Liquid scintillator nonlinearity measurement for experiment JUNO

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Motivation

- Many experiments that measure oscillations of reactor neutrinos use liquid scintillators for their central detectors:
  - Daya Bay, Double Chooz, Kamland, Reno, in future JUNO
- Neutrinos typically interact via inverse beta decay:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- Neutrino energy can be deduced from the positron energy
- Measurement of the positron energy is affected by nonlinear response of LS

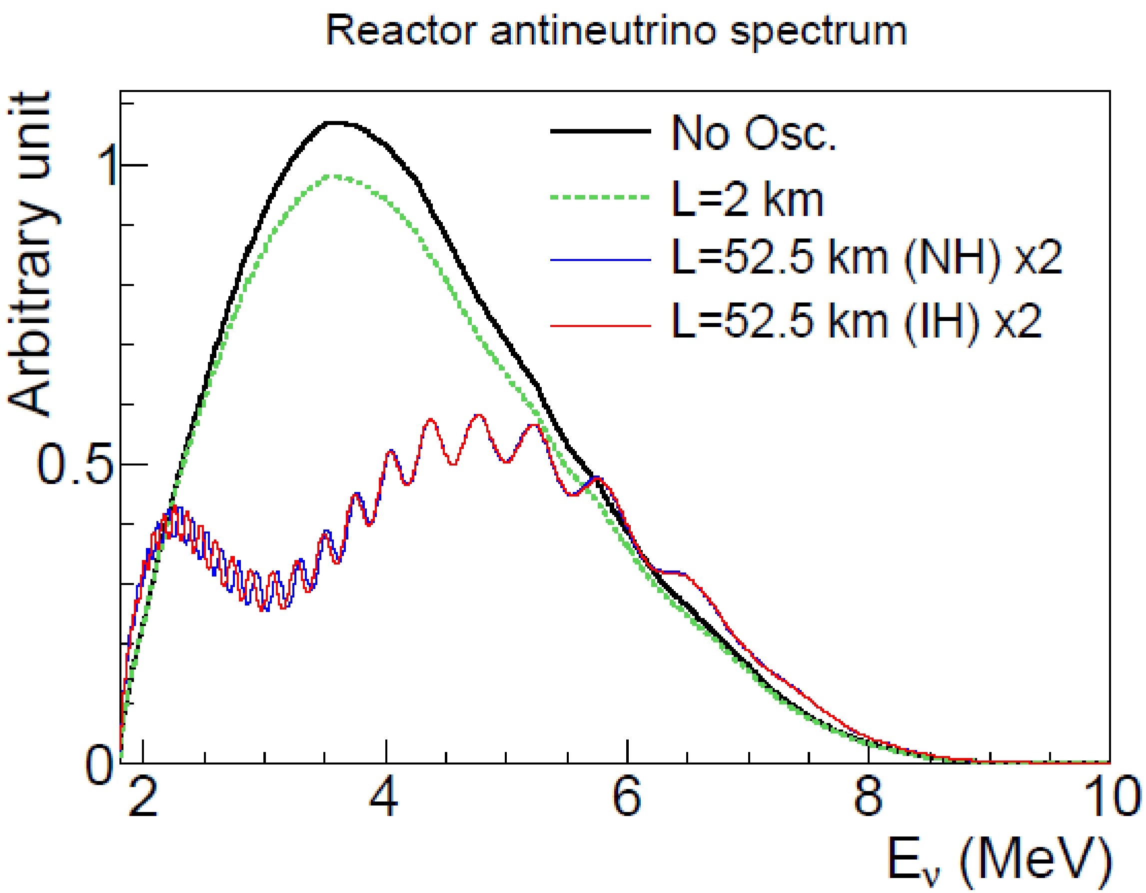
JUNO

(Jiangmen Underground Neutrino observatory)

- Under construction in China
- Measurement of $\bar{\nu}_e$ from nuclear power plants Taishan (17,4 GW) and Yangjiang (9,2 GW) in mean distance 52.5 km
- Goals:
  - Precise measurement of neutrino oscillation parameters:
    - $\sin^2 2\theta_{12}$, Δm^2_{21} , Δm^2_{32}
  - Determination of neutrino mass hierarchy
- Excellent energy resolution necessary (< 3% @ 1 MeV)
- Knowledge of (non)linear response of the detector necessary

