Simulating The Secondary Scintillation Signal in a Two-Phase Xenon Detector

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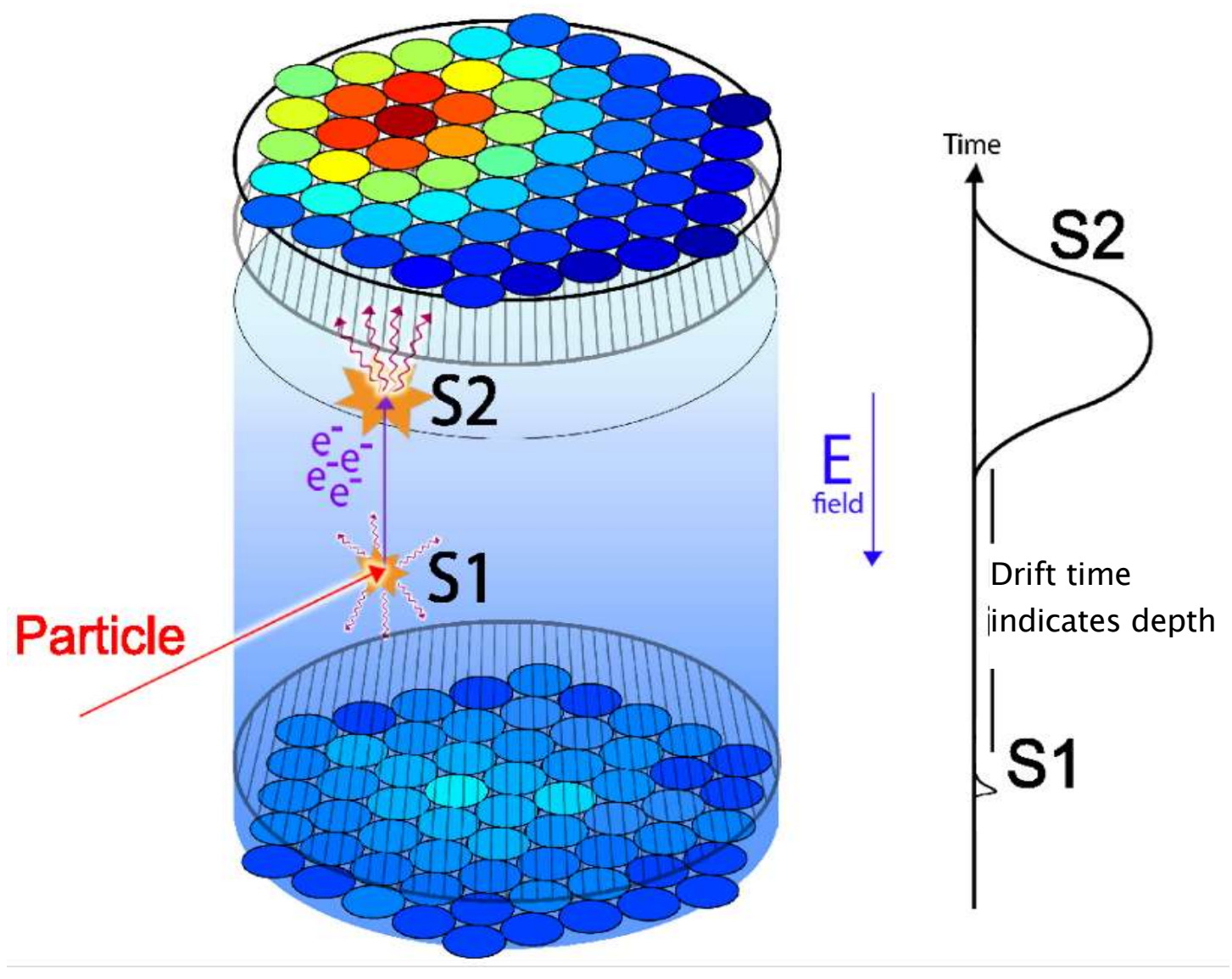
Introduction:

A two-phase direct dark matter detector relies on data from two scintillation signals, a primary one in liquid (S1) and a secondary one in gas (S2). The time between the S1 and S2 signals allows for a first-order determination of the depth of an event, but in order to have a better handle on event position reconstruction it is best to understand the depth dependence of S2 width in time. Simulations of the S2 process were made knowing the electron drift velocity in the gas volume, the estimated mean free path before scintillation in the gas, and the diffusion constant of electrons drifting in liquid. With the right choice of parameters, one can achieve reasonable agreement between Monte Carlo results and past experimental data.

