# Fast parameterizations for ray tracing in optical calorimetry

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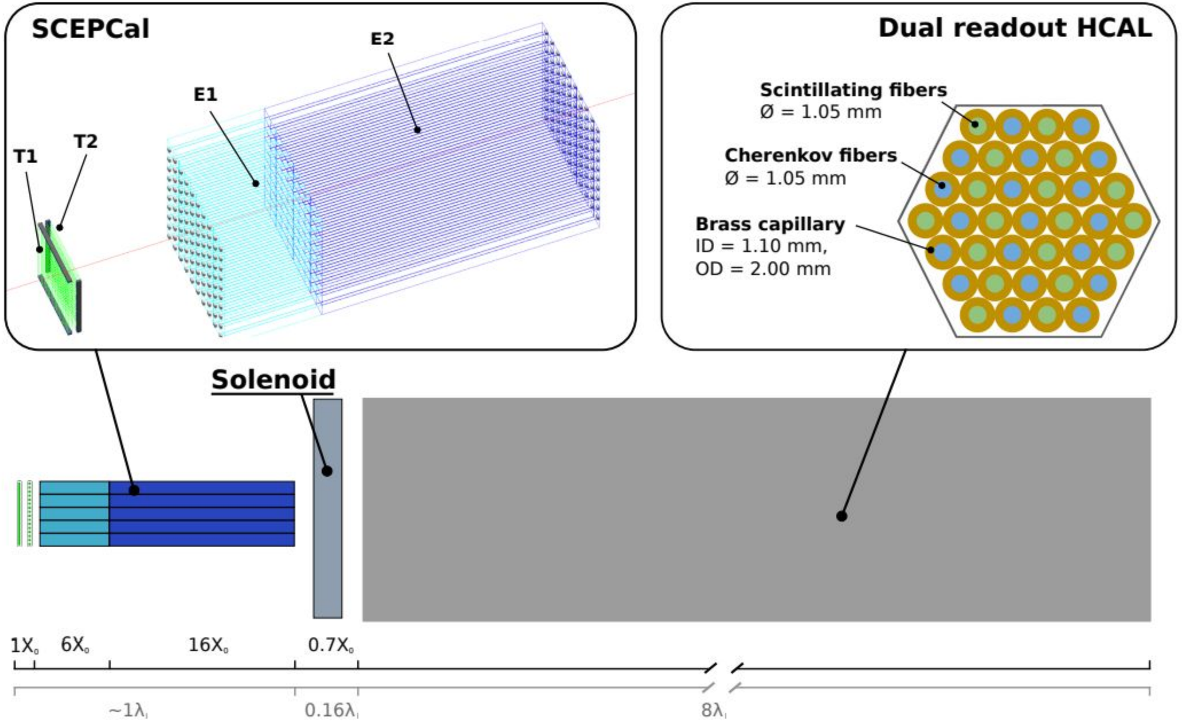
# Motivation: Calvision Detector




Lucchini et al. (2020)

- **Goal:** Model (and separate in a real detector) scintillation and cherenkov photons in order to apply dual readout techniques.
- Cherenkov light component from ultrarelativistic particles is proportional to EM component of showers, allowing better energy resolution for hadronic showers.

- **This Project:** Model the distribution of arrival times at the SiPM of scintillation photons within the E2 ECAL layer given an incident particle (e.g. muon or electron).

