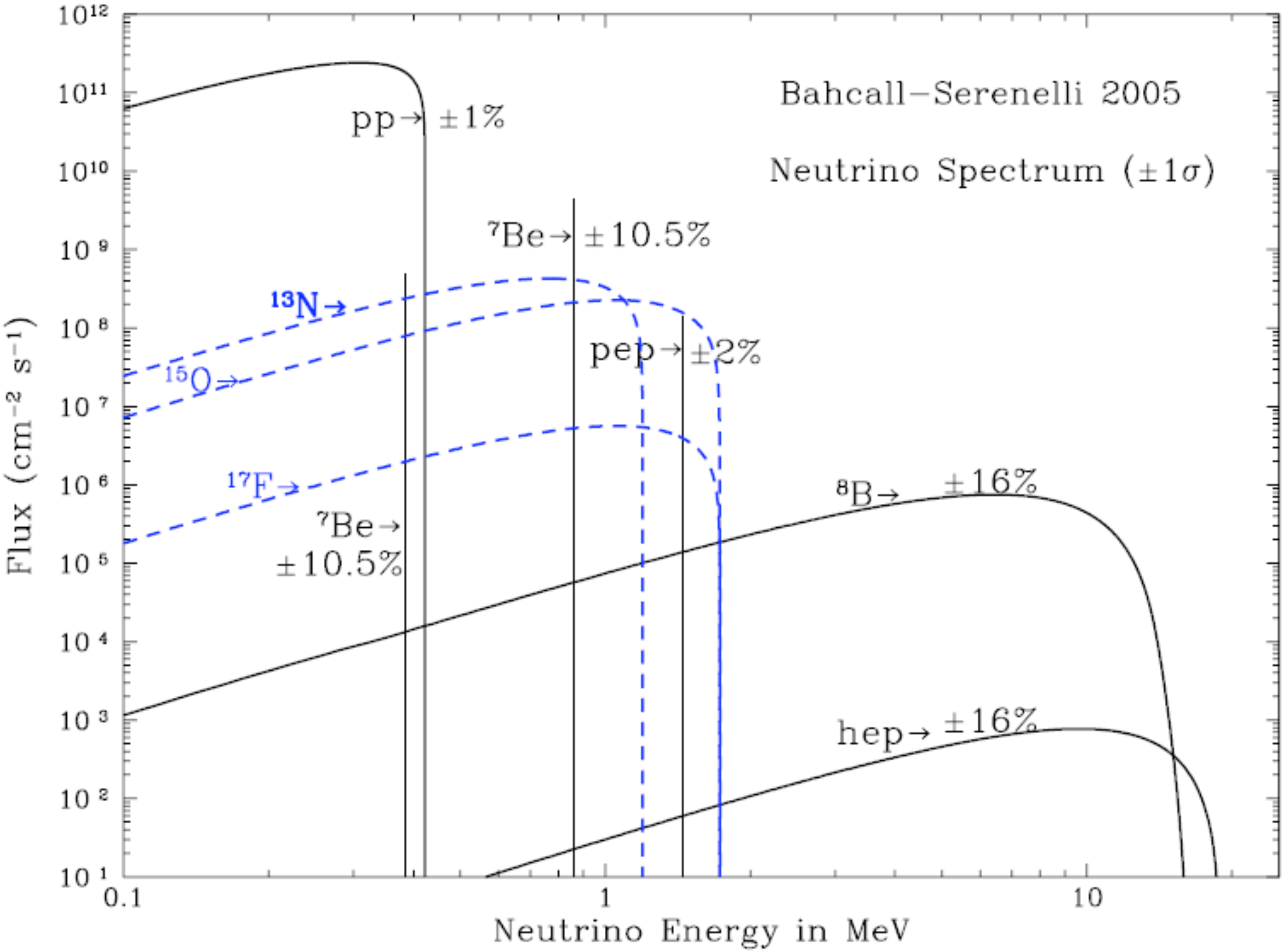
Into the Muck:
Results from SNO's Low Energy Threshold Analysis

- Solar Neutrinos and the MSW Effect
- Motivations for a Low Threshold Measurement
- Analysis Details
- Results

Josh Klein, for the SNO Collaboration
University of Pennsylvania

Solar Neutrino Disappearance

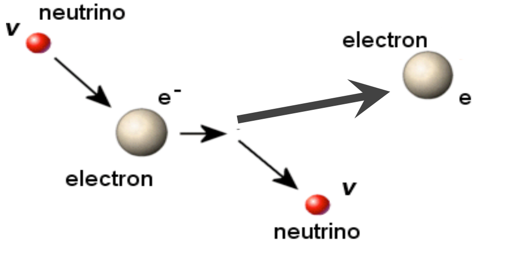
- Before SNO



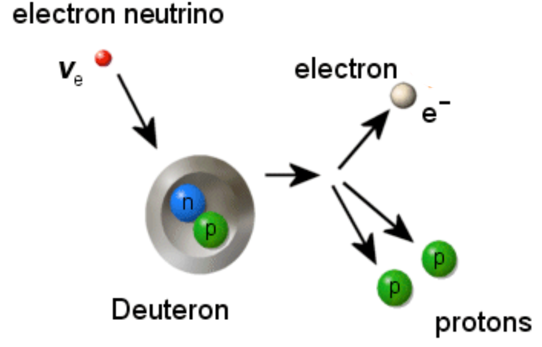
Solar Neu

- SNO neutri

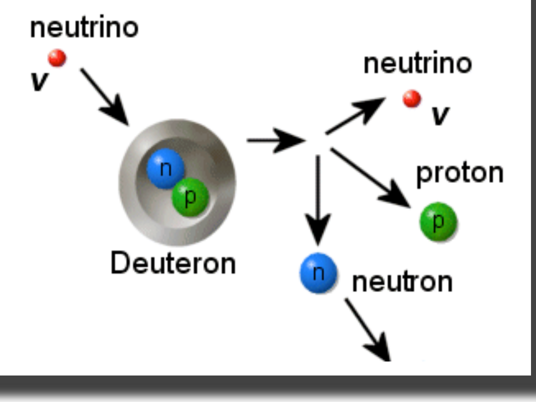
Neutrino-Electron Scattering (ES)



Charged Current (CC)



Neutral Current (NC)



Sign

fit

Three Phases of SNO

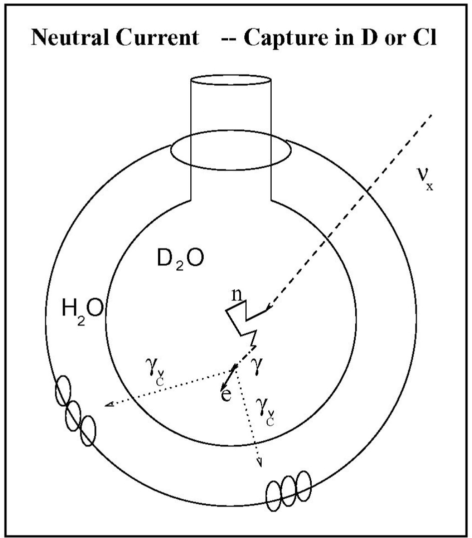
✓ Phase I: Just D_2O

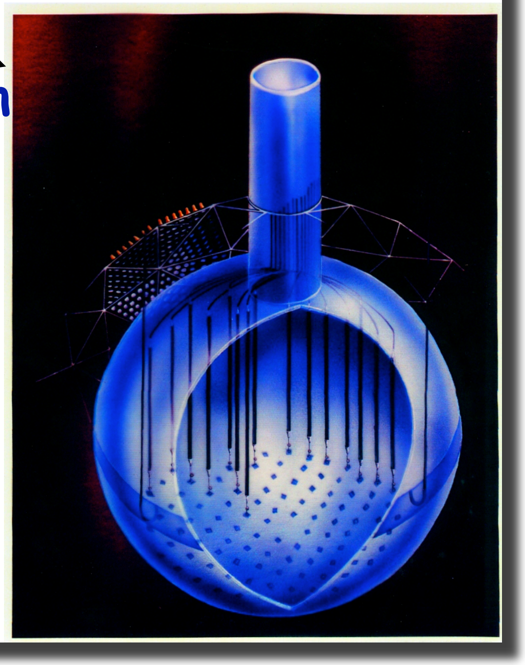
- Simple detector configuration, clean measurement
- Low neutron sensitivity
- Poor discrimination between neutrons and electrons

✓Phase II: D_2O + NaCl

- Very good neutron sensitivity
- Better neutron electron separation

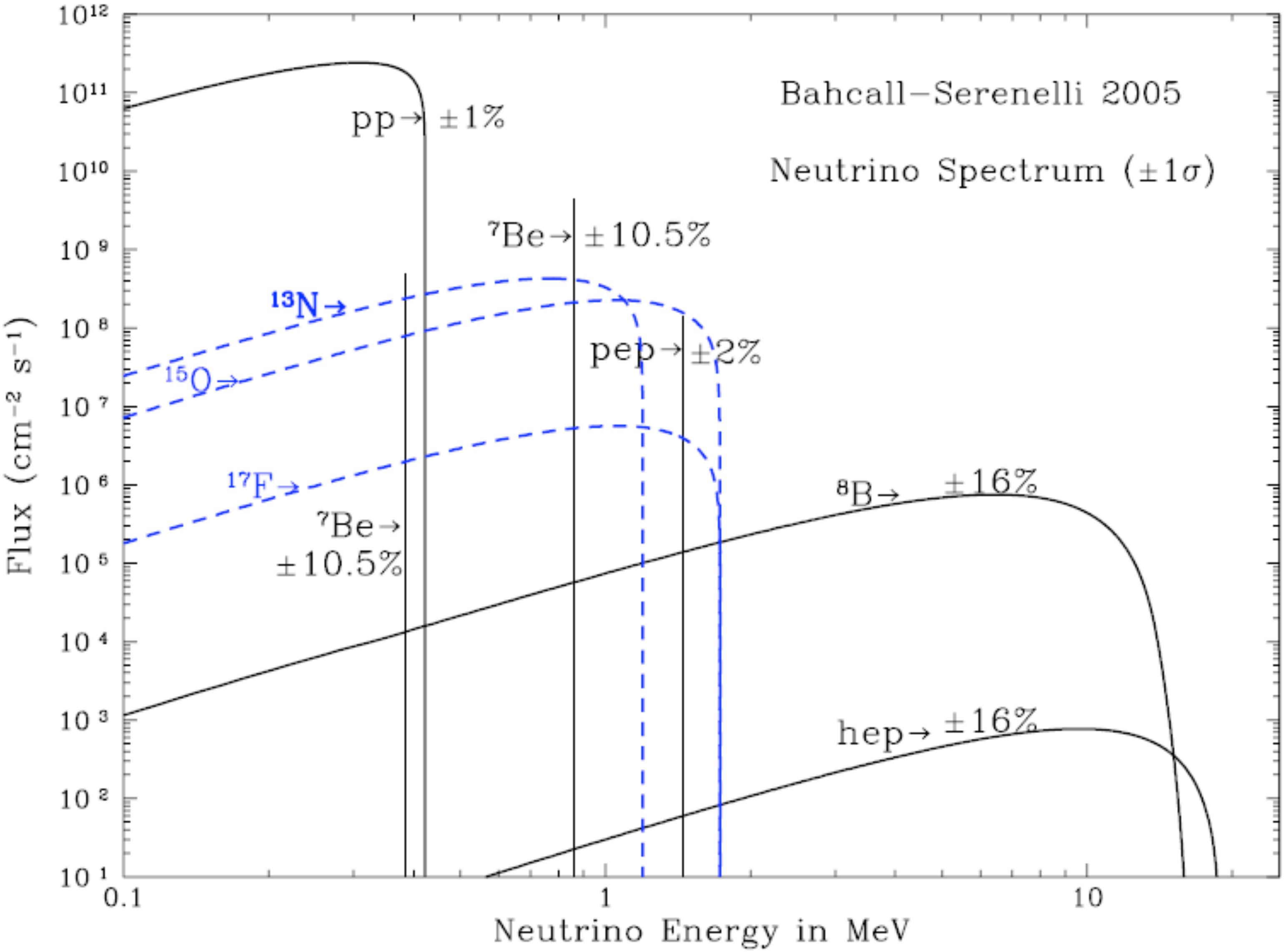
- Phase III: D_2O + ^{3}He Proportional Counters
  - Good neutron sensitivity
  - Great neutron/electron separation





Solar ν Measurements

- Global Summary



SNO End-of-Run

- Draining

What We've Learned in Past ~ 10 years

Three known flavors of νs are massive and mixed like quark sector:

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

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$

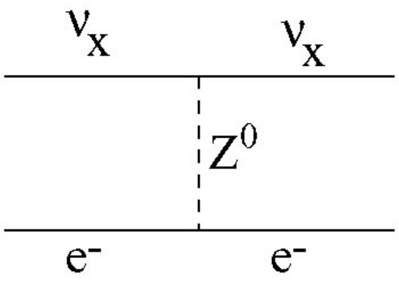
As in quark sector, δ leads to differences in processes for matter and antimatter: $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$

We thus have a model with at least 7 new independent parameters: 3 masses + 3 angles + 1 phase

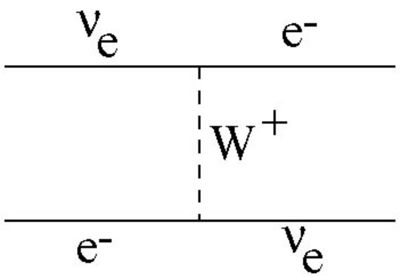
→ Need only 4 parameters ≠ 0 to describe all existing data! → $P_{\upsilon_l \to \upsilon_l} = 1 - \sin^2 2\theta \; \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$

Neutrinos and Flavor Transformation

Oscillations in Matter (MSW Effect)



All neutrino flavors



Only electron neutrinos

$$< \nu_e | H_W | \nu_e > = \sqrt{2} G_F N_e$$

$$\tilde{H} = \tilde{H}_f + \tilde{H}_W$$

Bulk matter just treated as a potential term!

Neutrinos and Flavor Transformation

Oscillations in Matter (MSW Effect)

Hamiltonian matrix now has new `matter' eigenvalues and -vectors:

$$\imath\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\sqrt{2}G_fN_e - \frac{\Delta m^2}{2p}\cos^2\theta & \frac{\Delta m^2}{4p}\sin 2\theta\\ \frac{\Delta m^2}{4p}\sin 2\theta & -\frac{\Delta m^2}{2p}\sin^2\theta\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

$$\begin{aligned}\nu_{1m} > &= \cos\theta_m|\nu_e > - \sin\theta_m|\nu_\mu >\\ \nu_{2m} > &= \sin\theta_m|\nu_e > + \cos\theta_m|\nu_\mu >\end{aligned}$$

Which evolve again as $P(E_{\nu_e}, x, \theta, \Delta m^2) = 1 - \sin^2\theta_m \sin^2\frac{\pi x}{L_m}$

But with

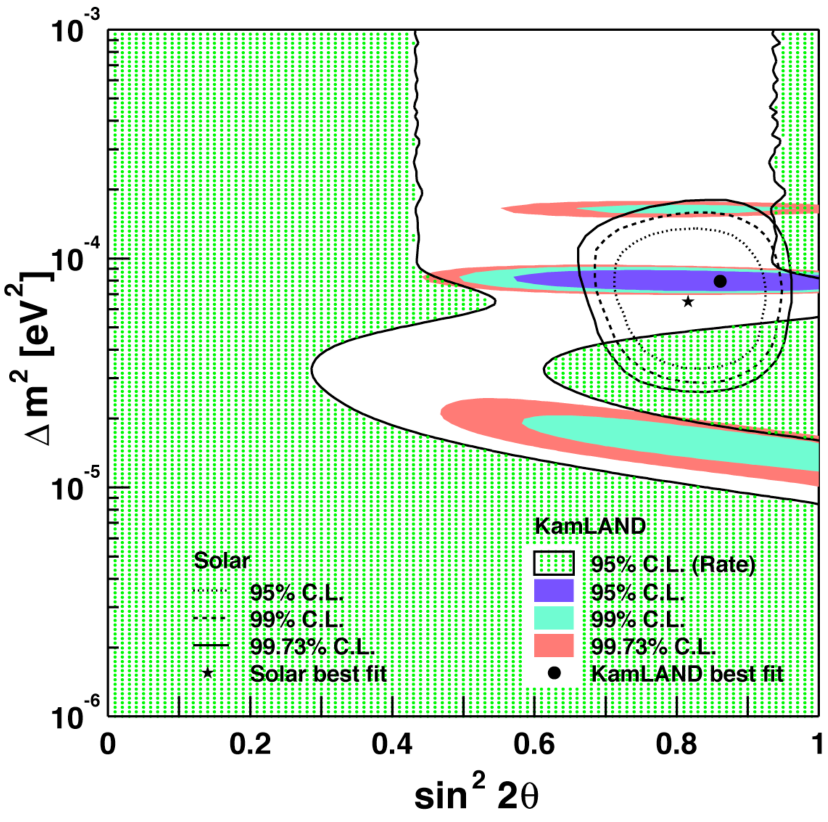
$$\tan 2\theta_m = \frac{\frac{\Delta m^2}{2E}\sin 2\theta}{\frac{\Delta m^2}{2E}\cos 2\theta - \sqrt{2}G_F N_e}$$

Resonance when → $\sqrt{2}G_fN_e - \frac{\Delta m^2}{2E}\cos 2\theta = 0$

Anything that distinguishes flavors (or mass states) alters the pattern

Testing the New Neutrino Model

Given KamLAND measurements, model *predicts* solar parameters



KamLAND Collaboration

$$P(E_{\nu_e}, x, \theta, \Delta m^2) = 1 - \sin^2\theta_m \sin^2 \frac{\pi x}{L_m}$$

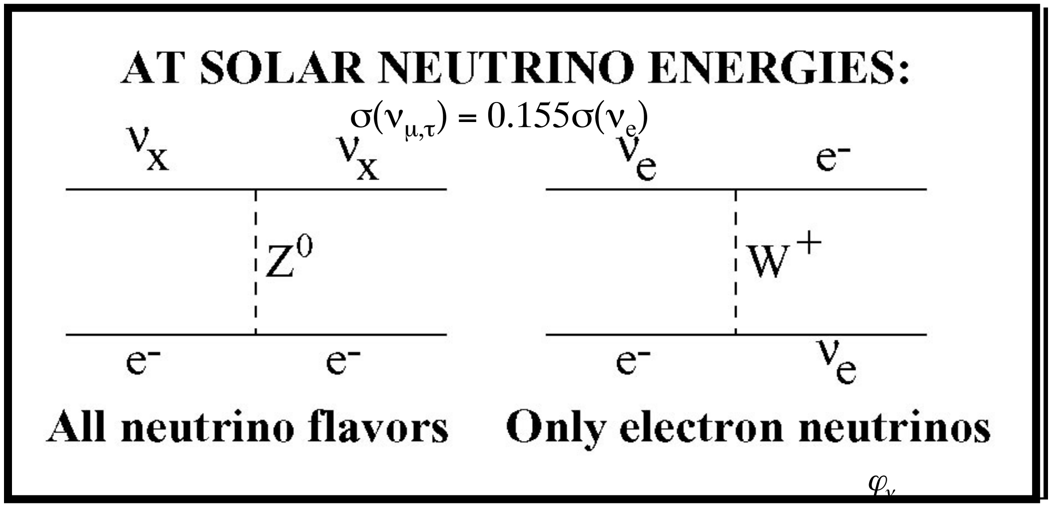
	Reactor	Solar
E	2-10 MeV	0.1-15 MeV
L	150 km	1.5 x 10^8 km
MSW	No	Yes
ν	**Anti-ν_e**	**ν_e**

$$P_{\nu_e \to \nu_e} = 1 - \sin^2 2\theta_{12} \sin^2\left(\frac{1.27\Delta m_{12}{}^2 L}{E}\right)$$

Only(?) Standard Model predicts these 2 experimental regimes see the same effect

Neutrinos and Flavor Transformation

➢ MSW (Matter Effect) Phenomenology

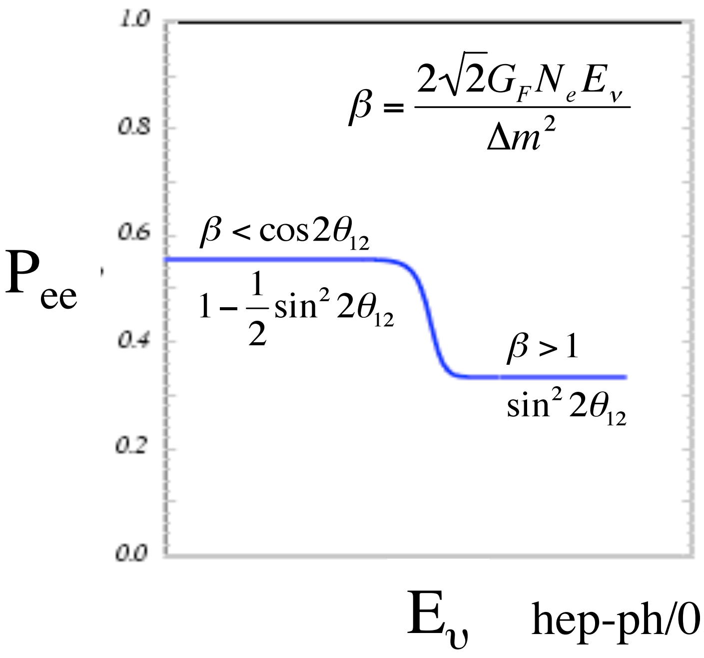


AT SOLAR NEUTRINO ENERGIES:

$\sigma(\nu_{\mu,\tau}) = 0.155\sigma(\nu_e)$

All neutrino flavors **Only electron neutrinos**

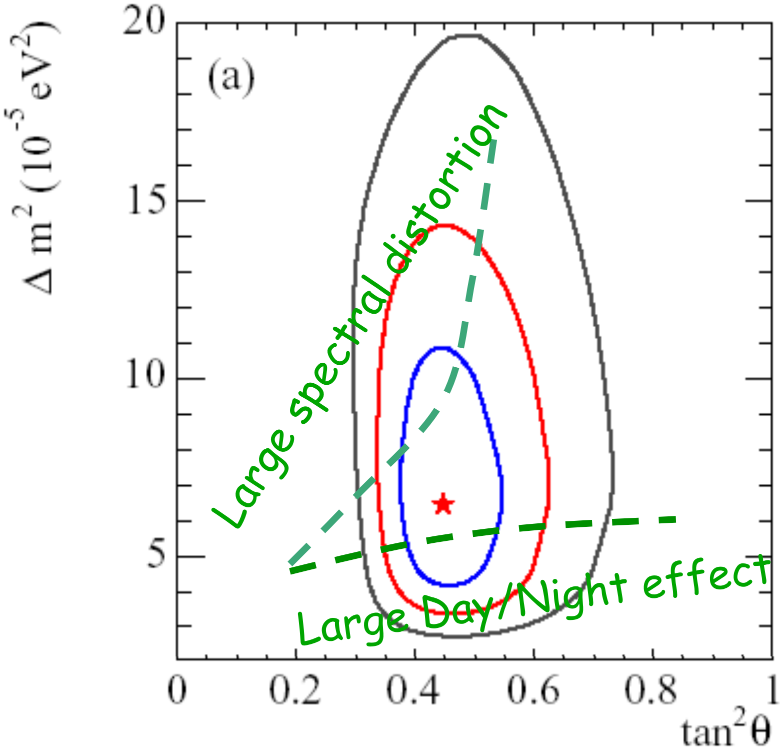
Day/Night ν_e Asymmetry



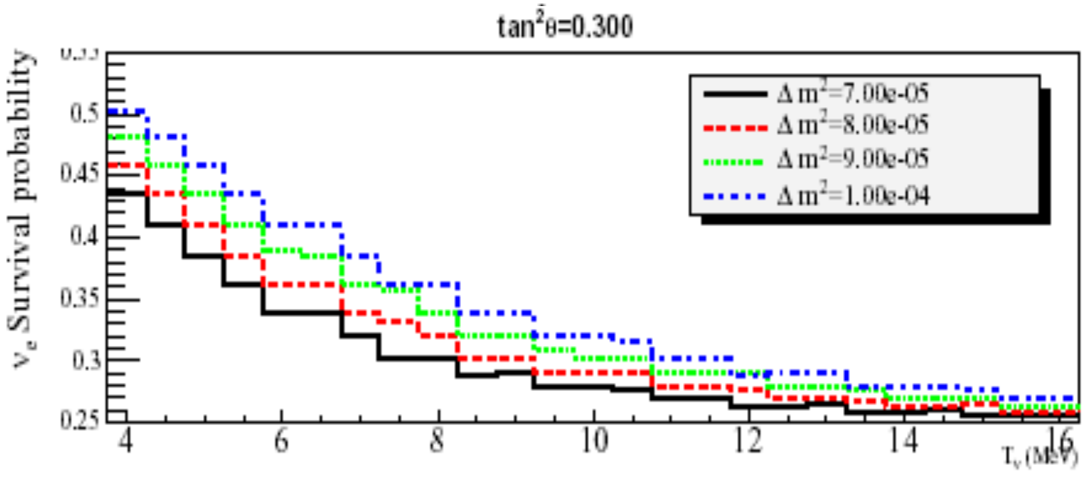
hep-ph/0305159

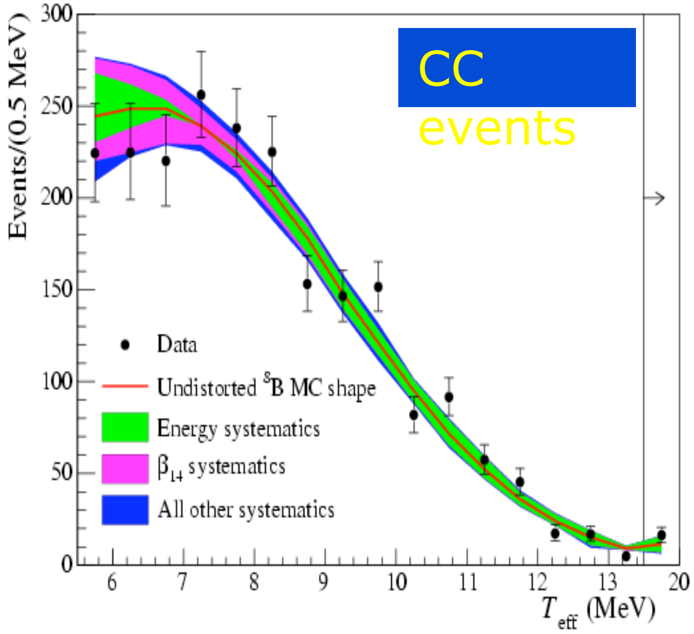
← Rise of survival probability at low T_ν as we approach vacuum-average value of $1-(1/2)\sin^2 2\theta$

Unlucky Parameters



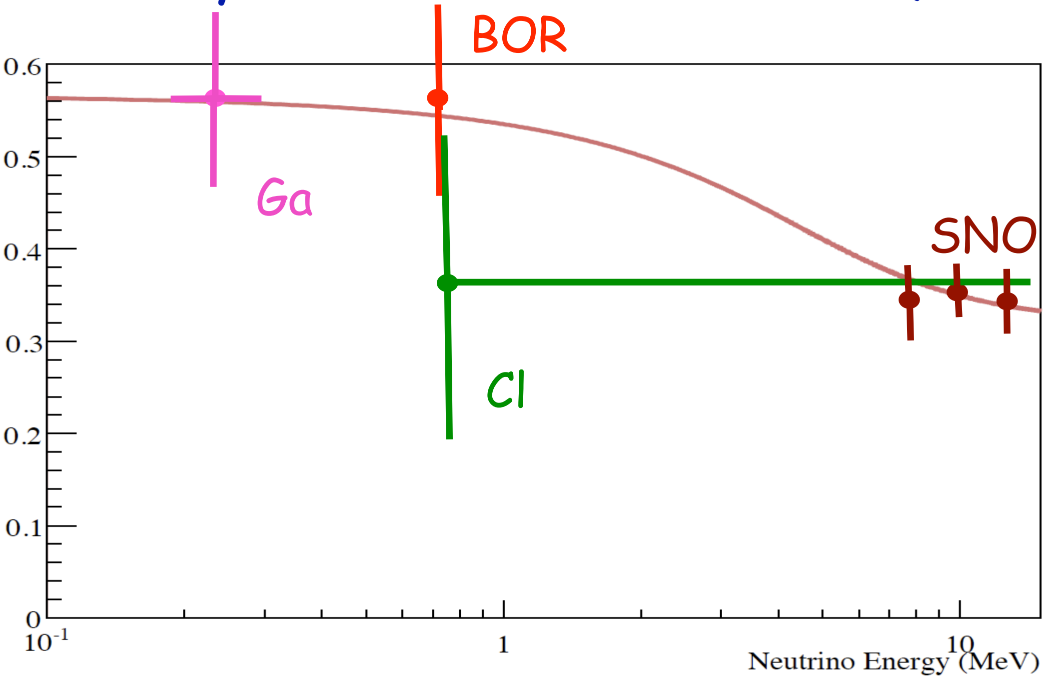
So far, it seems that Nature has picked out one of the few regions where we'd miss a direct MSW signature—
`unlucky' parameters

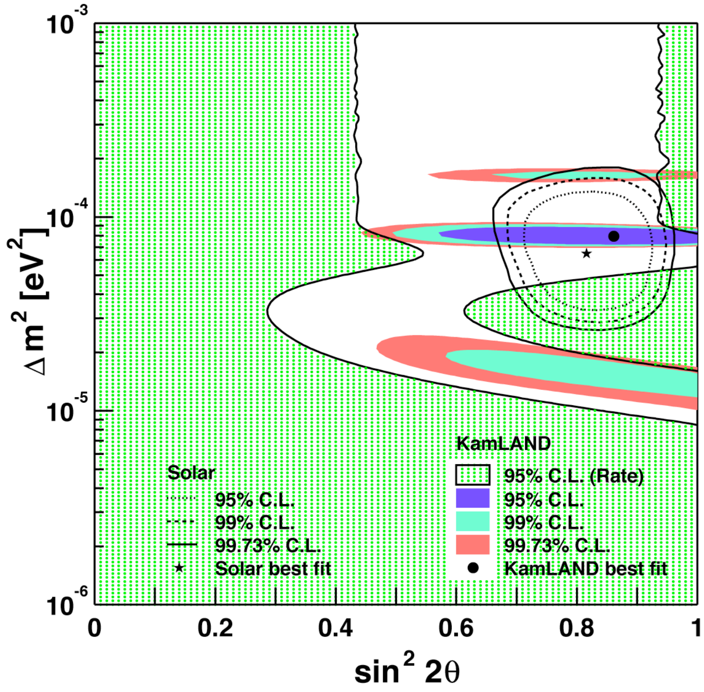




So What?

- Clearly standard oscillations (+MSW) are dominant effect





- But oscillations provide a sensitive *interferometer*
- And ν's are cleanly sensitive to any sub-weak phenomena

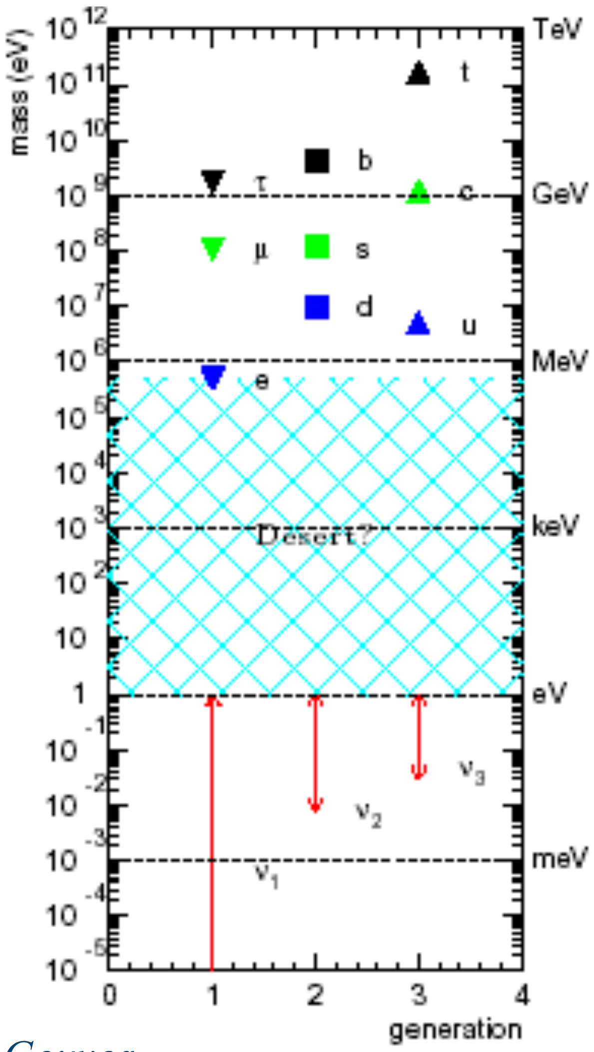
But is there any New Physics to Find Here?

Some possibilities:

- ν+Gravity
- New interactions
- ν+Dark Energy
- `Sterile' neutrinos

Other Motivations for Low Threshold

- Example: Non-standard interactions

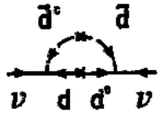


A. de Gouvea

ν masses are amazingly tiny…why?

