Neutrino factories from muon storage rings

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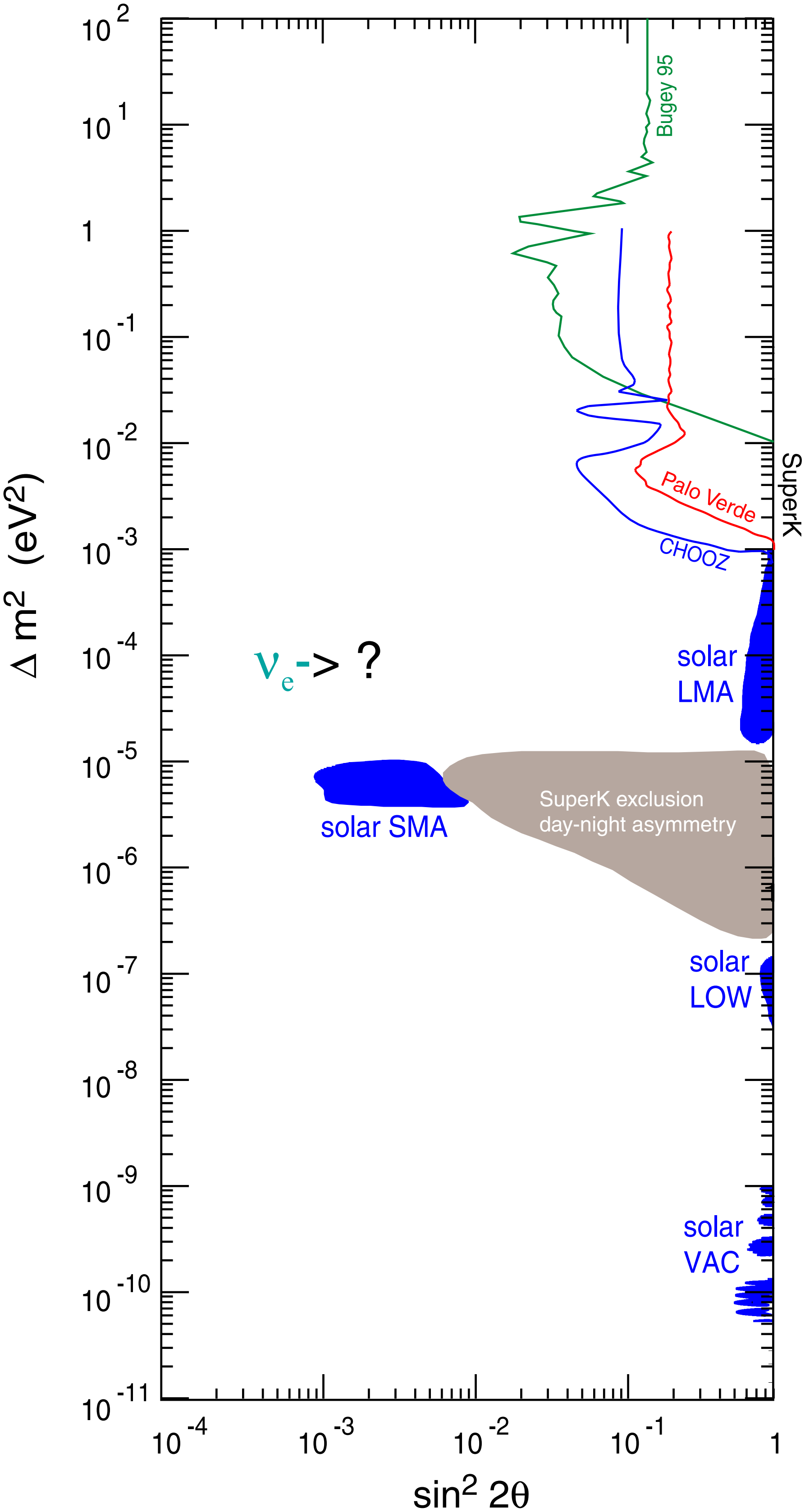
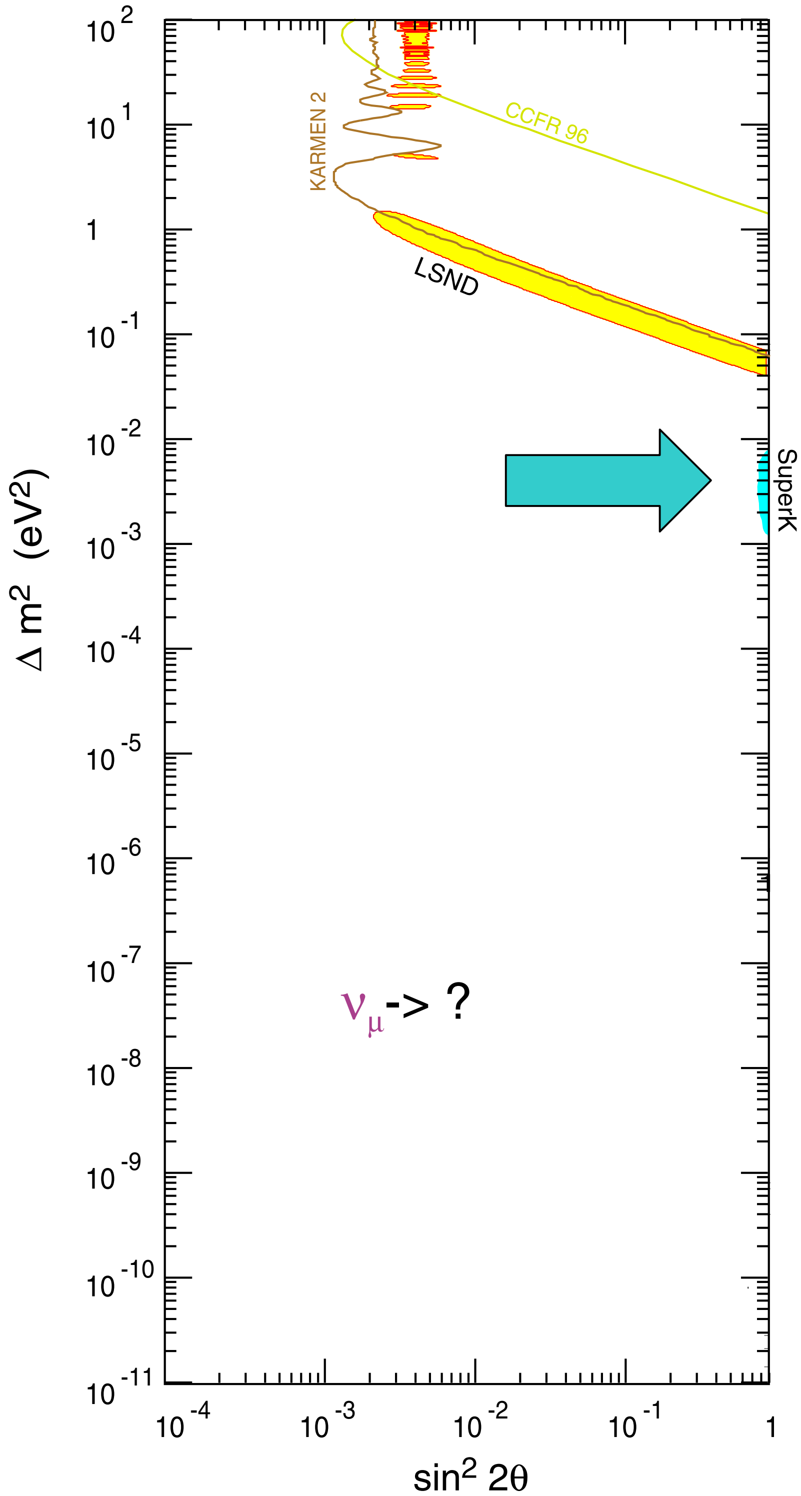
Several studies of neutrino factory experiments

- 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 doe we know about electron neutrino oscillations

- Solar neutrinos give low mass region
- Reactor experiments explore high Δm^2 region



What we know about muon neutrino oscillations

- From SuperK, Soudan, Macro … know $\sin^2 2\theta_{23} \sim 1$.
- K2K, CGS, MINOS will tell us more.
- Muon neutrino expts require high energy, hence long baselines to be sensitive to low Δm^2

3-flavor mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e2} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

3angles θ_{12} θ_{13} and θ_{23}
and complex phase δ

$$P(\nu_\alpha \to \nu_\beta) = \left| \langle \nu_\beta | e^{-iH_0 L} | \nu_\alpha \rangle \right|^2 = \sum_{i,j} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} e^{-i\delta m^2_{ij} L/2E}$$

3 masses -> only 2 mass differences
So far we know:

θ_{23} is large (atmospheric)
Δm_{23}^2 is > 10^{-3} ev^2 (atmospheric)
θ_{13} is small (reactor)

$$
\begin{aligned}
P(\nu_\mu \to \nu_\mu) &\simeq 1 - 4|U_{\mu 3}|^2(1-|U_{\mu 3}|^2)\sin^2(\tfrac{\delta m^2_{atm} L}{4E}) \\
&= 1 - 4\sin^2(\theta_{23})\cos^2(\theta_{13})(1-\sin^2(\theta_{23})\cos^2(\theta_{13}))\sin^2\left(\tfrac{\delta m^2_{atm} L}{4E}\right)
\end{aligned}
$$

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) &\simeq 4|U_{e3}|^2|U_{\mu 3}|^2\sin^2\left(\tfrac{\delta m^2_{atm} L}{4E}\right) \\
&= \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2\left(\tfrac{\delta m^2_{atm} L}{4E}\right)
\end{aligned}
$$

LSND?

$$
\begin{aligned}
P(\nu_\mu \to \nu_\tau) &\simeq 4|U_{\mu 3}|^2|U_{\tau 3}|^2\sin^2(\tfrac{\delta m^2_{atm} L}{4E}) \\
&= \sin^2(2\theta_{23})\cos^4(\theta_{13})\sin^2\left(\tfrac{\delta m^2_{atm} L}{4E}\right)
\end{aligned}
$$

Δm_{23}^2, θ_{23}

$$
\begin{aligned}
P(\nu_e \to \nu_e) &\simeq 1 - 4|U_{e3}|^2(1-|U_{e3}|^2)\sin^2\left(\tfrac{\delta m^2_{atm} L}{4E}\right) \\
&= 1 - \sin^2(2\theta_{13})\sin^2\left(\tfrac{\delta m^2_{atm} L}{4E}\right) ,
\end{aligned}
$$

$$
\begin{aligned}
P(\nu_e \to \nu_\mu) &\simeq 4|U_{e3}|^2|U_{\mu 3}|^2\sin^2\left(\tfrac{\delta m^2_{atm} L}{4E}\right) \\
&= \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2\left(\tfrac{\delta m^2_{atm} L}{4E}\right) ,
\end{aligned}
$$

θ_{13}

$$
\begin{aligned}
P(\nu_e \to \nu_\tau) &\simeq 4|U_{\tau 3}|^2|U_{e3}|^2\sin^2\left(\tfrac{\delta m^2_{atm} L}{4E}\right) \\
&= \sin^2(2\theta_{13})\cos^2(\theta_{23})\sin^2\left(\tfrac{\delta m^2_{atm} L}{4E}\right)
\end{aligned}
$$

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 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

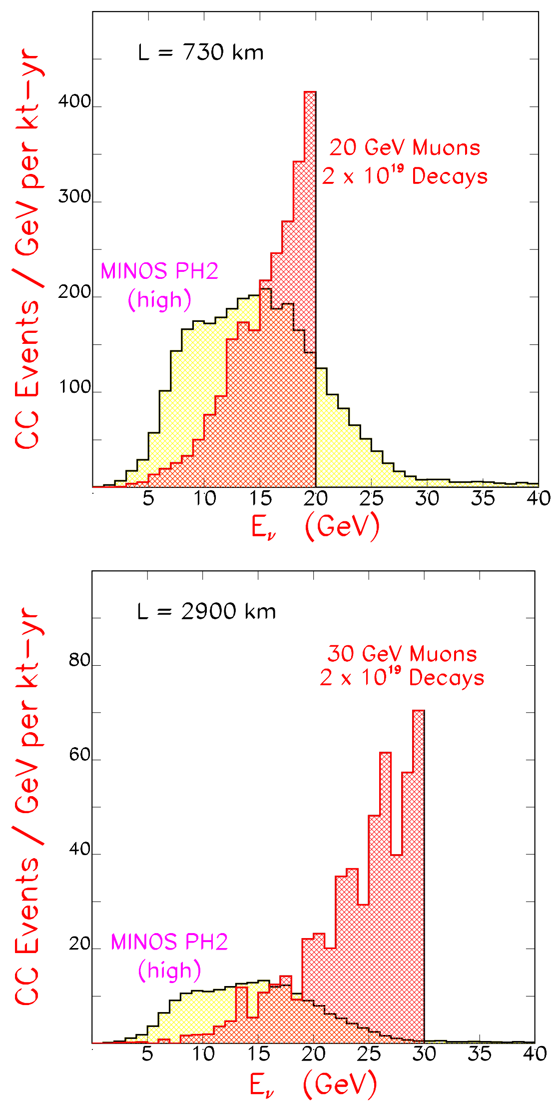
ν_e<->ν_e	ν_μ<->ν_e	
ν_e <-> ν_μ	ν_μ <-> ν_μ	and anti-particles
ν_e <-> ν_τ	ν_μ <-> ν_τ	

