DETERMINATION OF NEUTRINO OSCILLATION PARAMETERS AT A NEUTRINO FACTORY

K. Whisnant

Nu Fact '00

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Collaborators: V. Barger, S. Geer, R. Raja

IMPORTANT EXPERIMENTAL PARAMETERS

N # of decaying μ's in straight section

typical designs have 10^{19}–10^{21}

E_μ Energy of decaying μ's

$\mu^- \to e^- \nu_\mu \bar{\nu}_e \qquad \mu^+ \to e^+ \bar{\nu}_\mu \nu_e$

$\langle E_{\nu_\mu} \rangle = 0.7 \langle E_\mu \rangle, \ \langle E_{\nu_e} \rangle = 0.6 \langle E_\mu \rangle$ (unpol. μ's)

typical designs have $E_\mu = 10$–50 GeV

L Baseline distance

S Detector size (10–50 kt for μ's, 1–5 kt for τ's)

Flux in forward direction (beam strongly collimated for $E_\mu \gg m_\mu$)

$$\Phi \simeq \frac{N \left(\frac{E_\mu}{m_\mu}\right)^2}{\pi L^2}$$

$\sigma_{cc}^{\bar{\nu}} \simeq \frac{1}{2} \sigma_{cc}^{\nu} \qquad \sigma \propto E_\nu \propto E_\mu$

$\sigma_{cc}^{\nu_\tau}$ suppressed (τ production threshold $E_\nu = 3.5$ GeV)

Emphasize μ detection ($\nu_\mu \to \nu_\mu$, $\nu_e \to \nu_\mu$)

sign of $\mu \Rightarrow \nu_\mu \to \nu_\mu$ and $\bar{\nu}_e \to \bar{\nu}_\mu$ distinguishable

requires E of detected μ > few GeV

Also consider τ detection ($\nu_\mu \to \nu_\tau$, $\nu_e \to \nu_\tau$)

NEUTRINO EVOLUTION FOR 3 ν's

$$\nu_\alpha = \sum_j U_{\alpha j} \nu_j \qquad \alpha = e, \mu, \tau \qquad j = 1, 2, 3$$

$$i\frac{d\nu_\alpha}{dx} = \sum_\beta \frac{1}{2E_\nu}\left[\delta m^2_{31} U_{\alpha 3} U^*_{\beta 3} + \delta m^2_{21} U_{\alpha 2} U^*_{\beta 2} + A\delta_{\alpha e}\delta_{\beta e}\right]\nu_\beta .$$

$$A = 2\sqrt{2}\, G_F N_e E_\nu = 1.52 \times 10^{-4}\, \mathrm{eV}^2 \left(\frac{N_e}{N_A \cdot \mathrm{cm}^3}\right)\left(\frac{E}{\mathrm{GeV}}\right)$$

Standard parametrization of U $\qquad c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$

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

All calculations done with numerical integration of ν evolution

Use Preliminary Reference Earth Model for density distribution

Strong matter effects for $L \gtrsim 2000$ km

Parameters to determine:

δm^2_{32} , δm^2_{21}

θ_{23}, θ_{12}, θ_{13}

δ

LEADING OSCILLATION (δm^2_{32}, atmos ν's)

In vacuum

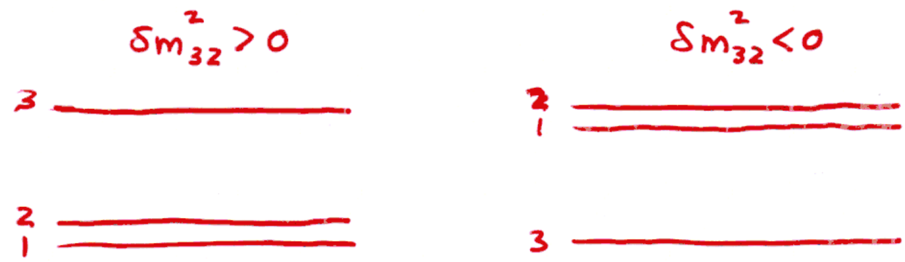
$$P(\nu_e \to \nu_\mu) \simeq \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\, \delta m^2_{32} L/E)$$
$$P(\nu_e \to \nu_\tau) \simeq \cos^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\, \delta m^2_{32} L/E)$$
$$P(\nu_\mu \to \nu_\tau) \simeq \cos^4\theta_{13} \sin^2 2\theta_{23} \sin^2(1.27\, \delta m^2_{32} L/E)$$

δm^2_{32} in eV^2, L in km, E in GeV

$|\delta m^2_{32}| \sim (2 - 5) \times 10^{-3}\, eV^2$

$\sin^2 2\theta_{23} \sim 0.88 - 1.00$

$\sin^2 2\theta_{13}$ – determines amount of $\nu_\mu \to \nu_e$ in atmos. (small)



$\overset{(-)}{\nu_e} \to \overset{(-)}{\nu_\mu}$ rates sensitive to $\mathrm{sgn}(\delta m^2_{32})$ for large L and $\sin^2 2\theta_{13}$ not too smal

GOALS FOR ν FACTORY:

- Better measurements of δm^2_{32}, θ_{23}
- Measure or put upper bound on θ_{13}
- Determine $\mathrm{sgn}(\delta m^2_{32})$ through matter effects

SUBLEADING OSCILLATION (δm^2_{21}, solar ν's)

In vacuum $P(\nu_e \to \nu_e) \simeq 1 - \frac{1}{2}\sin^2 2\theta_{13} - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(1.27\,\delta m^2_{21} L/E)$

	Vacuum	Small angle MSW	Large angle MSW
δm^2_{21} (eV^2)	10^{-10}	10^{-5}	10^{-5}–10^{-4}
$\sin^2 2\theta_{12}$	0.6–1.0	0.01	0.5–1.0

δ not determined from solar measurements
(no CP violation in diagonal channel)

GOALS FOR ν FACTORY:

- See evidence for subleading osc. in $\nu_e \to \nu_\mu$ (visible even if $\theta_{13} = 0$?)
- Determine existence of CP violation ($\delta \neq 0$)

What luminosity/size needed to achieve each of these goals?
Which goals are possible even for a modest, entry-level machine?

