



Solar Neutrino Results From Borexino

HEP Seminar, University of Pennsylvania
November 8th, 2011

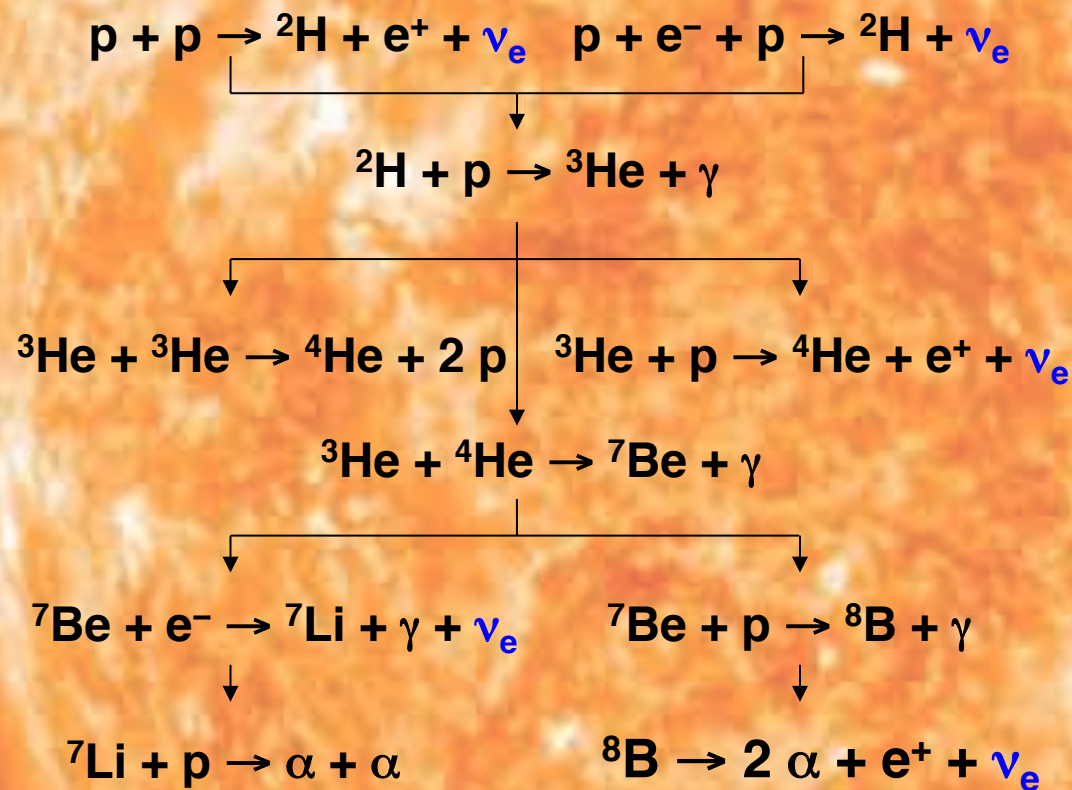
Alex Wright
Princeton University
for the Borexino Collaboration

Outline

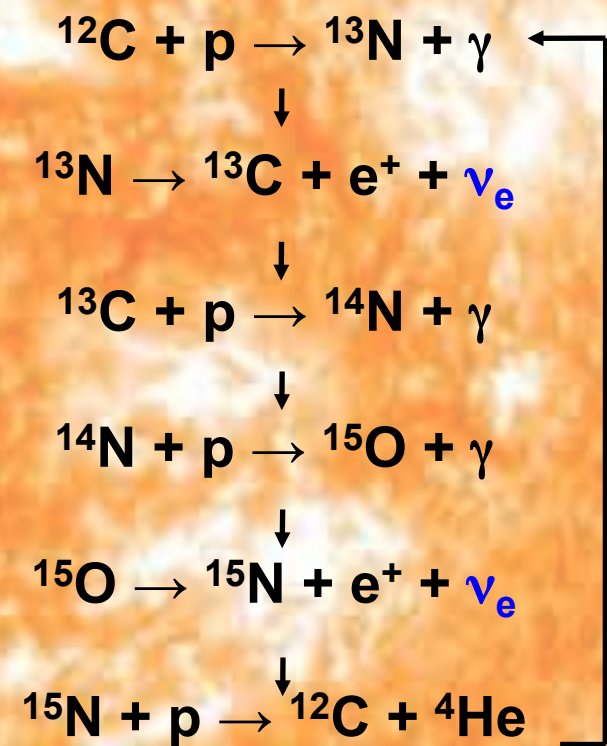
- Quick review of solar neutrinos and neutrino oscillations
- Introduction to Borexino
- Recent results and implications
- Outlook

Solar Fusion Reactions

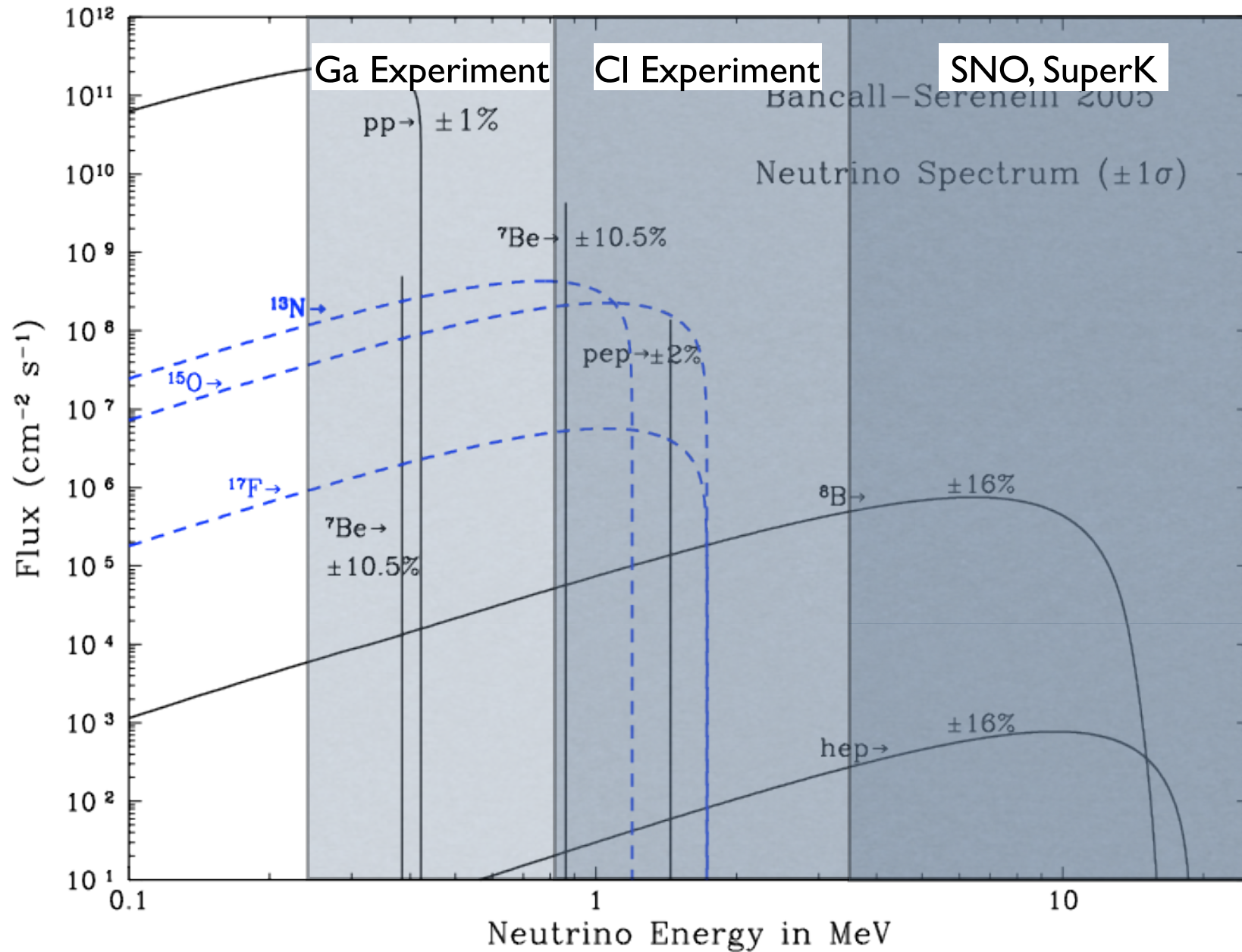
p-p Solar Fusion Chain



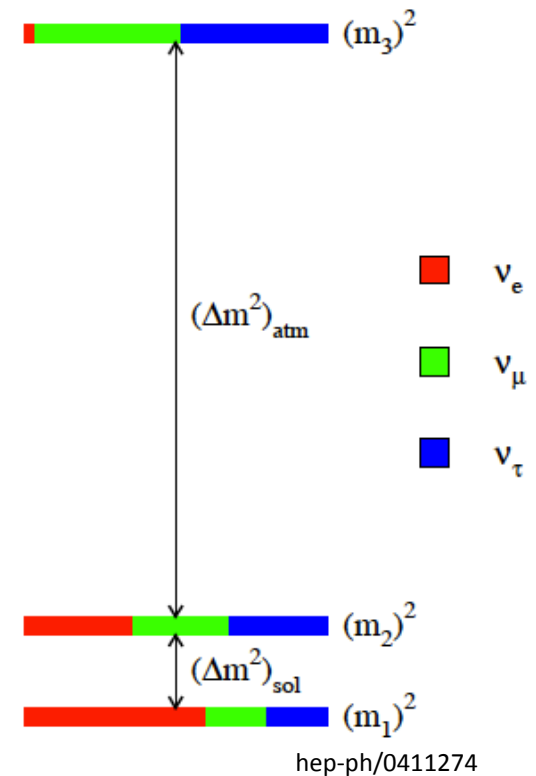
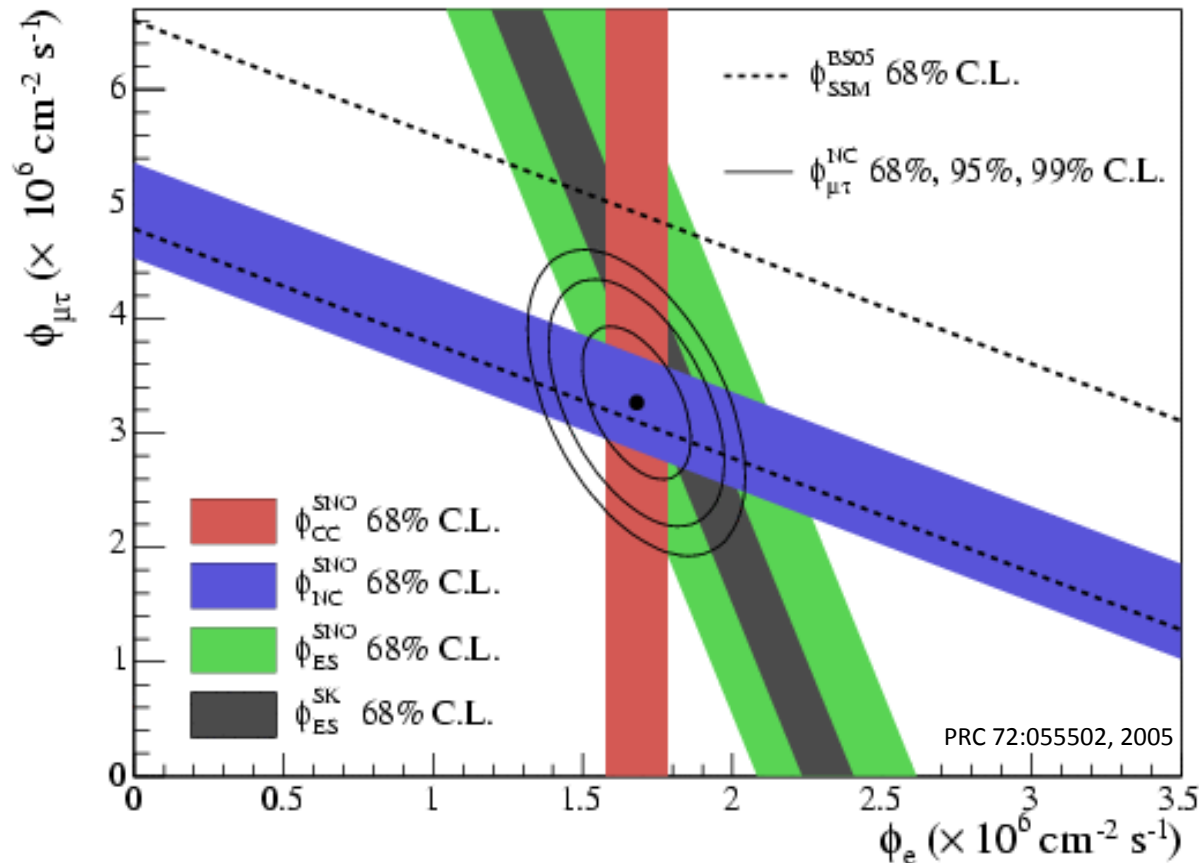
CNO Solar Fusion Cycle



Solar Neutrinos



Solar Neutrino Oscillations



- Neutrinos are produced and detected in flavour eigenstates, but propagate in a superposition of mass eigenstates (CKM matrix $\rightarrow$ PMNS matrix)
- Phase differences acquired in mass eigenstate propagation change apparent flavour content

“MSW” Neutrino Oscillations

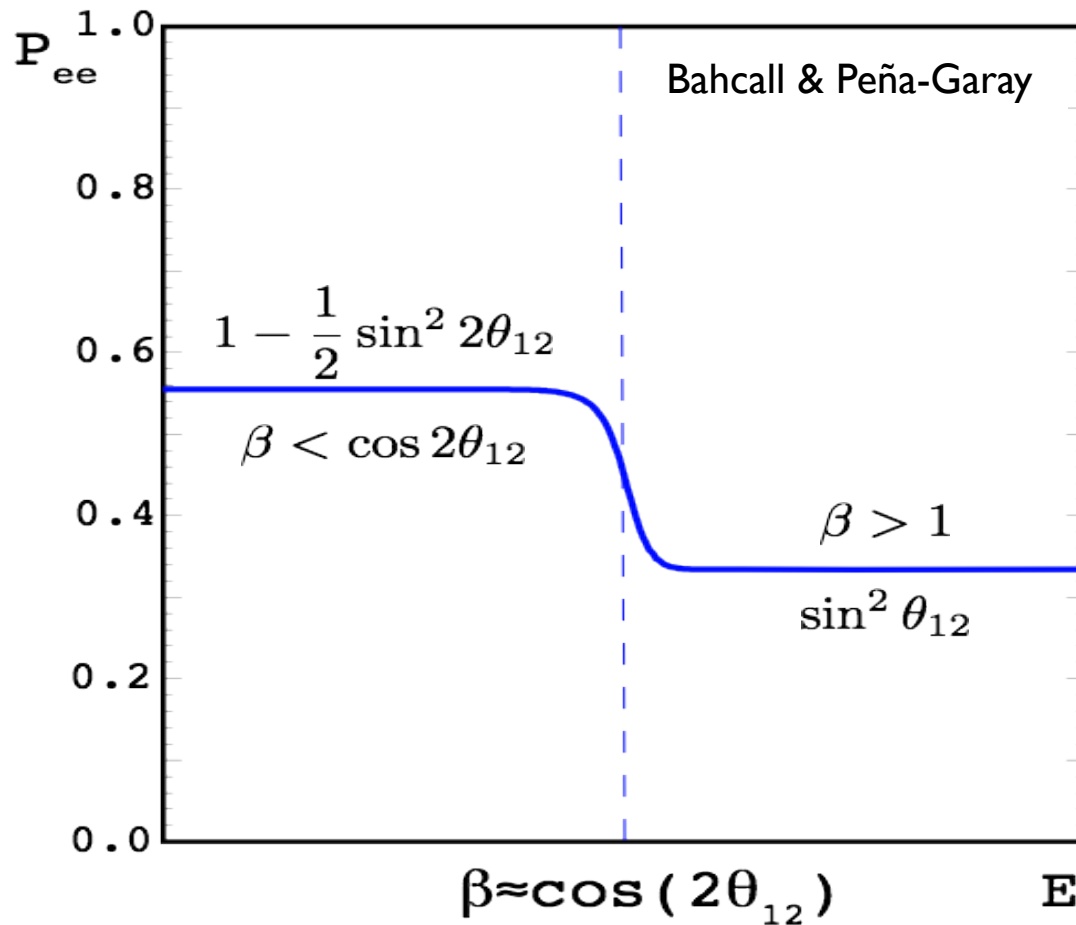
- When neutrinos propagate in matter, charged current interactions add an additional term to ν_e flavour in mass matrix:

$$\begin{pmatrix} -\frac{\Delta m_{12}^2}{4E} \cos 2\theta_{12} + \sqrt{2}G_F N_e & \frac{\Delta m_{12}^2}{4E} \sin 2\theta_{12} \\ \frac{\Delta m_{12}^2}{4E} \sin 2\theta_{12} & \frac{\Delta m_{12}^2}{4E} \cos 2\theta_{12} \end{pmatrix}$$

- As neutrinos propagate out of the sun, the matter effect can lead to a resonant enhancement of the transition probability
 - “Strength” of the effect is energy dependant:

$$\frac{2^{3/2}G_F N_e E}{\Delta m^2}$$

MSW Oscillation Regimes

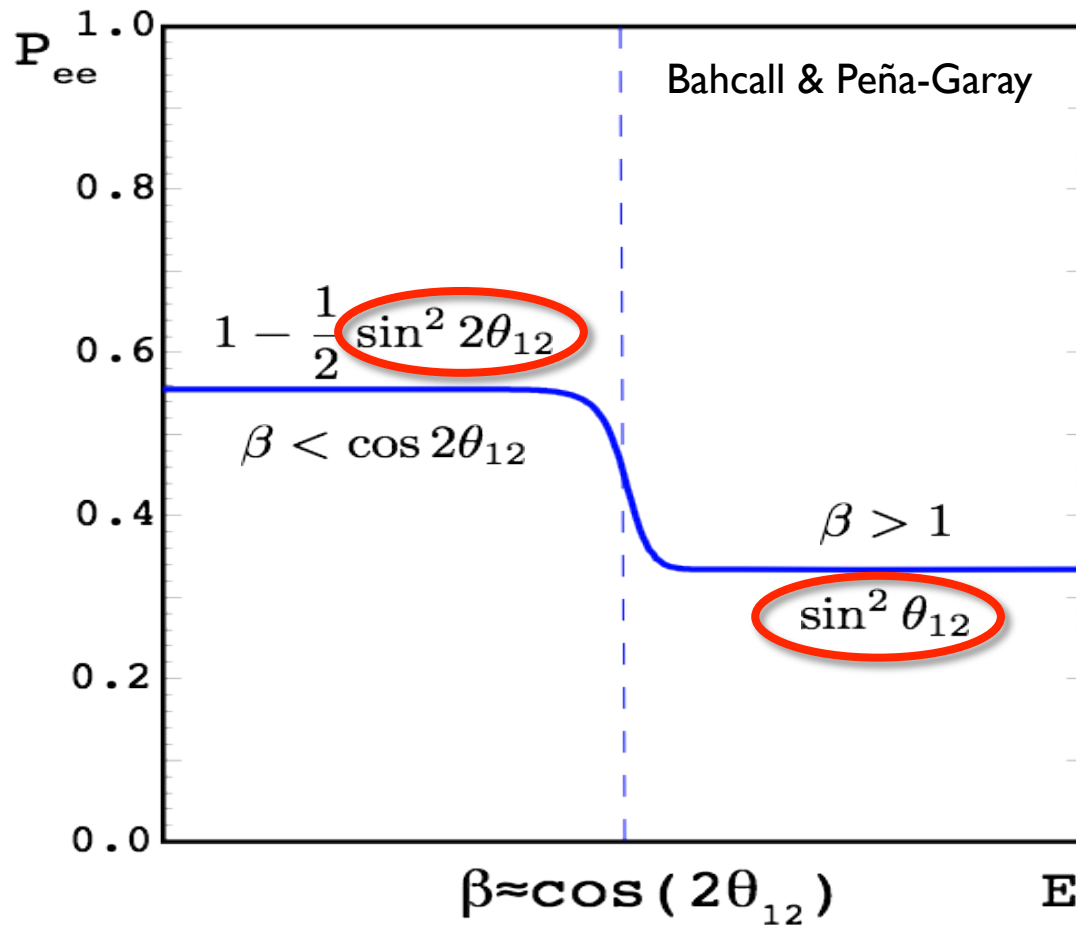


$$\beta = \frac{2^{3/2} G_F N_e E}{\Delta m^2}$$

Low energy: Phase-averaged vacuum oscillations

High energy: Matter-dominated “resonant conversion”

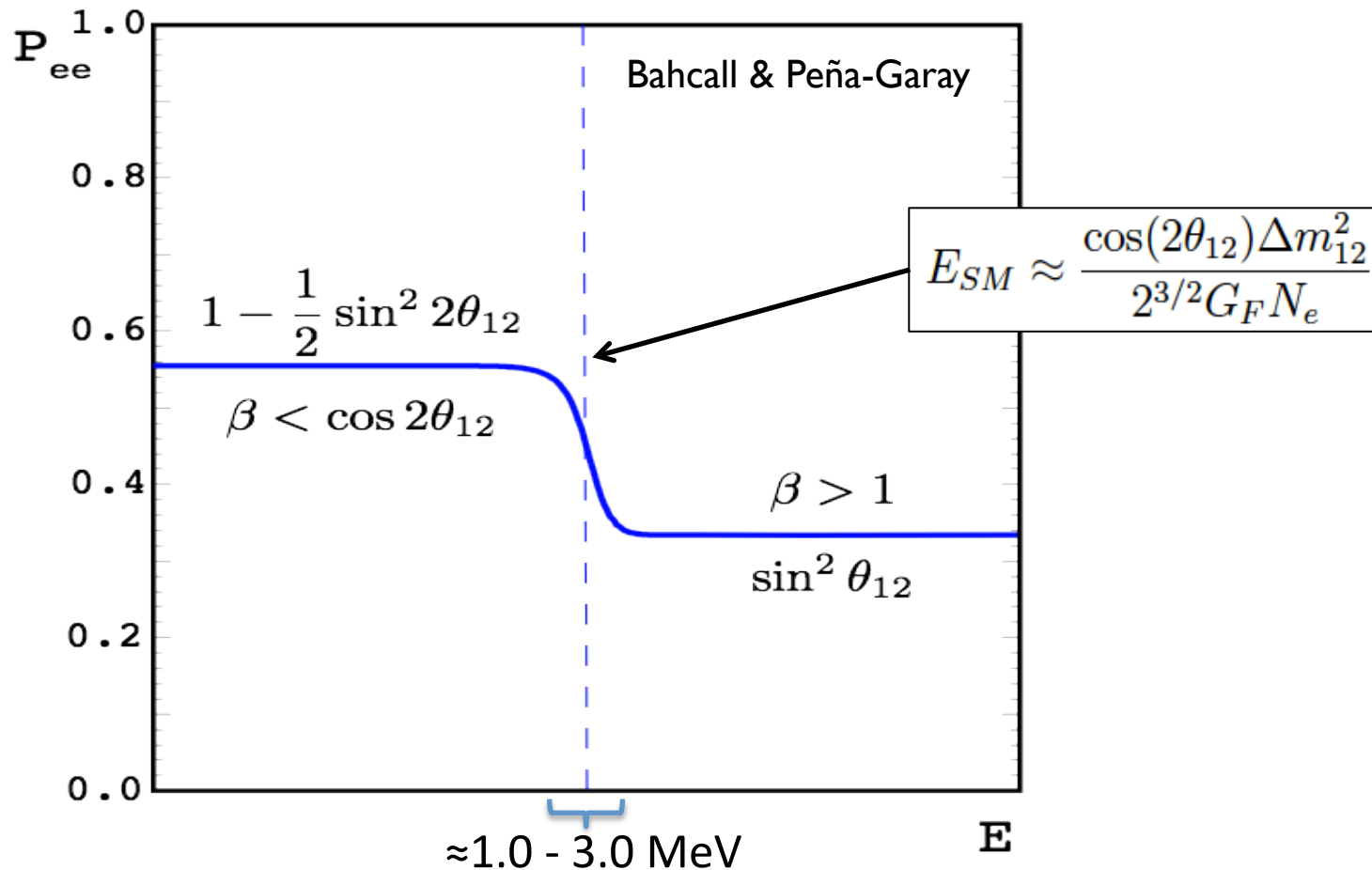
MSW Oscillation Regimes



$$\beta = \frac{2^{3/2} G_F N_e E}{\Delta m^2}$$

In these regimes, P_{ee} depends only on θ_{12} , not on the mass splitting or the details of the neutrino-matter interaction

MSW Oscillation Regimes

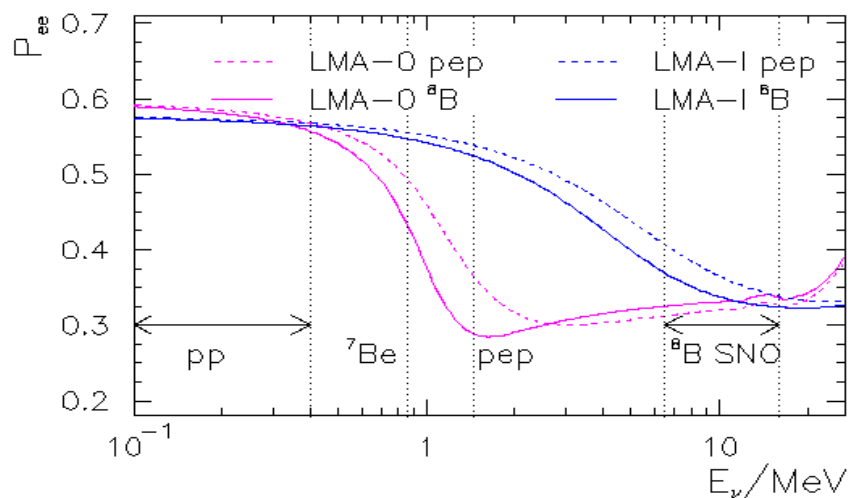


Look in “transition region” to confirm MSW and that we know what is going on!

