GEANT4 simulation of the Borexino solar neutrino experiment.

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On behalf of the Borexino Collaboration

Borexino Collaboration

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ISTITUTO NAZIONALE DI FISICA NUCLEARE INFN

LNGS Laboratori Nazionali del Gran Sasso

Dubna JINR (Russia)

RRC "Kurchatov Institute" (Russia)

Jagiellonian U. Cracow (Poland)

Max-Planck-Institut für Kernphysik

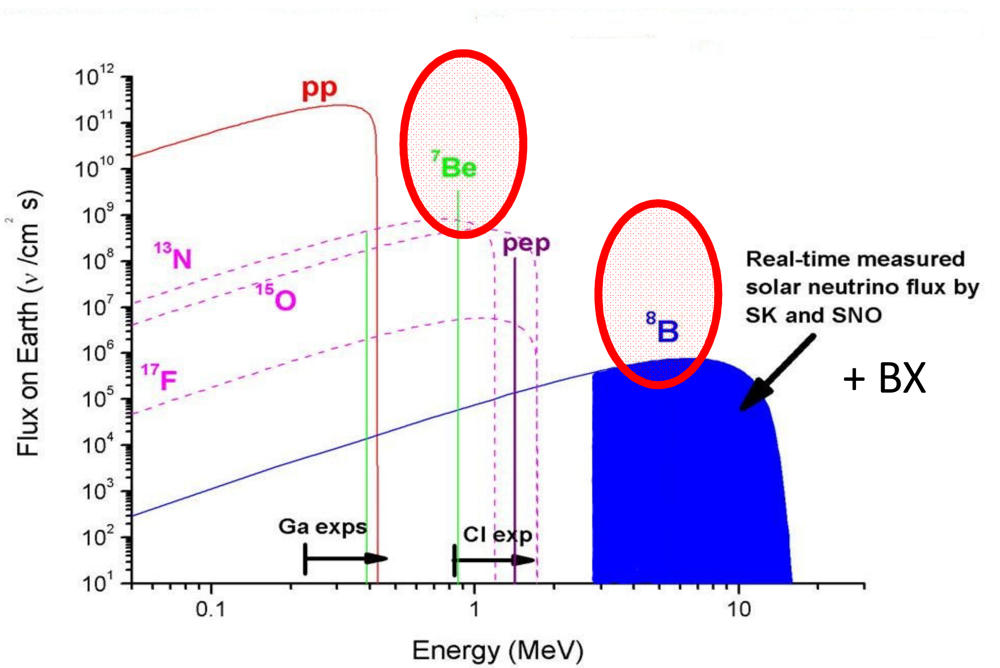
Heidelberg (Germany)

TECHNISCHE UNIVERSITÄT MÜNCHEN

Munich (Germany)

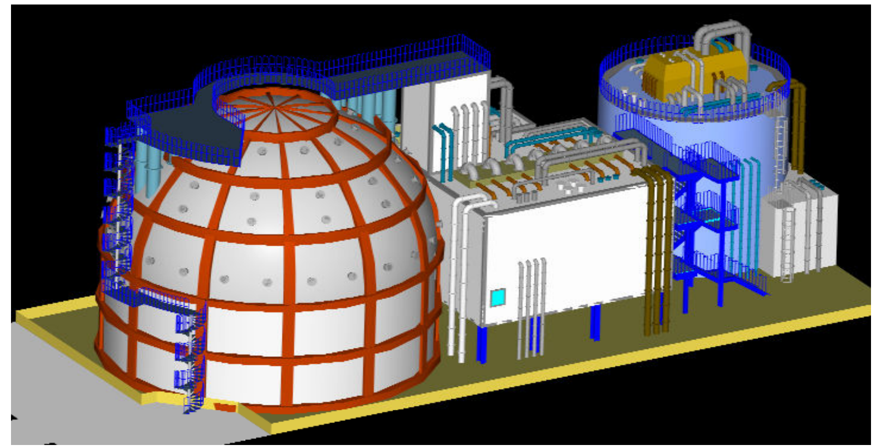
Borexino Physics

- Solar program:
  - ^{7}Be neutrinos
    (E = 0.862 MeV);
  - ^{8}B neutrinos
    (2.8 MeV < E < 14.06 MeV);
  - *Possibly*
    pp-, *pep*- and CNO-neutrinc
- Study of geo-neutrinos;
- Reactor antineutrinos;
- Supernovae neutrino detection;
- Beyond SM
  - neutrino magnetic moment,
  Pauli principle violation,
  rare decays etc.



The solar neutrino spectrum

Borexino detector



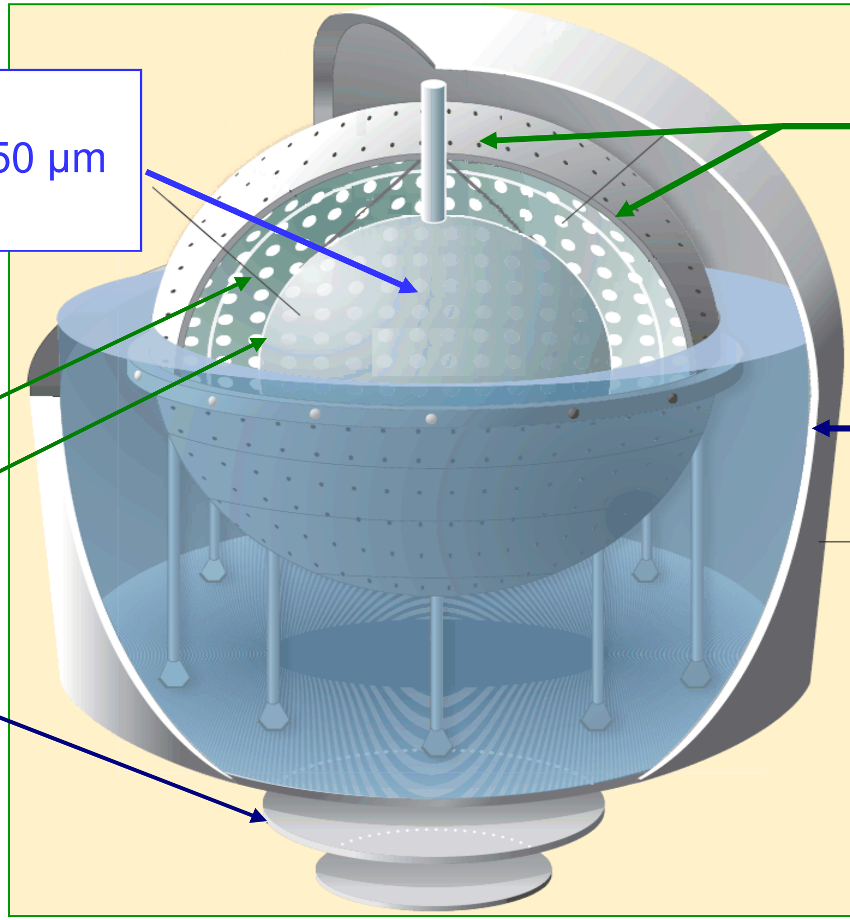
- …located at the Gran Sasso underground laboratory (3800 m.w.e.), central Italy.
- Detection via the scintillation light in organic liquid scintillator, target mass is 278 tons. Light yield ~ 12000 Photons/MeV
- Energy threshold ~60 keV, counting rate ~30 Hz!
- Energy resolution 6% @ 1 MeV (14% FWHM).
- Spatial resolution 14 cm @ 1 MeV.
- Detector is fully operative since 15 May 2007.

