Status of JUNO Simulation Software

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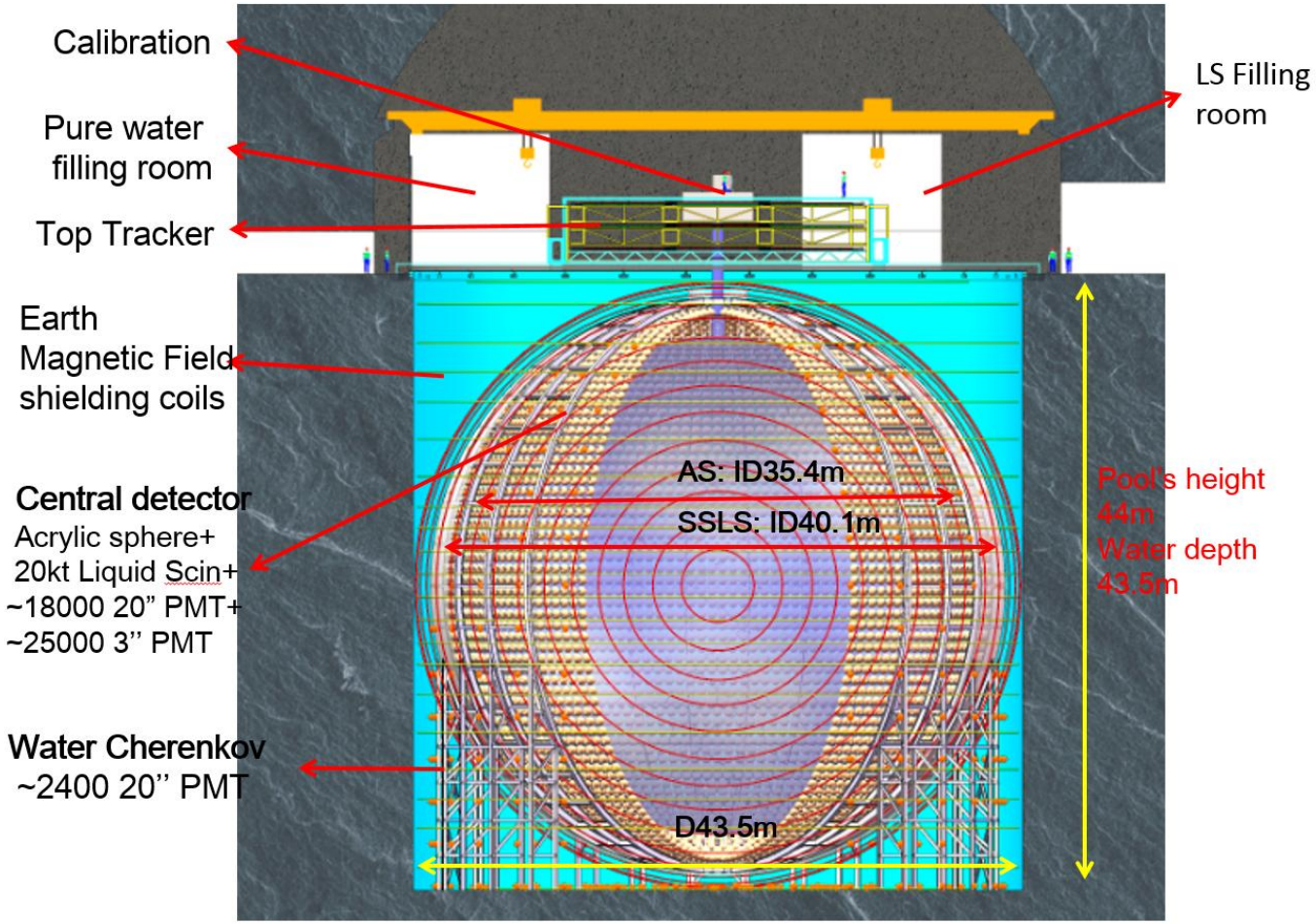
The JUNO Experiment

Jiangmen Underground Neutrino Observatory, a multiple-purpose neutrino experiment



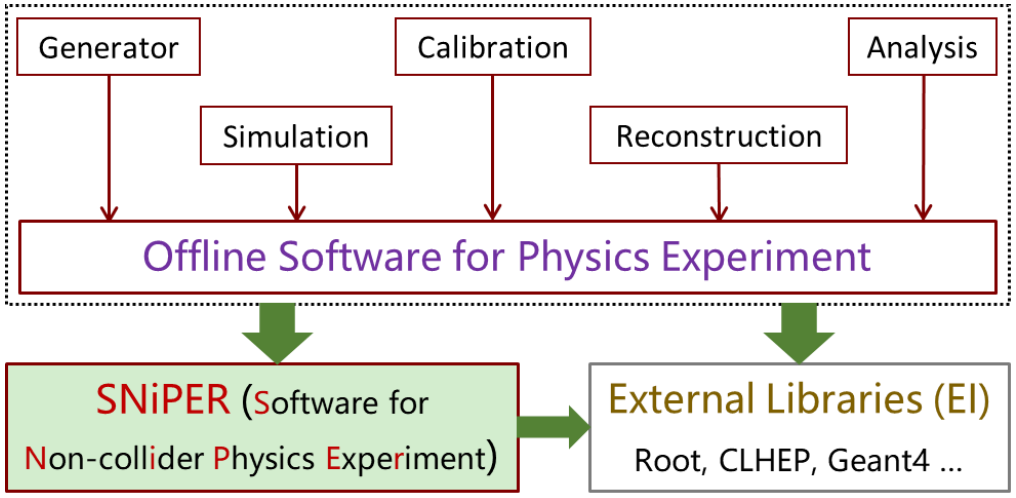
AS: Acrylic sphere; SSLS: stainless steel latticed shell

- 20 kton liquid scintillator detector
- 3% energy resolution at 1MeV
- 700 m underground
- Rich physics program
  - Reactor neutrino: for **Mass Hierarchy** and precision measurement **of oscillation parameters**
  - Supernova neutrino
  - Geo-neutrino
  - Solar neutrino
  - Atmospheric neutrino
  - Proton decay
  - Exotic searches

Complete the construction by 2021

SNiPER Framework

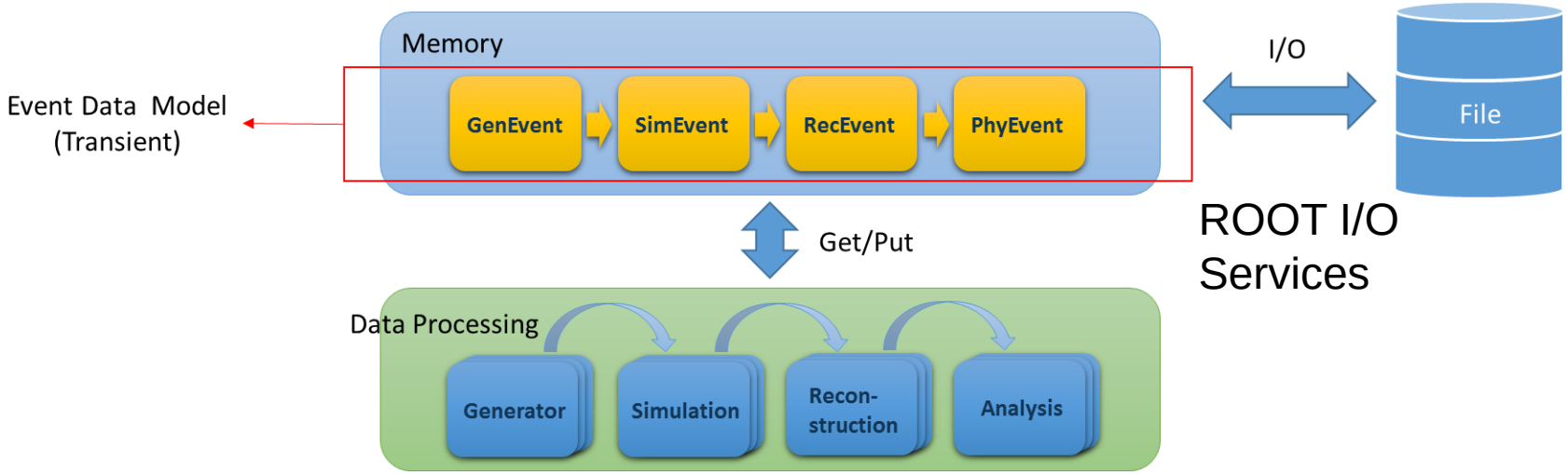
- SNiPER: Software for Non-Collider Physics Experiment
  - Lightweight
  - High efficiency
  - Modularized
  - Extensible
  - Easy to use



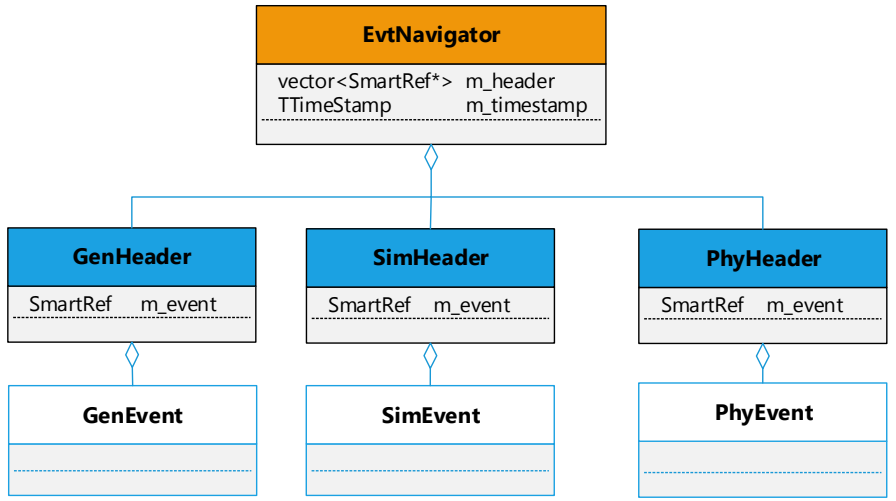
- Help physicists to simplify their own code
  - Common modules & conventions for software standardization
- Attractive features for JUNO
  - Event correlations in data buffer with a time window
  - Event splitting/mixing with multiple-tasks

