

*The Sudbury Neutrino  
Observatory Presents:*



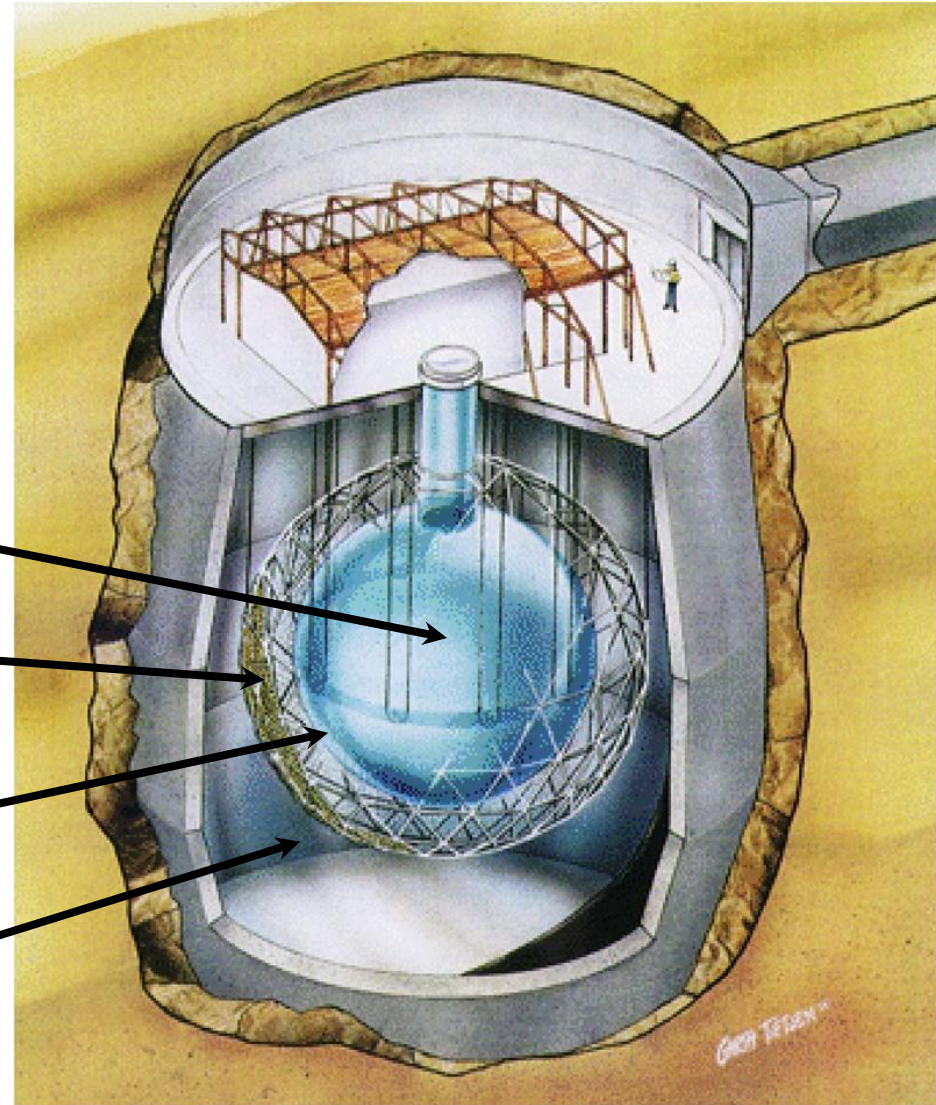
# **The Low Energy Threshold Analysis ('LETA')**

Gabriel Orebi Gann  
University of Pennsylvania  
Neutrino Champagne  
19<sup>th</sup> Oct 2009



# The Sudbury Neutrino Observatory

- 1000 tonnes  $D_2O$
- Support structure for 9500 PMTS  
54% coverage
- 12 m diameter acrylic vessel
- 7000 tonnes  $H_2O$  shielding



# The Sudbury Neutrino Observatory

3 phases:

1. Pure  $D_2O$

2.  $D_2O + NaCl$

3.  $D_2O + {}^3He$

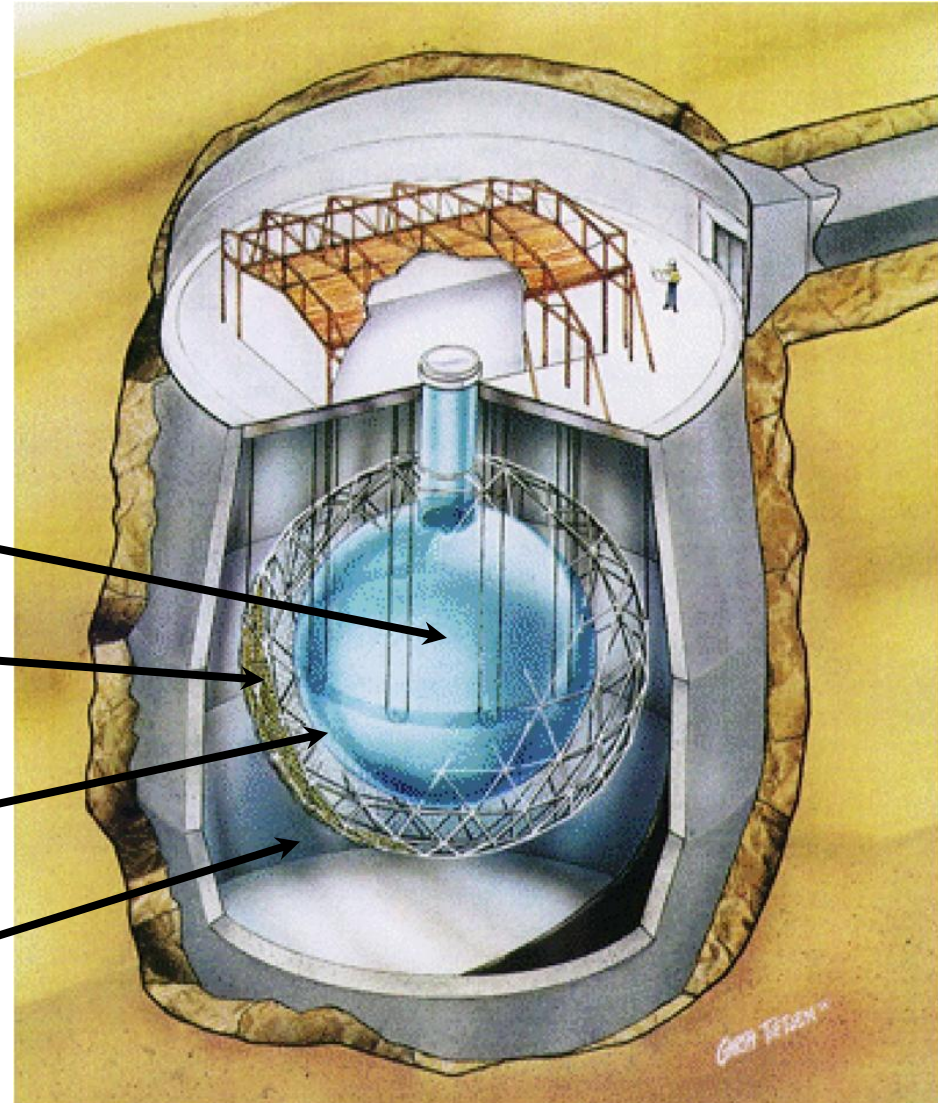
proportional counters

1000 tonnes  $D_2O$

Support structure for 9500 PMTS  
54% coverage

12 m diameter acrylic vessel

7000 tonnes  $H_2O$  shielding



# The Sudbury Neutrino Observatory

3 phases:

1. Pure  $D_2O$

2.  $D_2O + NaCl$

3.  $D_2O + {}^3He$

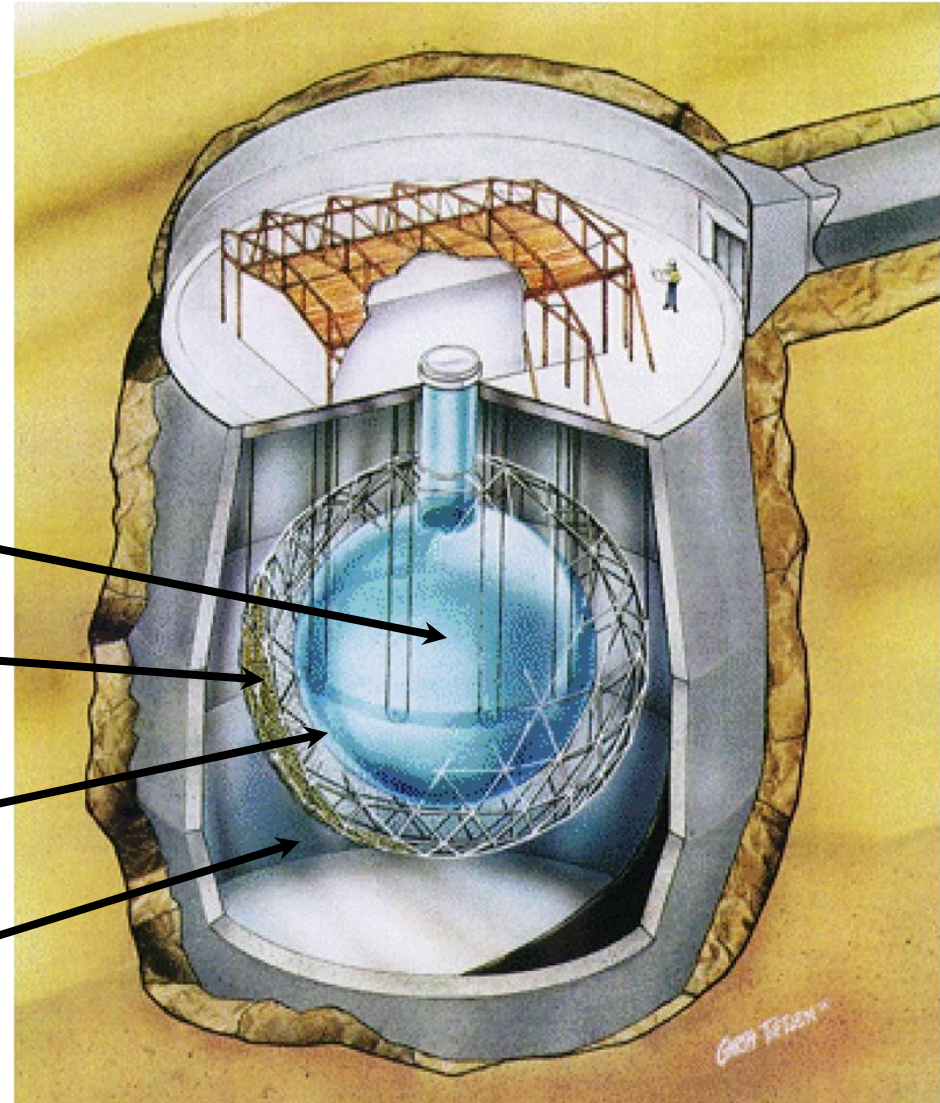
proportional counters

1000 tonnes  $D_2O$

Support structure for 9500 PMTS  
54% coverage

12 m diameter acrylic vessel


7000 tonnes  $H_2O$  shielding





# Analysis Improvements:

1. Lower threshold to 3.5MeV
2. Combine 2 phases in a joint-phase fit
3. Reduce backgrounds
4. Improve MC simulation
5. Reduce systematic uncertainties
6. Create PMT  $\beta$ - $\gamma$  PDF directly from data
7. Improved Signal Extraction approach
8. Improved oscillation analysis

# Analysis Improvements:

1. Lower threshold to 3.5MeV 
2. Combine 2 phases in a joint-phase fit
3. Reduce backgrounds
4. Improve MC simulation
5. Reduce systematic uncertainties
6. Create PMT  $\beta$ - $\gamma$  PDF directly from data
7. Improved Signal Extraction approach
8. Improved oscillation analysis

# Analysis Improvements:

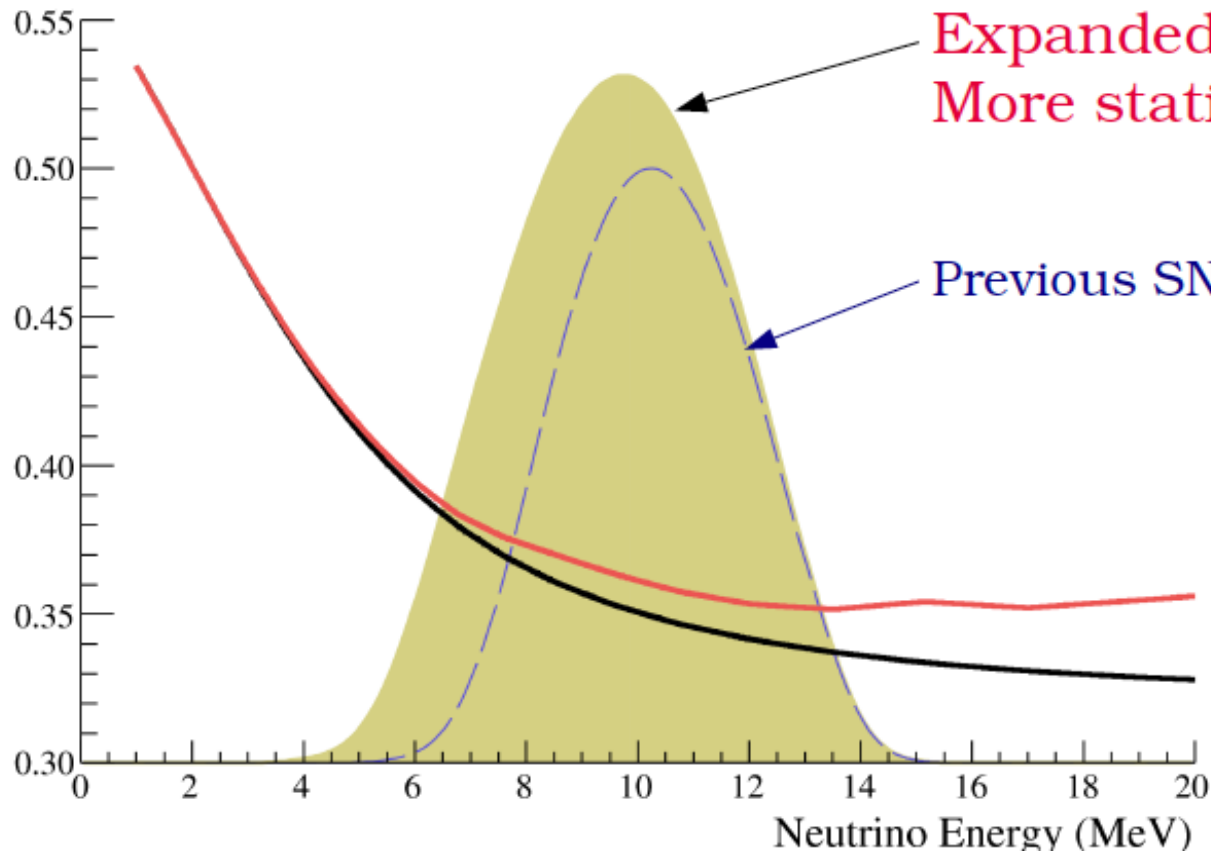
1. Lower threshold to 3.5MeV 
2. Combine 2 phases in a joint-phase fit
3. Reduce backgrounds
4. Improve MC simulation
5. Reduce systematic uncertainties
6. Create PMT  $\beta$ - $\gamma$  PDF directly from data
7. Improved Signal Extraction approach 
8. Improved oscillation analysis

# 1) 3.5 MeV Analysis Threshold

*CC statistics*

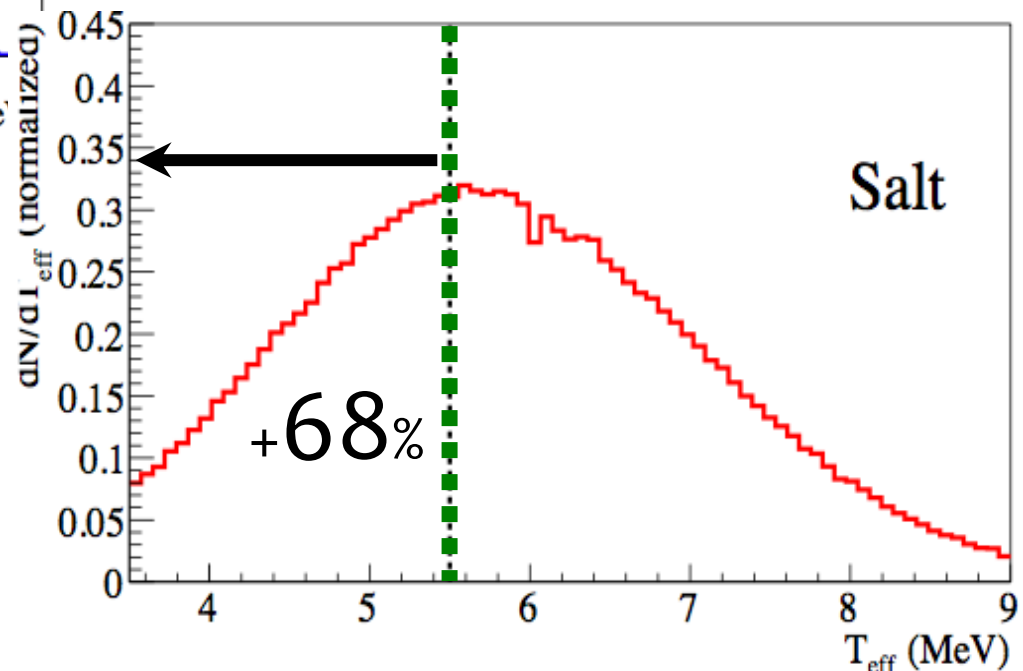
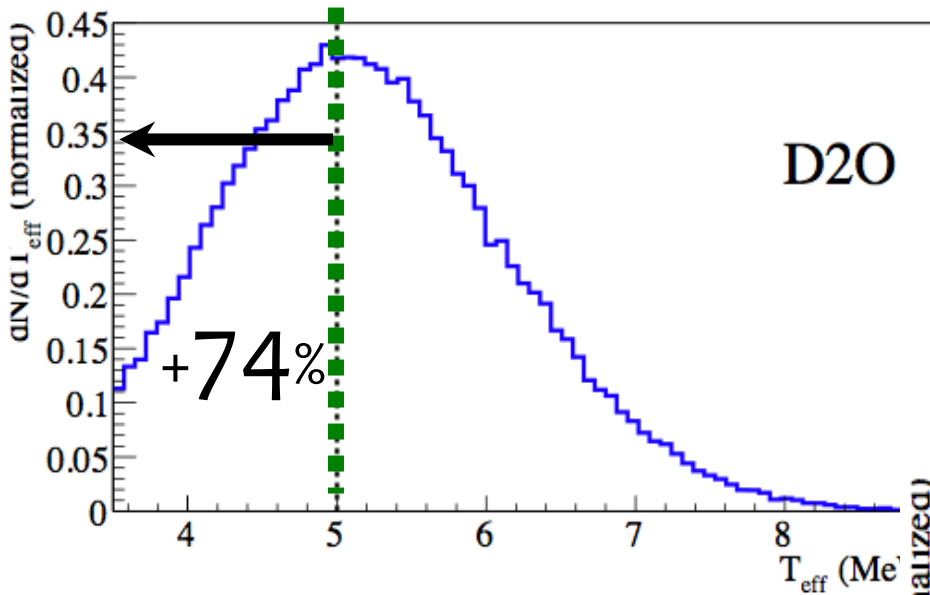
Typical  
LMA  
curves

Survival Probability



# 1) 3.5 MeV Analysis Threshold

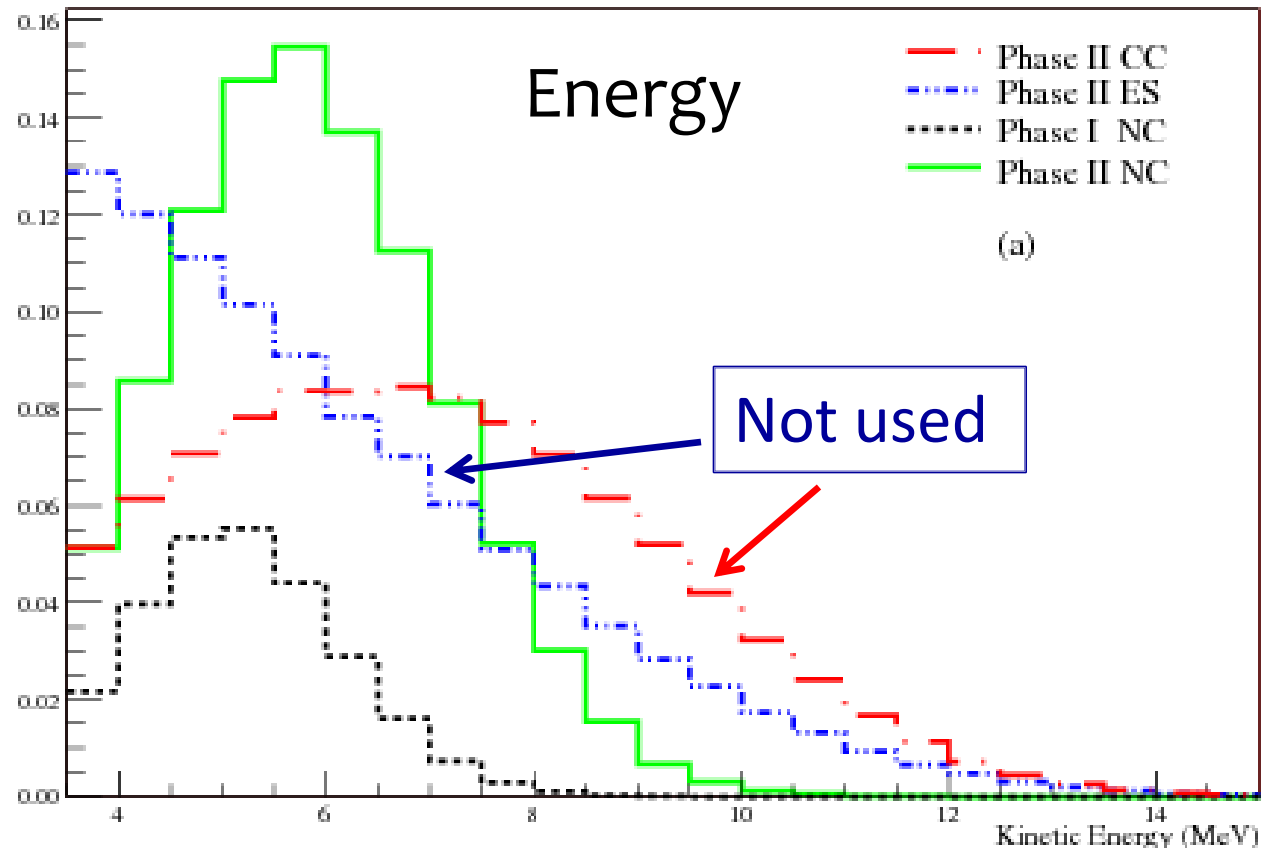
*NC statistics*



# 7) Signal Extraction Technique

## a) Fit for all signals + backgrounds

- Charged Current (CC)
- Elastic Scattering (ES)
- Neutral Current (NC)

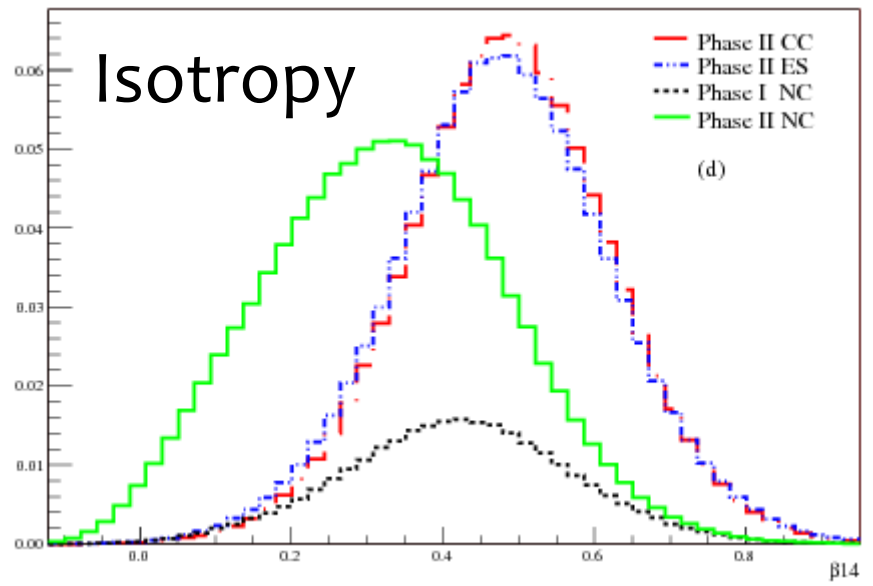
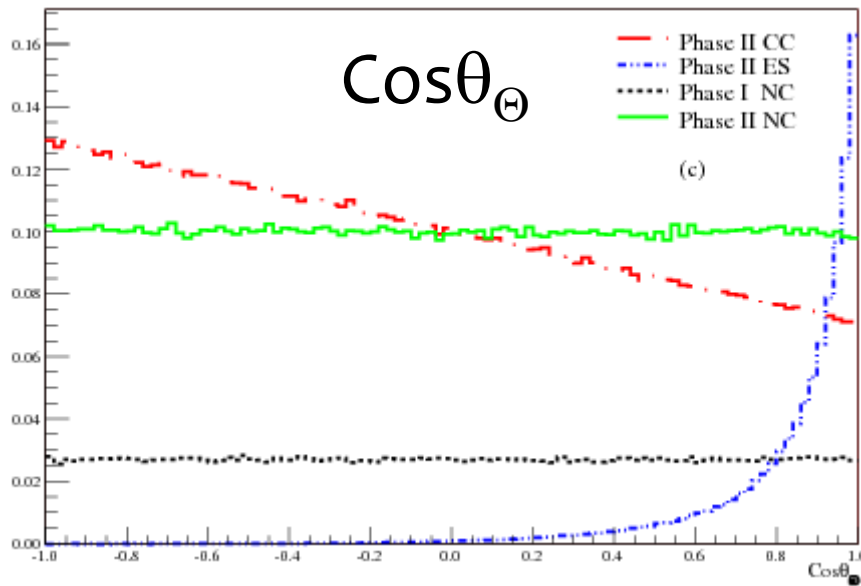
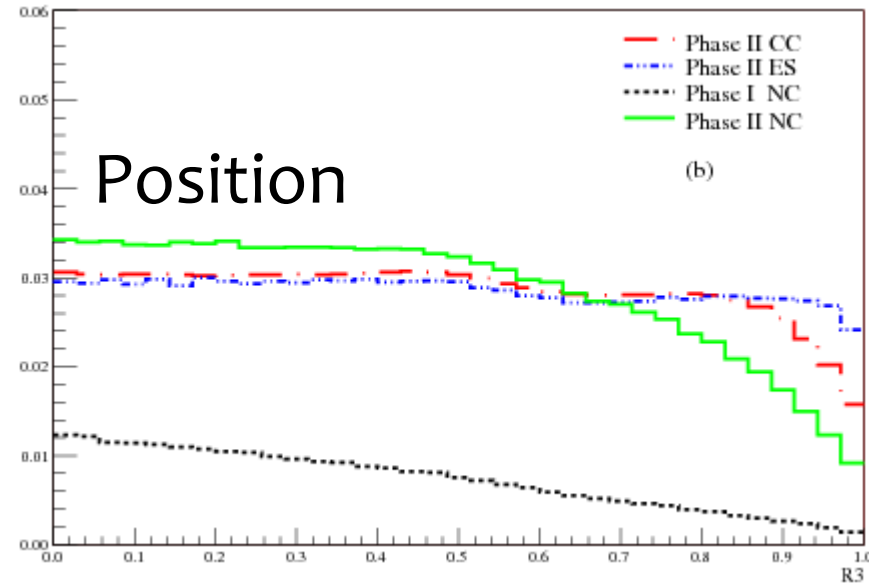


