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Nuclear Physics for geo-neutrino studies

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Nuclear physics for geo-neutrino studies

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Towords Neutrino Technologies
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- This work in collaboration with:
  - G. Fiorentini, M. Lissia, F. Mantovani and O. Smirnov
- Data from the Borexino coll.

Determine the GeoNeutrino Signal

- GeoNeutrino signal (via inverse-β decay) from β decays in ^{238}U and ^{232}Th chains

$$S = N_p \cdot t \cdot \sum_i \phi_i \cdot \int_{1.806MeV}^{E_\nu^{\max}} dE_\nu \sigma_{\nu p}(E_\nu) \cdot \lambda_i(E_\nu)$$

- N_p = target protons
- t = data taking time
- Φ_i = incoming flux for i-th β decay source
- λ_i = normalized i-th β spectrum

Uncertainties in the expected signal

- GeoNeutrino predicted signal depends on:

$$s_i = \int_{1.806MeV}^{E_\nu^{\max}} dE_\nu \sigma_{\nu p}(E_\nu) \cdot \lambda_i(E_\nu)$$

- Main uncertainty on s_i due to β decay spectrum
- At present only "universal shape" transitions considered

The β decay spectrum

- Universal shape spectrum assumes momentum independent transition nuclear matrix

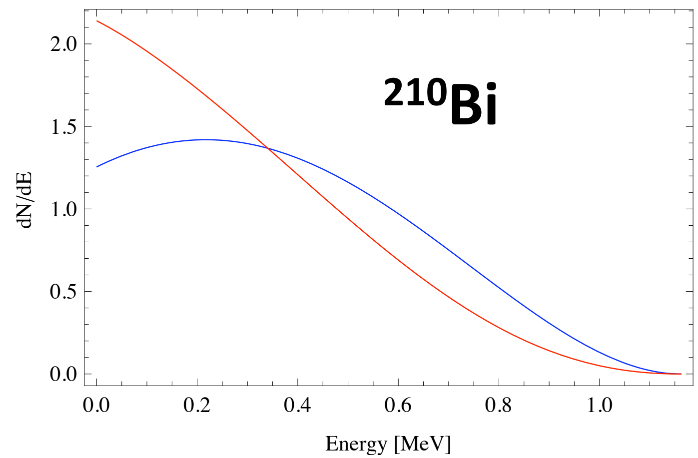
$$d\Gamma \propto \left|M_{if}\right|^2 F(Z,T_e)\, p_e^2 \left(Q_\beta - T_e\right)^2 dp_e$$

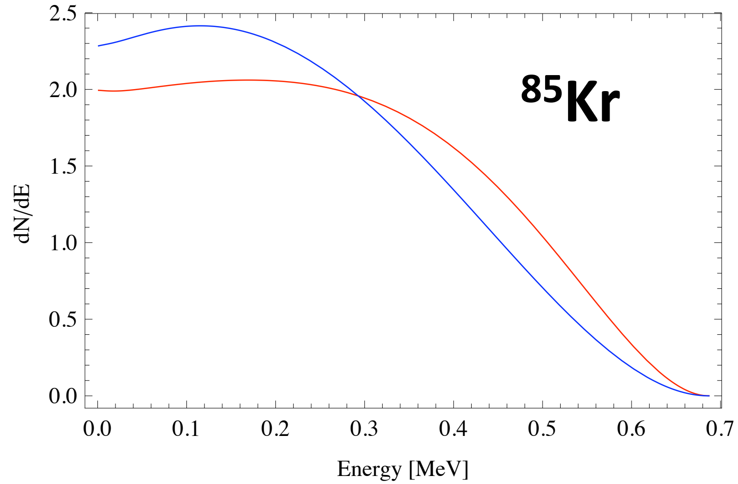
- Allowed transitions have $\log_{10}(ft_{1/2}) = 3.5 \div 7$
- When lepton pair carries orbital angular momentum > 0 we speak about forbidden transitions ($\Delta J>1$, $\Delta\pi>0$)
- Forbidden transitions have $\log_{10}(ft_{1/2}) > 6.5$
- Forbidden transitions may be represented by introducing a "shape factor"
- Experimentally Kurie Plots allow to determine the shape factor (in particular at high energy and for single decays)

Forbidden decays of interest in Low Counting Detectors

gnd -> gnd

- ^{85}Kr ($9/2^+$ -> $5/2^-$)
- ^{39}Ar ($7/2^-$ -> $3/2^+$)
- ^{40}K (4^- -> 0^+)
- ^{210}Bi (1^- -> 0^+)
- ^{214}Bi (1^- -> 0^+)
- ^{212}Bi (1^- -> 0^+)





