The Low Energy Threshold Analysis of the First Two Phases of the Sudbury Neutrino Observatory

Stanley Seibert
Los Alamos National Laboratory
INFO09, July 6, 2009

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The Low Energy Threshold Analysis of the First Two Phases of the Sudbury Neutrino Observatory

"We're not dead yet!"

Stanley Seibert
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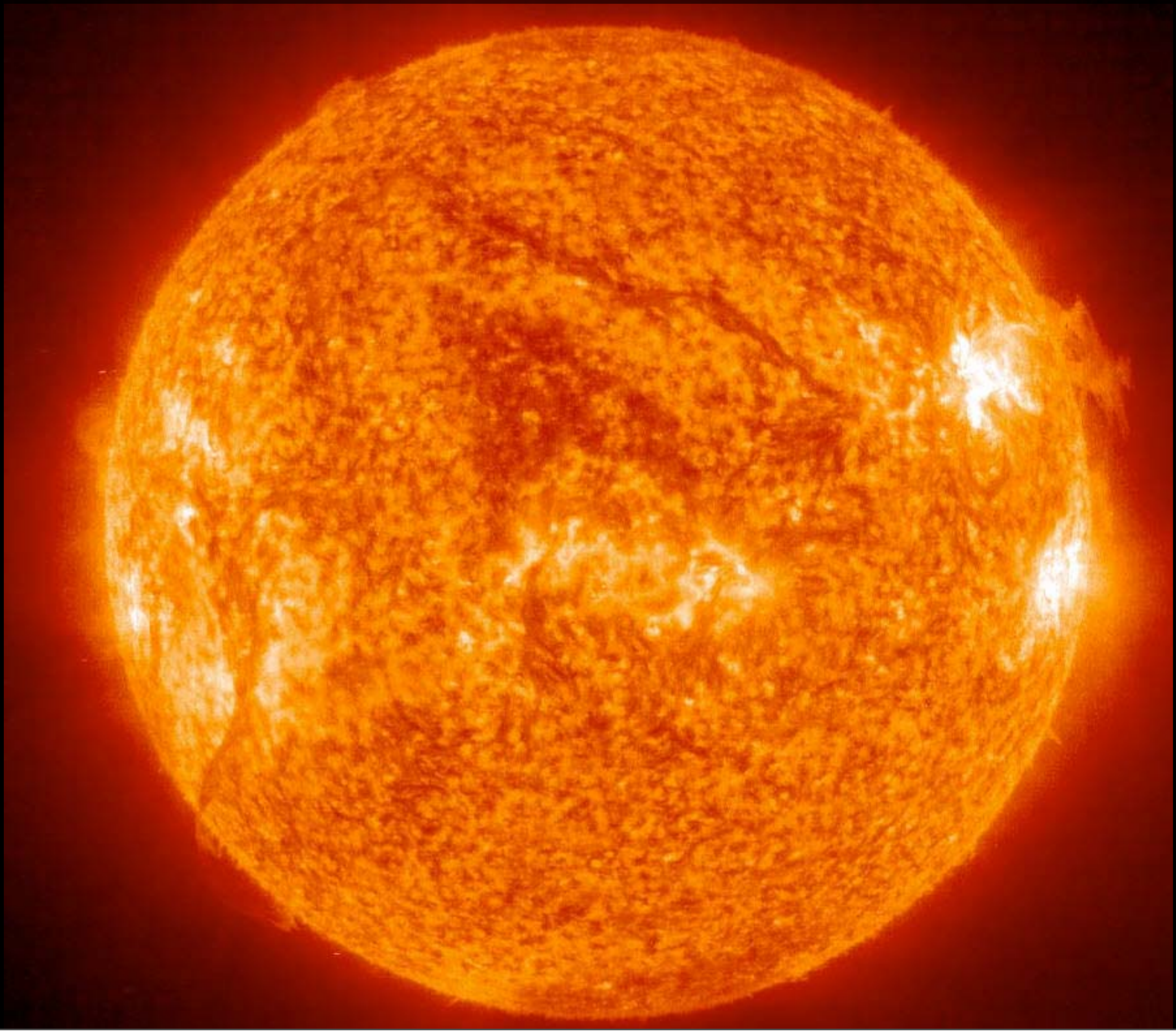
Disclaimer:

Final results will not be shown in this talk.

(But you will see some data and a few uncertainties...)

The Sun: A Massive Neutrino Source



Solar ν Energy Spectrum

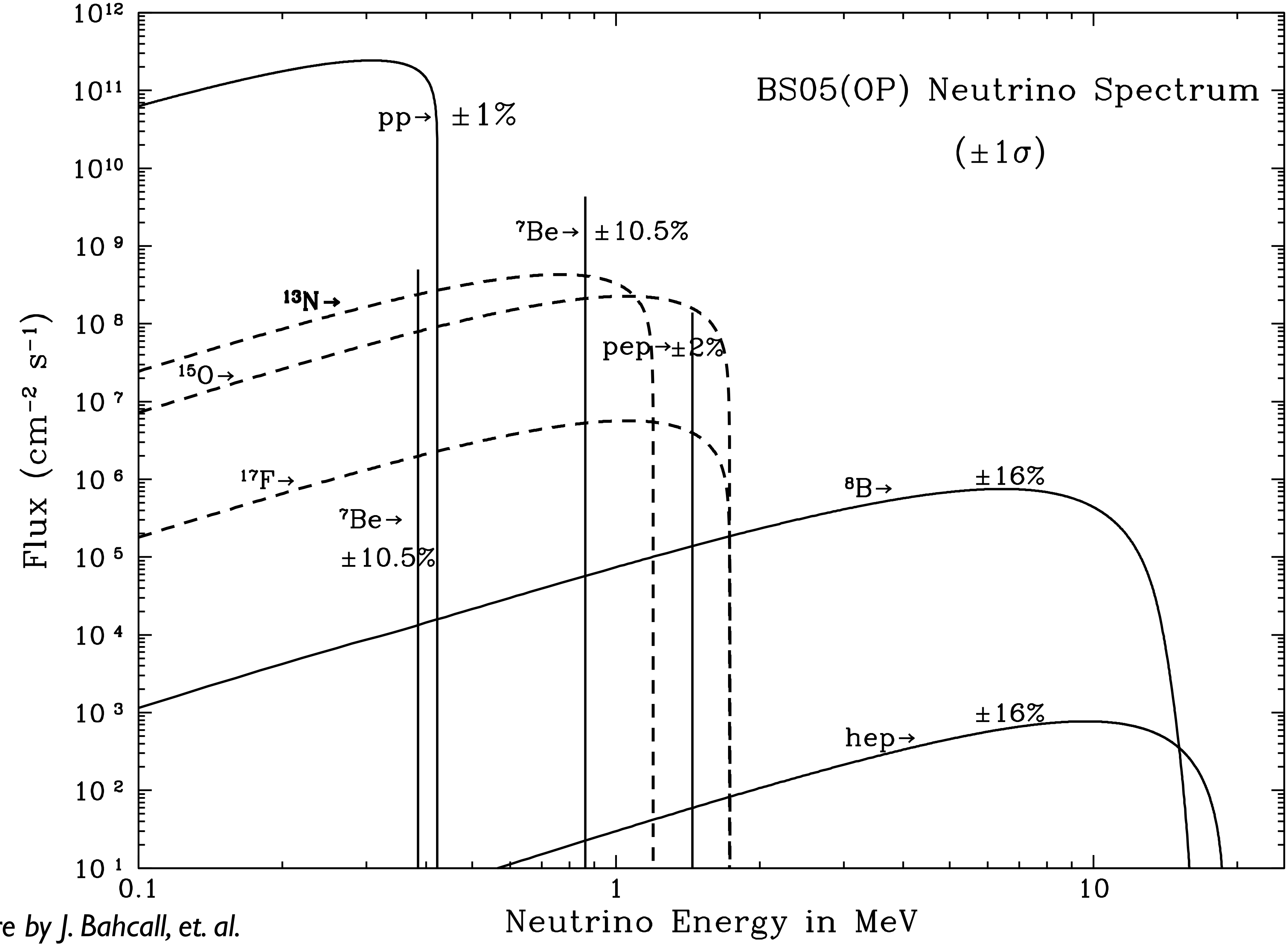


Figure by J. Bahcall, et. al.

Solar ν Energy Spectrum

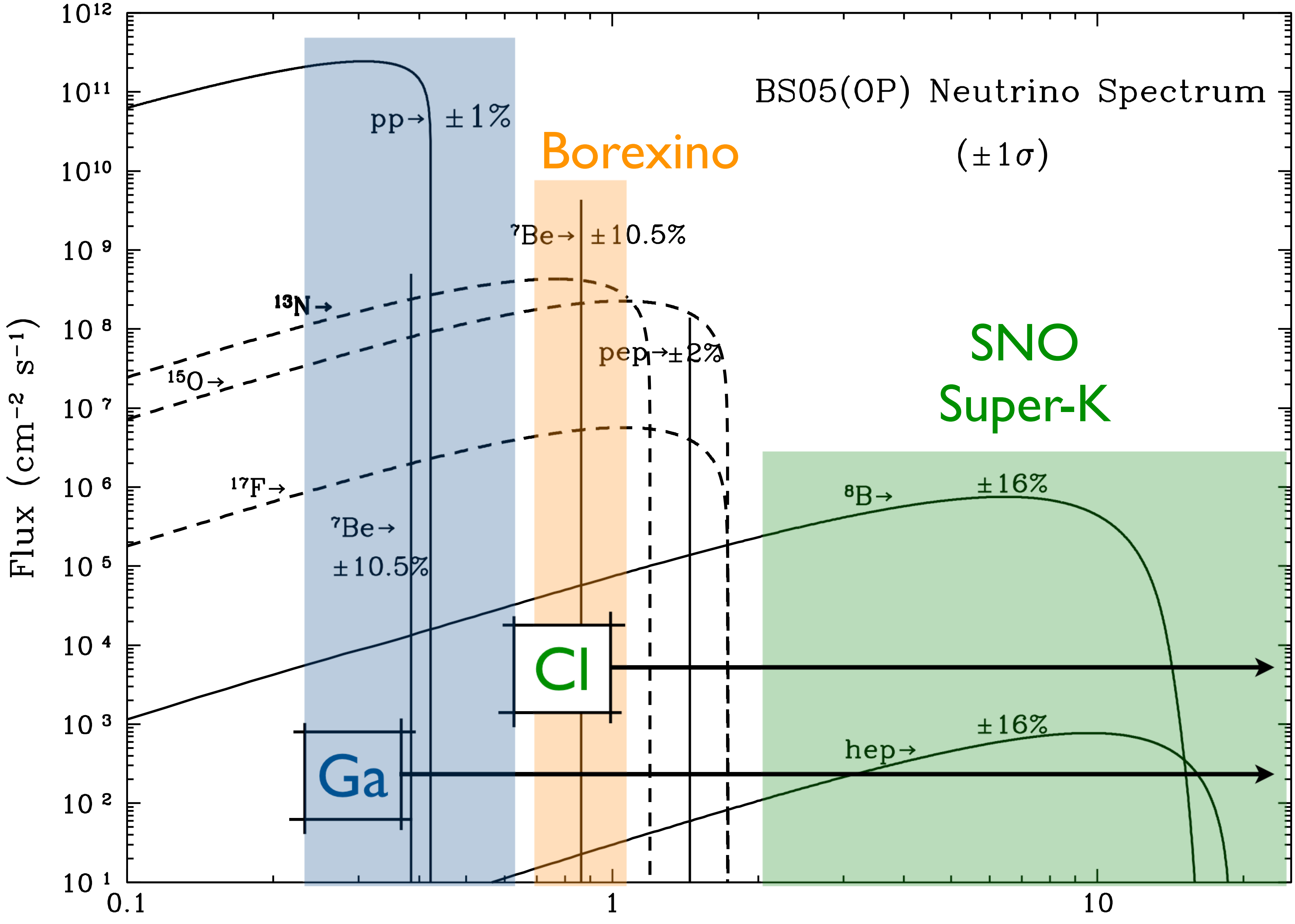


Figure by J. Bahcall, et. al.

Solar ν Energy Spectrum

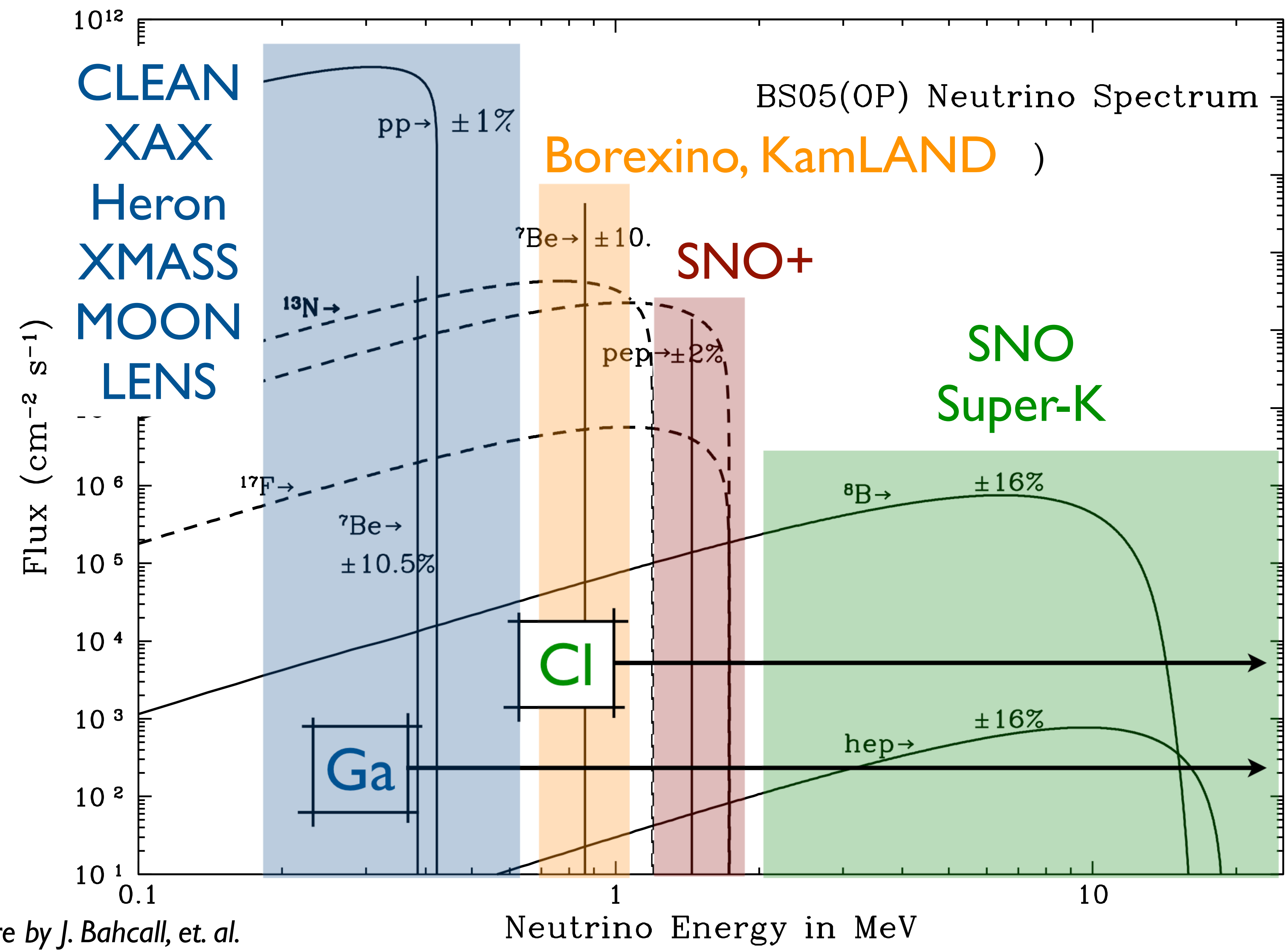
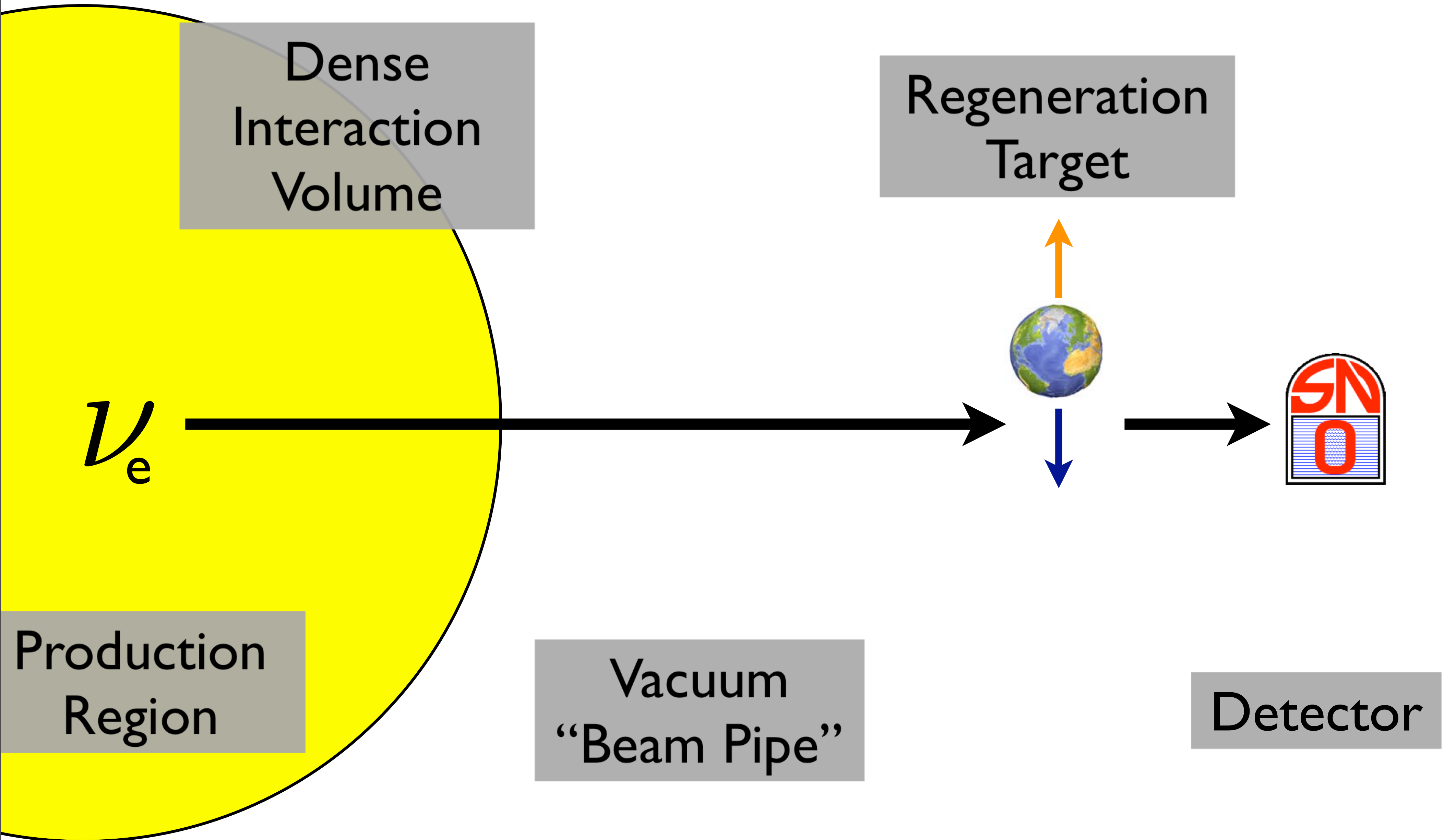


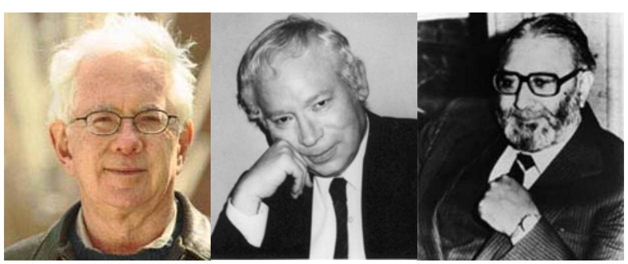
Figure by J. Bahcall, et. al.

Solar Neutrino Experiments

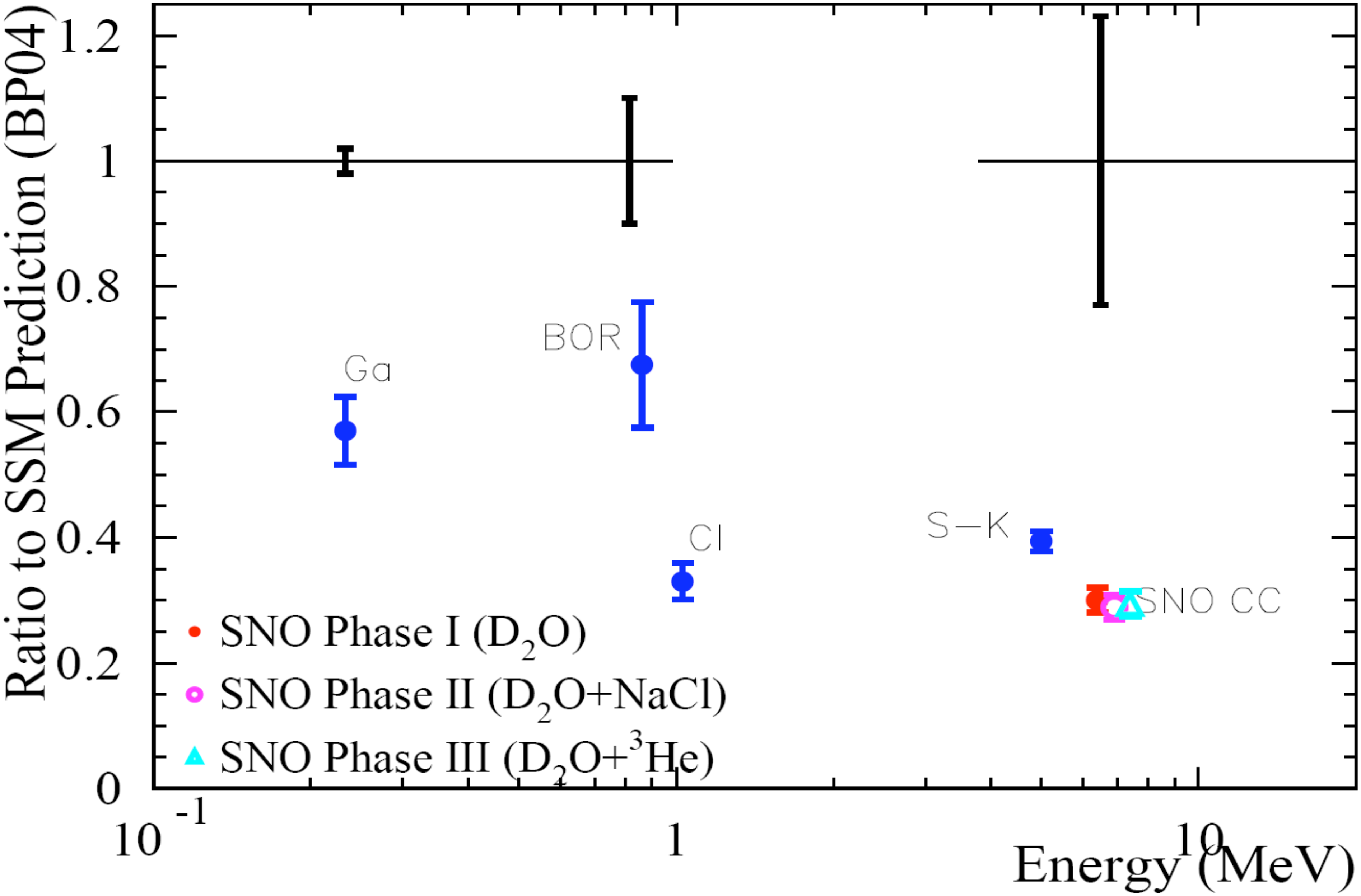


A Tale of Two Models
(Homestake era)

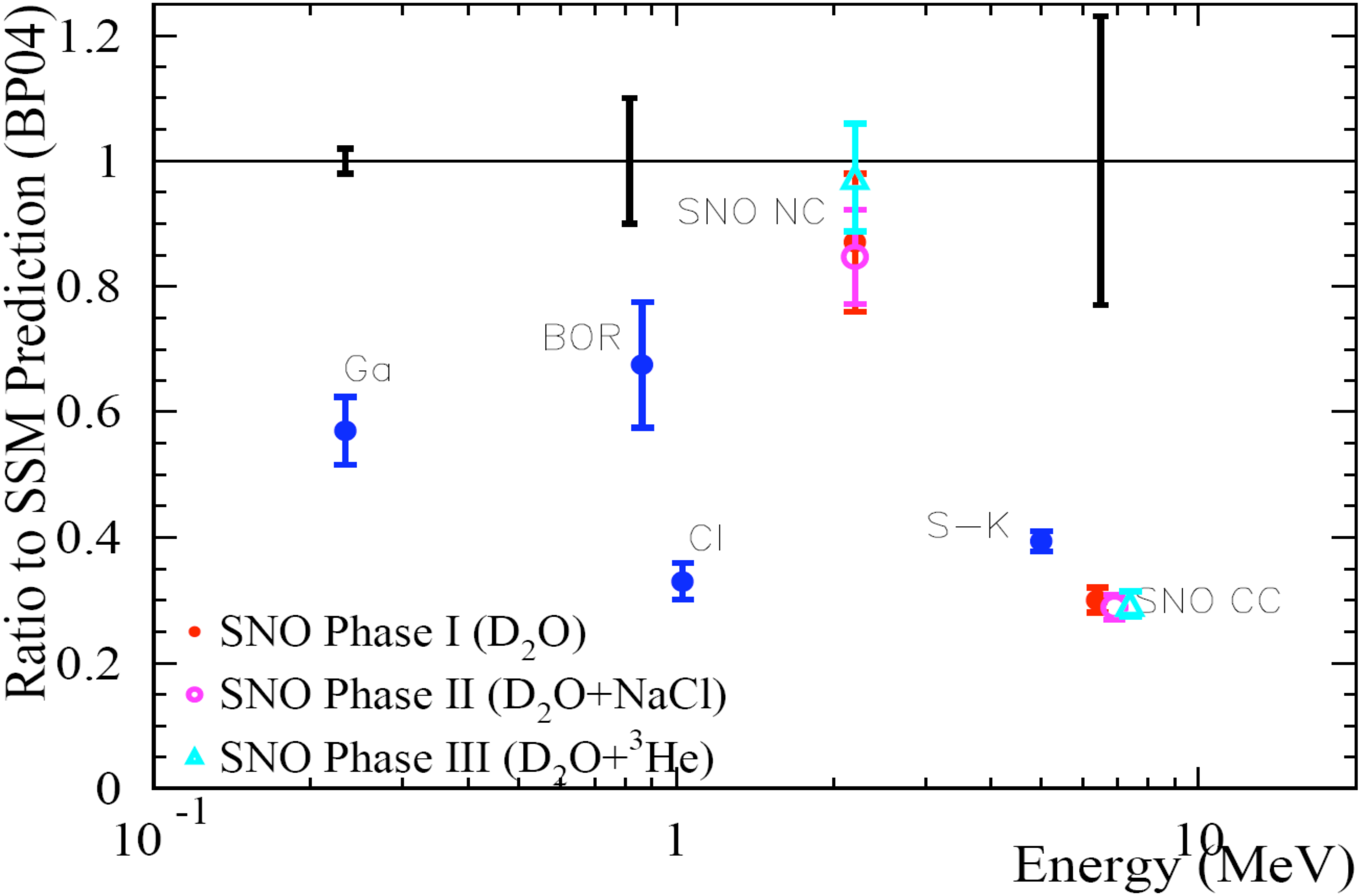
Electroweak Model of Leptons	Standard Solar Model
Massless, stable neutrinos	pp-chain/CNO cycle
Lepton flavor conservation	standard nuclear cross-sections
	initial elemental abundance matches surface