Borexino detector design

Scintillator:
278 t PC+PPO in a 150 μm thick nylon vessel

Nylon vessels:
Outer: 5.50 m
Inner: 4.25 m

Carbon steel plates



Stainless Steel Sphere:
2212 PMTs
1350 m^3

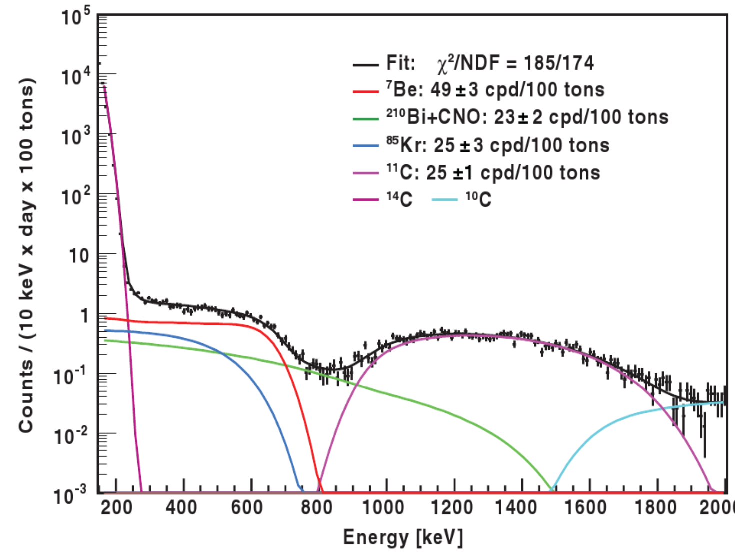
Water Tank:
γ and **n** shield
μ water Čh detector
208 PMTs in water
2100 m^3

Borexino is a liquid scintillator detector with mass of **278 tons of PC, C_9H_{12}**. The scintillator is contained in a thin nylon vessel and is surrounded by two concentric PC buffers doped with DMP component quenching the PC scintillation light. The two PC buffers are separated by a thin nylon membrane to prevent diffusion of radon. The scintillator and buffers are contained in Stainless Steel Sphere (SSS) with diameter 13.7 m.

The measurement of the 7 Be flux

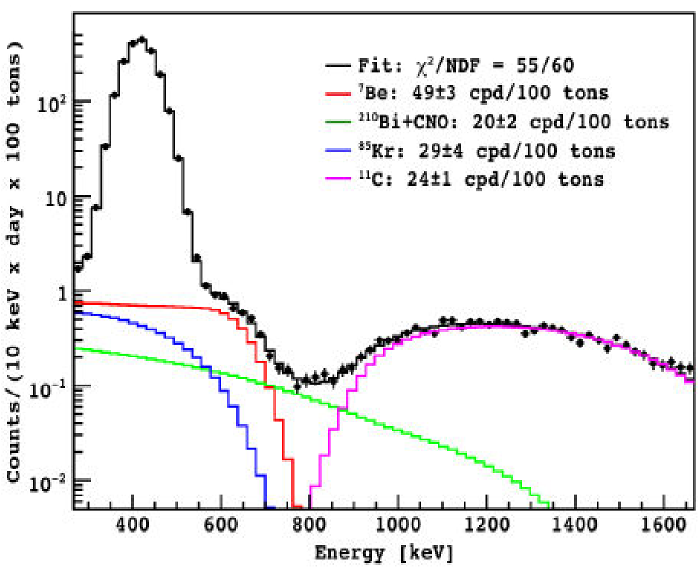
(192 days of live time)

C. Arpesella *et al*. (Borexino Collab.), Direct measurement of the ^{7}Be solar neutrino flux with 192 days of Borexino data, Phys. Rev. Lett. **101**, 091302 (2008).



Measured rate is:

$R(^7\text{Be})$ = 49 ± 3(stat) ± 4(sys) cpd/100 t



	Expected rate (cpd/100 t)
No oscillation	78 ± 5
High-Z SSM	48 ± 4
Low-Z SSM	44 ± 4

The low threshold measurement of the 8B solar neutrinos

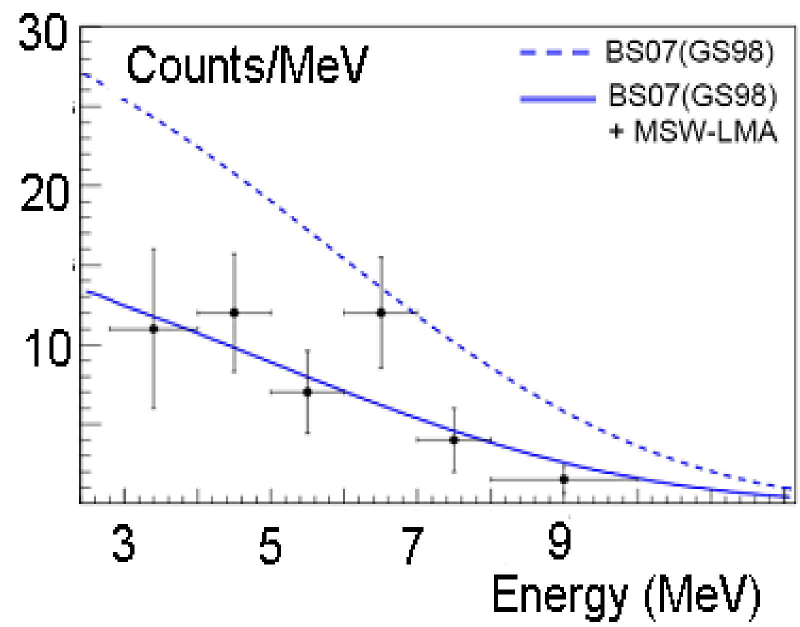
<u>MSW-LMA prediction:</u>
expected ^{8}B neutrinos rate in 100 tons fiducial volume of BX scintillator above 2.8 MeV:

$R(^{8}B) = 0.27 \pm 0.03$ cpd

Measured rate in 100 tons fiducial volume:
$R(^{8}B) = 0.26 \pm 0.04 \pm 0.02$ cpd

astro-ph > arXiv:0808.2868

The Borexino ^{8}B spectrum

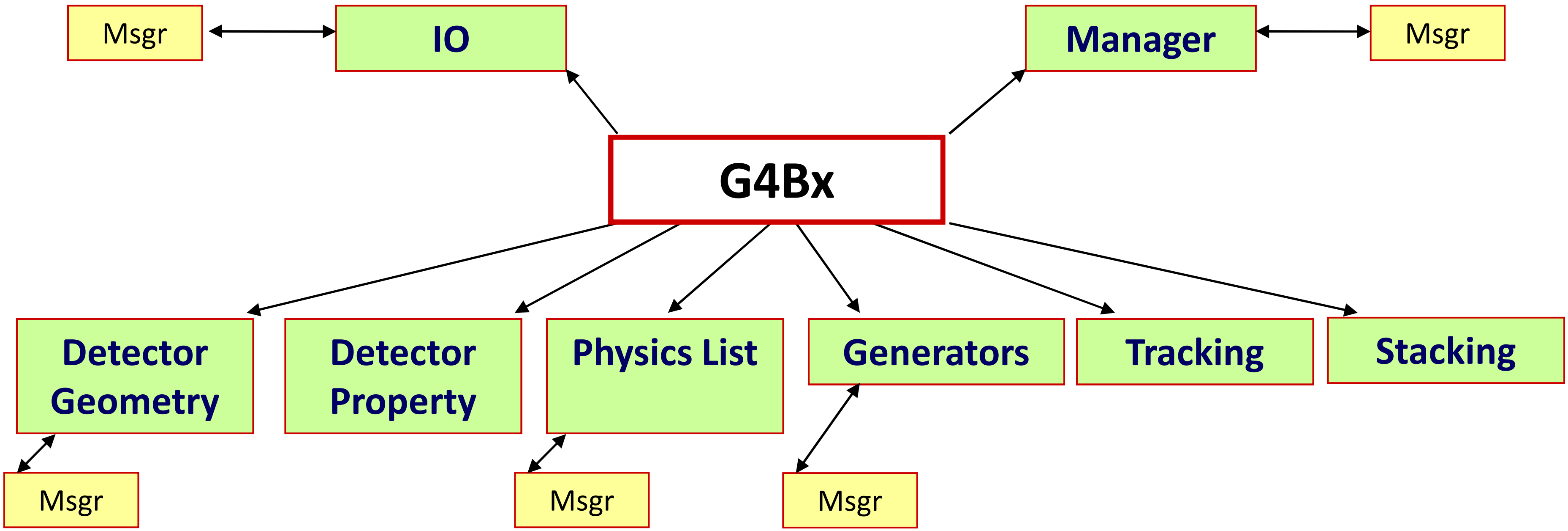


- Simultaneous spectral measurement in vacuum-dominated (^{7}Be-neutrinos) and matter-enhanced (^{8}B-neutrinos) oscillation (LMA) regions was done for the first time by single detector.