Event Data Model

- EDM: the data unit to be processed in offline data processing

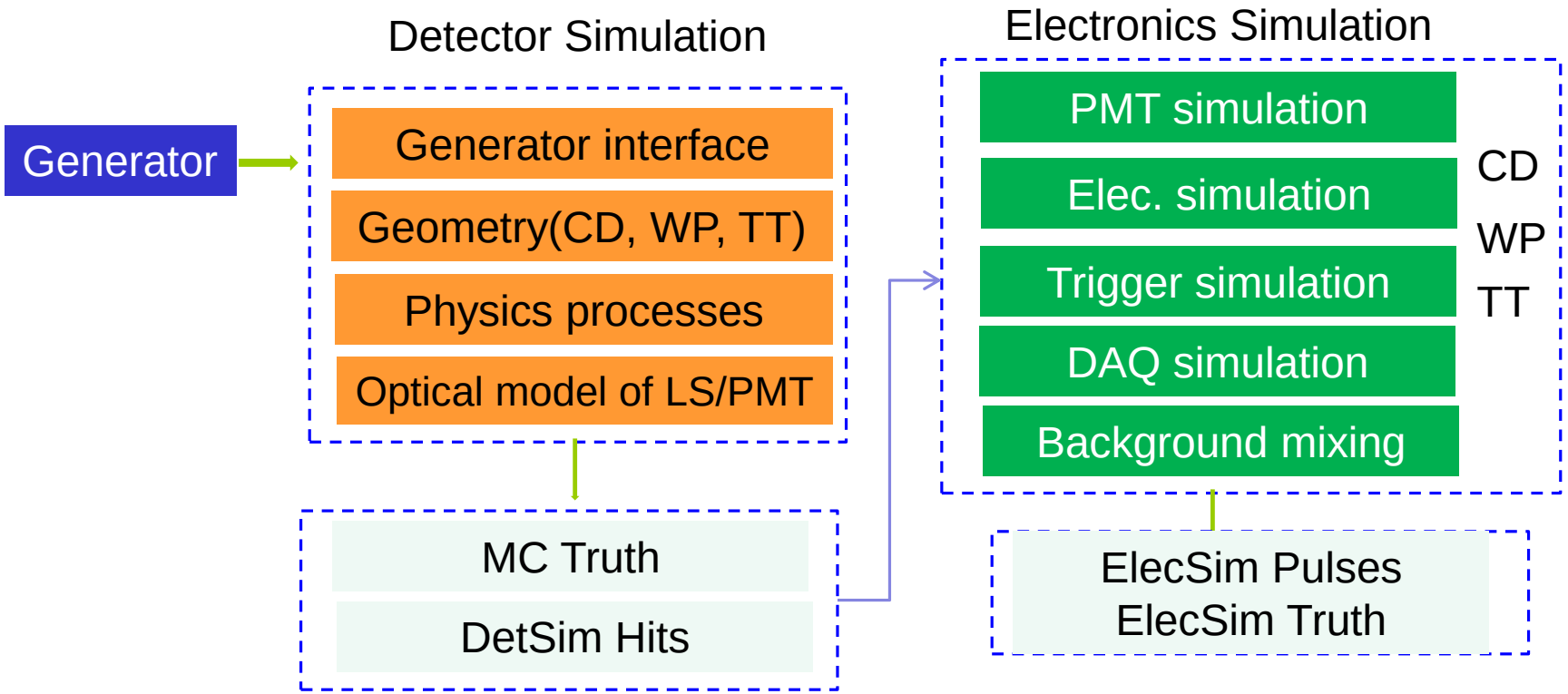


- Design of EDM
  - Two-layer : Header and Event
  - Header contains lightweight data, like “tag”
  - Event contains large and detail data



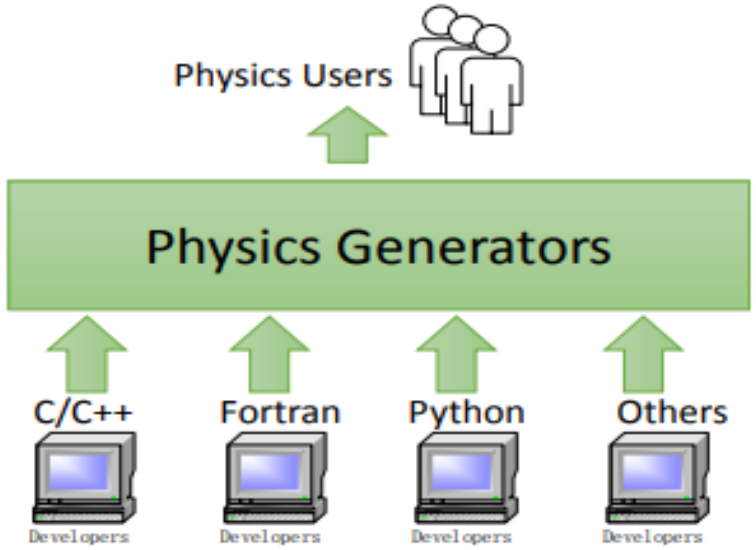
Simulation Software

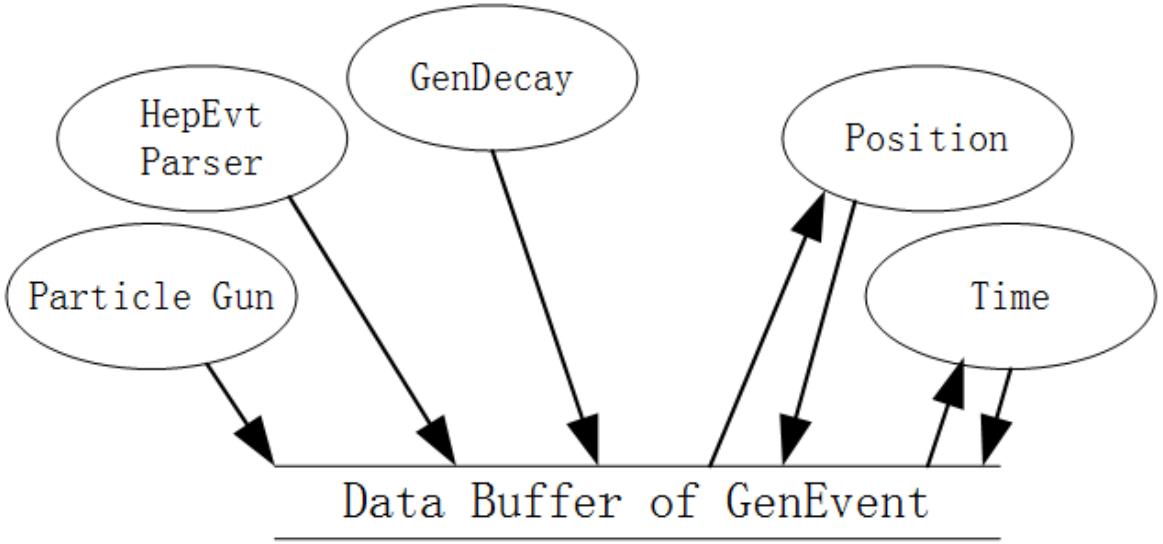
- Detector simulation of JUNO is developed based on Geant4 within SNiPER framework, since 2012
- All components in simulation have been designed and implemented, now focusing on improving and optimizing the simulation software



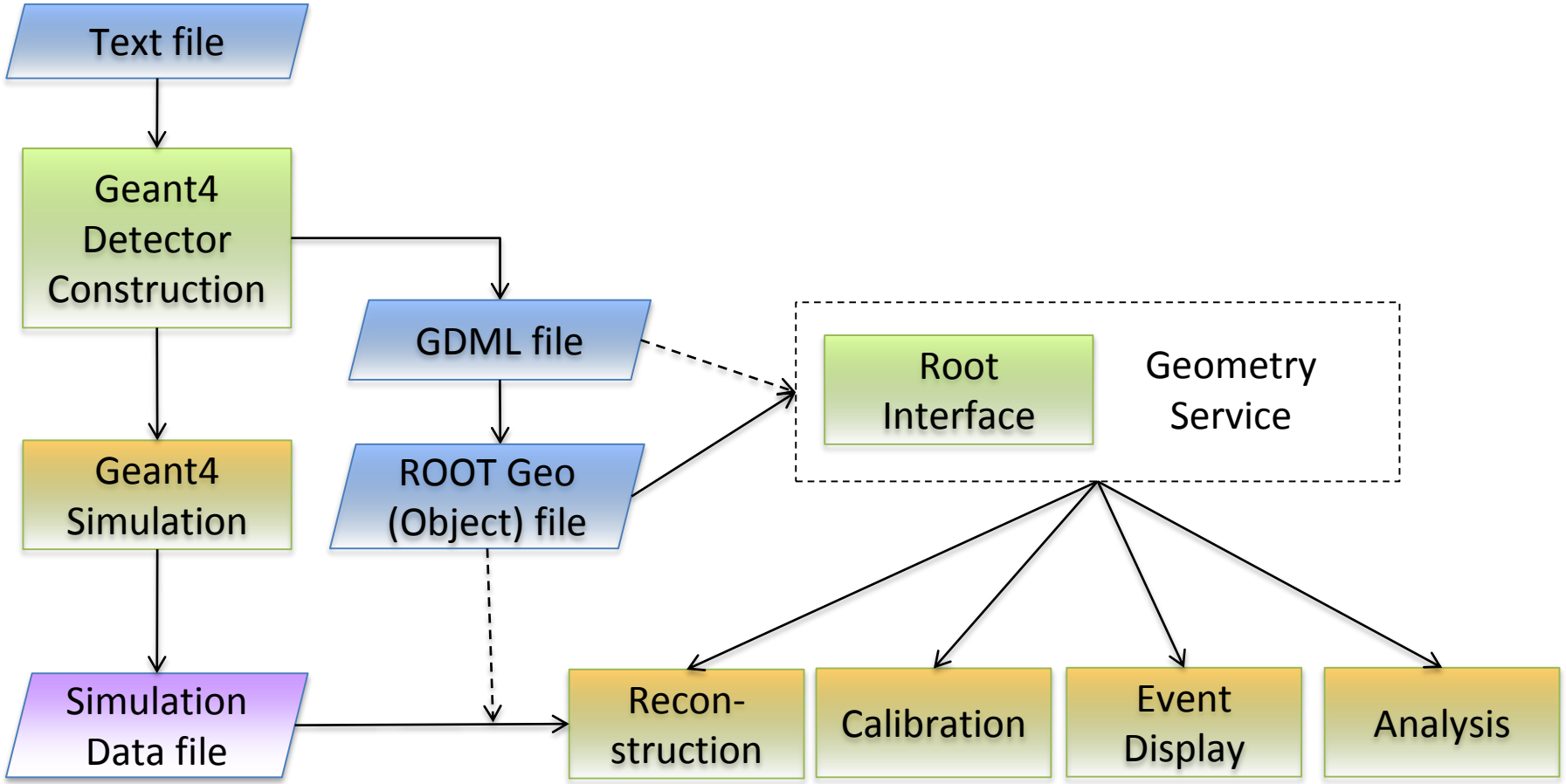
Generators

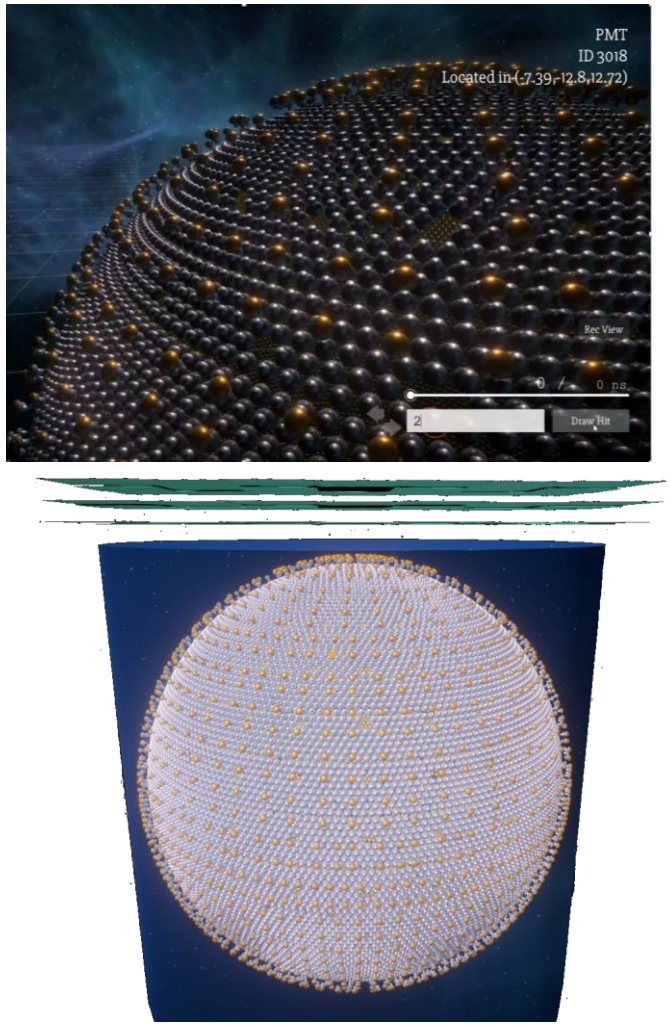
- A flexible generator interface is implemented to handle different types of generators (C/C++, Fortran, Python, …)
- Several tools are developed to extend the functionality, such as positioner tool, time tool, etc.
- A long list of available generators
  - Reactor, DSNB, supernova, solar, atmospheric, geo-neutrinos, radioactivities, calibration, cosmic rays, etc.





