Neutrino Oscillation Working Group

Progress Report And Next Steps Towards NuF 00

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The Physics Scenario

- Pessimistic hypothesis ⇒ LSND WRONG
- Then Solar ⊕ Atmospheric Anomalies ⇒

  3 ν oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = V_{CKM} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad (+\ \Delta m^2_{23}\ ,\ \Delta m^2_{12})$$

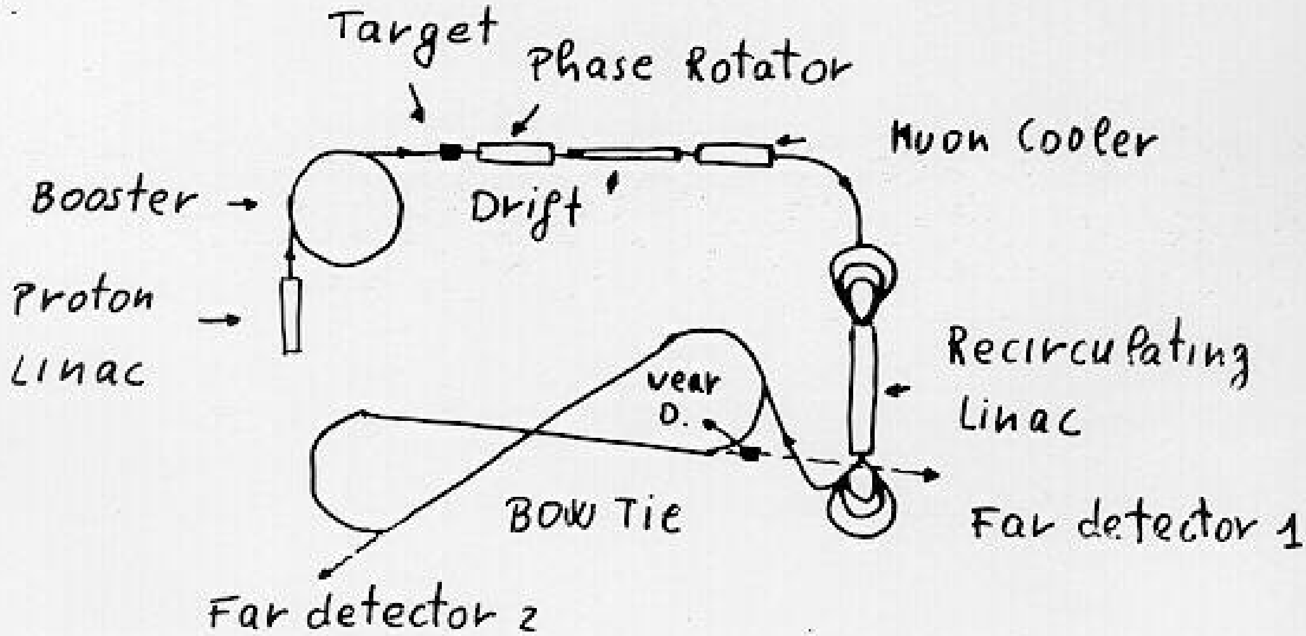
$$\Delta m^2_{23} = \Delta m^2_{atm} \qquad \Delta m^2_{12} = \Delta m^2_{sun}$$

$$V_{CKM}(\theta_{13}, \theta_{23}, \theta_{12}, \delta) = U(\theta_{23})\, U(\theta_{13})\, U(\theta_{12}, \delta)$$

- It is expected, from Solar-ν Experiments
  - Measurement of Δm^2_{12}, θ_{12}
  - In particular stablish
    - LMSN $\Delta m^2_{12} \sim 10^{-4}$ $\sin^2\theta_{12} \sim 1$
    - SMSN $\Delta m^2_{12} \sim 10^{-5}$ $\sin^2\theta_{12} \sim 10^{-3}$
- And, from Atmospheric-ν Experiments + LONG BASELINE Experiments
  - Δm^2_{23}, θ_{23} (not precision measurement)
  - upper limit on θ_{13} (Chooz)
  - Nothing on δ

The Lyon Consensus for the Machine

- Bow-Tie Design
- $N_\mu \sim 10^{21}$ per year
- E_μ up to 50 GeV
- Two beams pointing in different directions



- L = 730 km ⇒ inclination angle of 3°

  5000 km ⇒ " " " 23°

- No spin precession (no magic E_μ for P_μ)

  $P_\mu \simeq$ 30-40% if required.

Physics Goals of NuF

- Measurement of "oscillation parameters" ($\theta_{13}, \theta_{23}, \Delta m^2_{23}$)
  - θ_{13} largely unknown $\Rightarrow$ Precision measurement or stringent limit
  - Precision measurement of $\theta_{23}, \Delta m^2_{23}$

- Measurement of CP
  - Only feasible if LMSW in Sun
  - coupled to ($\theta_{13}, \theta_{23}, \Delta m_{23}$ ...)
  - Coupled to Matter effects
  - Requires knowledge of $\sigma \nu_\mu : \sigma \bar{\nu}_\mu$ to ~ 1%.

In addition $\Rightarrow$ Standard ν Physics
Exotic ν Physics
Charm Physics

IN near detector

Measurement of $\theta_{13}, \theta_{23}, \Delta m^2_{23}$

Dominant mass aproximation $(\Delta m^2_{12} << \Delta m^2_{23})$

$$P(\nu_e \to \nu_\mu) = \sin^2(\theta_{23}) \cdot \sin^2(2\theta_{13}) \cdot \sin^2 \phi$$

$$P(\nu_e \to \nu_\tau) = \cos^2(\theta_{23}) \cdot \sin^2(2\theta_{13}) \cdot \sin^2 \phi$$

$$P(\nu_\mu \to \nu_\tau) = \cos^4(\theta_{13}) \cdot \sin^2(2\theta_{23}) \cdot \sin^2 \phi$$

