Neutrino Oscillation Physics
WG1 Summary
(Experimental)

- R Bernstein
FNAL
NuFact 00

Three Groups

"Spanish"	Fe/Scint	Cervera
ICANOE	LAr	Campanelli
FNAL	Fe/Scint	RHB

Plus

H_2O	Casper (SuperK)	
MONOLITH	Geiser	} Fe/Scint
NuTest	Santin	

- Consensus on Goals, Future Work
- Disagreement on Methods

Areas of Consensus

a) Highest Energy Best

b) H_2O is Promising!

c) Overall Goals

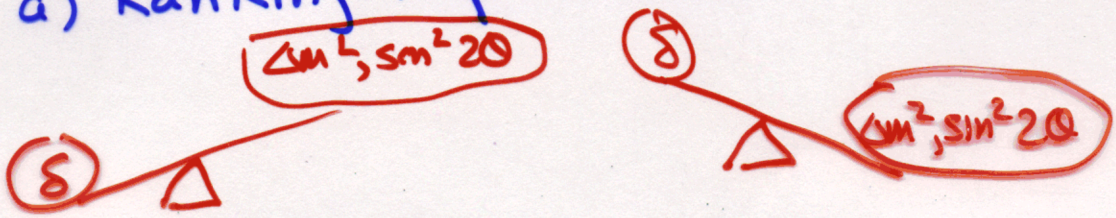
Δm^2_{23} $\sin^2 2\theta_{13}$

$\sin^2 2\theta_{23}$ δ

d) Future Work for Each Group

Areas of Disagreement

a) Ranking Physics Goals



Iron Pyrite of the ν Factory?

"New SeeSaw"

⇒ What is the best baseline?

a) 1000 km too short

⇒ b) 3000 or 7000 km ⇐

New Emphasis on Systematic Errors

a) Flux is a Four-Letter Word (Dave Finley)

i) heard at beginning:

"we can do << 1% for sure"

"we can't do < 1% for sure"

ii) heard at end:

"we can do << 1% for sure"

"we can't do < 1% for sure"

(+) "we should tell machine people they must do less than 1%"

- progress! A new position on the issue...

b) Backgrounds

Spanish / FNAL Groups

- agree on levels

- don't agree on resolutions

⟹ good place for more work + collaboration

Why Do We Care?

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

$$= \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \Delta m^2_{23} \frac{L}{E}$$

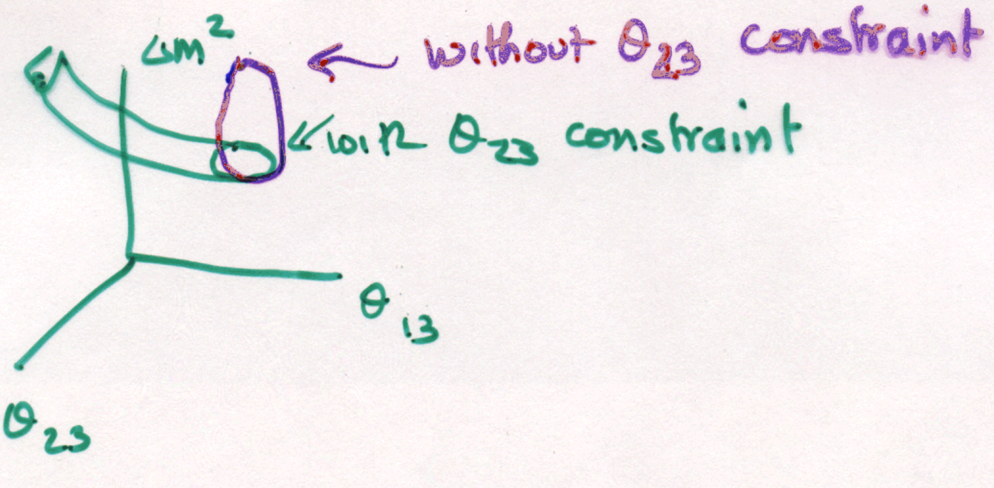
$\pm$ CP terms

$P(\nu_e \to \nu_\tau)$

$$= \cos^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \Delta m^2_{23} \frac{L}{E}$$

$\pm$ CP terms

Need θ_{23} to get θ_{13}



Normalization / Flux

$\Longrightarrow$ Potentially Biggest Error in θ_{23}

1 Why Do We Need to Measure the Cross-Section?

- We want to Measure $\mathcal{P}(\nu_\mu \to \nu_\mu)$

(the Harris relation)

$$\mathcal{P}(\nu_\mu \to \nu_\mu) \Leftrightarrow \frac{\Phi_{far} \times \sigma(\nu, CC) \times N_{\text{scatt,far}}}{\Phi_{near} \times \sigma(\nu, CC) \times N_{\text{scatt,near}}}$$

not trivial

- So technically it's just the product we need
- Suppose there's no near detector — what are the errors?

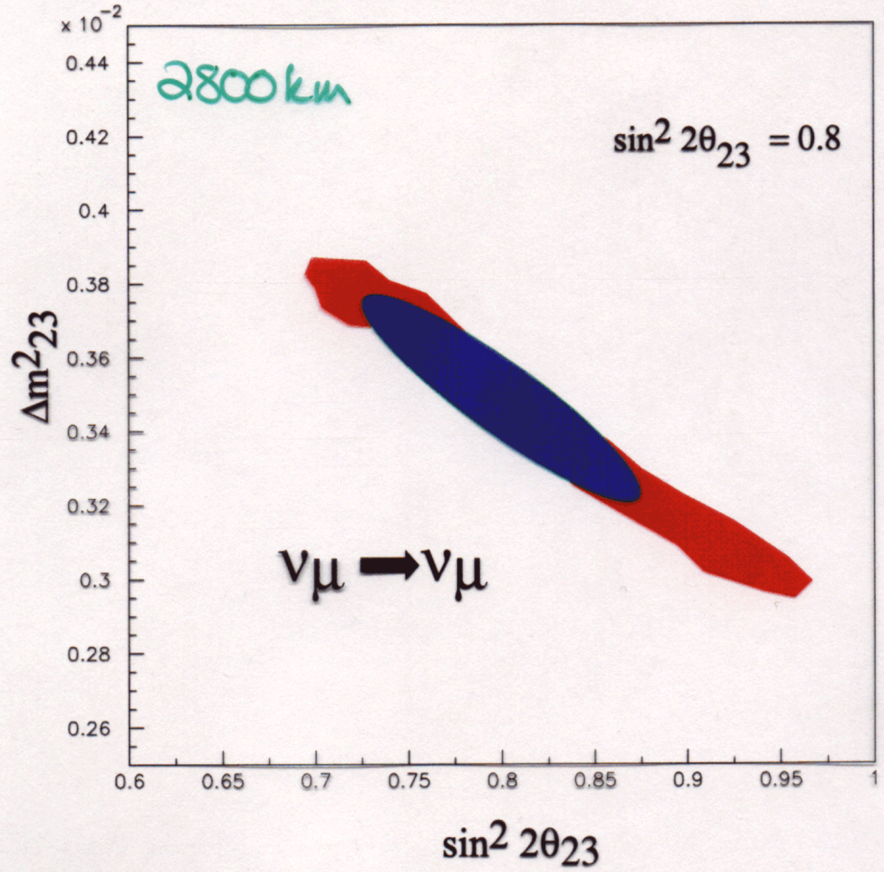
Source	Error	
Flux	~~2%~~	1%? 0%
Cross-Section	2%	1%? 0%
Detector Mass	1%	1%? 0%
Total	*3.0%*	

still, sum of errors is what counts.

