CC Disappearance and ν_e Appearance in the NuMI Off-Axis Beam

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NuFact '03

Outline

- CC Disappearance:
  - Physics and Detector Assumptions
  - Correlations and the Physical Boundary
  - Results
- ν_e Appearance:
  - Detector Choices
  - Results
  - Conclusions

Physics and Detector Assumptions for CC Disappearance

- Searching for $\nu_\mu \rightarrow \nu_\tau$
- Off-Axis Detector: 10 km at 735 km
- Un-magnetized Detector with Calorimetry from Hit Counting:

§1. $\sigma/E = 1.0/\sqrt{E}$ as in FMMF (R. Hatcher, priv. comm.)

(Contrast to $0.8/\sqrt{E}$ CCFR and $0.55/\sqrt{E}$ NuMI)

§2. No μ Tracking or Pattern-Recognition

Two Points Above Imply No Spectral Information, so

- Σ events from 1–3 GeV so total rate test, *relies on "δ-fcn" beam:*
  - ν_μ at 2 GeV after oscillation won't reconstruct at 2 GeV

- Choices somewhat Arbitrary,
  Based On Notion that
  NC Contamination Dominates Error

Choice	Reason	Alternative
1–3 GeV Range	Around Peak and 1σ	Tune
Hit-Counting	No Calorimetry	Calorimeter
No Muon Tracking	π/μ's Look Identical	H_2O Ch.
Total Rate	No Spectral	Calorimetry

- Algorithm: ν_μ Oscillates to:

Channel	CC	NC
ν_τ	below threshold	Identical to ν_μ NC
ν_e	ignore	ignore

For now, ignore ν_τ NC interactions
which pass cuts...

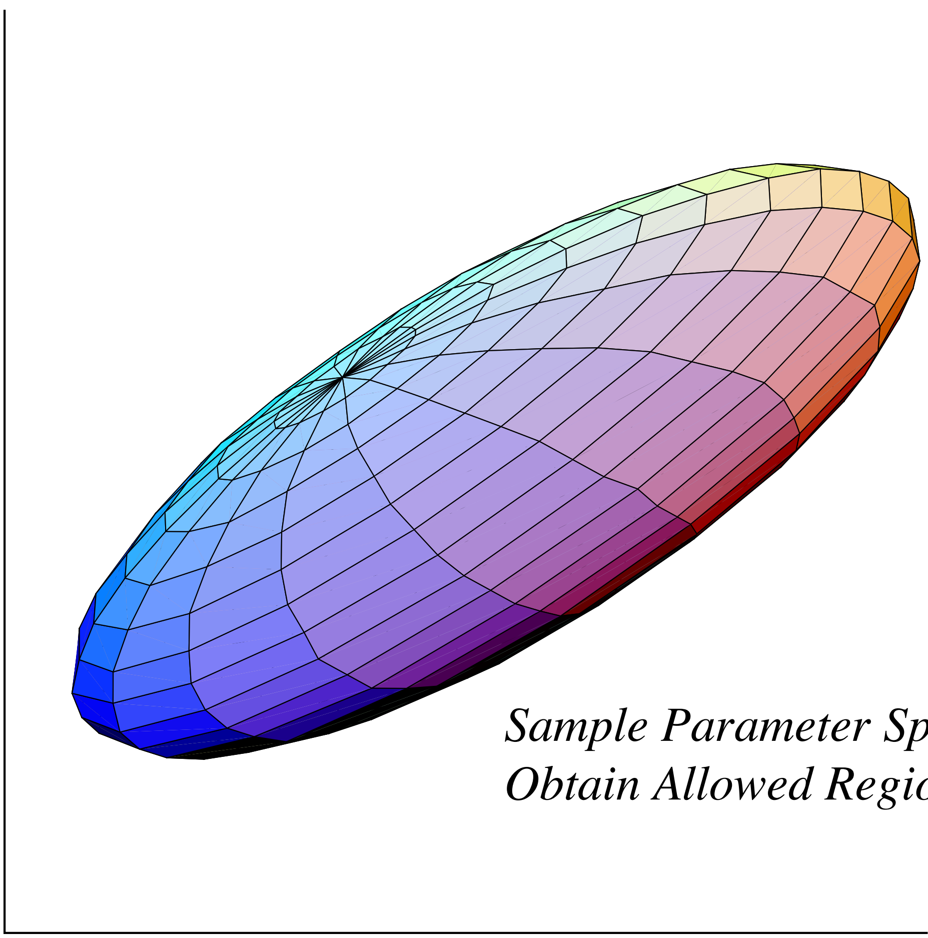
- Suggestion:

§1. Investigate Spectral Test

§2. Quasi-Elastics

Neyman-Pearson Hypothesis Test

- *aka* Feldman-Cousins
- "Most Powerful" Accept-Reject
- Constructs Confidence Levels
- Correctly Handles Physical Boundary and Correlated Errors



Sample Parameter Space to Obtain Allowed Region

Generate $\Delta\chi^2$ Distribution Before Experiment Ever Runs

- Choose point in $\Delta m^2, \sin^2 2\theta$ space
- Run Many "Experiments"
  From that Point:
- Allow All Errors to Fluctuate Acccording to Hypothesized Error Dist

  §1. Gaussian, Flat, Poisson, . . . *etc.*

  §2. Throw Correlated Errors Together
- *e.g.*, correlated flux: affects entire data set
  $\Rightarrow$ Each "experiment" throws a single different correlated flux error
- End Up With Distribution in Error Space With all Correlations Properly Handled and Weighted According to Probability Distribution for Each Error

- For each point in $(\Delta m^2 \sin^2 2\theta)_{\text{true}}$:

§1. Throw errors and form a fake experiment

§2. *Fit* that experiment to some $(\Delta m^2 \sin^2 2\theta)_{\text{best fit}}$
$\Rightarrow$ *not true point in general!*

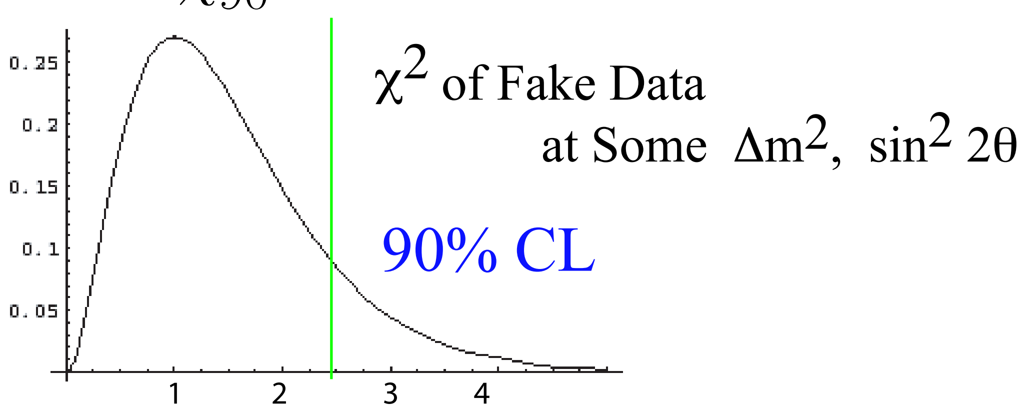
§3. Compare to each point in parameter space: calculate

$$\Delta\chi^2 = \chi^2 - \chi^2(\text{best fit})$$

for one of which, best-fit point, $\Delta\chi^2 = 0$

§4. Form $\Delta\chi^2$ over ensemble of fake experiments from original $\Delta m^2_{\text{true}} \sin^2 2\theta_{\text{true}}$

§5. Integrate distribution out to 90% for 90% CL $= \chi^2_{90}$



- $\Delta\chi^2$ is what is used to determinine confidence levels

Compare Data to Distribution

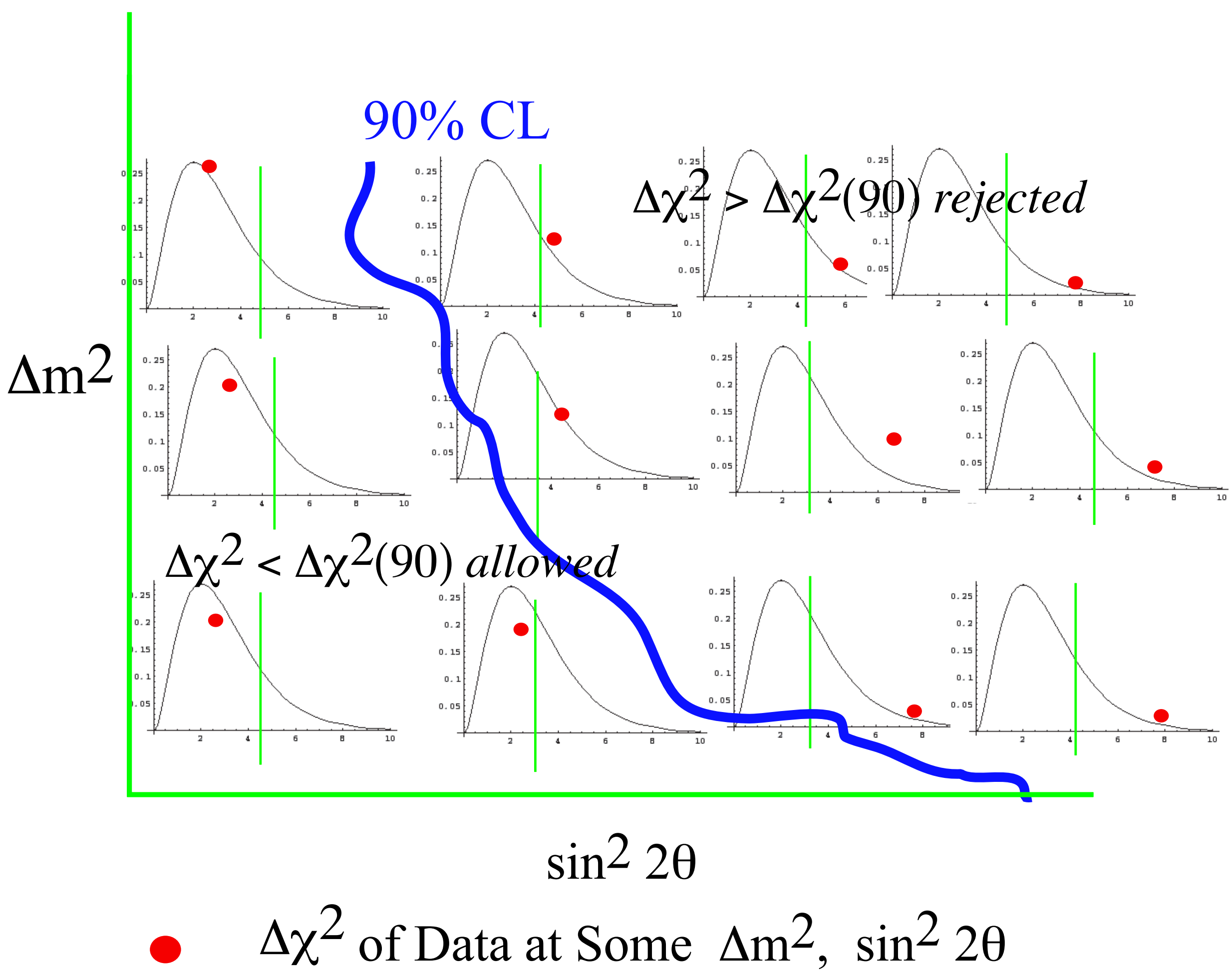
– Do the experiment, take data, and treat it *exactly* like one of the ensemble of "fake experiments"

