Fermilab

SBND Photon Propagation Simulation: Semi-Analytical Model

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SBND
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SBND Photon Model

- I will give an overview of the photon model/library that is used in SBND: the **Semi-Analytical Photon Model**

- this presentation is essentially a summary of the following paper:

Predicting transport effects of scintillation light signals in large-scale liquid argon detectors

  - written by Diego Garcia-Gamez, Patrick Green, and Andrzej Szelc

- this model is used for the photon propagation simulation inside the active volume of SBND, and is also used to generate flash hypotheses for charge-light matching

Semi-Analytical Model: tldr;

- “analytical” → the foundation of the photon transport model, for both # of photons and the arrival times, is based on *geometric (analytical) functions*

- “semi”→ corrections are necessary to account for realistic effects, such as Rayleigh scattering, reflection on detector edges, and more
    - ***corrections are obtained empirically*** by comparing a full optical simulation with Geant4 with the geometric (analytical) functions
    - corrections are always parametrized by:
        1. distance between energy deposition and a photodetector
        2. angle between energy deposition and a photodetector

Generic Model for Photon Propagation

# of photons arriving to a photodetector

$$D_\gamma = \Delta E \times S_\gamma(\mathscr{E}) \times Q \times Q_{det} \times Q_{abs}(d) \times Q_{trans}(\theta) \times P(d,\theta) \times T(d,\theta)$$

- ΔE: energy deposit
- $S_\gamma(\mathscr{E})$: scintillation yield
- Q: quenching
- Q_{det}: detector efficiency
- $Q_{abs}(d)$: absorption loss
- $Q_{trans}(\theta)$: transmission loss
- $P(d,\theta)$: geometric coverage
- $T(d,\theta)$: other transport effects

~# of deposited photons ($\Delta E \times S_\gamma(\mathscr{E}) \times Q$)

~detector/LAr effects ($Q_{det} \times Q_{abs}(d) \times Q_{trans}(\theta)$)

related parameters, more complicated, focus of the paper! ($P(d,\theta) \times T(d,\theta)$)

photon arrival time

$$t_\gamma = t_E + t_t(d,\theta) + t_{WLS} + t_{det}$$

- t_E: emission time
- $t_t(d,\theta)$: **transport time, focus of the paper**
- t_{WLS}: relaxation time due to wavelength-shifter
- t_{det}: detector response

Direct (VUV) Light

- ideal case: # of photons arriving at a photodetector (PD) is purely the geometric acceptance of the PD w.r.t. the scintillation point with absorption effects

absorption — solid angle — # of photons

$$N_\Omega = e^{-\frac{d}{\lambda_{abs}}} \Delta E \cdot S_\gamma(\mathscr{E}) \frac{\Omega}{4\pi}$$

- corrections are needed to this ideal geometric case due to:

  1. Rayleigh scattering aka photon scattering → corrected by Gaisser-Hillas (GH) functions, which happen to accurately describe the distributions

  2. detector edge effects → linear corrections to the GH functions

- the form and parameters of the corrections are obtained by empirically comparing the photon model to a full Geant4 optical simulation