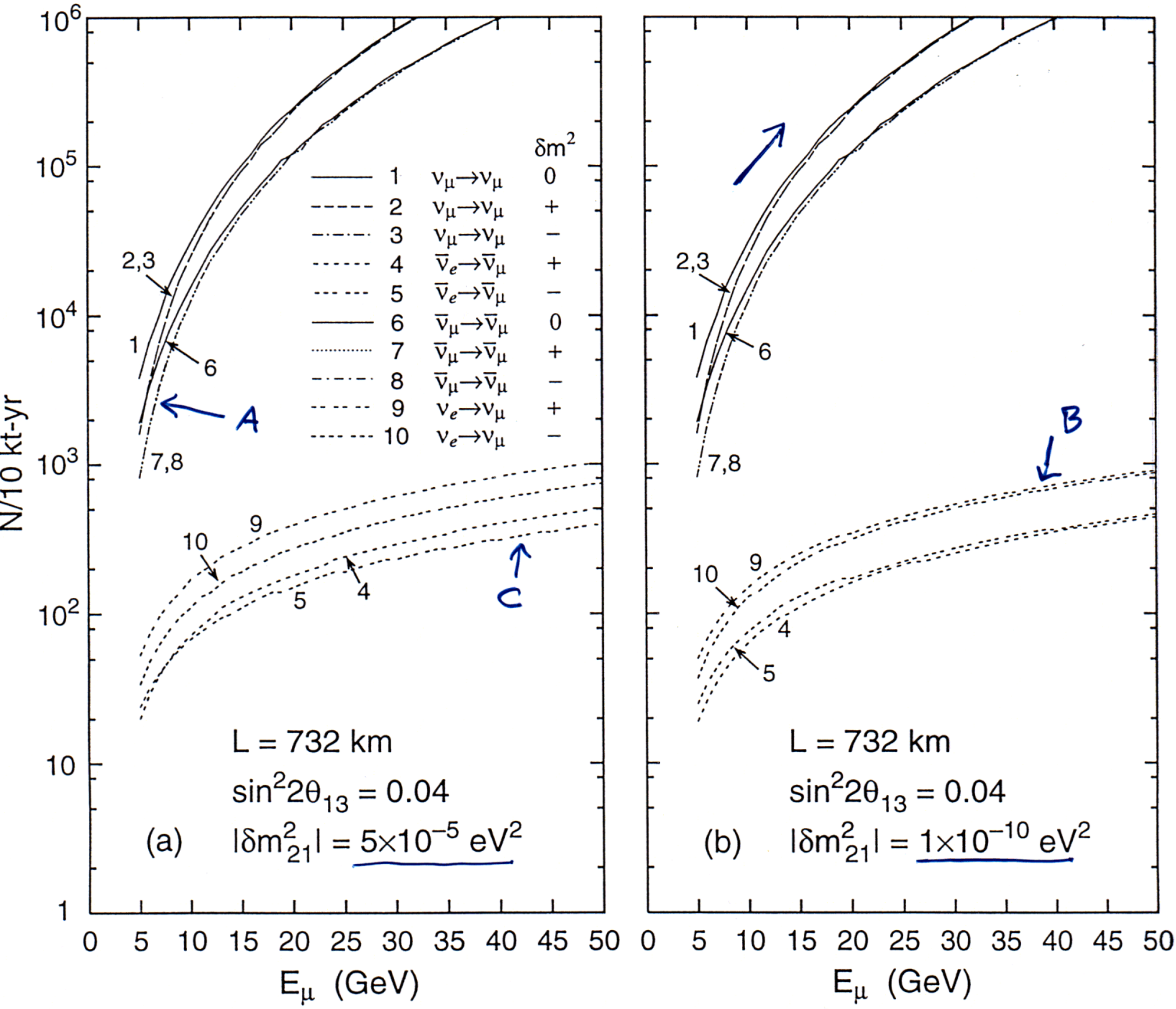
Default Scenario: 1A1 of Fermilab Study

$|\delta m^2_{32}| = 3.5\times 10^{-3}\,eV^2$ $\quad \sin^2 2\theta_{23} = 1.0$ (atmos)

$\delta m^2_{21} = 5\times 10^{-5}\,eV^2$ $\quad \sin^2 2\theta_{12} = 0.8$ (LAM)

$\delta = 0$ (CP) $\quad \sin^2 2\theta_{13} = 0.04$ (ν_e in atmos)

"SHORT" L $\qquad$ $2 \times 10^{20}\ \mu^{\pm}$

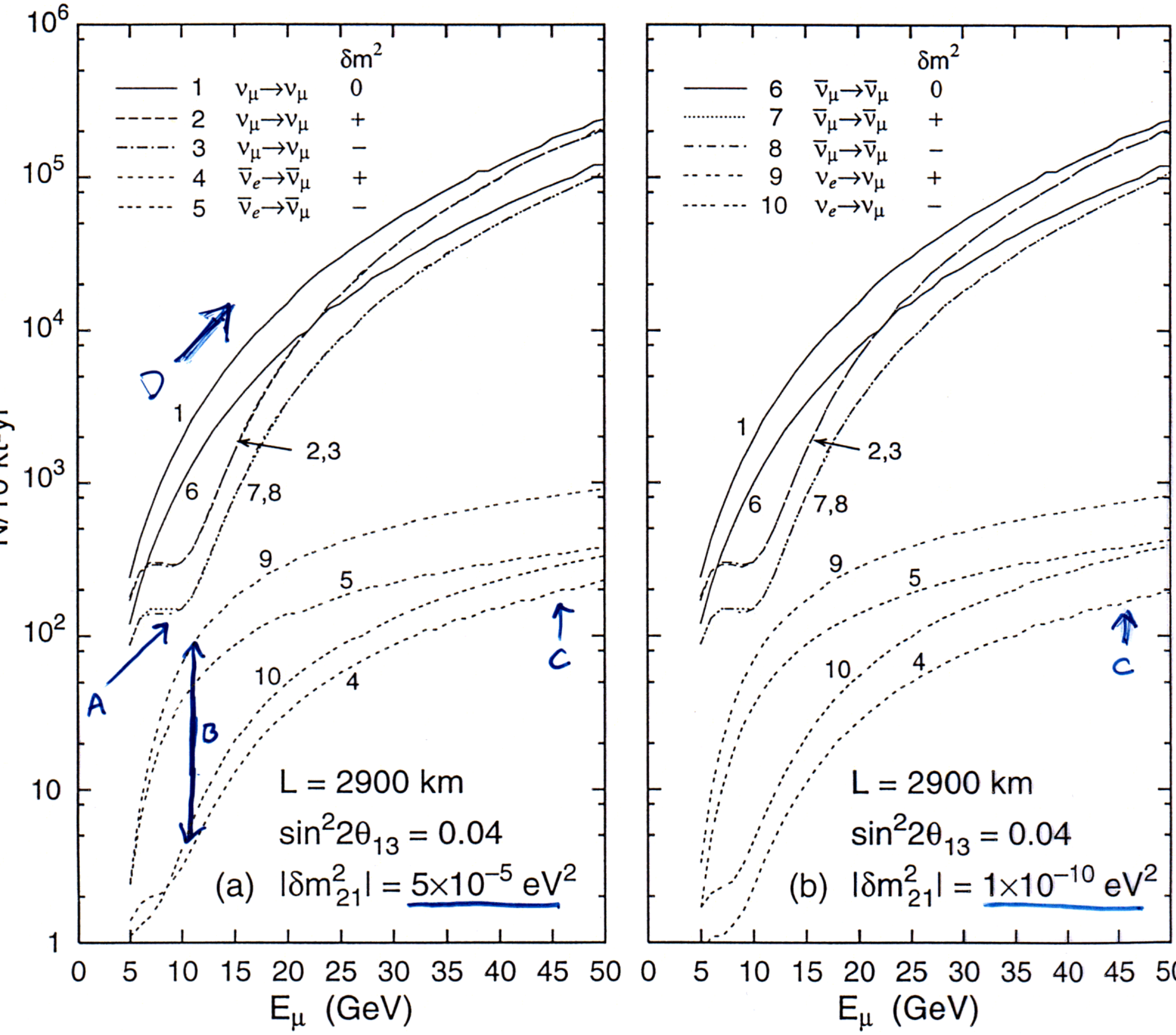


A $\quad \nu_\mu \to \nu_\mu$ osc. not well-developed $\qquad$ D Larger $E_\mu \Rightarrow$ larger rates

B $\quad$ Matter effects small (little dependence on $\mathrm{sgn}(\delta m^2_{32})$)

C $\quad$ Subleading scale effects (for LAM)