S2 Pulse (Electroluminescence):

Production:

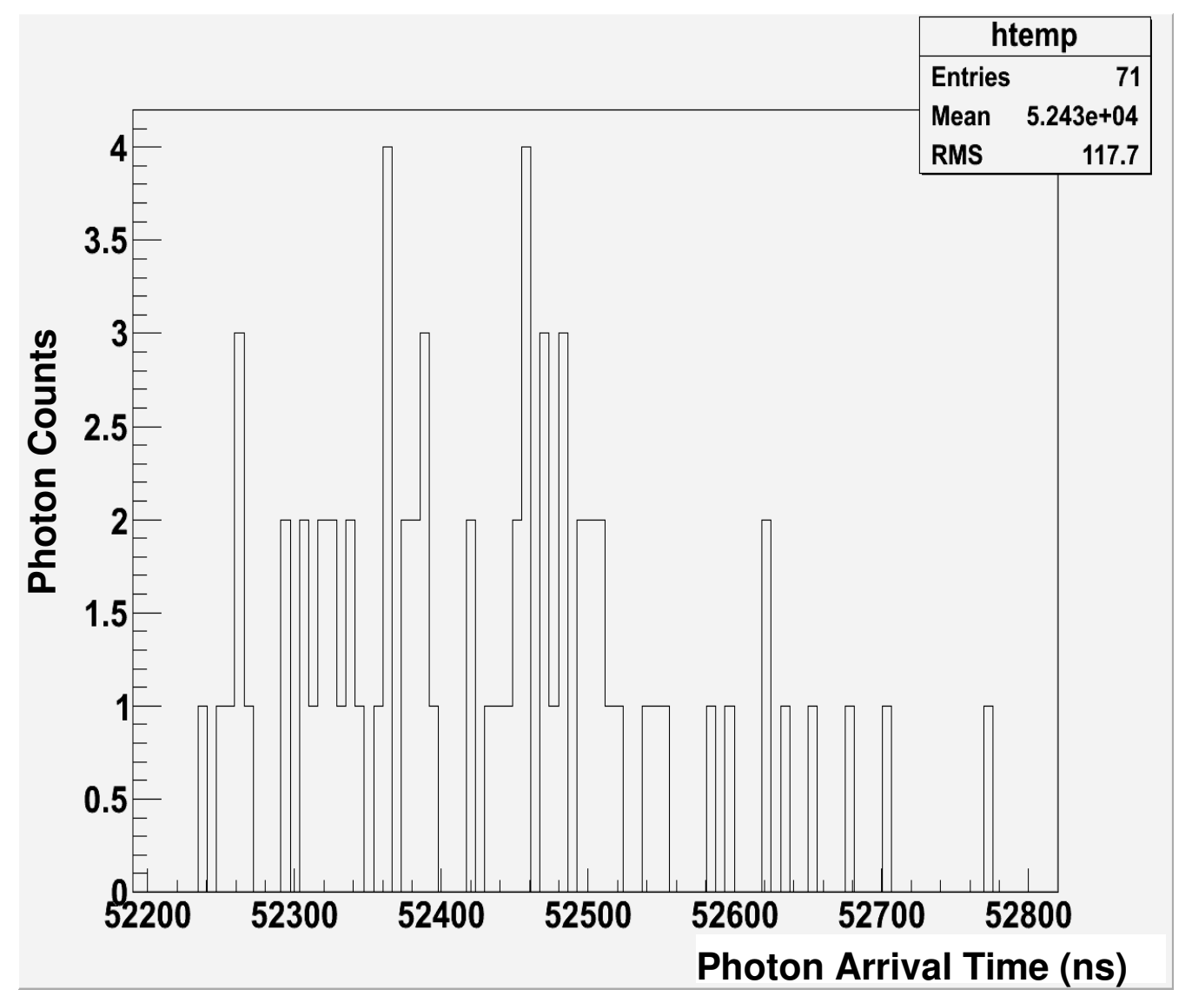
As a particle enters a liquid xenon volume it excites and ionizes atoms. Excited atoms cause S1 light by leading to the formation of excited molecular states (excimers) which release VUV photons upon de-excitation. Ionized electrons may fail to recombine, and if so drift upward in the presence of an electric field. The electrons then scintillate in gaseous xenon in a higher-field region. The photons thus produced reach photo-sensitive detectors in a real experiment.