3 Flavor Scenarios

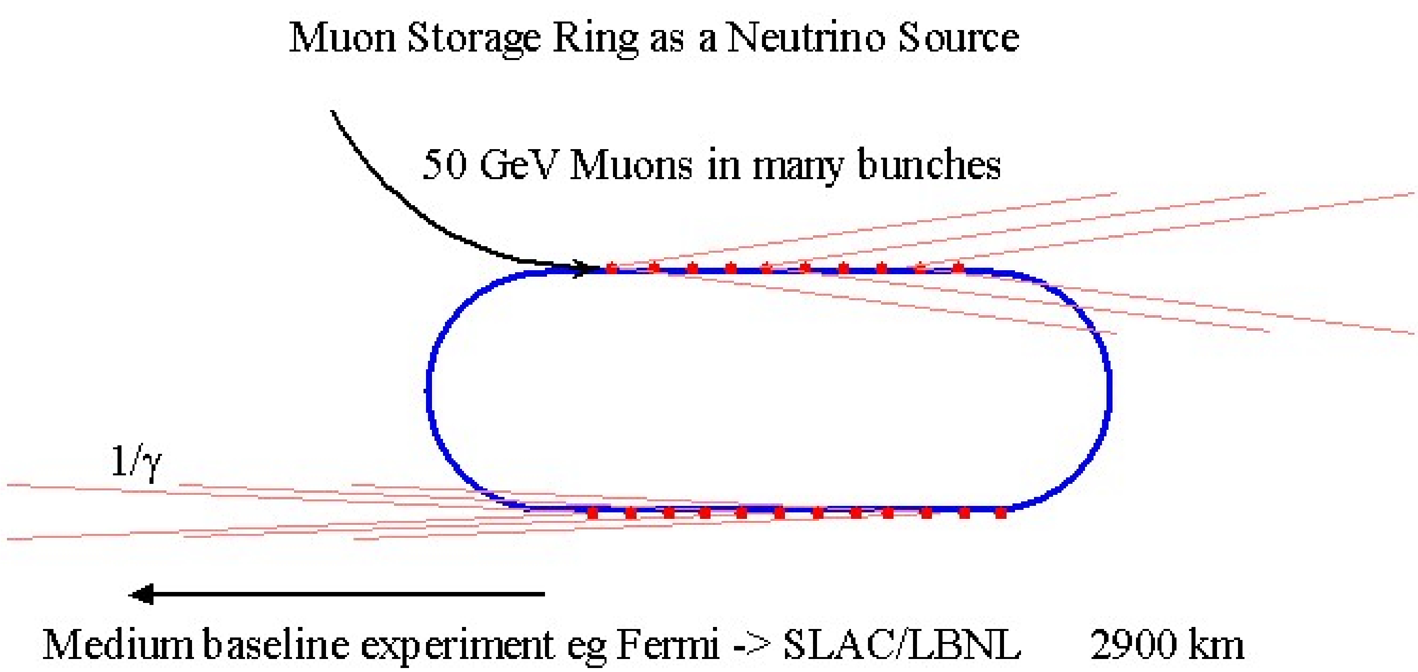
parameter	IA1	IA2	IA3	1B1	1C1
δm^2_{32} (eV^2)	3.5×10^{-3}	3.5×10^{-3}	3.5×10^{-3}	3.5×10^{-3}	0.3
δm^2_{21} (eV^2)	5×10^{-5}	6×10^{-6}	1×10^{-7}	0.3	7×10^{-4}
$\sin^2 2\theta_{23}$	1.0	1.0	1.0	1.0	0.53
$\sin^2 2\theta_{13}$	0.04	0.04	0.04	0.015	0.036
1 $\sin^2 2\theta_{12}$	0.8	0.006	0.9	0.015	0.89
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.



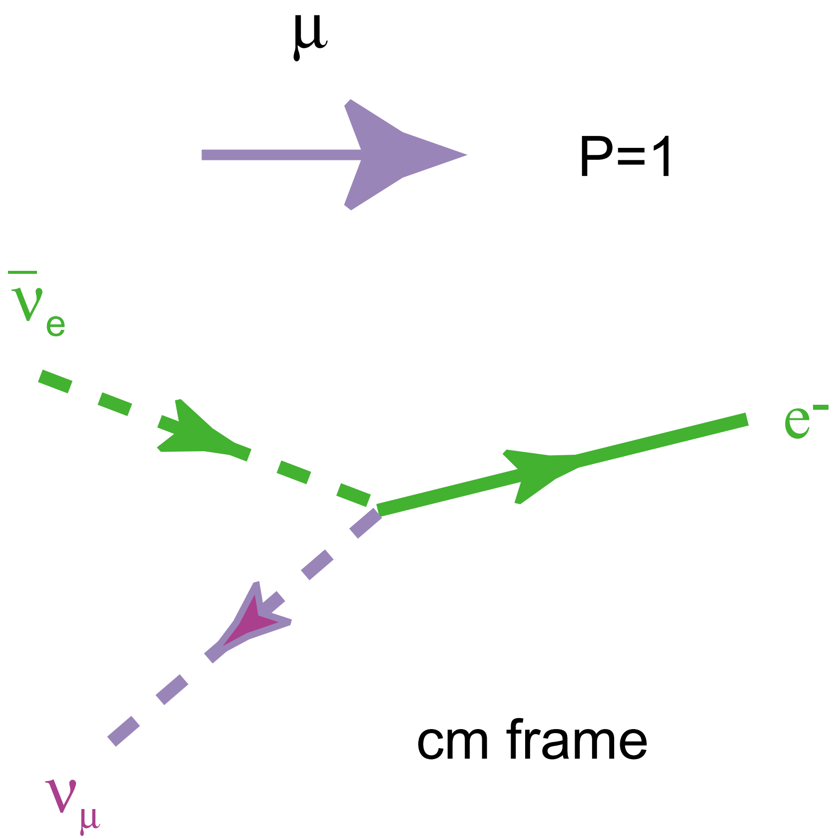
The Neutrino Source



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 μ $= 1/\gamma$	mrad	2.0
Beam angle $(\sqrt{\varepsilon}/\beta_o) = (\sqrt{\varepsilon}\,\gamma)$	mrad	0.2
Lifetime $c*\gamma*\tau$	m	$3\text{x}10^5$

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

Properties of neutrino beams from muon decay



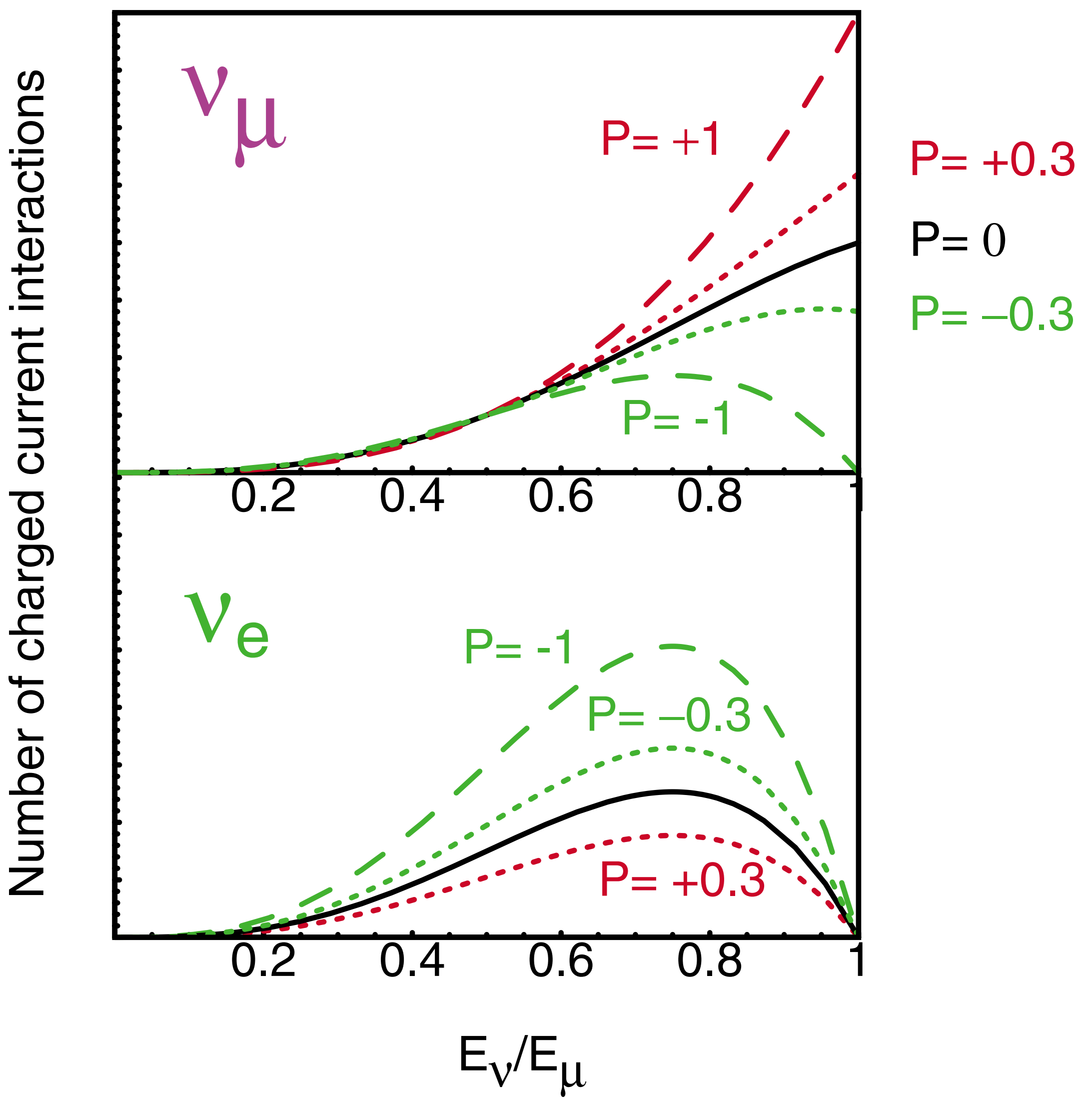
$$\frac{dN(\nu_\mu)}{dz d\cos\theta_{CM}} = 2z^2[(3-2z) \mp P(1-2z)\cos\theta]$$

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

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

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

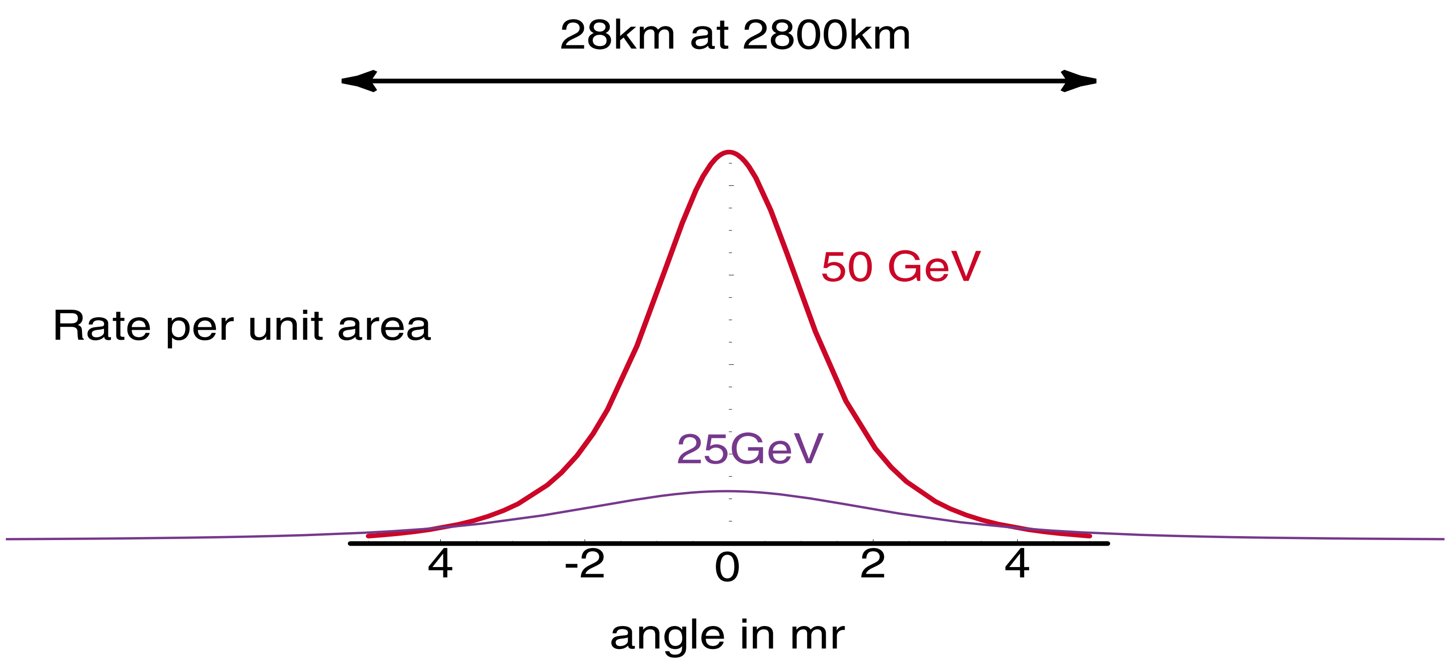
  (~3% at FNAL high energy ν beam)
  - Then accelerate
  - 40% of muons decay in the right direction
- Very well understood source
  - Only one decay process
  - Parent particles ~ monochromatic
  - Around long enough to monitor

