The measurement of liquid scintillator nonlinear response and intrinsic energy resolution

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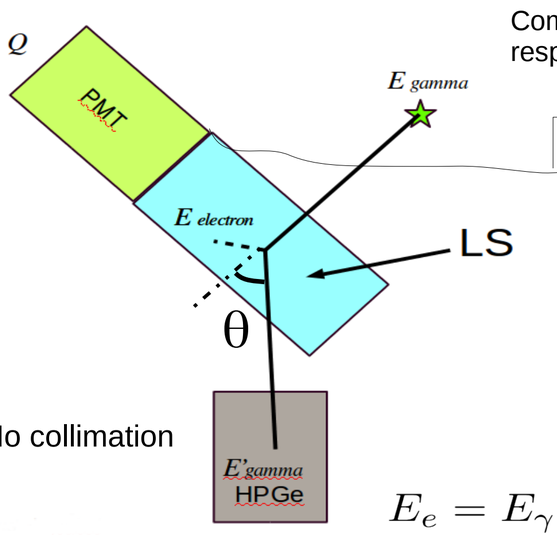
Motivation

- The Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kton multi-purpose underground liquid scintillator detector, with a primary physics goal to determine the neutrino Mass Hierarchy.
- < 1 % uncertainty on the energy scale and 3 % at 1 MeV resolution requirement for the Mass Hierarchy determination in JUNO
- Intrinsic energy resolution was never yet robustly measured for liquid organic scintillators

Experimental technique

Compton coincidence: liquid scintillator response to "monoenergetic" electrons



70 *ps* laser for gain stability monitoring and PMT scale calibration (N_{pe} *and* v_m)

- No collimation

$$E_e = E_\gamma - E'_\gamma$$

Scattering angle $\theta \approx 20$ *deg*

Energy response

Non-linearity

$$L(T, kB) = Y_p \int_0^L dx \frac{dE/dx}{1 + kB dE/dx} = Y_p \int_0^T \frac{dE}{1 + kB dE/dx}$$

Q_{pmt} is proportional to the emitted light L(T,kB)

Light yield phot / MeV

Quenching constant cm/MeV

Differential energy losses

Energy resolution

$$\left(\frac{\sigma_E}{E}\right)^2 \approx \left(\frac{\sigma_Q}{Q}\right)^2 = v_p + v_d + v_{st} + v_{int}$$

Light collection term

Dark noise term (negligible)

Statistical term:

$$v_{st} = \frac{1+v_m}{N_{pe}}$$

Intrinsic energy resolution term

$$v_{int} = v_Q - v_{st} - v_p$$

$$v_m = \left(\frac{\sigma_s}{m_s}\right)^2$$

However, from the experiment we can only determine:

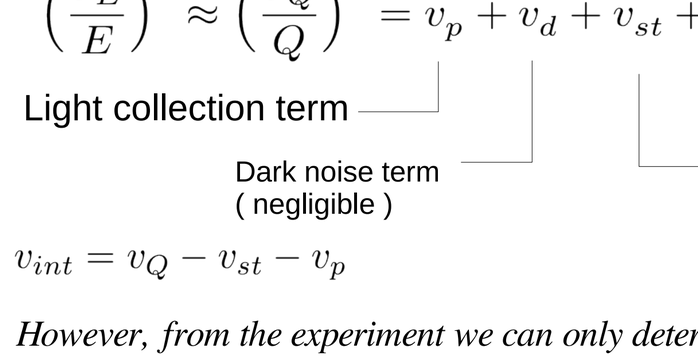
$v_\Delta = v_{int} + v_p$ *as* $v_\Delta = v_\Delta(Q, \sigma_Q, m_s, \sigma_s) = \left(\frac{\sigma_Q}{Q}\right)^2 - \frac{1 + \left(\frac{\sigma_s}{m_s}\right)^2}{Q/m_s}$