Measured Solar Neutrino Fluxes

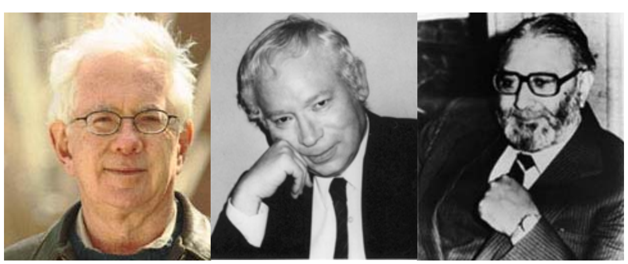


Measured Solar Neutrino Fluxes



A Tale of Two Models
(revised)

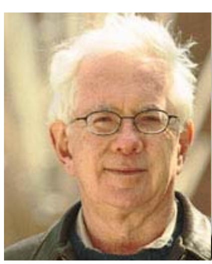
Electroweak Model of Leptons	Standard Solar Model
Massive ~~Massless~~, stable neutrinos	pp-chain/CNO cycle
	standard nuclear cross-sections
Lepton ~~flavor~~ number conservation	initial elemental abundance matches surface



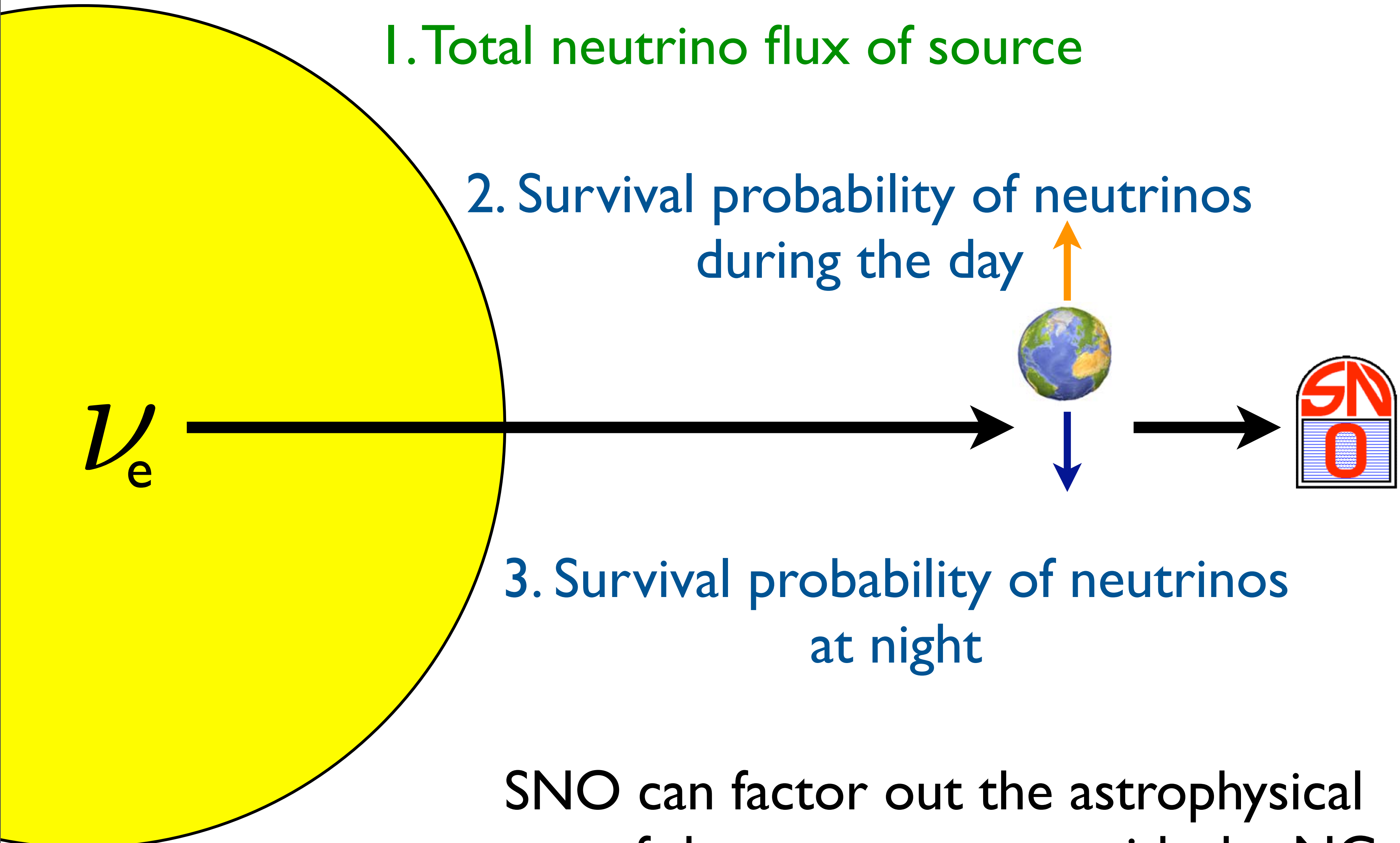
A Tale of Two Models

Electroweak Model of Leptons	Standard Solar Model
Massless, sta	NO cycle
Lepton flavor	cross-sections
	l abundance urface

Solar neutrino experiments are both particle physics and astrophysics experiments!




What are the physical quantities of interest to SNO?



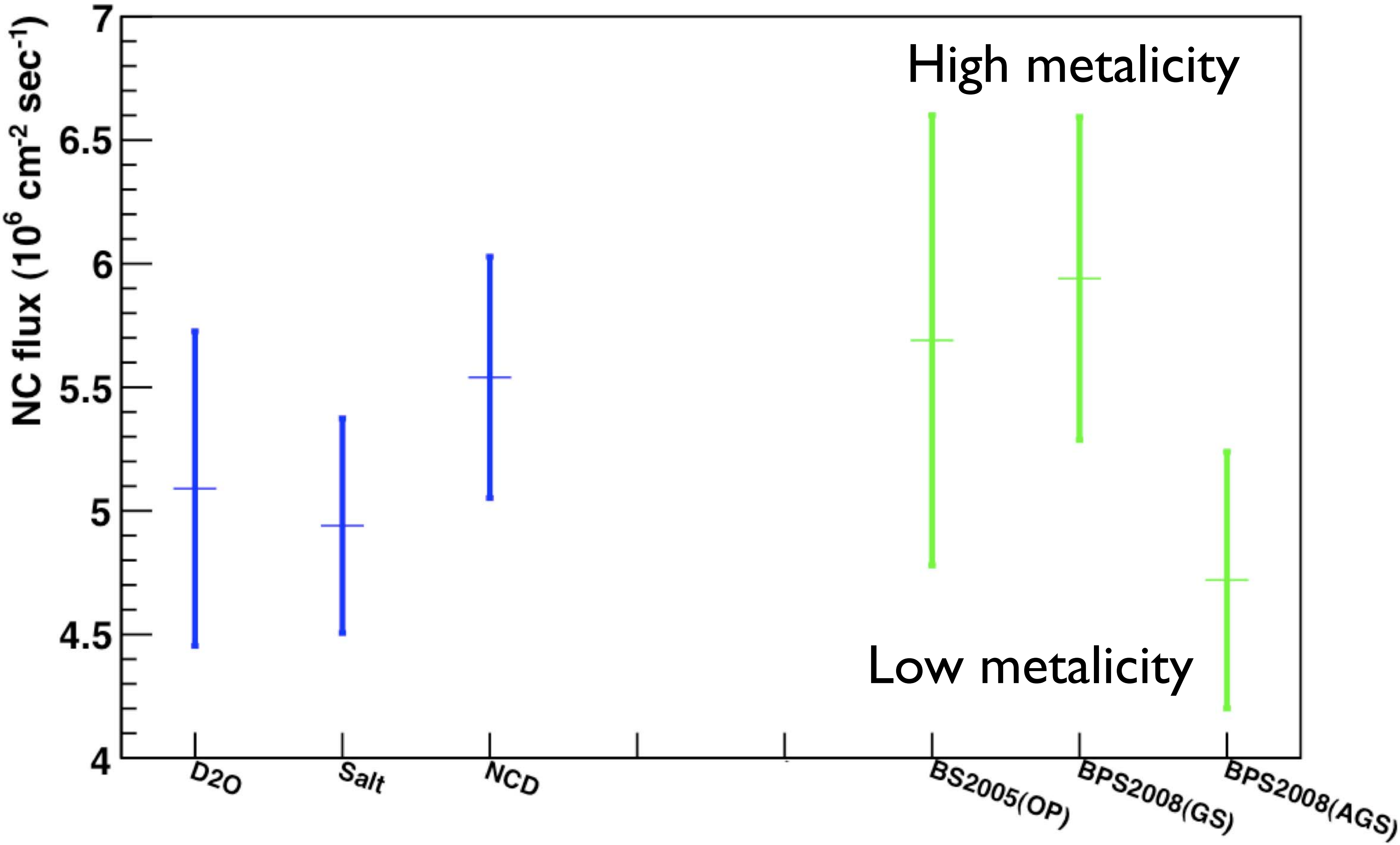
1. Total neutrino flux of source

2. Survival probability of neutrinos during the day

3. Survival probability of neutrinos at night

SNO can factor out the astrophysical part of the measurement with the NC

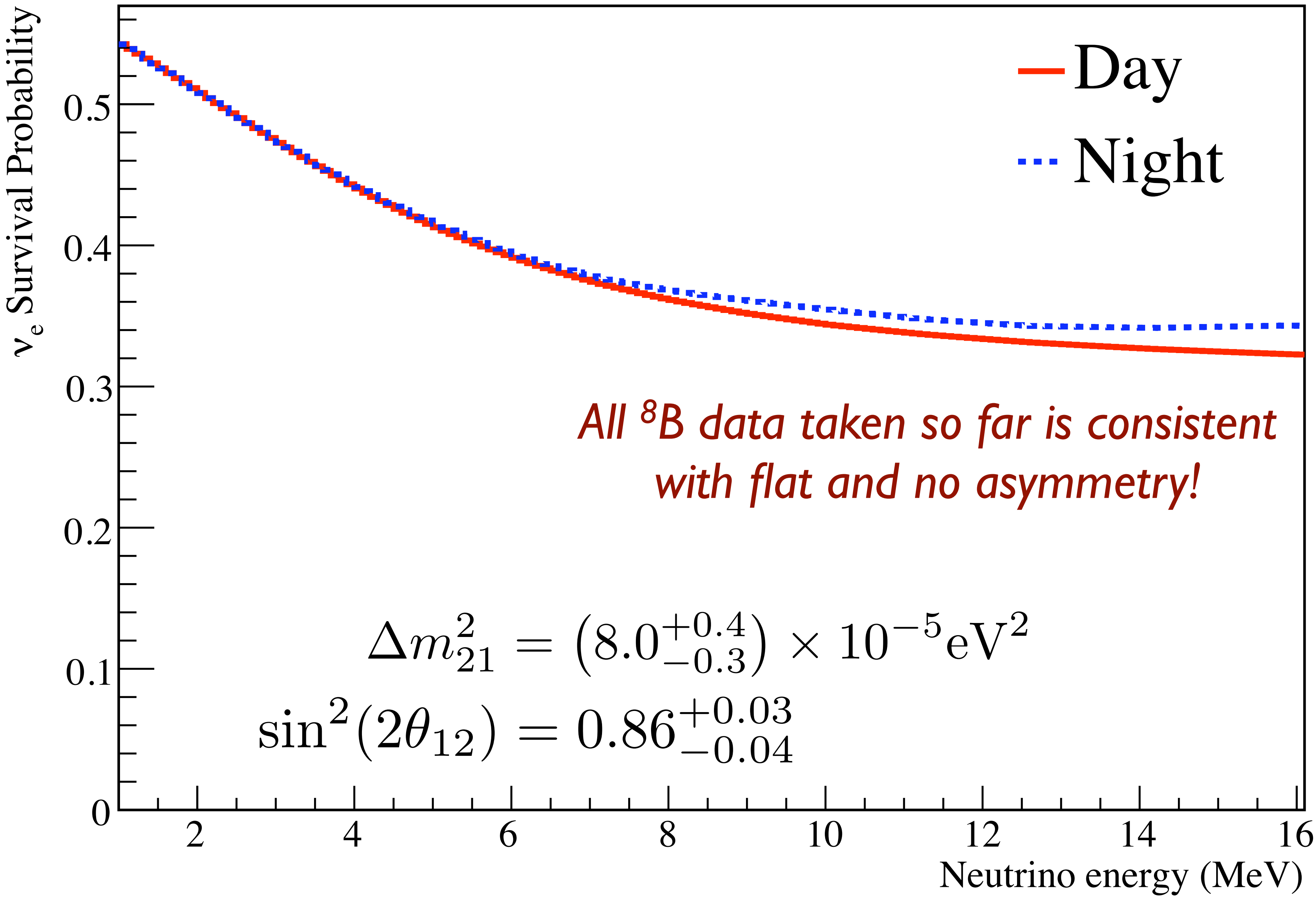
SNO compared to solar models



A Tale of Two Models
(revised, again?)

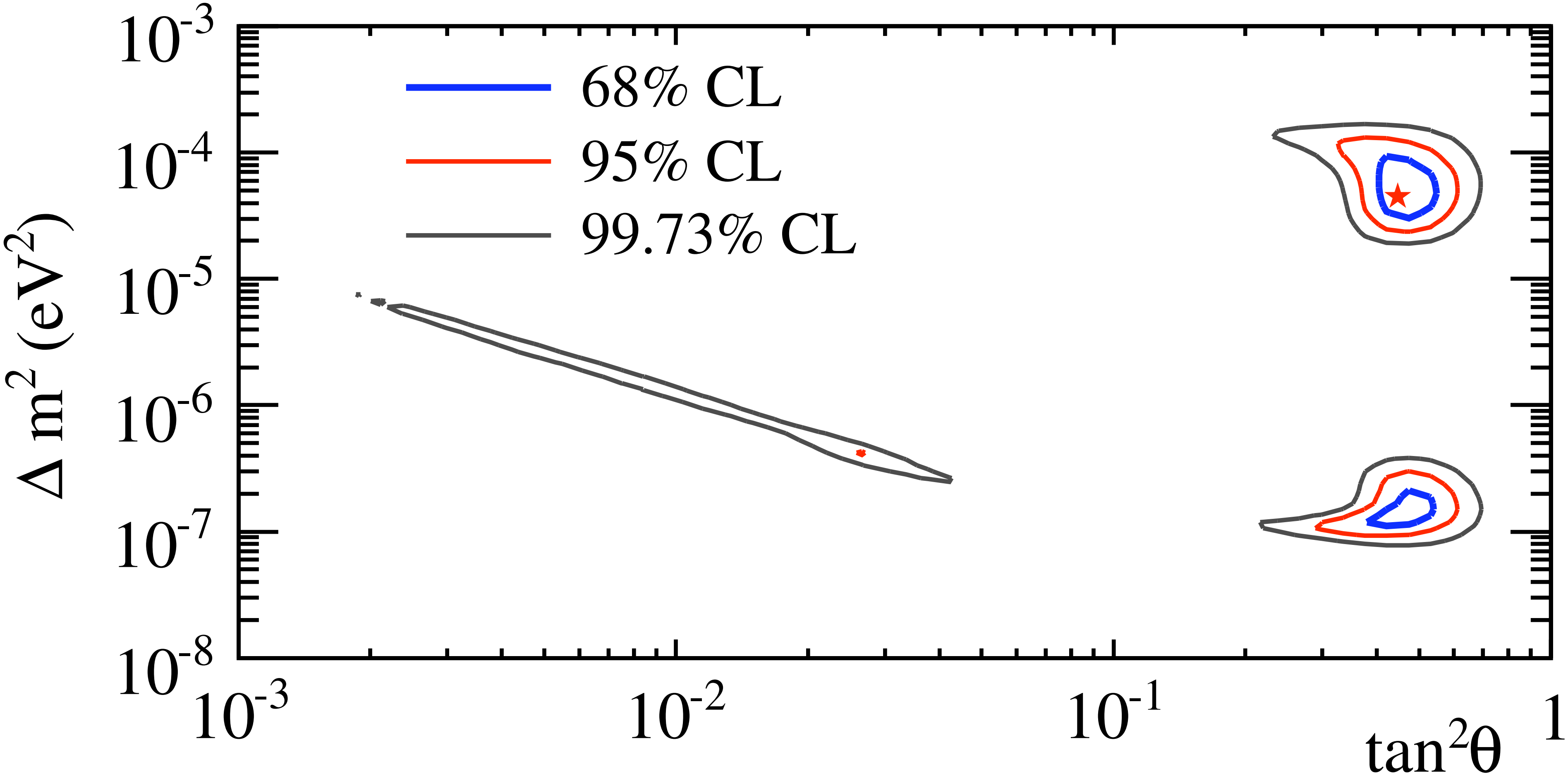
Electroweak Model of Leptons	Standard Solar Model
~~Massless~~ Massive, stable neutrinos	pp-chain/CNO cycle
	standard nuclear cross-sections
Lepton ~~flavor~~ number conservation	initial elemental abundance matches surface ?

LMA ν_e Survival Probability



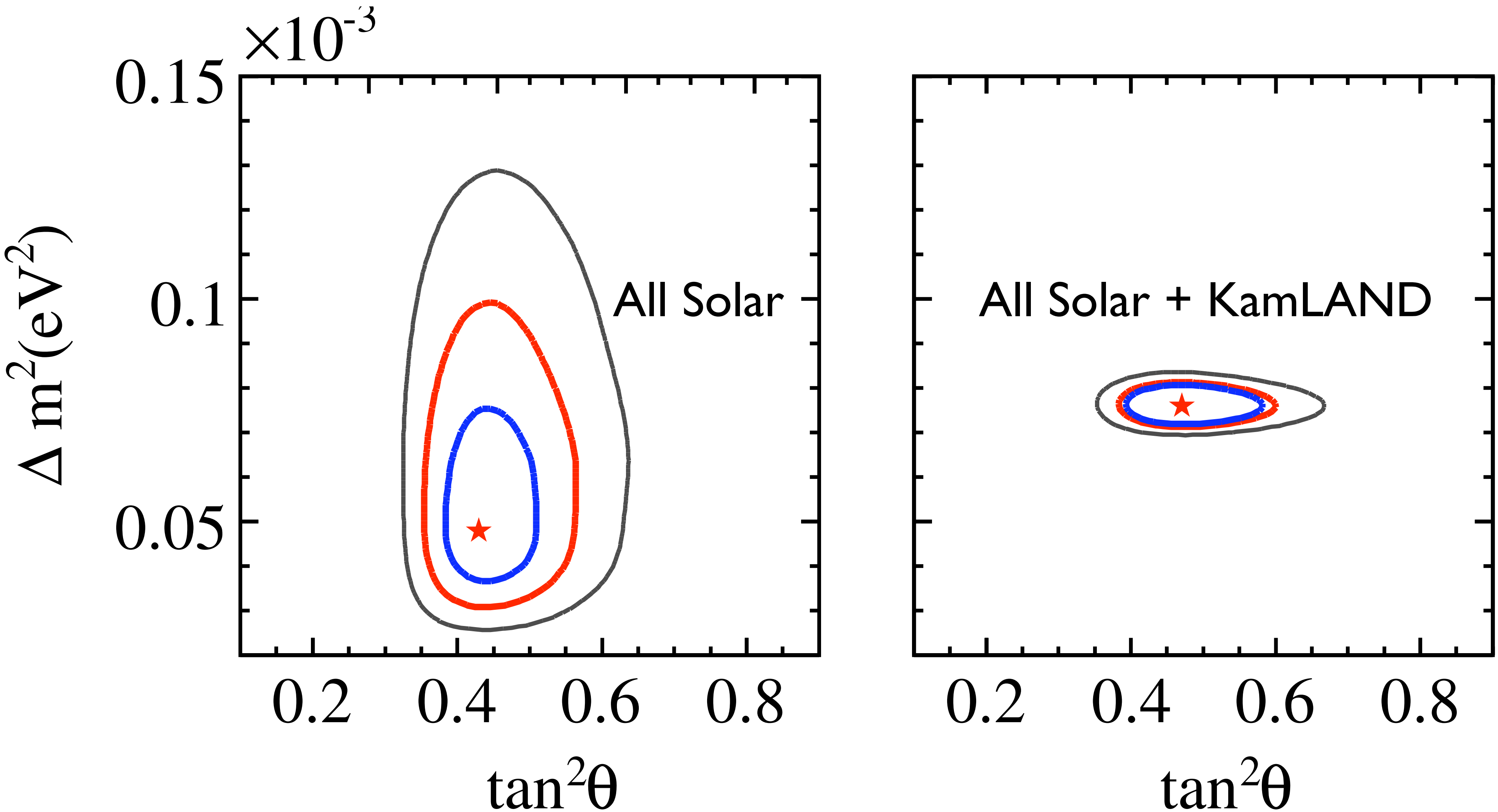
Calculation provided by O. Simard

SNO-only Contours

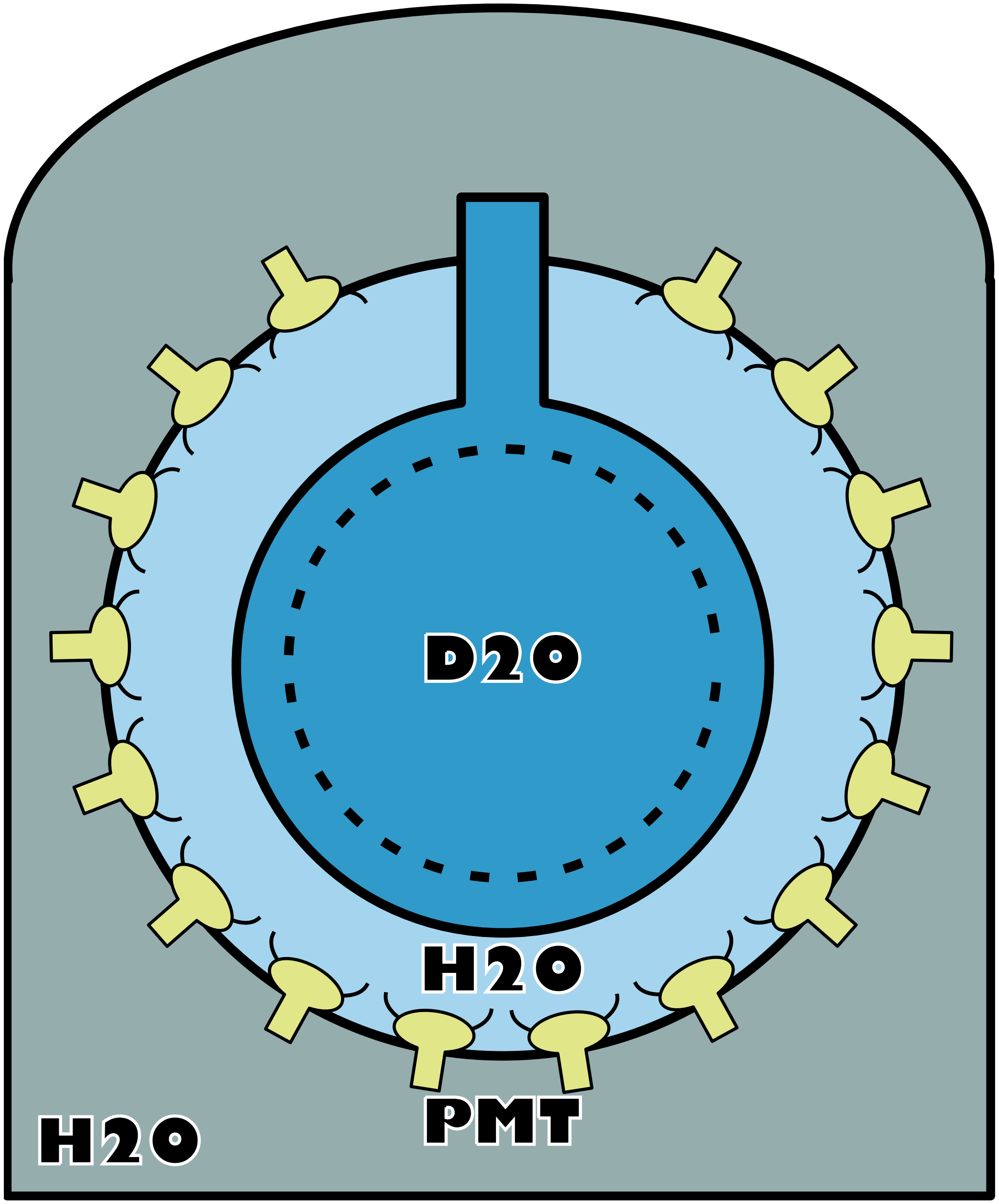


(D2O/Salt spectra + NCD fluxes)

Global Contours



The SNO Detector



1 kiloton D2O target
1.7 kiloton inner H2O shield
5.7 kiloton outer H2O shield
9456 PMTs
➡54% solid angle coverage

R = 550 cm fiducial volume
R = 600 cm acrylic vessel

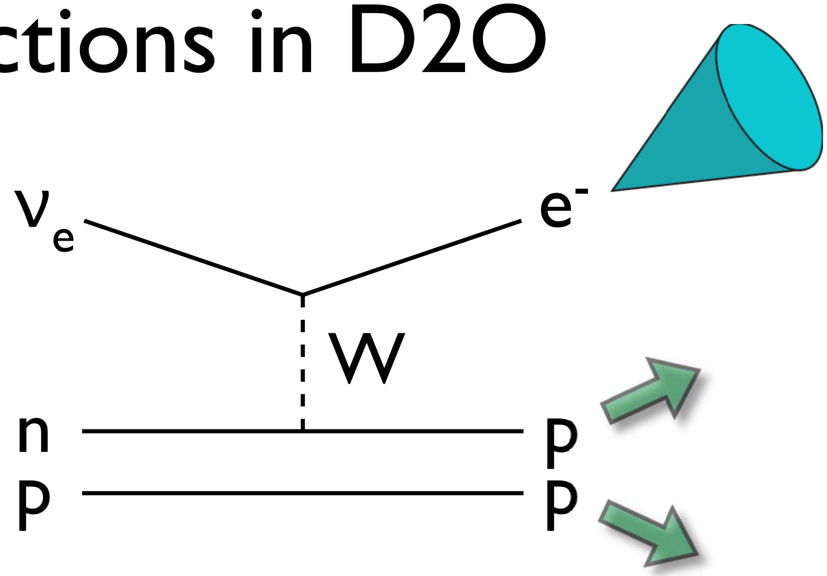
Contamination:
D2O U/Th < 10^{-14} g/g
H2O U/Th < 5×10^{-13} g/g