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

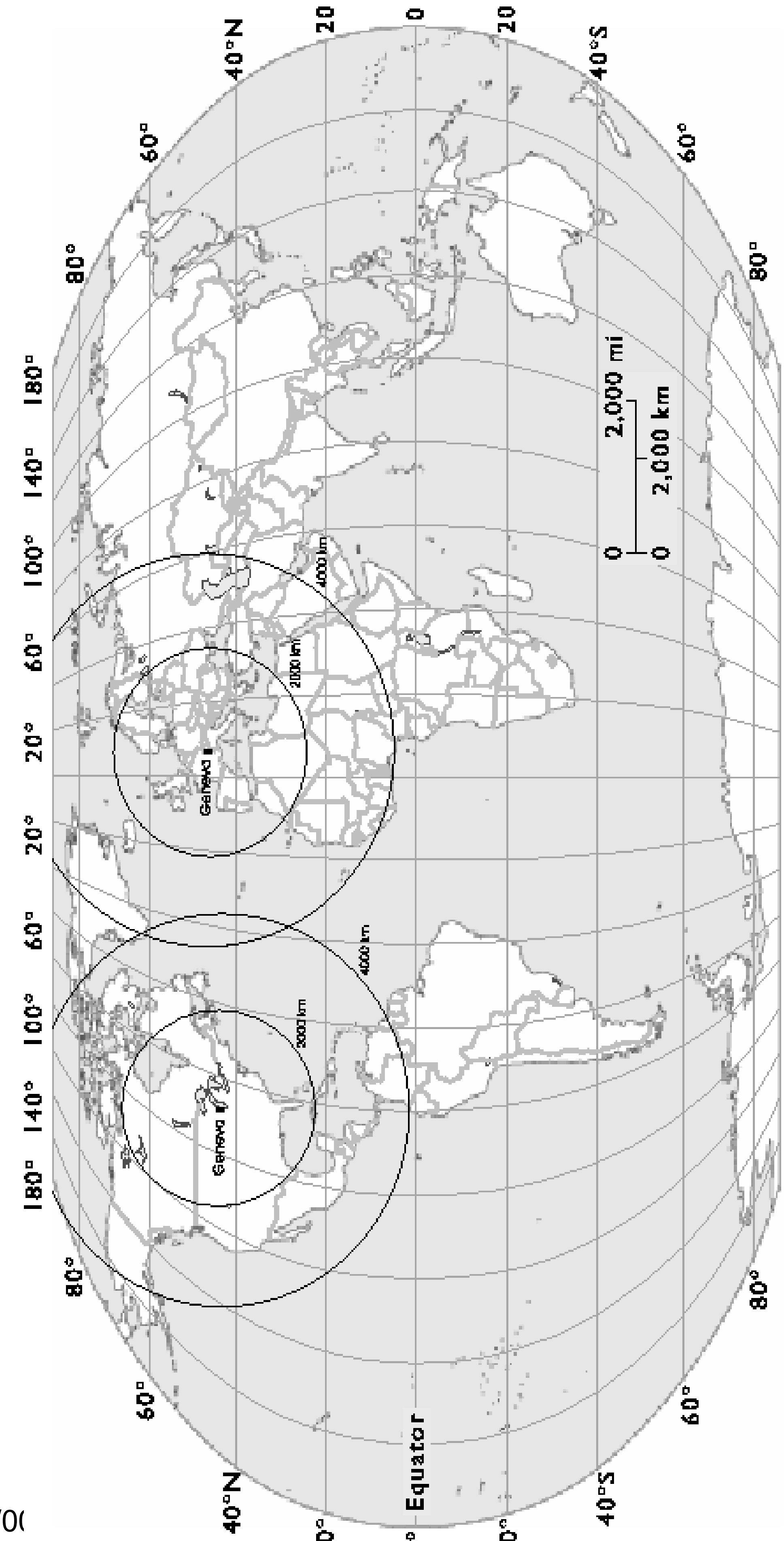
Neutrino Event rates vs angle

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



Equator
40°N
20°
0°
40°S
60°
80°
180°
160°
140°
120°
100°
80°
60°
40°W
20°
0°
40°E
0
2,000 mi
2,000 km
Geneva
2000 km
4000 km

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

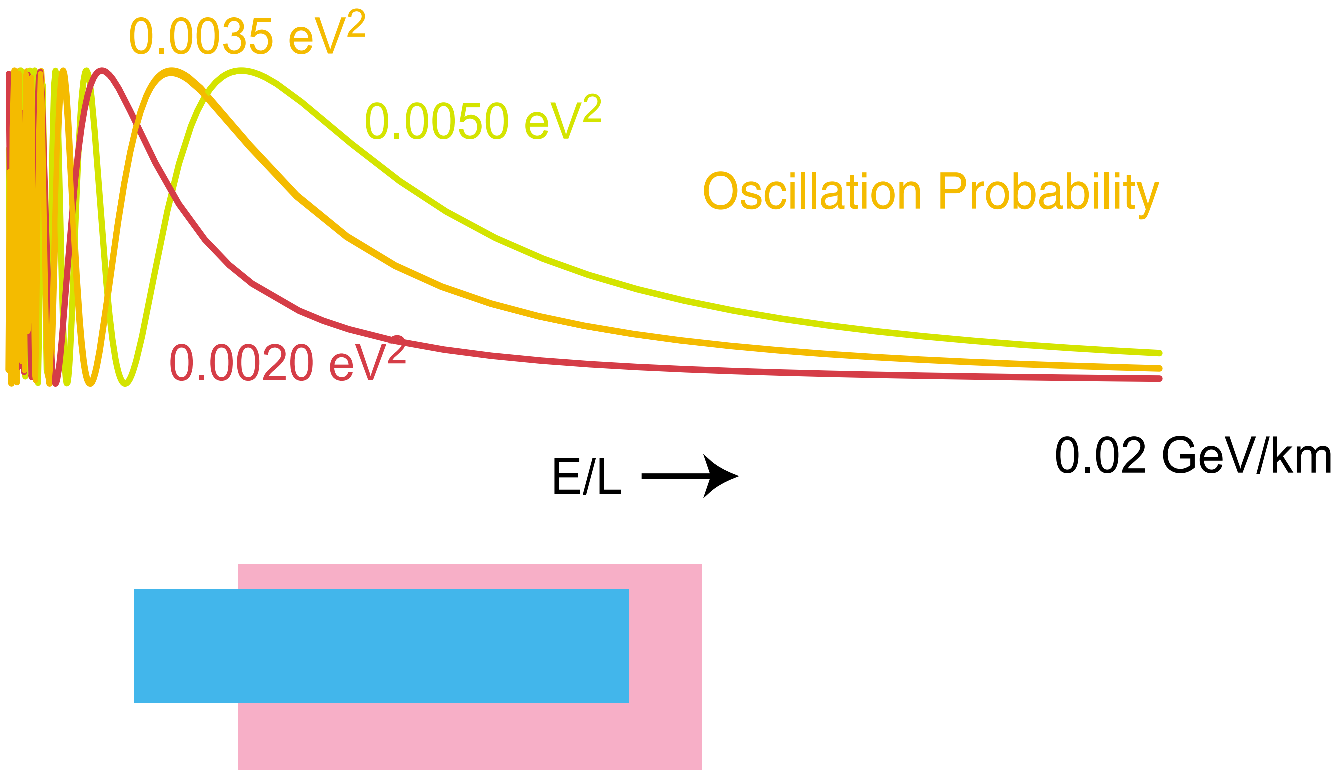
E_μ=30 GeV

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

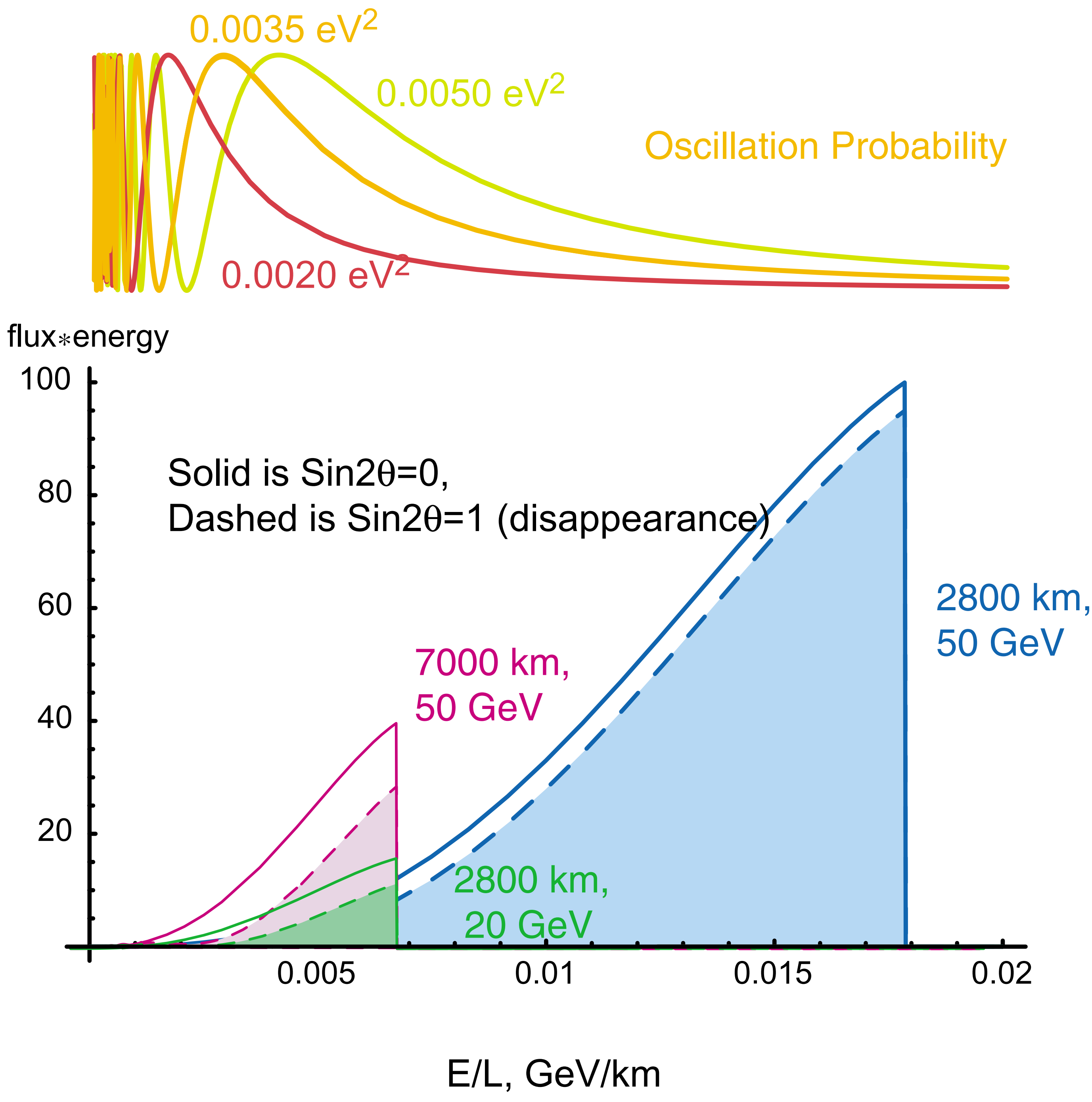


If E/L << Δm^2, $P(\nu_\alpha \to \nu_\beta) \sim \frac{1}{2} \sin^2 2\theta$

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



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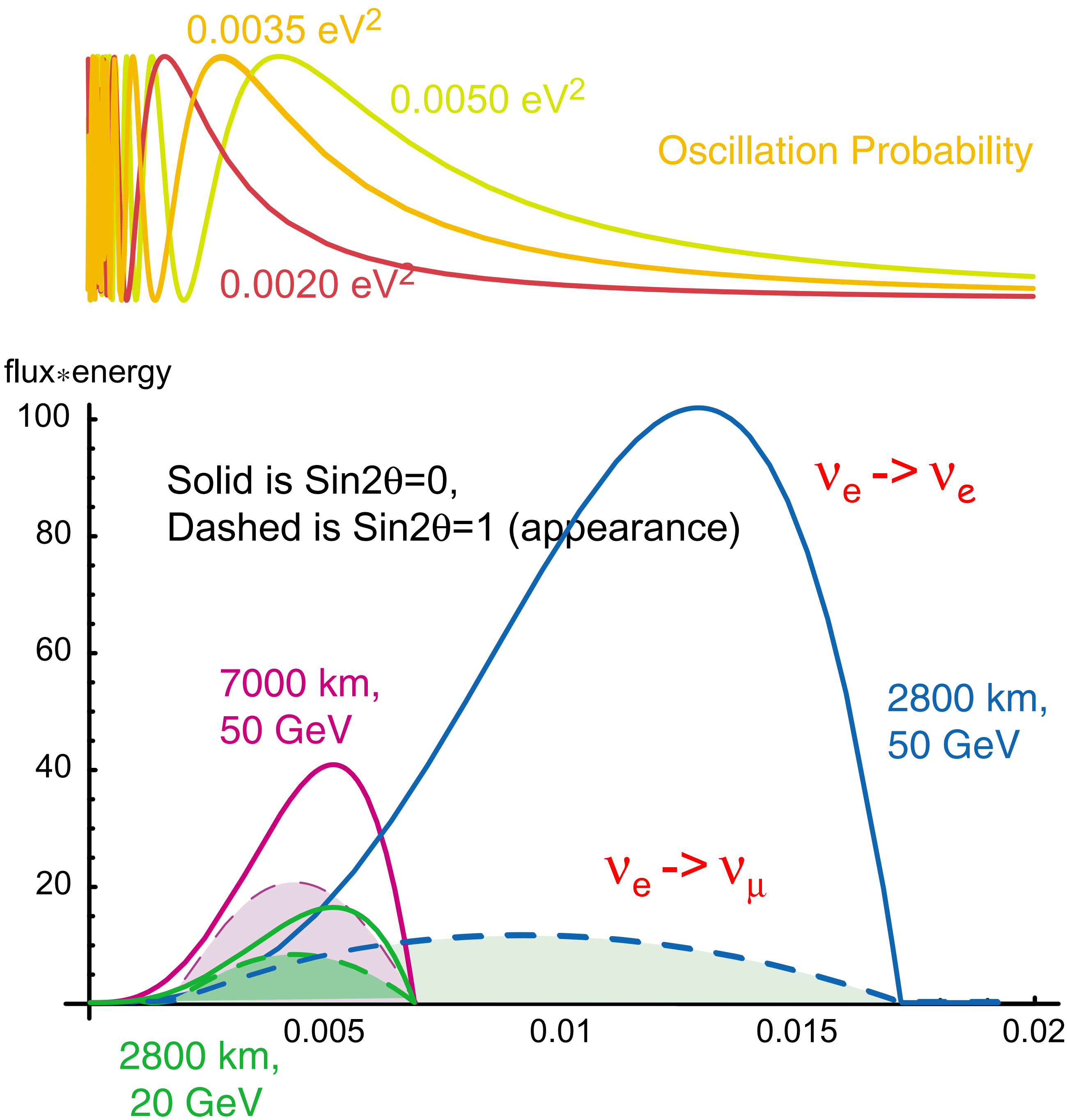
Numbers of electron neutrino interactions for fixed number of muon decays Δm^2=0.0035 eV^2

