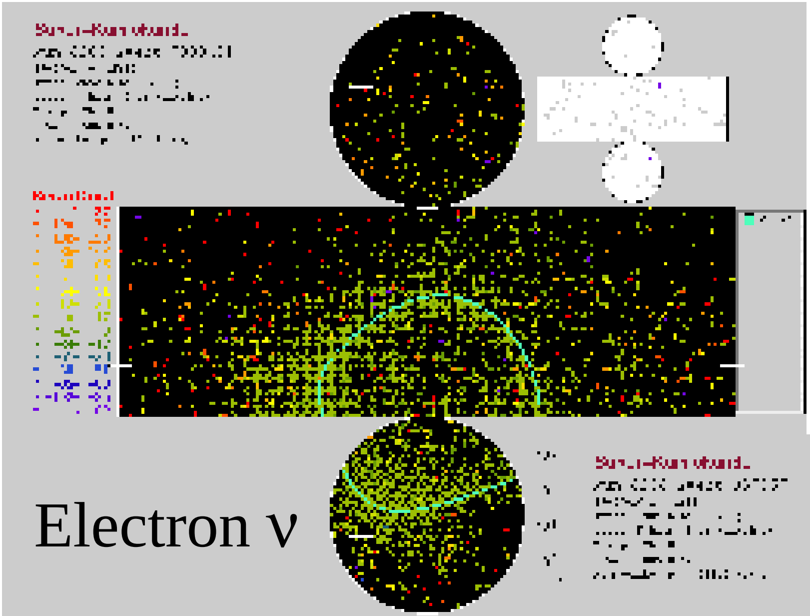
Neutrino factories from muon storage rings

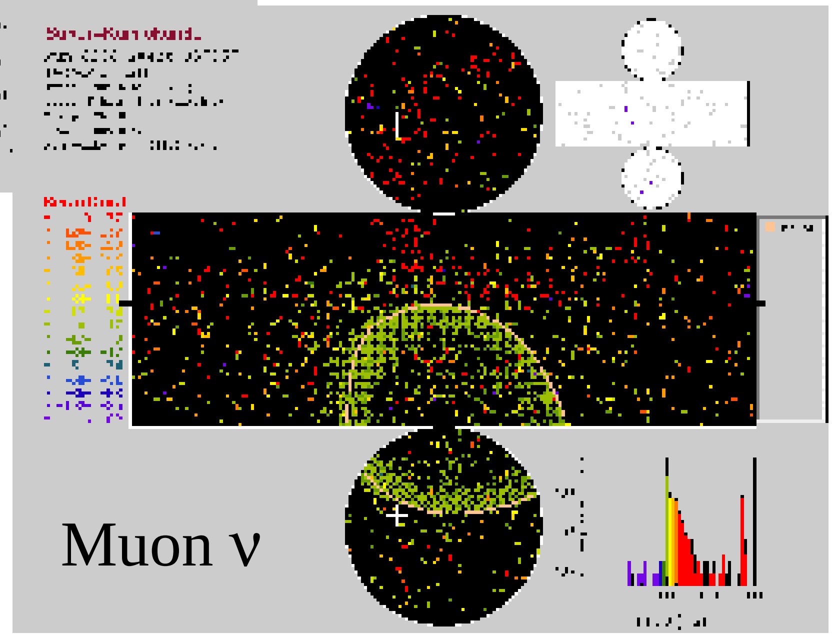
H. Schellman
Northwestern University/FNAL

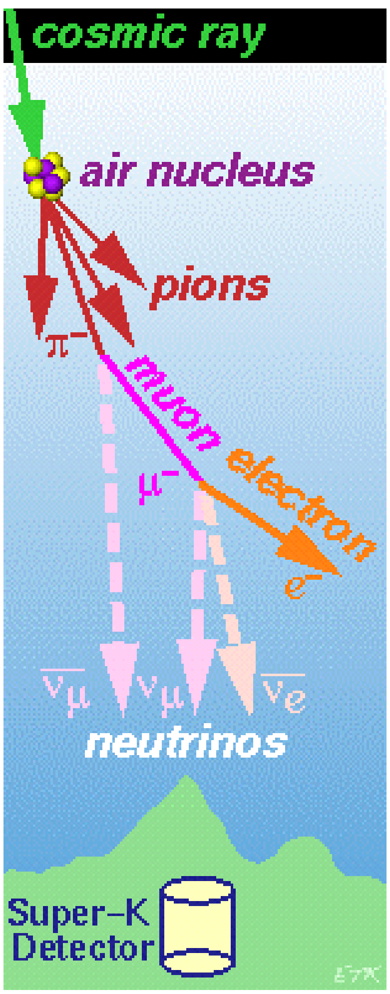
Study Participants

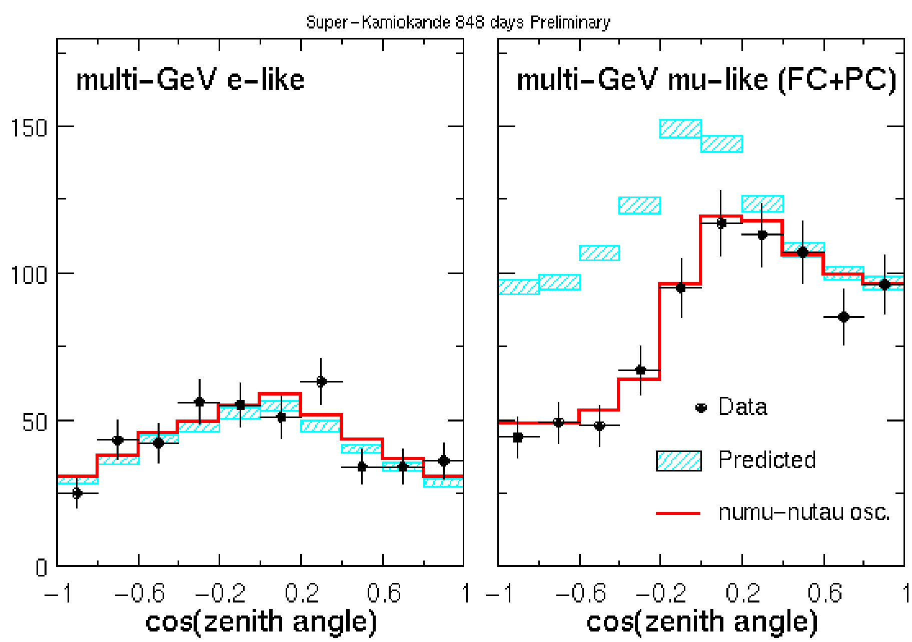
C.Albright, G.Anderson, V.Barger, R.Bernstein, G.Blazey, A.Bodek, E.Buckley—Geer, A.Bueno, M.Campanelli, D.Carey, D.Casper, A.Cervera, C.Crisan, F.DeJongh, S.Eichblatt, A.Erner R.Fernow, D.Finley, J.Formaggio, J.Gallardo, S.Geer, M.Goodman, D.Harris, E.Hawker, J.Hill, R.Johnson, D.Kaplan, S.Kahn, B.Kayser, E.Kearns, B.J.King, H.Kirk, J.Krane,D.Krop Z.Ligeti, K.McFarland, I.Mocioiu, J.Morfin, H.Murayama, J.Nelson, D.Neuffer, P.Nienaber, R.Palmer, S.Parke, Z.Parsa, R.Plunkett, E.Prebys, C.Quigg, R.Raja, S.Rigolin, A.Rubbia, H.Schellman, M.Shaevitz, P.Shanahan, R.Shrock, P.Spentzouris,R.Stefanski, J.Stone, L.Sulak, G.Unel, M.Velasco, K.Whisnant, J.Yu, E.D.Zimmerman

Super Kamiokande Sees $\nu_\mu \rightarrow \nu_\tau$?







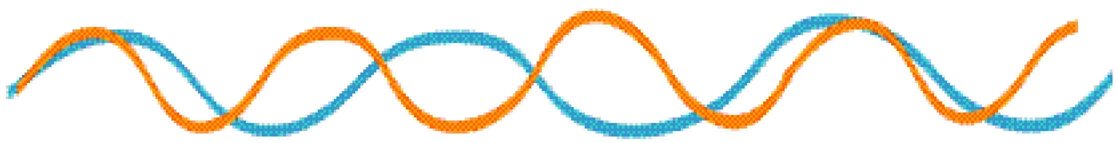


ν oscillations

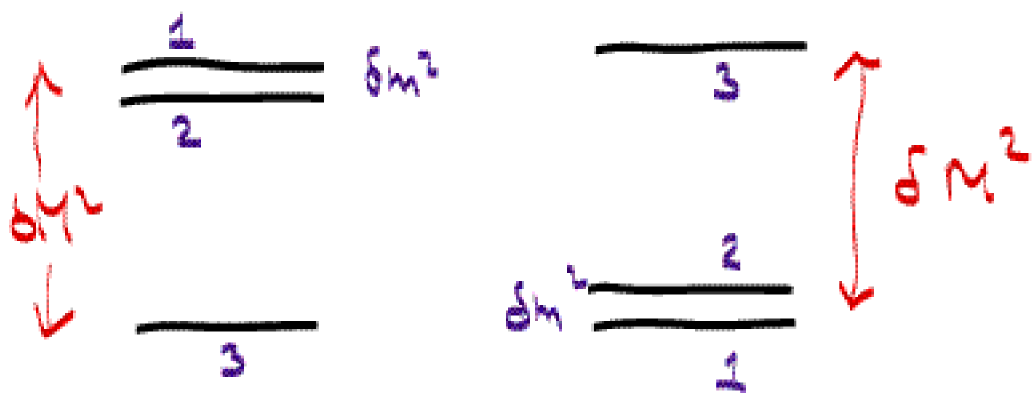
$$P(\nu_x \to \nu_y) \sim \sin^2 2\theta \, \sin^2 \frac{\delta m^2 L}{4E}$$

weak states $\nu_e \; \nu_\mu \; \nu_\tau$

mass states $\nu_1 \; \nu_2 \; \nu_3$

ν_e  ν_τ

$\delta m^2 \ll \delta M^2$



3 mixing angles

1 CP - phase

2 mass differences

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{23} \cos^4 \theta_{13} \sin^2\left(\frac{\delta M^2 L}{4E}\right)$$

Atmospheric ν tell us

$$\sin^2 2\theta_{23} \sim 1$$

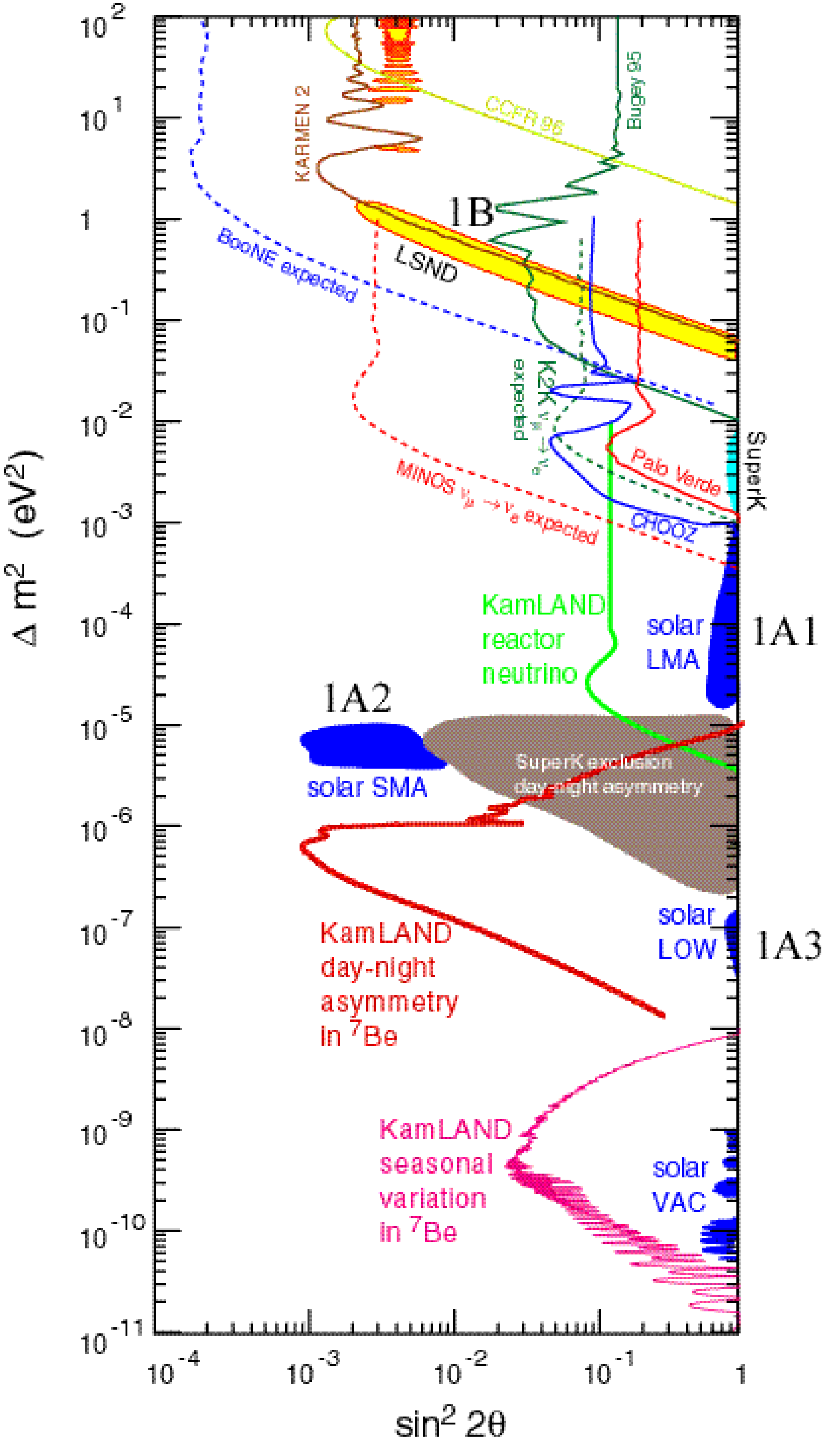
$$\delta M^2 \sim 0.0035\ \mathrm{eV}^2$$

$$P(\nu_e \to \nu_\mu) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{\delta M^2 L}{4E}\right)$$

CHOOZ / Palo Verde

$$\sin^2 2\theta_{13} < 0.1$$

LSND $\delta m_{12}^2 \gg \delta M^2 \sim 1\ \mathrm{eV}^2$



KARMEN 2
CCFR 96
Bugey 95
1B
LSND
BooNE expected
K2K $\nu_\mu \to \nu_e$ expected
MINOS $\nu_\mu \to \nu_e$ expected
Palo Verde
CHOOZ
SuperK
KamLAND reactor neutrino
solar LMA
1A1
1A2
solar SMA
SuperK exclusion day-night asymmetry
solar LOW
1A3
KamLAND day-night asymmetry in ^{7}Be
KamLAND seasonal variation in ^{7}Be
solar VAC
Δm^2 (eV^2)
$\sin^2 2\theta$

3 Flavor Scenarios

parameter	IA1	IA2	IA3	IB1	IC1
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^{-5}
$\sin^2 2\theta_{23}$	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

What we are looking for

Assume Δm^2_{23} and θ_{23} are well measured

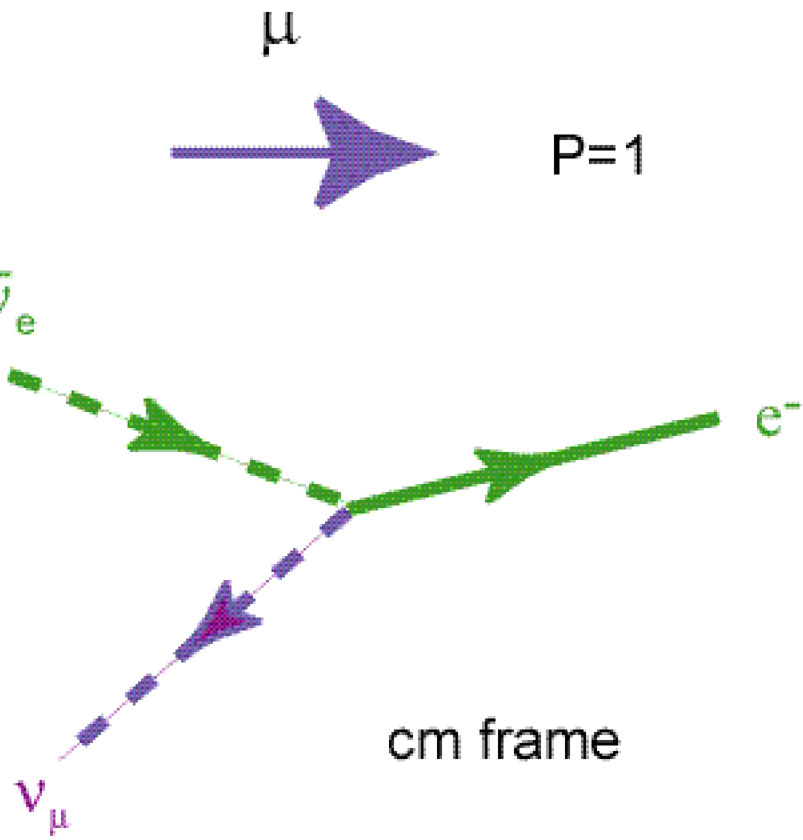
- Measure $\sin^2\theta_{13}$ to ~ 0.001
- See ν_e<->ν_τ
- Measure sign of ΔM^2
- Measure CP violation?