The SNO Detector

Neutrino Interactions in D2O

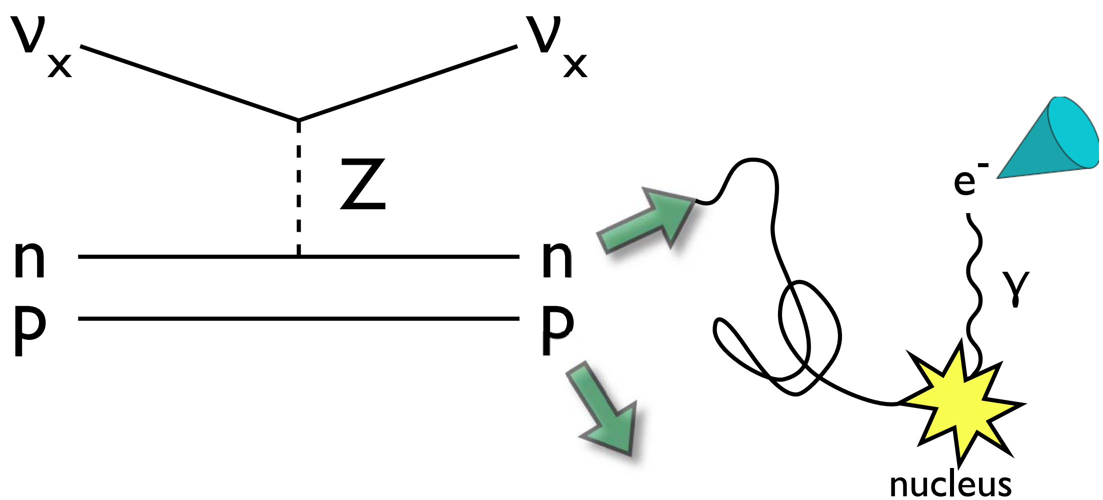
Charged Current (CC)

$$\nu_e + d \to p + p + e^-$$



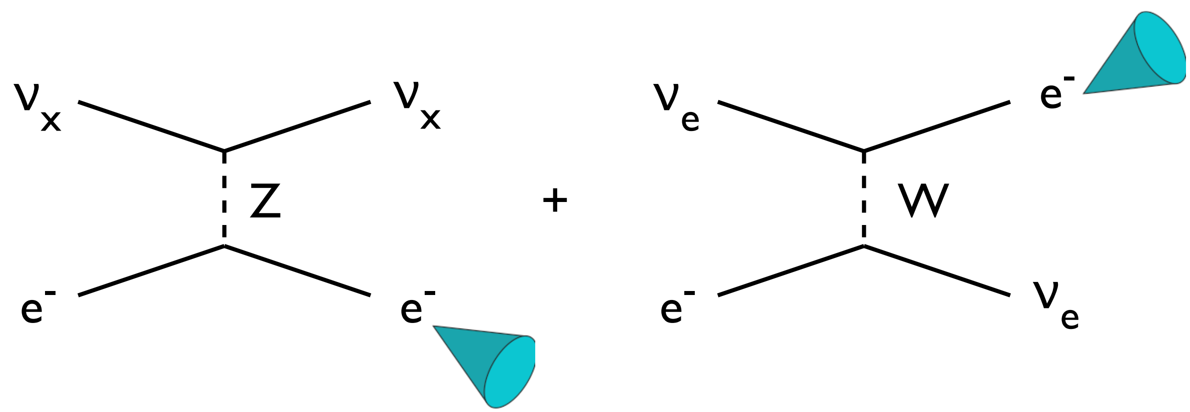
Neutral Current (NC)

$$\nu_x + d \to p + n + \nu_x$$

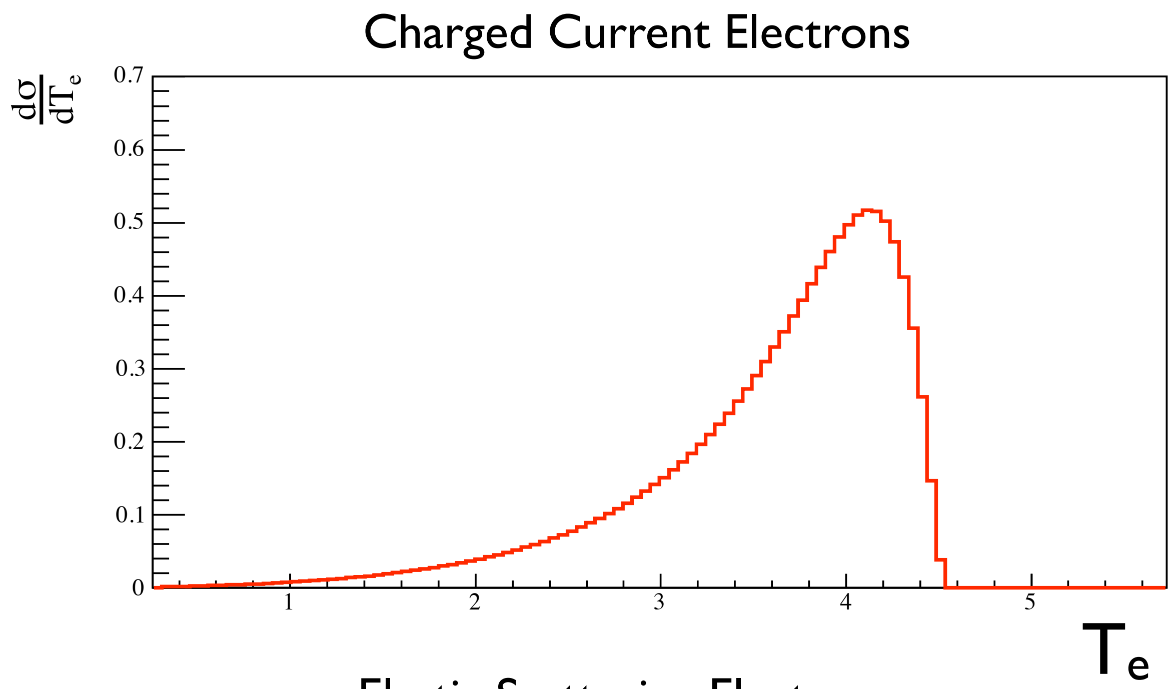


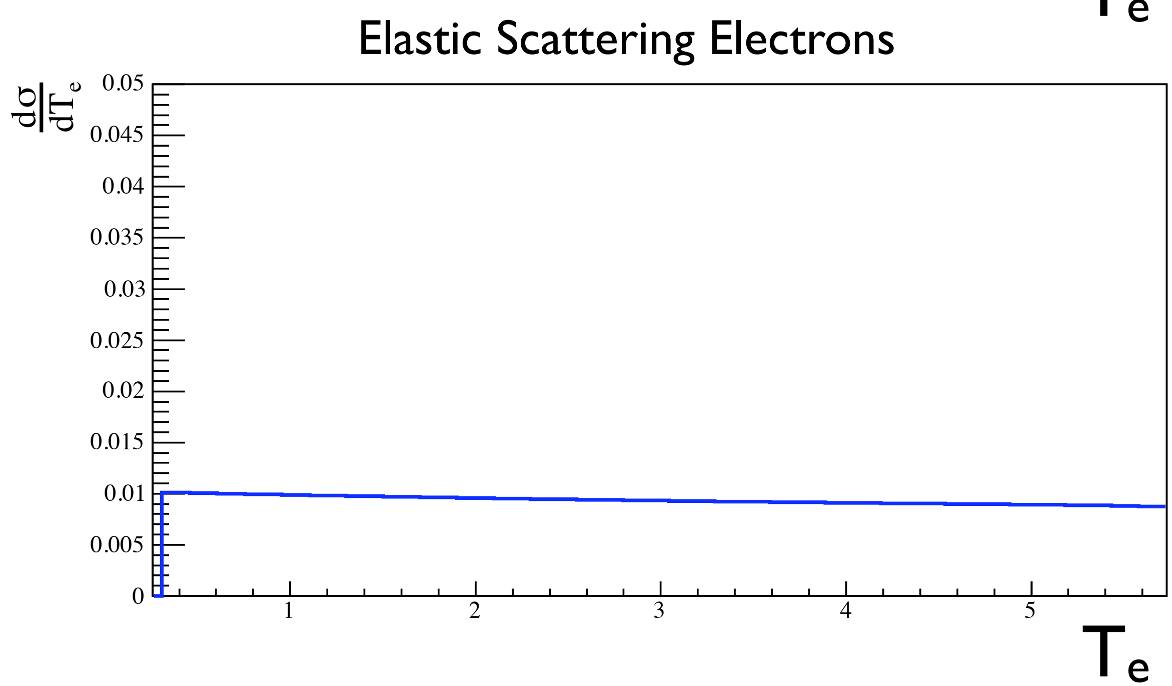
Elastic Scattering (ES)

$$\nu_x + e^- \to \nu_x + e^-$$



CC Electrons as measure of ν energy





T_ν = 6 MeV

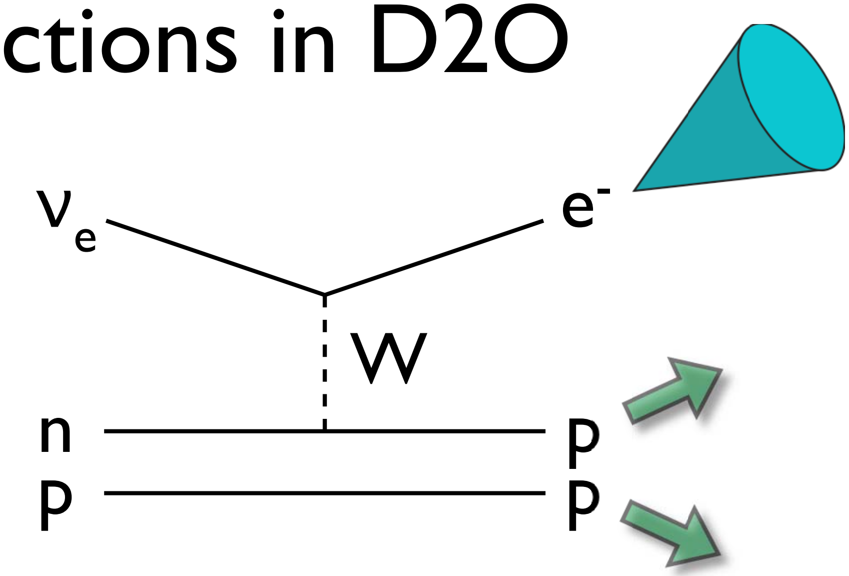
Phases of SNO

Phase 1 "D2O"	Target Material:	1 kton 99.92% pure D2O
	Neutron Capture Cross Section:	0.5 mb on ^{2}H
	Neutron Signature:	6.25 MeV γ
Phase 2 "Salt"	Target Material:	1 kt D2O + 2 ton NaCl
	Neutron Capture Cross Section:	44 b on ^{35}Cl
	Neutron Signature:	8.25 MeV γ cascade
Phase 3 "NCD"	Target Material:	1 kt D2O + ^{3}He counters
	Neutron Capture Cross Section:	5333 b on ^{3}He
	Neutron Signature:	764 keV $p+^{3}H$ track

Neutrino Interactions in D2O

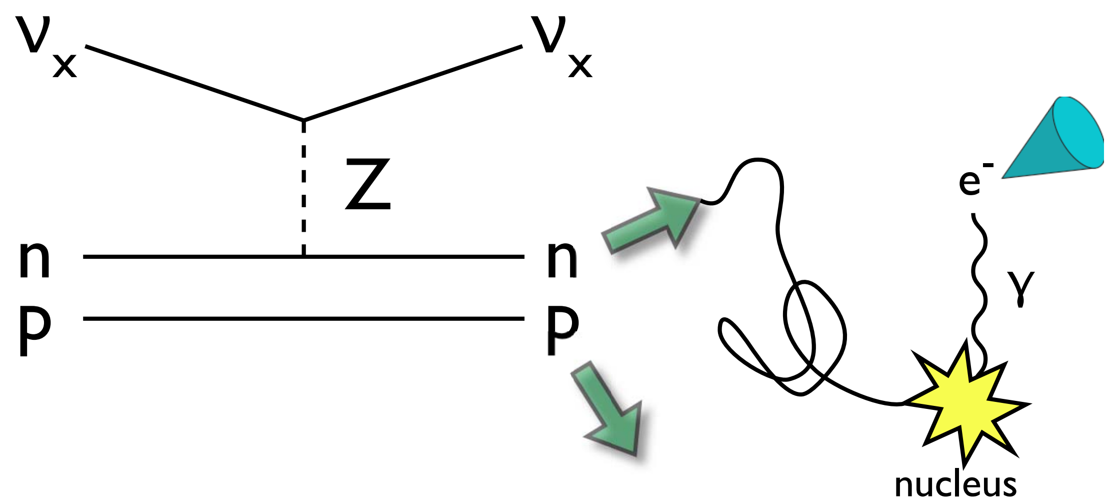
Charged Current (CC)

$$\nu_e + d \rightarrow p + p + e^-$$



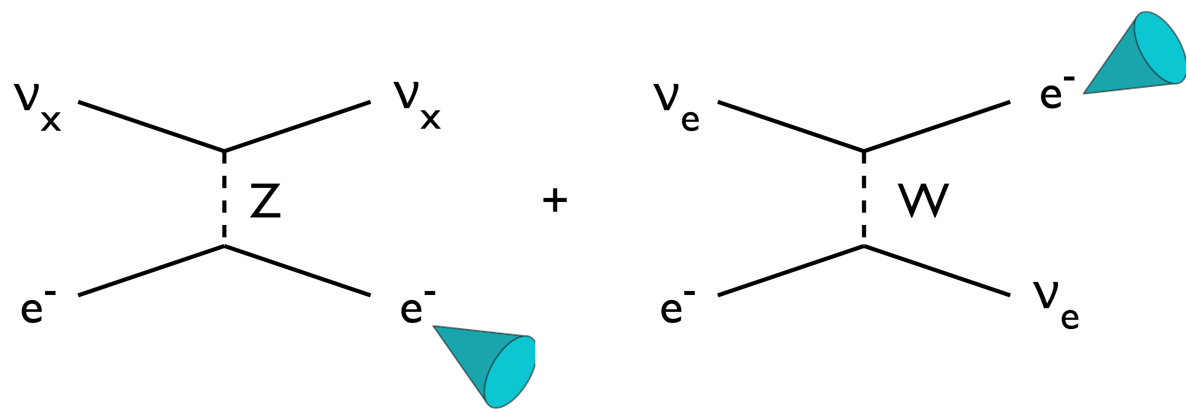
Neutral Current (NC)

$$\nu_x + d \rightarrow p + n + \nu_x$$



Elastic Scattering (ES)

$$\nu_x + e^- \rightarrow \nu_x + e^-$$



Neutrino Interactions in D2O

Charged Current (CC)

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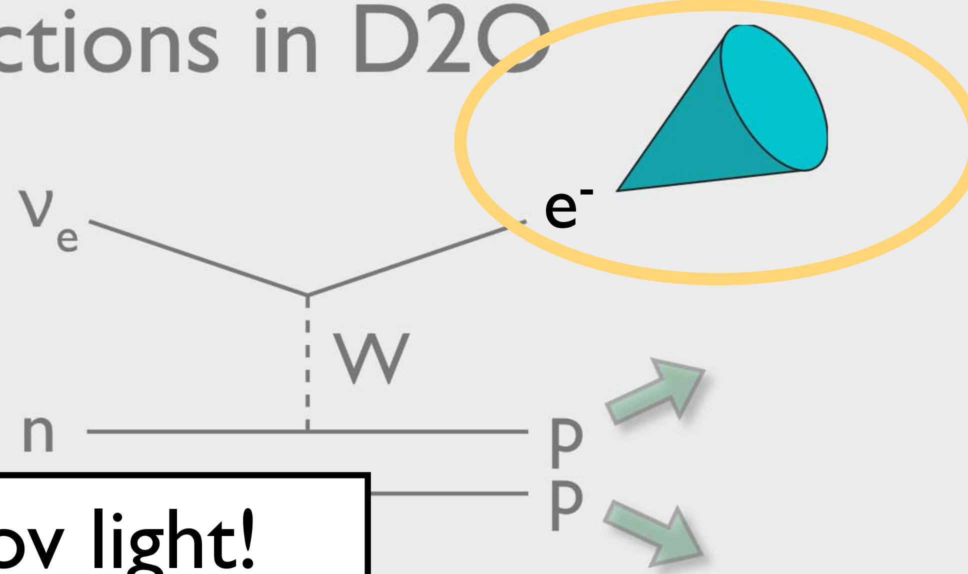
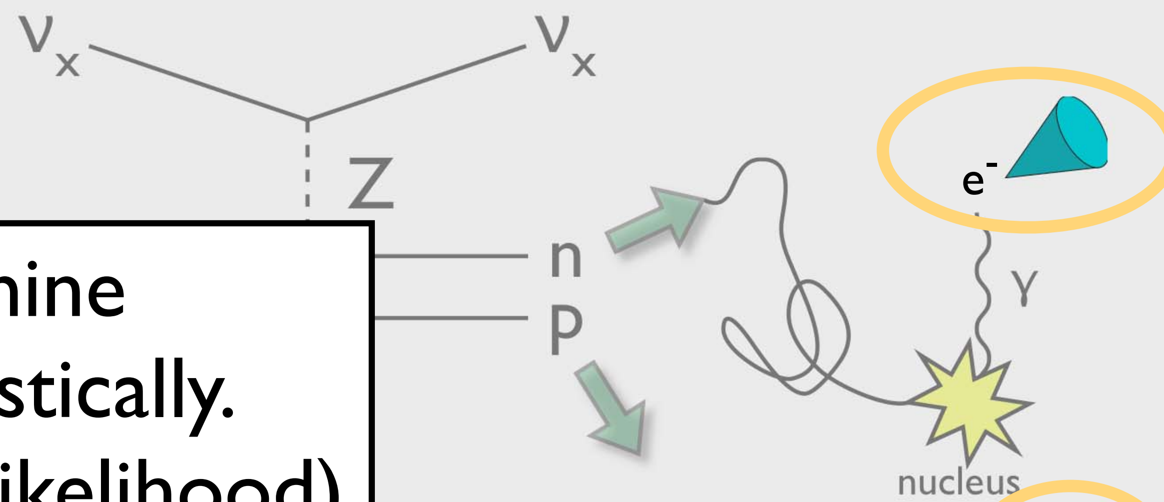


It's all just Cherenkov light!

Neutral Current (NC)

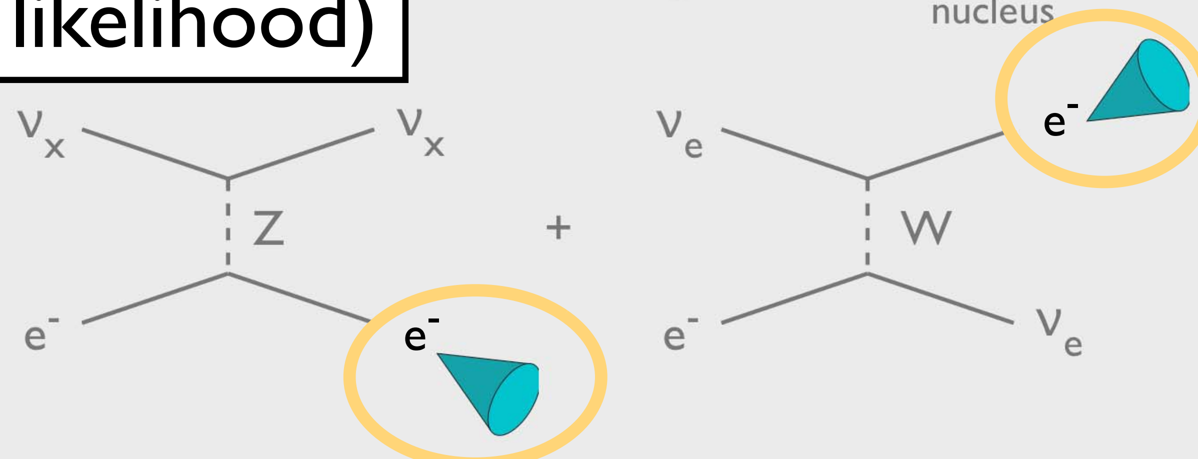
$$\nu_x + d \rightarrow p + n + \nu_x$$



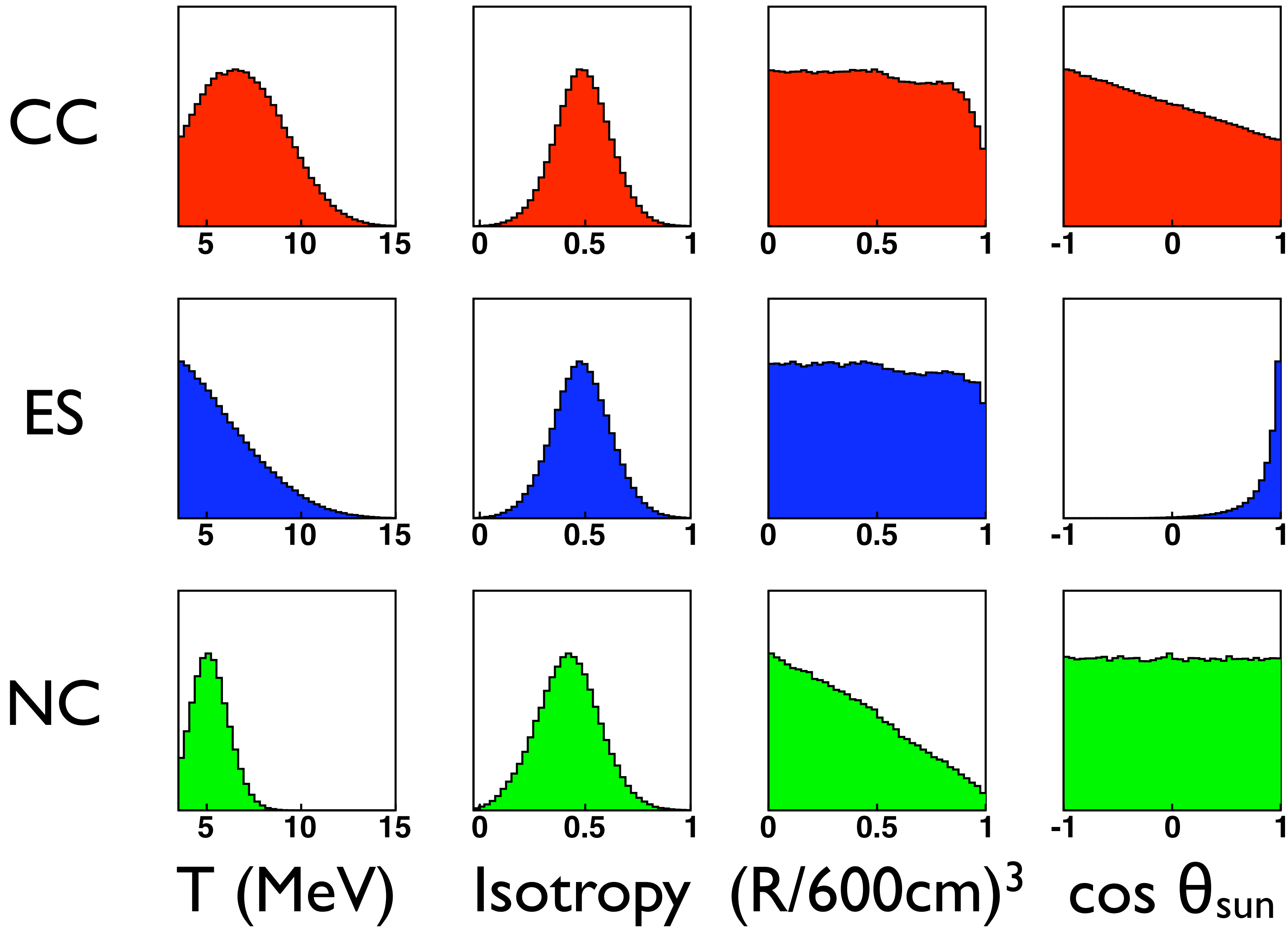
Need to determine reaction rates statistically. (Extended maximum likelihood)

El

$$\nu_x + e \rightarrow \nu_x + e$$



Separating the Signals (D2O phase)



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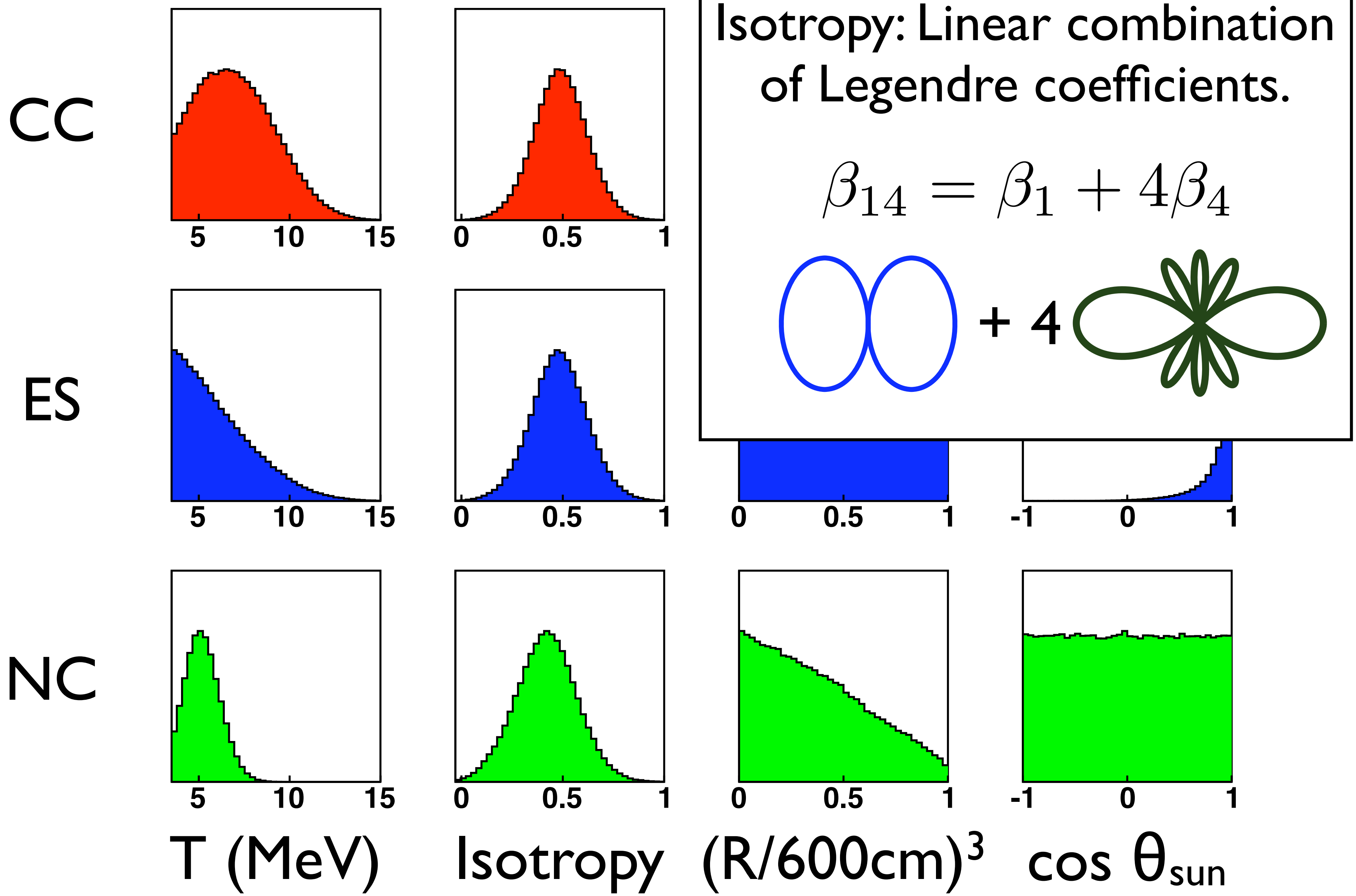
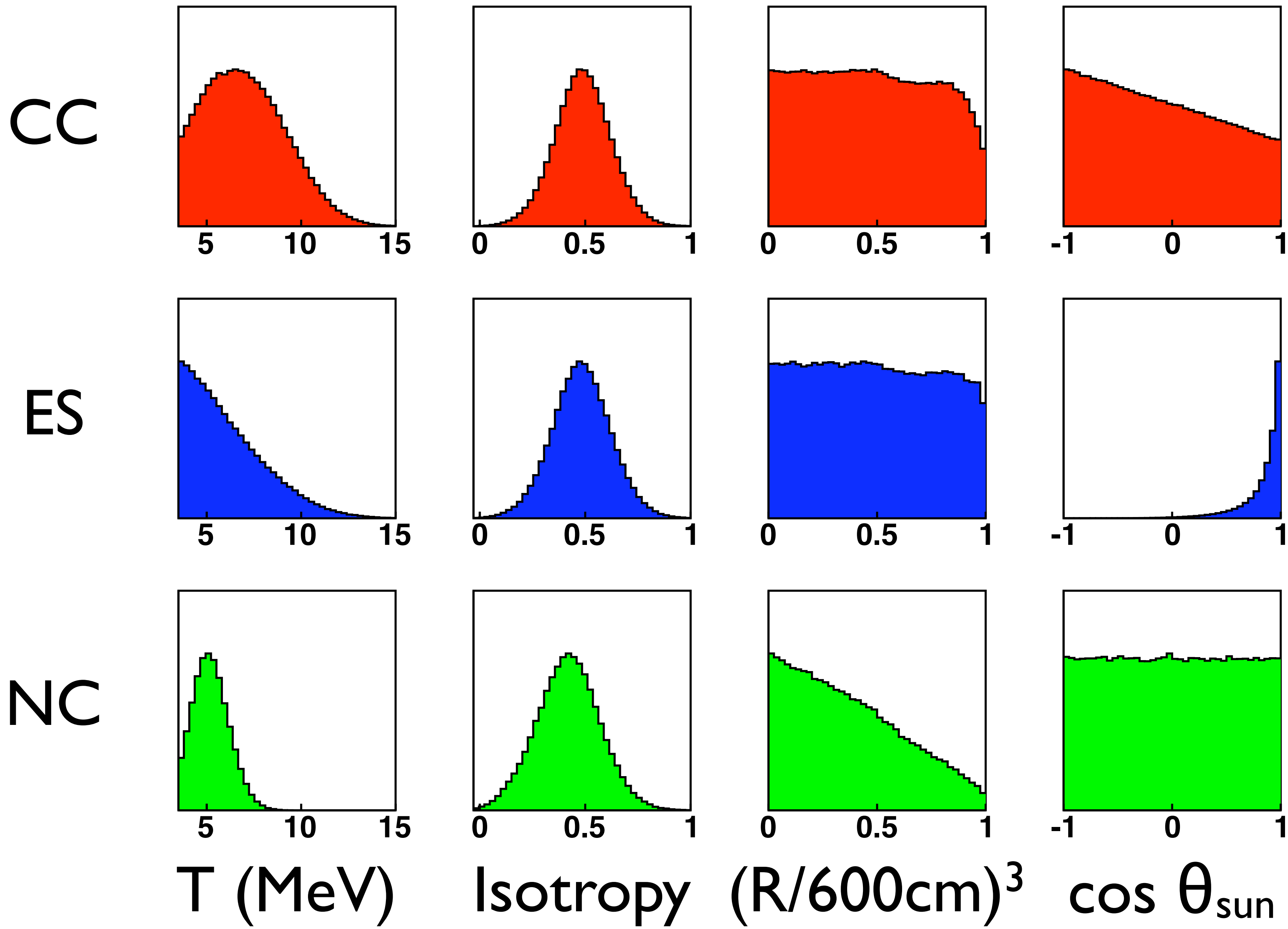