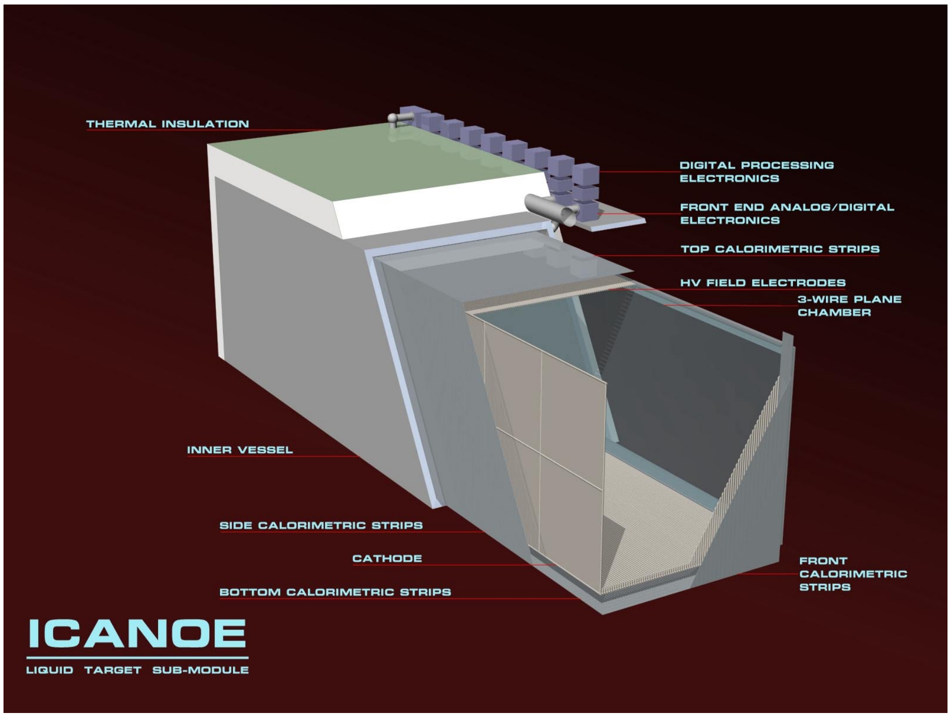


Detectors

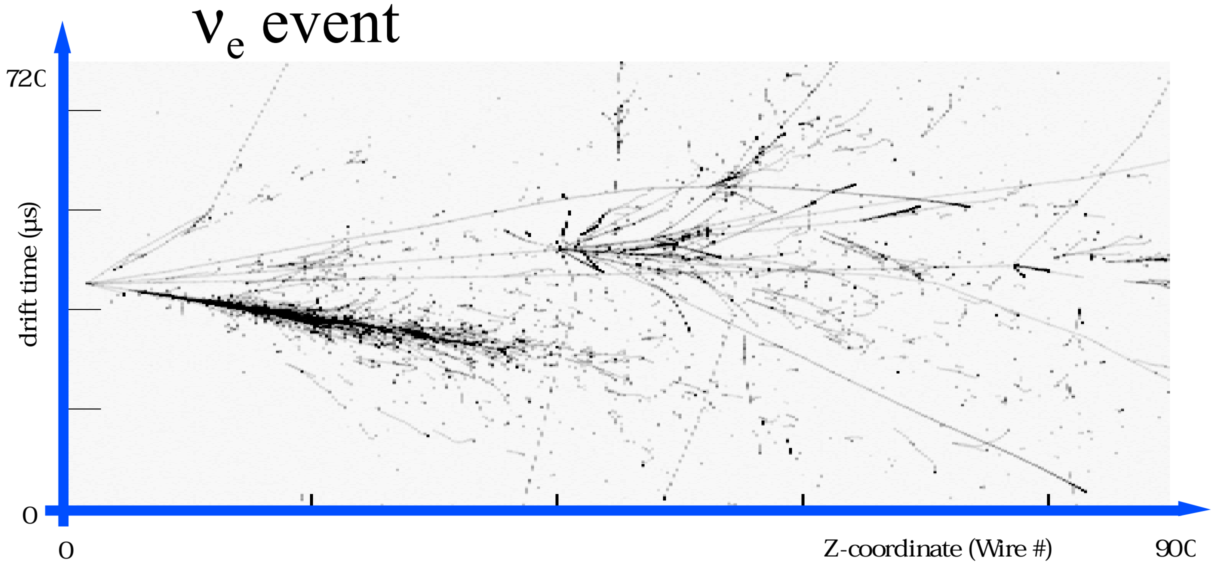
`Protons are cheaper than muons'

- 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

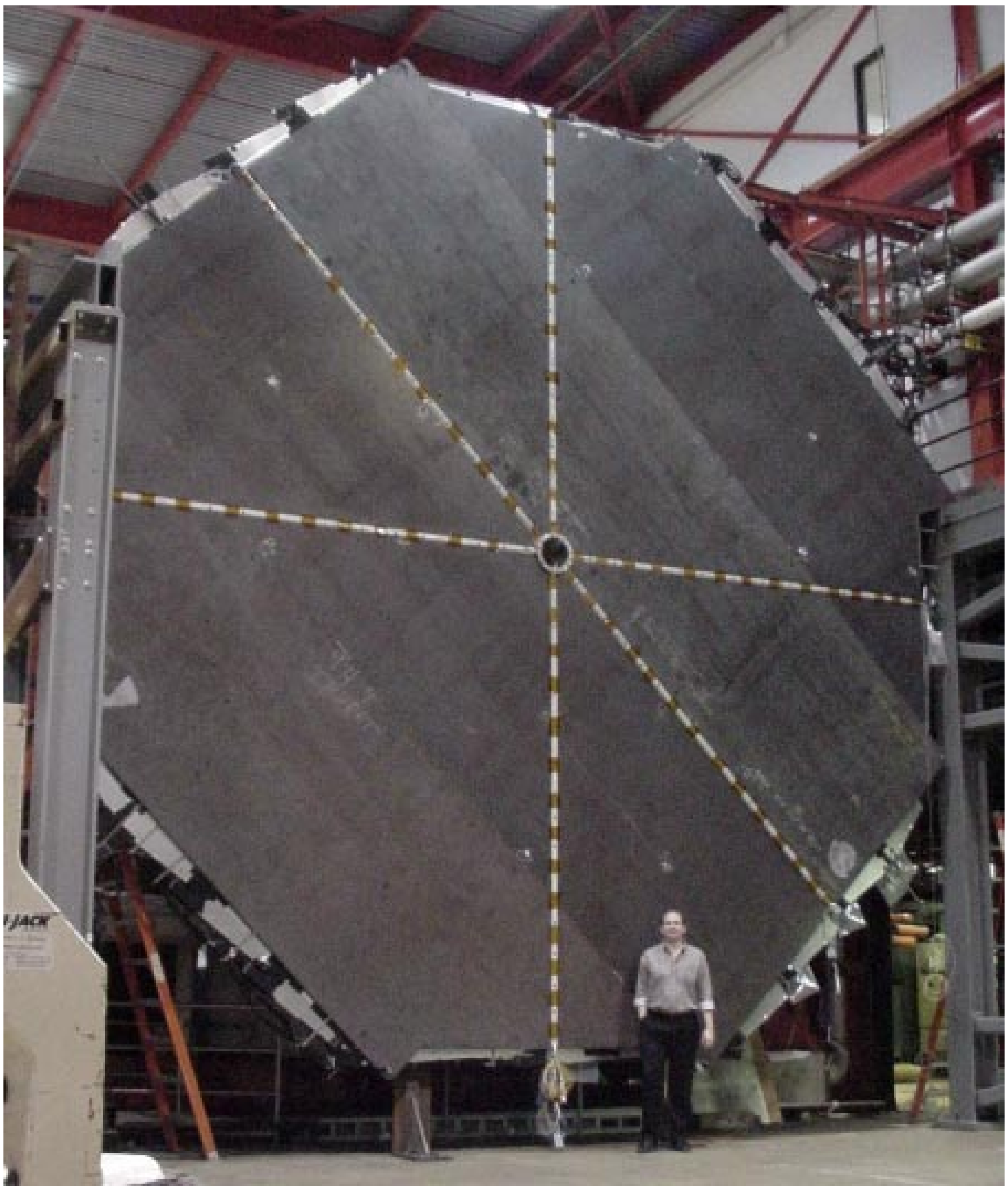
Liquid Argon with drift readout



ν_e event



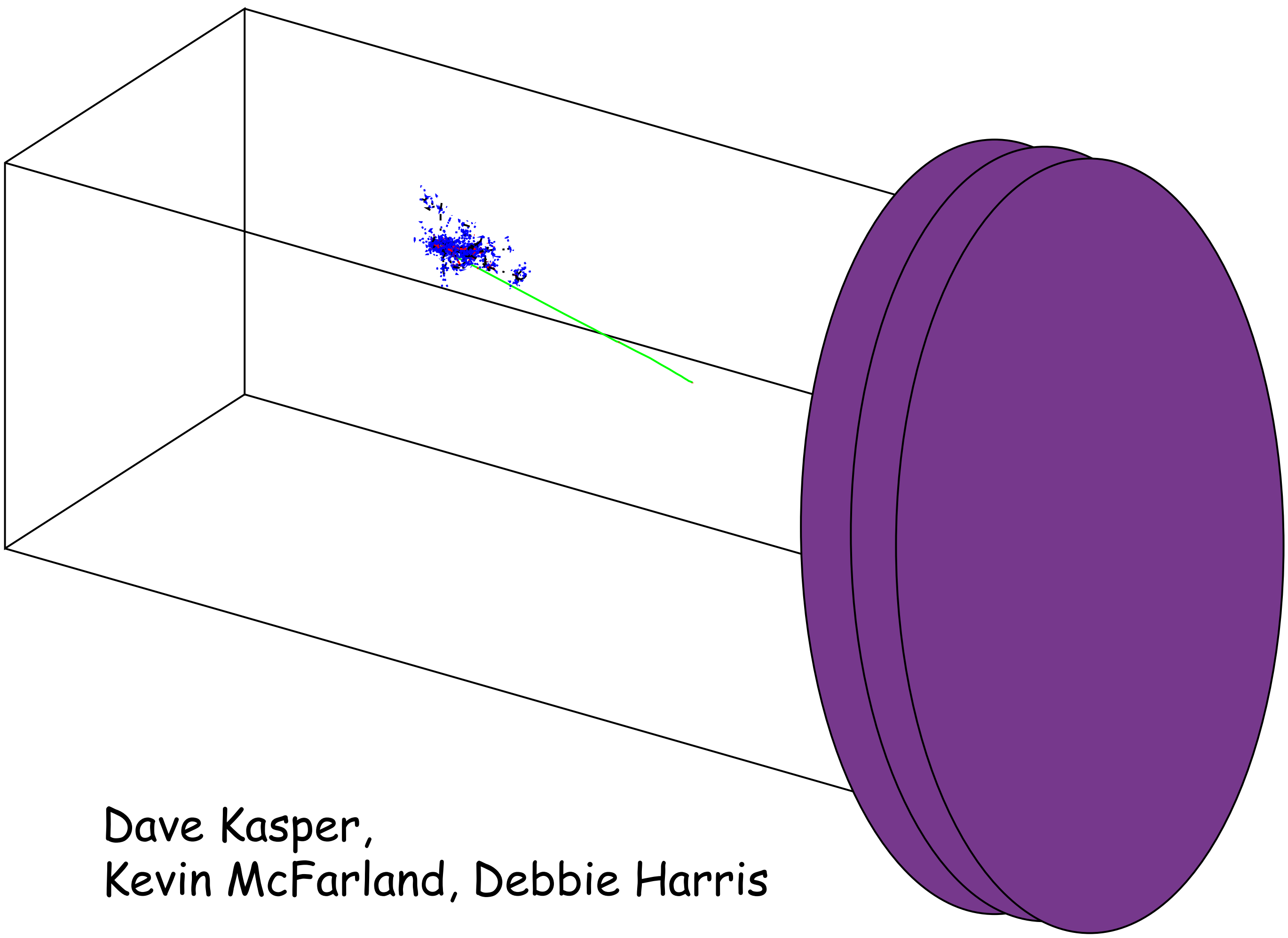
Steel-Scintillator MINOS/MONOLITH/anon.



50 kT version of MINOS

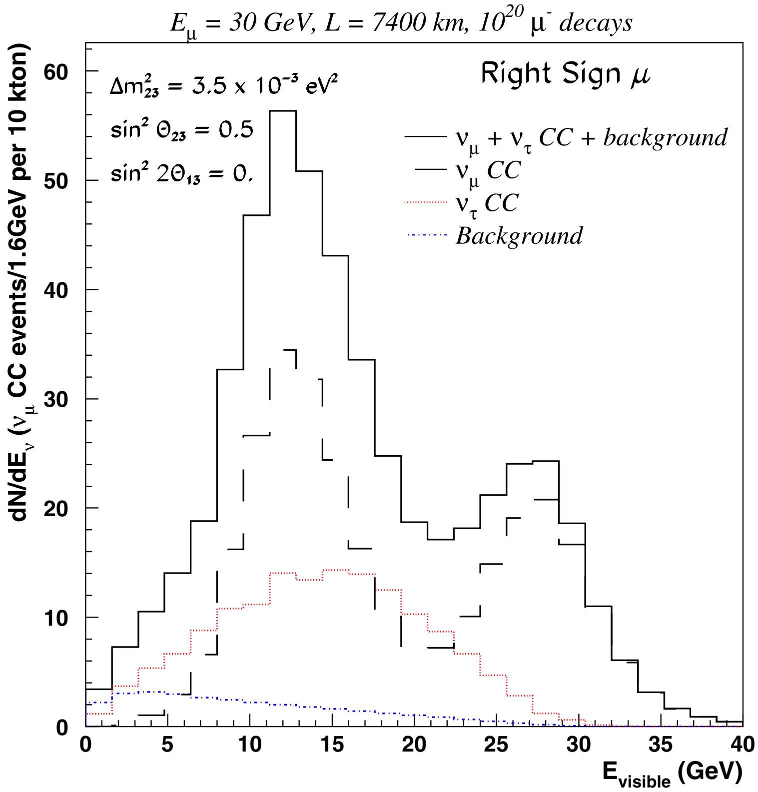
10xSuperK?

