Short-baseline analysis techniques

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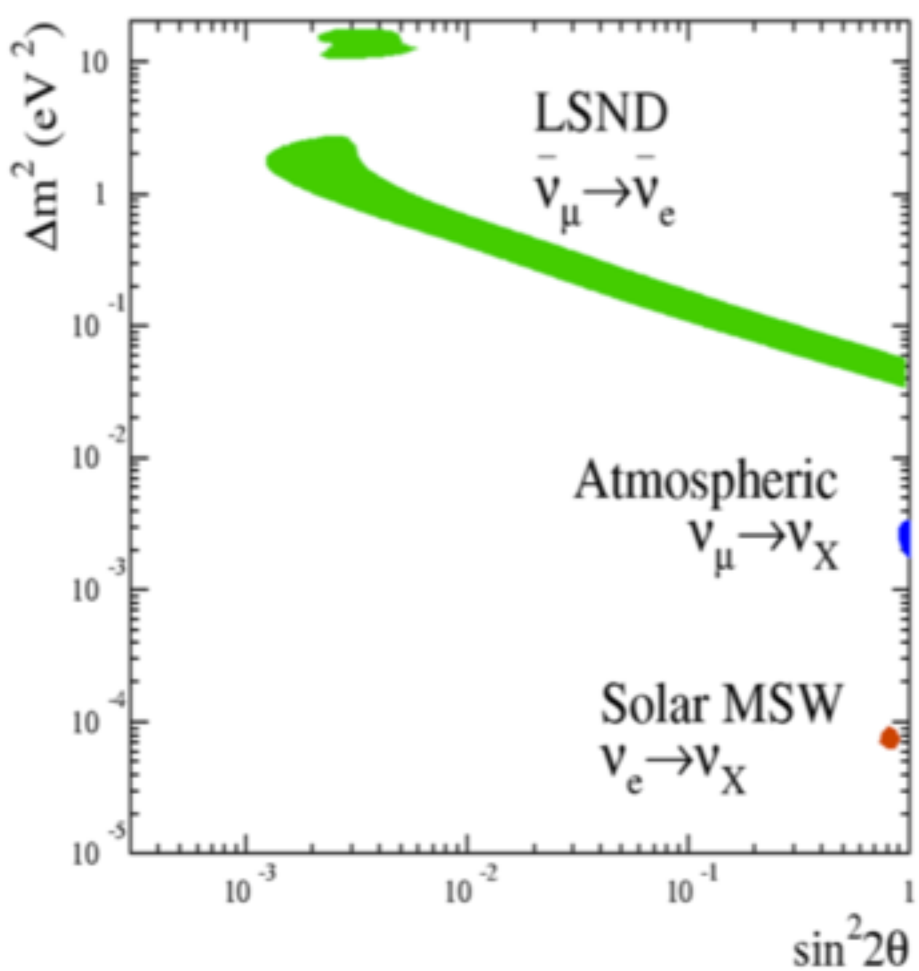
Introduction

- Few short baseline experiments observed anomalous signals

Experiment	Type	Channel	Significance
LSND	DAR	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	3.8σ
MiniBooNE	SBL accelerator	$\nu_\mu \to \nu_e$ CC	3.4σ
MiniBooNE	SBL accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	2.8σ
GALLEX/SAGE	Source - e capture	ν_e disappearance	2.8σ
Reactors	Beta-decay	$\bar{\nu}_e$ disappearance	3.0σ

arXiv:1204.5379

- Can't be reconciled with atmospheric and solar neutrino oscillations, only 2 independent Δm^2
- Possible solution is existence of light sterile neutrino(s) driving oscillations at $\Delta m^2 \sim 1eV^2$
- Short baseline program at Fermilab will test the sterile neutrino oscillation hypotheses at $>5\sigma$



Introduction

- I'll focus on MiniBooNE analysis here

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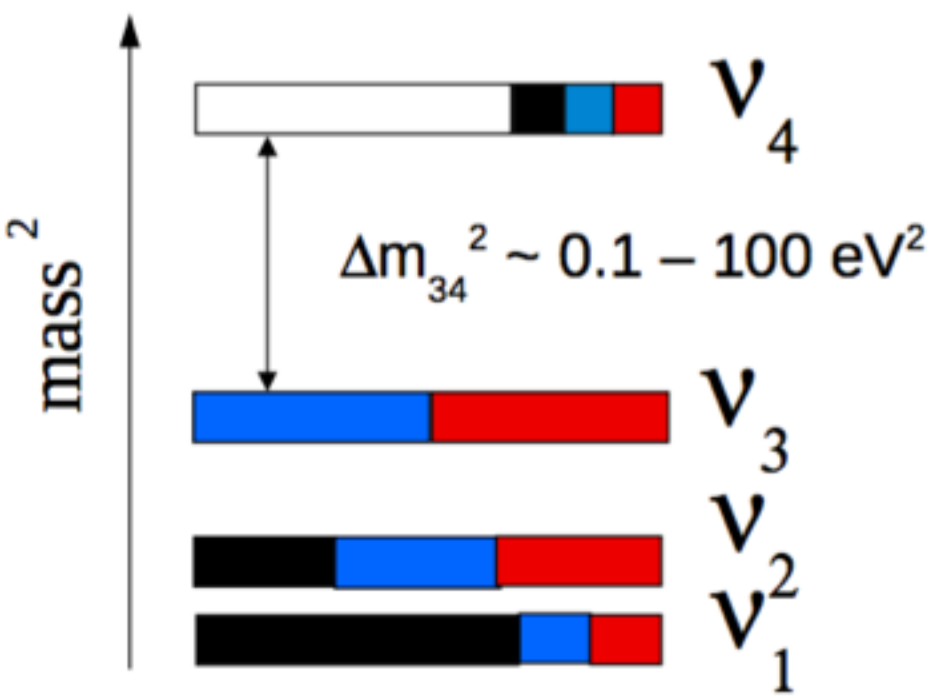
- Analysis techniques for MicroBooNE and SBN program are under development, however initial studies were done by adapting similar techniques

Sterile neutrinos

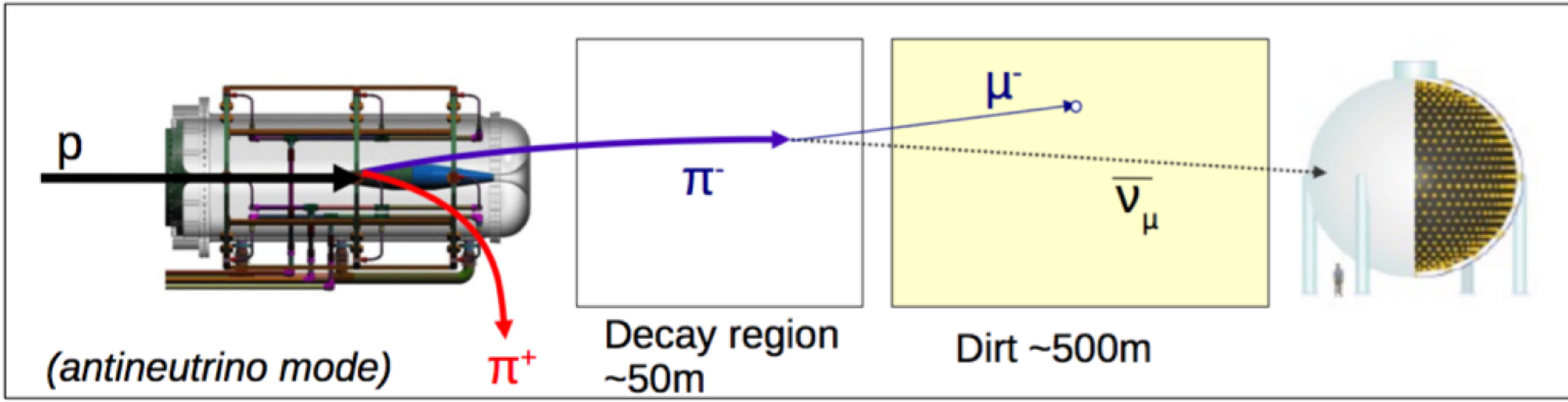


- Have no Standard Model interactions but can oscillate into active state
- 3+N models (N=1,2…)
  - short-baseline CP violation for N>1

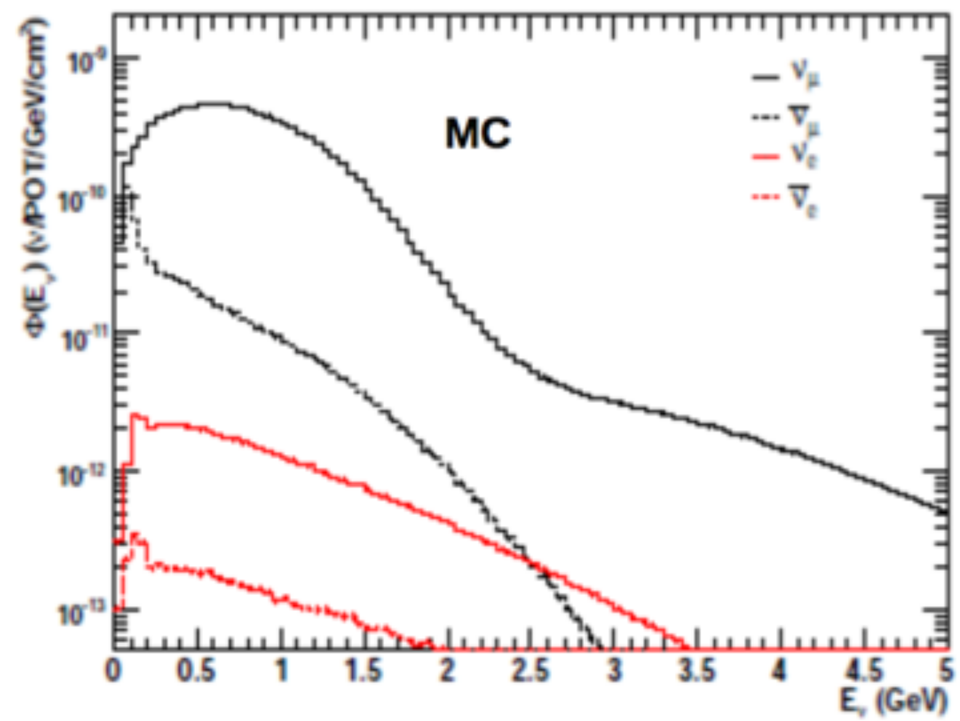
$$P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$$

- Model ties together appearance and disappearance probabilities for ν_e and ν_μ
- Affects long-baseline experiments as well