$$\phi = \frac{1.27 \cdot \Delta m^2_{23}(eV^2) \cdot L\,(km)}{2E\,(GeV)}$$

Measurement of $P(\nu_e \to \nu_\mu)$

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

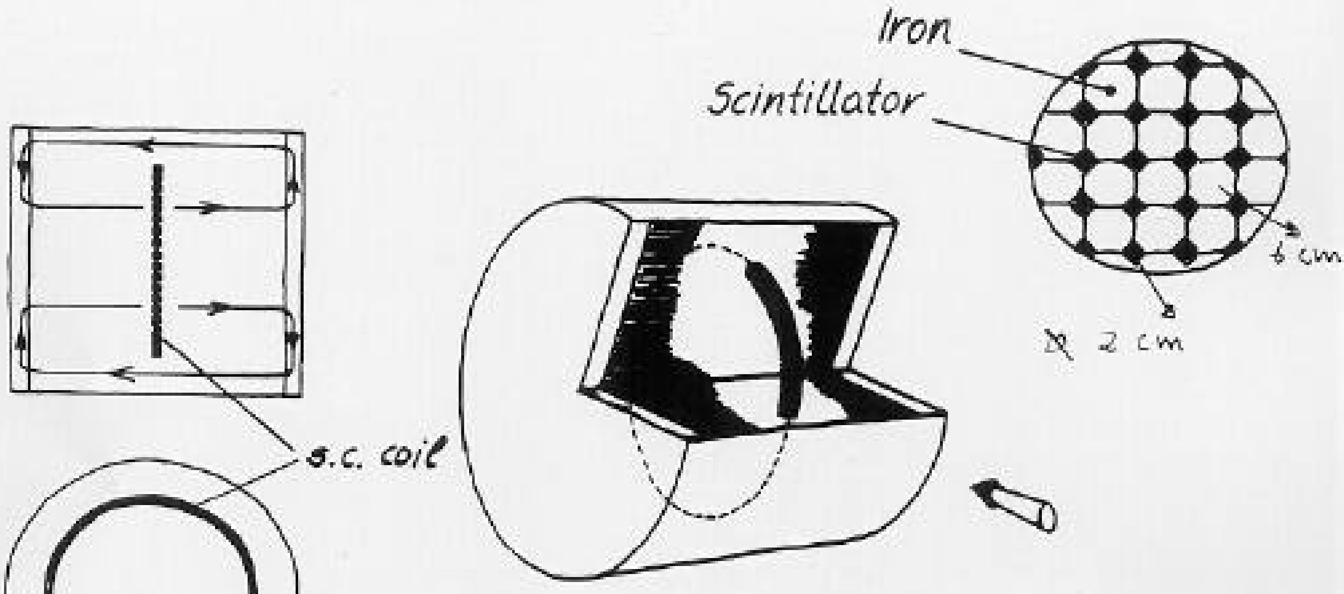
$$\nu_e \rightsquigarrow \nu_\mu$$

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

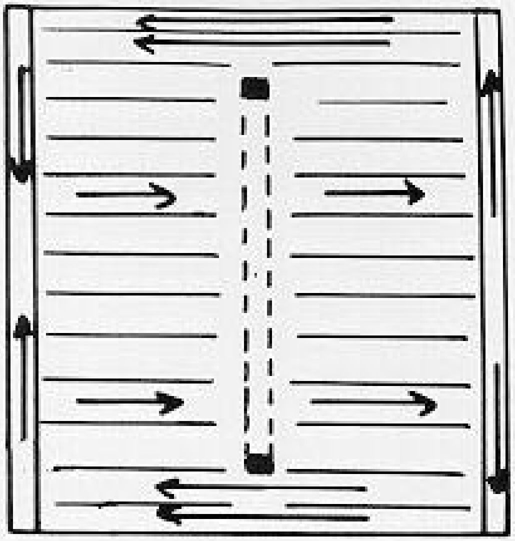
$$\nu_\mu + N \to \mu^- + X$$

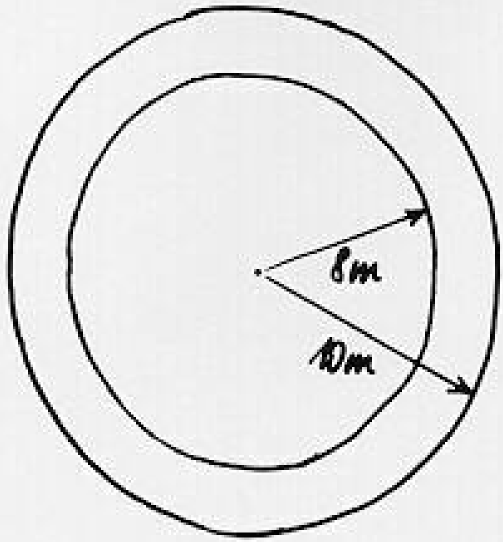
- Technique $\Rightarrow$ Separate (μ^- / μ^+) (ADR, BG, PH)
- Can be done with $\Rightarrow$ Large Magnetized Calorimeter
  - LMC Conceptual Design and Performance $\to$ Lyon (AC, FD, JJG)

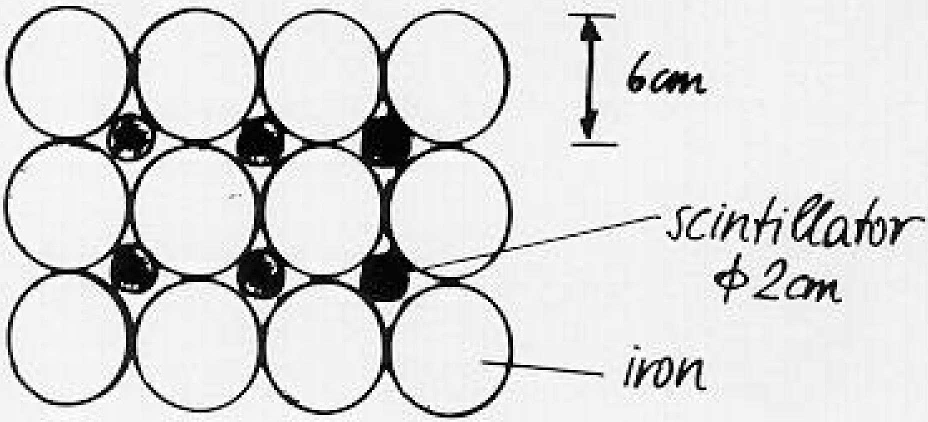
MAGNETIZED IRON CALORIMETER



Radius (m)	10
Length (m)	20
Mass (kt)	40
S.c. coil (A.turns)	130k
Coil radius (m)	7
Scintillator (t)	800







86 k Fe rods à 450 kg = 38 kt

1 CHF/kg → 38 MCHF

500 t scintillator 5 MCHF

Physical motivation

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

$\bar{\nu}_\mu + N \longrightarrow$ ■ $+ X$ CC

write sign muon

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

$\nu_e \overset{\text{osc}}{\sim} \nu_\mu$

$\nu_\mu + N \longrightarrow$ ■ $+ X$ SIGNAL

wrong sign muon

Having a very pure neutrino beam

50 % $\bar{\nu}_\mu$ 50 % ν_e

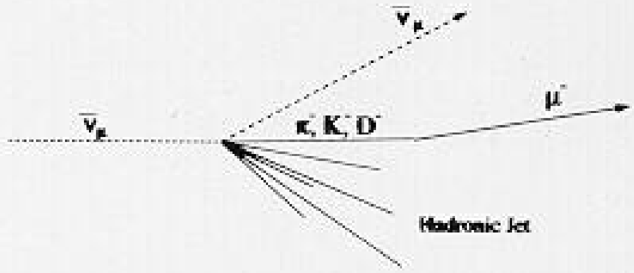
the neutrino oscillation search is very clear

$\Longrightarrow$ Wrong sign muons

Potencial Backgrounds

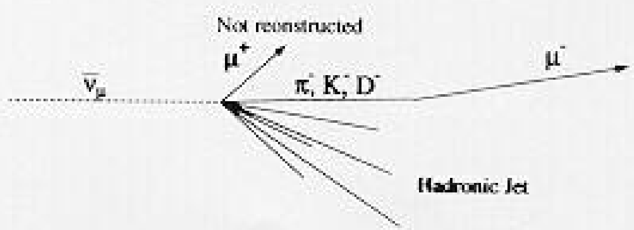
Neutral currents

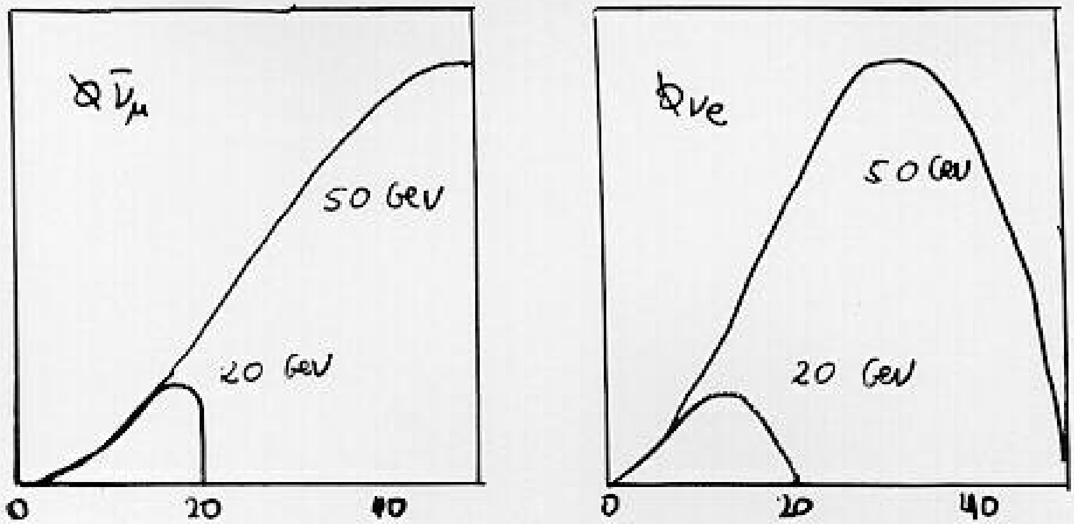
- $\pi^- \longrightarrow \mu^-$ decay
- $K^- \longrightarrow \mu^-$ decay
- Associative Charm production followed by $D^- \longrightarrow \mu^-$ decay



Charged currents

- The weak μ^+ is not recontructed and some particle of the hadronic jet decays into a μ^-





- NuF fluxes are "elastic"
  - At $E_\mu = 50$ GeV you get the same events up to any other energy (lower) ($E_\mu = 20$ GeV) than you would if $E_\mu = 20$ GeV.

- $N_{cc} \sim \Phi \cdot \sigma \propto E^2 \cdot E = E^3$ (for a fixed L)

- Nota Bene:

$$N_{osc} \sim \Phi \cdot \sigma \cdot P_{osc} \propto E^2 \cdot E \cdot \frac{1}{E^2} = E$$

$$\Rightarrow N_{osc}/N_{cc} \sim S/B \sim E/E^3 \sim \frac{1}{E^2}$$

Thus the ratio of signal to potential background decreases with $1/E^2$

But rejection of backgrounds become more efficient at higher energies.

Dependence of the background with the beam Energy

As shown the leading background is charm in CC events when we lose the leading muon.

