Neutrino factories from muon storage rings

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Several studies of neutrino factory experiments

- FNAL++ study
  - 20-50 GeV
  - 10^{19}-10^{20} muon decays
  - 732km, 3000 km, 7000km
- CERN/Espana …
  - 50 GeV
  - 10^{20}-10^{21} muon decays
  - 732km, 3500 km, 7000 km
- Lots of new work shown at NUFACT00
  - Bueno *et al.* hep-ph 0005007
  - *Cervera et al.* hep-ph 0002108
  - Albright *et al.* FNAL-FN 692
  - Barger *et al.*, hep-ph 9911524 + later

What we are looking for in 10-15 years?

Assume Δm^2_{23} and θ_{23} are well measured the next things to do are:

- Measure $\sin^2\theta_{13}$ to ~ 0.001
- See $\nu_e <-> \nu_\tau$
- Measure sign of ΔM^2
- Measure CP violation?

- All of these need a measurement of $\nu_e <-> \nu_X$

- A complete check of 3-flavor requires

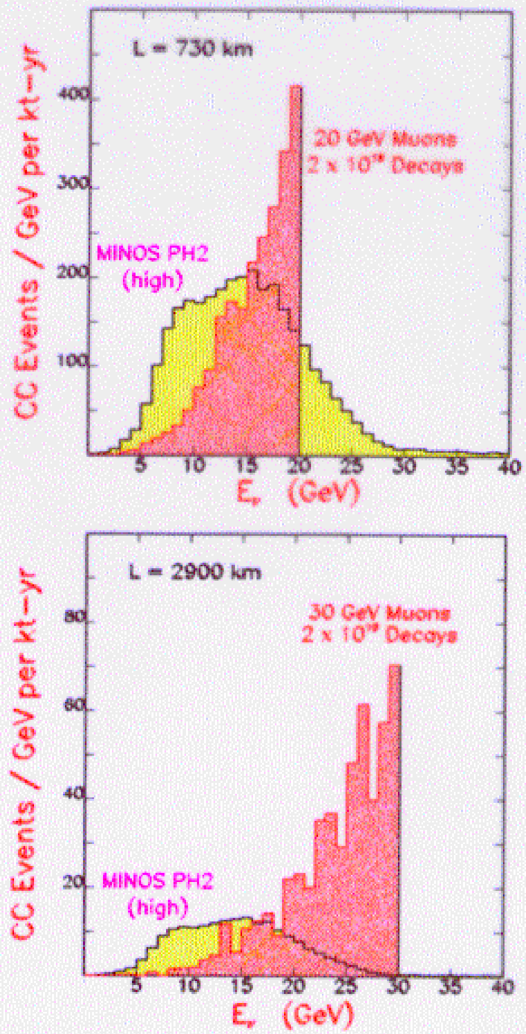
$\nu_e <-> \nu_e$	$\nu_\mu <-> \nu_e$	
$\nu_e <-> \nu_\mu$	$\nu_\mu <-> \nu_\mu$	and anti-particles
$\nu_e <-> \nu_\tau$	$\nu_\mu <-> \nu_\tau$	

3 Flavor Scenarios

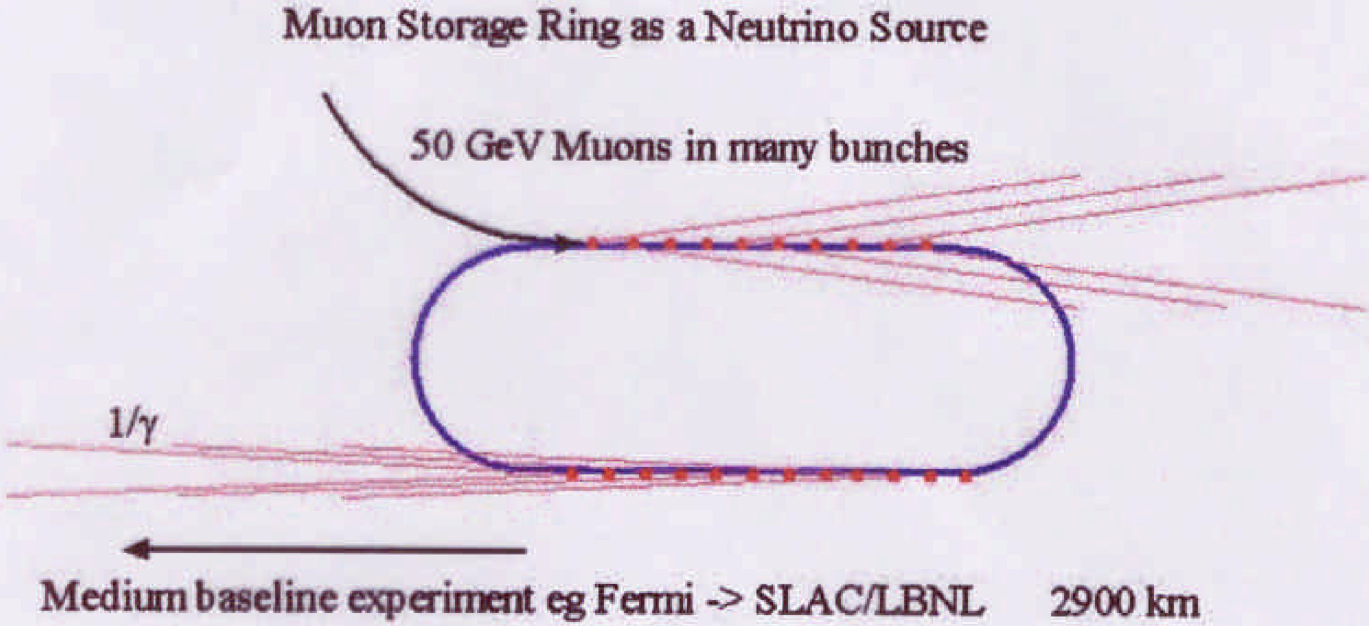
	LMA	SMA	LOW	LSND	
parameter	IA1	IA2	IA3	1B1	1C1
δm^2_{32} (eV^2)	3.5×10^{-3}	3.5×10^{-3}	3.5×10^{-3}	3.5×10^{-3}	0.3
δm^2_{21} (eV^2)	5×10^{-5}	6×10^{-6}	1×10^{-7}	0.3	7×10^{-4}
$\sin^2 2\theta_{23}$	1.0	1.0	1.0	1.0	0.53
$\sin^2 2\theta_{13}$	0.04	0.04	0.04	0.015	0.036
$\sin^2 2\theta_{12}$	0.8	0.006	0.9	0.015	0.89
δ	$0,\pm\pi/2$	$0,\pm\pi/2$	$0,\pm\pi/2$	$0,\pm\pi/2$	$0,\pm\pi/2$
$\sin^2 2\theta_{atm}$	0.98	0.98	0.98	0.99	-
$\sin^2 2\theta_{reac}$	0.04	0.04	0.04	0.03	-
$\sin^2 2\theta_{solar}$	0.78	0.006	0.88	-	-
$\sin^2 2\theta_{LSND}$	-	-	-	0.03	0.036
J	0.02	0.002	0.02	0.002	0.015

Why not use conventional beam

- Conventional beam is great for measuring ν_μ related parameters to ~1%.
- Limitations are electron detection in hadron showers limits ν_μ->ν_e
- To go beyond 1% on ν_μ<–>ν_e or get mass effects and CP violation, need:
  - long baseline,
  - higher energy,
  - way to see ν_μ<–>ν_e transitions with better accuracy.



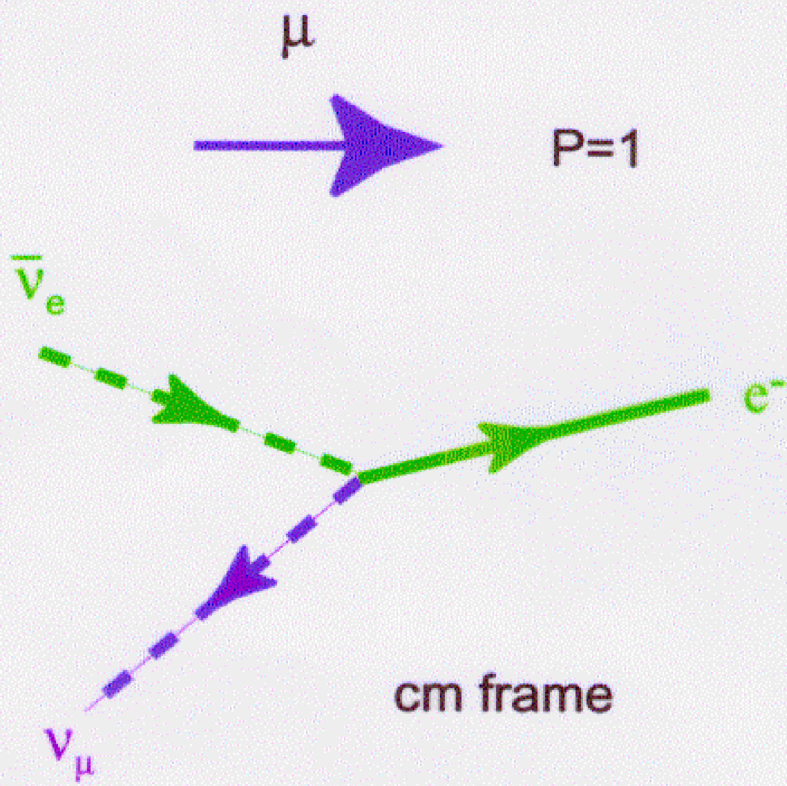
The Neutrino Source



Parameters for the Muon Storage Ring		
Energy	GeV	50
decay ratio	%	>40
Designed for inv. Emittance	m*rad	**0.0032**
Cooling designed for inv. Emitt.	m*rad	**0.0016**
β in straight	m	160
N_μ/pulse	10^{12}	6
typical decay angle of $\mu = 1/\gamma$	mrad	2.0
Beam angle $(\sqrt{\varepsilon}/\beta_o) = (\sqrt{\varepsilon}\,\gamma)$	mrad	0.2
Lifetime $c*\gamma*\tau$	m	$3x10^5$