# 7) Signal Extraction Technique

## a) Fit for all signal

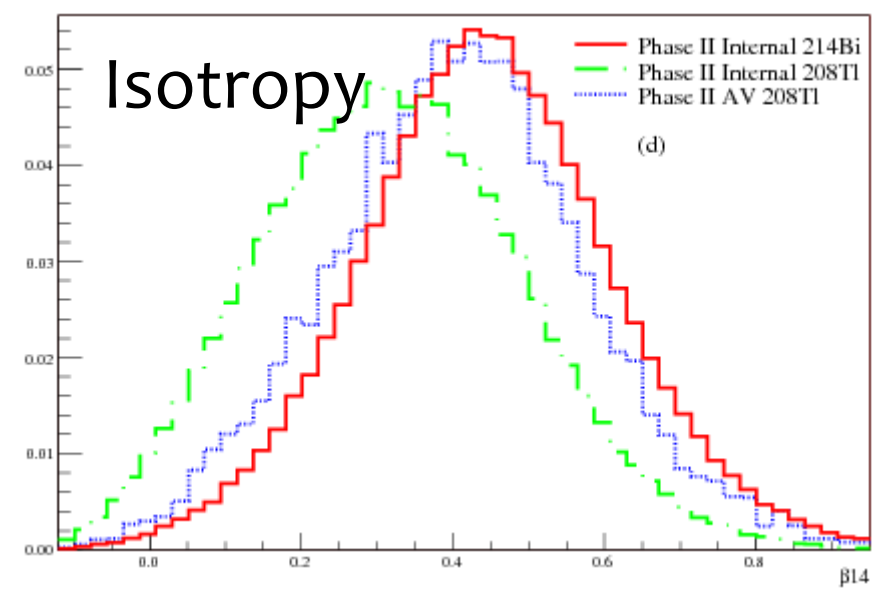
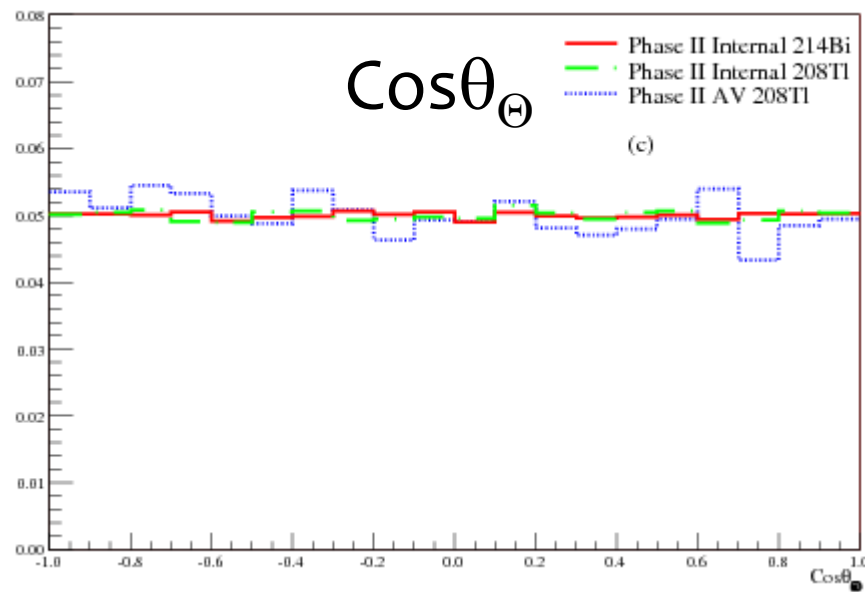
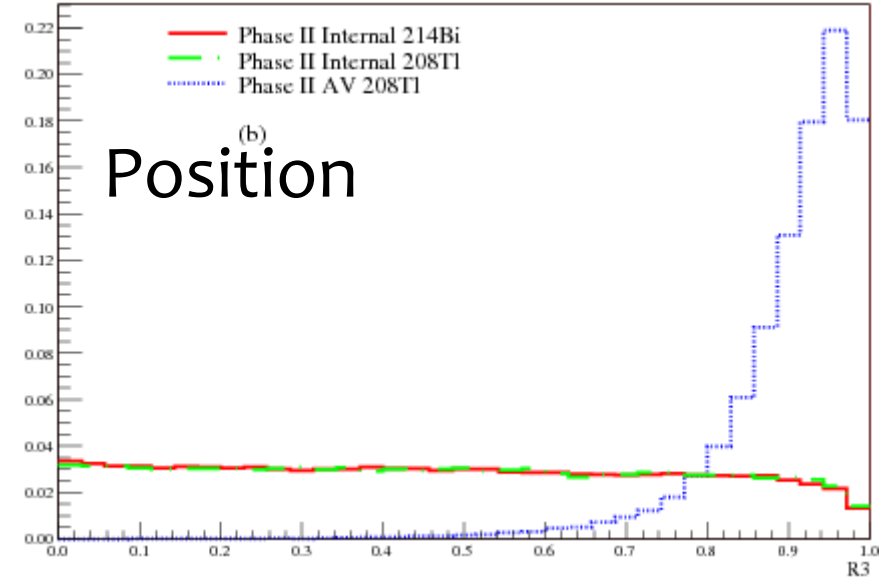
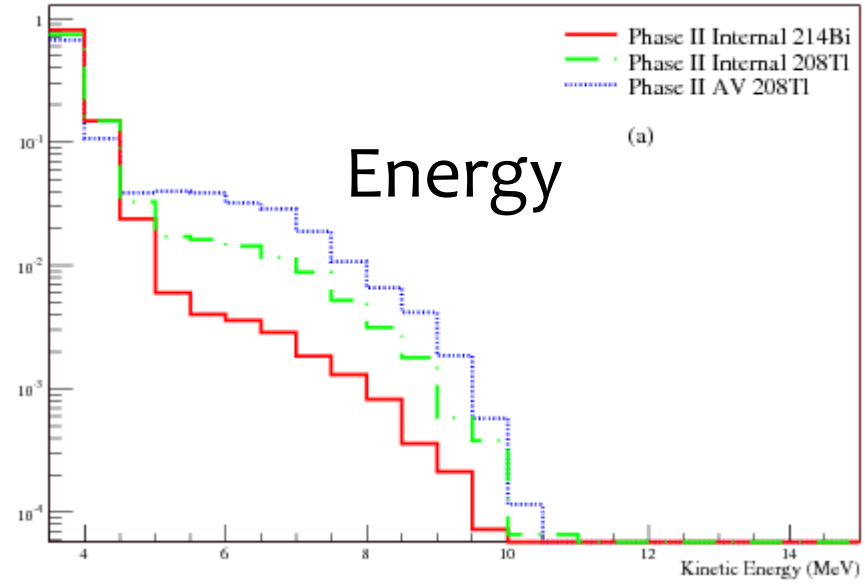
- Charged Current (CC)
- Elastic Scattering (ES)
- Neutral Current (NC)

### Fully 4D PDFs for CC & ES



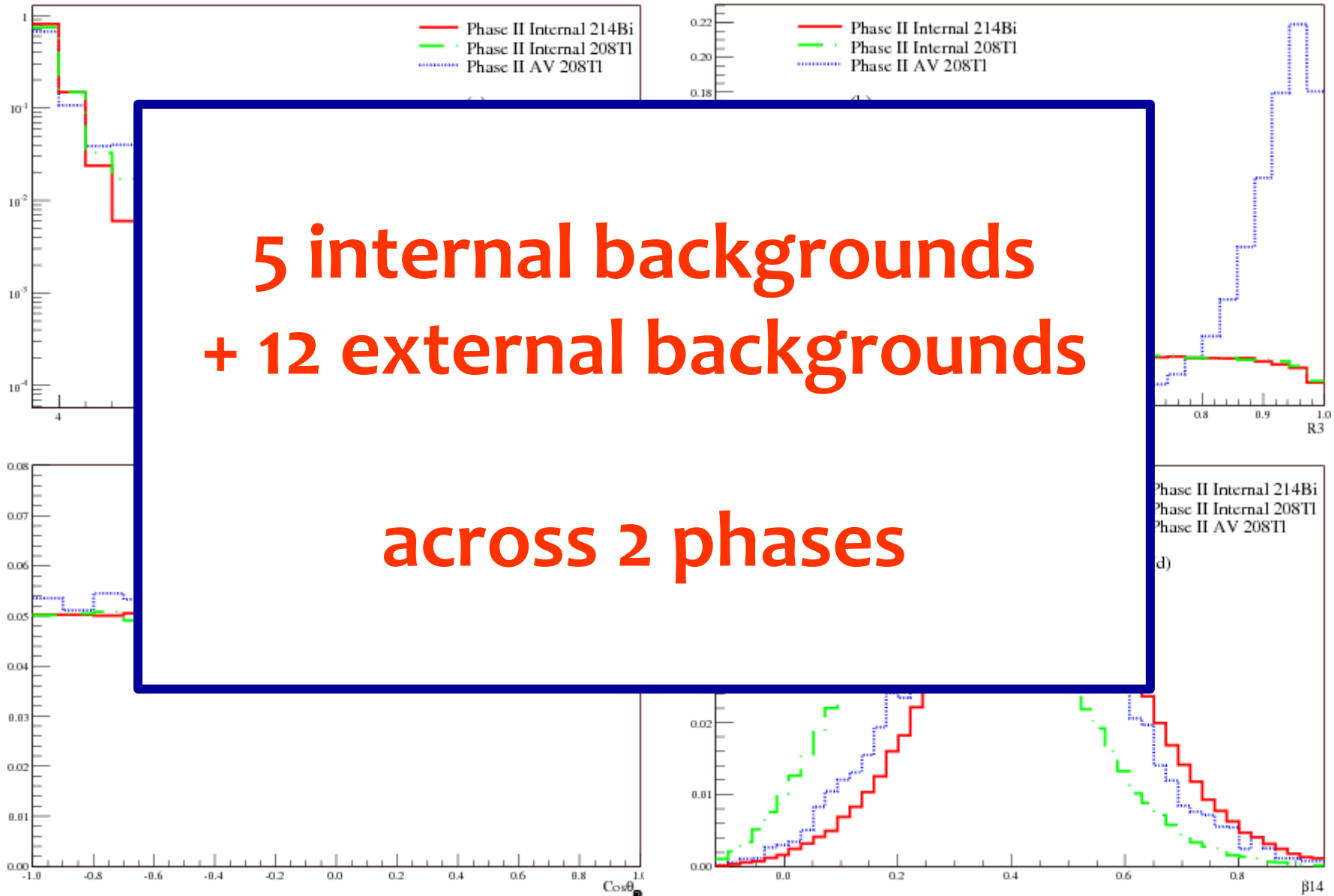
# 3D PDFs for NC & bkg (flat $\text{Cos}\theta_{\odot}$ )

- Internal  $^{214}\text{Bi}$
- Internal  $^{208}\text{Tl}$
- AV  $^{208}\text{Tl}$



# 3D PDFs for NC & bkg (flat $\text{Cos}\theta_{\odot}$ )

- Internal  $^{214}\text{Bi}$
- Internal  $^{208}\text{Tl}$
- AV  $^{208}\text{Tl}$