We illustrate the dependence of the background with the beam energy considering this leading background

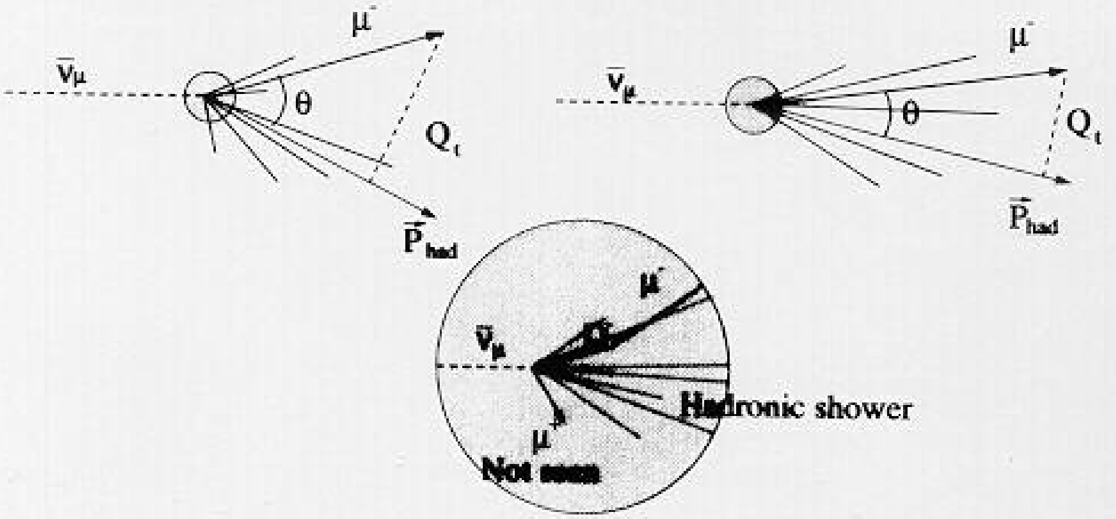
Energy	Charm production(%)	Lost muon (%)	Charm background(%)
10	0.17	46	0.078
20	0.7	11	0.079
50	1.2	1.3	0.026

- Charm production rate rises with energy
- But muon identification efficiency also increases wiht energy

The combined effect is beneficial at high energy

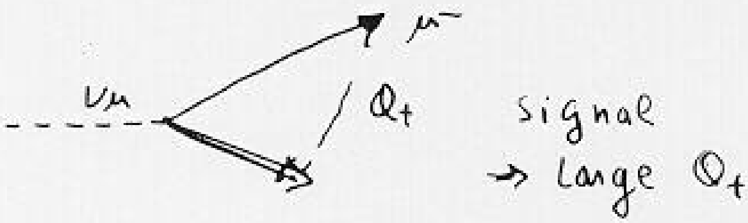
Low energy — Charm is quite open → High Q_t

High energy — Charm is collimated → Low Q_t

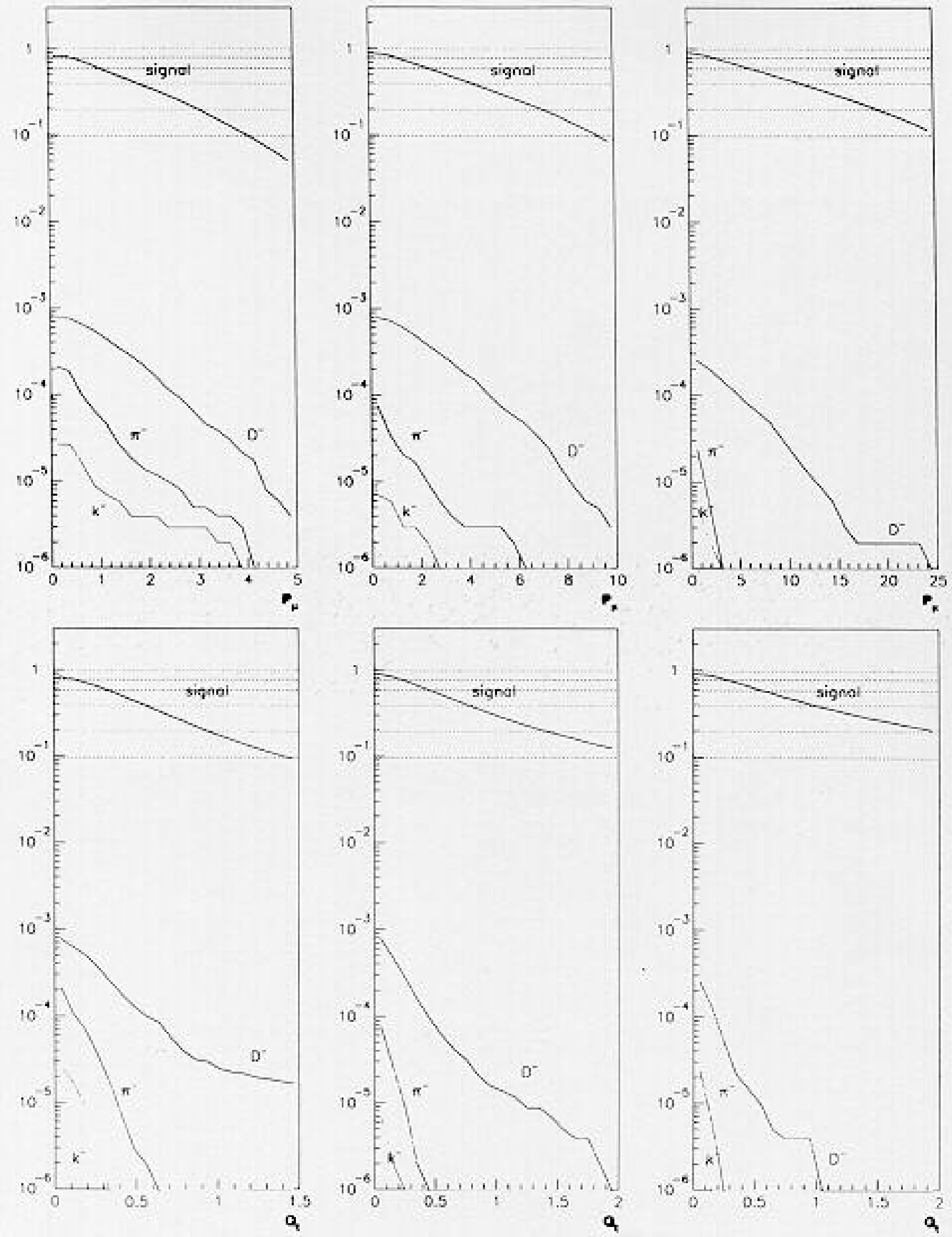


- Potential charm **background rate** decrease with energy
- The separation **between signal** and background raise with energy

⟹ Background **rejection power** ⇑ Energy



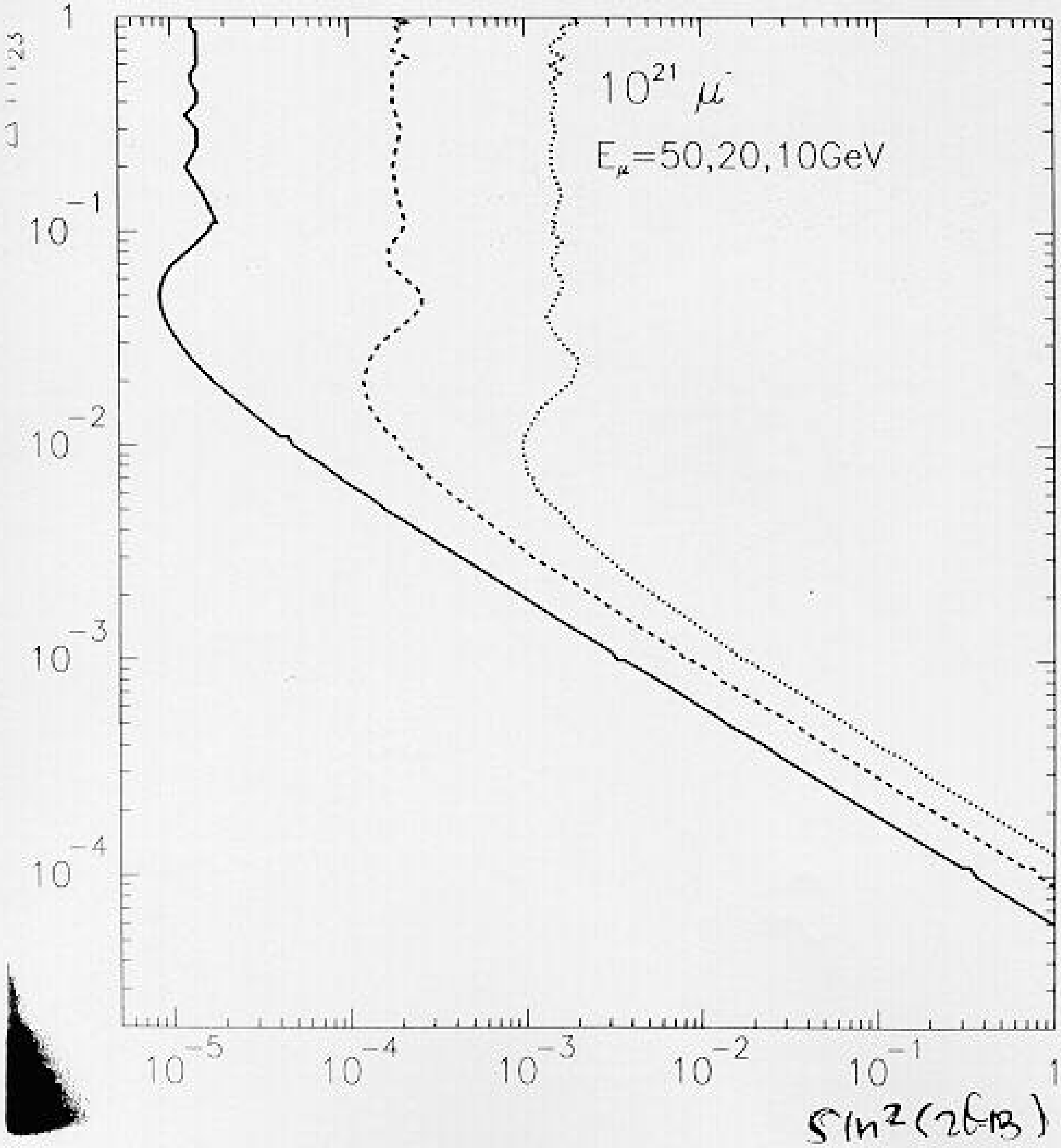
10 GeV 20 GeV 50 GeV



Efficiency ($P_\mu > 5$ GeV, $Q_t > 1$ GeV) ~30%

$\varepsilon_{bkgnd} \sim 5 \times 10^{-6}$

L ≈ 732km



$10^{21}\ \mu^-$
E_μ=50,20,10GeV
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2(2\theta_{13})$

