Neutrino Cross-Section Measurements at the Neutrino Factory

R. Bernstein
NuFact 2000
Monterey

- correct actual work done by
D. Harris
P. Spentzouris
- incorrect work
RHB

- Outline
  - Why Do We Need to Measure the Cross-Section?
  - What Are the Ingredients?
  - Proposal for Specific Measurement

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

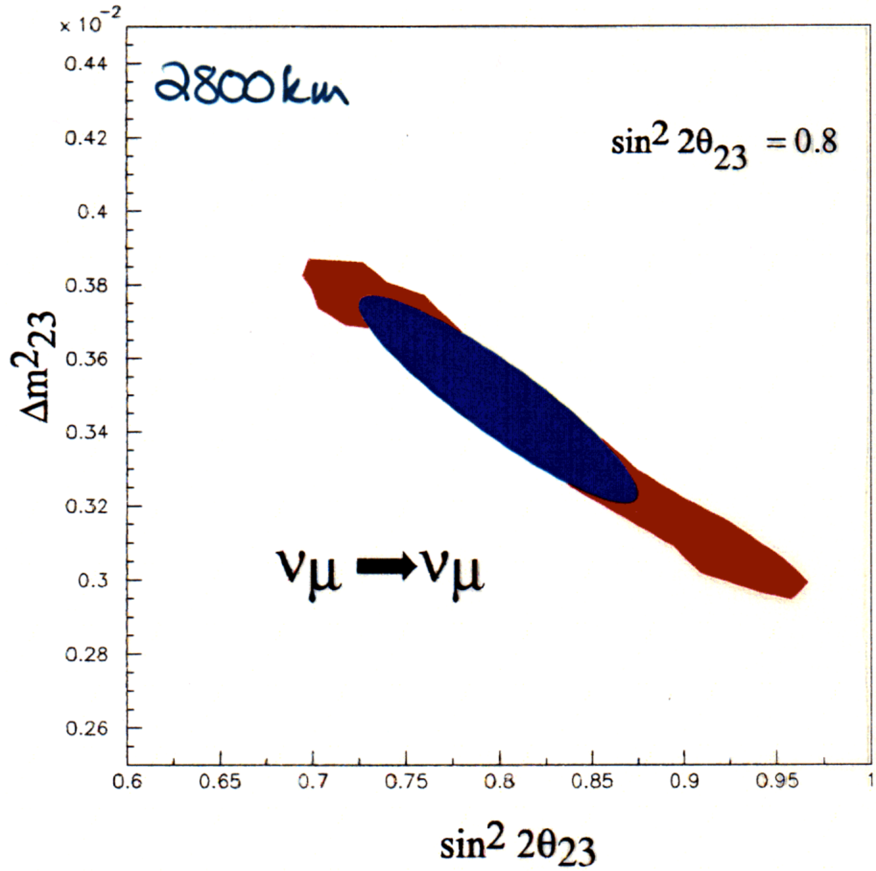
- We want to Measure $\mathcal{P}(\nu_\mu \to \nu_\mu)$
(the Harris relation)

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

- So technically it's just the product we need ? not trivial
- Suppose there's no near detector — what are the errors?

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

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

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

Flux Error really means flux $\oplus$ cross-sectio $\oplus$ N_{scatt}

How Well Do We Know the Cross-Section?

TABLE II. Measurements of the neutrino total cross section on iron. (The CHARM result has not been included in the averages since the systematic errors are correlated with CDHSW.)

Experiment	s^{n}/E	s^{n}/E	s^{n}/s^{n}	Ref.
CCFR (E616)	0.6696 0.024	0.3466 0.020	0.4986 0.025	(MacFarlane et al., 1984)
CDHSW	0.6866 0.020	0.3386 0.009	0.4956 0.010	(Berge et al., 1987)
CHARM	0.6866 0.020	0.3356 0.011	0.4886 0.013	(Allaby et al., 1988)
CCFR (E701)	0.6596 0.039	0.3076 0.020	0.4676 0.028	(Auchincloss et al., 1990)
CCFR (E744/770)			0.5096 0.010	(Seligman et al., 1997a, 1997b)
World Ave.	0.6776 0.014	0.3346 0.008	0.5066 0.007	

Rev. Mod. Phys., Vol. 70, No. 4, October 1998

$$\sigma_{\nu} = 0.6676 \pm 0.014$$

(2.1%)

$$\sigma_{\bar{\nu}} = 0.335 \pm 0.008$$

(2.4%)

- So Our knowledge of the ν Cross-Section is Already a Significant Error
- Given likely Flux Errors, *etc.*
  Let's Try for 1%

In a glorious tradition of ν Experiments

We Propose P-1A

(FNAL P–1A was Cline, Mann, Rubbia's high-y anomaly)

- Inverse Muon Decay

$$\nu_\mu e^- \rightarrow \mu^- \nu_e$$

$$\frac{\sigma}{E_\nu} = \frac{2 m_e G_F^2}{\pi}\left(1 - \frac{m_\mu^2}{s}\right)^2 (1+\lambda)$$

where

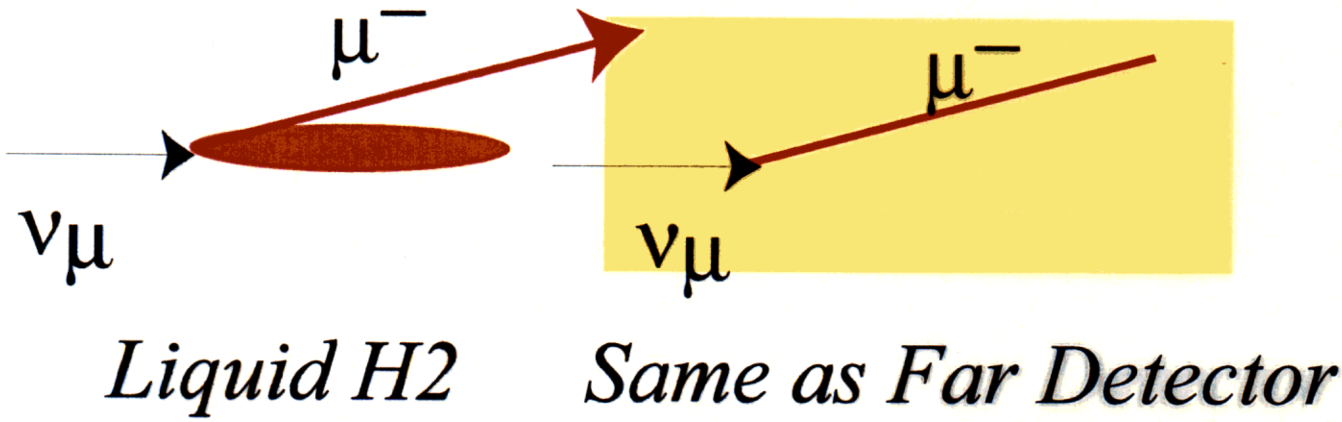
$$\lambda = \frac{2\Re[g_V^\dagger g_A]}{g_V^2 + g_A^2}$$

- Predicted in Standard Model

$$= 17.4 \times 10^{-42} E_\nu$$

$$\approx 0.1 \times 10^{-2} \text{ of CC rate}$$

Experimental Idea



- *Predict* Rate in
  "Easy-to-Calculate" Liquid Hydrogen
  $\Rightarrow$ Absolute Flux
- Use Absolute Flux to Measure ν Cross-Section
  in Near Copy of Far Detector

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

$$\times \frac{\sigma(\nu, CC, \mathrm{Fe}, \mathrm{Spectrum}, \mathrm{Acceptance}, \ldots)}{\sigma(\nu, CC, \mathrm{Fe}, \mathrm{Spectrum}, \mathrm{Acceptance}, \ldots)}$$

Technique

- Detector Dependent, Lots of Other Ways, But:

$$\frac{d^2\sigma}{dx\,dy}(\nu q) = \frac{G_F^2 x s}{\pi}\left[q(x) + \bar{q}(x)(1-y)^2\right]$$

$$\frac{d^2\sigma}{dx\,dy}(\bar{\nu} q) = \frac{G_F^2 x s}{\pi}\left[q(x)(1-y)^2 + \bar{q}(x)\right]$$

so at $y = E_{\rm had}/E_\nu = 0$

$$\frac{d^2\sigma}{dx\,dy}(\nu q) = \frac{G_F^2 x s}{\pi}\left[q(x) + \bar{q}(x)\right]$$
$$\frac{d^2\sigma}{dx\,dy}(\bar{\nu} q) = \frac{G_F^2 x s}{\pi}\left[q(x) + \bar{q}(x)\right]$$

and the cross-sections are equal

- $y = 0$ Acceptance for IMD effectively same as for ν DIS
- Use $\bar{\nu}$ to measure and subtract from ν

VOLUME 63, NUMBER 2 PHYSICAL REVIEW LETTERS 10 JULY 1989

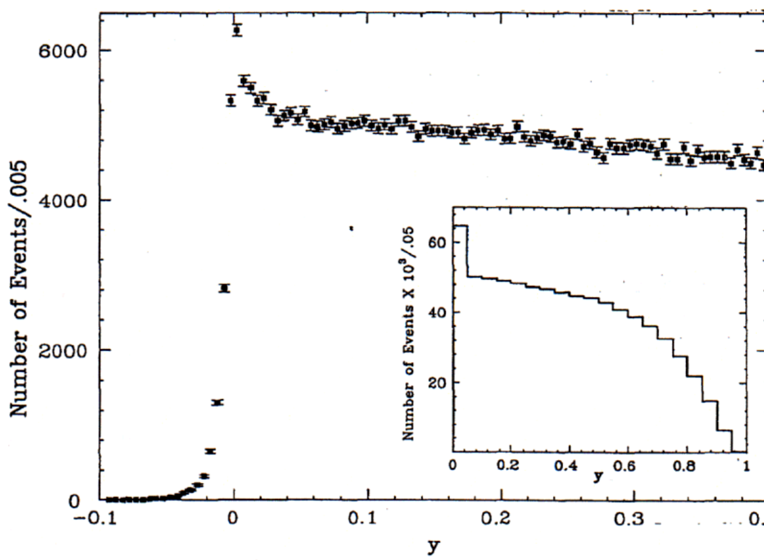


FIG. 1. Distribution of the variable $y = E_{HAD}/E_\nu$, $-0.1 \le y \le 0.05$, for ν_μ-induced CC events. The calorimetric resolution smearing due to "muon-tail subtraction" in the shower region (Ref. 6) causes events with $E_{HAD} < 0$ (and hence $y < 0$). Inset: y distribution in the entire kinematical range $0 \le y \le 1$, where events with $y < 0$ are presented in the $y = 0$ bin.