Possible New Physics in Transition Region

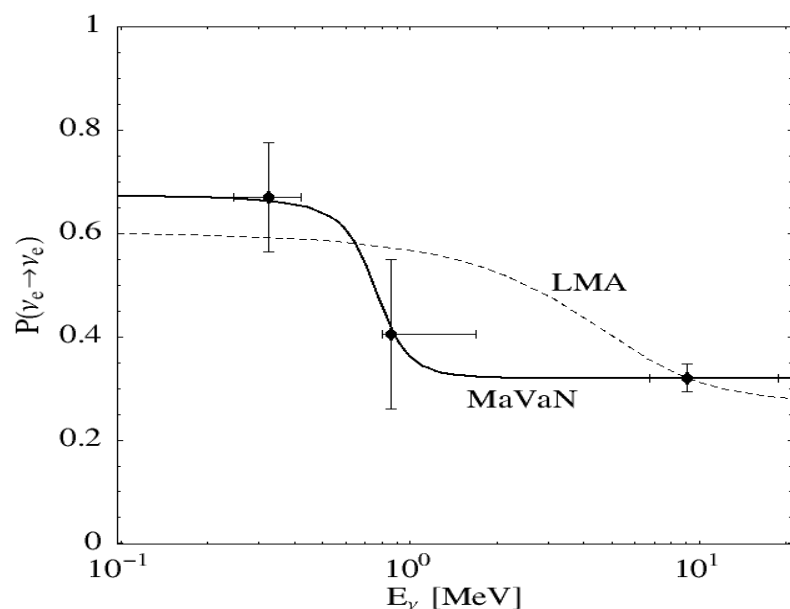
Non-Standard Interactions

Friedland *et al.*, PLB 594 (2004)



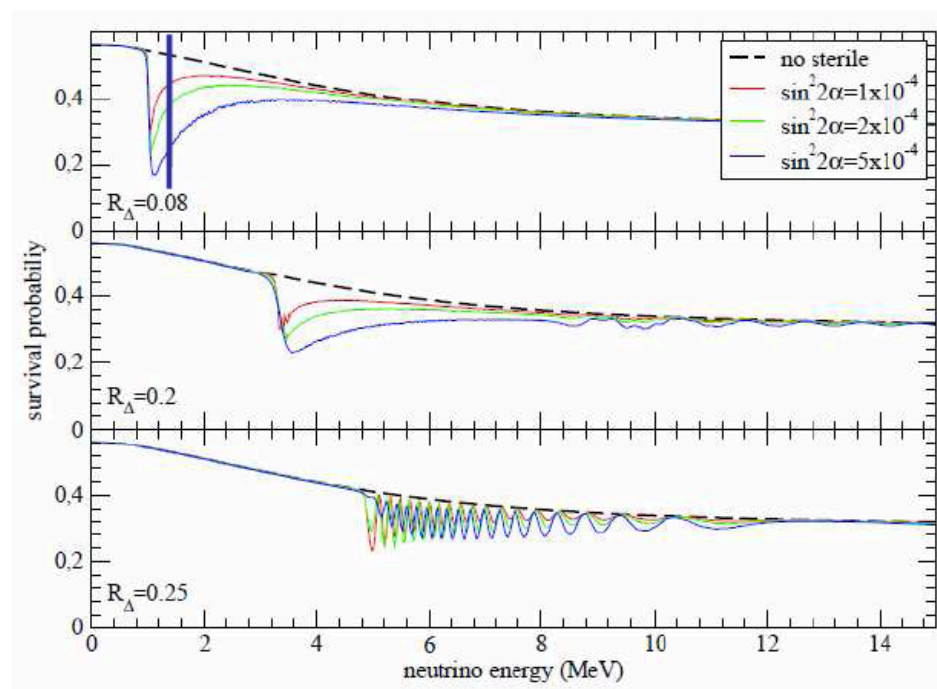
Mass Varying Neutrinos

Barger *et al.* PRL 95 (2005)

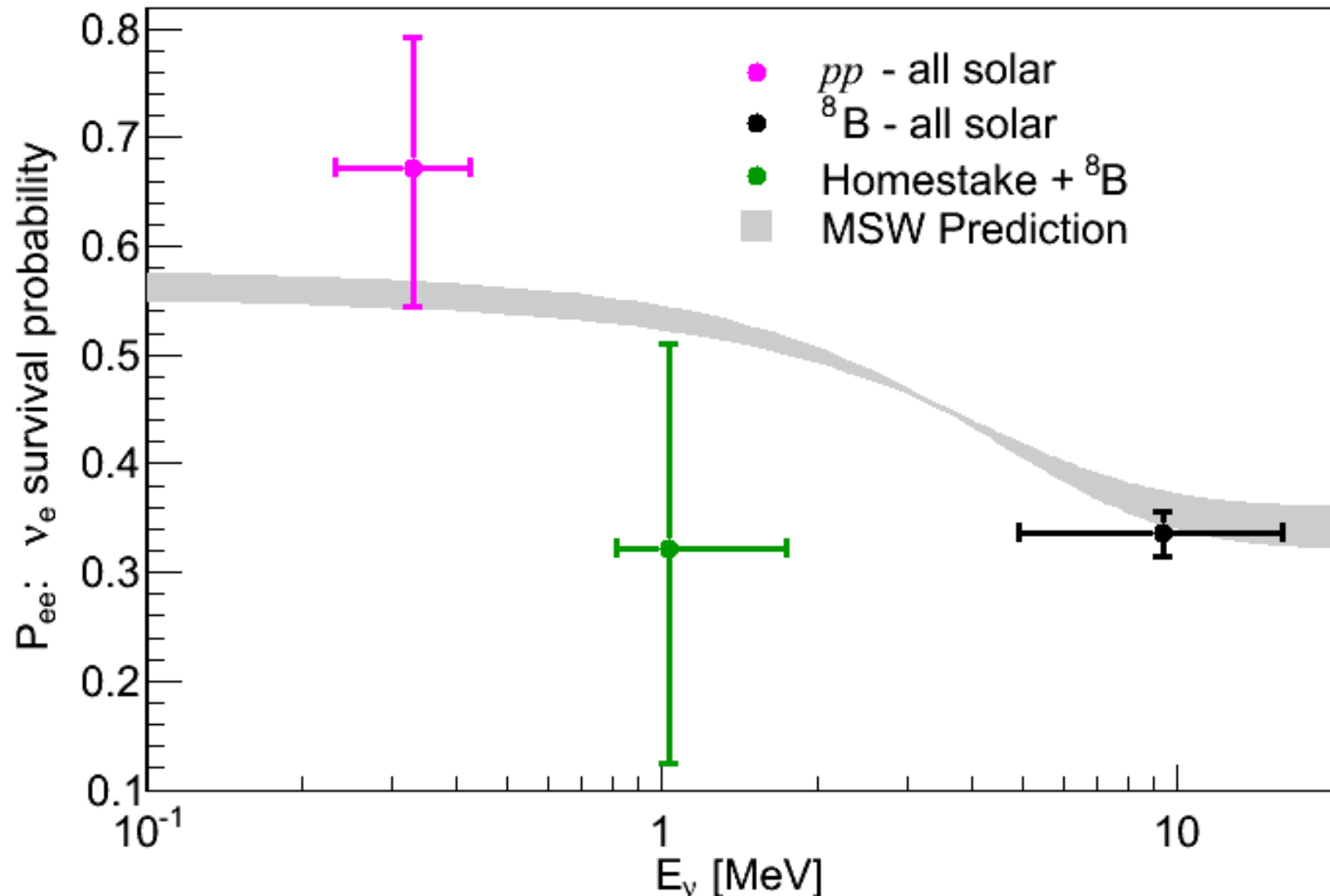


Sterile Neutrinos

Holanda and Smirnov, arXiv:1012:5627 (2010)

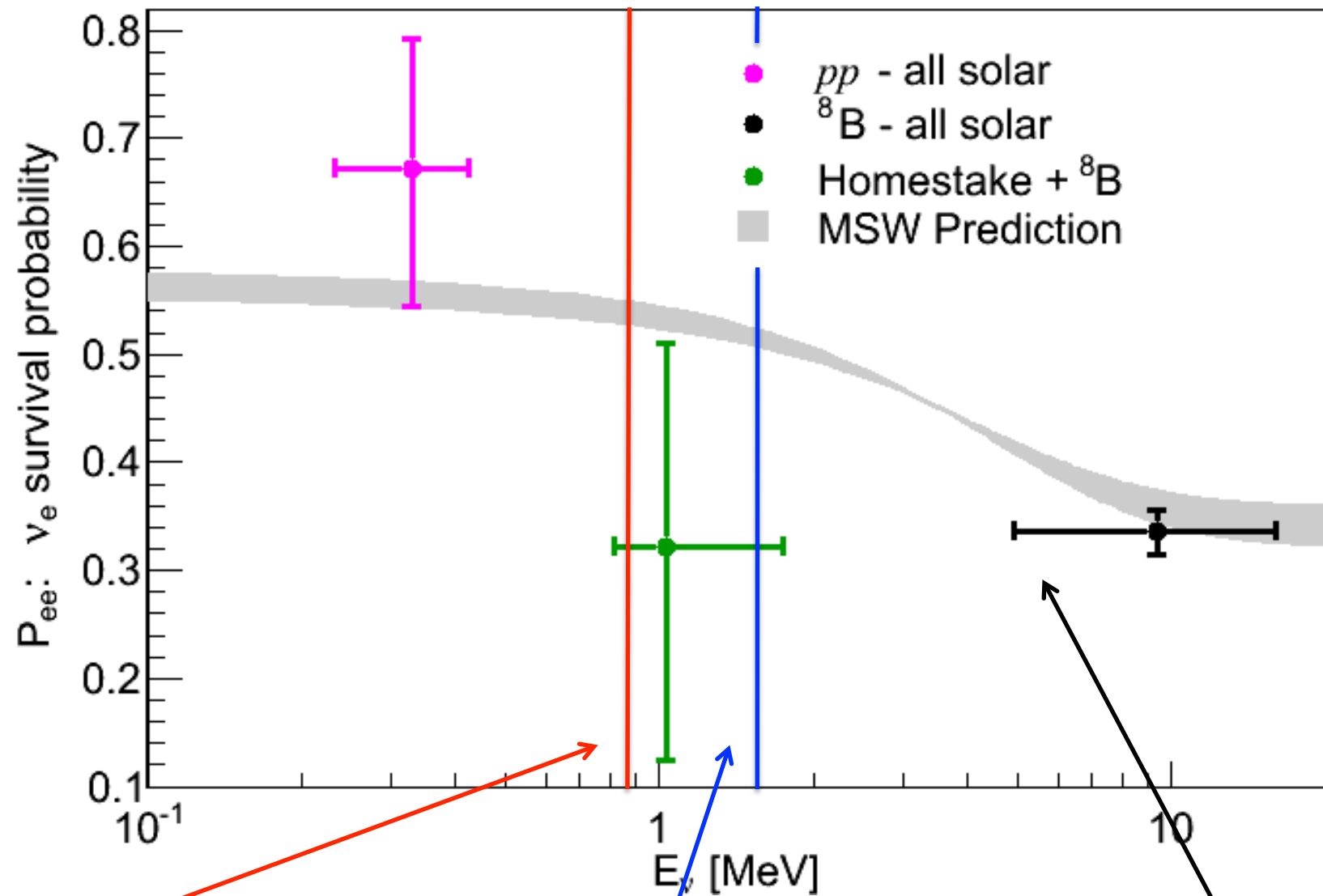


Pre-Borexino Constraints on Transition Region



Subtractions required in interpreting the radiochemical results mean that the data points are (anti-) correlated. *Real-time measurements needed in the transition region.*

Probing the Transition Region



862 keV ^7Be neutrinos:
High flux, monoenergetic,
Constrain T.R. from below.

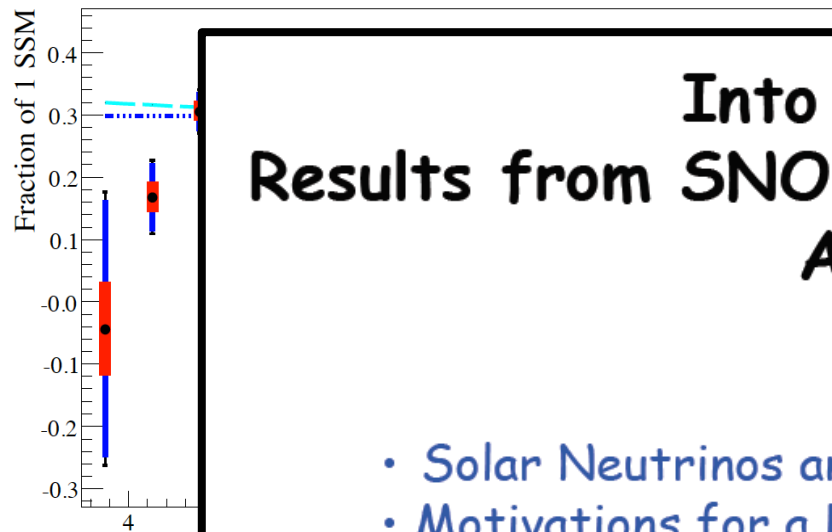
pep neutrinos:
Ideal energy for testing new physics,
precise SSM flux prediction.

Low energy ^8B neutrinos:
Enter T.R. from above.

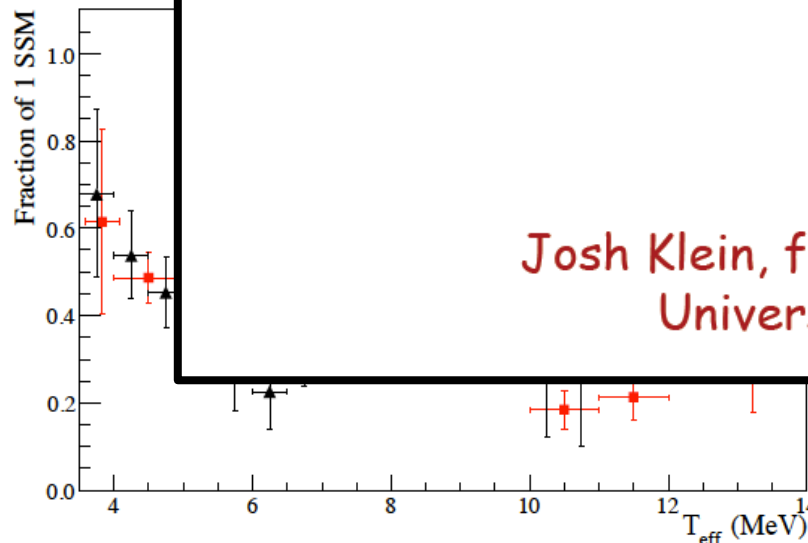
SNO Low Energy Threshold Analysis

Charged Current: $T_{\text{eff}} = E_{\nu} - 1.44 \text{ MeV}$

Quadratic Fits to P_{ee}



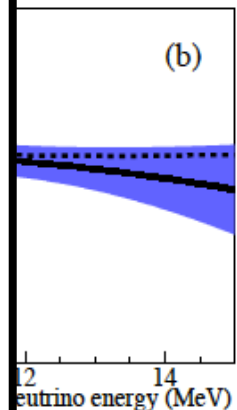
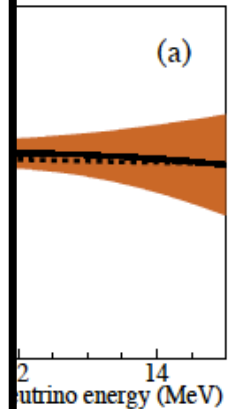
Elastic Sc



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

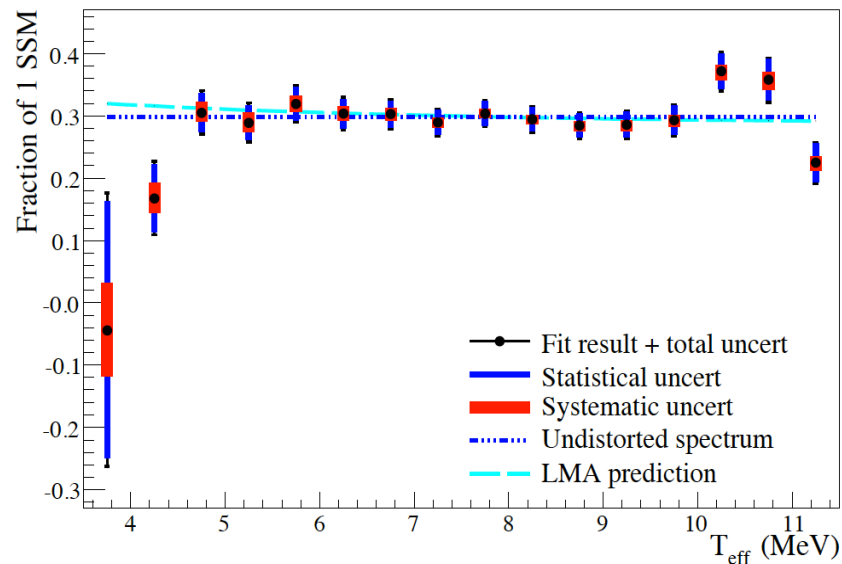
Josh Klein, for the SNO Collaboration
University of Pennsylvania



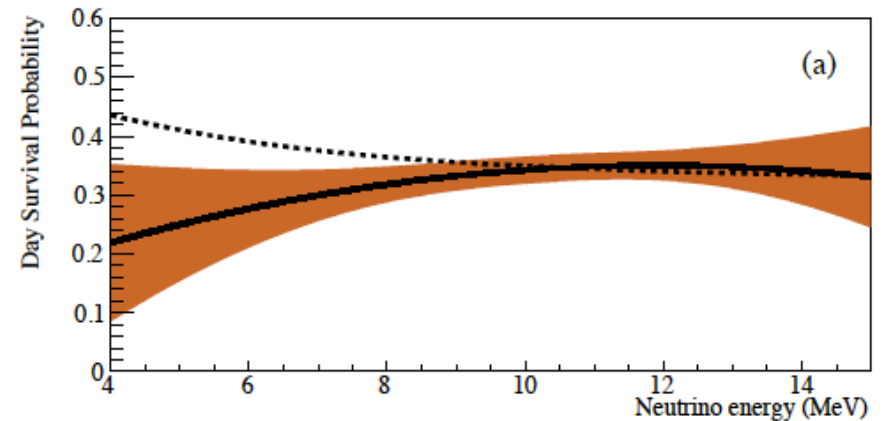
(Phys. Rev. C 81 (2010) 055504,
arXiv:1109.0763)

SNO Low Energy Threshold Analysis

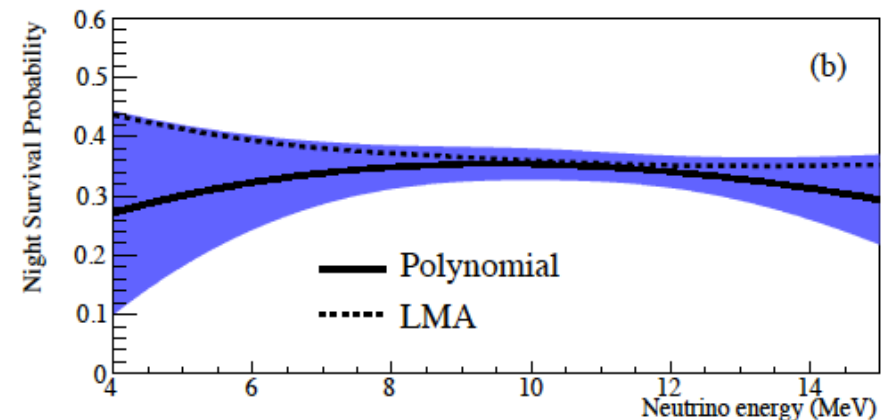
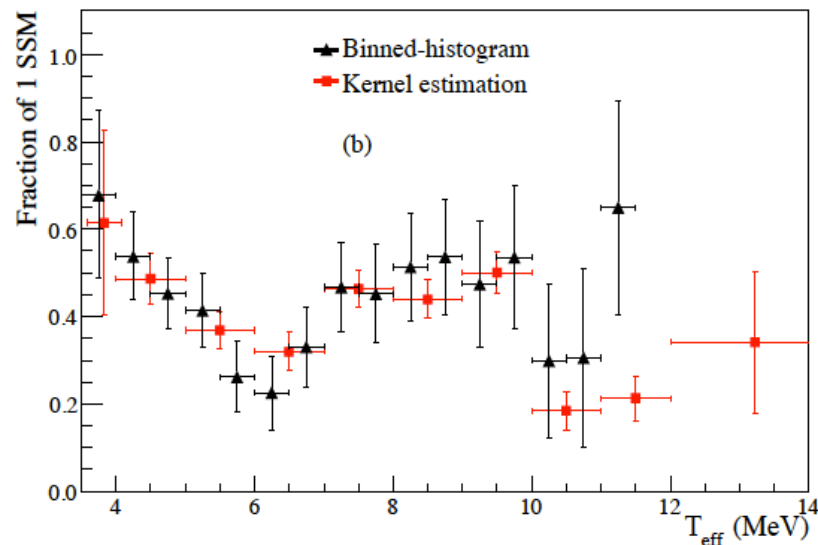
Charged Current: $T_{\text{eff}} = E_\nu - 1.44 \text{ MeV}$



Quadratic Fits to P_{ee}

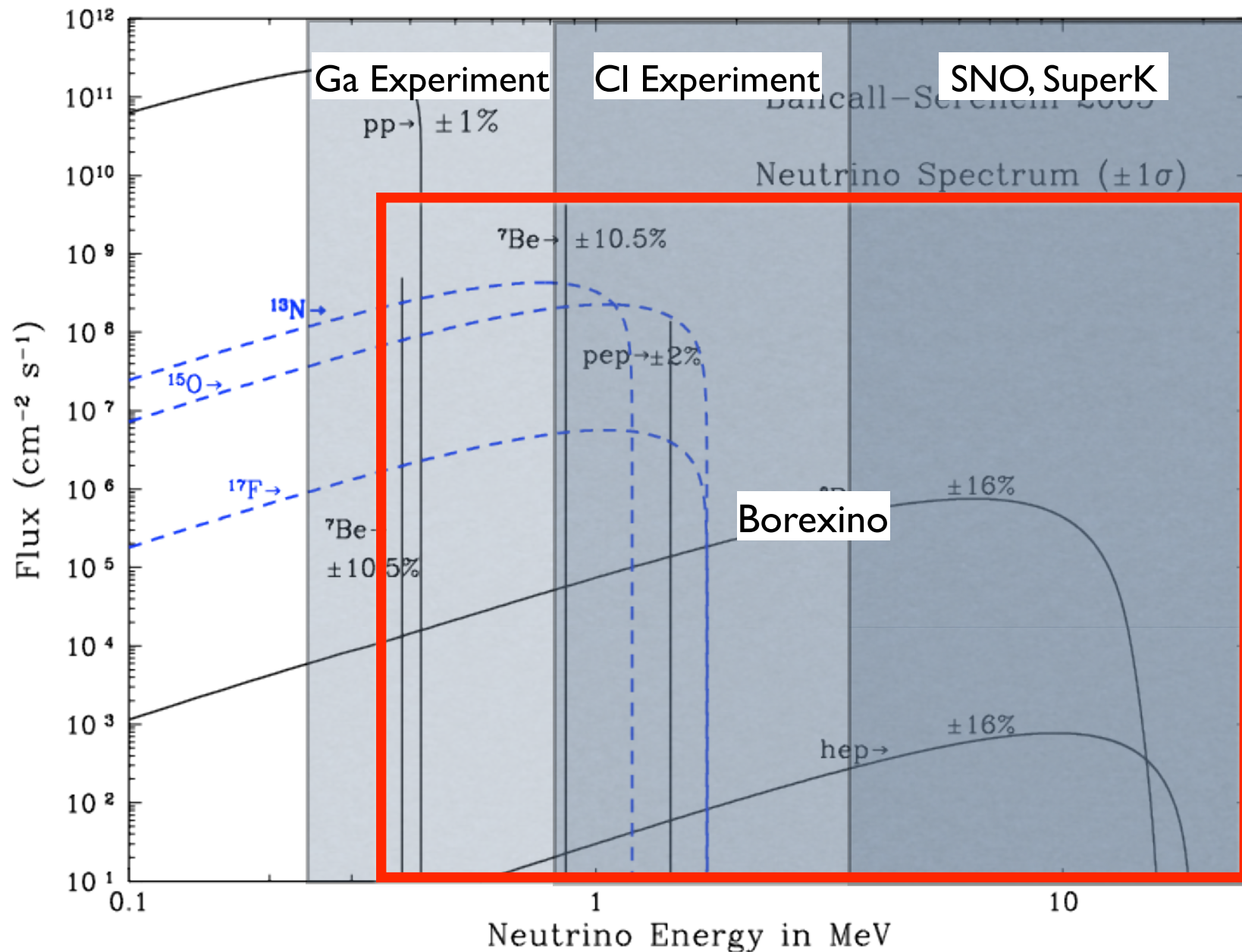


Elastic Scattering: $0 \leq T_{\text{eff}} \lesssim E_\nu - 0.24 \text{ MeV}$



(Phys. Rev. C 81 (2010) 055504,
arXiv:1109.0763)

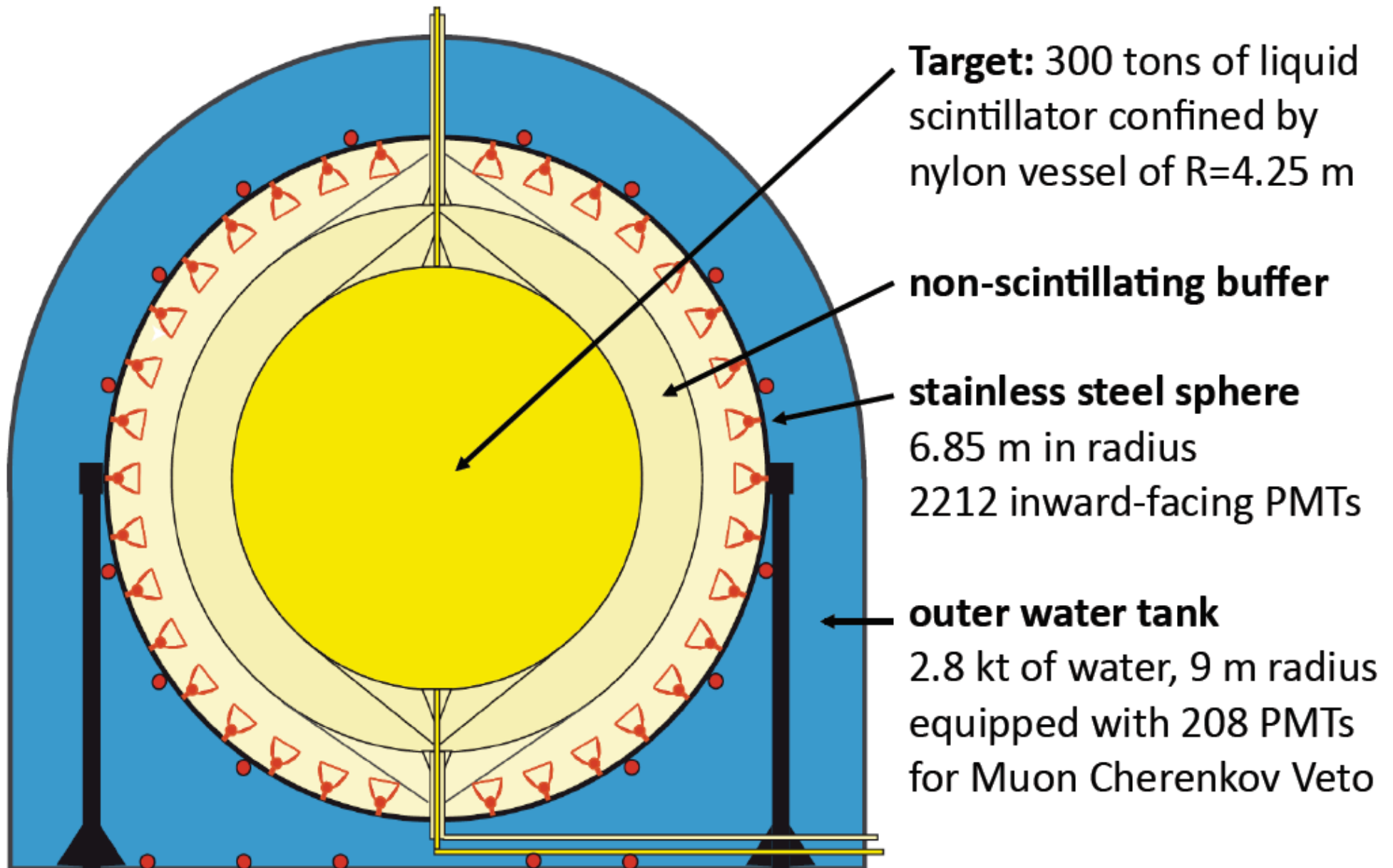
Borexino: Real-time Detection Below 100 keV



