Semi-analytical light simulation in DUNE

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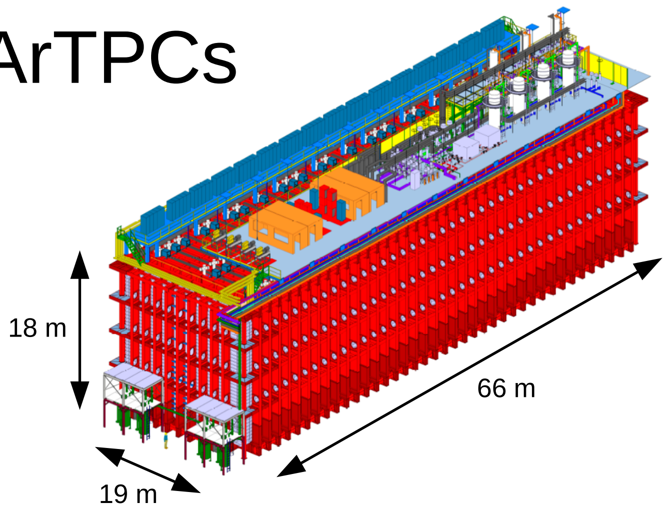
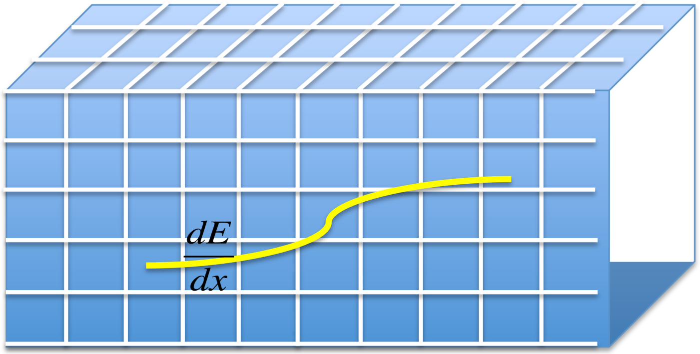
Optical simulation in LArTPCs

- LAr scintillation: ~24000 VUV photons/MeV @ E = 500 V/cm
- Geant4 tracking of individual photons prohibitively slow:
  - high energy beam neutrino interactions: O(1 GeV)
  - large detector volumes: O(100t) –> O(10kt)
- Simplified approaches to light simulation required for high statistics MC sample generation:
  - sacrifice some accuracy, but gain speed
- Past approach was to use optical libraries:
  - look-up table of photo-detector “visibilities”
  - fast, but memory intensive and scales very poorly: not viable for DUNE, requires >> 10GB memory to load
  - predicts only number of photons, not when they arrive





$$\langle N \rangle_{PMT-hits} = \left(\frac{dE}{dx}_{step} \cdot Length_{step} \right) \cdot LY \cdot visibility_{step}^{PMT}$$

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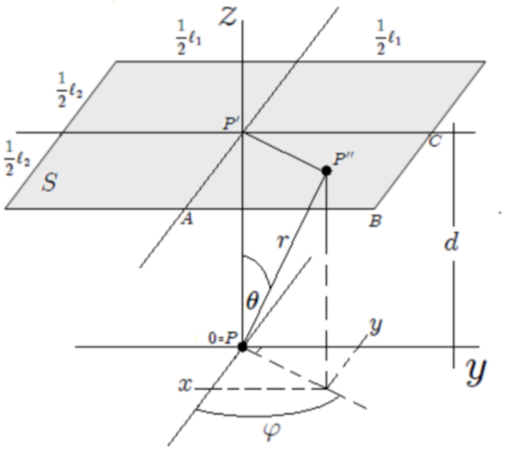
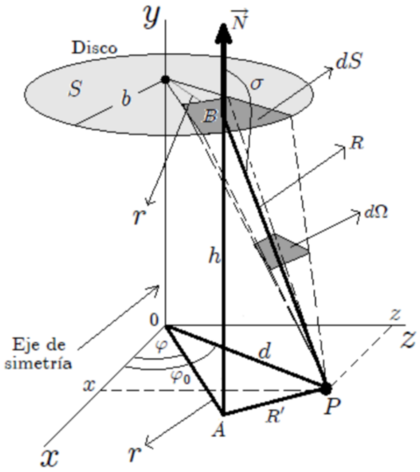
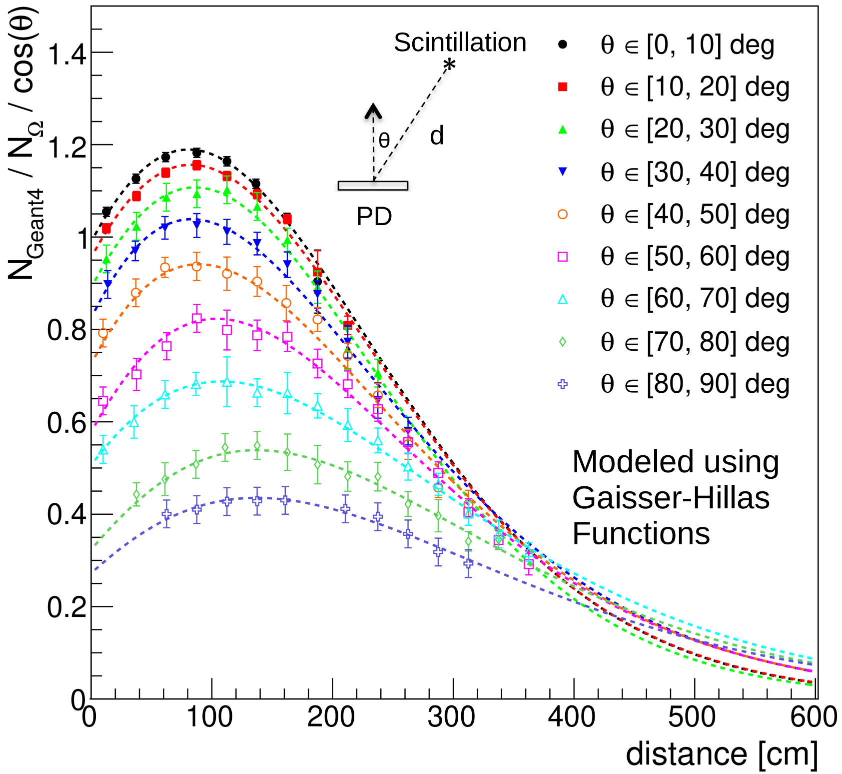
Semi-analytical model

