Neutron Calibration

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S1 and S2 signals

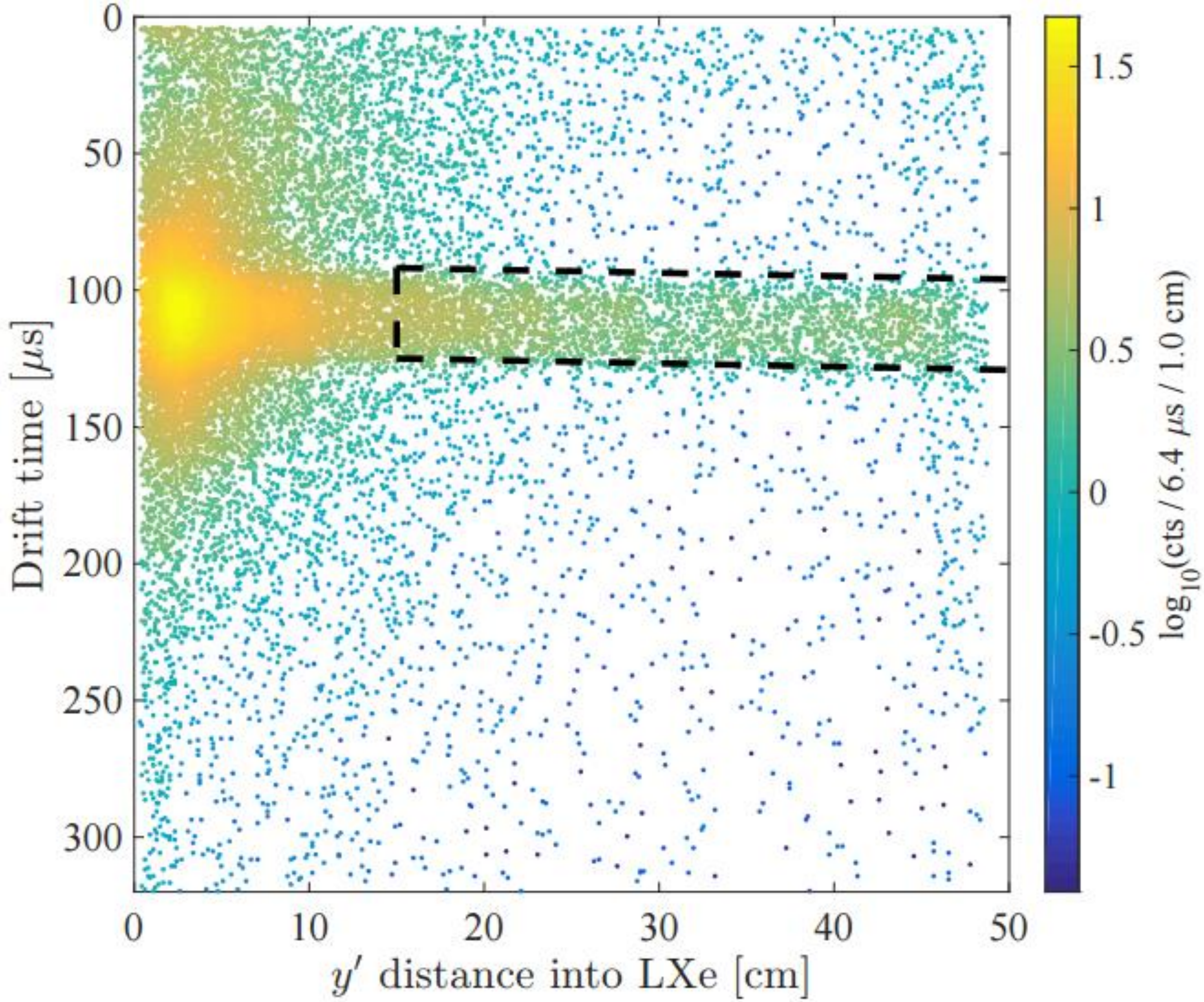
- $S2 = Enr \times Qy(Enr, E) \times g2$
  - S2 is the number of photons detected from the drifted electron signal
  - Enr is the energy of the nuclear recoil
  - E is the magnitude of the electric field
  - Qy(Enr, E) is the charge yield (how drifted electrons come from a given event) this is what our calibration tries to find
  - g2 is the number of photons detected for each ionization electron
- $S1 = Enr \times Ly(Enr, E) \times g1$
  - S1 is the number of photons detected from liquid Xenon Scintillation
  - Ly is the light yield (how much light comes from a given event) this is also what our calibration tries to find
  - G1 is the number of photons detected for each scintilation photon

Qy Calibration

- The Qy calibration is done using double scatter neutron events created by the neutron generator previously discussed.
- The double scatter provides a very precise measure of the energy deposited in the first scatter.