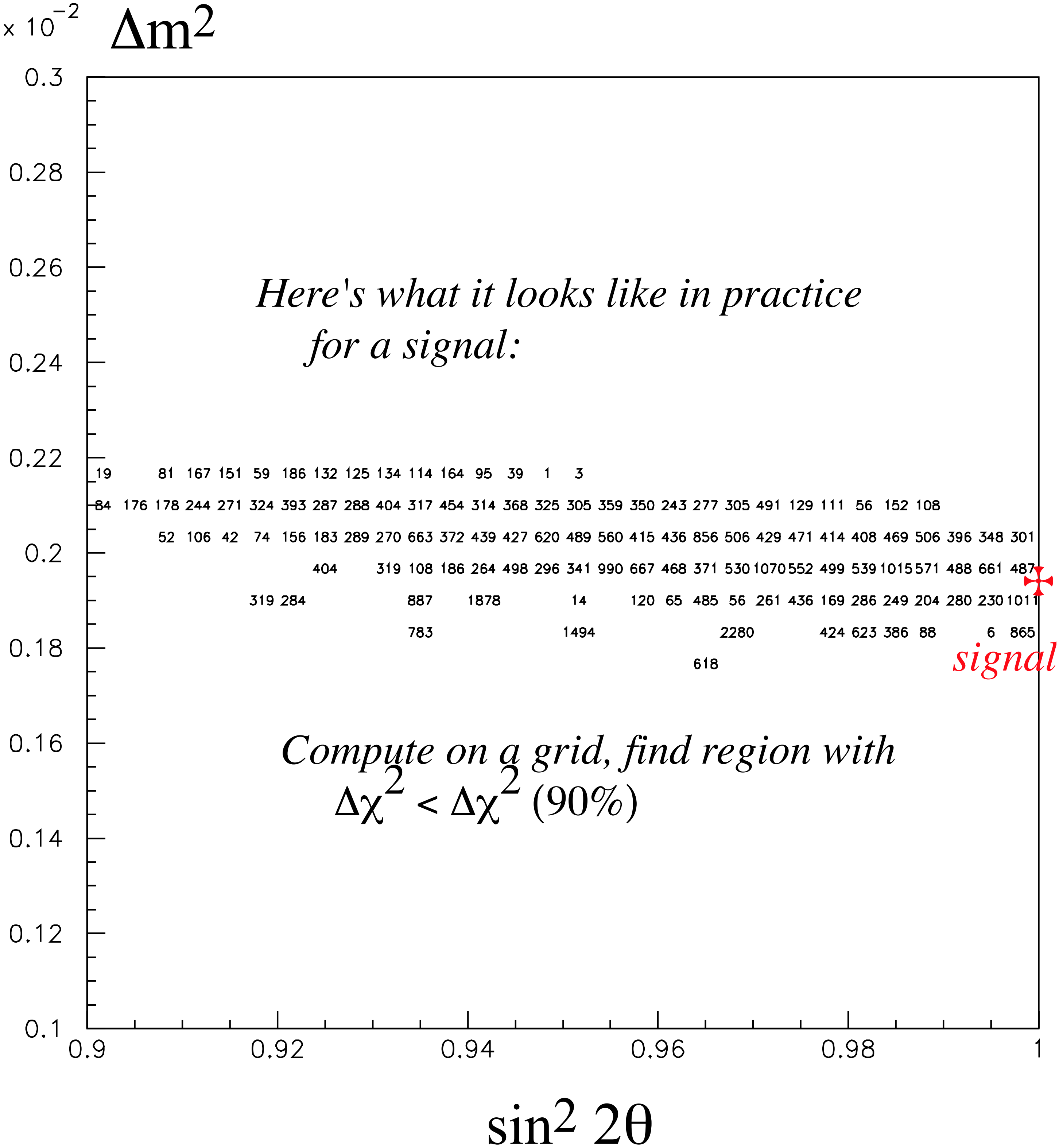
– Is $\Delta\chi^2 < \chi^2_{90}$ for some point in paramter space?

§1. Yes: In Allowed Region

§2. No: Not Allowed

– *Same* for Signal and Exclusion!




x 10^{-2}
Δm^2
0.3
0.28
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
Here's what it looks like in practice for a signal:
19 81 167 151 59 186 132 125 134 114 164 95 39 1 3
84 176 178 244 271 324 393 287 288 404 317 454 314 368 325 305 359 350 243 277 305 491 129 111 56 152 108
52 106 42 74 156 183 289 270 663 372 439 427 620 489 560 415 436 856 506 429 471 414 408 469 506 396 348 301
404 319 108 186 264 498 296 341 990 667 468 371 530 1070 552 499 539 1015 571 488 661 487
319 284 887 1878 14 120 65 485 56 261 436 169 286 249 204 280 230 1011
783 1494 2280 424 623 386 88 6 865
618
signal
Compute on a grid, find region with
$\Delta\chi^2 < \Delta\chi^2$ (90%)
0.9
0.92
0.94
0.96
0.98
1
$\sin^2 2\theta$

$$\Delta\chi^2 = \chi^2 - \chi^2(\text{best fit})$$

Advantages

§1. Separate Hypothesis Testing
from "Goodness-of-Fit"

§2. Can Have Poor χ^2 Distribution but
Still Finds Right Region

§3. Handles Correlations
and Boundaries Correctly

§4. "Simple" to
Rigorously Combine Experiments

Disadvantages

§1. If Best Fit is bad,
subtraction gives small $\Delta\chi^2$

§2. Separate Hypothesis Testing
from "Goodness-of-Fit"

§3. Can Have Poor χ^2 Distribution but
Still Finds Some Allowed Region

e.g. Combined LSND/KARMEN fits

- Errors:

Statistical	100 kt· years	

Beam		
Correlated Flux Random Flux Shape	3% 2% in any 1 GeV bin $A \sin(\lambda E_\nu/5. + \phi)$ $-.10 < A < .10$ flat $0 < \lambda < 2\pi \times 5$ flat $0 < \phi < 2\pi$ flat	From studying hep-ex/0110001, 0110032

Detector		
Hadronic Energy Muon Momentum	$1.0/\sqrt{E}$ not separately seen include with hadron shower energy	

