Fermilab
U.S. DEPARTMENT OF ENERGY | Office of Science

HEP Example

Soon Yung Jun (Fermilab)

12th International Geant4 Tutorial in Korea,

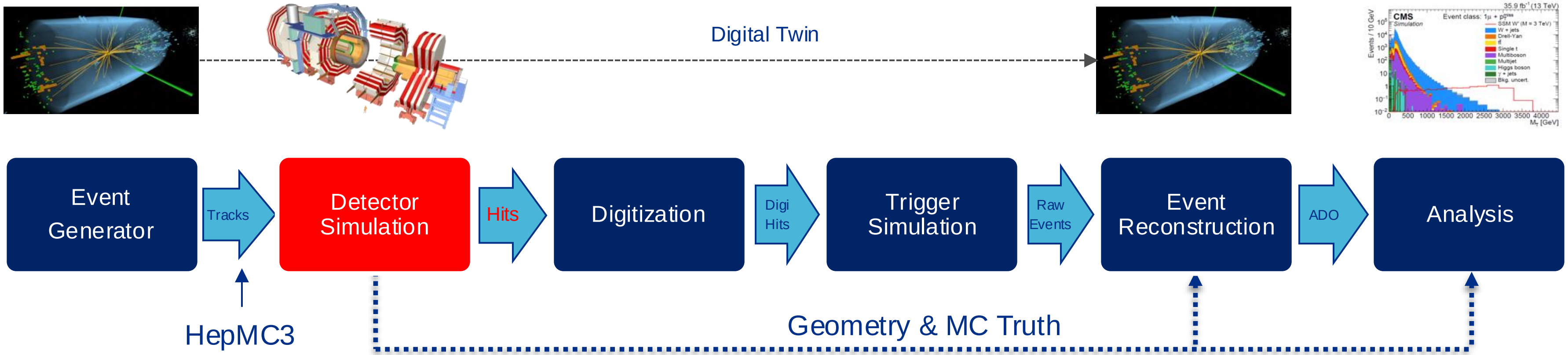
Feb 3-7, 2025@Pohang Accelerator Laboratory, Pohang

Contents

- A quick review of HEP experiments
  - Selected on-going and upcoming experiments
  - Geant4 and MC expert guidelines (personal view)
- HEP Examples
  - Selected Geant4 examples for HEP
  - Hands-on/Homework

Typical HEP Detector Simulation Workflow

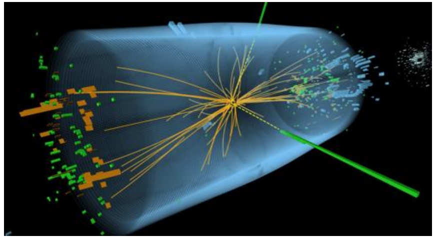
- Typical sequence of HEP detector simulation



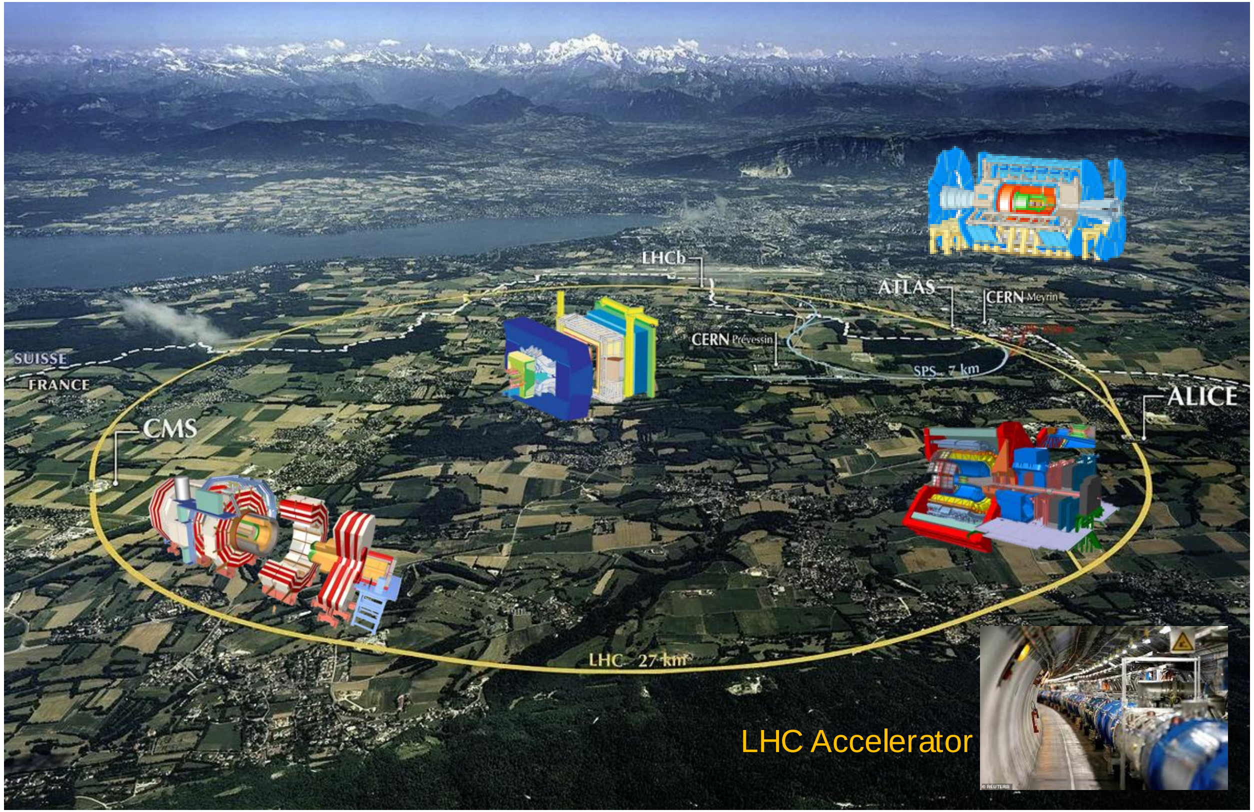
  - Event Generator: Parton Level (Madgraph, Serpa, …), PYTHIA, HERWIG, etc.
  - Event Decayer: EvtGen, tauolar, etc.
  - Detector design, optimization and event simulation: Geant4 (de-factor standard)
- Offline framework: CMSSW, Athena, Gaudi/Gaussino, BACCARAT, art, dd4hep, key4hep, …
  - Workflow management

Energy Frontier: Experiments at Large Hadron Collider (LHC)

- LHC → HEP Events



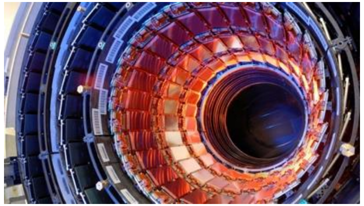
- Detectors at LHC
  - ATLAS
  - ALICE (Heavy Ion, QGP)
  - CMS
  - LHCb (B-factory)
- PhysicsLists
  - FTFP variants

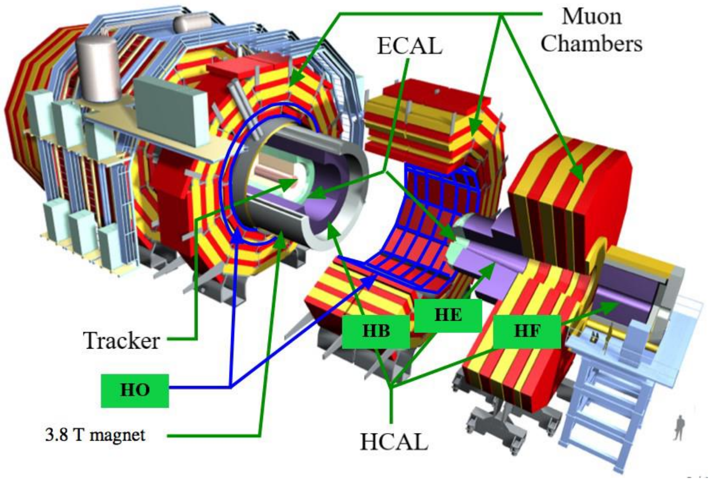


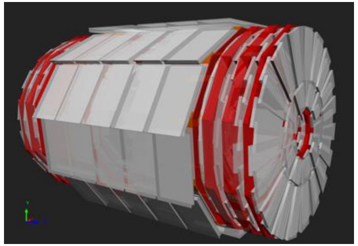
- ATLAS/CMS: study the properties of the Higgs boson, search for DM and BSM, etc.