Double Scatter Selection

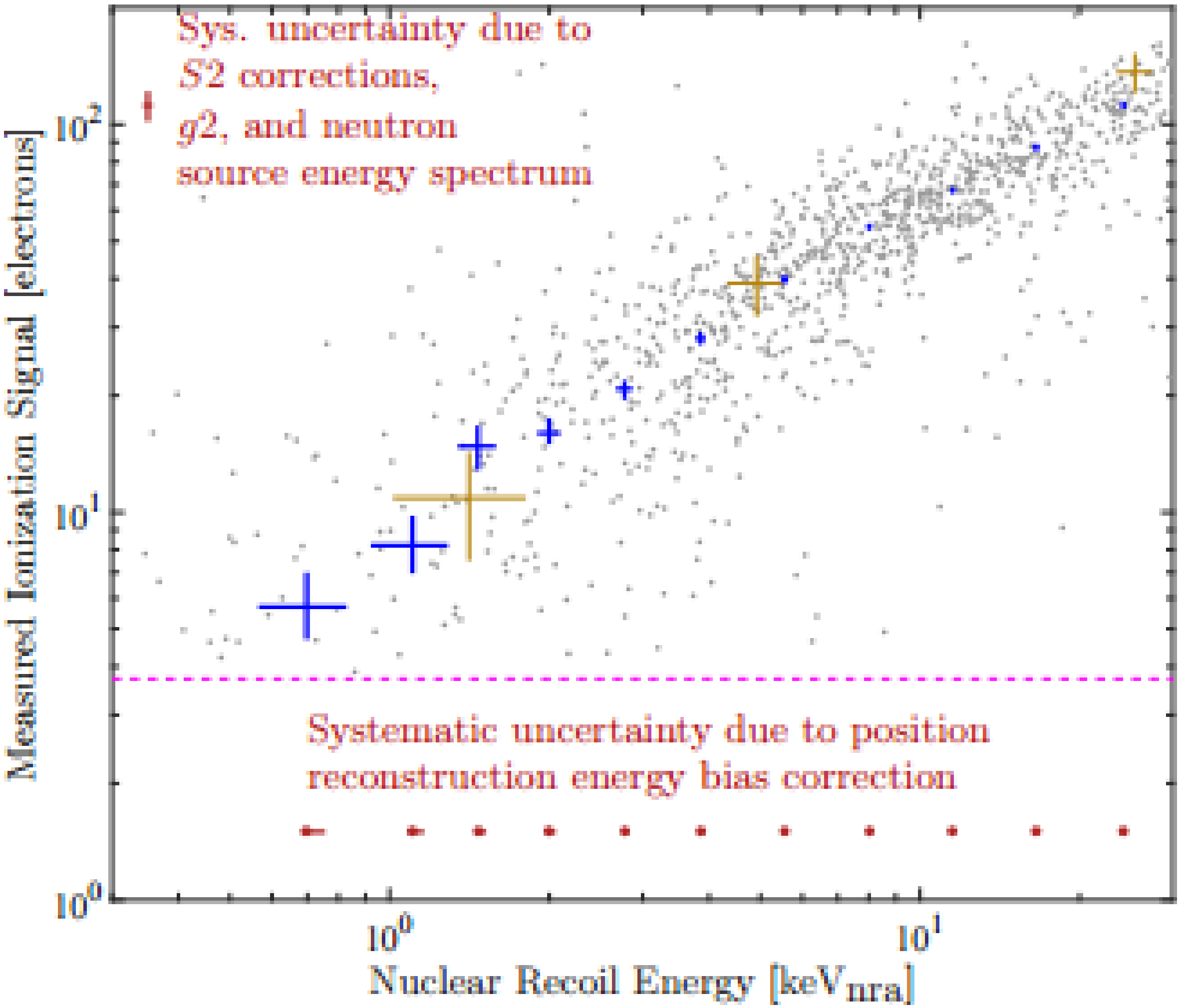
- One S1 followed by two S2 pulses.
- Upper limit on S2 pulse RMS < 775 ns (cuts double scatters close in z)
- First scatter is >15 cm inward from the wall and within radius of the tube.
- Only one scatter within radius of the tube unless the one further in has S2 <1500 phd (can't tell which one is first easily)



