

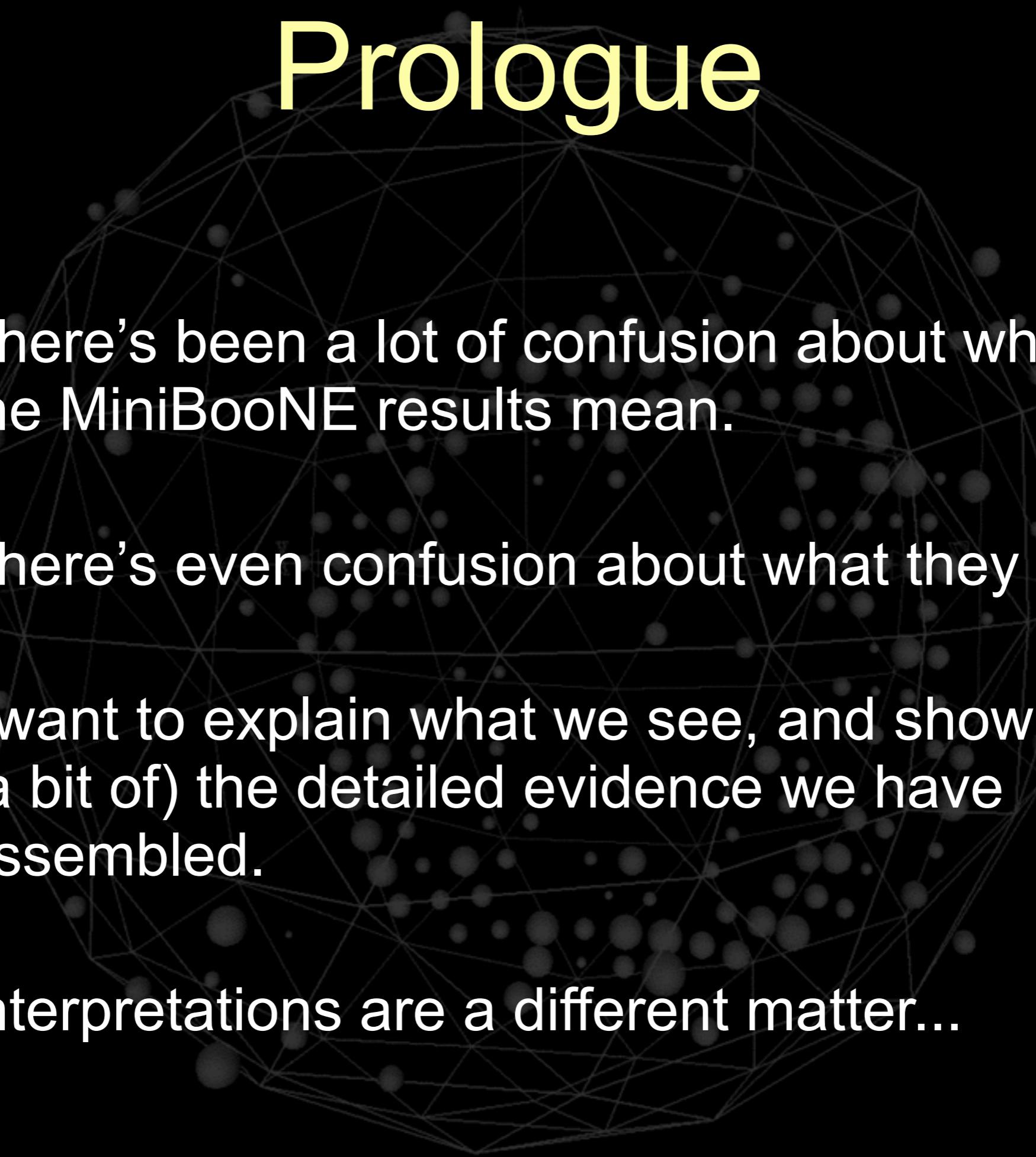


Search for sterile neutrinos at $\Delta m^2 \sim 1$ eV with MiniBooNE

Morgan O. Wascko
Imperial College London

IOP Half Day Meeting
2011 04 18

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 (a bit of) the detailed evidence we have assembled.
- Interpretations are a different matter...

Outline

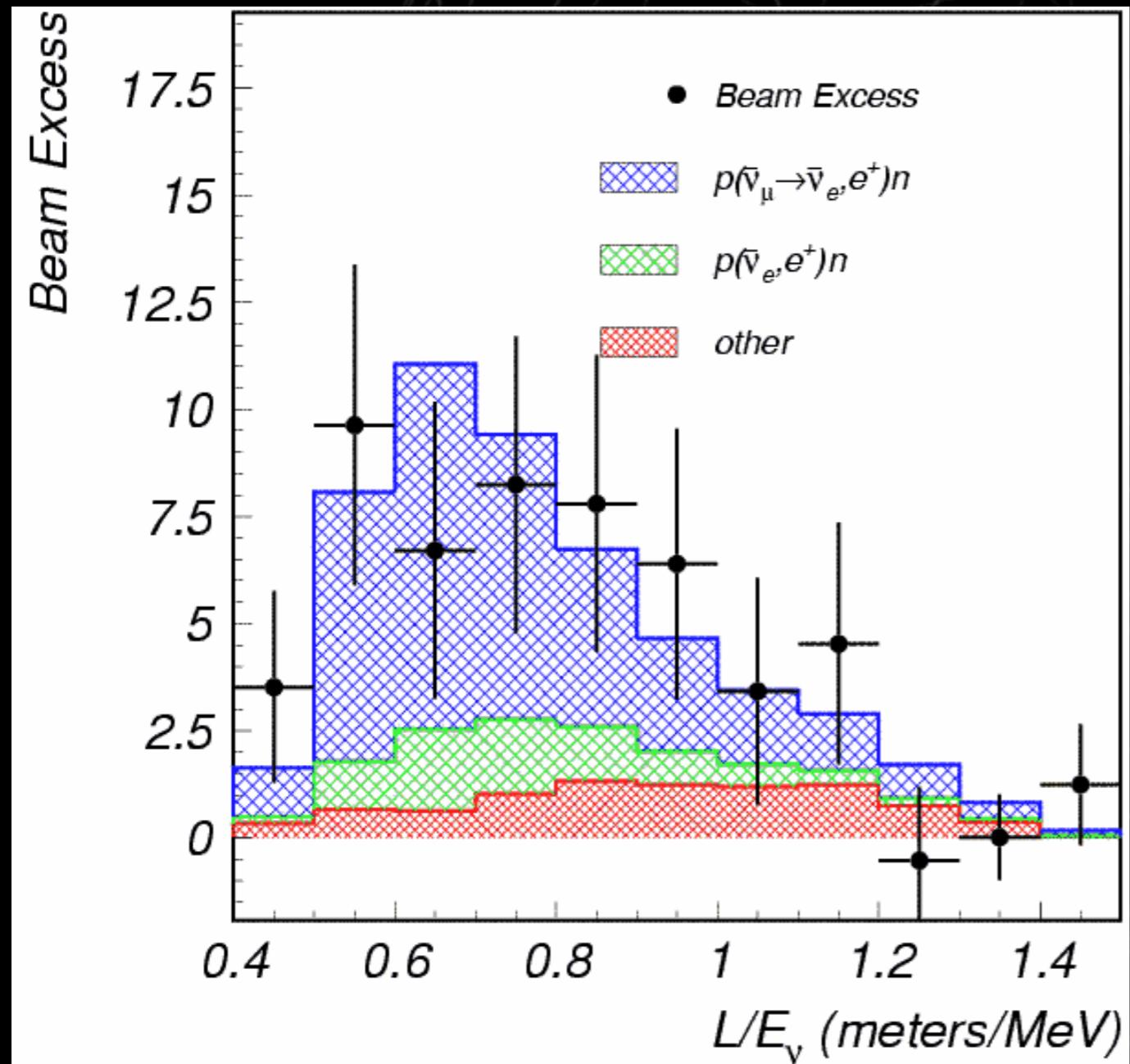
- Motivation
- MiniBooNE description
- MiniBooNE oscillation analysis & results
- Summary and outlook

The LSND signal

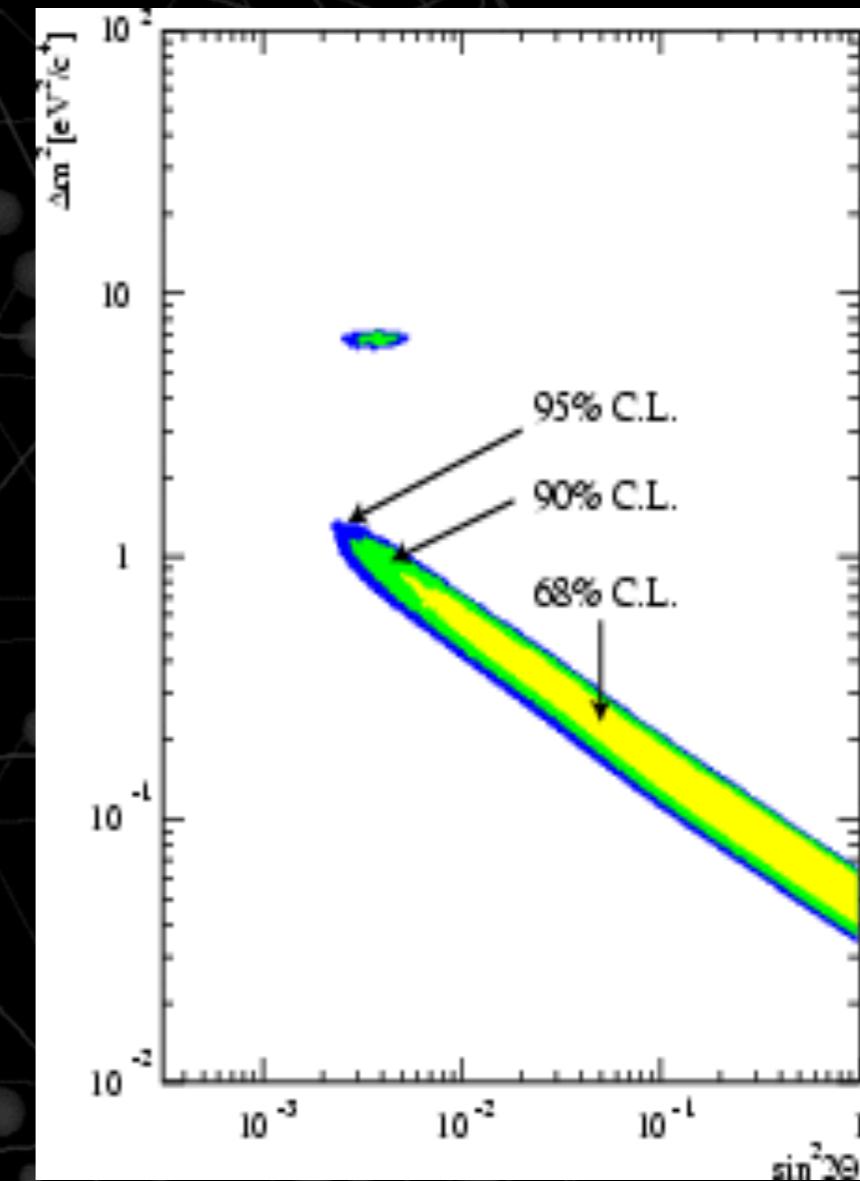
- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation probability:

$$0.264 \pm 0.067 \pm 0.045\%$$

3.8 σ excess!



[hep-ex/0104049](#)



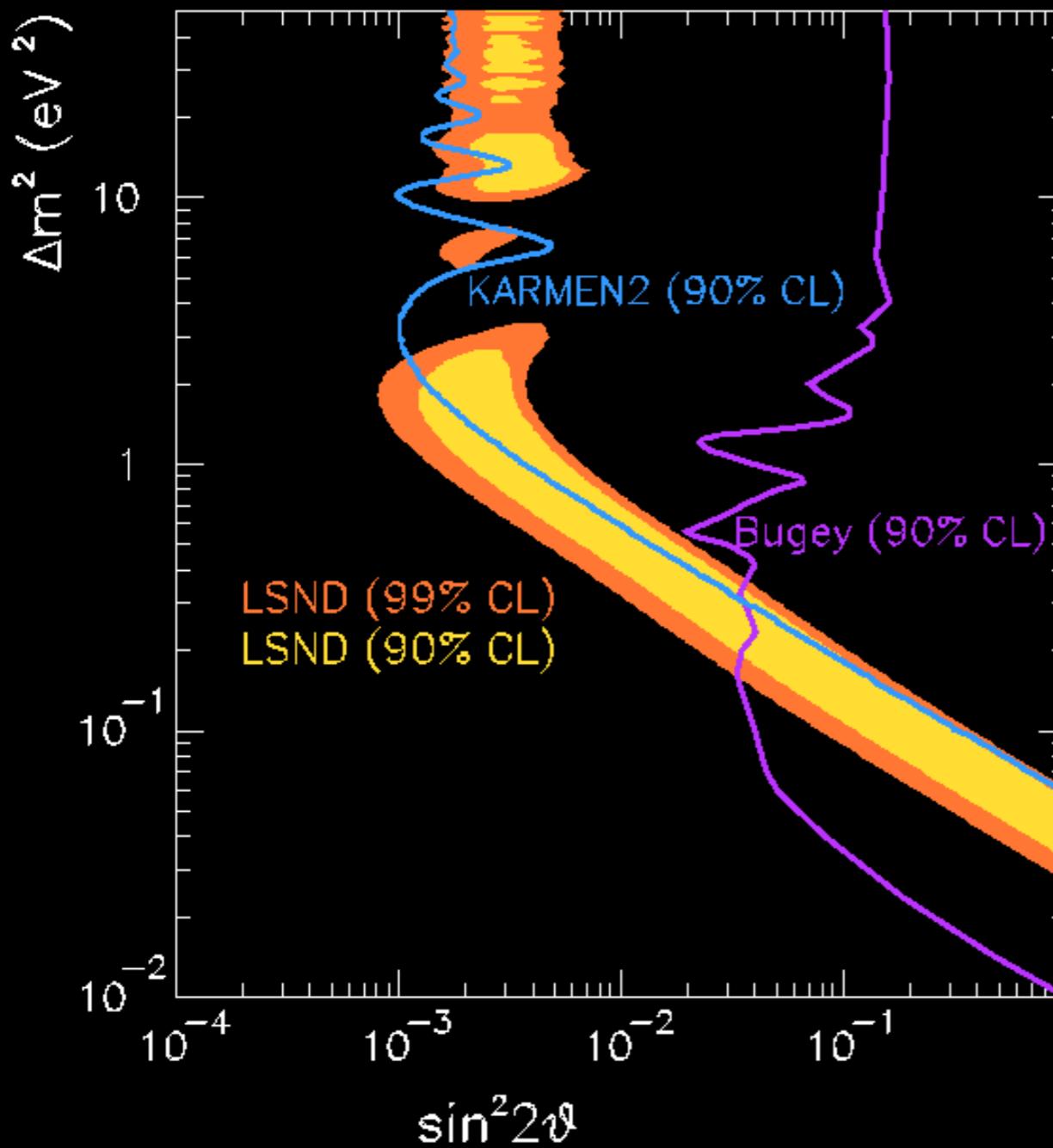
KARMEN2 and LSND collaborators performed joint analysis on both data sets - allowed regions remain!

$$\Delta m^2 \sim 1 \text{ eV}^2, \theta \sim 2^\circ$$

[hep-ex/0203023](#)

Verifying LSND

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



- LSND interpreted as 2 ν oscillation
- Verification requires same (L/E) and high statistics
- Different systematics
- MiniBooNE chose higher L and higher E
- Strategy:
 - First, ν_e excess in ν_μ beam?
 - Then, $\bar{\nu}_e$ excess in $\bar{\nu}_\mu$ beam?

MiniBooNE Collaboration

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Blacksburg, VA 24061

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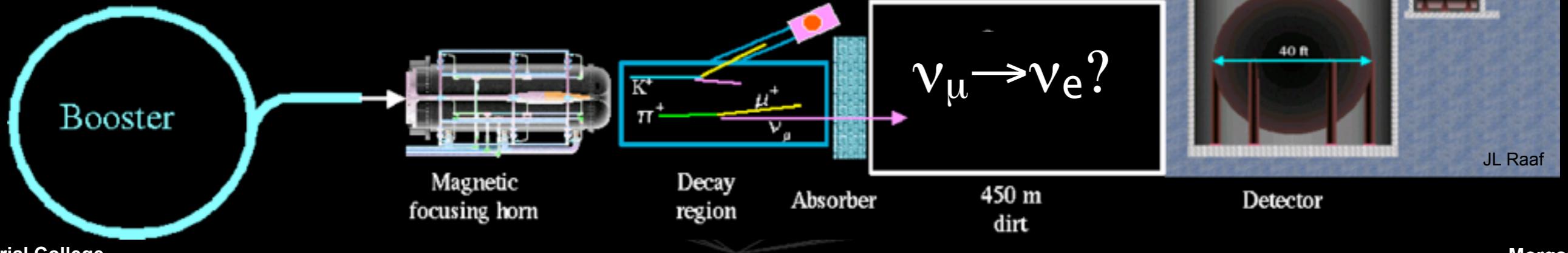
¹⁶ Yale University, New Haven, CT 06520



Overview



MiniBooNE Overview

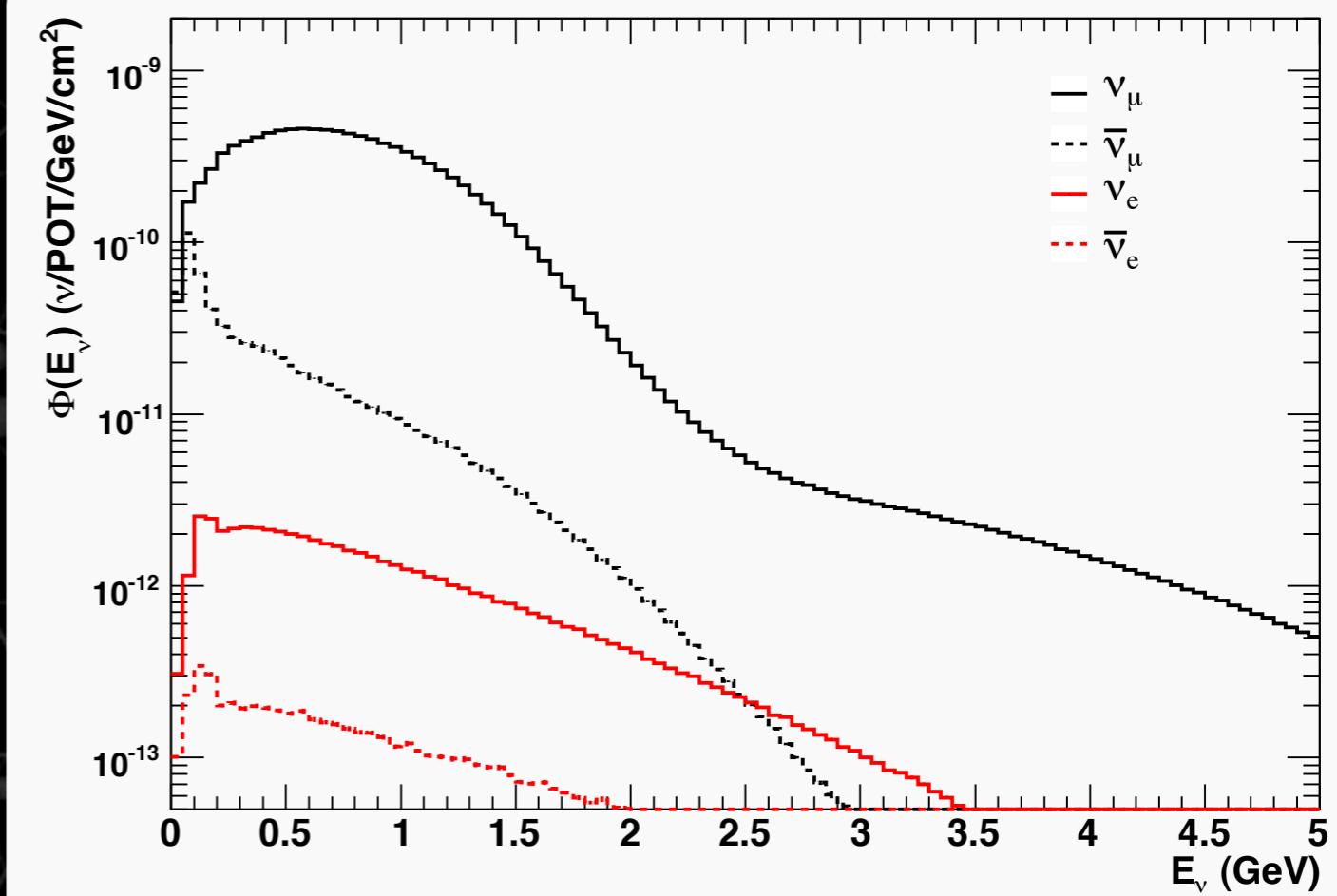


ν Flux

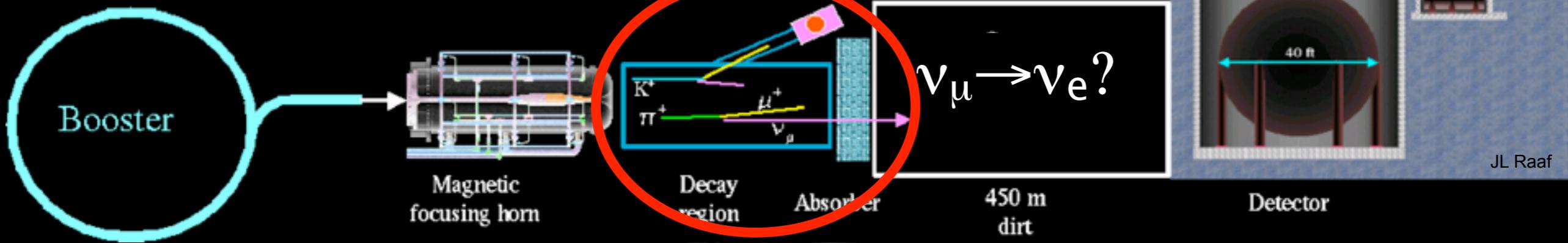
Neutrino Mode

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



MiniBooNE Overview

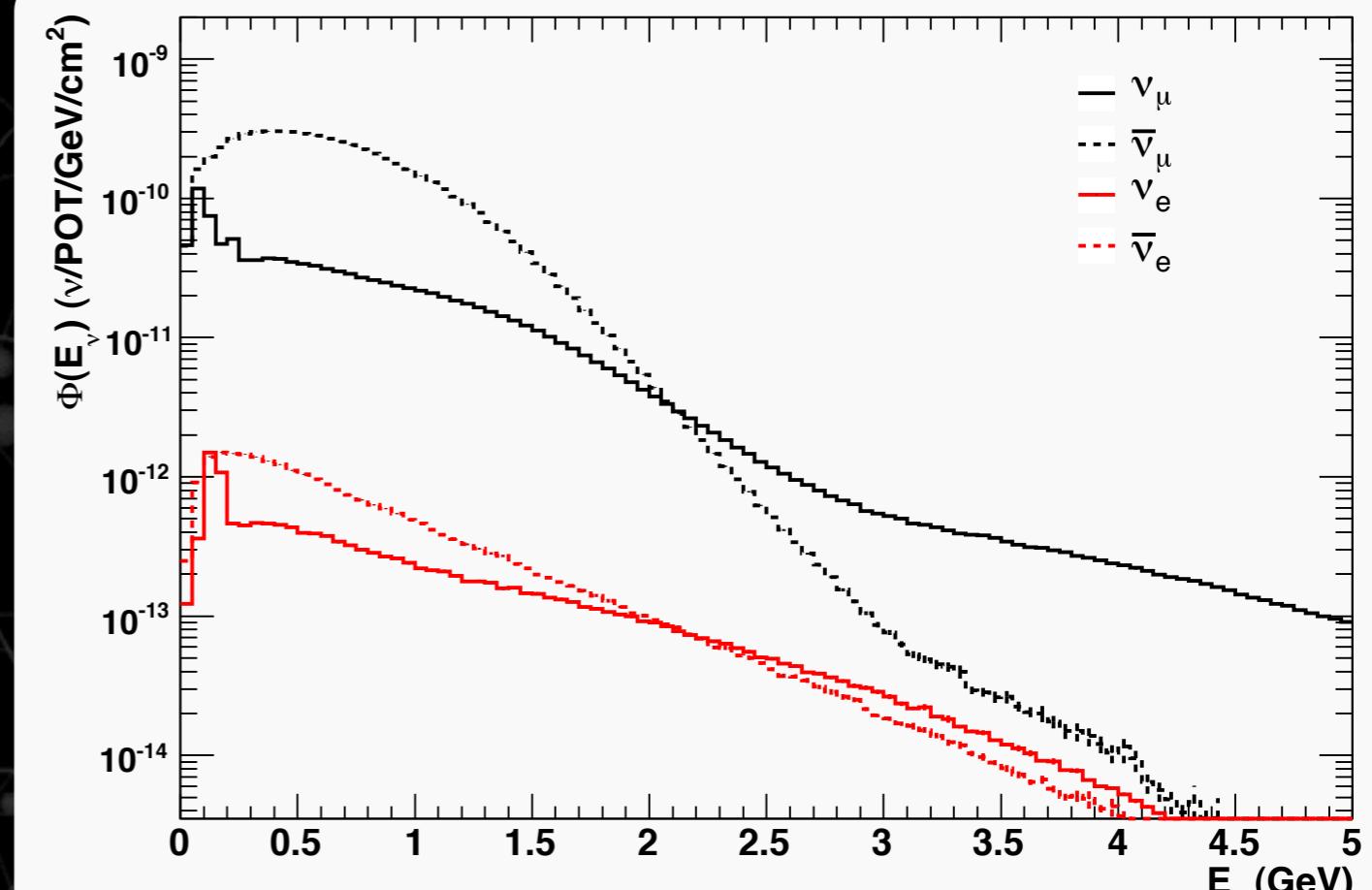


$\bar{\nu}$ Flux

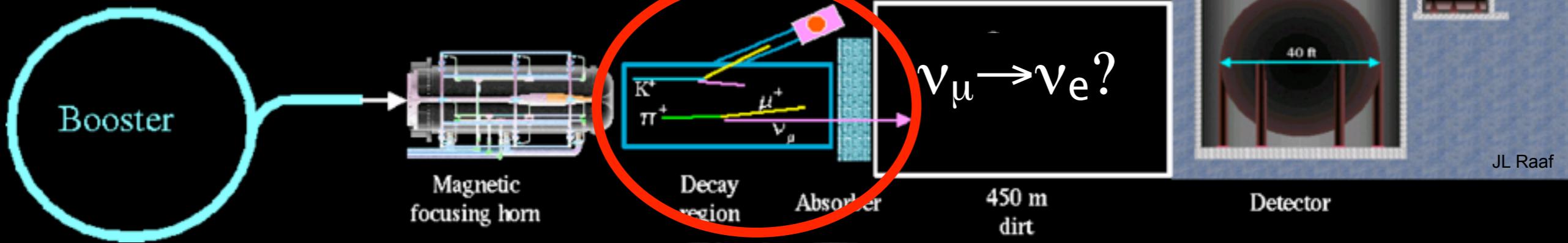
Antineutrino Mode

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

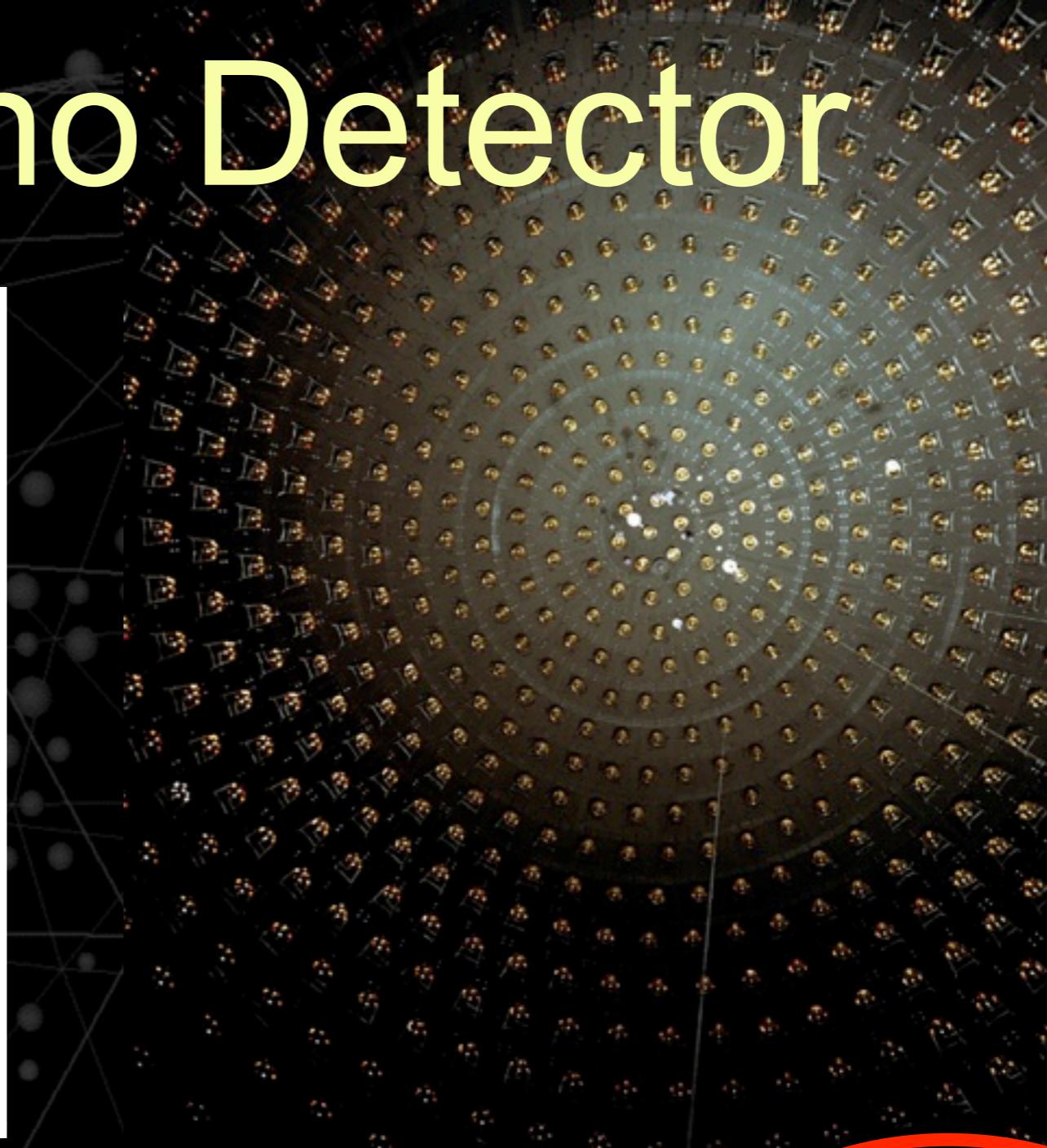
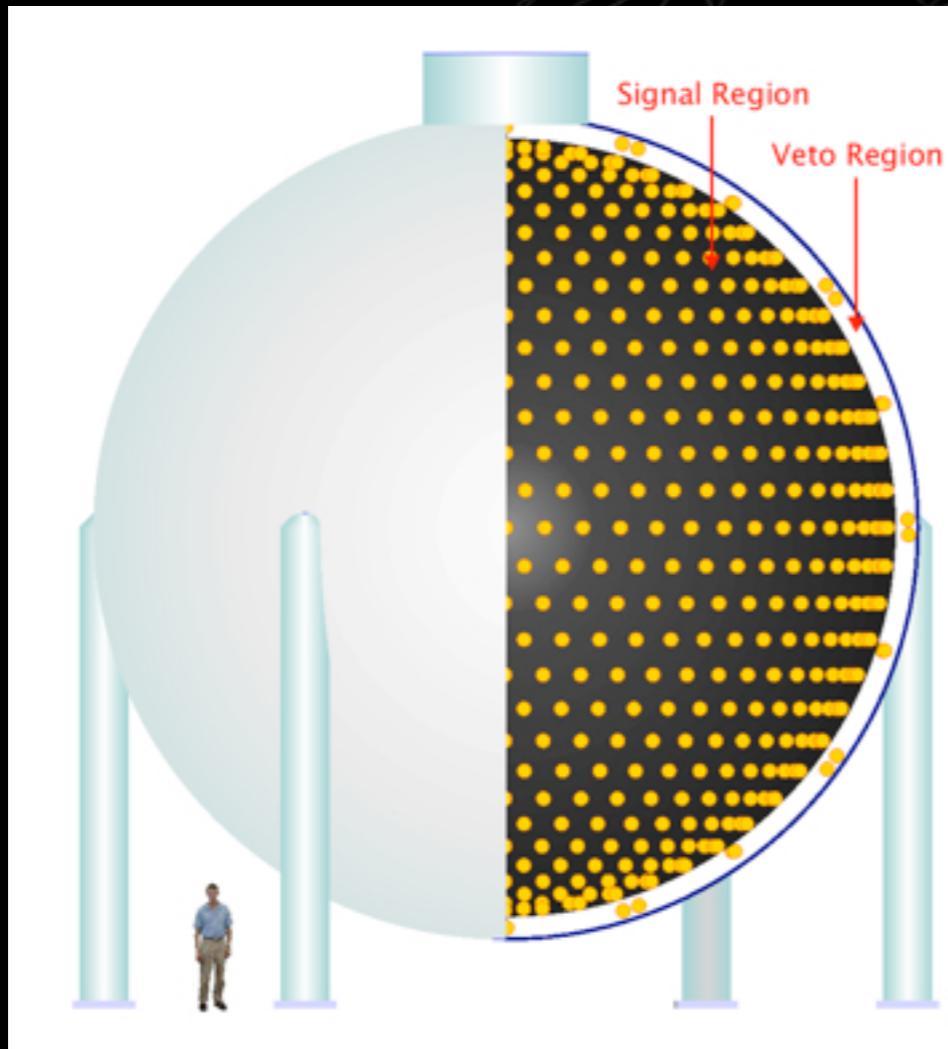


MiniBooNE Overview

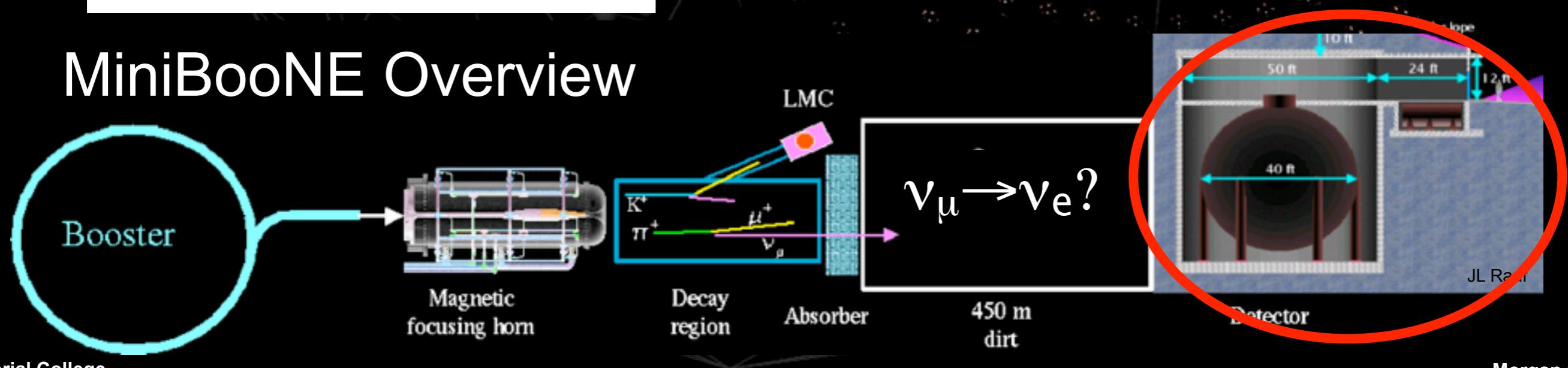


Neutrino Detector

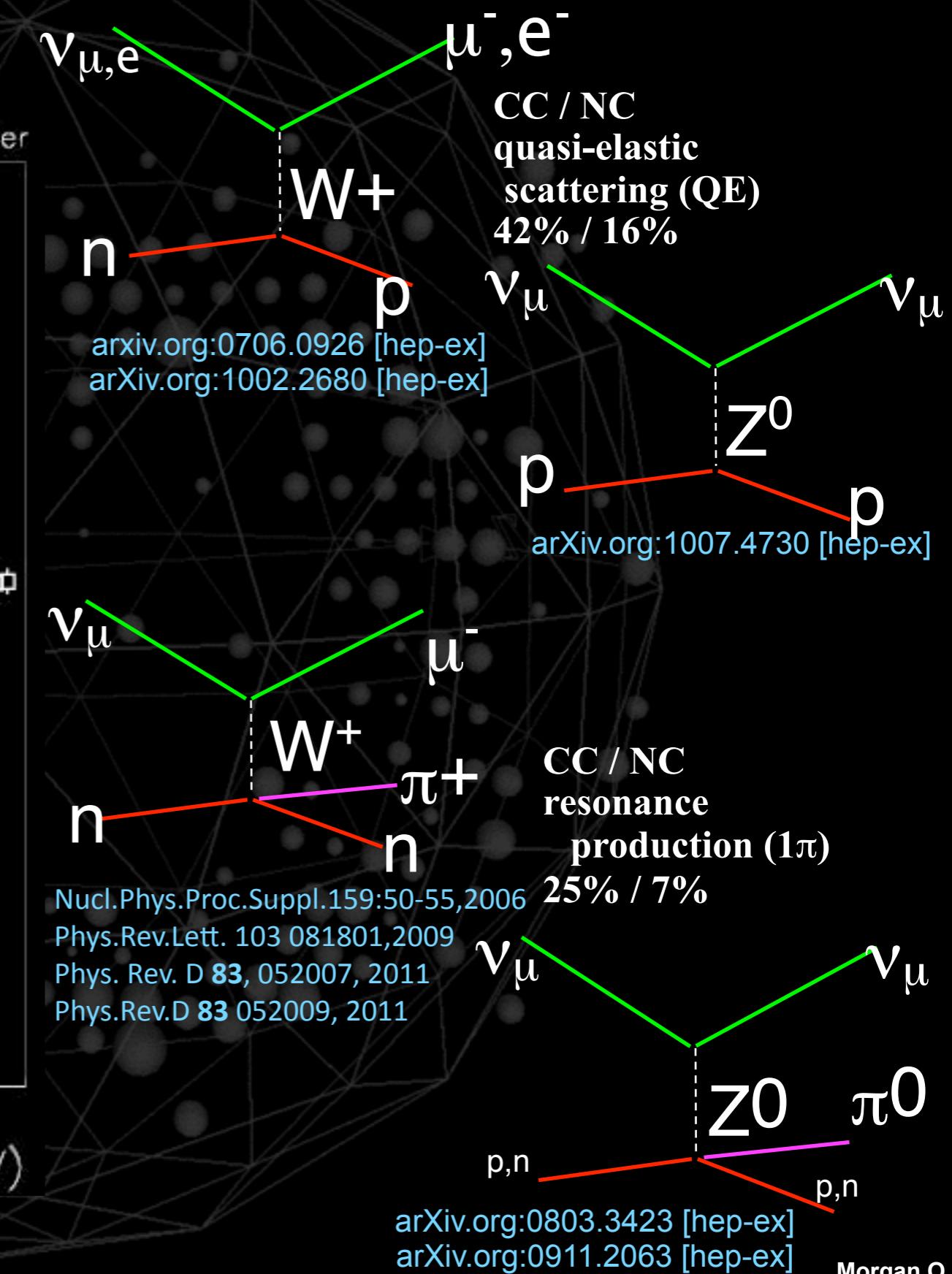
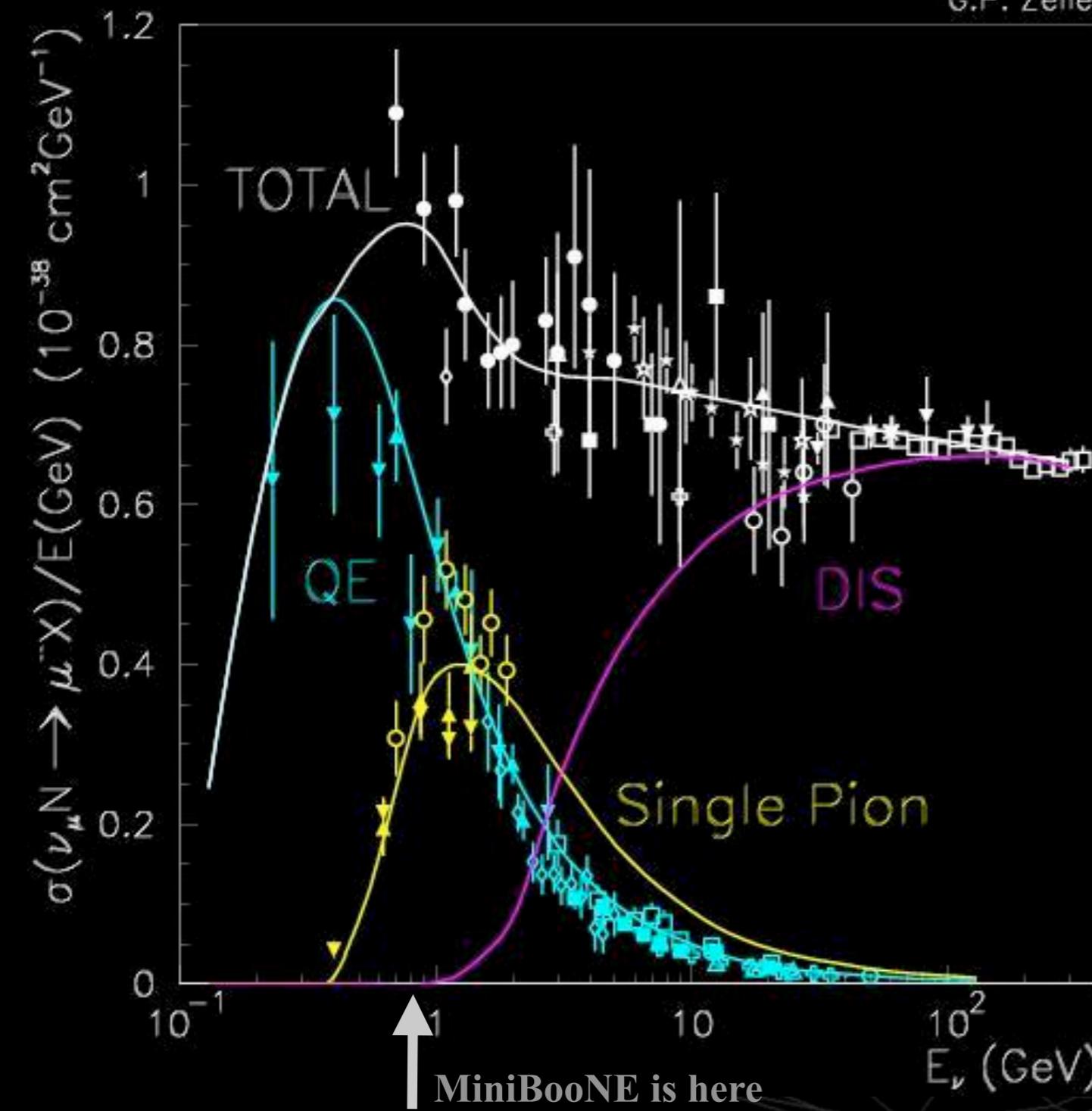
NIMA 599 (2009) 28-46



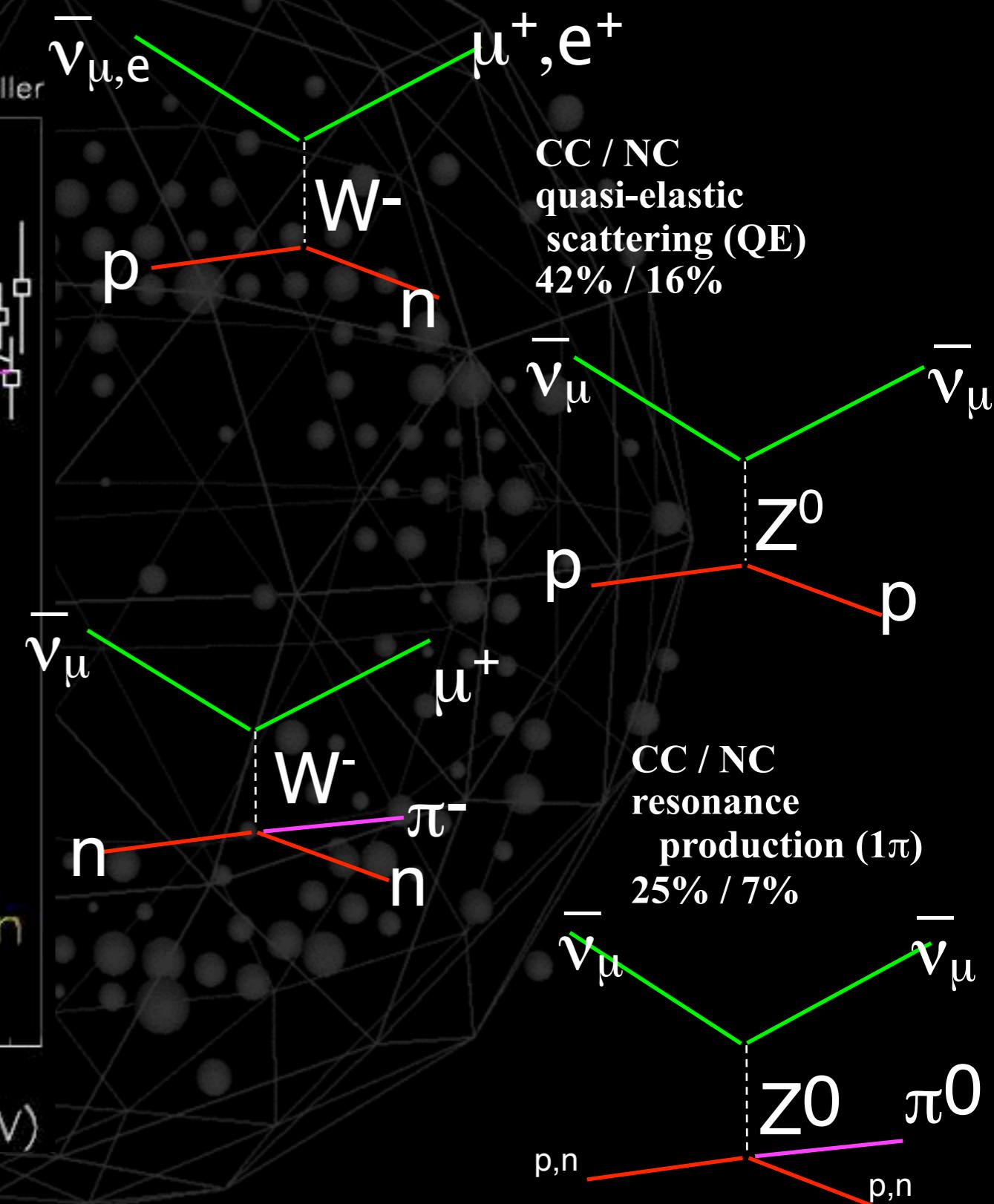
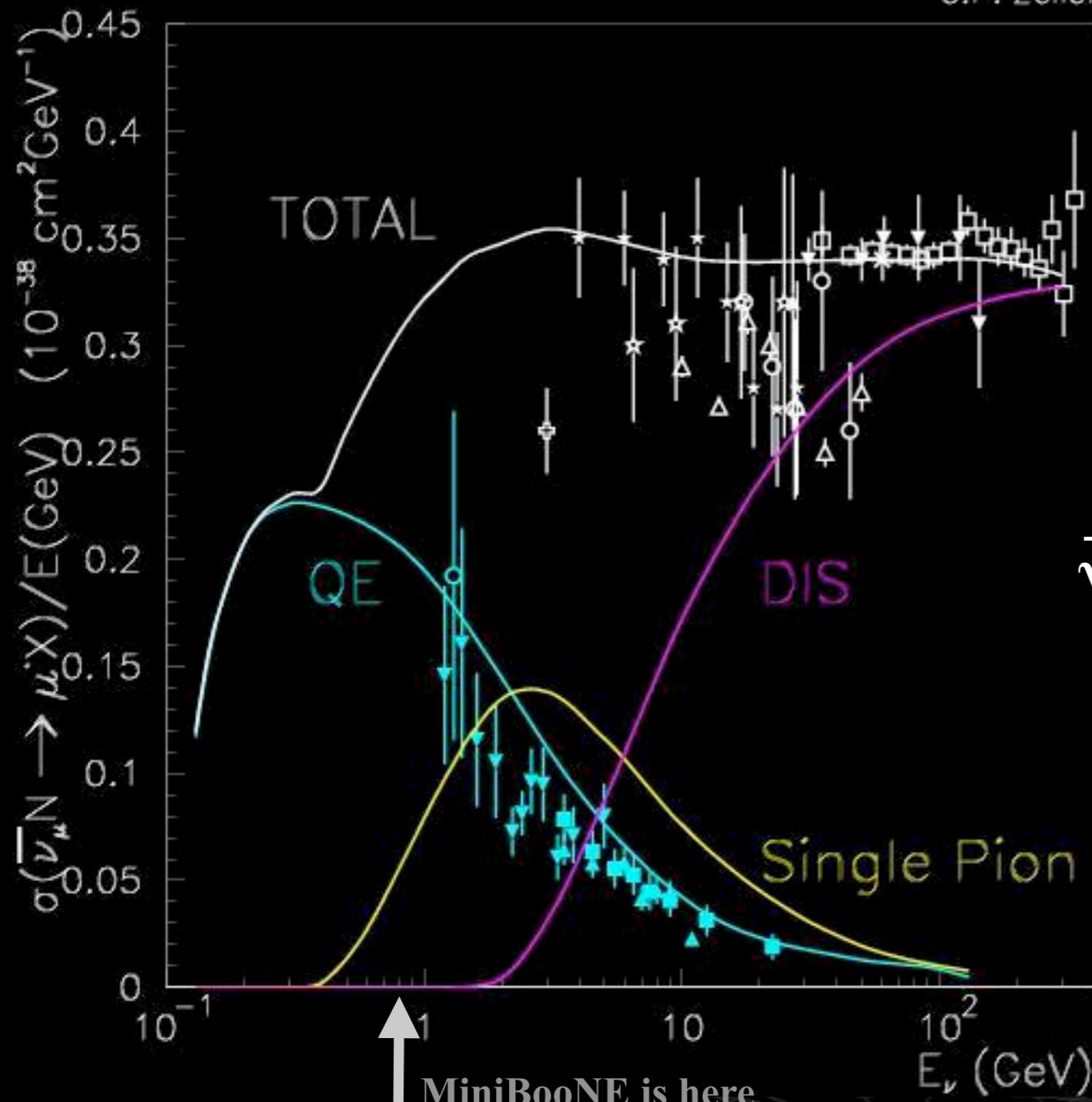
MiniBooNE Overview



ν Interactions

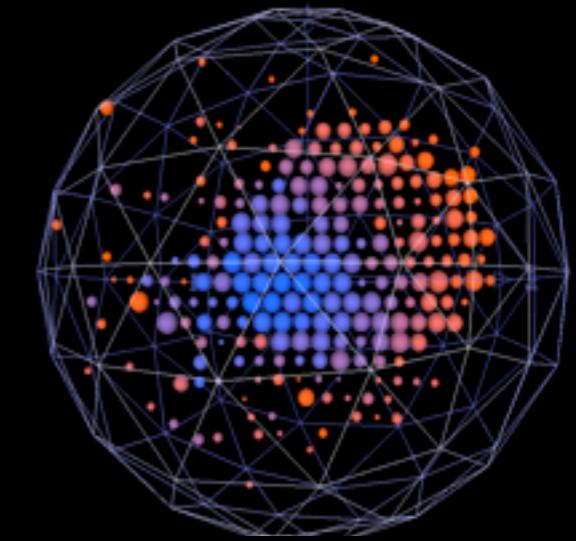
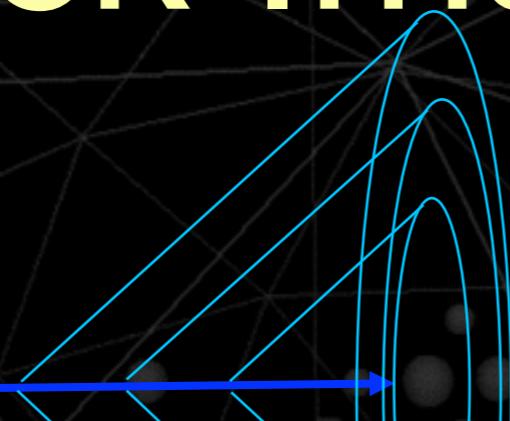


v Interactions

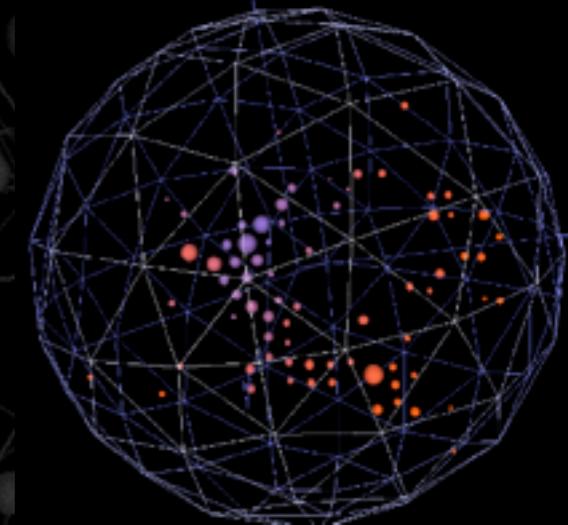
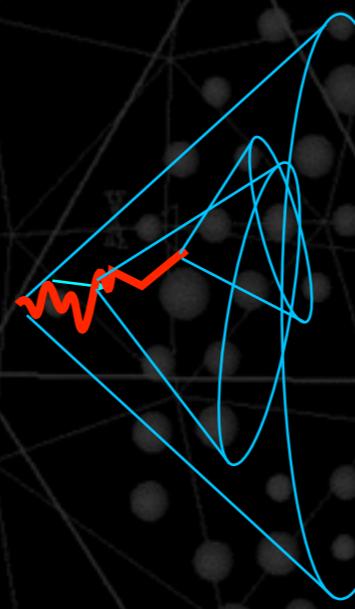


Track Images

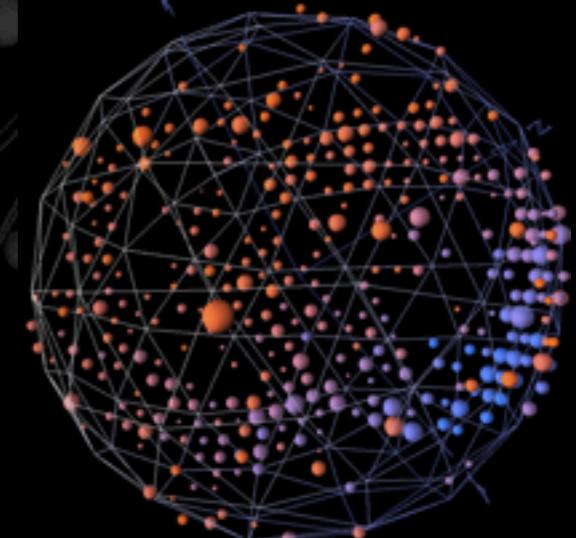
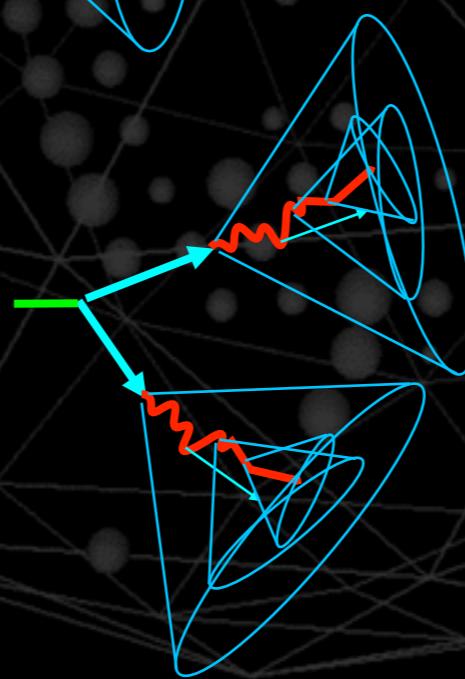
- Muons
 - full rings