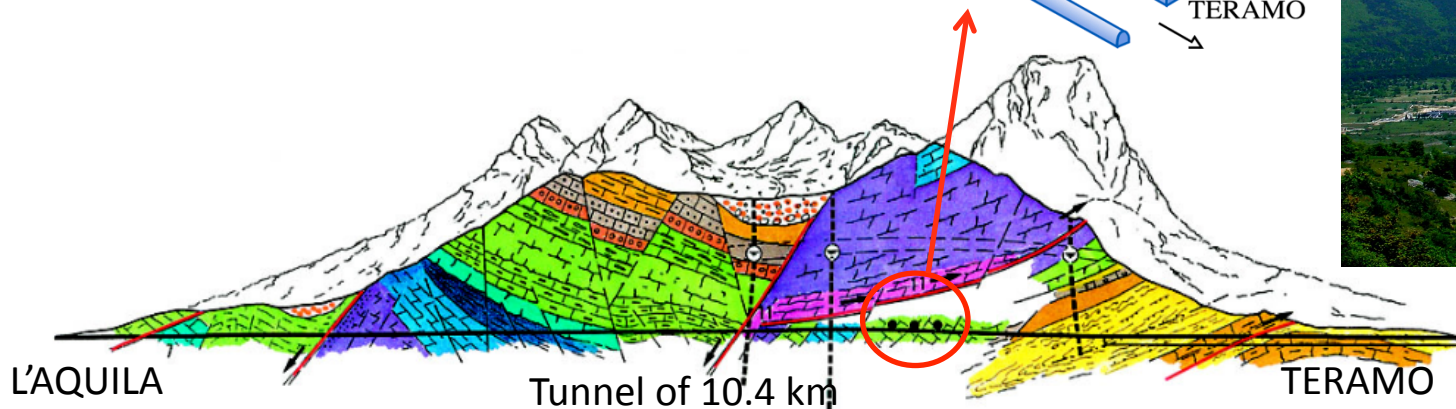
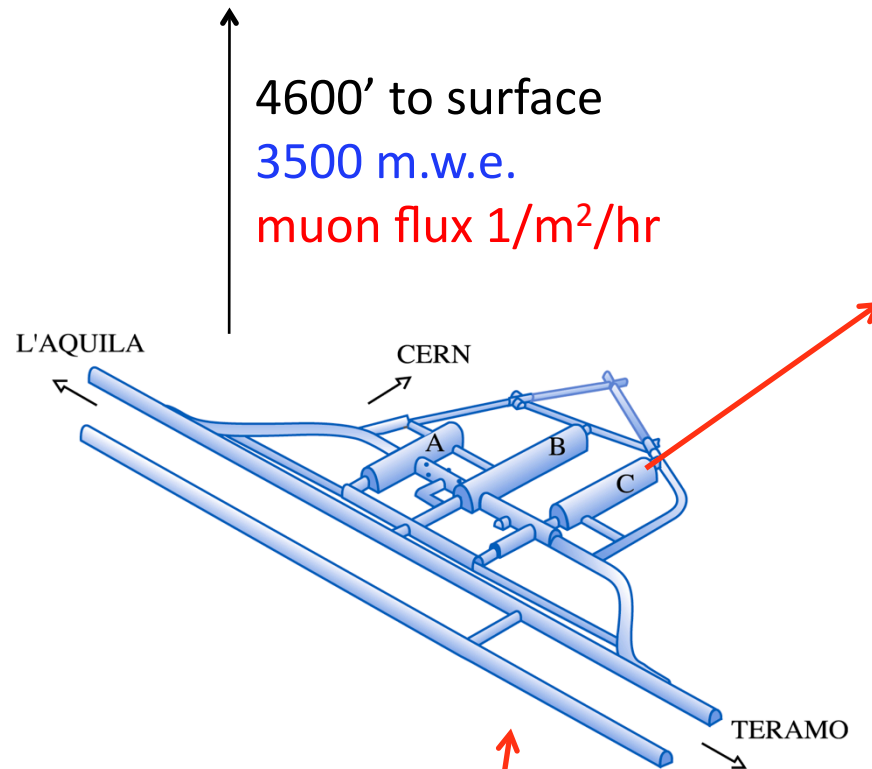
Borexino Solar Neutrino Results

- ^7Be Flux
 - ($\pm 30\%$) – Phys. Lett. B **658**:101 (2008).
 - ($\pm 10\%$) – Phys. Rev. Lett. **101**:091302 (2008).
 - ($\pm 5\%$) – Phys. Rev. Lett. **107**:141302 (2011).
- ^7Be Day-Night Asymmetry
 - arXiv:1104.2150 (2011).
- ^8B Flux + Spectrum ($T_{\text{eff}} > 3.0 \text{ MeV}$)
 - Phys. Rev. D **82**:033006 (2010).
- *pep* and CNO flux
 - arXiv:1110.3230 (2011).

The Borexino Detector



Laboratori Nazionali del Gran Sasso



Borexino Collaboration

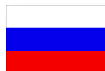
Astroparticle and Cosmology Laboratory – Paris, France 

INFN Laboratori Nazionali del Gran Sasso – Assergi, Italy 

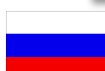
INFN e Dipartimento di Fisica dell'Università – Genova, Italy 

INFN e Dipartimento di Fisica dell'Università – Milano, Italy 

INFN e Dipartimento di Chimica dell'Università – Perugia, Italy 

Institute for Nuclear Research – Gatchina, Russia 

Institute of Physics, Jagellonian University – Cracow, Poland 

Join Institute for Nuclear Research – Dubna, Russia 

Kurchatov Institute – Moscow, Russia 

Max-Planck Institute fuer Kernphysik – Heidelberg, Germany 

Princeton University – Princeton, NJ, USA 

Technische Universität – Muenchen, Germany 

University of Massachusetts at Amherst, MA, USA 

University of Moscow – Moscow, Russia 

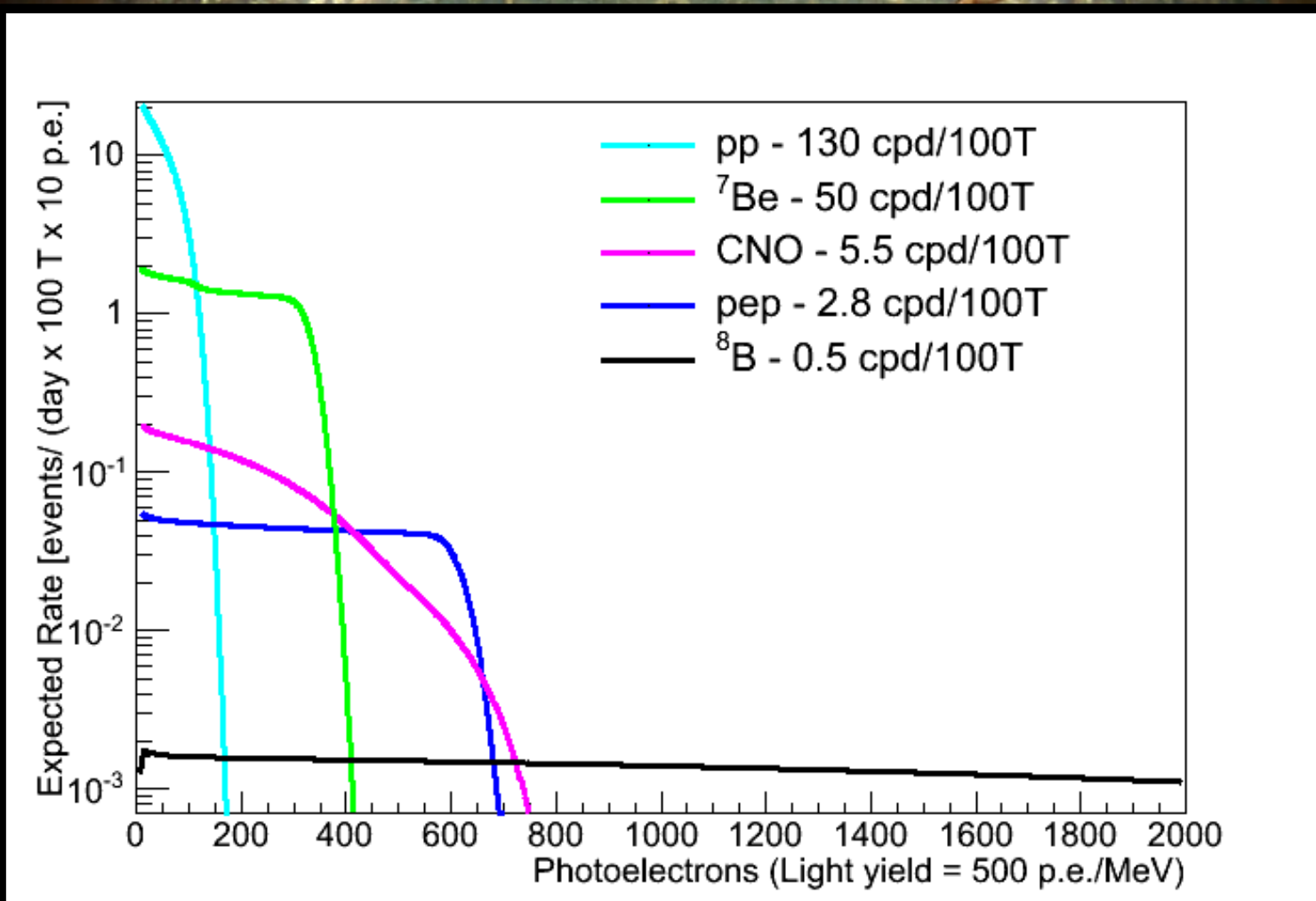
Virginia Tech – Blacksburg, VA, USA 

Neutrino Detection With Liquid Scintillator

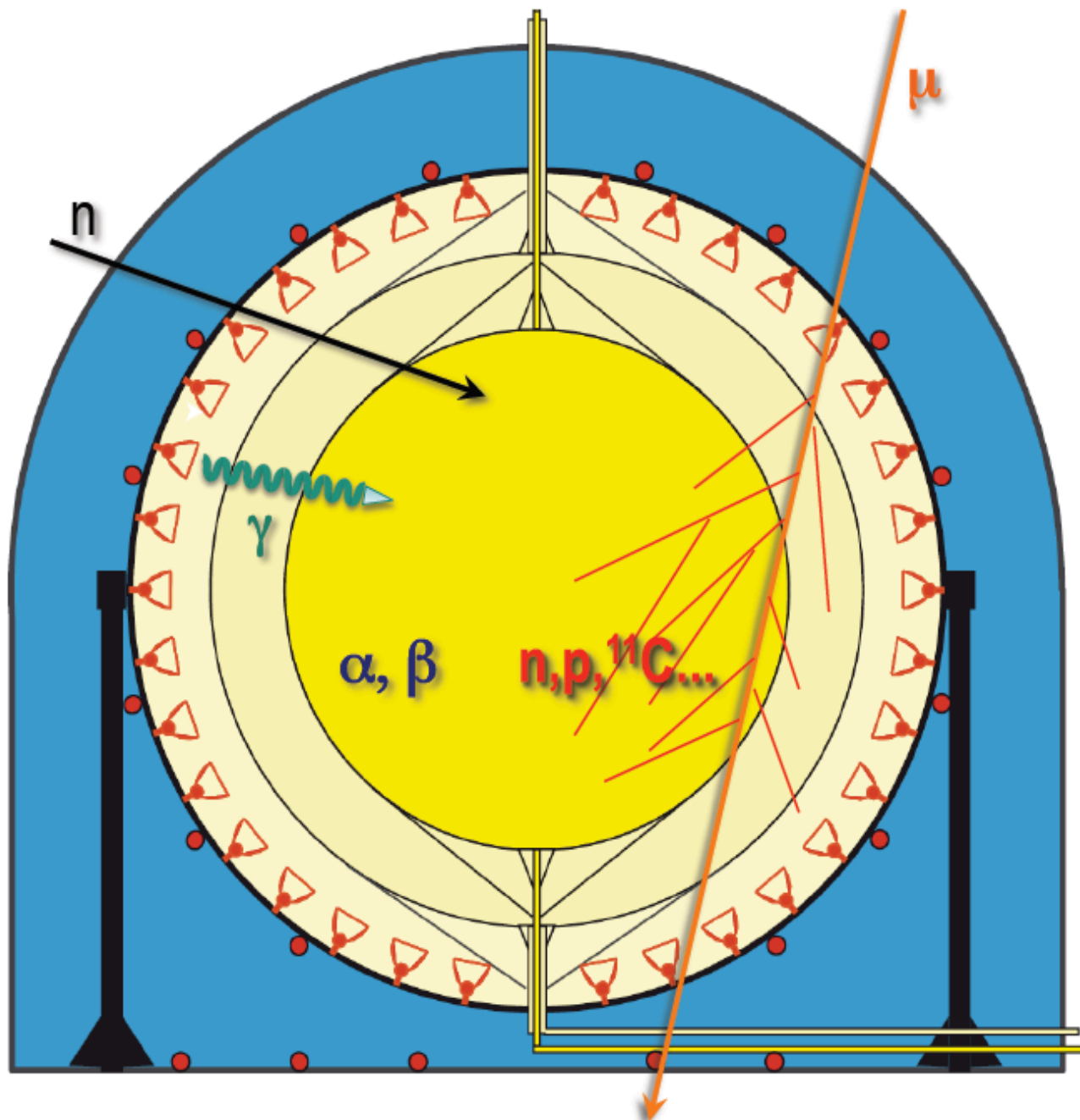
- Neutrino detection via neutrino-electron elastic scattering
- Detect scintillation light from recoiling electron
 - Good position reconstruction (10-15cm) from time-of-flight
 - Low energy threshold ($\sim 60\text{keV}$)
 - Good energy resolution ($\sim 500\text{p.e./MeV}$)
- Calorimetric measurements only, no directional sensitivity
 - Can't distinguish neutrino events from β/γ backgrounds



Neutrino Detection With Liquid Scintillator



Central Challenge: Background Reduction



Internal Radioactivity

traces of radioisotopes in the scintillator (U/Th, ${}^{40}\text{K}$)

External Gamma-Rays

from buffer, steel sphere, PMT glass (${}^{40}\text{K}$, ${}^{208}\text{Tl}$...)

Cosmic Muons

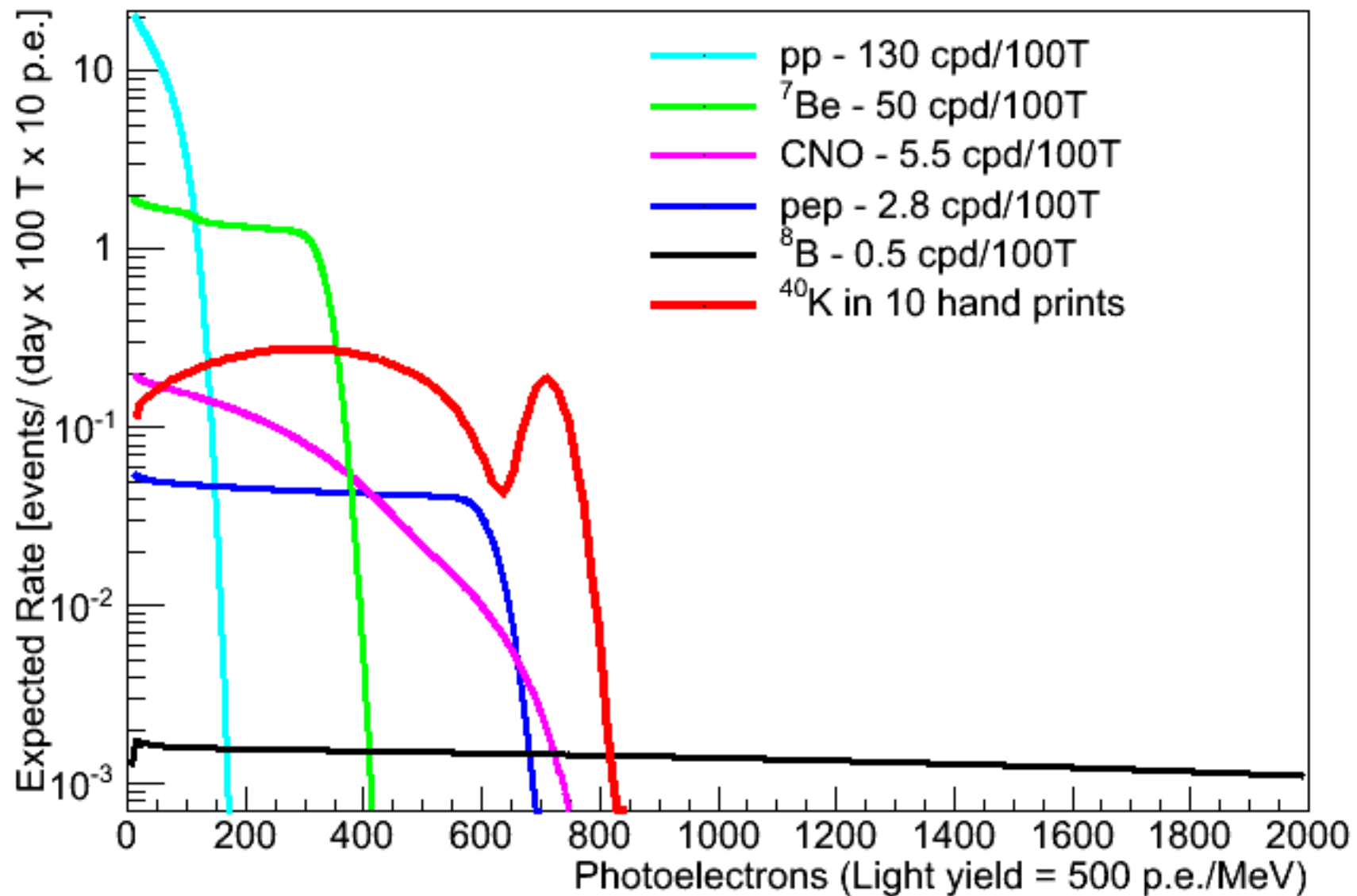
Cosmogenics

neutrons and radionuclides from muon-spallation and hadronic showers

Fast Neutrons

from external muons

Central Challenge: Background Reduction



***Borexino achieved
unprecedented low levels of
internal background.***



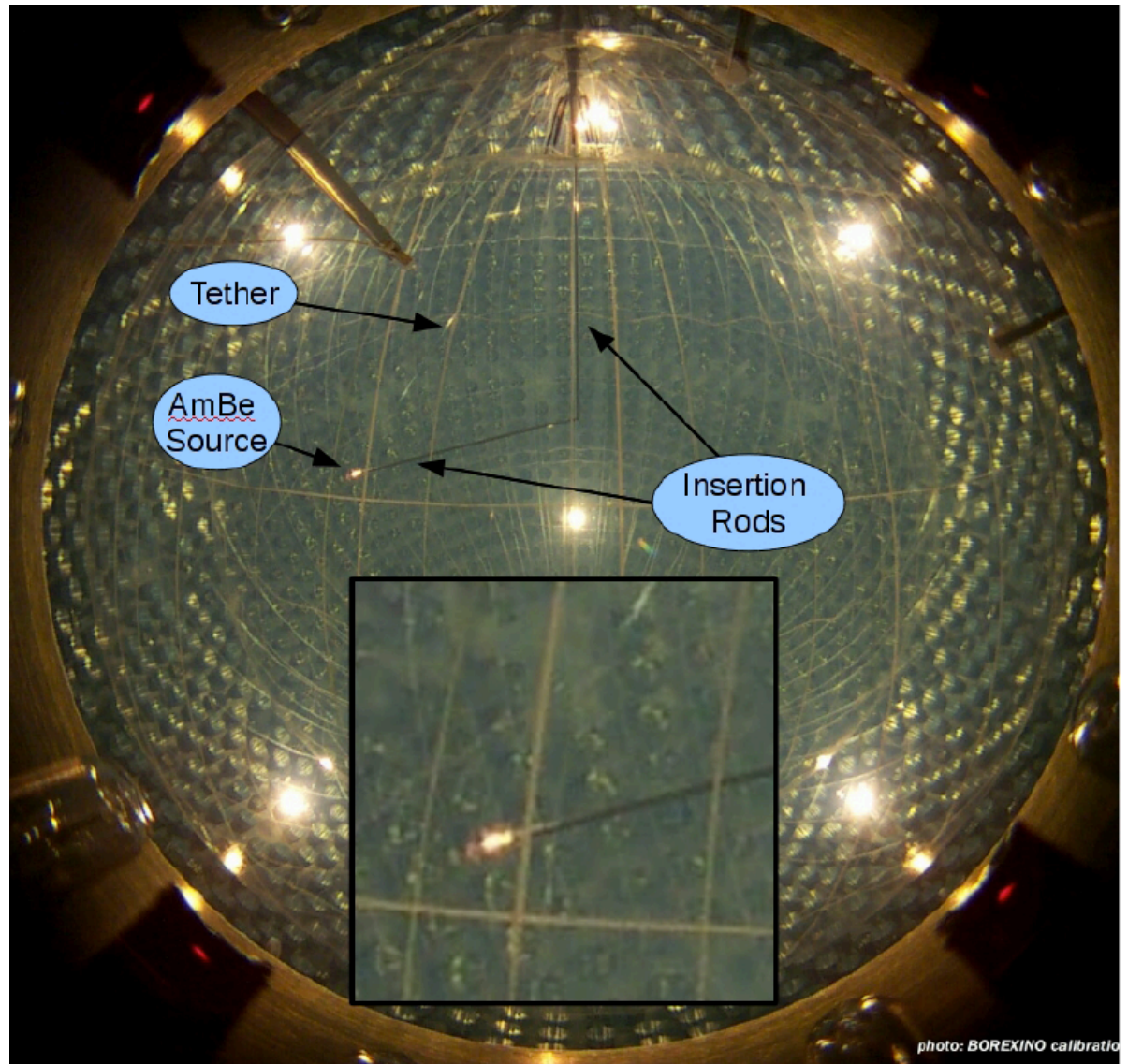
Image: Borexino Collaboration

The Counting Test Facility III

Contaminant	Source	Normal Conc.	Borexino Achieved	Reduction Method
^{14}C	Scintillator	10^{-12} g/g	10^{-18} g/g	Old oil
^{238}U	Dust	10^{-6} g/g	$\sim 5 \times 10^{-18} \text{ g/g}$	Purification
^{232}Th	Dust	10^{-6} g/g	$\sim 4 \times 10^{-18} \text{ g/g}$	Purification
^{85}Kr	Air	1 Bq/m^3	$\sim 2 \times 10^{-3} \text{ Bq/m}^3$	LAKN
^{222}Rn	Air	$20\text{-}100 \text{ Bq/m}^3$	$< 10^{-6} \text{ Bq/m}^3$	Air exclusion
K_{nat}	Dust	$\sim 10^{-3} \text{ g/g}$	$< 2 \times 10^{-19} \text{ g/g}$	Purification
μ	Cosmic	$200 \text{ s}^{-1}\text{m}^{-2}$	$10^{-10} \text{ s}^{-1}\text{m}^{-2}$	Underground, active veto

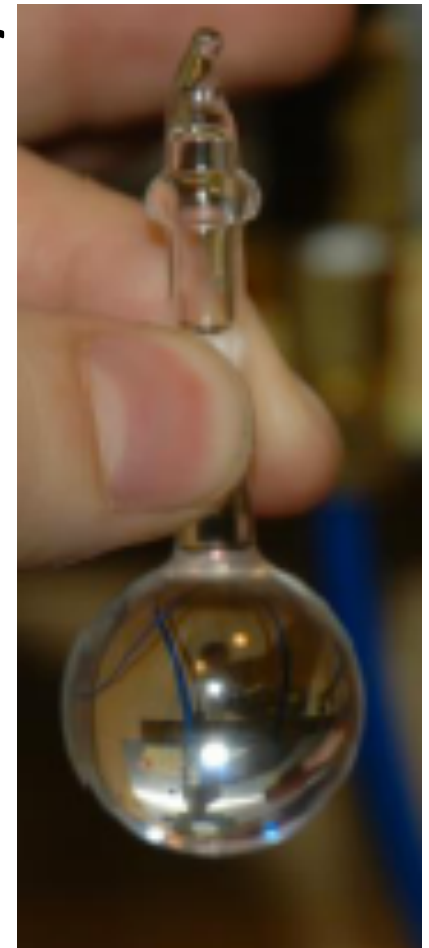
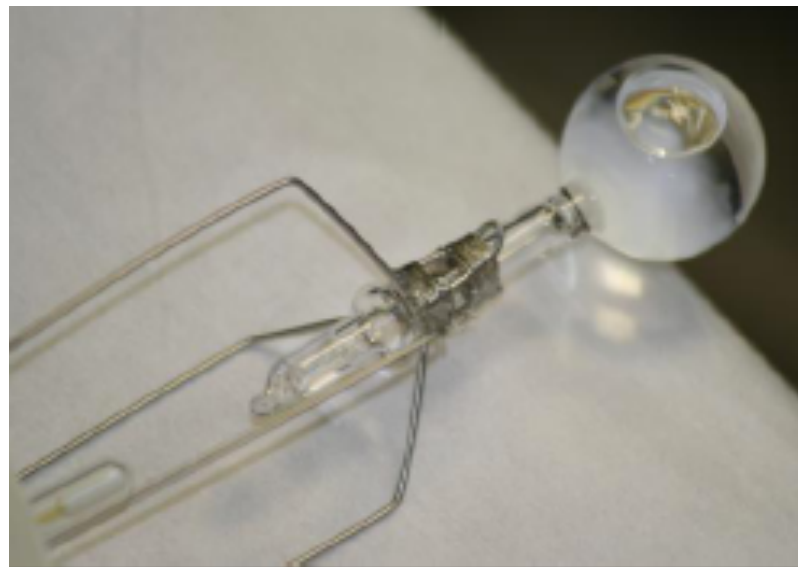
Borexino Internal Calibrations

