First evidence of pep solar neutrinos by direct detection in Borexino 1

arXiv:1110.3230v1
to appear in PRL

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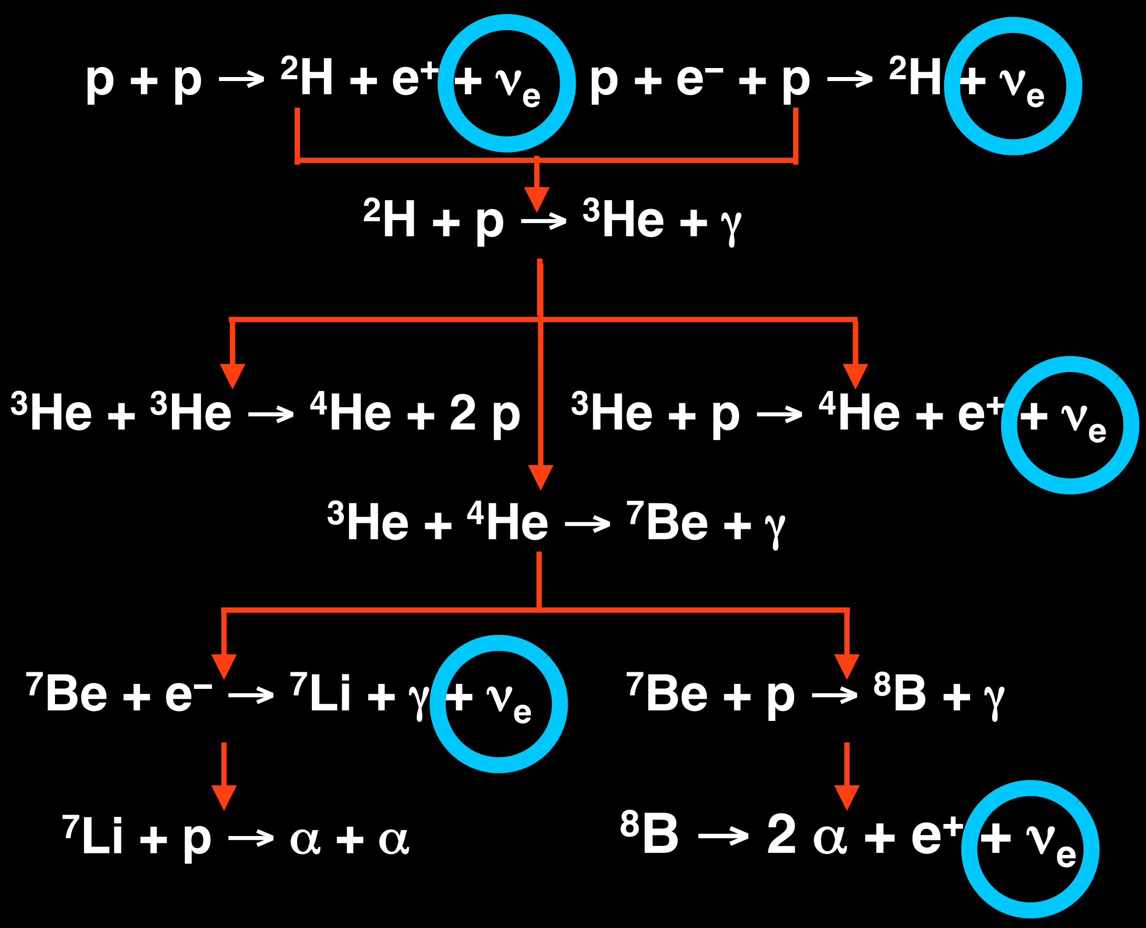
Borexino Collaboration

Outline

- Solar neutrinos.
- The Borexino Detector.
- ^{11}C background suppression.
- Other backgrounds.
- Fitting strategy.
- Results.
- Future prospects.

Solar Neutrinos

p-p Solar Fusion Chain



$p + p \rightarrow {}^{2}H + e^{+} + \nu_e$ $\quad$ $p + e^{-} + p \rightarrow {}^{2}H + \nu_e$

${}^{2}H + p \rightarrow {}^{3}He + \gamma$

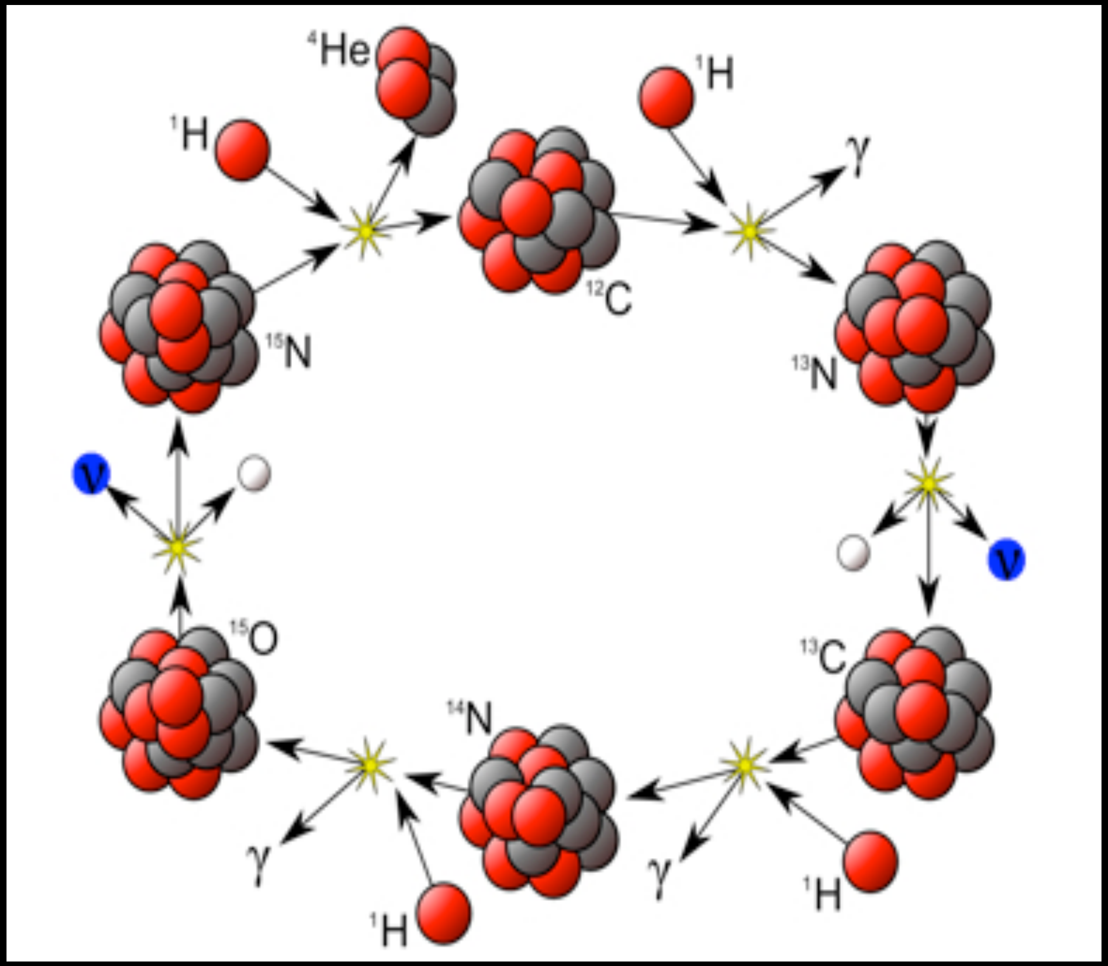
${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2\,p$ $\quad$ ${}^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu_e$

${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \gamma + \nu_e$ $\quad$ ${}^{7}Be + p \rightarrow {}^{8}B + \gamma$

${}^{7}Li + p \rightarrow \alpha + \alpha$ $\quad$ ${}^{8}B \rightarrow 2\,\alpha + e^{+} + \nu_e$

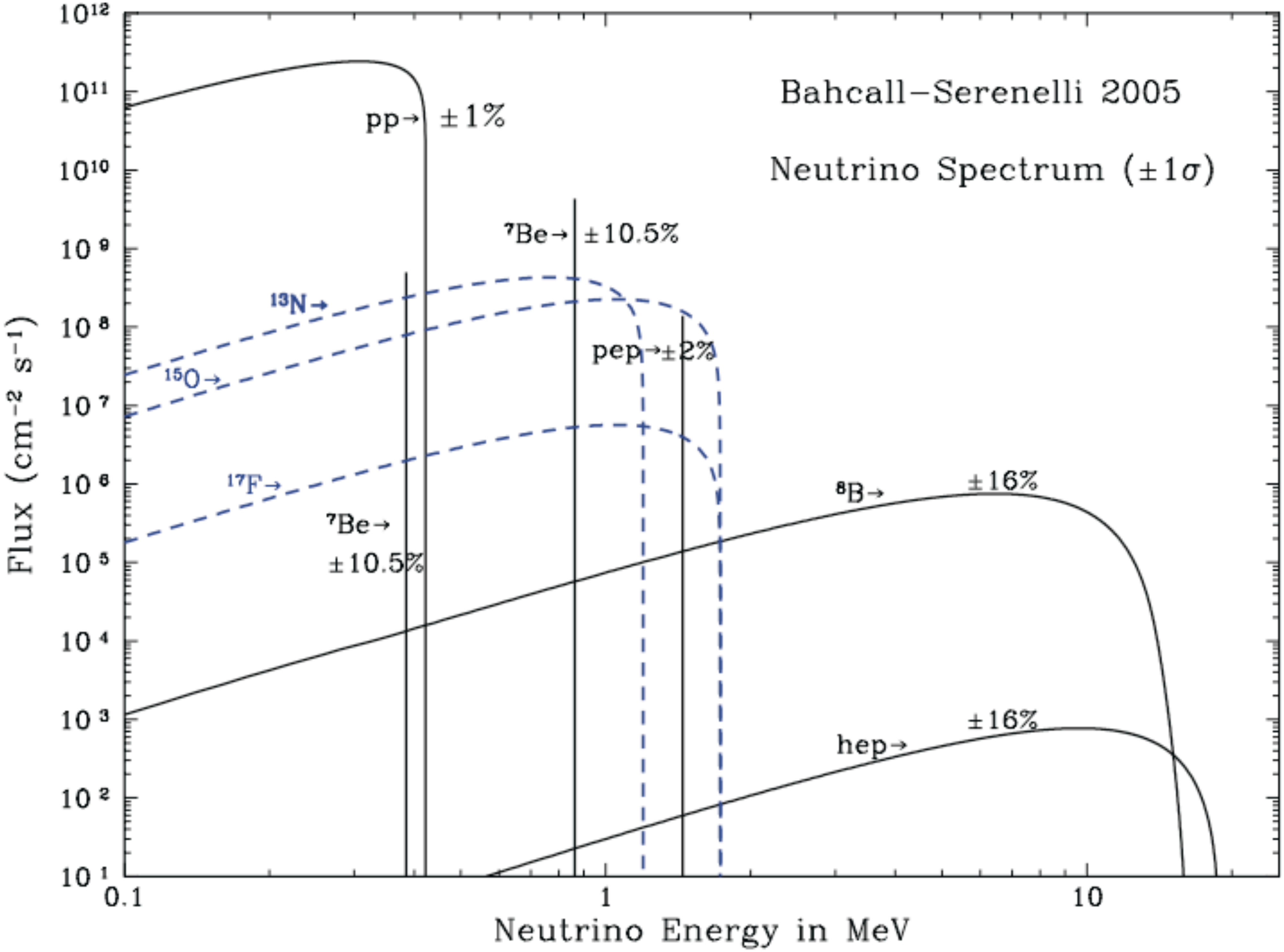
CNO Cycle



Dominant fusion mechanism in the Sun

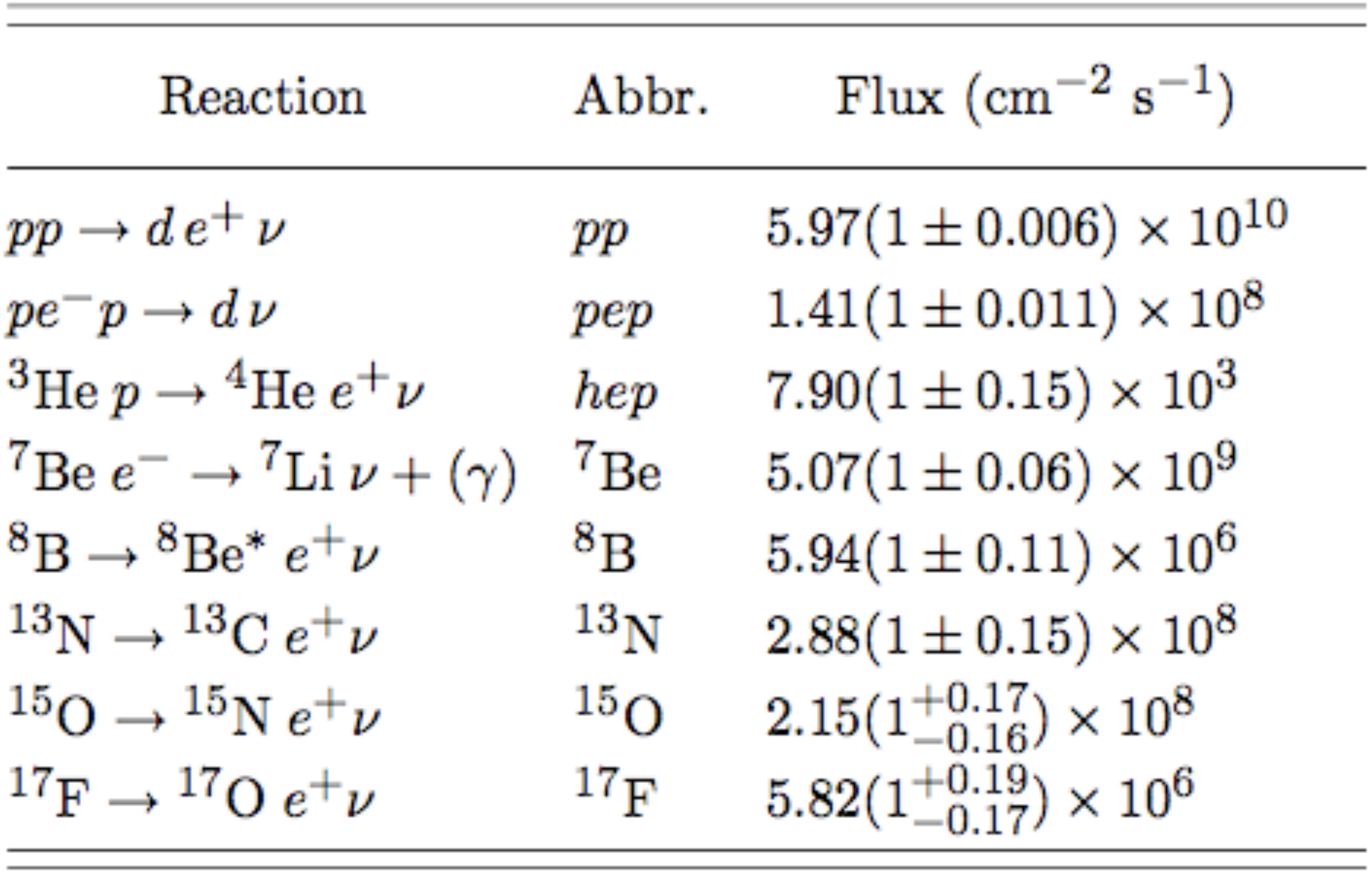
Related to solar metallicity
Important in larger stars
Contribution in Sun ?

Solar Neutrinos



Solar **S**tandard **M**odels predict spectra, fluxes of solar ν
Solar Neutrino experiments can test SSM

Solar Standard Model predicted ν fluxes



Reaction	Abbr.	Flux ($\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$)
$pp \to d\, e^+ \nu$	pp	$5.97(1 \pm 0.006) \times 10^{10}$
$pe^- p \to d\, \nu$	pep	$1.41(1 \pm 0.011) \times 10^{8}$
$^3\mathrm{He}\, p \to {}^4\mathrm{He}\, e^+ \nu$	hep	$7.90(1 \pm 0.15) \times 10^{3}$
$^7\mathrm{Be}\, e^- \to {}^7\mathrm{Li}\, \nu + (\gamma)$	$^7\mathrm{Be}$	$5.07(1 \pm 0.06) \times 10^{9}$
$^8\mathrm{B} \to {}^8\mathrm{Be}^*\, e^+ \nu$	$^8\mathrm{B}$	$5.94(1 \pm 0.11) \times 10^{6}$
$^{13}\mathrm{N} \to {}^{13}\mathrm{C}\, e^+ \nu$	$^{13}\mathrm{N}$	$2.88(1 \pm 0.15) \times 10^{8}$
$^{15}\mathrm{O} \to {}^{15}\mathrm{N}\, e^+ \nu$	$^{15}\mathrm{O}$	$2.15(1^{+0.17}_{-0.16}) \times 10^{8}$
$^{17}\mathrm{F} \to {}^{17}\mathrm{O}\, e^+ \nu$	$^{17}\mathrm{F}$	$5.82(1^{+0.19}_{-0.17}) \times 10^{6}$

Small uncertainties

Large uncertainties

Tension between High and Low Metallicity SSM

High Z SSM (GS) → older model, higher heavy element abundances, agrees with helioseismology

Low Z SSM (AGS) → new model based on solar atmospheric spectroscopy, lower heavy element abundances, does not agree with helioseismology

Solar Neutrino Propagation

Solar neutrinos (ν_e) undergo **oscillation**

Interaction with **matter** can affect oscillation (**W**olfenstein)

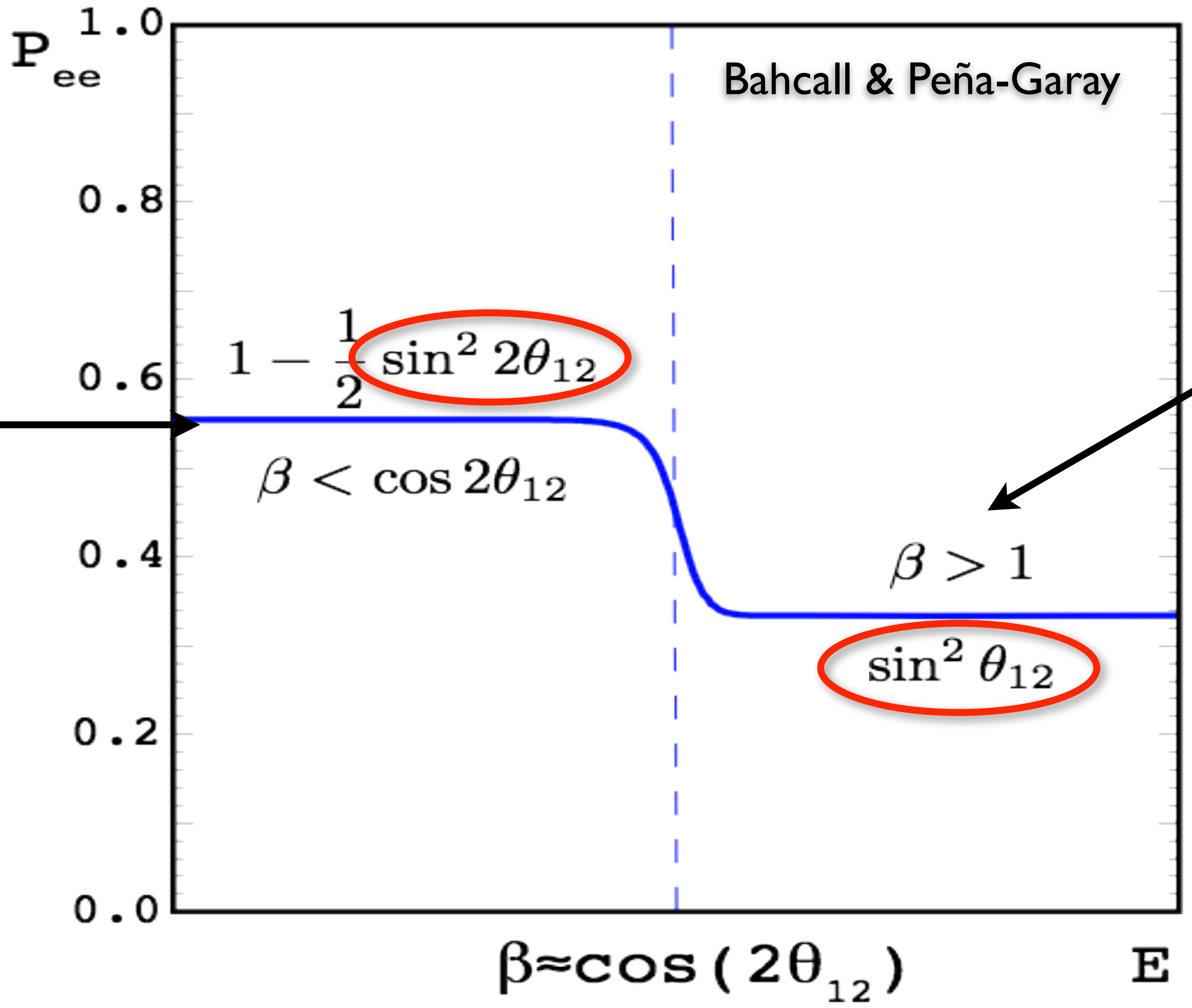
The oscillation probability can be enhanced by a resonance (**M**ikheyev & **S**mirnov)