Measurement of $P(\nu_e \to \nu_\tau)$, $P(\nu_\mu \to \nu_\tau)$

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

$$\nu_e \sim \nu_\tau$$

$$\bar{\nu}_\mu \sim \bar{\nu}_\tau$$

$$\bar{\nu}_\tau + N \to \tau^+ + X$$

$$\nu_\tau + N \to \tau^- + X$$

- Ideally $\Rightarrow$ Separate τ^+/τ^- $\Rightarrow$

  Magnetized Iron-Emulsion Calorimeter

  (AP, DH)

- No Real conceptual Design yet
- No evaluation of Performance yet

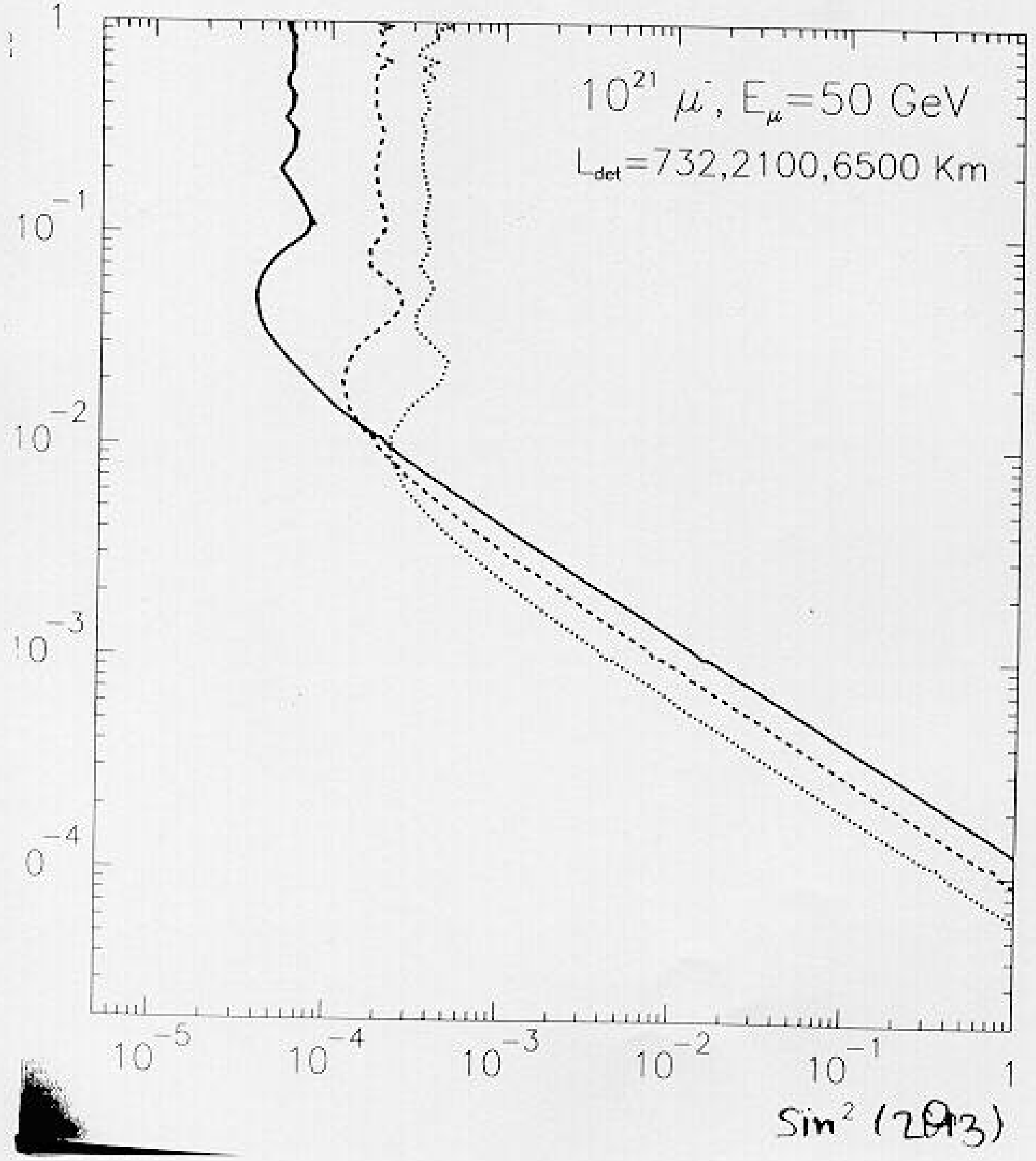
  Notice that:

  $$\nu_e \sim \nu_\tau \to \tau^- + N$$

  $$\tau^- \to \mu^- + \nu\nu$$

  feed through to μ^-/μ^+ search!

- Should be no problem ($\theta_{23} \sim 45^\circ \Rightarrow P(\nu_e \to \nu_\mu) \equiv P(\nu_e \to \nu_\tau)$)
- Under study (AC, JJG)



10^{21} μ^-, E_μ=50 GeV
L_{det}=732,2100,6500 Km
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
Sin^2 (2θ13)

Beam Parameters for Measurement of $\theta_{13}, \theta_{23}, \Delta m^2_{23}$

- $P(\nu_e \to \nu_\mu)$ via μ^-/μ^+ in LMC
- $P(\nu_e(\nu_\mu) \to \nu_\tau)$ " τ^-/τ^+ in EIMC
- then extract $\theta_{13}, \theta_{23}, \Delta m^2_{23}$
- For $P(\nu_e \to \nu_\mu)$ → **$E_\mu \sim 50$ GeV**
- For $P(\nu_e(\nu_\mu) \to \nu_\tau)$ not evaluated yet but almost certainly, $E_\mu \sim 50$ GeV ok ($\sigma\,\nu_\tau$, kinematics for τ/D separation)

What about L?

- For $P(\nu_e \to \nu_\mu)$ sensitivity to θ_{13} changes little between $L \sim 1000 - 5000$ km (at $\Delta m^2_{23} \sim 3 \times 10^{-3}$ eV^2) and is better at $L \sim 1000$ km for $\Delta m^2_{23} \geq 10^{-2}$ eV^2
- This is because bkgnds are already small at $L \sim 10^3$ km
- For $P(\nu_\mu \to \nu_\tau)$ bkgnds will be higher but signal is very strong ⇒ easy to subtract.
- At $L \sim 10^3$ km CP → 0 and Matter effects → 0

Best L, probably ~ 10^3 km.

Polarization AND Beam Divergence

- Effects of P_μ => Presented at workshop (AB)
- Change ratio ν_μ / ν_e

$$\mu^+ \rightarrow \bar{\nu}_\mu \; \nu_e$$

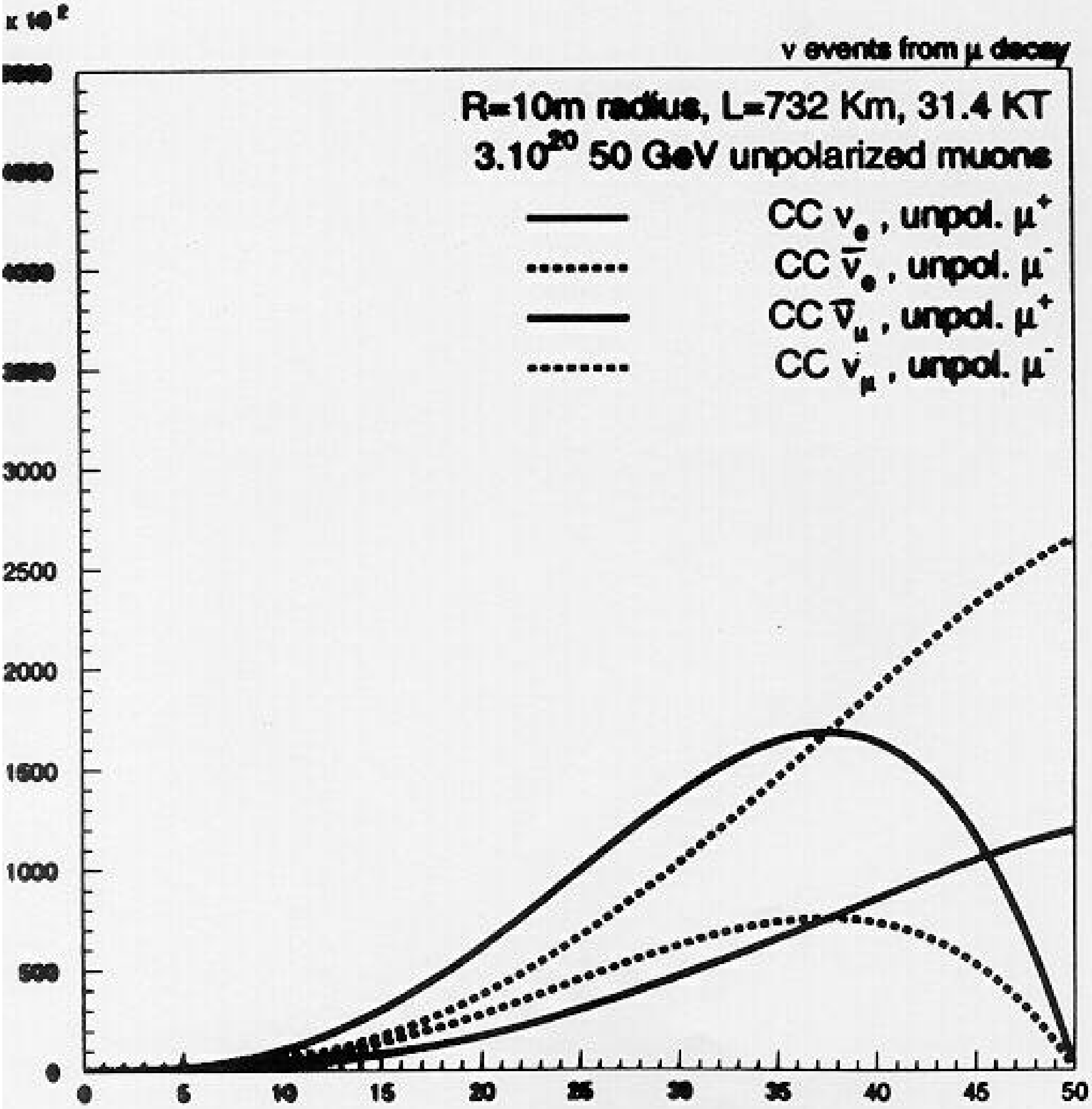
- If unpolarized $\bar{\nu}_\mu$ (50%) ν_e (50%)
- To reduce background-to-signal in $\nu_e \rightarrow (\nu_\mu, \nu_e)$, one could consider $P_{\mu^+} = -1$ ($\nu_e / \bar{\nu}_\mu \gg 1$)
- OR to study T-odd asymmetries one could consider $P_{\mu^+} = +1$ ($\nu_e / \bar{\nu}_\mu \sim 0$)