# 7) Signal Extraction Technique

b) 2 independent methods

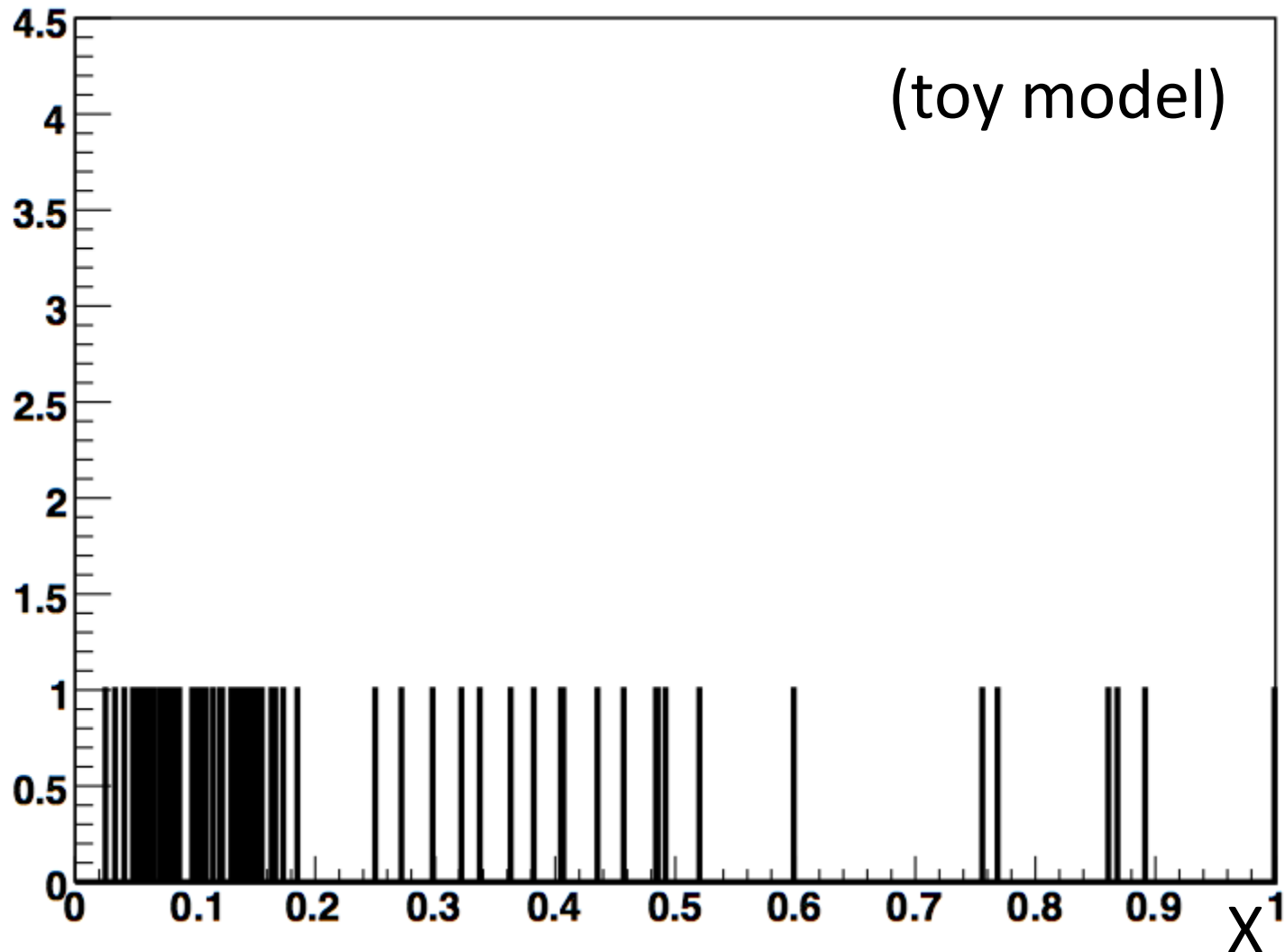
Binned histogram PDFs

VS

Kernel estimated PDFs

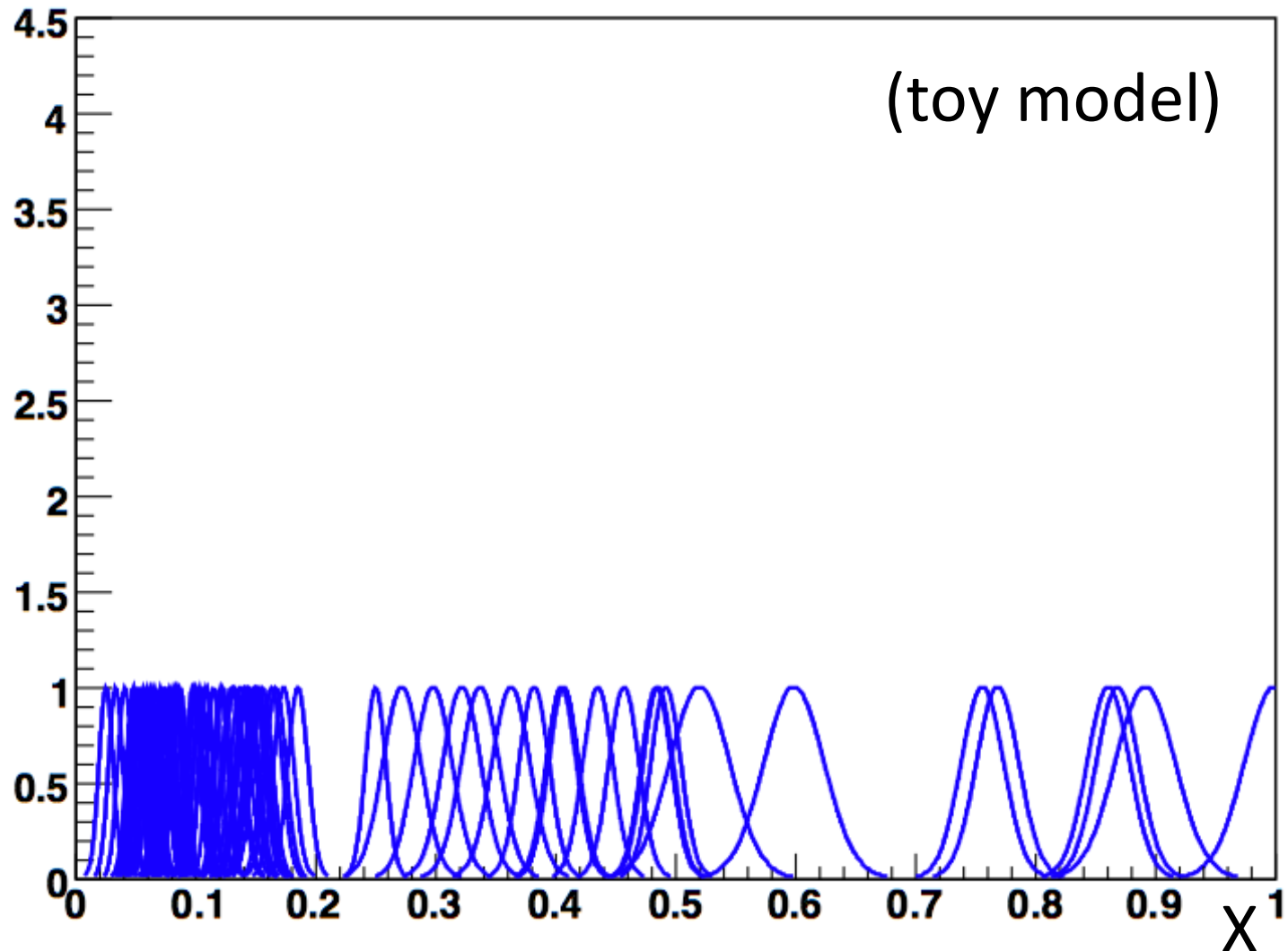
# 7) Signal Extraction Technique

## b) 2 independent methods



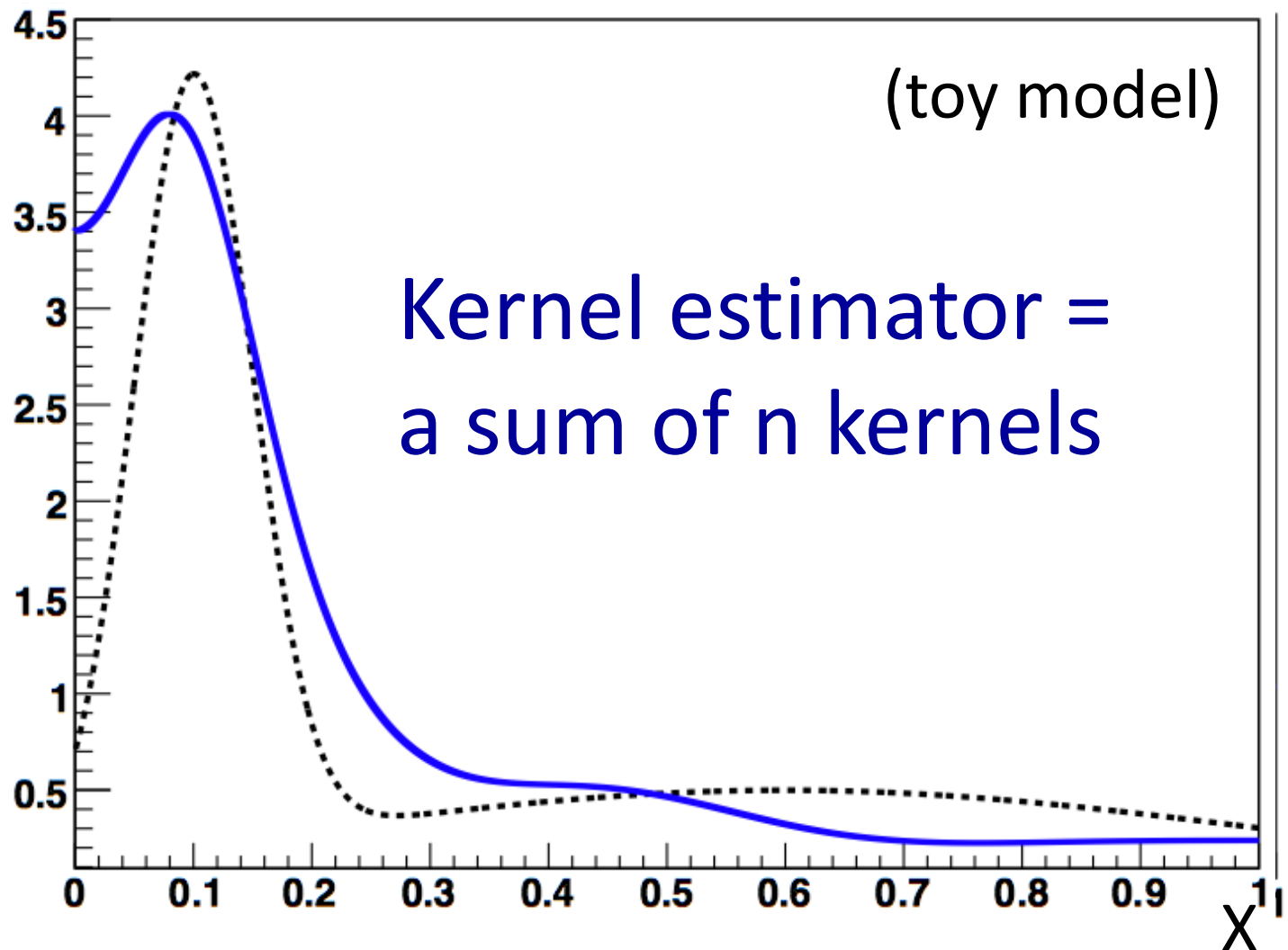
# 7) Signal Extraction Technique

b) 2 independent methods



# 7) Signal Extraction Technique

b) 2 independent methods



# 7) Signal Extraction Technique

c) 'Float' dominant systematic uncertainties

Binned histogram PDFs

*Iterative scan of likelihood space*

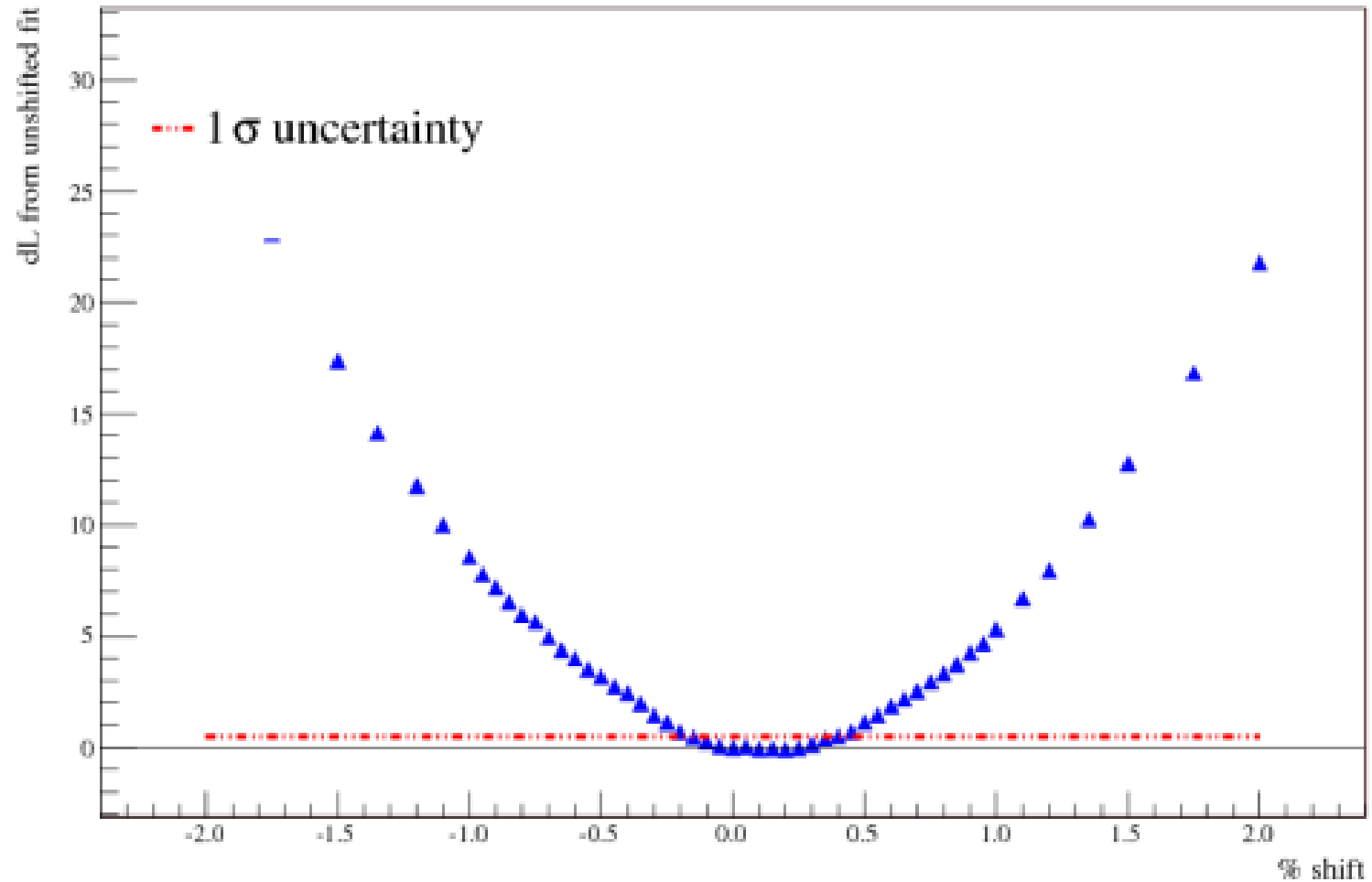
VS

Kernel estimated PDFs

*Directly float systematics as parameters  
in the fit*

# 7) Signal Extraction Technique

## c) 'Float' dominant systematic uncertainties

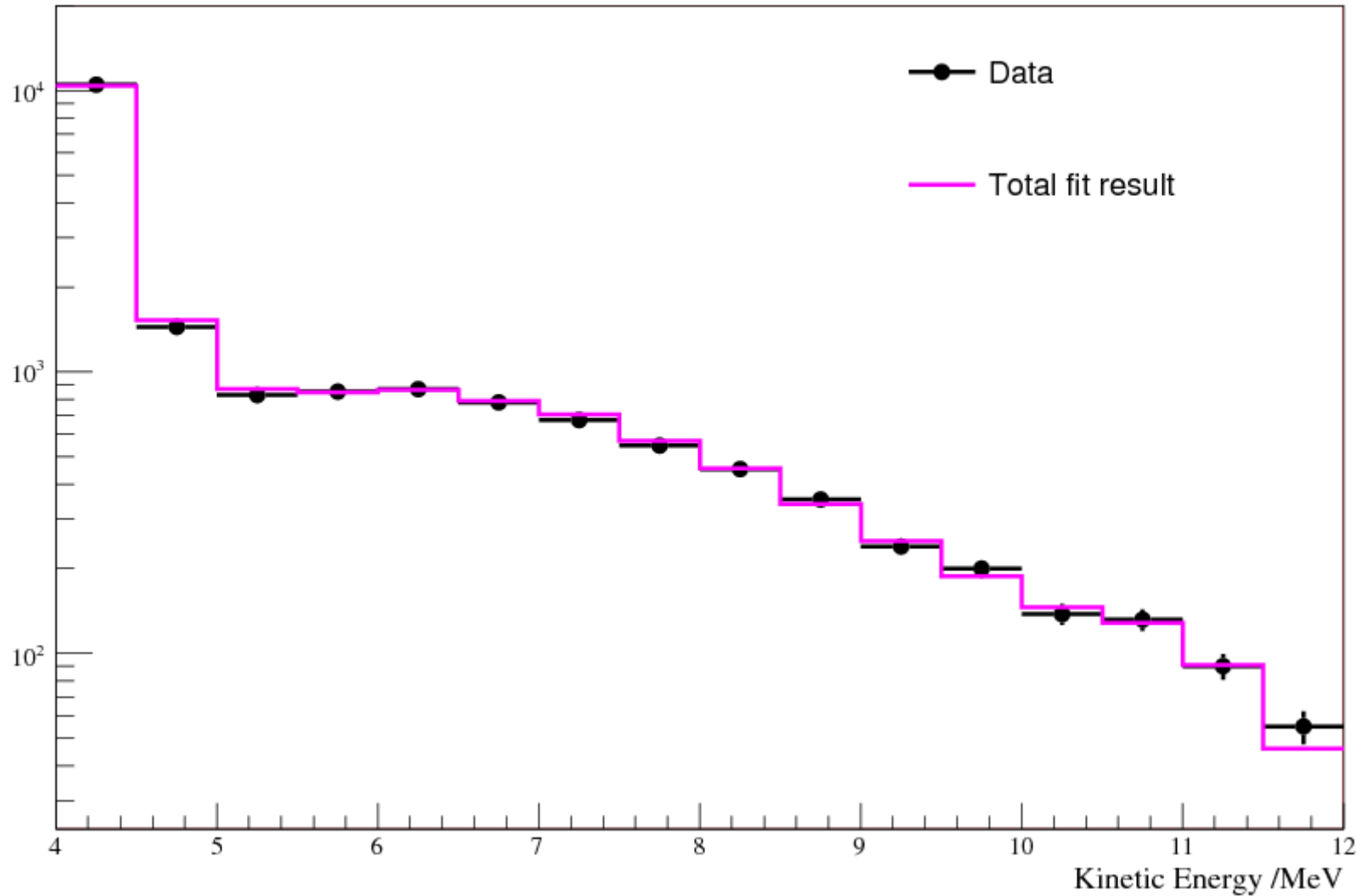


# Final Results

$$\chi^2 = 13.6 / 16$$

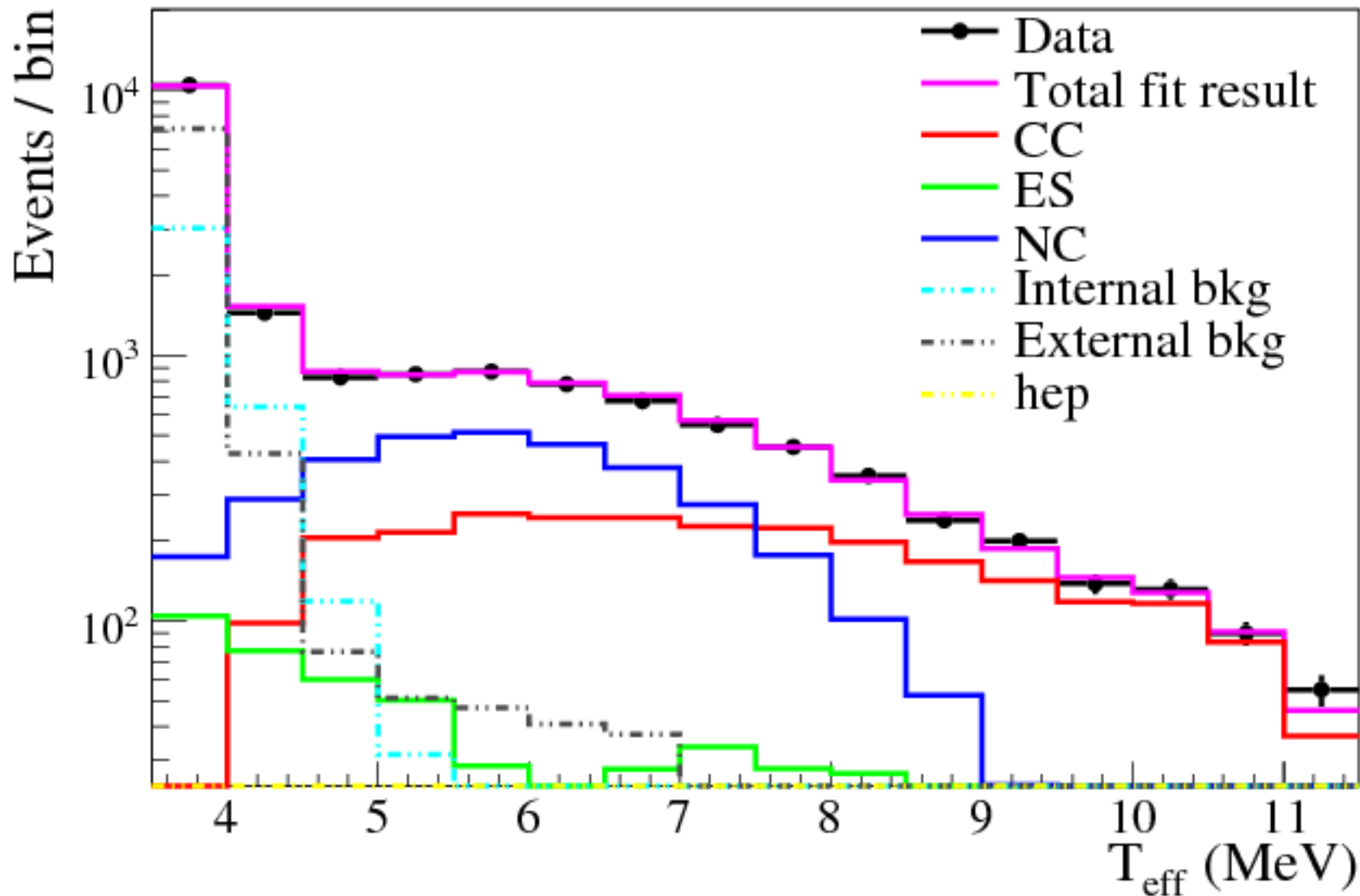
# Fit Result

Salt Energy fit



$\chi^2 = 13.6 / 16$

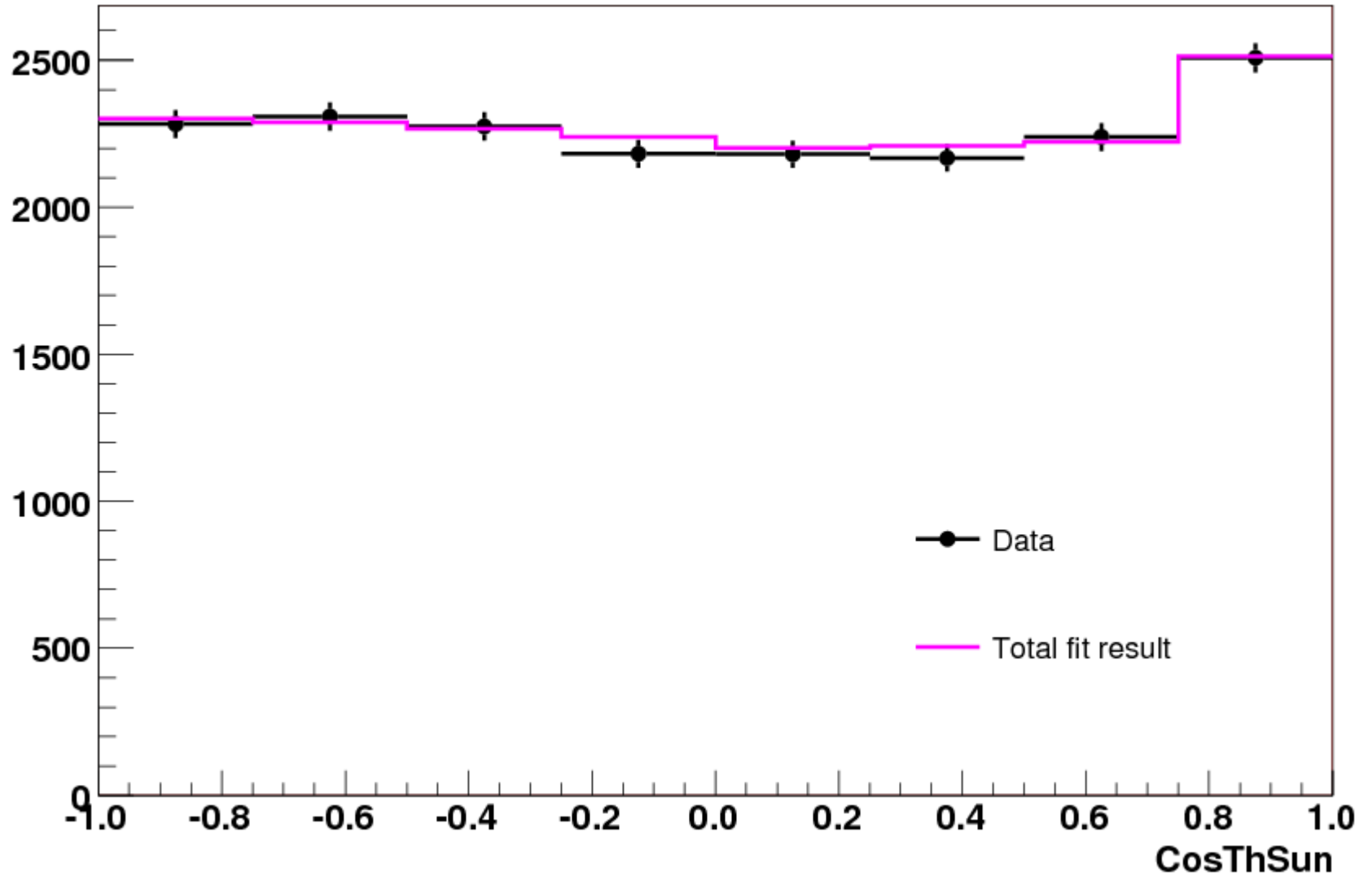
# Fit Result



$$\chi^2 = 3.1 / 8$$

# Fit Result

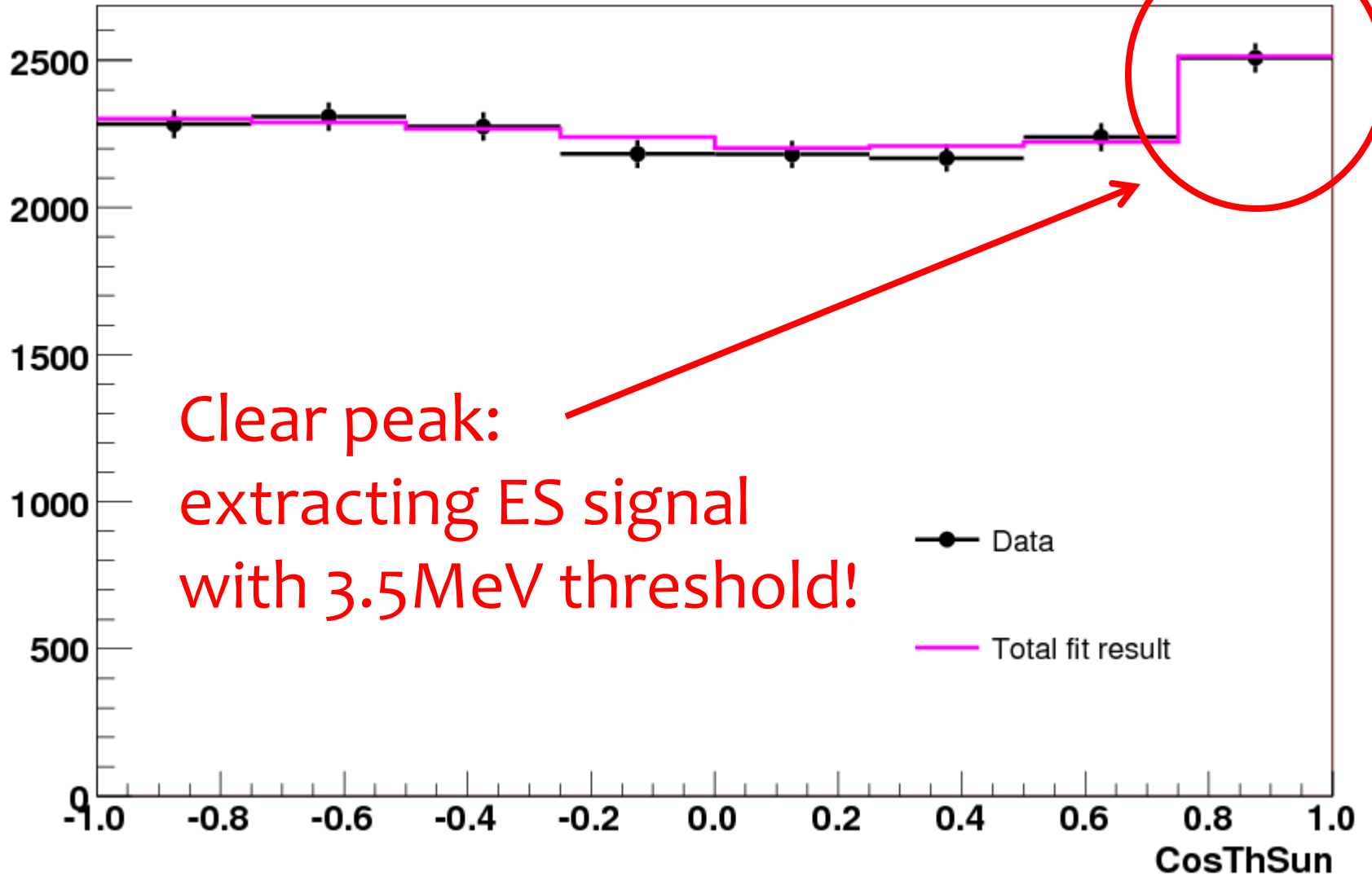
Salt CosThSun fit



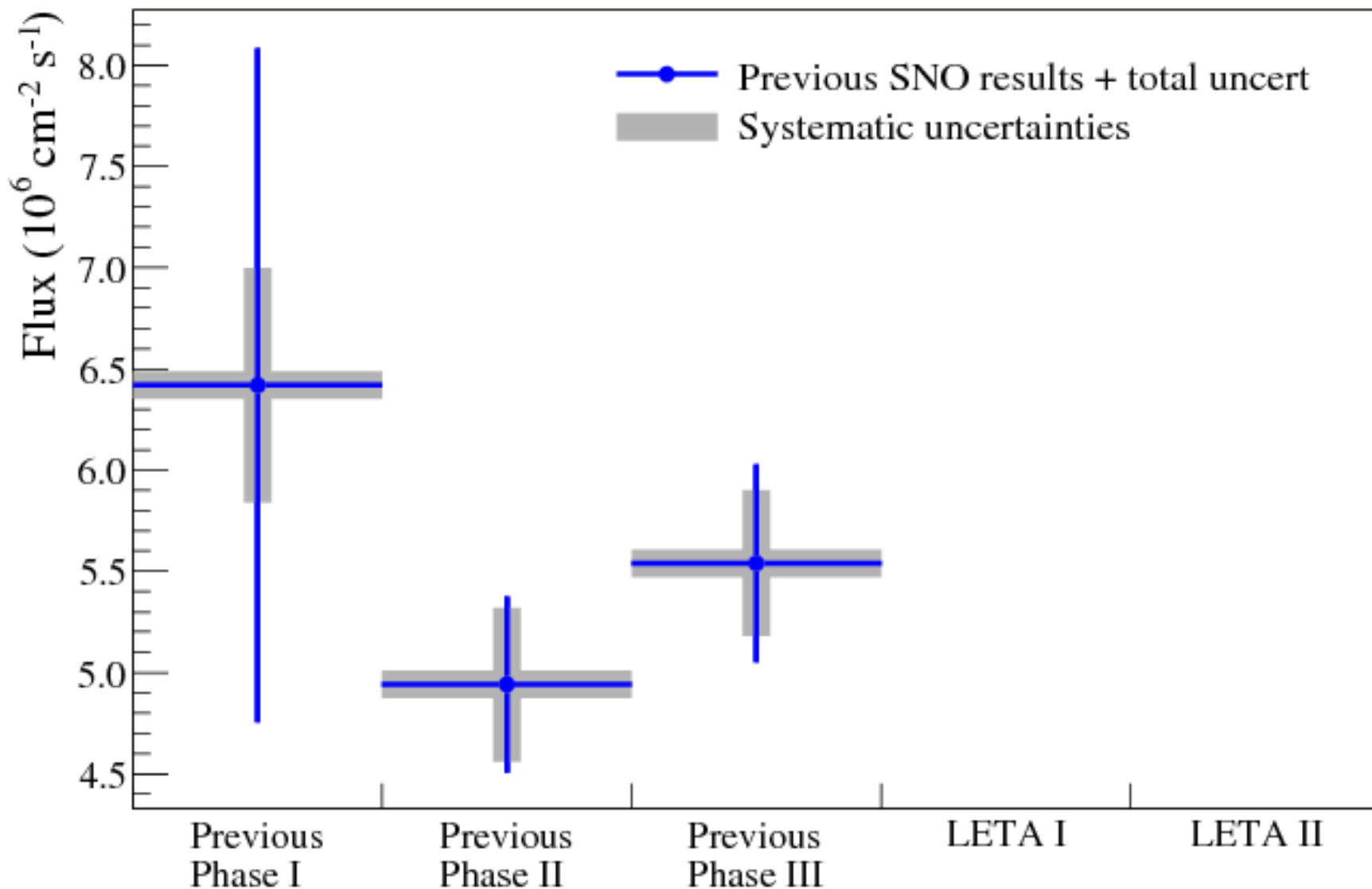
$$\chi^2 = 3.1 / 8$$

# Fit Result

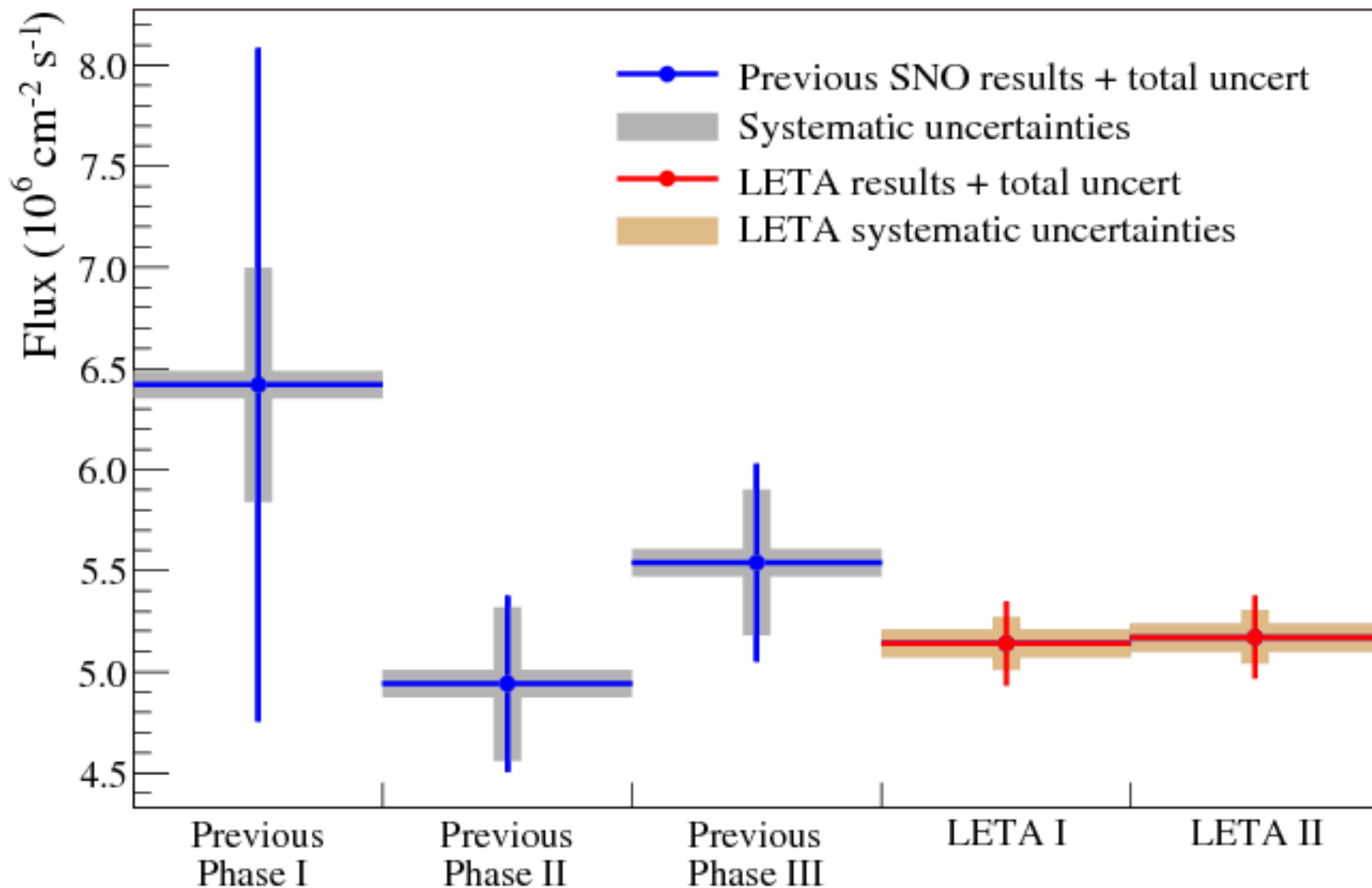
Salt CosThSun fit



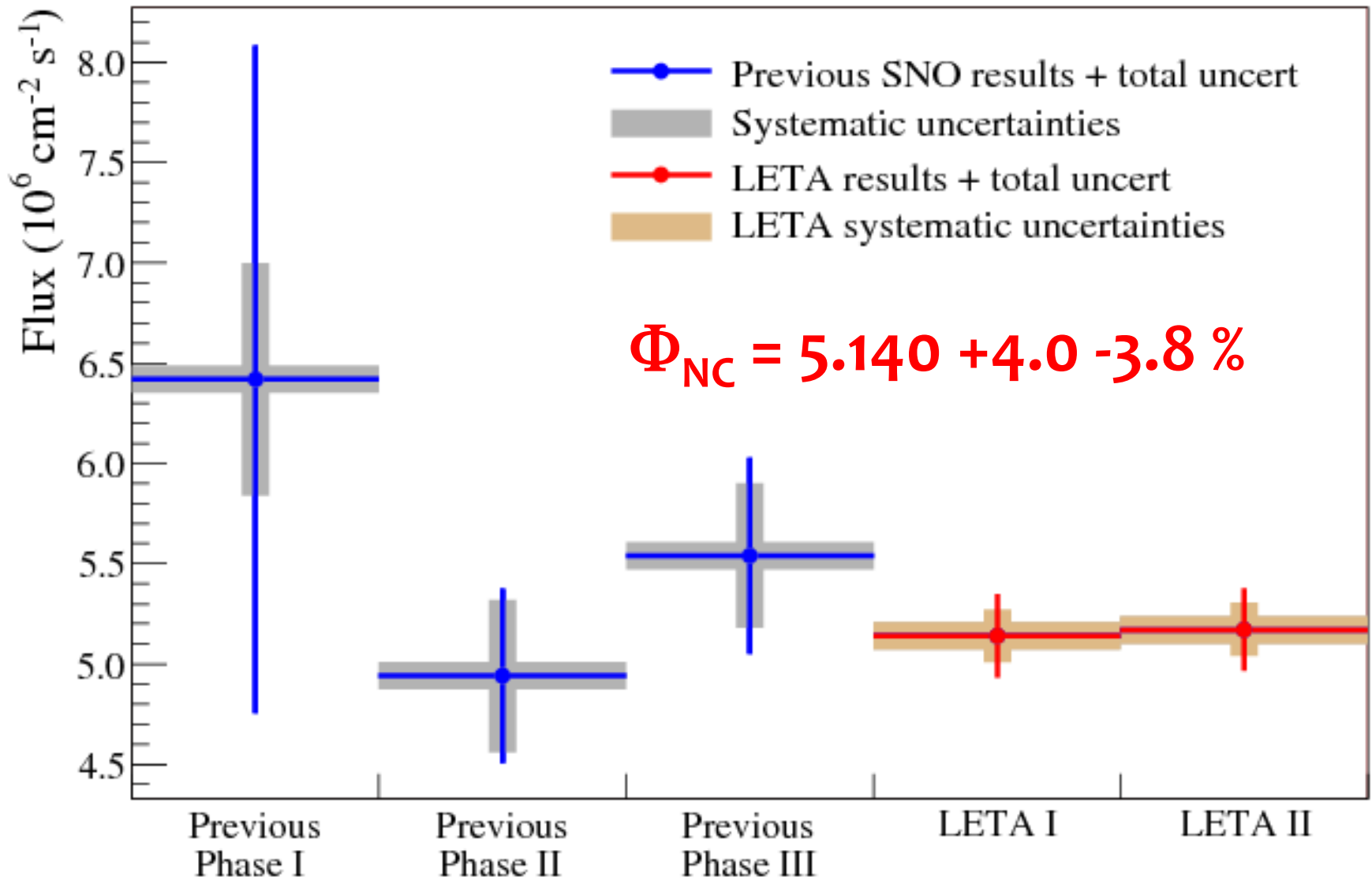
# $^8\text{B}$ Flux Result



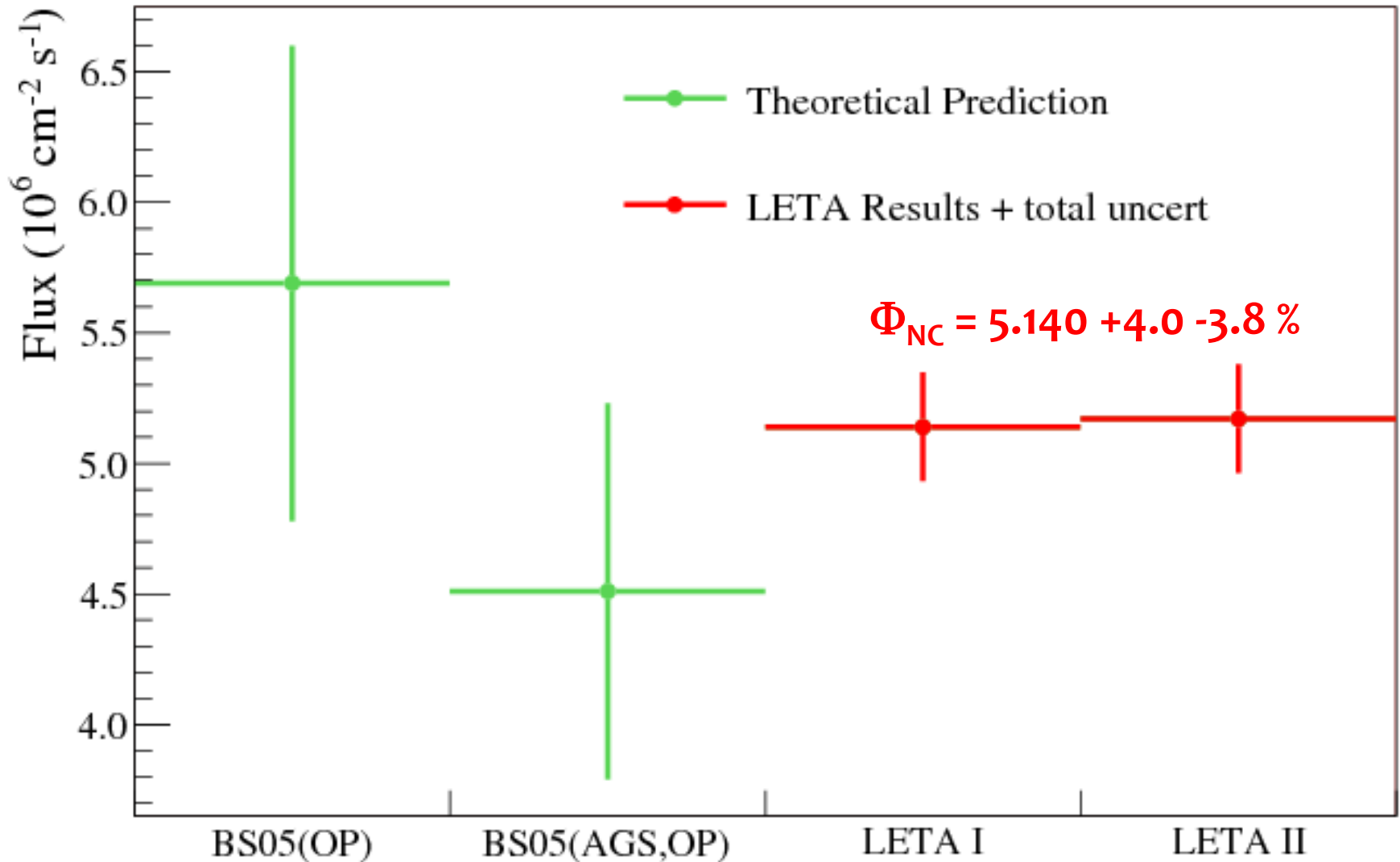
# $^8\text{B}$ Flux Result



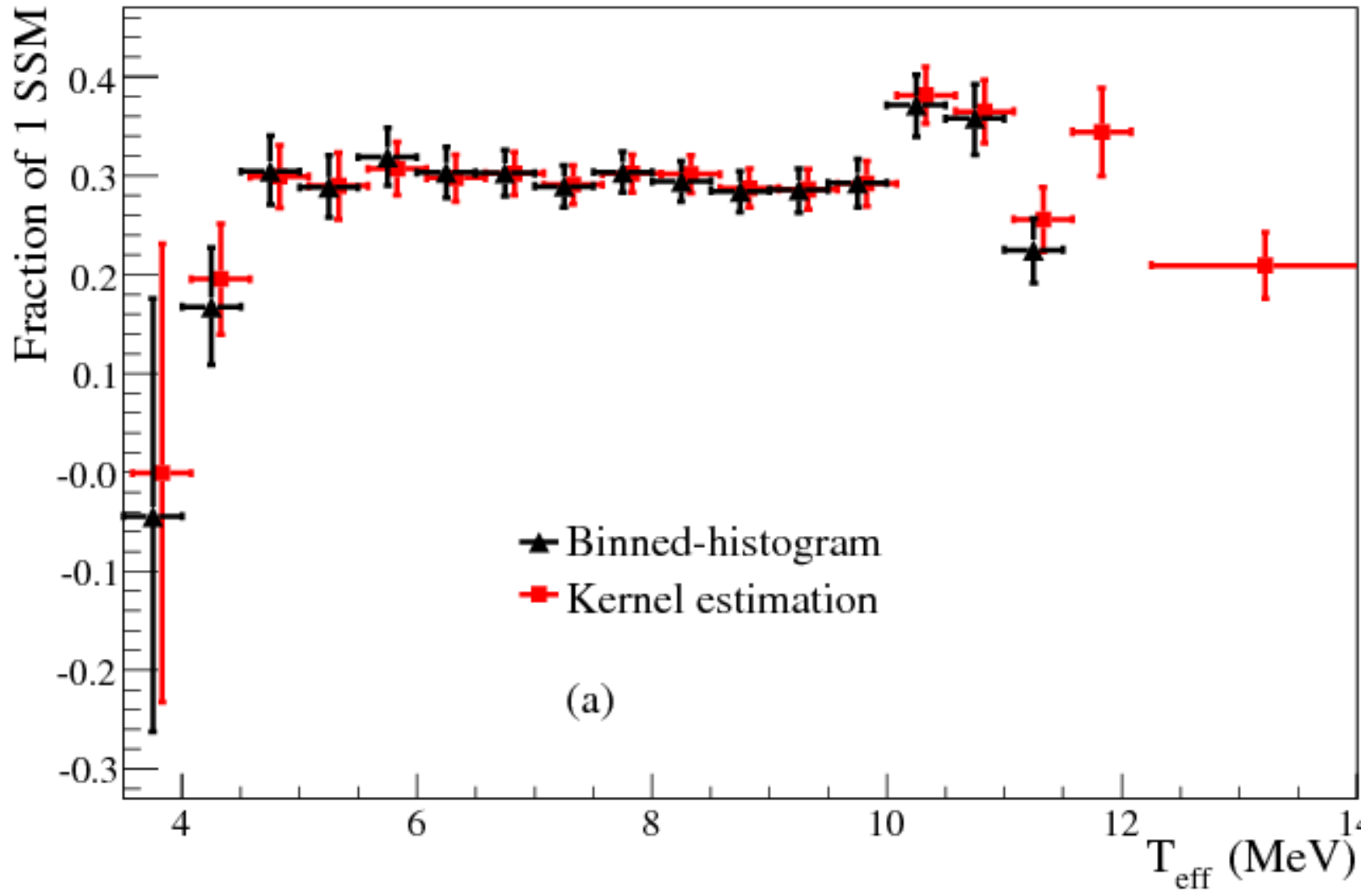
# $^8\text{B}$ Flux Result



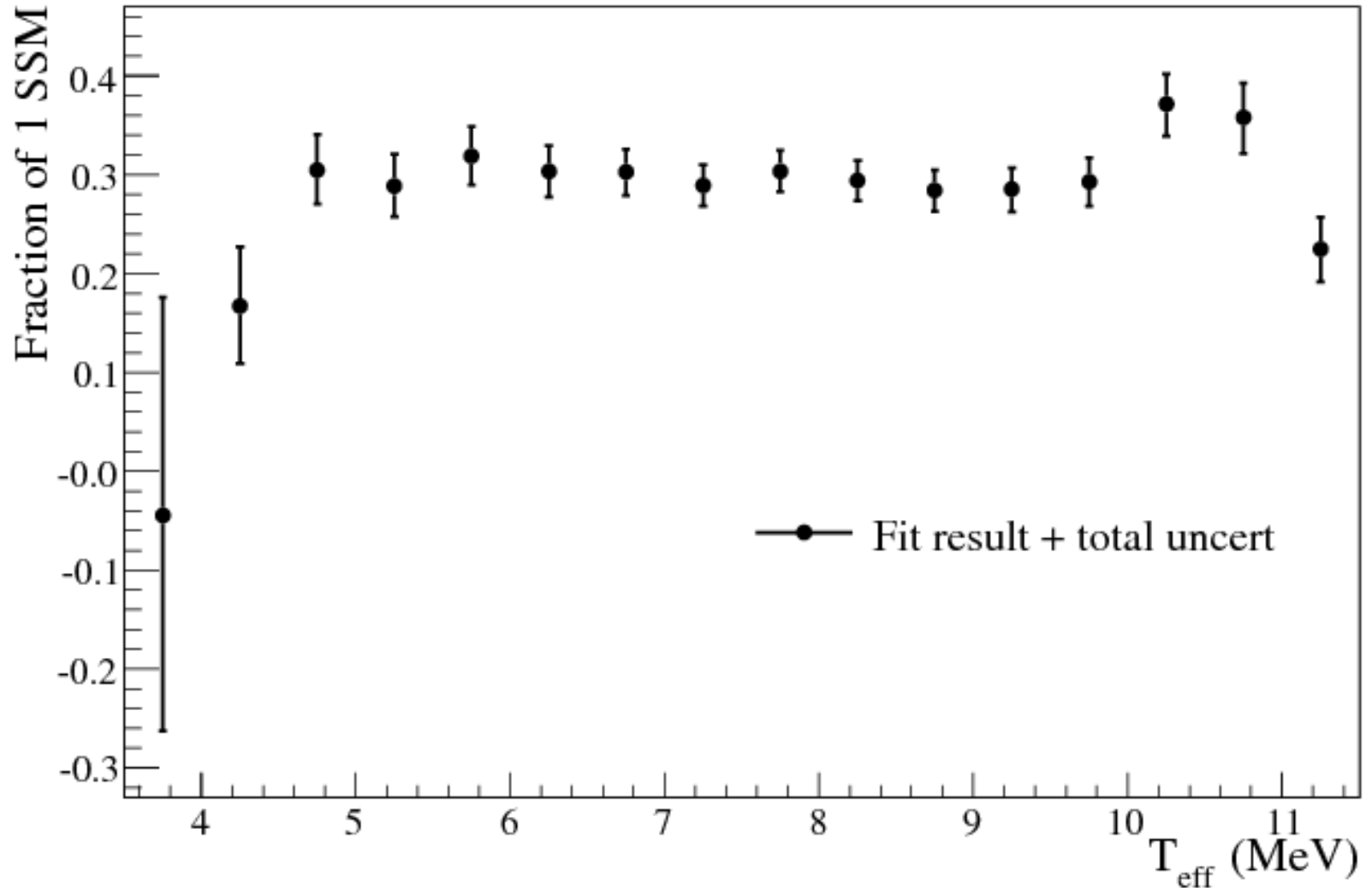
# $^8\text{B}$ Flux Result



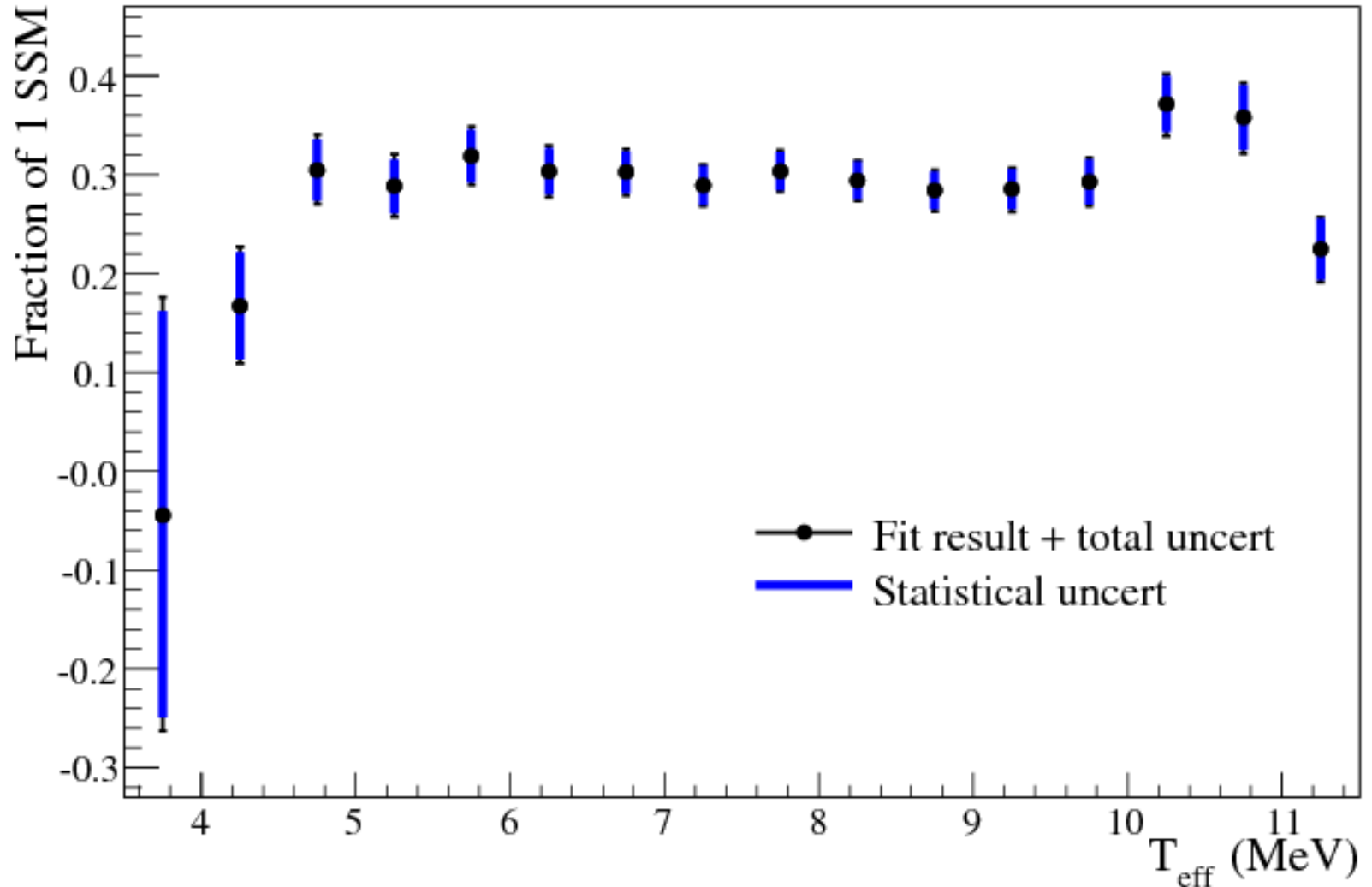