Semi-analytical model consists of two steps:

1) Geometric prediction of number of incident photons
2) Parameterized corrections accounting for propagation effects (Rayleigh scattering)



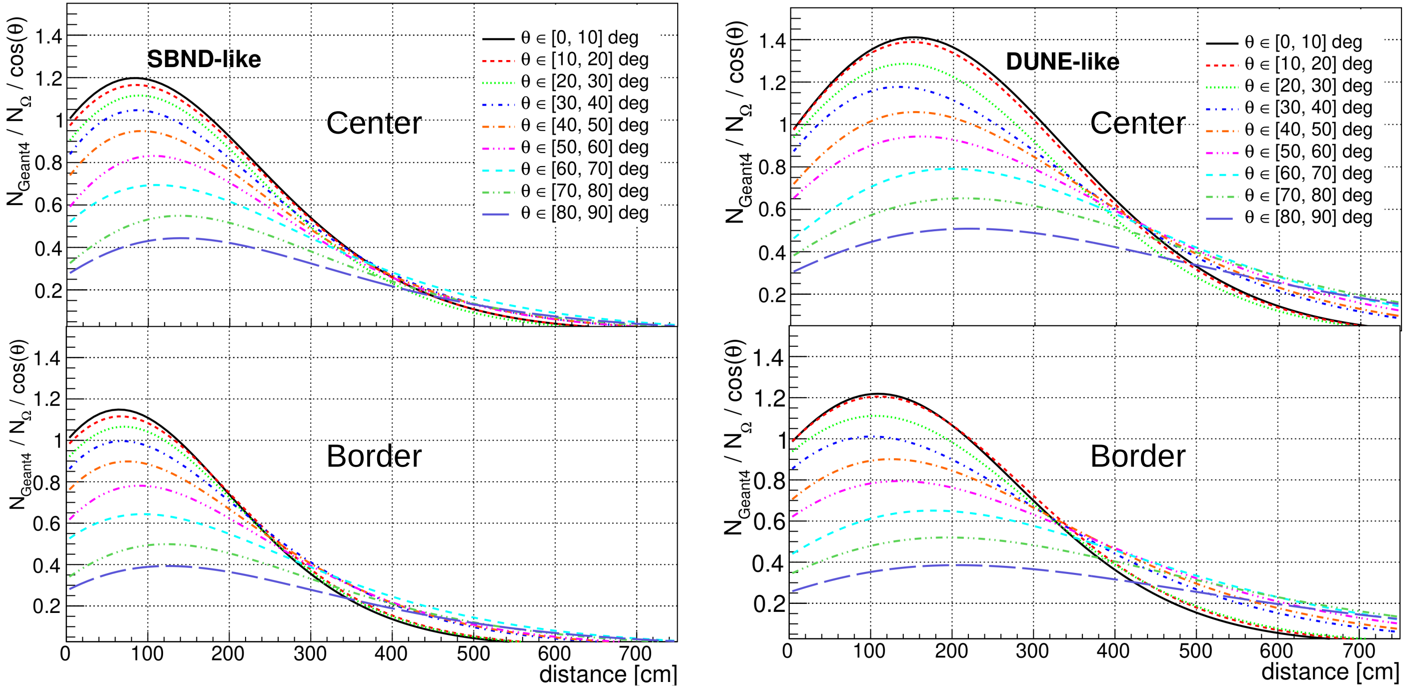




Accounting for boundary effects

Need to account for finite size of realistic detectors:

- size of liquid argon volume affects impact from Rayleigh scattering + walls of detector can absorb/reflect light