# Modeling Optical Photons

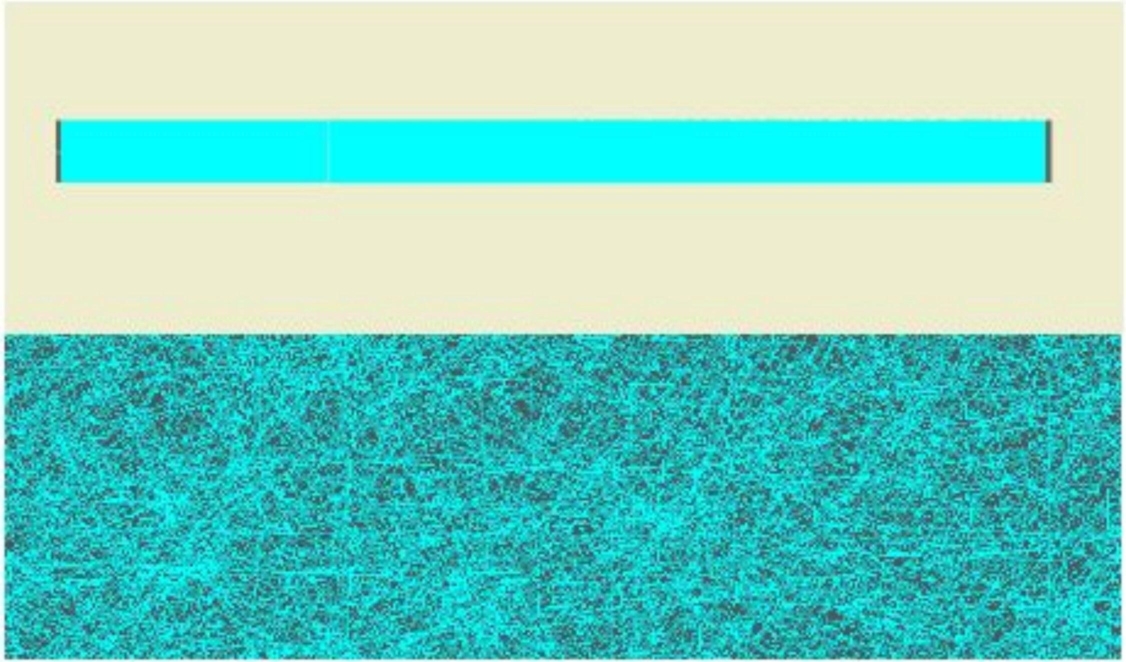
**Ray tracing algorithms propagate optical photons.**

- Accounts for the medium’s optical properties: transmission/reflection at boundaries, absorption, scattering, wavelength shifting, etc.
- Detailed simulations are valuable for optimizing detector designs.

**Issue: Ray tracing is computationally expensive.**

- Many optical photons are generated in one event, leading to a heavy computational load which is prohibitively expensive for a large detector system.
- Fast parameterization reduces this load.

# Density of Photons in EM Showers



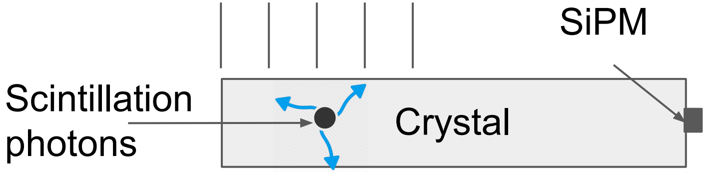
**Above:** A simulation of an incident muon at 1 GeV on two lead tungstate scintillators. A total of 21,885 Cerenkov photons and 119,926 scintillation photons were produced in this event, causing the blue photon traces to fully eclipse the crystal.

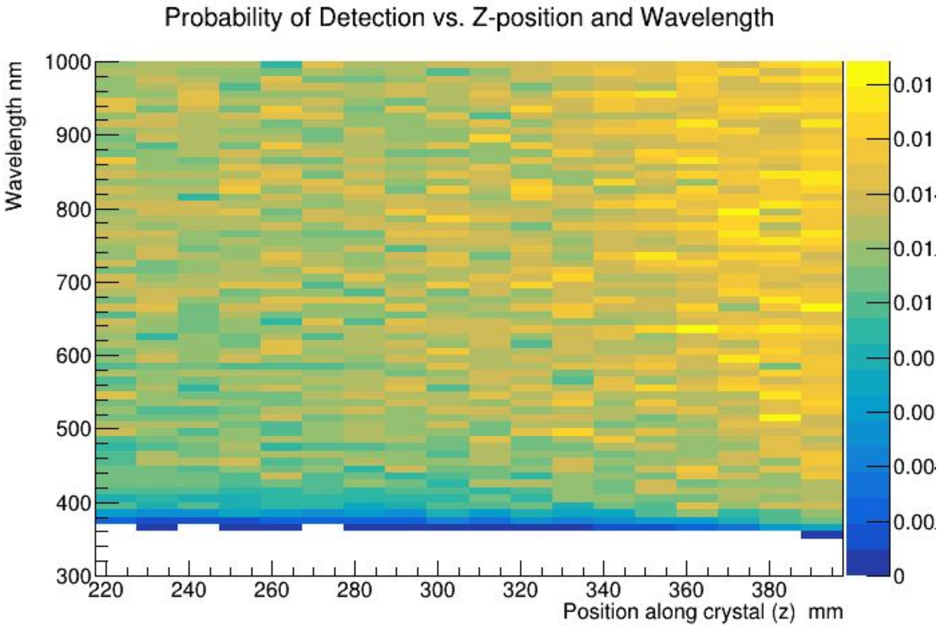
**Below:**
Zooming into the crystal shows the density of the photon paths that Geant4 has to simulate.