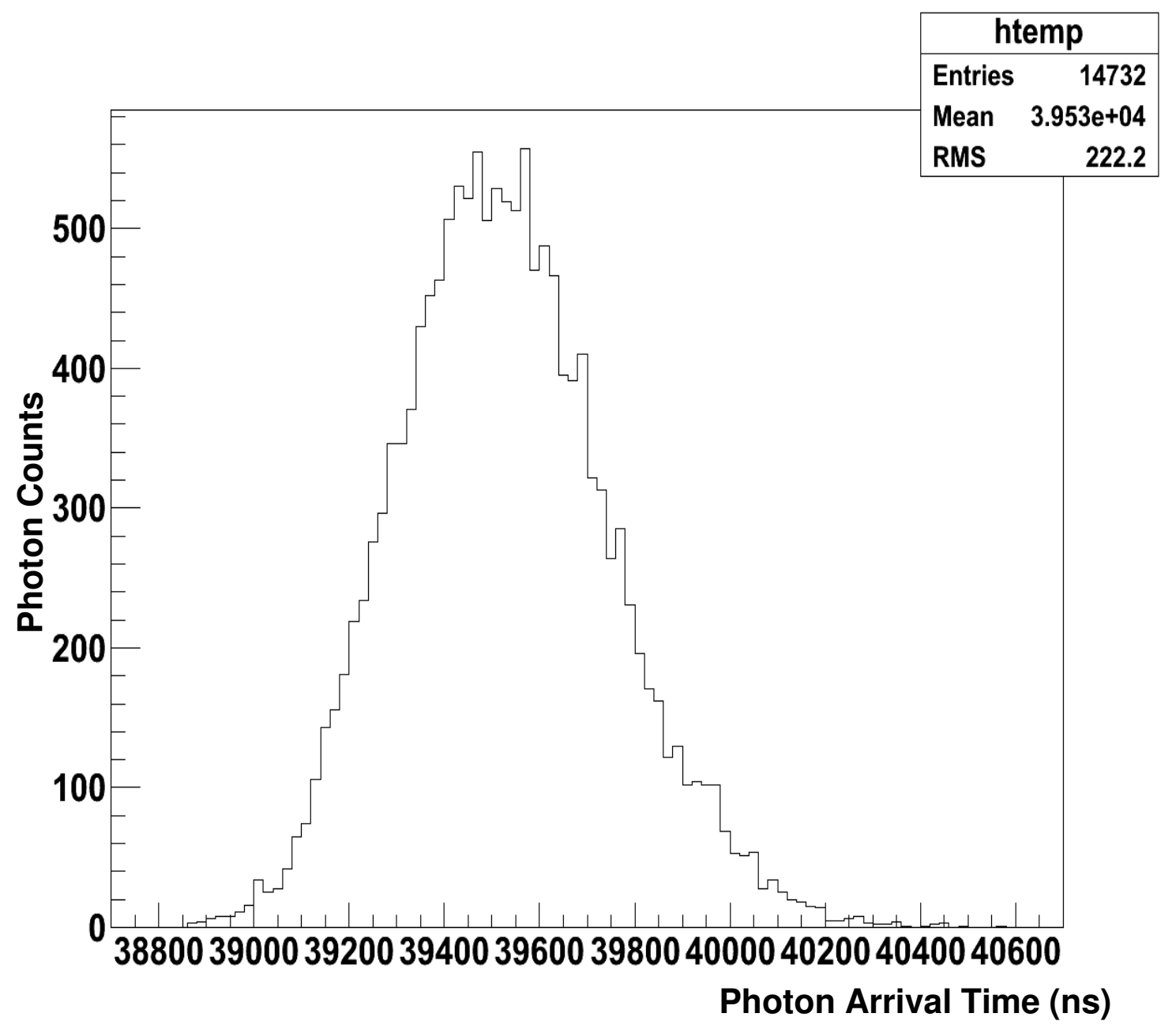
http://teacher.pas.rochester.edu:8080/wiki/pub/Lux/LuxFigures/LUX_Event_white.eps

Pulse Shape:

The number of ionized electrons depends on the energy and type of incident particle. At right is an example photon arrival time histogram for an individual scintillating electron. Below is an example of many ionized electrons scintillating in the gas. As these electrons drift through the liquid they become more diffuse.