Geometry Management

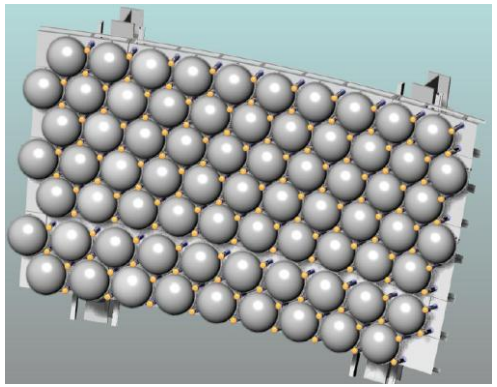


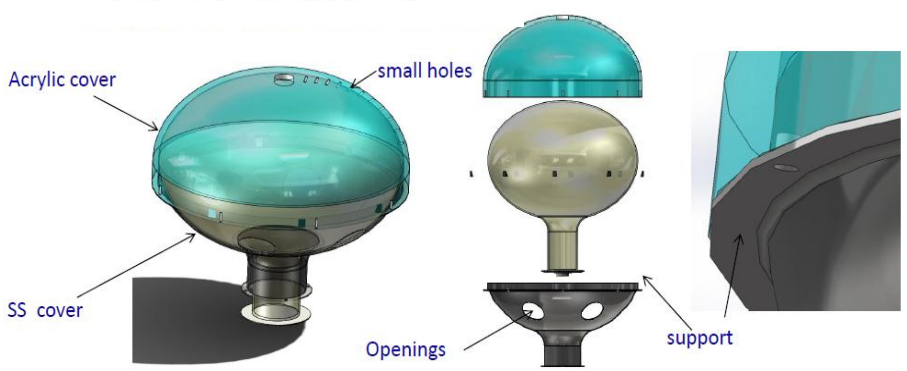


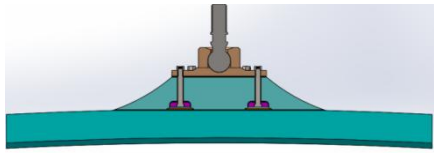
- Geometry bundle with data for consistency.
- The geometry is managed by the geometry service, provided a unified interface to simulation, calibration, reconstruction, etc.

Central Detector Simulation

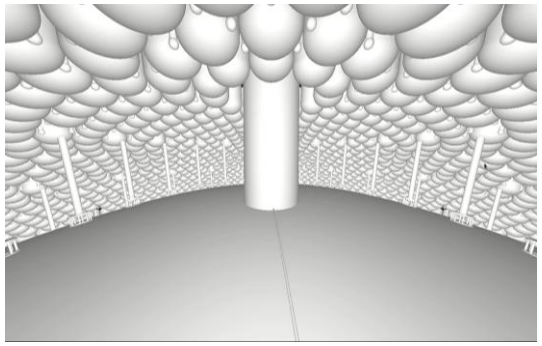
- The geometry of CD has been implemented in simulation, updated to the latest design
  - 17613 20-inch PMTs, 25600 3-inch PMTs
  - Stainless steel connection bars, acrylic node, chimney, PMT protection cover
- SimPMTHit: pmtID, hitTime, timewindow, localtheta, localphi

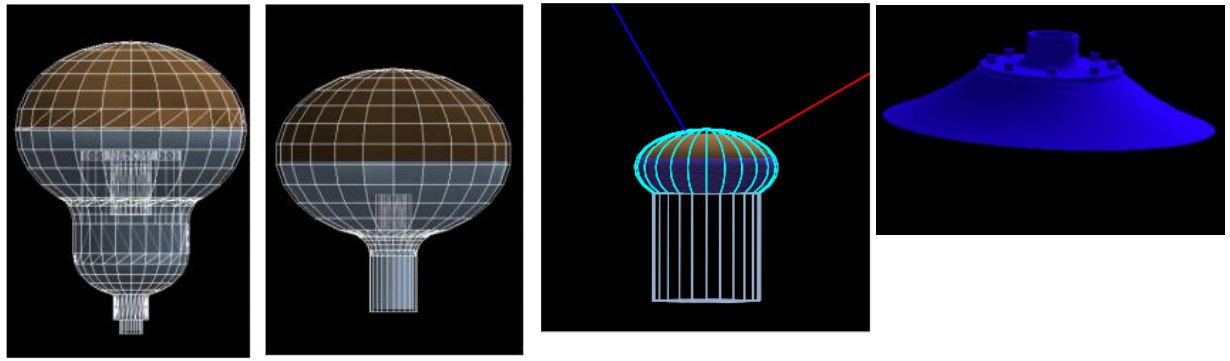






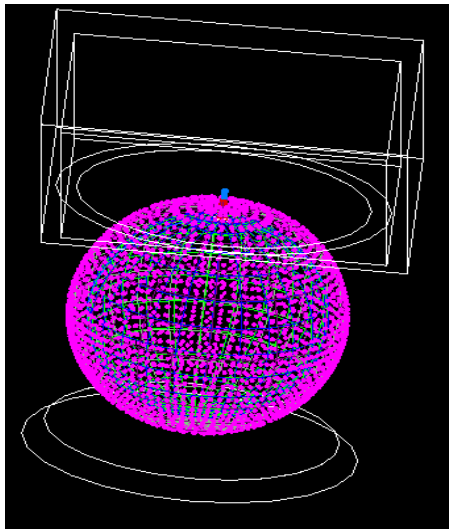
Acrylic node

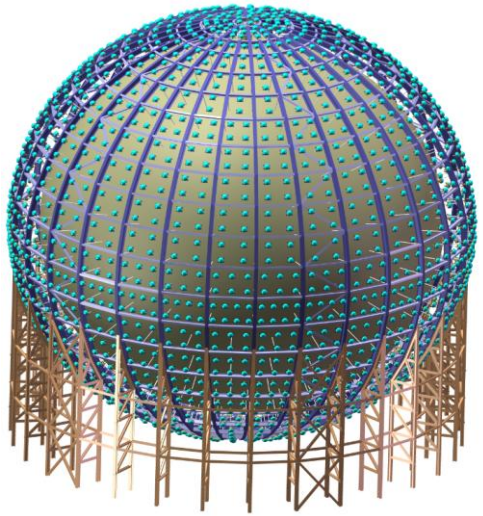




Simulation in Water Cherenkov Detector

- Geometry
  - Veto PMTs on the stainless steel frame updated according to the final design
  - Total veto PMTs: 2400
  - Tyvek are coated on ball surface and water pool wall surface
- PMT Hit
  - Same type as central detector, distinguish from CD PMT hit by ID

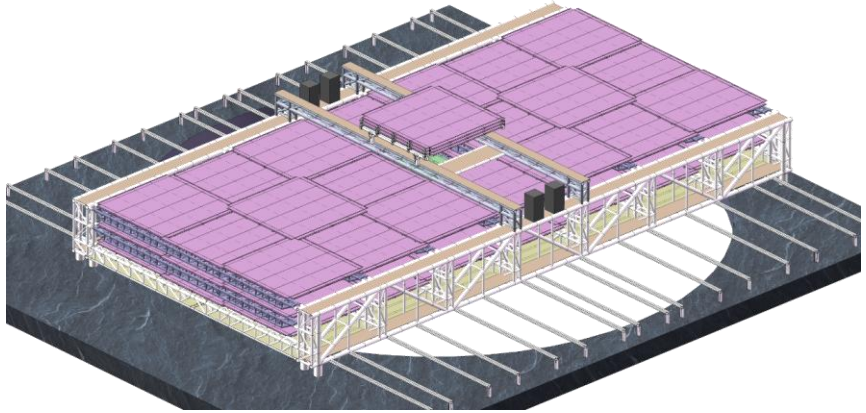


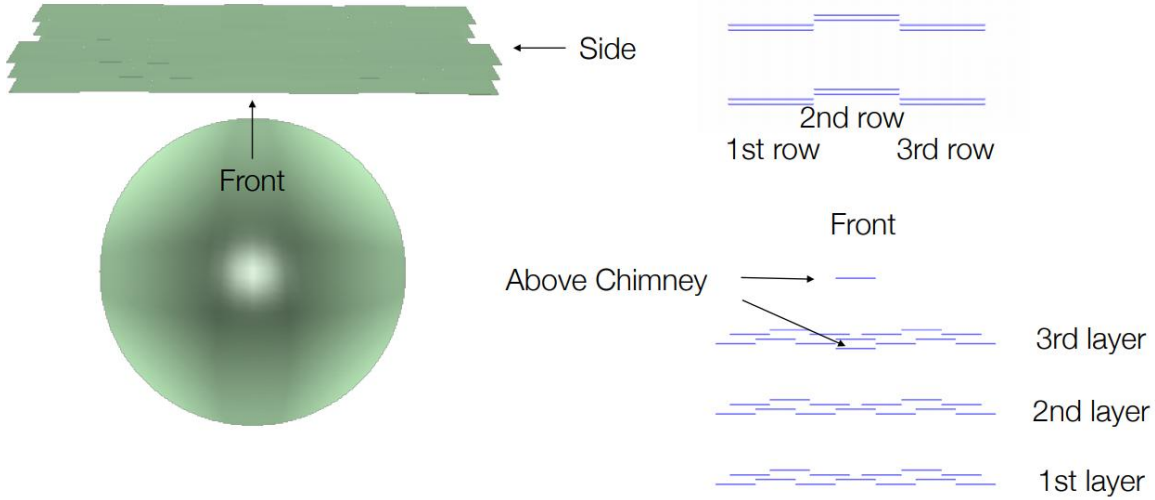


Physics Generator	GenHeader	HepMC	
Detector Simulation	SimHeader	SimEvent	SimTrack SimPMTHit SimTTHit
Electronics Simulation	ElecHeader	ElecEvent SpmtElecEvent WpElecEvent	
	ElecTruthHeader	LpmtElecTruthEvent SpmtElecTruthEvent	