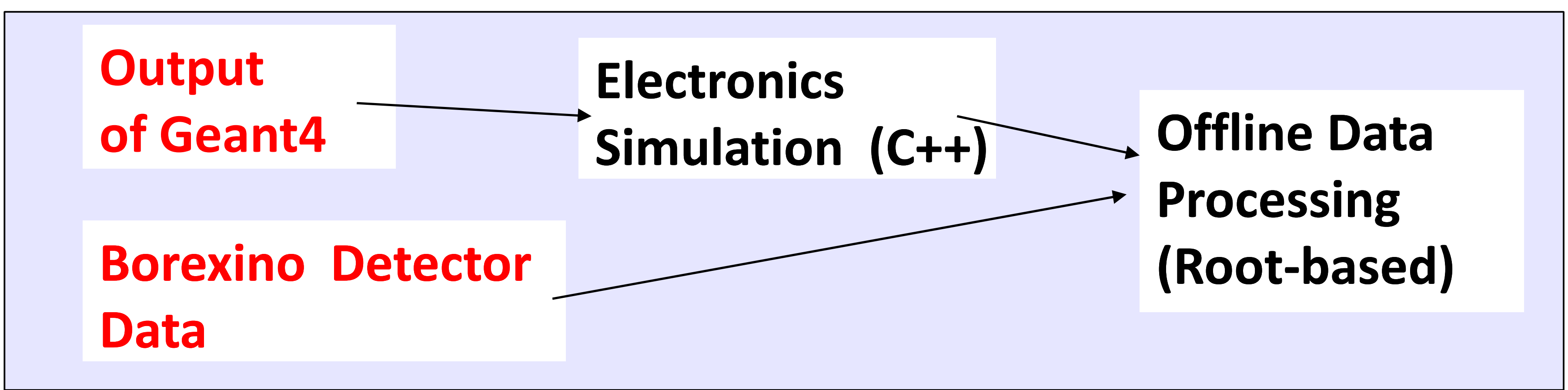
- Borexino 8B flux above 5 MeV agrees with existing data

- Neutrino oscillation is confirmed by the 8B of Borexino at 4.2 sigma

Basic Structure of Geant4 Borexino Code



Full Monte-Carlo Simulation Chain



Generators used for Borexino Monte-Carlo

GENEB
independent generator code of radioactive decays and single particles

- Geneb Reader
- Geneb Reader + Cherenkov

Single particle or isotope internal generators: several spatial and energy distributions

- BxGun
- RDM
- Carbon isotopes
- RDM Chain

Pre-defined energy and spatial distributions according to Borexino location and physics

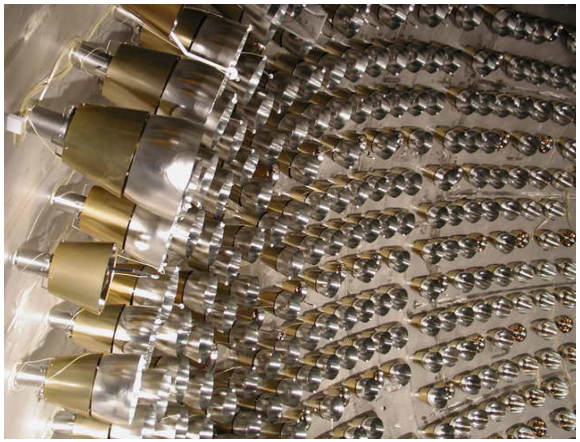
- Solar Neutrinos
- Reactor and Geo Antineutrino
- Neutrons from the rock at Gran-Sasso lab
- Cosmic Muons
- Muons from the CERN neutrino beam
- AmBe neutron source
- Laser Timing
- Laser Fibers

Geant4 structure allows simple addition of new Generators into the code

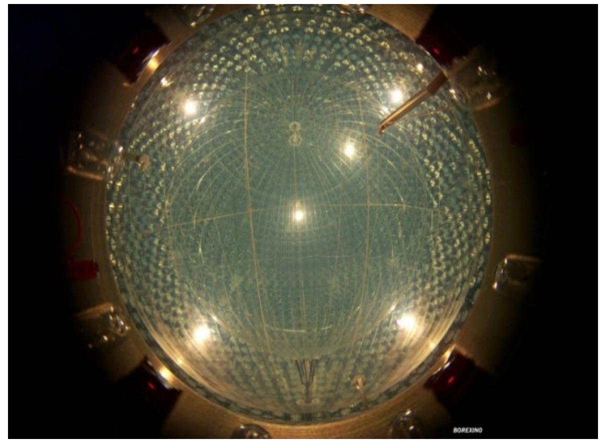
Borexino detector geometry in Geant4

- Inner Part of the Detector

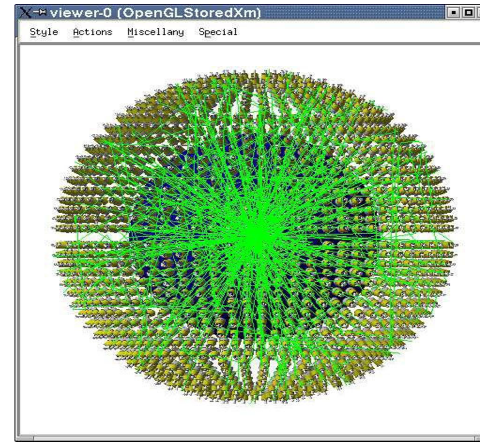
PMT inside view



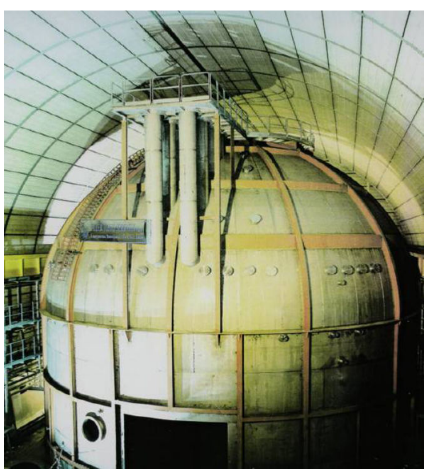
Liquid scintillator



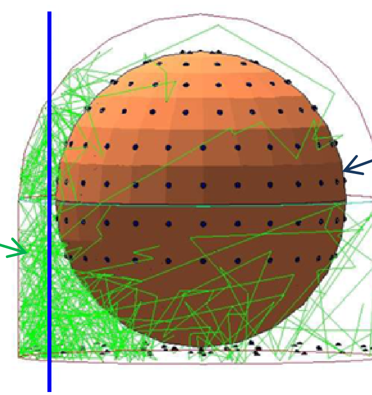
Scintillation event in Borexino



- Muon Outer Veto Cherenkov detector



Vertical muon in Outer Detector.



VETO PMT

Cherenkov photons,
reflected from
diffusive
Tyvec surfaces.

Physics of optical processes was implemented for Borexino code

● Special attention is devoted to the propagation and detection of scintillation photons.

● Photon tracking takes into account the interactions of the emitted photons with scintillator (Pseudocumene + 1.5g/l PPO), Pseudocumene (PC + DMP) buffer and nylon vessel films. This processes include:
● Elastic Raleigh scattering of photons in scintillator and PC buffer.
● Absorption and reemission of photons on PPO molecules.
● Absorption of photons by DMP quencher molecules in PC buffer.
● Photon absorption in thin Nylon vessels.
● The cross-sections for this interactions also as time characteristics of reemission process were experimentally measured for different light wavelengths [NIM, A440, (2000), 360].