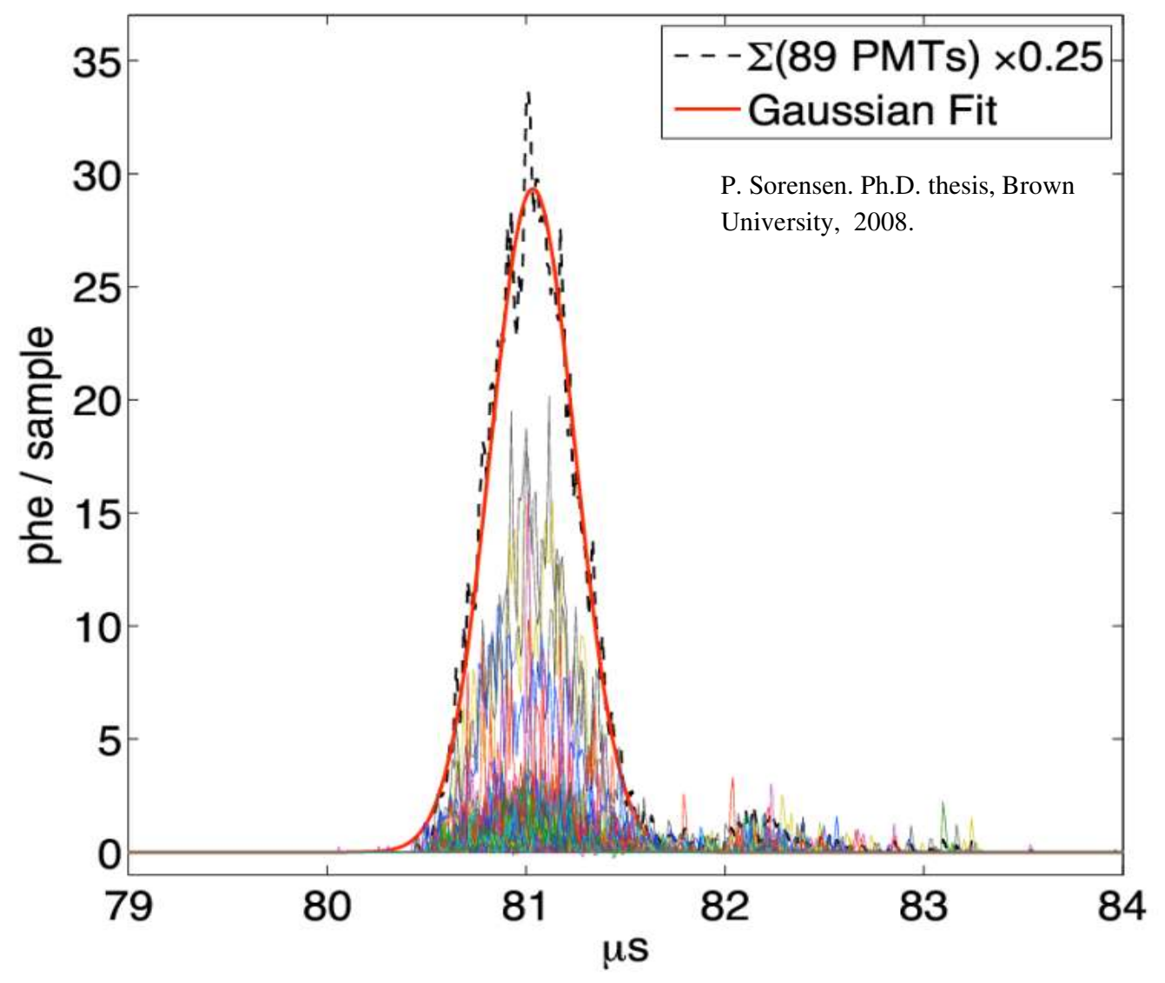


Therefore,as the depth of the originating event increases, the width of the S2 pulse also increases. Due to the cylindrical nature of real-life detectors we duplicate this symmetry in our simulation. Thus the effect of the depth dominates the pulse shape. We currently do not simulate quantum efficiency or a full data acquisition system, only idealized S2 pulses as photon arrival times.