MiniBooNE



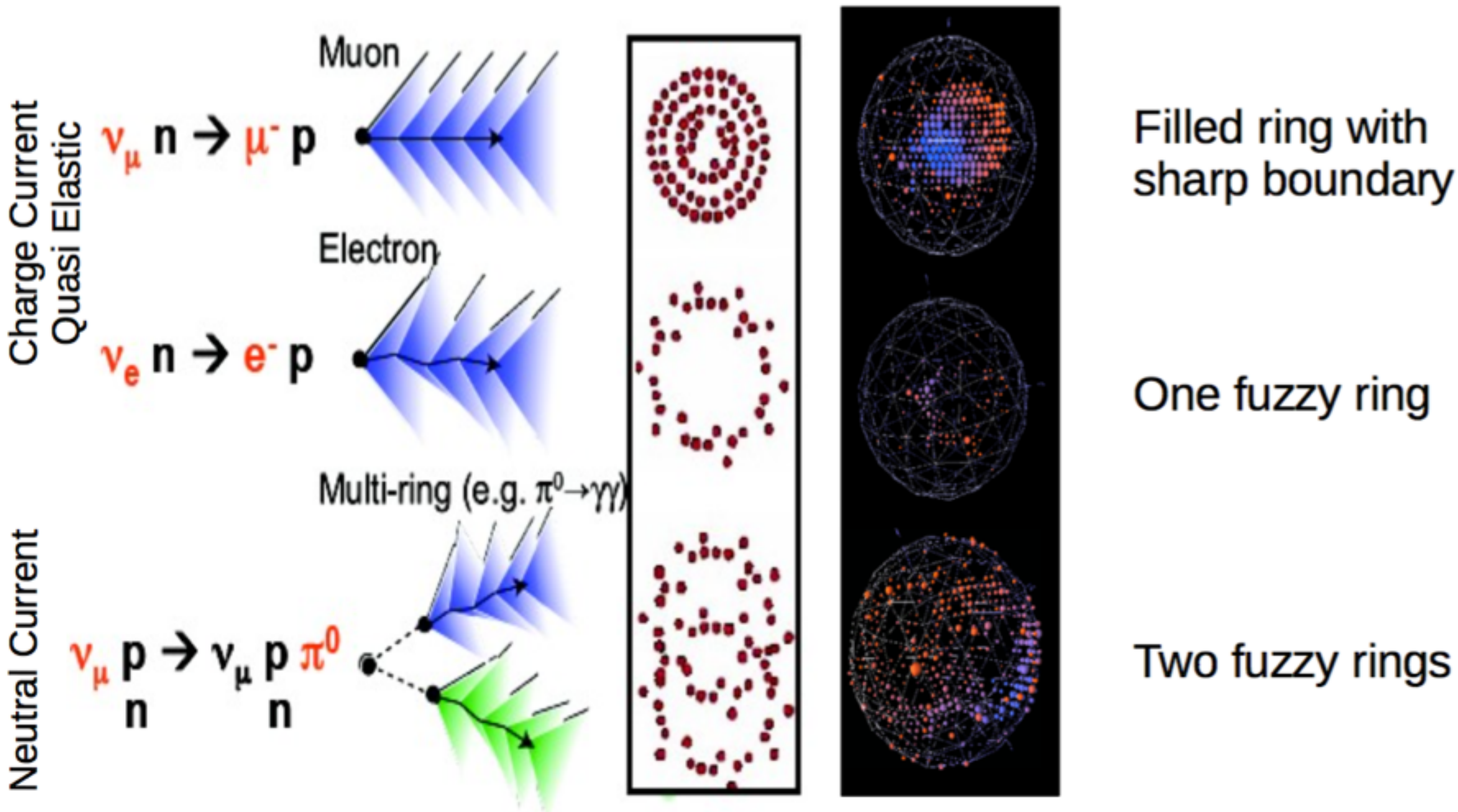
- Booster Neutrino Beamline - 8GeV protons on Be
- Operated in neutrino and anti-neutrino configuration
- MiniBooNE is mineral oil Cherenkov detector
- Similar L/E as LSND:
  - MiniBooNE: ~500m/500MeV
  - LSND: ~30m/30MeV



Phys. Rev. D79, 072002 (2009)

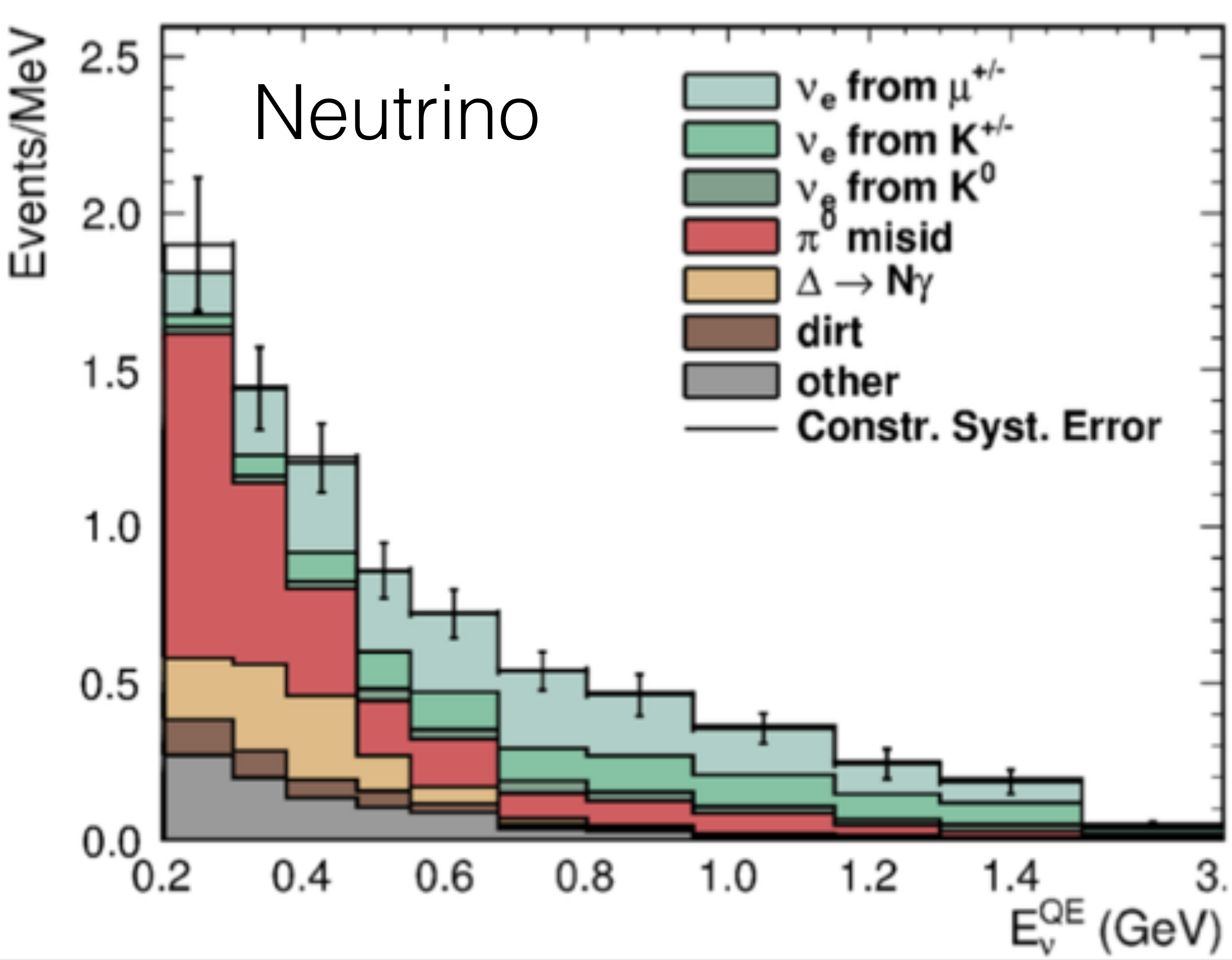
Events in MiniBooNE

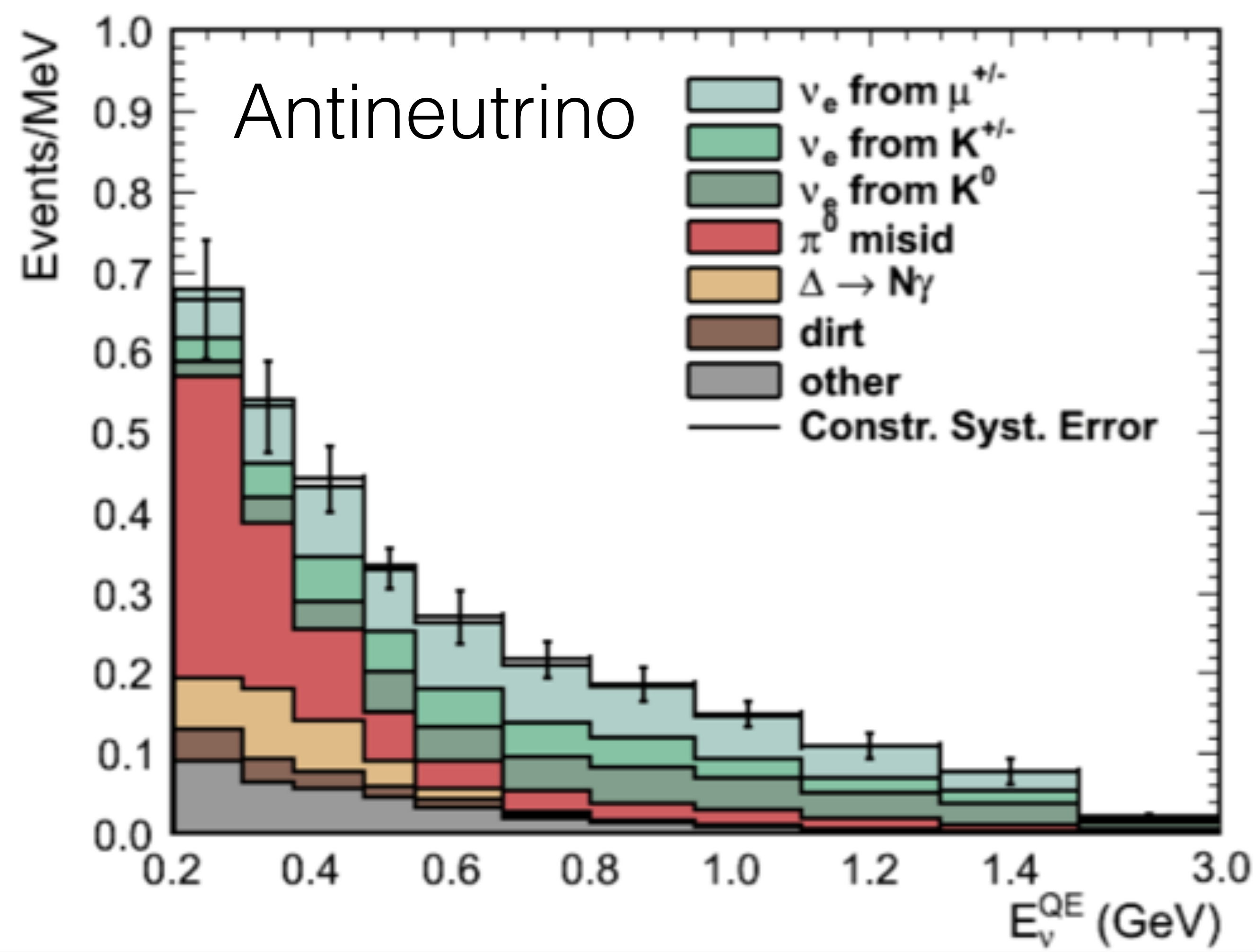
- Identify events using timing and hit topology
- Use primarily Cherenkov light



Appearance analysis

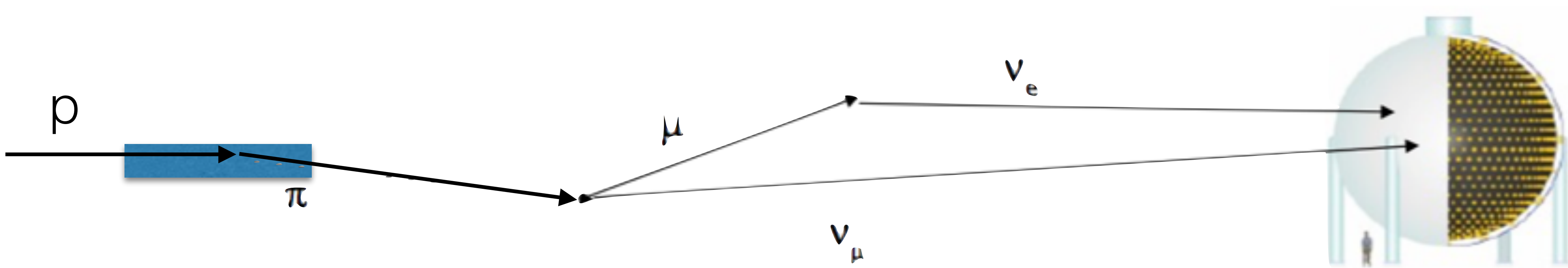
- Look for excess events in ν_e sample and fit assuming $\nu_\mu \rightarrow \nu_e$ oscillations as a function of (dm2,s2t)
- Backgrounds similar in neutrino and antineutrino mode
- Constrained using external and MiniBooNE data