Specially developed class BxAbsorbtionReemission

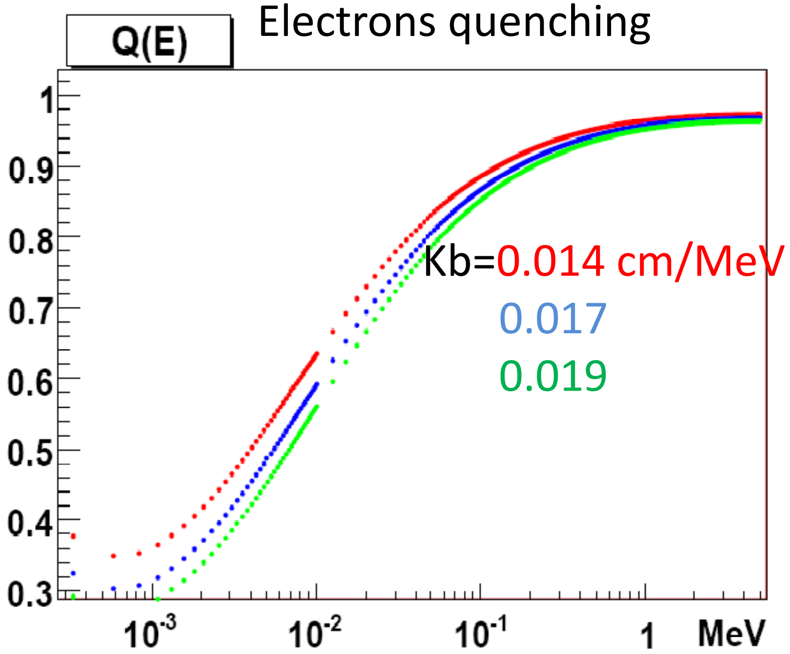
Quenching for electron, proton and alpha particles in Borexino scintillator

The amount of light L_e emitted by an organic liquid scintillator when excited by electrons is related to the amount E of energy lost by the electrons through a non linear law. Significant deviations from linearity are observed for low electron energies (below some hundreds keV) and they become more and more important as long as the electron energy is getting smaller and the ionization density is getting higher and higher.

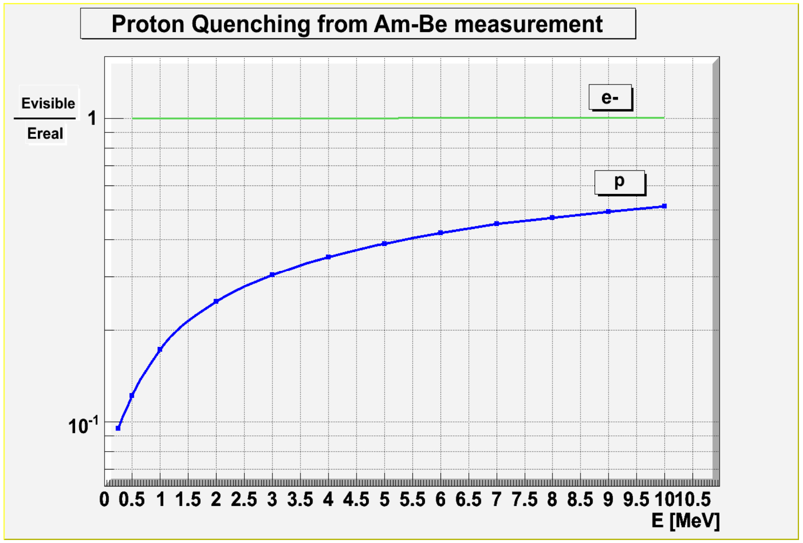
The Birks formula is one of the possible ways to describe this behavior (ionization quenching) for different particles

$$L_e = Y \int_0^E \frac{dE}{1 + kb\frac{dE}{dx}} \qquad Q(E) = \frac{1}{E}\int_0^E \frac{dE}{1 + kb\frac{dE}{dx}} \qquad L_e = YEQ(E)$$

Electrons quenching

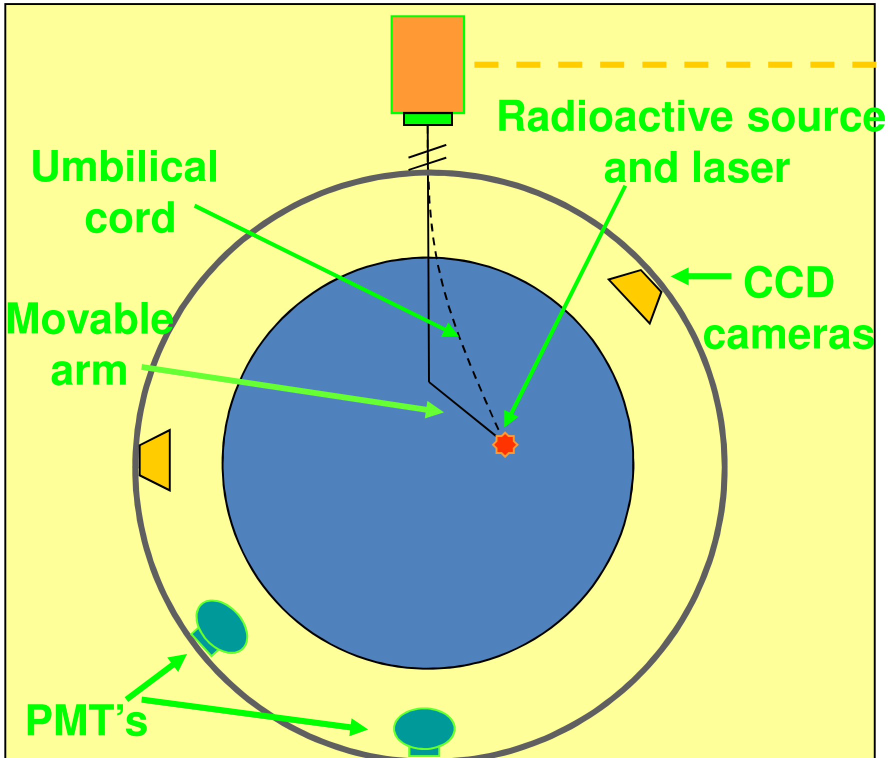


Protons quenching

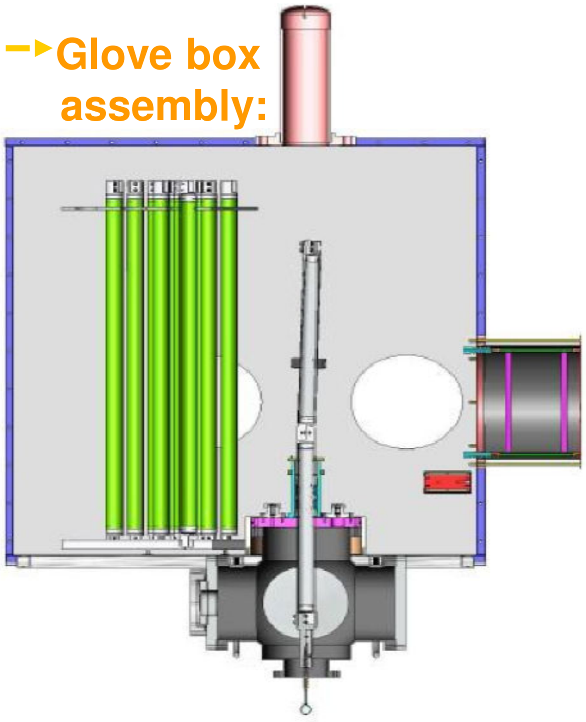


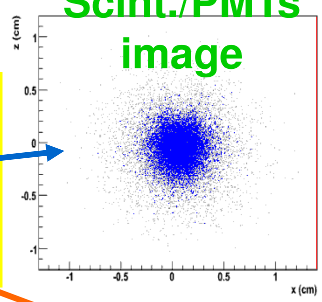
Calibration of Borexino detector

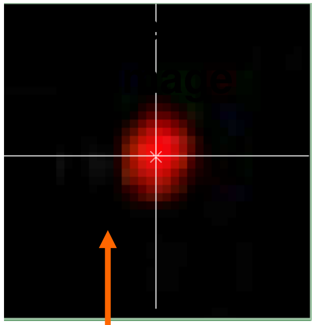
A movable arm insertion system has been developed by the Virginia Tech Group