What happens with 2%?

6

And What Would this Do?



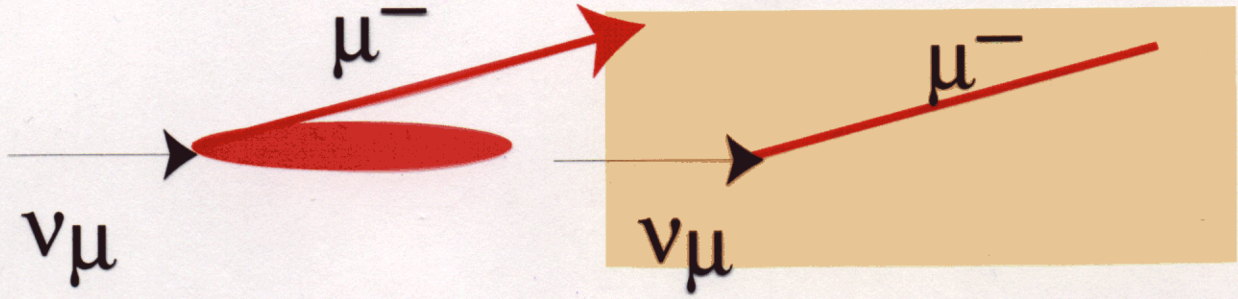
$\Delta m^2 = 0.0035$, $\sin^2 2\theta_{13} = 0.04$, 30 GeV, 2E20 Decays, 10 kt Fiducial,
2% Overall Flux / *0% Flux Error*

2% at 1σ on

$$\frac{\Phi_{far} \times \sigma(\nu, CC) \times N_{\text{scatt,far}}}{\Phi_{near} \times \sigma(\nu, CC) \times N_{\text{scatt,near}}}$$

Experimental Idea : Inverse Muon Decay

$\nu_\mu e \to \mu \nu_e$



Liquid H2 *Same as Far Detector*

- *Predict* Rate in $\sigma = 17.4 \times 10^{-42} E_\nu$, well-known in SM
  "Easy-to-Calculate" Liquid Hydrogen
  $\Rightarrow$ Absolute Flux

- Use Absolute Flux to Measure ν Cross-Section
  in Near Copy of Far Detector

$$\frac{\Phi_{\text{far}}}{\Phi_{\text{near}}} \times \frac{N_{\text{scatt,far}}}{N_{\text{scatt,near}}}$$

$$\times \frac{\sigma(\nu, CC, \text{Fe}, \text{Spectrum}, \text{Acceptance}, \dots)}{\sigma(\nu, CC, \text{Fe}, \text{Spectrum}, \text{Acceptance}, \dots)}$$

All Groups Agree

a) Normalization Error must be included

b) Normalization Error must be minimized

c) We need to measure Flux, σ, N as well as possible

⇒ Should collaborate with machine builders for best results

⇒ no one should make conclusions about L yet

Status of Efforts

	Spanish	ICANOE	FINAL
systematics	no flux	no flux	flux included
bkgs	Fe/Scint agrees with FINAL	Seeming x10 Disagreement	Fe/Scint agrees with Spanish
resolution	+++ needs work on tails	needs work +++	needs work but based on CCFR/MINOS – good base of real data
CP	+++	++	not started
	a) most developed	a) bkg's don't agree	a) potentially most complete treatment
	b) tracking/MSCAT perhaps wrong	b) needs flux	b) analysis unsophisticated (more cuts besides p_μ)
	c) needs flux to make conclusions on θ_{13}, δ	c) must move past fast MC	c) must study CP

All Groups Rely on Wrong-Sign Muons

- charge Mis-ID
  ← big criticism of Spanish group

- π, K in shower
- charm from NC
  ← big criticism of ICANOE

- use p_ℓ, p_T^2 to eliminate bkg
  ← big criticism of everyone!
  - a) FNAL too crude
  - b) ICANOE too good
  - c) Spanish too optimistic on tails