- Electrons
 - fuzzy rings

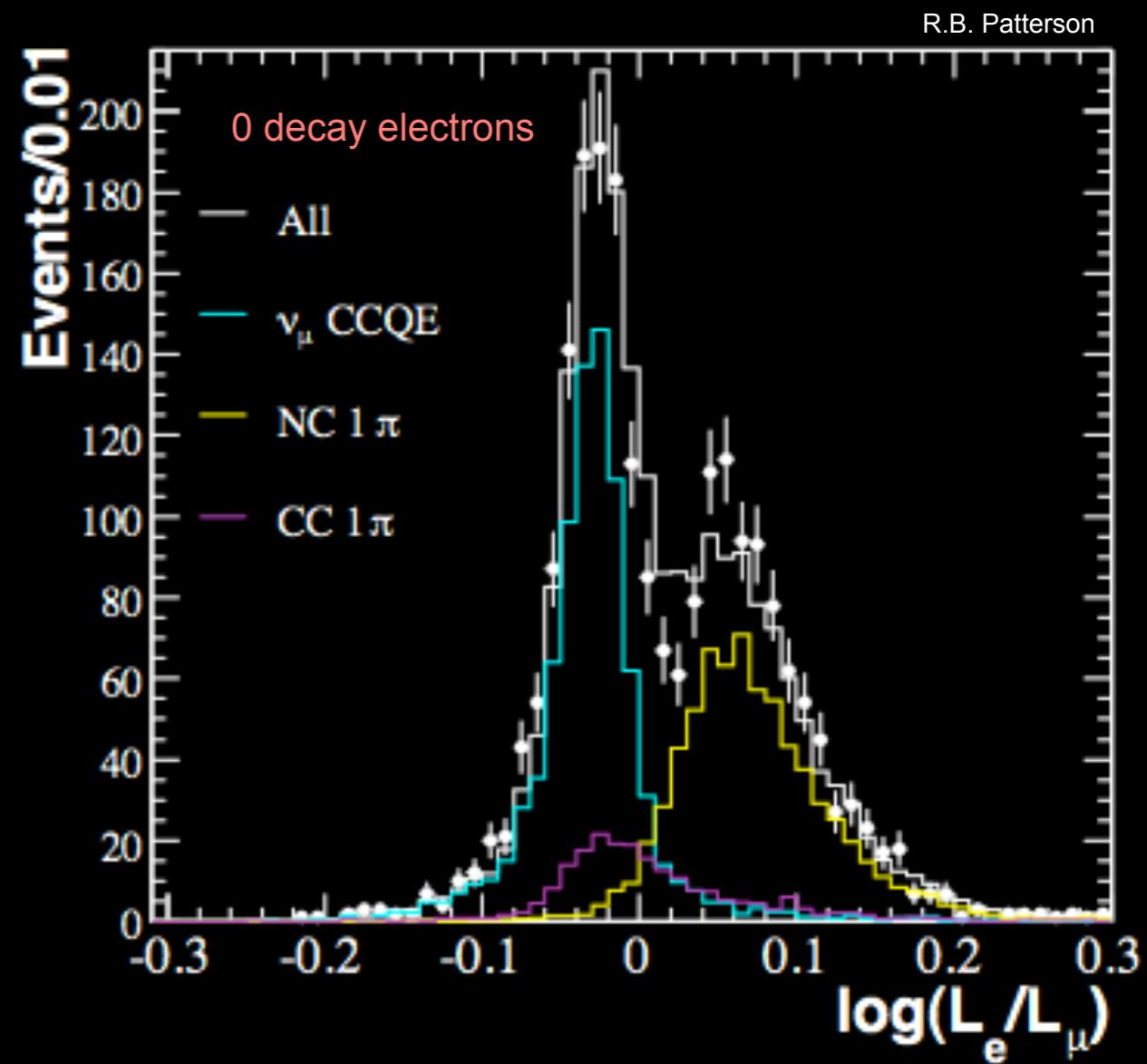
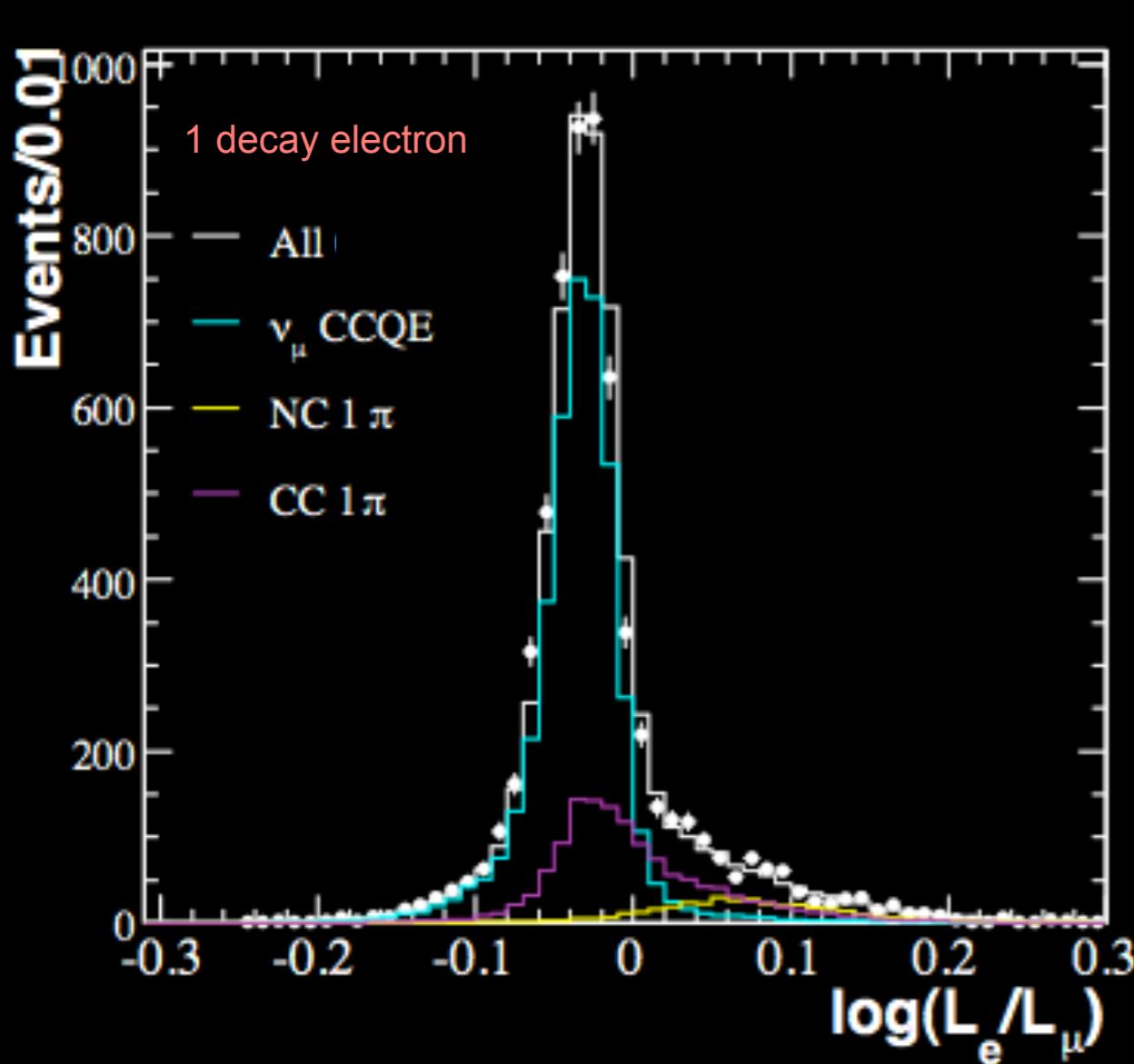


- Neutral pions
 - double rings



e/ μ Likelihood

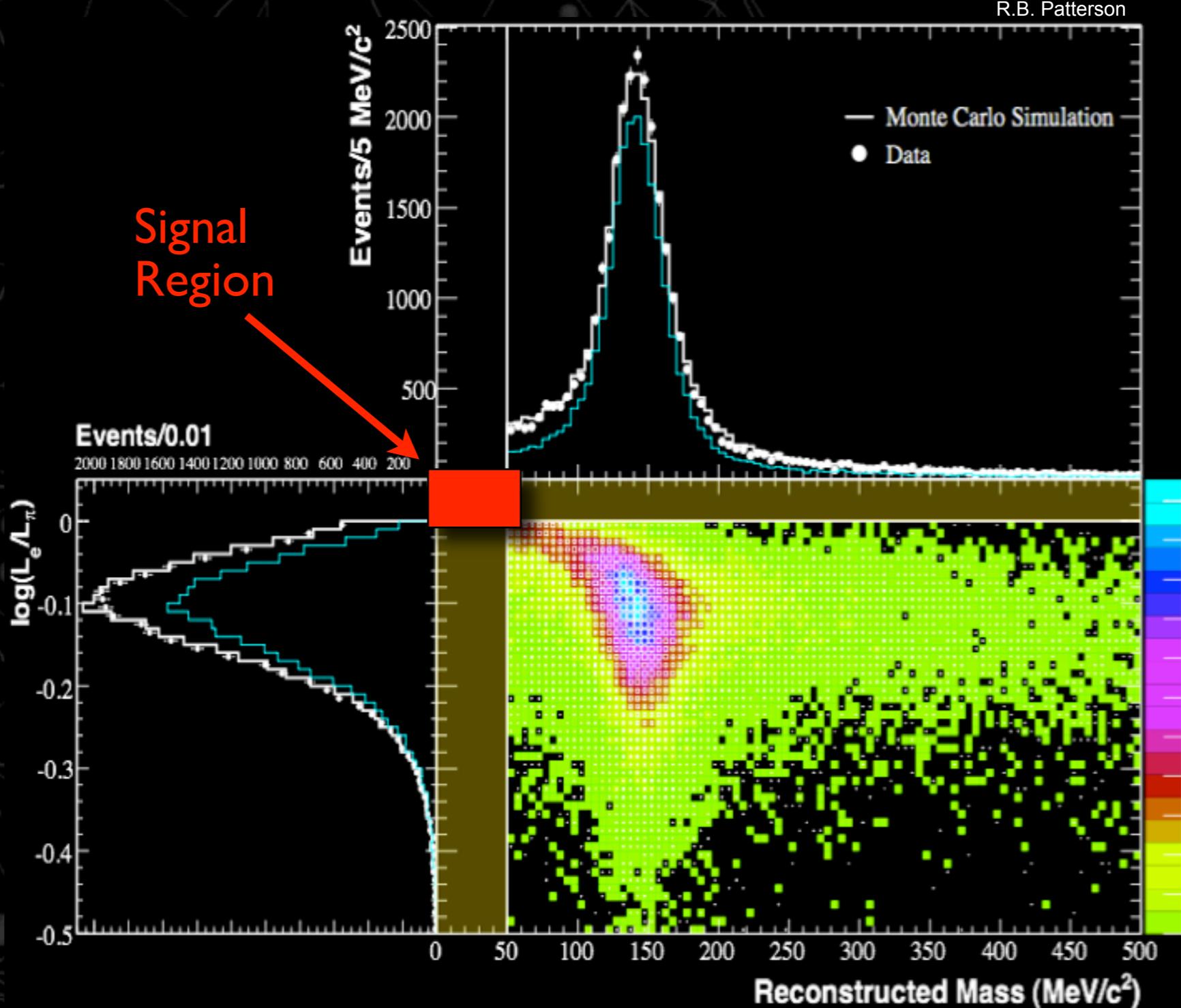
- ν_μ CCQE data (with muon decay electron) compared to ν_μ data with no decay electrons (“All but signal”)
- Removes most muon events



[arXiv:0902.2222 \[hep-ex\]](https://arxiv.org/abs/0902.2222)

e/ π^0 Likelihood

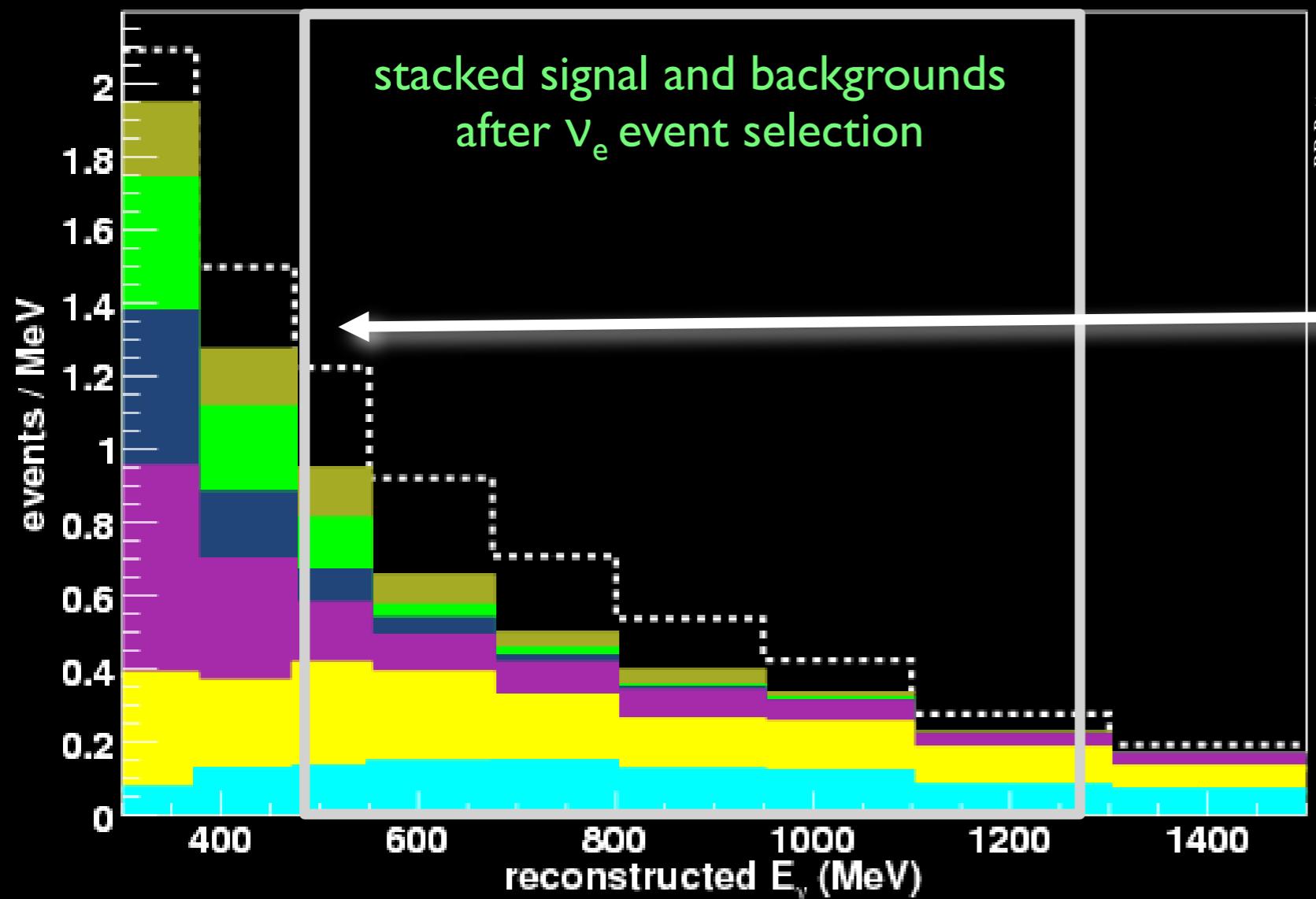
- Data and MC
- PID uses cuts on
 - likelihood ratio
 - reconstructed π^0 mass
- Study sidebands before unblinding full data sample



Oscillation Analysis

Signal & Backgrounds

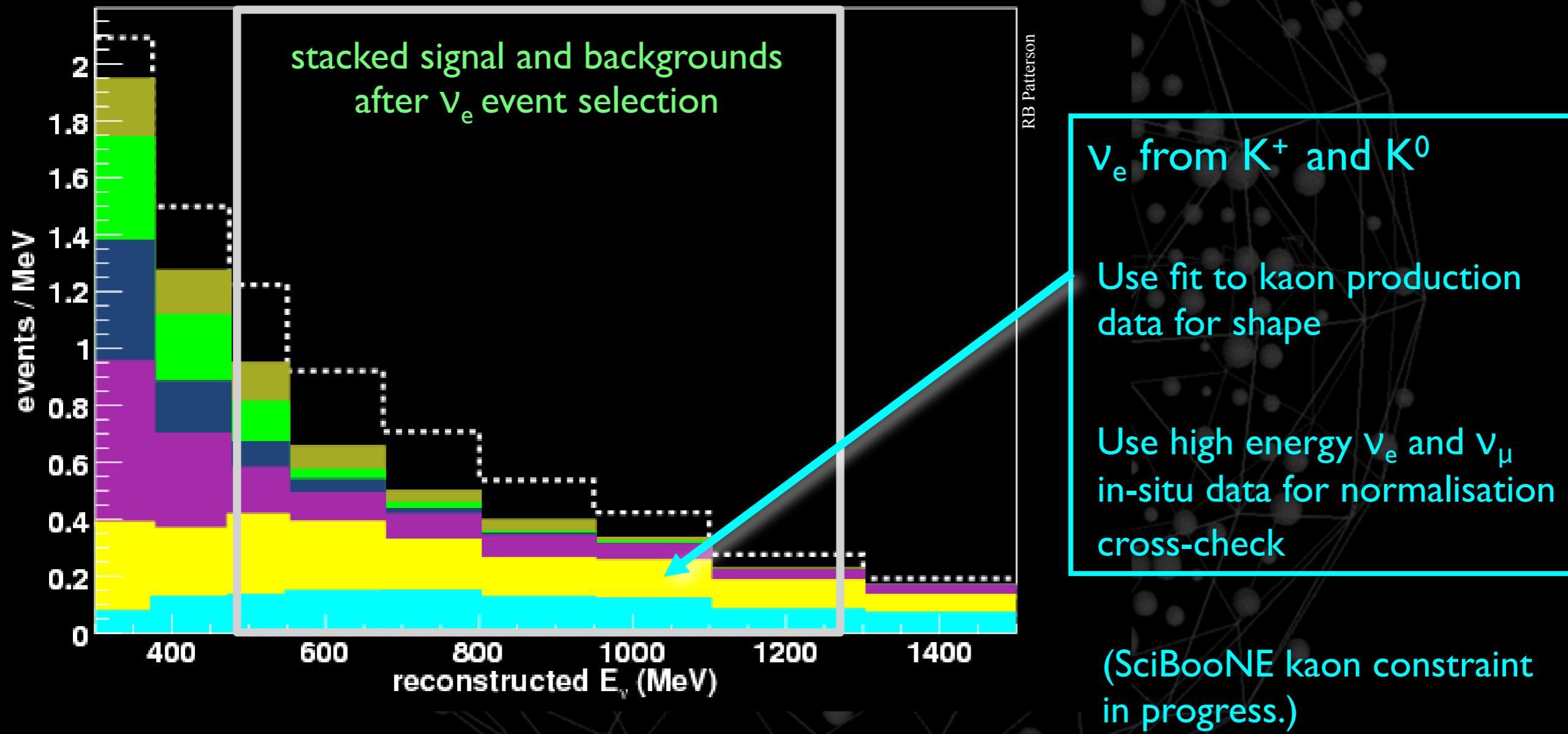
Example from neutrino mode



Oscillation ν_e
Example oscillation signal
 $\Delta m^2 = 1.2 \text{ eV}^2$
 $\sin^2 2\theta = 0.003$
Fit for excess as a function of
reconstructed ν_e energy

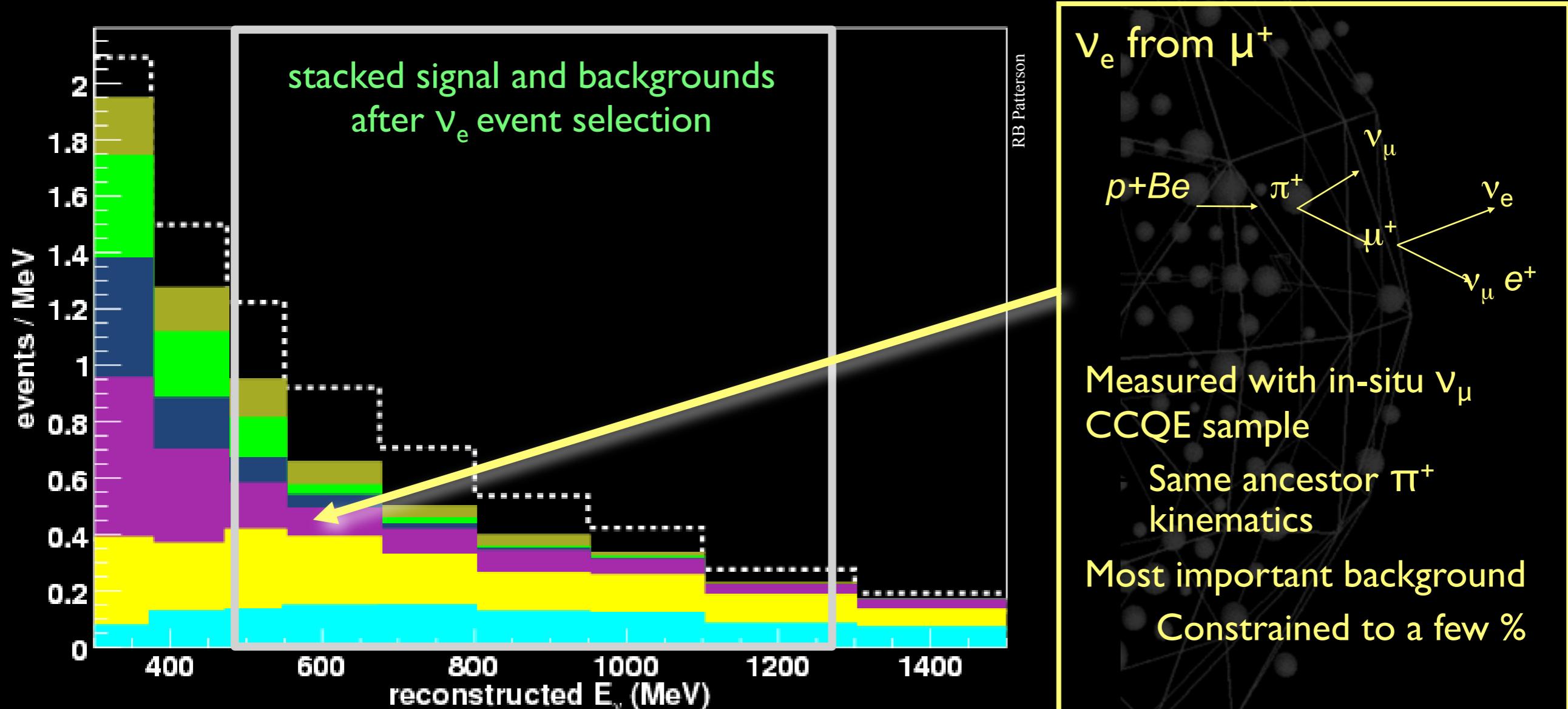
Signal & Backgrounds

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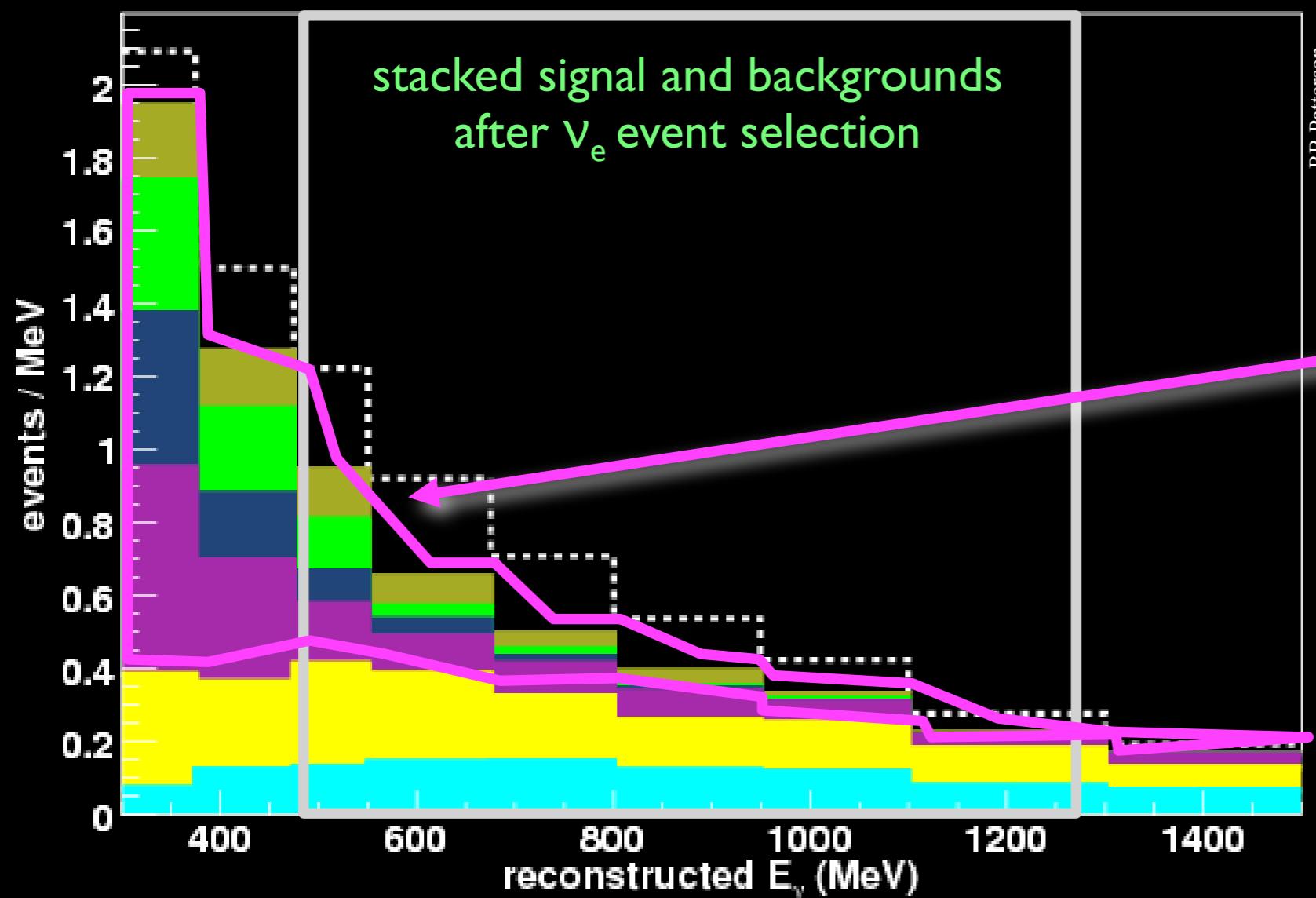
Signal & Backgrounds

Example from neutrino mode



Signal & Backgrounds

Example from neutrino mode



MisID ν_μ
~46% π^0
Determined by clean π^0
measurement
~16% $\Delta \gamma$ 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

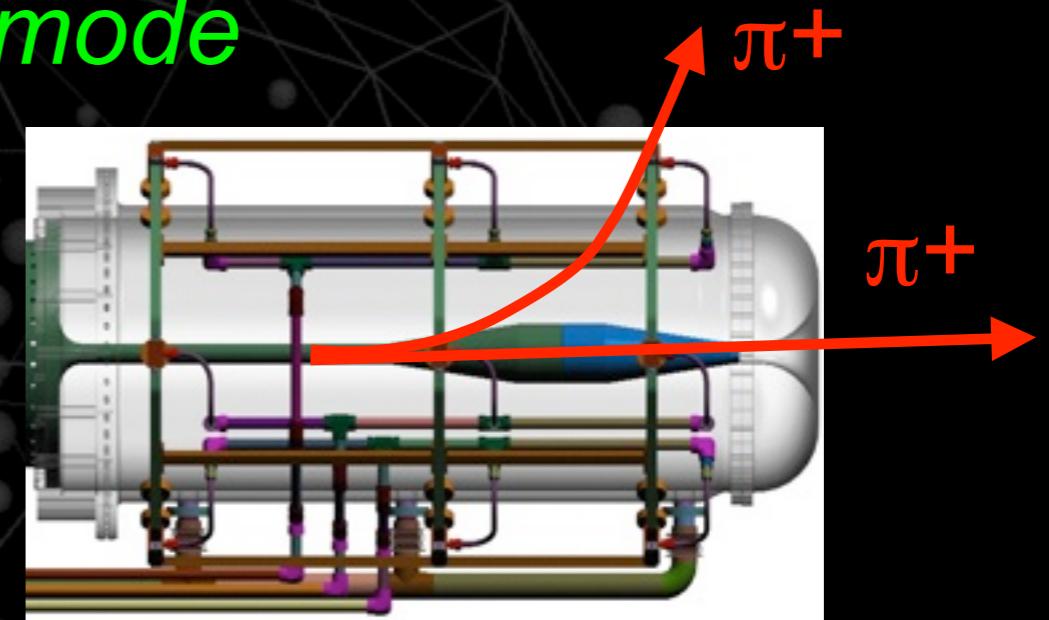
Additional Background

Antineutrino mode

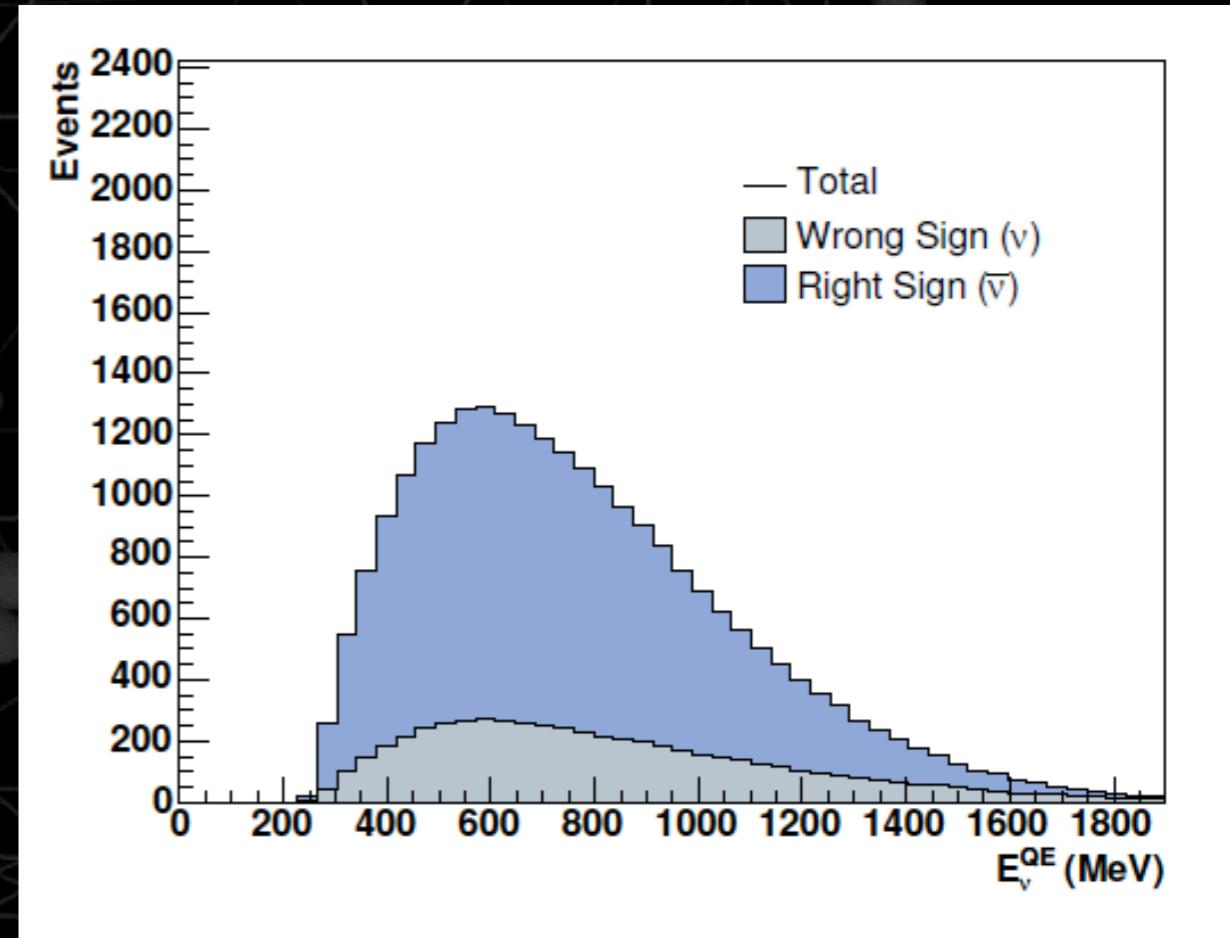
- Antineutrino beam contains significant fraction of “wrong sign” neutrino events
 - Stem from unfocussed pions in secondary beam
 - ~20% of reconstructed events in nubar mode
- MinBooNE cannot sign select events
 - Need other methods to constrain WS BGs

MiniBooNE Phase II Letter of Intent

Nucl.Phys.Proc.Supp.159:79-84,2006



G. Karagiorgi



Combined fit of ν_μ & ν_e data

- For each $E\nu$ bin i ,

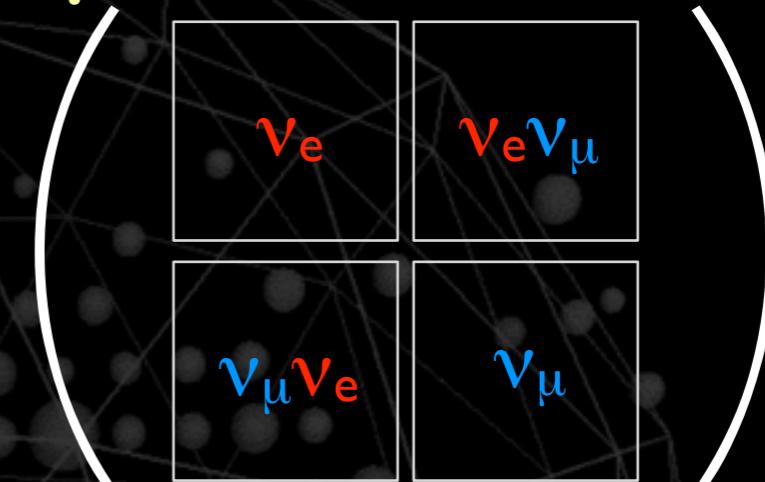
$$\Delta_i = N_i^{DATA} - N_i^{MC}$$

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

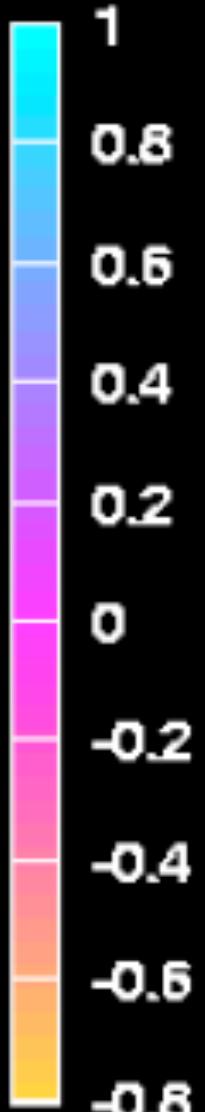
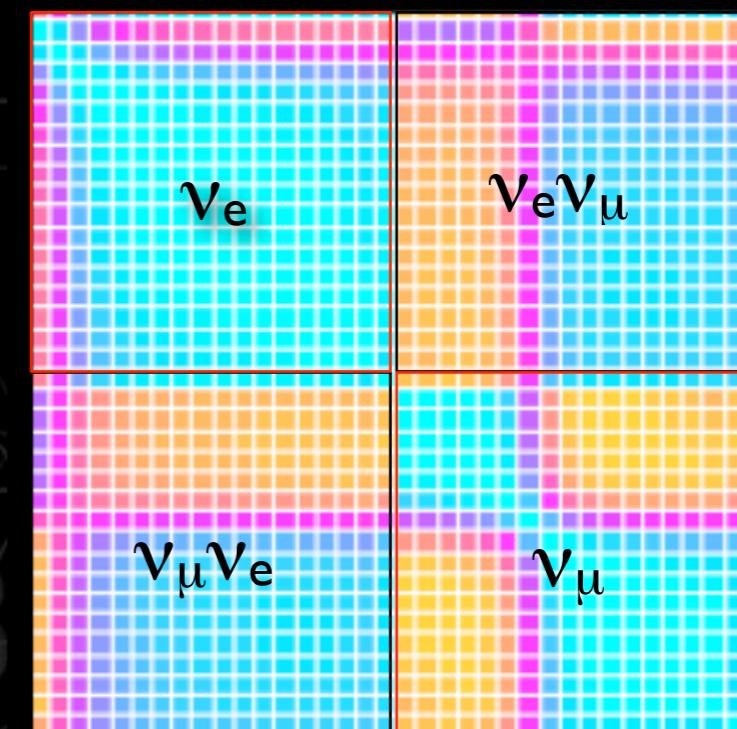
$$-2 \ln(\mathcal{L}) = \vec{\Delta M}^{-1} \vec{\Delta T} + \ln(|M|)$$

- Systematic error matrix includes uncertainties for ν_e and ν_μ

ν_μ data plays role of near detector



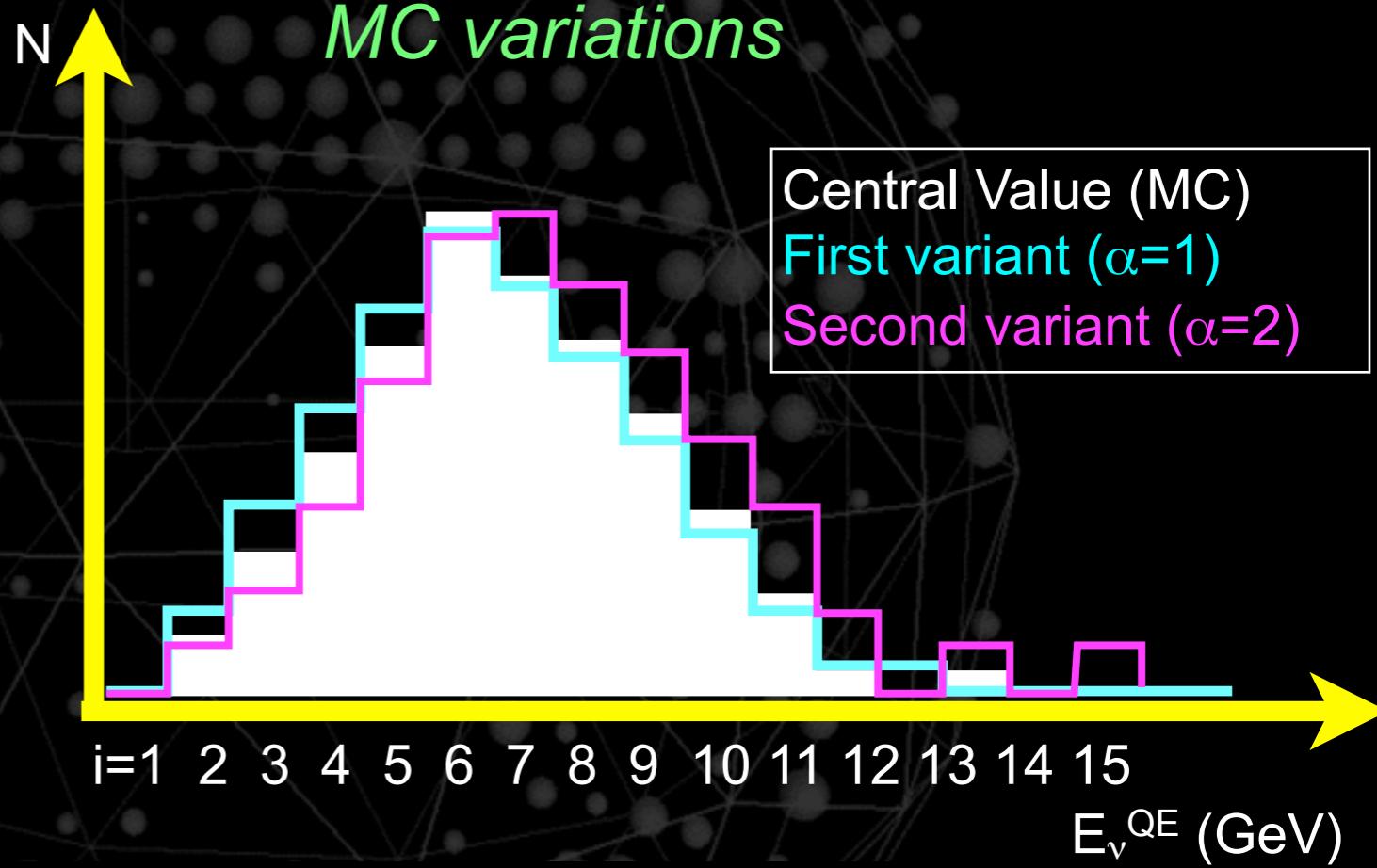
Correlations between E_ν^{QE} bins from the optical model:



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 E_ν distributions for several MC variations



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

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

BG systematic errors (%)

	Antineutrino		Neutrino	
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

Analysis results

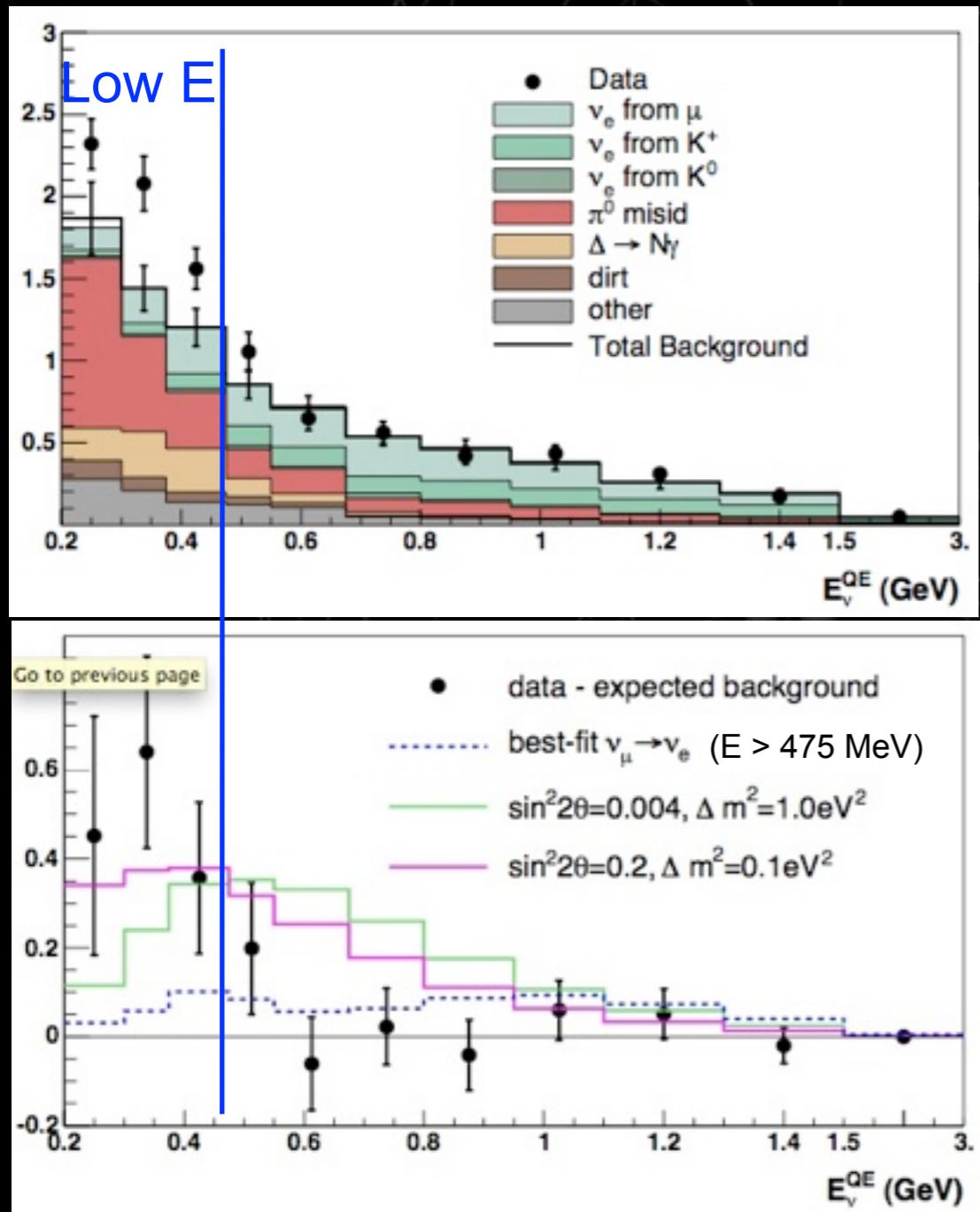
Training for a blind search



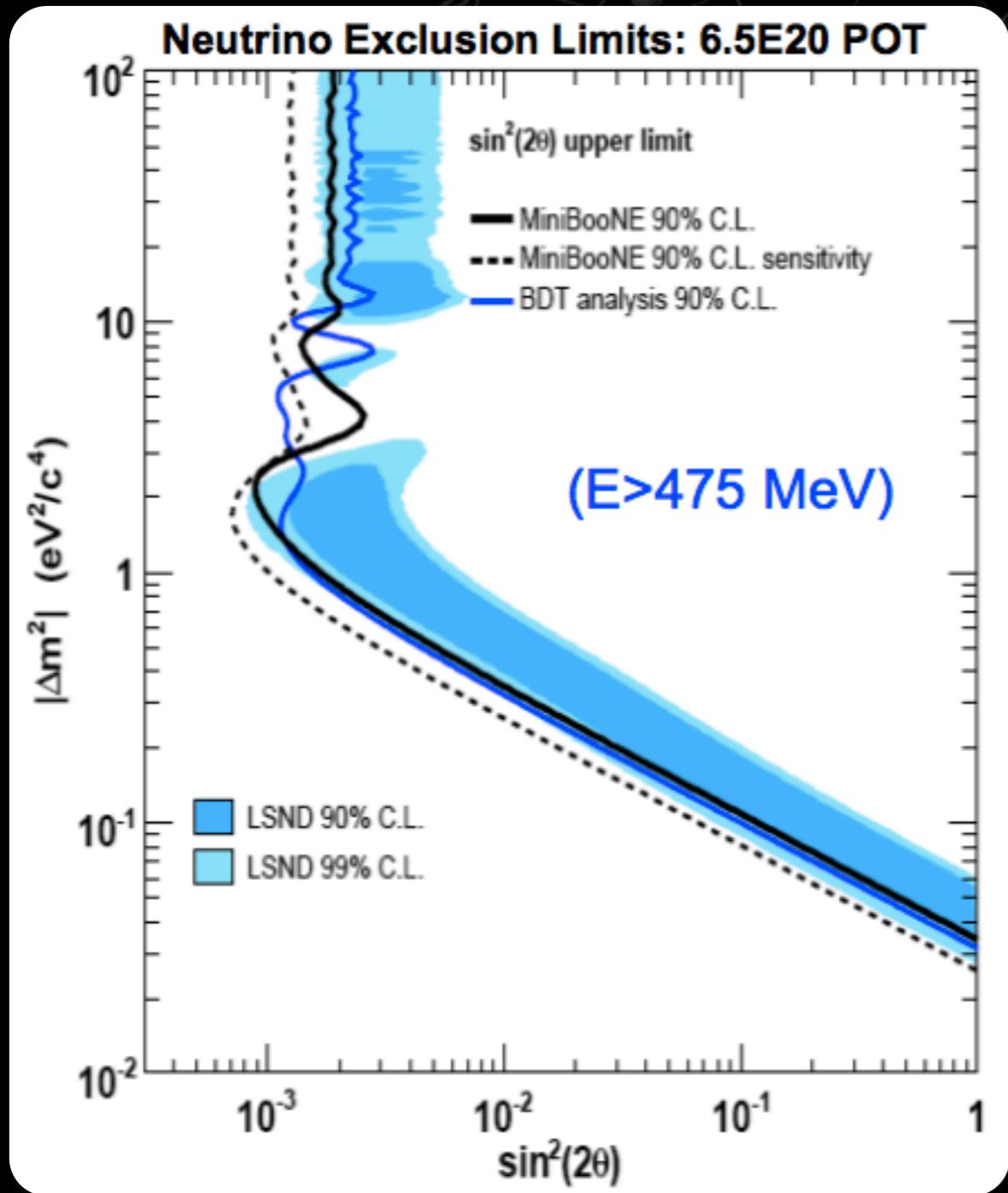
MOW c. 2002
(blinded)

ν_e Search

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



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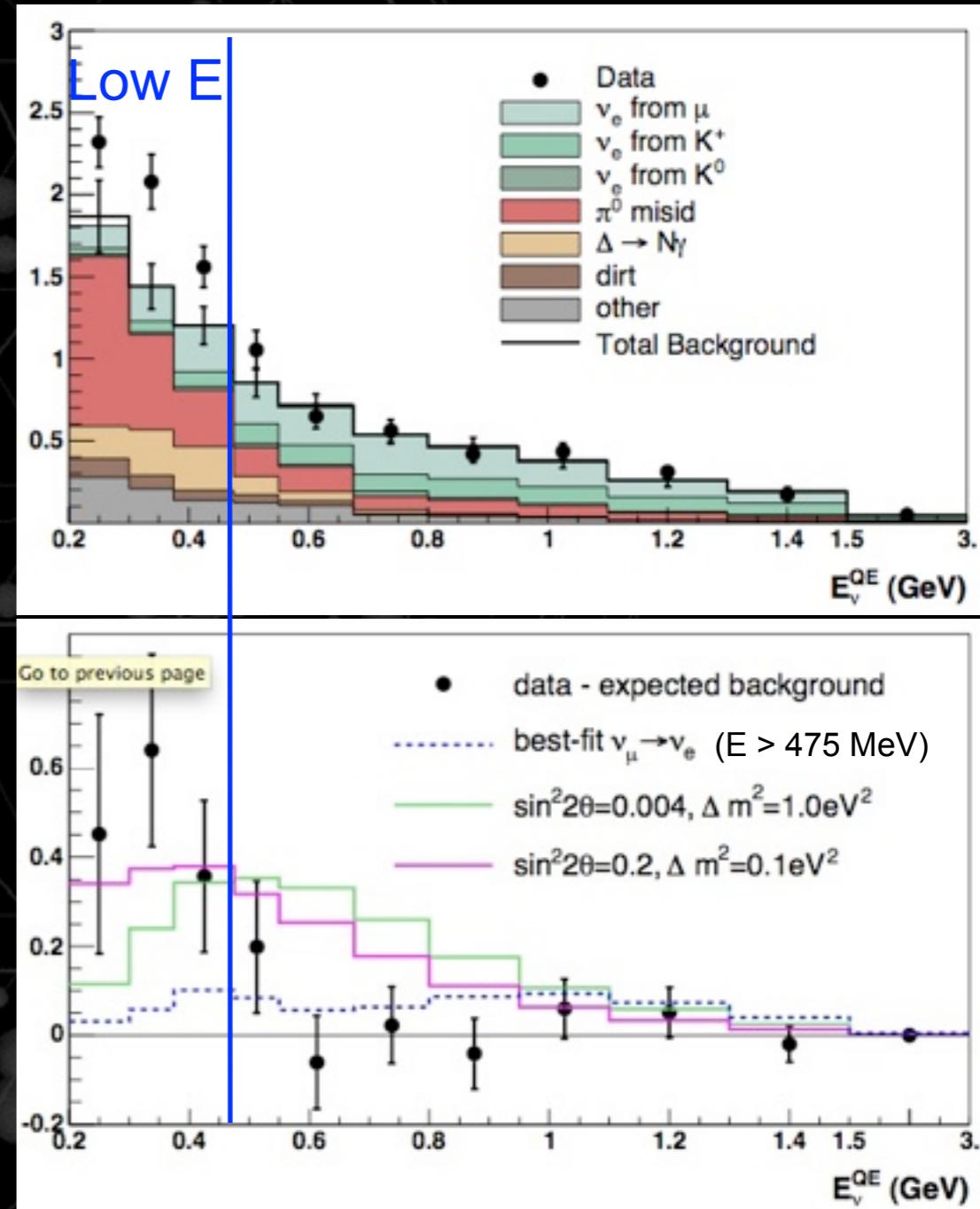
Phys.Rev.Lett.98:231801,2007

ν_e Search

- Below 475 MeV...
 - Find 544 events, expect $415 \pm 20(\text{stat}) \pm 39(\text{syst})$
 - Excess is $128 \pm 20(\text{stat}) \pm 39(\text{syst})$ events

How much would BGs need to fluctuate to produce excess?

