^{11}C measurement and the CNO and pep fluxes in Borexino

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Outline

- Detector status
- Borexino Physics: an update
- Background issues & goals, projected sensitivity
- ^{11}C measurement in CTF
- Borexino potential in CNO and pep

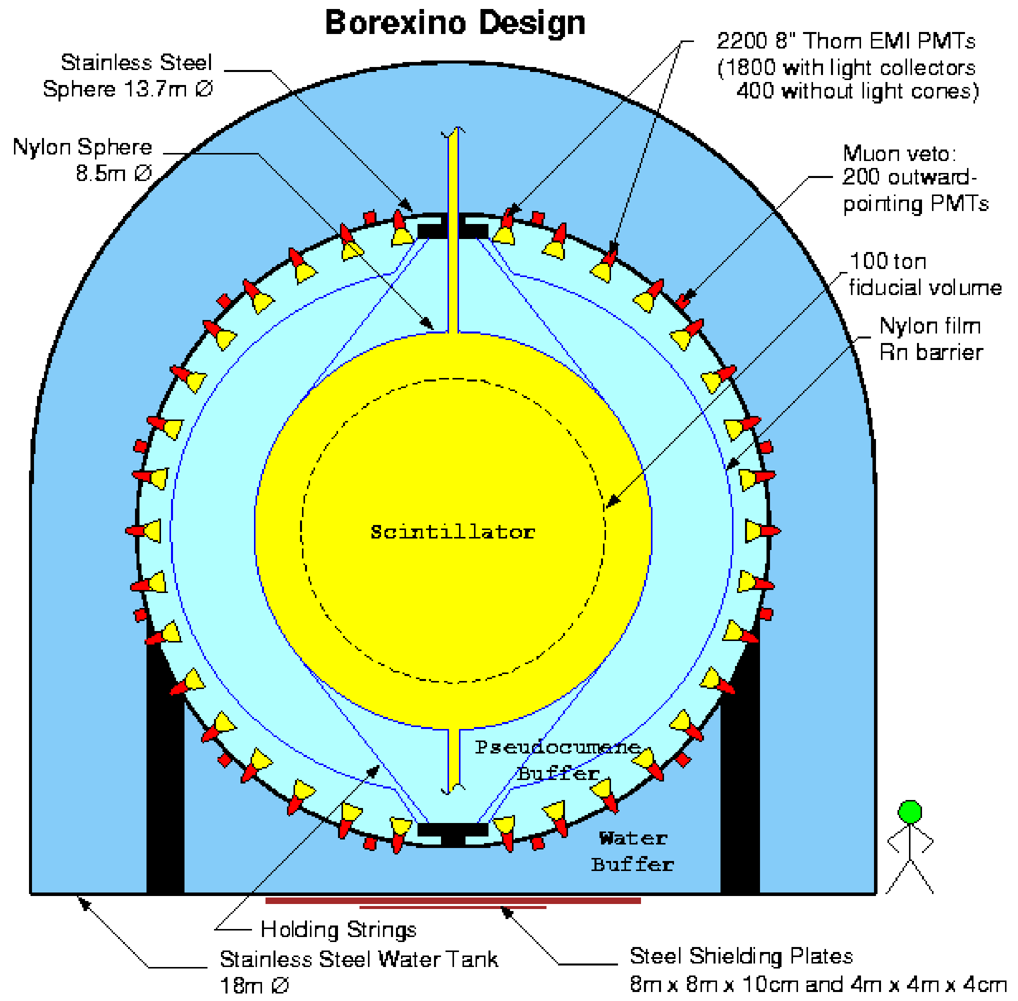
2004, August 11th

The Judicial Authority removed the seal from the Borexino equipments, from the whole Hall C and from the nearby tunnels

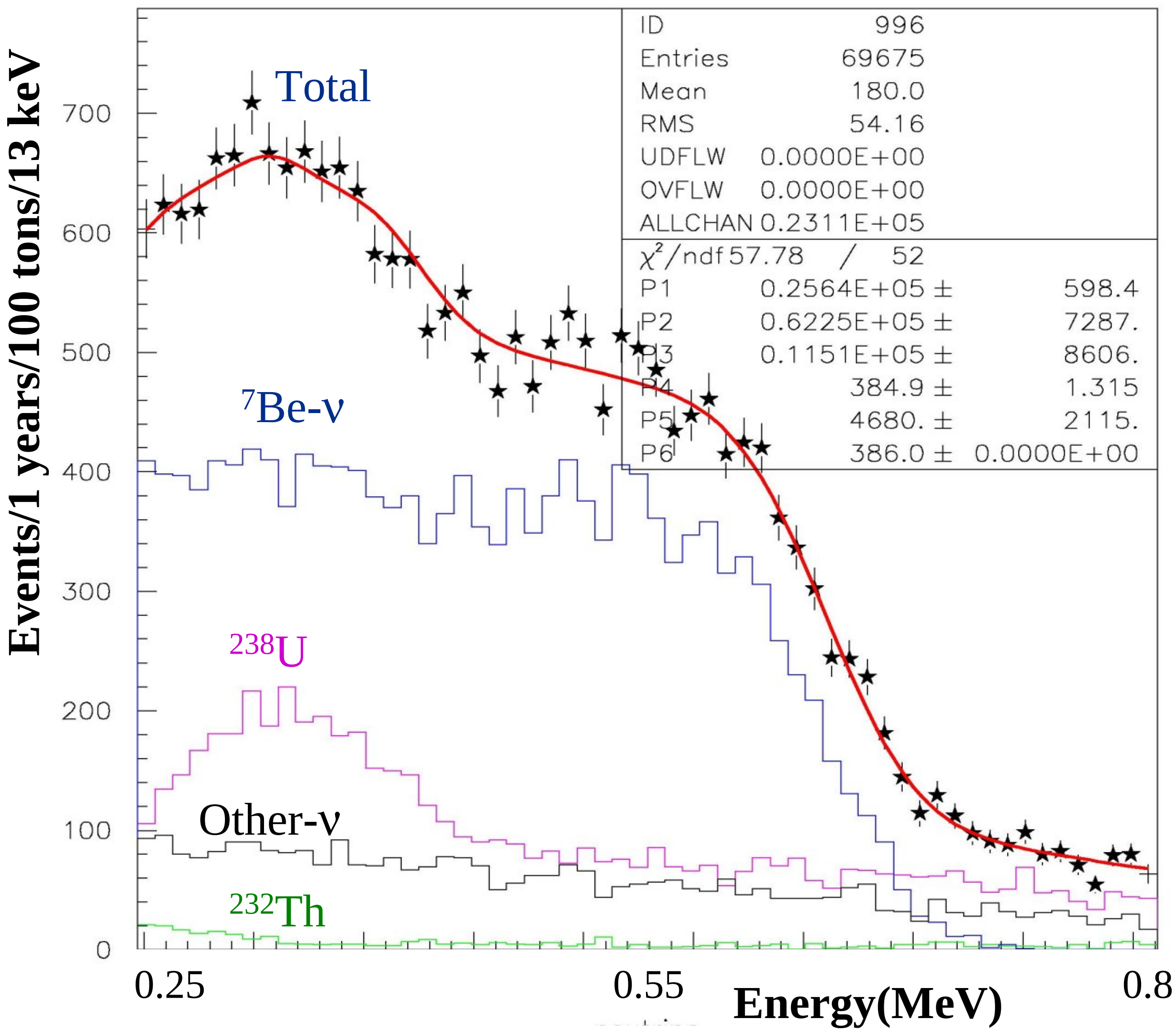
LNGS hydraulic system is under restructuring for safety compliance. Thus, in agreement with the laboratory Directorate, the resuming of operations involving liquid is deferred until a careful review of the status of the systems will be completed.

Borexino at a glance

- Electron scattering in organic liquid scintillator
- Scintillator 300 tons PC+PPO (1.5 g/l); 100 tons of fiducial mass
- Two buffers 900 tons PC+quencher; water 2200 tons
- 2200 PMTs, optical coverage 30%
- Muon flux $1/m^2/h$;
- 250 keV analysis threshold (^{14}C)