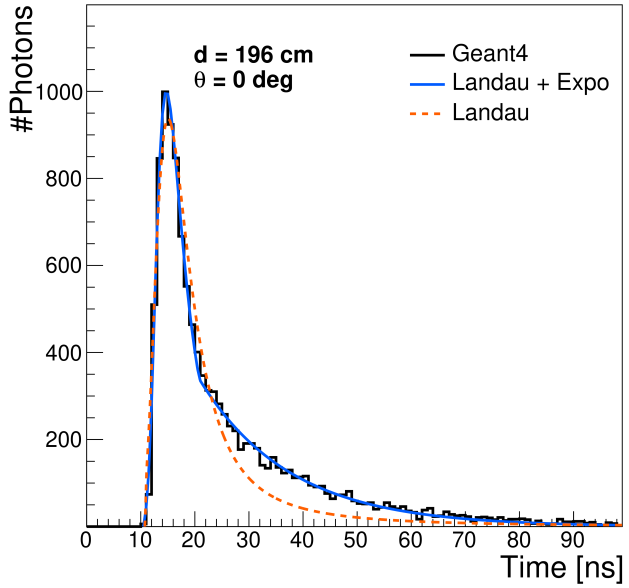
Corrections are trained for each detector geometry/size

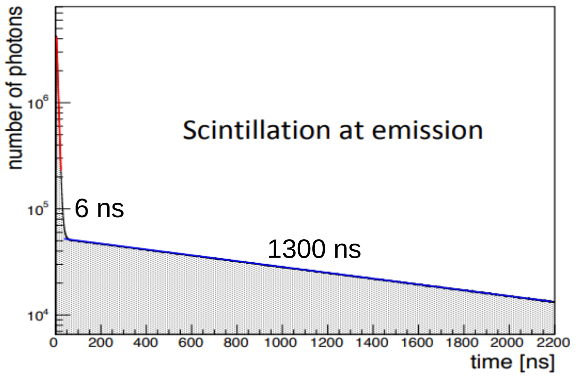
Impact of detector walls:

- modeled by adjusting parameters of Gaisser-Hillas functions
- very simple model: linear variation as function of distance from the center

Photon transport time

- Detection time of photons smeared due to transport effects:
  - direct propagation time + Rayleigh scattering
- Transport time model:
  1) geometric prediction of direct propagation time
  2) Landau+Exponential parameterisation of transport time distributions





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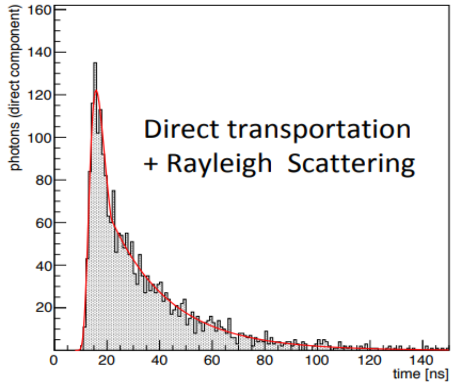

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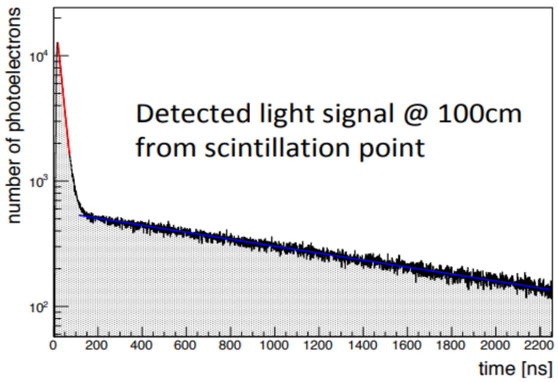
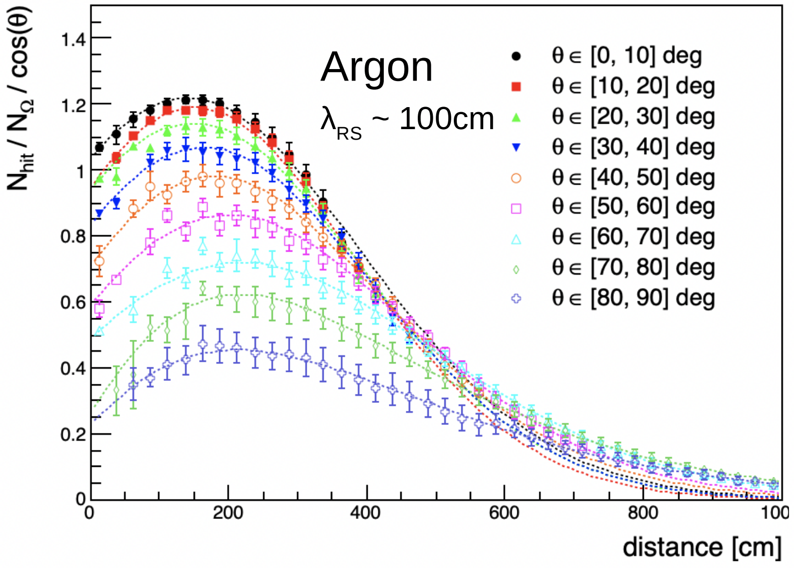
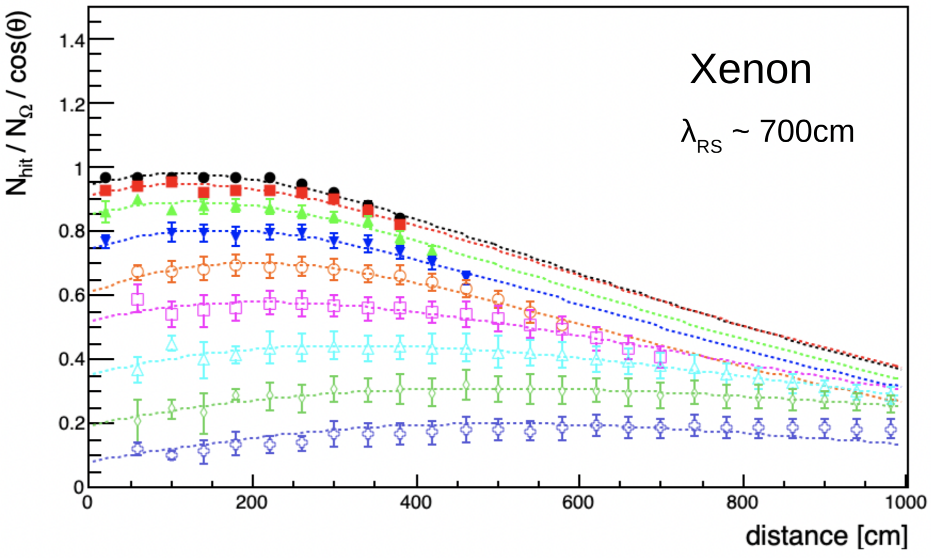