$\gamma = (1-\alpha^2)/\beta$

Properties of neutrino beams from muon decay



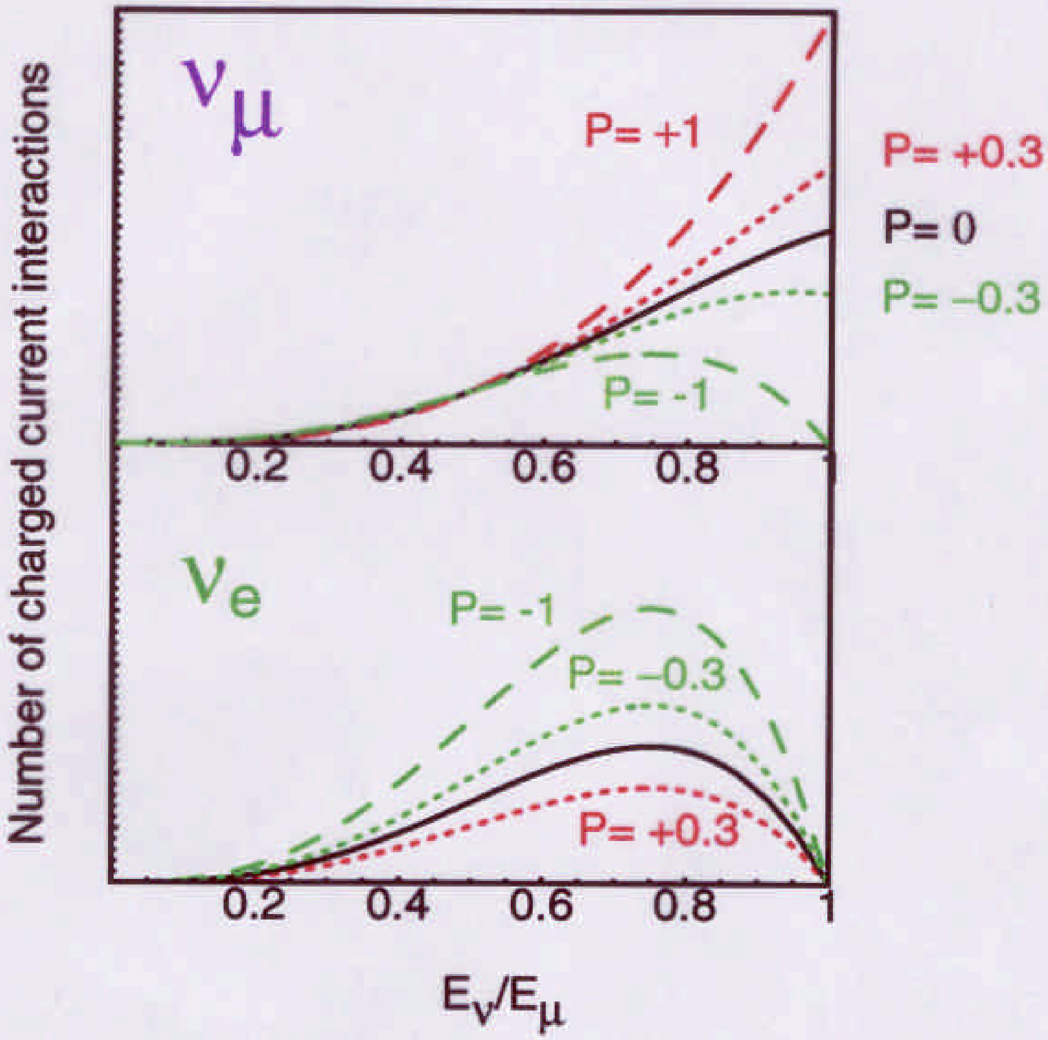
$$\frac{dN(\nu_\mu)}{dz\,d\cos\theta_{CM}} = 2z^2[(3-2z) \mp P(1-2z)\cos\theta]$$

$$\frac{dN(\nu_e)}{dz\,d\cos\theta_{CM}} = 6z^2[(1-z) \mp P(1-z)\cos\theta]$$

$$z = \frac{E_\nu}{E_{max}} \quad \text{where} \quad E_{max} = \ m_\mu/2$$

Single decay mode and well defined kinematics

Neutrino interaction rates as a function of scaled neutrino energy



Beam is a mixture of ν_μ and anti-ν_e or ν_e and anti- ν_μ.Peaked towards high energies, Polarization is hard to get but can be used to remove backgrounds from the mixture.

Why bother with muon decay?

- Goal is maximum neutrino/proton
  - Decay pions/kaons at low energy
  - More decay in decay volume

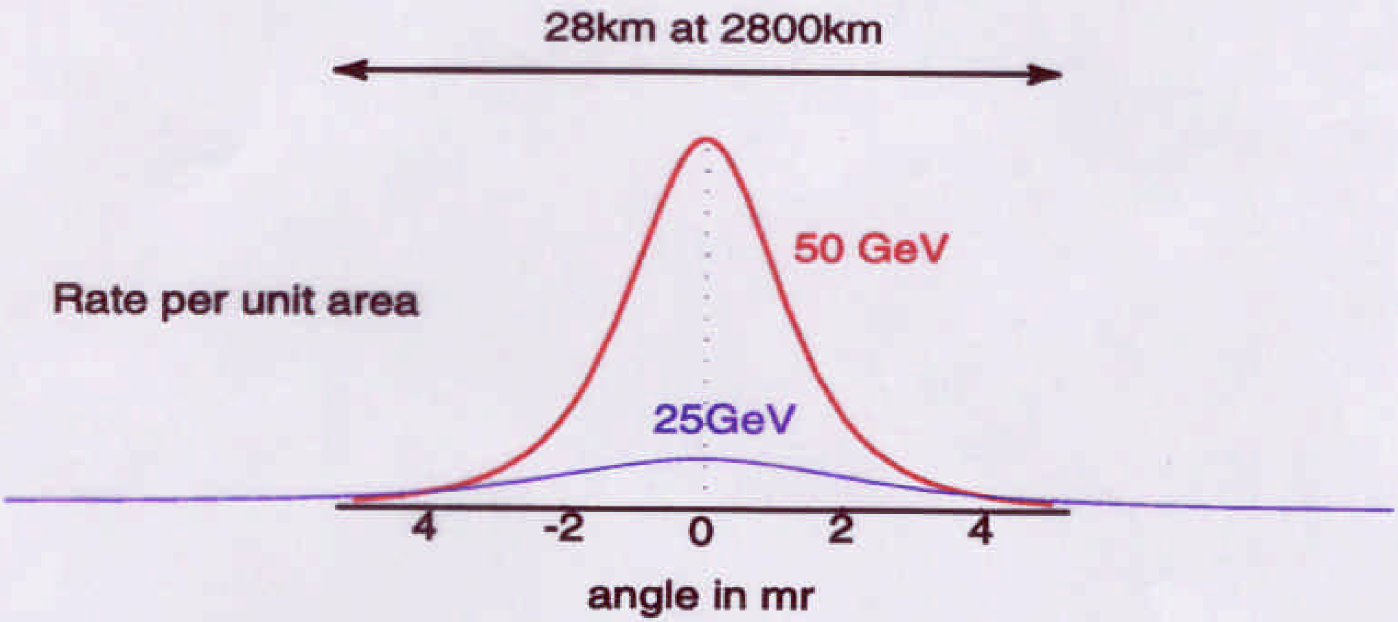
  (~3% at FNAL high energy ν beam)
  - Then accelerate
  - 40% of muons decay in the right direction
- Very well understood source
  - Only one decay process
  - Parent particles ~ monochromatic
  - Around long enough to monitor

See $\nu_e \to \nu_\mu$ in the $\nu_e \sim> \nu_\mu \to \mu^- + X$ channel 'Wrong sign muons'

$\bar{\nu}_\mu \sim> \bar{\nu}_\mu \to \mu^+ + X$ is the conventional muon source

Neutrino Event rates vs angle

θ typical is ~$1/\gamma$



Spread of beam scales as $1/E^2$
Event rate/neutrino scales as E
For same L event rate/unit area scales as E^3

Spread of beam scales as L^2
For fixed E/L, event rate/unit area scales as E

Mario Campanelli

Event rates for a 10 kton detector

Rates				
		L=732 km	L=2900 km	L=7400 km
μ^- 10^{20} decays	ν_μ CC	226000	14400	2270
	ν_μ NC	67300	4120	680
	$\bar{\nu}_e$ CC	87100	5530	875
	$\bar{\nu}_e$ NC	30200	1990	300
μ^+ 10^{20} decays	$\bar{\nu}_\mu$ CC	101000	6380	1000
	$\bar{\nu}_\mu$ NC	35300	2240	350
	ν_e CC	197000	12900	1980
	ν_e NC	57900	3670	580

