Simulation in Fermilab Neutrino Experiments

Alex Himmel

HSF Detector Simulation WG

March 25th, 2020

Introduction

Organized around the stages of simulation in ν exps:

- Neutrino Beams
- Neutrino Interaction Generation
- Particle Tracking
  - Notes on G4 interfaces
  - Special cases: optical photons
- Looking Forward:
  - Features
  - Performance
  - Architectures

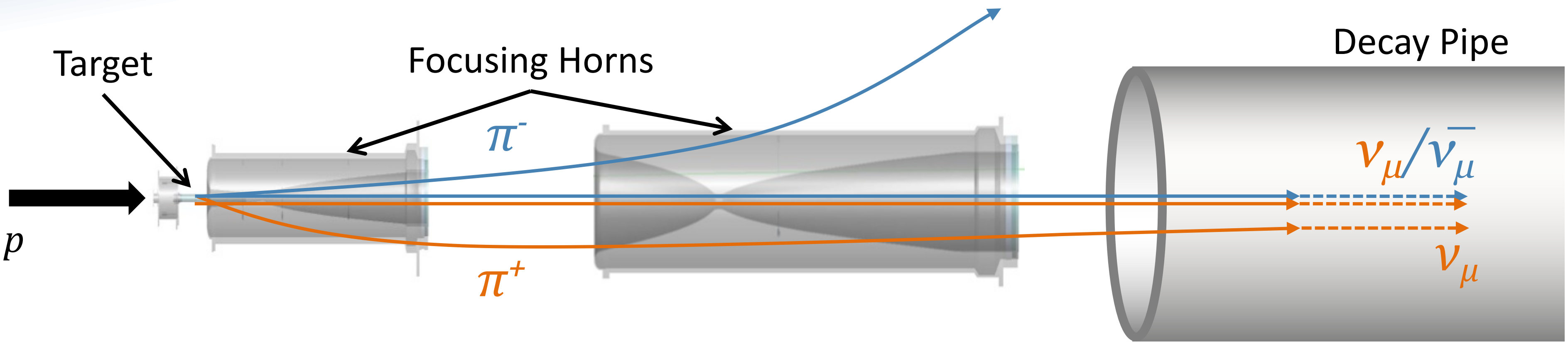
Which experiments, exactly, are we talking about?

- Segmented organic scintillator
  - NOvA
- Liquid Argon
  - MicroBooNE
  - SBND
  - ICARUS
  - DUNE FD, Single/Dual
  - ProtoDUNEs
  - LArIAT
- Water Cherenkov
  - ANNIE
- Multi-component
  - DUNE ND

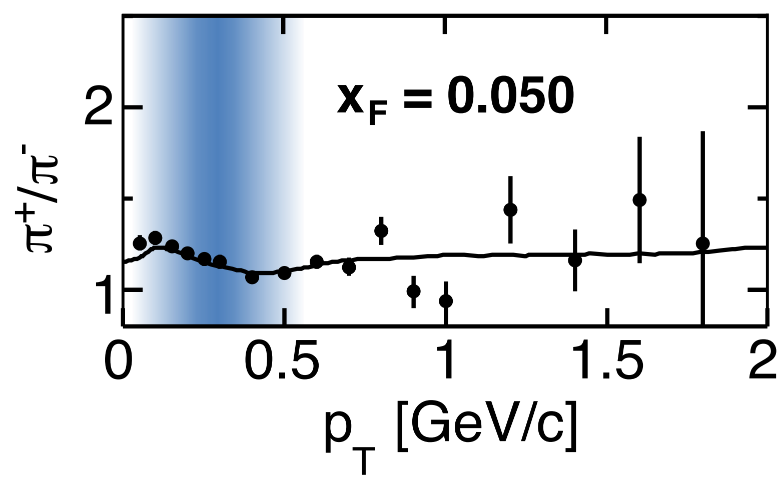
Introduction

- Who am I?
  - DUNE Far Detector Simulation+Reconstruction Convener
  - DUNE Single Phase Photon Detection Simulation+Physics Convener
  - NOvA Analysis Coordinator, previously Computing Coordinator
  - Former simulation expert on Super-K/Hyper-K.
- So, I can speak about NOvA and DUNE FD with more authority, but I sought input from across the program.

