Neutrino & Antineutrino Oscillation Searches at MiniBooNE

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Prologue

- There's been a lot of confusion about what the MiniBooNE results mean.
- There's even confusion about what they *are*.
- I want to explain what we see, and show the detailed evidence we have assembled.
- Interpretations are a different matter...

Outline

- Motivation and History
- MiniBooNE Description
- MiniBooNE Analysis Methods
  - Summary of past results
- Antineutrino Results
- Future Prospects

Motivation & History

Neutrino Oscillation

Pontecorvo, Maki, Nakagawa, Sakata

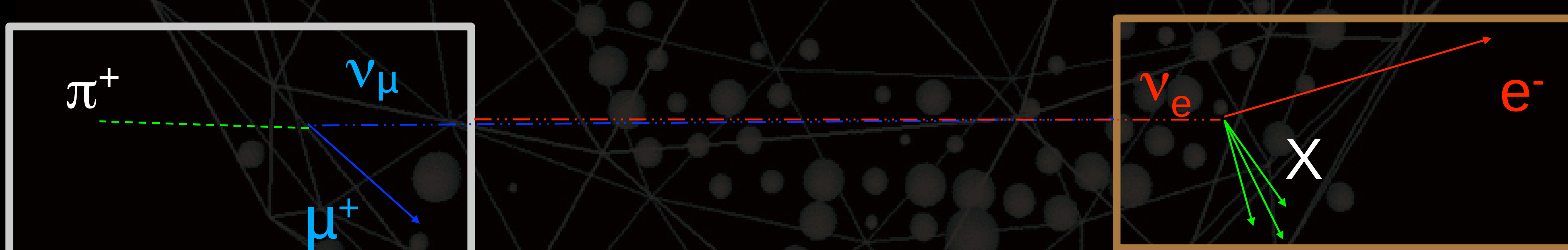
if neutrinos have mass...

a neutrino that is produced as a ν_μ

- (e.g. $\pi^+ \rightarrow \mu^+ \nu_\mu$)

might some time later be observed as a ν_e

- (e.g. $\nu_e\, n \rightarrow e^- p$)

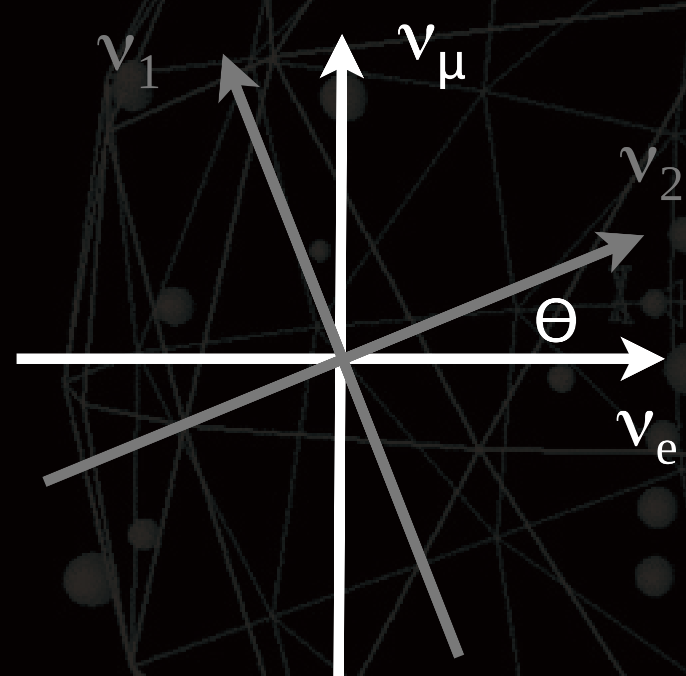


ν source

ν detector

Neutrino Oscillation

$$\begin{pmatrix} \nu_\mu \\ \nu_e \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



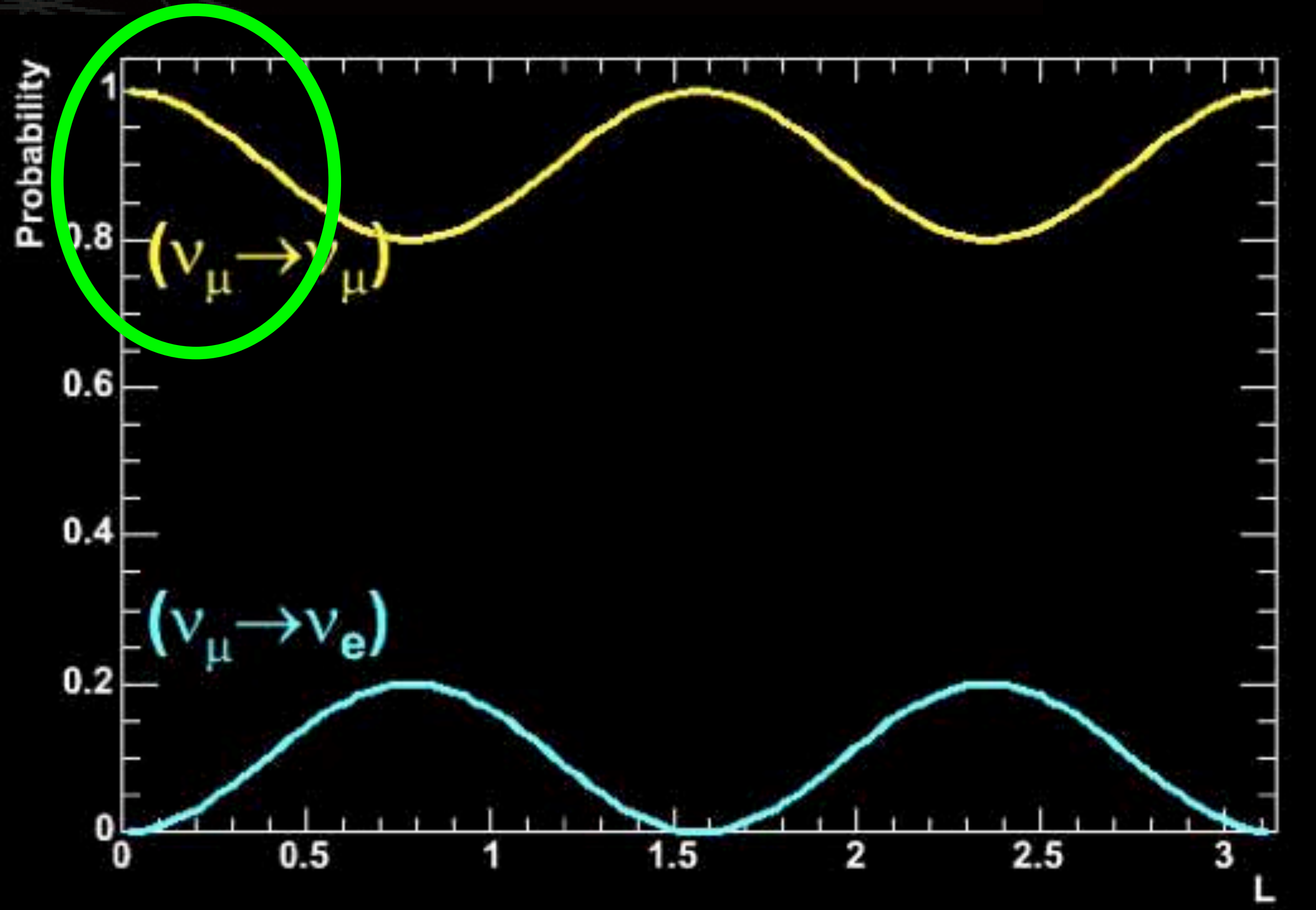
- Consider only two types of neutrinos
- If weak states differ from mass states
  - i.e. $(\nu_\mu\ \nu_e) \neq (\nu_1\ \nu_2)$
- Then weak states are mixtures of mass states

$$|\nu(t)\rangle = -\sin\theta|\nu_1\rangle e^{-iE1t} + \cos\theta|\nu_2\rangle e^{-1E2t}$$

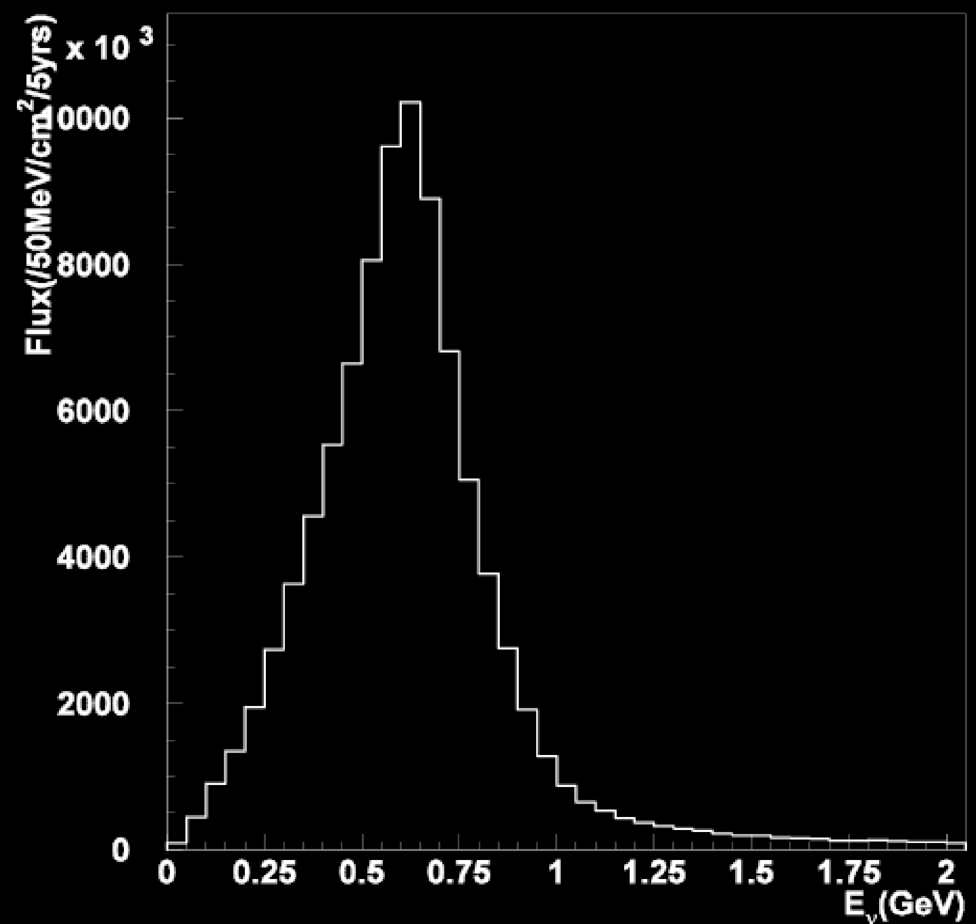
- Probability to find ν_e when you started with ν_μ

$$P_{osc}(\nu_\mu \rightarrow \nu_e) = |\langle\nu_e|\nu_\mu(t)\rangle|^2$$

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12}\frac{L}{E})$$



- 2 fundamental parameters
  - Δm^2_{12} (=m_1^2-m_2^2) ↔ period
  - θ_{12} ↔ magnitude
- 2 experimental parameters
  - L = distance travelled
  - E = neutrino energy
- Tune L&E for Δm^2 range, uncertainties determine θ sensitivity
- Neutrino disappearance and appearance



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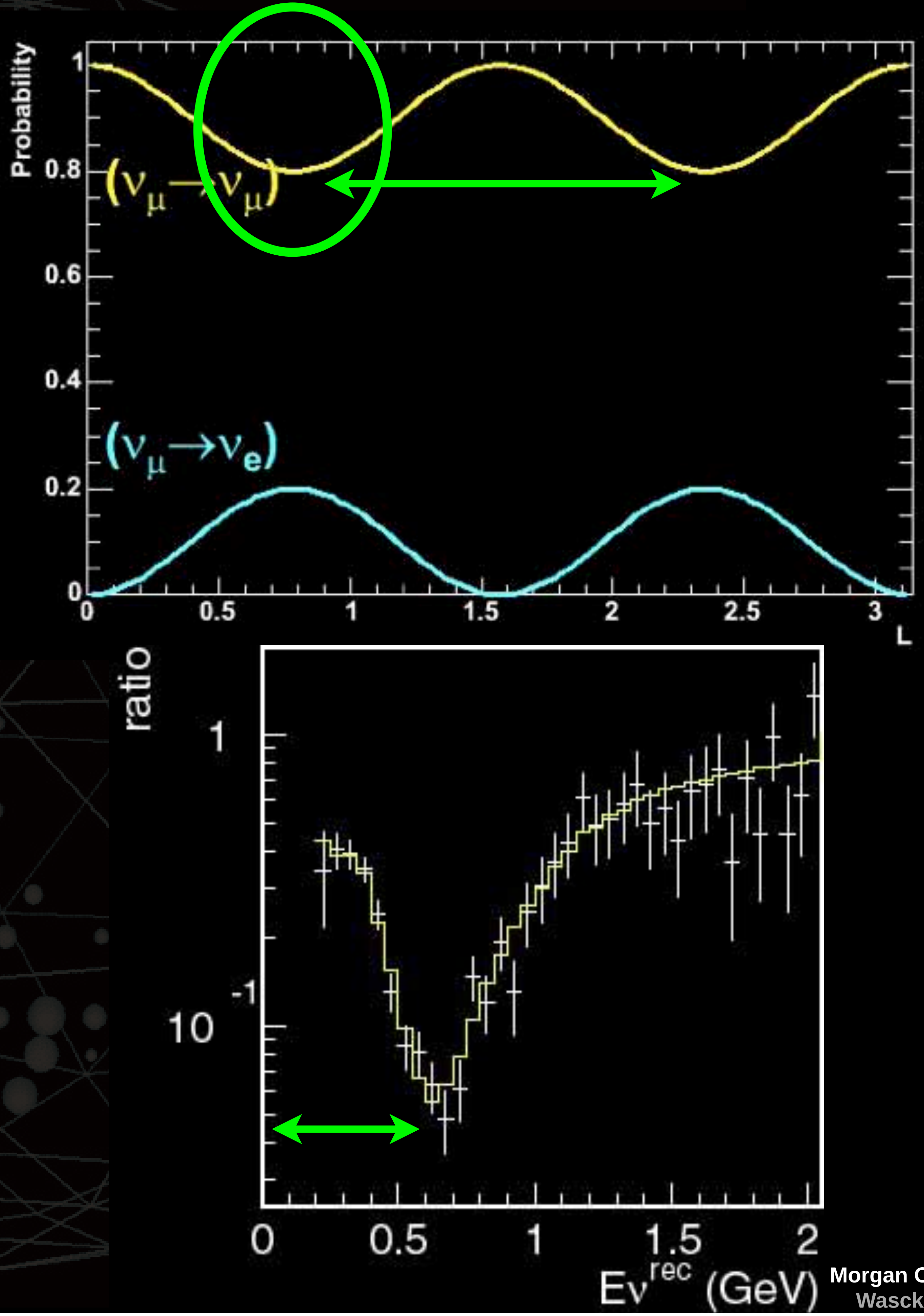

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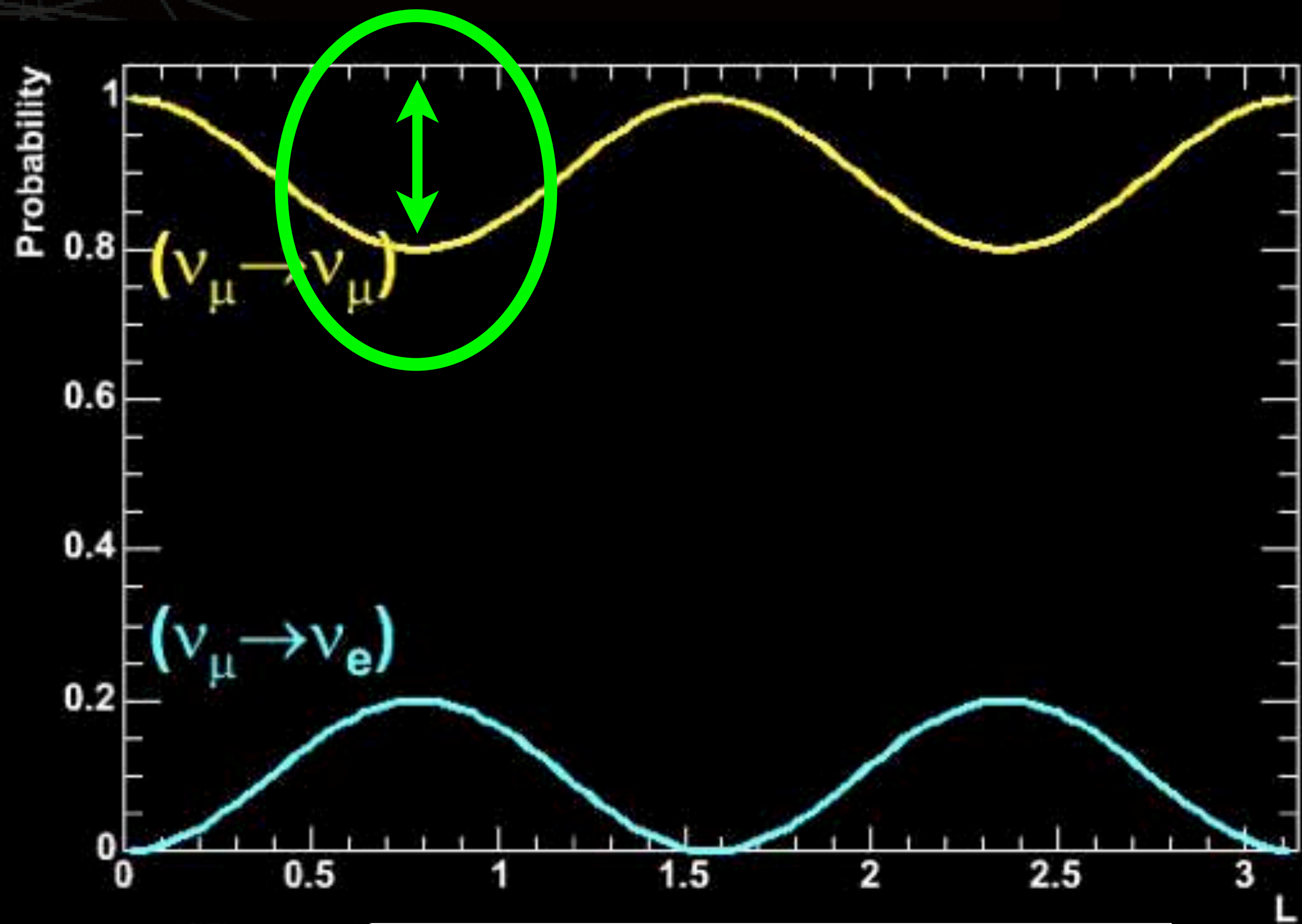

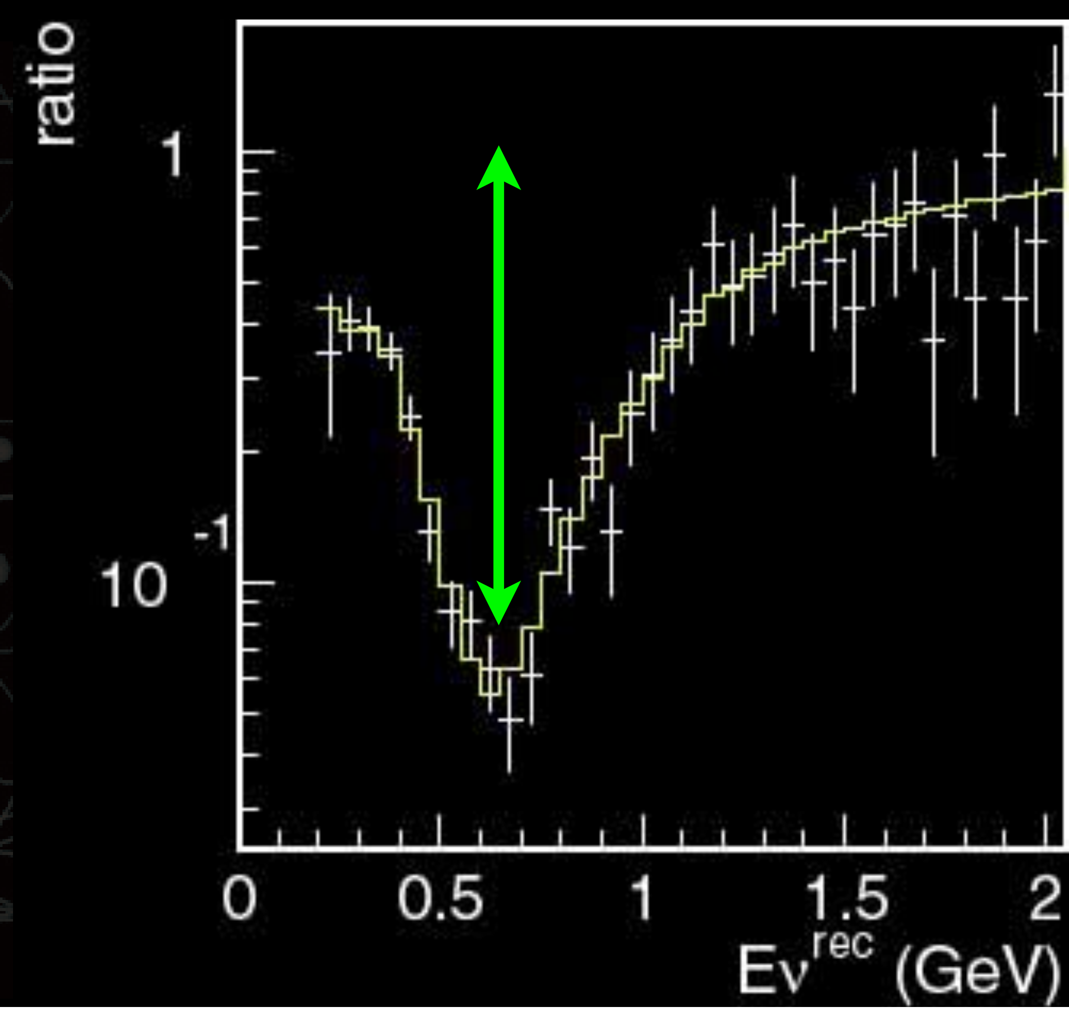

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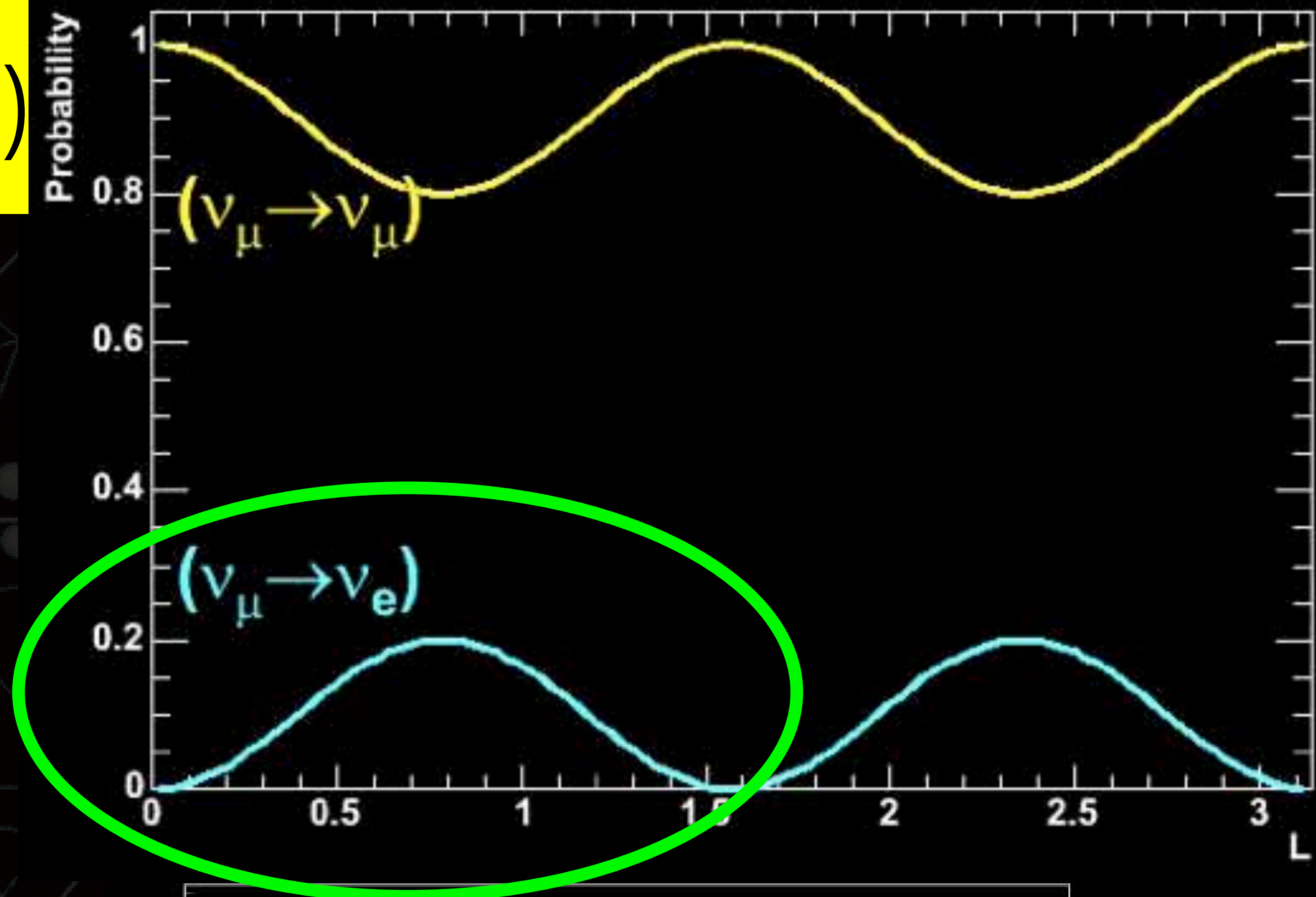
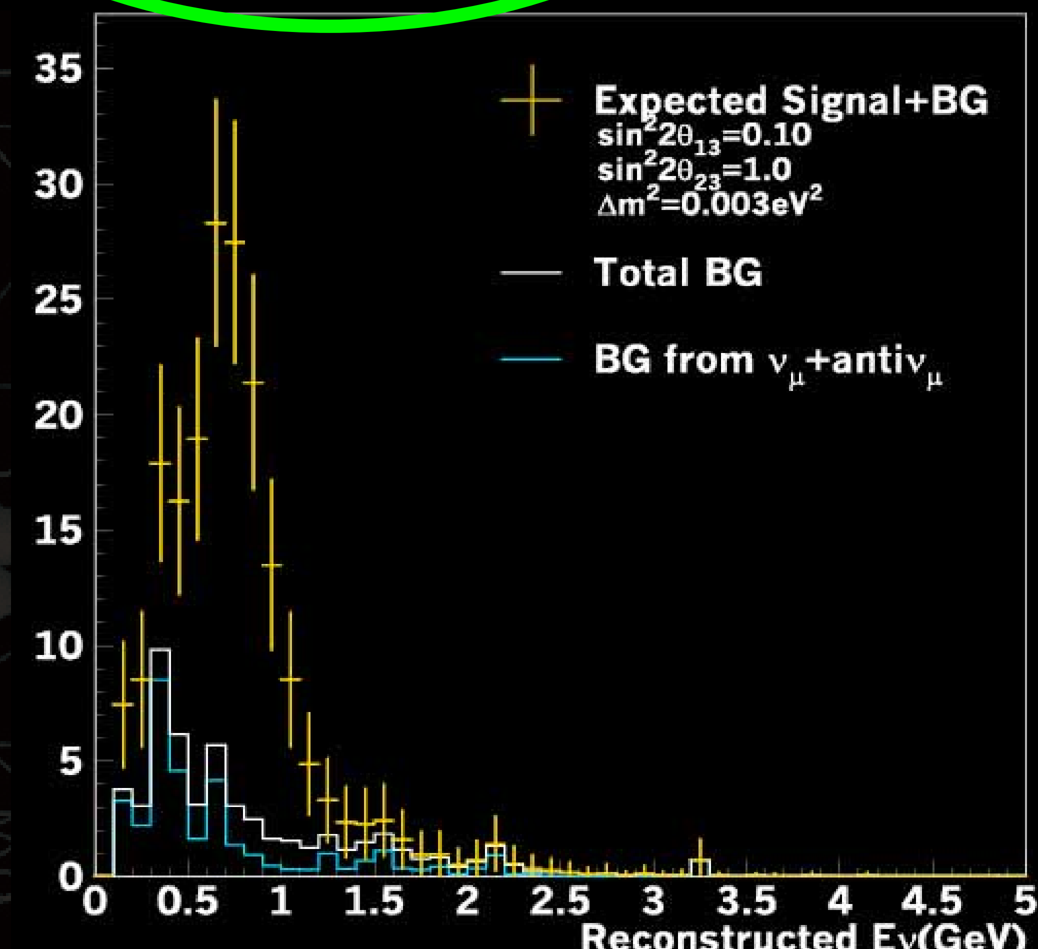
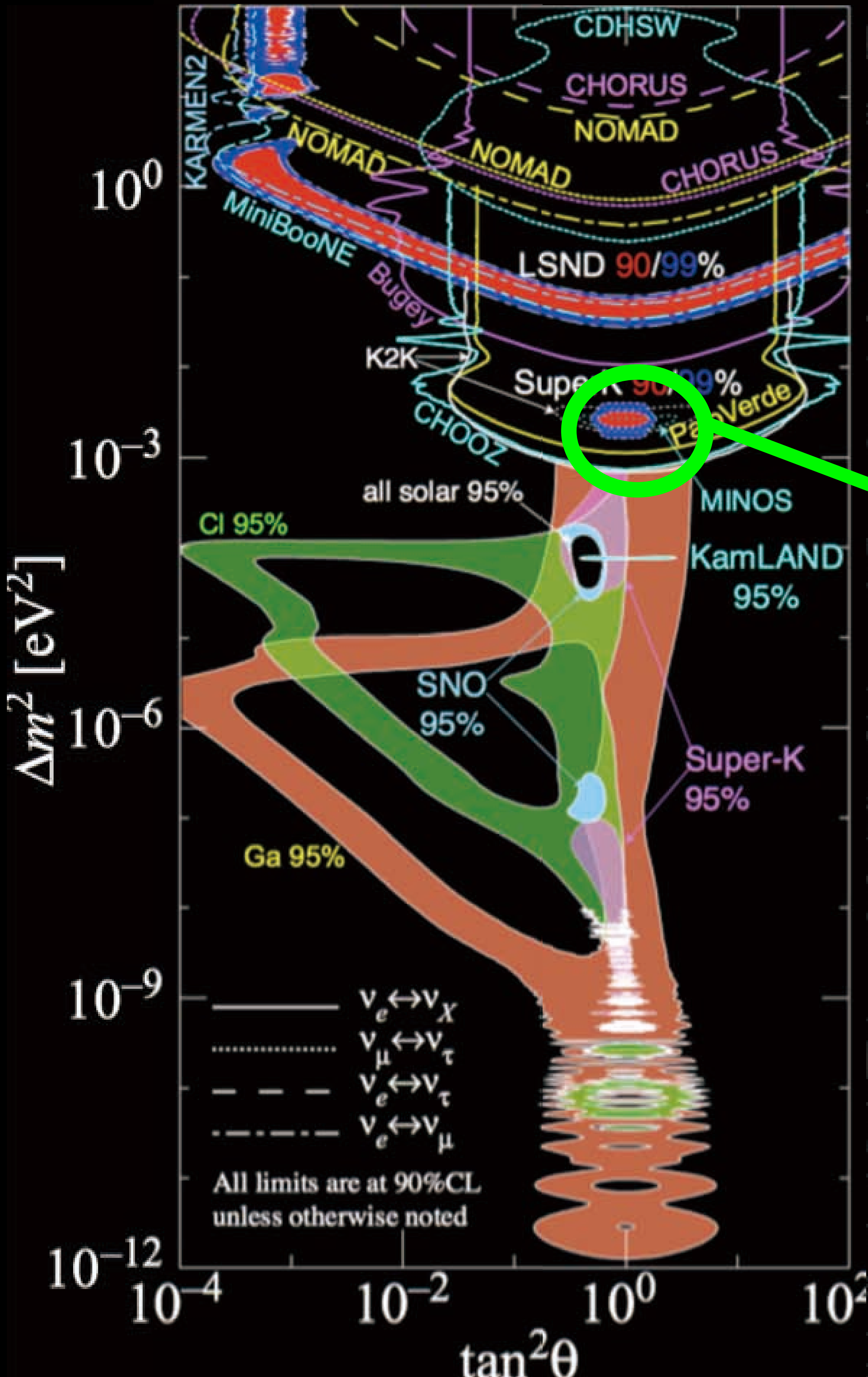
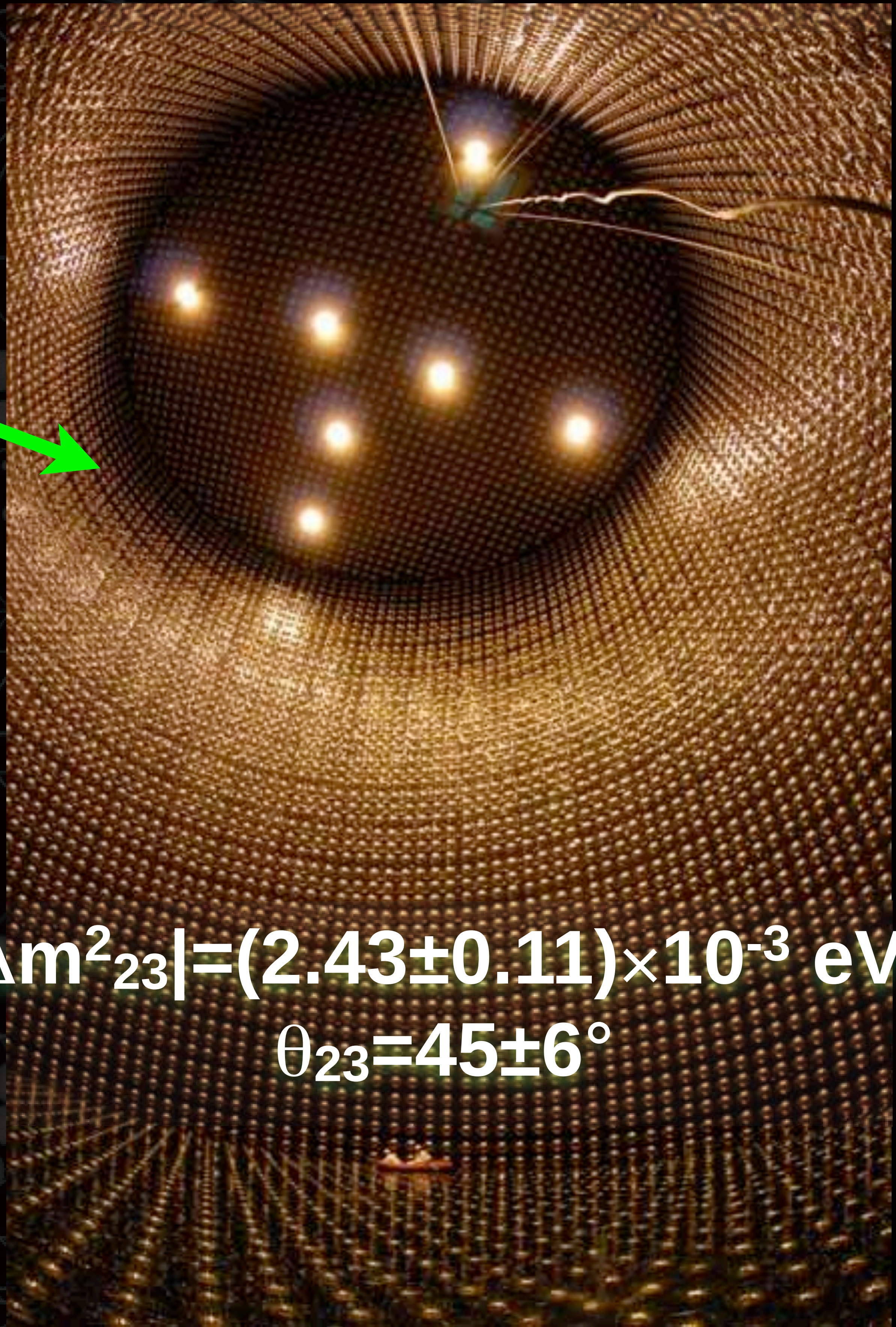


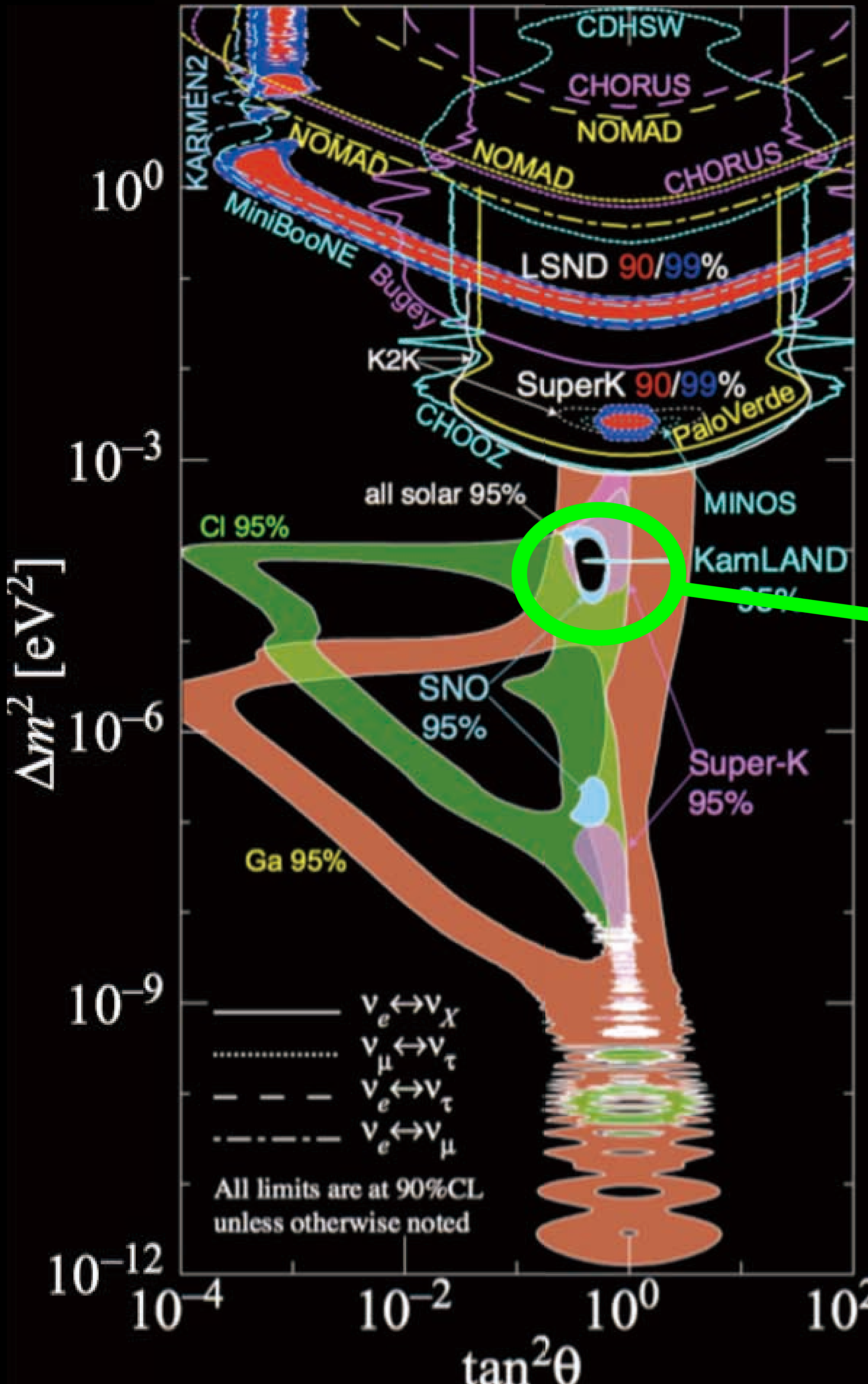


Atmospheric

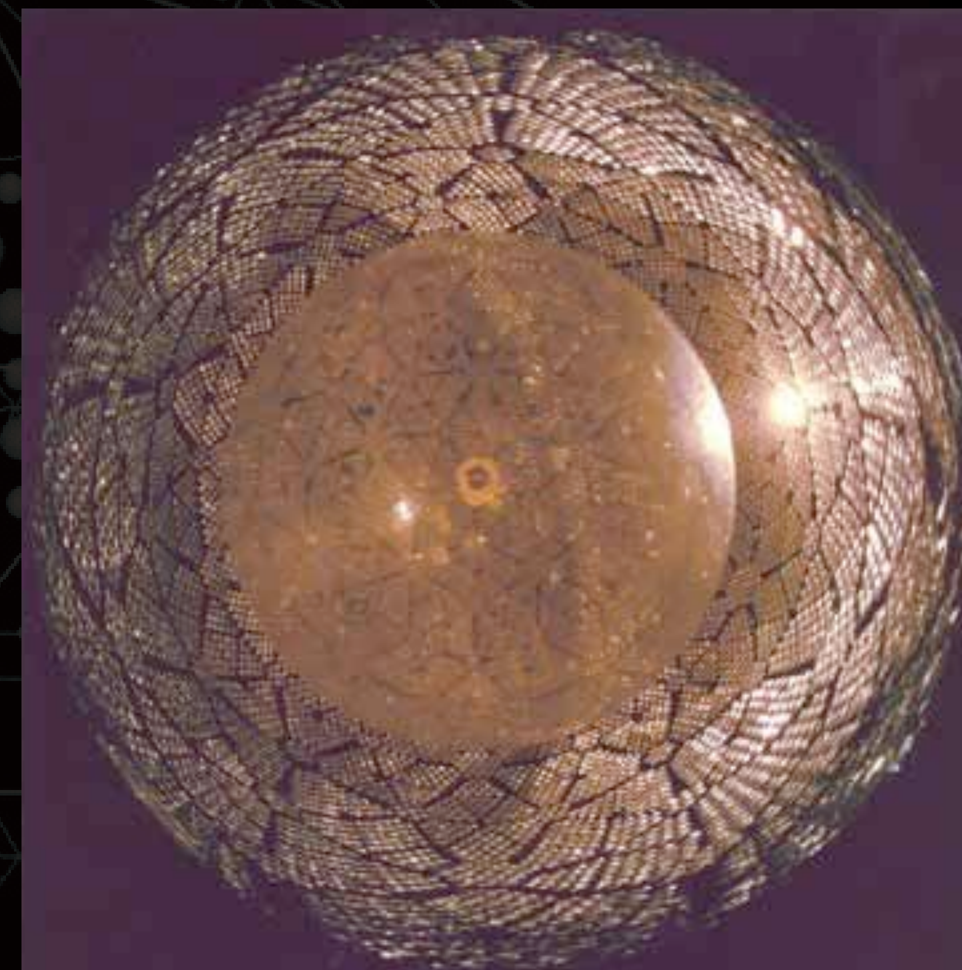




http://hitoshi.berkeley.edu/neutrino



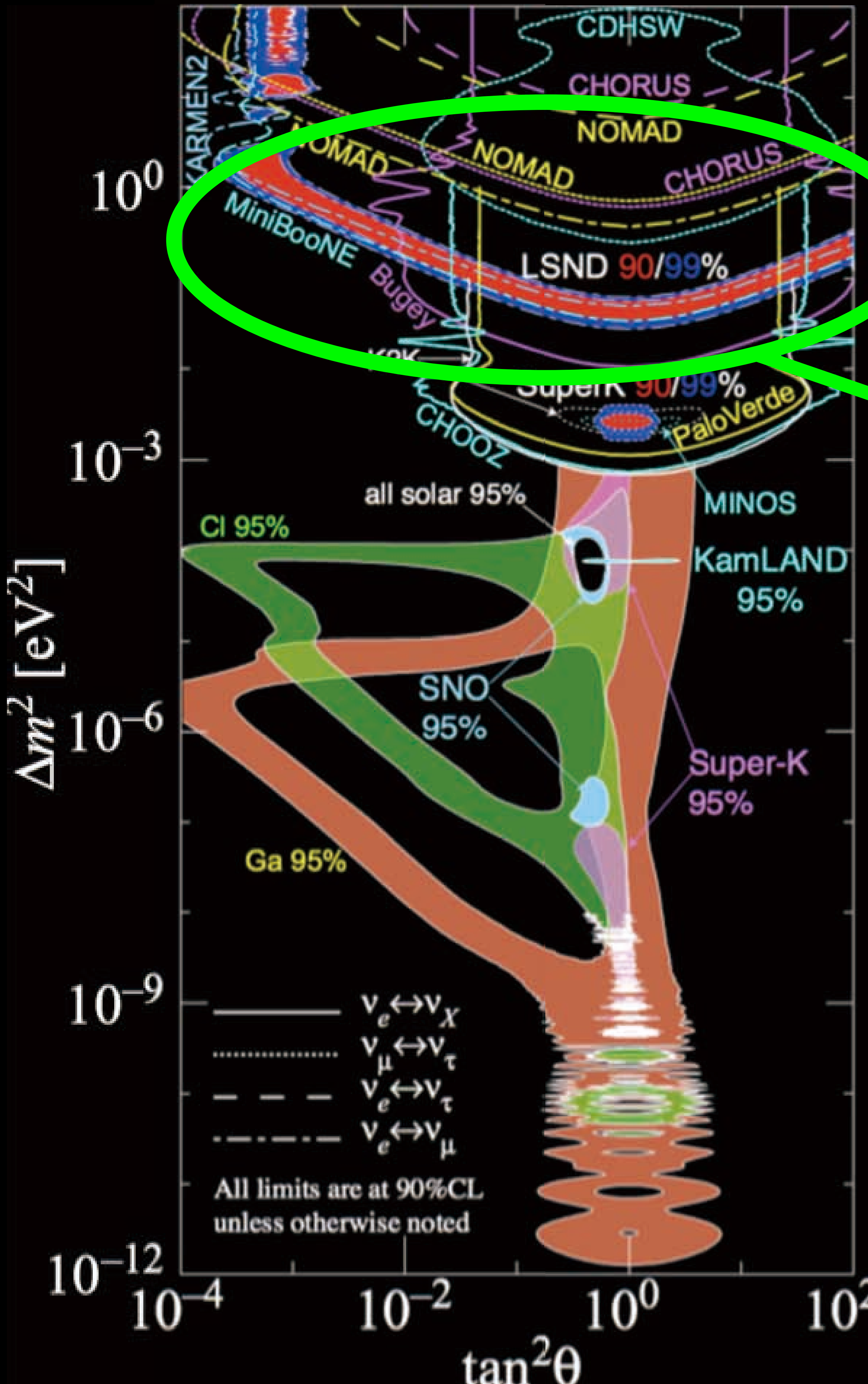
Solar

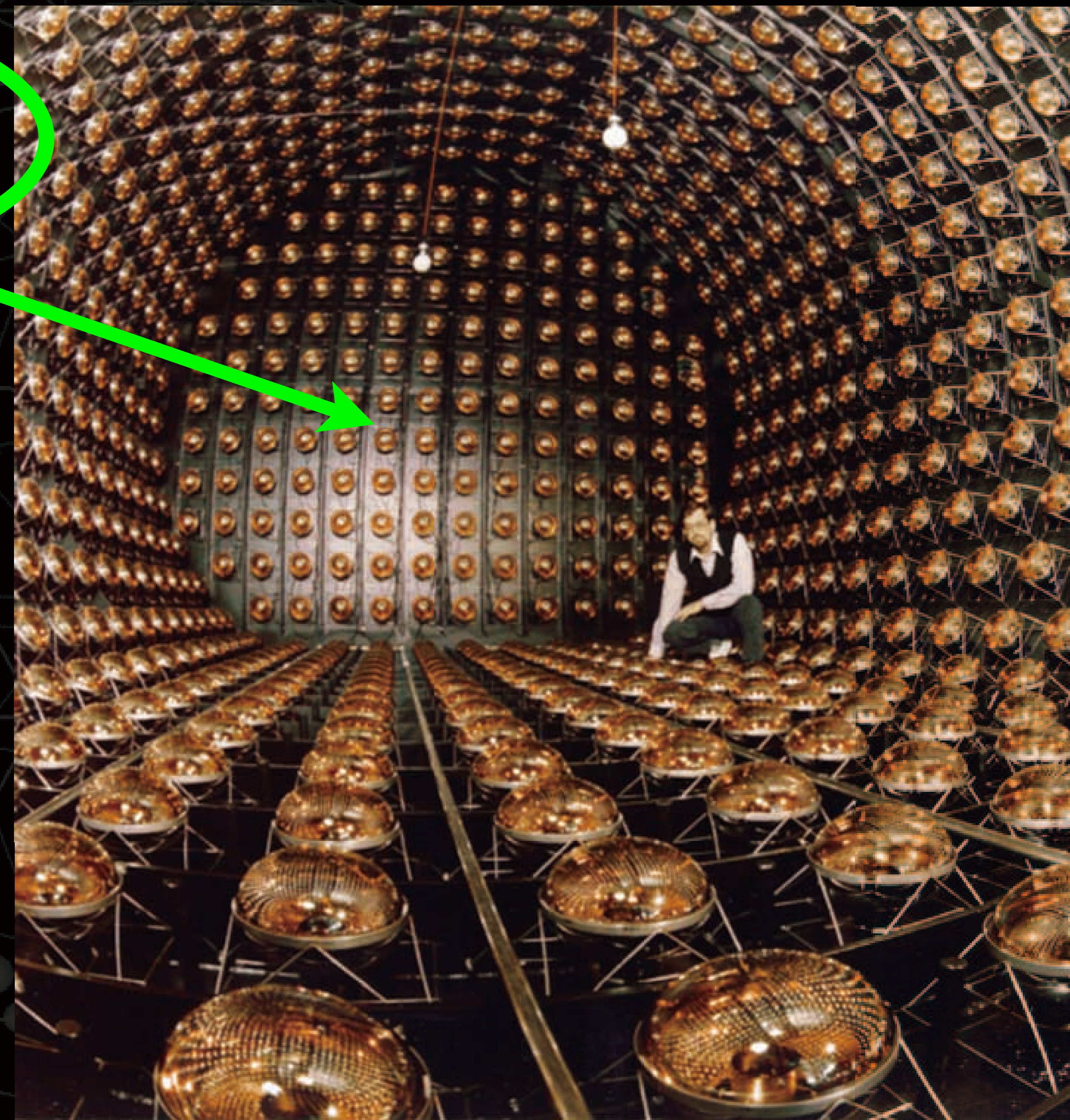


$$\Delta m^2_{12} = (7.59 \pm 0.21) \times 10^{-5}\ \text{eV}^2$$

$$\theta_{12} = 34.4°\ ^{+1.6}_{-1.5}$$

Short baseline





$\Delta m^2_{\mu e} \sim eV^2$

$\theta_{\mu e} \sim 2°$

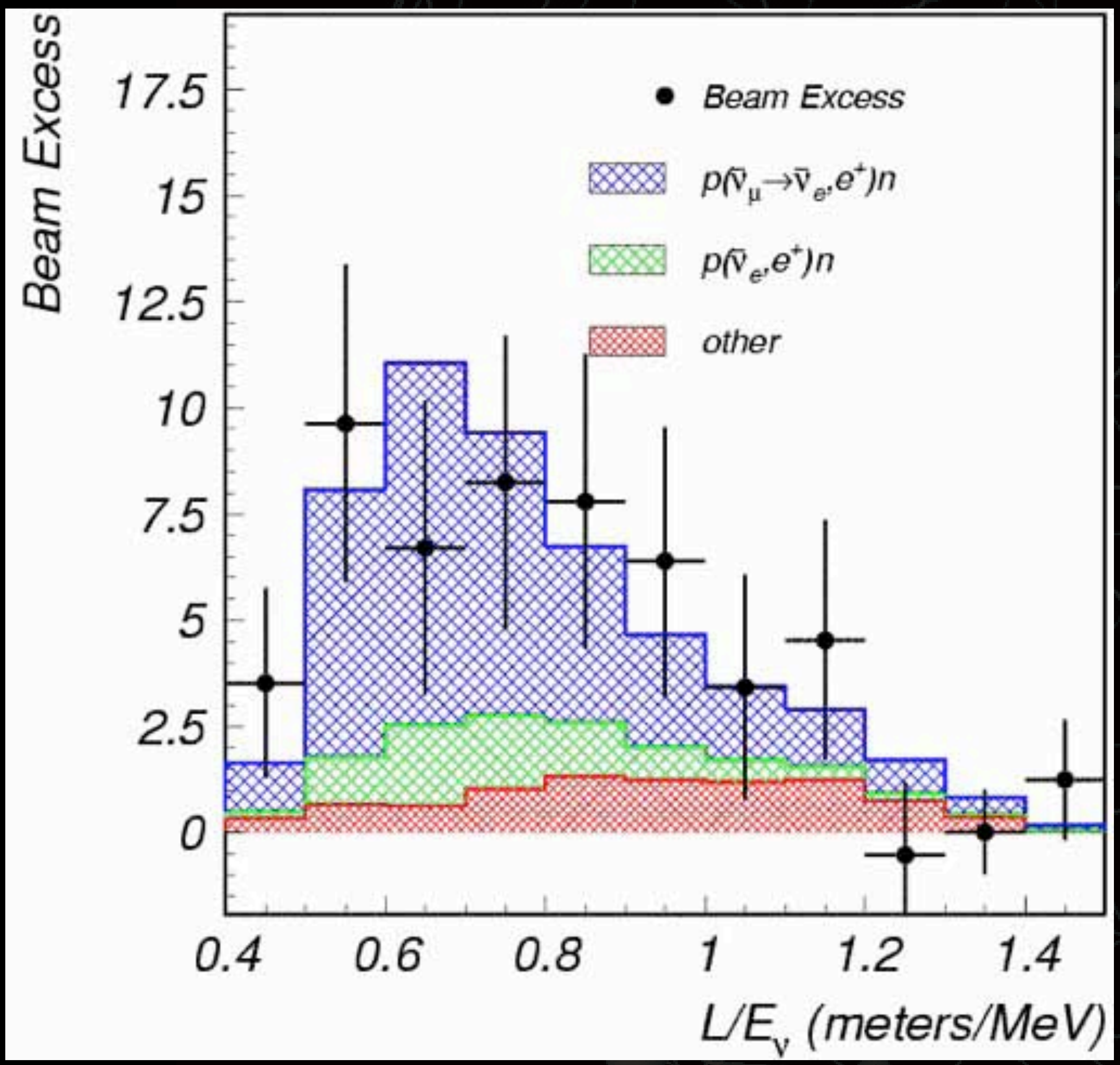
http://hitoshi.berkeley.edu/neutrino

The LSND signal

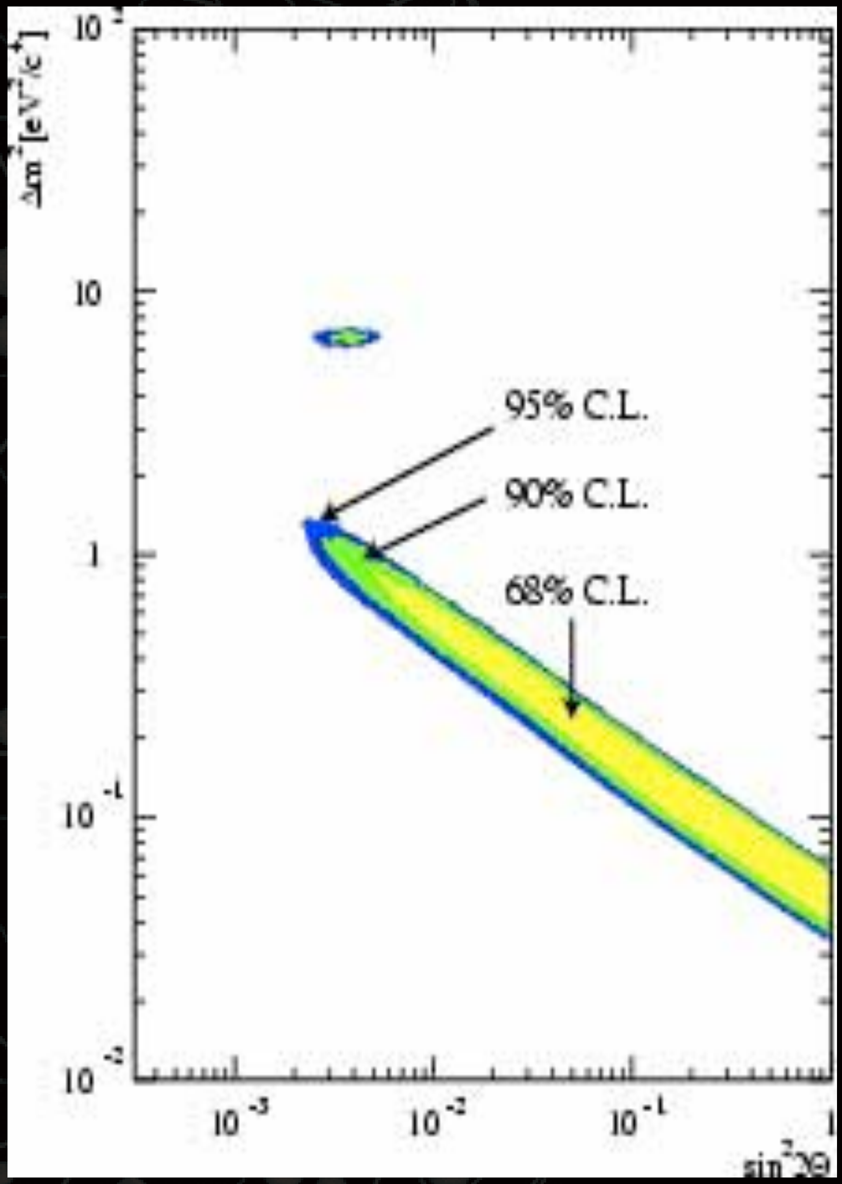
- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation probability:

0.264±0.067±0.045%

3.8σ excess!



hep-ex/0104049



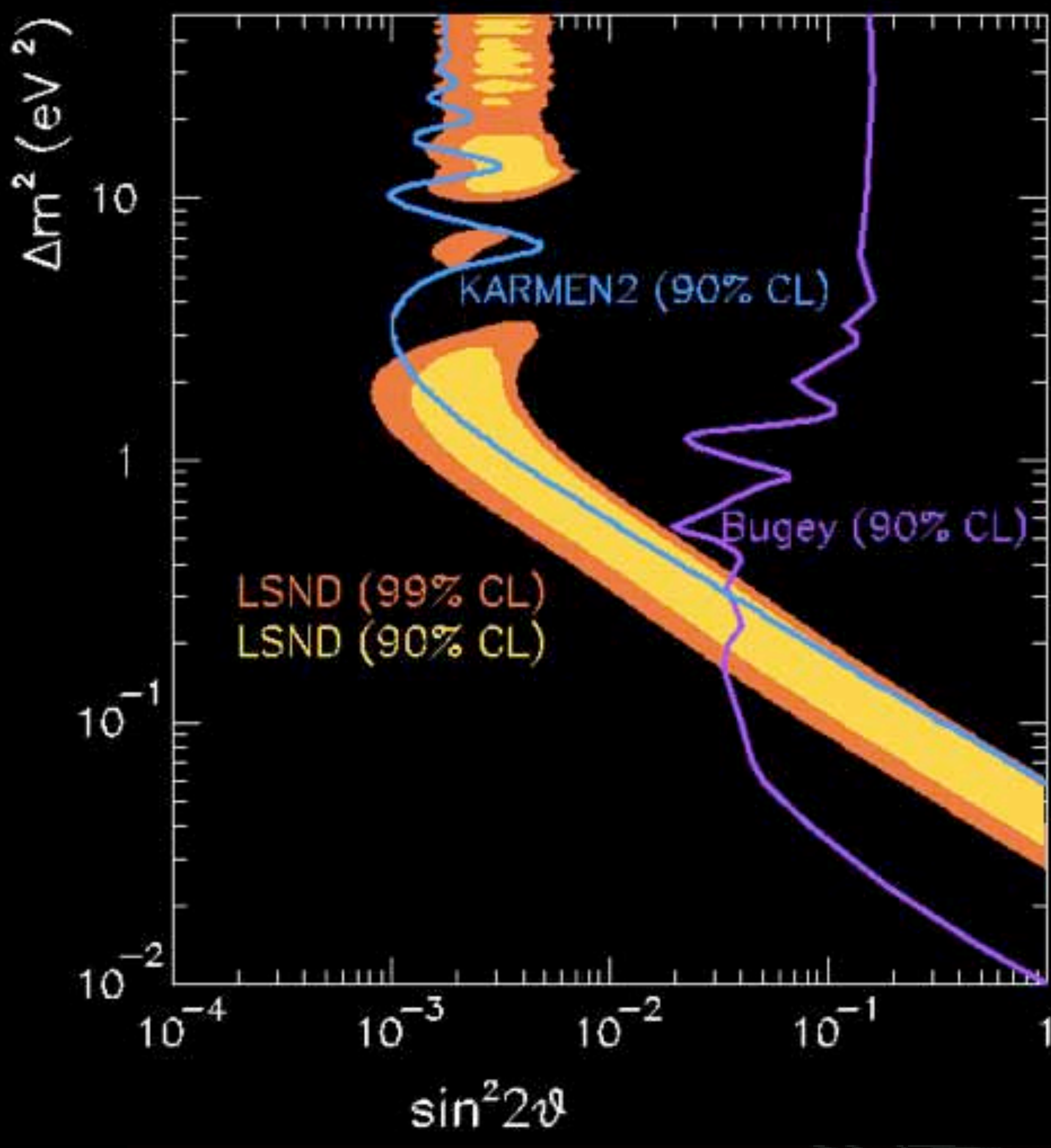
hep-ex/0203023

KARMEN2 and LSND collaborators performed joint analysis on both data sets - allowed regions remain!