Combined fit

- MiniBooNE was single detector experiment, no Near Detector to constrain the systematics
- Fit simultaneously large statistics ν_μ CCQE sample and the ν_e sample
- ν_μ CCQE sample constrains the ν_e background and signal since many systematics are correlated (flux, xsec)



Combined fit (cont'd)

- Calculate likelihood given with:

$$-2\ln(L) = (x_1 - \mu_1, ...x_n - \mu_n)M^{-1}(x_1 - \mu_1, ...x_n - \mu_n)^T + \ln(|M|)$$

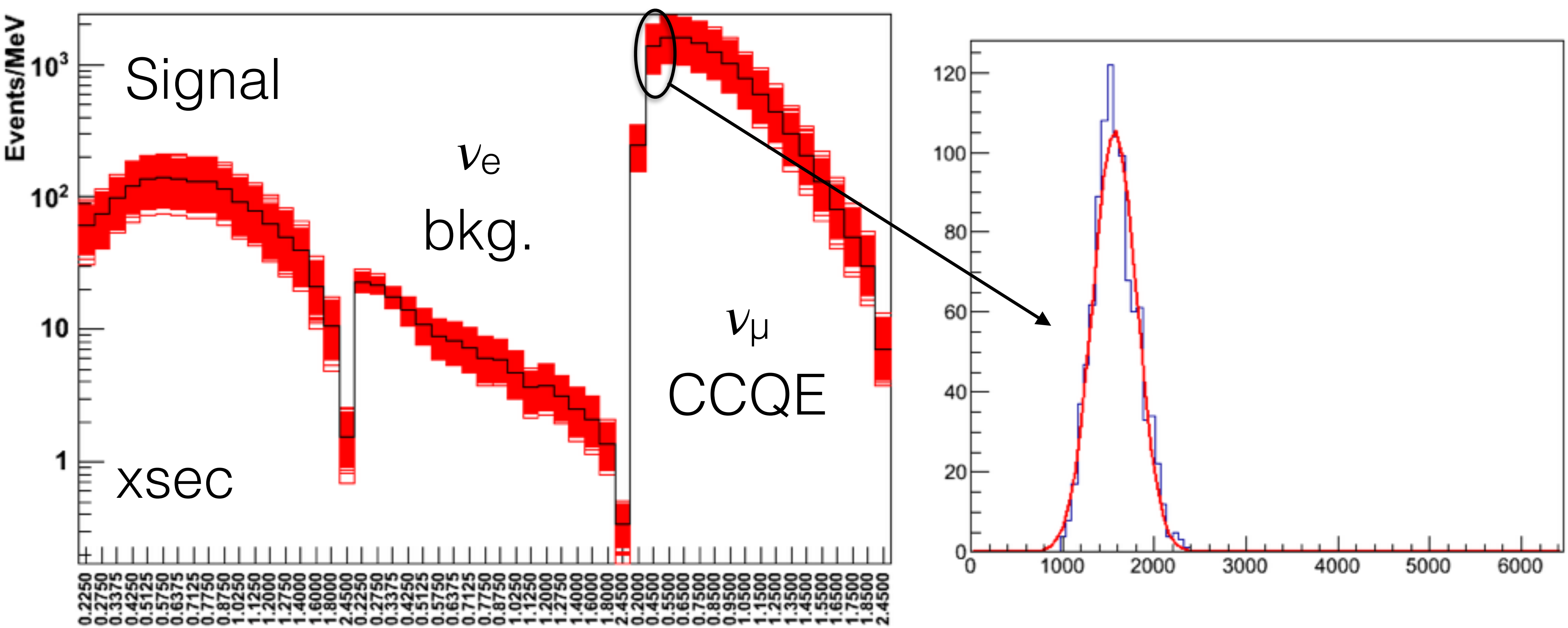
  where x_i is the prediction at a certain (dm2,s2t);
  i runs over ν_e sample, and ν_μ sample bins

- At each (dm2, s2t) recalculate x and M (actually only ν_e , ν_μ doesn't change)

- Use Δ(-2ln(L)) surface to plot limit curves

Error matrix (step 1)

- Many universe approach, for each systematic generate many MC predictions
- Change underlaying systematic parameters using input error matrix
  - for example HARP error matrix for pi+- production, or MiniBooNE pi0 measurement



Error matrix (step 2)

- Using many MC predictions (N) form an error matrix for systematic σ:

$$\mathcal{M}_{ij}^{\sigma} = \frac{1}{\mathcal{N}} \sum_{n=1}^{\mathcal{N}} \left(P_i - V_{i,n}^{\sigma}\right) \times \left(P_j - V_{j,n}^{\sigma}\right)$$

where P_i is the central value MC prediction for bin i

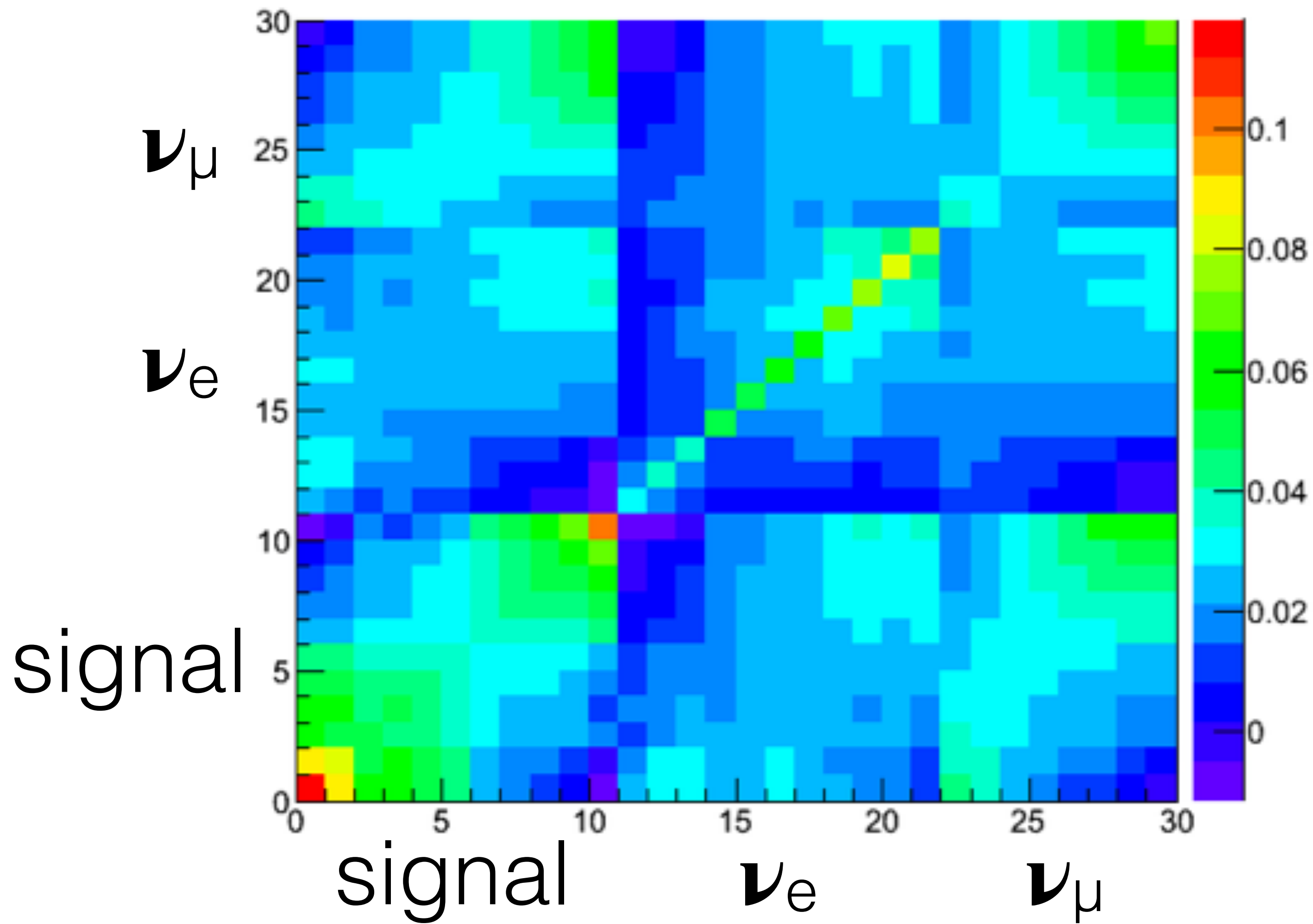
Error matrix (step 3)

- Add all systematic error matrices to find the total error matrix

$M_{ij}=M_{ij}(\pi^{+})+M_{ij}(\pi^{-})+M_{ij}(K^{+})+M_{ij}(K^{-})+M_{ij}(K^{0})+M_{ij}(beam)+M_{ij}(xsec)+M_{ij}(CC\pi^{+})+M_{ij}(\pi^{0})+$

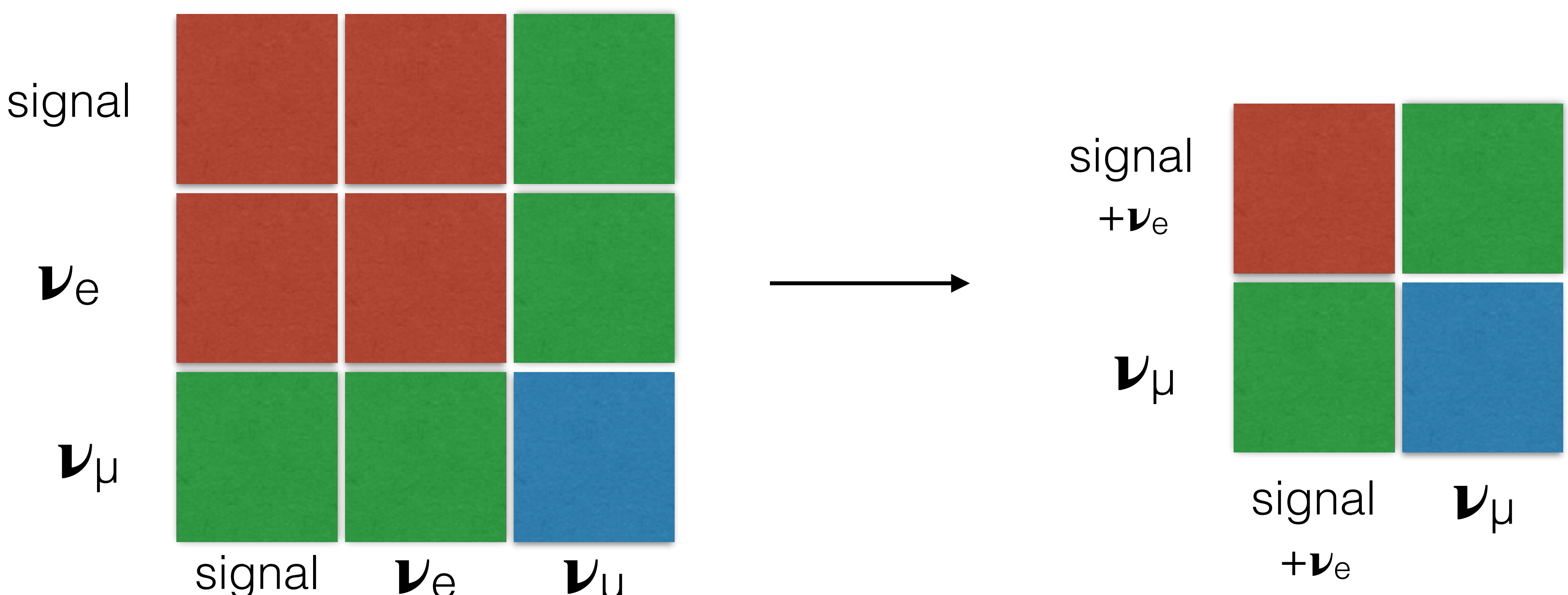
$M_{ij}(hadronic)+M_{ij}(dirt)+M_{ij}(OM)+M_{ij}(detector)$

