arXiv:2203.07614v3 [hep-ex] 20 Apr 2022

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Detector and Beamline Simulation for Next-Generation High Energy Physics Experiments

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case of detector and beam simulations, elements of the program involve adaptation and extensions of the existing software as well as efforts to write new packages or modules to eliminate constraints resulting from many years of evolution of legacy codes.

A. Specific R&D Efforts

Some of the elements of a proposed R&D program which play to the strengths of the US simulation teams are listed below (and described in subsequent sections or their own, separate white papers or other documents). More information on machine learning based projects is provided in Section V B below.

Celeritas a project that implements a growing set of physics for detector simulation targeted at GPU-powered HPC platforms [30, 31]; a component of the project, "Acceleritas", provides interfaces between Geant4 and Celeritas, to enable a hybrid CPU/GPU workflow with selected tasks executed on the GPUs;

Simulating Optical Photons in HEP experiments on GPUs is an effort to integrate recent versions of Geant4 and Opticks [8, 32] in a hybrid CPU/GPU application using Geant4 Tasking a Task-Level Parallelization approach introduced in Geant4 v11 [33–35];

Simulation on HPCs proposes to investigate the interconnection of HPC systems for event simulation and task scheduling [36];

Simulations of Low-Energy Crystal Physics for Dark Matter Detectors describes the needs of a certain class of Dark Matter (DM) experiments and presents ideas on how to address them [37];

Optimizing Geant4 parameters and enabling estimating related systematic uncertainties is an activity described in Ref. [22].

As the projects need to be seen in a worldwide HEP context, one should also mention two related European HEP efforts:

G4HepEm an R&D project to make electron/positron/gamma transport faster by restructuring, specializing and separating underlying libraries, targeting optimization of execution on CPU as well as on GPU [38, 39]

and

VI. NEED FOR EXPERTS AND THEIR TRAINING (THE "HUMAN CHALLENGE")

Detector simulation tools require e ort for code modernization, improvement of physics models, maintenance, and long-term support. Evolving computing architectures demand signi cant investment to adapt and optimize simulation software to run e ciently and exploit the available hardware at modern HPC centers. The above e orts are not viable without comprehensive and intensive training plans for both application developers and end users.

Due to the long lifetimes of current and future HEP experiments, it is crucial to continuously recruit, train, and retain teams of experts, as well as to create attractive career paths for people developing and maintaining the software. Most importantly, detector modeling requires multidisciplinary teams consisting of software developers and physicists with specializations in low-energy, electromagnetic, and weak interactions, as well as condensed matter physics. Continuous funding is therefore required for High-Energy and Nuclear physicists in these roles, as well as software developers throughout the life cycles of HEP software toolkits.

To set the scale of the required detector simulation R&D and operations e ort, we can use the Geant4 toolkit and the GeantV R&D project [43] as examples. Geant4 is maintained by an almost 30-year-old collaboration of well more than 100 members (and more than 30 FTEs) distributed worldwide, serving a very diverse set of user domains. Its developer and user bases extend from HEP to astronomical and radiation studies and medical applications. GeantV was an R&D project to redesign Geant4 to exploit the bene ts of vectorization and increased code and data locality. It took about 5 years (it ended in 2020) and 30 FTE-years to implement only a fraction of all Geant4 modules within GeantV, mainly in the transport and electromagnetic domains, leaving most of the code unvectorized (the cited paper describes the lessons learned from writing the prototype). Based on this recent R&D experience and the personpower requirements implied by the size of the international Geant4 collaboration, it is critical that the US HEP community contributes a substantial portion of the global detector simulation e ort, commensurate with the needs. A team of highly-skilled physicists and engineers is required to provide the necessary support and developments for Geant4, and the packages extending it, to meet the needs and challenges within the scope of the US HEP experimental program. This must also include su cient support for developers with domain expertise in the software frameworks of HEP experiments, who can properly and e ciently utilize new or updated simulation toolkits provided by the Geant4 collaboration and/or other detector simulation groups. The realization of Geant4 running on exascale computing hardware will require additional personpower a team whose expertise lies in parallel and high-