"MEDIUM" L



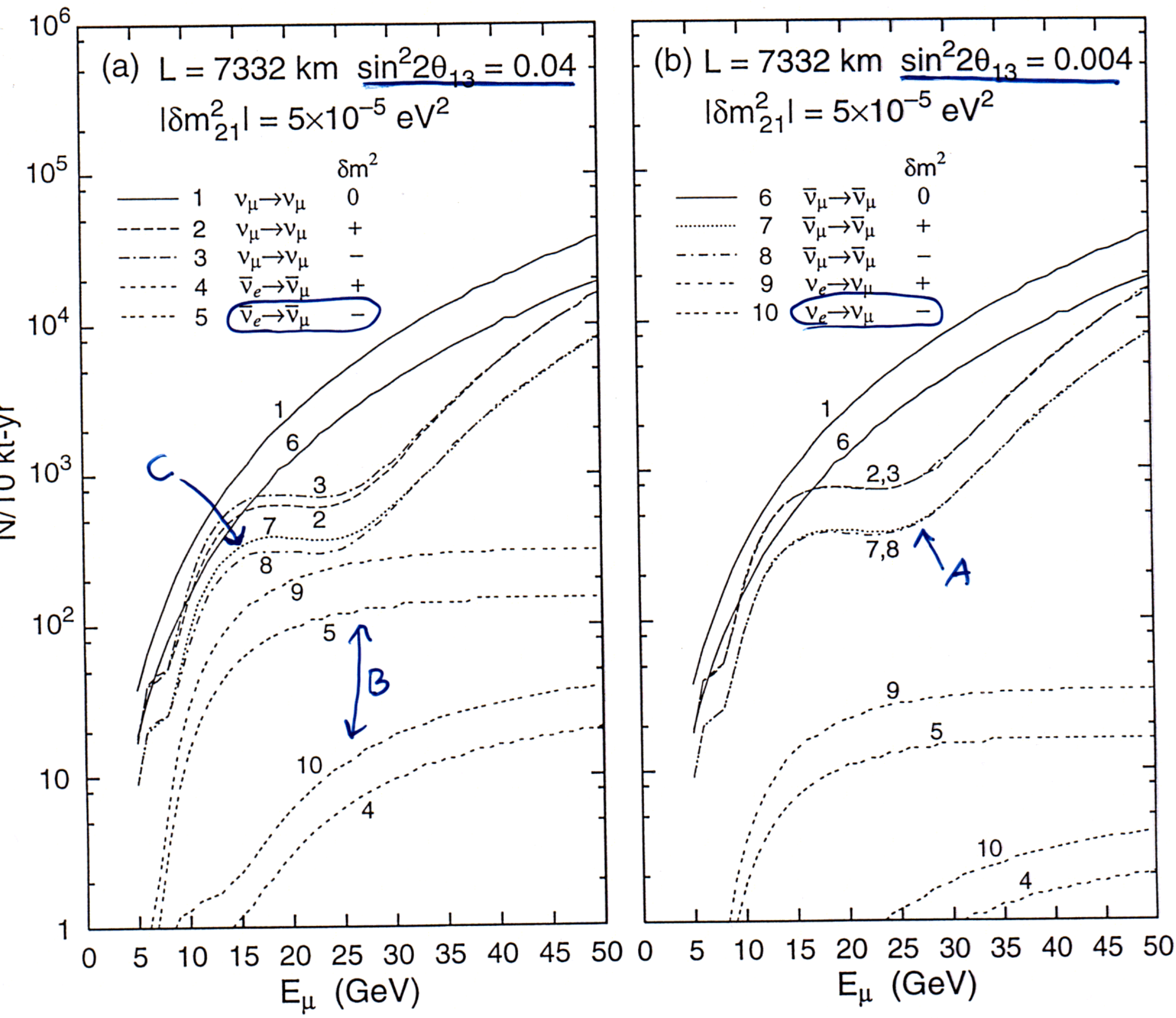
A Significant suppression of $\nu_\mu \to \nu_\mu$ at lower E_μ

B $\nu_e \to \nu_\mu$ sensitive to $\mathrm{sgn}(\delta m^2_{32})$ due to matter effects

C Subleading osc. has smaller relative effect than at $L = 732$ km

D Rates higher at higher E_ν

"LONG" L



A Significant suppression of $\nu_\mu \to \nu_\mu$ at higher E_μ

B $\nu_e \to \nu_\mu$ very sensitive to $\mathrm{sgn}(\delta m^2_{32})$

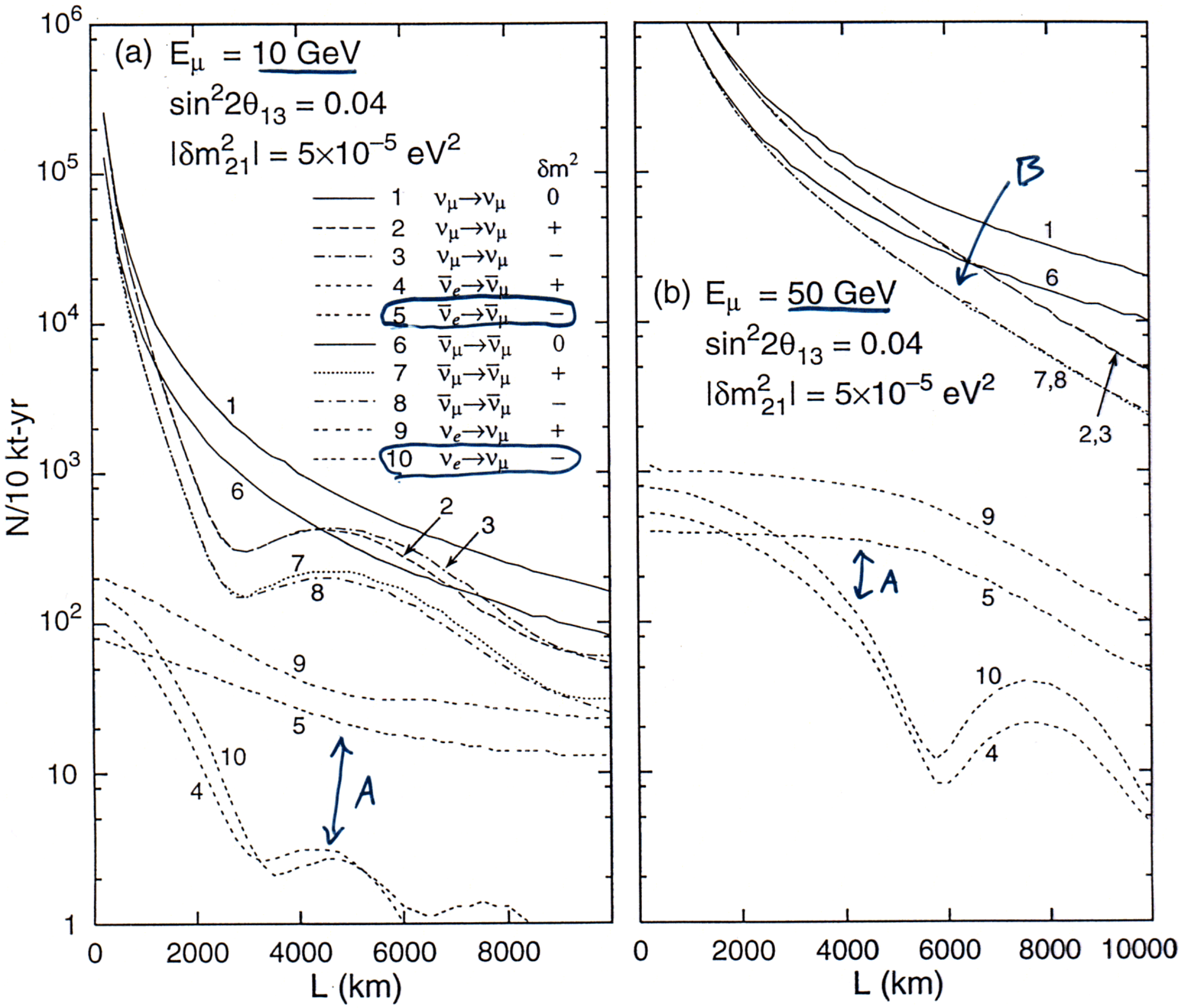
C $\nu_\mu \to \nu_\mu$ somewhat sensitive to $\mathrm{sgn}(\delta m^2_{32})$ for $\sin^2 2\theta_{13} > 0.01$

D Insensitive to subleading osc.