Energy Dependent Survival Probability $\mathbf{P_{ee}}$

If SSM predicts ν flux with high precision → probe neutrino oscillations

MSW Oscillation Regimes

Phase-averaged vacuum oscillations

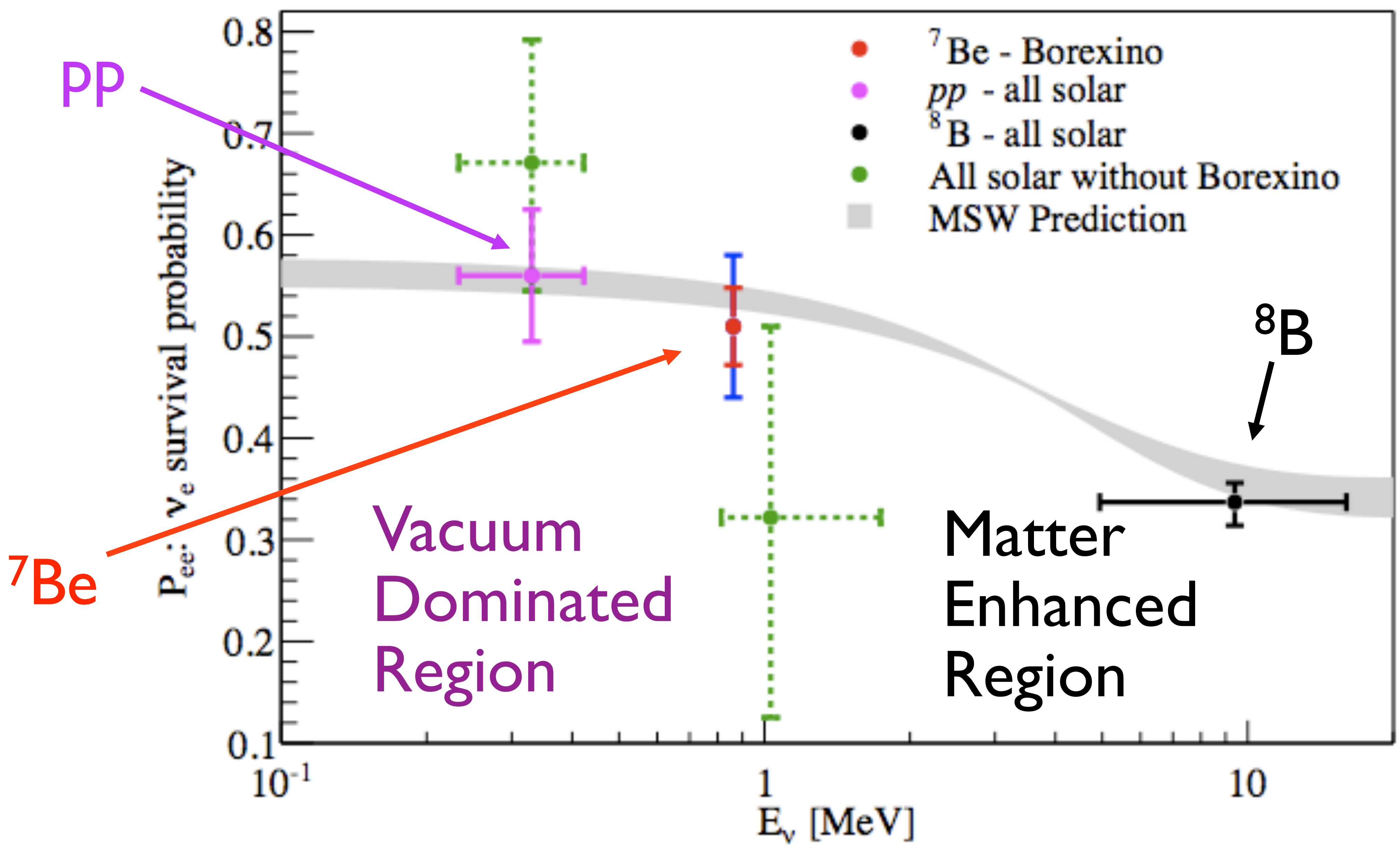


Matter enhanced

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

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

Solar Neutrino Propagation



MSW-LMA scenario: current understanding of solar neutrino oscillation

Physics beyond Standard Model can affect Energy dependence of P_{ee}

Solar Neutrino and Astrophysics wish list

- Particle physics:
  - Test **MSW-LMA** P_{ee} with high accuracy
  - Probe the **P_{ee}** in the **transition region**, sensitive to Physics beyond Standard Model
- Solar Astrophysics:
  - Test SSM predictions, prove **CNO** cycle in Sun
  - Test two competing models of **SSM**: **High** and **Low Metallicity**

Solar pep and CNO νs

pep reaction, part of the proton-proton chain, at a rate ~1/400 of pp reaction:

$p + e^- + p \longrightarrow d + \nu$ (1.44 MeV)

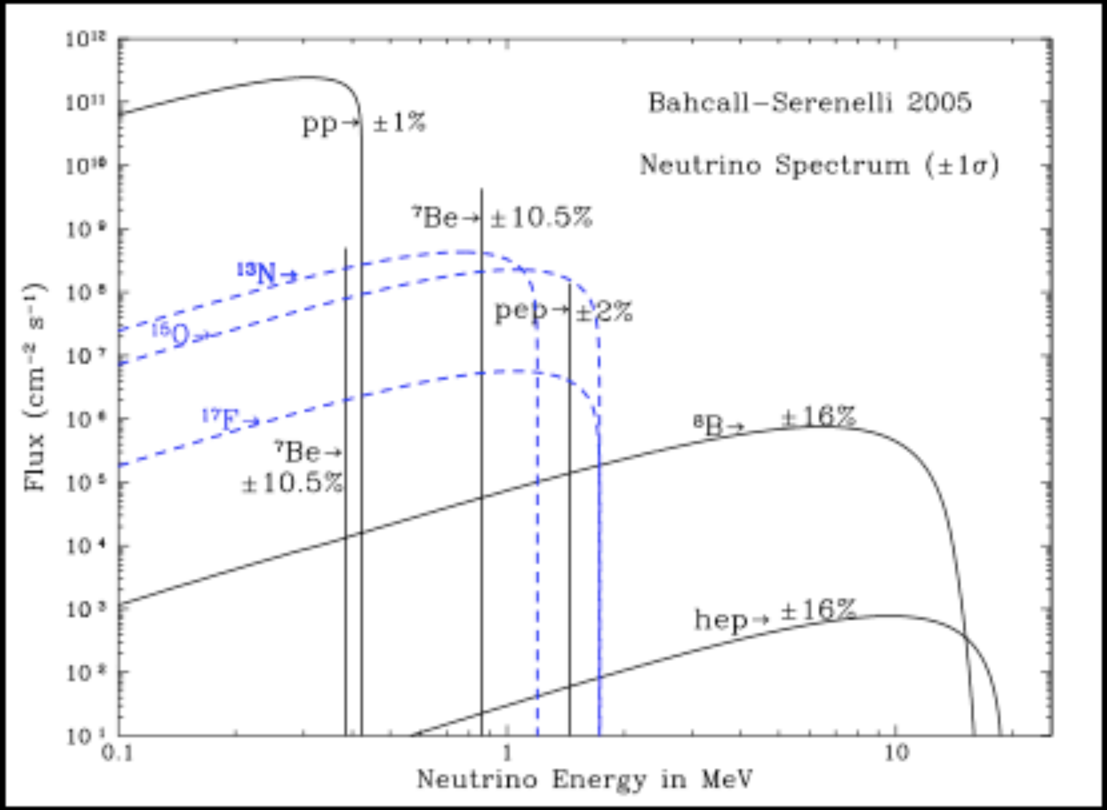
$\boxed{\text{~3 cpd/100 tons}}$

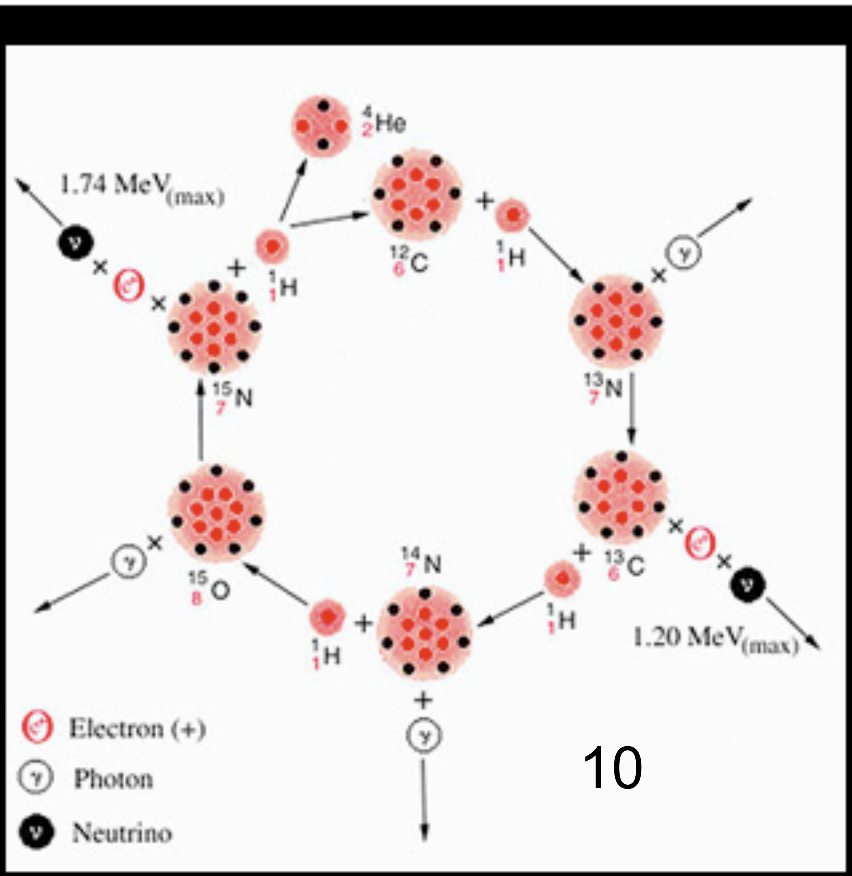
CNO cycle, alternate energy production mechanism in the Sun

ν from ^{13}N (E_{max} = 1.20 MeV)

ν from ^{15}O (E_{max} = 1.74 MeV)

$\boxed{\text{~3 - 5 cpd/100 tons}}$



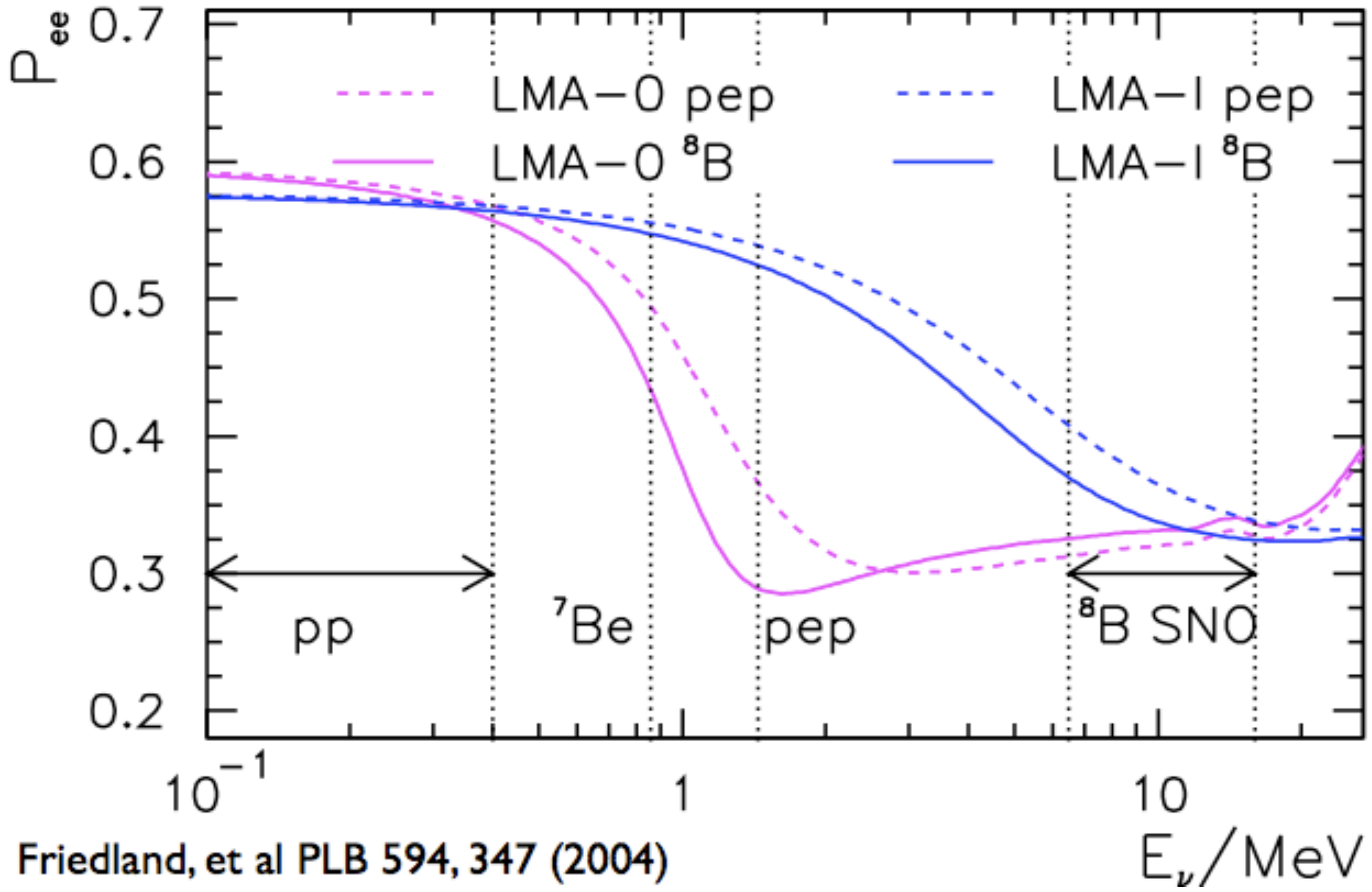


pep ν measurement motivations

pep neutrino **flux predicted** with **high precision**: 1.2% SSM uncertainty

pep neutrino energy (1.44 MeV) in P_{ee} **transition region,** sensitive to Physics beyond the Standard Model

Allows for more **stringent tests** of oscillation models



Friedland, et al PLB 594, 347 (2004)

CNO ν measurement motivations

Detecting CNO ν prove that CNO cycle happens in Sun

Abundance of heavy elements in Sun have high impact on CNO ν flux magnitude

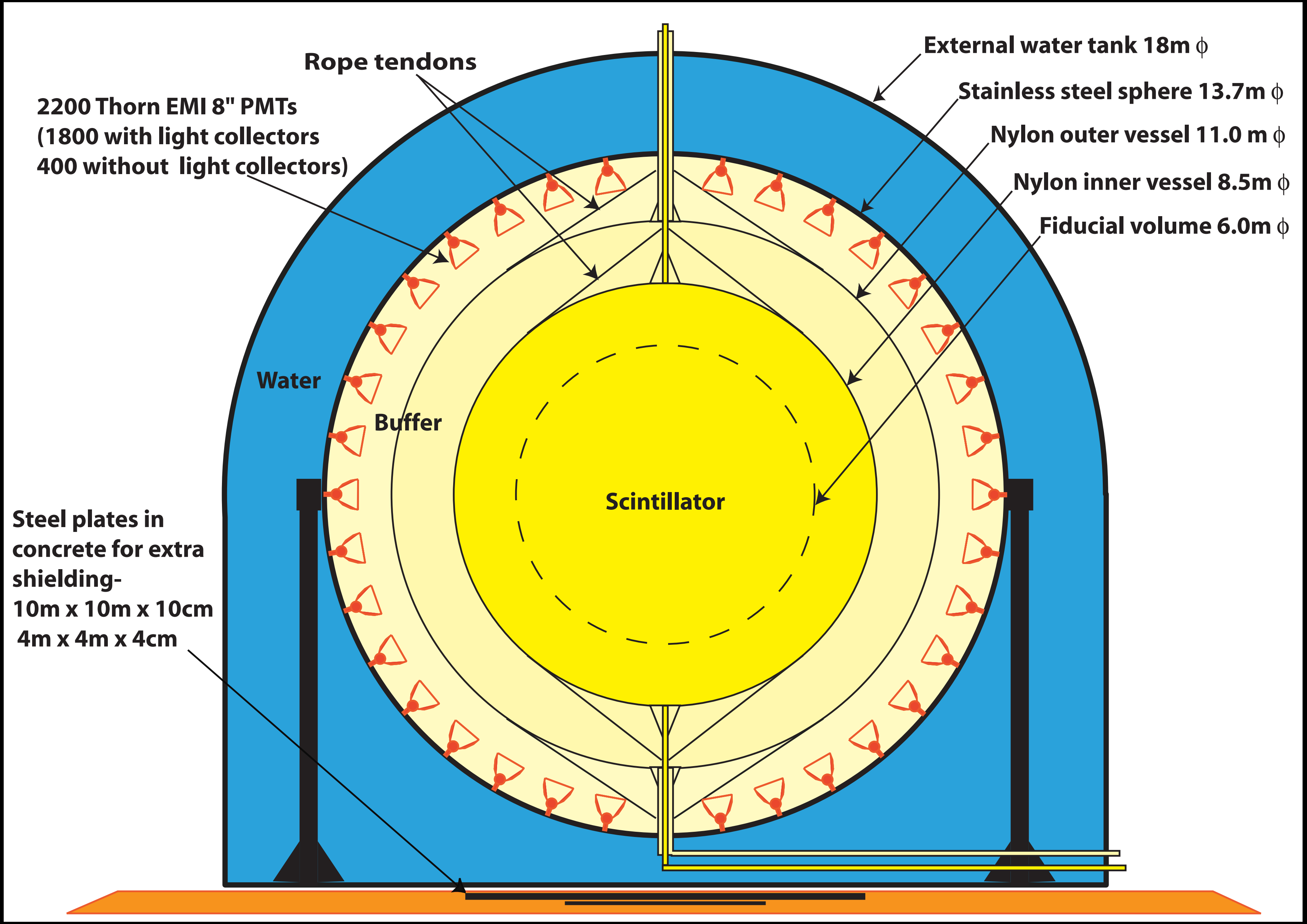
Test of High vs Low Z SSM

Serenelli, Haxton, Pena-Garay arXiv 1104.1639	**CNO** FLUX (10^8 cm^{-2} s^{-1})
HIGH Z SSM	5.24 ± 0.84
LOW Z SSM	3.76 ± 0.60
ΔΦ	28%

Borexino Detector

Design based on principle of graded shielding

In LNGS, 3800 m.w.e. overburden



Exterior instrumented water tank (Cherenkov detector)

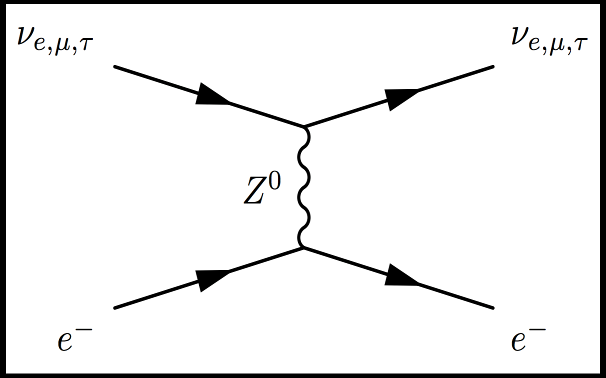
Stainless Steel Sphere with ~2200 PMTs

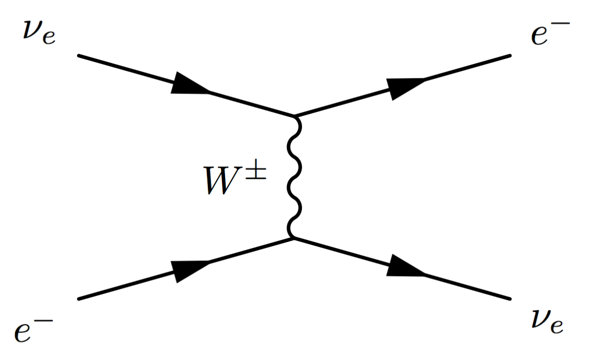
898 tons of quenched scintillator as buffer

278 tons of active scintillator

Fiducial Mass ~ 75 tons

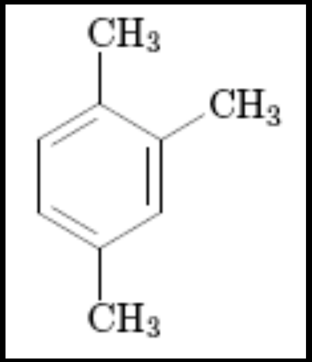
Borexino Detector

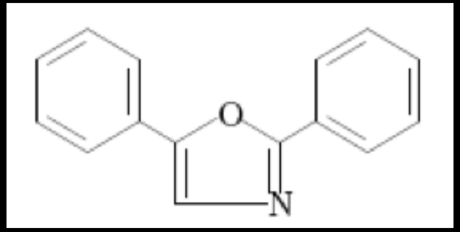




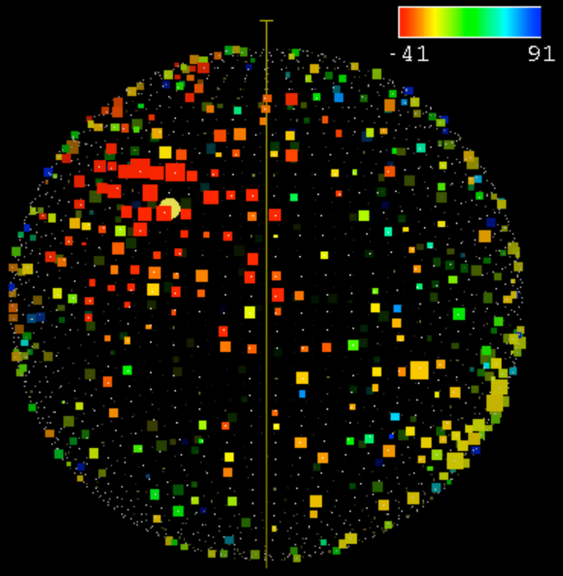
Neutrinos are detected through elastic scattering on electrons

Recoiling electrons excite scintillator molecules which emit light

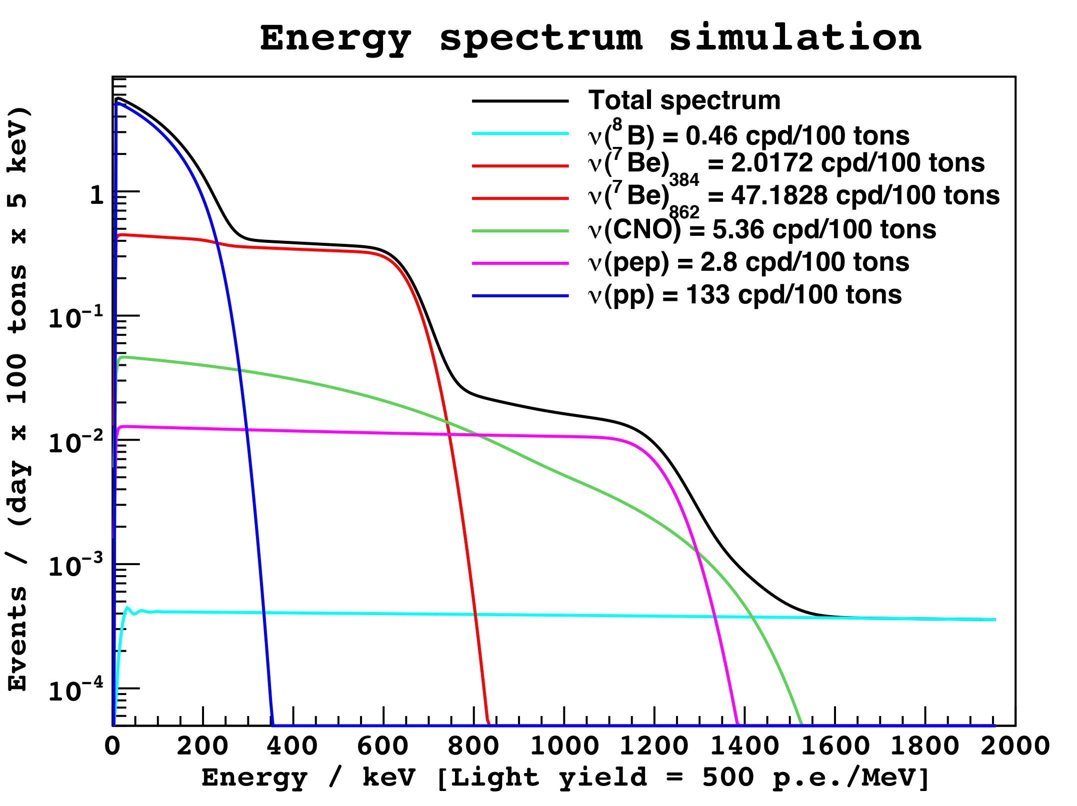




PC + 1.5g/l PPO



Scintillation light is detected by photomultiplier tubes



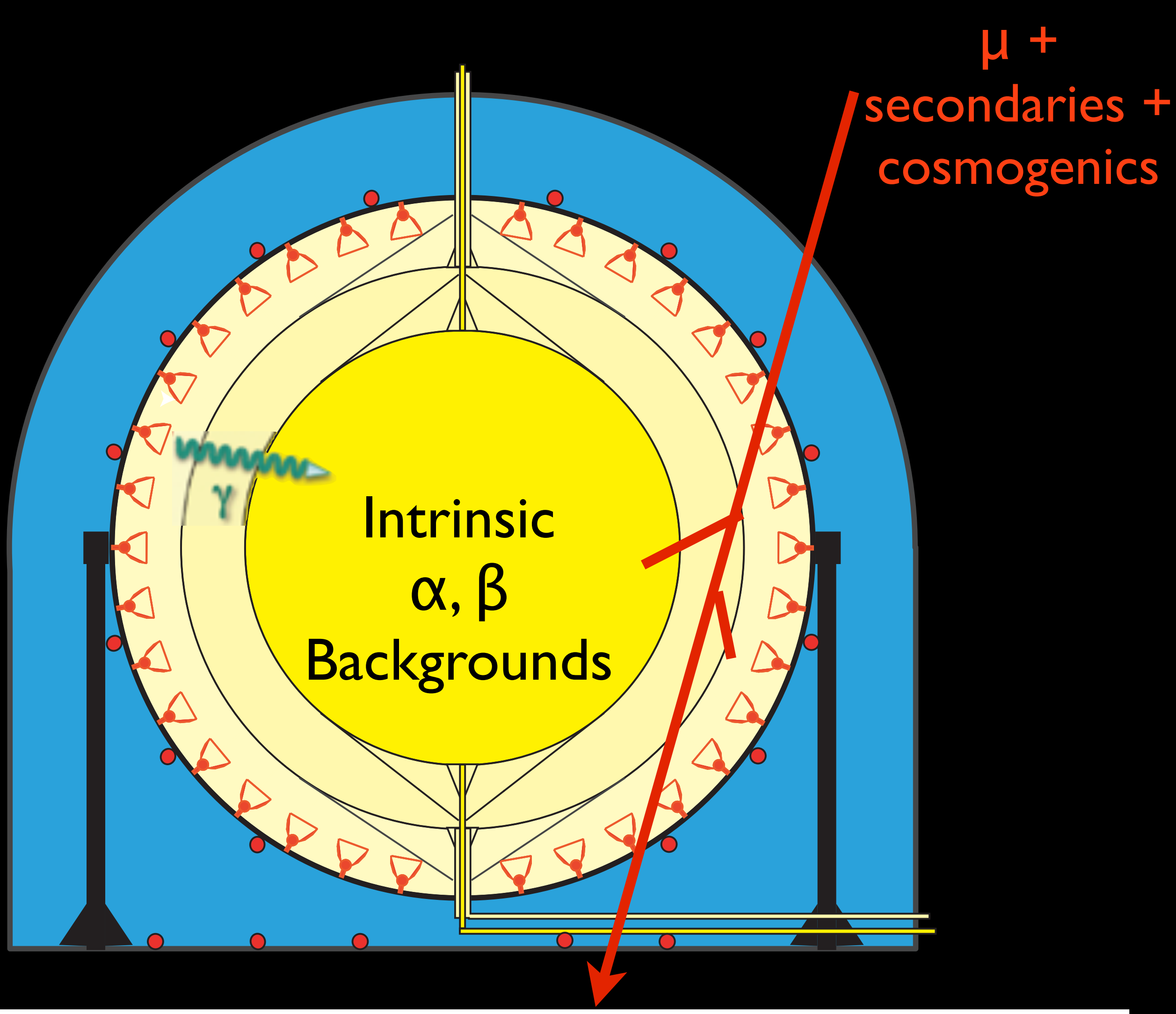
Amount and timing of light give energy and position information