- Study detector position and energy response by deploying radioactive and laser sources in the detector
- 3D source deployment system developed at Virginia Tech



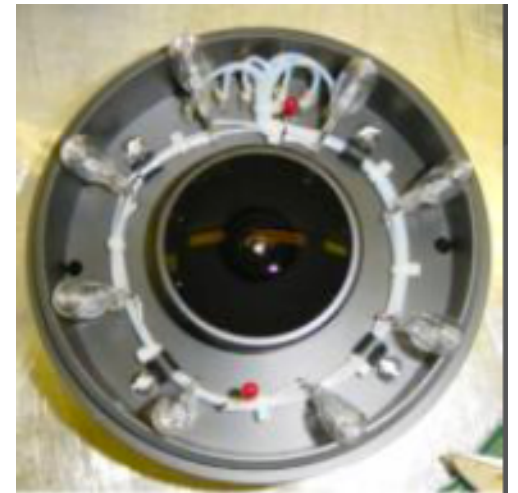
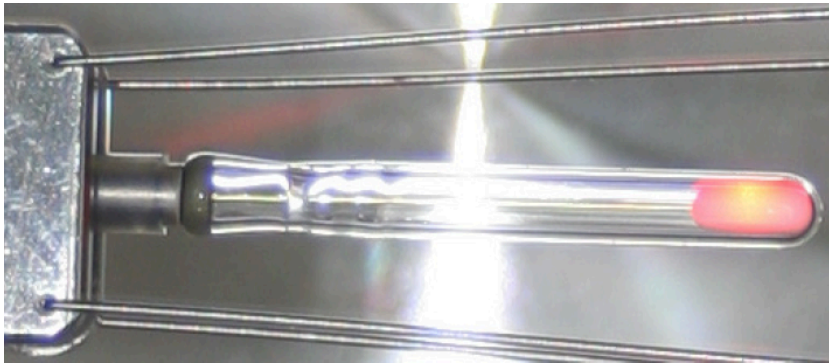
Sources

- Aqueous γ -sources in flame-sealed quartz vials
- α and β sources in vials of scintillator
- Encapsulated AmBe



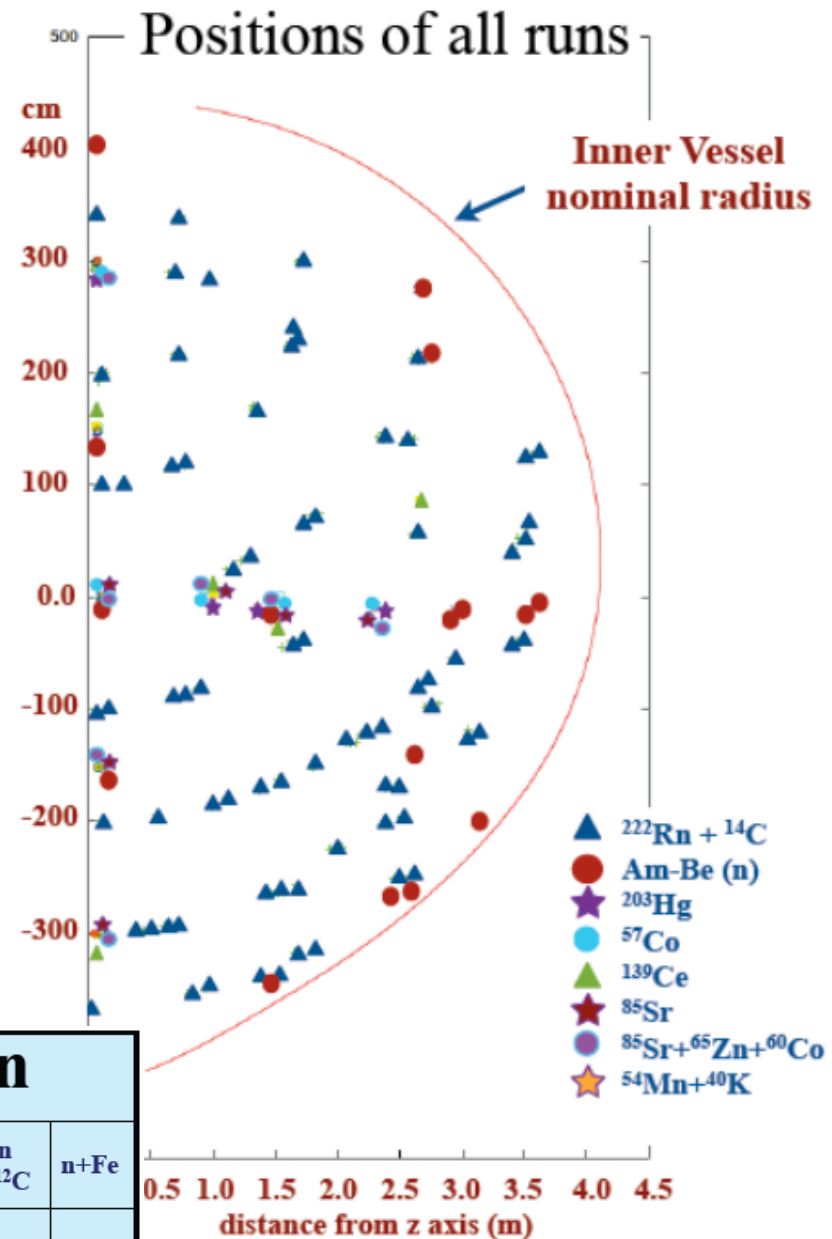
Determining Source Location

- Red light from a diffuser on the source mount recorded by 7 CCD cameras
- Designed to measure source position to 2 cm

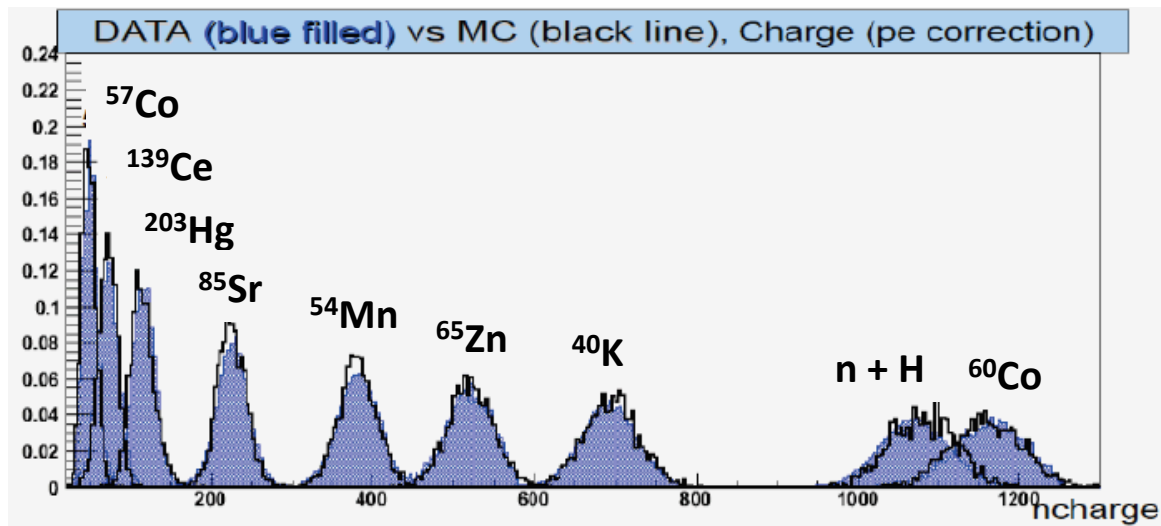


Borexino Calibration Campaigns

- 4 major calibration campaigns (Oct '08, Jan '09, June '09, July '09)
- 35 livedays of calibration data with sources in 295 positions



	γ								β		α	n		
	^{57}Co	^{139}Ce	^{203}Hg	^{85}Sr	^{54}Mn	^{65}Zn	^{60}Co	^{40}K	^{14}C	^{214}Bi	^{214}Po	n-p	$\frac{n}{+^{12}\text{C}}$	n+Fe
energy (MeV)	0.122	0.165	0.279	0.514	0.834	1.1	1.1, 1.3	1.4	0.15	3.2	7.8	2.226	4.94	~7.5

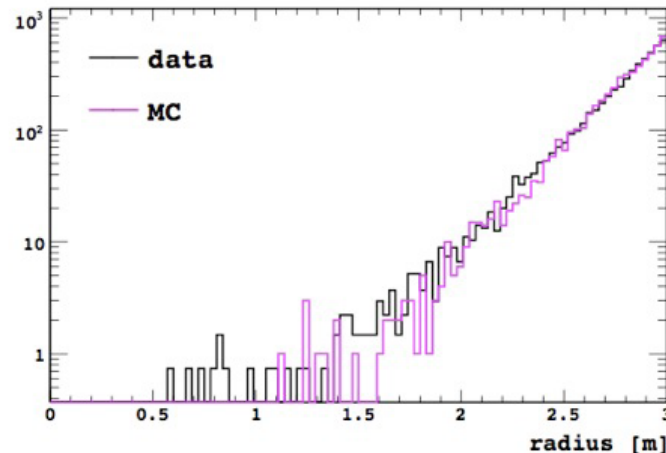
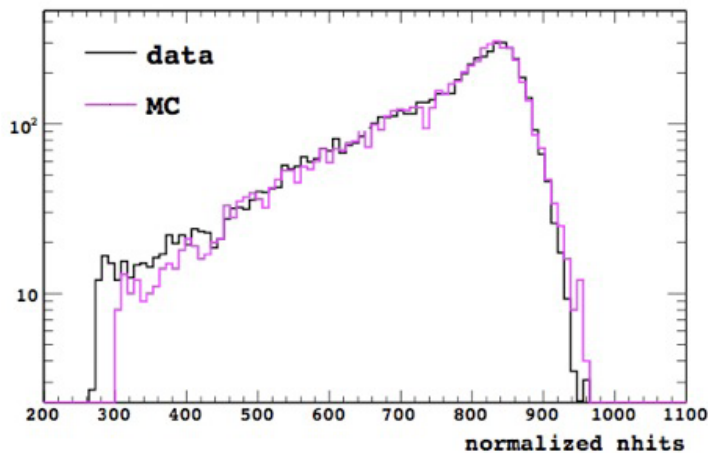
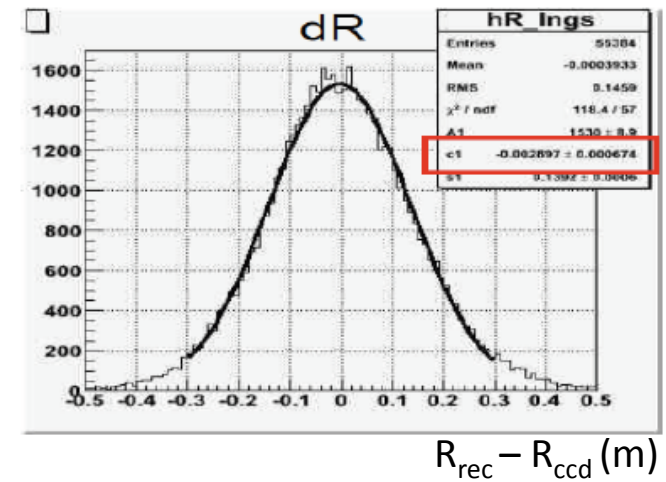
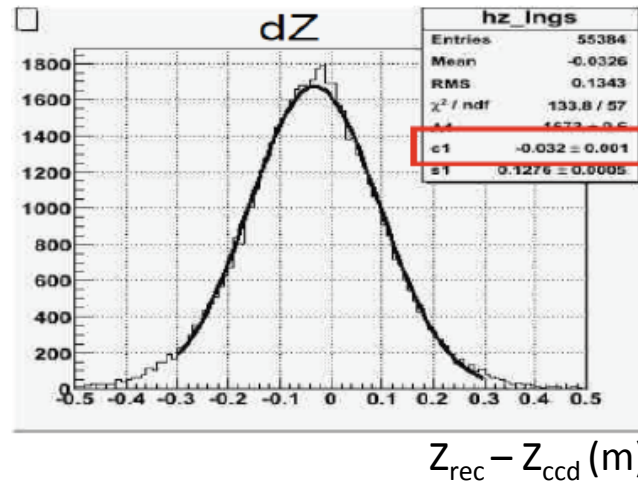


Study light yield, quenching, position variation.

→ *Data-MC mean light yields agree to 1% in F.V.*

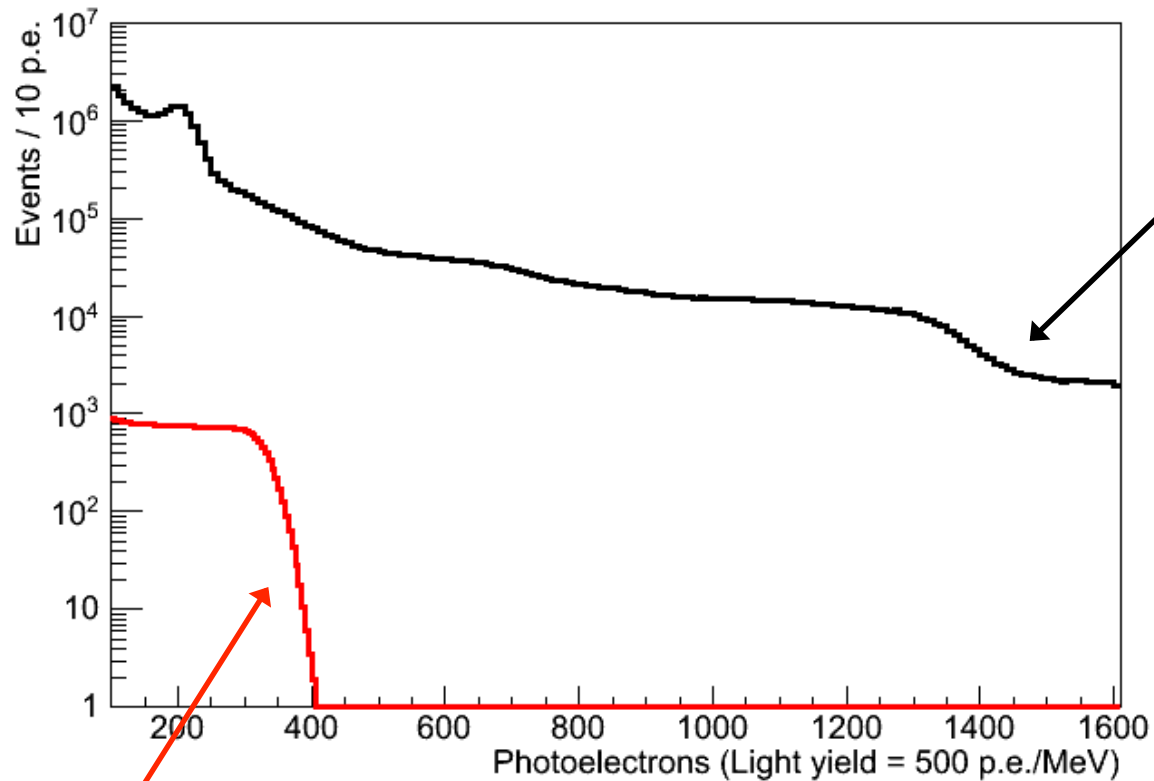
Measure position resolution: 10 – 12 cm

→ *Fiducial Volume:*
 $1.0^{+0.005}_{-0.013}$



Confirm energy/radial PDF for external background.