- All of these need a measurement of ν_e<->ν_X

- A complete check of 3-flavor requires

ν_e<->ν_e	ν_μ<->ν_e	
ν_e <-> ν_μ	ν_μ <-> ν_μ	and anti-particles
ν_e <-> ν_τ	ν_μ <-> ν_τ	

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

Why not use conventional beam

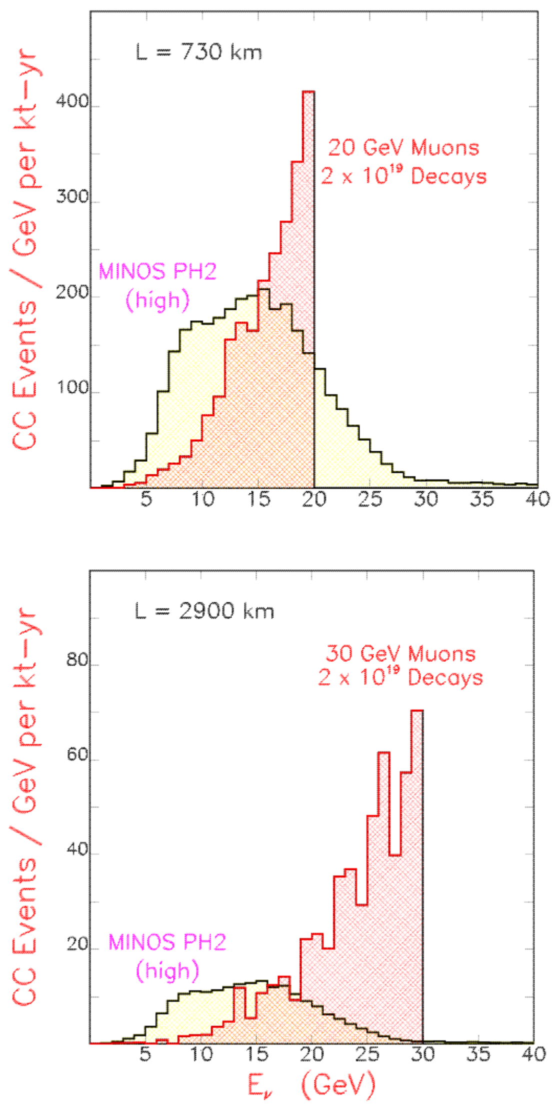
Conventional beam is great for measuring ν_μ related parameters to ~1%.

Limitations are electron detection in hadron showers

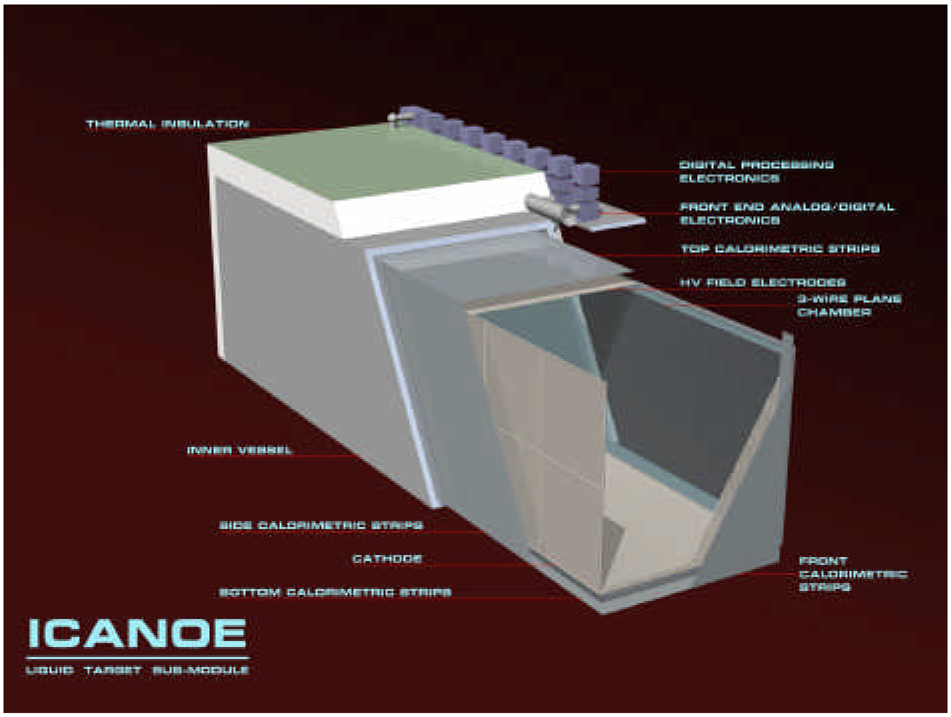
limits $\nu_\mu \rightarrow \nu_e$

To go beyond 1% on $\nu_\mu \leftrightarrow \nu_e$ or get mass effects and CP violation, need:

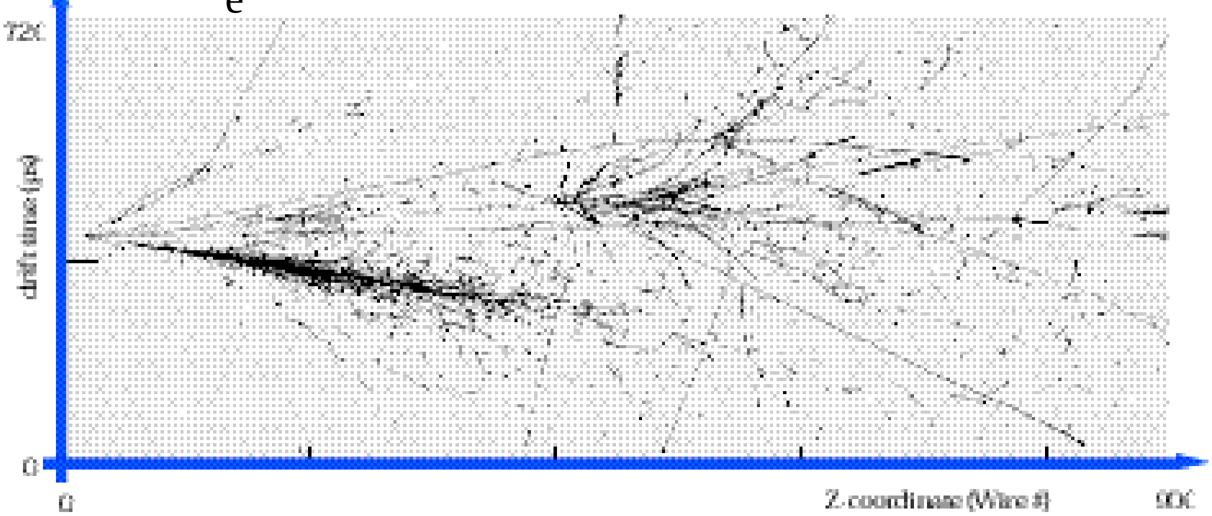
- long baseline,
- higher energy,
- way to see $\nu_\mu \leftrightarrow \nu_e$ transitions with better accuracy.