Neutrino Beam Simulation



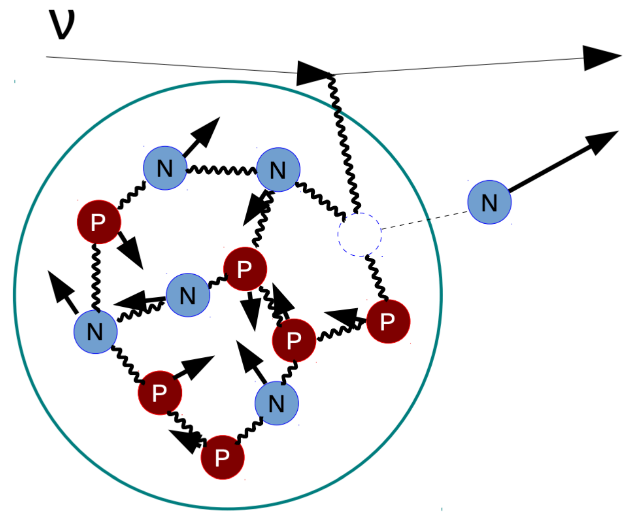
- **Everyone uses GEANT4**
- Big uncertainties in hadroproduction, no well-tuned physics list.
- Largely mitigated in multi-detector experiments, but a major concern in cross-section measurements.
  - In NOvA, 10% before extrapolation, < 2% after extrapolation.
- NOvA uses PPFX to reweight to hadroproduction data
  - Developed by MINERVA
  - Also creates systematic variations.

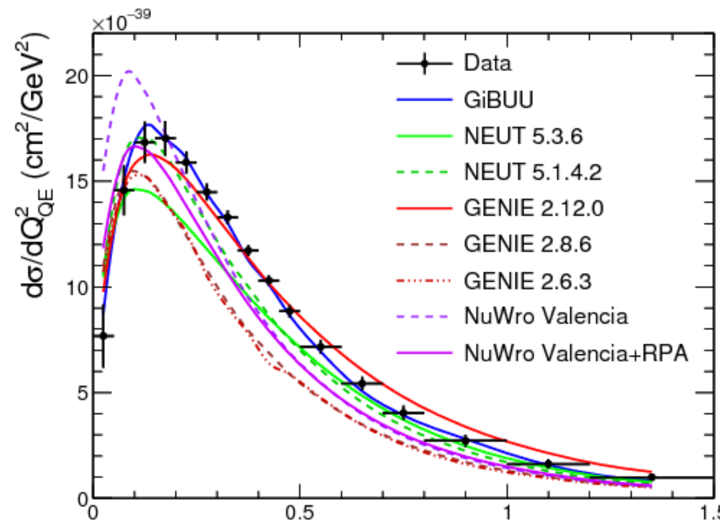


NA49, Eur. Phys. J. C 49 897 (2007)

Stages of Simulation in Neutrino Experiments

- **Neutrino Event Generation: GENIE**
- GENIE is the primary generator used at FNAL, but there a bunch of others out there
  - NEUT, NuWro, GiBUU, MARLEY, etc.
- Even within GENIE, there are many choices of models available for use.
- This is another area where there are significant uncertainties, which are partially reduced in multi-detector experiments.
  - In NOvA, extrapolation reduces uncertainty from ~15% to ~5%.
  - The goal for DUNE is ~1%, so additional work is needed here, but that's out of scope of this group.