- these are reasonable disagreements which will drive progress

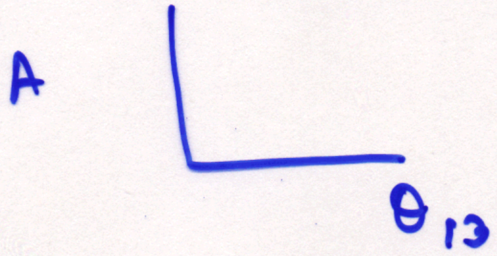
Spanish Group

a) Extensive Work on Bkgs

b) Plots of

i) Δm^2_{23} vs $\sin^2\theta_{13}$

ii) $A = \sqrt{2} G_F n_e$



iii) Nothing here on

i) $\sin^2 2\theta_{23}$

ii) Δm^2_{23} vs $\sin^2 2\theta_{23}$

⇒ strong emphasis on CP-related quantities

NOT INCLUDED IN SPANISH/ICANOE

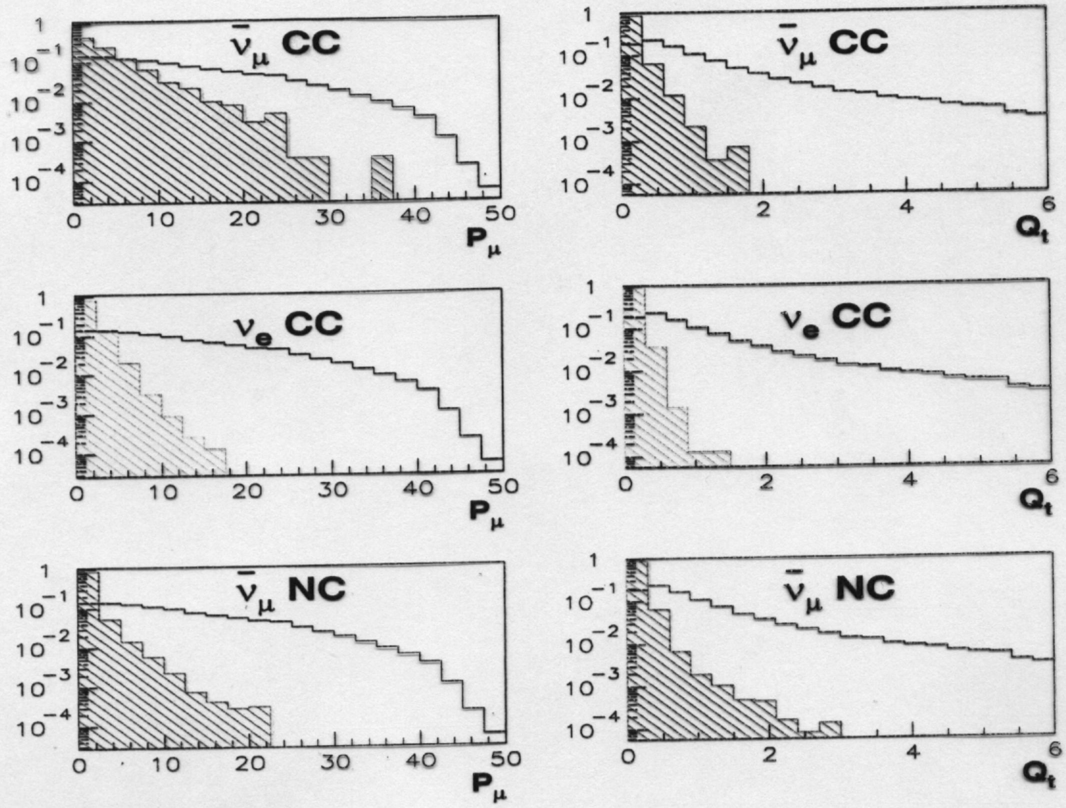
FINAL includes

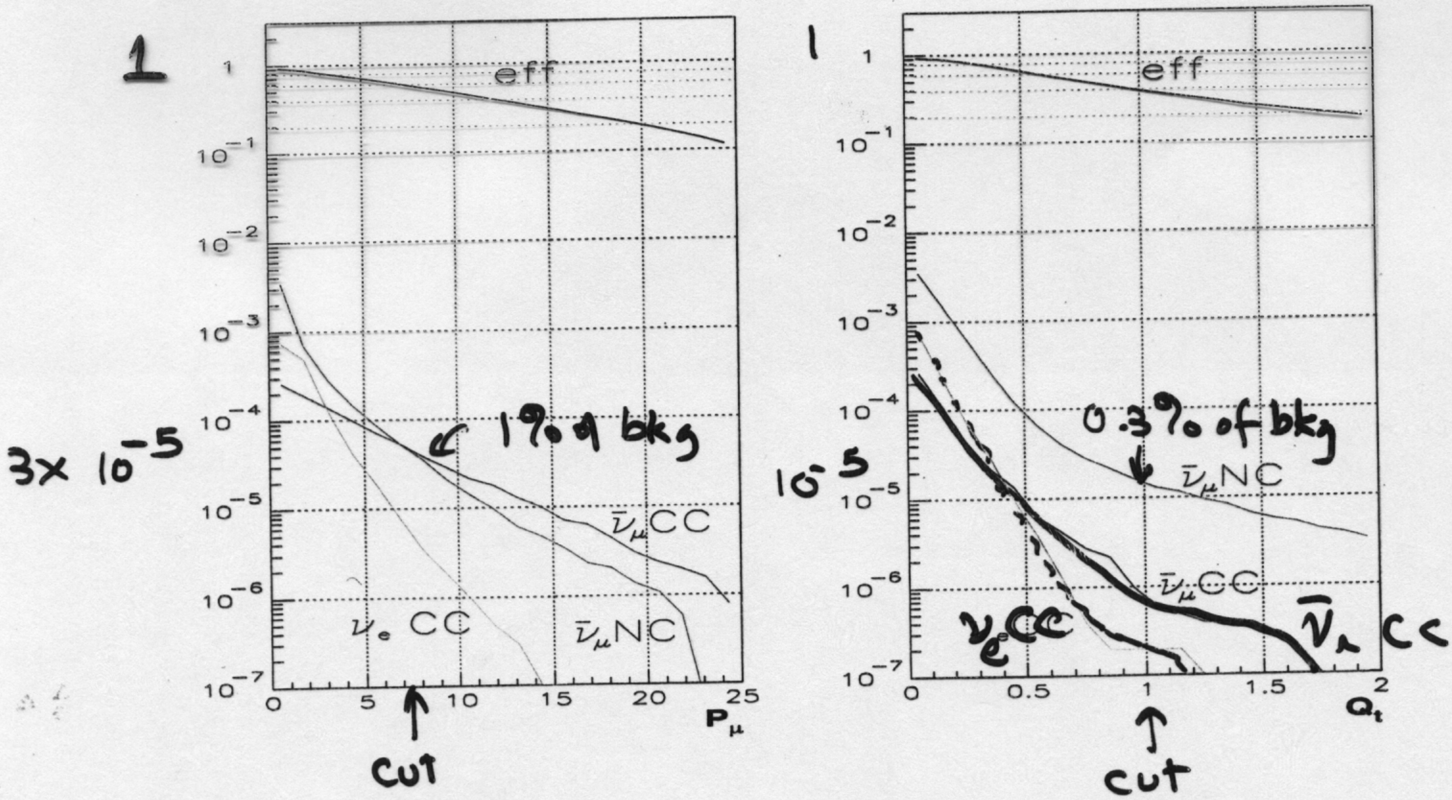
iv) But from before,

need $\sin^2 2\theta_{23}$ to get $\sin^2 2\theta_{13}$

to get δ !