E overall rates lowe

F Higher $E_\mu \Rightarrow$ higher rate

Matter effects increase with L

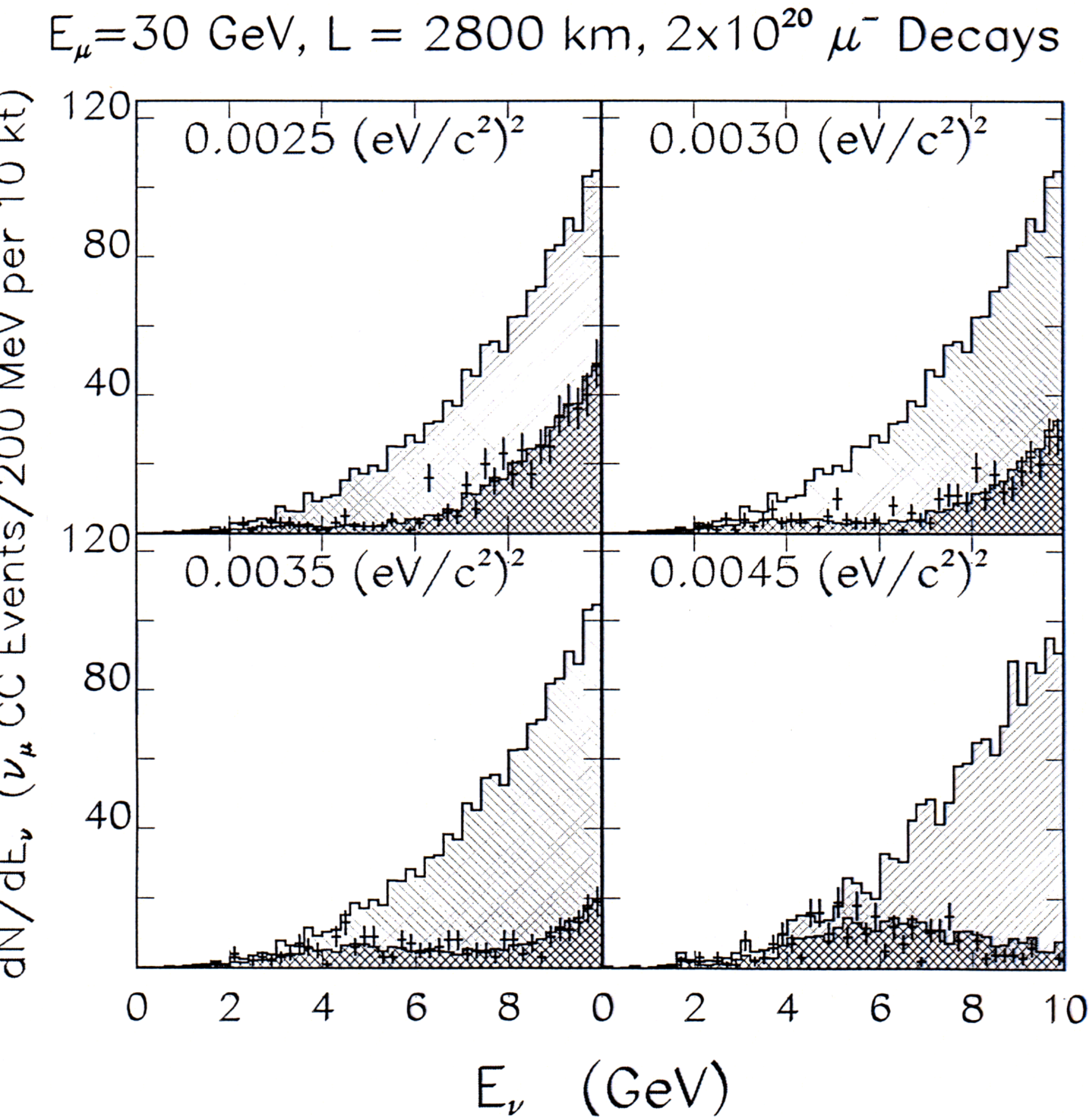


A Matter effects (separation of $\nu_e\to\nu_\mu$ and $\bar\nu_e\to\bar\nu_\mu$) turn on as L increases

B $\nu_\mu\to\nu_\mu$ suppression less at high E_μ

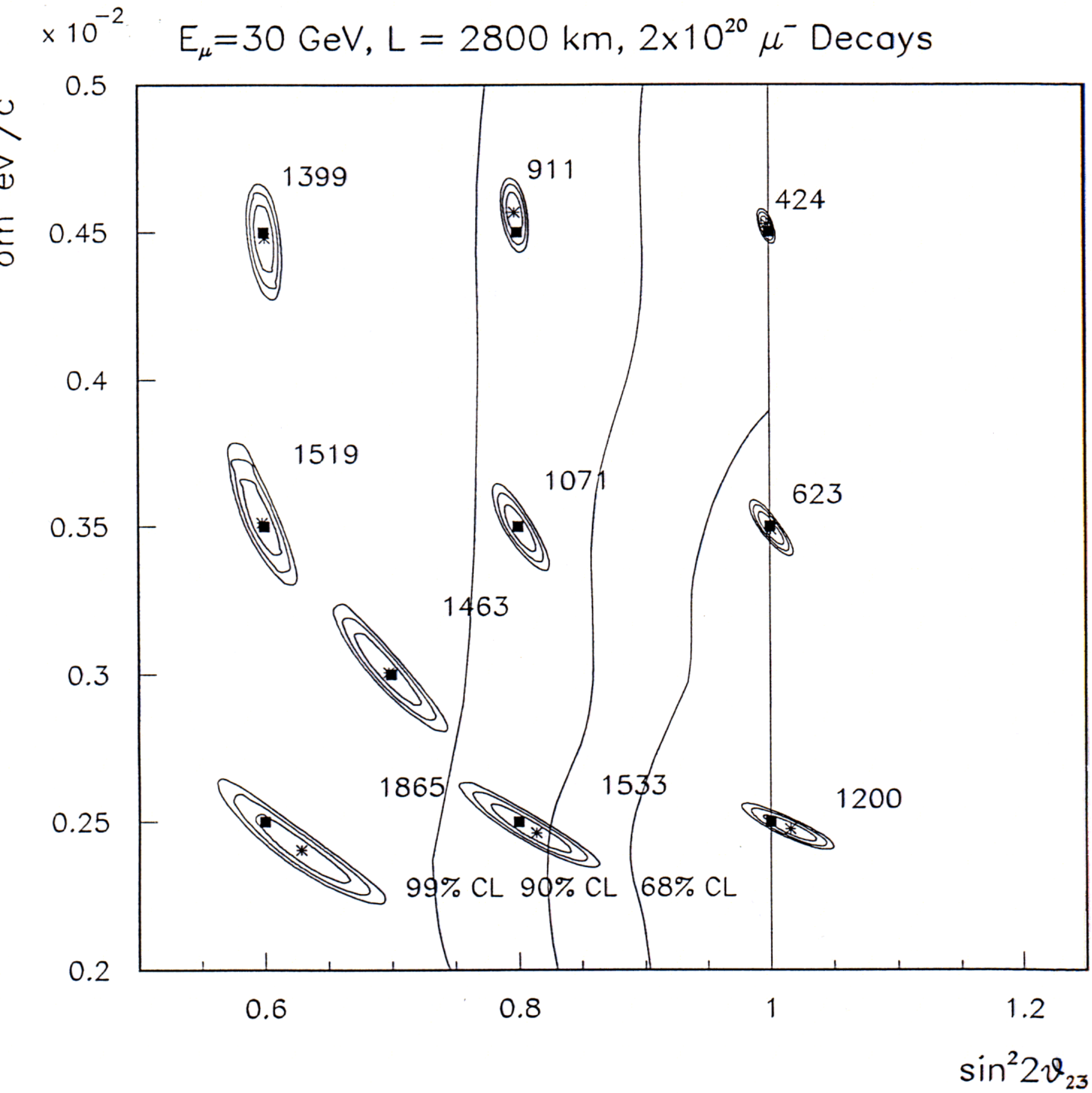
δm^2_{32} affects shape of $\nu_\mu \to \nu_\mu$ suppression