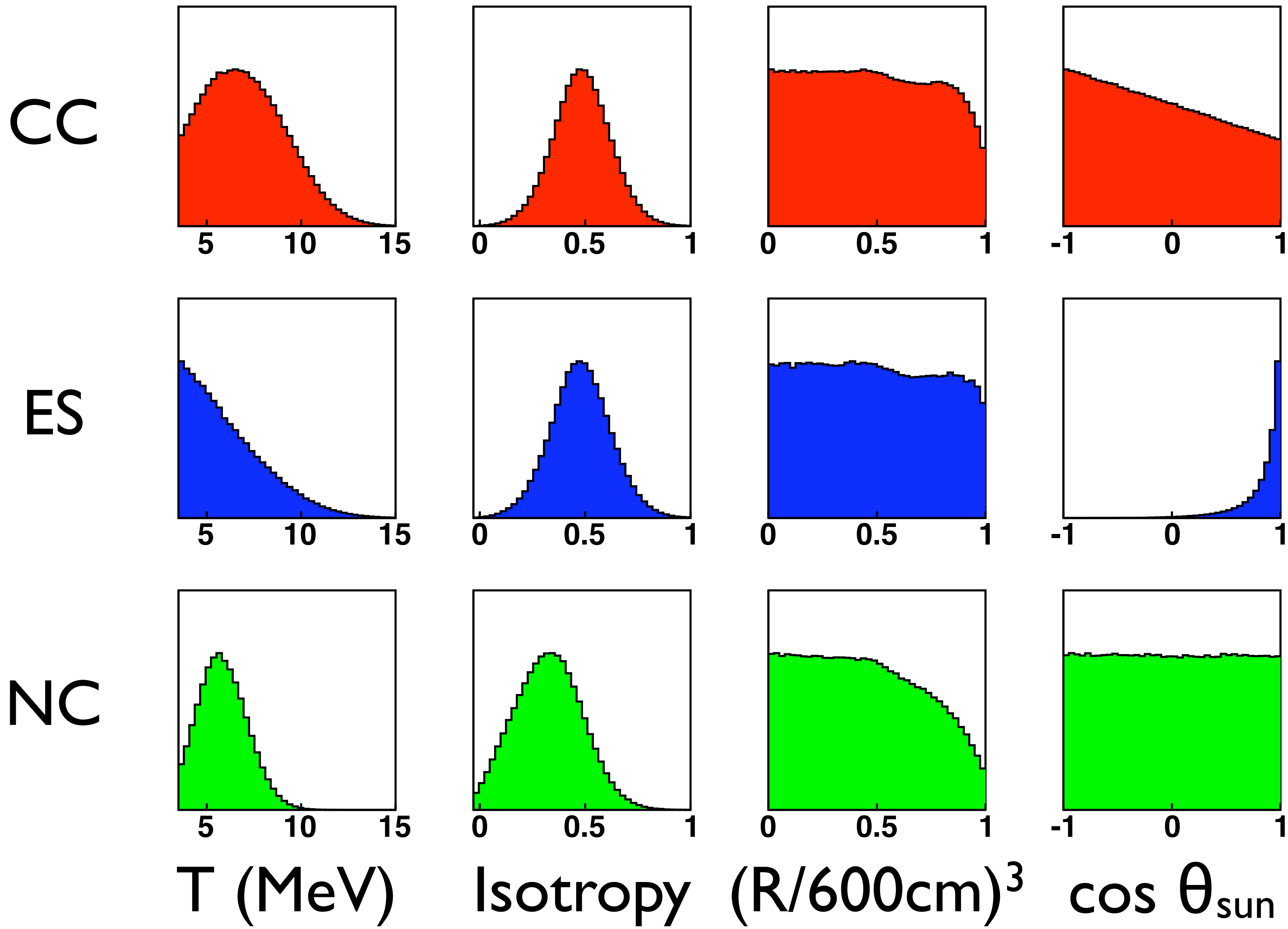
Isotropy: Linear combination of Legendre coefficients.

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

Separating the Signals (D2O phase)



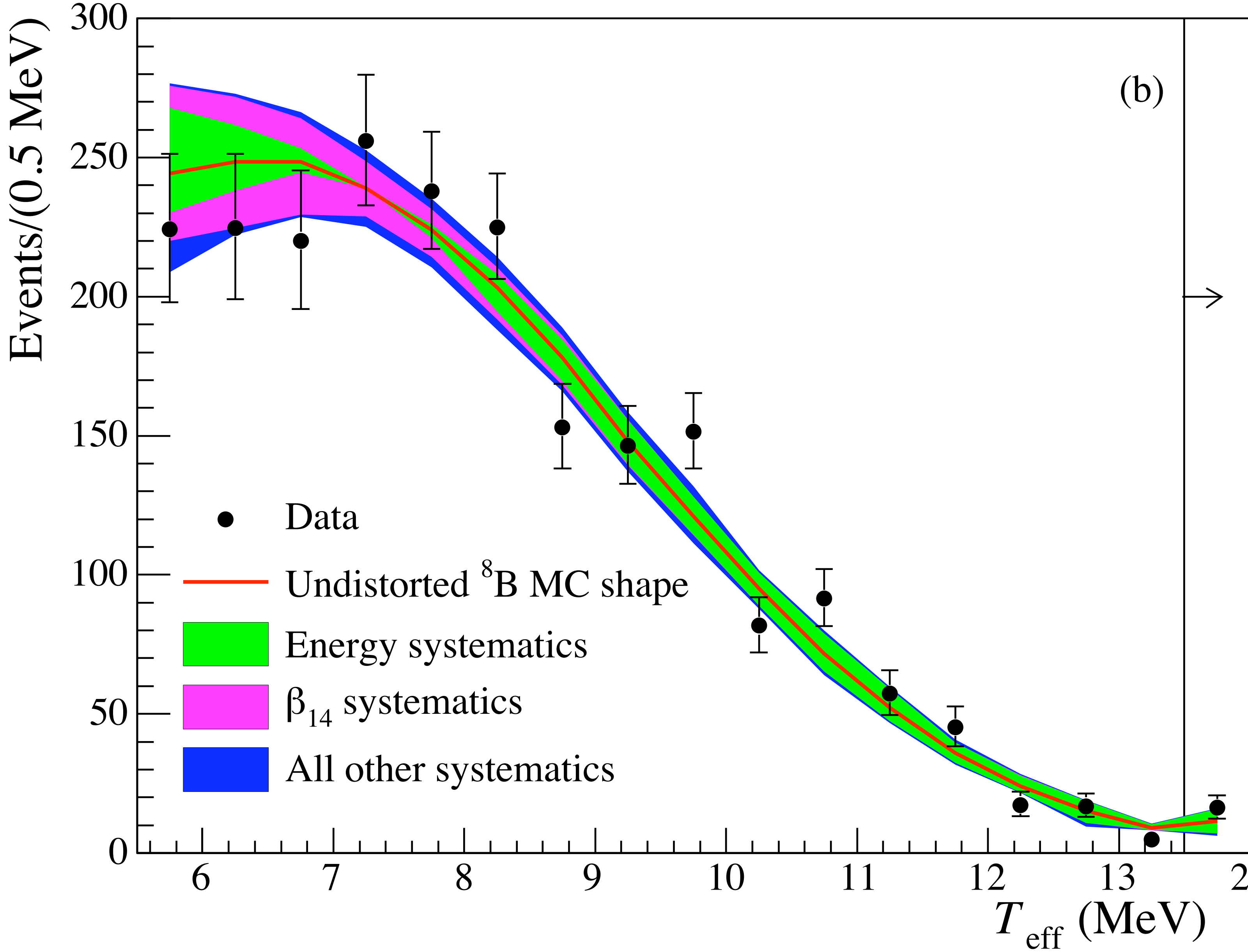
Separating the Signals (Salt phase)



Signal Extraction

- Cut events < 5 (phase 1) or 5.5 (phase 2) MeV
- Only signals left: CC, ES, NC and photo-disintegration from gamma backgrounds outside D2O volume
- Fit for # of CC and ES in 0.5 MeV bins, total # of NC, and total # of external neutrons
- Estimate and subtract out contamination to CC and NC from internal backgrounds (small)

Signal Extraction



Salt phase, nucl-ex/0502021

Can we do better than these original analyses?

Can we do better than these original analyses?

Yes, if we are willing to work for it....

Pareto's Principle:

80% of the work is required to achieve the last 20% of the results

(Very loosely translated from "80% of the land is owned by 20% of the Italians.")

The Low Energy Threshold Analysis

(A "last 20% analysis" of the first two phases)

- SNO recorded data in the first two phases with a trigger threshold of 2.5 MeV!
  (100% efficient at 3 MeV)
- Original papers were very conservative:
  Analysis threshold = 5 MeV (D2O), 5.5 MeV (salt)
- Go lower in energy (3.5 MeV) and put background PDFs into the fit.
- Fit both phases simultaneously.
- Tune up Monte Carlo based on 5 years of operational experience

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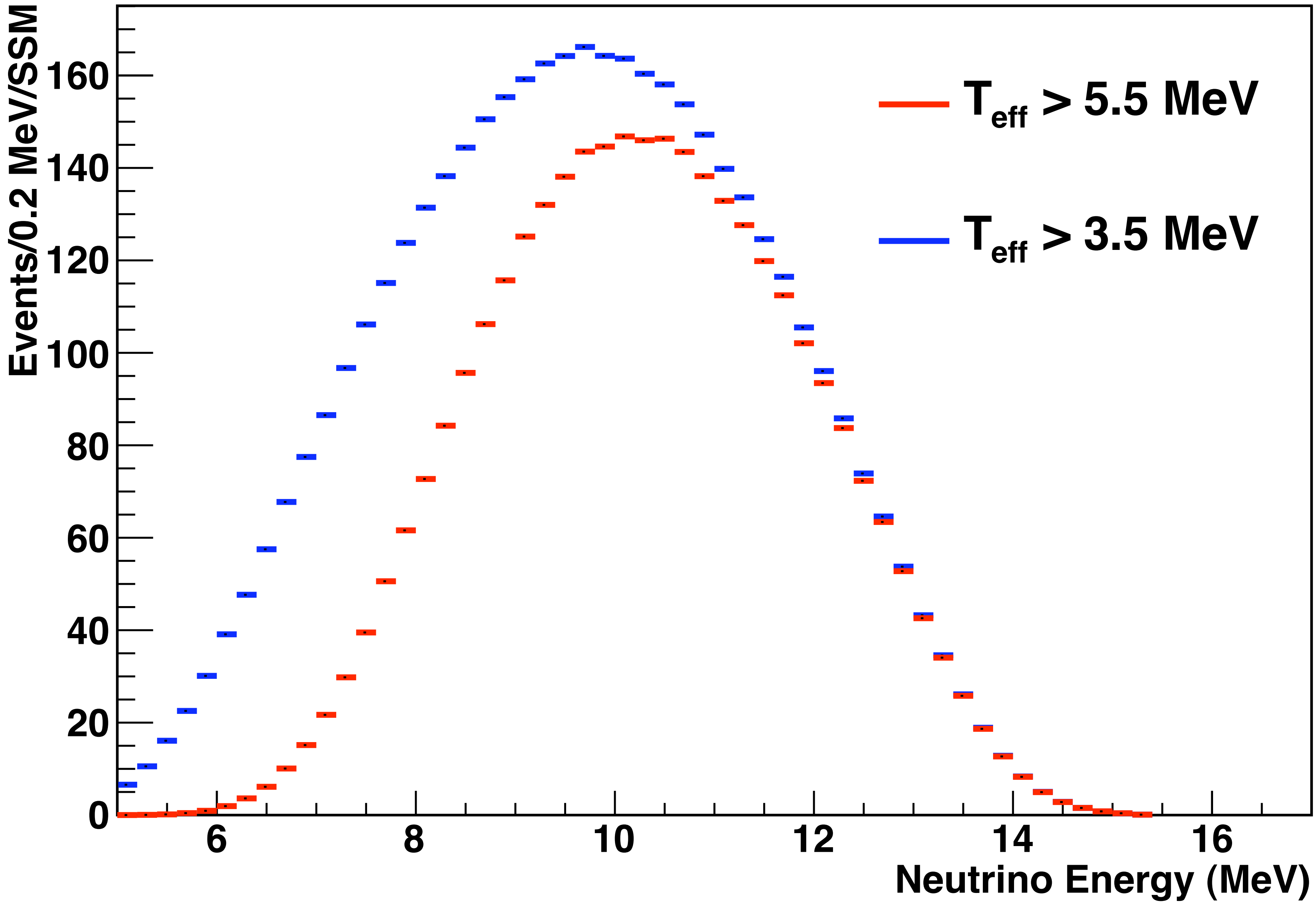
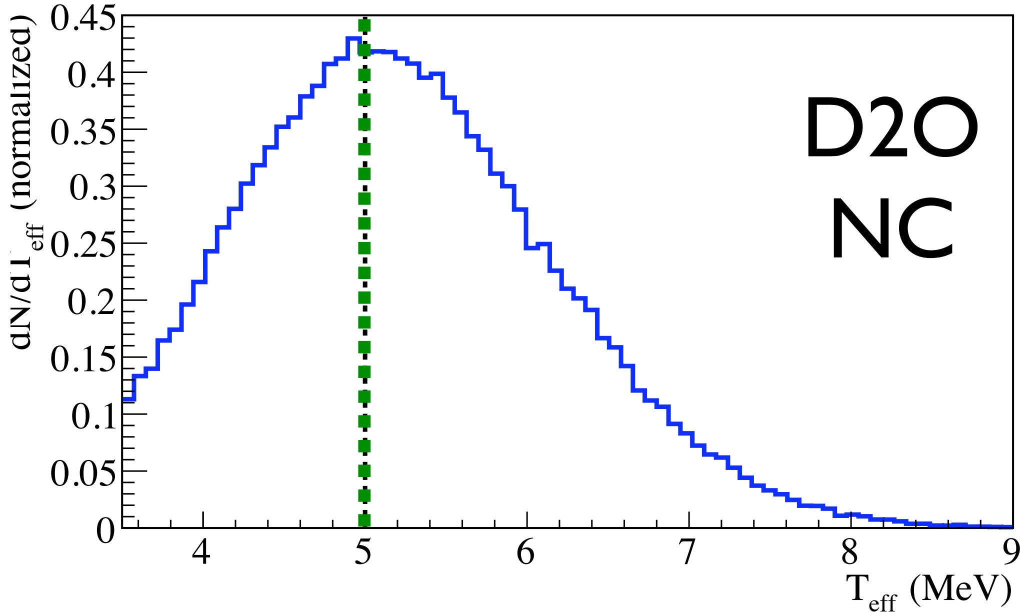
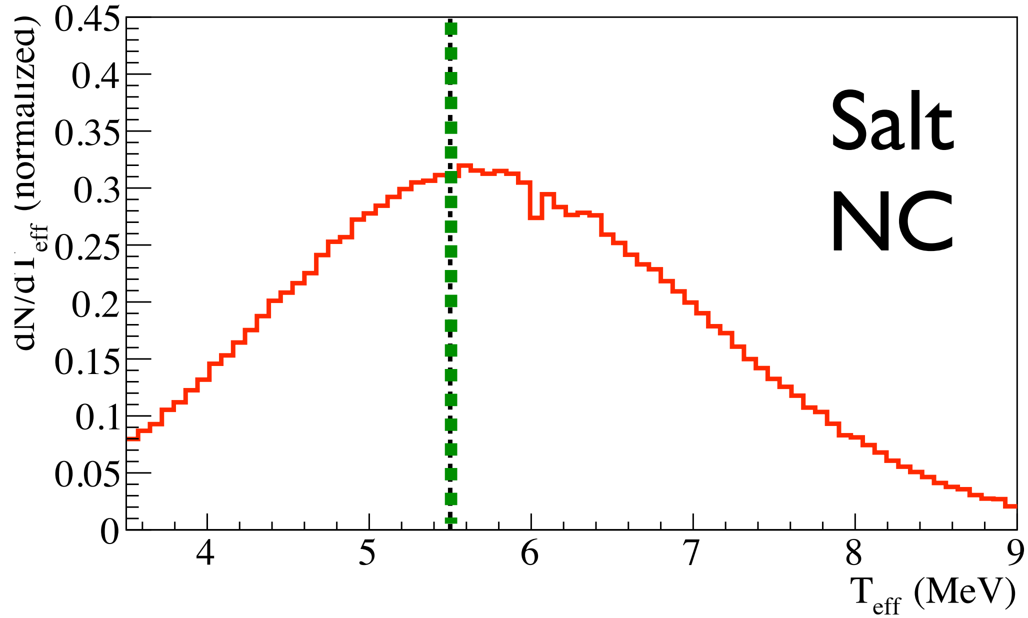
OK, what's the benefit?

Low Energy CC

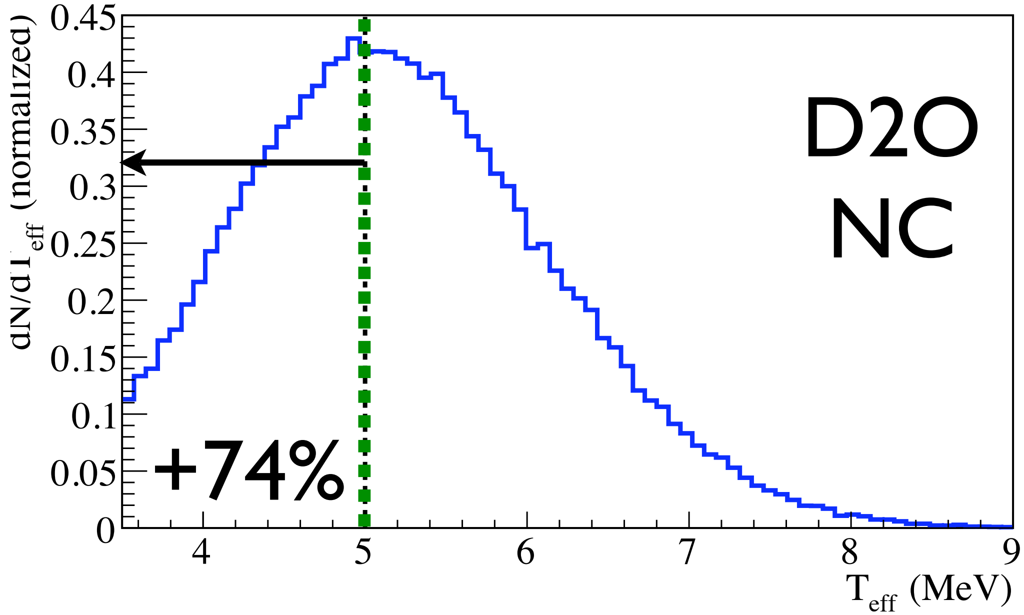


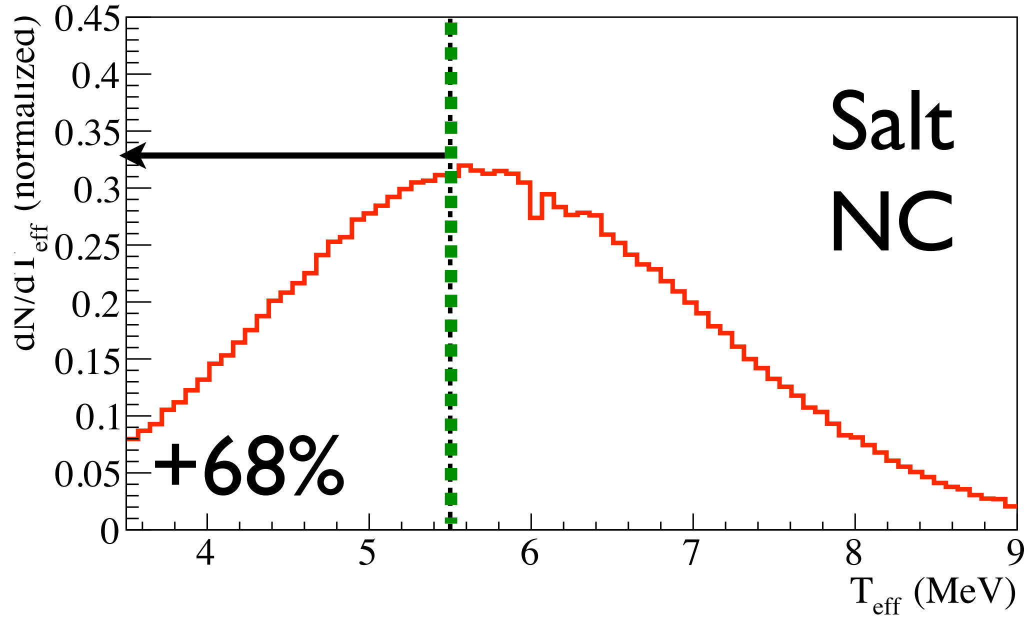
More NC


D2O
NC
dN/dT_{eff} (normalized)
T_{eff} (MeV)

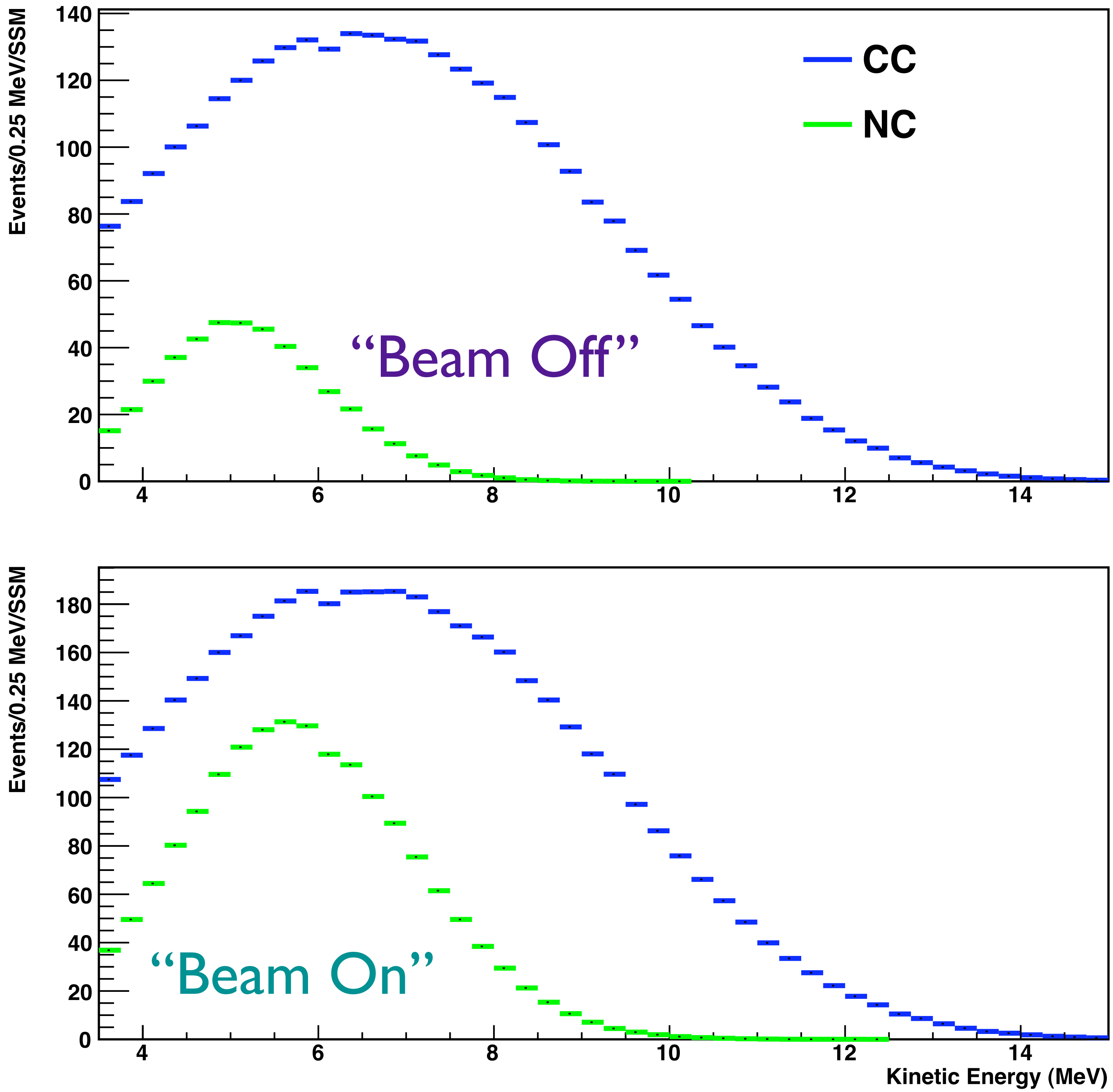

Salt
NC
dN/dT_{eff} (normalized)
T_{eff} (MeV)

More NC


0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
dN/dT$_{eff}$ (normalized)
4
5
6
7
8
9
T_{eff} (MeV)
D2O
NC
+74%


0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
dN/dT$_{eff}$ (normalized)
4
5
6
7
8
9
T_{eff} (MeV)
Salt
NC
+68%