No oscillations

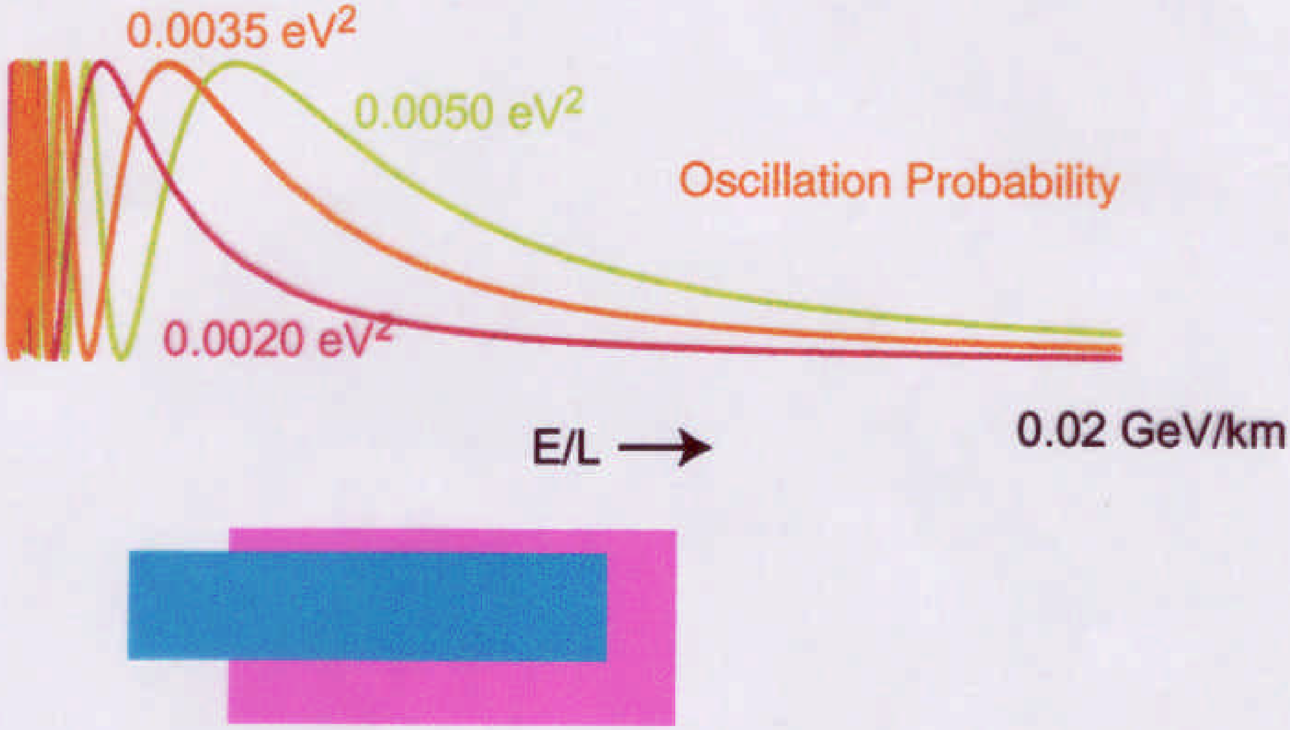
E_μ=30 GeV

No polarization

No beam divergence

Experiments can be described by their E/L coverage

- $P(\nu_\alpha \to \nu_\beta) \sim \sin^2 2\theta \, \sin^2[1.27 \Delta m^2 \, L/E]$
- m in eV, L in km, E in GeV

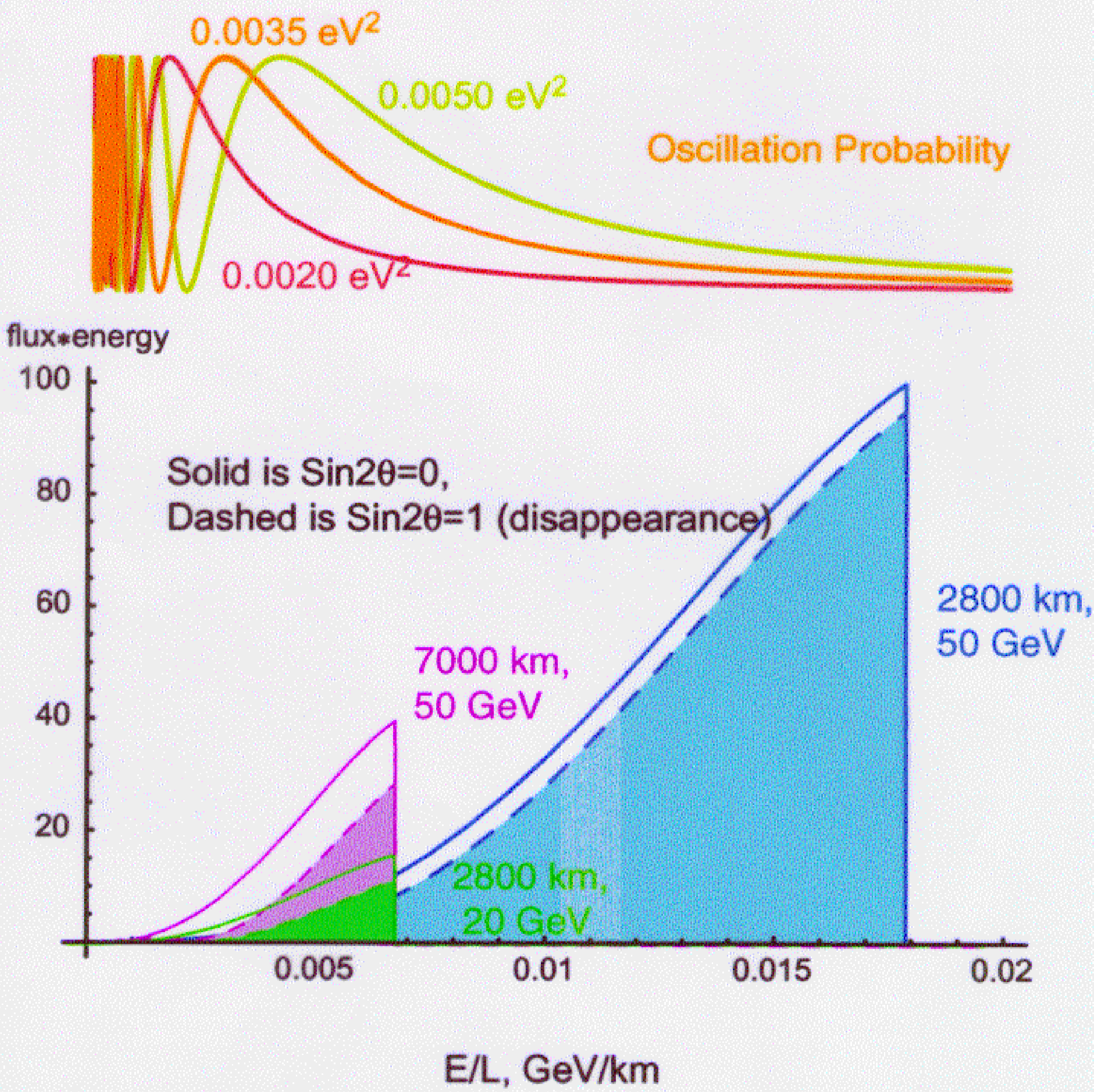


If E/L << Δm^2, $P(\nu_\alpha \to \nu_\beta) \sim \frac{1}{2} \sin^2 2\theta$

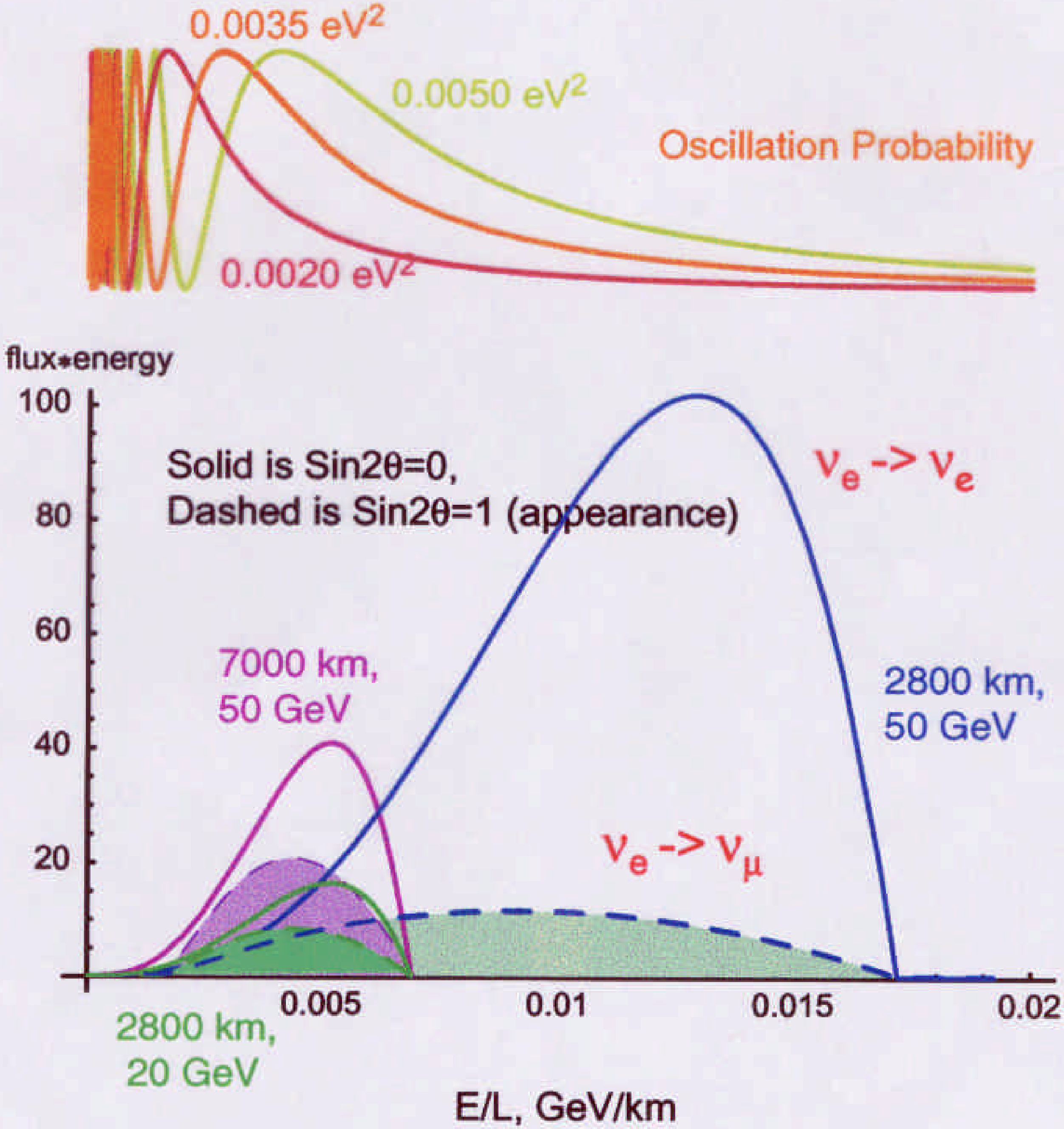
If E/L >> Δm^2, $P(\nu_\alpha \to \nu_\beta) \sim 0$