Xenon / xenon-doped argon

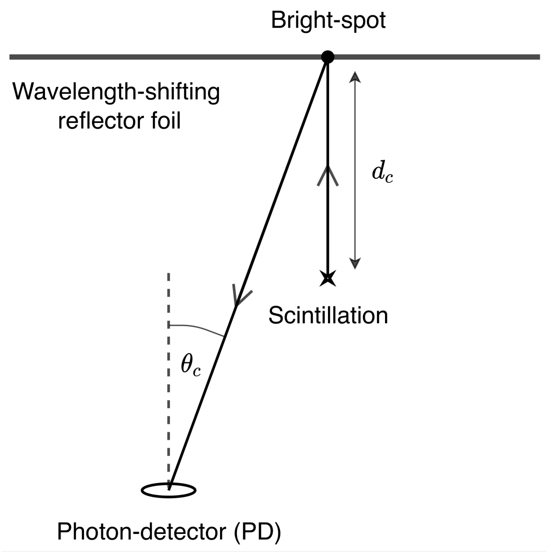
- Xenon wavelength scintillation can be modeled using same approach:
  - λ_{RS} ~700 cm (c.f. ~100 cm in Argon) –> smaller corrections from geometric prediction required
- Xenon-doped argon can be modeled using mixture of the argon and xenon cases

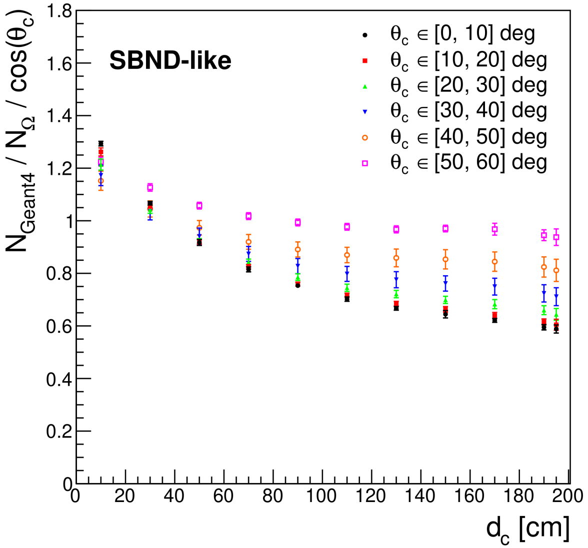


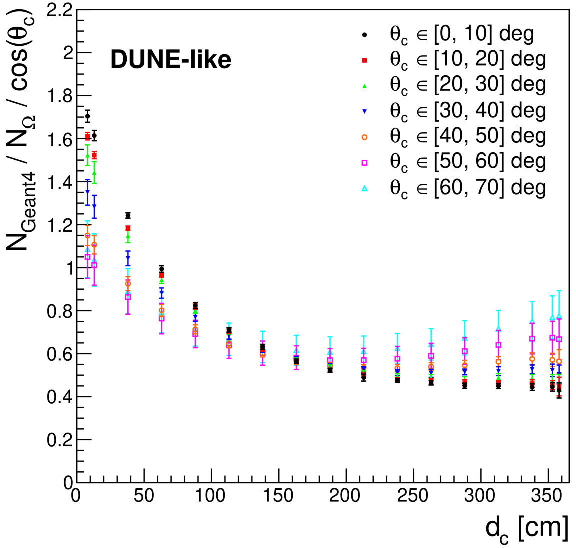


Wavelength-shifting reflective foils

- Can also model light reflected by TPB/PEN coated wavelength-shifting reflective foils:
  - located on the cathode of detector to boost light yield uniformity, e.g. in SBND
- Same approach used to model reflections from anode for xenon-doped light in DUNE-VD