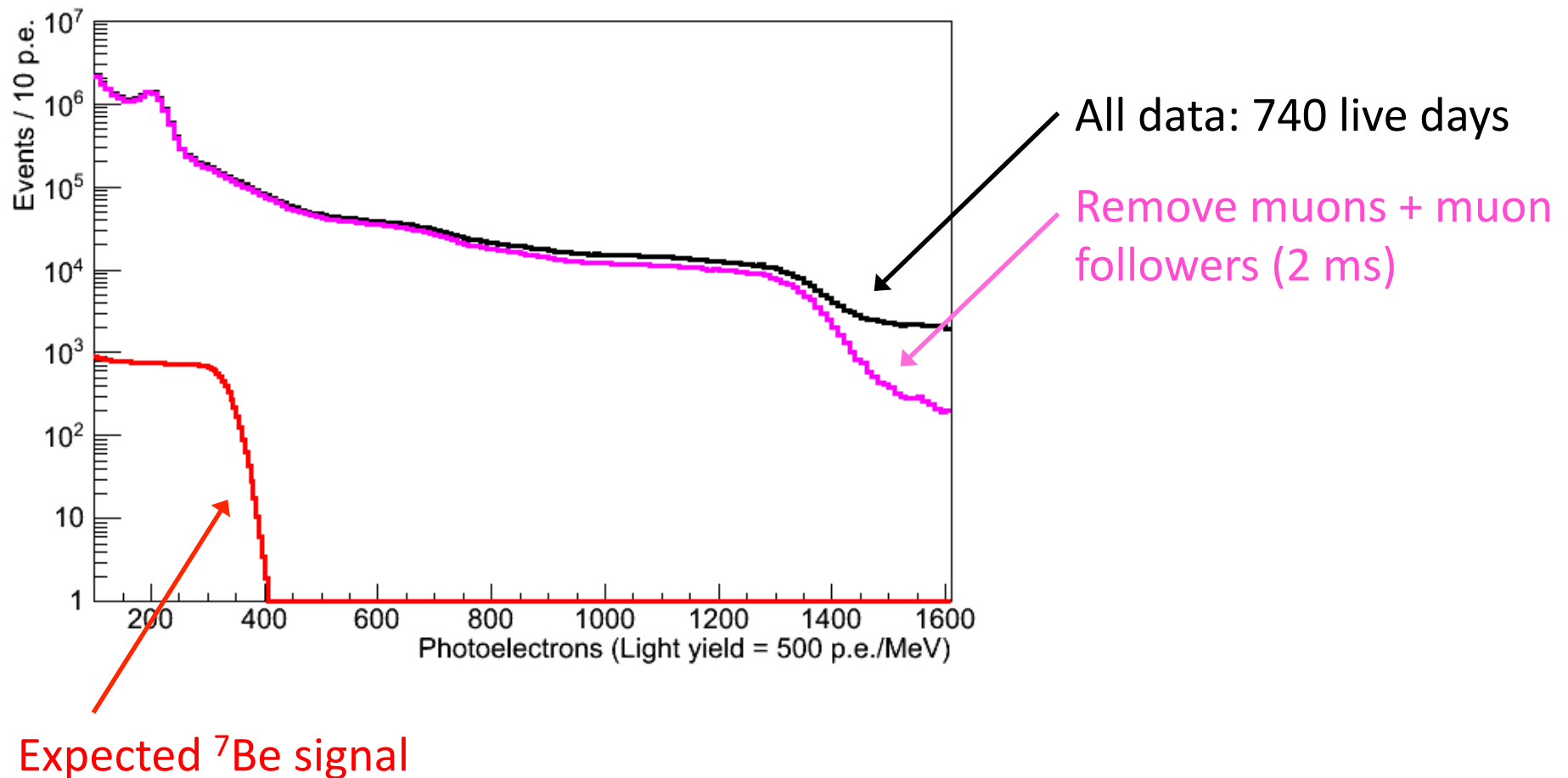
Borexino Data



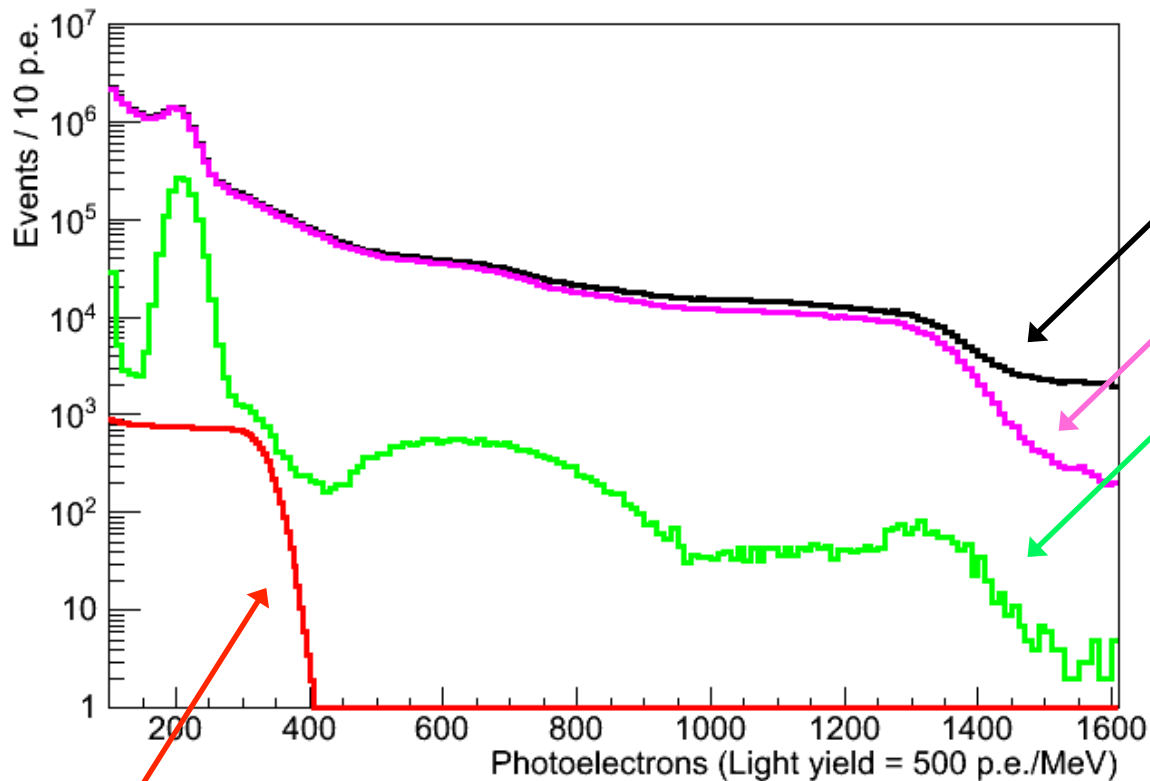
All data: 740 live days

Expected ^7Be signal

Borexino Data



Borexino Data



Expected ^7Be signal

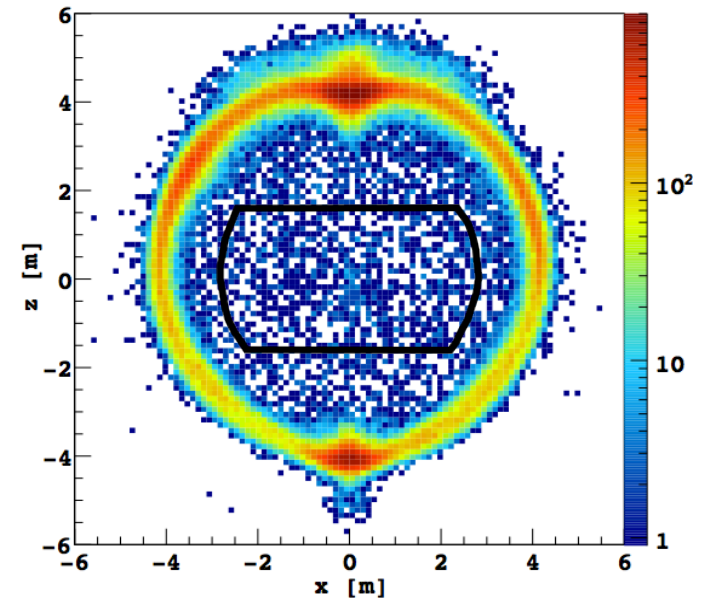
All data: 740 live days

Remove muons + followers

Fiducial Volume + high level

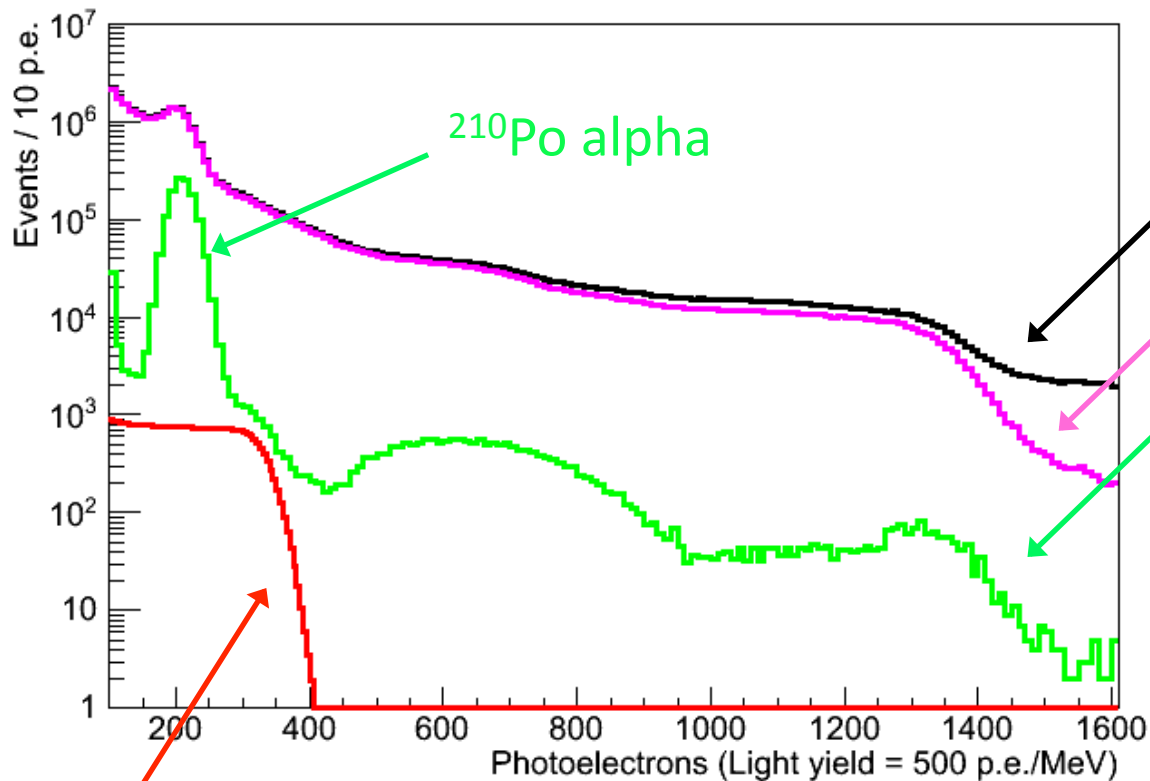
$R < 3.02\text{m}$

$|z| < 1.67\text{m}$



Fiducial mass = 75.6 tonnes

Borexino Data



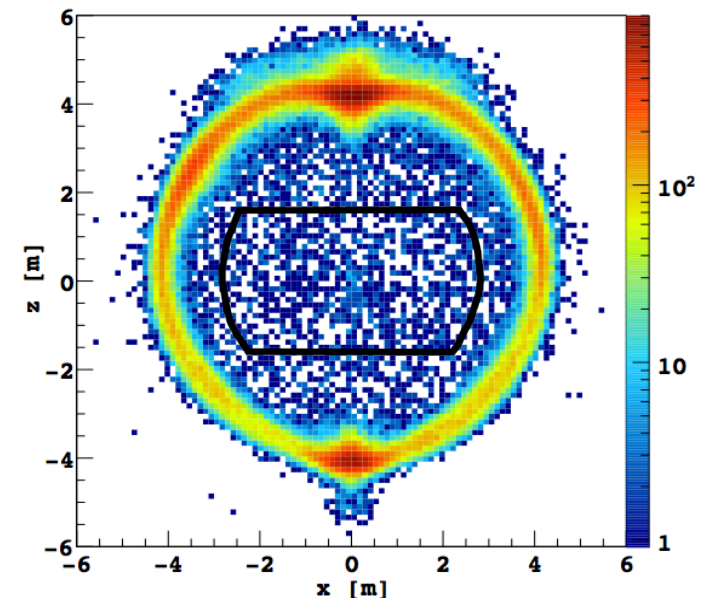
All data: 740 live days

Remove muons + followers

Fiducial Volume + high level

$R < 3.02\text{m}$

$|z| < 1.67\text{m}$



Fiducial mass = 75.6 tonnes

Pulse Shape Discrimination

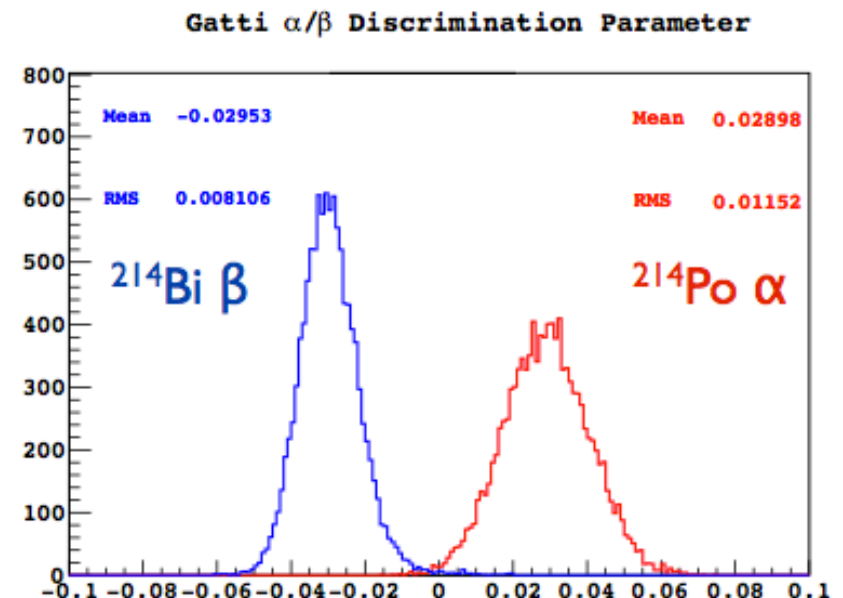
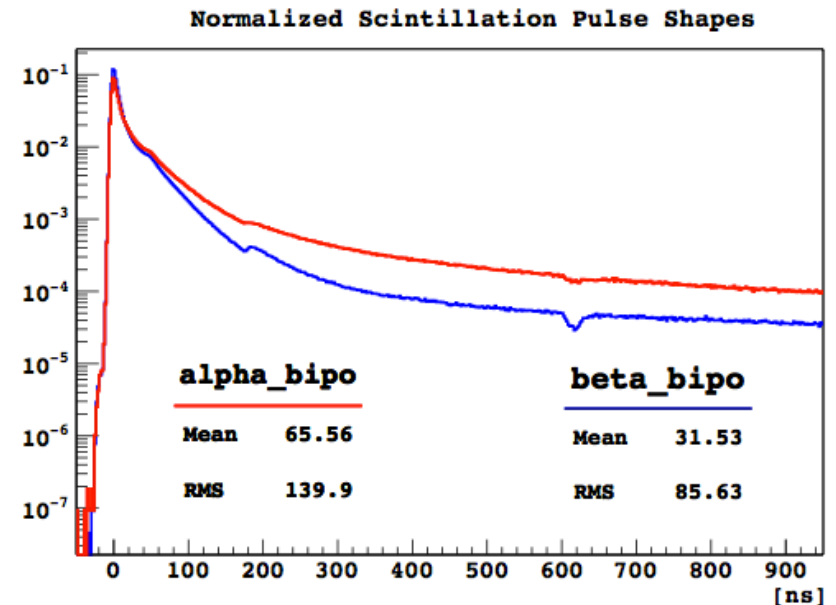
- Particles with higher ionization density produce more slow light
- Separate by comparing to reference α and β events using the “Gatti Parameter”

$$g_e \equiv \sum_{t=0}^{\infty} e[t] \cdot w[t]$$

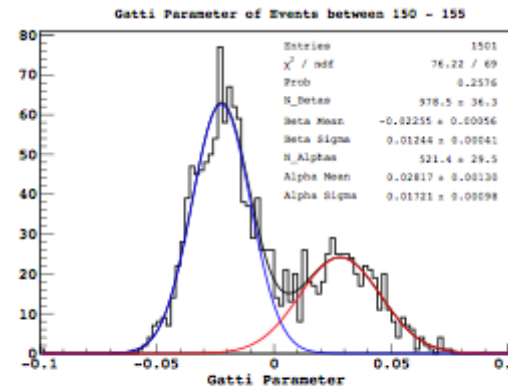
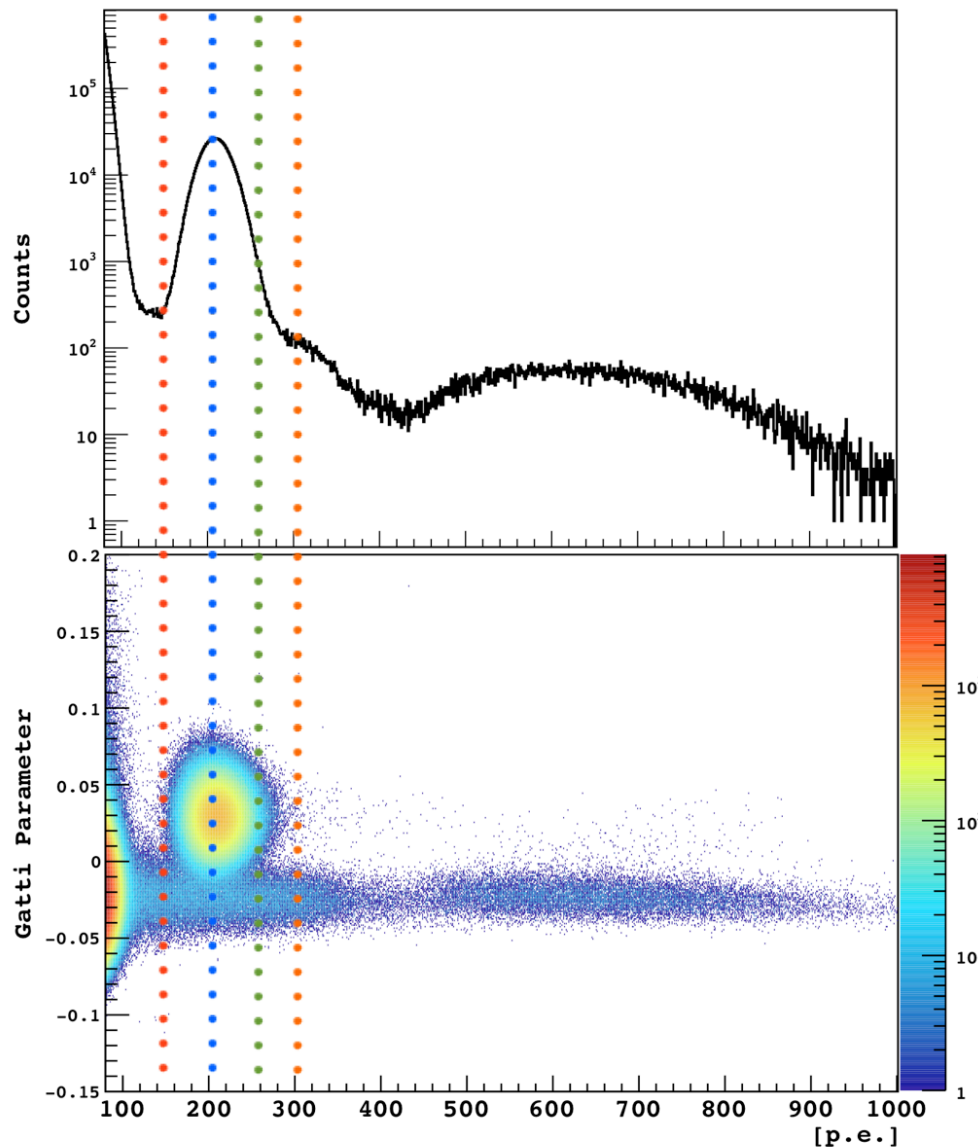
$$w[t] \equiv \frac{r_{\alpha}[t] - r_{\beta}[t]}{r_{\alpha}[t] + r_{\beta}[t]}$$

$e[t]$: Event Time Profile

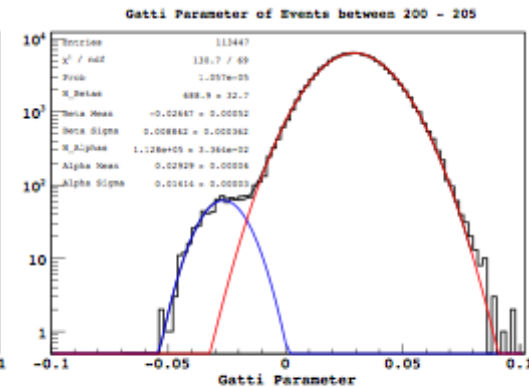
$r_{\alpha/\beta}[t]$: Reference time profile



Alpha Statistical Subtraction



150 p.e.

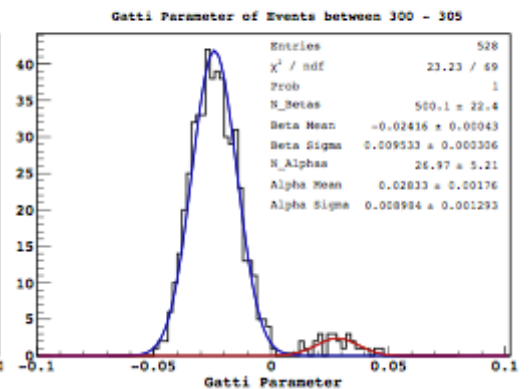
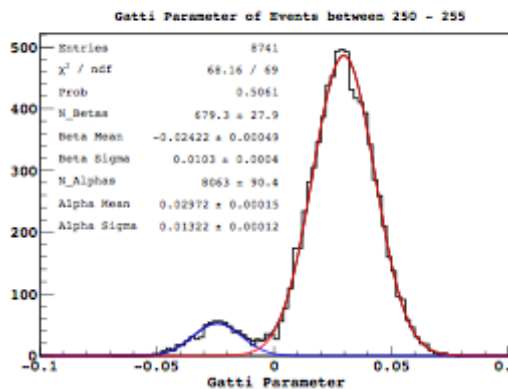


200 p.e.

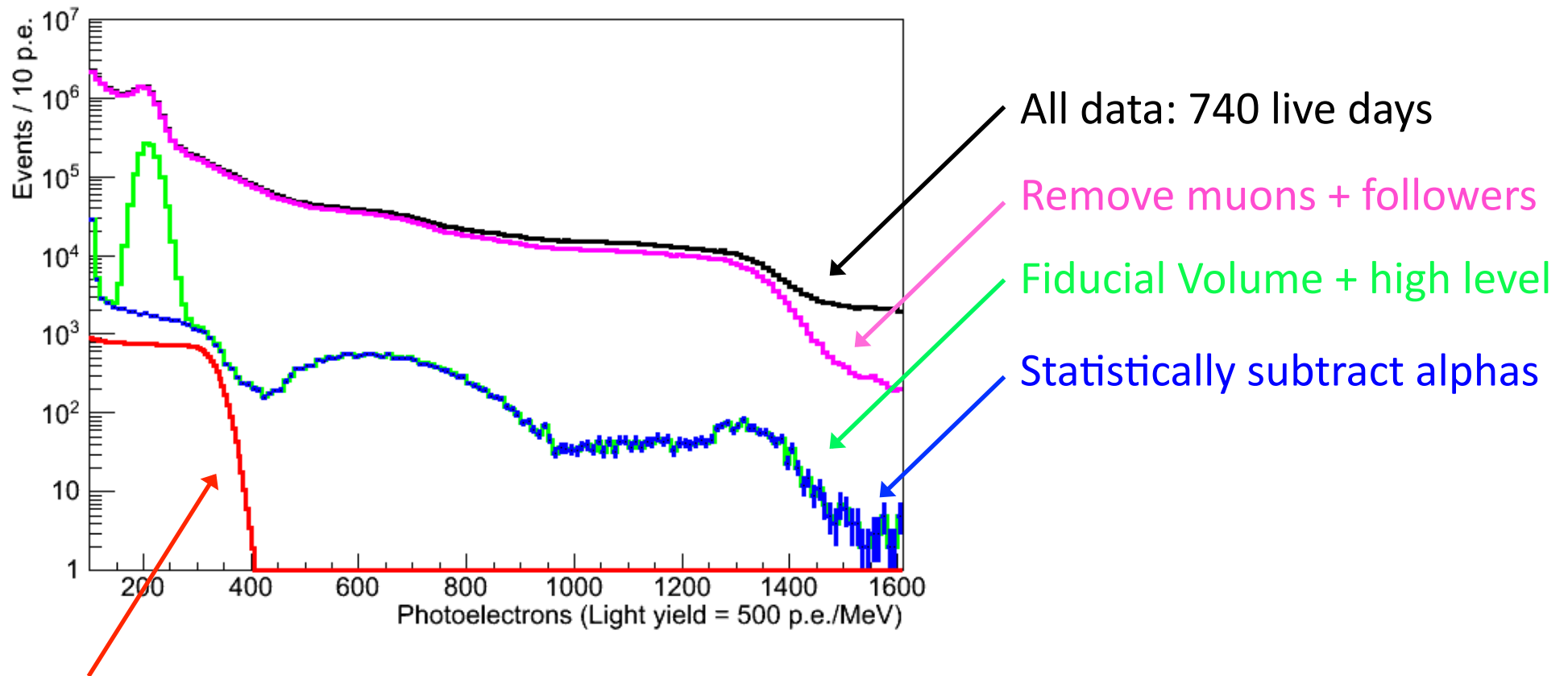
Fit each energy bin with the
sum of two Gaussians

250 p.e.

300 p.e.

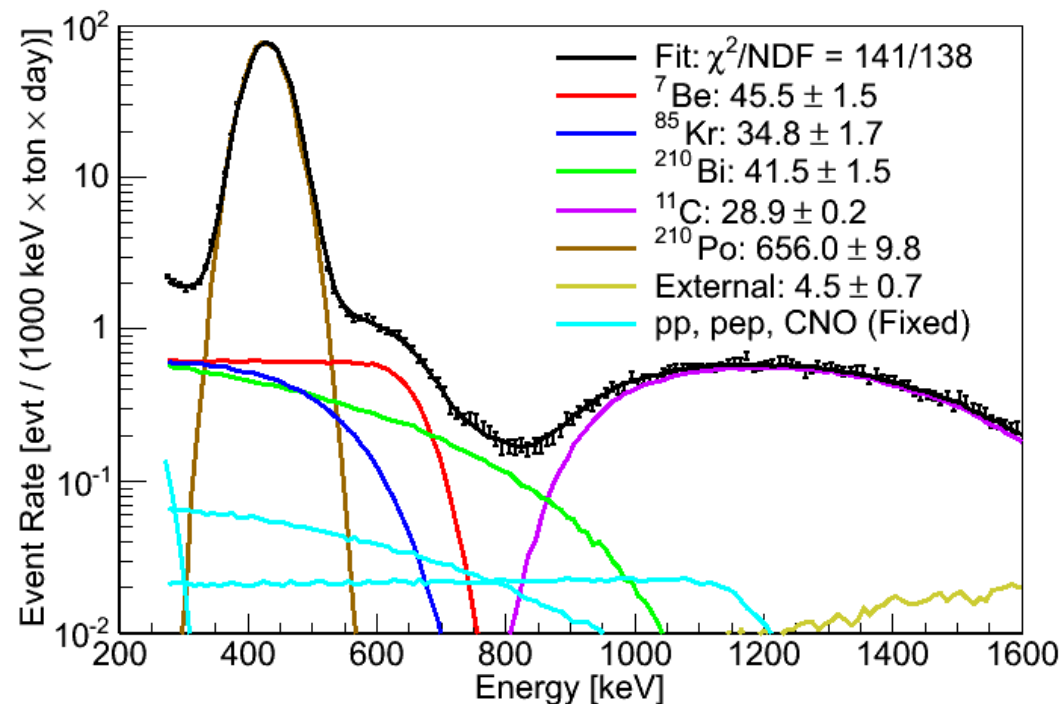


Borexino Data



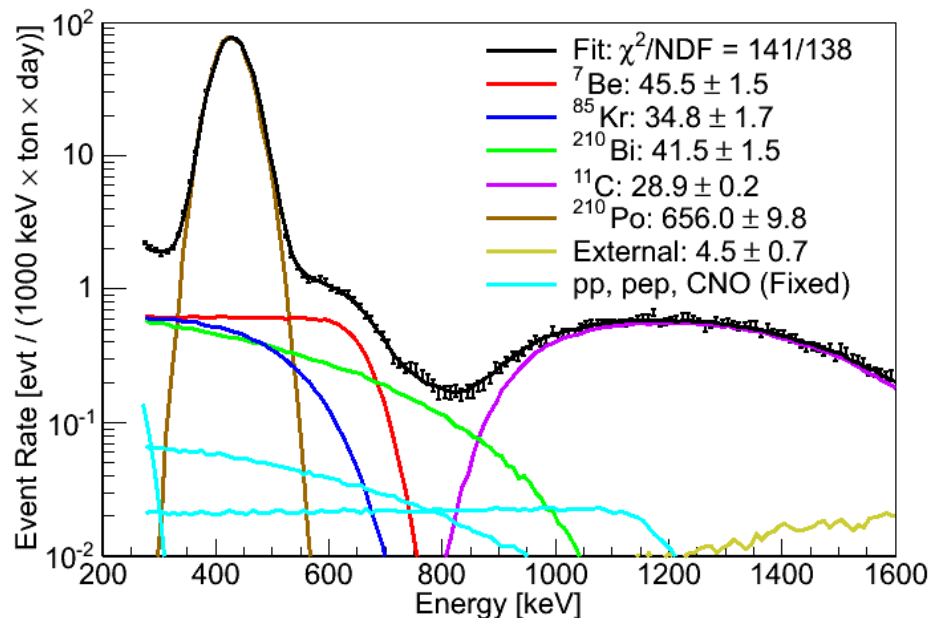
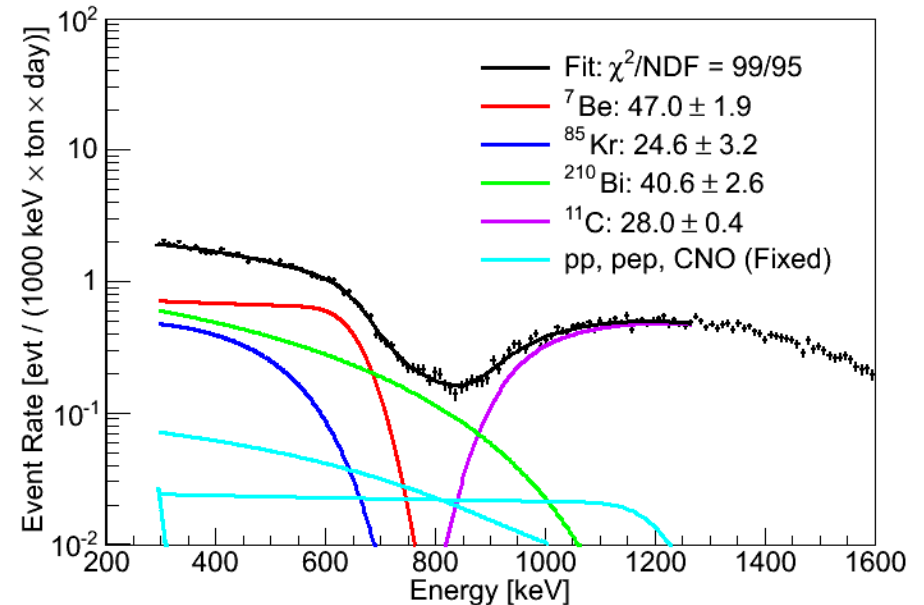
^7Be Signal Extraction

- 1-D binned likelihood fits in energy
- ^7Be , ^{210}Po , ^{85}Kr , ^{11}C , ^{210}Bi weights floated
- pp , pep , ^8B , and CNO fixed to SSM fluxes + LMA
- ^{222}Rn , ^{218}Po , and ^{214}Pb weights constrained by ^{214}Bi - ^{214}Po co-incidence



^7Be Signal Extraction

- Analytical fits
 - Analytic description of detector response based on calibration data
 - Float energy scale, resolution in fit



- Monte Carlo fits
 - Tune MC detector response on calibration data
 - Energy scale, resolution fixed in fit
 - Include external backgrounds, increase fit range

Precision ^7Be Flux Result

Borexino 862 keV ^7Be counting rate: $46.0 \pm 1.5_{\text{stat}}^{+1.5}_{-1.6 \text{ sys}} / (\text{d } 100\text{T})$

$$\longrightarrow \Phi_{^7\text{Be}} = (4.84 \pm 0.24) \times 10^9 \text{ cm}^{-2}\text{s}^{-1} \quad \longrightarrow P_{\text{ee}}(862 \text{ keV}) = 0.51 \pm 0.07$$

Systematics

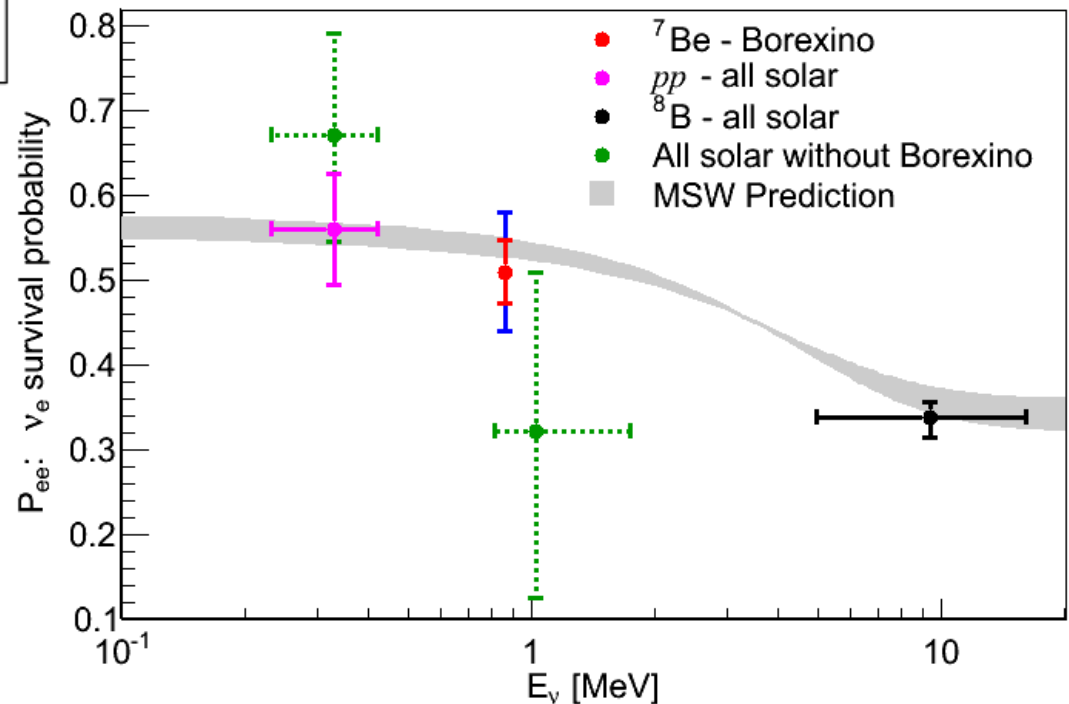
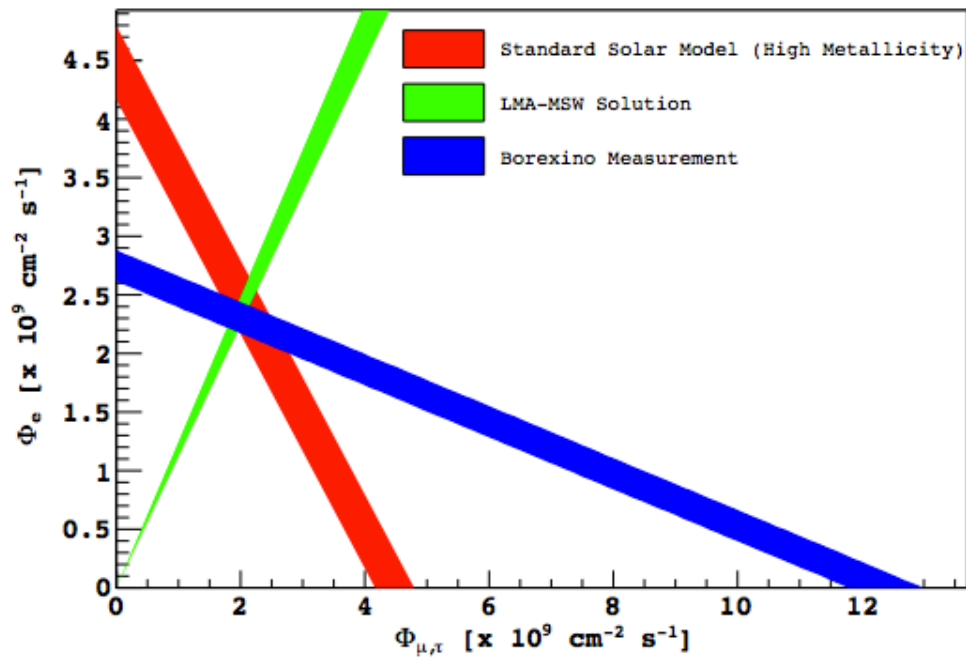
Trigger Efficiency	0.1%
Scintillator Density	0.05%
Livetime	0.04%
Cut Sacrifice	0.1%
Fiducial Mass	$+0.5\%$ -1.3%
Energy Scale	2.7%
Fit Methods	2.0%
Total	$+3.4\%$ -3.6%

Previously:

Systematics

Scintillator Density	0.2%
Livetime	0.1%
Cut Sacrifice	0.3%
Fiducial Mass	6.0%
Detector Response	6.0%
Total	8.5%