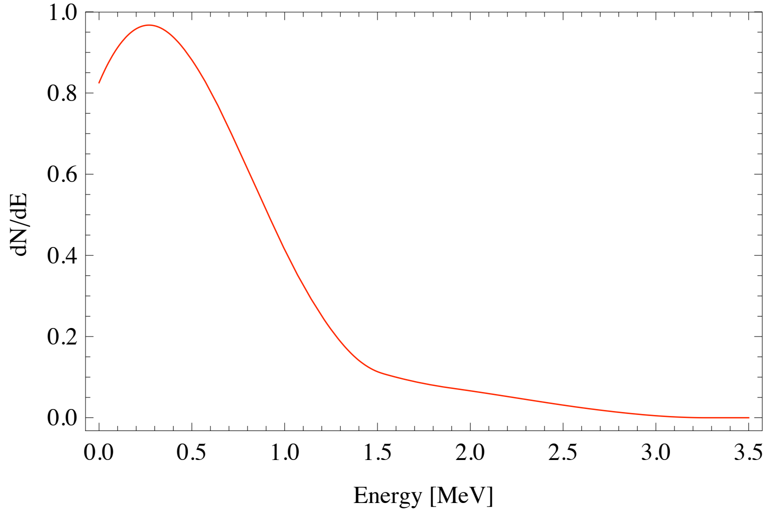
Allowed shape

With a shape factor

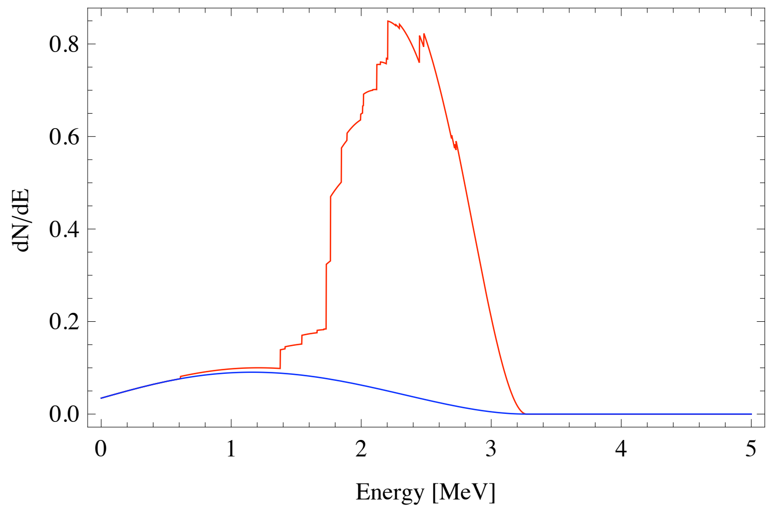
^{214}Bi β decay

- $Q_{\beta\beta}$=3.272 MeV; $J^{\pi}=1^{-}$ to $J^{\pi}=0^{+}$ for ^{214}Po
- 82 excited states reported in WWW table of isotopes (ToI)
- $\log_{10}(ft_{1/2})$ ranges from 6.48 to 10.4

^{214}Bi beta β and β+γ spectra



β spectrum



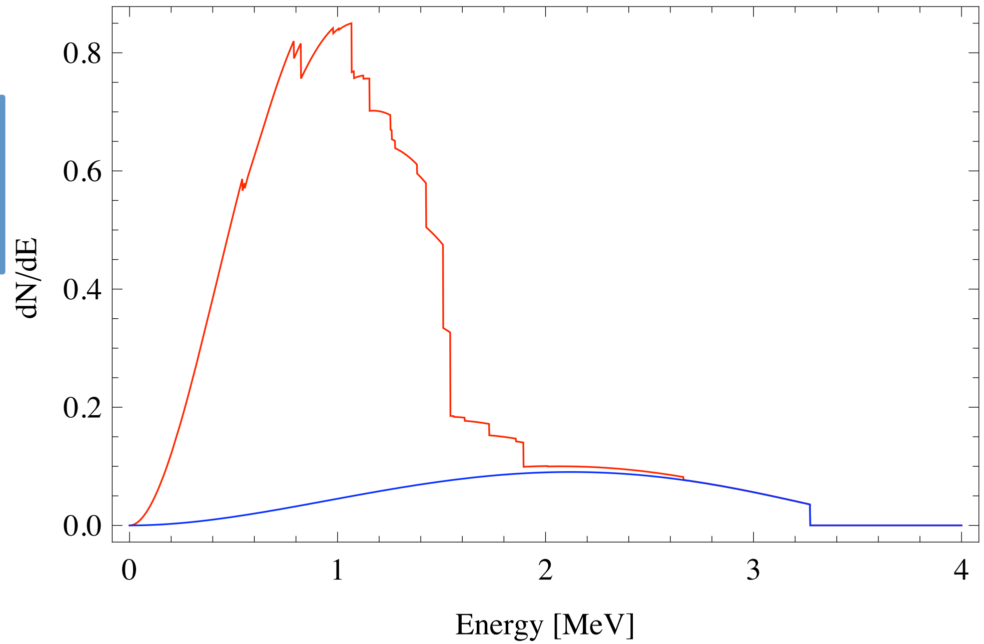
β+γ spectrum
<E>=2.13 MeV
Blue line: transition to ground state 18.2% (ToI)