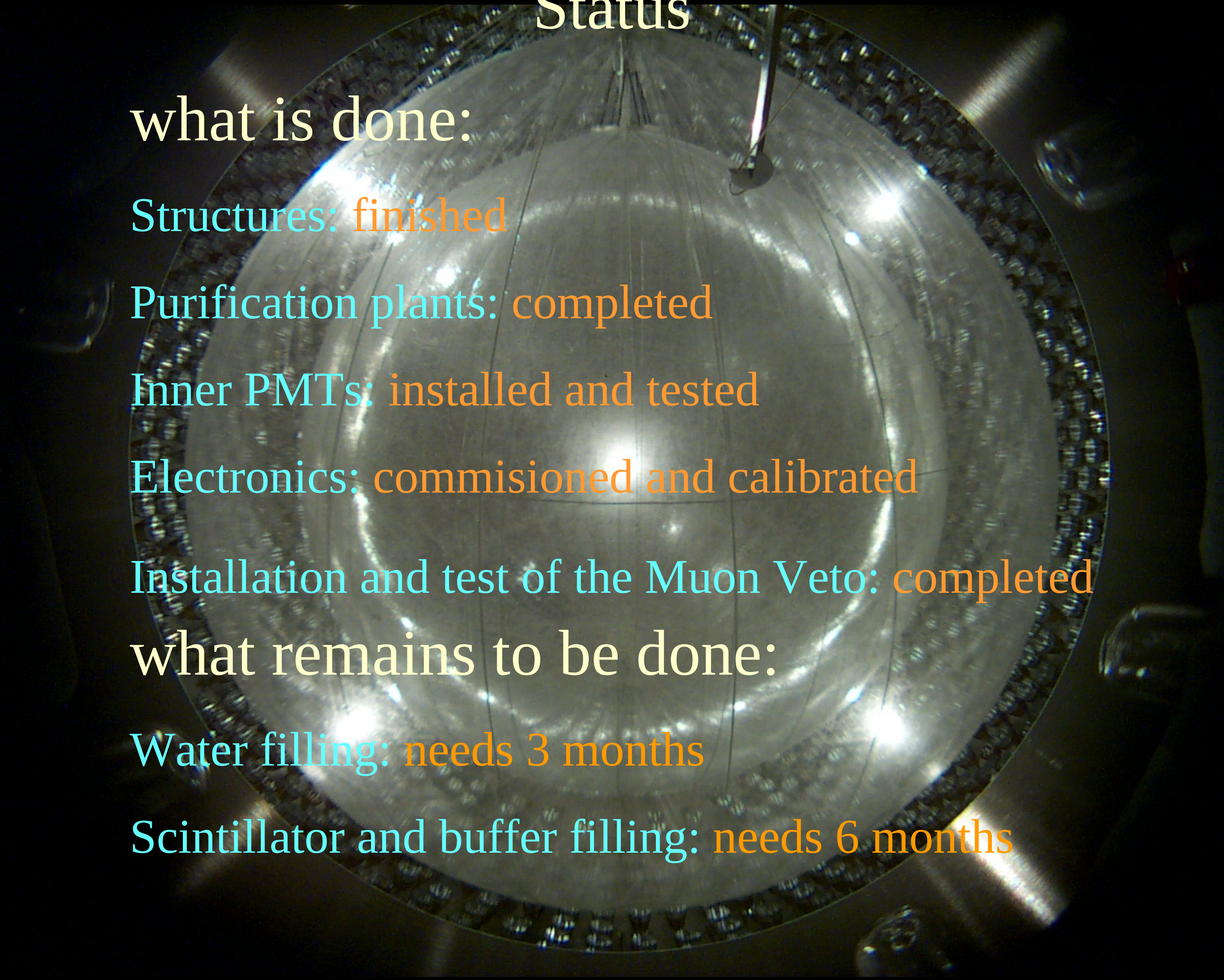
Borexino MC Spectrum



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

Assuming:

- 1 year statistics
- Neutrino window (0.25 – 0.8 MeV)
- BP2000+LMA (no LUNA)
- ^{238}U & ^{232}Th ~ 10^{-16} g/g
- Secular equilibrium



Status

what is done:

Structures: finished

Purification plants: completed

Inner PMTs: installed and tested

Electronics: commisioned and calibrated

Installation and test of the Muon Veto: completed

what remains to be done:

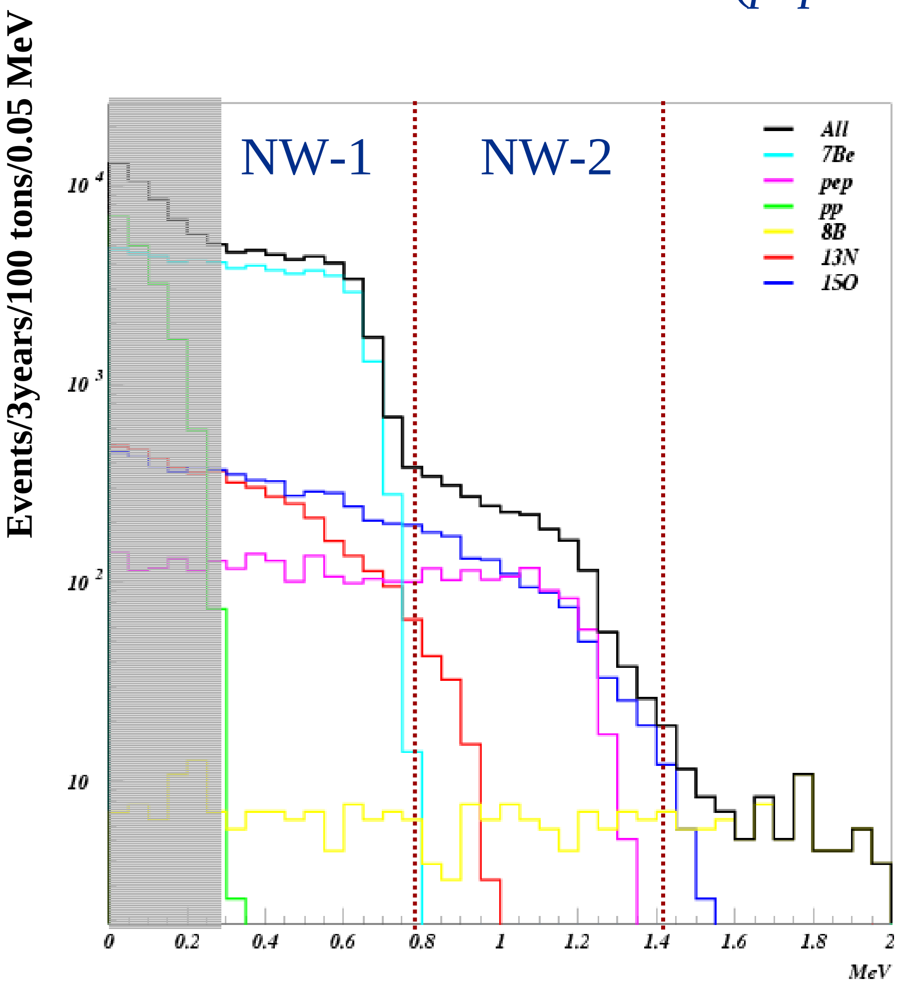
Water filling: needs 3 months

Scintillator and buffer filling: needs 6 months

ν-spectrum in Borexino

NW-1 = 0.25 – 0.8 MeV (^{7}Be)

NW-2 = 0.8 – 1.4 MeV (*pep* & CNO)



- LMA –BP2004 – LUNA
- 3 years statistics
- 100 tons

Source	Number of events in 3 y	
	NW-1	**NW-2**
^{7}Be	28470	0
pep	1095	986
pp	1095	0
^{8}B	44	33
^{13}N	1260	66
^{15}O	1533	593
All	33497	1634

Borexino Physics Goals (1)

• Real time observation of low energy neutrinos: only 1/2000 of solar flux measured in real time so far... Surprises at low energy?

• ^{7}Be measurement improves the determination of the total solar luminosity

• Theoretical uncertainty of SSM on ^{7}Be is 12% (BP04)

• Large experimental uncertainty of ^{7}Be flux:

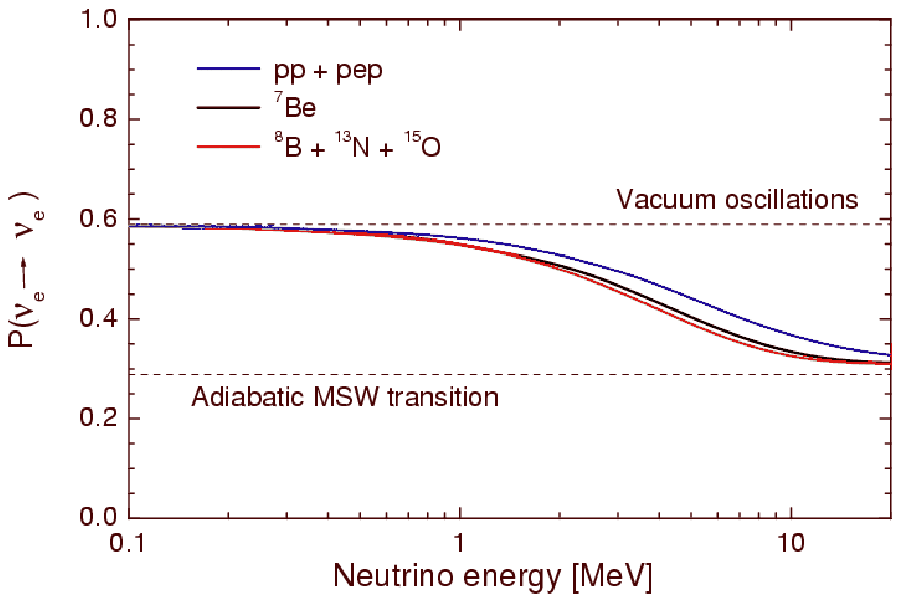
$$(0.91^{+0.24}_{-0.62})\ \Phi(^{7}\mathrm{Be})_{\mathrm{theory}}\ \text{(BP04)}$$