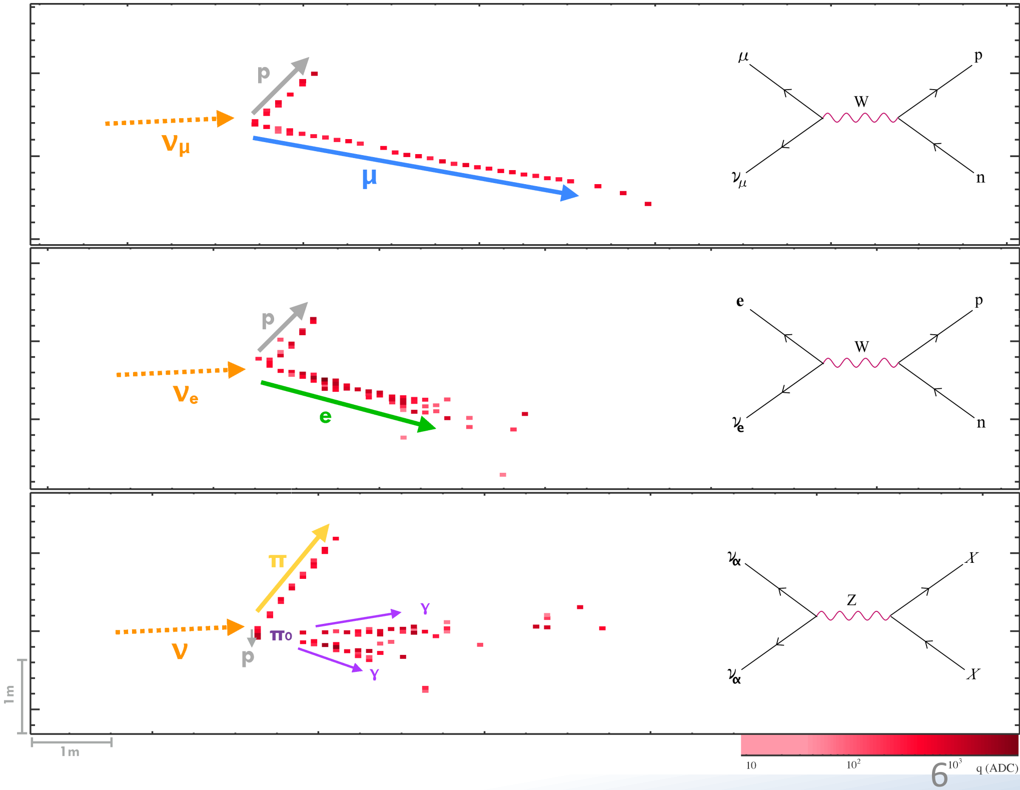




https://nuisance.hepforge.org/

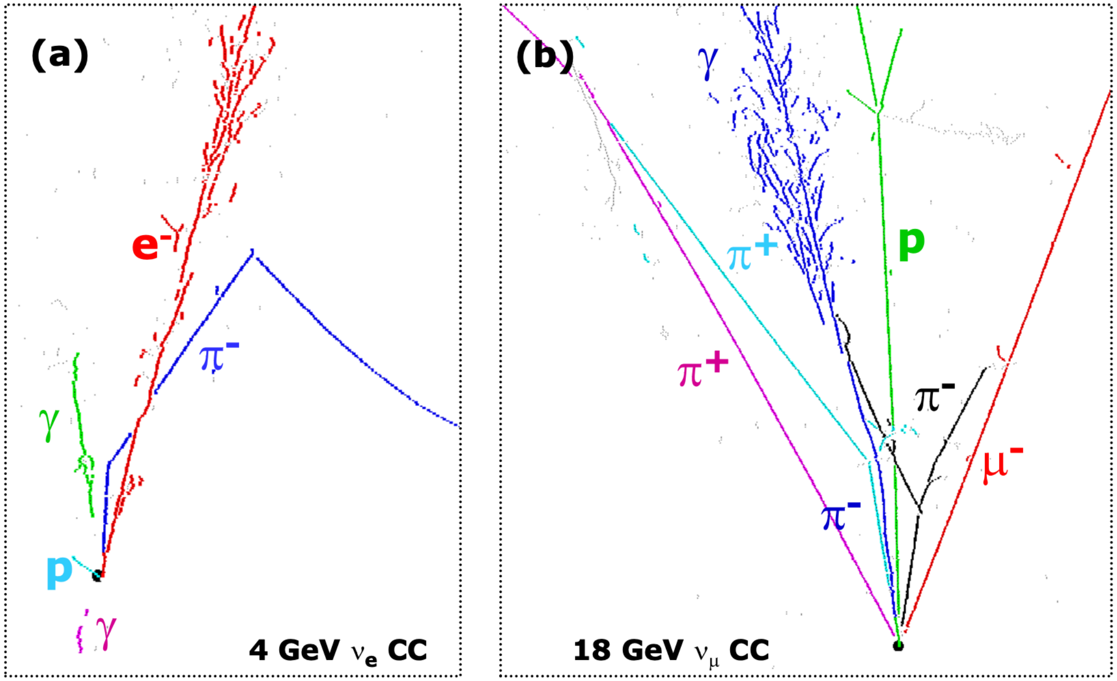
Tracking Particles in the Detector

- **Everyone uses Geant4**
  - Though we often use different versions across experiments.
    - Upgrading major externals like G4 is a lot of work, so the algorithm is usually to get current when the opportunity arises every 1-2 years.
  - NOvA: 4.10.4 p02b
    - Probably for a while
  - LArSoft: 4.10.3 p03e
    - DUNE, SBN, μBooNE…
    - Discussing 4.10.6 p01 now