From β to antineutrino spectrum

$E_\nu = Q_\beta - T_e$

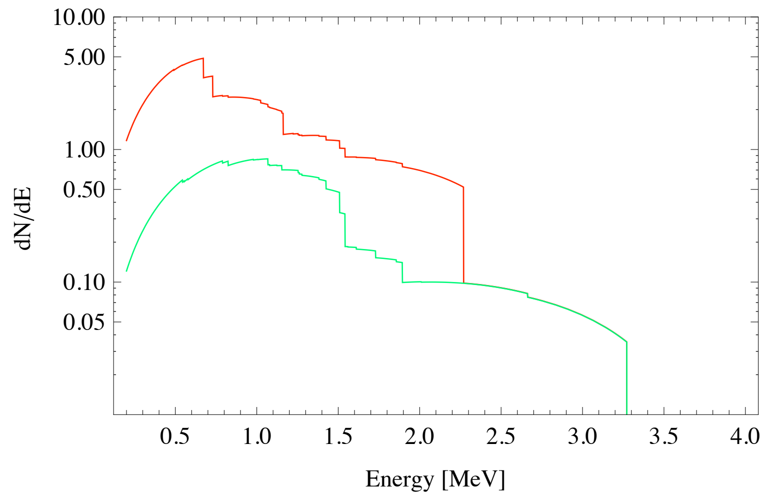
Total ^{214}Bi

Only transition to ground state



Geoneutrino spectrum from ^{238}U

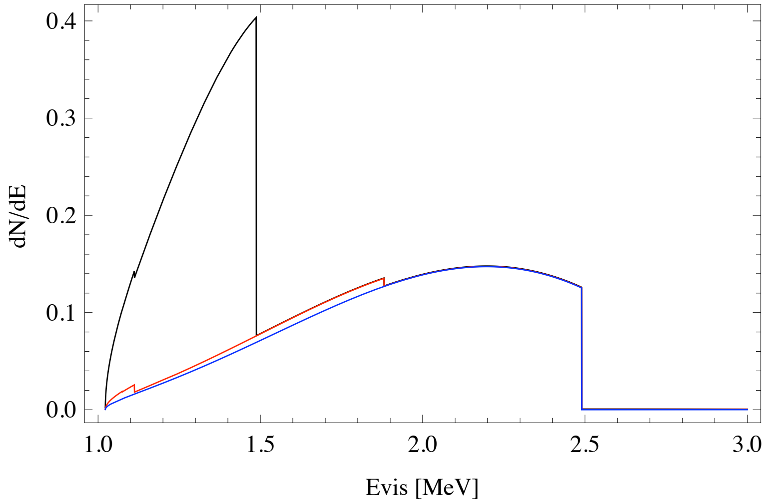
Total from ^{238}U
Only ^{214}Bi



$$s(^{214}Bi) = p_{3.272}\langle\sigma\rangle_{3.272} + p_{2.663}\langle\sigma\rangle_{2.663} + p_{1.849}\langle\sigma\rangle_{1.849} \approx p_{3.272}\langle\sigma\rangle_{3.272} + p_{2.663}\langle\sigma\rangle_{2.663}$$