Energy of first Scatter

- $E_r = E_n \frac{4 m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1 - \cos(\theta_{CM})}{2}$
- Since the angle of scattering can be determined via position reconstruction.
- E_n is 2.45 MeV from our mono-energetic neutron source.

Qy measurement



For each event, one can get the ionization signal (n_e) by dividing S_2/g_2.

Qy measurement (2)

- The data is collected into energy bins (nr equivalent).
- The distribution of the ionization signals in each bin are fit to the combination of a signal model and background model using a log likelihood letting n_e float.
- $\ln L = -(N_s + \ N_b) \ - \ \ln(N!) + \ln\left[\frac{1}{\sqrt{2\pi}\sigma_R} e^{\frac{(R-R_0)^2}{2\sigma_R^2}}\right] + \sum_{i=1}^{N} \ln[N_s p_s(x_i|n_e, R) + \ N_b p_b(x_i)]$
  - N_s is number of signal events
  - N_b is number of background events
  - R is resolution (whatever that means)
  - p_s and p_b are the signal and background models.

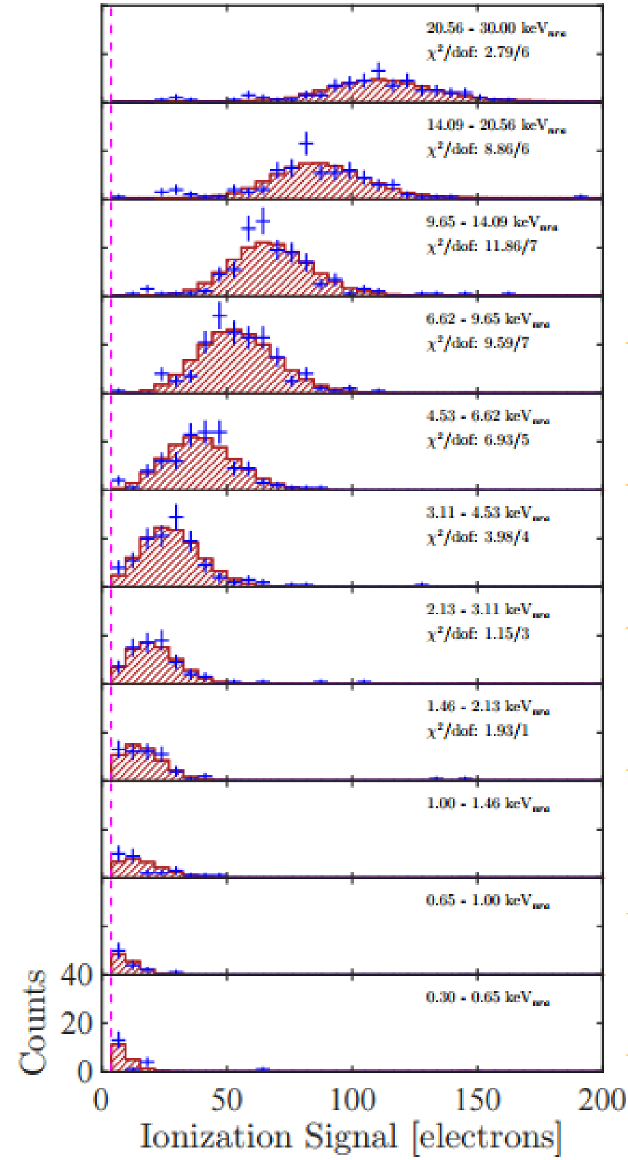


FIG. 4. Histogram of the measured ionization signal with best fit model for each keV$_{nra}$ bin. The D-D neutron data is shown in blue with Poisson error bars. The red shaded histogram is the best fit model to the data in each bin. The best fit parameters were determined using an unbinned optimization. The bins are for visualization and were used to calculate χ^2/dof values for energy bins where dof > 0. The magenta line represents the approximate location of the lower S2 threshold. The axes' limits are similar for each bin.