Water detector followed by analyzing magnet

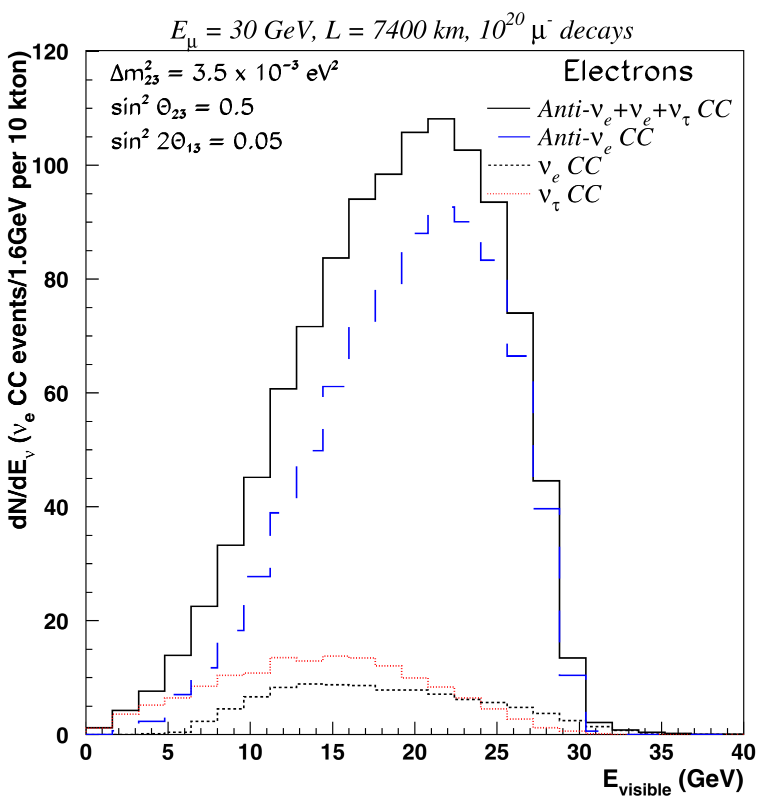


Dave Kasper,
Kevin McFarland, Debbie Harris

10^{20} muon decays



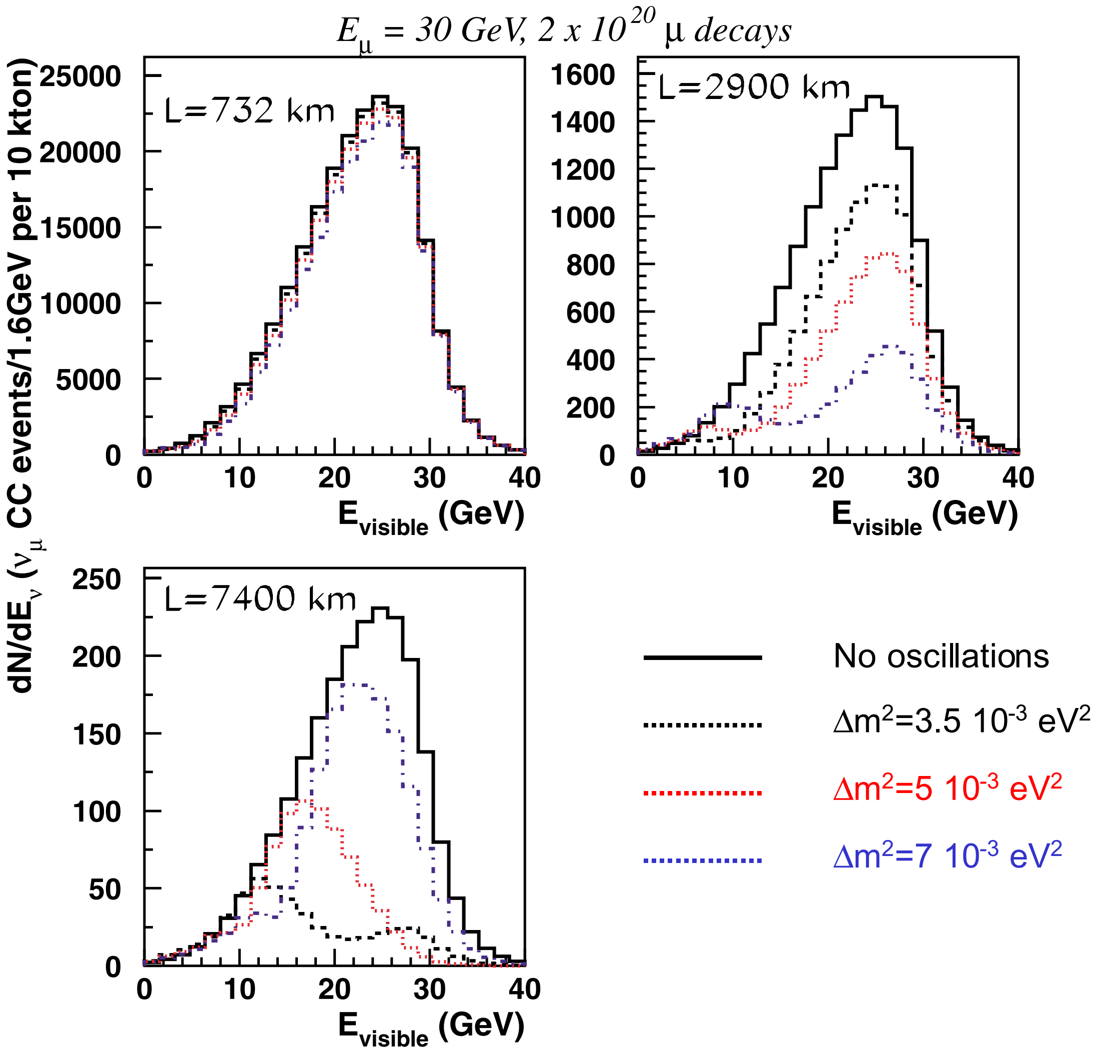
- Right sign muons
  - Dip due to oscillation
- Tau's contribute
  - Signal?
  - Background?



ν_e N -> e+X

Bueno et al.

Disappearance Experiment ν_μ->ν_τ



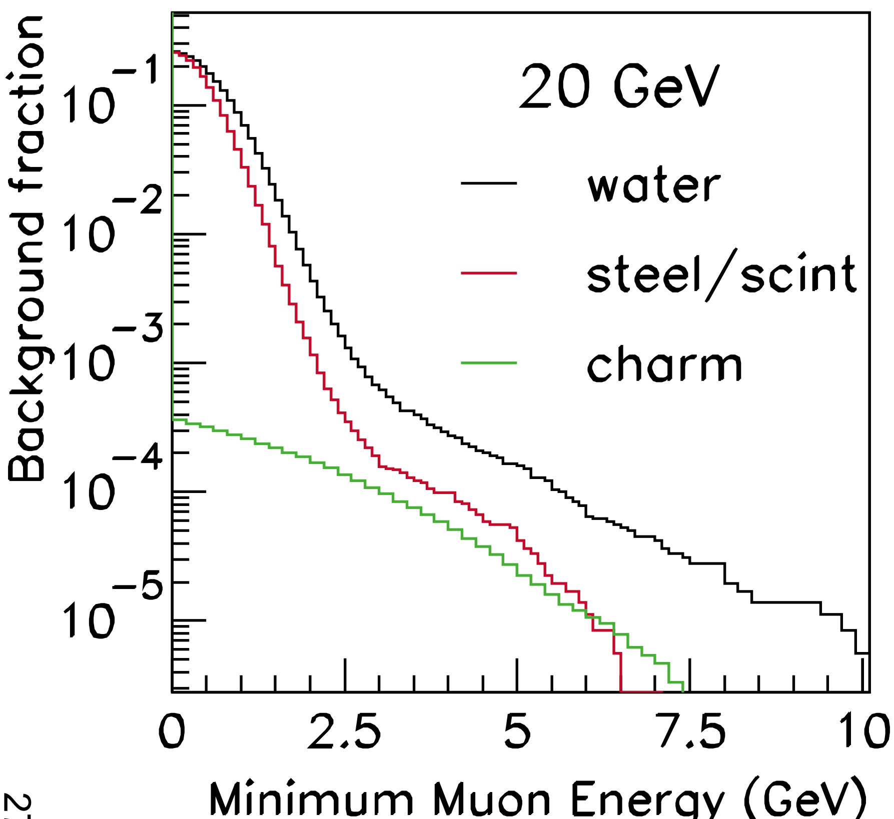
Mario Campanelli, ETH Zurich

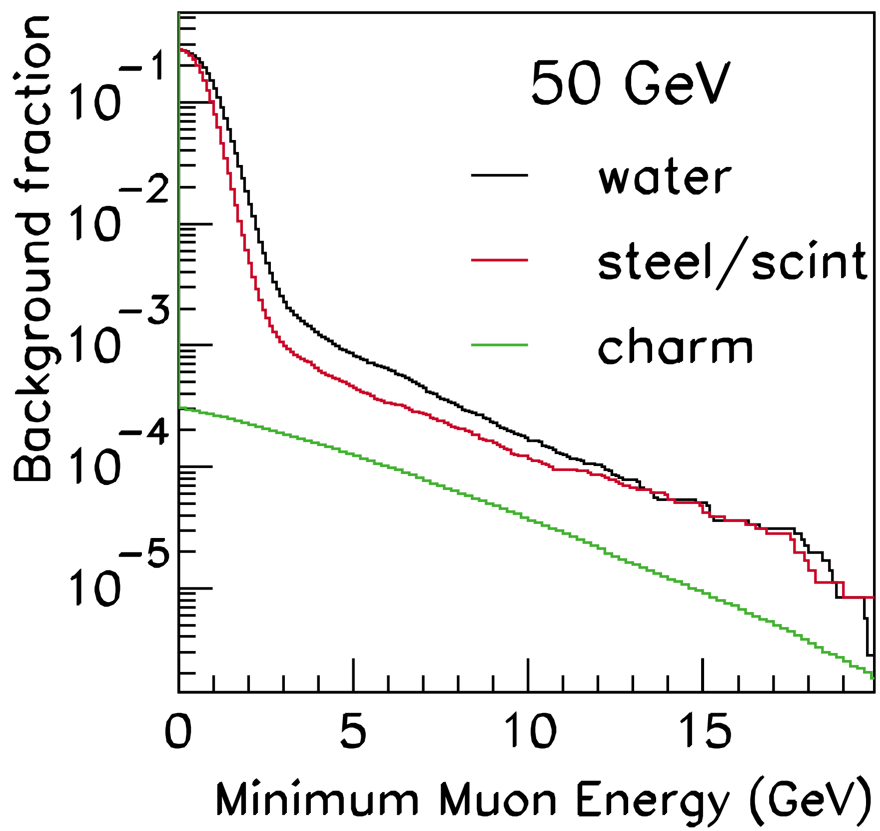
What determines the machine energy?

- We're interested in ν_e->ν_μ
- 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?

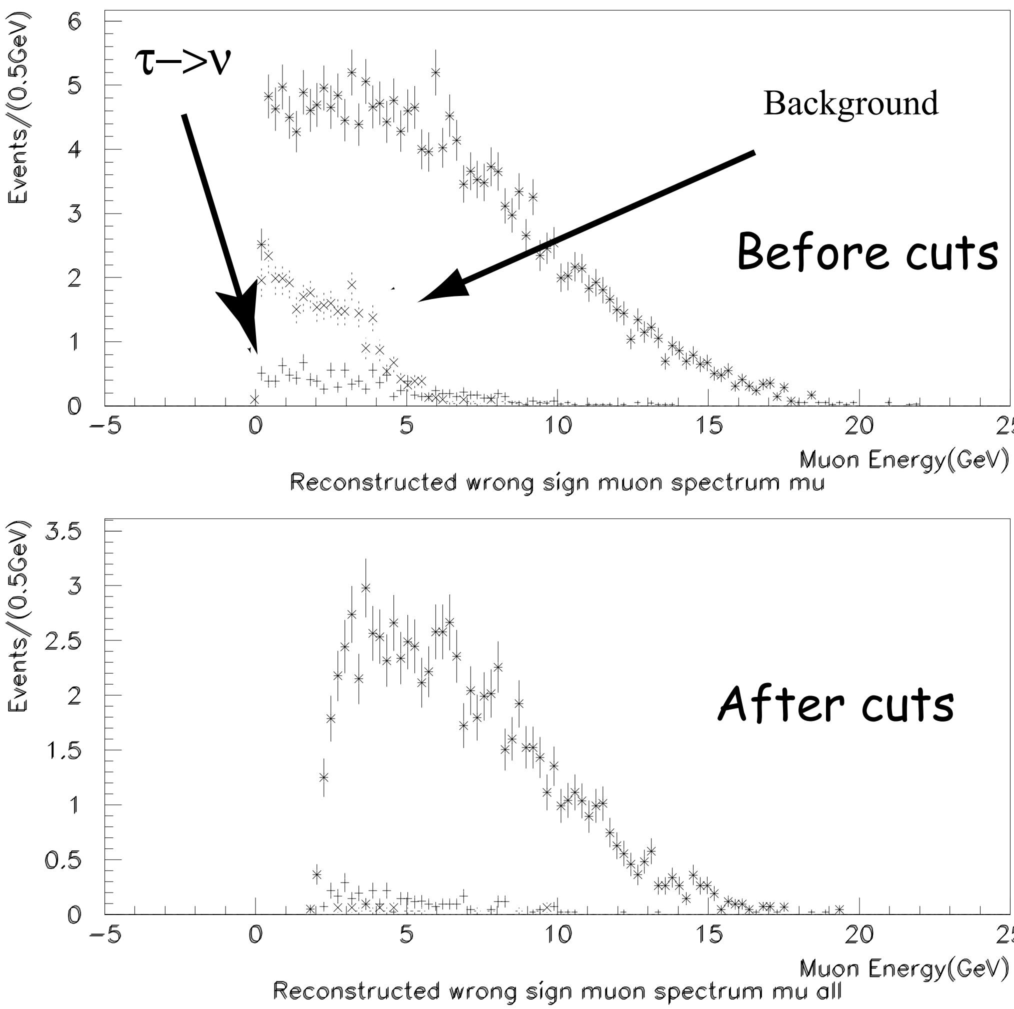
Backgrounds to $\bar{\nu}_e \to \bar{\nu}_\mu \to \mu^+$

Pions which do not interact!