Visible Energy: $E_{vis} = E_{\nu} - 0.78$ MeV

Total from ^{238}U
Only ^{214}Bi
Only transition to ground state in ^{214}Bi

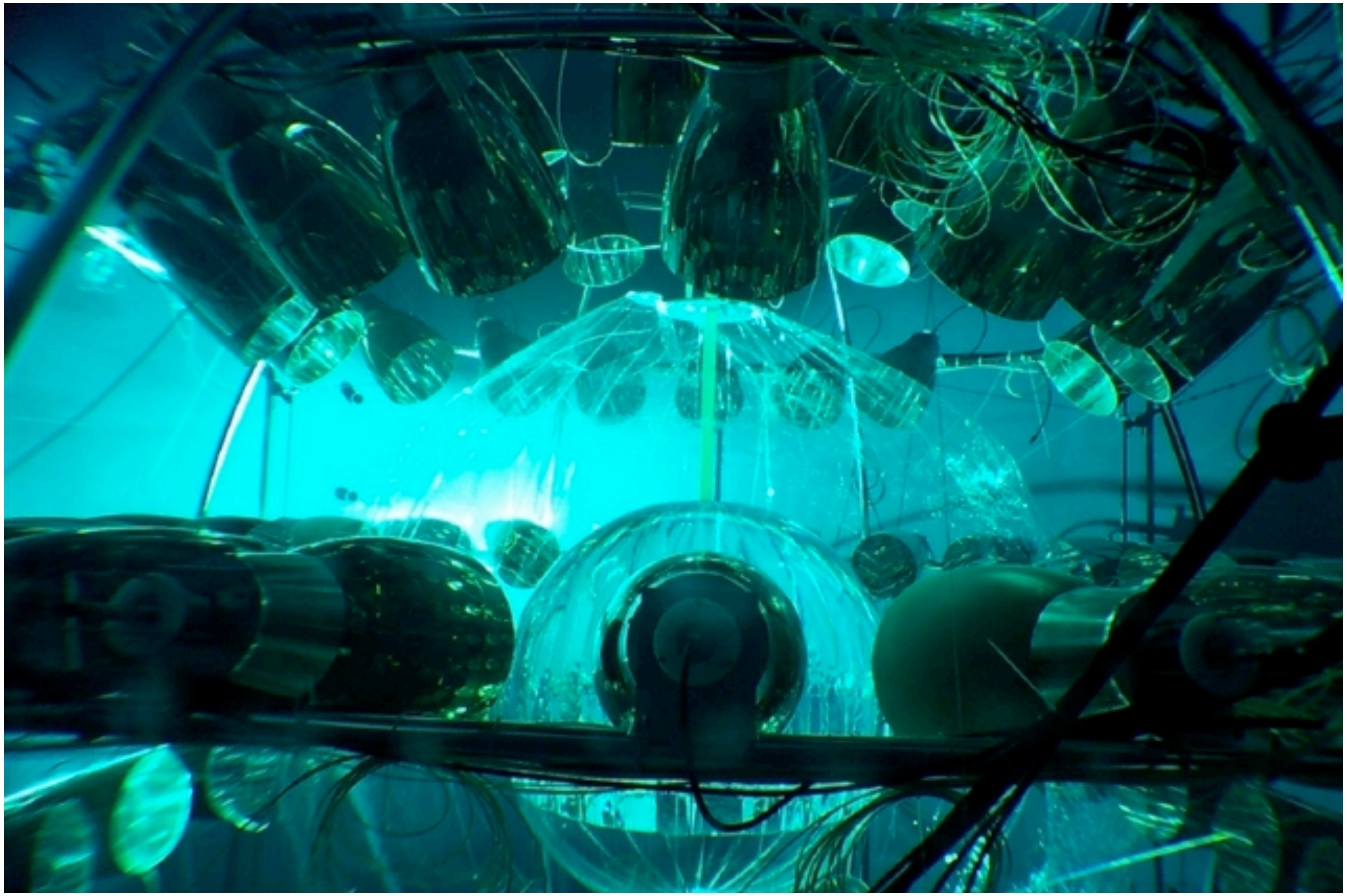


Measurement of ^{214}Bi β spectrum

- The purpose of our work:
  - Meaure the feeding probability to ground state for ^{214}Bi
    - In ToI measured by subtraction using excited states data
  - Probe allowed vs not-allowed shape
  - Determine effect on geoneutrino signal
- Method:
  - Make use of the Borexino Counting Test Facility and Rn data

Counting Test Facility at Gran Sasso

Prototype of Borexino detector:
- 100 PMTs
- 4tons of LS



^{214}Bi-^{214}Po tagging

$^{214}Bi^{131}_{83}$ (β decay; Q_{β}=3.27 MeV) ->^{214}Po (α decay; Q_{α}=7.83 MeV; τ= 237.04μs)

The sequence ^{214}Bi-^{214}Po can be tagged to remove event-by-event background with an efficiency larger than 95% in Liquid Scintillators

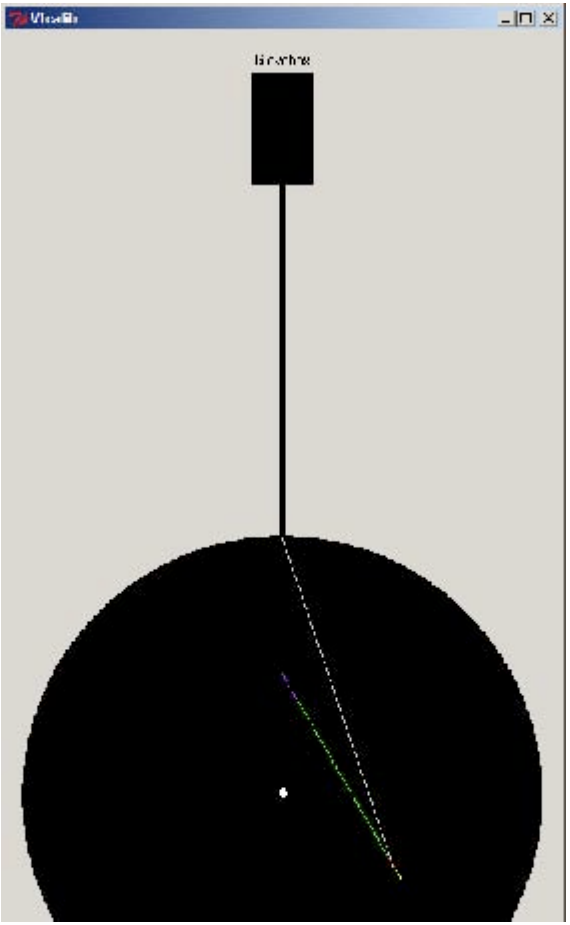
1. **Select correlated events in time : 20μs < Δt < 600μs**
2. **Select α event in well specified energy range considering quenching**
3. **Select events with ΔR < 60cm**
4. **Reduce accidental coincidences by a radial cut (Fiducial Volume)**

