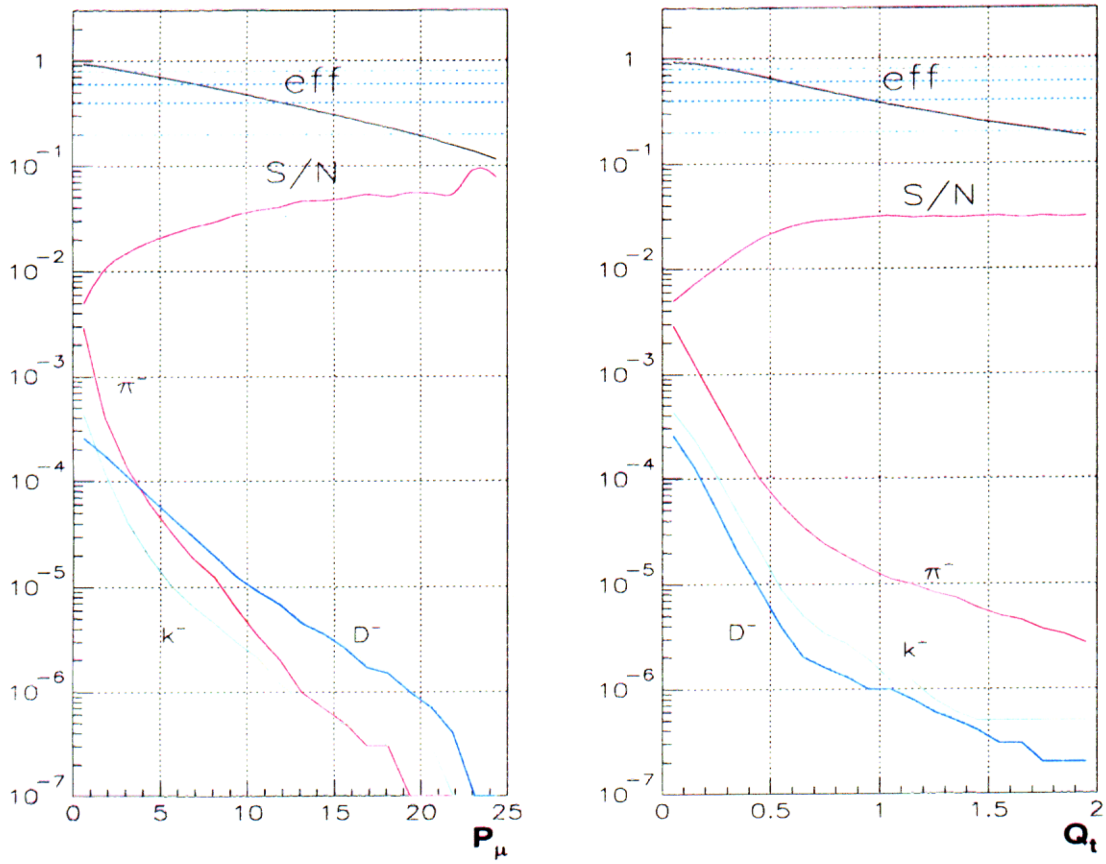


- Charm production has the oposite sign!! (D^- is marginal)
- π and K can be easely controled with momentum and Q_t cuts
- 10^{-7} is achievable with more than 40% efficiency
- This is not a serious background

Neutral current backgrounds

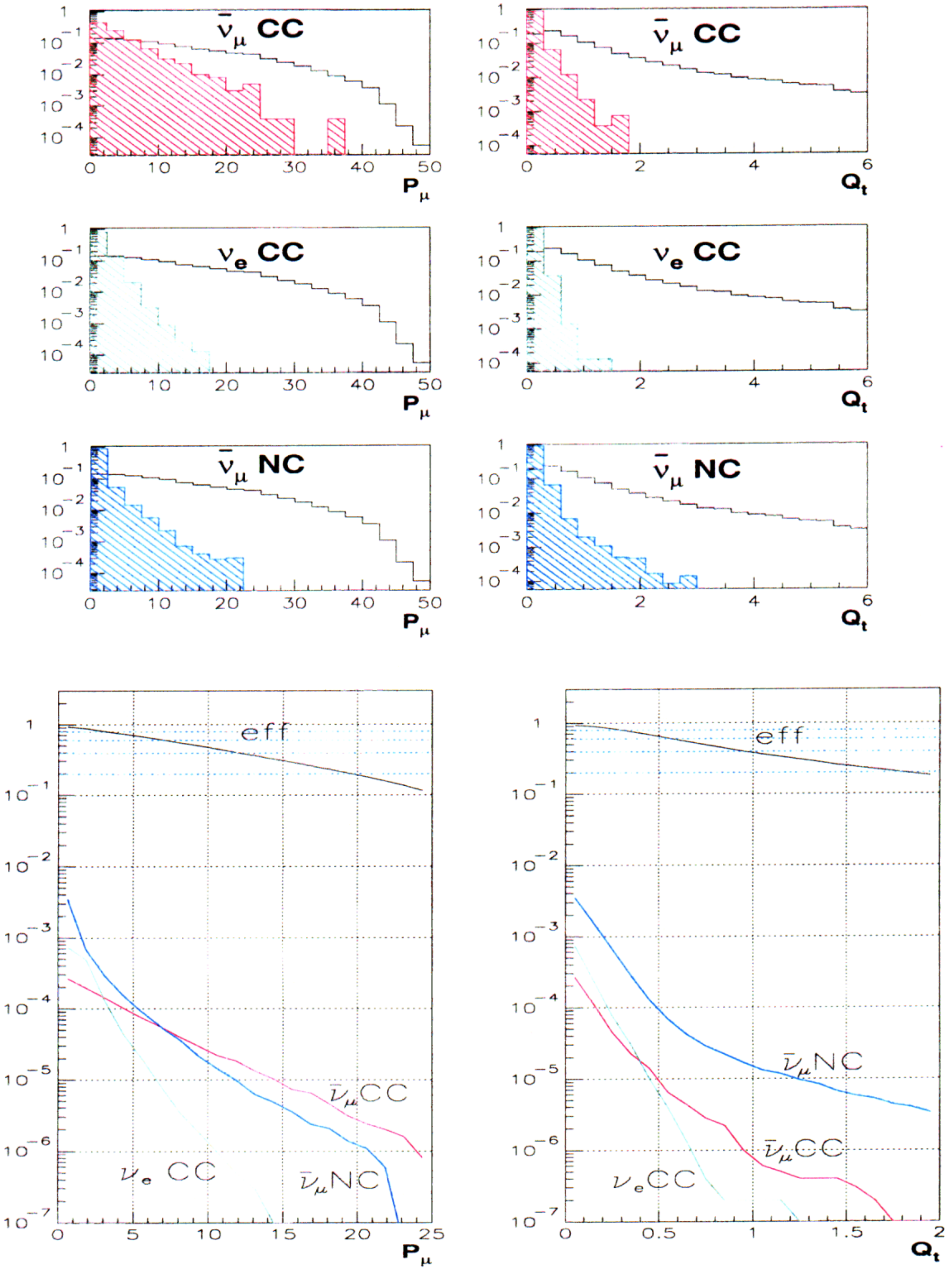
- Study based in 10^7 $\overline{\nu}_\mu$NC events
- The ν_eNC analysis is completely equivalent
- π and K decays momentum spectra is much softer than the signal spectrum but they have a long tail in Q_t
- $D^- \rightarrow \mu^-$ spectrum is soft because charm is not leading