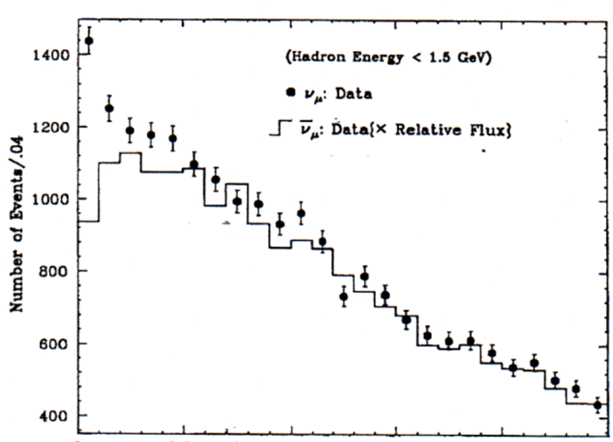


FIG. 2. Distribution of $Q^2 = E_\nu E_\mu \theta_\mu^2$ for events with $E_{HAD} \le 1.5$ GeV. The ν_μ events are shown by solid circles. The $\bar{\nu}_\mu$ events, scaled up by the relative ν_μ to $\bar{\nu}_\mu$ flux, are shown by the solid line.

interaction, $M_{W_R} > 1.8 M_{W_L}$. It should be noted that μ-decay experiments constrain these parameters with high

TABLE II. The inverse-μ-decay signal: Raw and corrected (for acceptance, kinematical cuts, and isoscalar target and threshold effects) number of signal events in E_{VIS} bins. The first bin, in addition, has been corrected for the cut $E_\mu > 15$ GeV. The bottom row shows the cumulative signal extracted after fitting the above eight numbers for a rate with respect to CC using a Monte Carlo simulation.

Bin No.	Raw signal	Corrected signal
1	162.8 ± 31.6	531.5 ± 103.2
2	131.2 ± 27.5	219.0 ± 45.9
3	138.7 ± 24.9	206.2 ± 37.1
4	126.8 ± 24.0	177.6 ± 33.6
5	61.7 ± 15.8	83.8 ± 21.4
6	32.4 ± 16.3	43.6 ± 21.9
7	3.9 ± 8.2	5.1 ± 10.8
8	3.0 ± 4.5	3.9 ± 5.8
Total	660.5 ± 59.7	1151.2 ± 104.1

Detector Studies at FNAL

R. Bernstein
NuFact 2000
Monterey

Outline

- Design Criteria:
  - What Are the Oscillation Signatures?
  - What Are the Backgrounds?
  - Limiting Systematics?
- Interplay of Detector and Signal
  - Which Measurements Emphasize Statistics?
  - Which Measurements Emphasize Systematics?

Personal Bias

- Look at "Scenario IA"

$$\Delta m^2_{23} = 3.5 \times 10^{-3}, \sin^2 2\theta_{23} = 0.8 - 1$$

for

– $\sin^2 2\theta_{13} = 0.04$,

– $\sin^2 2\theta_{13} = 0.01$

measure product, need two channels

$$\mathcal{P}(\nu_e \to \nu_\mu) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2 1.27\Delta m^2_{23}\frac{L}{E} \quad (1)$$

$$\mathcal{P}(\nu_e \to \nu_\tau) = \cos^2\theta_{23}\sin^2 2\theta_{13}\sin^2 1.27\Delta m^2_{23}\frac{L}{E} \quad (2)$$

$$\mathcal{P}(\nu_\mu \to \nu_\tau) = \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2 1.27\Delta m^2_{23}\frac{L}{E} \quad (3)$$

n.b. cheat: used $\tau \to \mu$ of 0.16, no τ suppression

- Likely Signal $\nu_\mu \to \nu_\tau$
- Possible Signal $\nu_e \to \nu_\tau$
- Don't Rule Out Others

  But Make Sure of These!

- Concentrate on $\nu_\mu \to \nu_\tau$, $\nu_e \to \nu_\tau$

§1. $\nu_\mu \to \nu_\tau$ by Disappearance

§2. $\nu_e \to \nu_\tau$ by Muon Appearance

Physics Channel	Disappearance Tests	Appearance Tests	$\tau \to \mu$	$\tau \to e$	$\tau \to$ hadrons
$\nu_\mu \to \nu_e$	CC Rate/Spectrum	NC/CC			
$\nu_\mu \to \nu_\tau$	CC Rate/Spectrum	NC/CC	NC/CC	NC/CC, η_3	NC/CC
$\bar{\nu}_e \to \bar{\nu}_\tau$	CC Rate/Spectrum	WSM	WSM	NC/CC, η_3	NC/CC
$\bar{\nu}_e \to \bar{\nu}_\mu$	CC Rate/Spectrum	WSM			

Table 1: Signal

Physics Channel	Disappearance Tests	Appearance Tests	$\tau \to \mu$	$\tau \to e$	$\tau \to$ hadrons
$\nu_\mu \to \nu_e$	Beam ν_e	Beam ν_e			
$\nu_\mu \to \nu_\tau$	$\nu_\mu \to \nu_\tau \to \mu$			Beam ν_e	NC/CC
$\bar{\nu}_e \to \bar{\nu}_\tau$		WSM	WSM	Beam ν_e	Electron Mis-ID
$\bar{\nu}_e \to \bar{\nu}_\mu$		WSM			

Table 2: Backgrounds

Physics Channel	Disappearance Tests	Appearance Tests	$\tau \to \mu$	$\tau \to e$	$\tau \to$ hadrons
$\nu_\mu \to \nu_e$	Muon ID/$\vec{p}$				
$\nu_\mu \to \nu_\tau$	Muon ID/$\vec{p}$		Muon ID/$\vec{p}$	e ID	Muon ID
$\bar{\nu}_e \to \bar{\nu}_\tau$			Muon ID/$\vec{p}$	e ID	e ID
$\bar{\nu}_e \to \bar{\nu}_\mu$		Muon ID/$\vec{p}$			

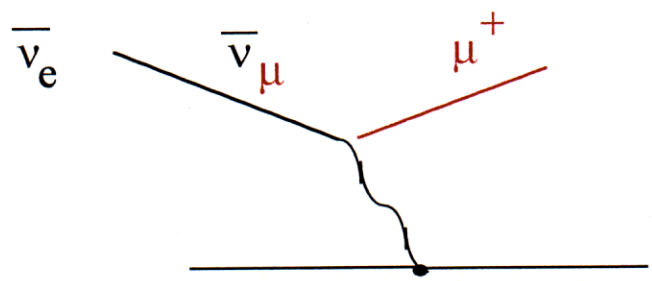
Table 3: Detector Properties

Physics Channel	Disappearance Tests	Appearance Tests	$\tau \to \mu$	$\tau \to e$	$\tau \to$ hadrons
$\nu_\mu \to \nu_e$	μ MisRec	e Mis-ID, π^o			
$\nu_\mu \to \nu_\tau$	FLUX		π/K	Beam ν_e	NC
$\bar{\nu}_e \to \bar{\nu}_\tau$			WSM	Beam ν_e	e Mis-ID
$\bar{\nu}_e \to \bar{\nu}_\mu$		μ MisRec			

Table 4: Limiting Systematics

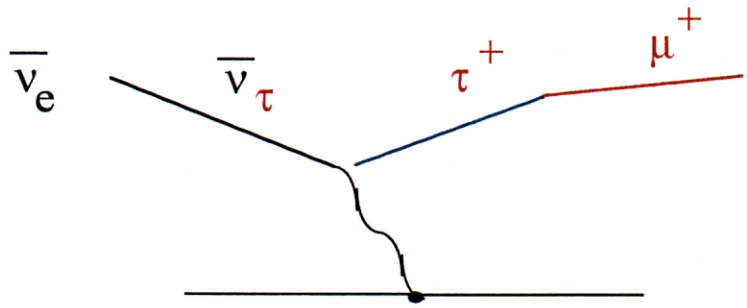
Signals:

- $\nu_e \rightarrow \nu_\mu$ Oscillations



- Wrong-Sign Muon Signal
- Hardest Spectrum of All Sources
- $p_\perp$ Balance
- Just Need Tracking/Momentum
- Theme: Can Use $\bar{\nu}_e$:
  - y-Dist yields Stiffer Muons for AntiNeutrinos
  - Helps Distinguish From Backgrounds

- $\nu_e \longrightarrow \nu_\tau$ Oscillations



- Muons Softer by
  Two Consecutive y-Distributions
- Lose Factor of Six from BR($\tau \rightarrow \mu$)
- Just Need Tracking/Momentum
- Theme: Can Use $\bar{\nu}_e$ as Before

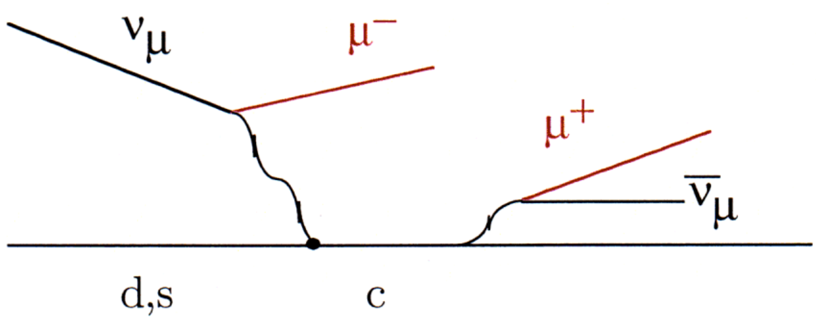
Can We Pick Up Other Channels?