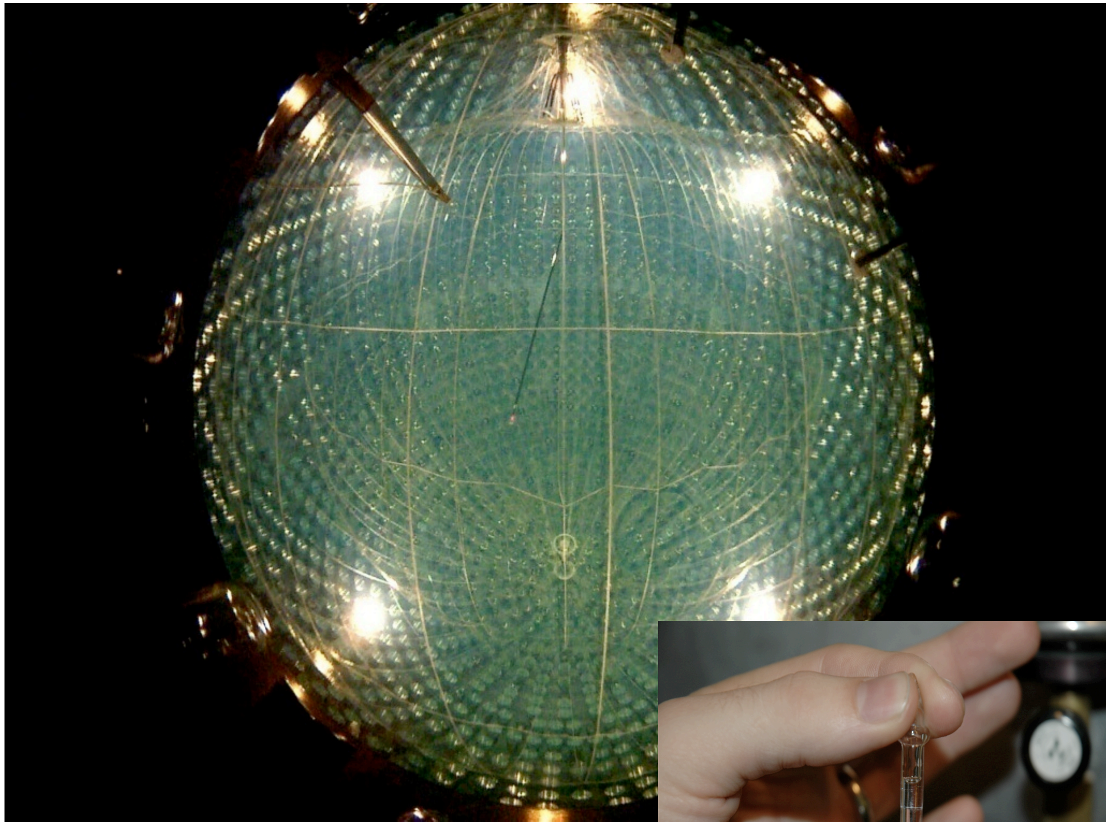
^{214}Bi-^{214}Po events can be used to determine α/β discrimination properties of the Liquid Scintillator

^{222}Rn sources

- Make of diffused Rn contamination in the FV
- Make use of a Rn source
  - Start with high intensity ^{226}Ra source
  - Sparge nitrogen into sample of Liquid Scintillator
  - Fill quarz vial with Rn-loaded LS
  - Use insertion system to deploy the source inside the detector

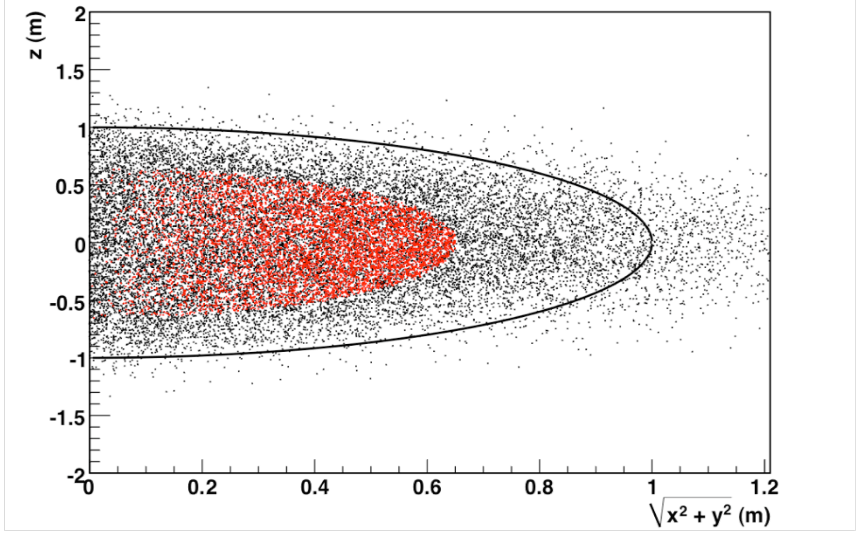
Source Insertion System in Borexino



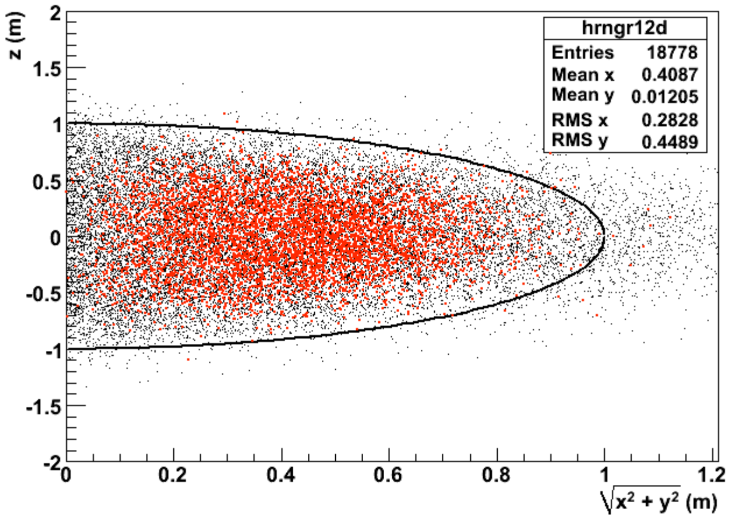


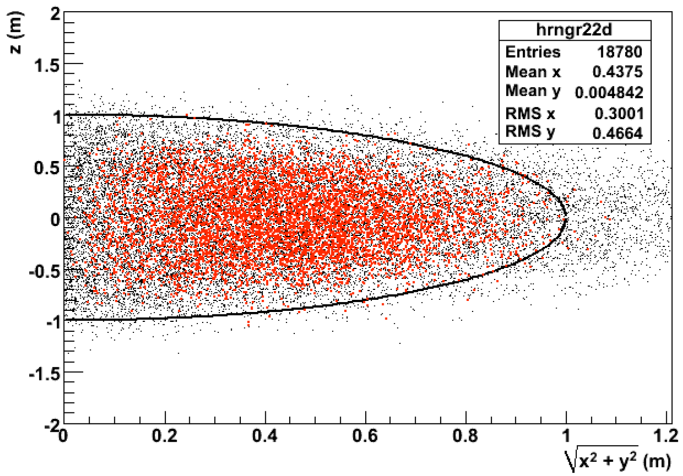
Distribution of Bi-Po events in CTF for a diffused Rn source