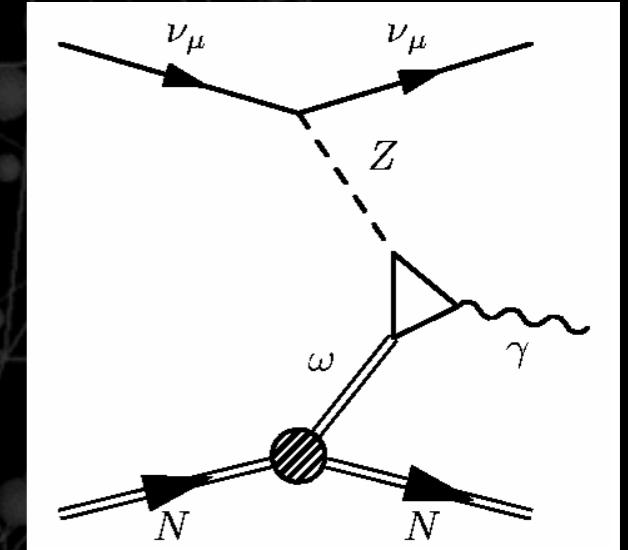
BG Source	BG Counts	Increase Needed	Syst Error*
ν_μ CCQE	26.4	487%	~30%
NC π^0	181.3	71%	~20%
Rad. Δ	67.0	192%	~25%
$\nu_e (\mu)$	58.1	222%	~25%
$\nu_e (K)$	17.4	740%	~40%
dirt	23.8	544%	~15%



Phys.Rev.Lett.102:101802,2009

low energy excess

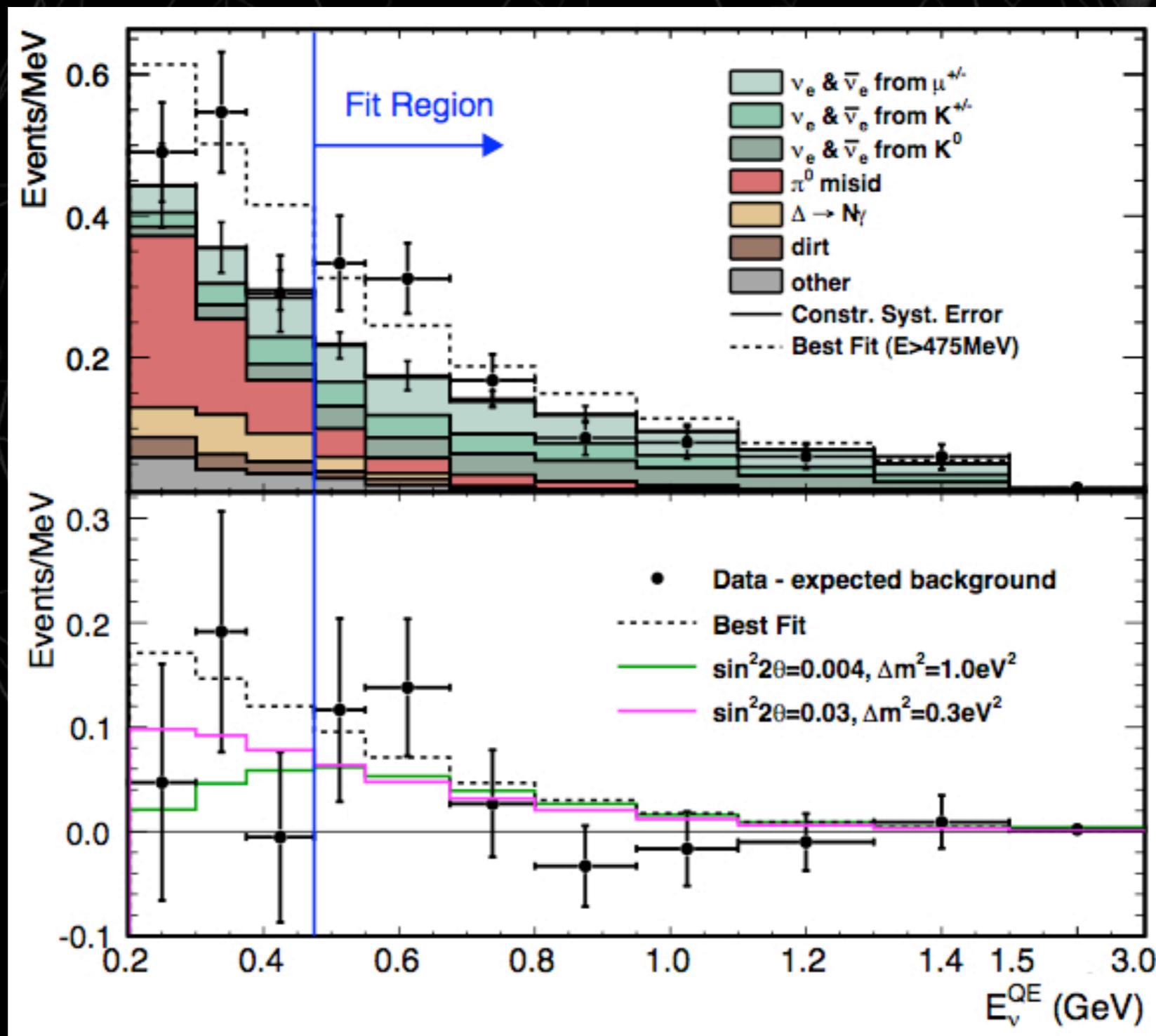
- Several possible explanations
 - 3+2 with CP violation
[Maltoni and Schwetz, hep-ph0705.0107 ; G. K., NuFACT 07 conference]
 - Anomaly mediated photon production
[Harvey, Hill, and Hill, hep-ph0708.1281]
 - New light gauge boson
[Nelson, Walsh, Phys. Rev. D 77, 033001 (2008)]
 - ...
- Some have concrete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



$\bar{\nu}_e$ results

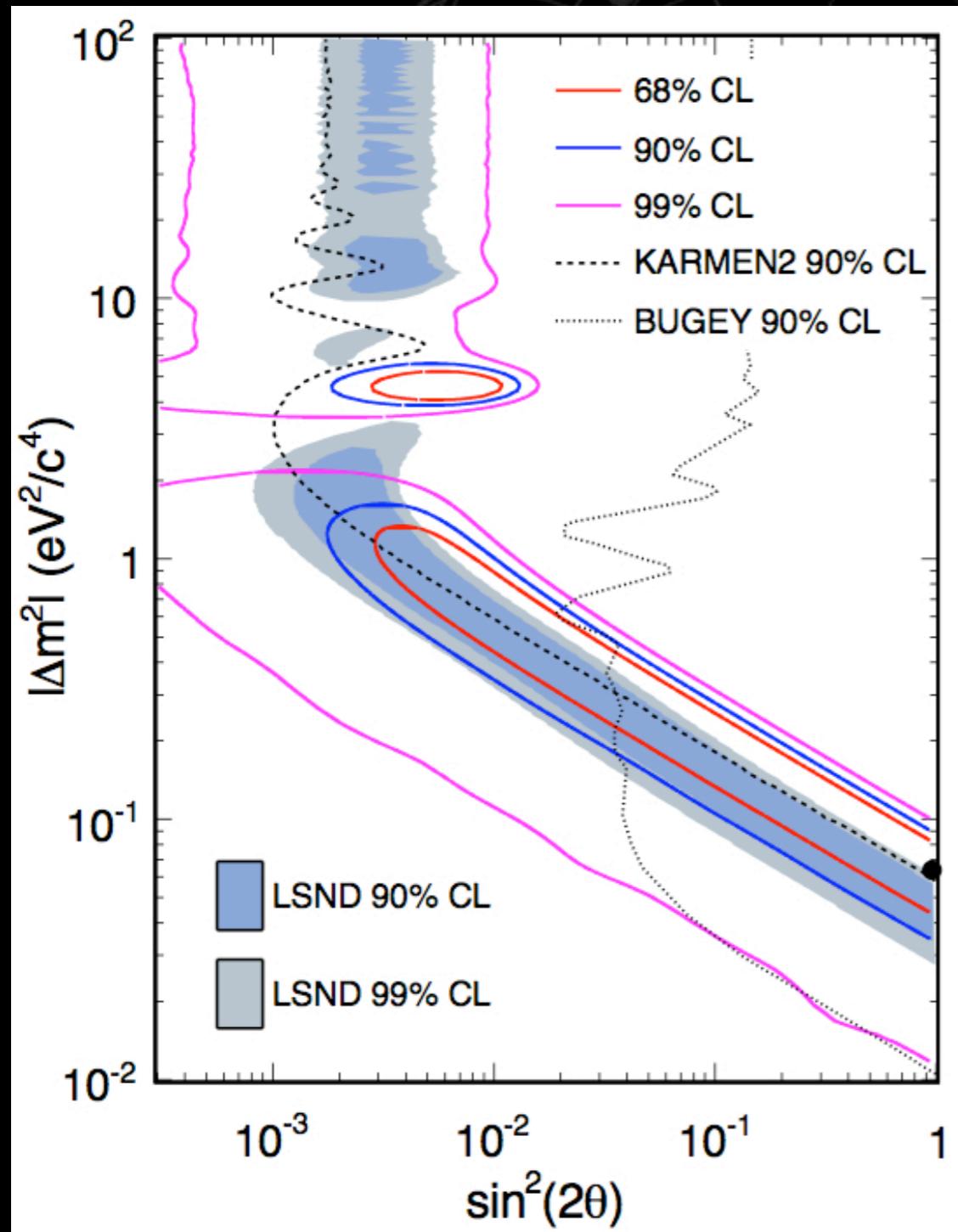
Phys.Rev.Lett.105:181801,2010

5.6E20 POT



$\bar{\nu}_e$ results

Phys.Rev.Lett.105:181801,2010



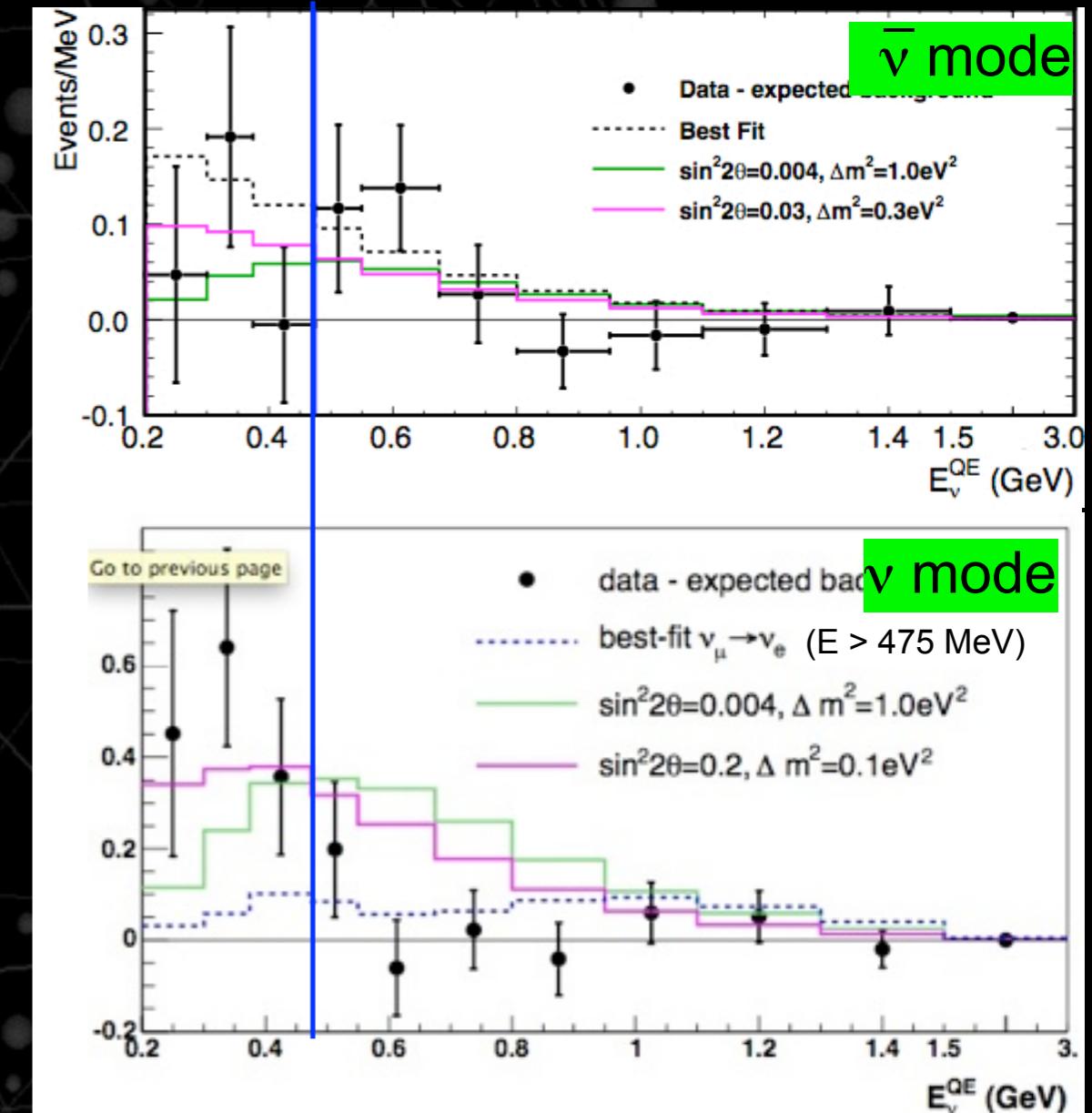
- Above 475 MeV...
- In 475-1250 MeV, excess 20.9 ± 14 events (1.4σ)
- True significance comes from fit over entire > 475 MeV energy region + ν_μ constraint
- Best fit preferred over null at 99.4% CL (2.7σ)
- Probability of null hypothesis (no model dep.) is 0.5% in 475-1250 MeV signal region

Low energy results

- Below 475 MeV...
 - Find 119 events, expect $100 \pm 10(\text{stat}) \pm 10(\text{syst})$
 - Excess is $18.5 \pm 10(\text{stat}) \pm 10(\text{syst})$ events
 - Inconsistent with many hypotheses explaining the $\bar{\nu}$ mode low E excess

BG Source	ν_e excess extrapolated to $\bar{\nu}_e$
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

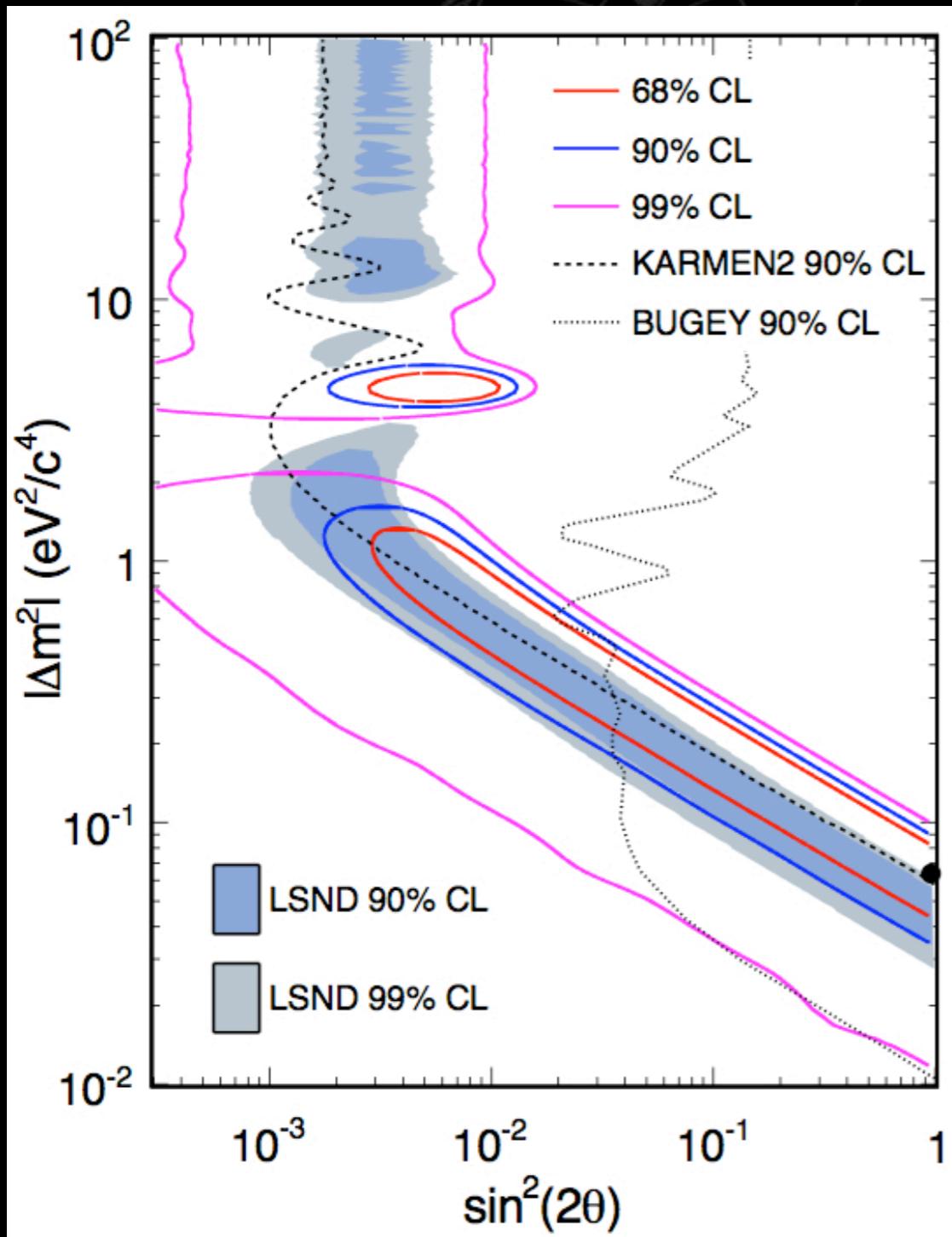
Phys.Rev.Lett.105:181801,2010



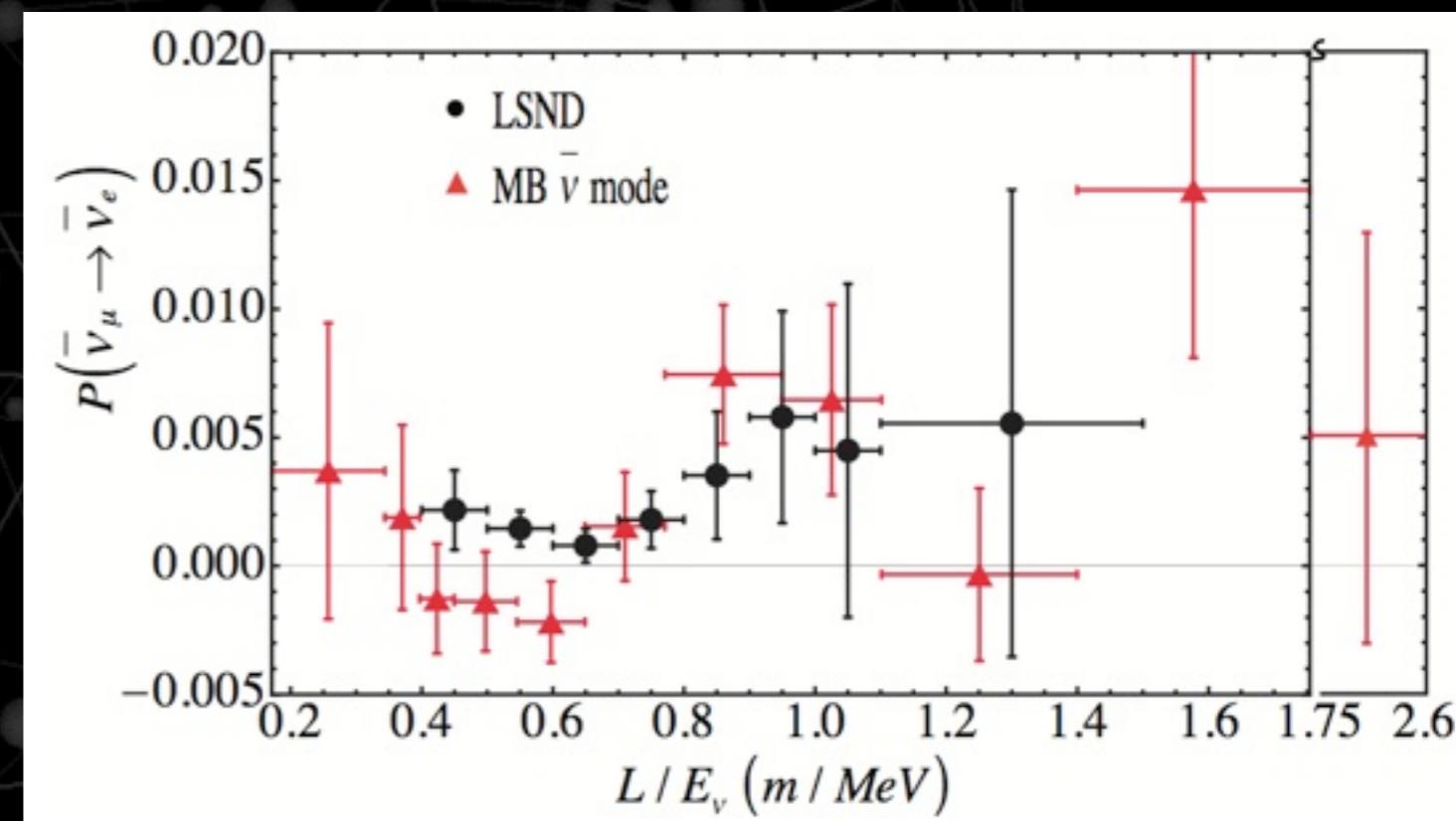
Comparing to LSND

Fit to 2ν mixing model

Phys.Rev.Lett.105:181801,2010



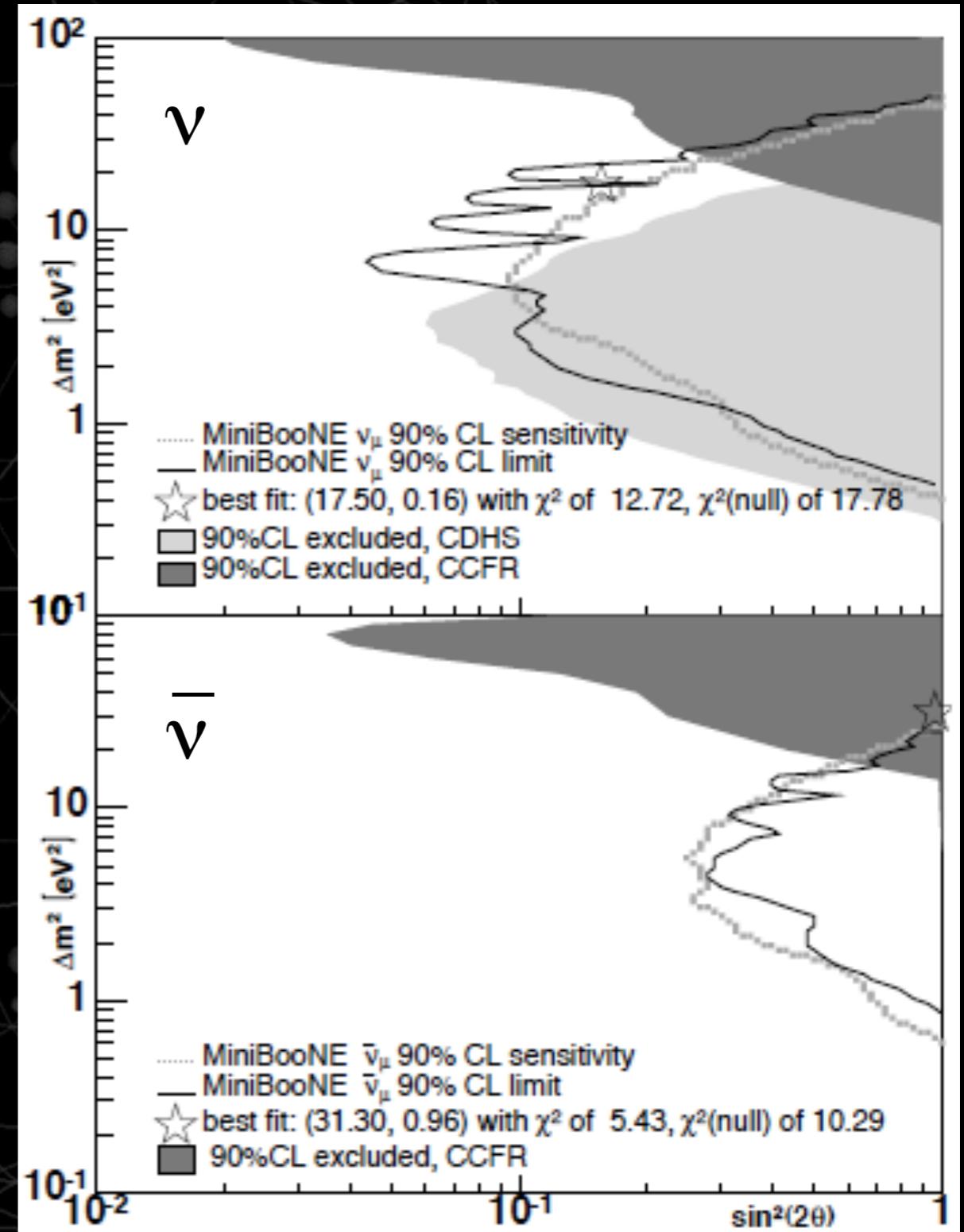
Model-independent plot of inferred oscillation probability



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 regions unexplored by past experiments, especially as there are no tests of antineutrino disappearance between $\Delta m^2 = 10 \text{ eV}^2$ and atmospheric Δm^2

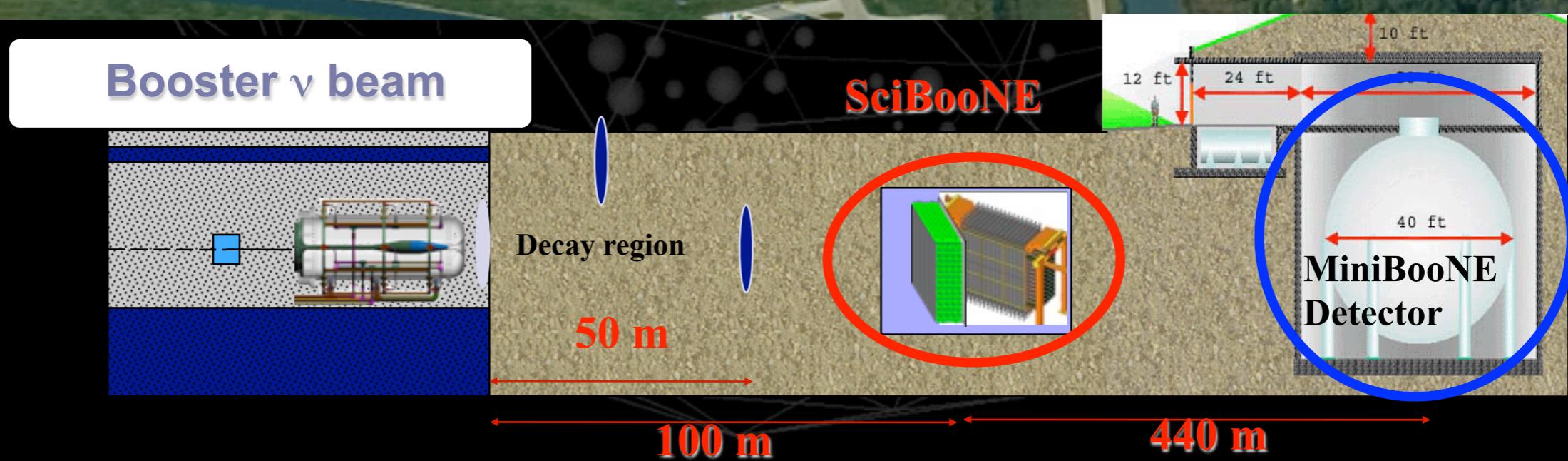


K.B.M. Mahn

Overview

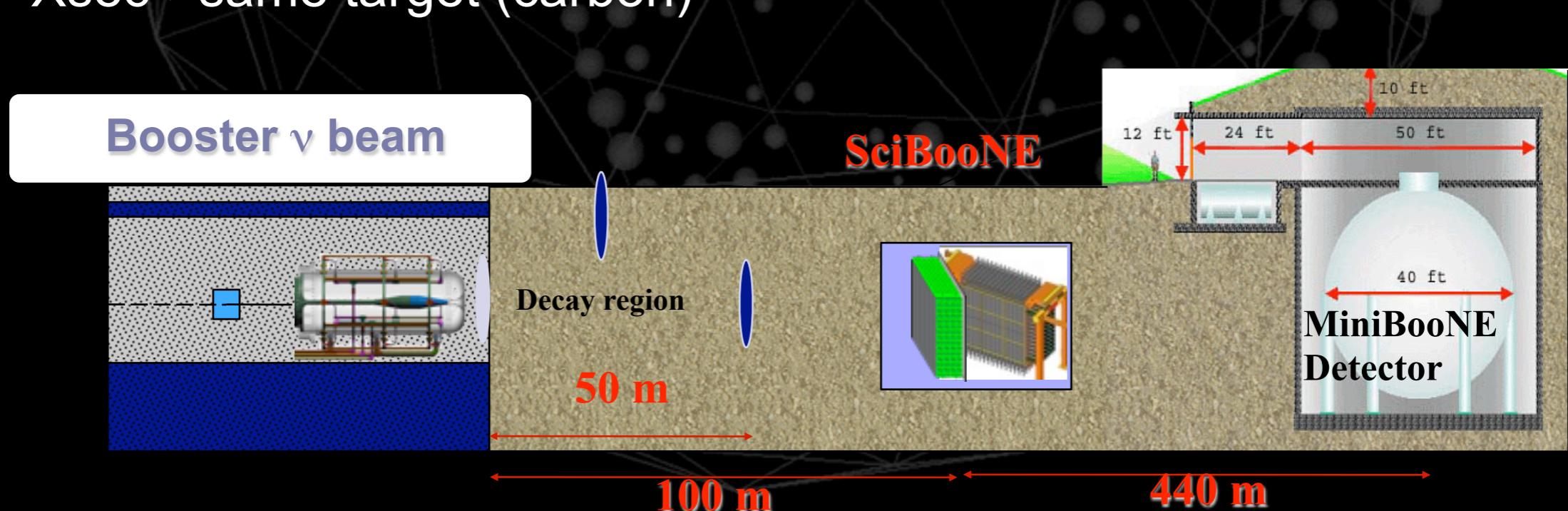
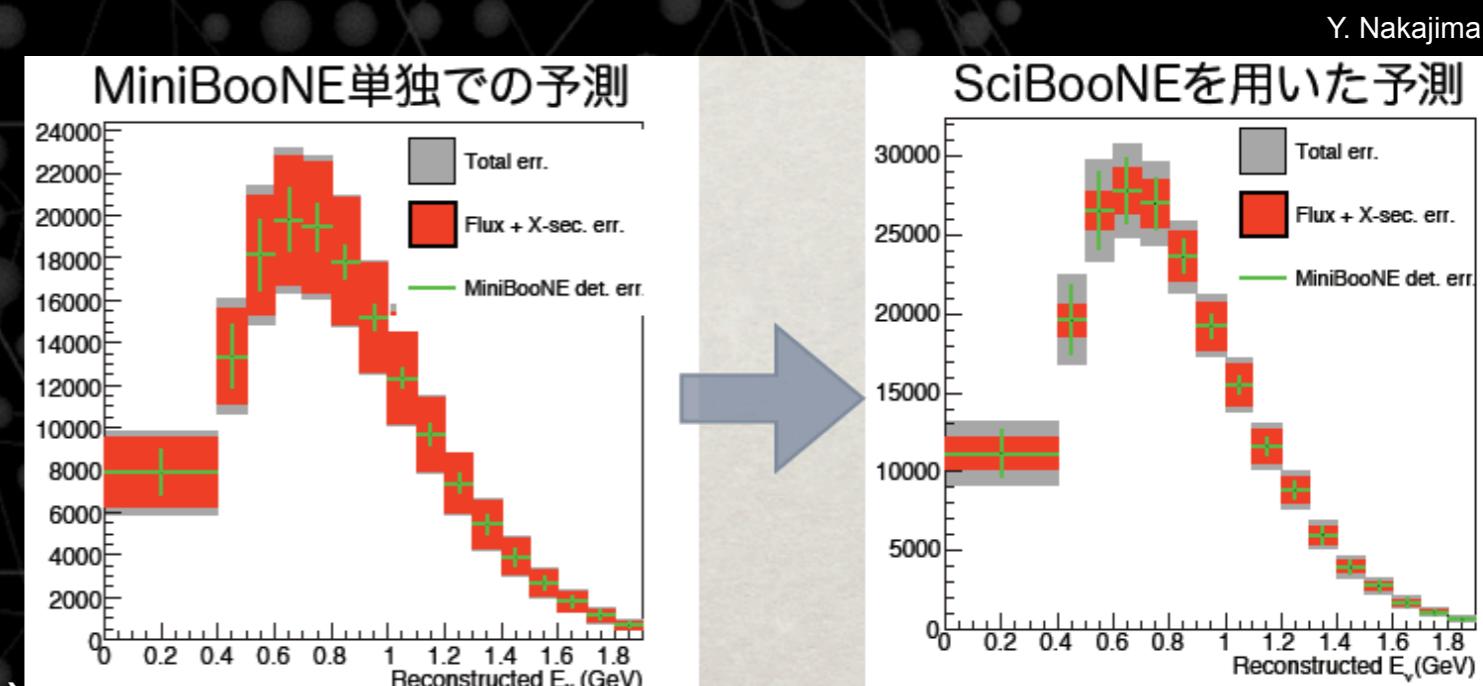


Fermilab Visual Media Services



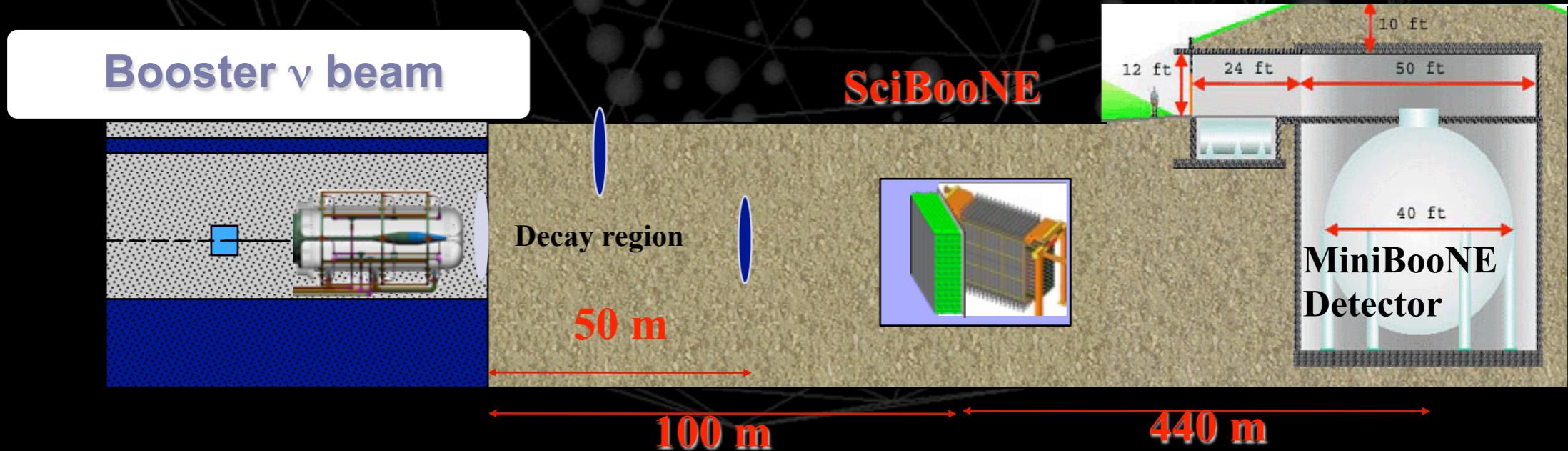
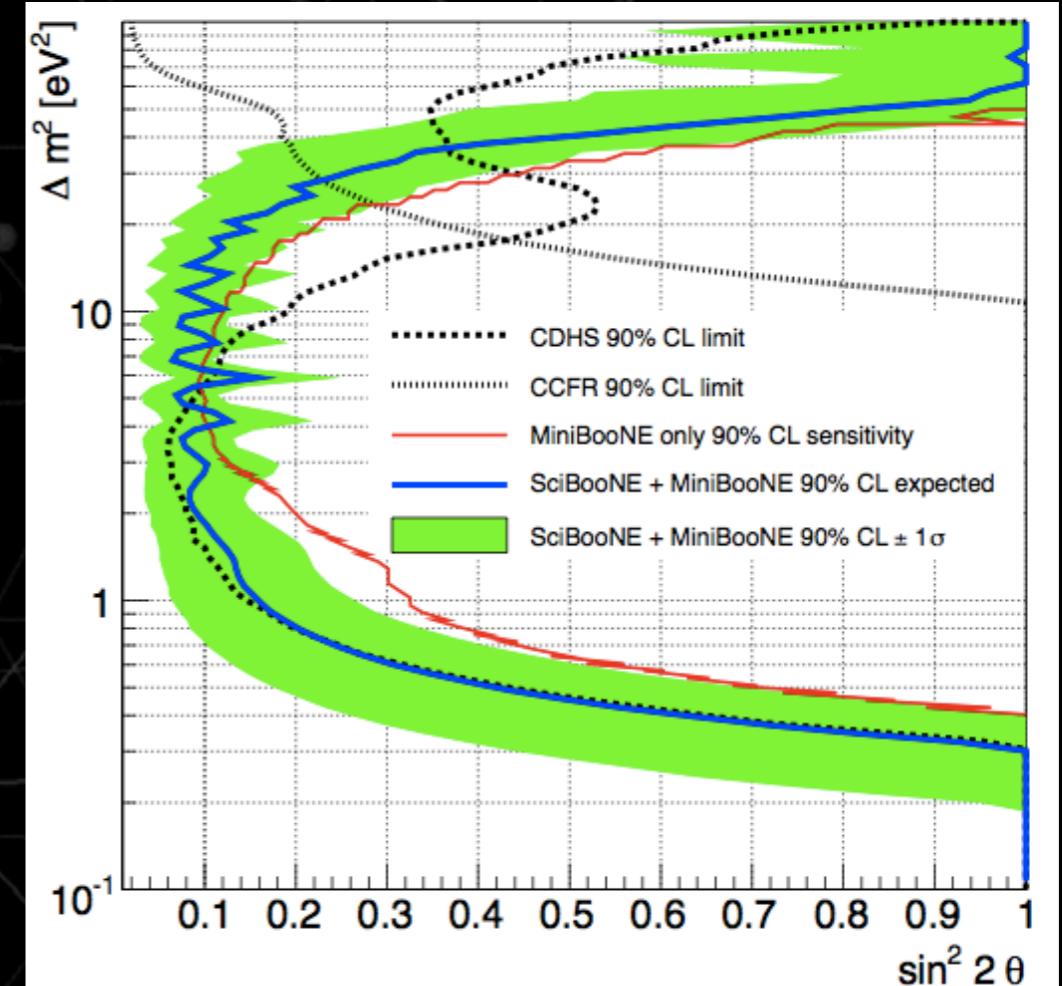
ν_μ disappearance

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



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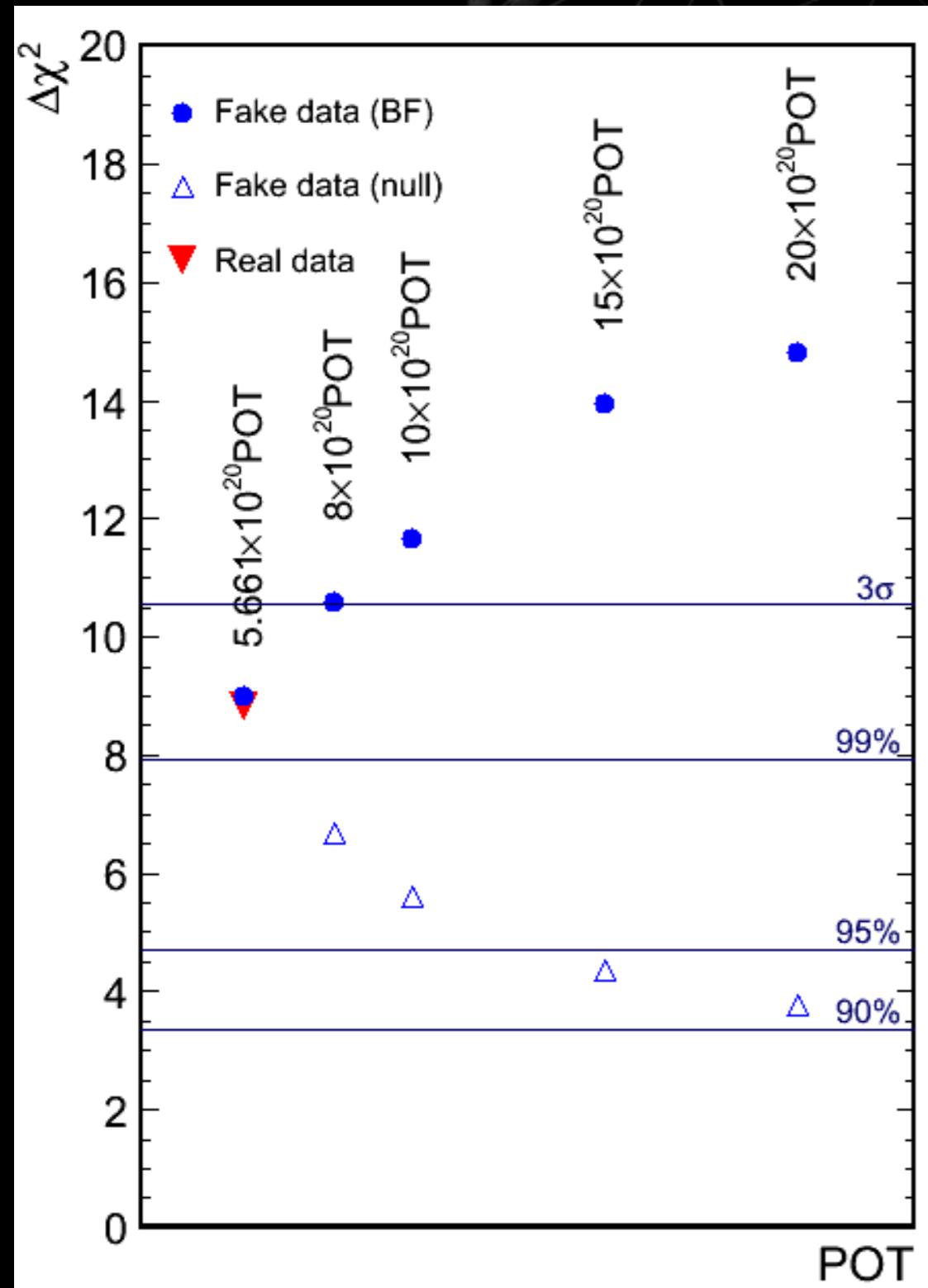


Summary & Outlook

What does MiniBooNE claim?

1. No ν_e excess in ν_μ beam above 475 MeV.
 - Maximal oscillation 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.

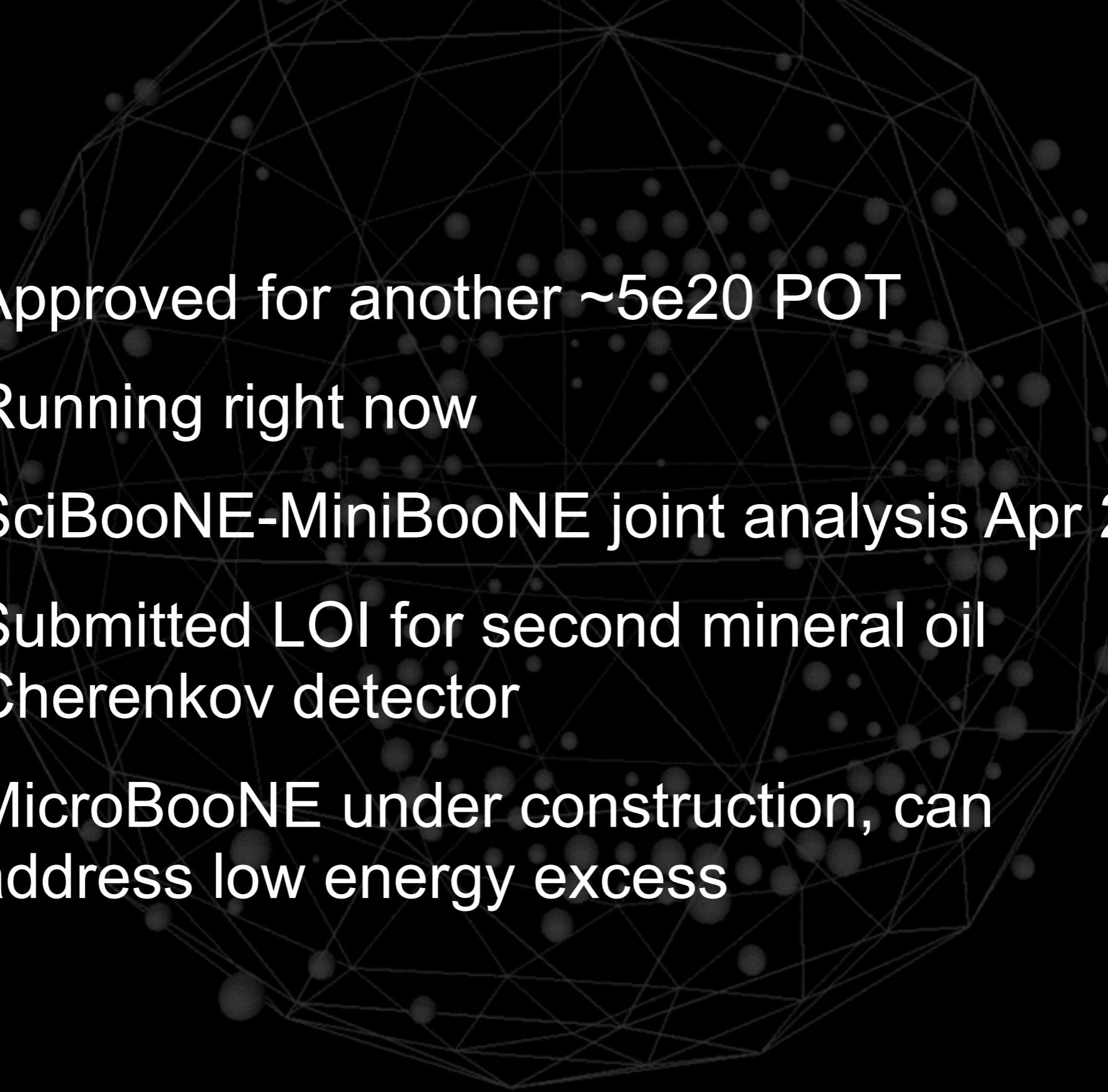
What now?



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

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

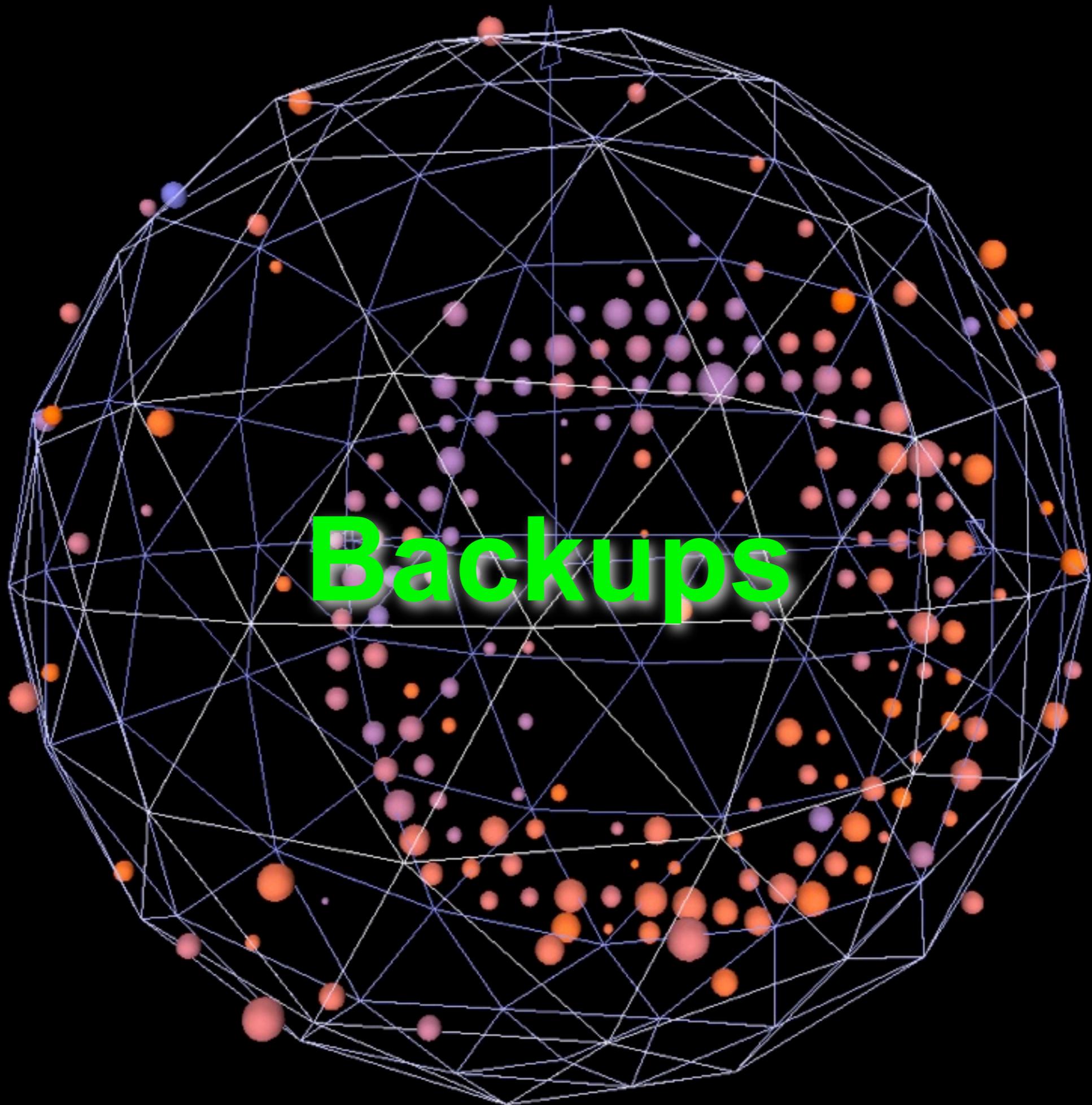
MiniBooNE outlook



- Approved for another $\sim 5 \times 10^{20}$ POT
- Running right now
- SciBooNE-MiniBooNE joint analysis Apr 29
- Submitted LOI for second mineral oil Cherenkov detector
- MicroBooNE under construction, can address low energy excess

A photograph of a long, narrow tunnel or underpass. The ceiling and walls are made of a light-colored material, possibly concrete or metal, with large, curved support arches. The floor is a smooth, light-colored surface. In the distance, there are some industrial-looking structures and equipment. The lighting is bright, coming from fixtures attached to the ceiling. The overall atmosphere is clean and modern.

Thank you!



Neutrino Oscillation



Бруно Понтеорво

Pontecorvo, Maki, Nakagawa, Sakata

if neutrinos have mass...

a neutrino that is produced as a ν_μ

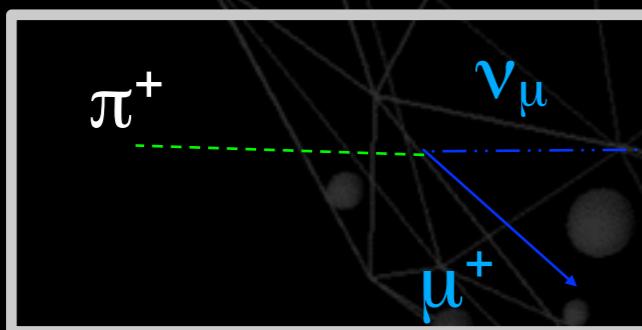
- (e.g. $\pi^+ \rightarrow \mu^+ \nu_\mu$)

might some time later be observed as a ν_e

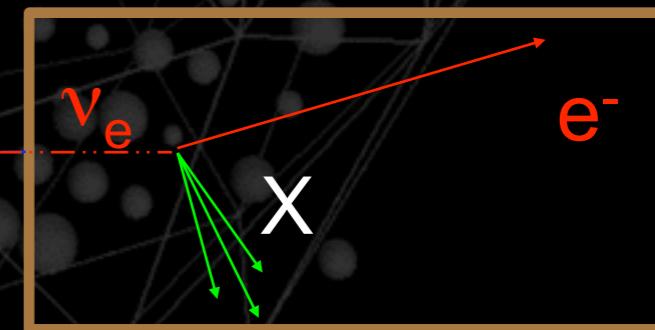
- (e.g. $\nu_e n \rightarrow e^- p$)



Шиоичи Саката



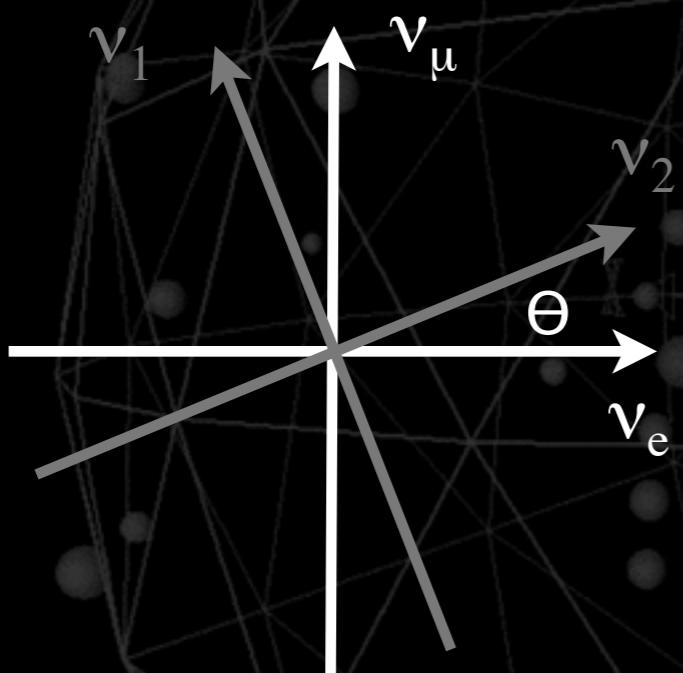
ν source



ν detector

Neutrino Oscillation

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



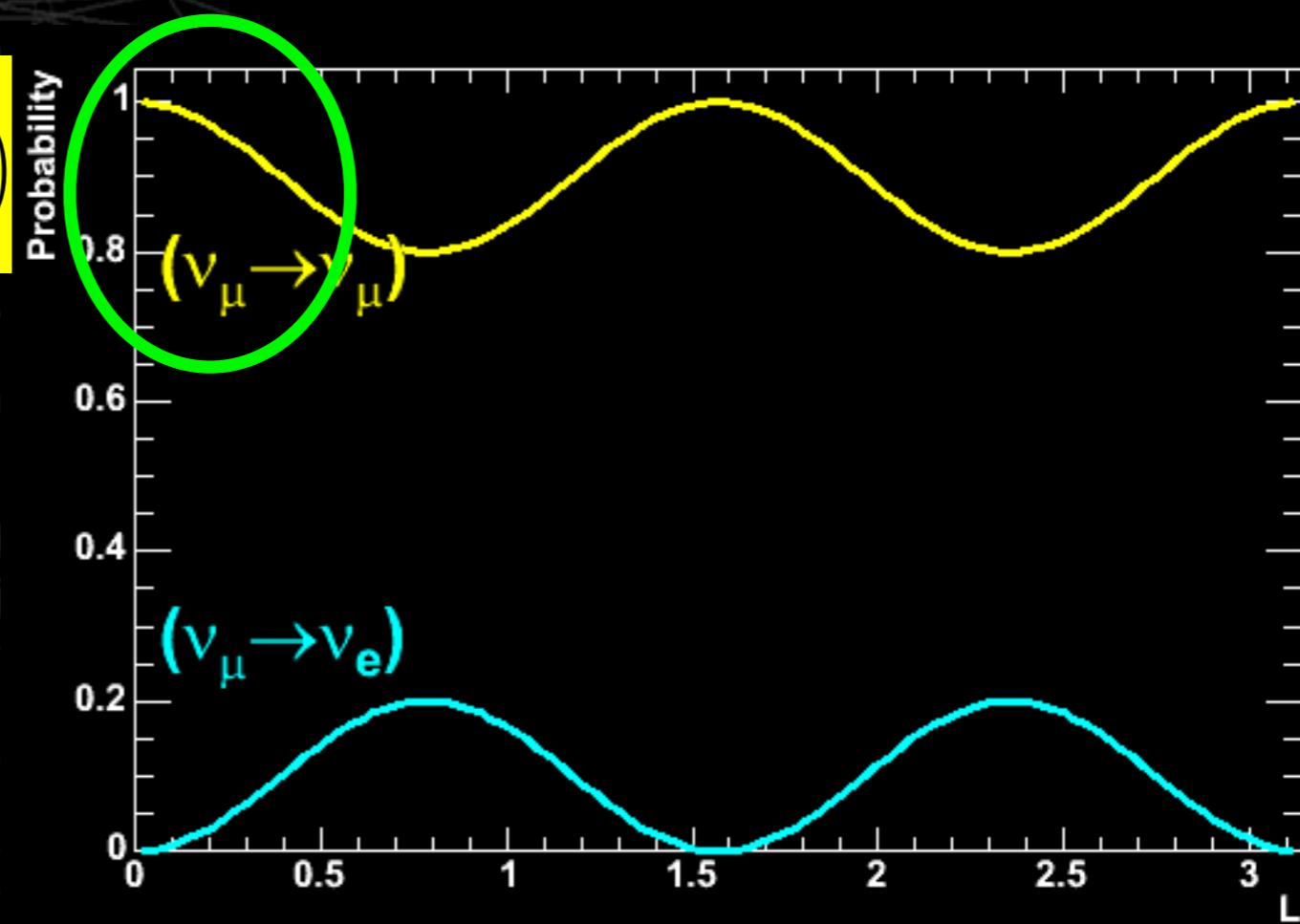
- Consider only two types of neutrinos
- If weak states differ from mass states
 - i.e. $(\nu_\mu \nu_e) \neq (\nu_1 \nu_2)$
- Then weak states are mixtures of mass states

$$|\nu(t)\rangle = -\sin \theta |\nu_1\rangle e^{-iE_1 t} + \cos \theta |\nu_2\rangle e^{-iE_2 t}$$

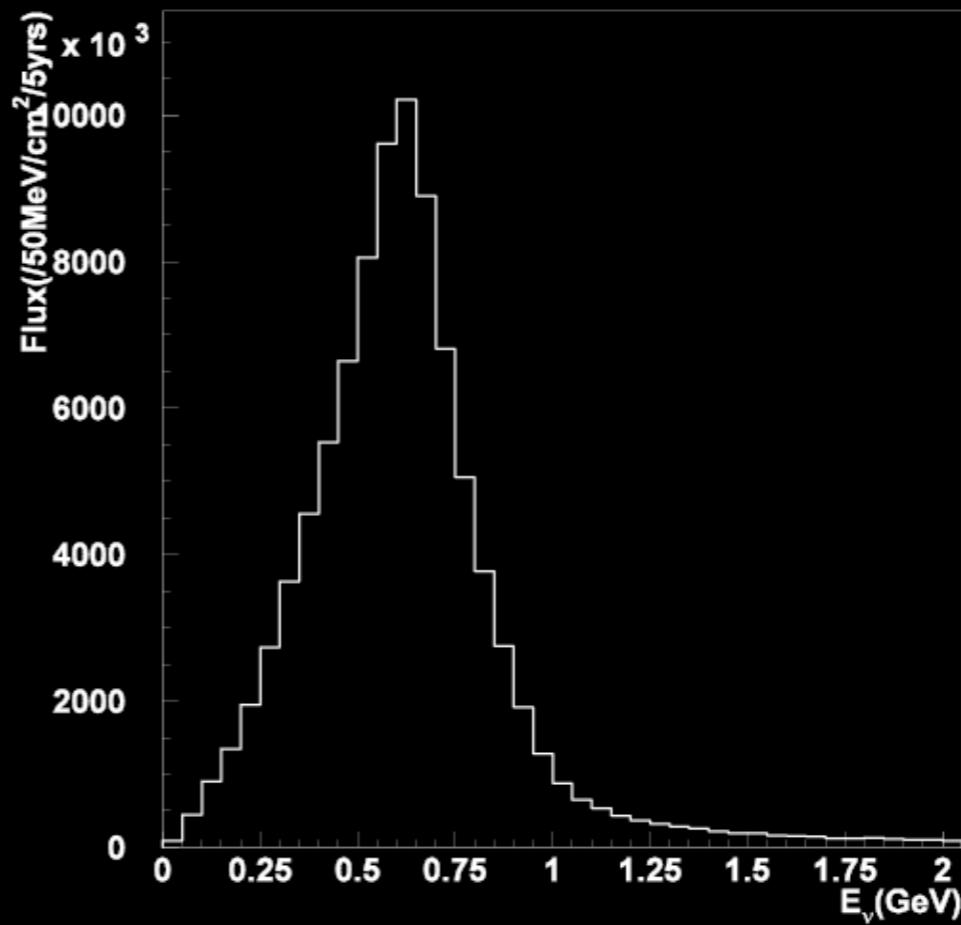
$$P_{\text{osc}}(\nu_\mu \rightarrow \nu_e) = | \langle \nu_e | \nu_\mu(t) \rangle |^2$$