- $\tau \longrightarrow$ hadrons tough because of NC
- π^o Production
- Hadronic/EM Confusion

Challenge for ICANOE

Backgrounds

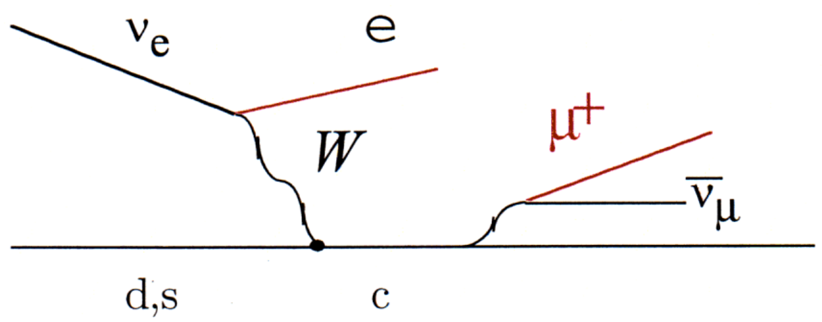
Opposite Sign Dimuon:



- Level $\approx$ 5% $\times 0.16(\tau \rightarrow \mu)$
- Need to Lose First Muon
  - Tracking?
  - p_μ Softer than for $\tau \rightarrow \mu$
  - For Now, Cut at $p_\mu < 4$ GeV
    —about the length of a shower
  - $p_\perp^2$ Should be Large

Fine Grained Tracking Calorimeter
Best For Rejection

Wrong-Sign Backgrounds:

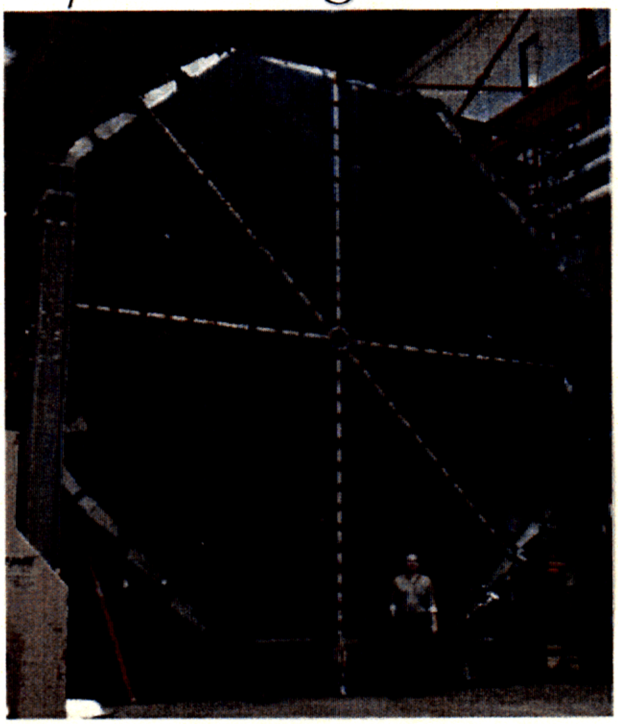


- Level $\approx 5\% \times 0.16(\tau \to \mu)$
- *No First Muon*
  - See Electromagnetic Event?
  - For Now, Cut at $p_\mu < 4$ GeV
    —about the length of a shower
  - $p_\perp^2$ Should be Large

Fine Grained Tracking Calorimeter
Better if We Can Reliably Cut EM Shower

- π^o Production
- Hadronic/EM Confusion

- 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

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

Few Points About Simulations

a) y-dist from CCFR $\geq$ 8 GeV
from GMINOS $\leq$ 8 GeV (will quasi)

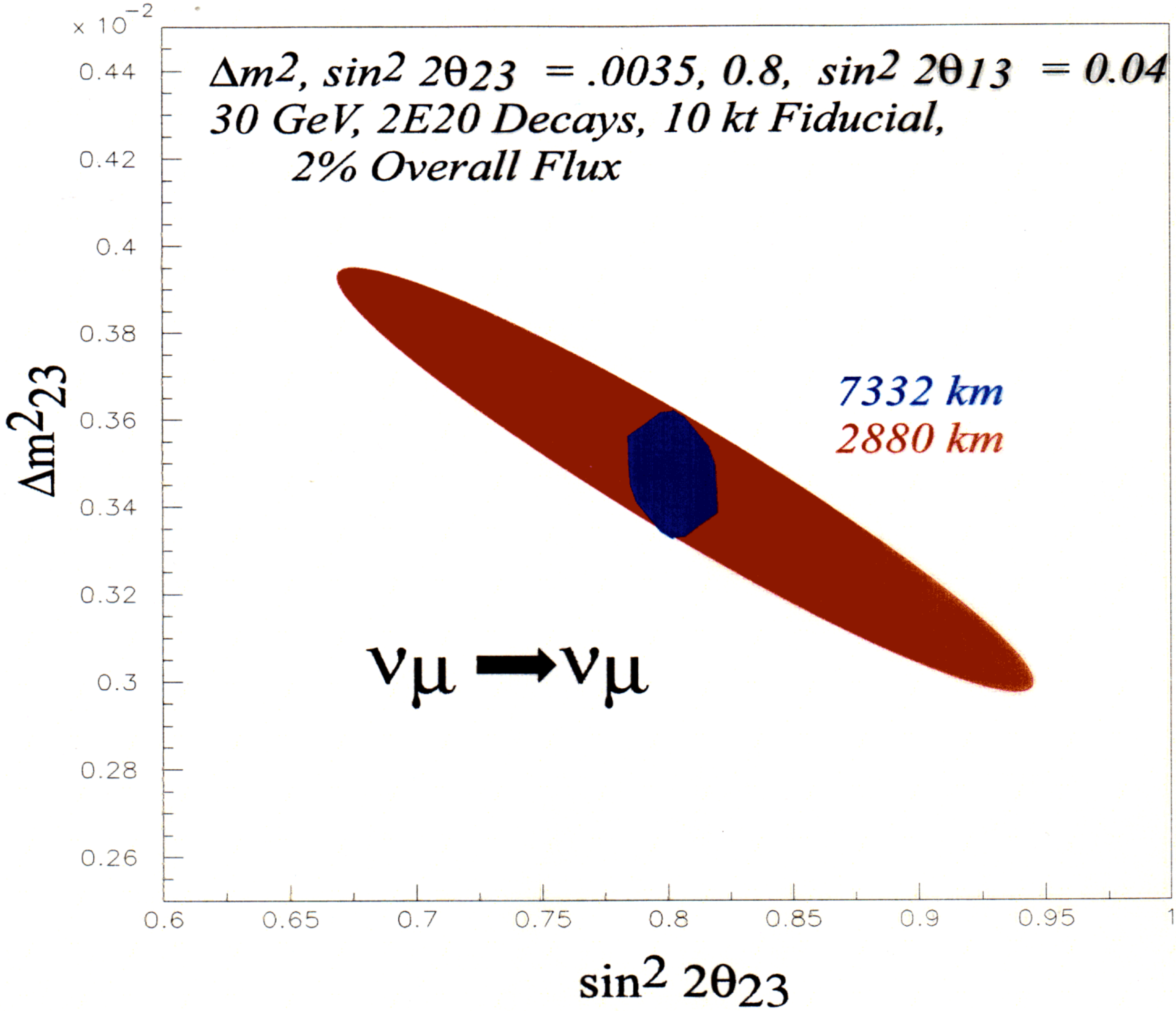
b) Backgrounds from GEANT
tuned to CCFR

$\pi, K \to \mu$ $\qquad$ $c \to \mu$

c) $p_\mu > 4$ GeV (30 GeV ν fact)
↳ working on p_T^2 cut

d) Flux Error
2% overall
2% bin-to-bin 1 GeV

e) Bkg Level
± 10% on level
no shape warping yet



Flux = 1% flux ⊕ 1% cross-section ⊕ 1% Nscatt ~2%

Effect of Flux Error (obvious...)

→ In order to extract

$\sin^2\theta_{13}$

→ must have

$\sin^2\theta_{23}$

so errors are correlated!

→ dominant error on $\sin^2 2\theta_{23}$ is overall flux

→ can't extract "real" errors on $\sin^2 2\theta_{13}$ without including overall flux

- Disappearance Sanity Check:
  - We have 32K $\bar{\nu}_\mu$
  - Average Oscillation Probability $\approx$ 12%
    - Expect 3840 Disappeared $\bar{\nu}_\mu$

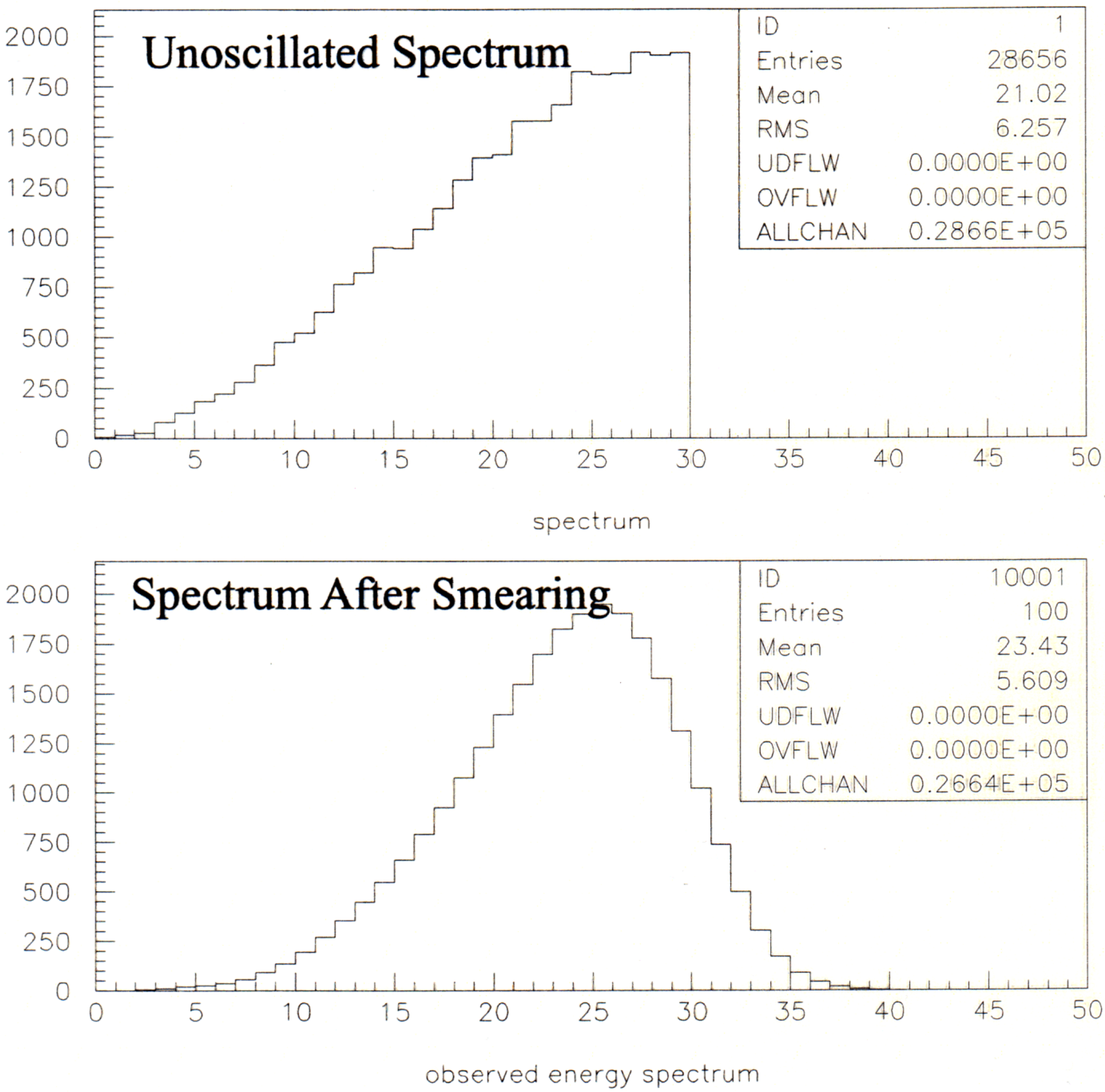
$$\Delta \sin^2 2\theta_{23} = \sin^2 2\theta_{23} \times \frac{1}{\sqrt{3840}}$$
$$\Rightarrow 0.8 \pm 0.0129$$