- In practice use fractional error matrix to recalculate total error matrix at each point in fit



Total error matrix

- At each point in (dm2,s2t) recalculate signal events and vector P_i where i=signal, ν_e, ν_μ bins
- Multiply fractional error matrix with P_i
- Collapse error matrix (sum blocks with same colors)

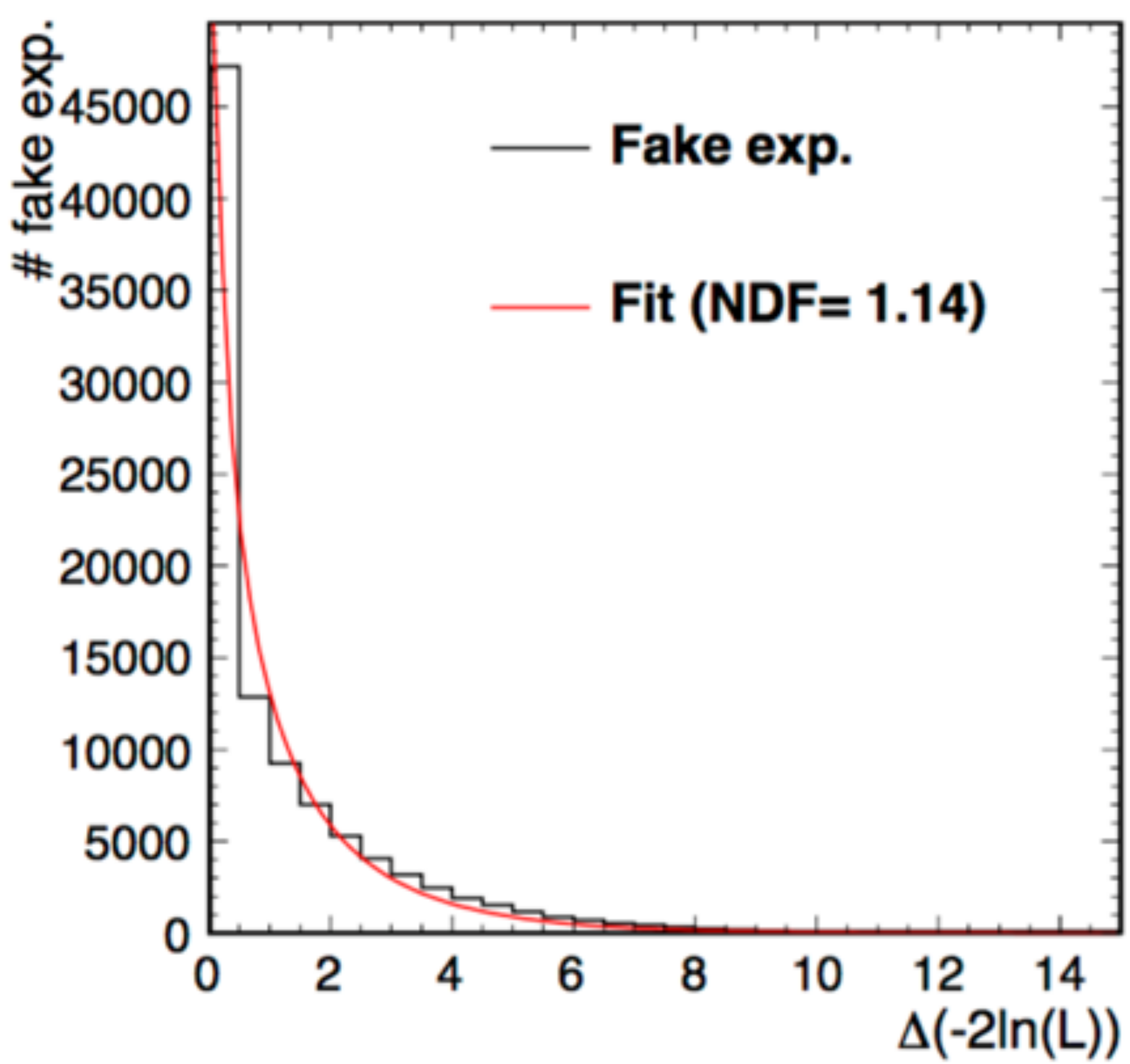


Confidence limit

- Frequentist approach
- Generate large number of fake data experiments at each point in (dm2, s2t) - pulling from total error matrix
- Fit each experiment, and from distribution of $\Delta(-2\ln(L))$ find the cut at each (dm2, s2t) corresponding to particular CL

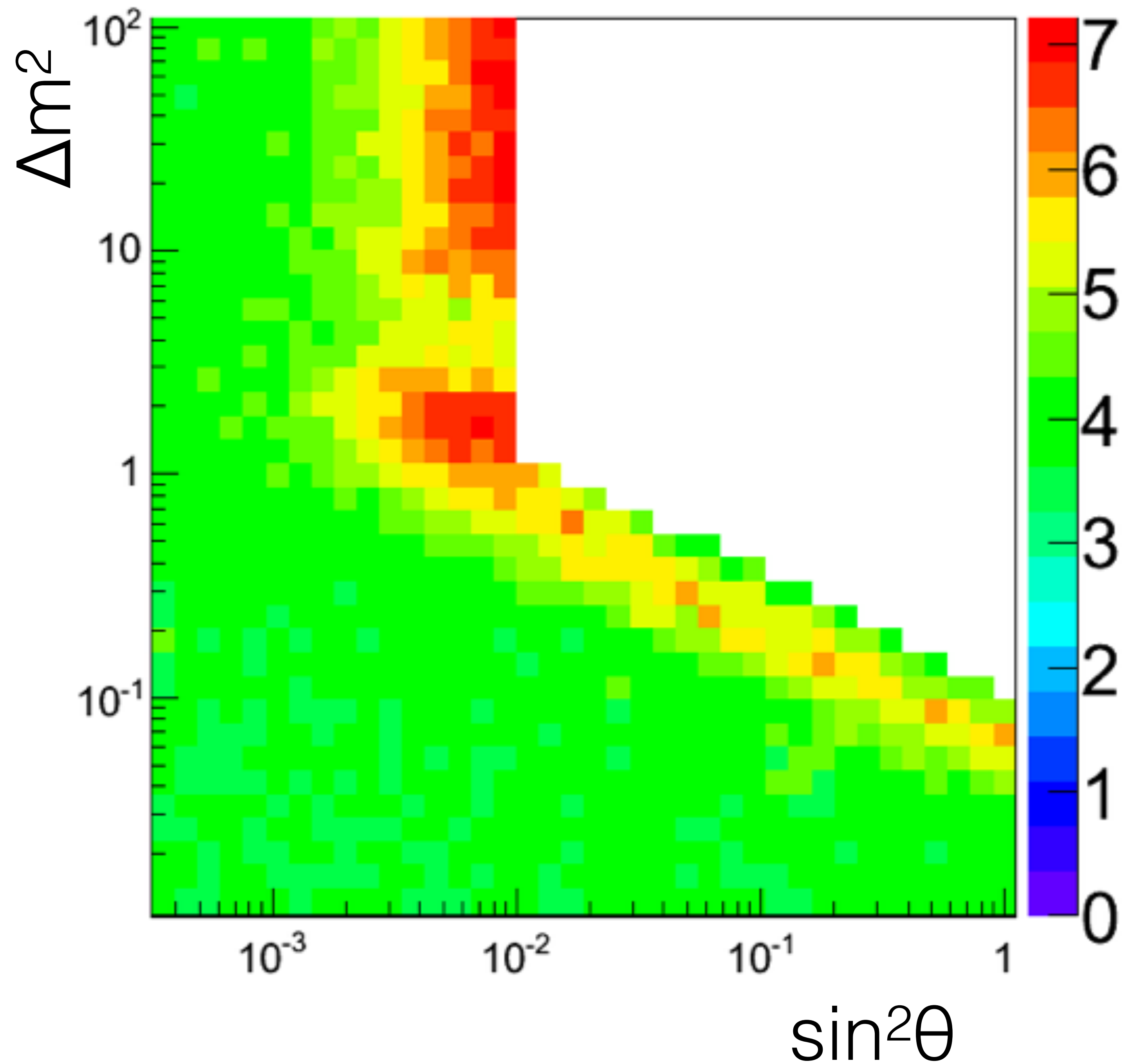
Null point

- Fitting for 2 parameters (dm2, s2t)
- From fake exp. distribution find the cut corresponding to particular CL



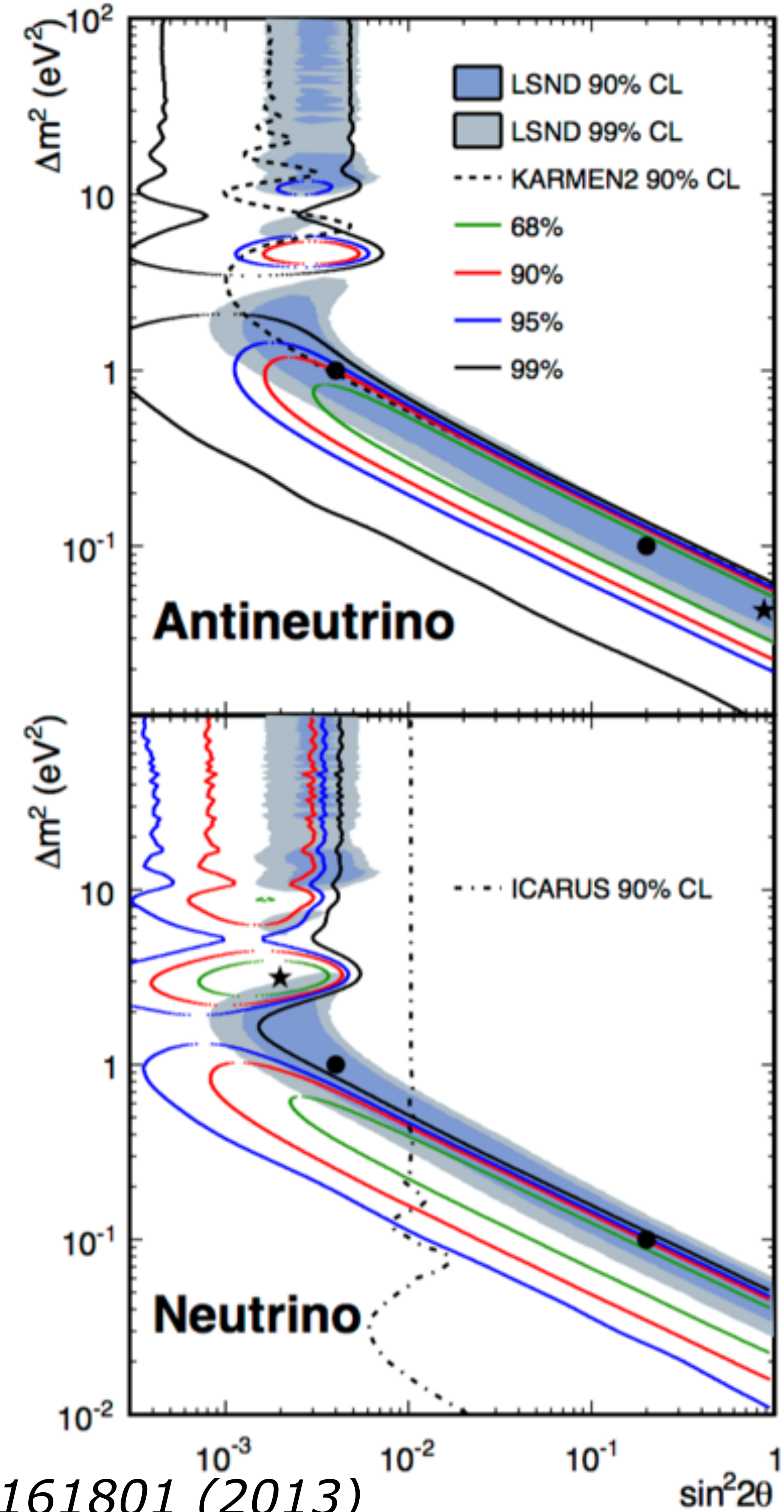
(dm2,s2t) space

- Similarly find the cuts at all other points and map out whole (dm2,s2t) space
- CL is then found at intersection of this cut surface and data Δ(-2ln(L))