Top Tracker Simulation

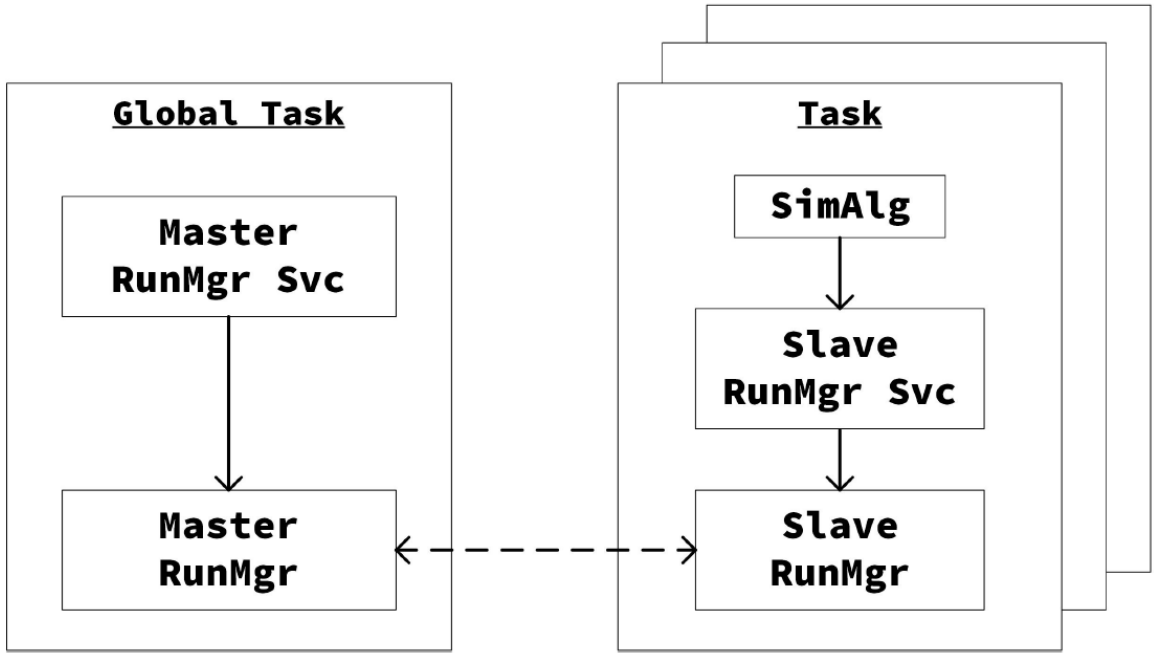
- Geometry
  - TT bars made of plastic scintillator
  - A module is made of 64 bars, a plane is made of 4 modules, a wall is made of 2 planes
  - 3 layers of walls, 1.5 m distance in Z
- PMT Hit
  - SimTTHit

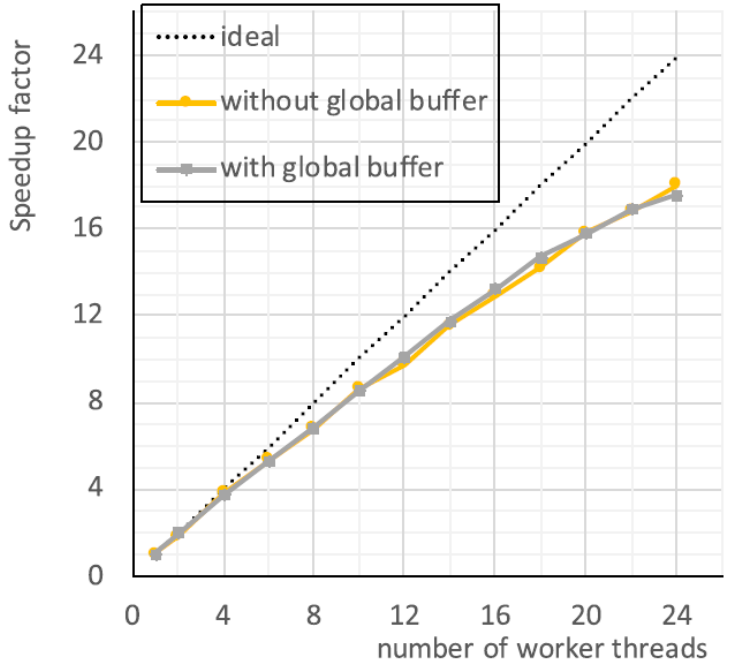




Geant4 Update From 9.4 to 10.4

- Geant4.9.4 release in 2012, only Geant4.10.X support multi-threading
- "Status of the parallelized JUNO simulation software" by Tao Lin at CHEP 2018
  - https://doi.org/10.1051/epjconf/201921402008

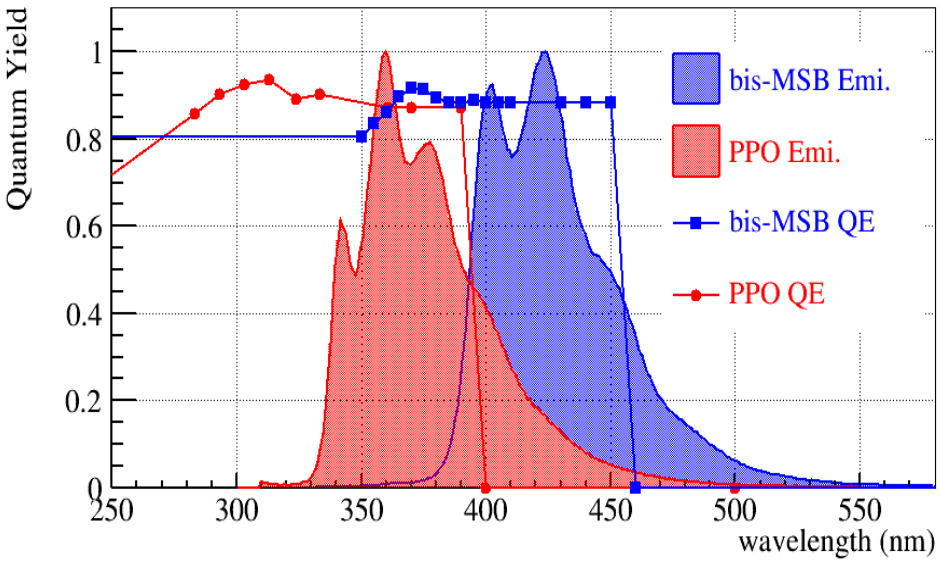




- Latest progress is about the validation of physics processes used in JUNO simulation software based on Geant4.10.4

Physics List in Geant4.10.4

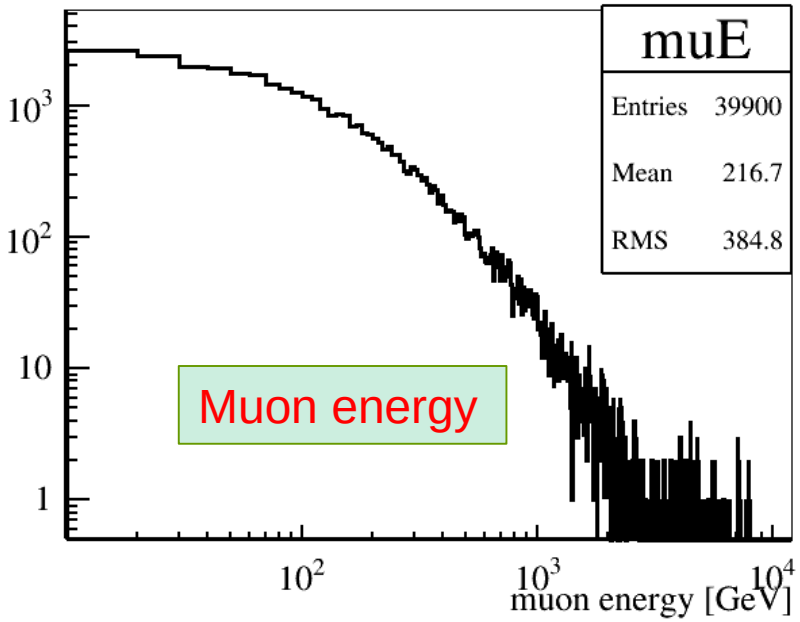
- G4EmLivermorePhysics
- G4EmExPhysics
- G4DecayPhysics
- G4RadioactiveDecayPhysics
  - Modify Li9 and He8 decay
- G4HadronElasticPhysicsHP
- G4HadronPhysicsQGSP_BERT_HP
  - Modify neutron capture
- G4StoppingPhysics
- G4Scintillation
  - Add re-emission in liquid scintillator
- G4OpBoundaryProcess
- G4OpAbsorption
- G4OpRayleigh
- G4Cerenkov

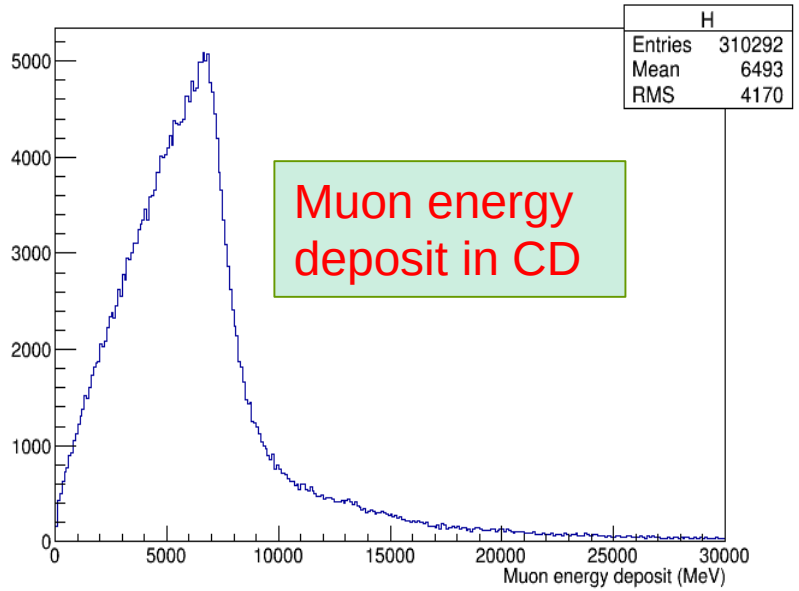


Physics constructors from Geant4.10.4 added into JUNO physics list.
Li9/He8 decay, refer to some papers, modify the RadioactiveData files of Geant4.
Neutron capture, modify gamma energy spectrum and multiplicity.

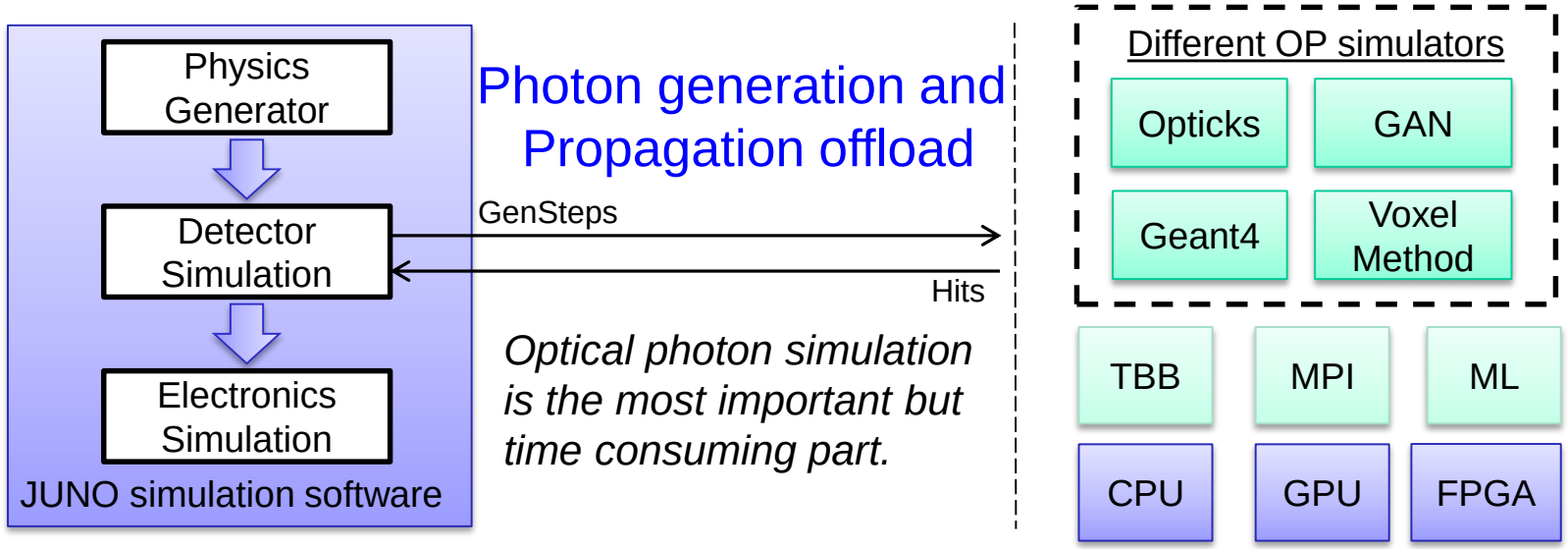
Muon Simulation in Central Detector

- JUNO muon flux level 0.0037 Hz/m^2, central detector muon rate: 4 Hz
- Main backgrounds are cosmic muon induced
- Large simulated muon samples are essential to minimize veto time/volume
- Millions of optical photons to be propagated in liquid scintillator
  - Light yield: 10^4/MeV, deposit 6.5 GeV: generated 65 million photons
- It takes several hours to simulate one event, huge CPU memory + time expense