  - ANNIE: 4.10.1/2
- We use G4 to track final state particles which leave the nucleus.
- Track through any interactions and record energy deposits.



What are we tracking?

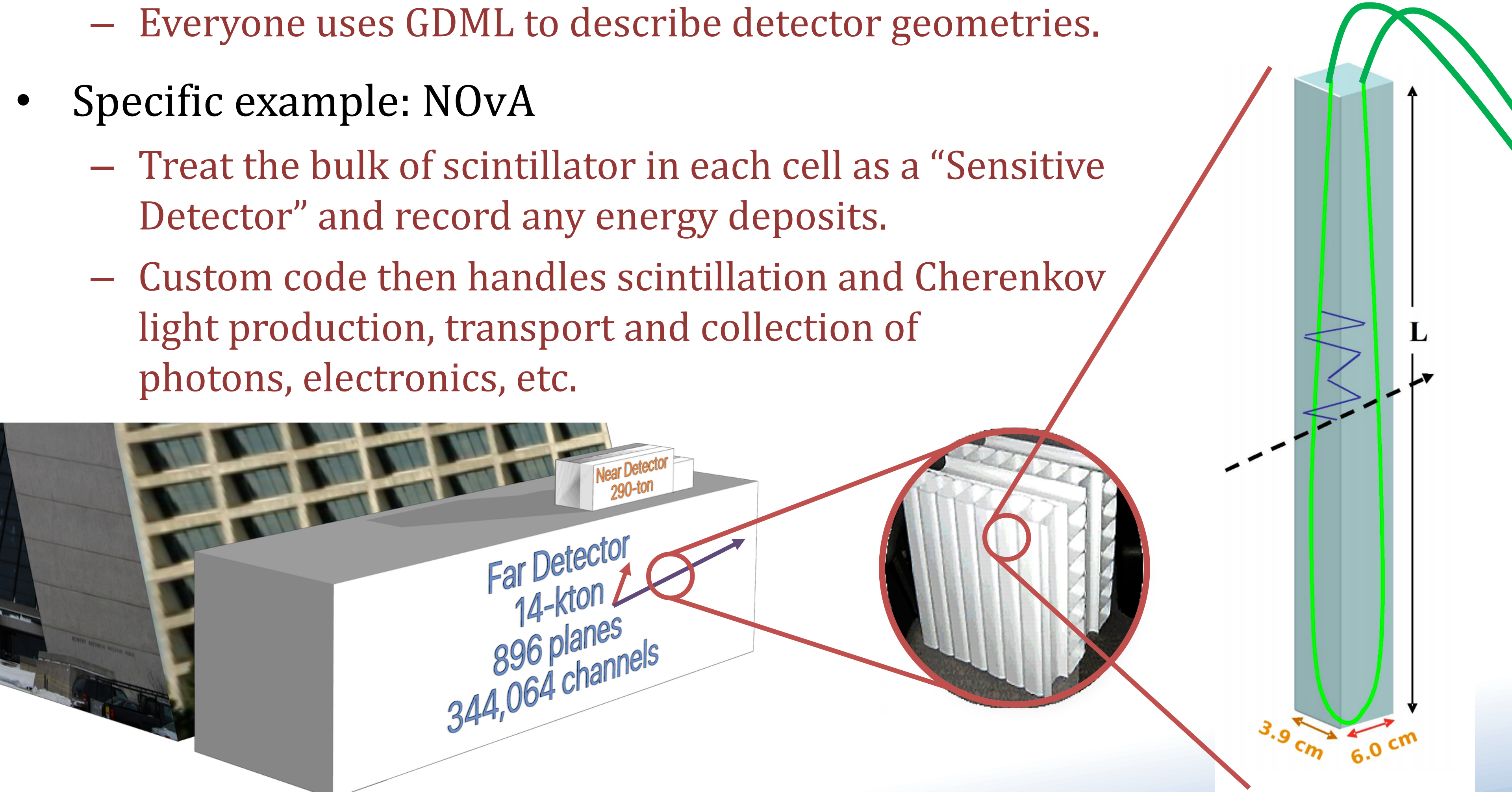
- Which particles?
  - $\mu, e, p, n, \pi, \gamma, K, \tau$
- Which processes?
  - Ionization
  - EM showering
  - Scattering
    - hard, MCS
  - Decays (μ, π, K)
  - Captures (μ, n)
  - Nuclear de-excitation
    - particularly important for Supernova ν
  - Neutron thermalization