Experimental challenges

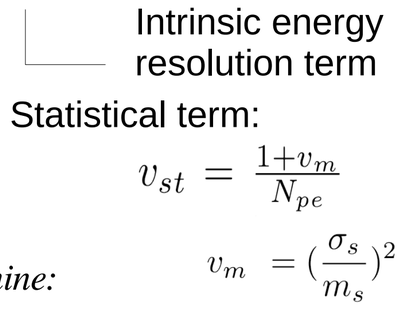
- Stability of HPGe and PMT scales
- Experimental threshold
- Multiple Compton scattering

- Inhomogeneous light collection
- PMT, electronics and DAQ non-linear effects
- Statistical v_{st} and light collection v_p terms

Monte Carlo simulation

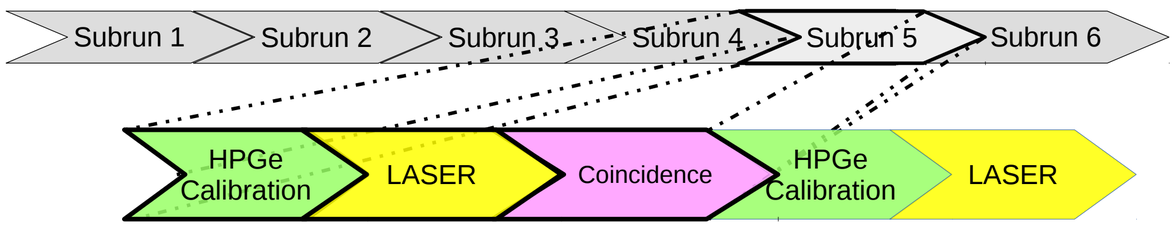


- Estimation of multiple Compton scattering and inhomogeneous light collection effects
- Light collection term estimation



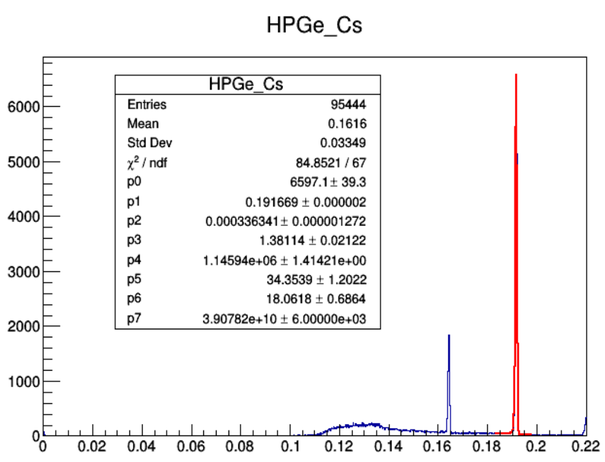
Data acquisition strategy

- Stability control and calibrations

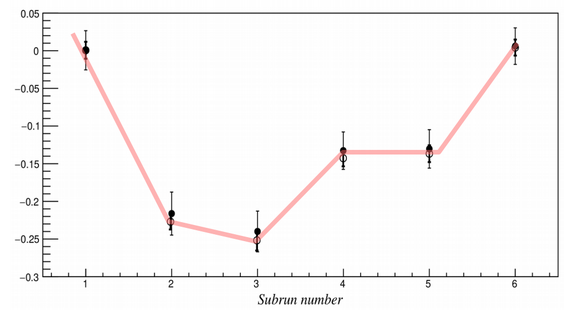


HPGe calibrations and stability

HPGe Calibration



HPGe stability control with ^{137}Cs and ^{207}Bi:



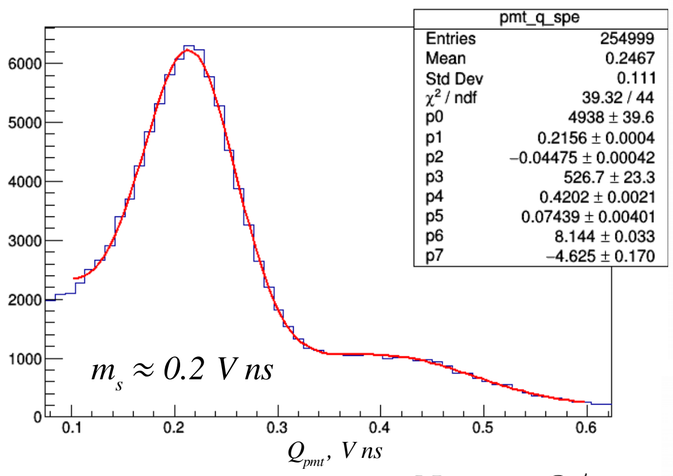
HPGe energy scale corrections:

$$E = K(t) \times Q + B(t)$$

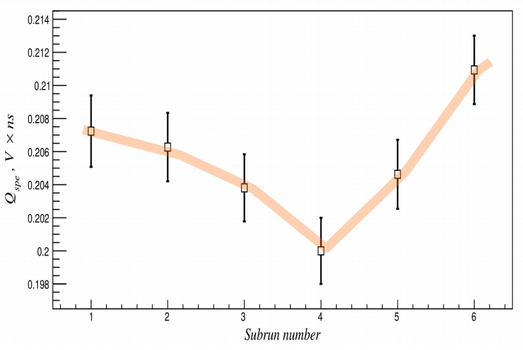
PMT absolute calibration and gain stability

LASER

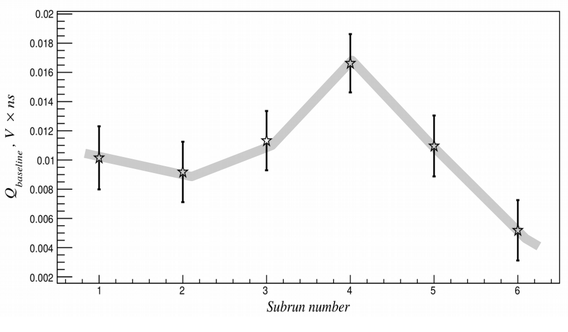
PMT response to low intensity light (trigger from the laser):



Singe photo electron response



Baseline residual instability



PMT scale calibration: $N_{p.e.} = Q/m_s$

PMT gain and baseline corrections: $Q = \frac{0.2(Q - b(t))}{m_s(t)}$

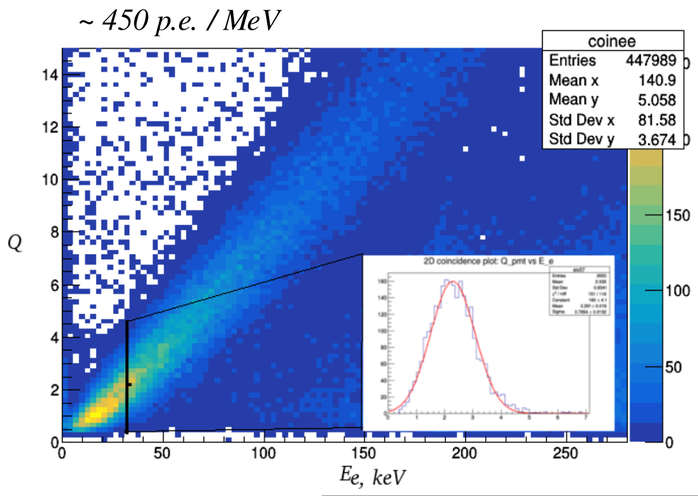
$v_m = 0.0496 \pm 0.0010(stat) \pm 0.0014(sys)$

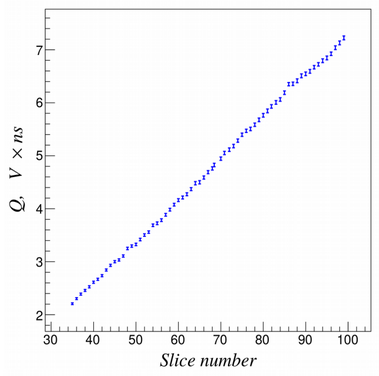
Statistical term extraction now possible!