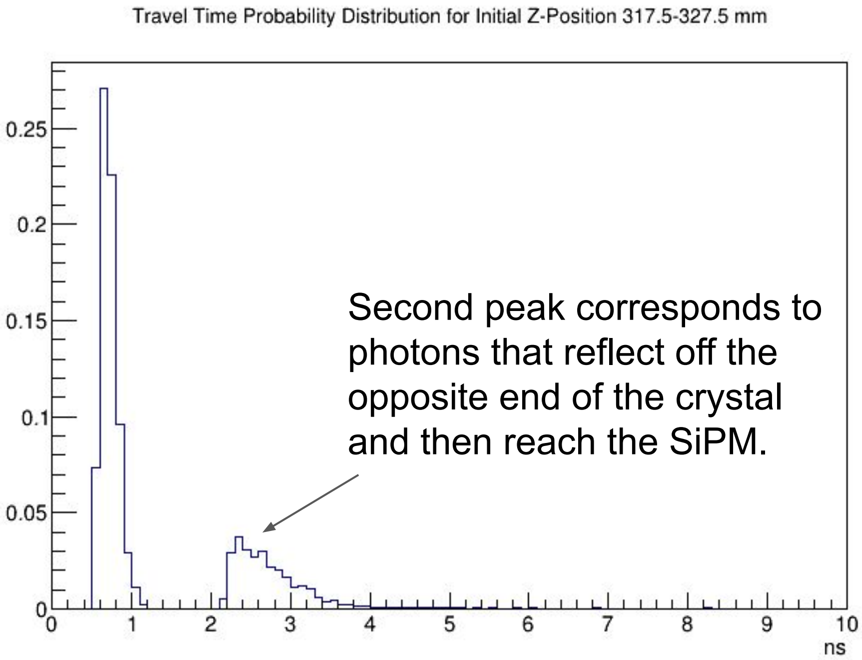
# Fast Parameterization Method

1. Perform ray tracing of many single optical photons uniformly distributed in wavelength and initial z position within the crystal.
    a. Extract probabilities of detection and travel time distributions.
2. For a given Geant scenario (e.g. muons or electrons incident on the crystal), run the simulation but record only ionization energy deposition (“hit”) information.
    a. Hit information: energy deposited, position of deposition, time of deposition.
    b. No ray tracing is done by Geant in this step.
3. Use the hit information, the information from the single photon raytracing, and knowledge of the material properties (scintillation spectrum, yield, decay time) to construct expected distribution of photons arriving at SiPM.
4. Check for consistency with full Geant simulation.