Qy measurement (3)

- The n_e from the fits of the 11 bins (blue crosses) are used to fit a Lindhard (dashed) and a Bezrukov (dot-dashed but looks solid) model in NEST (we use the Lindhard model in LUX).

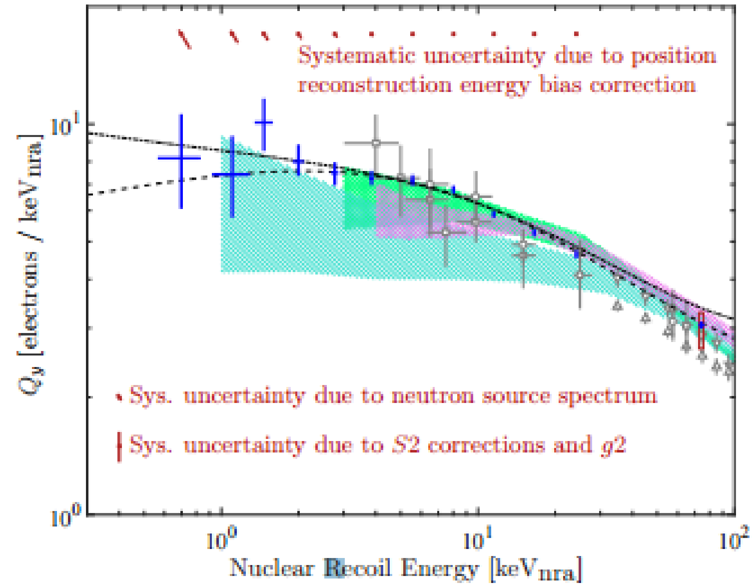


Figure 6. The LUX measured low-energy ionization yield at 180 V/cm is represented by the blue crosses. The red error bars at the bottom left of the plot represent systematic uncertainties with a constant scaling across all points, including the uncertainty in the mean neutron energy from the D-D source, $S2$ position-based corrections, and the LUX measured $g2$. The red error bars at the top of the plot represent the systematic uncertainty associated with the Eddington bias correction for the mean energy of each bin due to position reconstruction uncertainties as determined by simulation. The red box represents the associated systematic uncertainty on the measured endpoint yield at 74 keV$_{nra}$. The gray data points represent other angle based measurements with an absolute (keV$_{nra}$) energy scale. The gray squares (□) and circles (◯) correspond to measurements at 1 kV/cm and 4 kV/cm, respectively [11]. The gray triangles were measured at 0.3 kV/cm (▽) and 0.1 kV/cm (△) [33]. The hatched bands represent simulated spectrum based measurements with a best-fit (keV$_{nr}$) energy scale. The purple single right-hatched (///) band was measured at an average field of 3.6 kV/cm [8]. The teal single left-hatched (\\\) band corresponds to a measurement at 730 V/cm [7]. The green cross-hatched band was measured at 530 V/cm [9]. The dashed (dot-dashed) black line corresponds to the Lindhard-based (Bezrukov-based) LUX best-fit NEST model as described in Sec. VII.

Ly Calibration

- Single Scatter events
- The calibration of energy from Qy determines the energy of the scatter

Single Scatter Selection

- One S1 followed by one S2
- Same upper limit RMS cut
- S1 > .25 phd, S2 > 55 phd
- Only events within the tube projection accepted.

Measuring Ly

- The same process is undertaken as before, except that the photon yield (n_{ph}), obtained by S_1/g_1, are binned in S_2 instead of NR equivalent energy.