Neutrinos may acquire mass in a way very differently from the other fermions

Non-Standard Models (e.g. Supersymmetry) provide mechanisms



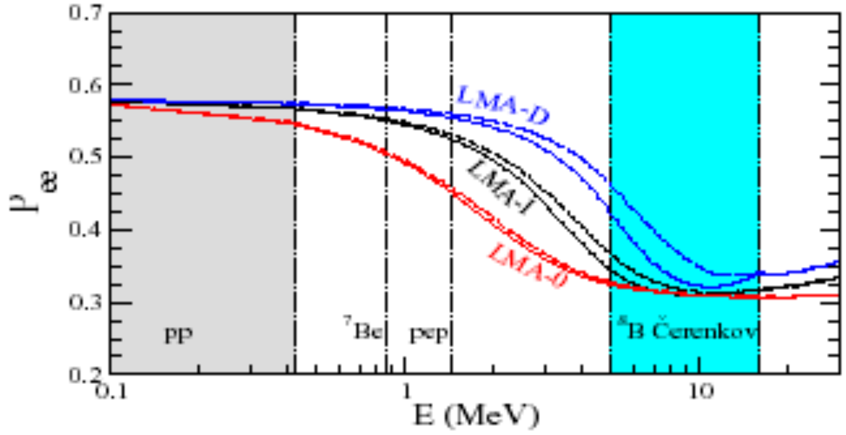
But they also can predict that different flavors have different interaction strengths so

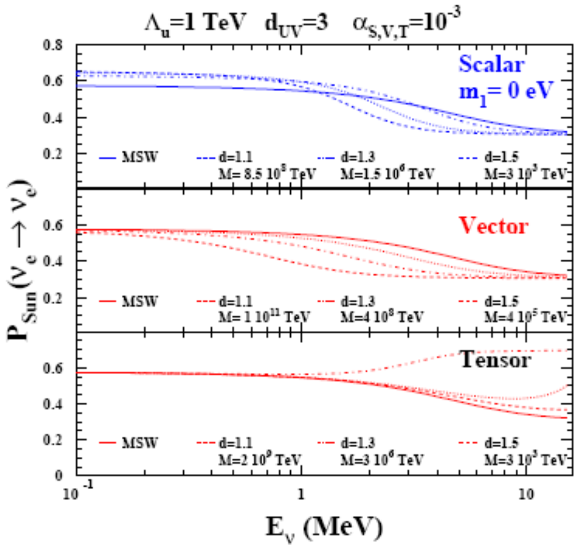
$$\tan 2\theta_m = \frac{\left(\frac{\Delta m^2}{2E}\right)\sin 2\theta + 2\sqrt{2}G_F\varepsilon N_d}{\frac{\Delta m^2}{2E}\cos 2\theta - \sqrt{2}\,G_F\,N_e + \sqrt{2}\,G_F\varepsilon'\,N_d}$$

Other Motivations for Low Threshold Analysis

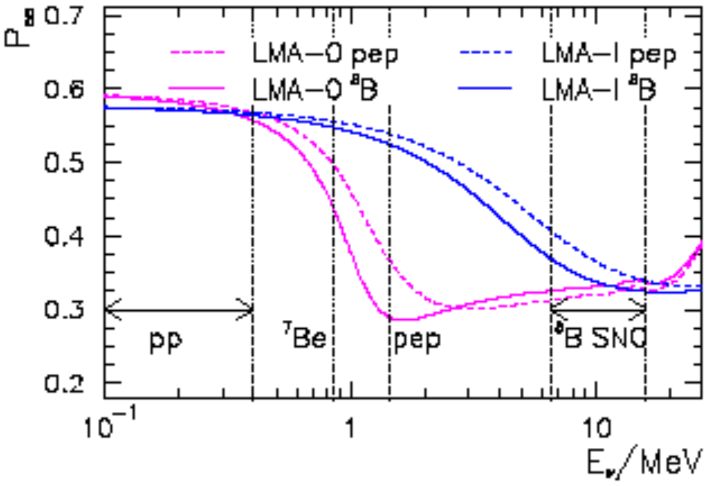
Nonstandard effects can be enhanced by MSW-like resonance

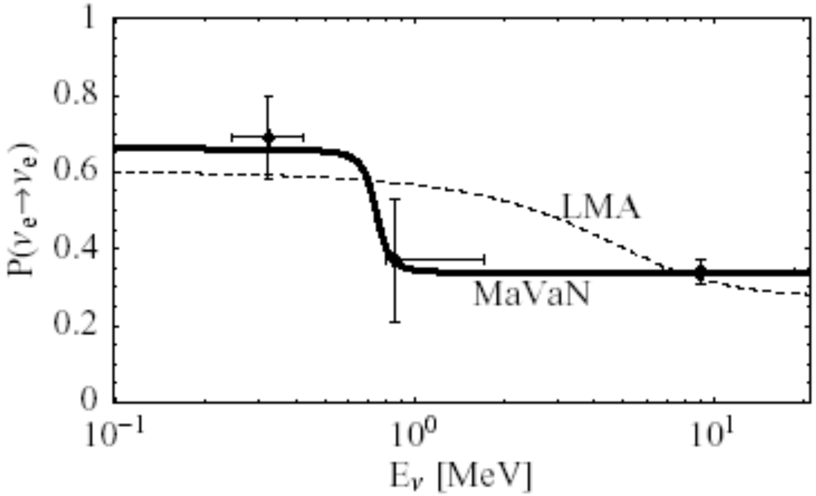
Miranda, Tortola, Valle, hep-ph/0406289 (2005)





M. C. Gonzalez-Garcia, P. C. de Holanda,
E. Masso and
R. Zukanovich Funchalc,
hep-ph/0803.1180



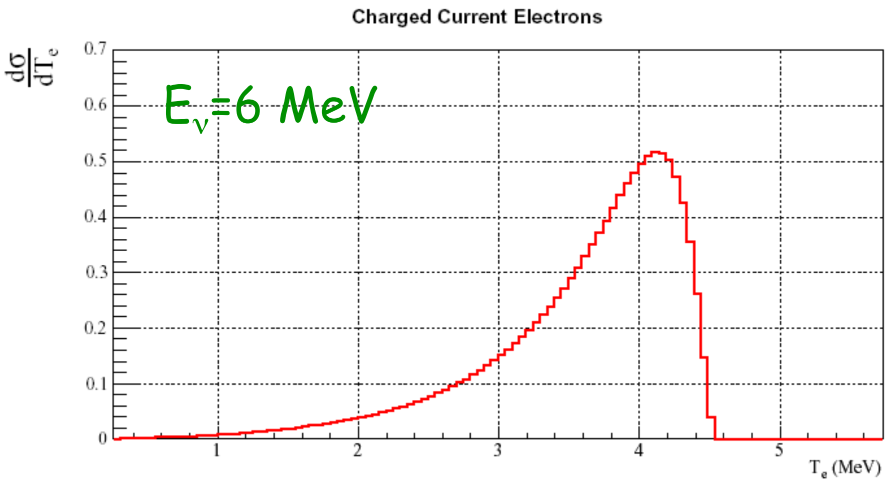


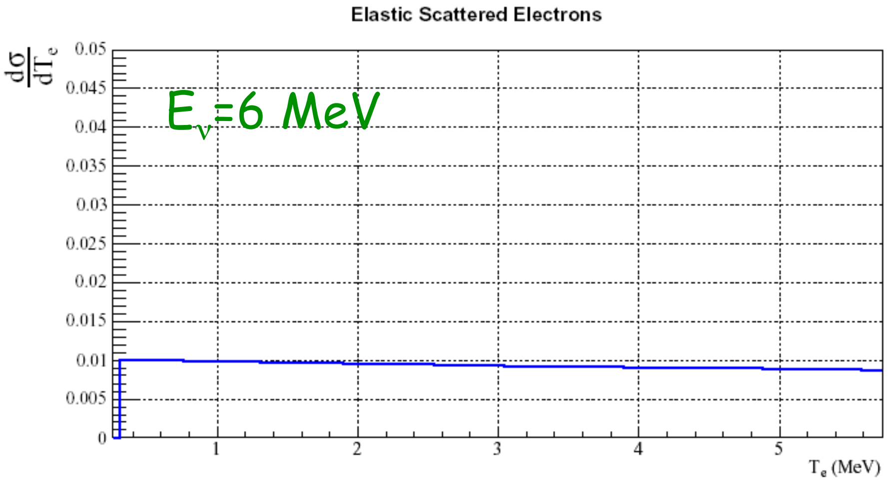
Friedland, Lunardini, Peña-Garay, PLB 594, (2004)

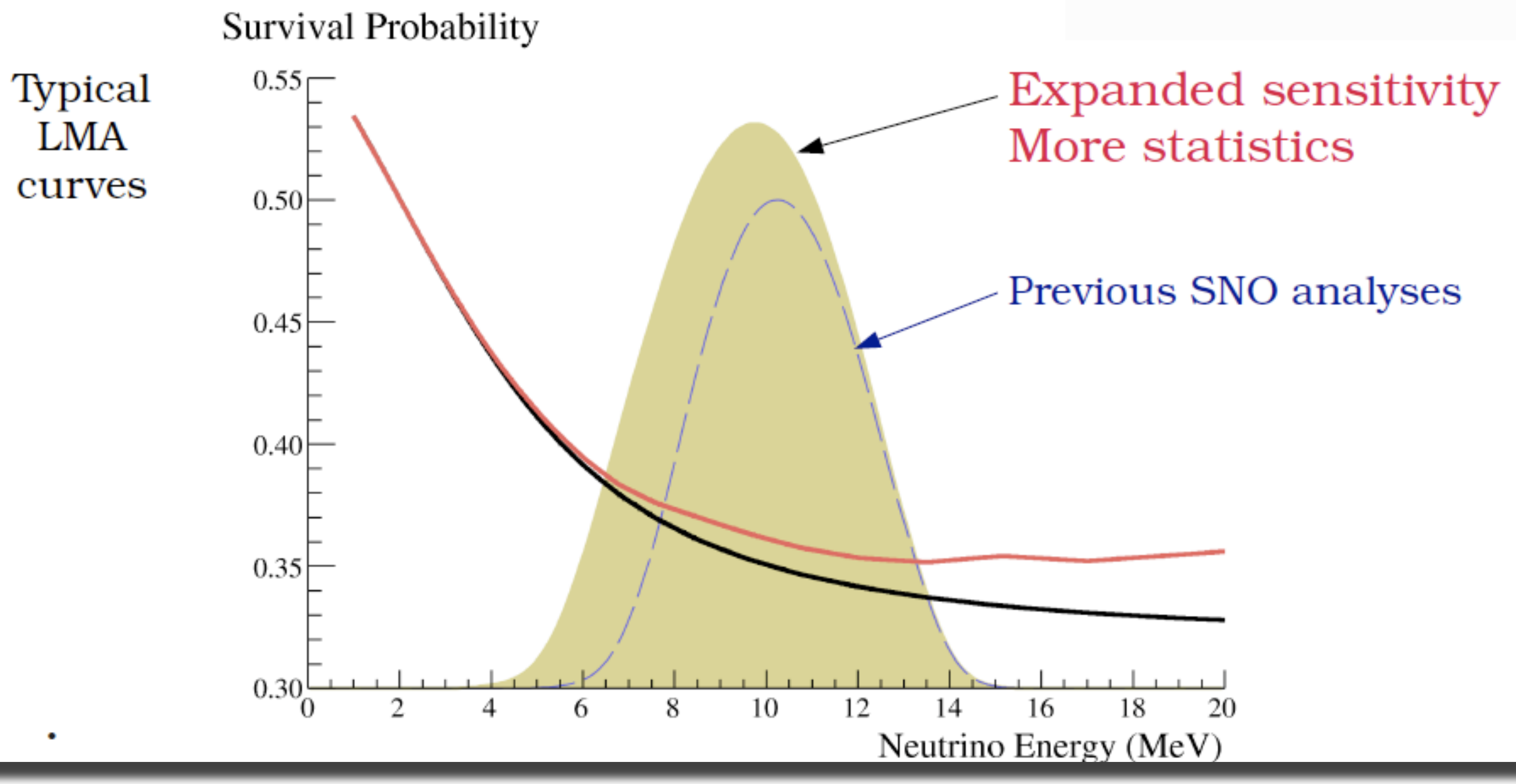
Barger, Huber, Marfatia, PRL95, (2005)

Advantages of Low Threshold Analysis

- ν_e Statistics

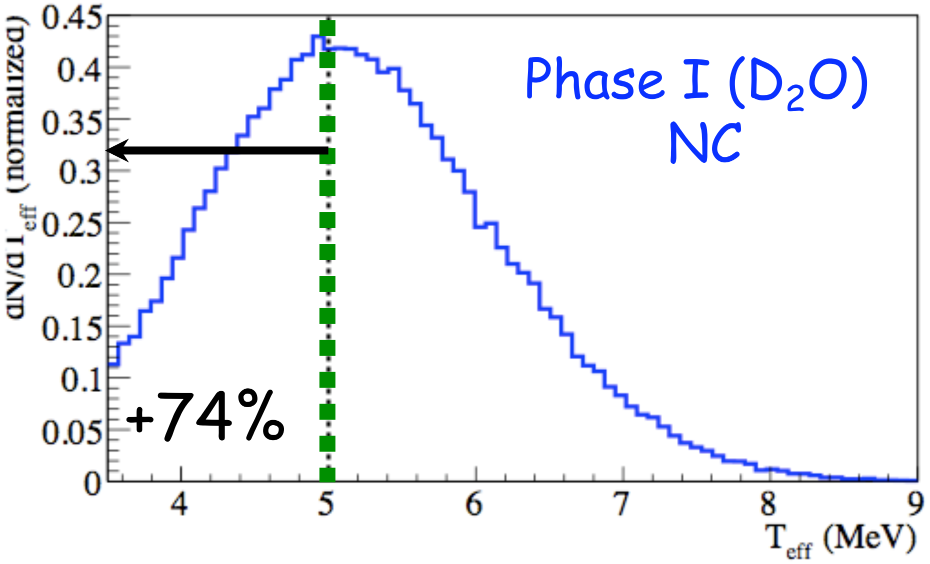

Charged Current Electrons

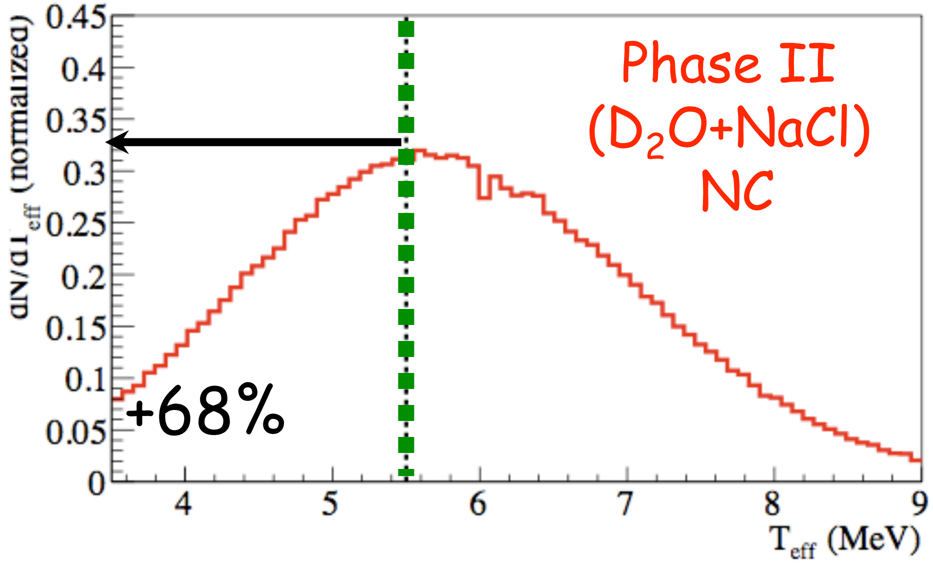

Elastic Scattered Electrons


Survival Probability

Advantages of Low Threshold Analysis

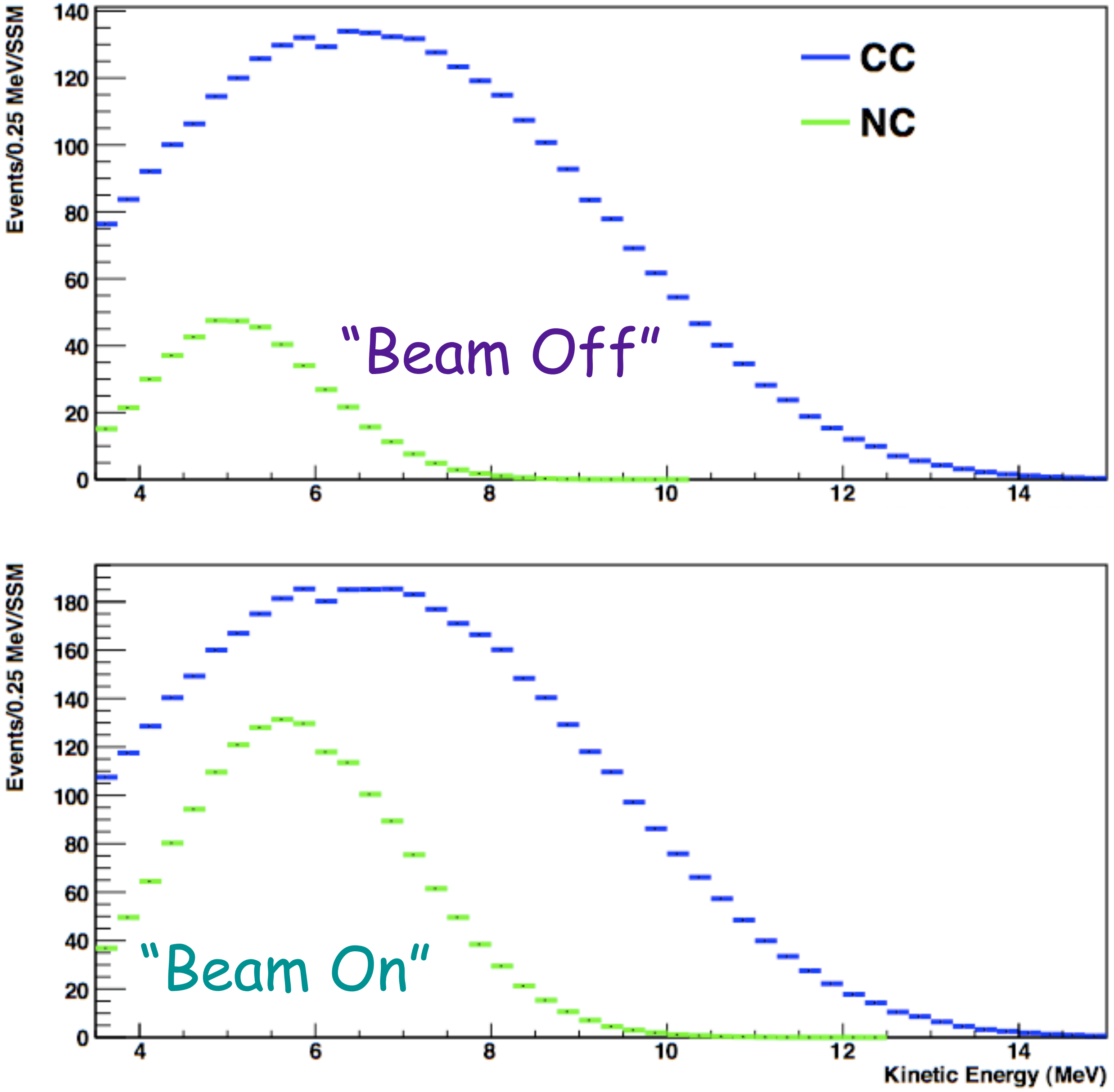
- ν_x (NC) Statistics





Advantages of (2-Phase) Low Threshold Analysis

- Breaking NC/CC Covariance



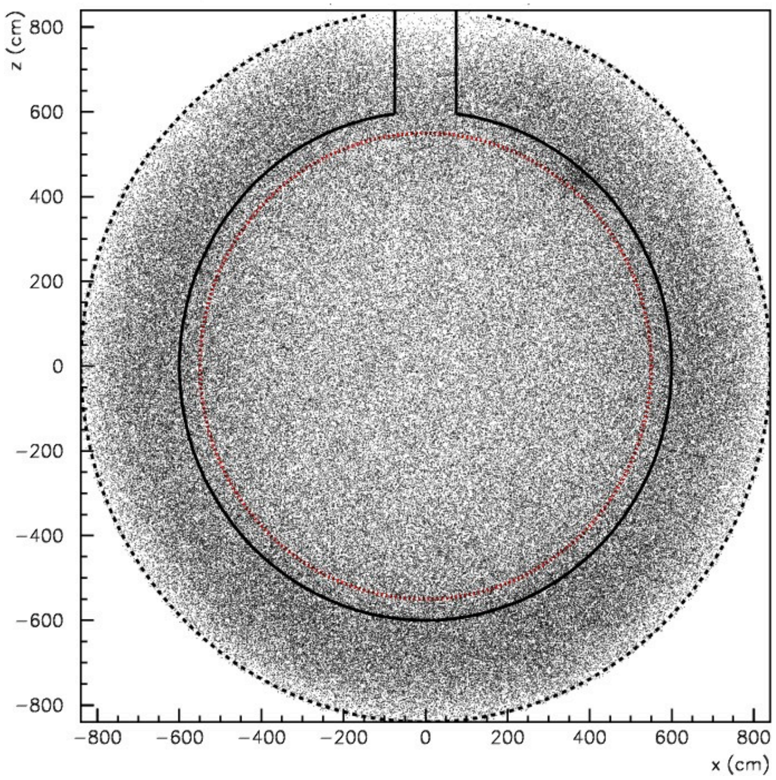
Phase I
(D_2O)

Phase II
(D_2O+Salt)

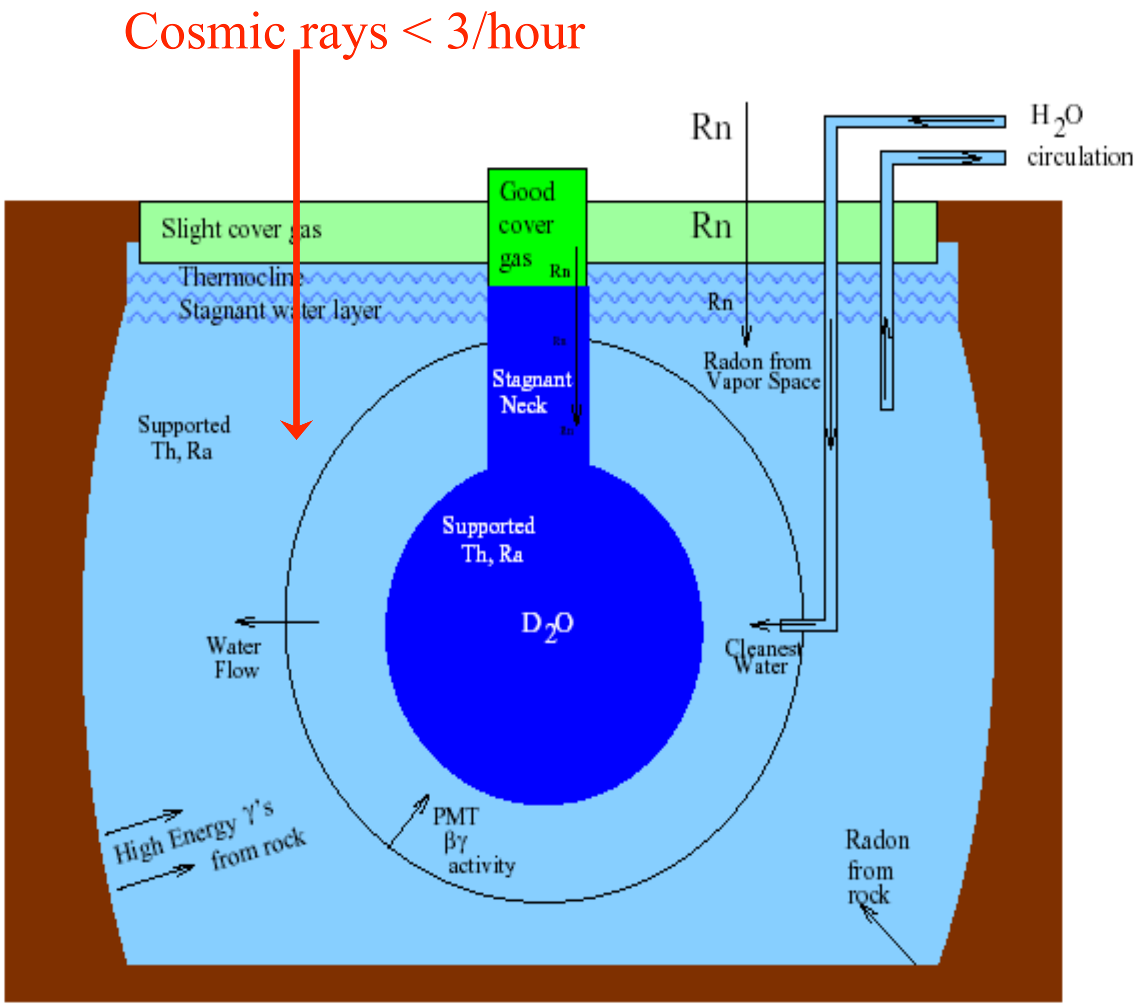
Challenges of a Low Threshold Measurement

- Low Energy Backgrounds

T_{eff}>3.5 MeV

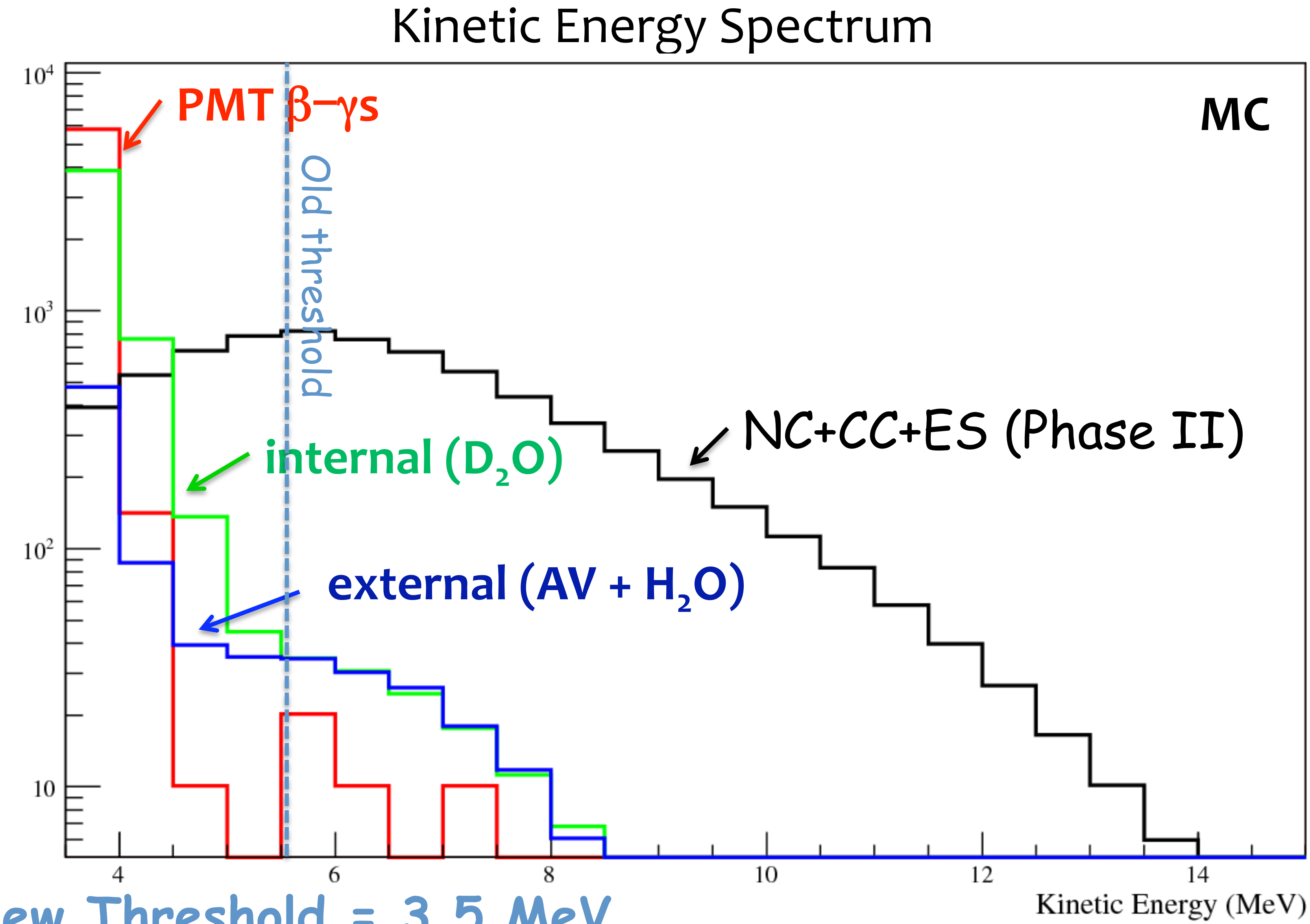


All events
(before background reduction);
~5000 νs



Challenges of a Low Threshold Measurement

- Low Energy Backgrounds



New Threshold = 3.5 MeV

How to Go Lower?

To make a meaningful measurement, we need:

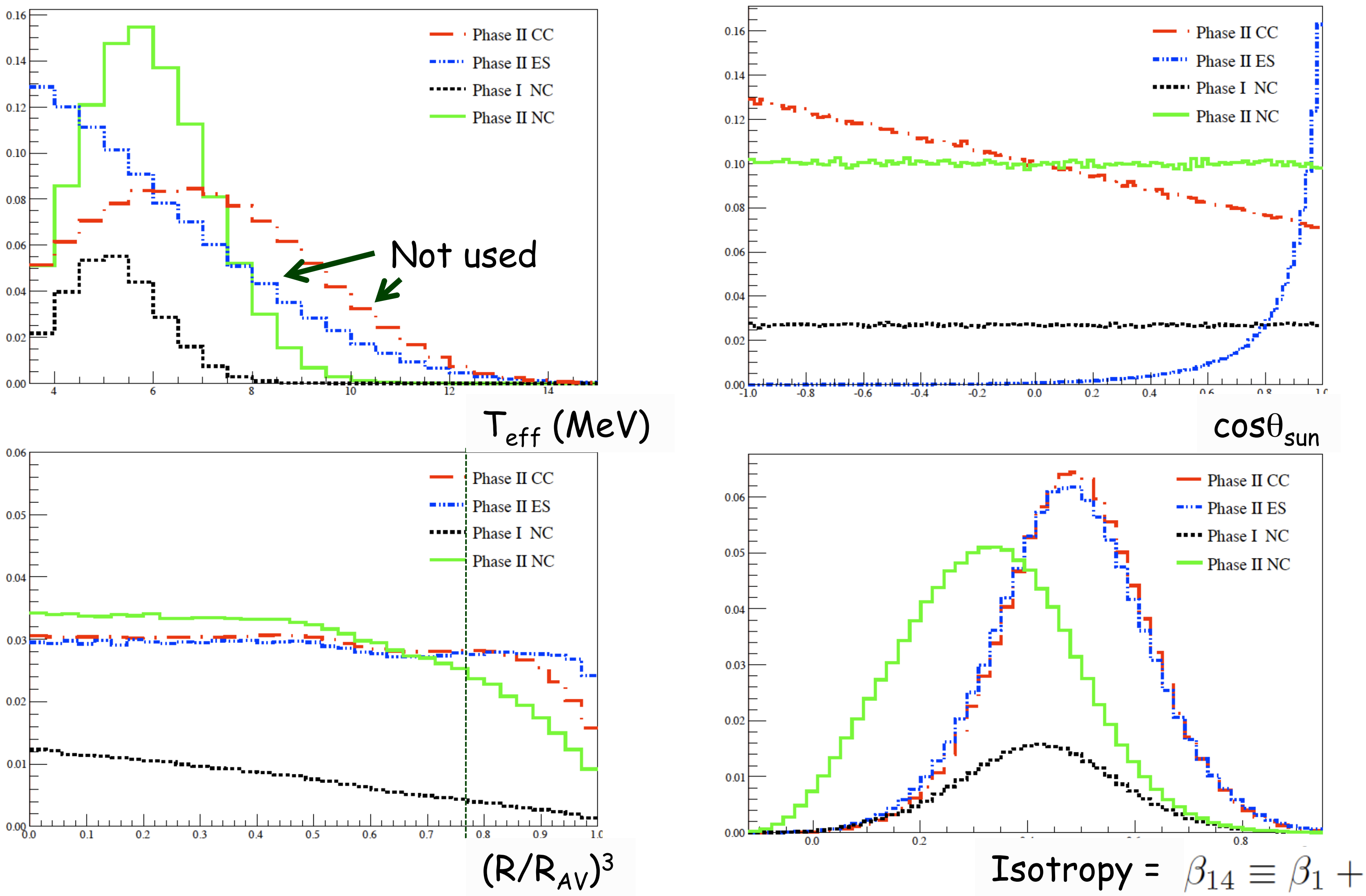
- Lower backgrounds
- More signal statistics (D_2O+Salt~700 days)
- Smaller uncertainties

This is a `war of attrition'.

Our attitude was, `If we can improve it, we should, even if we think it is a small effect.'