Precision ^7Be Flux Result



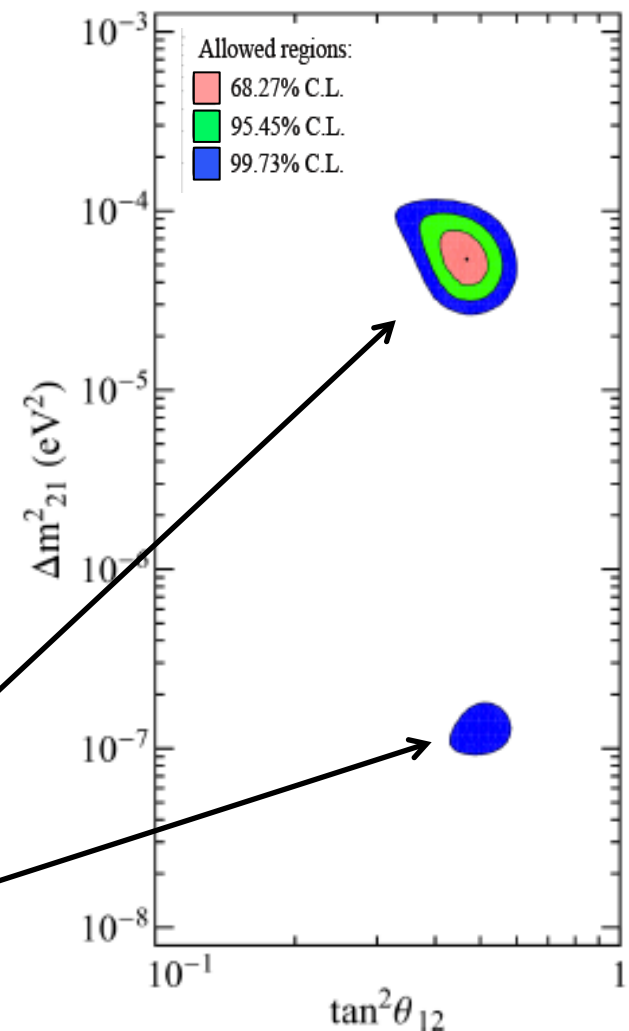
^7Be Day-Night Effect

- As solar neutrinos (adiabatically) enter the earth, ν_e can be coherently regenerated
- Size of the effect depends on mixing parameters, can cause the effective day and night neutrino fluxes to be different

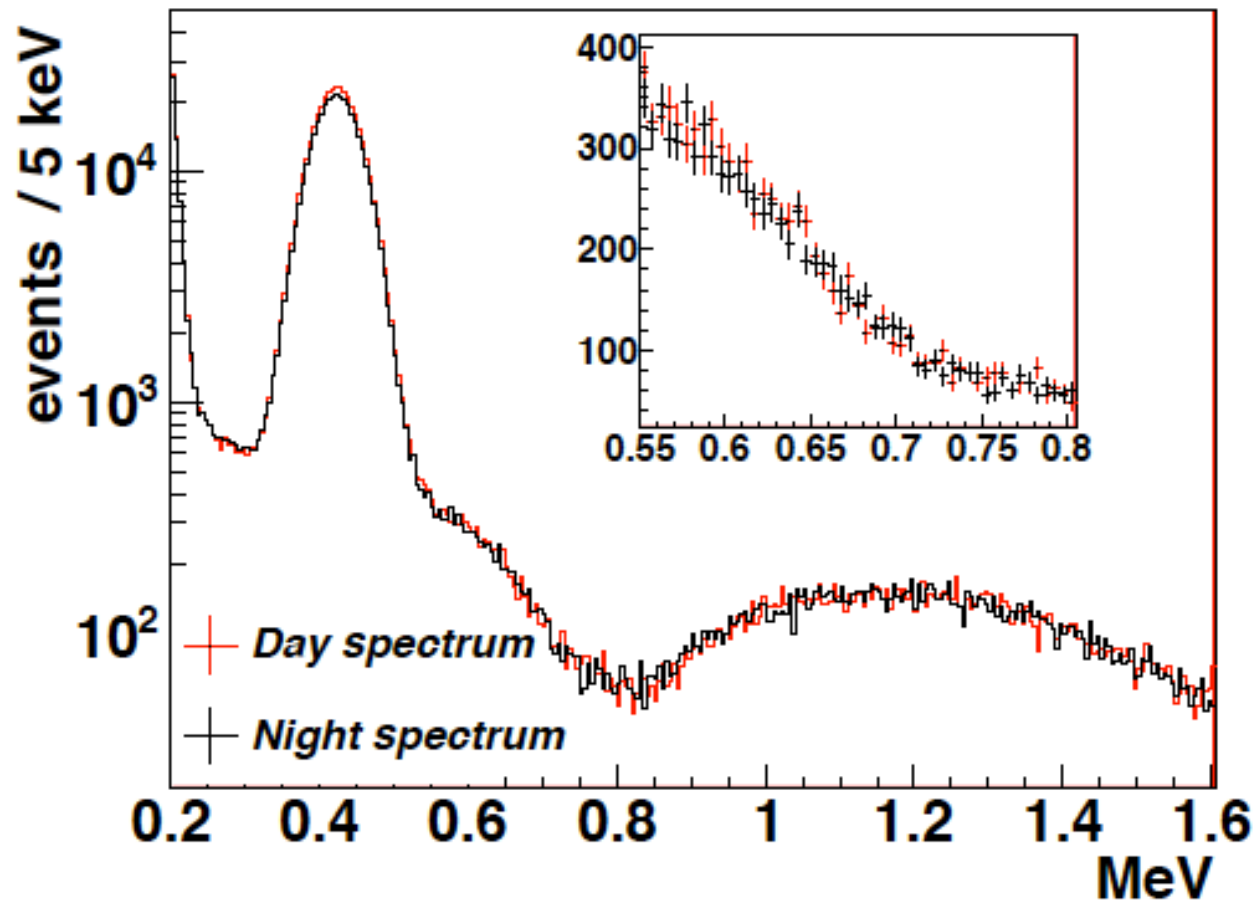
$$A_{dn} = 2 \frac{R_n^{^7\text{Be}} - R_d^{^7\text{Be}}}{R_n^{^7\text{Be}} + R_d^{^7\text{Be}}} = \frac{R_{diff}}{R}$$

Model	Predicted A_{dn} (862 keV)
LMA	<0.001
LOW	0.11 - 0.80
MaVaN	~ 0.20

Global Solar without
Borexino



^7Be Day-Night Asymmetry Search I

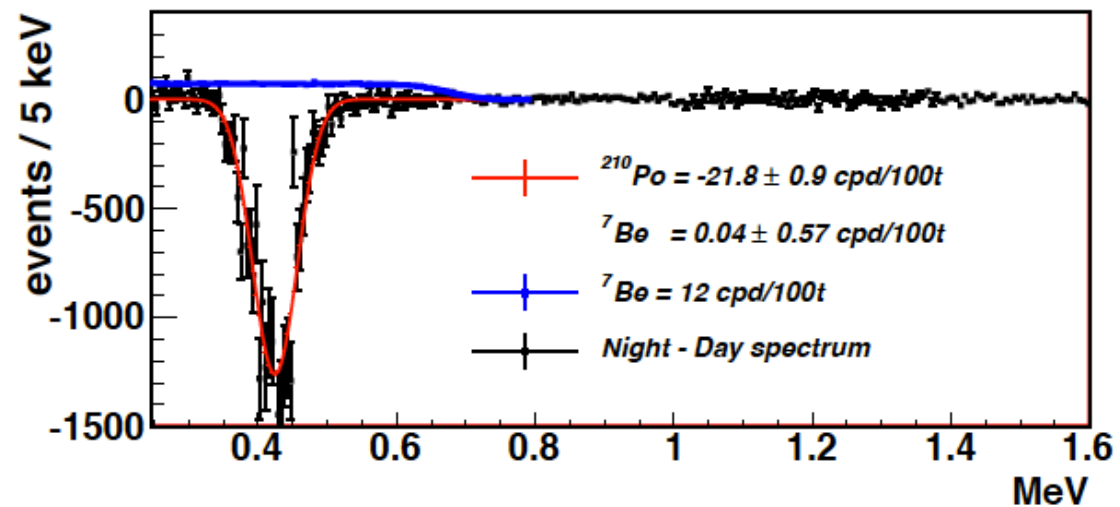


- Fit the day and night spectra separately

→ $A_{\text{dn}}(862 \text{ keV}): 0.007 \pm 0.073$

^7Be Day-Night Asymmetry Search II

- Normalize the day and night spectra to the day livetime
- Fit the difference for ^7Be and ^{210}Po (decay maps to day-night effect)
- More precise result by assuming backgrounds are day-night invariant

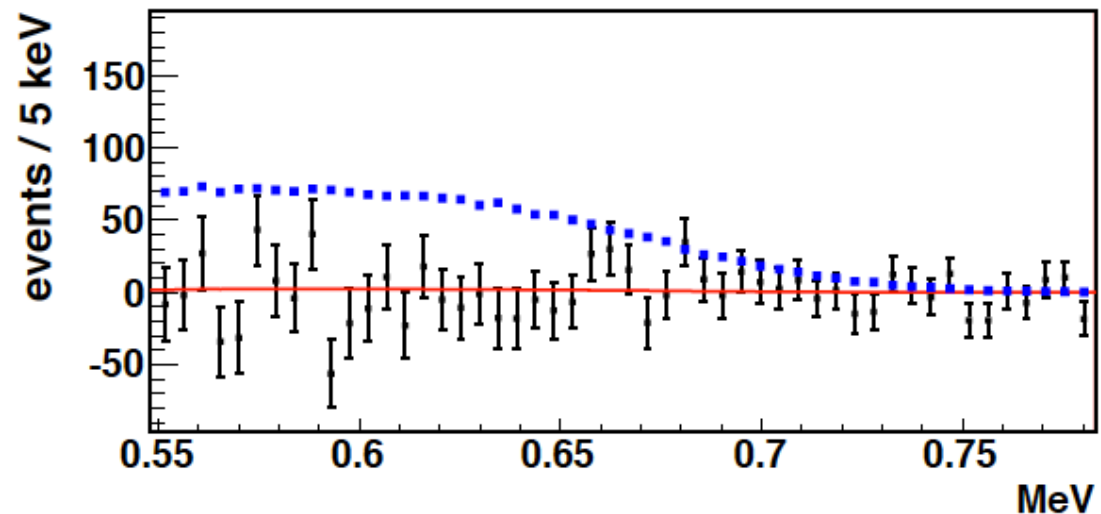


$$A_{\text{dn}}(862 \text{ keV}): 0.001 \pm 0.012_{\text{stat}} \pm 0.007_{\text{sys}}$$

Source of error	Error on A_{dn}
Live-time	$< 5 \cdot 10^{-4}$
Cut efficiencies	0.001
Variation of ^{210}Bi with time	± 0.005
Fit procedure	± 0.005
Total systematic error	0.007

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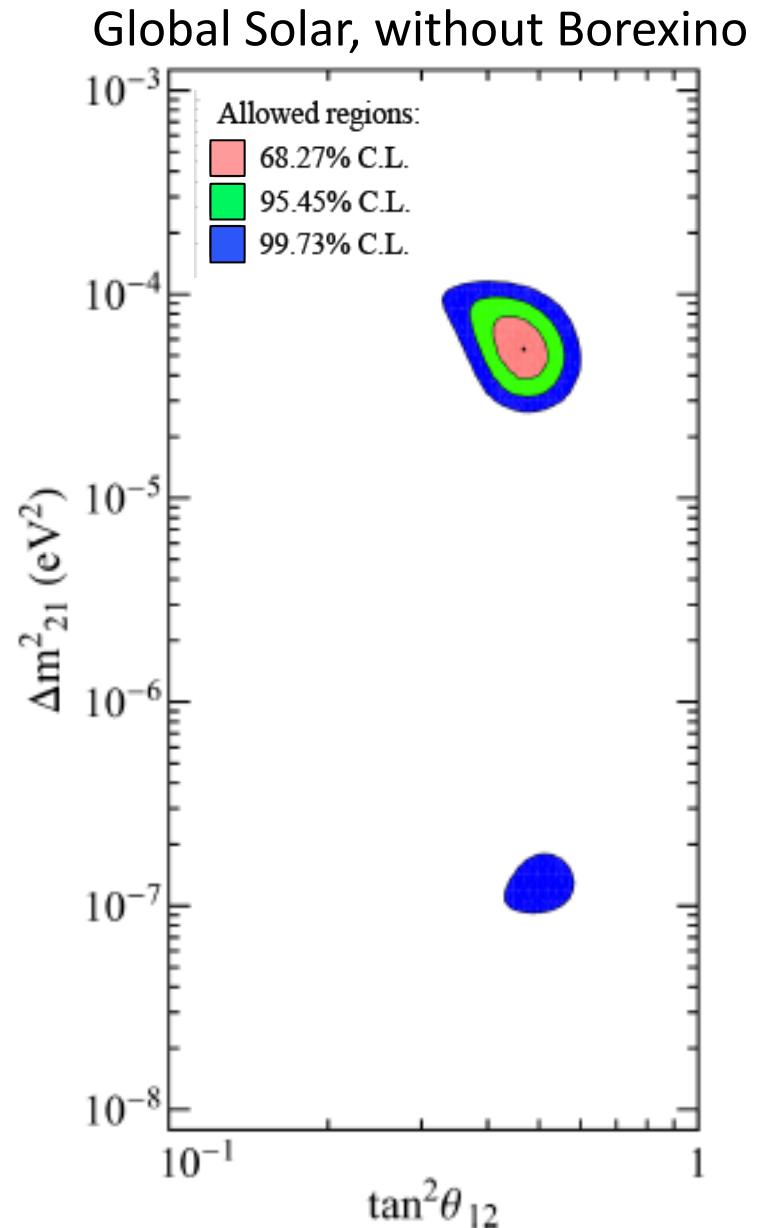


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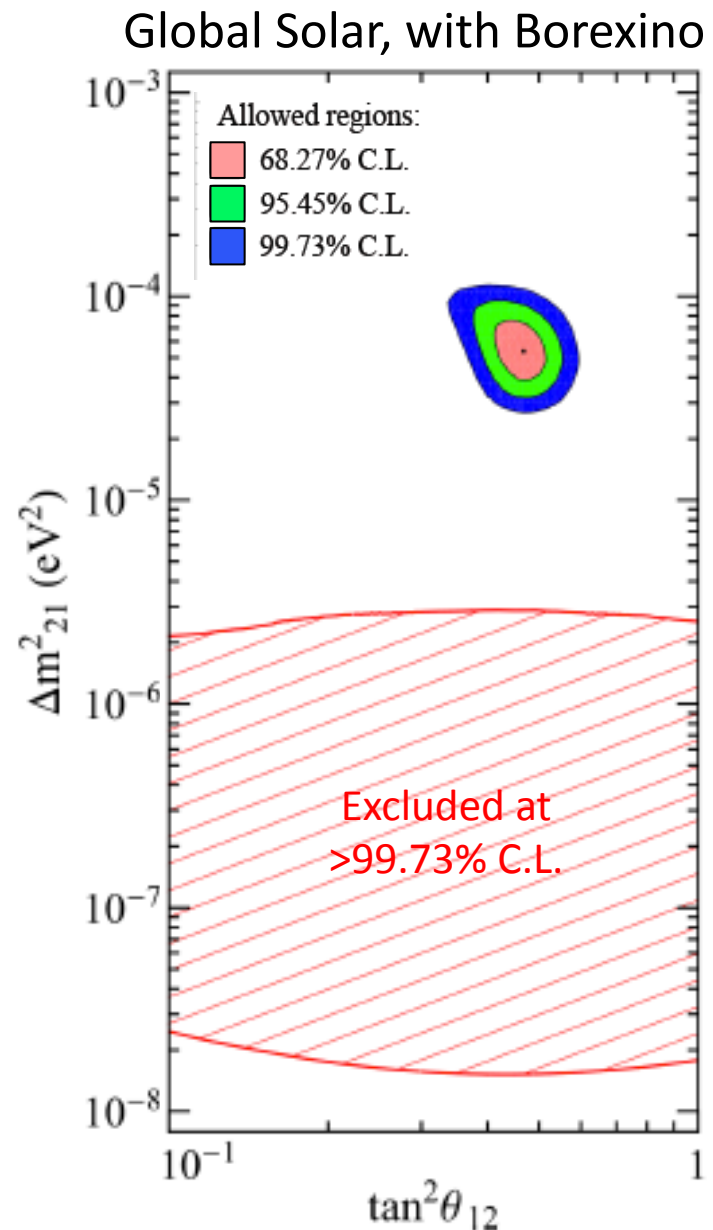
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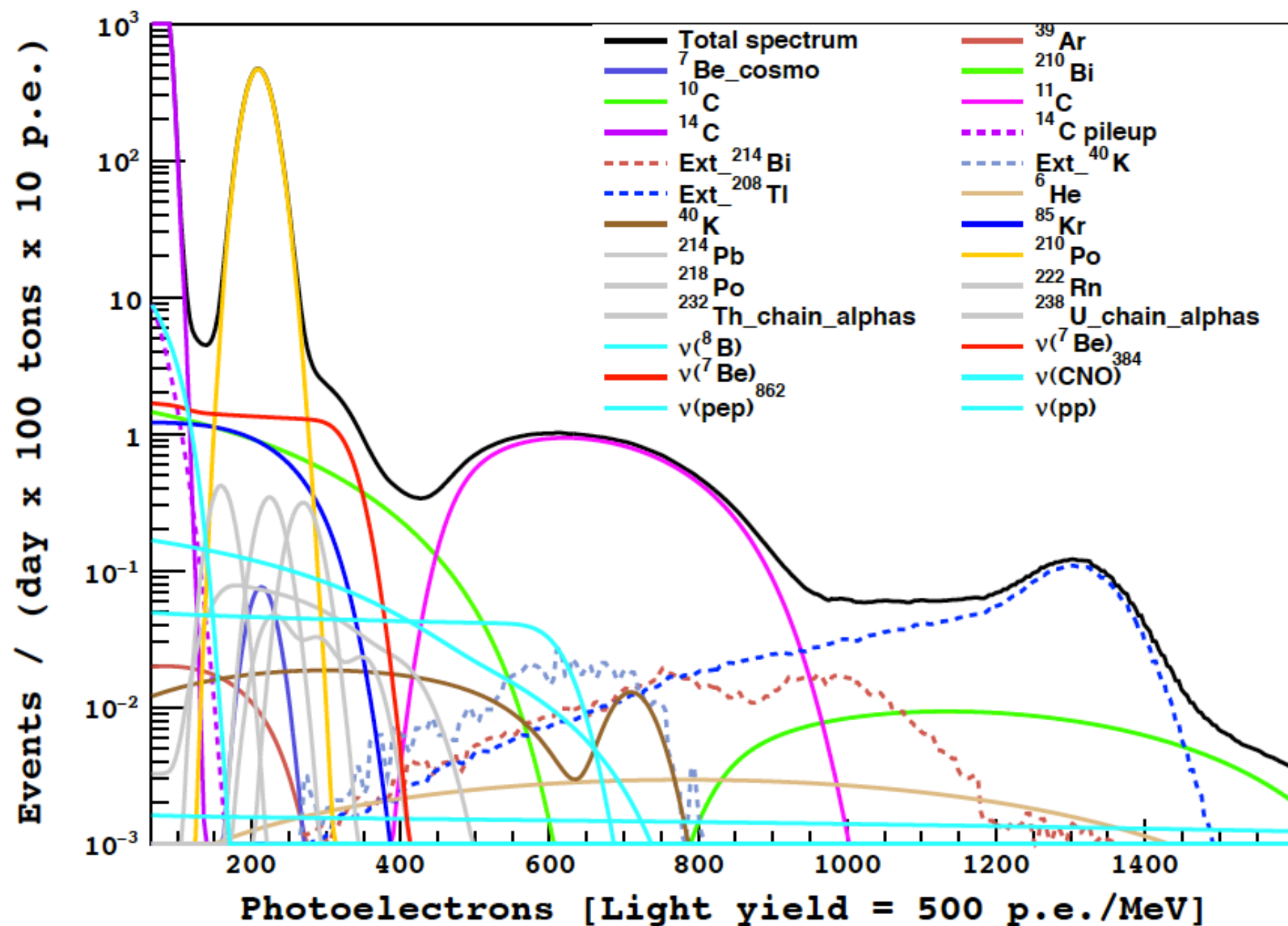


^7Be Day-Night Asymmetry Search II

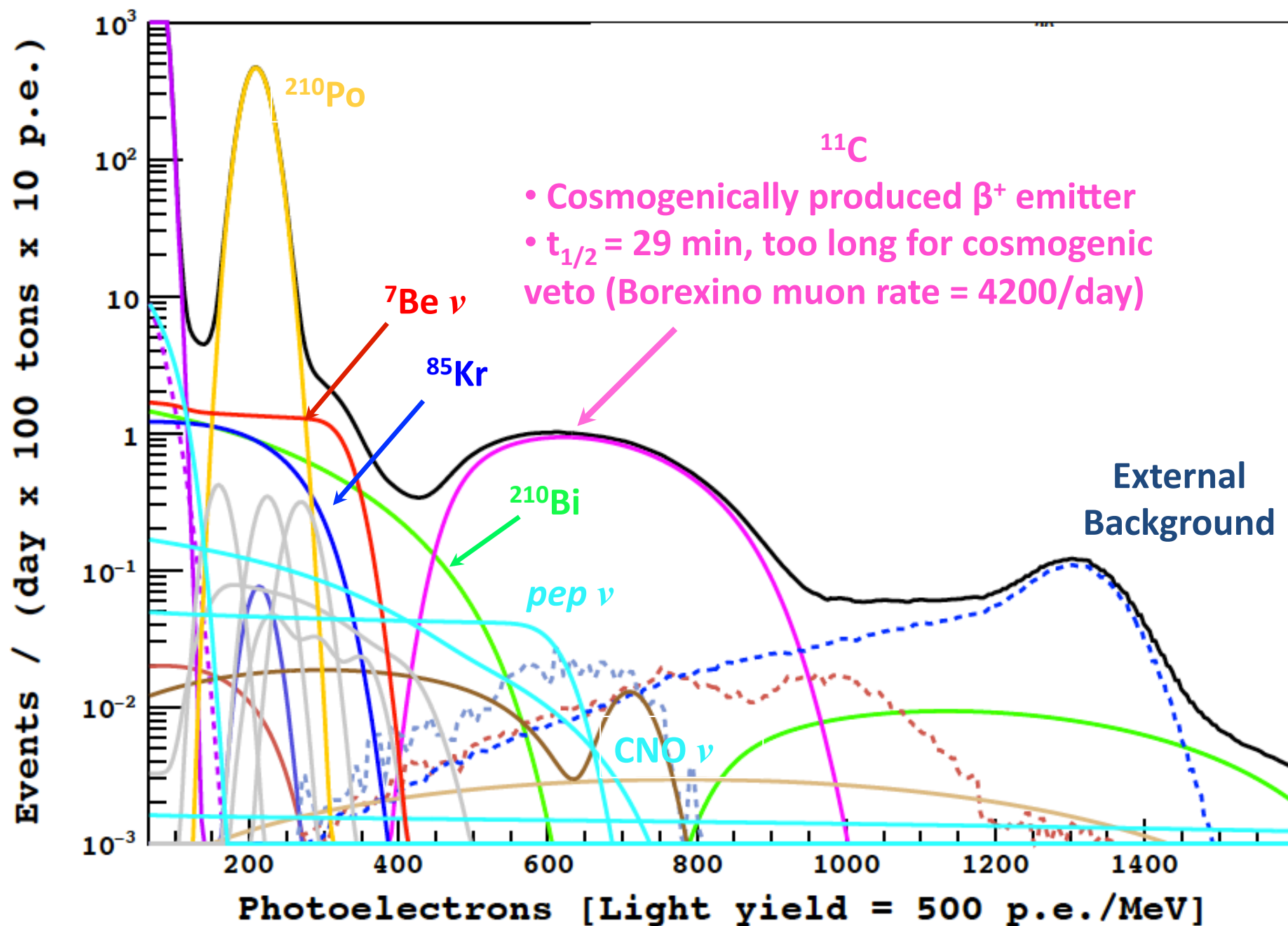
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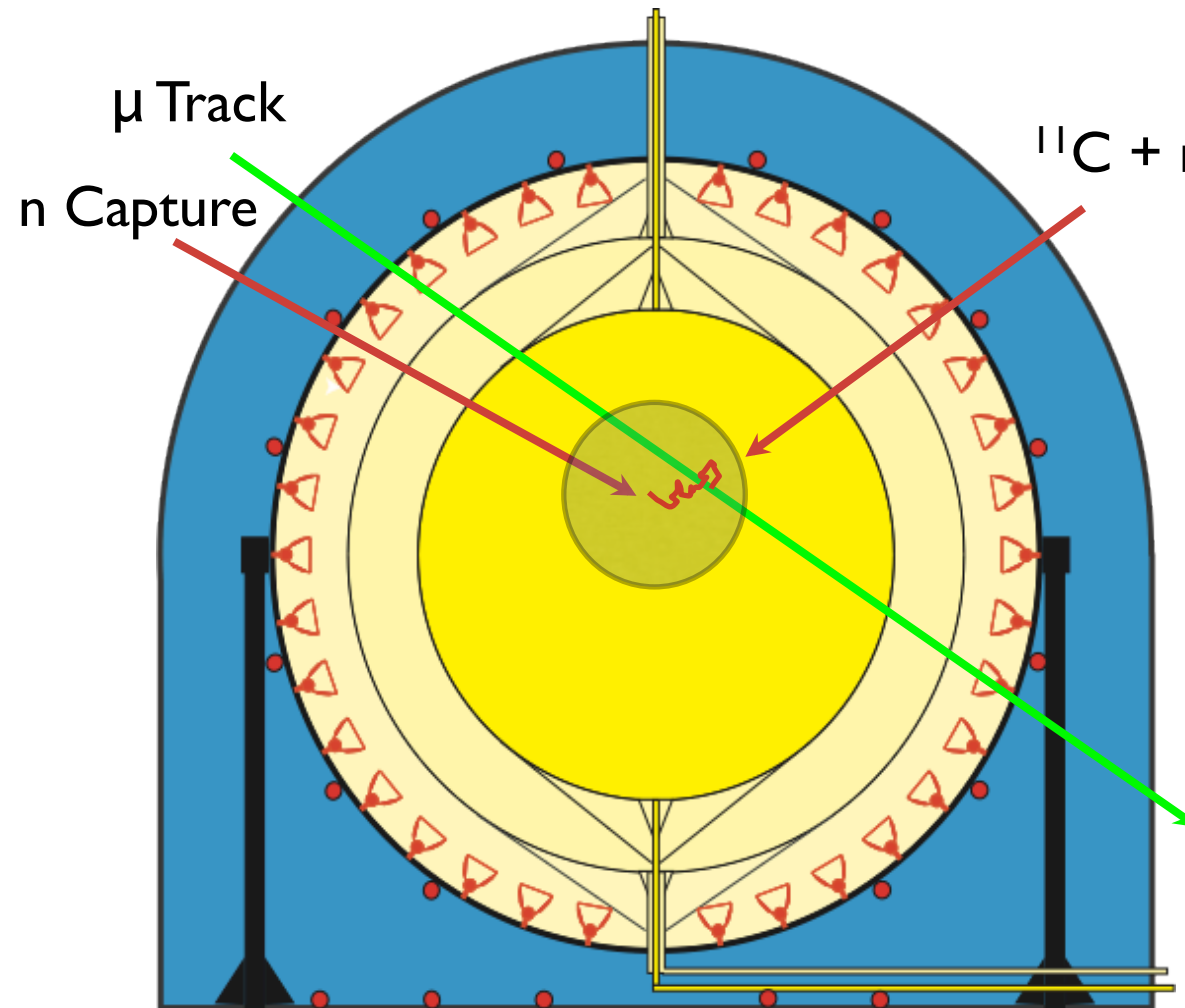
“Into the Muck”: *pep* and CNO Neutrinos