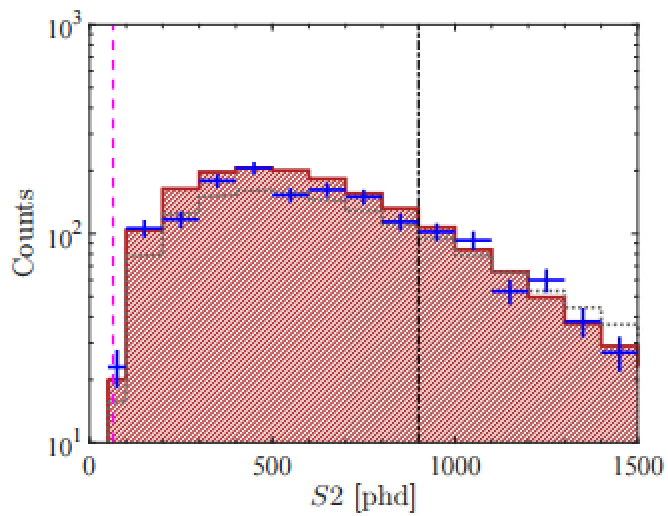


Figure 9. The single-scatter $S2$ spectrum from data after all L_y analysis cuts are applied is shown in blue. The corresponding simulated $S2$ spectrum is represented by the shaded red histogram. The simulated $S2$ spectrum produced using an alternative nuclear database (ENDF/B-VII.1 [35]) is shown by the gray dotted line. The statistical uncertainty on the simulated spectra is negligible. The black dot-dashed line at 900 phd $S2$ demarcates the measurement region from the normalization region. The simulation is normalized to match the total number of counts observed in data between 900-1500 phd, while the L_y points are determined using the events in the region $50 < S2 < 900$. The raw $S2 > 55$ phd threshold is represented by the vertical dashed magenta line in corrected $S2$ space (~64 phd).

