EIC-Opticks – Integration of the Opticks framework into Geant4 simulation of optical photons on GPU

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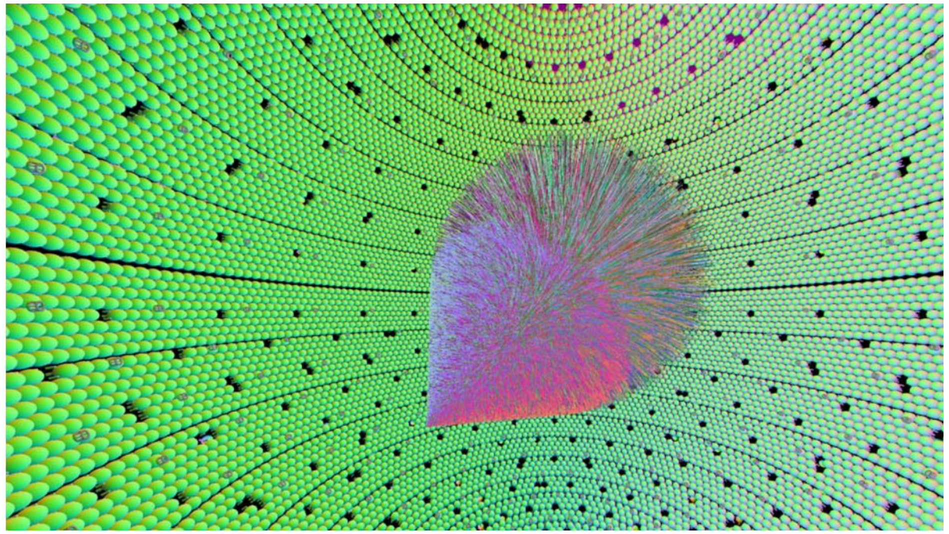
Simulation WG meeting

Outline

- Introduction to Opticks and EIC-Opticks
- Optical photons often dominate simulation time; GPU ray tracing (OptiX) can simulate O(10^7) photons/s
- What was added in EIC-Opticks (new features, dd4hep integration)
- Validation of Opticks and EIC-Opticks and performance quantification
- Potential usage in ePIC (and beyond)
- Limitations: NVIDIA only backend, limited geometry primitives
- Plans: Implement more physics and additional shapes (e.g. trapezoids), support G4Tasking and multi-GPU use

Opticks[1]

- Developed by Simon Blyth for the JUNO experiment
- Uses NVIDIA's OptiX[2] ray tracing engine to implement optical photon propagation on GPUs in Geant4 -> simulate 10^7 photons in 1 second
- Geometries:
  - Opticks can import 10 "primitives" (eg. box, sphere, torus…) either from GDML or Geant4 automatically



Photons simulated @ JUNO with Opticks[1] from 200 GeV muon (~10^7 photons)

[1] Opticks: GPU Optical Photon Simulation via NVIDIA OptiX EPJ Web of Conferences 295, 11014 (2024)

[2] https://developer.nvidia.com/rtx/ray-tracing/optix

Opticks

- Opticks is used by: JUNO, NEXT-CRAB0, LHCb RICH 1, VPG4
  - Initiatives in: LZ, MOLLER, AMoRE, nEXO, KM3NeT, DUNE experiments
  - Existing official G4 example using Opticks: CaTS
- Physical processes ported from G4 to GPU code:
  - Bulk absorption
  - Bulk reemission
  - Rayleigh scattering
  - Mie scattering
  - Surface processes (eg. absorption, diffuse, specular reflection…)
  - Photon wave effects: transfer matrix method
  - (Missing: wavelength shifting)