If E/L ~ Δm^2, can measure both Δm^2 and $\sin^2 2\theta$

Numbers of muon neutrino interactions for fixed number of muon decays Δm^2=0.0035 eV^2



Numbers of electron neutrino interactions for fixed number of muon decays $\Delta m^2=0.0035\ eV^2$



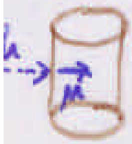
Detectors

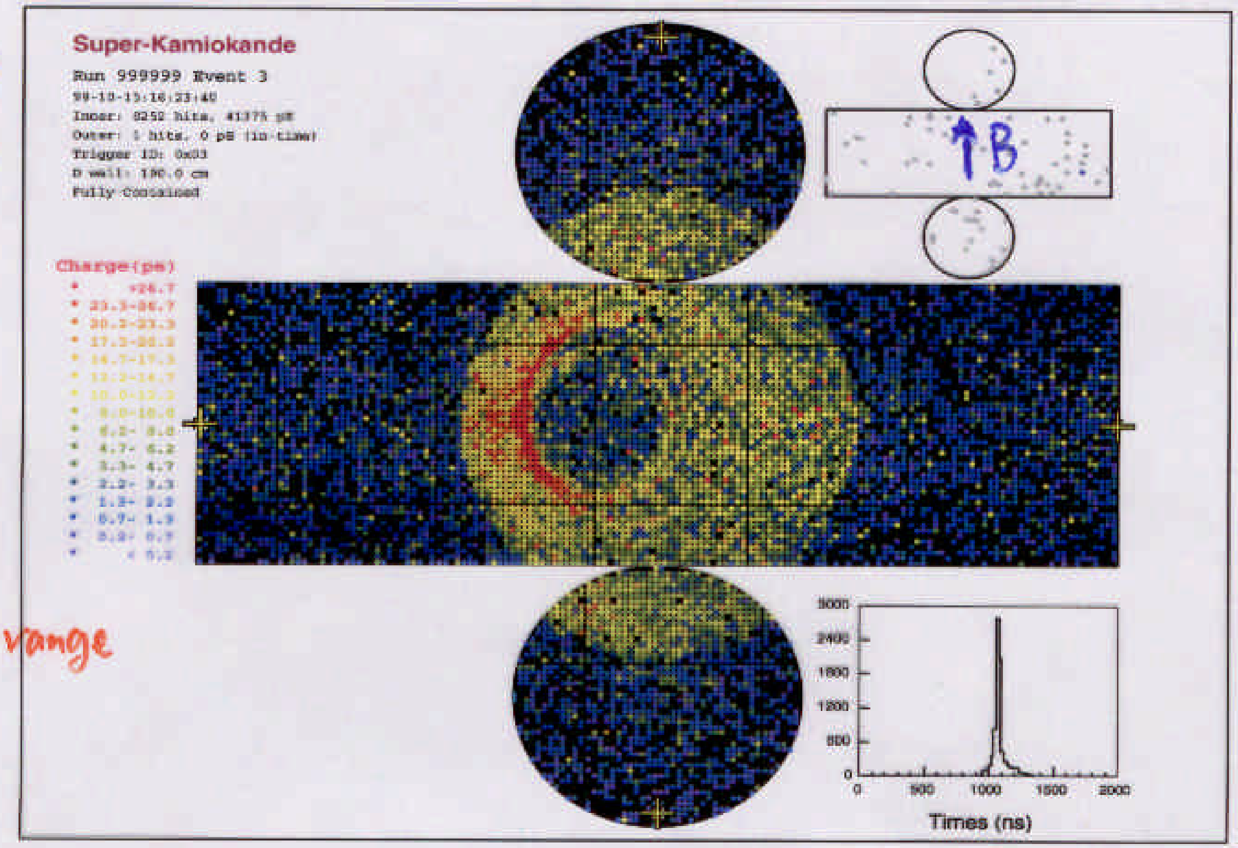
`Protons are cheaper than muons'

- Tau detection
  - Emulsion/msgc ~ 1-20 kTons
  - Tau id, electron id
- Liquid argon drift
  - 10-20 kTons
  - Electron id!
- Magnetized Iron Scintillator
  - 20-100 kTons
  - Good muon id!
- Water Cerenkov with magnet tail
  - 50-500 kTons
  - Electron id, limited muon charge

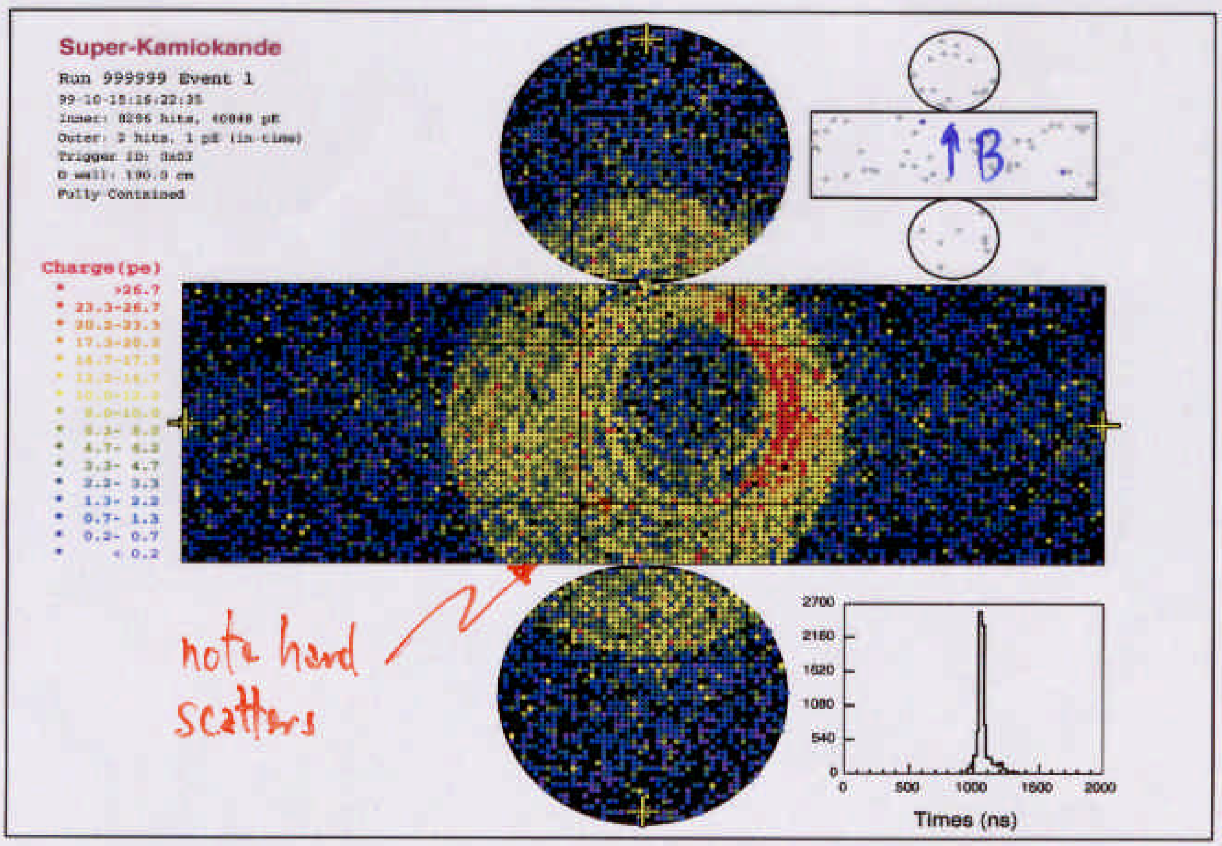
... horizontal 5 GeV muons from ν_μ at tank edge