Two Phase Subtraction Effect

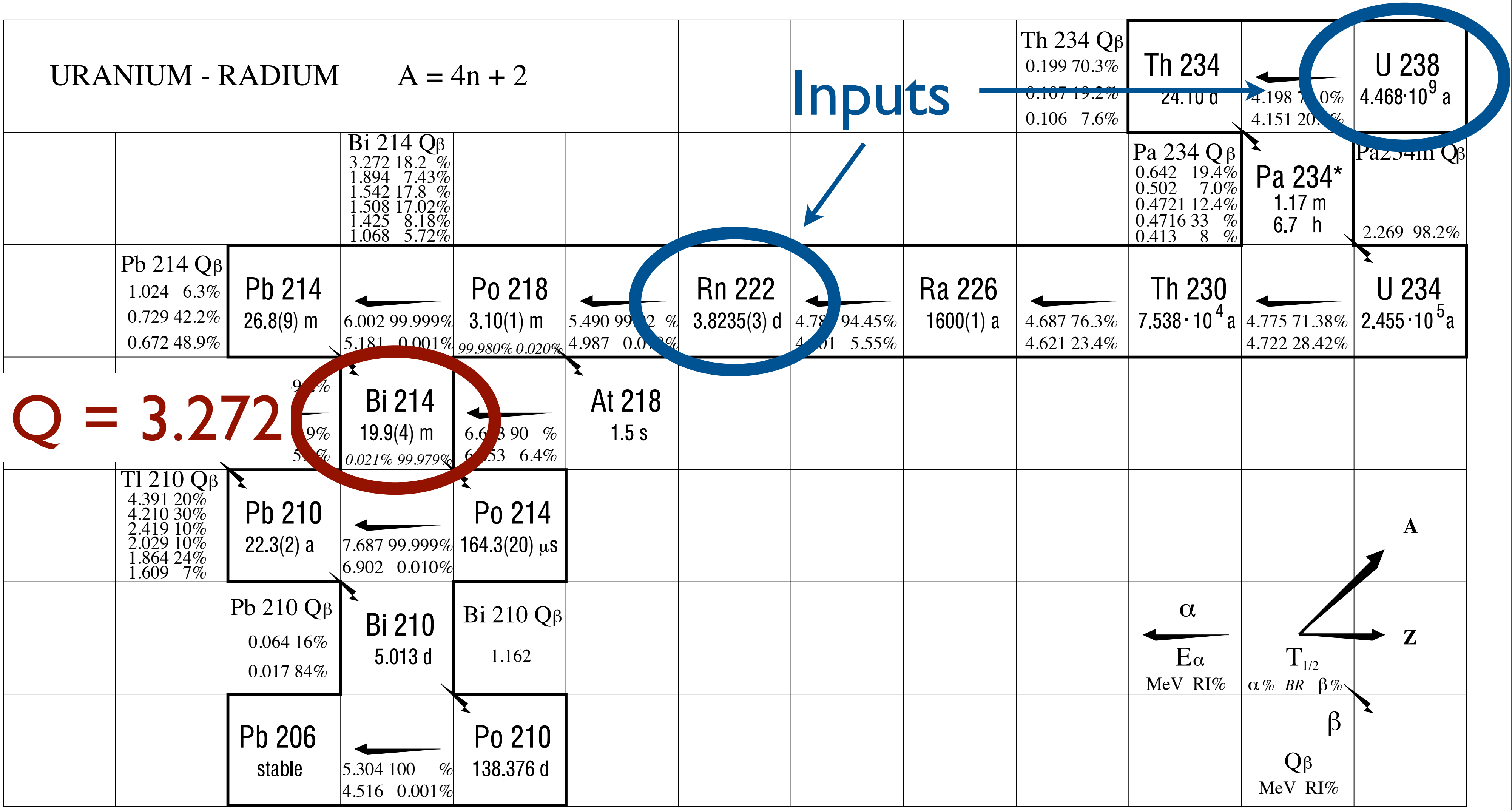


D2O

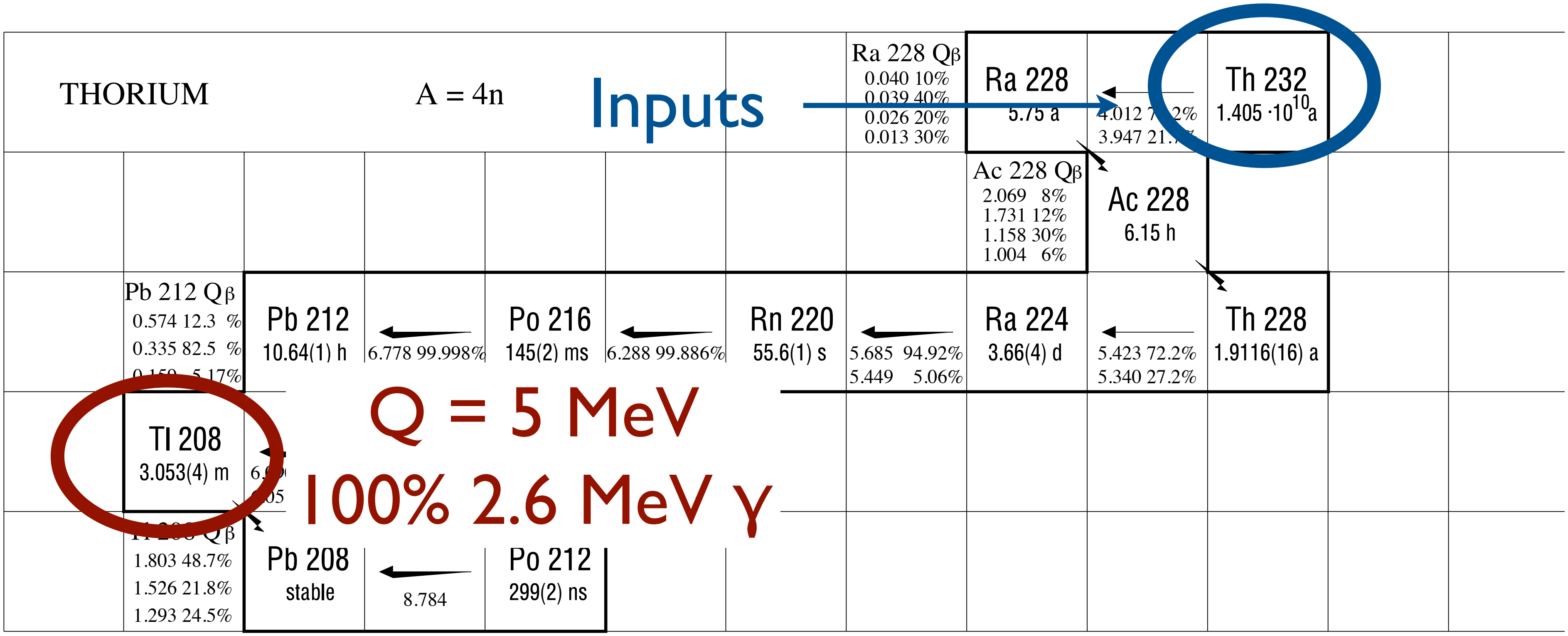
Salt

- Problem #1: Backgrounds
- Problem #2: Systematic Uncertainties
- Problem #3: Signal Extraction

Problem #1: Backgrounds (U-chain)



Problem #1: Backgrounds (Th-chain)



Many Backgrounds and Volumes...

D2O
Acrylic Vessel
H2O

×

^{214}Bi *(Uranium/Radon)*
^{208}Tl *(Thorium)*

+

PMT ^{208}Tl

+

^{24}Na *(Neutron activation of salt)*

+

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

Why do we see these backgrounds?

- An energy threshold of 3.5 MeV is above the visible energy of Bi-214, and the Tl-208 gamma.
- Visible backgrounds entirely due to statistical fluctuations in the number of detected photons

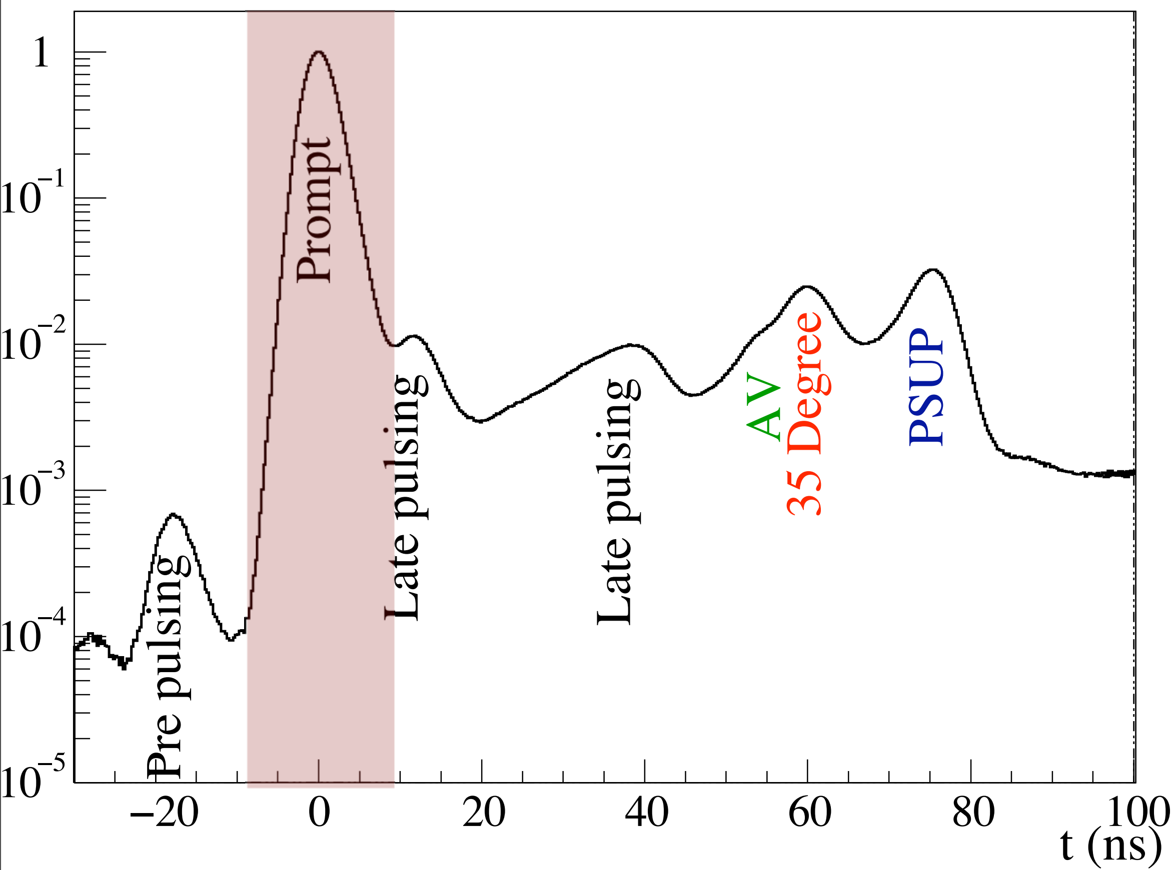
➡ Energy resolution is the key!

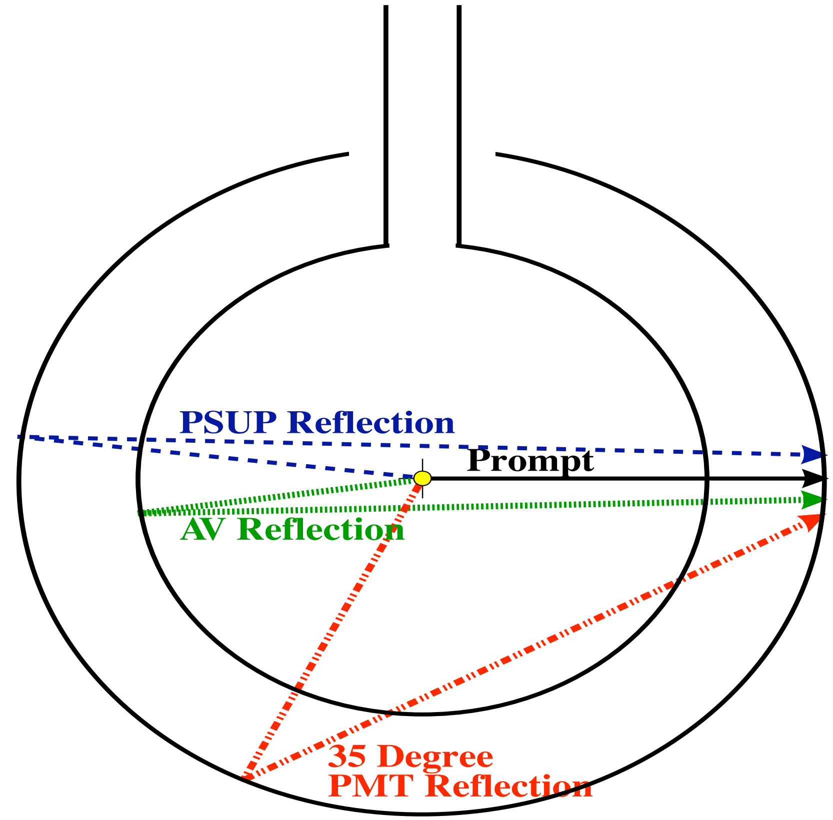
Can we improve our resolution?

➡ Yes, with a new energy estimator!

FTK: A Total Light Fitter

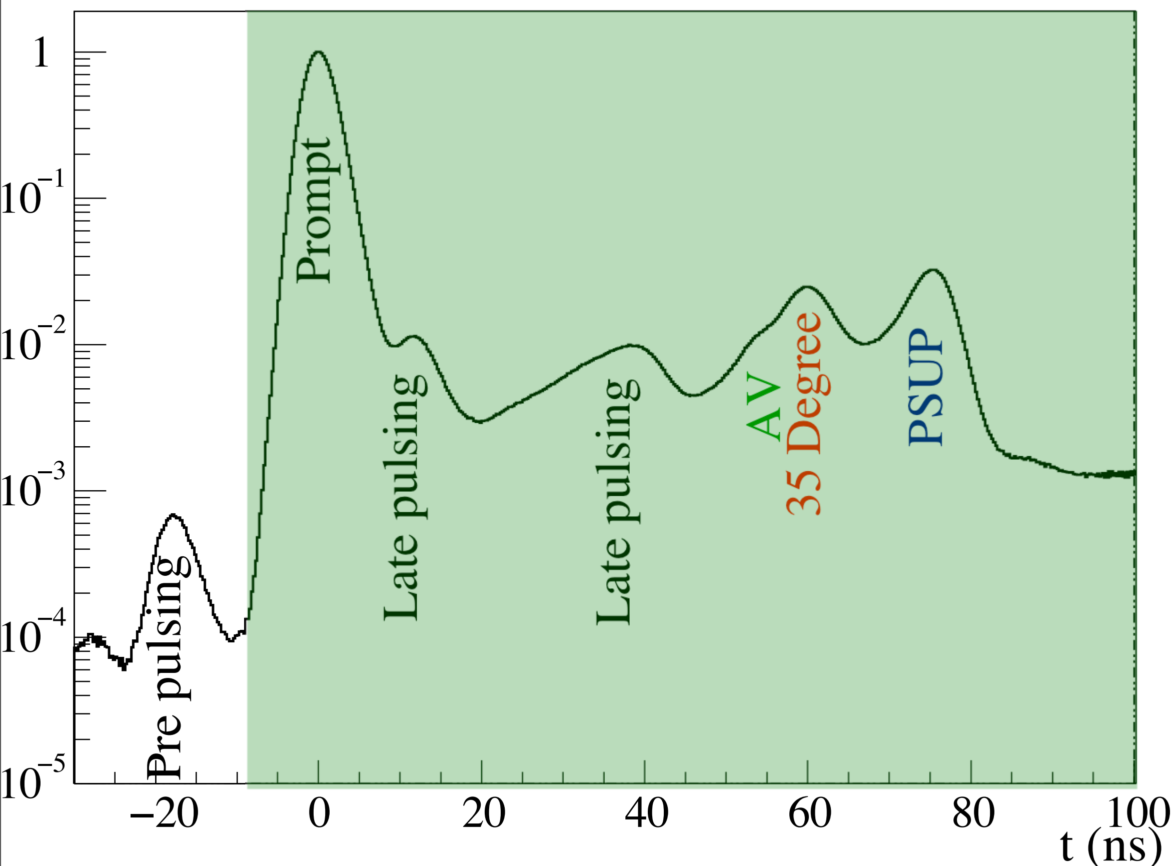
Original SNO energy estimator used prompt light only





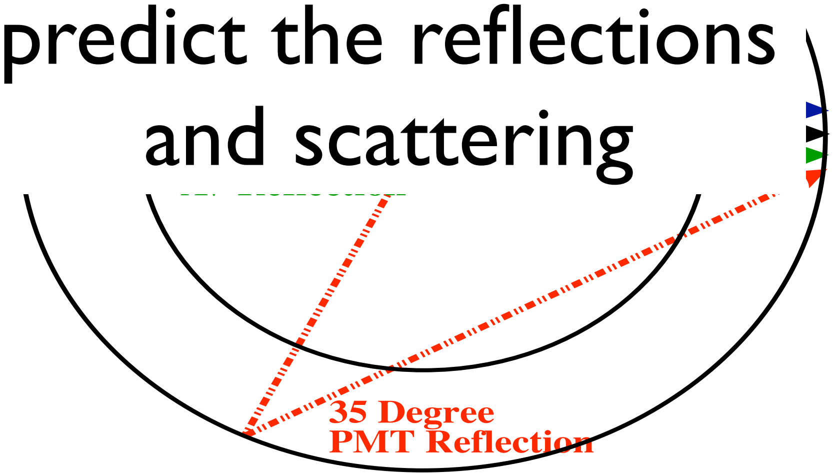
FTK: A Total Light Fitter

FTK uses all hit PMTs, even "late" PMTs



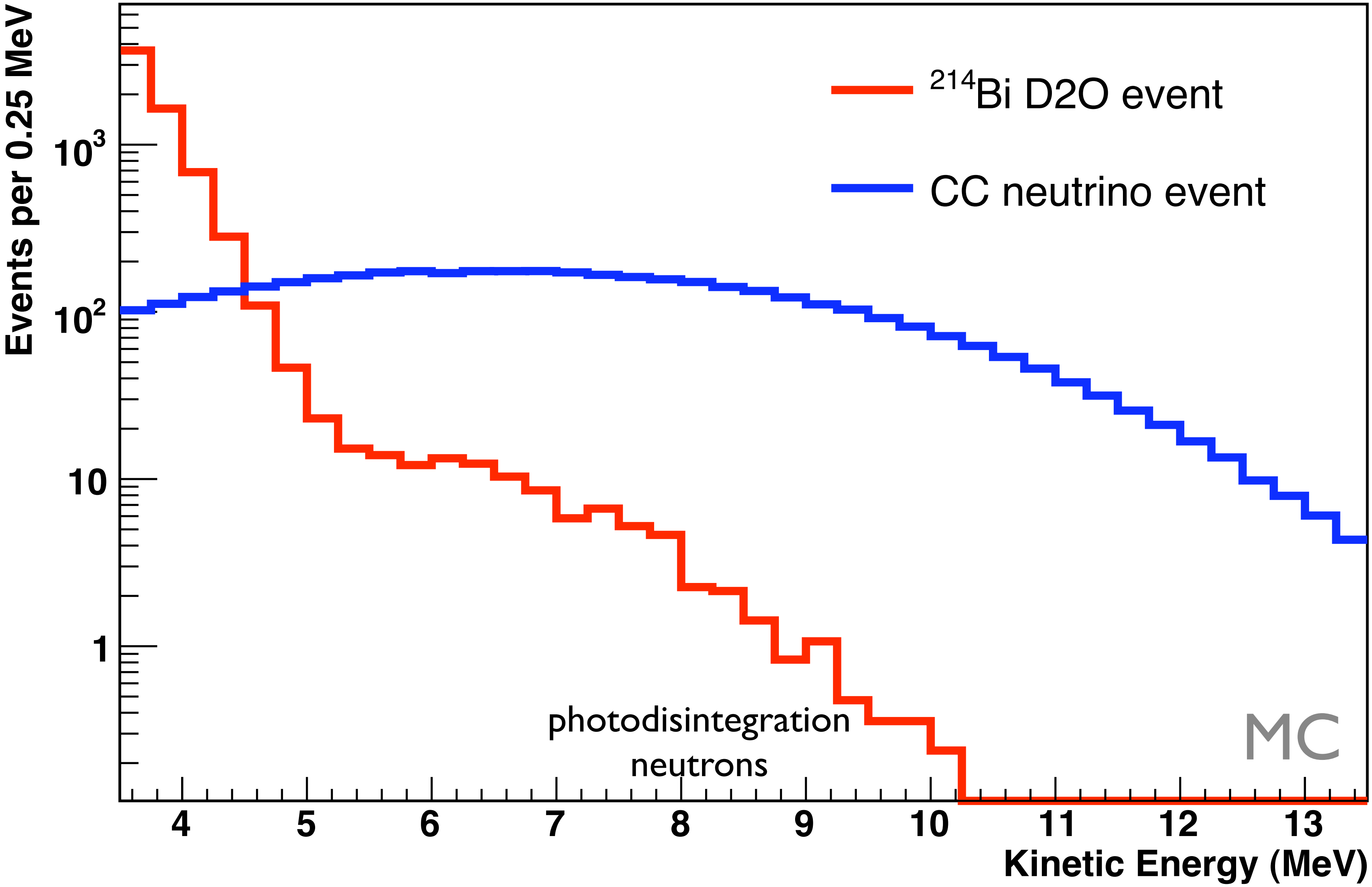
||

Create a fast optical model with the MC to predict the reflections and scattering

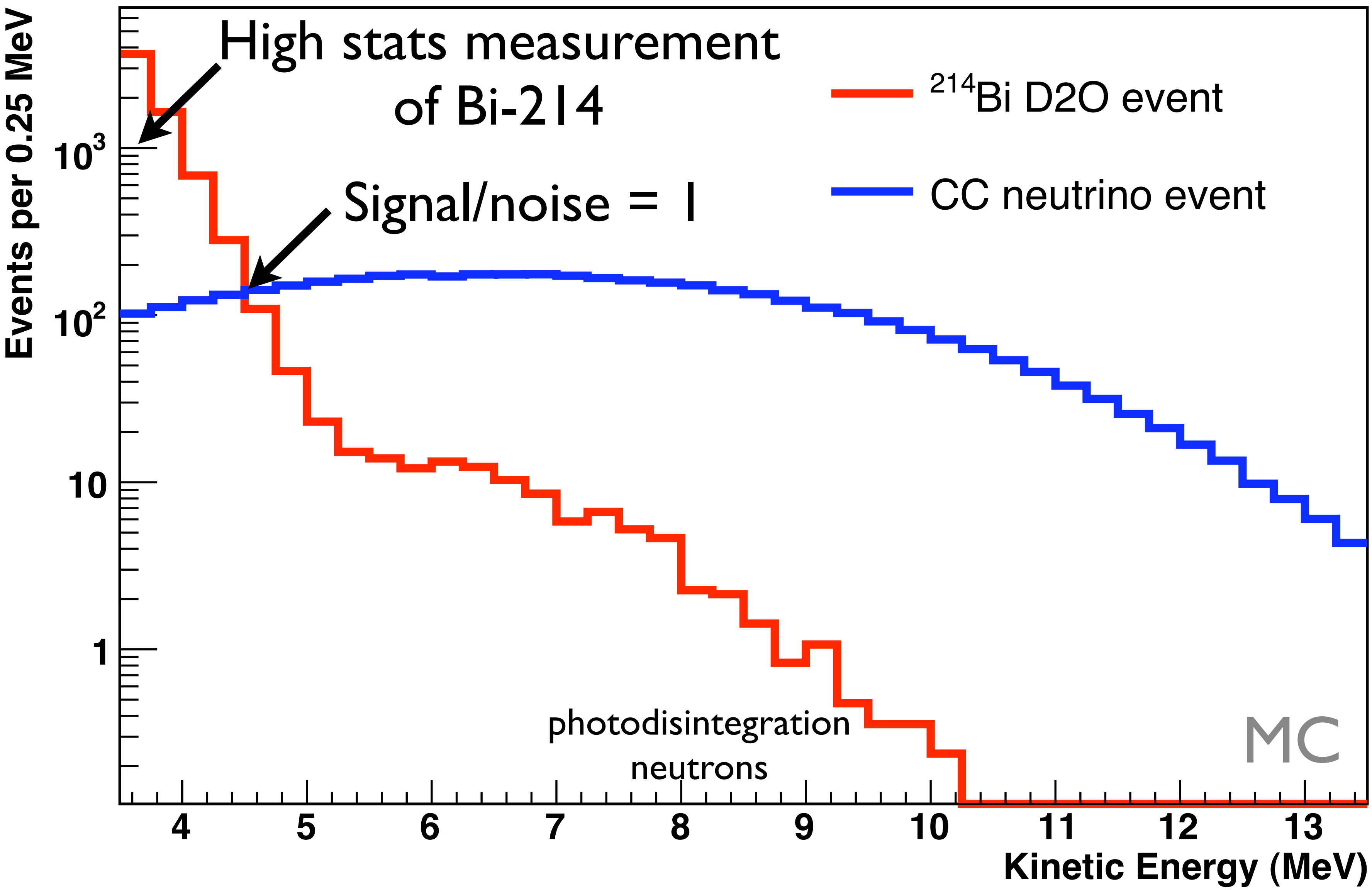


12% more hits = 6% better resolution
= 60% lower backgrounds

The Background Wall after FTK

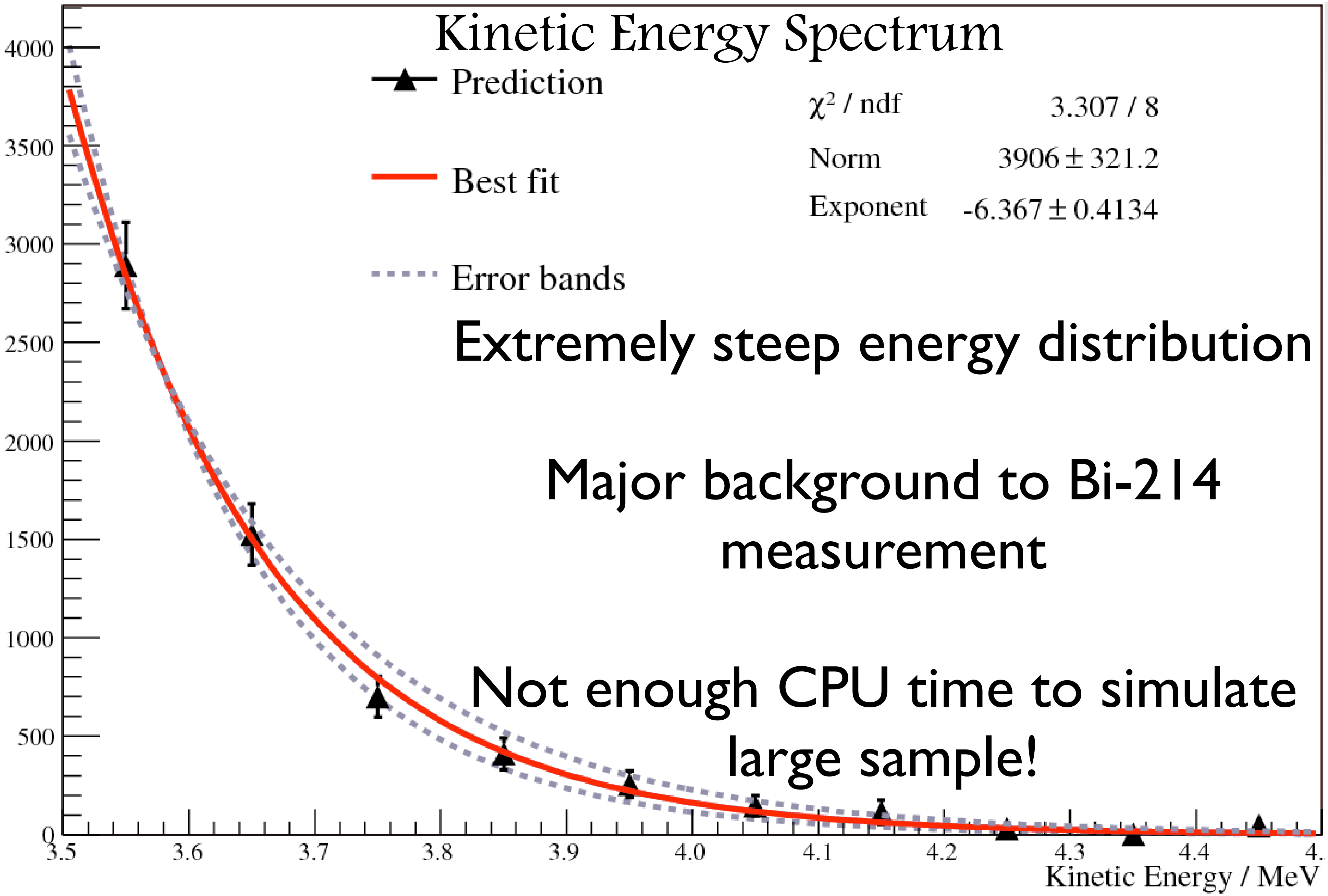


The Background Wall after FTK



Setting energy threshold to 3.5 MeV
gives better measure of CC at 4 MeV!