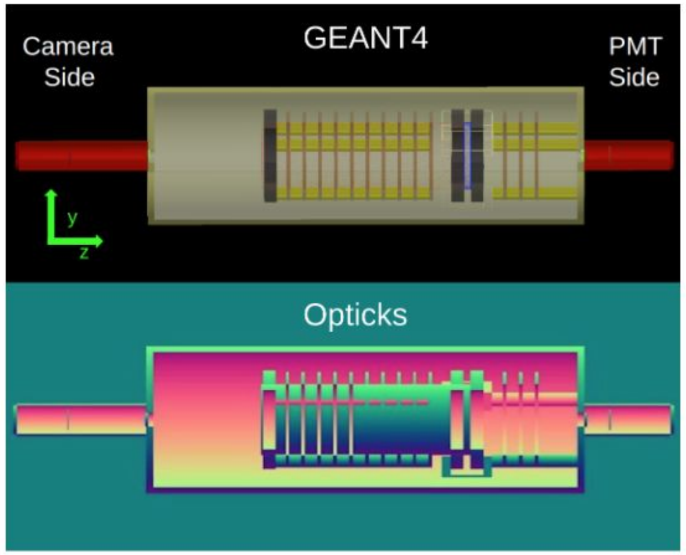
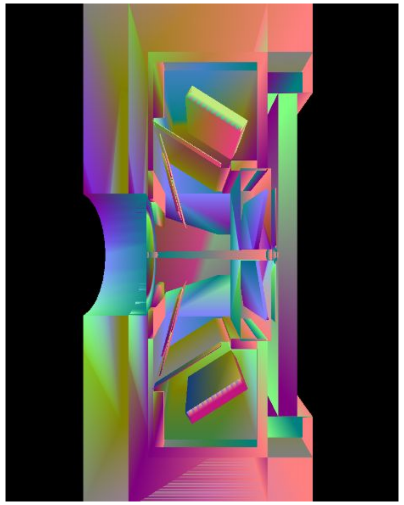


Fig. 3 Geometry rendering of `NEXT-CRAB-0` in `Opticks` and `Geant4`. The z direction points along the drift axis (with $z = 0$ closest to the electroluminescence region), while the x and y coordinates are perpendicular to this.

NEXT Collaboration. Eur. Phys. J. C 85, 910 (2025)



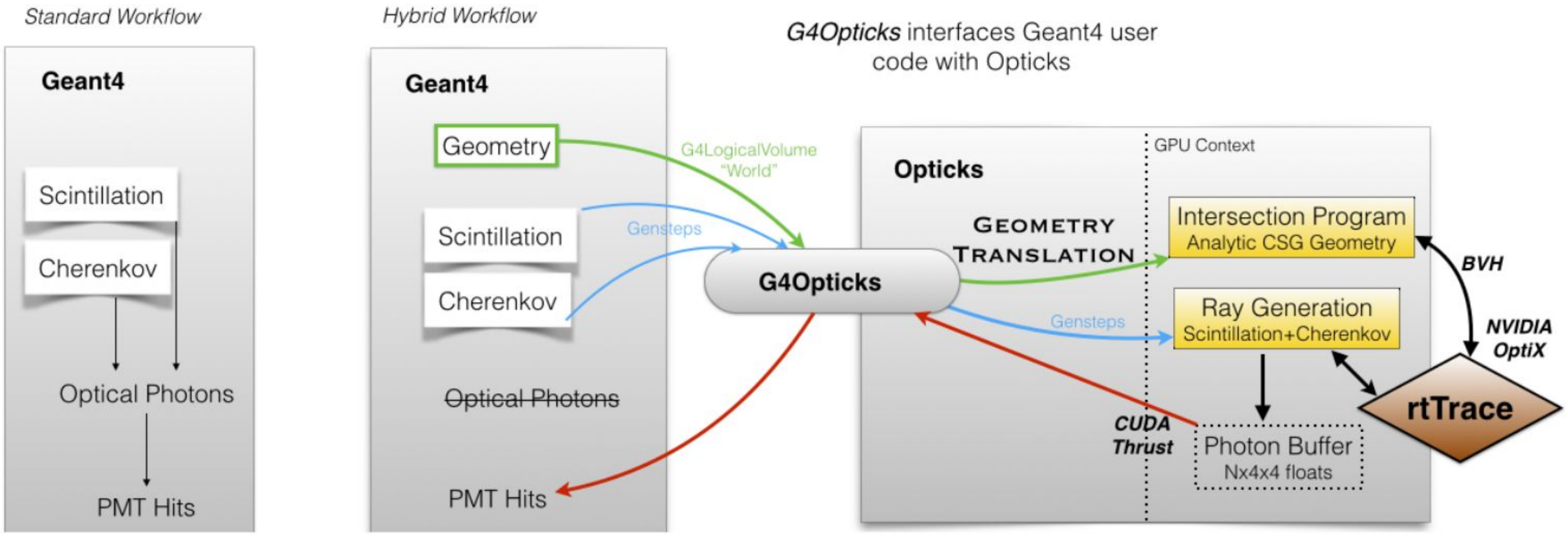
Yunlong Li et al.: GPU-based optical photon simulation for the LHCb RICH 1 Detector

Opticks video of Daya Bay and JUNO

- NVIDIA Optix was designed for visualization
- Can visualize detectors too!
- Example:
  https://www.youtube.com/watch?v=CBpOha4RzIs