• MSW-LMA scenario signal & projected sensitivity

- ~ 30 ev/day above threshold
- Well positioned from statistical point of view:
  - 11000 ev in 1 yr (1%)
  - 22000 ev in 2 yrs (0.7%)
  - 44000 ev in 4 yrs (0.5%)
- Accuracy of Borexino measurement most likely determined by background and systematics

Borexino Physics Goals (2)

• Probe the transition matter-vacuum oscillation, expected (2-3 MeV) in favoured MSW-LMA



• Geo anti-neutrinos (20 events/yr expected)

• Neutrinos from Super Novae (electronics improved)

• New results on background 1-2 MeV: opportunity for pep+CNO observation

Background

- Background from long-lived isotopes
  - ^{238}U, ^{232}Th : feasibility of ~ 10^{-16} g/g achieved in CTF

- ^{14}C: feasibility of $^{14}C/^{12}C \sim 10^{-18}$ achieved in CTF

- Noble gases (^{85}Kr, ^{39}Ar) (removable with LAK nitrogen):
  - Search commercial LN_2 with specs: achieved!
  - <1 c/d for each source in the FV

- Radon daughters (^{210}Bi-^{210}Po-^{210}Pb) removal still in progress:
  - Helps vessel built in clean conditions
  - Further testing needed in CTF

- Cosmogenic Background
  - Fast decaying background removed by tagging with muon
  - CNO-pep NW: ^{11}C problem

The ^{11}C problem in the CNO-pep NW

Expected ν-rate in Borexino in 100 ton (BP2004 + LUNA + LMA) in the energy range [0.8 – 1.4] MeV:

- pep-ν: 0.9 c/d
- CNO-ν: 0.6 c/d

Internal background in [0.8 – 1.4] MeV: 0.6 ev/day @ 10^{-17} g/g U, Th

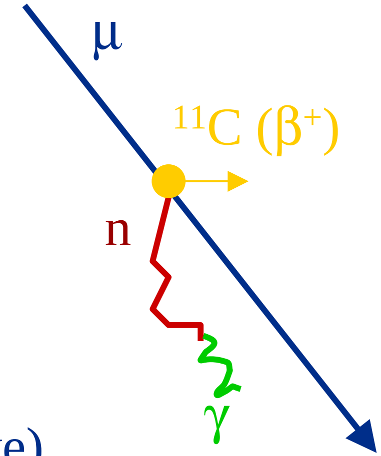
In situ production muon-induced ^{11}C:

- 7.5 c/d in the range [0.8 – 1.4] MeV

⇒ required reduction factor > 10

Goal: tagging and removing ^{11}C event by event!!!

μ-induced ^{11}C: the net reaction



$$\mu + {}^{12}C \rightarrow {}^{11}C + n$$

$\langle E_\mu \rangle = 320 \pm 4_{stat.} + 11_{syst.}$ GeV @ LNGS (3600 mwe)

$$n + p \rightarrow d + \gamma$$

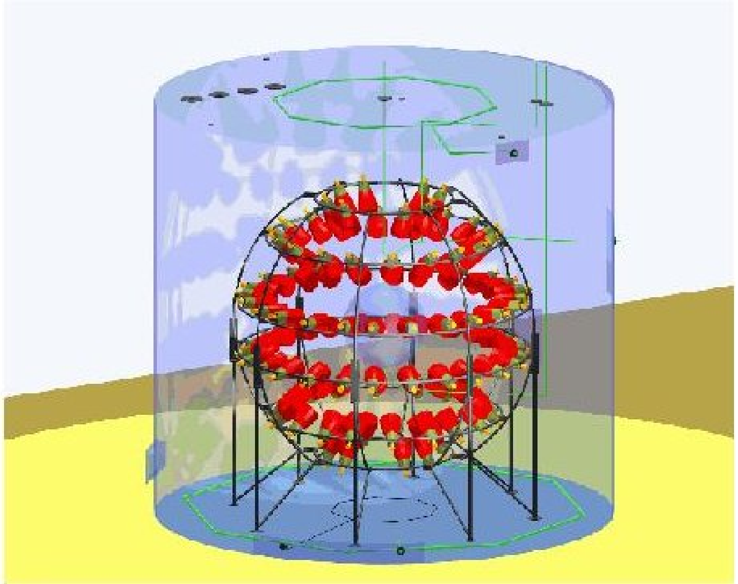
$$\begin{cases} \tau \sim 200\ \mu s \\ E_\gamma = 2.2\ \text{MeV} \end{cases}$$

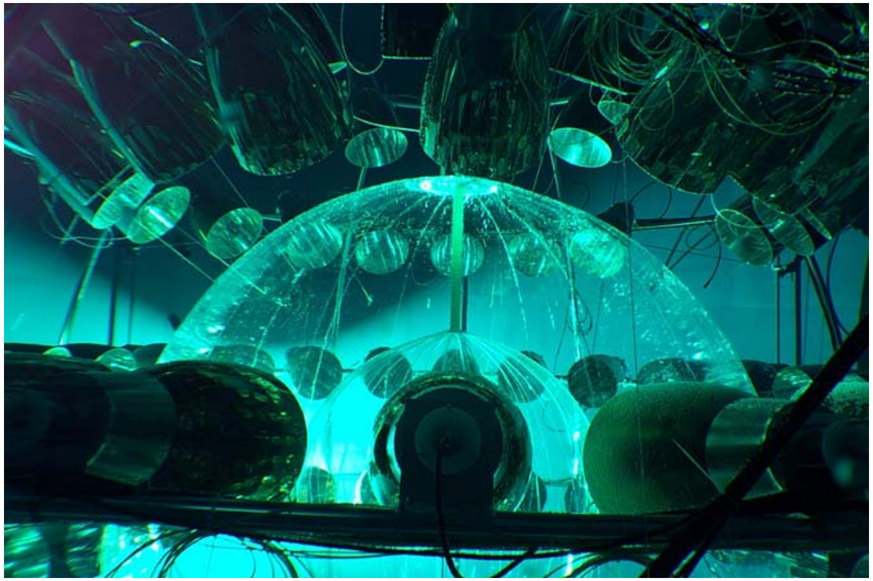
$$\boxed{{}^{11}C \rightarrow {}^{10}C + e^+ + \nu_e}$$

$$\begin{cases} \tau \sim 30\ \text{min!!!} \\ E \in [1.02 - 1.98]\ \text{MeV} \end{cases}$$

The Counting Test Facility

CTF is a small scale prototype of Borexino. It is devoted to the study of the background in the scintillator and to the purification system tests of Borexino.





- ~ 4 tons of scintillator
- 100 PMTs
- Buffer of water
- Muon veto
- Vessel radius: 1 m

Muon-induced contaminants in CTF

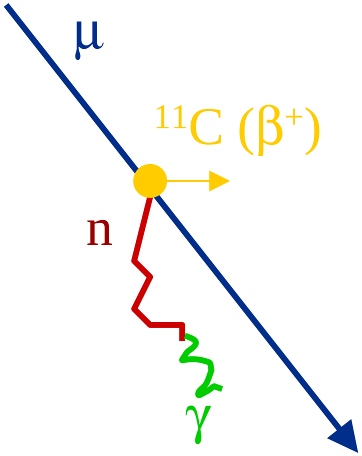
Experiment @ CERN(*):
cross sections measured with μ-beams of 100 and 190 GeV on ^{12}C target

Scaling to CTF, ^{11}C represents 80% of all the muon-induced contaminants and more than 99% in the NW-2

Isotopes	c/d(*) in the full energy range in CTF
^{11}C	0.54 ± 0.06
^{7}Be	$(1.3 \pm 0.1) \times 10^{-2}$
^{11}Be	$< 10^{-3}$
^{10}C	$(7.3 \pm 0.8) \times 10^{-2}$
^{8}Li	$(2.5 \pm 0.6) \times 10^{-3}$
^{6}He	$(3.7 \pm 0.1) \times 10^{-2}$
^{8}B	$(4.0 \pm 0.7) \times 10^{-3}$
^{9}C	$(2.8 \pm 0.9) \times 10^{-3}$
$^{9}Li + ^{8}He$	$(1.3 \pm 0.2) \times 10^{-3}$