# CC Recoil-Electron Spectrum



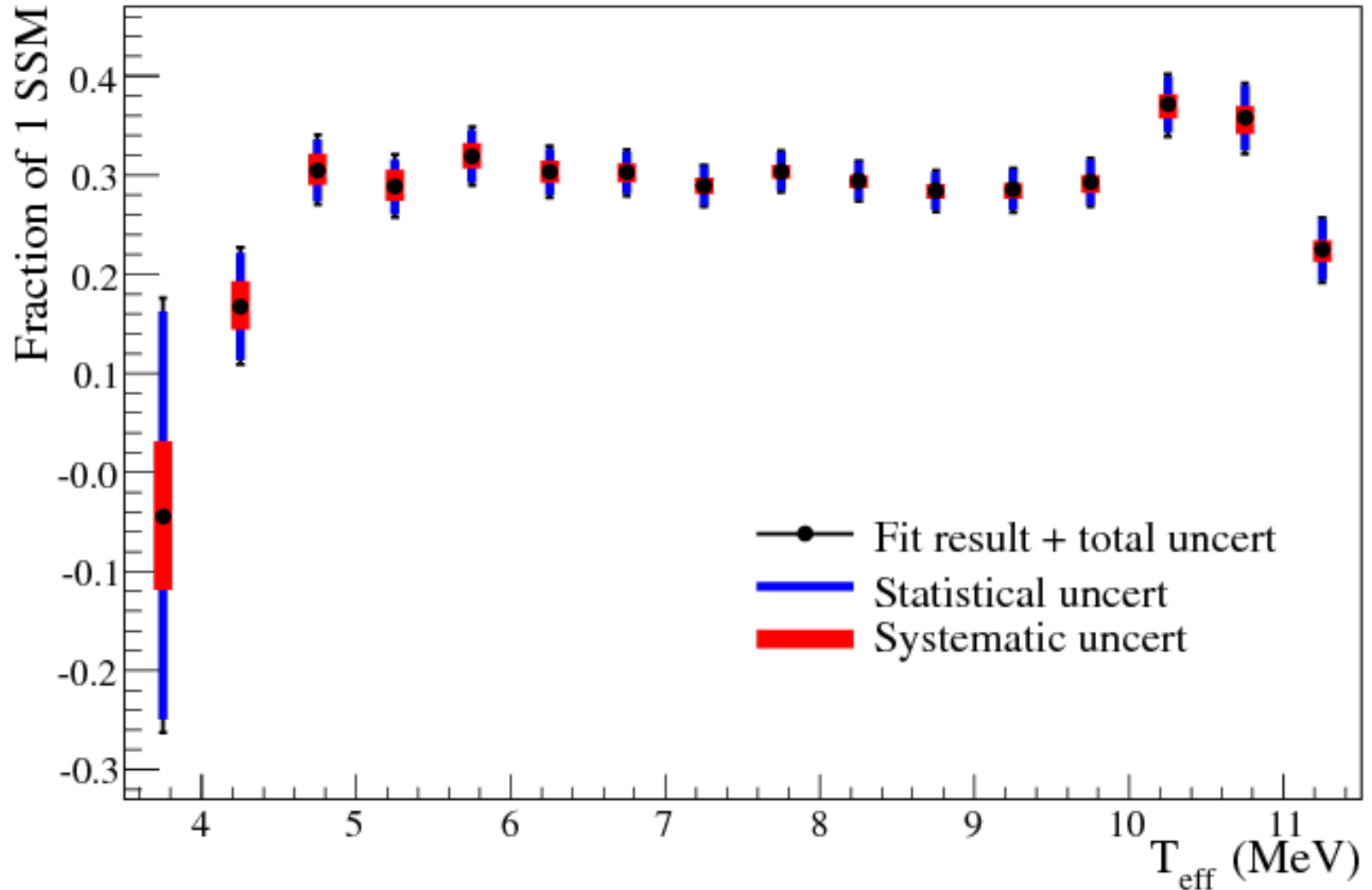
# CC Recoil-Electron Spectrum



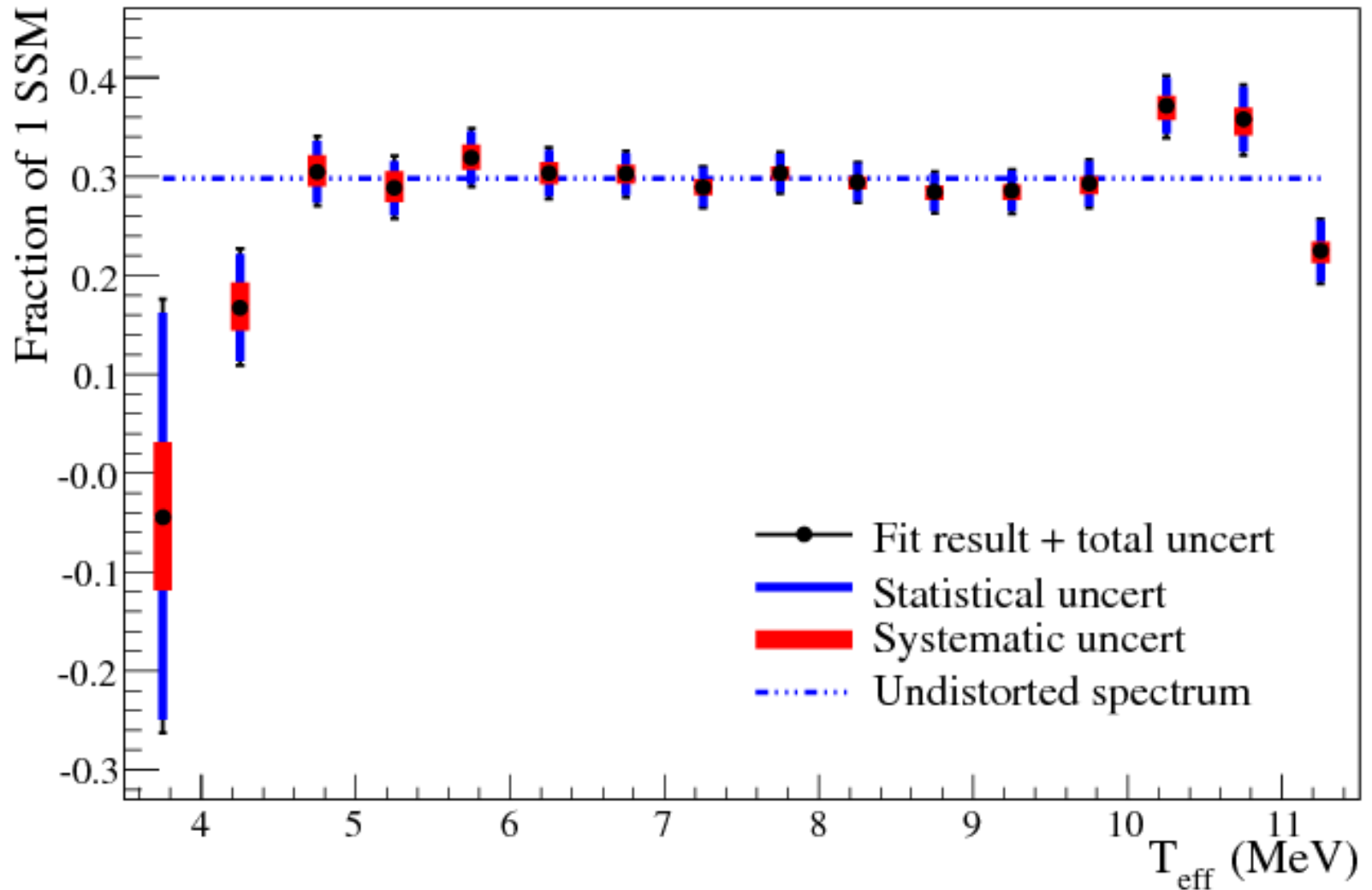
# CC Recoil-Electron Spectrum



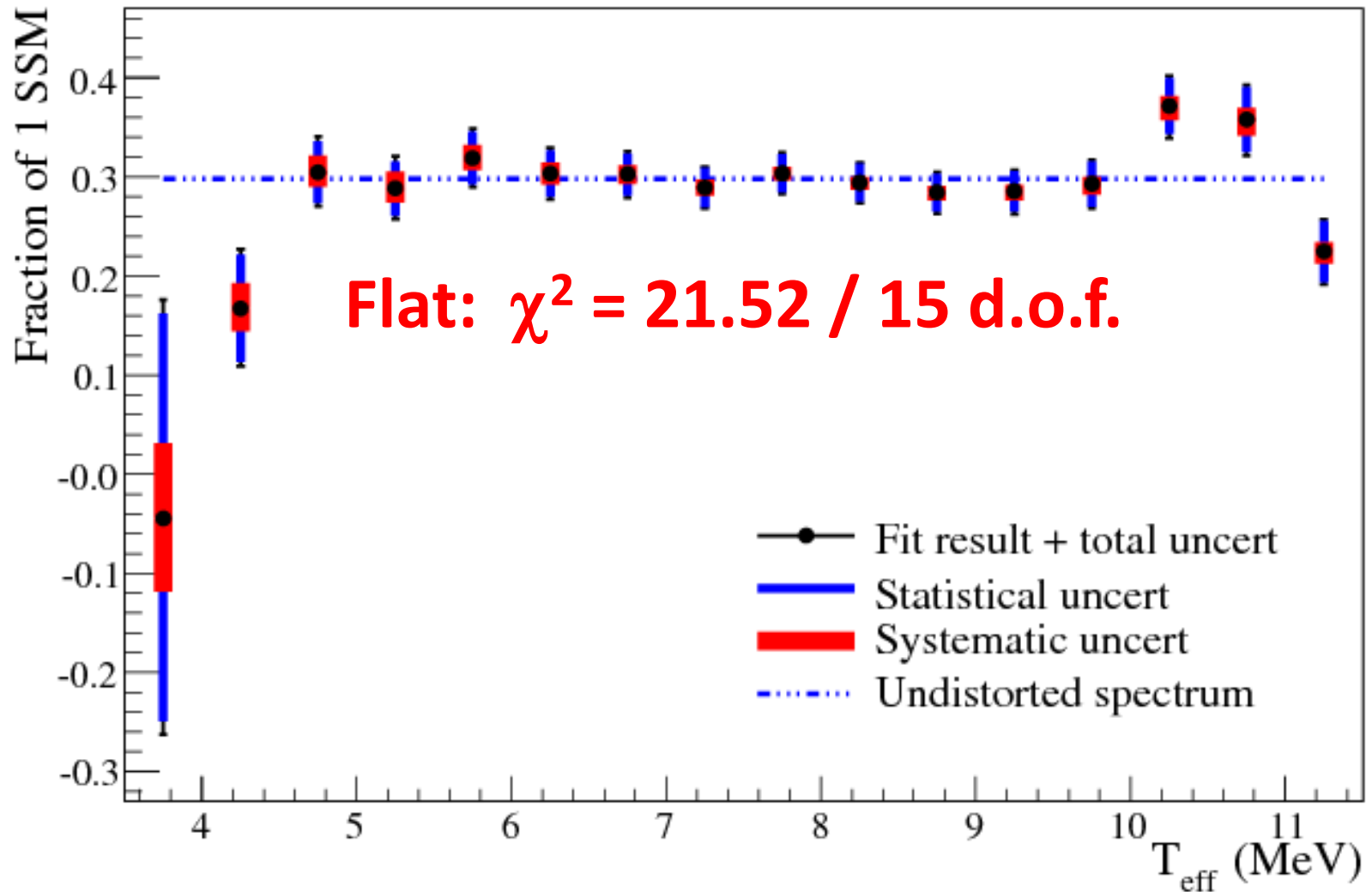
# CC Recoil-Electron Spectrum



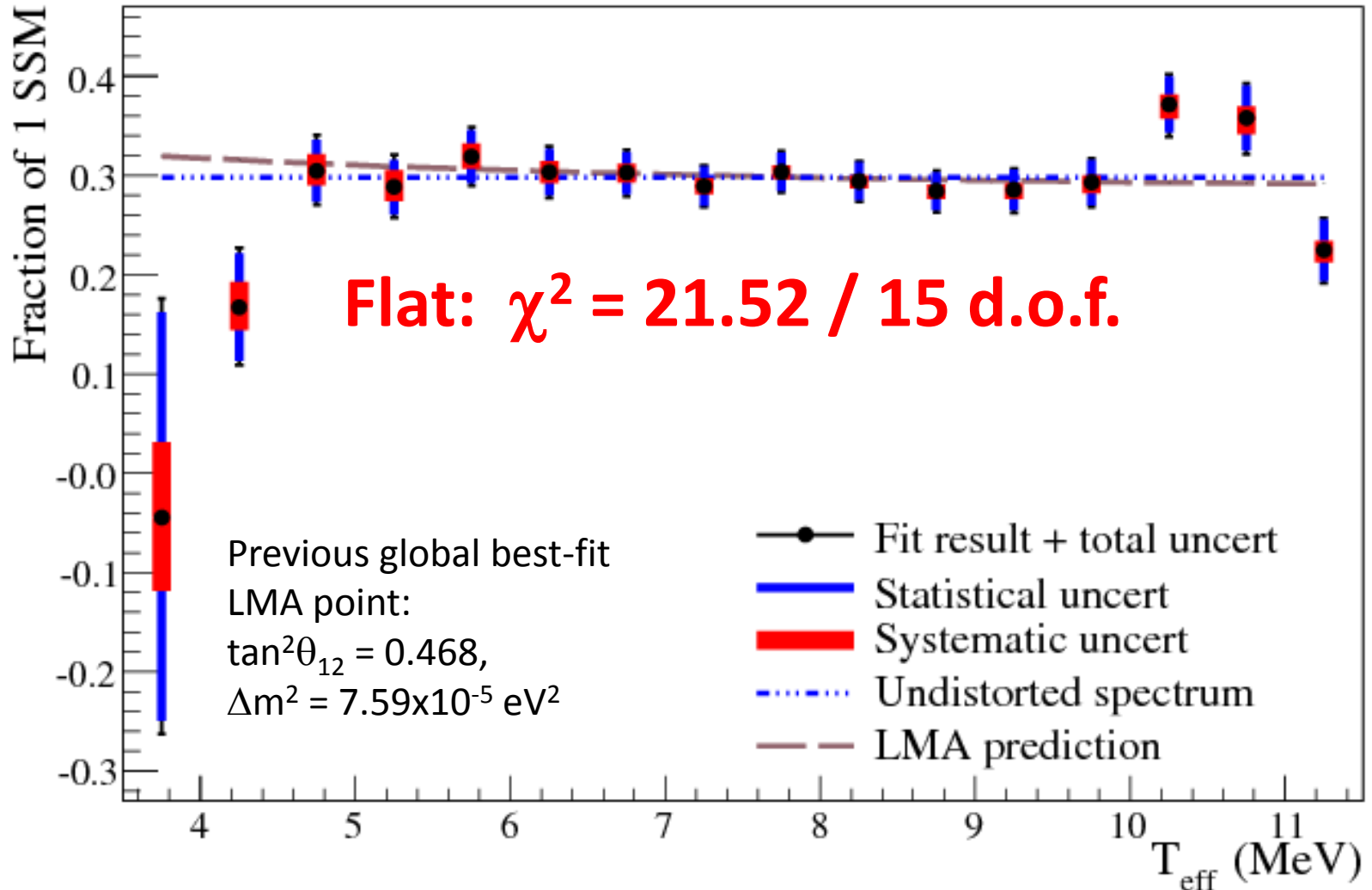
# CC Recoil-Electron Spectrum



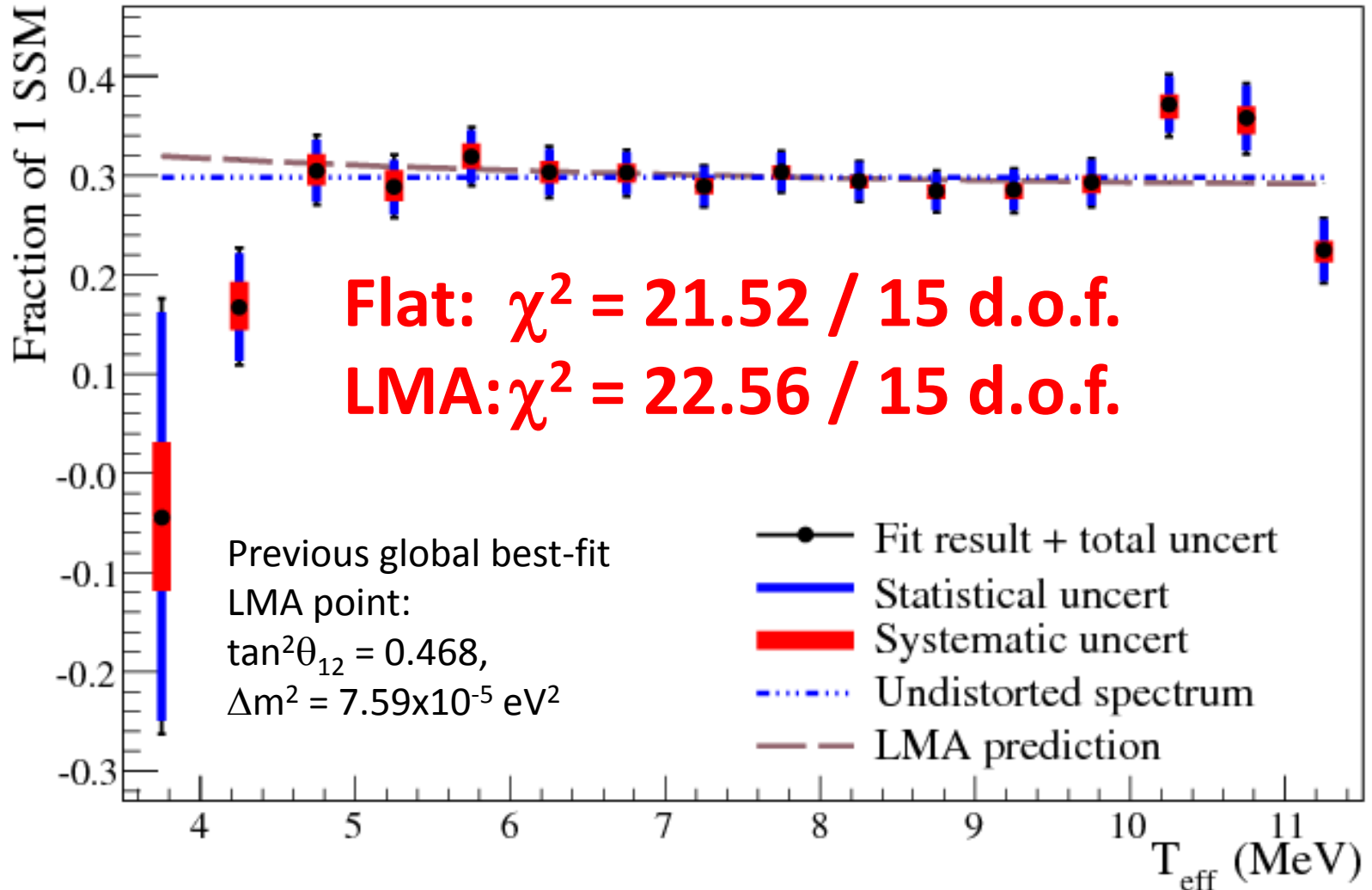
# CC Recoil-Electron Spectrum



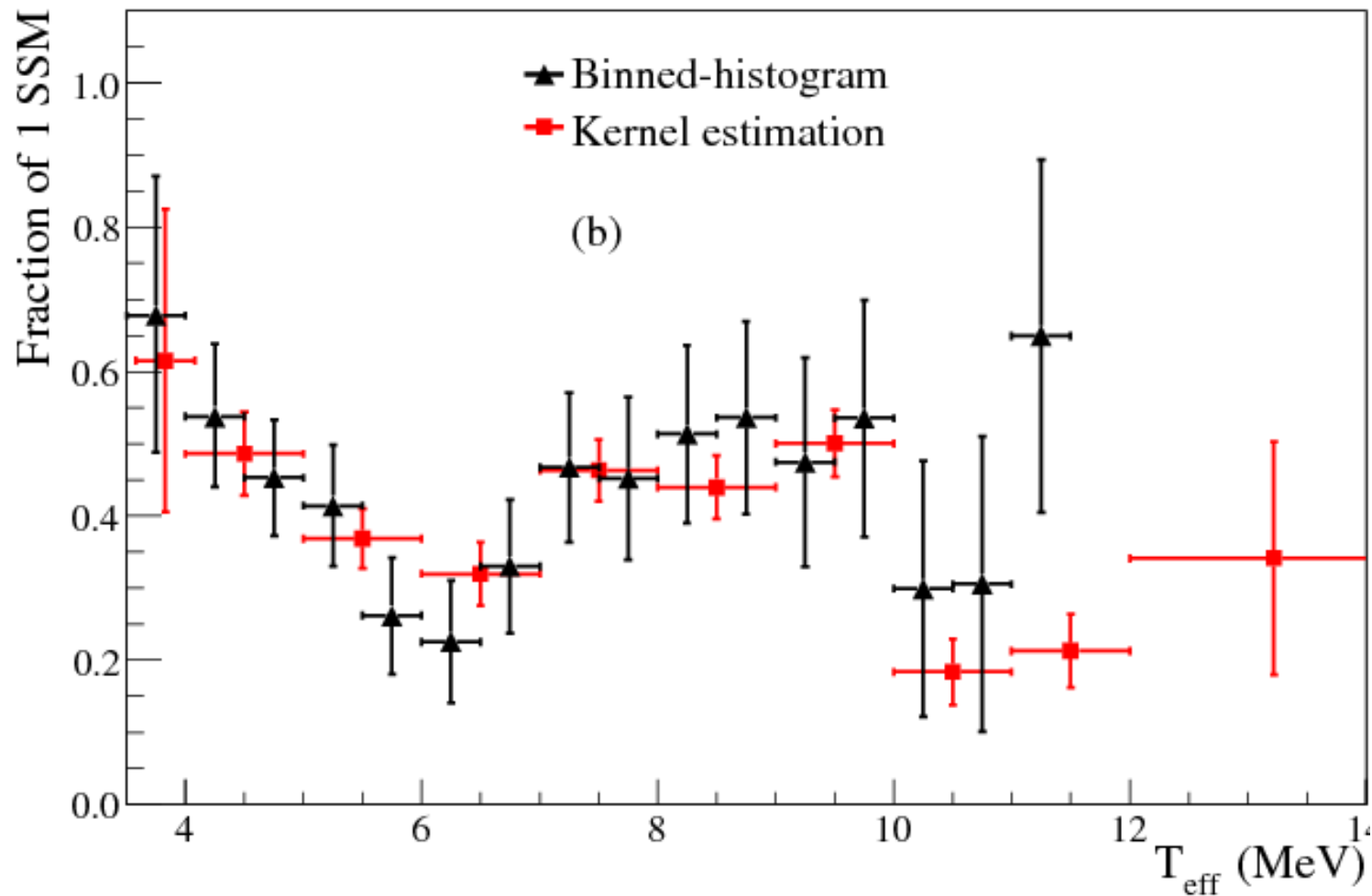
# CC Recoil-Electron Spectrum



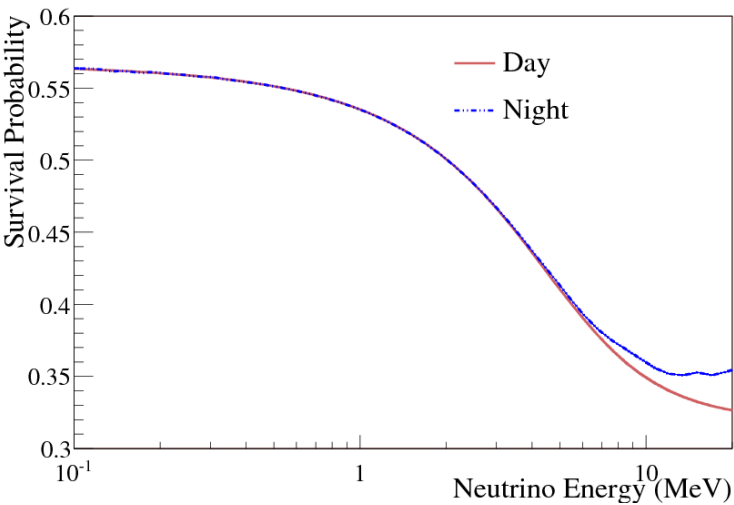
# CC Recoil-Electron Spectrum



# ES Recoil-Electron Spectrum



# Direct Fit for Energy-Dependent Survival Probability

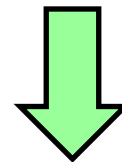


Neutrino signal directly described by 6 parameters:

1.  $\Phi_{8B}$ : total  $^8B$  neutrino flux
2.  $c0, c1, c2$ : quadratic expansion of the  $\nu_e$  daytime  $P_{ee}$  around  $E_\nu = 10$  MeV
3.  $a0, a1$ : linear expansion of a day/night asymmetry around  $E_\nu = 10$  MeV

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

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

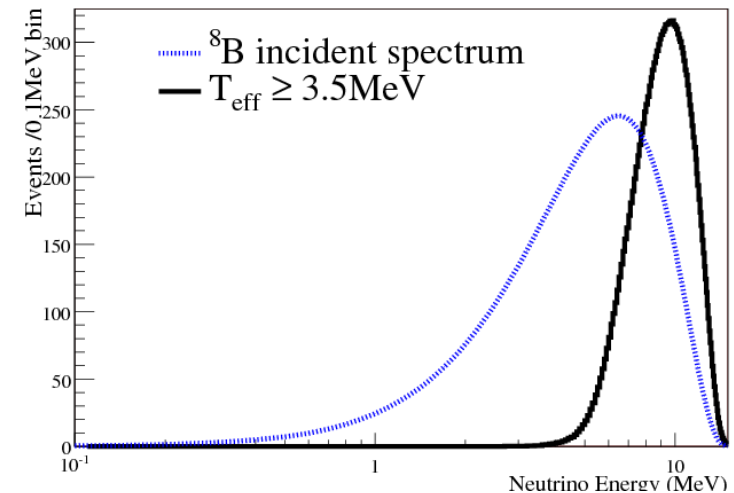
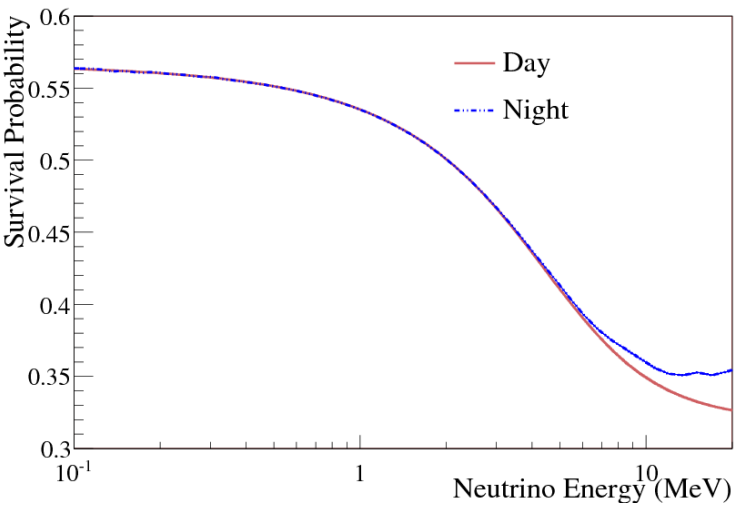


$$P_{ee}^{NIGHT}(E_\nu) = P_{ee}^{DAY}(E_\nu) \times \frac{[1 + (1/2) * P_{ee}^{ASYM}(E_\nu)]}{[1 - (1/2) * P_{ee}^{ASYM}(E_\nu)]}$$

# Direct Fit for Energy-Dependent Survival Probability

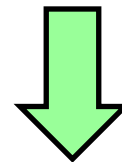
Neutrino signal directly described by 6 parameters:

1.  $\Phi_{8B}$ : total  $^8B$  neutrino flux
2.  $c_0, c_1, c_2$ : quadratic expansion of the  $\nu_e$  daytime  $P_{ee}$  around  $E_\nu = 10$  MeV