Architecture

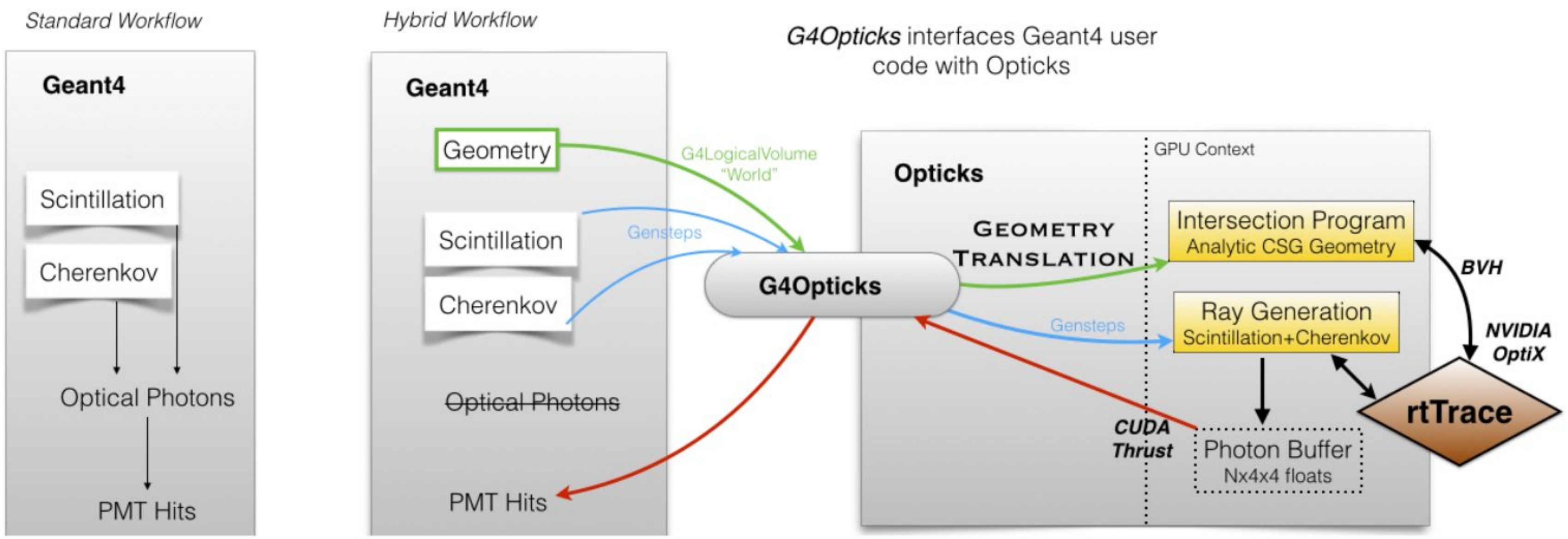
- EM, Hadronic done in Geant4 with CPU
  - For Cherenkov/scintillation, Geant4 calls G4Opticks API instead of creating photons
- G4Opticks records production distributions (position, direction, polarization, Nγ, event ID, …)
- EIC-Opticks uses these records to generate and propagate photons on the GPU with NVIDIA OptiX
- Hits are sent back through G4opticks and the user can do whatever they want -> DD4Hep, ROOT…
- Geant4 and EIC-Opticks share the same geometry and optical properties → same physics, much faster optical part



Simon Blyth, EPJ Web of Conferences 245, 11003 (2020)