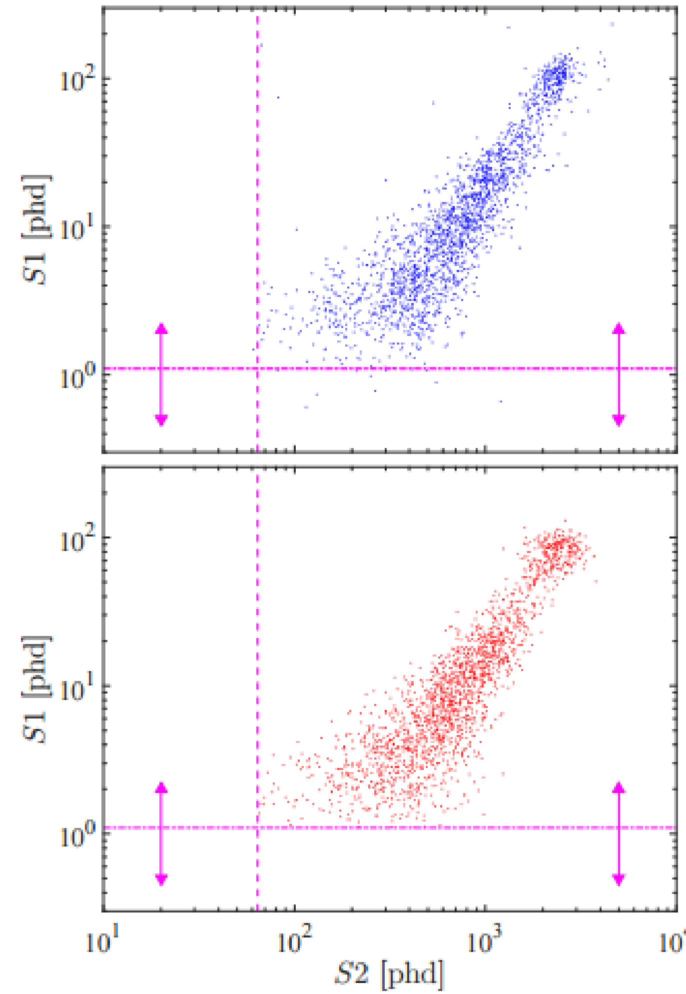
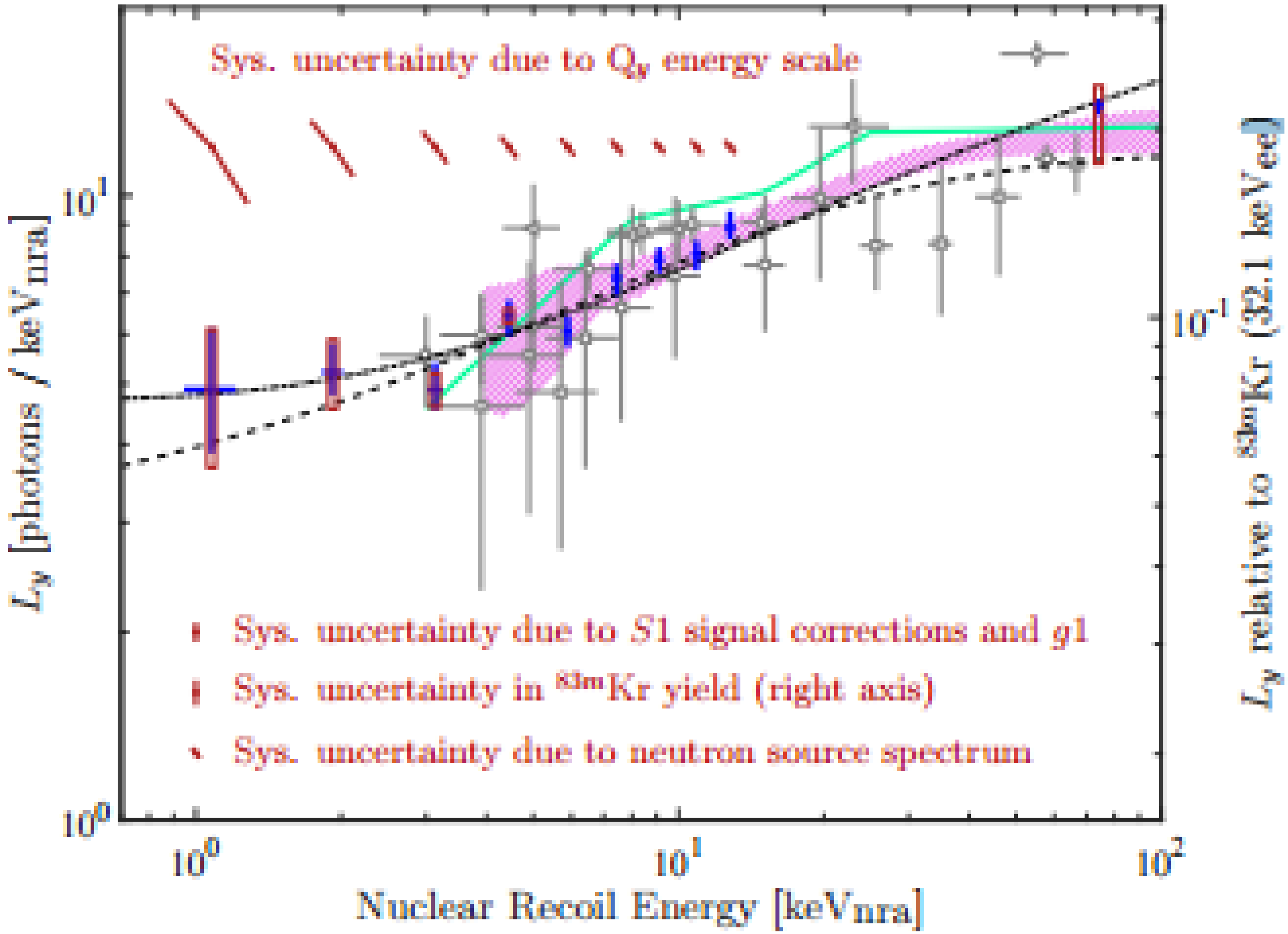


Figure 8. $S1$ vs. $S2$ single-scatter distribution for the L_y measurement. The 1931 events in data after all L_y analysis cuts are shown in this plot in blue in the upper frame. For comparison, a randomly selected sample consisting of the same number of simulated events, produced by the Lindhard-based NEST model described in Sec. VII, is shown in red in the lower frame. The raw $S2 > 55$ phd threshold is represented by the vertical dashed magenta line in corrected $S2$ space (~64 phd). The modeled S1 threshold requires that two photons contribute signal in the PMTs and that the resulting summed area is above the horizontal dot-dashed magenta line. This cutoff is varied over the range indicated by the magenta arrows, and the analysis is repeated to estimate the systematic uncertainty due to S1 threshold effects.