Low Energy Threshold Analysis

➢Signal Extraction Fit (Signal PDFs)



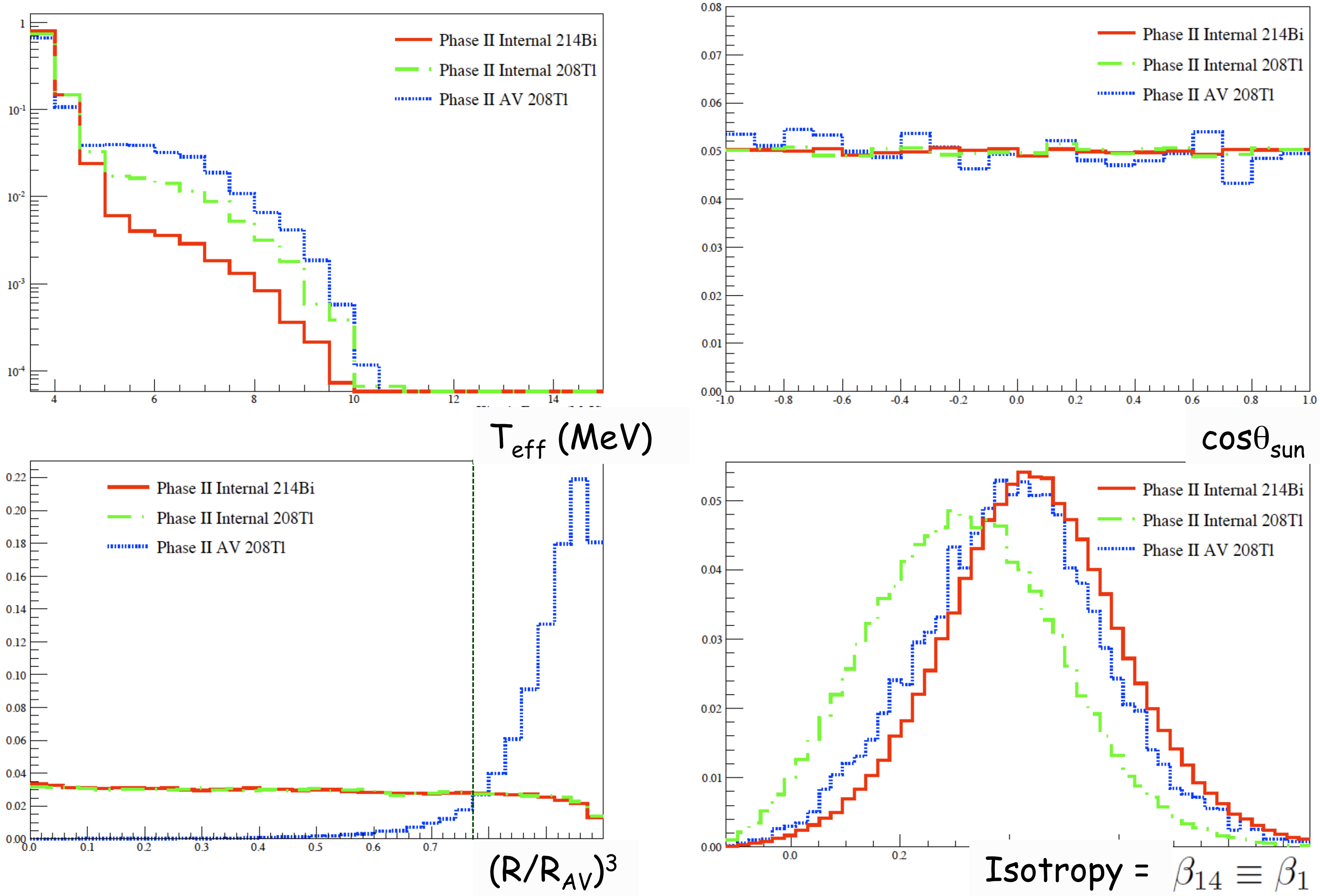
Isotropy = $\beta_{14} \equiv \beta_1 + 4\beta_4$

$$\beta_l = \frac{2}{N(N-1)}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} P_l(\cos\theta_{ij})$$

1 D projections

Low Energy Threshold Analysis

➢Signal Extraction Fit (Some Background PDFs)



$$\beta_{14} \equiv \beta_1 + 4\beta_4$$

$$\beta_l = \frac{2}{N(N-1)} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} P_l(\cos\theta_{ij})$$

1 D projections

Low Energy Threshold Analysis

➢The Basic Approach

Ability to *resolve* signals from each other and from backgrounds depends on:

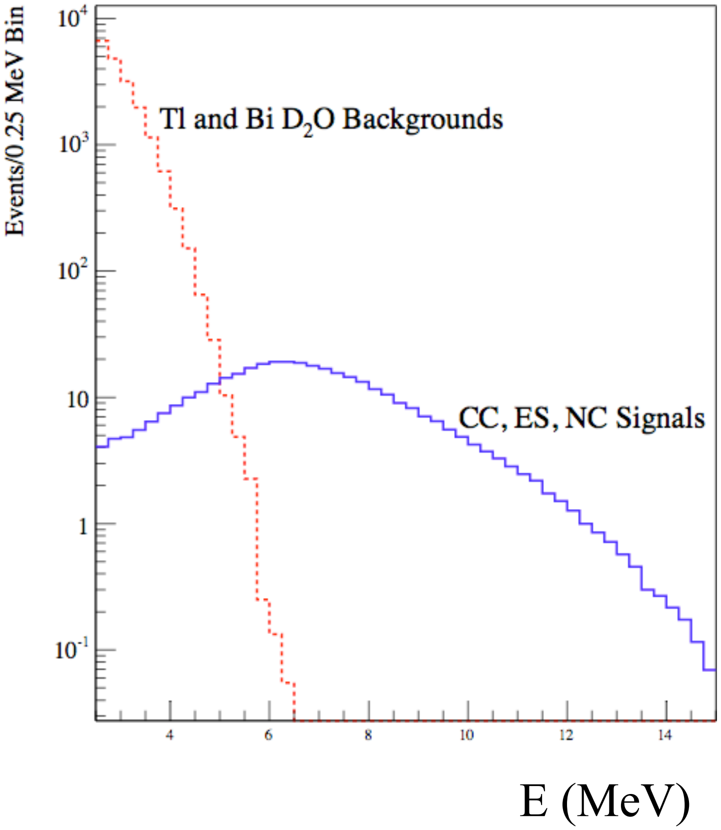
1. Differences in pdfs shapes (in 3D or 4D)
2. Knowledge of the pdf shapes (in 3D or 4D)
3. The level of backgrounds.

Needed to rework SNO's entire analysis chain and simulation, from measurement of charge pedestals to final fit methods.

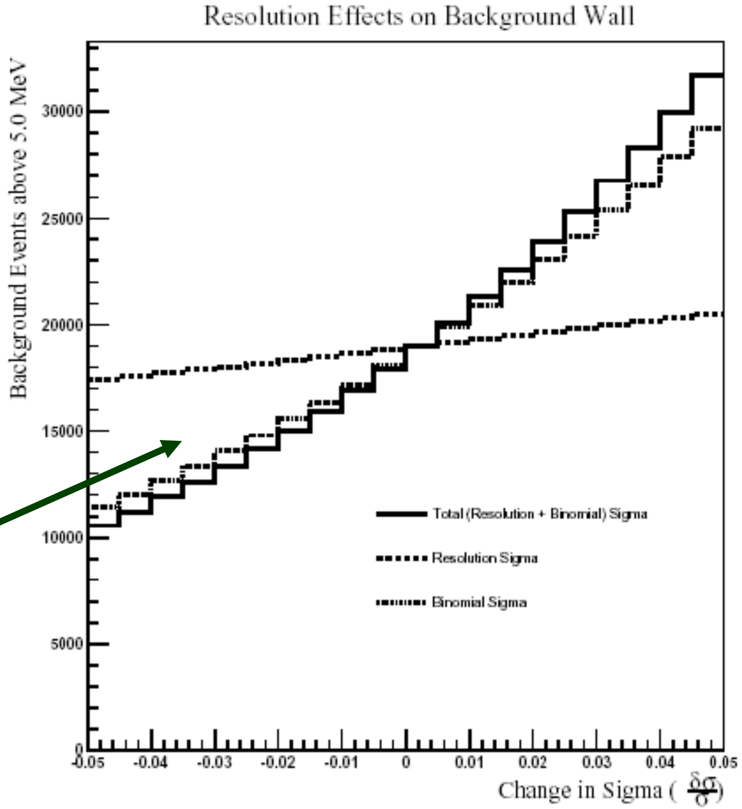
Focus today on just:

- Energy resolution (1 and 3 above)
- Some improvements to Monte Carlo simulation (2 above)
- Uncertainties on energy, position, and `isotropy' (2 above)
- Some new cuts (3 above)
- Special case of PMT β-γ events (1 and 2 above)

Energy Resolution

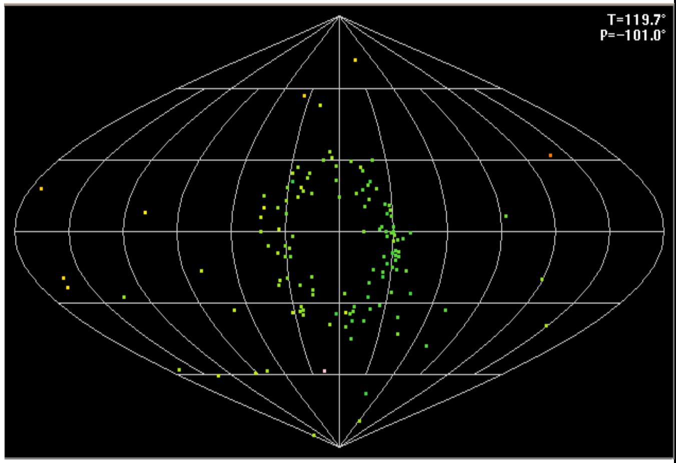


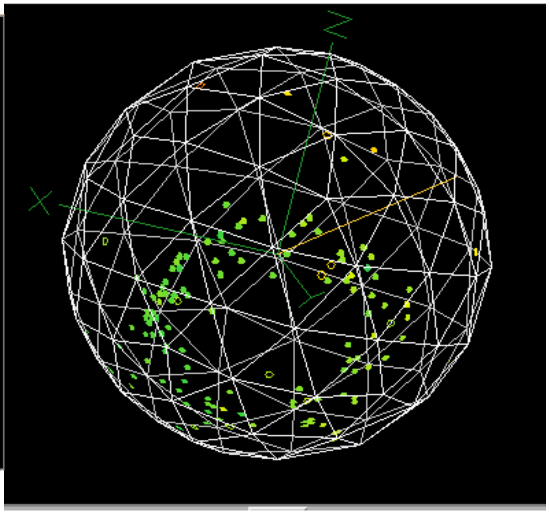
Narrow energy resolution -> smaller leakage and better signal separation



For every 1% improvement in energy resolution, total backgrounds above threshold drop by 10%!

Energy Resolution





In a Cherenkov detector:

Number of hit PMTs ~ num. photons ~ path length ~ energy

Depends on PMT efficiencies, optical attentuation lengths, scattering, reflection coefficients…

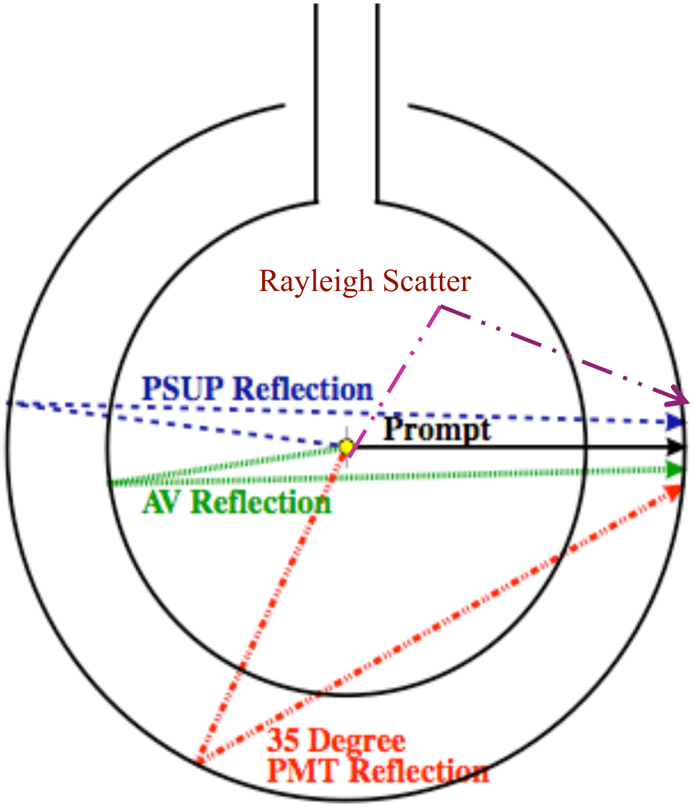
$$\sigma(E) \propto \sigma(N_{Hit}) \propto \sqrt{N_{Hit}}$$

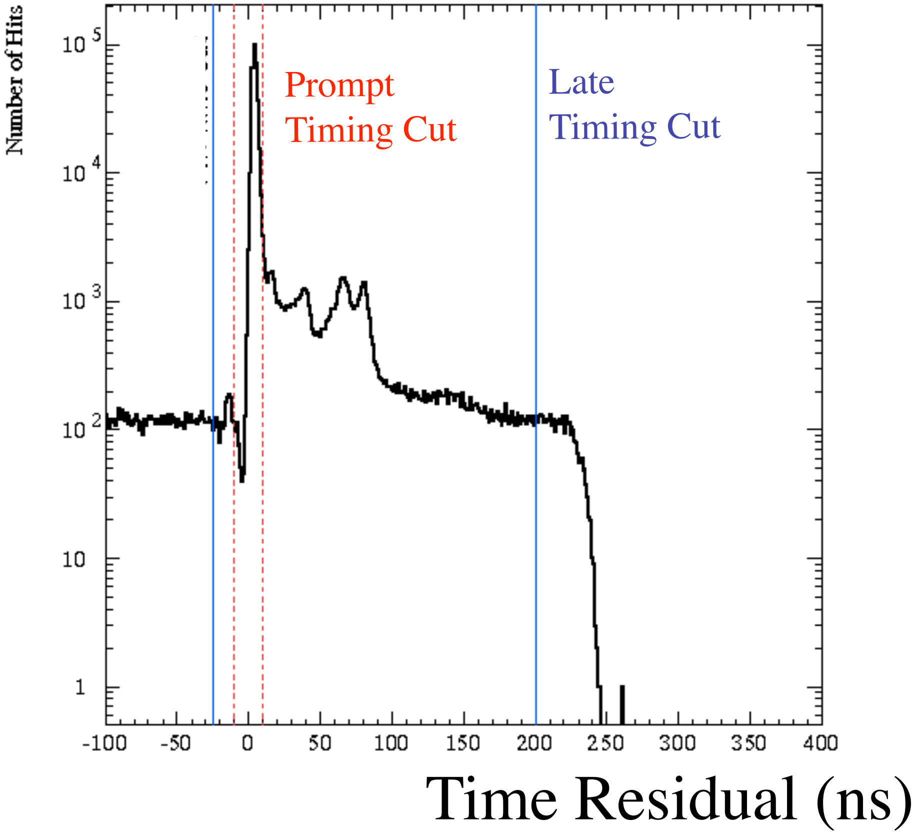
Big win if we can increase hit statistics…
…But data has already been taken.

Energy Resolution

- Increasing the Number of Hit PMTs

$$t = t_0 - t_{pmt} - \frac{d}{c}$$





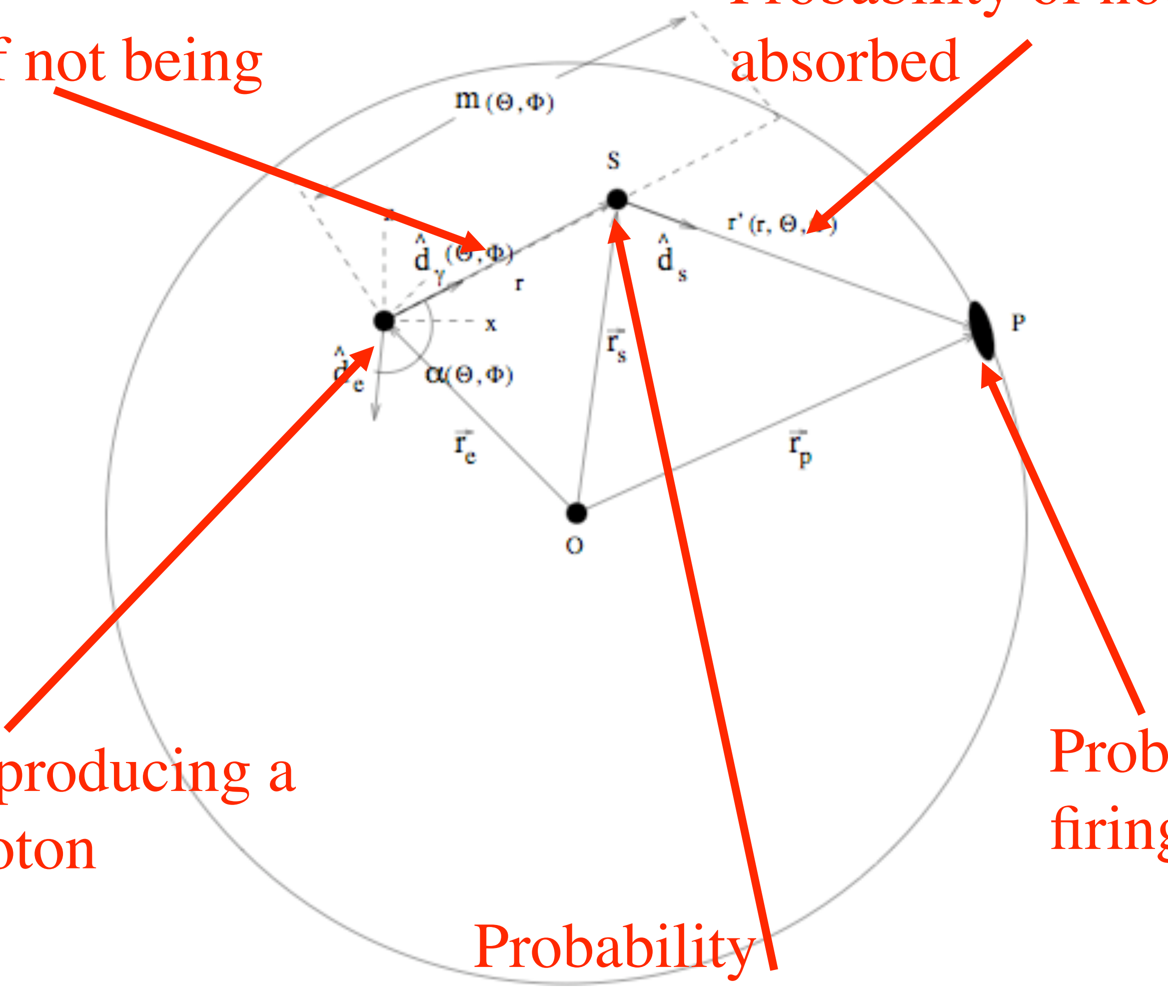
`Prompt' (direct) light easy to model: we know the path traveled

Using all hits increased hit statistics by ~12%
->6% reduction in resolution

Energy Resolution

➢ Increasing the Number of Hit PMTs

Example: Rayleigh scattered photons



Probability of not being absorbed

Probability of not being absorbed

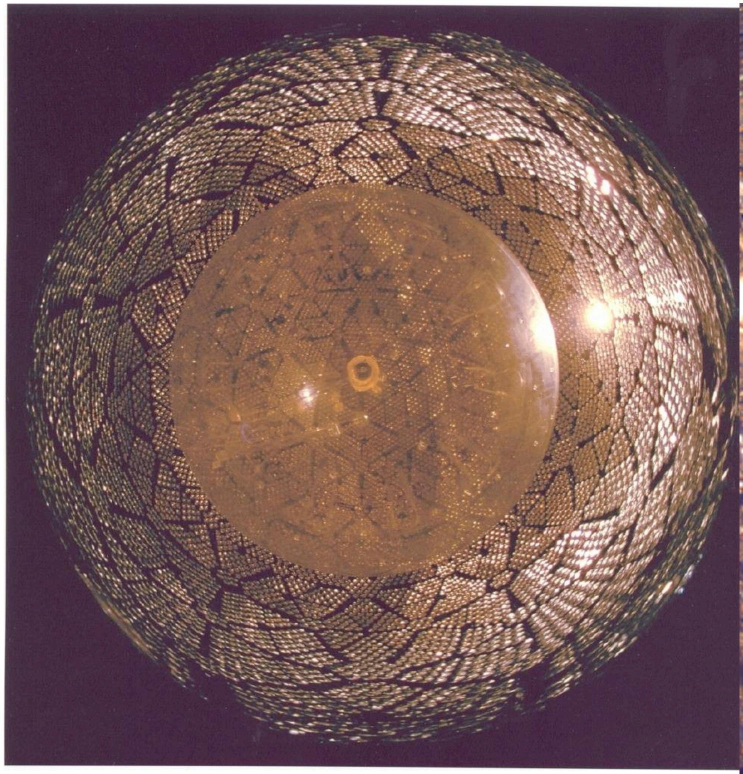
Probability of producing a Cherenkov photon

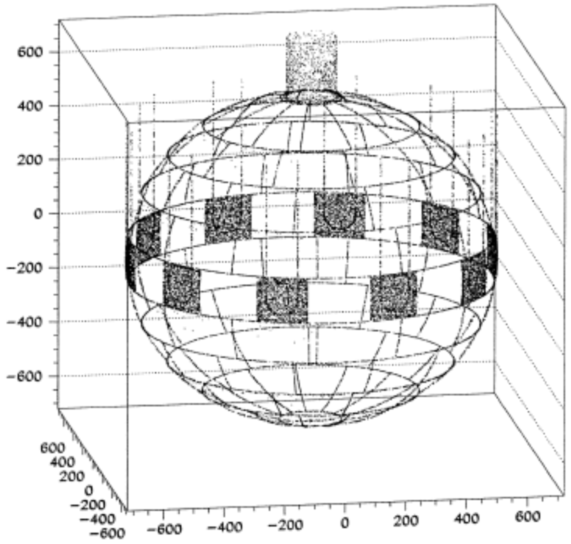
Probability of scattering

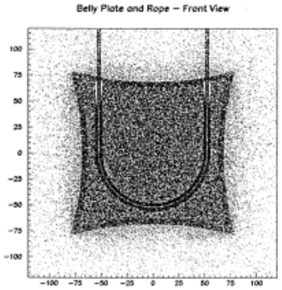
Probability of firing PMT

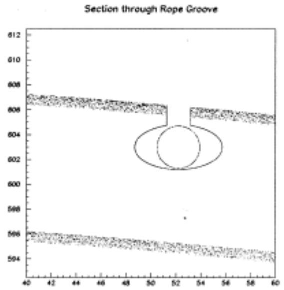
Monte Carlo Upgrades

Detector is *intentionally* simple to model:









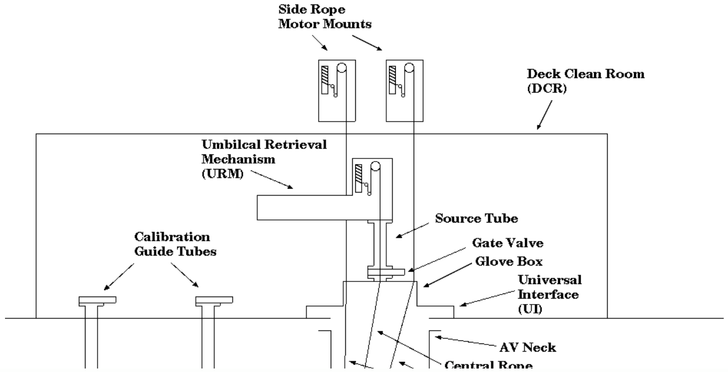
Response depends only on:

- Particle propagation and Cherenkov light (EGS)
- Optics (Jackson, etc.)
- Photomultiplier response: charge, time, and efficiency

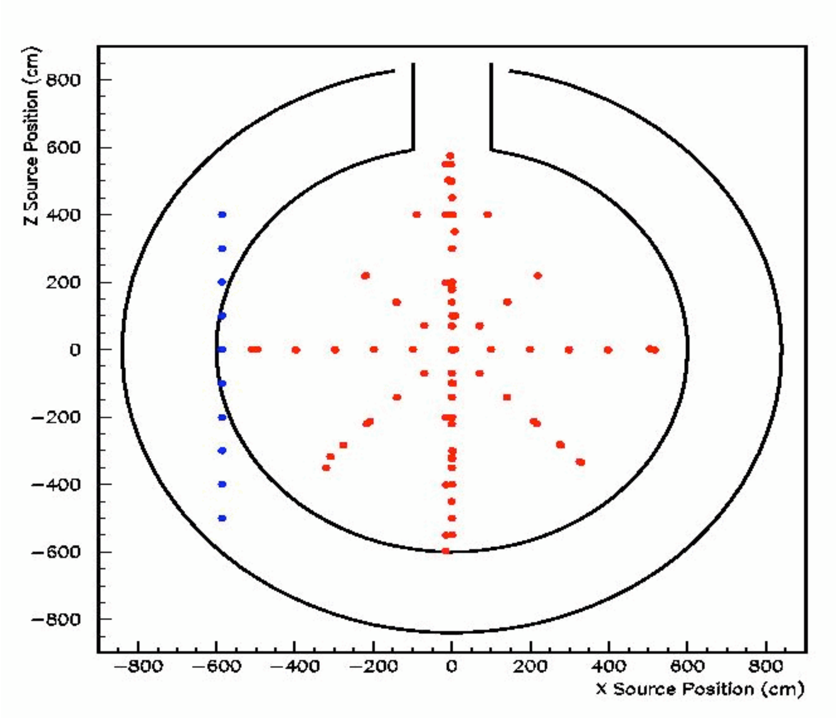
Monte Carlo Upgrades

➢Calibrations

Parameters for simulation measured and tested with sources

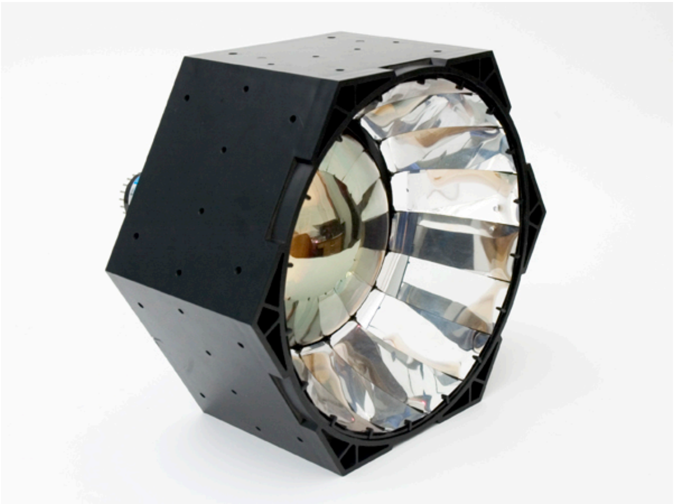


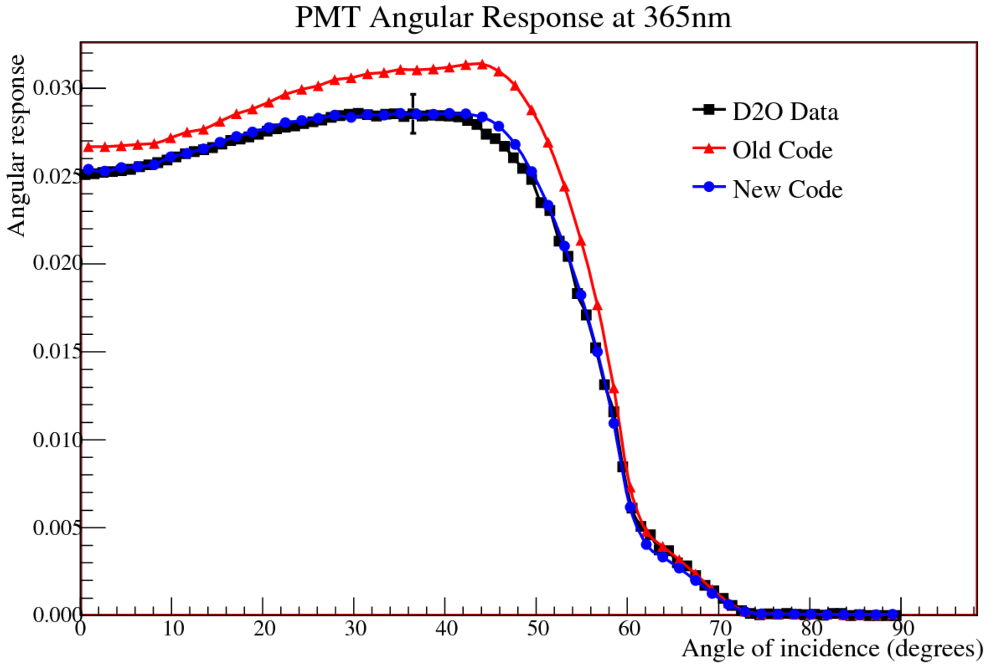
- Laser source (optics/timing)
- ^{16}N → 6.13 MeV γ's
- Radon `spikes'
- Neutrons→ 6.25 MeV γ's
- pT → 19.8 MeV γ's
- ^{8}Li → β's, E<14 MeV
- Encapsulated U and Th sources

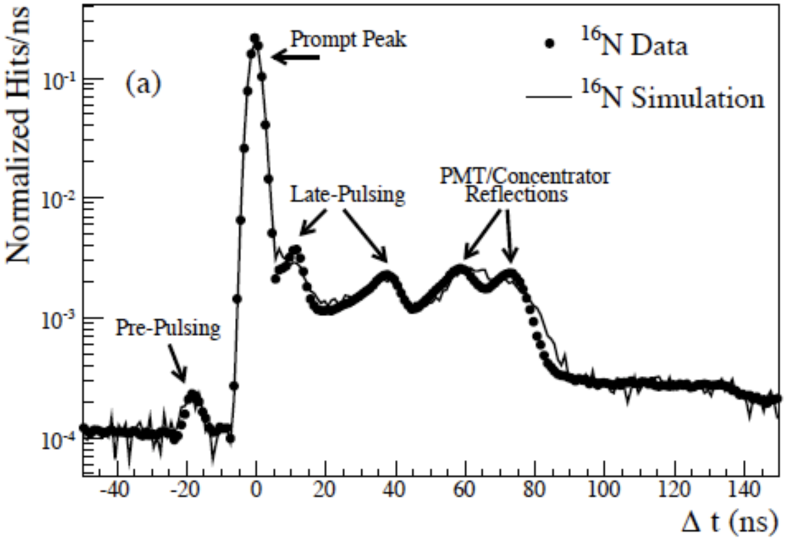


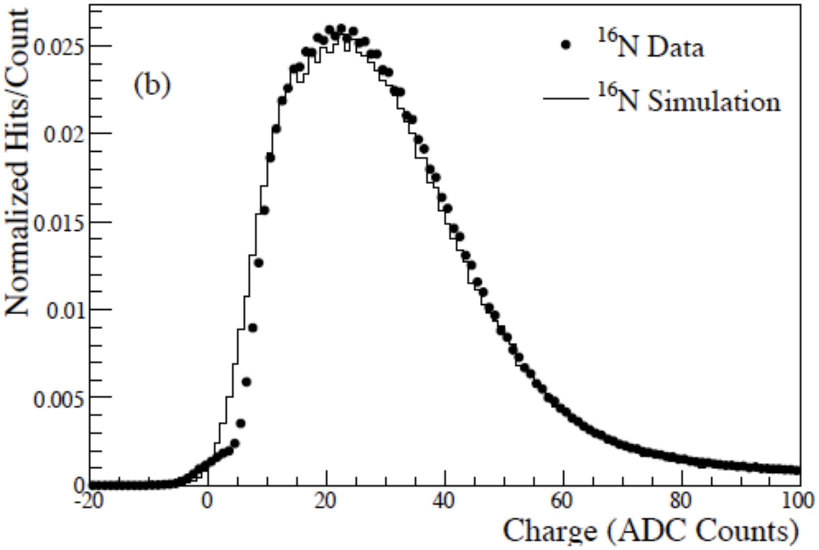
Monte Carlo Upgrades

➢ PMT Response



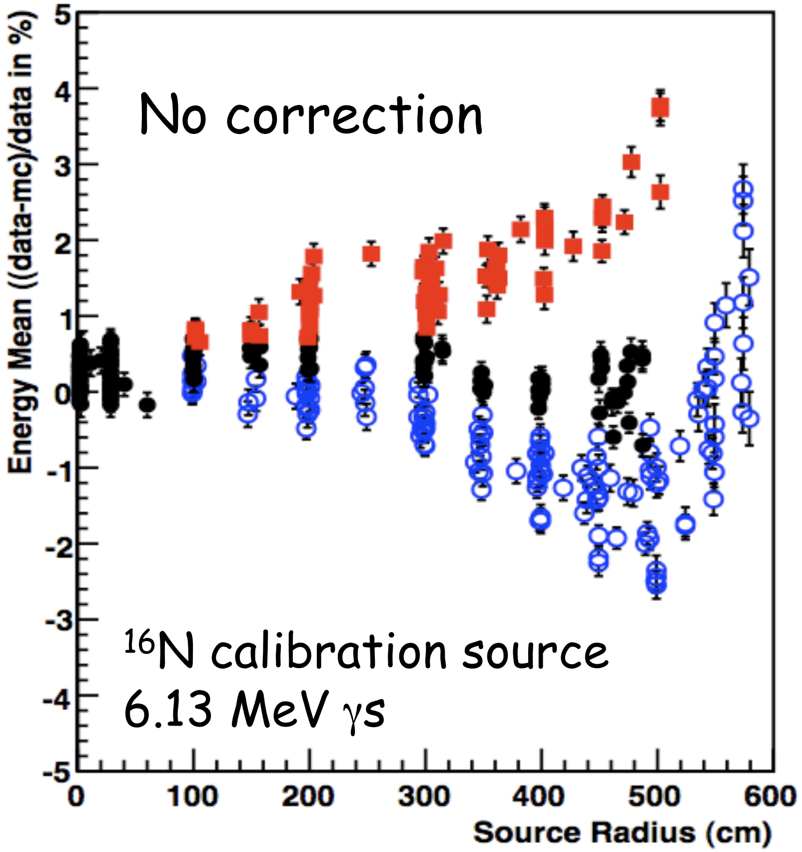


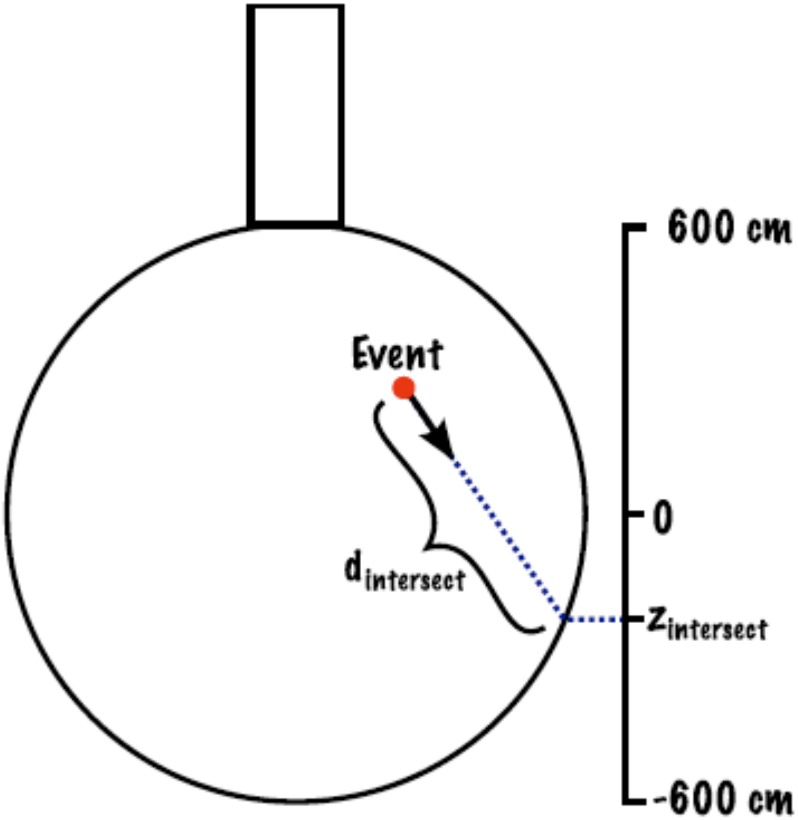




Systematic Uncertainties

➢Energy Scale





Volume-weighted uncertainties:

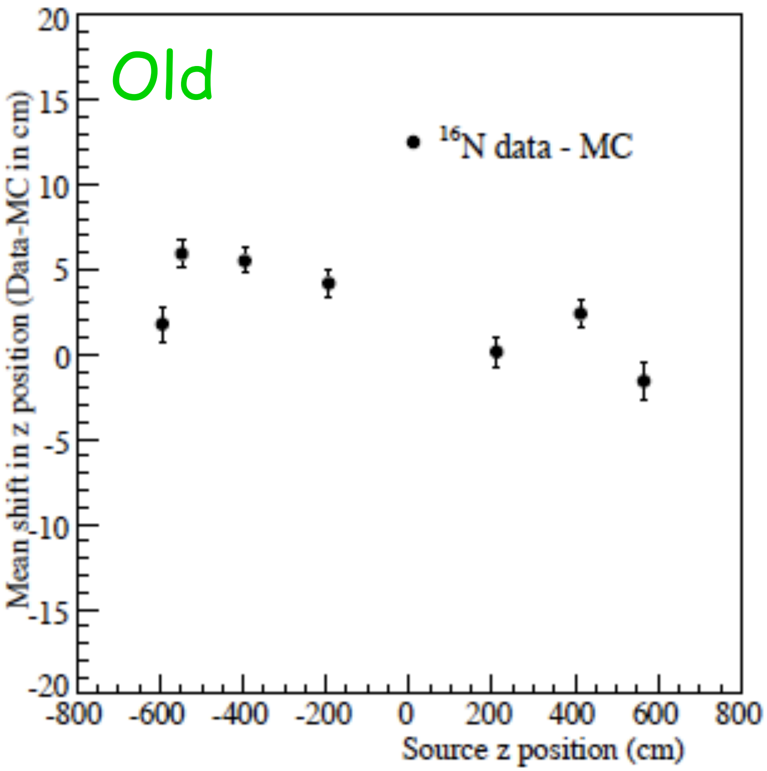
Old: Phase I = ±1.2% Phase II = ±1.1%

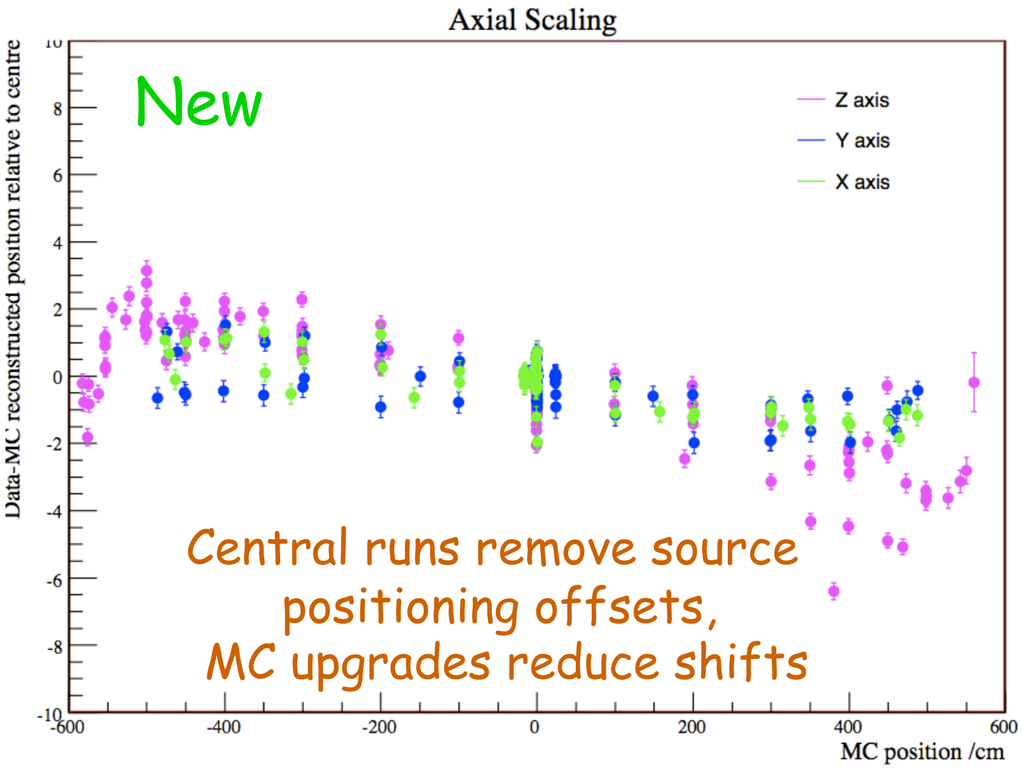
New: Phase I = ±0.6% Phase II = ±0.5% (about half Phase-correlated)

⟶Tested with: Independent ^{16}N data, n capture events, Rn `spike' events...

Systematic Uncertainties

➢Position





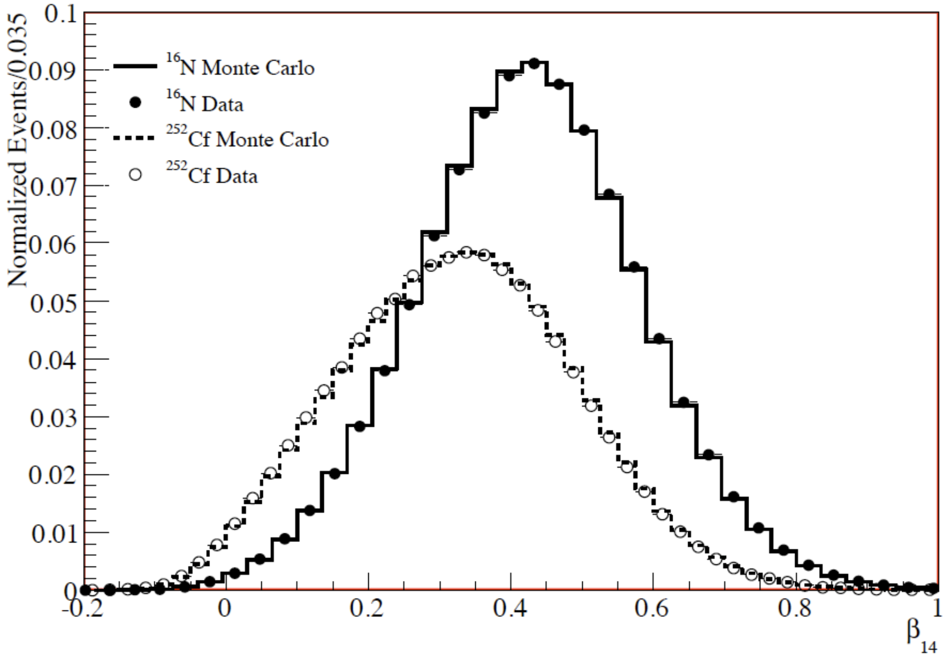
Central runs remove source
positioning offsets,
MC upgrades reduce shifts

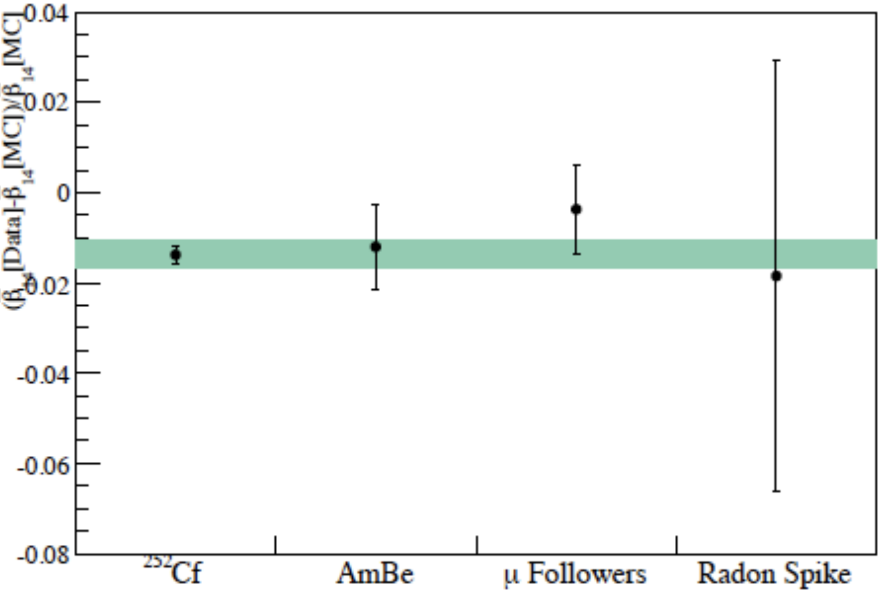
Fiducial volume uncertainties:
Old: Phase I ~ ±3% Phase II ~ ±3%
New: Phase I ~ ±1% Phase II ~ ±0.6%

⟶Tested with: neutron captures, ^{8}Li, outside-signal-box vs

Systematic Uncertainties

➢Isotropy (β_{14})





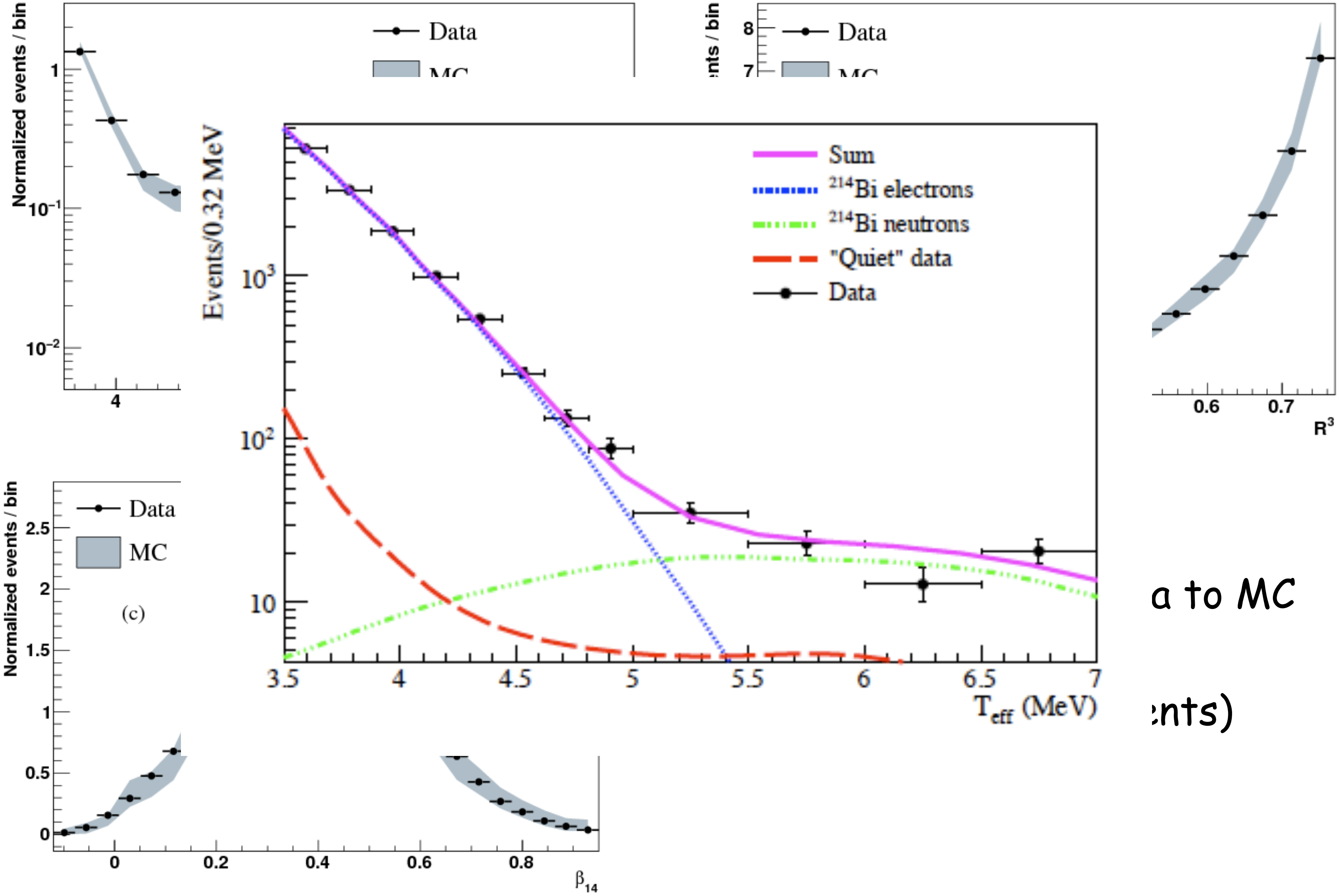
MC simulation upgrades provide biggest source of improvement
Tests with muon `followers', Am-Be source, Rn spike

β_{14} Scale uncertainties:

Old: Phase I --- , Phase II = ±0.85% electrons, ±0.48% neutrons
New: Phase I ±0.42%, Phase II =±0.24% electrons, $^{+0.38\%}_{-0.22\%}$ neutrons

Systematic Uncertainties

➢Tests of PDF shapes



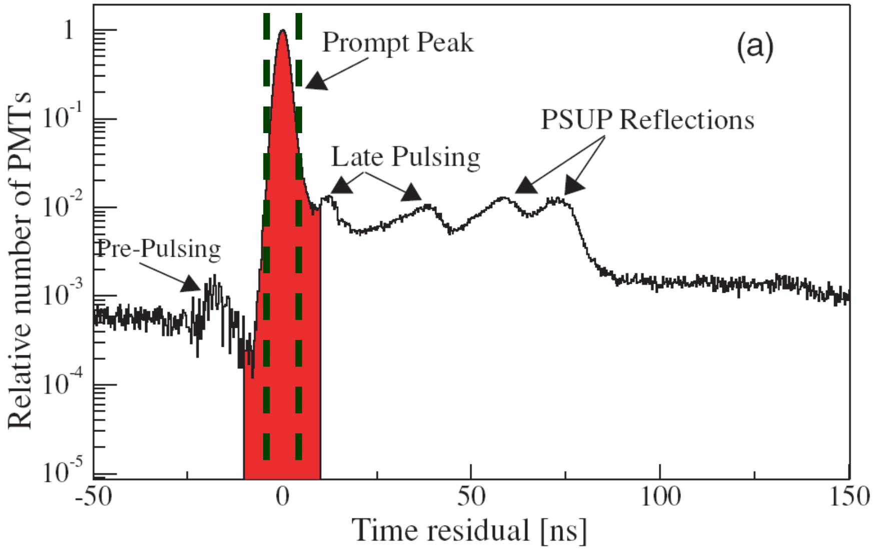
a to MC

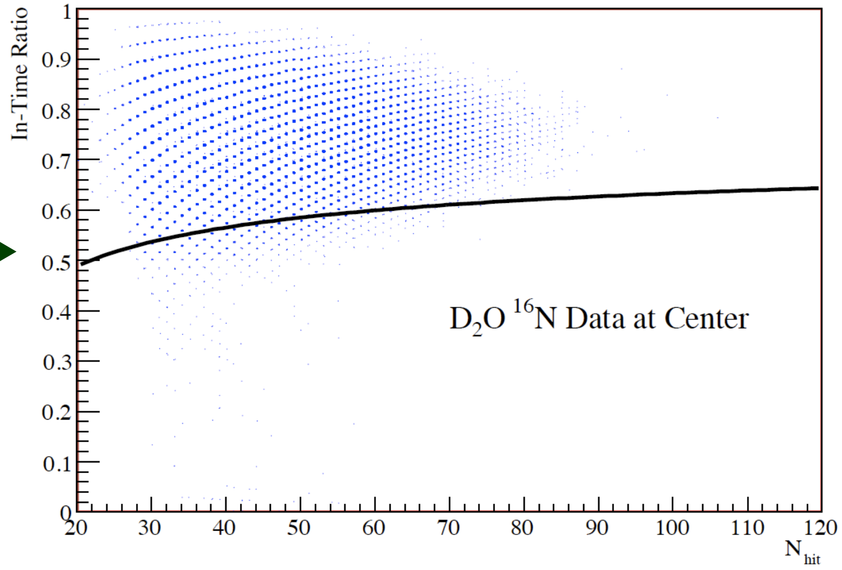
nts)

New Cuts

Only information is PMT charges, times, and hit patterns

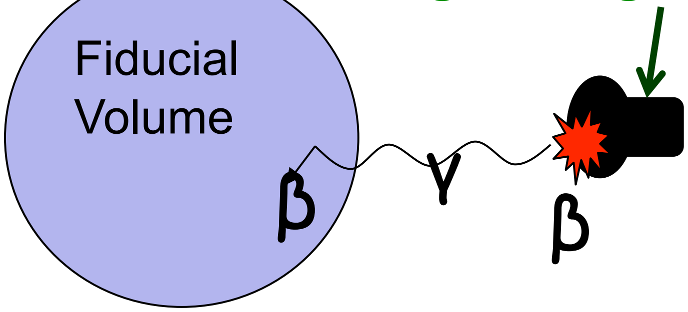
- 4 KS tests of PMT pattern against single Cherenkov e^-
- 1 KS test of PMT times against Cherenkov e^-
- 3 cuts on various isotropy parameters
- 2 cuts on energy reconstruction uncertainty
- In-time ratio vs. N_{hit}



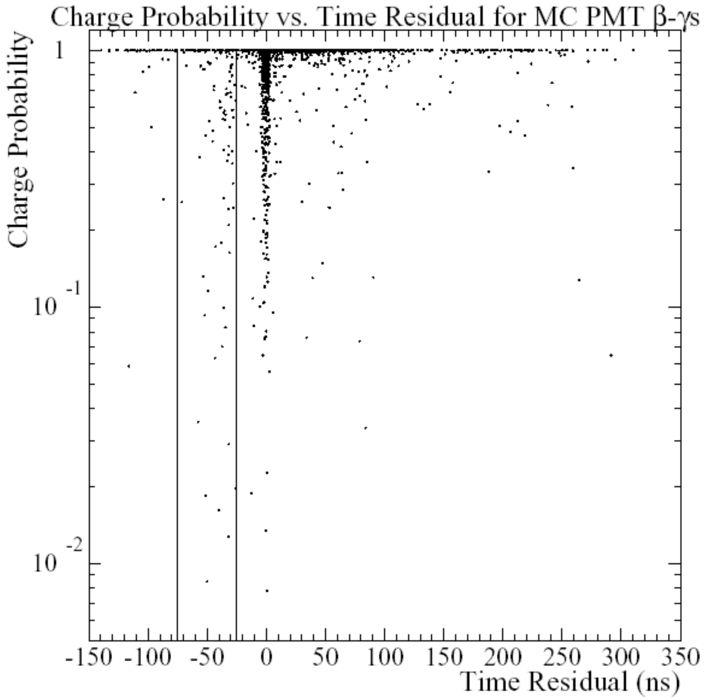


New Cuts

- Charge vs. Δt



High charge early in time

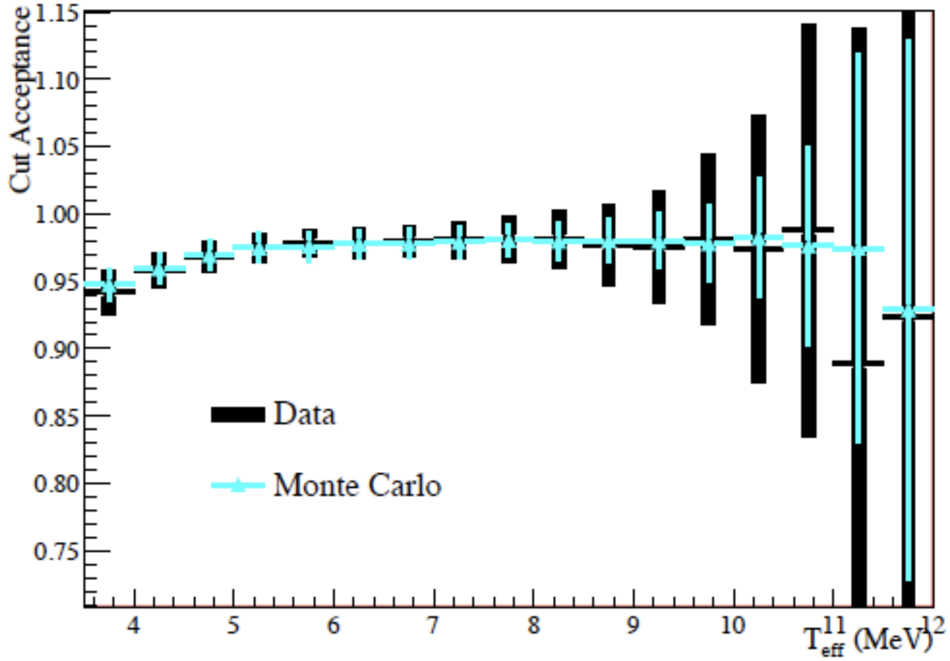


Note: This would have been impossible if we hadn't fixed `little' things like charge pedestals

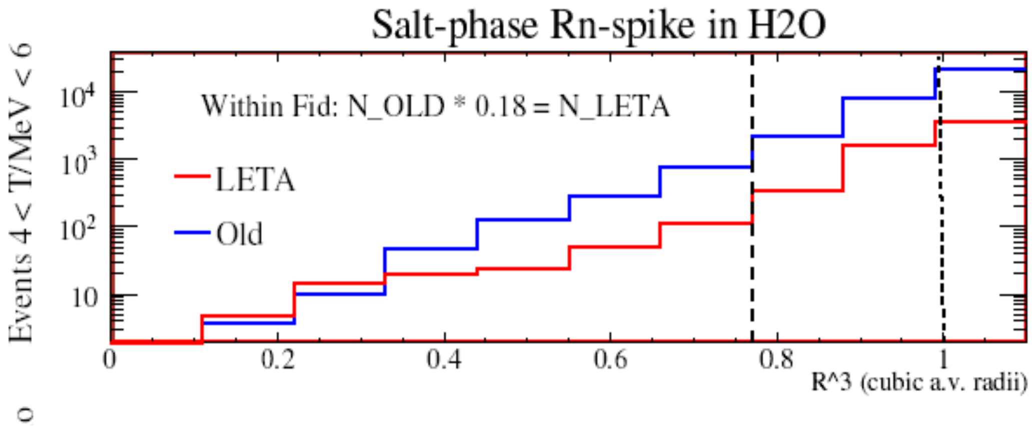
New Cuts

➢ Summary

Events	Phase I	Phase II
Full data set	128421119	115068751
Instrumental	115328384	102079435
Reconstruction	92159034	77661692
Fiducial volume (<550 cm)	11491488	8897178
Energy range (3.5–20 MeV)	25570	40070
High-level cuts	9346	18285
Coincidence cut	9337	18228



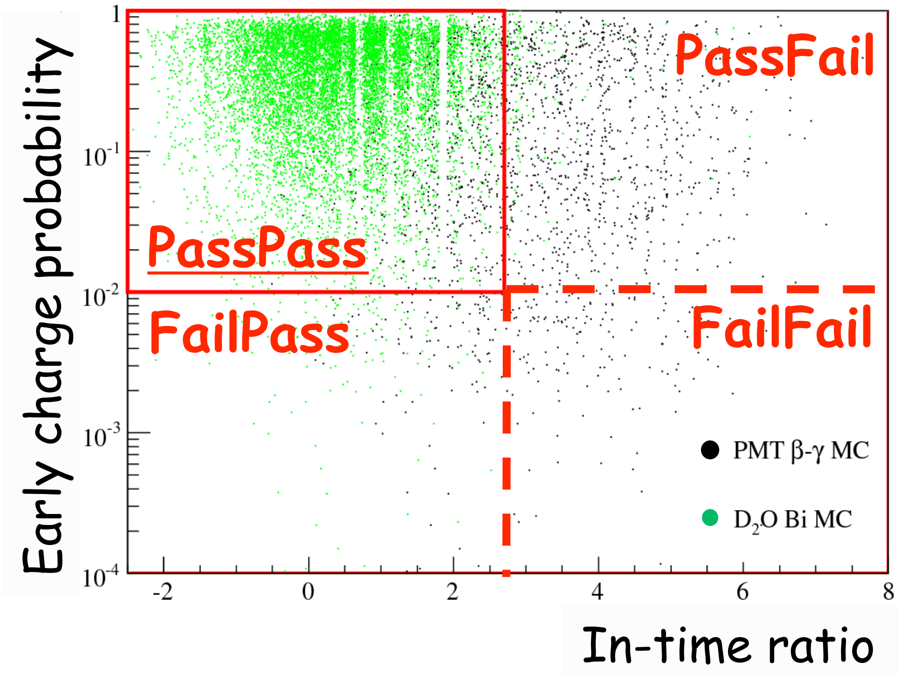
~80% reduction in external bkds

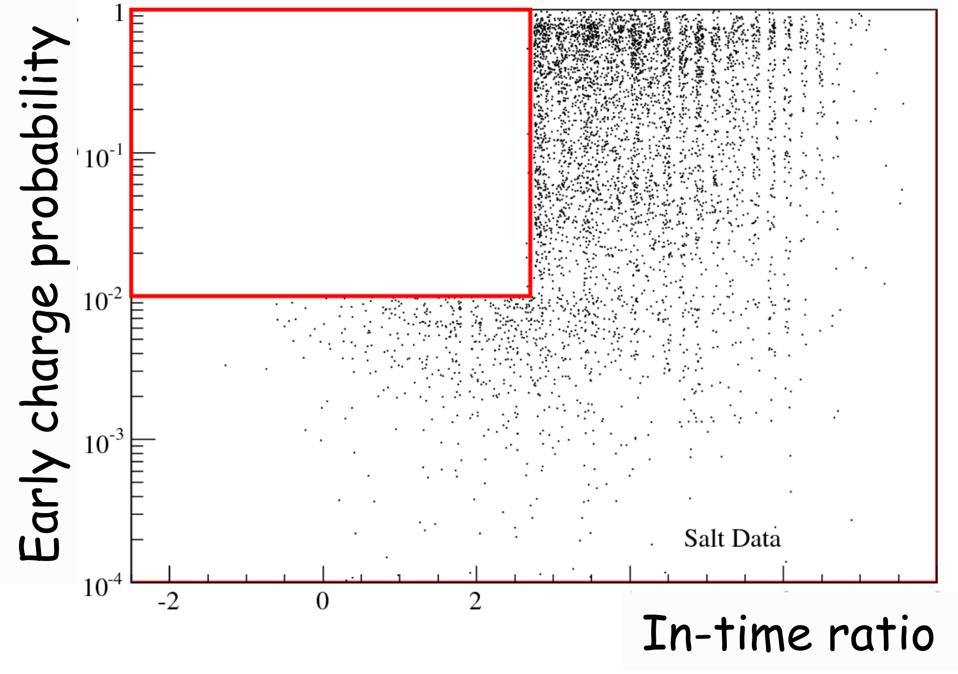

Salt-phase Rn-spike in H2O

PMT β-γ PDFs

➢Special Case

Not enough CPUs to simulate sample of events→ Use data instead





‘Bifurcated’ analysis

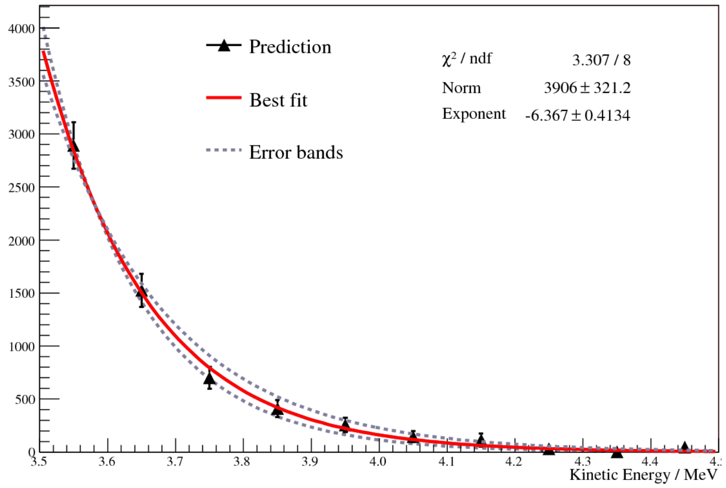
$$N_{PF} = \varepsilon_1(1-\varepsilon_2)N_b$$

$$N_{FP} = (1-\varepsilon_1)\ \varepsilon_2 N_b$$

$$N_{FF} = (1-\varepsilon_1)(1-\varepsilon_2)N_b$$

$$N_{PP} = \varepsilon_1\varepsilon_2 N_b + N_s$$

$$\begin{aligned} N_{PMT} &= N_{PP} - N_s \\ &= N_{FP} * N_{PF} / N_{FF} \end{aligned}$$



Signal Extraction Fit Techniques

- Two Methods

1. Maximum likelihood with binned histogram PDFs
2. Maximum likelihood using `kernel estimated' PDFs

PDF dimensions for both techniques:

$P(\beta_{14}, R^3, \cos\theta_{\odot})$ ES, CC (bin-by-bin in energy)

$P(T_{\mathrm{eff}}, \beta_{14}, R^3) \times P(\cos\theta_{\odot})$ NC, backgrounds

---

Background included in fit:

$$\left.\begin{array}{l} D_2O \\ \text{Acrylic Vessel} \\ H_2O \end{array}\right\} \times \left\{\begin{array}{ll} {}^{214}\mathrm{Bi} & (\mathrm{U, Rn}) \\ {}^{208}\mathrm{Tl} & (\mathrm{Th}) \end{array}\right.$$

+

PMT ^{208}Tl

+

Acrylic Vessel Surface Neutrons [(α,n) reactions]