- ~~Flux~~ Normalisation Error 2%
  - Uncertainty of $.02 \times 32000 = 640$ events

$$\Delta \sin^2 2\theta_{23} = \sin^2 2\theta_{23} \times (640/3840)$$
$$= 0.8 \pm 0.13 \pm 0.013$$

- $\sin^2 2\theta_{23}$ Completely Dominated by Flux

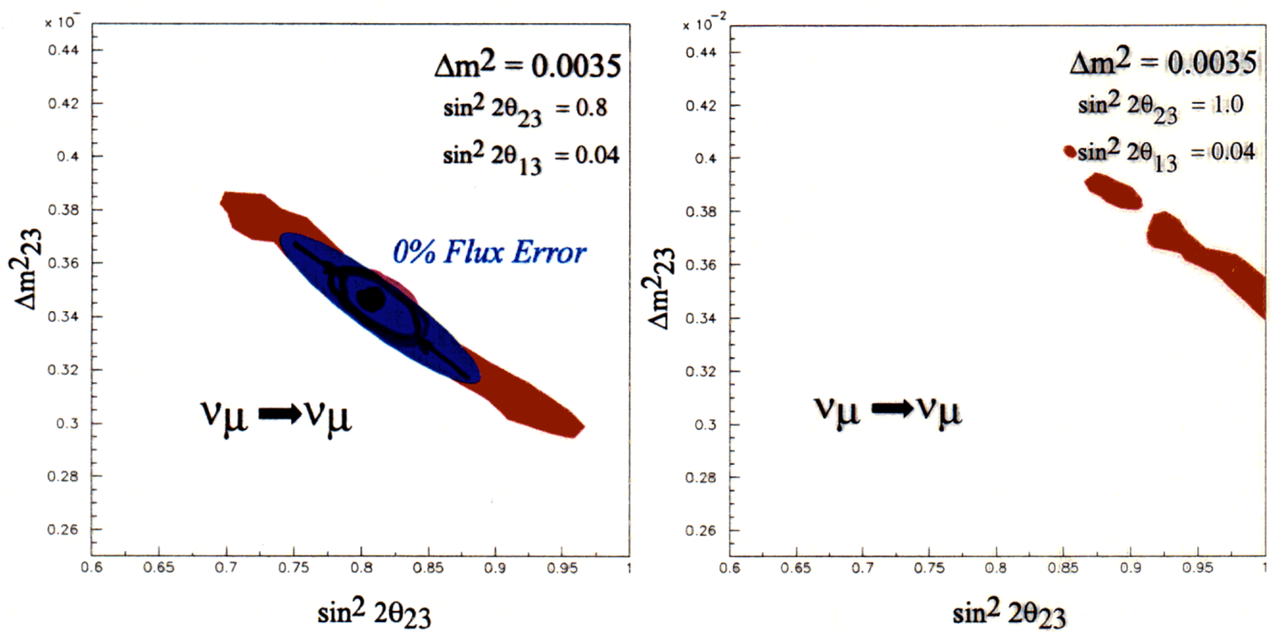
ν_μ Disappearance Test



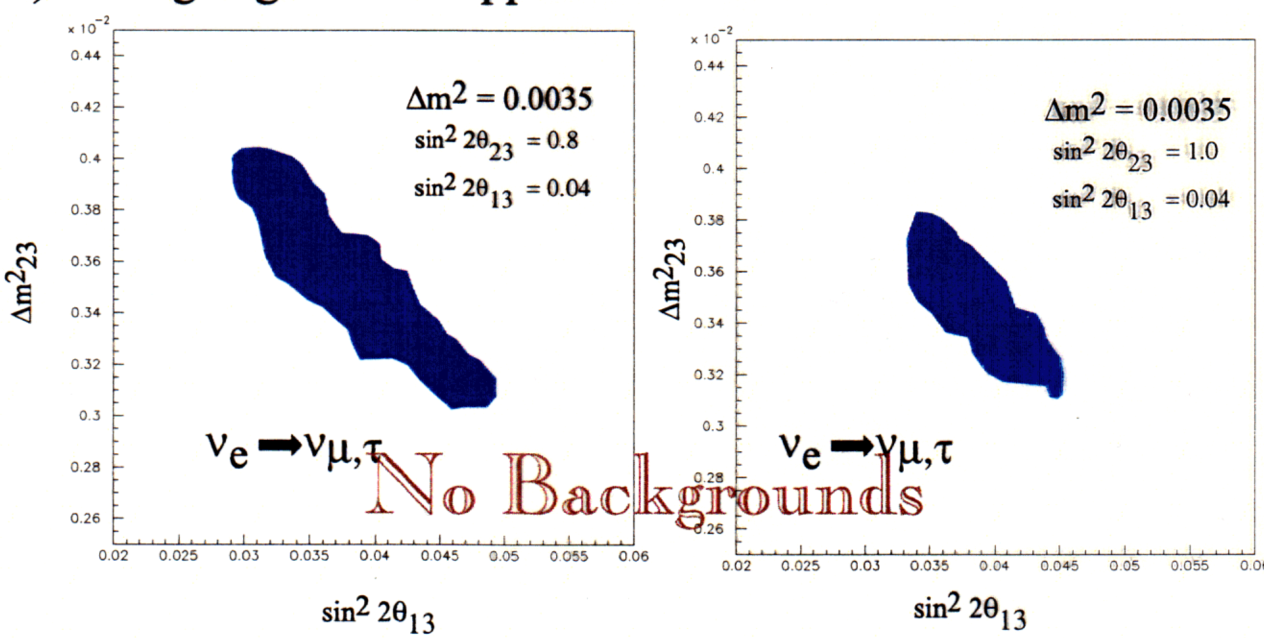
2880 km, 30 GeV, 2E20 Decays, 10 kt Fiducial