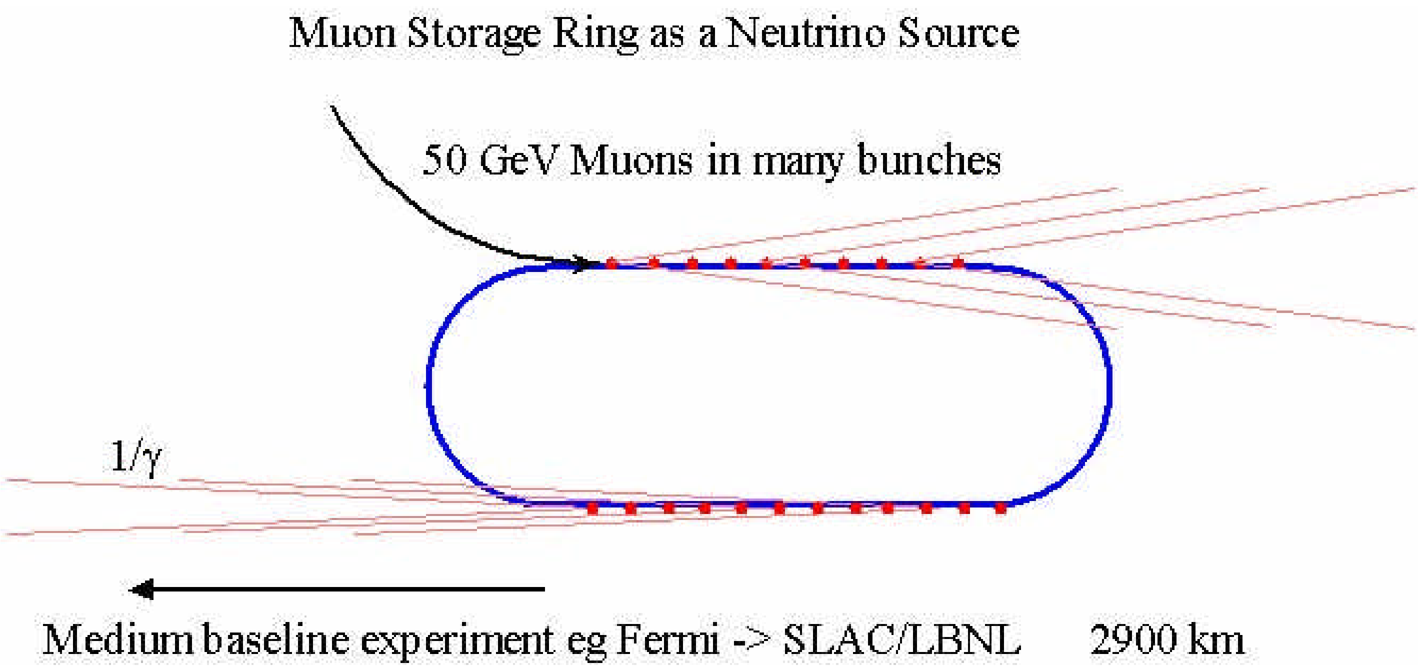
Liquid Argon with drift readout



ν_e event



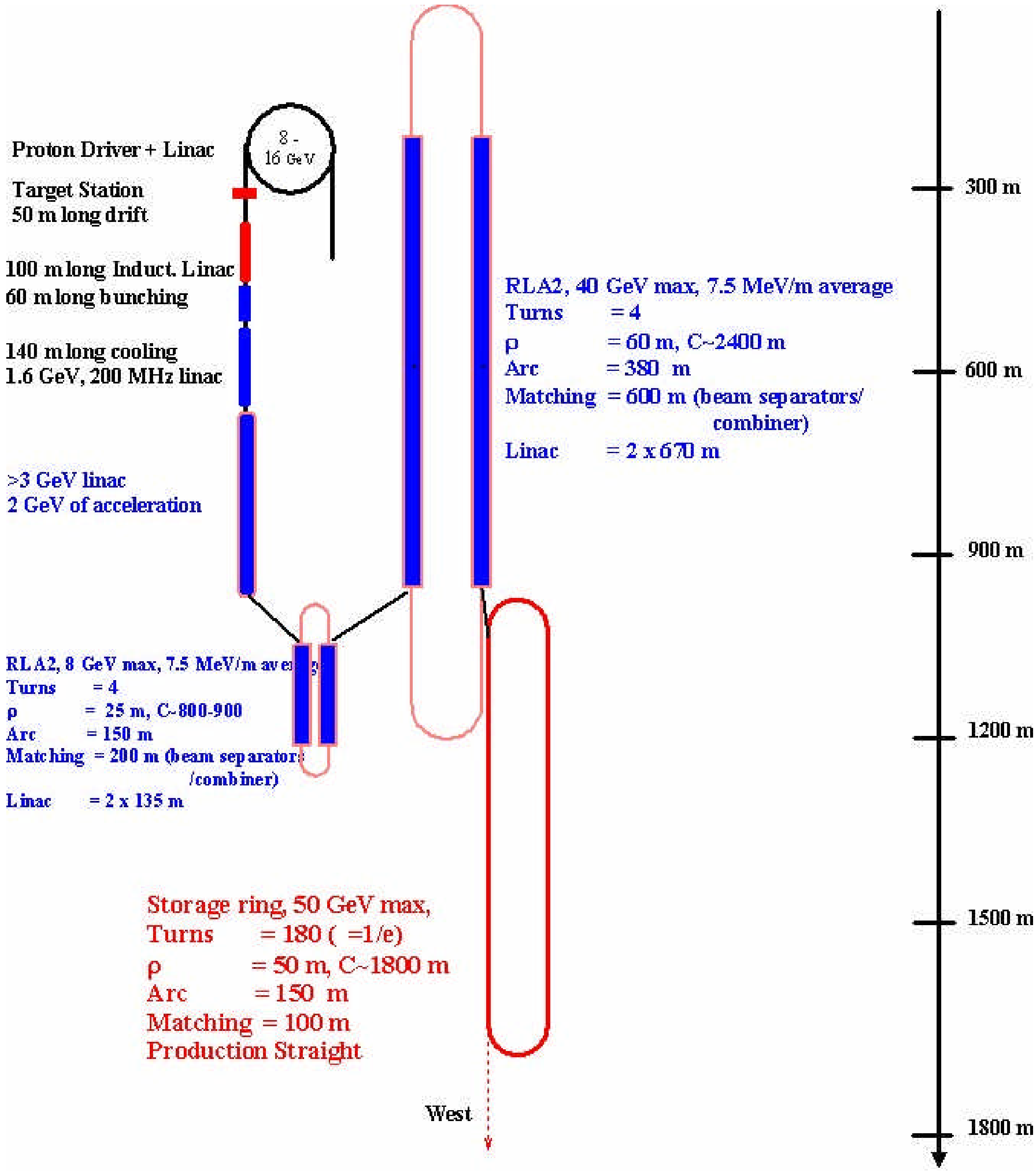
The Neutrino Source



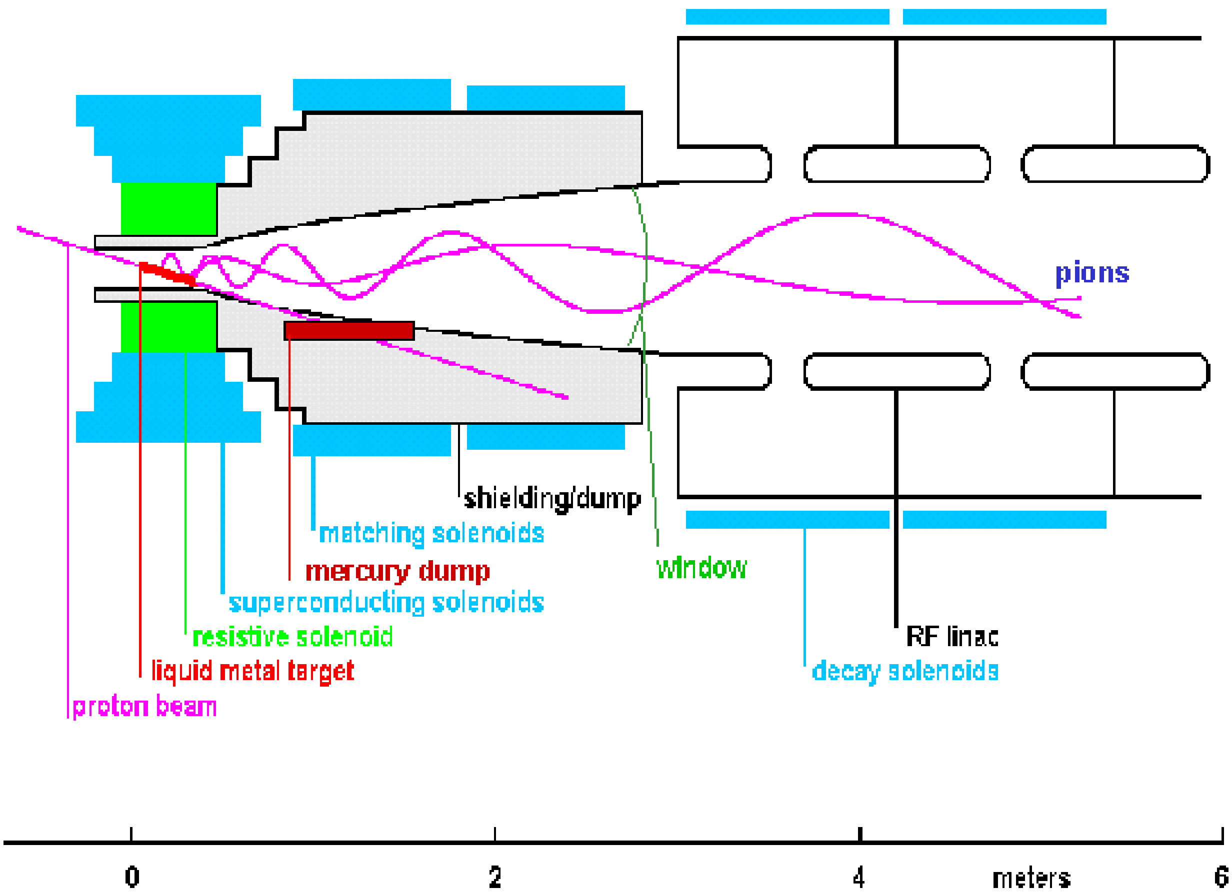
Parameters for the Muon Storage Ring		
Energy	GeV	50
decay ratio	%	>40
Designed for inv. Emittance	m*rad	**0.0032**
Cooling designed for inv. Emitt.	m*rad	**0.0016**
β in straight	m	160
N_μ/pulse	10^{12}	6
typical decay angle of $\mu = 1/\gamma$	mrad	2.0
Beam angle $(\sqrt{\varepsilon}/\beta_o) = (\sqrt{\varepsilon}\,\gamma)$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

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

Footprint for a 50 GeV Neutrino Source



Target and production



1MW 16 GeV proton source
15Hz to get 6 10^{20} stored muons/year

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

In lab frame distribution is same but energy scale is different

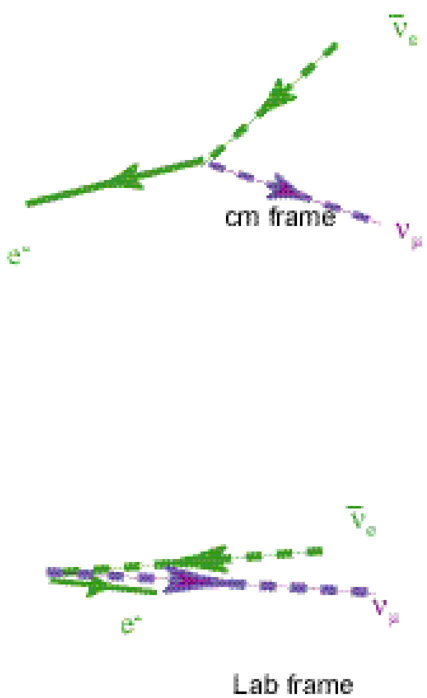
$$\frac{dN(\nu_\mu)}{dz\,d\cos\theta_{CM}} = 2z^2[(3-2z) \mp P(1-2z)\cos\theta]$$

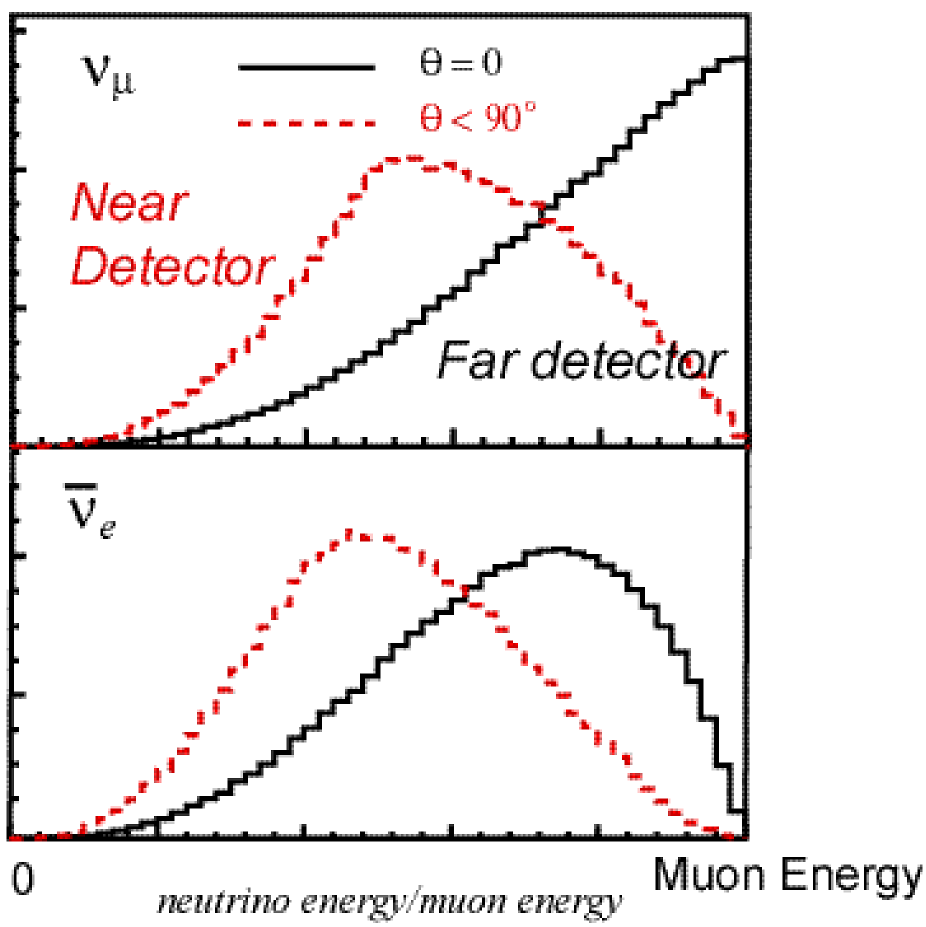
$$\frac{dN(\nu_e)}{dz\,d\cos\theta_{CM}} = 6z^2[(1-z) \mp P(1-z)\cos\theta]$$

$$z = \frac{E_\nu}{E_{max}} \quad \text{where} \quad E_{max} = \gamma m_\mu/2(1+\beta\cos\theta_{CM})$$