- Pion decays is the most serious background in NC
- A combined cut $P_\mu - Q_t$ gives us 2×10^{-6} bg rejection power at 30% efficiency

All backgrounds



Expected background and signal

- Beam intensity: 10^{21} useful μ^+ ($2 \times 10^{20} \times$ 5 years)
- Beam energy: 50 GeV
- Detector mass: 40 Kton
- Oscillation parameters:
  - $\theta_{13} = 13^o$
  - $\theta_{23} = 45^o$
  - $\Delta m^2_{13} = 4 \times 10^{-3}\, eV^2$

Baseline (Km)	$\overline{\nu}_\mu$CC	ν_eCC	$\overline{\nu}_\mu + \nu_e$NC	ν_μCC (signal)
732	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

- $bg \sim 1/L^2$
- signal $\sim \frac{1}{L^2}\, sin^2(\frac{\Delta m^2\, L}{E}) \sim$ constant
  (below 3500 Km. For higher distances the sinus is no linear and matter effects became important)

Analysis results

- The optimal cuts are $P_\mu > 7.5\,GeV$ and $Q_t > 1\,GeV$
- Signal efficiency and background rejection power

$\overline{\nu}_\mu$CC	ν_eCC	$\overline{\nu}_\mu$+ ν_eNC	ν_μCC (signal)
3.0×10^{-7}	1.0×10^{-7}	1.8×10^{-6}	0.3

- Events surviving the cuts

Baseline (Km)	$\overline{\nu}_\mu$CC	ν_eCC	$\overline{\nu}_\mu$+ ν_eNC	ν_μCC (signal)
732	10.5	6	56	33000
3500	~ 0.3	~ 0.2	2.2	30000
7332	< 0.1	< 0.1	~ 0.4	13000

- At 732 Km backgrounds are important, limiting sensitivity.
- Backgrounds become negligible for distances > 3500 km
- The optimal distance is 3500 km (see talk of S. Rigolin)

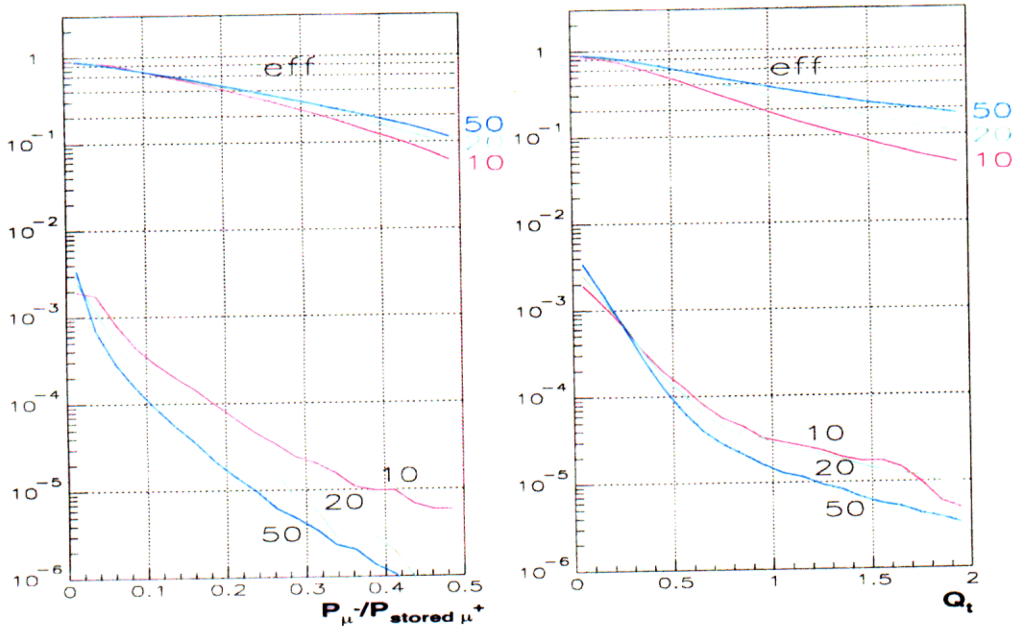
Dependence of the backgrounds on the muon-beam momentum