$\sin^2 2\theta_{23}$ affects amount of $\nu_\mu \to \nu_\mu$ suppression

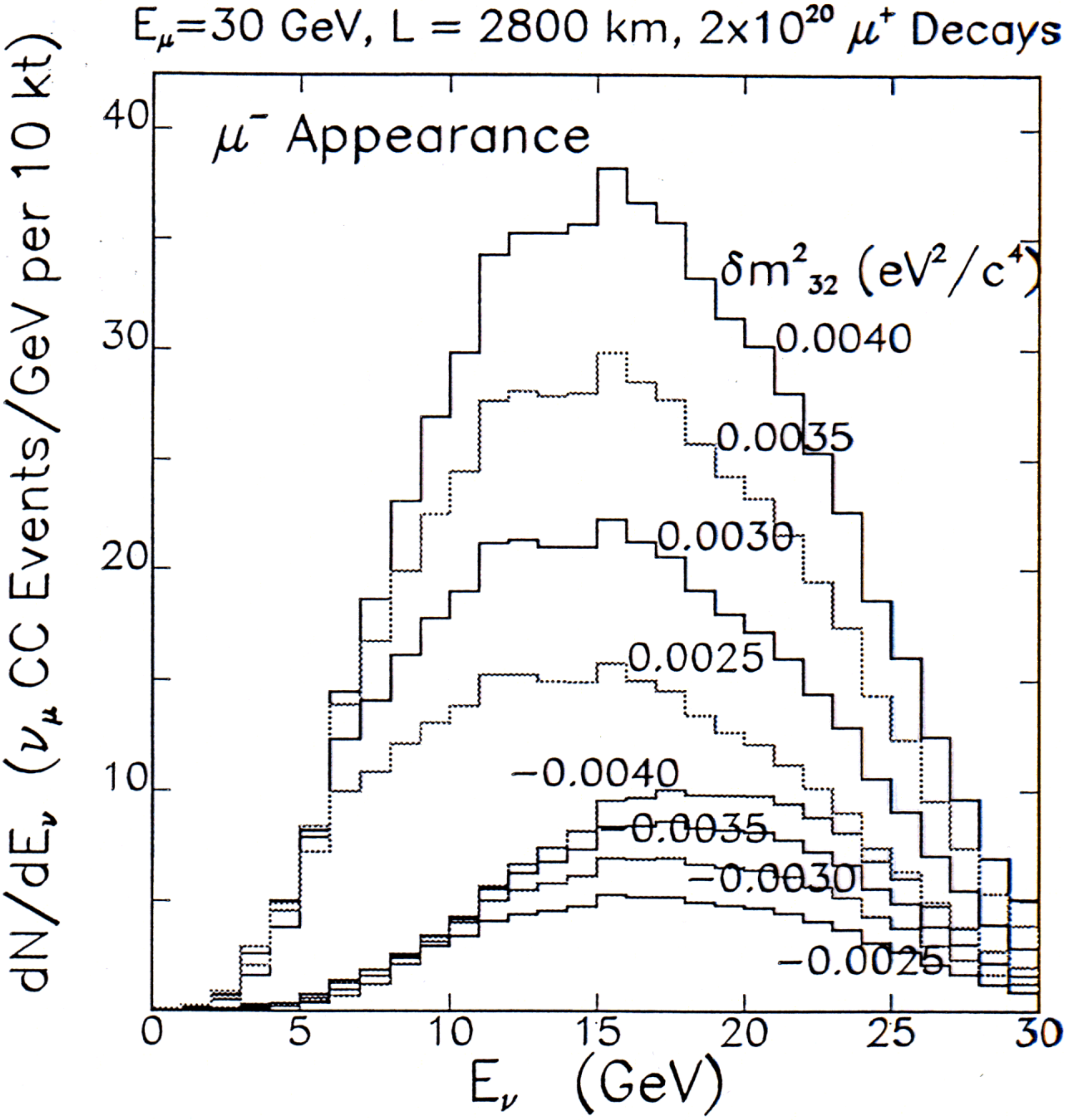


$\nu_\mu \rightarrow \nu_\mu$

Fit to δm^2_{32} and $\sin^2 2\theta_{23}$



$\nu_e \rightarrow \nu_\mu$ sensitive to $\mathrm{sgn}(\delta m^2_{32})$



Summary of Leading Oscillation Measurements

L (km)	E_μ (GeV)	$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$: δm^2_{32}	$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$: $\sin^2 2\theta_{23}$	$\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_\mu$: $\sin^2 2\theta_{13}$	$\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_\mu$: 3σ sgn(δm^2_{32})
732	10	6.7%	7.6%	.002	>0.1
	30	8.9%	14%	.0005	0.1
	50	12%	17%	.0003	>0.1
2800	10	2.4%	1.1%	.008	0.1
	30	3.2%	2.0%	.0007	.005
	50	4.9%	1.8%	.0004	.003
7332	10	6.3%	13%	.02	>0.1
	30	1.2%	0.57%	.001	.04
	50	1.4%	0.64%	.002	.02