General-Purposed Detectors for High Energy Physics

- Collider detectors designed with extensive hermetic coverage
  - Vertex detectors and central trackers: vertex, momentum → Si Pixels/Strips, gaseous or fiber trackers
  - EM and Hadron calorimeters: energy, jet → crystals, sampling (MWPCs, plastic scintillator, LAr, etc.)
  - Muon detectors: muon momentum → wire chambers, RPC, etc.
  - Particle identification (RICH), timing, etc.



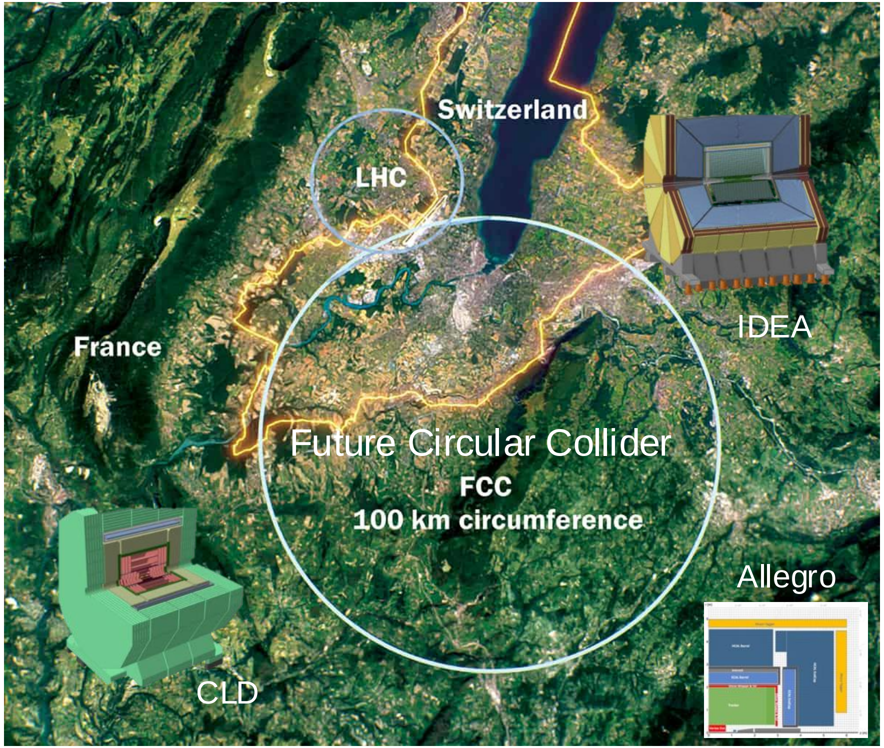


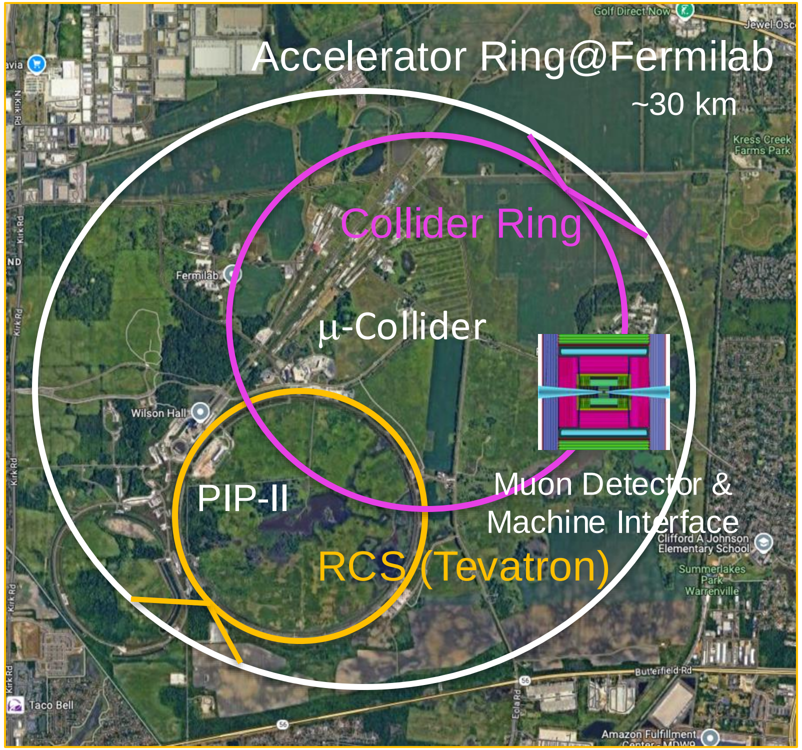


Future Colliders and Detector Concepts (I)

91-240-365 GeV

- Higgs Factory and the beyond (proposals and R&D): FCC-ee/hh (100TeV), μ-collider (10TeV)

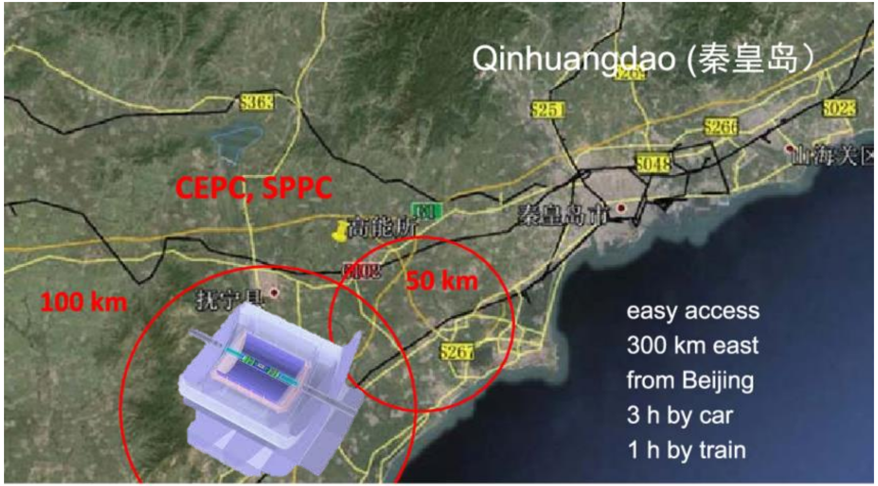




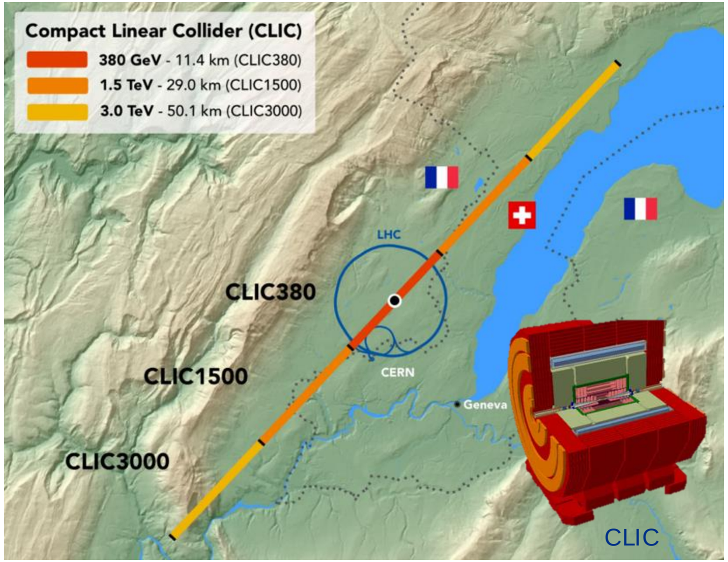
- Geant4 plays a crucial role for developing, optimizing detector concepts and machine interfaces