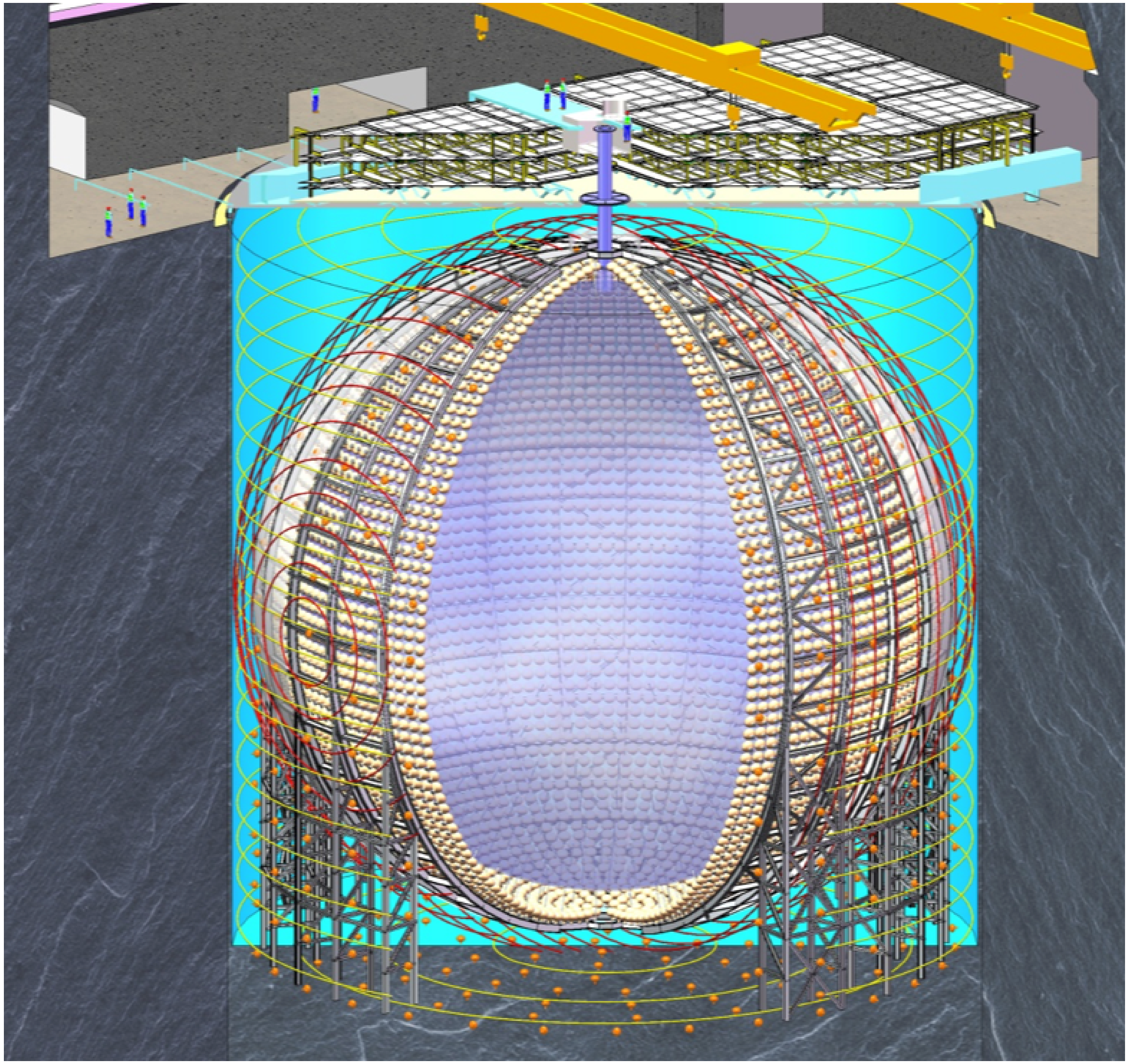
JUNO

- Expected neutrino spectrum:



JUNO DETECTOR

- 700 m underground
- Muon veto:
  - Top tracker
  - Cherenkov water pool
- Neutrino detector
  - 20 kt of LS in acrylic sphere
  - 18 000 large PMT (20'')
  - 25 000 small PMT (3'')
- Near detector is also planned



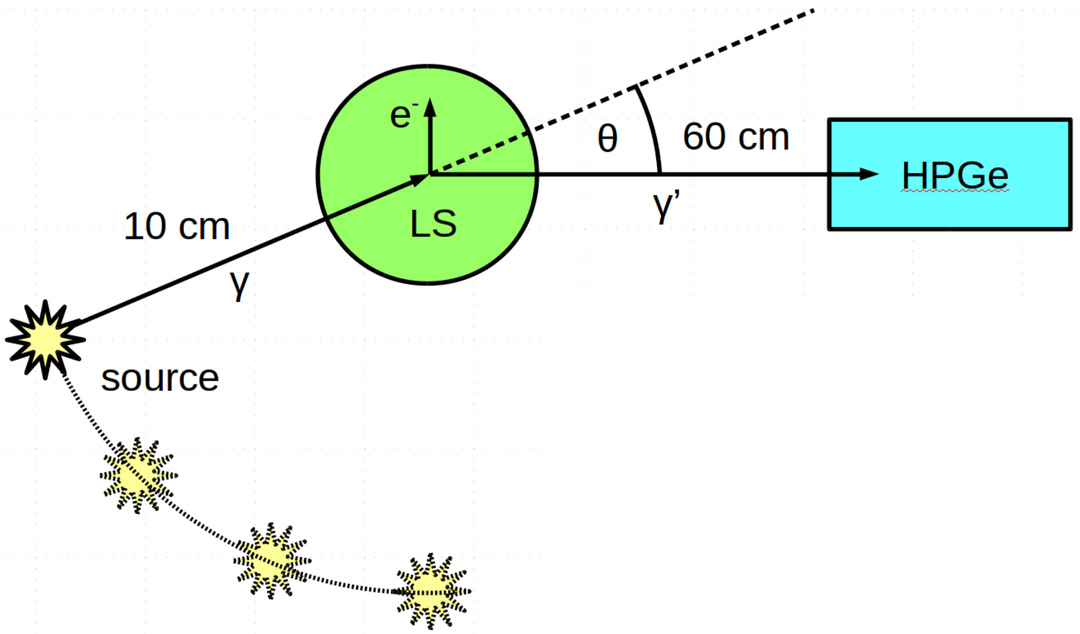
Organic liquid scintillators

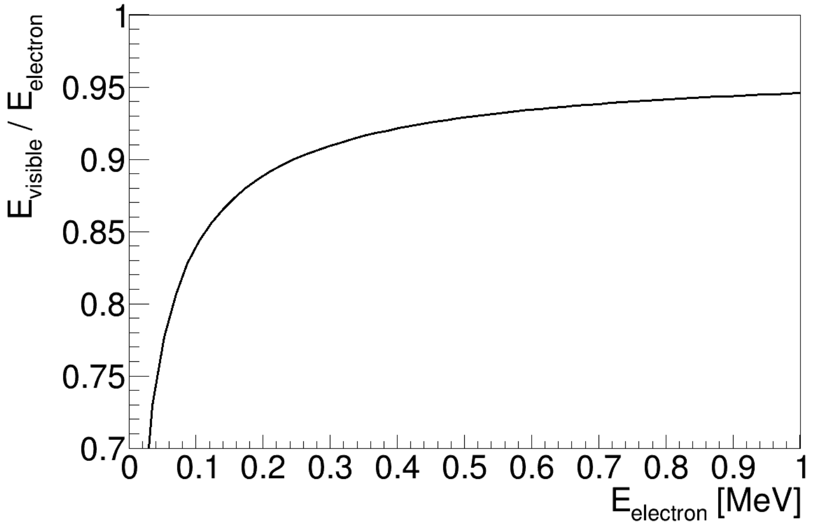
- Hydrocarbon compounds containing benzene-ring structures
- Ionizing particles excite scintillator molecules which then emit light that can be detected by a PMT
- The dependence of the amount of scintillation light L on the energy E deposited by the incident particle is not exactly linear.
  - The deviation is due to quenching interactions between the excited molecules along the path of incident particle, i.e., interactions which drain energy which would otherwise go into luminescence.
- Nonlinearity can be described by semi-empirical Birk's formula:

$$\frac{dL}{dx} = \frac{A\frac{dE}{dx}}{1 + k_B \frac{dE}{dx}}$$

Compton scattering method

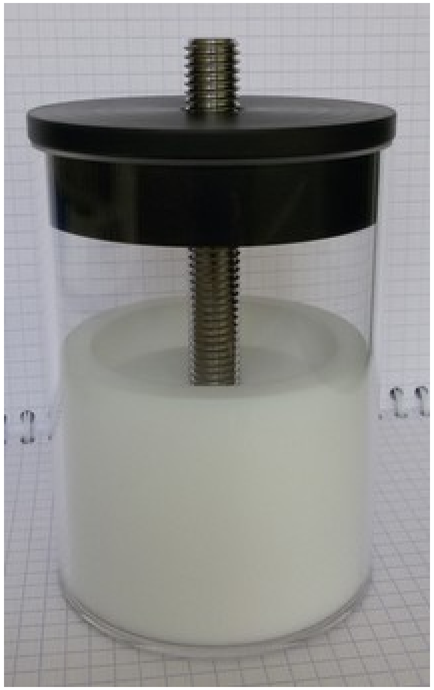
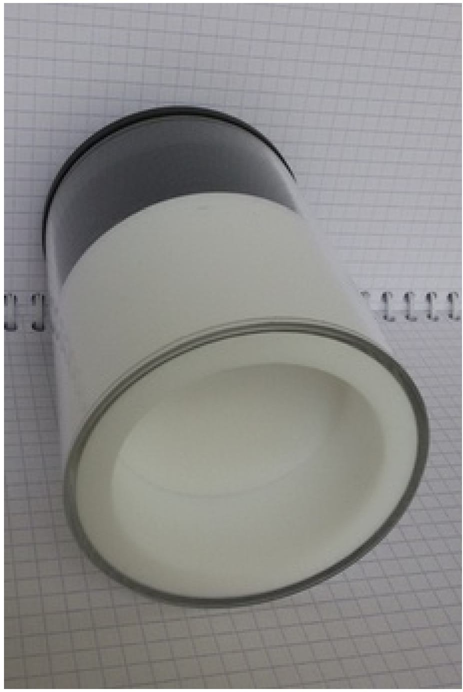
- Gamma of known energy interacts via Compton scattering in LS transferring part of its energy to an electron.
- Recoiled electron causes production of scintillation light which is detected by a PMT.
- Energy of the scattered gamma is precisely measured by a HPGe detector. Thus the energy deposited in the LS can be determined.
- Signal from the LS is compared to the energy determined by the HPGe detector.





Setup

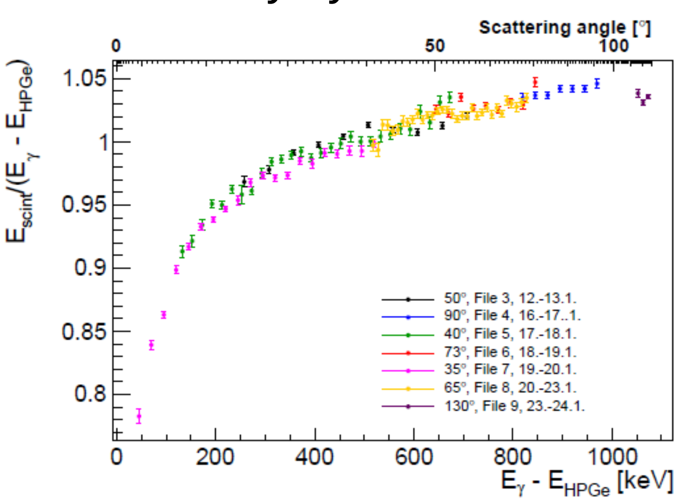
- Detectors placed on solid Al frame with turnable table and platform for collimation and shielding.
- Quarz vessel for LS with thick teflon reflector.
- Placed in room with controlled temperature.

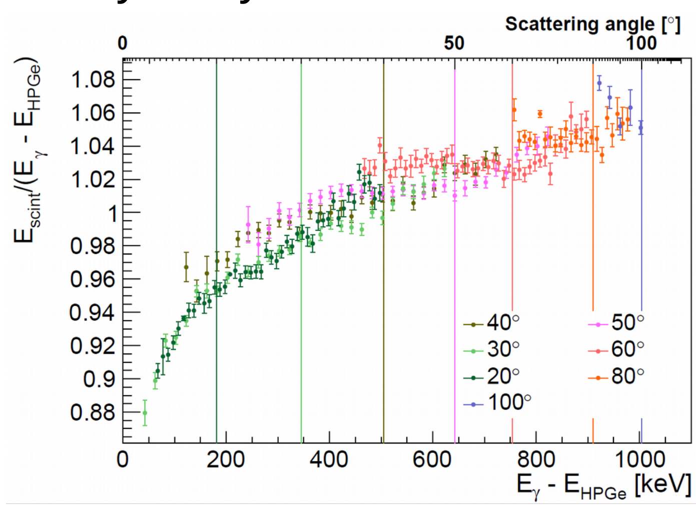
Older results

- LS nonlinearity observed.
- Observed potential sources of systematics that need to be addressed:
  - PMT, HPGe nonlinearity
  - PMT, HPGe unstability
  - Light collection nonuniformity