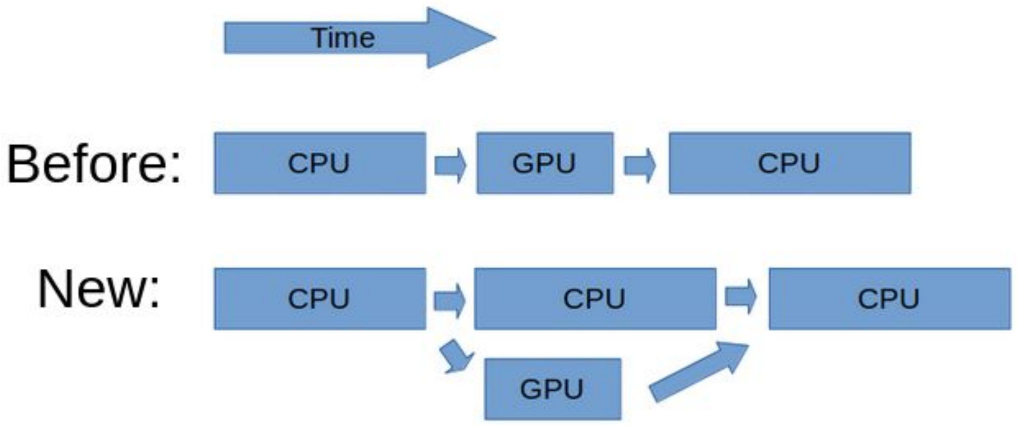
API/integration snippet

- Standalone example: esi-g4ox: https://github.com/BNLNPPS/esi-g4ox/tree/PerformanceAnalysis
- In **G4DetectorConstruction** call **G4CXOpticks::SetWorld()** transforms geometry into CSG (Constructive Solid Geometry) and then BVH (Bounding Volume Hierarchy) for NVIDIA
- In **G4SteppingAction** call **U4::CollectGenstep_G4Cerenkov_modified()** and pass Cerenkov distribution parameters (similar for scintillation)
- In G4RunAction or G4EventAction call
  - **G4CXOpticks->simulate()** runs the GPU ray tracing
  - **SEvt::Get_EGPU()->getHit()** returns the hits from GPU



EIC-Opticks

- EIC-Opticks[1]: fork of Opticks
- Modifications:
  - Opticks can only simulate one G4Event in a GPU simulation
    - Very large overhead when simulating less than 1M photons in a GPU call
  - EIC-Opticks extended usability to cases with much fewer photons (as in most EIC applications)
    - Added G4Event ID to GPU simulated photons
  - Asynchronous CPU, GPU launches



[1] github.com/BNLNPPS/eic-opticks

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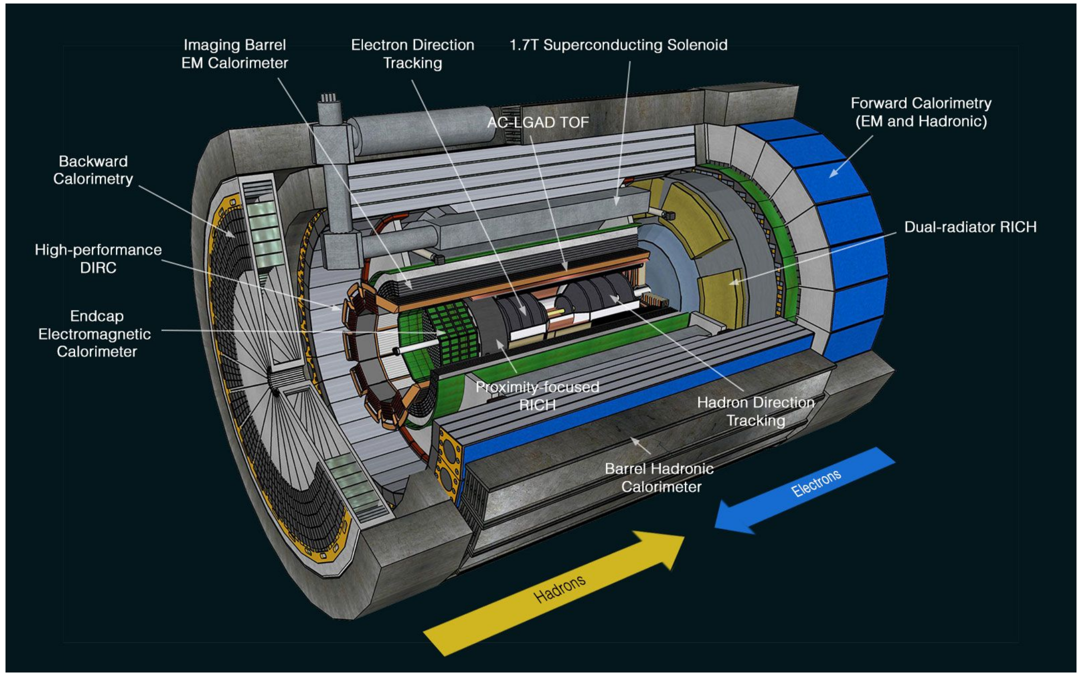
  - Asyncronous CPU, GPU launches
  - Fixed some bugs in Opticks, eg. some cones shapes were not working
  - Created a spack package
  - Tested NERSC Perlmutter
  - Installed in eic_cude container
  - Integrating eic-opticks now into dd4hep:
    - Soon can be used through dd4hep in eic_cuda containers
- Besides EIC there is interest from medical physics community:
  - Harvard scientist testing it now
  - We are integrating eic-opticks into opengate sim. framework