Reflected (VIS) Light

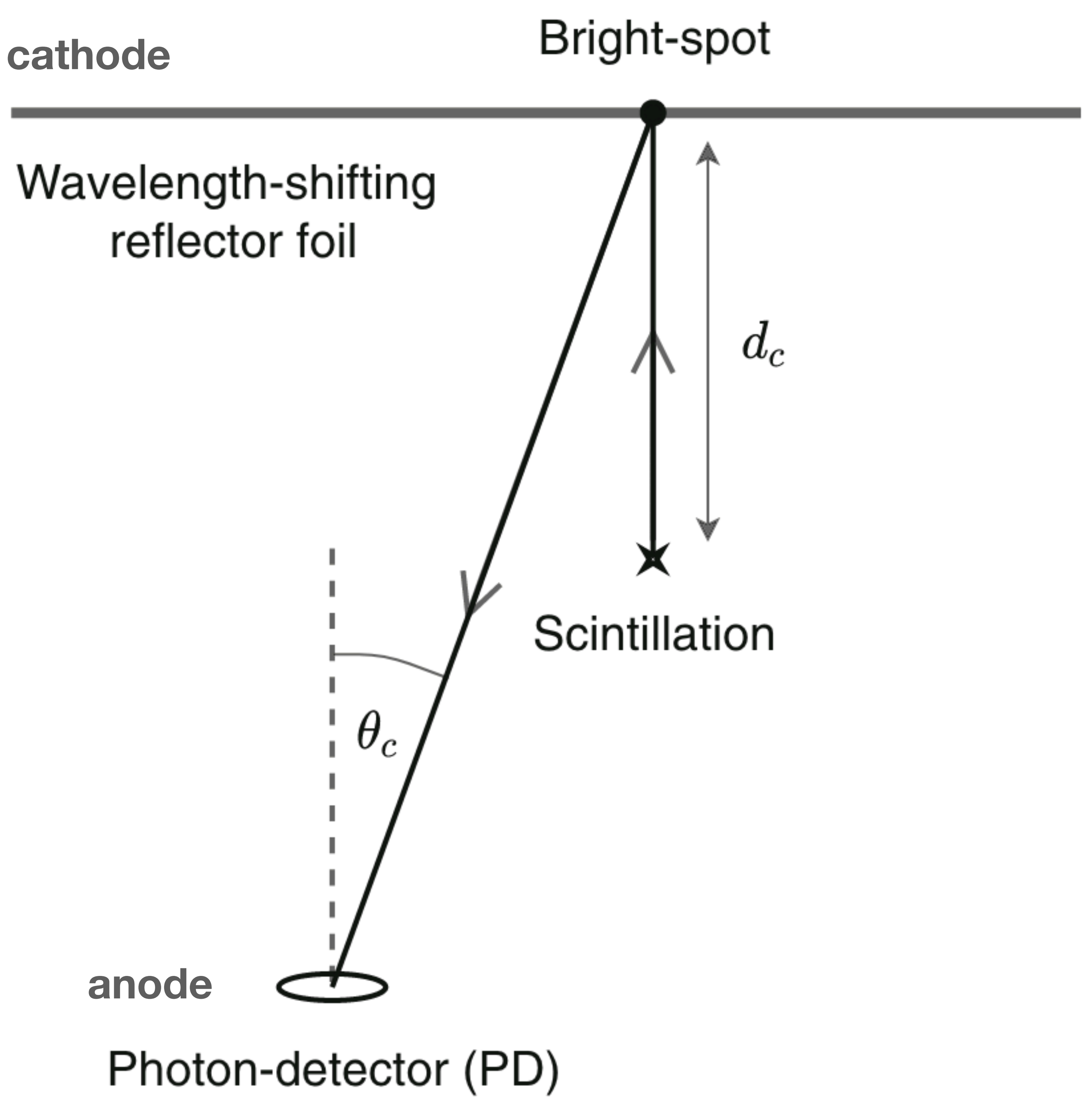

Fig. 8 Diagram illustrating the geometric model for predicting the number of photons incident on the PDs as a result of wavelength-shifting reflector foils on the detector cathode and predicting the arrival time distribution of these photons on the PDs

- in this case, reflected light means **light that was re-emitted/reflected by the cathode,** which is covered WLS-coated reflector foils (wavelength shifter)
- photons are re-emitted ~isotropically, so the source of photons is approximately the “bright-spot” on the cathode … + corrections
  - # of reflected photons purely from geometry:

WLS eff.

$$N_{\Omega,reflected} = N_{\gamma,direct} \times Q_r \times \frac{\Omega_{PD}}{2\pi}$$