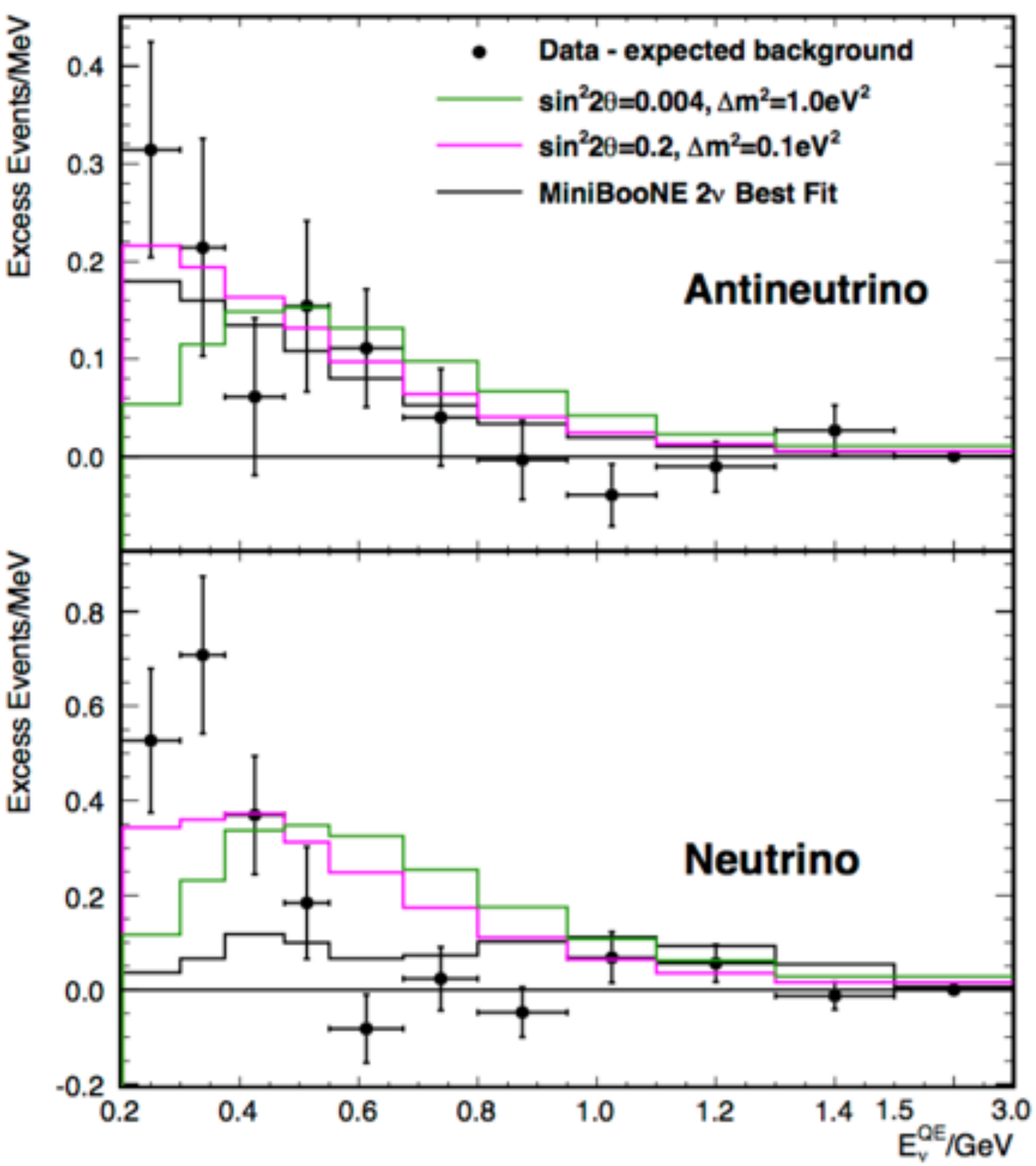
MiniBooNE result

- 2 neutrino oscillation fit (3+1 model)
- Δ(-2ln(L)) observed with neutrinos (antineutrinos) seen in 2% (0.5%) of fake experiments
- Star shows the best fit point, but chi2 fairly flat as you move along dm2



Phys. Rev. Lett. 110, 161801 (2013)

MiniBooNE result



- Neutrino excess:
  162±28.1(stat.)±38.7(syst.) (3.4σ)

- Antineutrino excess:
  78.4±20.0±20.3 (2.8σ)

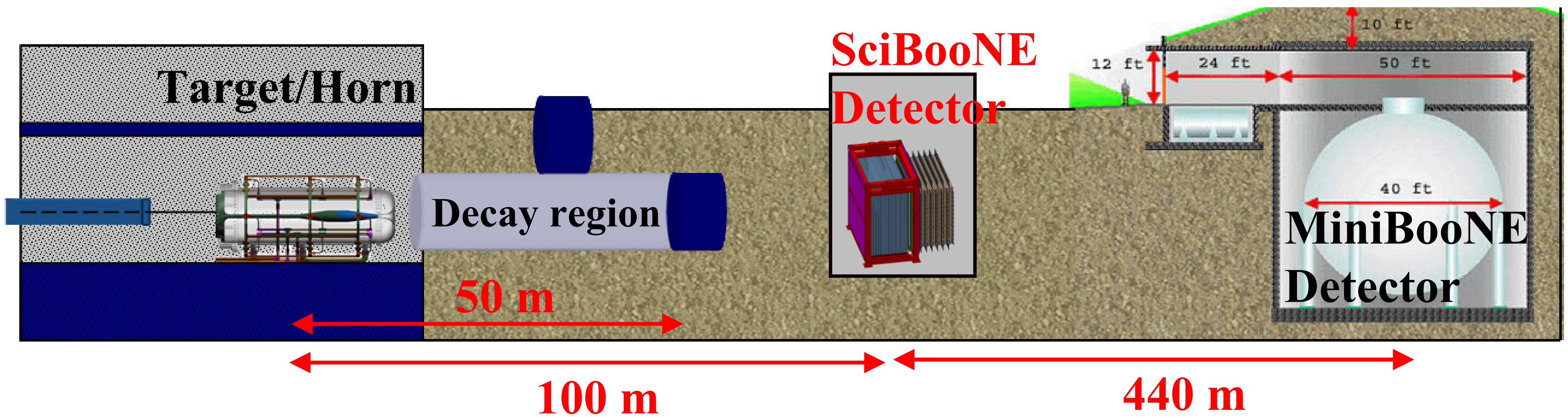
- Poor fit to neutrino data

  - shape inconsistent with simple 2 neutrino oscillations

  - better fit with 3+2 and 3+3 models (tensions when doing global fits)

Phys. Rev. Lett. 110, 161801 (2013)