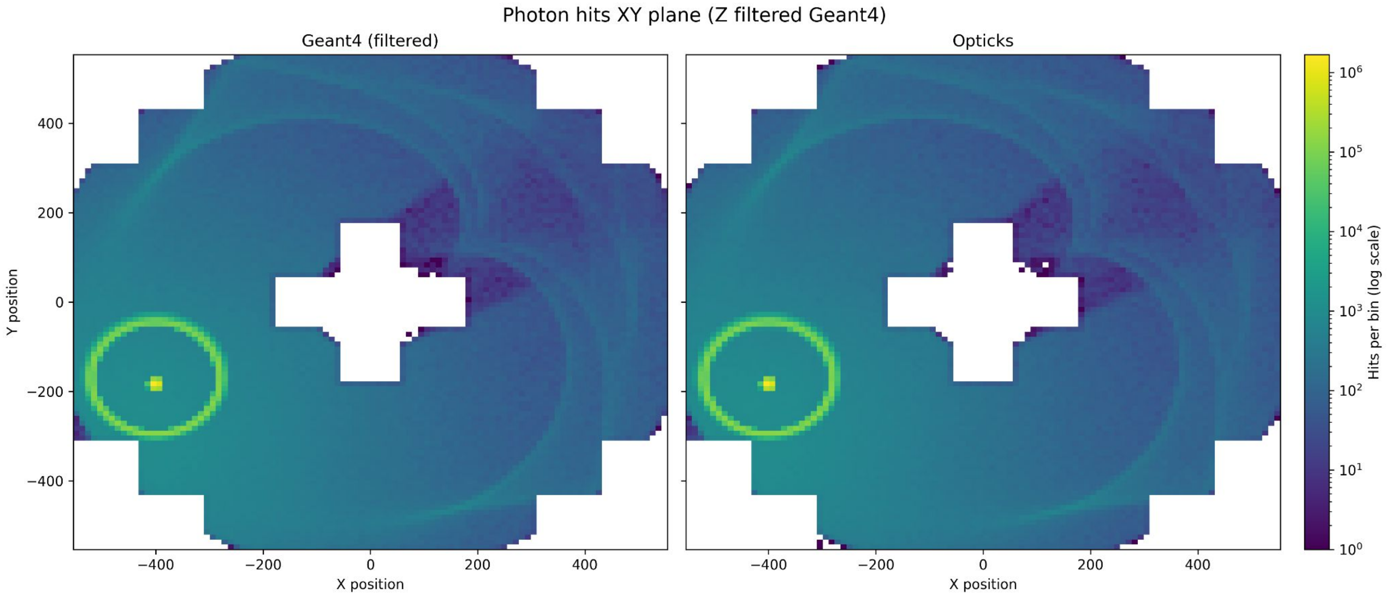
[1] github.com/BNLNPPS/eic-opticks

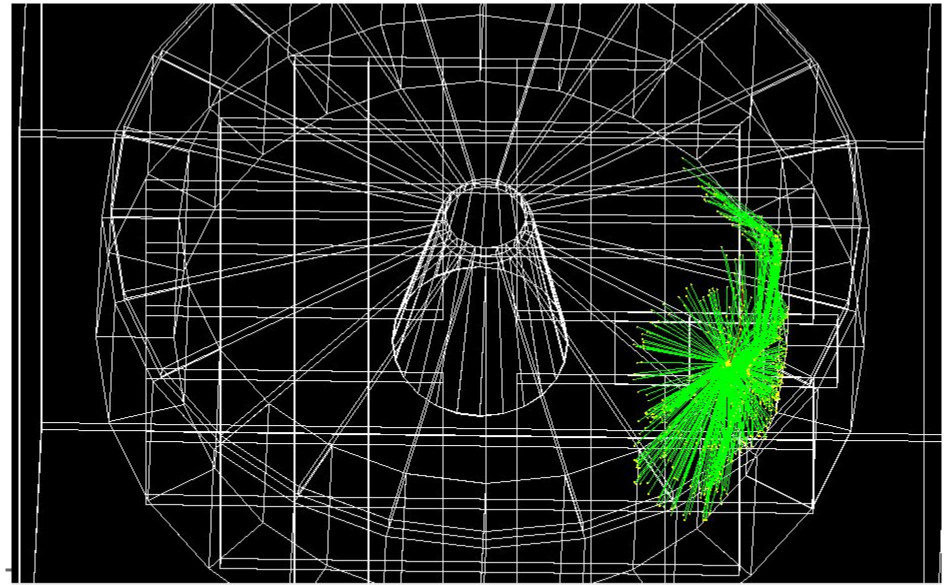
Validation of EIC-Opticks vs G4 w. pfRICH geometry