(*) T. Hagner et al., Astr. Part. Phys. 14 (2000) 33-47

Strategy in CTF

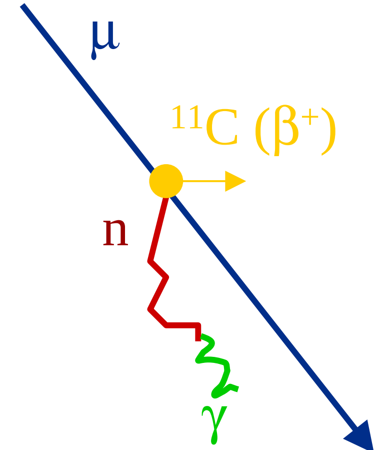


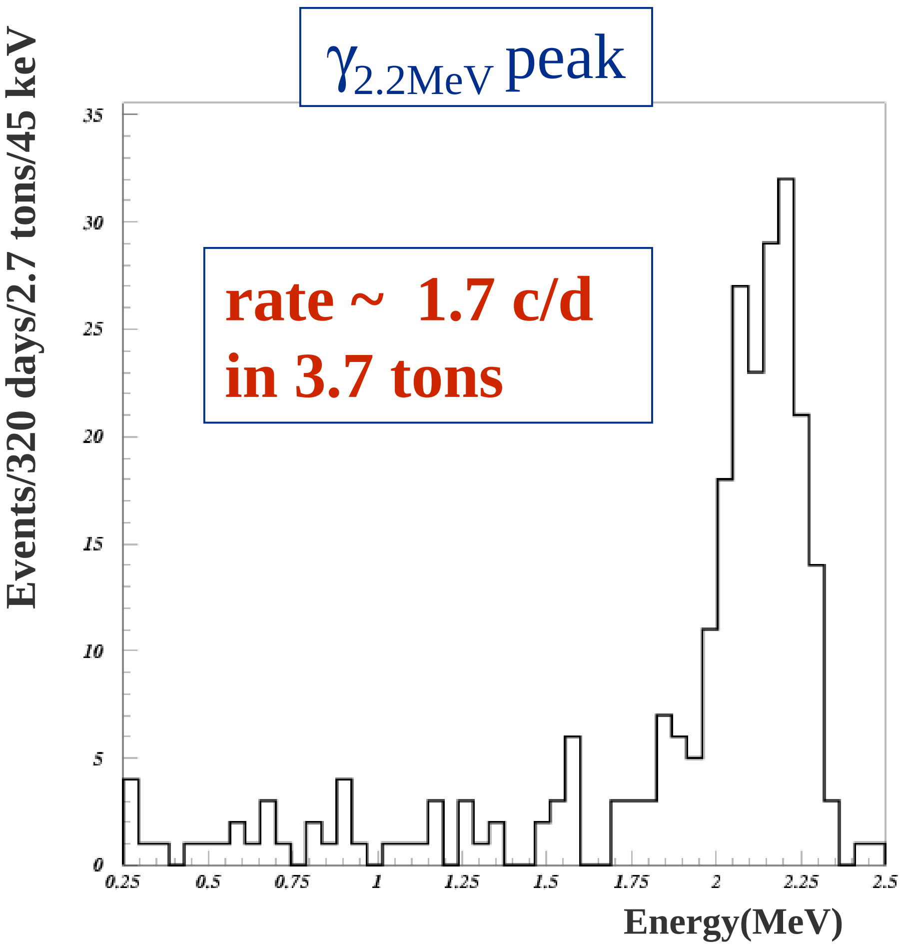
1. Tagging cosmic muons with the muon veto:
   - $\mu_{<320\ GeV>}$, crossing the scintillator, fires the detector
   - cut on the number of photoelectrons detected by the muon-veto (ε_μ **~ 1**)
2. Tagging $\gamma_{2.2MeV}$ from the neutron capture:
   - for each tagged $\mu_{<320\ GeV>}$, a temporal gate of [1 μs - 2ms] is opened
   - cut: $E_\gamma > 1.8$ MeV
   - ε_γ and $\varepsilon_{neutron}$ (spill-in/spill-out effect) have been evaluated via Monte Carlo
3. Collecting data sample including ^{11}C events:
   - after each $\gamma_{2.2MeV}$ a temporal gate of 300 min (10 x τ) in the [1.10 – 1.65] MeV energy window (ε_{energy} **= 0.82**)
   - Radial cut: ε_r has been evaluated via Monte Carlo

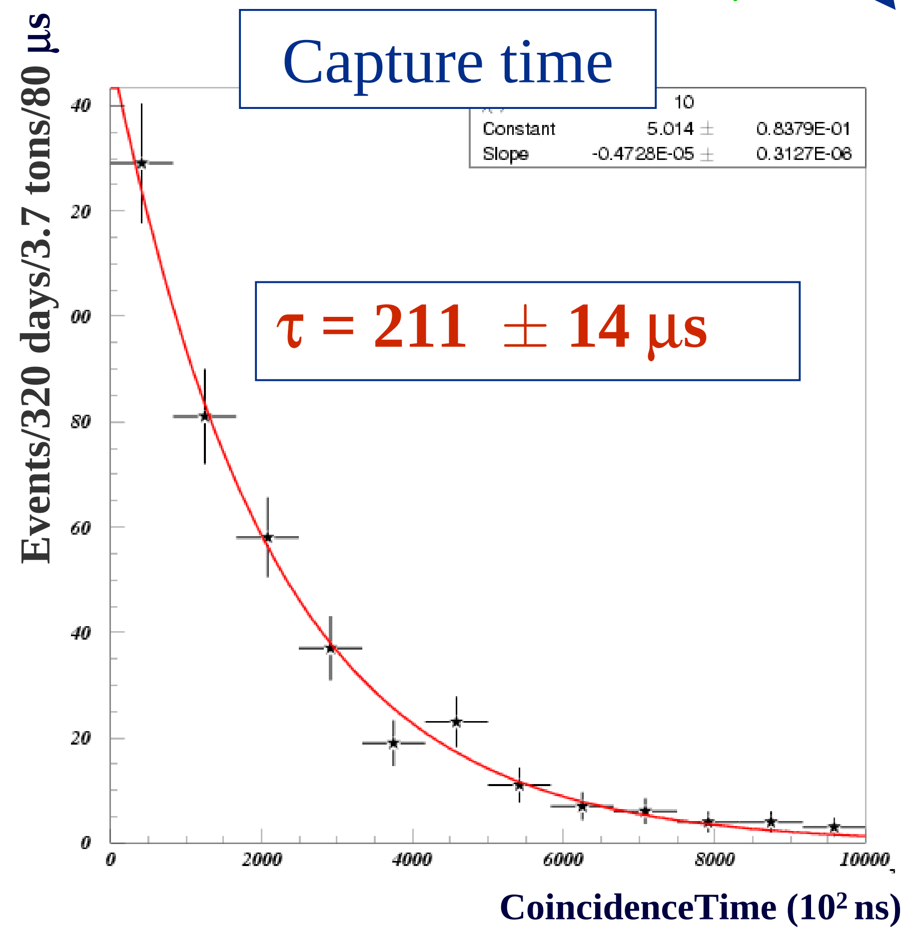
Neutron capture

$$n + p \longrightarrow d + \gamma_{2.2\ \mathrm{MeV}}$$

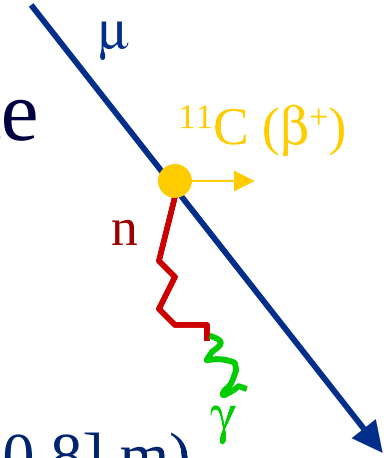
capture time ~ 200 μs







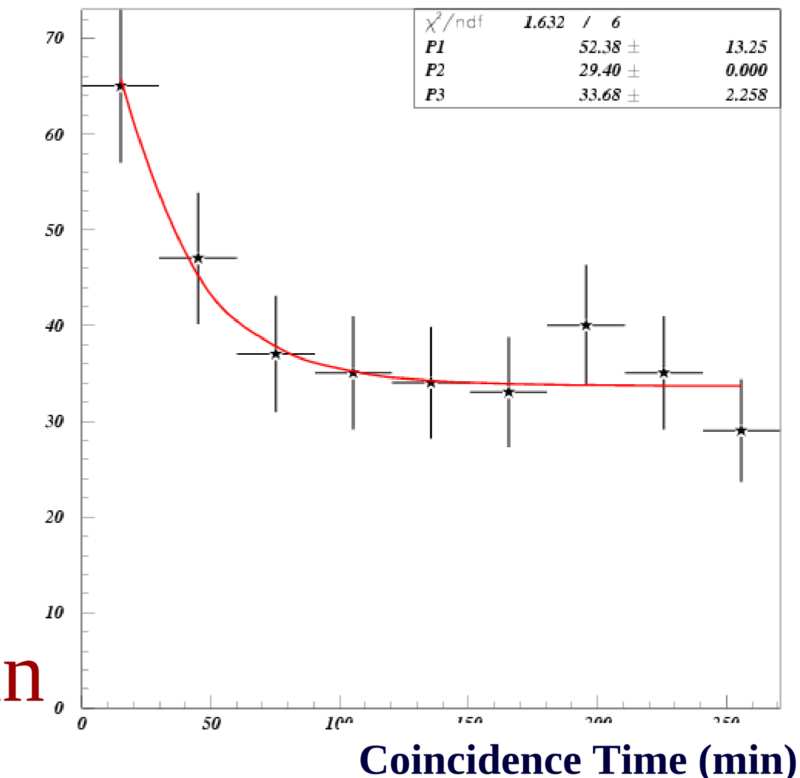
Detection of in situ produced ^{11}C rate



- Effective data taking: 320 days
- Radial cuts arount the center of the detector ($r \in [0.7 - 0.8]$ m) for avoiding optical effects at different medium interface
- Assuming a constant background *B*