$$\tan\theta_{lab} = \frac{\sin\theta_{CM}}{\gamma(\cos\theta_{CM}+\beta)}$$

Neutrino Fluxes from an Unpolarized Muon Beam





Event rates for a 10 kton detector

Mario Campanelli

		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

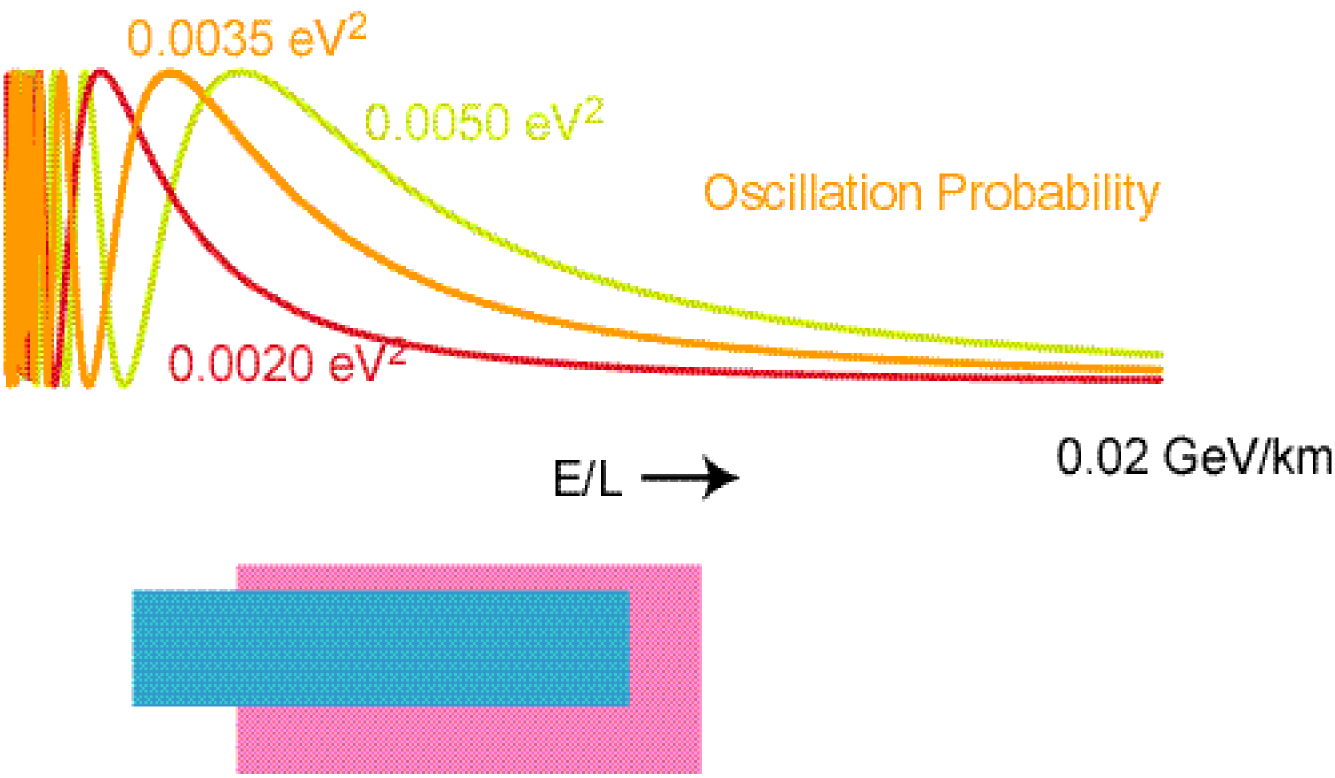
No oscillations

E_μ=30 GeV

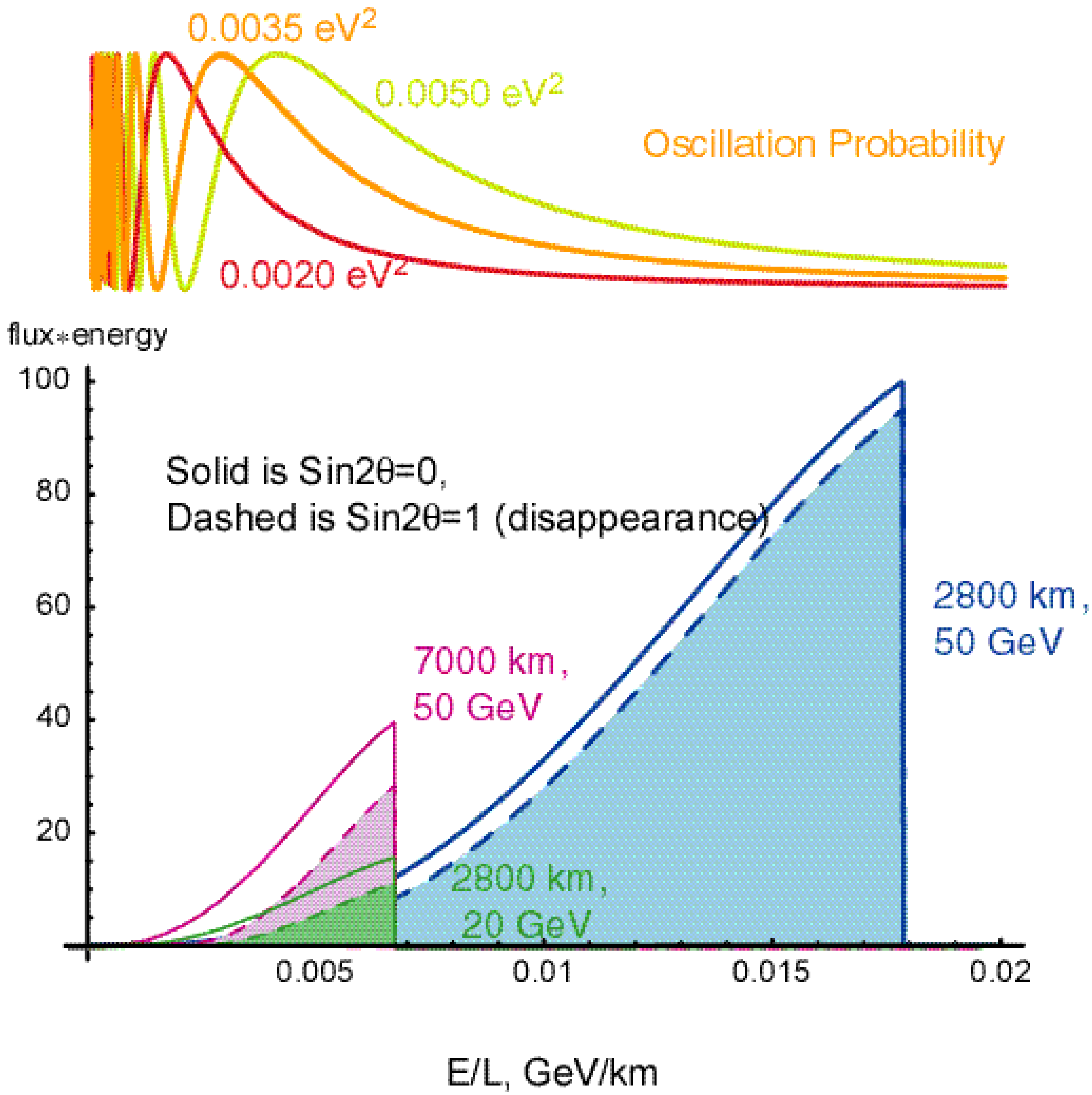
No polarization

No beam divergence

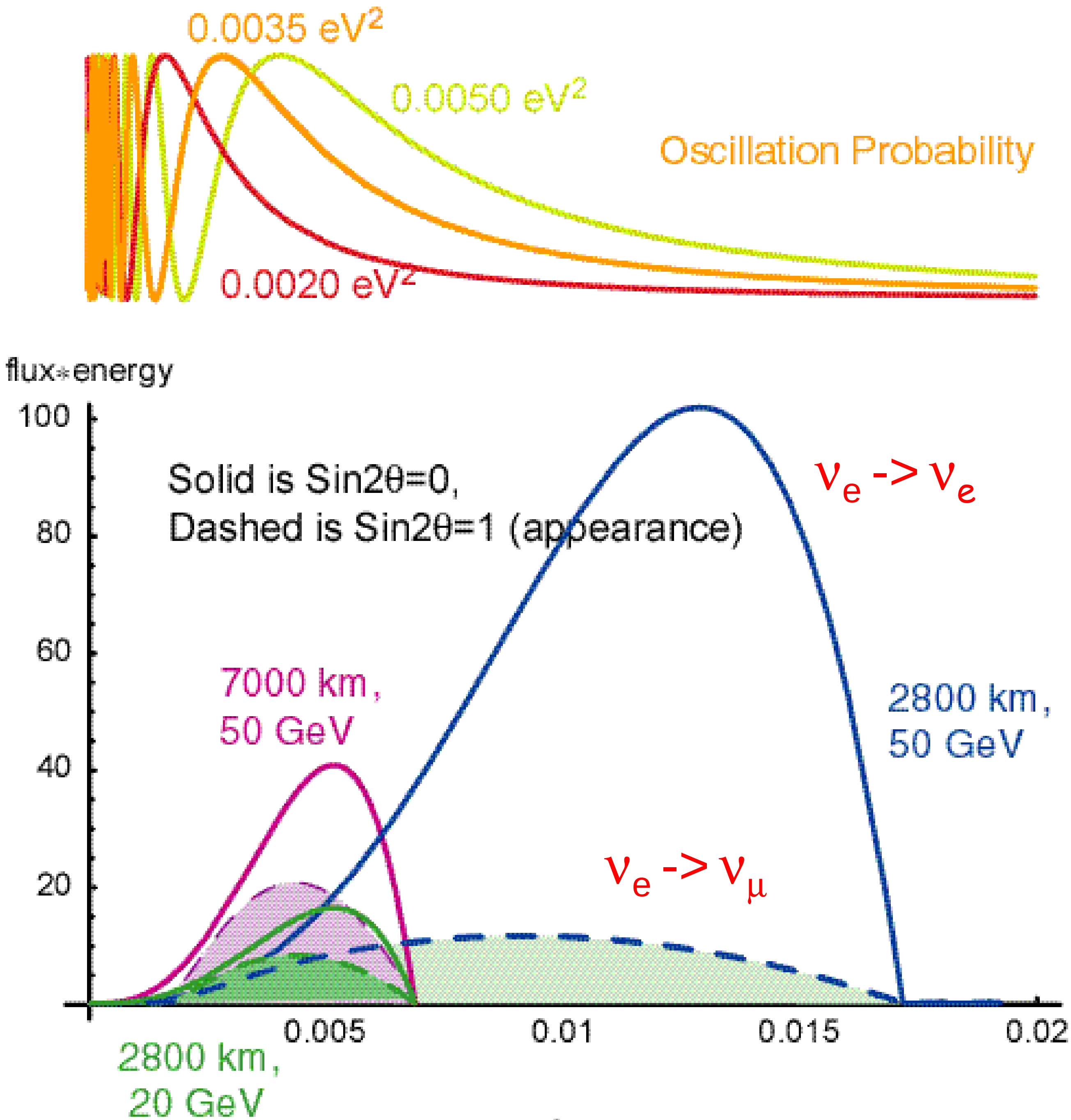
Experiments can be described by their E/L coverage



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

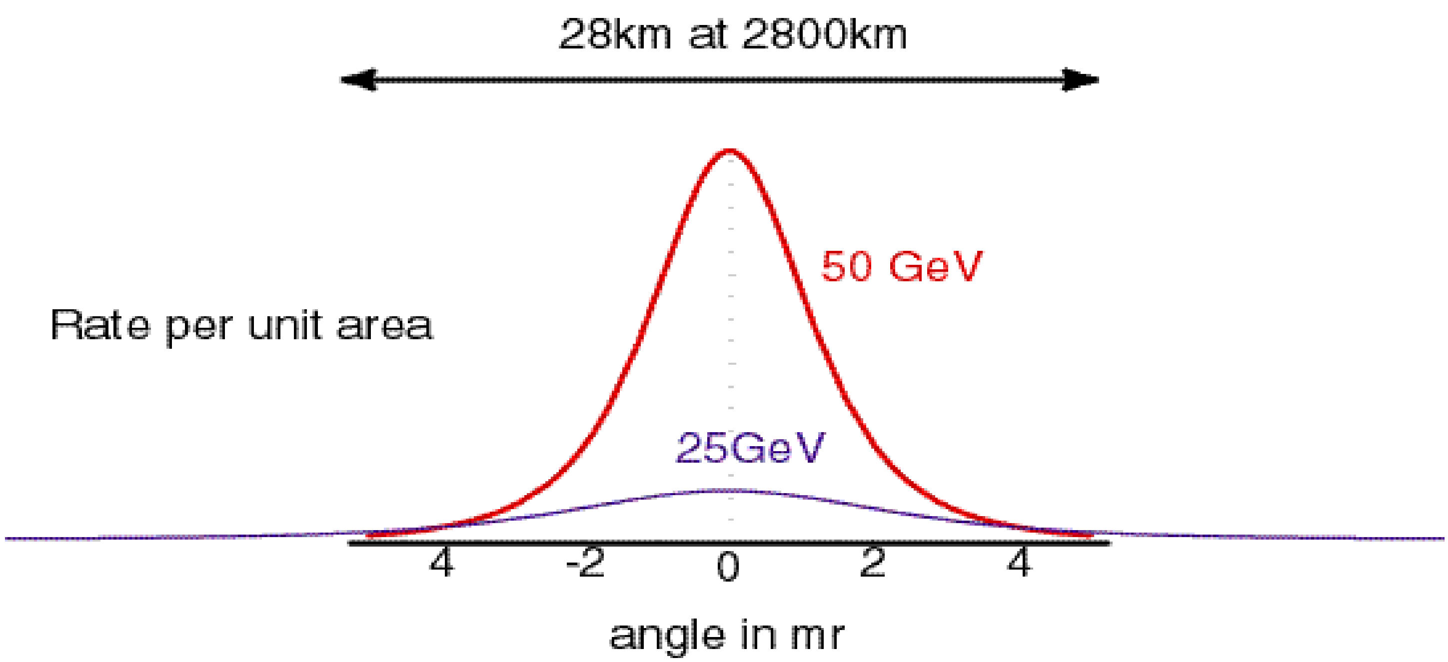


Numbers of electron neutrino interactions for fixed number of muon decays
$\Delta m^2 = 0.0035\ eV^2$



Neutrino Event rates vs angle

θ typical is $\sim 1/\gamma$



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

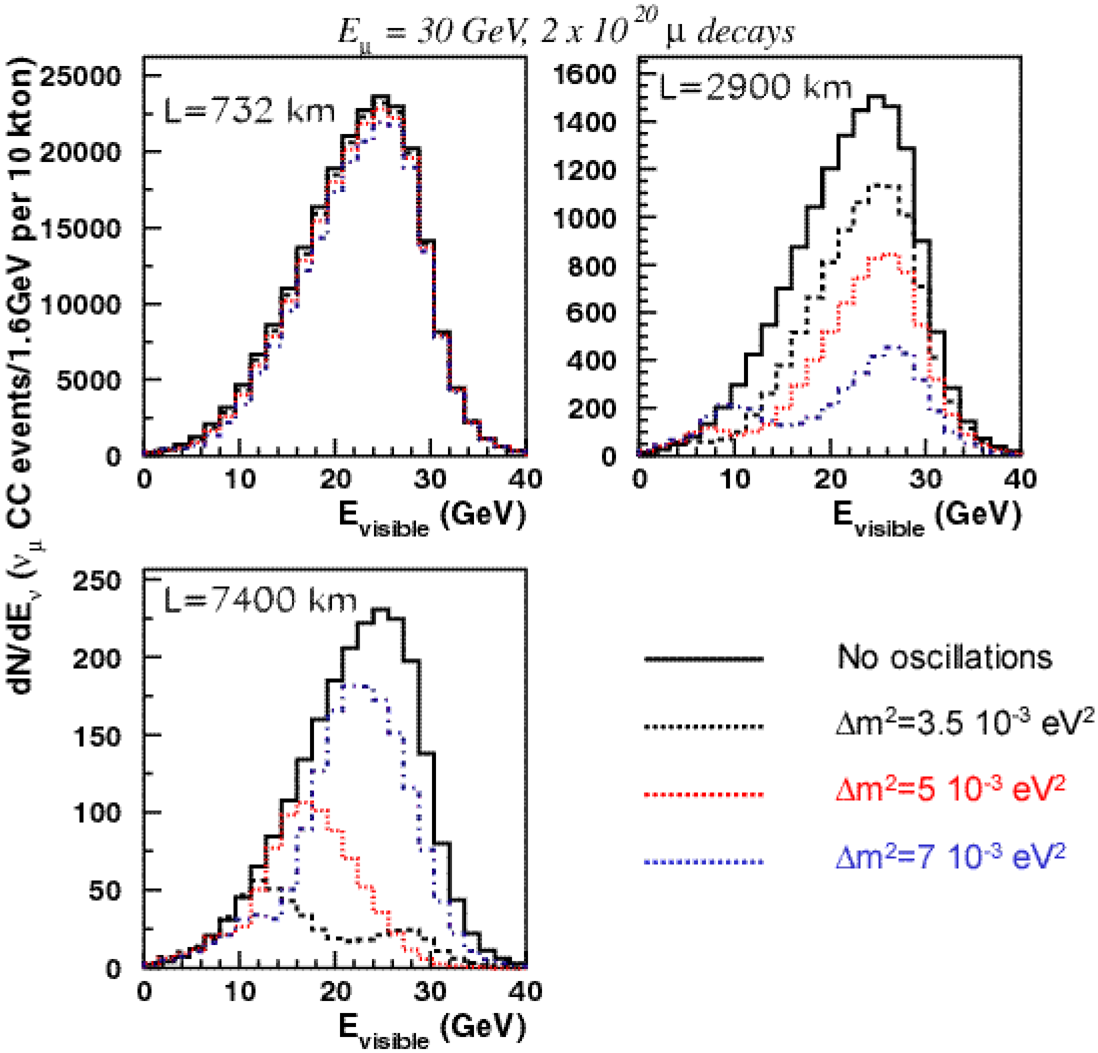
Spread of beam scales as L^2
For fixed E/L, event rate/unit area scales as E

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

Disappearance Experiment ν_μ->ν_τ



Mario Campanelli, ETH Zurich

What determines the machine energy?

- We're interested in $\nu_e \rightarrow \nu_\mu$

  Need to tag wrong sign muons with very low backgrounds

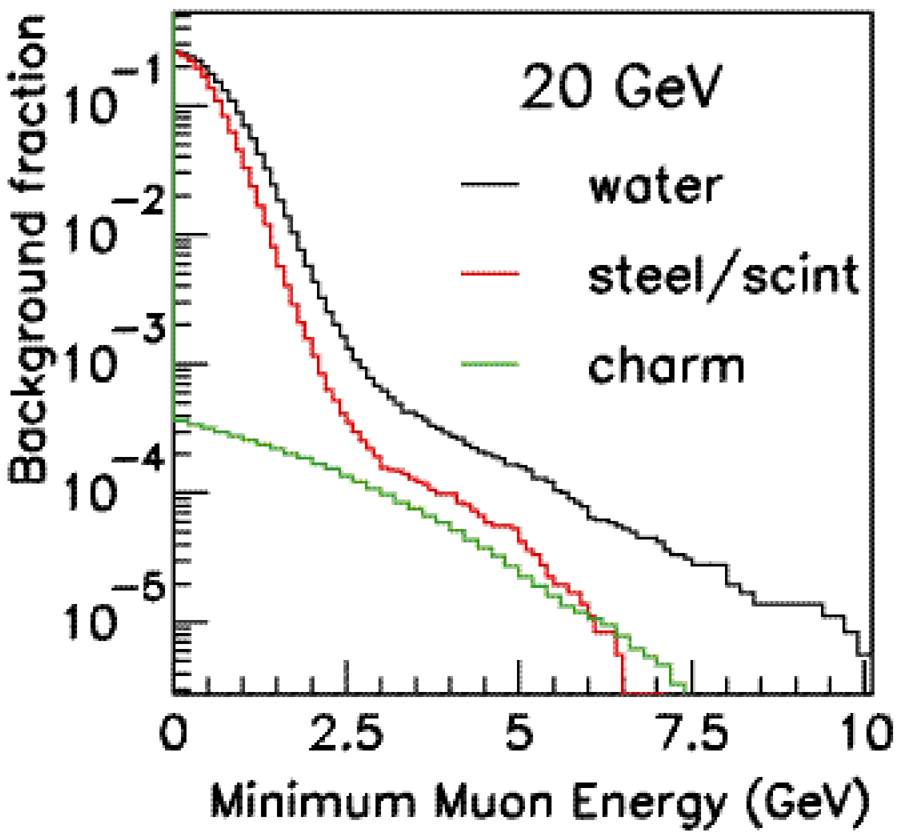
  there are also anti- ν_μ in the beam

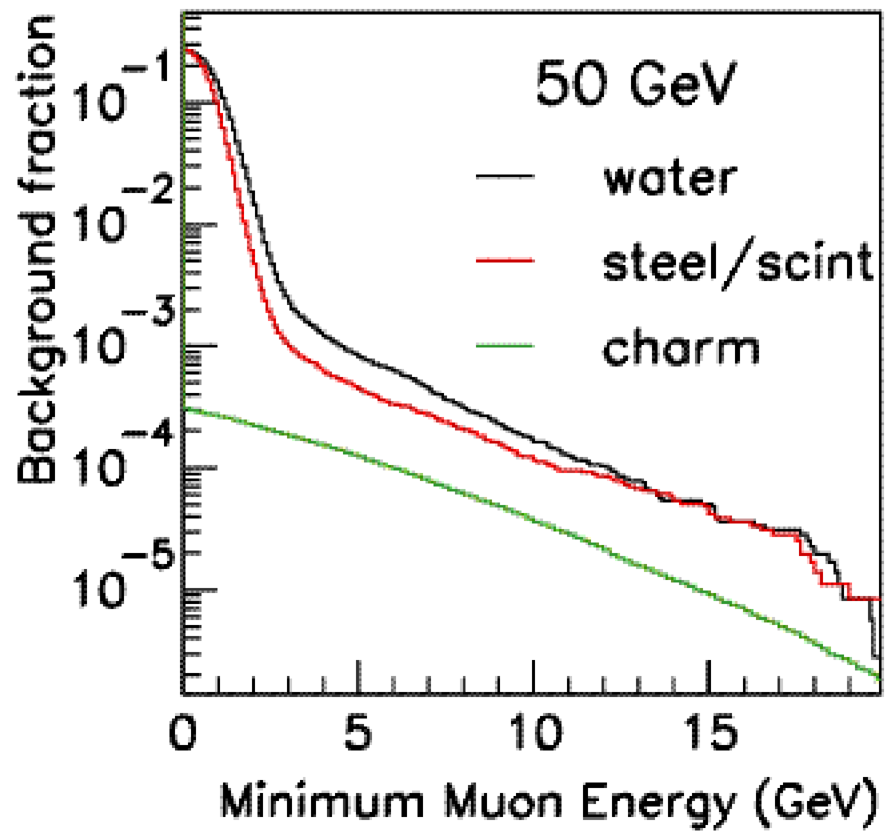
  Wrong sign muons from
  - Hadron decay
  - Charm decay
  - Non-interacting hadrons
  - Charge confusion

  How do you tell a 2 GeV pion from a 2 GeV muon at the 0.01% level?