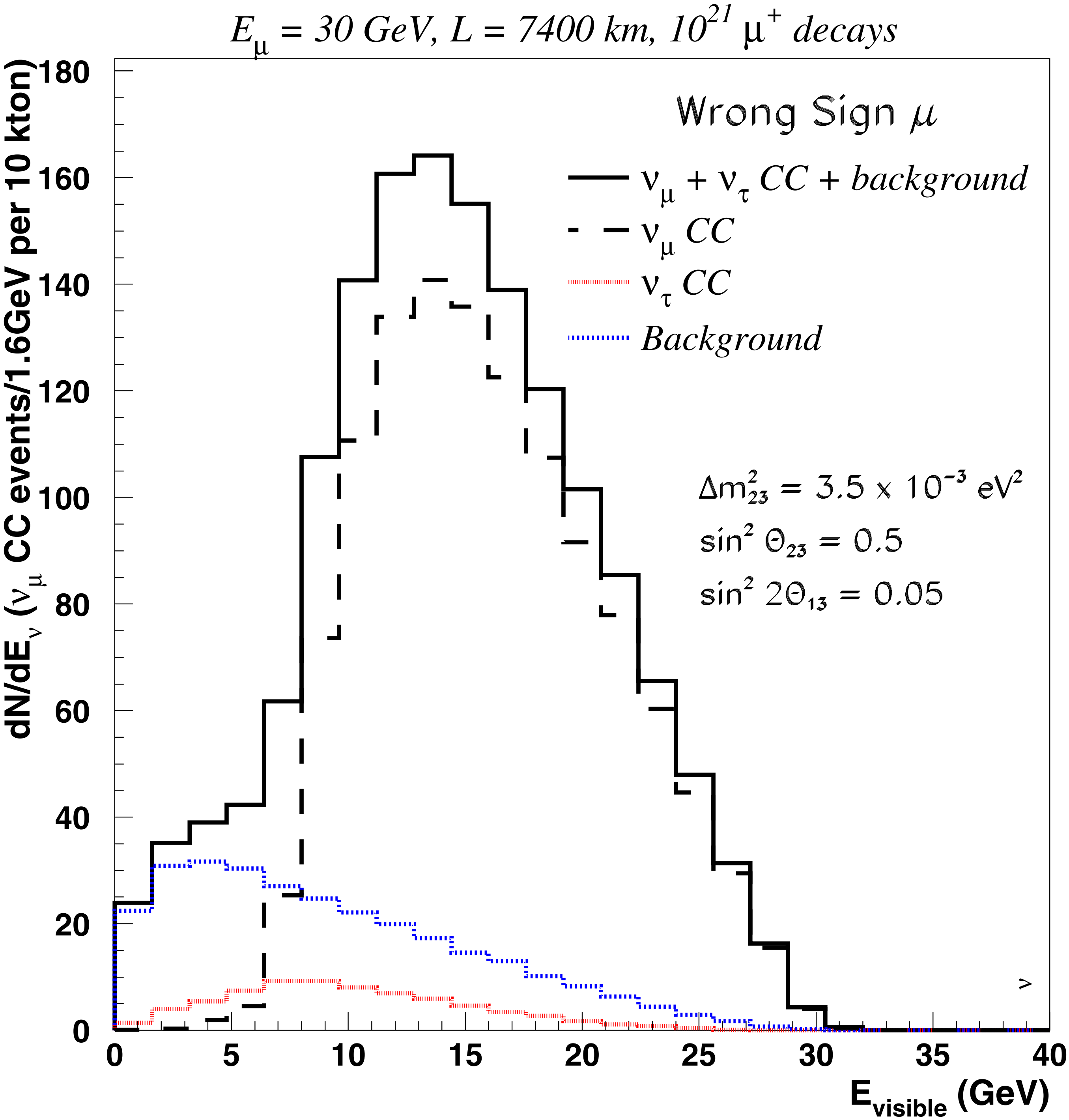


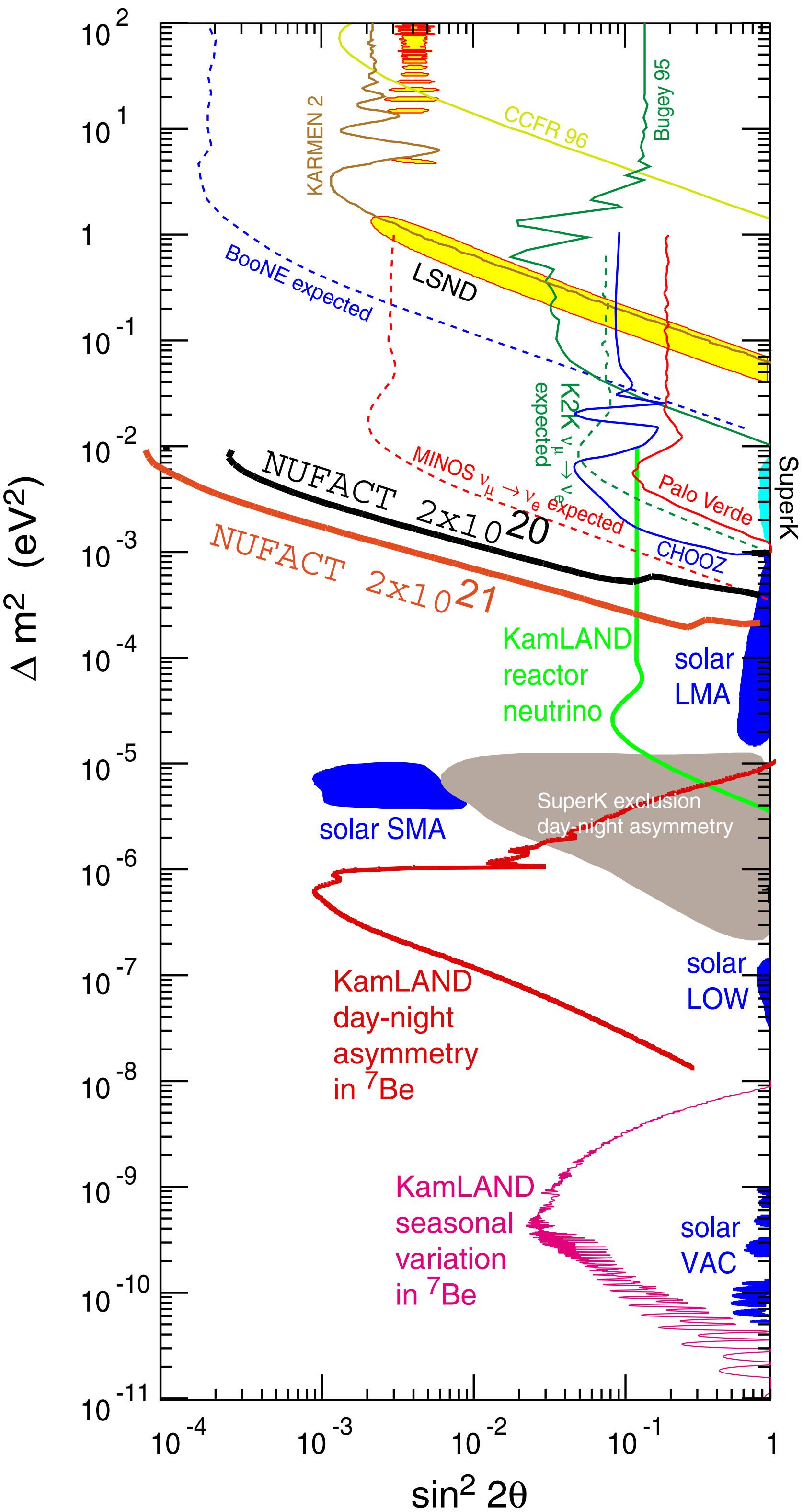
Wrong sign muon signal
10 kt Iron-scintillator detector
20 GeV muon decay
10^{20} decays



Bernstein, Harris, McFarland, Spentzouris

10^{21} muon decays



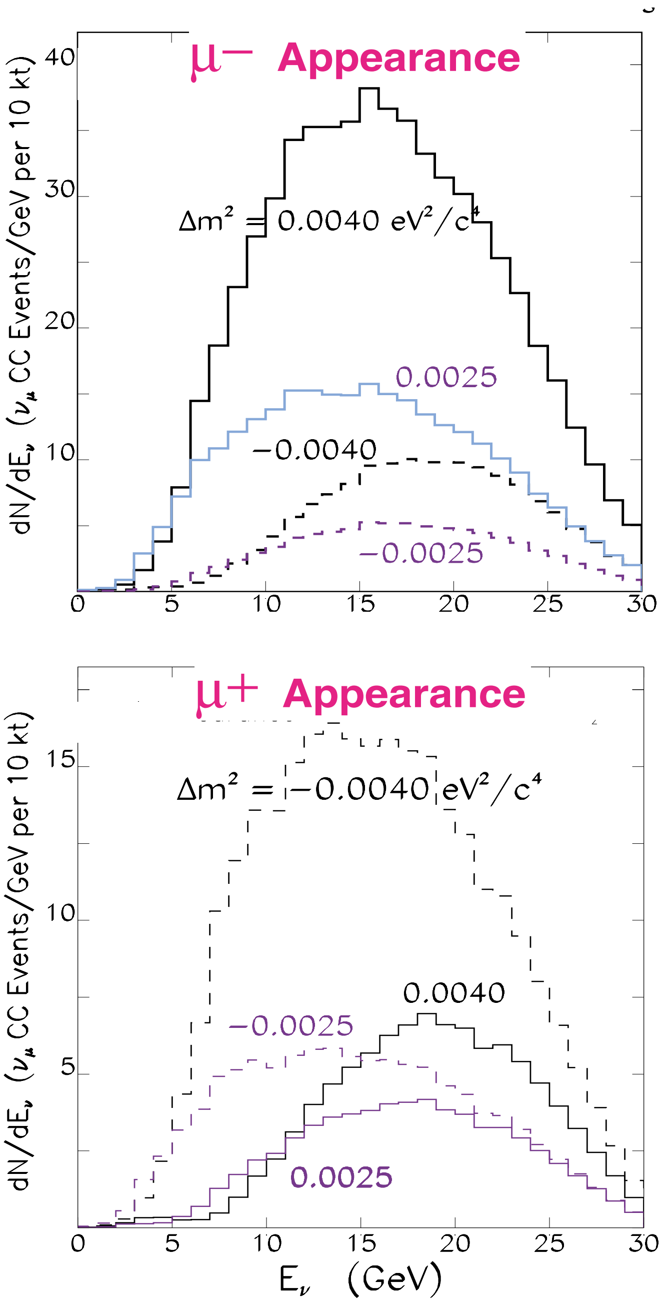


Limits on $\sin^2\theta_{13}$ for a 10kt detector 7400 km away.

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

Δm^2_{21}= 5 x 10^5 eV^2/c^4

$\sin^2 2\theta_{23}$ = 1 δ = 0

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

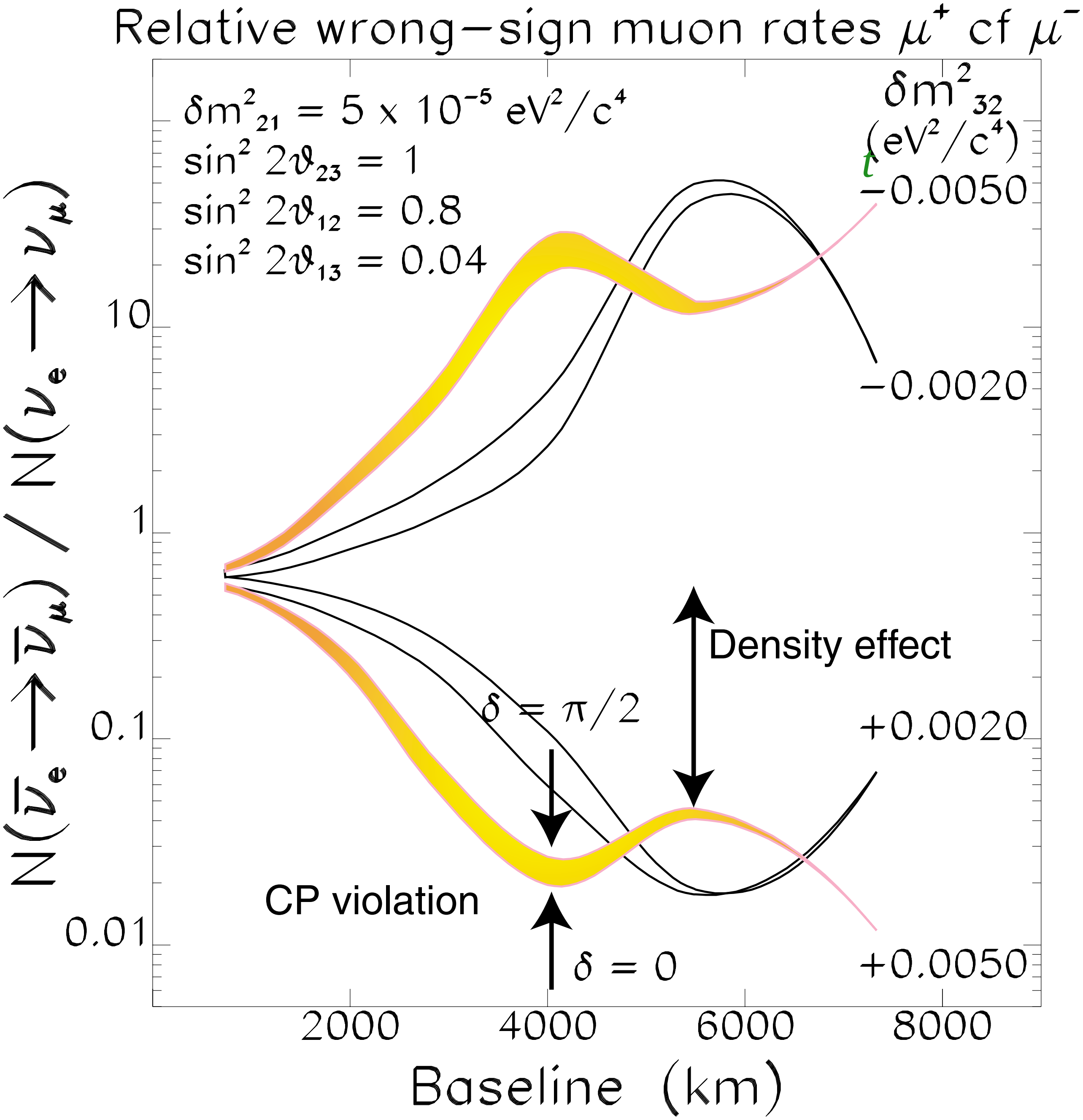
$\sin^2 2\theta_{31}$ = 0.04

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

Barger Geer Raja Whisnant
FermilabPub 99341

CP violation?