Fit function:

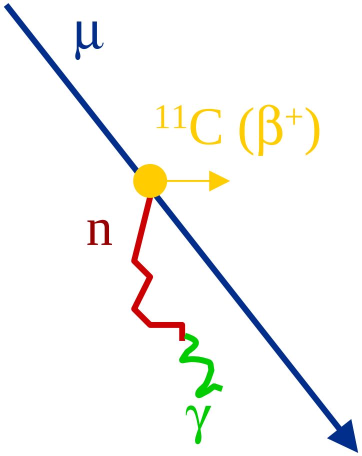
$$\boxed{F(t) = \frac{N}{\tau} e^{-t/\tau} + B}$$



From the fit: $\tau = 29 \pm 13$ min

(others analyses provide a lower uncertainty on τ)

Result: ^{11}C rate in CTF



- Fixing τ = 29.4 min
- r = 0.7 m (m_r = 1.4 ton)
- T = 320 days
- Energy window [1.1 – 1.65] MeV: ε_{en} = 0.82

$$R(r < 0.7m) = \frac{N}{T \cdot \varepsilon_{energy} \cdot \varepsilon_r \cdot \varepsilon_n \cdot \varepsilon_\gamma} = \frac{(0.17 \pm 0.04)}{\varepsilon_r \cdot \varepsilon_n \cdot \varepsilon_\gamma} c/d$$

Note: less than 1 event every 5 days

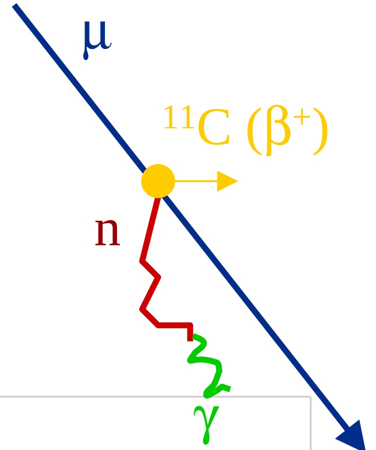
Efficiencies: Monte Carlo Simulation

FLUKA has been already tested succesfully in muon-induced neutron production (LVD, etc)

Simulation strategy:

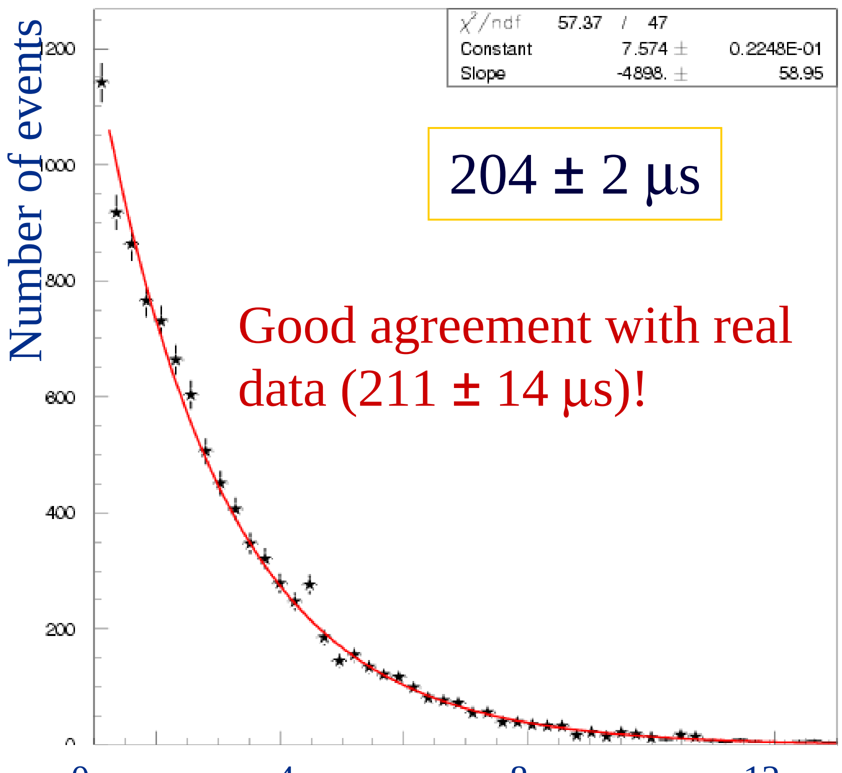
- FLUKA:
    - detector geometry
    - vertical muon beam spread over the whole detector surface
    - neutron tracking in scintillator and water
- CTF tracking code:
    - tracking of $\gamma_{2.2MeV}$ starting from the neutron capture position
- CTF reconstruction code:
    - reconstruction of the center of mass of the $\gamma_{2.2MeV}$ deposited energy

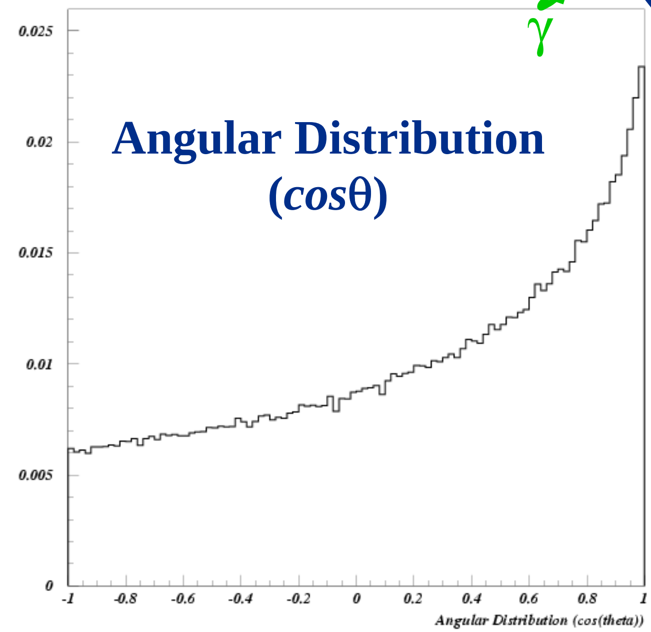
Results from the MC (1)

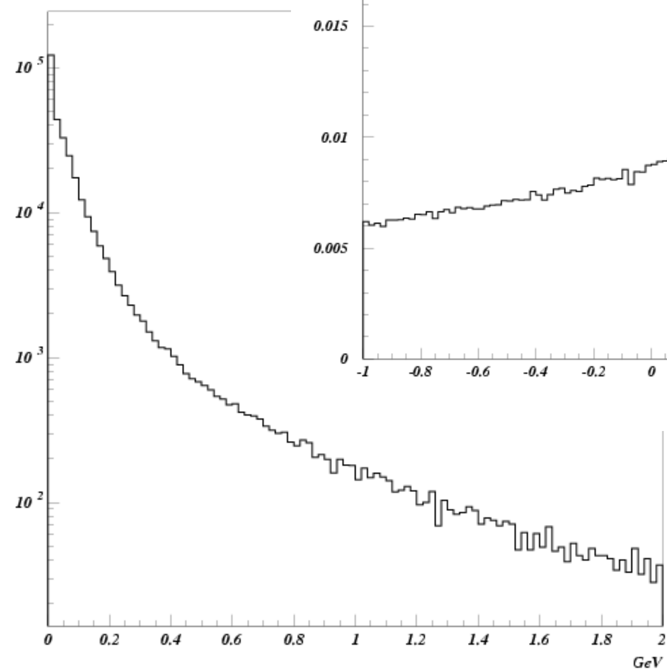


Events in water and in scintillator

Neutron capture in scintillator and water

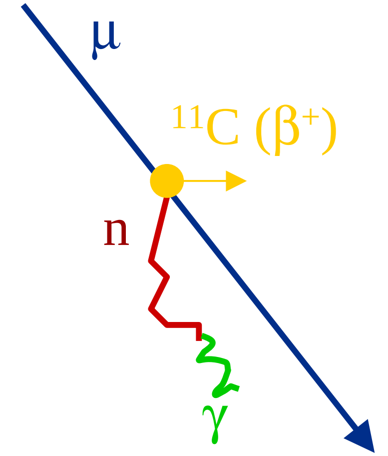






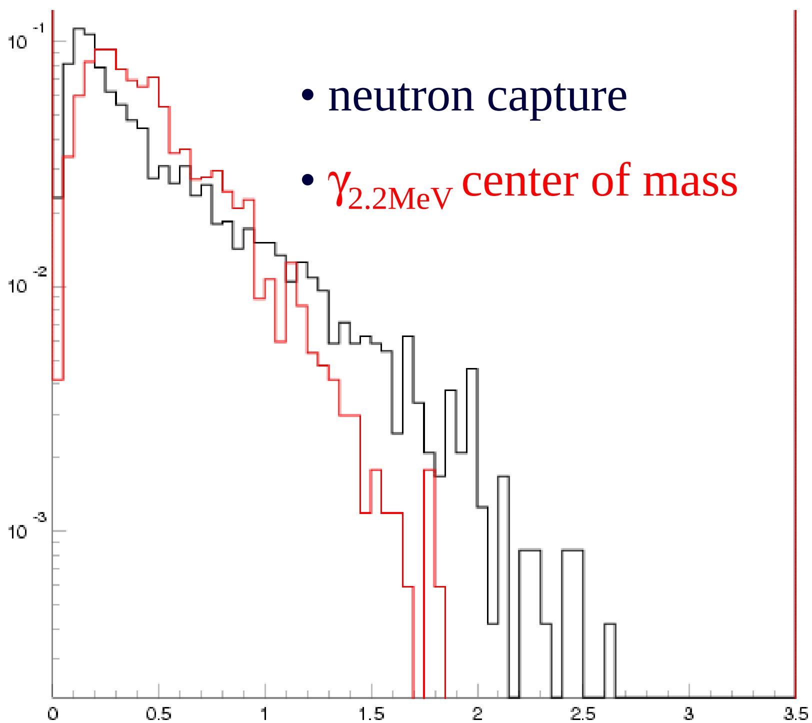
Energy Distribution
(*GeV*)