“Into the Muck”: *pep* and CNO Neutrinos



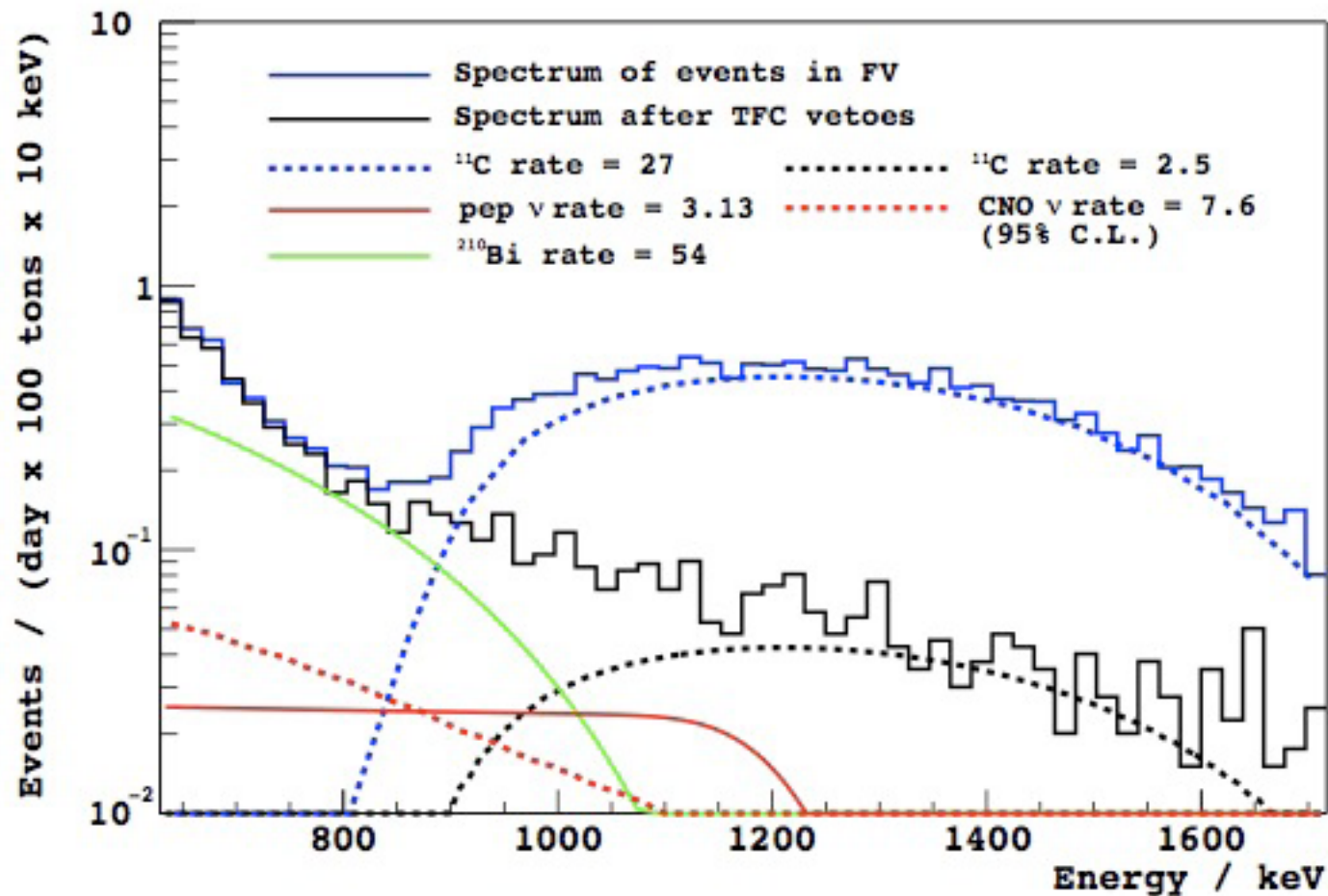
Three-Fold Coincidence



- Most ^{11}C produced via $^{12}\text{C} \rightarrow ^{11}\text{C} + n$
- Delayed neutron capture signal identifies when and where ^{11}C was produced
- Special triggers and analogue DAQ system to identify muon + neutron

The ~125 muon-neutron coincidences/day can be vetoed without excessive loss of live time.

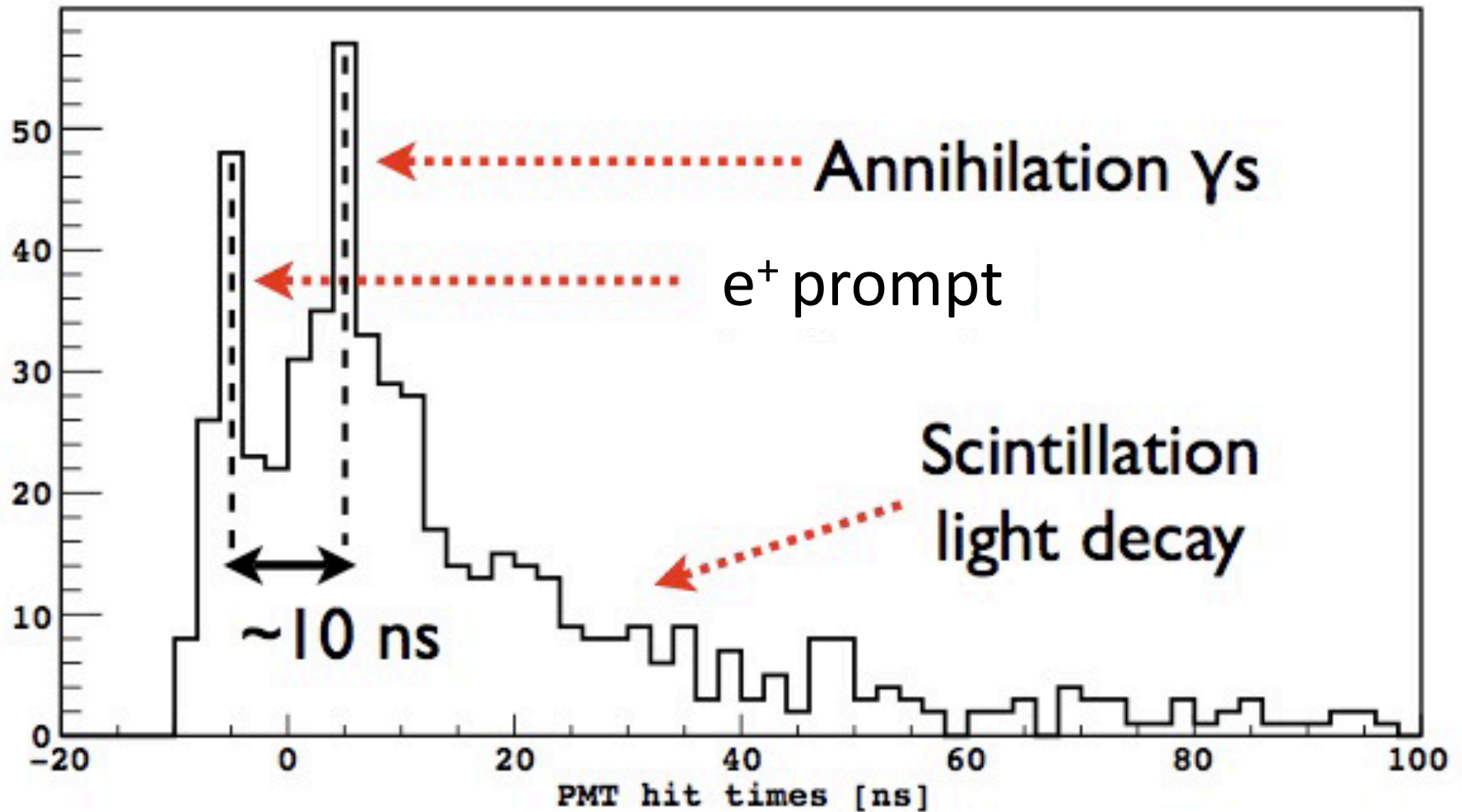
Three-Fold Coincidence



Remove 91% of ^{11}C with a livetime sacrifice of 51.5%.

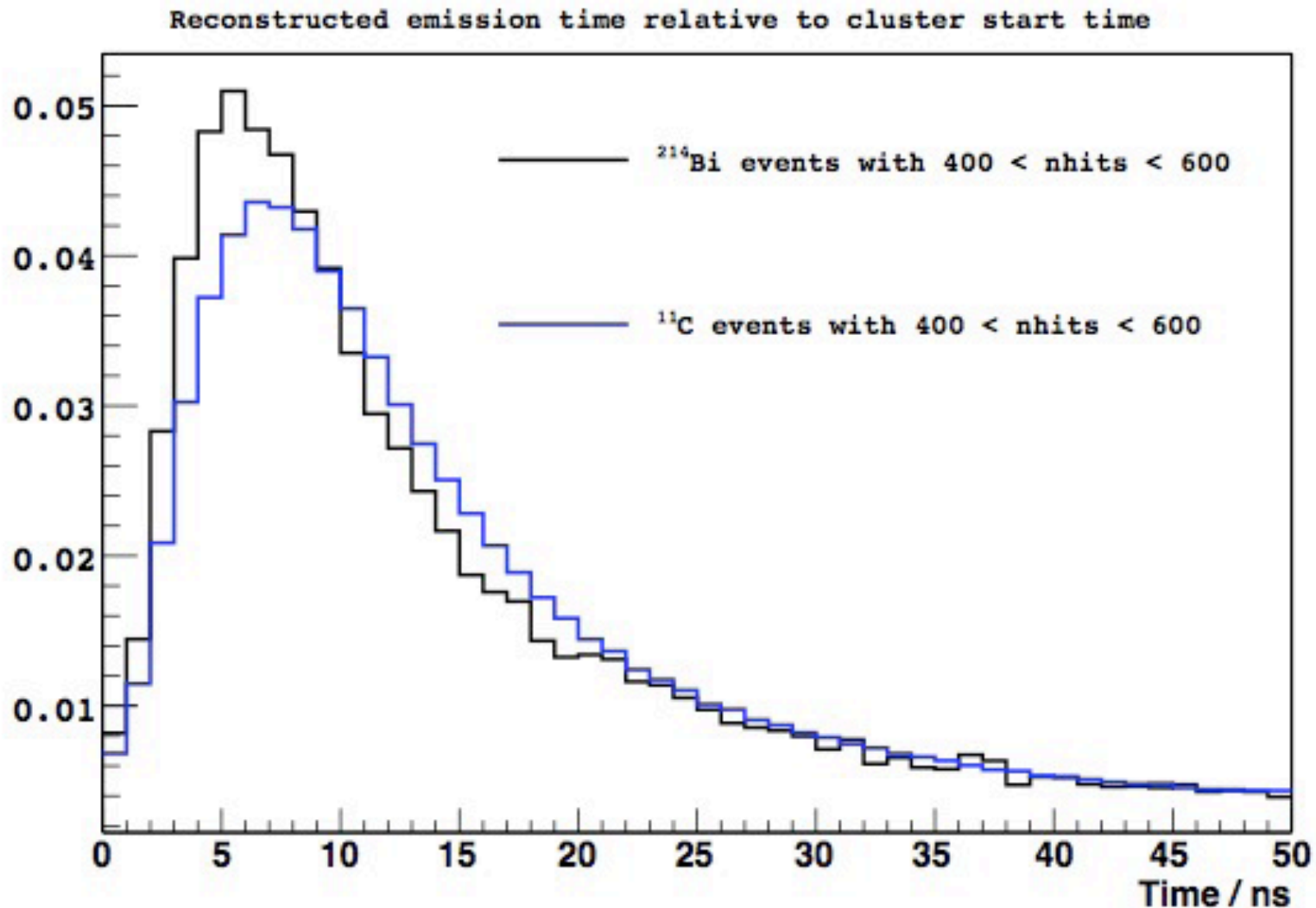
e^+/e^- Pulse Shape Discrimination

Hit Emission Times (Run 8622, Event 272752)



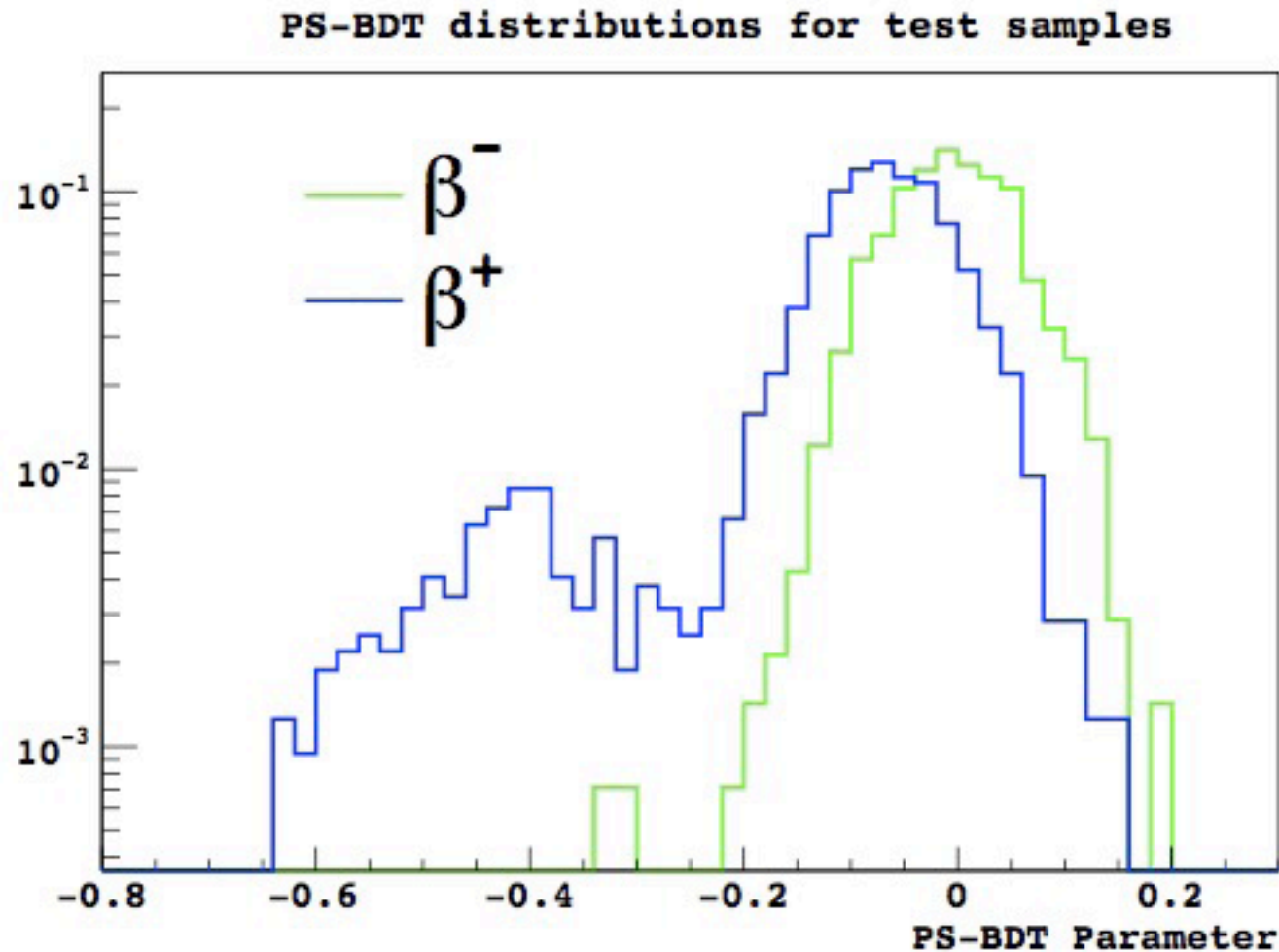
- 50% of β^+ decays give *ortho*-positronium ($t_{1/2} = 3$ ns).
- Gammas give multi-site topology.

e^+/e^- Pulse Shape Discrimination



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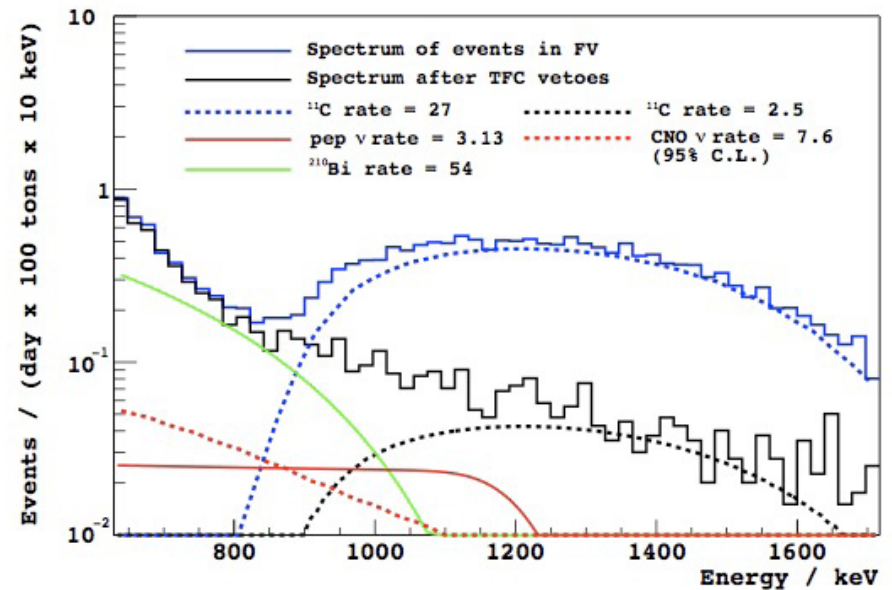
e^+/e^- Pulse Shape Discrimination



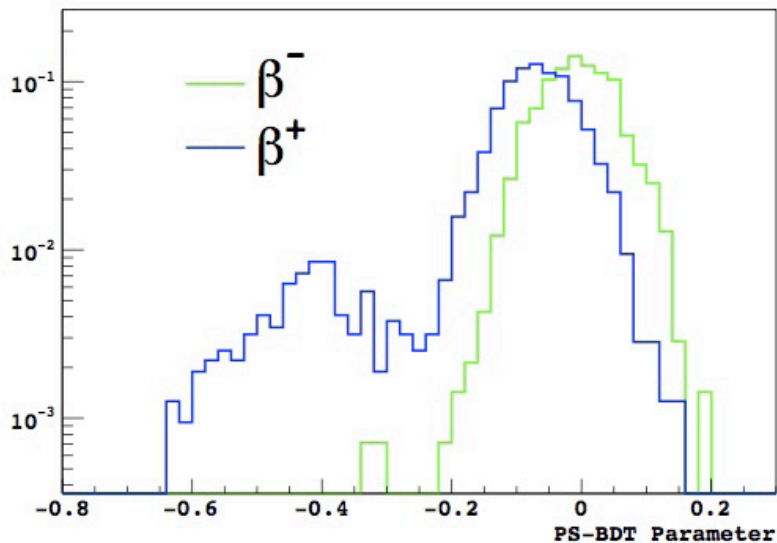
- Use boosted decision tree to optimize discrimination.
 - Train, test, and build PDF with events cut by TFC.
 - Include BDT variable in signal extraction.

Multi-Dimensional Fit

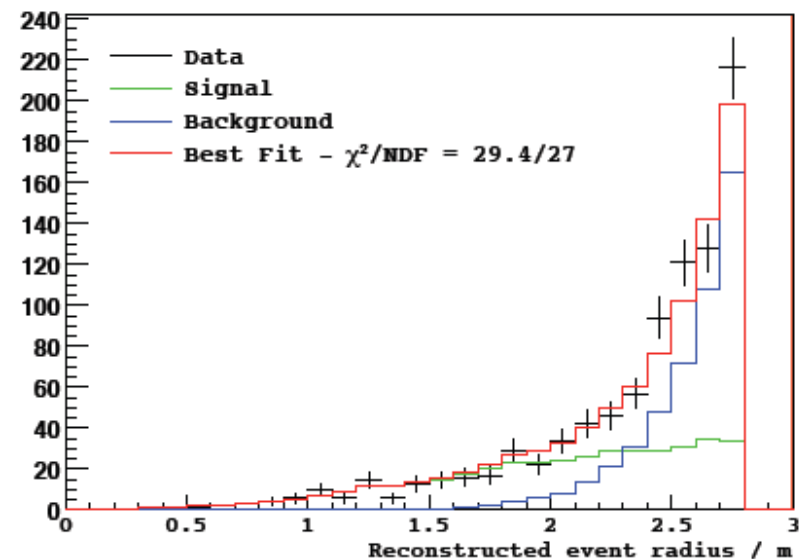
- Binned likelihood fits in energy, radius, and BDT
- 2D energy-radius and energy-BDT PDFs
- Simultaneous fits to TFC accepted and rejected spectra (double background statistics).



PS-BDT distributions for test samples



Radial distribution of candidates



Multi-Dimensional Fit

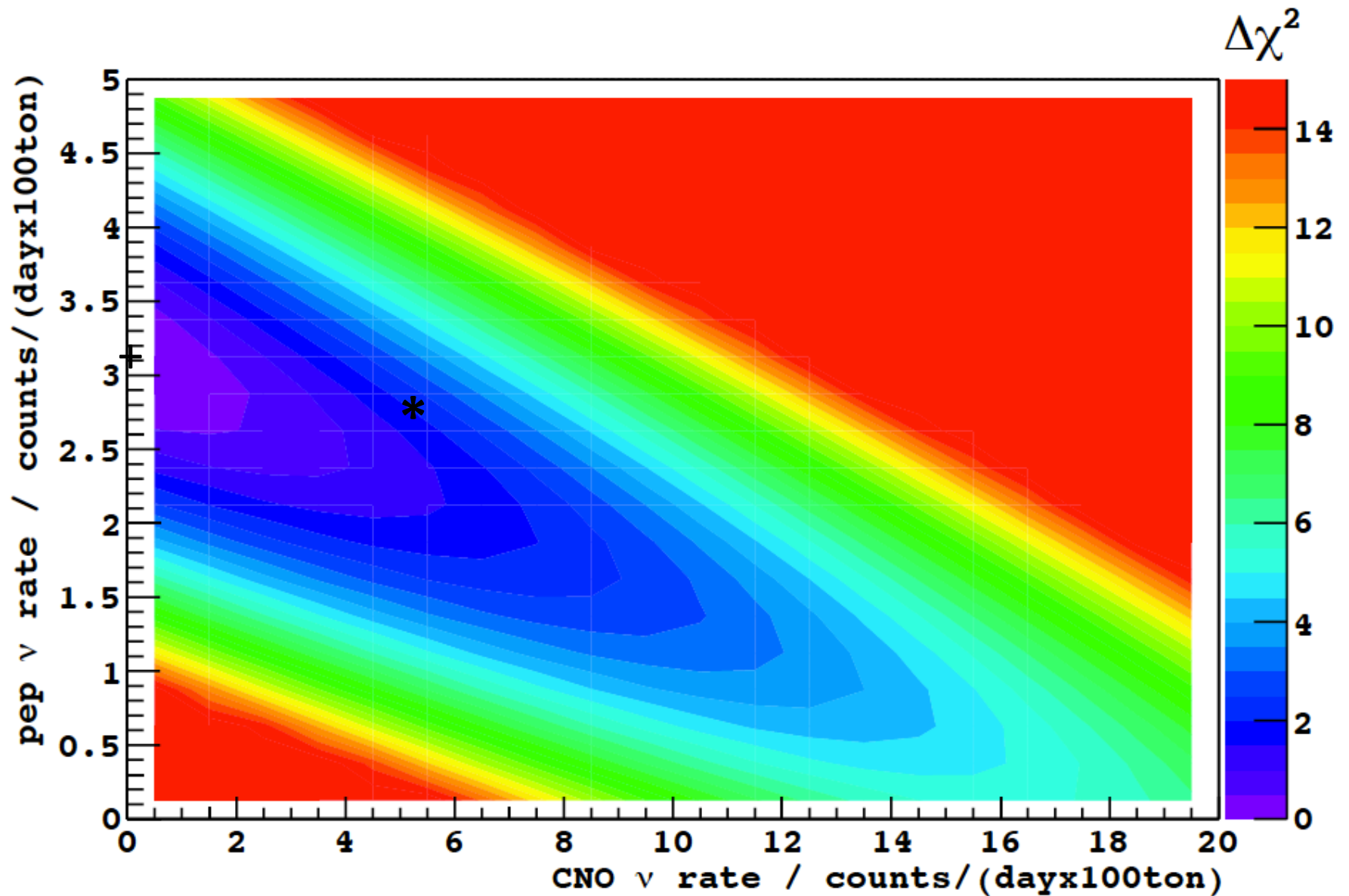
Species	Rate free or fixed	Common to both spectra	In PS-BDT fit	In radial dist. fit
pep ν	free	Yes	β^-	Bulk
CNO ν s	free	Yes	β^-	Bulk*
$^7\text{Be } \nu$	free	Yes	β^-*	Bulk*
pp ν	fixed to 133 cpd/100t	Yes	β^-*	Bulk*
$^8\text{B } \nu$	fixed to 0.46 cpd/100t	Yes	β^-	Bulk
^{214}Pb	fixed to 1.95 cpd/100t	Yes	β^-	Bulk*
^{210}Bi	free	Yes	β^-	Bulk*
^{10}C	free	No	β^+	Bulk
^{11}C	free	No	β^+	Bulk
Ext. ^{214}Bi	free	Yes	β^-	External
Ext. ^{40}K	free	Yes	β^-	External
Ext. ^{208}Tl	free	Yes	β^-	External
^6He	free	No	β^-	Bulk
^{40}K	free	Yes	β^-	Bulk
^{85}Kr	free	Yes	β^-*	Bulk*
^{234m}Pa	free	Yes	β^-	Bulk