Future Colliders and Detector Concepts (II)

- Chines Circular Electron Positron Collider & Super Proton-Proton Collider (70 TeV, 100km)



- Future Linear Colliders (???)
  - Compact Linear Collider (CLIC)
  - *HW, Ht, HHH* couplings and …

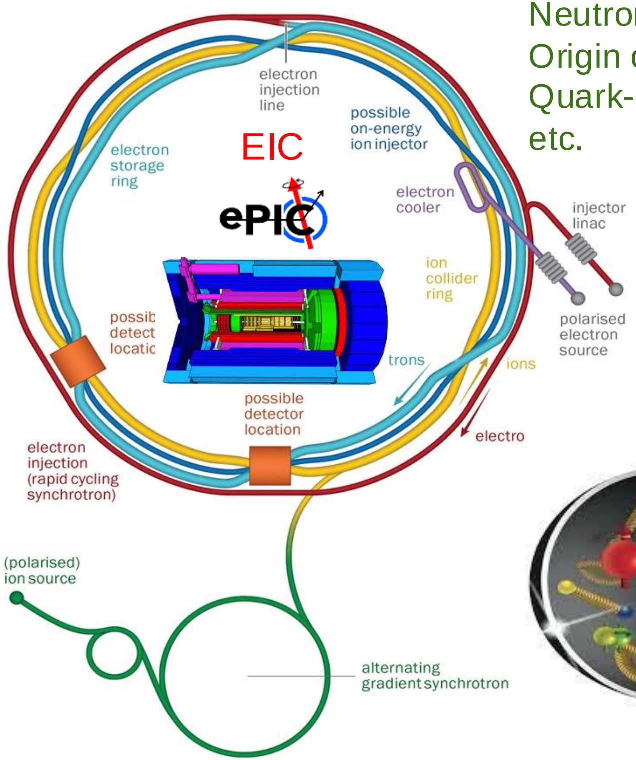


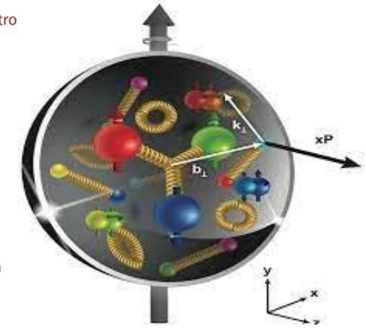
  - International Linear Collider (ILC) in Japan

Future Colliders (III) – *ep* Facilities and Detectors

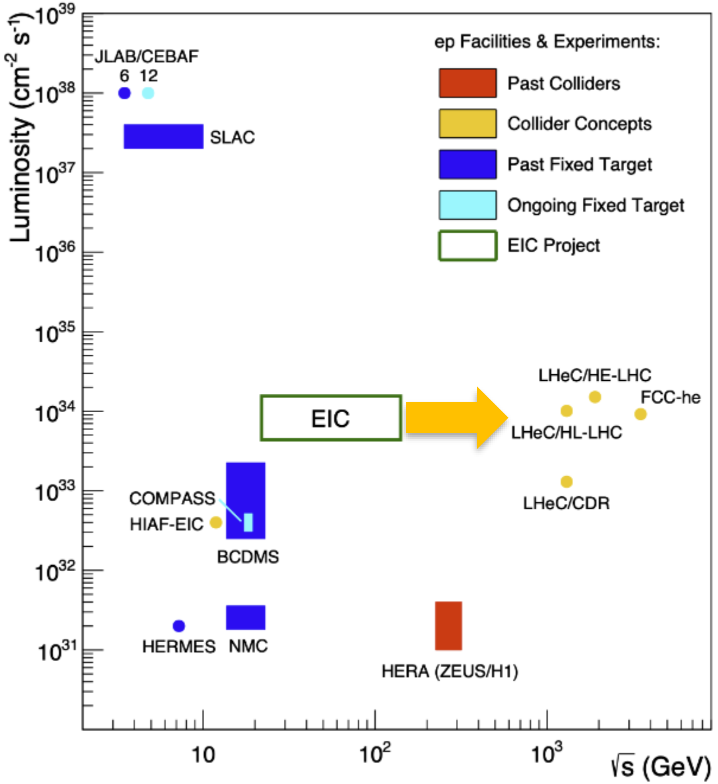
- EIC (Electron-Ion Collider): High-luminosity e-p collider (US BNL/JLab) and ePIC detector

Neutron structure
Origin of neutron mass
Quark-Gluon Plasma
etc.





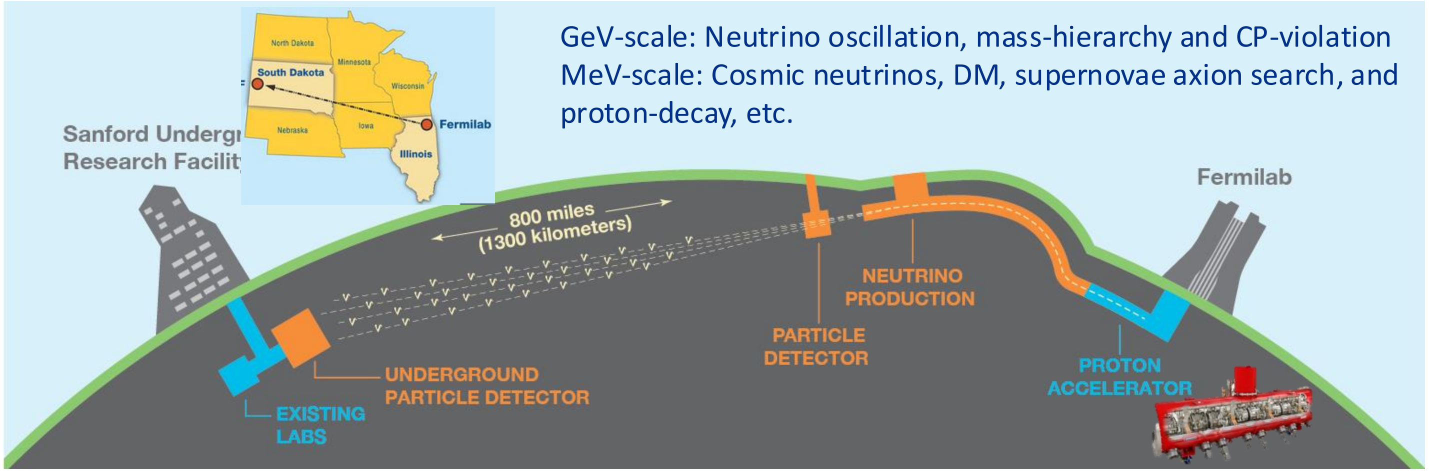
Future *ep* Collider Concepts



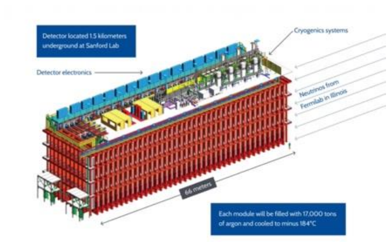
Neutrino Experiments and Detector Technologies

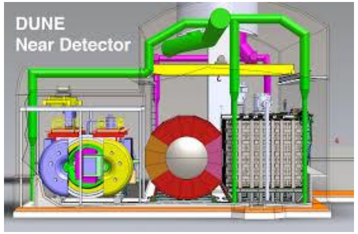
- DUNE (Deep Underground Neutrino Experiment)/LBNF@US with LAr-TPC

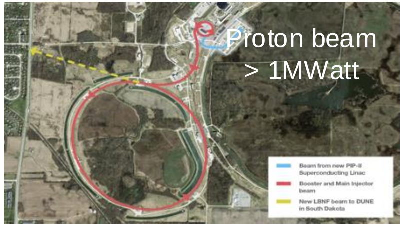
GeV-scale: Neutrino oscillation, mass-hierarchy and CP-violation
MeV-scale: Cosmic neutrinos, DM, supernovae axion search, and proton-decay, etc.