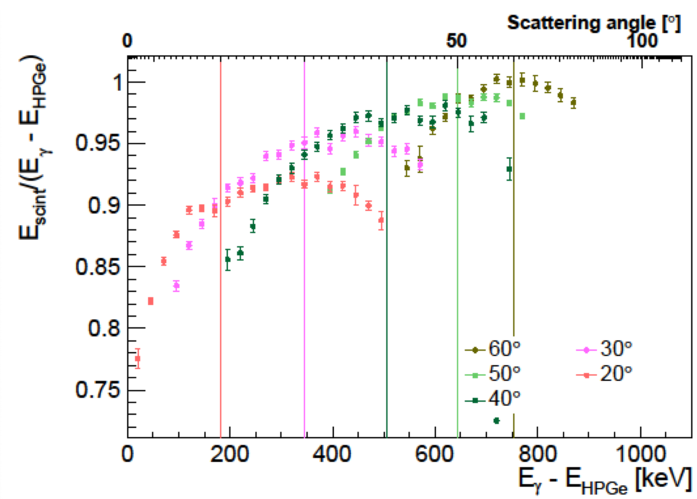
Polystyrene



Daya Bay LS in vessel 1

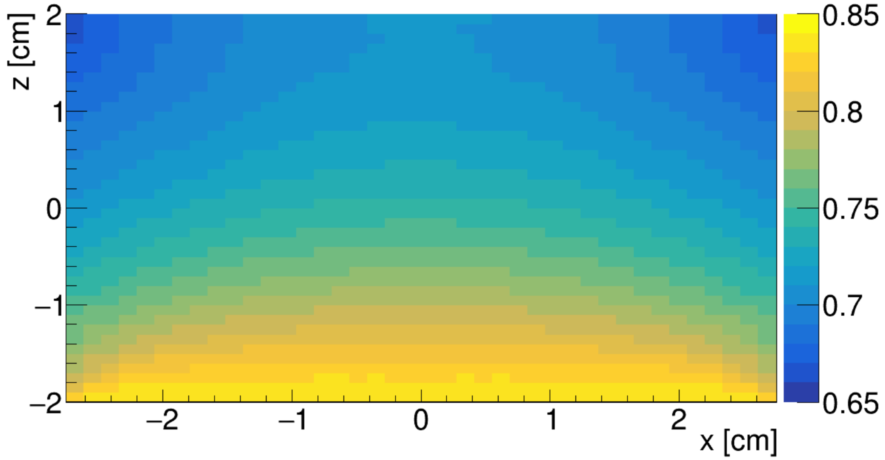


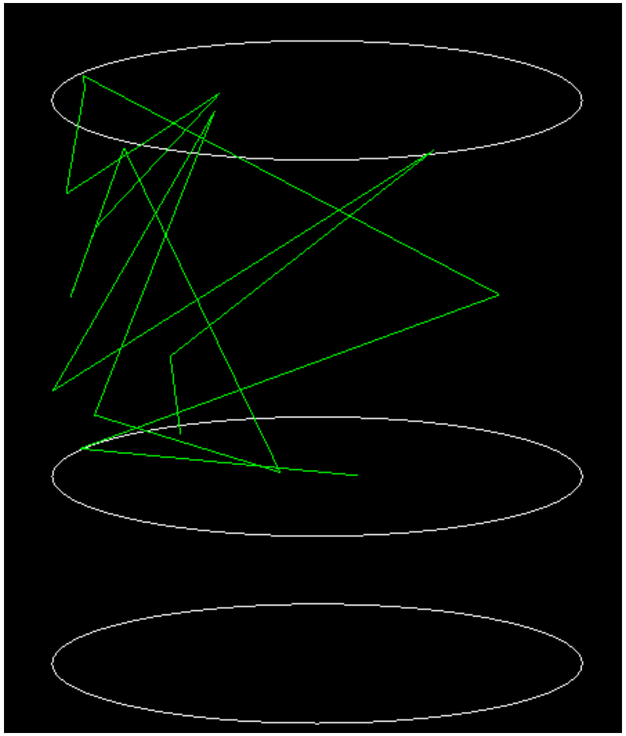
Daya Bay LS in vessel 2



Light collection nonuniformity

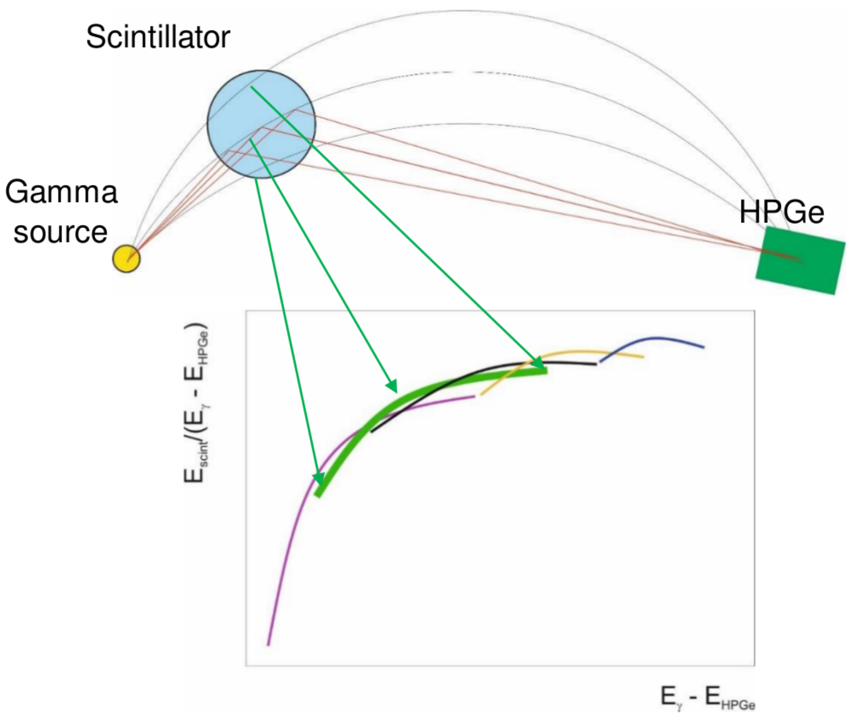
- Light collection efficiency is not constant within the LS volume
- MC simulations using Geant4
- Determination of space distribution of light collection efficiency
- Investigation of its effect on the nonlinearity measurement and possible corrections