- Shape Error from

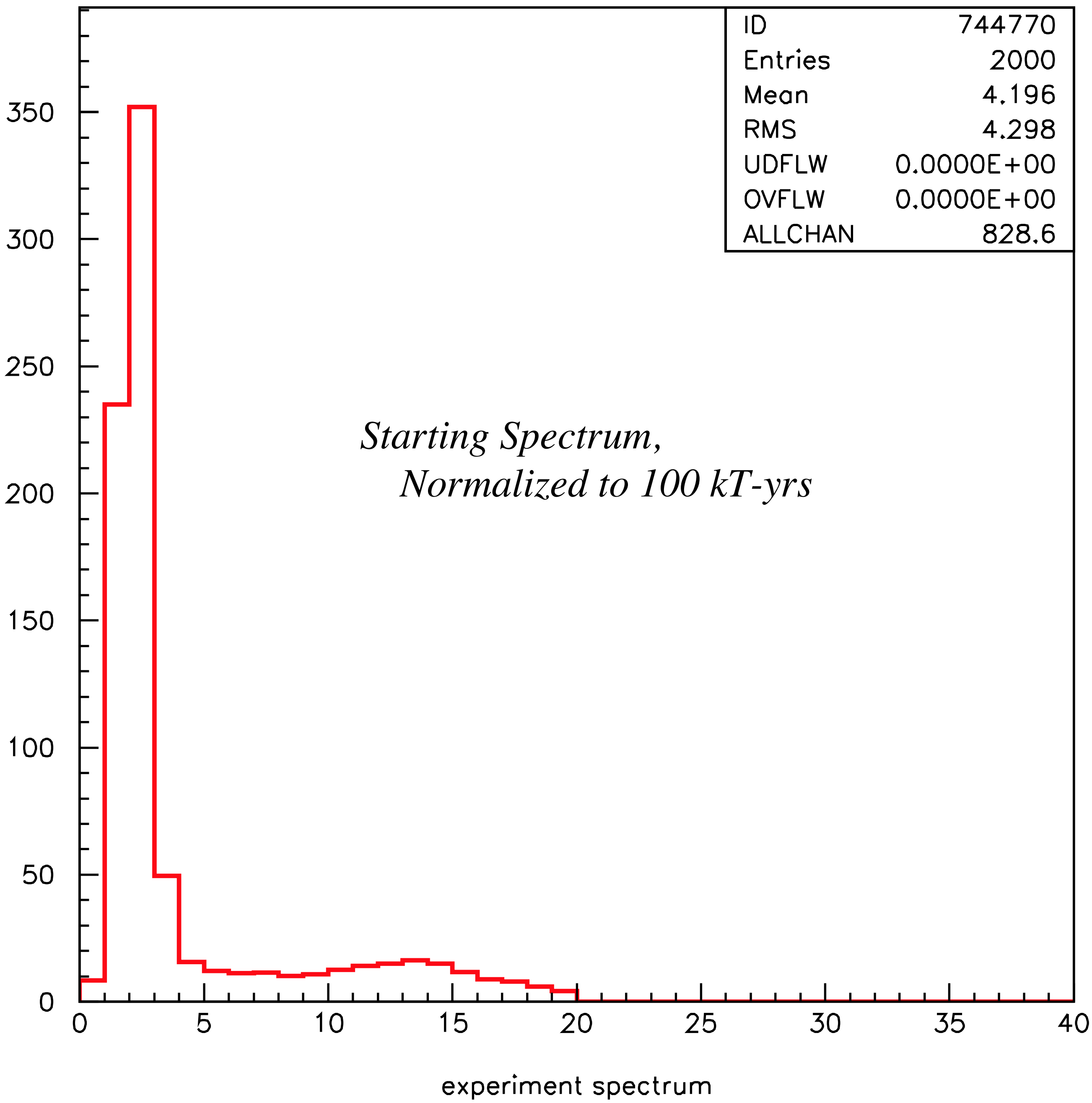
§1. Extrapolation from Near Detector

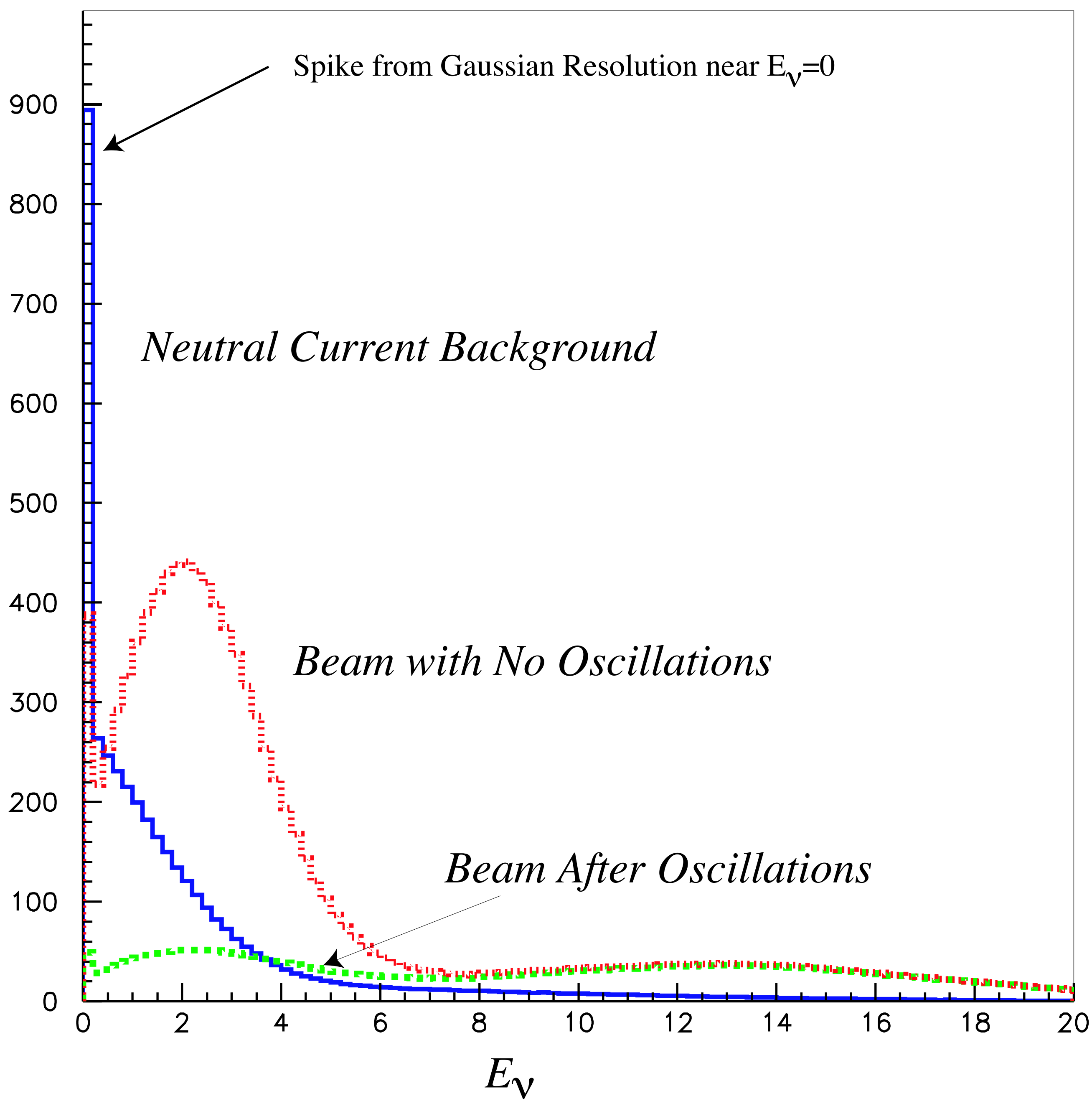
§2. Magnetic Horn Elements

§3. GEANT/FLUKA/...

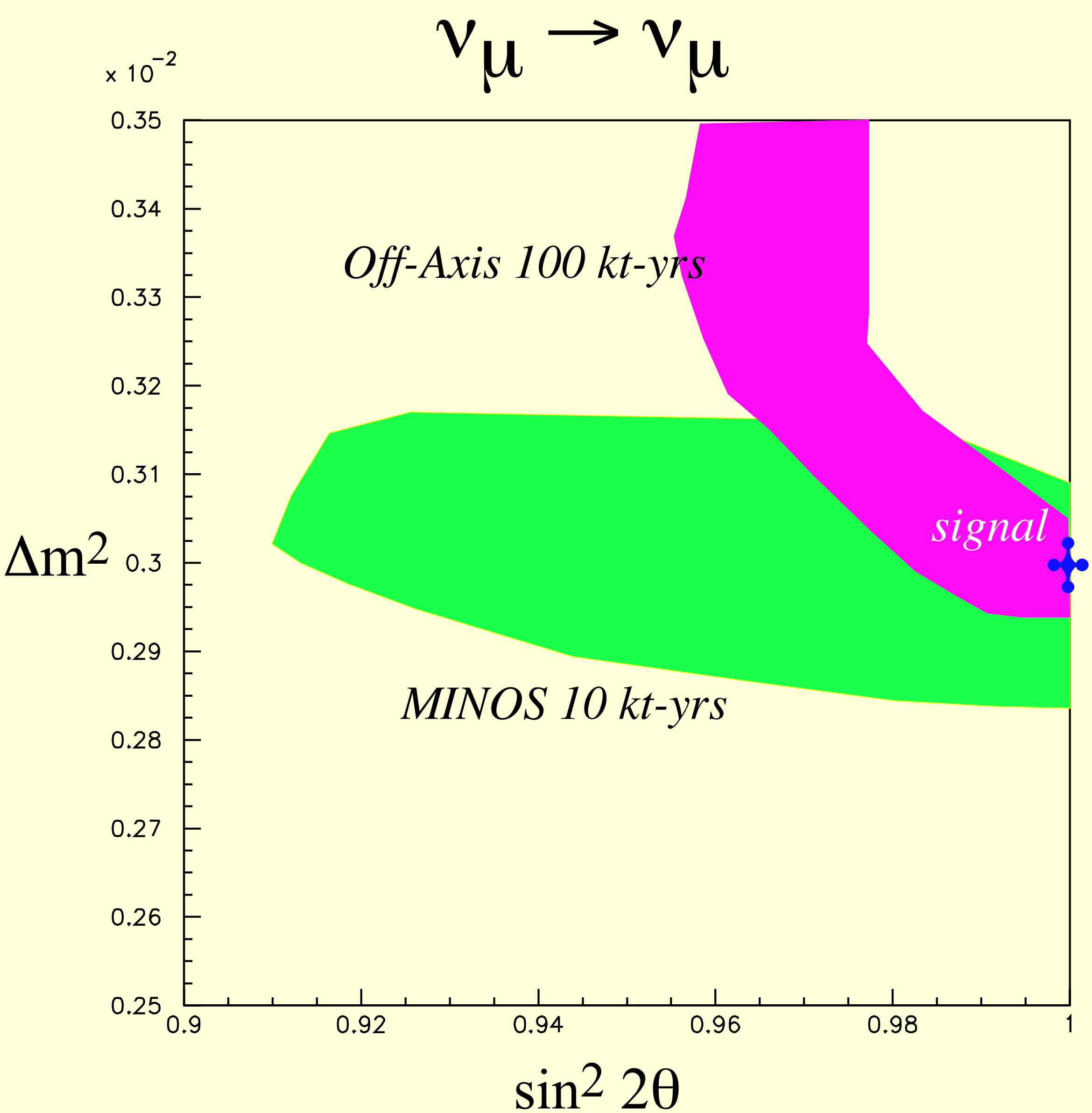
- Correlated Flux from

§1. Fiducial Volume and Mass of Near, Far Detectors


ID 744770
Entries 2000
Mean 4.196
RMS 4.298
UDFLW 0.0000E+00
OVFLW 0.0000E+00
ALLCHAN 828.6
Starting Spectrum,
Normalized to 100 kT-yrs
0
50
100
150
200
250
300
350
0
5
10
15
20
25
30
35
40
experiment spectrum



Spike from Gaussian Resolution near E$_\nu$=0
Neutral Current Background
Beam with No Oscillations
Beam After Oscillations
900
800
700
600
500
400
300
200
100
0
0
2
4
6
8
10
12
14
16
18
20
E_ν



- $\Delta m^2 \approx (2.95\text{–}3.15) \times 10^{-3}$ at 90% CL

Can We Do Better?