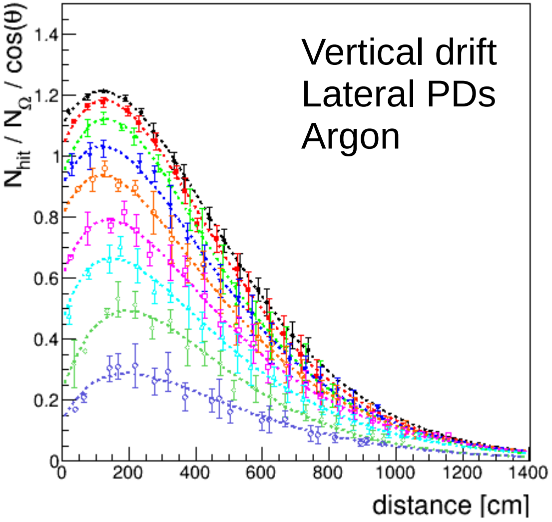


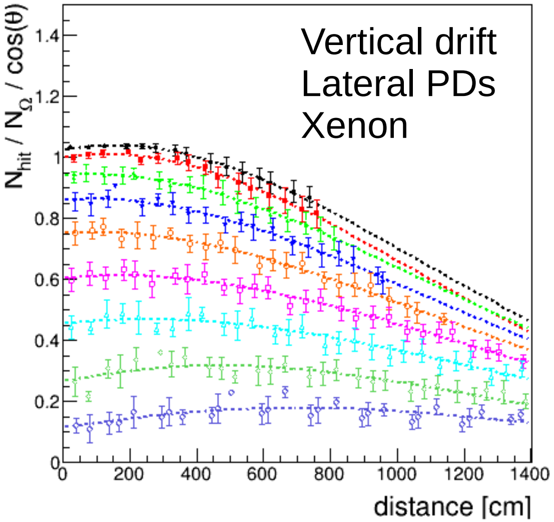




Applying to DUNE

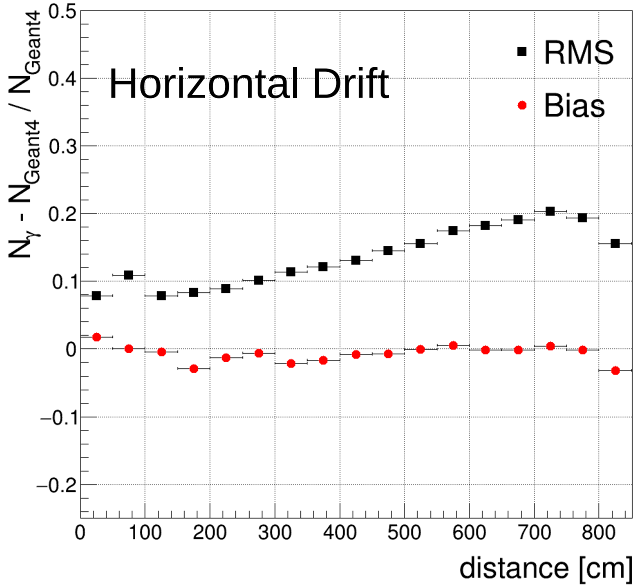
- Standard approach used to simulate the light for both DUNE far detector designs:
  - argon and xenon-doped argon modeled in both cases
- DUNE horizontal drift:
  - position and angle dependent wire-shadowing
  - wavelength shifting reflective foils (optional)
- DUNE vertical drift:
  - cathode and lateral photo-detector specific parameters
  - field cage-shadowing
  - reflections from anode (xenon wavelength)