Results from the MC (2)



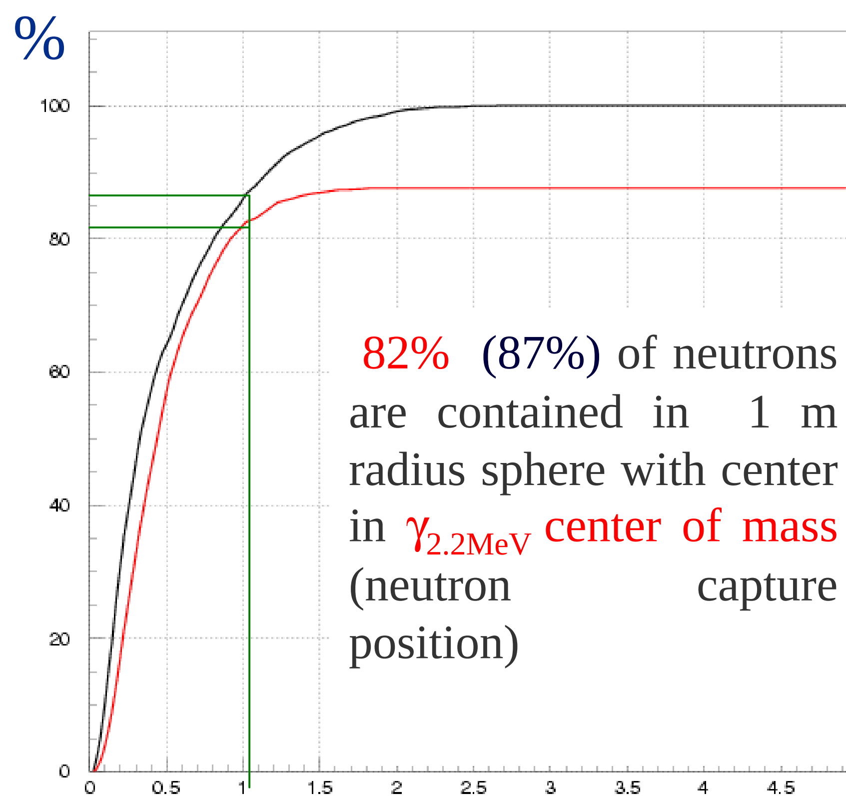
Only internal events

Distance from neutron production position to (normalized spectra):



Distance (m)

Cumulative probability:



Distance (m)

Efficiencies and final results

$$R(r < 0.7m) = \frac{(0.17 \pm 0.04)}{\varepsilon_r \cdot \varepsilon_n \cdot \varepsilon_\gamma} c/d$$

From MC:

$$\varepsilon_r \cdot \varepsilon_n \cdot \varepsilon_\gamma = 0.29$$

Including the systematics due to:

- scintillator mass
- light yield: energy scale conversion

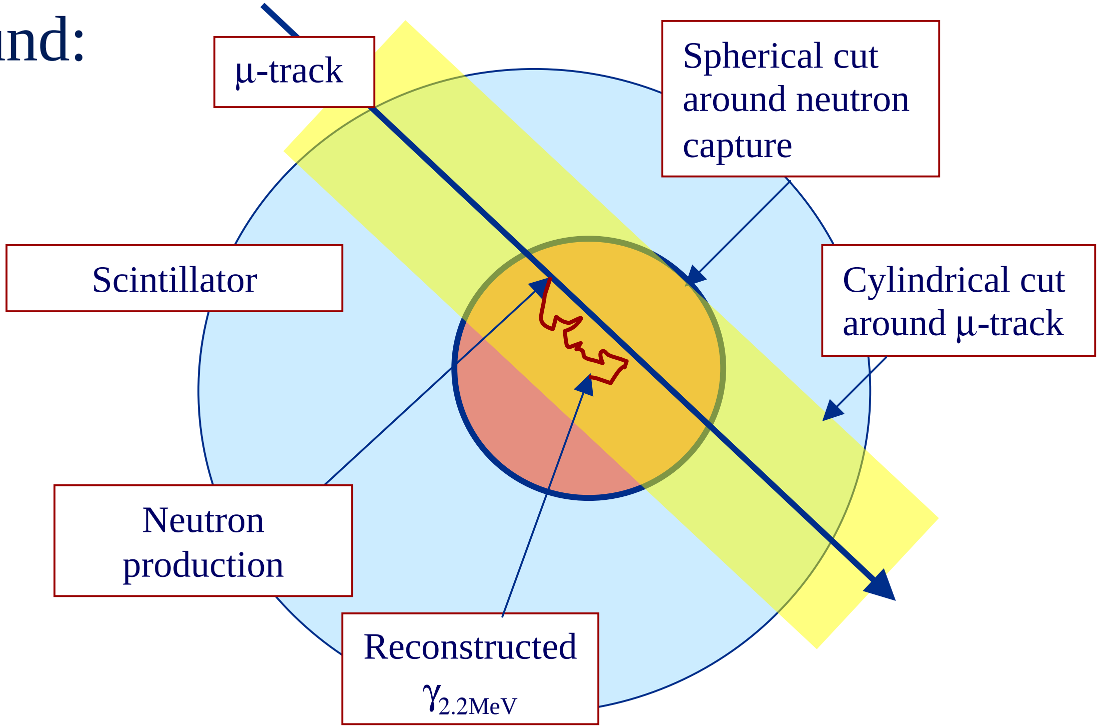
$$R_{measured} = 0.60 \pm 0.14(stat.)^{+0.06}_{-0.04}(syst.)\ c/d$$

$$R_{expected} = 0.54 \pm 0.06\ c/d$$

Implication in Borexino

How to reduce ^{11}C background:

- **Software cut**
  – spherical volume around the reconstructed $\gamma_{2.2\ MeV}$
- **Muon veto cut**
  – cylindrical volume around the muon track



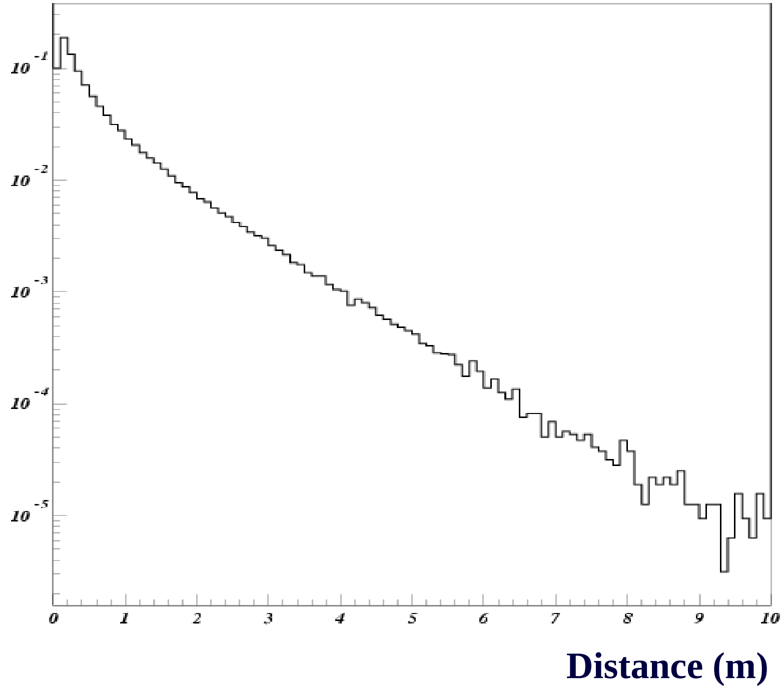
^{11}C is removed <u>blinding</u> the intersection of the two volumes for 5-10 ^{11}C-lifetime

Main challenge: keeping low the total <u>dead volume x time</u>

Summarizing

Assuming:

- ν-signal (pep+CNO) rate: 1.5 c/d
- trace contaminants rate 0.6 c/d (^{238}U and ^{232}Th ~ 10^{-17} g/g)
- distribution of the distance covered by neutrons from FLUKA simulation
- expected 46 neutrons/day
- 100 tons of fiducial mass
- only the spherical cut
- NW-2: 0.8 – 1.4 MeV



Preliminary results

Dead Volume-Time Fraction	Signal/Background Ratio
5%	1
20%	1.2
50%	1.5

Signal-to-backround ratio ~ 1 implies a loss of volume-time detector fraction ~ 5%

Conclusions and perspectives

- Borexino installation and test are completed

=> waiting for water/scintillator filling

- Good agreement ^{11}C rate measured/expected in CTF
- ^{11}C is tagged event by event
- Loss of volume-time detector fraction is minimized in Borexino
- Improvements: cylindrical cut, neutron distribution from ^{12}C, etc.