Super-K with 1 kG $\vec{B}$, $+\hat{z}$





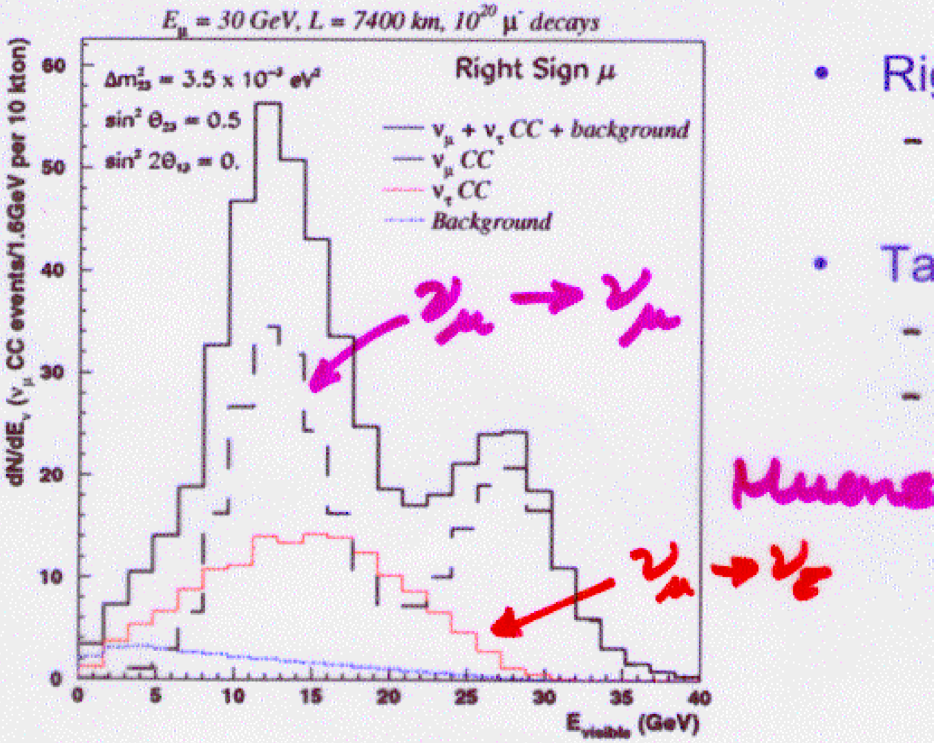
μ−
bent left
~25 m range



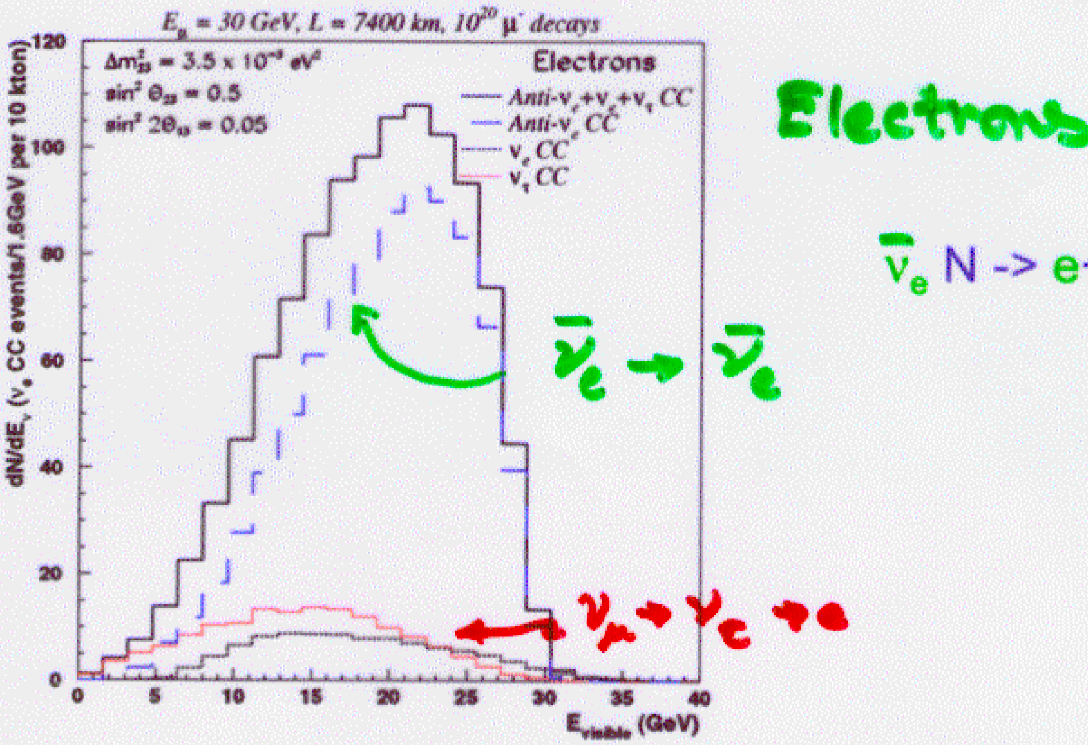
μ+
bent right

A. Habig

10^{20} muon decays



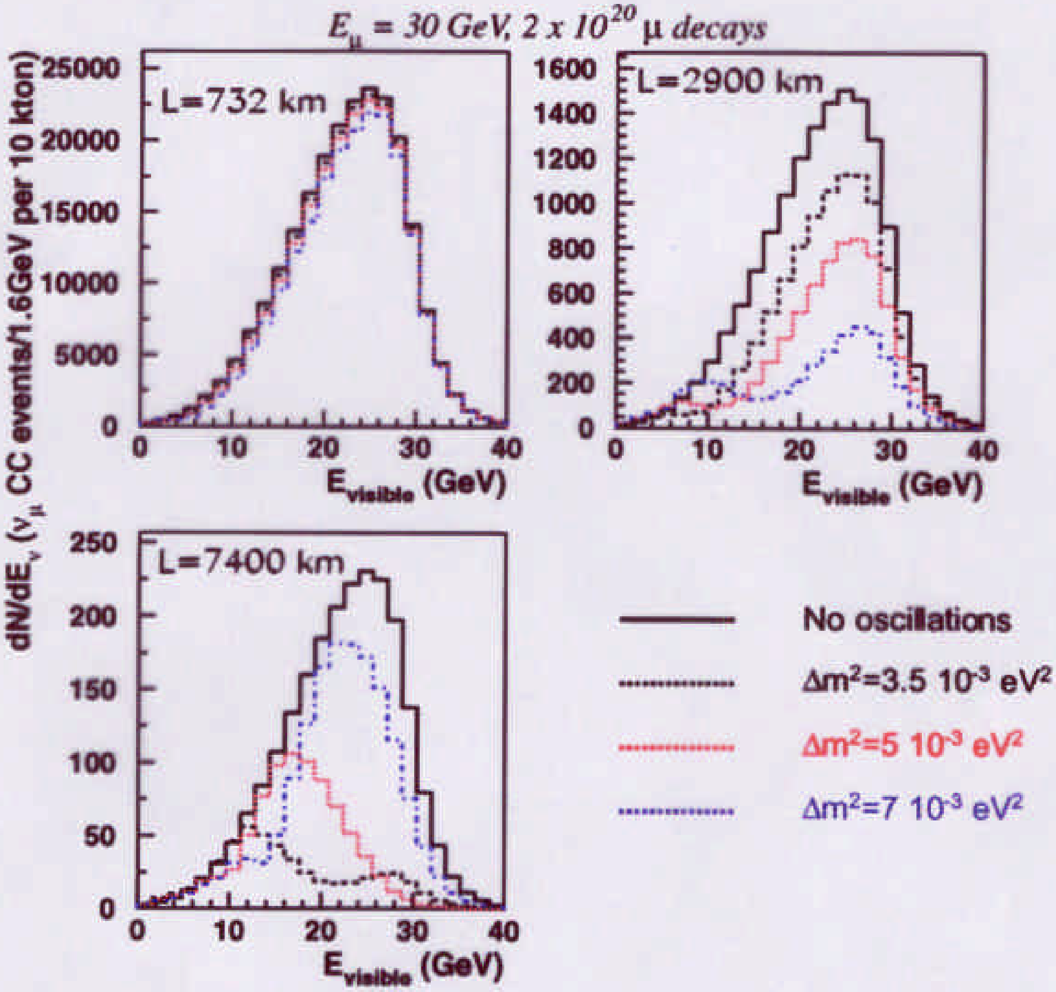
- Right sign muons
  - Dip due to oscillation
- Tau's contribute
  - Signal?
  - Background?



$\bar{\nu}_e$ N -> e+X

Bueno et al.