The Sleeping Dragon: PMT backgrounds

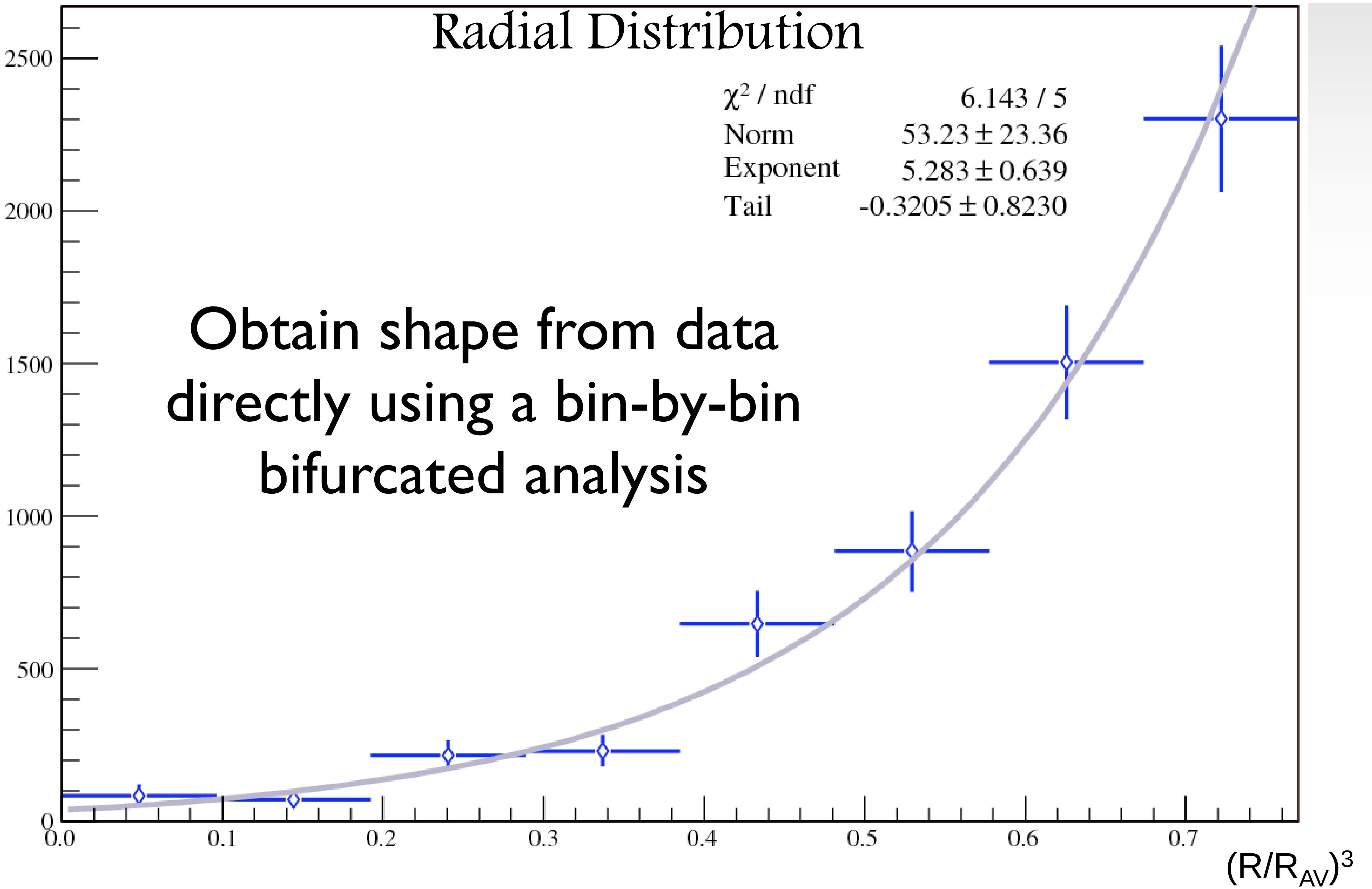


Extremely steep energy distribution

Major background to Bi-214 measurement

Not enough CPU time to simulate large sample!

The Sleeping Dragon: PMT backgrounds



- Problem #1: Backgrounds
- Problem #2: Systematic Uncertainties
- Problem #3: Signal Extraction

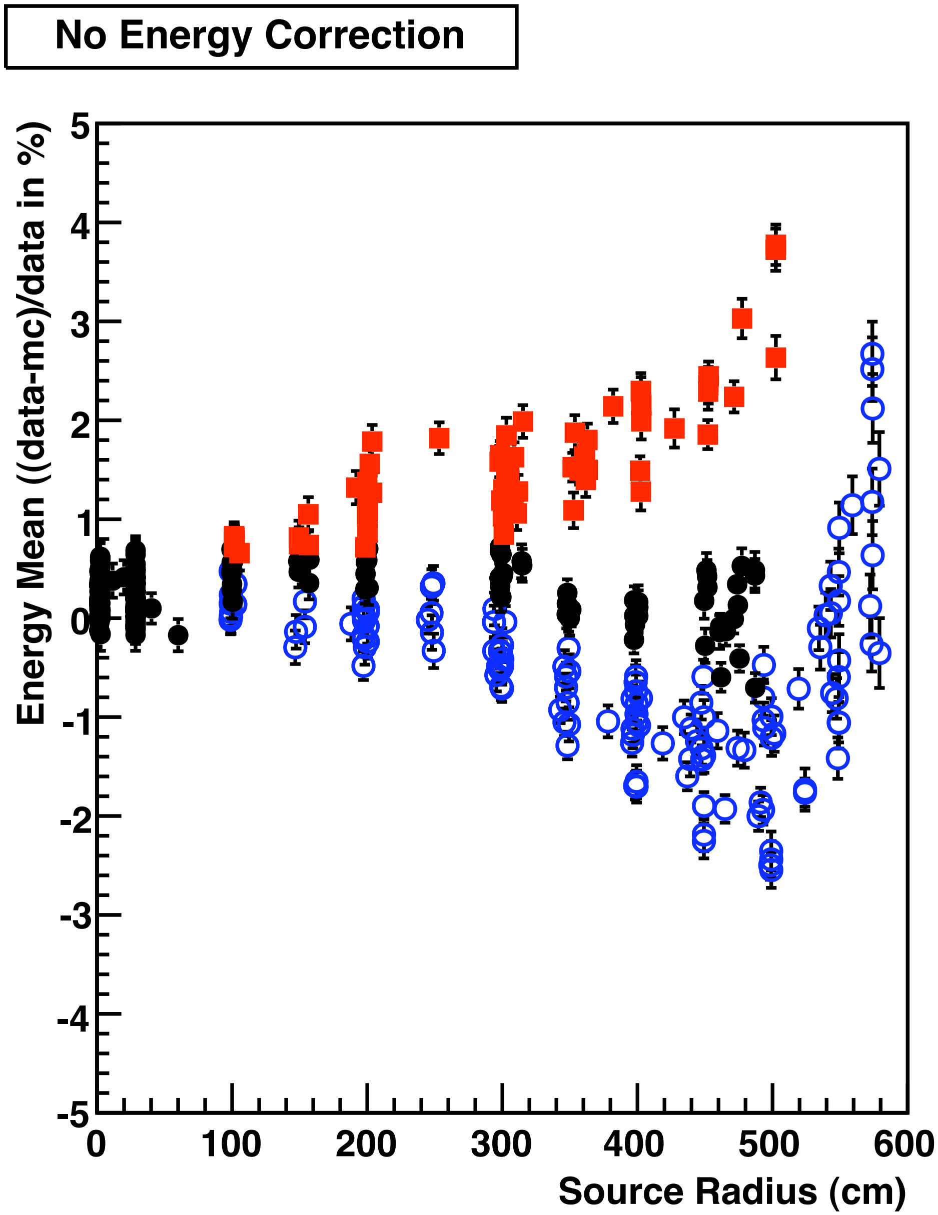
Reassessing systematics

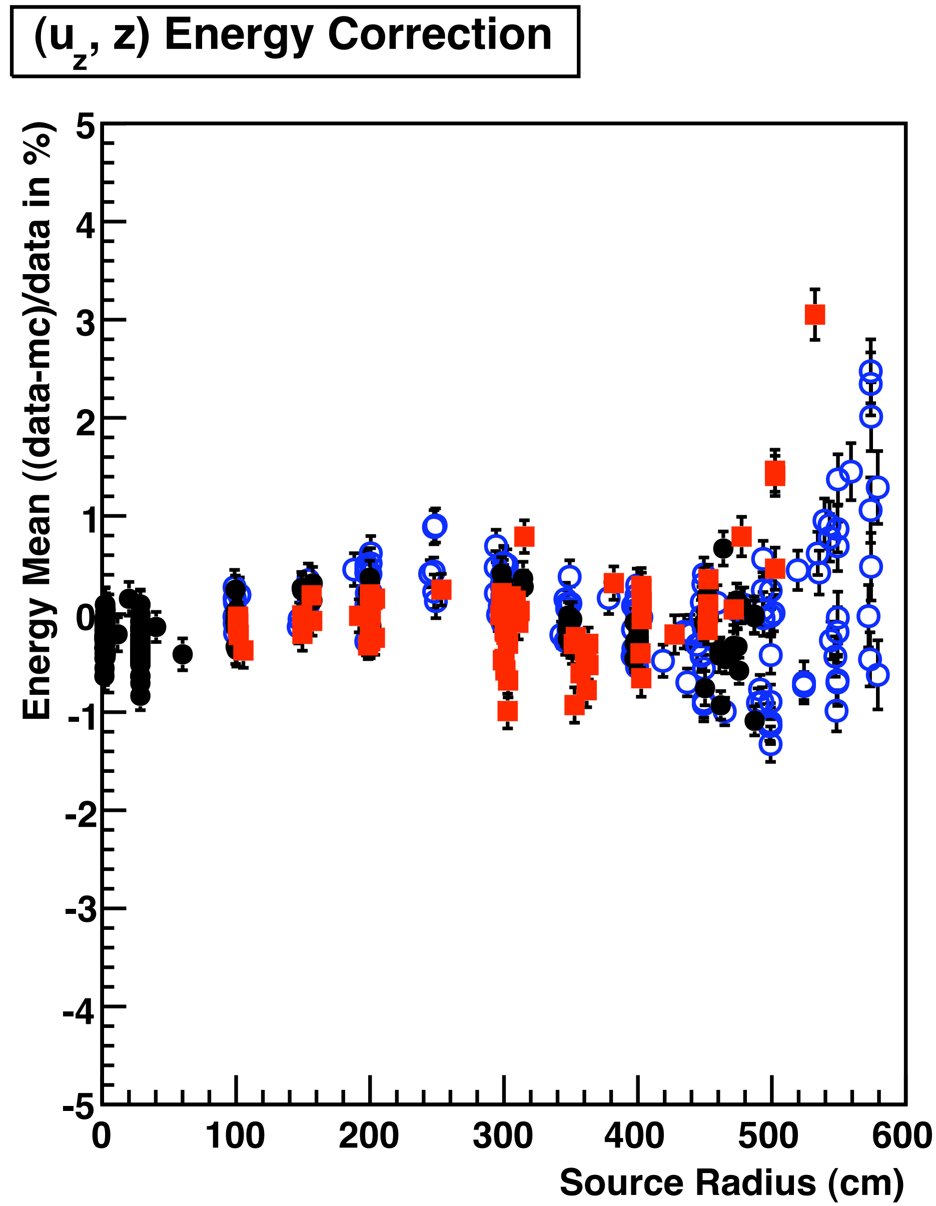
- New energy estimator requires reprocessing all data and Monte Carlo
- Improved many aspects of simulation:
  - Detector geometry (AV position)
  - PMT optical model (using laserball data)
  - DAQ simulation & correction of rate effects
- Made better use of diverse SNO calibration sources:
  - ^{16}N, ^{8}Li
  - Canned U and Th, deliberate Rn spikes
  - AmBe, Cf, spallation neutrons from muons

Systematics Categories

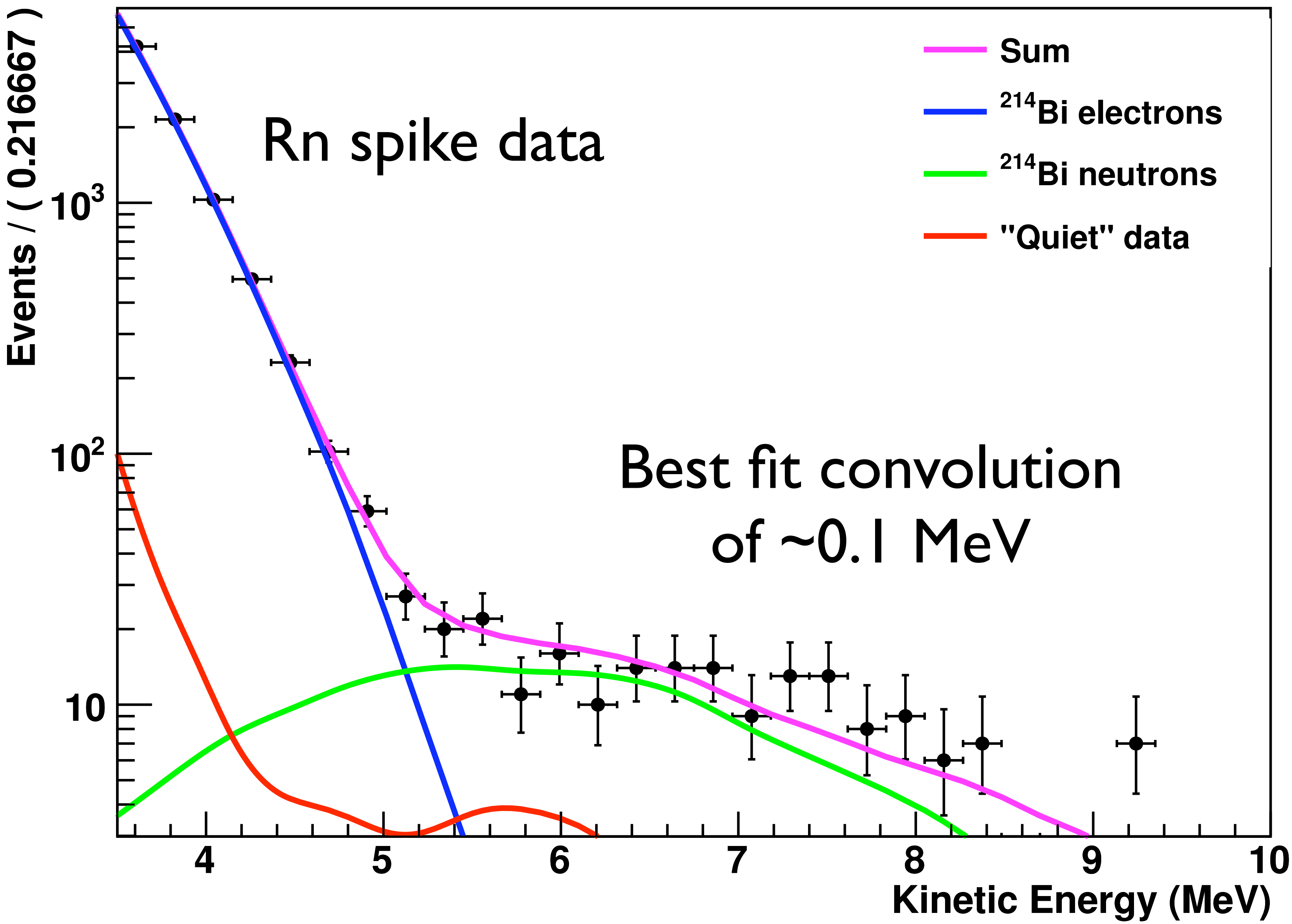
Energy
β_{14}
R^3
$\cos\theta_{sun}$
"Contamination"
Normalization (neutrons, others)
PMT

Energy Scale

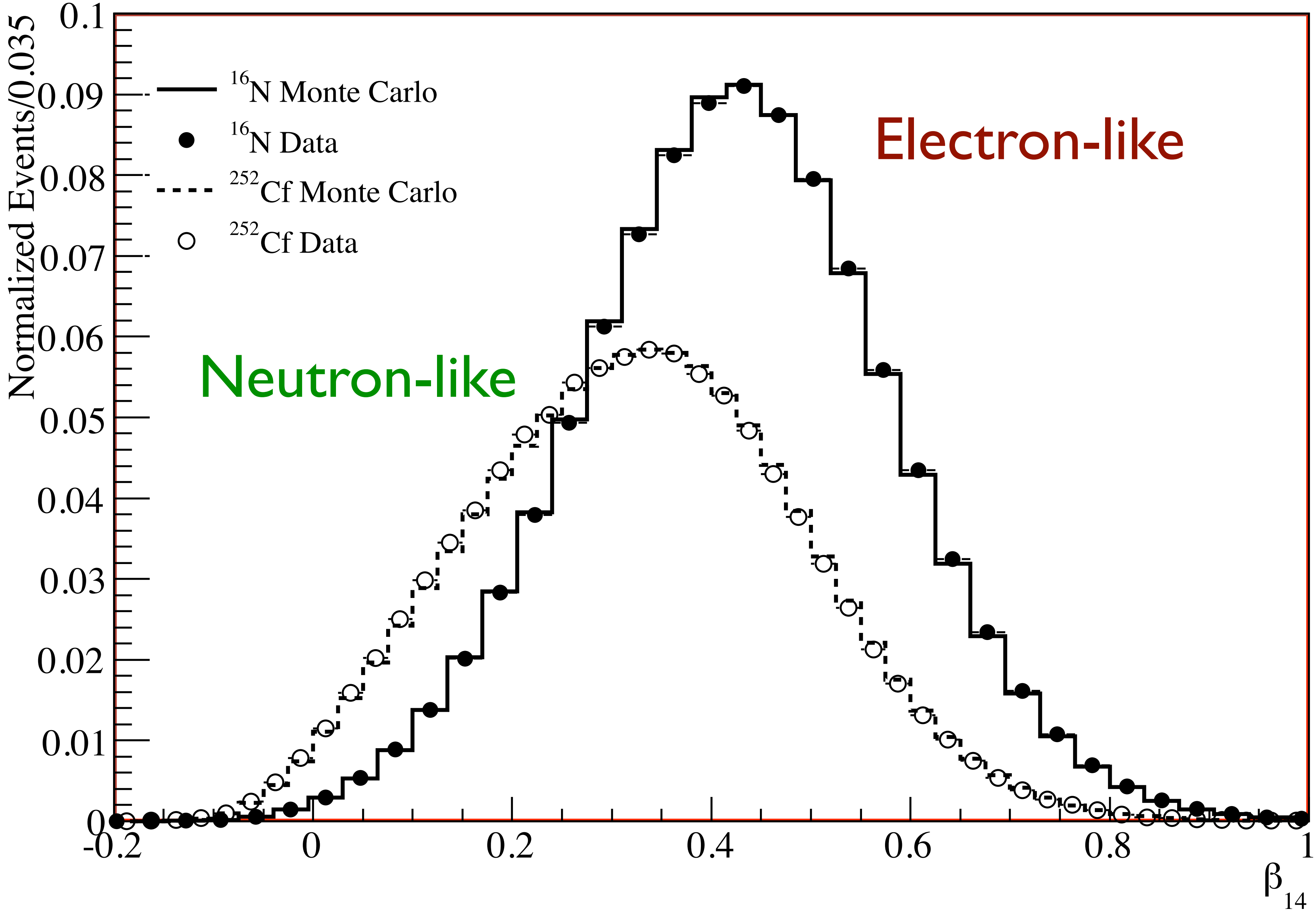




Energy Resolution

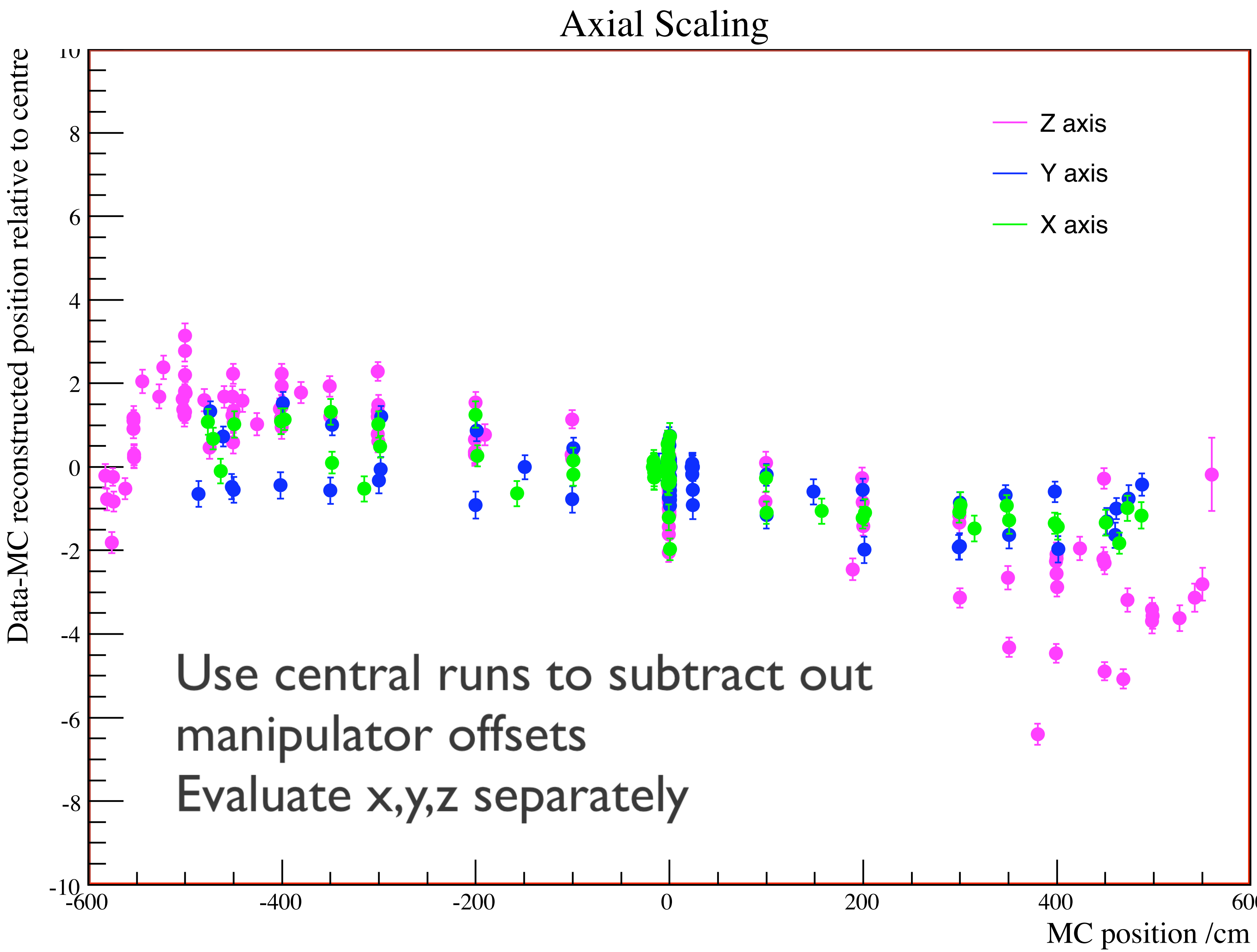


Isotropy

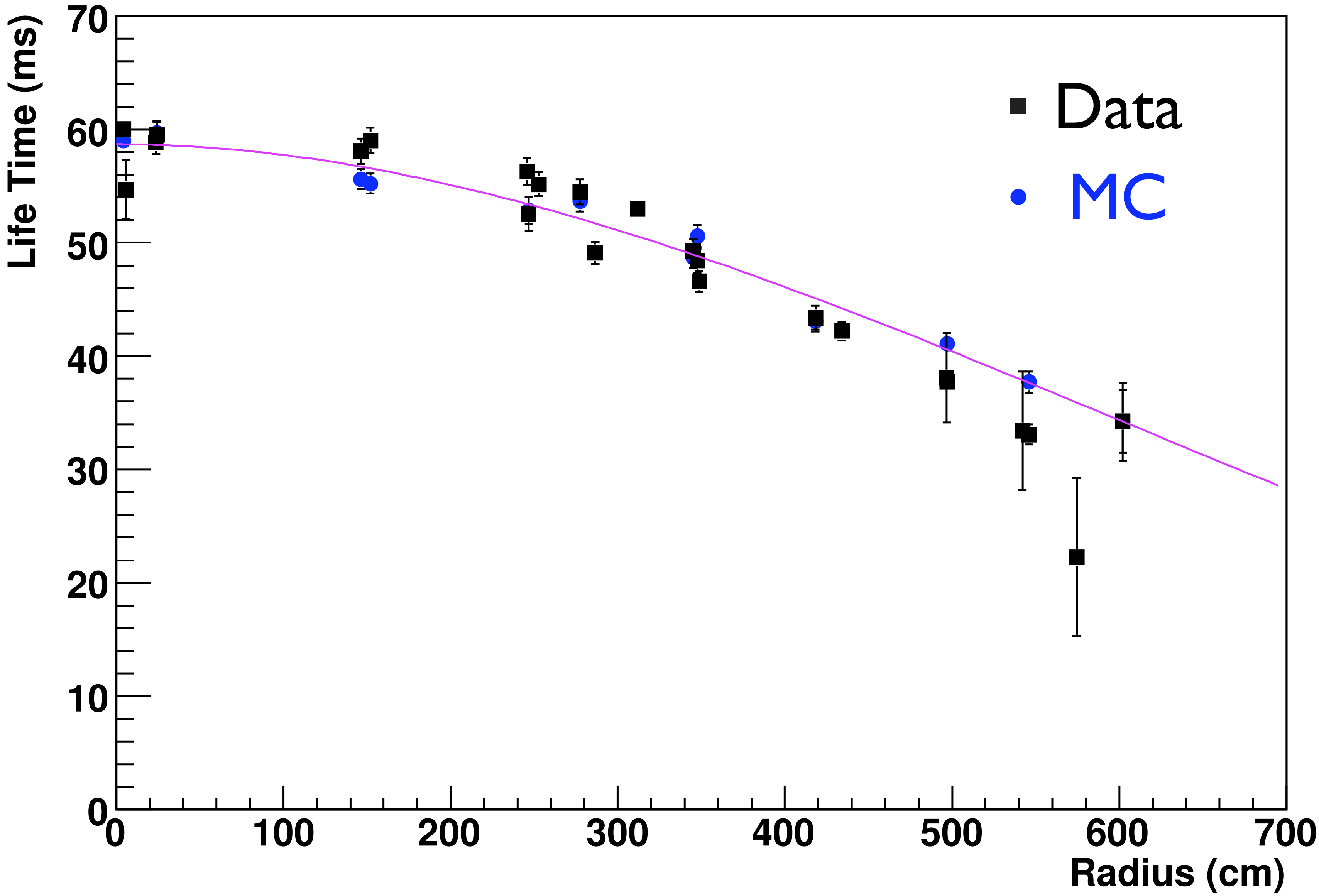


Normalized Events/0.035
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.2
0
0.2
0.4
0.6
0.8
1
β_{14}
^{16}N Monte Carlo
^{16}N Data
^{252}Cf Monte Carlo
^{252}Cf Data
Electron-like
Neutron-like

Position

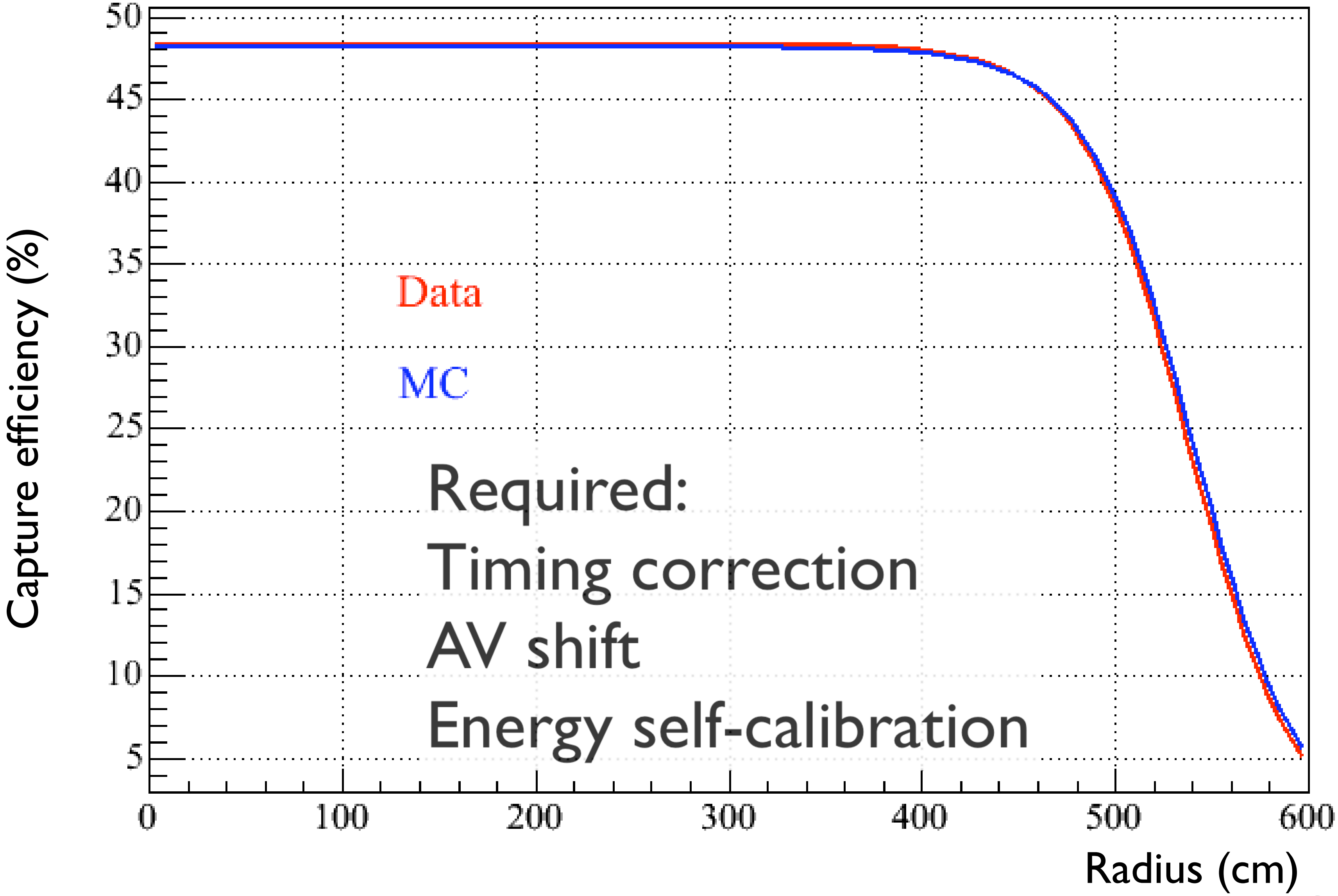

Axial Scaling
Data-MC reconstructed position relative to centre
MC position /cm
Z axis
Y axis
X axis
10
8
6
4
2
0
-2
-4
-6
-8
-10
-600
-400
-200
0
200
400
600
Use central runs to subtract out manipulator offsets
Evaluate x,y,z separately