2% Overall ~~Flux~~ Normalization

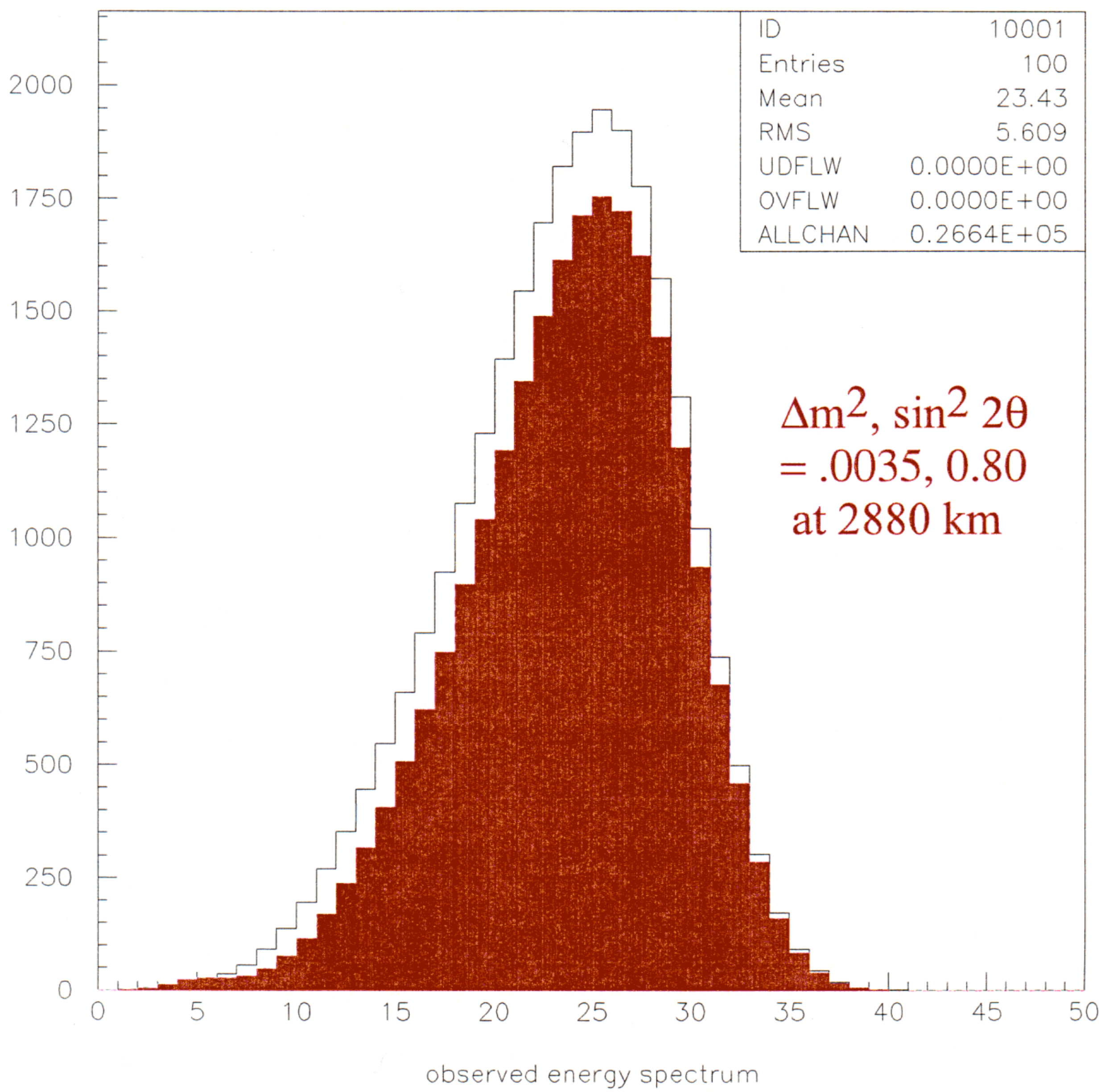
a) Disappearance Test



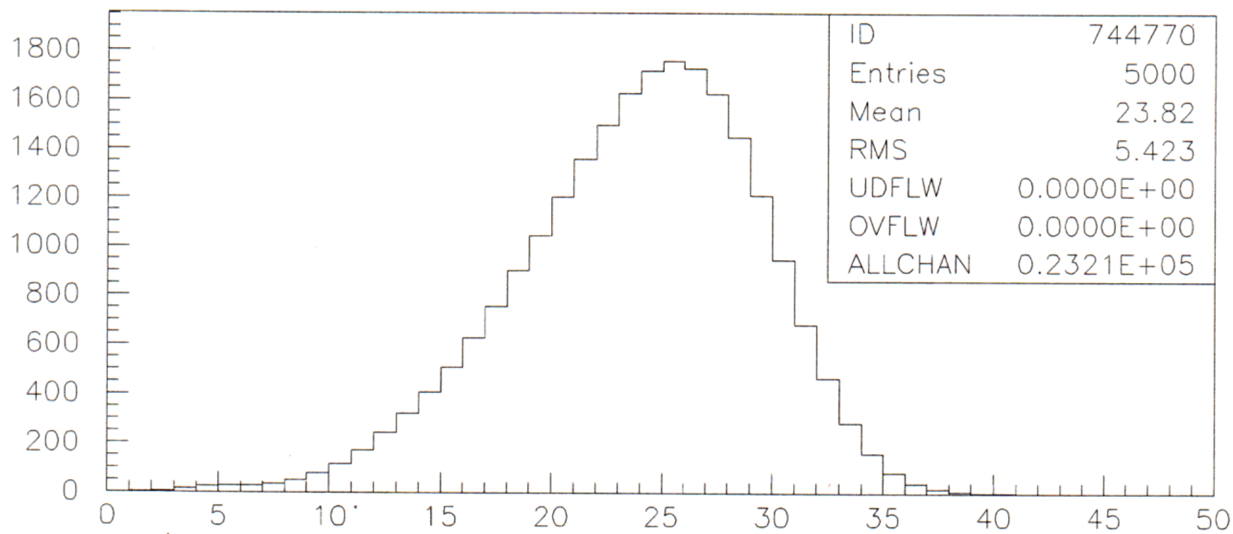
b) Wrong-Sign Muon Appearance Test



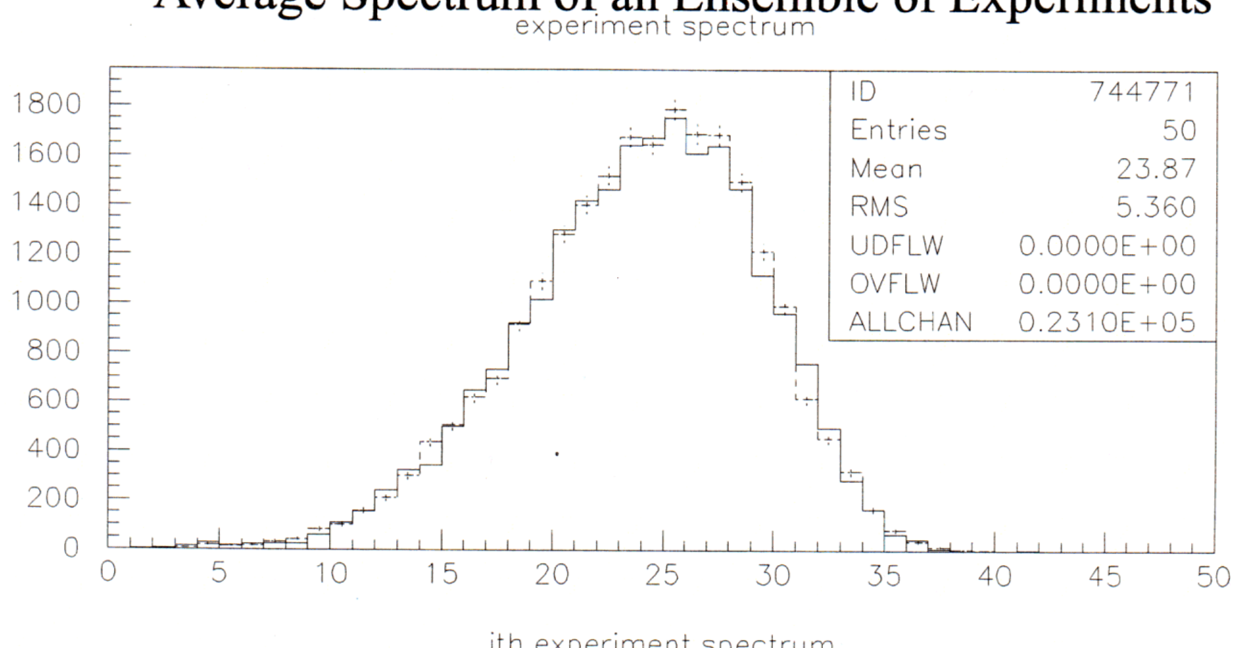
How Different Are These Spectra?
-- generated from two Δm^2, $\sin^2 2\theta$ points



What Does the Spectrum Look Like?

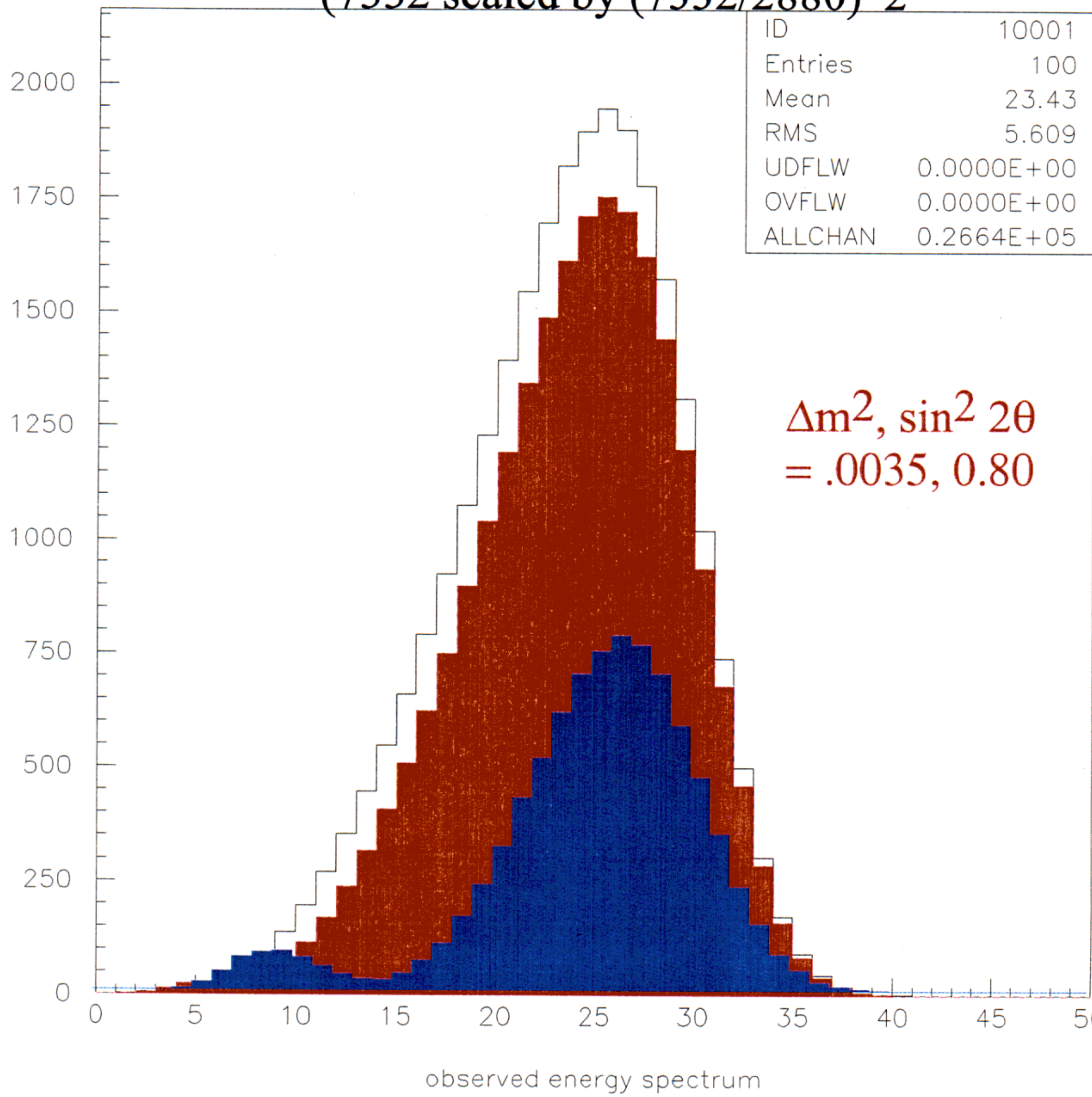


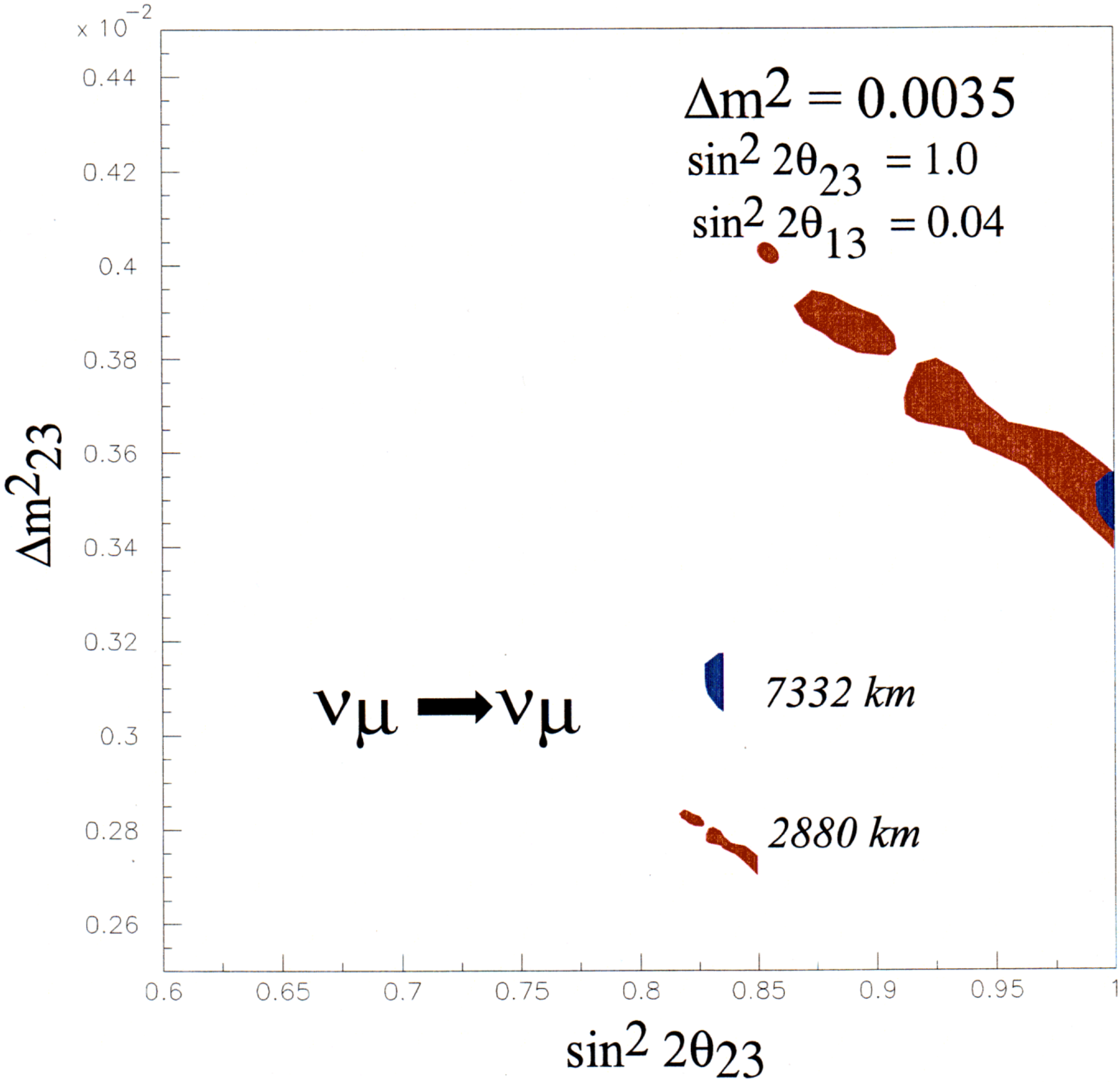
Average Spectrum of an Ensemble of Experiments