$\Delta m^2 \sim 1 eV^2$, $\theta \sim 2°$

Verifying LSND

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12}\frac{L}{E})$$



- LSND interpreted as 2 ν oscillation
- Verification requires same (L/E) and high statistics
  - Different systematics
- MiniBooNE chose higher L and higher E
- Strategy: search for ν_e excess in ν_μ beam

MiniBooNE Collaboration

A. A. Aguilar-Arevalo[5], A. O. Bazarko[12], S. J. Brice[7], B. C. Brown[7], L. Bugel[5], J. Cao[11], L. Coney[5], J. M. Conrad[5], D. C. Cox[8], A. Curioni[16], Z. Djurcic[5], D. A. Finley[7], B. T. Fleming[16], R. Ford[7], F. G. Garcia[7], G. T. Garvey[9], J. A. Green[8,9], C. Green[7,9], T. L. Hart[4], E. Hawker[15], R. Imlay[10], R. A. Johnson[3], P. Kasper[7], T. Katori[8], T. Kobilarcik[7], I. Kourbanis[7], S. Koutsoliotas[2], E. M. Laird[12], J. M. Link[14], Y. Liu[11], Y. Liu[1], W. C. Louis[9], K. B. M. Mahn[5], W. Marsh[7], P. S. Martin[7], G. McGregor[9], W. Metcalf[10], P. D. Meyers[12], F. Mills[7], G. B. Mills[9], J. Monroe[5], C. D. Moore[7], R. H. Nelson[4], P. Nienaber[13], S. Ouedraogo[10], R. B. Patterson[12], D. Perevalov[1], C. C. Polly[8], E. Prebys[7], J. L. Raaf[3], H. Ray[9], B. P. Roe[11], A. D. Russell[7], V. Sandberg[9], R. Schirato[9], D. Schmitz[5], M. H. Shaevitz[5], F. C. Shoemaker[12], D. Smith[6], M. Sorel[5], P. Spentzouris[7], I. Stancu[1], R. J. Stefanski[7], M. Sung[10], H. A. Tanaka[12], R. Tayloe[8], M. Tzanov[4], M. O. Wascko[10], R. Van de Water[9], D. H. White[9], M. J. Wilking[4], H. J. Yang[11], G. P. Zeller[5], E. D. Zimmerman[4]

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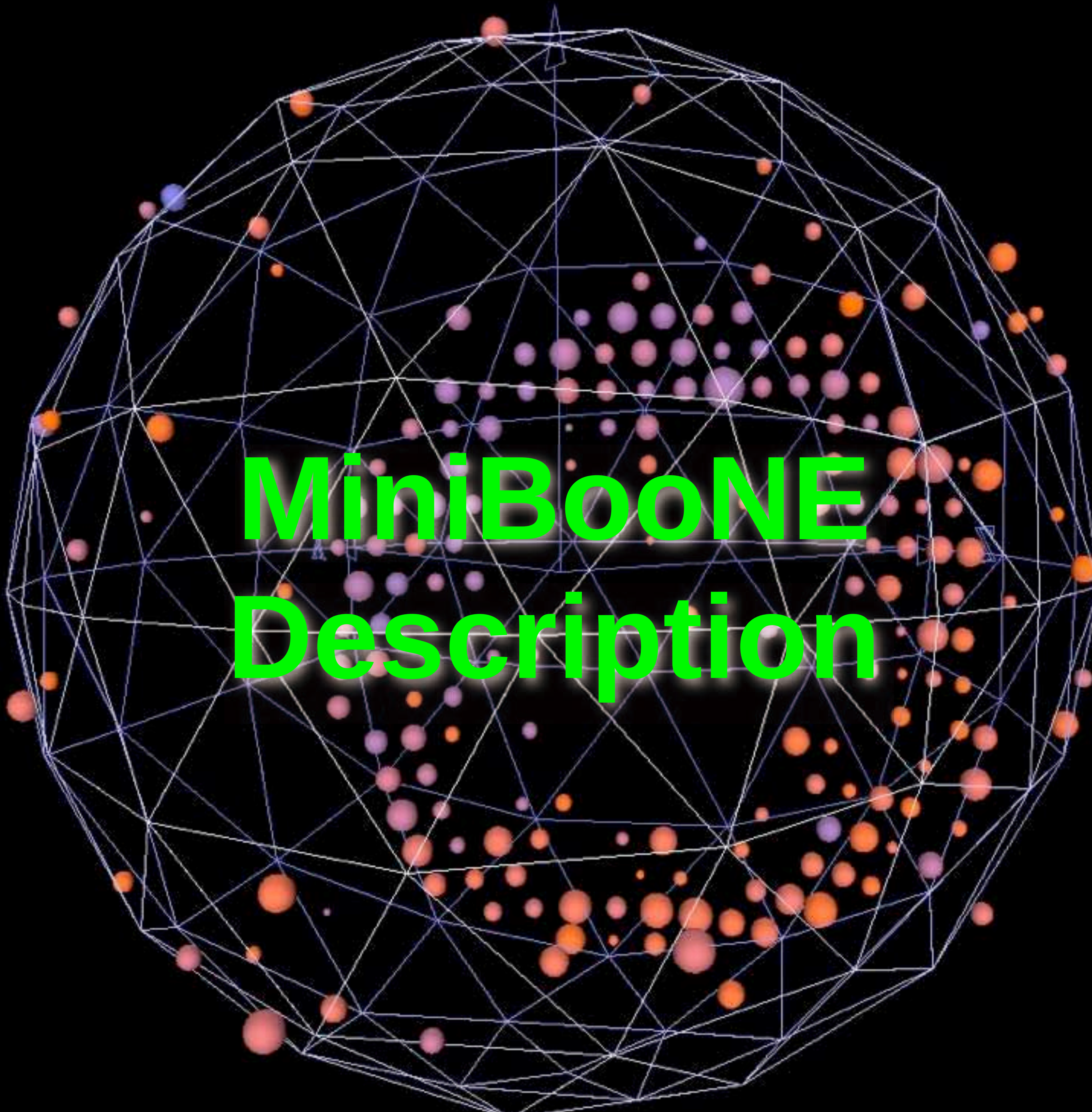
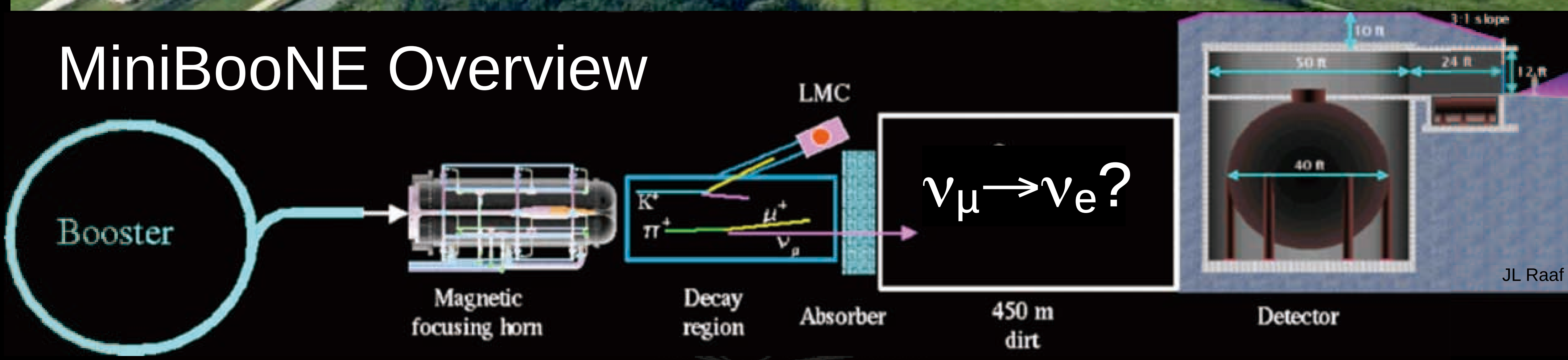
[2] *Bucknell University, Lewisburg, PA 17837*
[3] *University of Cincinnati, Cincinnati, OH 45221*
[4] *University of Colorado, Boulder, CO 80309*
[5] *Columbia University, New York, NY 10027*
[6] *Embry Riddle Aeronautical University, Prescott, AZ 86301*
[7] *Fermi National Accelerator Laboratory, Batavia, IL 60510*
[8] *Indiana University, Bloomington, IN 47405*
[9] *Los Alamos National Laboratory, Los Alamos, NM 87545*
[10] *Louisiana State University, Baton Rouge, LA 70803*
[11] *University of Michigan, Ann Arbor, MI 48109*
[12] *Princeton University, Princeton, NJ 08544*
[13] *Saint Mary's University of Minnesota, Winona, MN 55987*
[14] *Virginia Polytechnic Institute & State University, Blacksburg, VA 24061*
[15] *Western Illinois University, Macomb, IL 61455*
[16] *Yale University, New Haven, CT 06520*

MiniBooNE Description

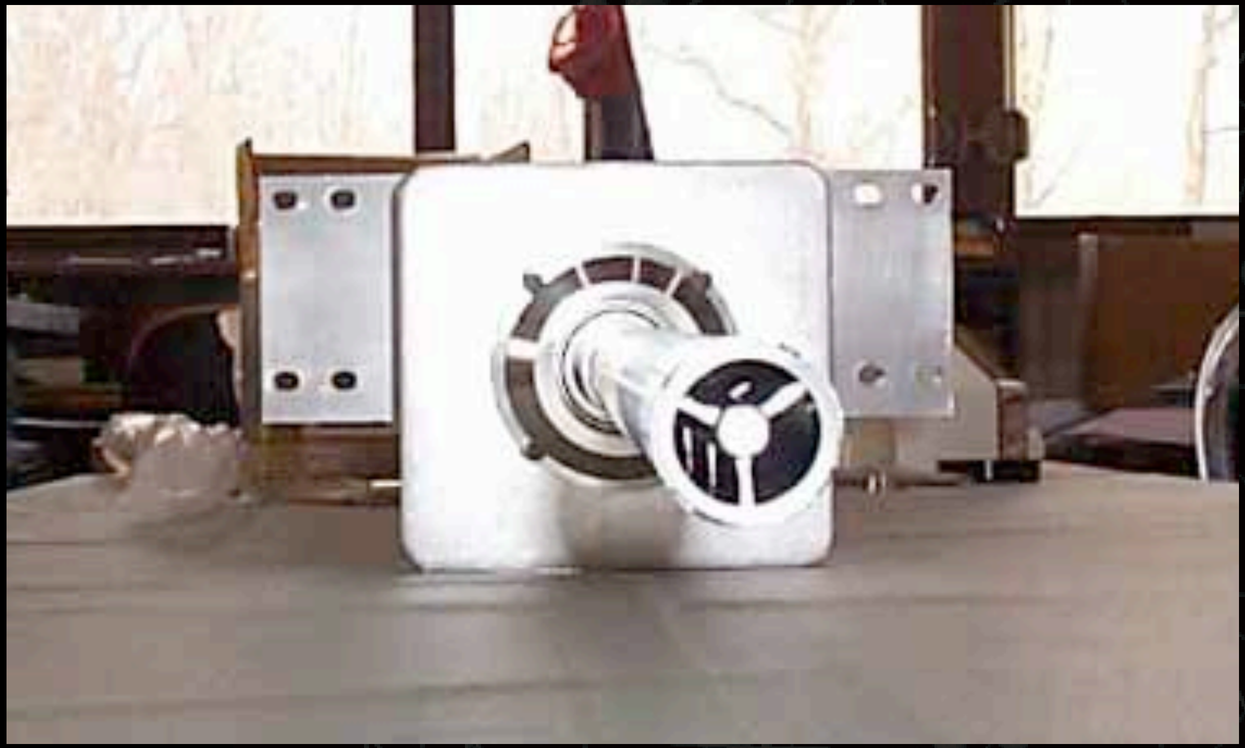


Overview


Fermilab Visual Media Services

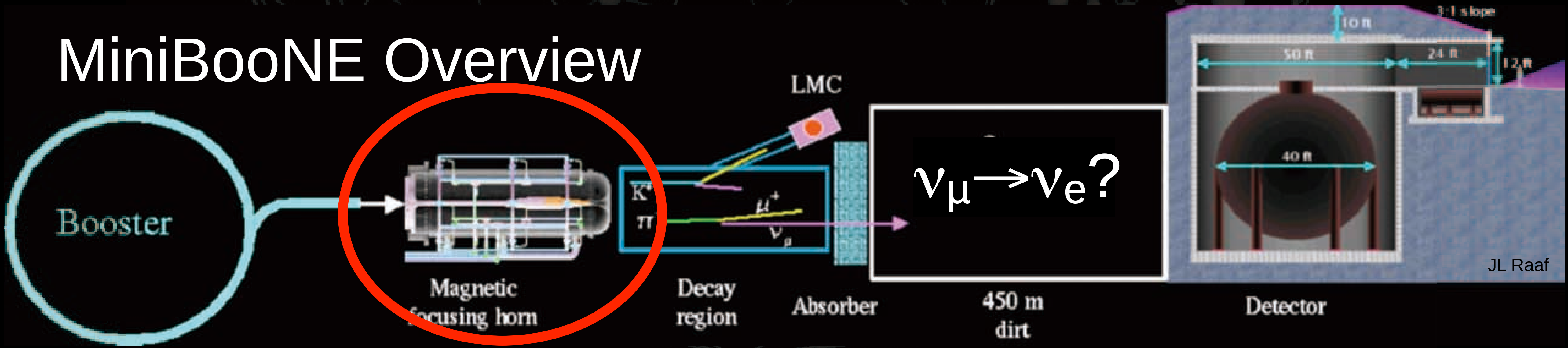

MiniBooNE Overview
LMC
Booster
Magnetic focusing horn
Decay region
Absorber
450 m dirt
Detector
$\nu_\mu \rightarrow \nu_e$?
10 ft
3:1 slope
50 ft
24 ft
12 ft
40 ft
JL Raaf

Target & Horn

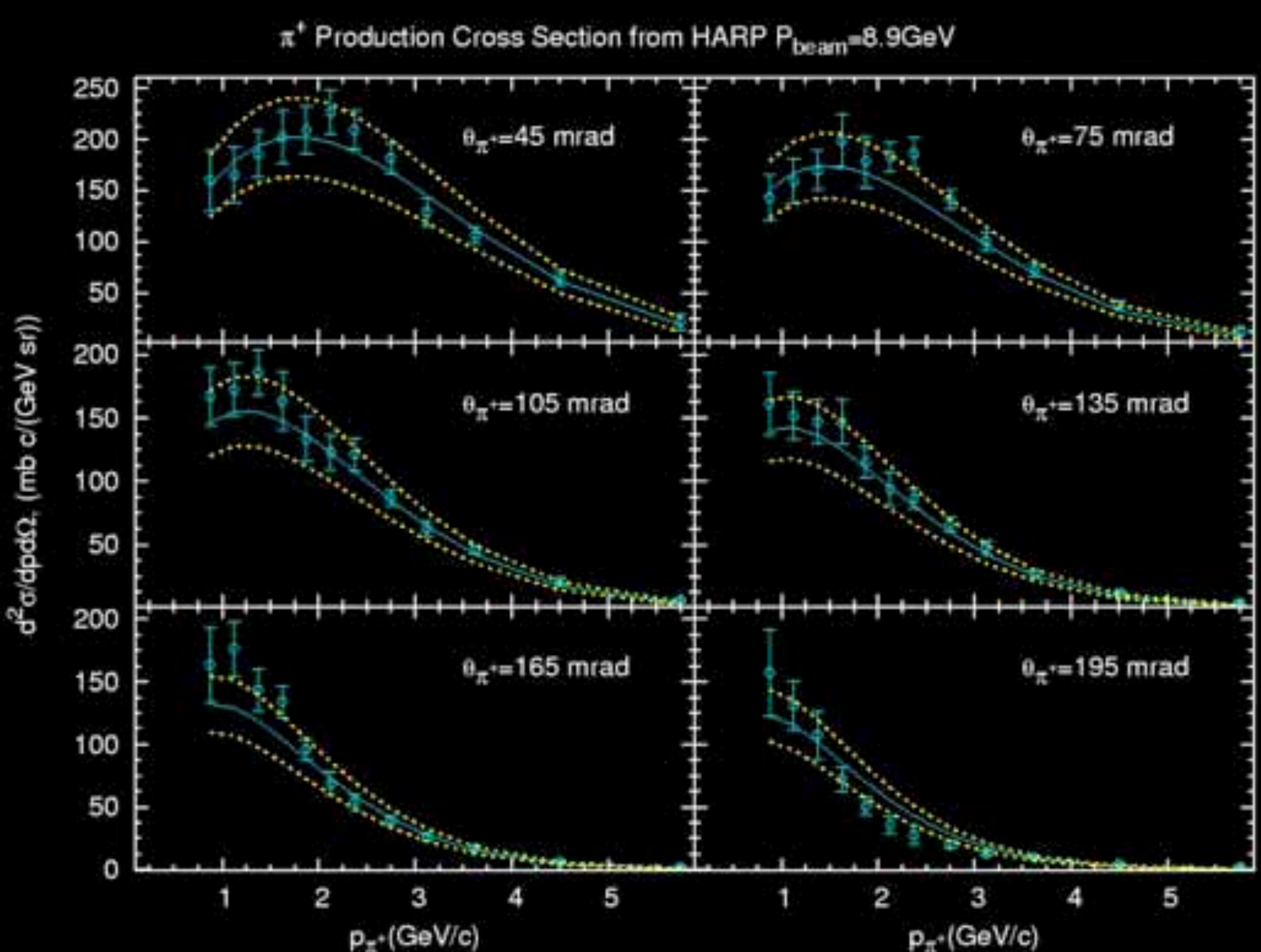


Main components of Booster Neutrino Beam (BNB)

(96M and 298M+ pulses)

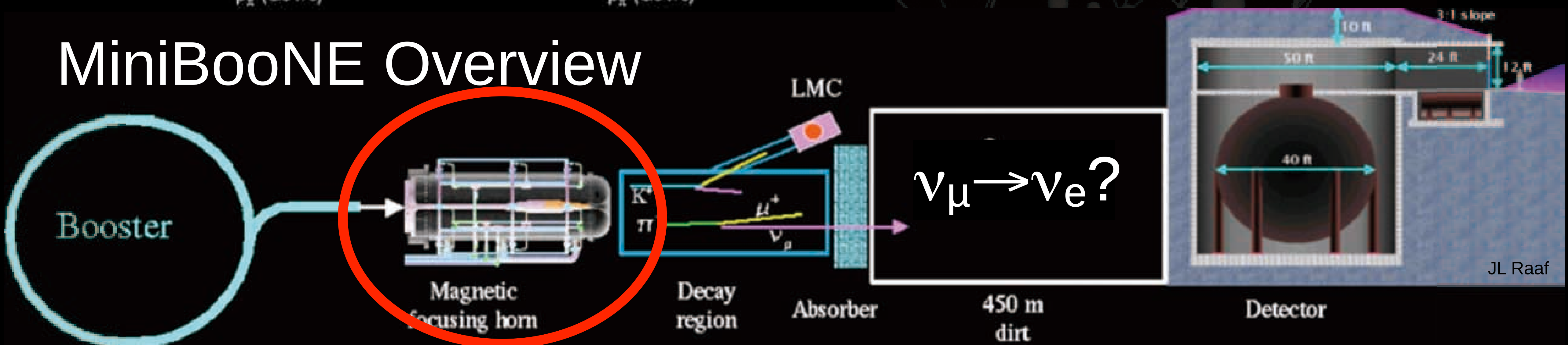


Meson Production



*PRD **79** 072002 (2009)*

- External meson production data
  - HARP data (CERN)
- Parametrisation of cross-sections
  - Sanford-Wang for pions
  - Feynman scaling for kaons
- Use of HARP data reduces total flux error to ~9%

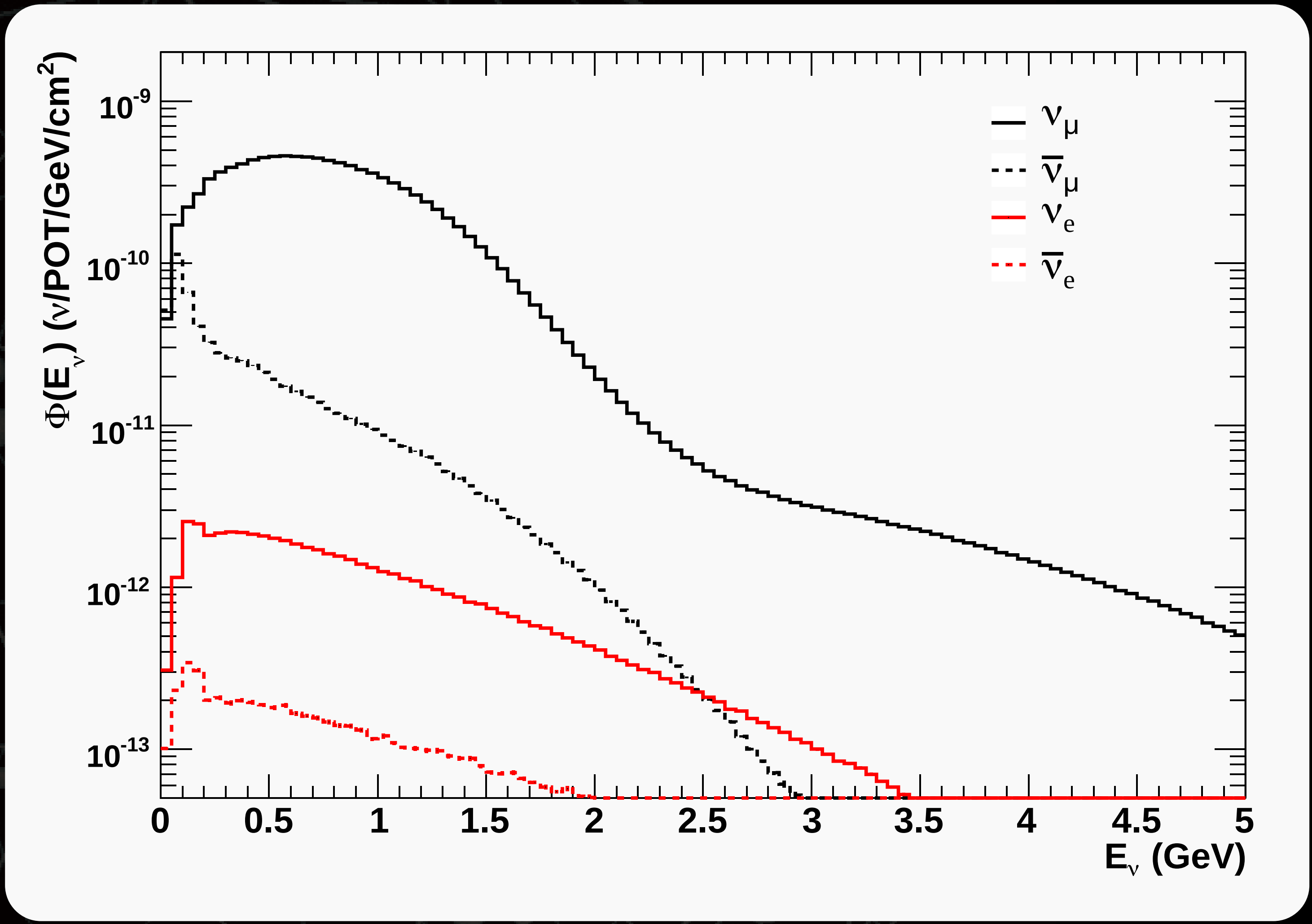


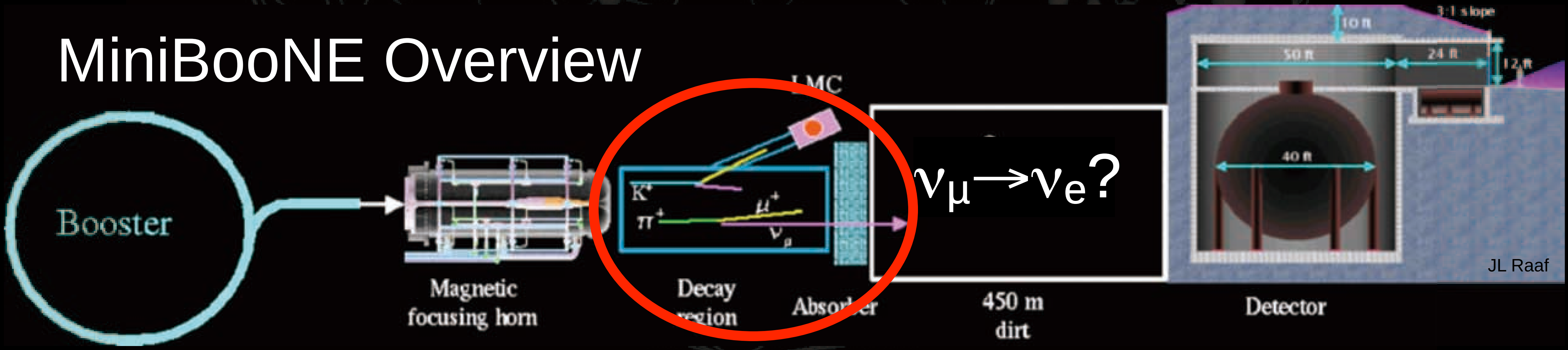
ν Flux

*PRD **79** 072002 (2009)*

- 99.5% pure muon flavour
  - 0.5% intrinsic ν_e
  - Constrain ν_e content with ν_μ measurements
- $\bar{\nu}$ mode contains large ν contamination

Neutrino Mode





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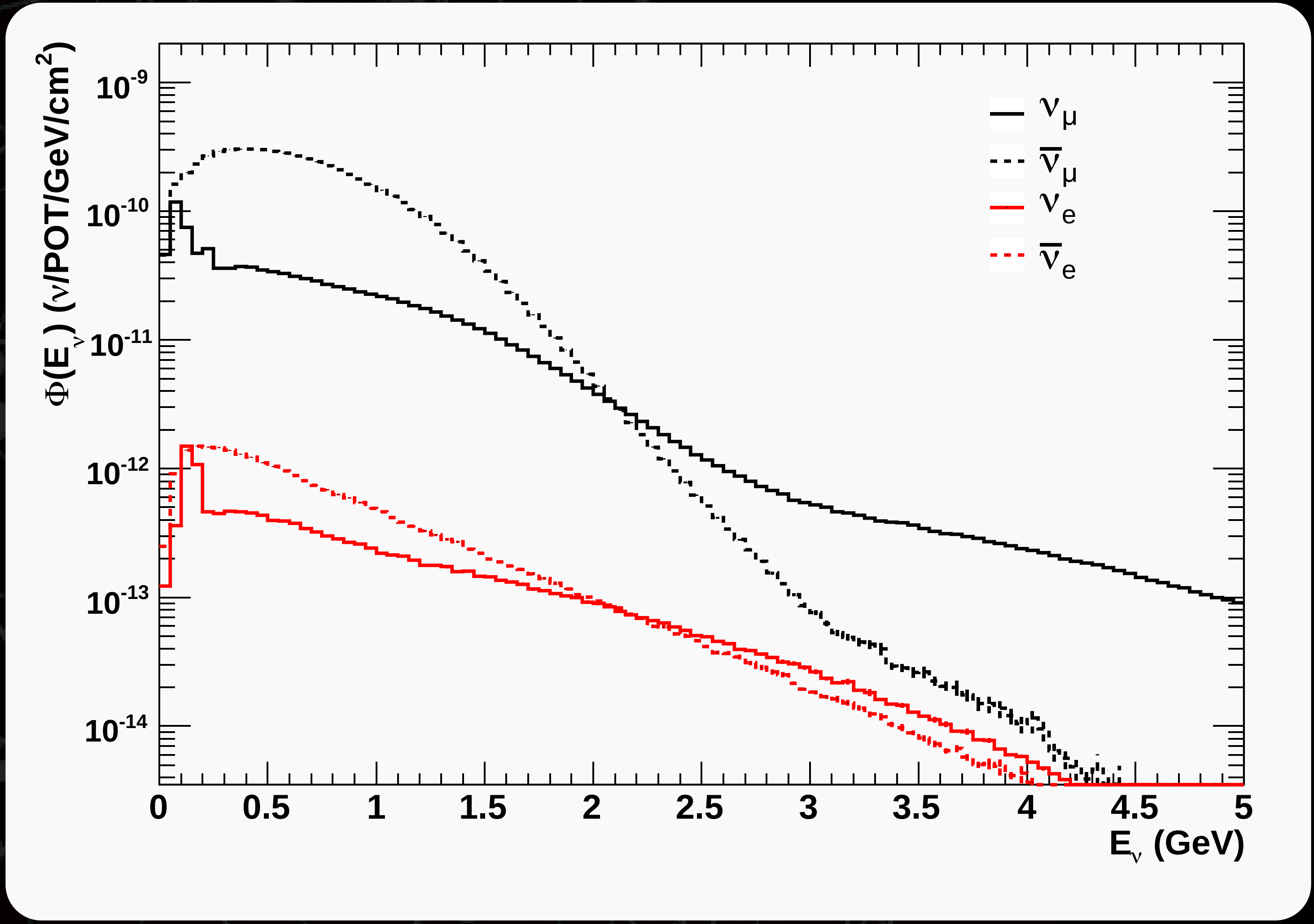
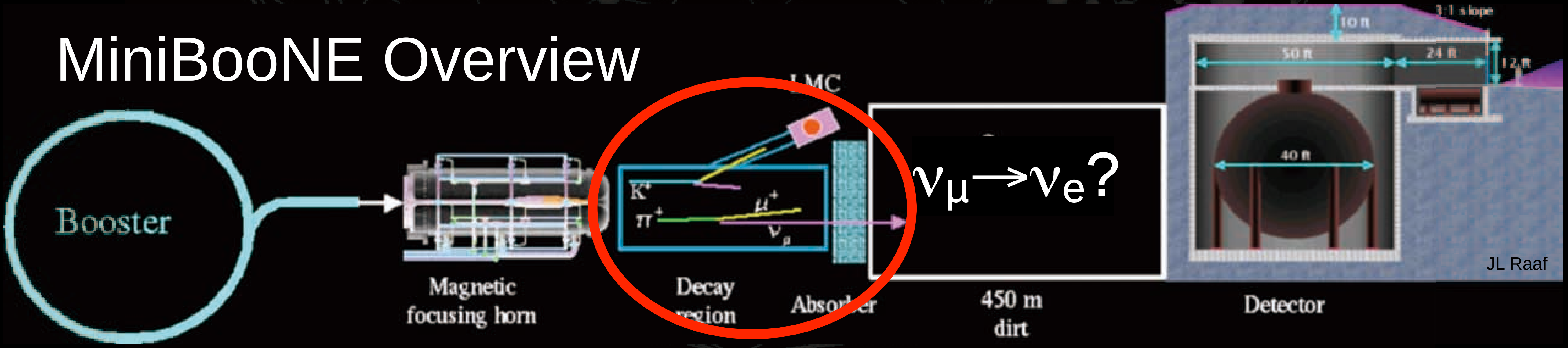
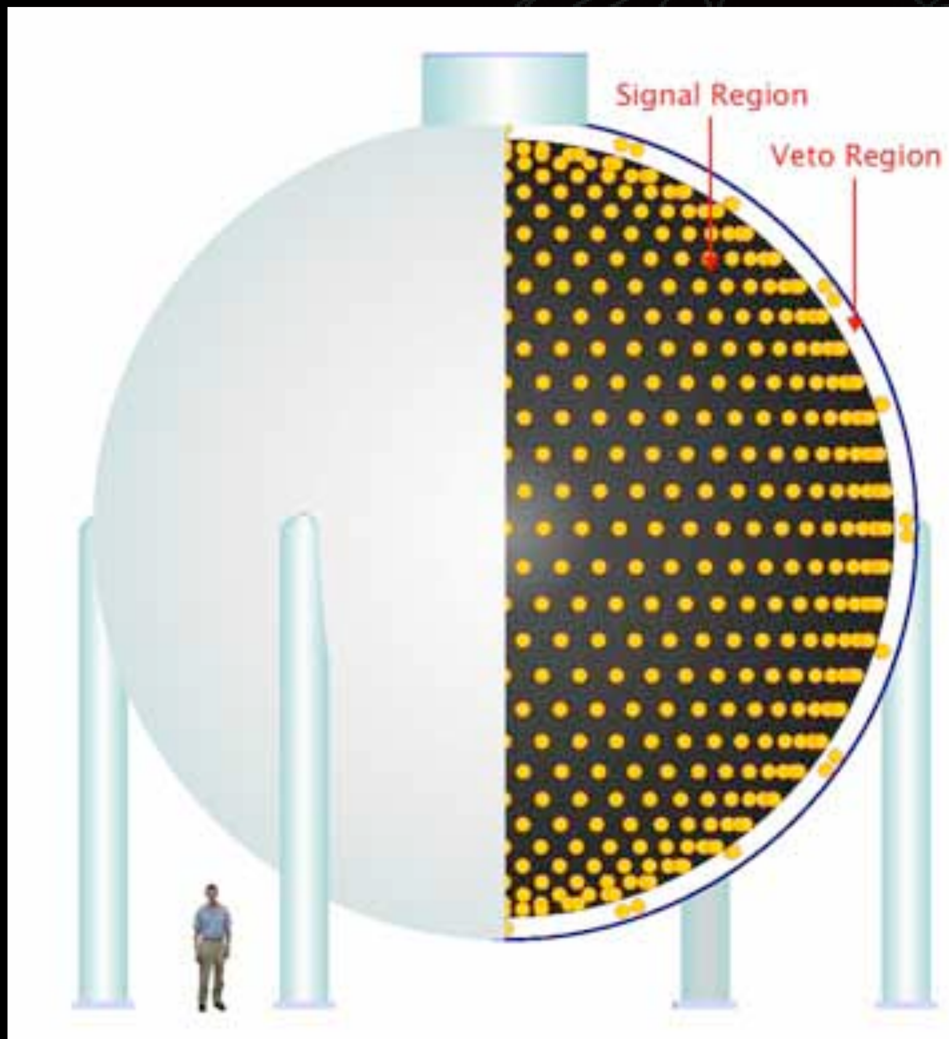
Antineutrino Mode

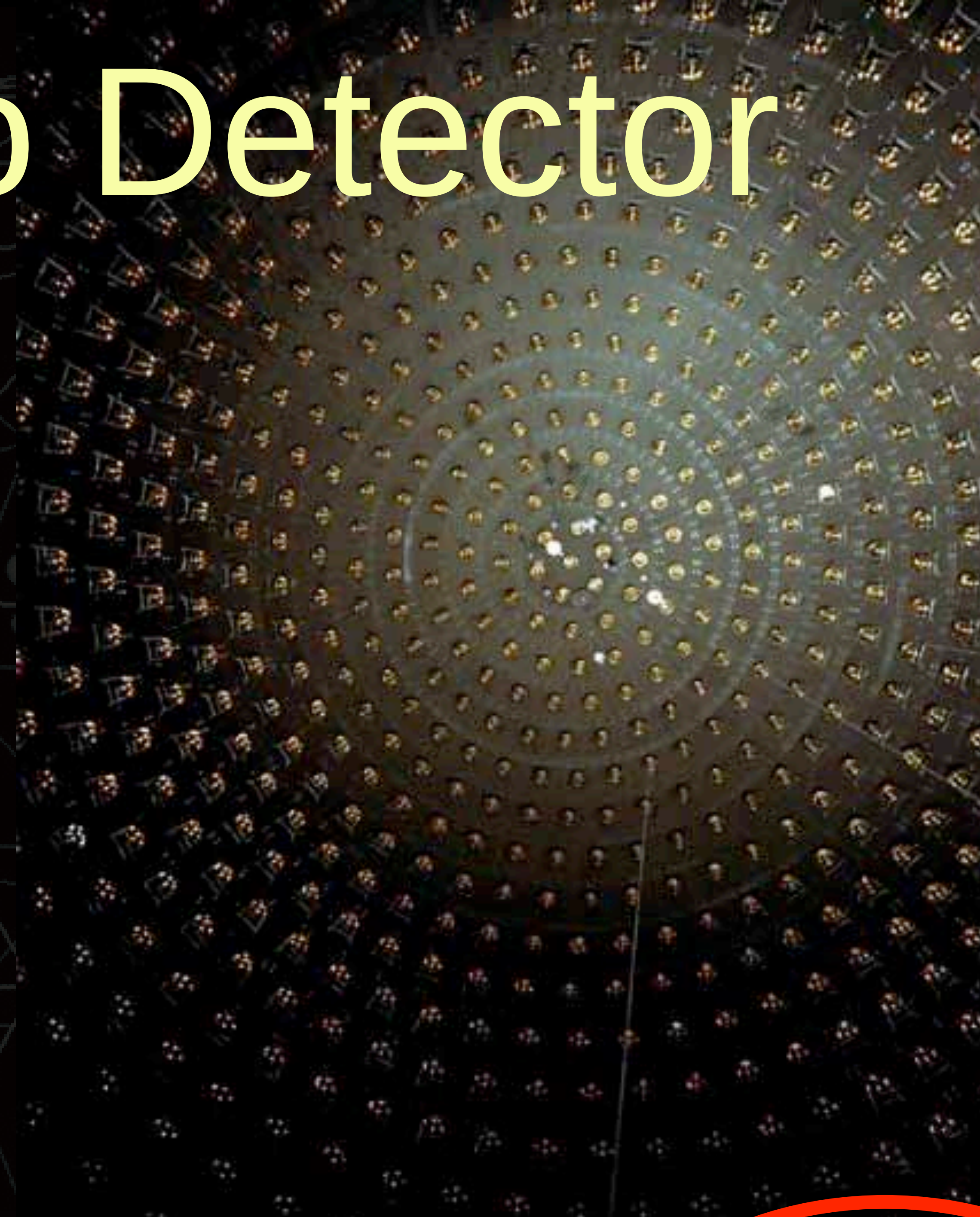


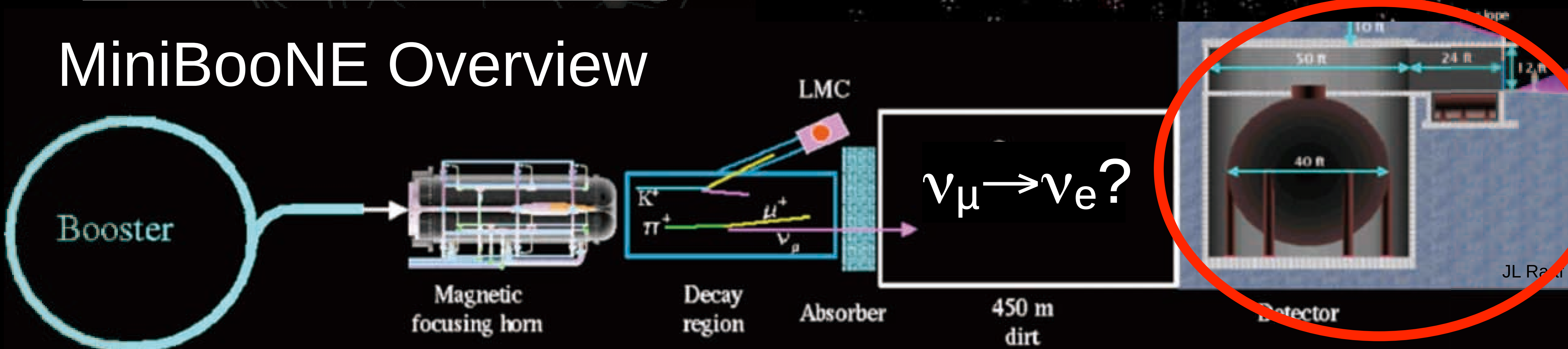


Neutrino Detector

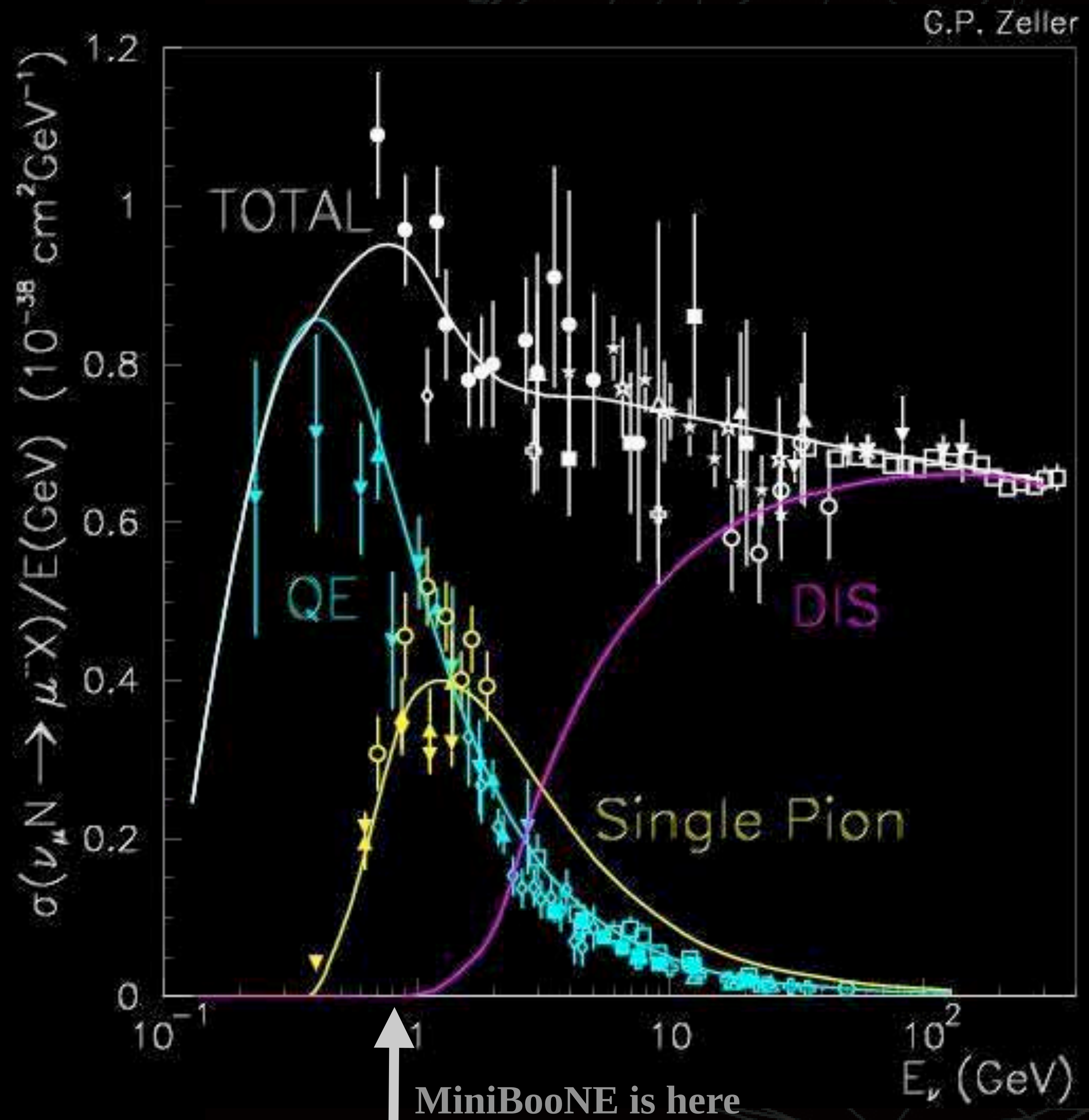
*NIM A **599** (2009) 28-46*

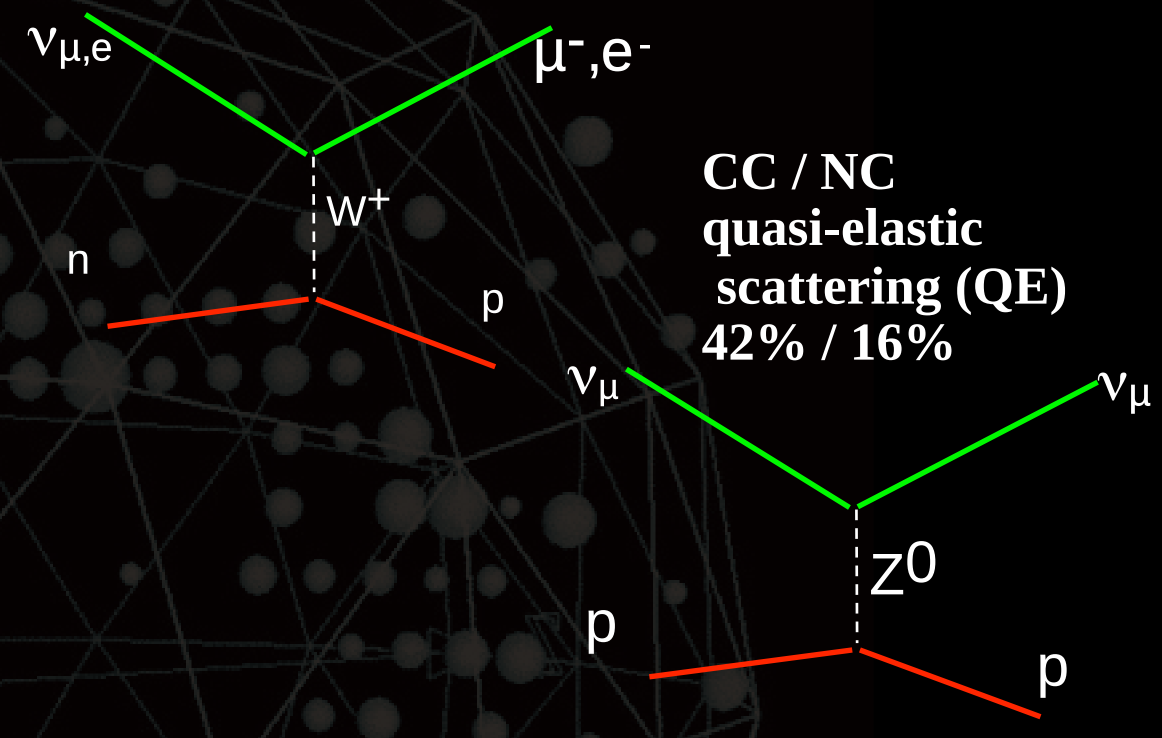




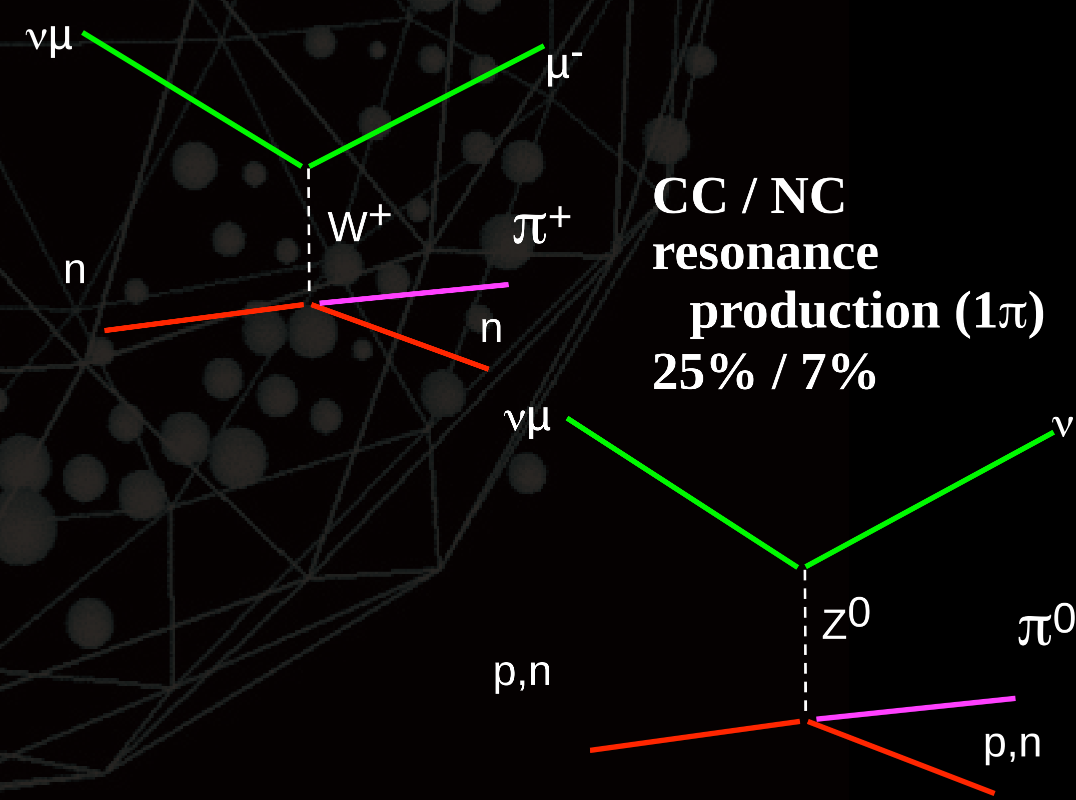


ν Interactions



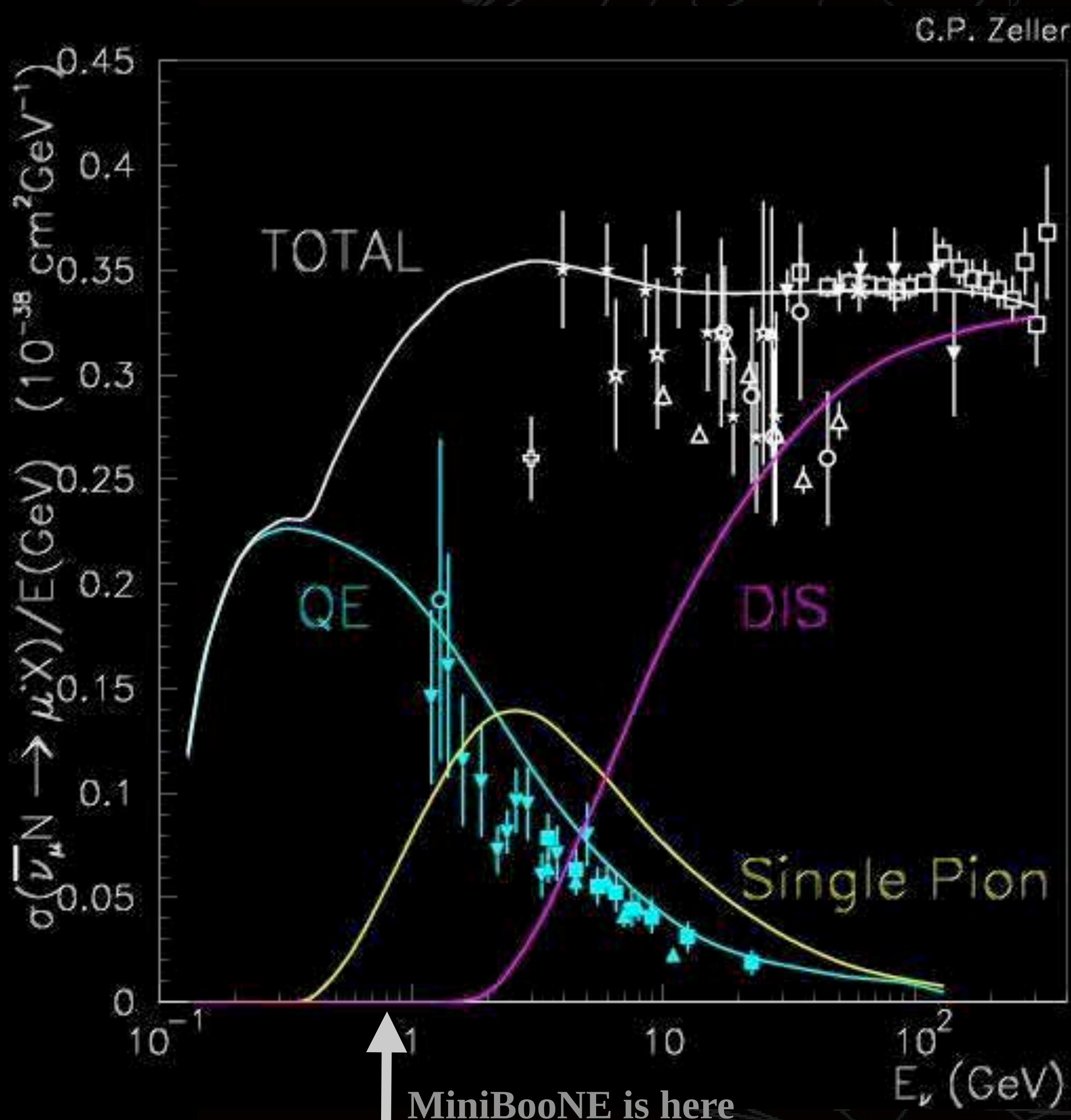


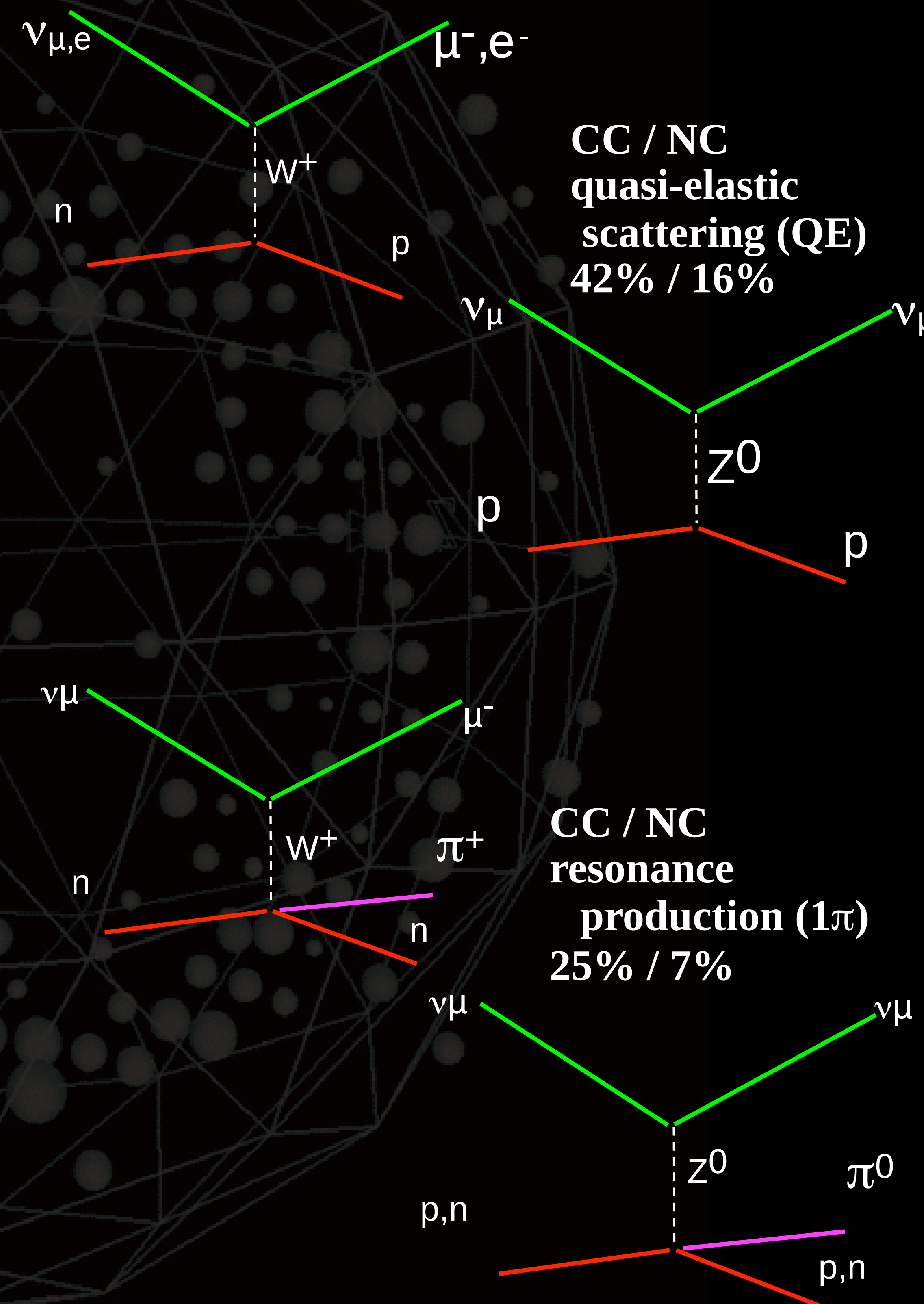
CC / NC quasi-elastic scattering (QE)
42% / 16%



CC / NC resonance production (1π)
25% / 7%

$\bar{\nu}$ Interactions





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42% / 16%

CC / NC resonance production (1π)
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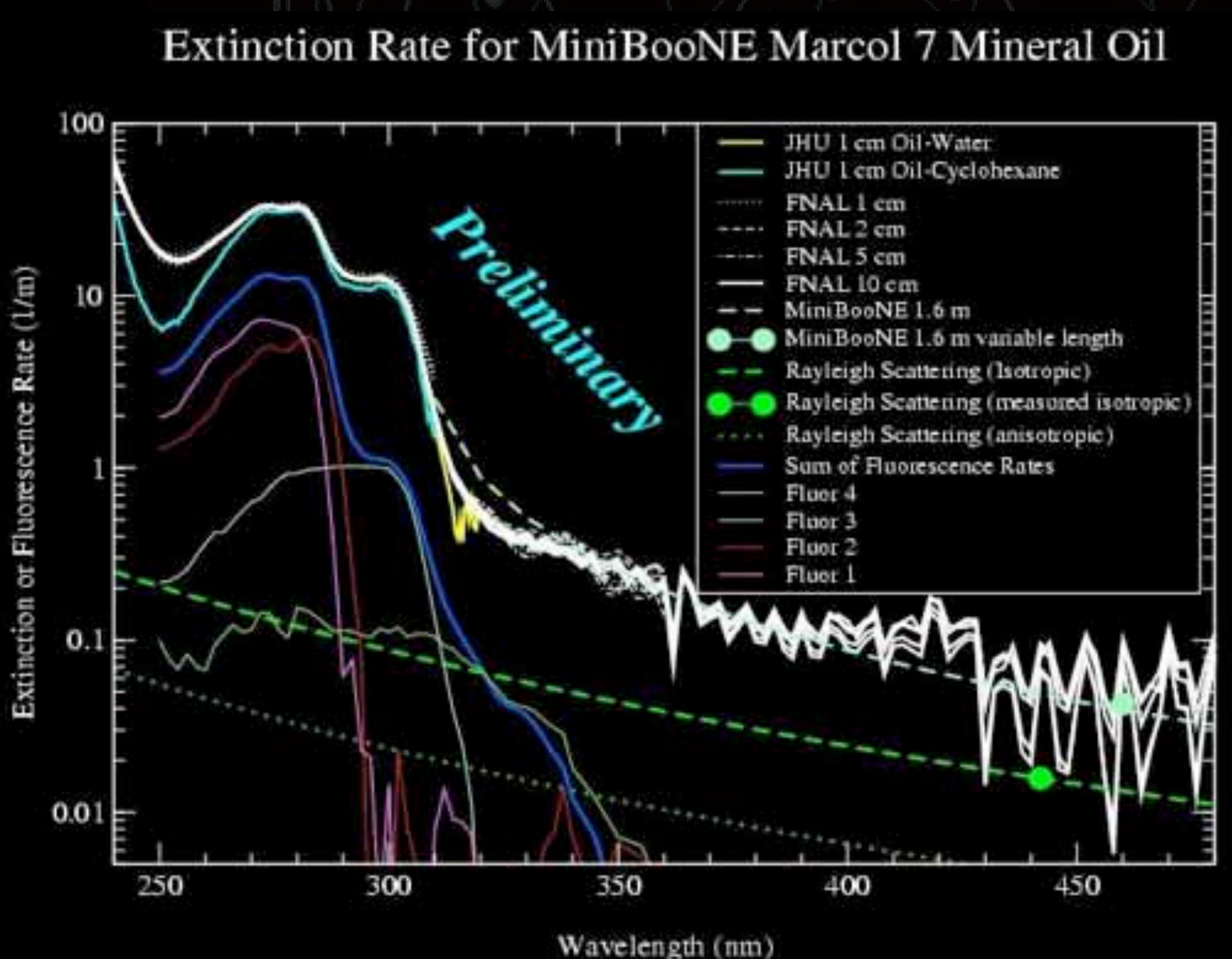
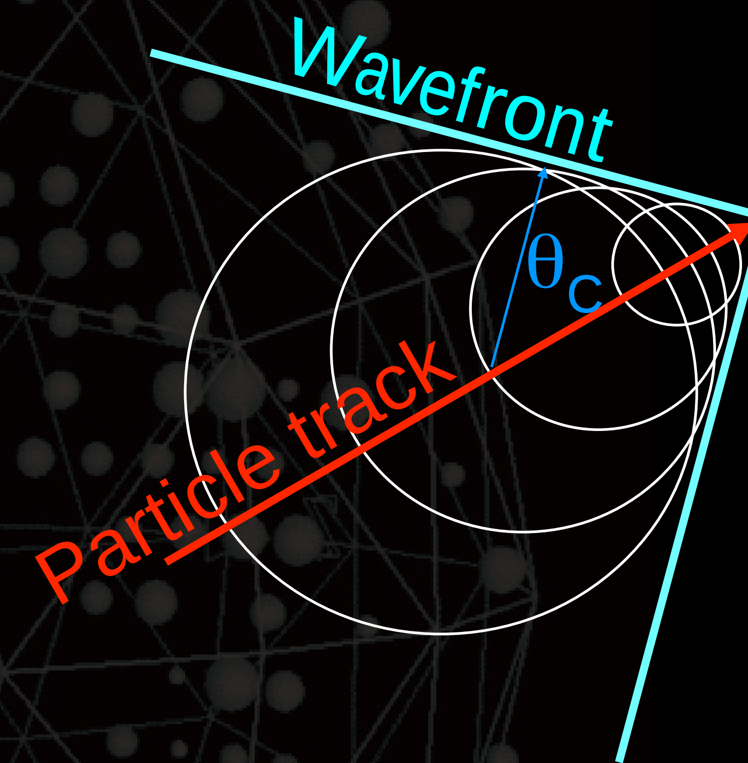
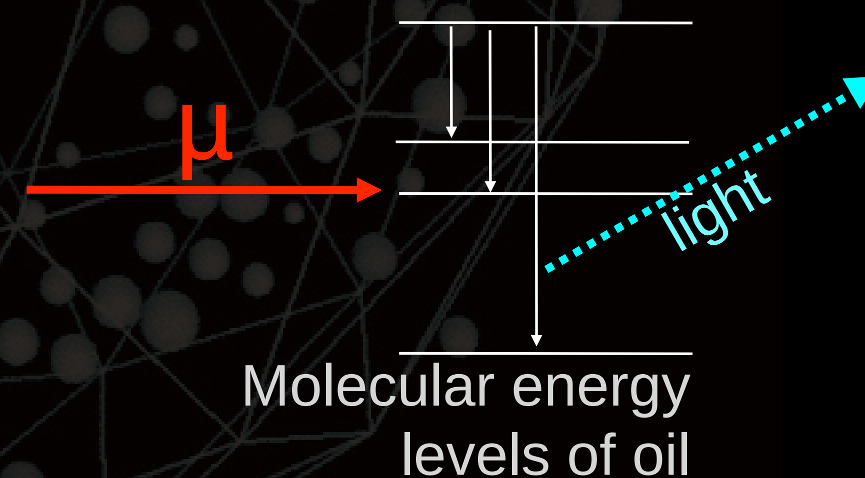
Mineral Oil Optics