# Single Optical Photon Raytracing

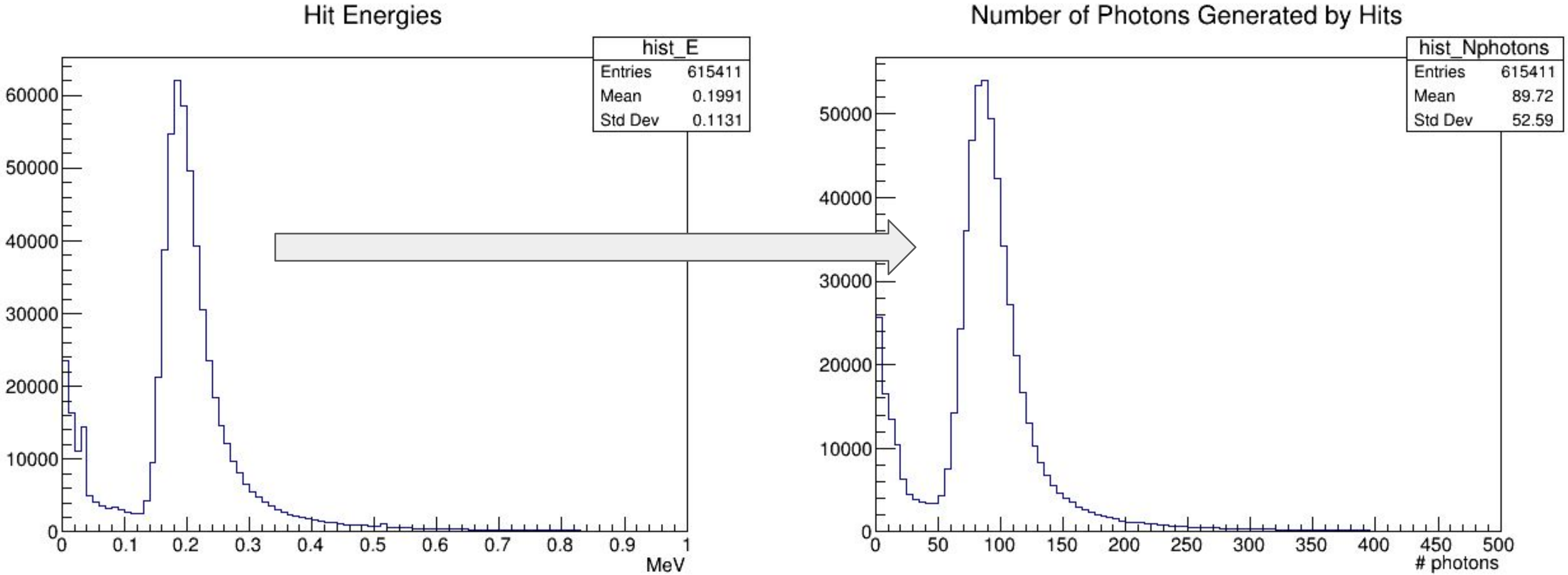


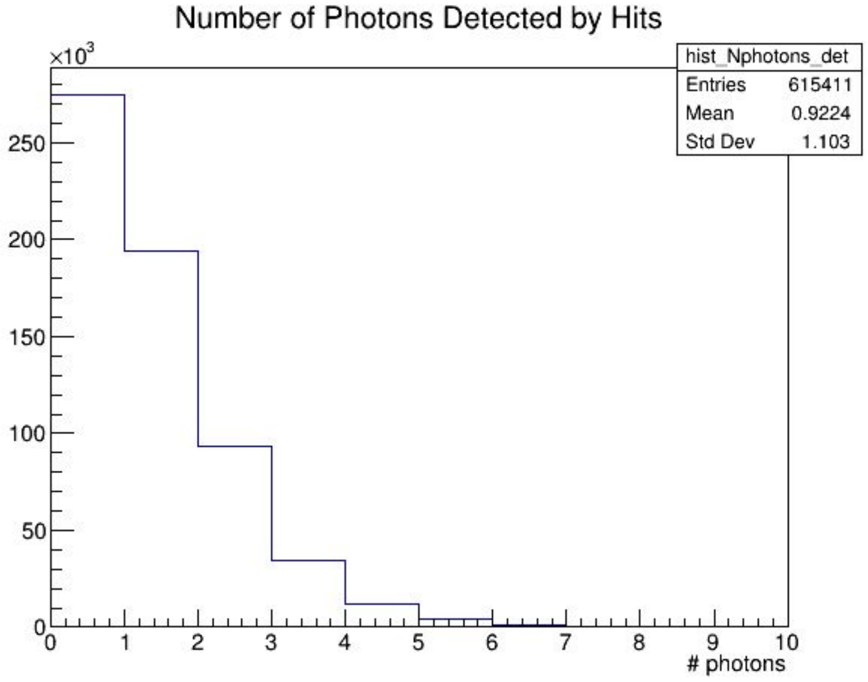

- Generate many (~10 million) optical photons uniformly distributed within the crystal and in wavelength.
- For each wavelength and position bin along crystal, estimate:
  - Fraction detected = probability of detection
  - Normalized distribution of travel times = probability distribution of travel times