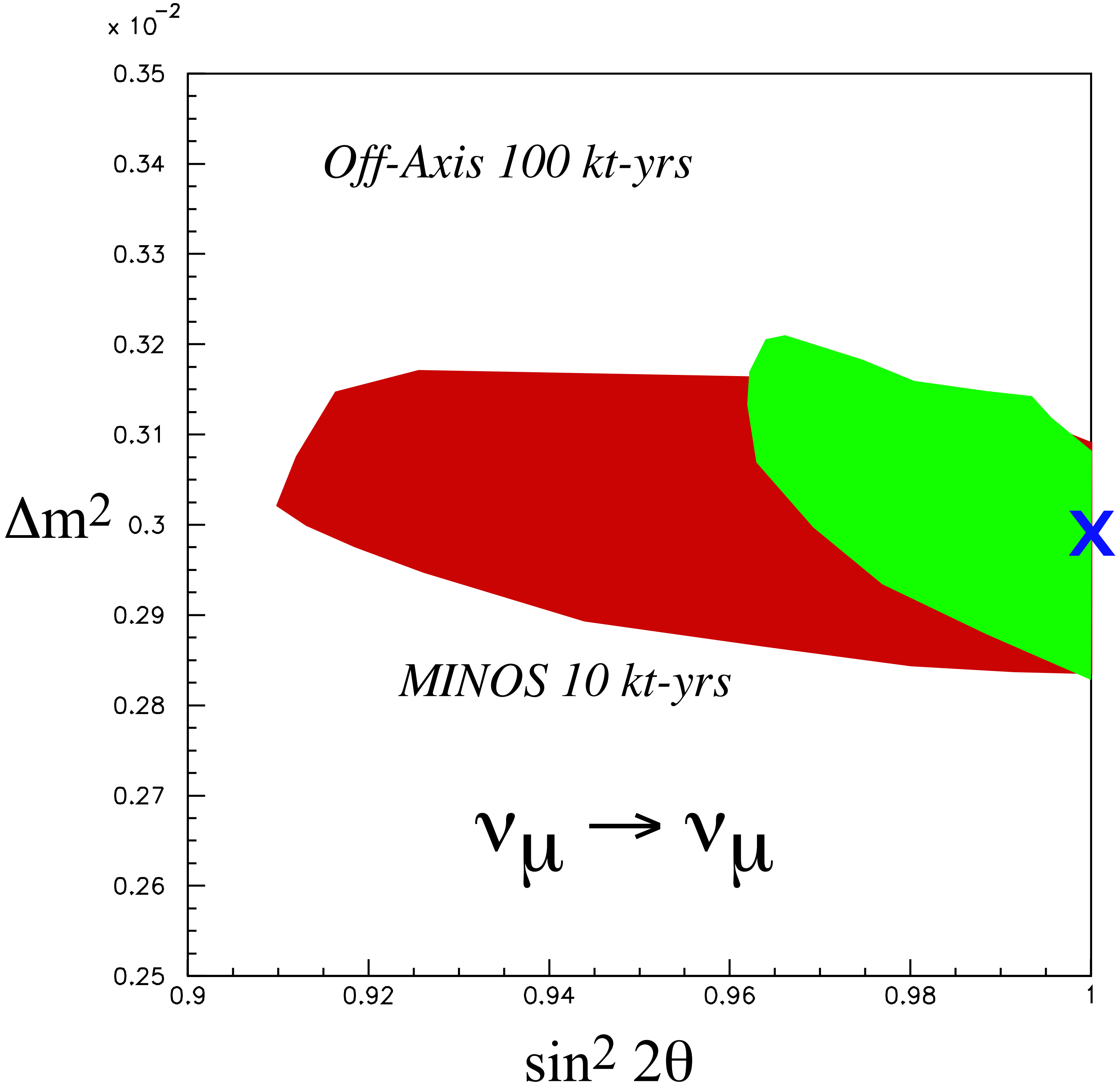
- Doing Better on $\sin^2 2\theta$:
  - Flux Prediction $< 1\%$
  - Fiducial Mass $< 1\%$

    §1. Weigh Every Detector Element

    §2. Understand Fiducial Volume (internal alignment, gaps, dead regions, . . .
- Doing Better on Δm^2

  §1. Need Calorimetry and Muon Tracking

  §2. Cost Goes Way Up, but see next part of talk. . .


x 10^-2
0.35
0.34
0.33
0.32
0.31
0.3
0.29
0.28
0.27
0.26
0.25
Δm2
Off-Axis 100 kt-yrs
MINOS 10 kt-yrs
νμ → νμ
x
0.9
0.92
0.94
0.96
0.98
1
sin2 2θ

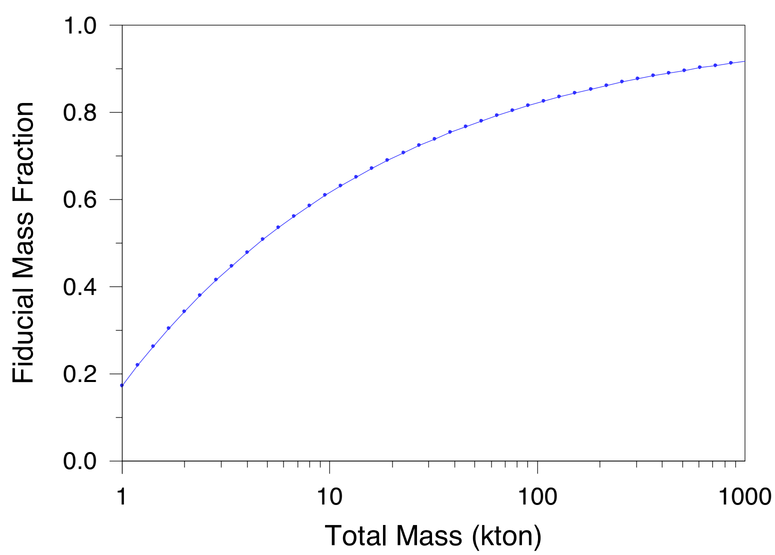
Electron Neutrino Appearance

- Simulated LAr and Fe/Scint:
  100 kt·yr exposure
- NuMI Medium Energy Beam
- ν_e Rate from r = 10 km, z = 735 km

Detector	Signal Efficiency	NC Fake Rate	Res
LAr	0.90	0.001	$0.1/\sqrt{E}$
Fe/Scint	0.40	0.002	$0.55/\sqrt{E}$

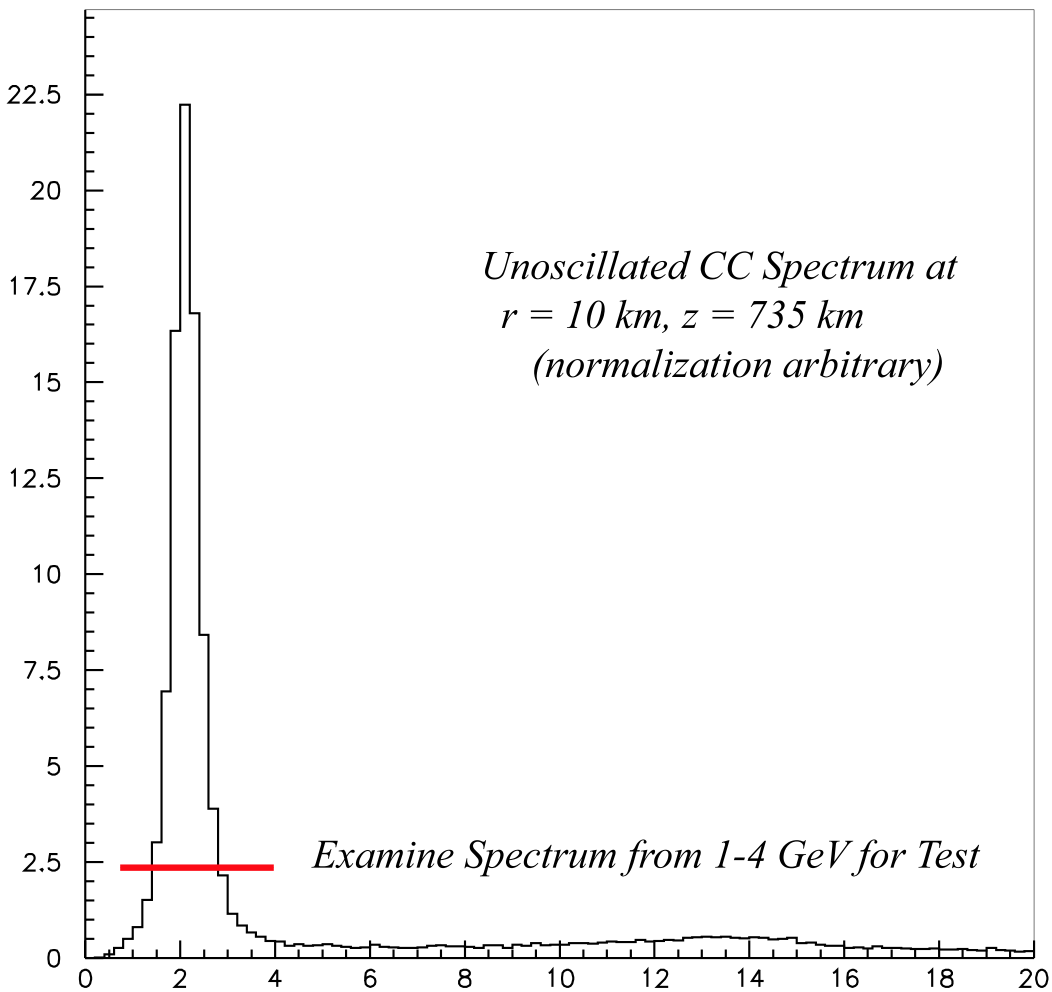
See D.A. Harris *et al.*, hep-ex/0304017

- Fiducial Mass for LAr for 20 kt:
- Fiducial Mass for Fe/Scint 80%



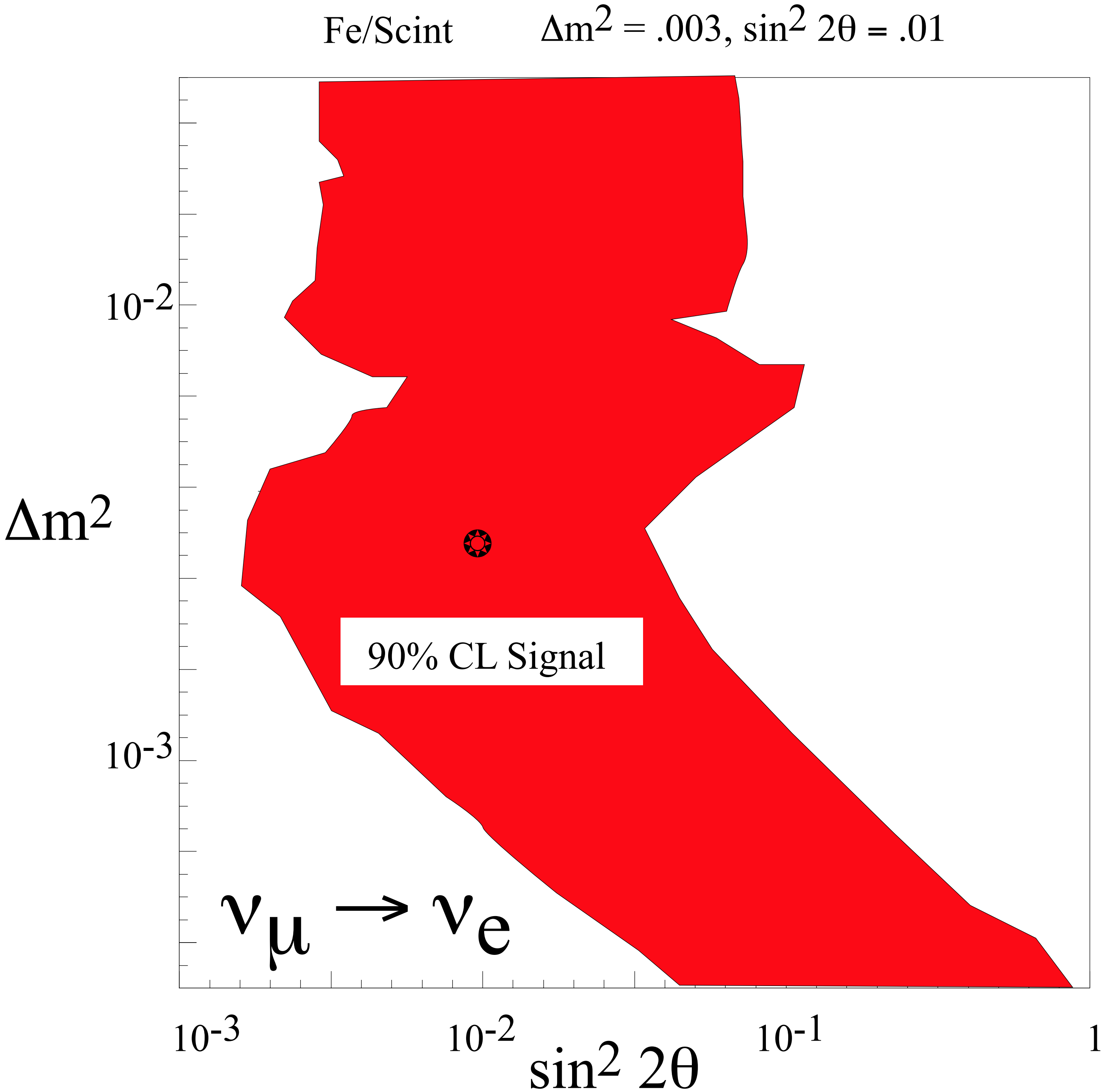
- Ignore CP/Matter, just plot as if in vacuum