- Production:
  - Cherenkov and scintillation
- Secondary:
  - Fluorescence and scattering (Raman, Rayleigh)

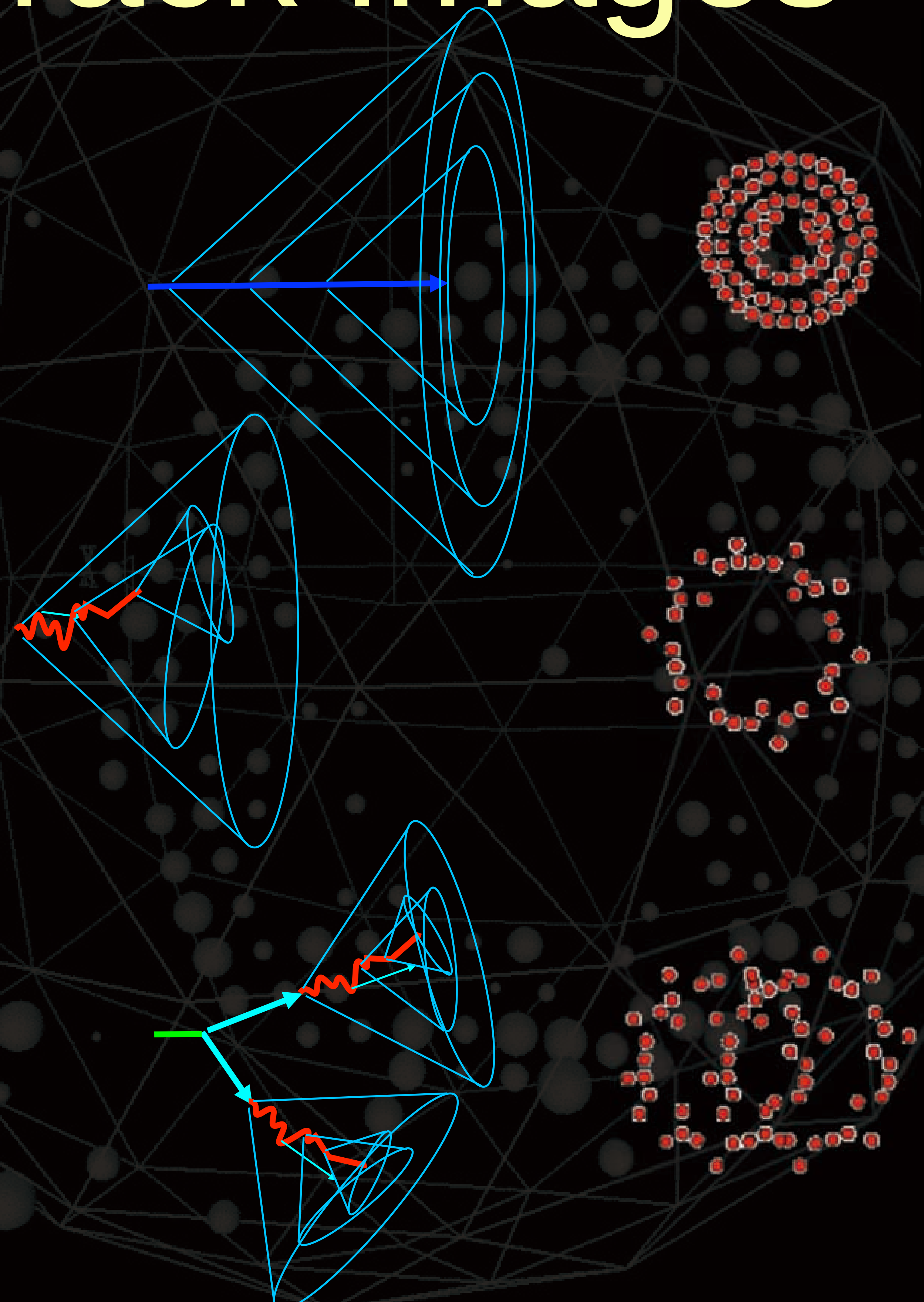


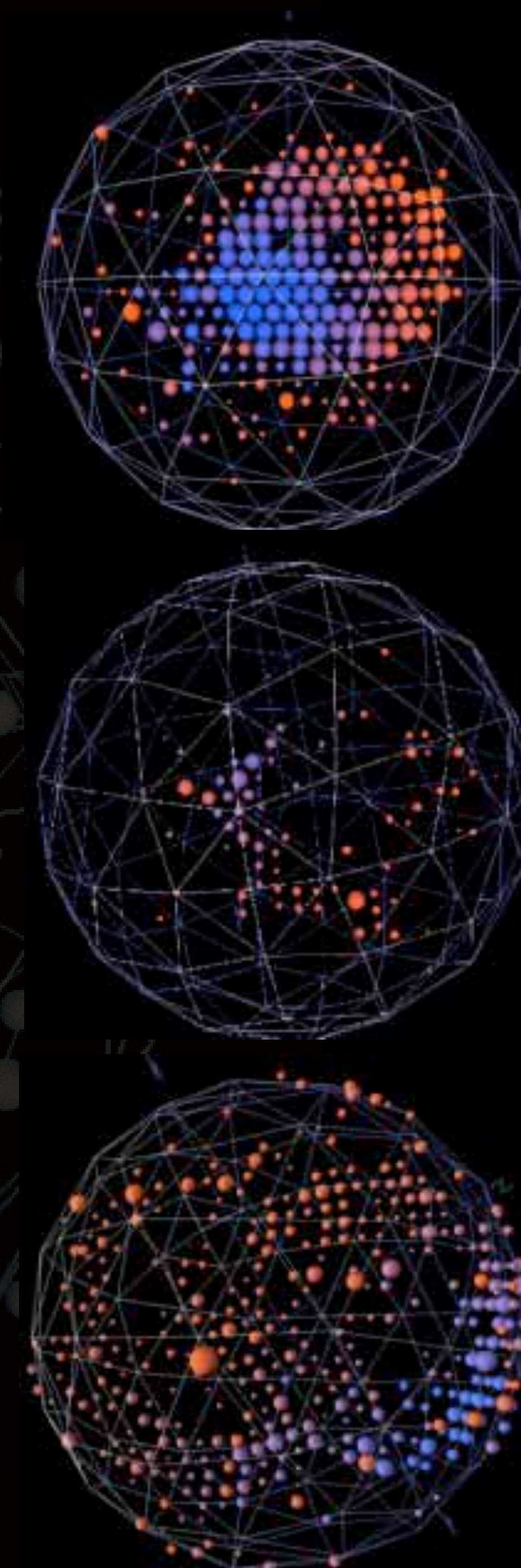




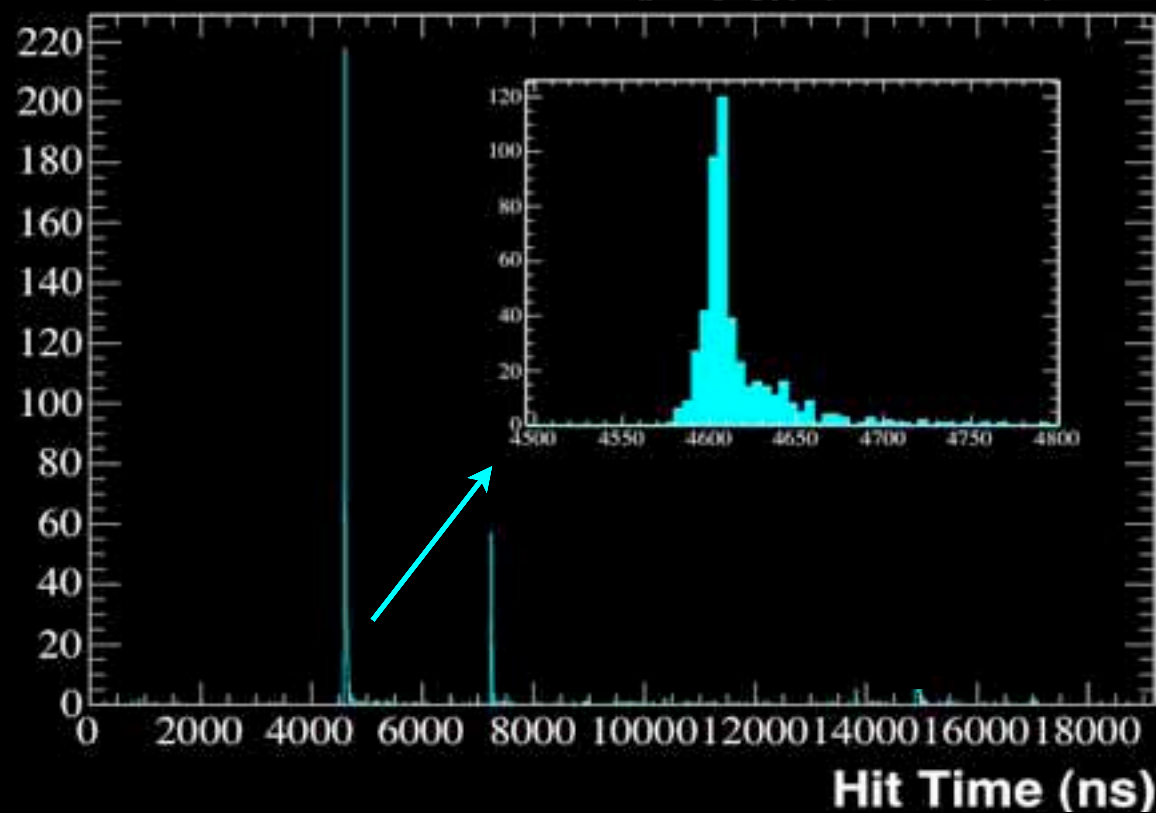
Track Images

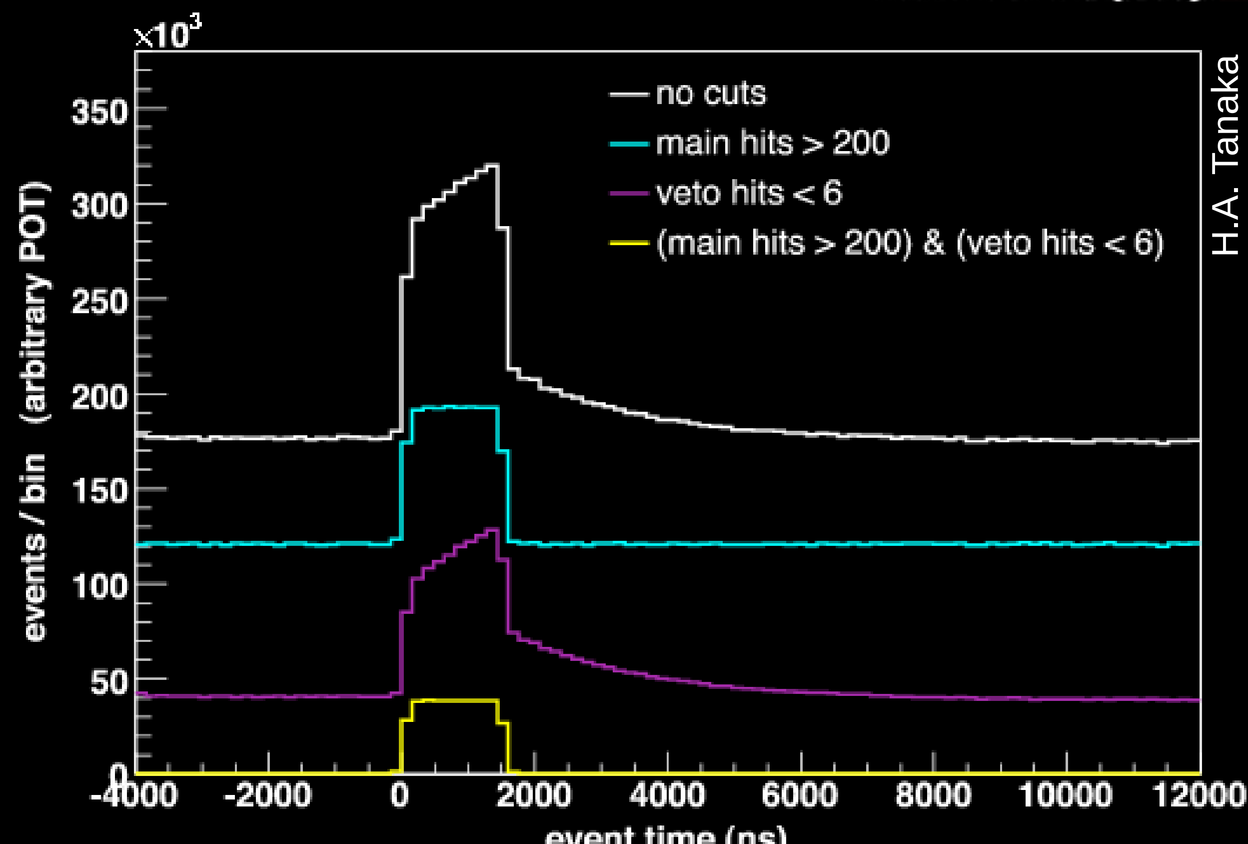
- Muons
  - full rings
- Electrons
  - fuzzy rings
- Neutral pions
  - double rings





PMT Hit Clusters





H.A. Tanaka

- PMT hits clusters in time form "subevents"
- ν_μ events have 2 subevents
    - μ, followed by e
- ν_e events have 1 subevent
- Simple cuts on subevents remove cosmic backgrounds
    - "pre-cuts"

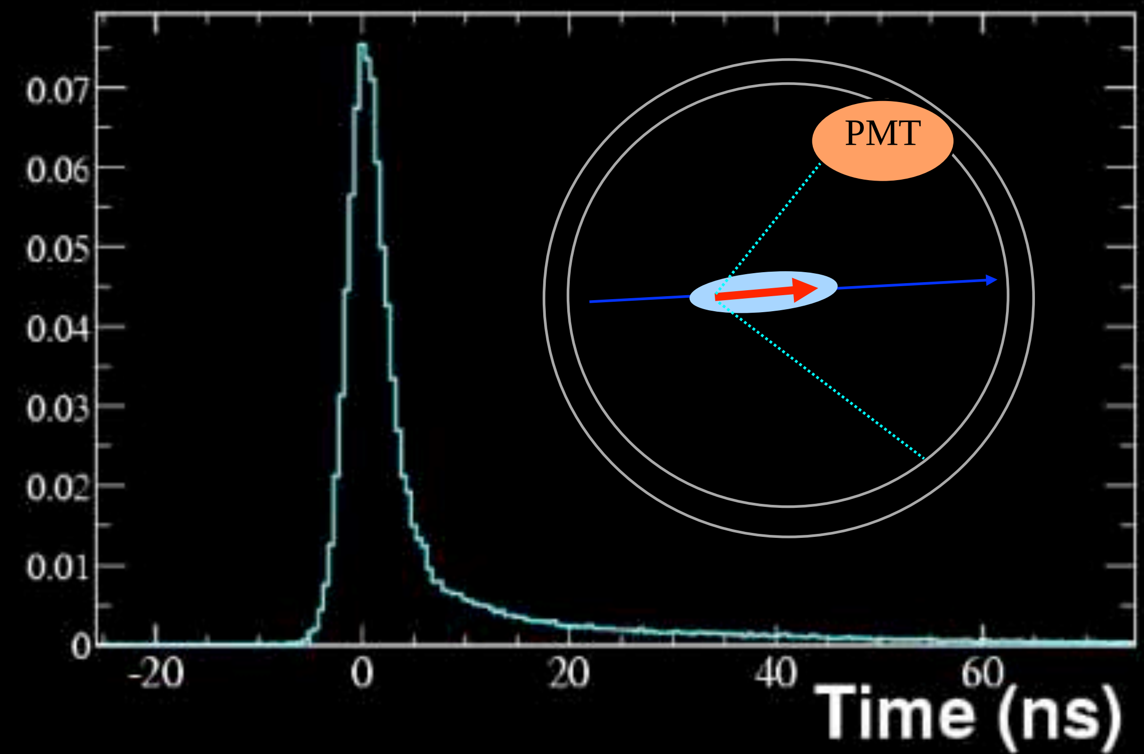
Track Reconstruction

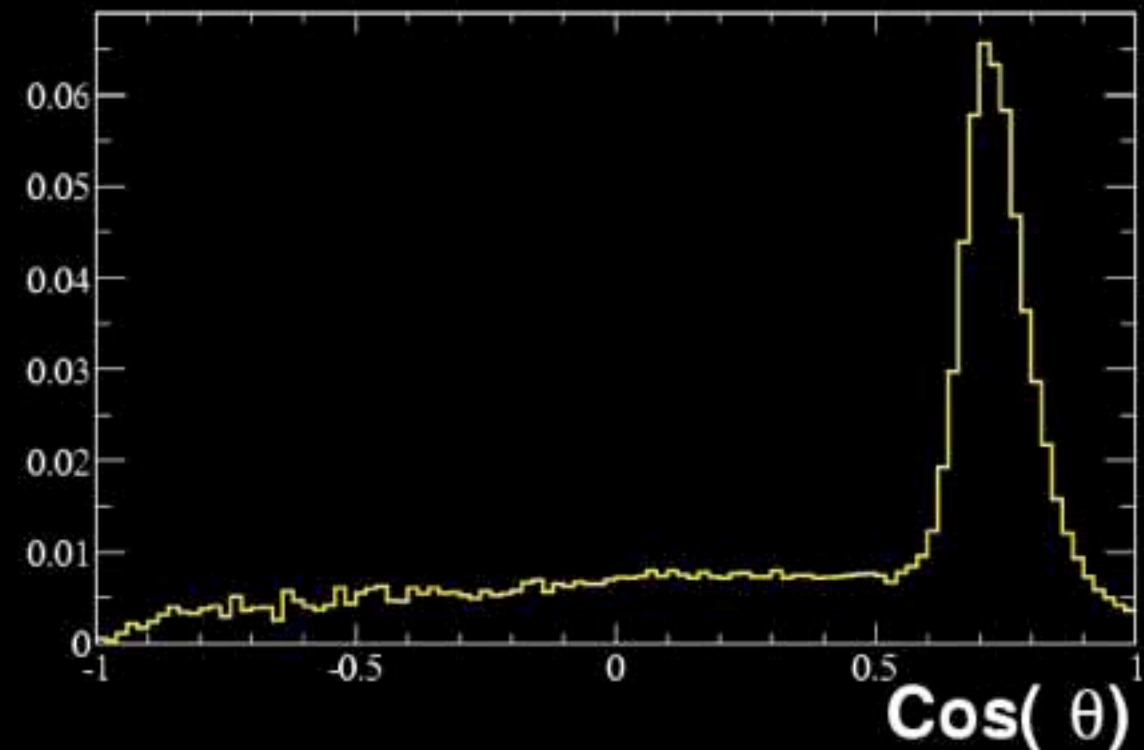
Charged particles produce
Cherenkov and scintillation light in oil

PMTs collect photons, record t,Q

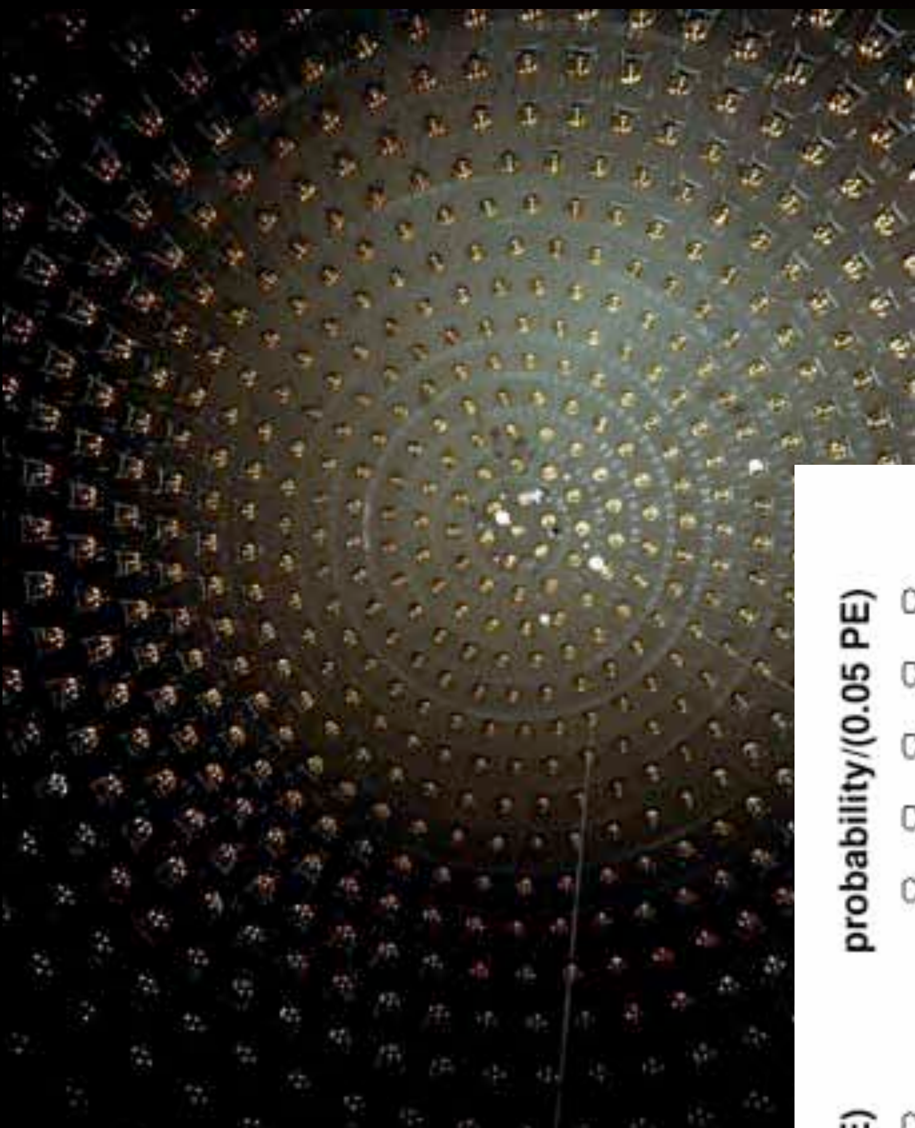
Reconstruct tracks by fitting time and angular distributions

Find position, direction, energy



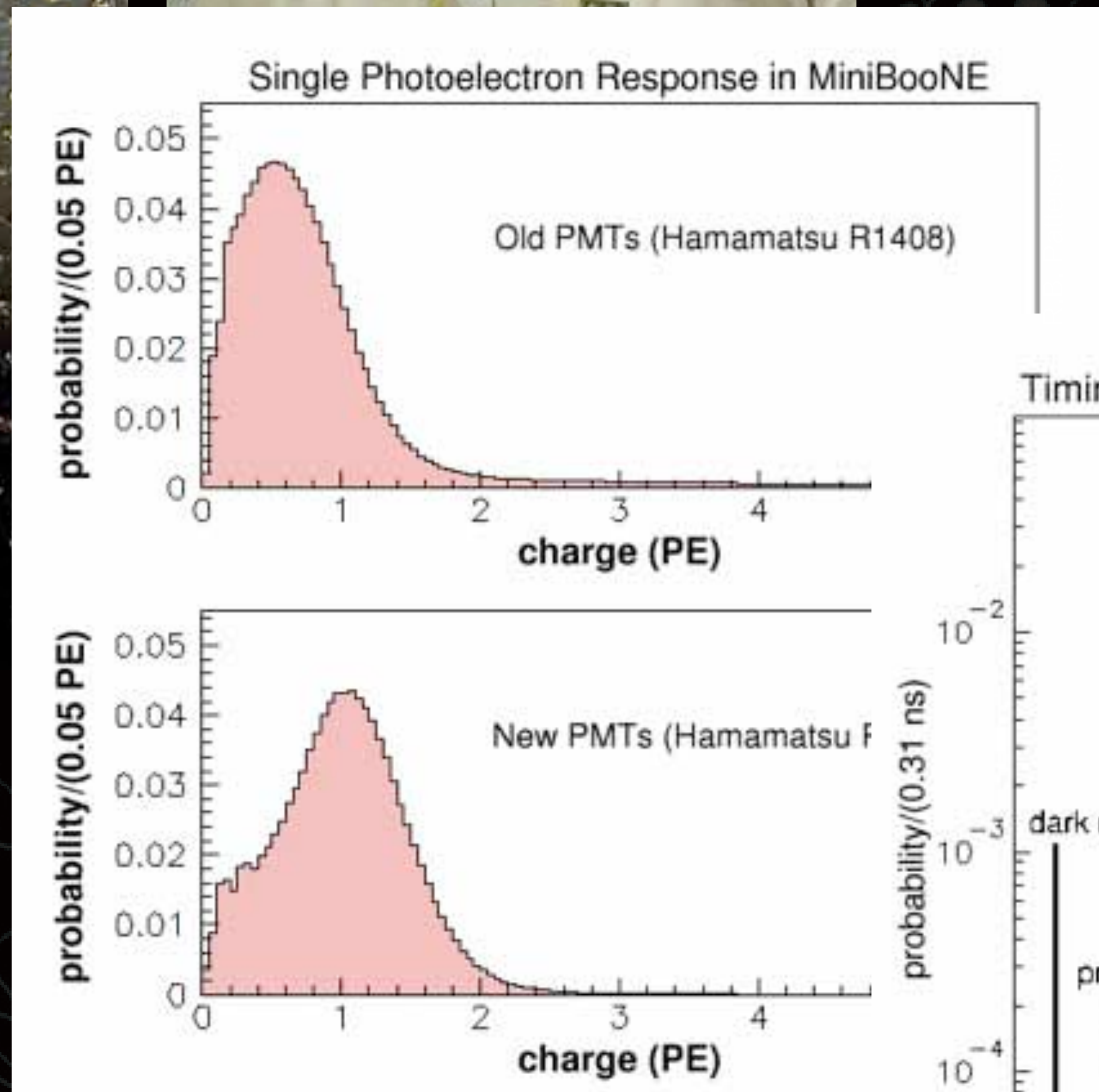


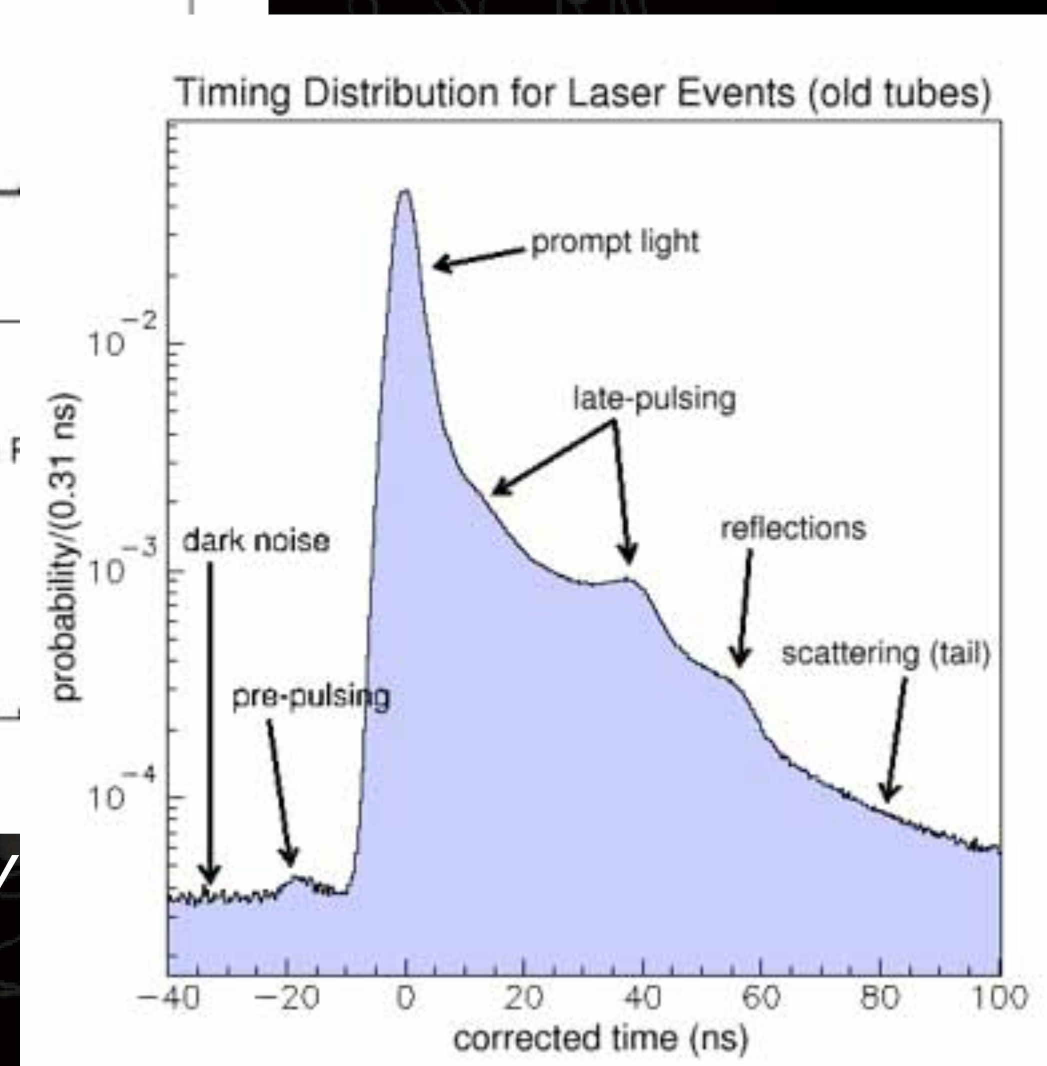
PMT Calibration



PMTs are calibrated with a laser + 4 flask system

Charge Res: 1.4 PE, 0.5 PE
Time Res: 1.7 ns, 1.1 ns





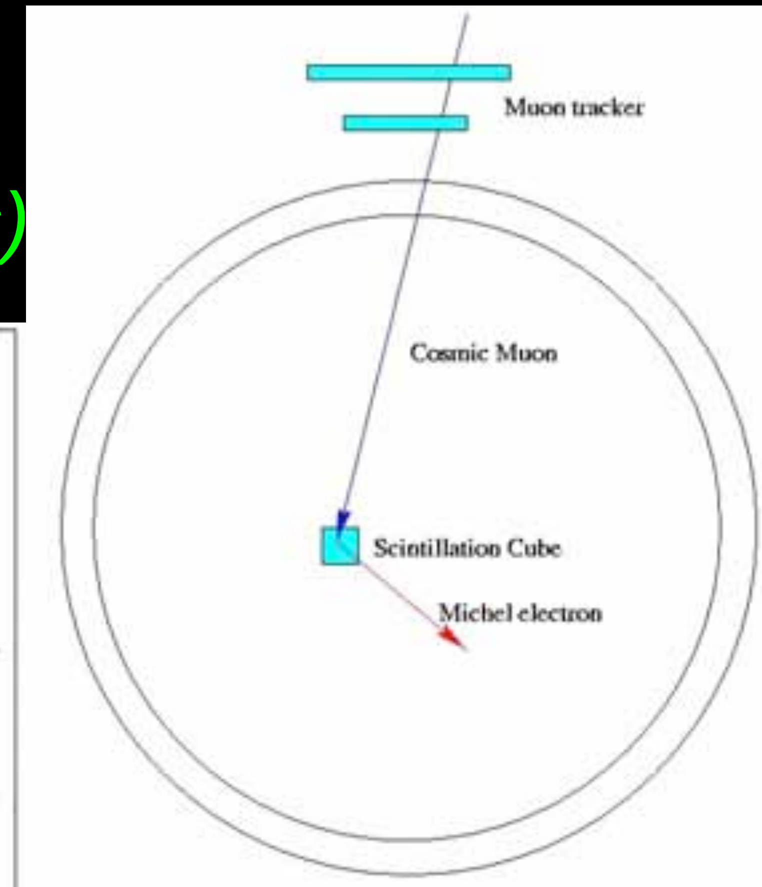
10% photo-cathode coverage

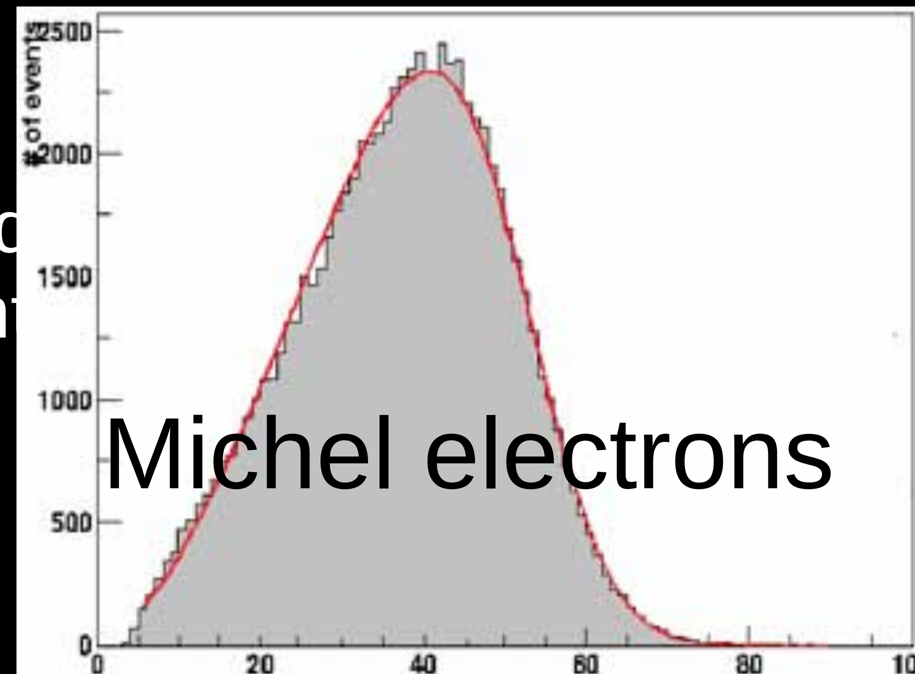
Two types of 8" Hamamatsu Tubes: R1408, R5912

Laser data are acquired at 3.3 Hz to continuously calibrate PMT gain and timing constants

Cosmic μ calibration

use cosmic muons and their decay electrons (Michels)



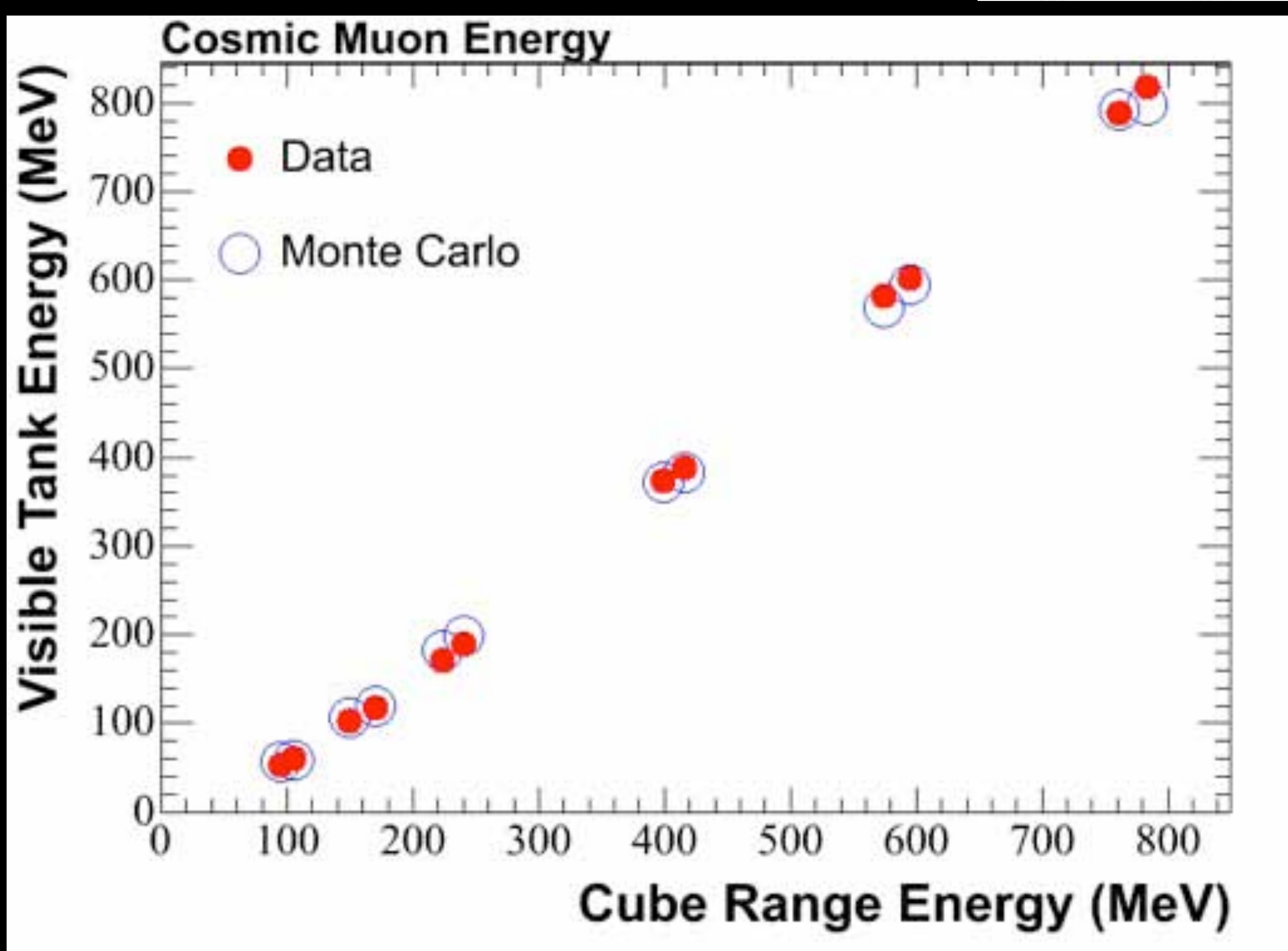


Michel electrons:

-set absolute energy scale and resolution at 53 MeV endpoint

-optical model tuning

Muon tracker
7 scintillator cubes



Cosmic muons which stop in cubes:

-test energy scale extrapolation up to 800 MeV

- measure energy, angle resolution

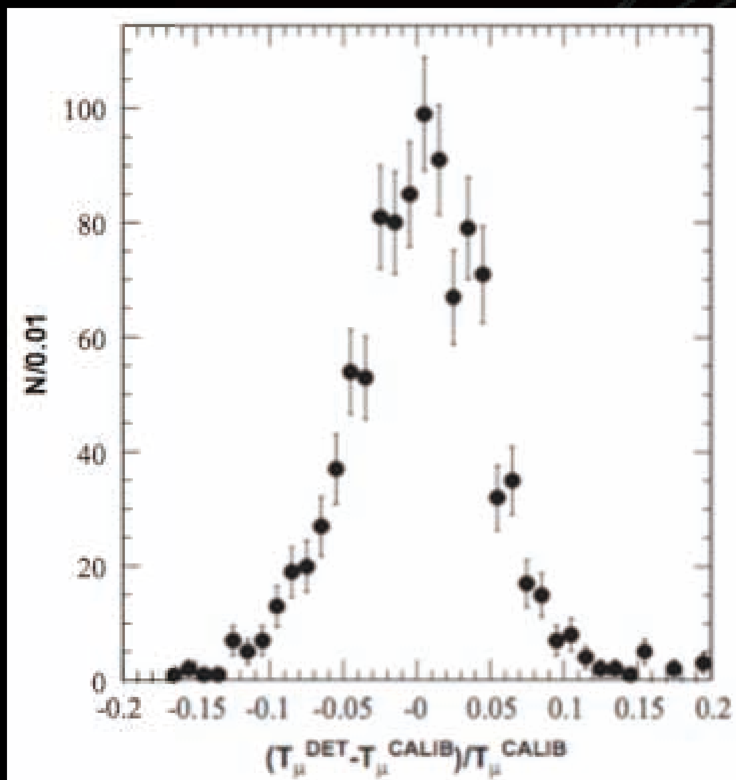
- compare data and MC

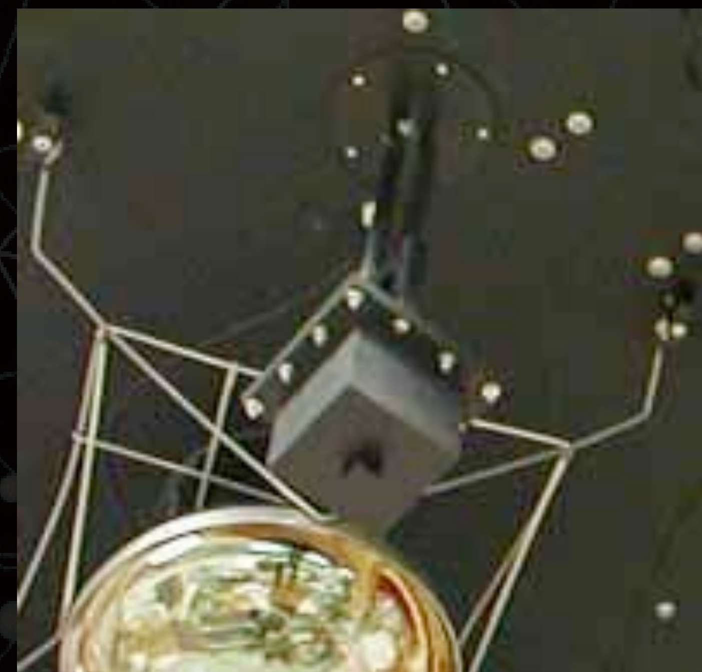
Muon tracker + cube calibration data continuously acquired at 1 Hz

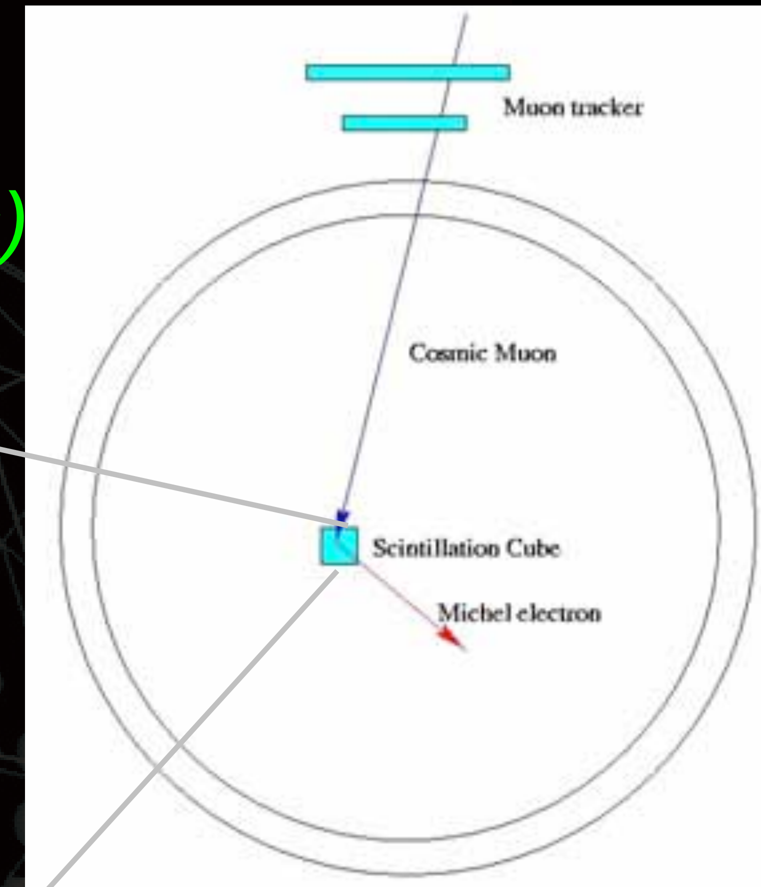
Cosmic μ calibration

use cosmic muons and their decay electrons (Michels)

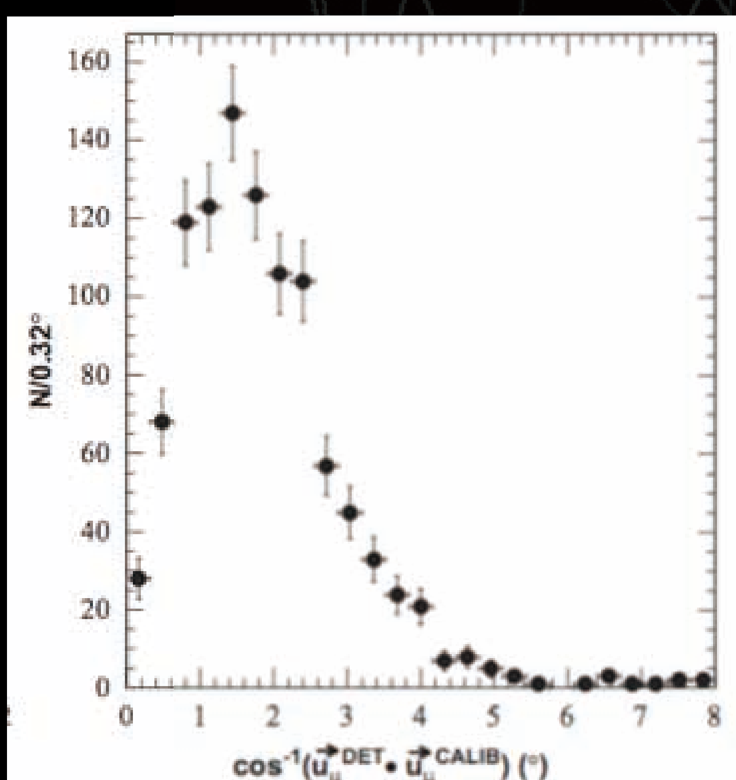
*NIM A **599** (2009) 28-46*





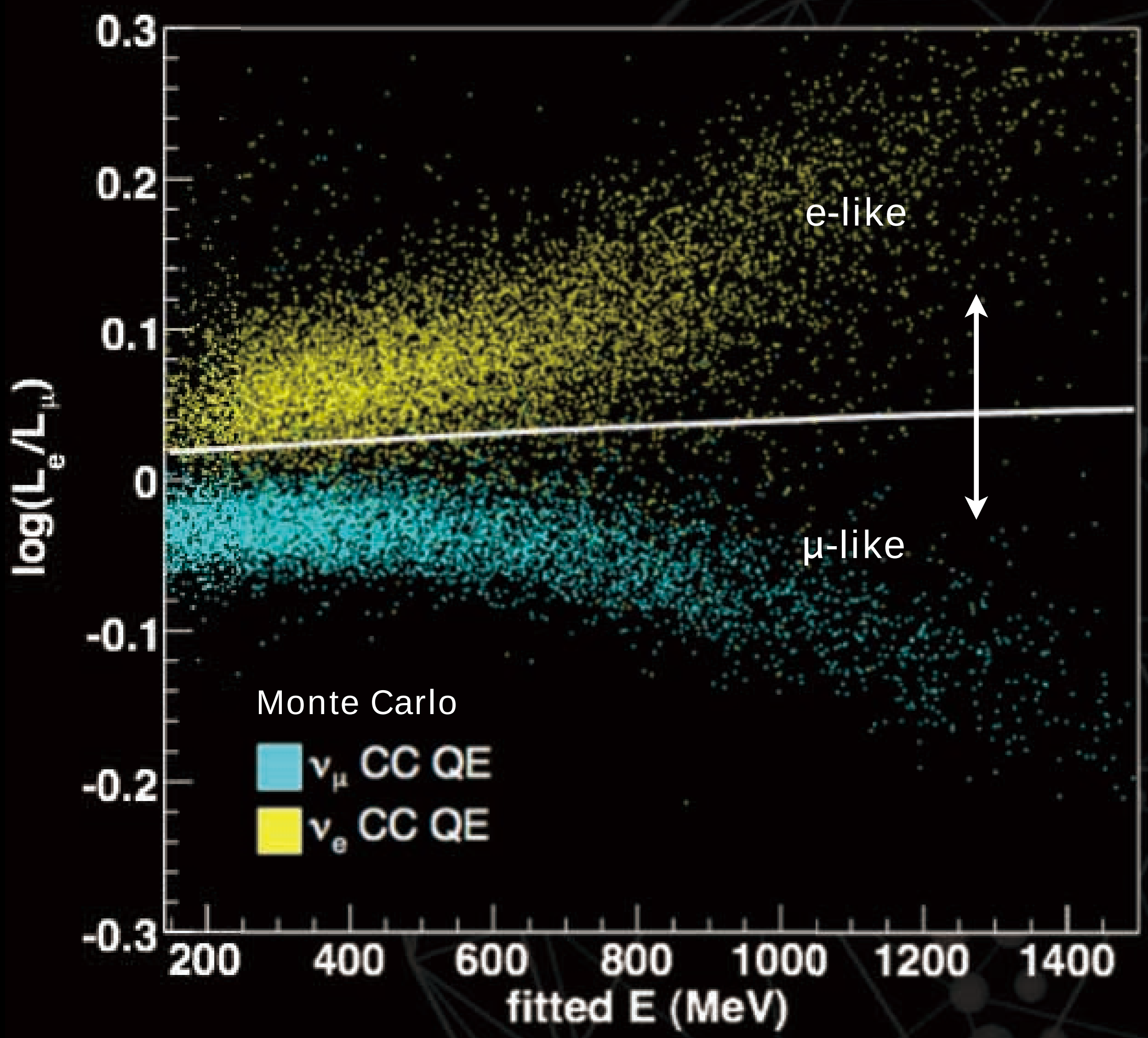


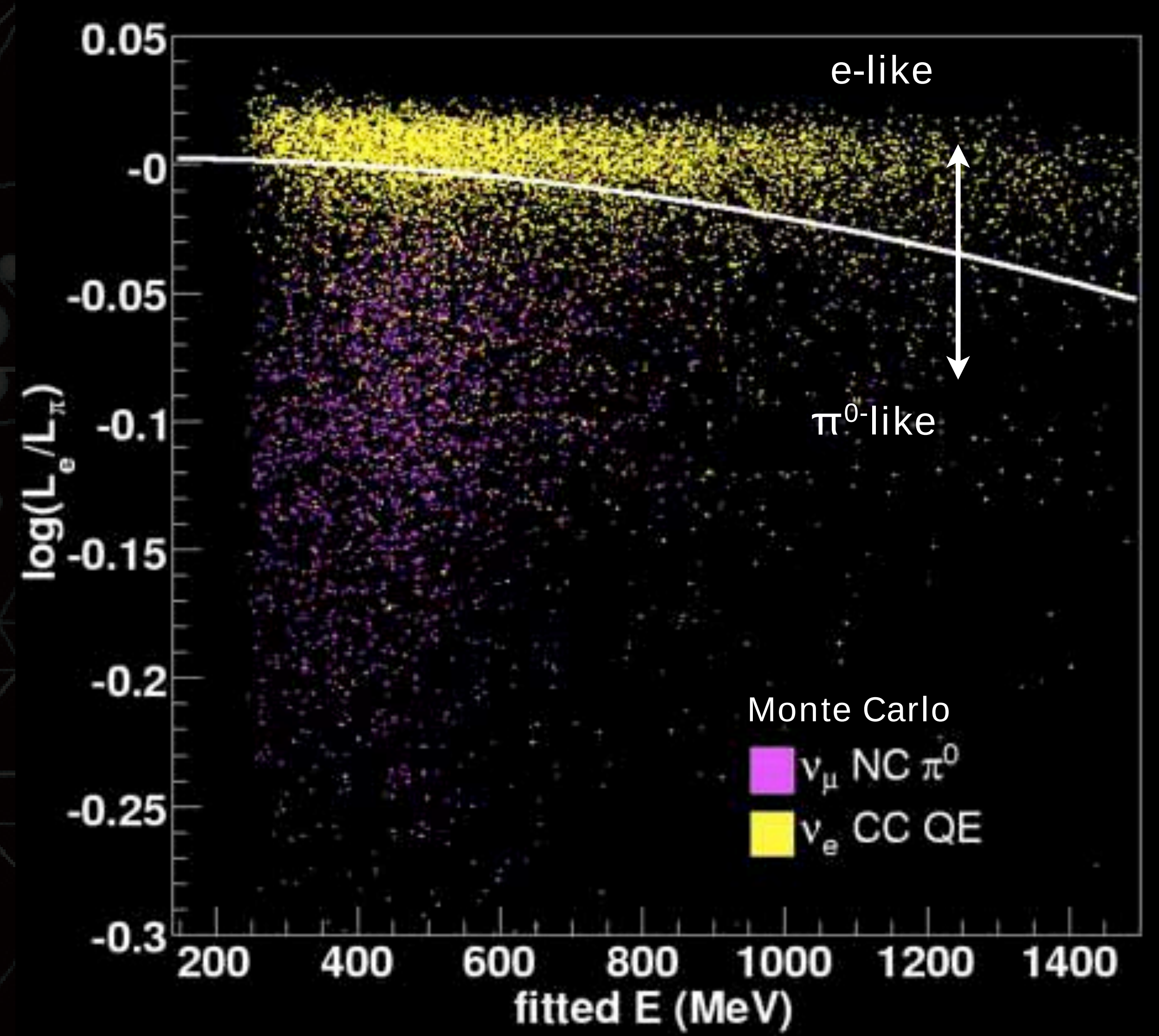
Muon tracker
7 scintillator cubes



Energy (MeV)	θ_{res}(°)	E_{res}(%)
94±4	5.4	12
155+5	3.2	7.0
229±7	2.2	7.5
407±9	1.4	4.6
584±9	1.1	4.2
771±9	1.0	3.4

Particle Identification

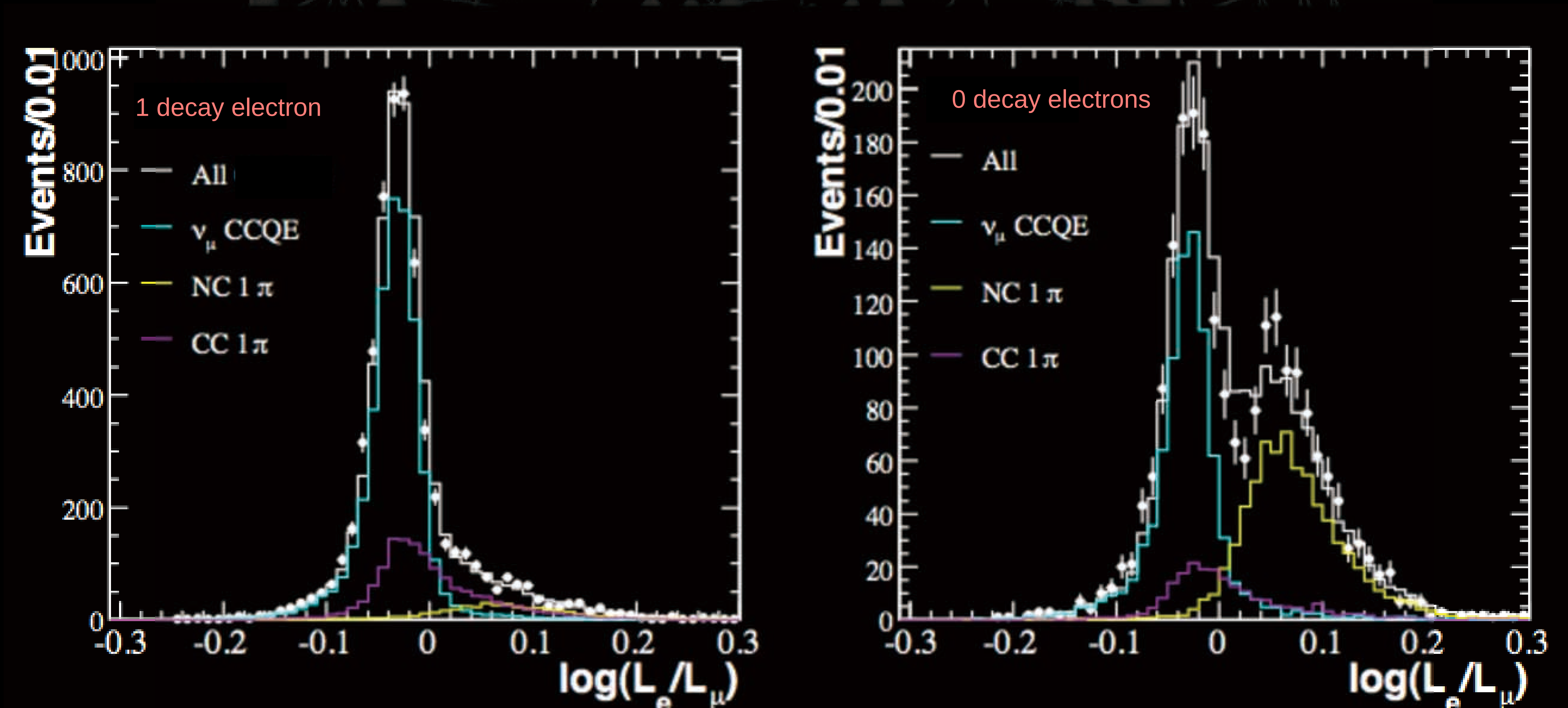




- Reconstruct under 3 hypotheses: μ-like, e-like and π^0-like
- ν_e particle ID cuts on likelihood ratios
  - chosen to maximise $\nu_\mu \rightarrow \nu_e$ oscillation sensitivity

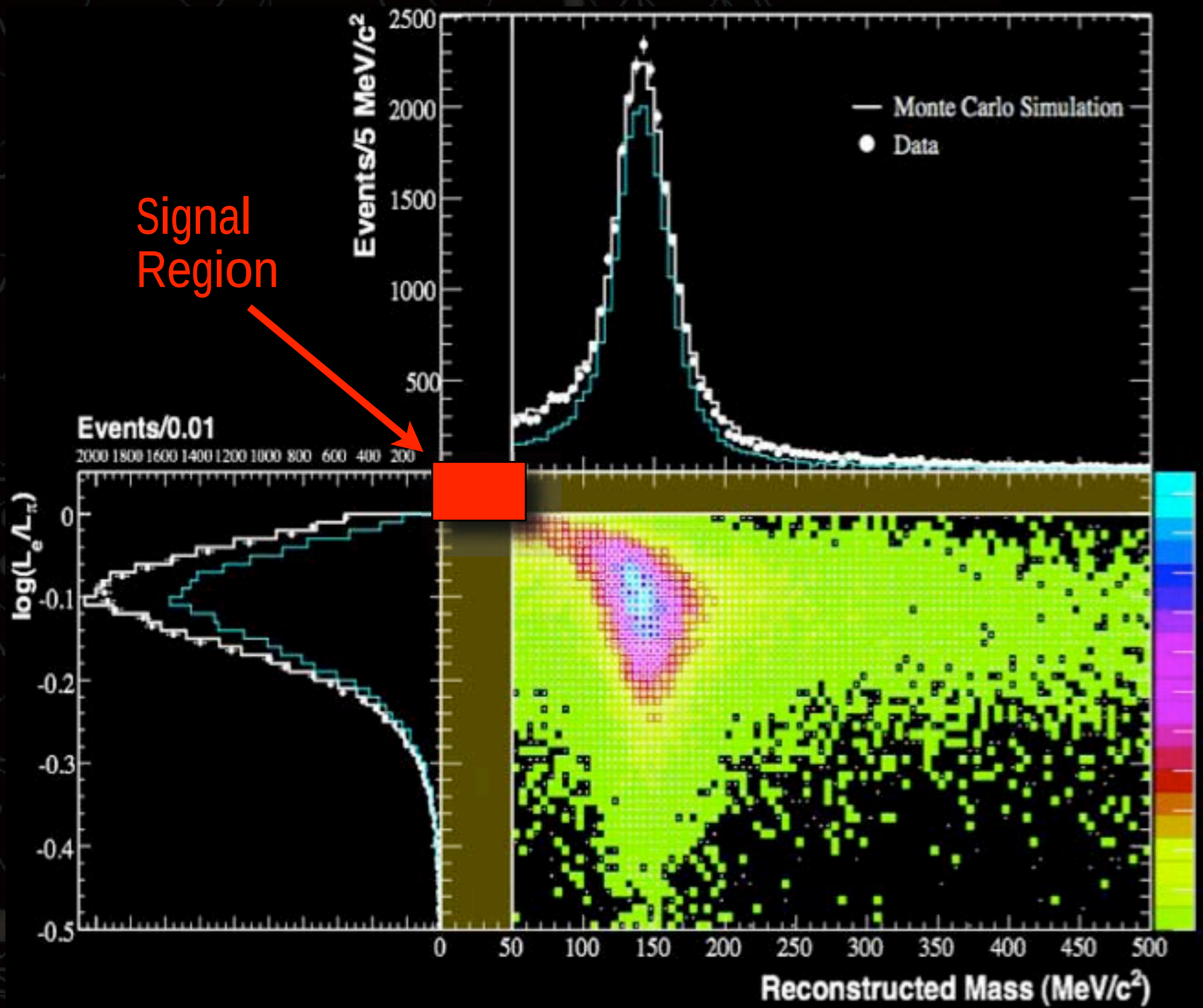
e/μ Likelihood

- ν_μ CCQE data (with muon decay electron) compared to ν_μ data with no decay electrons ("All but signal")
- Removes most muon events