Backgrounds

No directional information from scintillation light

Cannot discriminate between electron recoils and β/γ backgrounds

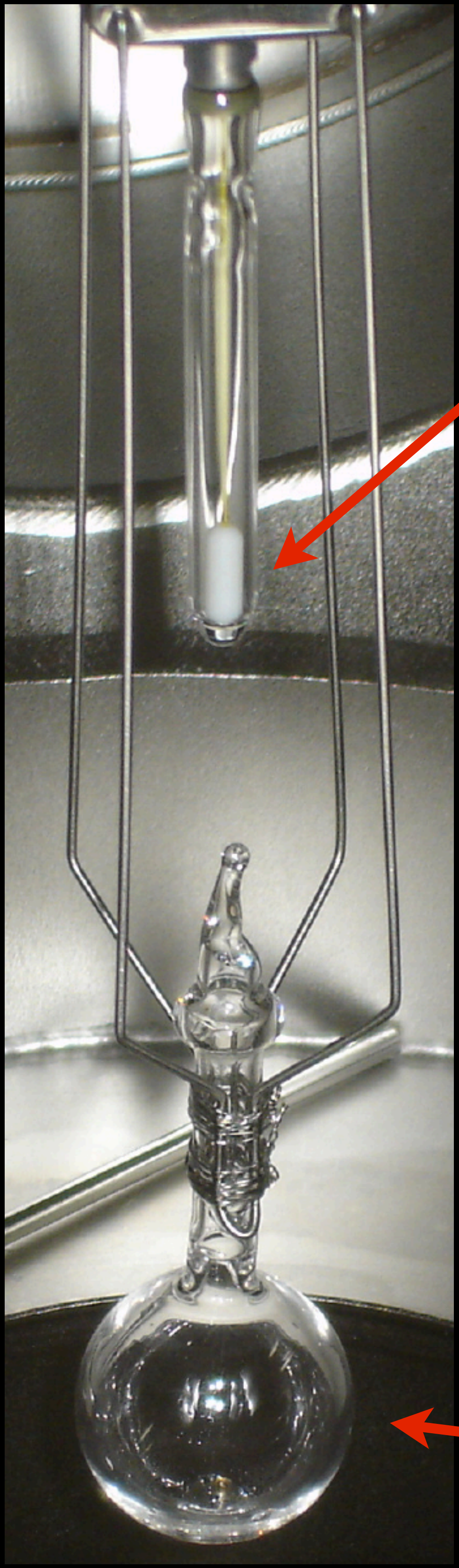
Need unprecedented low levels of background



Background	Source	Typical Concentration	Borexino Levels (per scintillator mass)	Reduction Method
^{14}C	Scintillator	10^{-12} g/g	10^{-18} g/g	Underground Source
^{238}U	Dust	10^{-5} g/g (Dust)	10^{-18} g/g	Purification
^{232}Th	Dust	10^{-5} g/g (Dust)	10^{-18} g/g	Purification
^{85}Kr	Air	10^{7} cpd/ton (Air)	0.3 cpd/ton	LAKN
^{40}K	PPO	10^{-6} g/g (Dust)	$<10^{-19}$ g/g	Purification
^{210}Po	^{210}Pb	10^{6} cpd/ton (Water)	20 cpd/ton	Purification
^{210}Bi	^{210}Pb	10^{6} cpd/ton (Water)	0.4 cpd/ton	Purification

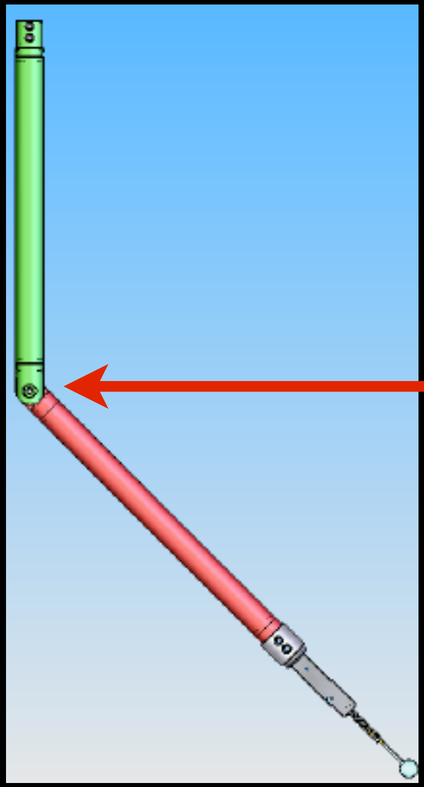
Detector Calibration

Study position and energy reconstruction by deploying radioactive sources throughout active volume

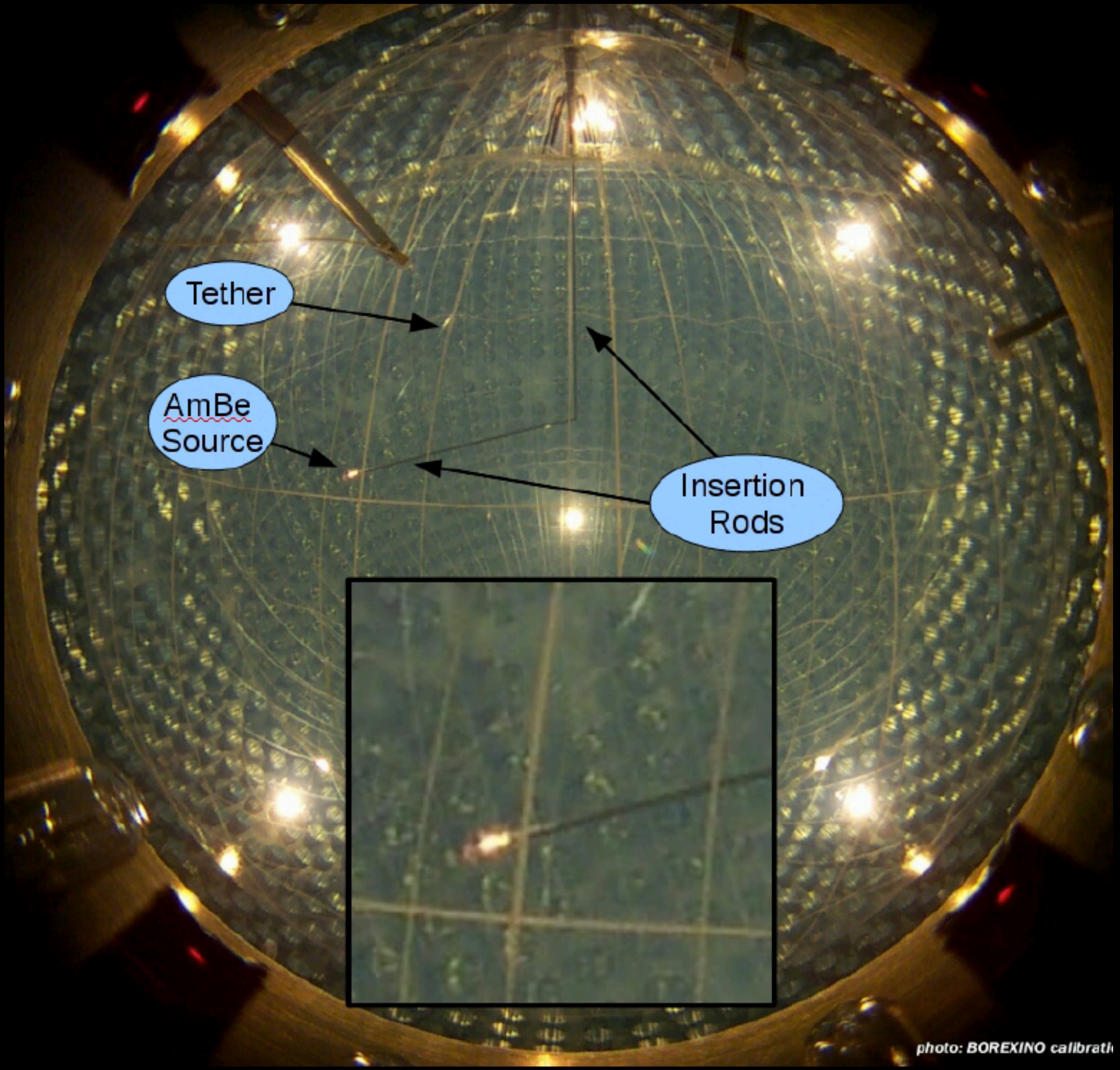


Laser Diffuser

Source Vial

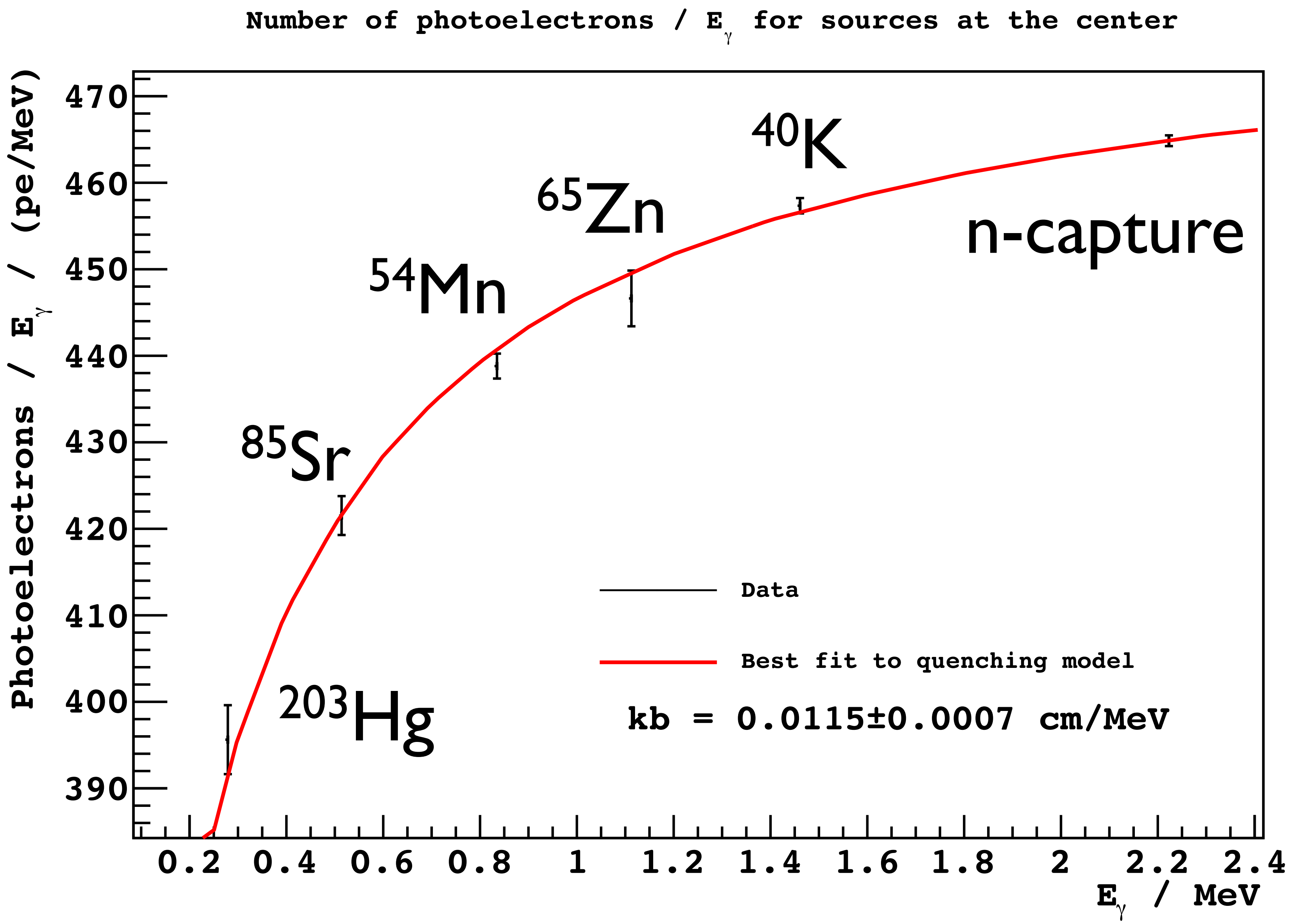


Pivot for off-axis deployment



Steve Hardy (Thesis)

β Energy Scale determination

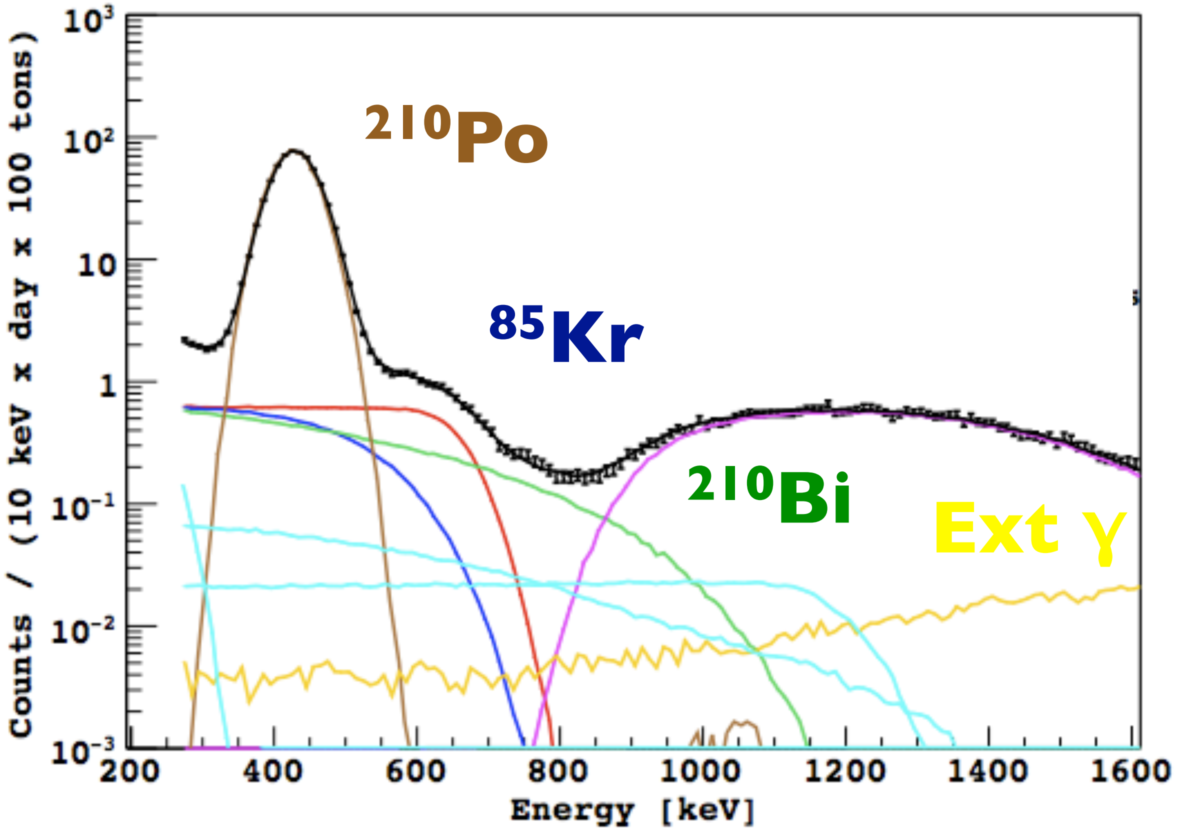


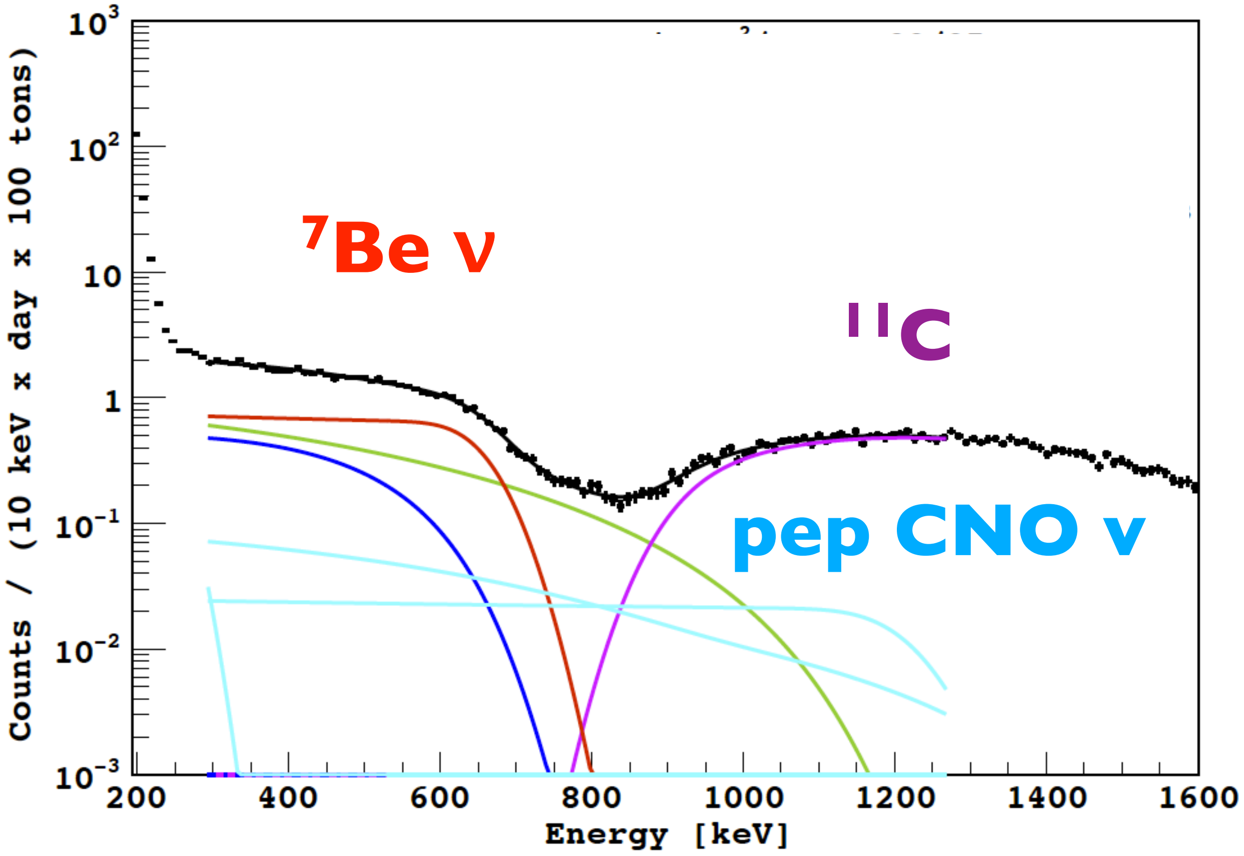
Use MonteCarlo to obtain effective γ quenching due to multiple electron scatters

Use Birk’s model for electron quenching

Result independent of source position (< 0.5% difference in quenching)