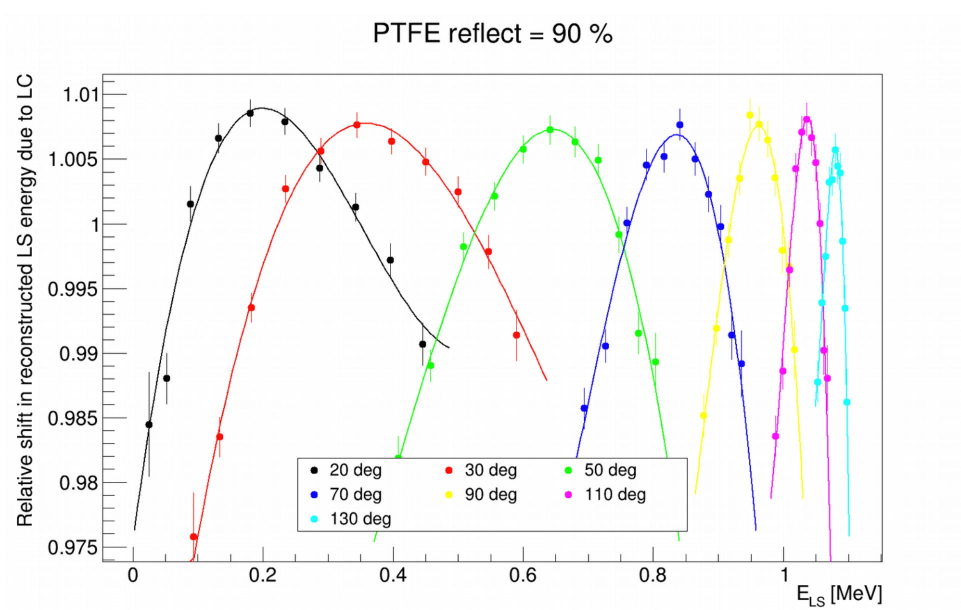




Effect of light collection nonuniformity

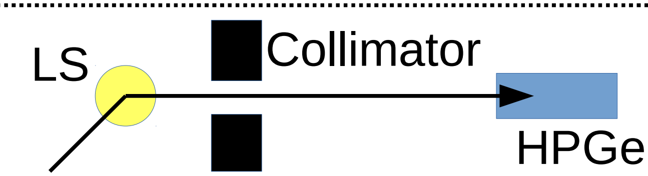
- Scattering energy depends on the scattering angle
- Light collection efficiency decreases towards the walls
- As a results we observe characteristic pattern of arcs



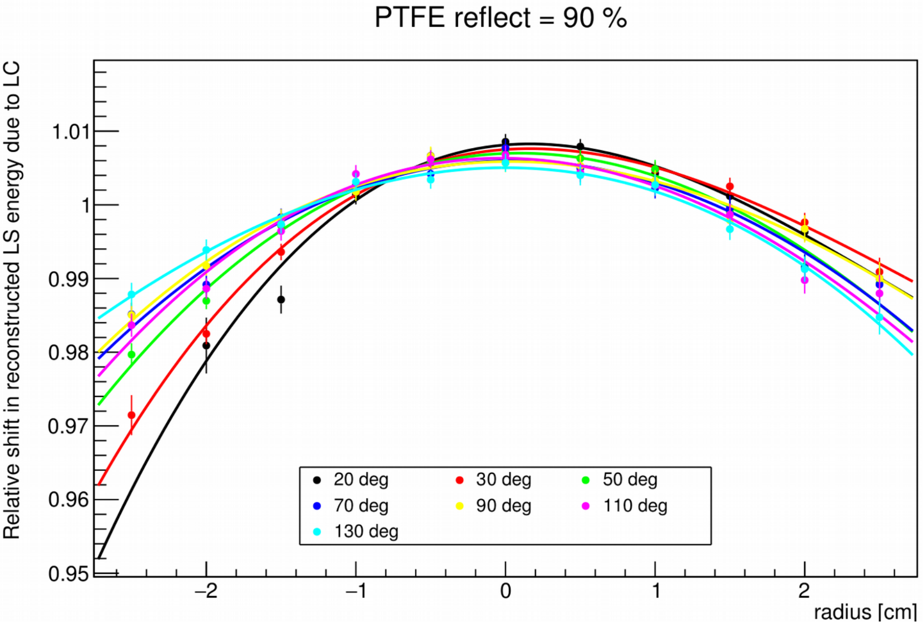


Correction for light collection nonuniformity

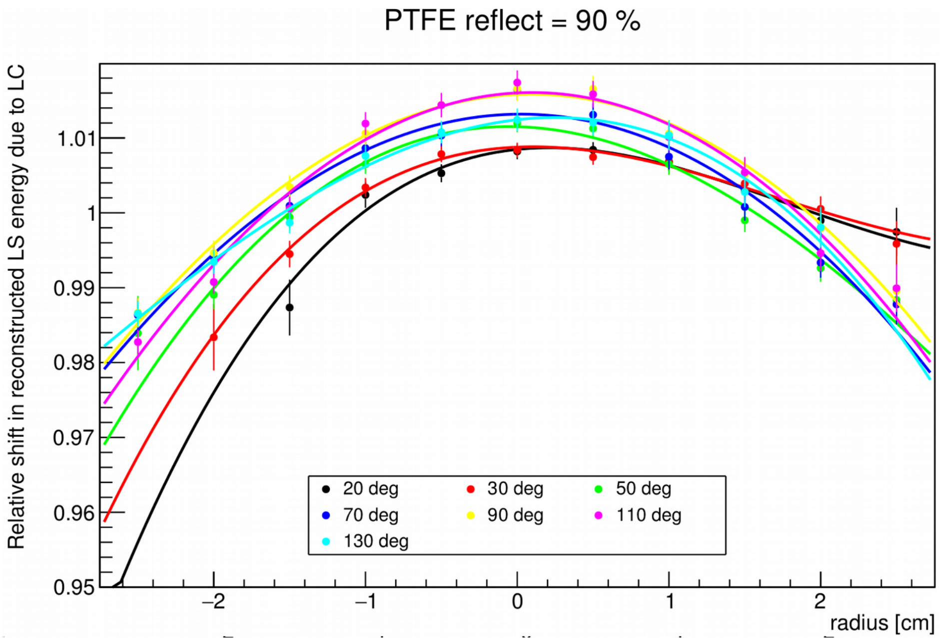
- We can choose energy windows in HPGe so that they correspond to equally wide stripes passing in varius distances from the center of LS and compare them.