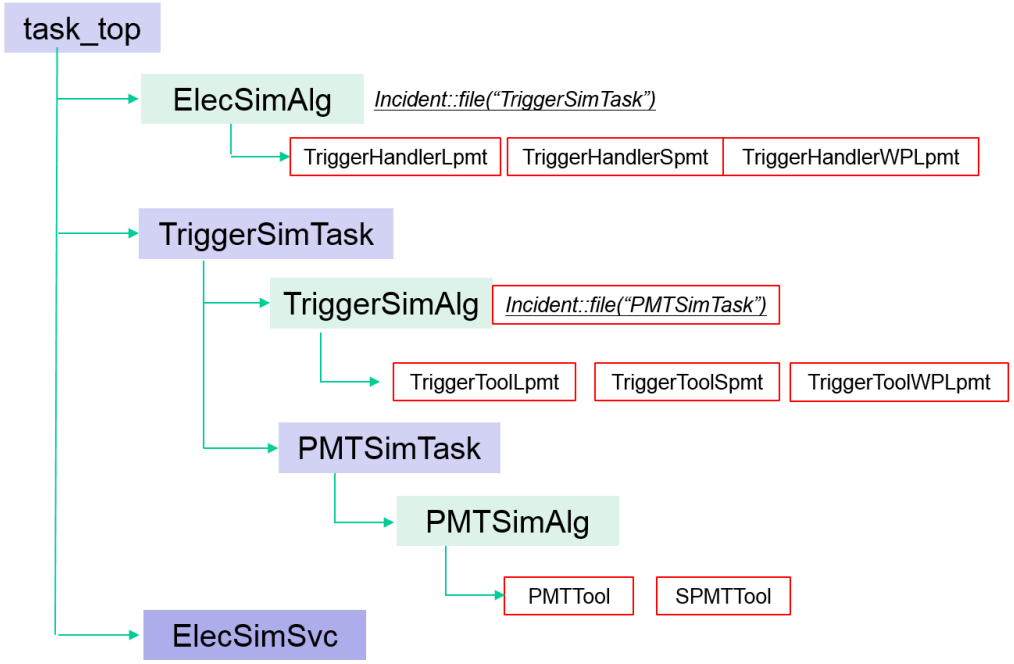
Unified Defered Optical Propagation

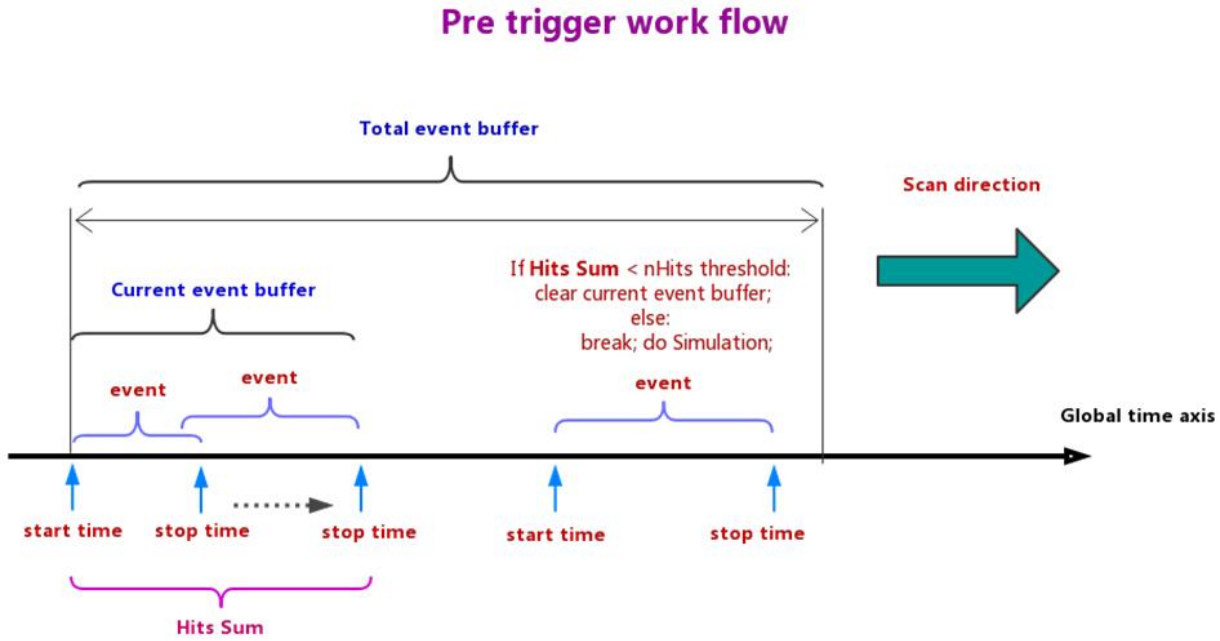


- The key idea is to offload the photon generation and propagation.
  - Speedup: using different accelerators (GPU/FPGA/ML).
  - Memory: reducing the memory usage in the CPU side, e.g. muon & proton decay.
- One of the important features is to defer the OP simulation until we are interested in the events.
- Design: Unified "GenStep" interface
  - General interface "GenStep" for the different OP simulators in different platforms.
  - A modified Geant4 to produce "GenStep" and collect "P.E." asynchronously.

Electronics Simulation

- "Back-driven" strategy is designed and developed for electronics simulation
  - Well handling of time correlation, well management of memory
- Work in pipe-line mode; "hit-level" background mixing
- PMTSim: use numbers from PMT testing
- Detailed implementation for electronics and trigger based on current design

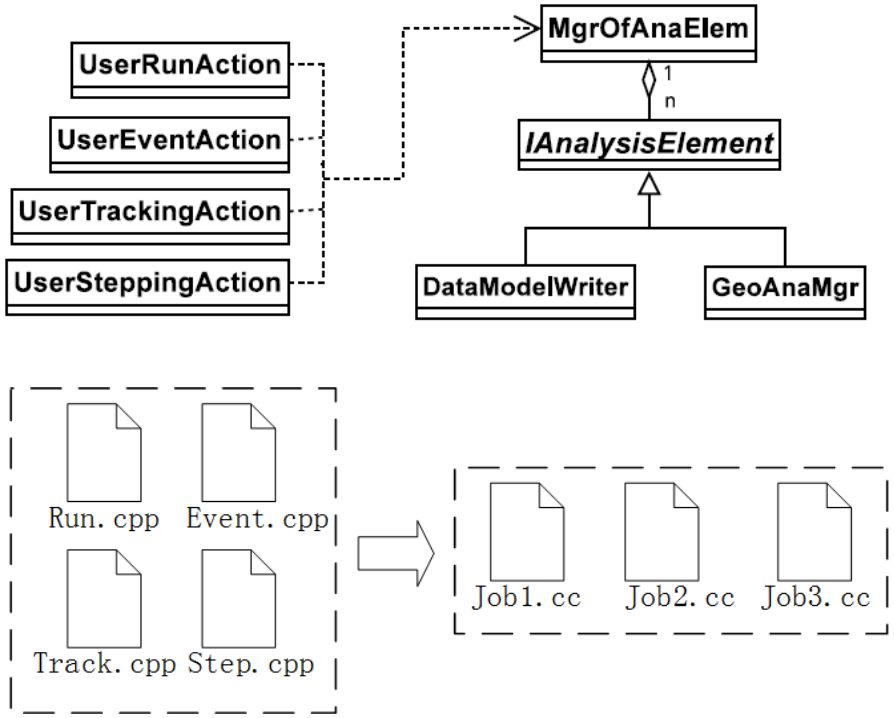


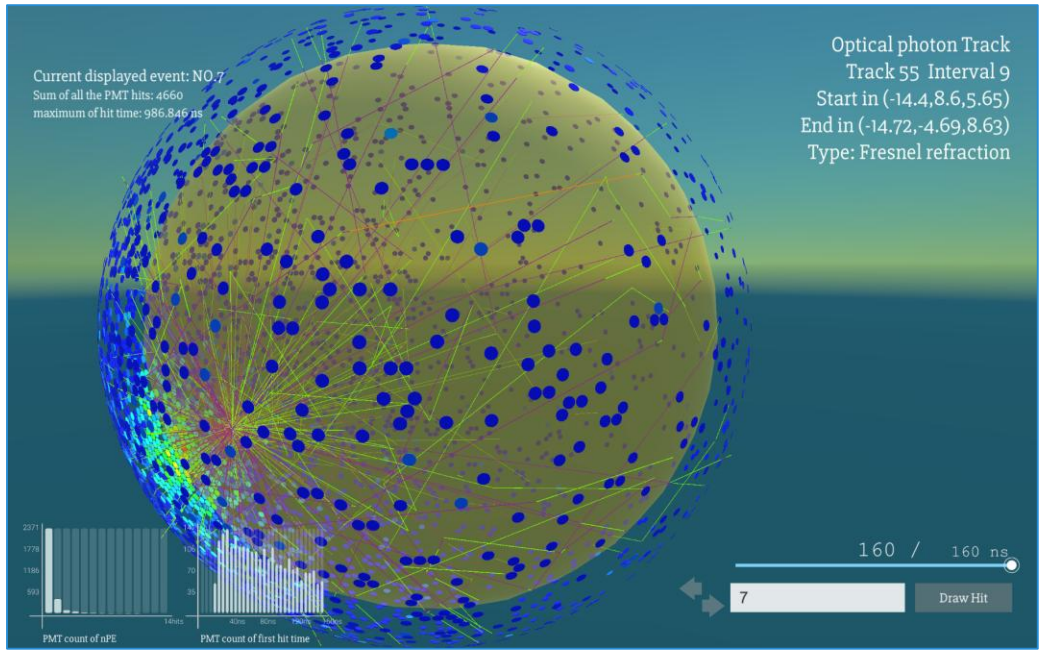


Add nHits and timeWindow in DetSim SimHeader

MC Truth

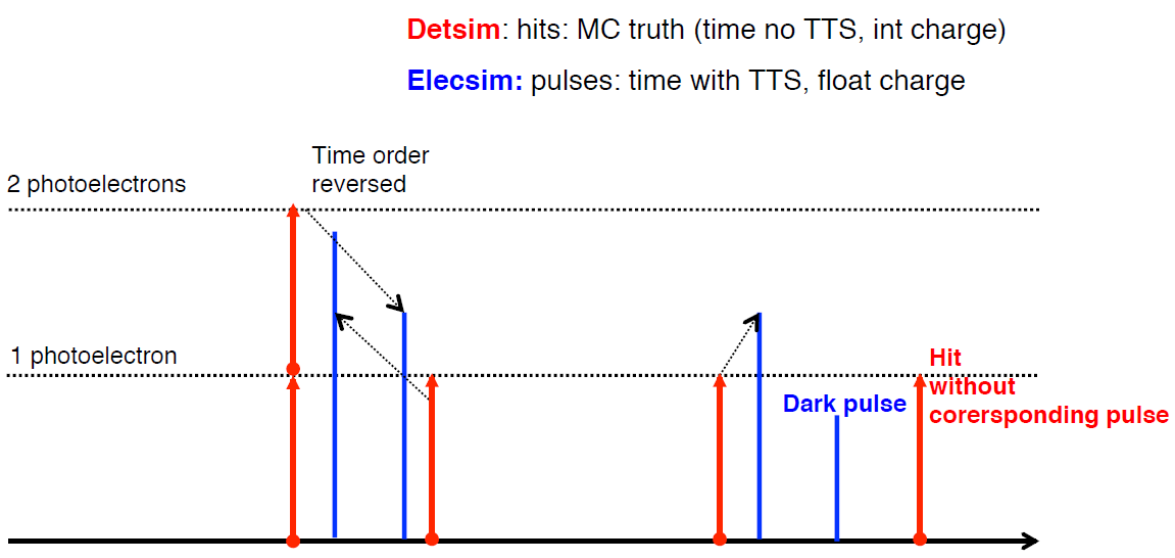
- Detector simulation
  - Analysis element as independent Tool in SNiPER framework
  - Each kind of analysis element for one dedicated kind of MC truth information
  - Can record truth info during Geant4 Run/Event/Tracking/Stepping