- Energy range:
  - Lowest: few hundred KeV (e.g. de-excitation gammas)
  - Typical: 10's of MeV to a few GeV
  - Highest: a few TeV (cosmic ray muons)

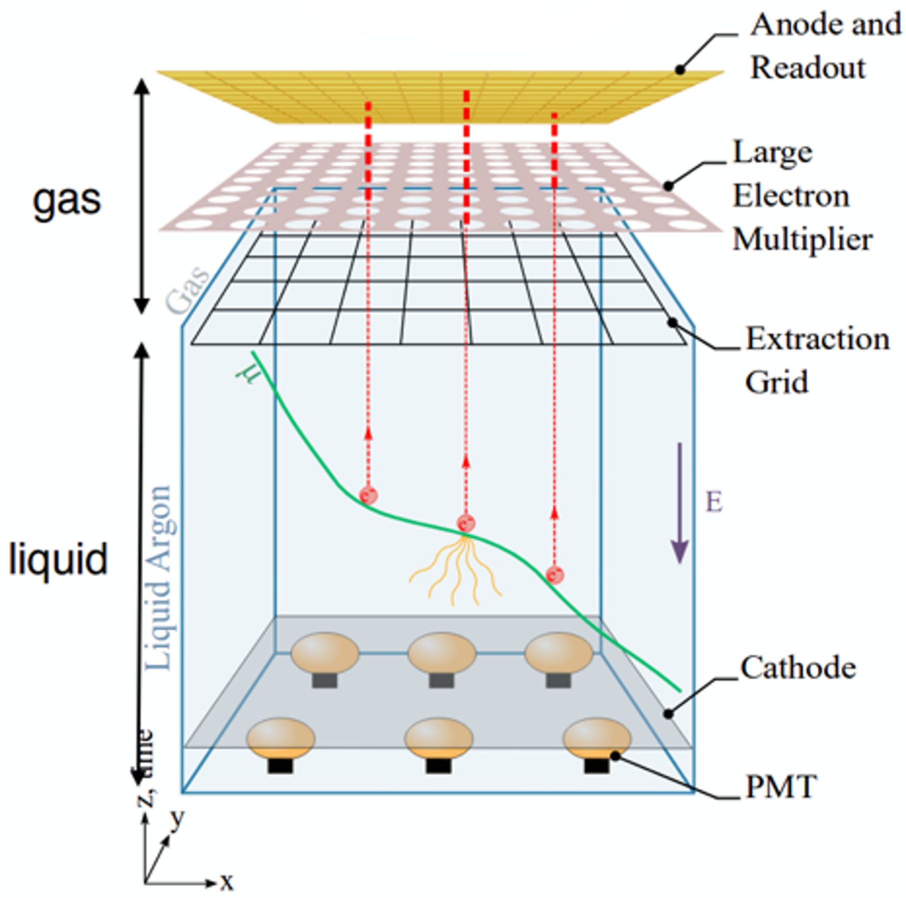
Geant4 Interfaces

- We all use a common analysis framework called ART, which has a built-in interface to Geant4.
  - Coordinates input from flux and event generator, output to custom parts of simulation.
  - Everyone uses GDML to describe detector geometries.
- Specific example: NOvA
  - Treat the bulk of scintillator in each cell as a “Sensitive Detector” and record any energy deposits.
  - Custom code then handles scintillation and Cherenkov light production, transport and collection of photons, electronics, etc.