Solar Neutrino Spectroscopy





arXiv: 1104.1816

Purification → Low background rates

High light yield → High Energy resolution

Calibration → Detector response understood

pep and CNO neutrino measurement

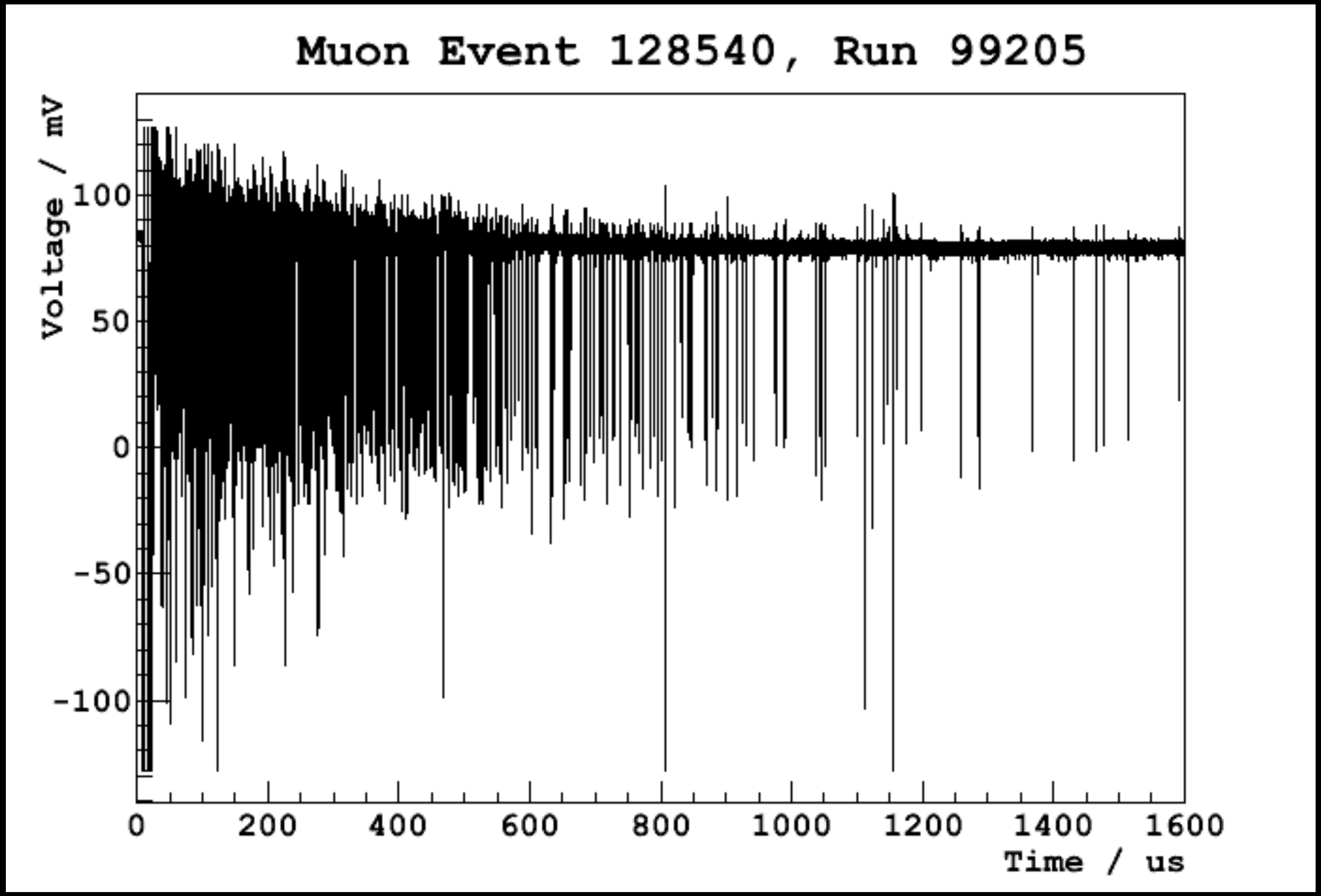
- More **challenging** than ^{7}Be ν measurement
- **Low rates**: few interaction per day/100tons
- Dominant **background** in pep energy region:
  - **β+ emitter cosmogenic ^{11}C** (27 cpd/100tons)
- Adoption of **novel techniques** to suppress ^{11}C:
  - Three Fold Coincidence
  - e+/e- pulse shape discrimination

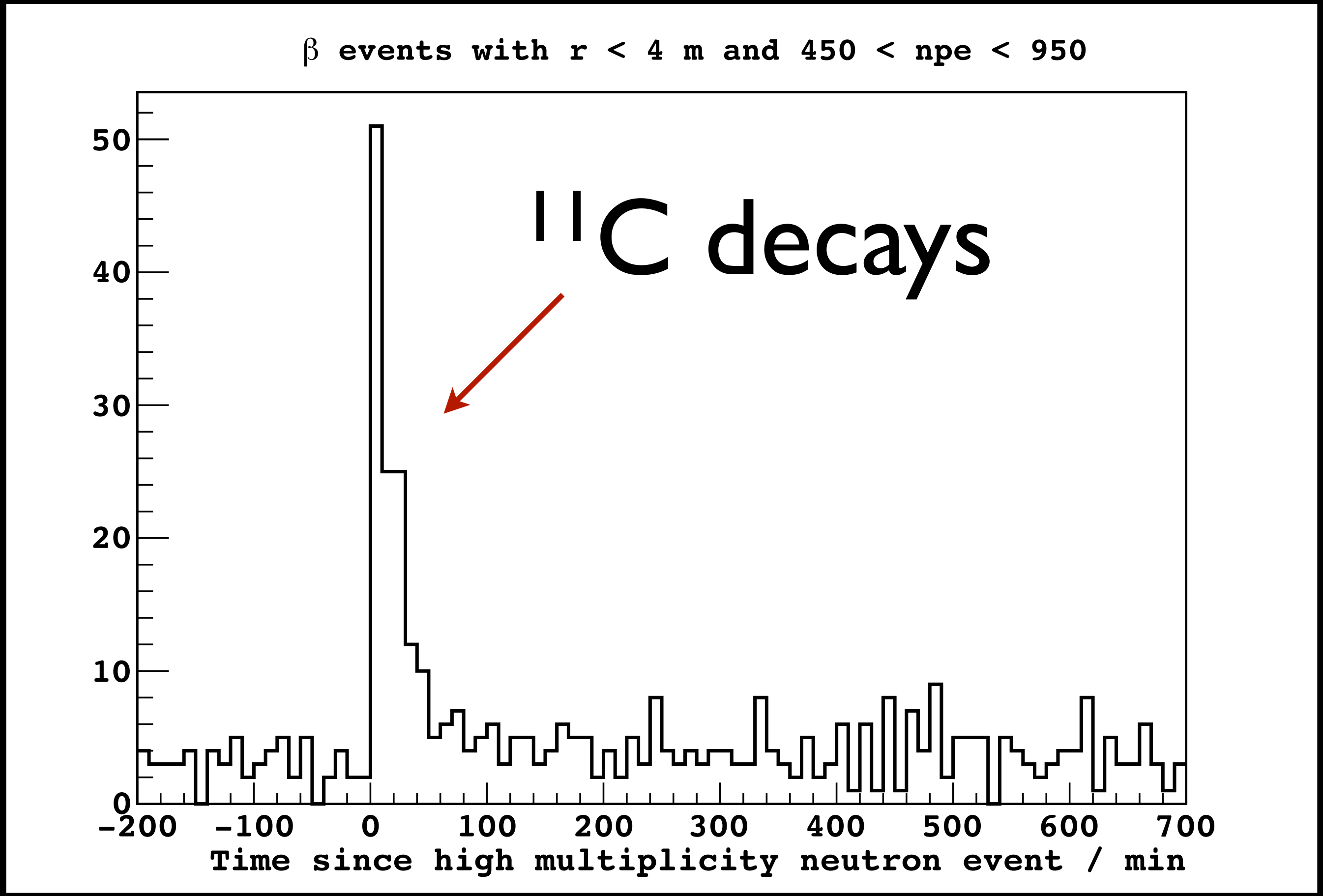
^{11}C background

- β+ emitter with Q-value = 1.98 MeV. Starts past the ^{7}Be ν energy region (~1 MeV) and spans the pep + CNO ν regions.
- ^{11}C rate in the scintillator is 28.5 ± 0.7 cpd/100 tons (~10x pep rate).
- Produced by spallation processes on ^{12}C nuclei by cosmogenic μs. Neutron production correlated with ^{11}C.
- Free neutrons captured by H in scintillator after thermalization (τ = ~255 μs, 2.2 MeV capture-γ).

Detecting cosmogenic neutrons

- Borexino electronics are not good for fast rate of events after cosmic rays: boards saturate, energy of the events is degraded to the point where often even clusters are missed.
- Detecting cosmogenic neutrons is <u>crucial</u> for ^{11}C suppression.
- In 2007 I installed 500 MHz single channel DAQ system to see cosmogenic neutrons. Triggered by the muon veto.
- System has proven very useful to characterize main DAQ response, count neutrons efficiently and observe very high multiplicity events.
- Also the parent of the Borexino Supernova Alarm System.





4000 μ/day
70 produce n

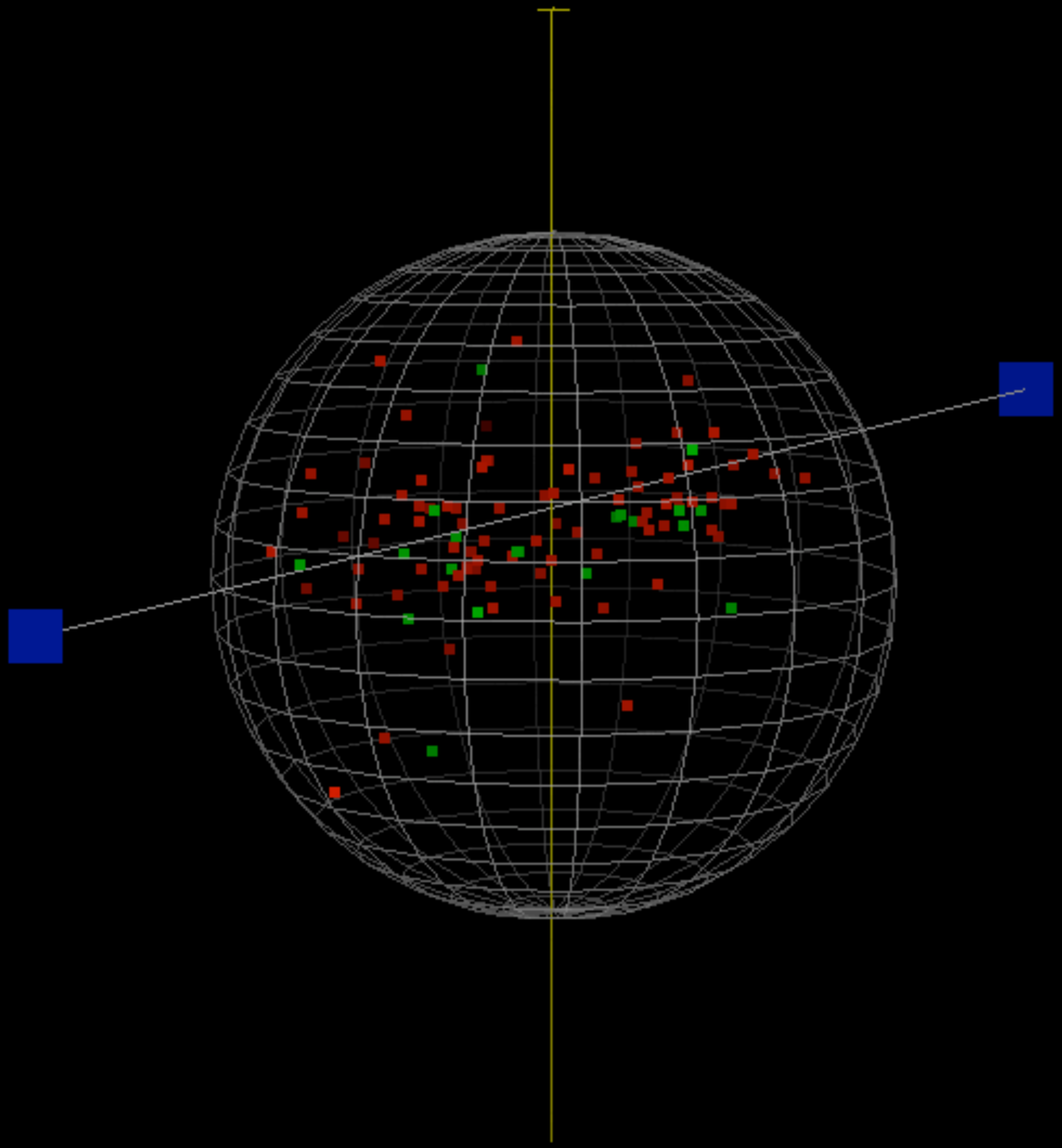
Example of high multiplicity event

~1375 neutrons after μ detected

(capture time ~255 μs)

Coinciding with neutron burst, we have a burst of ~100 events in ^{11}C energy region within the next hours

(^{11}C lifetime is 29 min)



🟦 Reconstructed μ entry/exit points

🟥 Reconstructed position of neutron

🟩 Reconstructed position of ^{11}C

Spatial correlation

Lower multiplicity event

Track of the parent μ

Neutrons within 1.6 ms after μ

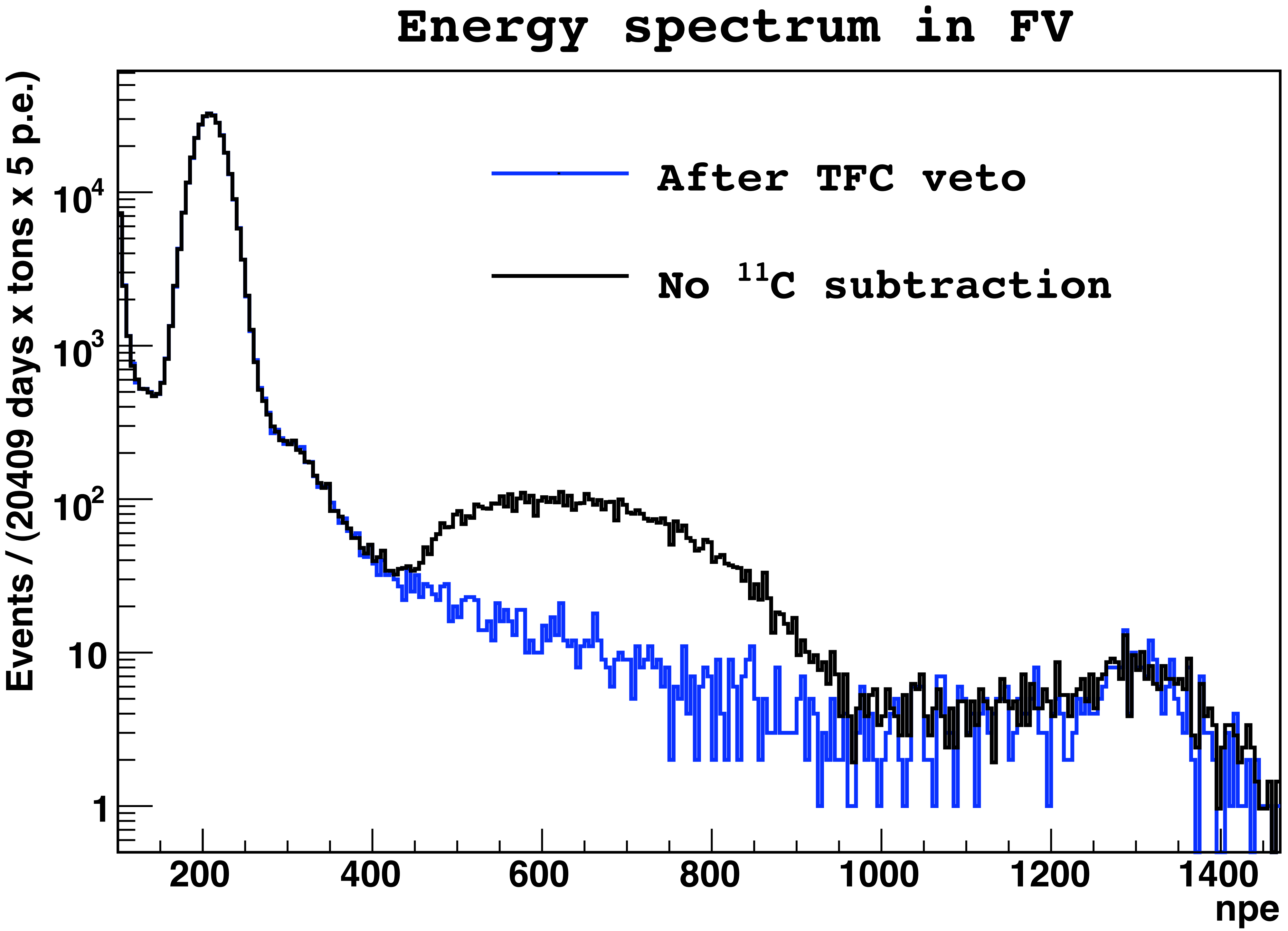
^{11}C candidates within 2 h after μ

Clear spatial correlation!

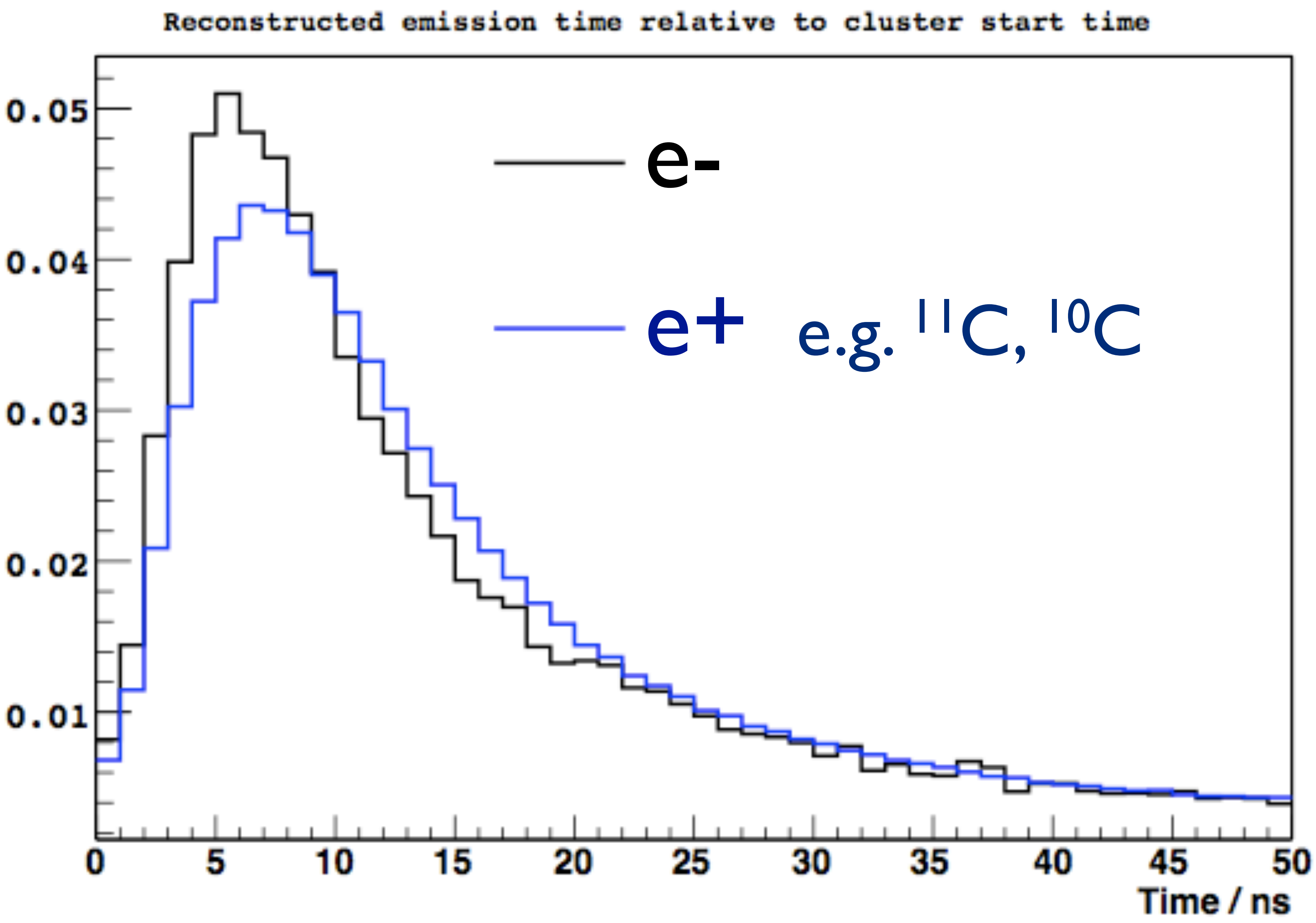
Three-fold coincidence

- We can take advantage of the time + space correlation between cosmogenic neutrons and ^{11}C decays to effectively decrease the ^{11}C background.
- We perform vetoes in space and time regions after μ + n coincidences to preferentially select regions with decreased ^{11}C background.
- Rely on position reconstruction of the cosmogenic neutrons and the track reconstruction of the parent muon.

Removed 91% of ^{11}C, keeping 48.5% exposure
^{11}C rate: 27 → 2.5 counts/day/100tons

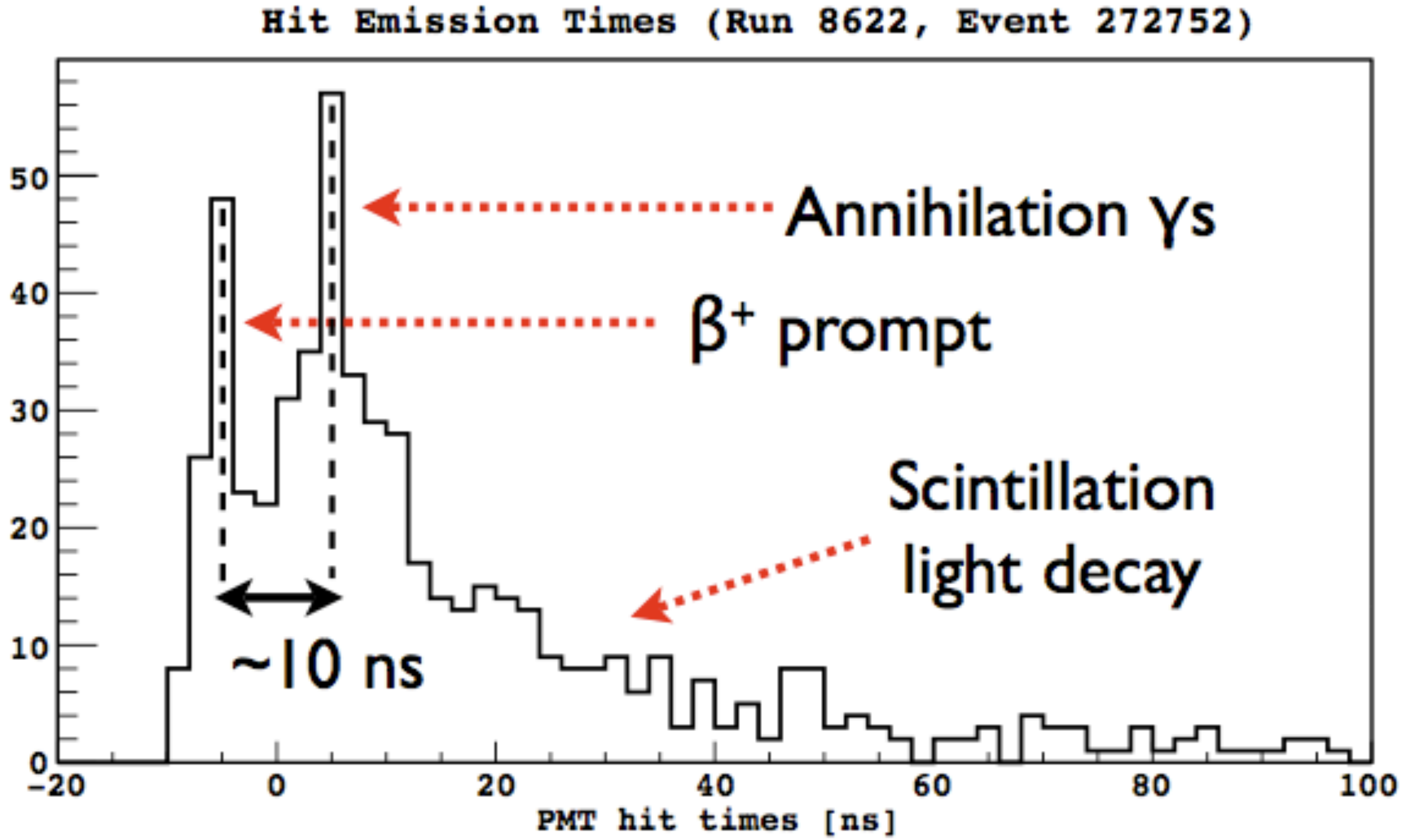


e^+/e^- Pulse Shape Discrimination



Delayed **time** distribution of $\mathbf{e^+}$ respect to $\mathbf{e^-}$ scintillation **signals** [Phys. Rev. C 83, 0105504]