- Probability to find ν_e when you started with ν_μ

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

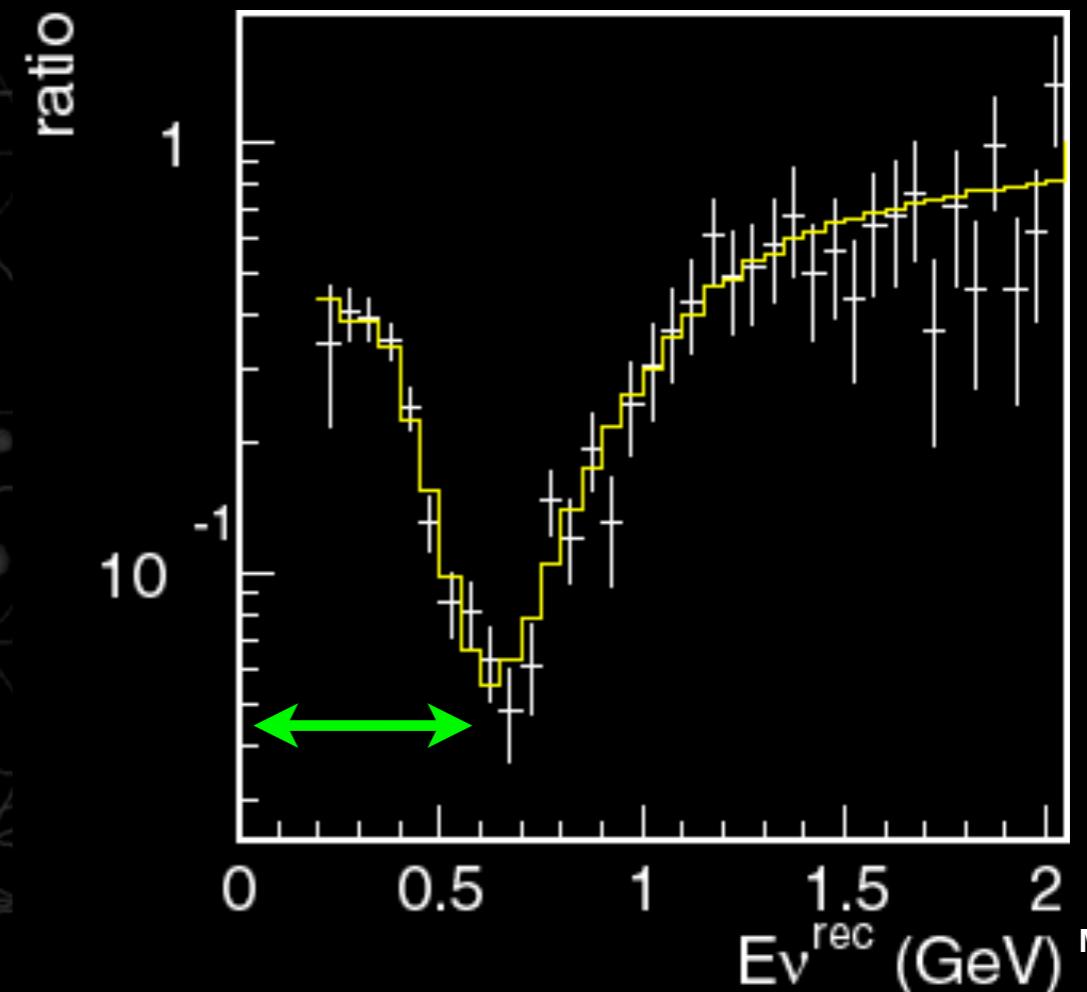
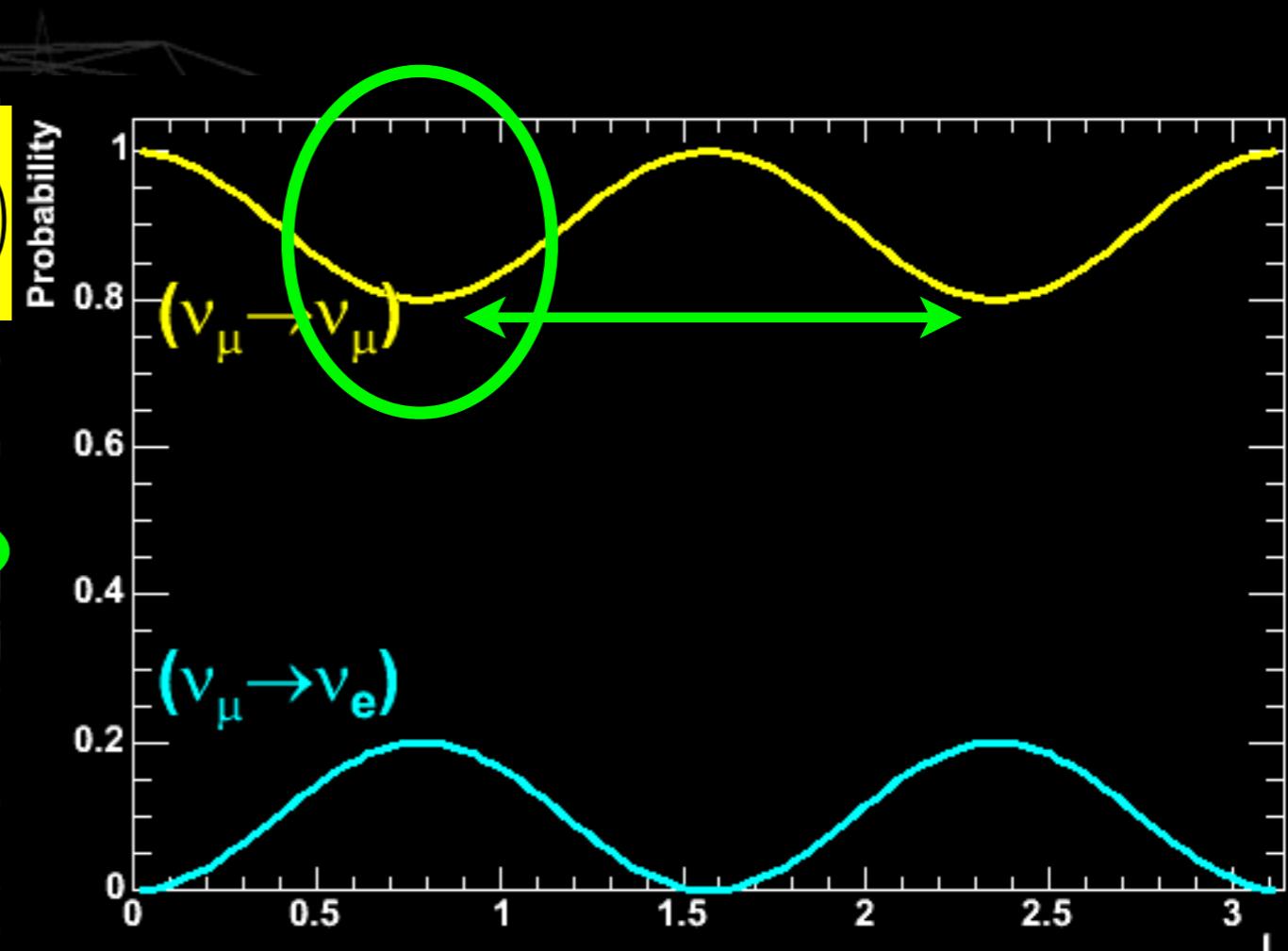


- 2 fundamental parameters
 - $\Delta m_{12}^2 (=m_1^2-m_2^2)$ \leftrightarrow period
 - θ_{12} \leftrightarrow magnitude
- 2 experimental parameters
 - L = distance travelled
 - E = neutrino energy
- Tune $L \& E$ for Δm^2 range, uncertainties determine θ sensitivity
- Neutrino disappearance and appearance



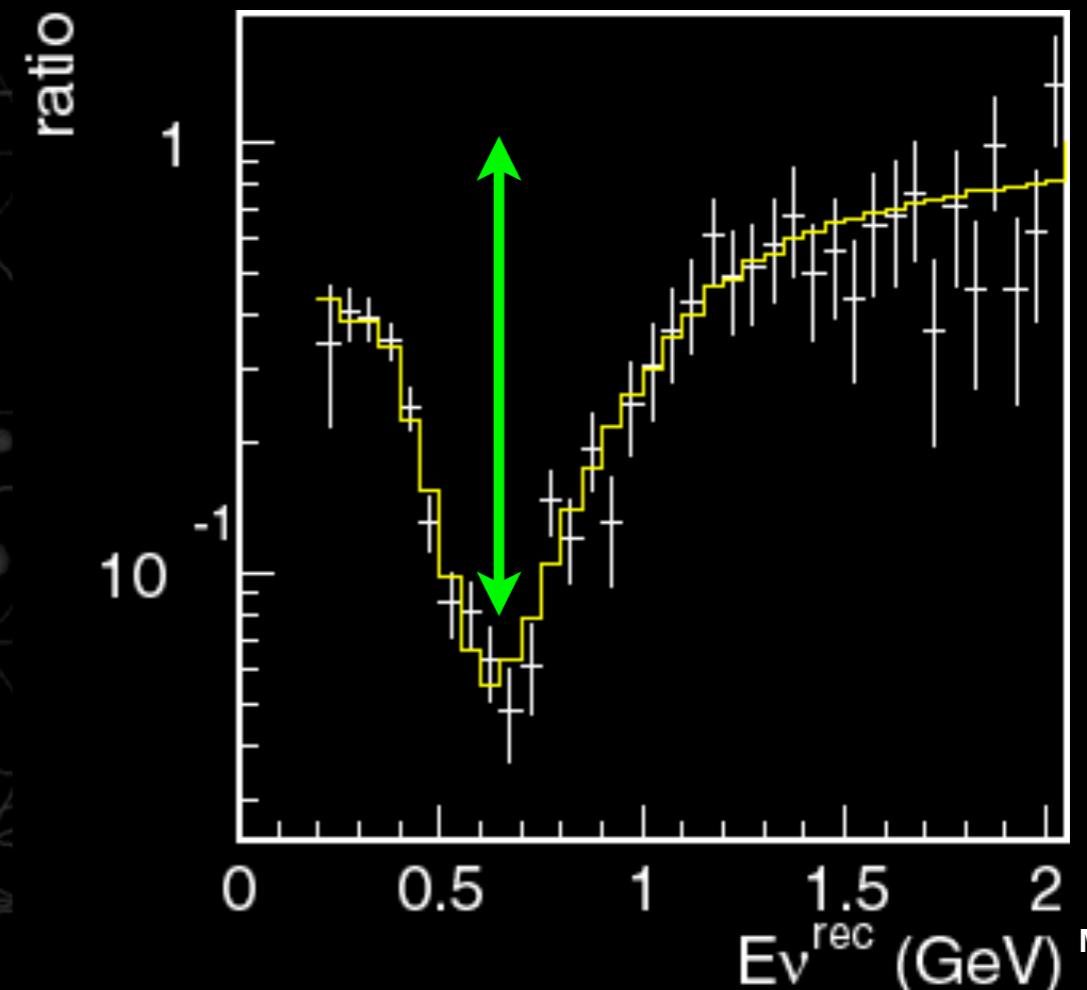
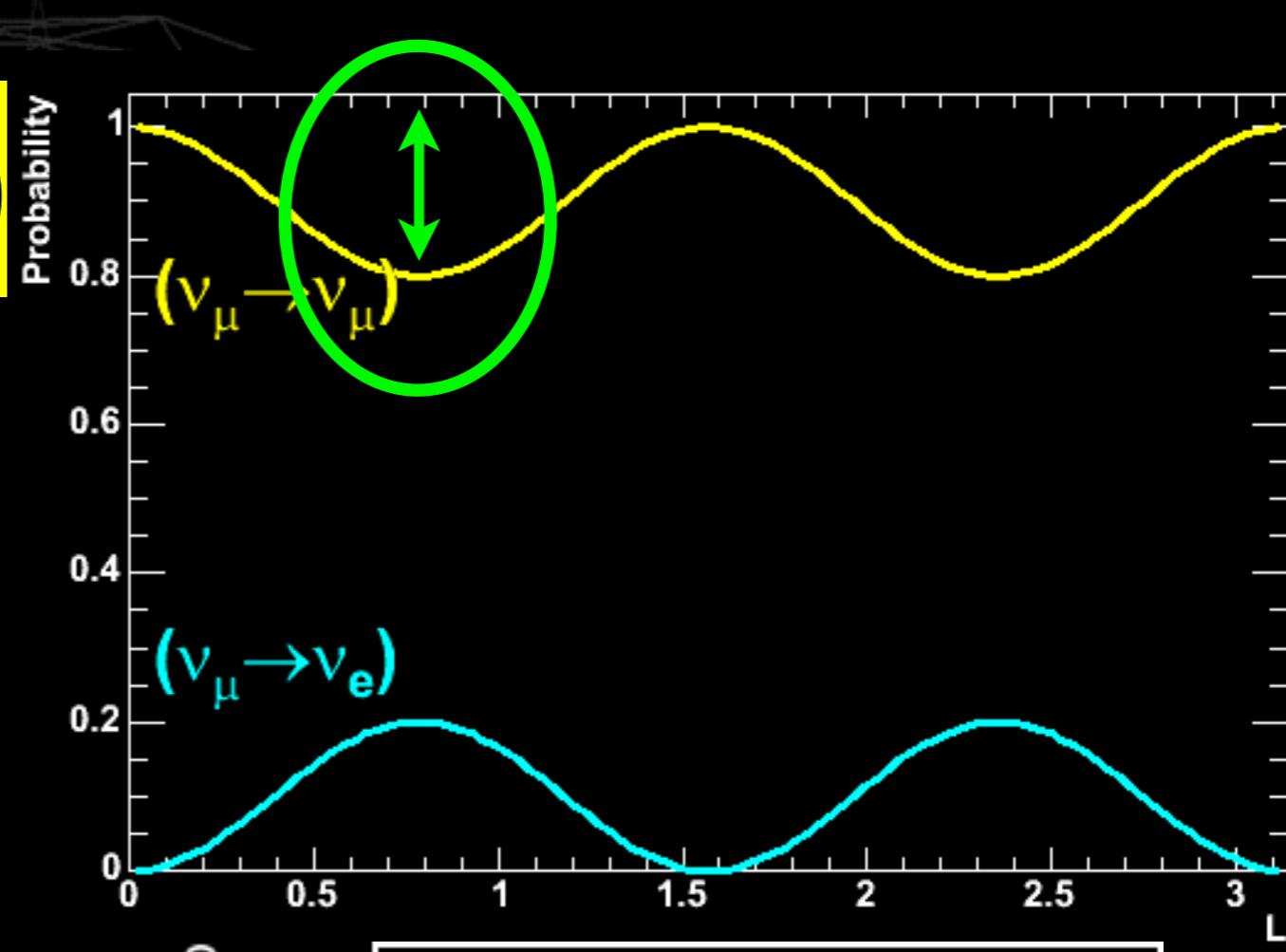
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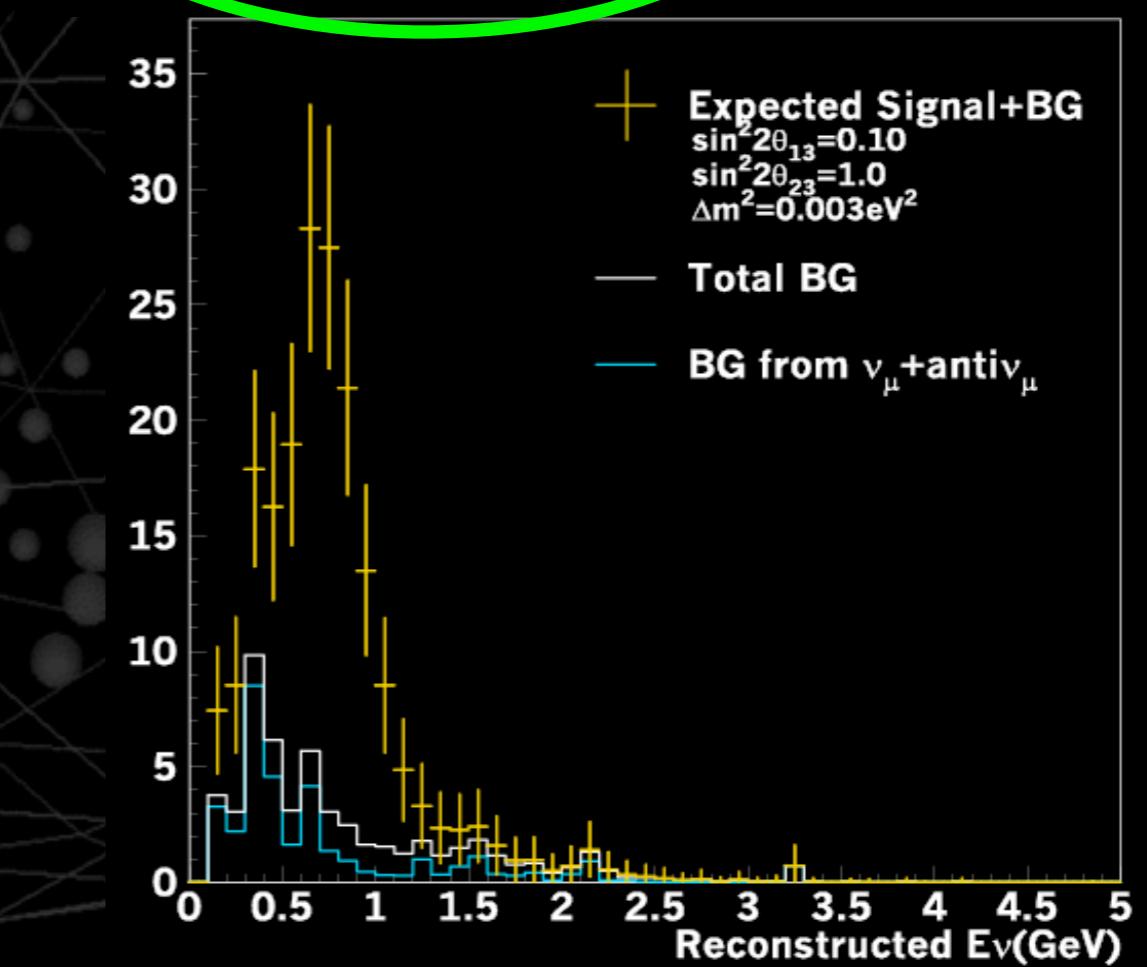
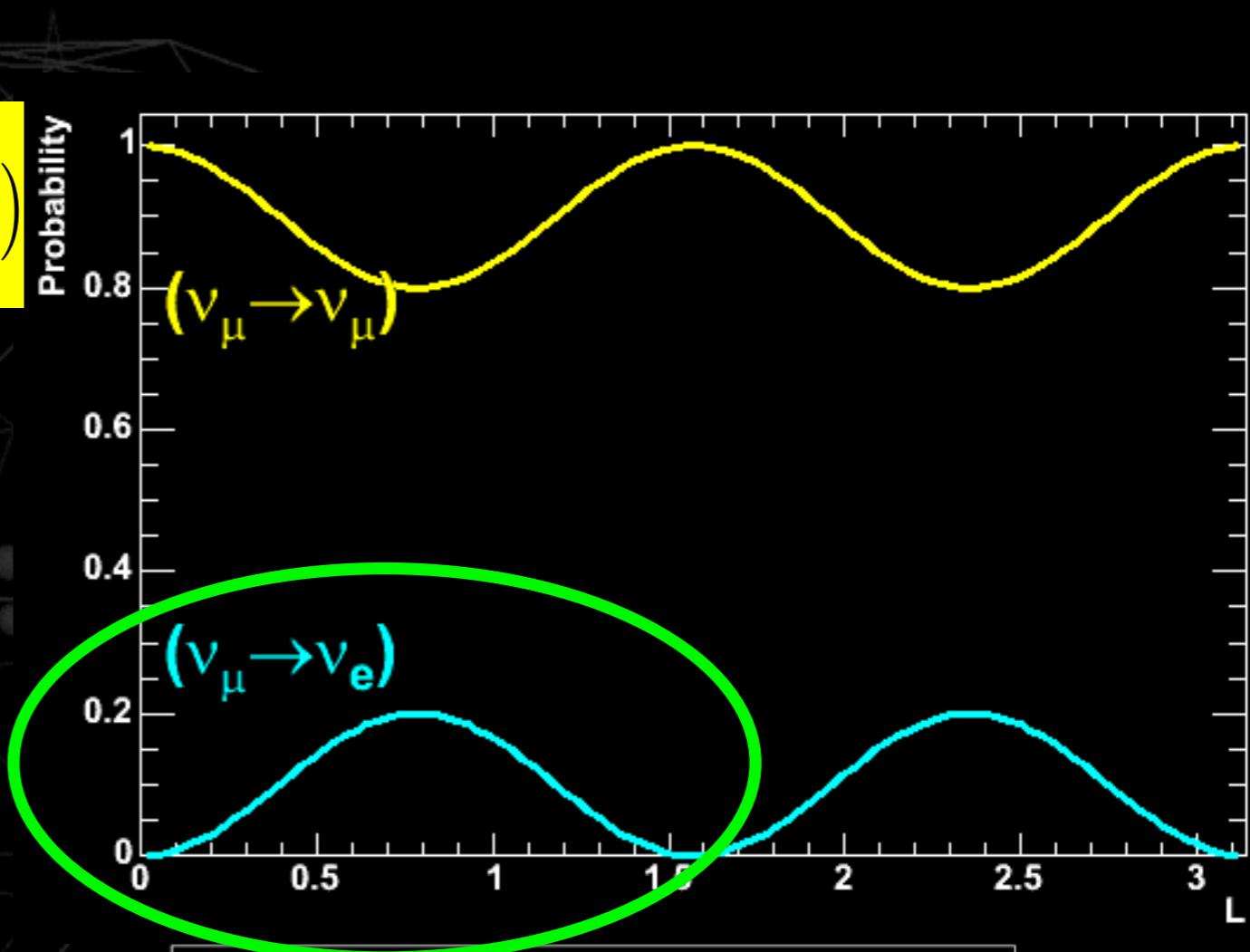
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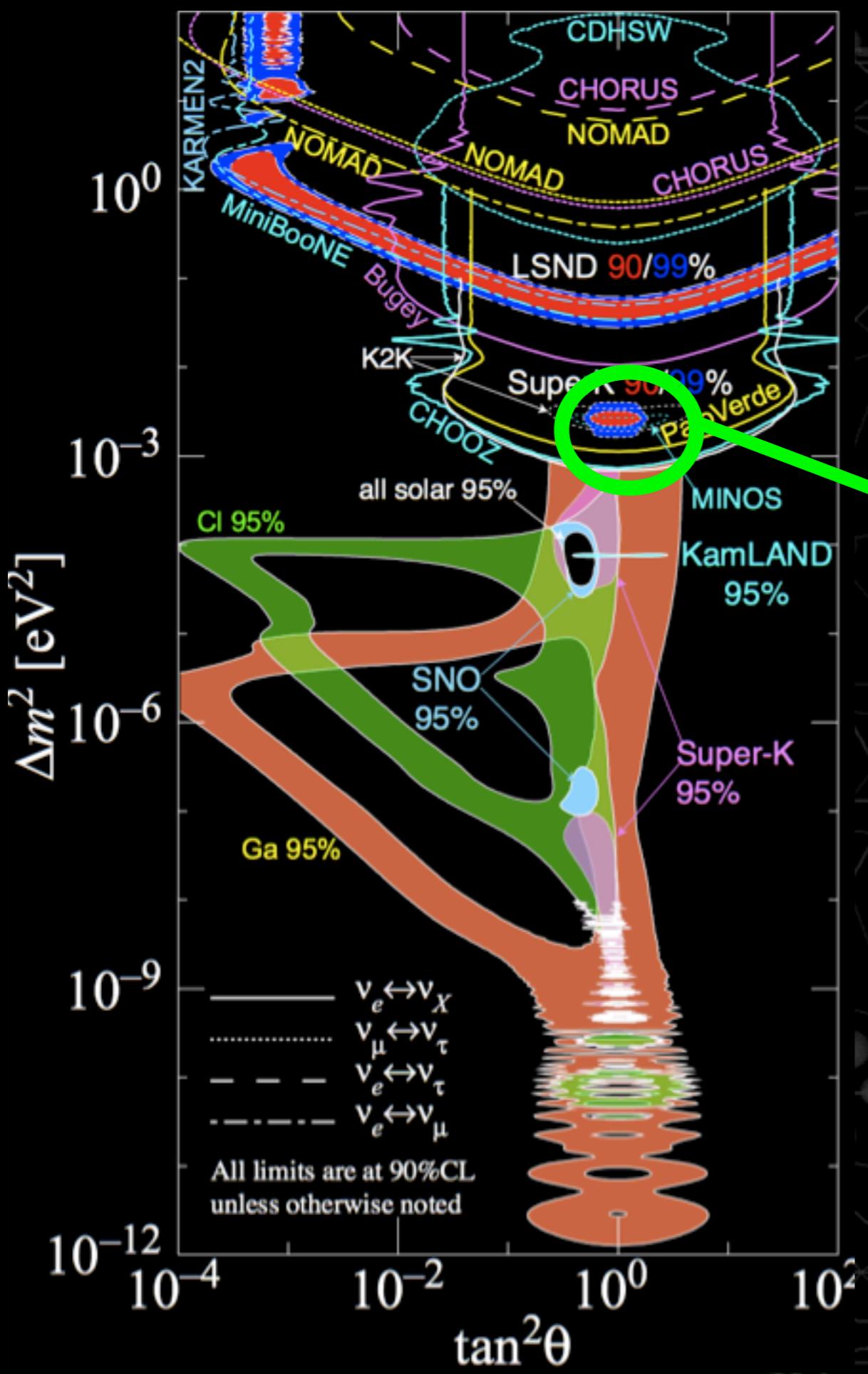


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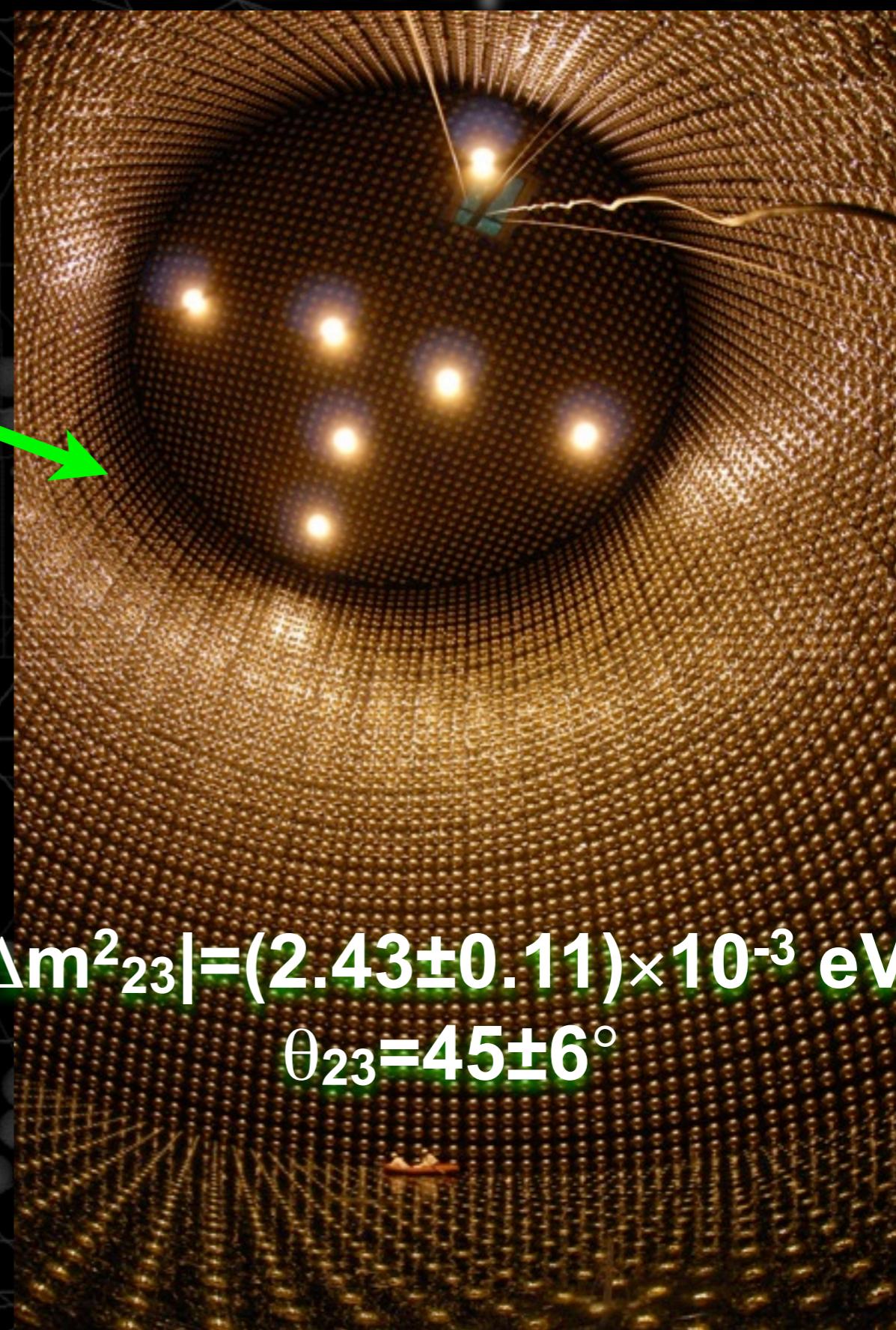
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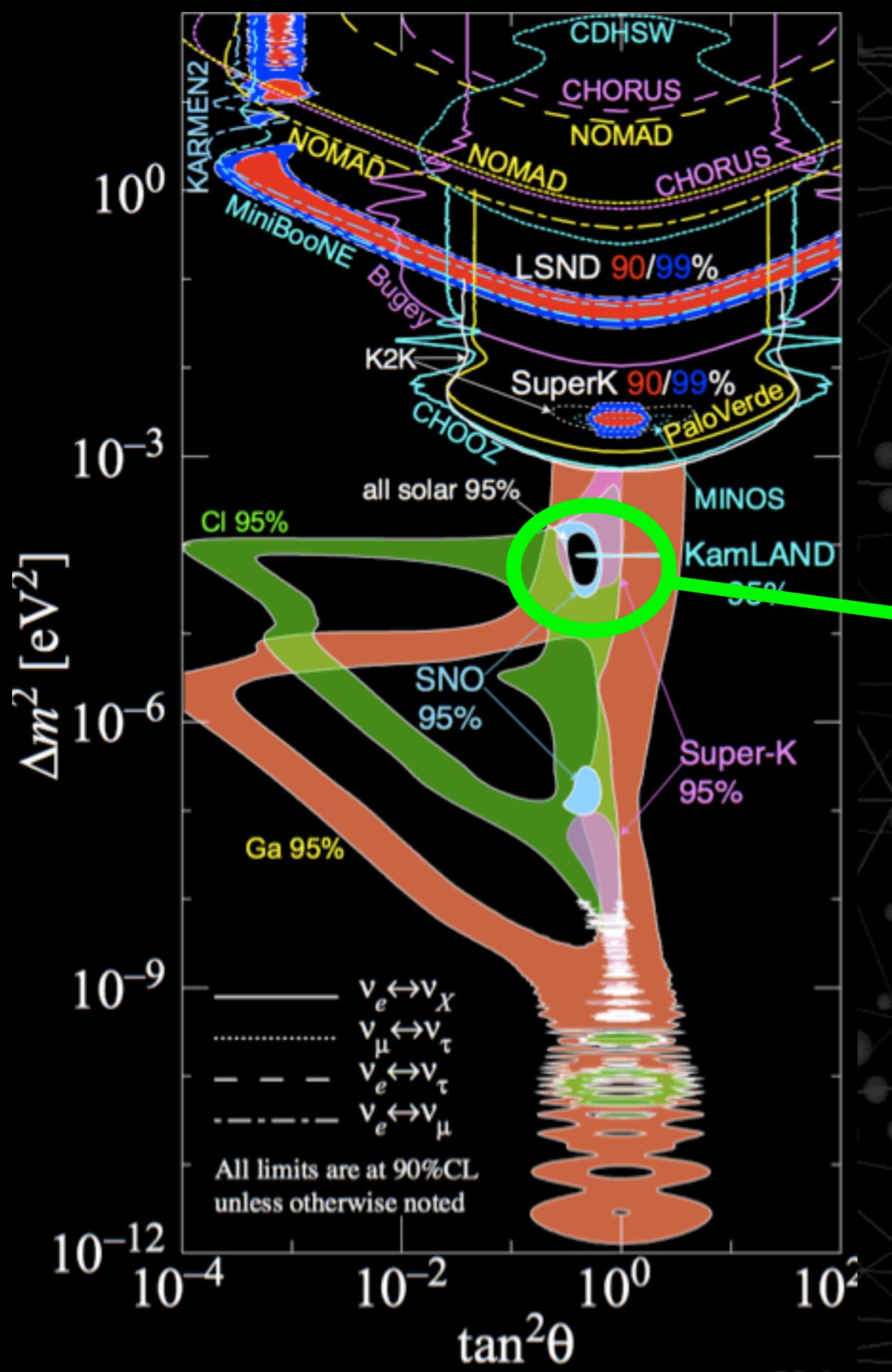


Atmospheric

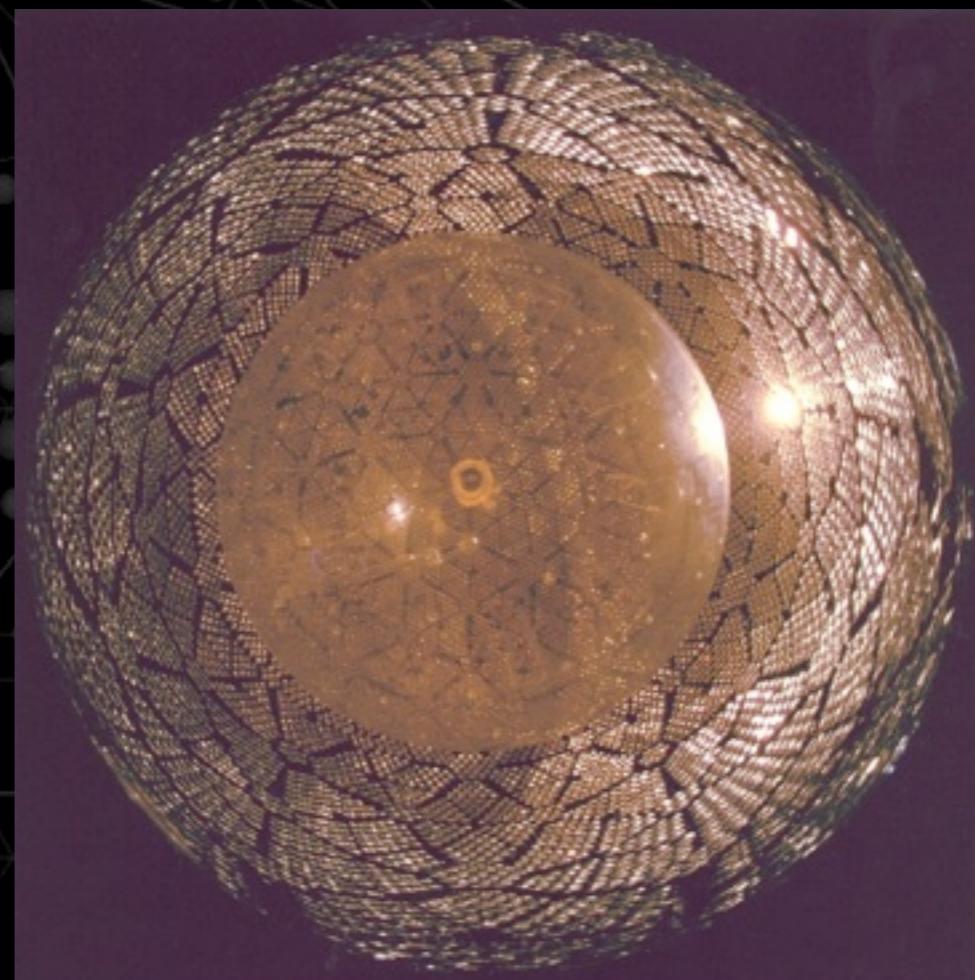


$|\Delta m^2_{23}| = (2.43 \pm 0.11) \times 10^{-3} \text{ eV}^2$
 $\theta_{23} = 45 \pm 6^\circ$





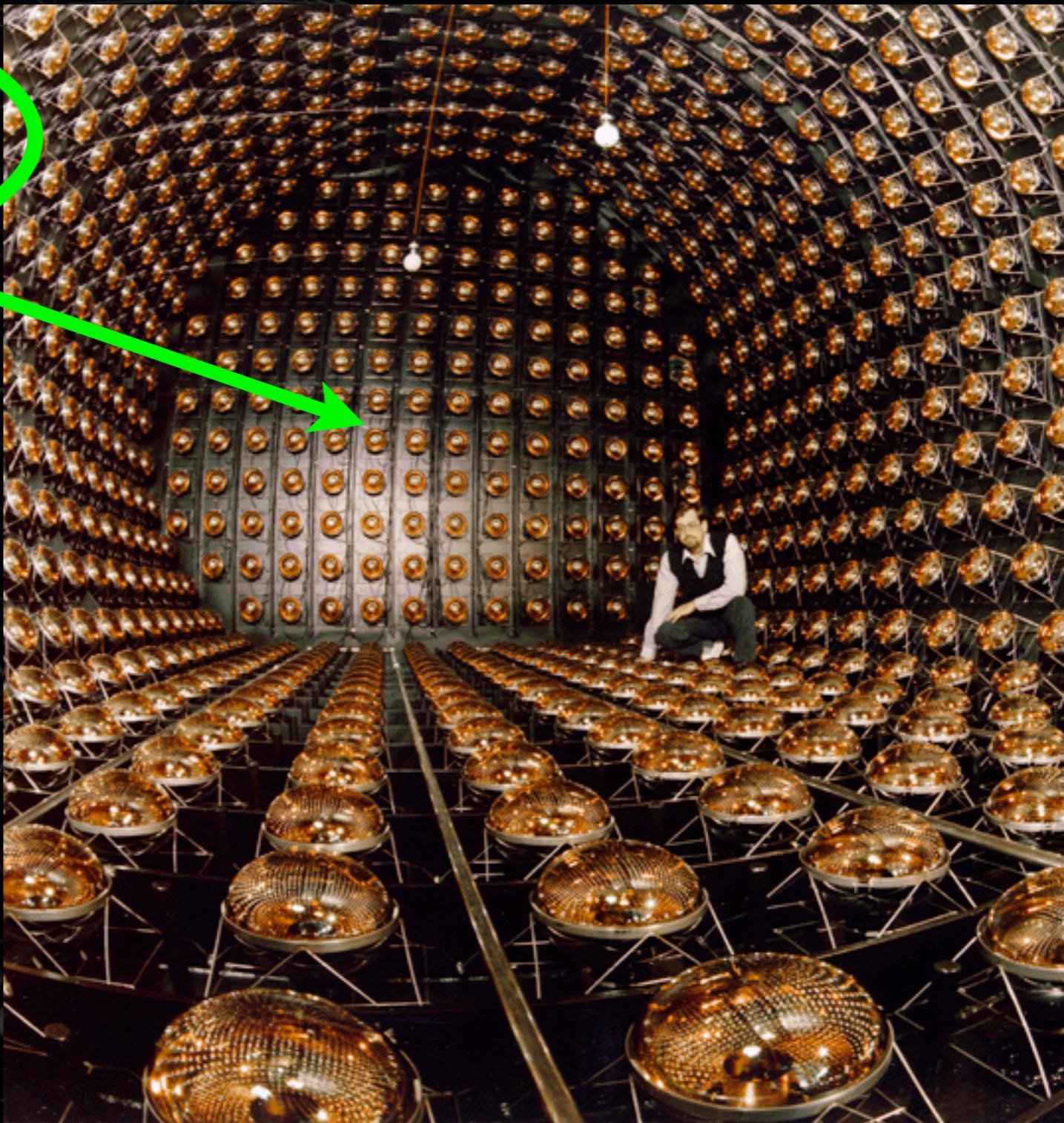
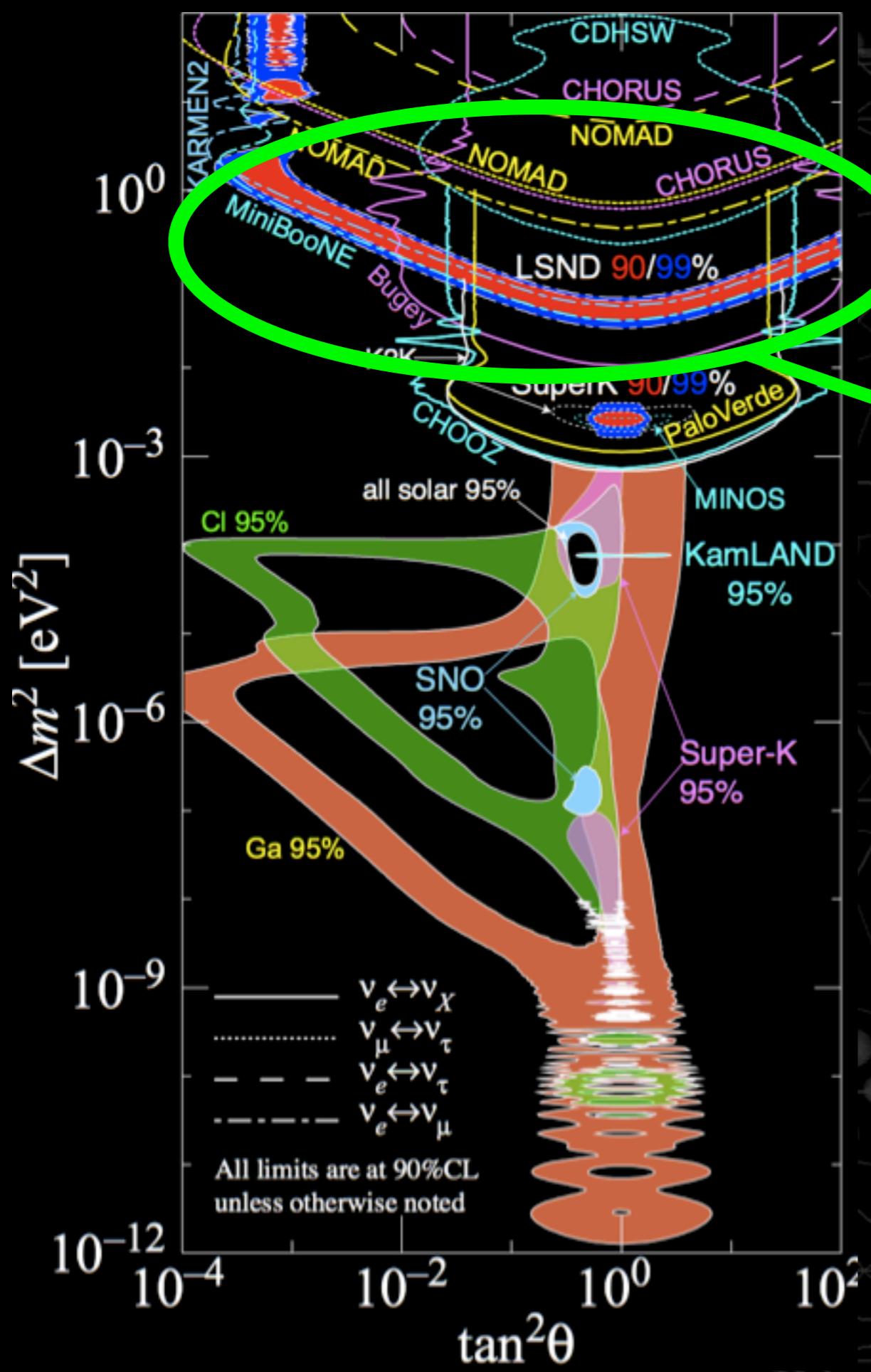
Solar



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

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

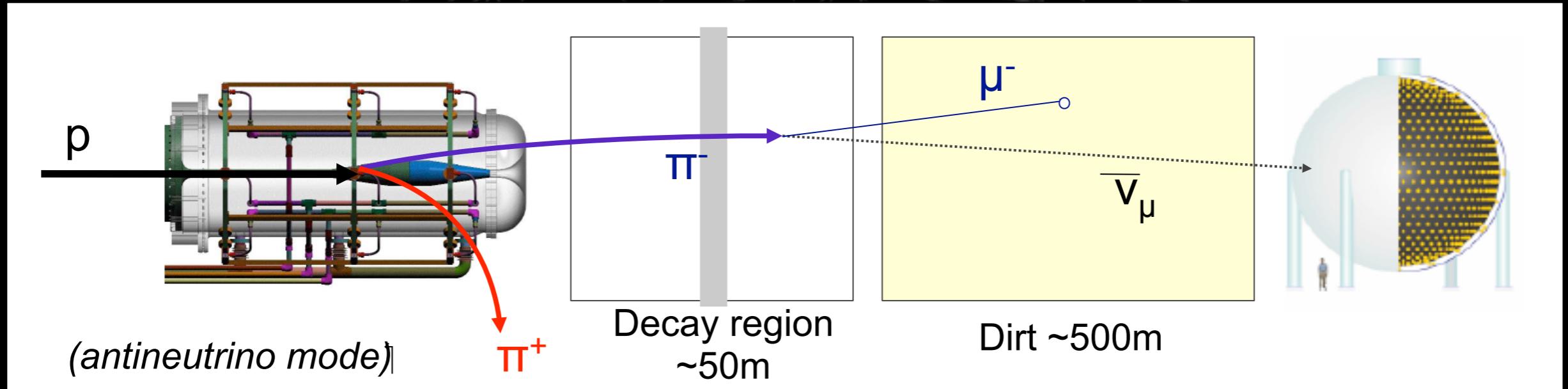
Short baseline



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

$$\theta_{\mu e} \sim 2^\circ$$

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

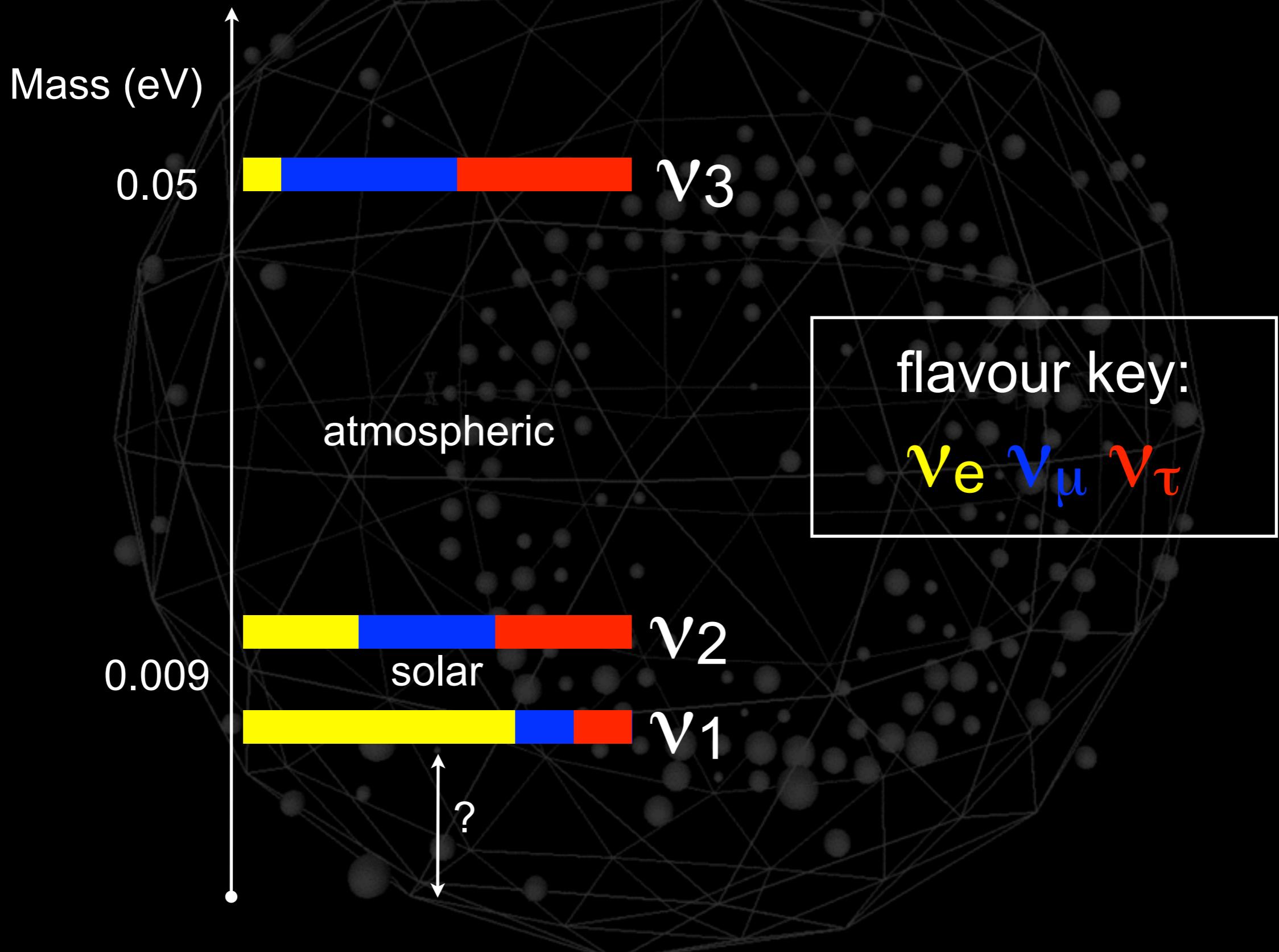
3 Flavours

$$|\nu_\alpha\rangle_{\text{flavor}} = \sum_i U_{\alpha i} |\nu_i\rangle_{\text{mass}}$$

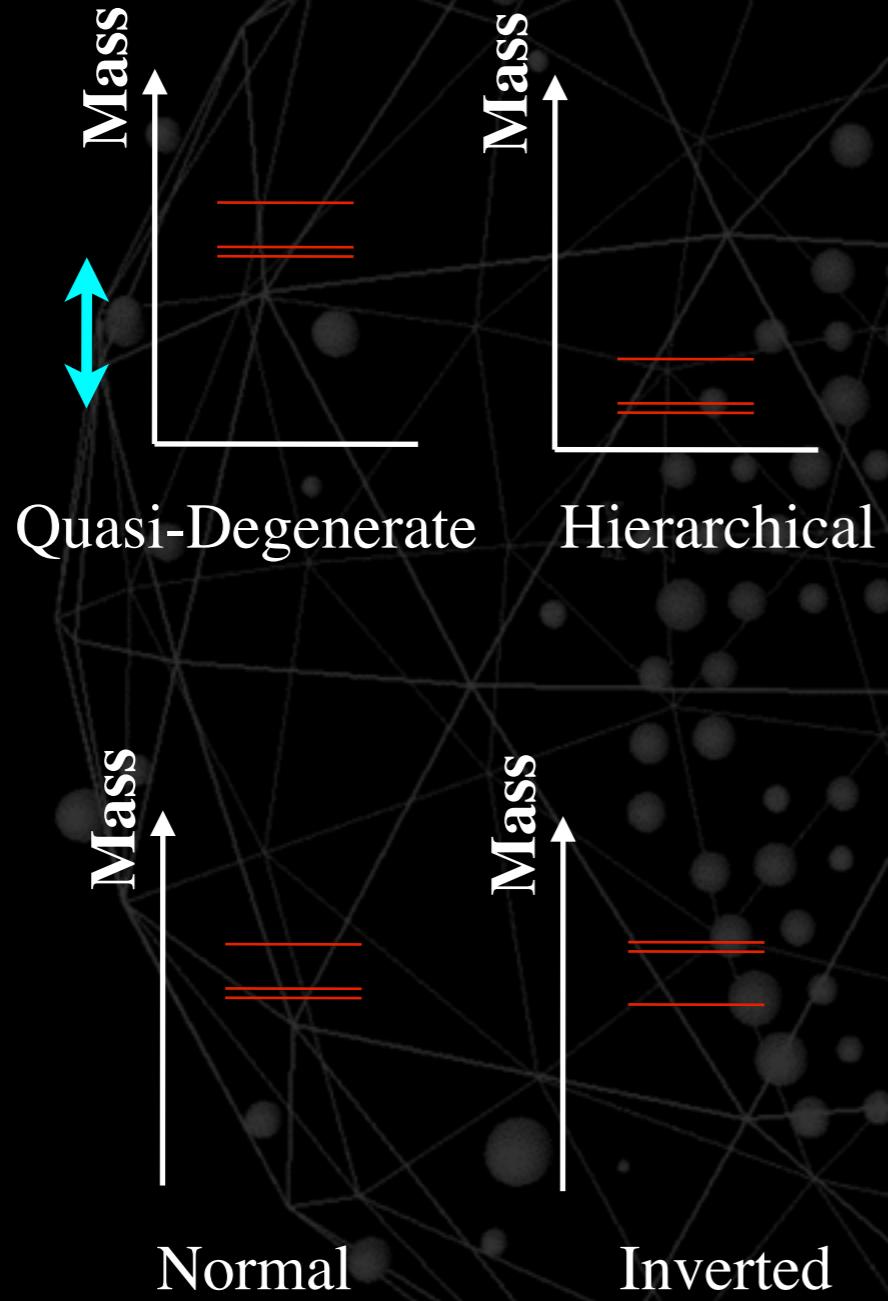
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

3 Flavours

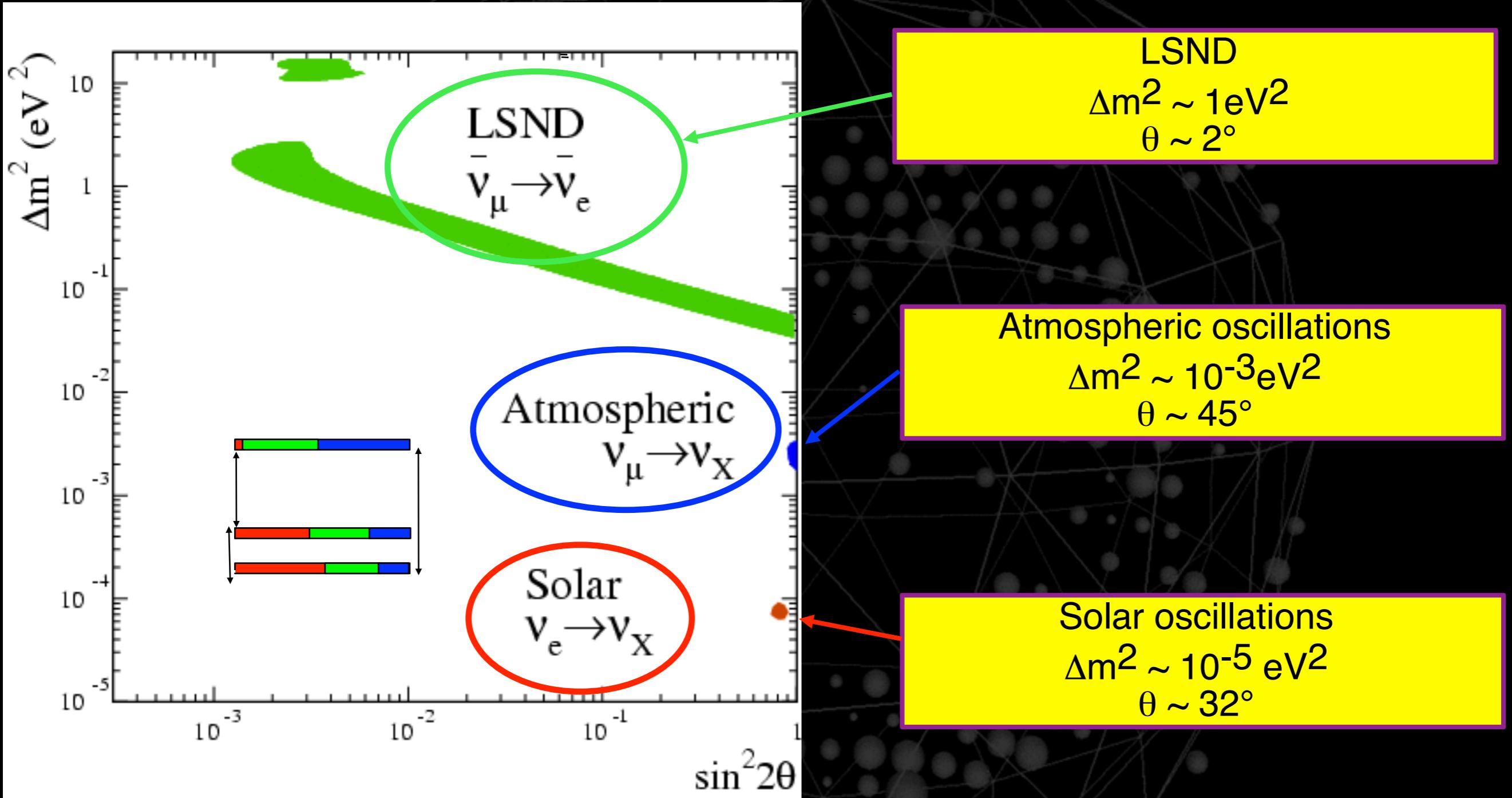


Today's Open Questions



- 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



- Problem: That's too many Δm^2 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

$L/E \sim 1\text{m}/\text{MeV}$

$L \sim 30\text{m}$

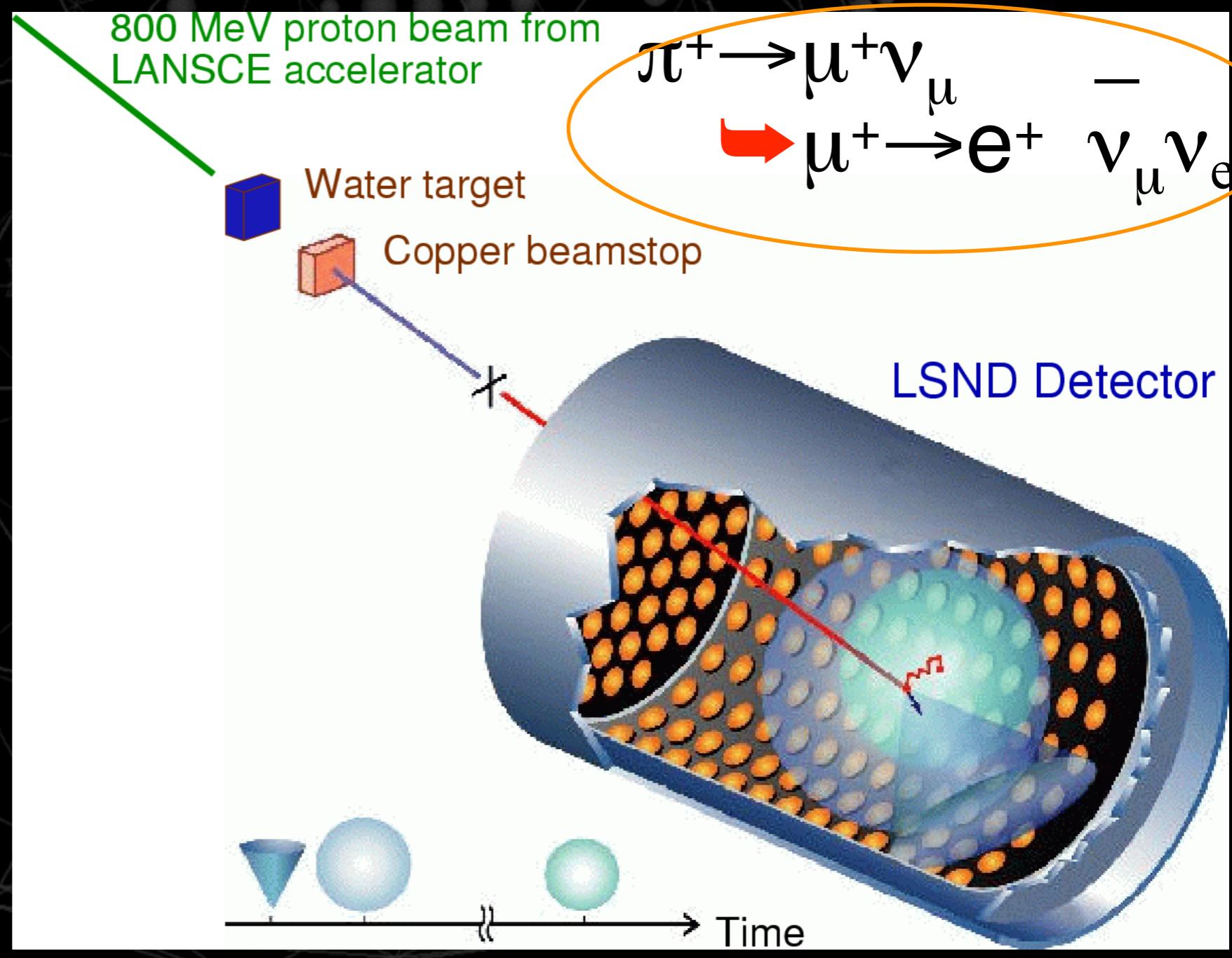
$20 < E_{\bar{\nu}} < 53\text{ MeV}$

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e ?$

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.