- Validated EIC-Opticks vs pure Geant4 for a simplified pfRICH geometry
  - Shooting 50k electrons to the same place
  - 50k 5 MeV e$^-$ yields:
    - Geant4 hits : 13’840’638 ± 3720
    - Opticks hits : 13’840’566 ± 3720
- Opticks was validated by JUNO, Crab, LHCb



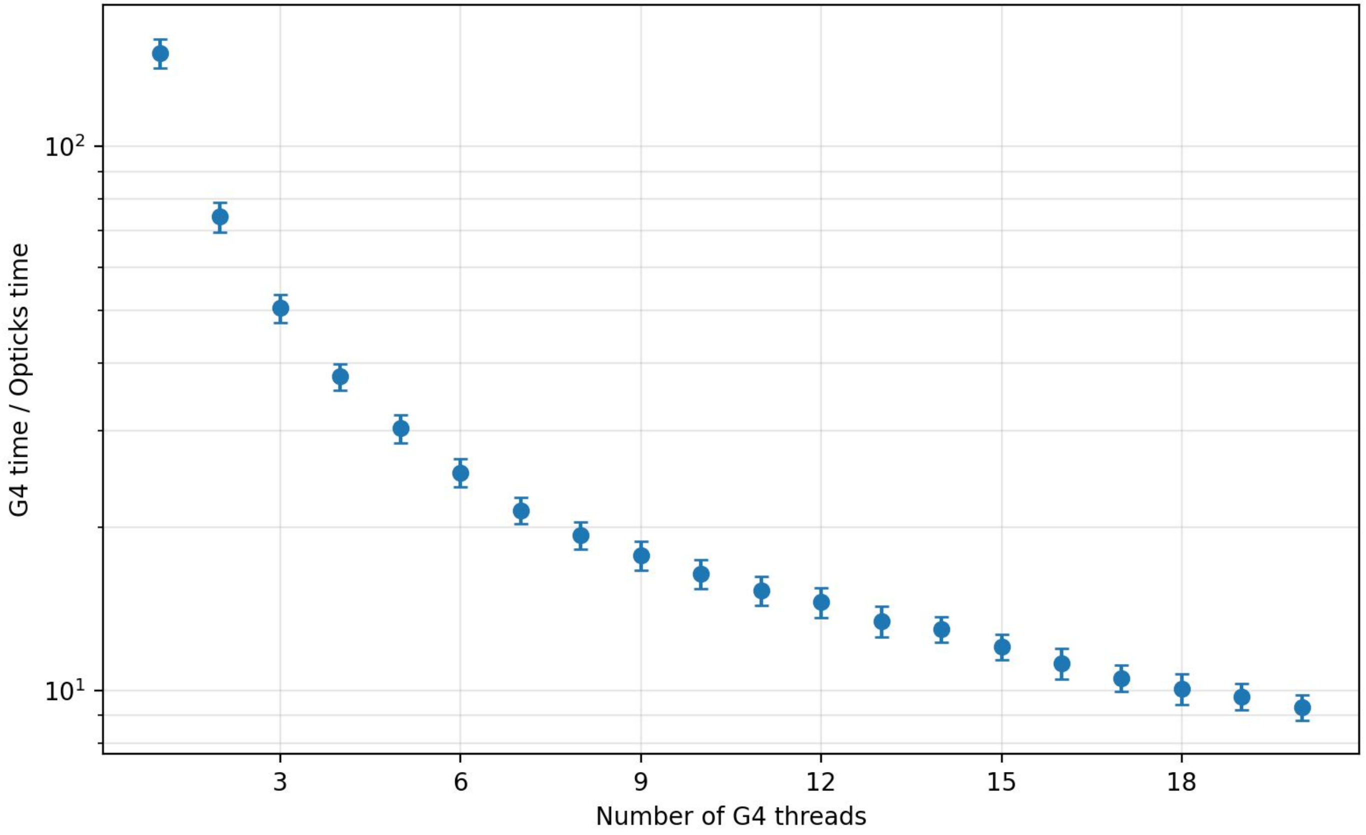
Imaging Barrel EM Calorimeter
Electron Direction Tracking
1.7T Superconducting Solenoid
AC-LGAD TOF
Forward Calorimetry (EM and Hadronic)
Backward Calorimetry
Dual-radiator RICH
High-performance DIRC
Endcap Electromagnetic Calorimeter
Proximity-focused RICH
Hadron Direction Tracking
Barrel Hadronic Calorimeter
Electrons
Hadrons