Muon-beam momentum (GeV/c)	Signal $\sim E$	$\overline{\nu}_\mu$NC $\sim E^3$	S/N $\sim 1/\sqrt{E}$
10	1.8×10^4	0.1×10^6	57
20	4.2×10^4	0.8×10^6	47
50	11×10^4	11.7×10^6	32

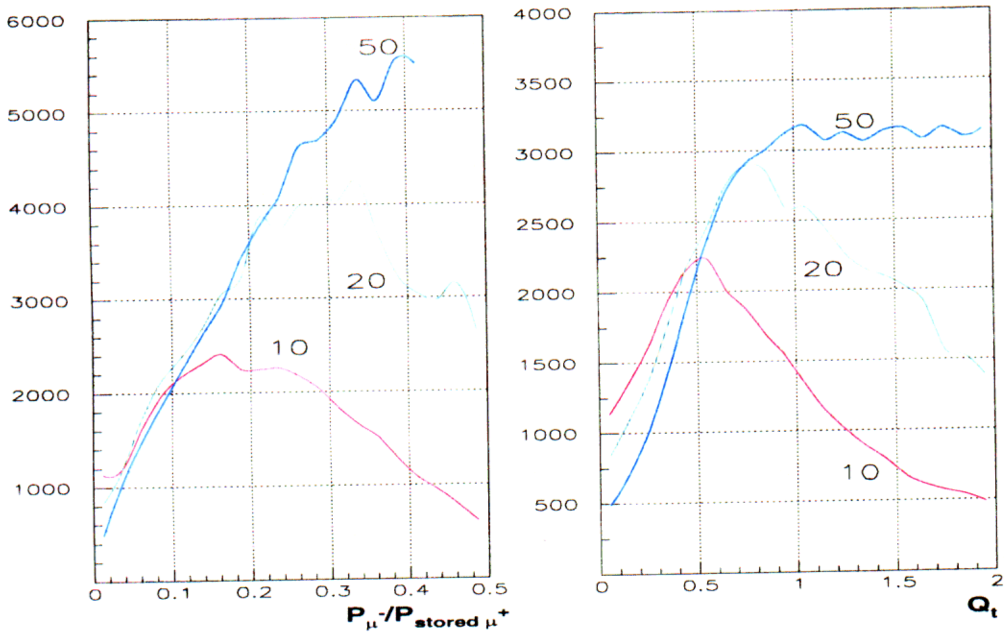
$$S/N = \frac{signal}{error\ in\ the\ background\ subtraction}$$

- $N = \sqrt{bg}$ $bg > 10$ events
- $N =$ poisson $bg \leq 10$ events

Efficiency and bg-reject for $\overline{\nu}_\mu$NC



Signal to noise for $\overline{\nu}_\mu$NC



Study of both polarities

- CP violation effects
- Matter effects

We considder now stored negative muons

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

$$\bar{\nu}_e \overset{\text{osc}}{\sim} \bar{\nu}_\mu$$

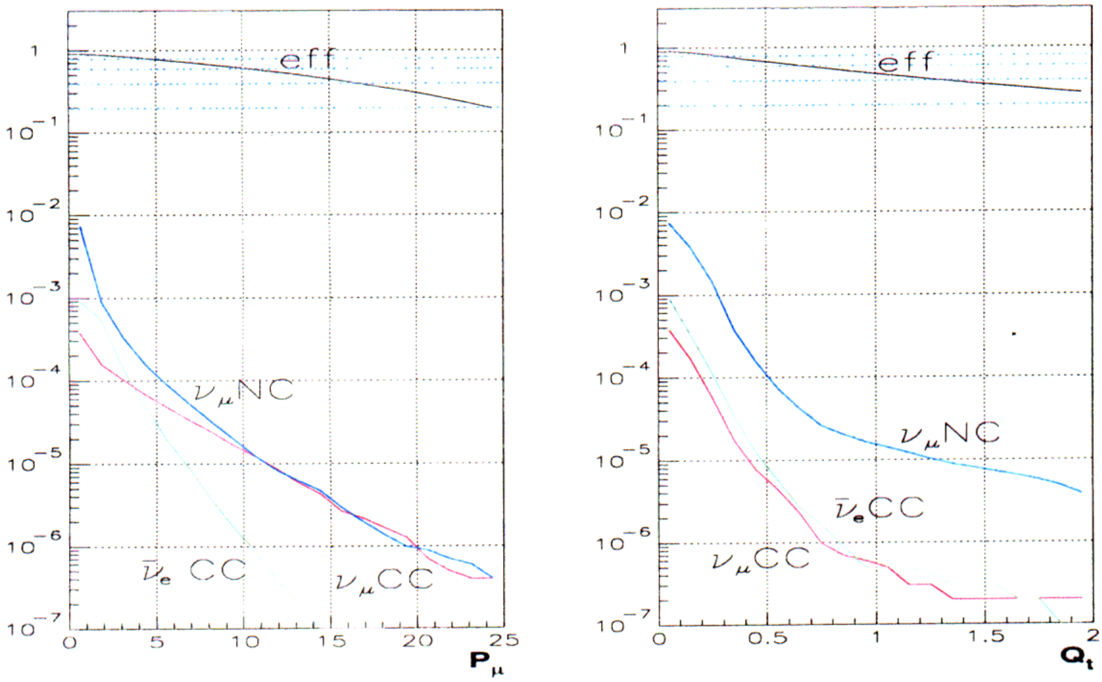
$$\bar{\nu}_\mu + N \longrightarrow \boxed{\mu^+} + X$$