No collimator



3 cm horizontal collimator

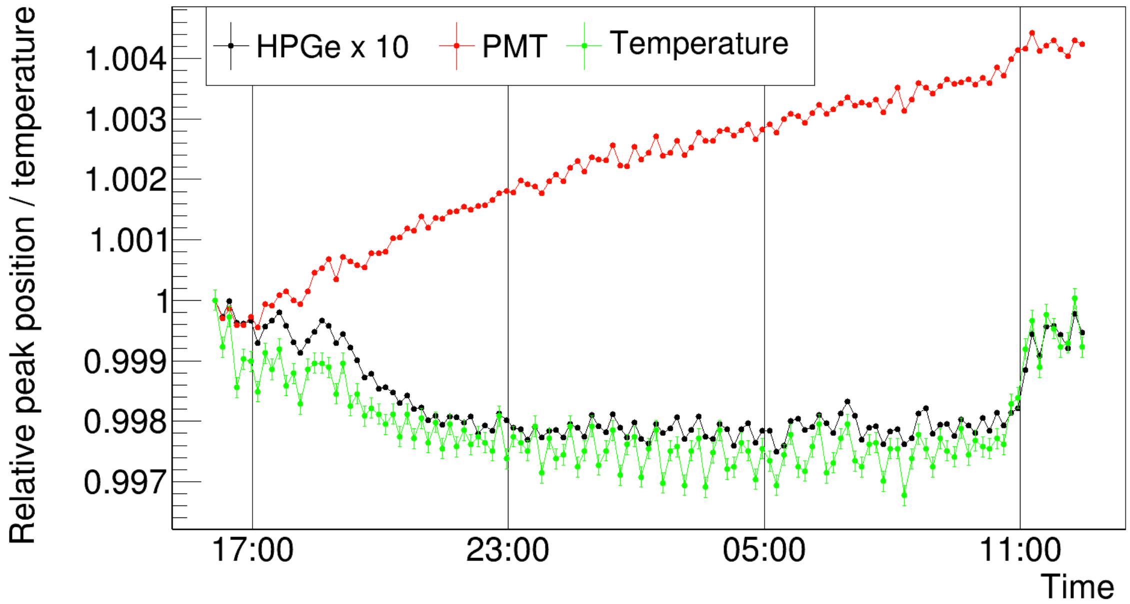


Multiple Compton scattering in LS

- Energy is divided between more electrons which leads to more quenching than for single Compton scattering
- Experimentally we cannot distinguish between single and multiple Compton
- Depends on the geometry of the experiment
- In our geometry, with proper data selection it should have < 0.1% effect on energy readout from LS compared to purely single Compton events

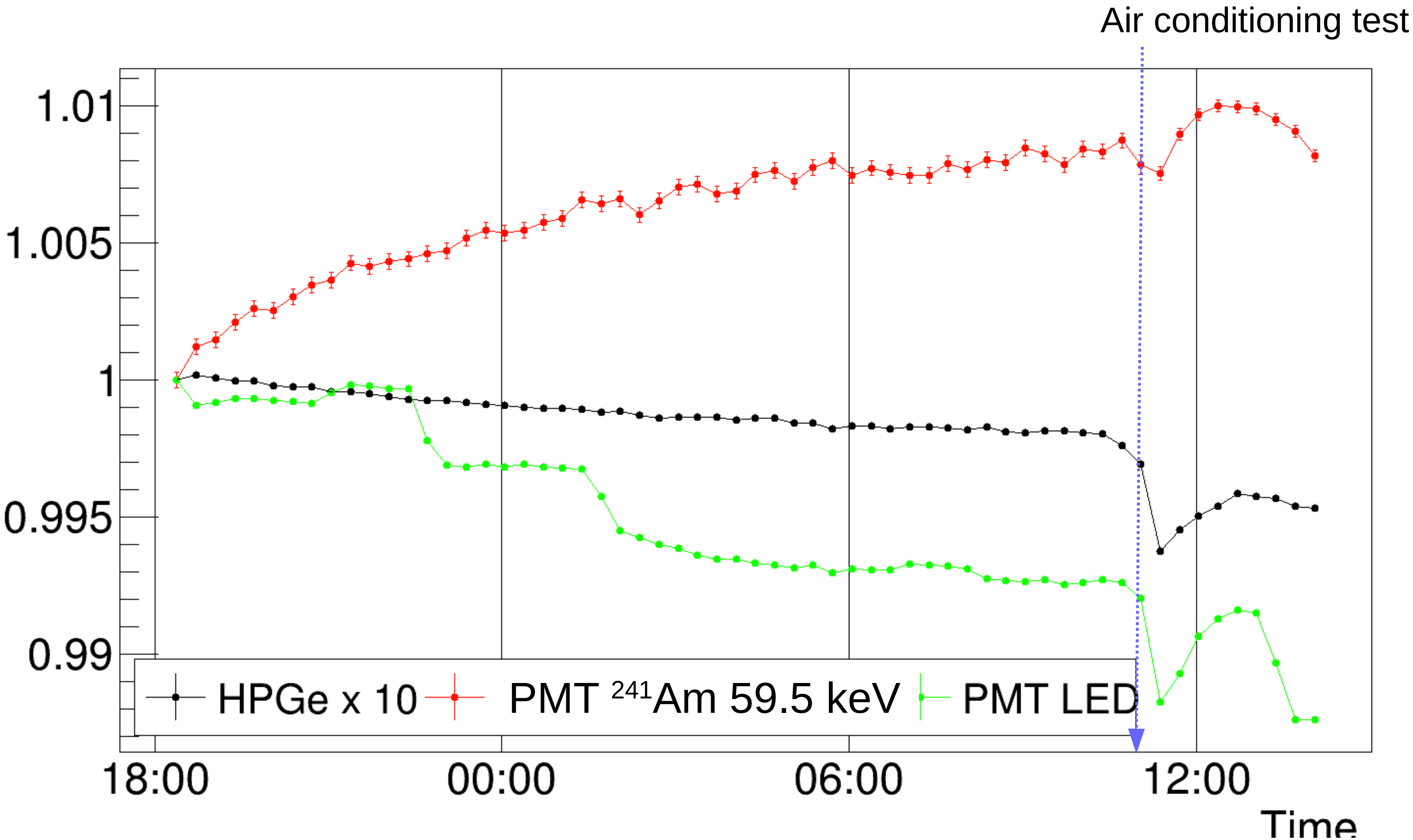
Detector stability

- Air temperature, positon of 1332 keV peak in HPGe and position of LED flasher peak in PMT measured simultaneously:



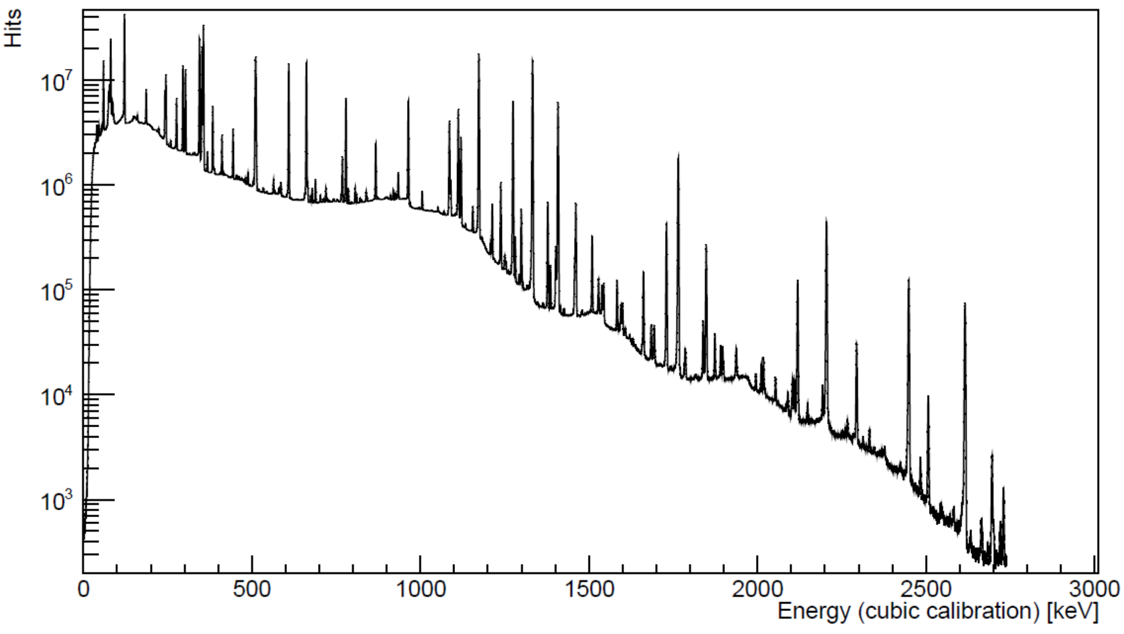
- HPGe - peak position mainly follows temperature, variations up to 0.1% - corrections possible.
- PMT/LED - peak positions affected by temperature, but also by previous workload, variations up to 1.5%, corrections should be applied.

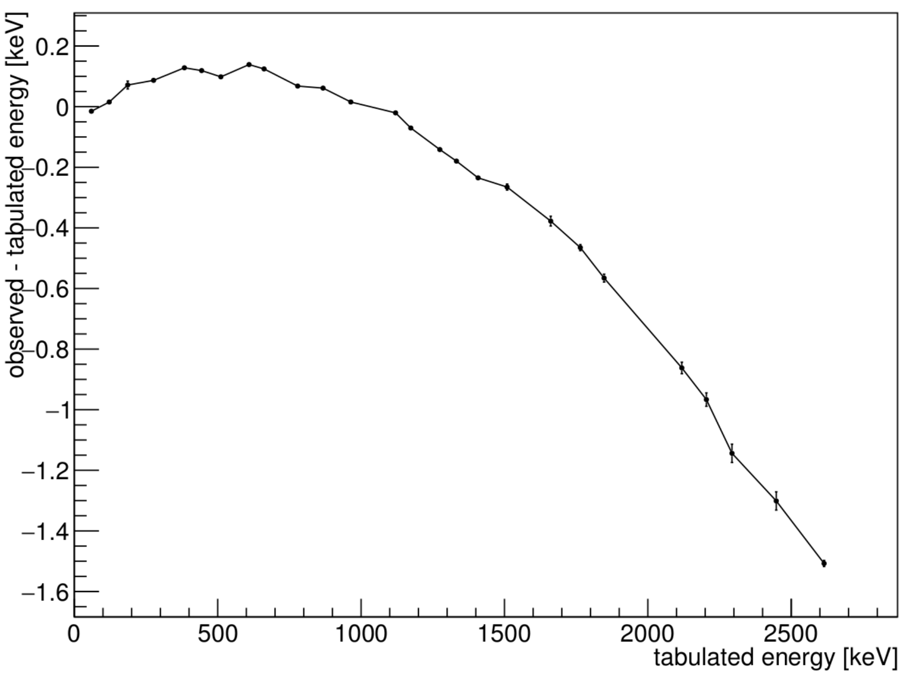
Detector stability



HPGe nonlinearity

- Set of 7 radioisotopes with gamma lines covering wide energy range was used.
- Deviation from linearity is <1.5 keV within range 2.5 MeV (<0.06%)





PMT nonlinearity

- Different intensities of light pulses from the LED A and LED B are set via PC and the LEDs controller provided by JINR Dubna. LEDs are triggered/synchronized with the same pulse generator 1kHz.
- Two setups were used with the PMT:

1) Scintipack incorporating HV supply, voltage divider and preamplifier.

2) Standalone voltage divider, HV supply, preamplifier.

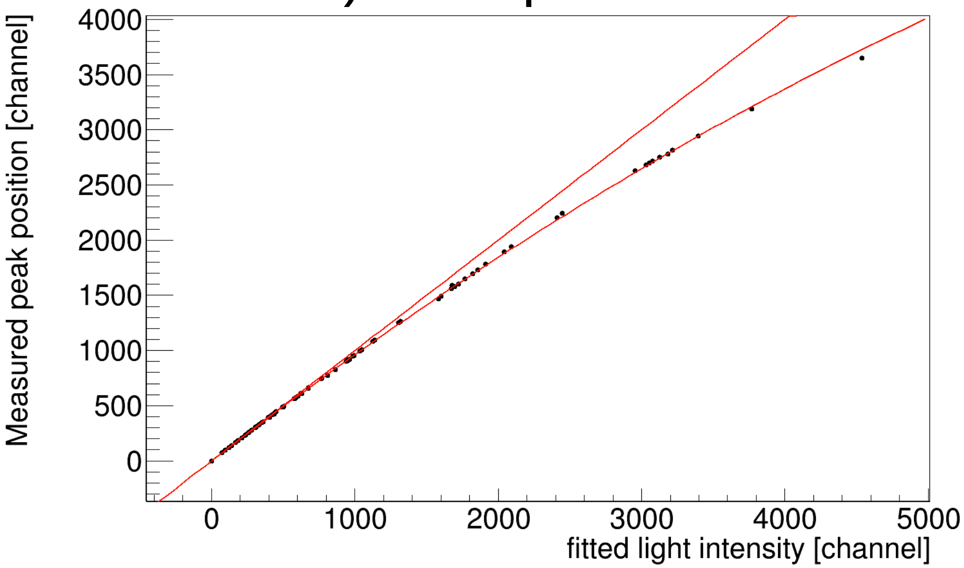
PMT nonlinearity

- In our basic model, PMT signal *S* depends on light intensity *L*:

$$S = L - \beta L^2$$

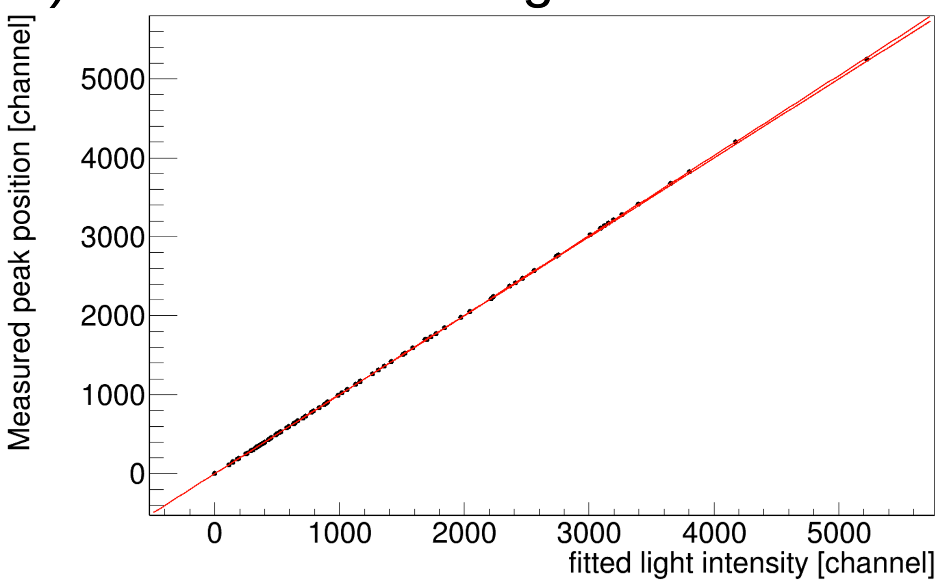
- In the region of interest (i.e. light intensity corresponding to < 1 MeV deposited in LS) we observed big difference between the setups:

1) Scintipack:



$\beta = 39 \cdot 10^{-6}\ \mathrm{chn}^{-1}$

2) Standalone voltage divider etc.:



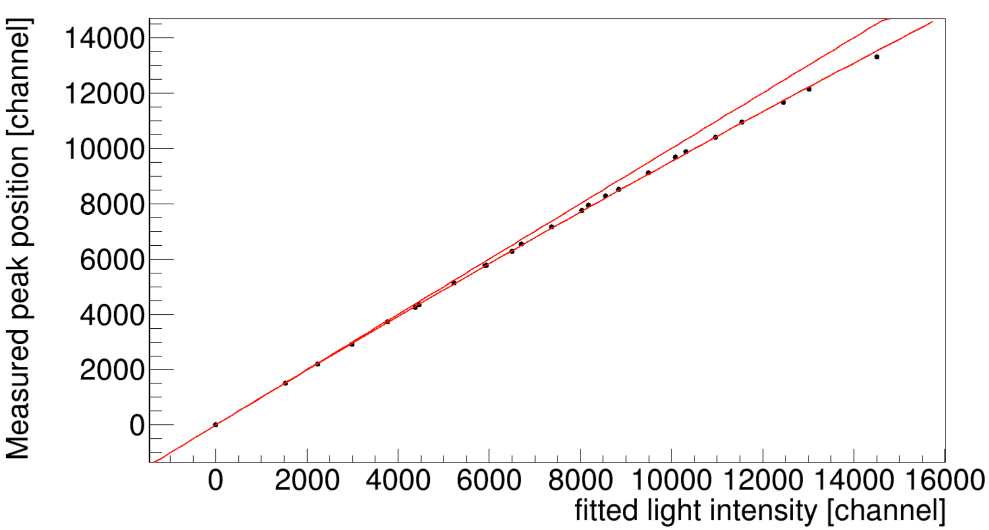
$\beta = -1.7 \cdot 10^{-6}\ \mathrm{chn}^{-1}$

PMT nonlinearity

- With scintipack we expect >20% reduction of signal at 1 MeV; with standalone voltage divider, HV supply and preamplifier we expect <1% deviation from linearity
- With higher light intensity, PMT & readout nonlinearity gets obvious even with the second setup
- It seems that simple

  $S = L - \beta L^2$ model is not

  sufficient enough



Outlook

- New measurement run with upgraded setup starting soon
- New sources of gamma radiation available:
  - ^{24}Na with sufficient activity
  - ^{88}Y but its activity probably too low

Thank you for your attention!

PMT nonlinearity – 2 LEDs method

The PMT is illuminated with two LEDs – A and B at the same time. Different combinations of light intensities L_i^A and L_j^B are applied and corresponding PMT responses S_{ij}^{exp} are measured. Nonlinearity parameter β is fitted as well as L_i^A and L_j^B.

L_i^A	$i = 1..m$	light from LED A	Fitted parameters
L_j^B	$j = 1..n$	light from LED B	
β	nonlinearity parameter		
S_{ij}^{exp}	measured PMT signal caused by $L_i^A + L_j^B$		Exp. data
σ_{ij}	uncertainty of S_{ij}^{exp}		

Model – theoretical PMT signal caused by $L_i^A + L_j^B$:

$$S_{ij}^{th}(L_i^A, L_j^B, \beta) = S(L_i^A + L_j^B, \beta) \qquad S(L, \beta) = L - \beta L^2$$

Search for minimum of $$\chi^2 = \sum_{i,j=1}^{m,n} \frac{\left(S_{ij}^{th}(L_i^A, L_j^B, \beta) - S_{ij}^{exp}\right)^2}{\sigma_{ij}^2}$$