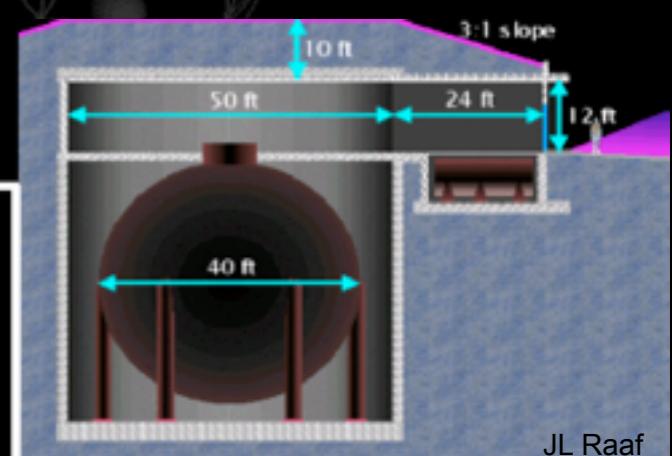
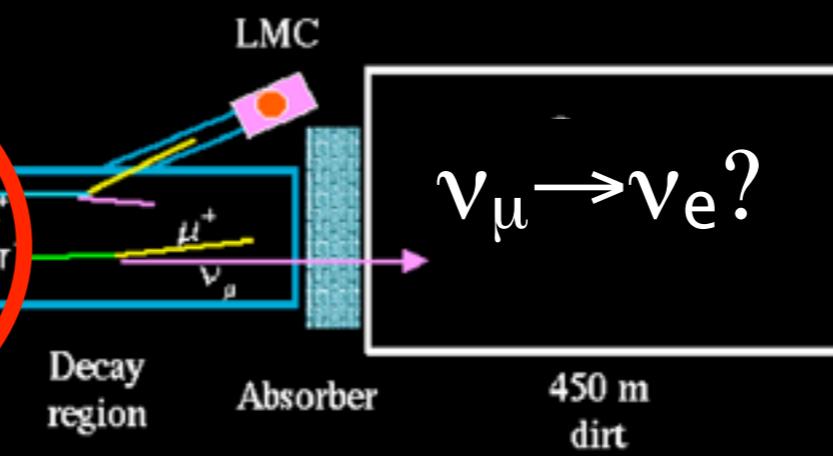
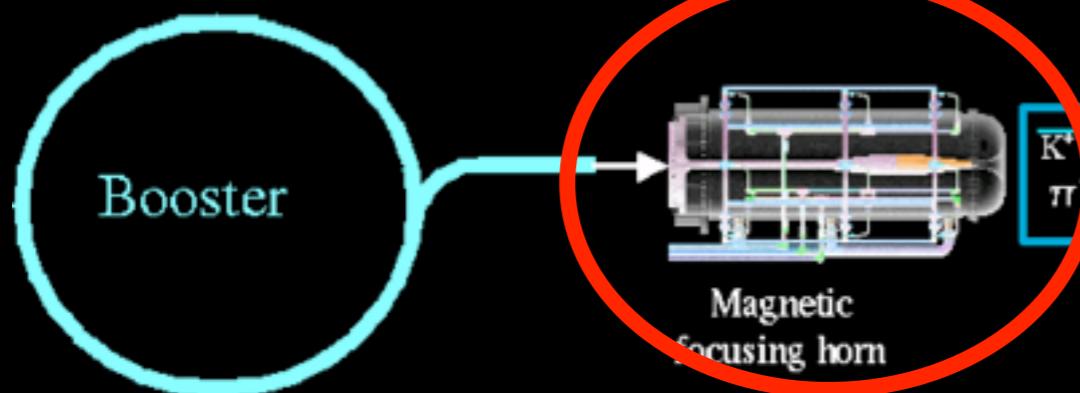
Note that LSND measures the correct rate of $\nu_\mu p \rightarrow \mu^+ n$ interactions, which confirms the p- production and background estimates. Note also, that FLUKA & GEANT4 are not as reliable as MCNP at 800 MeV!

Target & Horn



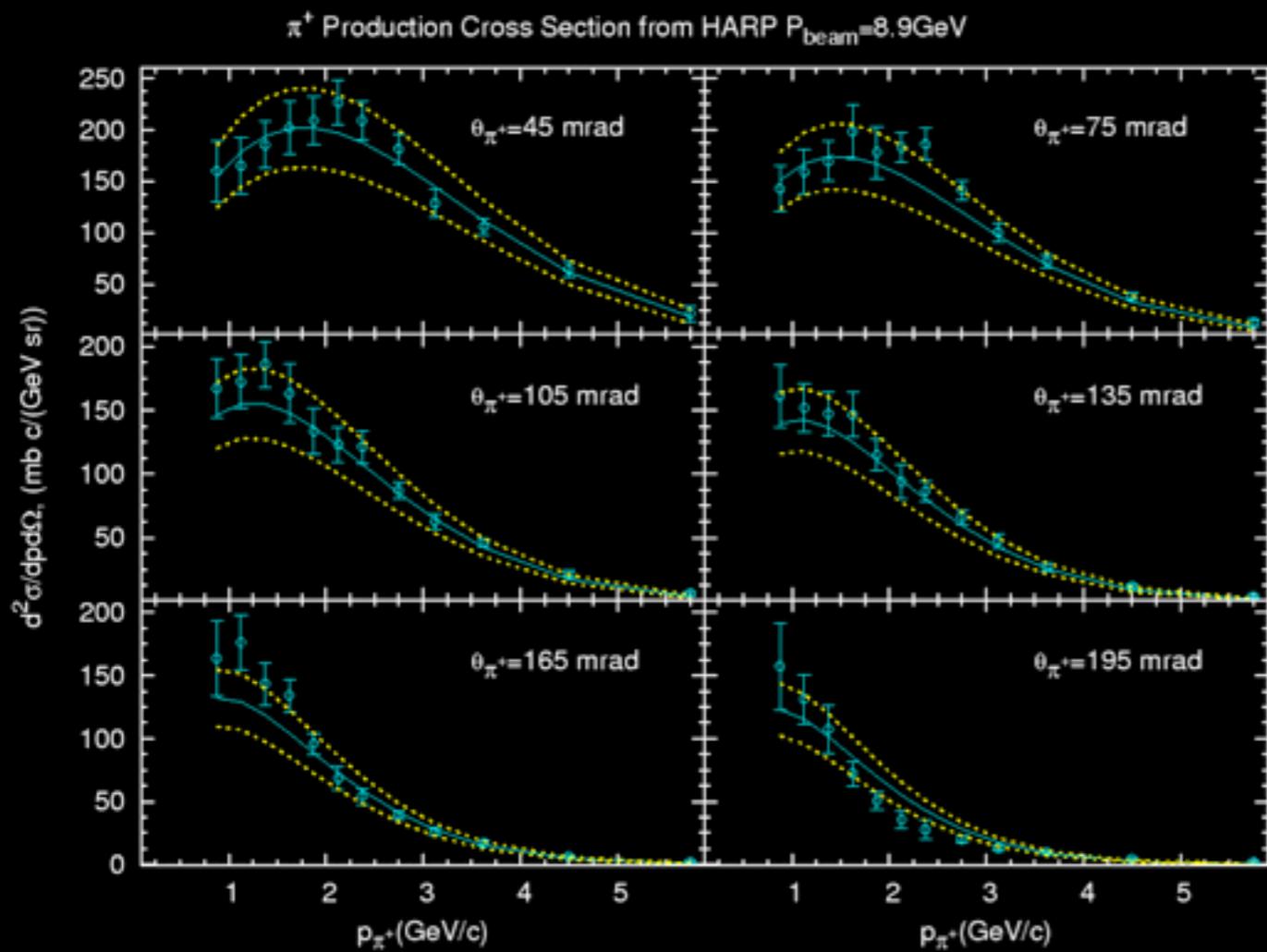
Main components of Booster Neutrino Beam (BNB)
(96M and 313M+ pulses)

MiniBooNE Overview



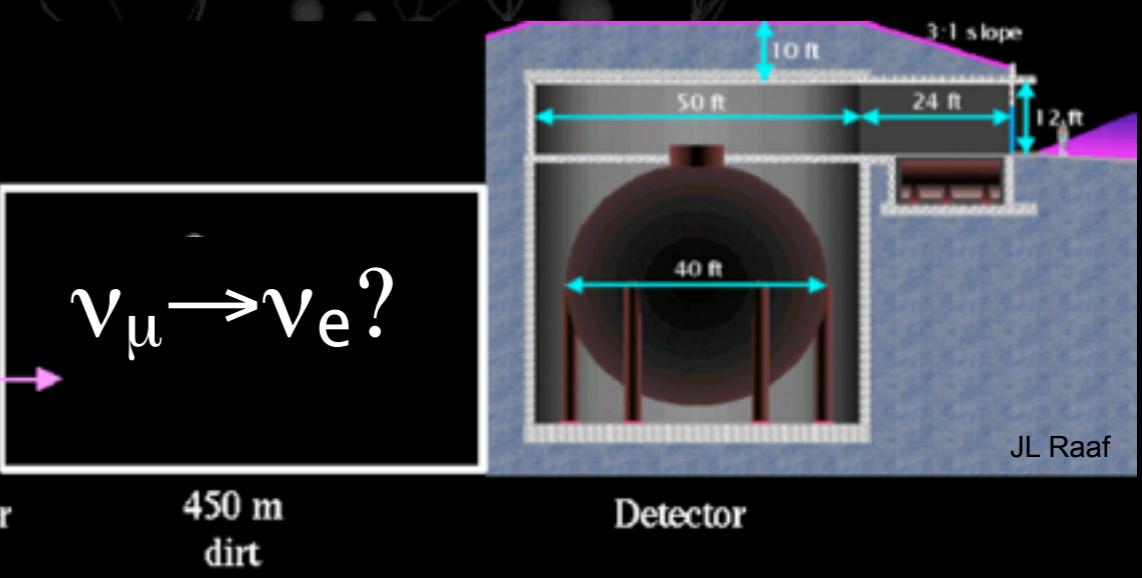
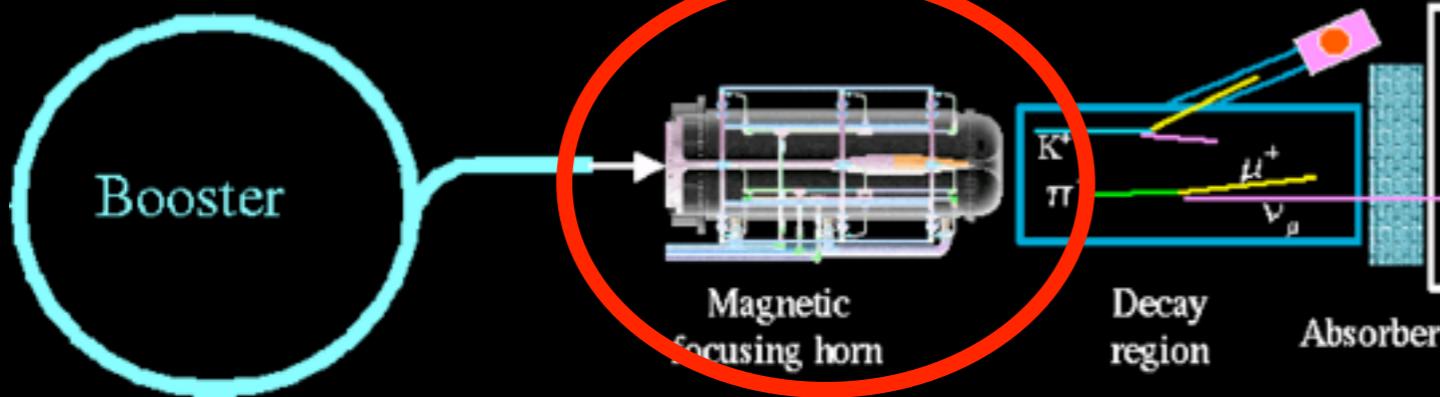
Meson Production

PRD 79 072002 (2009)



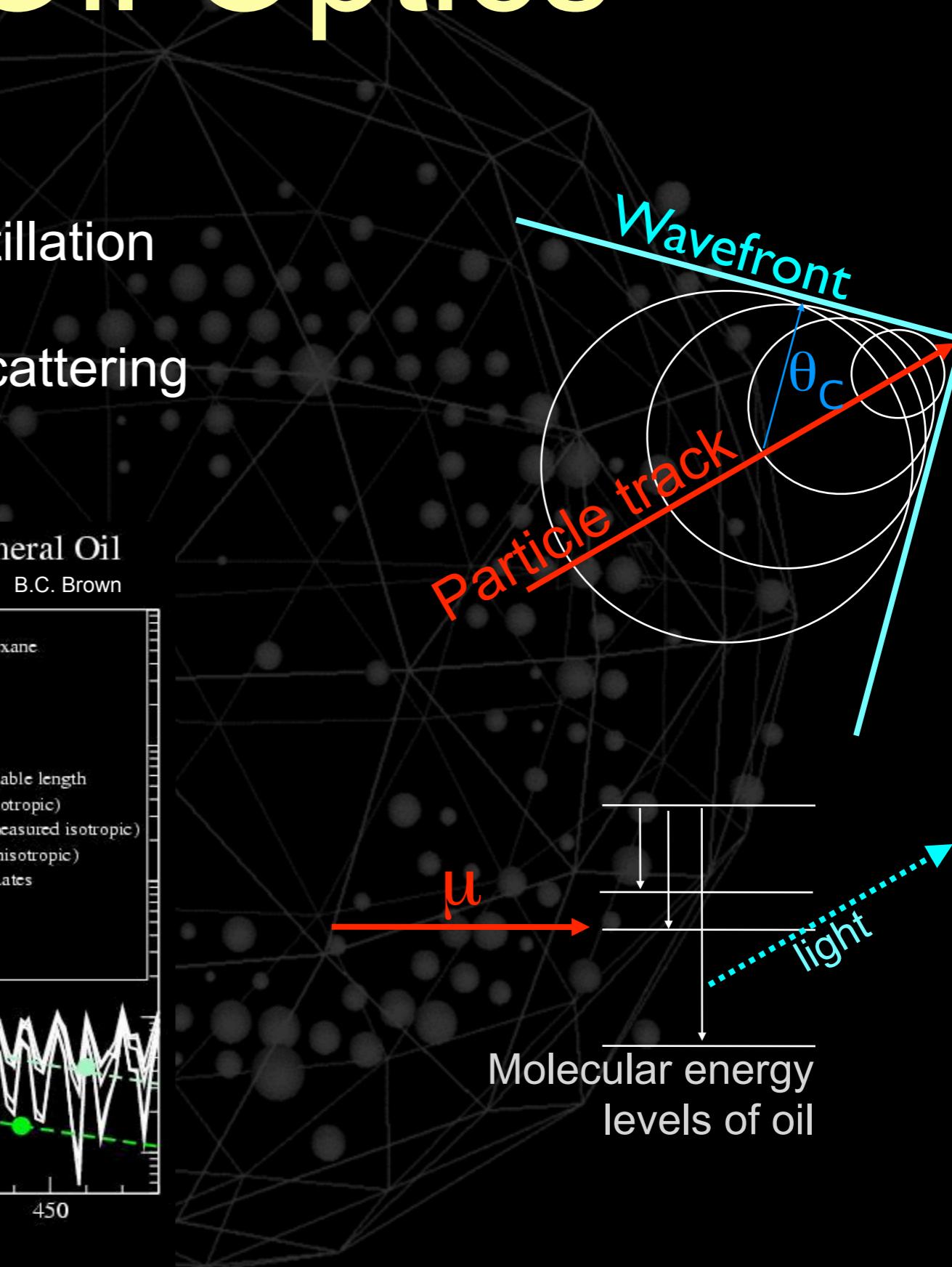
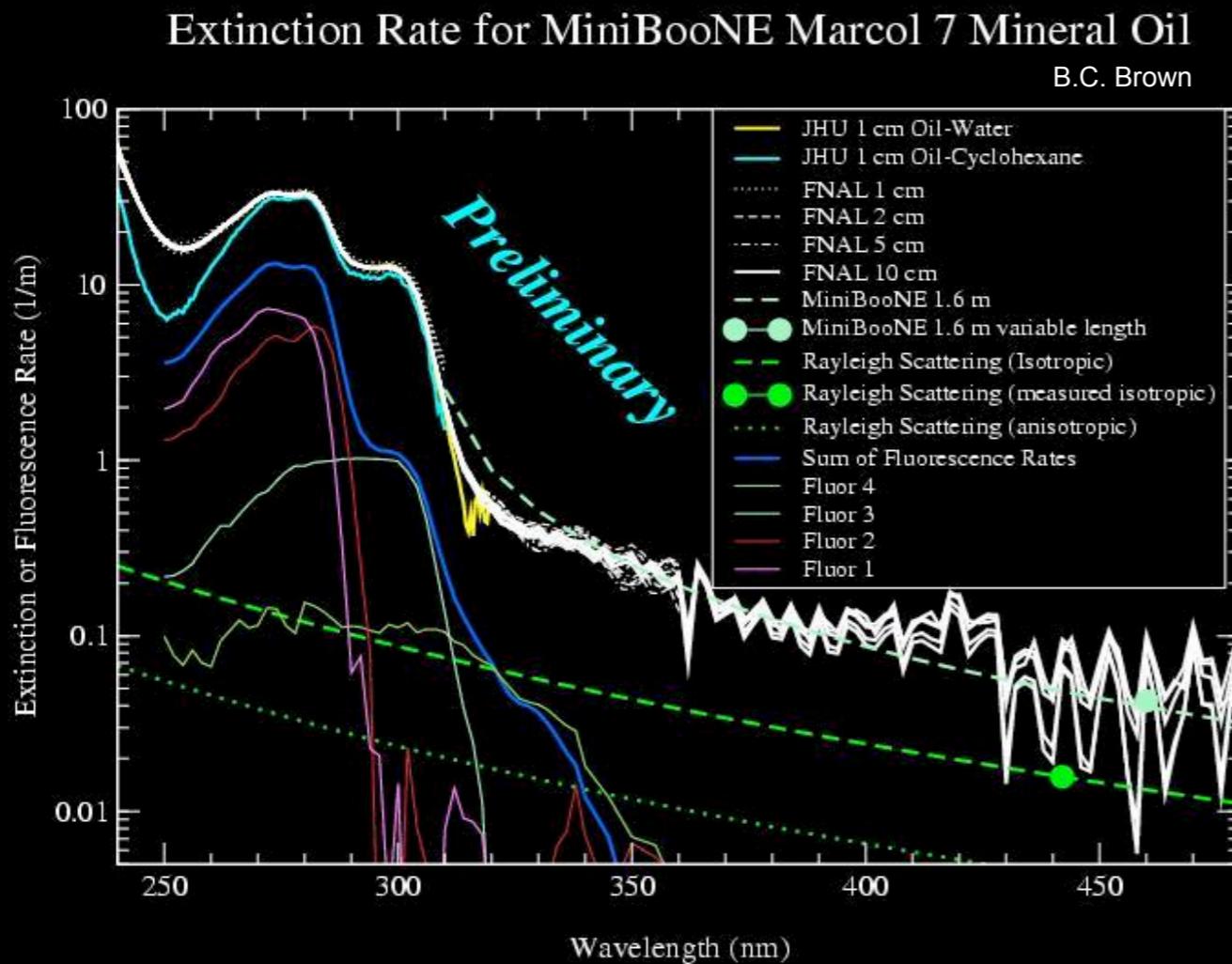
- External meson production data
 - HARP data (CERN)
- Parametrisation of cross-sections
 - Sanford-Wang for pions
 - Feynman scaling for kaons
- Use of HARP data reduces total flux error to ~9%

MiniBooNE Overview



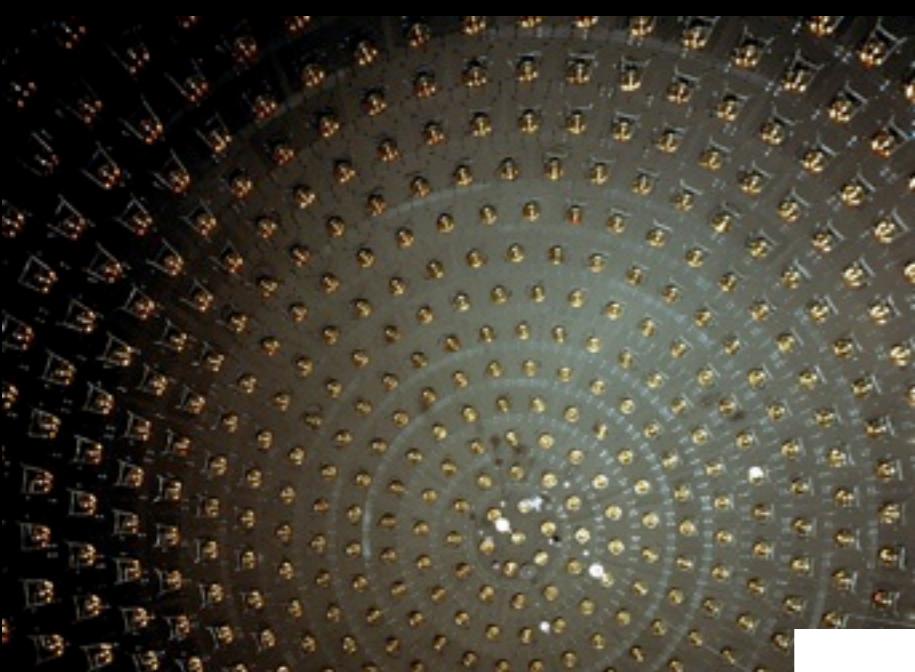
Mineral Oil Optics

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



PMT Calibration

PMTs are calibrated with a laser + 4 flask system

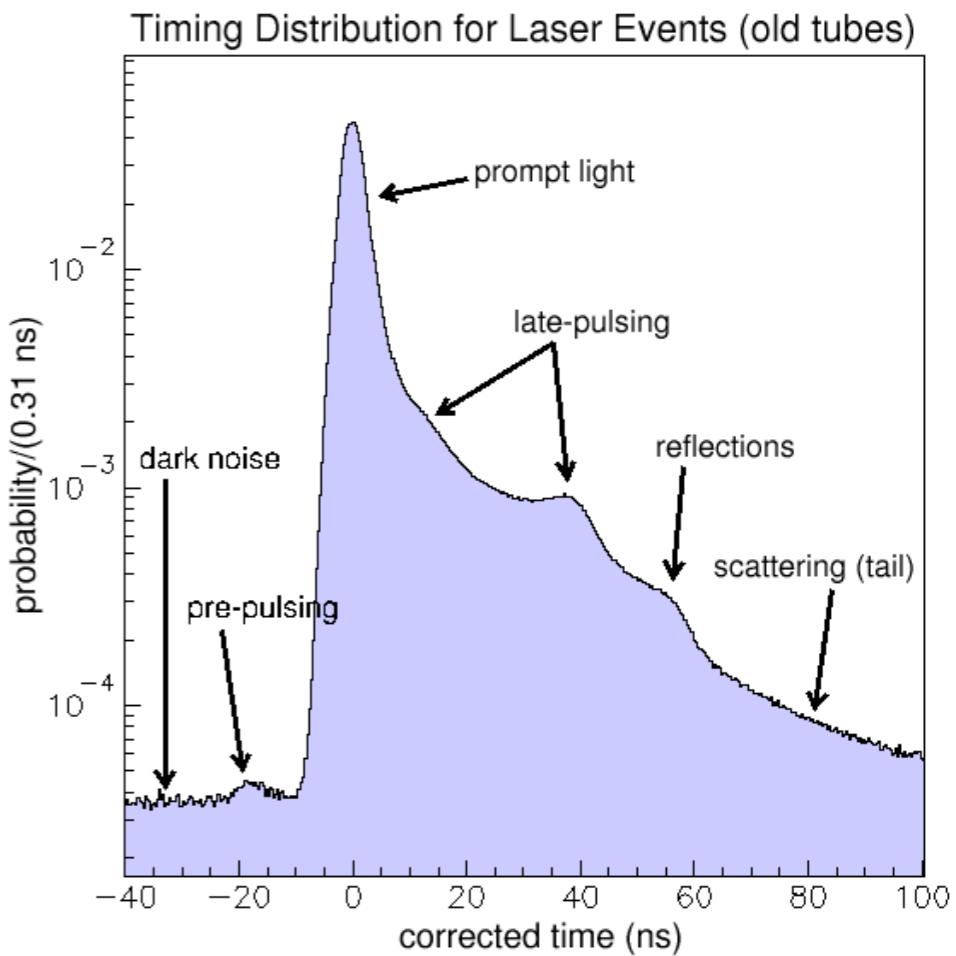
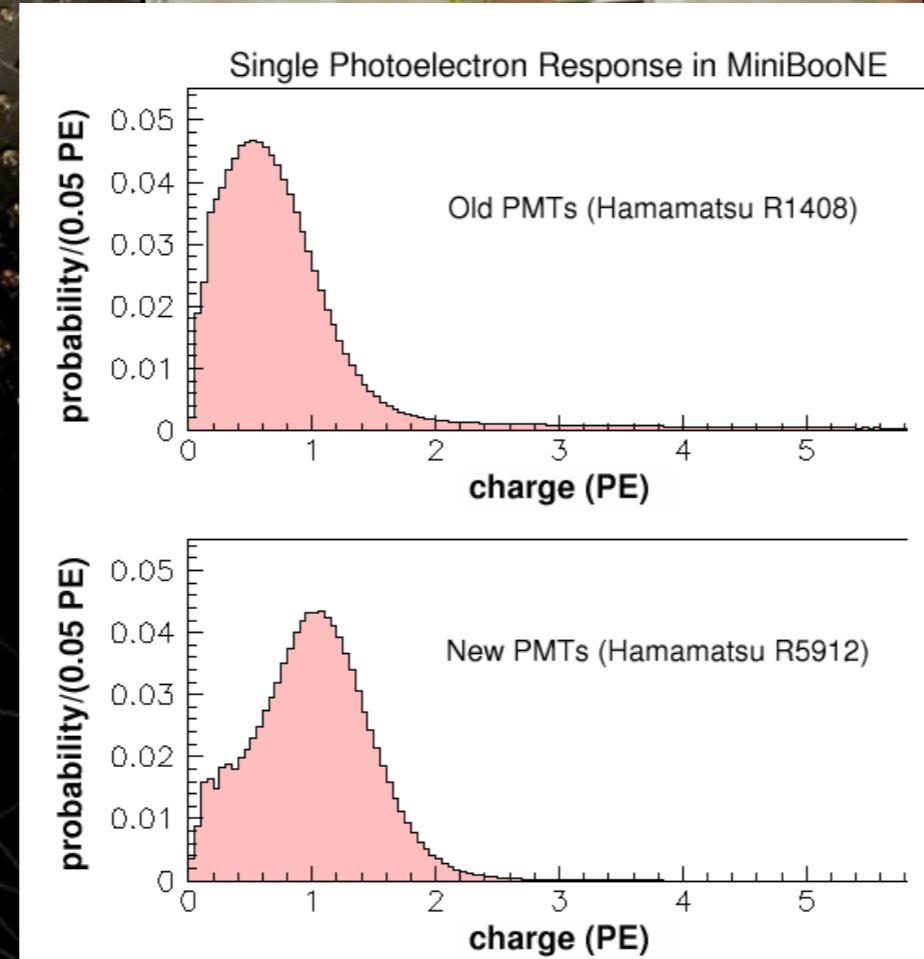


Charge Res: 1.4 PE, 0.5 PE
Time Res: 1.7 ns, 1.1 ns

R.B. Patterson

10% photo-cathode coverage

Two types of 8"
Hamamatsu Tubes:
R1408, R5912



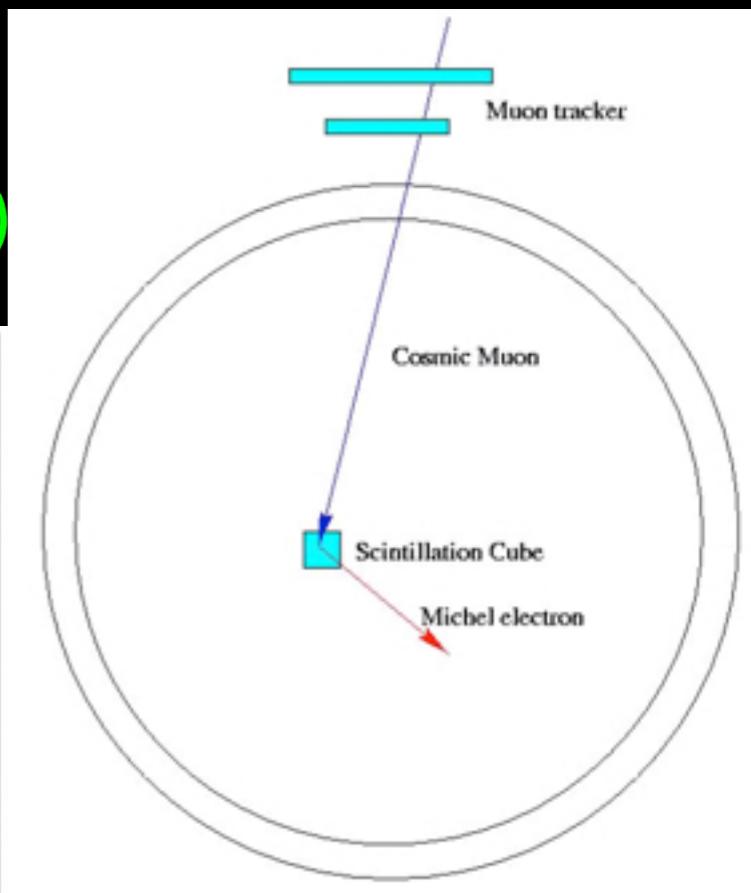
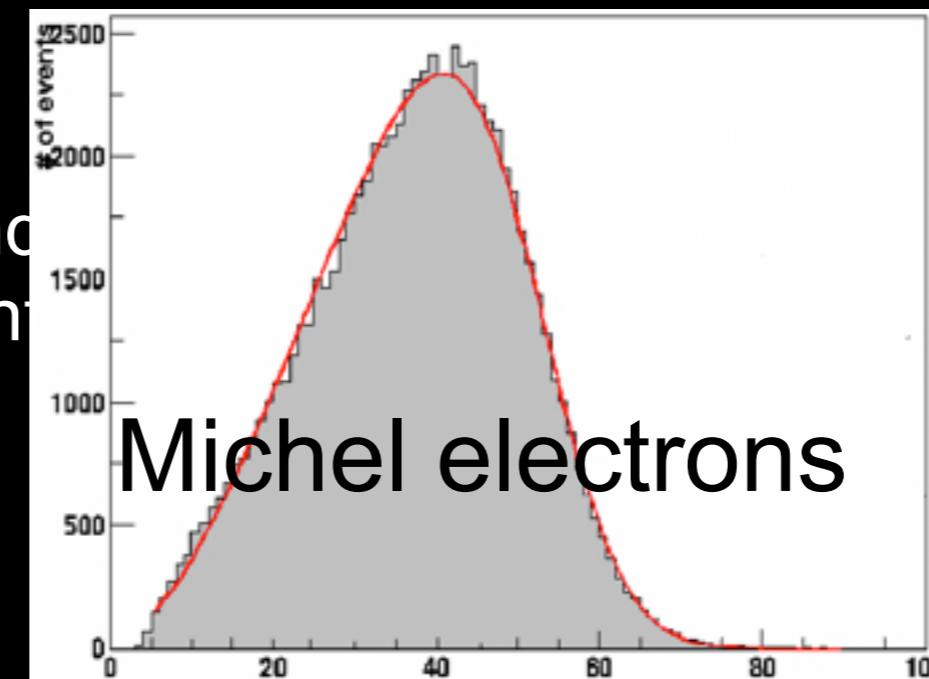
Laser data are acquired at 3.3 Hz to continuously calibrate PMT gain and timing constants

Cosmic μ calibration

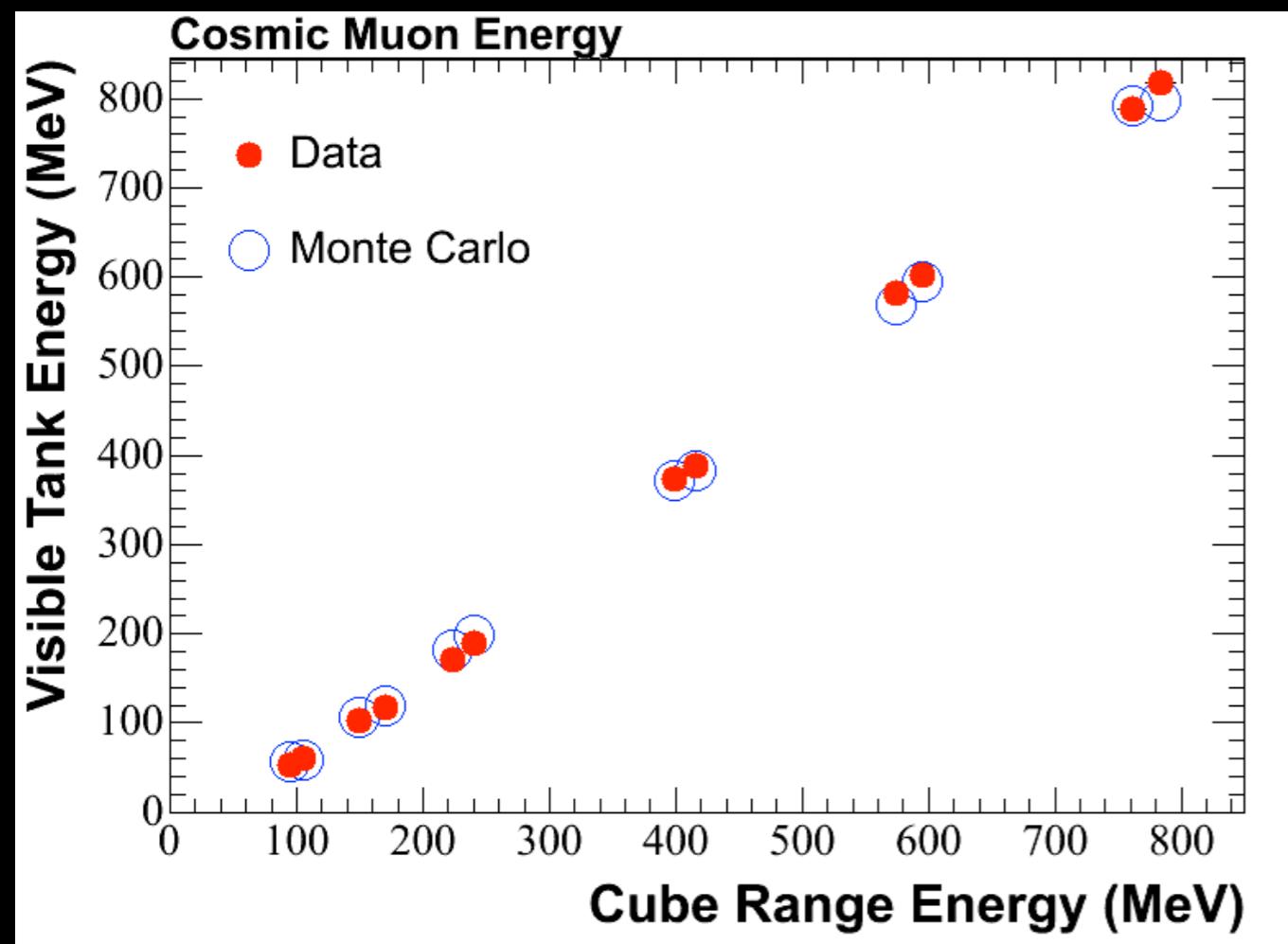
use cosmic muons and their decay electrons (Michels)

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:

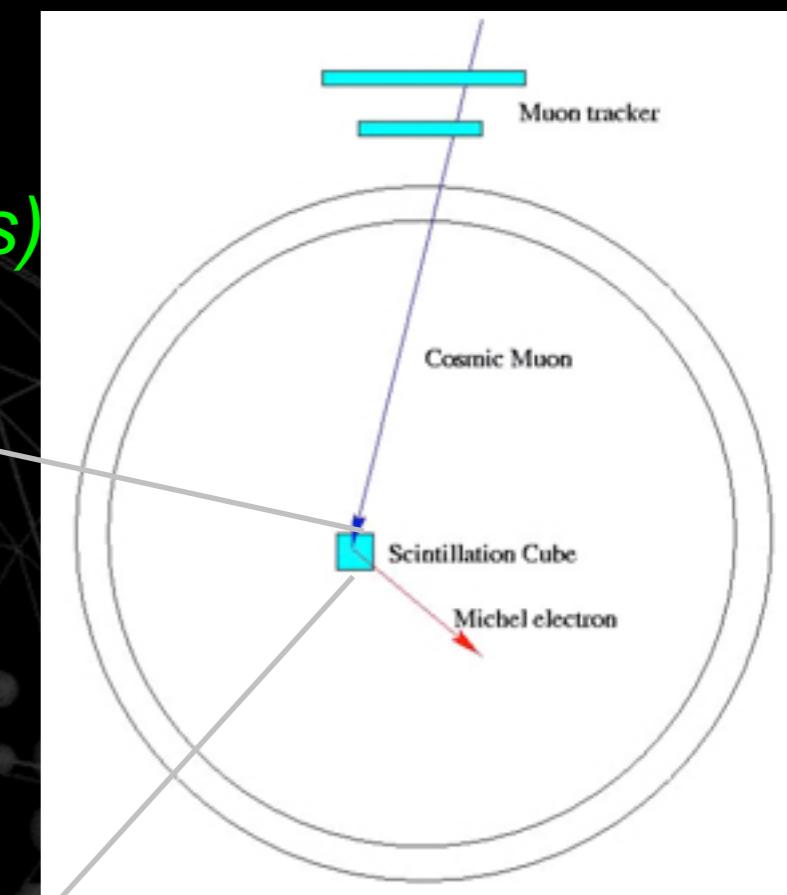
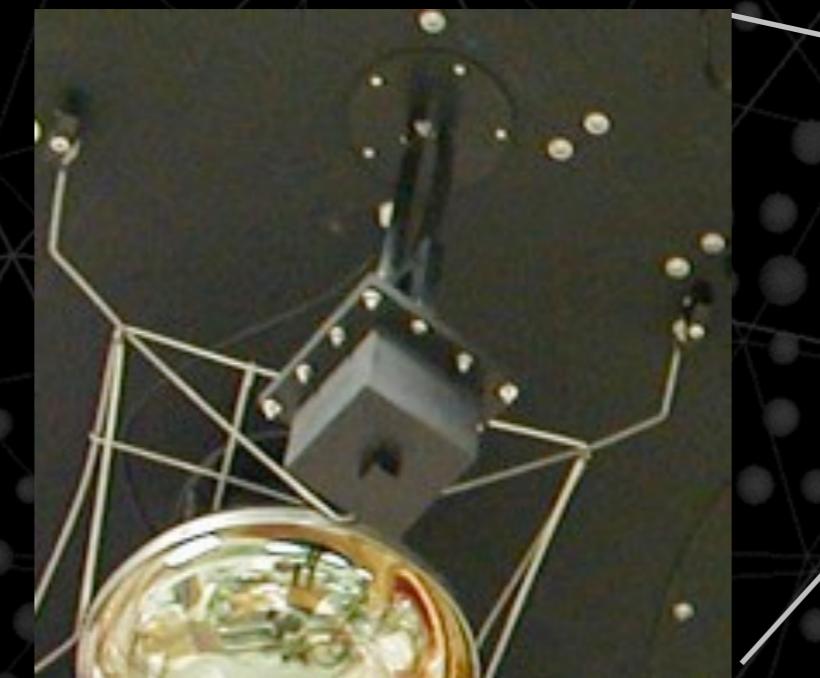
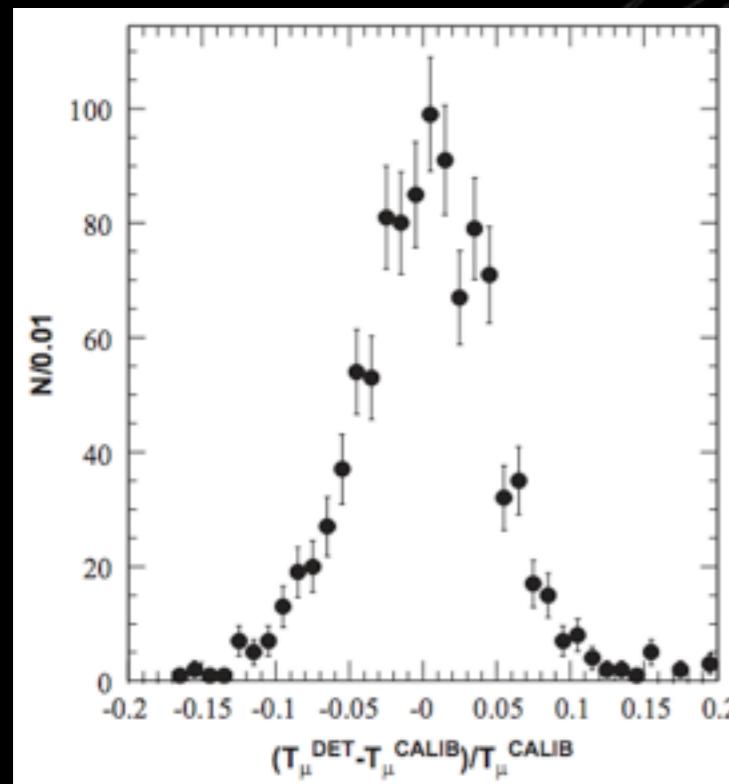
- test energy scale extrapolation up to 800 MeV
- measure energy, angle resolution
- compare data and MC

*Muon tracker + cube calibration
data continuously acquired at 1 Hz*

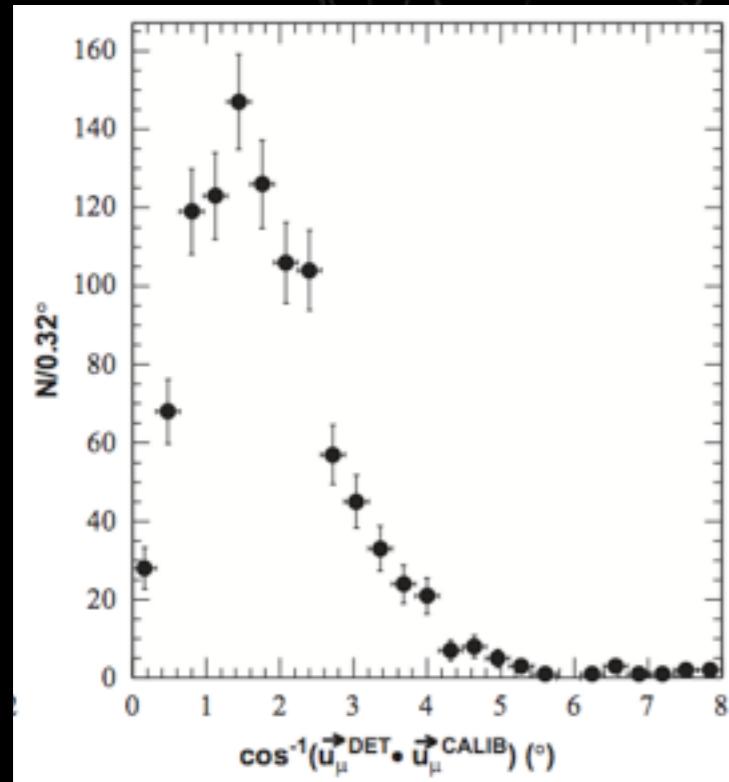
Cosmic μ calibration

use cosmic muons and their decay electrons (Michels)

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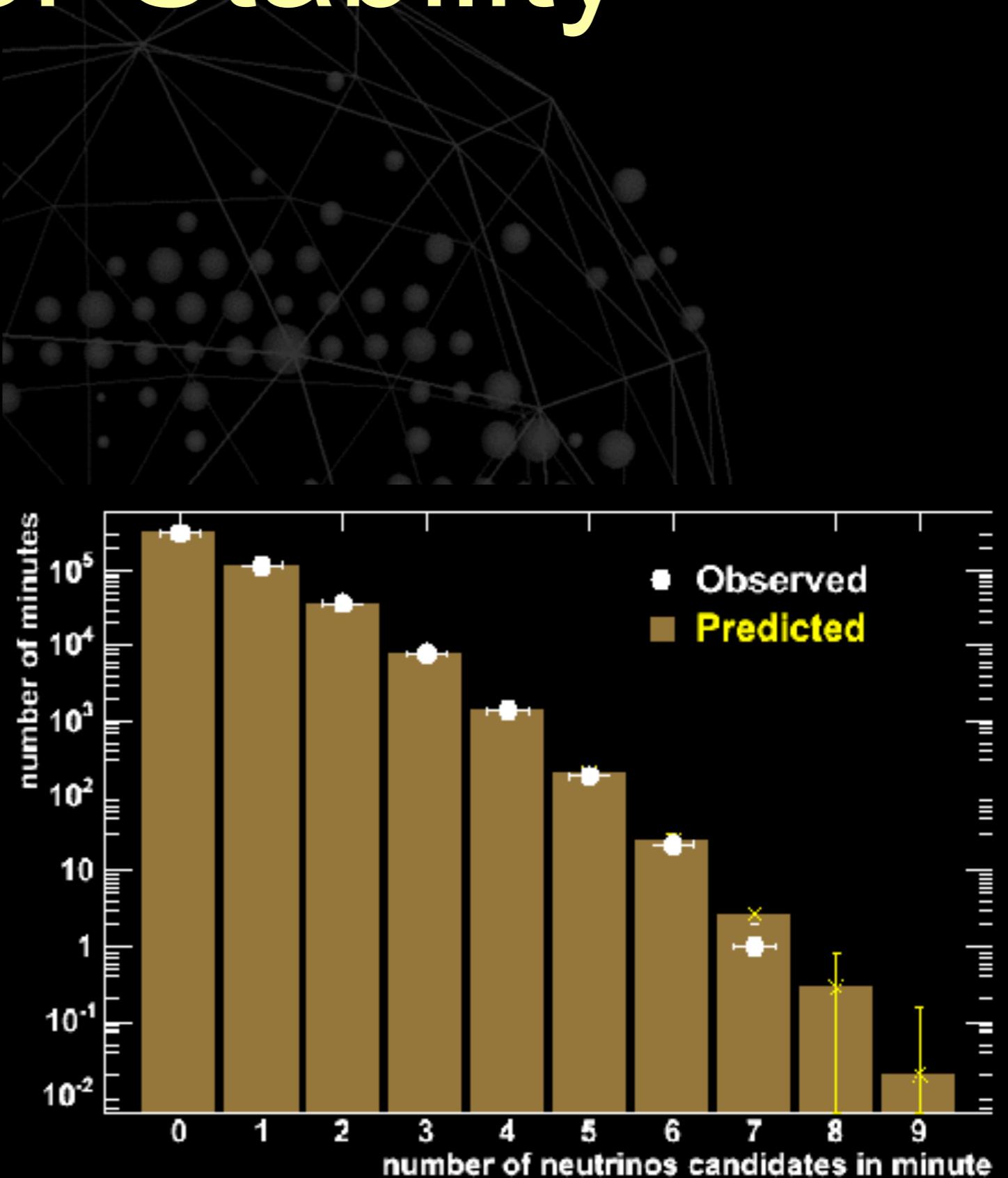
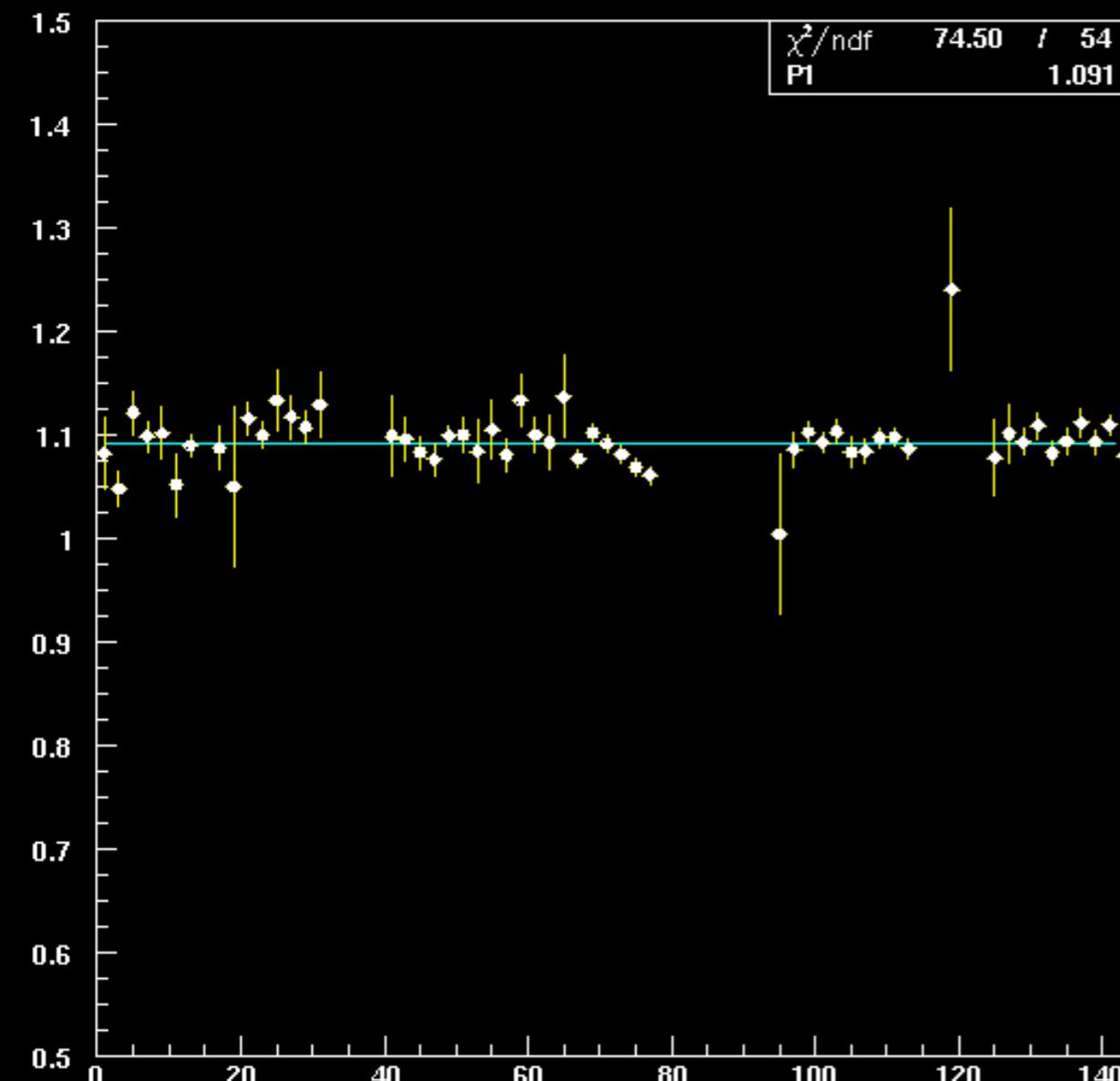
Muon tracker
7 scintillator cubes



Energy (MeV)	$\theta_{\text{res}}(\circ)$	$E_{\text{res}}(\%)$
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