SIGNAL

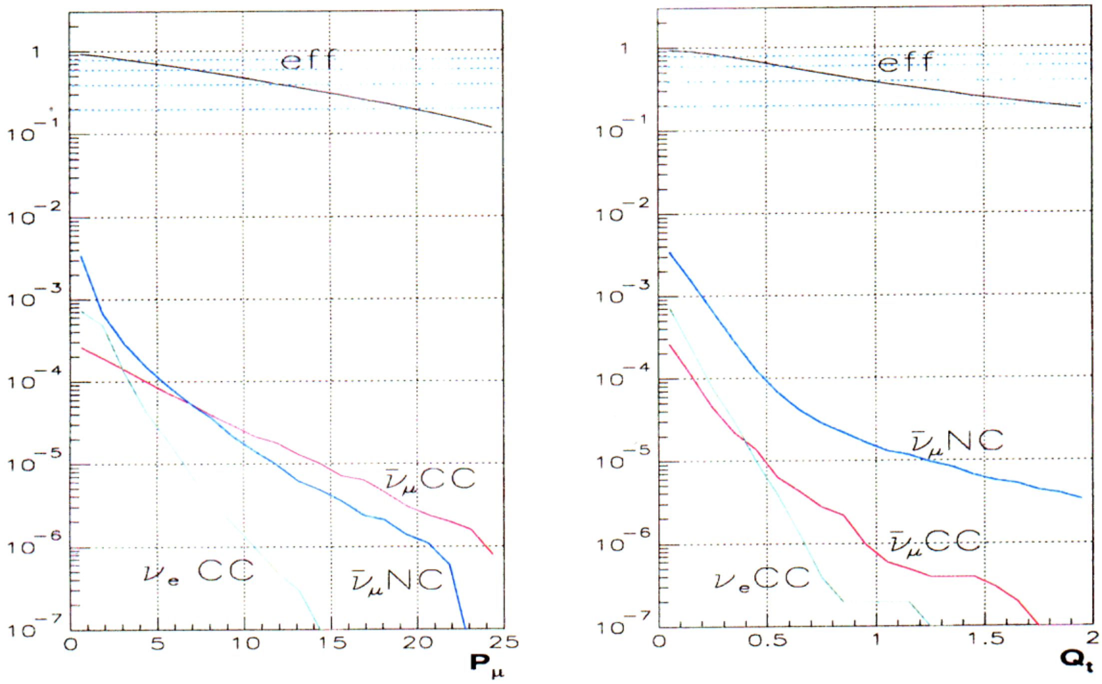
wrong sign muon

Baseline (Km)	ν_μCC	$\bar{\nu}_e$CC	ν_μ+ $\bar{\nu}_e$NC	$\bar{\nu}_\mu$CC (signal)
732	6.8×10^7	3.0×10^7	3.1×10^7	5×10^4
3500	2.3×10^6	1.3×10^6	1.2×10^6	1.6×10^4
7332	2.6×10^5	3.0×10^5	2.1×10^5	0.2×10^4