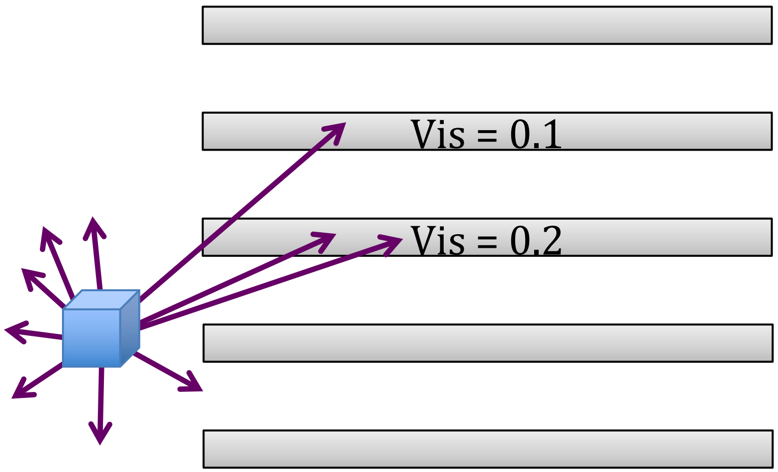
Geant4 Interfaces

- Specific example: liquid argon
  - Note: describing what we call "new LArG4," a new interface developed by Hans Wenzel based on artg4tk.
- Treat the whole LAr volume as the sensitive detector.
  - Record "SimEnergyDeposits" frequently with limited step lengths.
- These energy deposits then passed to other framework modules to handle:
  - Scintillation and ionization
    - Photons and drift electrons
    - Box model, NEST, etc.
  - Drift of electron to readout plane
    - Including simulation of field response (see arXiv:1802.08709)
  - Fast simulation of optical photons.



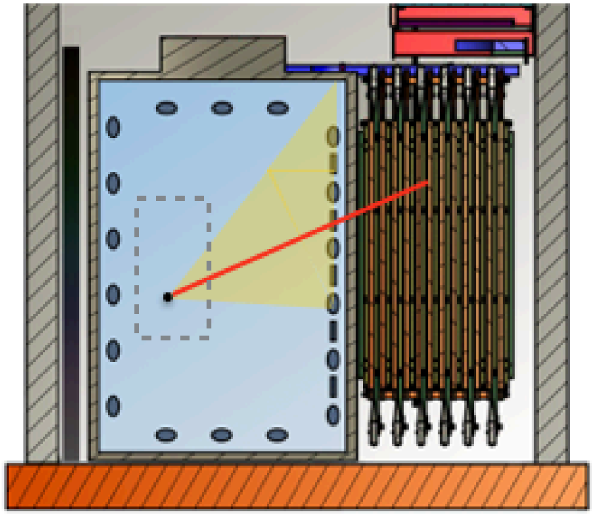
Special Case: Optical Photons in LAr

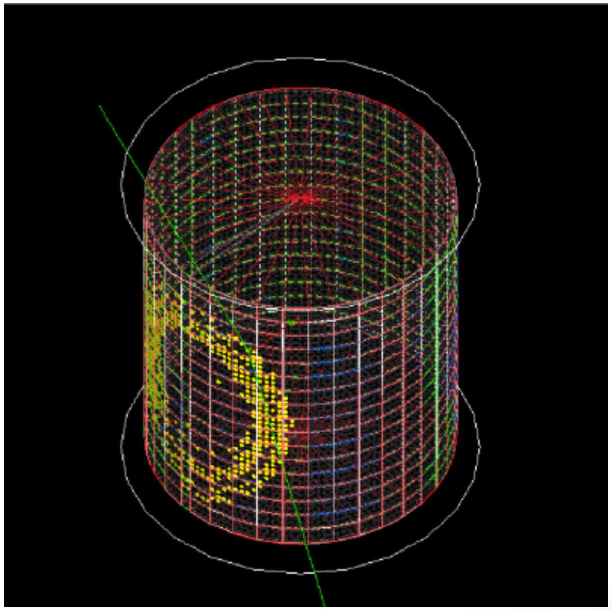
- Photons in LAr
  - LAr is a strong scintillator – 40k γ/MeV.
  - It is prohibitively slow (minutes/event) to track every photon
- A variety of fast simulation approaches, all trained on full Geant4.
  - Take advantage of scintillation light being isotropic to generate "bombs" of photons distributed in the geometry.
  - Most LAr experiments have used a 4D look-up library.
  - DUNE geometries are too large for the library, so we're now using a semi-empirical parameterization, exploring ML solutions.
- These tricks all break for directional Cherenkov light.
  - So far, we are mostly ignoring this few-percent contribution.
- If fast (GPU?) photon tracking became available in Geant4, I think there would be significant interest in adopting it.