SciBooNE/MiniBooNE

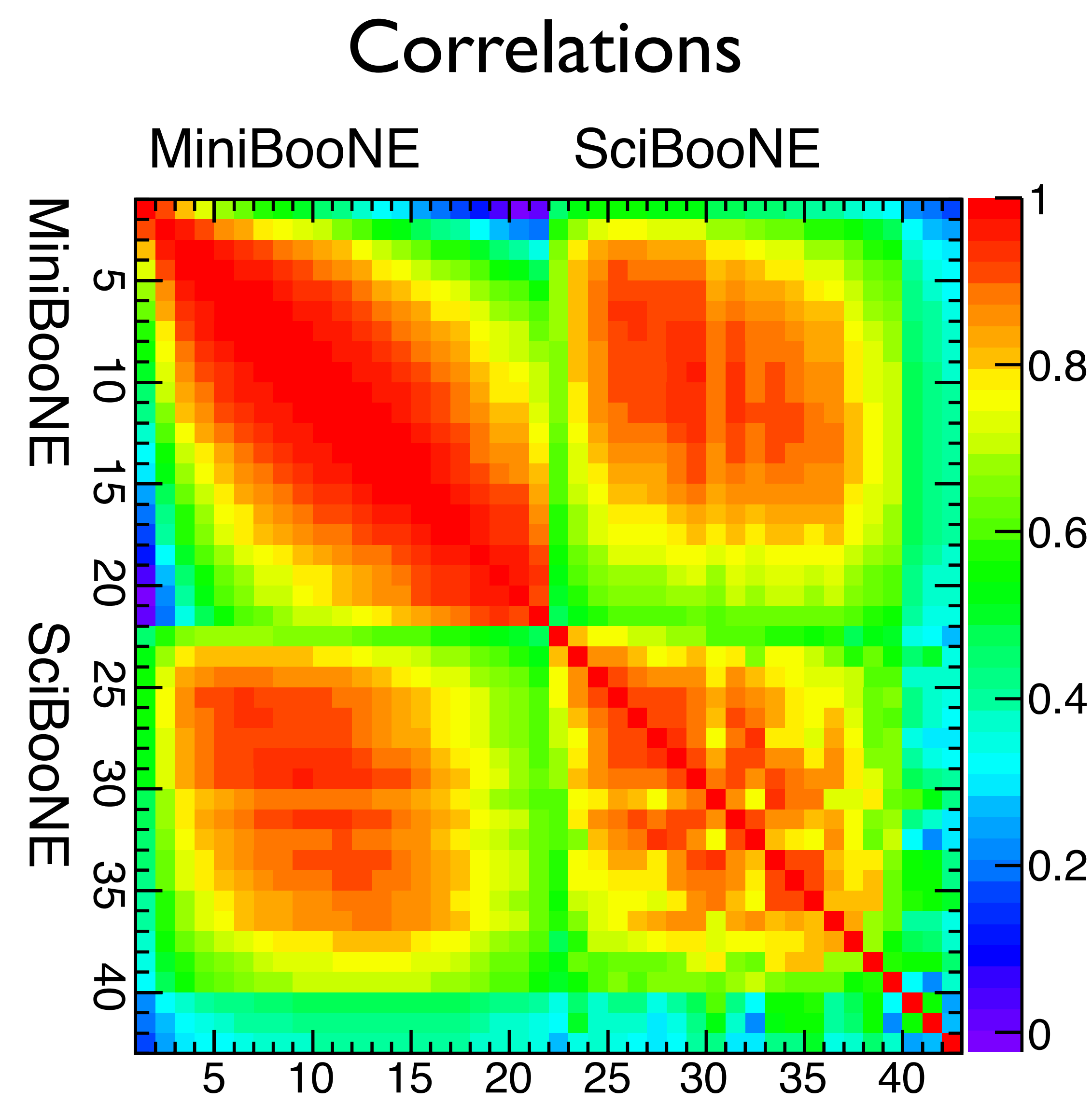


- SciBooNE detector ran within BNB along with MiniBooNE

- Can be used as near detector for numu(bar) disappearance analysis

SciBooNE/MiniBooNE

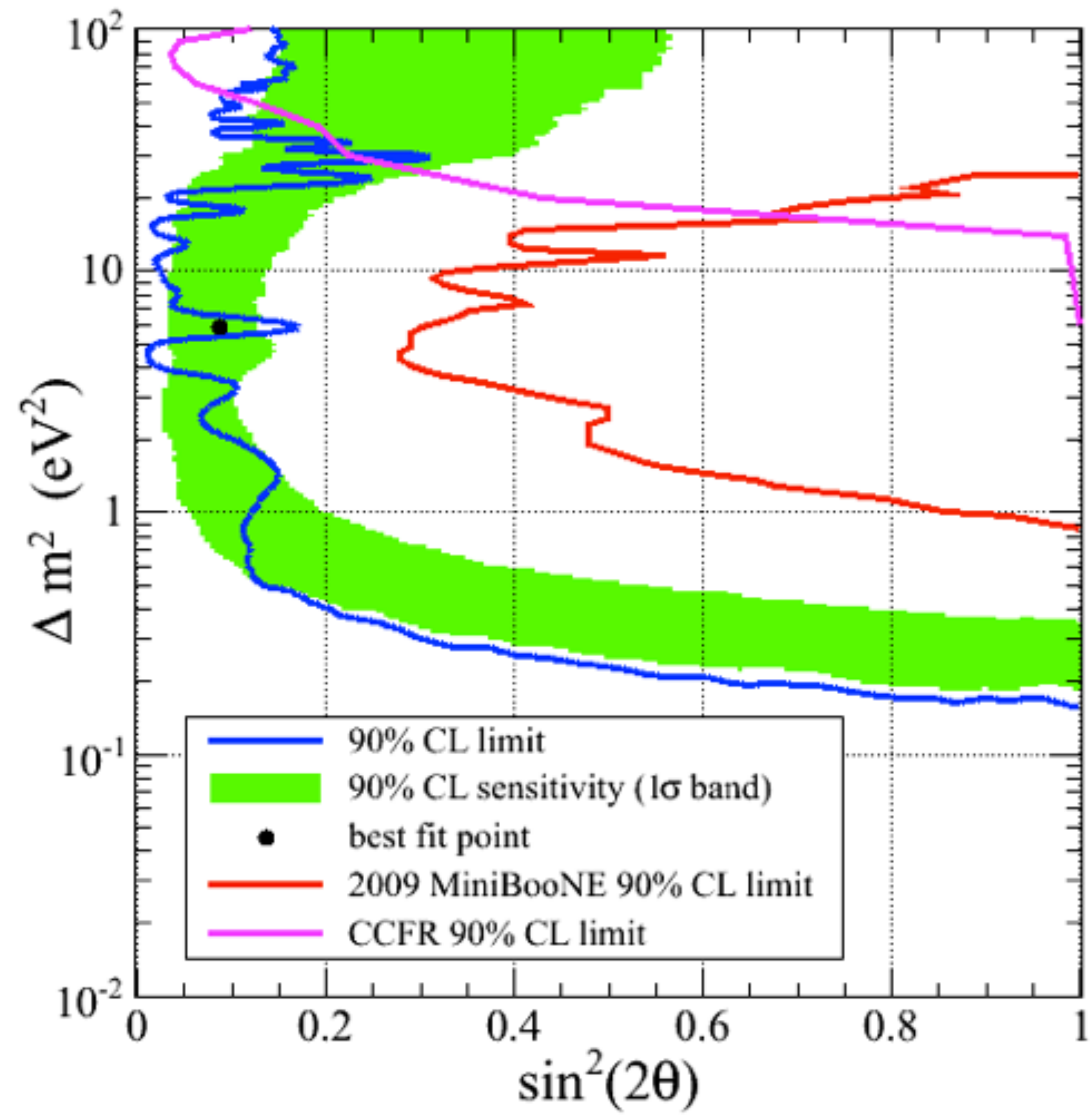
- Build error matrix using many MC universes correlating MiniBooNE and SciBooNE prediction
- Flux and cross section correlated, but detector systematics uncorrelated between detectors



Phys. Rev. D86, 052009 (2012)

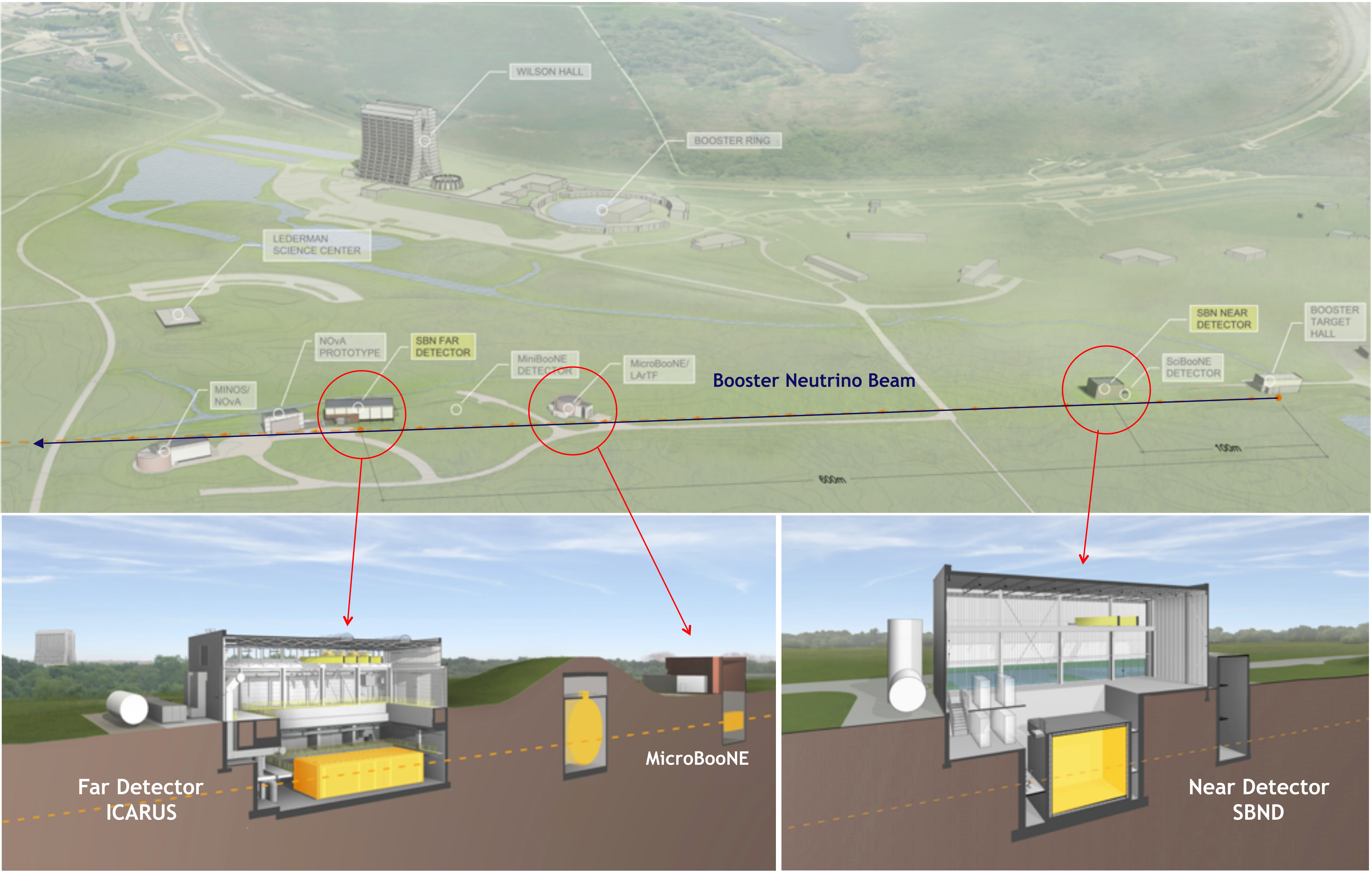
SciBooNE/MiniBooNE

- Used $\Delta\chi^2$ as test statistics
- Fake data studies to evaluate probabilities
- Consistent with no oscillations



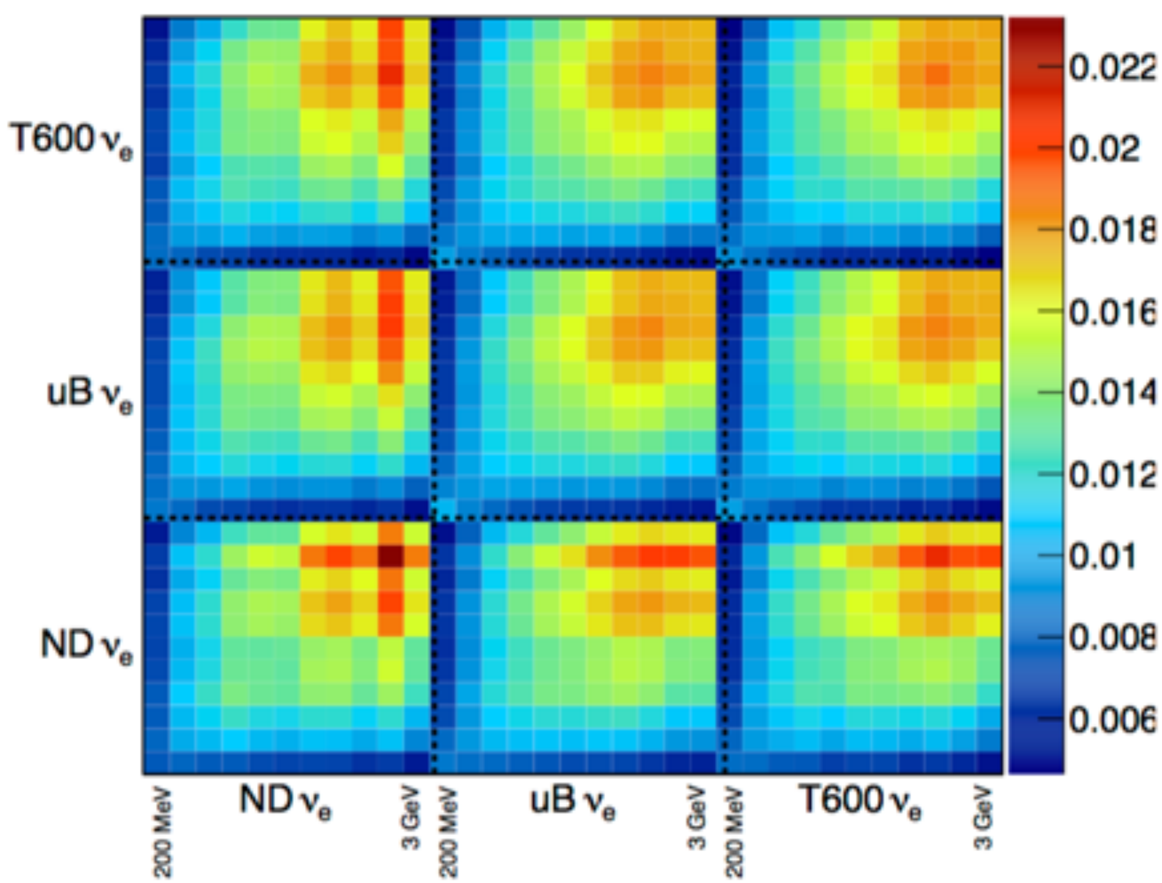
Phys. Rev. D86, 052009 (2012)

