Ionization/Scintillation Yields and Energy Scale in Liquid Xenon Detectors

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Outline

- Motivation
- Introduction to the physics models in NEST
  - Motivation, parametrization
- Global fit procedure for NR
  - Light yield, charge yield, ratio of the two
- Fit results
  - Parameters
  - Detector-independent quantities
- Comparison to other work
- Summary

Dual-phase xenon emission detectors

- Measure low energy particle interactions by combining two signals:
  - Scintillation **light** (S1)
  - Ionization **charge** (S2)
- Discrimination between electronic recoils (ER) and nuclear recoils (NR)
- Applications in direct dark matter, coherent neutrino scattering searches (along with argon).
- Need to understand the physics of nuclear and electronic recoils to understand low-energy response, discrimination

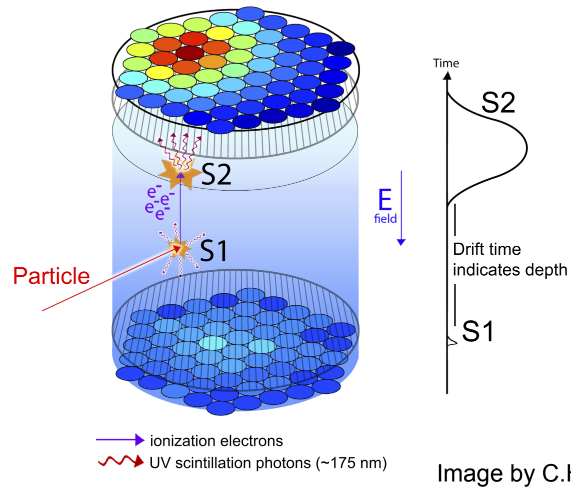
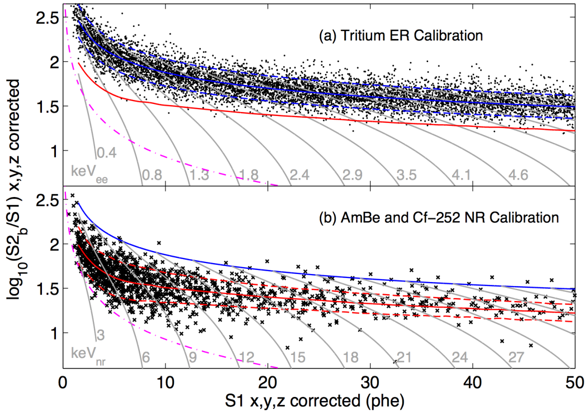


Image by C.H. Faham (LBL)



D. Akerib *et al.*, *Phys. Rev. Lett.* 112 (2014) 091303.

NEST algorithm

$$N_q = \frac{E_{\text{dep}}}{W}$$

NR

$$N_q = N_q \; L$$

ER

$$N_{\text{ion}} = \frac{N_q}{1 + (N_{ex}/N_{ion})}$$

$$N_{\text{ex}} = N_q - N_{\text{ion}}$$

$$n_e = (1 - r) N_{\text{ion}}$$

$$n_\gamma = (N_q - n_e)\,\frac{1}{1 + \alpha\,\epsilon^{\beta}}$$

Thomas-Imel recombination model

$$r = 1 - \frac{\ln(1 + N_i\,\varsigma)}{N_i\,\varsigma}$$

Step 1:
Quanta are generated. If it's a nuclear recoil, Lindhard quenching is applied.

$$L = \frac{k\,g}{1 + k\,g}$$

Step 2:
Quanta are split initially into ions and excitons. The exciton-to-ion ratio differs between ER and NR.

Step 3:
Electron/ion pairs recombine to produce photons. The Thomas Imel box model is implemented at this stage, as well as Penning quenching.

NEST algorithm

$N_{\ldots}$ E_{dep}

$N_{\ldots}$

NEST predicts absolute number of electrons AND number of photons.