Disappearance Experiment ν_μ->ν_τ



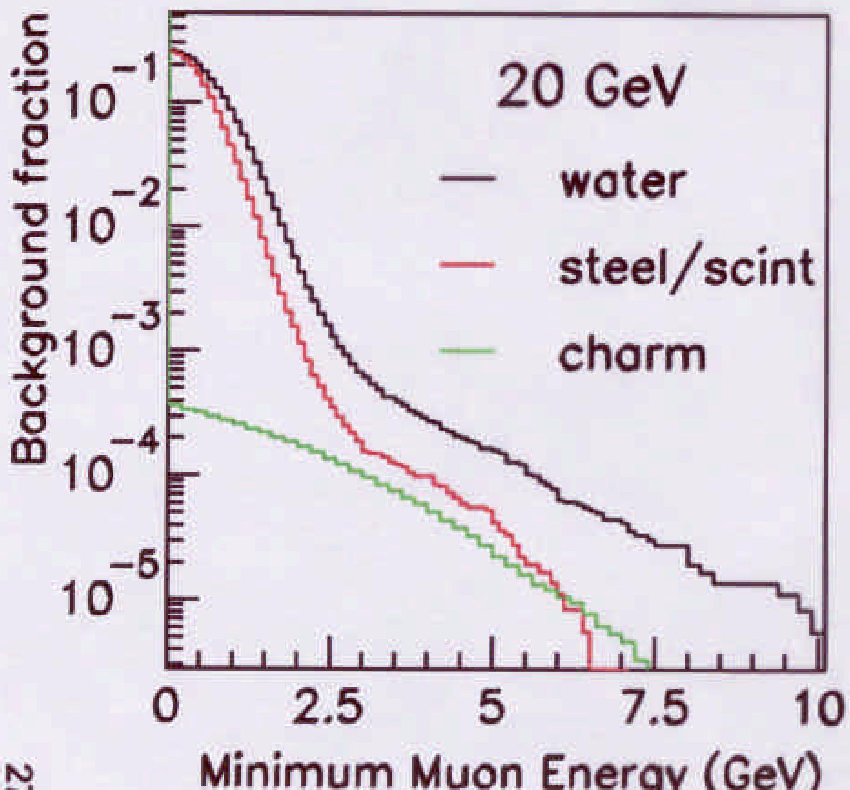
Mario Campanelli, ETH Zurich

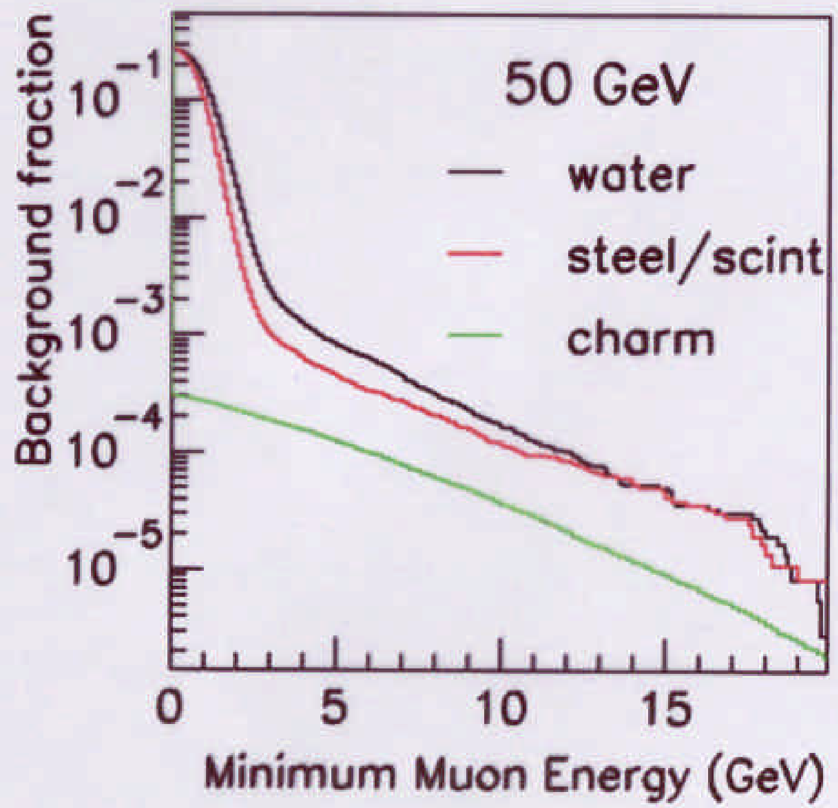
What determines the machine energy?

- We're interested in $\nu_e \to \nu_\mu$
- Need to tag wrong sign muons with very low backgrounds
- there are also anti- ν_μ in the beam
- Wrong sign muons from
  - Hadron decay
  - Charm decay
  - Non-interacting hadrons
  - Charge confusion
- How do you tell a 2 GeV pion from a 2 GeV muon at the 0.01% level?

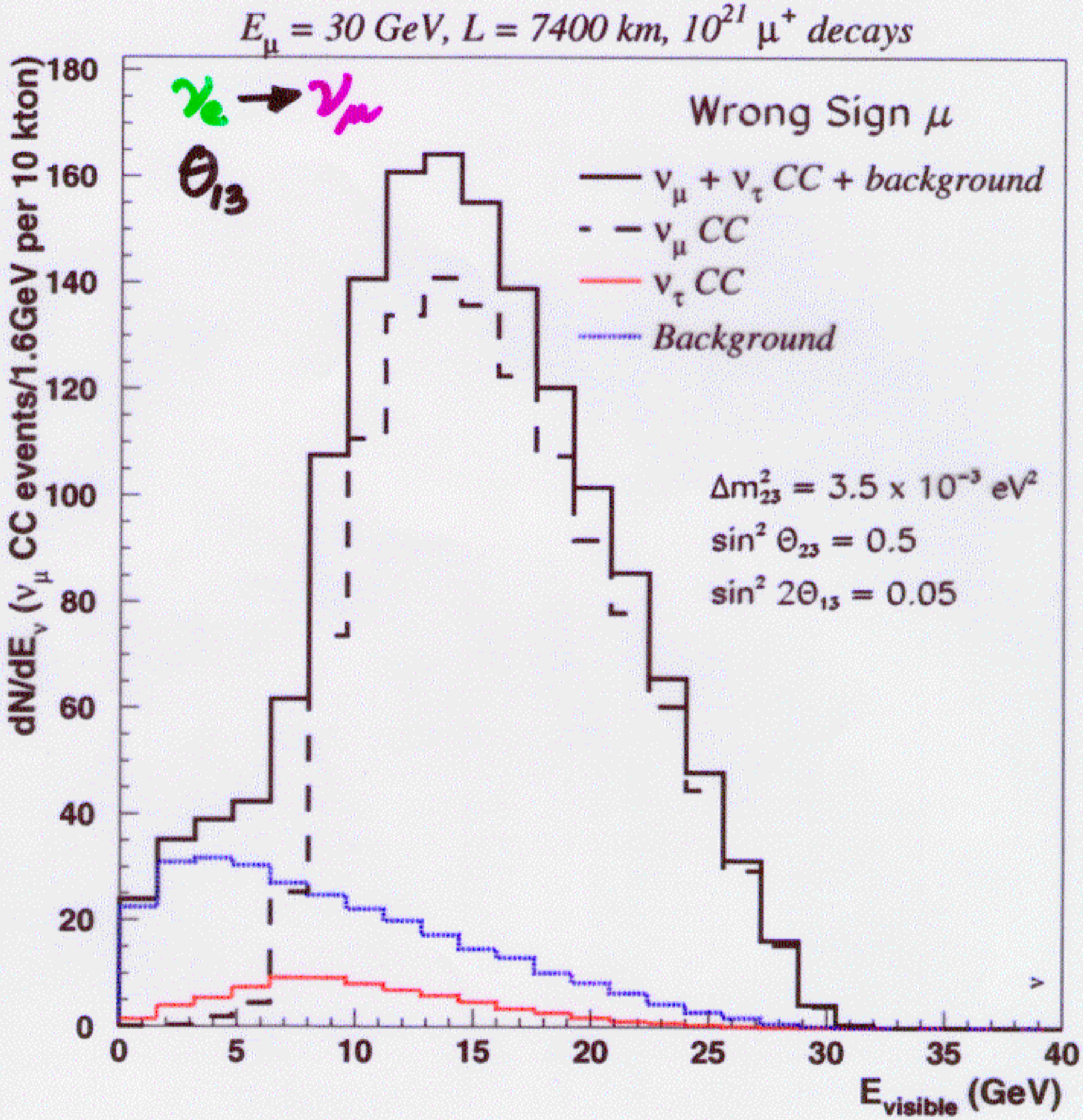
Backgrounds to $\bar{\nu}_e \rightarrow \bar{\nu}_\mu \rightarrow \mu^+$

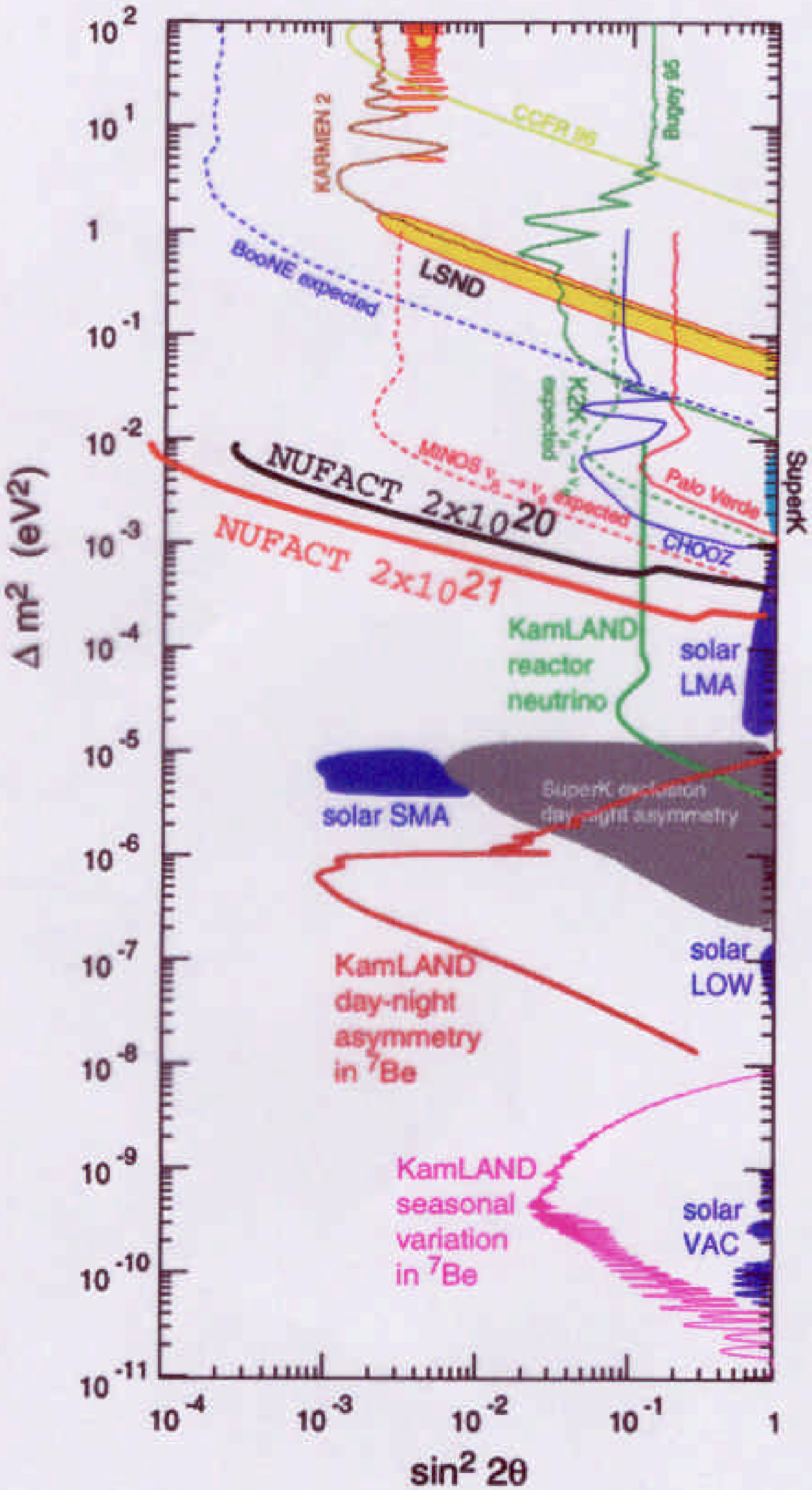
Pions which do not interact!