3.  $a_0, a_1$ : linear expansion of a day/night asymmetry around  $E_\nu = 10$  MeV



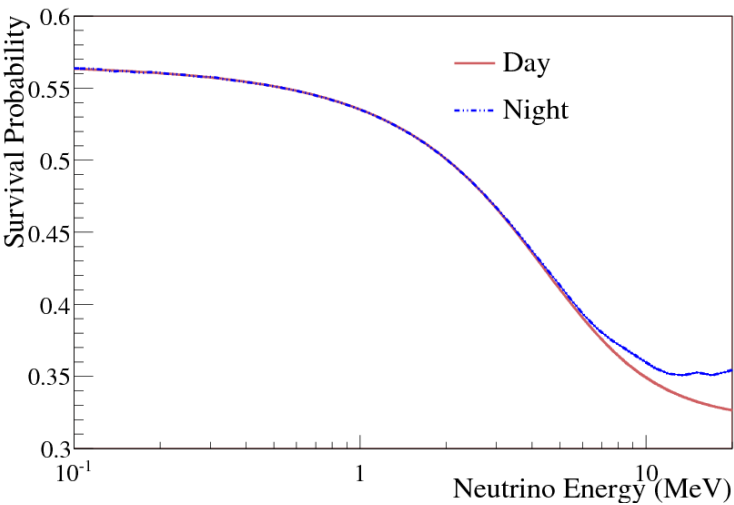
$$P_{ee}^{DAY}(E_\nu) = c_0 + c_1 (E_\nu - 10 \text{ MeV}) + c_2 (E_\nu - 10 \text{ MeV})^2$$

$$P_{ee}^{ASYM}(E_\nu) = a_0 + a_1 (E_\nu - 10 \text{ MeV})$$



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

# Direct Fit for Energy-Dependent Survival Probability



$$\Phi_{8B} = 5.046$$

$$+3.8 -3.9 \%$$

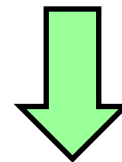
*Assuming unitarity*

Neutrino signal directly described by 6 parameters:

1.  $\Phi_{8B}$ : total  $^8B$  neutrino flux
2.  $c0, c1, c2$ : quadratic expansion of the  $\nu_e$  daytime  $P_{ee}$  around  $E_\nu = 10$  MeV
3.  $a0, a1$ : linear expansion of a day/night asymmetry around  $E_\nu = 10$  MeV

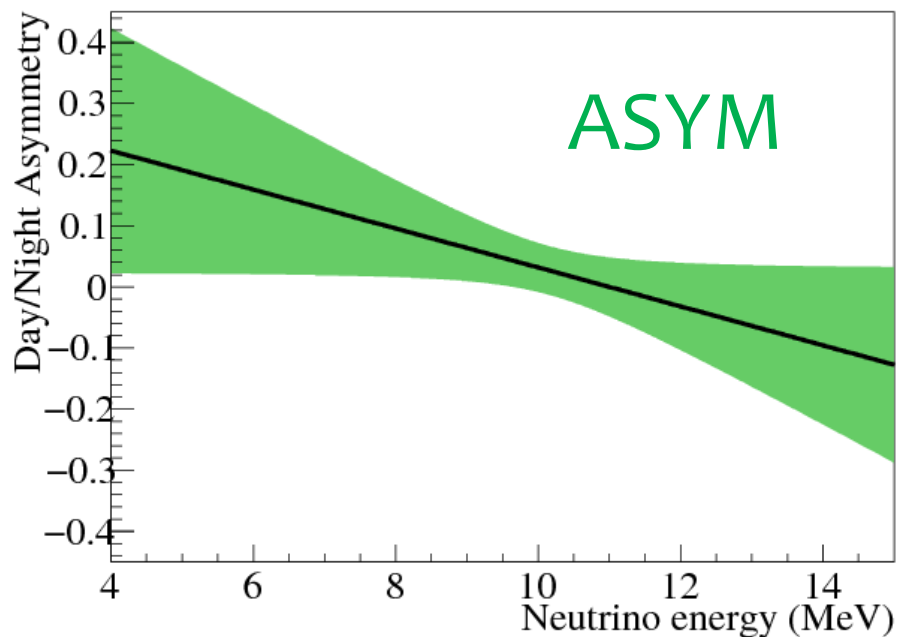
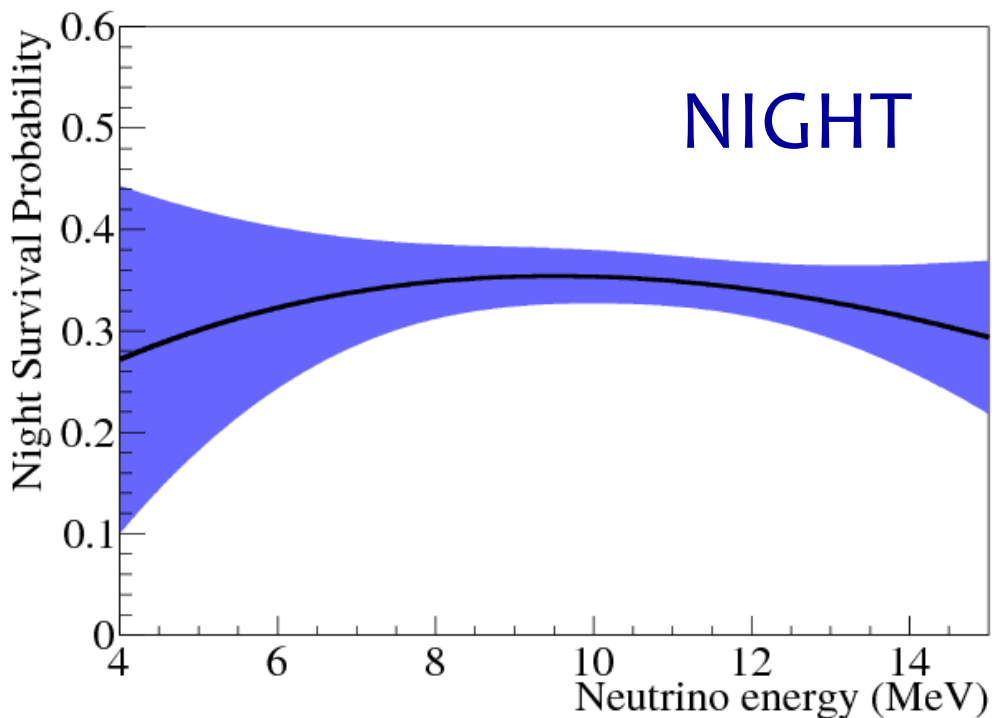
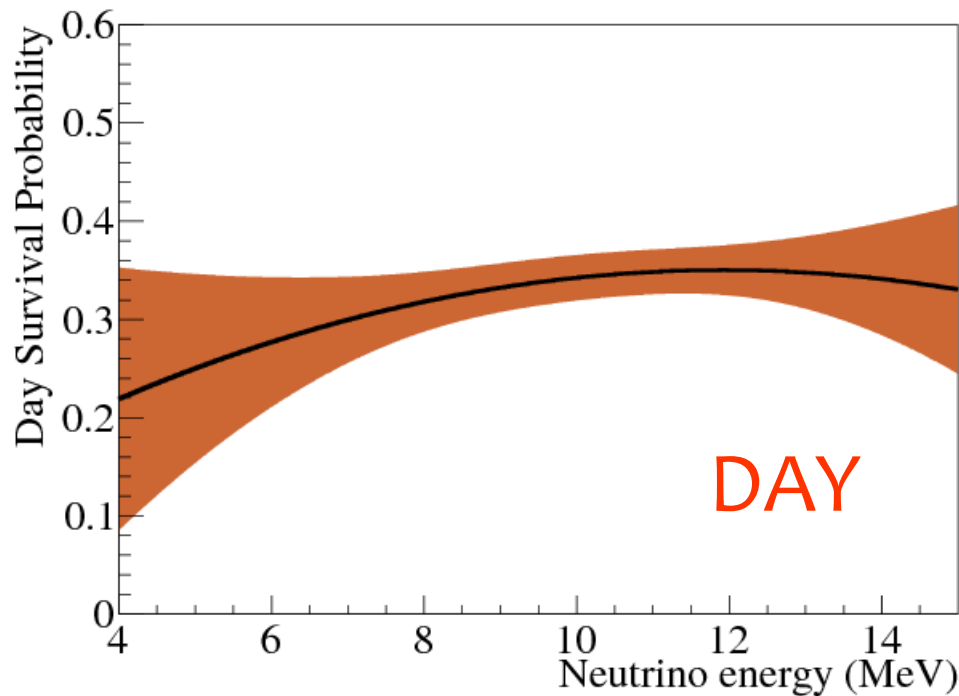
$$P_{ee}^{DAY}(E_\nu) = c0 + c1 (E_\nu - 10 \text{ MeV}) + c2 (E_\nu - 10 \text{ MeV})^2$$

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



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

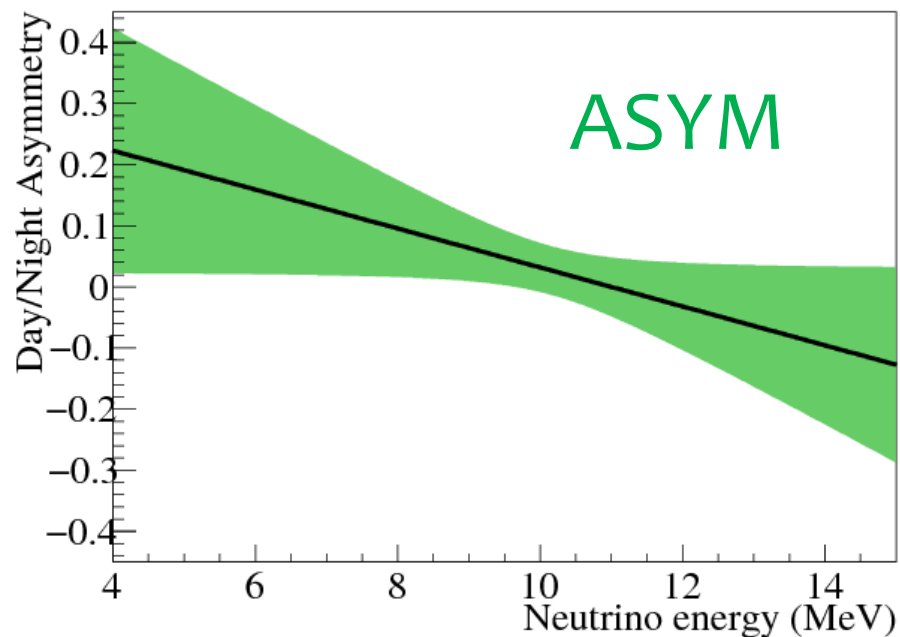
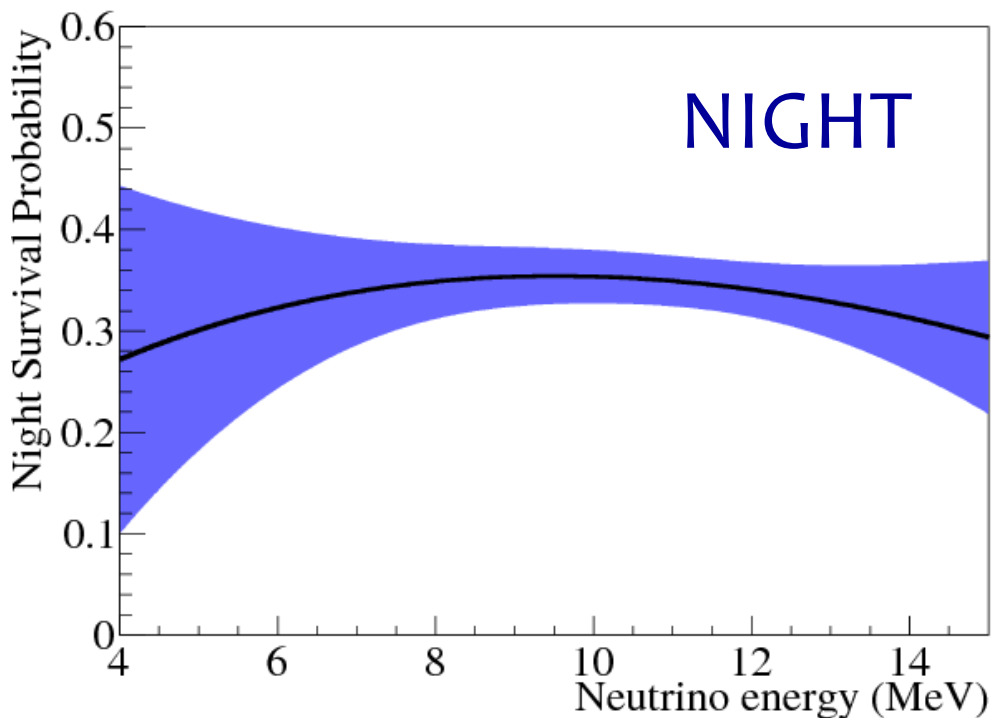
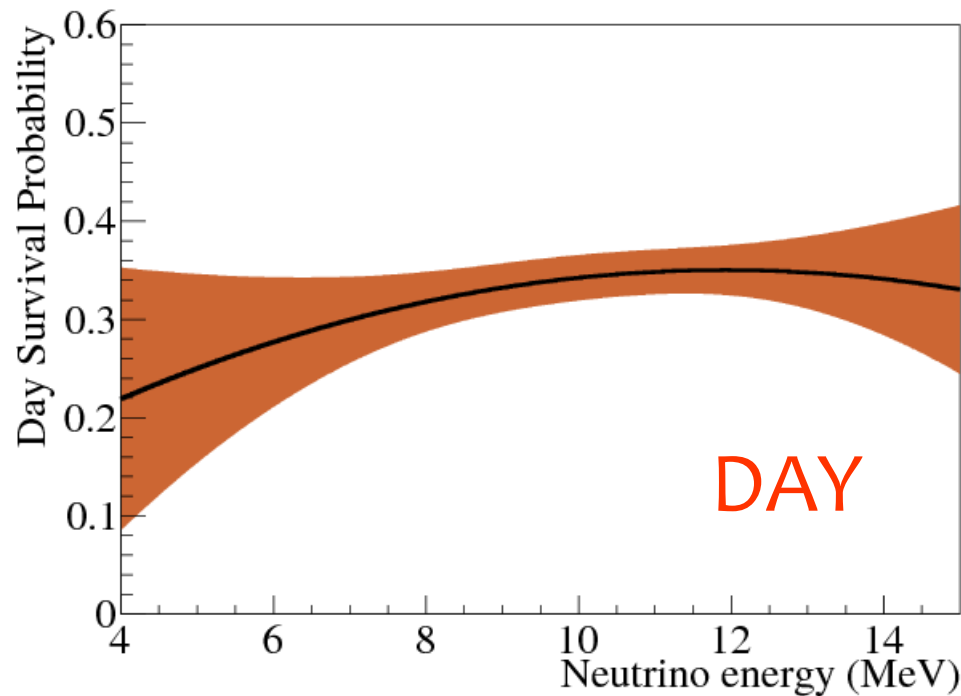
# Direct Fit for Energy-Dependent Survival Probability



# Direct Fit for Energy-Dependent Survival Probability

No distortion, no a/s:

$$\Delta\chi^2 = 1.94 / 4 \text{ d.o.f.}$$



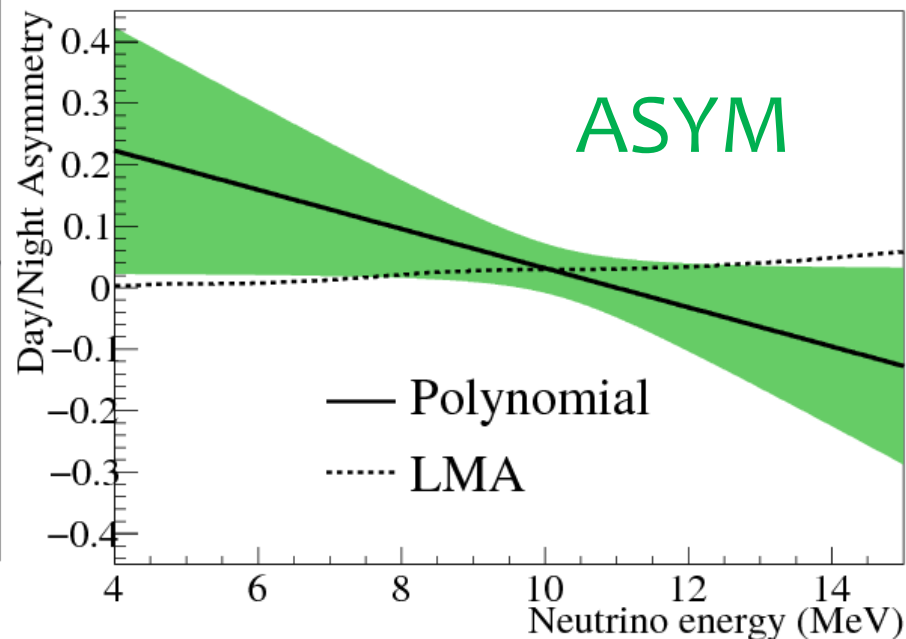
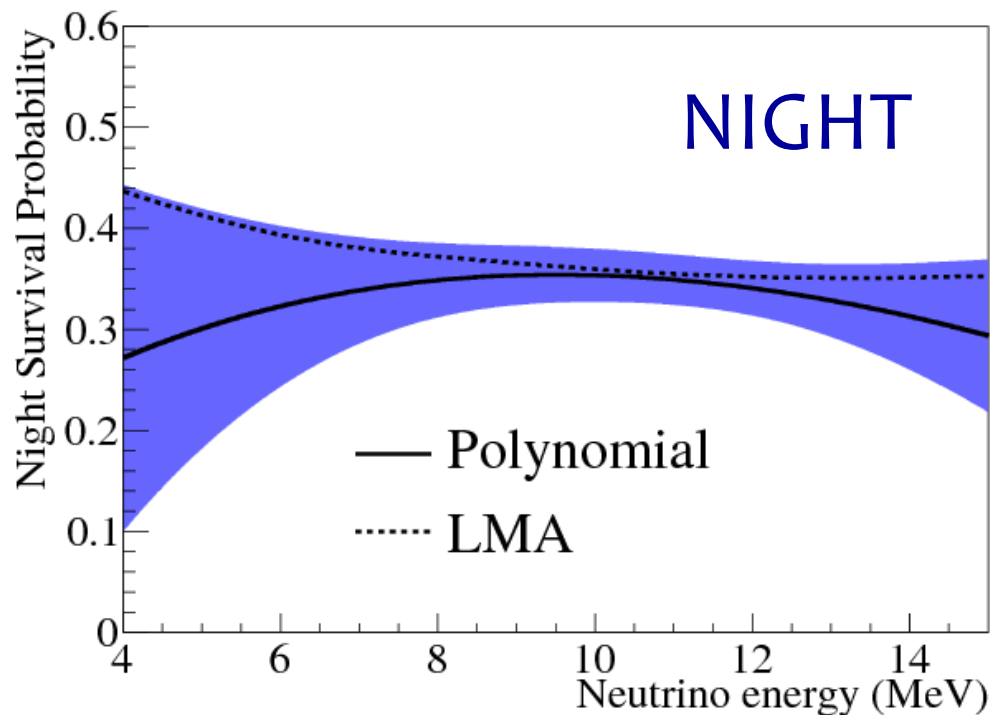
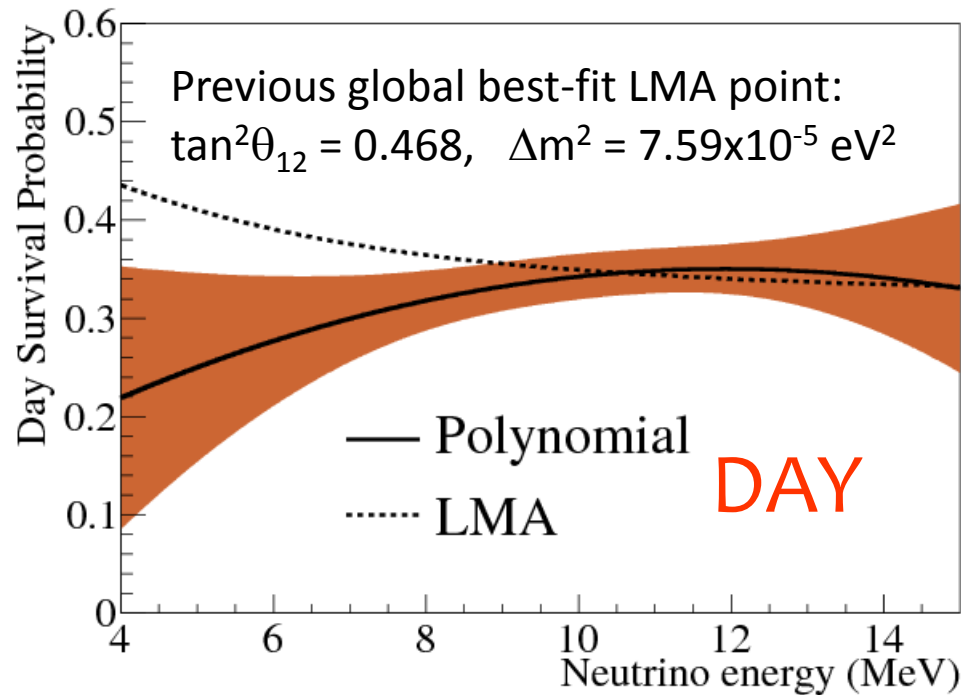
# Direct Fit for Energy-Dependent Survival Probability