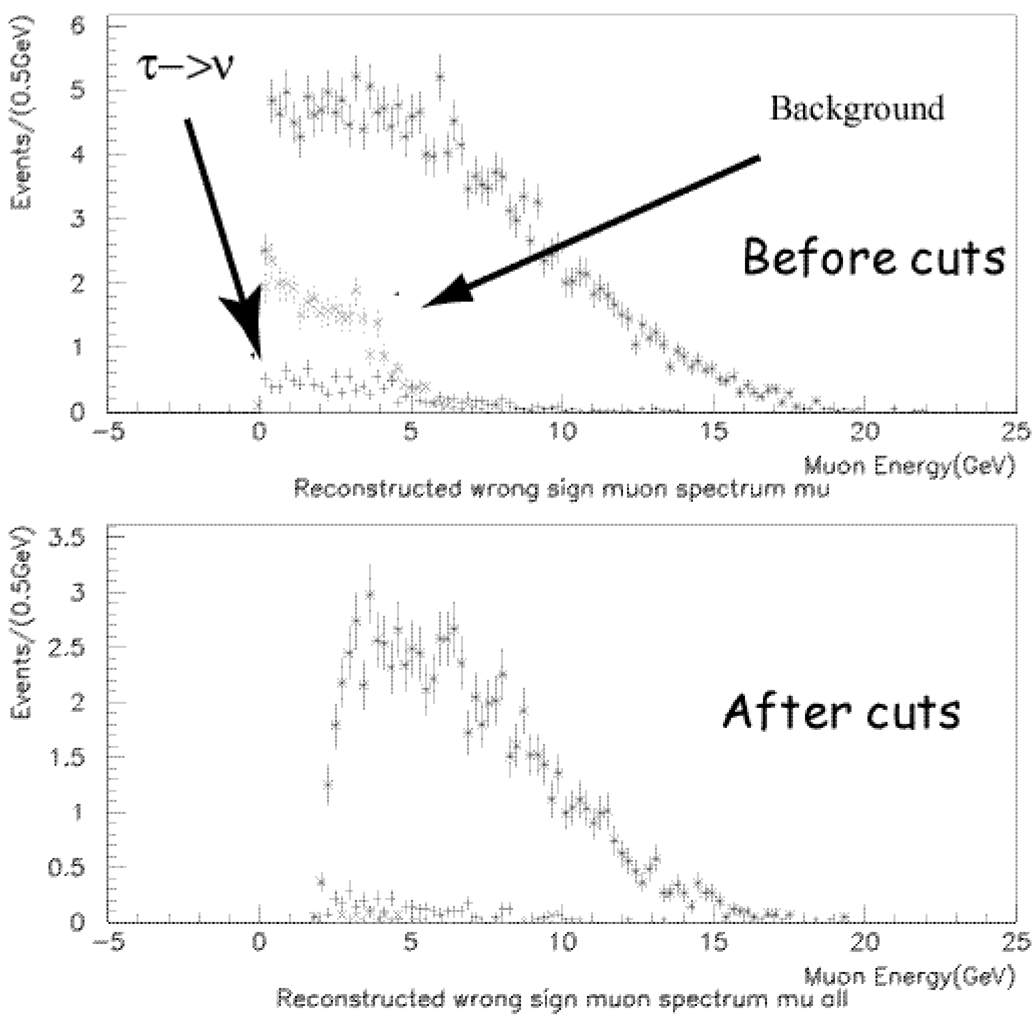
Backgrounds to $\overline{\nu}_e \to \overline{\nu}_\mu \to \mu^+$

Pions which do not interact!





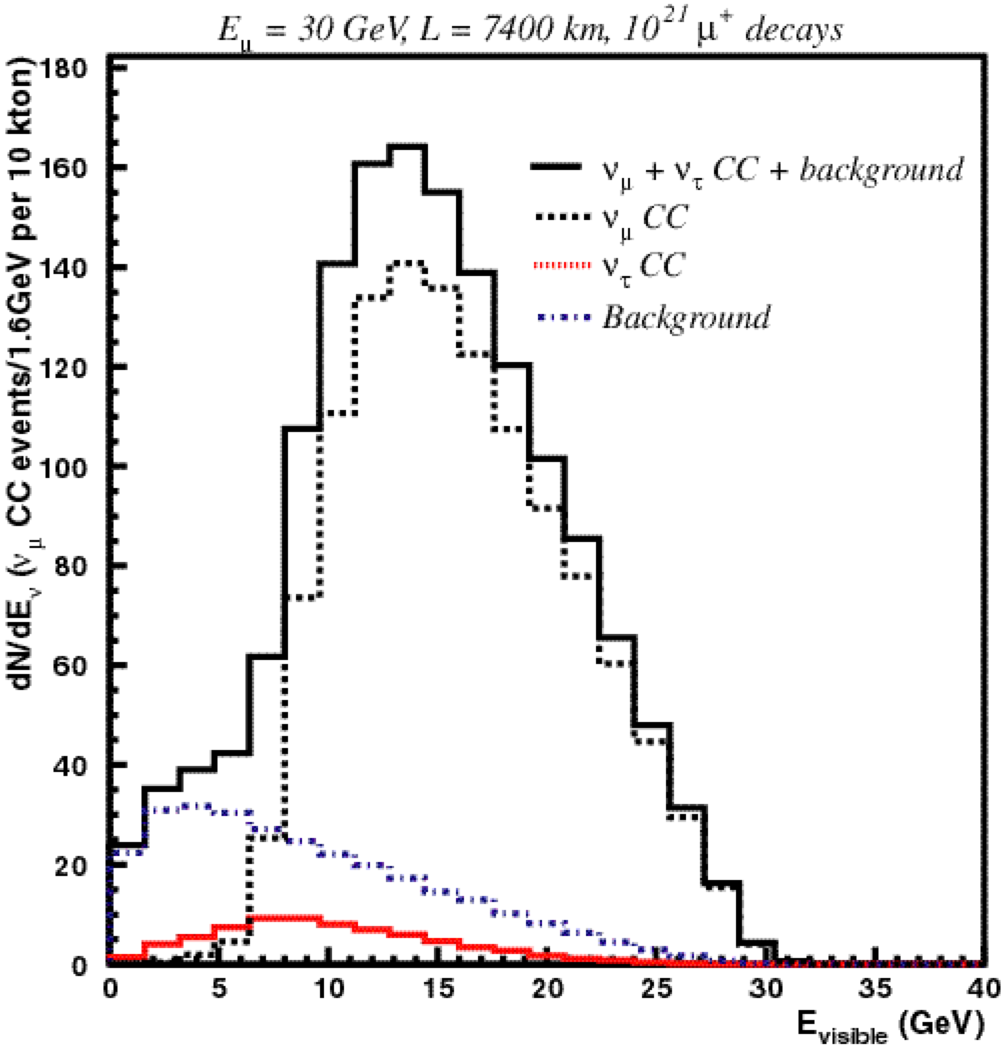
Wrong sign muon signal
10 kt Iron-scintillator detector
20 GeV muon decay
10^{20} decays



Bernstein, Harris, McFarland, Spentzouris

Can measure $\sin^2 2\theta_{13}$ to 0.005 with 2 x10 ^{20} μ

'Wrong Sign' Muons $\nu_e \to \nu_\mu \to \mu^-$

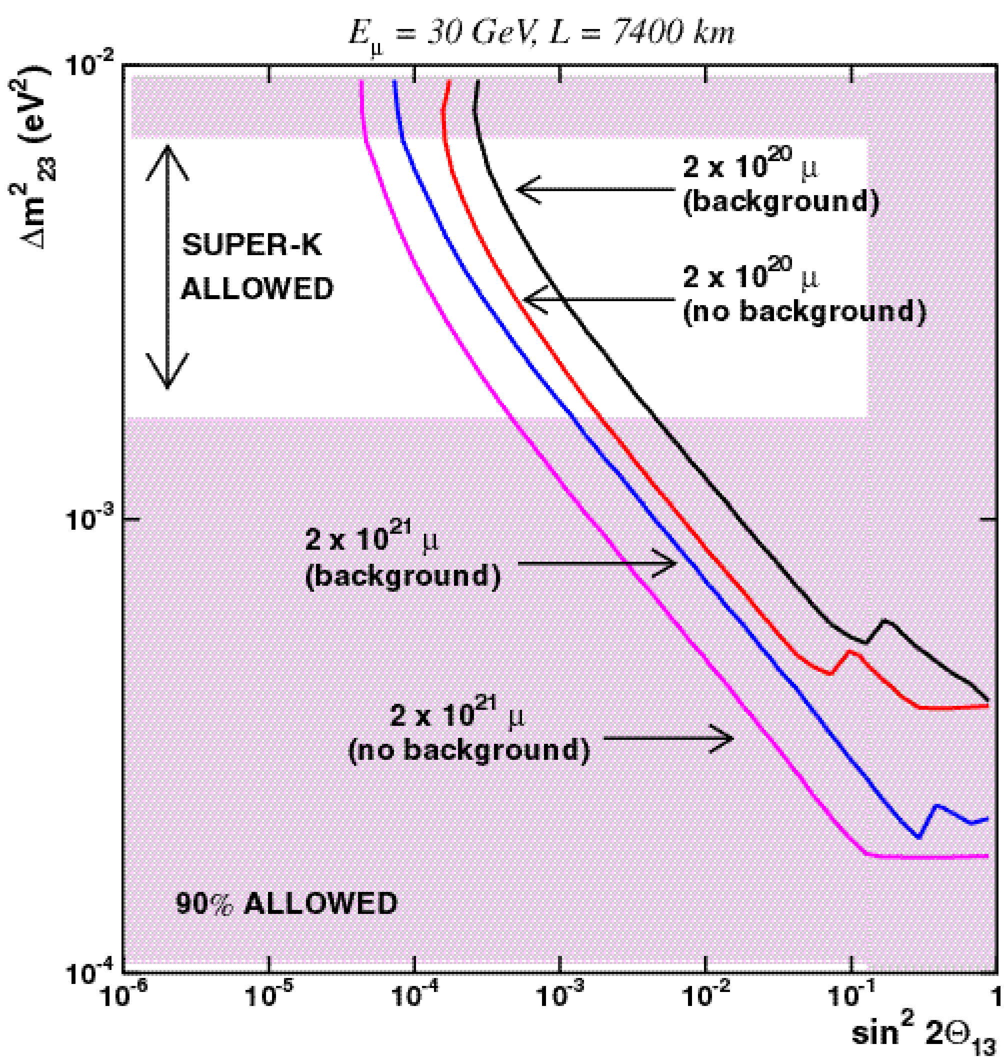


10kT ICANOE Detector

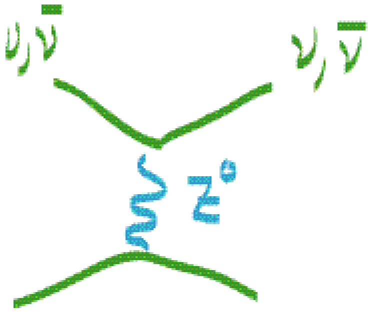
Note that Background dominates at low E

Mario Campanelli

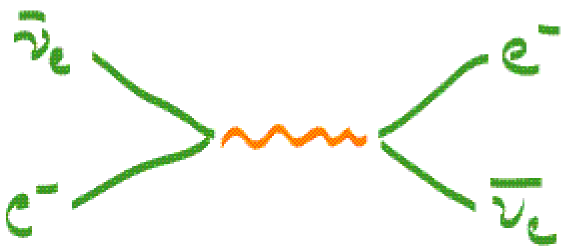
10kT ICANOE limits on $\nu_e \to \nu_\mu$

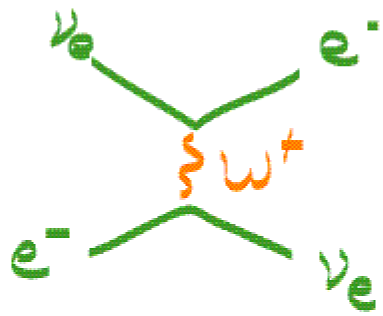


M. Campanelli et al.



all ν can interact with matter





electron ν have additional interactions

$$\mathcal{L}_0 = \frac{2\pi}{\sqrt{2}\, G_F N_e} \approx \frac{1.6\ 10^4\ \mathrm{km}}{\rho\ Z/A}$$

shifts L^e_{osc} by $\sim 1 \pm 2 \frac{\mathcal{L}_{osc}}{\mathcal{L}_0} \cos 2\theta$