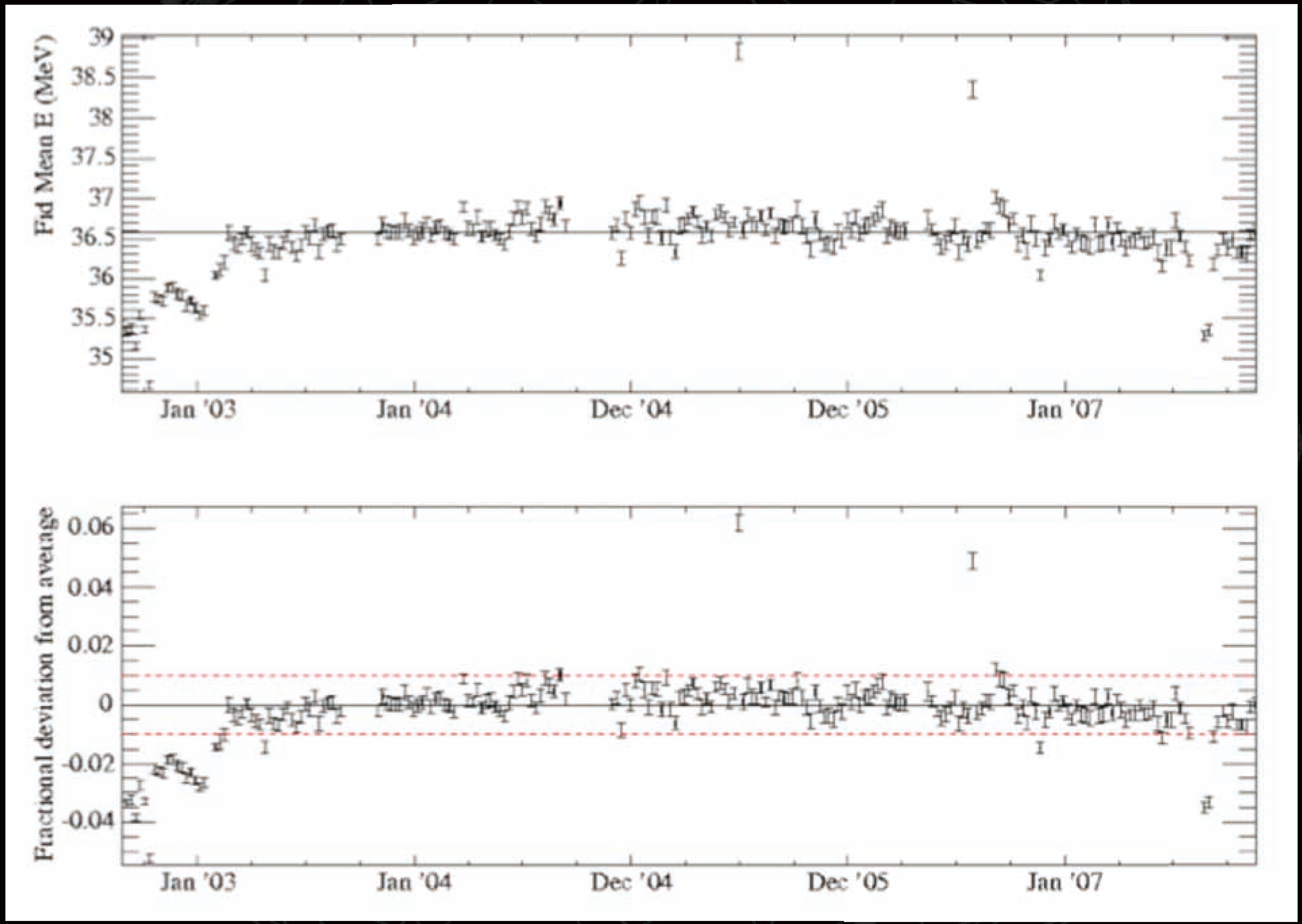


e/π⁰ Likelihood

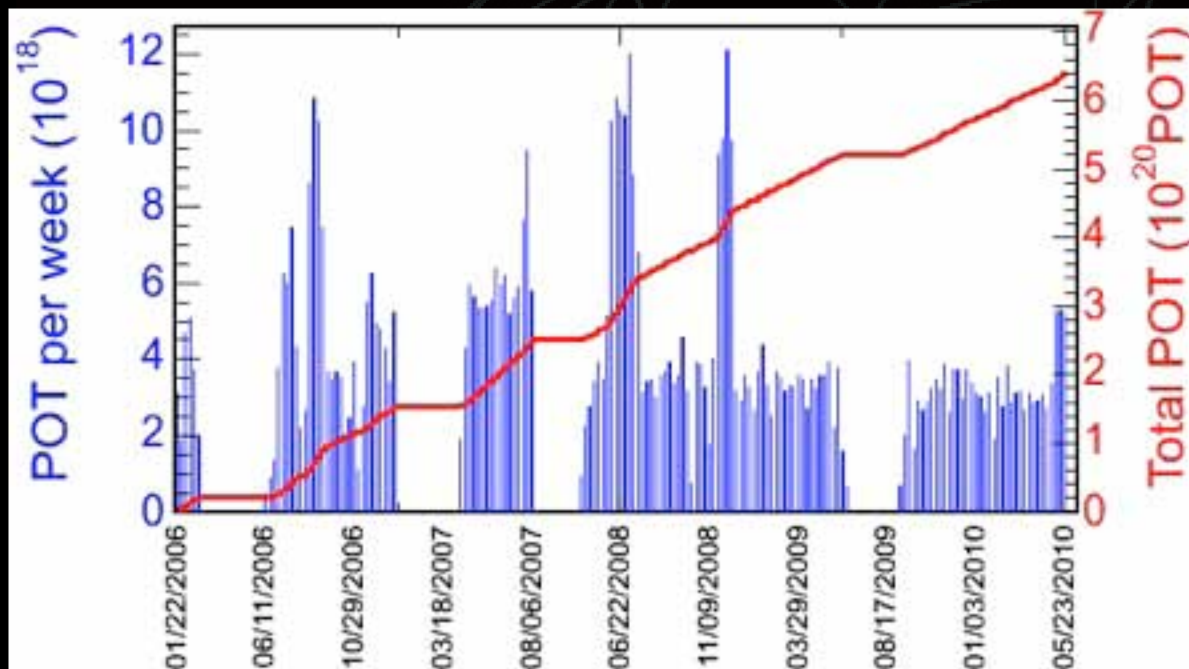
- Data and MC
- PID uses cuts on
  - likelihood ratio
  - reconstructed π^0 mass
- Open sidebands before unblinding full data sample

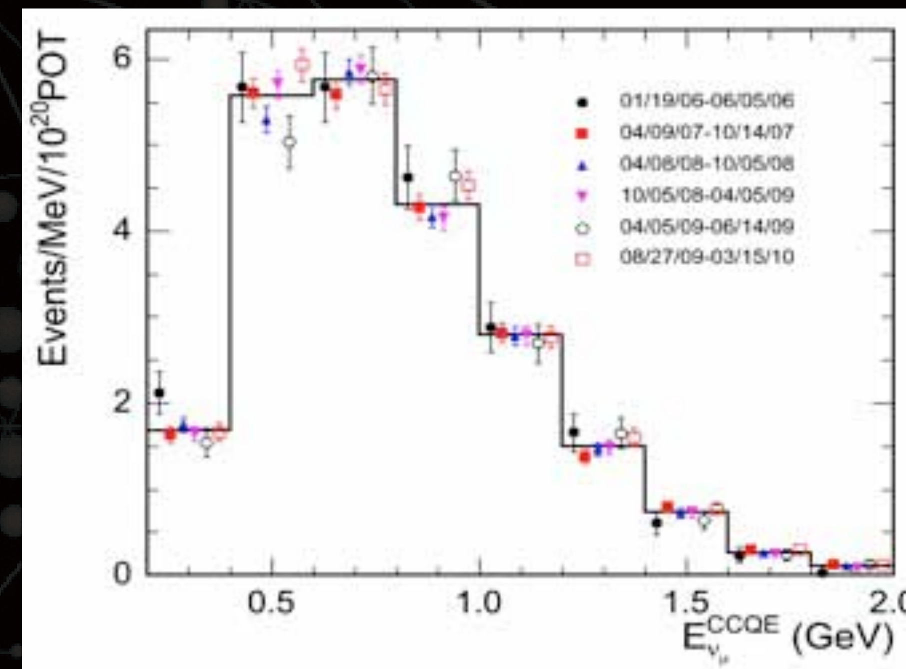


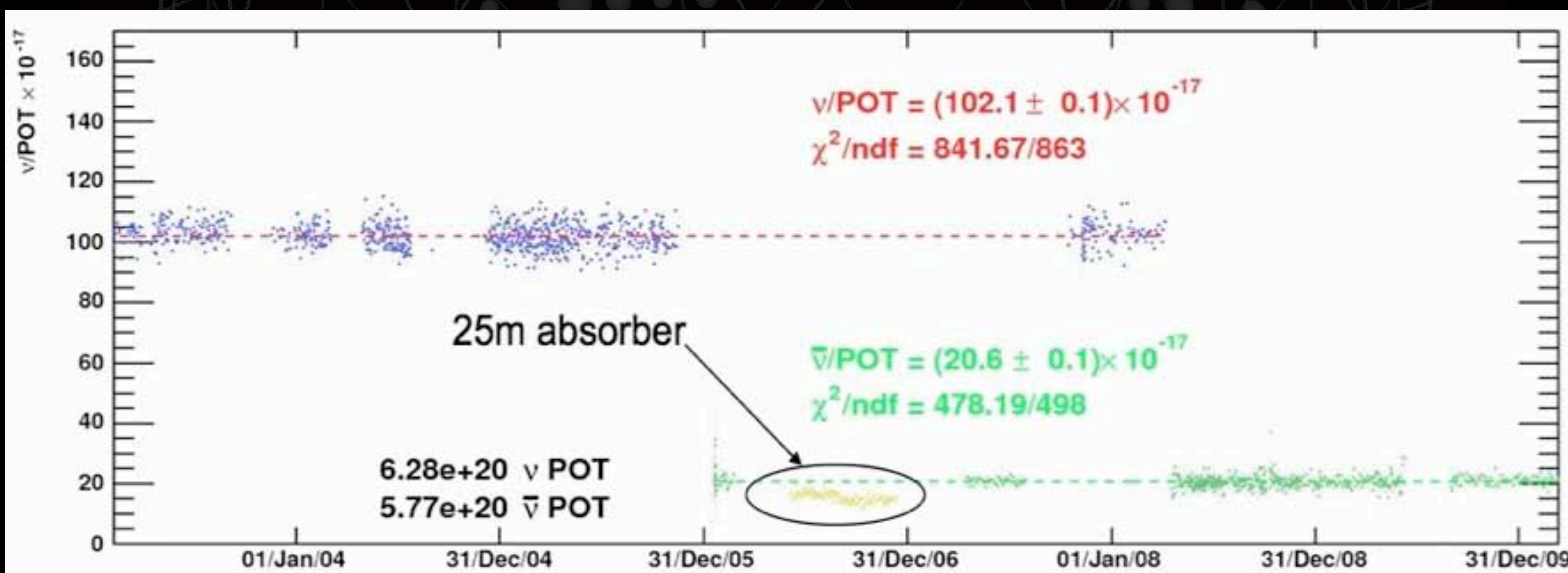
Detector Stability

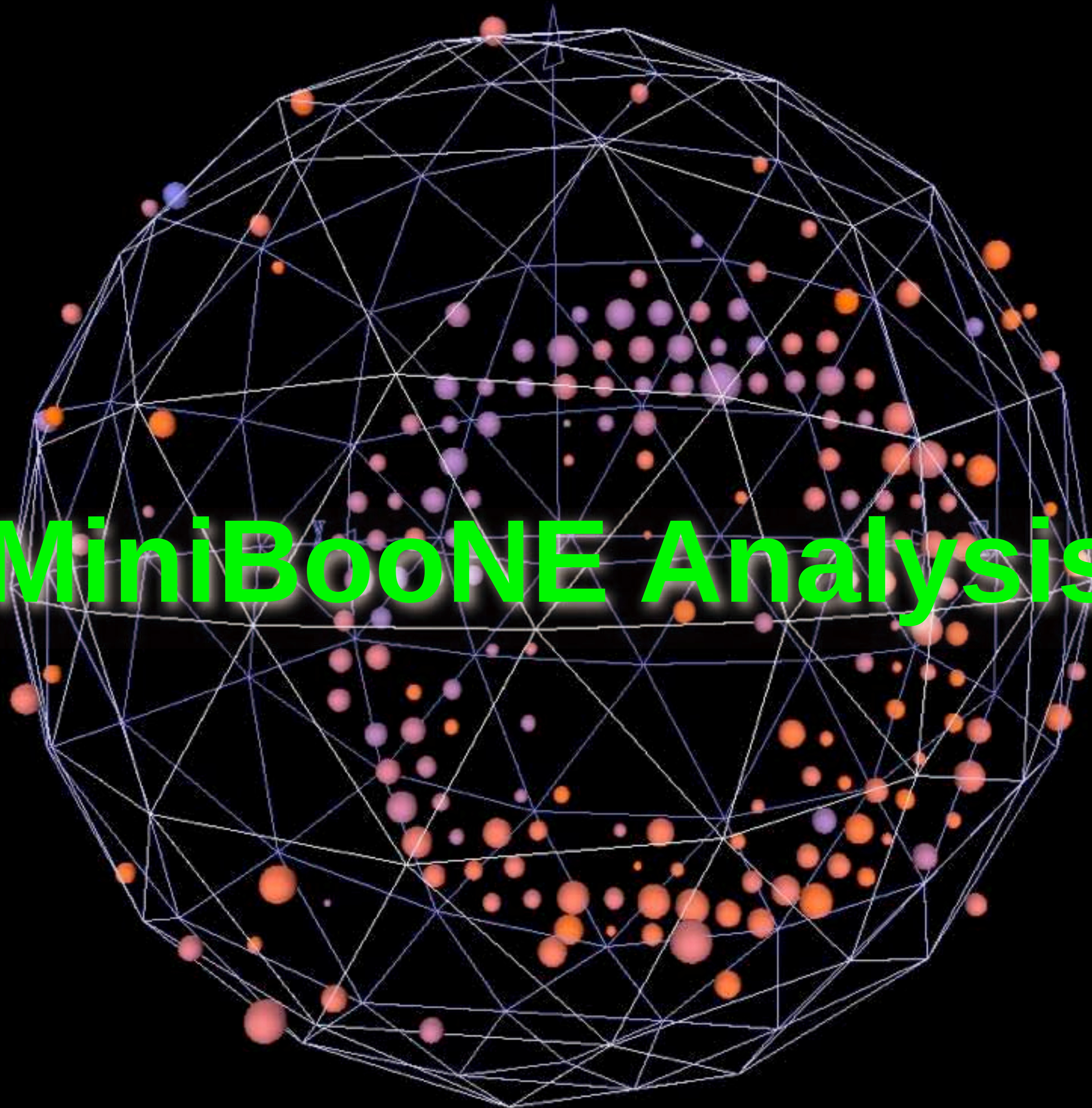


Experiment Stability









MiniBooNE Analysis

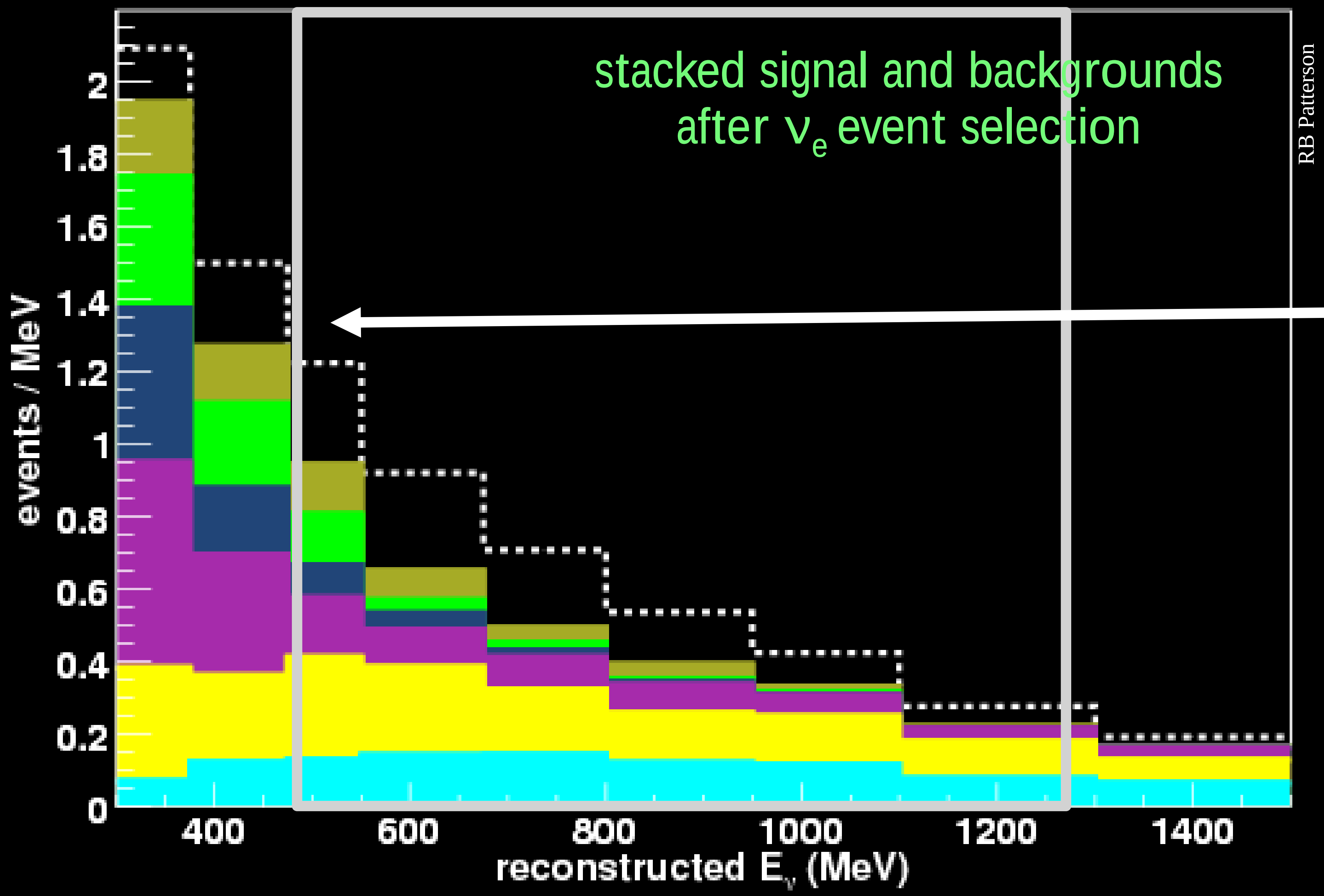
$\bar{\nu}_e$ appearance analysis

Beam Flux Prediction → **Cross Section Model** → **Optical Model** → **Event Reconstruction** → **Particle Identification** → **Simultaneous Fit to $\bar{\nu}_\mu$ and $\bar{\nu}_e$ events**

- **Beam Flux Prediction:** Start with a Geant 4 flux prediction for the $\bar{\nu}$ spectrum from π and K produced at the target
- **Cross Section Model:** Predict $\bar{\nu}$ interactions using the Nuance event generator
- **Optical Model:** Pass final state particles to Geant 3 to model particle and light propagation in the tank
- **Event Reconstruction:** Use track-based event reconstruction
- **Particle Identification:** Use hit topology and timing to identify electron-like or muon-like Cherenkov rings and corresponding charged current neutrino interactions
- **Simultaneous Fit:** Fit reconstructed energy spectrum for oscillations

Signal & Backgrounds

Example from neutrino mode



Oscillation ν_e

Example oscillation signal

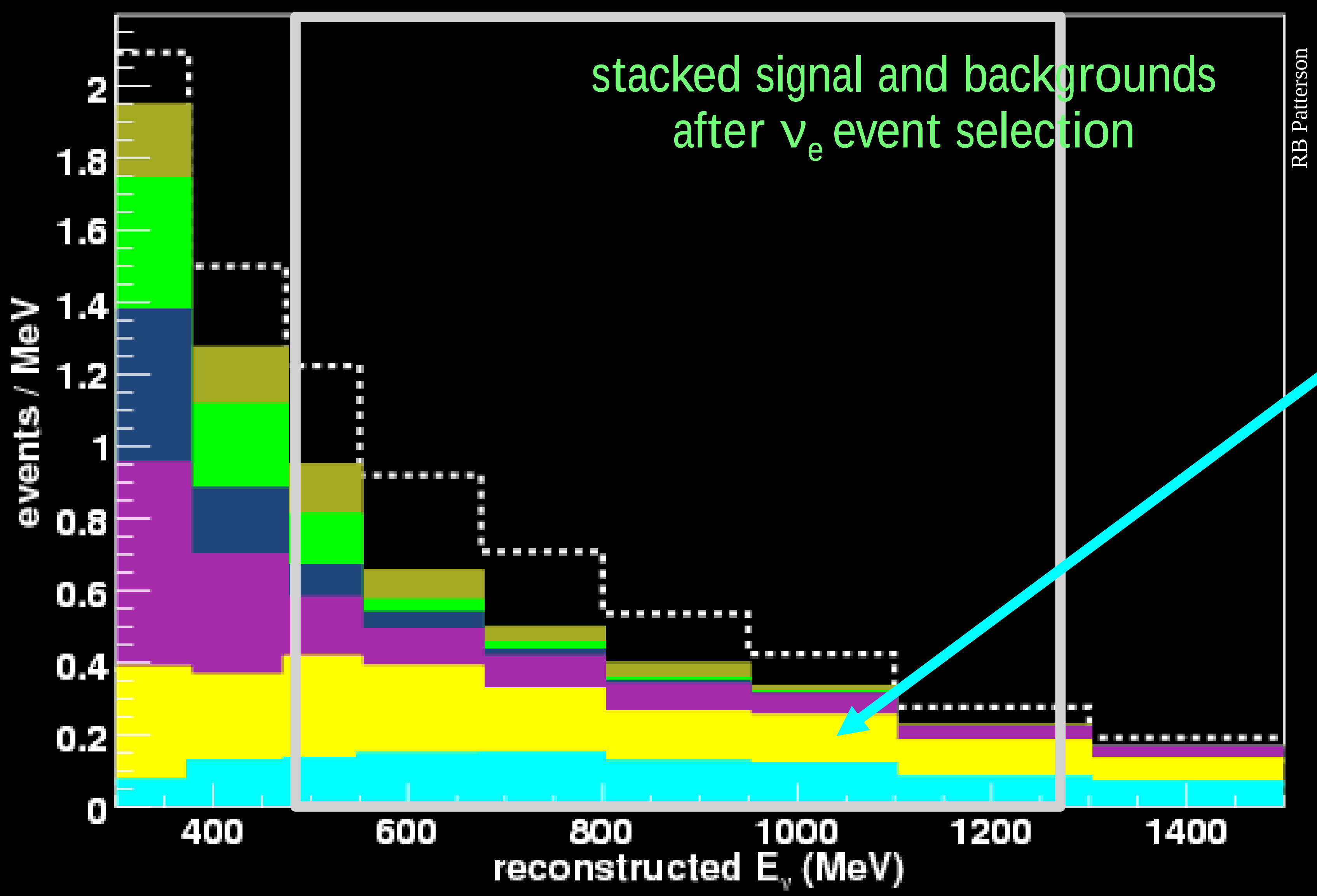
$\Delta m^2 = 1.2$ eV^2

$\sin^2 2\theta = 0.003$

Fit for excess as a function of reconstructed ν_e energy

Signal & Backgrounds

Example from neutrino mode



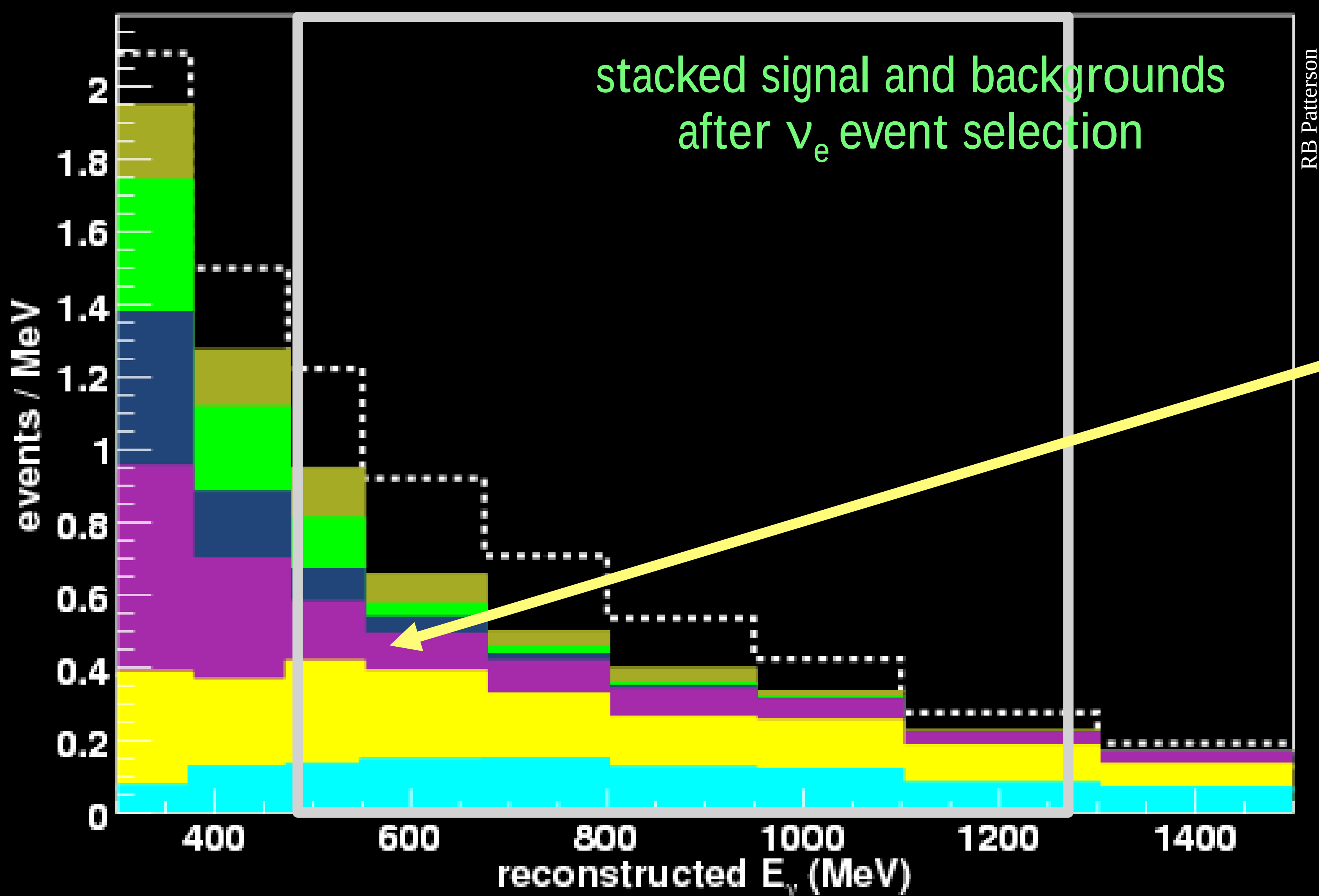
ν_e from K^+ and K^0

Use fit to kaon production data for shape

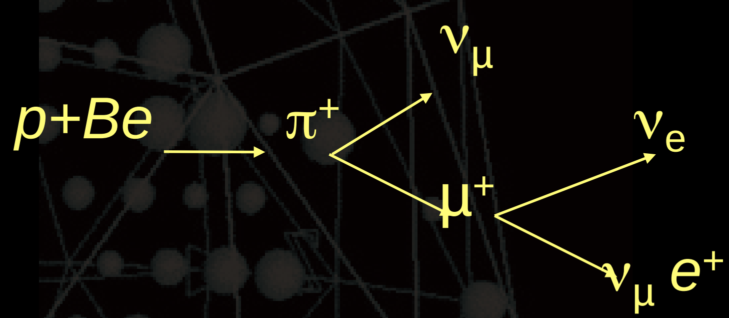
Use high energy ν_e and ν_μ in-situ data for normalisation cross-check

Signal & Backgrounds

Example from neutrino mode



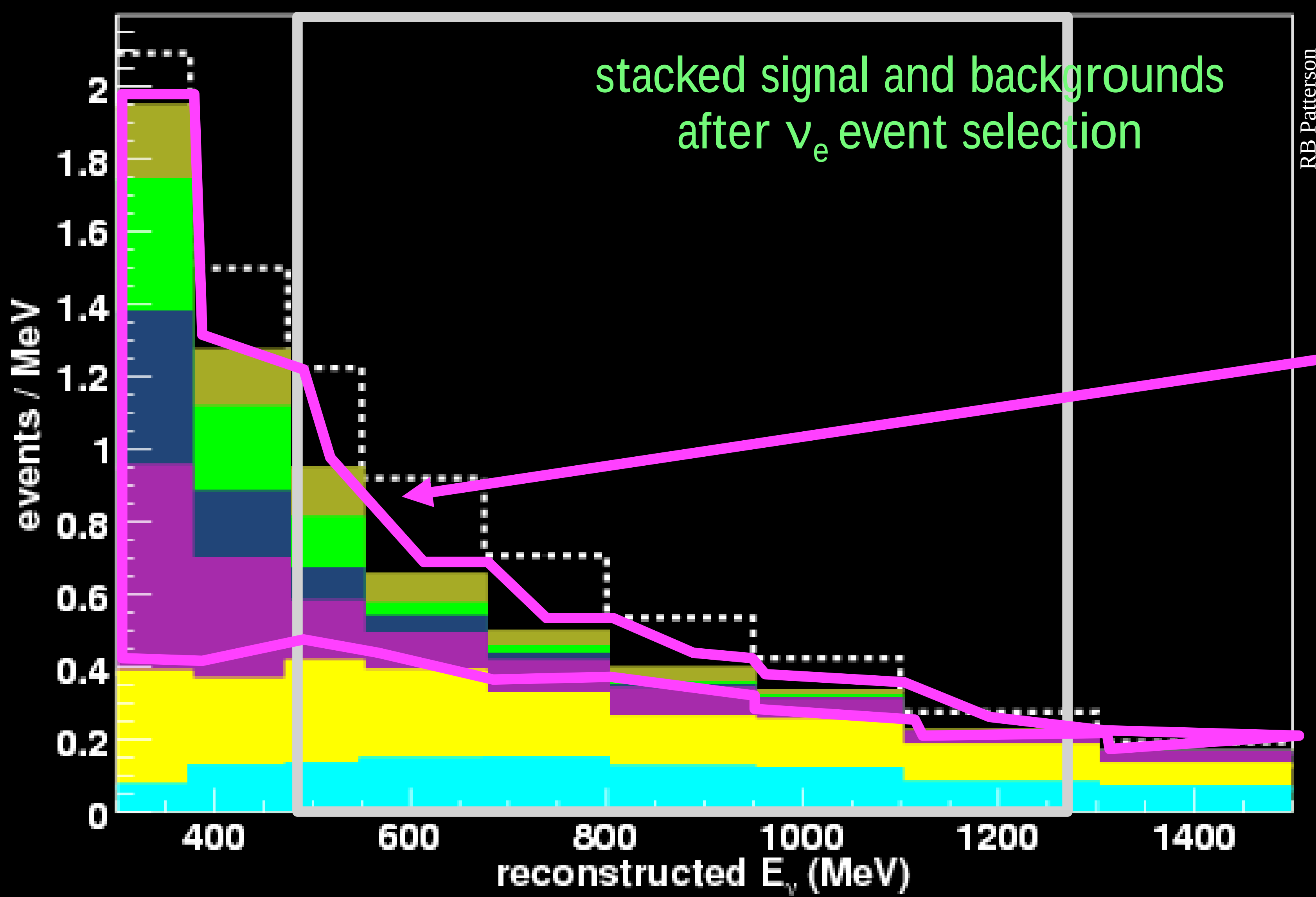
ν_e from μ^+



- Measured with in-situ ν_μ CCQE sample
  - Same ancestor π^+ kinematics
- Most important background
  - Constrained to a few %

Signal & Backgrounds

Example from neutrino mode



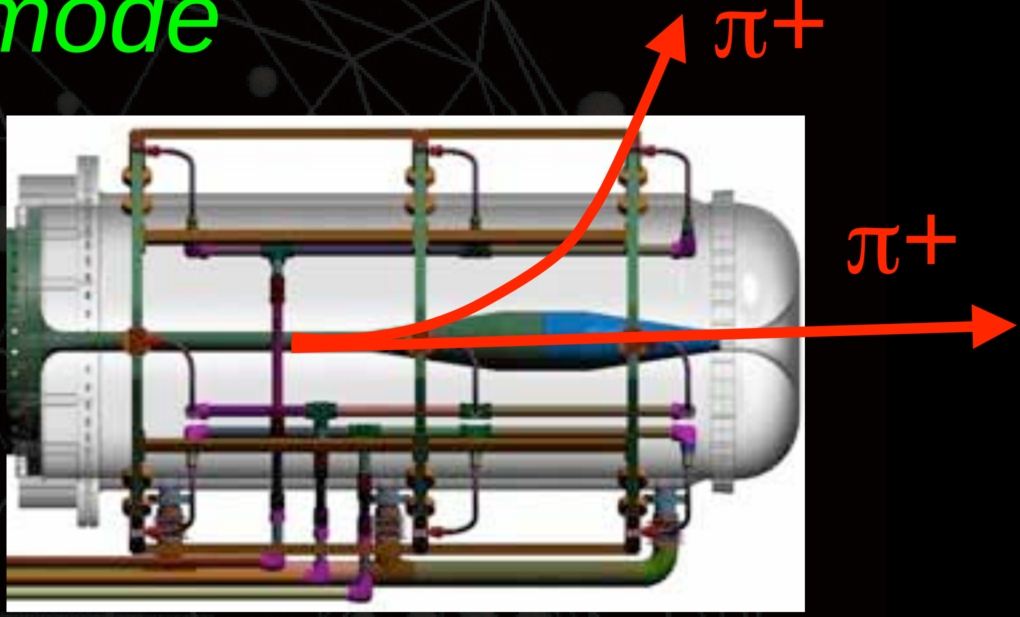
MisID ν_μ

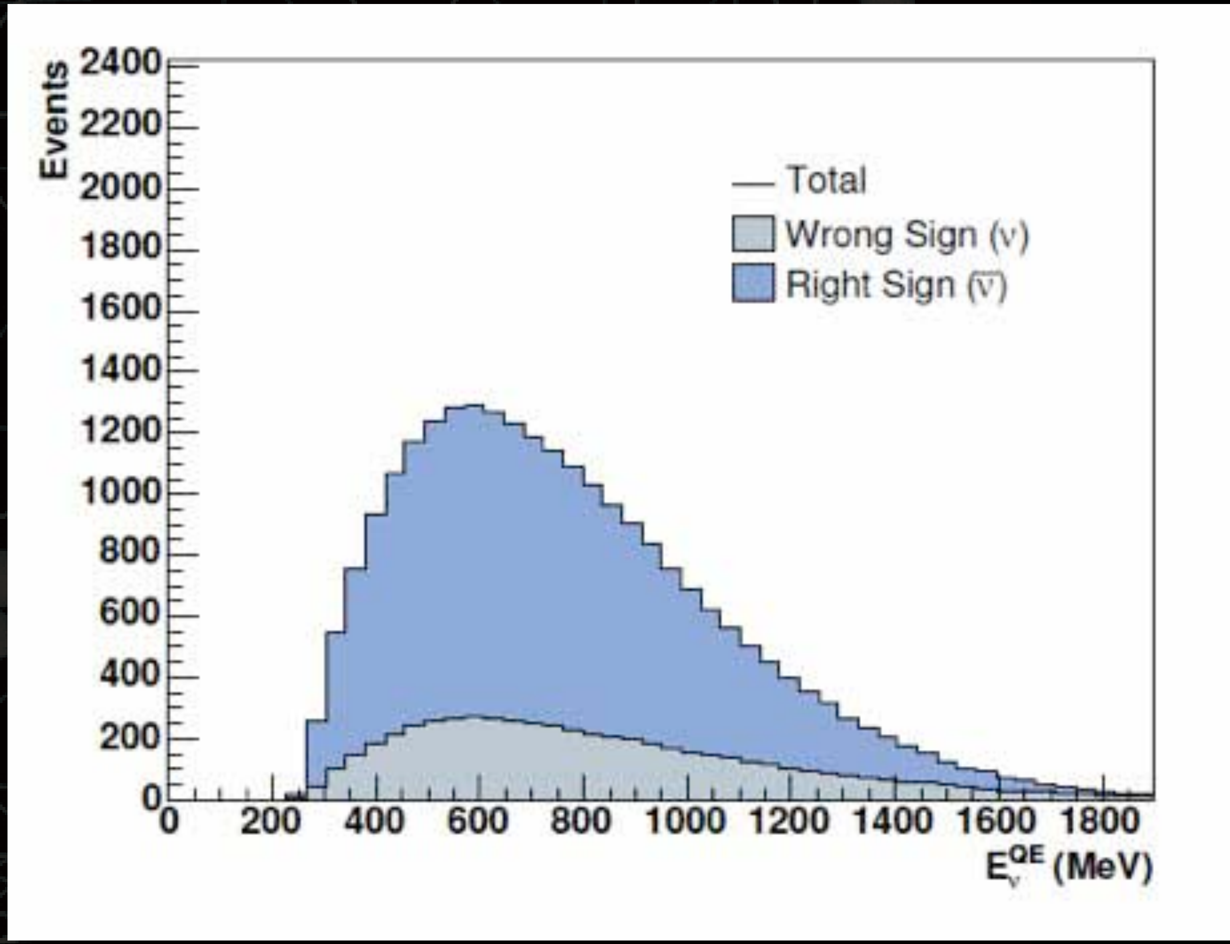
- ~46% π^0
  - Determined by clean π^0 measurement
- ~16% Δ γ decay
  - π^0 measurement constrains
- ~14% "dirt"
  - Measure rate to normalise and use MC for shape
- ~24% other
  - Use ν_μ CCQE rate to normalise and MC for shape

Additional Background

Antineutrino mode

- Antineutrino beam contains significant fraction of "wrong sign" neutrino events
  - Stemming from unfocussed pions in secondary beam
  - ~20% of reconstructed events
- MinBooNE cannot sign select events
  - Need other methods to constrain WS BGs

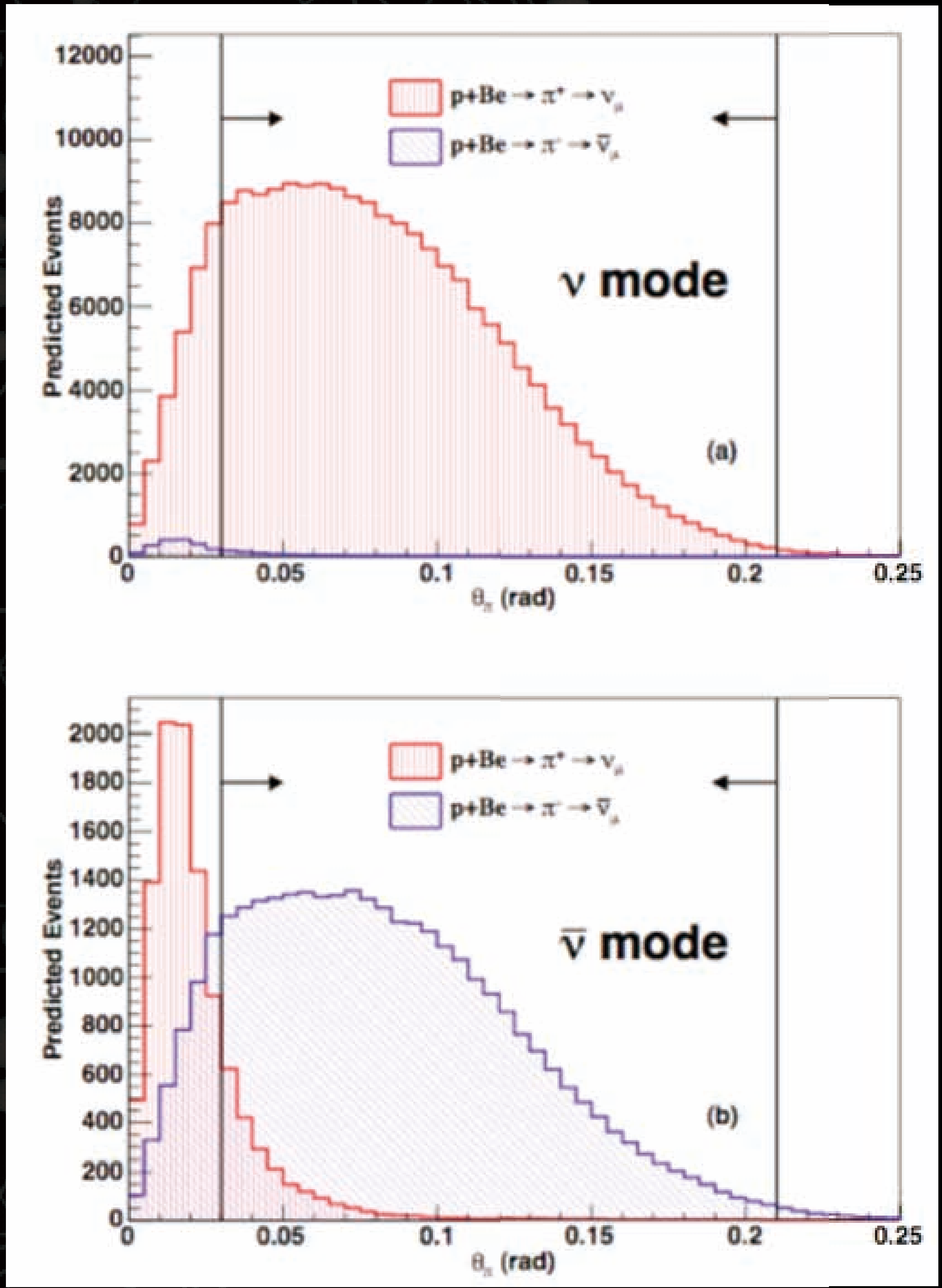




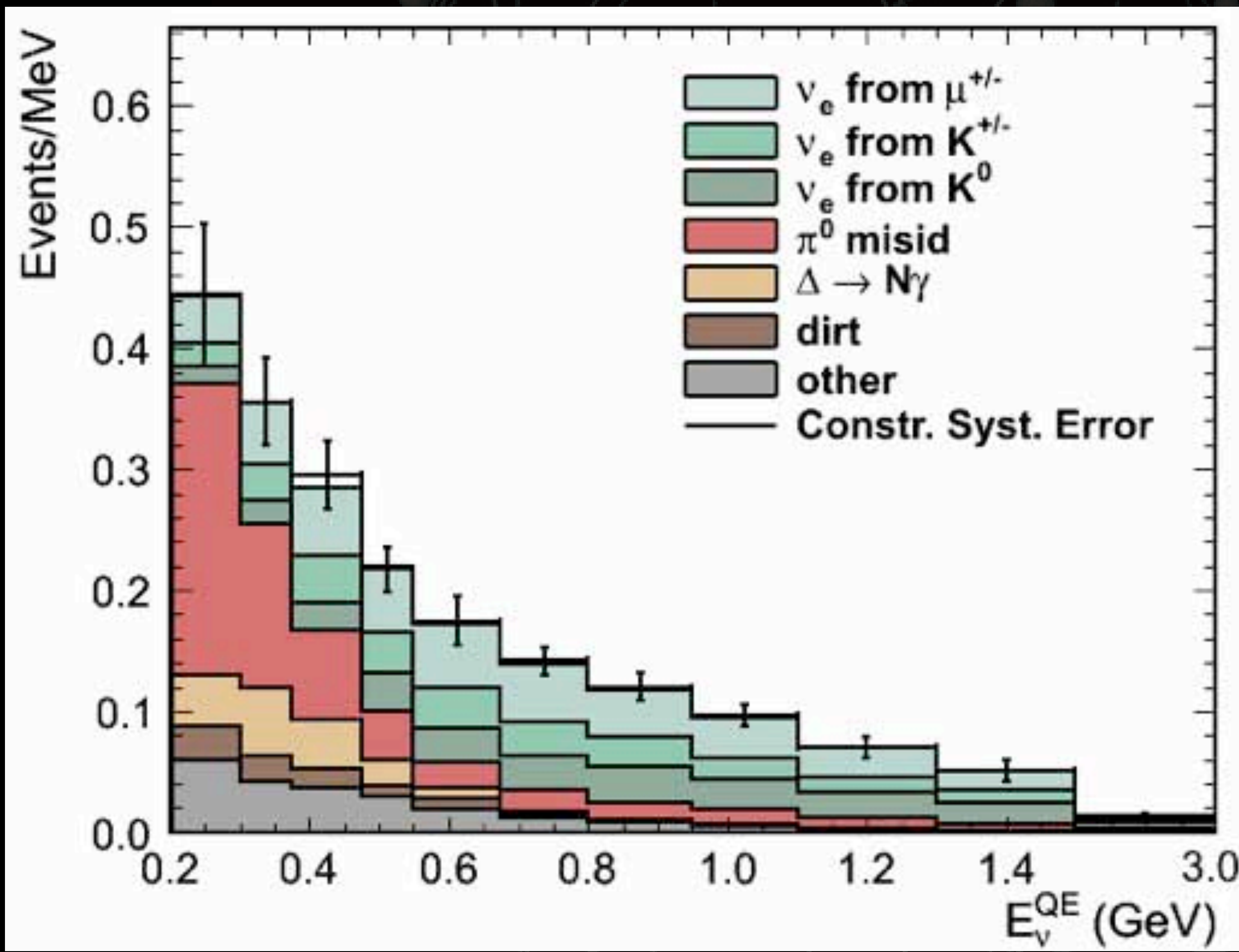
Additional Background

Antineutrino mode

- Antineutrino beam contains significant fraction of “wrong sign” neutrino events
  - Stemming from unfocussed pions in secondary beam
  - ~20% of reconstructed events in nubar mode
- MinBooNE cannot sign select events
  - Need other methods to constrain WS BGs



$\bar{\nu}_e$ BG prediction

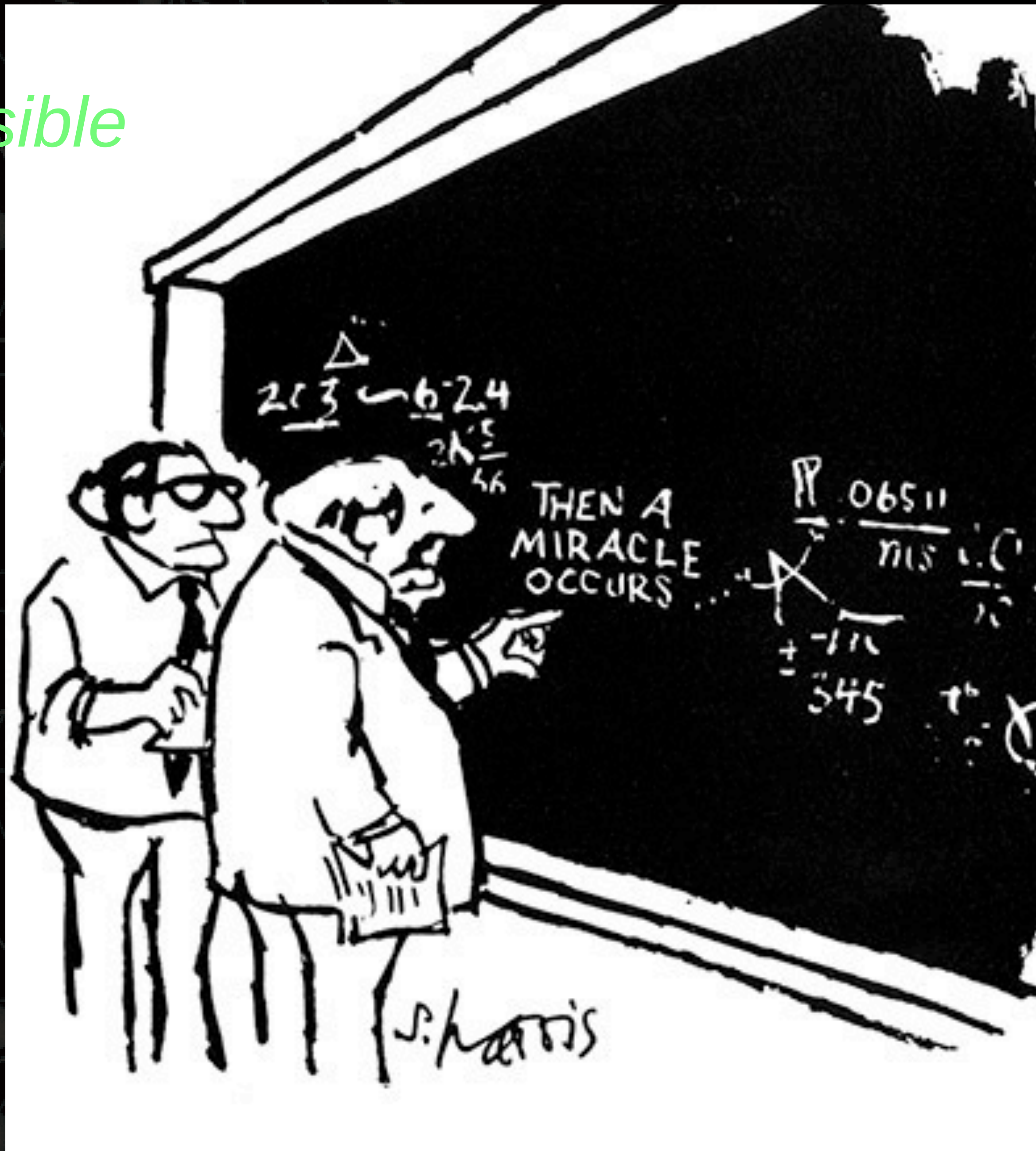


5.66e20 POT			
Source	200-475	475-1250	
$\mu^\pm$	13.4	31.4	Intrinsic ν_e
$K^\pm$	8.2	18.6	
K^0	5.1	21.2	
other ν_e	1.3	2.0	
$NC\pi^0$	41.6	12.6	Mis-ID ν_μ
$\Delta \rightarrow \gamma$	12.4	3.4	
dirt	6.2	2.6	
ν_μ CCQE	4.3	2.0	
other ν_μ	7.0	4.2	
TOTAL	**99.5**	**98.0**	

Strategy

Incorporate in-situ data whenever possible

- MC tuning with calibration data
  - energy scale
  - PMT response
  - optical model
- MC tuning with neutrino data
  - CCQE - constrain BG with data
  - π^0 rate constraint
  - “Dirt” backgrounds
  - WS backgrounds
- Constraining systematic errors with neutrino data
  - ratio method: ν_e from μ decay



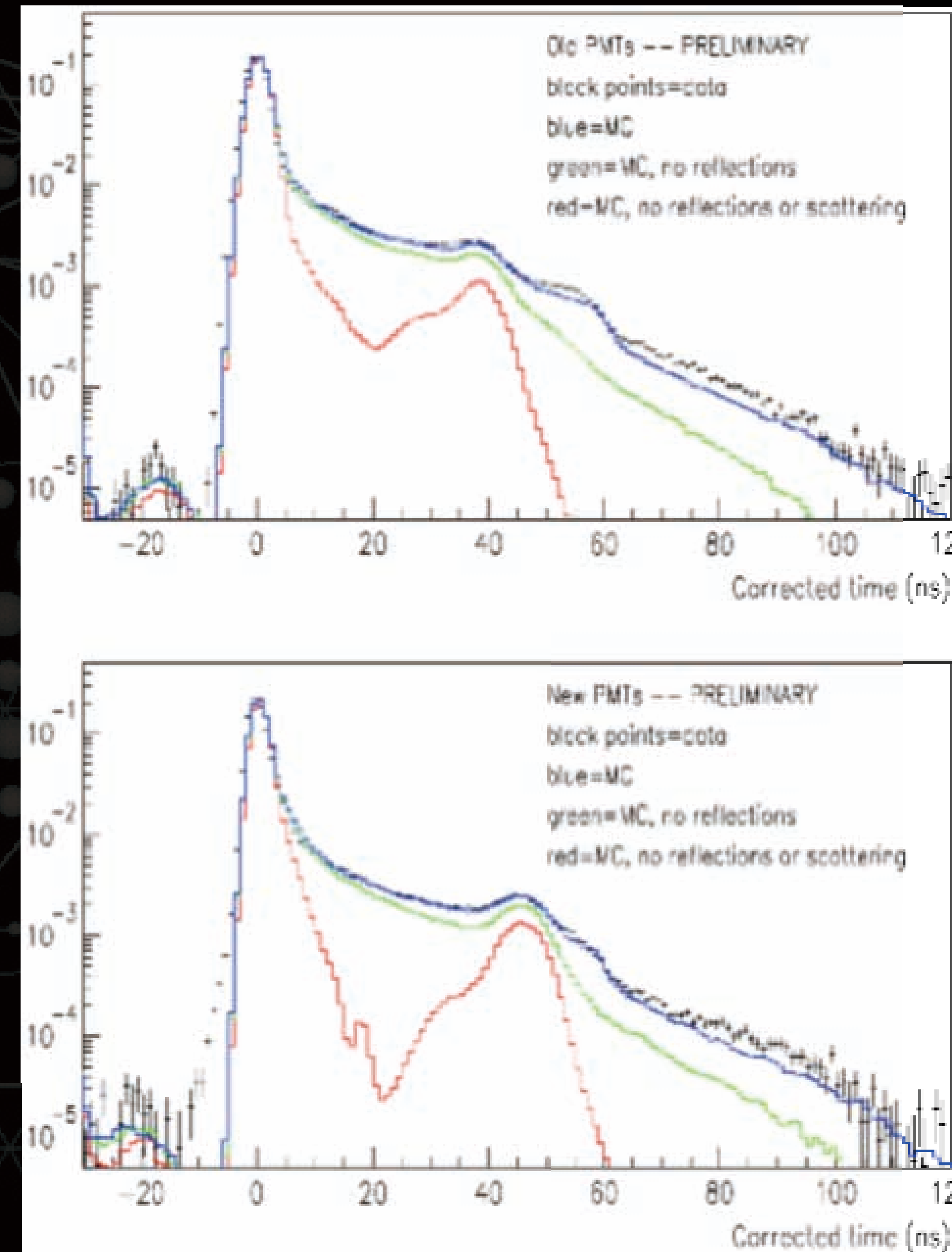
“I think you should be more explicit here in step two.”