Measuring Ly (2)



Endpoints

- A separate analysis can be done to try and nail down the Ly and Qy values at the specific energy of 74 keV.
- 74 keV is the maximum energy transferable to a Xe neucleus in a single scatter, so the value where the S1 and S2 signals drop off should correspond to an energy of 74 keV.
- This can then be used to directly get a value for Ly and Qy.

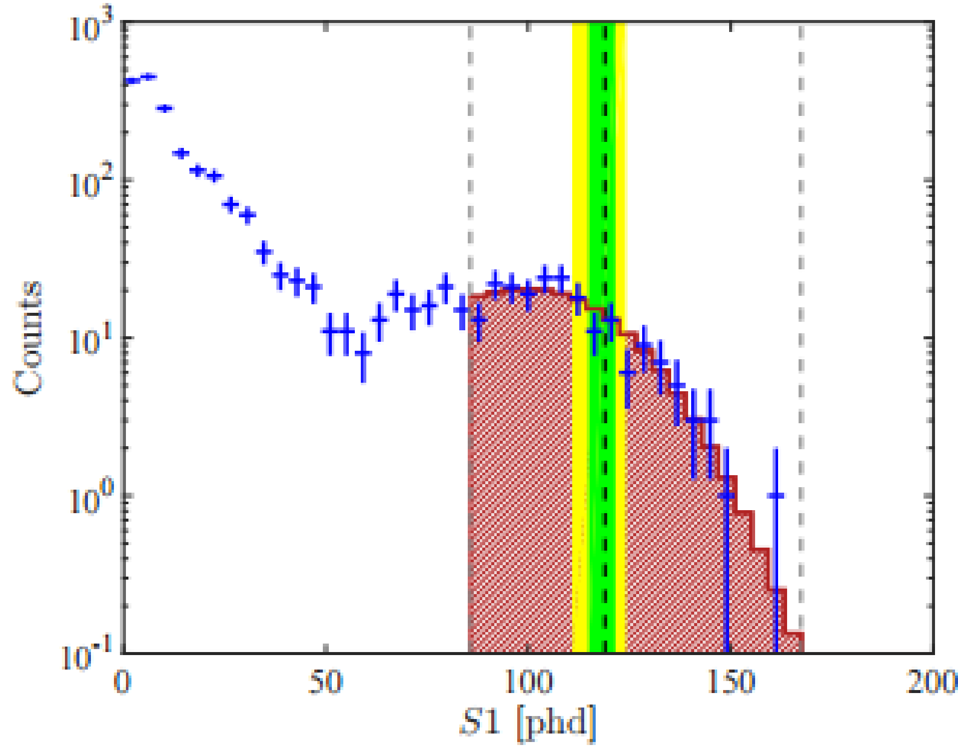


FIG. 11. Result of the L_y endpoint optimization. The single-scatter $S1$ spectrum after all cuts is shown in blue. The best fit endpoint model is represented by the red shaded histogram. The binned maximum-likelihood optimization was performed between the gray dashed lines. The fit has a $\chi^2/\text{dof} = 7.5/9$ yielding a p-value of 0.59. The black dashed line is the best fit endpoint in $S1$ space, with 1σ and 2σ statistical uncertainties represented by the green and yellow regions, respectively.

Endpoints (2)