stored μ^-

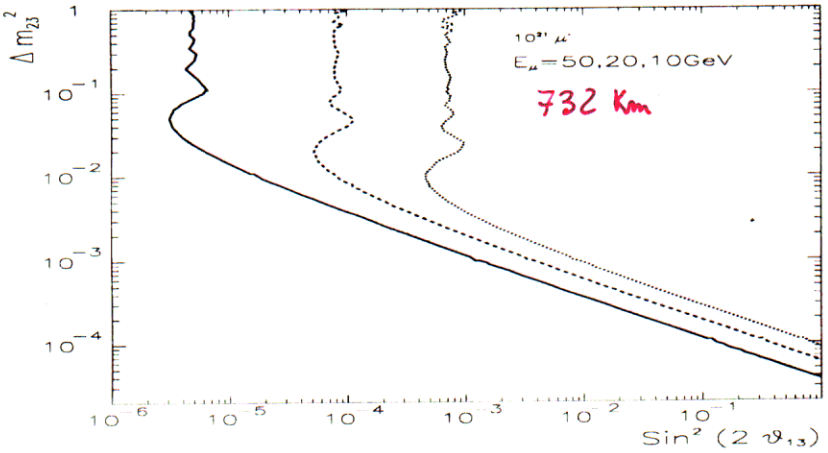


stored μ^+

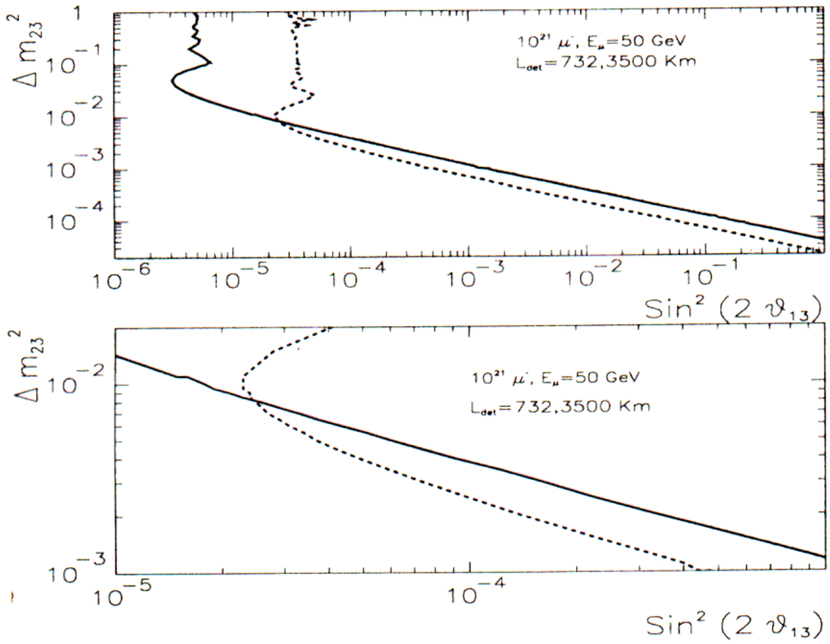


Sensitivity to θ_{13}

- Muon-beam momentum dependence



- Baseline dependence



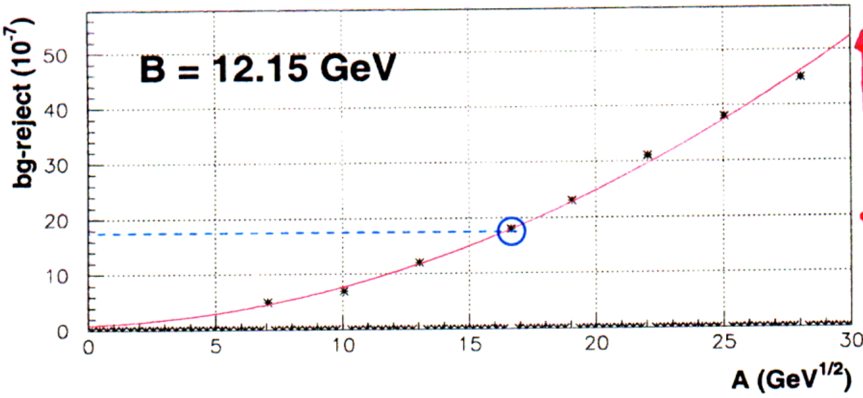
For complete results see S. Rigolin talk

Dependence of the backgrounds on the smearing

- We consideer the ramaining dominant background ($\overline{\nu}_\mu$NC) after the cuts ($P > 7.5\,GeV$, $Q_t > 1\,GeV$)
- Depends strongly on the tails of the Q_t distributions
  $\longrightarrow$ dominated by hadronic angular resolution

$$\delta\theta_{had} = \frac{A}{\sqrt{E}} + \frac{B}{E}$$

- The nominal values A=16.67, B=12.15

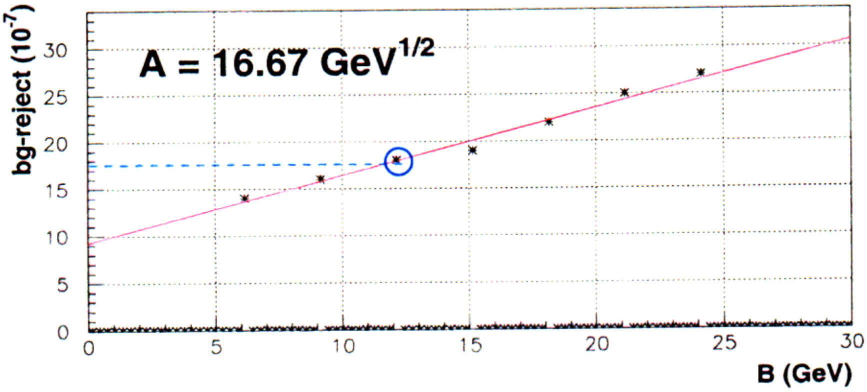


$\frac{\sqrt{52}}{\sqrt{18}}$

52

18

$\left(\frac{S}{N}\right)_{A=\cancel{30}\,17} = \boxed{1'7}\left(\frac{S}{N}\right)_{30}$



Charge Identification (preliminary !!)

Events in whose the charge of the μ^+ from a $\overline{\nu}_\mu$CC is misidentified are a potential background

We have done the following simulation

- We generate a parabolic track with momentum following the $\overline{\nu}_\mu$CC distributions after the cuts ($P_\mu > 7.5$ GeV and $Q_t > 1GeV$)

$$y = A + Bz + Cz^2$$

$$C = \frac{q\,0.3\,B_{mag}}{2\,P}$$

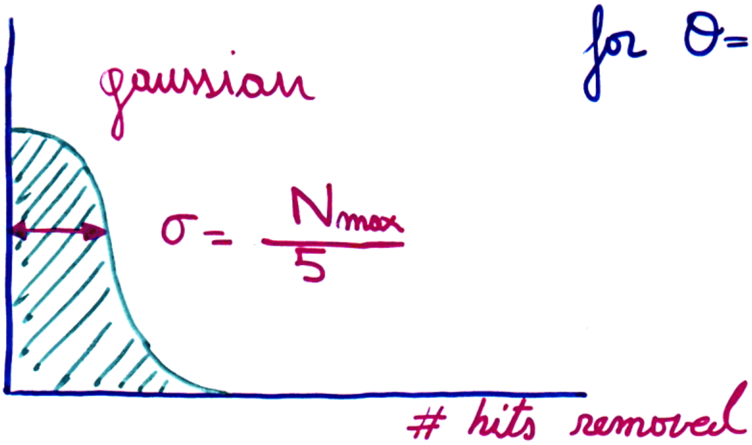
- Calculate the intersection with the measurement planes (hits)
- Remove some hits randomly as poor approach to pattern recognition
- Smear the transverse cordenate of the hits taking into account multiple scattering and transverse resolution ($\epsilon = 6mm$)