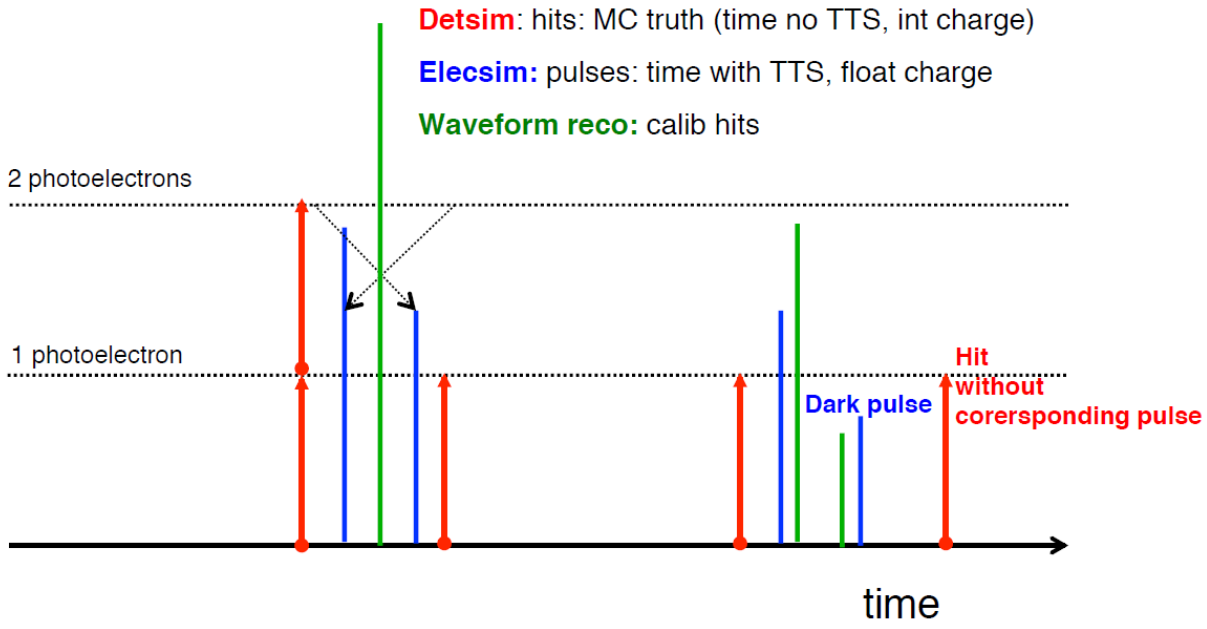




MC Truth

- Electronics simulation
  - ElecTruthHeader added to match DetSim hits and ElecSim pulses
  - LPMT and sPMT ElecTruth added independently
  - Output ElecTruthHeader together with ElecHeader



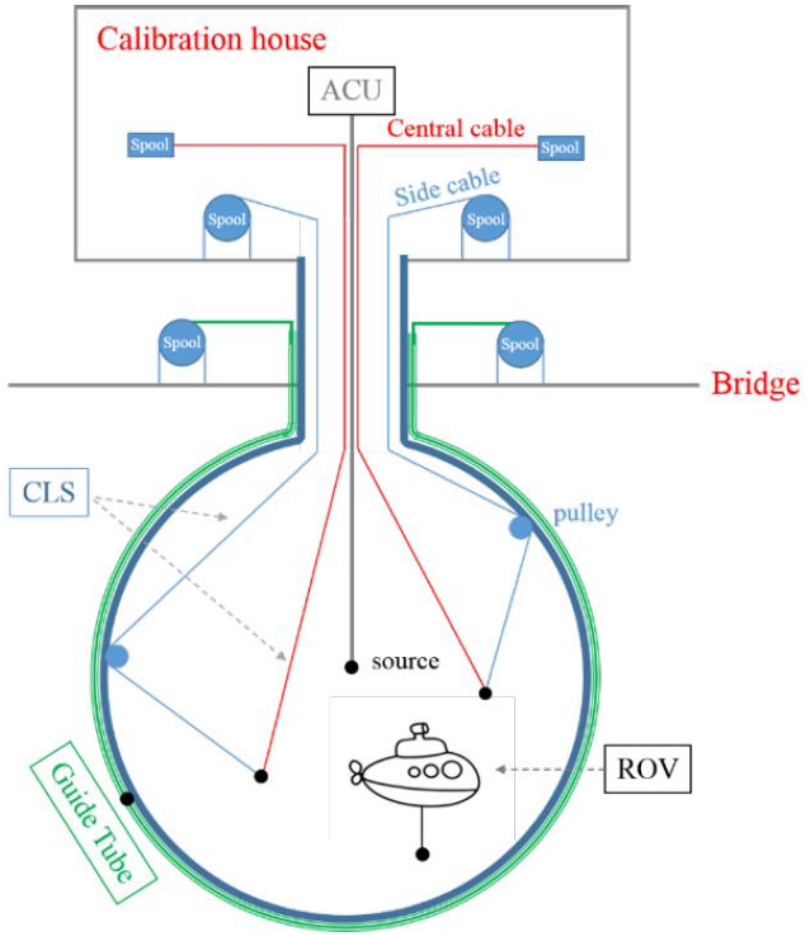


Computing Performance

- Calibration samples have been generated to study the calibration strategy
  - Calibration source, 100 Hz
    - ^{60}Co, ^{68}Ge, ^{137}Cs, Am-C, Laser
  - Background mixing, ^{14}C, 40000 Hz
  - Position: ACU/CLS/GT calibration system

Calibration source, Co60, 1.33 MeV+1.17 MeV)	
Detector Simulation	
Size/event	0.09 MB
CPU time/event	3.7 s
Electronics Simulation	
Size/event	4.9 MB
CPU time/event	1.2 s

ACU: Automatic Calibration Unit
CLS: Cable Loop System
GT: Guide Tube
ROV: Remotely Operated under-liquid-scintillator Vehicles

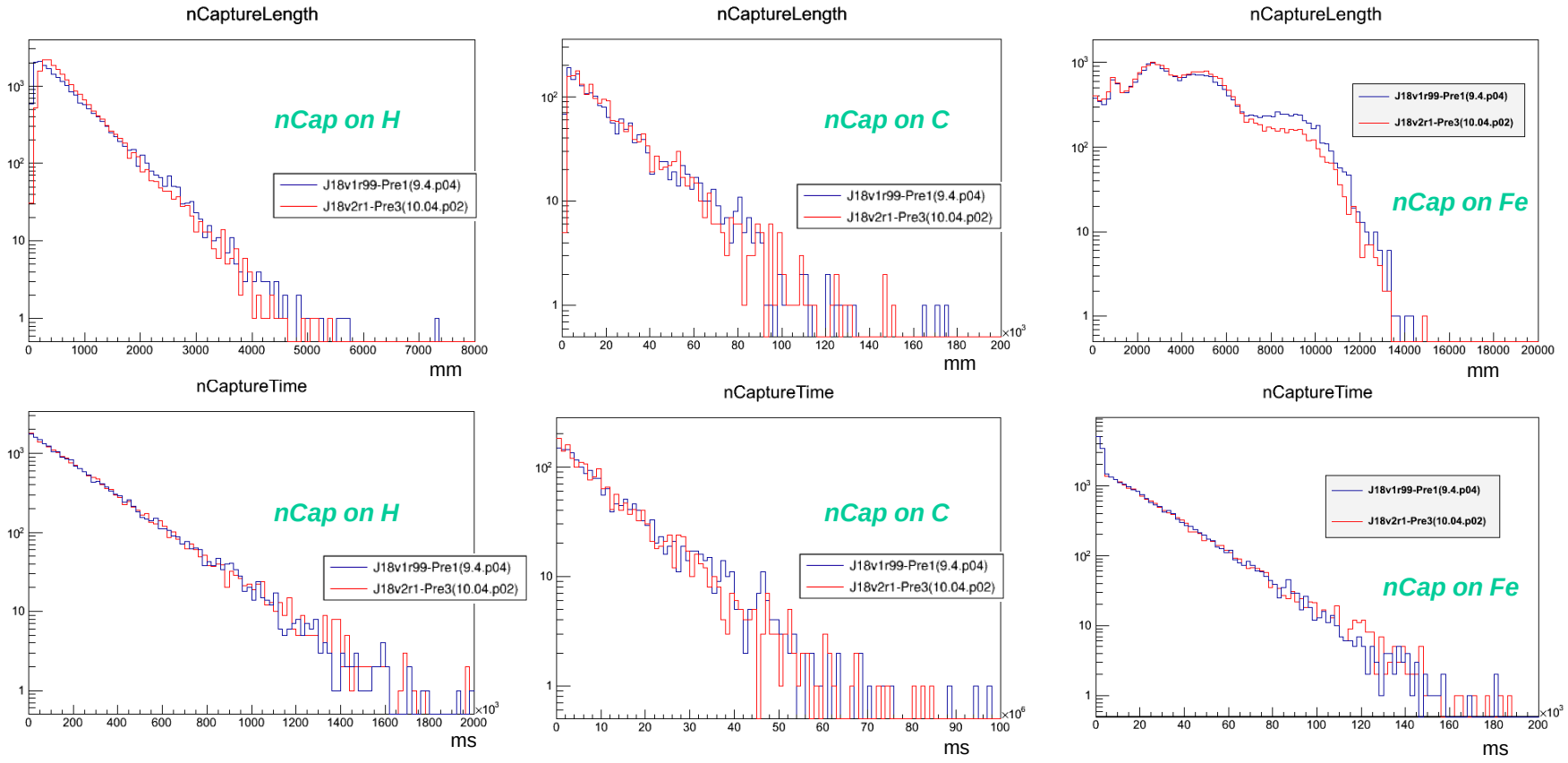


Summary and Outlook

- All components in simulation have been designed and implemented in SNiPER framework
- Latest detector simulation software released based on Geant4.10.4, with some physics processes modified for JUNO experiment
- Electronics simulation supports “PULL” workflow, allows hit level mixing
- The full data processing chain and data production is ready
- Muon simulation is a big challenge
  - GPU optical photons simulation based on Opticks is under validation
  - A unified deferred optical propagation is under development

backup

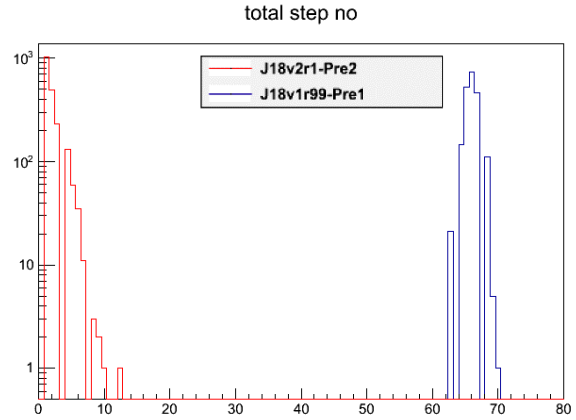
Validation of Geant4 update



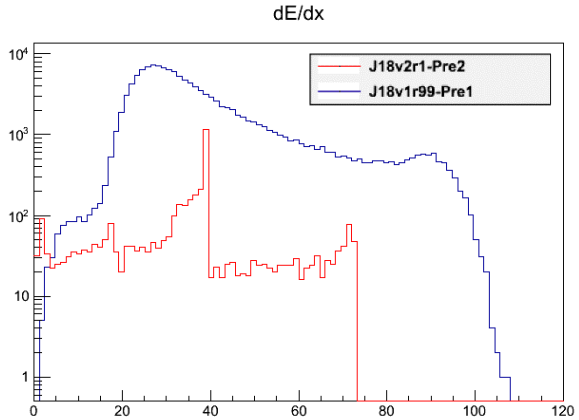
Neutron capture processes from DAYABAY replace the one in Geant4.10 G4HadronPhysicsQGSP_BERT_HP