Far Detector
10 kiloton
Liquid Ar-TPC



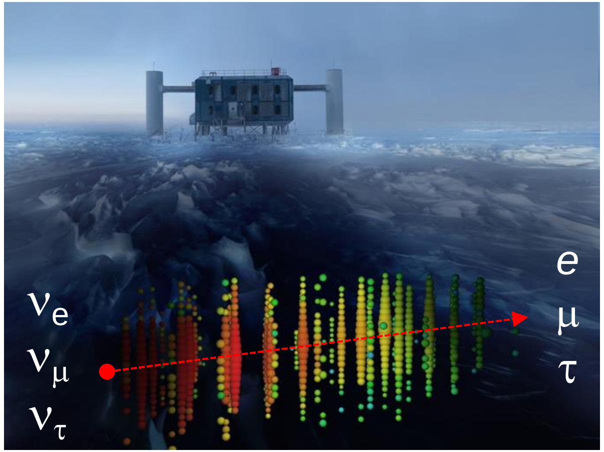


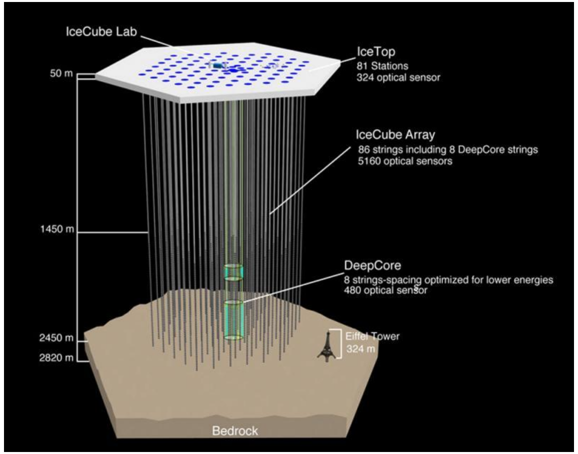


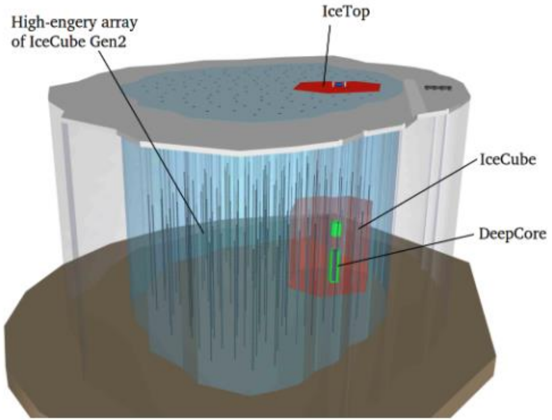
- Hyper-Kamiokande: a water (258 kton) Cherenkov detector, located 295 km from J-PARK

Cosmic Frontier

- IceCube at the South Pole
  - Detects high-energy cosmic neutrinos and probes astrophysical sources (100 GeV – PeV scale ν Cherenkov neutrino telescope) – Points source of high energy ν, gamma-ray burst, supernovae, etc.)
  - Neutrino oscillation and mass hierarchy, Indirect dark matter search (WIMP), sterile-ν search, etc.
  - Array of strings of digital optical modules (PMTs and a single module data acquisition board)
  - IceCube-Gen2 (~2033) for TeV to EeV scale ν physics for the new era of multi-messenger astronomy



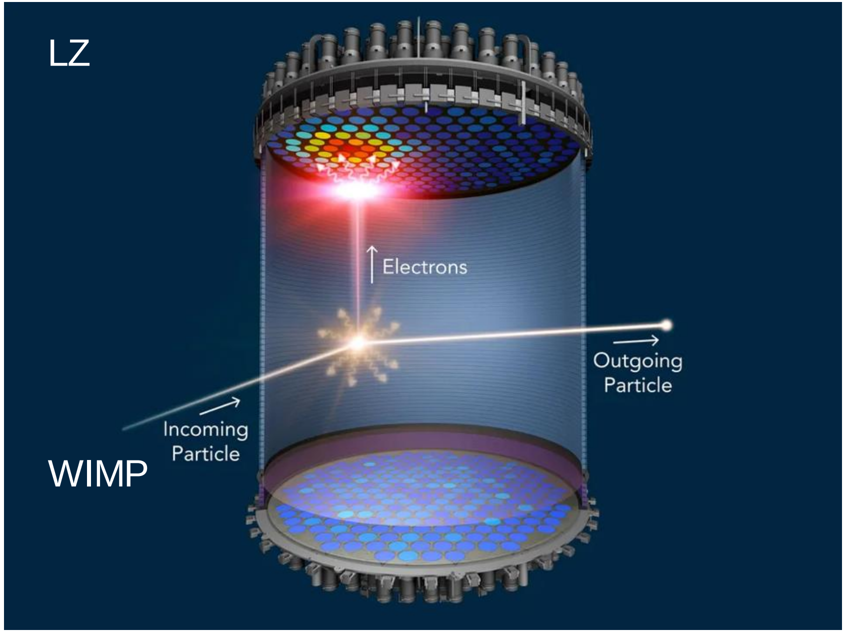


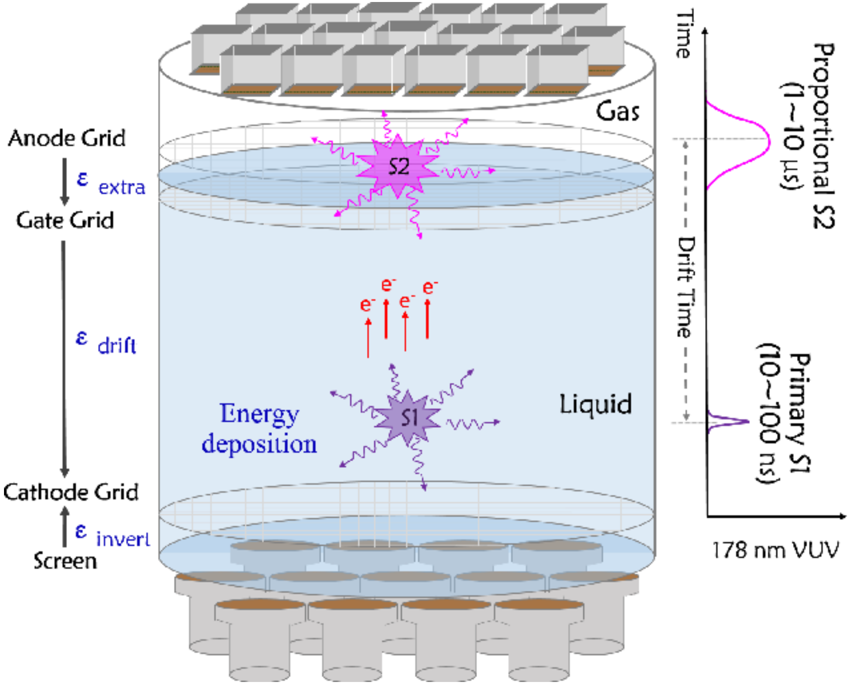


IceCube-Gen2, a ten-cubic-kilometer detector

Dark Matter Search Experiments

- LZ (WIMP search), XENONnT, PandaX (DM direct detection), etc.
  - Optical Photon Simulation (Liquid Xeon)