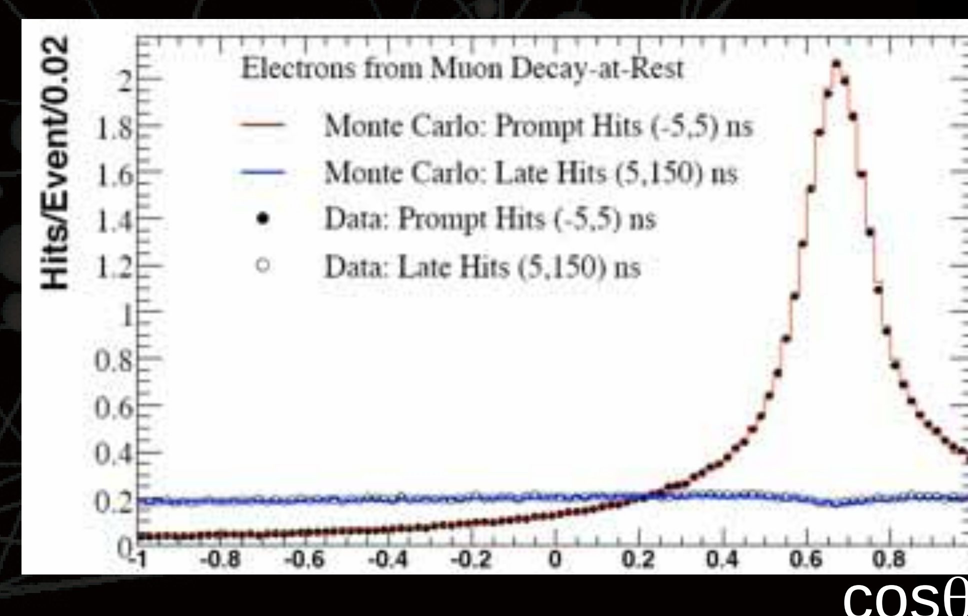
Recurring theme: good data-MC agreement

MC Tuning

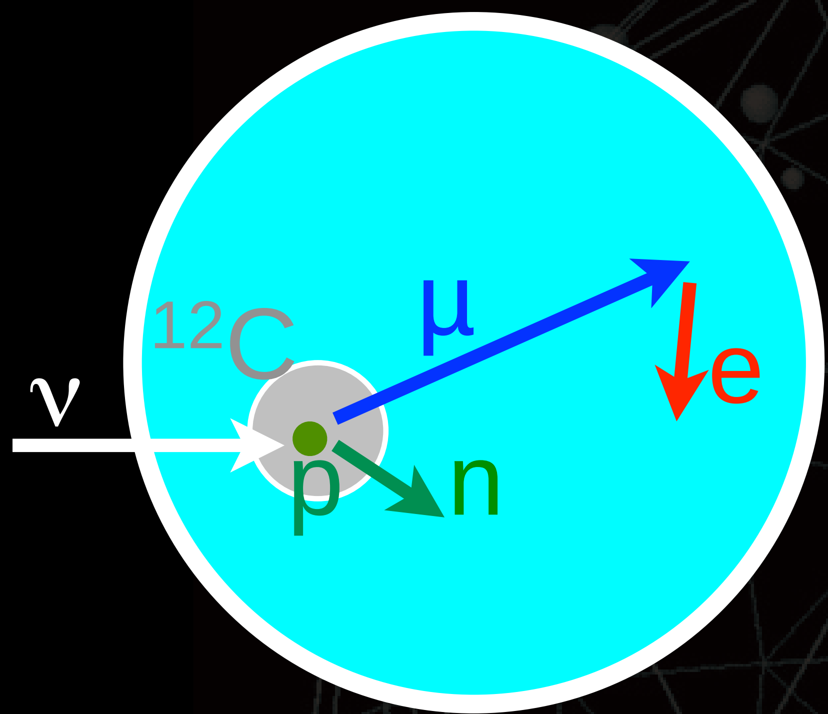
Good data/MC agreement

- Basic PMT hit distributions showing details of optical model
- Also have good agreement in aggregate PMT hit distributions showing gross detector behaviour





ν_μ CCQE events

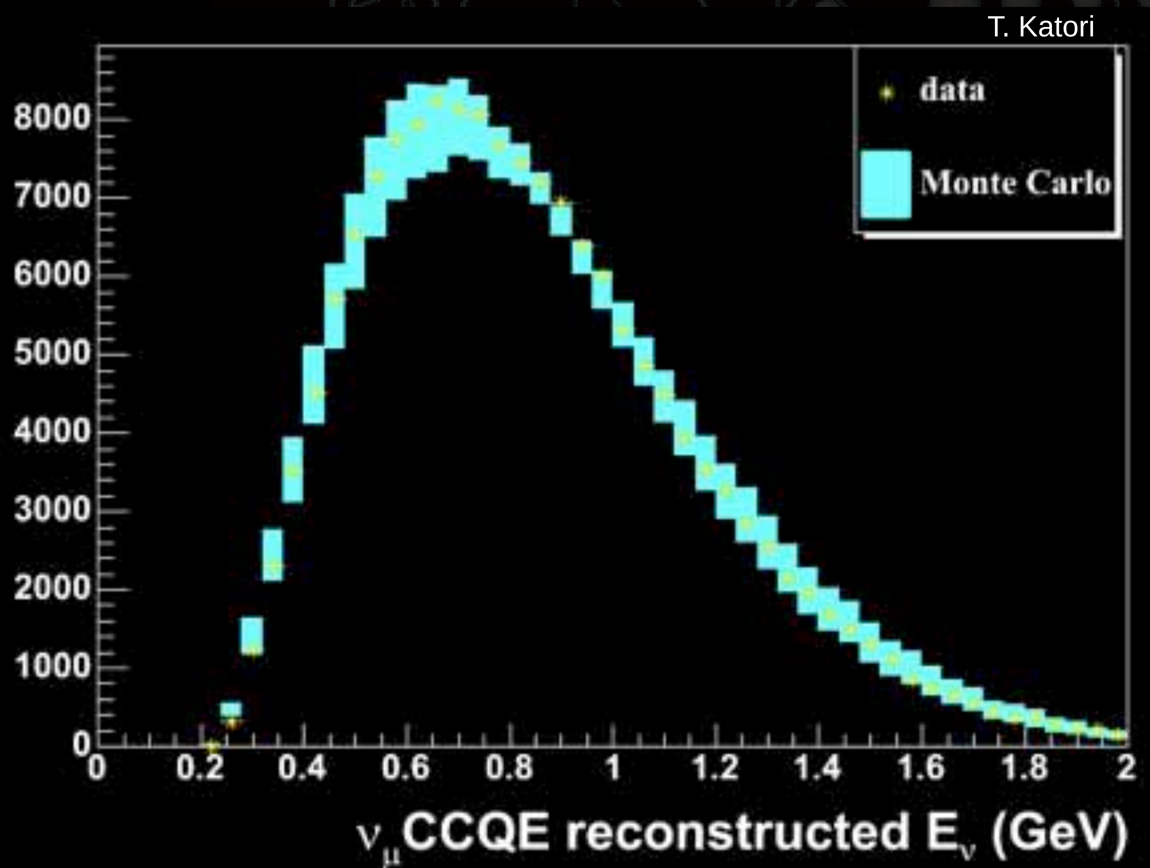


Used to measure flux and check E_ν^{QE} reconstruction

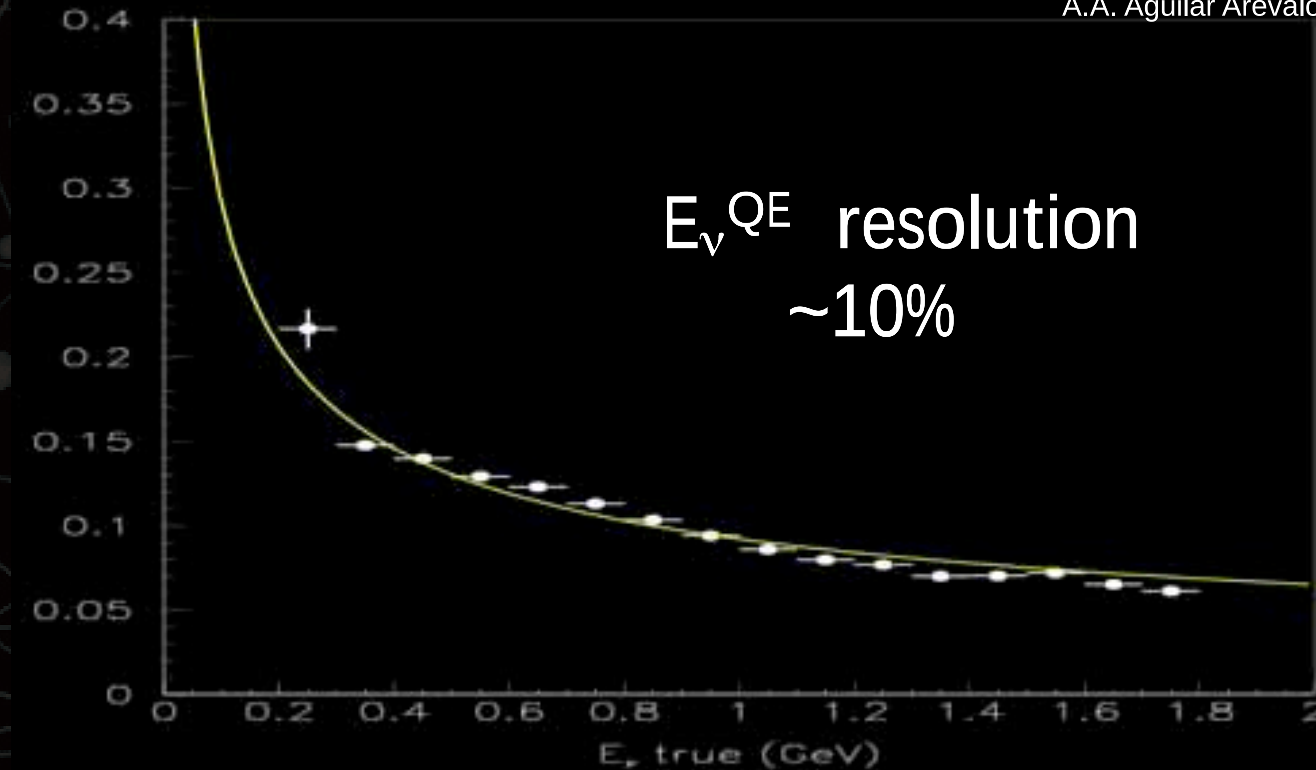
$$E_\nu^{QE} = \frac{1}{2}\frac{2M_pE_\mu - m_\mu^2}{M_p - E_\mu + \sqrt{(E_\mu^2 - m_\mu^2)}\cos\theta_\mu}$$

- 2 subevents: e, μ
  - Require e be located near end of μ track

T. Katori



A.A. Aguilar Arevalo



ν_μ CCQE tuning

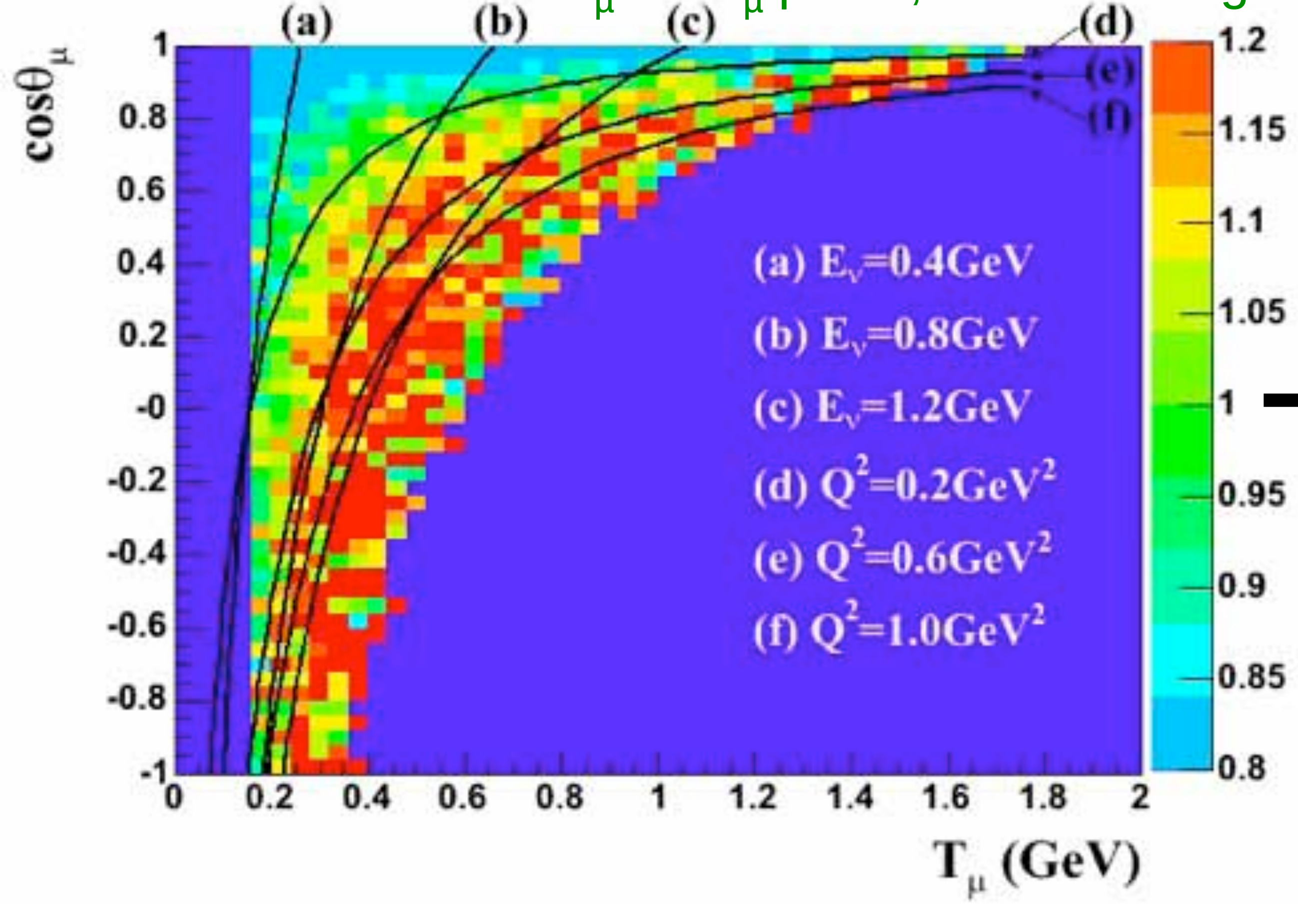
PRL100(2008)032301

- Need good flux model to study cross section

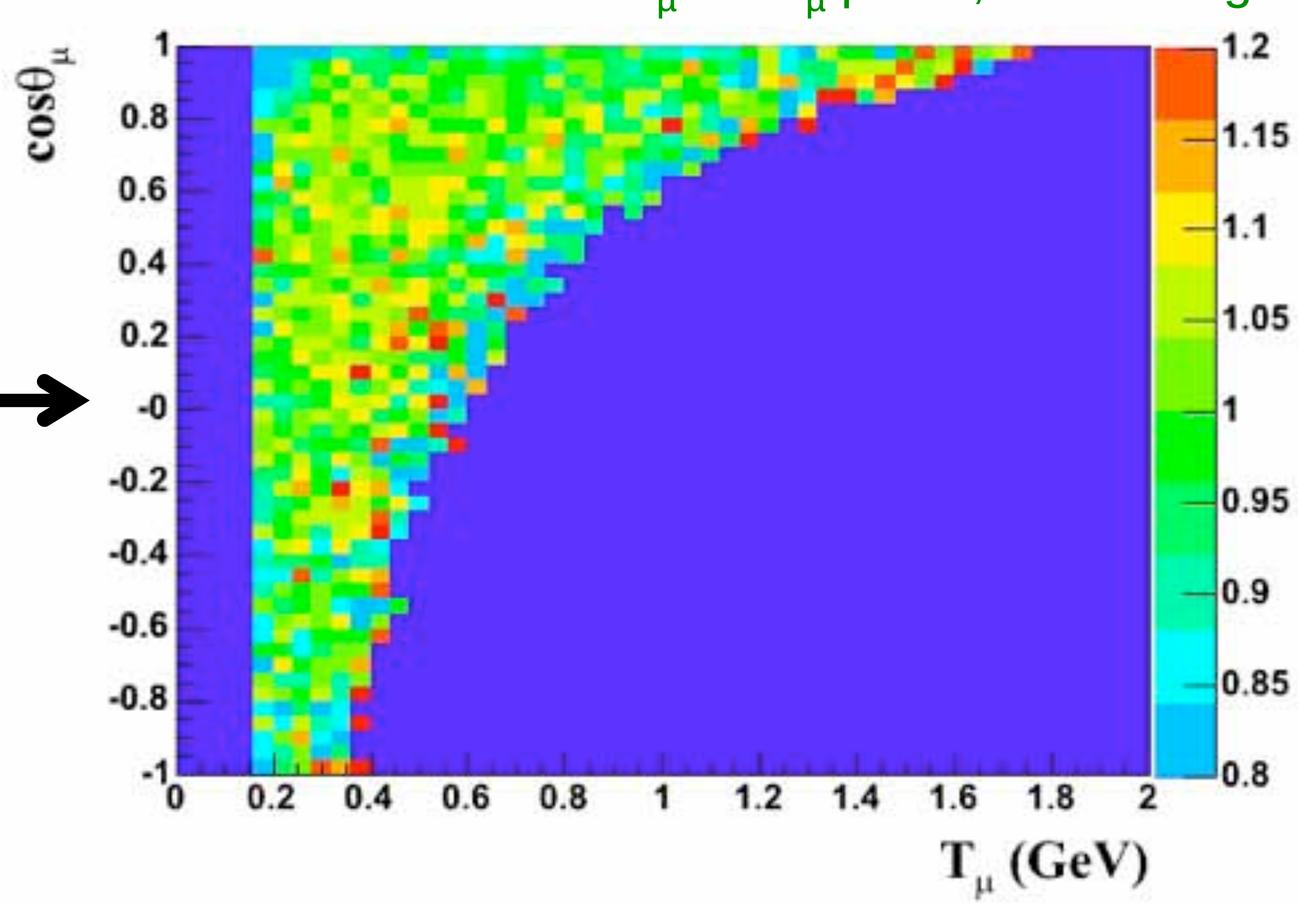
$$R(interaction[E_\nu, Q^2]) \propto \int (\Phi[E_\nu]) \times \sigma[Q^2])$$

- Data-MC mismatch follows Q2 lines, not Ev
  - Problem is not the flux prediction, but the cross section model

Data/MC ratio for T_μ-$\cos\theta_\mu$ plane, before tuning



Data/MC ratio for T_μ-$\cos\theta_\mu$ plane,after tuning

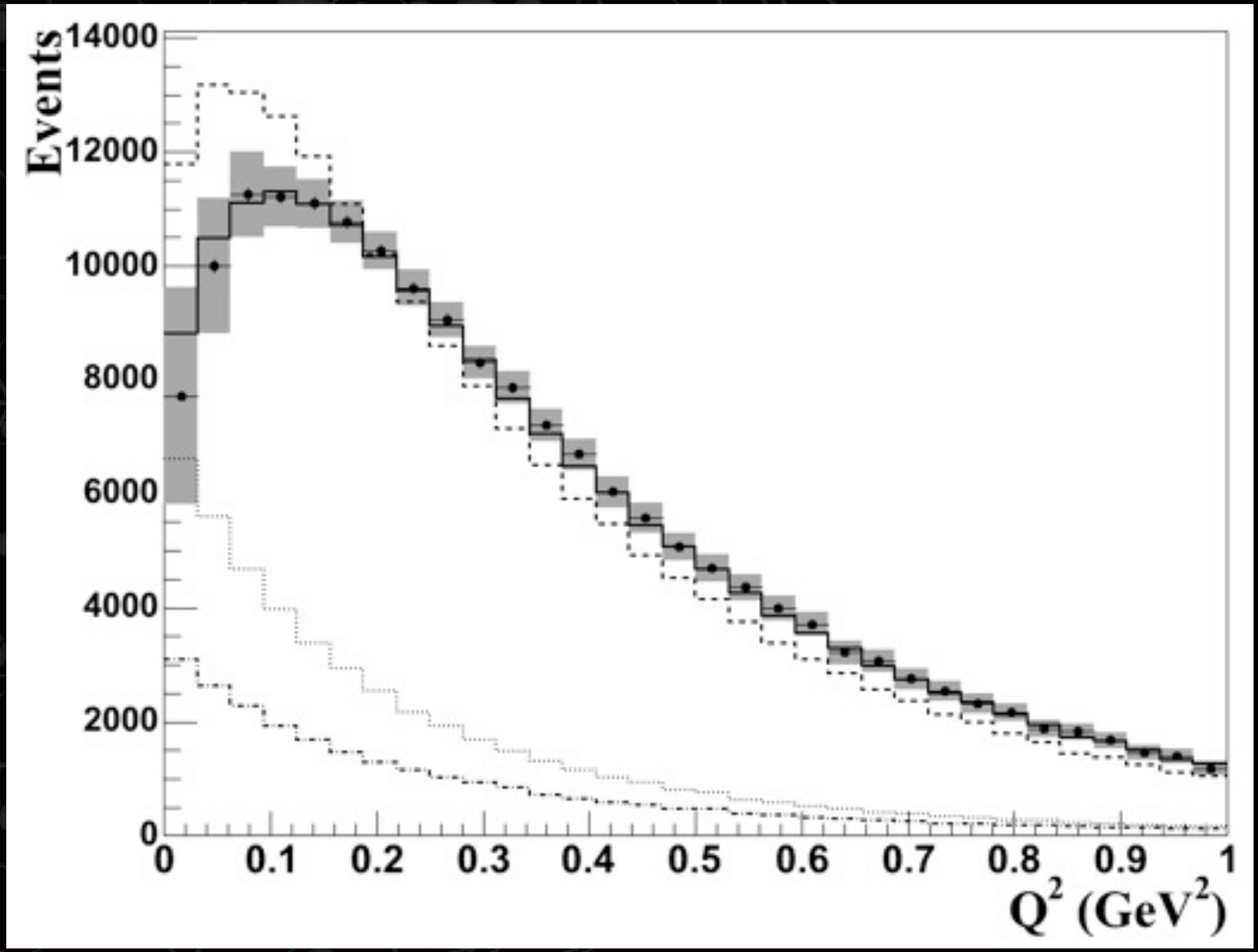


ν_μ CCQE tuning

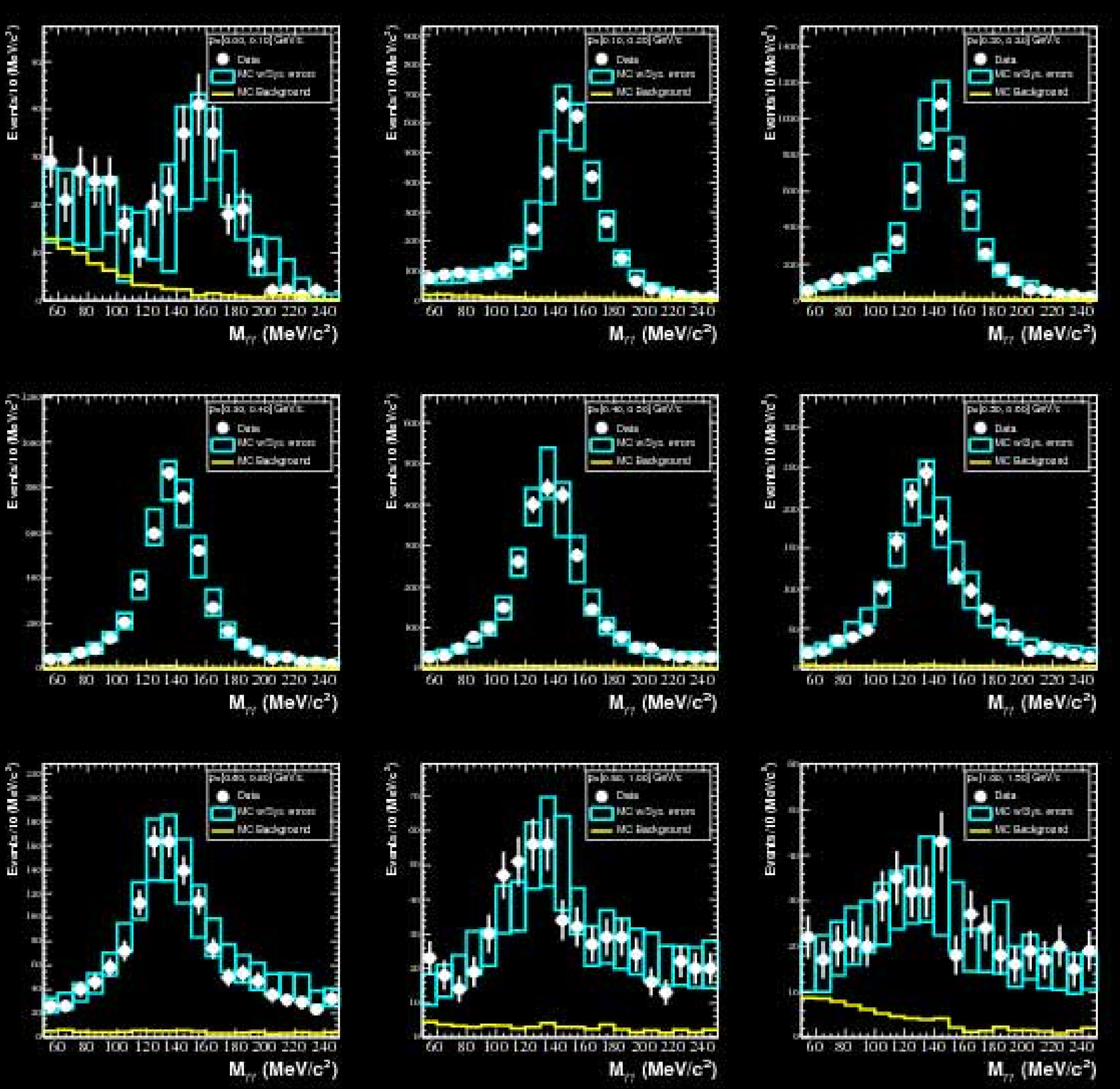
PRL100(2008)032301

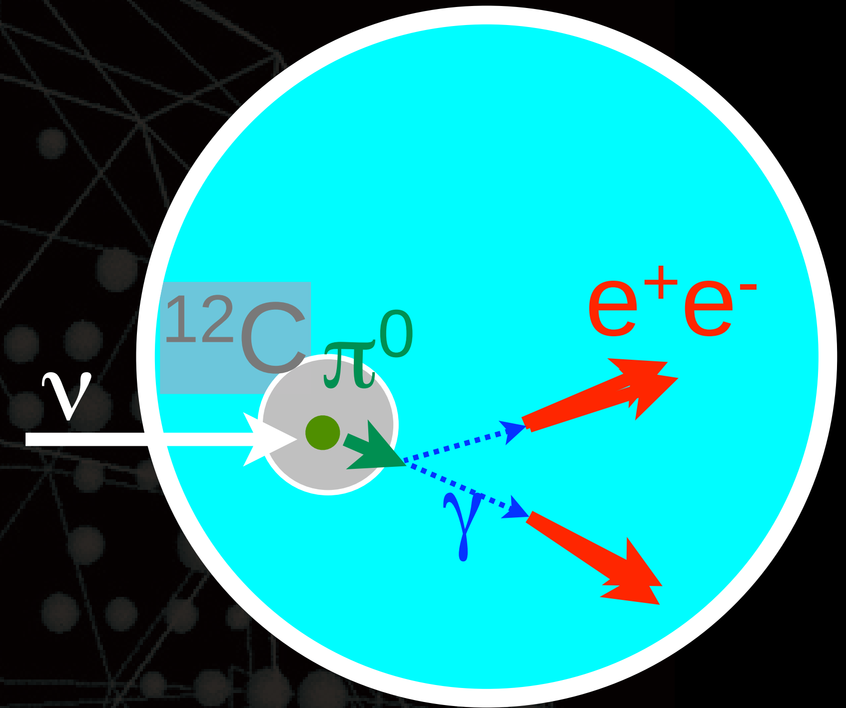
- Tuned nuclear parameters in Relativistic Fermi Gas model
  - Q^2 fits to MB $\nu\mu$ CCQE data using the nuclear parameters:
  - M_A^{eff} - effective axial mass
  - κ - Pauli Blocking parameter
- Relativistic Fermi Gas Model with tuned parameters describes ν_μ CCQE data well
- This improved nuclear model is used in ν_e CCQE model, too.

Q2 distribution before and after fitting



π^0 Mis-ID Backgrounds



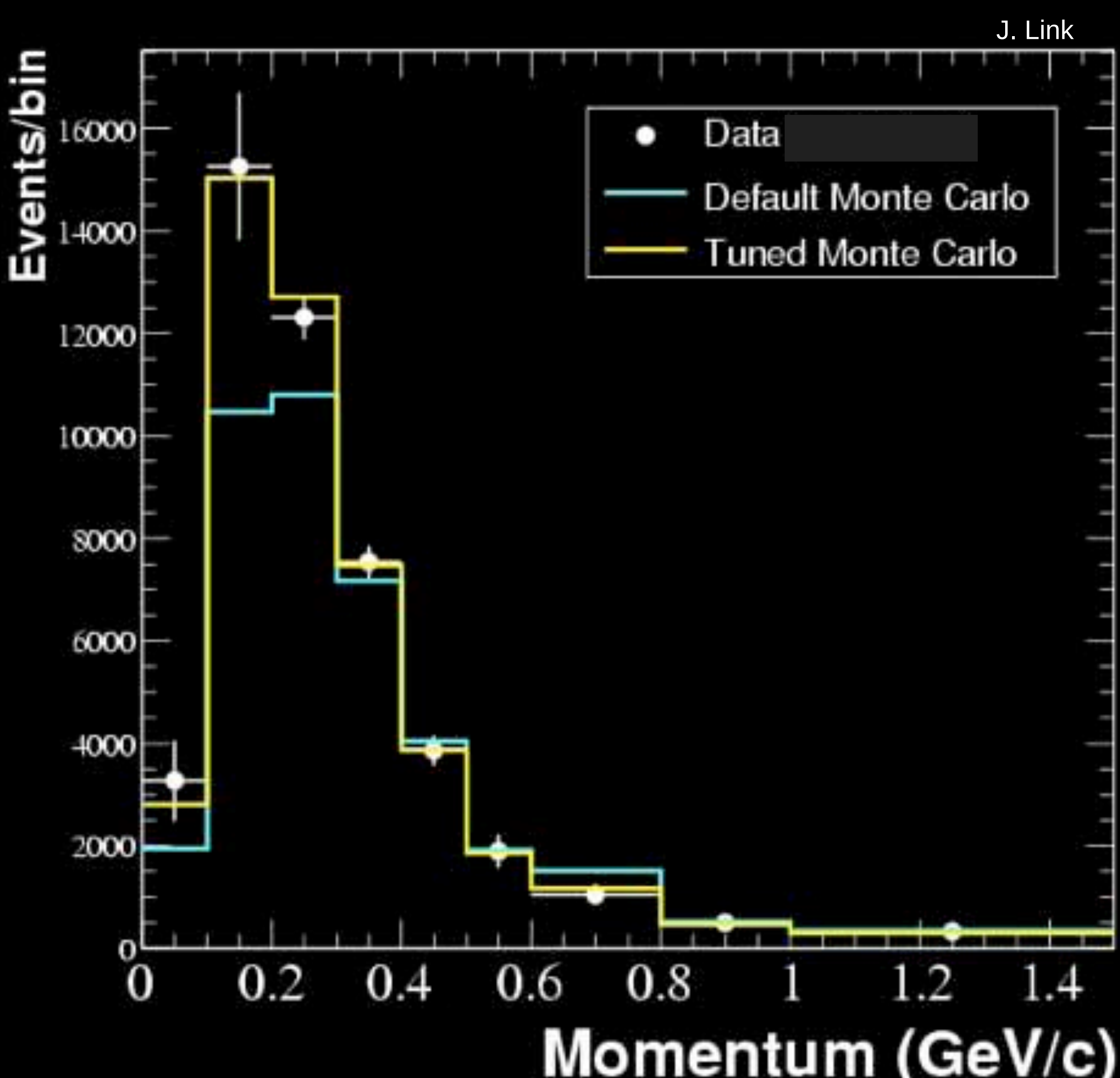


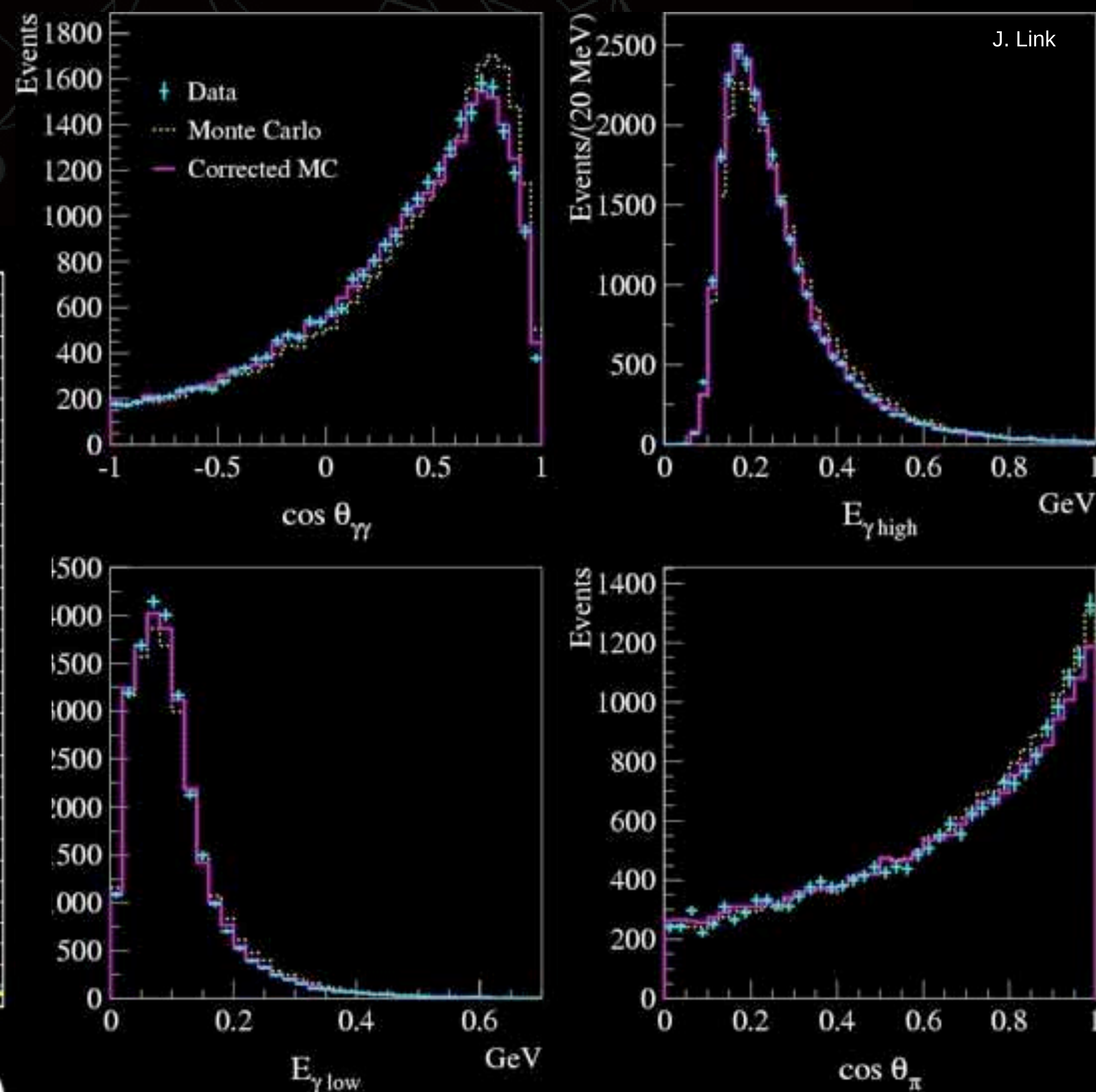
- π^0s are reconstructed outside mass peak if:
  - asymmetric decays fake 1-ring
  - 1 of 2 photons exits
  - high momentum π^0 decays produce overlapping rings

Tuning π^0 MC

*Phys.Lett. B**664**:41-46,2008*

The MC π^0 rate (flux × xsec) is re-weighted to match the measurement in p_π bins.

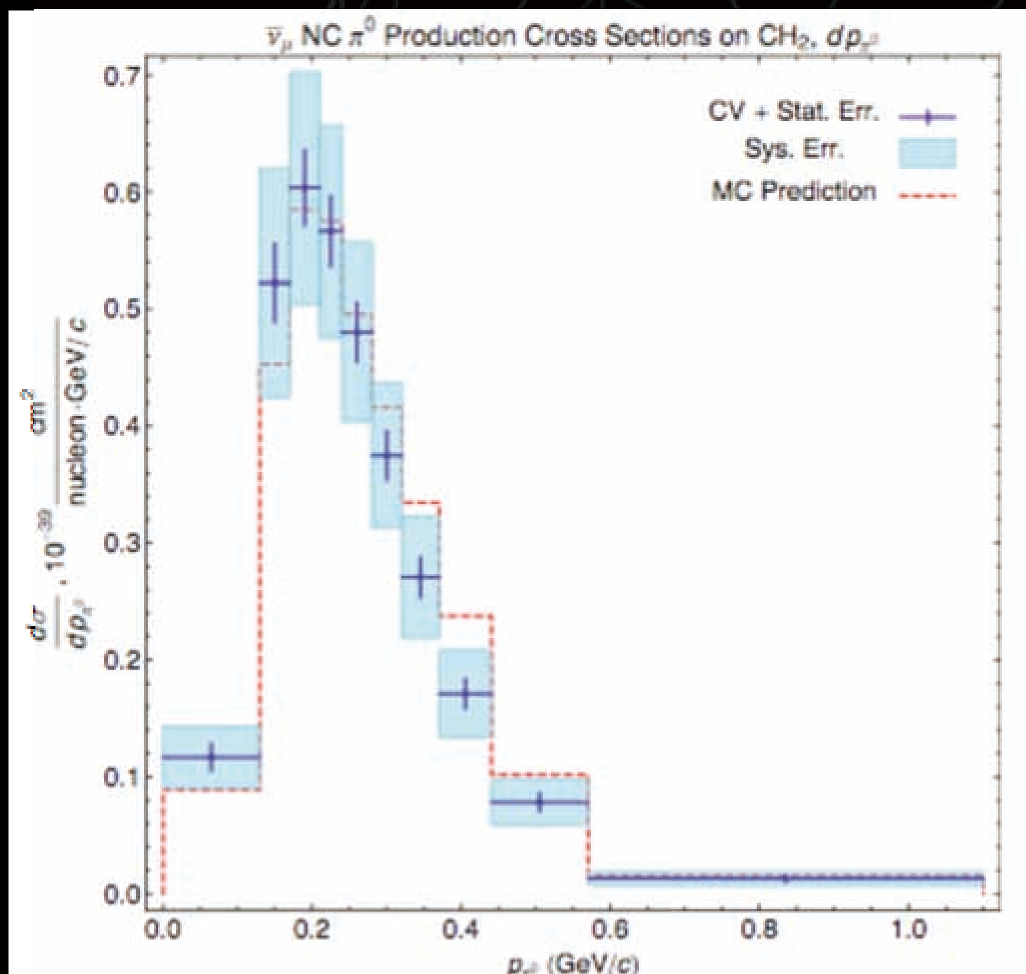


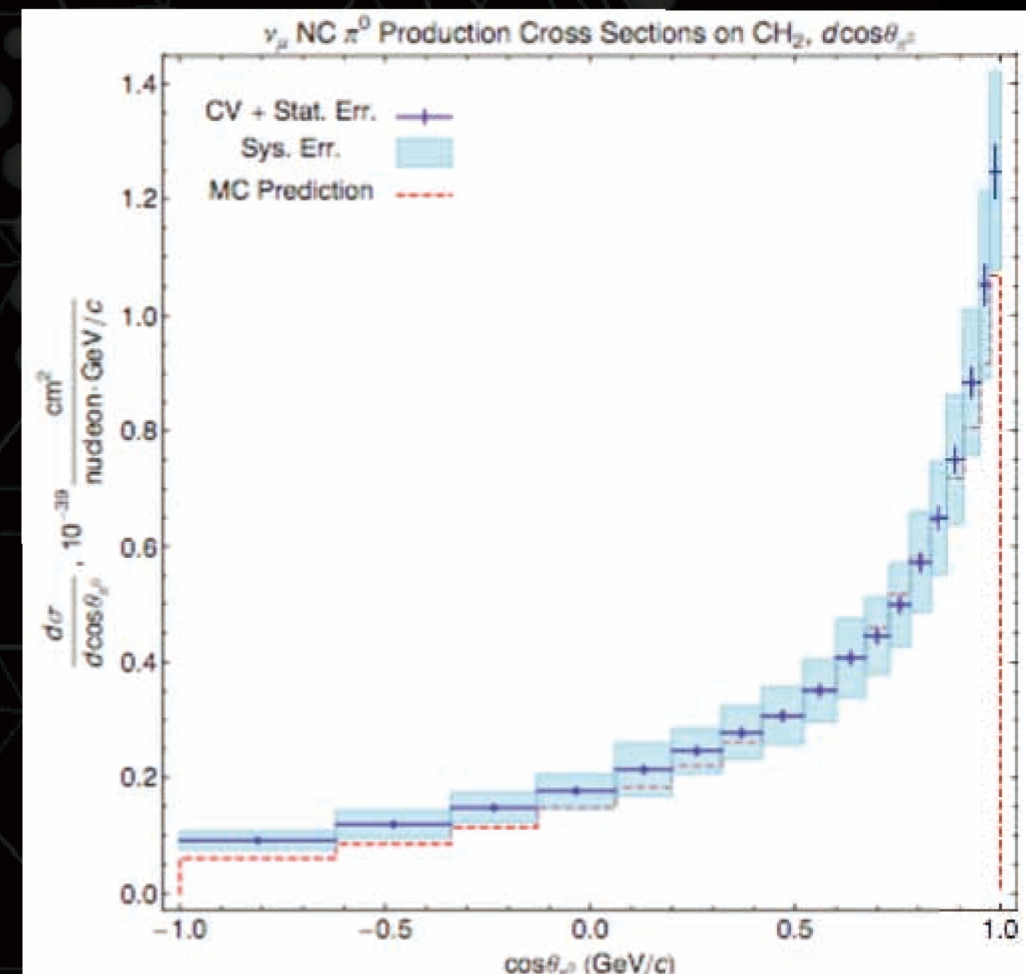


good data-MC agreement in variables not used in tuning!

Tuning $\bar{\nu}_\mu\, \pi^0$ MC

Phys.Rev.D ***81*** *013005 (2010)*



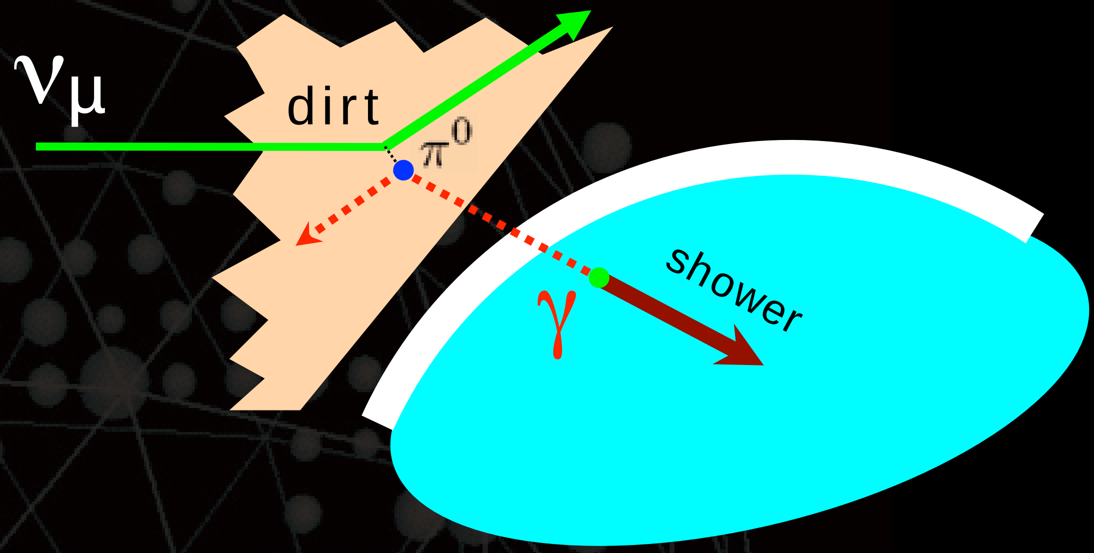


Use same techniques to tune MC model in antineutrino mode

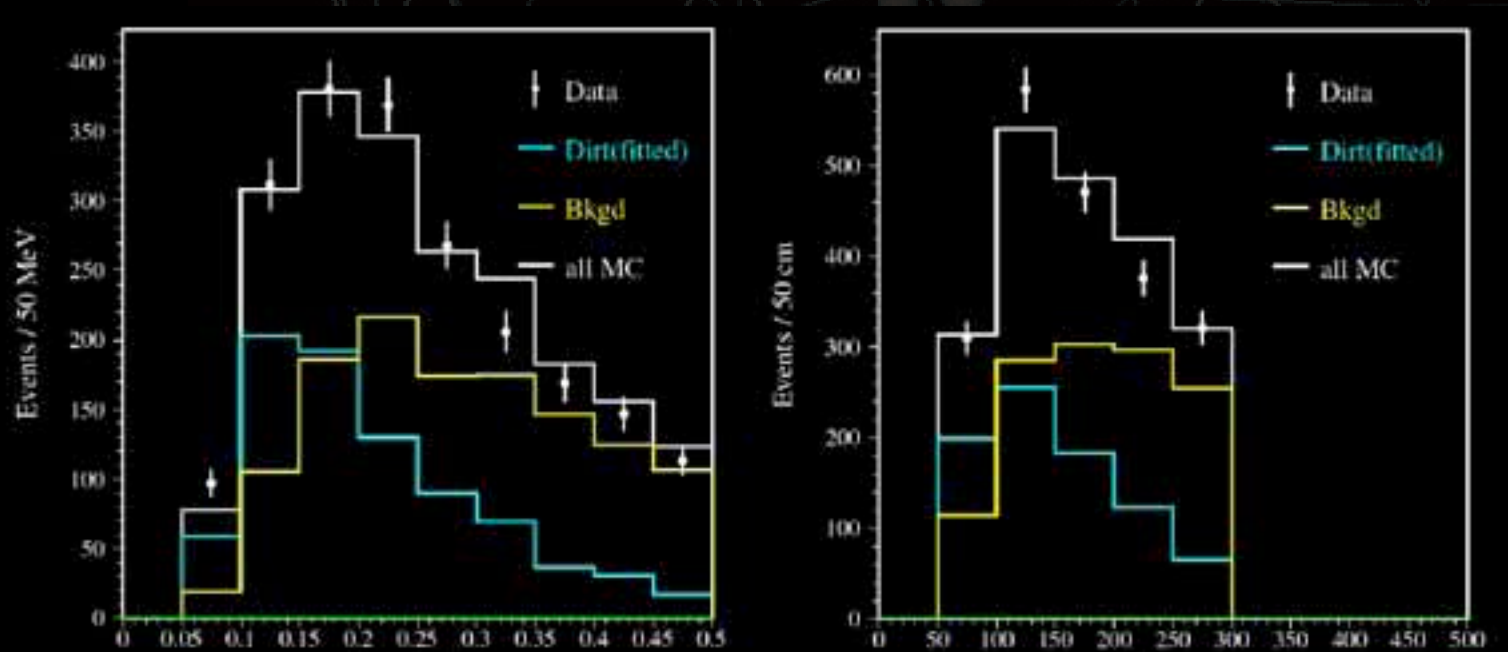
Also produced POT-normalised cross sections for NCπ^0 production by neutrinos and antineutrinos

"Dirt" Backgrounds

- Neutrinos interacting outside detector can cause BGs
  - n, γ enter detector and convert
- Events pile up at low energy near edge of tank
- Measure directly with "dirt enhanced" sample

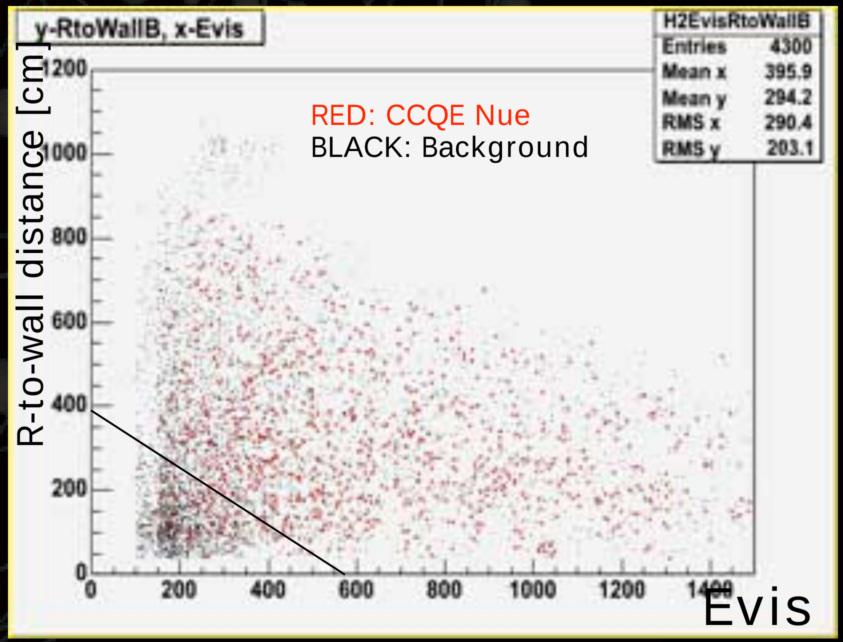


results from dirt-enhanced fits



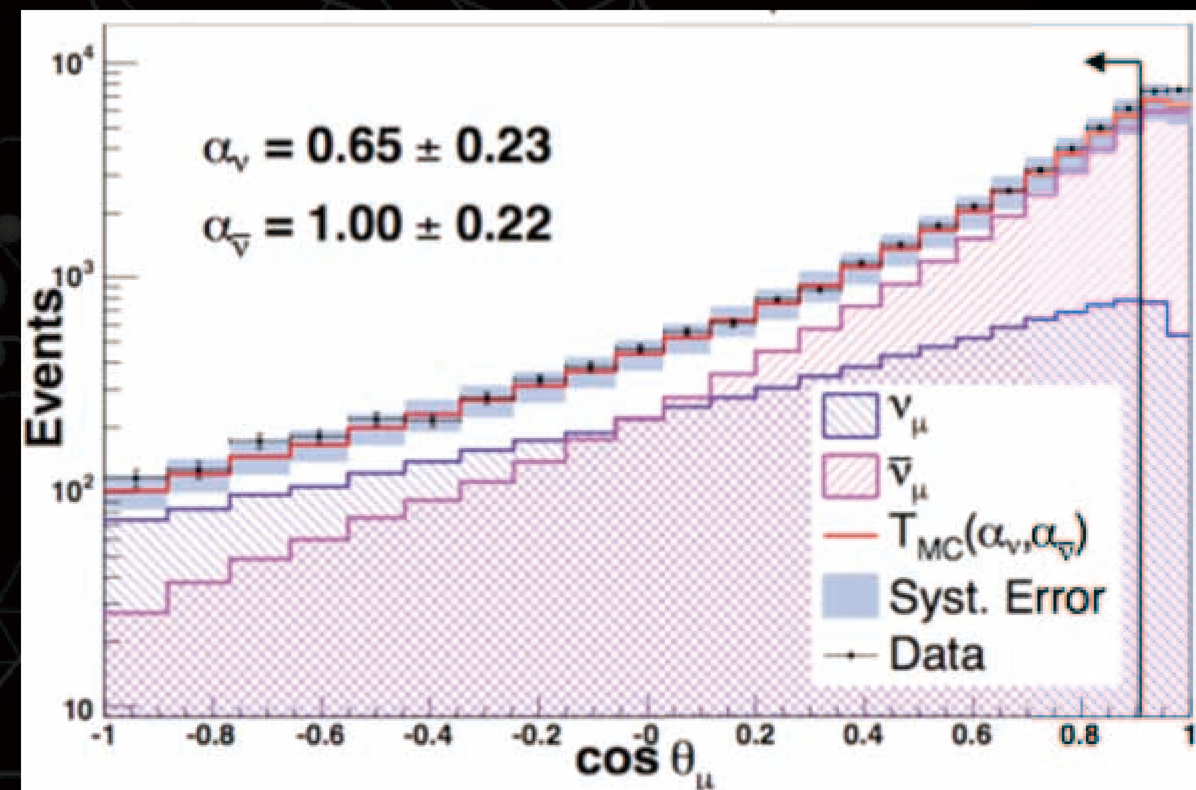
visible energy (GeV)   dist to tank wall along track (cm)

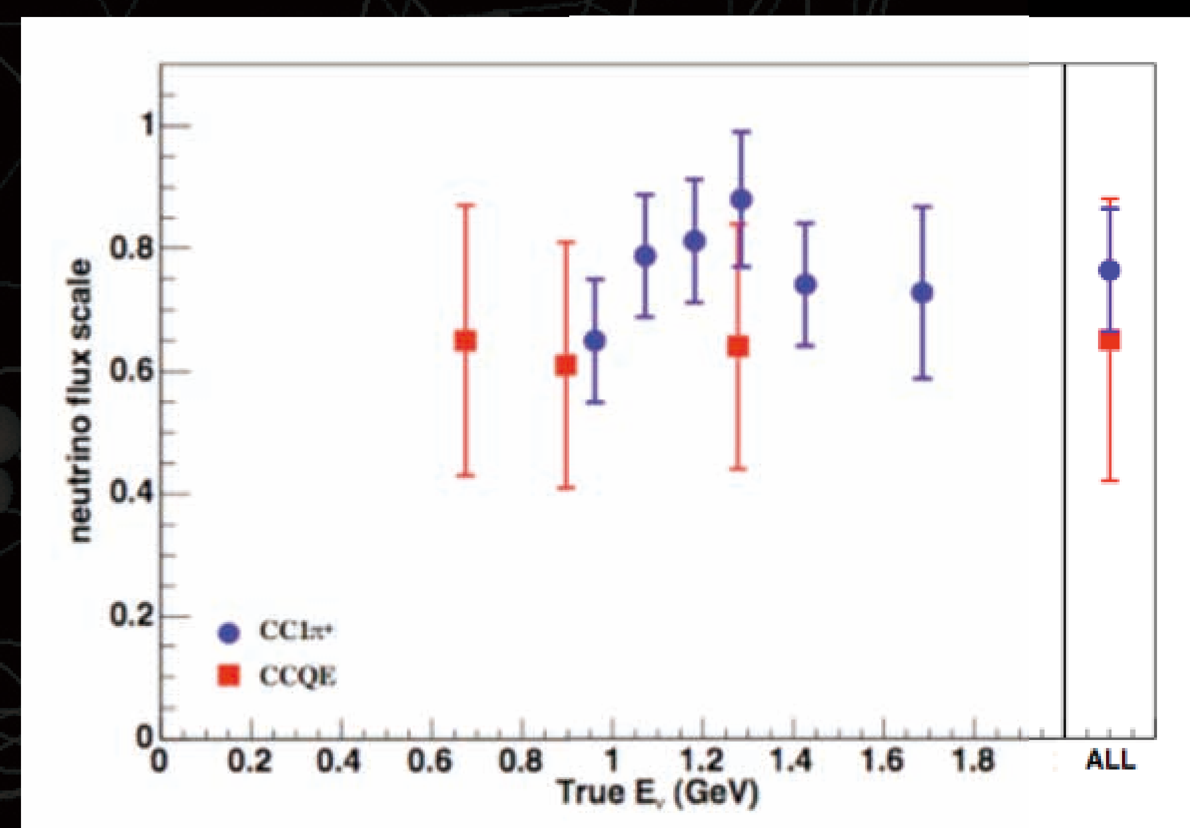
New 2D dirt cut



WS backgrounds

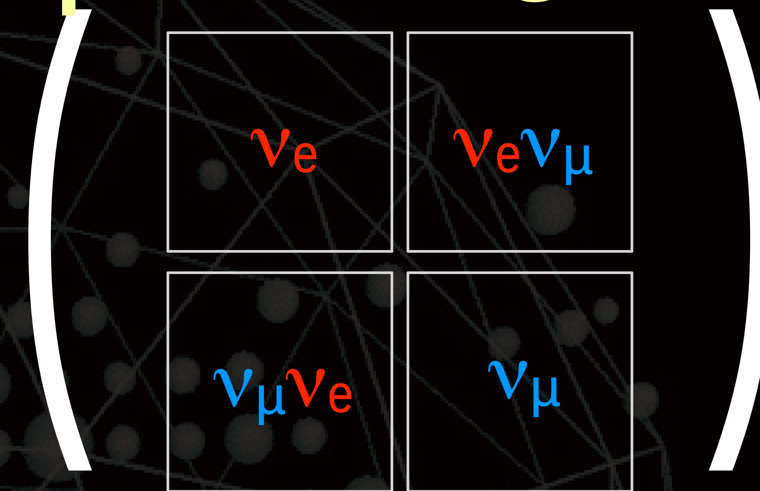
J. Grange





- Use two distinct and complementary data samples to constrain WS fraction
- $\bar{\nu}$ CCQE distribution has different angular distribution than ν events
  - helicity is different!
- $CC1\pi^{+}$ events stem almost entirely from nu events, not $\bar{\nu}$
- Result: WS BG prediction reduced by ~30%

Combined fit of ν_μ & ν_e data



- For each Eν bin i,

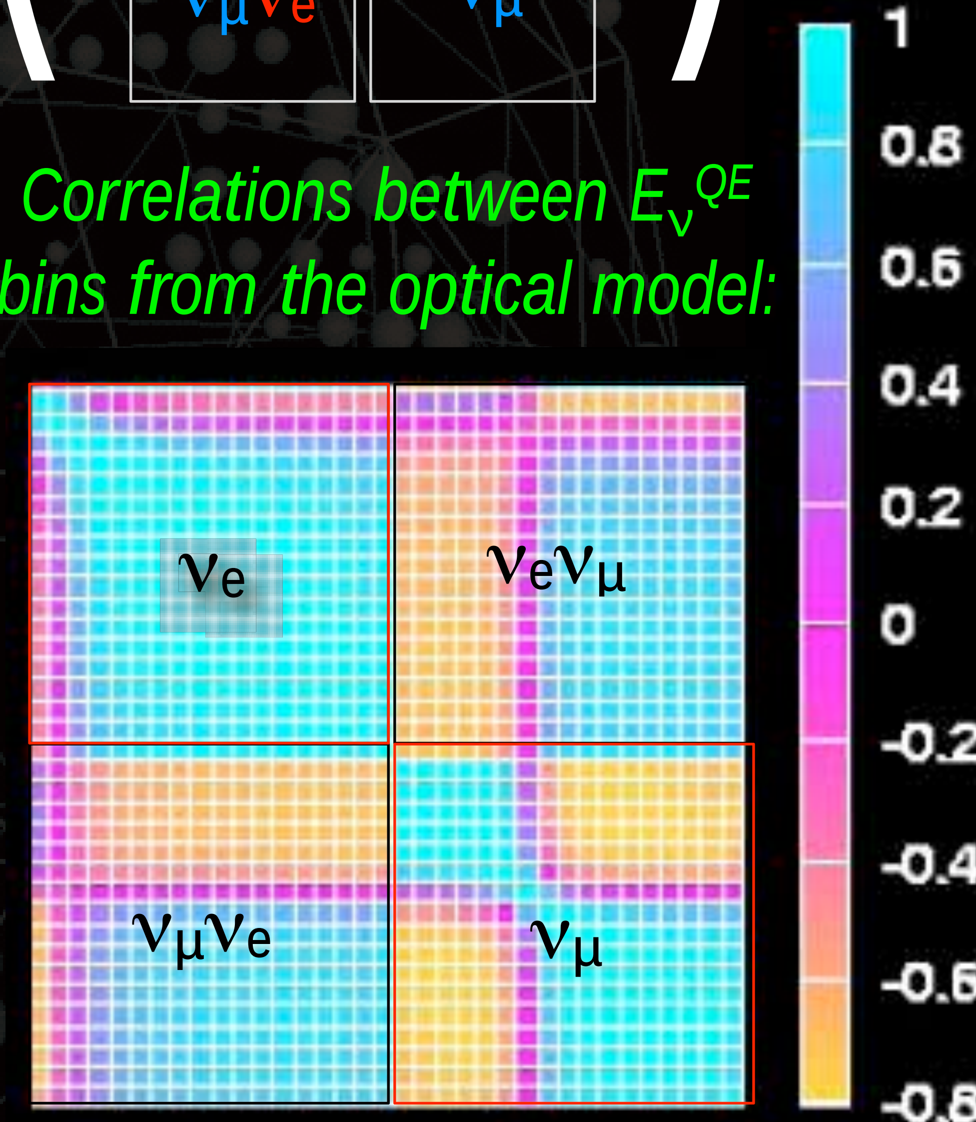
$$\Delta_i = N_i^{DATA} - N_i^{MC}$$

- Raster-scan in Δm^2 and $\sin^2 2\theta_{\mu e}$ to calculate -2ln*L* over ν_e and ν_μ bins

$$-2\ln(\mathcal{L}) = \vec{\Delta} M^{-1} \vec{\Delta}^T + \ln(|M|)$$

- Systematic error matrix includes uncertainties for ν_e and ν_μ

Correlations between E_ν^{QE} bins from the optical model:

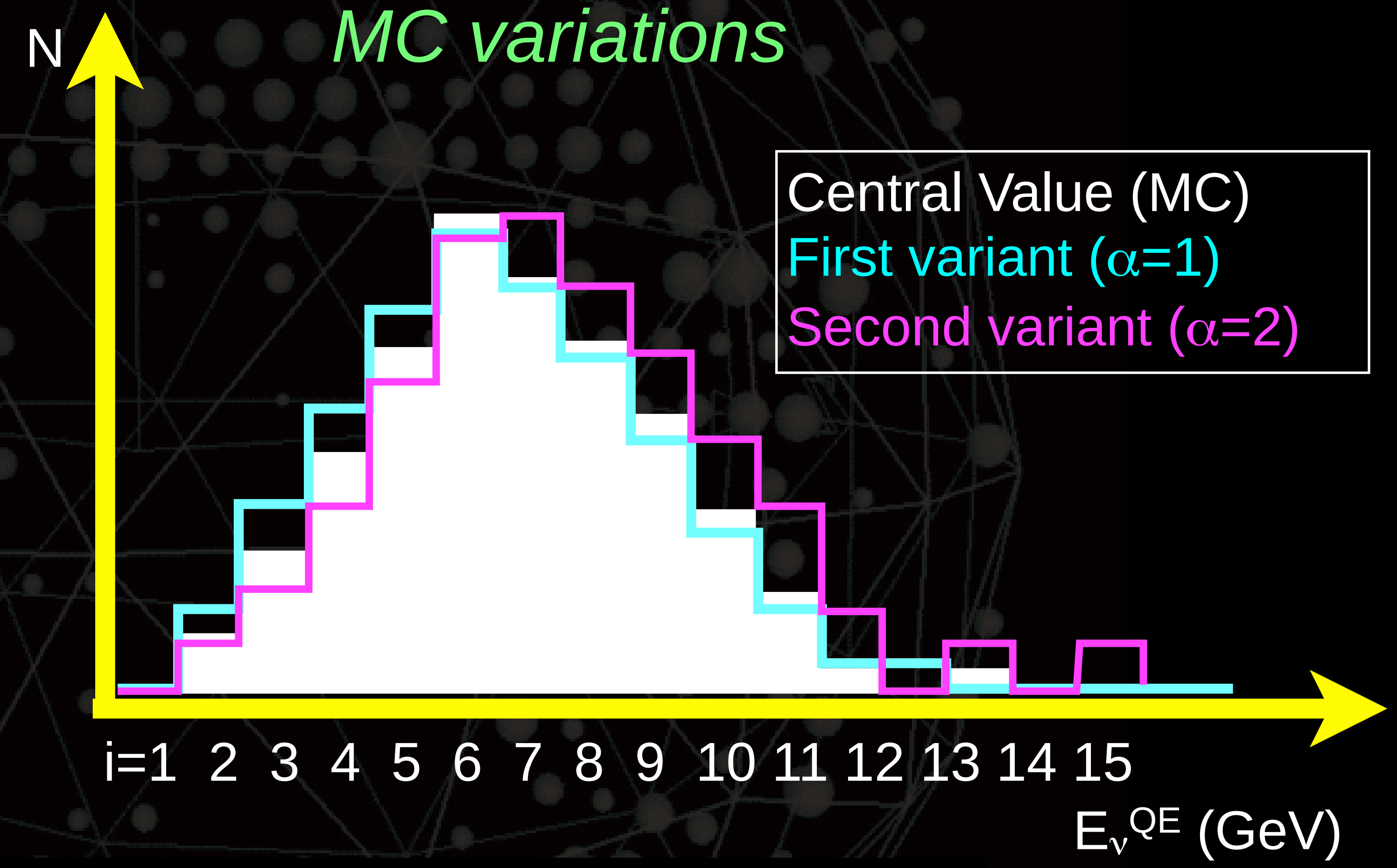


ν_μ data plays role of near detector

Error Matrix

- Use MC variations to study systematic uncertainties
- Vary underlying parameters and compare to “central value” MC
- Total error matrix is sum of individual matrices

Example of Eν distributions for several MC variations

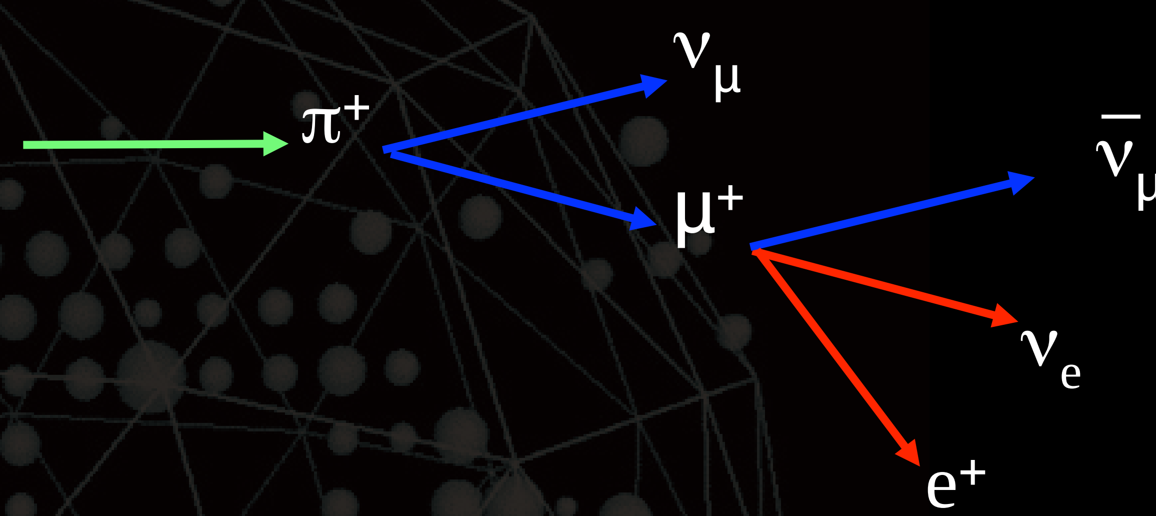


$$M_{ij} = \frac{1}{N_\alpha} \sum_{\alpha=1}^{N_\alpha} (N_i^\alpha - N_i^{MC})(N_j^\alpha - N_j^{MC})$$

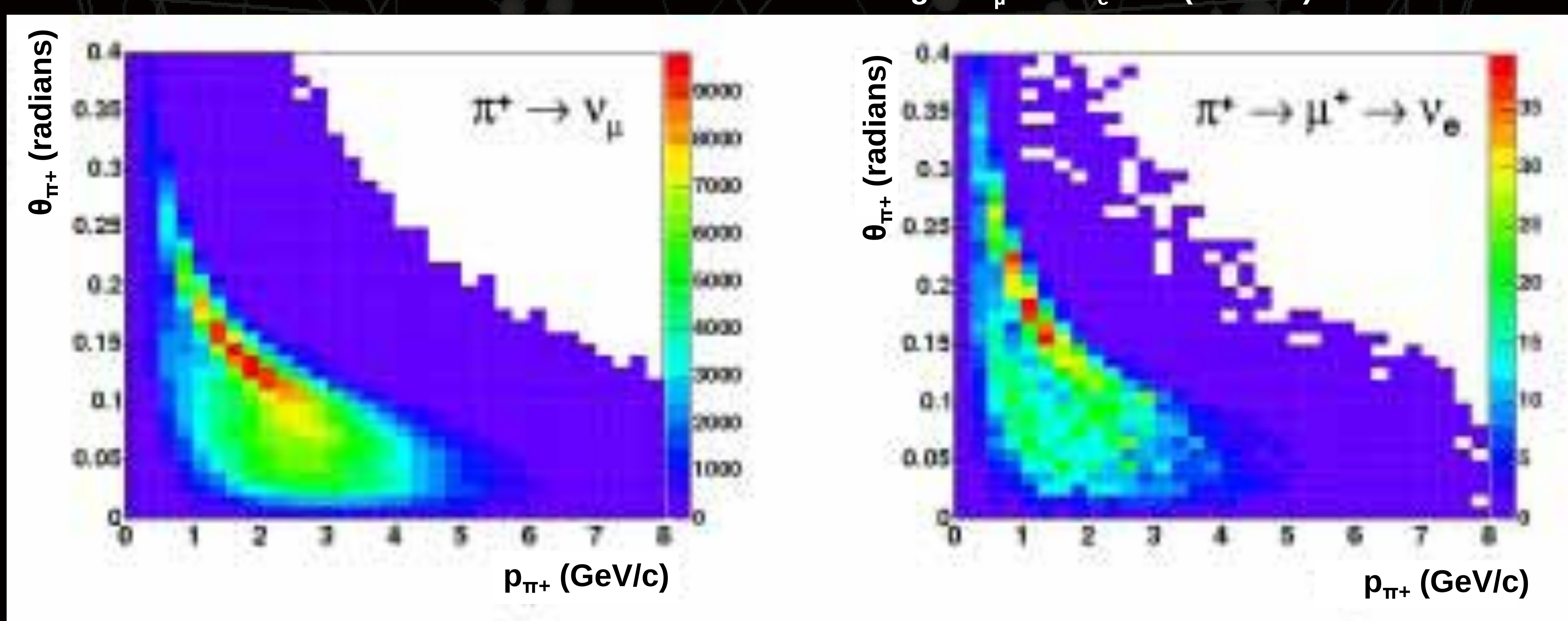
$$\mathcal{M}_{TOT} = \mathcal{M}_\Phi + \mathcal{M}_\sigma + \mathcal{M}_{detector} + \ldots$$