- The Qy Endpoint plot

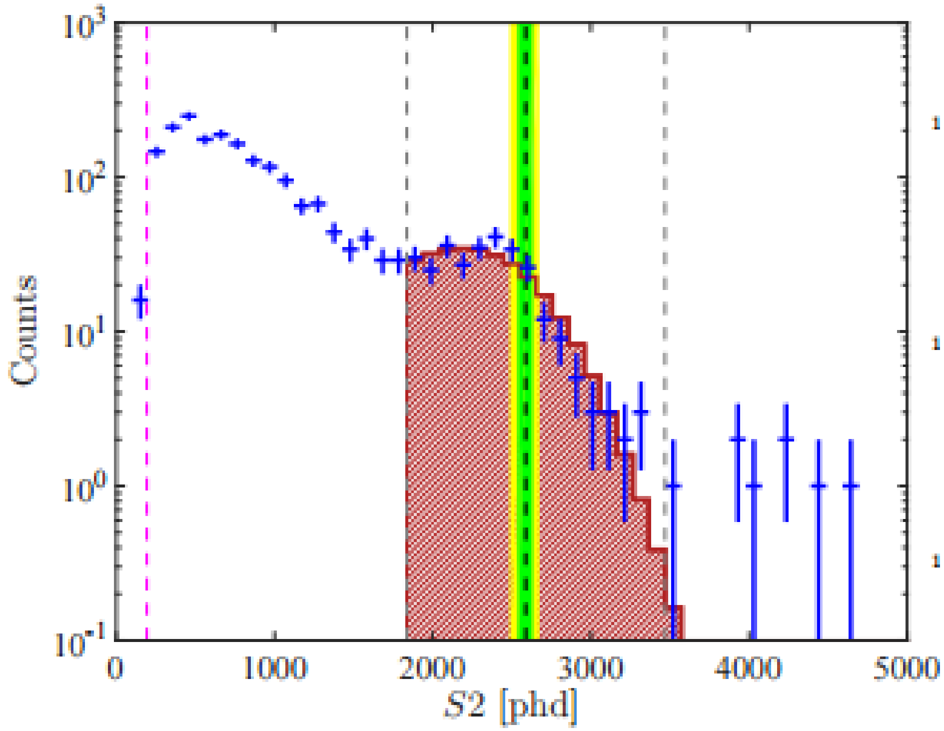


Figure 12. Result of the Q_y endpoint optimization. The single-scatter S2 spectrum after all cuts is shown in blue. The best-fit endpoint model is represented by the red shaded histogram. The binned maximum-likelihood optimization was performed between the gray dashed lines. The magenta dashed line depicts the location of the S2 threshold. The χ^2/dof is 14.7/9 dof yielding a p-value of 0.10. The black dashed line is the best-fit endpoint in S2 space, with 1σ and 2σ statistical uncertainties represented by the green and yellow regions, respectively.

Band Comparison with Simulation

This is the comparison of the LUX run03 calibration data with the simulation created using the calibration.

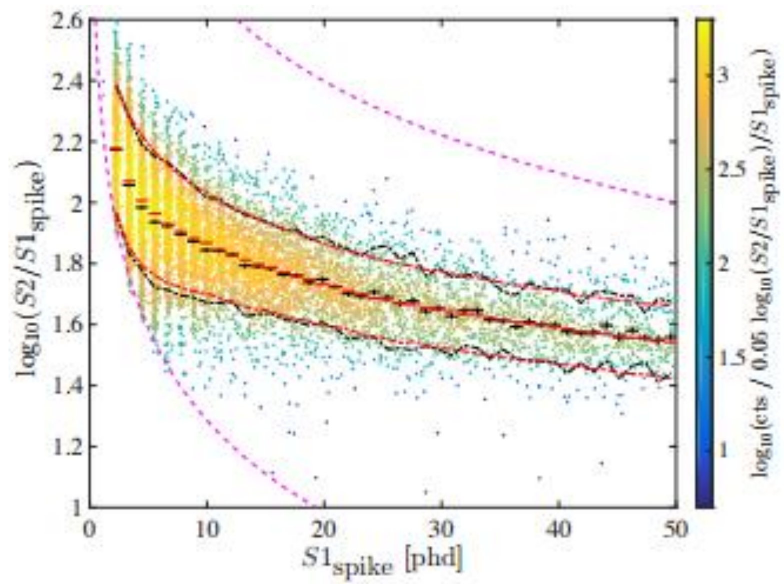


Figure 13. The measured events defining the nuclear recoil band are shown in the scatter plot. There are 9864 events remaining after all cuts with $S1_{\mathrm{spike}} < 50$ The black data points are the Gaussian fit mean values for each $S1_{\mathrm{spike}}$ bin. The red data points are corresponding Gaussian fit mean value for the simulated nuclear recoil band produced using the model described in Sec. VII. The black and red dot-dashed lines indicate the 90% one-sided limits from data and simulation, respectively. The magenta dashed lines indicate the lower S2 threshold at ~164 phd raw S2 and the upper S2 limit at 5000 phd. Error bars are statistical only.