E_μ = 20 GeV
E_{min} = 4 GeV

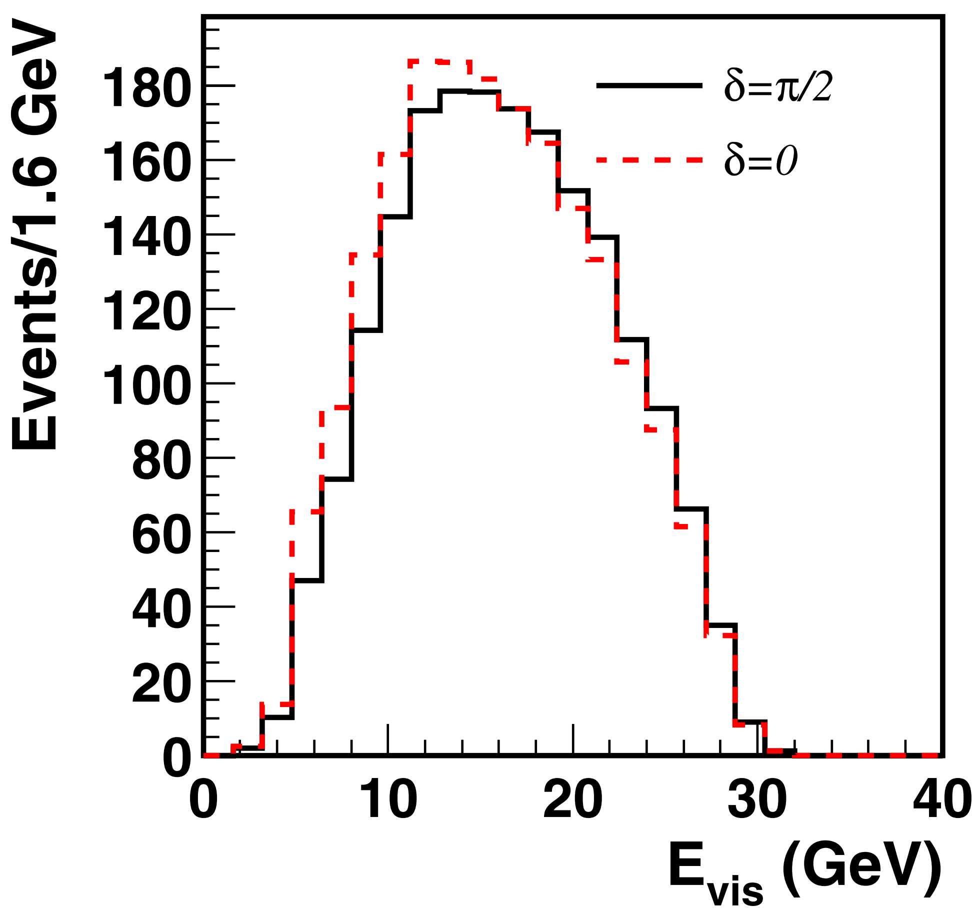


V. Barger, S. Geer, R.Raja, K. Whisnant

What optimal CP violation looks like

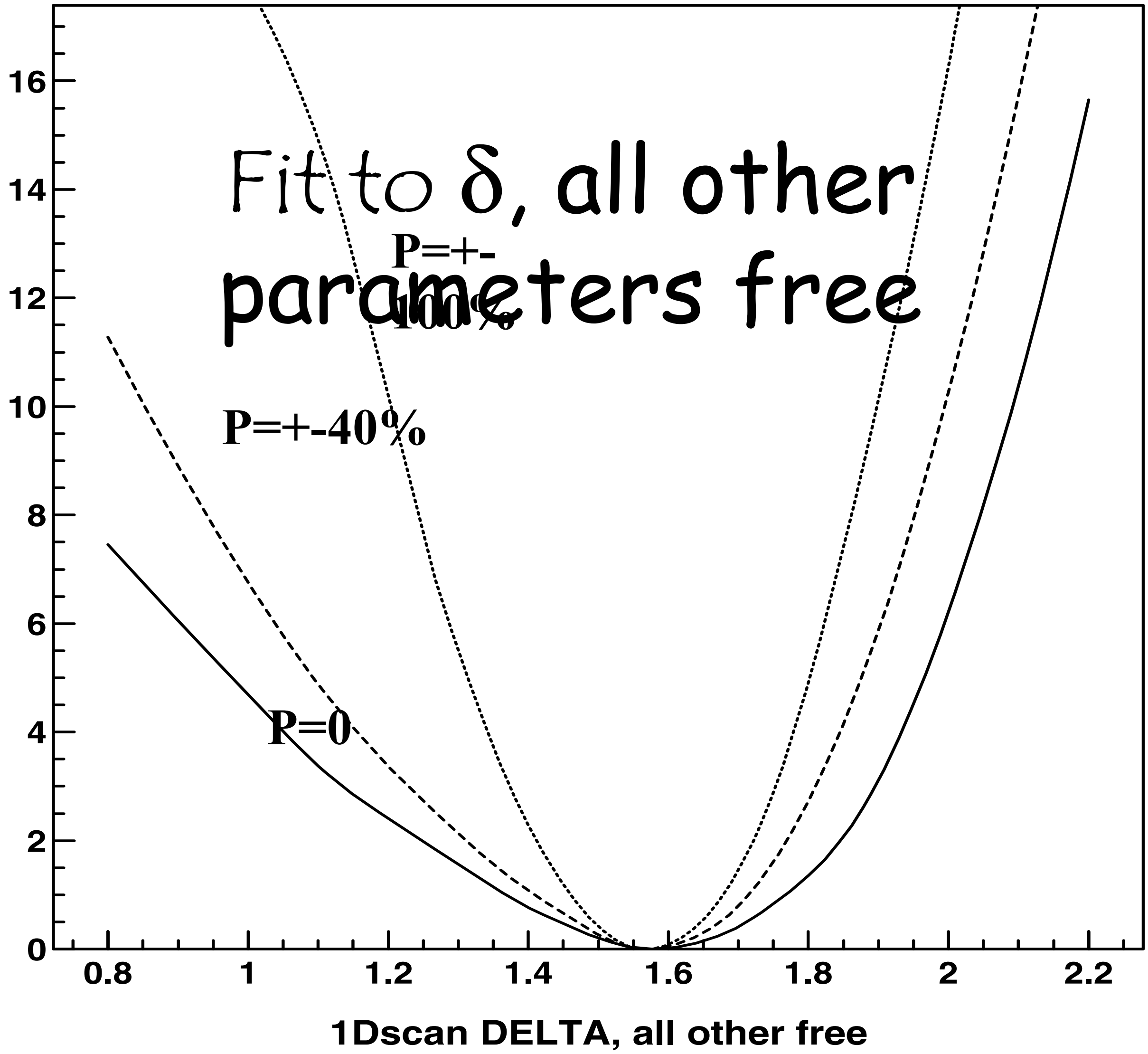
Assume Solar LMA solution, large θ_{12}, θ_{13}

Wrong-sign muons



10^{21} μ, 3500 km

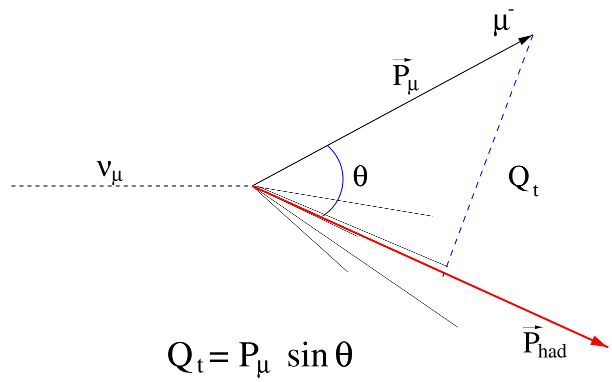
Fit to δ, all other parameters free



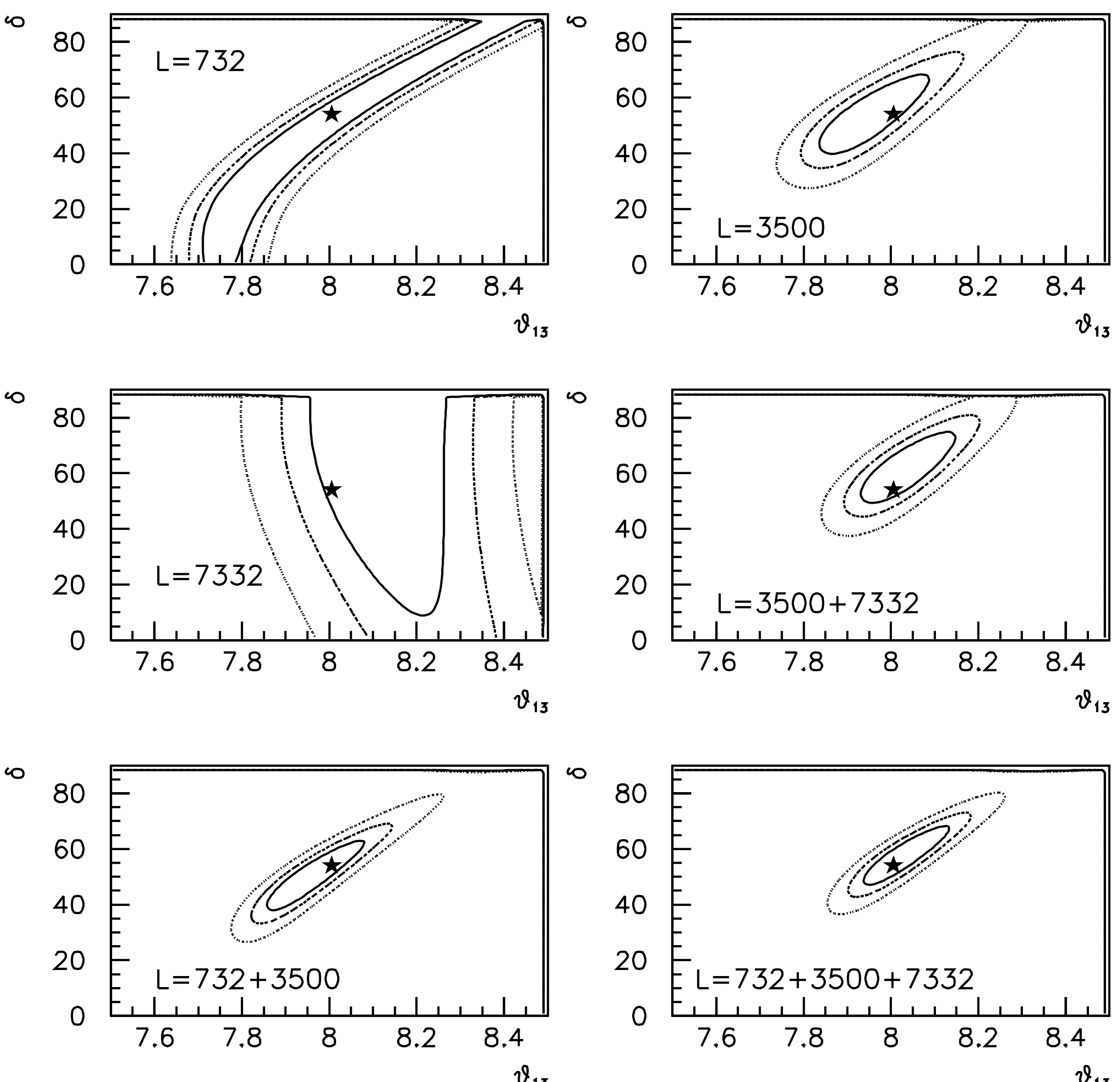
P = 0 :	$\delta = 1.57 \pm 0.20$
P= ±40%	$\delta = 1.57 \pm 0.15$
P= ±100%	$\delta = 1.57 \pm 0.10$

Kinematic cuts can increase sensitivity at high event rates.

Cervera et al.