Working principle sketch







Source positions reconstruction:

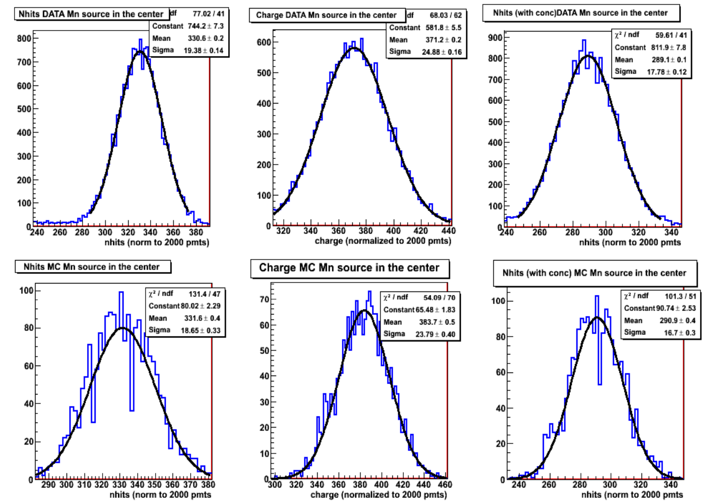
- Source decays induced scintillation light/PMT's
- Red laser light/CCD cameras (accuracy: < 2 cm)

Calibration of Borexino detector and comparison with Geant4 results

Several gamma sources used in different positions inside the detector:

- ^{57}Co (122 keV)
- ^{139}Ce (166 keV)
- ^{203}Hg (279 keV)
- ^{85}Sr (514 keV)
- ^{54}Mn (835 keV)
- ^{65}Zn (1115 keV)
- ^{60}Co (1173 + 1332 keV)
- ^{40}K (1461 keV)

Mn source in the center of Borexino



Alpha source ^{222}Rn source

^{14}C+^{222}Rn source

Neutron source ^{241}Am-^{9}Be

The agreement between Monte-Carlo and Calibration data peaks positions at different energies for the detector center is ~ 0.5-1 %

The quenching parameters for electrons and protons are extracted from the calibration data

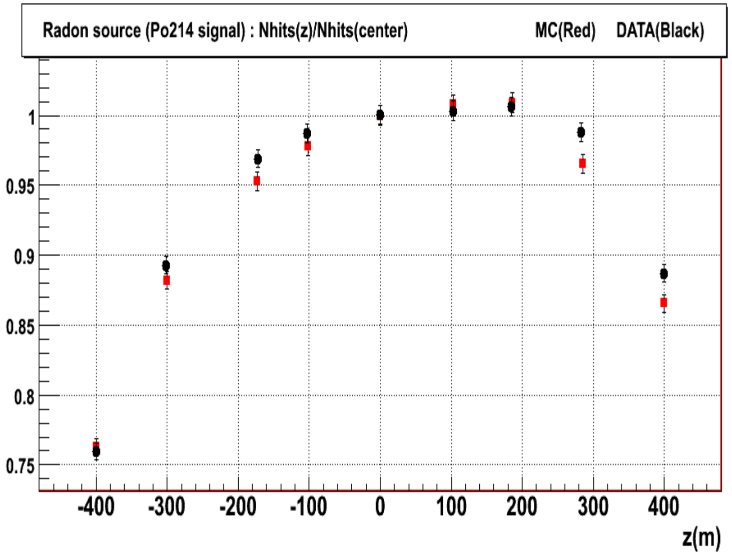
Radon source in different z position

Po214 peak of alpha-particles is quenched

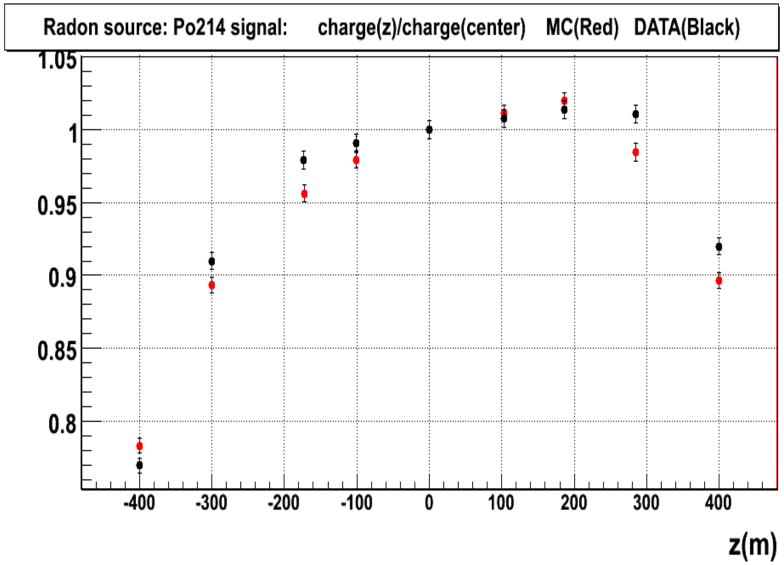
– not good for the absolute energy scale

– good for checking the energy scale vs the axial position

Hits variable

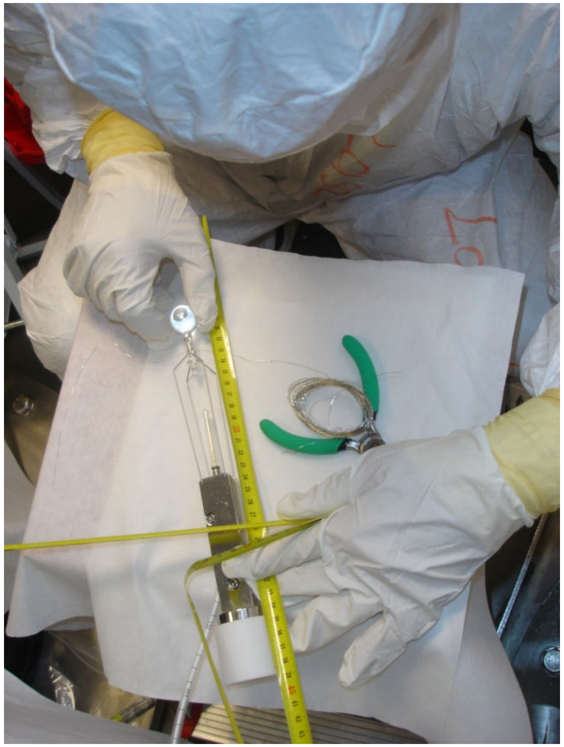


Charge variable

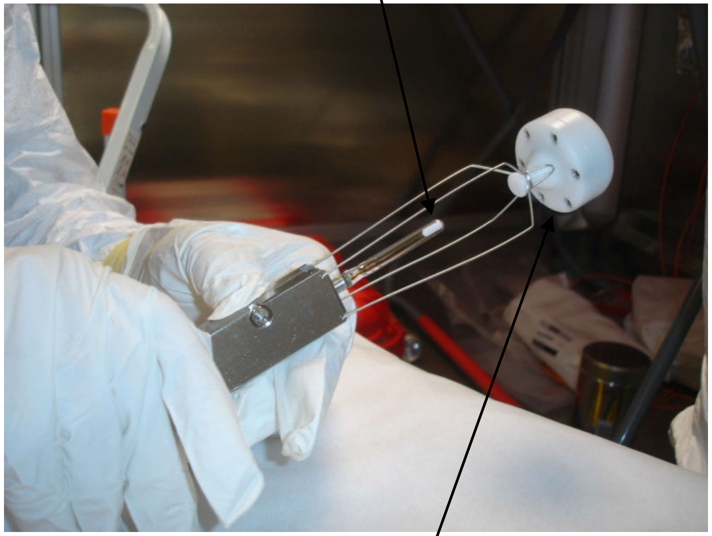


Monte-Carlo with high accuracy reproduces the position dependence of the calibration signal