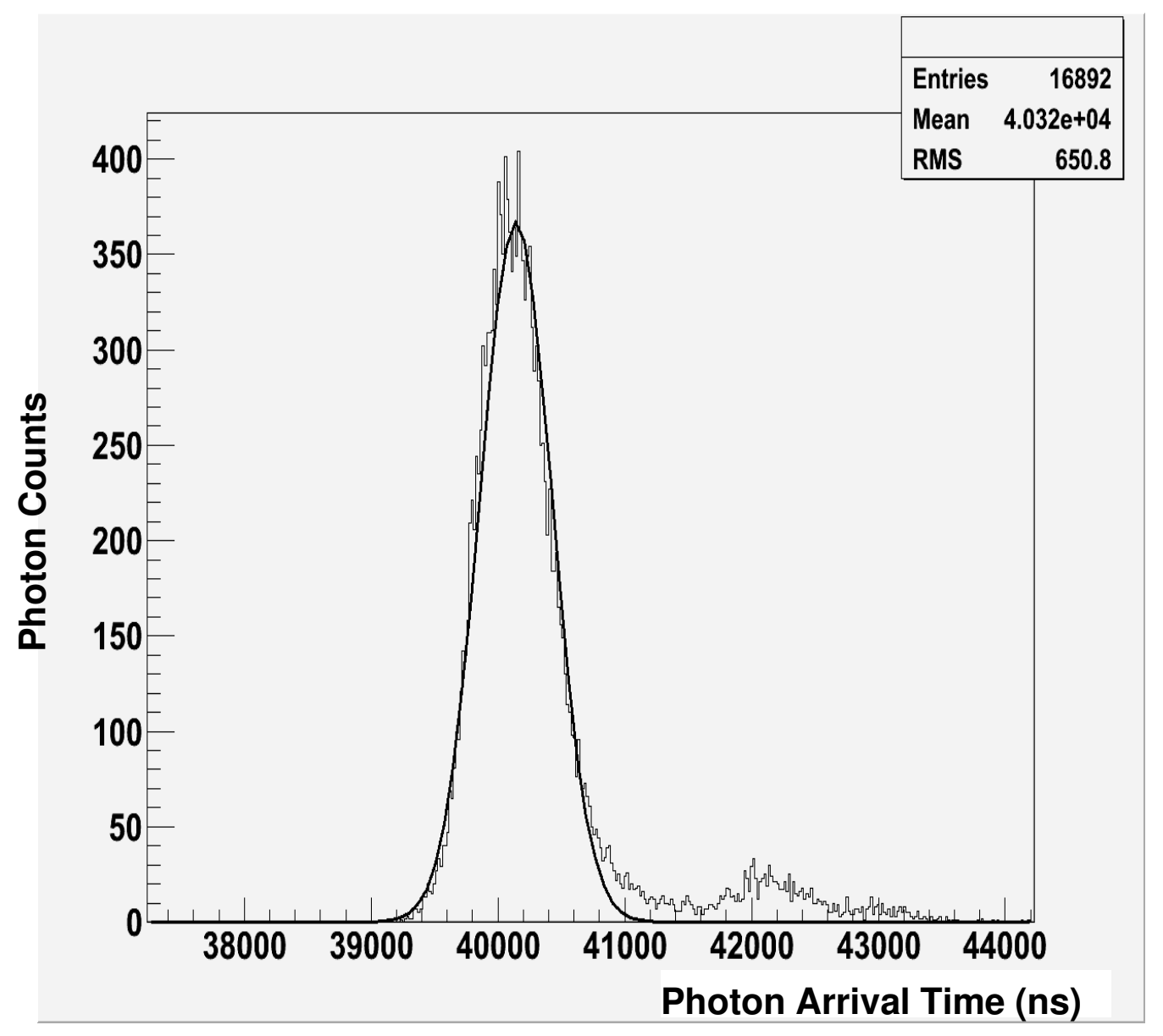


S2 pulses are approximately Gaussian, but include a slight tail structure dominated by the de-excitation time scale for excited xenon and the statistics of trailing individual electrons.