Special Case: Optical Photons in ANNIE

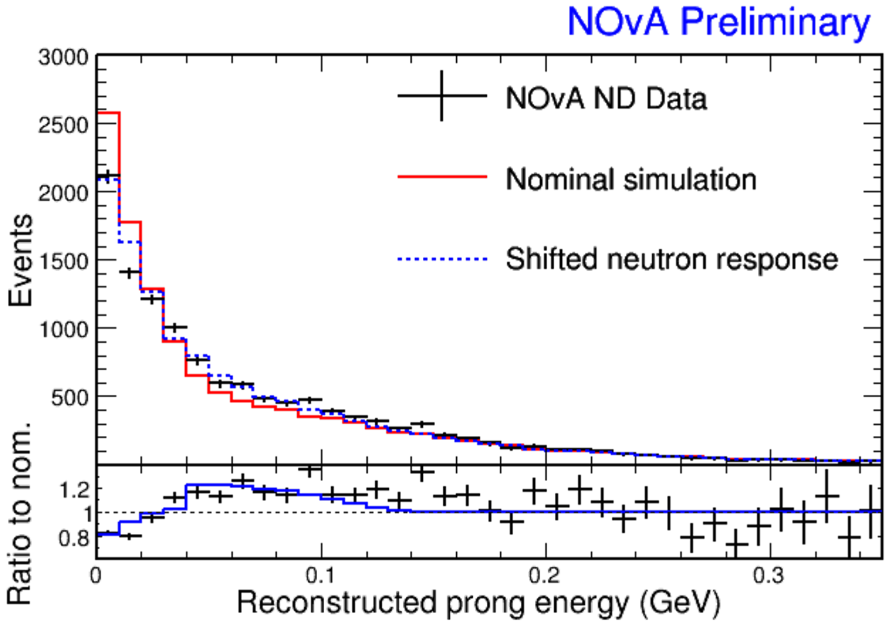
- ANNIE is a Water Cherenkov experiment, so photon tracking is vital to the simulation. They use 2 simulations:
- WCSim
  - Generic Geant4-based simulation package for WC detectors.
  - Uses full G4 optical photon tracking, though scaled down to detector QE to save computation time.
  - Currently the primary simulation for near-term analyses.
- RAT-PAC
  - Ray-tracing simulation developed for low energy (dark matter, 0νββ experiments).
  - Currently being used to study the eventual addition of water-based liquid scintillator, since this functionality is already available in this package.
- All simulation so-far is CPU-based, but obviously would be interested in GPU simulation if it becomes available.





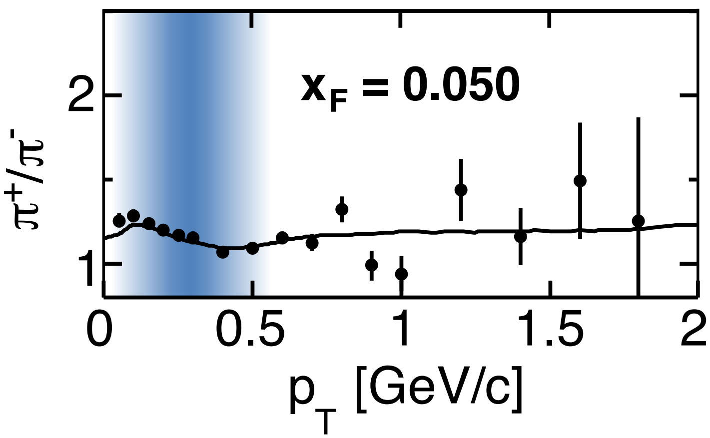
Looking Forward: Features

- (Largely my opinions)
- Improved neutron physics, or the ability to change models or adjust the behavior of the current model.
  - NOvA is putting a lot of effort into understanding the behavior of neutrons in our detector, and there are some clear discrepancies.
  - ANNIE's is explicitly measuring neutrons from neutrinos.
  - Useful both for tuning simulation to data, and for applying more physics-based systematic uncertainties.