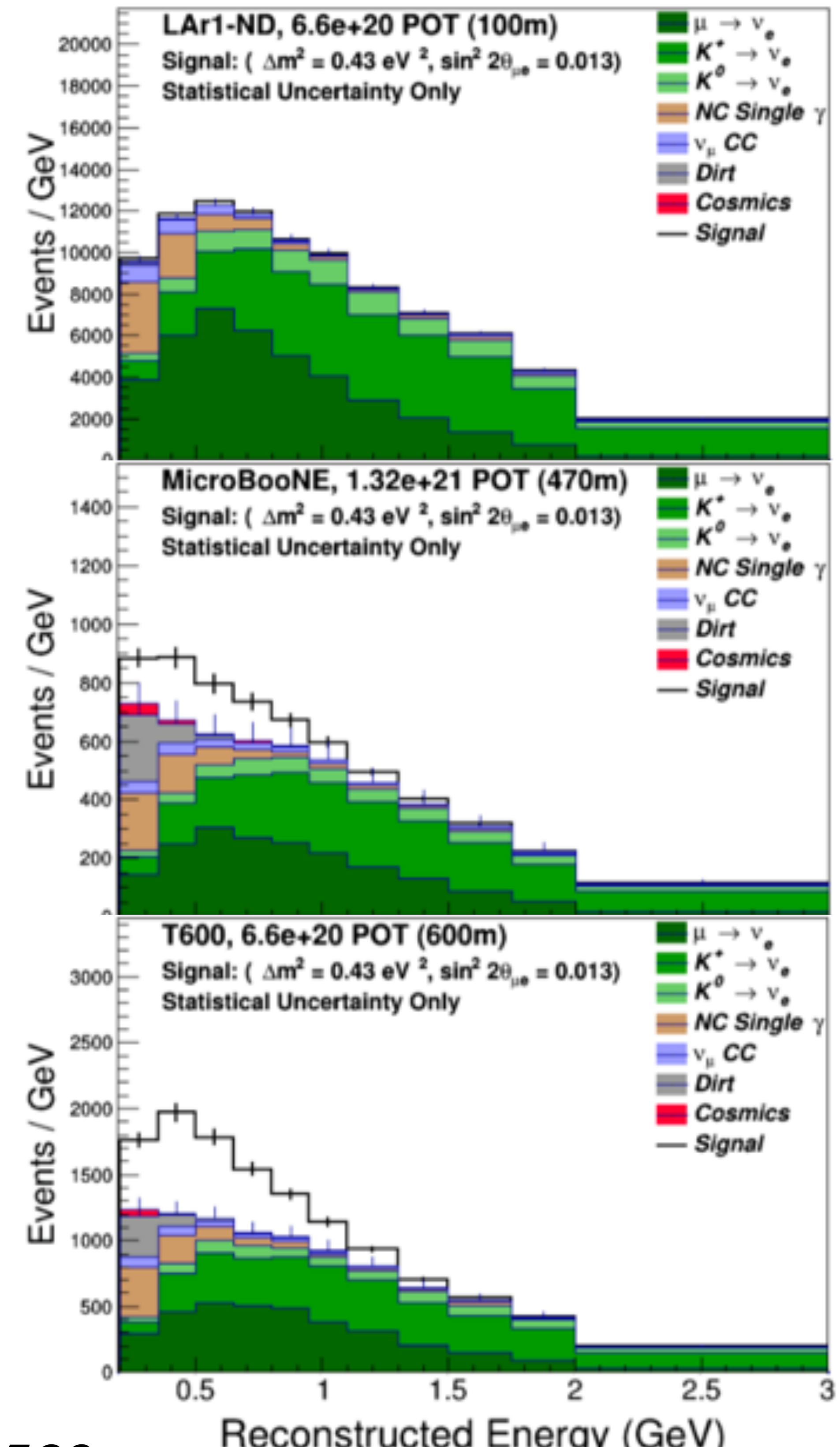
SBN program


WILSON HALL
BOOSTER RING
LEDERMAN SCIENCE CENTER
NOvA PROTOTYPE
SBN FAR DETECTOR
MiniBooNE DETECTOR
MicroBooNE/ LArTF
MINOS/ NOvA
Booster Neutrino Beam
SBN NEAR DETECTOR
SciBooNE DETECTOR
BOOSTER TARGET HALL
Far Detector
ICARUS
MicroBooNE
Near Detector
SBND

SBN program

- Similar analysis was used to evaluate SBN sensitivity
- Instead of numu constraint use multiple detectors





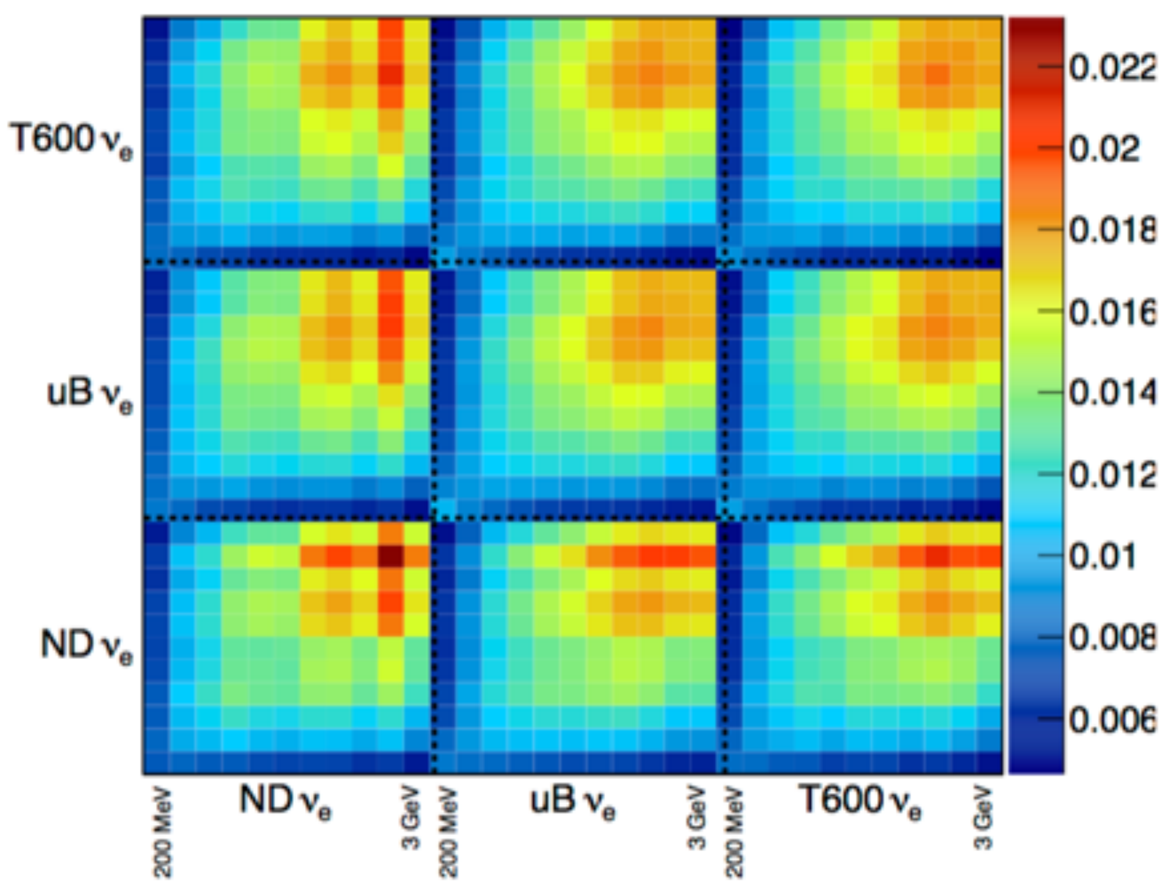
arXiv:1503.01520

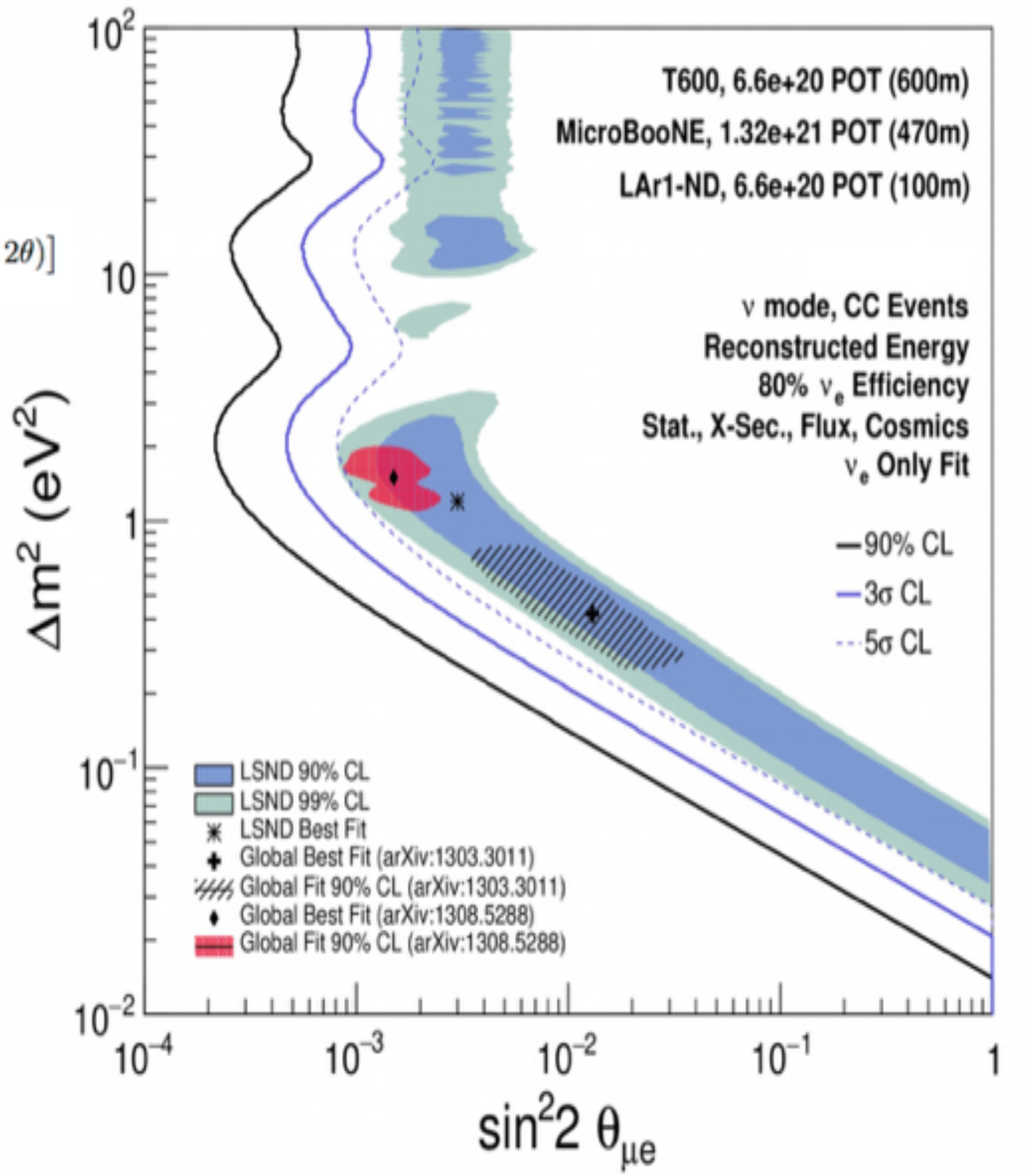
SBN program

- $\Delta\chi^2$ statistics:

$$\chi^2(\Delta m^2_{41}, \sin^2 2\theta) = \sum_{i,j} \left[N_i^{null} - N_i^{osc}(\Delta m^2_{41}, \sin^2 2\theta)\right] (E_{ij})^{-1} \left[N_j^{null} - N_j^{osc}(\Delta m^2_{41}, \sin^2 2\theta)\right]$$

$$E^{\text{syst}} = E^{\text{flux}} + E^{\text{cross section}} + E^{\text{cosmic bkgd}} + E^{\text{dirt bkgd}} + E^{\text{detector}}$$