e^+/e^- Pulse Shape Discrimination



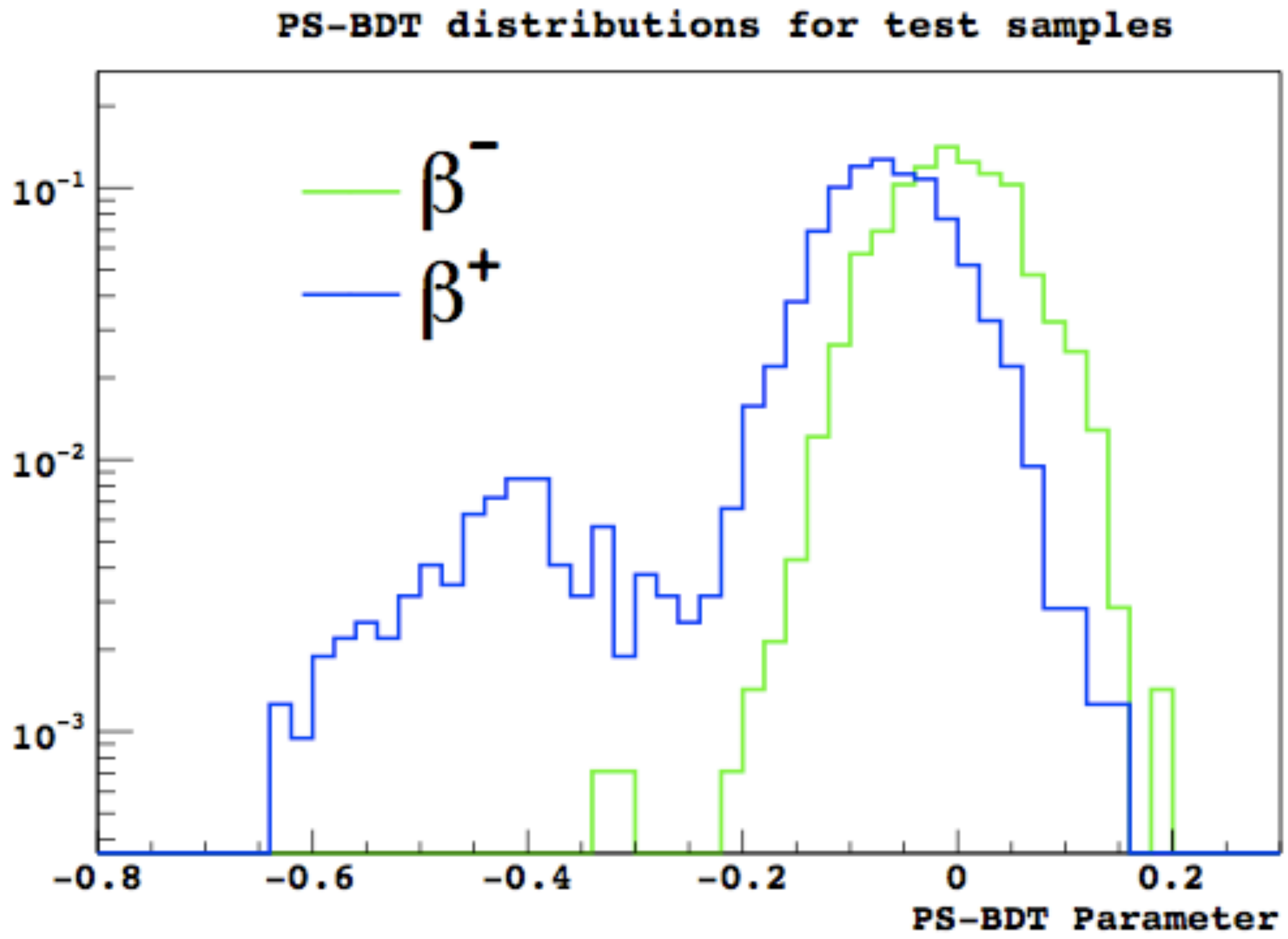
Pulse shape of ^{11}C events different from electron recoils and β^+ decays:

Finite lifetime of **O**rtho-**Positronium** (50% cases, 3ns)

Multi-site event **topology**

e^+/e^- Pulse Shape Discrimination

Optimized **p**ulse **s**hape parameter built using **B**oosted **D**ecision **T**ree algorithm

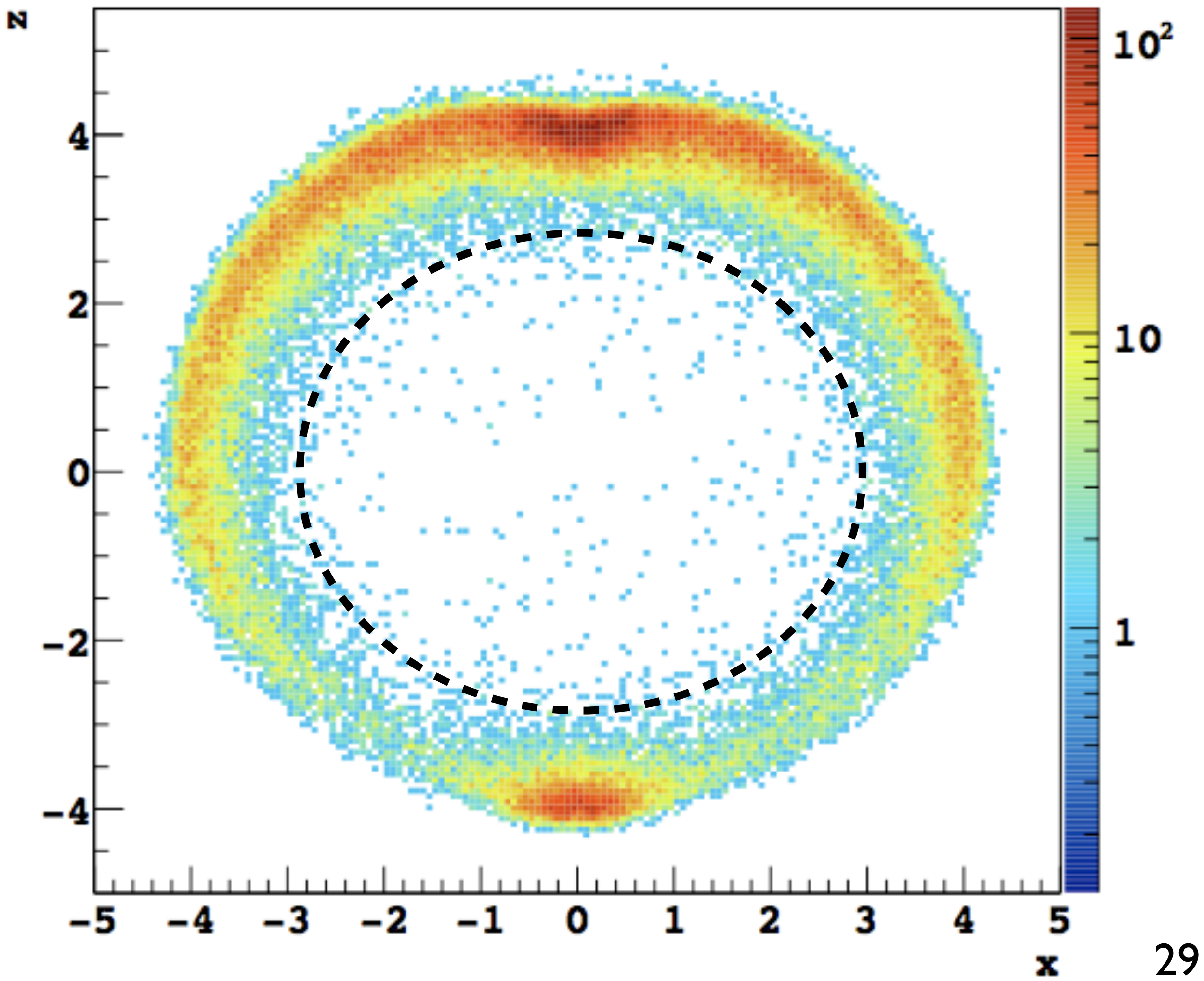


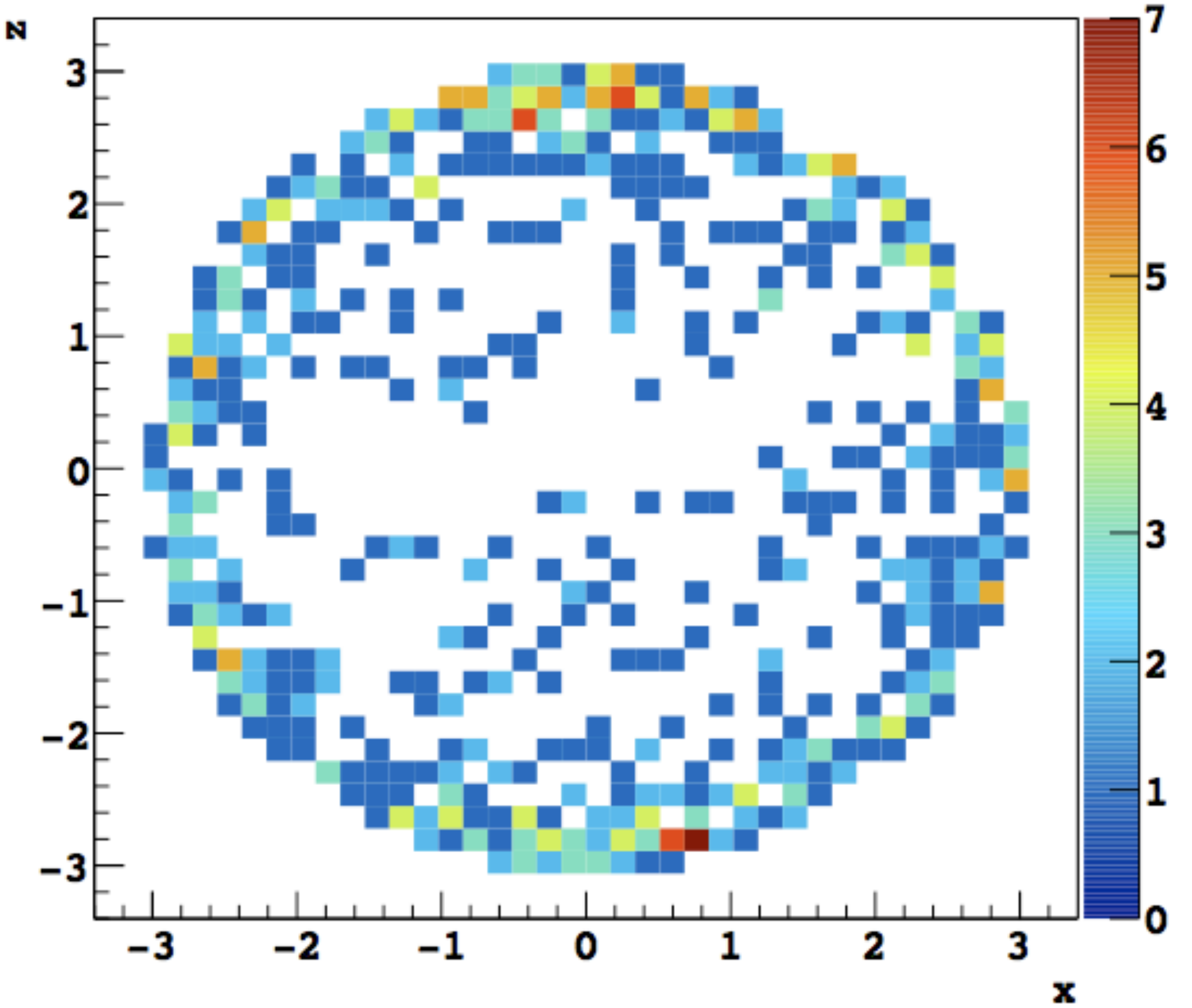
External γ-ray background

Decay of contaminants in detector **peripheral** structure

^{208}Tl, **^{214}Bi** from PMTs, Stainless Steel Sphere ...

Fiducial Volume: minimize penetration of γ-rays, without sacrificing too much exposure



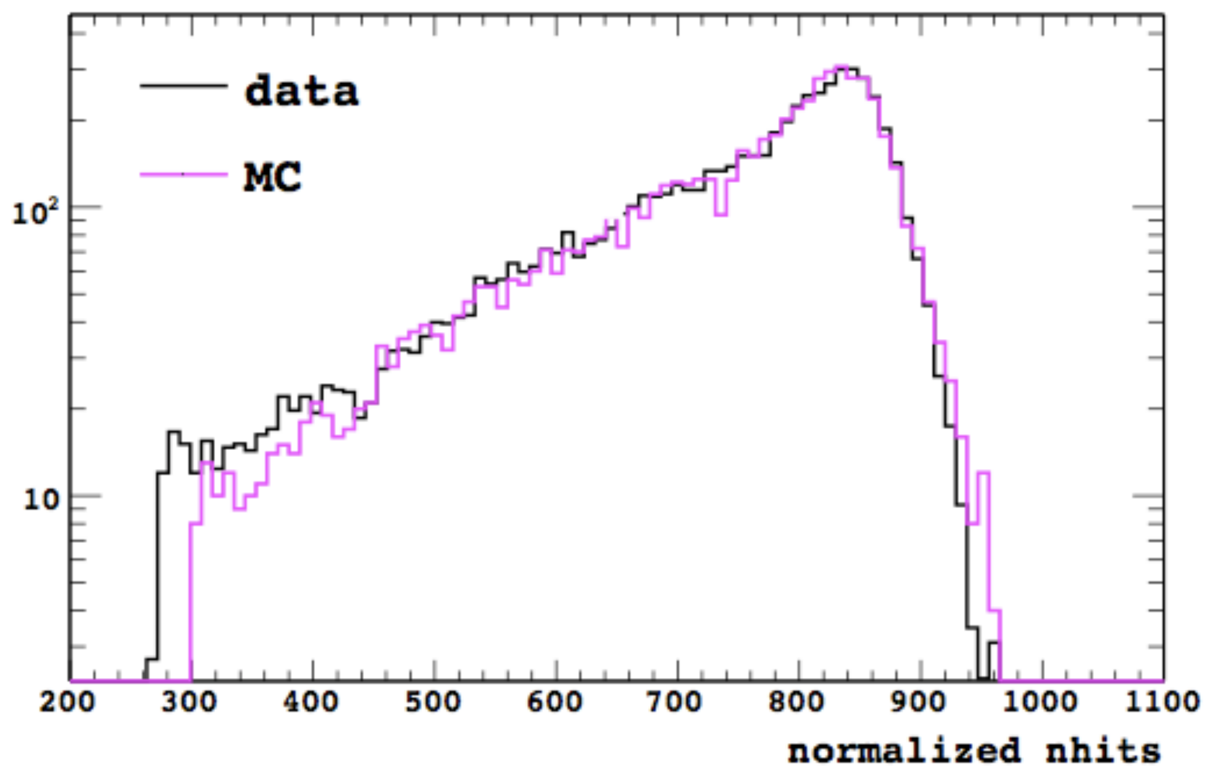


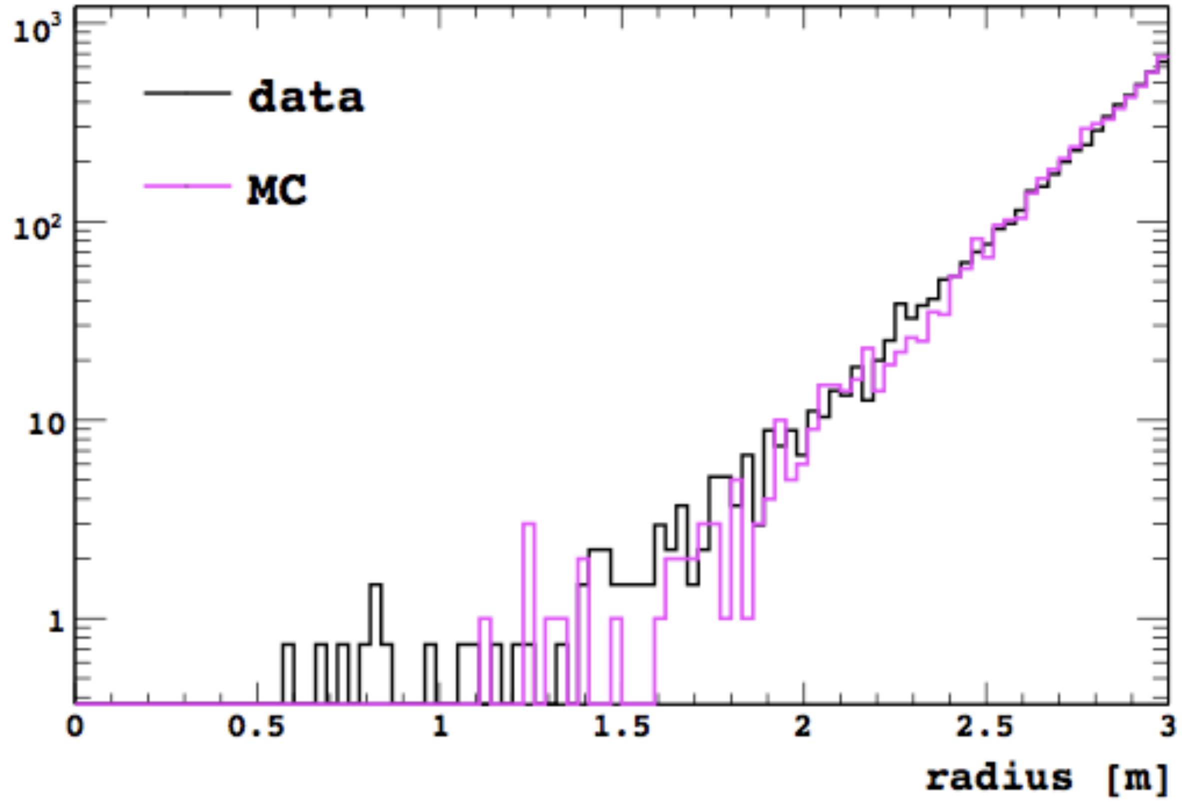
External γ-ray background

Energy spectra and **space distribution** from full Geant4-based Monte Carlo **simulation**

Simulation validated with **calibration** data:

High activity external ^{228}Th source





Short-lived cosmogenics

Power law exponent (from MC)

Rate in KamLAND

$$R = R^0 \left(\frac{E_\mu}{E_\mu^0} \right)^\alpha \frac{\Phi_\mu}{\Phi_\mu^0}$$

Rate in BX

Ratio of mean muon energies

Ratio of muon fluxes

Verified to be reliable to ~10% in ^{8}B analysis. Used to estimate ^{11}Be rate.

Isotope	Q-value (E_γ) MeV	Residual rate cpd/100tons	Residual differential rate at 1.22 MeV cpd/100tons/MeV
n	(2.22)	< 0.005	0
^{12}B	13.4	$(7.1 \pm 0.2) \times 10^{-5}$	$(2.49 \pm 0.07) \times 10^{-6}$
^{8}He	10.6	0.004 ± 0.002	$(2.6 \pm 1.2) \times 10^{-4}$
^{9}C	16.5	0.020 ± 0.006	$(1.6 \pm 0.5) \times 10^{-3}$
^{9}Li	13.6	0.022 ± 0.002	$(1.4 \pm 0.1) \times 10^{-3}$
^{8}B	18.0	0.21 ± 0.05	0.017 ± 0.004
^{6}He	3.5	0.31 ± 0.04	0.15 ± 0.02
^{8}Li	16.0	0.31 ± 0.05	0.011 ± 0.002
^{11}Be	11.5	0.034 ± 0.006	$(3.2 \pm 0.5) \times 10^{-3}$
^{10}C	3.6	0.54 ± 0.04	0
^{7}Be	(0.48)	0.36 ± 0.05	0
pep ν	1.22 MeV	**2.80±0.04**	**2.30 ± 0.03**

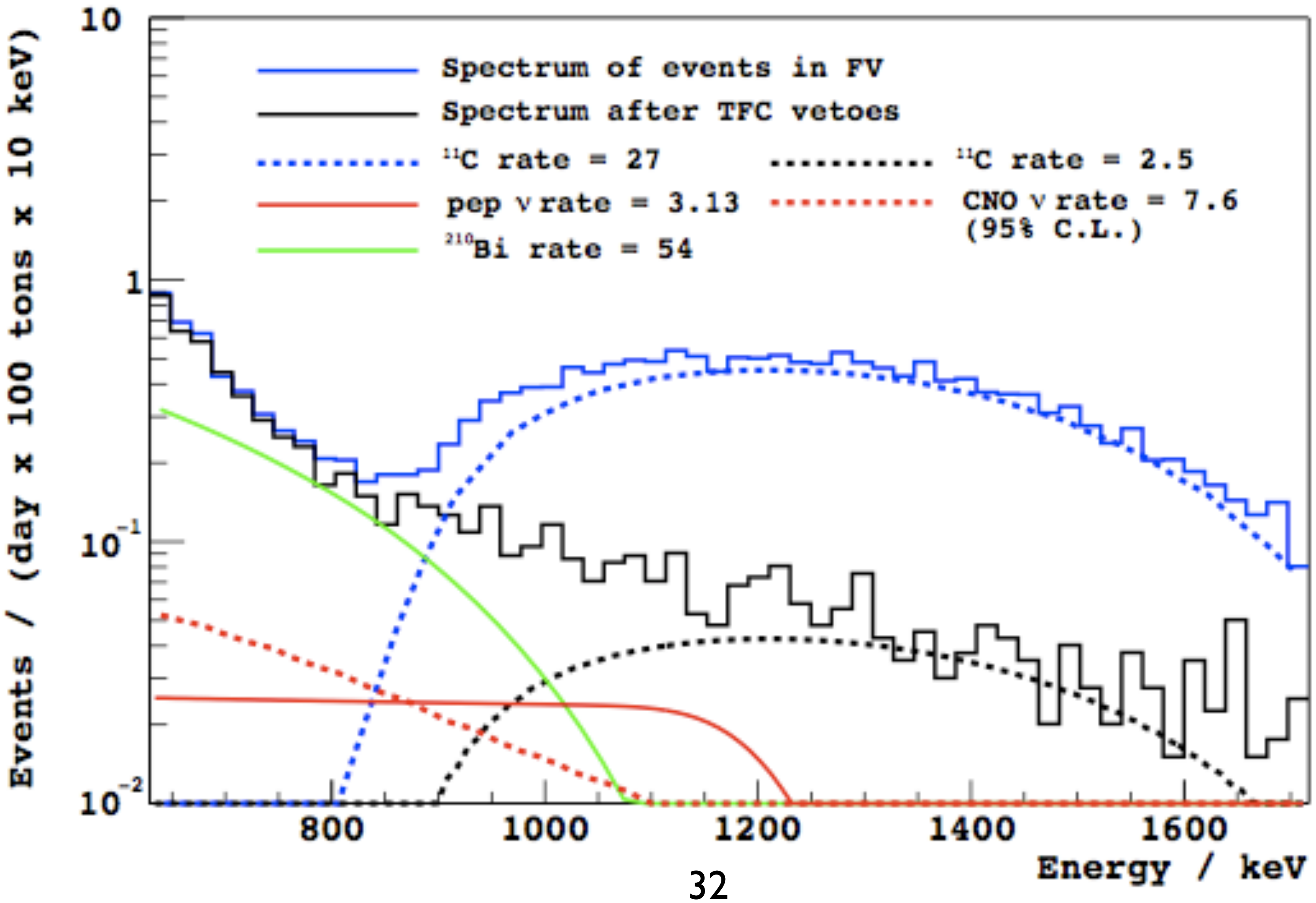
Considering 300 ms veto after cosmic muons

^{210}Bi Internal Background

^{210}Bi largest **background** in pep/CNO energy region

^{210}Bi and CNO νs energy spectra are **similar**

CNO solar neutrino spectroscopy is **tough**



Fitting Strategy

- Binned likelihood fit.
- Consider:
  - energy distribution
  - radial distribution
  - pulse shape distribution
- Fit to both spectrum of TFC-subtracted and TFC-vetoed events.