Neutron Capture Time



D_2O phase

Neutron Capture



Required:
Timing correction
AV shift
Energy self-calibration

Uncert: Corr=0.7%, D_2O=2%, Salt=1.2%

Salt phase

- Problem #1: Backgrounds
- Problem #2: Systematic Uncertainties
- Problem #3: Signal Extraction

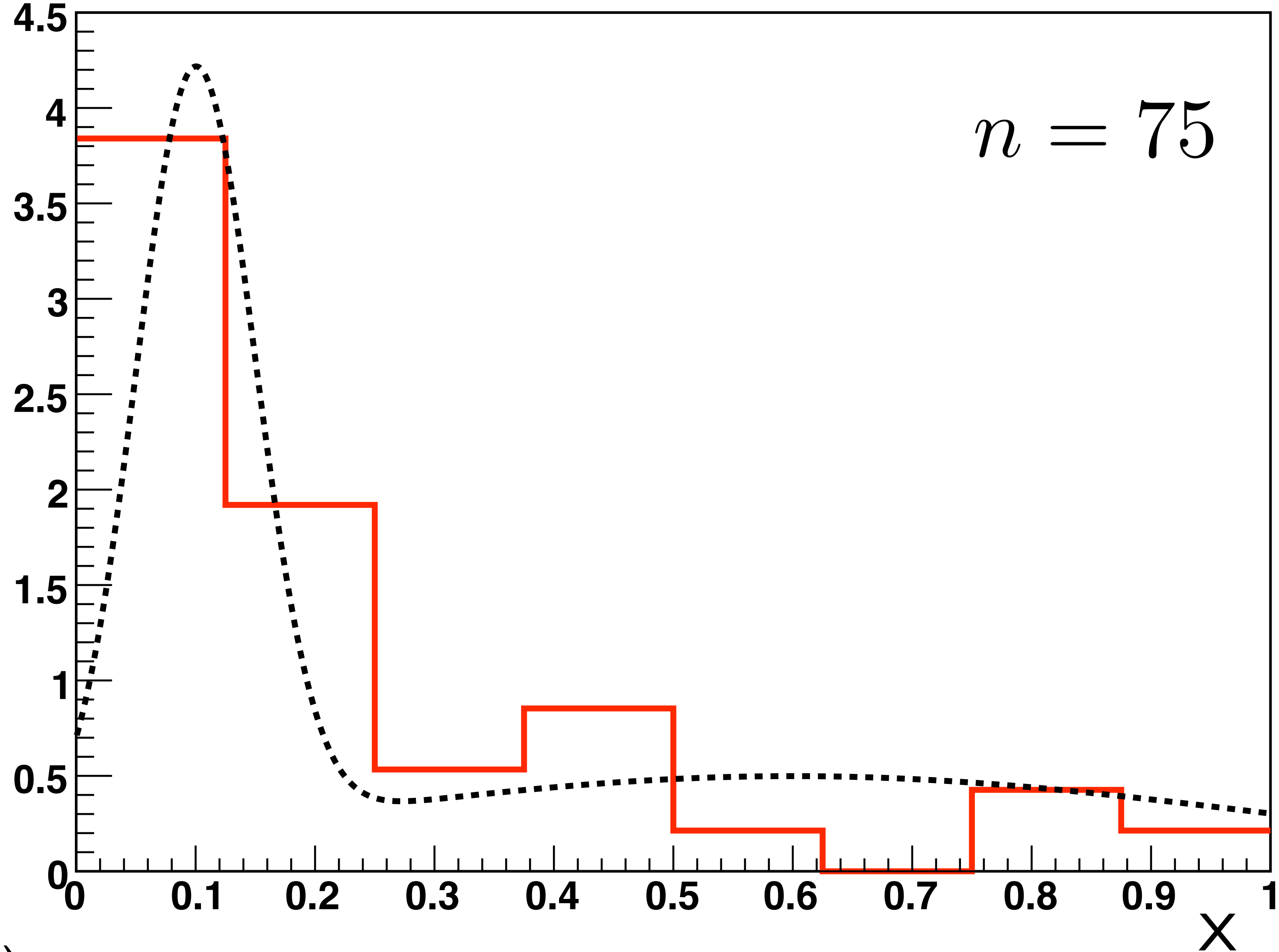
Signal Extraction

- Now we have 17 backgrounds + CC/ES/NC!
- Fortunately, we can separate them all from neutrino signal using energy (extrapolating from 3.5 MeV), isotropy (Tl gammas, PMTs), radius (external bkgs), and direction (all bkgs uncorrelated with Sun)
- Still very challenging: many free parameters, systematic uncertainties matter!
- Included dominant systematic uncertainties as free parameters in likelihood space, with constraints from calibration sources
- Extensive bias testing with synthetic data sets required for verification

Parallel Analyses

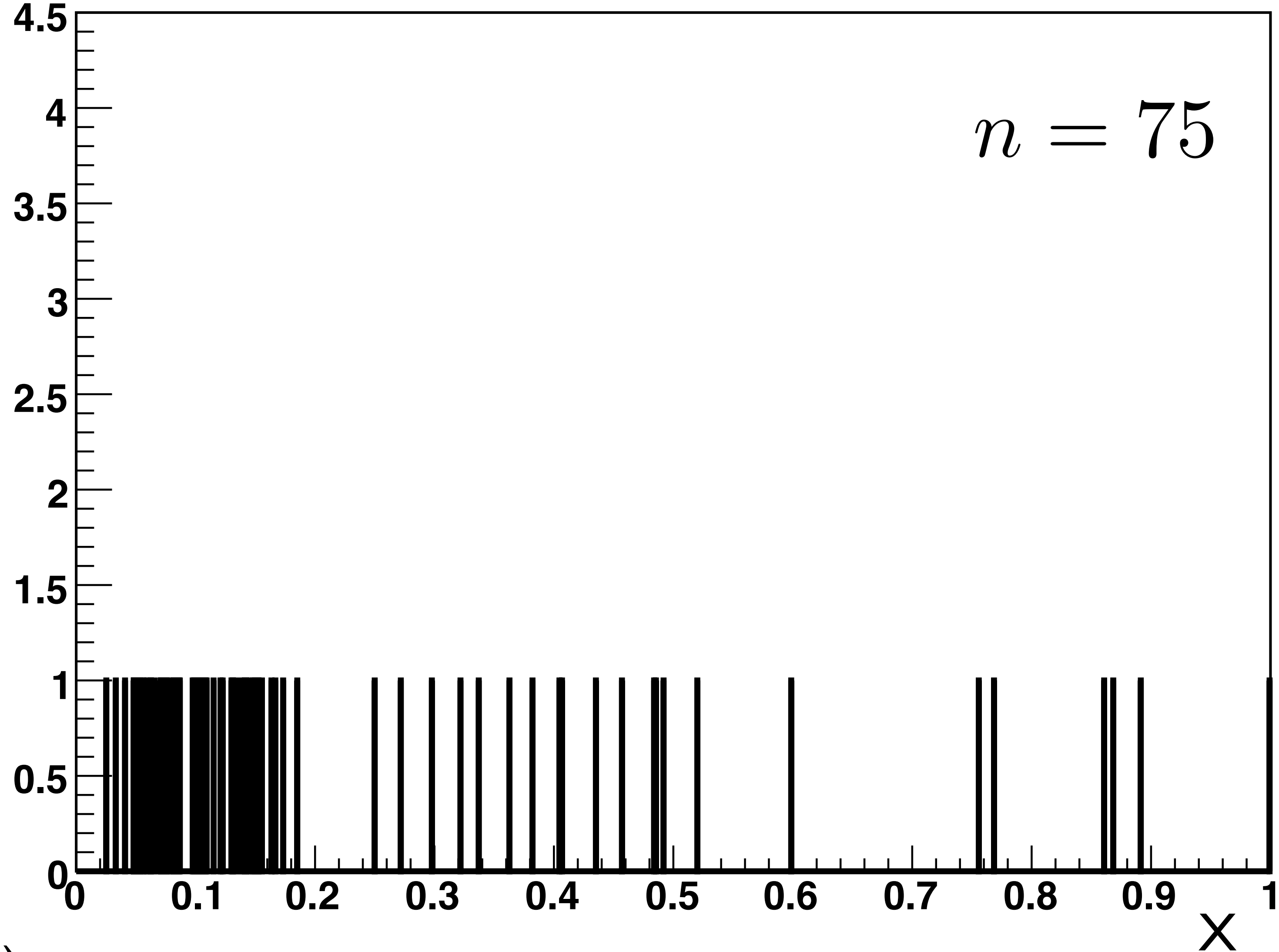
	A	B
Code	Extension of FORTRAN code used for previous papers	All new implementation in Python/C++
PDFs	Binned histograms	Unbinned kernel estimation
Systematic Parameters	Manual scan	Gradient descent with other parameters
Potential Pitfalls	Labor-intensive, difficult to treat correlations in detector systematics	Complex new code, computationally intense

Kernel Estimation in 3 Easy Steps



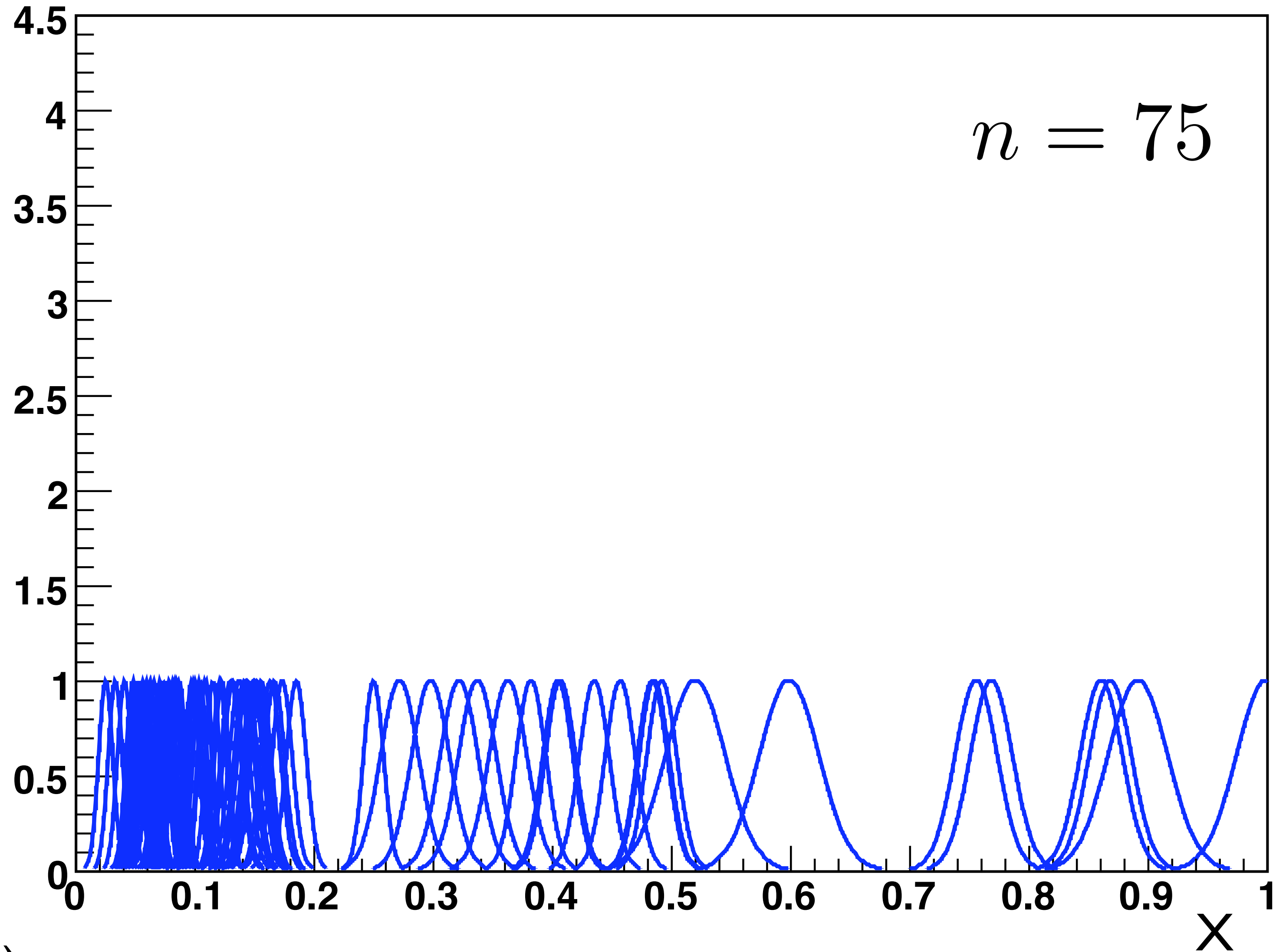
(toy model)

Kernel Estimation in 3 Easy Steps



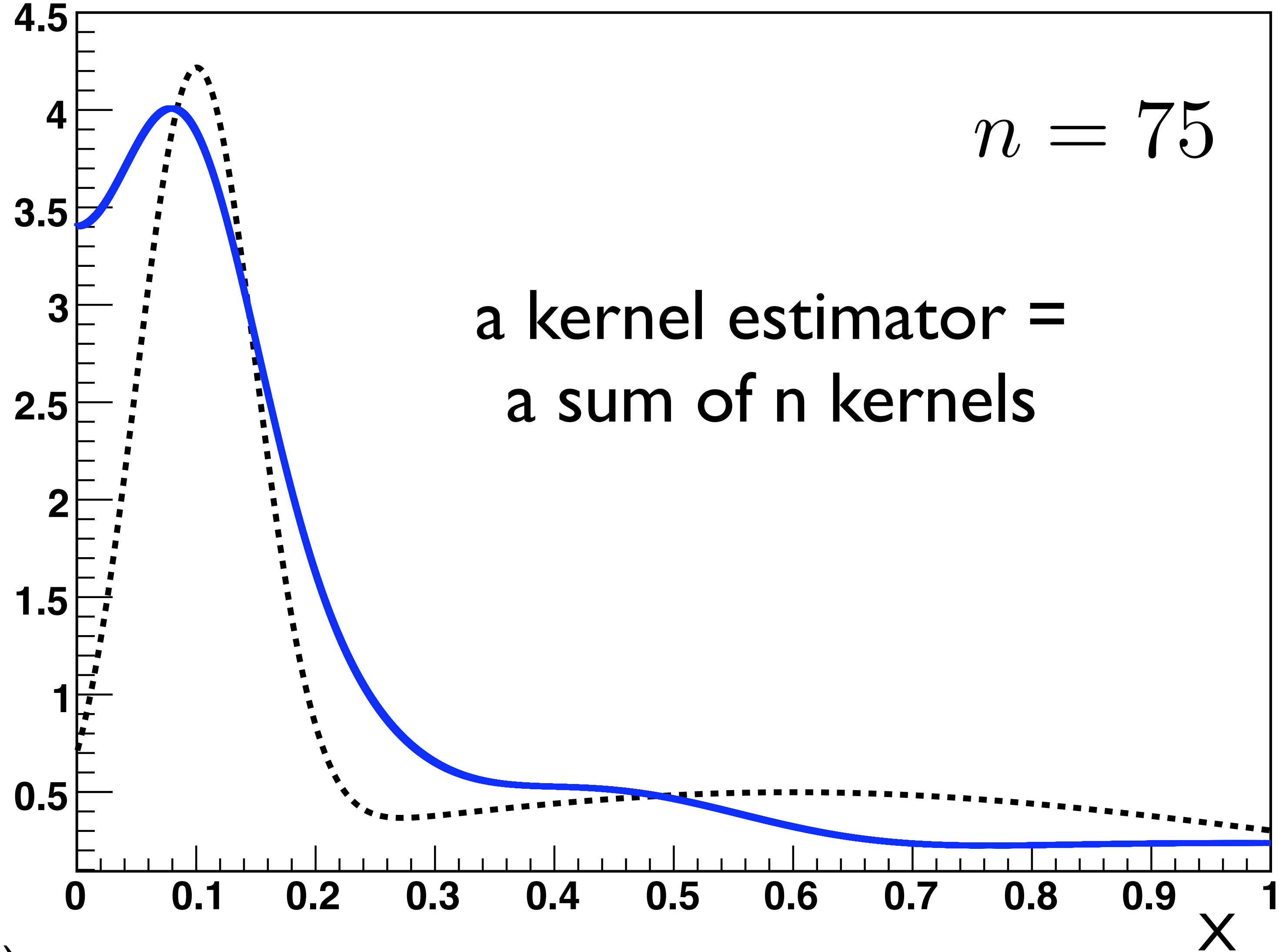
(toy model)

Kernel Estimation in 3 Easy Steps



(toy model)

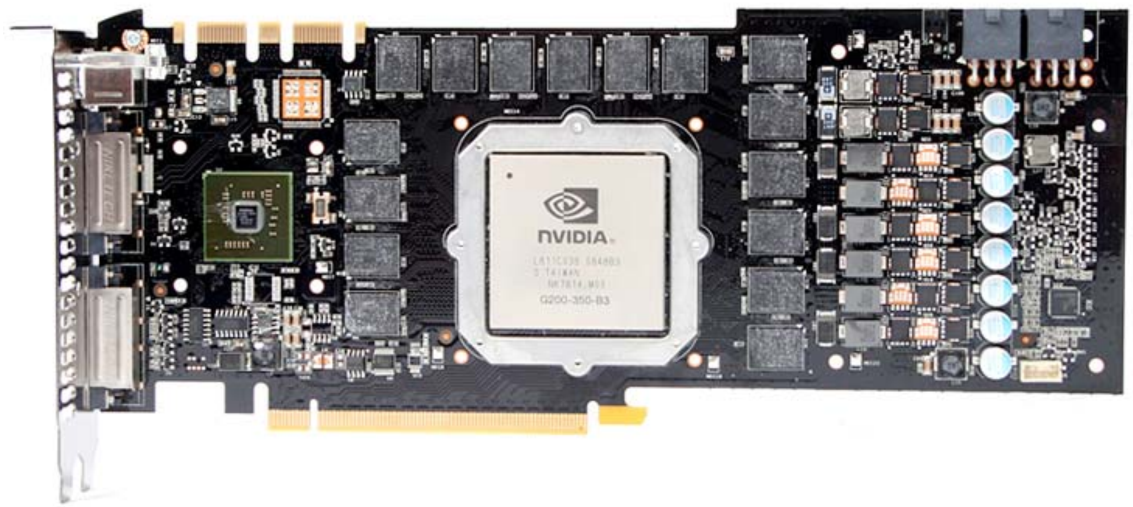
Kernel Estimation in 3 Easy Steps



(toy model)

Kernel Estimation at High Speed: Turning CPU weeks into hours

3D graphics cards are *designed* for data-parallel calculations, like kernel estimation.



- Floating point units:
  - 240 single precision
  - 30 double precision
- FPU clock: 1.476 GHz
- 512 bit memory bus, 1GB memory
- $350

CUDA accelerates calculation of kernel estimator by 10x!

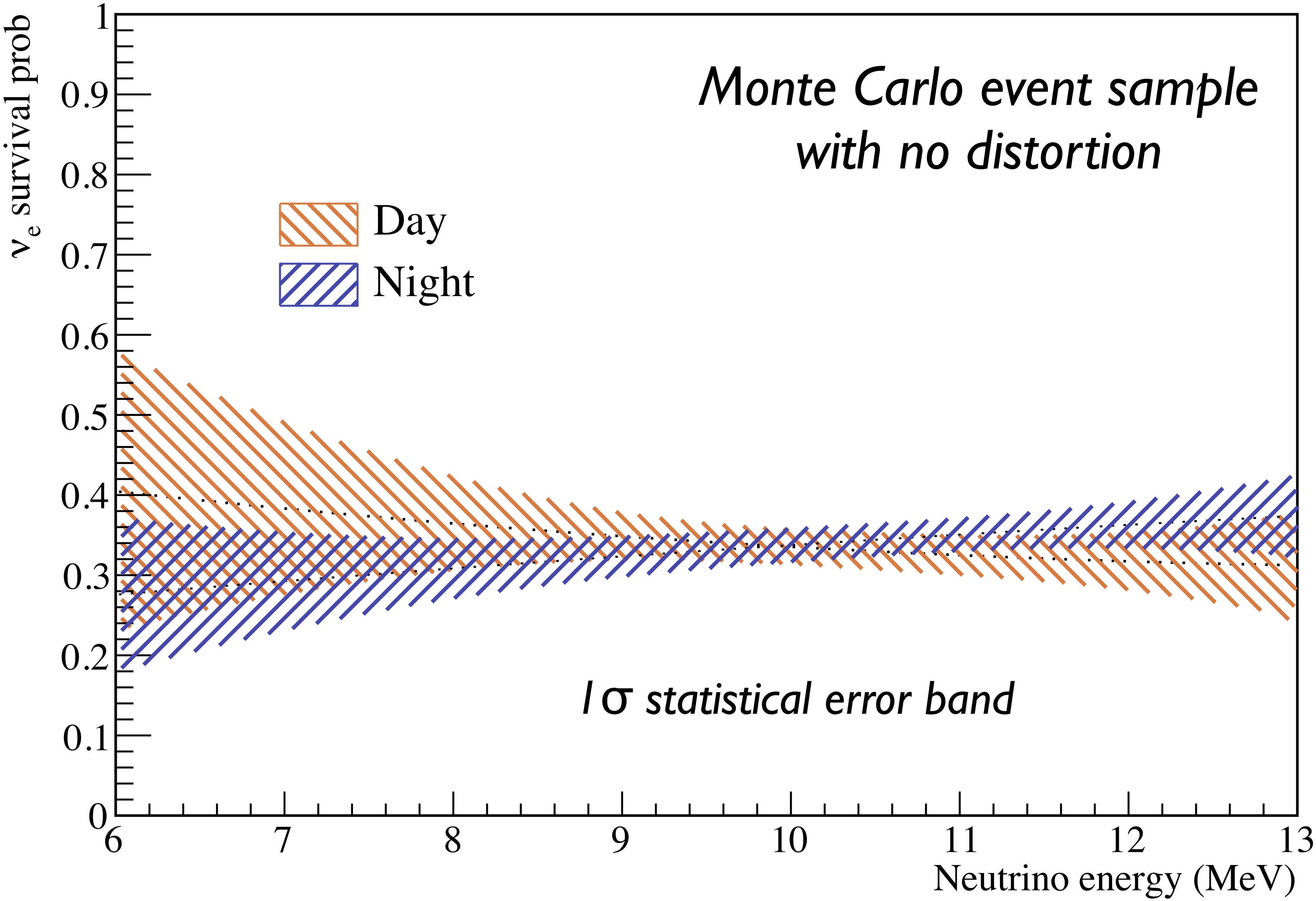
Signal Extraction

- Both methods agree remarkably well!
- Kernel estimation method opens up possibility of fitting in neutrino energy by reweighting CC/ES PDFs by the Monte Carlo-selected neutrino energy:

$$\begin{aligned} P_{\mathrm{avg}}(E_\nu) &= A + B(E_\nu - 10\,\mathrm{MeV}) \\ &\quad + C(E_\nu - 10\,\mathrm{MeV})^2 + D(E_\nu - 10\,\mathrm{MeV})^3 \\ P_{\mathrm{asym}}(E_\nu) &= F + G(E_\nu - 10\,\mathrm{MeV}) \end{aligned}$$

- Can also do binned neutrino energy fit (3 energy bins day and night)

Polynomial Survival Probability

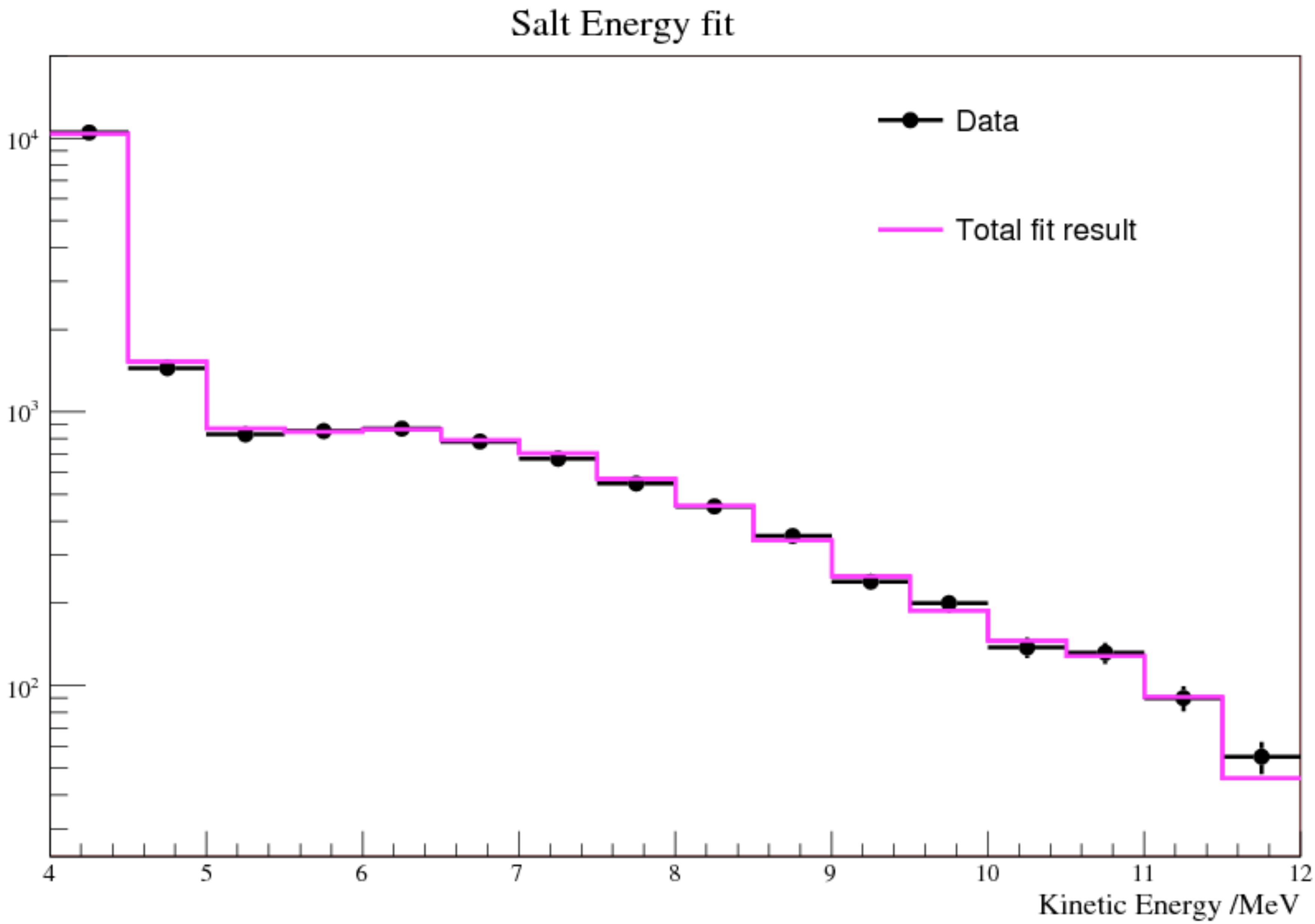


Results from the Low Energy Threshold Analysis are still being reviewed by the SNO collaboration.