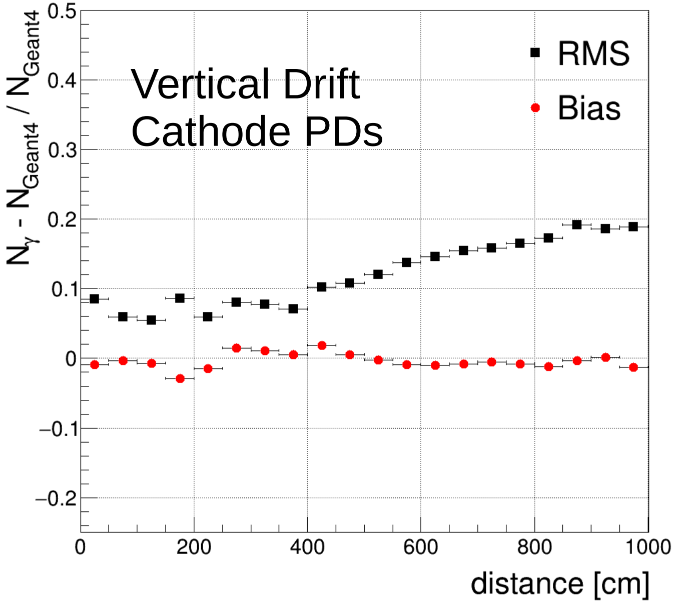


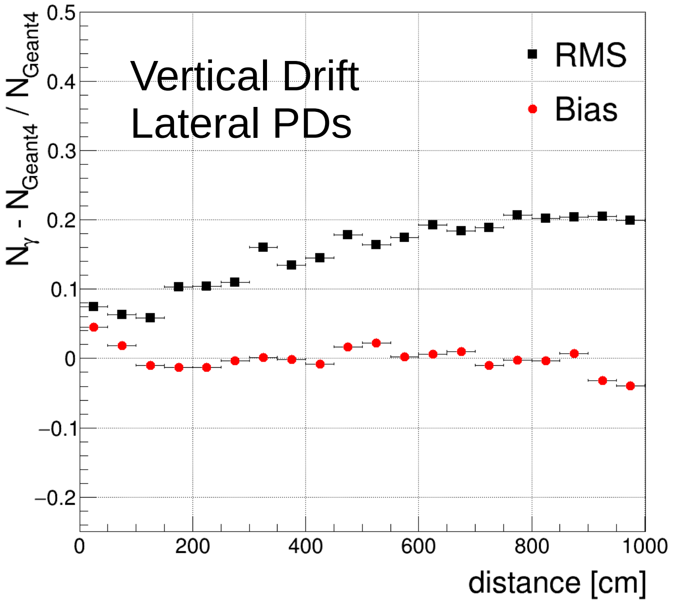


Performance in DUNE: Argon

- Model performs well in both detectors: minimal bias, resolution 10-20% depending on distance
- Computational performance: ~50-100x faster than Geant4, negligible memory footprint

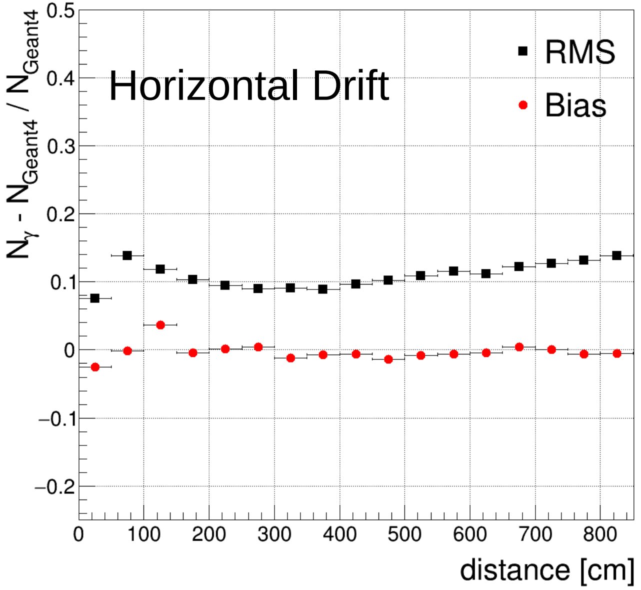


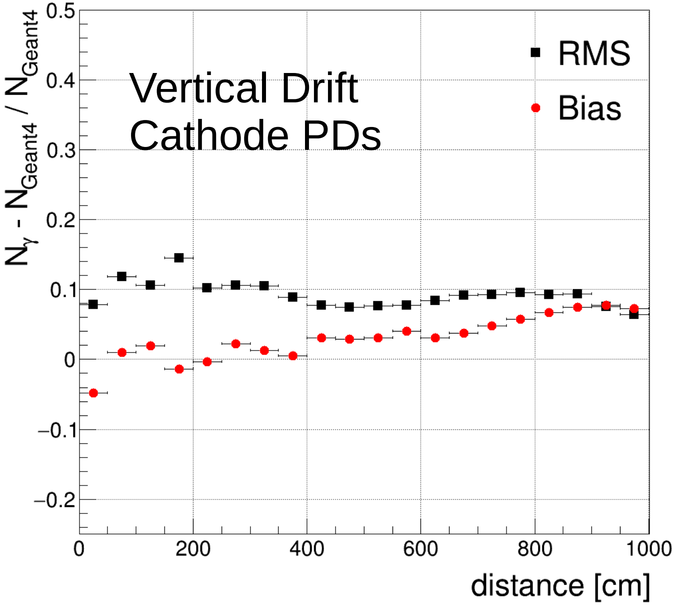


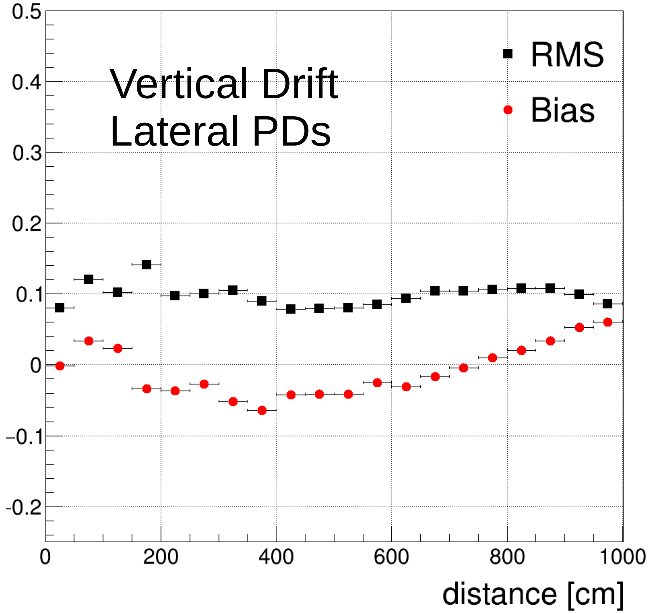


Performance in DUNE: Xenon

- Model performs well in both detectors: minimal bias, resolution ~10%
- Slightly worse bias in vertical drift case, future development will aim to address this