- Conserves energy
- Assumes anti-correlation

Energy scale uses combined information to improve resolution

$$E_{ER} = (n_\gamma + n_e)\,W$$

$$E_{NR} = \frac{(n_\gamma + n_e)\,W}{L}$$

Thomas-Imel recombination model

$$r = 1 - \frac{\ln(1 + N_i\,\varsigma)}{N_i\,\varsigma}$$

$$n_e = (1 - r)N_{\mathrm{ion}}$$

$$n_\gamma = (N_{i} - n_e)\,\frac{1}{1 + \alpha\,\epsilon^{\beta}}$$

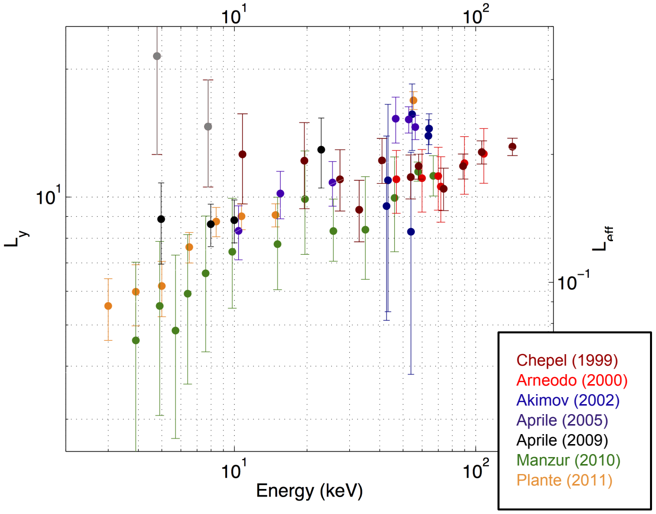
Step 1:
Quanta a…
a nuclear …
quenchin…

$L = \ldots$
$1 + k\,g$

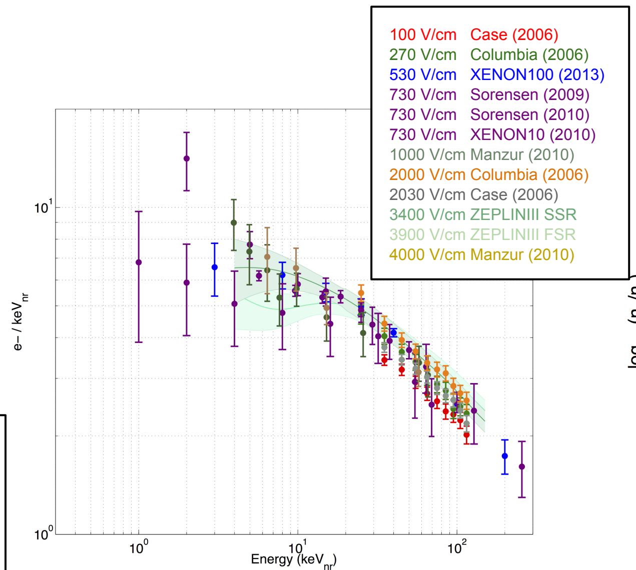
…e
…s
between ER and NR.

Step 3:
Electron/ion pairs recombine to produce photons. The Thomas Imel box model is implemented at this stage, as well as biexcitonic quenching.

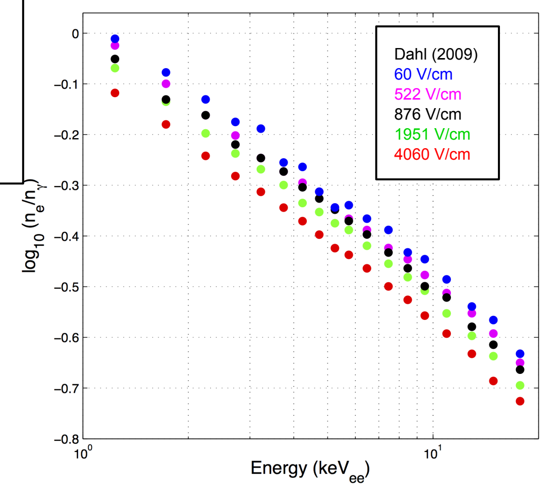
Global fit to the world's data (NR)



L_{eff} - scintillation yield



Q_y - ionization yield



Electron / photon ratio

To fit to all of these data, we construct a global likelihood function and optimize.

$$\mathcal{L} = \prod \frac{1}{\sqrt{2\pi}\,\sigma_{exp}} \exp\left(\frac{-(x_{exp}-\mu)^2}{2\,\sigma_{exp}^2}\right) \qquad \mu \in \left\{ \mathcal{L}_{eff},\, \mathcal{Q}_y,\, \frac{N_e}{N_{ph}} \right\}$$

Parameterization and best fits

Four quantities that are fit:

$\frac{N_{ex}}{N_i}$	Initial ionization
ς	Recombination
k	Nuclear recoil efficiency
$\frac{1}{1+\alpha\,\epsilon^{\beta}}$	Biexcitonic quenching