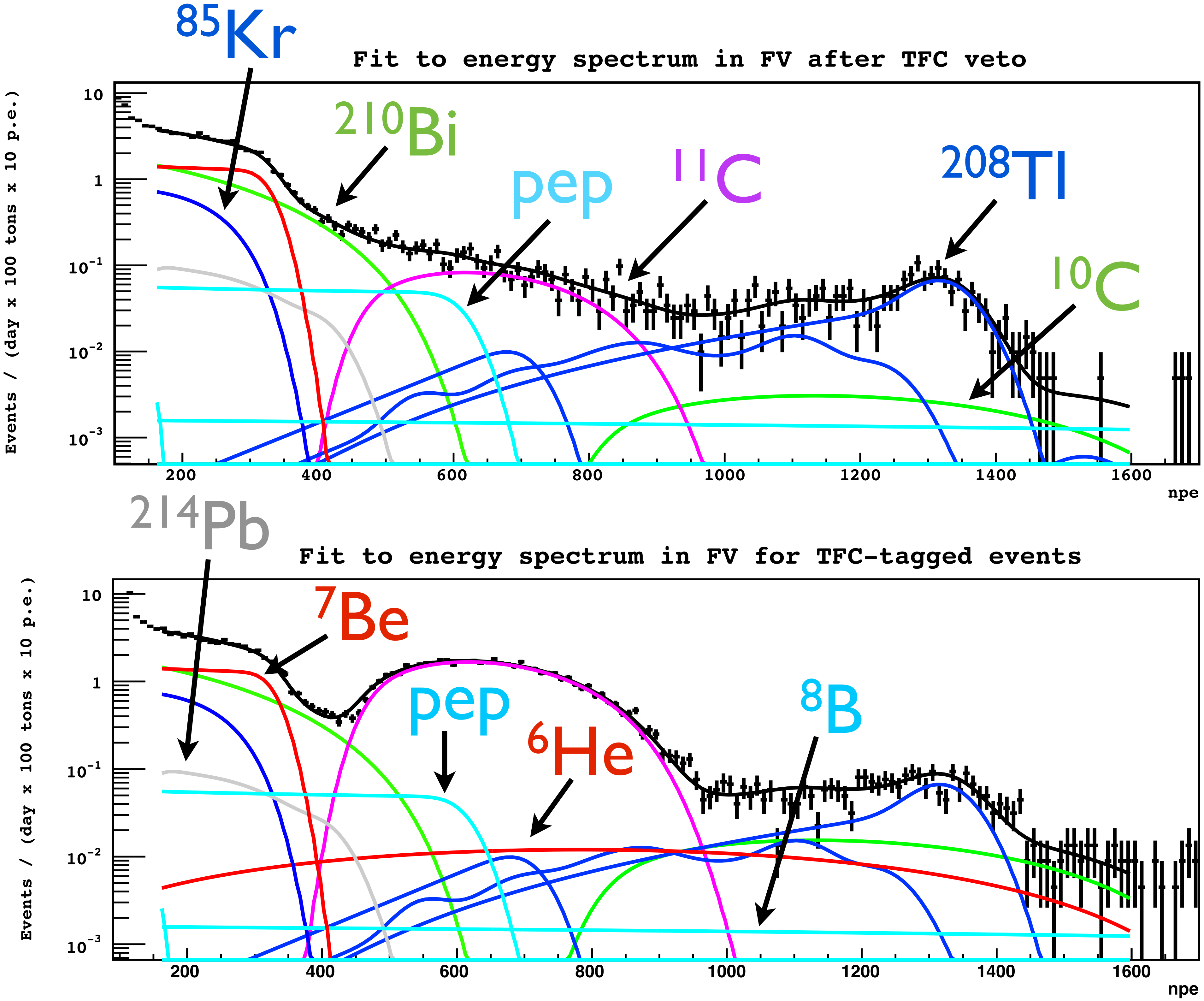
Species in the fit

Species	Rate free or fixed	Common to both spectra	In PS-BDT fit	In radial dist. fit
pep ν	free	Yes	β^-	Bulk
CNO νs	free	Yes	β^-	Bulk*
^{7}Be ν	free	Yes	β^-*	Bulk*
pp ν	fixed to 133 cpd/100t	Yes	β^-*	Bulk*
^{8}B ν	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
^{6}He	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 ^{8}B neutrinos fixed to expected values

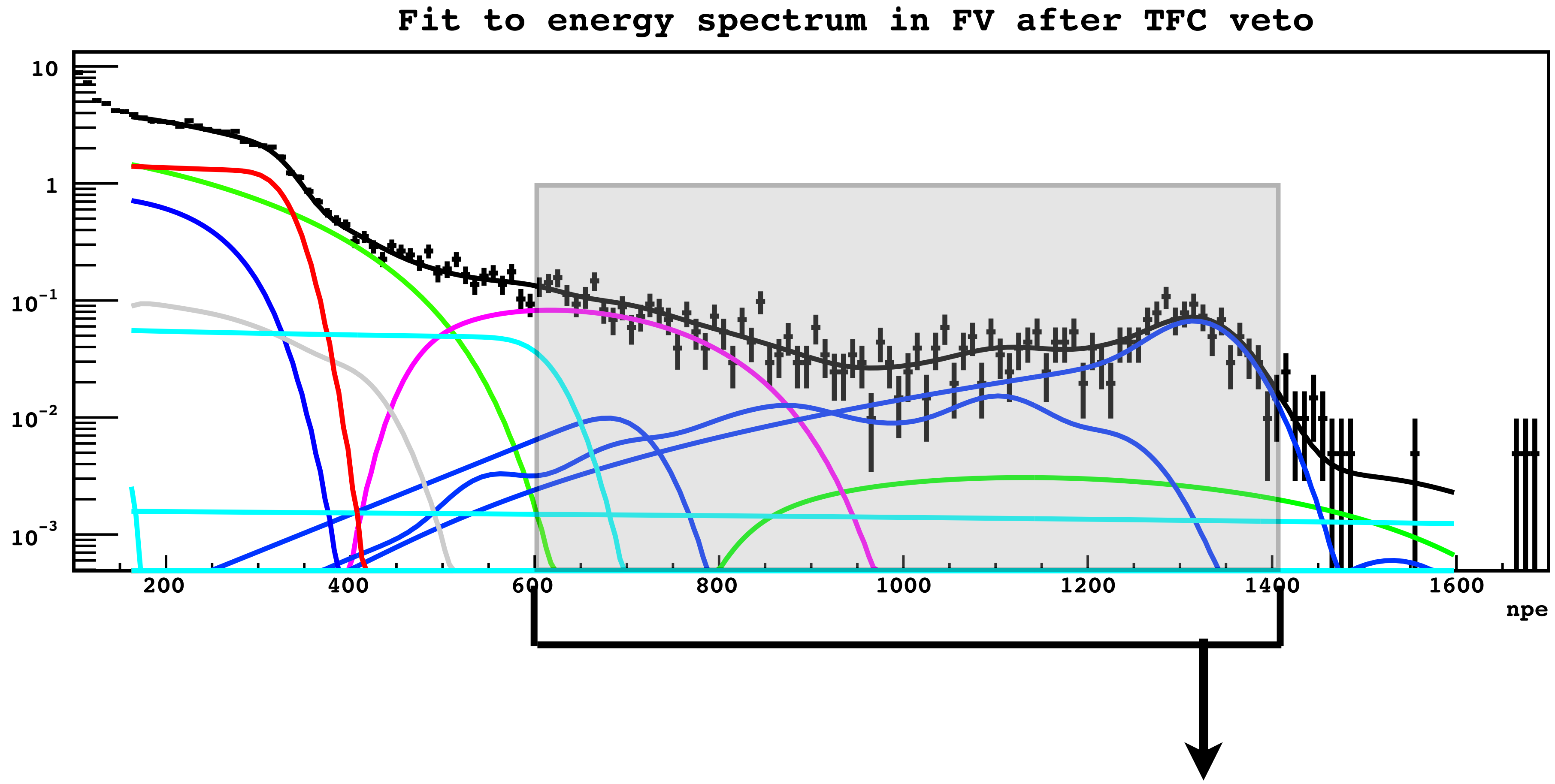
^{214}Pb fixed to value from ^{214}BiPo coincidences



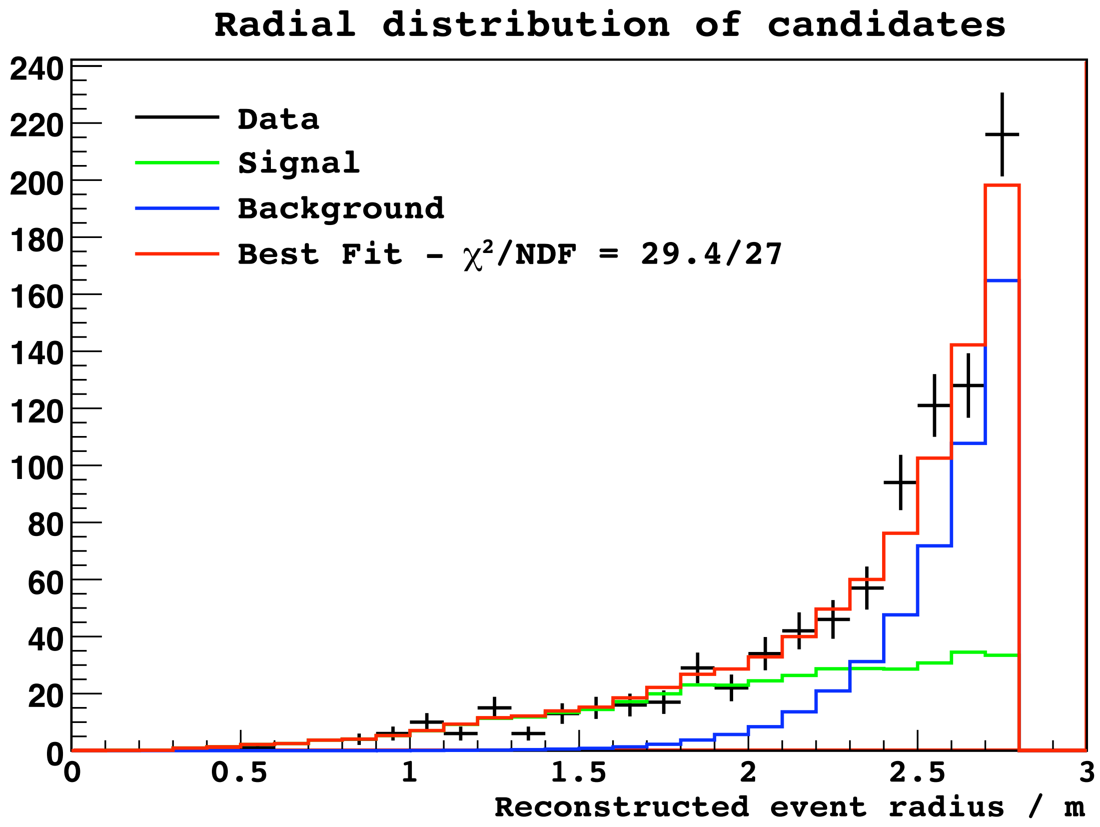
Fit to energy spectrum in FV after TFC veto

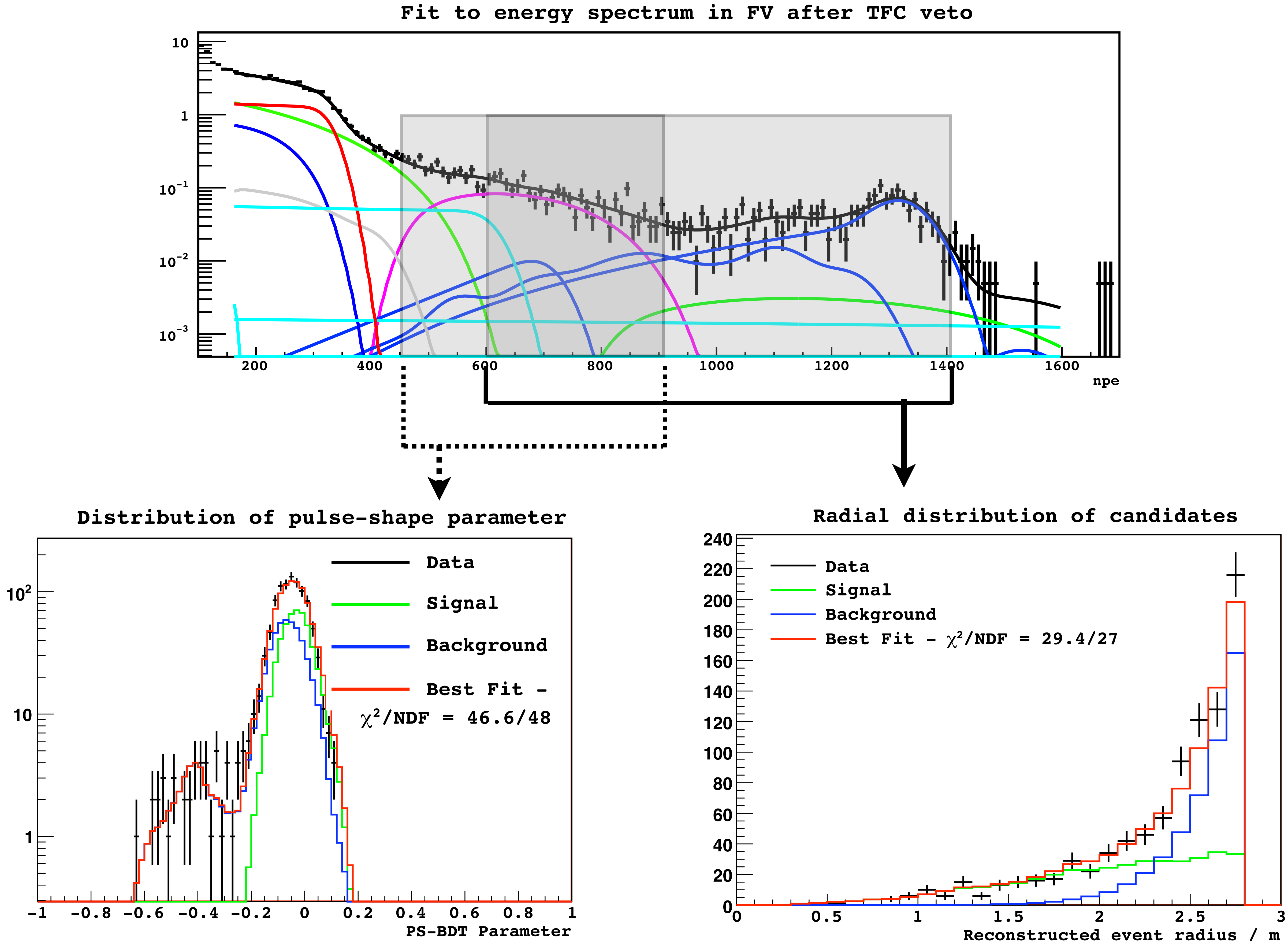
Fit to energy spectrum in FV for TFC-tagged events

Compute likelihood of hypothesis for energy spectra



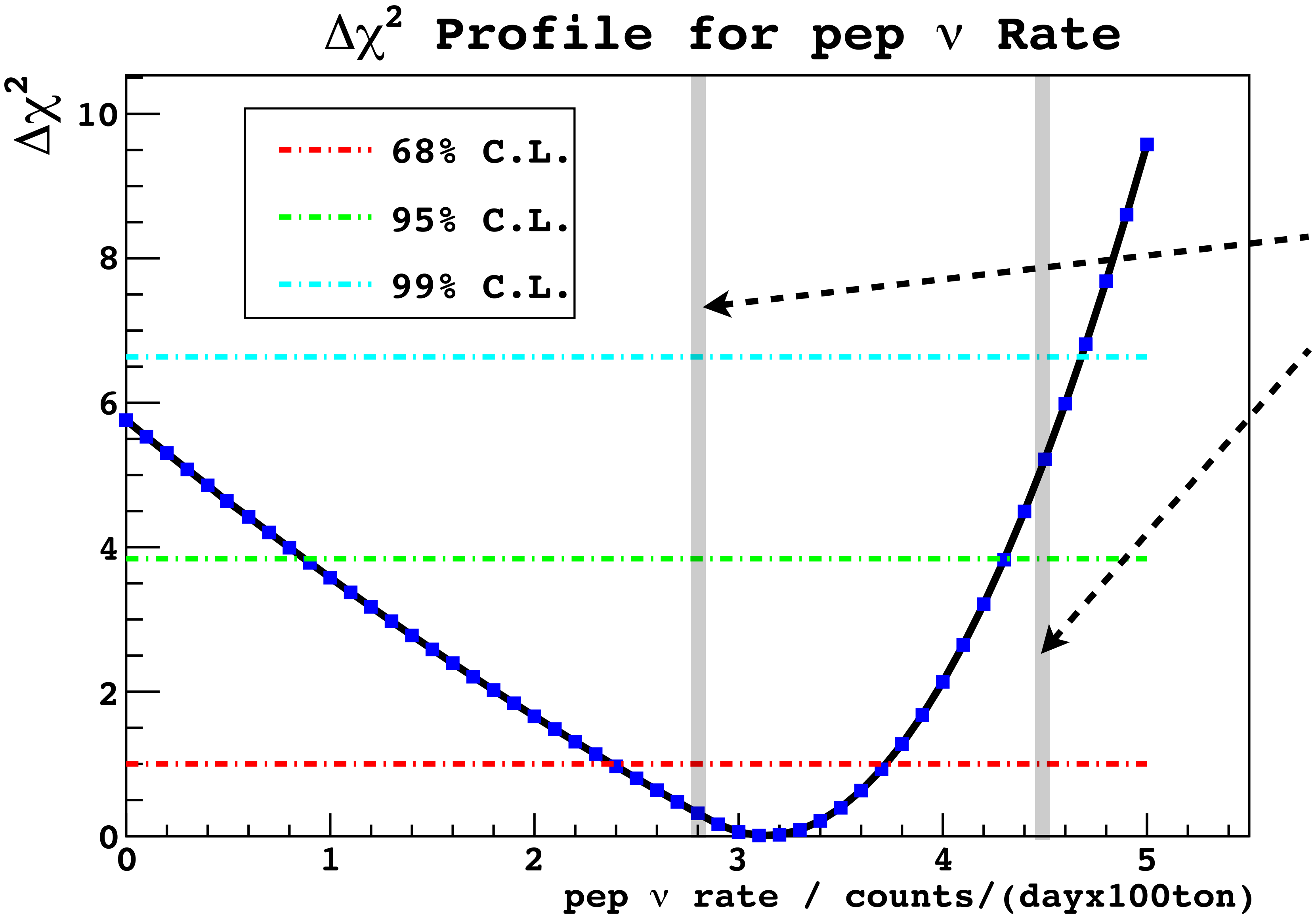
Then project region of spectrum into another parameter space, integrate signal and background components from energy spectrum and add corresponding likelihood term




Fit to energy spectrum in FV after TFC veto
10
1
10^{-1}
10^{-2}
10^{-3}
200
400
600
800
1000
1200
1400
1600
npe
Distribution of pulse-shape parameter
10^2
10
1
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
PS-BDT Parameter
Data
Signal
Background
Best Fit -
χ^2/NDF = 46.6/48
Radial distribution of candidates
240
220
200
180
160
140
120
100
80
60
40
20
0
0
0.5
1
1.5
2
2.5
3
Reconstructed event radius / m
Data
Signal
Background
Best Fit - χ^2/NDF = 29.4/27

Results

pep interaction rate



SSM Prediction:

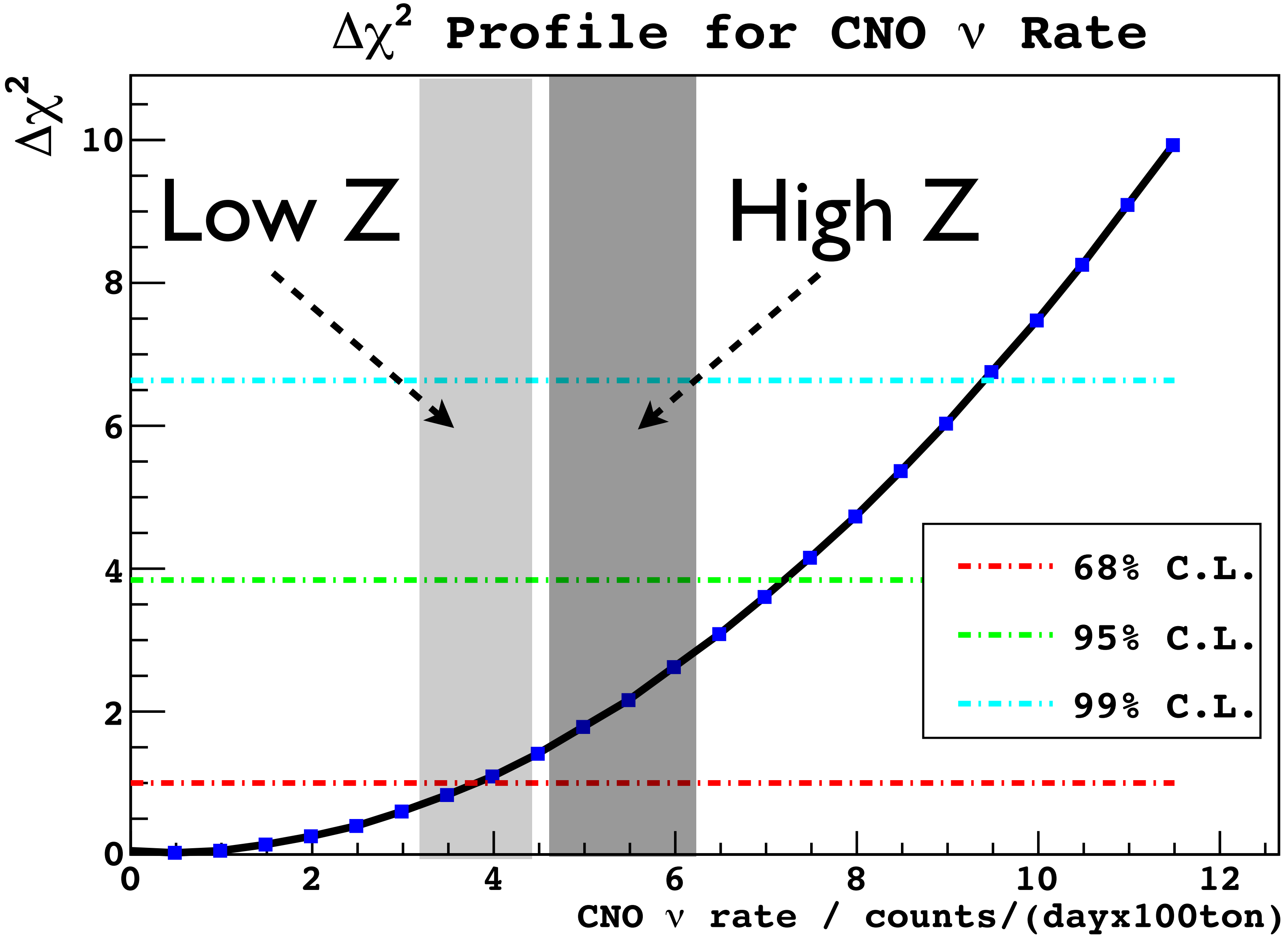
MSW-LMA

No Oscillation

Absence of
signal disfavored
at 98% C.L.