Spectra for Two Representative Experiments

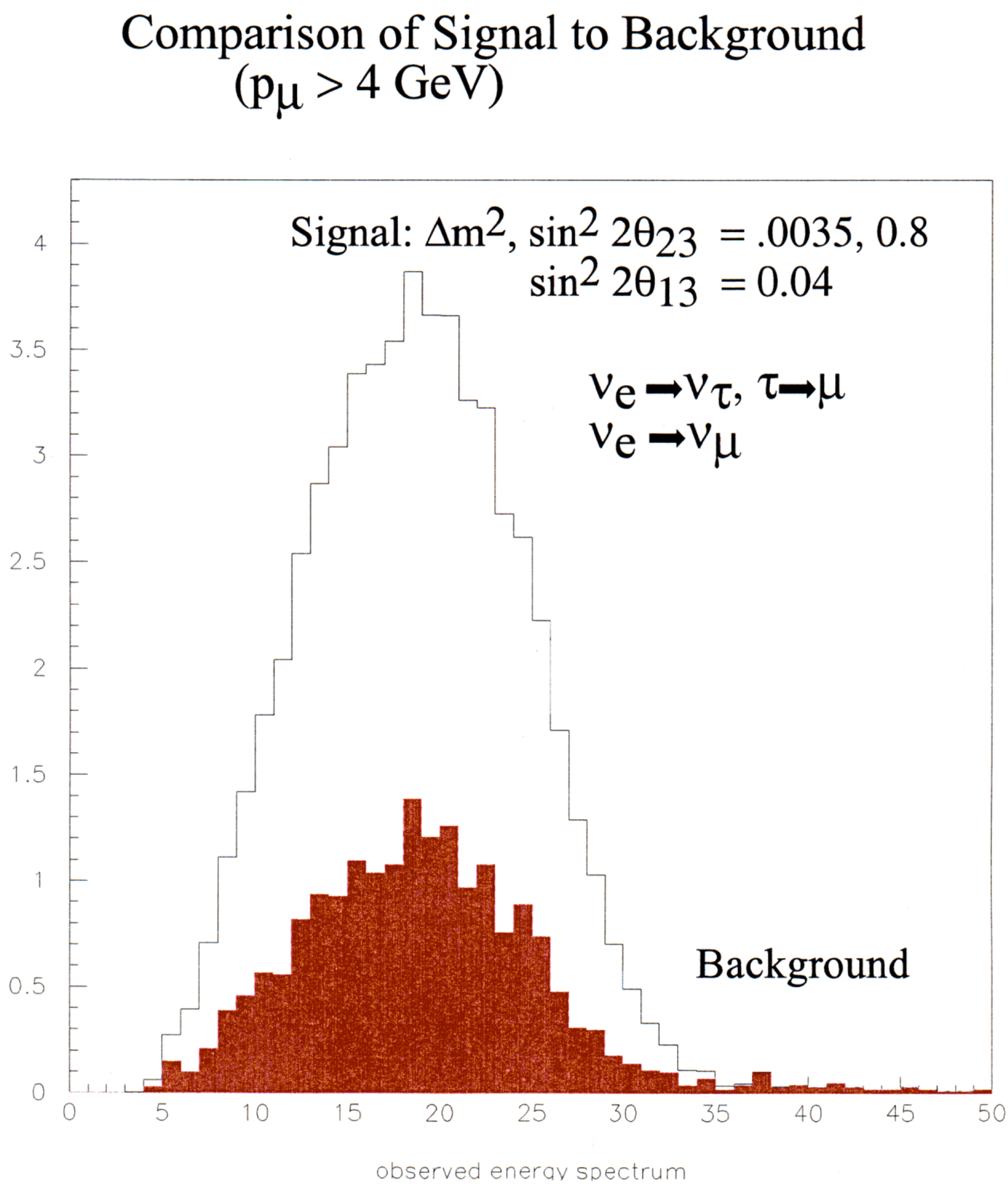
Change of Spectrum With Distance: Unoscillated to 2880 to 7332 km (7332 scaled by (7332/2880)^2





x 10^-2
0.44
0.42
0.4
0.38
0.36
0.34
0.32
0.3
0.28
0.26
Δm²23
Δm² = 0.0035
sin² 2θ23 = 1.0
sin² 2θ13 = 0.04
νμ ➡ νμ
7332 km
2880 km
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
sin² 2θ23

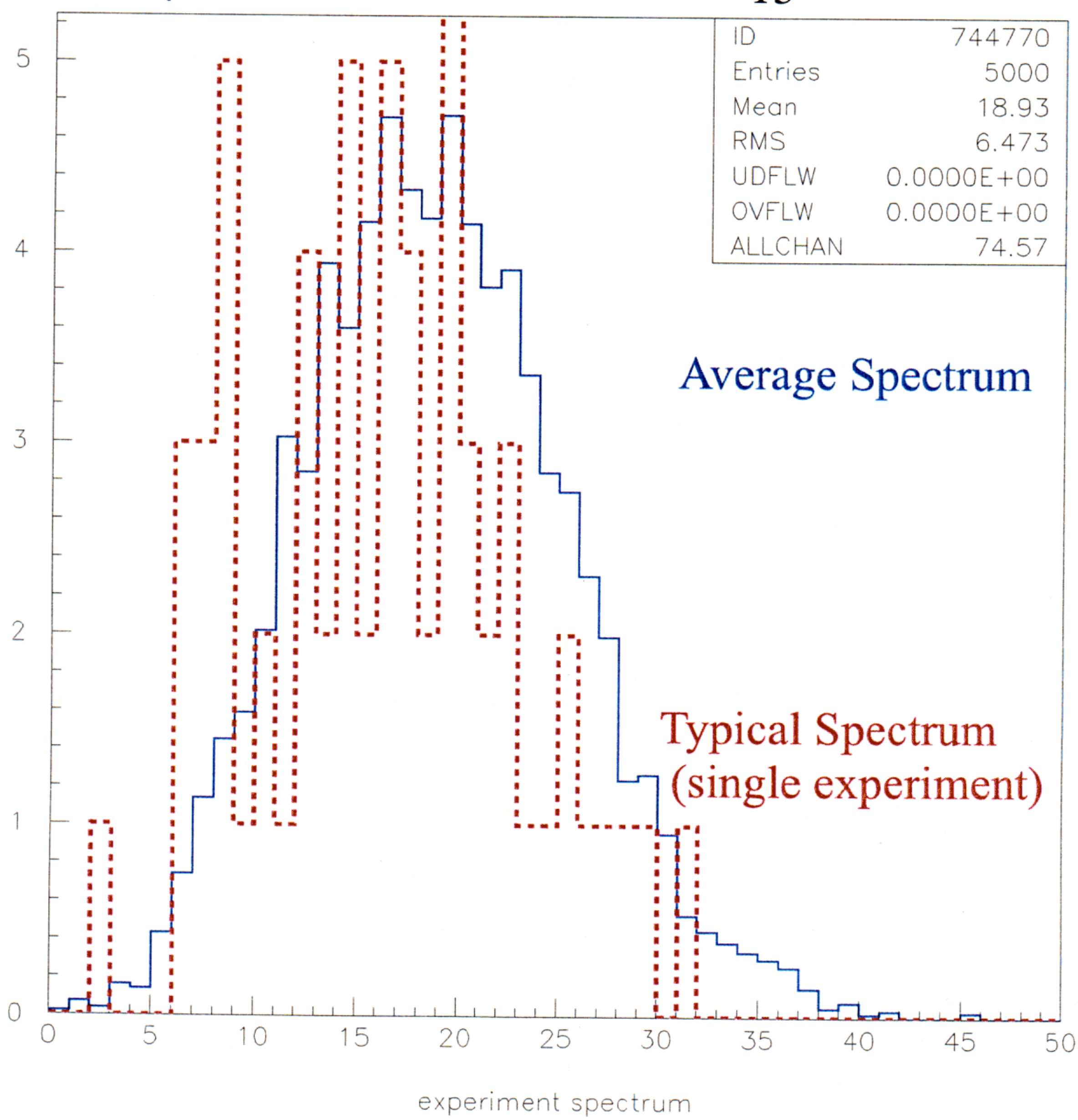
- What Does the Appearance Signal Look Like?