# of VUV photons incident on the **cathode**

solid angle

Reflected (VIS) Light + Corrections

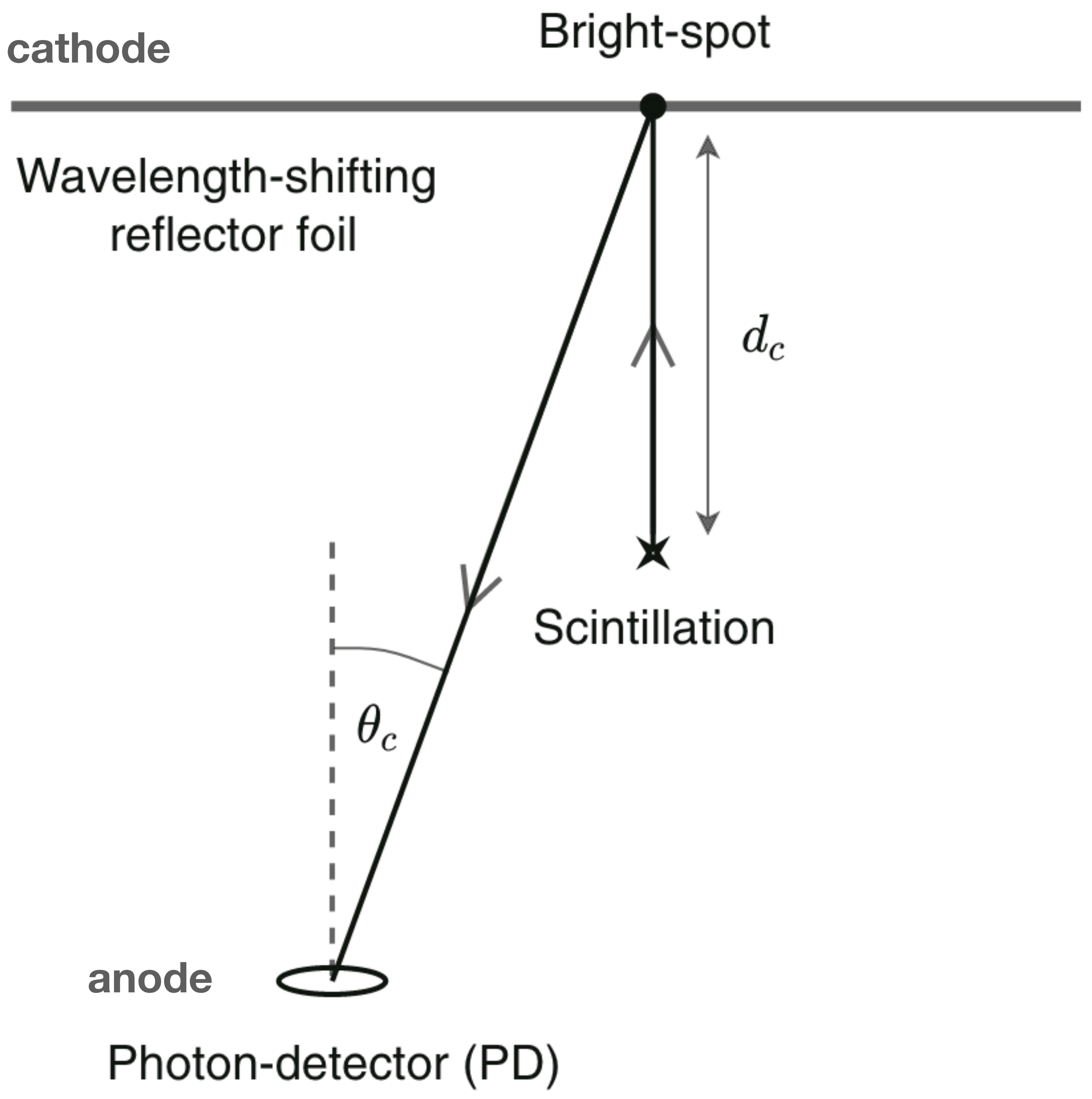

Fig. 8 Diagram illustrating the geometric model for predicting the number of photons incident on the PDs as a result of wavelength-shifting reflector foils on the detector cathode and predicting the arrival time distribution of these photons on the PDs

1. additional geometric corrections (PD position)
2. detector edge effects
   - VIS photons have slightly different effects (reflection vs. absorption on detector walls) compared to VUV

- all corrections are dependent on d_c and θ_c, obtained from comparing N_{G4} (from simulation) vs. N_Ω (geometric)

Photon Arrival Time: Direct (VUV) light

- generically, there will be a prompt component followed by a diffuse tail
  - prompt: earliest photons that arrive
  - tail: photons w/ other transport effects (reflection, re-emission for VIS, scattering)
- direct (VUV) parametrization: empirically determined to be approximately a Landau function (prompt) combined with an exponential function (tail) functions