+

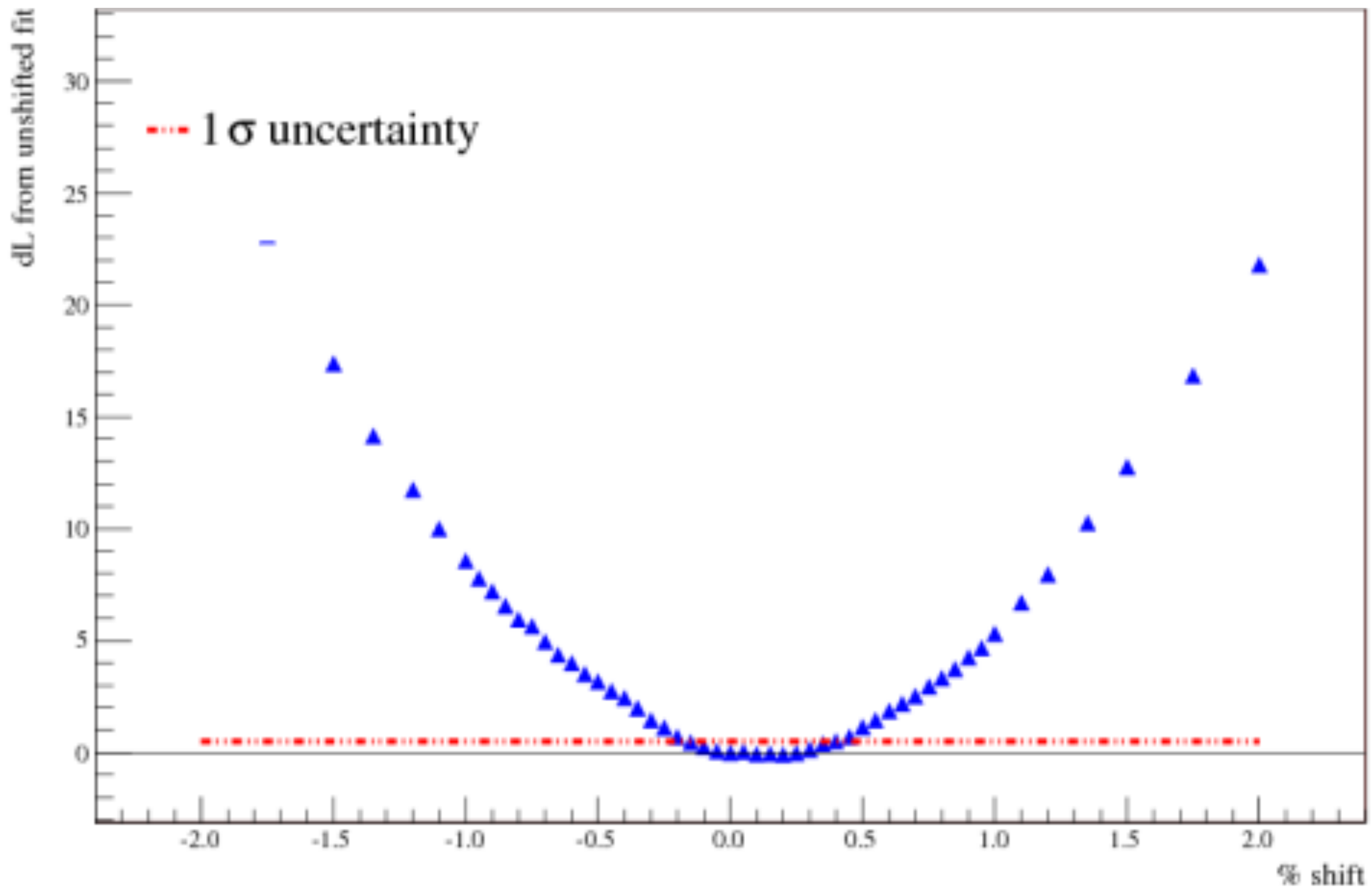
^{24}Na (neutron activation of salt)

= 12 external bkds + 5 internal bkds

Signal Extraction Fit Techniques

➢ `Floating' Systematics

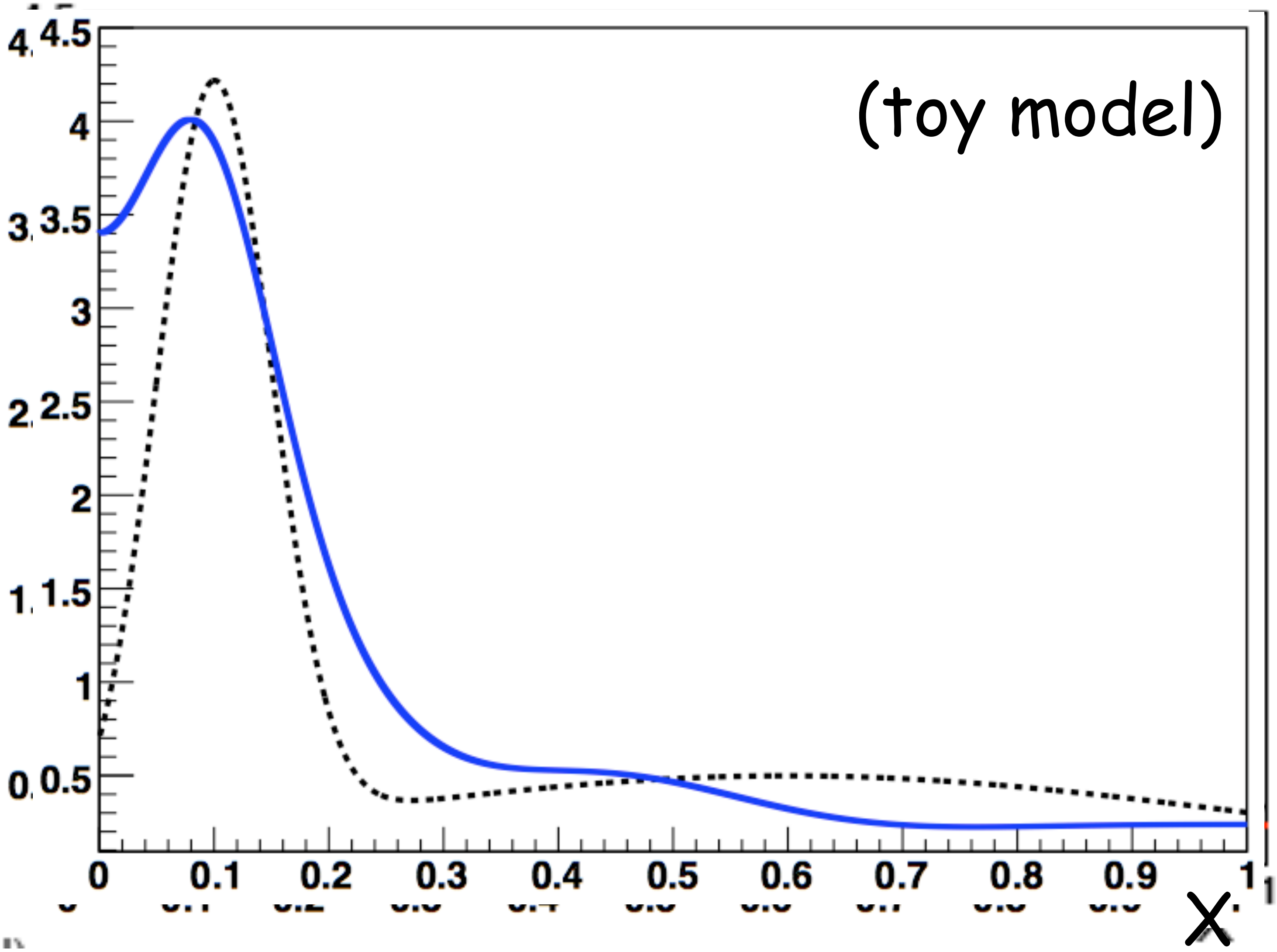
Binned histogram method: Manually scan likelihood space



Signal Extraction Fit Techniques

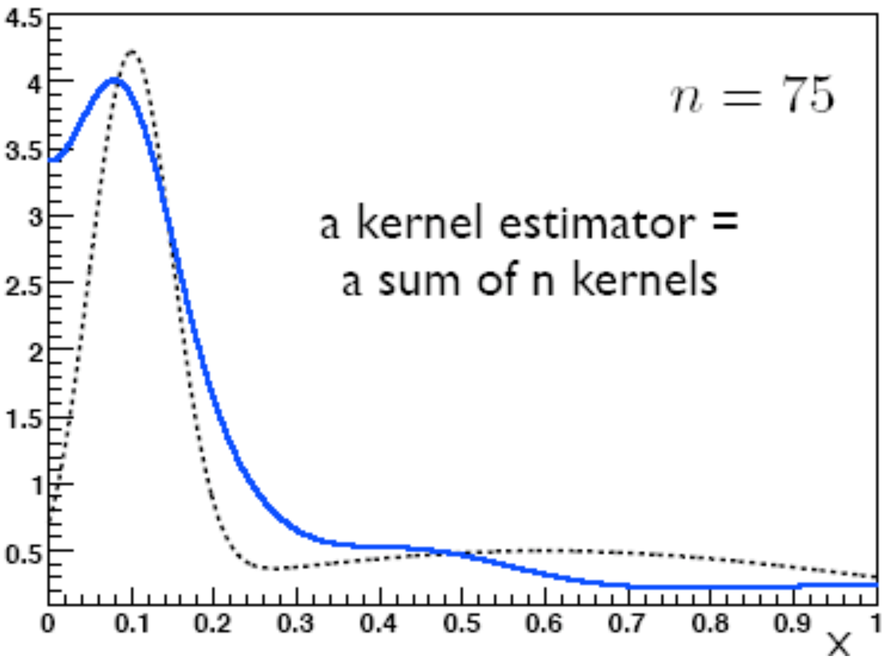
➢ `Floating' Systematics

Kernel Estimation: Allows direct parametric variation in pdfs



Signal Extraction Fit Techniques

- \`Floating' Systematics



To make it fast enough:

Lots of clever ideas+

3D Graphics Card

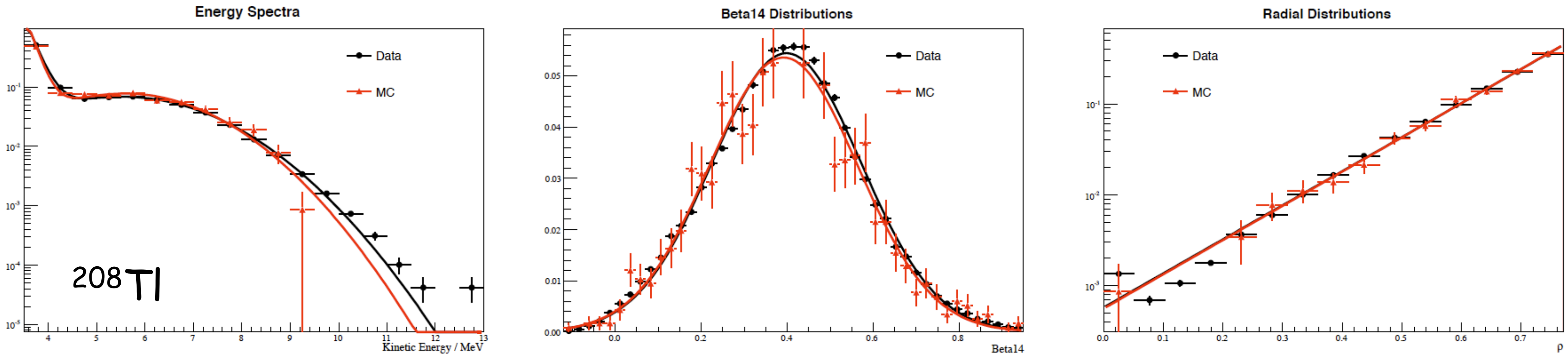
- 128 floating point units
- FPU clock: 1.2 GHz
- 384 bit memory bus
- 768 MB on board memory
- $550

1 year → 8 hours

Low Energy Threshold Analysis

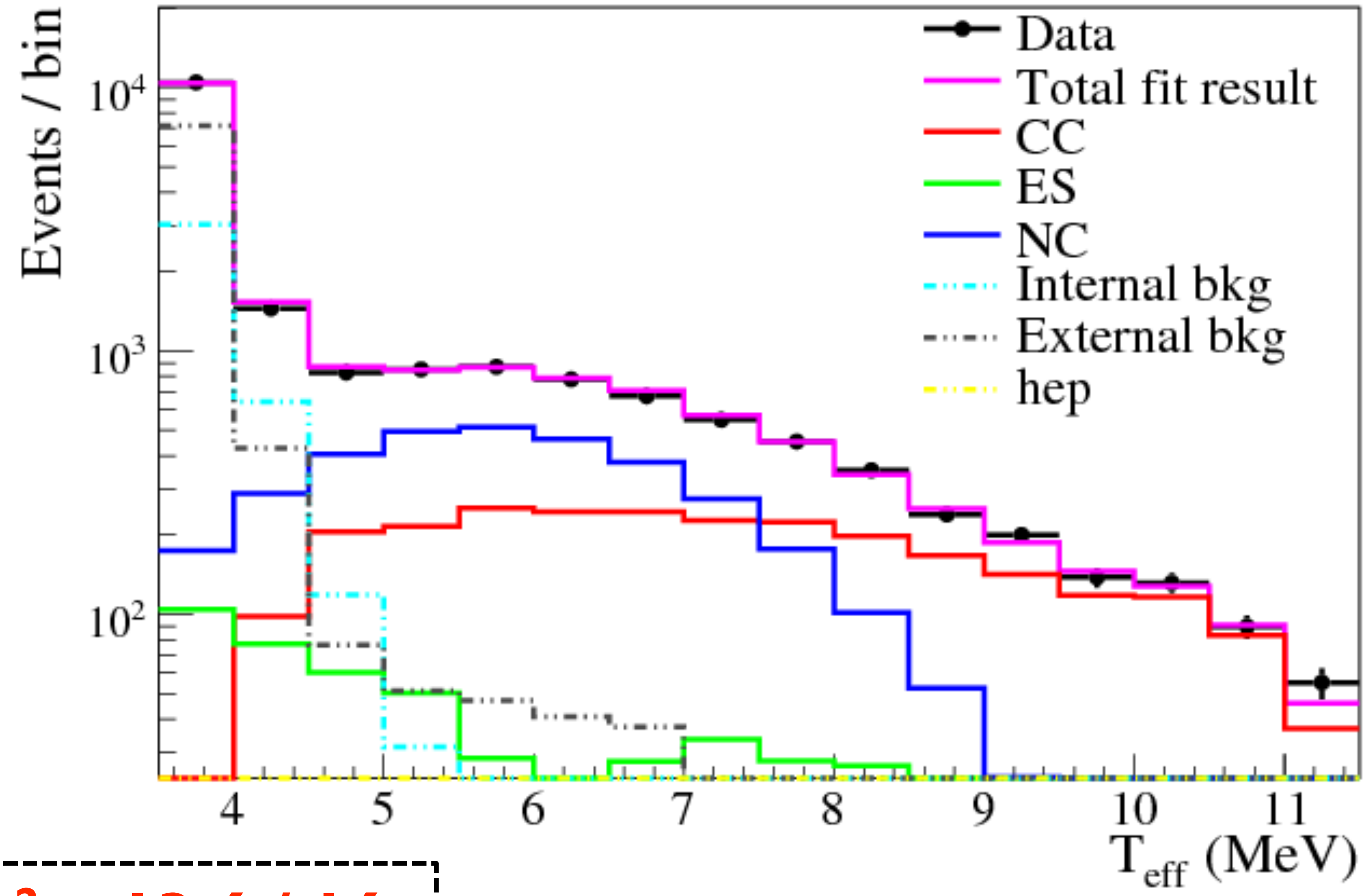
➢ Analysis Summary

- Fits are maximum likelihood in multiple dimensions (two methods)
- Most PDFs generated with simulation
- Systematics from data-MC comparisons
- In some cases, corrections applied to MC PDFS based on comps.
- Tested on multiple independent data sets



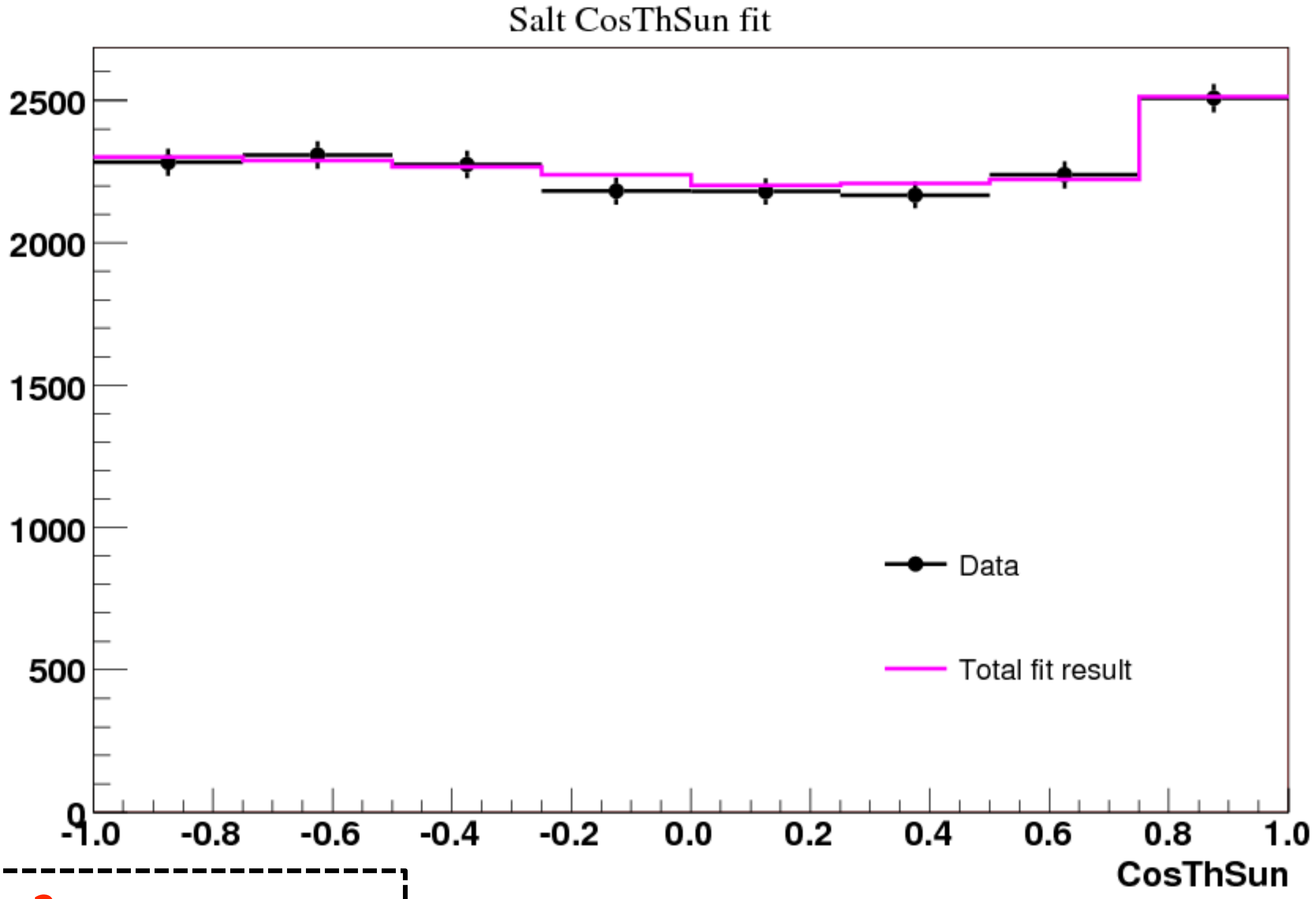
- PMT pdf generated from bifurcated analysis of data
- Tested on MC and with independent analysis using direction vs. R^3
- Dominant systematics (6/20) allowed to vary in fit
- Constrained by calibrations
- Note: many backgrounds look alike! But very few look like signal
- Some backgrounds have ex-situ constraints from radiochm. assays