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Conclusions

- Semi-analytical model developed for light simulation in liquid argon detectors
  - predicts number of photons and photon arrival time distribution
  - ~50-100x faster than Geant4 simulation
  - minimal memory footprint –> able to scale to size of DUNE without issues
- Default optical simulation approach used in DUNE horizontal and vertical drift detectors
  - also standard approach used in SBND, and in development for MicroBooNE
- The development of this model and its application to DUNE has been a predominantly UK-led effort
- Further details available at:
  - Garcia-Gamez, D., Green, P. & Szelc, A.M. Predicting transport effects of scintillation light signals in large-scale liquid argon detectors. Eur. Phys. J. C 81, 349 (2021).

Back-up

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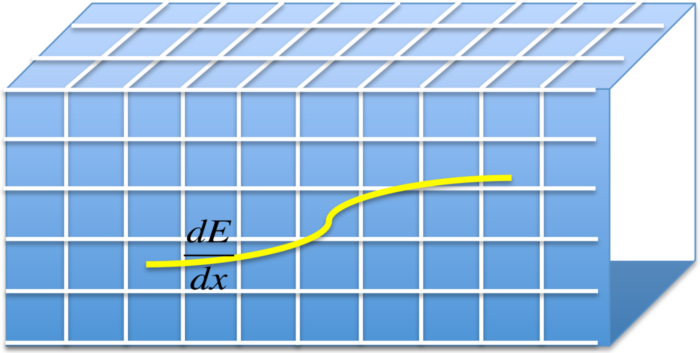
Optical look-up library approach

- Build look-up table for light simulation:
  - detector divided into voxels ~5-10 cm^3, each simulated in Geant4
  - probability photons from each voxel reach each photo-detector saved in table
- Fast, but memory intensive:
  - scales poorly with detector size and number of photo-detectors
  - impractical for larger detectors such as DUNE
- Only predicts number of photons:
  - not their propagation time

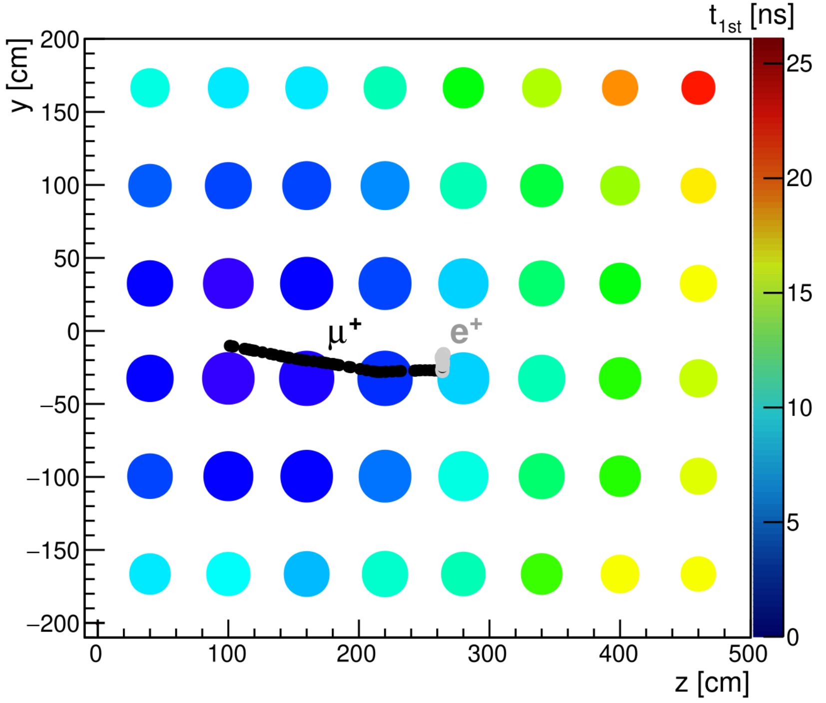


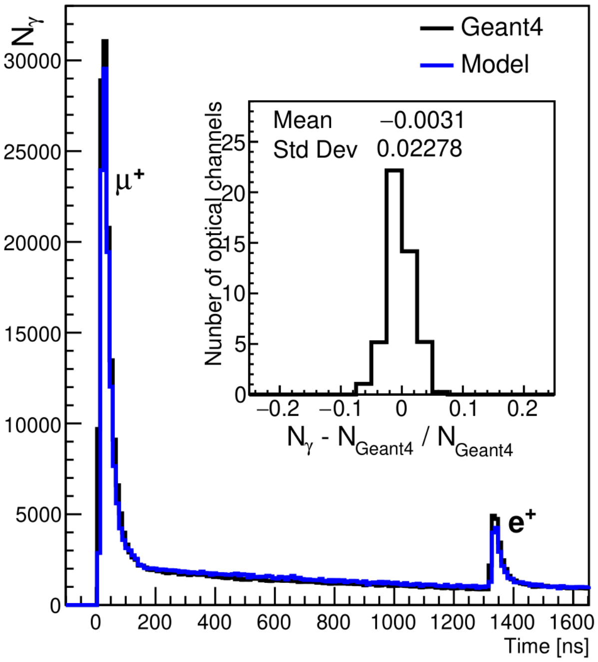
$$\langle N \rangle_{PMT-hits} = \left(\frac{dE}{dx}_{step} \cdot Length_{step} \right) \cdot LY \cdot visibility_{step}^{PMT}$$