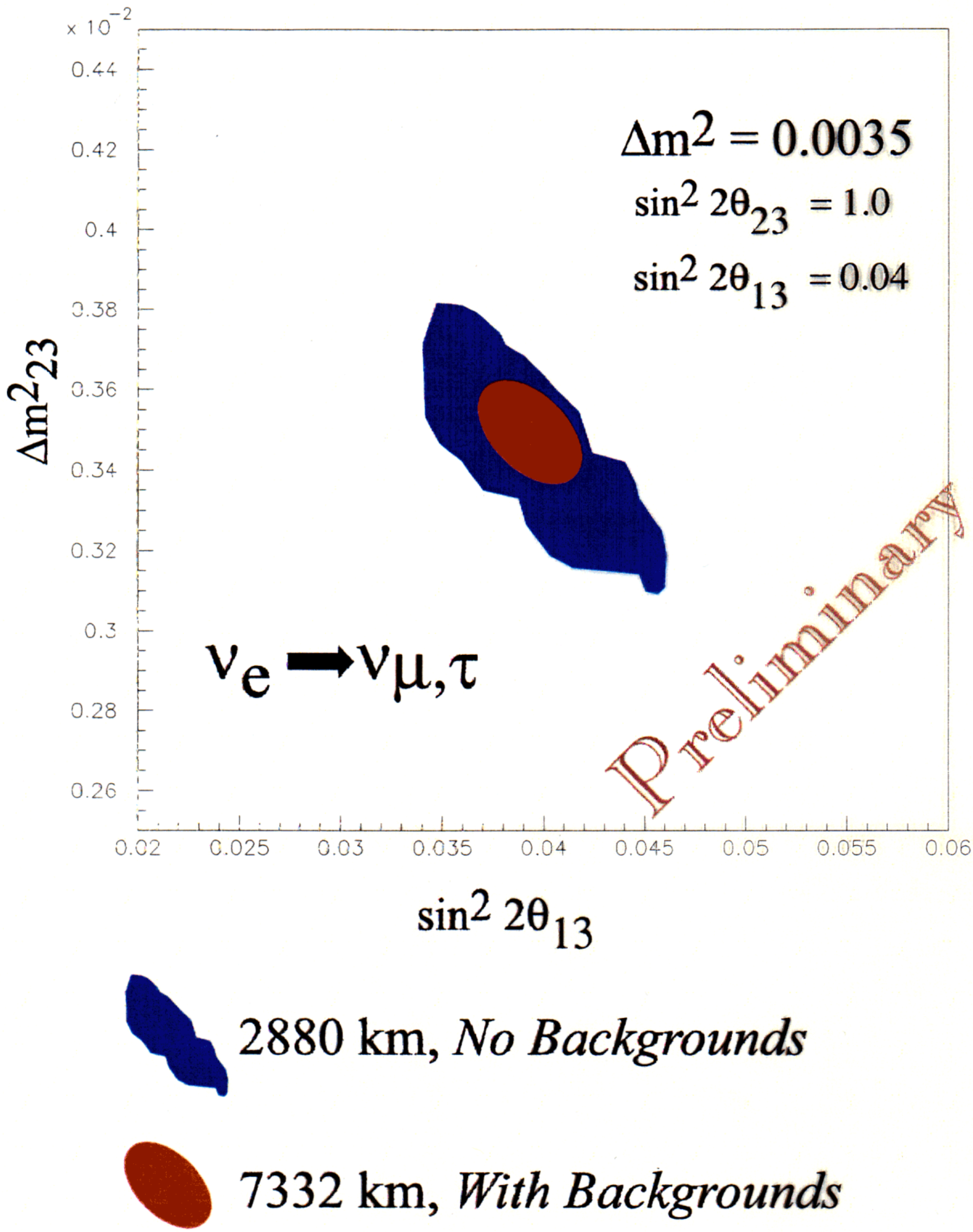


- Beware Nice-Looking MC!

What Does Data From a Run Look Like?
– 2E20, 30 GeV, 10 kT fiducial

$\nu_e \rightarrow \nu_\tau,\ \tau \rightarrow \mu$ Signal: $\Delta m^2, \sin^2 2\theta_{23} = .0035, 0.8$
$\nu_e \rightarrow \nu_\mu$ $\sin^2 2\theta_{13} = 0.04$





–Matter Effects
from Mocioiu + Shrock

What Does This Imply?

- Physics Case for Longer Baseline Very Strong

  §1. Use L/E to increase signal-to-background

  §2. Use matter enhancement to increase signal and measure parameters

  §3. Can match 10 kt, 3000 km statistics with 50 kt at 7000 km, not crazy

  Depends on What You Think About $\bar{CP}$ — two detectors at different baselines?

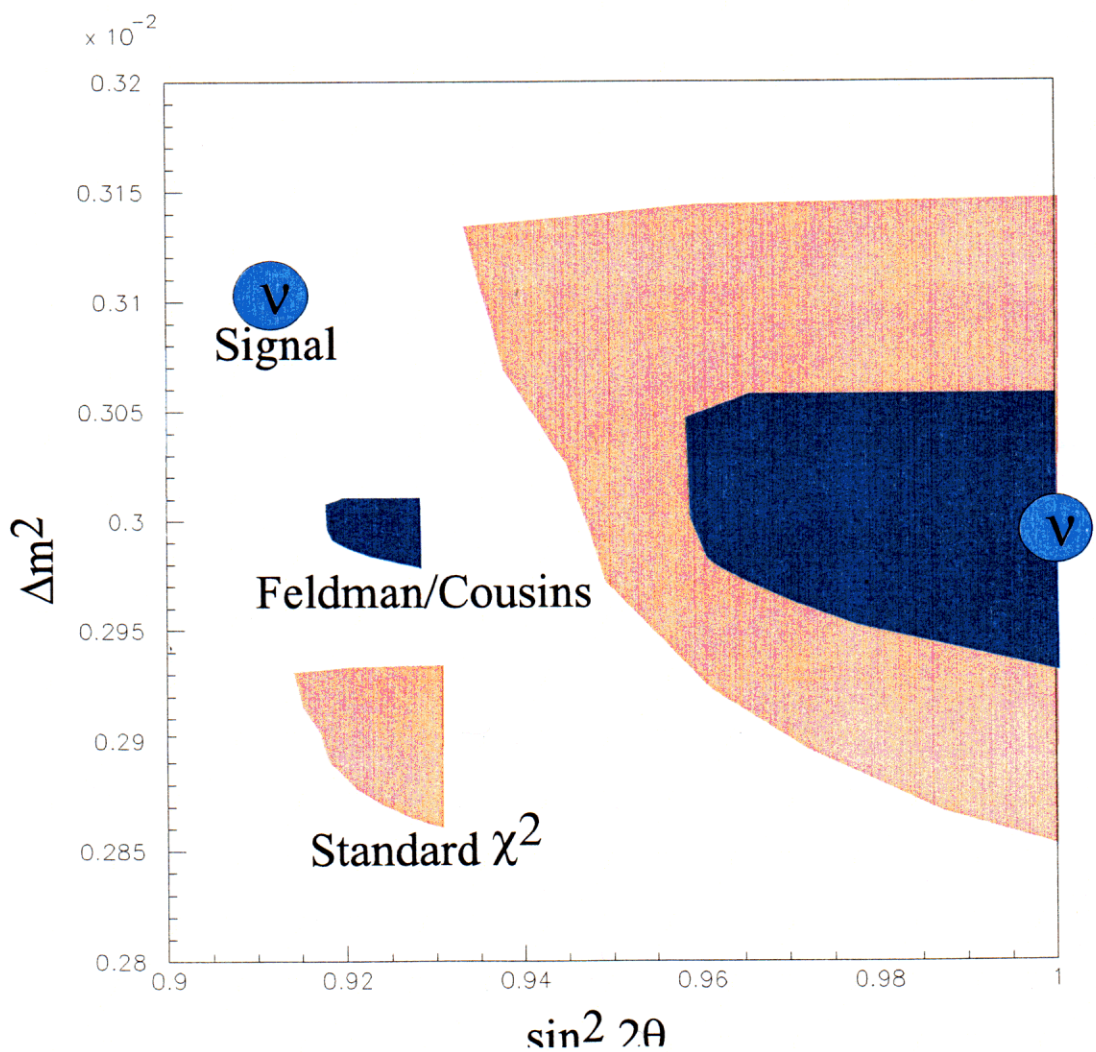
- For Appearance:

  §1. Either Fine-Grained for Better Resolution

  §2. $p_\perp^2$ Cuts and Good Resolution Essential
  - Increase L implies Loss in Statistics
  - Make Up with More Mass
  - Less Fine-Grained?

Fitting and Physical Boundaries

- *It Makes a Difference!*
  - SuperK result near Physical Boundary
  - Use Feldman/Cousins Unified
    ($aka\ Neyman/Pearson$)
    vs. Standard χ^2 like MINUIT



Method

- Choose point in $\Delta m^2, \sin^2 2\theta$ space
- Run Many "Experiments"
  Assuming Oscillations:
  Get Distribution of some χ^2
- For each point in oscillation space run many experiments allowing all errors to fluctuate as they would in a real experiment.
  $\Rightarrow$ "Natural" χ^2 Distribution
  for that Point in Parameter Space
- Fit the fluctuated Monte Carlo to the the hypothesis and extract the "best fit."
- After we have the best fit, calculate for each point in parameter space the statistic:

$$\Delta\chi^2 = \chi^2(\text{ this point in space}) - \chi^2(\text{ best fit})$$

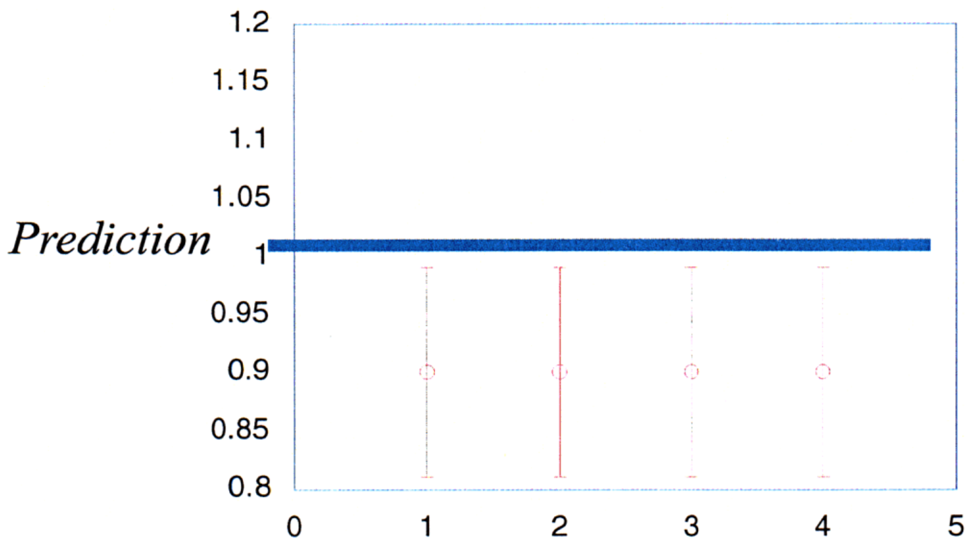
$\Rightarrow$ Do this all in MC, before taking Data