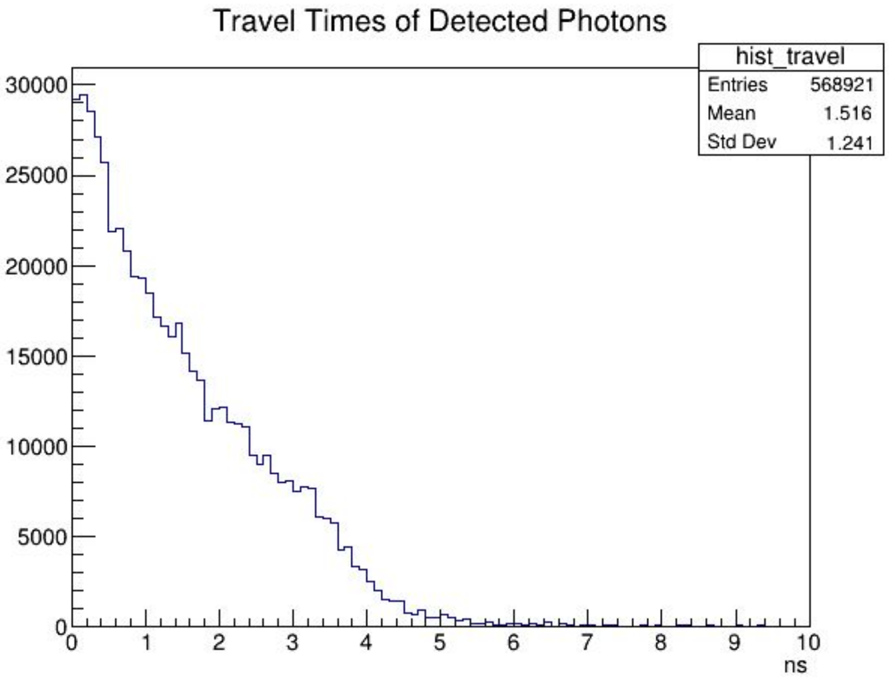
# Converting Geant Hits to Photons




- Assume yield for $PbWO_4$ crystal: 450 photons/MeV with Poisson photostatistics.
- Generated photons are assigned a wavelength randomly according to the scintillation spectrum.