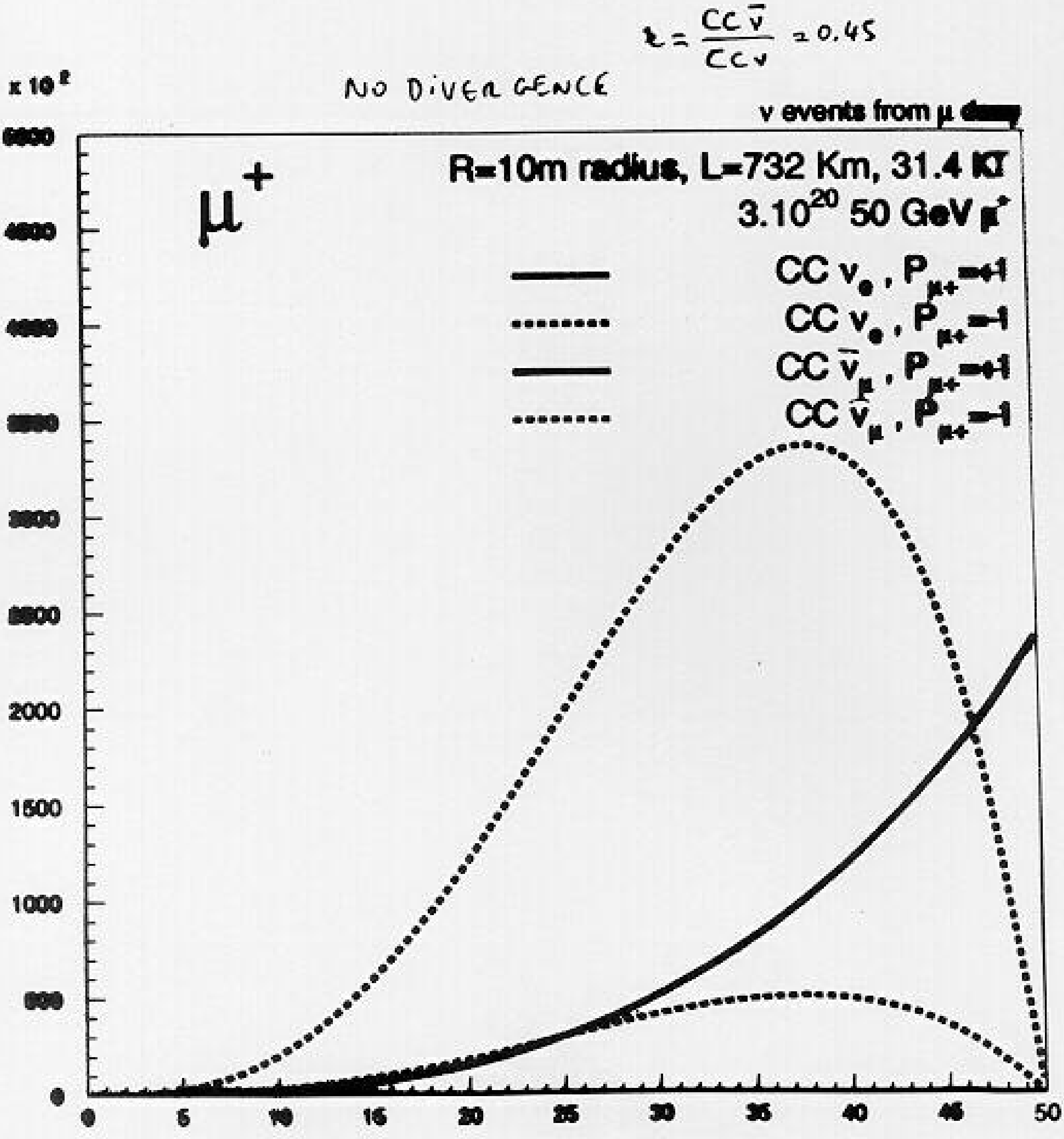
$$\mu^+ \rightarrow \bar{\nu}_\mu \; \not{\nu_e} \quad (P_{\mu^+} = +1)$$
$$\hookrightarrow \bar{\nu}_e$$

$$\mu^- \rightarrow \nu_\mu \; \not{\bar{\nu}_e} \quad (P_{\mu^-} = -1)$$
$$\hookrightarrow \nu_e$$

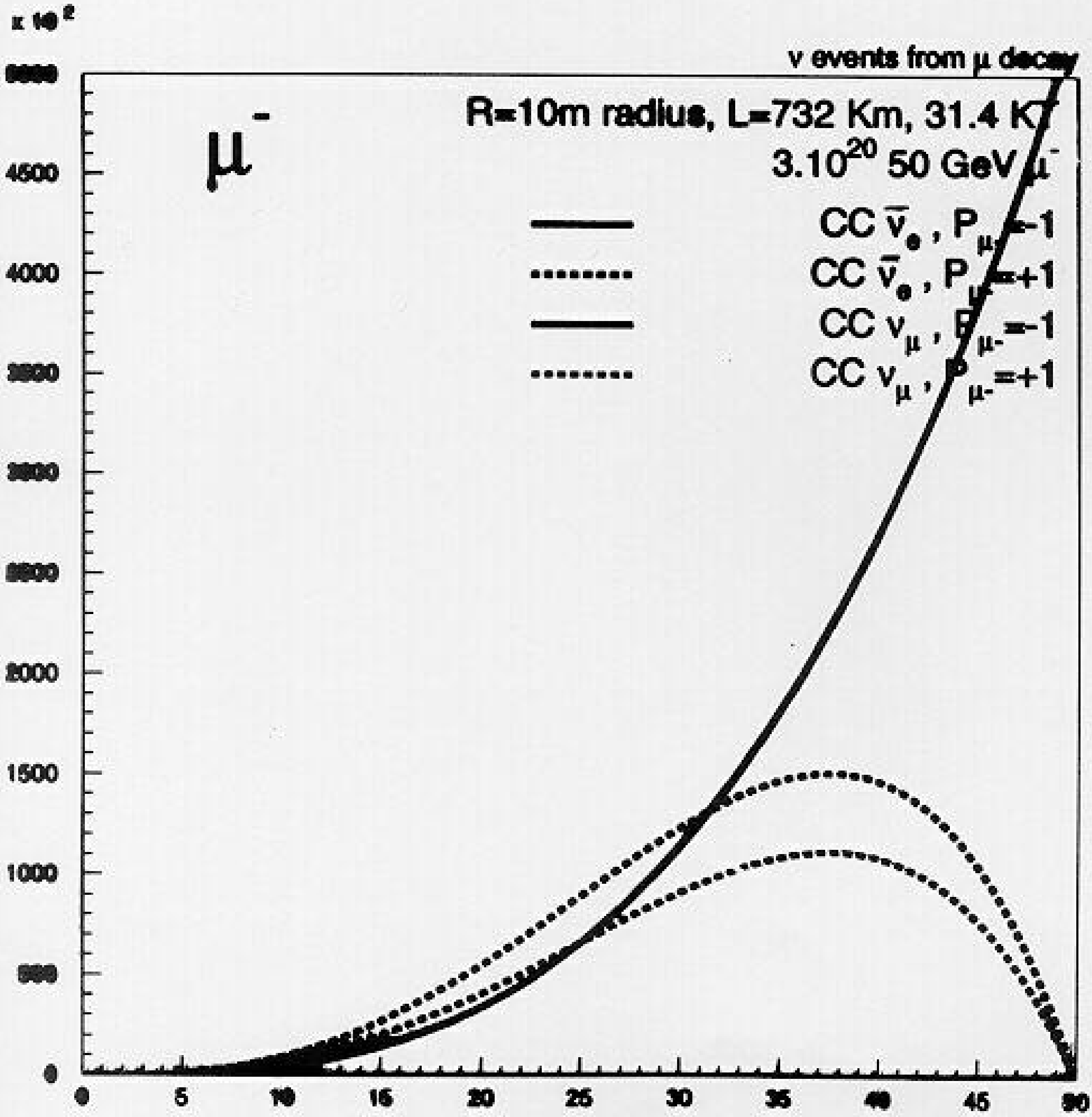
Merits of using P_μ must be evaluated quantitatively.