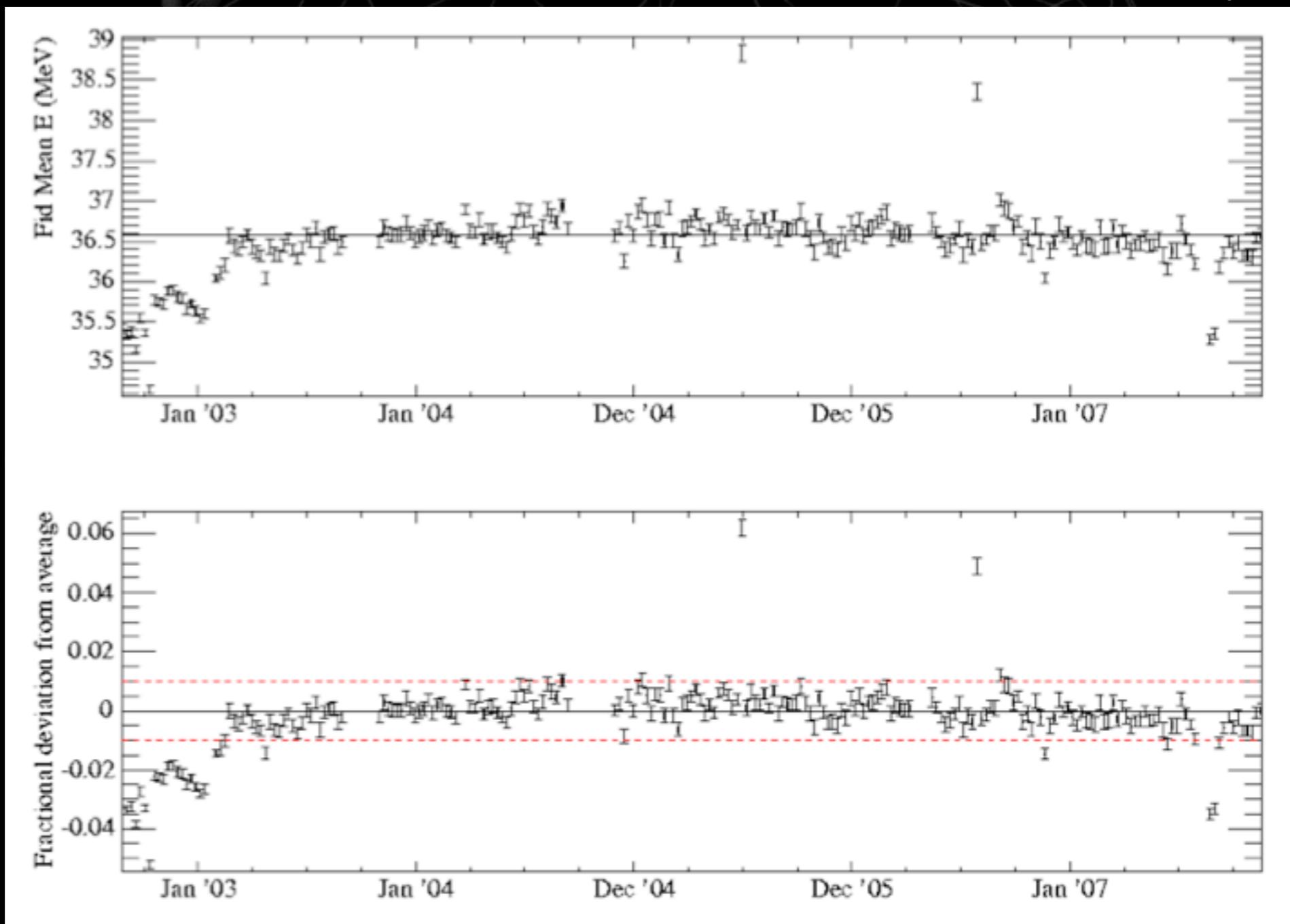
Detector Stability

Events per 1e15 POT vs Week



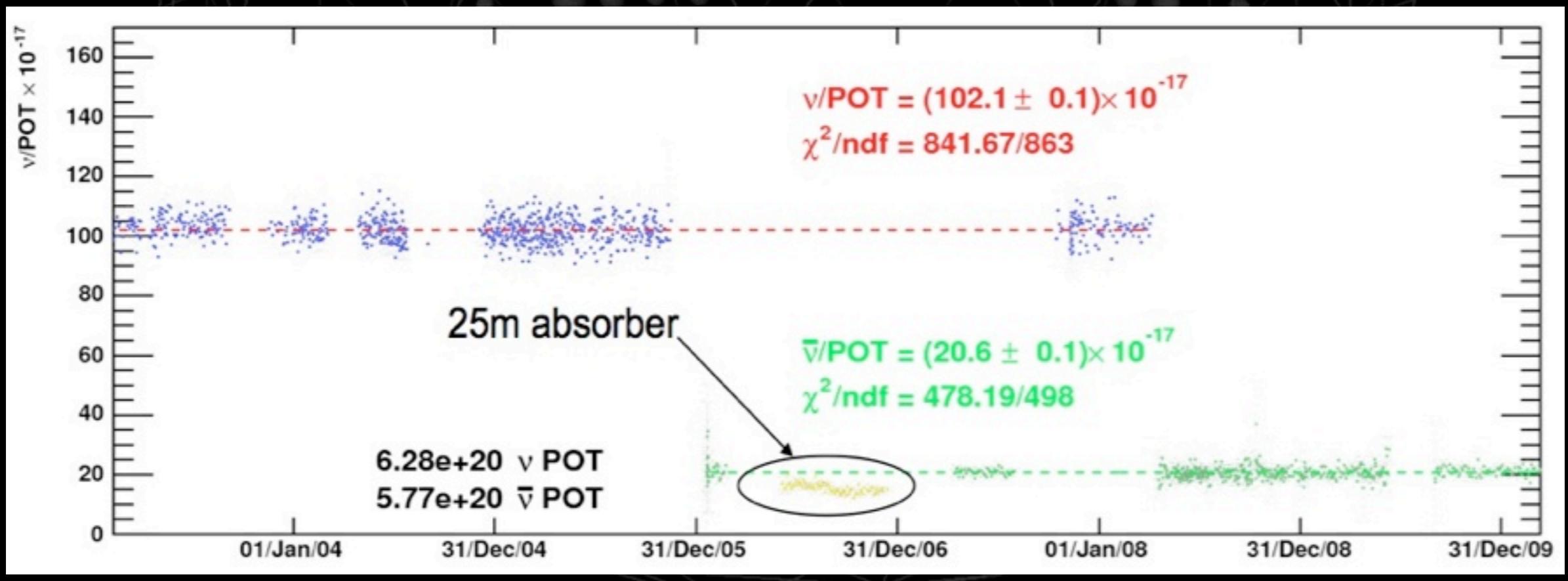
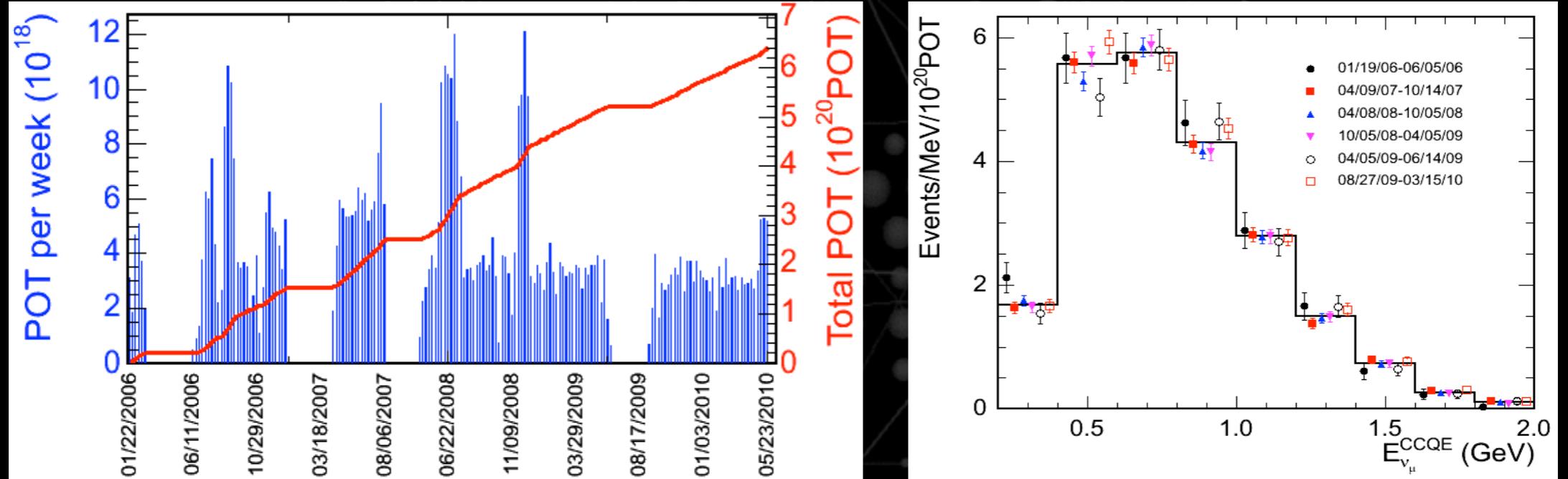
Detector Stability

B. Bolin

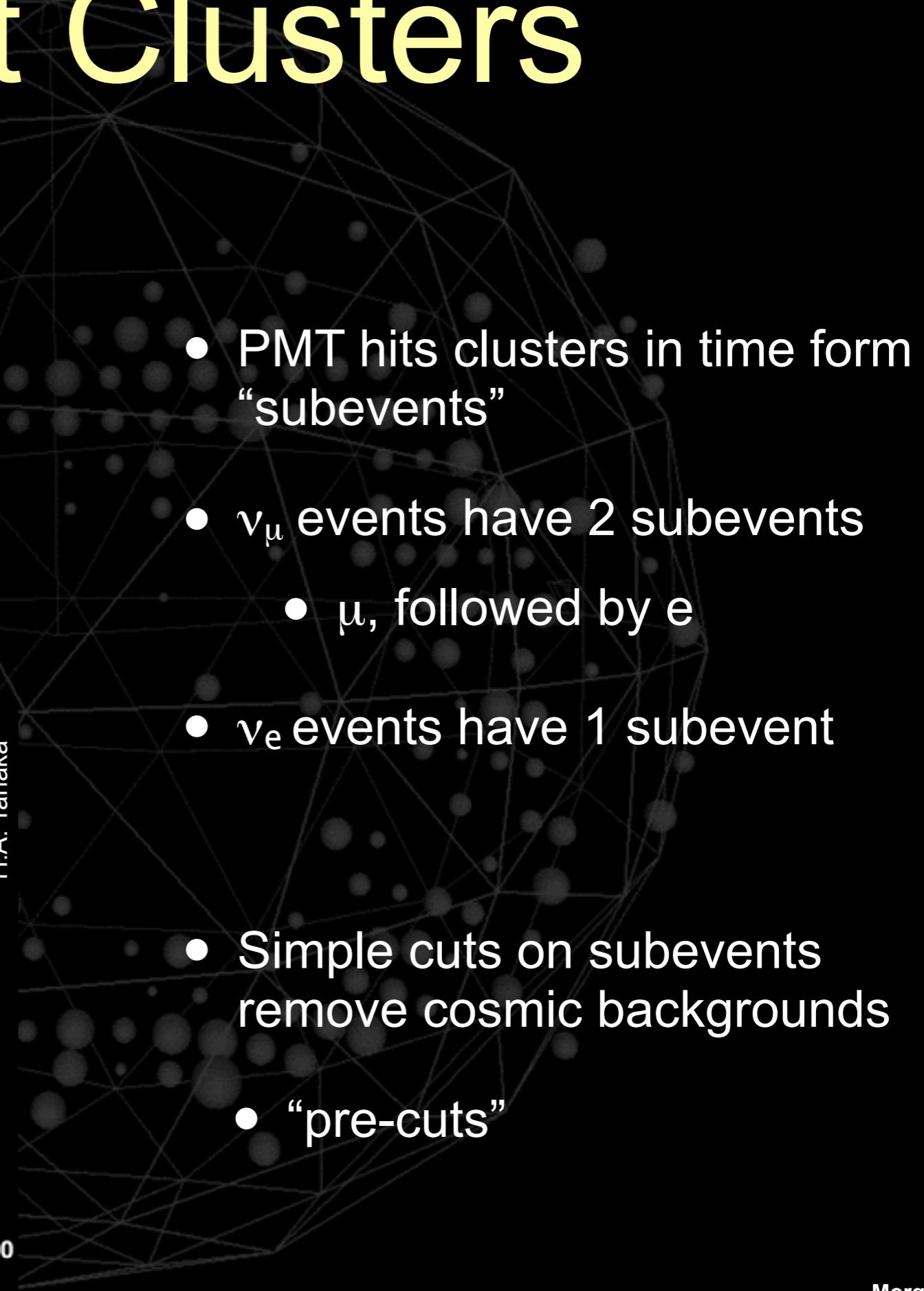
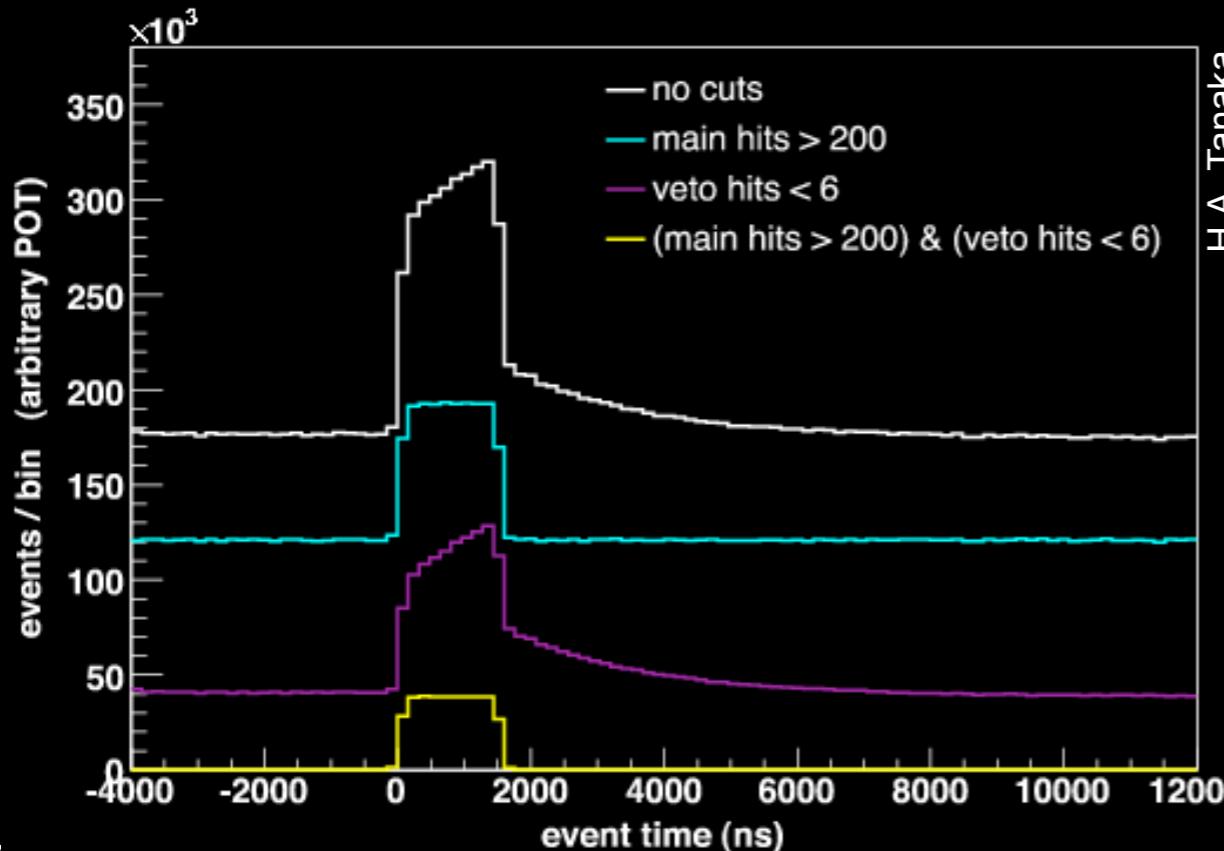
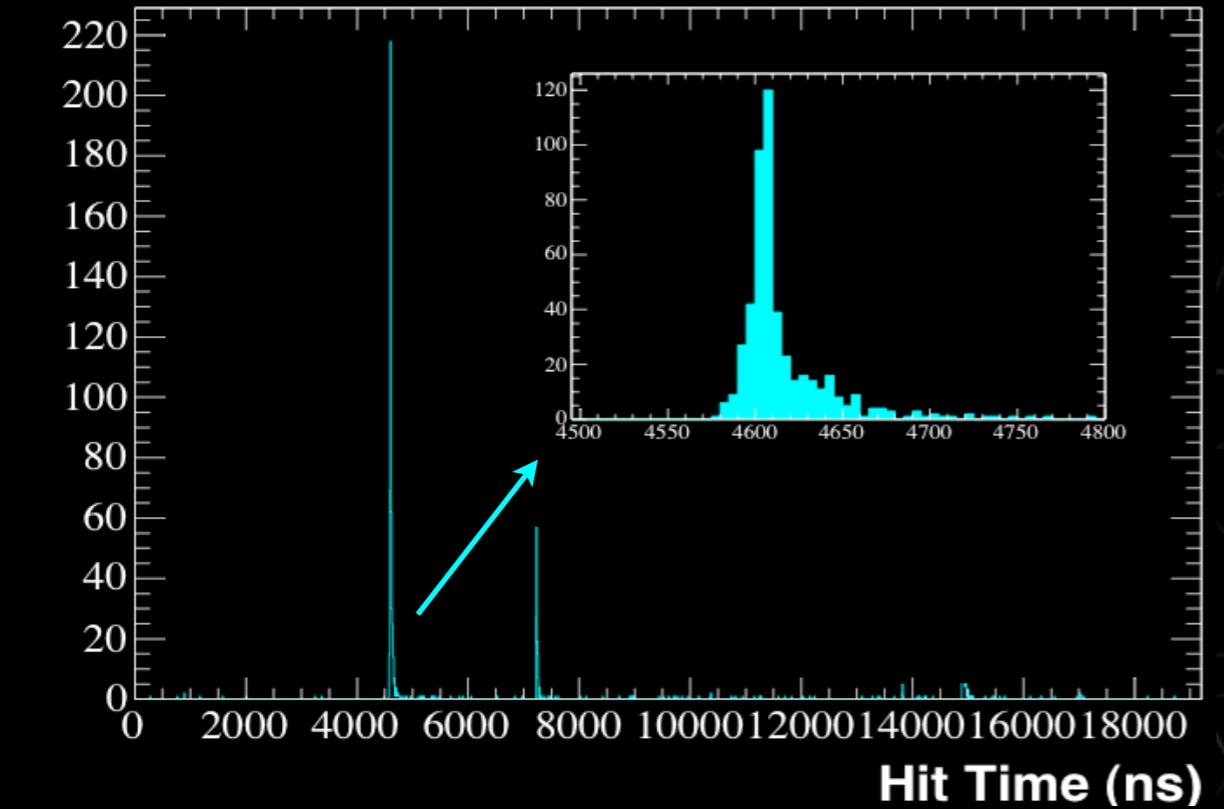


Michel electron mean energy

Experiment Stability

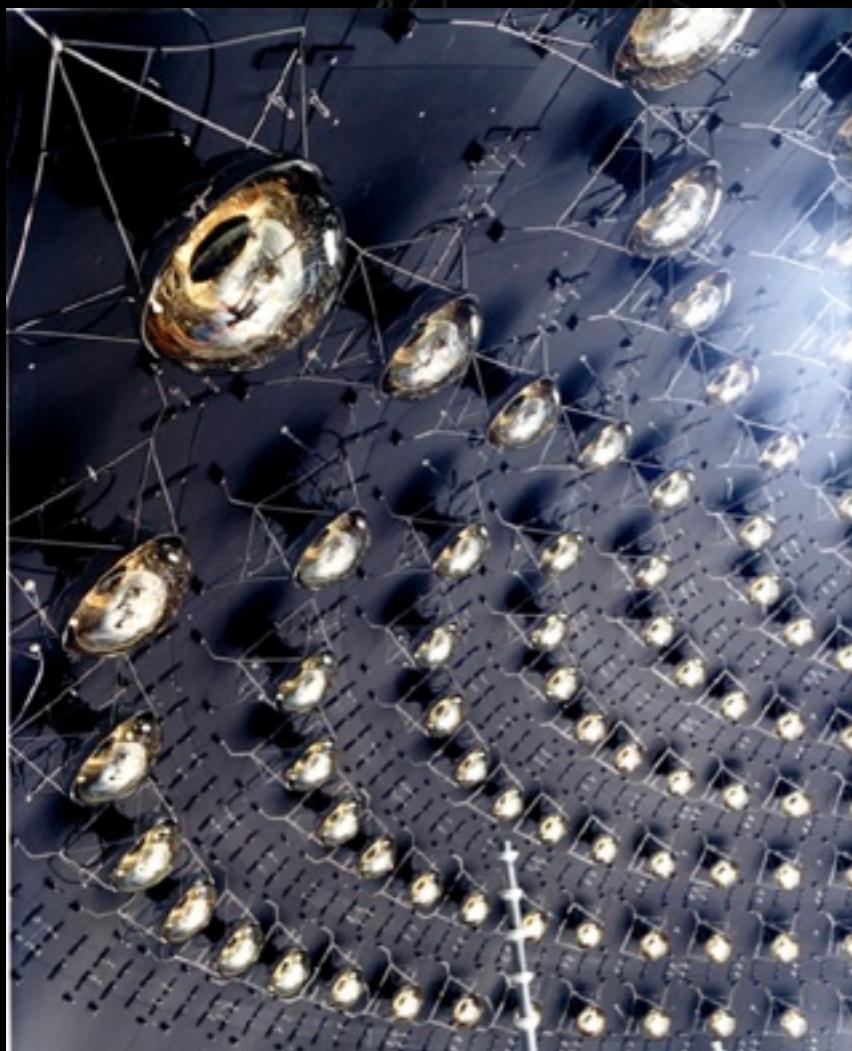


PMT Hit Clusters



Track Reconstruction

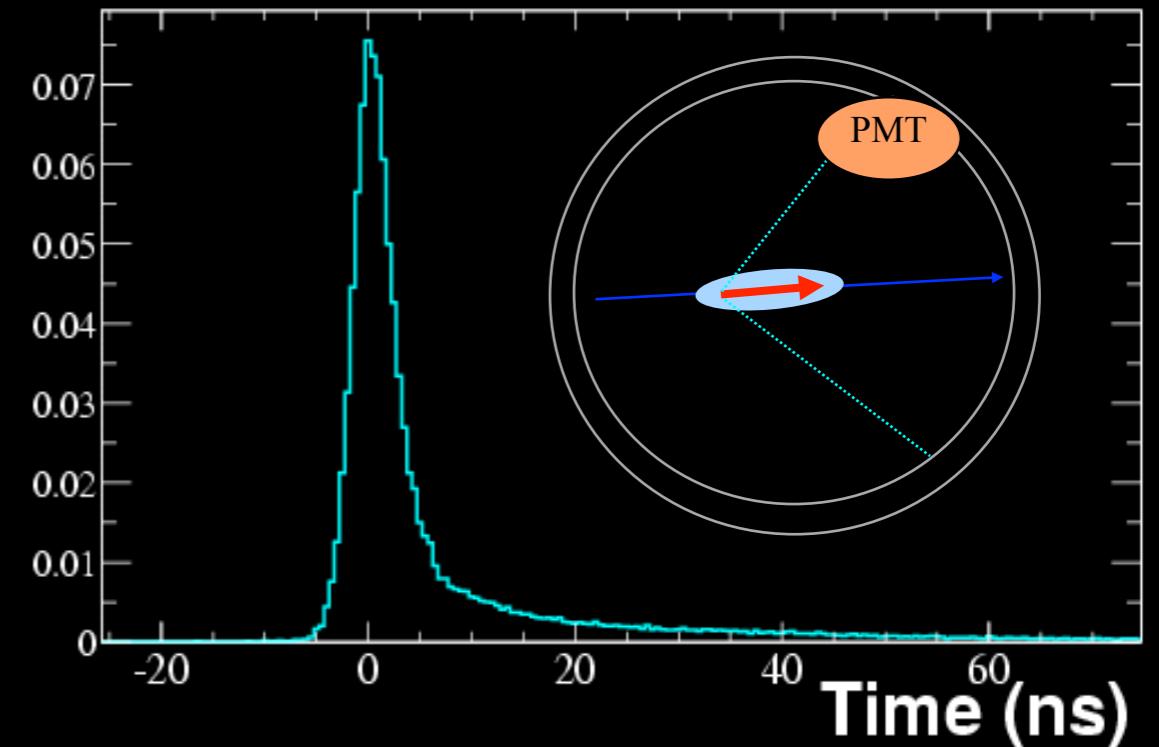
Charged particles produce
Cherenkov and scintillation light in oil



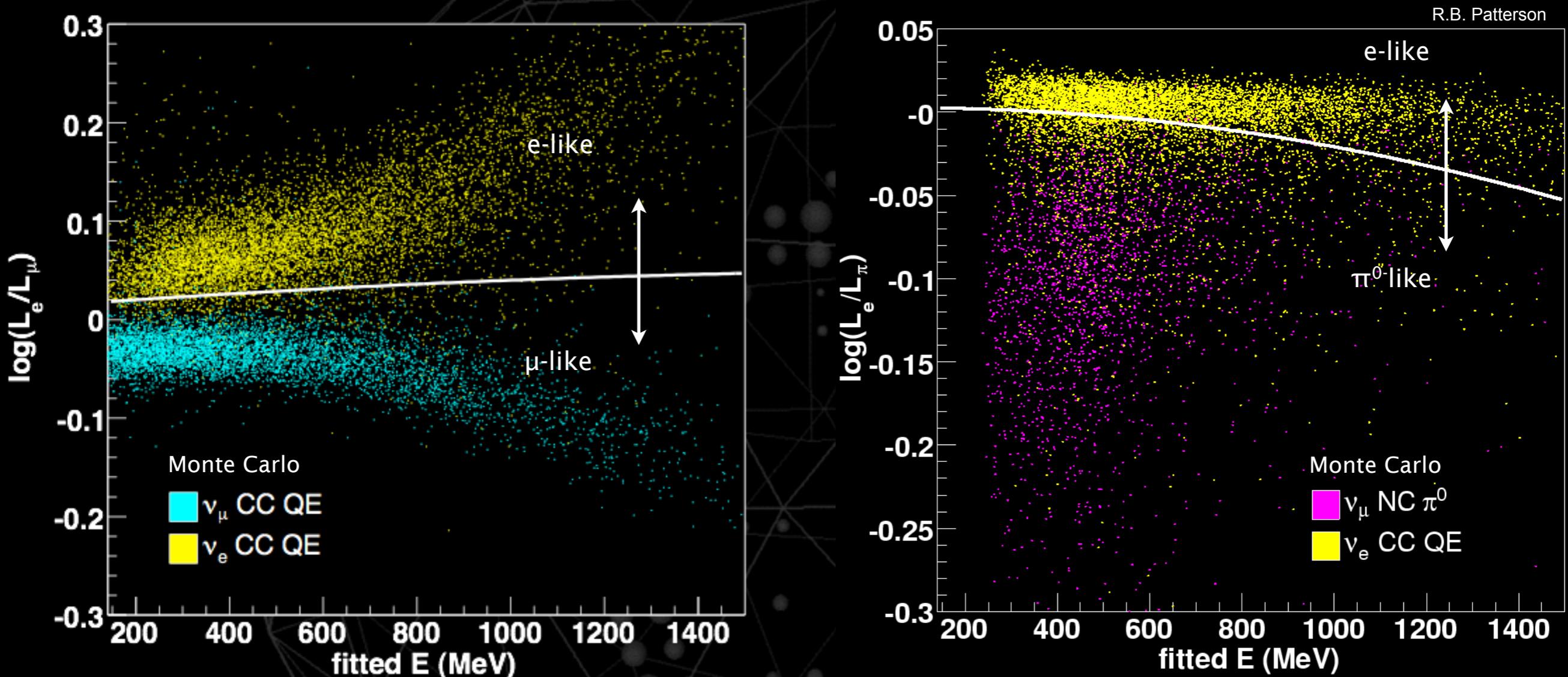
PMTs collect photons, record t,Q

Reconstruct tracks by fitting time and
angular distributions

Find position, direction, energy



Particle Identification

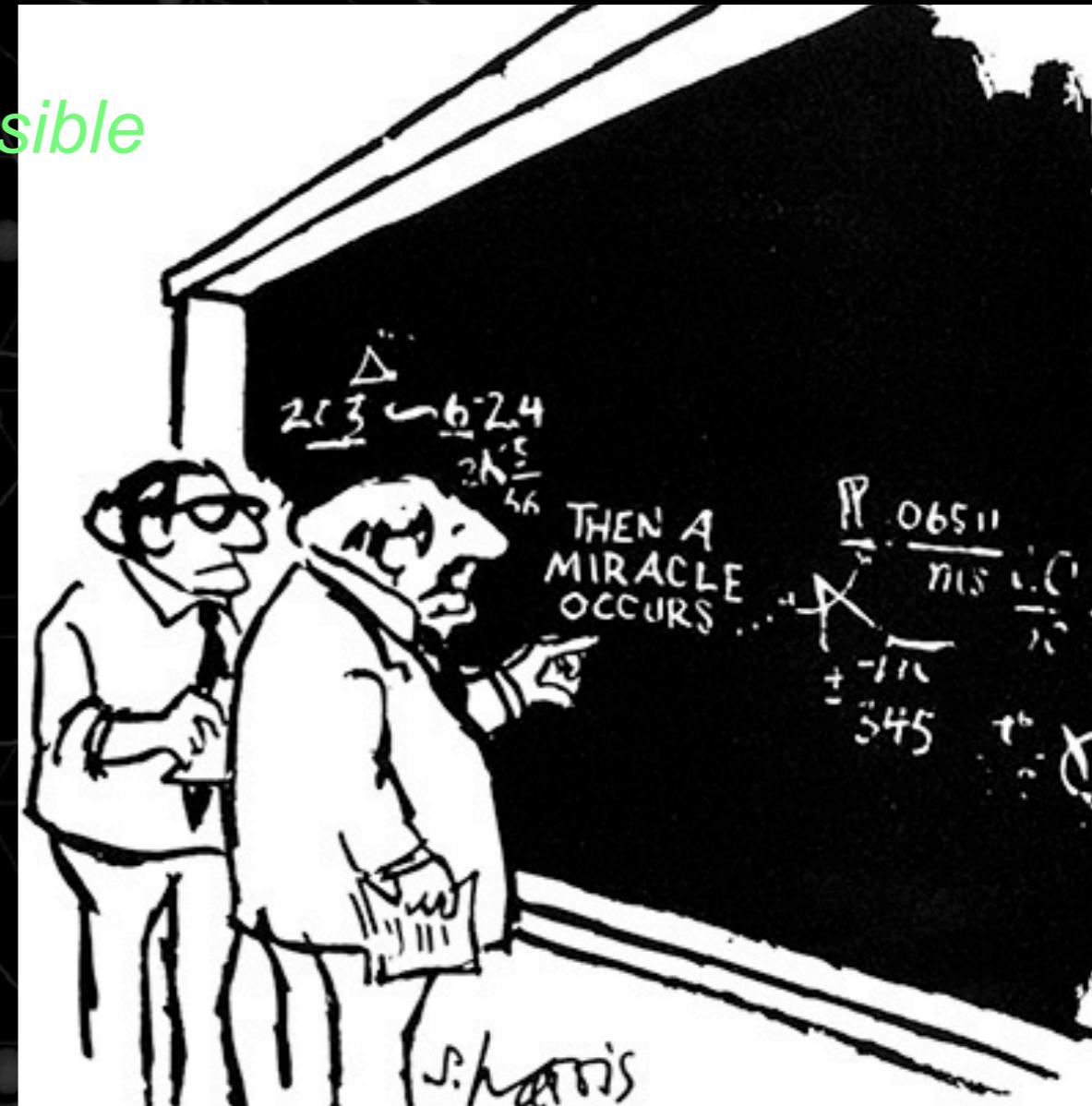


- Reconstruct under 3 hypotheses: μ -like, e -like and π^0 -like
- ν_e particle ID cuts on likelihood ratios
 - chosen to maximise $\nu_\mu \rightarrow \nu_e$ oscillation sensitivity

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



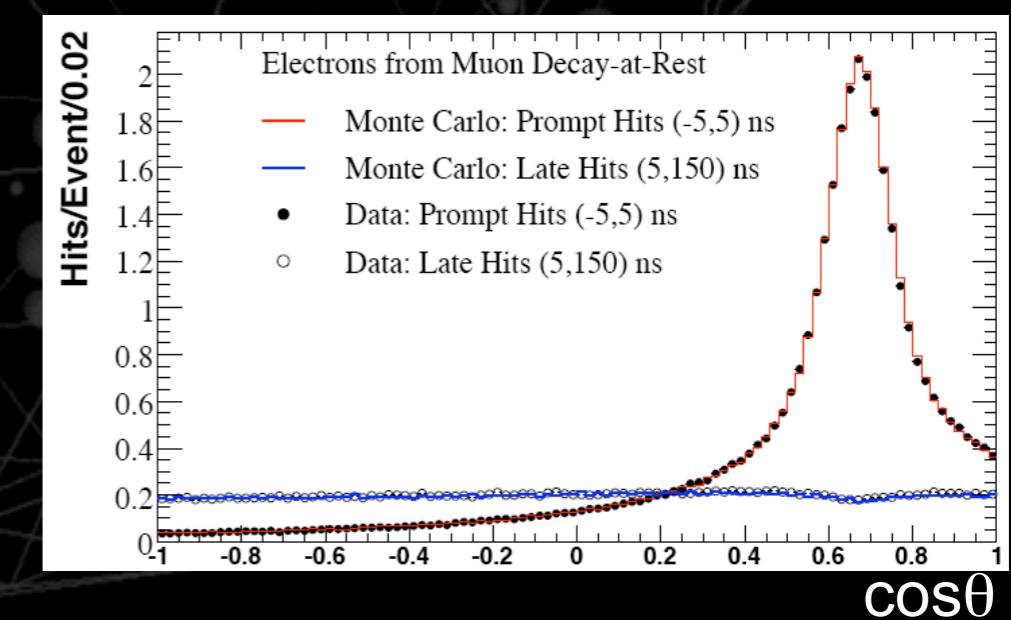
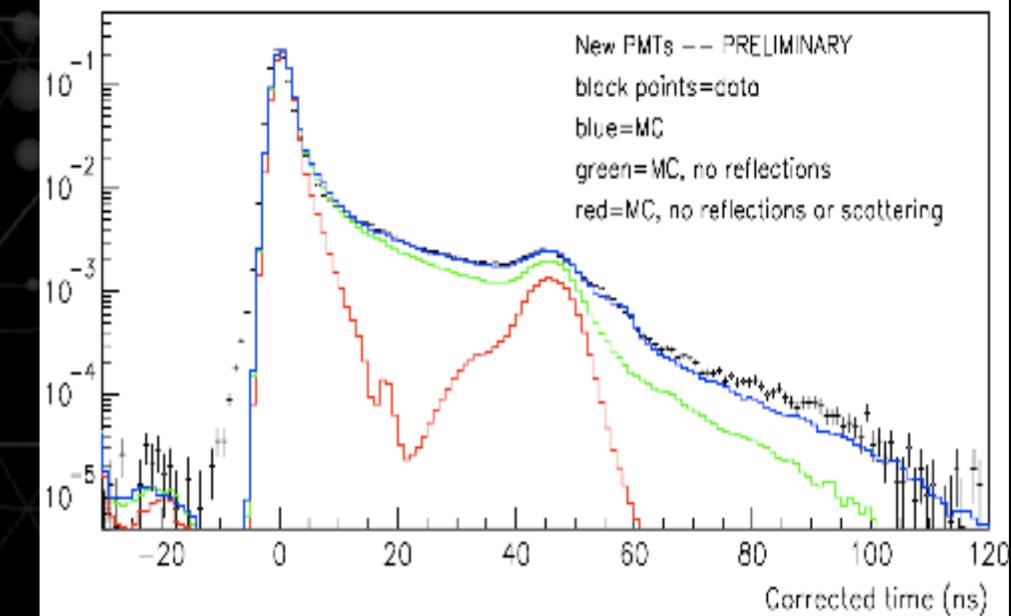
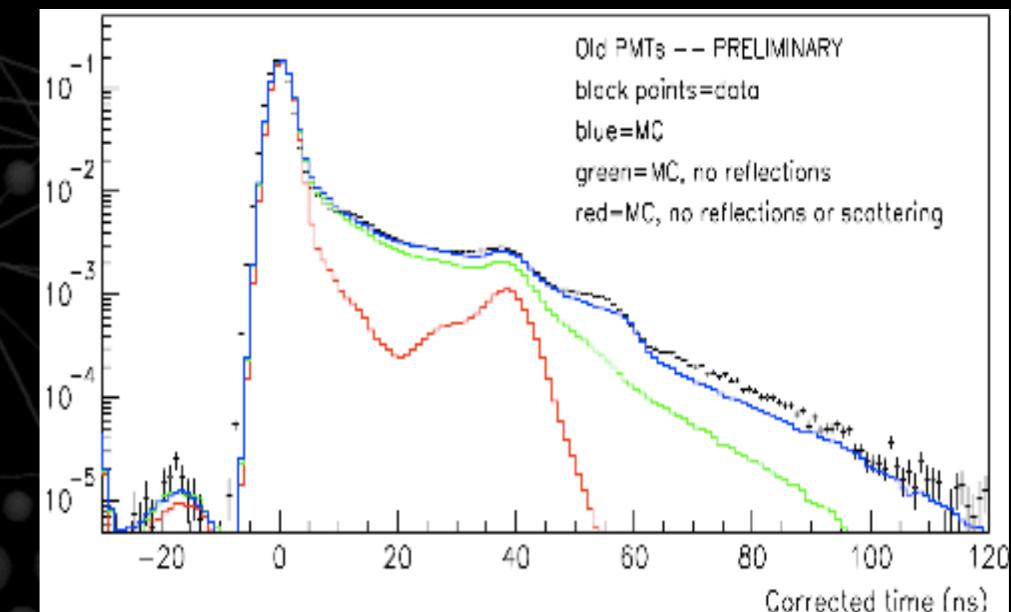
"I think you should be more explicit here in step two."

*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

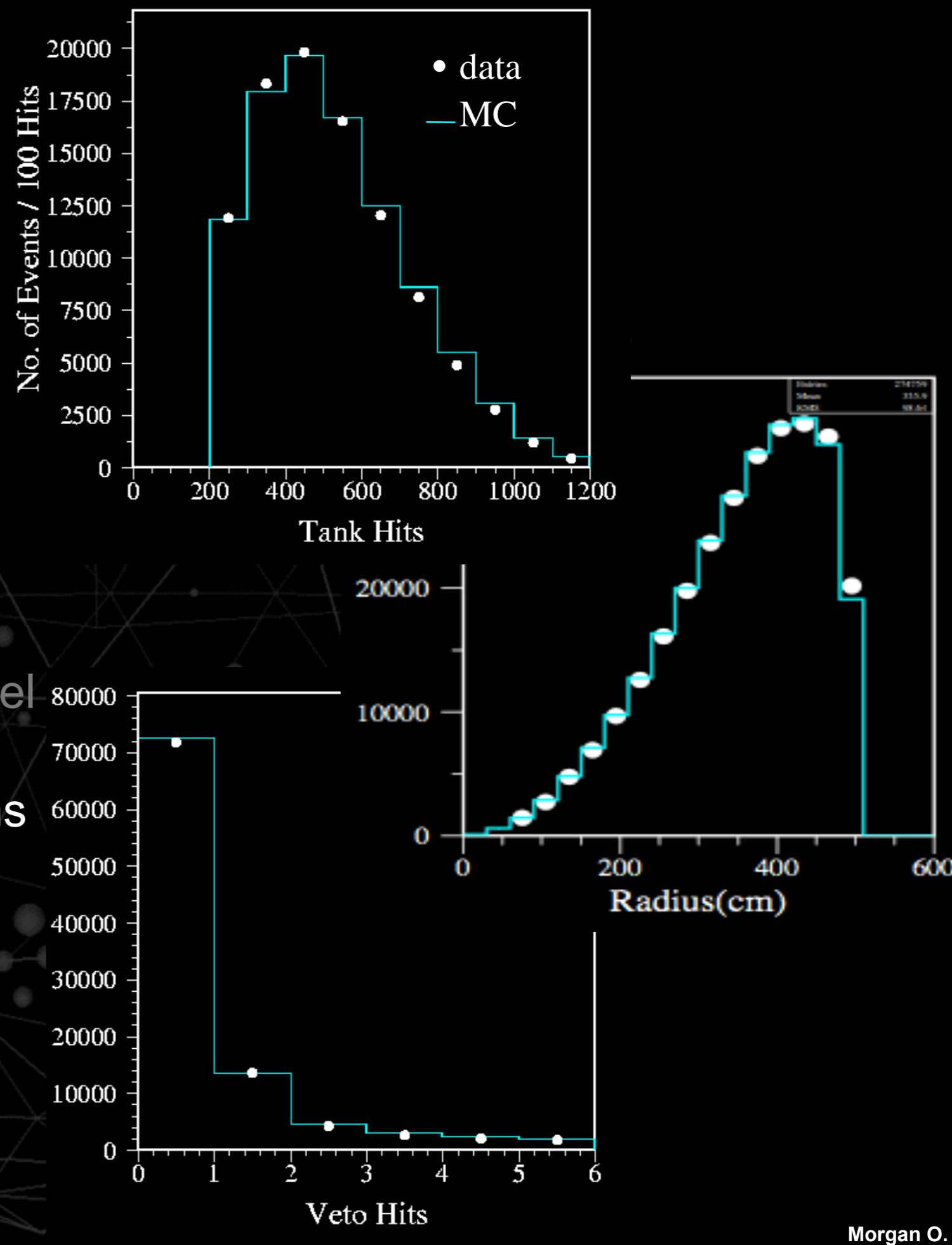


H.A. Tanaka

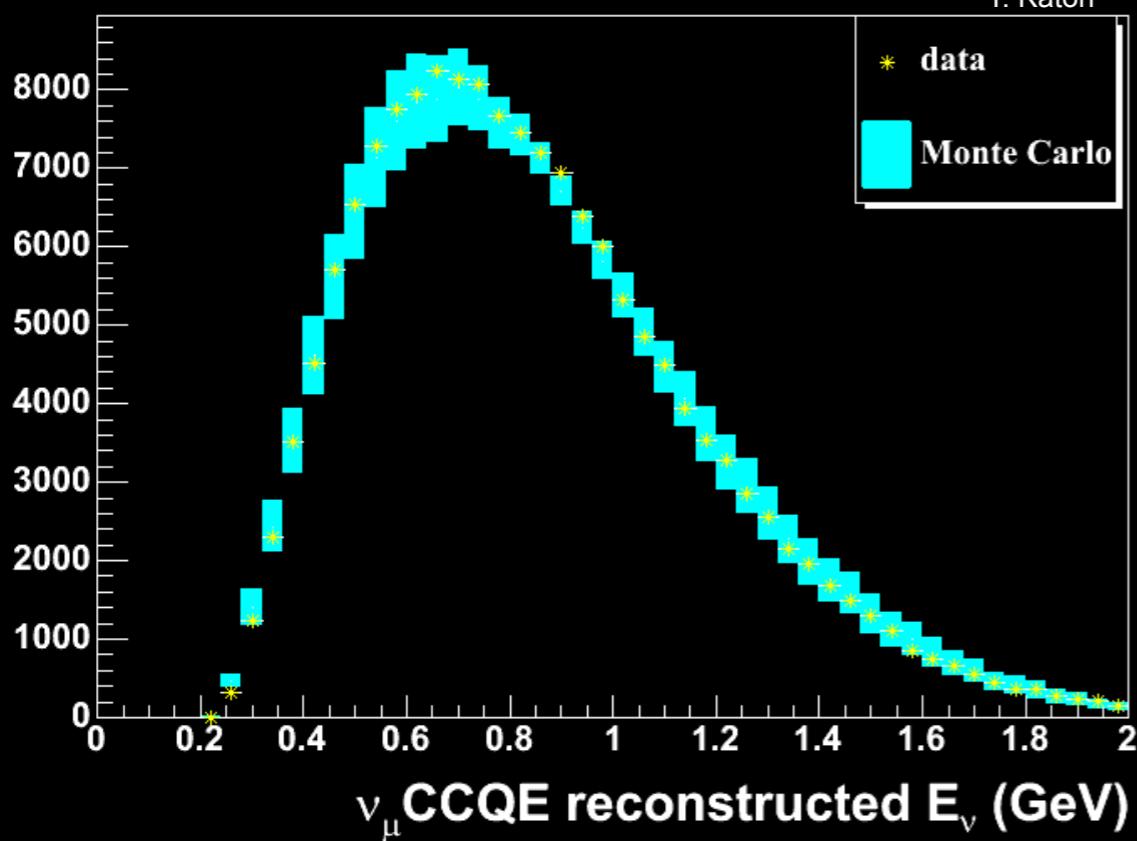
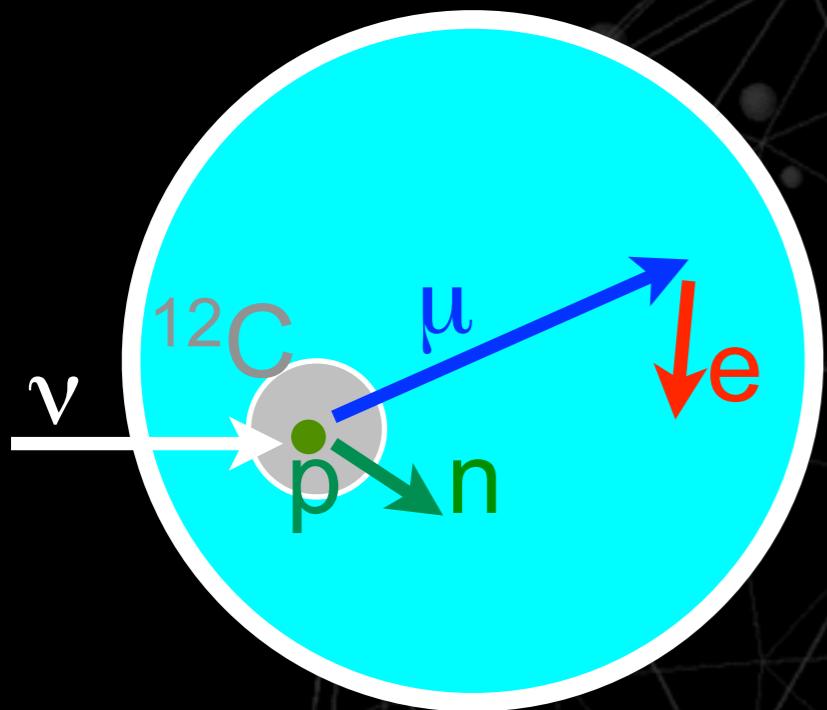
MC Tuning

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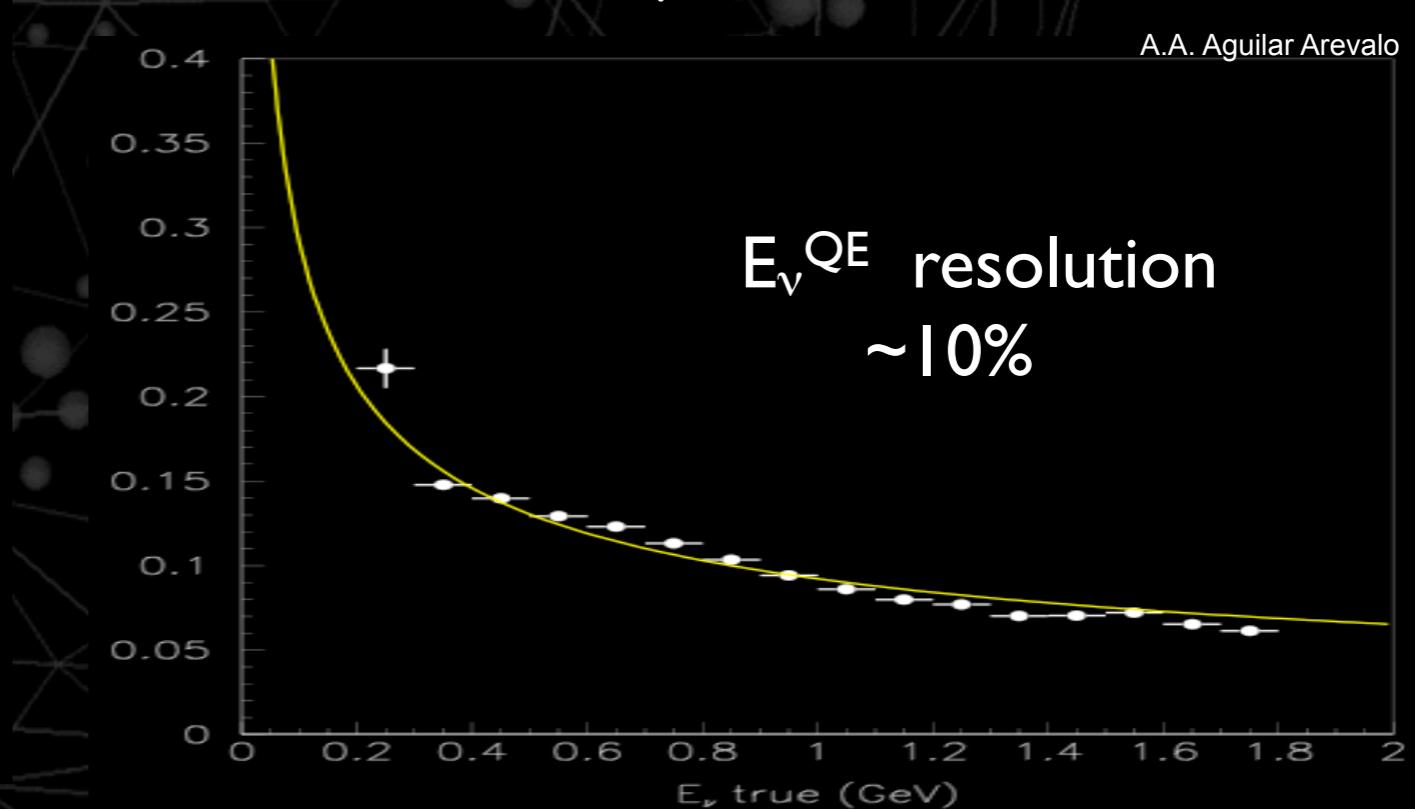
ν_μ CCQE events



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

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

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



ν_μ CCQE tuning

PRL100(2008)032301

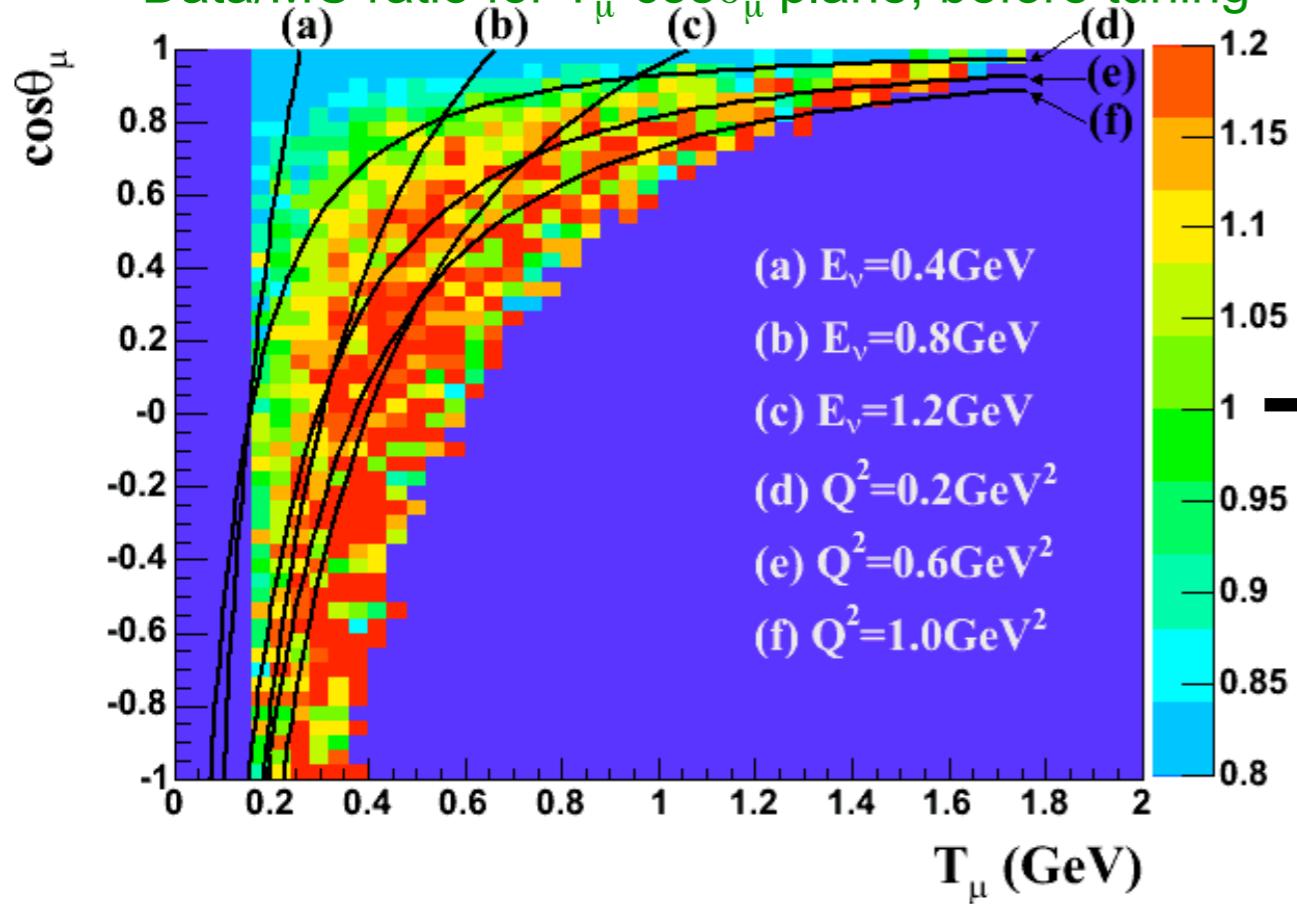
- Need good flux model to study cross section

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

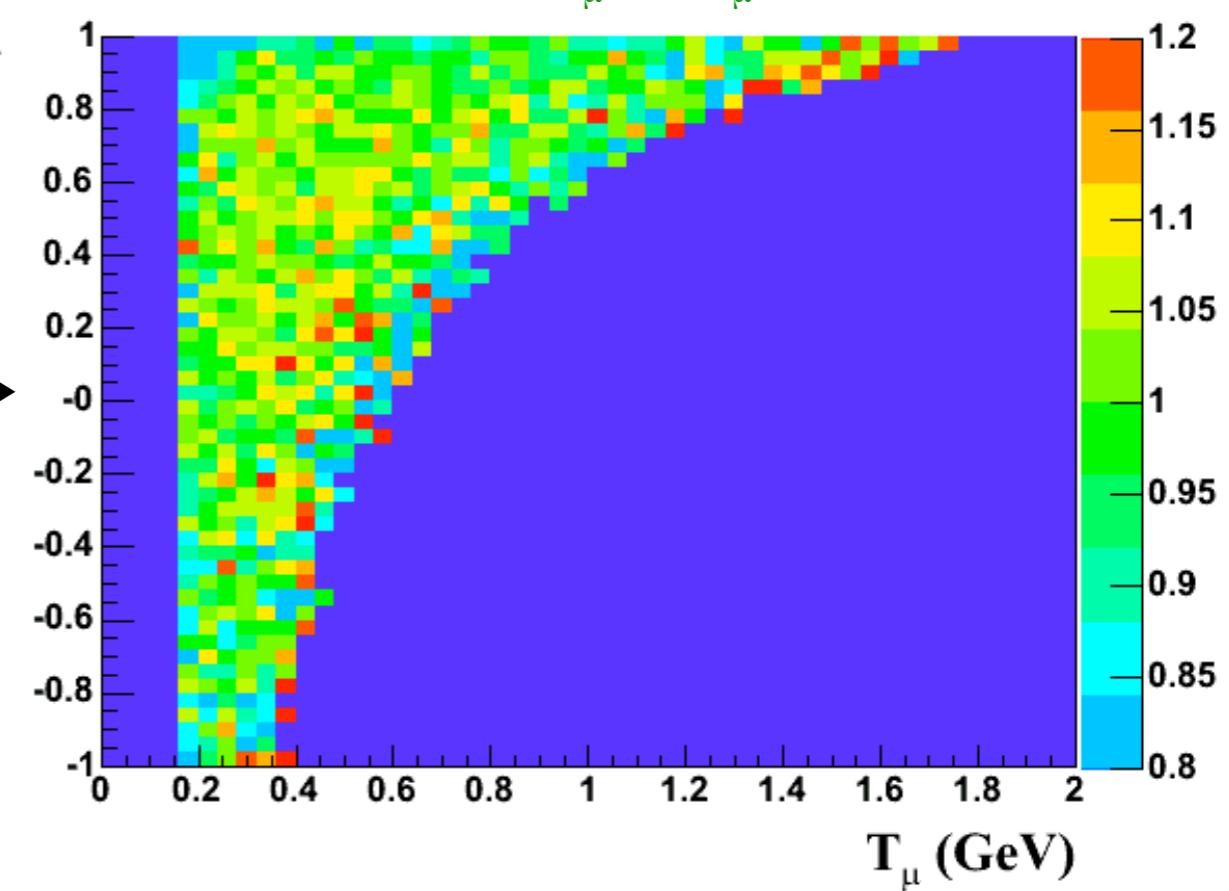
- Data-MC mismatch follows Q^2 lines, not E_ν
 - Problem is not the flux prediction, but the cross section model