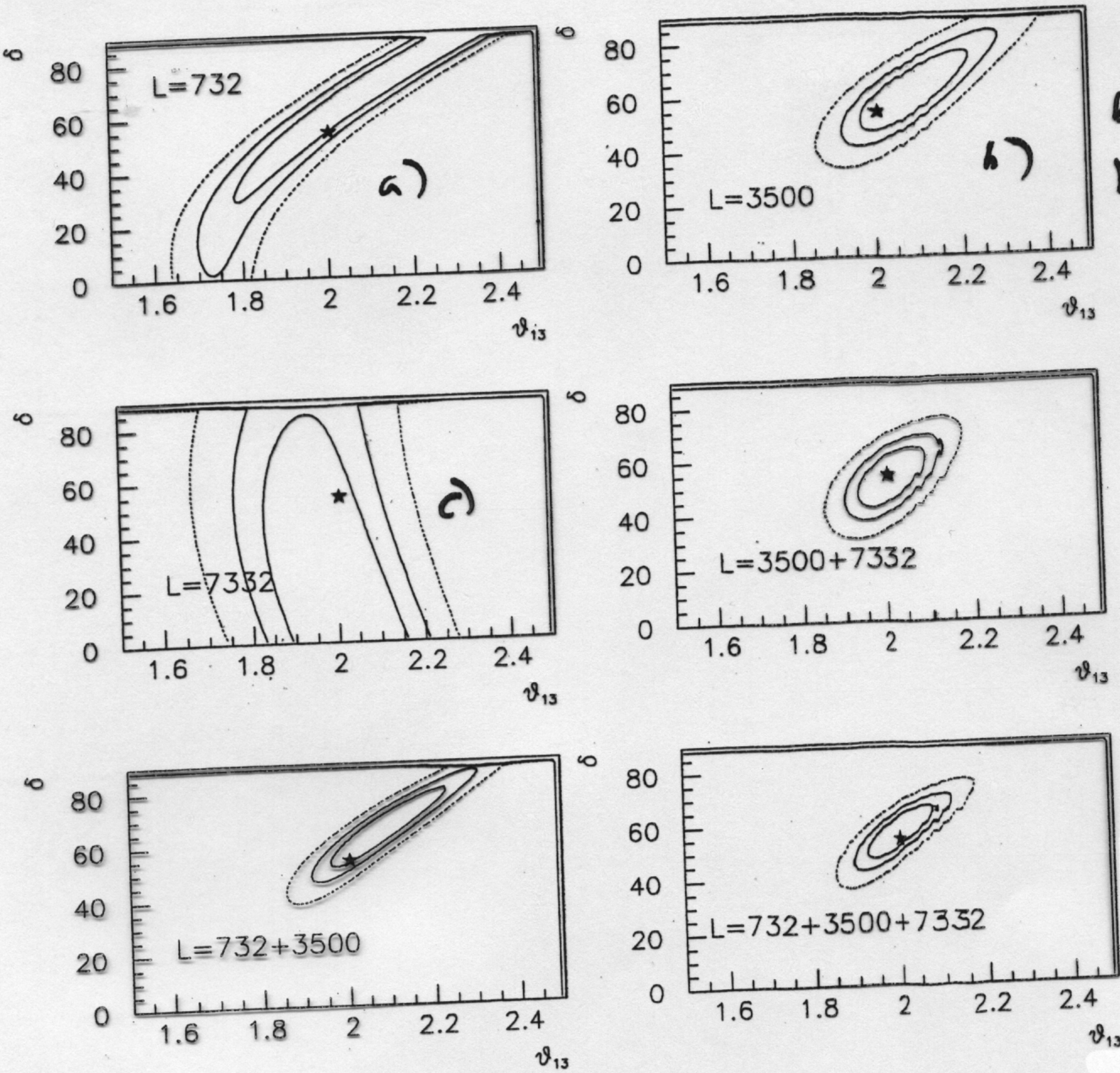
All backgrounds





Simultaneous determination of δ and ϑ_{13}

$\Delta m^2_{12} = 1 \times 10^{-4} eV^2 \longrightarrow$ LMA solution



b) is best

- Same conclusion also for $\vartheta_{13} = 2°$

⊛ STATISTICS + BACKGROUNDS + EFFICIENCIES

Detector simulation

ICANOE fully simulated for CNGS studies.

For this study, events fully simulated and passed through ICANOE fast simulation.

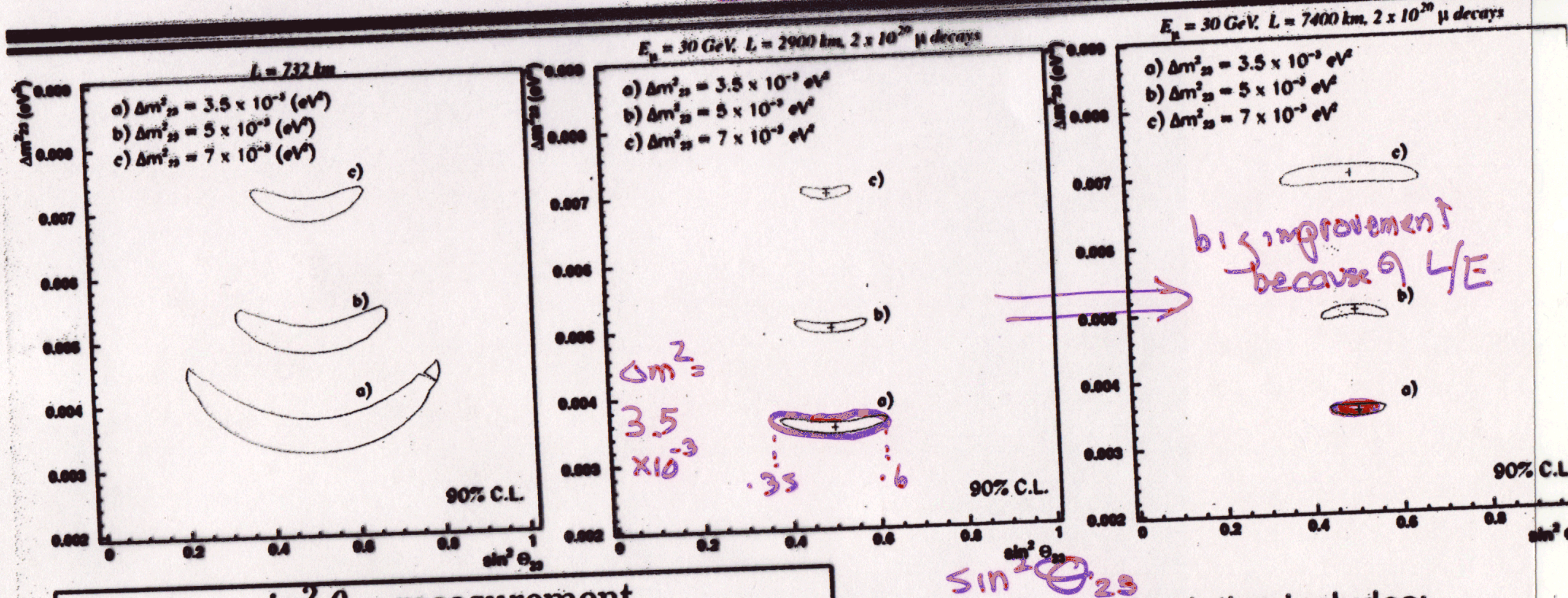
$$\frac{\sigma(E)_{e.m.}}{E} = \frac{3\%}{\sqrt{E(GeV)}} \quad \frac{\sigma(E)_{had}}{E} = \frac{20\%}{\sqrt{E(GeV)}} \quad \frac{\sigma(P_\mu)}{P_\mu} = 20\%$$

$$\frac{\sigma(\theta)}{\theta} = 130 mrad / \sqrt{p(GeV)}$$

Proper neutrino cross section used

Charged $\pi^\pm$, $K^\pm$ decay into $\mu^\pm$ for BG treatment

Sensitivity for $\Delta m^2_{23}, \theta_{23}$ measurements



$\sin^2\theta_{23}$ measurement		
Δm^2_{23} (eV²)	L=2900 km	L=7400 km
7×10^{-3}	0.50 ± 0.11	0.50 ± 0.04
5×10^{-3}	0.50 ± 0.06	0.50 ± 0.06
3.5×10^{-3}	0.50 ± 0.05	0.50 ± 0.09

Event simulation includes:

¥Background

¥Exclusive τ decays

¥Resolution

2% Beam systematics

Consistent with Barger et al. hep-ph/9911524

Error on Δm^2_{23}=1%

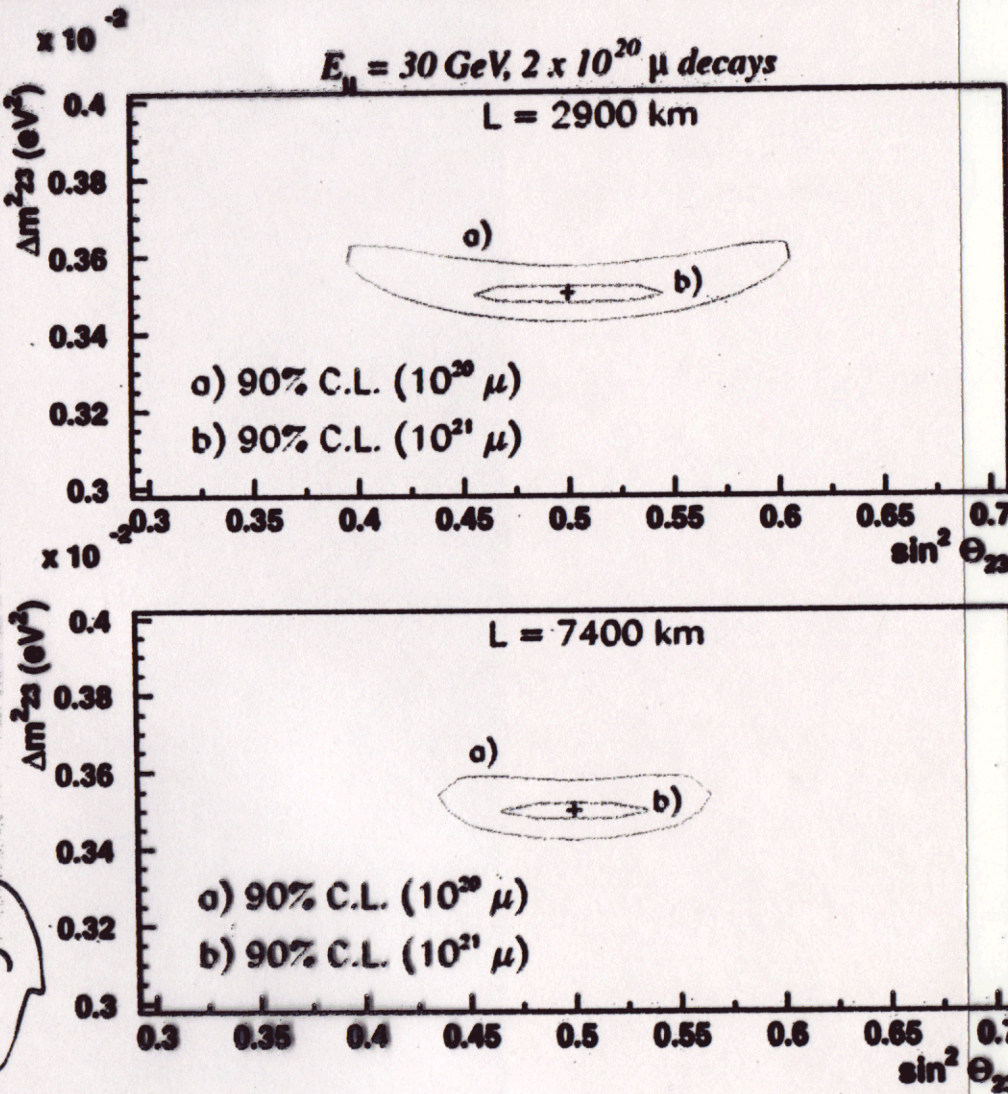
Statistical improvements

A factor 10 more statistics can still improve the measurement at very long distances

(2% systematics)

- no correlated systematics
- overall flux # cross-section error is ZERO

→ RHB comment

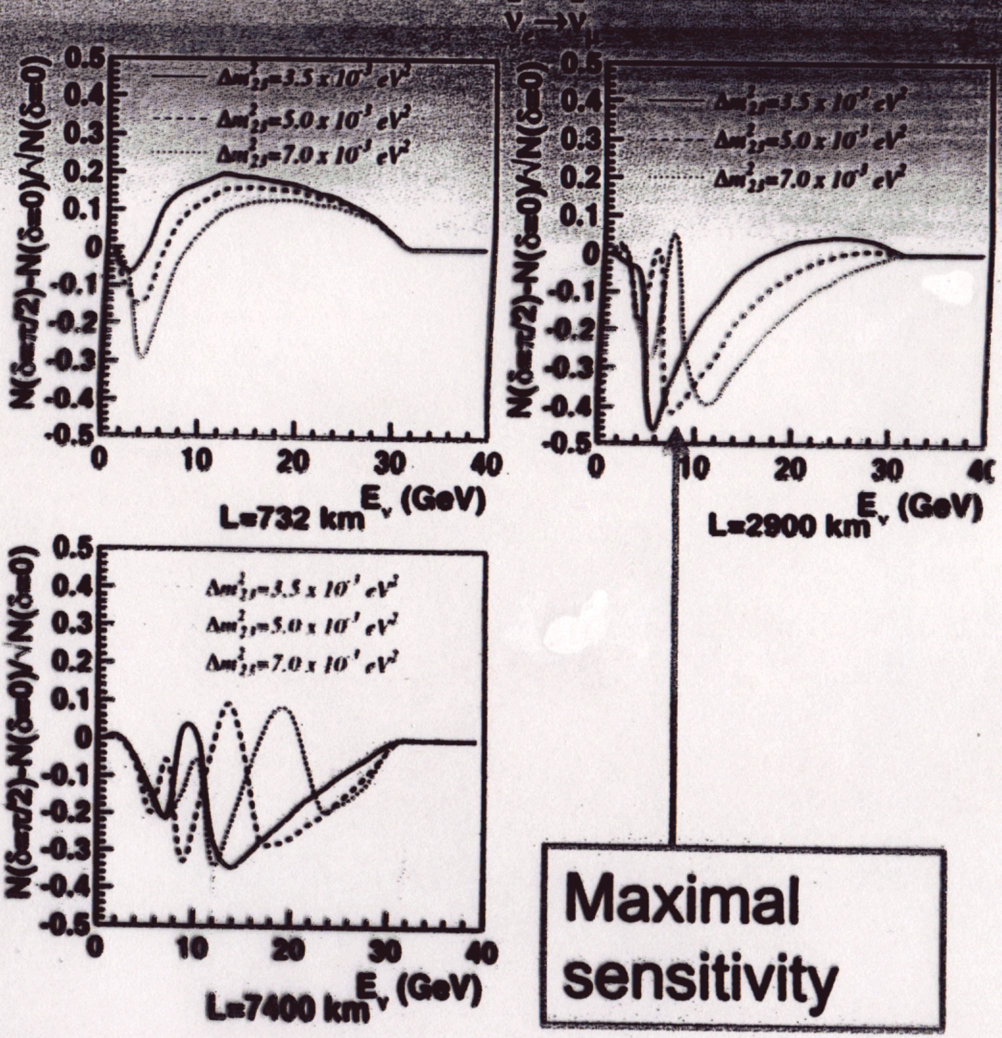


Sensitivity to CP violation

Sensitivity to CP for wrong-sign muons is maximal at L=2900 km, for neutrino energies around 10 GeV

