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Physics and Detector Simulations

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Narrative Themes

- What is “Physics and Detector Simulations”?
- Recent progress
  - A shift in emphasis: the “Intensity Frontier”
    - Strong focus on the physics problems at neutrino and muon experiments – materials, energies, etc.
    - Direct engagement with the community
  - The “Intensity Frontier” is comprised of a very different community than the “Energy Frontier”
    - Fewer large actors, more small-to-medium groups
    - Similar interests but little communication between experiments
    - Very different timescales and project sizes
      - We must develop and deploy in parallel
      - We must find a way to meet the needs of groups of very different sizes

Physics and Detector Simulations

- Physics simulations:
  - Pythia and GENIE are event generators (phenomenological and first-principles models for the core physics interaction under investigation).
  - Geant4 also involves these physics concerns. In many cases, the process being simulated cannot be based on first-principles or closed, analytic solutions.
  - Transparent physics validation is crucial!
- Detector simulations:
  - "Technical aspects" of Geant4
    - Efficiently describe and debug the geometry
    - Performance

GENIE

- GENIE (Generates Events for Neutrino Interaction Experiments) is a Neutrino MC Event Generator that simulates the interaction of a neutrino with a nuclear target.
  - Geant4 takes over at the boundary of the nucleus.
  - First-principles calculations are generally not possible – this is a non-perturbative, strongly-coupled, many-body problem. As such we employ a brew of well-grounded phenomenological models, and tune them to data as much as possible.
  - International collaboration of specialists (mostly experimentalists).
- Historically neutrino interactions have been very difficult to simulate. Fermilab expanded staff and resources specifically to meet this challenge at the request of the community.

GENIE, cont.

- GENIE is currently used (sometimes in conjunction with other generators or for specialized studies) by T2K, MINOS+, NOvA, MINERvA, ArgoNeut, MicroBooNE, ELBNF, INO, LAr1-ND and others.
  - Every running and planned neutrino experiment at the lab!
- Fermilab has joined the Executive Board and is driving more thorough physics validation and tuning process along with a more aggressive release schedule.
  - Short-term goals: improving the release procedure and validation; physics tuning is longer-term.
  - Very different process as compared to extending a perturbative calculation or fitting a PDF: no accepted global model to work with (the generator *is* the model).

Geant4

- Geant4 models the passage of particles through matter with diverse application in areas such as high energy, nuclear, medical, accelerator, and space physics.
- Fermilab is a member of the Geant4 Collaboration
  - Leads computing performance working group
  - Develops validation infrastructure
  - Participates in the of hadronic physics working group, especially as related to the production of neutrino beams, muons, and the interactions of hadrons in particle detectors.
  - Vigorous R&D program to transform G4 for the future (more on this later).

Geant4, cont.

- We pay special attention to the implementation of the physics processes relevant to Fermilab experiments and provide guidance and support regarding Geant4 usage to the lab community.
- Experiments make heavy use of new Fermilab software tools and infrastructure related to Geant4:
  – a fully-featured validation database
  – efforts such as new physics lists (a predefined combination of physics processes/models used in a simulation for a given set of particles), e.g. NuBeam.
  – artG4Tk (a toolkit to quickly put together realistic detector simulations for physics studies)

Community engagement for GENIE and Geant4

- We met with representatives from the IF experiments and jointly appointed liaisons from both sides.
- After initial discussions, we settled on a partnership-model for collaboration and designed a work program that includes:
  - GENIE physics model implementation and validation and an automated validation framework
  - Geant4 application support (geometry, physics), the artG4Tk interface, customized physics lists for beams, muon physics, and neutrino detectors
  - Activity tracked in Redmine

Community engagement, cont.

- GENIE – building a “developer’s hub” at the lab by involving experiments in tuning and validating models using standardized application infrastructure developed locally
  - Ran a workshop in Spring 2014 that lead to the creation of more than a half-dozen new models for imminent GENIE releases and another half-dozen projects with longer incubation times
- Geant4 – working with the Geant4 collaboration on enabling users to vary model parameters for evaluating systematics
  - Implementation will be model-by-model initially and based on a close partnership with an experiment.
  - Pilot projects are underway internally

Geant R&D

- Funded by CompHEP.
- This is not a “hobby,” but rather a vital necessity to face future computing challenges (e.g., LHC experiments need 10x more computing than they can afford).
  - We must fully exploit the opportunities offered by new computing architectures and paradigms (parallelism, concurrency).
  - Efficient running on modern hardware demands paradigm shifts in the code to utilize wide instruction sets and multicore processors – relying on Moore’s Law to deliver continued single-core performance is a failing strategy.
  - Developing for both GPUs (e.g., NVIDIA CUDA) and many-core co-processors (e.g., Intel Phi).

Geant R&D, cont.

- Partnerships with DOE ASCR to develop optimization (Geant4 time and memory performance) strategies and technical implementations for vectorized simulation modules; and with CERN, UNESP (Brazil) on a vectorized workflow framework, the Geant Vector Prototype (GeantV)
- “Co-processor prototype” developed at Fermilab to test propagation through material and magnetic fields.
- Associate R&D projects with initiatives like the HEP Software Foundation (HSF) and the DOE Center for HEP Computing Excellence - collaborate on common software, optimize services, leverage resources.
  - As a field we cannot afford duplication of effort or resources.

Contributions to the CMS simulation effort

- CMS simulation convenerships (2005-2007, 2010) during re-engineering of CMSSW framework and Run I commissioning
- Led (G4/Test Beam) physics validation effort to improve physics accuracy – outstanding G4 performance at LHC
- One of Pythia's three authors is part of the PDS
  - Led CMS Pythia transition from Pythia6 to Pythia8
- Led MC effort across physics groups to interpret physics results in the light of physics generators
- Leading detector simulation upgrade effort (2015)
  - Optimization and validation for the new detectors, with a long-term plan to explore the benefits of new computing architectures

Conclusions

- High-quality simulation is a pre-requisite for high-quality physics in today's computationally driven environment.
- Through GENIE and Geant4, we make critical contributions to every part of a neutrino experiment's simulation software "stack" – the beamline, the hard scattering event, and the detector performance.
- Geant4 is additionally critical to the most important stages of the new Muon Campus experiments simulation software.
- Of course, we continue to make substantial contributions to CMS both by improving Geant4 and researching new computing architectures for Geant, but also through the Pythia collaboration.

Conclusions, cont.

- Fermilab has joined the collaboration leadership structure for the most important neutrino event generator and is helping to drive the release schedule, validation procedures, and physics tuning.
- We are partnering directly with experiments at Fermilab to address their major simulation concerns.
  - Opening Geant4 models up with an interface and documentation to make it possible to explore the parameters and their impact on systematics is the best example of this partnership.
  - Working with neutrino experiments to characterize and improve the physics performance of GENIE using the data sets most relevant to their measurements is another example of how the PDS is engaging the laboratory community productively.