Fit Result



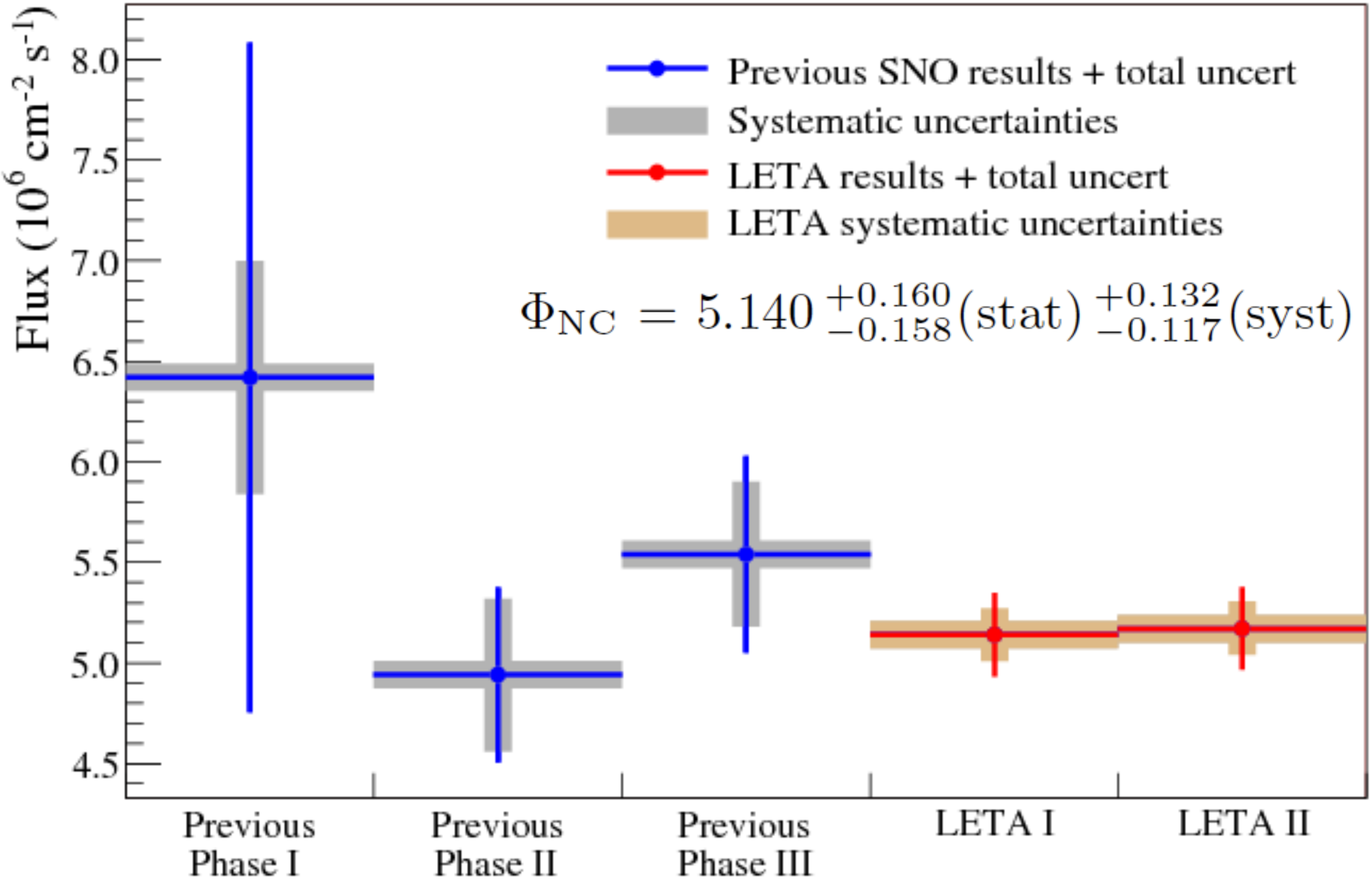
χ^2 = 13.6 / 16

Fit Result

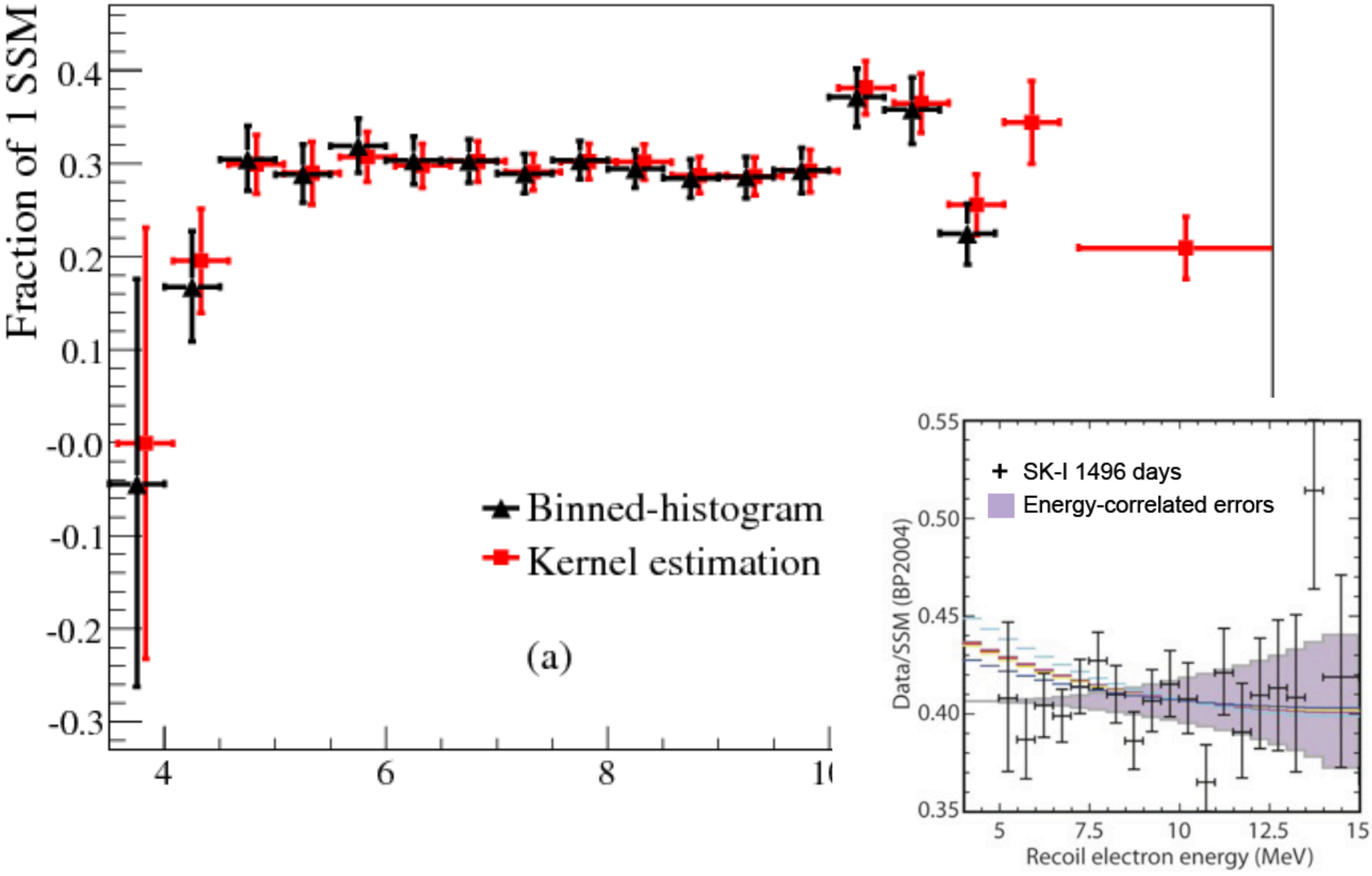


$\chi^2 = 3.1 / 8$

^{8}B Flux Result

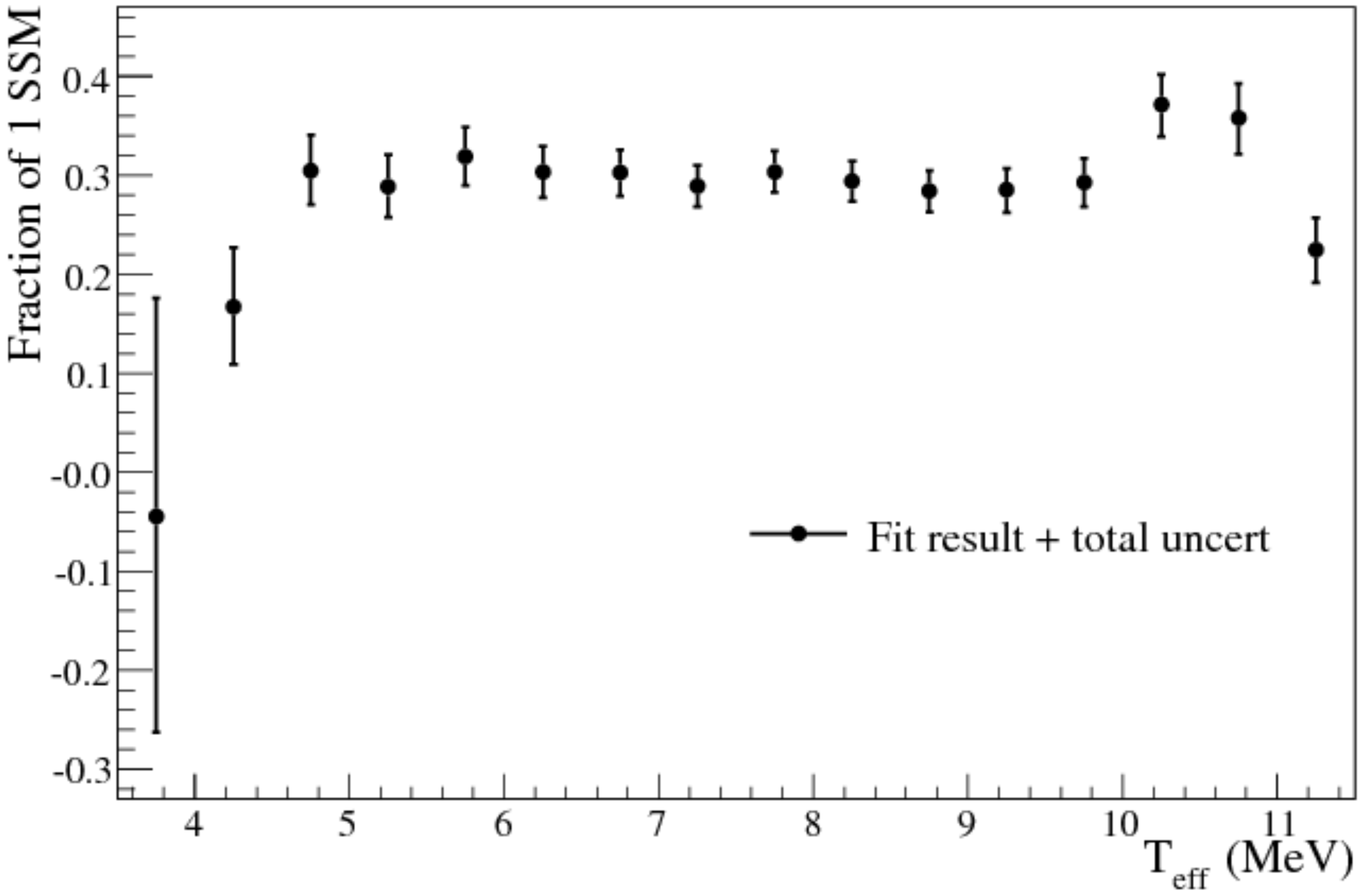


CC Recoil-Electron Spectrum

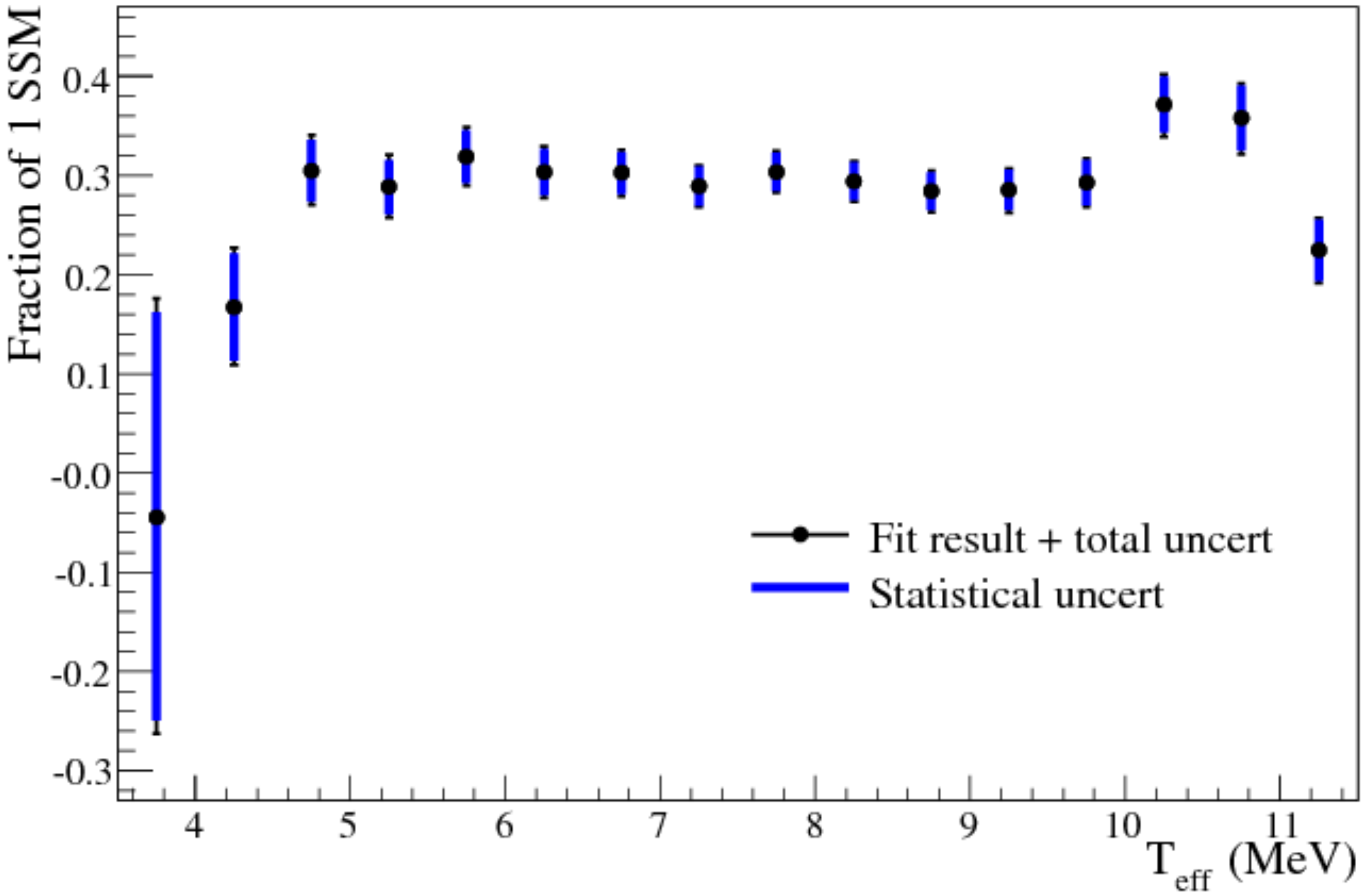


J.L. Raaf, Boston University

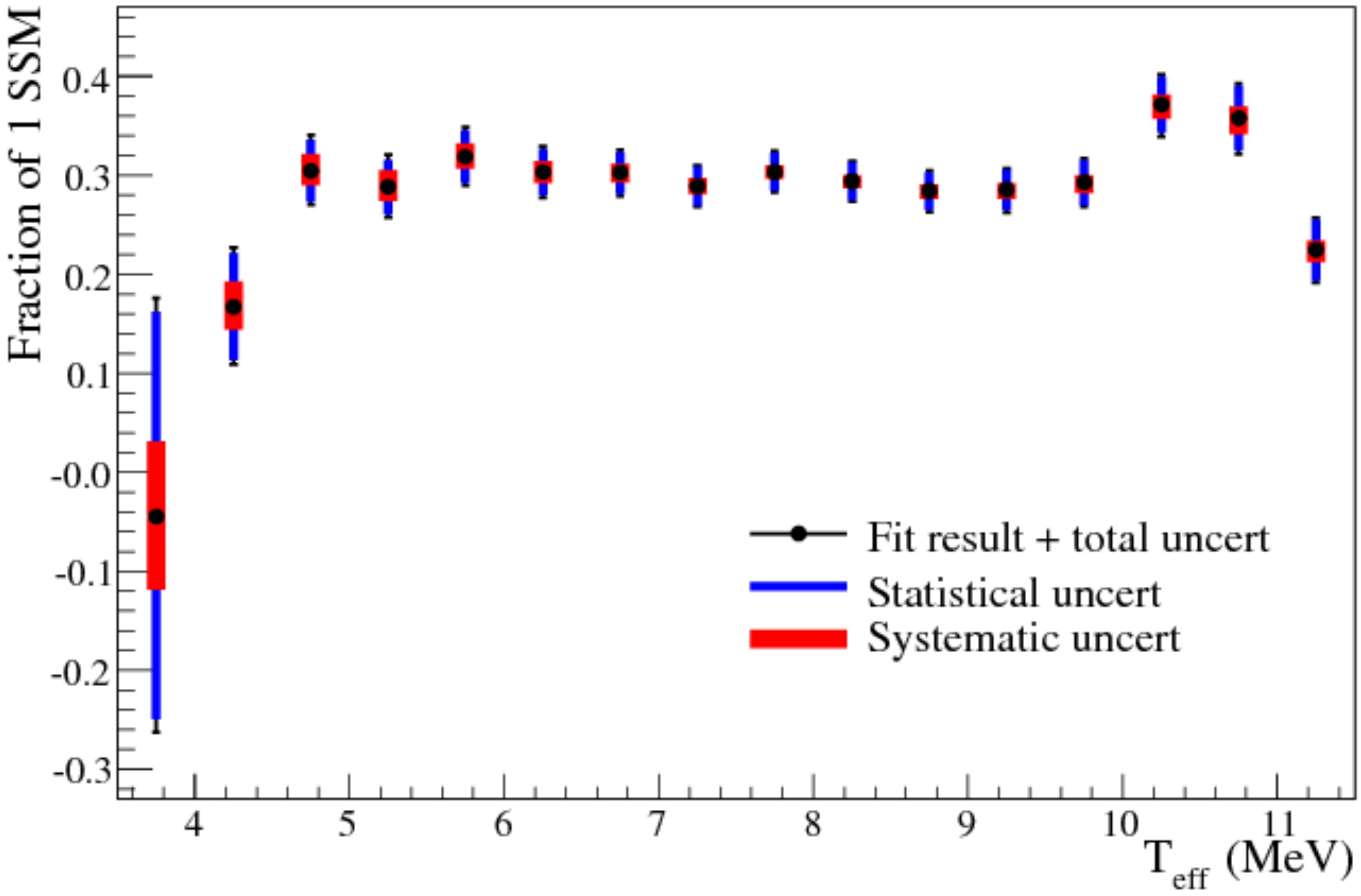
CC Recoil-Electron Spectrum



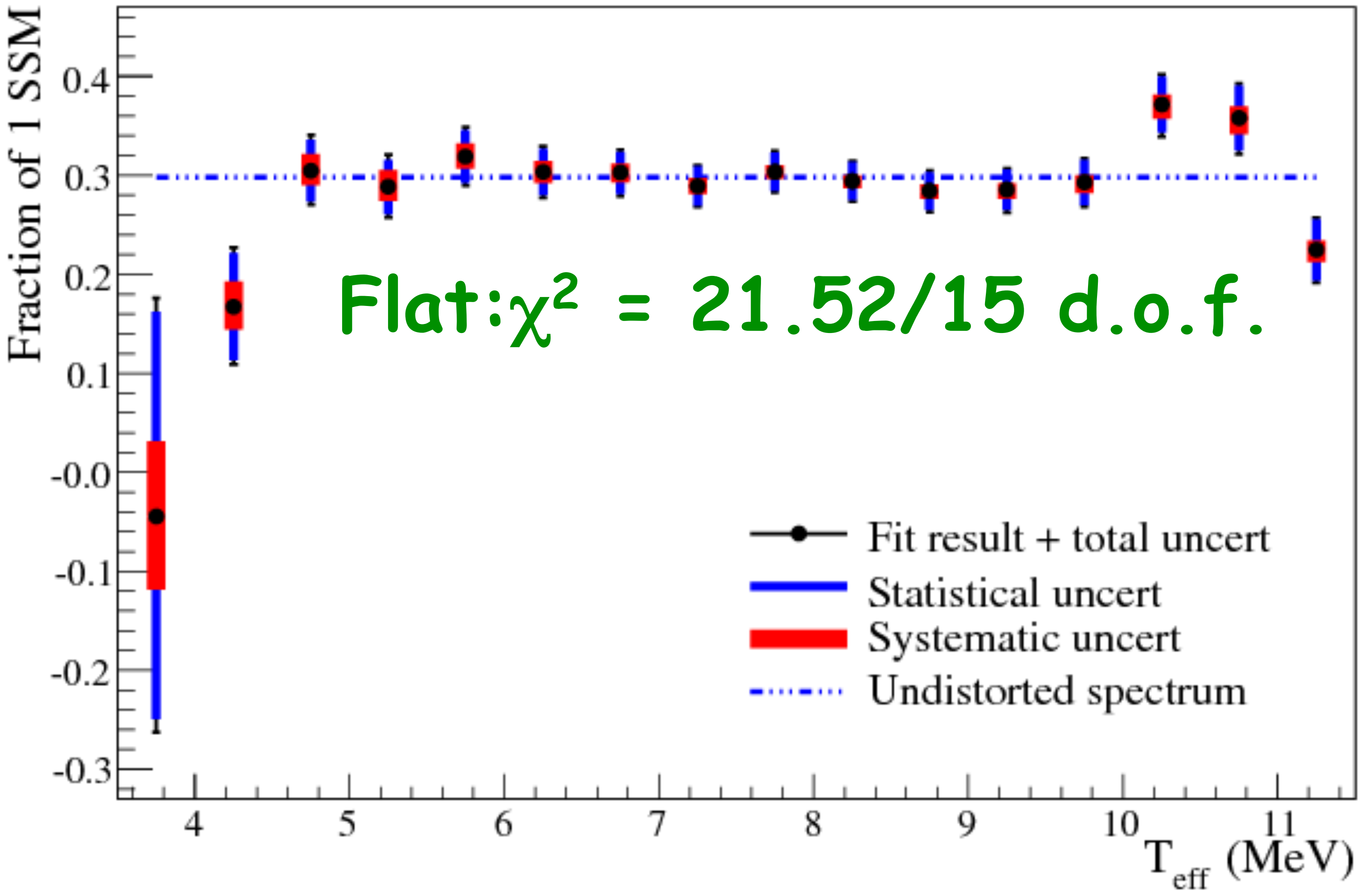
CC Recoil-Electron Spectrum



CC Recoil-Electron Spectrum

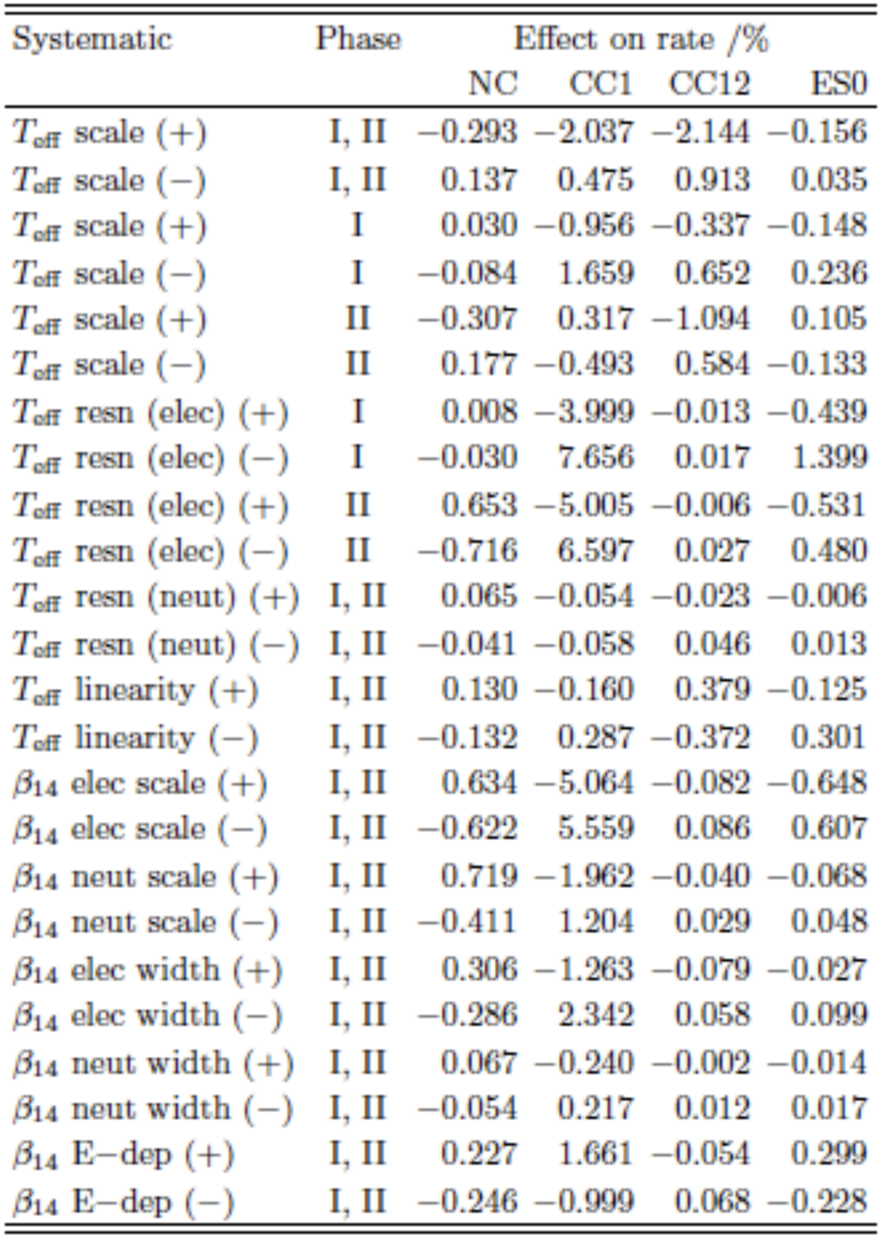


CC Recoil-Electron Spectrum



Flat:χ^2 = 21.52/15 d.o.f.

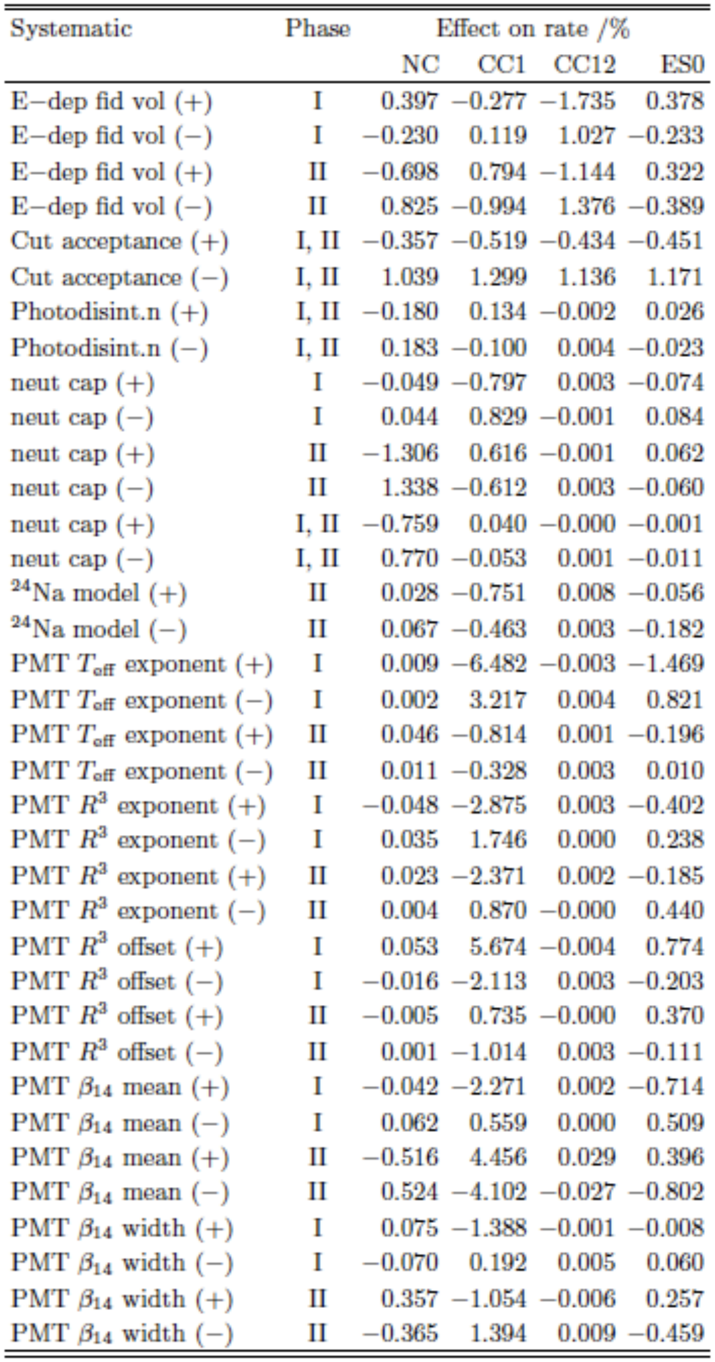
CC Recoil Electr



Systematic	Phase	Effect on rate /%			
		NC	CC1	CC12	ES0
$T_{\rm eff}$ scale (+)	I, II	−0.293	−2.037	−2.144	−0.156
$T_{\rm eff}$ scale (−)	I, II	0.137	0.475	0.913	0.035
$T_{\rm eff}$ scale (+)	I	0.030	−0.956	−0.337	−0.148
$T_{\rm eff}$ scale (−)	I	−0.084	1.659	0.652	0.236
$T_{\rm eff}$ scale (+)	II	−0.307	0.317	−1.094	0.105
$T_{\rm eff}$ scale (−)	II	0.177	−0.493	0.584	−0.133
$T_{\rm eff}$ resn (elec) (+)	I	0.008	−3.999	−0.013	−0.439
$T_{\rm eff}$ resn (elec) (−)	I	−0.030	7.656	0.017	1.399
$T_{\rm eff}$ resn (elec) (+)	II	0.653	−5.005	−0.006	−0.531
$T_{\rm eff}$ resn (elec) (−)	II	−0.716	6.597	0.027	0.480
$T_{\rm eff}$ resn (neut) (+)	I, II	0.065	−0.054	−0.023	−0.006
$T_{\rm eff}$ resn (neut) (−)	I, II	−0.041	−0.058	0.046	0.013
$T_{\rm eff}$ linearity (+)	I, II	0.130	−0.160	0.379	−0.125
$T_{\rm eff}$ linearity (−)	I, II	−0.132	0.287	−0.372	0.301
β_{14} elec scale (+)	I, II	0.634	−5.064	−0.082	−0.648
β_{14} elec scale (−)	I, II	−0.622	5.559	0.086	0.607
β_{14} neut scale (+)	I, II	0.719	−1.962	−0.040	−0.068
β_{14} neut scale (−)	I, II	−0.411	1.204	0.029	0.048
β_{14} elec width (+)	I, II	0.306	−1.263	−0.079	−0.027
β_{14} elec width (−)	I, II	−0.286	2.342	0.058	0.099
β_{14} neut width (+)	I, II	0.067	−0.240	−0.002	−0.014
β_{14} neut width (−)	I, II	−0.054	0.217	0.012	0.017
β_{14} E−dep (+)	I, II	0.227	1.661	−0.054	0.299
β_{14} E−dep (−)	I, II	−0.246	−0.999	0.068	−0.228

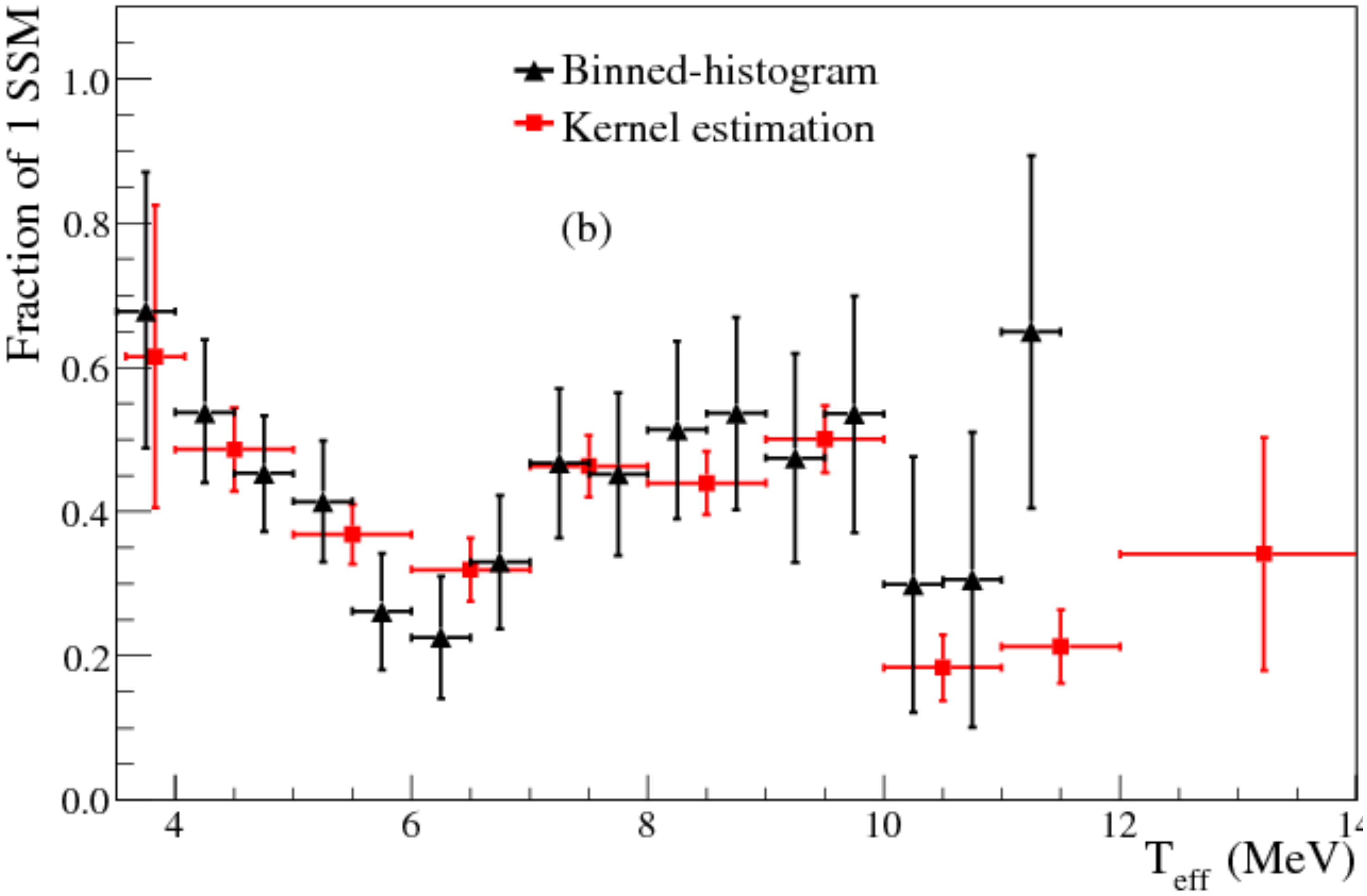
21

22



Systematic	Phase	Effect on rate /%			
		NC	CC1	CC12	ES0
E−dep fid vol (+)	I	0.397	−0.277	−1.735	0.378
E−dep fid vol (−)	I	−0.230	0.119	1.027	−0.233
E−dep fid vol (+)	II	−0.698	0.794	−1.144	0.322
E−dep fid vol (−)	II	0.825	−0.994	1.376	−0.389
Cut acceptance (+)	I, II	−0.357	−0.519	−0.434	−0.451
Cut acceptance (−)	I, II	1.039	1.299	1.136	1.171
Photodisint.n (+)	I, II	−0.180	0.134	−0.002	0.026
Photodisint.n (−)	I, II	0.183	−0.100	0.004	−0.023
neut cap (+)	I	−0.049	−0.797	0.003	−0.074
neut cap (−)	I	0.044	0.829	−0.001	0.084
neut cap (+)	II	−1.306	0.616	−0.001	0.062
neut cap (−)	II	1.338	−0.612	0.003	−0.060
neut cap (+)	I, II	−0.759	0.040	−0.000	−0.001
neut cap (−)	I, II	0.770	−0.053	0.001	−0.011
^{24}Na model (+)	II	0.028	−0.751	0.008	−0.056
^{24}Na model (−)	II	0.067	−0.463	0.003	−0.182
PMT $T_{\rm eff}$ exponent (+)	I	0.009	−6.482	−0.003	−1.469
PMT $T_{\rm eff}$ exponent (−)	I	0.002	3.217	0.004	0.821
PMT $T_{\rm eff}$ exponent (+)	II	0.046	−0.814	0.001	−0.196
PMT $T_{\rm eff}$ exponent (−)	II	0.011	−0.328	0.003	0.010
PMT R^3 exponent (+)	I	−0.048	−2.875	0.003	−0.402
PMT R^3 exponent (−)	I	0.035	1.746	0.000	0.238
PMT R^3 exponent (+)	II	0.023	−2.371	0.002	−0.185
PMT R^3 exponent (−)	II	0.004	0.870	−0.000	0.440
PMT R^3 offset (+)	I	0.053	5.674	−0.004	0.774
PMT R^3 offset (−)	I	−0.016	−2.113	0.003	−0.203
PMT R^3 offset (+)	II	−0.005	0.735	−0.000	0.370
PMT R^3 offset (−)	II	0.001	−1.014	0.003	−0.111
PMT β_{14} mean (+)	I	−0.042	−2.271	0.002	−0.714
PMT β_{14} mean (−)	I	0.062	0.559	0.000	0.509
PMT β_{14} mean (+)	II	−0.516	4.456	0.029	0.396
PMT β_{14} mean (−)	II	0.524	−4.102	−0.027	−0.802
PMT β_{14} width (+)	I	0.075	−1.388	−0.001	−0.008
PMT β_{14} width (−)	I	−0.070	0.192	0.005	0.060
PMT β_{14} width (+)	II	0.357	−1.054	−0.006	0.257
PMT β_{14} width (−)	II	−0.365	1.394	0.009	−0.459

ES Recoil-Electron Spectrum

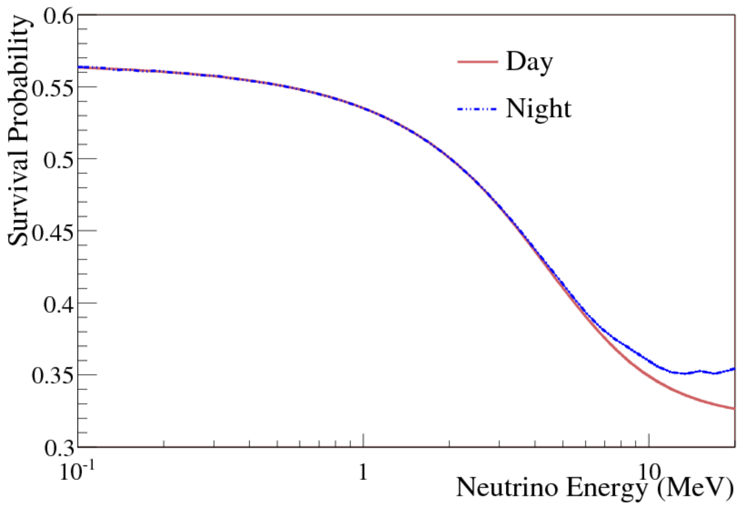


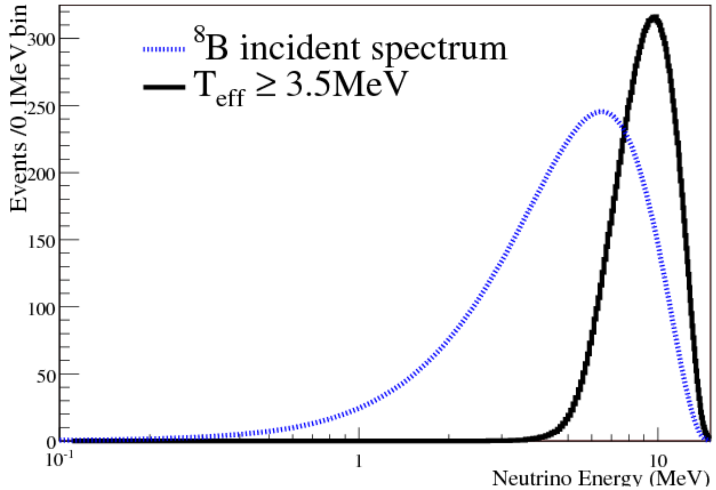
Flat:χ^2 = 17.05/15 d.o.f.

Direct Fit for Energy-Dependent Survival Probability

Parameterize distortion to ν_e spectrum with quadratic

Naturally imposes continuity of spectrum and unitarity of mixing matrix





$$P_{ee}^{DAY}(E_\nu) = c0 + c1\,(E_\nu - 10\text{ MeV}) + c2\,(E_\nu - 10\text{ MeV})^2$$

$$P_{ee}^{ASYM}(E_\nu) = a0 + a1\,(E_\nu - 10\text{ MeV})$$

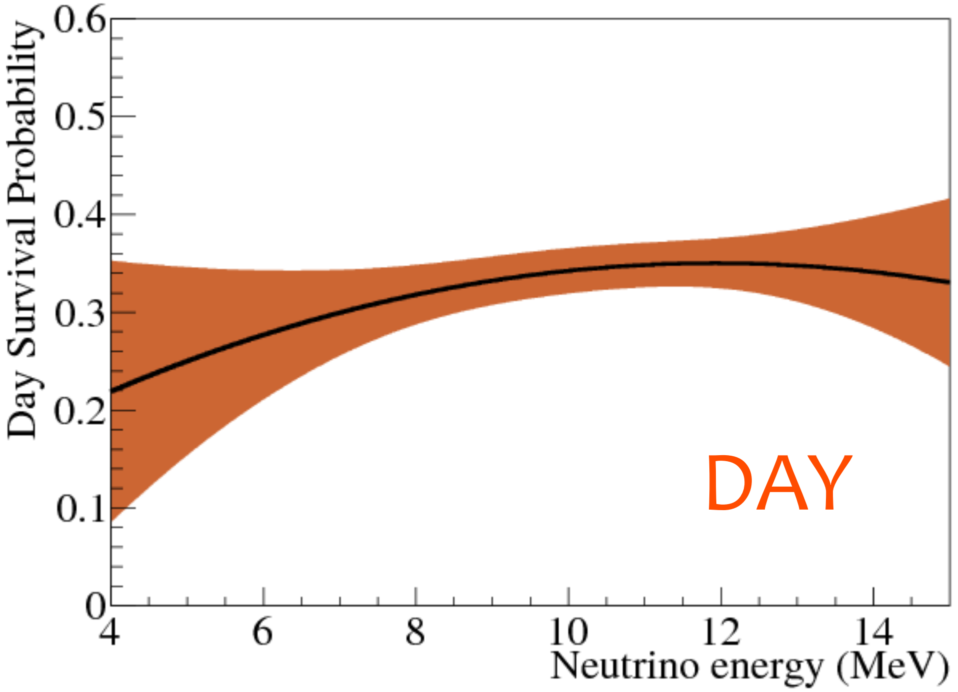
$$\Downarrow$$

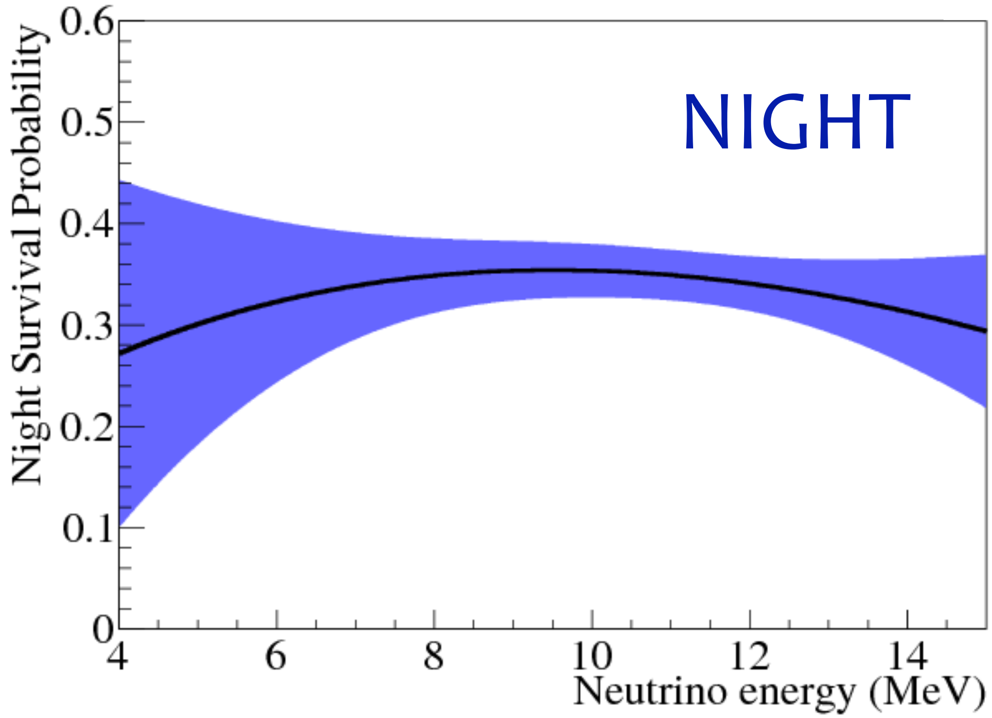
$$P_{ee}^{NIGHT}(E_\nu) = P_{ee}^{DAY}(E_\nu) \times \frac{[1 + (1/2)*P_{ee}^{ASYM}(E_\nu)]}{[1 - (1/2)*P_{ee}^{ASYM}(E_\nu)]}$$