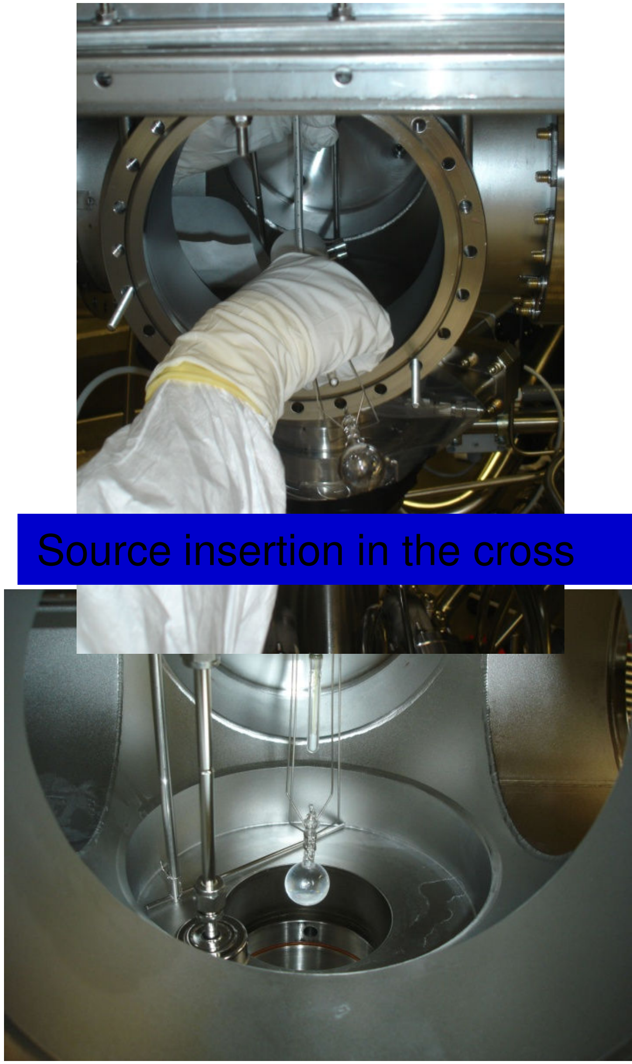
Calibration of Borexino detector: source mounting and insertion



Laser diffuser



Am-Be source
housing

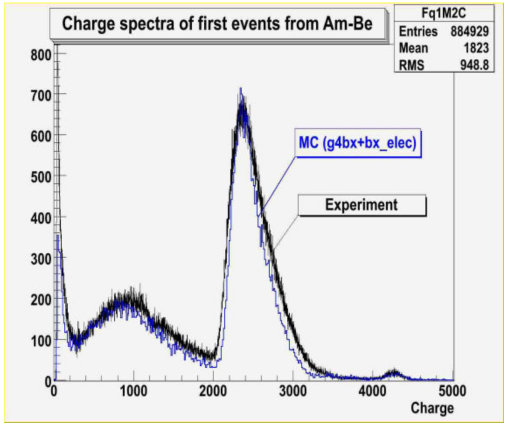


Calibration of Borexino response function for neutron and proton detection.

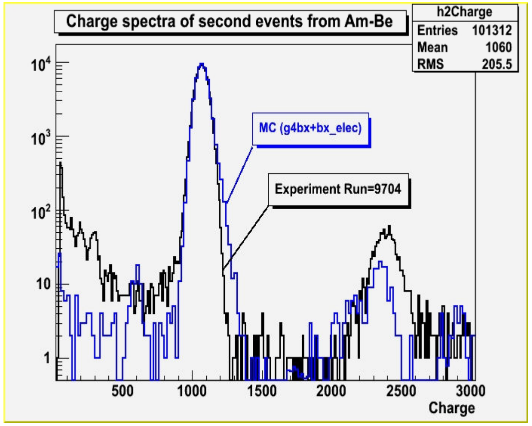
Am-Be source of fast neutrons was used for calibration of neutron detection efficiency, energy detector scale at high energies , proton quenching

$$\alpha + {}^{9}\text{Be} \rightarrow {}^{12}\text{C}^* + n \rightarrow {}^{12}\text{C} \qquad (\sim 86\%) \qquad (1)$$
$$\alpha + {}^{9}\text{Be} \rightarrow {}^{9}\text{Be}^* + \alpha' \rightarrow {}^{8}\text{Be} + n + \alpha' \qquad (\sim 14\%) \qquad (2)$$

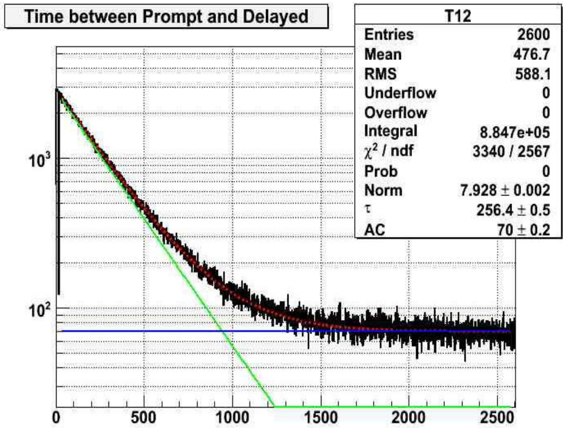
Good agreement between simulation and experiment for Birks parameters kB=0.0120 cm/MeV (for protons), kB=0.0190 cm/MeV (for electrons)