Nine free parameters - a, b, c, d, f, k, alpha, beta, "zero field"

$$\frac{N_{ex}}{N_i} = \mathrm{c}\ (\mathrm{E}_{field})^{\mathrm{d}}\ \left(1 - e^{-\mathrm{f}\ E}\right)$$

$$\varsigma = \mathrm{a}(\mathrm{E}_{field})^{\mathrm{b}}$$

$$k$$

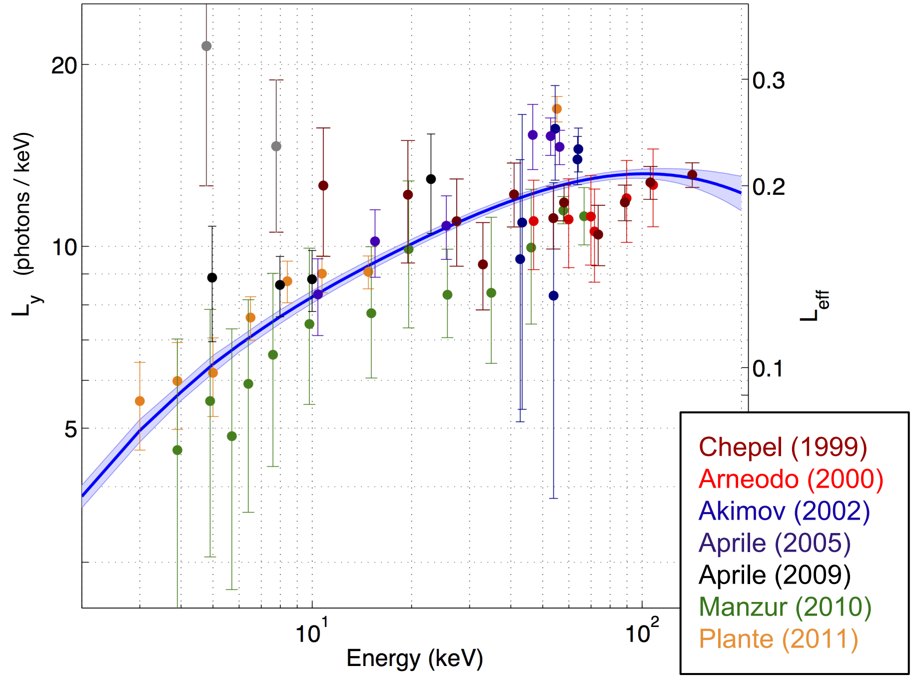
$\alpha\ ,\beta$ (biexcitonic quenching)

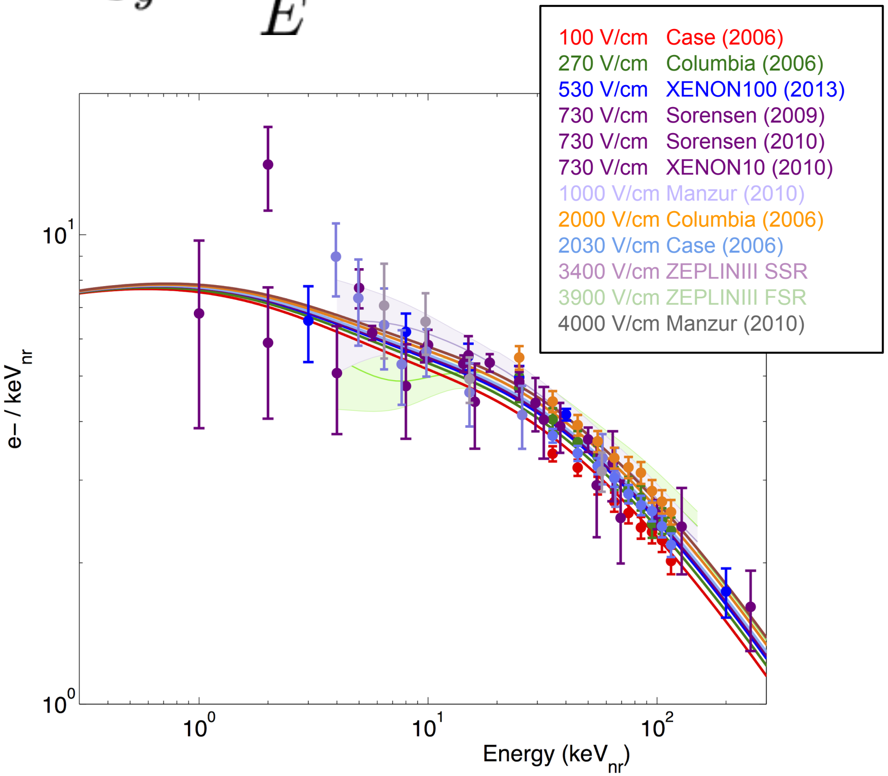
Variable	*a*	*b*	*c*	*d*	*f*	*k*	α	β	*0-field*
Best fit	0.0554	-0.0620	1.240	-0.0472	-239	0.1394	3.12	1.141	1.03
68% CL -	-0.0029	-0.0056	-0.079	-0.0088	-27.7	-0.0026	-0.38	-0.086	-1.03
68% CL +	+0.0023	+0.0065	+0.07	+0.0073	+9.0	+0.0032	+5.50	+0.453	+14