* Effectively excluded due to energy range

pp and ^8B neutrinos fixed to SSM values

^{214}Pb fixed to value from $^{214}\text{BiPo}$ coincidences

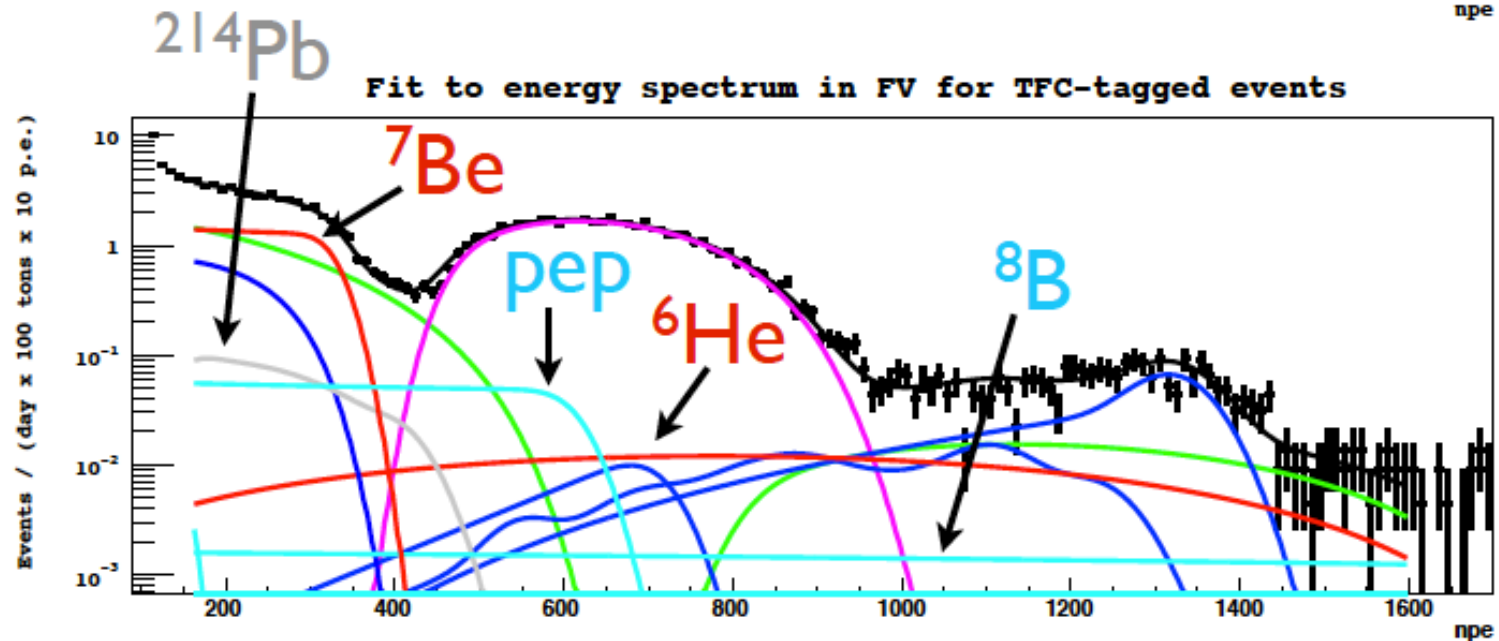
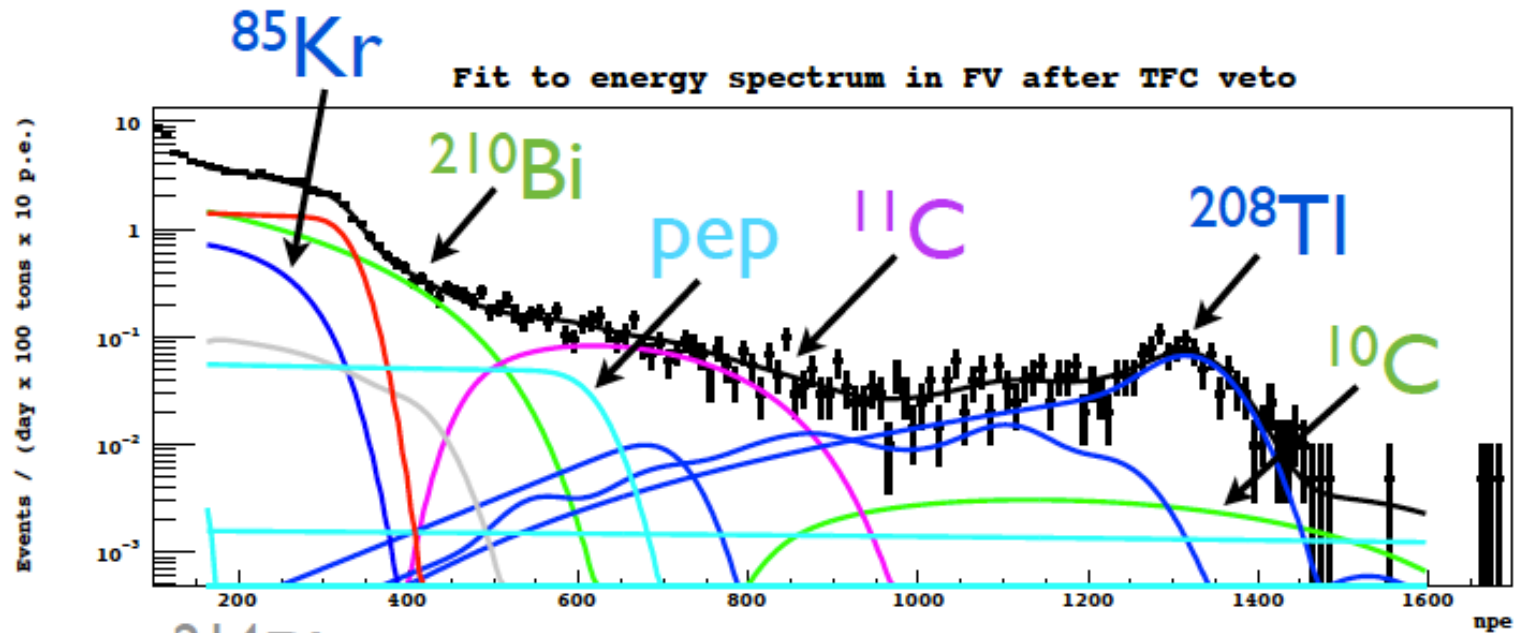
Fit Result



Best fit ('+'): (0, 3.13)

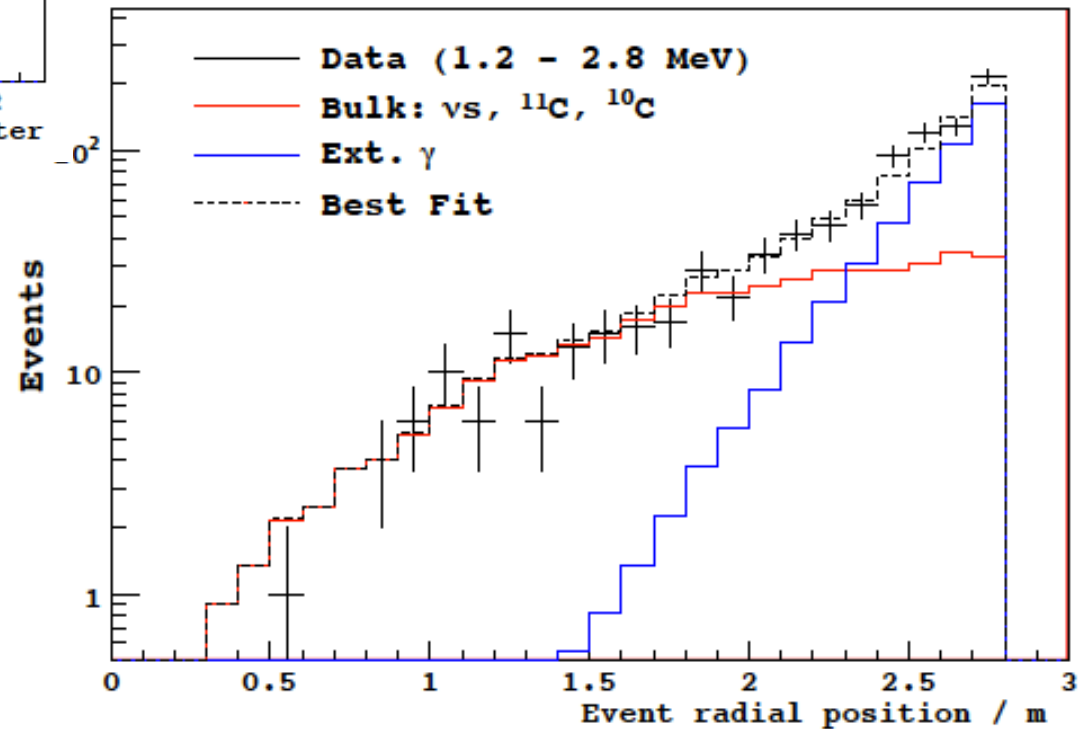
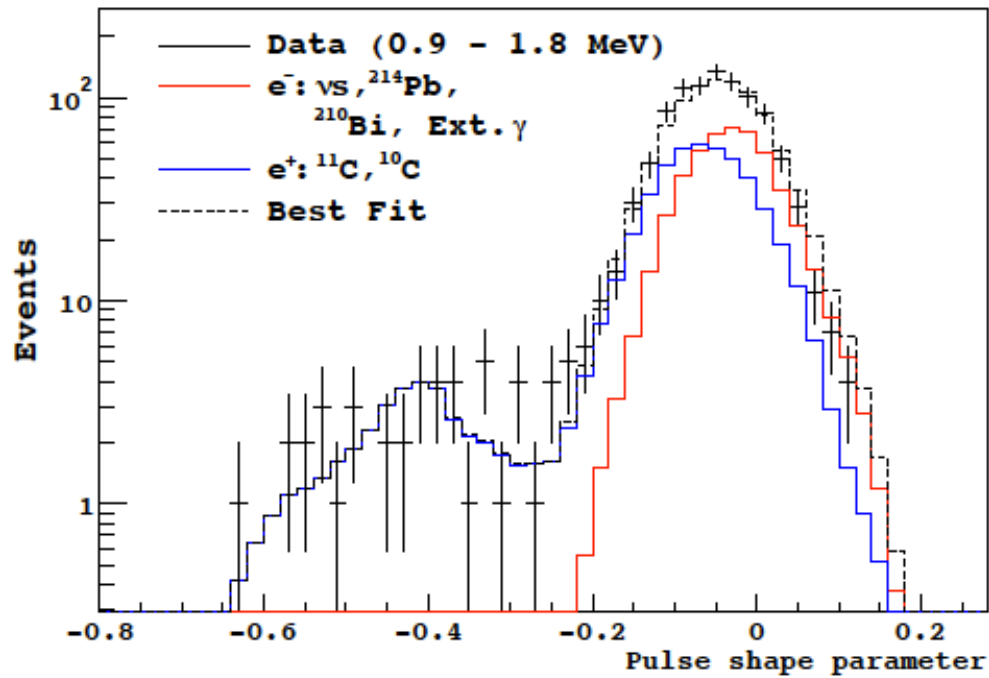
SSM + LMA prediction ('*'): (5.3, 2.8)

Fit Results



Fit p-value = 0.3 (from ensemble tests)

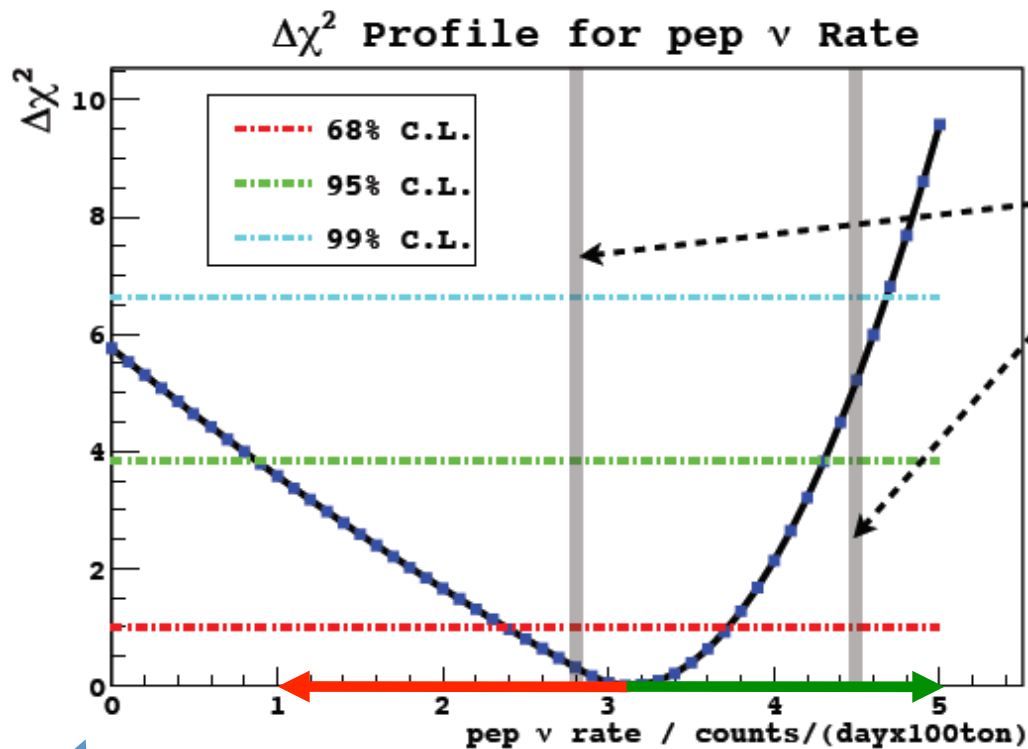
Fit Results



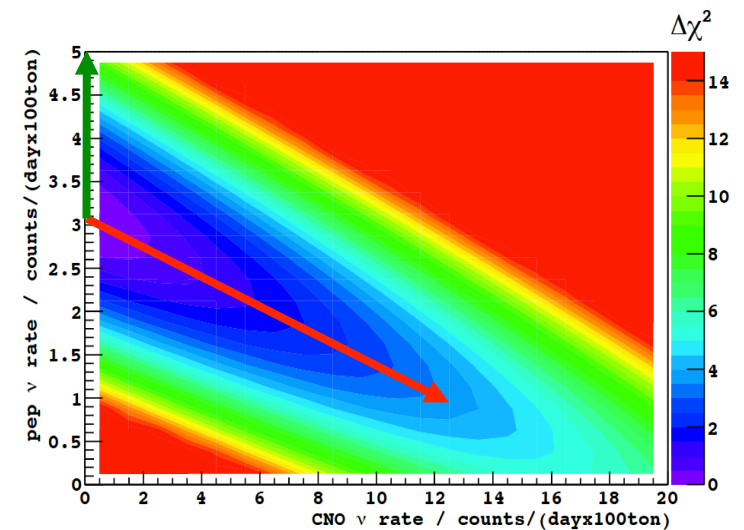
pep Result

Borexino *pep* counting rate: $3.1 \pm 0.6_{\text{stat}} \pm 0.3_{\text{sys}} / (\text{d } 100\text{T})$

$$\rightarrow P_{ee}(1.44 \text{ MeV}) = 0.62 \pm 0.17$$



SSM Prediction
MSW-LMA
No Oscillation

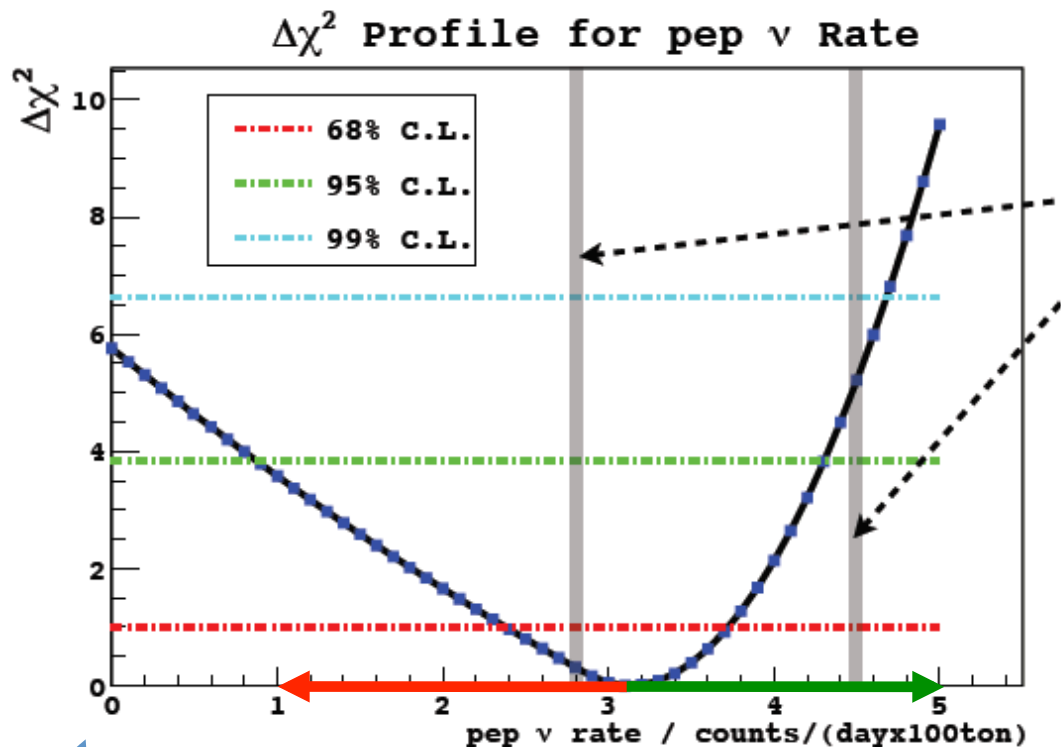


$\Phi_{\text{pep}} = 0$ disfavoured at 98% C.L.

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Systematics

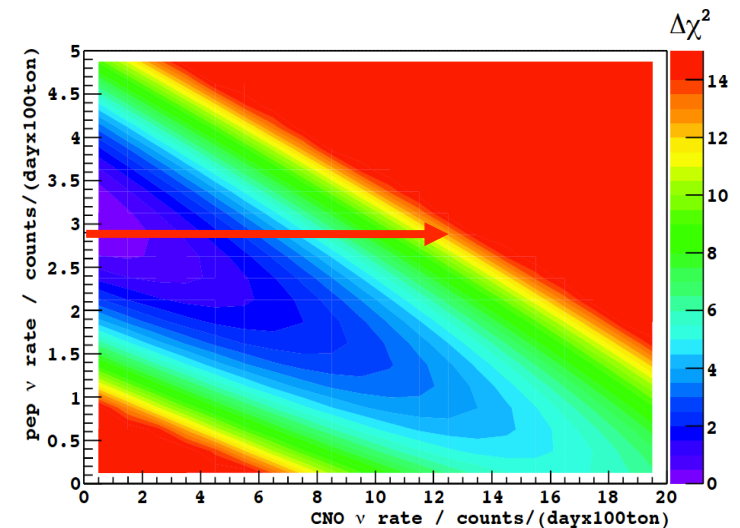
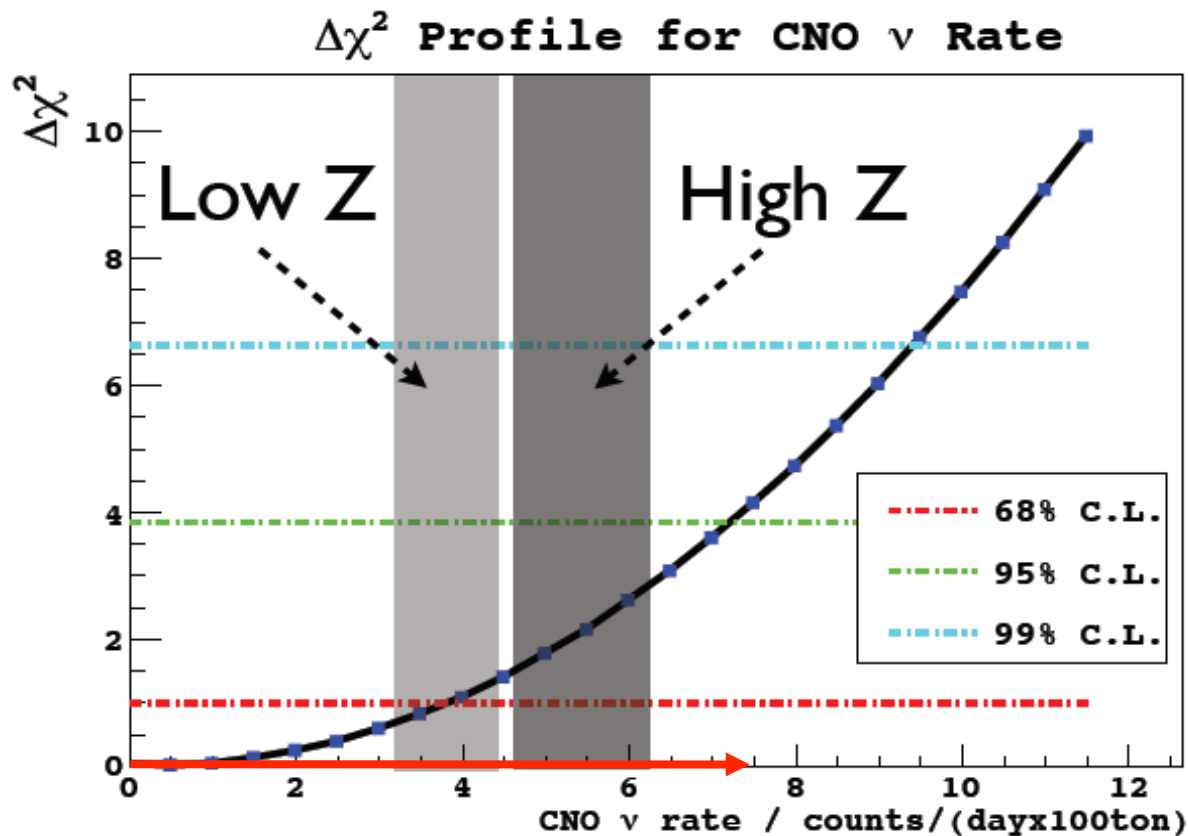
Fiducial Exposure	+0.6% -1.1%
Energy Response	4.1%
^{210}Bi shape	+1.0% -5.0%
Fit Methods	5.7%
^{85}Kr constraint	+3.9% -0.0%
γ -rays in BDT	2.7%
BDT PDF statistics	5.0%
Total	10%

$\Phi_{\text{pep}} = 0$ disfavoured at 98% C.L.

CNO Limit

Borexino CNO counting rate: < 7.9 ($< 7.1_{\text{stat only}}$) / (d 100T) (95% C.L)

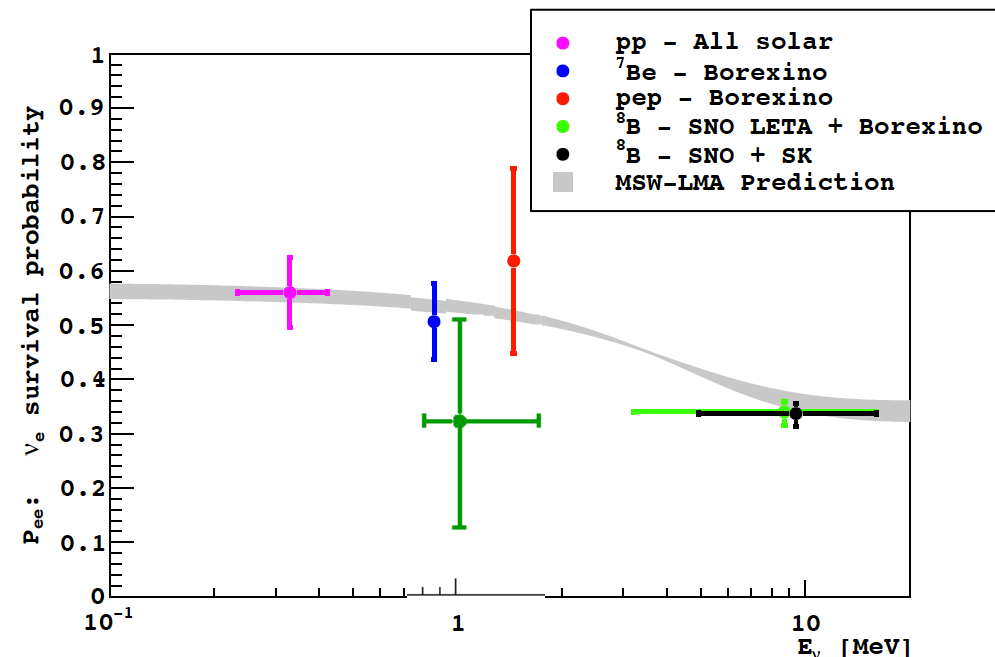
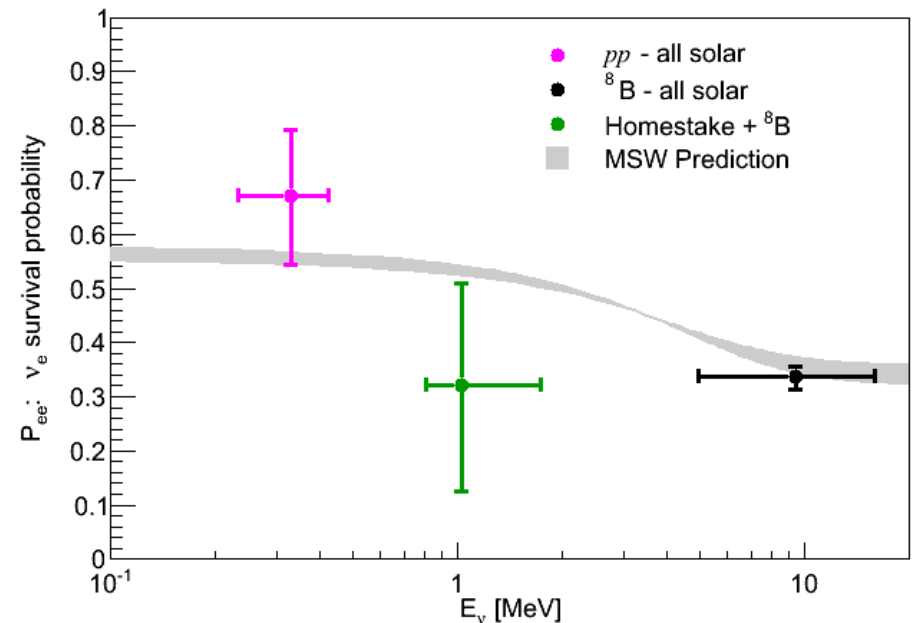
→ ($< 1.5 \times$ high Z SSM)



pep fixed at SSM prediction (2.8 ± 0.4) / (d 100T)

Summary

- Borexino has achieved unprecedented radiopurity and developed techniques to effectively suppress residual backgrounds
- ^7Be flux results significantly improve the experimental constraint on P_{ee} at low energy
- Day-night improves solar-only constraint on mixing parameters
- First direct study of the pep flux
- Most precise constraint on CNO flux



Borexino Future

- Procedures to (further!) purify the scintillator underway since July 2010
 - No sign of ^{85}Kr since January
 - Moderate reduction in ^{210}Bi
- Operations continue, with aim of further reducing ^{210}Bi , perhaps ^{210}Po
- Borexino will continue to take data for >3 more years
 - Improve measurements of low energy solar neutrinos, accrue further ^8B & geo-neutrino statistics