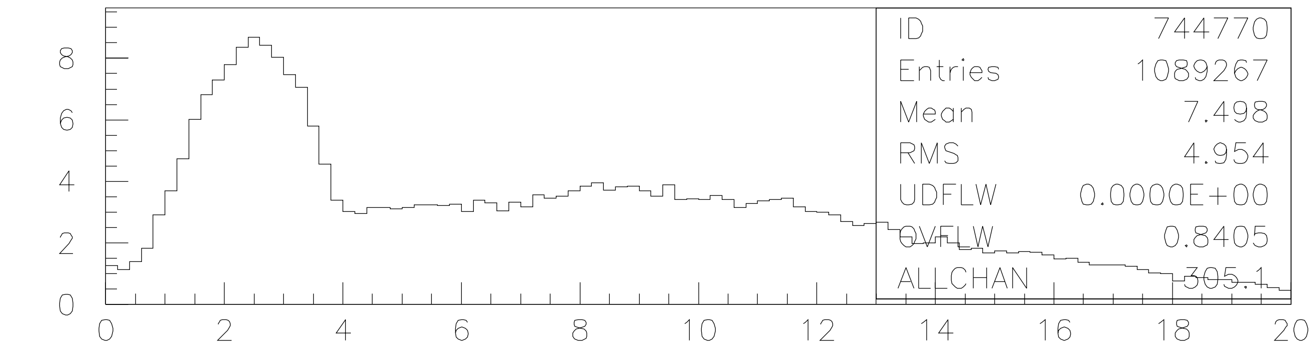
- Starting Spectrum:



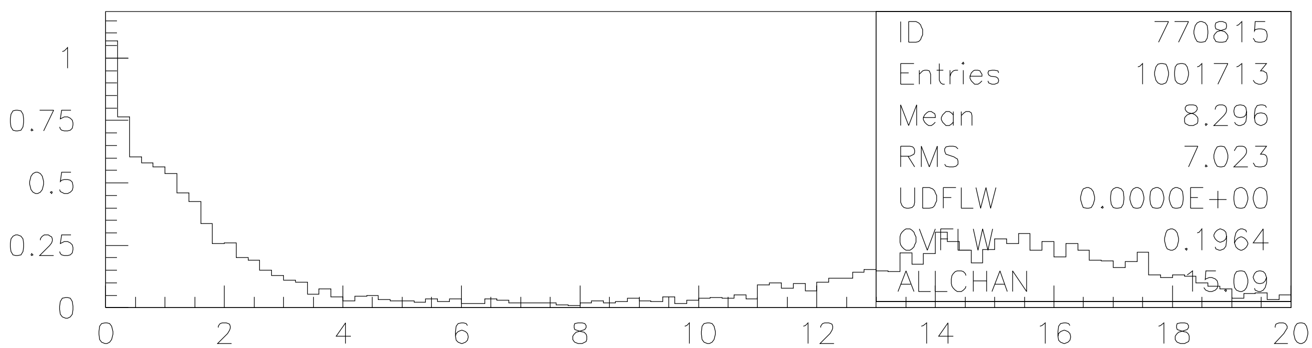
- Same Beam-Related Errors
  as in CC Disappearance
- Reconstruction Efficiency known exactly
- Backgrounds (*stat. fluctuations only*):
  - NC's that appear as ν_e
  - ν_e beam background

Results

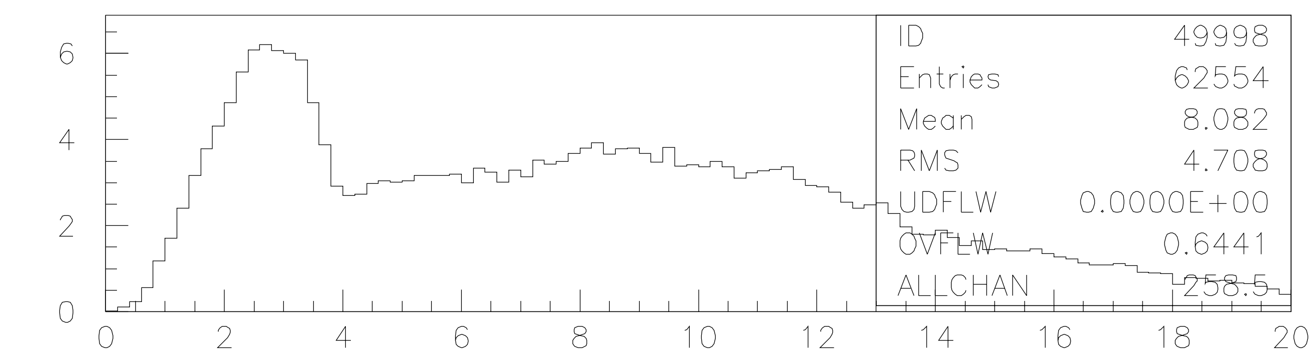

Fe/Scint
Δm2 = .003, sin2 2θ = .01
Δm2
10-2
10-3
90% CL Signal
νμ → νe
10-3
10-2
10-1
1
sin2 2θ