L_{eff} and Q_y - from best fit model

$$\mathcal{L}_{eff} = \frac{n_\gamma}{E} \times \frac{1}{n_\gamma(^{60}\mathrm{Co})}$$

$$\mathcal{Q}_y = \frac{n_e}{E}$$





Comparing alternative NR models

Lindhard quenching in liquid xenon is a source of uncertainty.

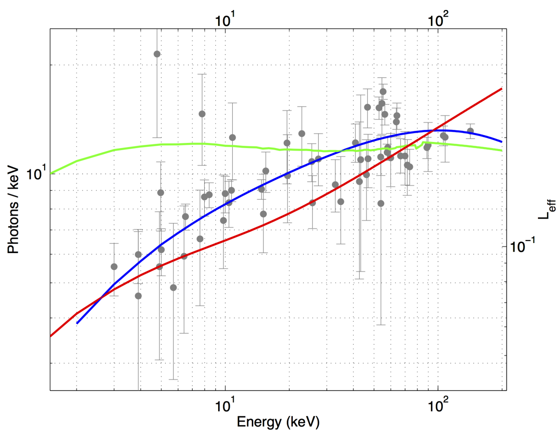
$$L = \frac{k\,g}{1 + k\,g} = \frac{s_e/s_n}{1 + s_e/s_n}$$

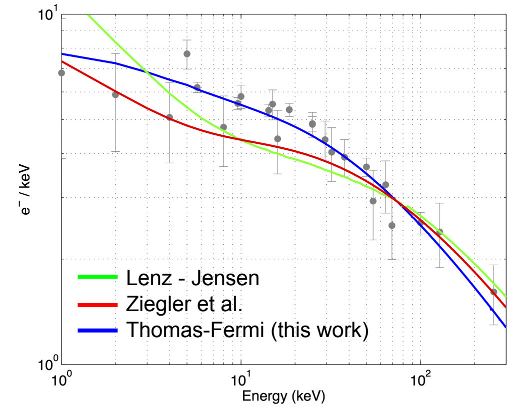
Directly affects number of quanta:

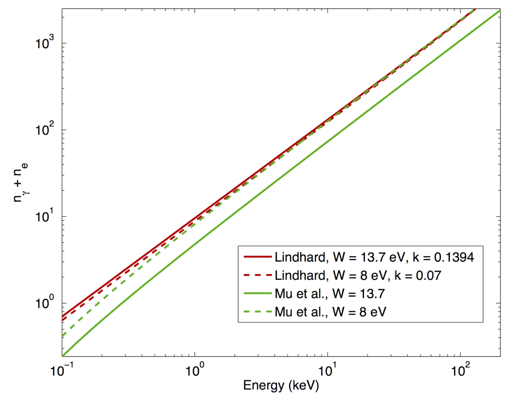
$$N_q = \frac{E_{dep}}{W} \times L$$

Alternatives exist in literature:

- F. Bezrukov et al., Astroparticle Physics 35 (2011) p. 119.
  - Alternative s_n models
- W. Mu, X. Xiong, X. Ji, Astroparticle Physics 61 (2015) p. 56
  - Alternative s_e model