Coincidence diagram analysis

Coincidence

~ 450 p.e. / MeV





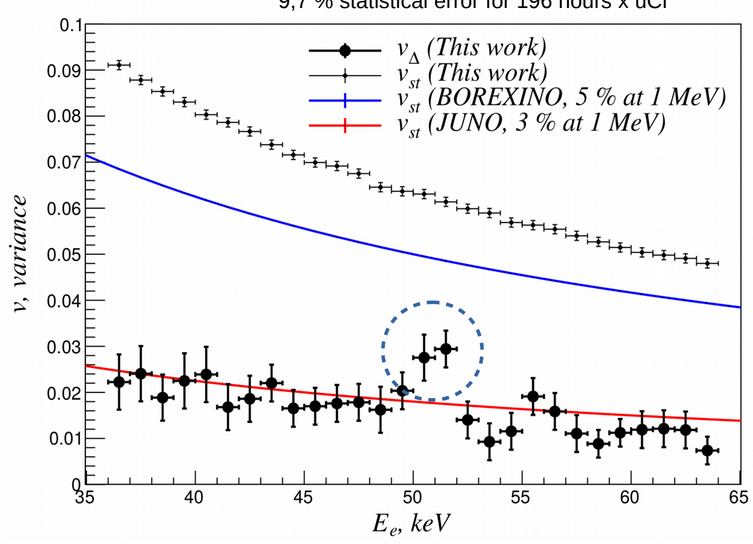
Results and conclusions

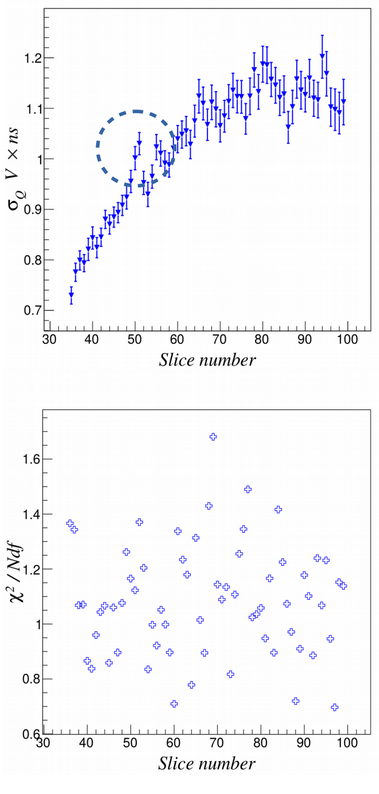
biased due to multiple Compton and light collection

HPGe scale systematic error ~ 0.5 keV

$$kB^{biased} = 0.0196 \pm 0.0019(stat) \pm 0.0030(sys)\ cm/MeV$$

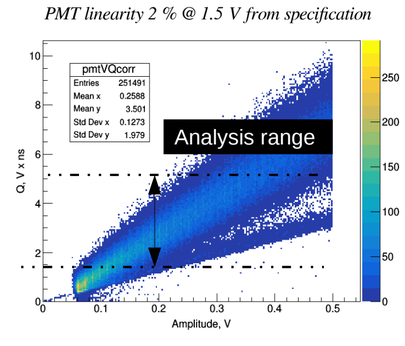
9,7 % statistical error for 196 hours x uCi





$$\left(\frac{\partial v_\Delta}{\partial \sigma_Q} \delta_{\sigma_Q}\right)^2 = 4 v_Q (\delta_{\sigma_Q})^2 / Q$$ - a dominating error

PMT linearity 2 % @ 1.5 V from specification



Analysis range 36.5 – 63.5 keV

- Instability of PMT and HPGe were controlled and the scales were corrected.
- With PMT calibration v_{st} term was measured.
- v_Δ 3-4 σ differs from zero
- For a precise kB measurement and a wider analysis range the resolution of DAQ system must be increased.
- An improvement of light collection (from 450 p.e. toward 1500 p.e.) is necessary to increase a precision of resolution measurement and to reduce contribution of v_p into v_Δ for successful v_{int} extraction.