experiment spectrum

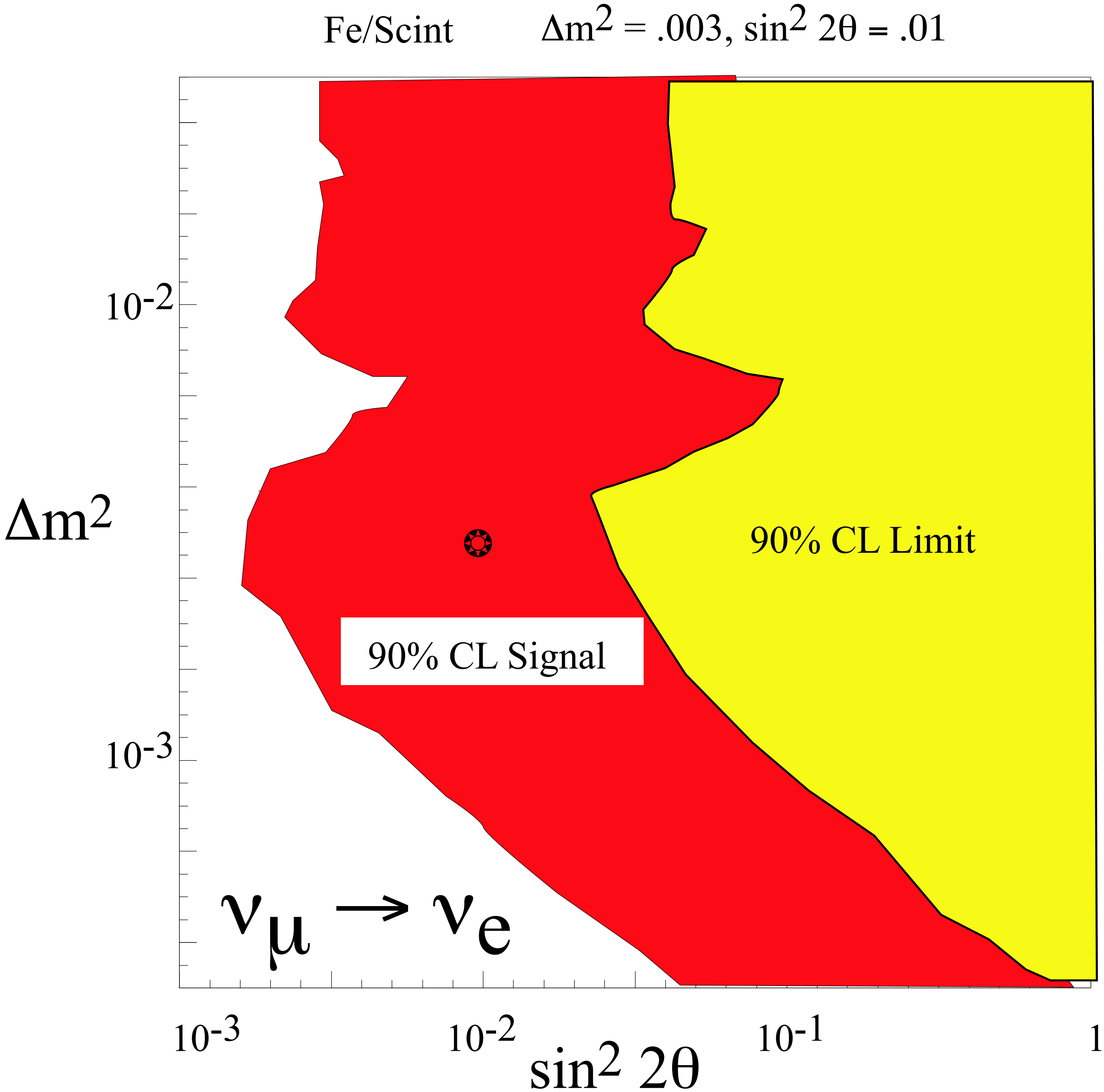


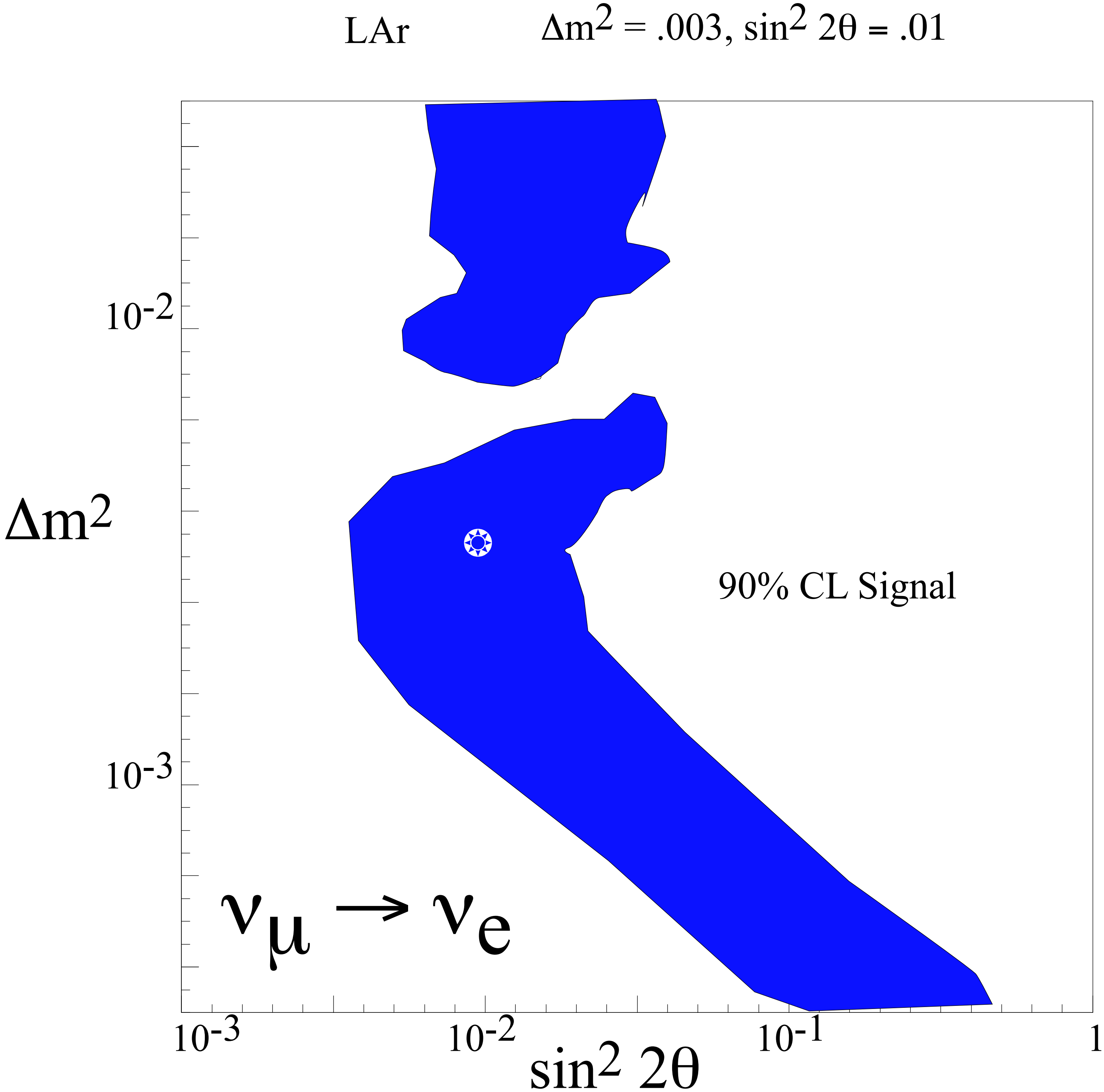
nc spectrum only

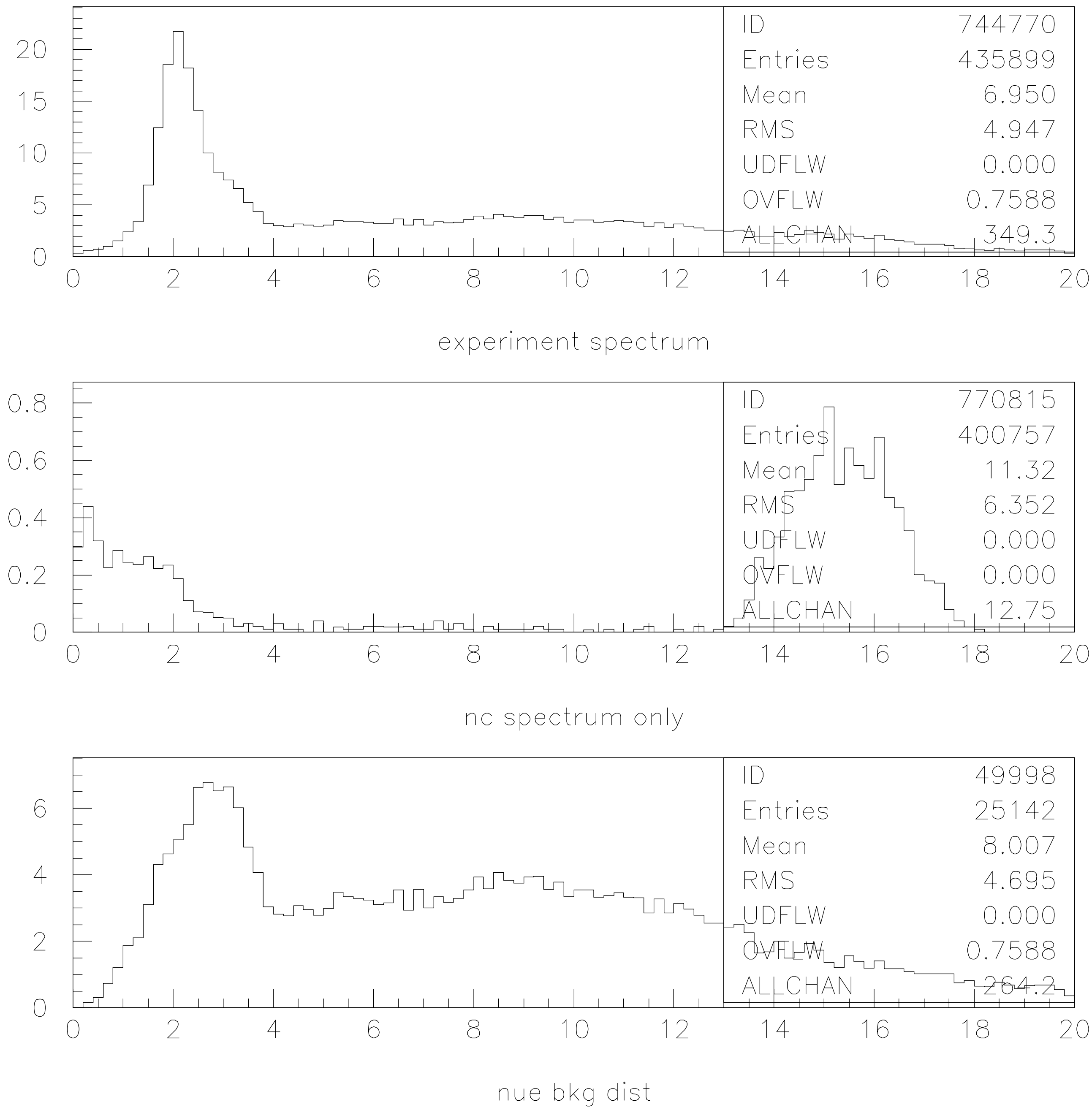


nue bkg dist

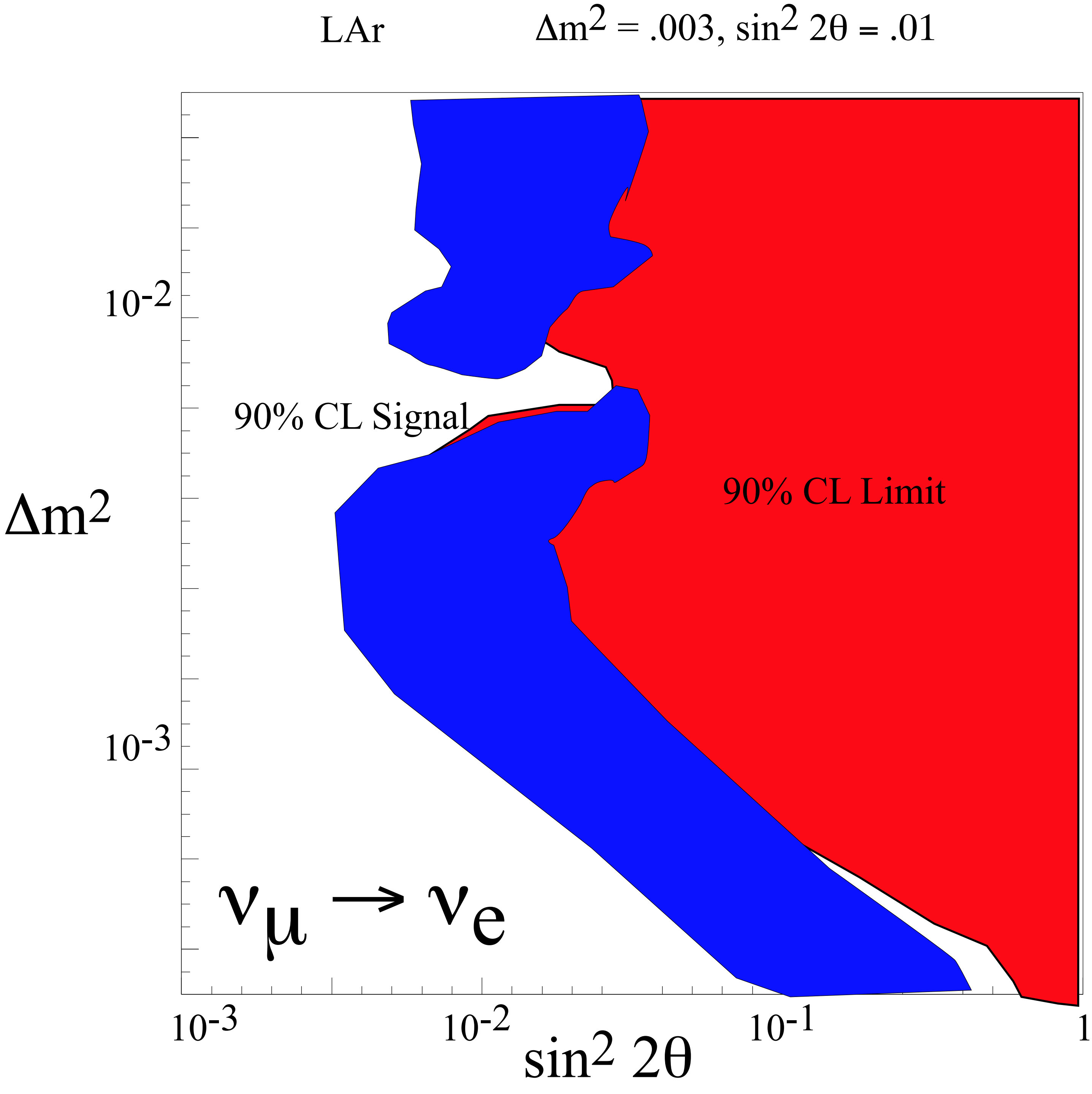
- Complete Spectrum
- NC's Only
- Background ν_e