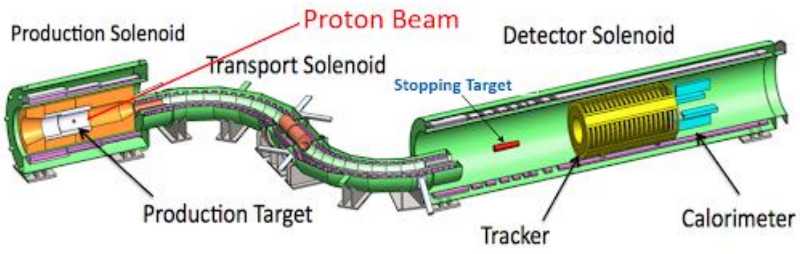


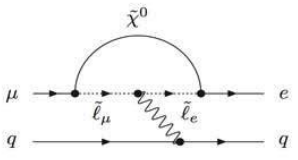


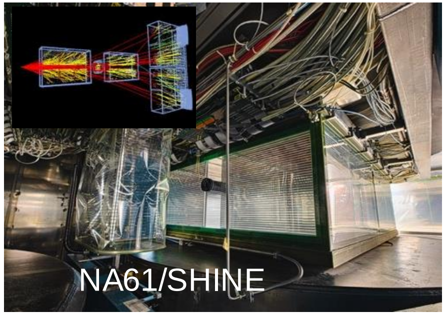
- CUP/IBS: AMoRE experiment ($0\nu\beta\beta$), COSINE (DM direct detection)

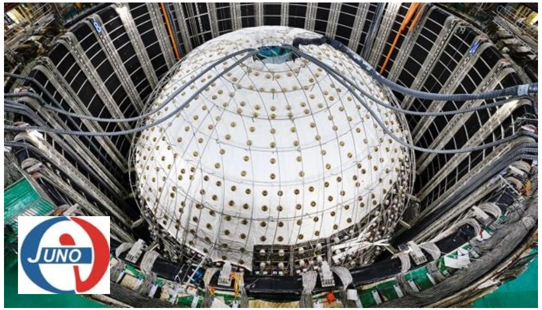
Many Other On-going and Upcoming Facilities

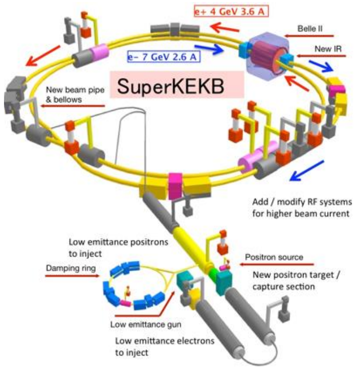
- Muon Experiments at Fermilab
  - Mu2e: Searches for charged lepton flavor violation
  - Muon g-2: Measures the anomalous magnetic moment
- CERN NA61, SHINE experiments
- JUNO (θ_{13} from ν_{e^-})
- Belle-II@Japan, BES-III@China, etc.

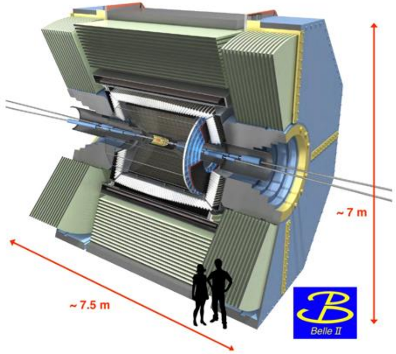






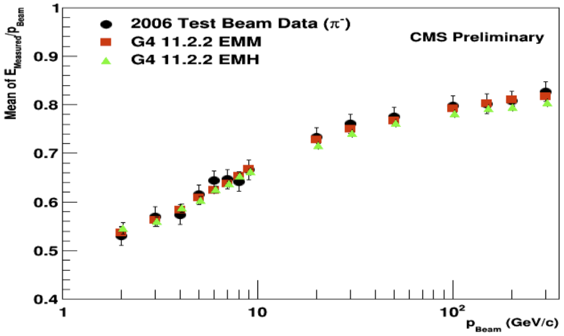


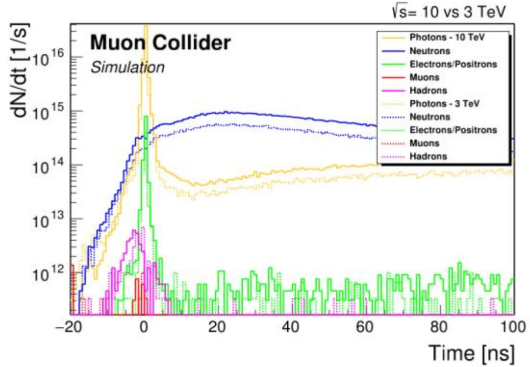


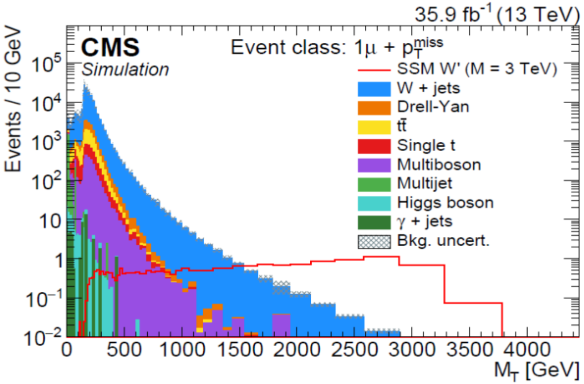


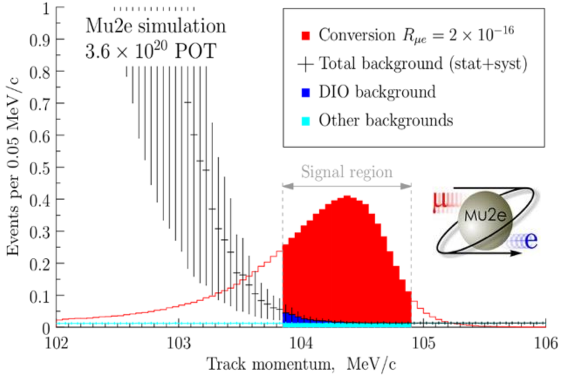
Geant4 Detector Simulation for HEP

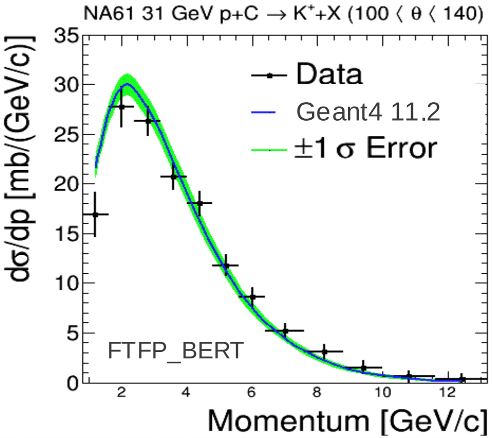
- Detector design and optimization
- Detector machine interface
- Detector performance studies
- Reconstruction efficiency
- Singal and background simulation
- Shielding or Veto studies, etc.