$3.1 \pm 0.6_{stat}$ counts/day/100ton

CNO interaction rate

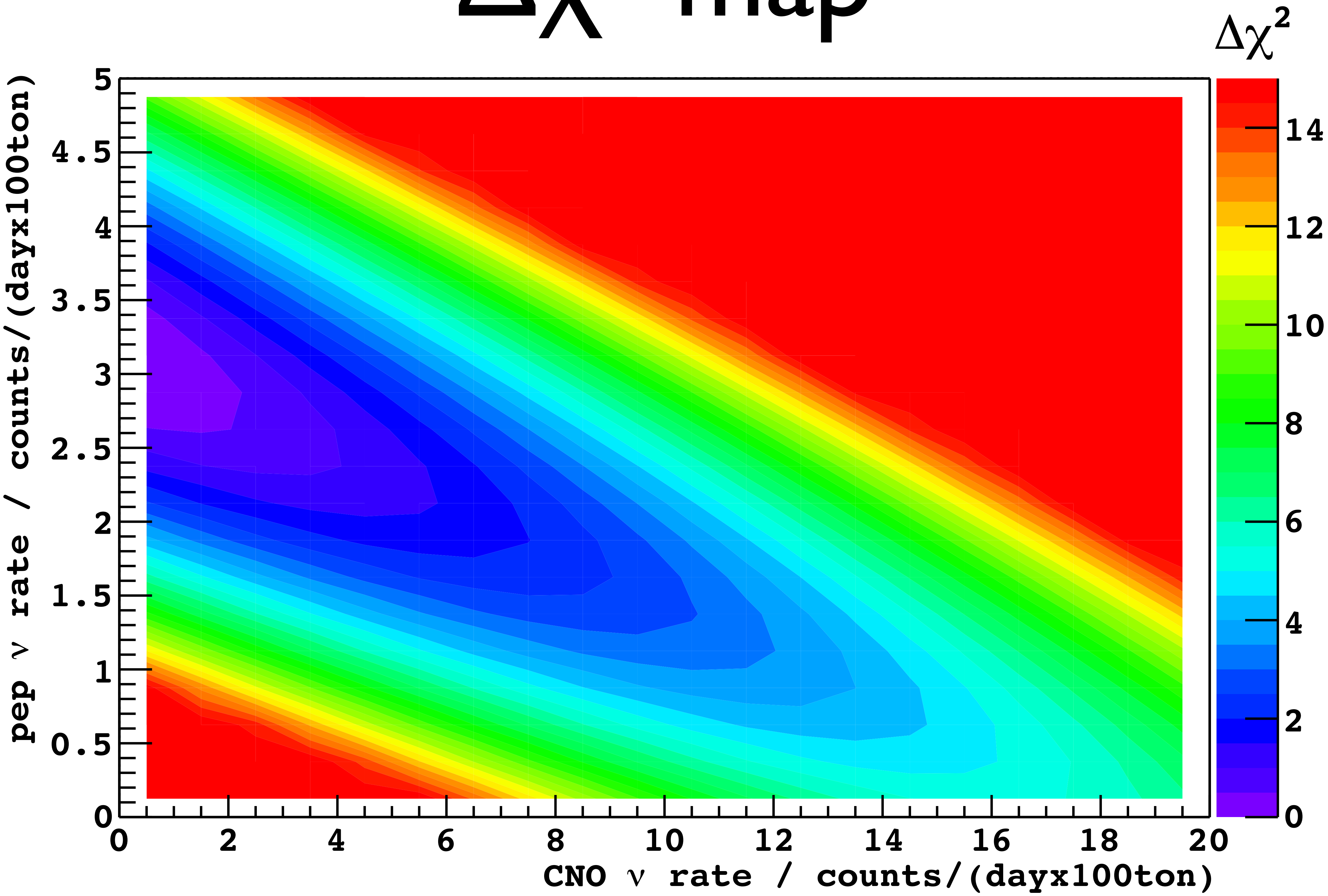


Assuming MSW-LMA

Upper limit (95% C.L.) <7.1 stat only counts/day/ 100ton

pep fixed at SSM predicted value: 2.8 counts/day/ 100ton

$\Delta\chi^2$ map



Systematic Uncertainties

- Fit stability under change of certain parameters (e.g. fit range, binning).
- Fit stability for different exposure.
- Event energy estimated by either number of PMTs hit or total charge of the event.
- Uncertainty in the spectral shape of the components.
- Statistical uncertainty in pulse shape parameter fitting PDFs.

Systematic Uncertainties

- Effect associated with γ-rays present in pulse shape distributions.
- Uncertainty in total exposure.
- Uncertainties in fixed rates (pp, ^{8}B, ^{214}Pb).
- Exclusion of short-lived cosmogenics and decays from ^{232}Th chain.

Total systematic uncertainty in pep rate: 10%
Increase of 0.8 counts/day/100ton in CNO limit

Background Results

Background	Interaction rate [counts/(day·100 ton)]	Expected rate [counts/(day·100 ton)]
^{85}Kr	19^{+5}_{-3}	30 ± 6
^{210}Bi	55^{+3}_{-5}	NA
^{11}C	27.4 ± 0.3	28 ± 5
^{10}C	0.6 ± 0.2	0.54 ± 0.04
^{6}He	< 2	0.31 ± 0.04
^{40}K	< 0.4	-
^{234m}Pa	< 0.5	0.57 ± 0.05
Ext. γ	2.5 ± 0.2	-

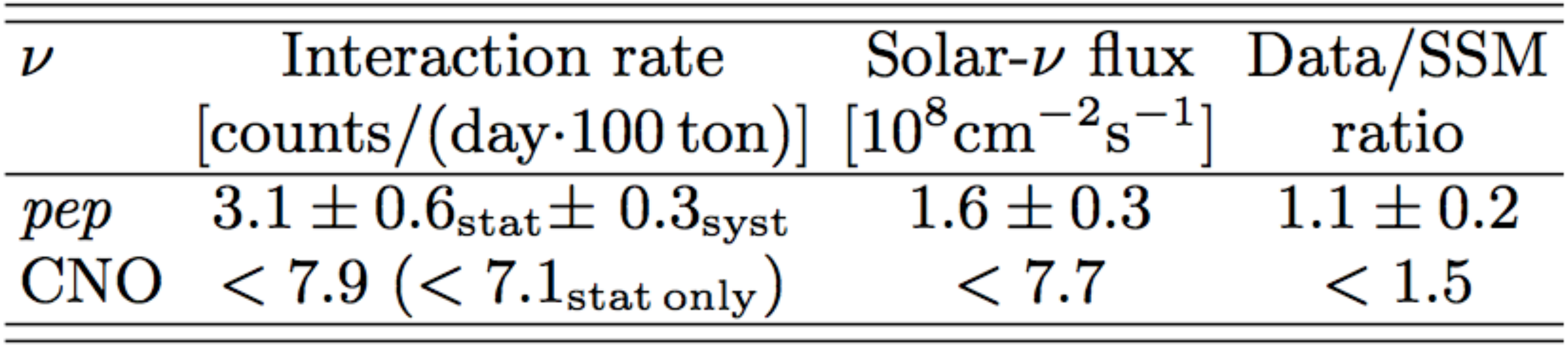
^{85}Kr - Rb coincidence

Extrapolated from KamLAND

^{214}Bi-Po coincidence

Backgrounds in agreement with expectations

Summary of results



ν	Interaction rate [counts/(day·100 ton)]	Solar-ν flux [$10^8 \mathrm{cm}^{-2}\mathrm{s}^{-1}$]	Data/SSM ratio
pep	$3.1 \pm 0.6_{\mathrm{stat}} \pm 0.3_{\mathrm{syst}}$	1.6 ± 0.3	1.1 ± 0.2
CNO	< 7.9 ($< 7.1_{\mathrm{stat\ only}}$)	< 7.7	< 1.5

Solar flux assuming MSW-LMA

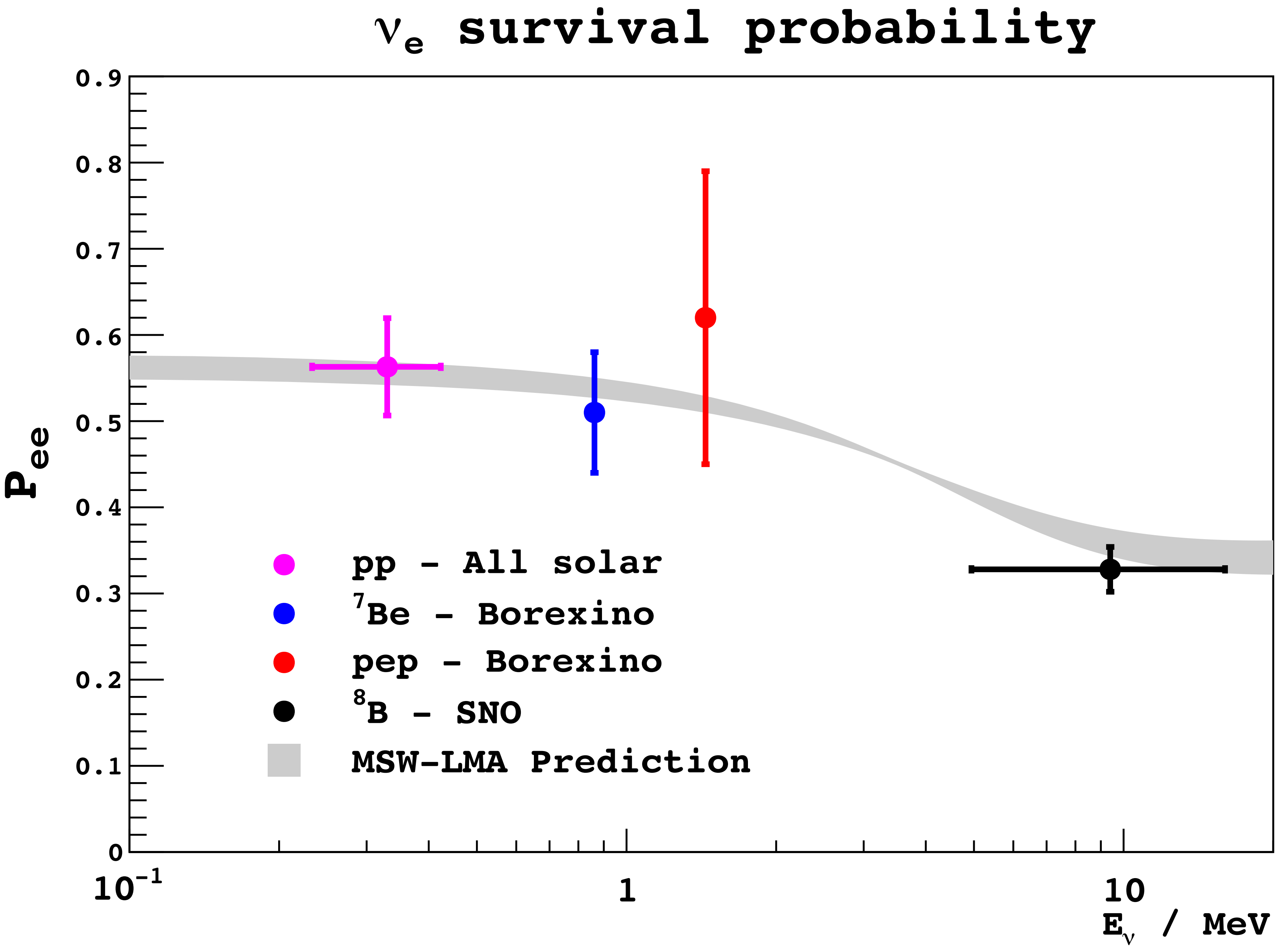
Ratio of High Metallicity SSM

CNO flux limit 1.5 times High Z prediction

Results consistent with MSW-LMA and SSM

Absence of solar neutrino signal ruled out at 99.97% C.L.

Survival probability



No oscillation hypothesis disfavored at 97% C.L.

Borexino Phase II

- Since July, 2010 we have undertaken a series of purification campaigns to decrease radioactive backgrounds.
- Nitrogen stripping has been successful at removing ^{85}Kr. No evidence since January.
- Moderate success at removing ^{210}Pb(Bi) by Water Extraction.
- Operations on-going and hope to decrease ^{210}Bi significantly and possibly ^{210}Po.
- Decrease of ^{210}Po may be necessary to obtain an independent estimate of ^{210}Bi contamination and a more precise measurement of CNO ν rate [arXiv:1104.1335v1].

Conclusion

- We have successfully decreased the dominant background, ^{11}C, by a factor of 10.
- We have performed a multivariate fit to measure for the first time pep solar neutrinos and place the strongest constraint on the CNO solar neutrino flux.
- Results are consistent with SSM + MSW-LMA.
- The future is promising.

THE END

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Technische Universität – Muenchen, Germany

University of Massachusetts at Amherst, MA, USA

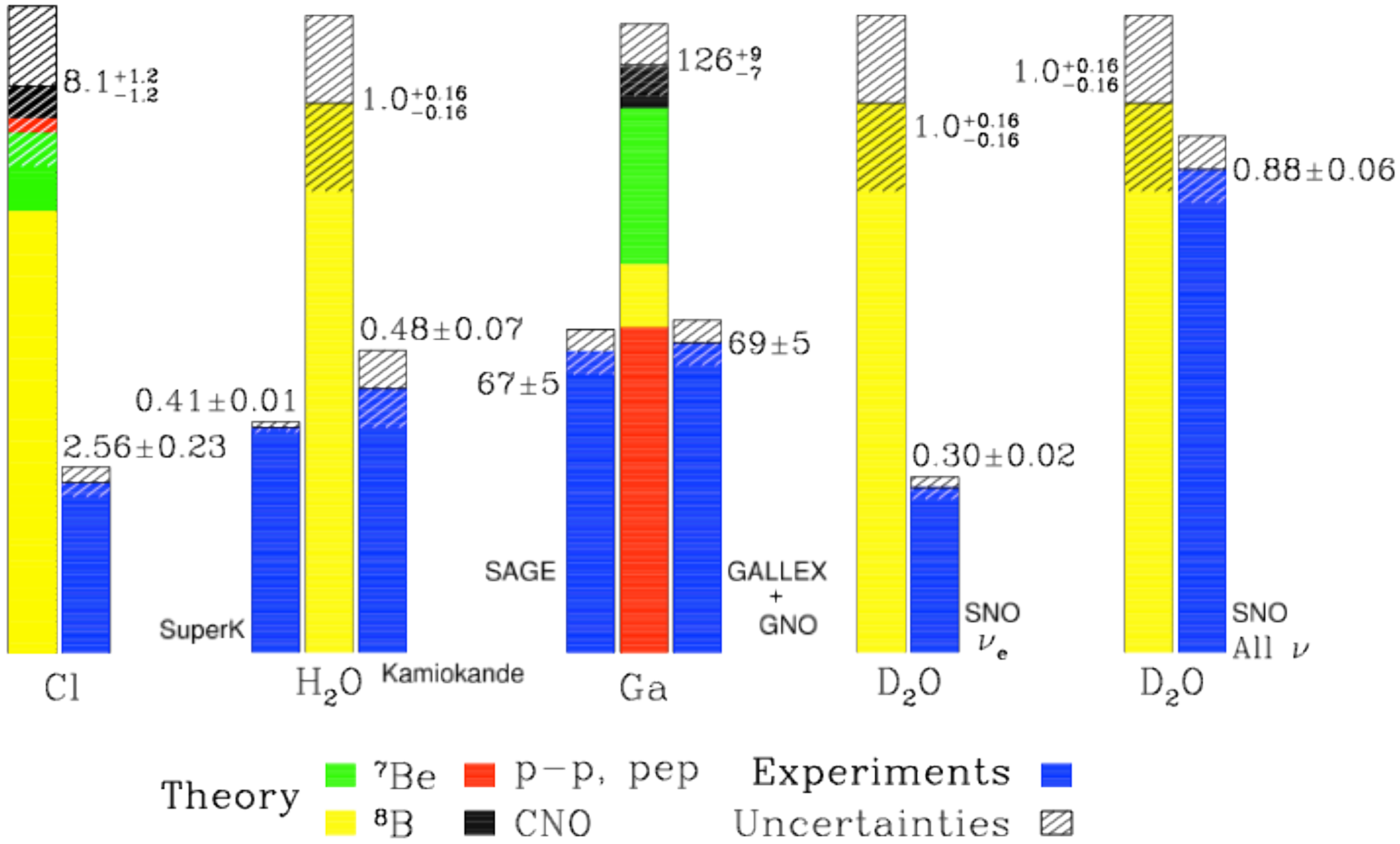
University of Moscow – Moscow, Russia

Virginia Tech – Blacksburg, VA, USA

University of Hamburg – Hamburg, Germany

Backup Slides

The Solar Neutrino Problem



Bahcall-Serenelli 2005 [BS05(OP)]

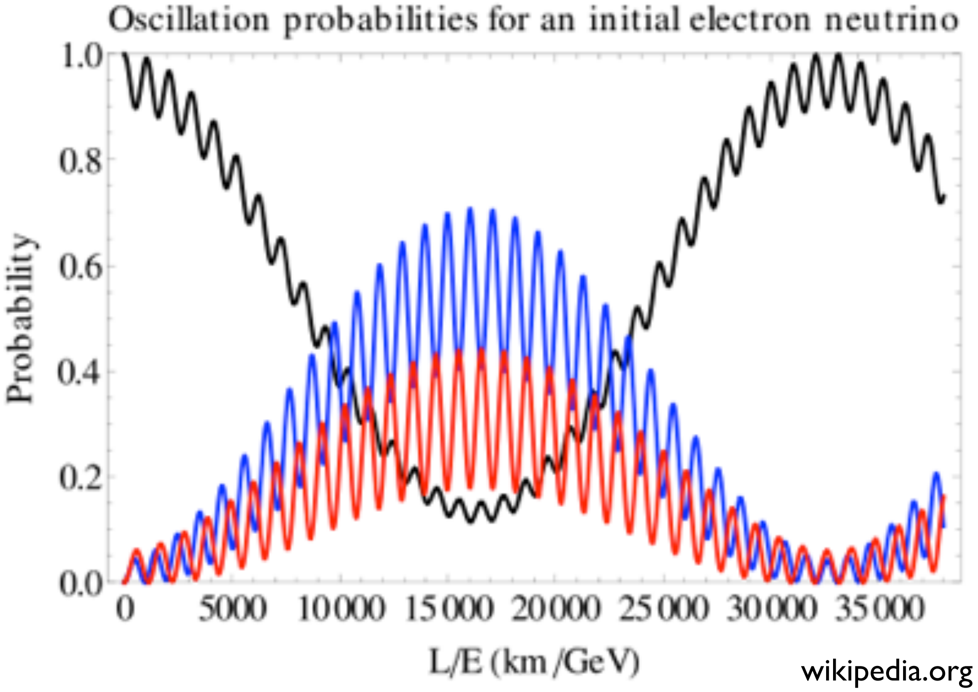
Neutrino Oscillations

- Producing a neutrino in a flavour eigenstate produces a superposition of mass eigenstates
- Phase differences acquired in mass eigenstate propagation change apparent flavor content
- In solar neutrinos we see a phase averaged survival probability:

$$P_{ee} = \cos^4(\theta_{13})\left(1 - \frac{1}{2}\sin^2(2\theta_{12})\right) + \sin^4(\theta_{13})$$

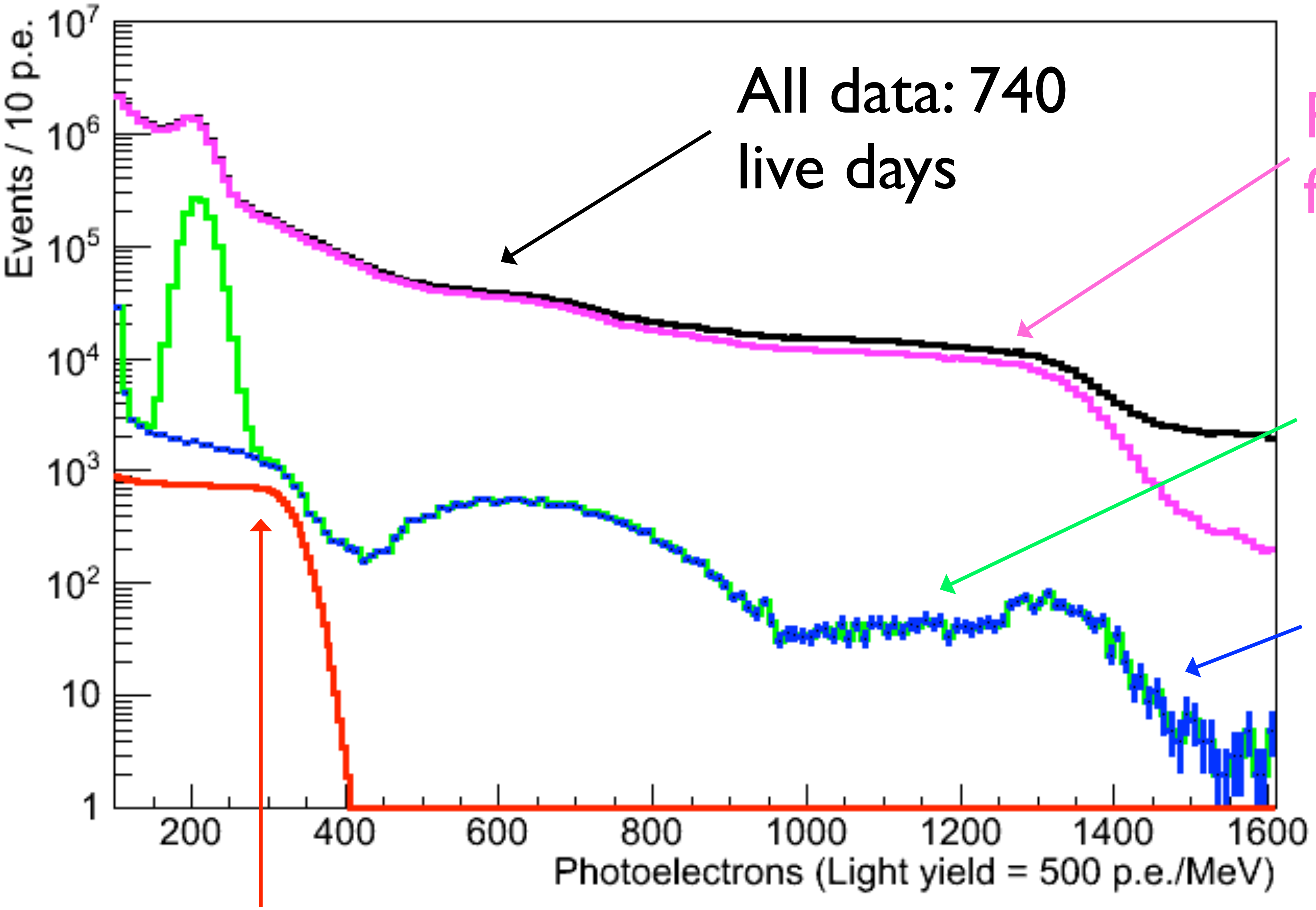
$$\sim \left(1 - \frac{1}{2}\sin^2(2\theta_{12})\right) \qquad (\theta_{13} = 0)$$