⇒ agrees with others

⇐ 3000 km best for CP



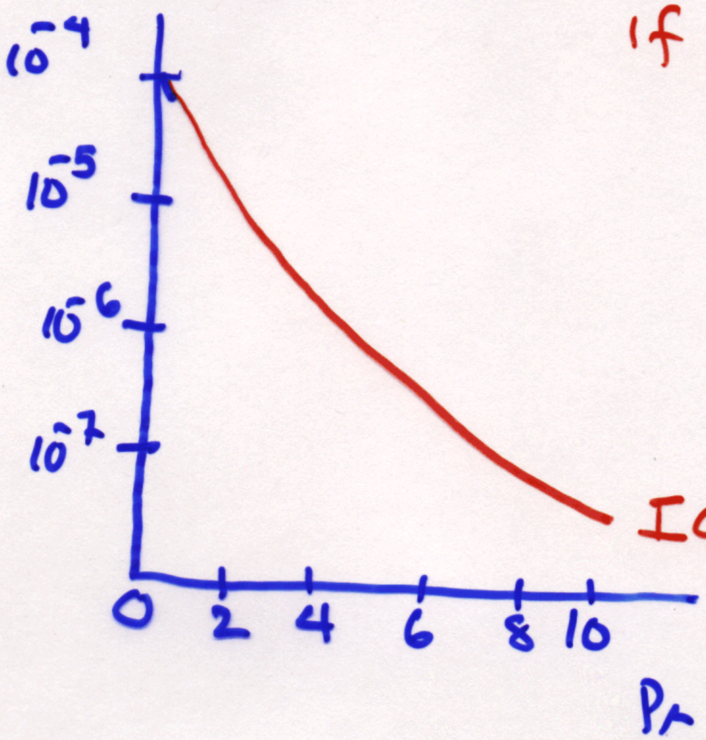
What Is WSM Bkg Rate?

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

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

lost ↳ WSM signal

Fractional Bkg



if $p_\mu < 2$, μ lost

But from y-distribution, typical

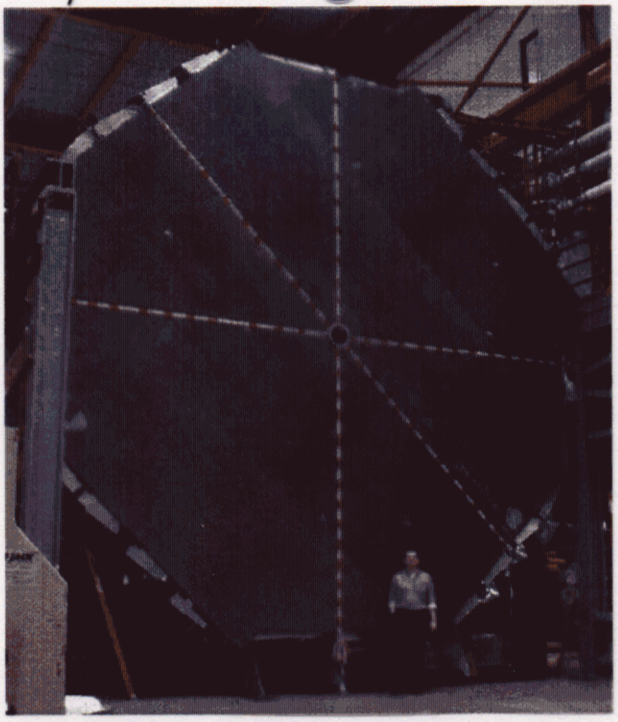
$\nu_\mu N \to \mu^- X$

$E_\nu \sim 30$ GeV

if y flat, $\frac{2}{30} \times \frac{\sigma(\mu^+\mu^-)}{\sigma_{\mu^-}}$ is bkg

$\approx$ $\gtrsim 10^{-3}$ × 10 higher ???

- Detector
  - Fe/Scint magnetized calorimeter (MINOS)



~~10 kT fiducial~~

  - Resolution:

$$\Delta E_{\rm had} = 0.65 \times \sqrt{E_{\rm had}}$$

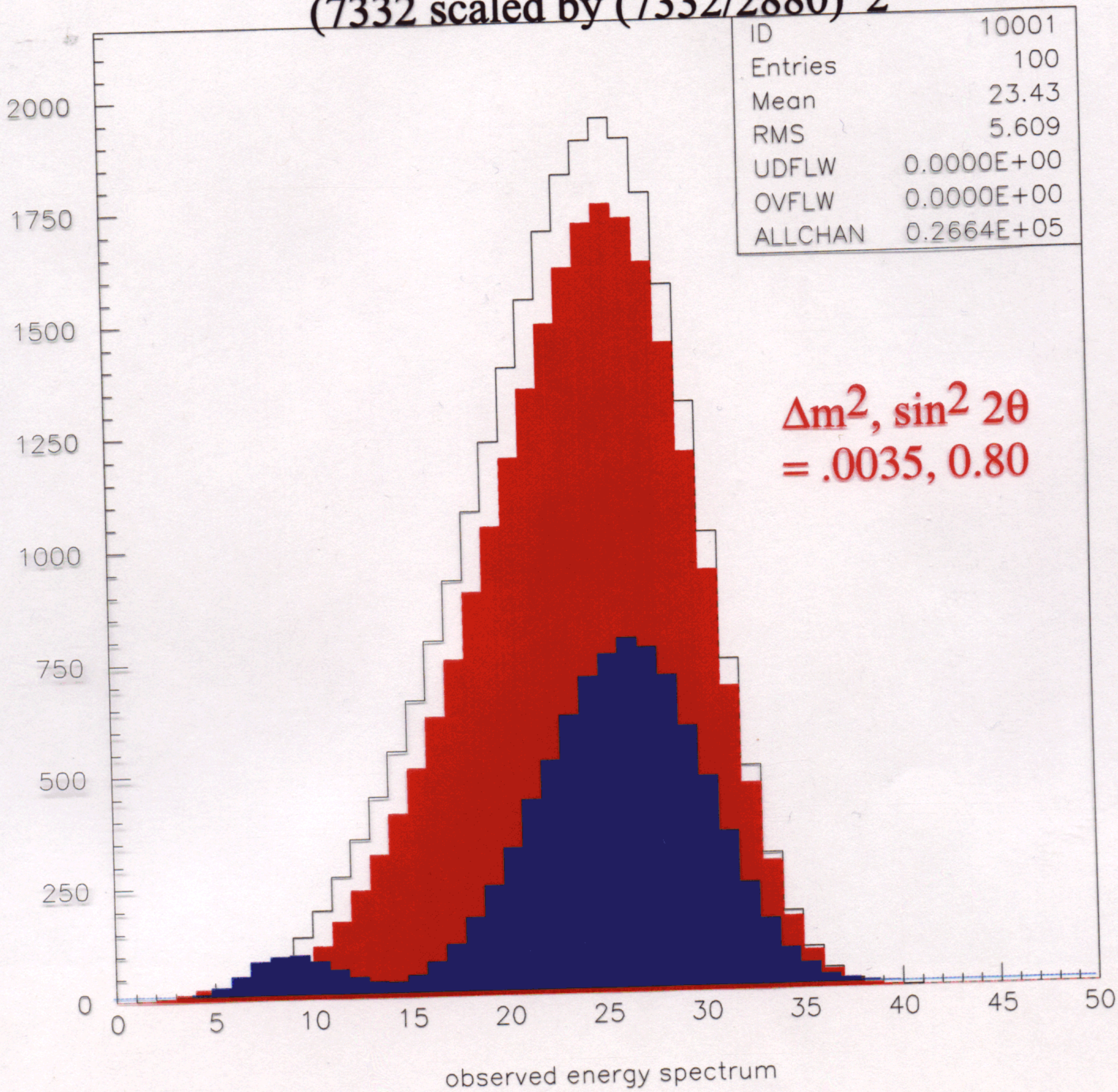
$$\Delta p_\mu = 0.11 p_\mu$$

  - Acceptance

criticized as too-pessimistic →

$$\epsilon_\mu = 0 \quad (p_\mu < 4\text{GeV})$$
$$\epsilon_\mu = 1 \quad (p_\mu \geq 4\text{GeV})$$