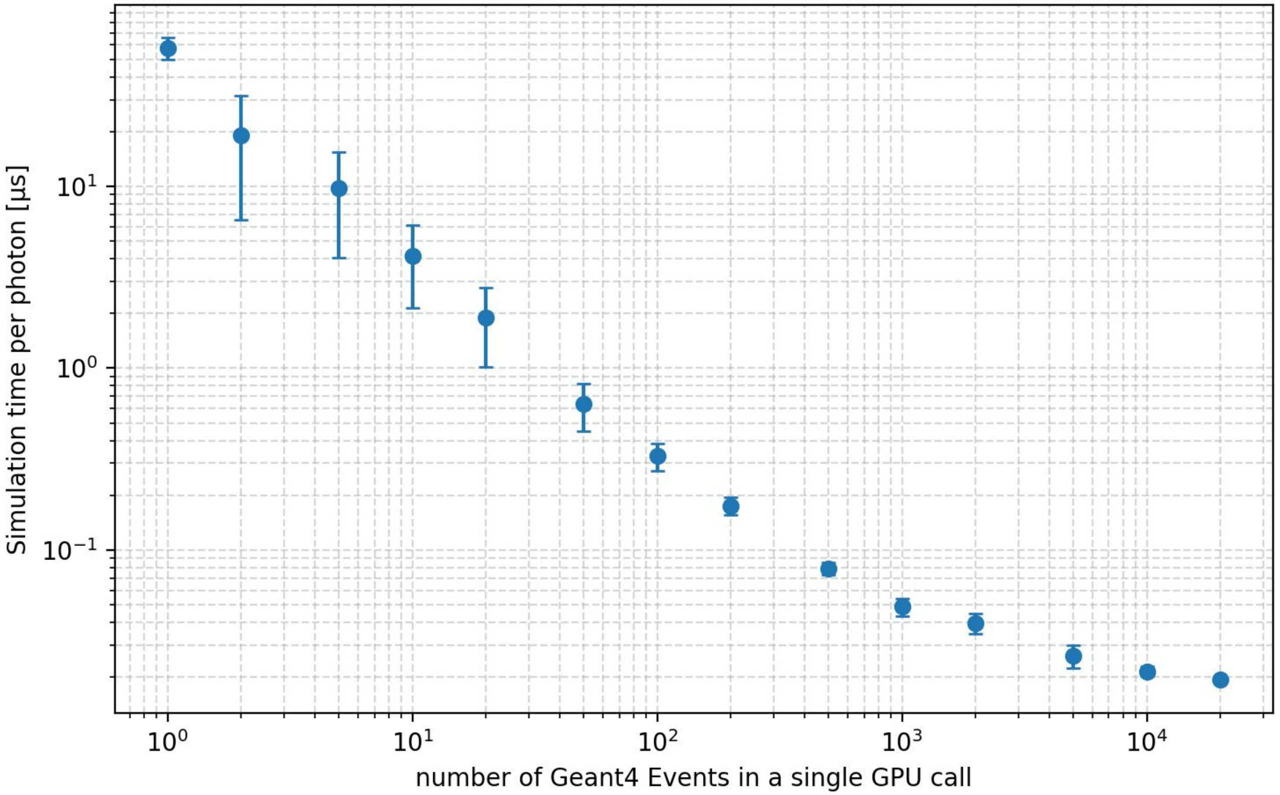
Performance

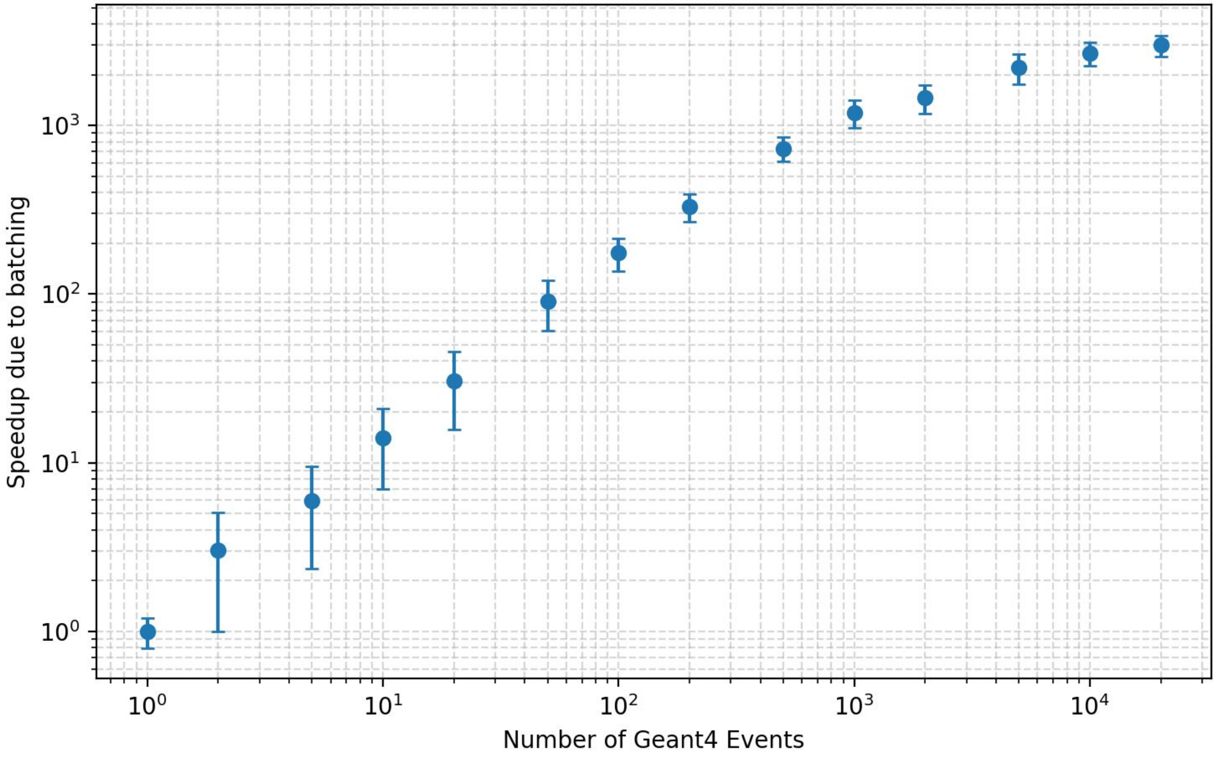
- Ran on our GPU server
- NVIDIA GeForce RTX 4090
- Intel(R) Xeon(R) w7-3445
- Time measurement for EIC-Opticks included:
  - Data movement from CPU -> GPU
  - Ray tracing
  - Copying results from GPU -> CPU
- 50k 5 MeV/c e^- → ~ 50M photons
  - EIC-Opticks vs Single thread G4 CPU
    148±9x speedup
  - 20 threads MT G4 CPU vs EIC-Opticks
    9.3±0.5x speedup



Event batching in EIC-Opticks

- We introduced event batching in EIC-Opticks
- Overhead, to start GPU simulation, run and return results
  - For low energy events too high
- In the case of pfRICH batching 50k event speeds up GPU simulation time 3000x

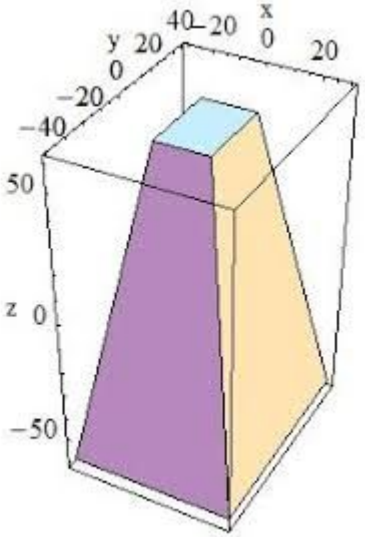




Brookhaven National Laboratory

Development plans

- Implement wavelength shifting process in the GPU code
- Implement a “scheduler” that would balance CPU, GPU node launches on clusters
- Implement support for trapezoid volumes into EIC-Opticks
- Investigate how to add support for triangulated volumes



Summary

- Optical photons can dominate Geant4 simulation time, limiting detailed and large-scale studies
- EIC-Opticks: OptiX-based GPU propagation integrated with Geant4, with event batching and reflection / ray-offset tuning
- GPU results agree with standard Geant4
- Large end-to-end speedups vs. CPU Geant4, including data transfer
- NVIDIA/OptiX-only, limited geometry primitives, and incomplete physics (e.g. WLS)
- Plan: Extend physics and geometry support, improve tasking/multi-GPU use
- In few weeks everybody can test eic-opticks in eic_cuda container, no need to install anything (except nvidia drivers..)

Thank you for your attention!