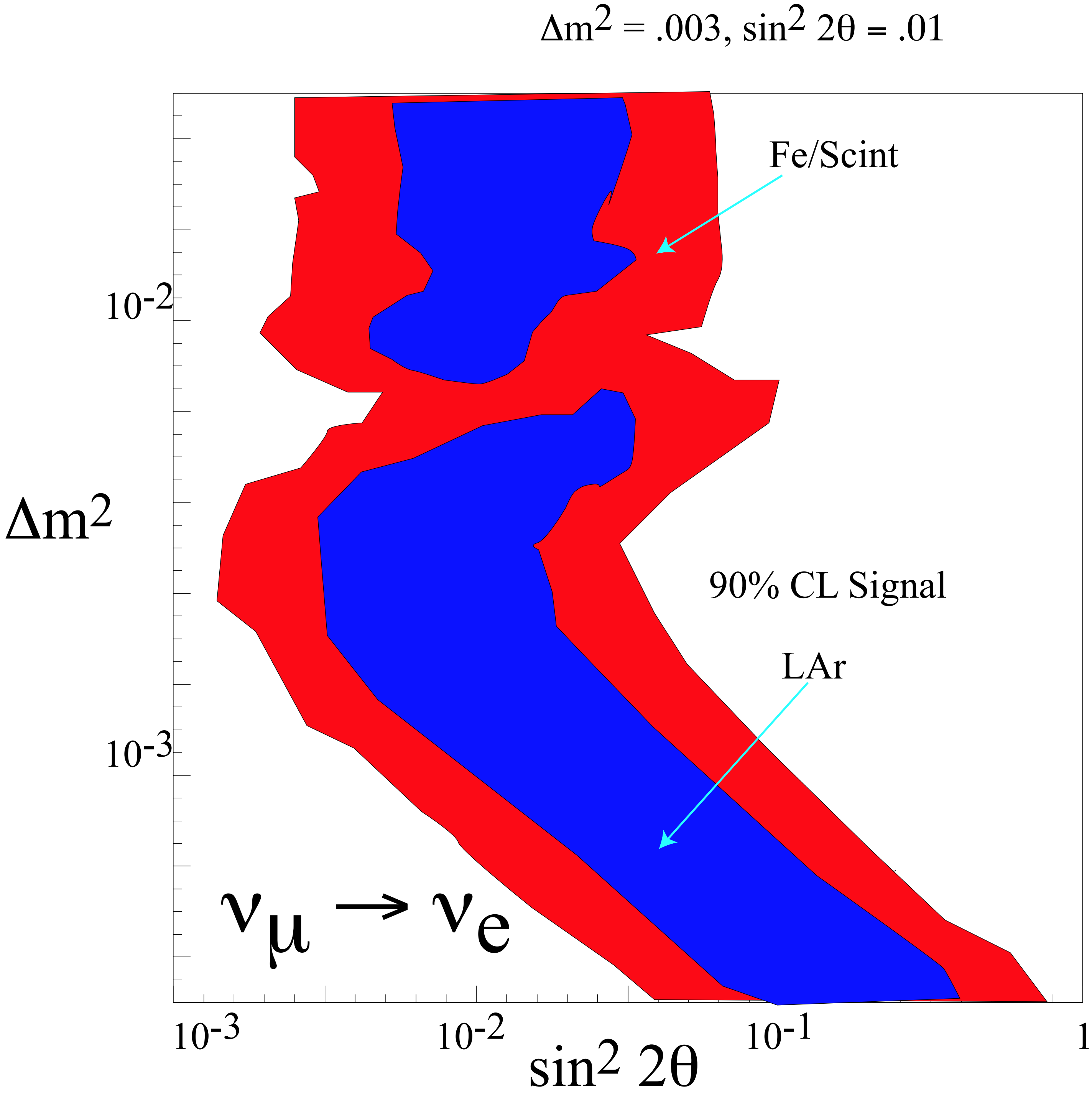

Fe/Scint
$\Delta m^2 = .003, \sin^2 2\theta = .01$
Δm^2
10^{-2}
10^{-3}
90% CL Limit
90% CL Signal
$\nu_\mu \rightarrow \nu_e$
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\theta$


LAr
Δm² = .003, sin² 2θ = .01
10⁻²
10⁻³
Δm²
90% CL Signal
νμ → νe
10⁻³
10⁻²
10⁻¹
1
sin² 2θ



- Complete Spectrum
- NC's Only
- Background ν_e

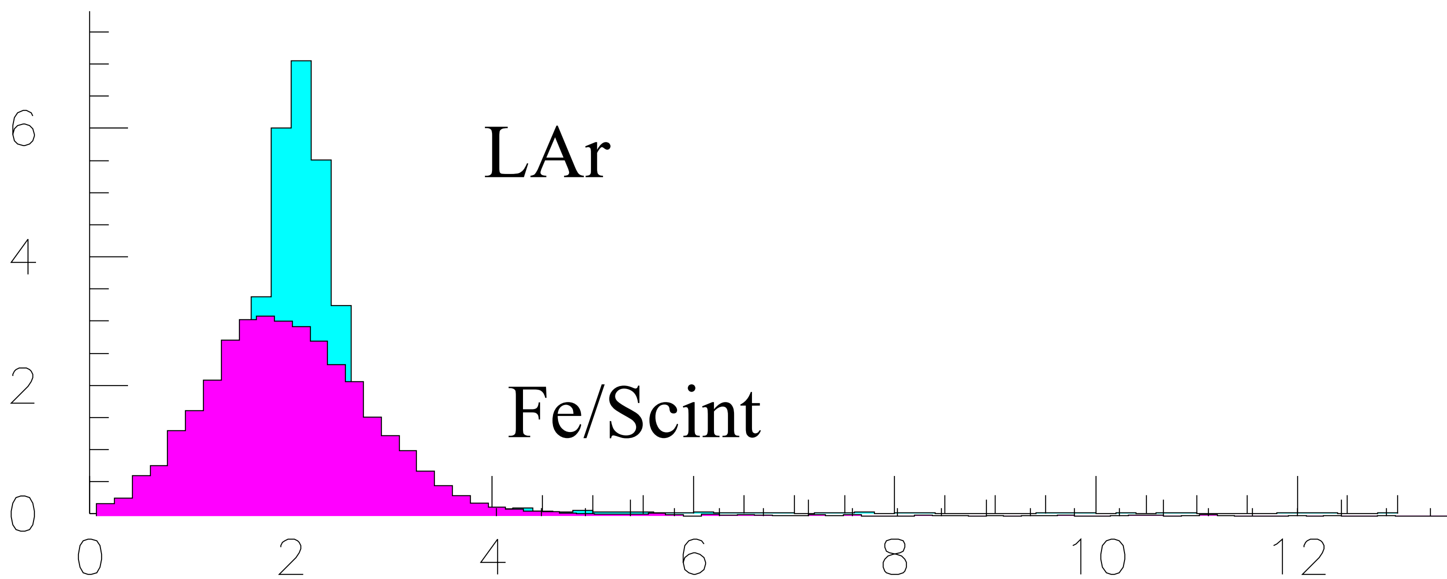

LAr
Δm2 = .003, sin2 2θ = .01
90% CL Signal
90% CL Limit
Δm2
10-2
10-3
νμ → νe
10-3
10-2
10-1
1
sin2 2θ