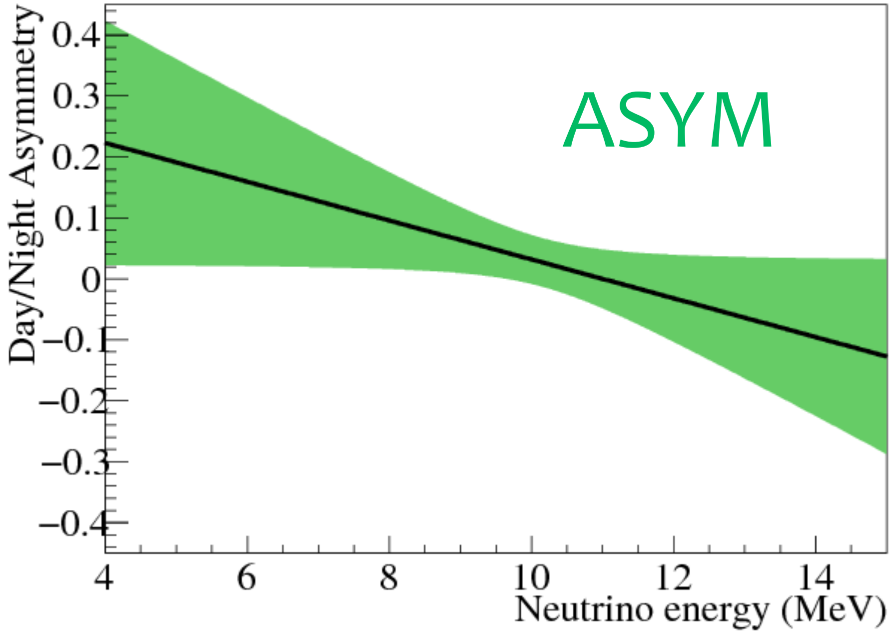
Note: Fit is now in E_ν, not T_{eff}

Direct Fit for Energy-Dependent Survival Probability

$\Phi_{8B} = 5.046\,^{+3.8}_{-3.9}\,\%$

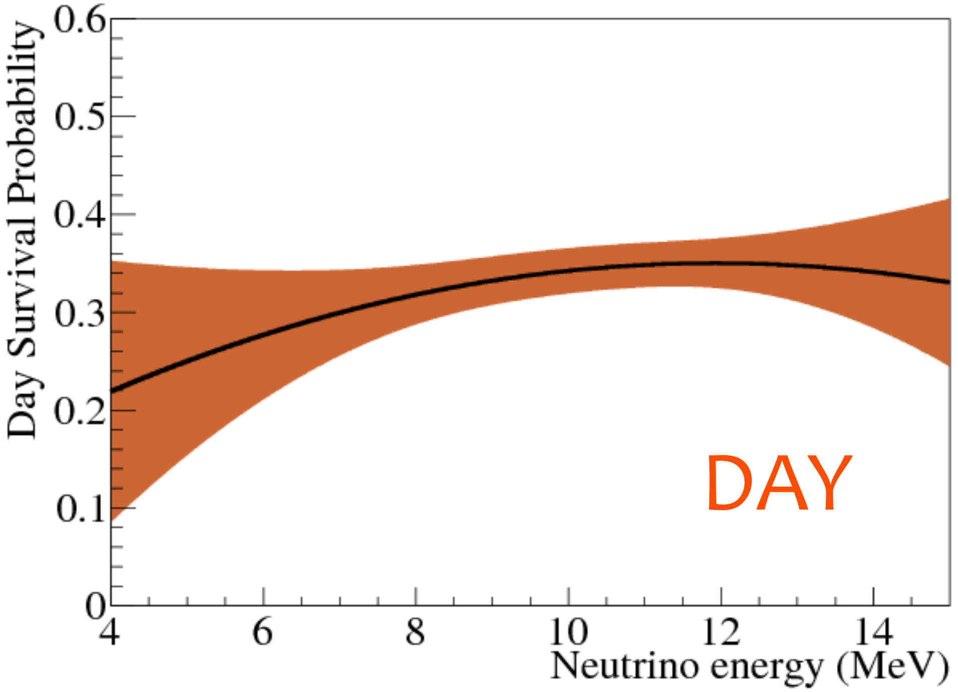


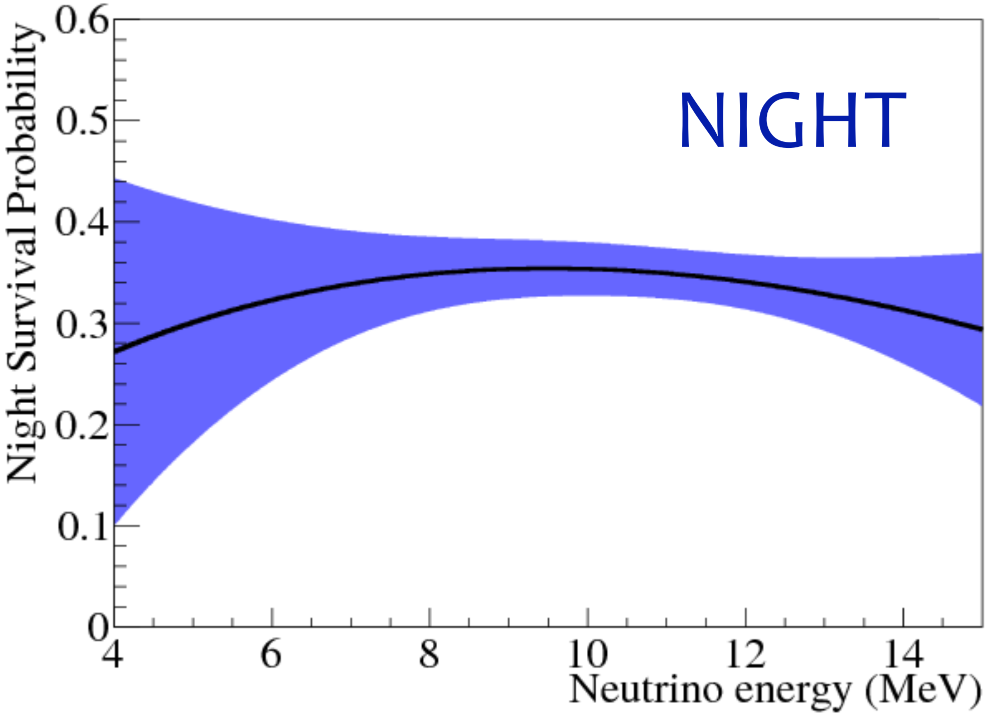


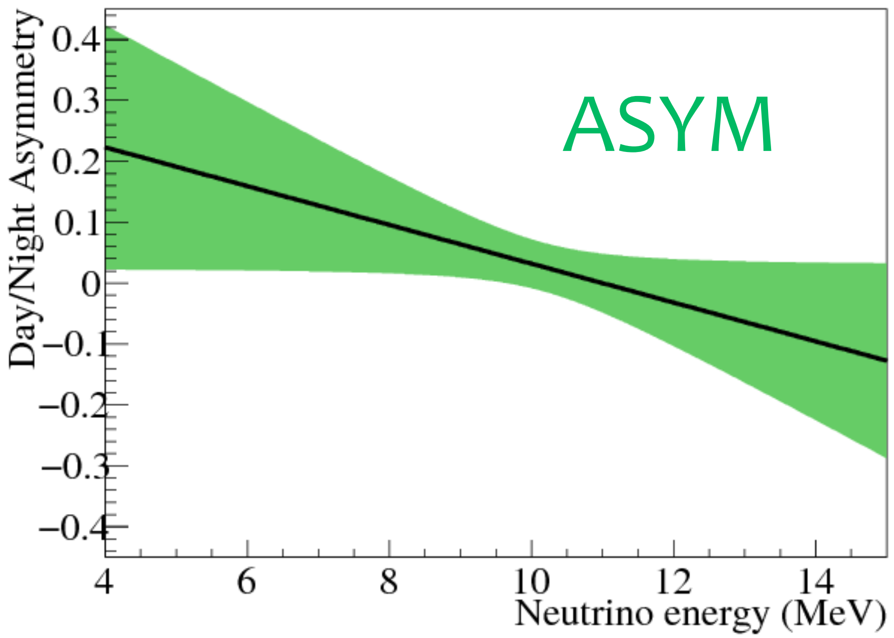


Direct Fit for Energy-Dependent Survival Probability

No distortion, no a/s:
$\Delta\chi^2$ = 1.94 / 4 d.o.f.

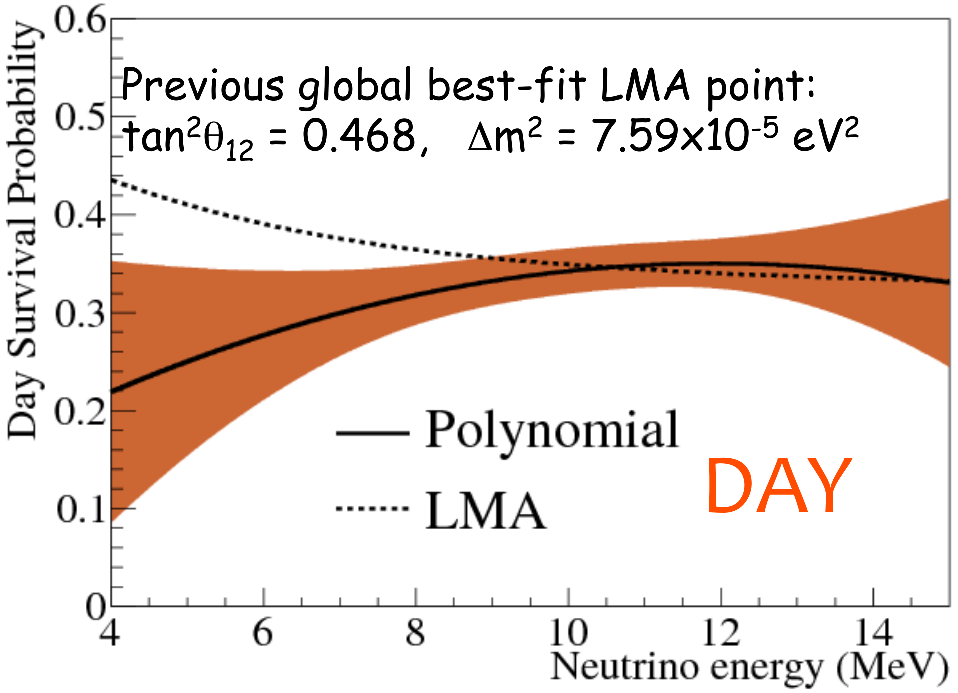


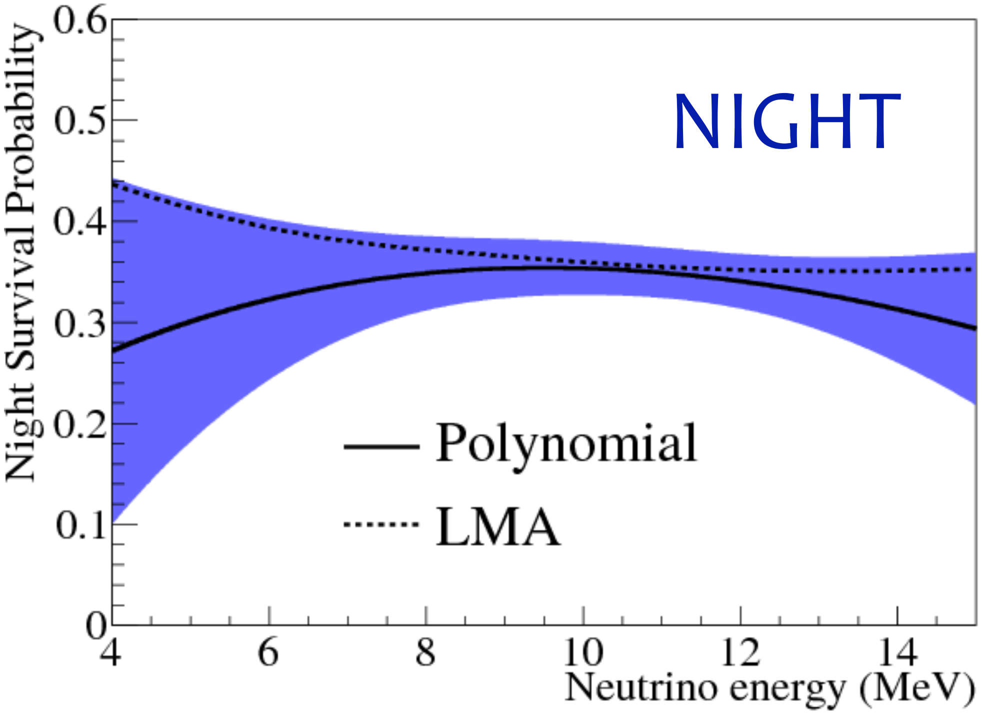


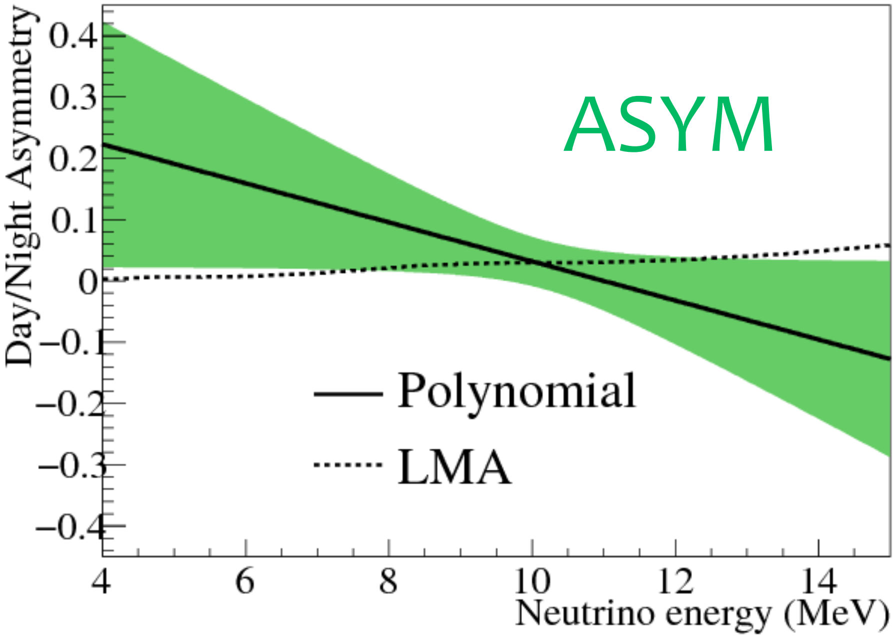


Direct Fit for Energy-Dependent Survival Probability

No distortion, no a/s:
$\Delta\chi^2$ = 1.94 / 4 d.o.f.
LMA-prediction:
$\Delta\chi^2$ = 3.90 / 4 d.o.f.

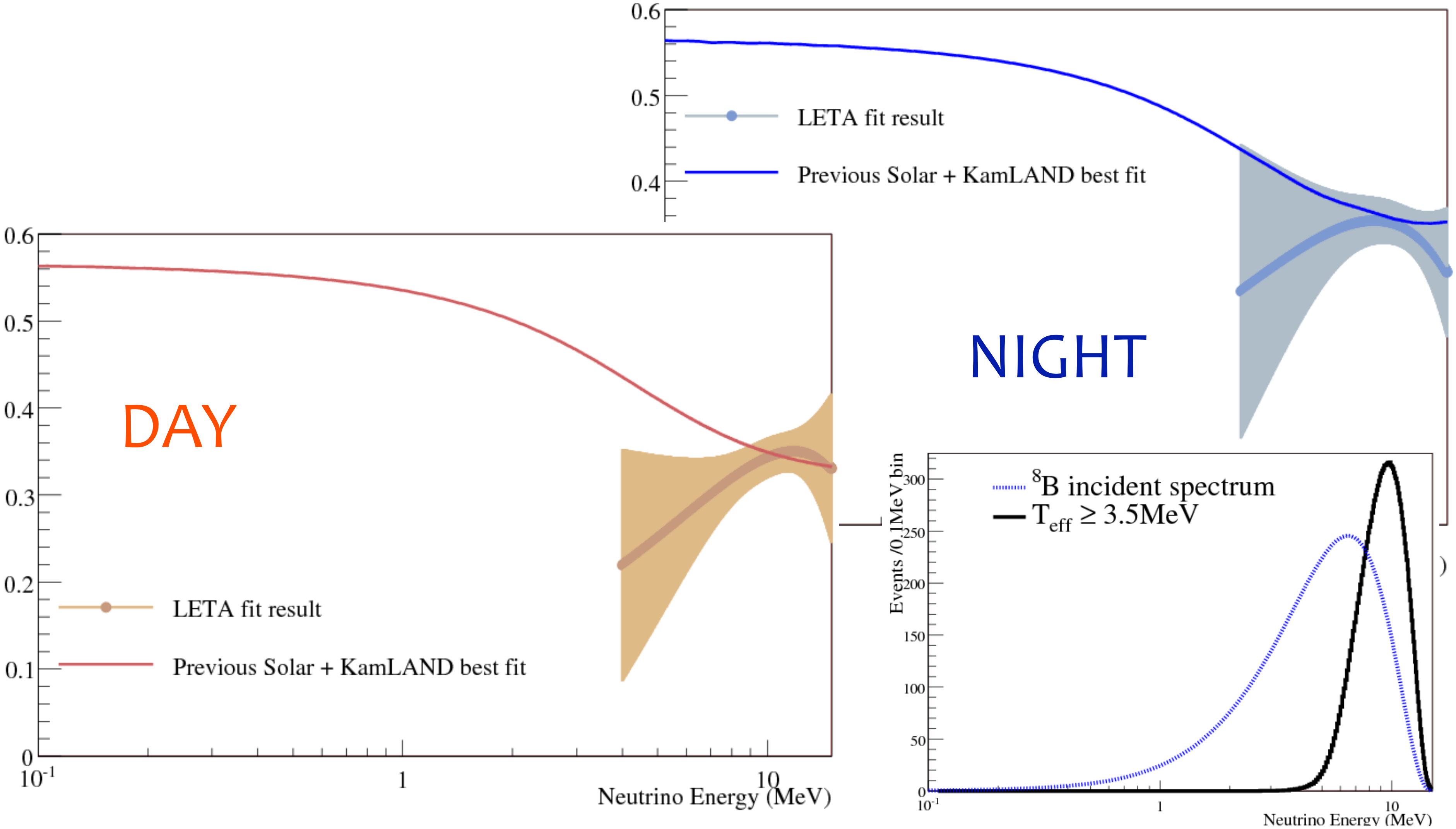

Previous global best-fit LMA point:
$\tan^2\theta_{12} = 0.468$, $\Delta m^2 = 7.59\times10^{-5}\ \mathrm{eV}^2$



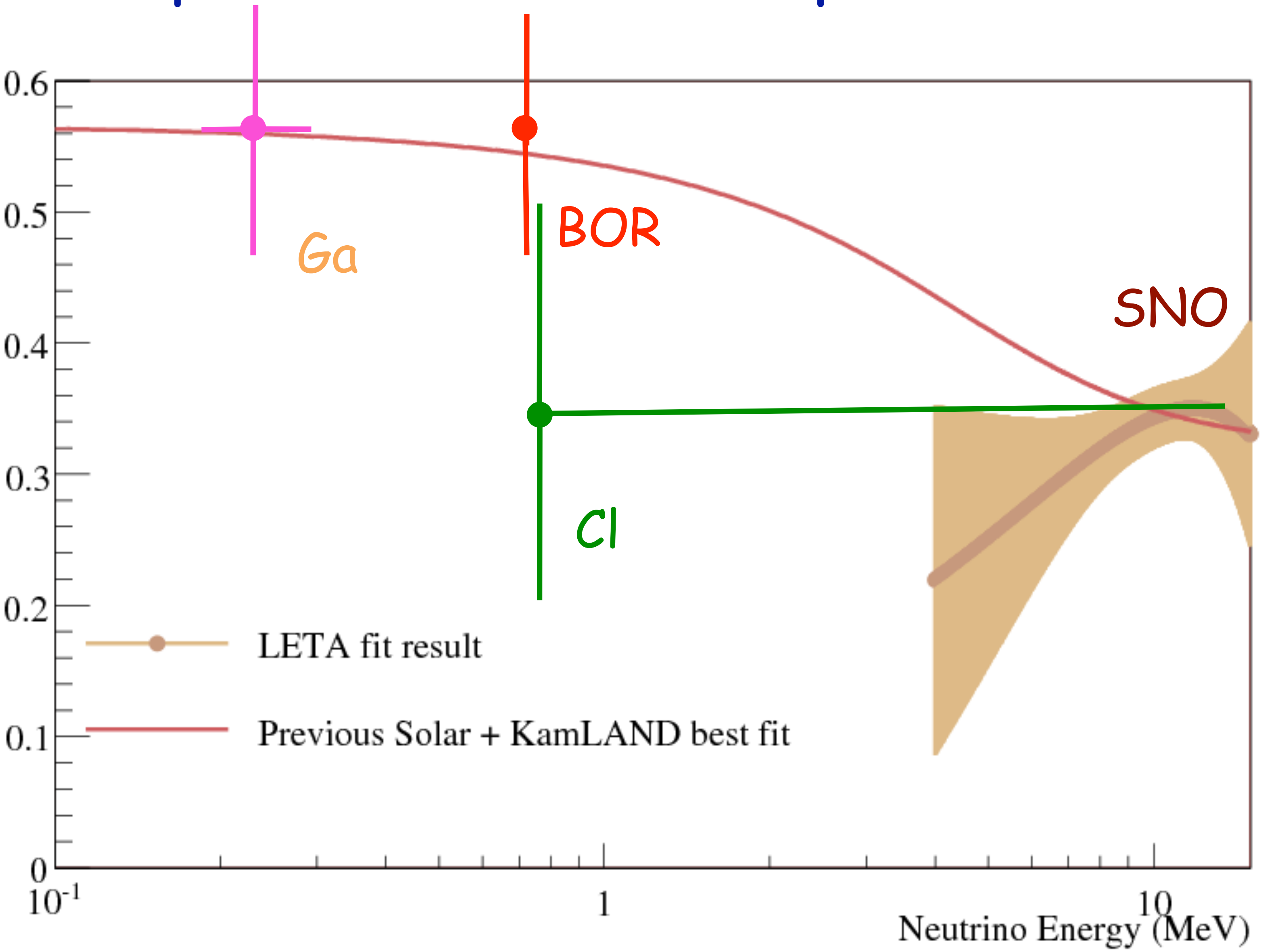


Direct Fit for Energy-Dependent Survival Probability

Previous global best-fit LMA point:
$\tan^2\theta_{12} = 0.468$, $\Delta m^2 = 7.59\times10^{-5}$ eV^2



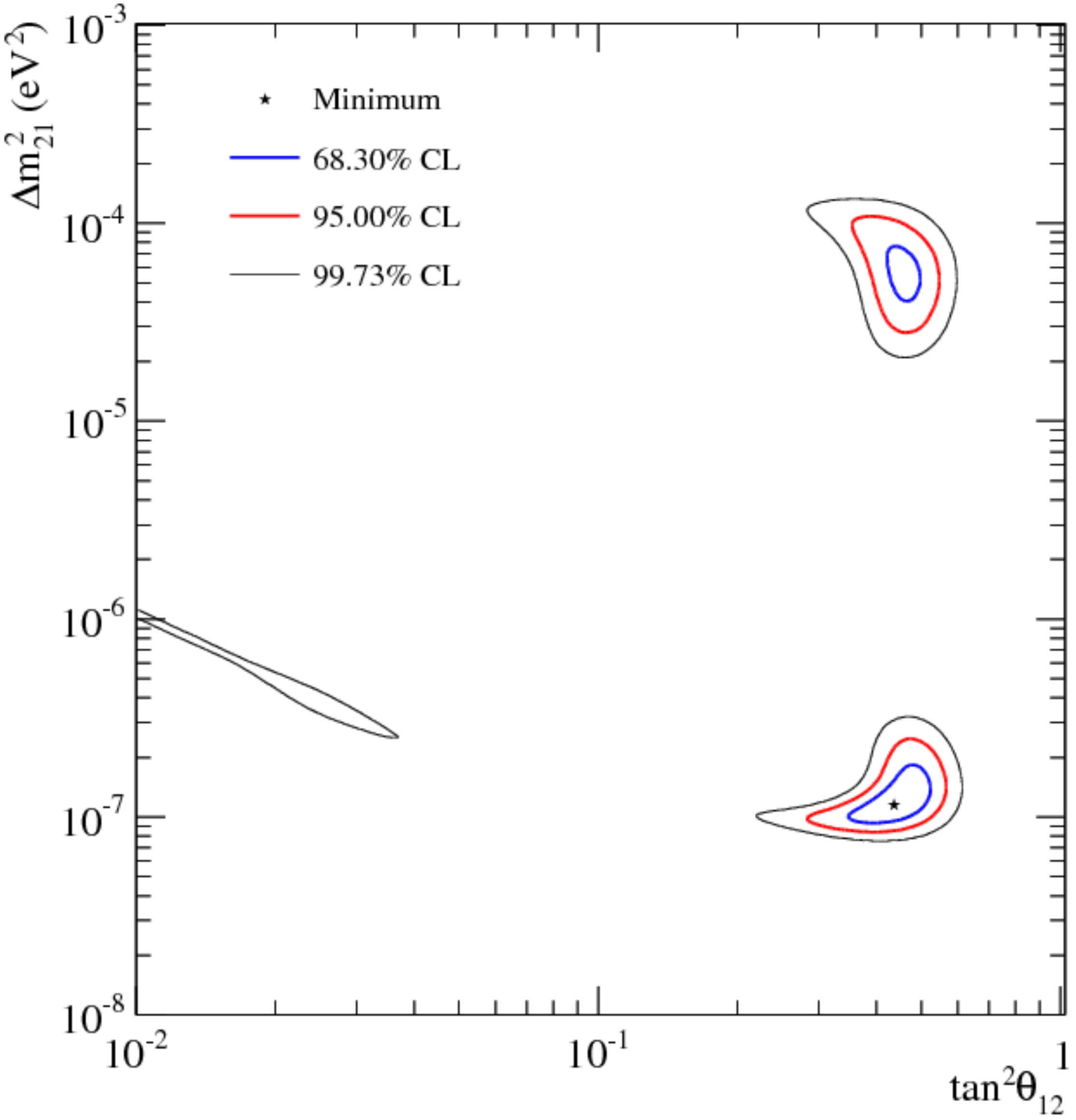
Comparison to Other Experiments



Oscillation Analyses: LETA

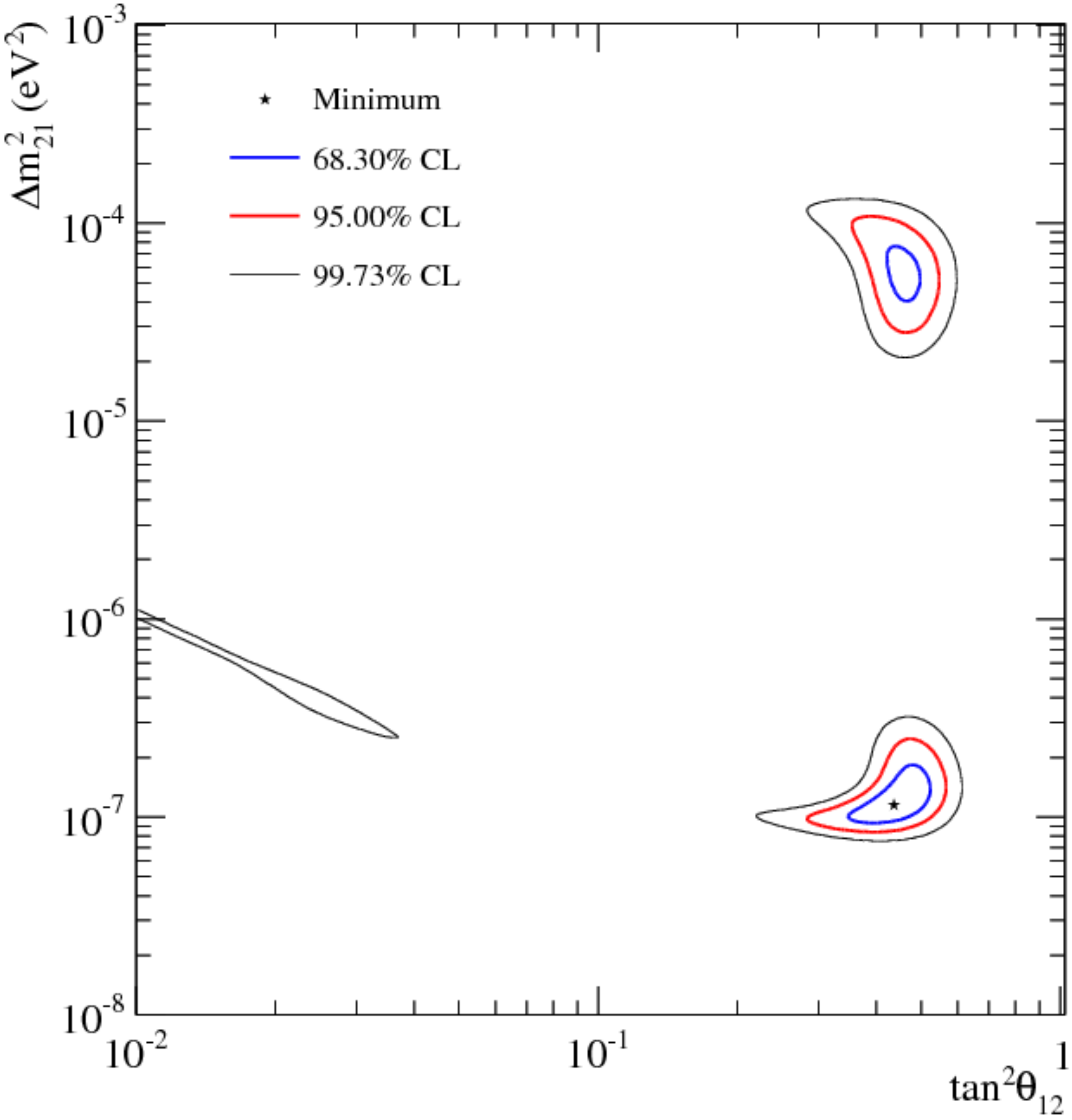
LETA paper 2009:
LETA joint-phase fit
+ Phase III

Best-fit point:
$\tan^2\theta_{12} = 0.437$,
$\Delta m^2 = 1.15\times10^{-7}\ eV^2$



Oscillation Analyses: LETA

LETA paper 2009:
LETA joint-phase fit
+ Phase III



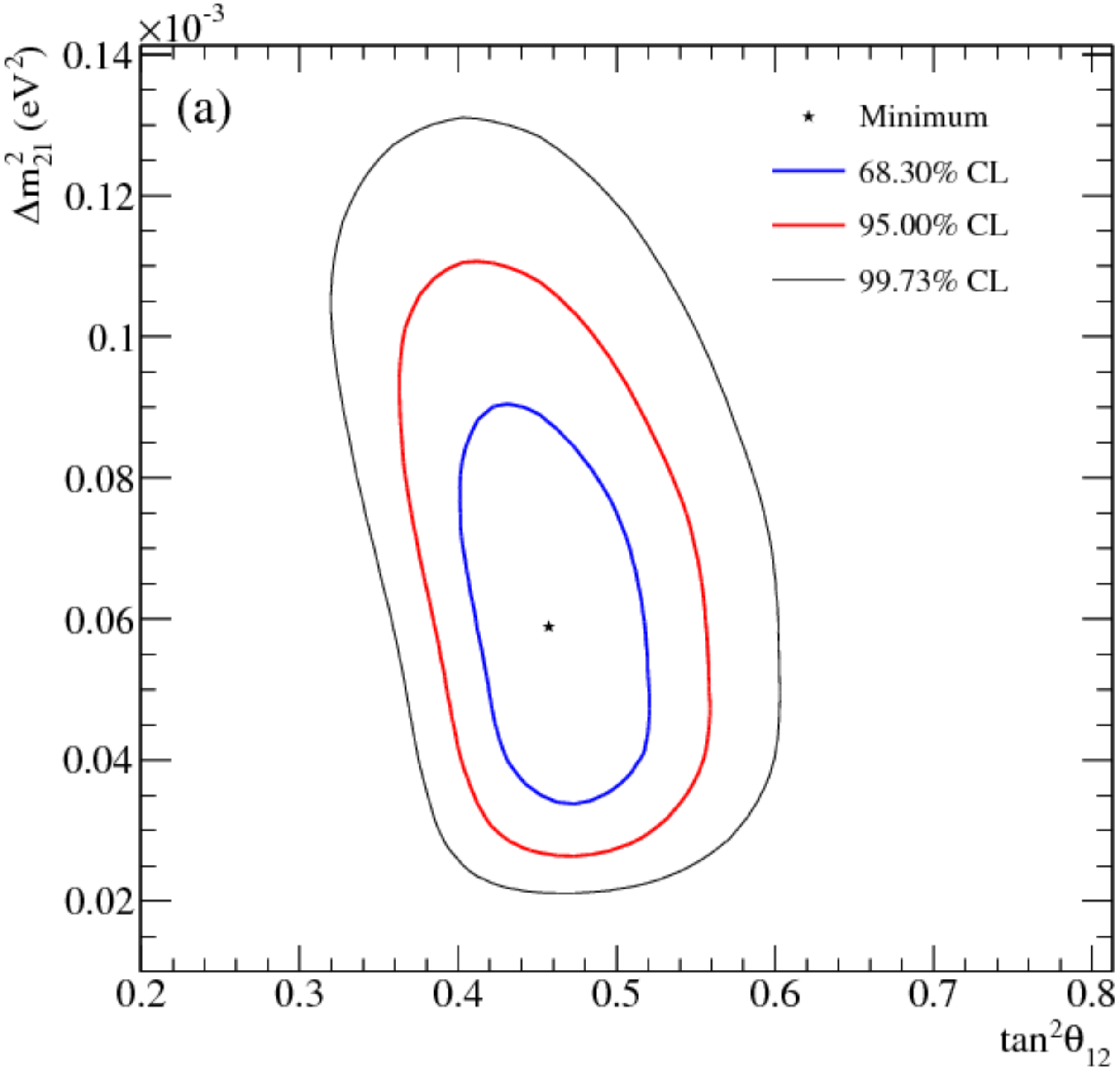
Best-fit LMA point:

$\tan^2\theta_{12} = 0.457$
(+0.038 -0.042)

$\Delta m^2 = 5.50\times10^{-5}$ eV^2
(+2.21 -1.62)

Oscillation Analyses: Global Solar

LETA paper 2009:
LETA joint-phase fit
+ Phase III
+ all solar expts



Best-fit LMA point:

$\tan^2\theta_{12} = 0.457$
(+0.038 -0.041)

$\Delta m^2 = 5.89\times10^{-5}$ eV^2
(+2.13 -2.16)