No distortion, no a/s:

$$\Delta\chi^2 = 1.94 / 4 \text{ d.o.f.}$$

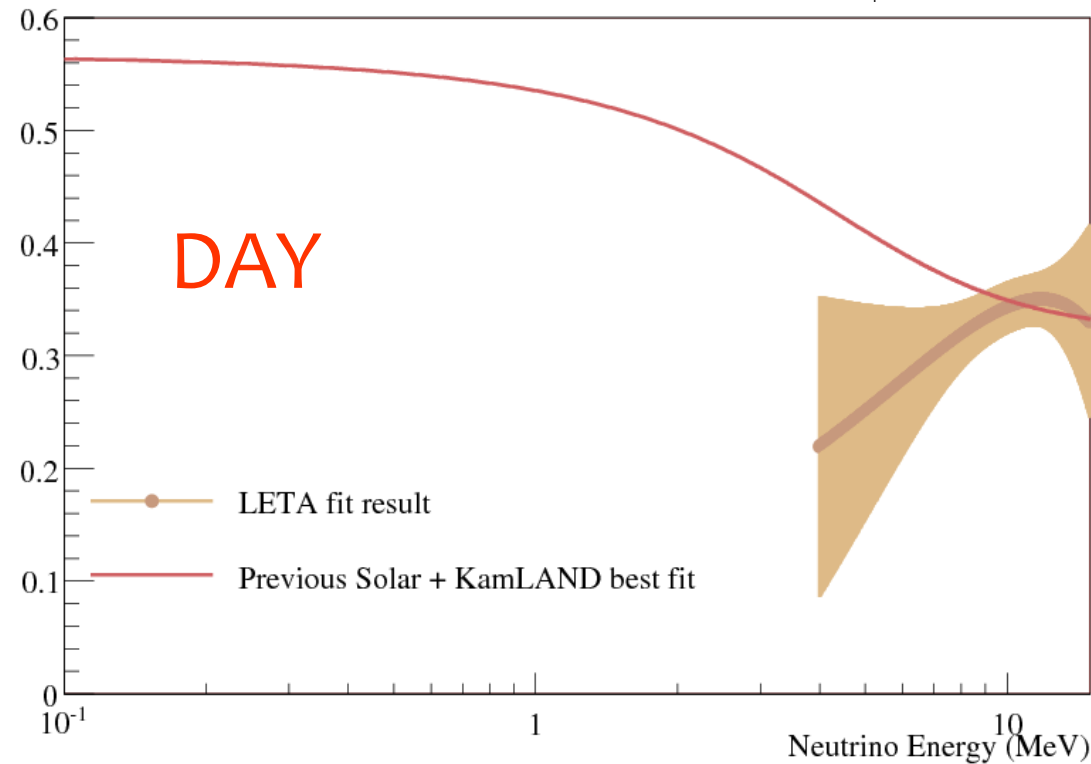
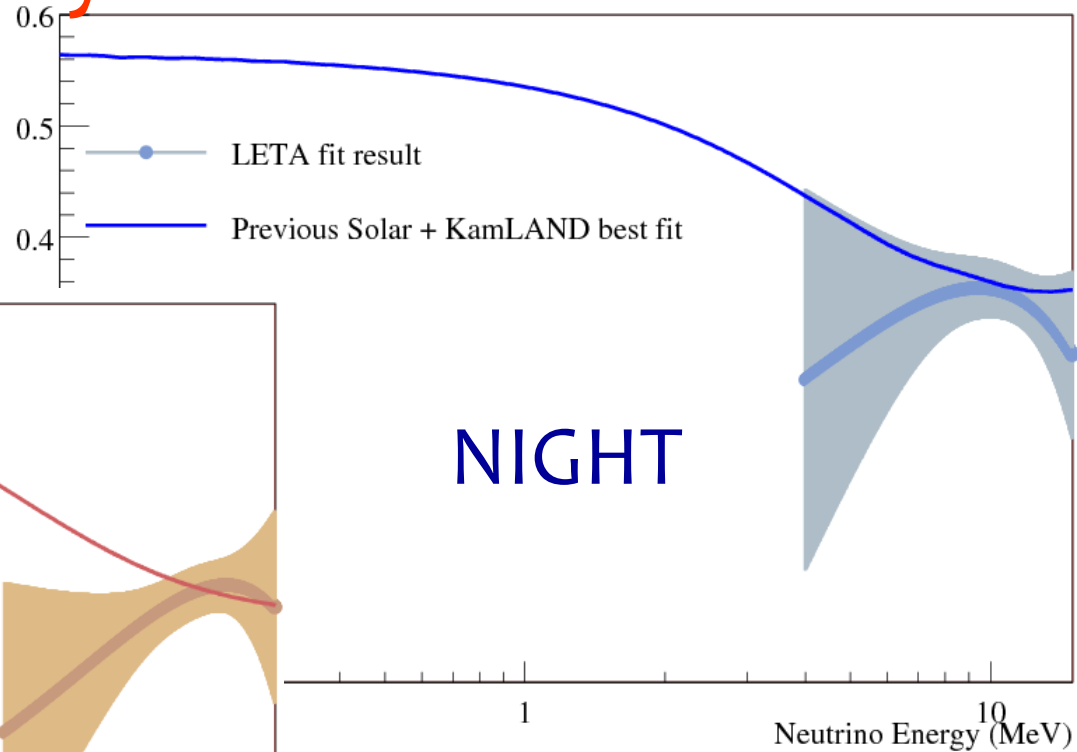
LMA-prediction:

$$\Delta\chi^2 = 3.90 / 4 \text{ d.o.f.}$$



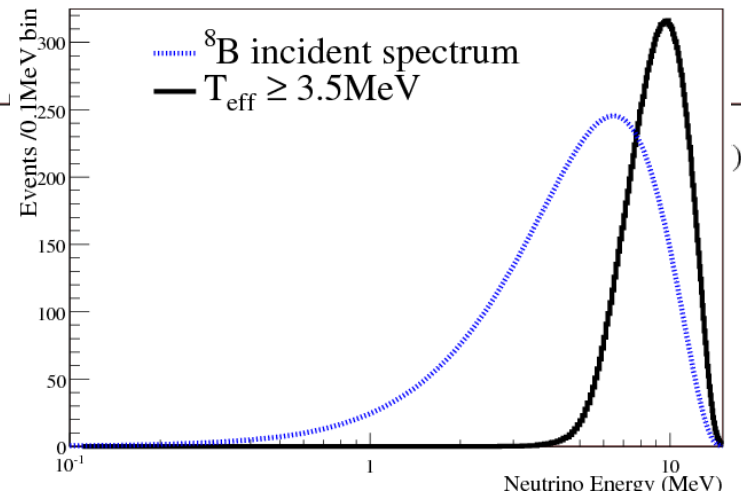
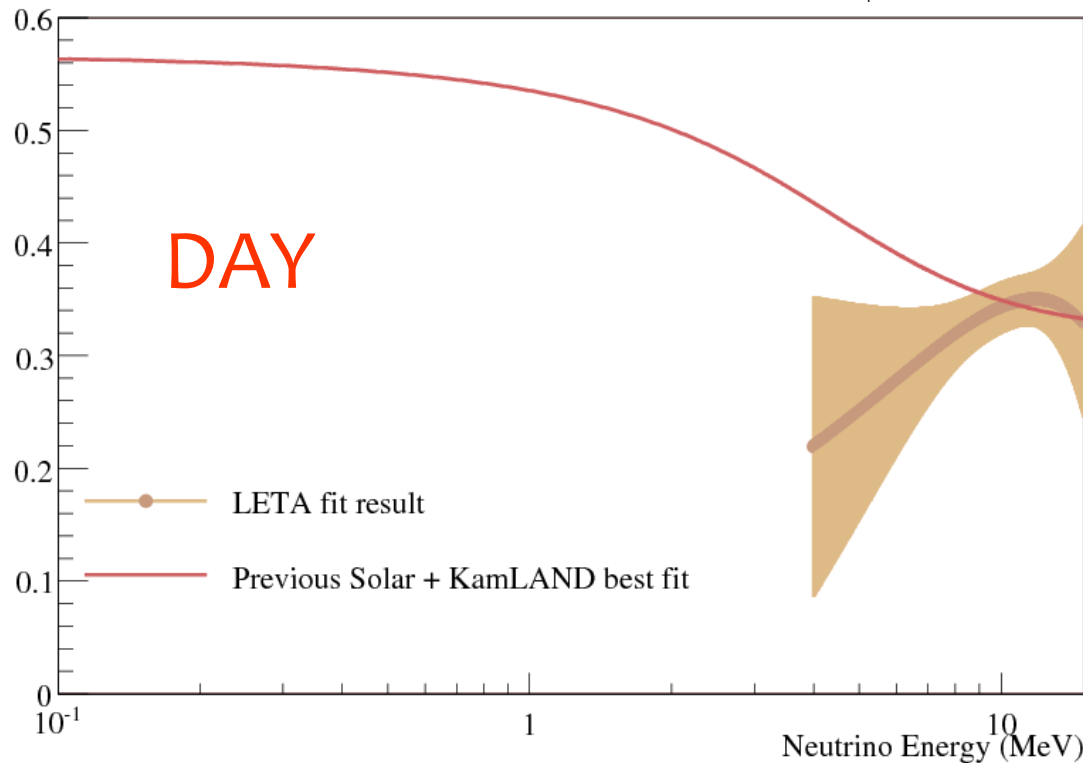
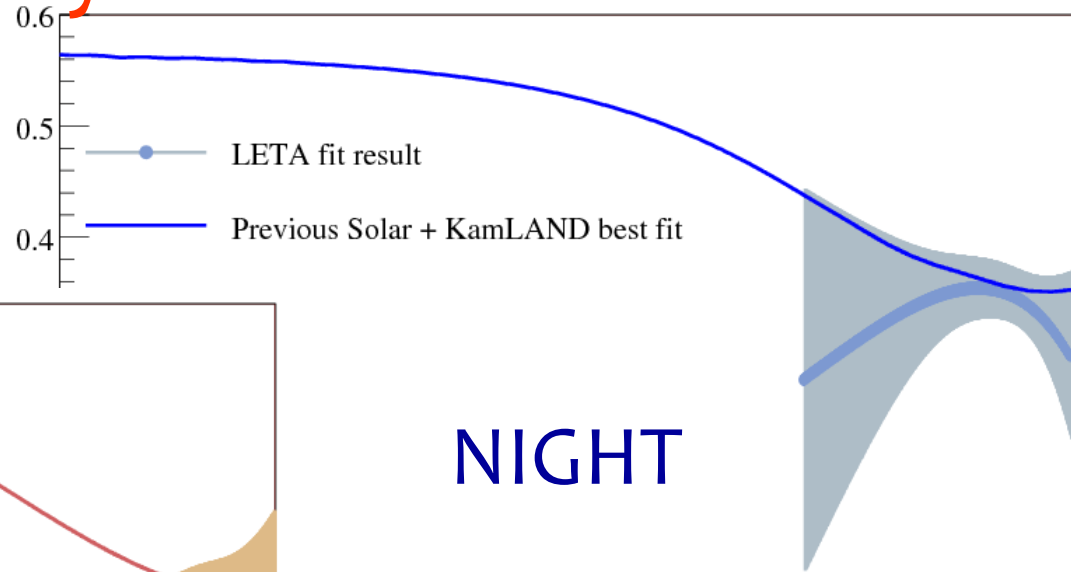
# Direct Fit for Energy-Dependent Survival Probability

Previous global best-fit LMA point:  
 $\tan^2\theta_{12} = 0.468$ ,  $\Delta m^2 = 7.59 \times 10^{-5} \text{ eV}^2$



# Direct Fit for Energy-Dependent Survival Probability

Previous global best-fit LMA point:  
 $\tan^2\theta_{12} = 0.468$ ,  $\Delta m^2 = 7.59 \times 10^{-5} \text{ eV}^2$



# Oscillation Analyses: LETA

SNO PRL 2008:

Phase I

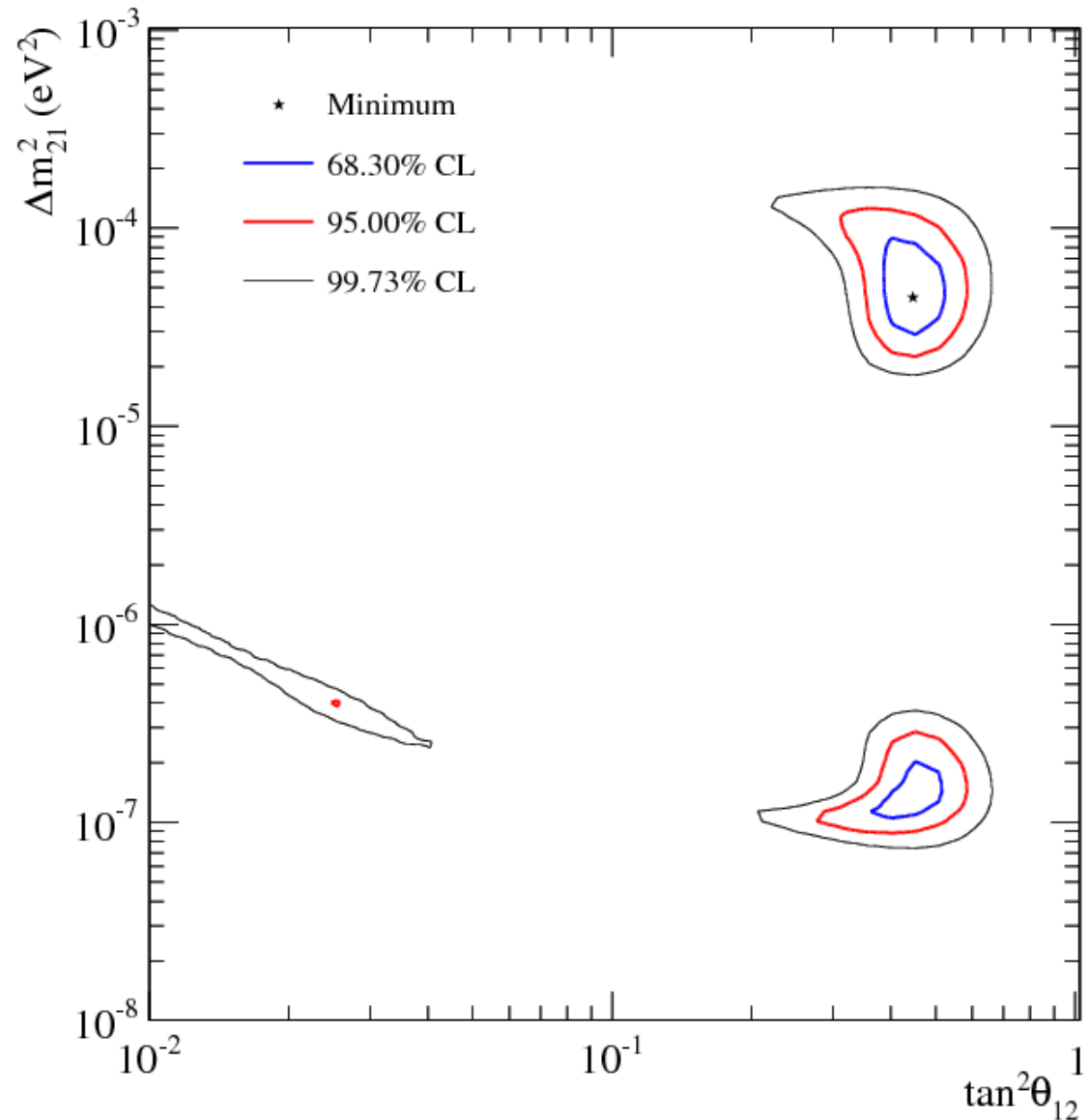
+ Phase II

+ Phase III

Best-fit point:

$$\tan^2\theta_{12} = 0.447,$$

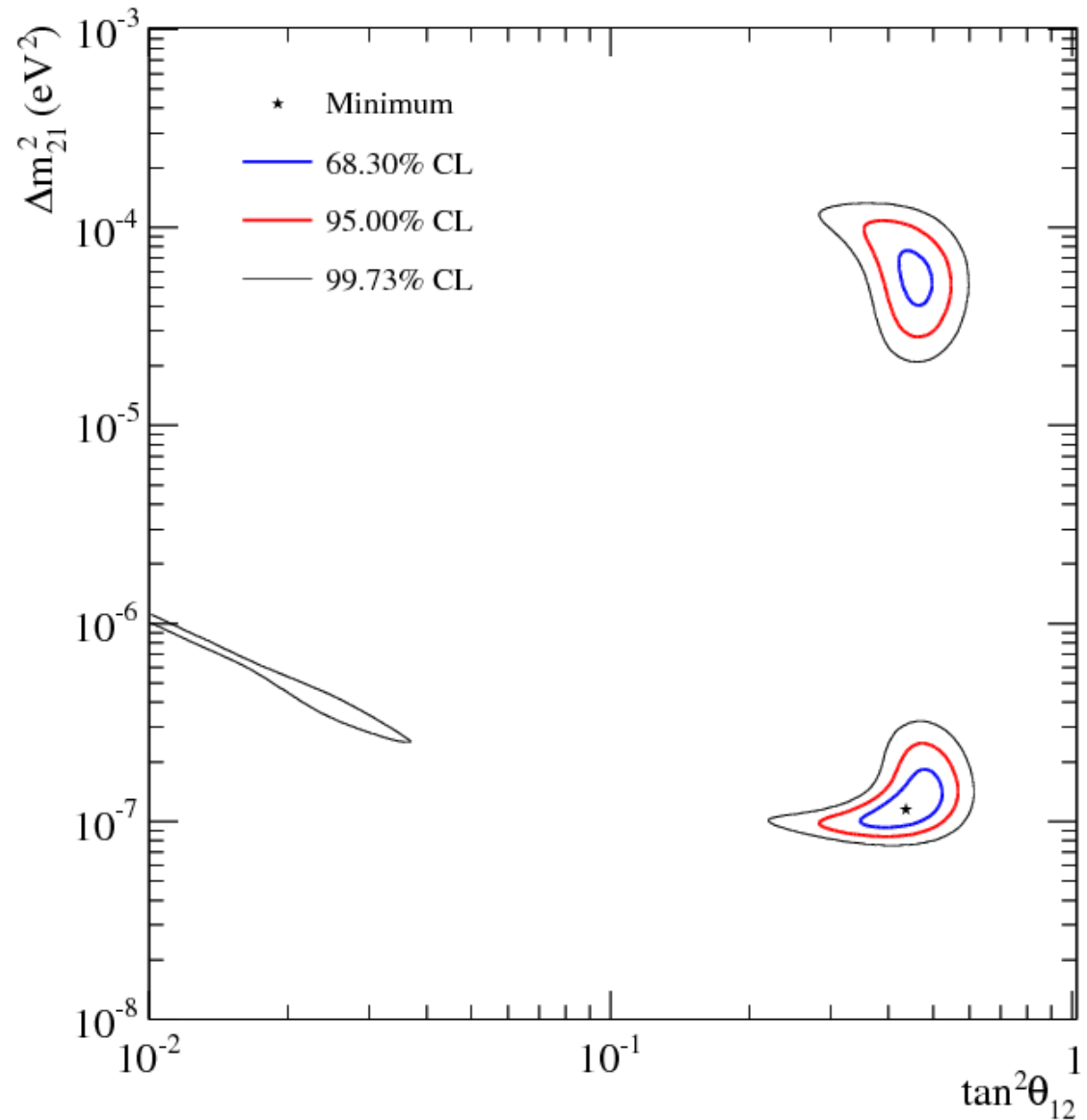
$$\Delta m^2 = 4.57 \times 10^{-5} \text{ eV}^2$$



# Oscillation Analyses: LETA

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

Best-fit point:  
 $\tan^2\theta_{12} = 0.437,$   
 $\Delta m^2 = 1.15 \times 10^{-7} \text{ eV}^2$



# Oscillation Analyses: LETA

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

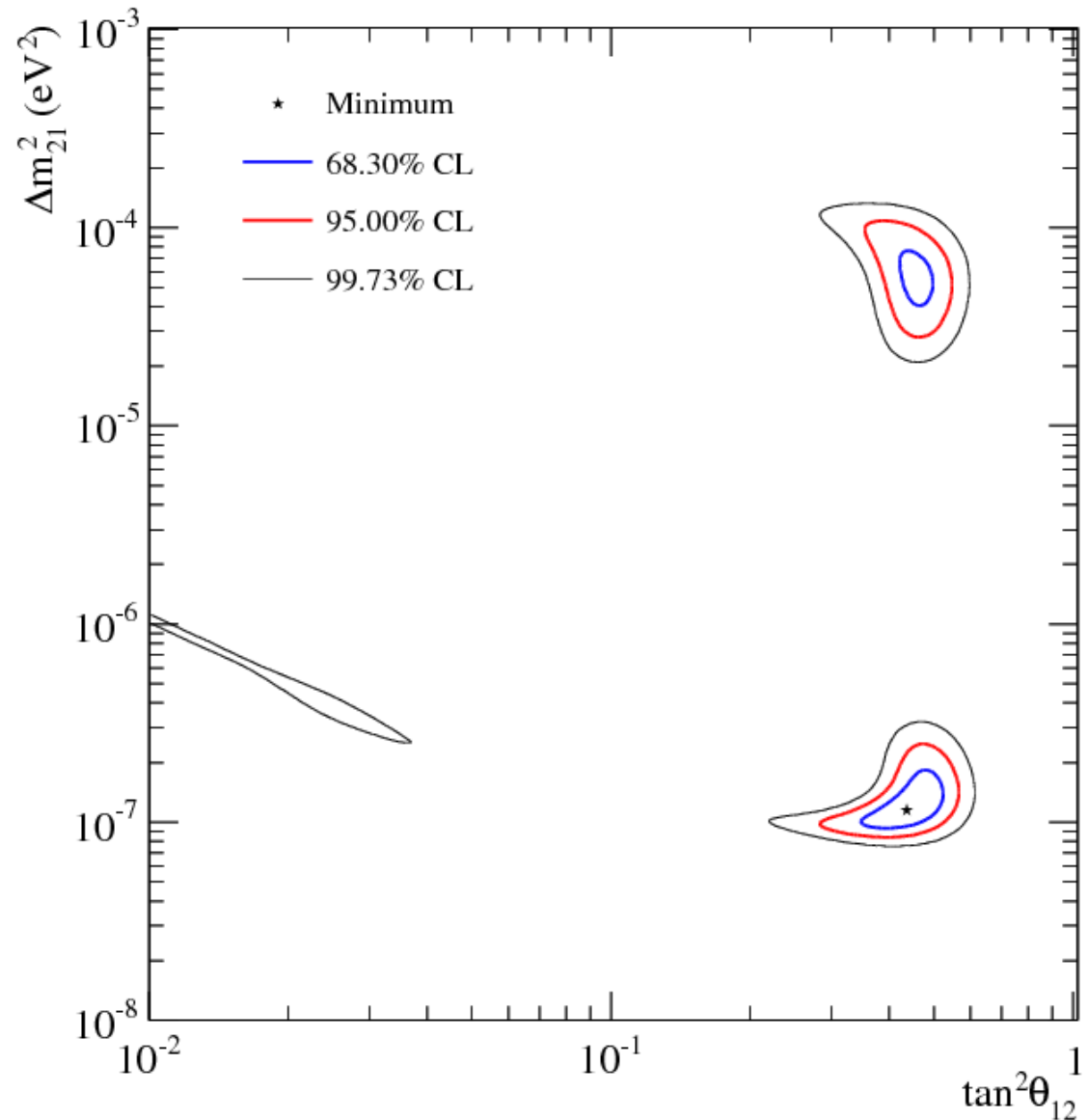
Best-fit LMA point:

$$\tan^2\theta_{12} = 0.457$$

(+0.038 -0.042)

$$\Delta m^2 = 5.50 \times 10^{-5} \text{ eV}^2$$

(+2.21 -1.62)



# Oscillation Analyses: Global Solar

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

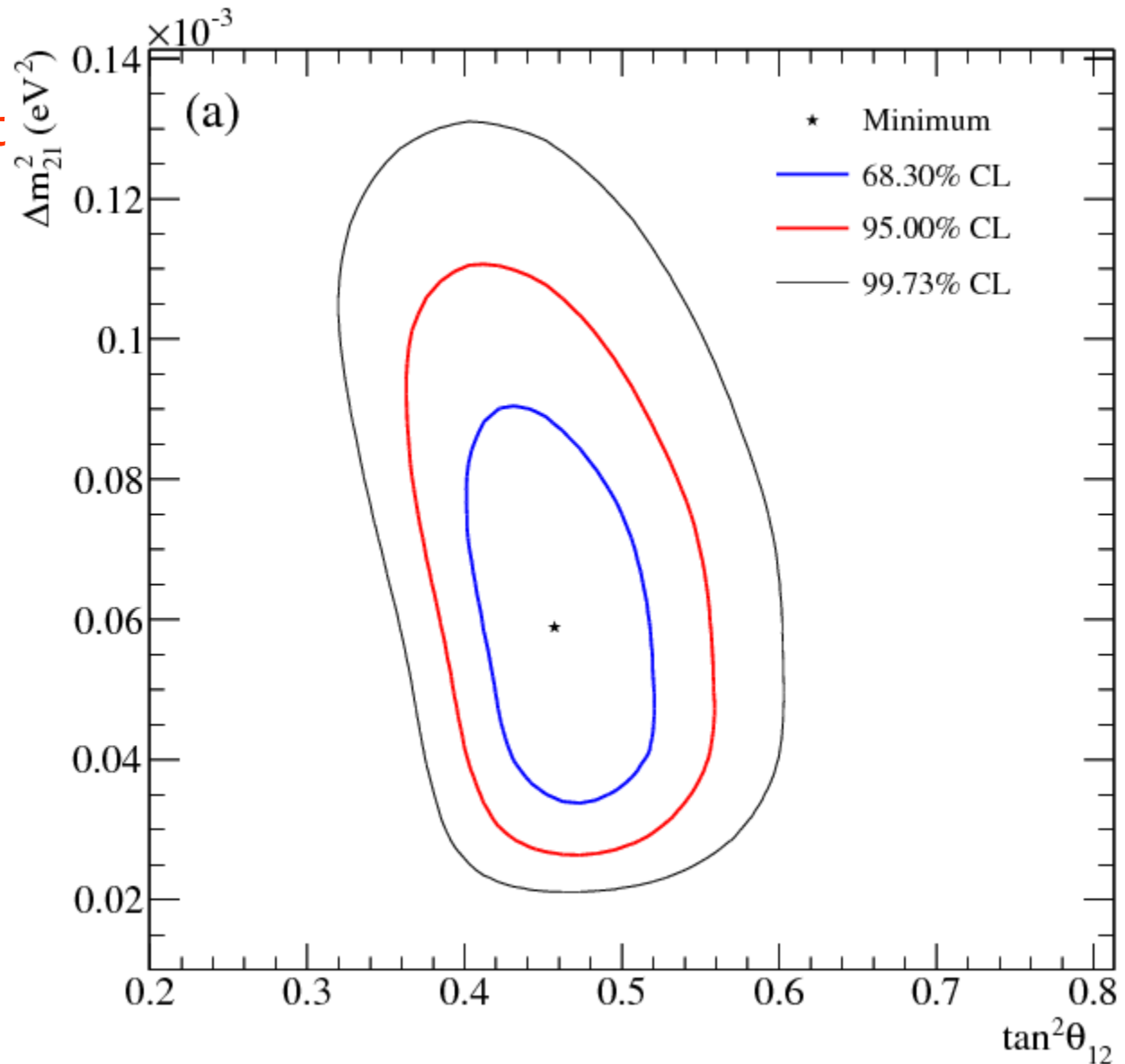
Best-fit LMA point:

$$\tan^2\theta_{12} = 0.457$$

(+0.038 -0.041)

$$\Delta m^2 = 5.89 \times 10^{-5} \text{ eV}^2$$

(+2.13 -2.16)