=> Borexino has the potential to probe pep and CNO νs

Spares

First-event analysis

Selection of the first event following each $\gamma_{2.2\ \mathrm{MeV}}$

in the energy range [1.1 – 1.65] MeV

- n event
  - from ^{11}C (α)
    - real event → $P_1 = \lambda \cdot e^{-(\lambda+b)t}$
    - false event → $P_2 = b \cdot e^{-(\lambda+b)t}$
  - from other reaction (1-α)
    - false event → $P_3 = b \cdot e^{-bt}$

$$P = \alpha \cdot (\lambda + b) \cdot e^{-(\lambda+b)t} + (1-\alpha) \cdot b \cdot e^{-b} t$$

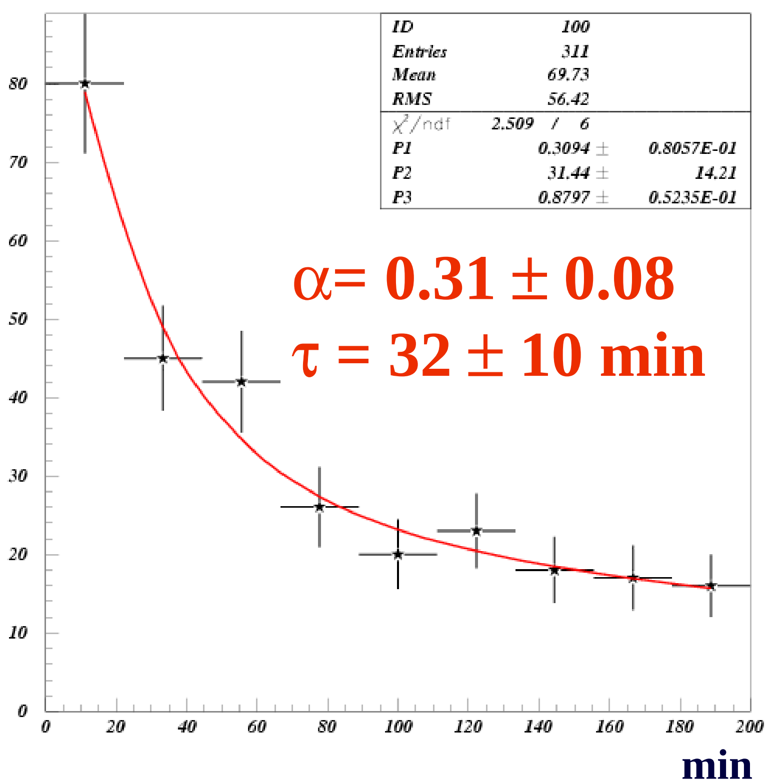
$1/\lambda$ = lifetime, b = rate of random coincidence

b is fixed to the measured rate in the temporal gate

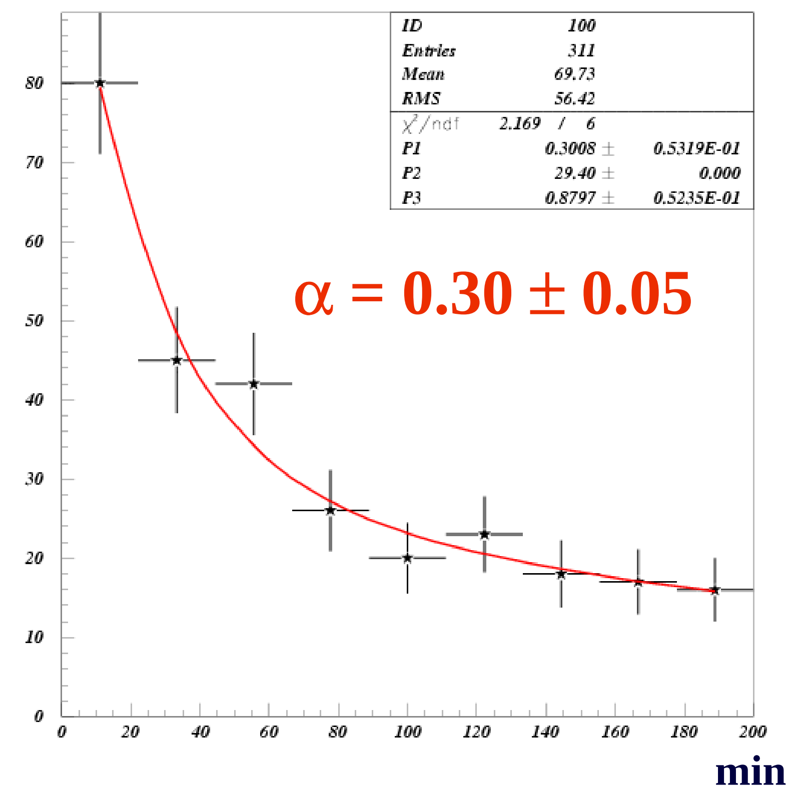
- after 2 h of the $\gamma_{2.2\ \mathrm{MeV}}$ detection
- in the same spherical cut centered in $\gamma_{2.2\ \mathrm{MeV}}$ (0.75 m)
- in the ^{11}C energy window [1.1 – 1.65] MeV

$$\alpha_{\mathrm{expected}} = \frac{R(^{11}C)}{R(n)} = \frac{0.54 \pm 0.06}{1.78 \pm 0.08} = 0.30 \pm 0.04$$

α and τ free



α free and τ fix



Simulation in Borexino

$$r(\varepsilon_r) = \lambda \ln \frac{1}{1-\varepsilon_r}$$

λ = neutron mean free path
ε_r = spatial efficiency

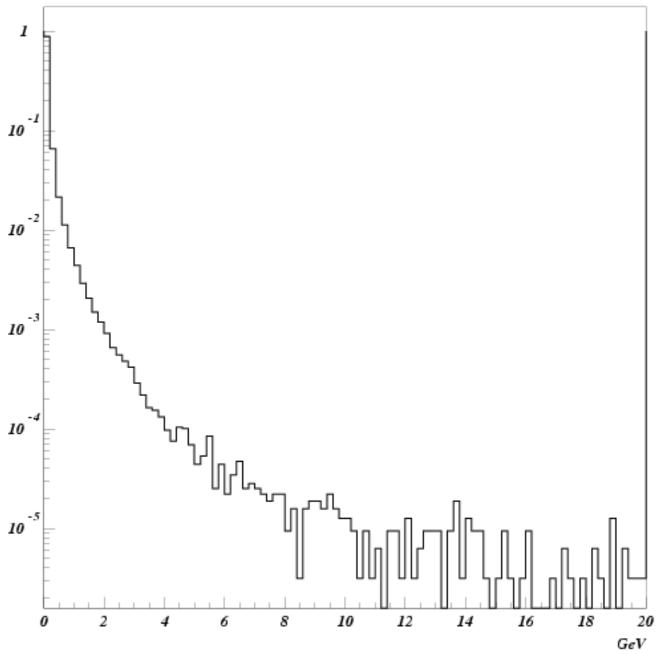
$$t(\varepsilon_t) = \tau \ln \frac{1}{1-\varepsilon_t}$$

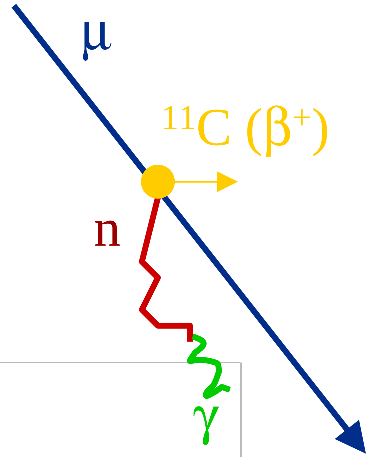
τ= ^{11}C life time
ε_t = time efficiency