Oscillation Analyses: Solar + KamLAND

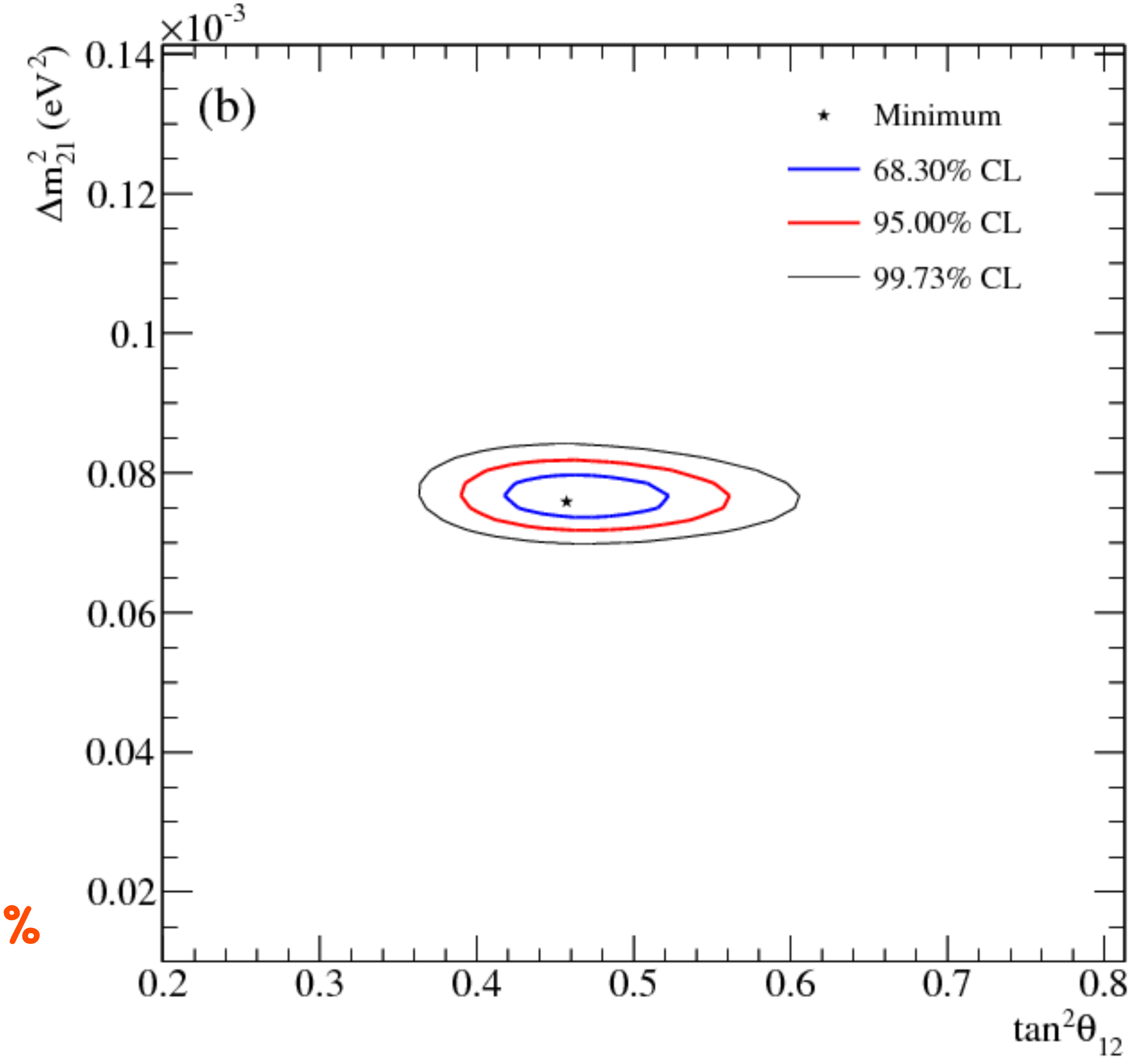
LETA paper 2009:
LETA joint-phase fit
+ Phase III
+ all solar expts
+ KamLAND

Best-fit LMA point:

$\tan^2\theta_{12} = 0.457$
$(+0.040\ -0.029)$

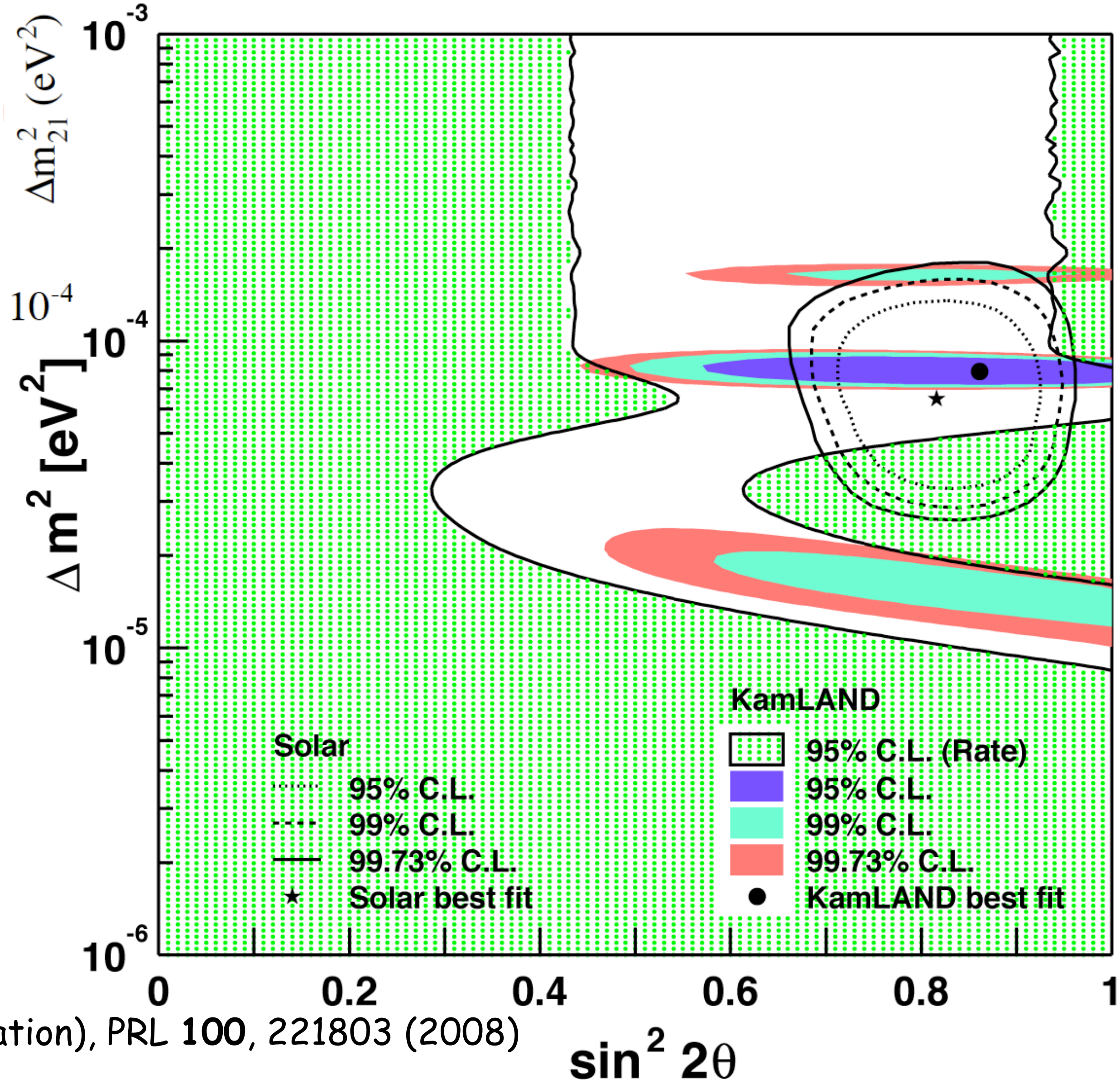
$\Delta m^2 = 7.59\times10^{-5}\ \mathrm{eV}^2$
$(+0.20\ -0.21)$

Φ_{8B} **uncert** $= {}^{+2.38}_{-2.95}\ \%$



Solar + KamLAND 2-flavor Overlay

LETA paper 2009:
LETA joint-phase f
+ Phase III
+ all solar expts
+ KamLAND

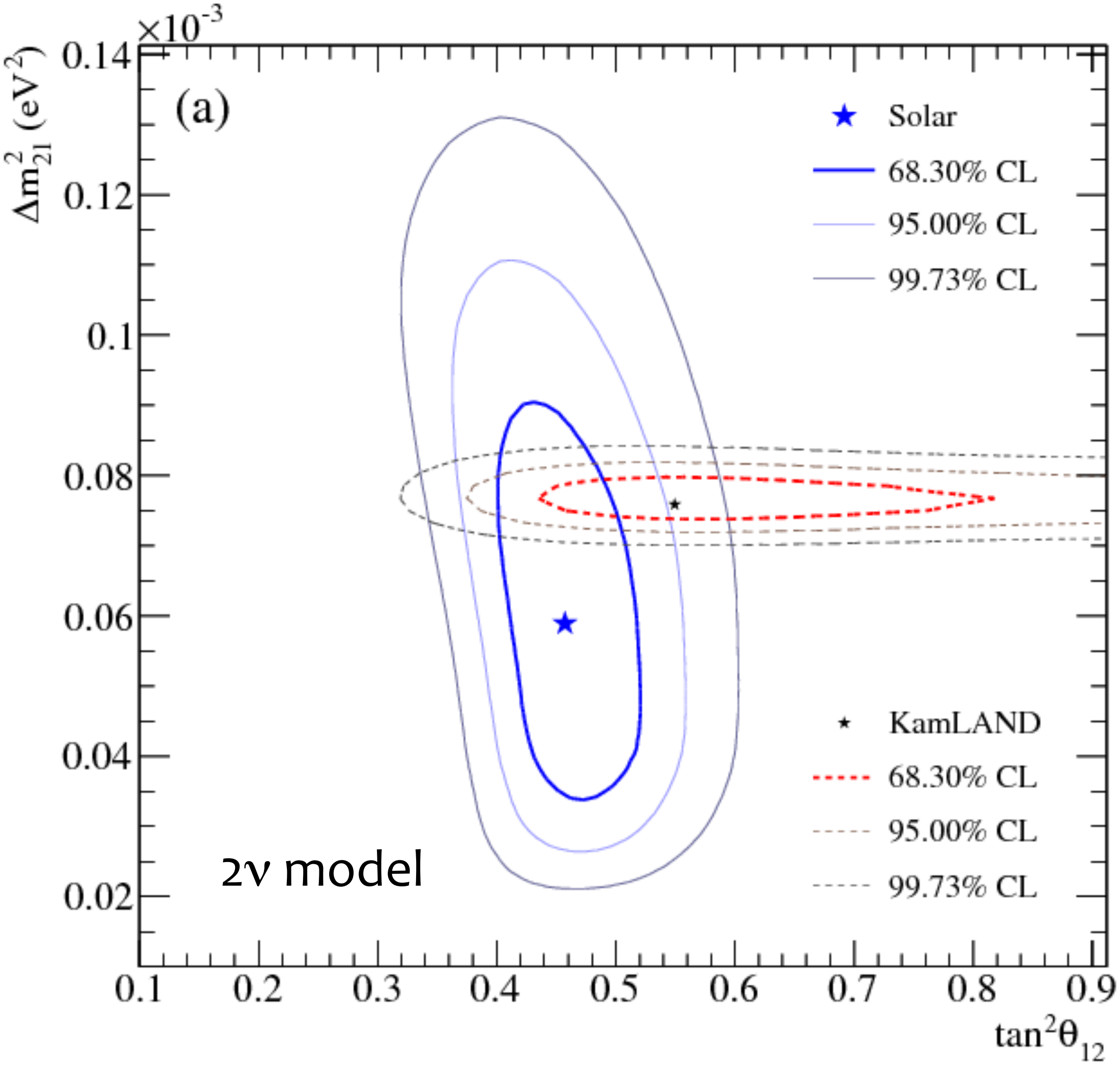


S. Abe *et al.* (KamLAND Collaboration), PRL **100**, 221803 (2008)

Solar + KamLAND 2-flavor Overlay

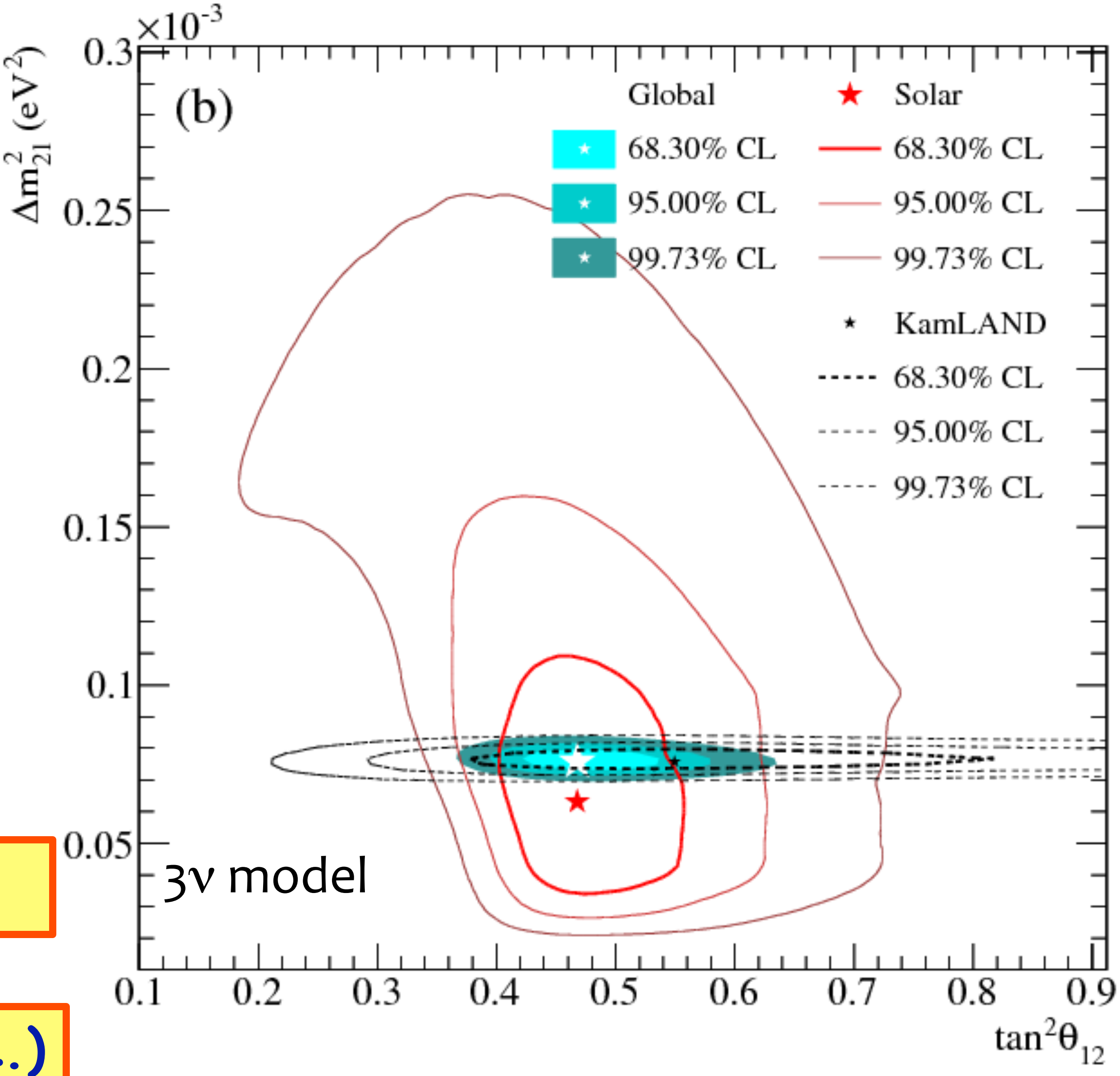
LETA paper 2009:
LETA joint-phase fit
+ Phase III
+ all solar expts
+ KamLAND

2-flavor overlay:



Solar + KamLAND 3-flavor Overlay

LETA paper 2009:
LETA joint-phase fit
+ Phase III
+ all solar expts
+ KamLAND



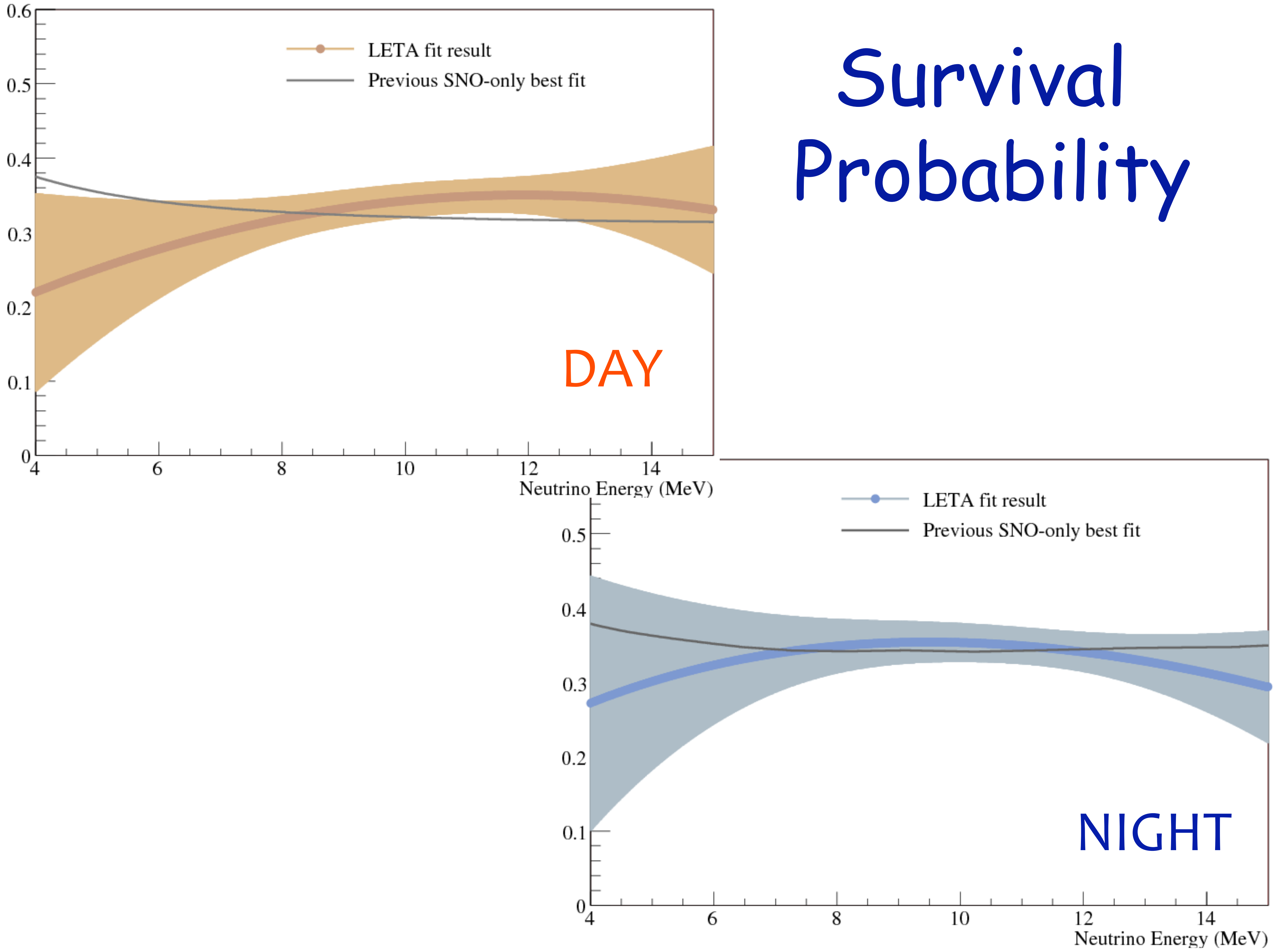
3-flavor overlay

Best-fit:

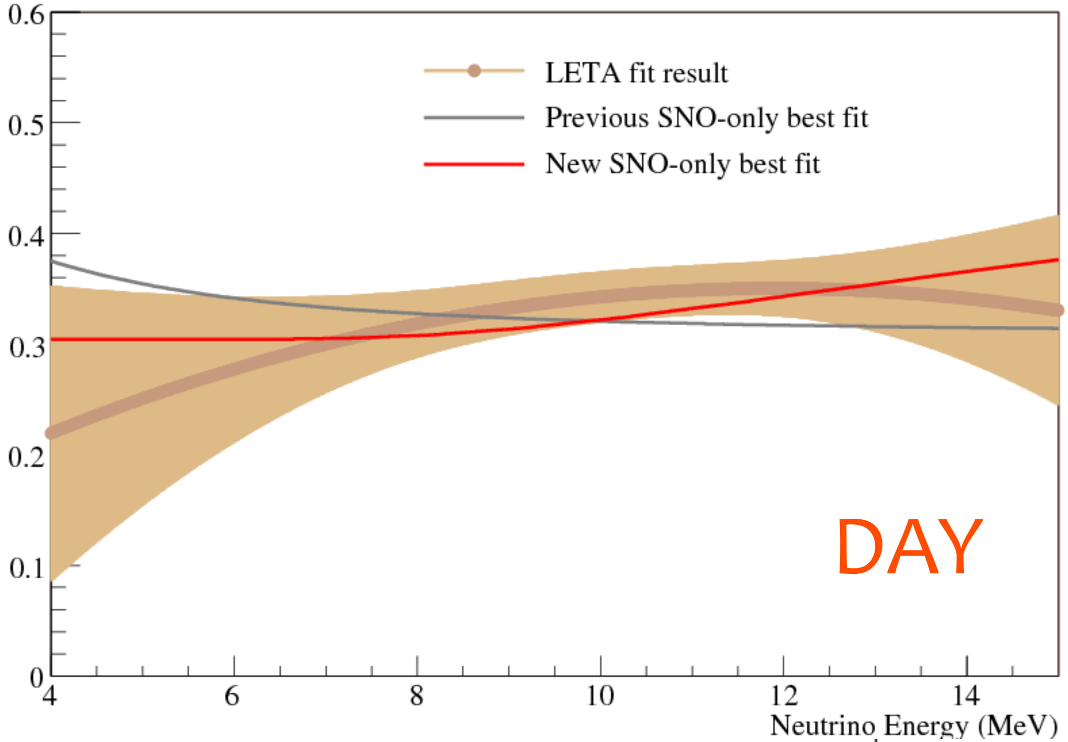
$\sin^2\theta_{13}=2.00\,^{+2.09}_{-1.63}\times 10^{-2}$

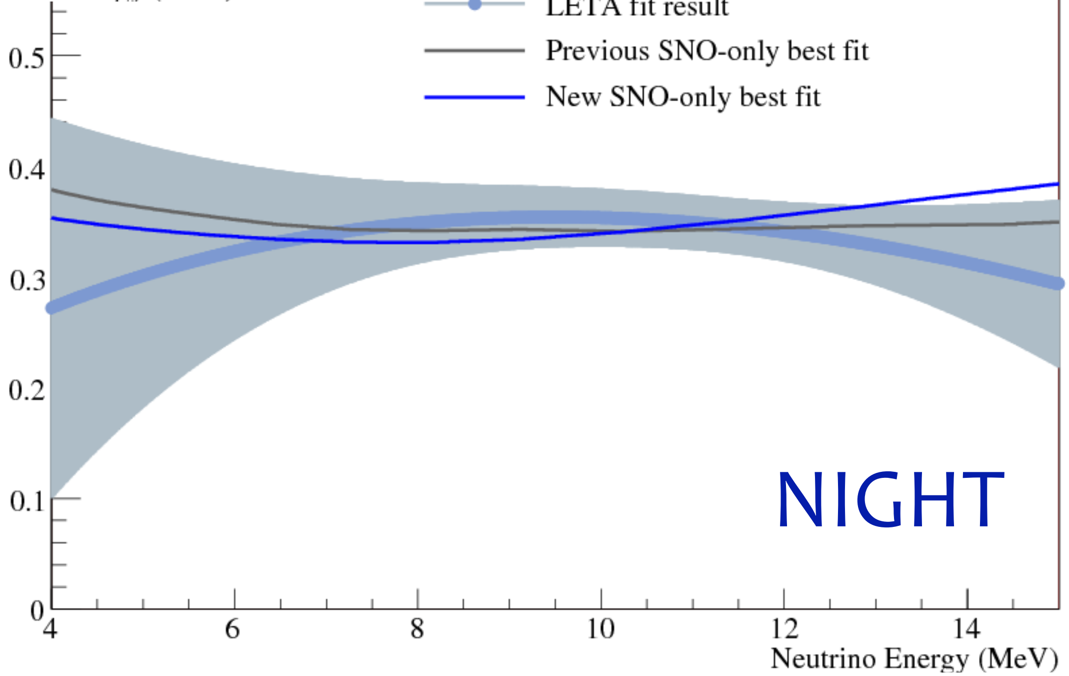
$\sin^2\theta_{13} < 0.057$ (95% C.L.)

Survival Probability

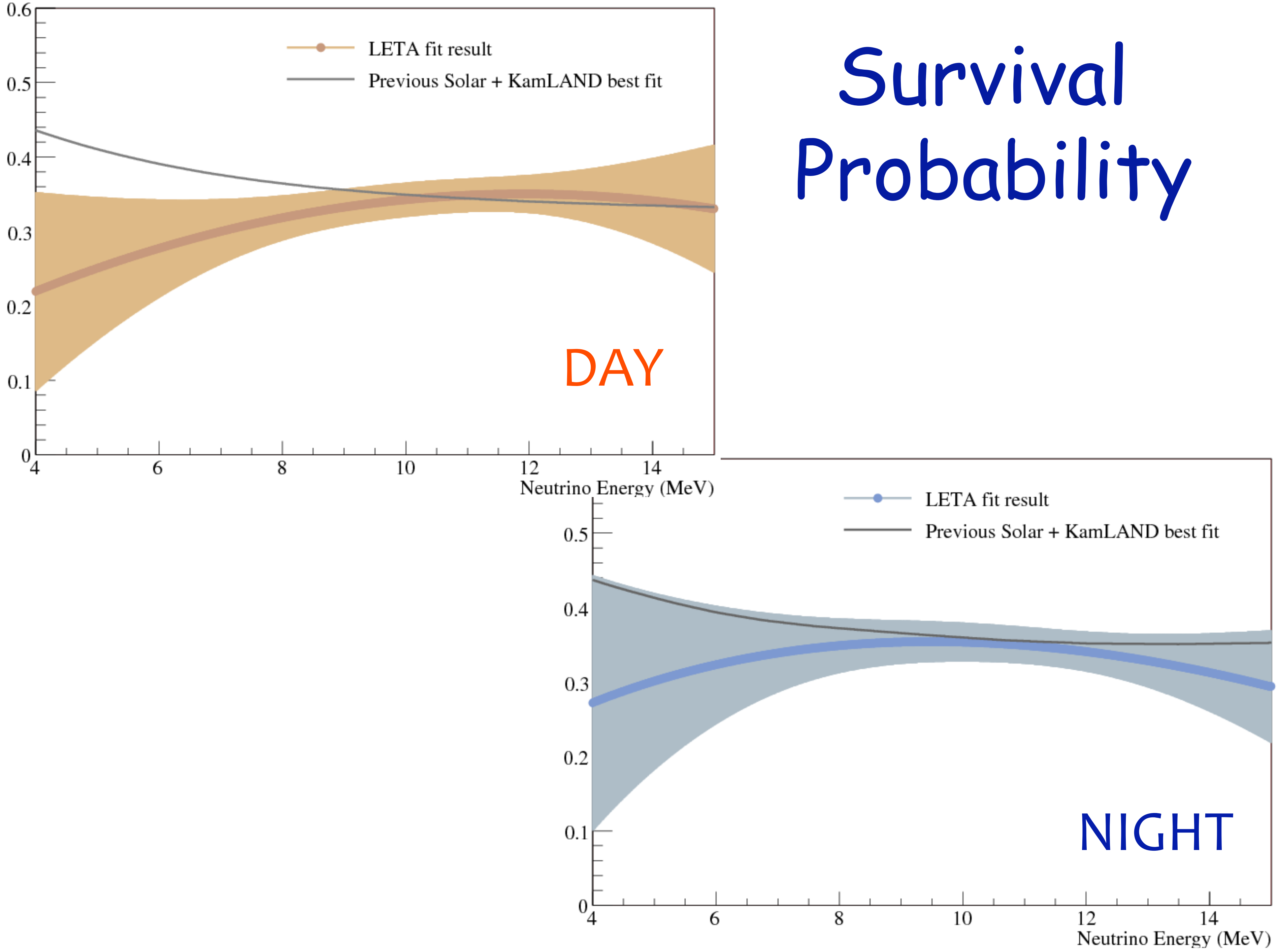


Survival Probability

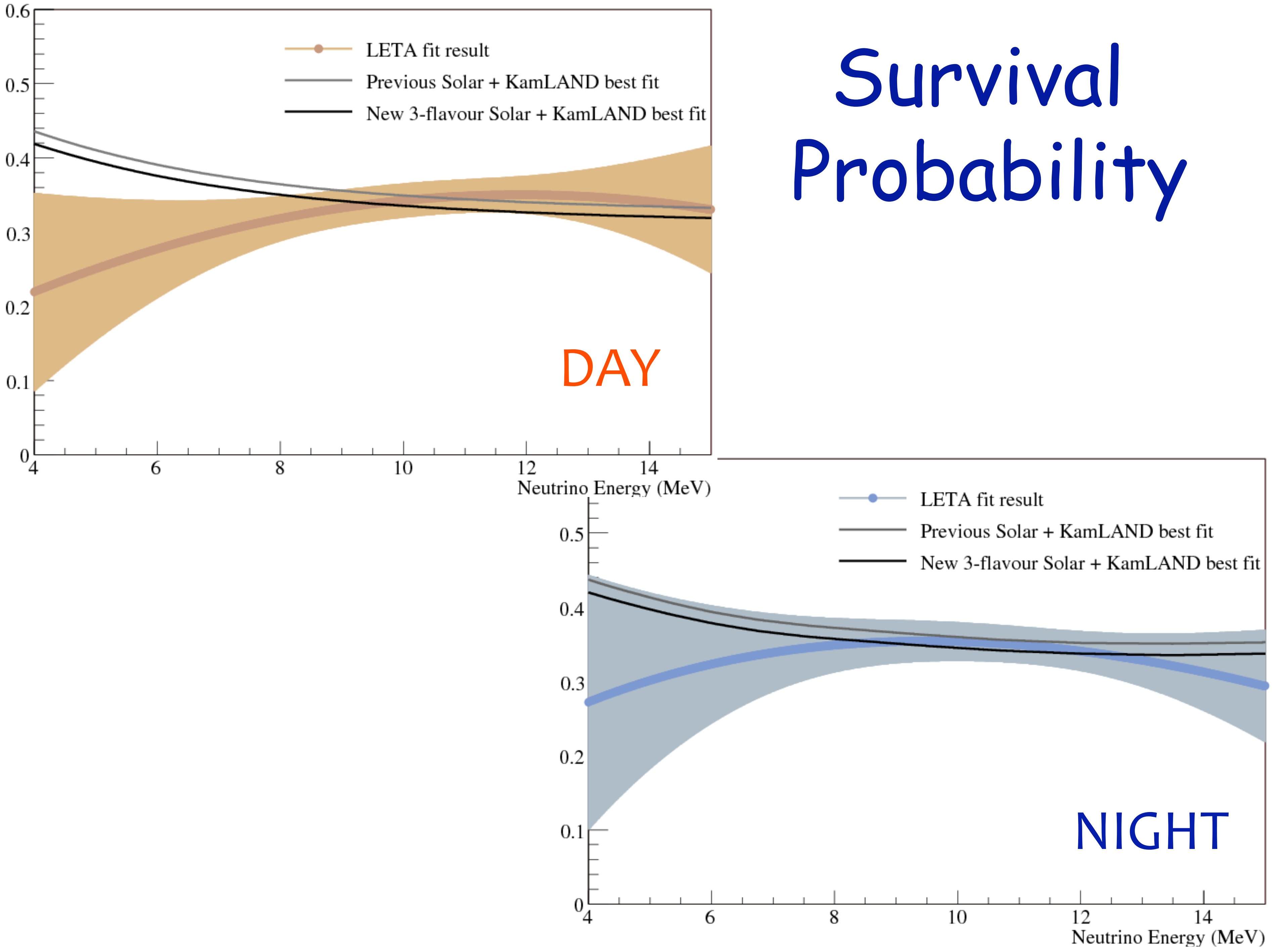




Survival Probability



Survival Probability



Summary

1. Lowest threshold yet achieved with water Cherenkov data
2. Spectrum consistent with `shallow' LMA but also just flat
3. Reduction in uncertainties on model-independent total ^{8}B flux by x2

$$\Phi_{NC} = 5.140\,^{+4.0}_{-3.8}\,\%$$

4. First direct fit for ν_e survival probability
5. Best fit global MSW parameters (2-flavor):

$$\tan^2\theta_{12} = 0.457^{+0.040}_{-0.029}$$

$$\Delta m^2 = 7.59\times10^{-5}\ \mathrm{eV}^2\,^{+0.20}_{-0.21}$$

$$\Phi_{8B}\ \mathrm{uncert} = ^{+2.38}_{-2.95}\,\%$$

6. 3-flavor analysis shows non-zero θ_{13} but consistent with θ_{13}=0:

$\sin^2\theta_{13}=2.00\,^{+2.09}_{-1.63}\times10^{-2}$ $\sin^2\theta_{13} < 0.057$ (95% C.L.)