S2 Pulse Reproduction:



Experimental S2 Pulse from XENON10.



Simulated S2 Pulse with a tail made up of single electron noise.

S2 Width Depth Dependence Parameters:

Longitudinal/Transverse Diffusion:

The ionized electrons are Gaussian distributed in space along both the longitudinal and transverse directions. This diffusion increases with travel time through the liquid as they drift upward toward the gas [1]:

$$\sigma = \sqrt{2Dt}$$

where σ is the length scale defining the standard deviation of the diffusion, D is the diffusion constant, and t is the time the electron is subject to the diffusion. Although the diffusion constant for the transverse dimension is considerably larger, longitudinal diffusion is a more significant effect. This is because it creates lag in photon arrival at the photon detector in an experiment. Although the electrons also diffuse in the gas volume, the high electric field and low density medium makes this effect negligible.

Mean Free Path to Luminescence:

The electrons can scintillate when they arrive in a gas region where a higher electric field than in the liquid increases their energy. Electrons travelling through the gas lead to the formation of excited singlet and triplet states which de-excite on ns-long timescales, releasing photons isotropically. Although the average distance between each scintillation event is not directly measured, the number of excited xenon molecules (equivalent to the number of photons generated) per electron per unit distance travelled is an empirically known function of field and pressure [2]:

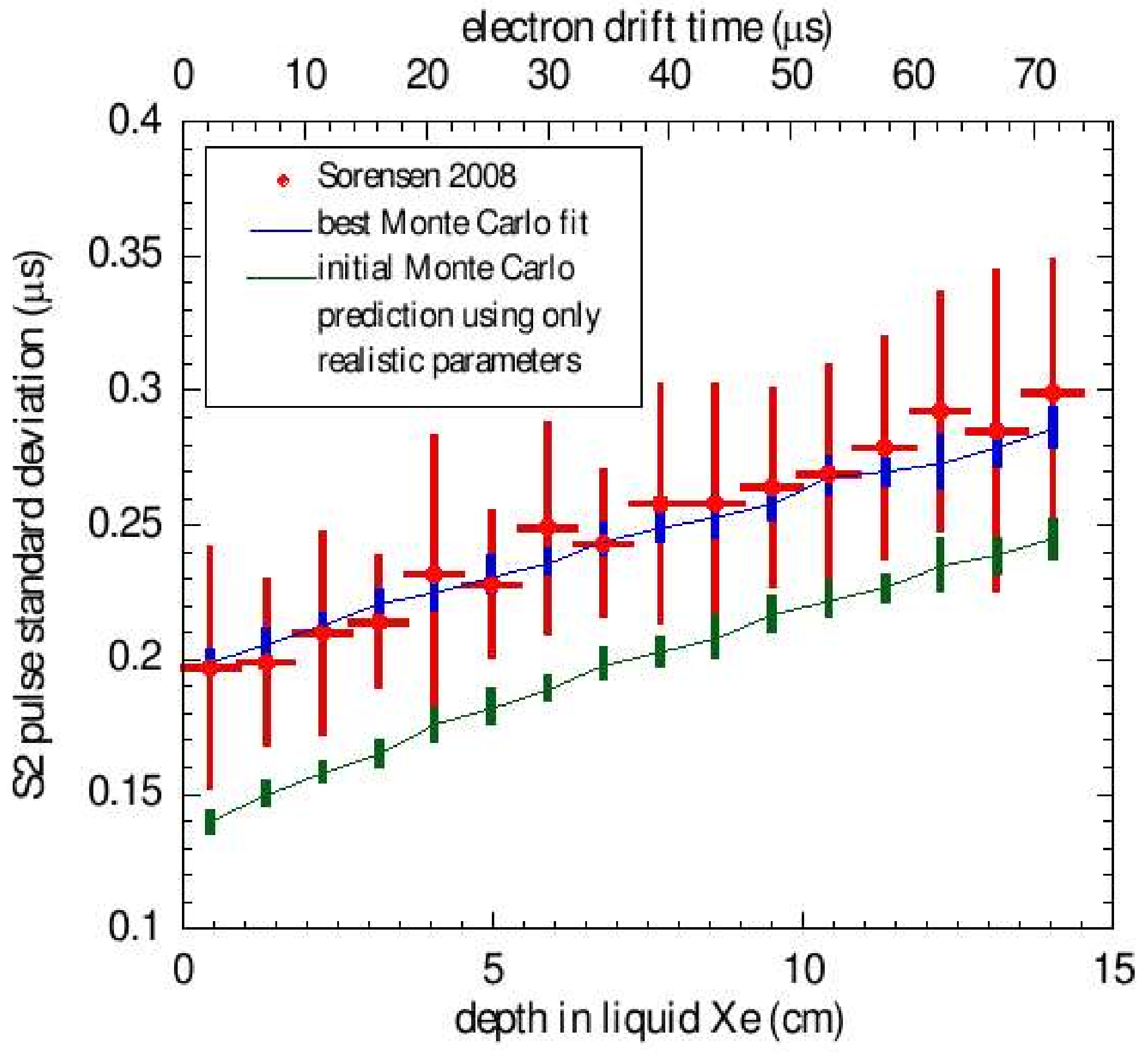
$$n_{ph}/x = 70\cdot\left(E_e/p - 1.0\right)\cdot p$$