10^{21} muon decays





Limits on $\sin^2\theta_{13}$ for a 10kt detector 7400 km away.

Bueno *et al.*

$\nu_e > \nu_\mu$ Appearance

FNAL>SLAC/LBNL (L = 2800 km) 10kT	E_μ = 30 GeV 2 x 10^{20} Decays

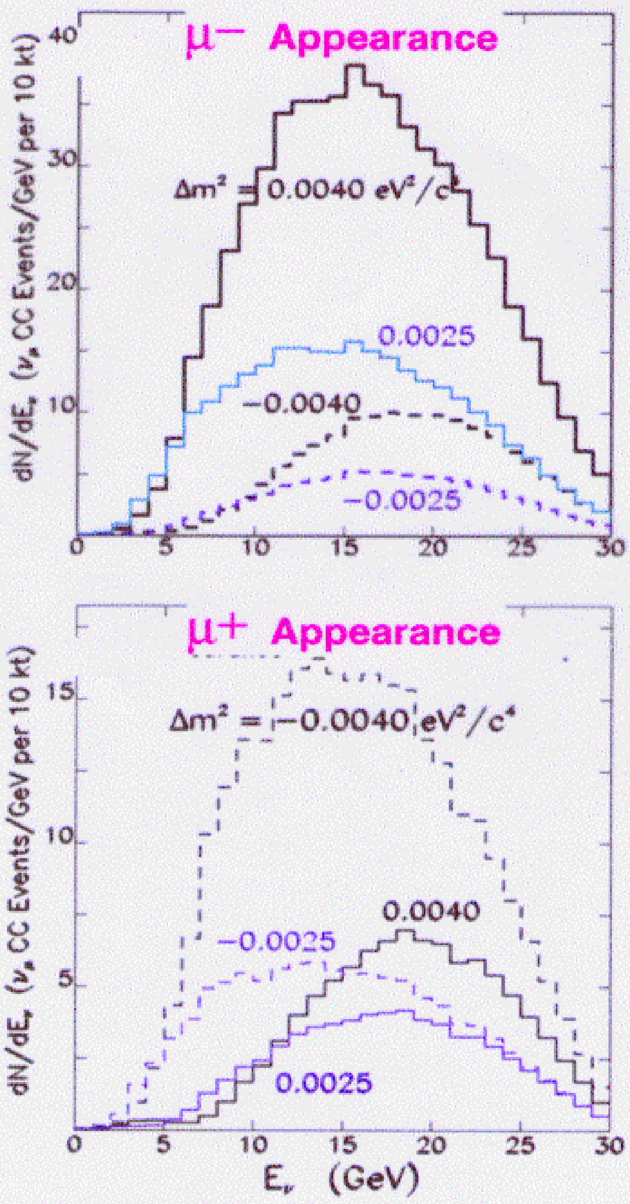
ThreeFlavor Mixing

$\Delta m^2_{21} = 5 \times 10^5$ eV^2/c^4

$\sin^2 2\theta_{23} = 1$ $\delta = 0$

$\sin^2 2\theta_{12} = 0.8$

$\sin^2 2\theta_{31} = 0.04$



$\nu_e \to \nu_\mu$

$\bar{\nu}_e \to \bar{\nu}_\mu$

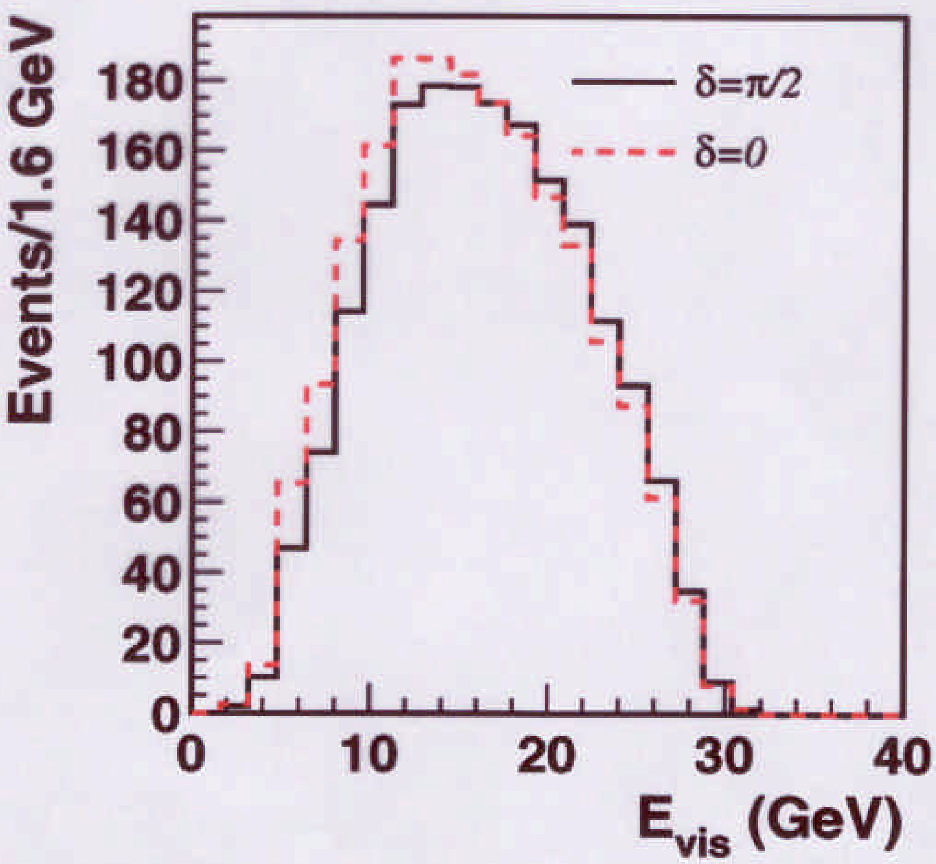
Sign of Δm^2 can be determined thanks to matter effects

Barger Geer Raja Whisnant
FermilabPub 99341

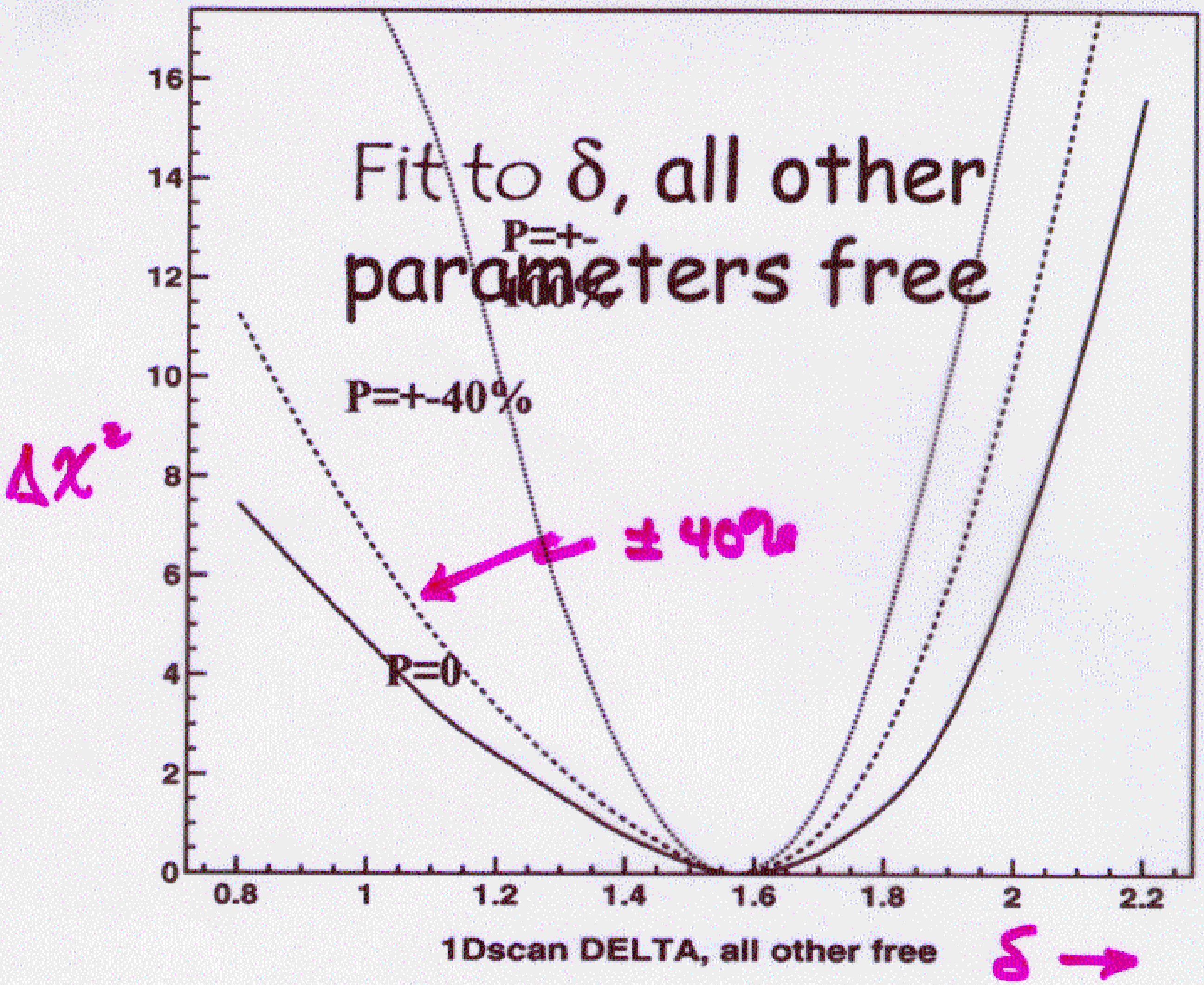
What optimal *CP* violation looks like

Assume Solar LMA solution, large θ_{12}, θ_{13}

Wrong-sign muons



10^{21} μ, 3500 km

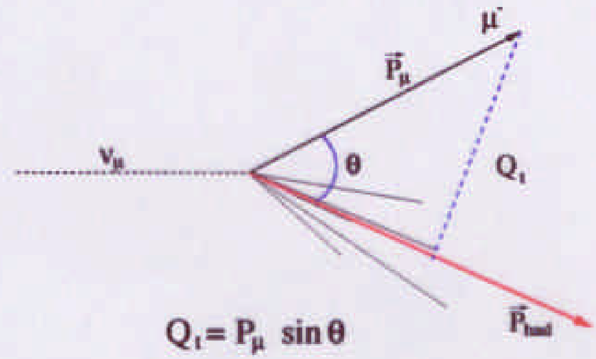


P = 0 :	$\delta = 1.57 \pm 0.20$
P= ±40%	$\delta = 1.57 \pm 0.15$
P= ±100%	$\delta = 1.57 \pm 0.10$