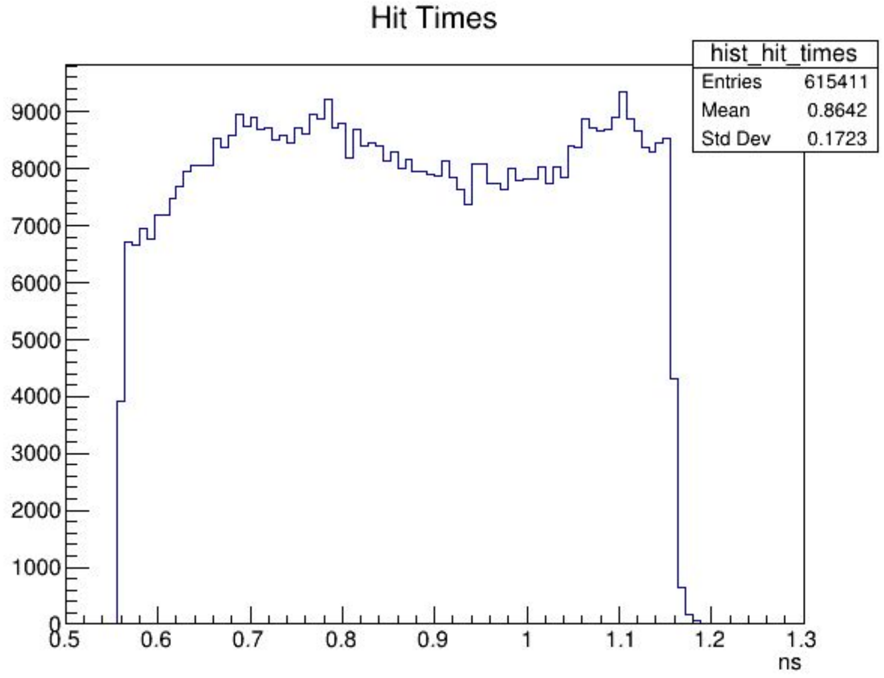
# Detected Photons and Travel Times

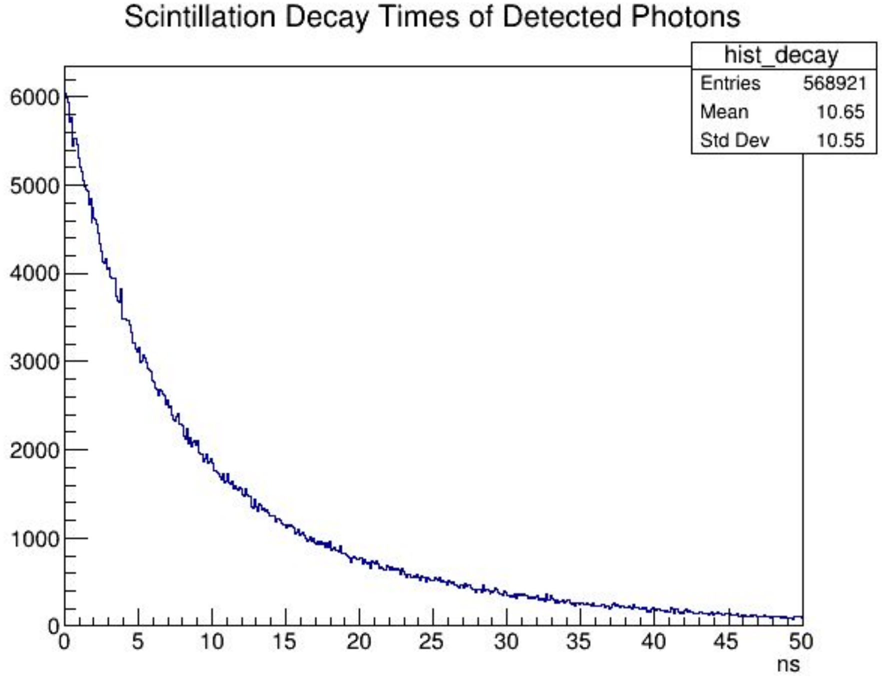



- Using the single optical photon probabilities $P_{det}(\mathbf{x},\lambda)$, randomly decide whether each photon is detected and, if detected, its travel time to the SiPM.

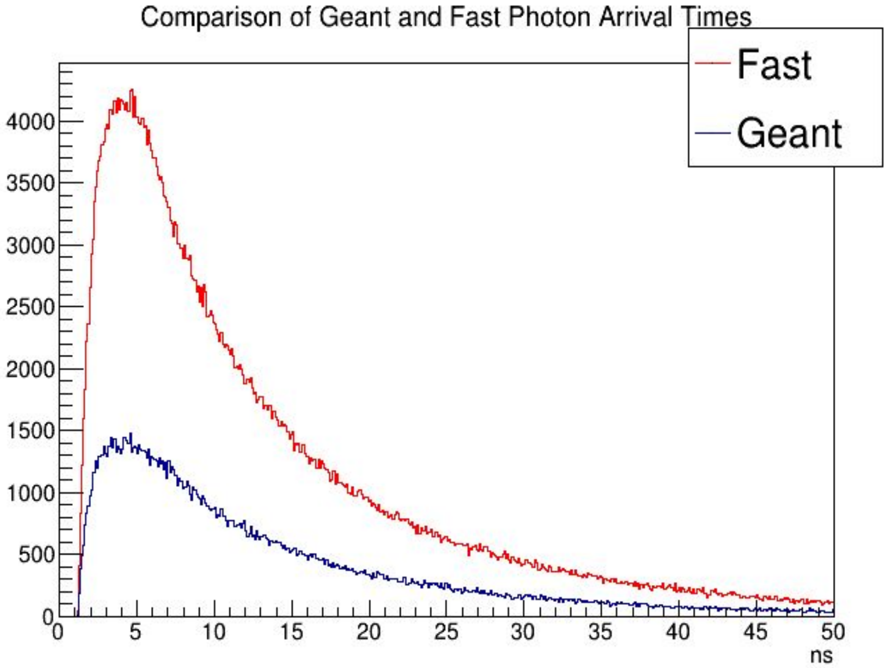
# Adding Hit and Scintillation Decay Times