However, I can show you the following:

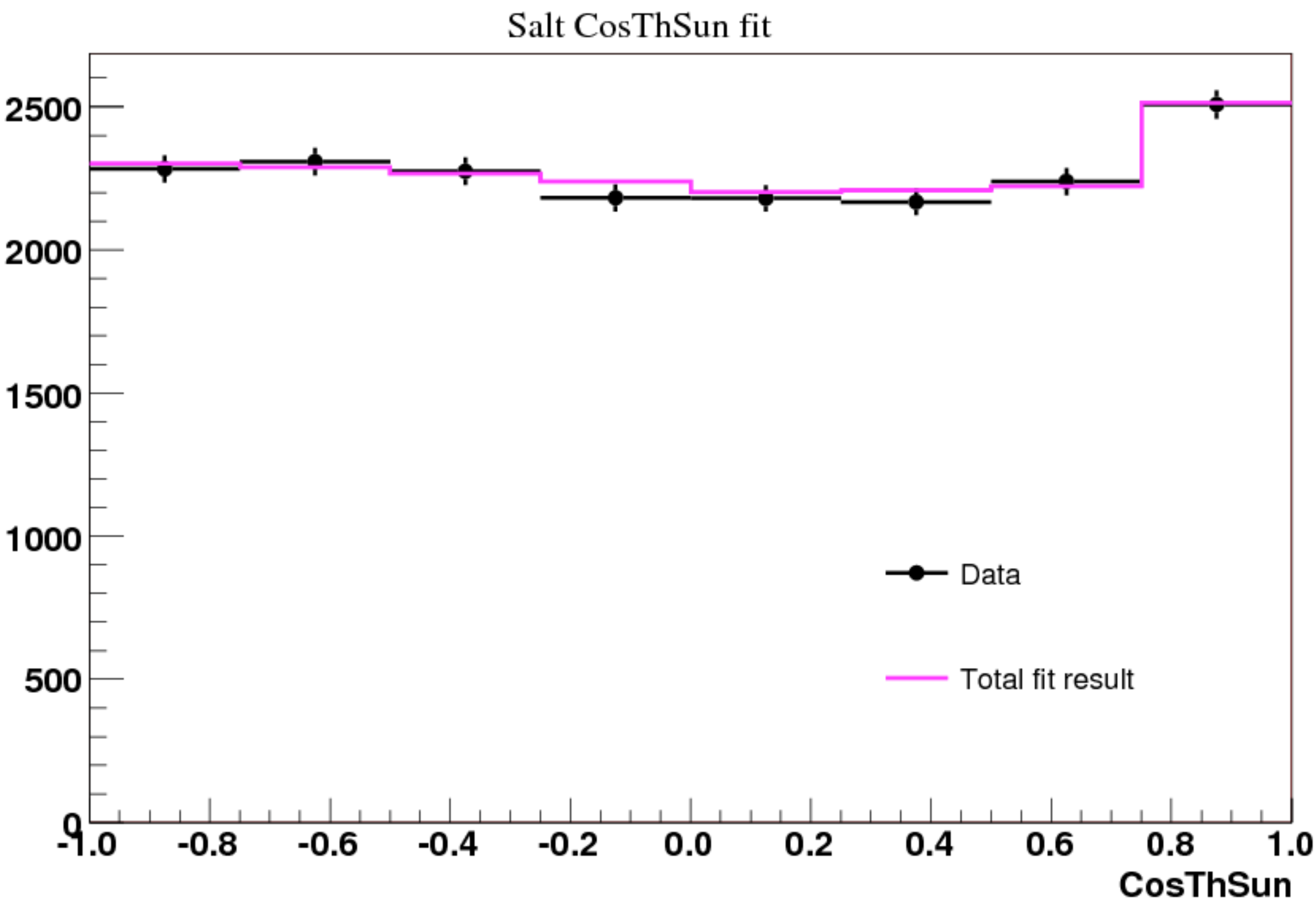
$\chi^2 = 13.5 / 15$

PRELIMINARY



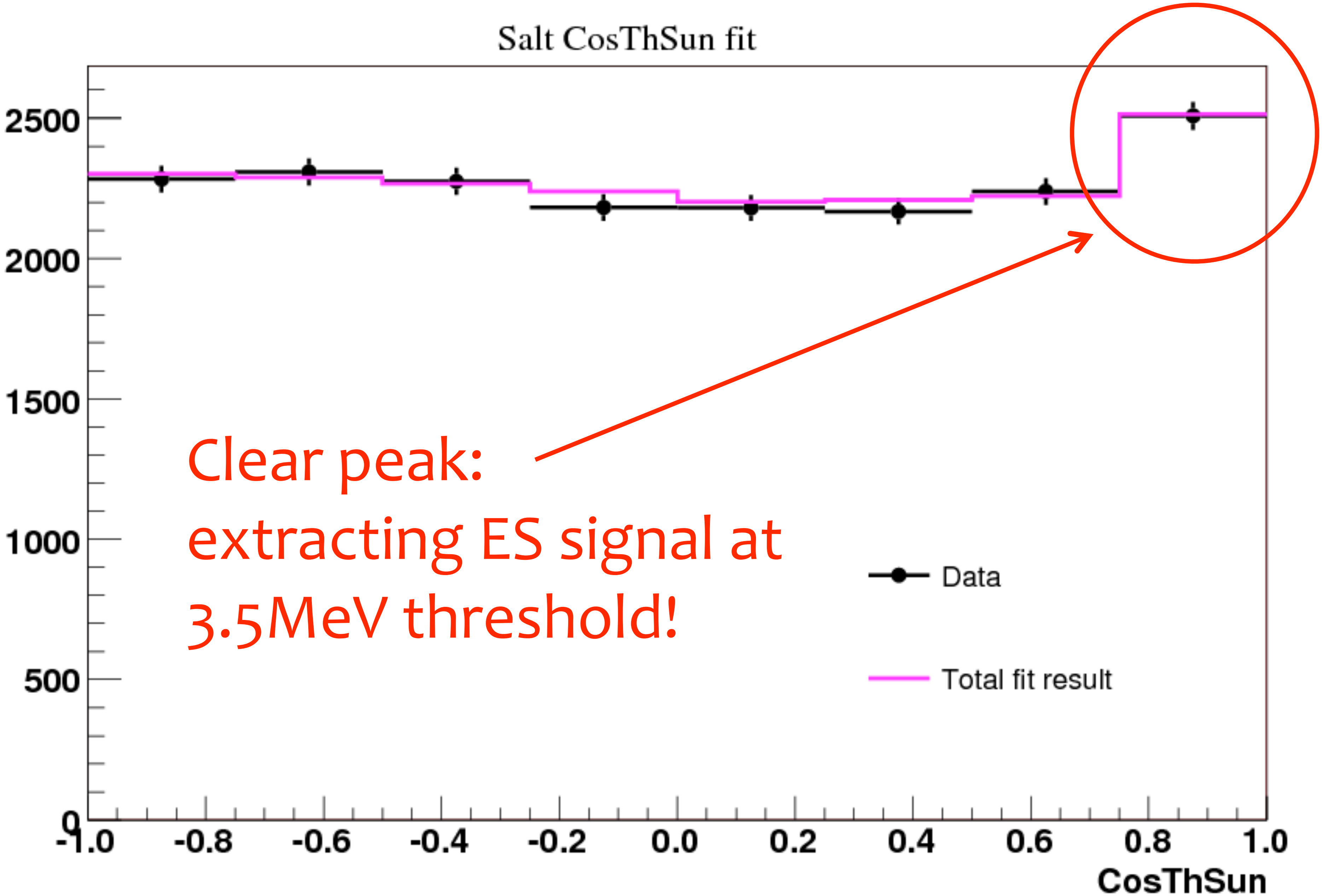
$\chi^2 = 3.0 / 7$

PRELIMINARY

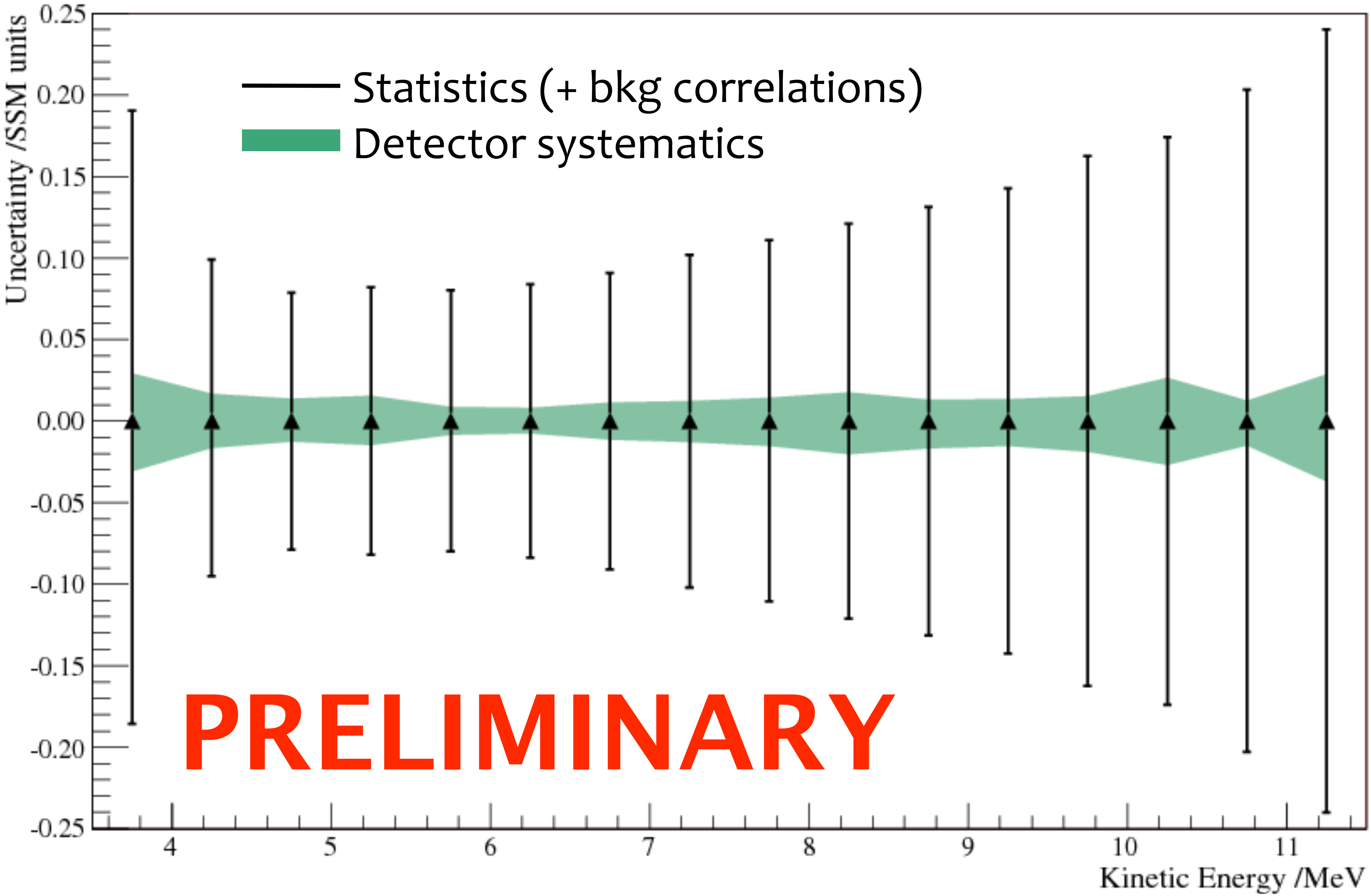


$\chi^2 = 3.0 / 7$

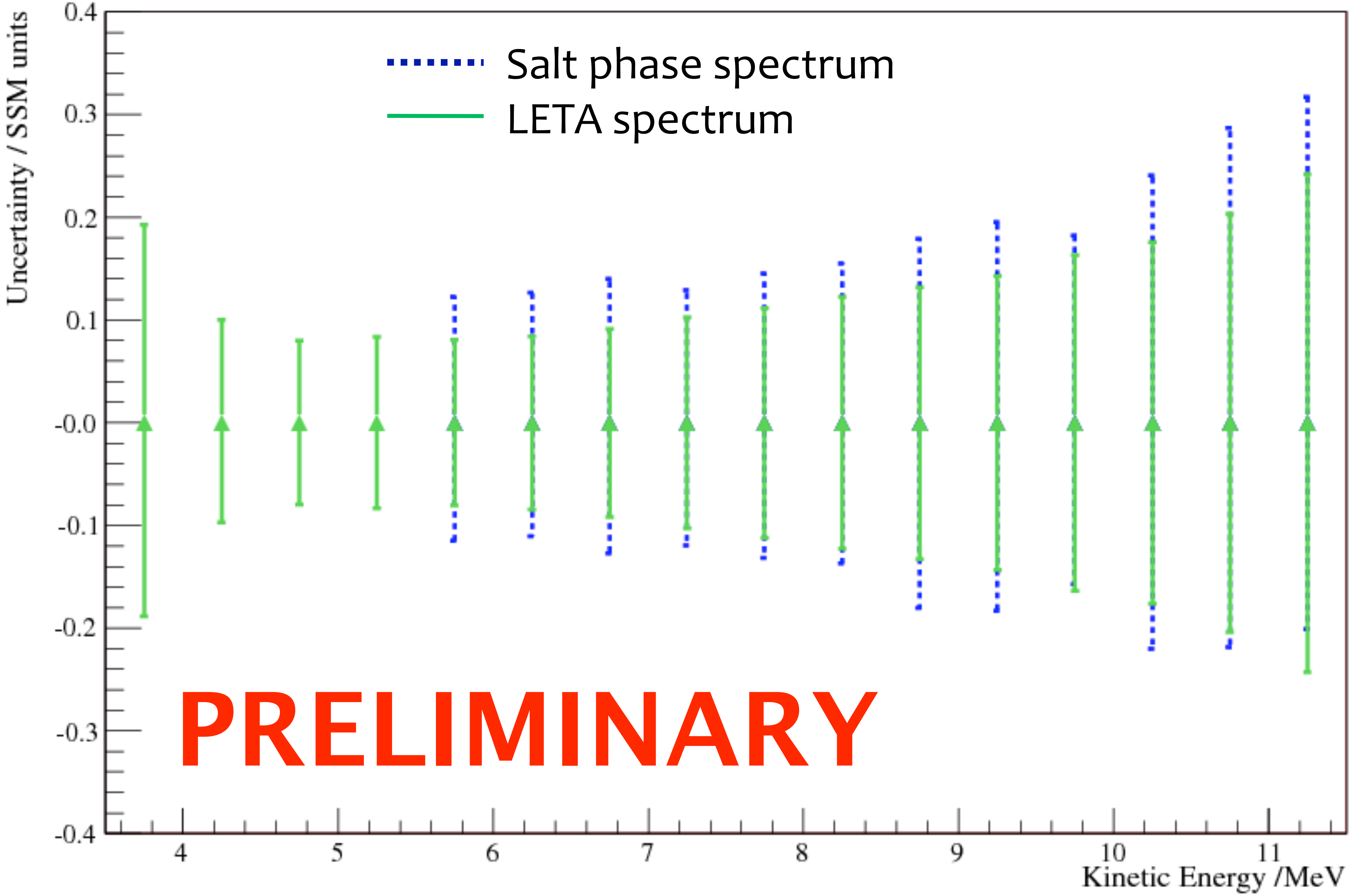
PRELIMINARY



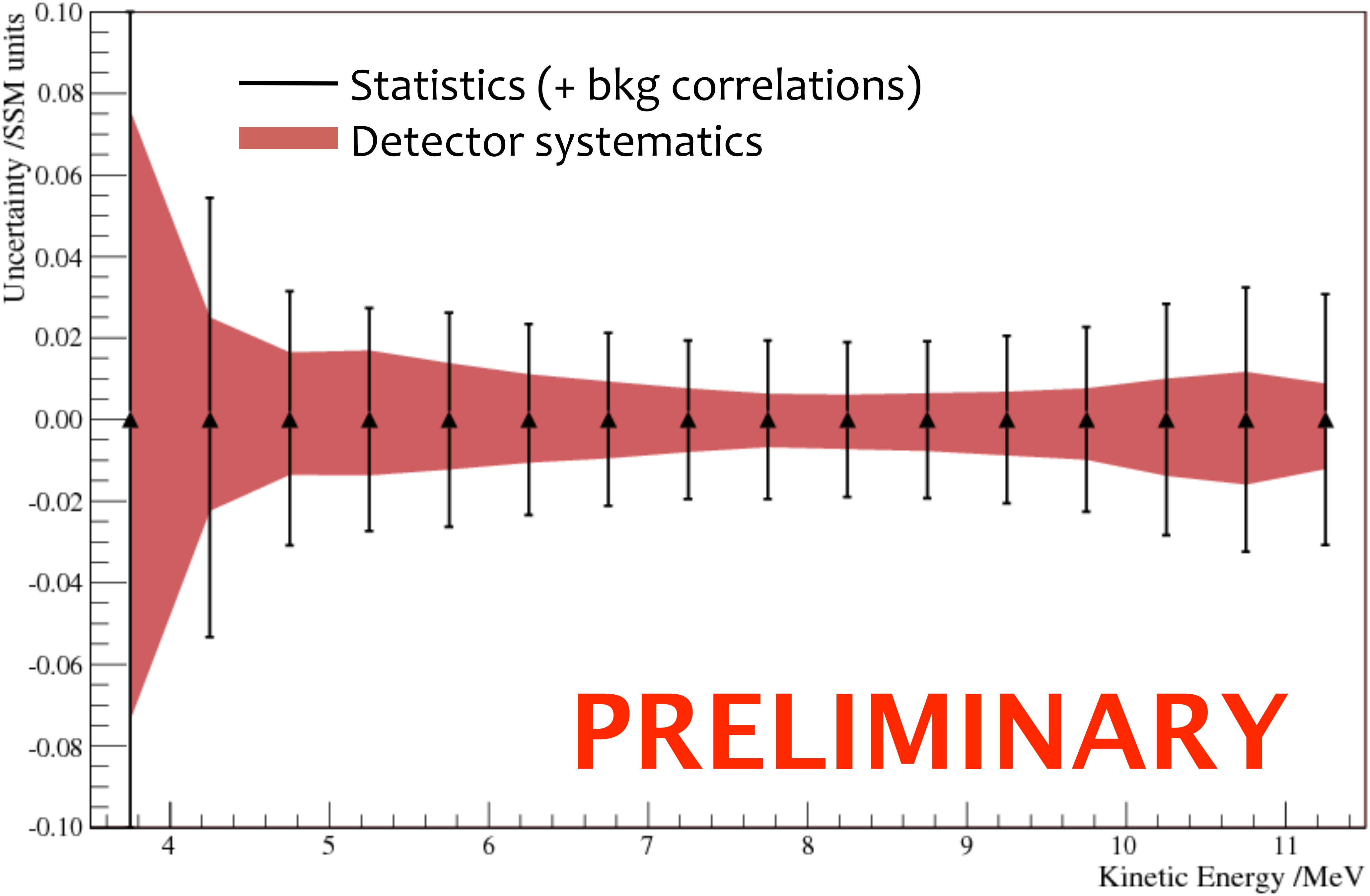
ES Spectrum **Uncertainties**



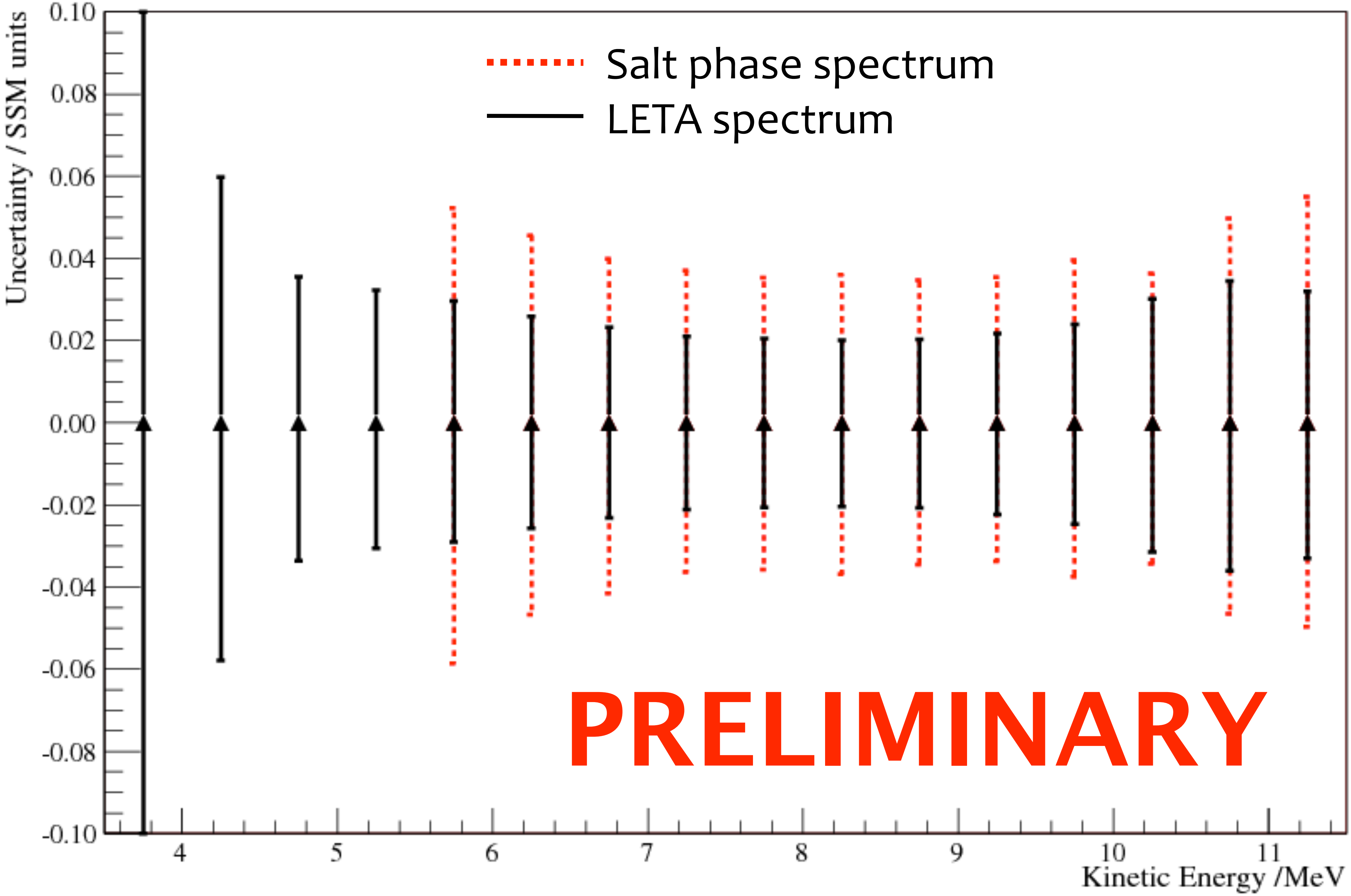
ES Spectrum **Uncertainties**



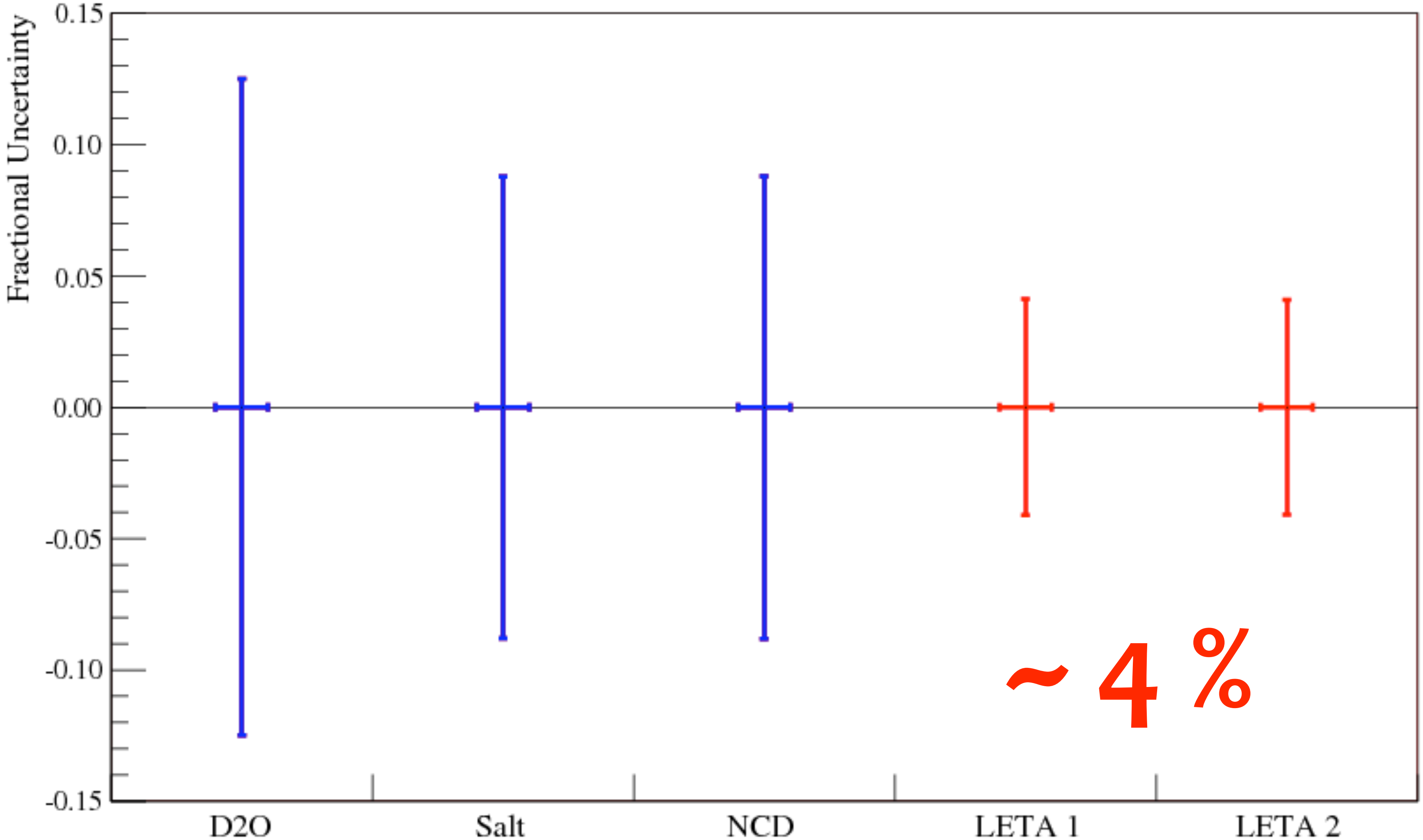
CC Spectrum **Uncertainties**



CC Spectrum **Uncertainties**



NC Flux Uncertainties



PRELIMINARY

SNO: Low Threshold Analysis

- 3.5 MeV energy threshold
- Joint analysis of D2O and salt phases
- Vastly improved systematics
- New spectral fits in neutrino energy, rather than reconstructed electron energy
- ~4% uncertainty in NC!

- Coming "soon" to an arXiv near you!

SNO: Plans for future

Papers in the pipeline:

- Low threshold ^{8}B analysis of D2O and Salt phase
- Cosmogenically-induced neutrons at SNOLAB
- Three phase hep neutrino analysis (3x more stats than first paper!)
- High frequency periodicity and burst search
- Three phase ^{8}B analysis
- Variety of technical papers and searches for exotic phenomena

SNO detector to be reused in SNO+:

- Funded by CFI, full steam ahead!