# Oscillation Analyses: Solar + KamLAND

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

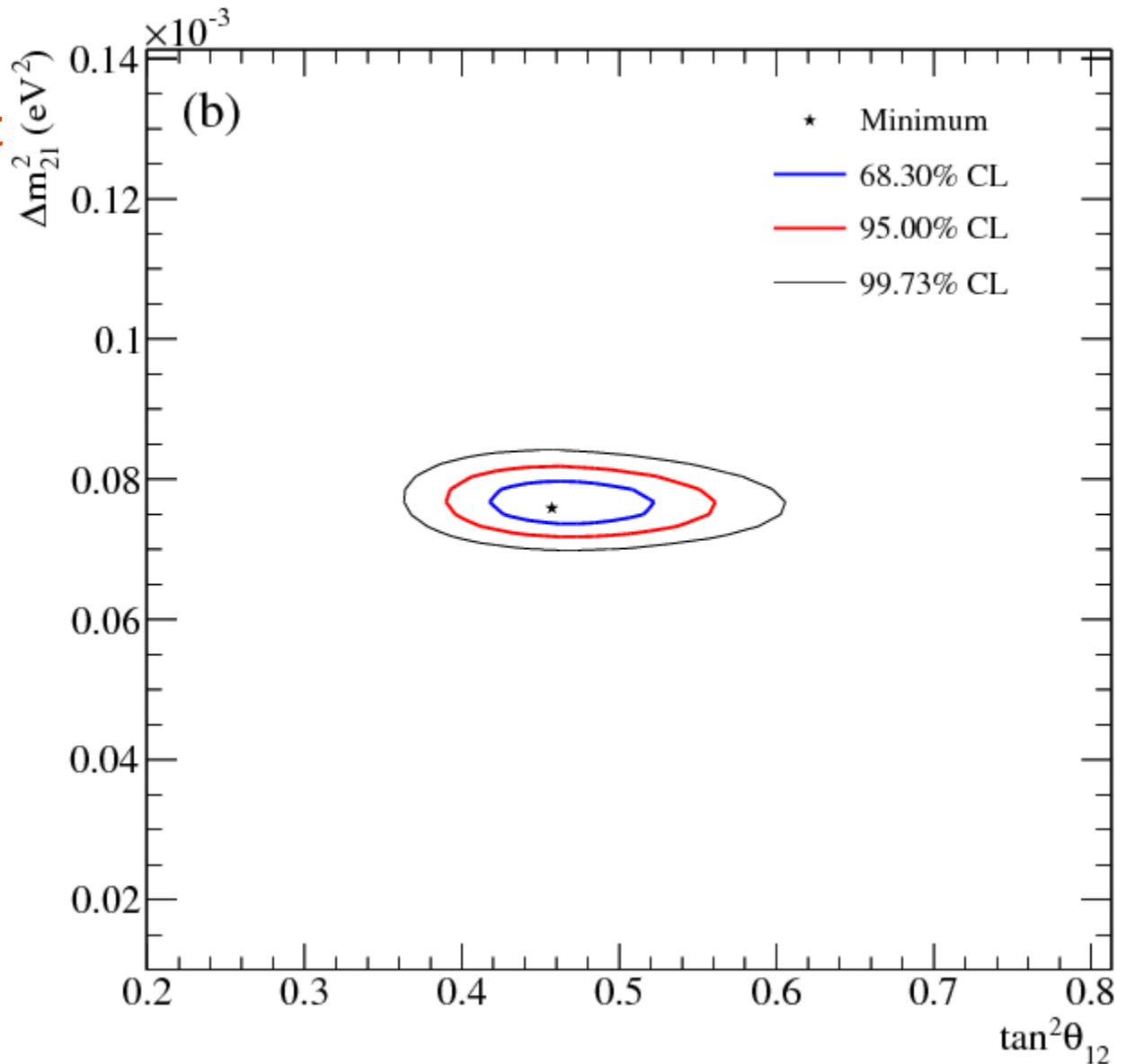
Best-fit LMA point:

$$\tan^2\theta_{12} = 0.457$$

(+0.040 -0.029)

$$\Delta m^2 = 7.59 \times 10^{-5} \text{ eV}^2$$

(+0.20 -0.21)



# Oscillation Analyses: Solar + KamLAND

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

Best-fit LMA point:

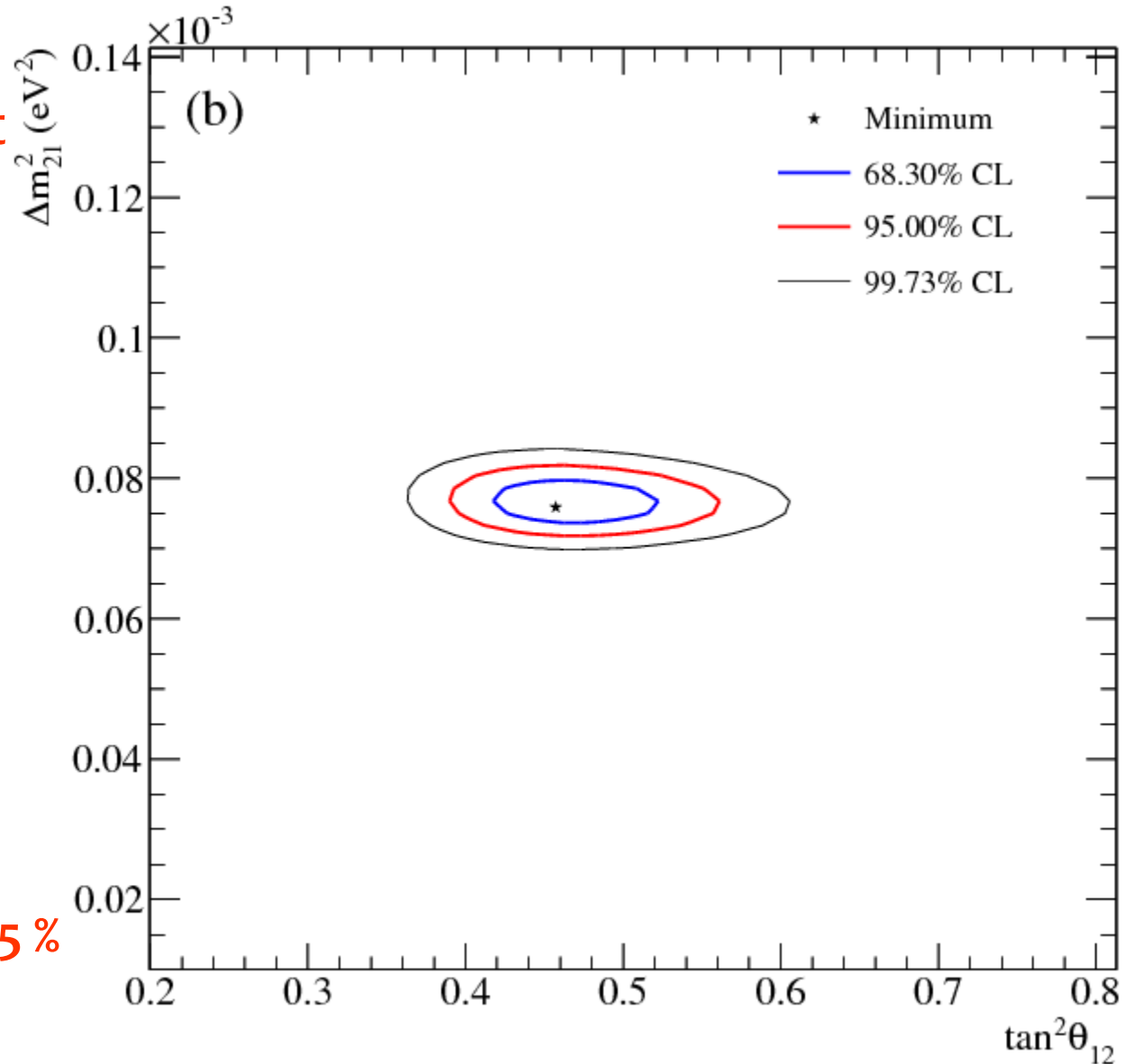
$$\tan^2\theta_{12} = 0.457$$

(+0.040 -0.029)

$$\Delta m^2 = 7.59 \times 10^{-5} \text{ eV}^2$$

(+0.20 -0.21)

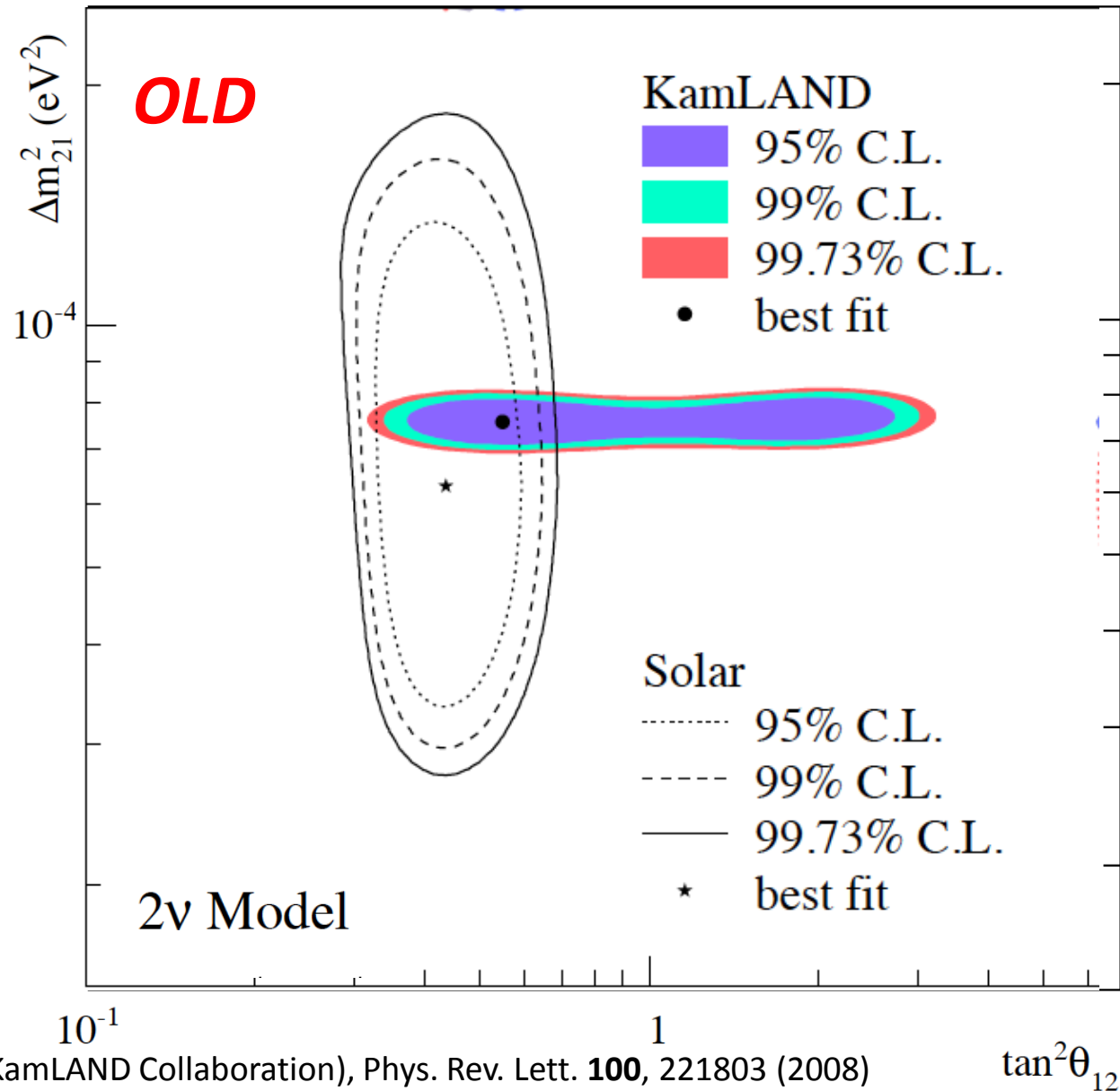
$$\Phi_{8B} \text{ uncert} = +2.38 -2.95 \%$$



# Solar + KamLAND 2-flavor Overlay

SNO PRL 2008:  
Phase I  
+ Phase II  
+ Phase III  
+ all solar expts  
+ KamLAND

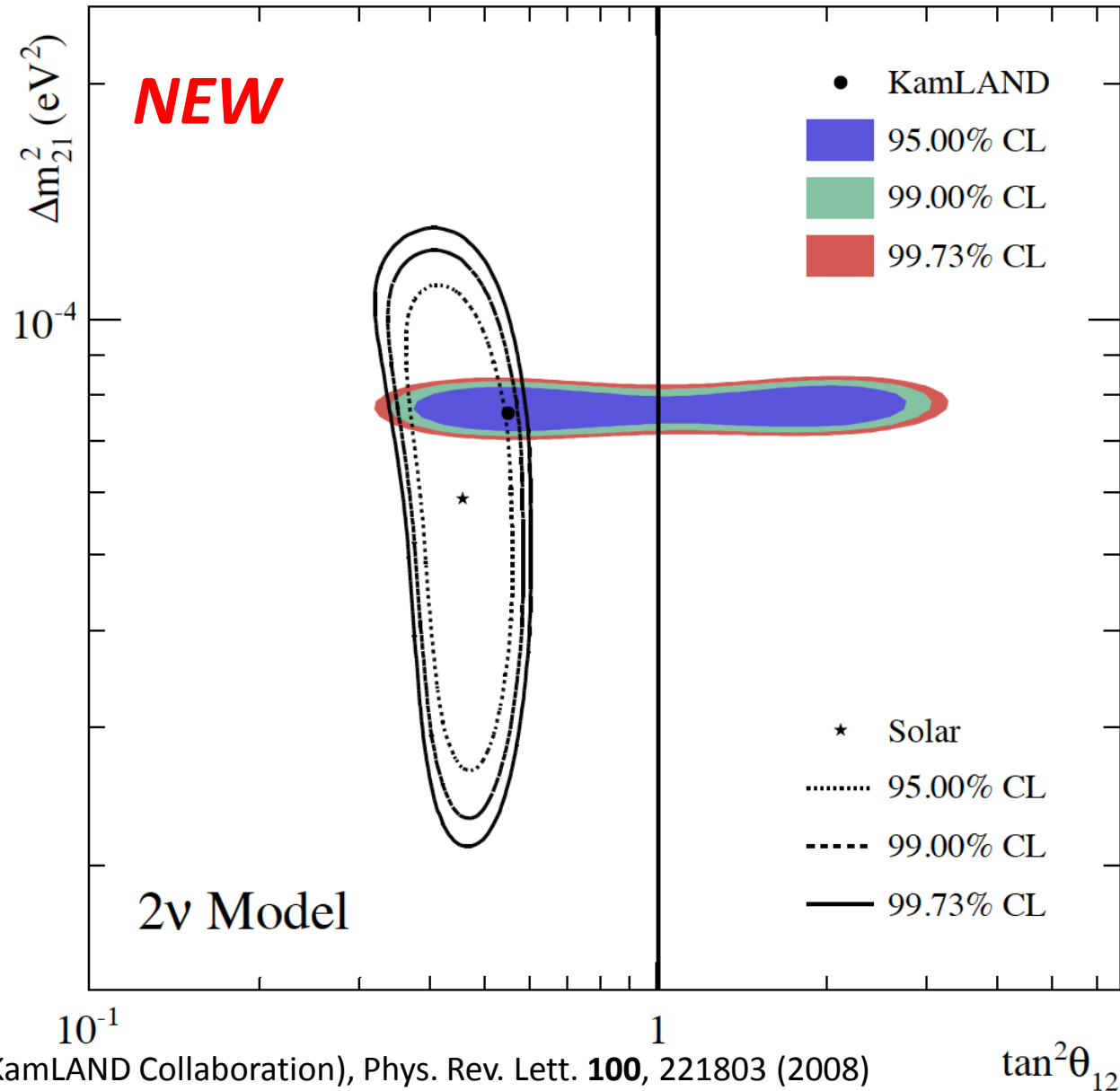
2-flavor overlay:



# Solar + KamLAND 2-flavor Overlay

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

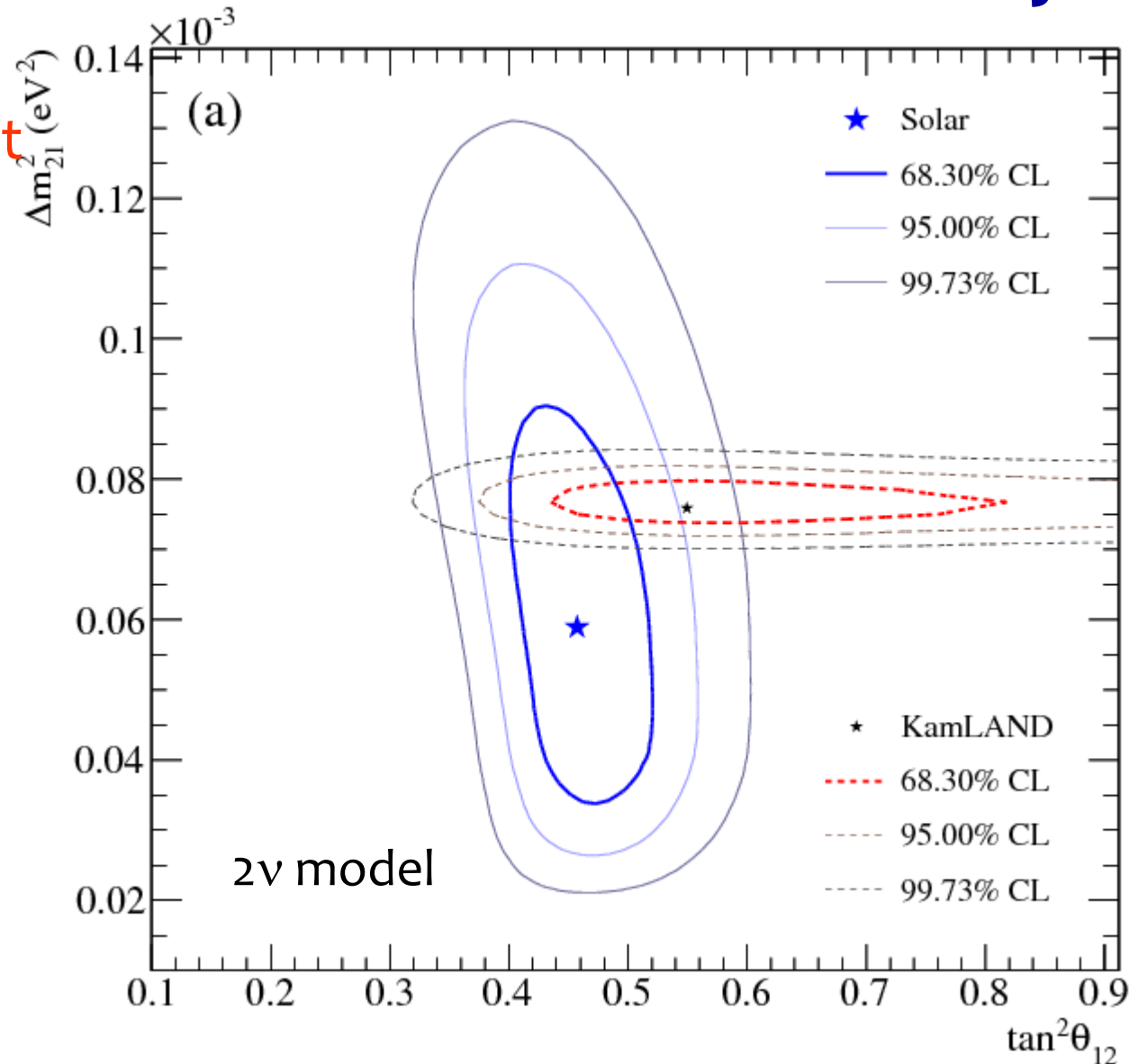
2-flavor overlay:



# Solar + KamLAND 2-flavor Overlay

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

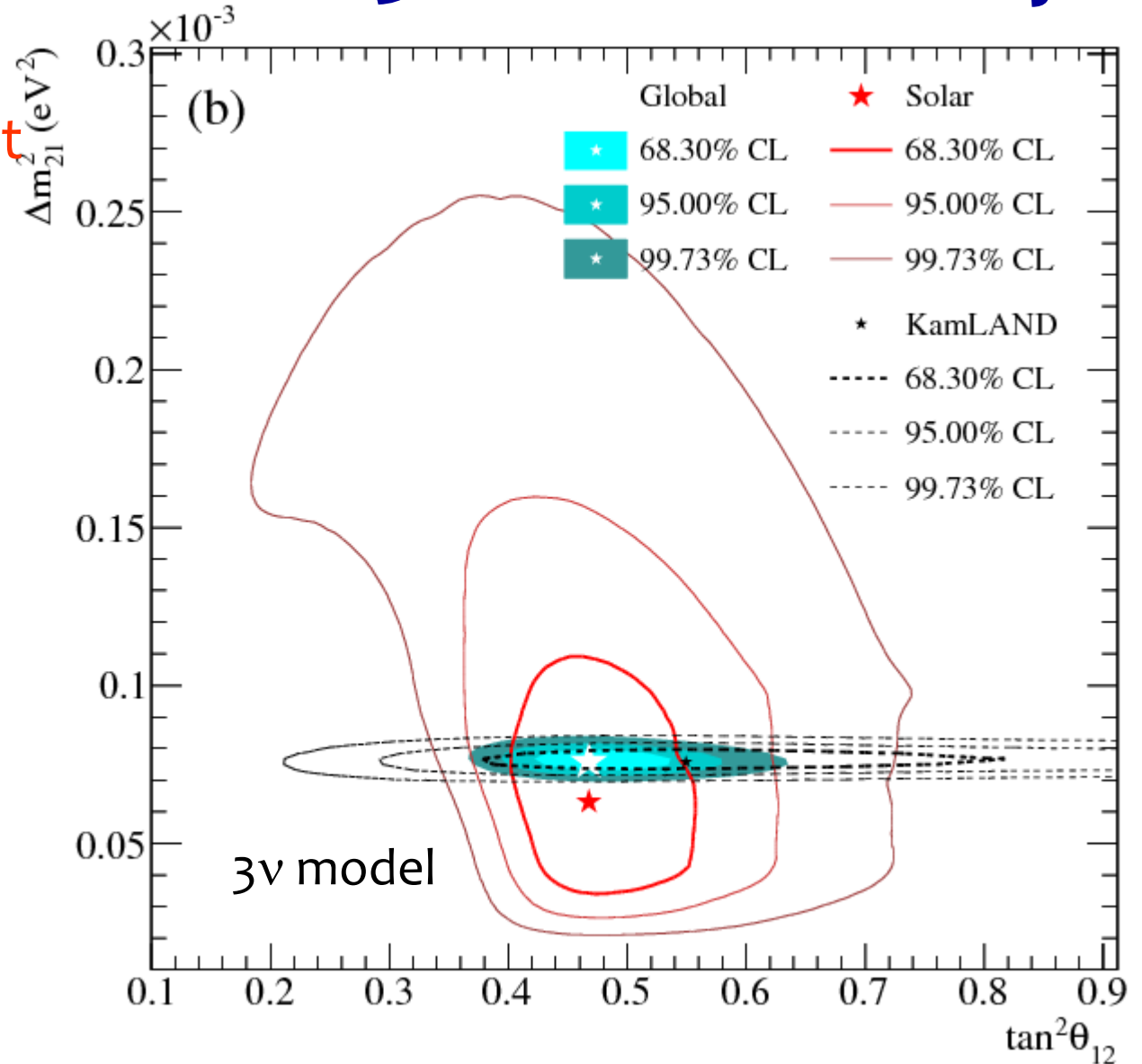
2-flavor overlay:



# Solar + KamLAND 3-flavor Overlay

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

3-flavor overlay:



# Solar + KamLAND 3-flavor Overlay

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

3-flavor overlay:

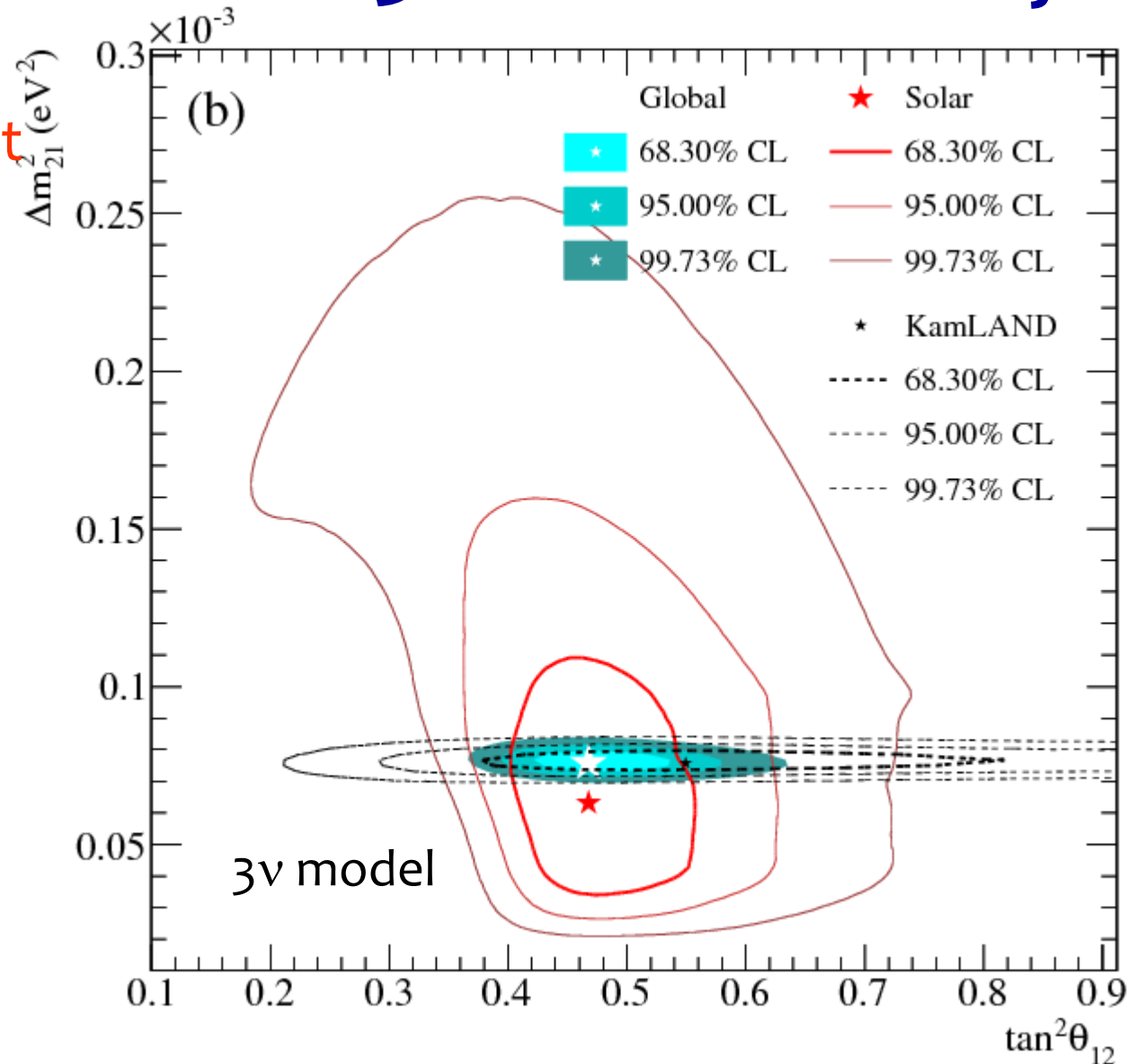
Best-fit LMA point:

$$\tan^2\theta_{12} = 0.468$$

(+0.042 -0.033)

$$\Delta m^2 = 7.59 \times 10^{-5} \text{ eV}^2$$

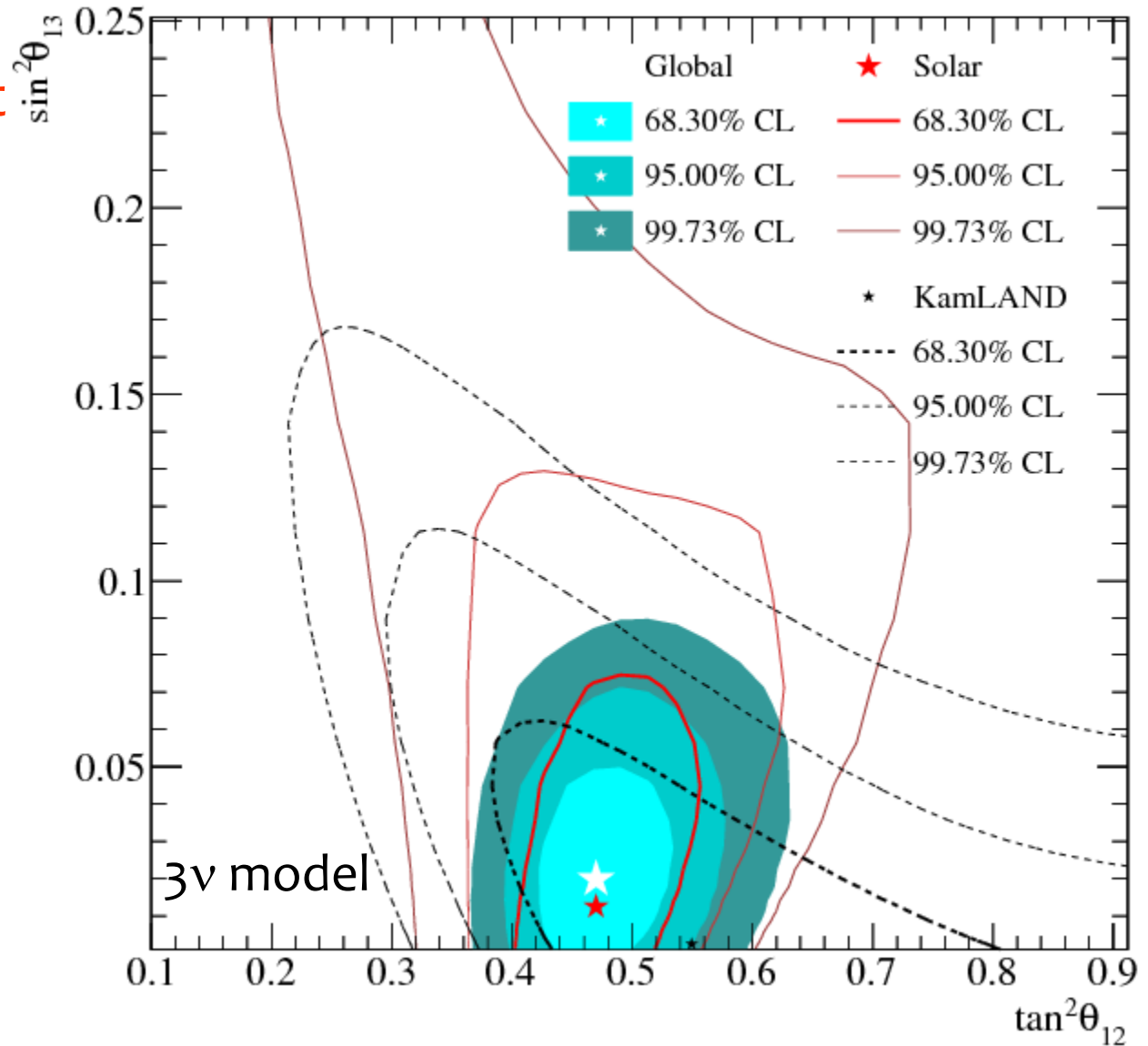
(+0.21 -0.21)