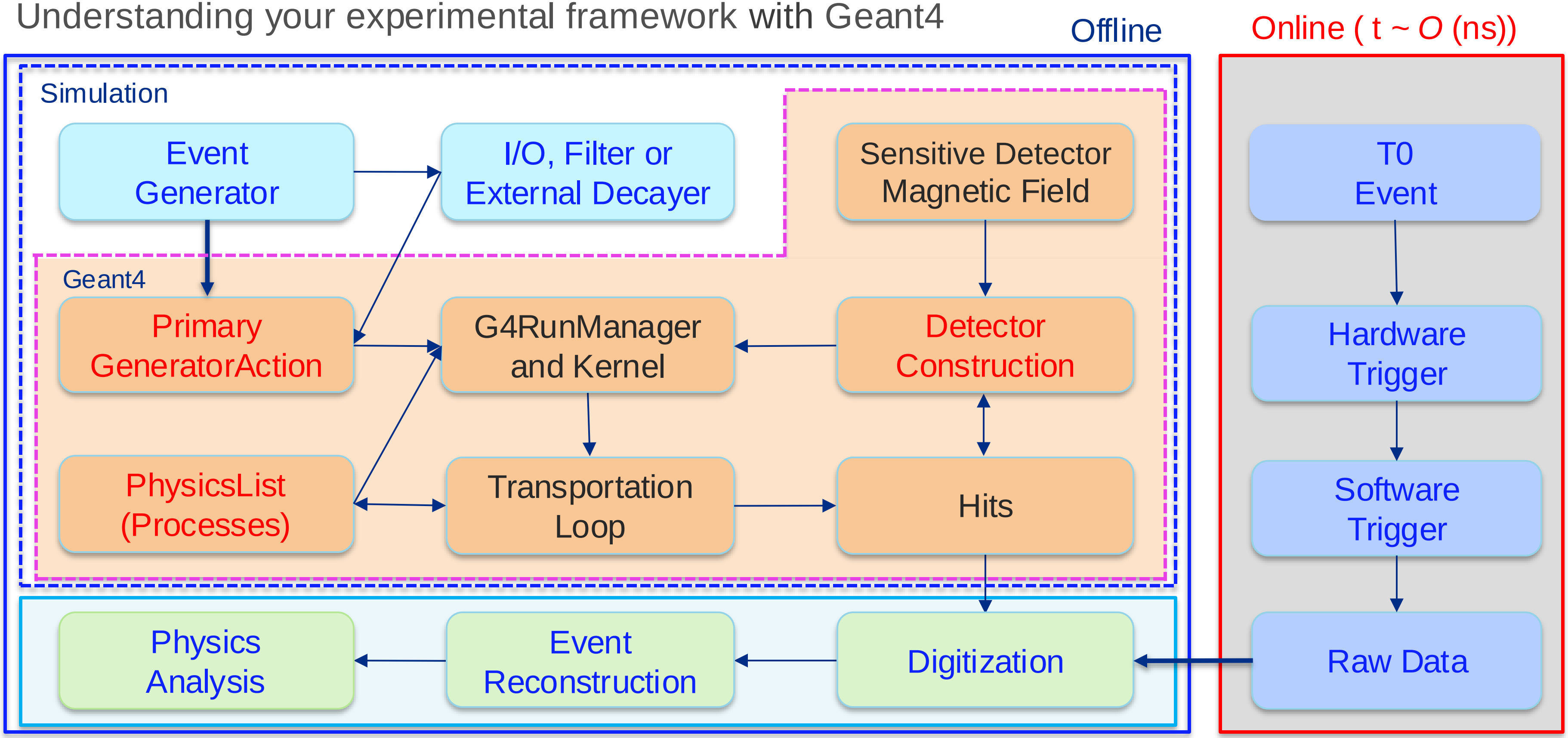






Software Framework and Integration

- Understanding your experimental framework with Geant4



MC Expert Guideline for HEP Experiments

- Define the scope of detector simulation
  - Distinguish between general-purpose and specialized studies tailored to specific research goals.
- Choose an optimal PhysicsList
  - Utilize region-specific physics models to balance simulation accuracy and computational performance.
  - Carefully define cuts and tune other parameters to optimize accuracy versus speed.
- Design efficient detector constructions
  - Break down detectors into manageable sub-components for debugging.
  - Use parameterized volumes and replicas for repetitive structures (and optimize field calculations, if any).
- Streamline I/O
  - Integrate flexible input sources and minimize output to essential data (e.g., sensitive hits or diagnostics).
- Leverage advanced techniques
  - Offload tasks to GPUs, explore AI/ML, FastSim or biasing techniques to enhance computing performance.

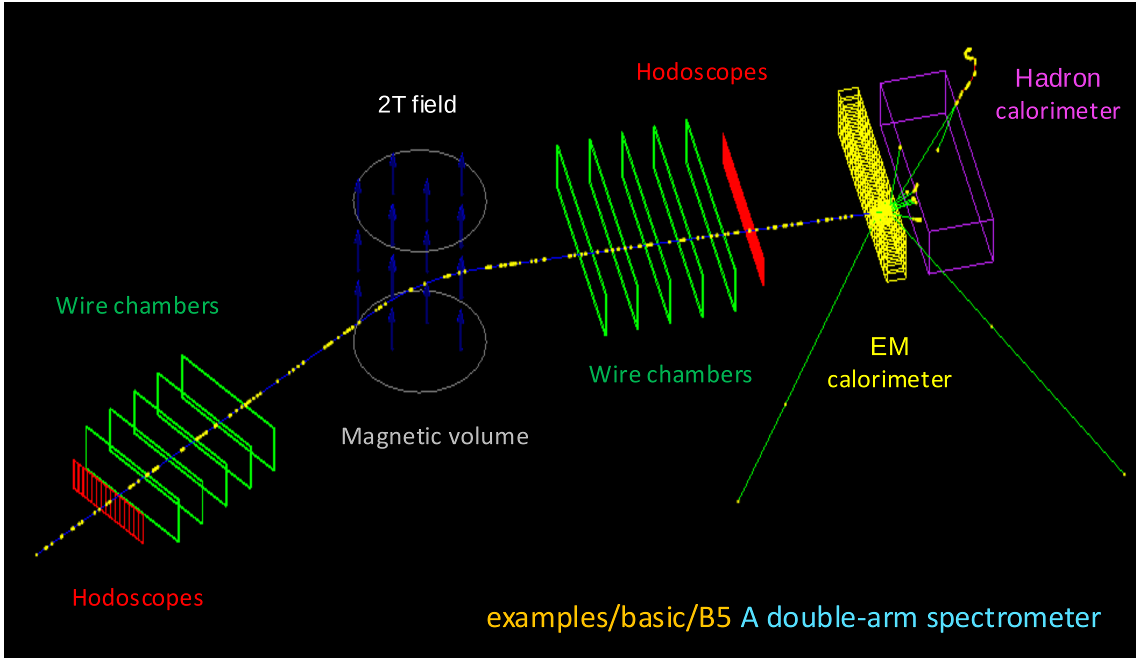
MC User Guideline for HEP Experiments

- Understand the scope of detector simulation
  - Clearly outline whether the simulation is for general studies or tailored to specific experiment goals.
- Start with a known workflow
  - Begin with initial tests and examples using a small number of events to verify functionality.
  - Validate results incrementally to ensure the simulation behaves as expected.
- Leverage Geant4 User Action Interfaces
  - Extract relevant quantities at various simulation stages to understand detector response.
  - Optimize cuts and eliminate redundant processes to improve efficiency.
- Evaluate computing performance and physics validation
  - Conduct end-to-end tests to ensure the entire simulation workflow meets performance requirements.
  - Validate physics models and account for systematic uncertainties by testing multiple parameter variations.