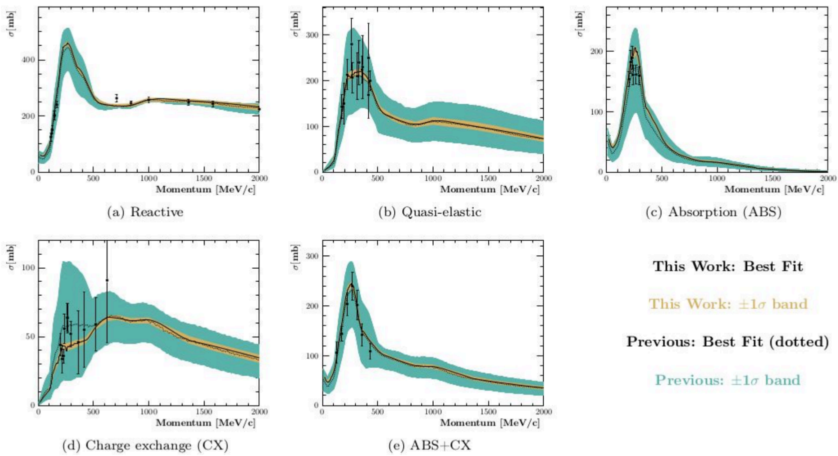


Looking Forward: Features

- Physics list designed for neutrino experiments.
  - Separate regimes: neutrino beam production, charged particles in detector, etc.
  - Would love to avoid model transitions in the middle of our energy regimes if we can.
  - If tuning made available to experiments, could tune against test beam experiments.
- Handles for creating hadronic interaction systematics.
  - Work is on-going now to introduce reweightable systematics for $\pi^{\pm}$ interactions in the detector.
  - Especially important for cross-section measurements with exclusive final states.



NA49, Eur. Phys. J. C 49 897 (2007)



P. Guerra et. al, PRD99, 052007 (2019)

Looking Forward: Performance

- Faster is obviously better, but how important speed is varies a lot with experiment and context.
  - Liquid argon:
    - The time spent in Geant4 is a relatively small part of the whole simulation-reconstruction chain.
    - Signal generation and processing and reconstruction tasks take longer by an order of magnitude.
  - NOvA:
    - NOvA has recently significantly sped up reconstruction, so now simulation is the dominant part of the chain.
    - However, the stage of the experiment is such that it may not be well-suited to pick up major speed-ups.
- Memory
  - Memory use is a significant concern for everyone since the way “slots” are accounted in grid systems charge penalties for using > 2 GB of RAM.
  - Supporting multi-threading could help this by allowing the extra CPUs which come with higher memory requests to be put to use.

Looking Forward: Architectures

- It seems clear that future computing is going to requires us to be versatile about the kinds of computing resources we use.
  - High-throughput computing (e.g. Open Science Grid)
  - High-performance computing (e.g. NERSC, ORNL, etc.)
  - Co-processors (GPUs, FPGAs, etc.)
- Ideally, we'd like simulation to be able to use the advantages provided by different environments (e.g. GPUs if they're available), but we want to avoid *requiring* them.
  - This allows us to remain flexible, being able to assign the right sorts of tasks to the right sorts of resources, but not be stuck if a particular resource isn't available.
- Special case: If GPU-accelerated photon tracking were available, I think there would be significant interest in putting it to use ASAP.

Conclusions

- Many experiments, but there's similarity in how the simulation runs.
  - Doubly so in the LAr program thanks to a shared framework.
- So far, most simulation "attention" in neutrino expeirments has gone to flux and cross section simulation and systematics.
  - Flux is, in principle, a GEANT situation, but expectations for the hadronic modeling have been low and the focus is post-hoc reweighting to data.
  - IMHO, having that tuning work feed back into the underlying GEANT models would be broadly beneficial.
- But, as flux and cross section systematics come down, the detector systematics become more important.
  - Work is beginning on how to develop post-hoc hadronic interaction systematics.
  - However, "first party" systematics (reweightable or not) from GEANT would be a very useful guide.