Symmetry Magazine



wikipedia.org

Borexino Data



All data: 740 live days

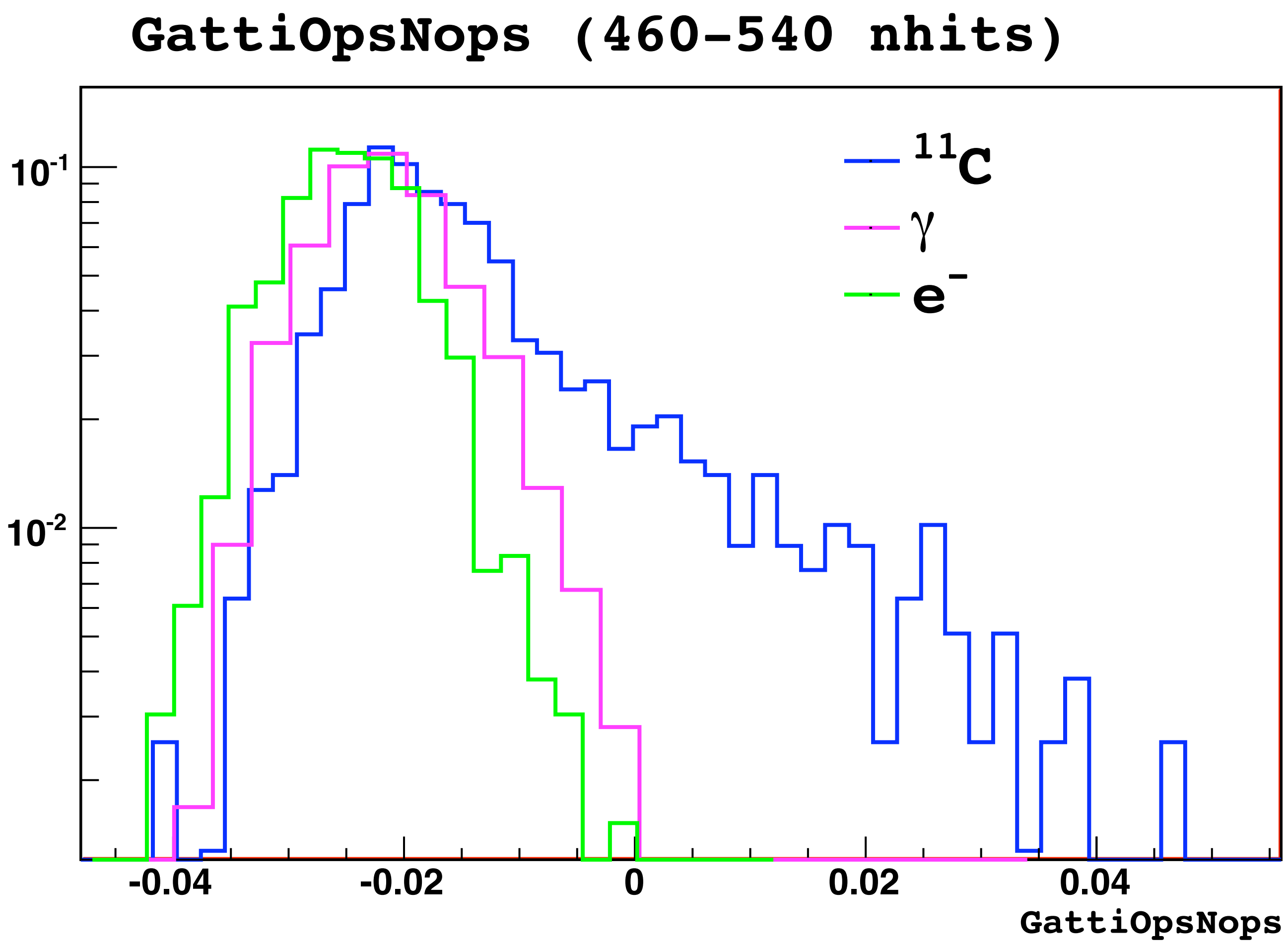
Remove muons + followers

Fiducial Volume + high level

Statistically subtract alphas

Expected ^{7}Be signal

e^+/e^- Pulse Shape Distribution



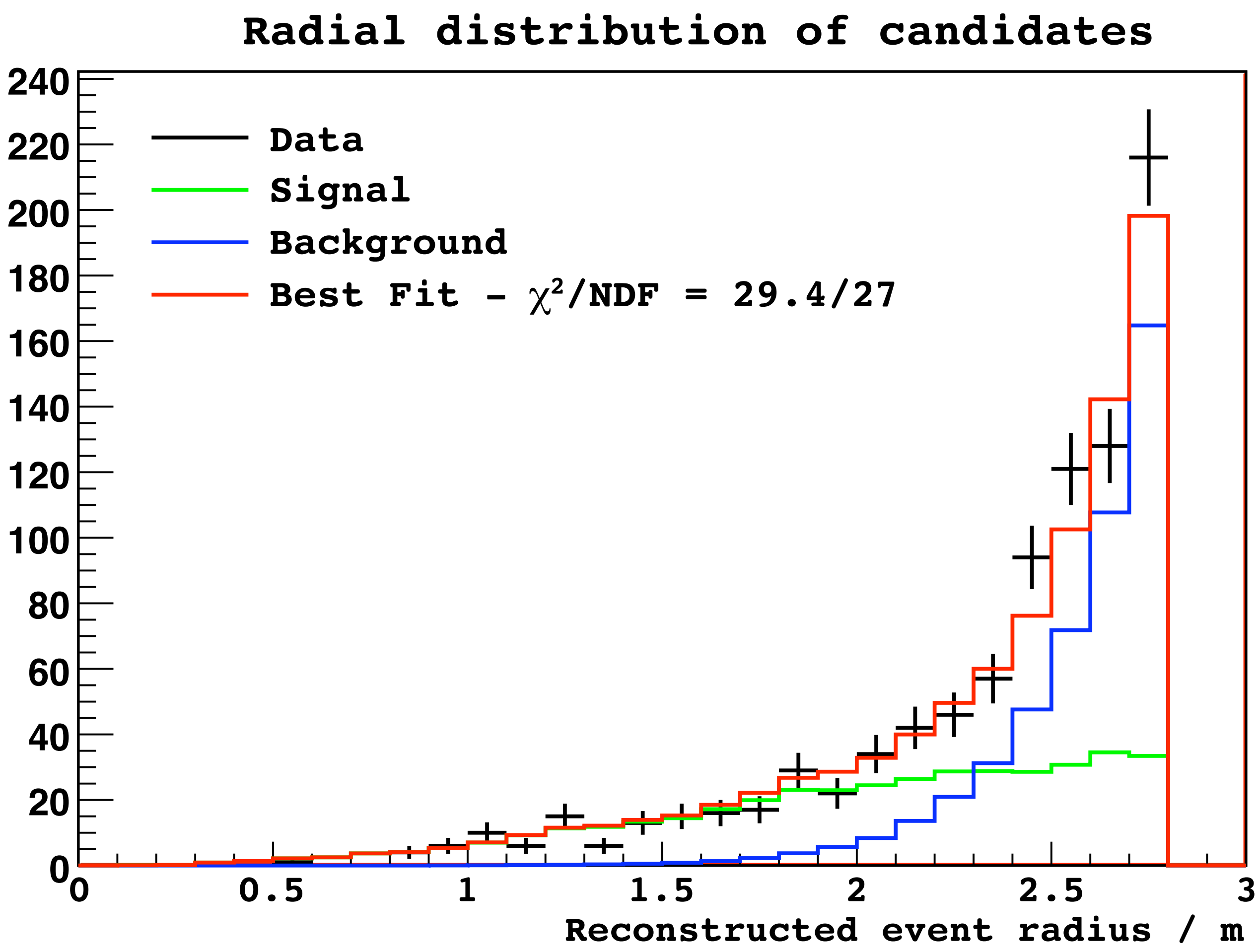
Easiest to understand by looking at one of the highest ranked of 36 variables

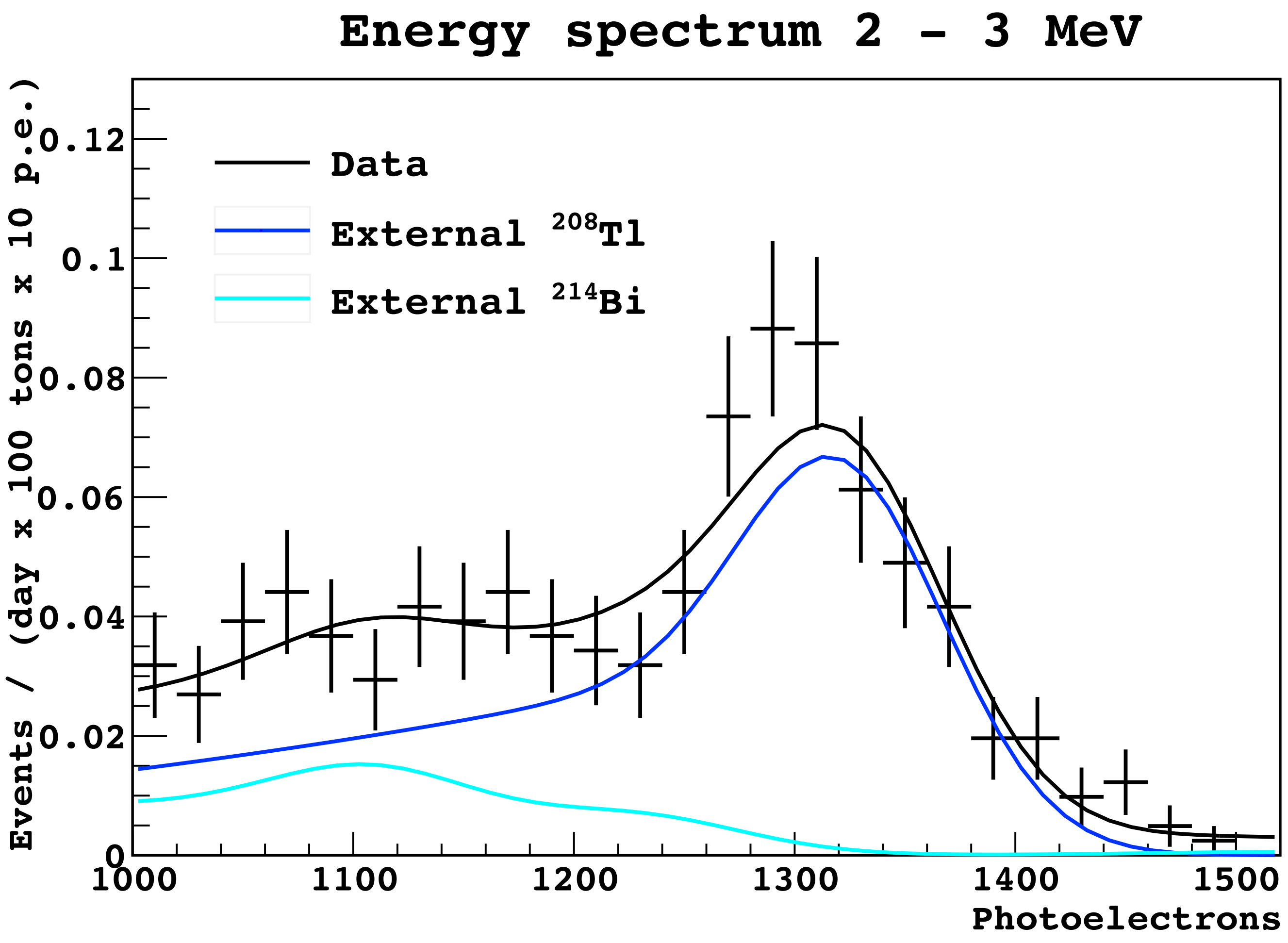
Well reproduced by full Monte Carlo

Shift in peak position due to difference in event topology

Tail in e^+ distribution due to increasing Δt of ortho-positronium event.

External γ background

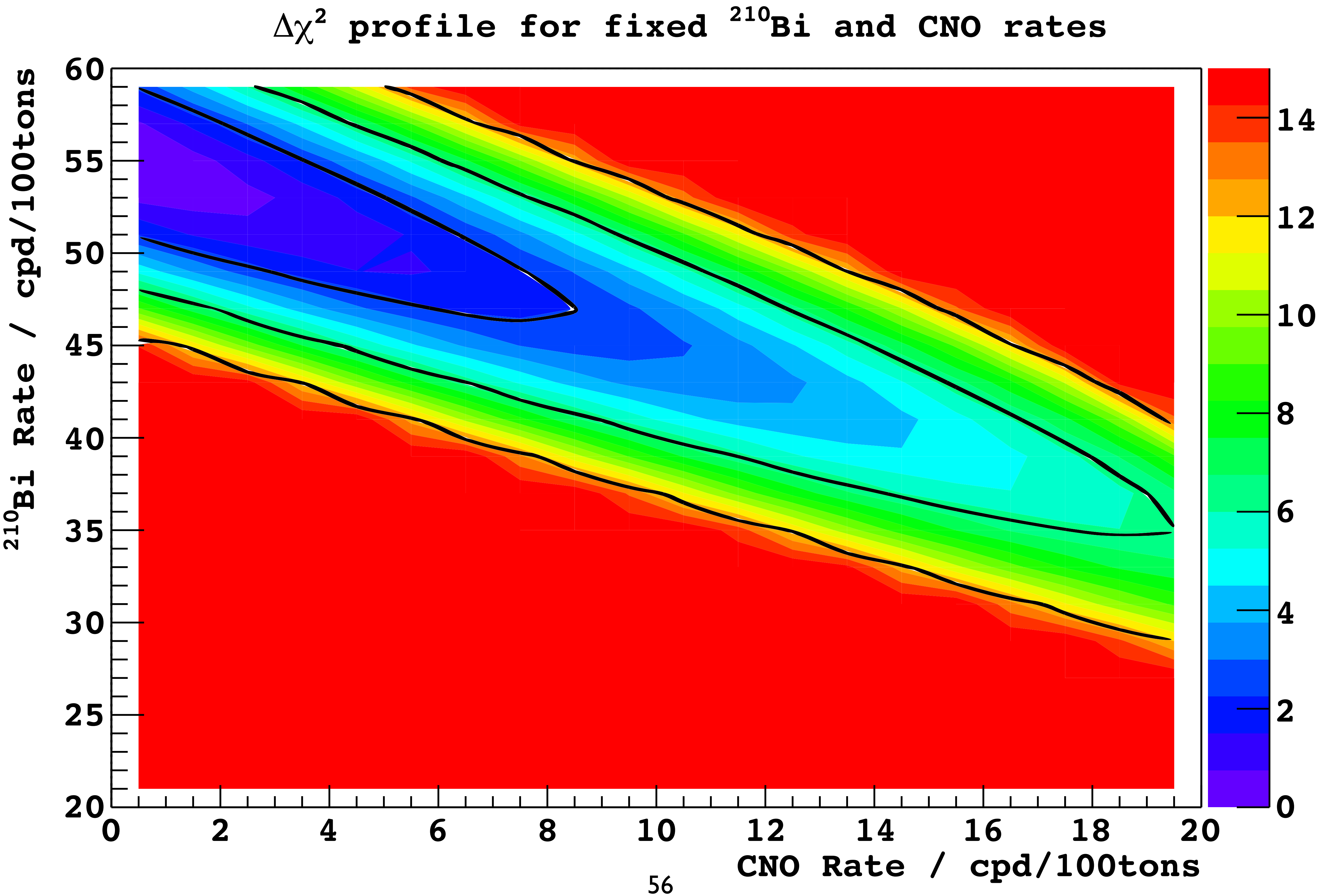




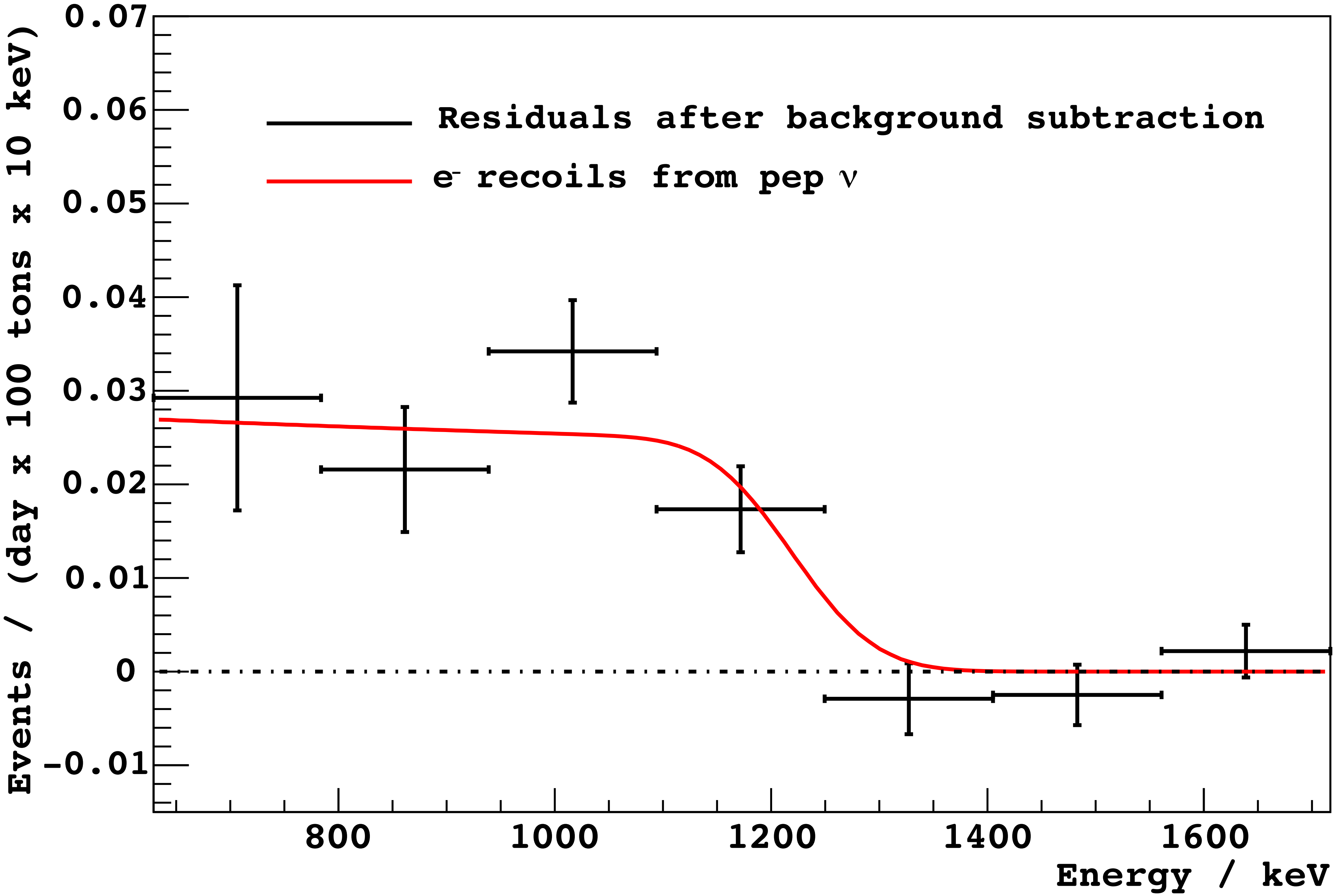
Well fit in both energy and spatial distribution

Reliable result from multivariate fit

^{210}Bi - CNO ν Correlation

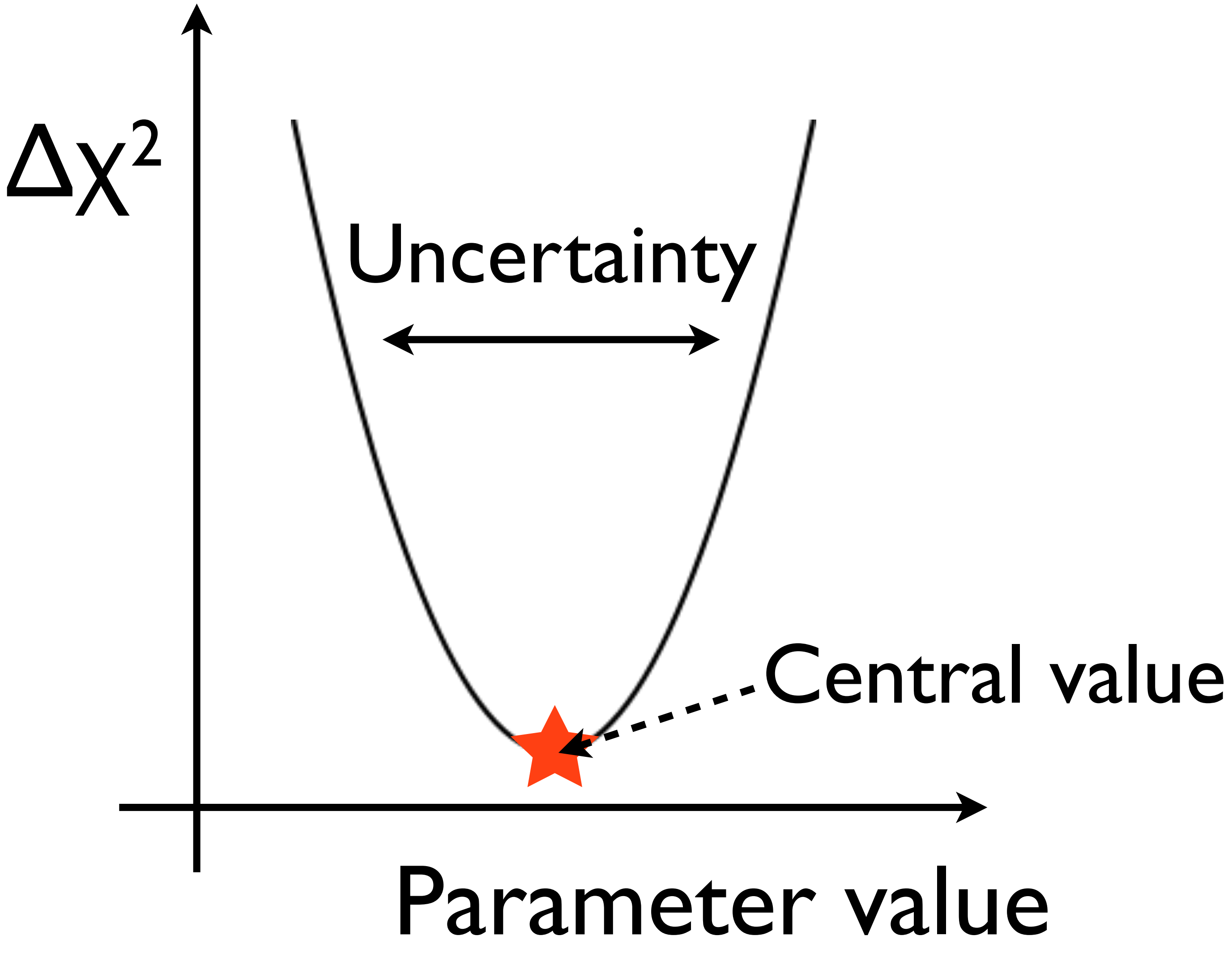


Residual spectrum



Fitting

- Find the maximum of the likelihood to obtain central value.
- Use likelihood ratio tests to calculate $\Delta\chi^2$ and the uncertainties.



MonteCarlo Test of Fitting

- Produce data-like samples from best fit result.
- Test that mean values and uncertainties from the fit are consistent with input.
- Obtained distribution of best-fit likelihood values to determine the p-value of our fit to real data to be 0.3.