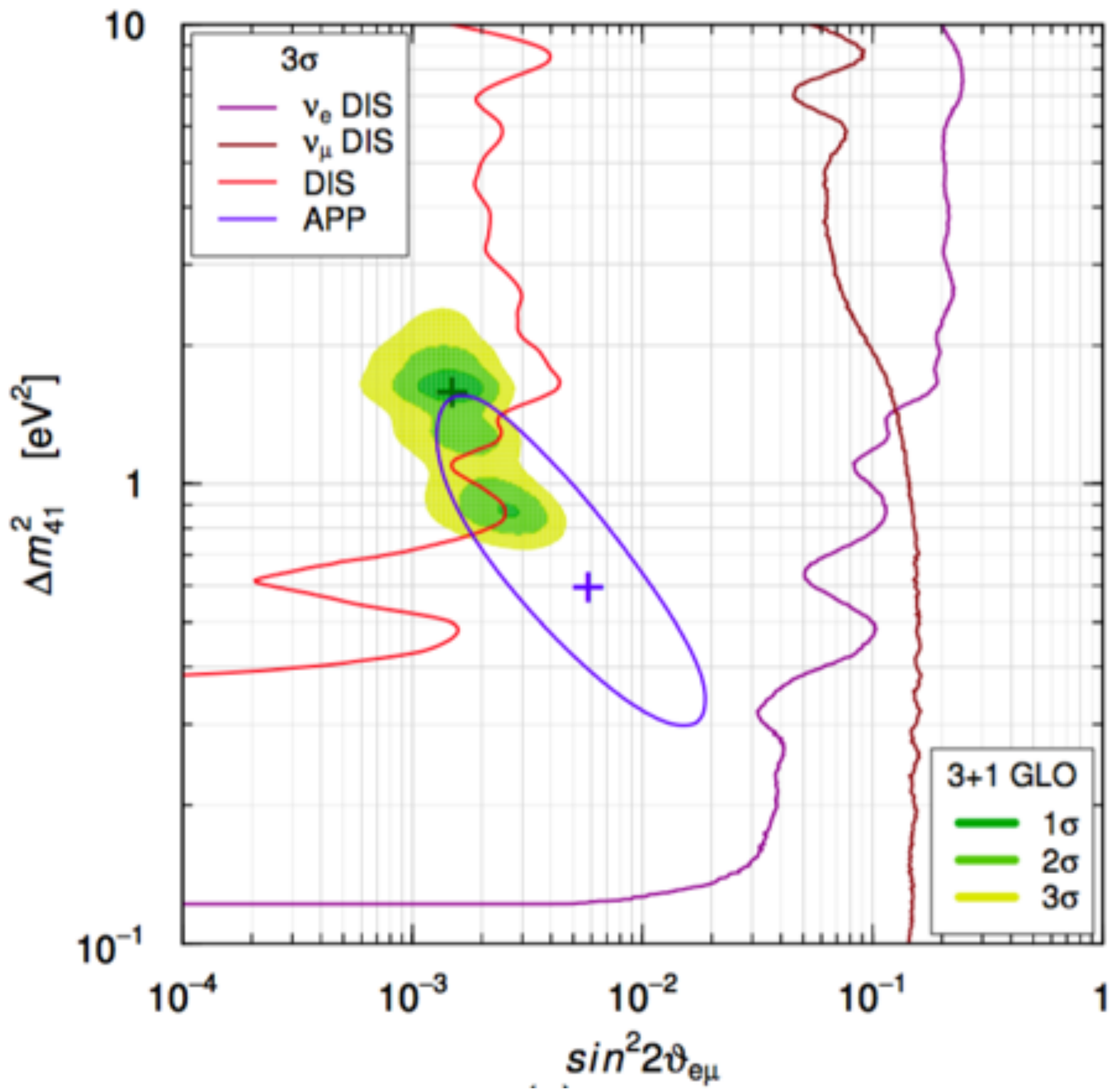




arXiv:1503.01520

Global fits

- Include data from appearance and disappearance experiments sensitive to sterile neutrinos
- Minimize χ^2
- Tension between appearance and disappearance experiments



arXiv:1609.04688

Compatibility between data sets

- Tension usually quantified using parameter goodness-of-fit (PG) (Phys. Rev. D68 033020 hep-ph/0304176)

$$\Delta\chi^2 = \chi^2_{min} - \chi^2_{min}(APP) - \chi^2_{min}(DIS)$$

- Assumes χ^2 distribution with degrees of freedom given by:

$$NDF = \sum_r P_r - P$$

where P_r is number of parameters involved in a fit to experiment r, and P is number of parameters in a global fit

- No fake data studies to check χ^2 distribution

	3+1 GLO	3+1 PrGLO	3+1 noMB	3+1 noLSND	3+2 GLO	3+2 PrGLO
χ^2_{min}	306.0	276.3	251.2	291.3	299.6	271.1
NDF	268	262	230	264	264	258
GoF	5%	26%	16%	12%	7%	28%
$(\chi^2_{min})_{APP}$	98.9	77.0	50.9	91.8	86.0	69.6
$(\chi^2_{min})_{DIS}$	194.4	194.4	194.4	194.4	192.9	192.9
$\Delta\chi^2_{PG}$	13.0	5.3	6.2	5.3	20.7	8.6
NDF_{PG}	2	2	2	2	4	4
GoF_{PG}	0.1%	7%	5%	7%	0.04%	7%
$\Delta\chi^2_{NO}$	49.2	47.7	48.1	11.4	55.7	52.9
NDF_{NO}	3	3	3	3	7	7
$n\sigma_{NO}$	6.4σ	6.3σ	6.4σ	2.6σ	6.1σ	5.9σ

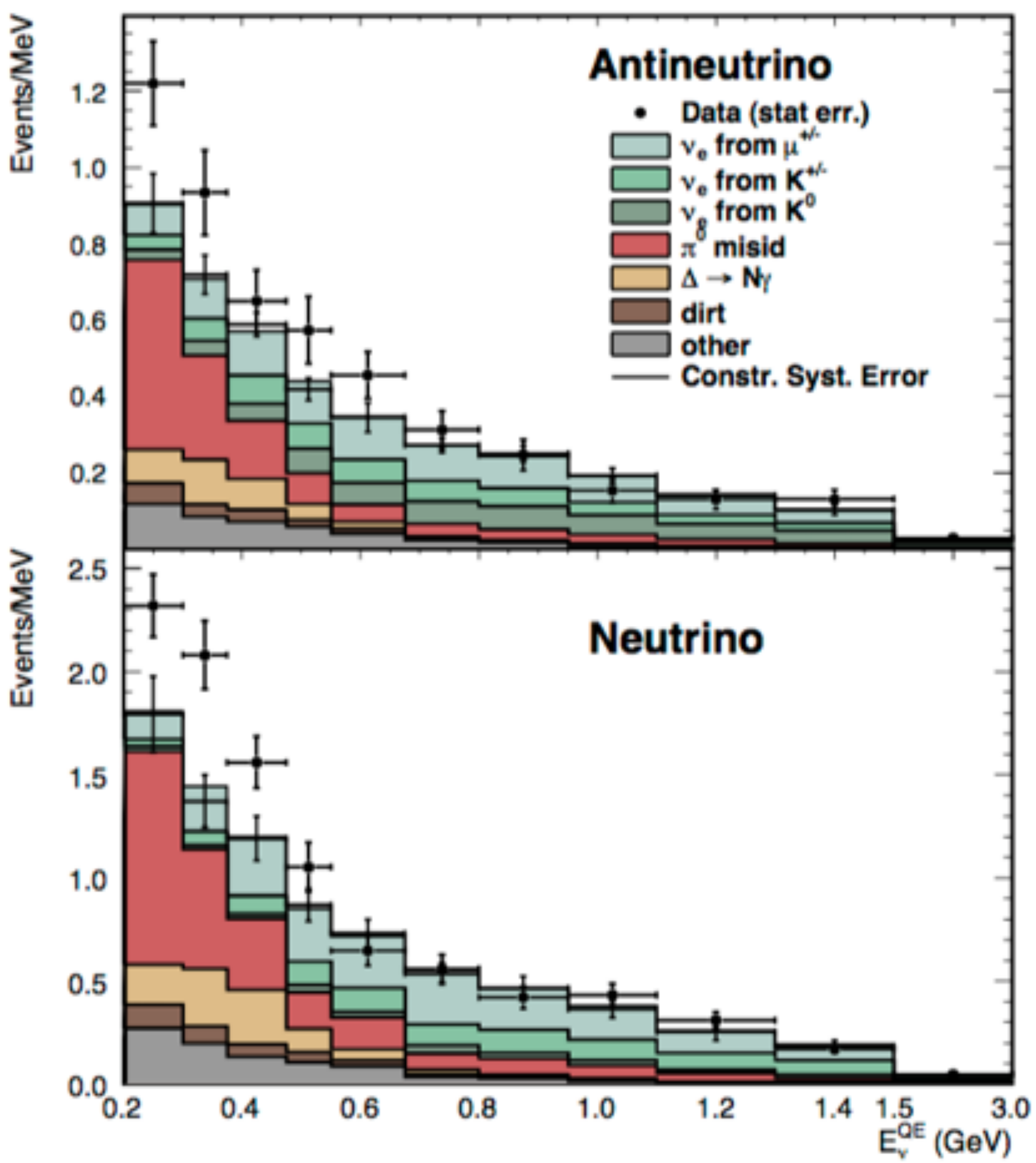
arXiv:1507.08204

Conclusion

- Several anomalous 3-4σ signals observed in short-baseline experiments
- Light sterile neutrino(s) could potentially explain these anomalies
    - major discovery with profound impact on fundamental physics
- Tensions when doing global fits and low compatibility between appearance and disappearance results

Backup

Plotting data



- When plotting error bars the diagonals of nue background block matrix do not show the effect of numu constraint
- For plots (not used in fits) MB shows constrained syst. error

ν_μ constraint

- Define chi2 with pull terms including data

$$\chi^2 = \sum_{ij}^{n_{\nu_e}+n_{\nu_\mu}} \Delta_i M_{ij}^{-1} \Delta_j + \sum_{k}^{n_{\nu_\mu}} \frac{(N_k^{fit} - N_k^{data})^2}{N_k^{data}}$$

- where:

$$\Delta_i = N_i^{fit} - N_i^{MC}$$

- find N_i^{fit} that minimize the chi2

$$\frac{\partial \chi^2}{\partial N_i^{fit}} = 2 \sum_{j=1}^{n_{\nu_e}+n_{\nu_\mu}} M_{ij}^{-1} \Delta_j + 2 \frac{(N_i^{fit} - N_i^{data}) \delta_{i(\nu_\mu \text{bin})}}{N_i^{data}} = 0$$

ν_μ constraint (cont'd)

- Defining

$$B_{ij}^{-1} = \begin{cases} M_{ij}^{-1} \text{ for } i \le n_{\nu_e} \text{ or } j \le n_{\nu_e} \\ M_{ij}^{-1} + \frac{1}{N_i^{data}} \text{ for } i > n_{\nu_e} \text{ and } j > n_{\nu_e} \end{cases}$$

we can show the solution to be:

$$N_i^{fit} = \sum_k B_{ik} \left(\sum_j M_{kj}^{-1} N_j^{MC} + \delta_{k(\nu_\mu \text{bin})} \right)$$

with covariance matrix:

$$\langle \delta N_i^{fit} \delta N_j^{fit} \rangle = B_{ij}$$