Prompt signal from Am-Be source



Delayed signal from Am-Be source

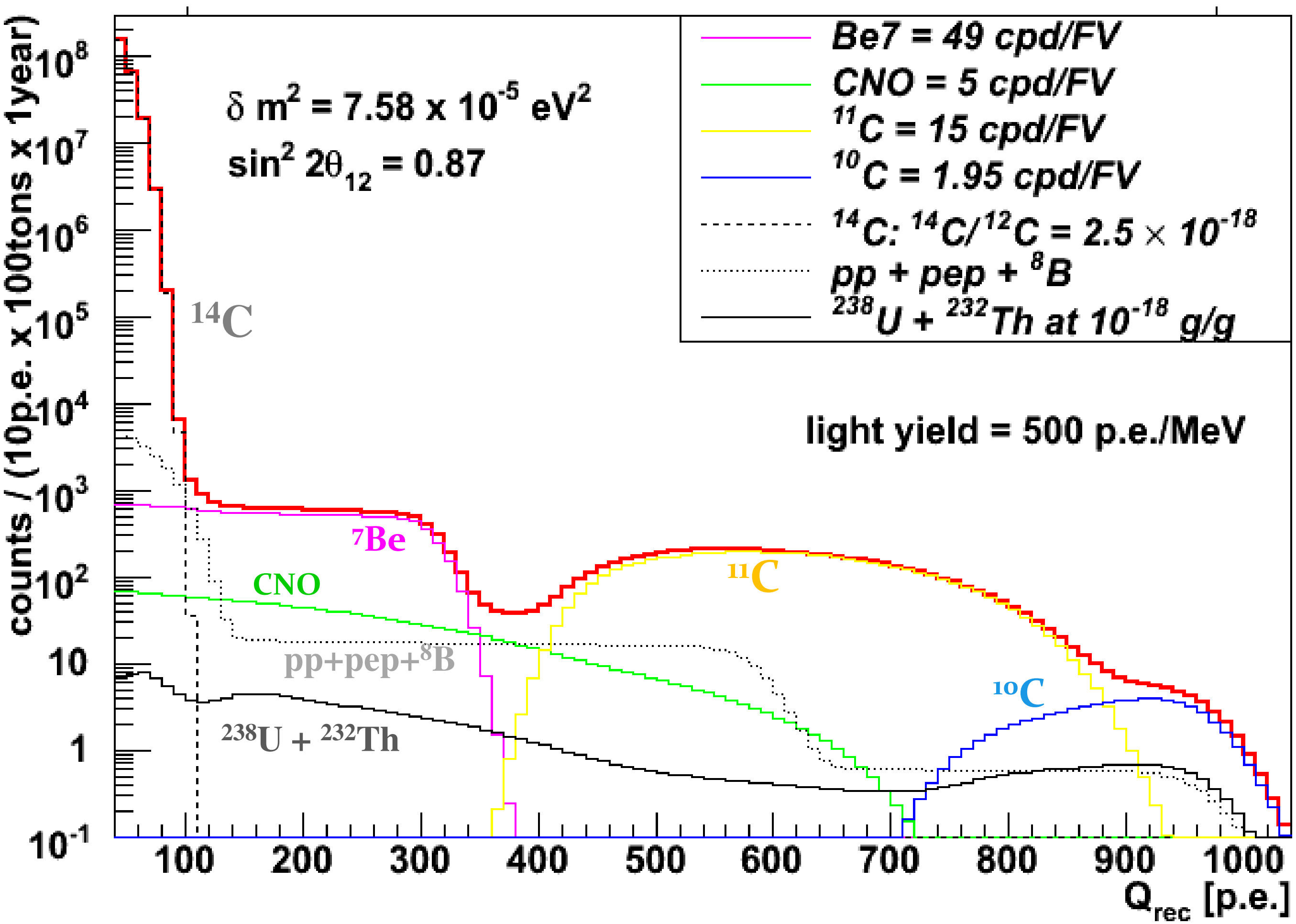


Time distribution between prompt and delayed events

measured and calculated life time of neutrons in the Borexino scintillator (PC + 1.5 g/l PPO)

τ_{geant4}= 254+-0.5 mcs, τ_{exp} = 256.4 +- 0.5 mcs

The expected signal and the background in Borexino – Monte-Carlo simulation

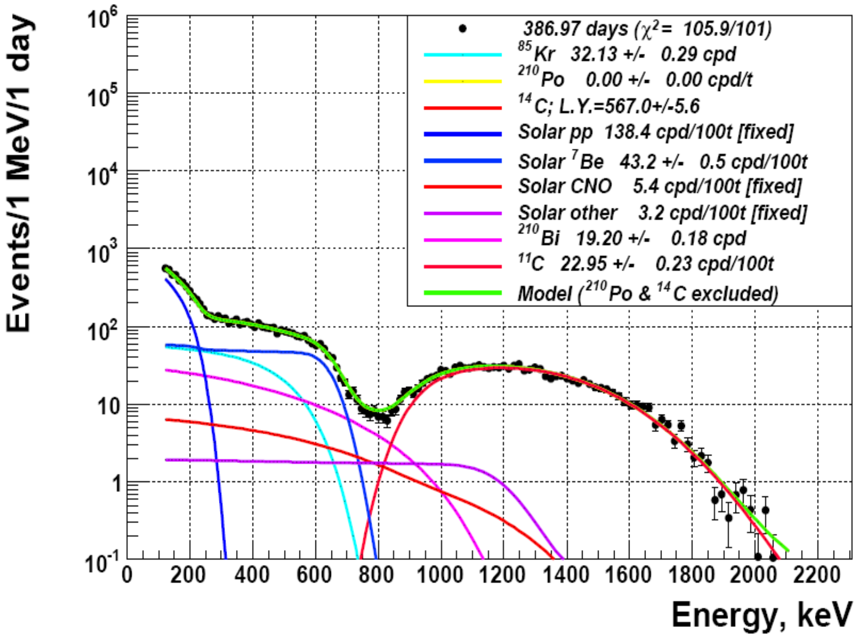


Monte-Carlo vs. Data – Quantitative test of the fit procedures for extracting 7Be neutrino signal

The MC spectra of neutrino signals and different detector backgrounds are submitted to the fit algorithms

The output of the fit procedure is compared with the precisely known composition of the MC spectra

In this way the effectiveness of the fit methodology to extract accurately the ^{7}Be flux can be thoroughly probed



Simulated MC specrum of Borexino detector
Input MC Composition :
^{7}Be 43.24 , ^{210}Bi 17.8, ^{11}C 23.06, ^{85}Kr 29

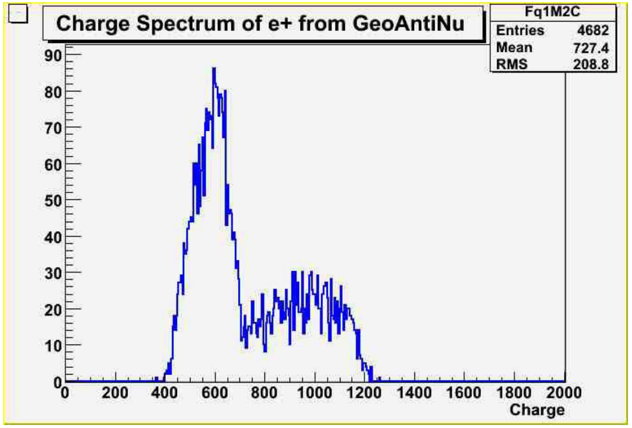
Recently developed method – Spectral fit of the Borexino detector signal using the Monte-Carlo calculated data

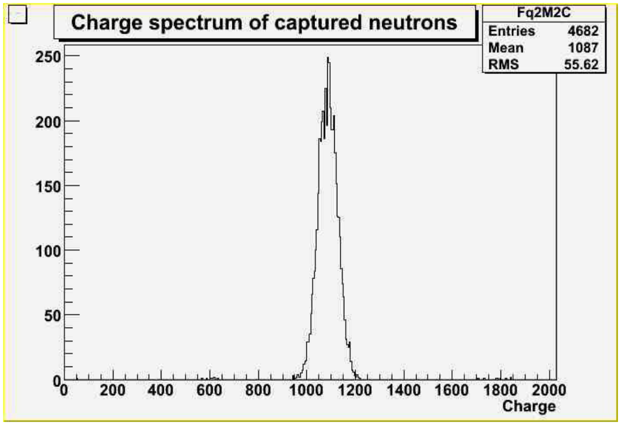
Search for Geo and Reactor antineutrinos

Detection reaction $\overline{\nu}_e + p \rightarrow n + e^+$

Expected antineutrino signal for 1 yr of the data taking			
	1-1.5 MeV	1.5-2.6 MeV	2.6-10 MeV
^{232}Th	1.2	0	0
^{238}U	2.1	2.3	0
Reactor	*0.5*	*3.3*	*8.5*
Total	*3.8*	*5.6*	*8.5*
Random	0.3	0.2	0.0

Geant4 is used to calculate the efficiency of antineutrino detection and backgrounds