Fit method example

strong correlations between $\bar{\nu}_e$ signal, background, and $\bar{\nu}_\mu$ CCQE sample

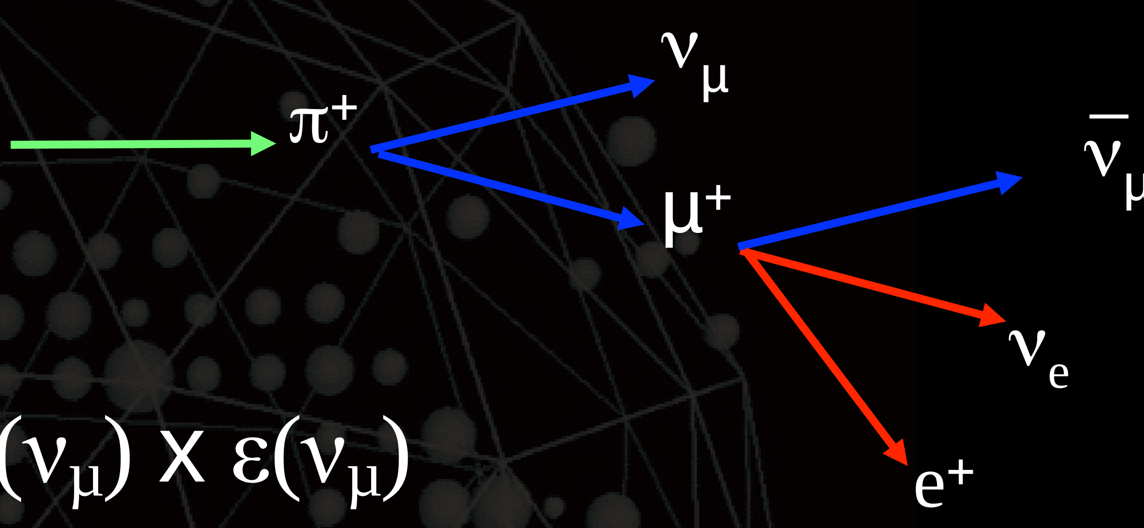


Kinematic distributions of π^+ contributing to ν_μ and ν_e flux (ν mode)



Fit method example

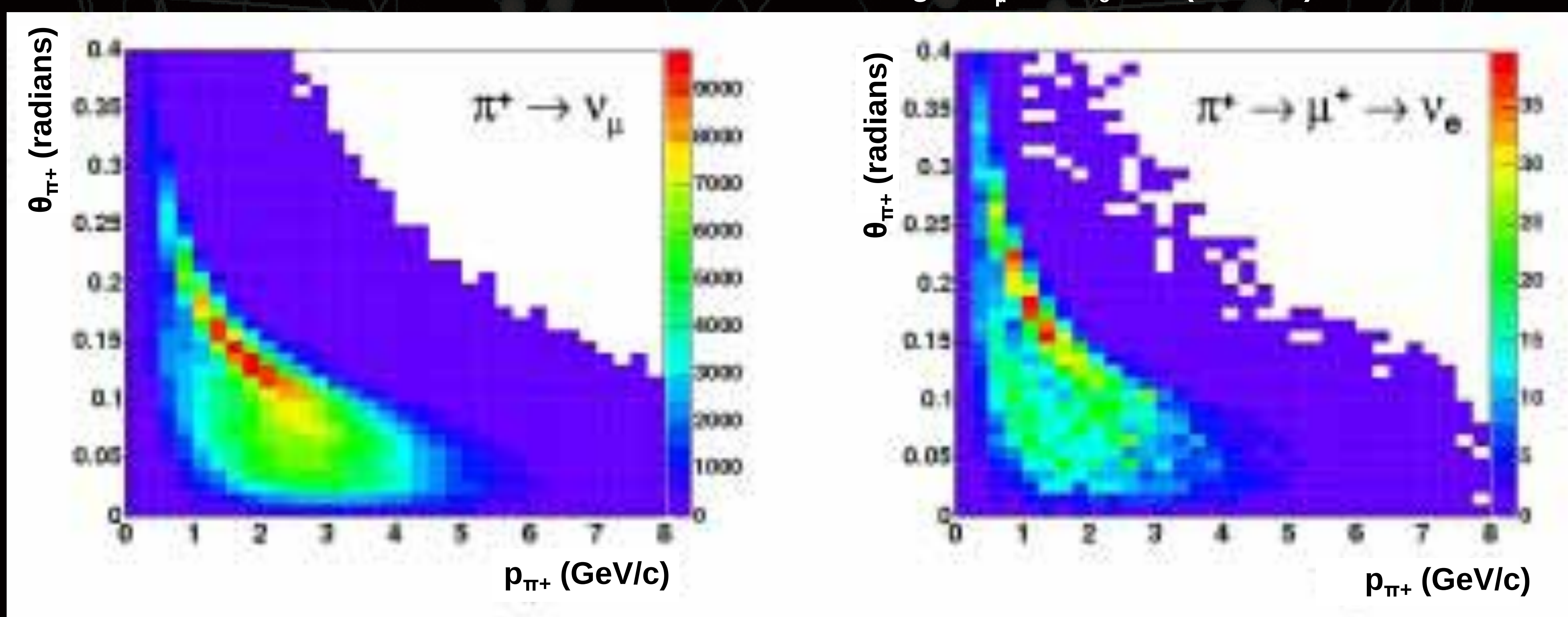
strong correlations between $\bar{\nu}_e$ signal, background, and $\bar{\nu}_\mu$ CCQE sample



$$R(\nu_\mu) = \Phi(\nu_\mu) \times \sigma(\nu_\mu) \times \varepsilon(\nu_\mu)$$

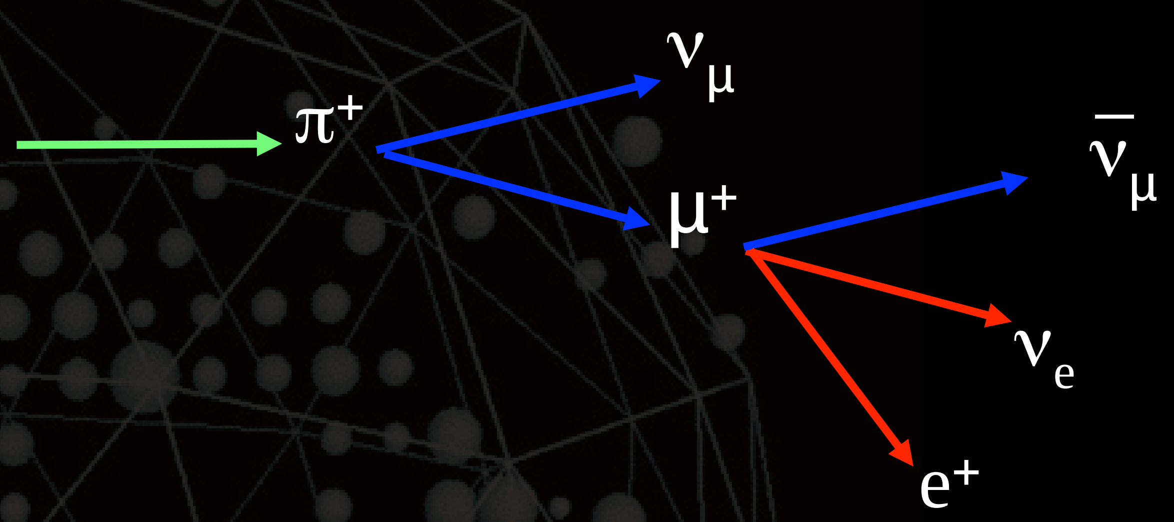
$$R(\nu_e) = \Phi(\nu_e) \times \sigma(\nu_e) \times \varepsilon(\nu_e)$$

Kinematic distributions of π^+ contributing to ν_μ and ν_e flux (ν mode)

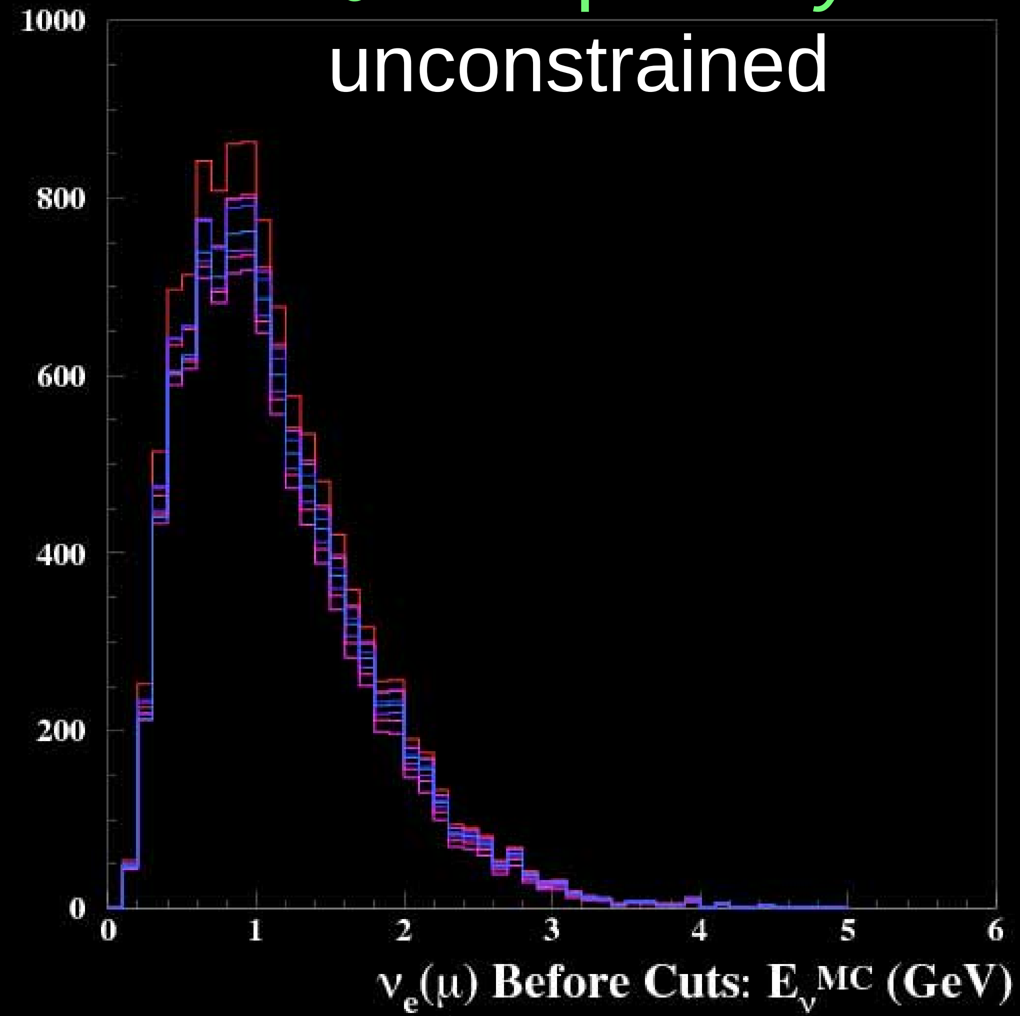


Fit method example

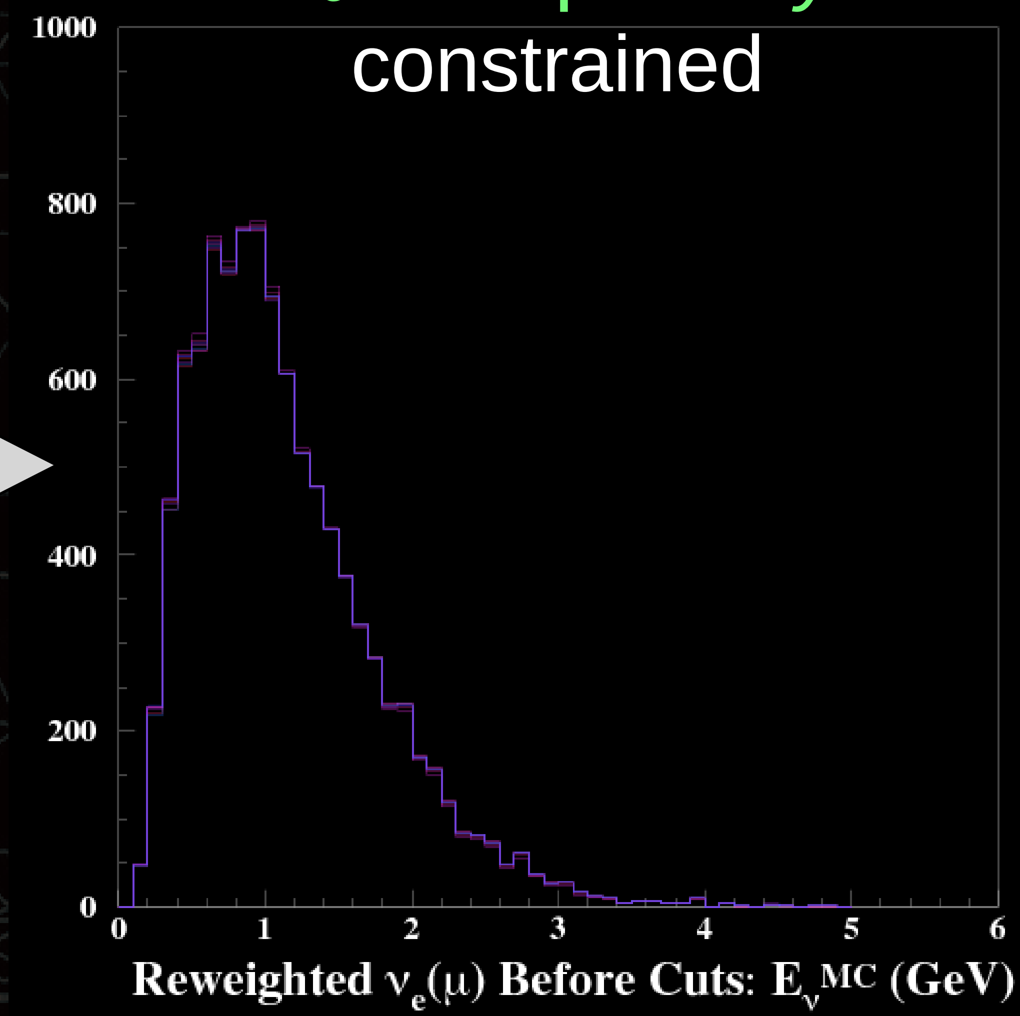
strong correlations between $\bar{\nu}_e$ signal, background, and $\bar{\nu}_\mu$ CCQE sample



ν_e from μ decay



ν_e from μ decay



Fit method example

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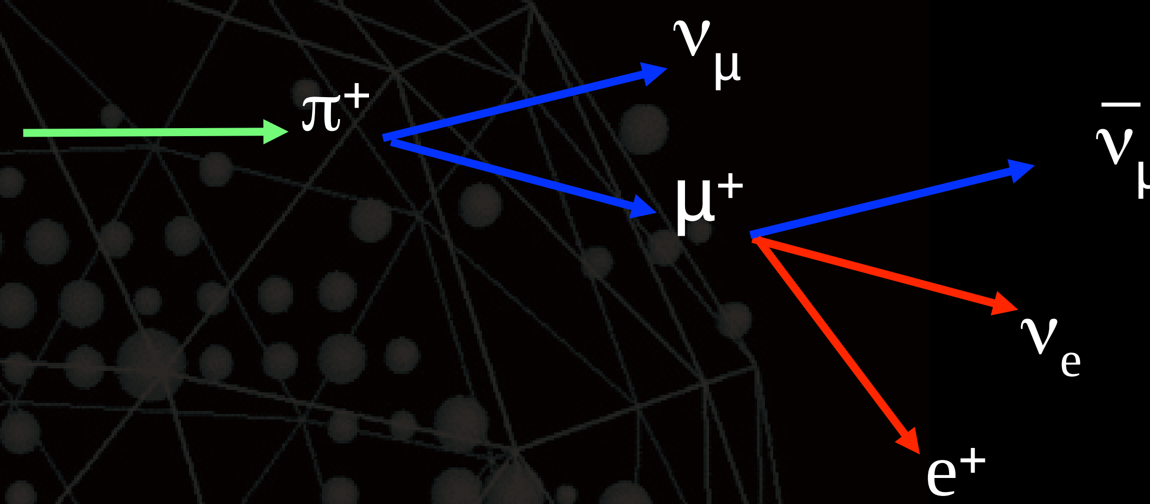
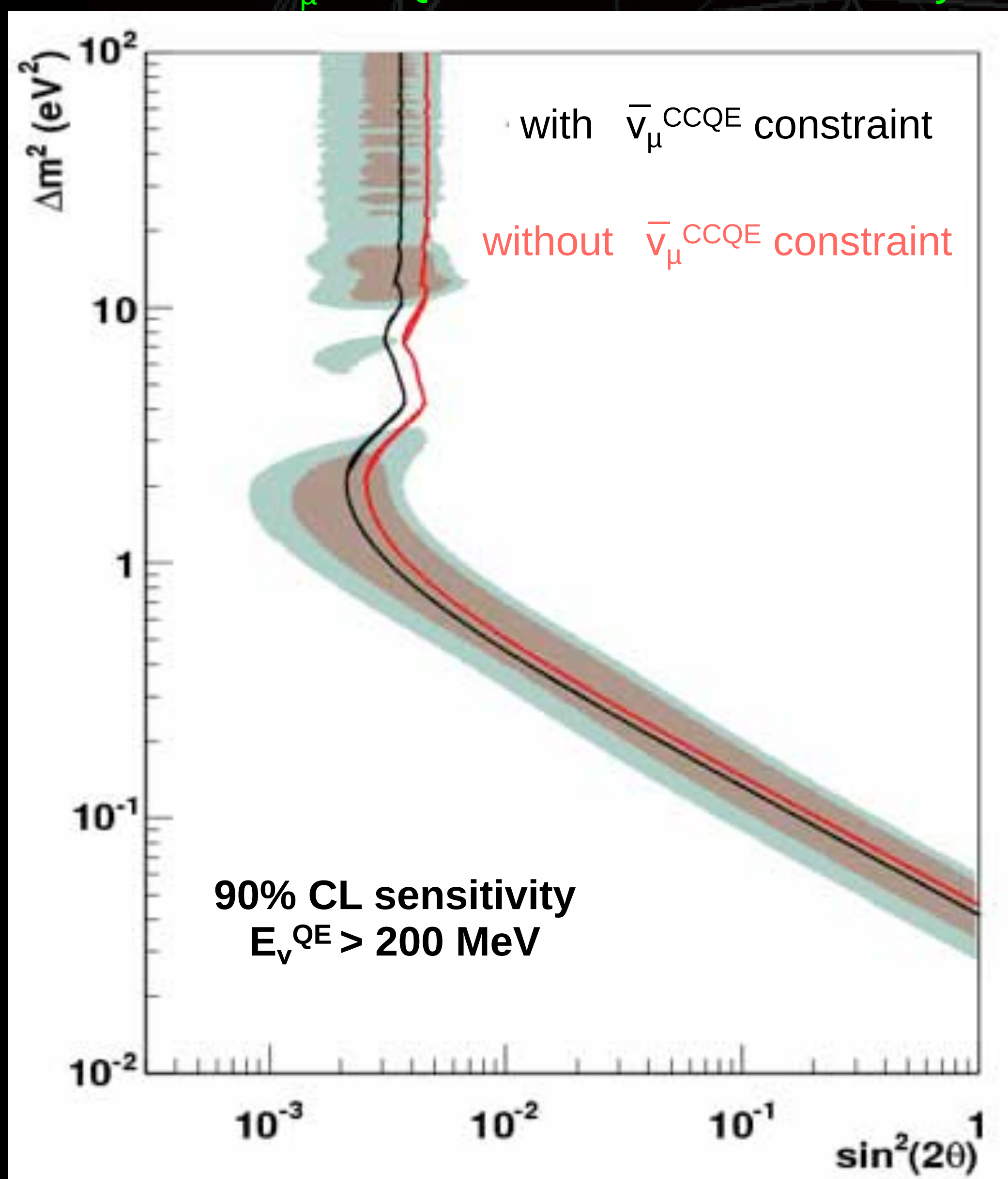


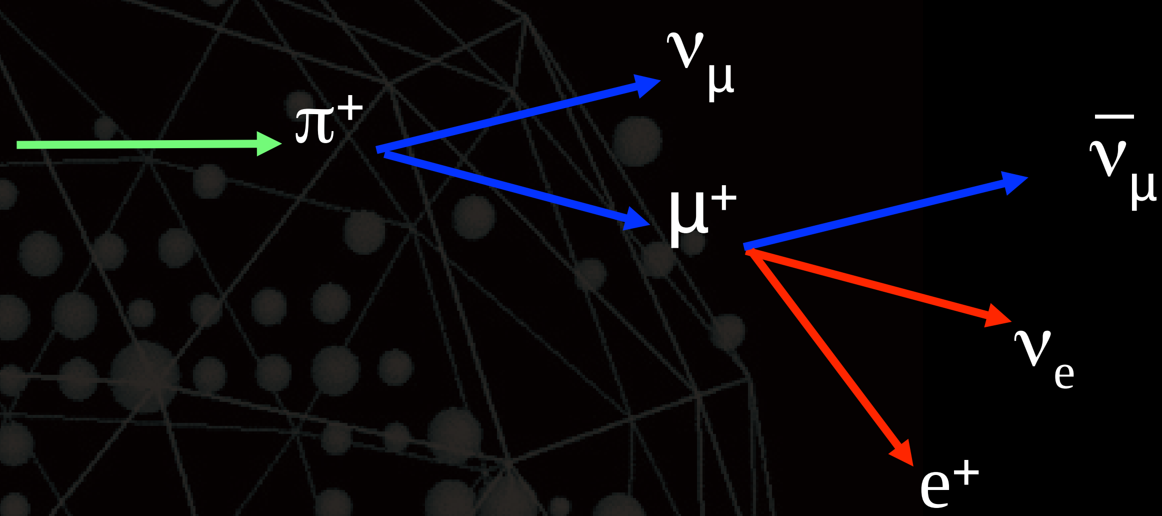
Effect of $\bar{\nu}_\mu$ CCQE constraint on sensitivity



←improves sensitivity and provides stronger constraint to oscillations

Fit method example

strong correlations between $\bar{\nu}_e$ signal, background, and $\bar{\nu}_\mu$ CCQE sample



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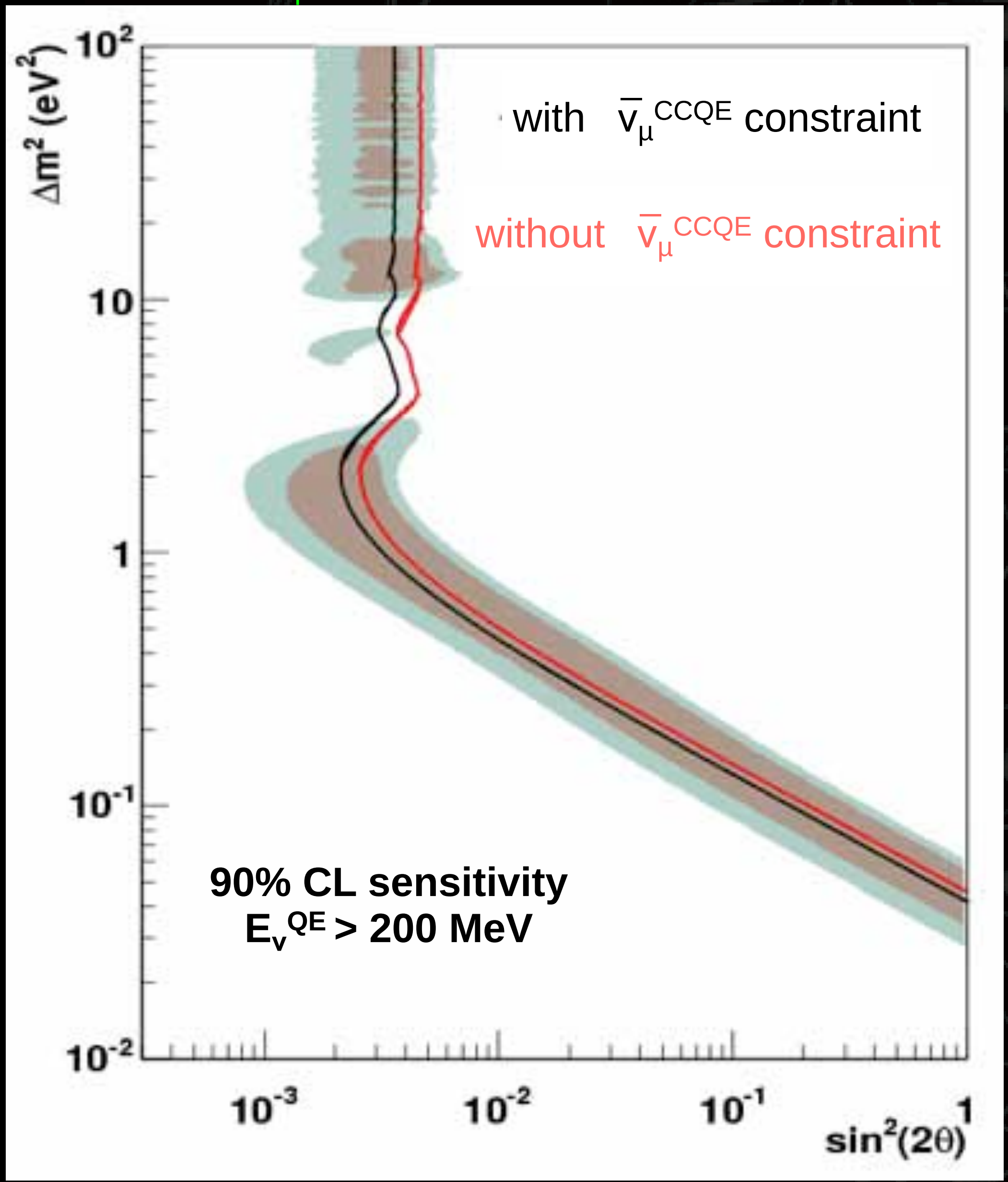


$$R(\nu_\mu) = \Phi(\nu_\mu) \times \sigma(\nu_\mu) \times \varepsilon(\nu_\mu)$$

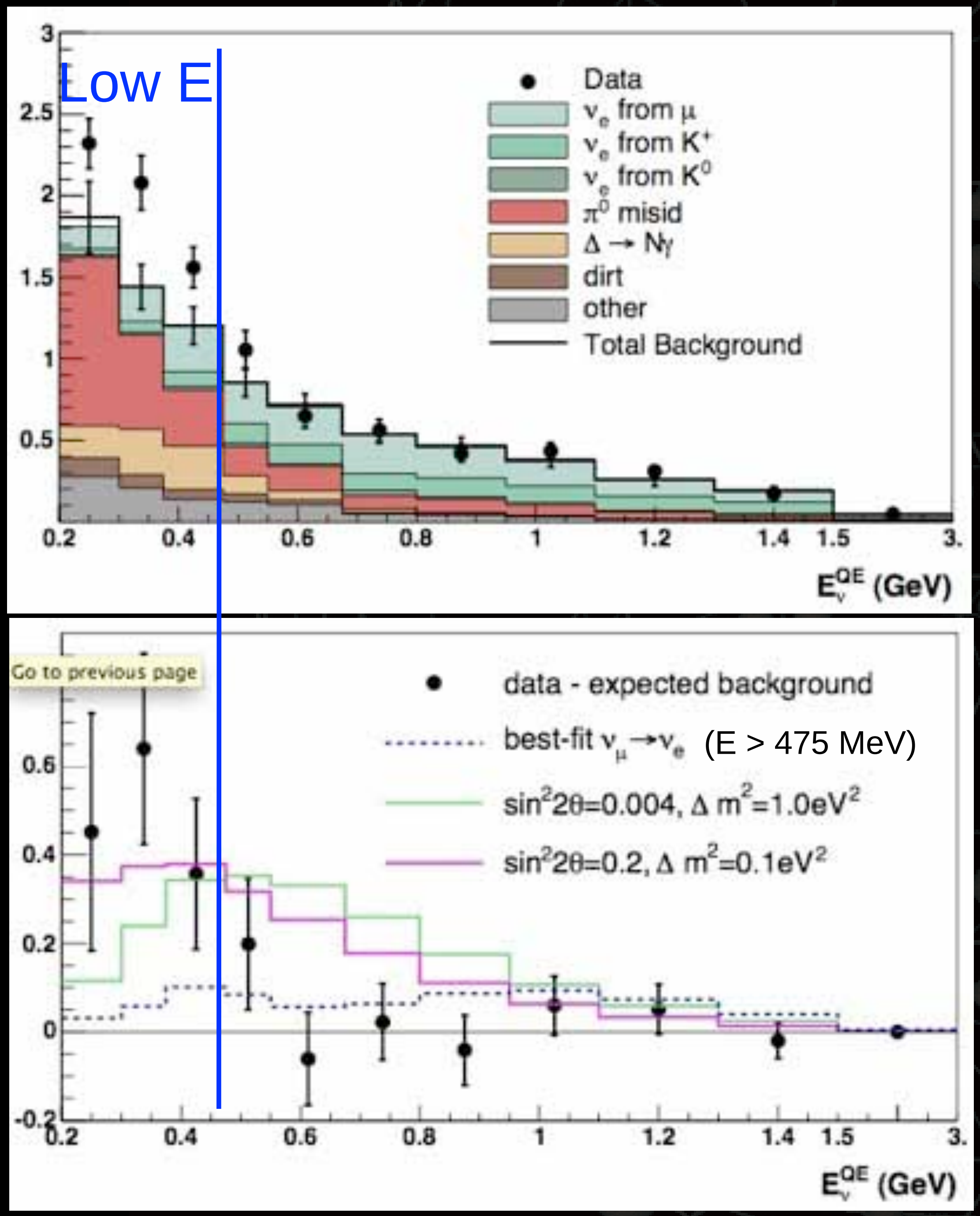
$$R(\nu_e) = \Phi(\nu_e) \times \sigma(\nu_e) \times \varepsilon(\nu_e)$$

←improves sensitivity and provides stronger constraint to oscillations

BG systematic errors (%)

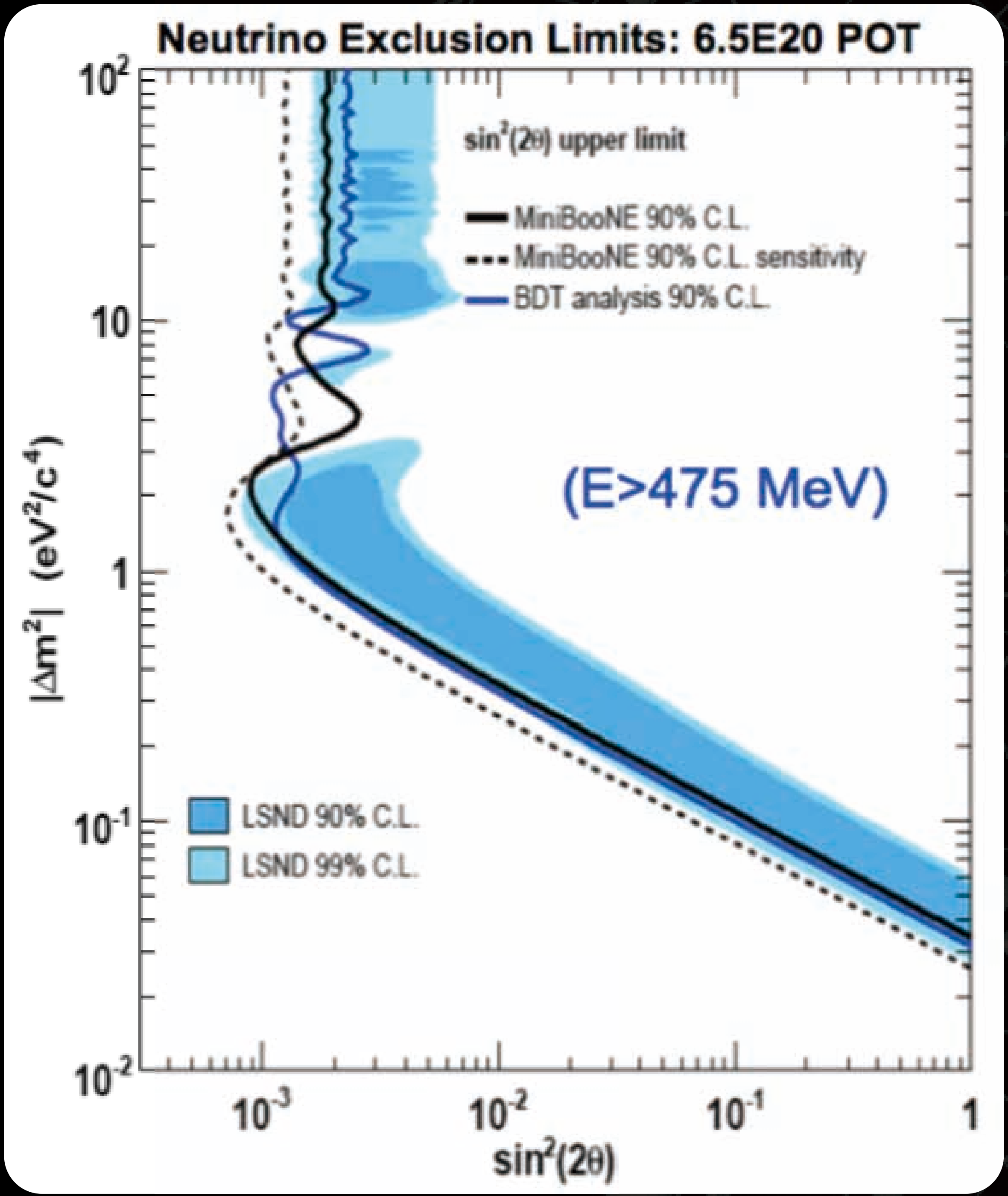
	Neutrino		Antineutino	
Source	**200-475**	**475-1100**	**200-475**	**475-1100**
Flux from π^+/μ^+ decay	0.4	0.9	1.8	2.2
Flux from π^-/μ^- decay	3.0	2.3	0.1	0.2
Flux from K^+ decay	2.2	4.7	1.4	5.7
Flux from K^- decay	0.5	1.2	-	-
Flux from K^0 decay	1.7	5.4	0.5	1.5
Target and beam models	1.7	3.0	1.3	2.5
ν cross section	6.5	13.0	5.9	11.9
NC π^0 yield	1.5	1.3	1.4	1.9
Hadronic interactions	0.4	0.2	0.8	0.3
External interactions (dirt)	1.6	0.7	0.8	0.4
Optical model	8.0	3.7	8.9	2.3
Electronics & DAQ model	7.0	2.0	5.0	1.7
TOTAL (unconstrained)	**13.5**	**16.0**	**12.3**	**14.2**

Reminder: ν_e Search



- Above 475 MeV...
  - Excellent agreement with background predictions
  - Find 408 events, expect 386 ± 20(stat) ± 30(syst)
  - Chi-square probability of 40% in 475-1250 MeV
  - Since this is the region of highest sensitivity to and LSND-like 2ν mixing hypothesis, can use it to exclude that model

Reminder: ν_e Search



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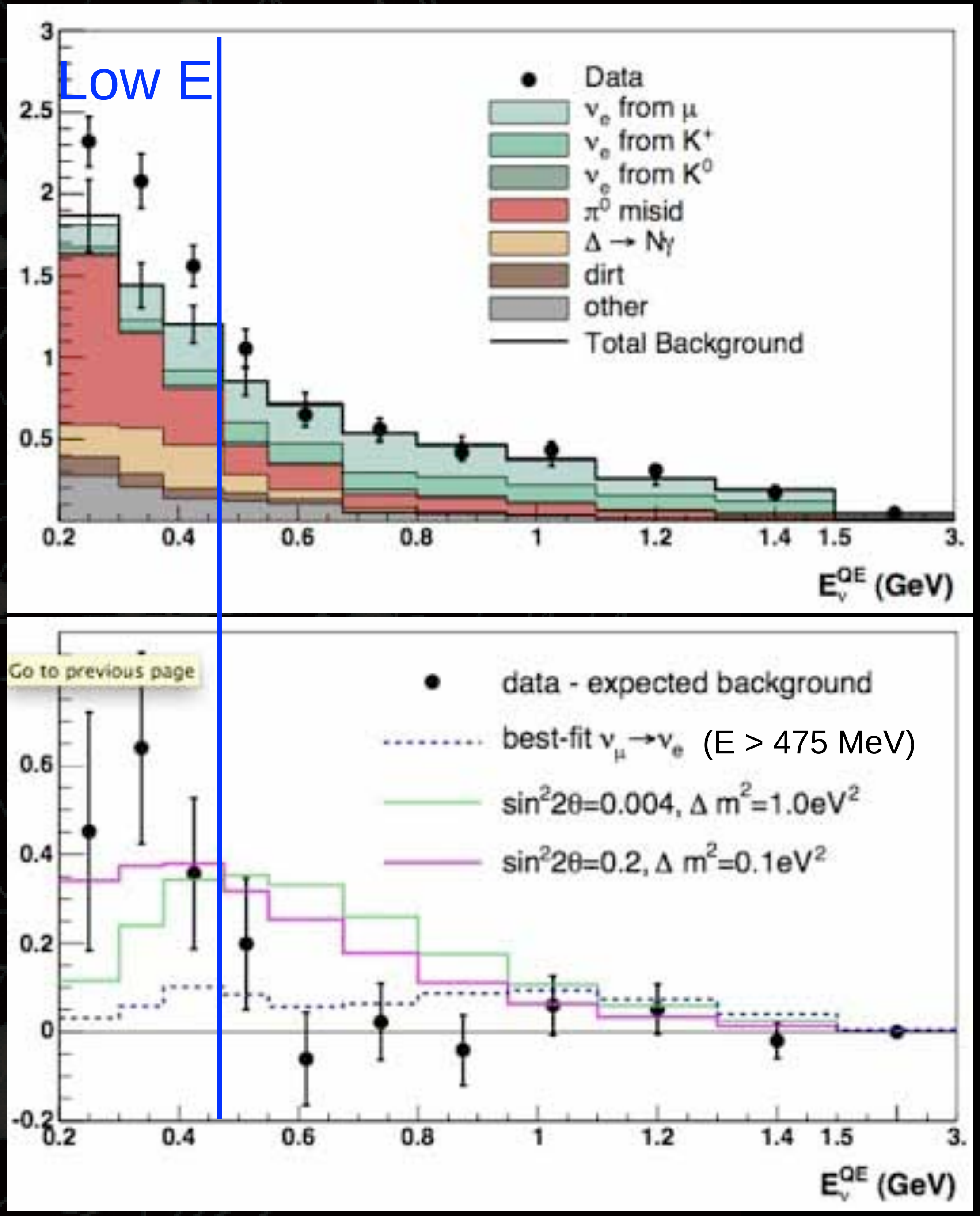
  - Since this is the region of highest sensitivity to and LSND-like 2ν mixing hypothesis, can use it to exclude that model

Reminder: ν_e Search

- Below 475 MeV...
  - Find 544 events, expect 415 ± 20(stat) ± 39(syst)
  - Excess is 128 ± 20(stat) ± 39 (syst) events

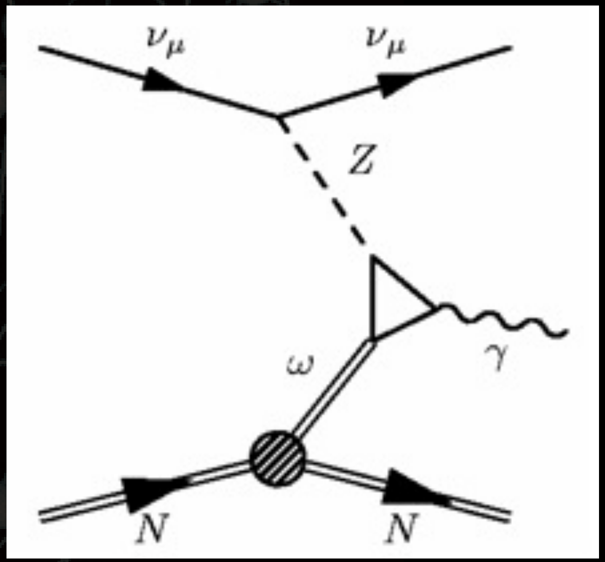
How much would BGs need to fluctuate to produce excess?



BG Source	BG Counts	Increase Needed	Syst Error*
ν_μ CCQE	26.4	487%	~30%
NC π^0	181.3	71%	~20%
Rad. Δ	67.0	192%	~25%
ν_e (μ)	58.1	222%	~25%
ν_e (K)	17.4	740%	~40%
dirt	23.8	544%	~15%

low energy excess

- Several possible explanations
  - 3+2 with CP violation
    [Maltoni and Schwetz, hep-ph0705.0107 ; G. K., NuFACT 07 conference]
  - Anomaly mediated photon production
    [Harvey, Hill, and Hill, hep-ph0708.1281]
  - New light gauge boson
    [Nelson, Walsh, Phys. Rev. D 77, 033001 (2008)]
  - …

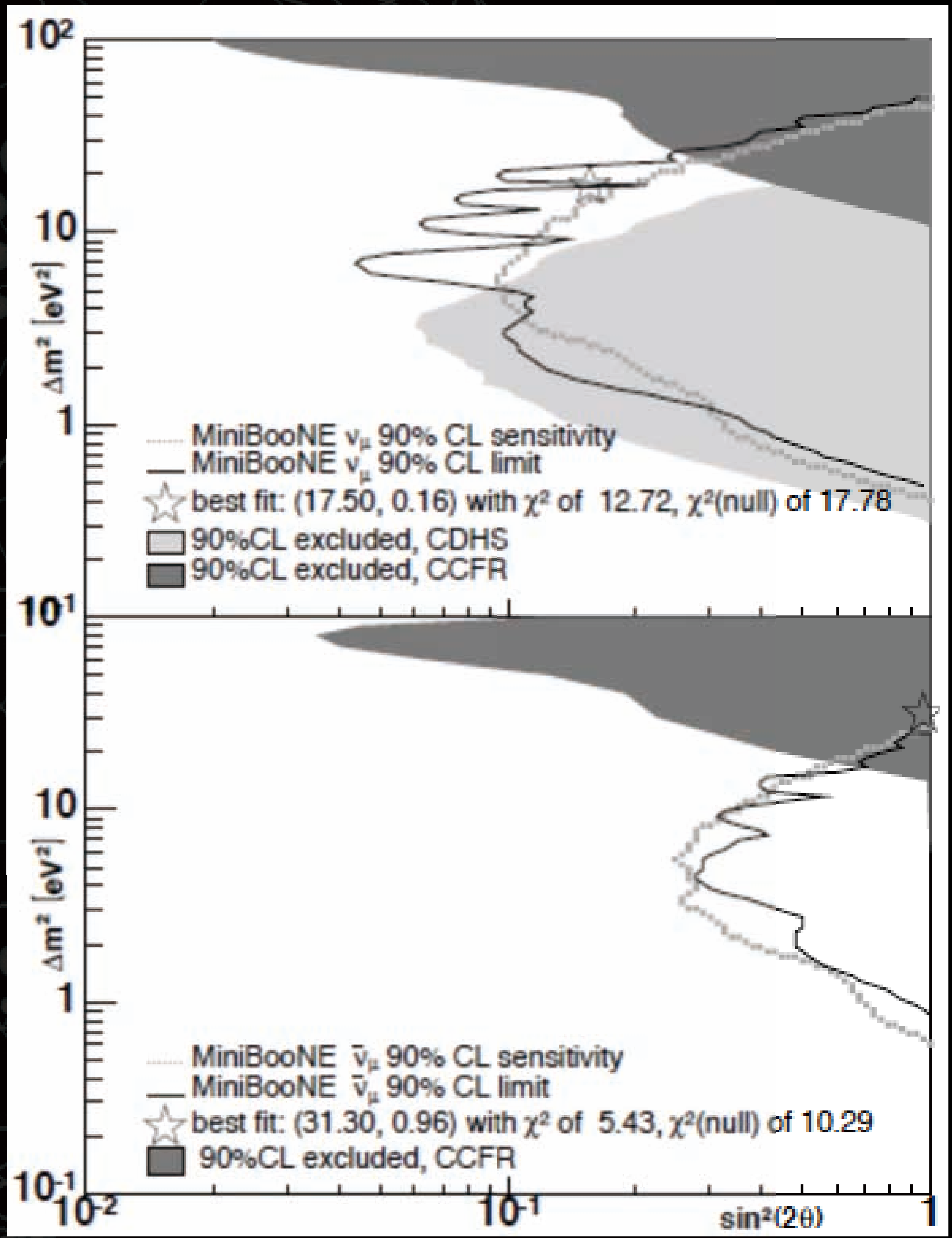


- Some have concrete predictions for MiniBooNE antineutrino mode running

ν_μ disappearance

PRL103(2009)061802

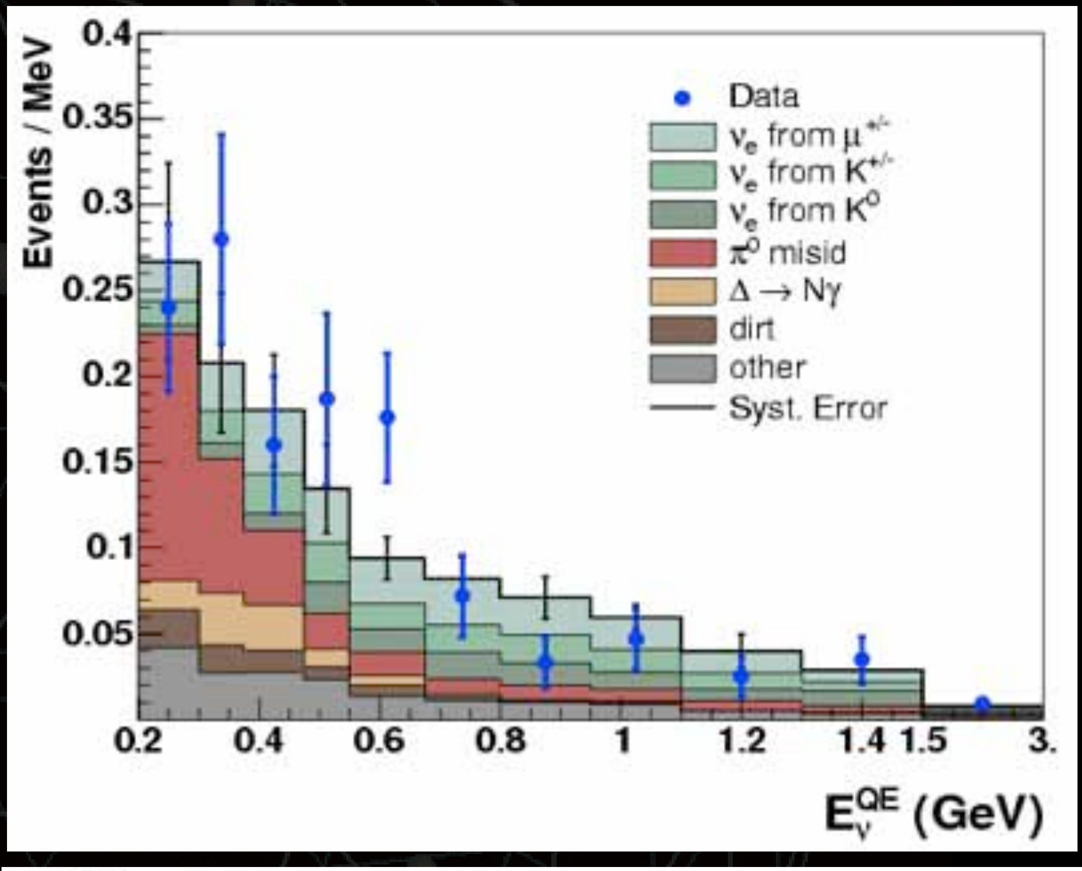
- ν_μ and $\bar{\nu}_\mu$ disappearance oscillation
- test is done by shape-only fit for data and MC with massive neutrino oscillation model.
- MiniBooNE can test unexplored region by past experiments, especially there is no tests for antineutrino disappearance between Δm^2=10eV^2 and atmospheric Δm^2

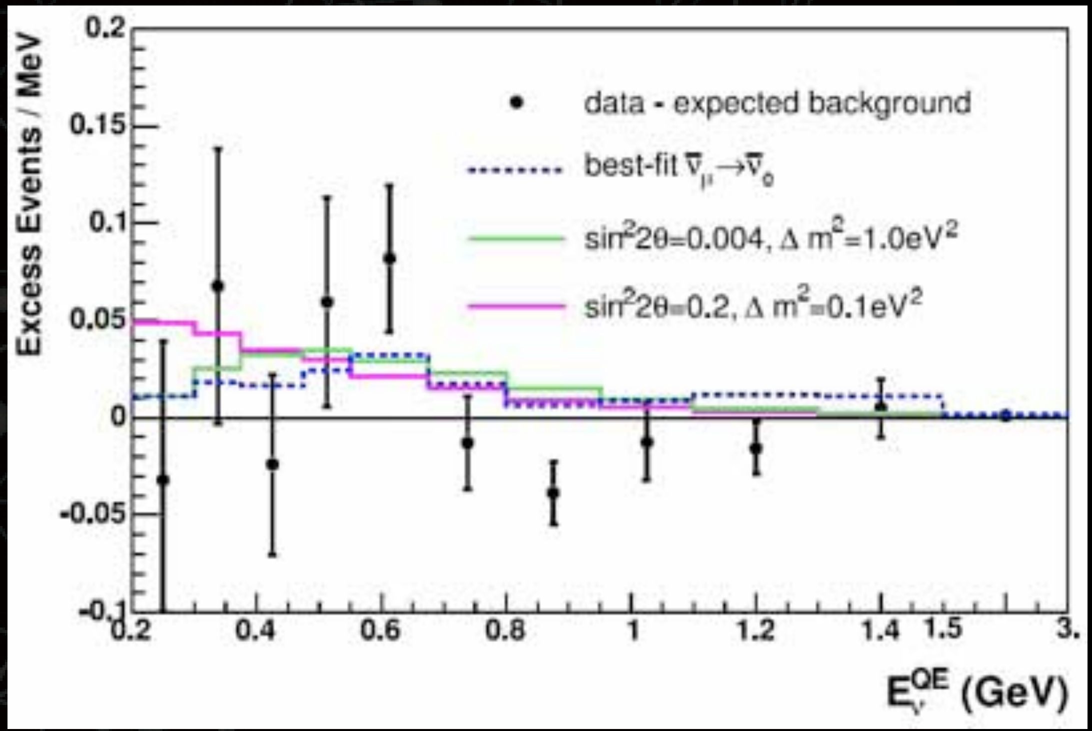


First $\bar{\nu}_e$ results

PRL 103,111801 (2009)

- 3.4E20 POT
- From 200-3000 MeV excess is 4.8 +/- 17.6 (stat+sys) events.
- No significant excess E < 475 MeV.
- Statistically small excess (more of a wiggle) in 475-1250 MeV region
  - Assume neutrinos do not oscillate in fit
  - Stat error too large to distinguish LSND-like from null





First $\bar{\nu}_e$ results

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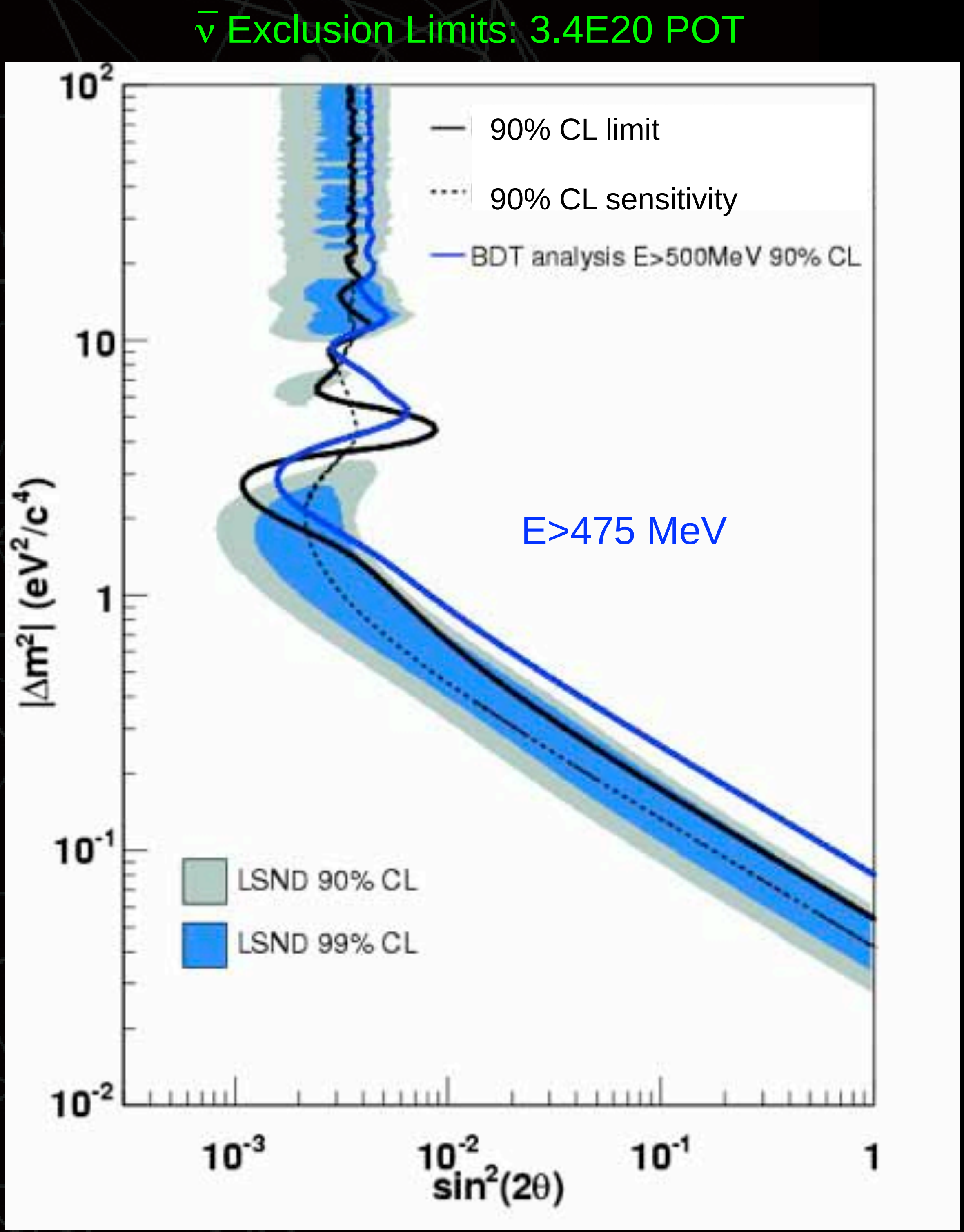
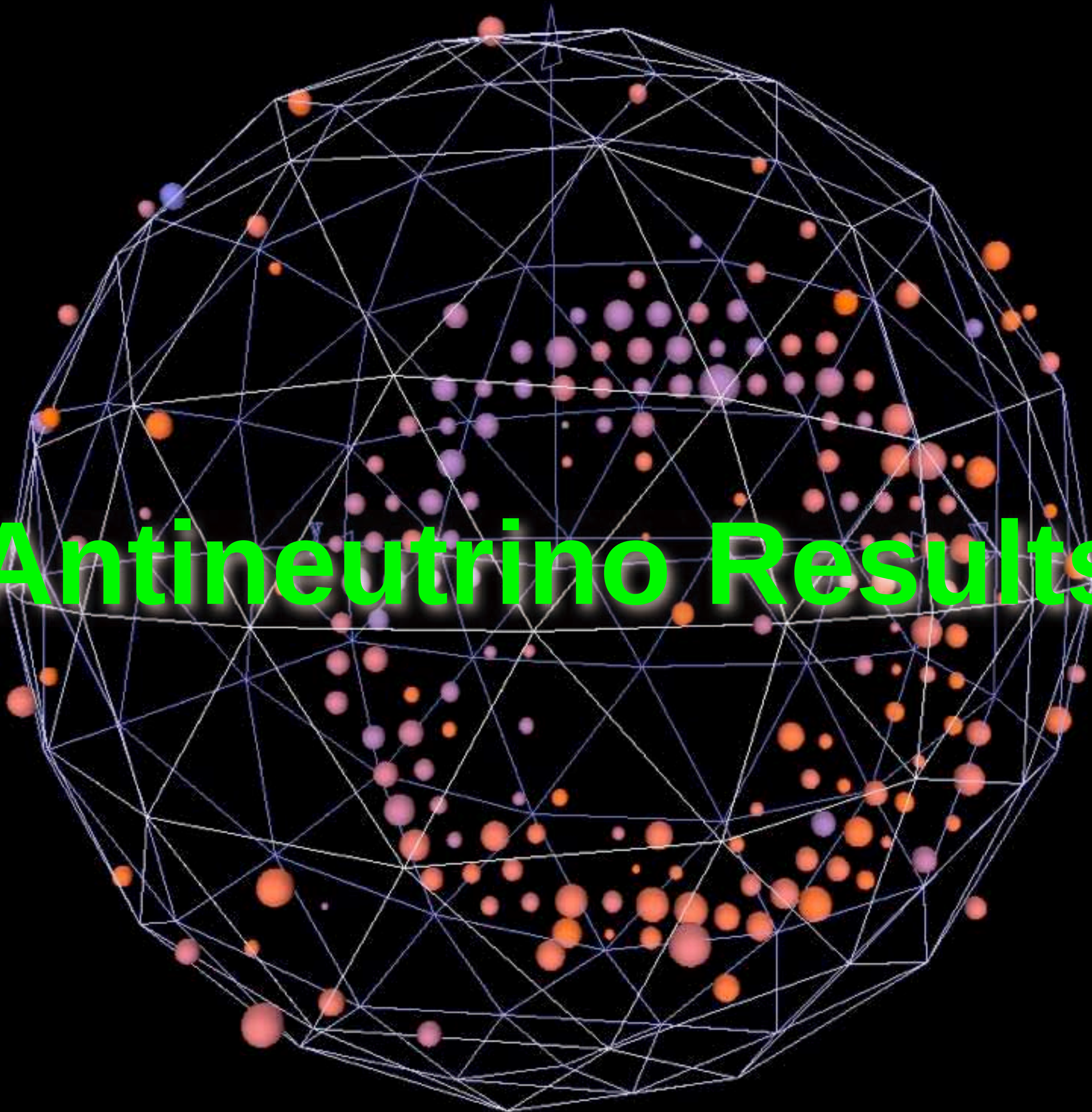


Antineutrino Results

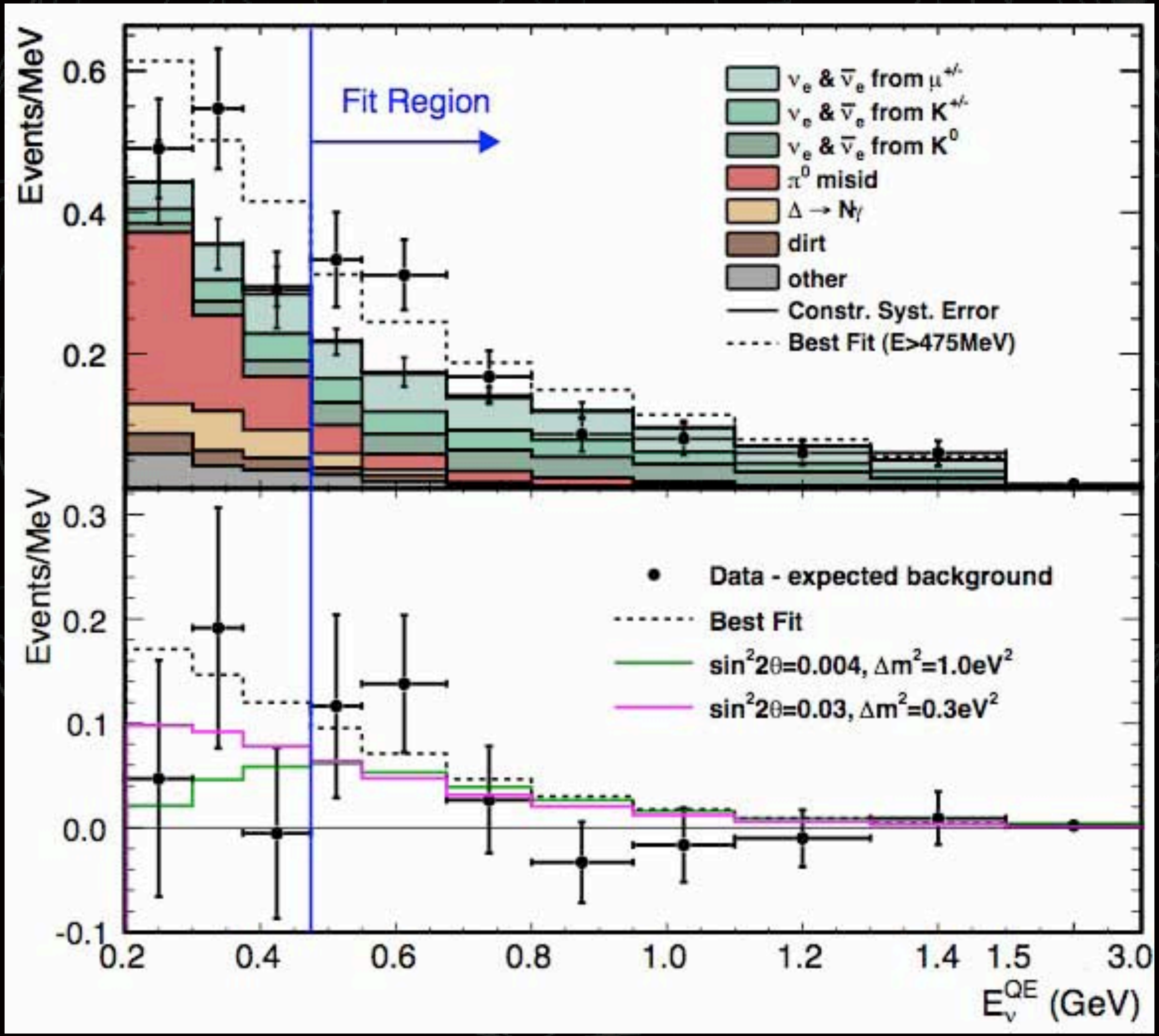


Training for a blind search

MOW c. 2002
(blinded)