Beam Divergence must be better $\sim \frac{1}{10\gamma}$


ν events from μ decay
R=10m radius, L=732 Km, 31.4 KT
3.10^20 50 GeV unpolarized muons
CC ν_e , unpol. μ^+
CC ν̄_e , unpol. μ^-
CC ν̄_μ , unpol. μ^+
CC ν_μ , unpol. μ^-
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
30
35
40
45
50

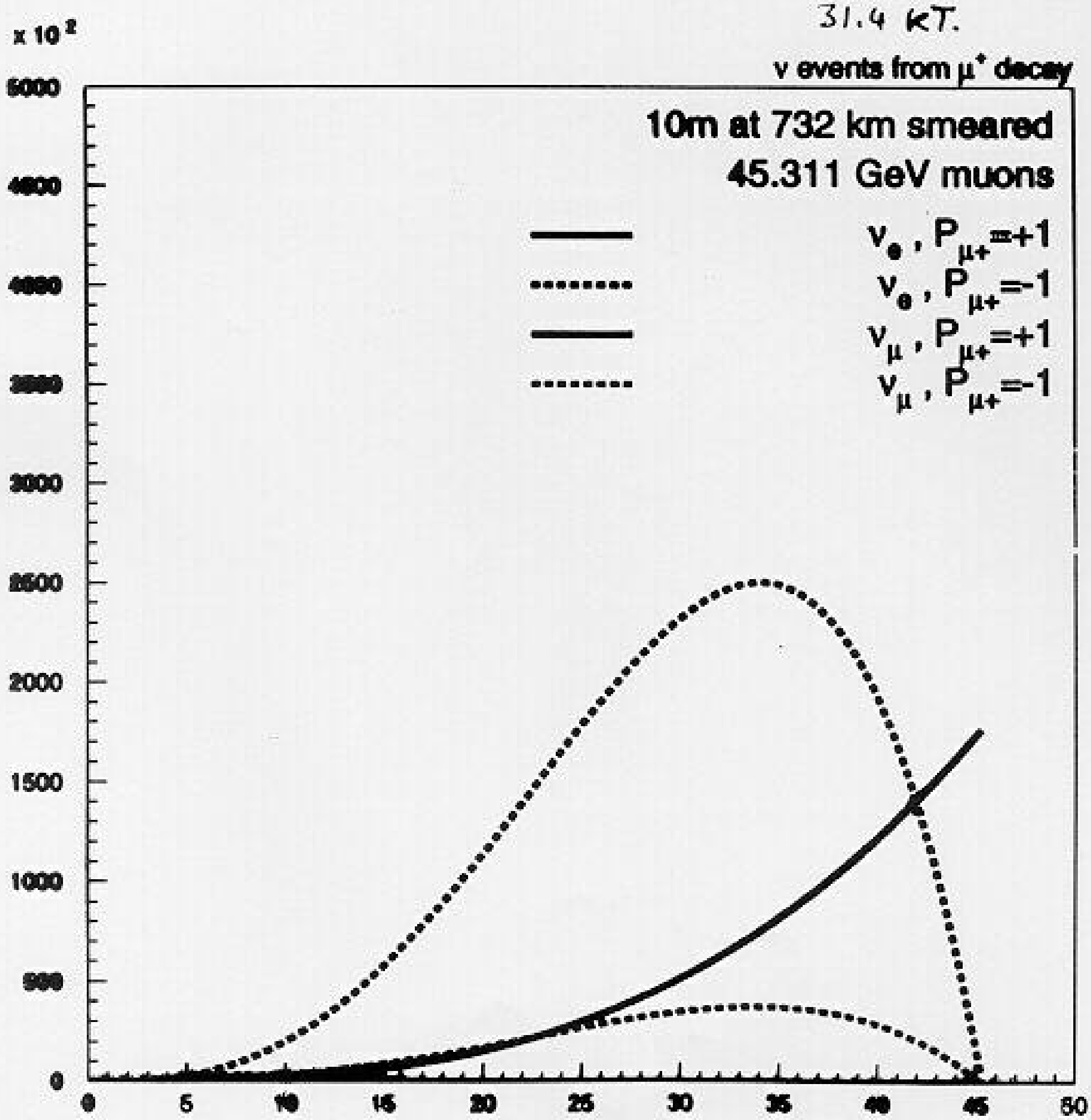


NO DIVERGENCE
$r = \frac{CC\bar{\nu}}{CC\nu} = 0.45$
x 10^2
ν events from μ decay
R=10m radius, L=732 Km, 31.4 KT
3.10^20 50 GeV μ+
μ+
CC νe , Pμ+=+1
CC νe , Pμ+=-1
CC ν̄μ , Pμ+=+1
CC ν̄μ , Pμ+=-1
0
500
1000
1500
2000
0
5
10
15
20
25
30
35
40
45
50


x 10^2
ν events from μ decay
μ^-
R=10m radius, L=732 Km, 31.4 KT
3.10^20 50 GeV μ^-
CC ν̄_e , P_μ-=-1
CC ν̄_e , P_μ-=+1
CC ν_μ , P_μ-=-1
CC ν_μ , P_μ-=+1
0
500
1000
1500
2000
4000
4500
0
5
10
15
20
25
30
35
40
45
50

$$\sigma_x = \sigma_y = \frac{1}{100\,\gamma_\mu}$$

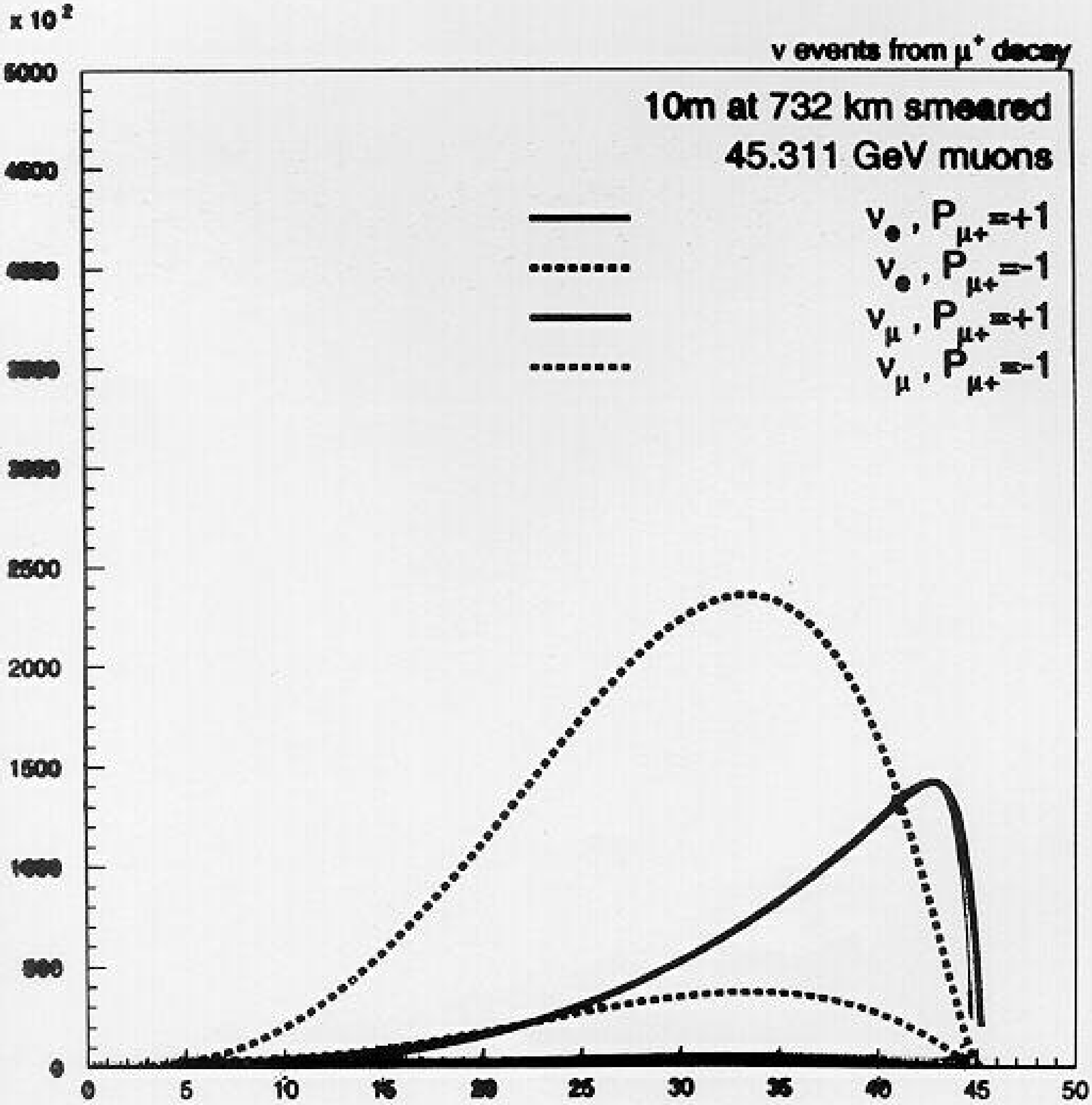
31.4 KT.