Search for Pauli forbidden transitions in ^{12}C nuclei

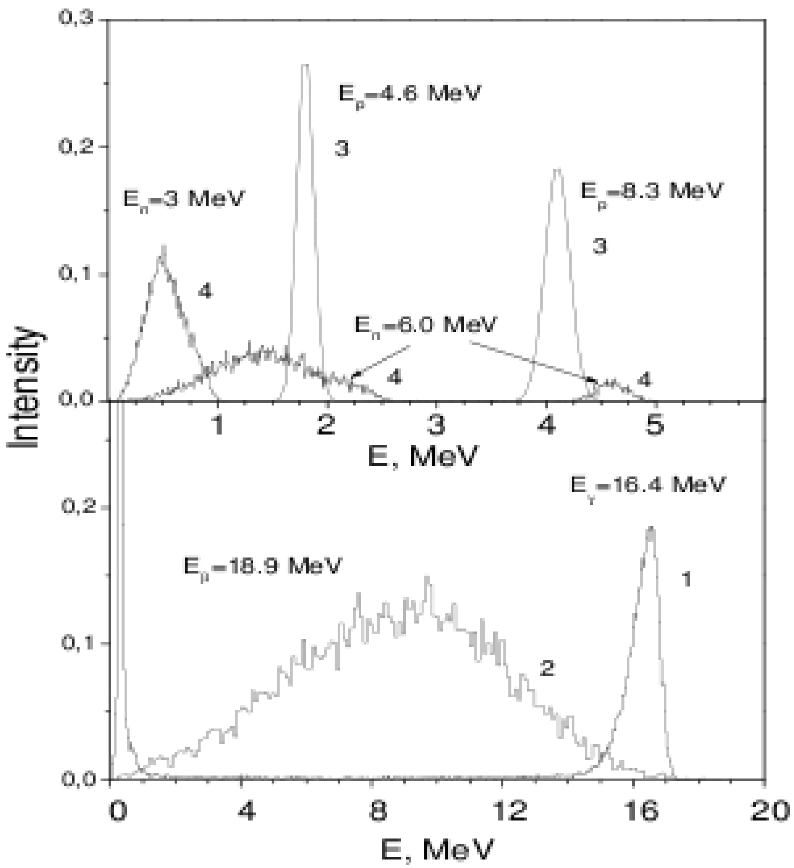
Borexino has unique parameters to study Non Paulian transitions with low Q (p or α emissions)

Channel	Q, MeV	E detected	
$^{12}C \rightarrow {}^{12}C^{NP} + \gamma$	17.5 ± 1	~17.5	E.M.
$^{12}C \rightarrow {}^{11}B^{NP} + p$	$(6.4 \div 7.8) \pm 1$	$2.0 \div 4.7$	
$^{12}C \rightarrow {}^{11}C^{NP} + n$	$(4.5 \div 6.5) \pm 2$	2.2	STRONG
$^{12}C \rightarrow {}^{8}Be^{NP} + \alpha$	3.0 ± 1	$0.06 \div 0.23$	
$^{12}C \rightarrow {}^{12}N^{NP} + e^{-} + \nu$	18.9 ± 2	$0.0 \div 18.9$	WEAK
$^{12}C \rightarrow {}^{12}B^{NP} + e^{+} + \nu$	17.8 ± 2	$0.0 \div 17.8$	

The signature of the transitions with two particle in the final state is a gaussian peak in the measured spectrum. In the case of neutrino emission the flat $\beta^{\pm}$ - spectra are registered.

Search for Pauli forbidden transitions in ^{12}C nuclei

To find the response of the scintillator detector (detected energy) one have to take into account the recoil energy of nuclei and quenching factor for protons.

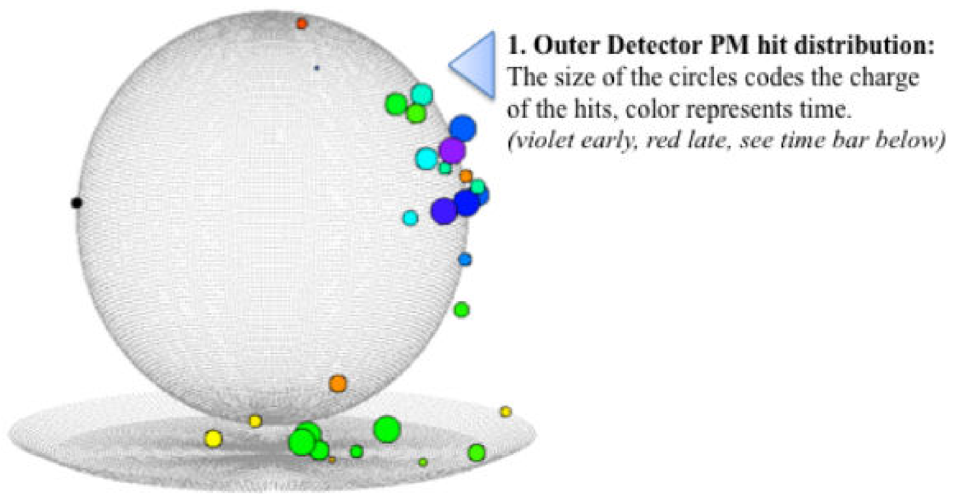


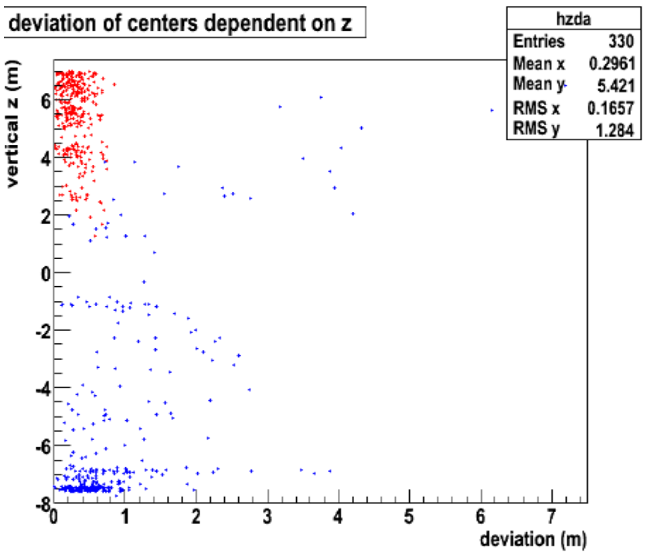
The response function of the Borexino detector from Monte-Carlo for Pauli forbidden transitions :

1) **$^{12}C \rightarrow {}^{12}C^{NP} + e^- + \gamma$ (16.4 MeV) decays in Inner Vessel and PC buffer**
2) **($^{12}C \rightarrow {}^{12}N^{NP} + e^- + \nu$) (18.9 MeV)**
3) **$^{12}C \rightarrow {}^{12}B^{NP} + p$ (4.6 and 8.3 MeV)**
4) **$^{12}C \rightarrow {}^{12}N^{NP} + n$ (3.0 and 6.0 MeV)**

Simulation of muon detection in Borexino

Geant4 simulation was used for the development and tuning of the muon track reconstruction algorithms, based on the time distribution and hitted PMT positions of detected photons





Monte Carlo test of the OD tracking: The distance of reconstructed entry points (red) and exit points (blue) to the input MC track are plotted versus the z-coordinate of the penetration points.
Entry points are reconstructed rather well, the mean distance from the track is 0.3 m. The quality of exit points depends on its z-coordinate: Points on the detector floor provide the best results. The overall mean distance of the exit point to the track is 1.0 m.

Conclusions

The Geant4 MC code for Borexino detector is the result of the work of several people during several years with continuous improving of the physics model

Accurate Borexino detector modeling due to GEANT4:
Exact detector geometry, scintillation photons are tracked one by one.

Typical CPU time for the code operation 1 sec/(1 MeV event)

Almost two years of real data + The calibration campaigns of Borexino gives excellent opportunity to tune with precision some input data parameters

High precision reproduction of the experimental response due to GEANT4 (energy response, timing, position… and spectral fit of solar neutrino signal)

Bug in Geant4 to be resumed

Wrong calculation of gamma energy spectra from thermal neutron capture on ^{12}C nuleus.
(this bug was reported ~ 2 years ago to GEANT4 team by Kamland – but still not resolved)

The same error is in calculation of gamma energy spectrum from thermal neutron capture on other nuclei – like Cl, Fe, Cr, Ni etc.

Why ?

1. The database for gamma-decays from thermal neutron capture on different nuclei is absent
2. According to nuclear physics after the capture of thermal neutron the total energy of all emitted gammas is fixed – but in GEANT4 it is simulated with some poissonian distribution (see G4NeutronHPPhotonsDist.cc)