T. Katori

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



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

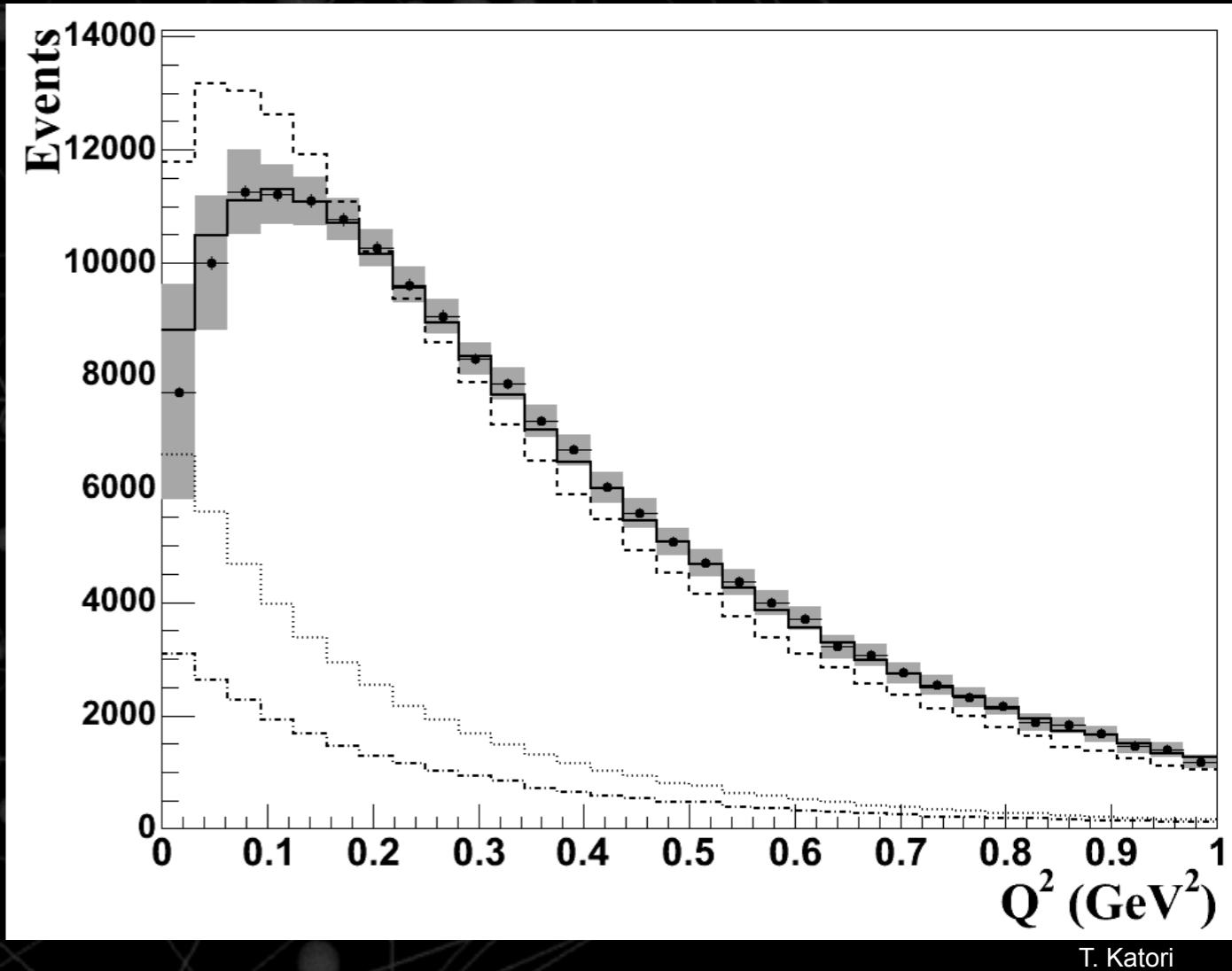


ν_μ CCQE tuning

PRL100(2008)032301

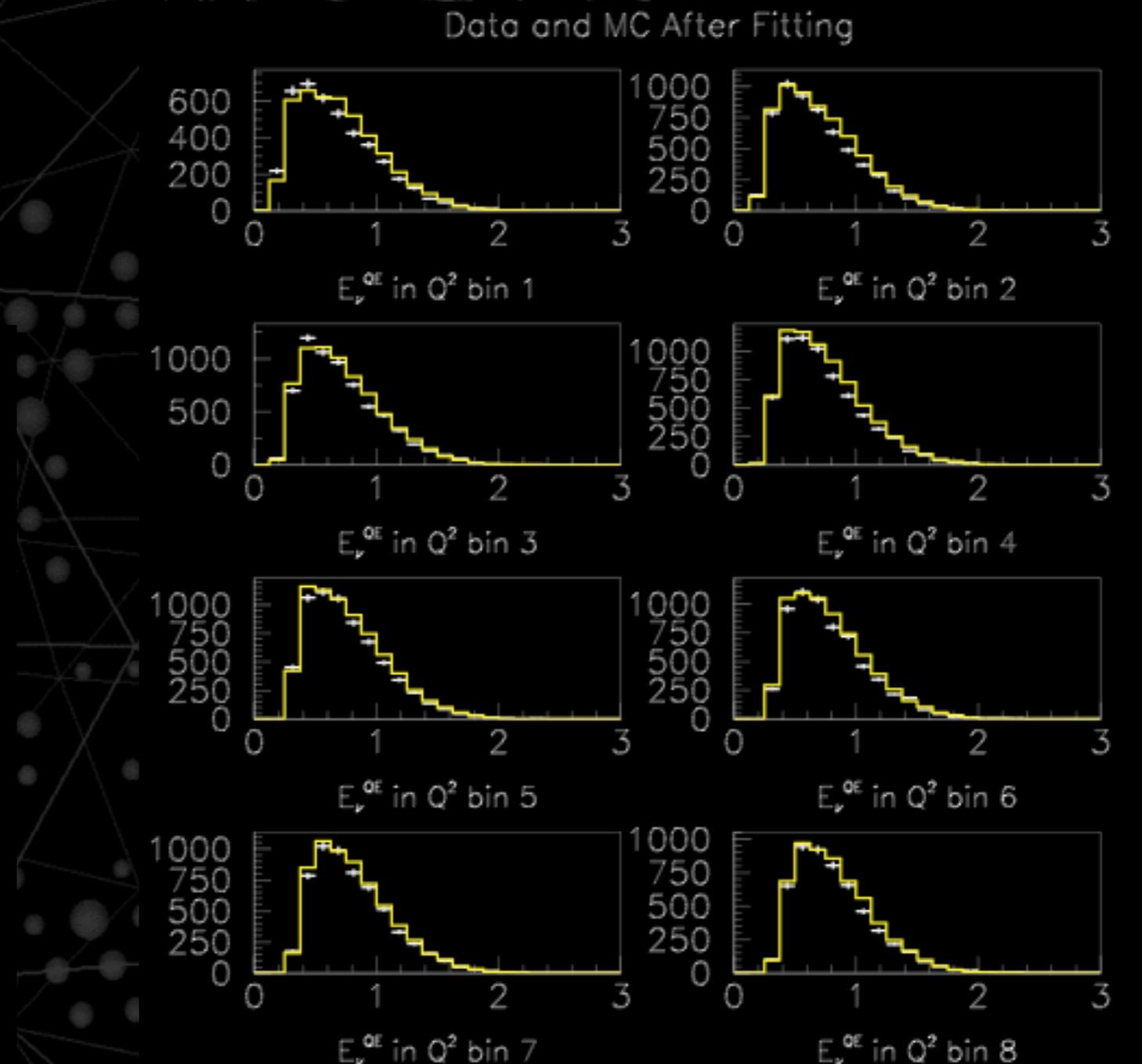
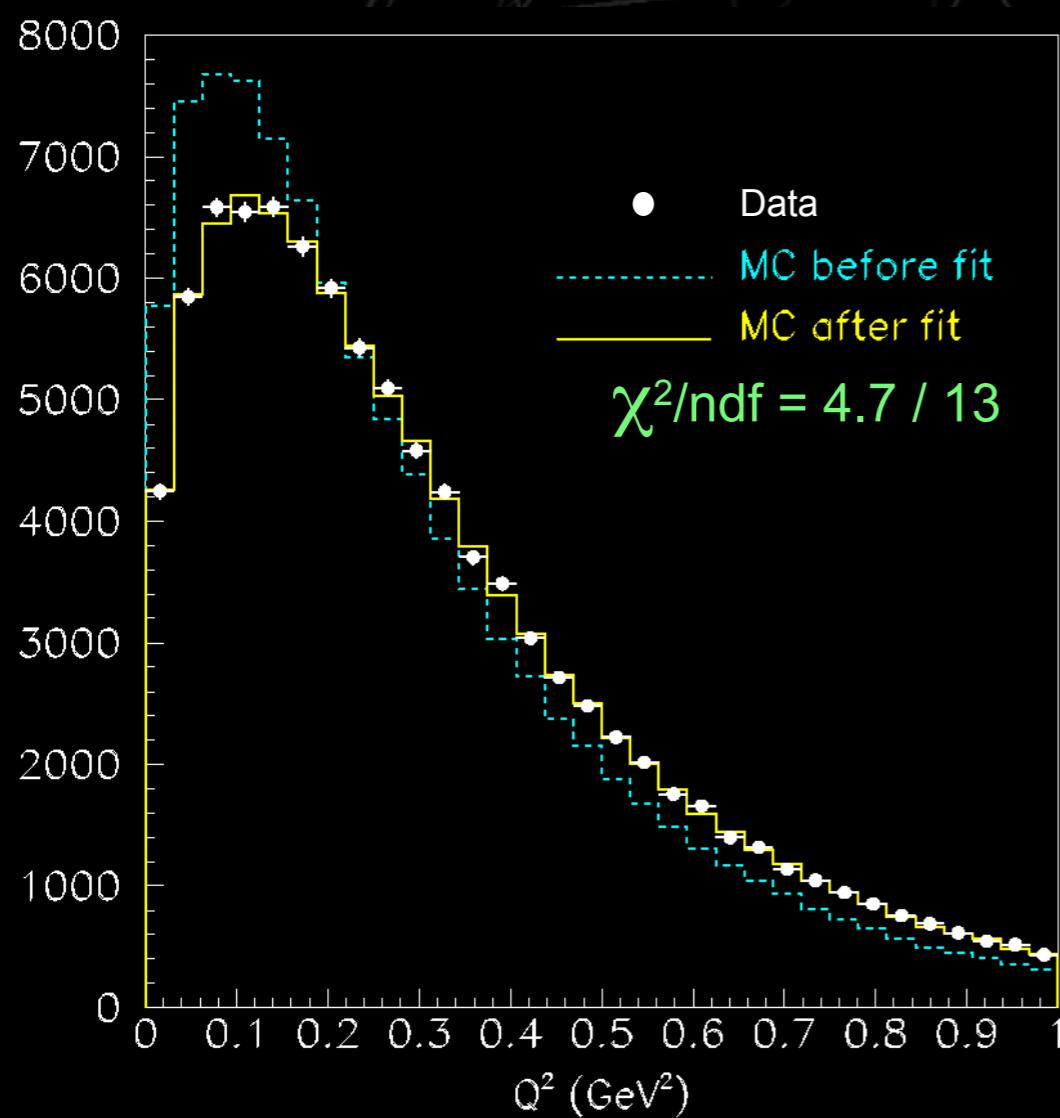
Q² distribution before and after fitting

- 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.



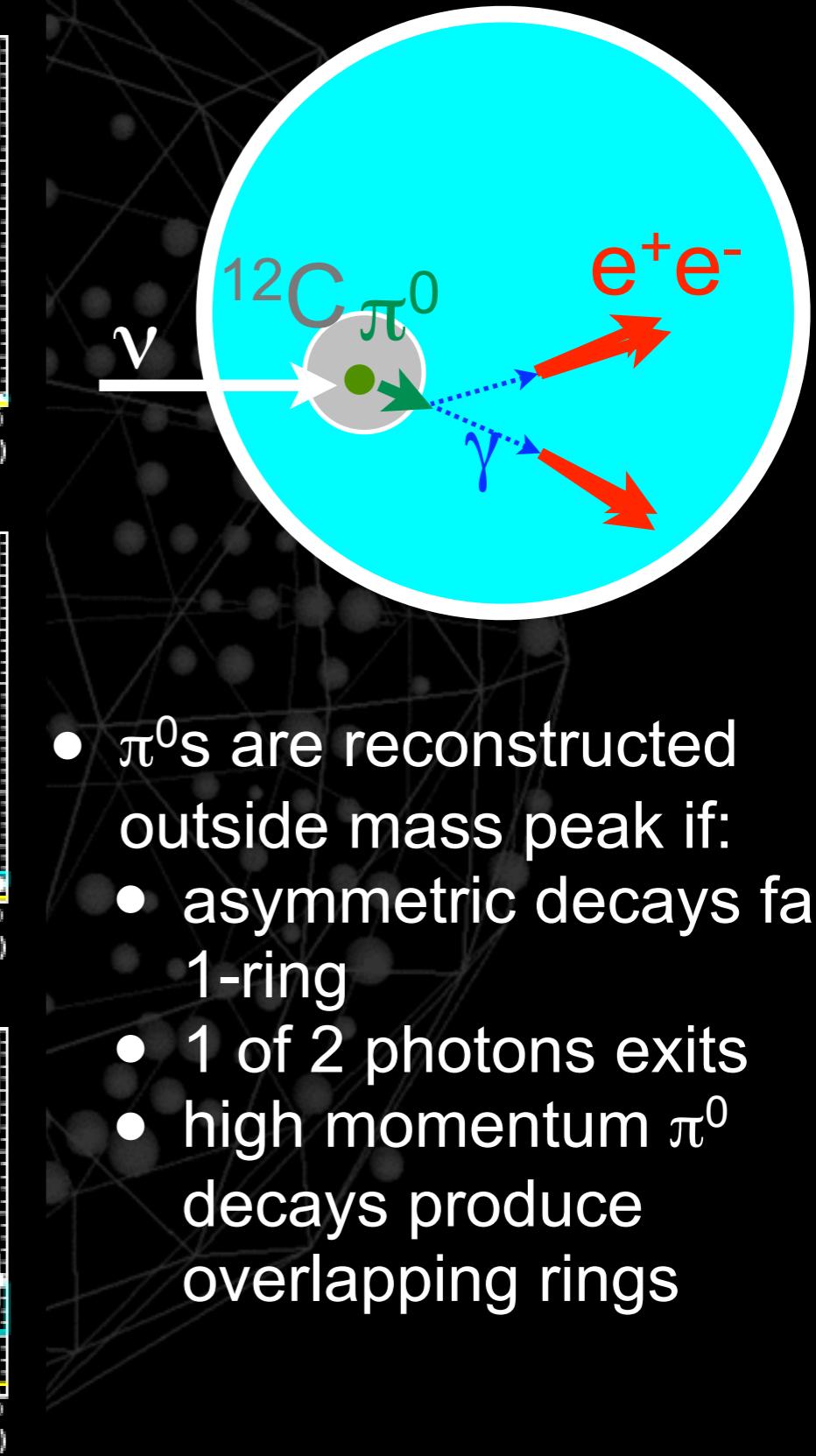
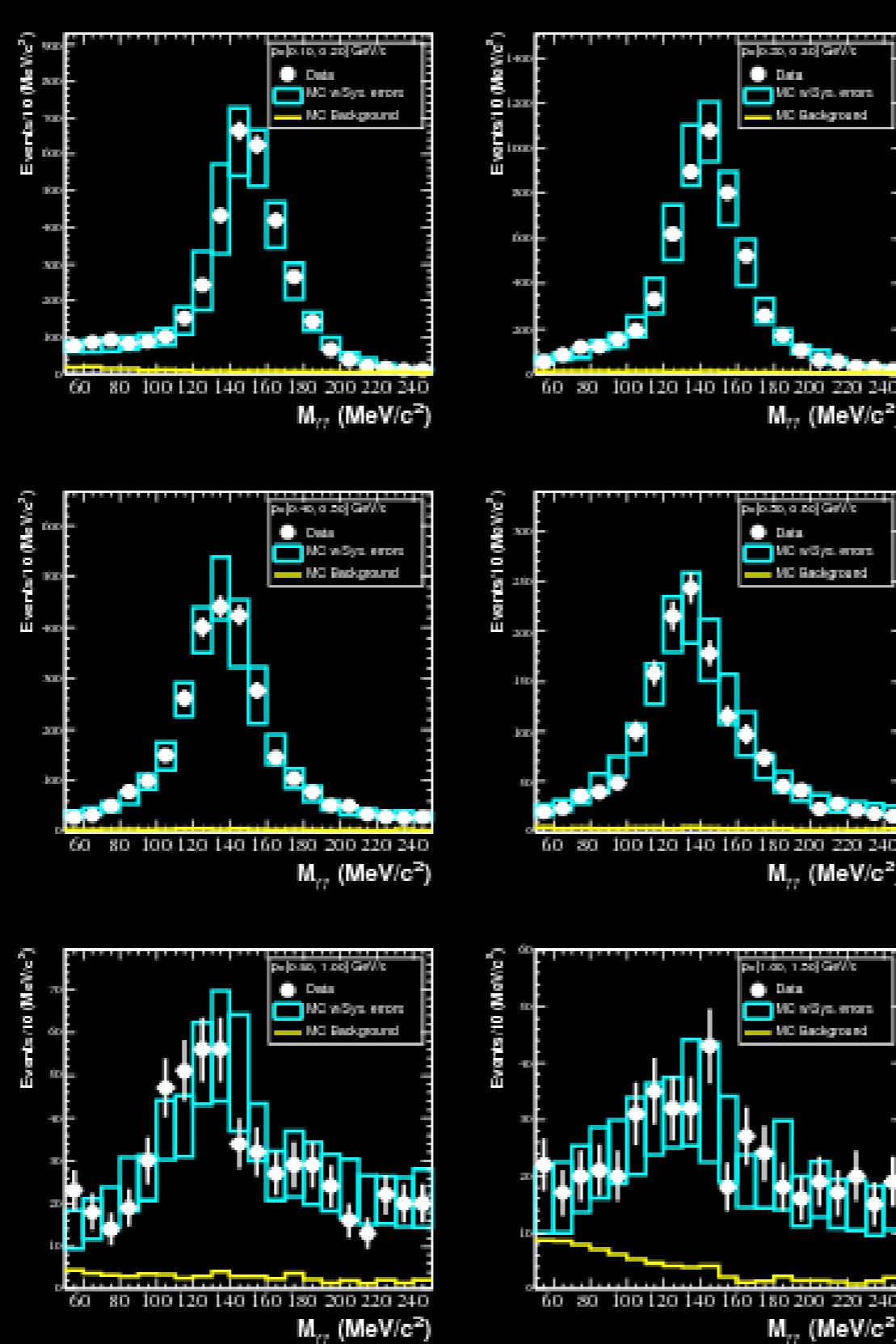
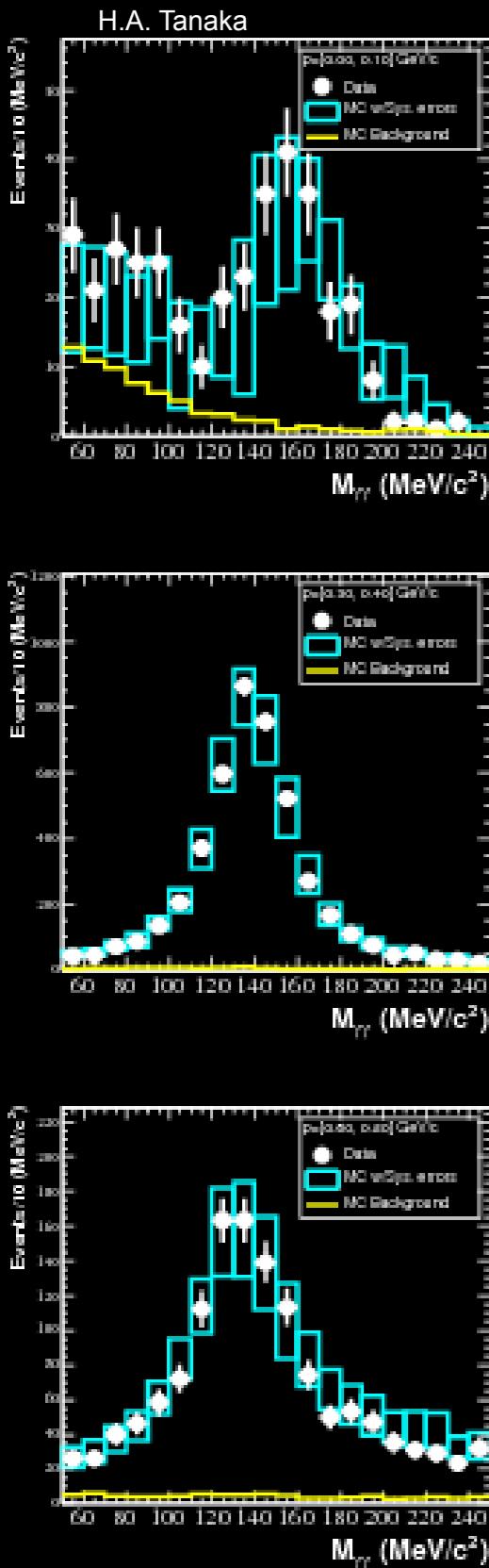
Tuning CCQE MC

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



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

π^0 Mis-ID Backgrounds

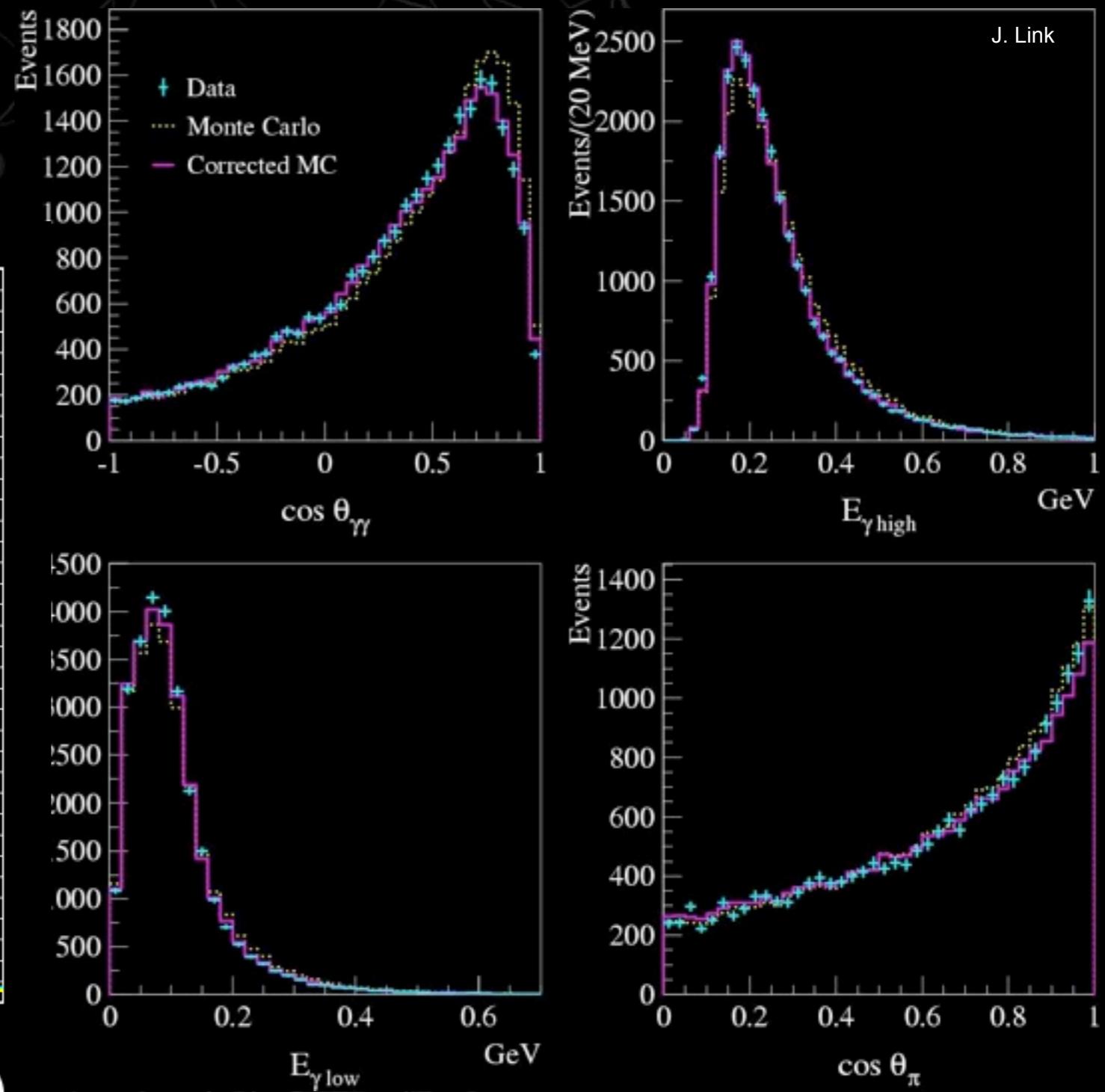
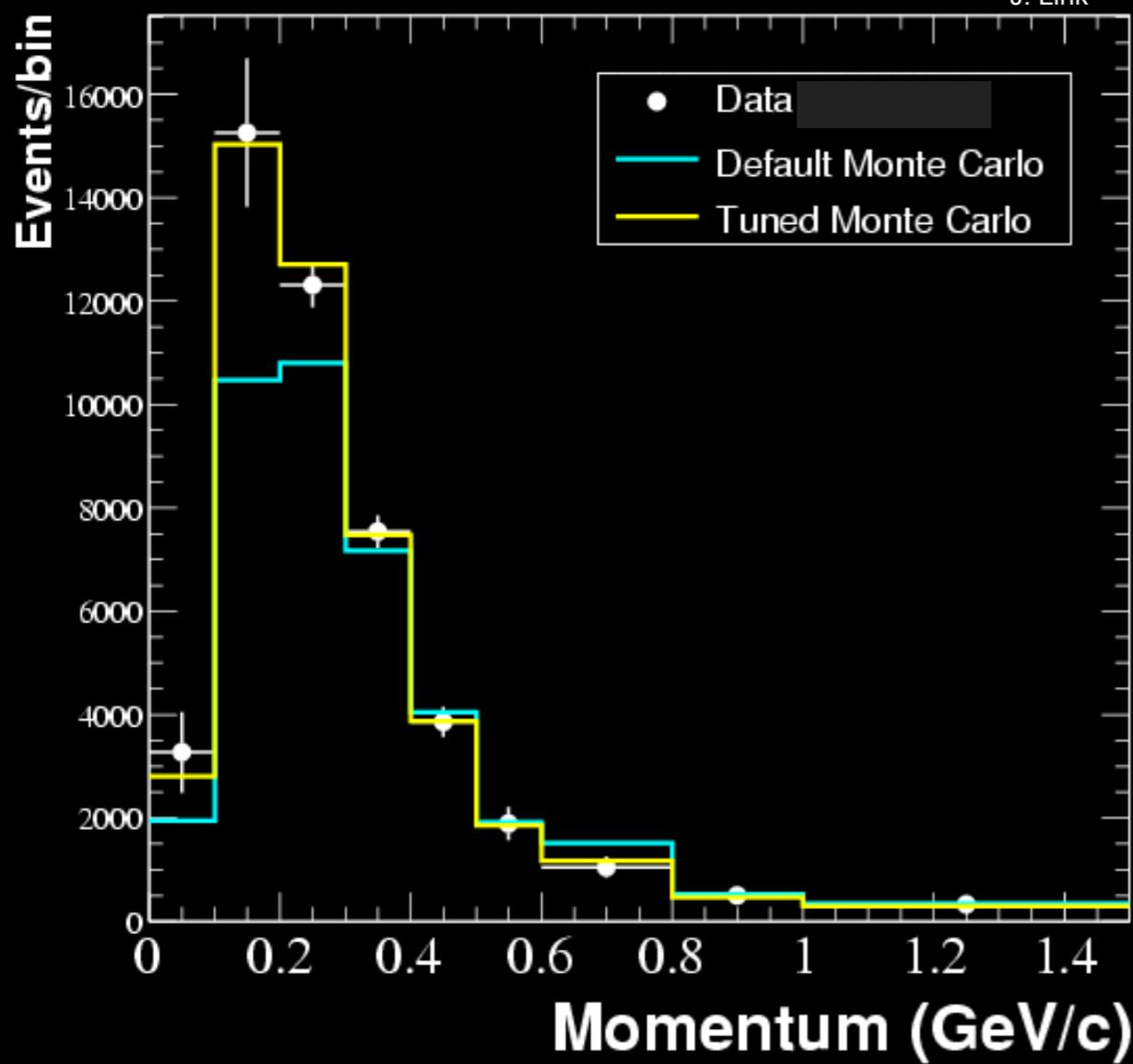


- π^0 s are reconstructed outside mass peak if:
 - asymmetric decays fake 1-ring
 - 1 of 2 photons exits
 - high momentum π^0 decays produce overlapping rings

Tuning π^0 MC

Phys.Lett. B664:41-46, 2008

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

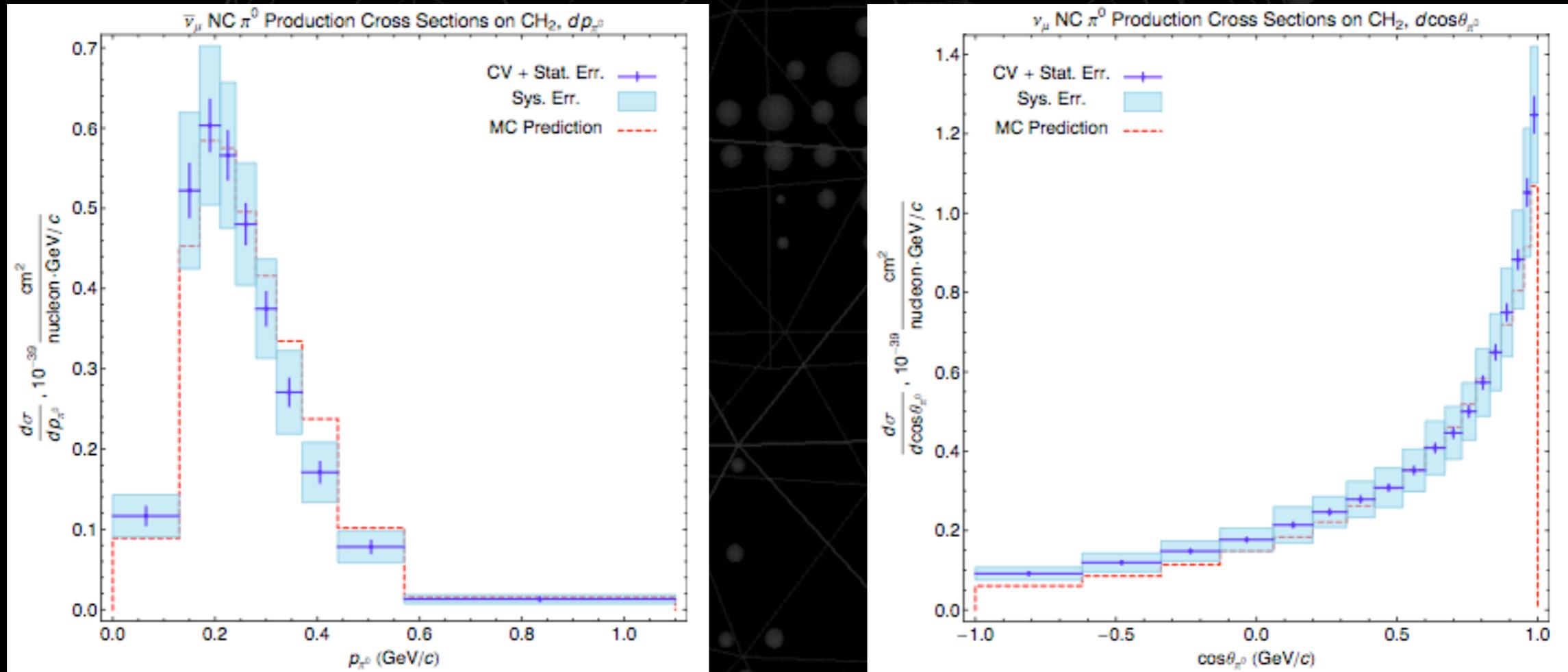


good data-MC agreement in variables not used in tuning!

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

Phys.Rev.D 81 013005 (2010)

C. Anderson

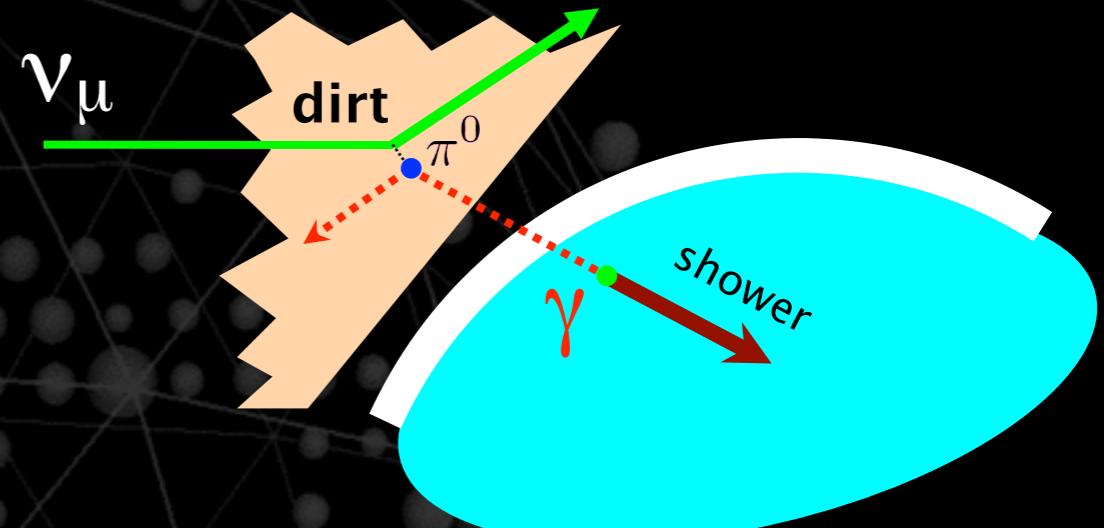


Use same techniques to tune MC model in antineutrino mode

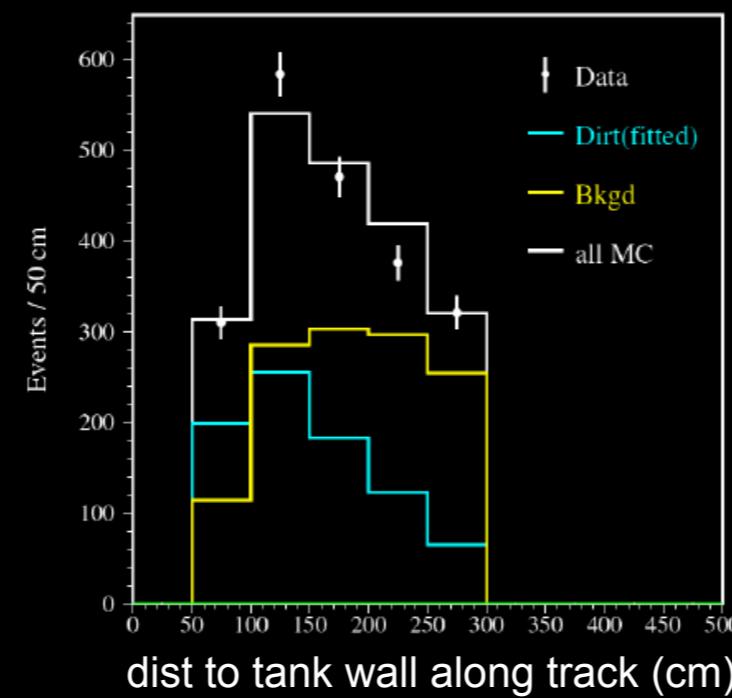
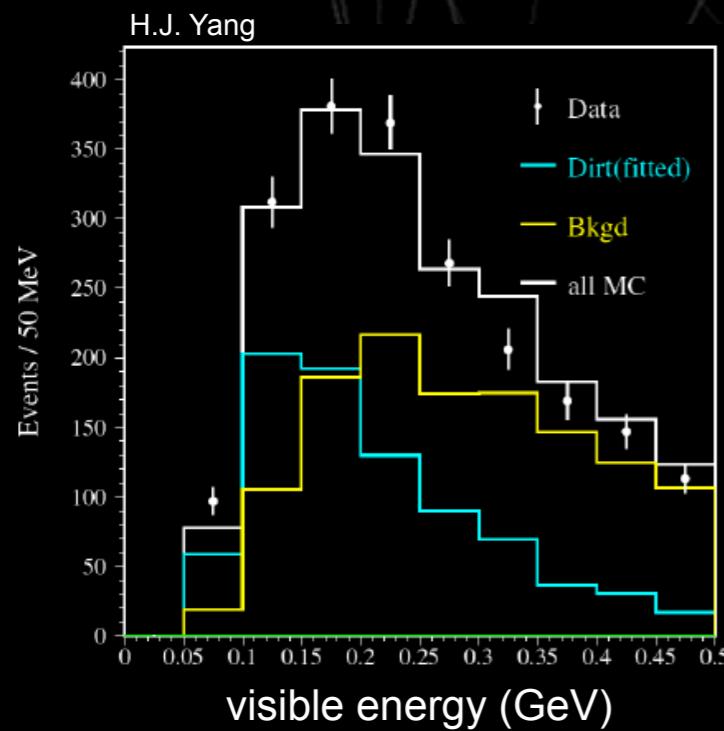
Also produced POT-normalised cross sections for $\text{NC}\pi^0$ production by neutrinos and antineutrinos

“Dirt” Backgrounds

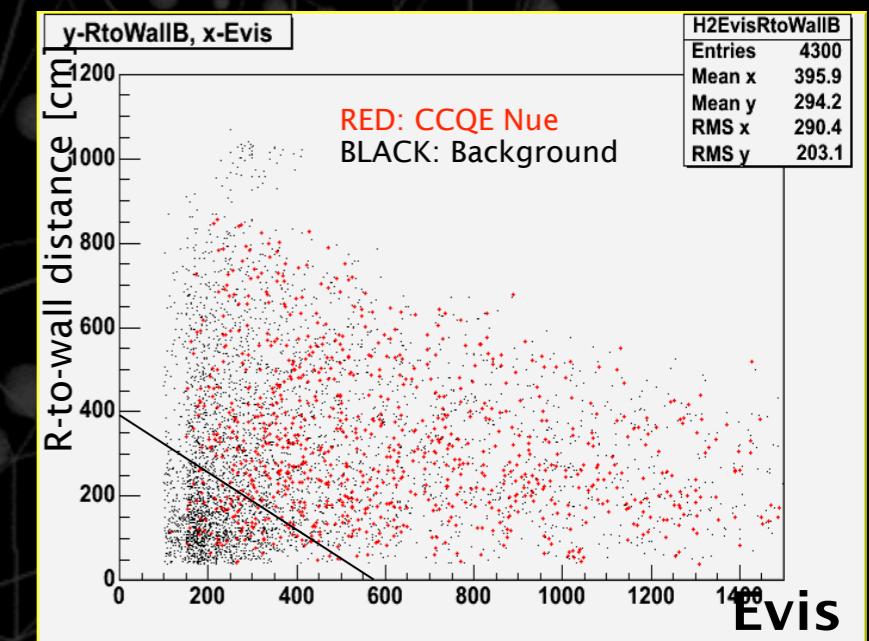
- Neutrinos interacting outside detector can cause BGs
 - n, γ enter detector and convert
- Events pile up at low energy near edge of tank
- Measure directly with “dirt enhanced” sample



results from dirt-enhanced fits

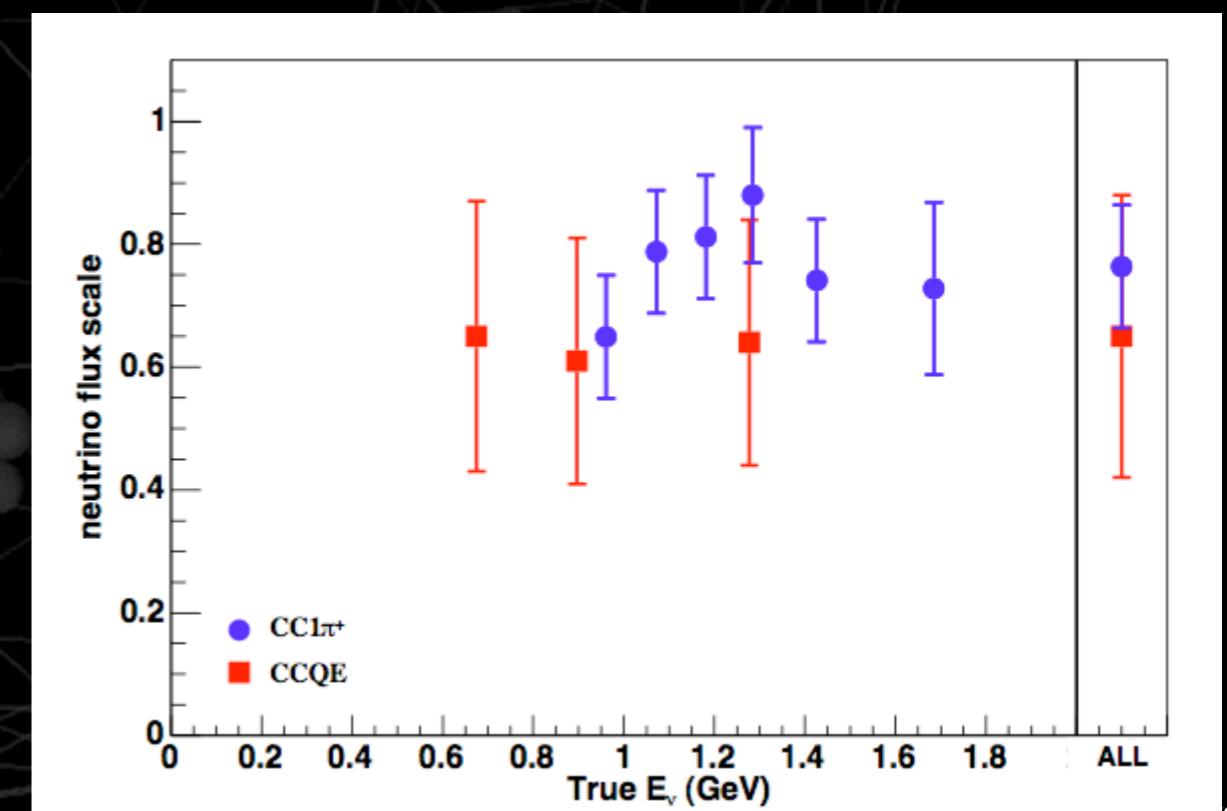
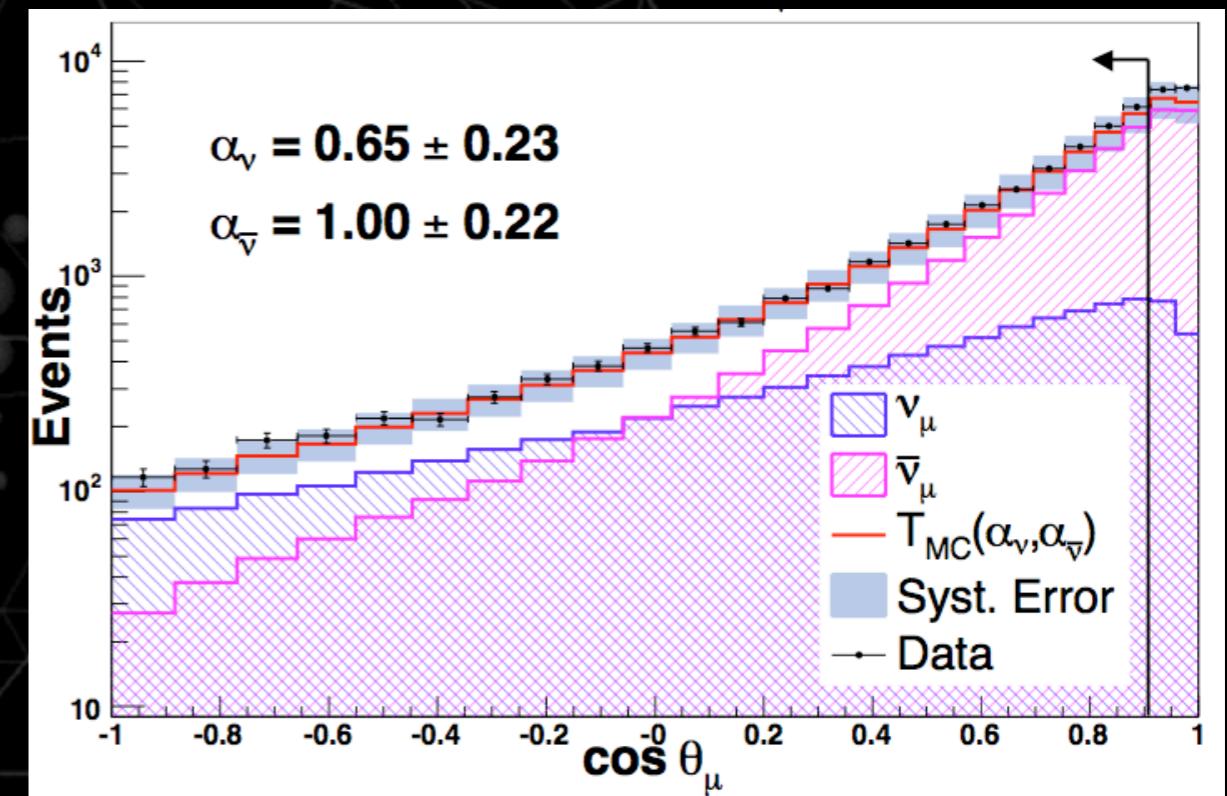


New 2D dirt cut

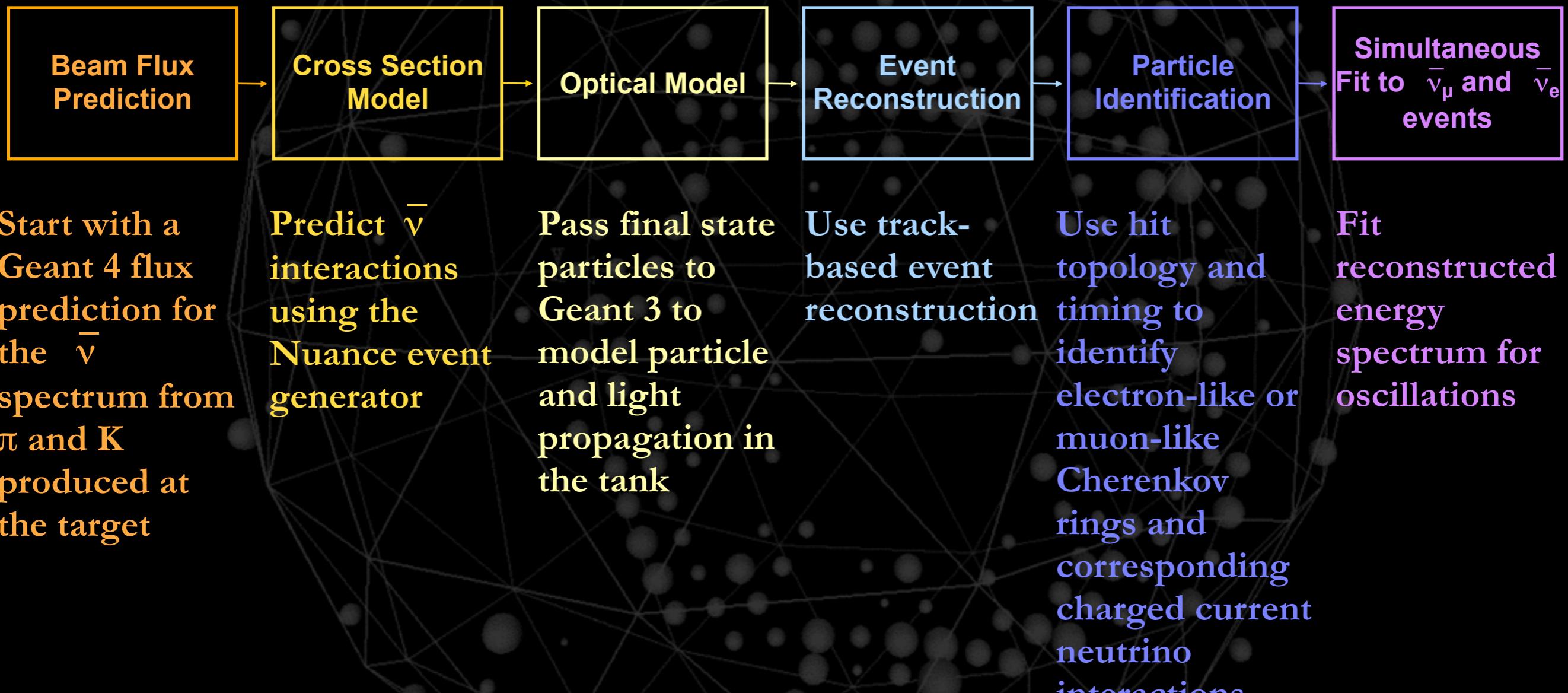


WS backgrounds

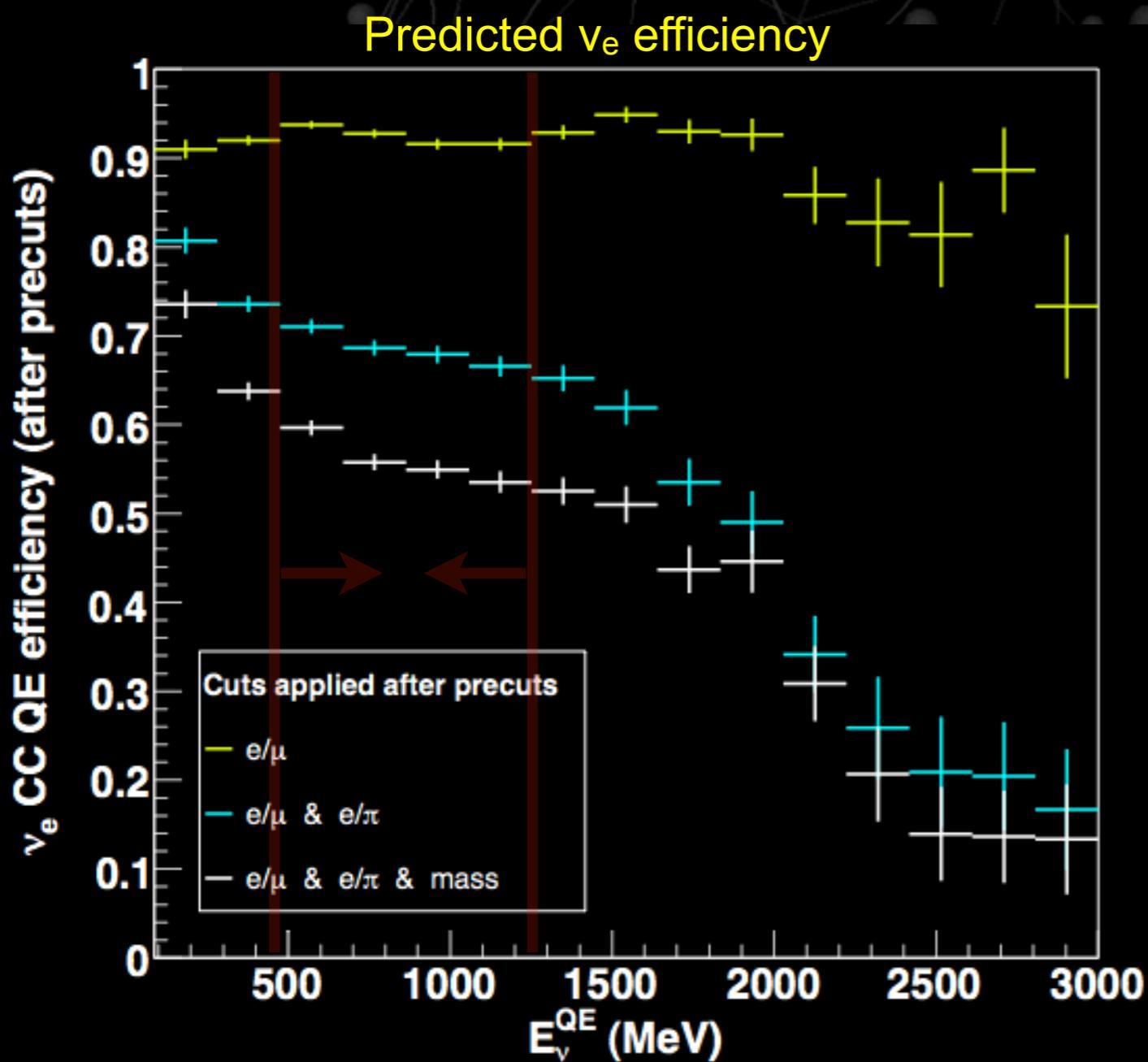
- Use two distinct and complementary data samples to constrain WS fraction
- $\bar{\nu}$ CCQE distribution has different angular distribution than ν events
 - helicity is different!
- CC1 π^+ events stem almost entirely from nu events, not $\bar{\nu}$
- Result: WS BG prediction reduced by ~30%



$\bar{\nu}_e$ appearance analysis



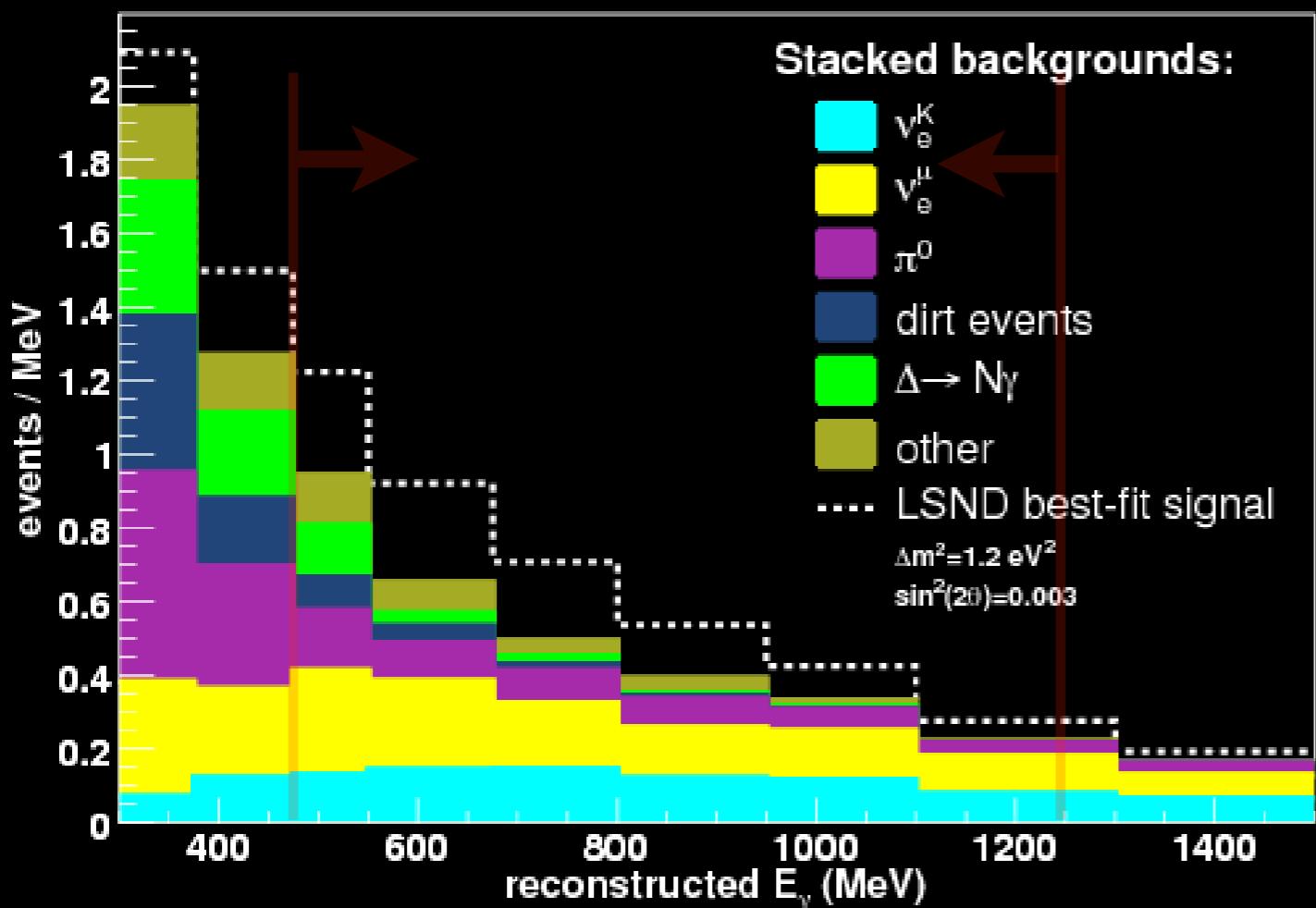
Signal and background



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

Signal and background

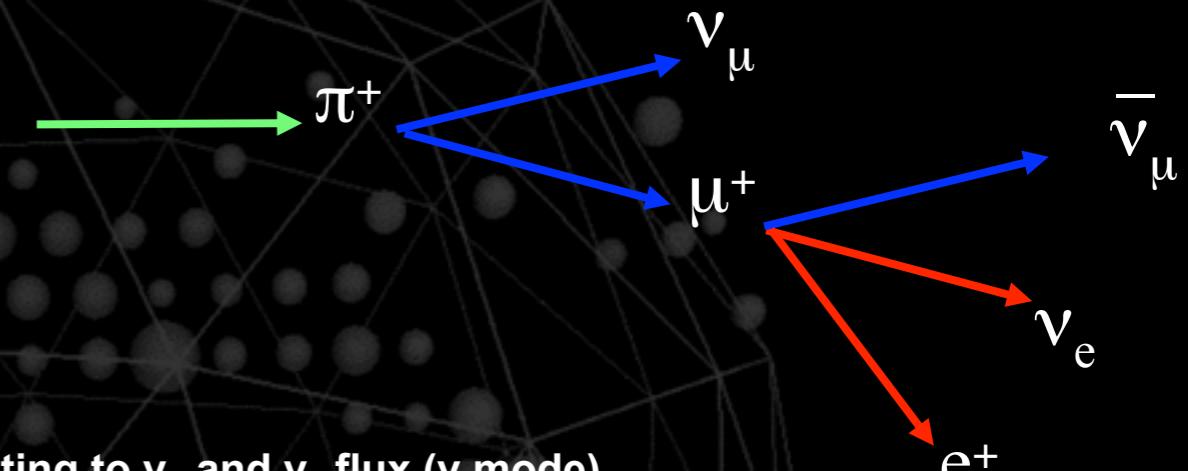
Predicted ν_e energy distribution



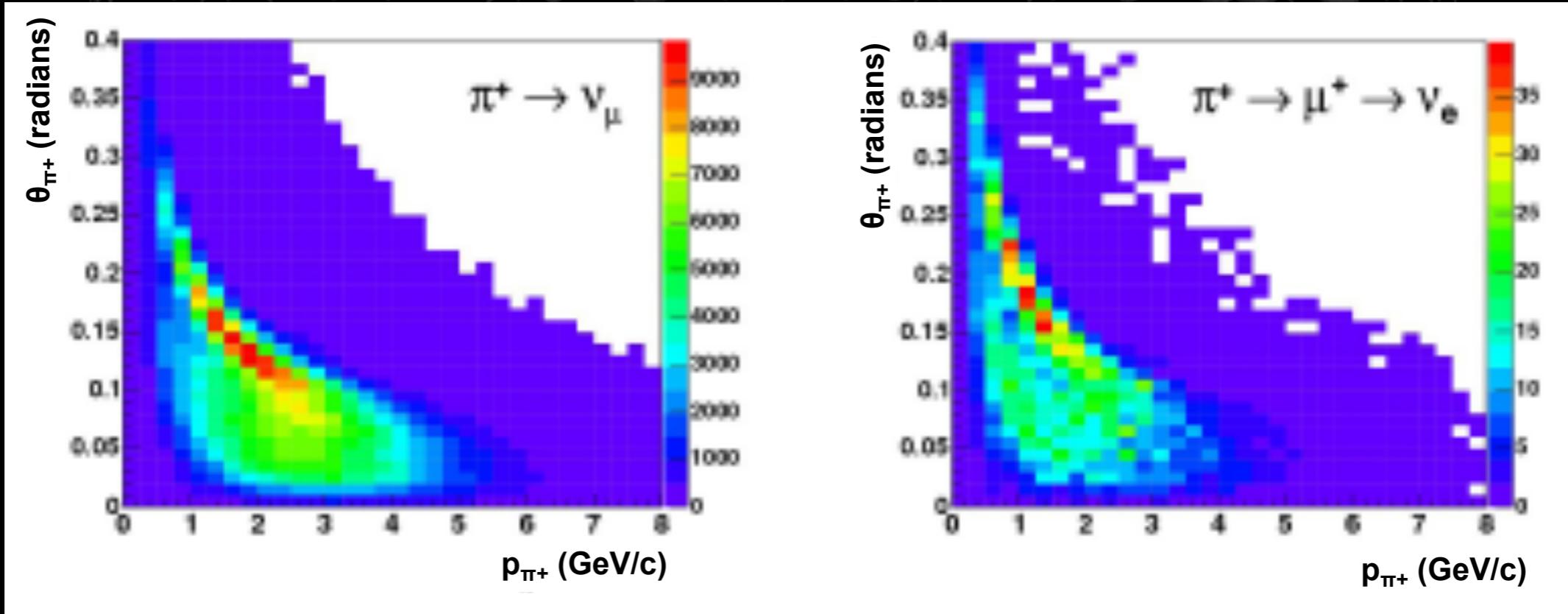
475-1250 MeV	
$\nu_e(\mu \text{ decay})$	132
$\nu_e(K \text{ decay})$	94
Radiative Δ	20
$NC\pi^0$	62
Dirt	17
Other	33
Total	358
Signal	163