$\nu_e > \nu_\mu$ Appearance

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

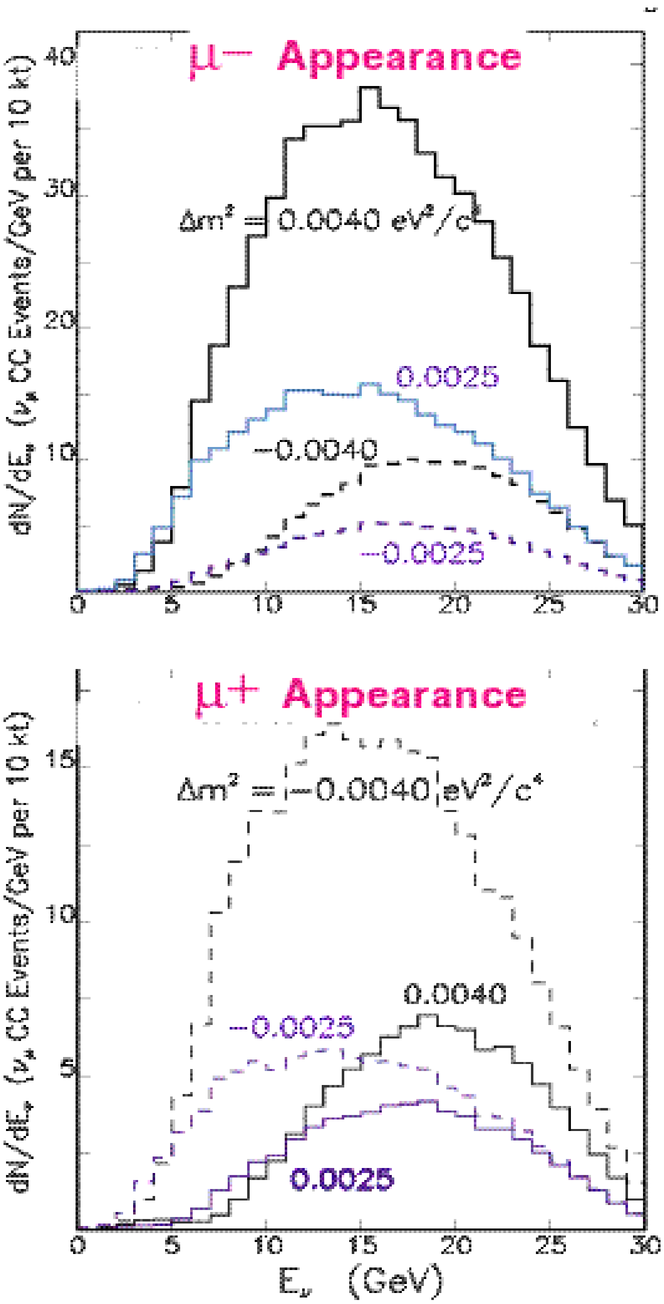
ThreeFlavor Mixing

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

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

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

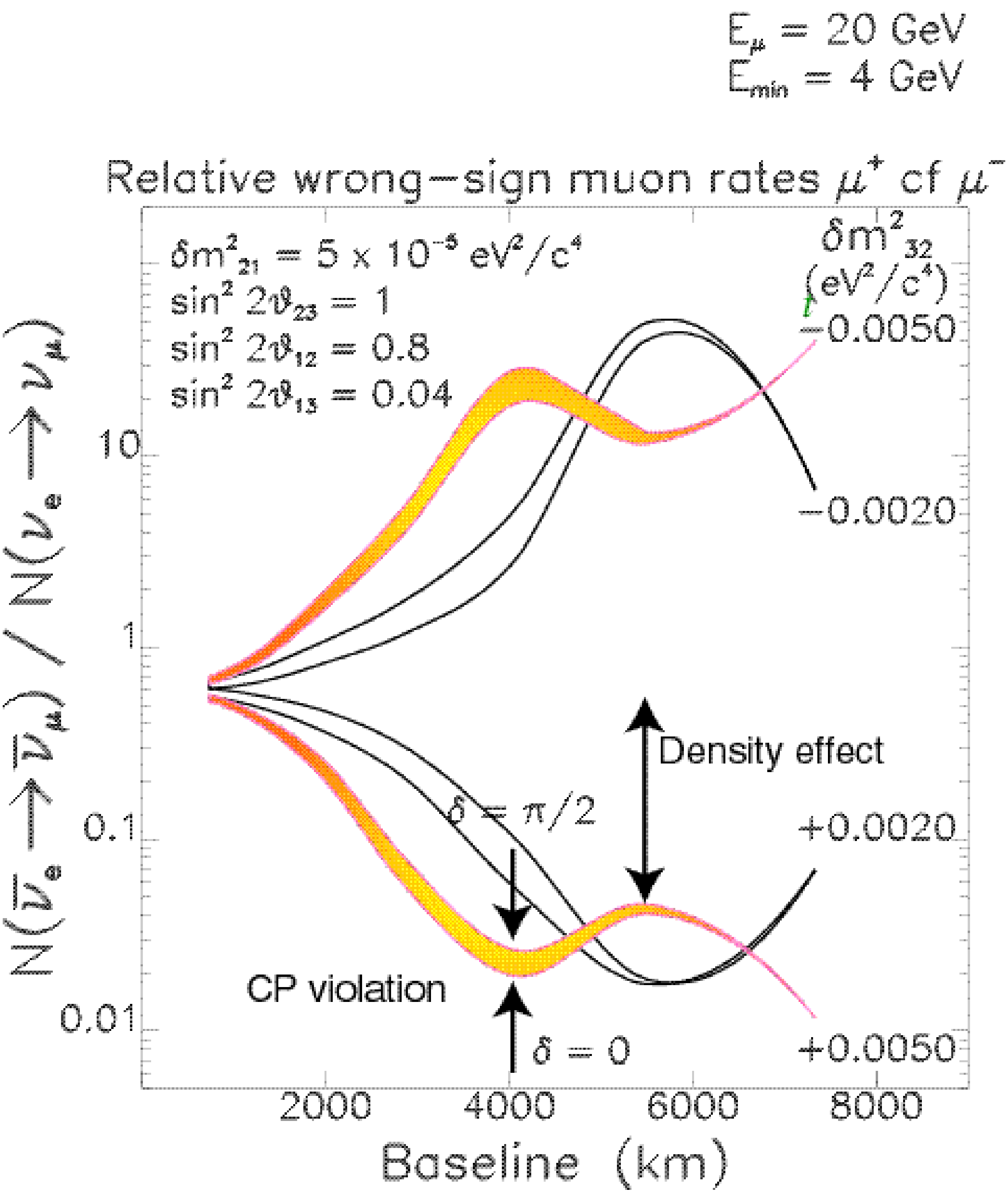
$\sin^2 2\theta_{31} = 0.04$



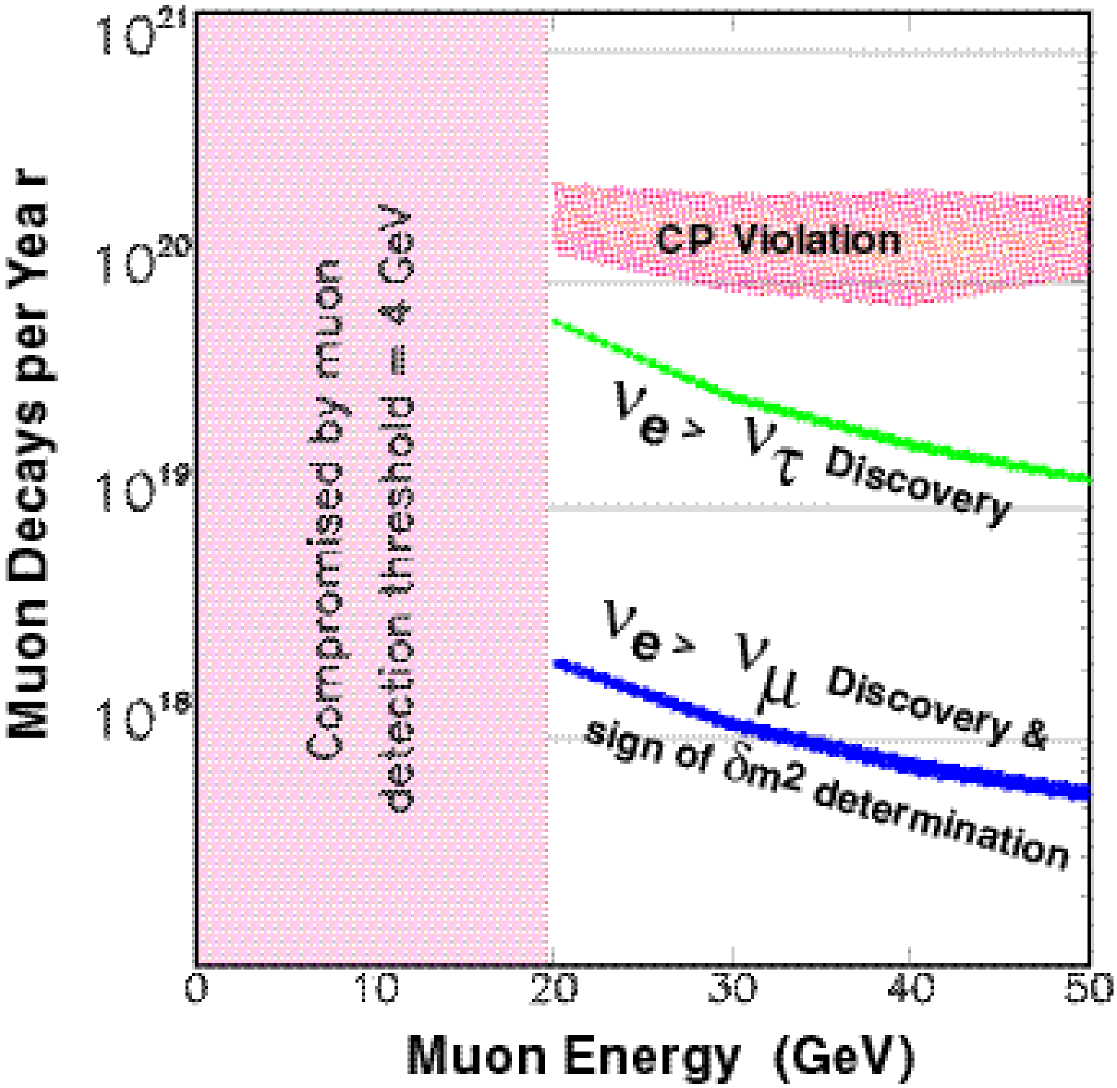
Sign of Δm^2 can be determined thanks to matter effects

Barger Geer Raja Whisnant
FermilabPub 99341

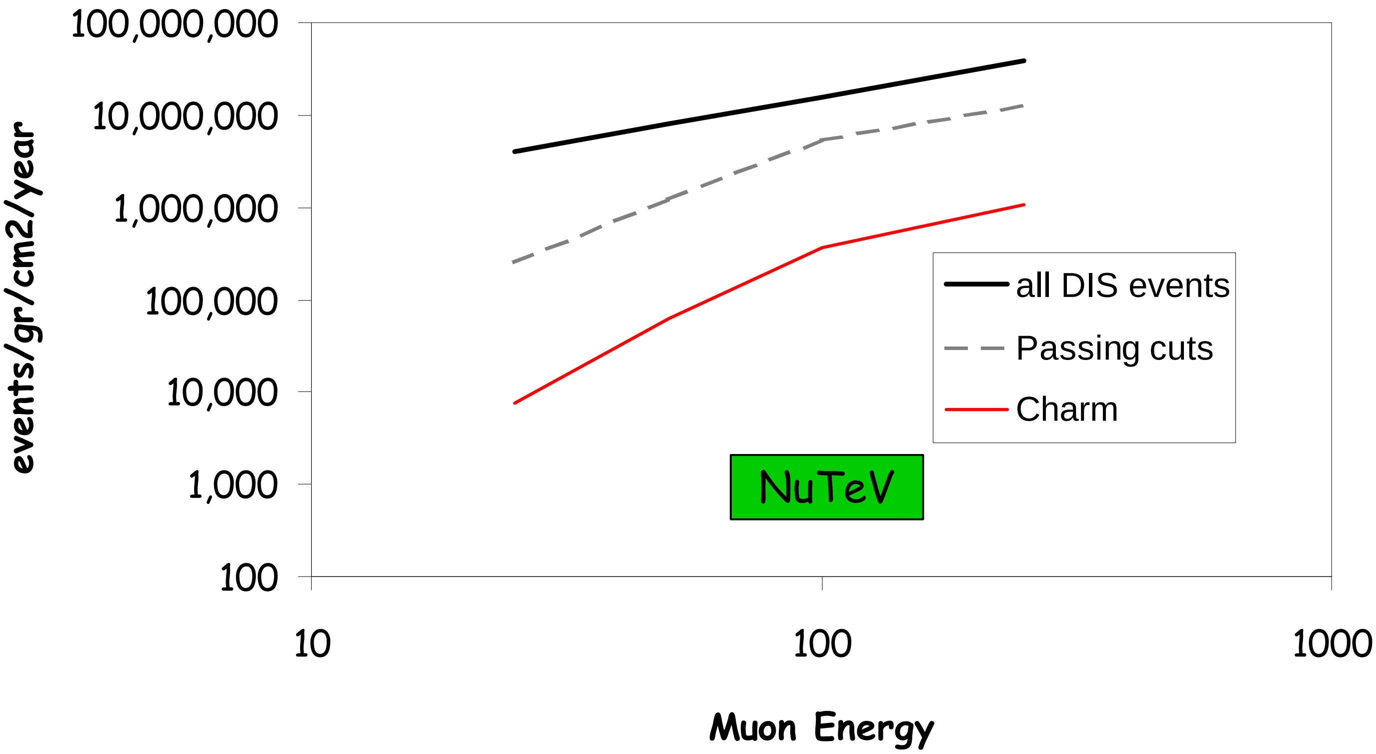
CP violation?



V. Barger, S. Geer, R.Raja, K. Whisnant


Muon Decays per Yea r
10^21
10^20
10^19
10^18
Compromised by muon
detection threshold = 4 GeV
CP Violation
νe > ντ Discovery
νe > νμ Discovery &
sign of δm2 determination
0
10
20
30
40
50
Muon Energy (GeV)

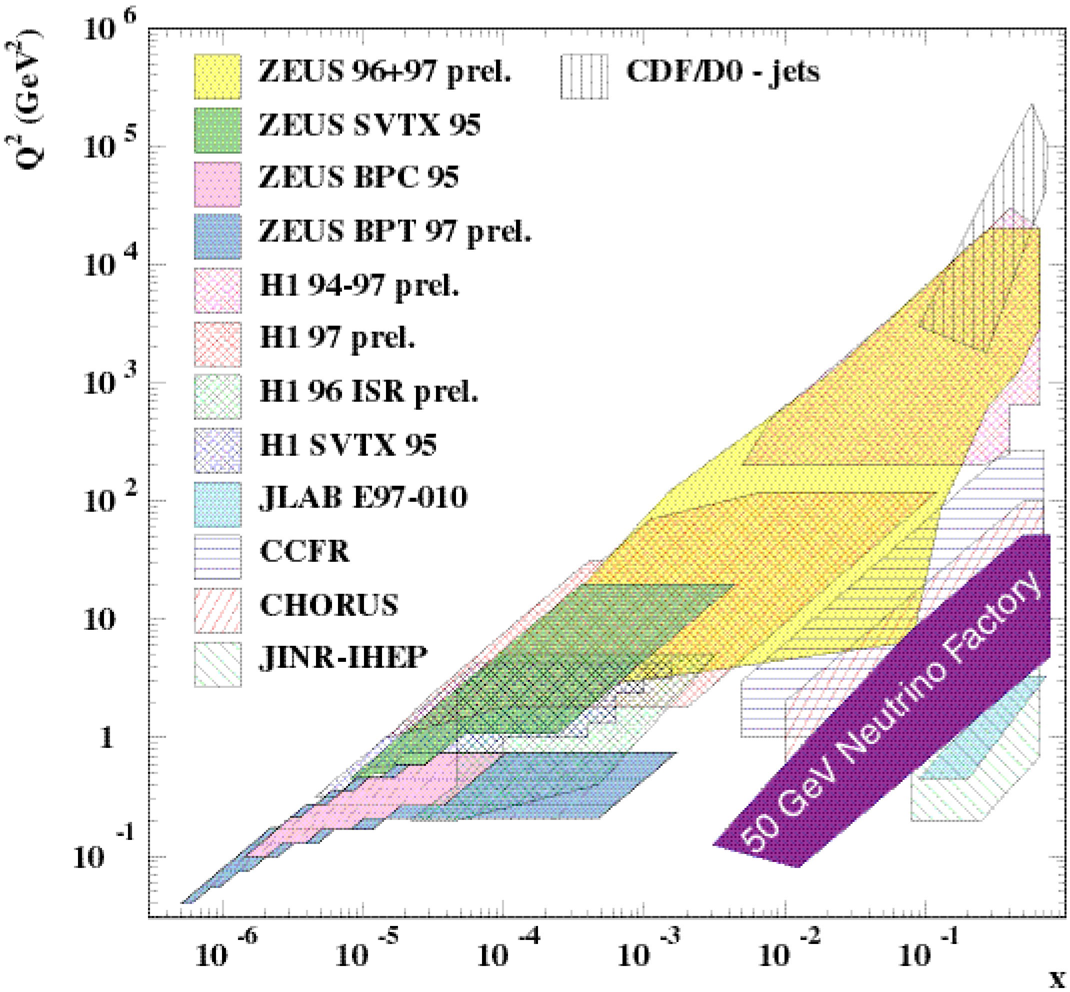
harged current event rates at near detectors

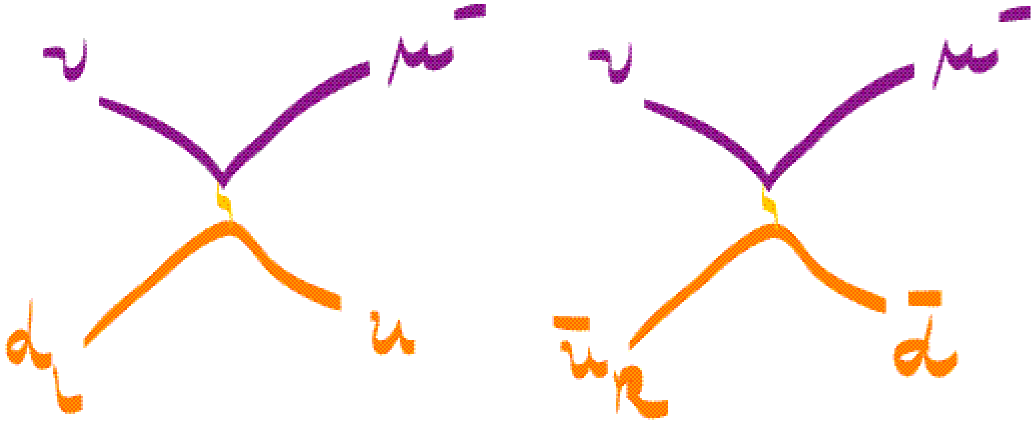


At 50 GeV, 7.9M events/gr/cm^2/year
But only 22% are within 20 cm radius
(82% pass loose kinematic cuts)

1000 times current experiments!