where n_{ph} is the number of emitted photons, x is the distance traversed by their originating electron (cm), E_e (kV/cm) is the applied field necessary to extract the electrons from the liquid and drift them through the gas region, and p is the gas pressure (atm). In our simulation, we took the following condition as a starting point: we set n_{ph} equal to 1 and solved for x. To fit real data best, it was necessary to lengthen this distance and increase the number of photons produced per interaction length to compensate. Not only does this lead to better agreement with observed depth dependence, but the S2 shape becomes a closer match to reality. (Depending on drift speed, a low mean free path may lead to unphysical shapes with large asymmetry and flat tops.)

Drift Velocity in Gas:

Electrons are assigned a constant drift velocity in our simulation, as per similar, seminal work in reproducing S2 pulse shapes in argon [3]. We use the Magboltz software toolkit to determine the magnitude of this drift velocity as a function of electric field, pressure, and temperature. The drift velocity for the conditions of the XENON10 experiment, the data from which we use to make comparisons with our simulation, was thus calculated to be ~8 mm/μs. As seen at the upper right, the S2 width depends strongly on the drift velocity. A slower velocity means a greater separation in time between excimer creation, thus implying greater width, which is what we observe.

S2 Depth Dependence:



The above graph compares the S2 width depth dependence of XENON10 with that of the simulation. The blue line represents the depth dependence using parameters chosen to fit the XENON10 data. These parameters include a too-low gas drift velocity of ~5 mm/μs and a mean free path of 0.22 mm to produce 15 excimers. The green line represents the predicted depth dependence using the physically well-motivated parameters of ~8 mm/μs gas drift velocity and mean free path of 0.014 mm to produce 1 excimer. The simulated S2 pulses are comparable in shape and near-Gaussian in both cases.

Further Investigations:

Although reasonable agreement is obtained, further investigation can be performed to understand the offset between the Monte Carlo depth dependence using physically motivated parameters and the experimental data. One possible explanation is that the simulation data does not include simulated PMTs with varying quantum efficiencies and gains, pulse digitization, nor a data analysis that is fallible when determining the width of real pulses. Some of these factors could serve to increase the S2 width. Another explanation could stem from our approximate, constant-velocity representation of the gas scintillation. If one implements a saw-tooth velocity dependence with time in which the electron loses most of its energy when it scintillates, only to re-accelerate afterwards due to the applied field, it may be possible to enhance the agreement between simulation and data. These concepts are currently under active investigation as ways to improve the simulation.

REFERENCES:

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[3] K. Kazkaz, T. Joshi. In Press.

[4] P. Sorensen, Nucl. Instr. Meth. A 635 (2011) 41-43.