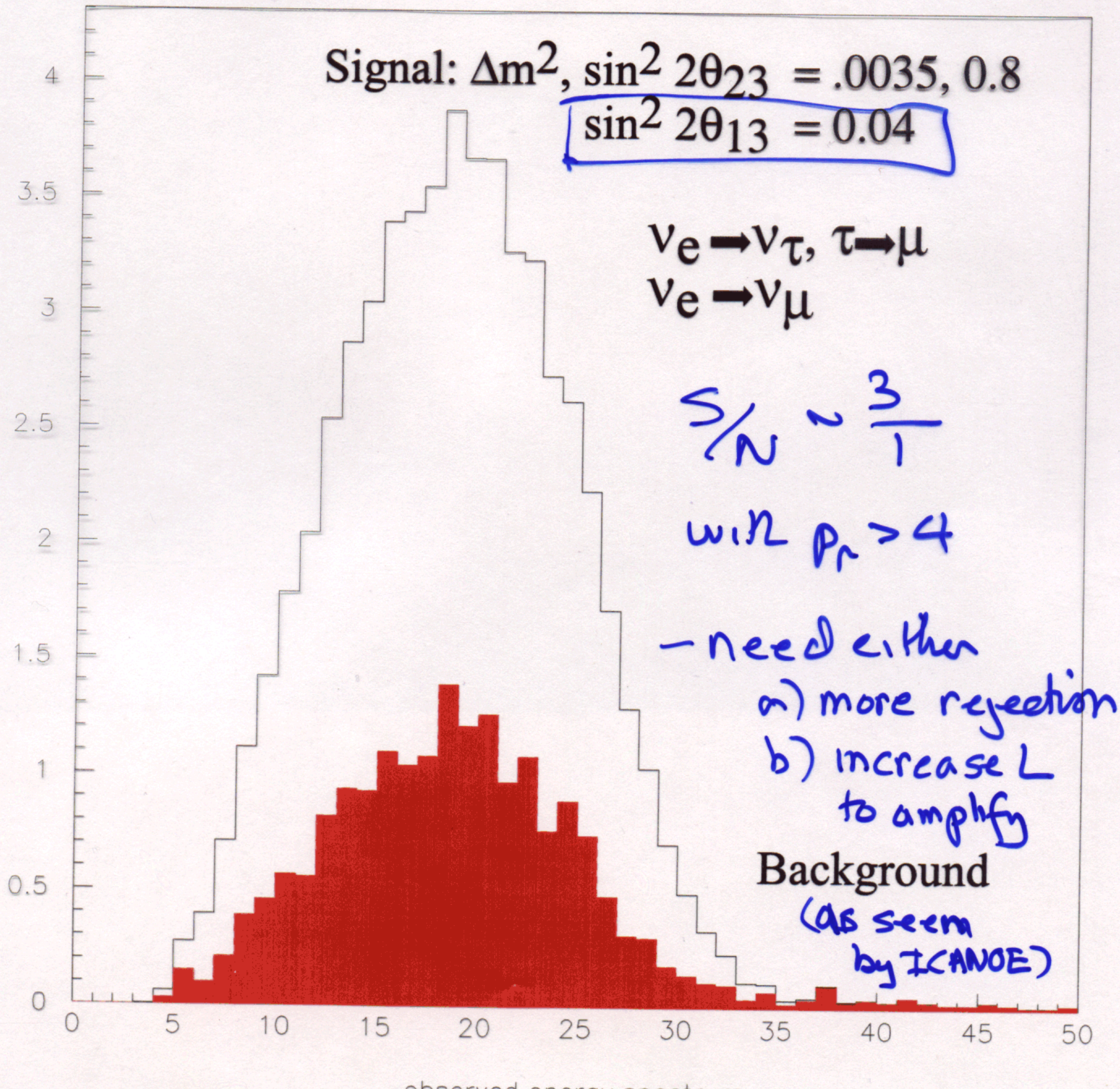
Change of Spectrum With Distance: Unoscillated to 2880 to 7332 km (7332 scaled by (7332/2880)^2



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

- What Does the Appearance Signal Look Like?

Comparison of Signal to Background ($p_\mu > 4$ GeV)