Selected Geant4 HEP Examples

Geant4 HEP basic example

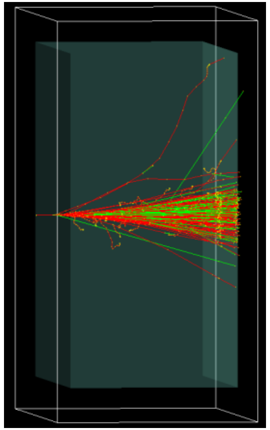
- examples/basic/B5 : A double-arm spectrometer with wire chambers, hodoscopes and (EM and Hadron) calorimeters
  - Geometry with rotation, replicas parameterization
  - Local constant magnetic field
  - Scoring via sensitive detectors: tracking chambers and calorimeter
  - Physics list with a step limiter
  - UI with G4GenericMessenger
  - Analysis (histograms and ntuples)
  - Plotting of histograms with visualization drivers (TSG)

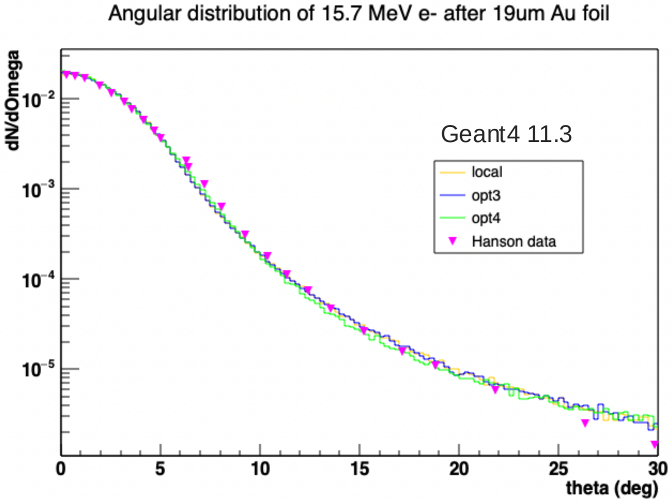


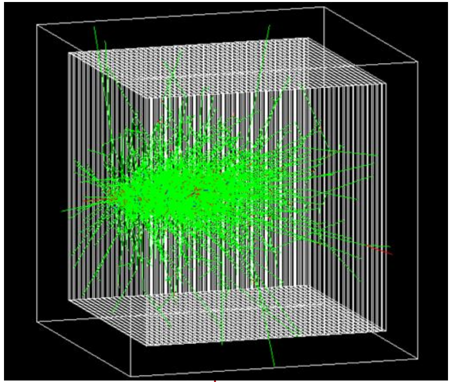
- A good starting exampe which demonstrates various features of Geant4

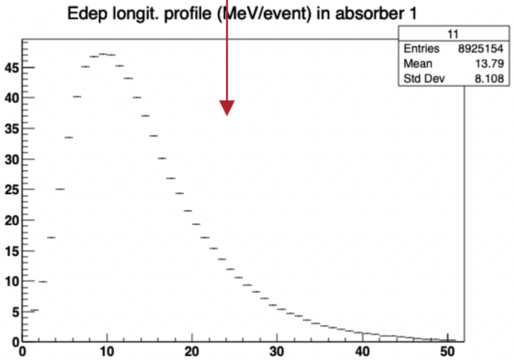
Geant4 HEP extended example 1 → Hands-On

- examples/extended/electromagnetic/
  - TestEm3 (Longitudinal energy profile)
  - TestEm5 (MSC comparison to Hanson data)







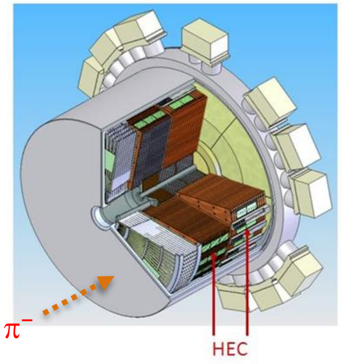


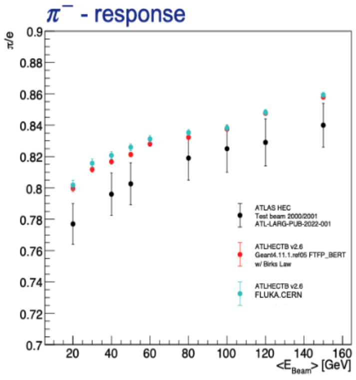
  - Good examples that demonstrates detail responses (physics model level) of a single detector setup

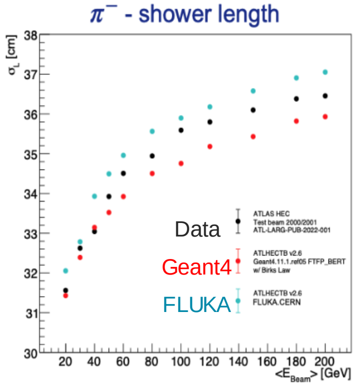
Geant4 HEP extended example 2

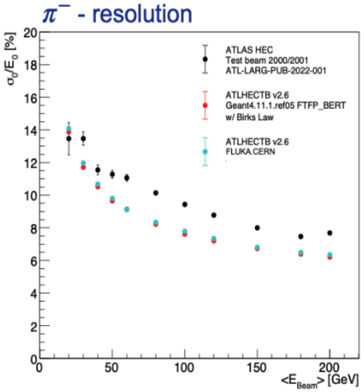
- examples/extended/FlukaCern (Geant4-FLUKA.CERN Interface)
- FLUKA: general purposed tool for calculations of particle transport and interactions with matter
- Geant4-FLUKA.CERN interface since Geant4 11.2 (Dec. 2023)
  - Provides an interface to get inelastic cross sections and final-states from FLUKA.CERN.
  - Use a custom FTFP_BERT Physics List that replaces the *G4HadronPhysicsFTFP_BERT* constructor with *FLUKAHadronInelasticPhysicsConstructor*

Comparison with the ATLAS@LHC HEC (hadronic end-cap calorimeter)