# Solar + KamLAND 3-flavor Overlay

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

3-flavor analysis:



# Solar + KamLAND 3-flavor Overlay

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

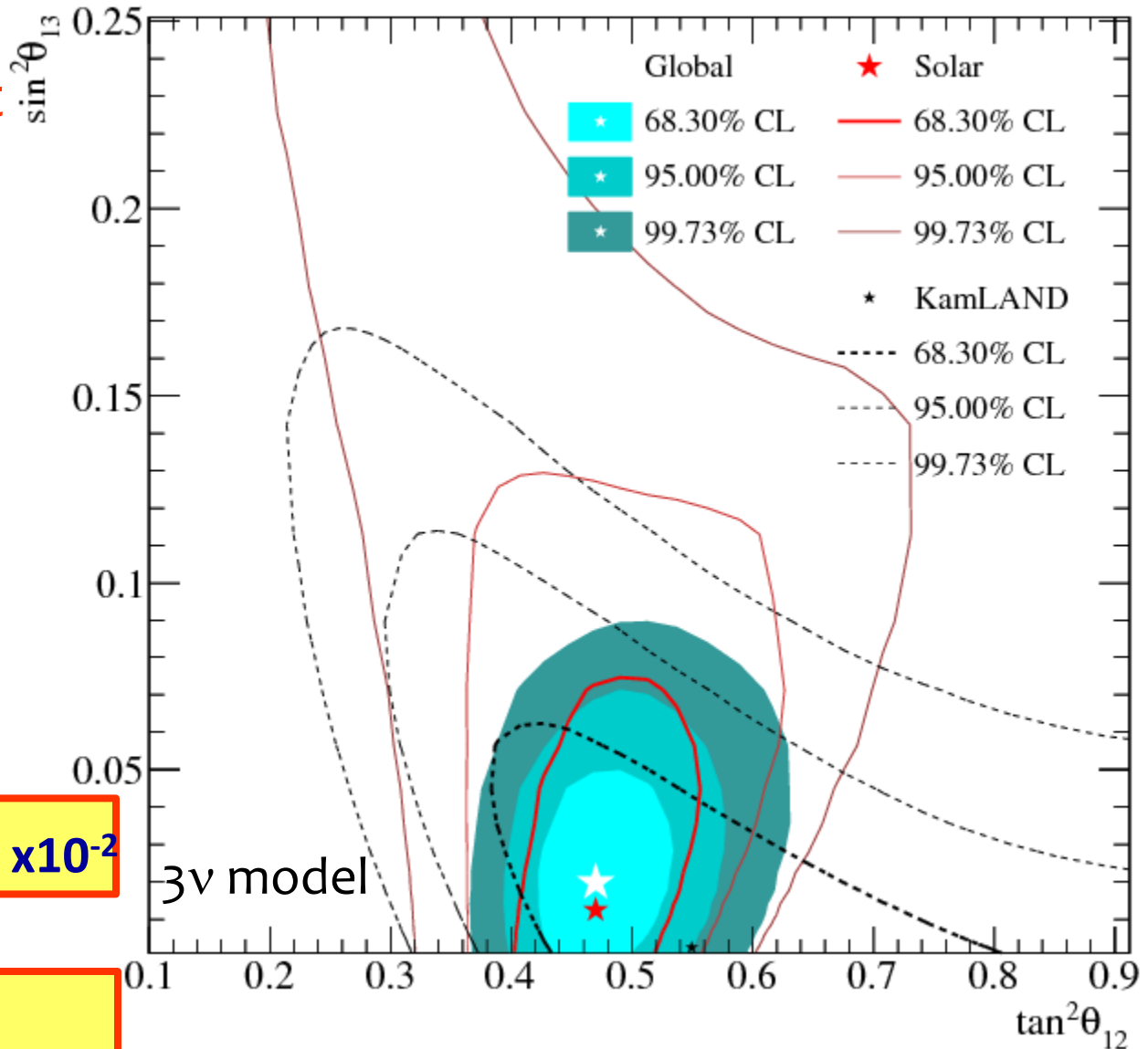
3-flavor analysis:

Best-fit:

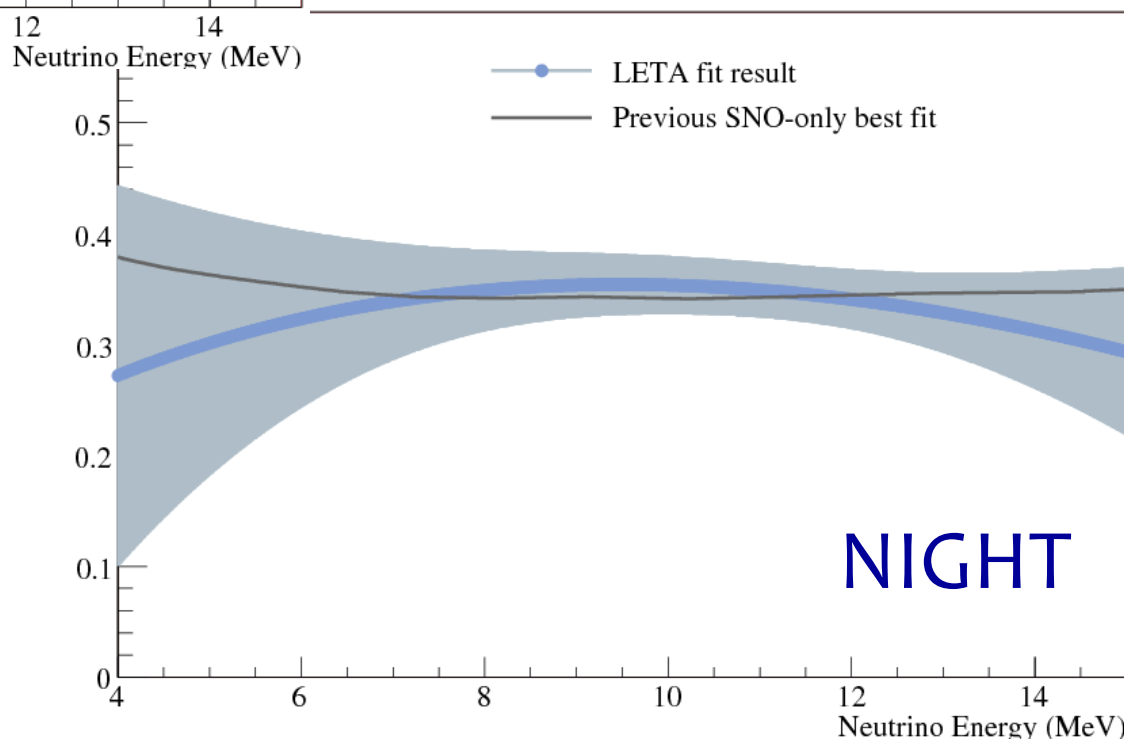
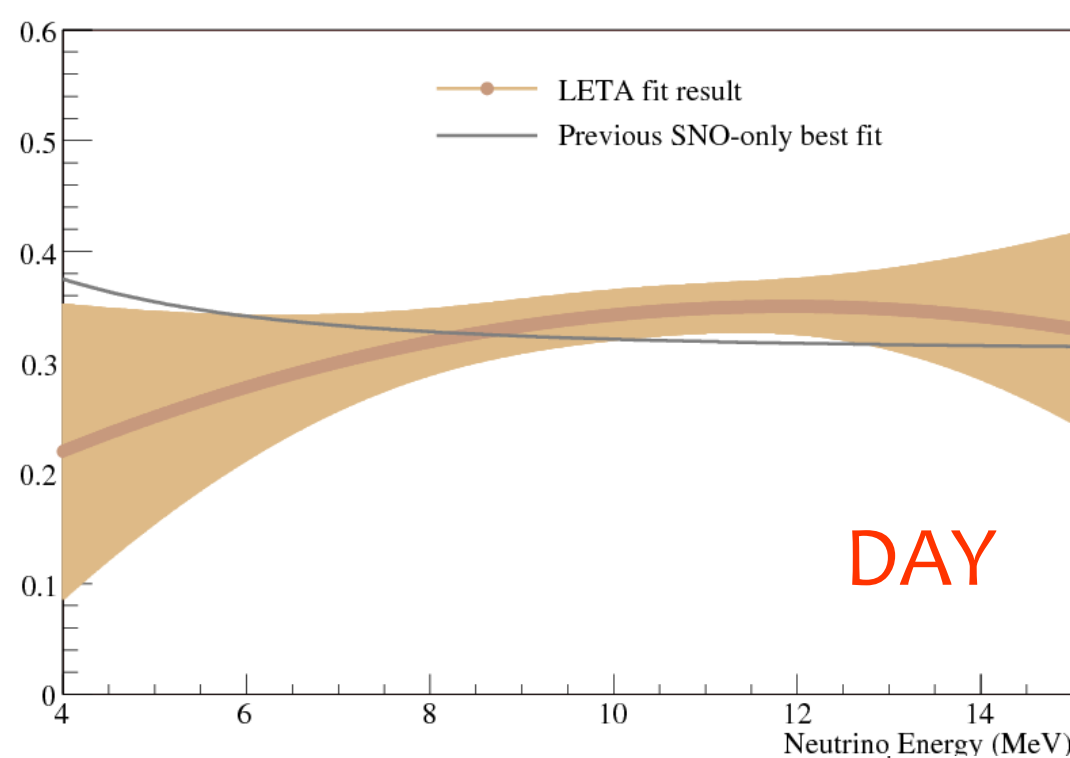
$$\sin^2\theta_{13} = 2.00 + 2.09 - 1.63 \times 10^{-2}$$

⇒

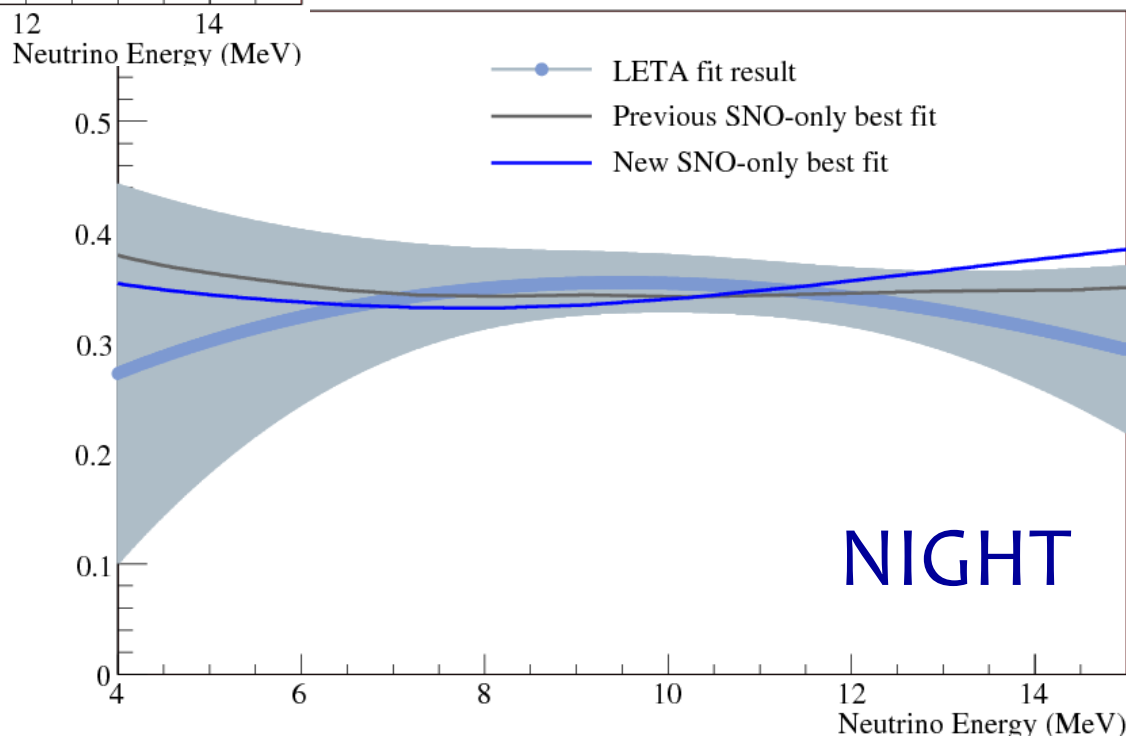
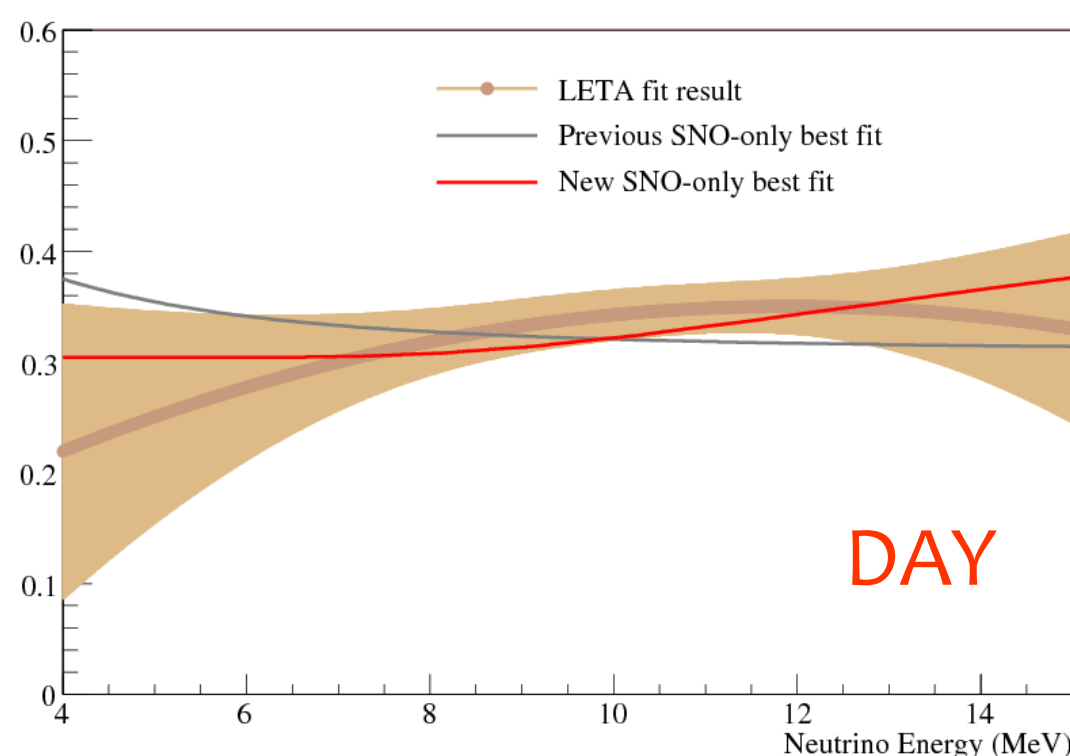
$$\sin^2\theta_{13} < 0.057 \text{ (95\% C.L.)}$$



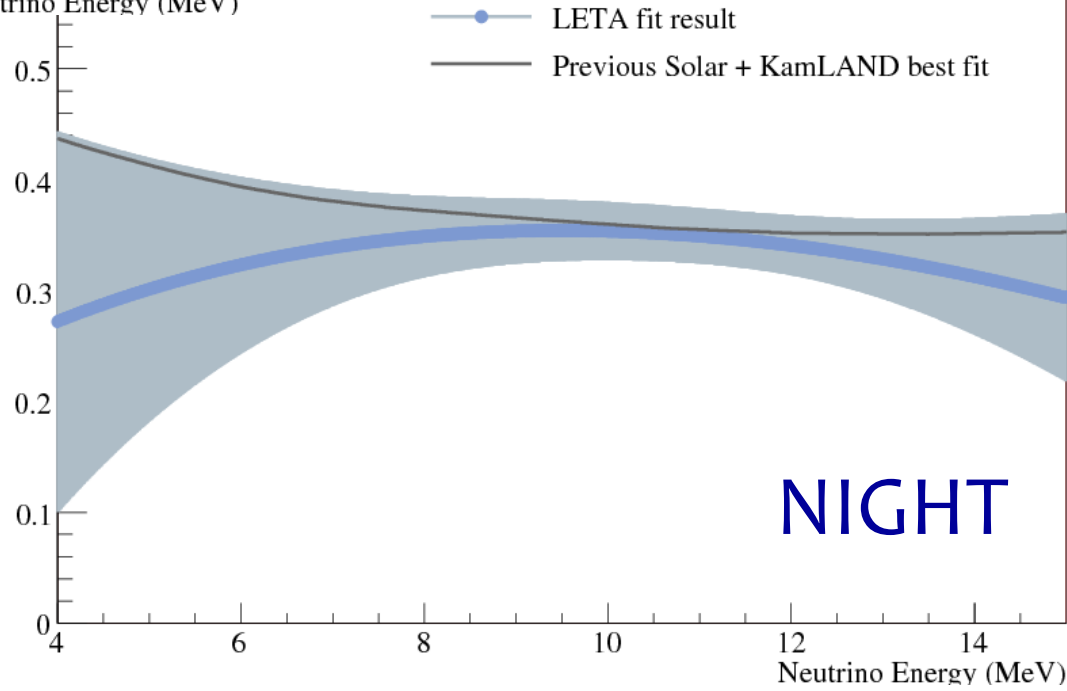
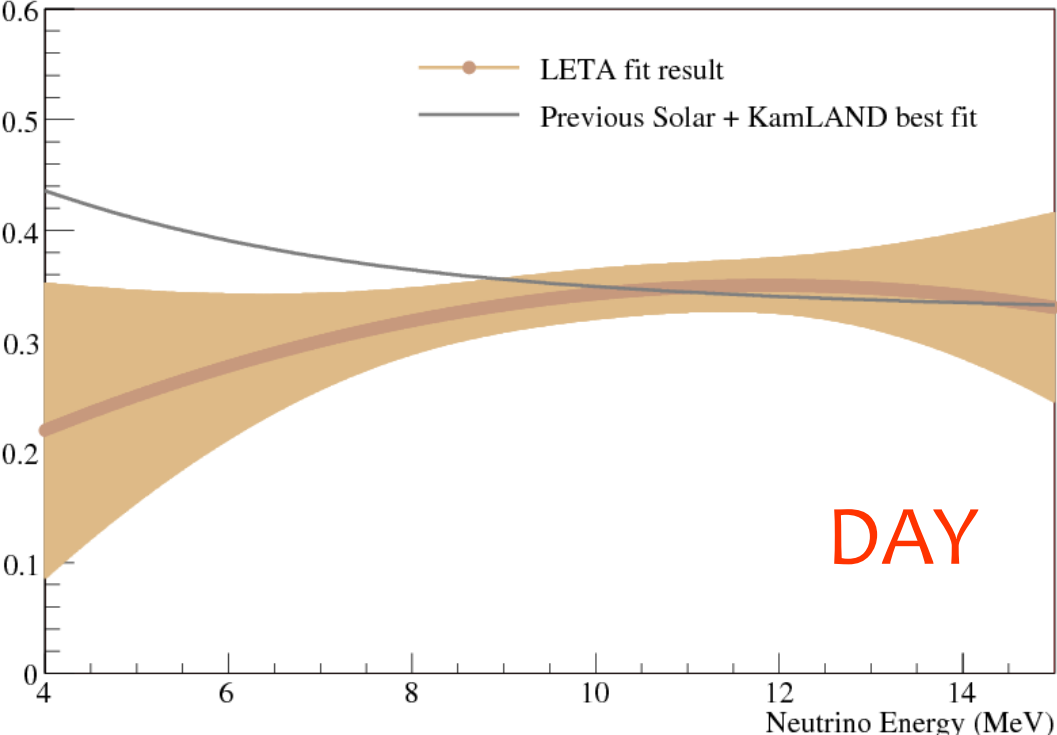
# Survival Probability



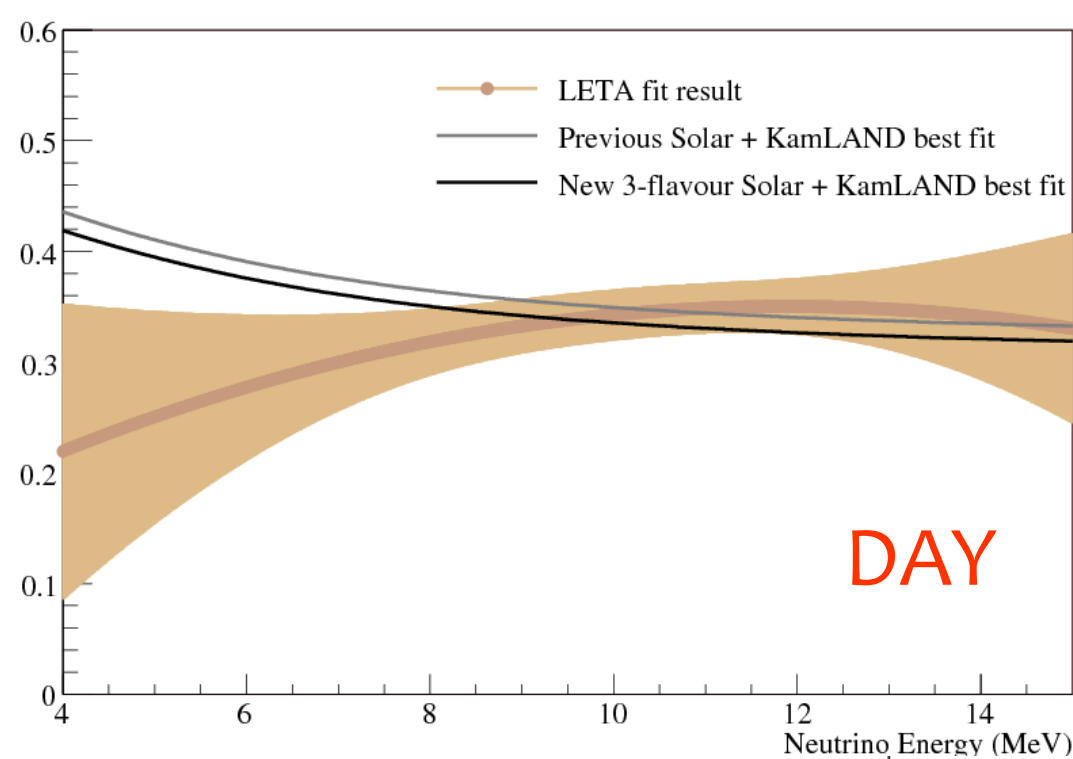
# Survival Probability



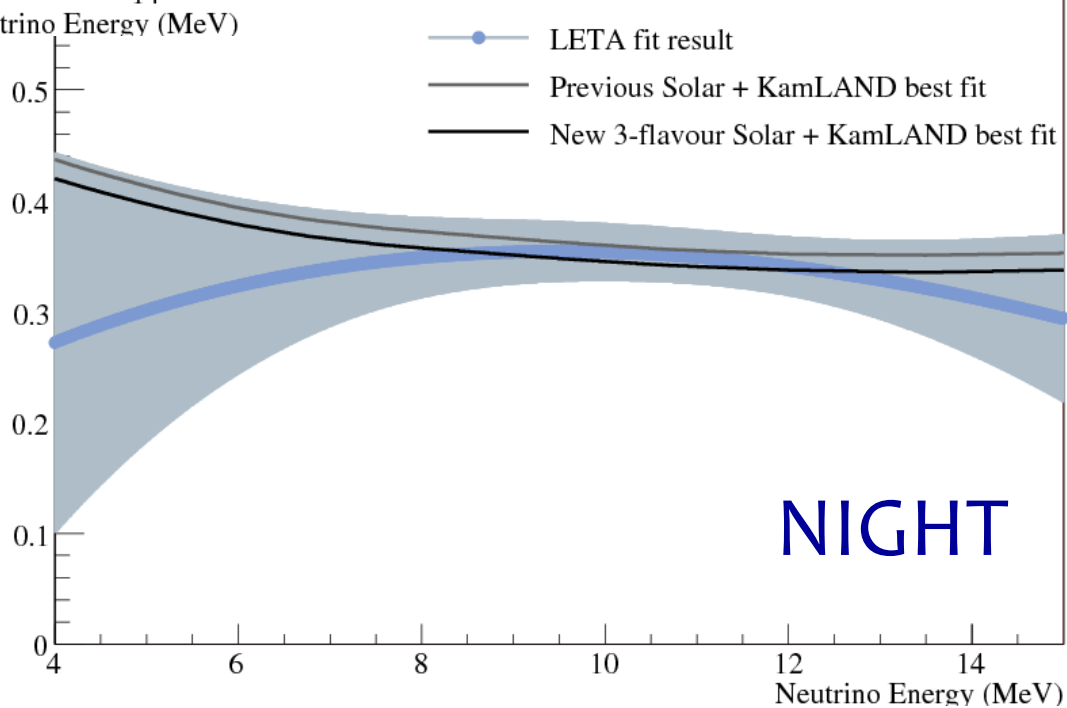
# Survival Probability



# Survival Probability



Neutrino Energy (MeV)



Neutrino Energy (MeV)

# Summary

1. Model-independent measure of the  $^8\text{B}$  flux:

$$\Phi_{\text{NC}} = 5.140 +4.0 -3.8 \%$$

# Summary

1. Model-independent measure of the  $^8\text{B}$  flux:

$$\Phi_{\text{NC}} = 5.140 +4.0 -3.8 \%$$

2. Measure of the  $^8\text{B}$  flux assuming unitarity:

$$\Phi_{8\text{B}} = 5.046 +3.8 -3.9 \%$$

# Summary

1. Model-independent measure of the  $^8\text{B}$  flux:

$$\Phi_{\text{NC}} = 5.140 +4.0 -3.8 \%$$

2. Measure of the  $^8\text{B}$  flux assuming unitarity:

$$\Phi_{8\text{B}} = 5.046 +3.8 -3.9 \%$$

3. Best fit global MSW parameters (2-flavor):

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

$$\Delta m^2 = 7.59 \times 10^{-5} \text{ eV}^2 \quad (+0.20 -0.21)$$

$$\Phi_{8\text{B}} \text{ uncert} = +2.38 -2.95 \%$$

# Summary

1. Model-independent measure of the  $^8\text{B}$  flux:

$$\Phi_{\text{NC}} = 5.140 +4.0 -3.8 \%$$

2. Measure of the  $^8\text{B}$  flux assuming unitarity:

$$\Phi_{8\text{B}} = 5.046 +3.8 -3.9 \%$$

3. Best fit global MSW parameters (2-flavor):

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

$$\Delta m^2 = 7.59 \times 10^{-5} \text{ eV}^2 (+0.20 -0.21)$$

$$\Phi_{8\text{B}} \text{ uncert} = +2.38 -2.95 \%$$

4. 3-flavor oscillation analysis:

$$\sin^2 \theta_{13} = 2.00 +2.09 -1.63 \times 10^{-2} \Rightarrow \sin^2 \theta_{13} < 0.057 (95\% \text{ C.L.})$$

For further details:

# SNO's Low Energy Threshold Analysis ('LETA') Paper

Now available on the arXiv:

**arXiv:0910.2984 [nucl-ex]**

Plus: "Searches for High Frequency Variations in the  
 $^8\text{B}$  Solar Neutrino Flux at the Sudbury Neutrino  
Observatory" - **arXiv:0910.2433 [astro-ph.SR]**