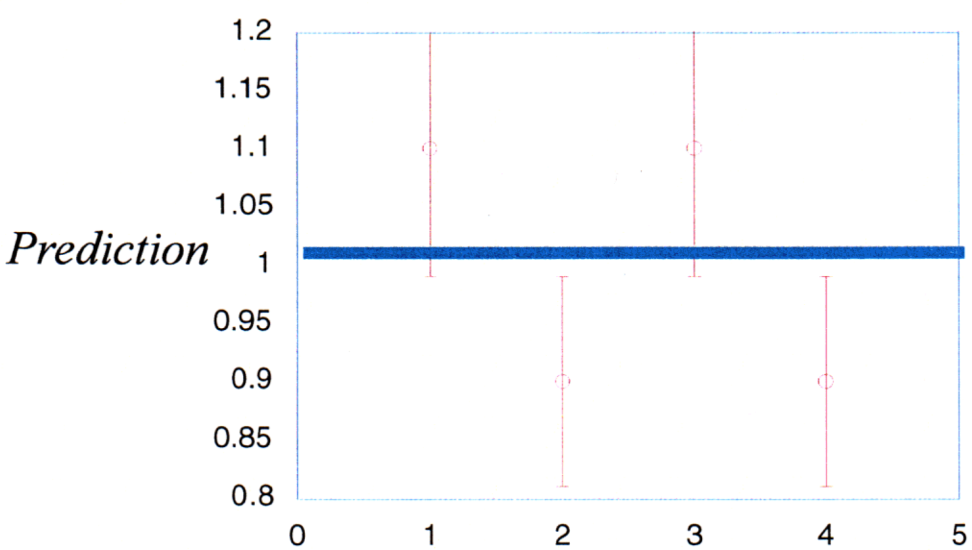
Compare Data to Distribution

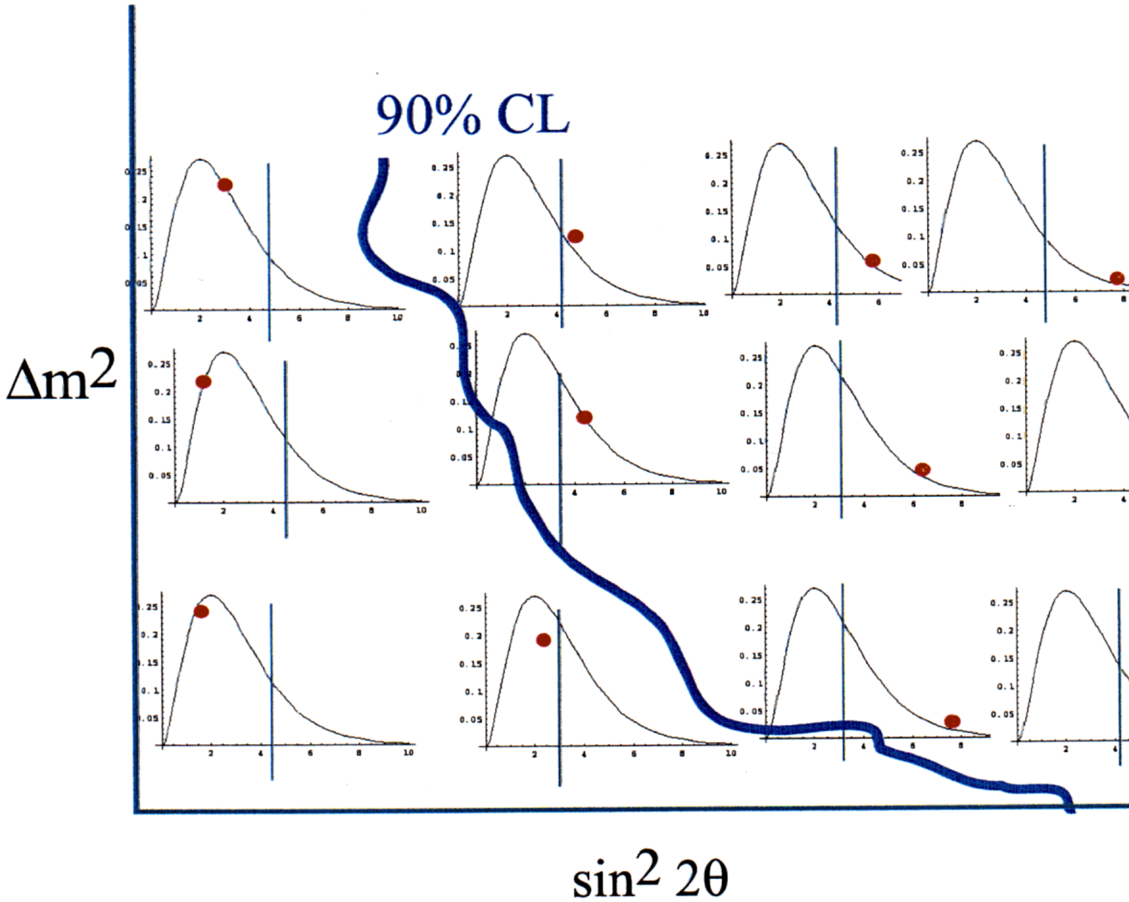
- Treat Data *Exactly* as Any of MC Ensembles
- Are Data Consistent With $\Delta\chi^2$ for that $\Delta m^2, \sin^2 2\theta$ at Chosen CL?
- *Same* for Signal and Exclusion!

$$\chi^2 = -2 \sum_{\text{momentum bins}} \ln \frac{e^{-\mathbf{O}} \ \mathbf{O}^{\mathbf{FO}}}{\Gamma(\mathbf{O}+1)}$$

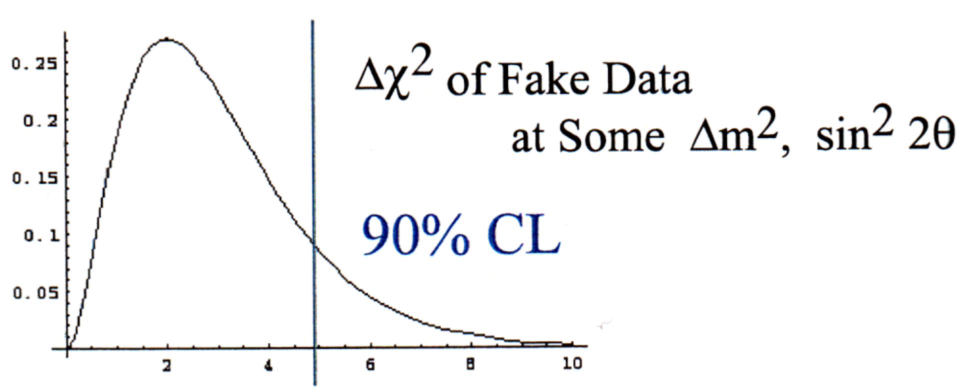
- Recall Problem of Standard χ^2:
  Doesn't Distinguish Systematic Shifts
  Important in $\sin^2 2\theta \leftrightarrow$Flux Errors?
- Investigating KS-Statistic — Promising!

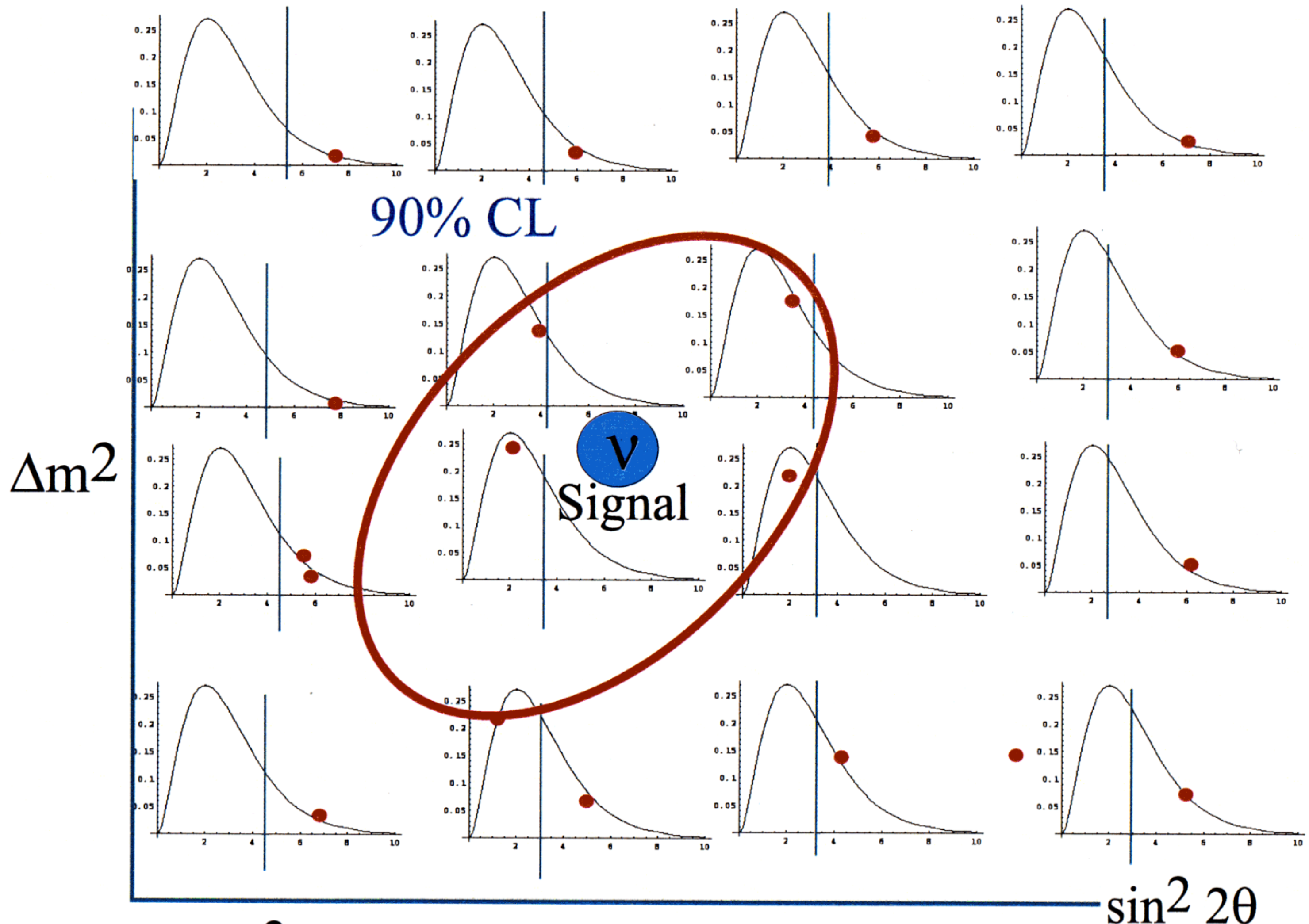

1.2
1.15
1.1
1.05
Prediction
1
0.95
0.9
0.85
0.8
0
1
2
3
4
5


1.2
1.15
1.1
1.05
Prediction
1
0.95
0.9
0.85
0.8
0
1
2
3
4
5



● $\Delta\chi^2$ of Data at Some Δm^2, $\sin^2 2\theta$





$\Delta\chi^2$ of Data at Some Δm^2, $\sin^2 2\theta$

● Compared to Fake Data at Each Point in Parameter Space