= .40 10^6

= 22.0

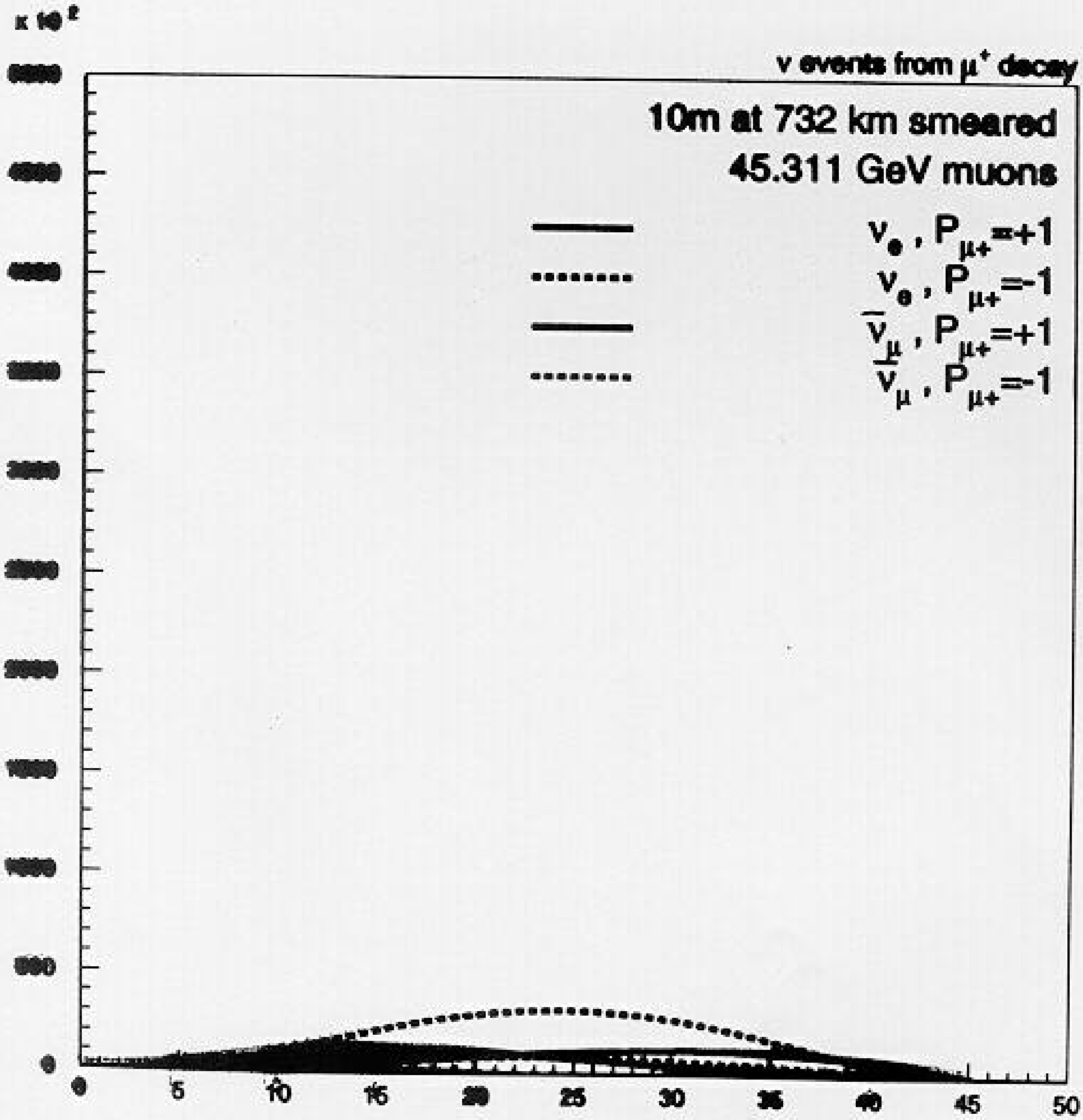
$$\sigma_x = \sigma_y = \frac{1}{10\gamma_\mu}$$



$CC_{\nu_e}^{+} = 1.1 \; 10^6$

$CC_{\bar{\nu}_e}^{-} = 3.2 \; 10^6$

$\sigma_x = \sigma_y = \frac{1}{\gamma_\mu} \Rightarrow$



Measurement of CP and Matter effect:

$$A_{\not{CP}} = P(\nu_i \to \nu_j) - P(\bar{\nu}_i \to \bar{\nu}_j) \propto$$

$$\propto \sin\theta_{13} \cdot \sin\theta_{12} \cdot \sin\theta_{23} \cdot \frac{\Delta m^2_{12} L}{2E} \sin^2 \frac{\Delta m^2_{23} L}{4E}$$

- Because of $\sin\theta_{12} \cdot \Delta m^2_{12}$ ⇒ Needs LMA
  ⇒ oterwise hopeless

$$A_{CP} = P(\nu_i \to \nu_j) + P(\bar{\nu}_i \to \bar{\nu}_j) \propto \sin^2\theta_{13}$$

$$\tilde{A}_{CP} = \frac{A_{\not{CP}}}{A_{CP}} \propto \frac{1}{\sin\theta_{13}}$$ (to the app. $\sin\theta_{13}$ not too small)

- Thus $\tilde{A}_{CP}$ depends on θ_{13} ⇒ Best to decouple $\tilde{A}_{CP}$ from θ_{13} ⇒ Measure the at L where $\tilde{A}_{CP} \to 0$

Max sensit. $\nu_e \leftrightarrow \nu_\mu$ $\nu_e \leftrightarrow \nu_\tau$

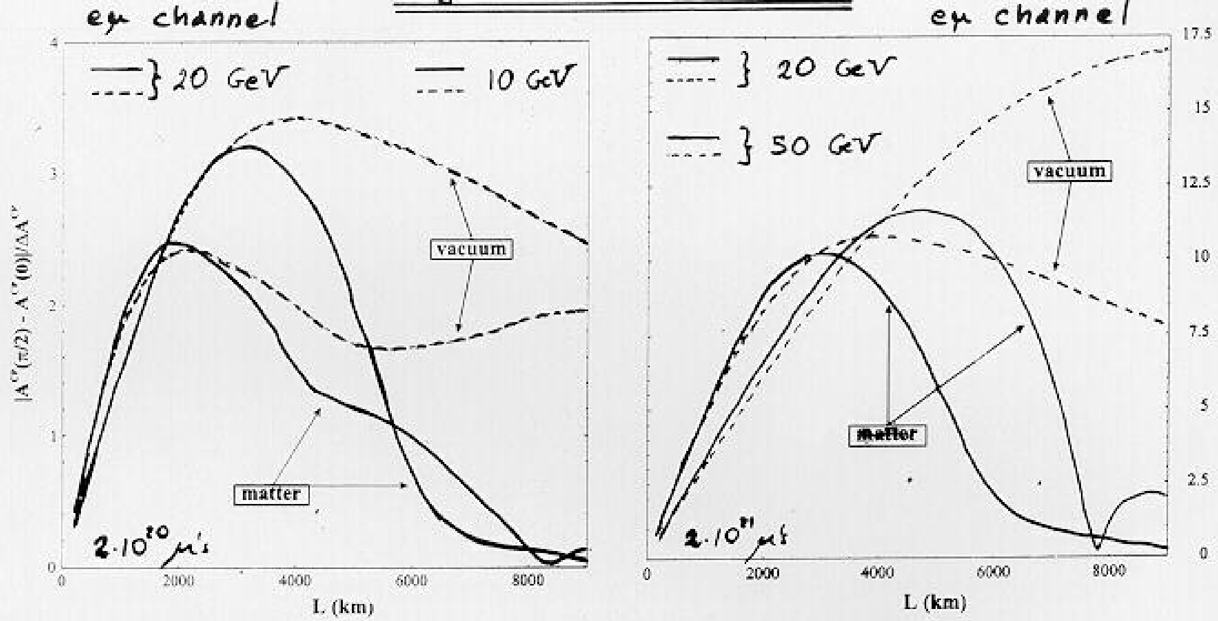
For $\nu_e \leftrightarrow \nu_\mu$ CP-odd type:

$$\tilde{A}_{CP} = \frac{P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu)}{+} = R \cdot \frac{N(\mu^-/\mu^+)_{\mu^-} - N(\mu^-/\mu^+)_{\mu^+}}{+}$$

$$\boxed{R = \frac{\sigma \nu_\mu}{\sigma \bar{\nu}_\mu}}$$ ⇒ Must be known to the 0.1 % [illegible]