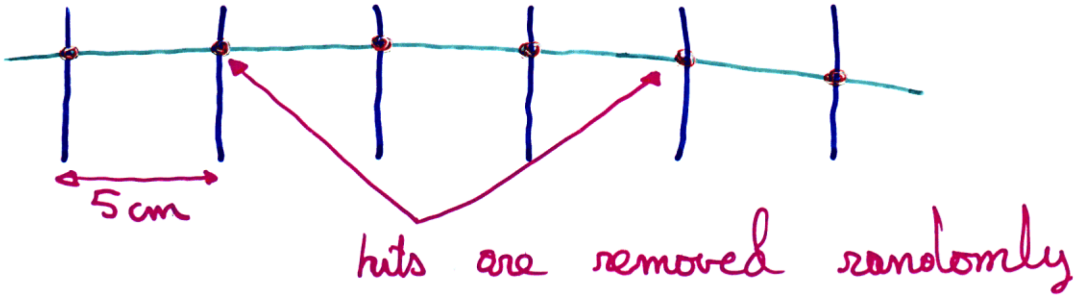
$$\delta y^2 = \delta y^2_{ms} + \delta y^2_{resol}$$

- Fit hits to a parabola

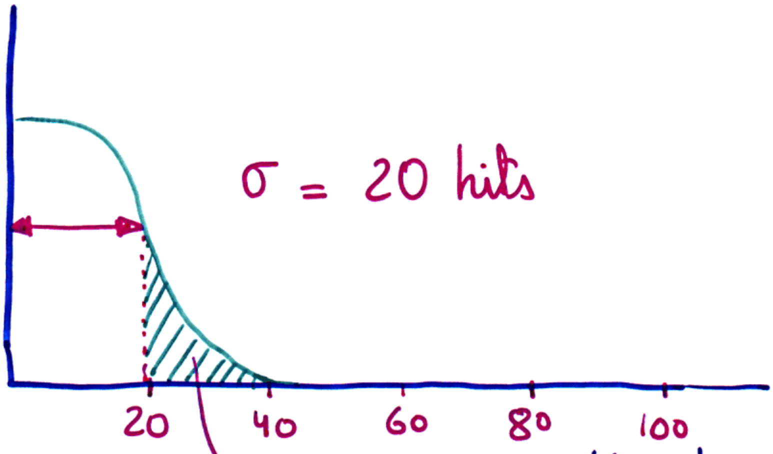
REMOVING HITS

for $\theta = 0$ $\quad N_{max} = \frac{\text{track length}}{5}$





For a $\boxed{5\,m}$ track $\quad N_{max} = 5\,m \cdot \frac{1\text{ hit}}{5\text{ cm}} = \boxed{100\text{ hits}}$



32% of the times we remove more than 20 hits (very pessimistic!!)

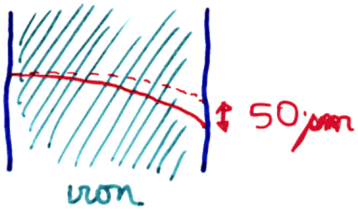
THE PARABOLIC APROXIMATION IS O.K.

For $P_\mu > 7'5$ GeV/c :

- Energy loss : $\delta E = 16$ MeV/cm

$$\delta E_{4cm} = 0'07 \text{ GeV}$$

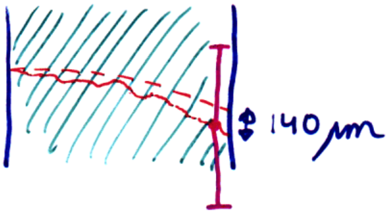
$$\delta y = \delta c \, \Delta z^2 = \frac{0'3 \cdot B}{2p^2}\,\delta p \,\underbrace{\Delta z^2}_{5cm} = \boxed{50 \mu m}$$



- Multiple scattering

$$\theta_{ms} \simeq \frac{0'0136}{7'5}\sqrt{\frac{4}{1'76}} = 2'7 \cdot 10^{-3}$$

$$\delta y_{ms} \simeq 5cm \cdot 2'7 \cdot 10^{-3} = \boxed{140 \mu m}$$



Transverse resolution = 6 mm

$\left.\begin{array}{l}\text{Energy loss}\\ \text{M.S}\end{array}\right\} \ll$ Transverse resolution $\Longrightarrow$ WE CAN FOLLOW THE TRACK USING THE KALMAN FILTER

THE FITTED PARAMETERS (A,B,C) WILL BE VERY SIMILAR TO THOSE IN ABSENCE OF multiple scattering and E. loss.