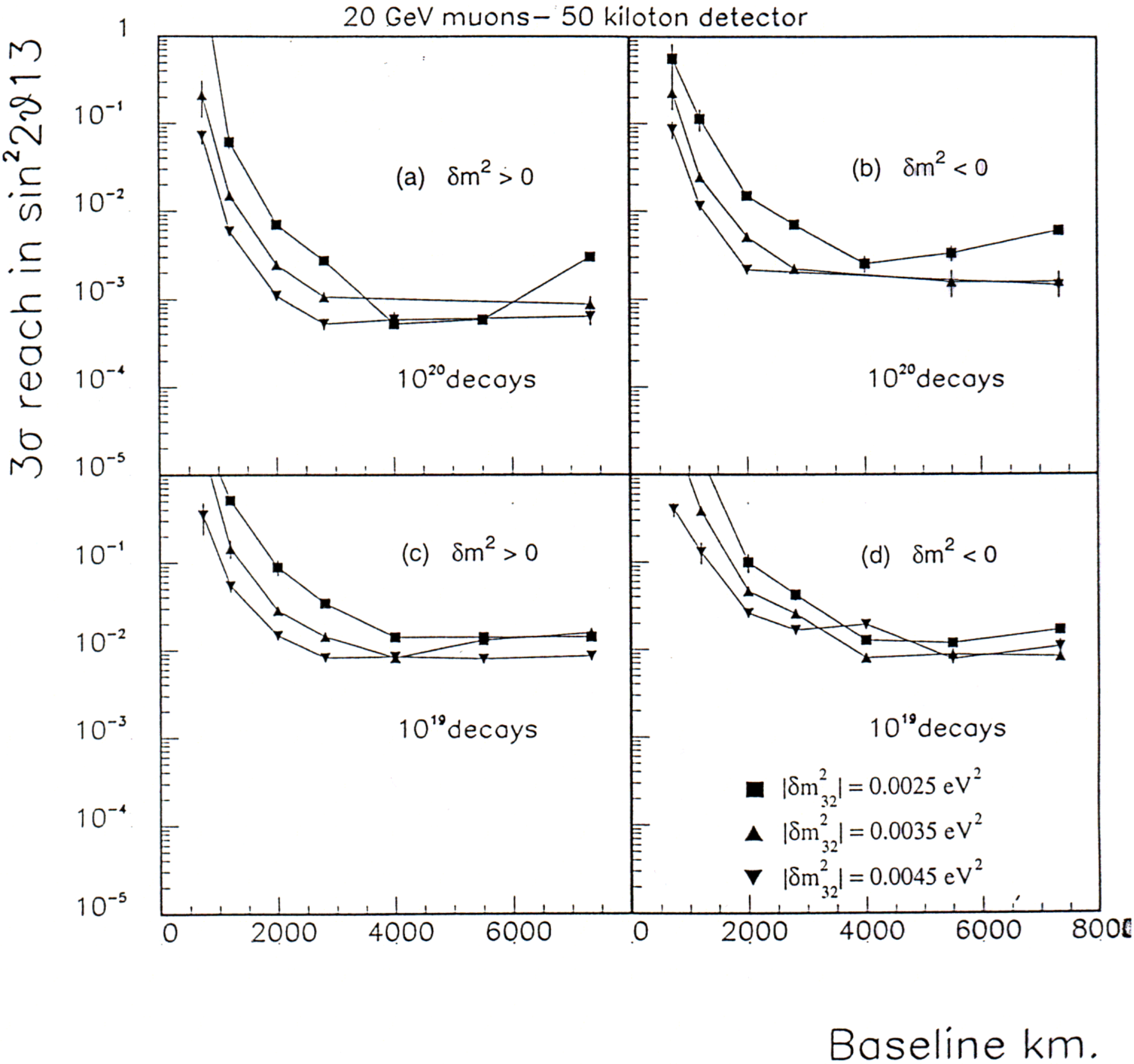
7332 best for large enough E_μ

2800 probably best after backgrounds added

$\nu_\mu \to \nu_\mu$ and $\bar{\nu}_e \to \bar{\nu}_\mu$ combined fit

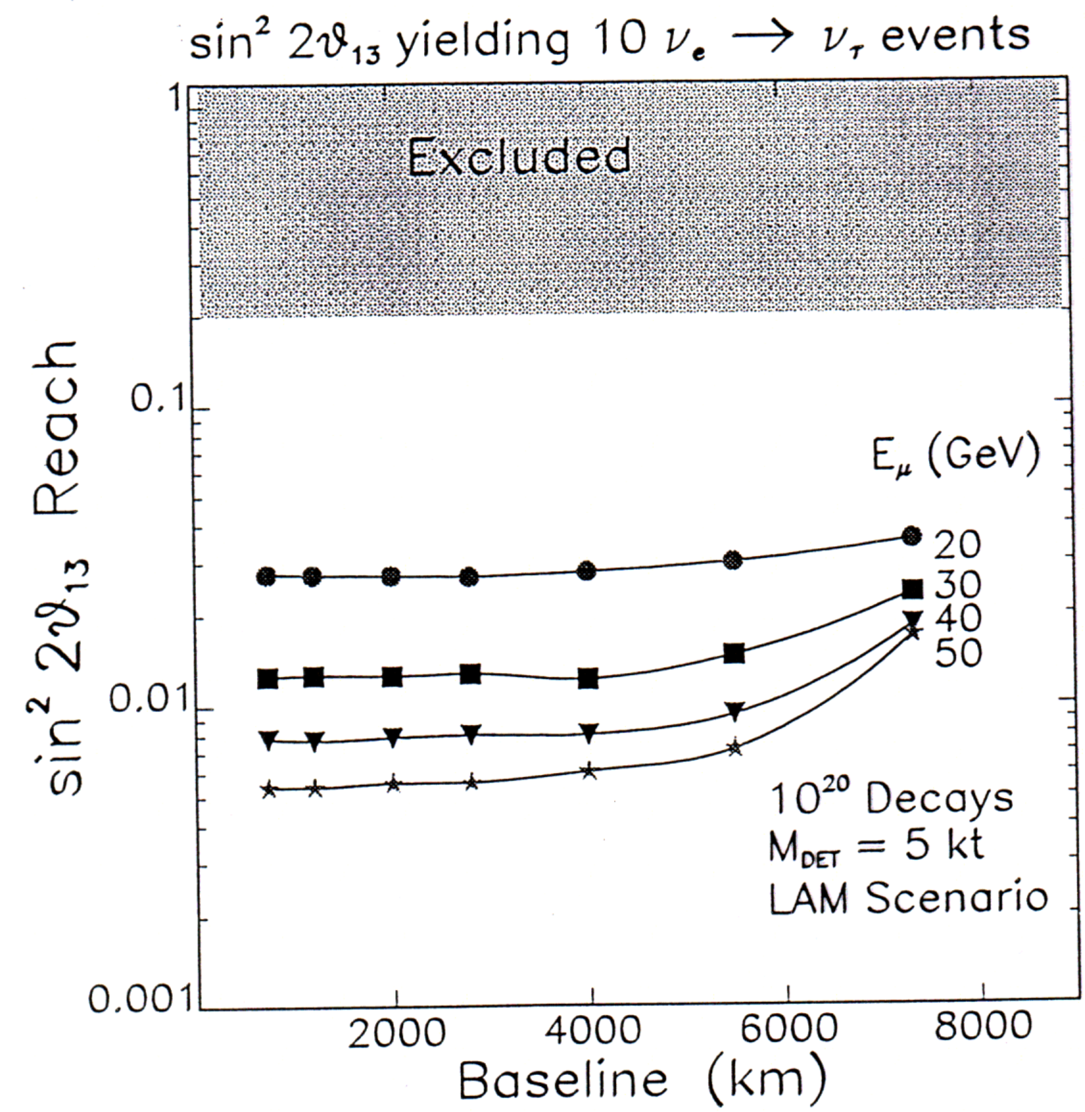
$\mathrm{sgn}(\delta m^2_{32})$