Summary of Leading Oscillation Measurements

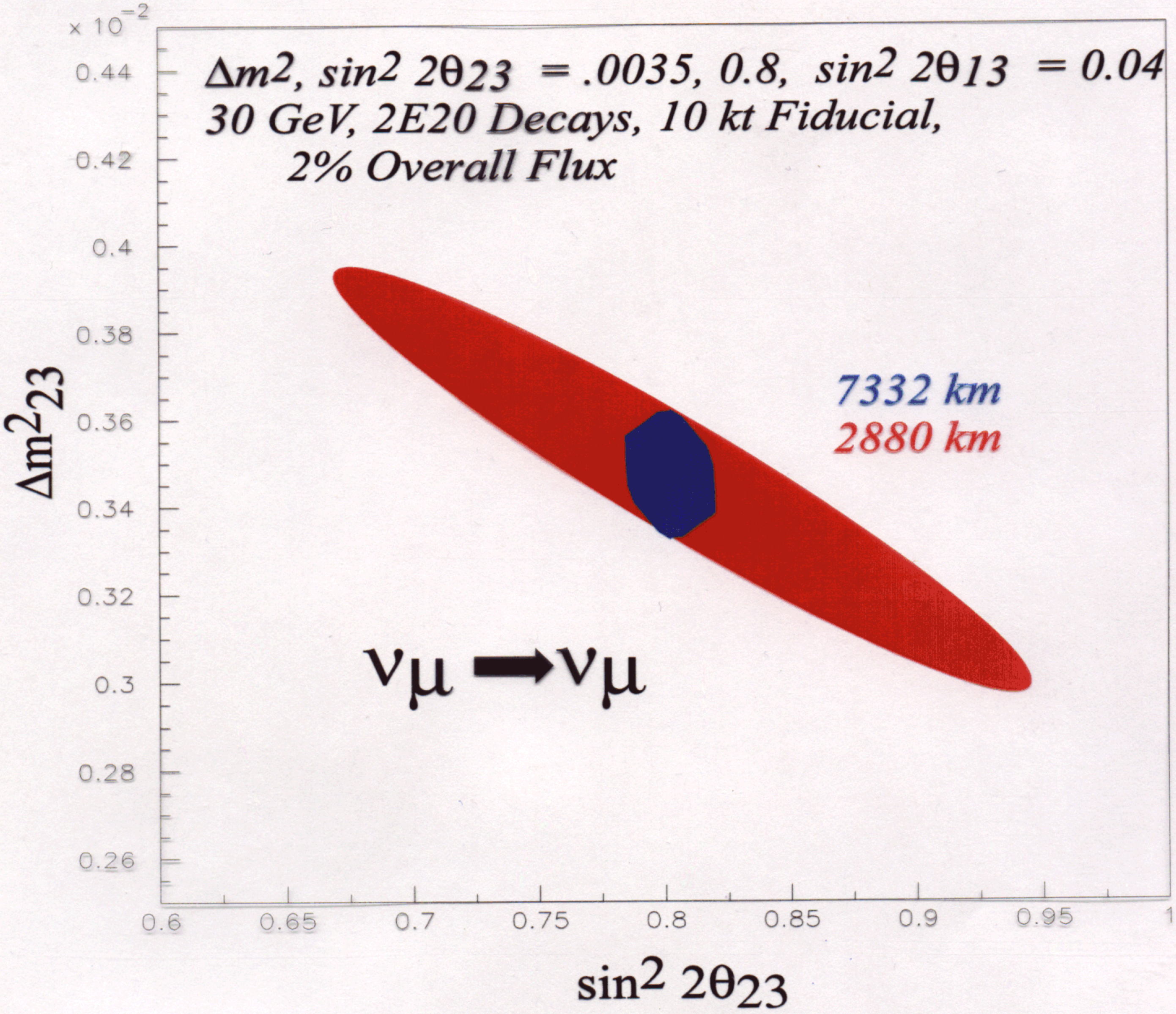
		$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu$		$\overset{(-)}{\nu}_e \rightarrow \overset{(-)}{\nu}_\mu$	
L (km)	E_μ (GeV)	δm^2_{32}	$\sin^2 2\theta_{23}$	$\sin^2 2\theta_{13}$	3σ sgn(δm^2_{32})
732	10	6.7%	7.6%	.002	>0.1
	30	8.9%	14%	.0005	0.1
	50	12%	17%	.0003	>0.1
2800	10	2.4%	1.1%	.008	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

ICANOE, FNAL agree

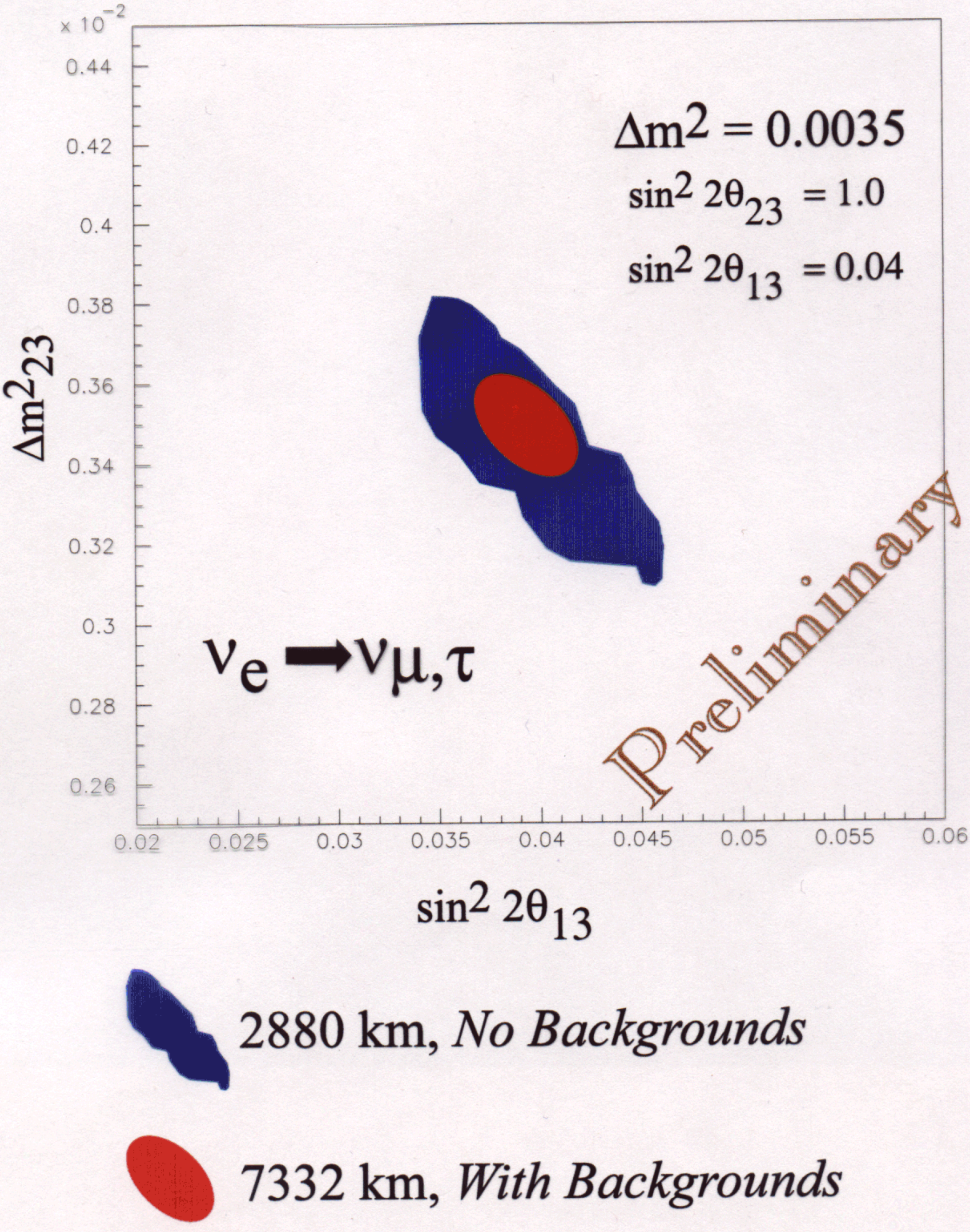
2800 probably best after backgrounds added

FNAL Disagrees



Argument for 7000 km is this Plot

- Make Flux Errors Small, Argument Gets weaker
- Still matter enhancement for sign of $\Delta m^2 \Rightarrow$ 7000 km



–Matter Effects
from Mocioiu + Shrock

Conclusions: More Agreement than Disagreement

A. All Groups Have Done Good Work

but all are flawed → improvements underway

B. Consensus that 3000 km is best for CP

7000 is bad for CP

C. Consensus that 7000 km best for Δm^2_{23}, $\sin^2 2\theta_{23}$, $\sin^2 2\theta_{13}$

- use L/E to amplify S/N
  - how much better?
- can study/use matter-enhancement

D. Because of normalization errors, hard to extract δ without precision $\sin^2 2\theta_{23}$

requires << 1% flux at 3000 km

E. **Two** Baselines Are Best

Use of Machine (3000/7000)

Very Long Baseline ~7000
Long Baseline ~3000