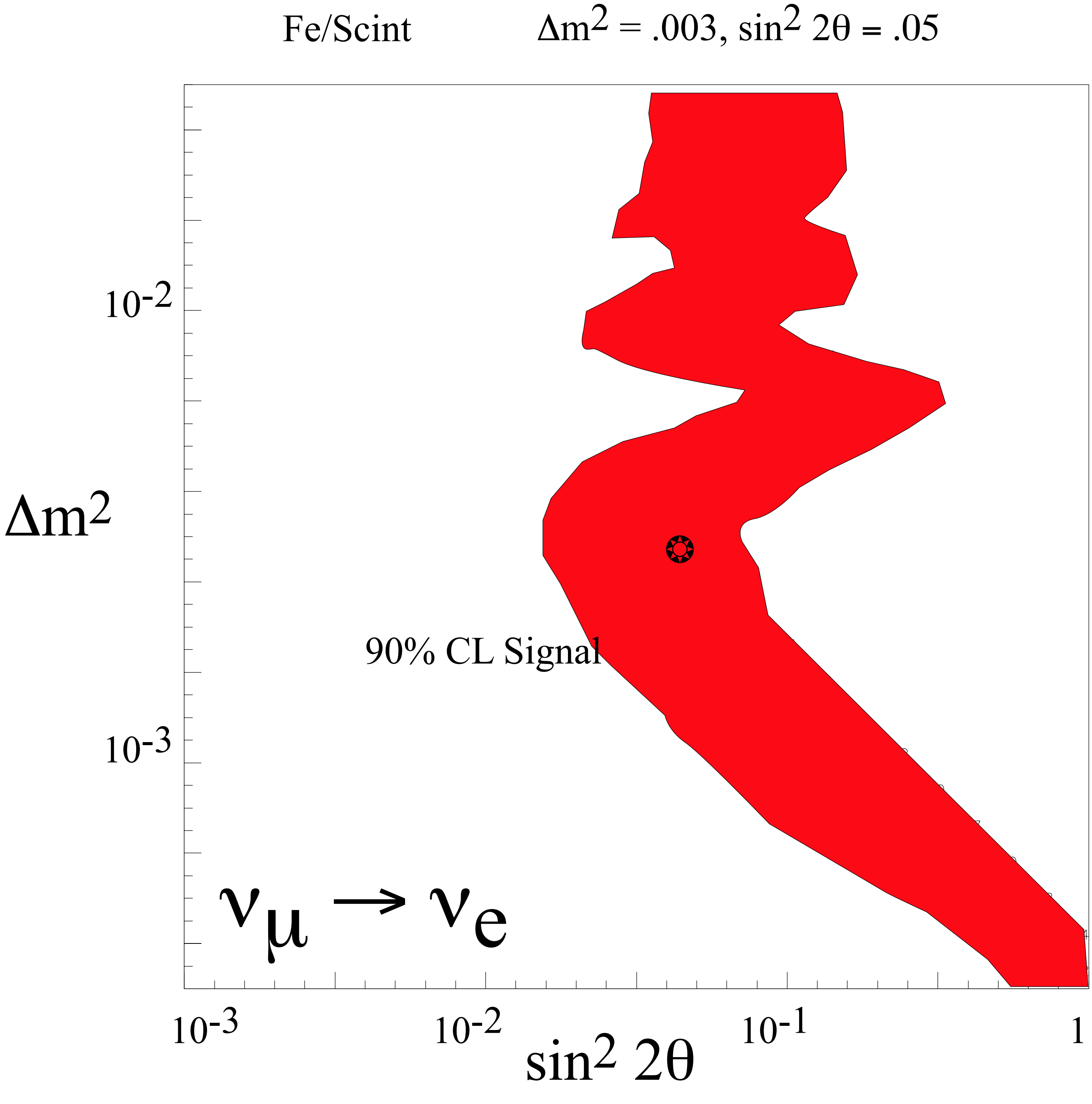

$\Delta m^2 = .003, \sin^2 2\theta = .01$
Fe/Scint
90% CL Signal
LAr
$\nu_\mu \rightarrow \nu_e$
Δm^2
10^{-2}
10^{-3}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\theta$

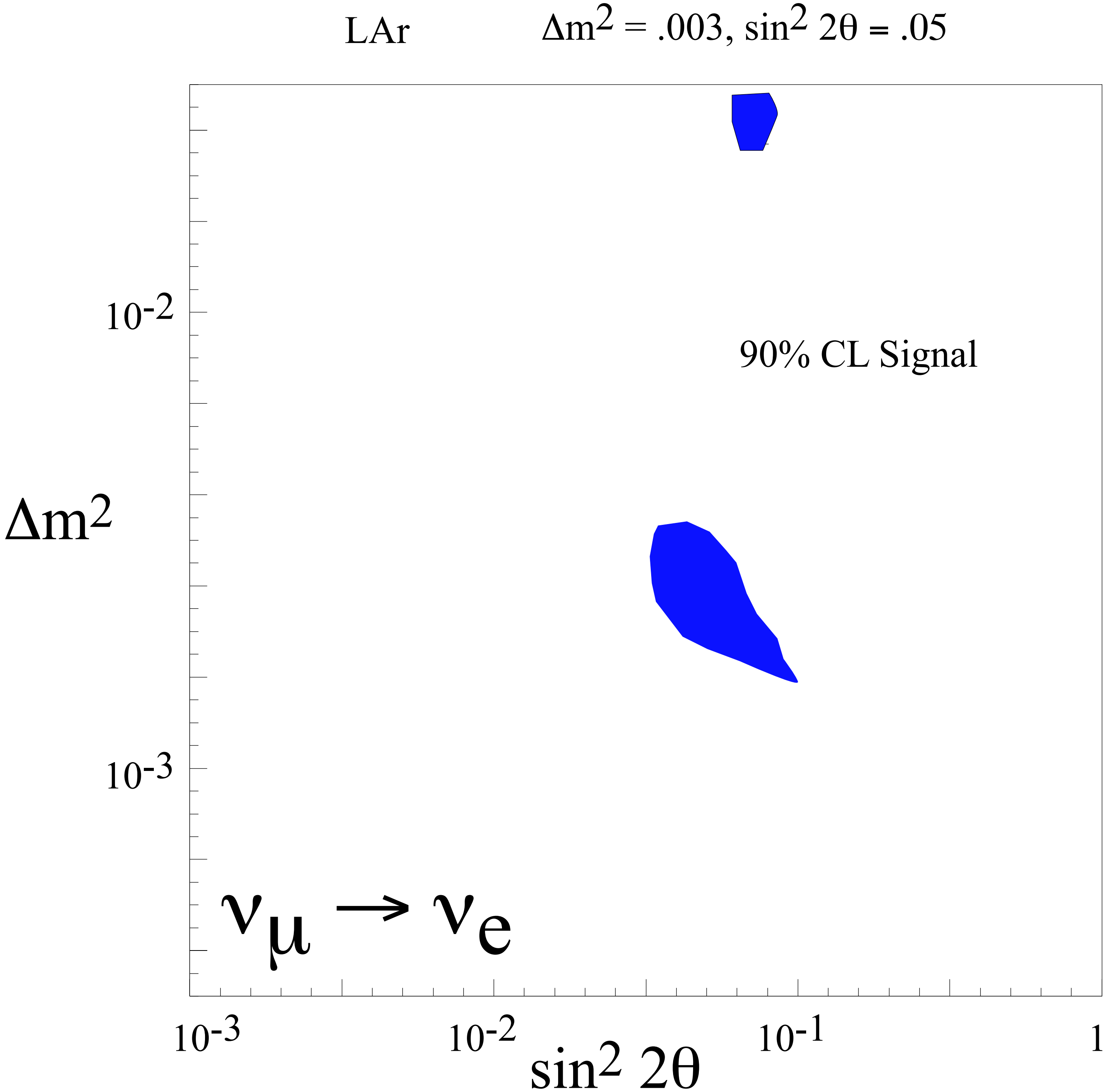
What Do These Plots Tell Us?

- Superior Resolution Makes LAr More Robust
- Less Sensitive to Level Fluctuations in Beam Backgrounds, etc.

normalized to same number in peak, so resolution effect only




Fe/Scint
Δm2 = .003, sin2 2θ = .05
Δm2
10-2
10-3
90% CL Signal
νμ → νe
10-3
10-2
10-1
1
sin2 2θ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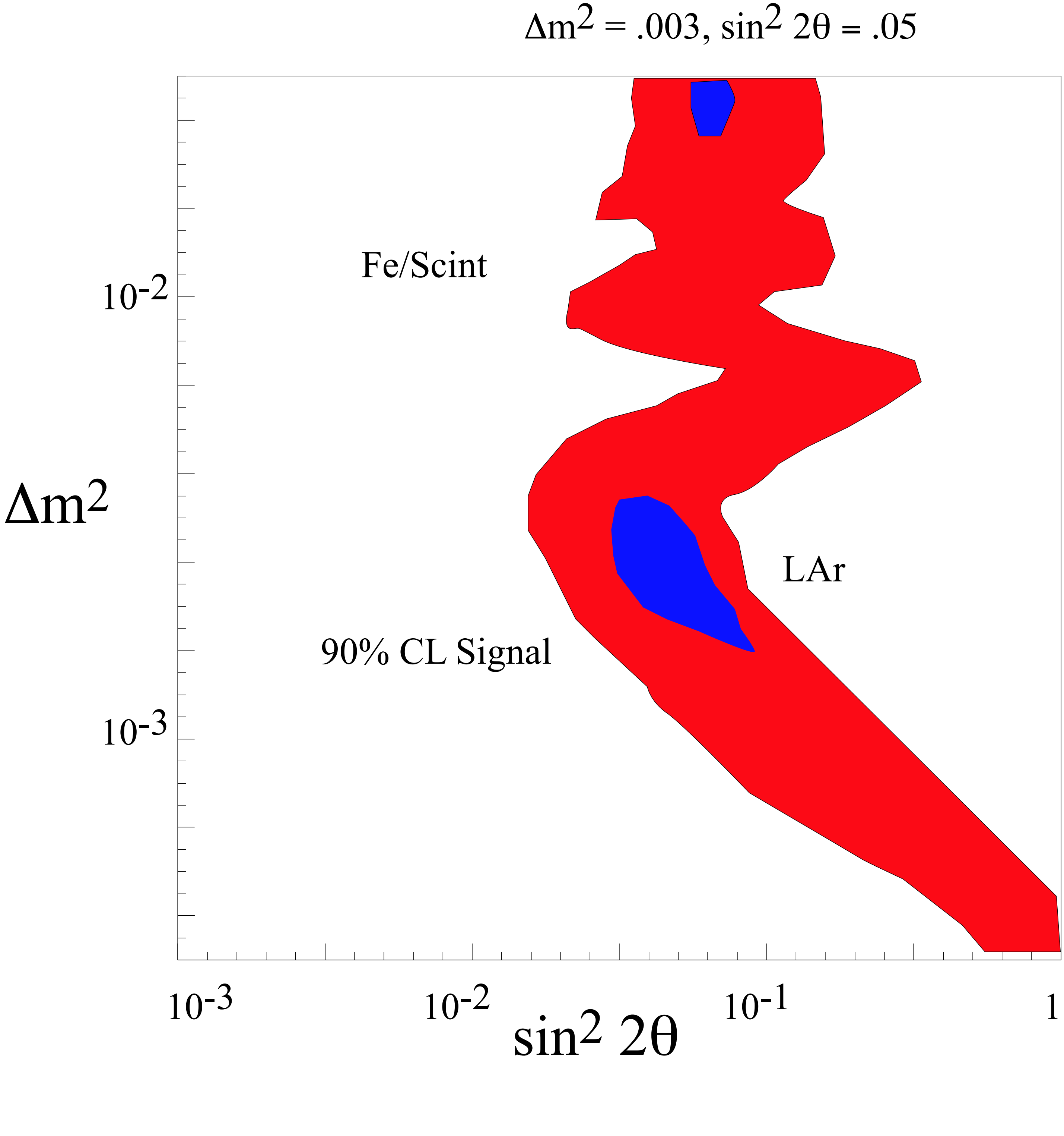
Δm² = .003, sin² 2θ = .05
90% CL Signal
Δm²
10⁻²
10⁻³
νμ → νe
10⁻³
10⁻²
10⁻¹
1
sin² 2θ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LAr
90% CL Signal
Δm^2
10^{-2}
10^{-3}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\theta$

Conclusions

- Can See Effects Down to $\sin^2 2\theta = 0.01$
- LAr Much Better
- Beam-Related Systematics
  Not Large Effect
- Fe/Scint “Running Out of Steam” at < 5 %
- Speaking of Steam, Need Help with H_2O