improvement over $\nu_e \to \nu_\mu$ alone



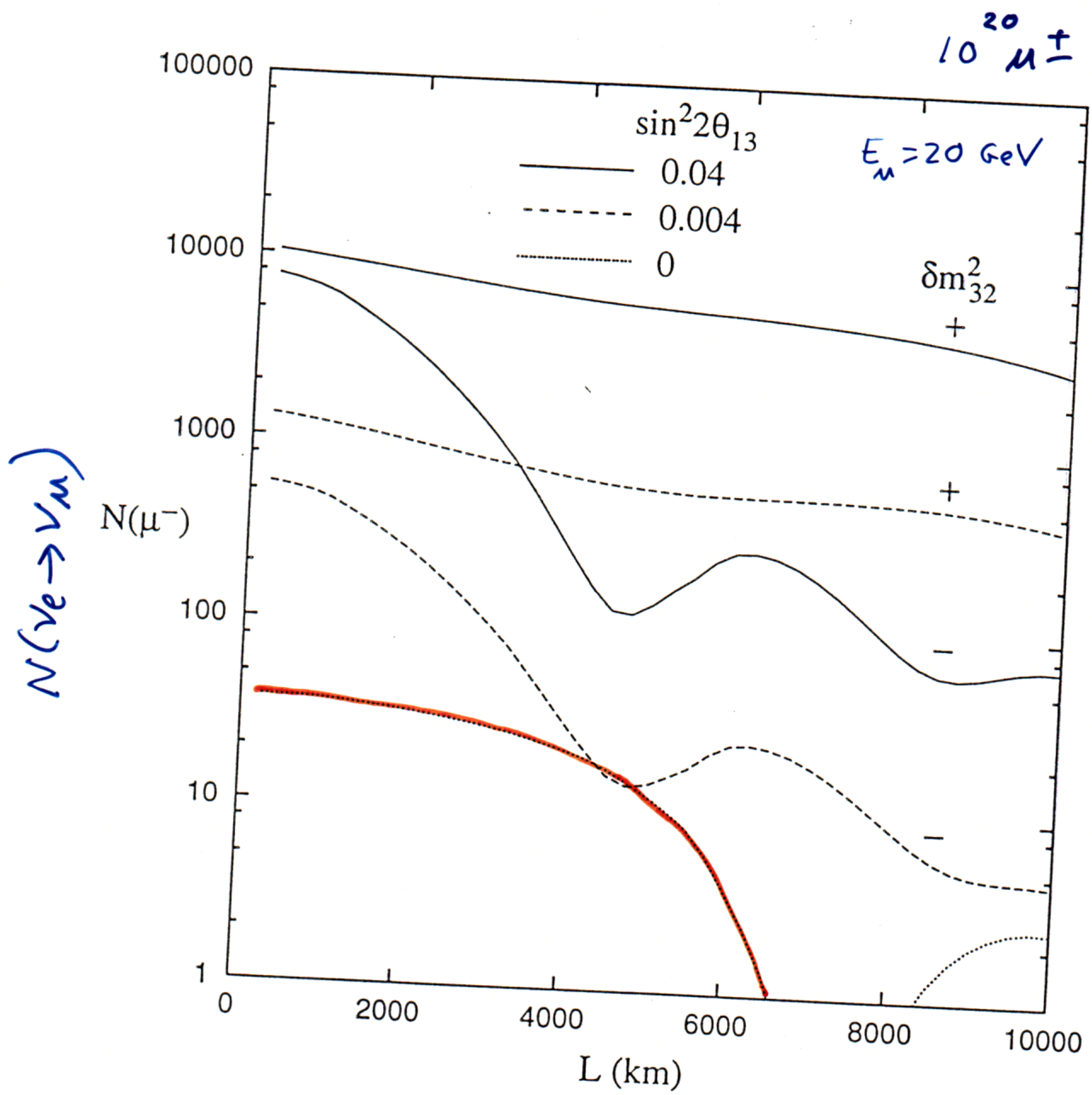
$\nu_e \to \nu_\tau$

Test θ_{13}



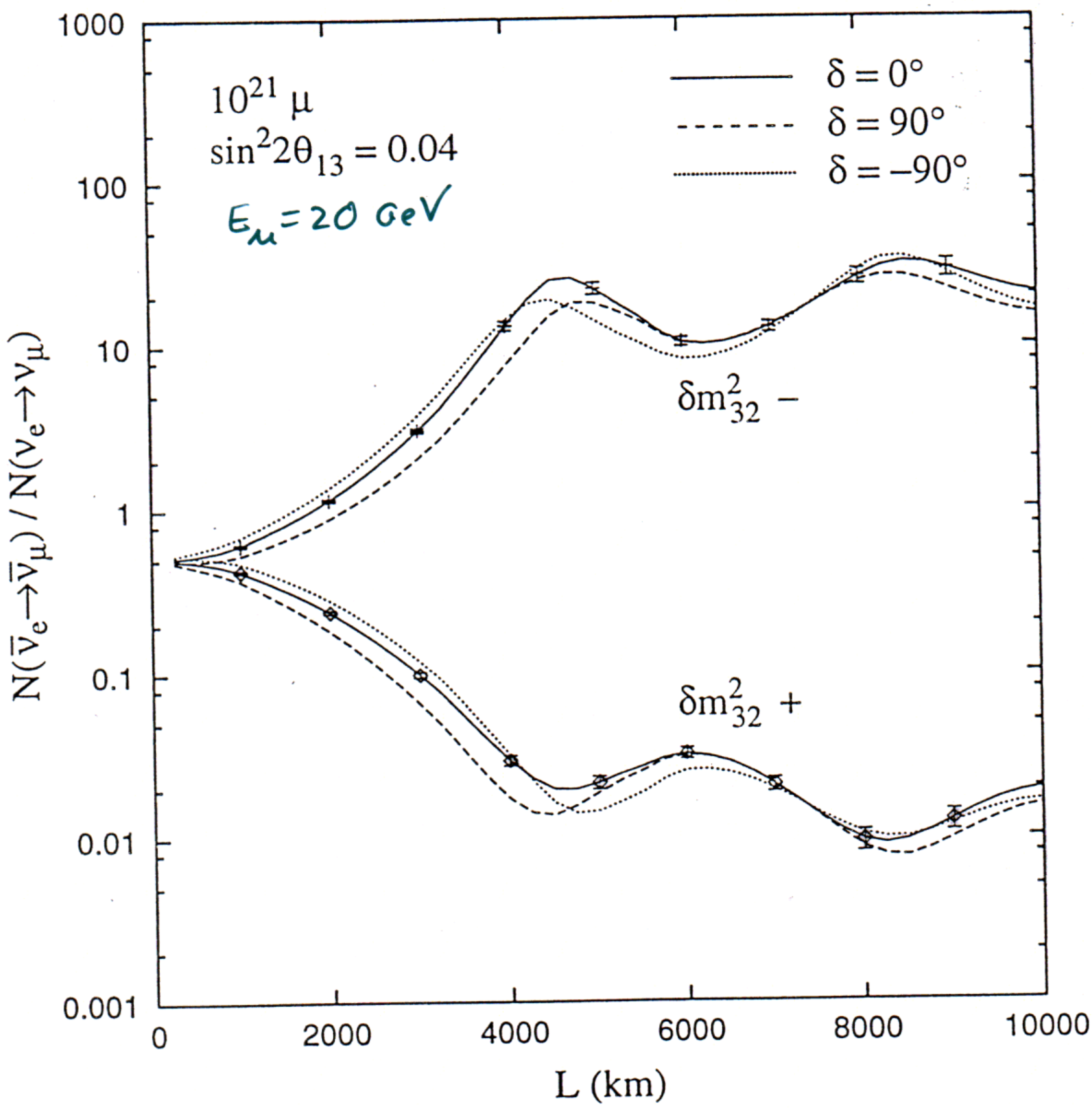
What if $\theta_{13} = 0$? (Bimaximal, Democratic)

Still sensitive to subleading (for LAM only, $L \leq 4000$ km)