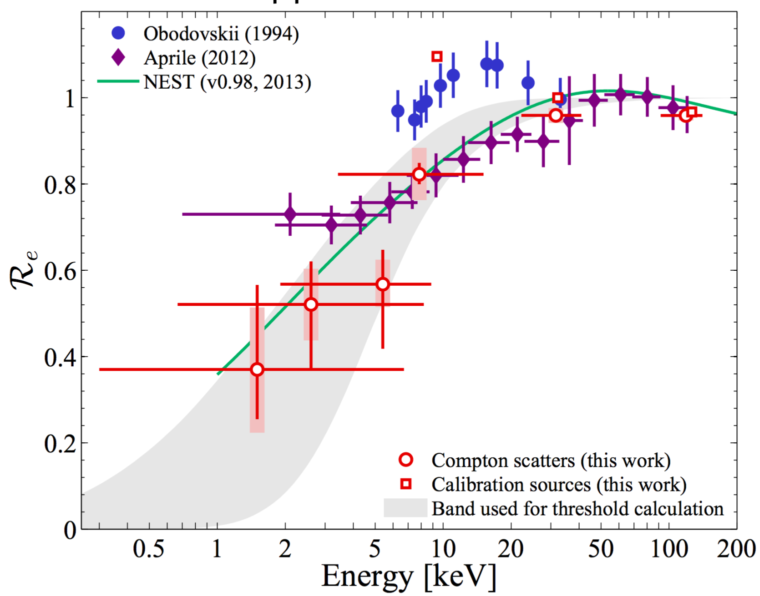




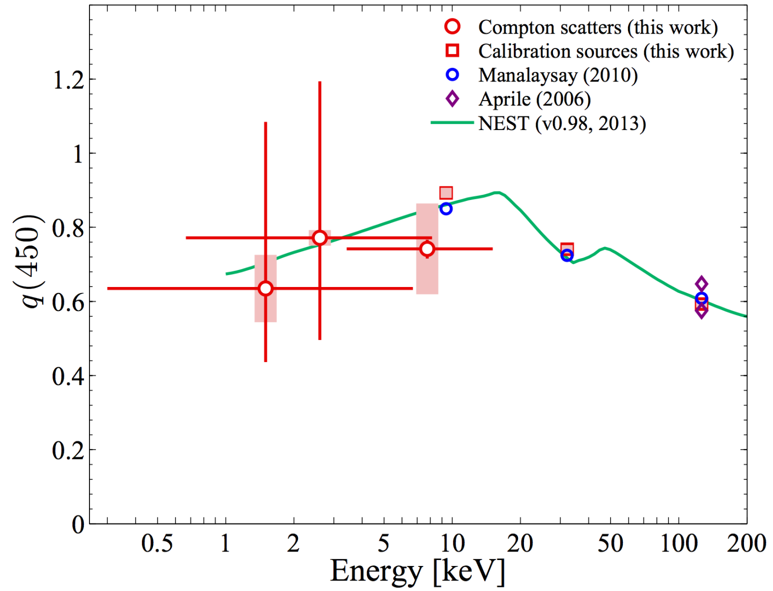
ER model

Older version of NEST predicts scintillation yield at different energies and fields:

No applied electric field



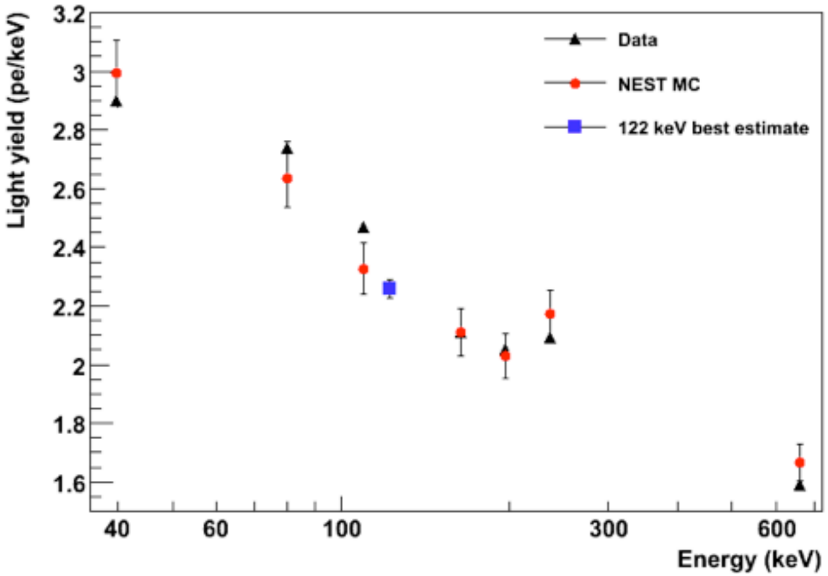
Quenching at 450 V/cm



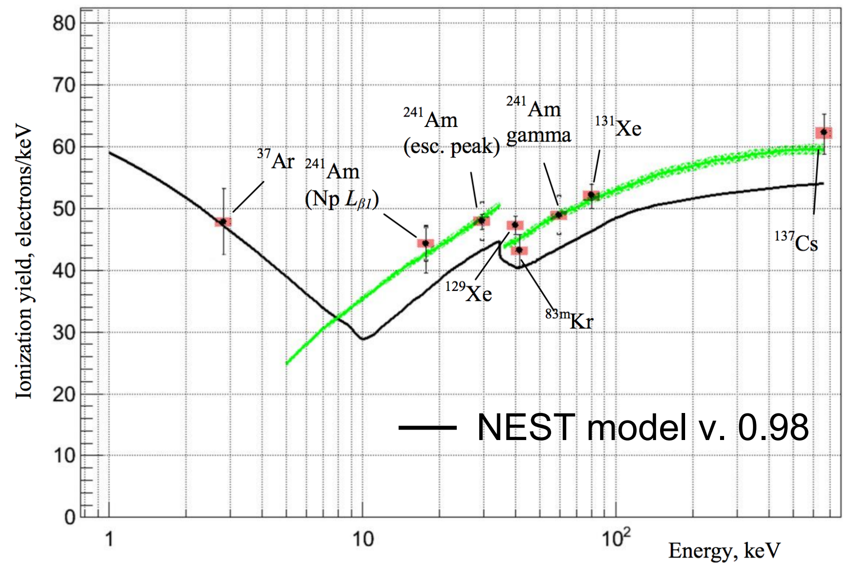
Baudis et al., Phys. Rev. D 87 (2013) 115015

ER model (cont.)

Data from XENON100 detector, 530 V/cm



Aprile, Dark Attack 2012



Akimov et al., arXiv:1408.1823

Newest version of NEST will fit to all available data in a global manner, and will be improved in light of LUX tritium calibration data.

Summary

- Model has been constructed
  - Incorporates multiple physics models
  - Predicts both light and charge yield given energy and applied field
- Globally fit to all available data
- Different physics models studied from global perspective, best fit found.
- Similar approach should be applicable to LAr, but has not yet been implemented

Publication of NR model forthcoming

Acknowledgements

Many people work on NEST, and have contributed directly to this work.

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  - Prof. Matthew Szydagis
- University of California, Davis
  - Prof. Mani Tripathi
  - Dr. Aaron Manalaysay
- Lawrence Livermore National Laboratory
  - Dr. Kareem Kazkaz
- The LUX collaboration

Backup slides

Free parameters in NEST (NR)

Four quantities that are allowed to vary

$\frac{N_{ex}}{N_i}$	Initial ionization
$\frac{\alpha}{a^2\, v}$	Recombination
k	Nuclear recoil efficiency
$\frac{1}{1+\alpha\,\epsilon^{\beta}}$	Biexcitonic quenching

Nine free parameters - a, b, c, d, f, k, alpha, beta, "zero field"

$$\frac{N_{ex}}{N_i} = \mathrm{c}\ (\mathrm{E}_{field})^{\mathrm{d}}\left(1 - e^{-\mathrm{f}\ E}\right)$$

$$\frac{\alpha}{a^2 v} = \mathrm{a}\ (\mathrm{E}_{field})^{\mathrm{b}}$$

k

$\alpha\ ,\beta$ (biexcitonic quenching)

We also introduce as a free parameter an "effective zero field". The scintillation efficiency is typically measured at zero field, but our model blows up.