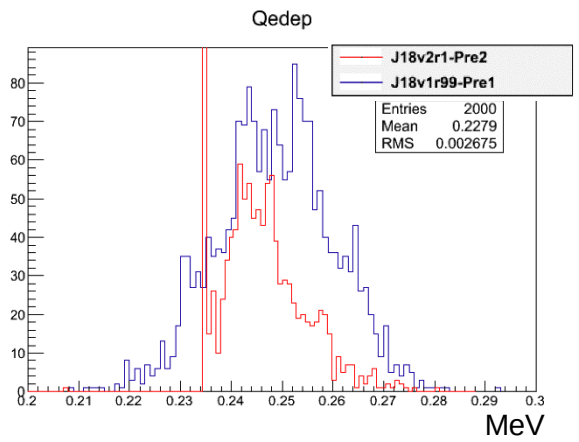
Validation of Geant4 update

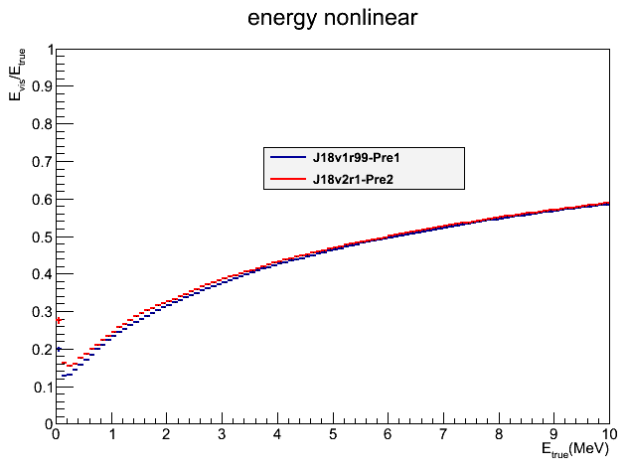
proton@(0, 0, 0) $E_k = 1MeV$



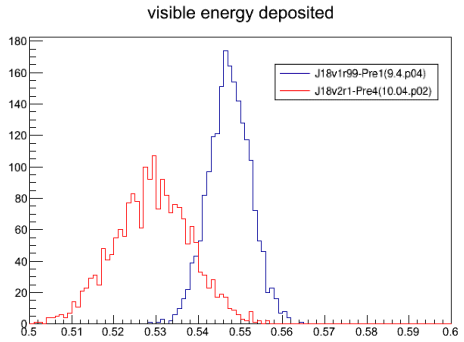
more steps in old version

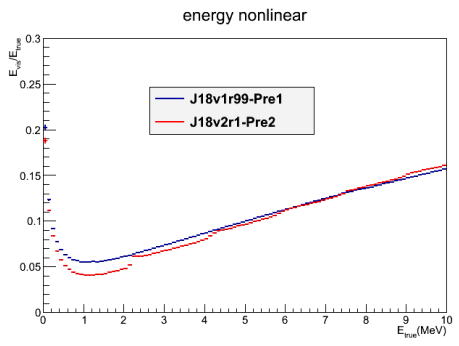






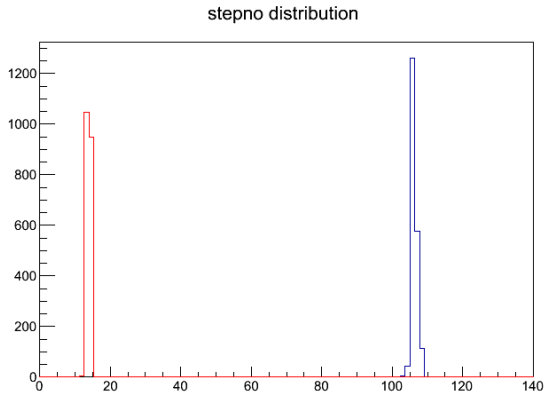
5.3MeV alpha@(0, 0, 0)

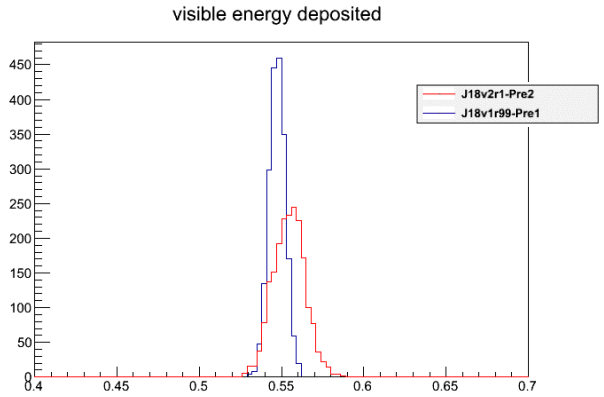


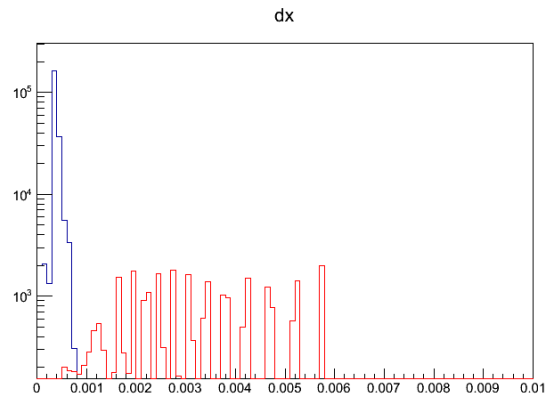


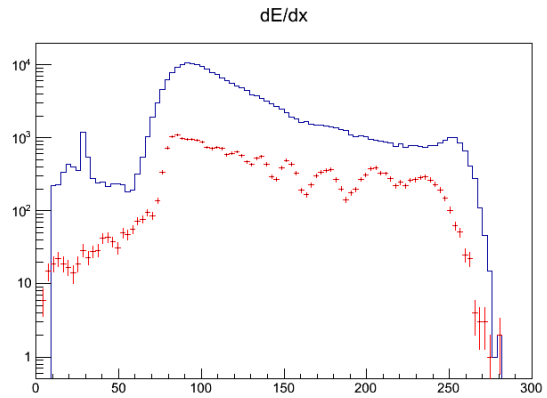
Different energy loss model at low energy, *G4hLowEnergyIonisation(G4.9)* changed to G4ionIonisation(*G4BraggIonModel) (G4.10),* ***SetStepFunction*** *can change the step number and dE/dx distribution*

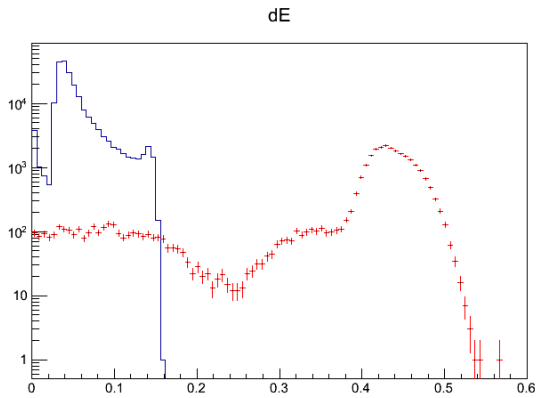
Geant4 update





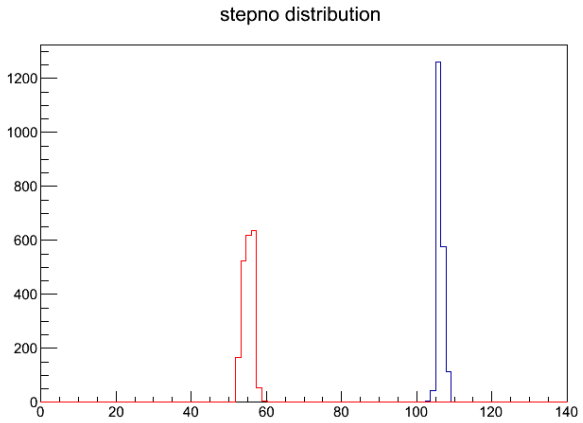


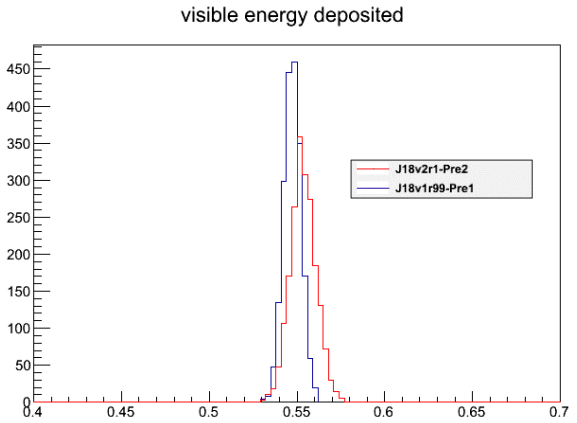


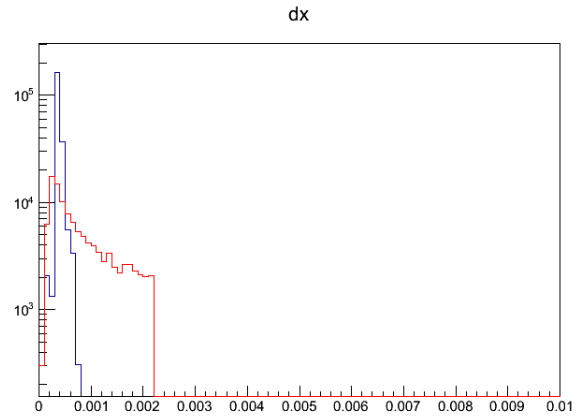


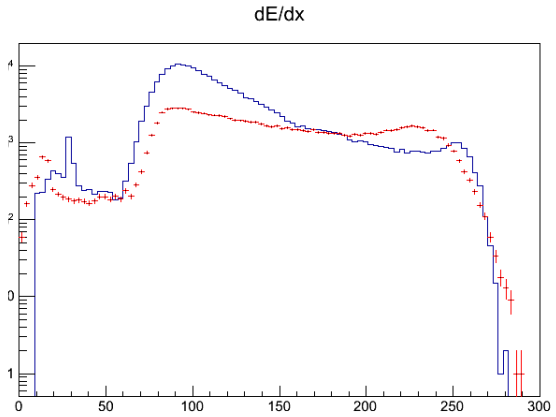
SetStepFunction(0.1, 1um)