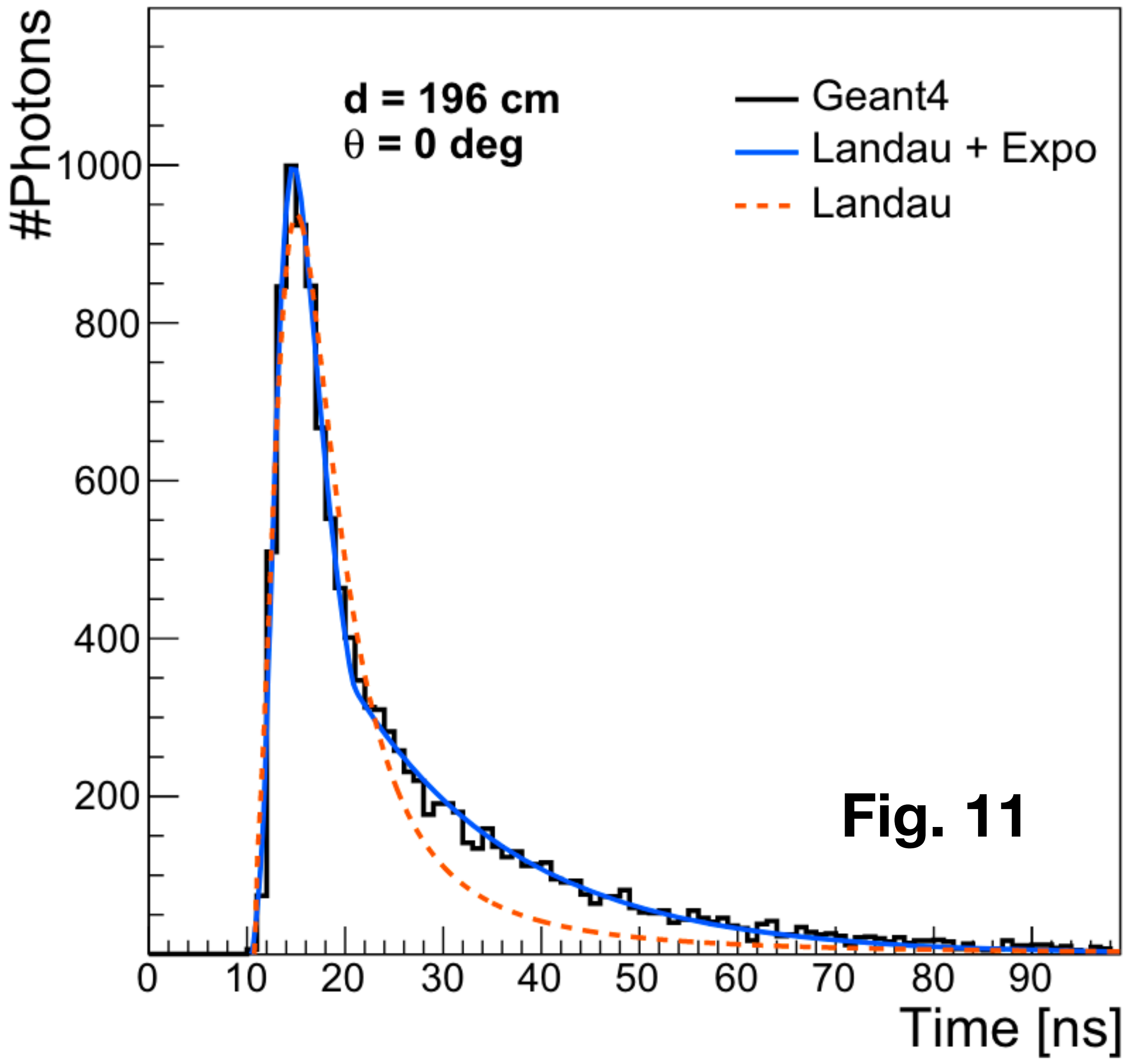

Fig. 11

$$t_t(x) = N_1 \frac{1}{\xi} \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} e^{\lambda s + s \log s} ds + N_2 e^{\kappa x}$$

Landau **exponential**

Photon Arrival Time: Reflected (VIS) light

- reflected (VIS) light time parametrization
  - detector walls are highly reflective for visible photons
  - a smearing factor is implemented to account for the broader distribution of photons arriving later

unsmeared arrival time

smearing factor

$$t_s = t + (t - t_f) \cdot [e^{-\tau \ln(x)} - 1]$$

smeared arrival time

fastest arrival time

Implementation in Charge-Light Matching

```
void PhotonLibHypothesis::FillEstimateSemiAnalytical(const QCluster_t& trk, Flash_t &flash) const
{
  for ( size_t ipt = 0; ipt < trk.size(); ++ipt) {

    /// Get the 3D point in space from where photons should be propagated
    auto const& pt = trk[ipt];

    geo::Point_t const xyz = {pt.x, pt.y, pt.z};

    double n_original_photons = pt.q;

    std::vector<double> direct_visibilities;
    _semi_model->detectedDirectVisibilities(direct_visibilities, xyz);

    std::vector<double> reflected_visibilities;
    _semi_model->detectedReflectedVisibilities(reflected_visibilities, xyz);

    //
    // Fill Estimate with Direct light
    //
    for (size_t op_det=0; op_det<direct_visibilities.size(); ++op_det) {

      const double visibility = direct_visibilities[op_det];
      double q = n_original_photons * visibility * _global_qe * _qe_v[op_det];

      if (trk.tpc_mask_v.at(op_det) == 0)
        flash.pe_v[op_det] += q;
      else
        flash.pe_v[op_det] = 0.;
    }
```

SBND light hypothesis generation: code link

- for charge-light matching, the arrival times are not too important, but the # of predicted/measured photons is!
- the model returns a *visibility map* depending on a geometric position

$$N_{\gamma,PD} = N_\gamma \cdot \text{vis} \cdot Q_{eff}$$

Summary

- I gave an overview of the photon propagation model used in SBND
- the paper covers model validation and performance for SBND-like and DUNE-like detector geometries
- Diego has confirmed that it is possible to make the code for the photon model standalone (separate from LArSoft implementation, thanks Ewerton!)
- I can also answer questions about flash-matching in SBND, which uses a similar methodology to WireCell charge-light matching