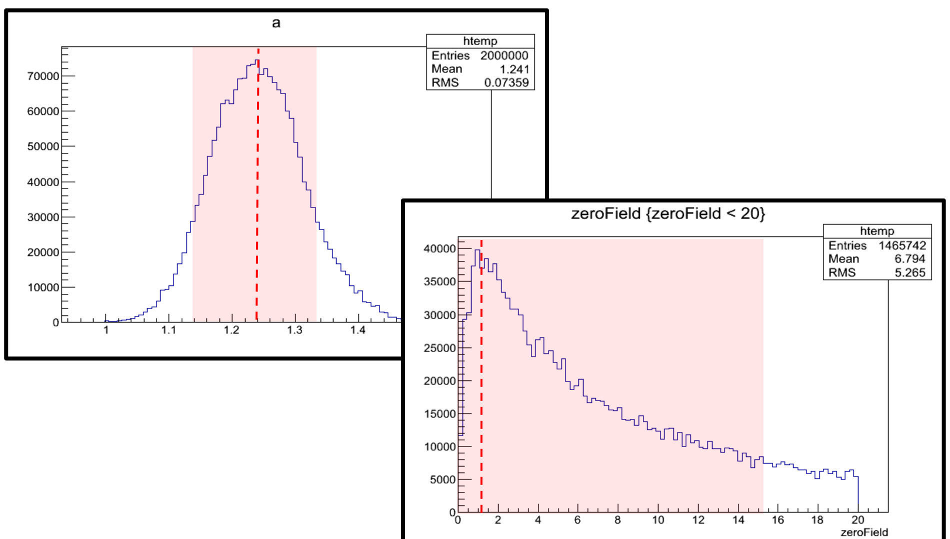
MCMC estimation of parameters

We assume that the likelihood function we've constructed is proportional to the probability of our model given this set of data:

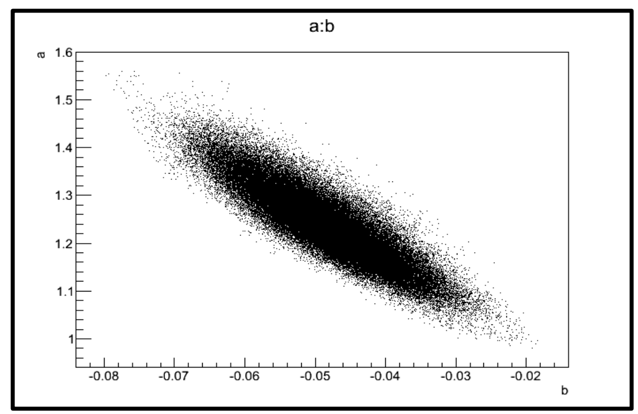
$$\mathcal{L}(\theta \,|\, x) \propto P(\theta \,|\, x)$$

Then, sampling gives us the underlying PDF, without solving analytically.

Best fits and errors can be found by histogramming the samples and reading off the maximum:



It's also easy to get covariances by histogramming samples in 2D. Helpful for error analysis.



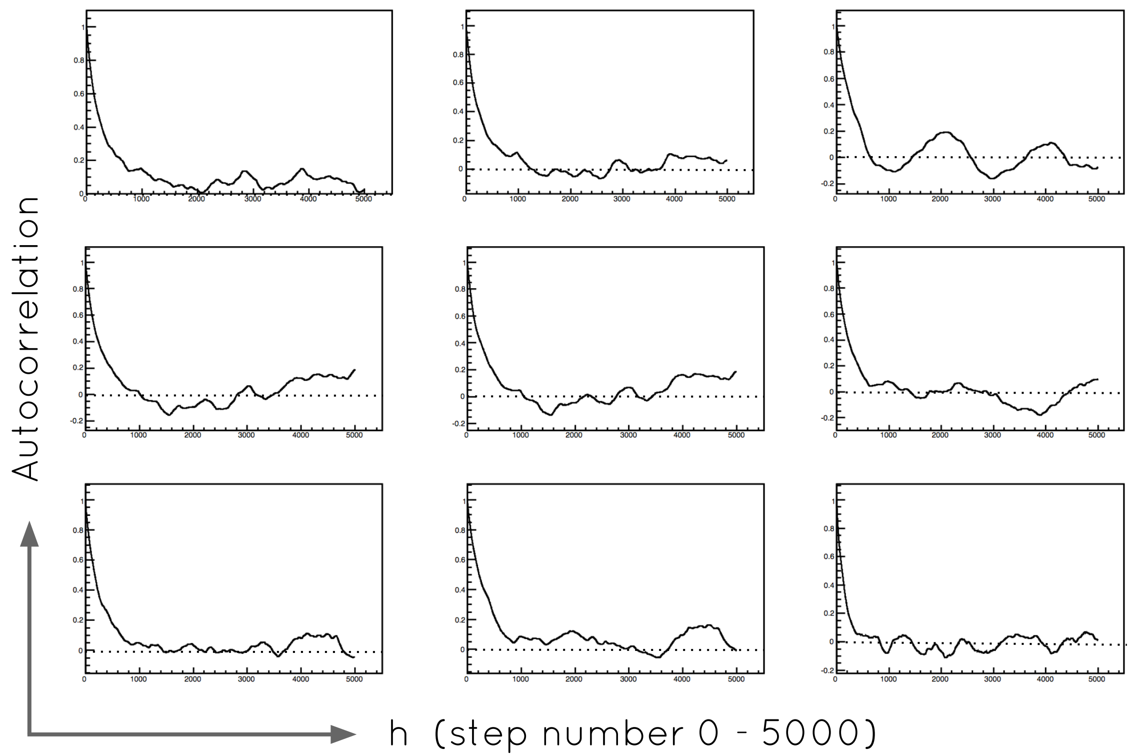
Ensuring a fair sample

We study the autocorrelation of each variable:

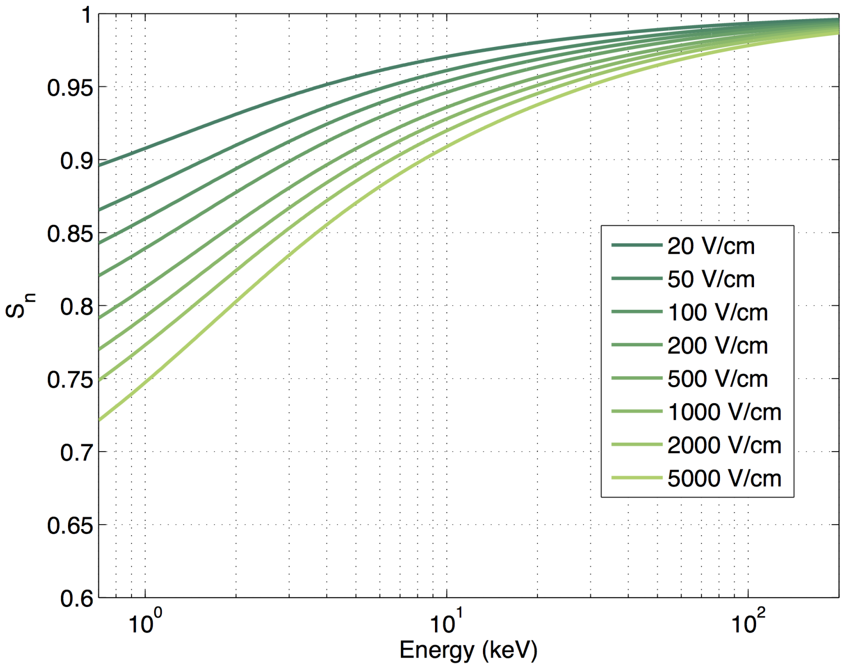
$$R(i, i+h) = \frac{\mathrm{E}\left[(X_i - \mu_i)\,(X_{(i+h)} - \mu_{(i+h)})\right]}{\sigma_i\,\sigma_{(i+h)}}$$

To ensure a fair sample, must be sure that $N_{samples}$ >> $Length_R$

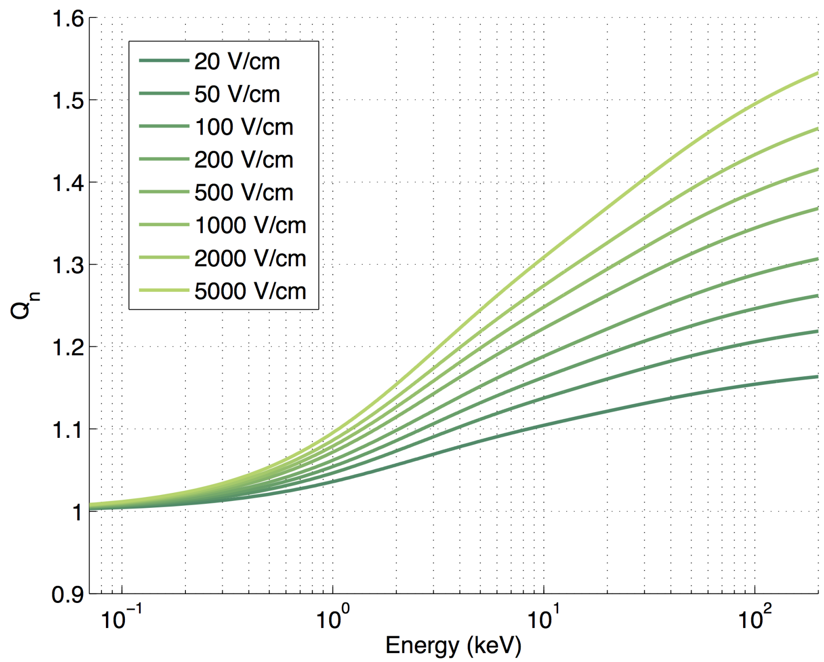
- In our case, we use 3,000,000 samples



Field dependence of scintillation / ionization



Light yield relative to 0 V/cm



Charge yield relative to 0 V/cm

Larger version of comparison to Mu et al.