Due to matter effects $\tilde{A}_{CP} \neq 0$ even [illegible]

Signal over Uncertainty



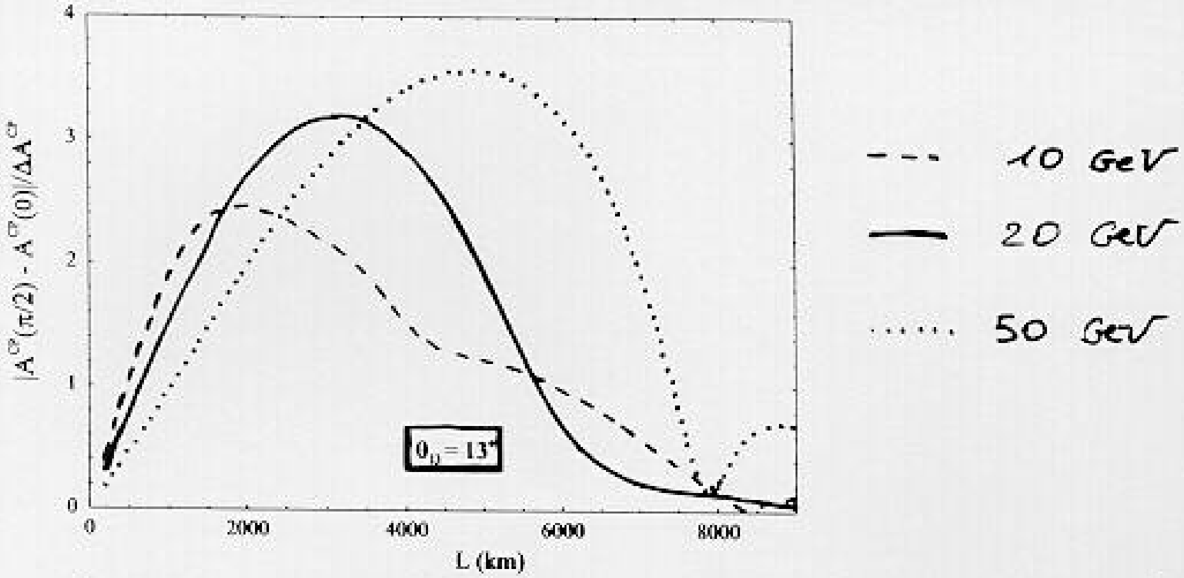
$\underline{\text{Uncertainty}}$ = statistic ($2\times10^{20/21}$ μ's) ⊕ background (10^{-5})

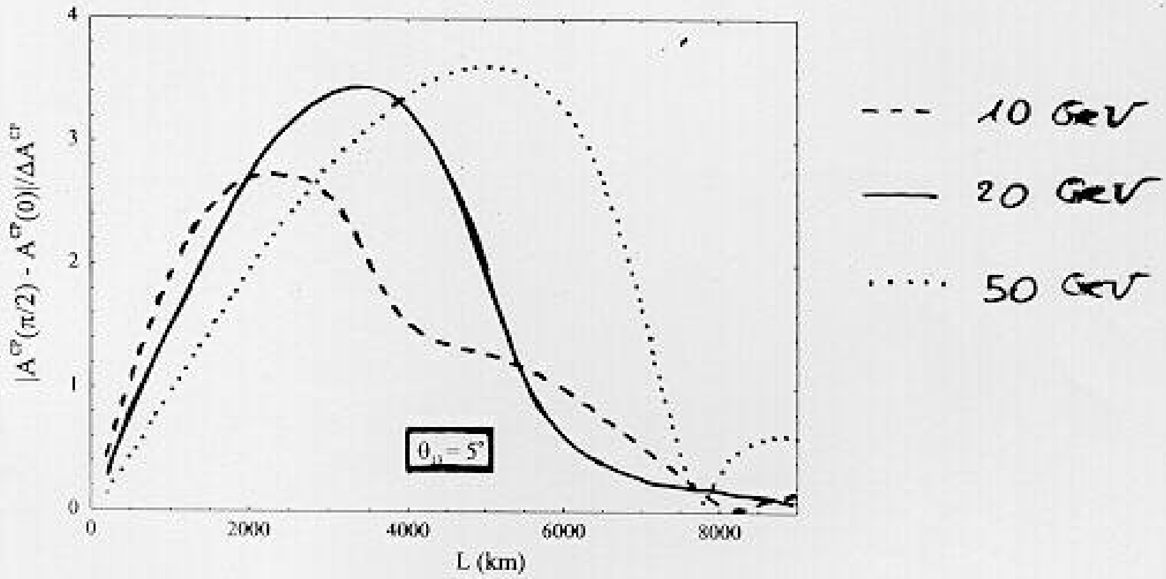
$\vartheta_{12} = 22.5^\circ$, $\vartheta_{13} = 13^\circ$, $\vartheta_{23} = 45^\circ$

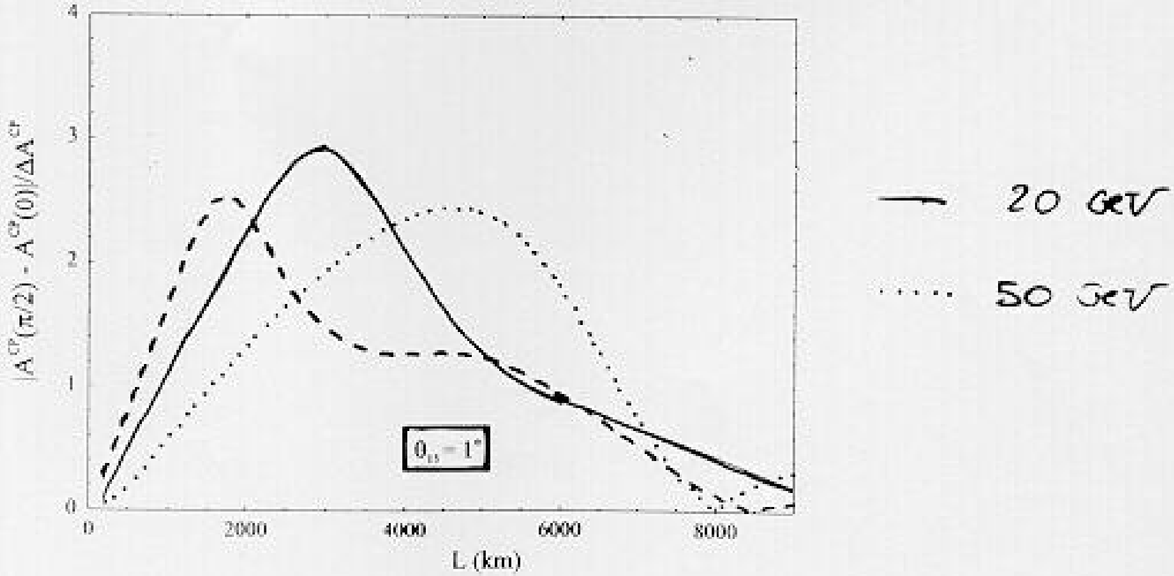
$\Delta m^2_{12} = 10^{-4}\,eV^2$, $\Delta m^2_{23} = 2.8\times10^{-3}\,eV^2$

(KG, AI, FH, AK)

"Subtracted" Asymmetry / Error (eμ channel)







OPTIMAL STRATEGY FOR CP [illegible]

. Presented in Lyon + WG (AD, SR, BG, PH)

- $A_{CP}(s) - A_{CP}(0)$ / δA_{CP} [illegible] as a function of L (and [illegible]) [illegible]
- Effect (marginally) [illegible] with $N_\mu = 10^{21}$ (10 kton detector
- Clearly observable with N_μ = [illegible] (or 50 kton LMC + 2 years [illegible])

Very Encouraging if LMSW !!

In PROGRESS

- Energy-dependent fit to A_{CP} (hope will allow disentangle of CP and matter effects)
- Experimental measurement → evaluation of bkgnds + sistematics (ie, energy resolution?

- Depending on θ13 L ~ 3000 - 5000 km

- A third detector at L = 500 [illegible] km

Conclusions

- Much progress seen in Lyon
  - Machine design converging
  - conceptual design + performance of LMC
  - Preliminary ideas for EIMC
  - Evaluation of sensitivity to oscillation parameters
    - θ_{13} including detector effects
    - $\delta\varphi$ + MSW statistics only (+ flat bkgd) but further studies on progress

- Preliminary evaluation of beam Parameters
  - $E_\mu = 50$ GeV
  - $N_\mu = 10^{21}$ per year
  - Far detector 1 $\simeq 10^3$ km
  - Far detector 2 $\simeq 3.5 \times 10^3$ km
  - $\theta_\mu < \frac{1}{10\gamma}$
  - P_μ option

Still Needed

- Consistent machine Design
- Design and Performance of τ detector
- Design of near detector to achieve

  $\sigma_{\nu_\mu, \bar{\nu}_\mu} \sim 0.1\ \%$

- How useful is P_μ? Strategy?
- Best strategy to simultaneously measure $\not{C}\not{P}$ + M.E.
- Effects of detector in $\not{C}\not{P}$ + ME

Much work ahead!