Deep Inelastic Scattering Experiments





νp scatter

$$\frac{d\sigma}{dx\,dy} \sim x d_L + x u_R (1-y)^2 + x s_L$$

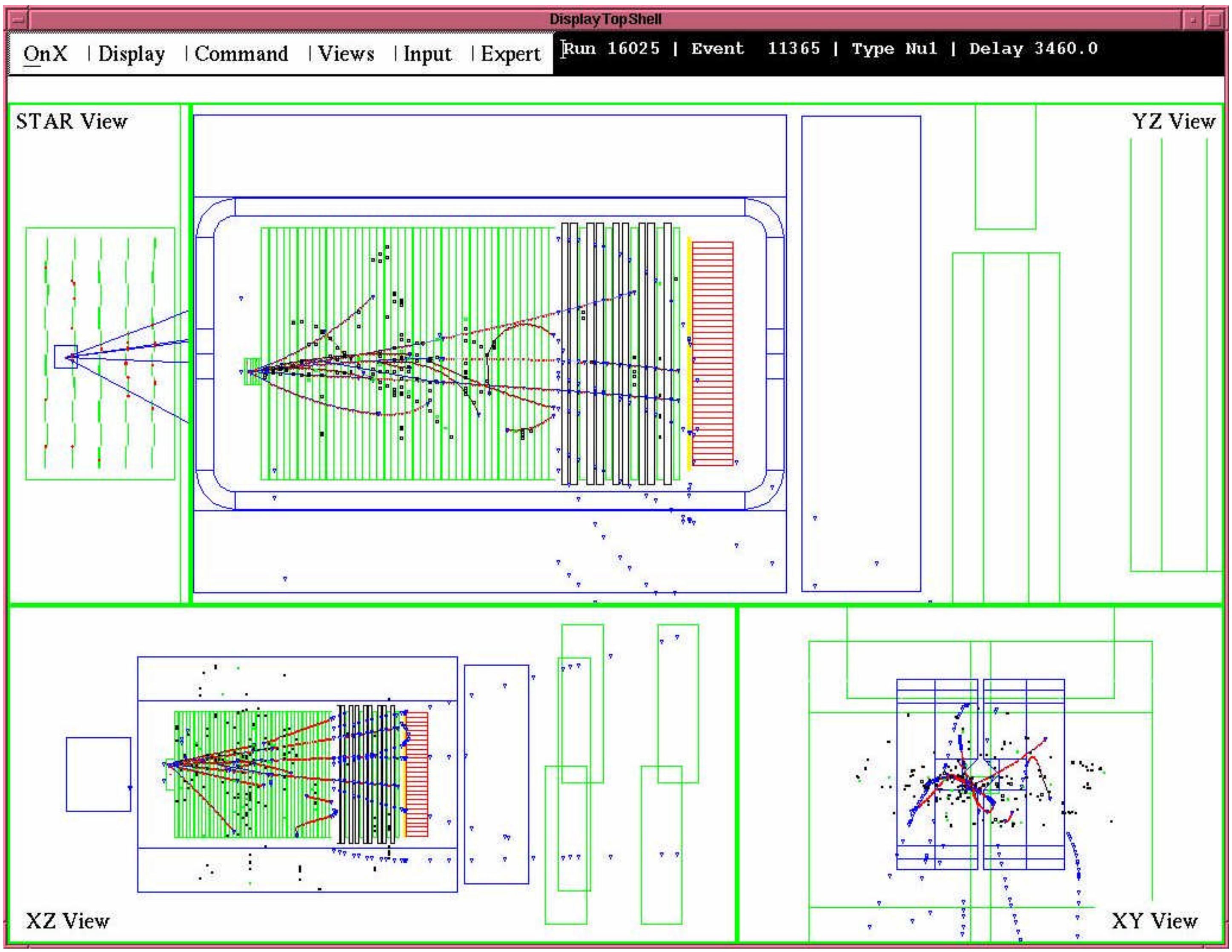
$$d_L = \frac{1}{2}(d + \delta d)$$

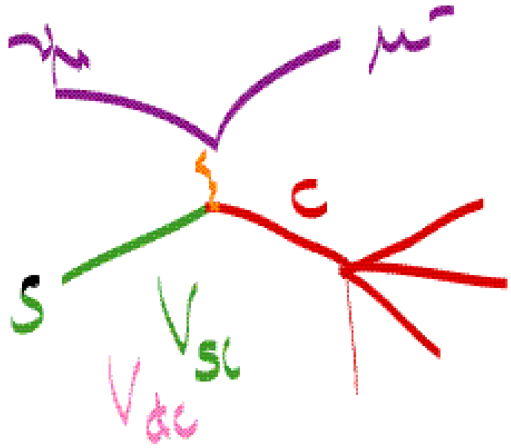
$$u_R = \frac{1}{2}(u - \delta u)$$

$$(\Delta d = \delta d + \delta \bar{d})$$

Detector like NOMAD

10 kg targets in front of tracking/calorimetry

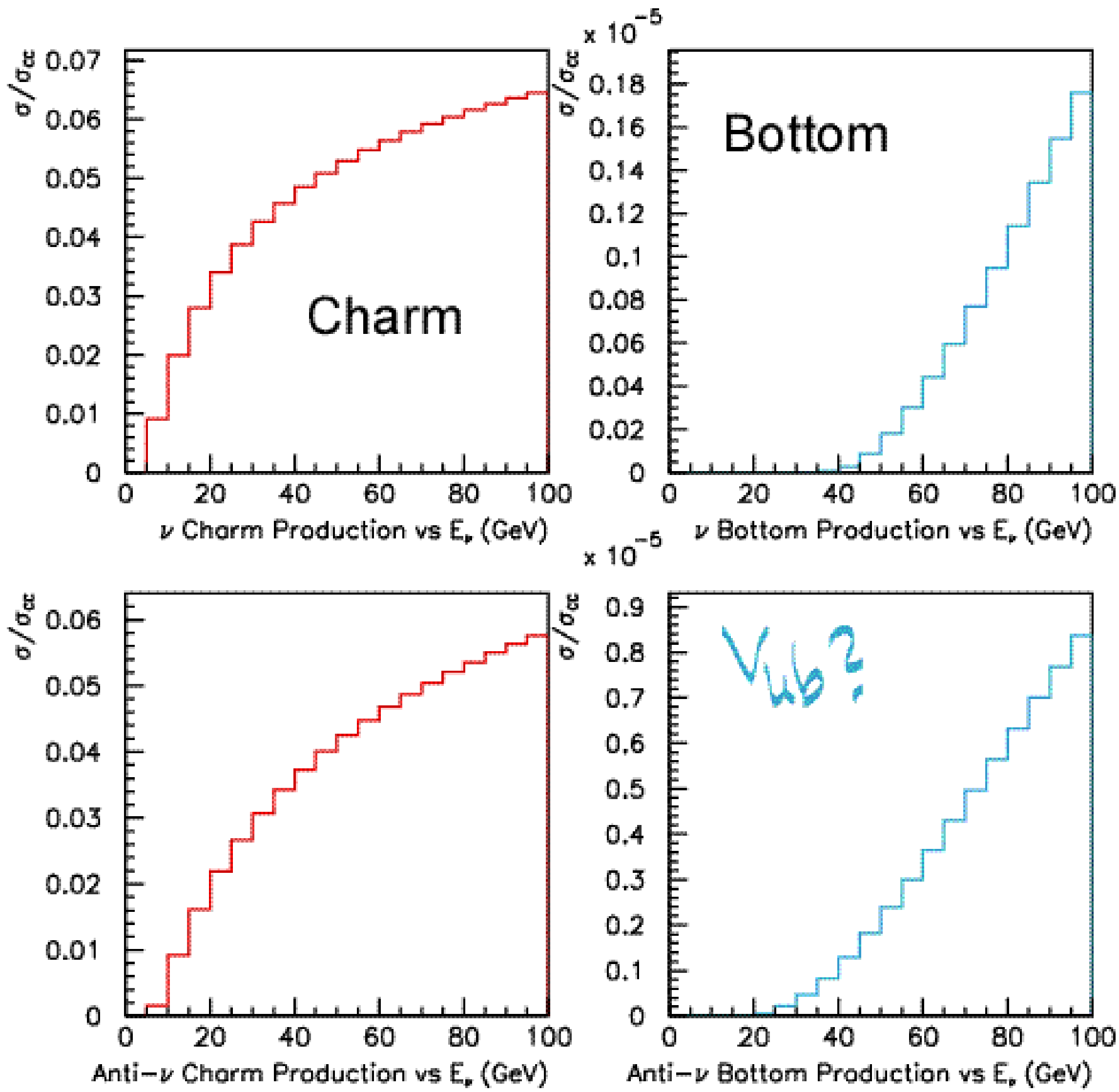




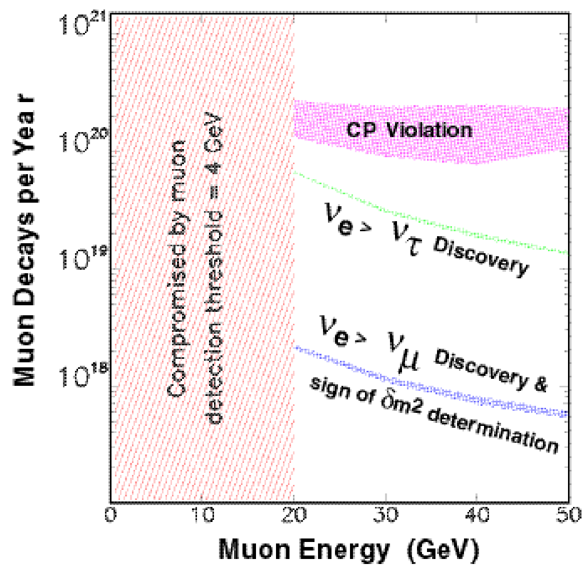
140 Si wafer target
17 M CC events
-> .5-1M charm

1 ton target
120 M charm

Heavy Flavor Production vs E_ν



onclusions



Machine energies were considered.

Baselines of ~3000-7000 are very interesting

Large detectors are needed

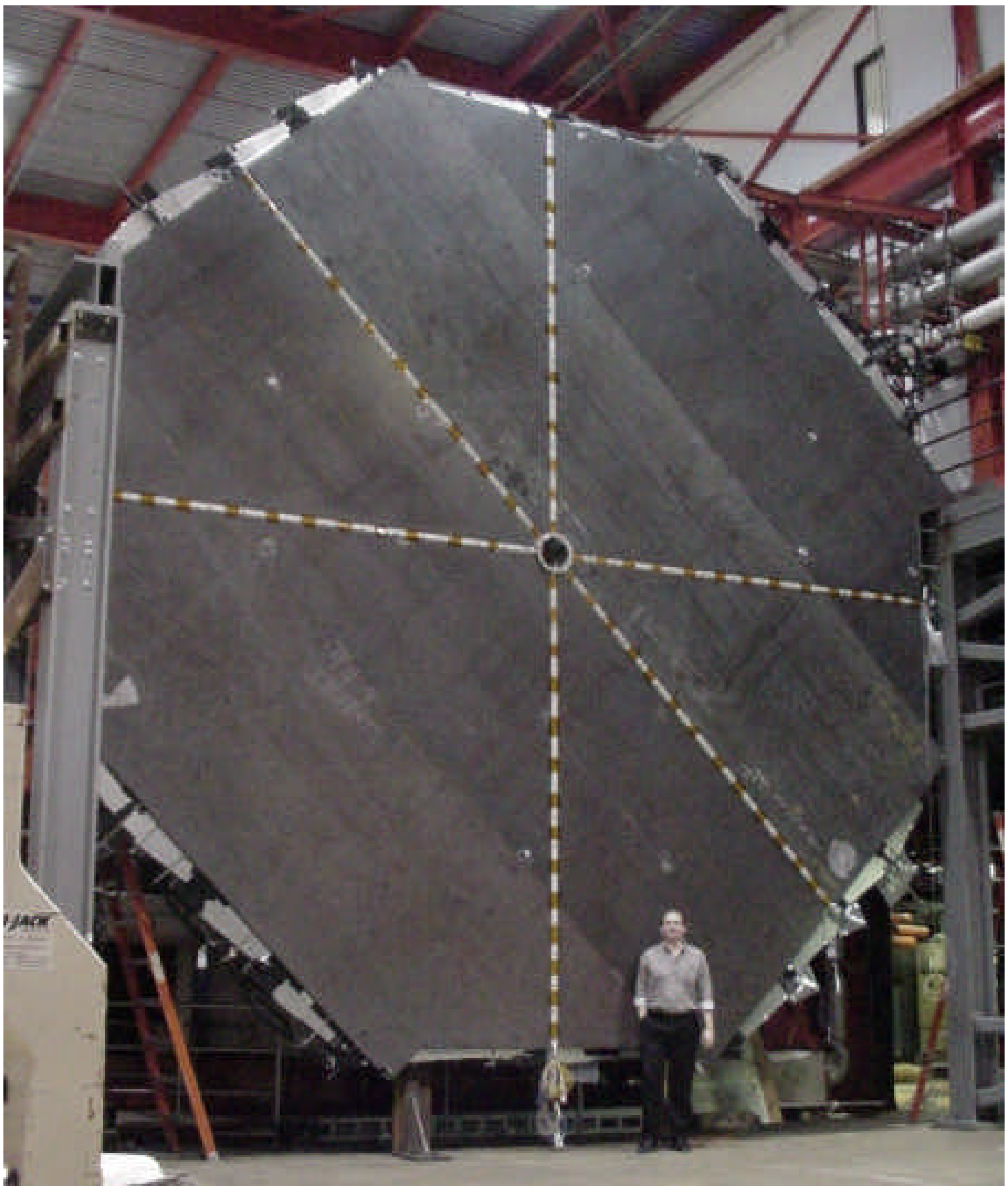
Intensities > 10^{19}/year open allow

- very accurate measure of Δm^2_{23} and θ_{23}
- Measure $\sin^2\theta_{13}$ and sign of Δm^2_{23}