$\overline{\nu}_e$ results

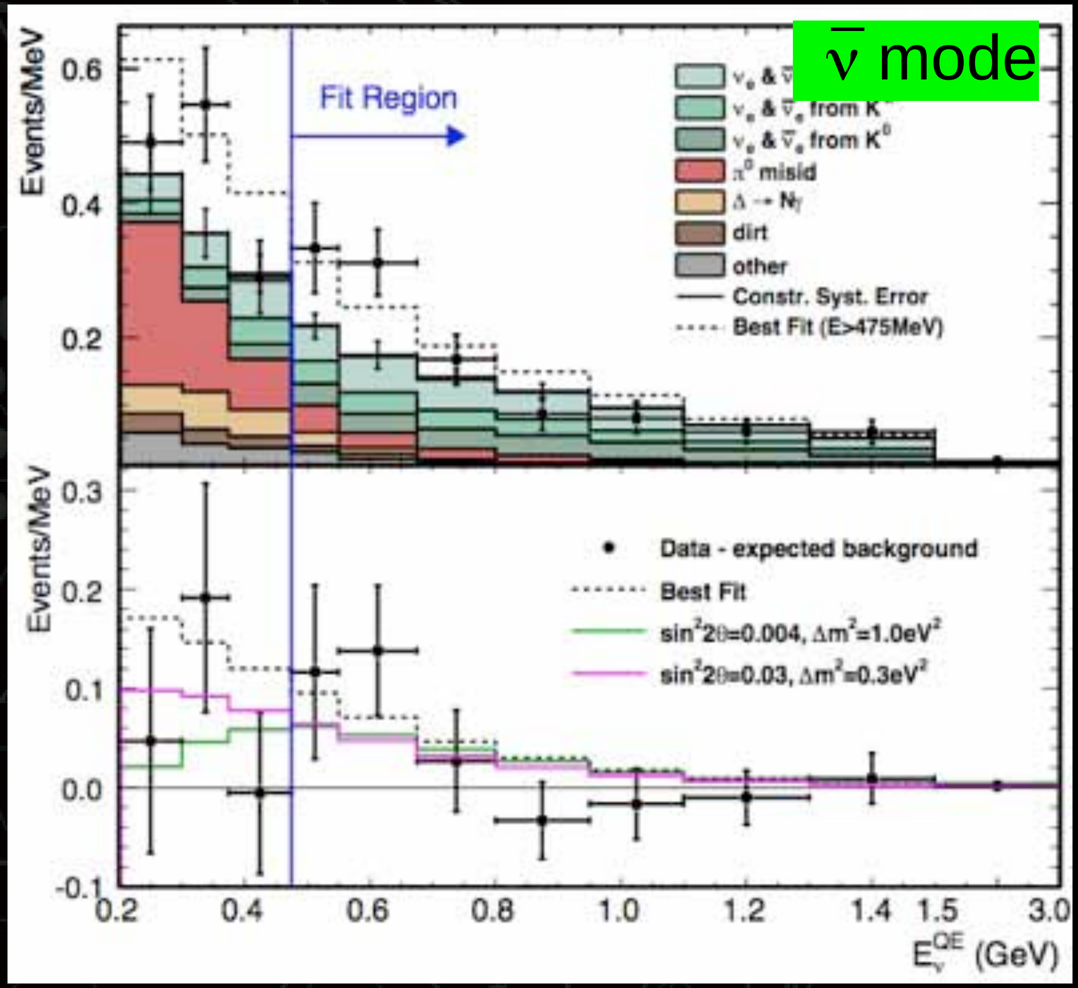
5.6E20 POT

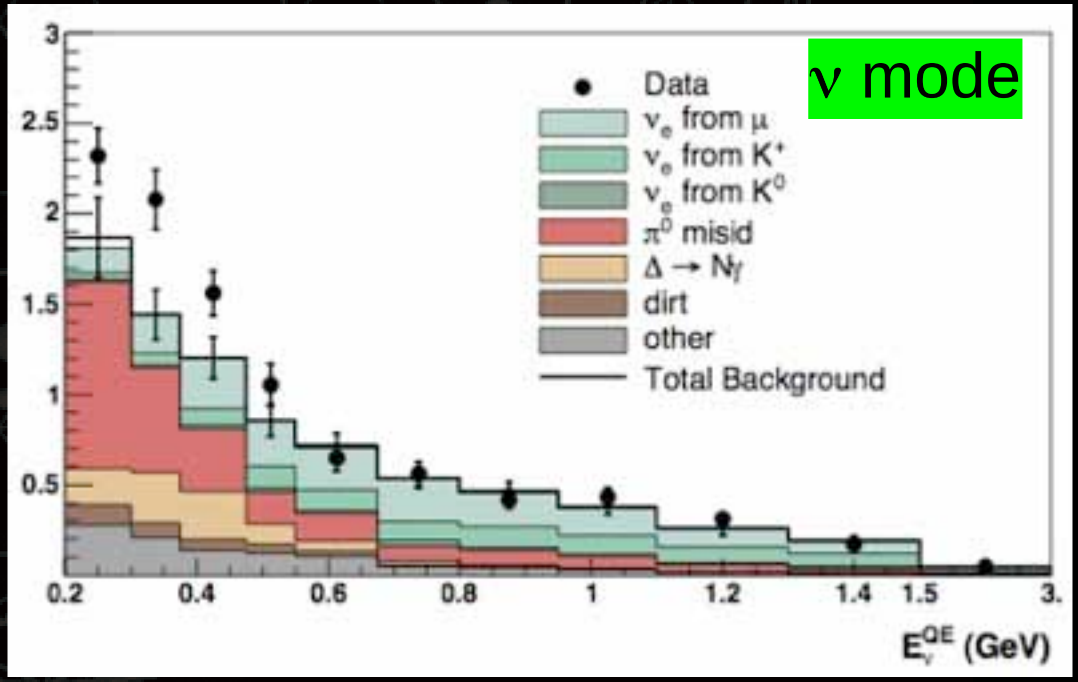


Low energy $\bar{\nu}_e$ results

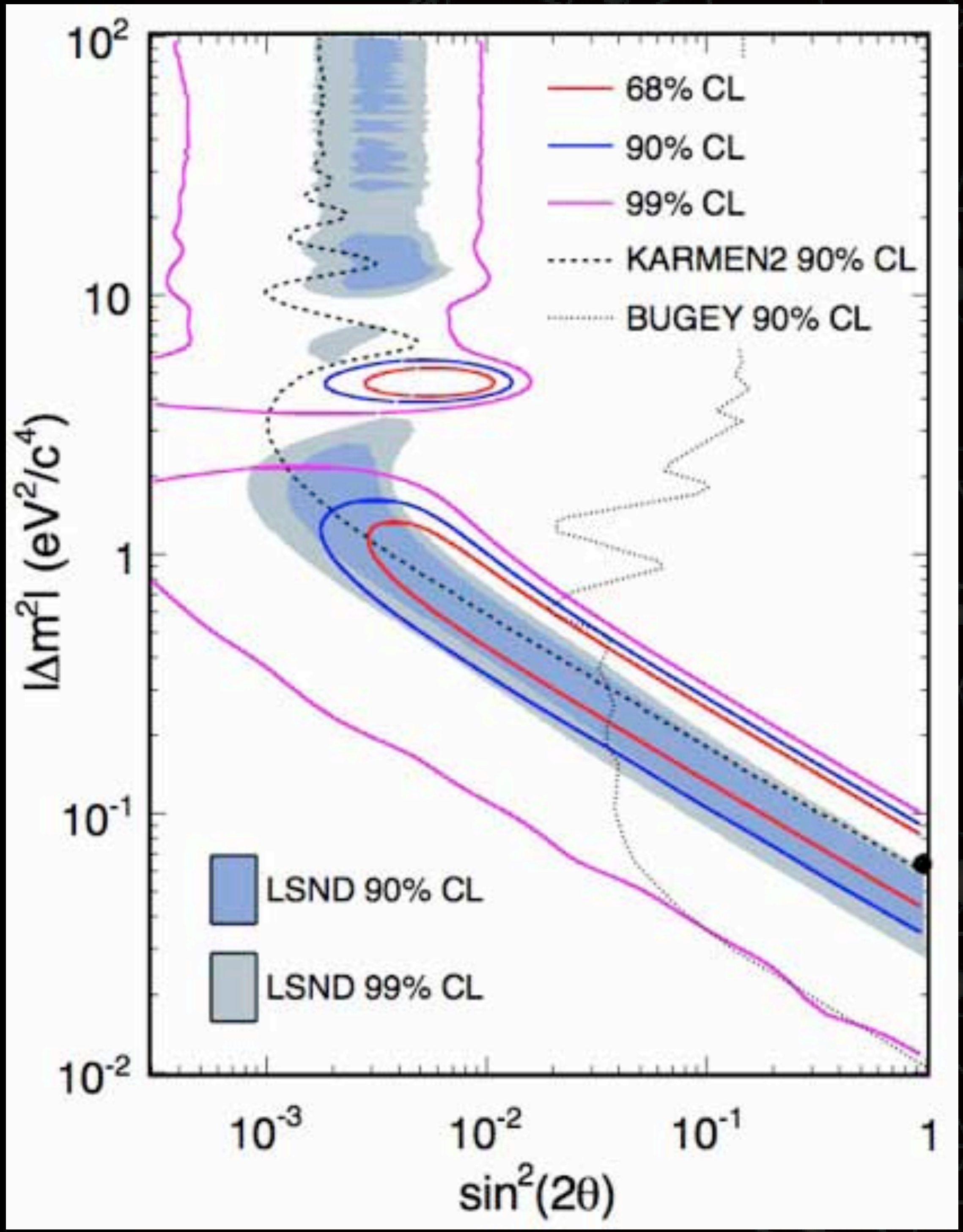
- Below 475 MeV...
  - Find 119 events, expect 100 ± 10(stat) ± 10(syst)
  - Excess is 18.5 ± 10(stat) ± 10 (syst) events
  - Inconsistent with many hypotheses explaining the ν mode low E excess

BG Source	$\bar{\nu}_e$ Prediction
CC bkgs	38.6
NC π^0	31
Rad Δ	24.9
K^0	114.3
charged K	38
WS neutrinos	12
same xsec	68





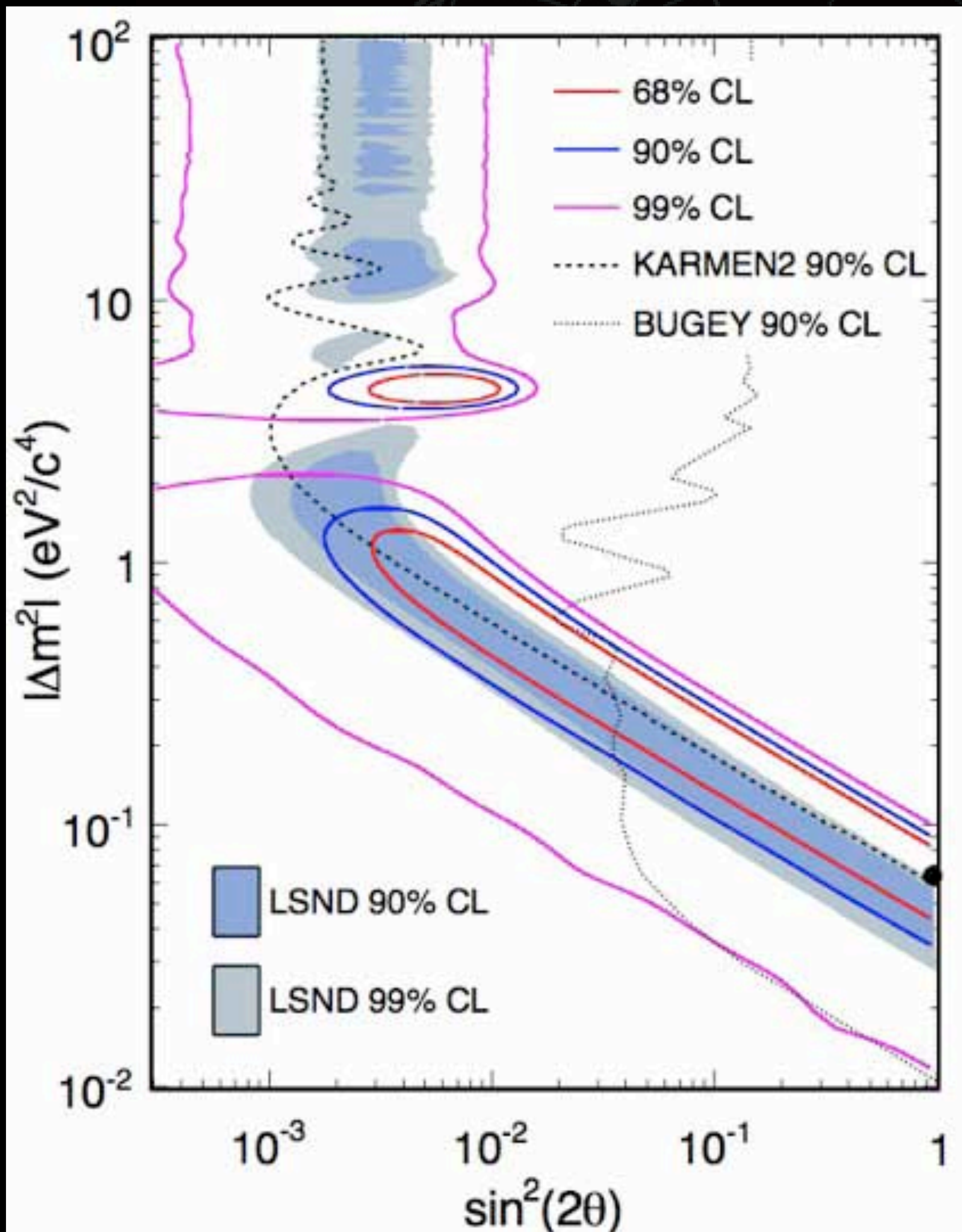
$\bar{\nu}_e$ results



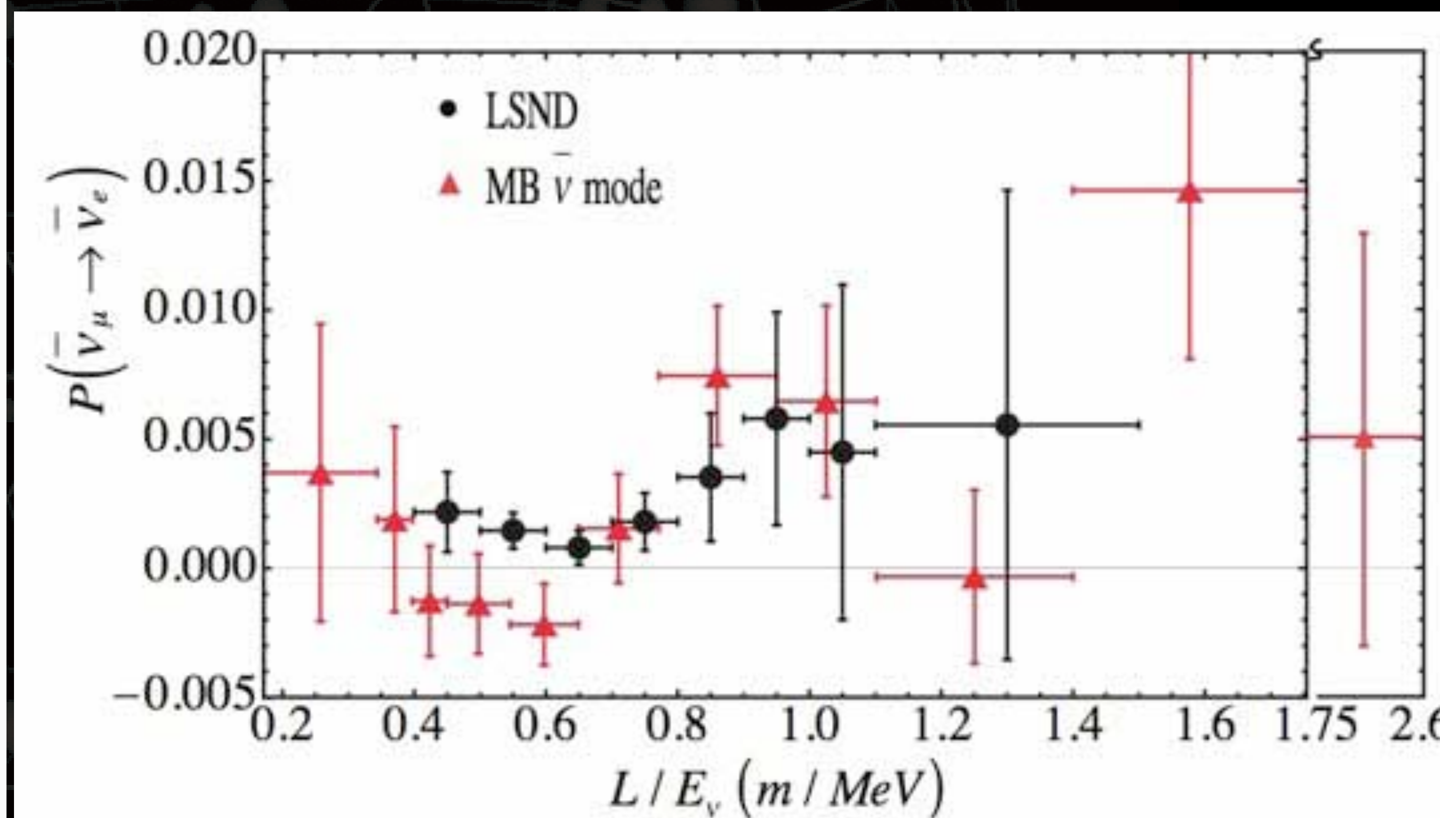
- Above 475 MeV...
  - In 475-1250 MeV, excess 20.9 ± 14 events (1.4σ)
  - True significance comes from fit over entire > 475 MeV energy region + ν_μ constraint
  - Best fit preferred over null at 99.4% CL (2.7σ)
  - Probability of null hypothesis (no model dep.) is 0.5% in 475-1250 MeV signal region

Comparing to LSND

Fit to 2ν mixing model



Model-independent plot of inferred oscillation probability



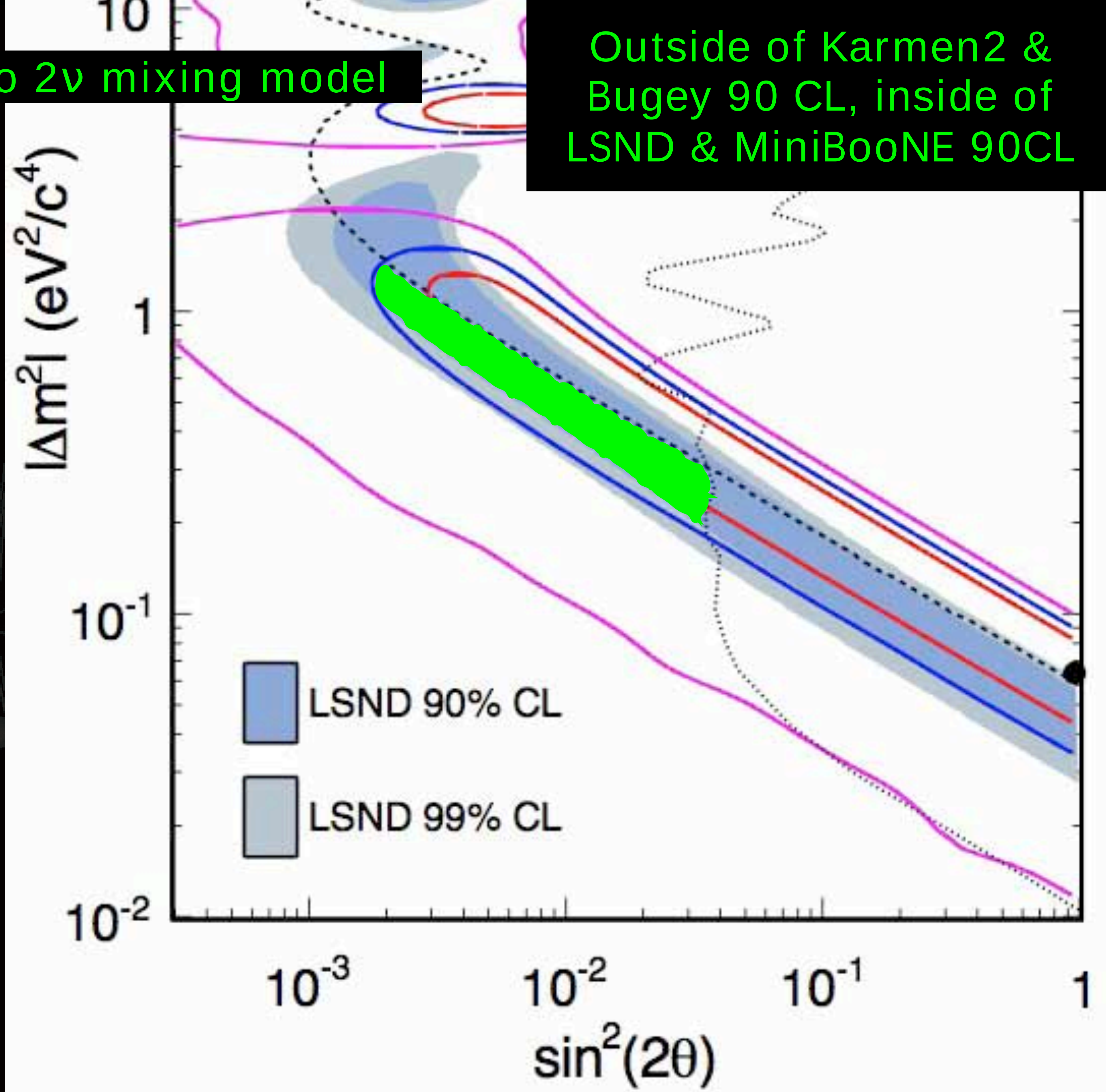
Another check

	E_ν^{QE} [MeV]		
Bkgd	200-475	475-1250	1250-3000
MC	100.5	99.1	34.2
Data	119	120	38
Excess	18.5 ± 10 ± 10	20.9 ± 10 ± 10	3.8 ± 5.8
LSND Best Fit	7.6	22.0	3.5
ν Low-E excess	11.6	~2	~0
LSND + Low-E	19.2	24.0	3.5

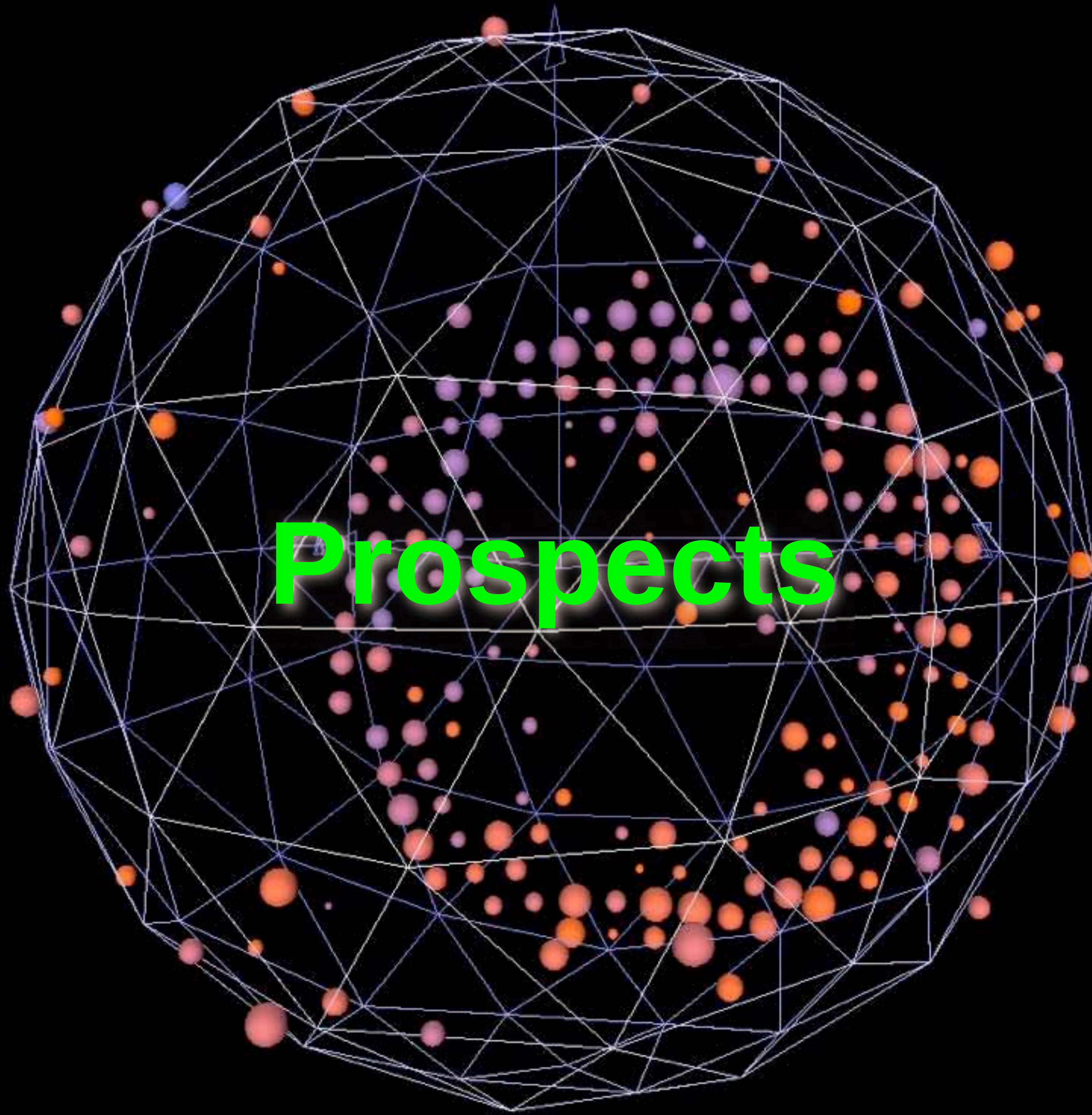
Assumes ν_e excess should be present for WS ν_μ in beam

Fit to 2ν mixing model

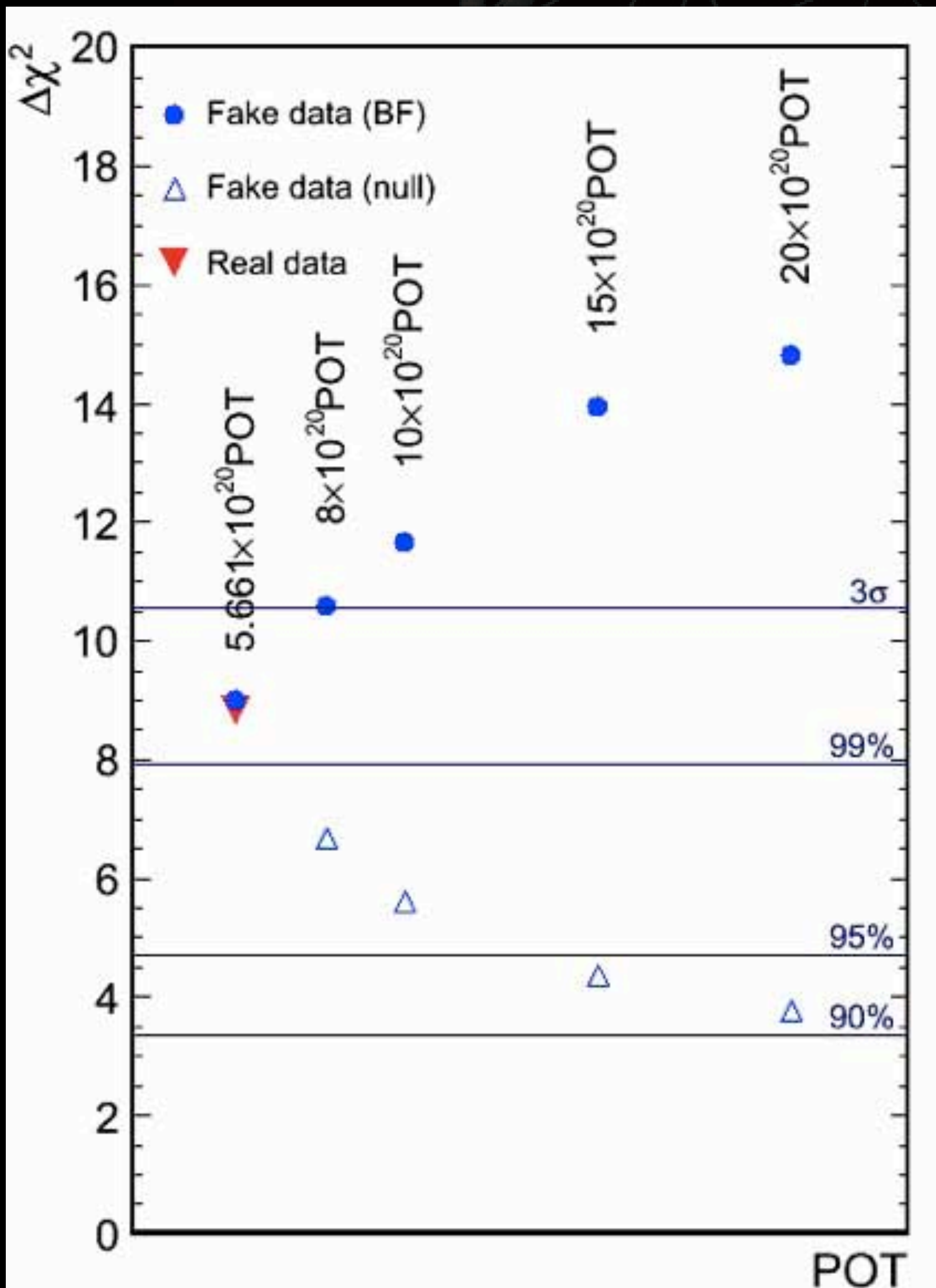
Outside of Karmen2 & Bugey 90 CL, inside of LSND & MiniBooNE 90CL



Prospects



What now?

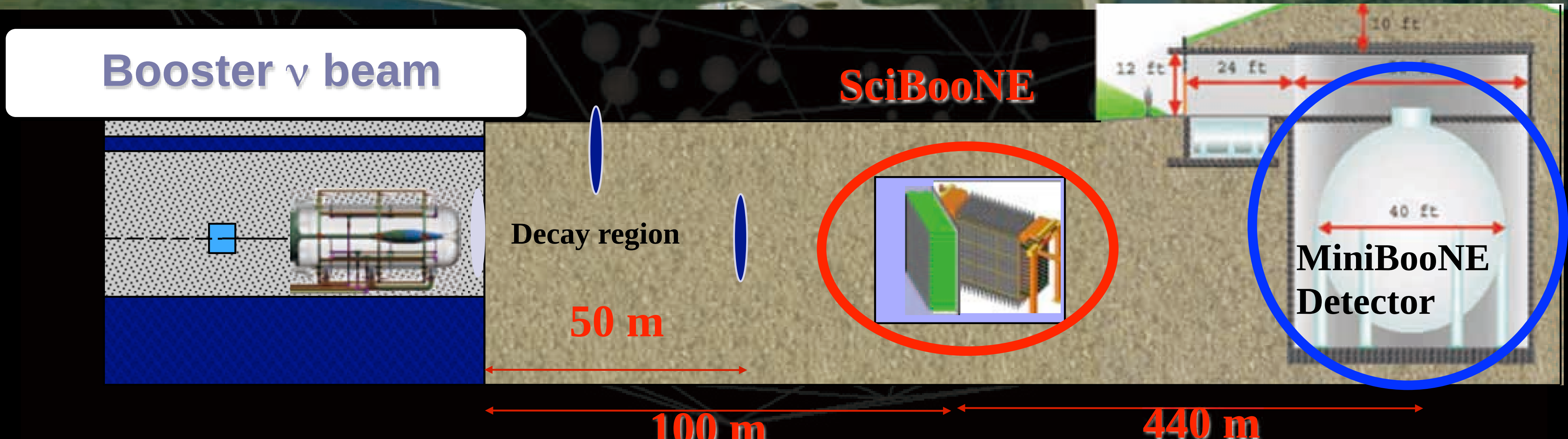


LSND $\bar{\nu}$=3.8σ, MB ν=3.0σ, MB $\bar{\nu}$=2.7σ...

- Step 1: $\bar{\nu}$ result is stat limited
  - need more data !
- Proposal to FNAL to collect 15e20 POT prior to March 2012 shutdown
- At 15e20, $\bar{\nu}$ significance could grow to 3.7σ… or drop below 95%
  - Possibility for ~20% analysis gain during this time

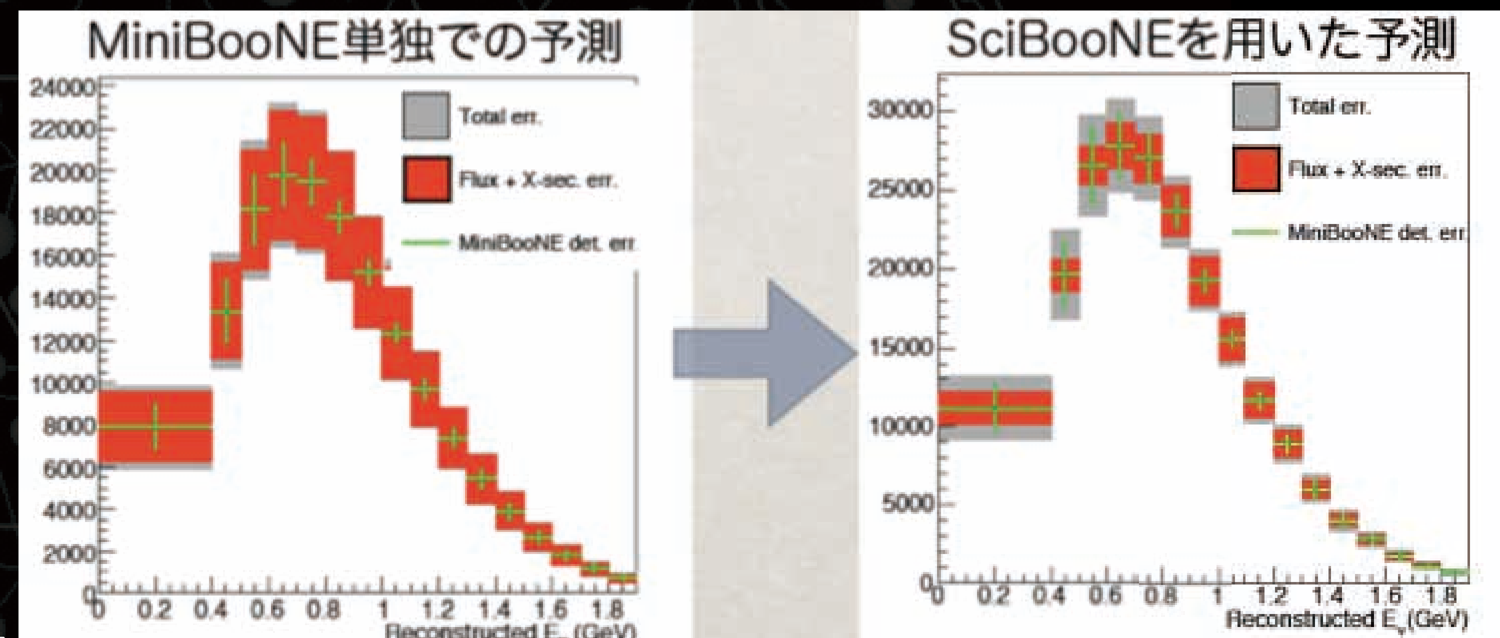
Overview

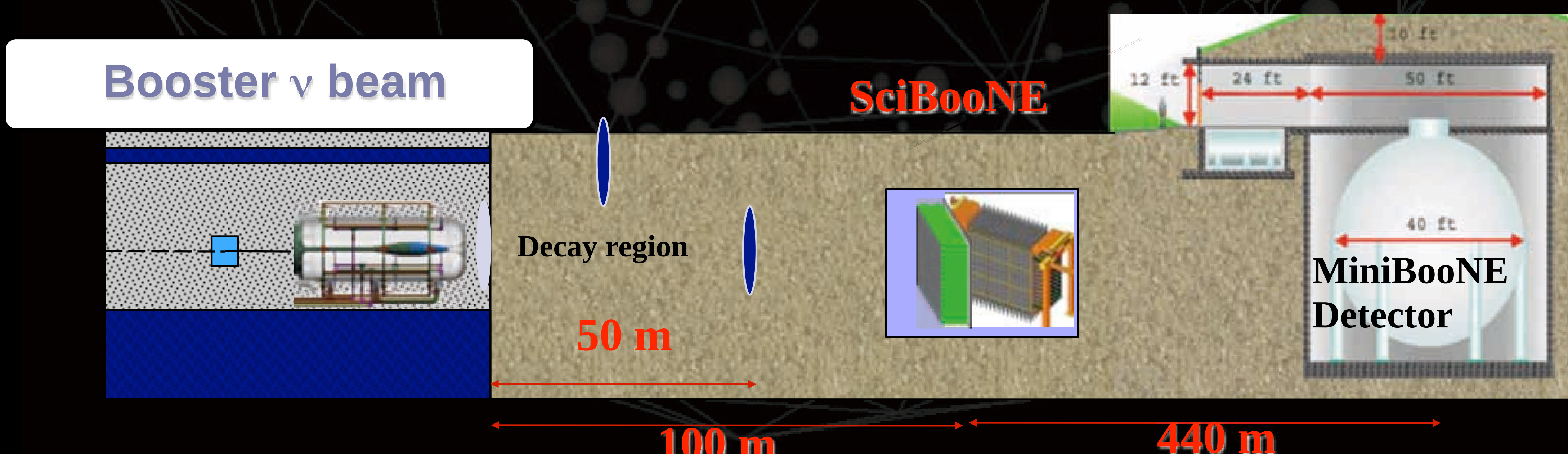

Fermilab Visual Media Services


Booster ν beam
SciBooNE
Decay region
50 m
12 ft
24 ft
10 ft
40 ft
MiniBooNE Detector
100 m
440 m

ν_μ disappearance

- MiniBooNE-SciBooNE combined νμ disappearance oscillation analysis
- combined analysis with SciBooNE can constrain Flux +Xsec error
  - Flux-> same beam line
  - Xsec->same target (carbon)





ν_μ disappearance

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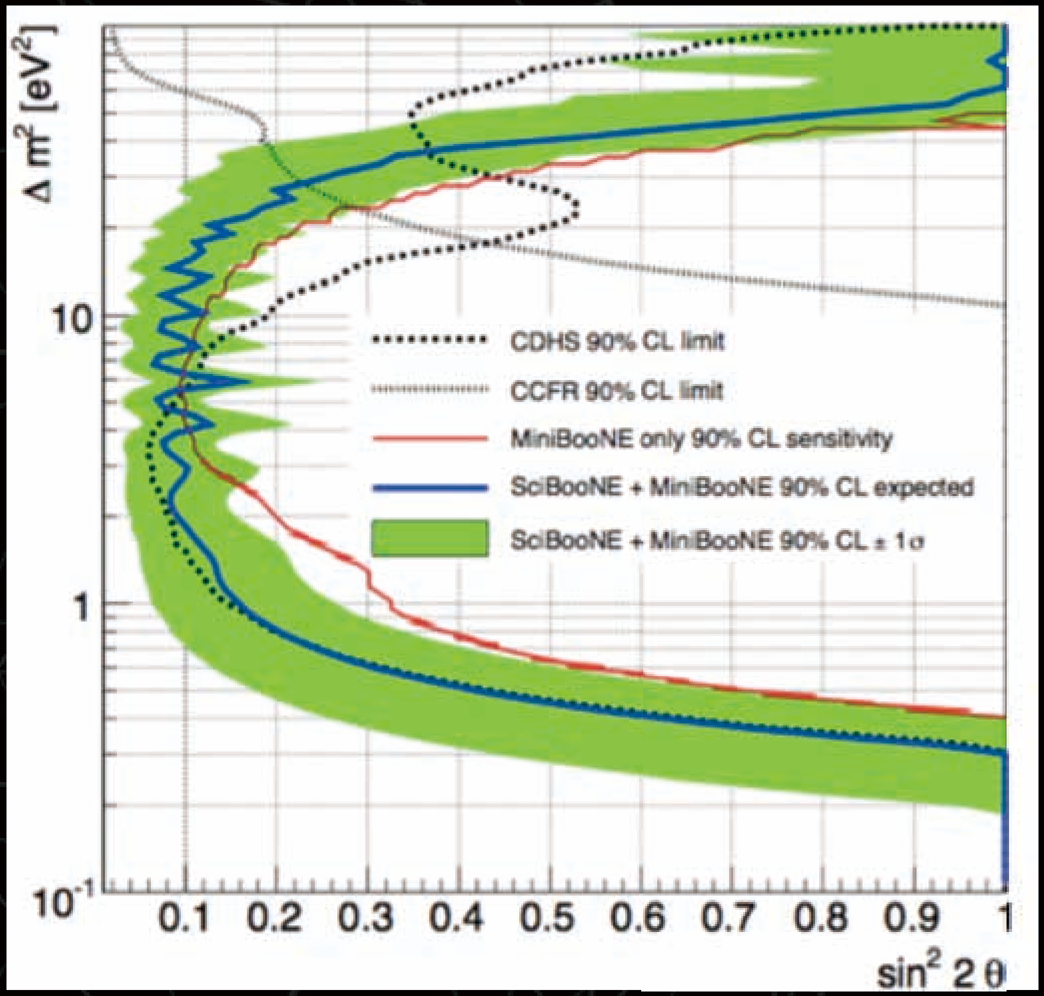
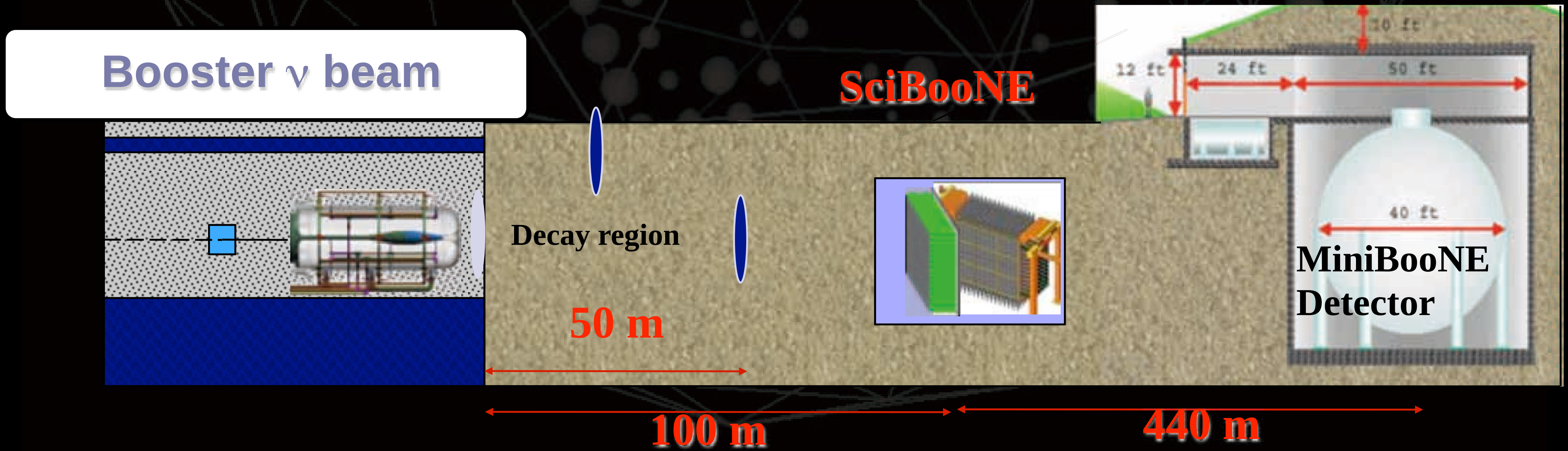
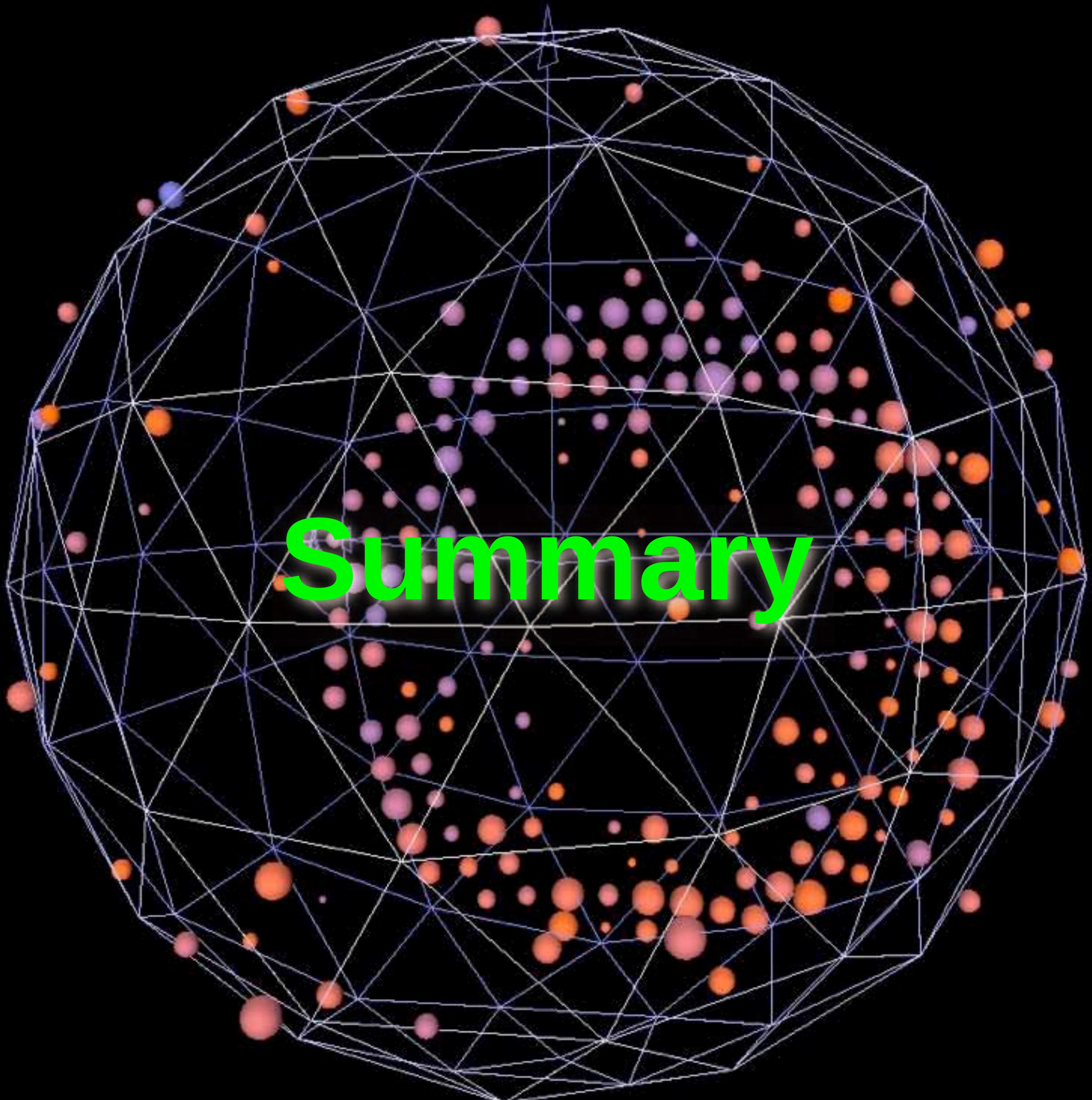




MiniBooNE outlook

- Approved for another ~5e20 POT
- Running right now
- SciBooNE-MiniBooNE joint analysis ready soon
- Submitted LOI for second mineral oil Cherenkov detector
- MicroBooNE under construction, can address low energy excess

Summary

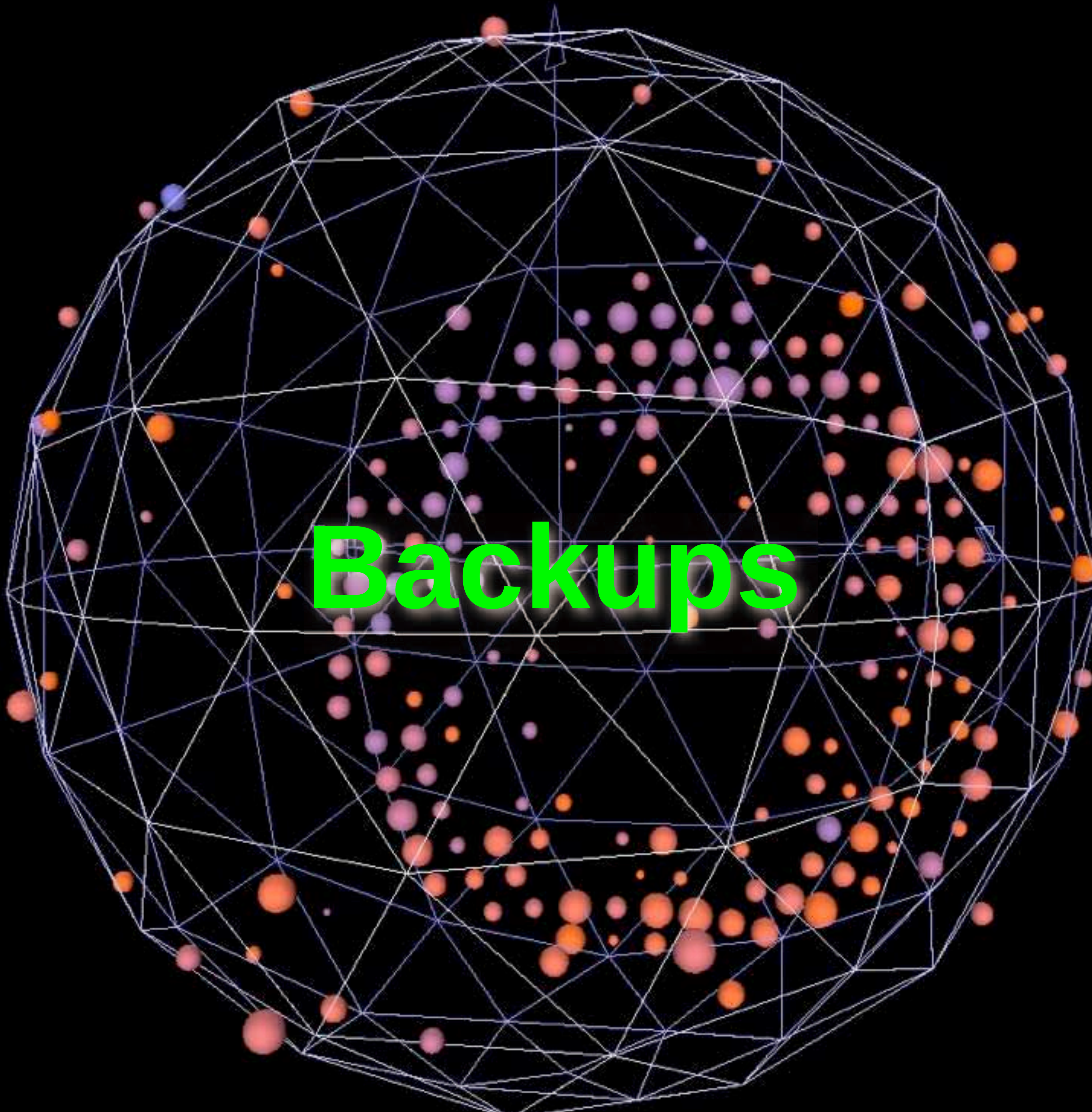


What does MiniBooNE claim?

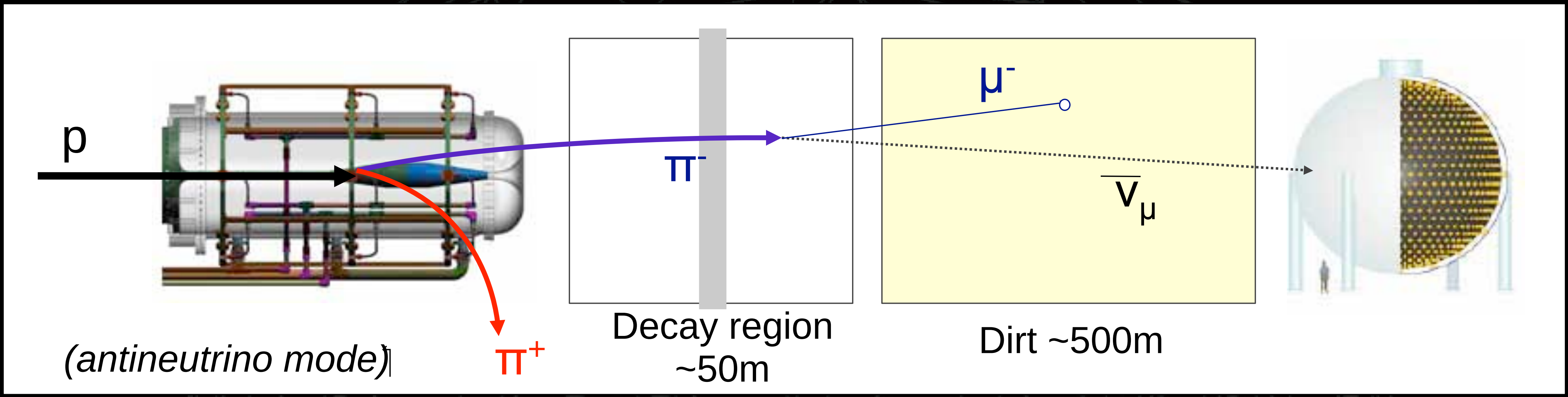
1. No ν_e excess in ν_μ beam above 475 MeV.
   - ➡ Maximal sensitivity if LSND is L/E and CPT invariant.
2. 3σ excess (128 ± 43) of ν_e candidates in ν_μ beam below 475 MeV.
   - ➡ Does not fit well to a 2ν mixing hypothesis
3. Small excess (18±14) below 475 MeV in $\bar{\nu}_\mu$ beam.
   - ➡ Rules out some ν_μ beam low-E excess explanations.
4. Small excess (20.9 ± 14) in $\bar{\nu}_\mu$ beam above 475 MeV.
   - ➡ Null hypothesis in 475-1250 MeV region is 0.5% probable
   - ➡ 2ν fit prefers LSND-like signal at 99.4% CL.


Thank you!

Backups



25m Absorber



Two periods of running with 1 & 2 absorber plates

1 absorber plate - 0.569E20 POT

2 absorber plates - 0.612E20 POT

Good data/MC agreement in high statistics samples (ν_μ CCQE, NC π^0, ...)

Data included in this analysis

3 Flavours

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$$

flavor   mass

3 Flavours

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$$

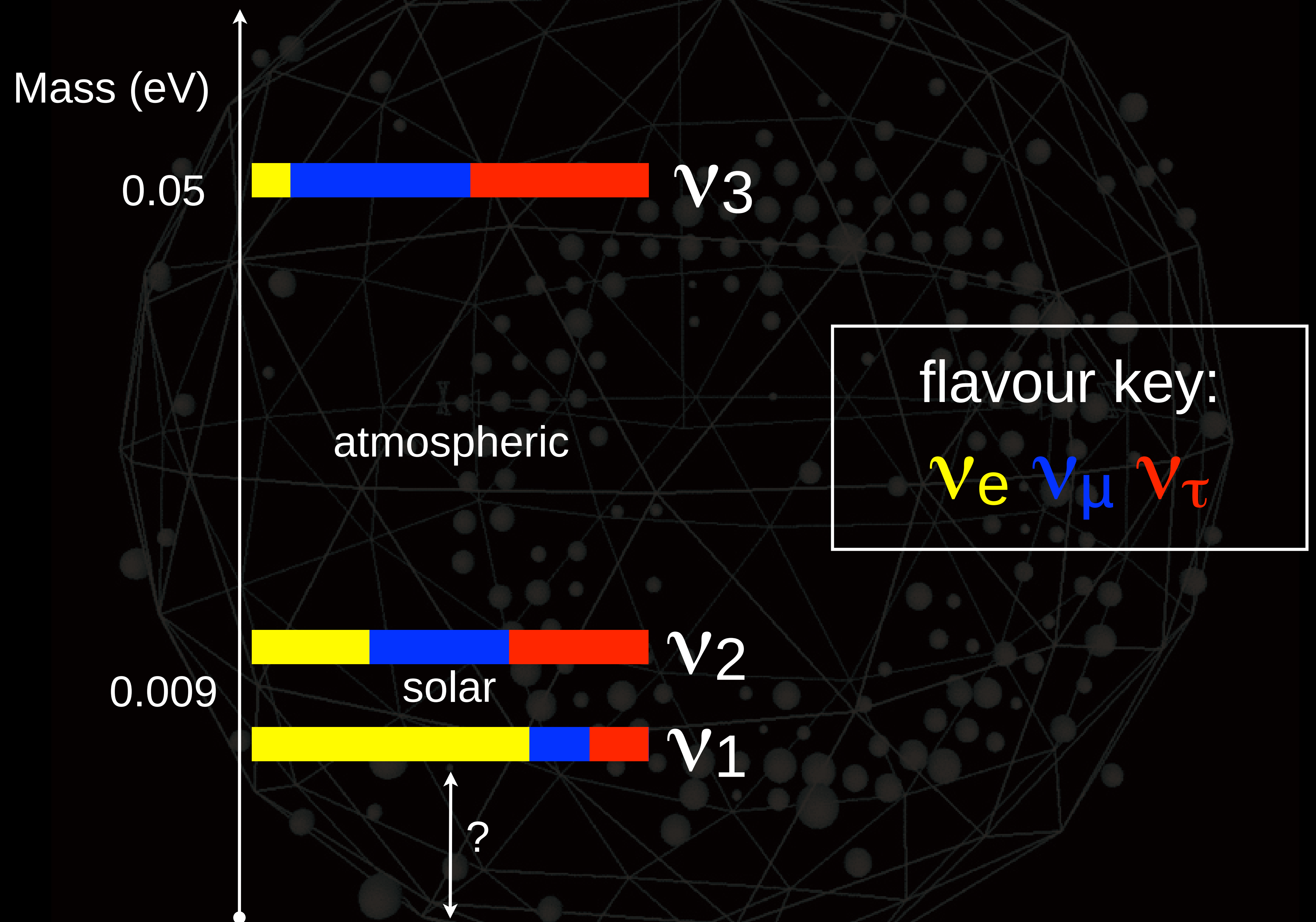
flavor mass

Atmospheric — Cross-Mixing — Solar

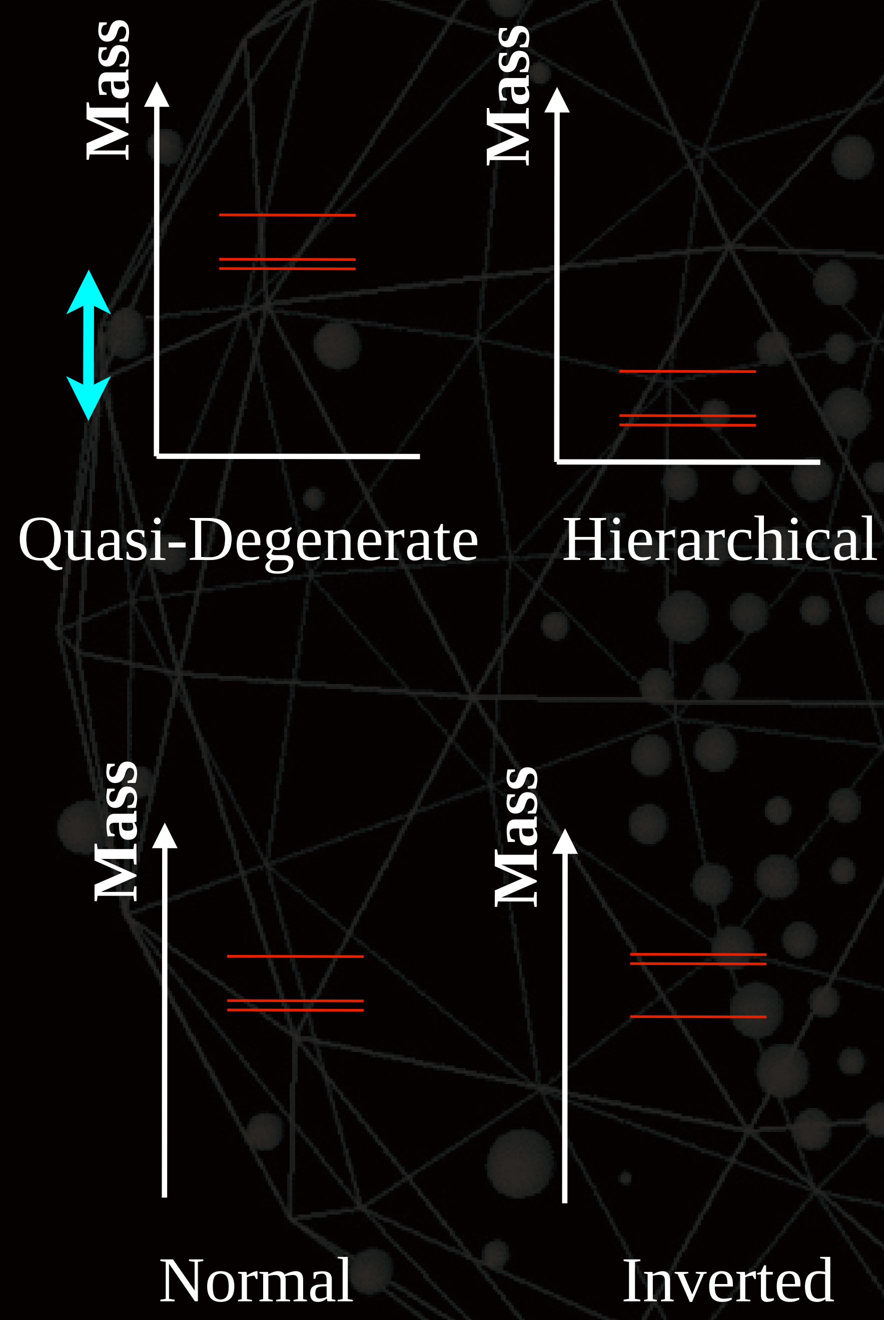
$$U=\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where $c_{ij} = \cos\theta_{ij}$, etc.