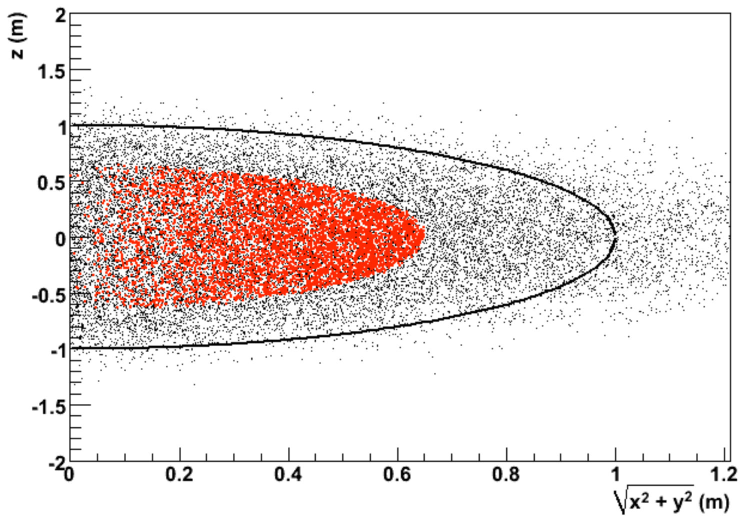
^{214}Bi selects FV



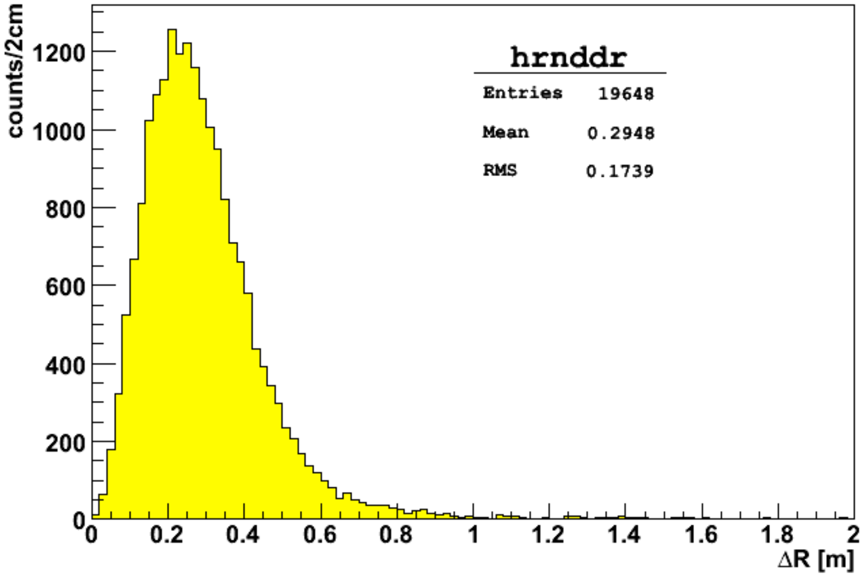
^{214}Po selects FV

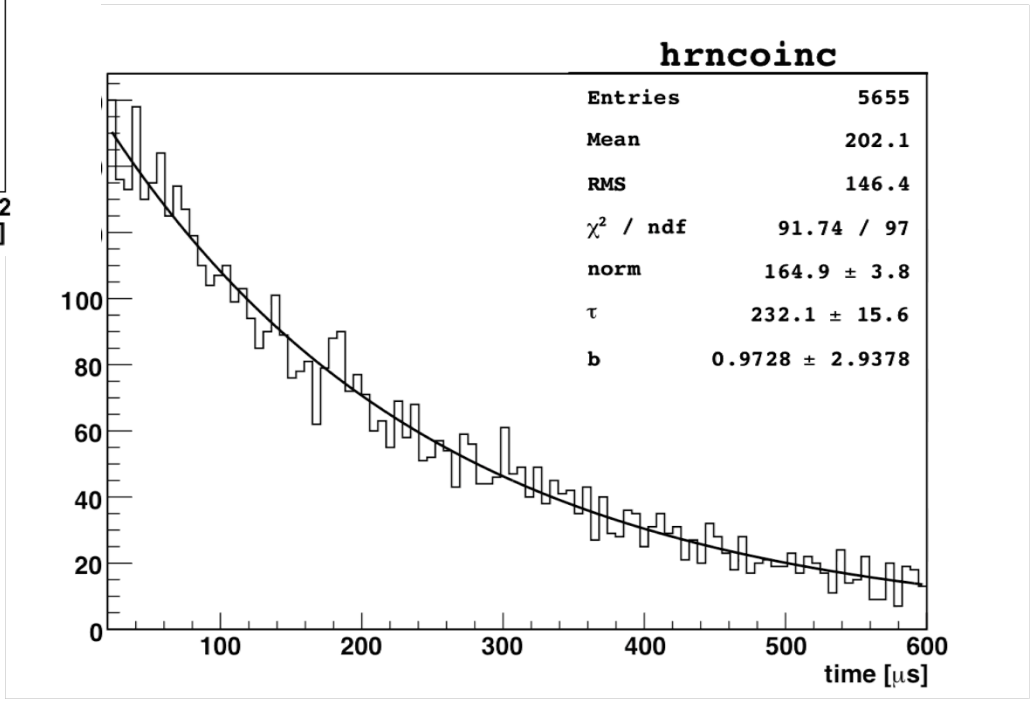






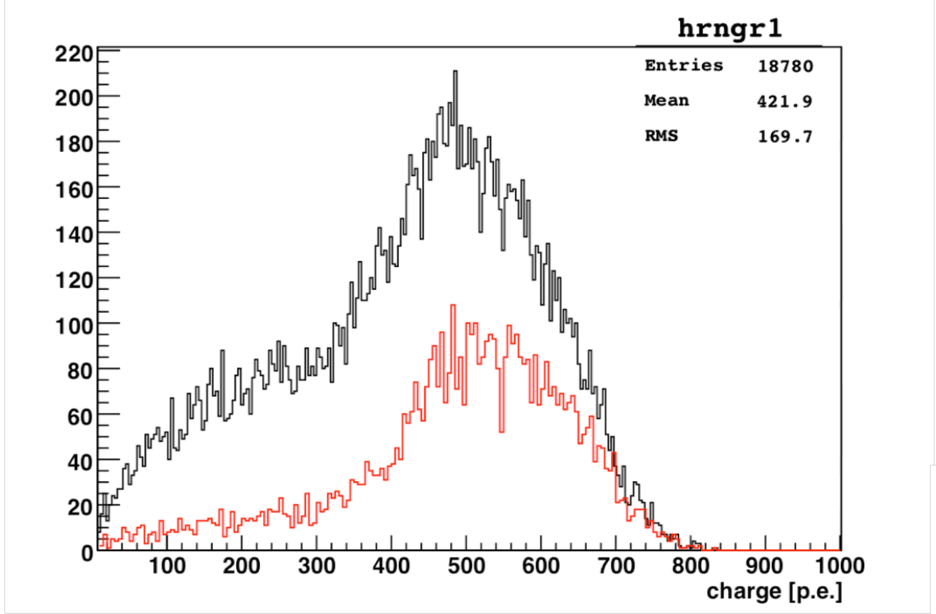