May be sensitive to CP violation at very high intensities

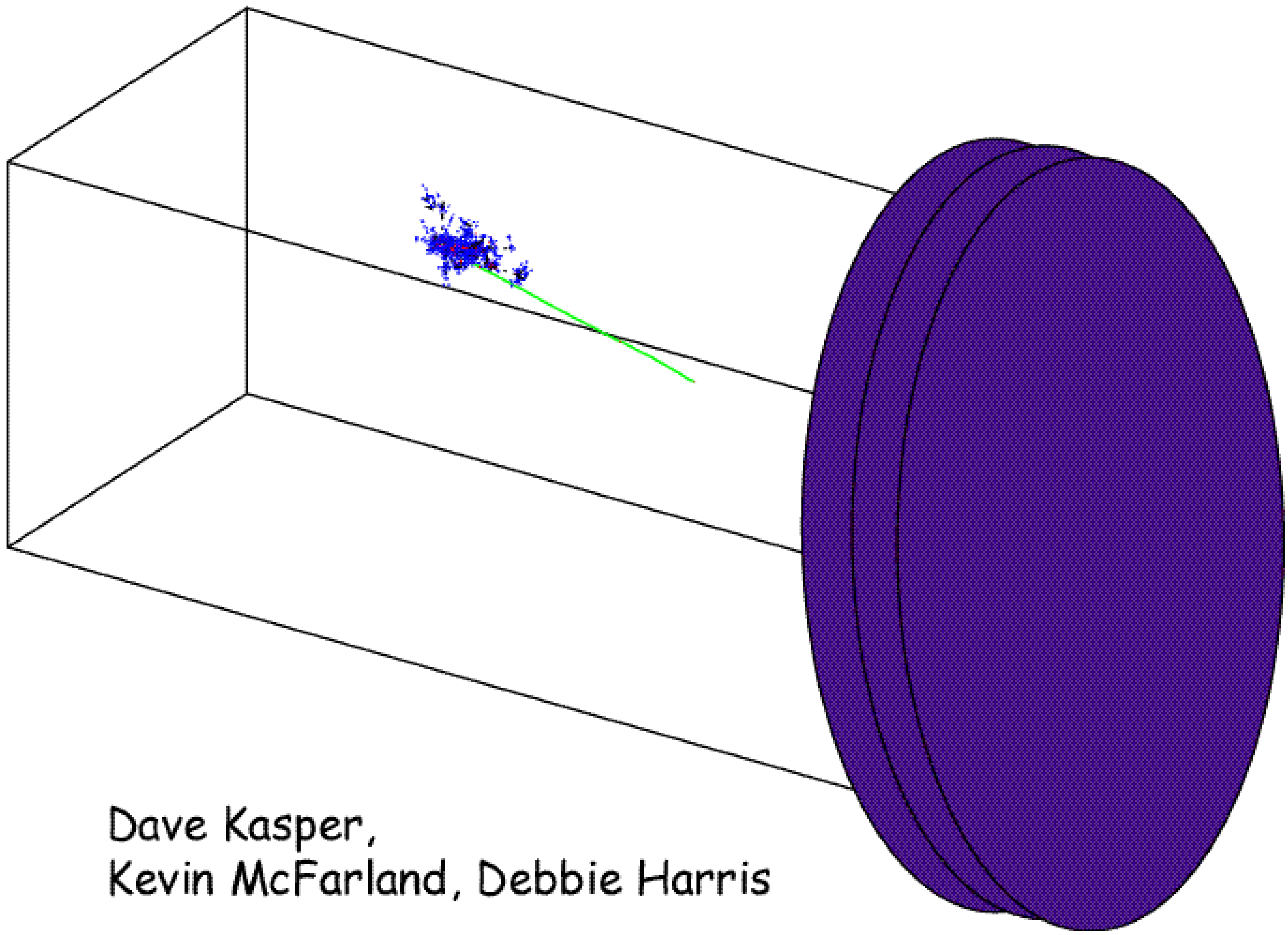
Near detector physics factor of 1000 better than present or foreseen expts.

Steel Scintillator



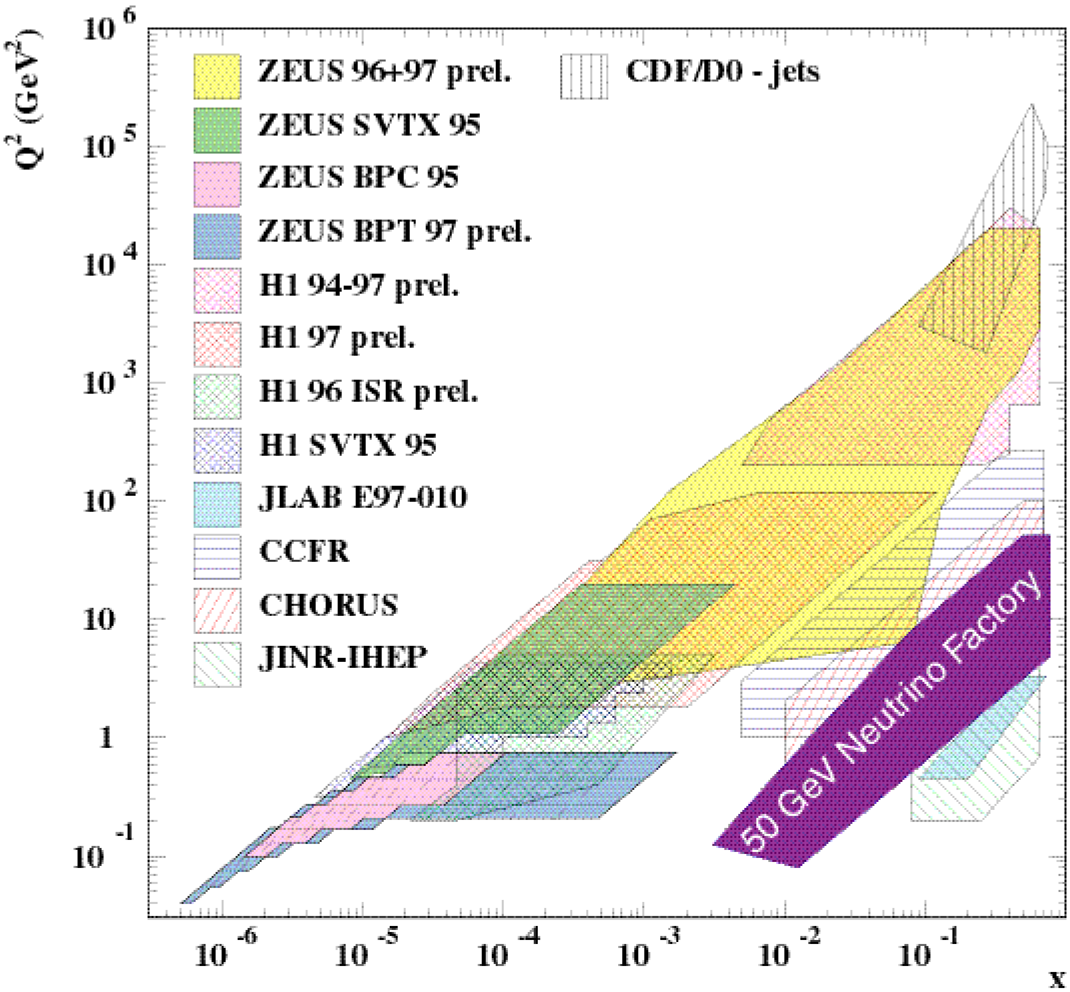
50 kT version of MINOS

Water detector followed by analyzing magnet



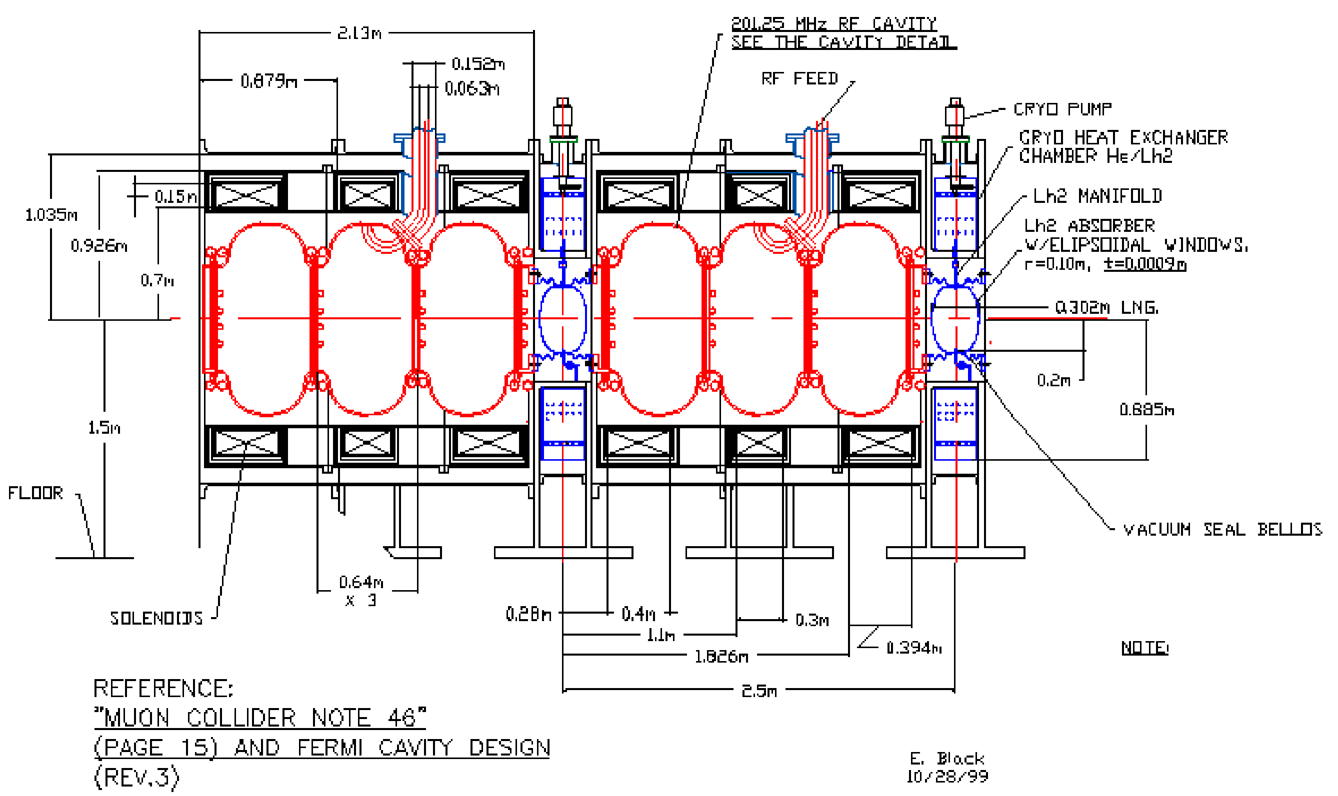
Dave Kasper,
Kevin McFarland, Debbie Harris

Deep Inelastic Scattering Experiments



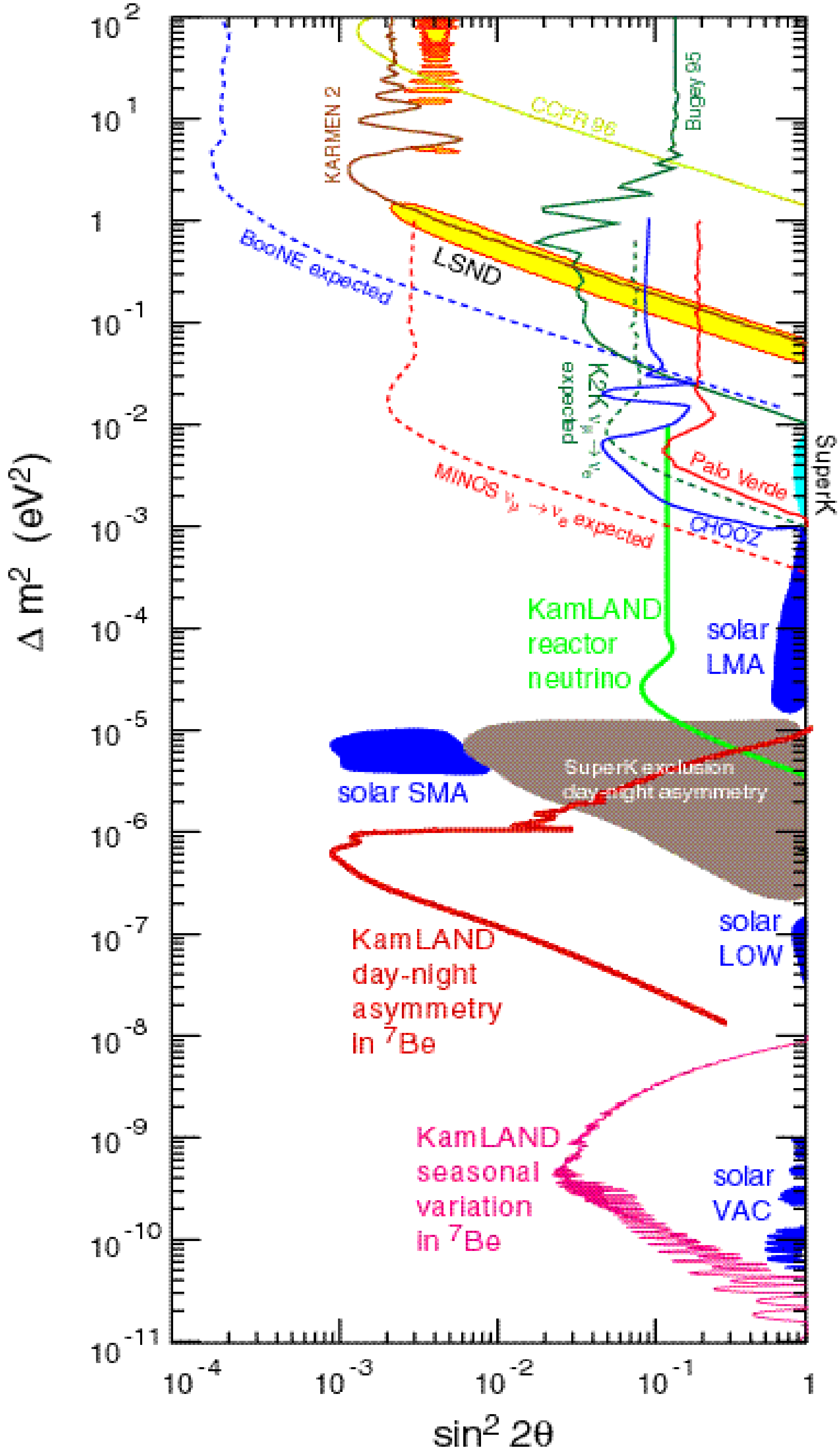
The eart of the ooling hannel for a Neutrino Factory

Need to reduce transverse beam by
a factor of 10.



B_z ~ 5 T max

E_{acc} ~ 15 MV/m @ 200 MHz



KARMEN 2
CCFR 96
Bugey 95
LSND
BooNE expected
K2K
expected
Palo Verde
SuperK
MINOS $\nu_\mu \rightarrow \nu_e$ expected
CHOOZ
KamLAND
reactor
neutrino
solar
LMA
solar SMA
SuperK exclusion
day-night asymmetry
solar
LOW
KamLAND
day-night
asymmetry
in ^{7}Be
KamLAND
seasonal
variation
in ^{7}Be
solar
VAC
Δm^2 (eV^2)
$\sin^2 2\theta$

Neutrino Factories from muon beams

- What they are
- How you make them (Norbert Holtkamp)
- Why you want them
- Some experimental details
- Prospects