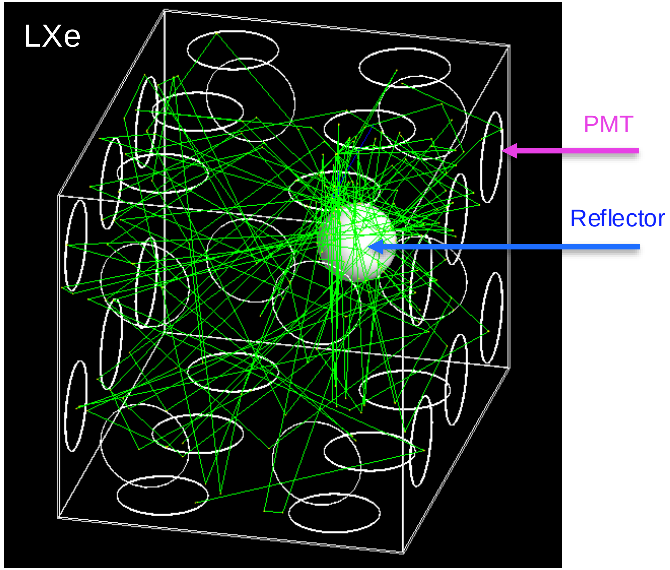


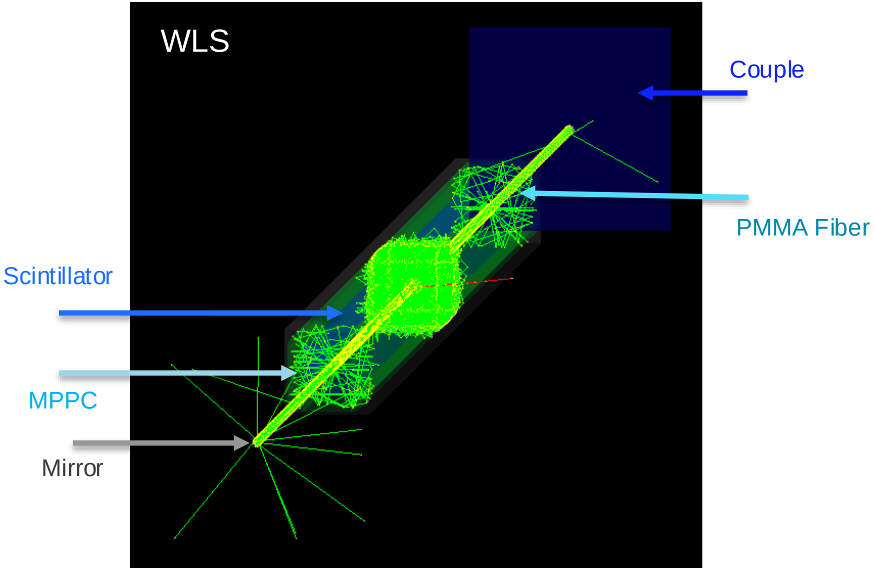




Geant4 HEP extended example 3

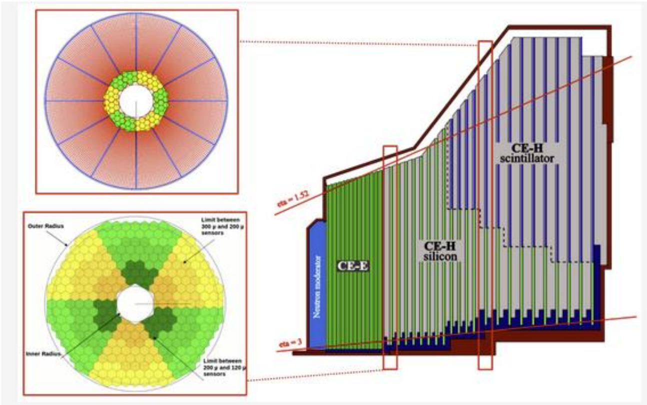
- examples/extended/optical
  - Lxe: demonstration of optical physics with a box of LXe, PMTs on surfaces and a reflective sphere
  - WLS: propagation of optical photons inside a wavelength shifting (WLS) fiber
  - Examples uses *G4OpticalPhysics, G4OpticalSurface, G4MaterialPropertiesTable, etc.*



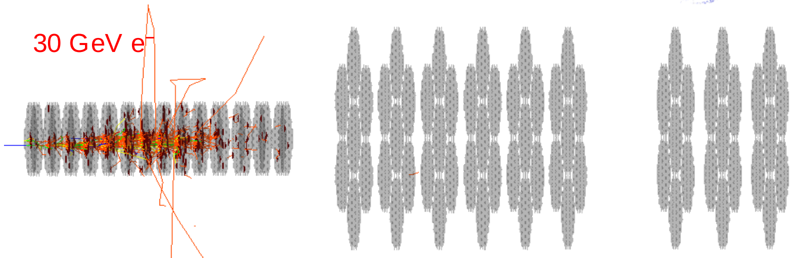


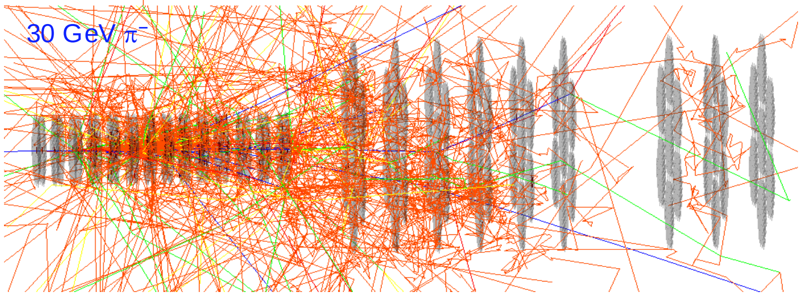
Geant4 HEP advanced example

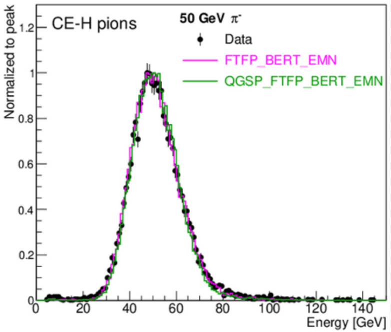
- examples/advanced/HGCal_testbeam
  - CMS High Granular Calorimeter

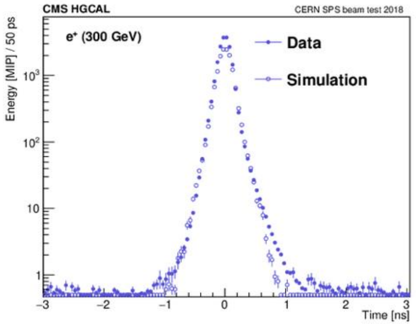


  - Detector construction: 3 configurations
  - Energy deposited within silicon pixels/SiPMs
  - TOA (time of arrival) with an energy threshold
  - Beam size (smearing) controls
  - Output (hits, timing) with ntuples



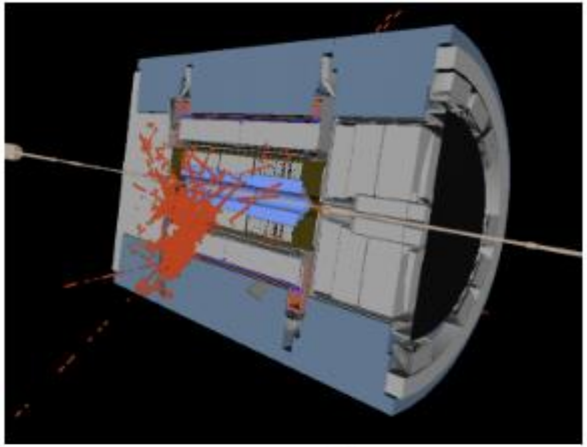


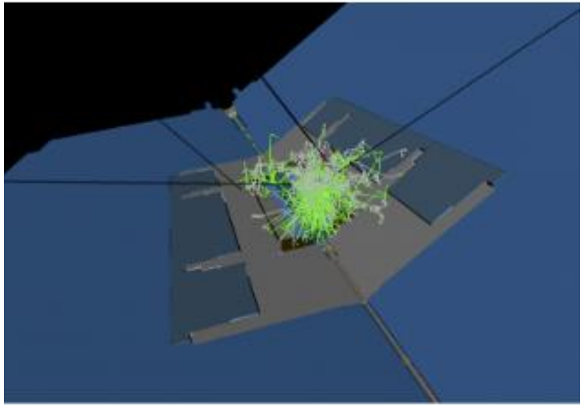




Homework: Realistic HEP Detector Simulation

- Standalone ATLAS detector simulation: fullSimLight
- Installation and run
  - wget https://g4cpt.fnal.gov/g4p/download/ATLAS.tar
  - tar czf ATLAS.tar
  - Follow ATLAS/HOW_TO_BUILD
  - Require
    - pythia
    - root
    - may need hdf5, eigen3, hepmc3, etc.
- Versions for offloading to GPUs will be publicly available from April 2025 (including B5, TestEm3 and HGCal_testbeam)
  - https://github.com/Geant4/gpu-delta-review-2025 (currently private)





Summary before Hands-on

- Geant4 is widely used for detector simulations in high-energy physics (HEP) experiments, supporting experiments that require precise modeling of particle interactions with matter.
- Geant4 plays a crucial role for developing and optimizing detector concepts for future HEP programs.
- Geant4 provides many examples (basic → extended → advance).
- Geant4 remains a critical tool for the HEP community and other application domains, continuously adapting to new computational paradigms and experimental requirements.