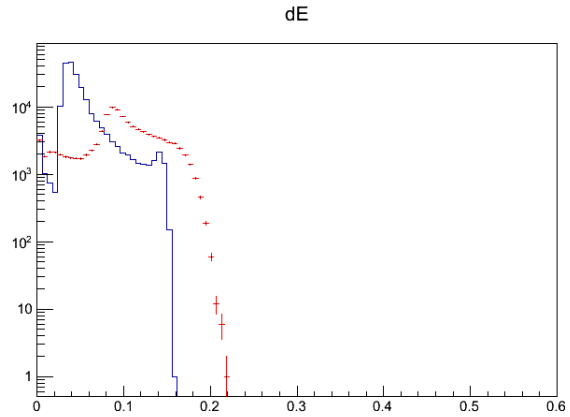
Geant4 update





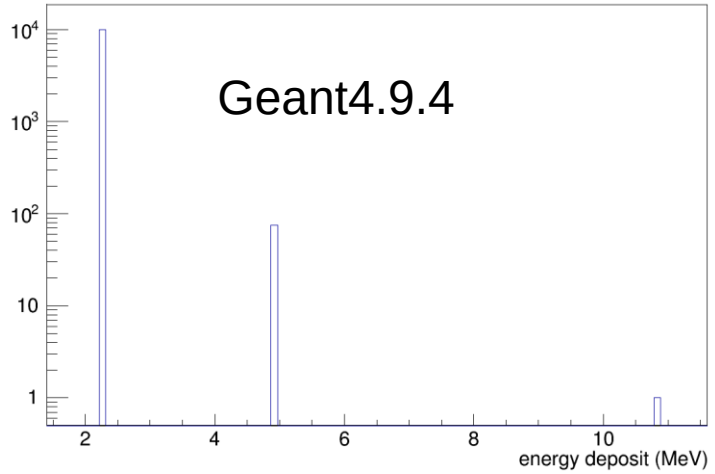


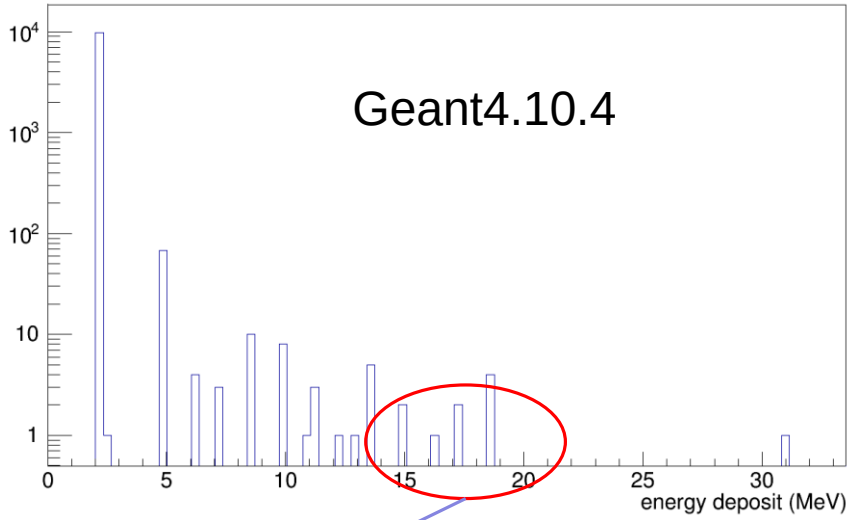




SetStepFunction(0.05, 0.1um)

Neutron capture

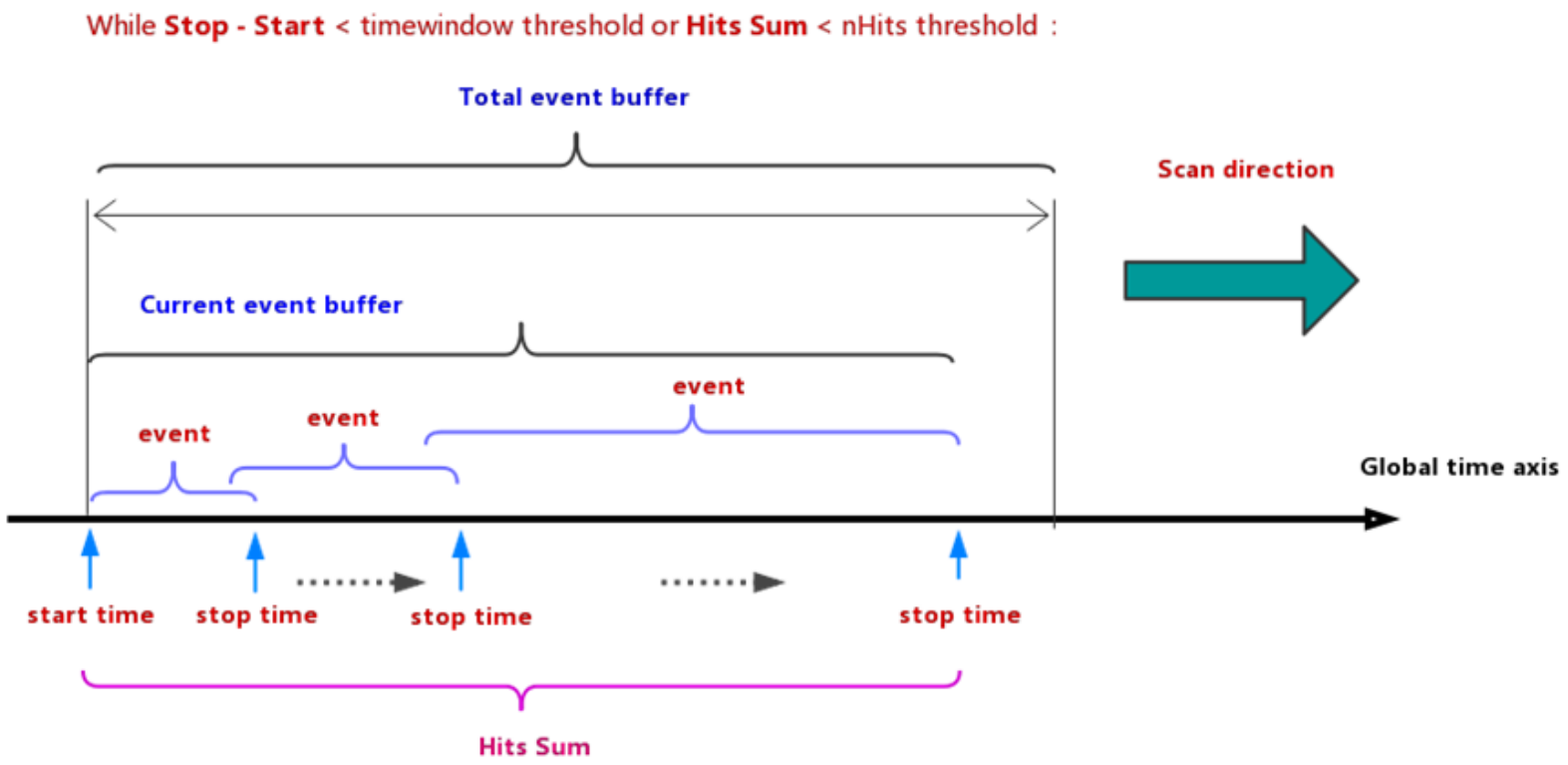




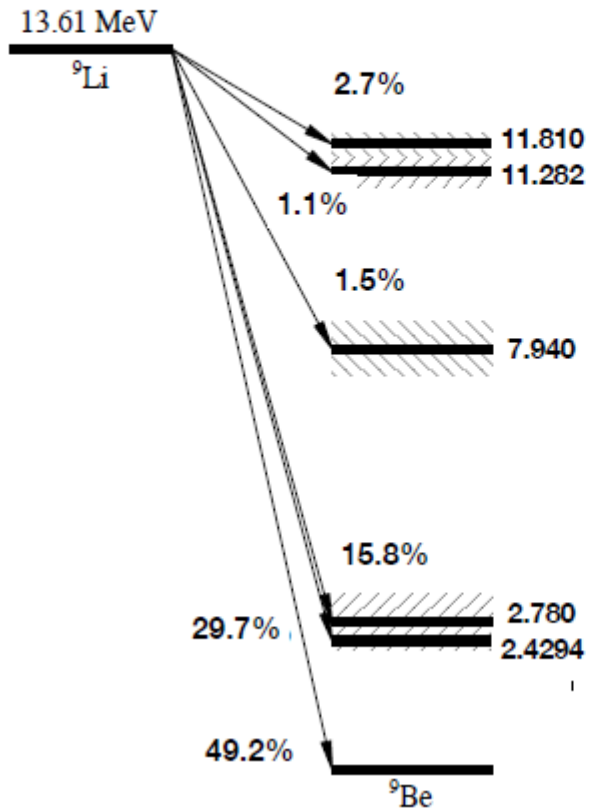
C13 + Gamma: 4.94651 Gamma: 4.94649 Gamma: 4.94651	C13 + Gamma: 4.9465 Gamma: 4.94649 Gamma: 3.68399 Gamma: 3.684	C13 + Gamma: 4.94651 Gamma: 4.94649 Gamma: 4.94651 Gamma: 3.68399	C13 + 4 Gamma: 4.9465 3 Gamma: 3.684

Electronics Simulation

Pre trigger work flow

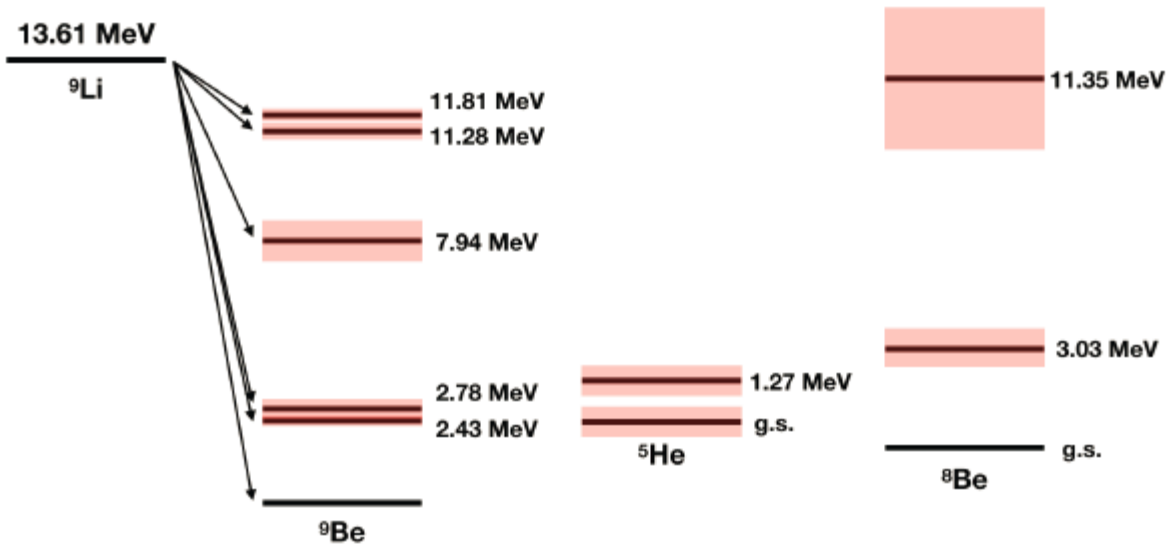


^{9}Li decay scheme



- ^{9}Li decays by β decay to ^{9}Be excited states.
- 6 branches are allowed.
- The hatches zone represents the uncertainty of the energy levels.
- In RadioactiveDecay5.3 of GEANT4 version 10, all the excited states decay to the ground state emitting a γ ray.

- In reality all the ^{9}Be states at energy above 1.57 MeV decay emitting 2α+1 neutron and therefore they constitute a background for IBD.



- For each excited state we looked for the correct decay scheme and we implemented it in RadioactiveData files of GEANT4.