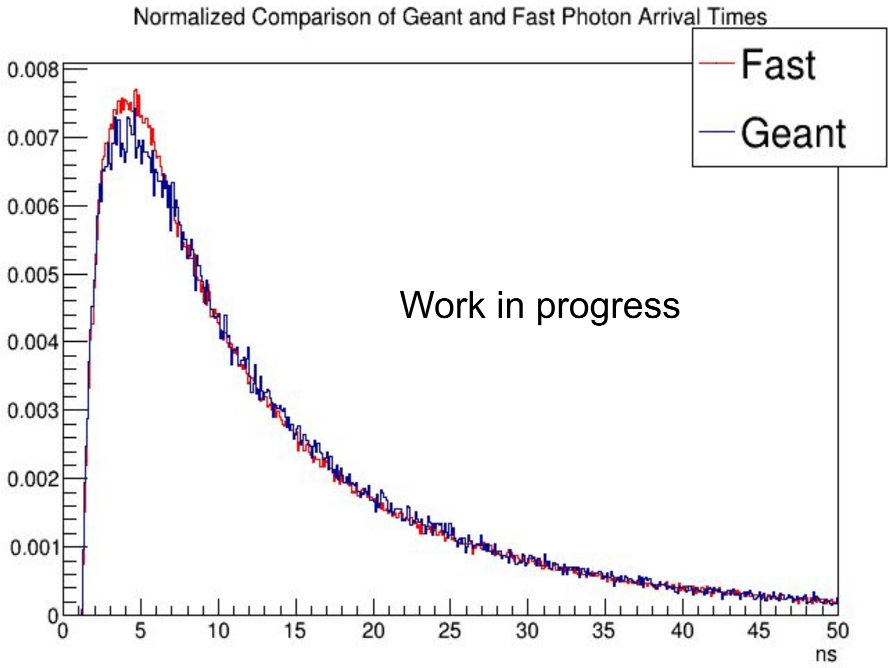



- Account for the hit time, the time at which the energy that produced the photon was deposited.
- Photons are then emitted according to scintillation decay distribution.
- Final photon arrival time = hit time + random scintillation decay time + random travel time

# Preliminary Comparison of Photon Arrival Times




- Shape of the photon arrival time information is well-reproduced.
- Differ by an overall normalization factor of 2.77, likely due to a discrepancy in the geometries used by the fast and full Geant methods that was missed.
- Geometries used by full Geant and fast method must be identical to obtain identical results.

# Method Time Comparison

- Full Geant simulation: 708.9 s per 100 events
- Fast parameterization:
  - 10 million single optical photons: 915 s
  - 10,000 events in “hit only” Geant: 4.5 s
  - Processing of hits into arrival times for 500 events: 30 s
- So for 500 events we need:
  - 59 min in full Geant
  - 15 min 15 s (one-time for single optical photons) plus 30.2 s for each 500 events

# Future Work

- Diagnose and correct difference in Geant and fast parameterization normalizations.
- Test sensitivity of method to cuts on hit energy.
- Test performance of further speedups (eg integrating over all photons in hits).
- New: try to apply method to Cherenkov photons.
  - More challenging due to the fact that these photons are not isotropically produced.
- Parallel work: add GPU accelerated ray tracing, compare computation times for full simulation.
  - Possibly develop a hybrid approach using fast simulation for scintillation and full simulation for cherenkov light where fewer photons are produced.

# Conclusions

- Understanding the properties of optical calorimetry is an important element of detector design in collider and neutrino applications, as well as dark matter searches, and other applications.
- Developing a framework to reliably calibrate and apply fast simulations can be very helpful in detector performance studies.
- Future work in GPU acceleration (eg Opticks, Celeritas frameworks) can also increase the efficiency for detector studies, however some form of fast simulation may continue to be an important tool for performing efficient calculations.

# Acknowledgements

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