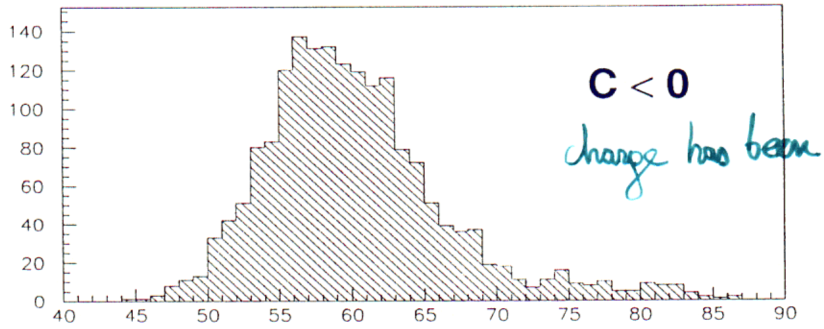
- ~~Fit the hits to a parabola~~
- ~~if C_{fit} [illegible] 0 the charge is positive~~

This study is very conservative

- We have simulate tracks with angle of 20 degrees which is the highest angle for $P_\mu > 7.5$ GeV and $Q_t > 1GeV$
- For smaller angles things will be better
- The pattern recognition approach is very ~~hard~~ pessimistic