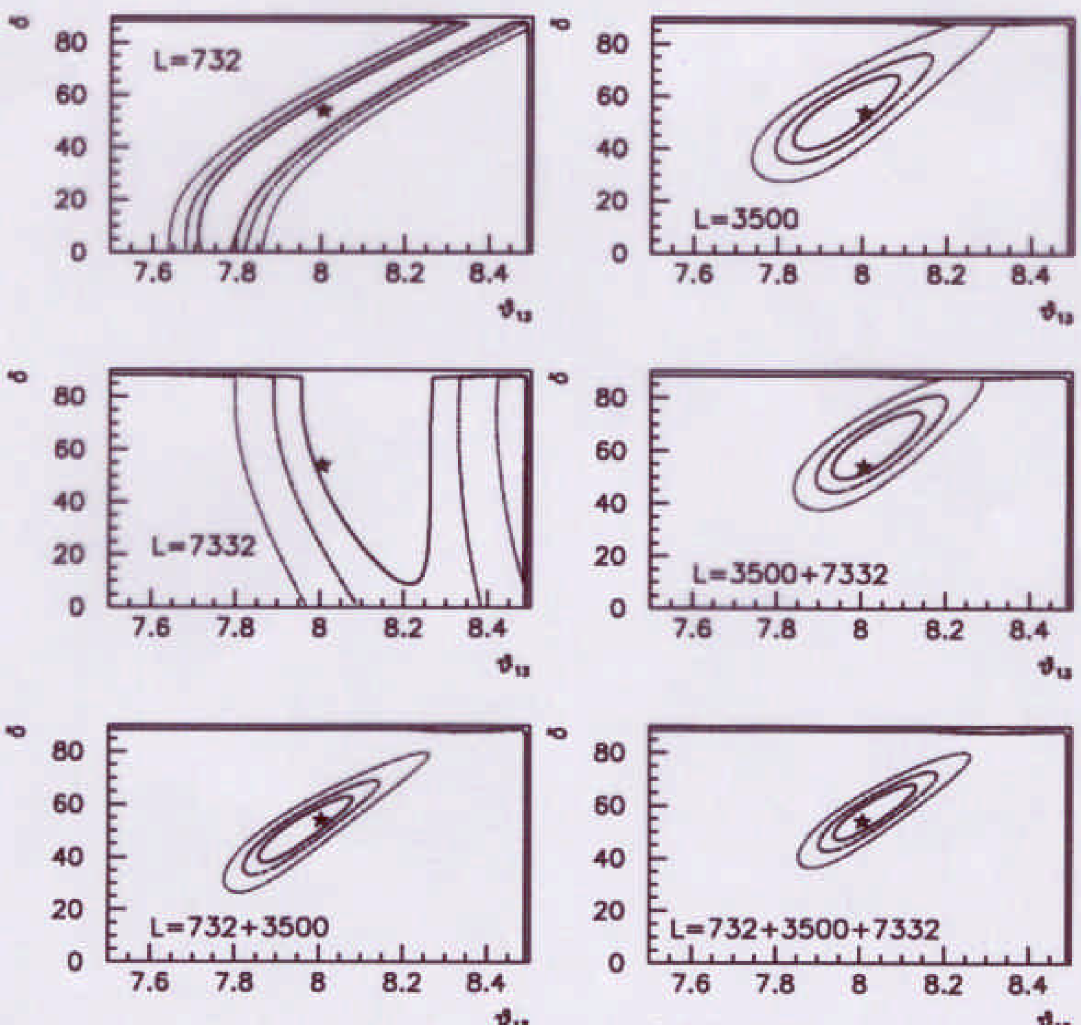
Blondel NUFACT00 - *CP/polarization*

Kinematic cuts can increase sensitivity at high event rates.

Cervera et al.



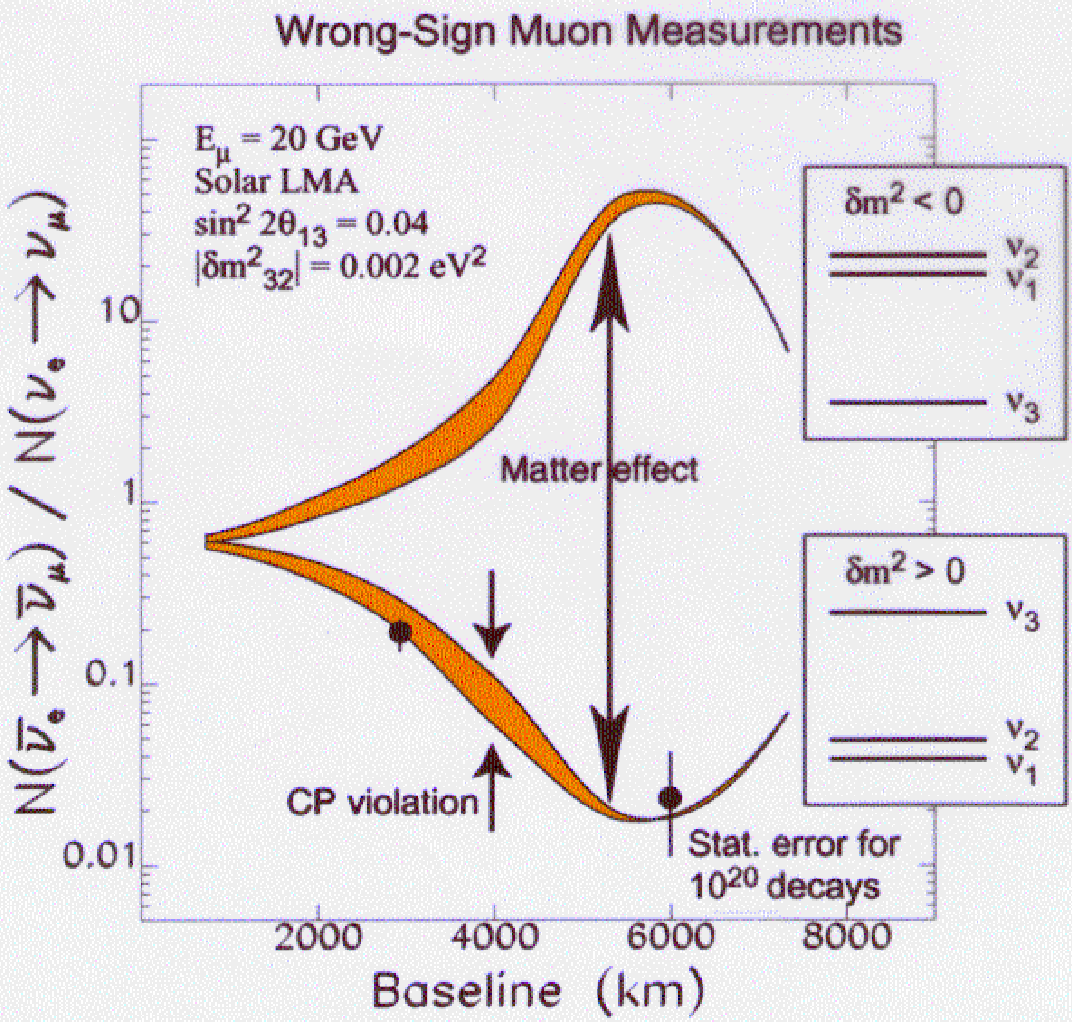
68, 90 and 99% confidence levels



Cervera et al.

To see CP violation, all 3 flavors must be involved. Only see it if Dm_{solar} is not too small and the Jarlskog factor J is large.

$$J = c_{12}c_{13}^2c_{23}s_{12}s_{13}s_{23}(\sin\delta) .$$



Conclusions

- Baselines of ~3000-7000 are very interesting
- Large detectors are needed (and the cheap way to go
- Intensities >~ 10^{20}/year open allow
  - very accurate measure of Δm^2_{23} and θ_{23}
  - Measure $\sin^2 2\theta_{13}$ and sign of Δm^2_{23}
- May be sensitive to CP violation if

  $\sin^2 2\theta_{13}$, $\sin^2 2\theta_{12}$ and Δm^2_{12} are large (lucky LMA solution)

Near detector physics factor of 1000 better than present or foreseen expts.

Standard Model of Elementary Particles

S: Charge / mass,MeV

	3 Generations of Fermions			Force Carriers	
Quarks	u 2/3 ~5	c 2/3 ~1350	t 2/3 175000	g 0 0	Strong Interactions
Quarks	d −1/3 ~9	s −1/3 ~175	b −1/3 ~4500	γ 0 0	Electro-magnetism
Leptons	ν_1 0?	ν_2 0?	ν_3 0?	Z^0 0 91187	Weak Interactions
Leptons	e 0.511	μ 105.66	τ 1777.2	$W^{\pm}$ ±1 81400	Weak Interactions

Masses are in MeV