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 (v mode)

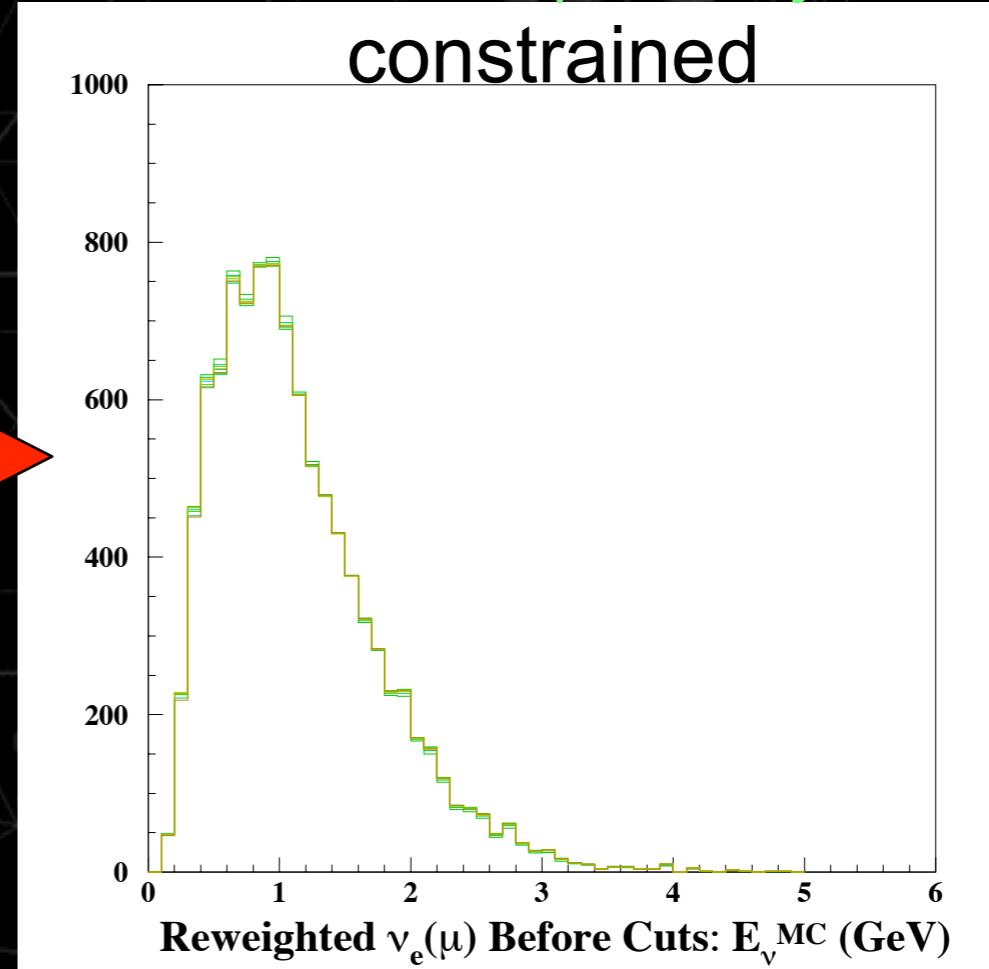
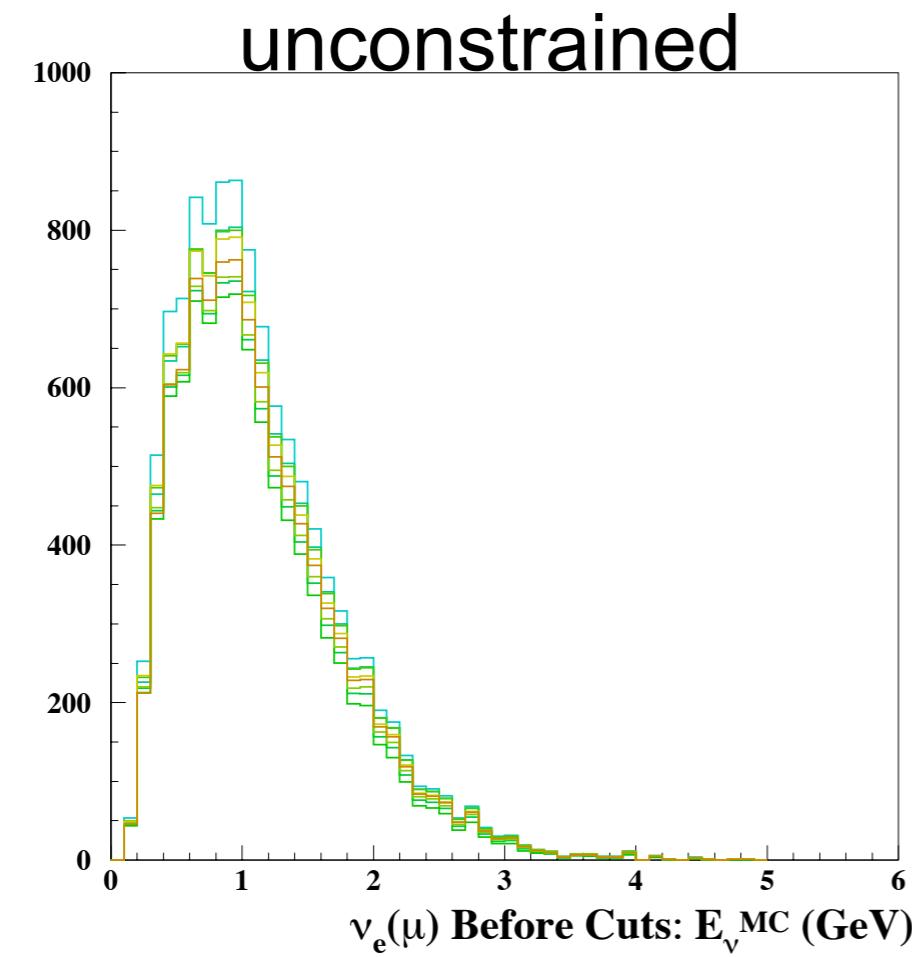


Fit method example

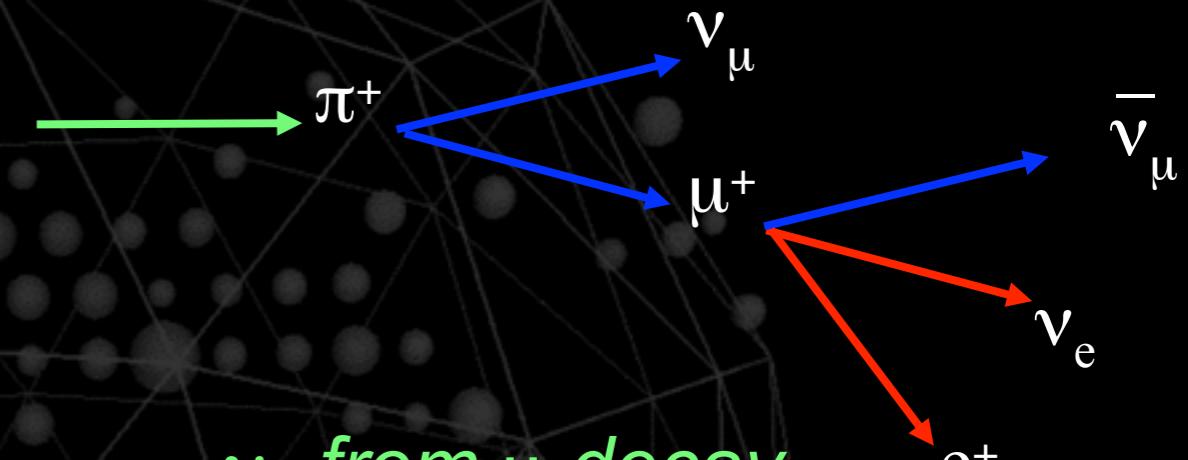
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$\bar{\nu}_e$ from μ decay

$\bar{\nu}_e$ from μ decay

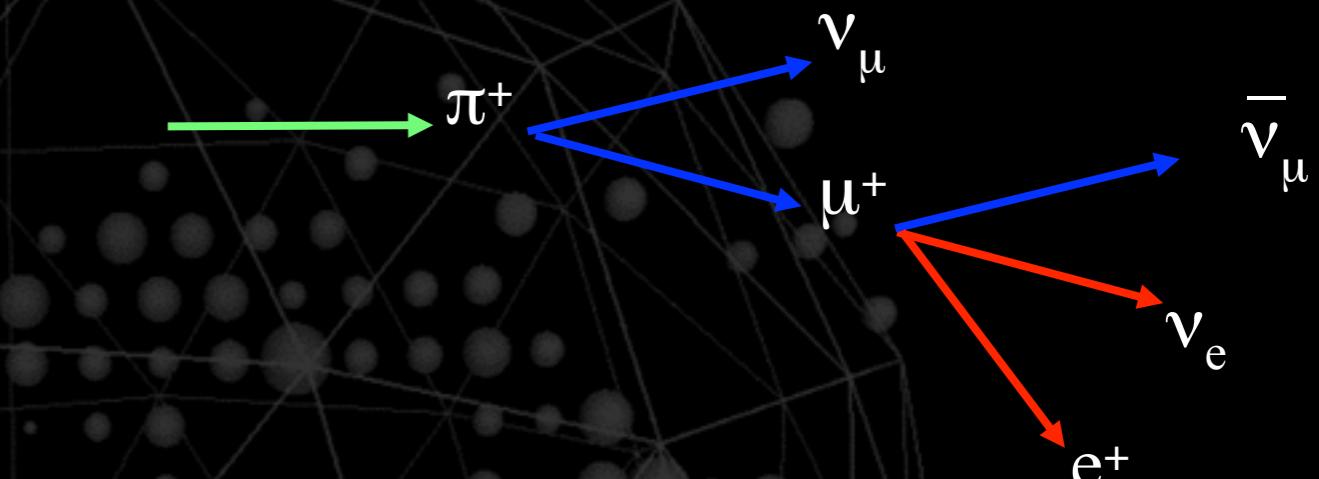
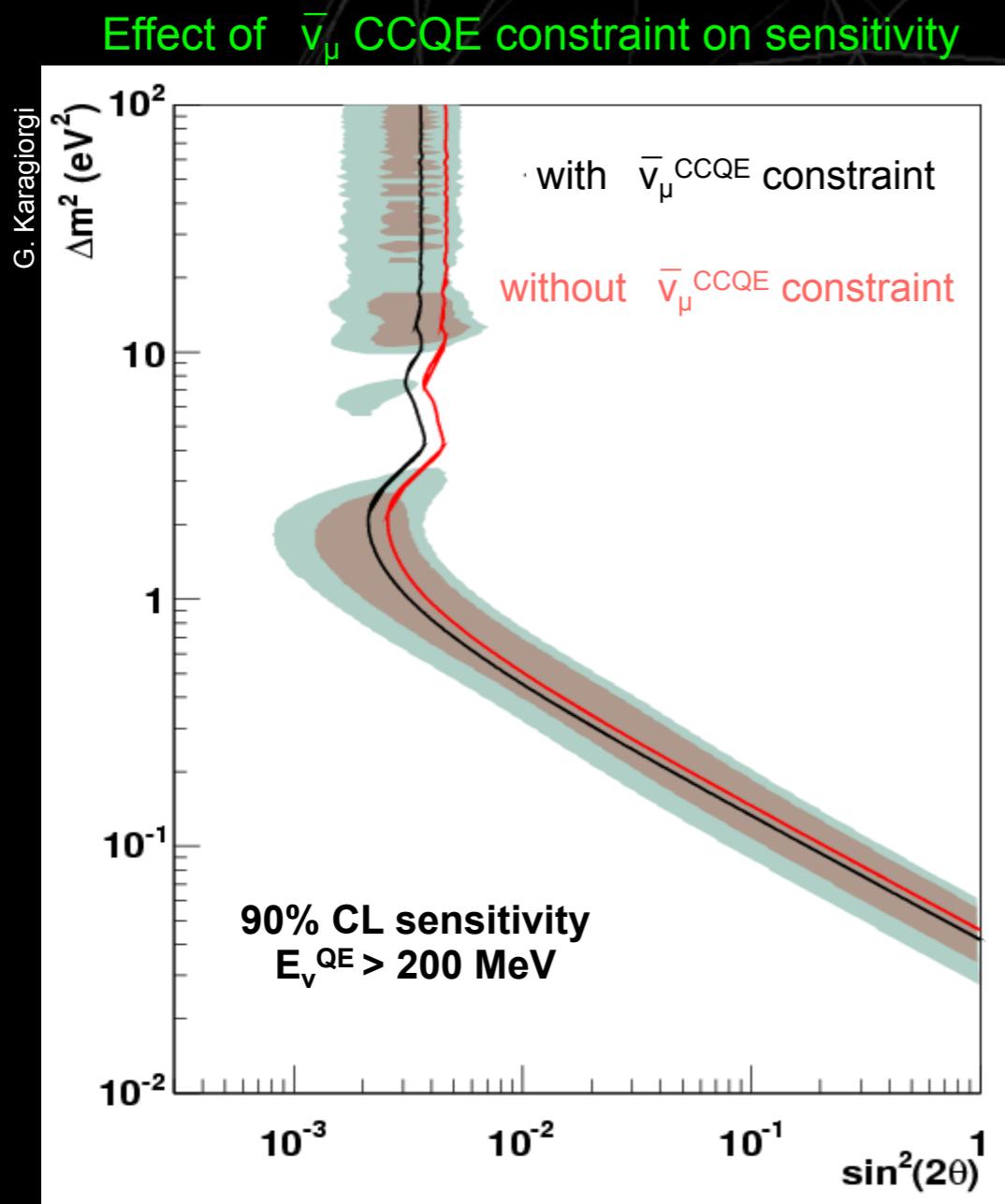


J. Monroe



Fit method example

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



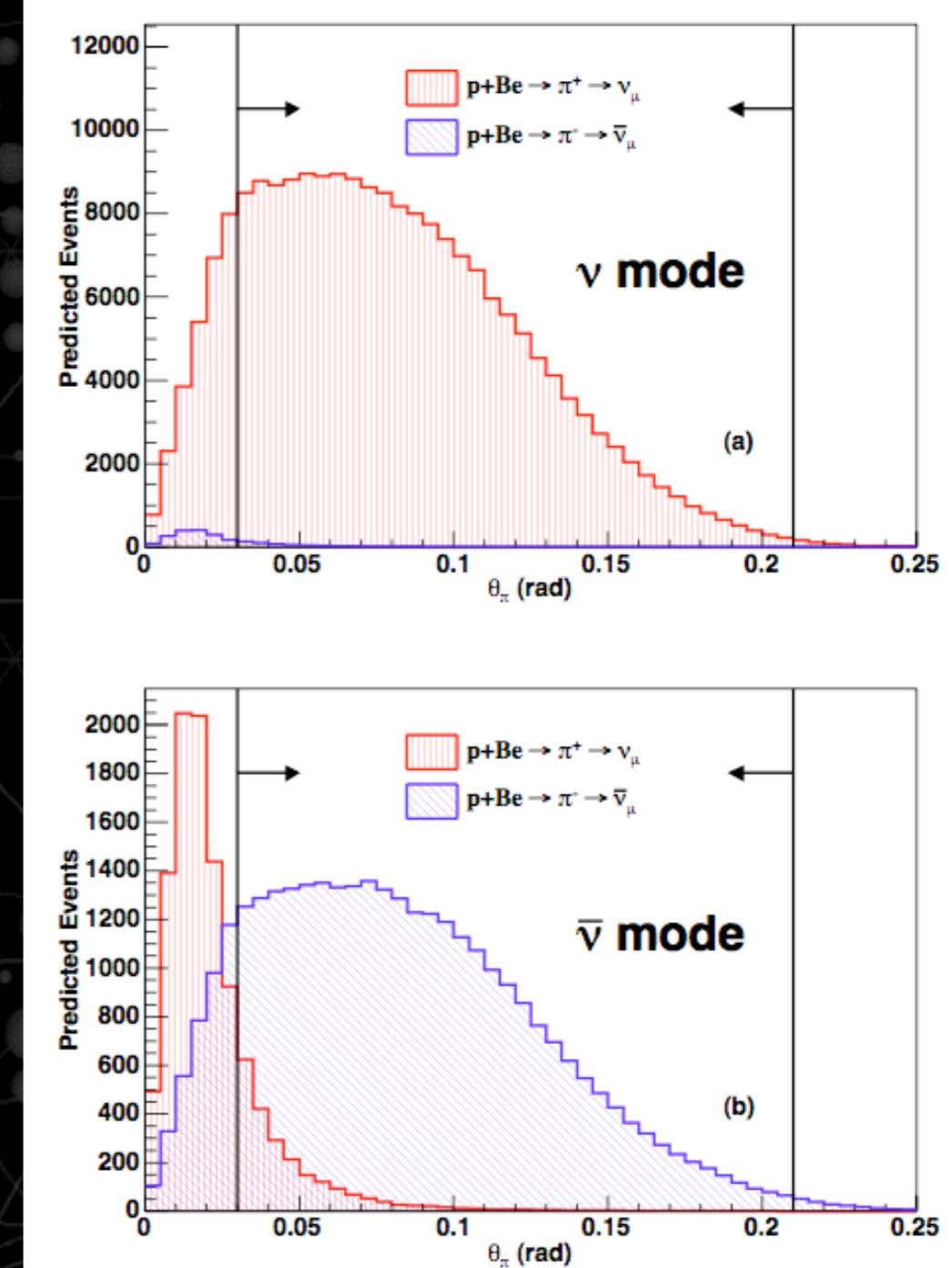
← improves sensitivity and provides stronger constraint to oscillations

Additional Background

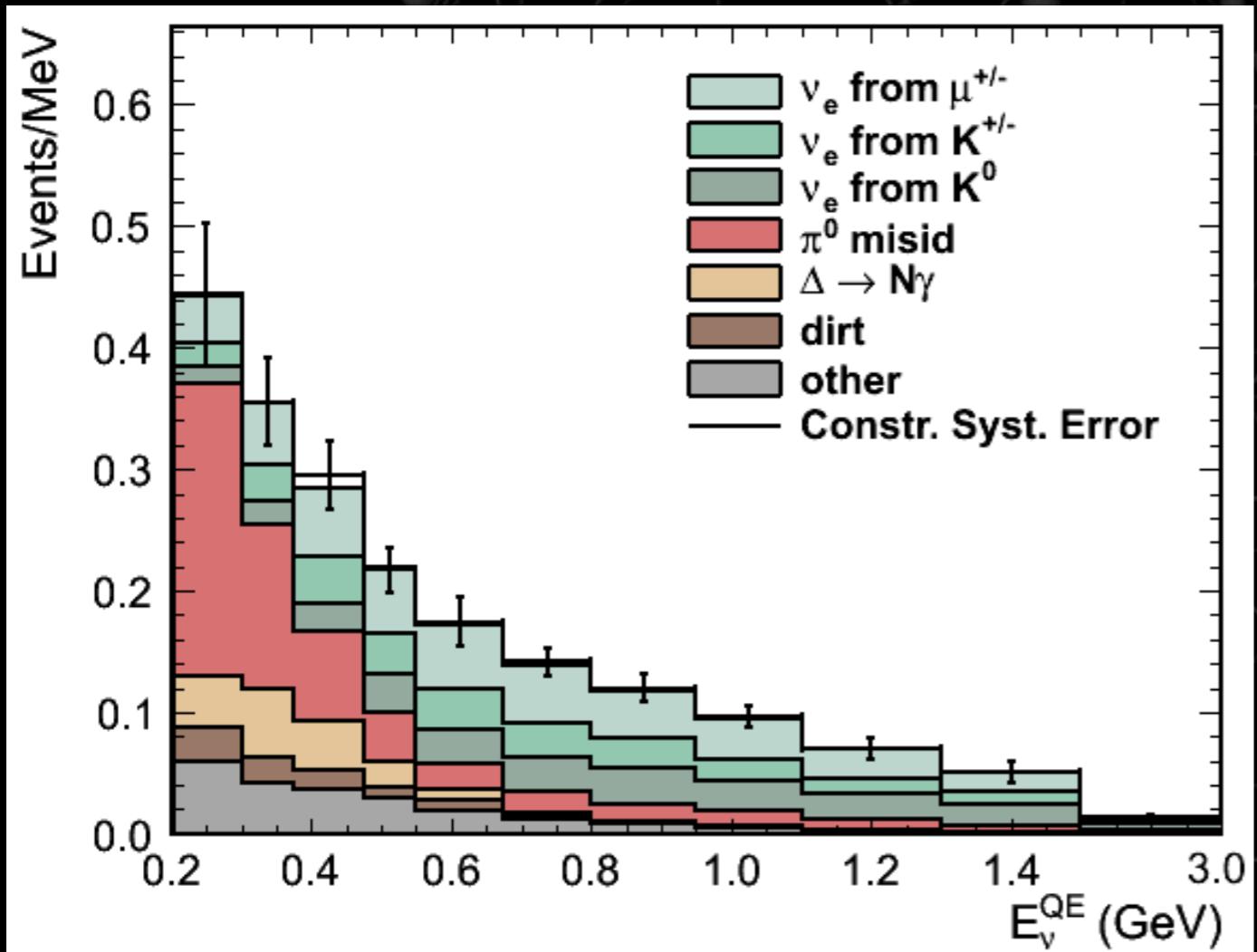
Antineutrino mode

J. Grange

- 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
μ^\pm	13.4	31.4
K^\pm	8.2	18.6
K^0	5.1	21.2
other ν_e	1.3	2.0
NC π^0	41.6	12.6
$\Delta \rightarrow \gamma$	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

Intrinsic ν_e

Mis-ID ν_μ

Systematic Errors

	<u>constraint?</u>
<i>Neutrino flux predictions</i>	
meson production cross sections	✓
meson secondary interactions	✓
focussing horn current	
target and horn system alignment	
<i>Neutrino interaction cross sections</i>	
nuclear model	✓
rates and kinematics for relevant processes	✓
resonance width and branching fractions	✓
<i>Detector modelling</i>	
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)

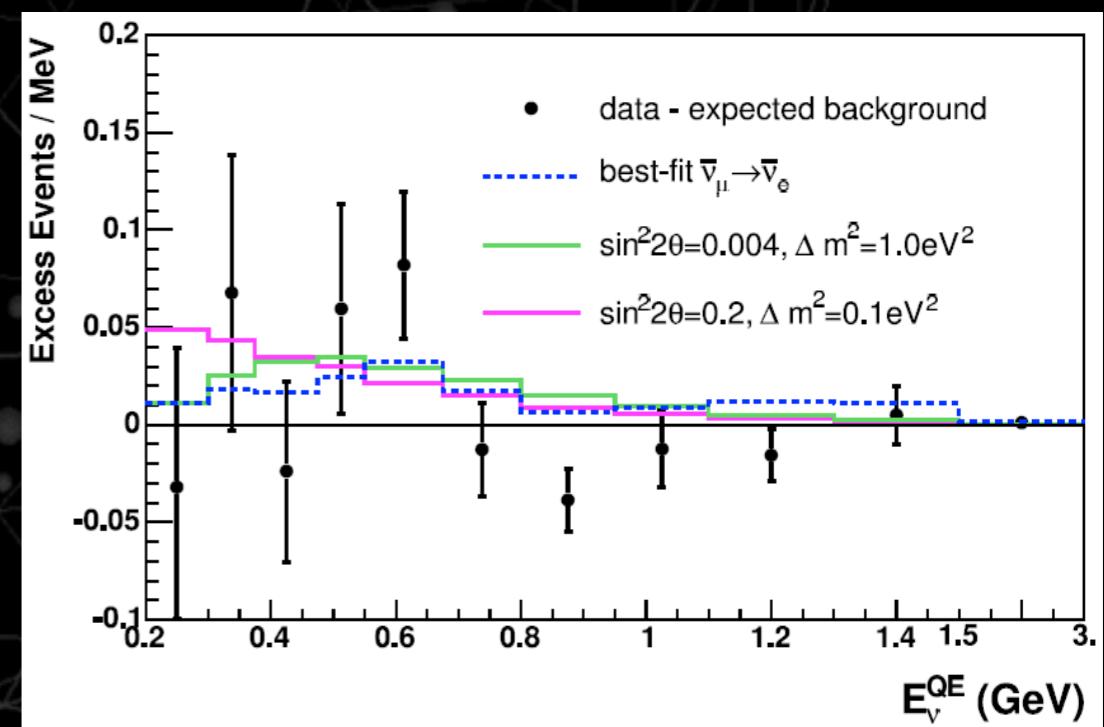
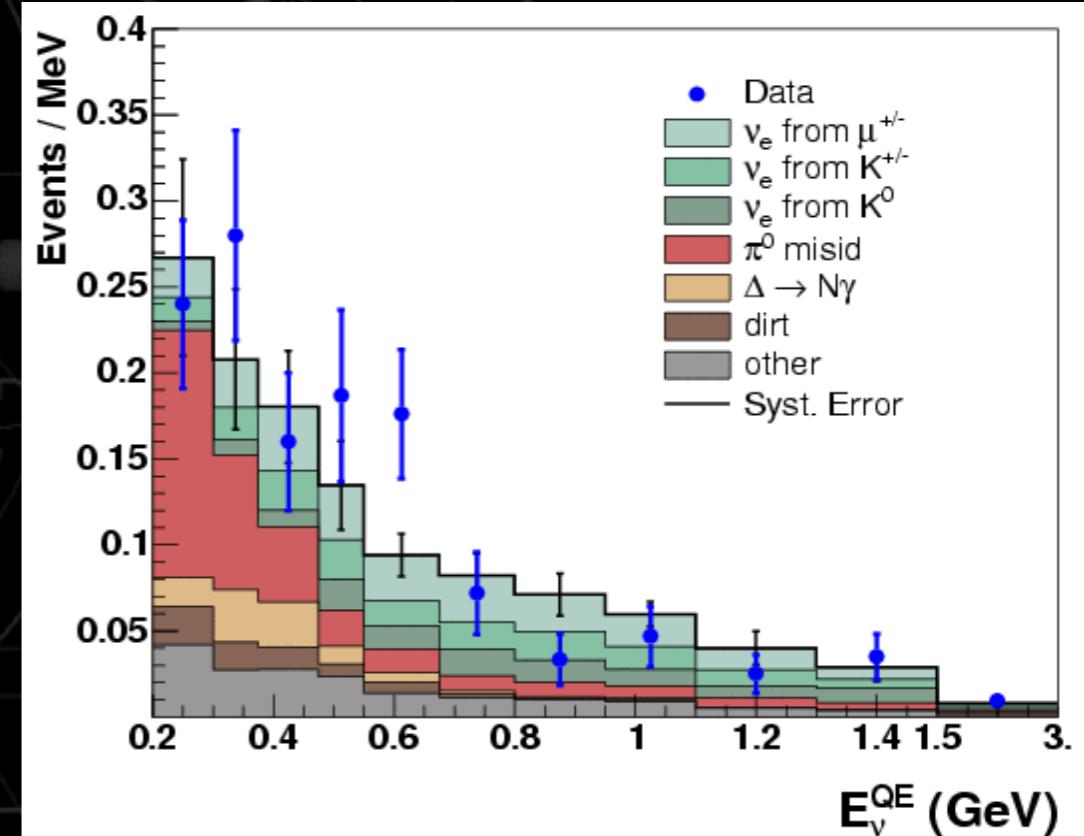
E_ν^{QE} range (MeV)		$\bar{\nu}$ mode ($3.386e20$ POT)	ν mode ($6.486e20$ POT)
200-300	<i>Data</i> $MC \pm \text{sys+stat (constr.)}$ Excess (σ)	24 27.2 ± 7.4 -3.2 ± 7.4 (-0.4 σ)	232 186.8 ± 26.0 45.2 ± 26.0 (1.7 σ)
300-475	<i>Data</i> $MC \pm \text{sys+stat (constr.)}$ Excess (σ)	37 34.3 ± 7.3 2.7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



First $\bar{\nu}_e$ results

PRL 103, 111801 (2009)

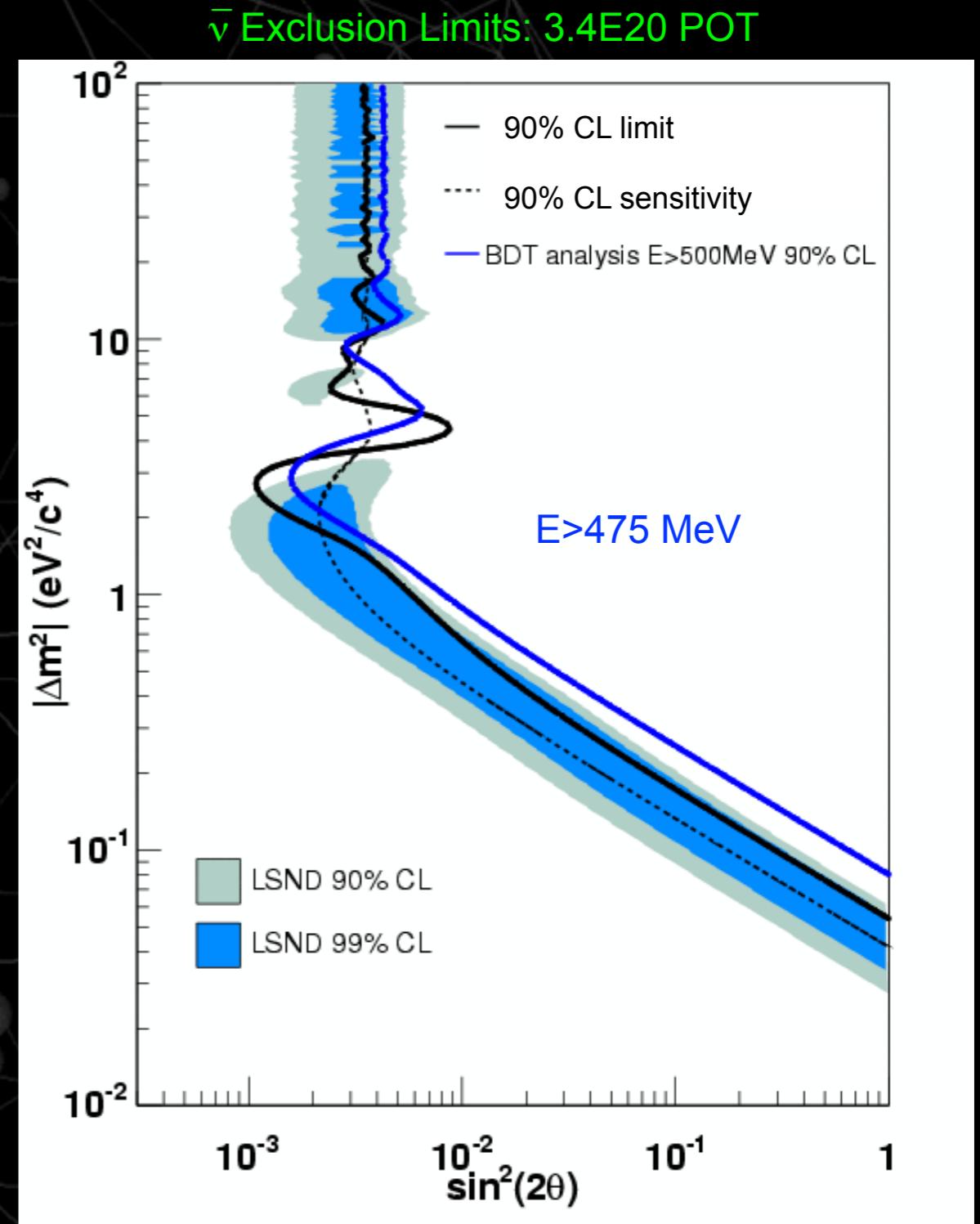
- 3.4E20 POT
- From 200-3000 MeV excess is 4.8 ± 17.6 (stat+sys) events.
- No significant excess $E < 475$ MeV.
- Statistically small excess (more of a wiggle) in 475-1250 MeV region
 - Assume neutrinos do not oscillate in fit
 - Stat error too large to distinguish LSND-like from null



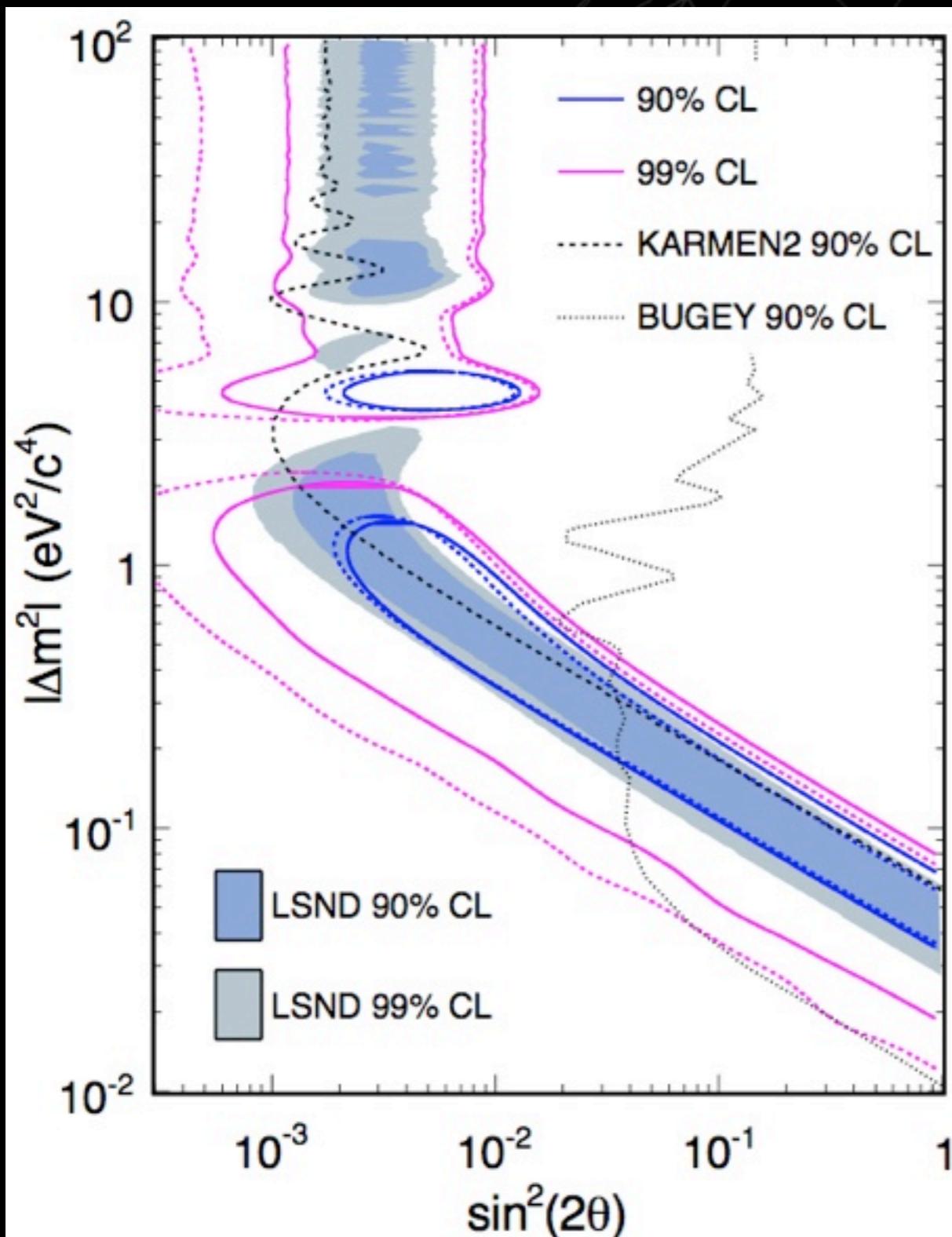
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Fitting down to 200 MeV

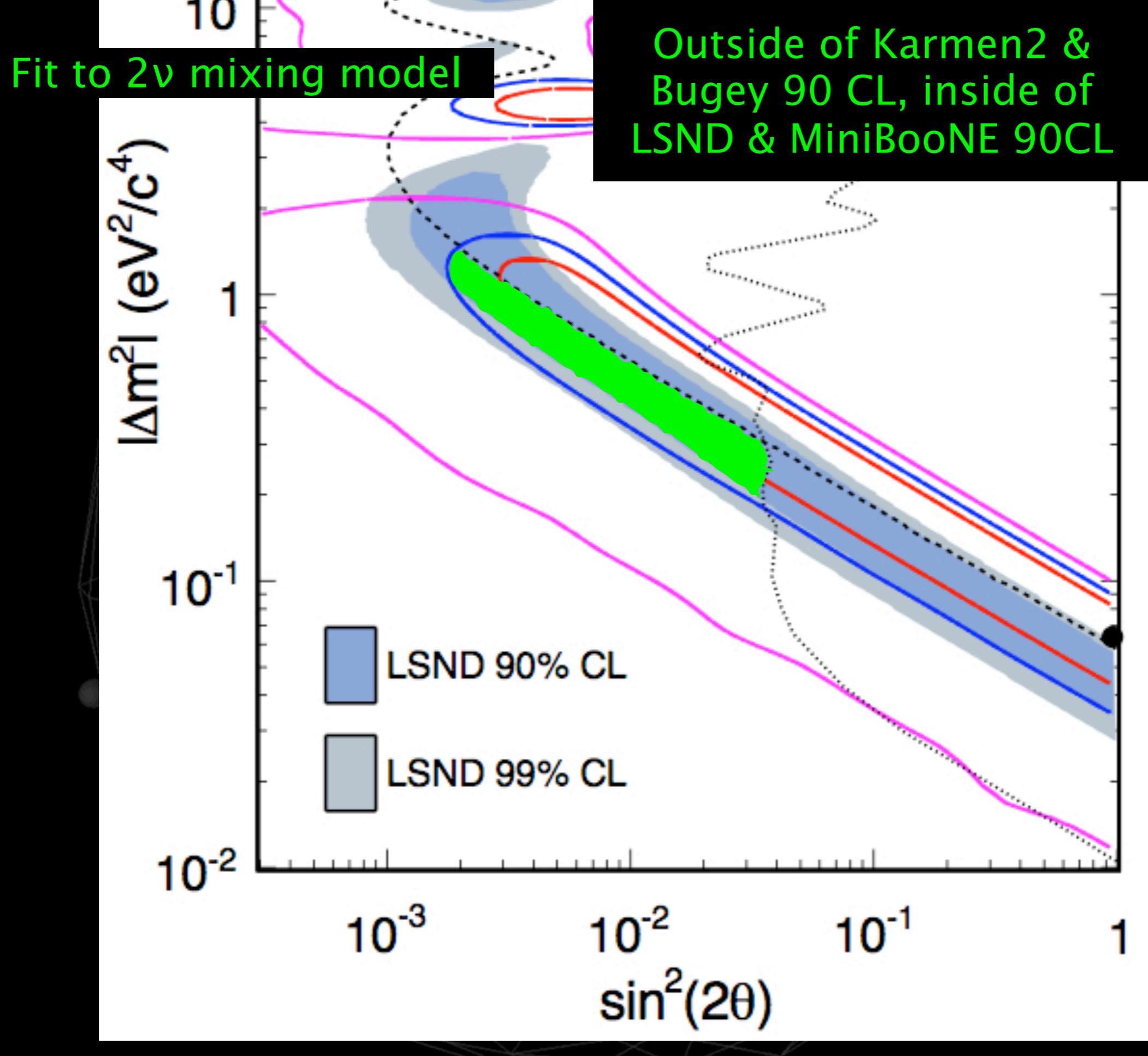


- Dashed pink and blue lines show fit result down to 475 MeV, solid lines extend fit down to 200 MeV
- Only nubar are assumed to oscillate
- No inclusion of low-E expectation
- Large backgrounds in 200-475 means the region carries little weight in the fit
- Get same result if 12 low E bkg events are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

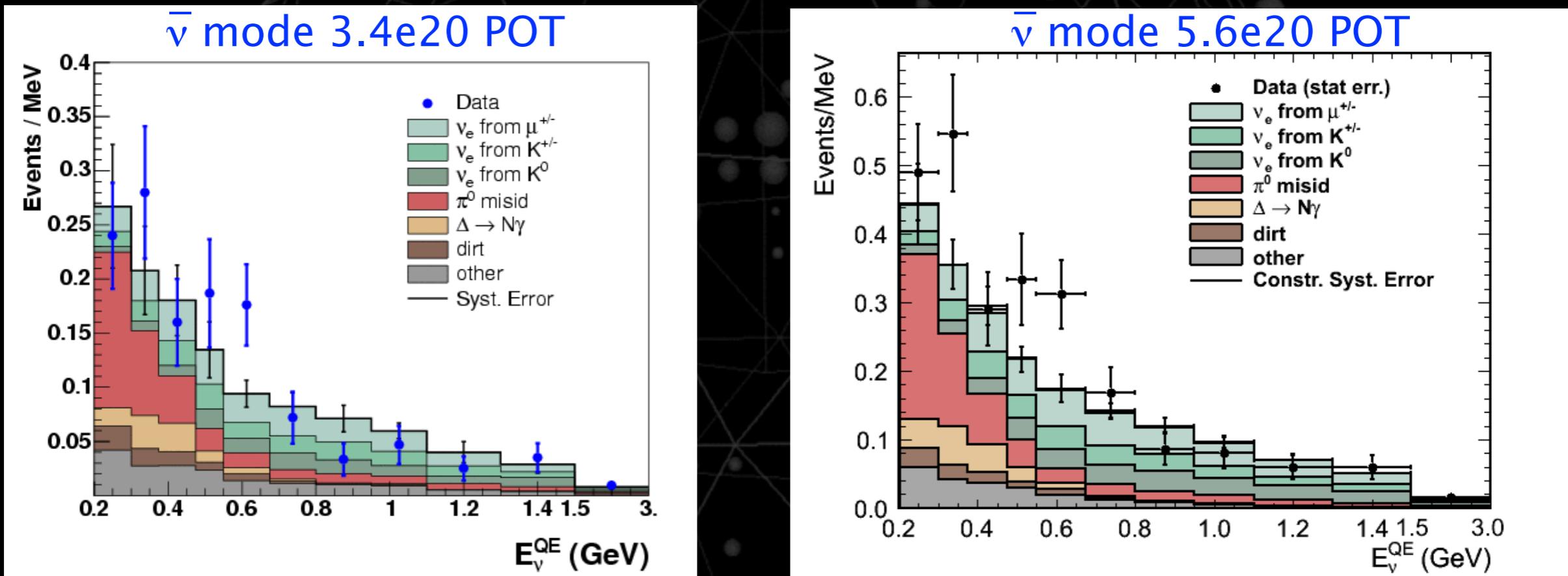
Another check

		E_{ν}^{QE} [MeV]		
Bkgd	200-475	475-1250	1250-3000	
MC	100.5	99.1	34.2	
Data	119	120	38	
Excess	$18.5 \pm 10 \pm 10$	$20.9 \pm 10 \pm 10$	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

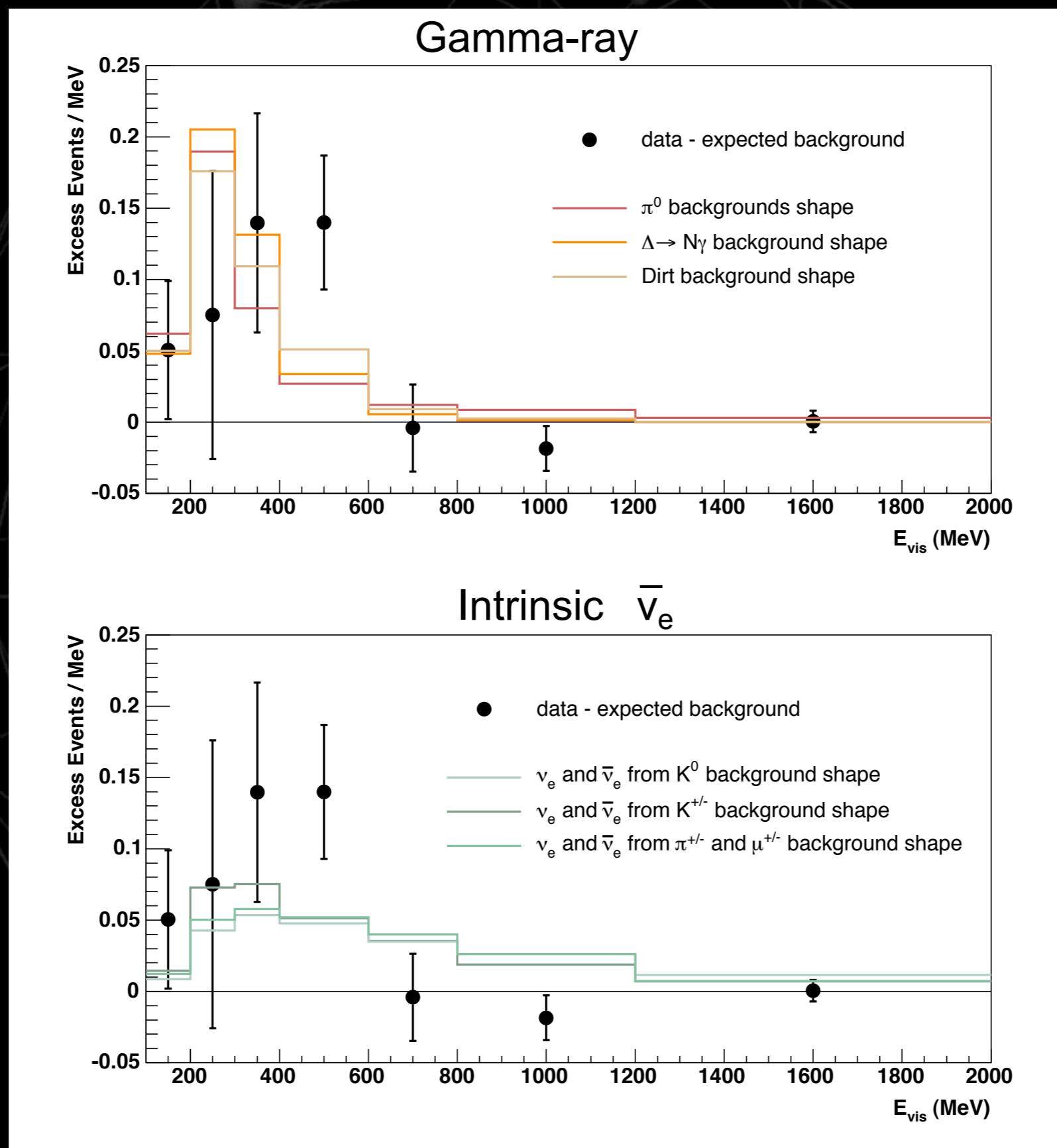


Comparing $\bar{\nu}$ results

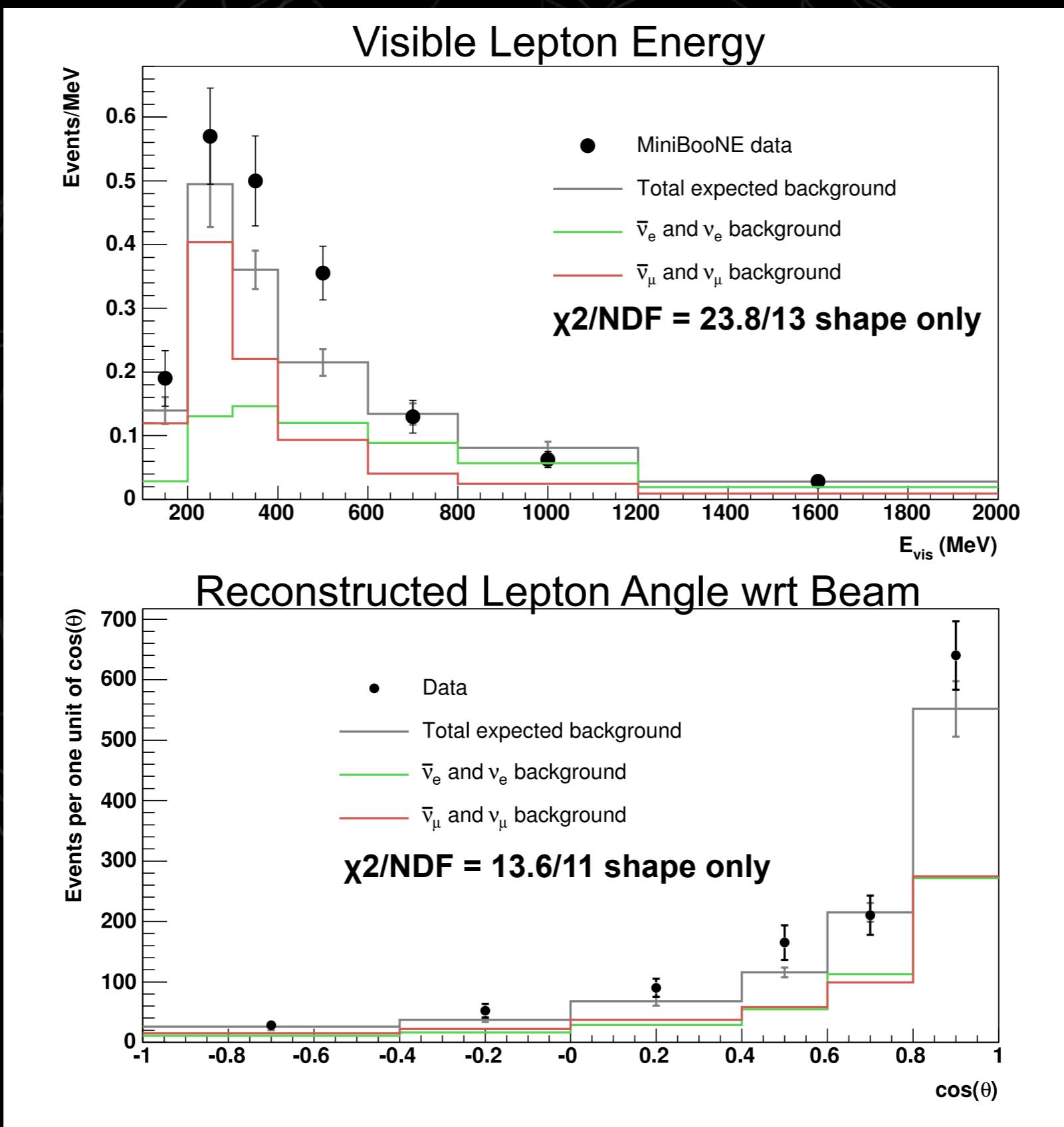


- Nubar beam contains a 20% WS background, fits (above 475 MeV) assume only nubar are allowed to oscillate
- BG composition fairly similar, BG constraints re-extracted
- Consistent at 1.5σ level

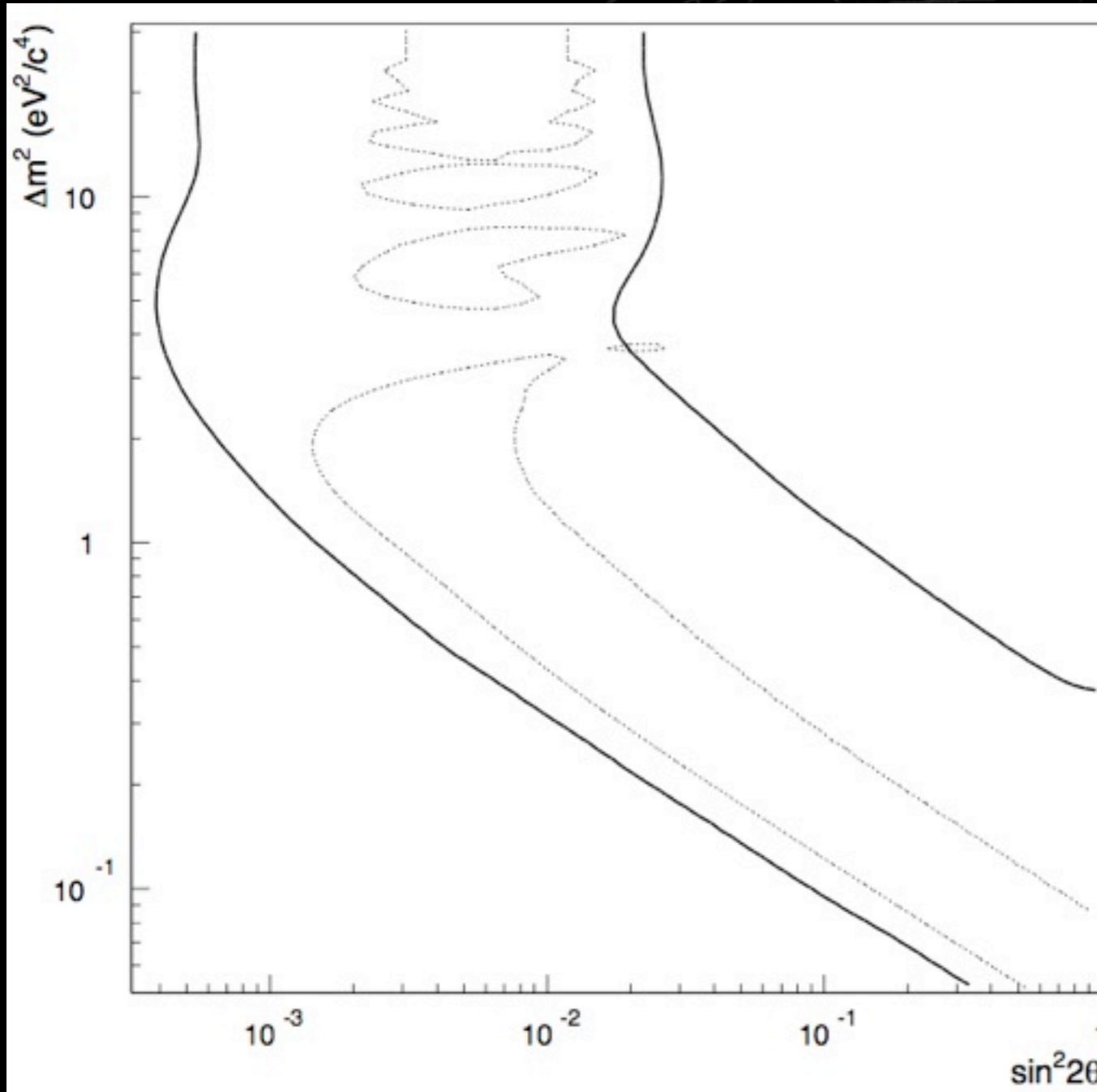
Background $\bar{\nu}_e$ E_{vis} distributions for 5.66E20 POT



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



LSND ν_μ result



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