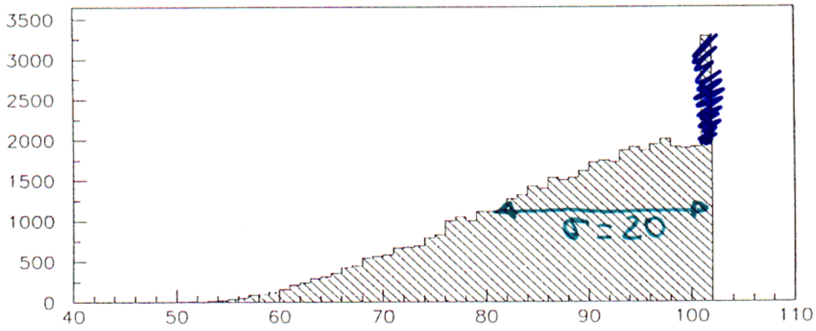
For $L_\mu = 5m$

N_{max} = 100 hits



charge has been misidentified

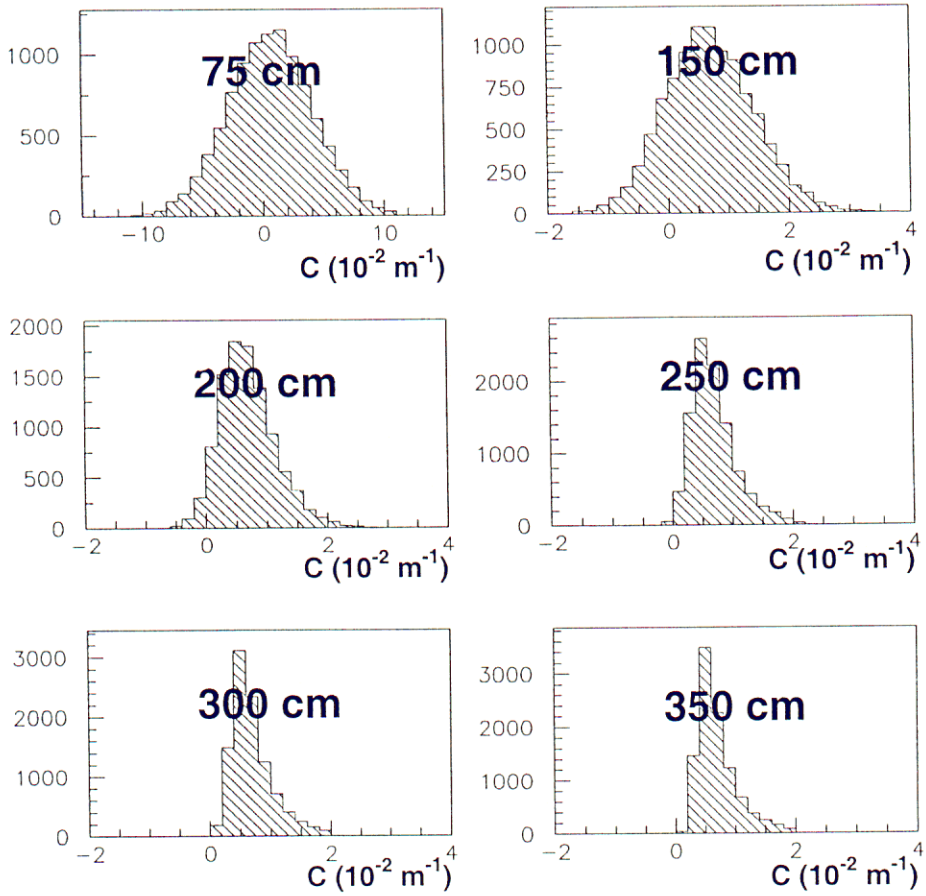
N_{hits} used in fit



N_{hits} used in the fit

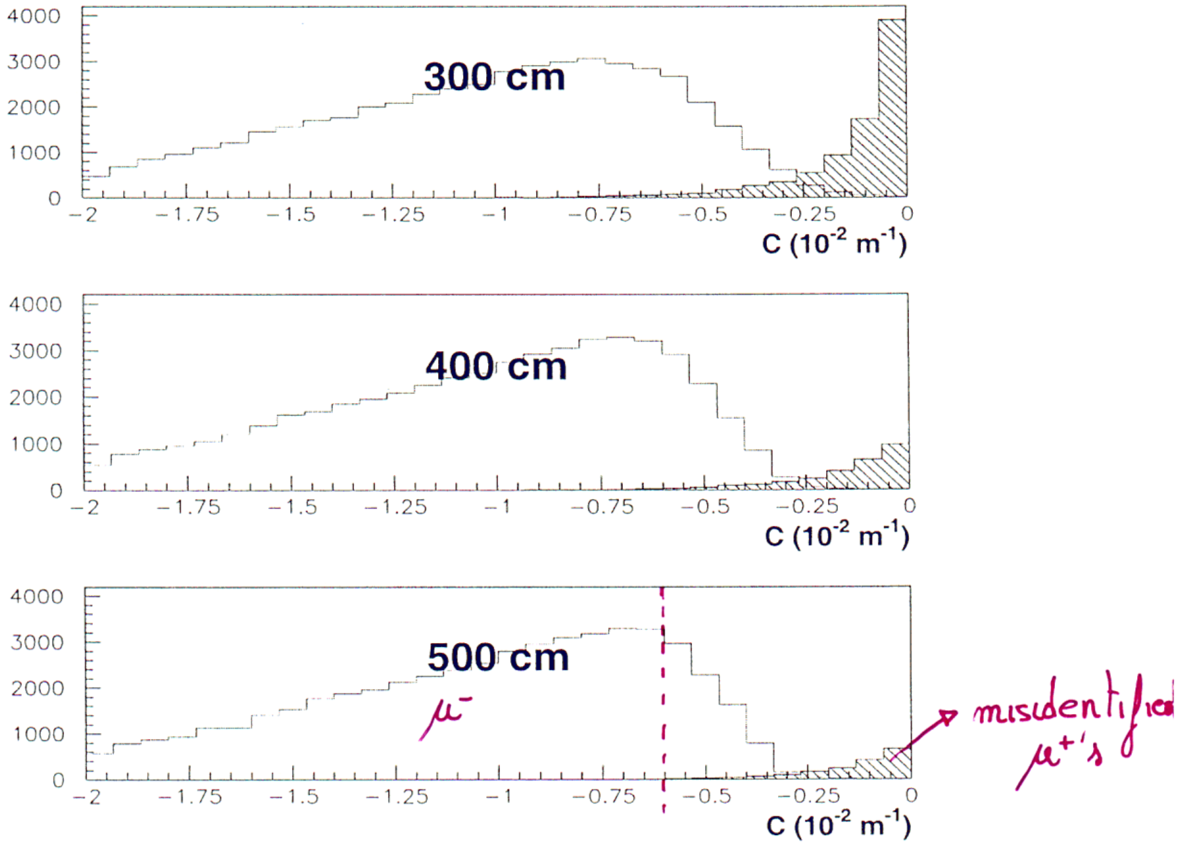
C distributions for μ^+ in $\overline{\nu}_\mu$CC

→ from fit



- 10^4 events
- below 300 cm the charge is misidentified
- we have to study the tails for $C < 0$ with much more statistics

C separation for μ^+ in $\overline{\nu}_\mu$CC and μ^- in ν_μCC

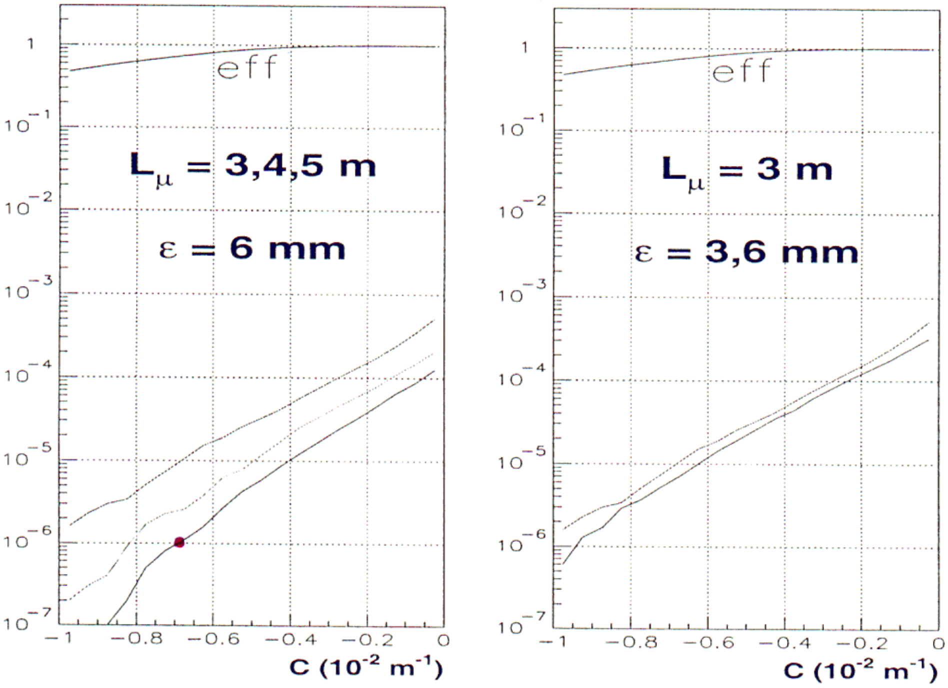


10^7 events

Signal efficiency and background rejection

ε = transverse resolution

L_μ = muon track length



- for $L_\mu = 5m$, 10^{-6} is achievable at 70% efficiency
- After the cuts $P_\mu > 7.5GeV$ and $Q_t > 1GeV$, $99\%$of the signal fulfils the condition $L_\mu > 5m$

Conclusions

- We have presented the conceptual design of a Large Magnetic Detector suitable for physics at the Neutrino Factory
- All sources of backgound has been studied with GEANT simulations
- For 50 GeV/c stored μ^+: bg rejection power better than 10^{-6} at 30% efficiency
- For stored μ^- things are very similar (in eff and bg-reject) but the signal ($\overline{\nu}_\mu$CC) is much less abundant
- The sensitivity improves considerabily with the muon-beam momentum
- For 50 GeV/c stored muons, the optimal baseline is about 3500 Km (See talk of Stefano Rigolin)
- A realistic change in the smearing is not relevant