Bi-Po correlated distance and time



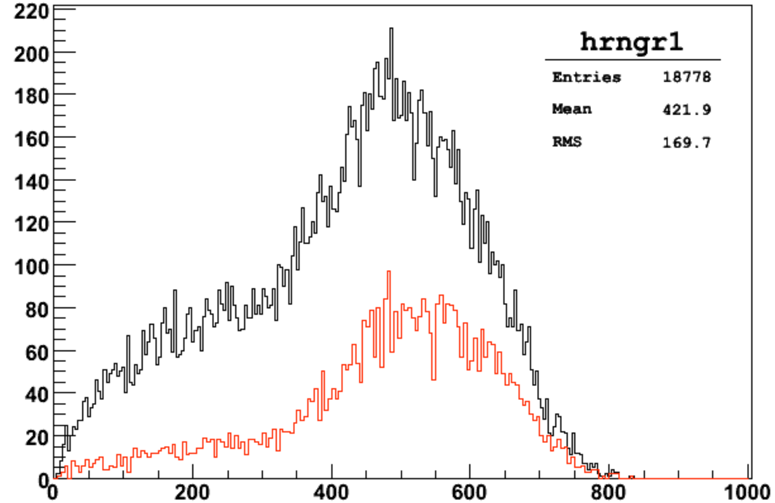


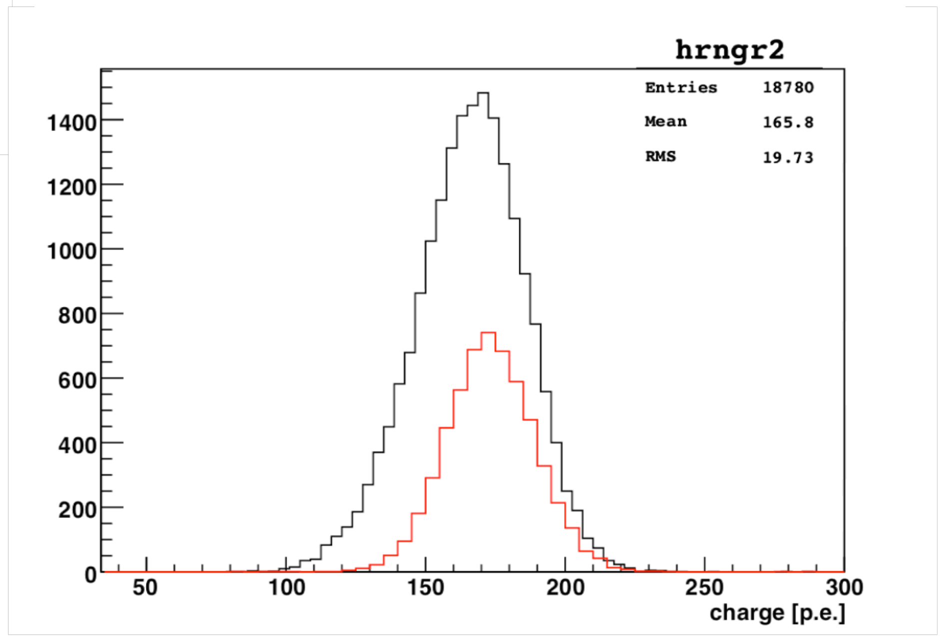
^{214}Bi and ^{214}Po measured spectra

^{214}Bi selects FV



^{214}Po selects FV





Energy resolution of CTF:

1. 5.6% @ 1MeV for 100 PMTs
2. 6.6% @ 1 MeV for presented data

Liquid Scint. response in the CTF

- MonteCarlo based on calibration data and quenching Birks' model

$$Q = LY \cdot T \cdot f_q(T, k_B) \cdot f_r(r)$$

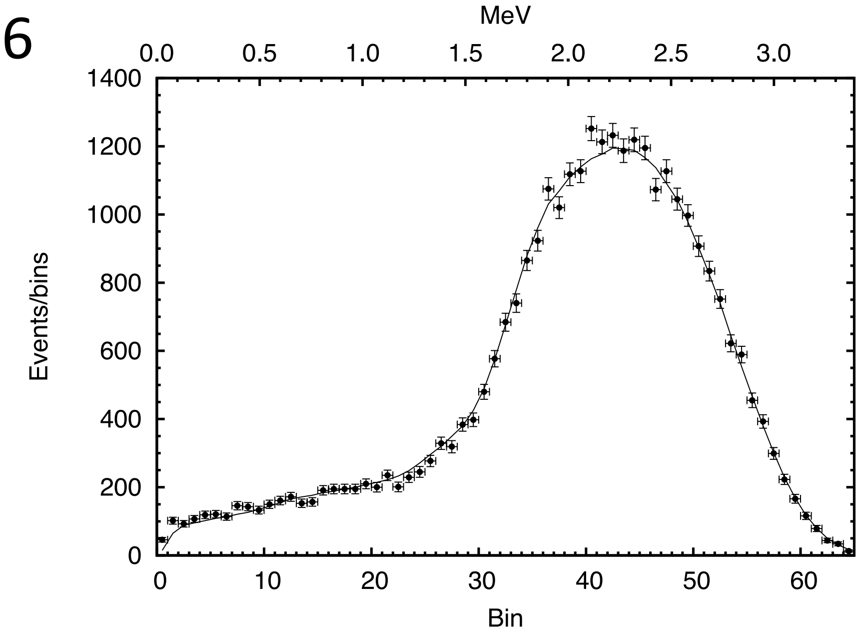
- Main systematics due to:
  - Not completely contained γ's
  - Light loss
  - Uncertainty on k_B~0.019 cm/MeV

Data reduction

- Data from diffused Rn contamination due to an accidental air leak in 2005
- 4.54×10^5 selected BiPo events
- α/β discrimination: 4.46×10^5
- Fiducial Volume cut at R=42cm: **3.14×10^4**

Ground state feeding probability

- Using allowed shape fit selected ^{214}Bi spectrum with three unknowns:
  - p_0, LY and normalization
- At minimum $\chi^2 = 61.7/(63-3)$
- **$p_0 = 0.177 \pm 0.004(\text{stat})^{+0.003}_{-0.001}(\text{sys})$ [~2.8%]**
- ToI reports: $p_0 = 0.182 \pm 0.006$



Probe shape factor

- For ground state transition release assumption on "universal shape"

$$\lambda_0(T_e) = \lambda_0^{univ}(T_e) \cdot \left(1 + y\frac{T_e - \langle T_e \rangle}{\langle T_e \rangle}\right)$$

- Assumed shape factor:
  - given in terms of dimensionless parameter y
  - does not change normalization, only shape
- Constraining p_0 and p_1 to ToI values (including errors): $y = -0.11 \pm 0.06(\mathrm{stat})$; $p_0 \sim 0.177$; $p_1 \sim 0.008$
- At minimum: $\chi^2 = 51.6/(65-5)$
- Statistical evidence of deformed shape is 2.4σ

Impact on GeoNeutrino Signal

$$s(^{214}Bi) = p_0 \langle \sigma \rangle_0 + p_1 \langle \sigma \rangle_1$$

- Using ToI: $s(^{214}\mathrm{Bi})=(1.46\pm0.05)\times10^{-44}\ \mathrm{cm}^2$
- Using CTF: $s(^{214}\mathrm{Bi})=(1.42\pm0.03^{+0.023}_{-0.008})\times10^{-44}\ \mathrm{cm}^2$
- Using deformed spectrum: $s(^{214}\mathrm{Bi})=(1.48\pm0.01\pm0.03)\times10^{-44}\ \mathrm{cm}^2$

- From our data: ground state transition gives ~57% of signal from ^{238}U

Future Plans

- Results can be improved using Rn source in quarz vial near the center of CTF
- Collect ~6×10^6 events to be able to compare error on p_0 to that on σ_0
- Use same method for ^{212}Bi
  – data already taken
  – much more difficult source preparation

Conclusions

- First attempt to determine uncertainty on geoneutrino signal due to β decay spectral shape using a 4ton LS low background detector
- Direct measurement of the feeding probability to ground state in ^{214}Bi
- Probed forbidden shape
- Attempt same method for other sources