Detector	LAr Volume	Number PDs	Loading Memory
MicroBooNE	170t	32	~ 100 MB
SBND	112t	320	~ 1 GB
DUNE	10kt / module	O(1000s)	>> 10 GB

Applying to a realistic event

- Realistic events can be simulated using same paradigm as Geant4:
  - interaction divided into ~point-like segments, each simulated separately then combined



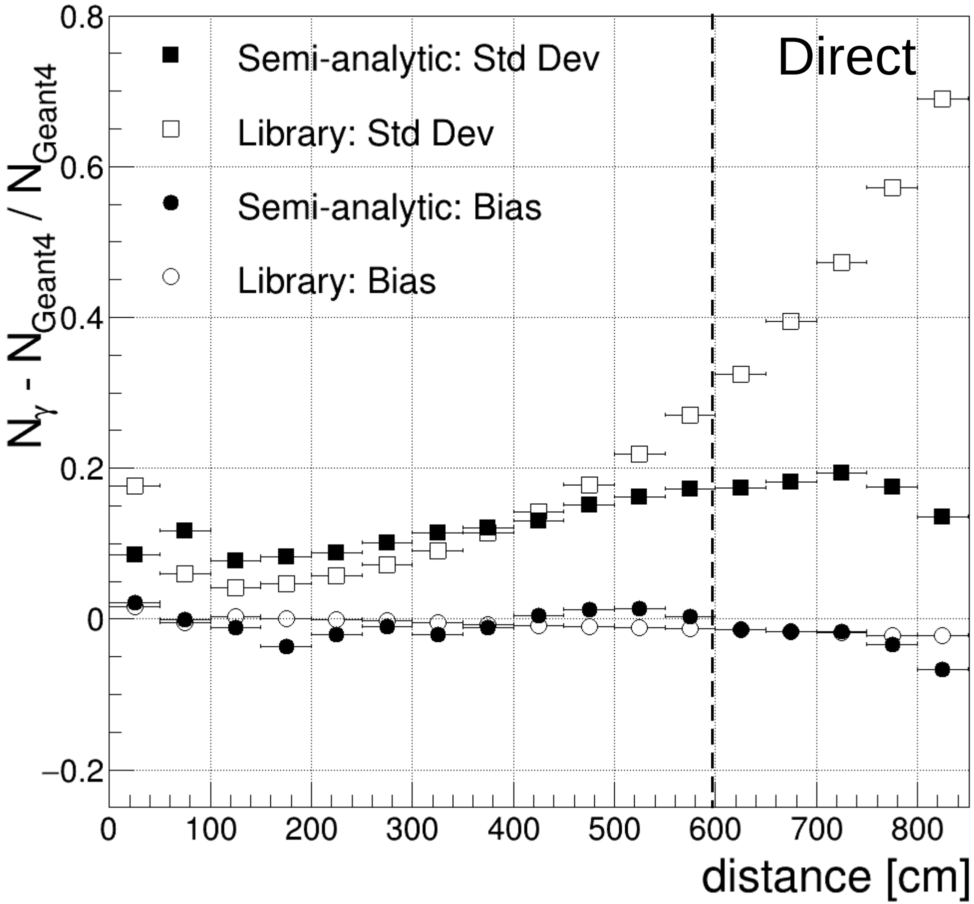


Library performance comparison

- New DUNE-SP 1x2x6 optical library generated [Diego Garcia-Gamez]:
  - 5x5x11 cm voxels
  - 500k photons / voxel
  - latest geometry with 480 optical channels (and incl. wires)
  - latest LAr properties - RS = 100 cm @ 128 nm
- Extremely slow to generate (Geant4):
  - ~3-4 weeks, compared with ~2-3 days for semi-analytic model
- Huge memory requirement to load in conventional manner:
  - ~12GB
  - 4 times larger than previous full resolution library that took ~3GB - 480 optical detectors compared with 120 (bars)

Library performance comparison

- Each method compared against full optical simulation in Geant4, 100M photons / point
- Library performance comparison:
  - worse very close to optical detectors – finite size of voxels
  - slightly better at medium distances, up to ~ drift length
  - much worse at large distances
- Severely under-sampled at large distances:
  - less than 10 incident photons used to make prediction above ~600 cm
  - using fewer photons makes this worse



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Outside of the field-cage - hybrid approach

- Regions outside of the field cage much more difficult to model geometrically:
  - more complex, larger impact of borders
  - impact of light from these regions can be non-negligible
- Model using hybrid approach:
  - semi-analytical model applied in active volume (bulk of detector)
  - slimmed down optical library used externally
  - proposed by Chris Backhouse
- Allows simulation of entire argon volume, while greatly reducing the memory impact of the library