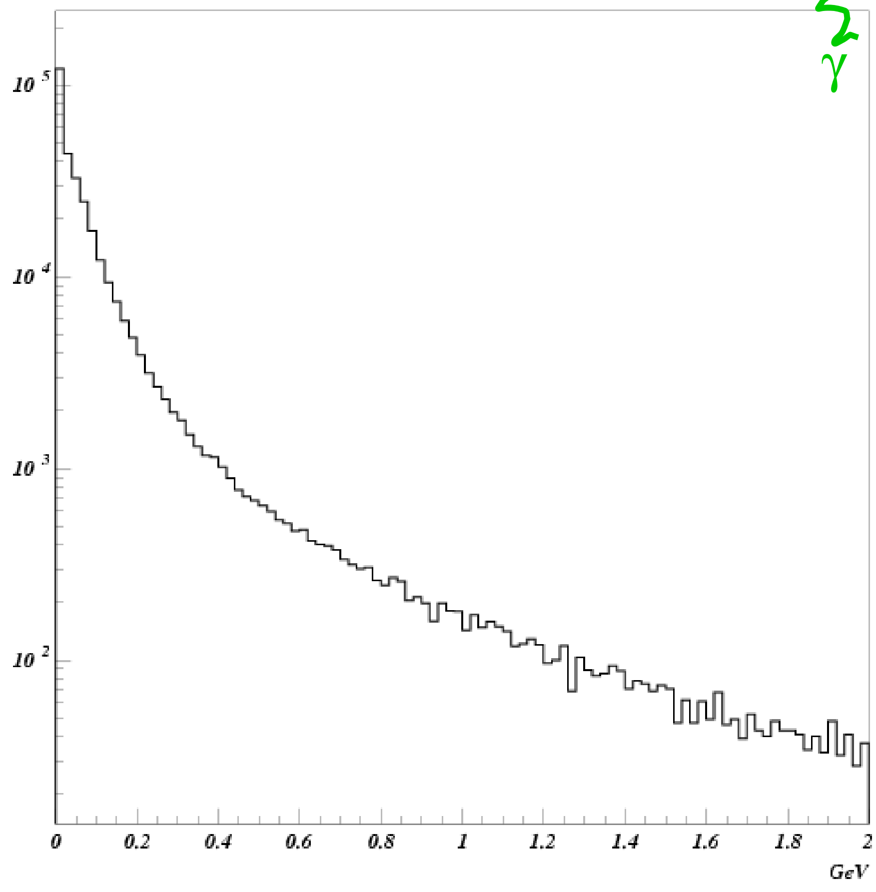
Dead volume time fraction including the pile-up effect:

$$D = 1 - \exp[-\left(\frac{r}{R}\right)^3 \frac{t}{T} N]$$

R = radius of the sphere
T = live-time of the detector
N = number of detected $\gamma_{2.2MeV}$ events

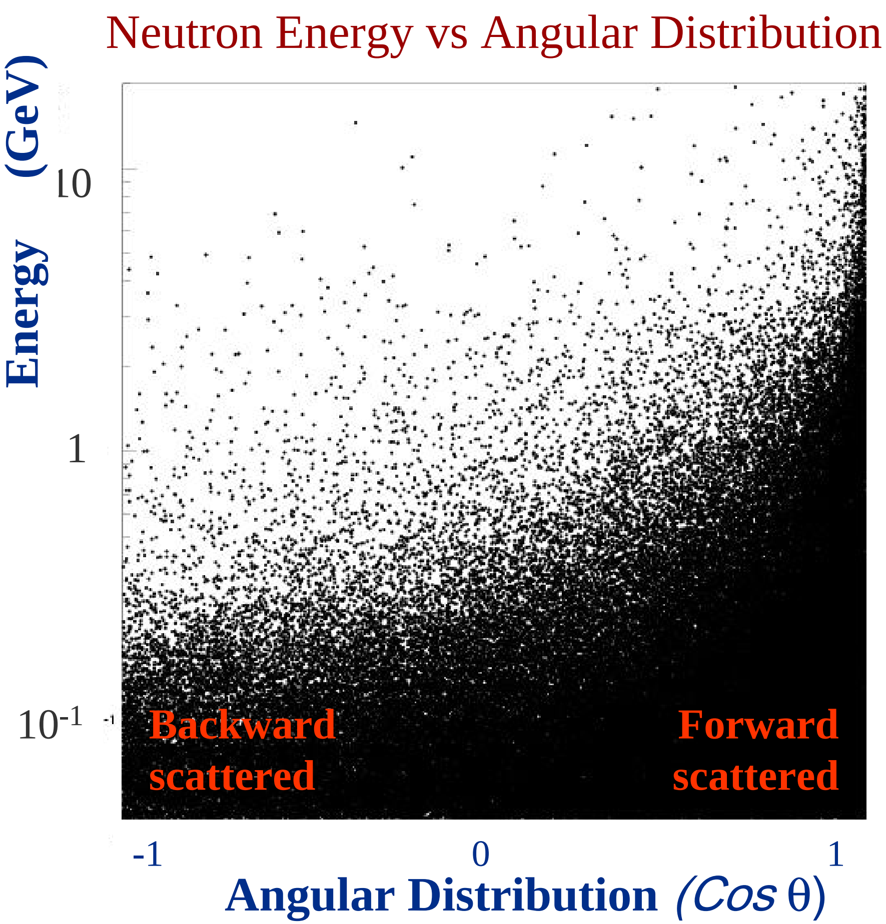


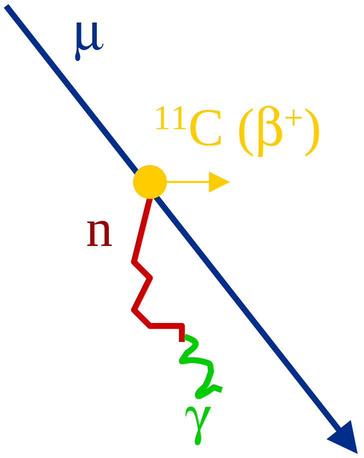


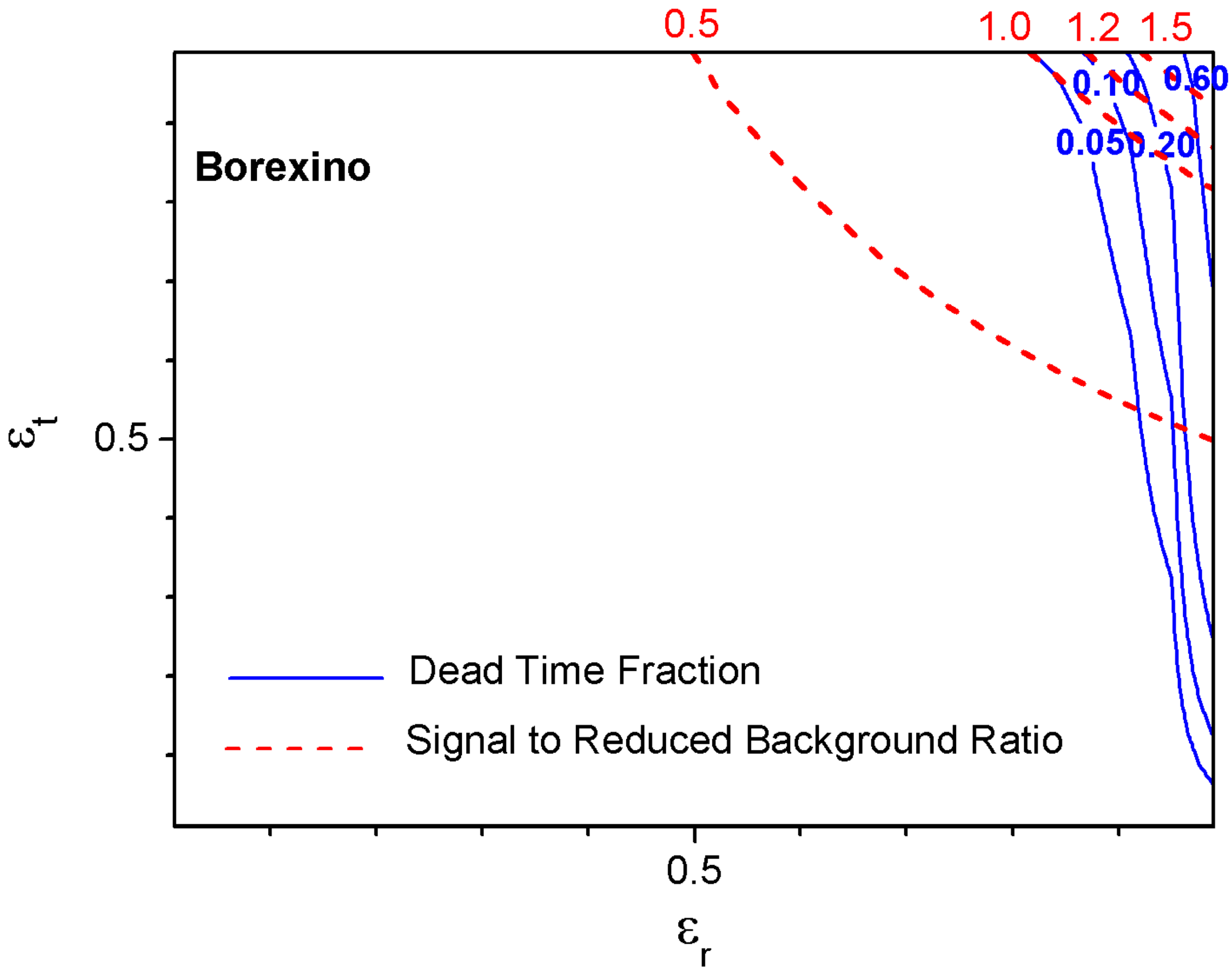


Neutron Energy Distribution

Neutron Angular Distribution






0.5
1.0
1.2
1.5
0.10
0.60
0.05
0.20
Borexino
Dead Time Fraction
Signal to Reduced Background Ratio
ε_t
0.5
0.5
ε_r