68, 90 and 99% confidence levels

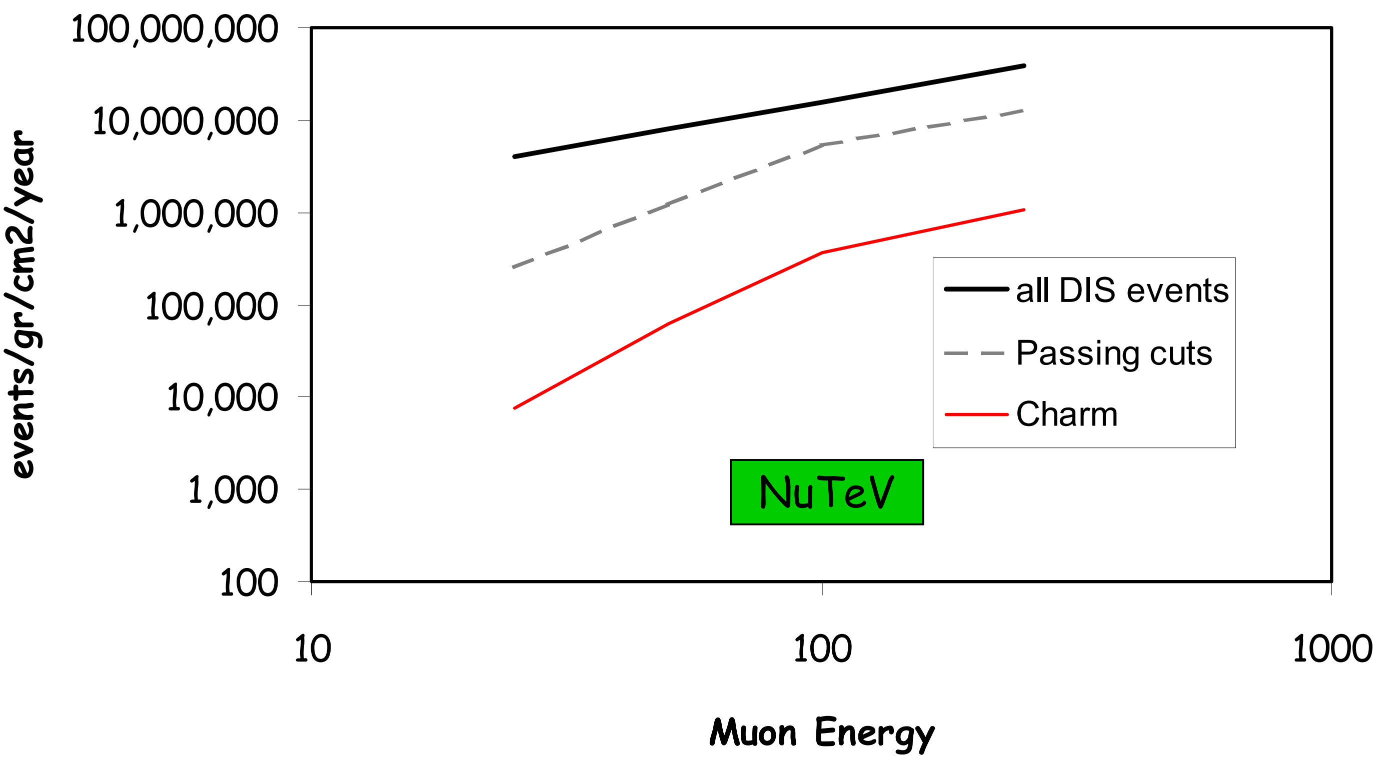


Cervera et al.

Near Experiments

- Place detectors 50 m from end of straight section
- Get 1000 times current statistics!
  - Hydrogen targets
  - Polarized targets
  - Charm
  - Beauty? (not at 50 GeV)
  - Rare phenomena

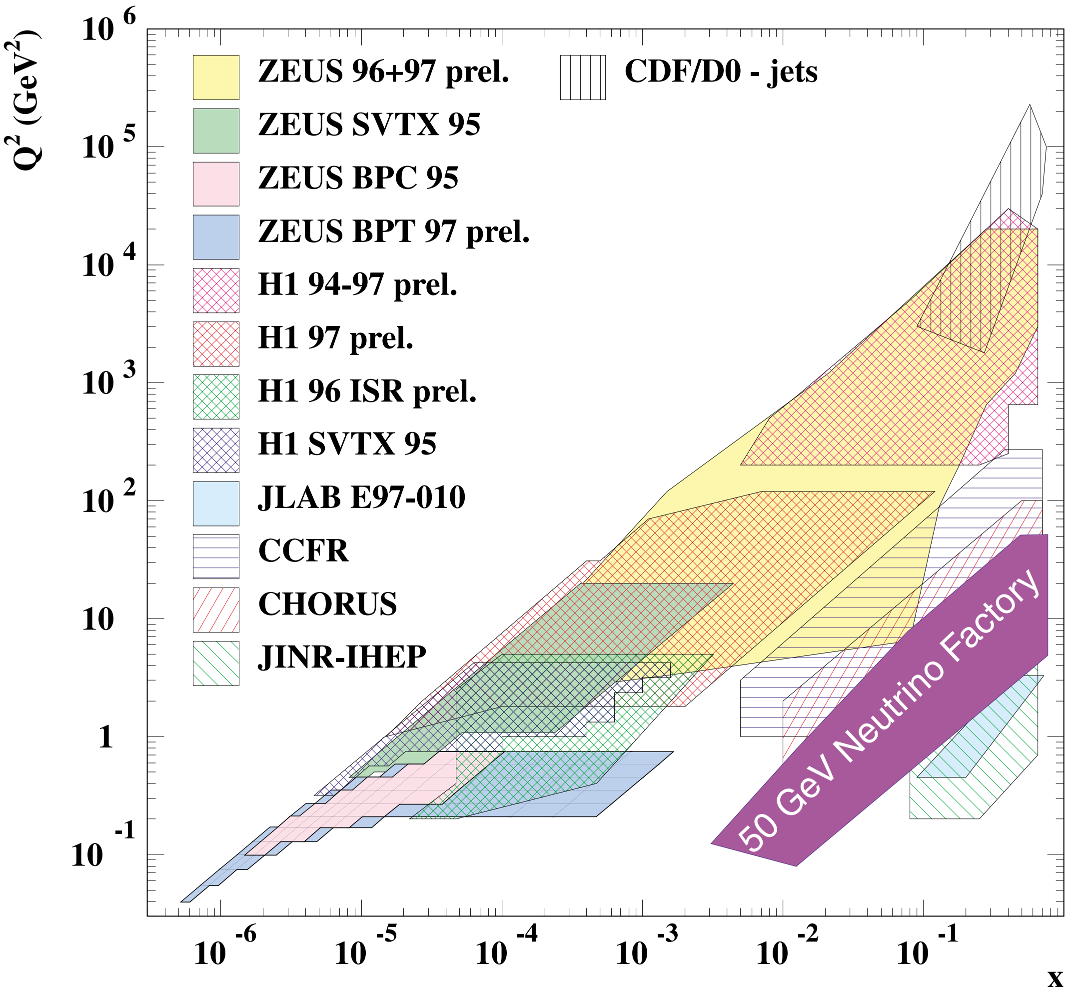
Charged current event rates at near detectors



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

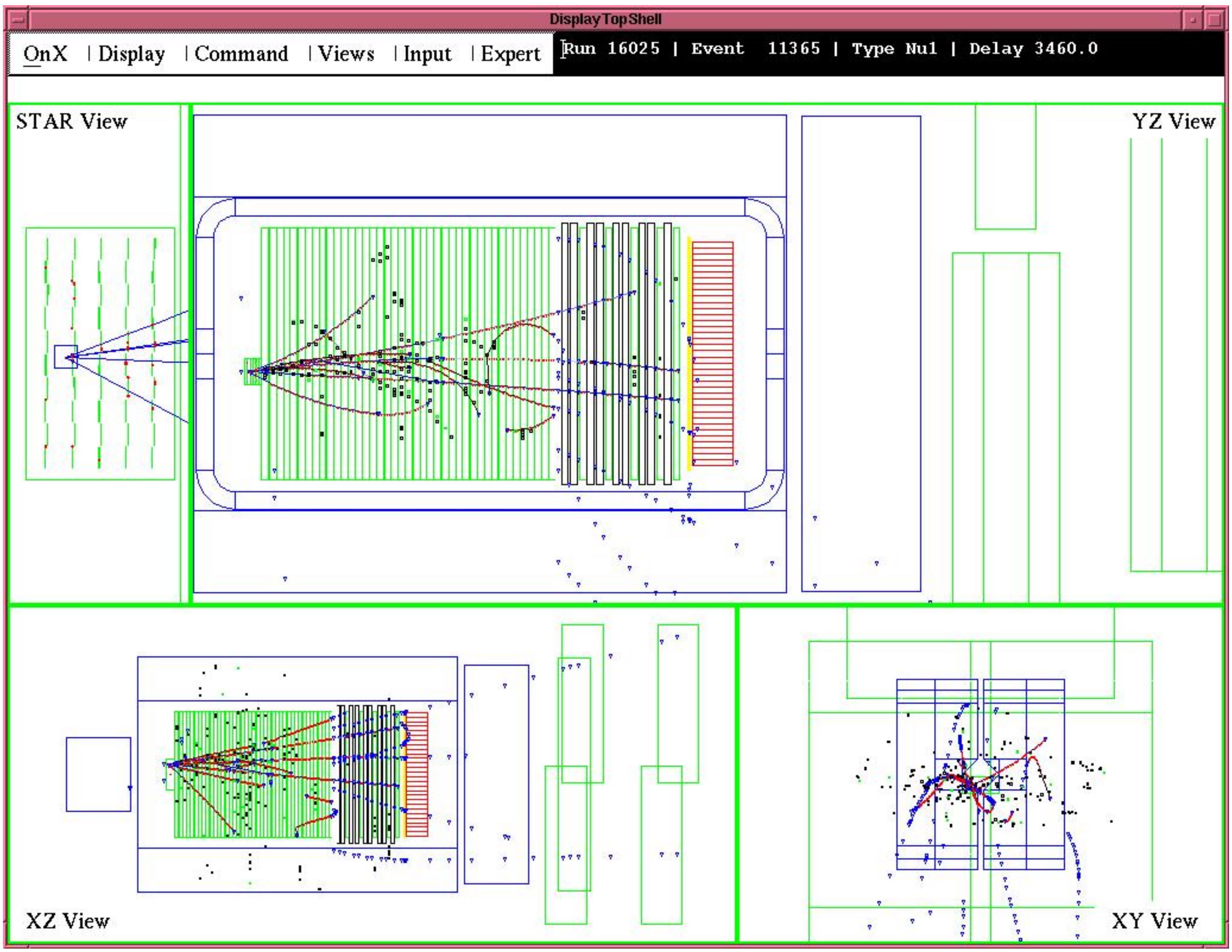
1000 times current experiments!

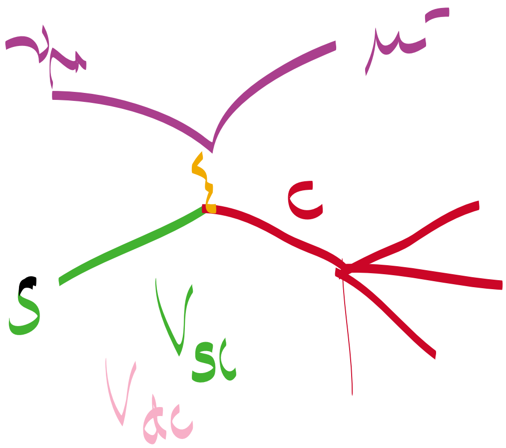
Deep Inelastic Scattering Experiments



Detector like NOMAD

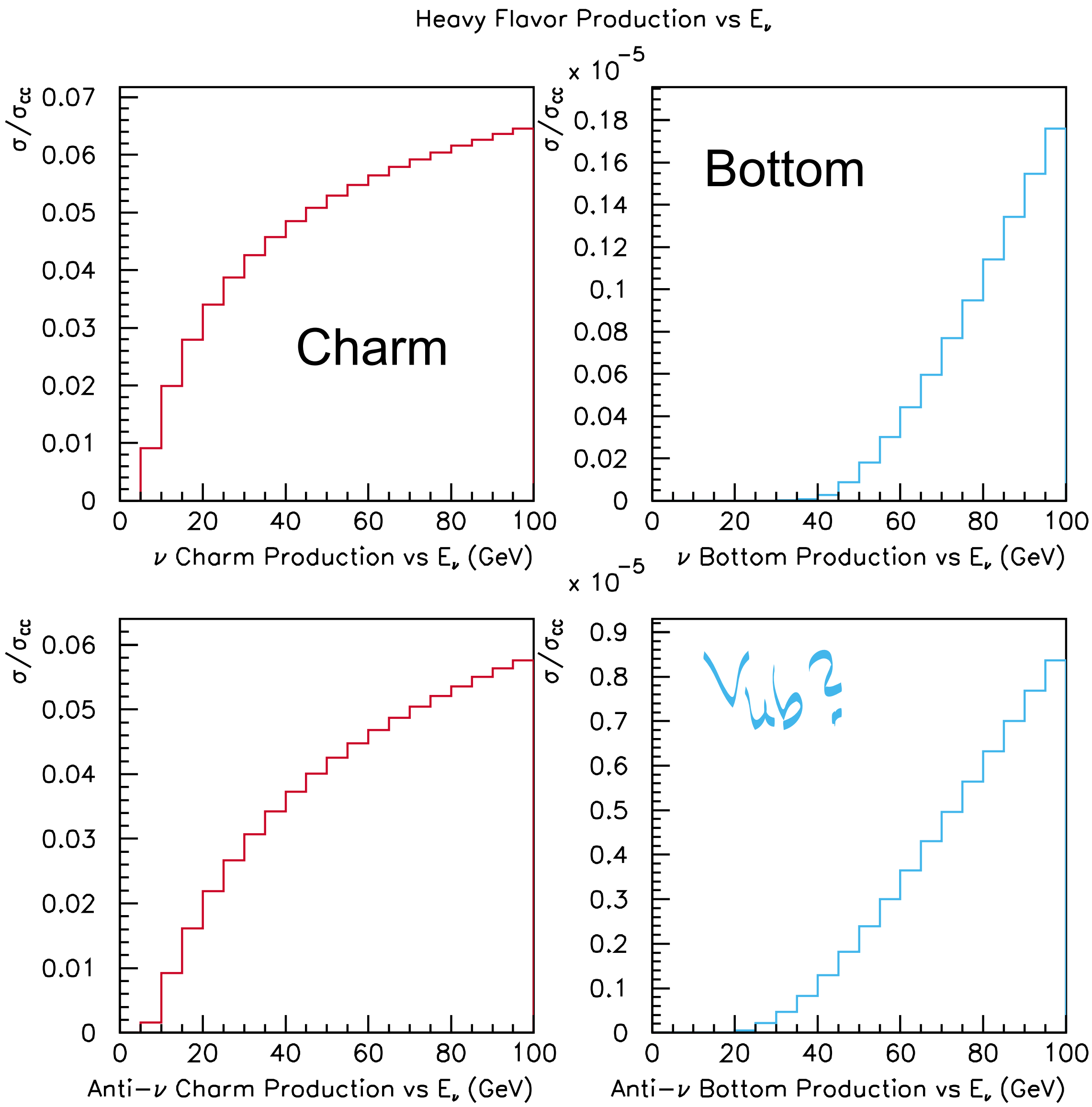
10 kg targets in front of tracking/calorimetry





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

1 ton target
120 M charm



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

(Key: Charge upper right; S = symbol; mass,MeV lower right)

3 Generations of Fermions | Force Carriers

				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

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