3 Flavours

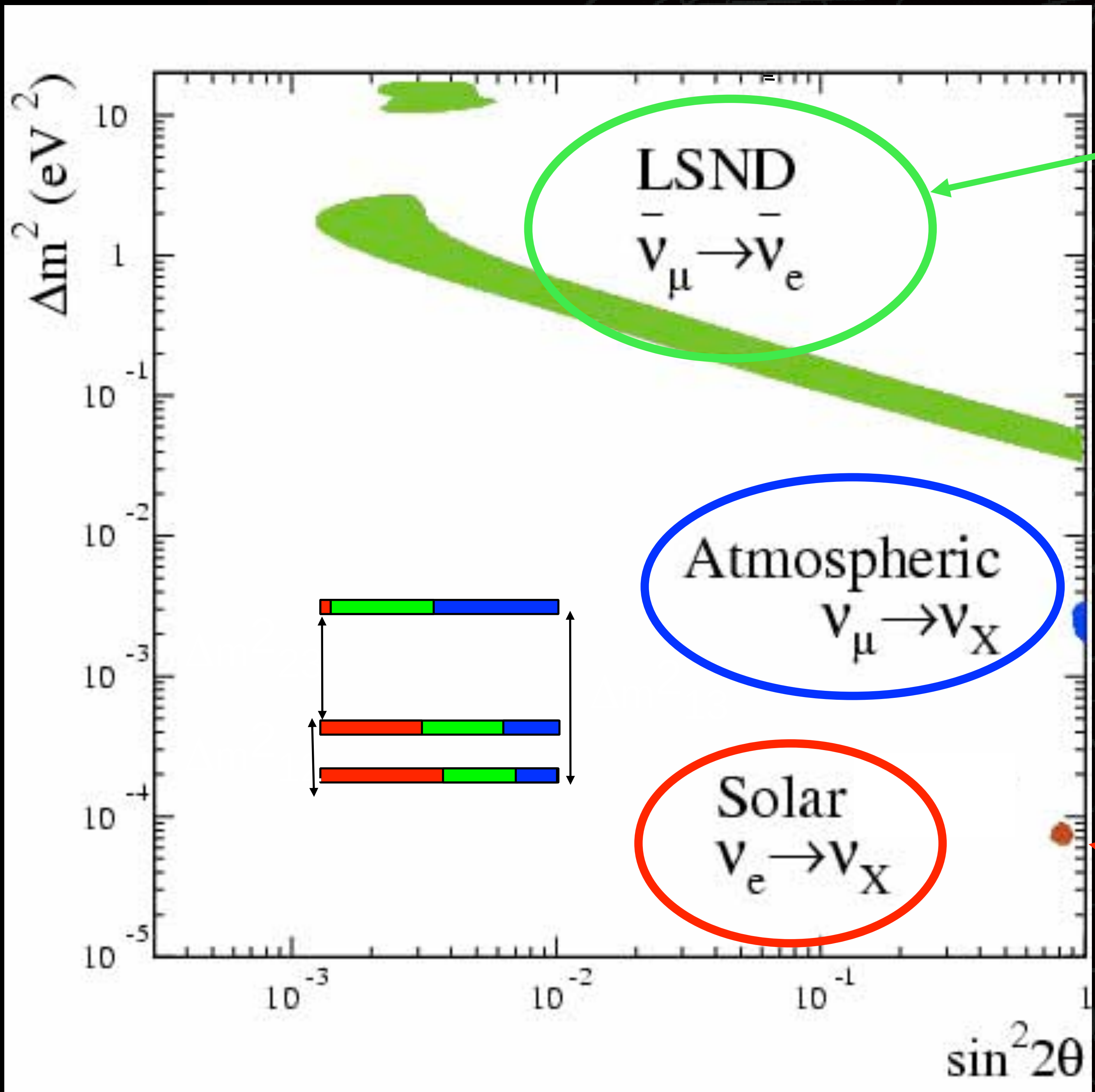

Mass (eV)
0.05
ν_3
atmospheric
flavour key:
ν_e ν_μ ν_τ
ν_2
0.009
solar
ν_1
?

Today's Open Questions



- What is the last mixing angle?
- What is the sign of Δm^2_{23}?
- Do νs and $\bar{\nu}$s oscillate with the same probability?
- What is absolute mass scale?
- Are they Majorana or Dirac particles? *i.e.*, $\nu = \bar{\nu}$?
- *How many species??*

Oscillation Summary



LSND
$\Delta m^2 \sim 1 eV^2$
$\theta \sim 2°$

Atmospheric oscillations
$\Delta m^2 \sim 10^{-3} eV^2$
$\theta \sim 45°$

Solar oscillations
$\Delta m^2 \sim 10^{-5}$ eV^2
$\theta \sim 32°$

- Problem: That's too many Δm2 regions!
  - Should find: $\Delta m^2_{12} + \Delta m^2_{23} = \Delta m^2_{13}$

$10^{-5} + 10^{-3} \neq 1$

Accelerator Neutrinos

Many null result SBL accelerator neutrino experiments

Positive result: LSND Experiment at LANL

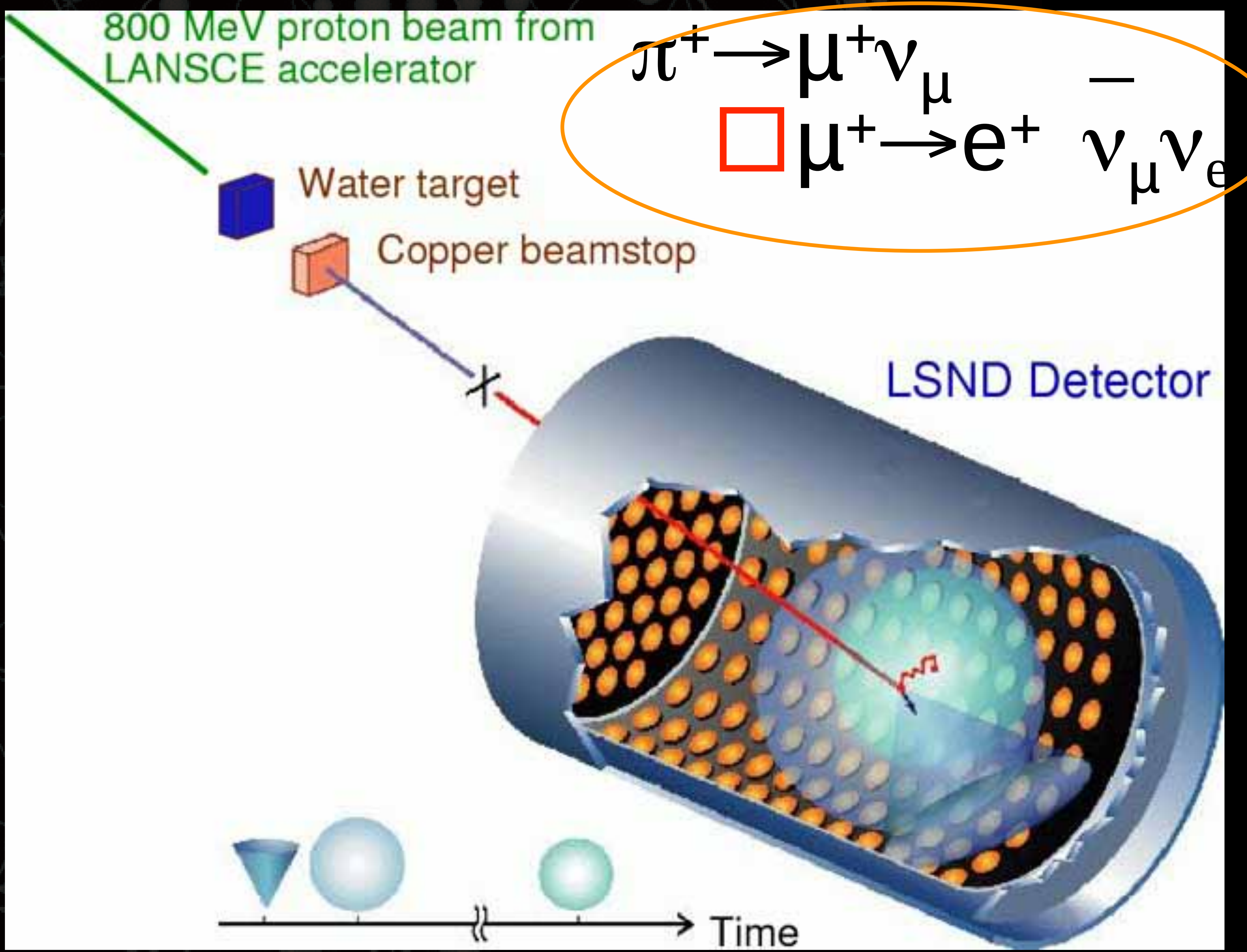
Beam: μ^+ decay at rest

- L/E ~ 1m/MeV
  - L ~ 30m
  - $20 < E_{\bar{\nu}} < 53$ MeV
- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$?

Appearance search

Clean detection signal

- Inverse β decay



LSND $\bar{\nu}_e$ Background Estimates

Estimate	$\bar{\nu}_e / \bar{\nu}_\mu$	$\bar{\nu}_e$ Bkgd	LSND Excess
LSND Paper	0.086%	19.5+-3.9	87.9+-22.4+-6.0
Zhemchugov Poster1	0.071%	16.1+-3.2	91.3+-22.4+-5.6
Zhemchugov Poster2	0.092%	20.9+-4.2	86.5+-22.4+-6.2
Zhemchugov Seminar	0.119%	27.0+-5.4	80.4+-22.4+-7.1

All $\bar{\nu}_e$ background estimates assume a 20% error. Note that the $\bar{\nu}_e / \bar{\nu}_\mu$ ratio determines the background!

LSND Paper: A. Aguilar et al., Phys. Rev. D 64, 112007 (2001); (uses **MCNP**)
Zhemchugov Poster1: **FLUKA** $\bar{\nu}_e / \bar{\nu}_\mu$ ratio presented at the ICHEP 2010 Conference, Paris
Zhemchugov Poster2: **GEANT4** $\bar{\nu}_e / \bar{\nu}_\mu$ ratio presented at the ICHEP 2010 Conference, Paris
Zhemchugov Seminar: **FLUKA** $\bar{\nu}_e / \bar{\nu}_\mu$ ratio presented at CERN on September 14, 2010

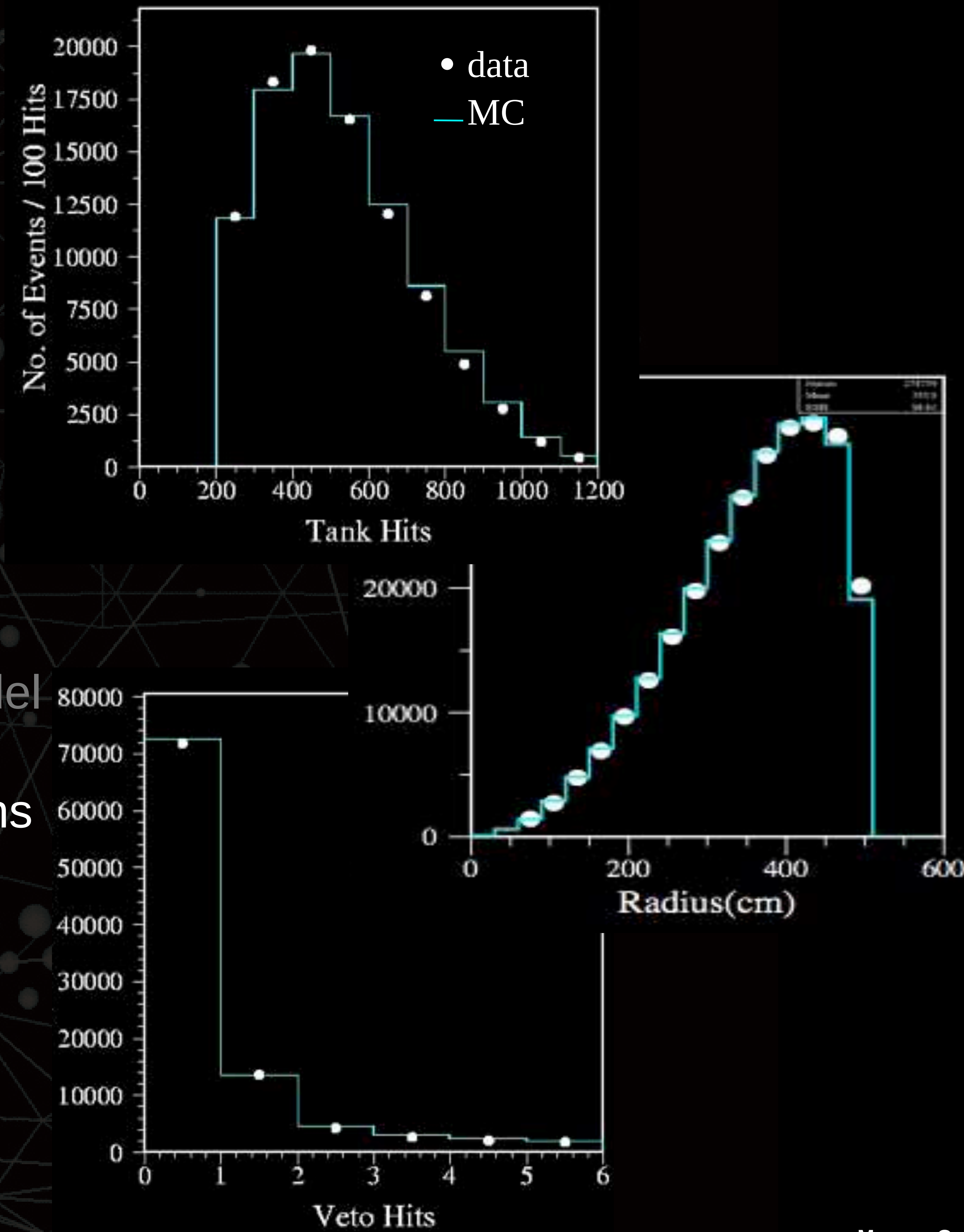
Although the analysis of Zhemchugov et al. is not fully understood or endorsed, their $\bar{\nu}_e / \bar{\nu}_\mu$ ratios agree reasonably well with the published LSND results.

Note that LSND measures the correct rate of $\nu_\mu p \rightarrow \mu^+ n$ interactions, which confirms the p^- production and background estimates. Note also, that FLUKA & GEANT4 are not as reliable as MCNP at 800 MeV!

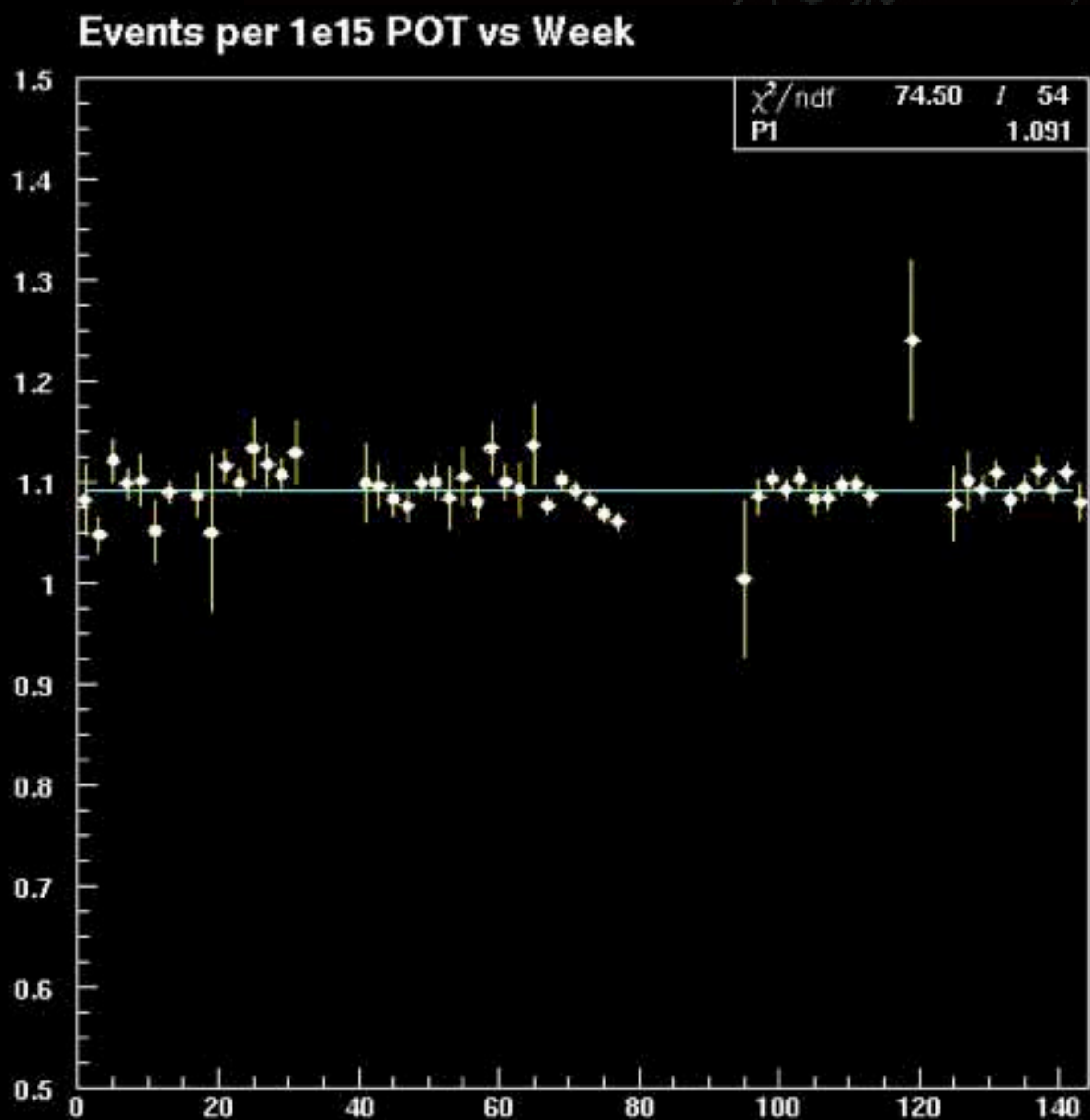
MC Tuning

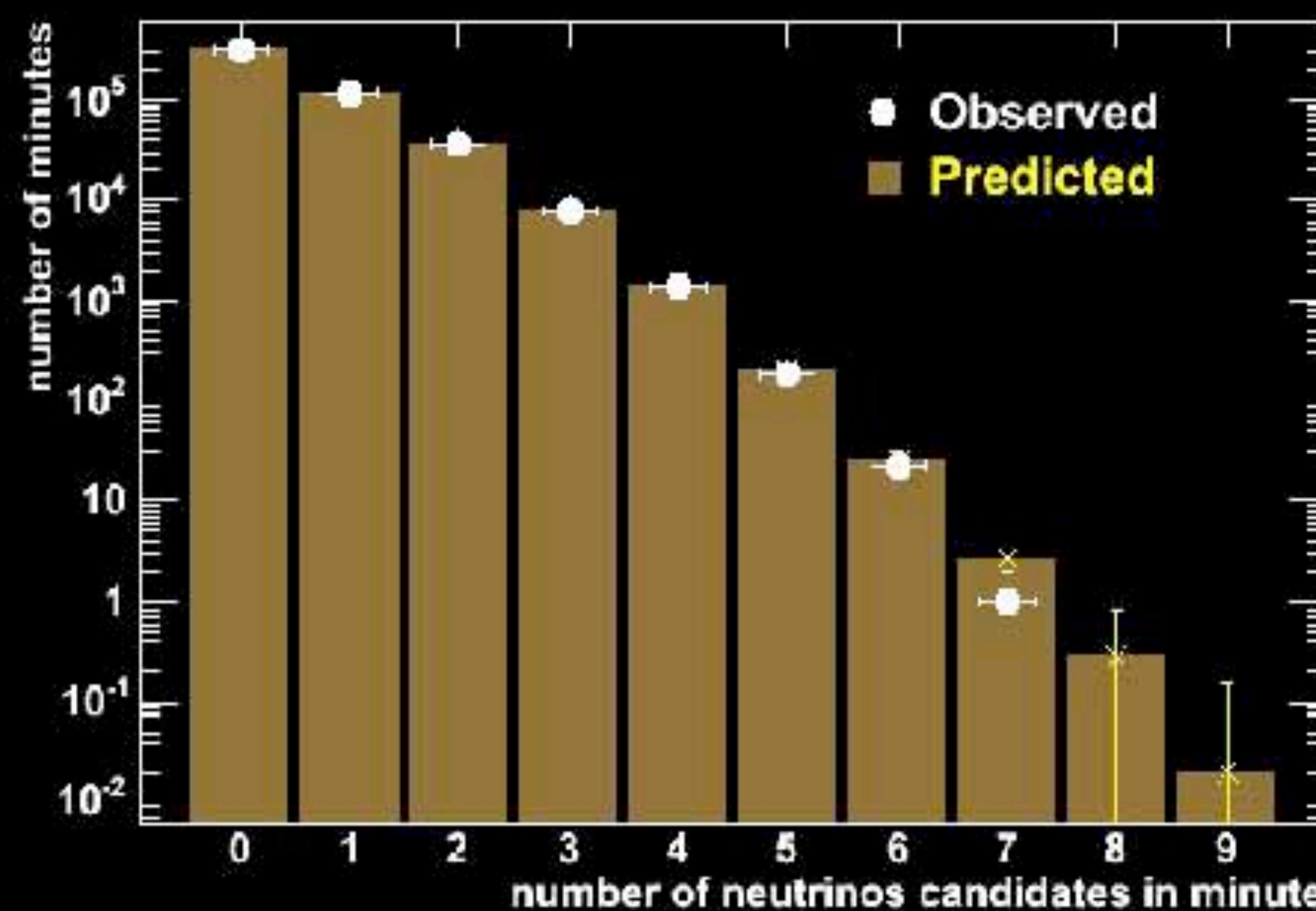
Good data/MC agreement

- Basic PMT hit distributions showing details of optical model
- Aggregate PMT hit distributions showing gross detector behaviour



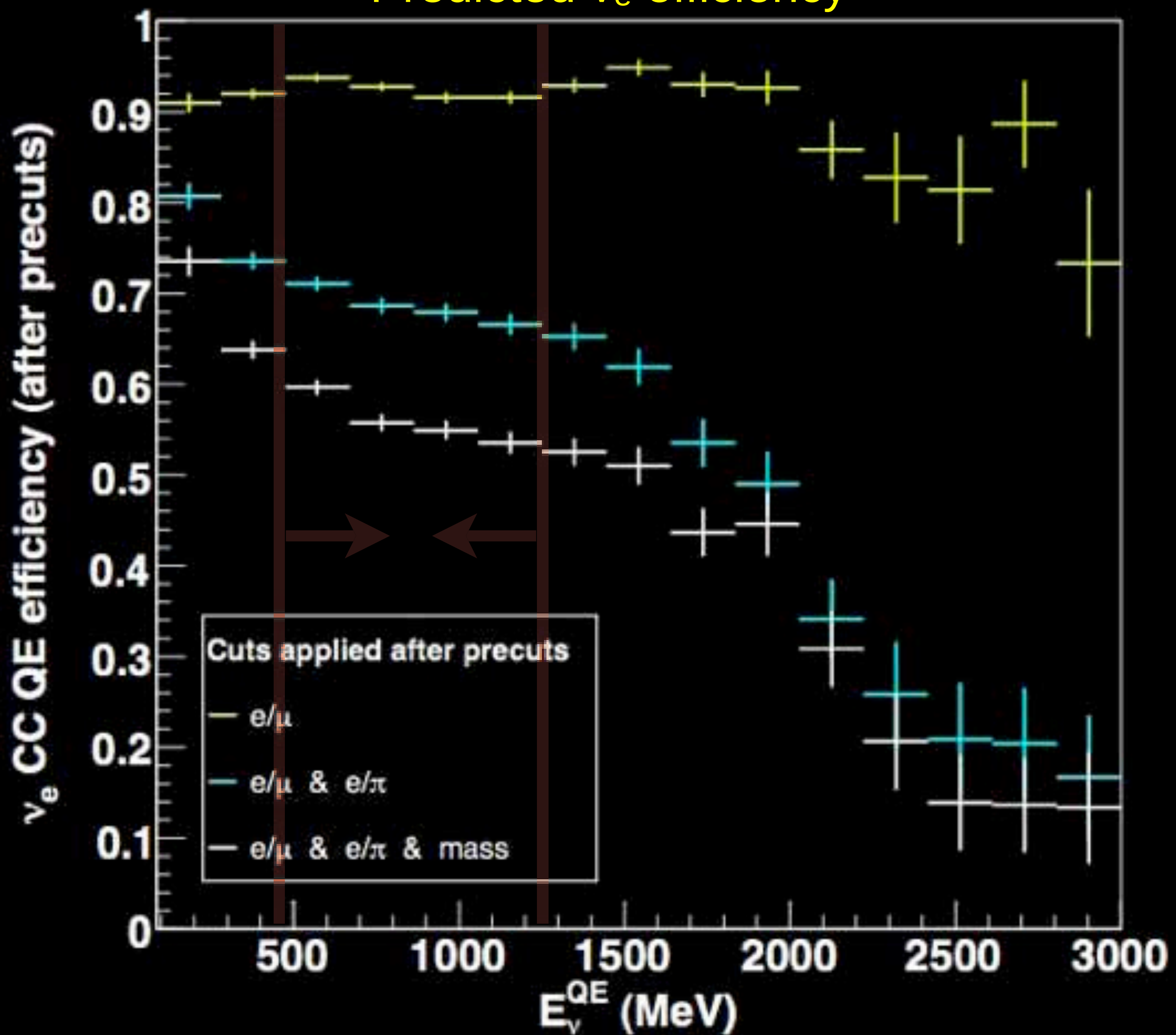
Detector Stability





Signal and background

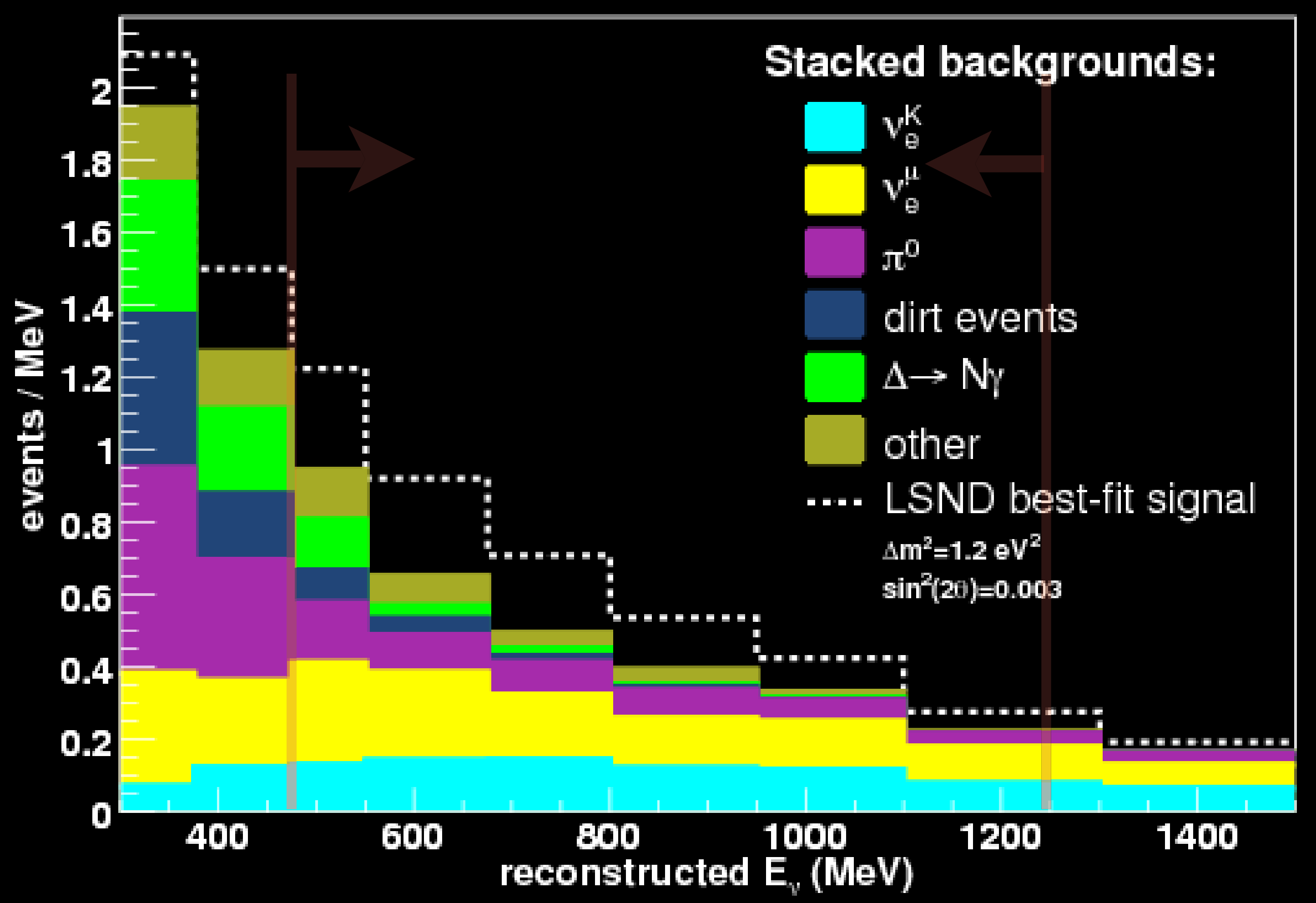
Predicted ν_e efficiency



- "Analysis region" defined to be 475-1250 MeV
- Signal efficiency higher at low energy
- Backgrounds higher there too...

Signal and background

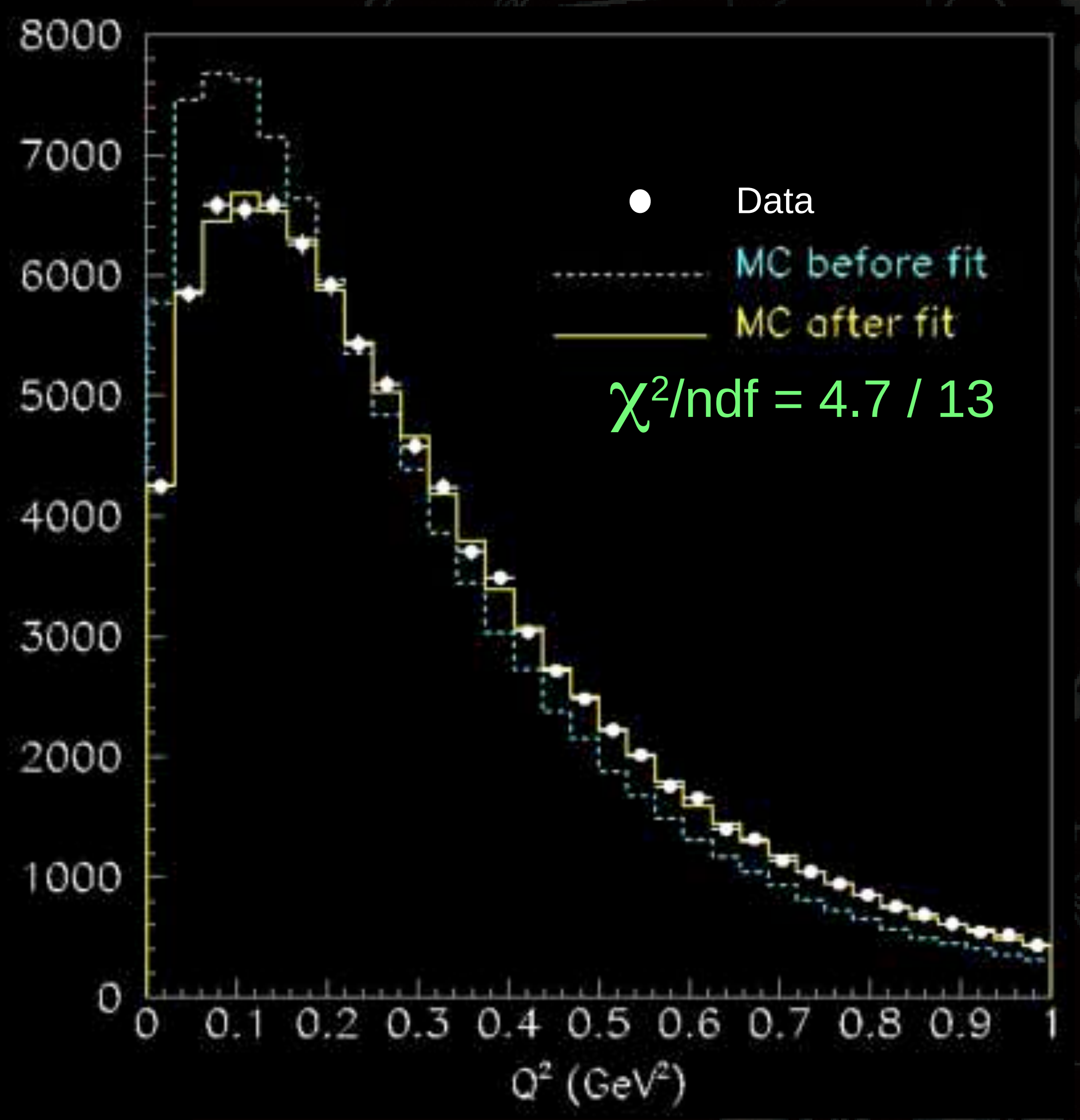
Predicted ν_e energy distribution

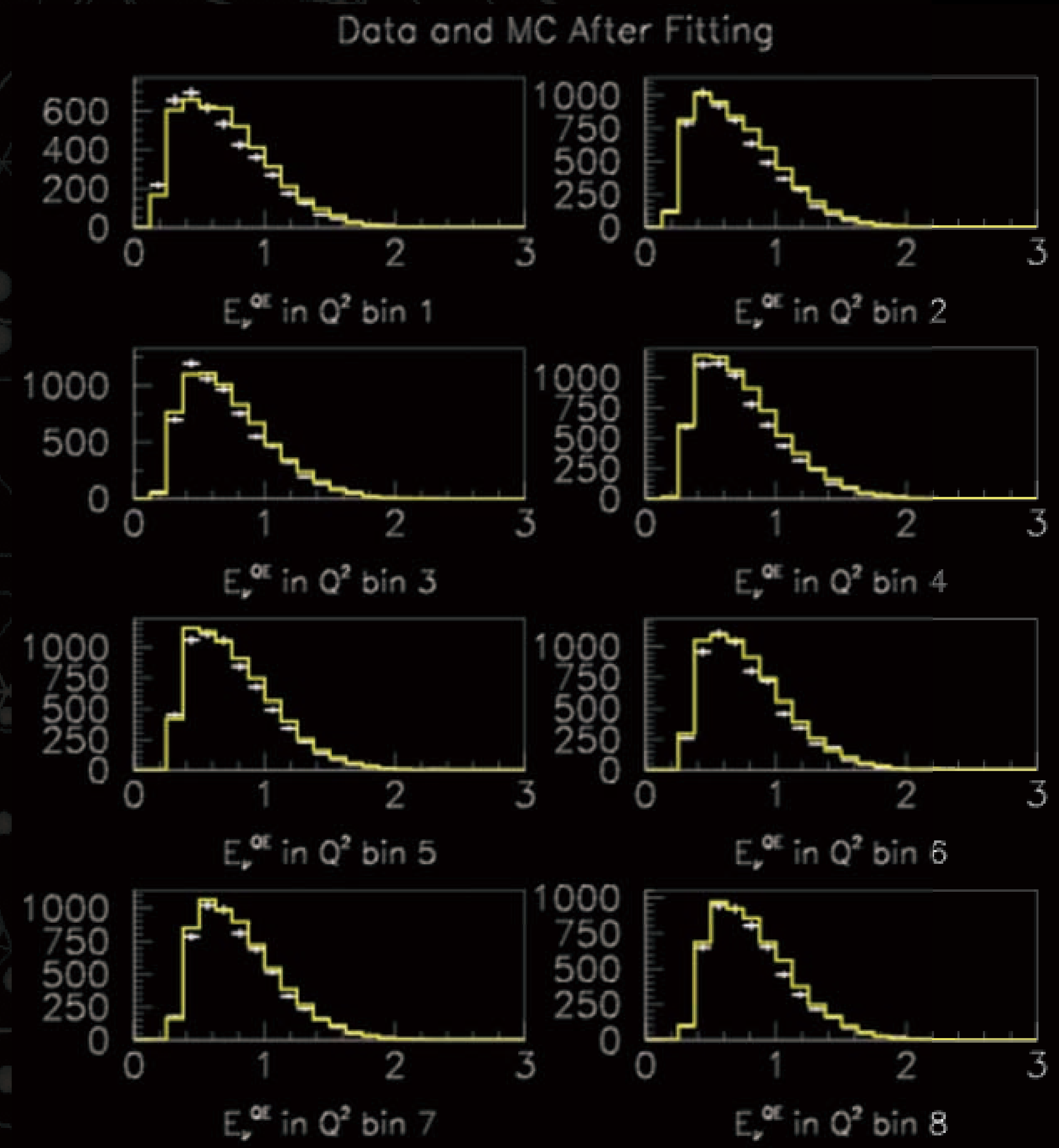


475-1250 MeV	
$\nu_e(\mu$ decay)	132
ν_e(K decay)	94
Radiative Δ	20
NCπ^0	62
Dirt	17
Other	33
Total	*358*
Signal	*163*

Tuning CCQE MC

Q^2 distribution fit to tune empirical parameters of nuclear model (^{12}C)





good data-MC agreement in variables not used in tuning!

Systematic Errors

	constraint?
Neutrino flux predictions	
meson production cross sections	✓
meson secondary interactions	✓
focussing horn current	
target and horn system alignment	
Neutrino interaction cross sections	
nuclear model	✓
rates and kinematics for relevant processes	✓
resonance width and branching fractions	✓
Detector modelling	
optical model of light propagation	✓
PMT charge and time response	✓
electronics & DAQ model	✓
neutrino interactions in dirt surrounding detector	✓

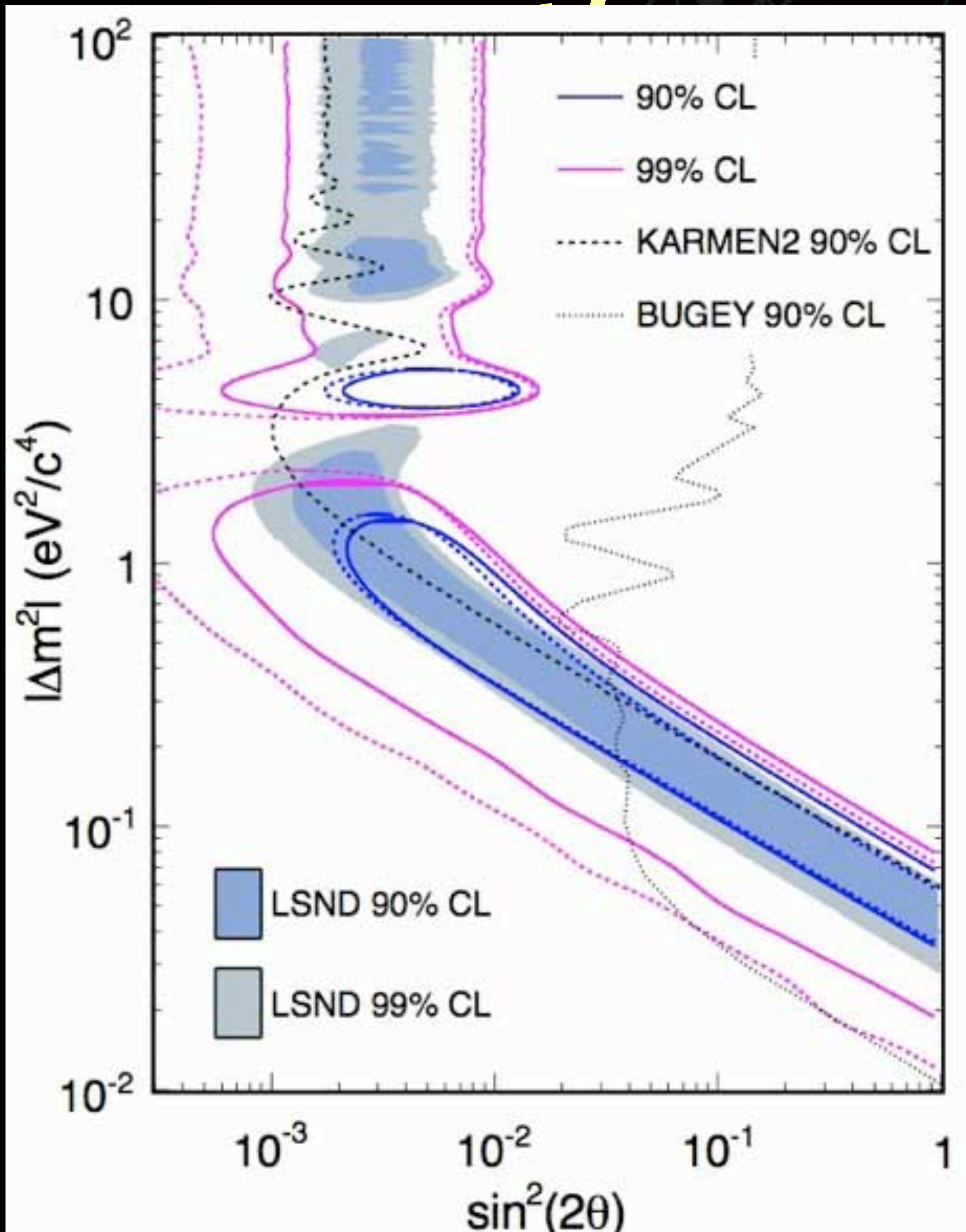
Events summary (constrained syst + stat uncertainty)

E_ν^{QE} range (MeV)		$\bar{\nu}$ mode (3.386e20 POT)	ν mode (6.486e20 POT)
200-300	Data	24	232
	MC ± sys+stat (constr.)	27.2 ± 7.4	186.8 ± 26.0
	Excess (σ)	-3.2 ± 7.4 (-0.4σ)	45.2 ± 26.0 (1.7σ)
300-475	Data	37	312
	MC ± sys+stat (constr.)	34.3 ± 7.3	228.3 ± 24.5
	Excess (σ)	2.7 ± 7.3 (0.4σ)	83.7 ± 24.5 (3.4σ)
200-475	Data	61	544
	MC ± sys+stat (constr.)	61.5 ± 11.7	415.2 ± 43.4
	Excess (σ)	-0.5 ± 11.7 (-0.04σ)	128.8 ± 43.4 (3.0σ)
475-1250	Data	61	408
	MC ± sys+stat (constr.)	57.8 ± 10.0	385.9 ± 35.7
	Excess (σ)	3.2 ± 10.0 (0.3σ)	22.1 ± 35.7 (0.6σ)

Excess

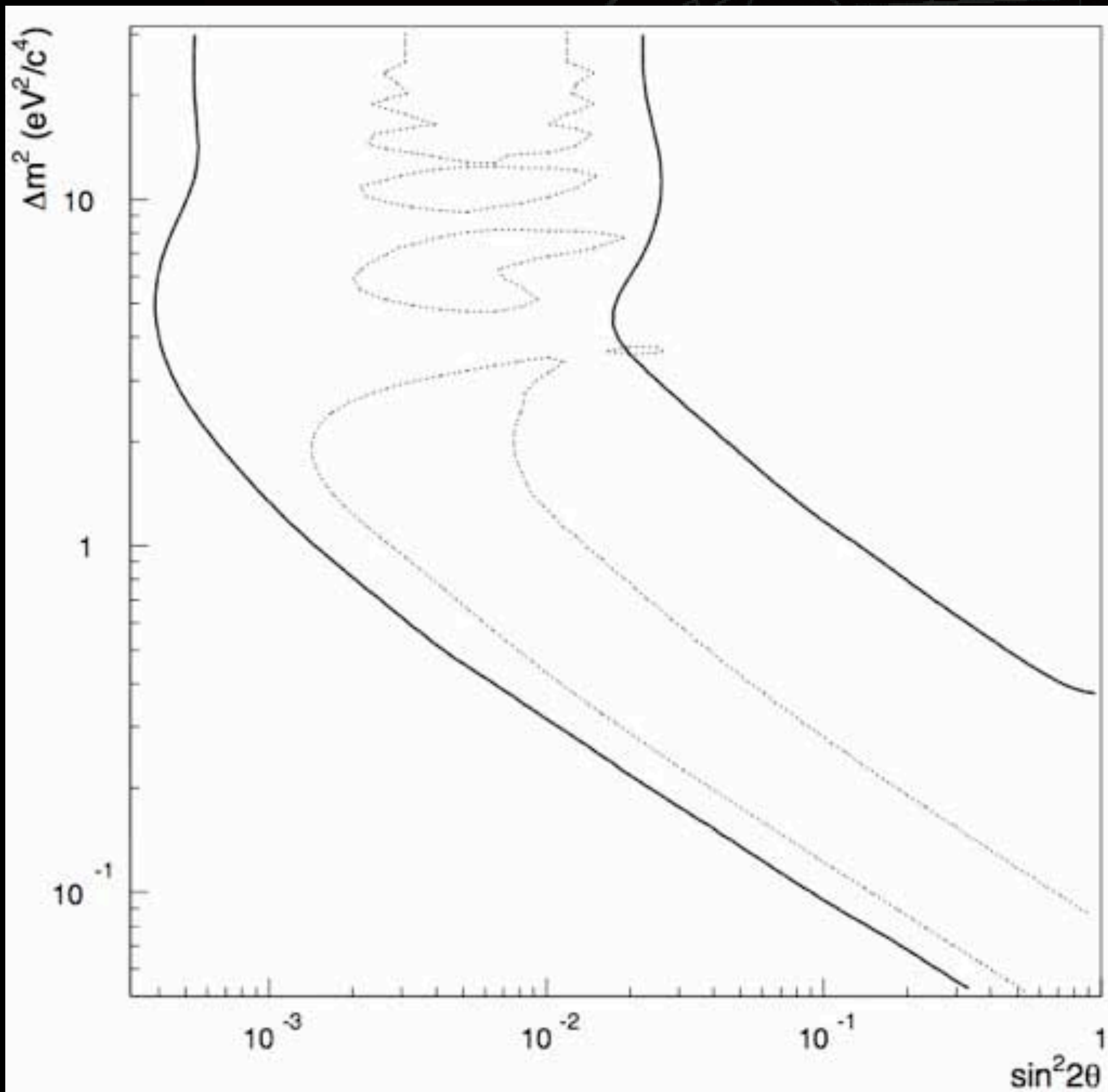
Deficit

Fitting down to 200 MeV

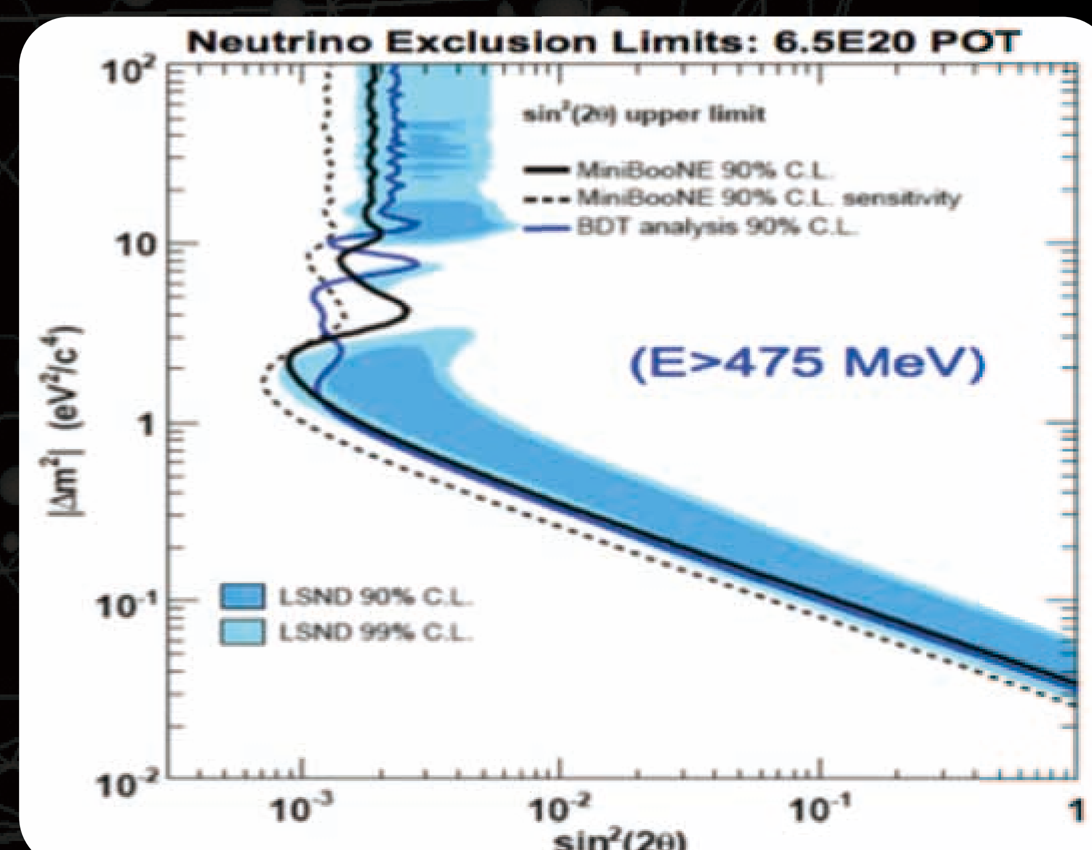


- Dashed pink and blue lines show fit result down to 475 MeV, solid lines extend fit down to 200 MeV
  - Only nubar are assumed to oscillate
  - No inclusion of low-E expectation
  - Large backgrounds in 200-475 means the region carries little weight in the fit
  - Get same result if 12 low E bkg events are added to low E region.

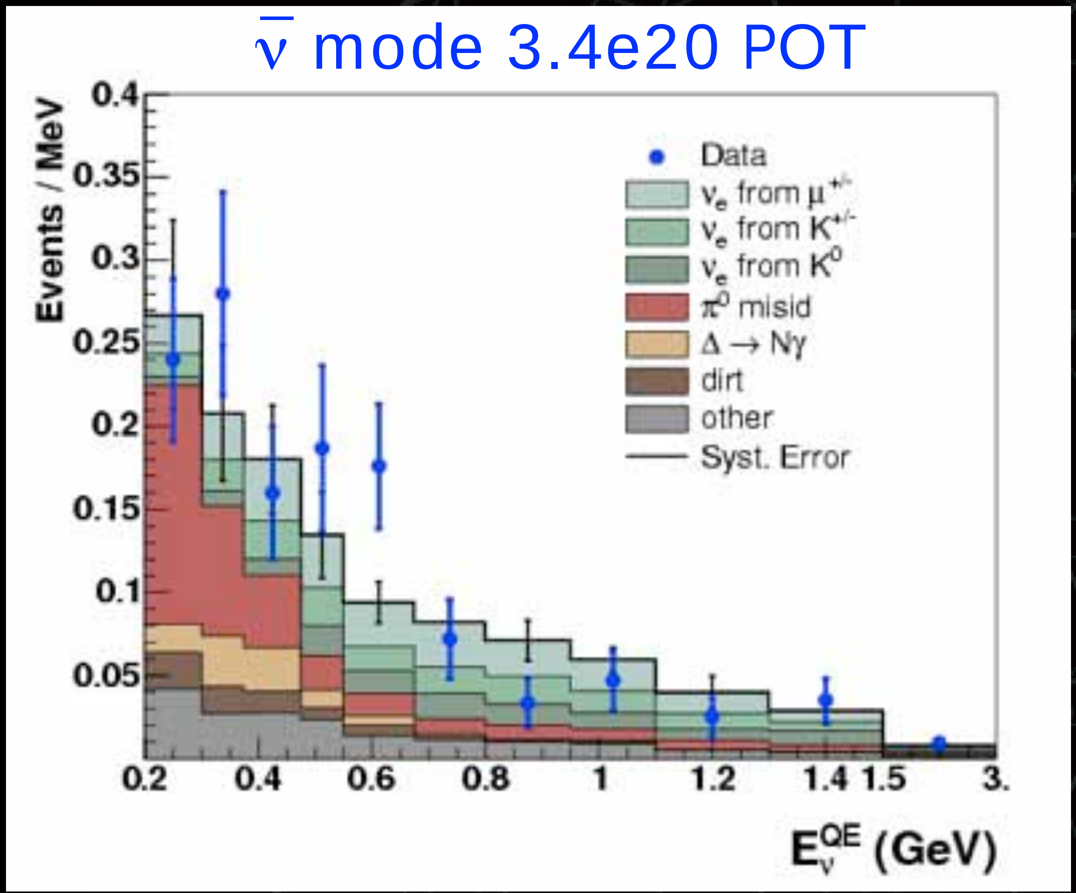
LSND ν_μ result

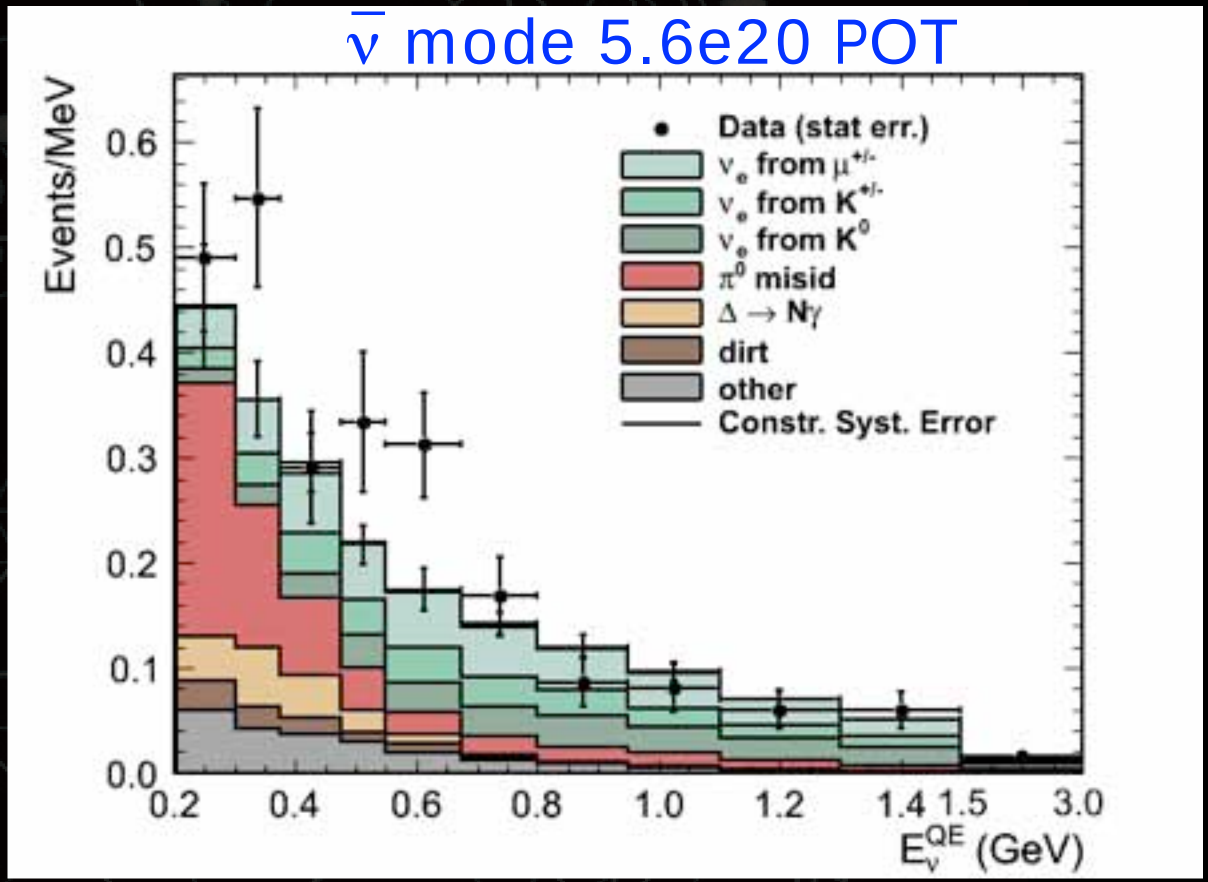


- LSND Found 40 events on a bkg of 21
- Excluded null at just > 2σ
- MB 90CL well within LSND 95CL
- Conclusion...some tension but it will be < 2σ



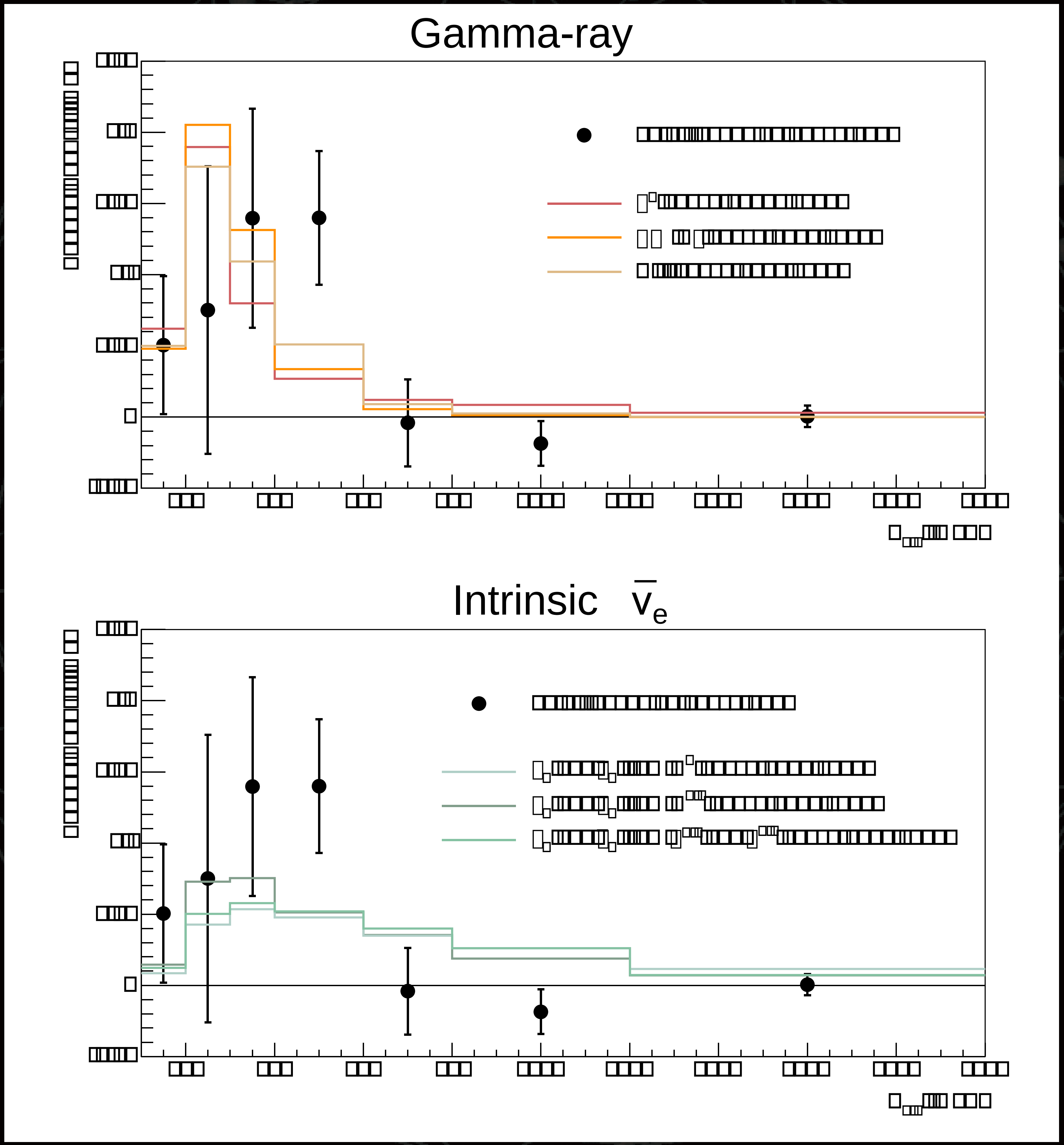
Comparing $\bar{\nu}$ results





- Nubar beam contains a 20% WS background, fits (above 475 MeV) assume only nubar are allowed to oscillate
- BG composition fairly similar, BG constraints re-extracted
- Consistent at 1.5σ level

Background $\bar{\nu}_e$ Evis distributions for 5.66E20 POT



Other $\bar{\nu}_e$ kinematic distributions for 5.66E20 POT