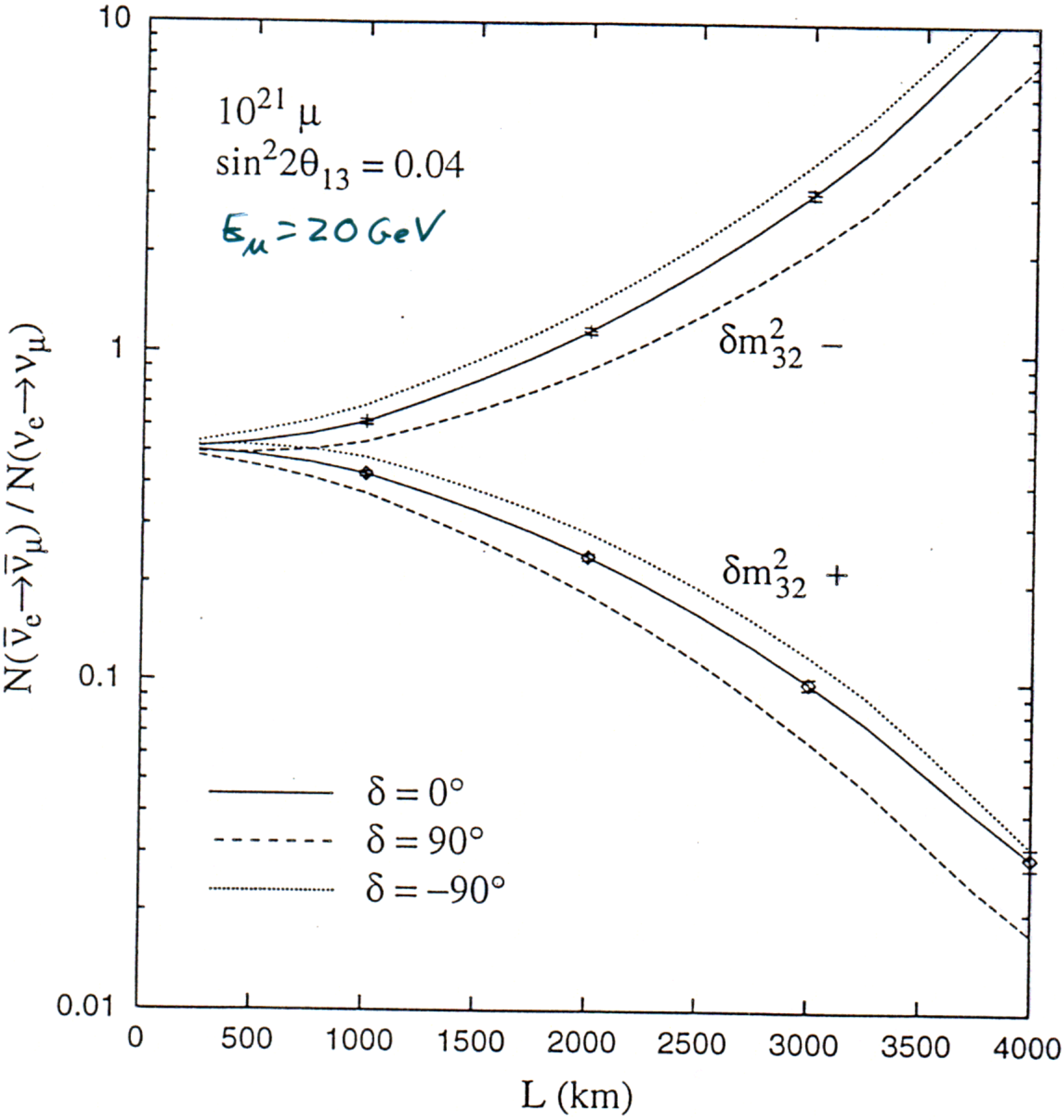


CP Violation

Compare $\bar{\nu}_e \to \bar{\nu}_\mu$ with $\nu_e \to \nu_\mu$

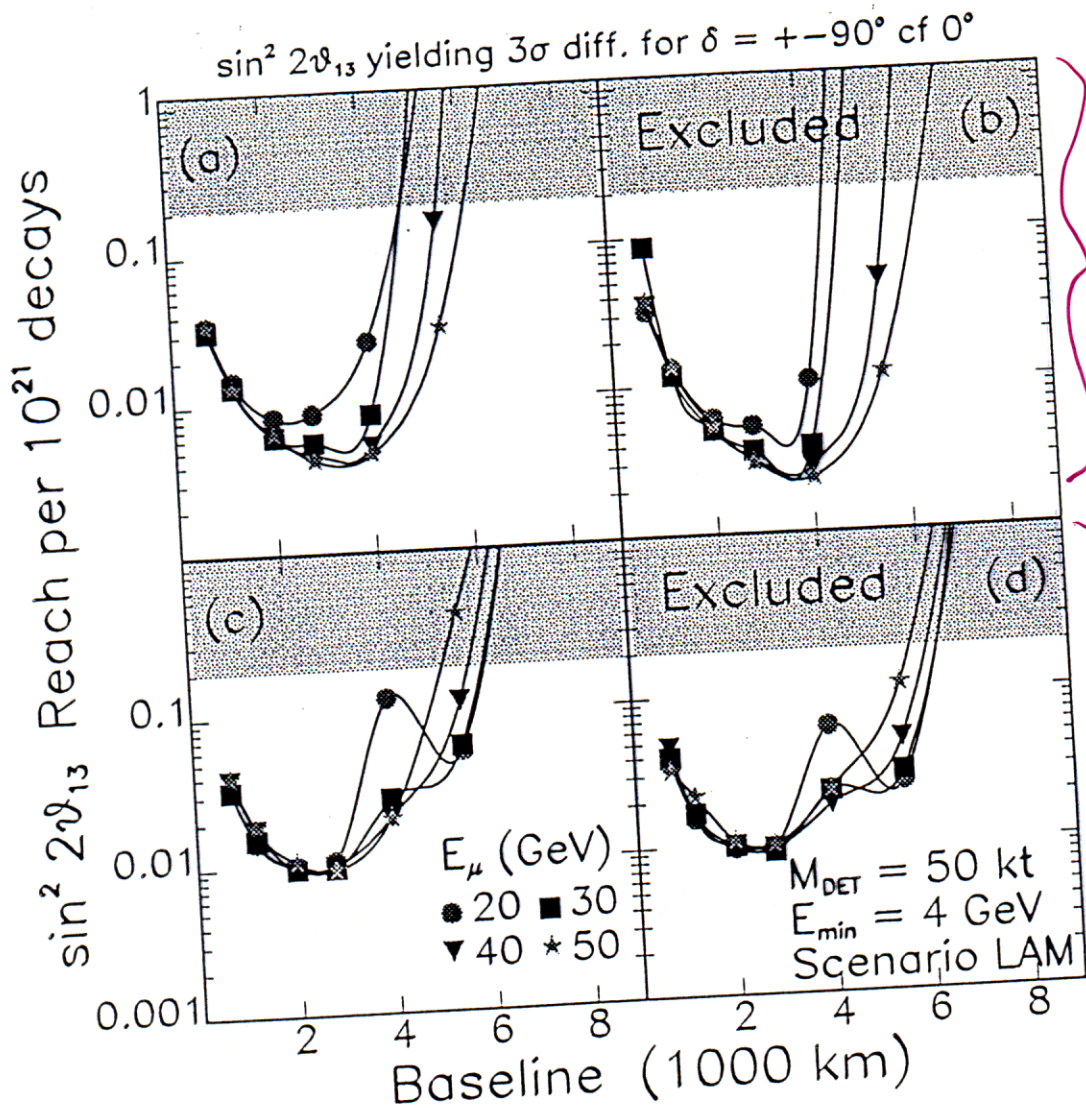


Most sensitive for 2000 km $\leq L \leq$ 4000 km



10^{21} μ
$\sin^2 2\theta_{13} = 0.04$
$E_\mu = 20$ GeV
δm^2_{32} −
δm^2_{32} +
$\delta = 0°$
$\delta = 90°$
$\delta = -90°$
$N(\bar{\nu}_e \to \bar{\nu}_\mu) / N(\nu_e \to \nu_\mu)$
L (km)
10
1
0.1
0.01
0
500
1000
1500
2000
2500
3000
3500
4000

Sensitivity to CPV



distinguish $\delta = 0$ vs. $\delta = \pi/2$

distinguish $\delta = 0$ vs. $\delta = -\pi/2$

$2000\text{ km} \leq L \leq 4000\text{ km}$ preferred

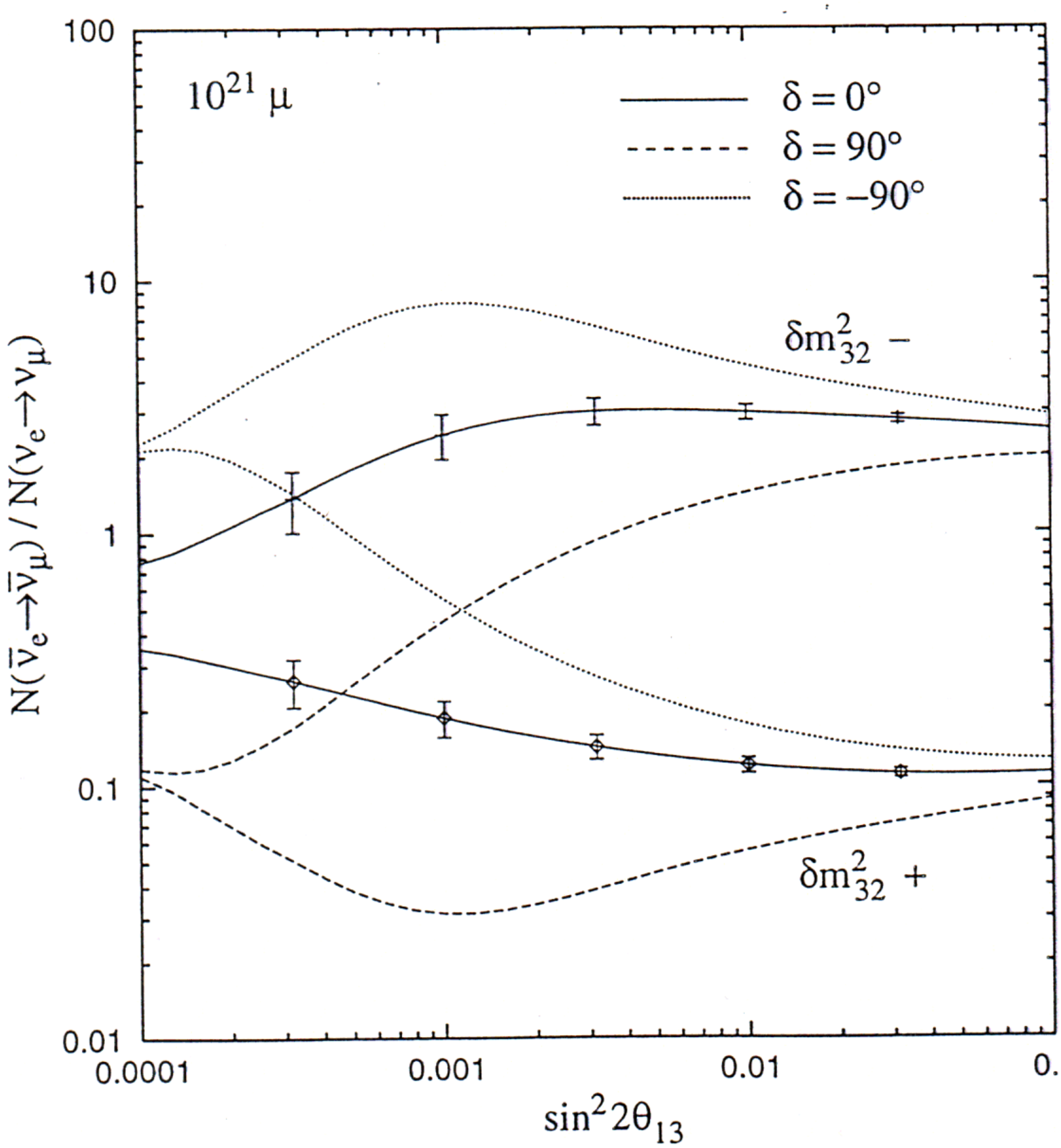
Matter vs. CPV

$L = 2900$ km

$E_\mu = 20$ GeV

50 kt

CPV dominates for small θ_{13}



matter dominates for large θ_{13}

RATINGS OF PHYSICS CAPABILITIES (SUBJECTIVE)

	L (km) <1000	L (km) 2000–4000	L (km) >6000	
δm^2_{32}, θ_{23}	*	**	***	"guaranteed"
θ_{13} from $\nu_e \to \nu_\mu$	***	**	**	Depends on U_{e3}
θ_{13} from $\nu_e \to \nu_\tau$	***	***	**	Depends on U_{e3}
sgn(δm^2_{32})	$\frac{1}{2}$*	***	**	Depends on U_{e3}
subleading	***	**		LAM only
CPV	*	***		LAM only

$E_\mu = 20$ GeV sufficient for most measurements

Higher E_μ improves sensitivity in many cases (esp. appearance)

N's (kt-μ's)		
	10^{20}	for δm^2_{32}, θ_{23}, θ_{13} from $\nu_e \to \nu_\mu$, sgn(δm^2_{32})
	2×10^{20}	for θ_{13} from $\nu_e \to \nu_\tau$
	10^{22}	subleading + CPV