Geant4 for EIC luminosity monitor

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EIC Software Tutorial
Introduction

- These slides give an overview of a standalone Geant4 project to simulate luminosity monitor for the EIC

- All the codes are in the following github repository:

  https://github.com/adamjaro/lmon

- References to individual parts will be given throughout the presentation

- The only prerequisites to start working with a standalone Geant4 are basic knowledge of C++ and CMake

- The EIC luminosity monitor here will serve as an illustration of Geant4 principles and functionalities

- In the following two tutorials this standalone Geant4 for luminosity monitor will be used to show how a standalone simulation can be integrated into existing detector full simulations
Mechanism of luminosity measurement at the EIC

- Luminosity is measured via elastic bremsstrahlung off electrons
- Independent of proton (nucleus) internal structure, large cross section \( \sim \text{mb} \)
- Luminosity monitor detects bremsstrahlung photons

Figure: Bremsstrahlung cross section as a function of photon energy \( E_\gamma \) and polar angle \( \theta_\gamma \)
Detector concept for luminosity measurement

- Following example of similar detector at ZEUS, HERA
- High luminosity demands two separate methods to count the bremsstrahlung photons:
  1. Photon conversion to $e^+e^-$ pairs for precise DIS cross sections
  2. Direct, non converted photons for instantaneous collider performance

![Diagram of ZEUS luminosity detector]

**Figure**: Layout of ZEUS luminosity detector

- Pairs are detected in spectrometer SPEC, direct photons in photon calorimeter PCAL

Basic Geant4 principles

- Calculates passage of ionizing radiation in matter
- Can simulate light collection of optical scintillation and Cerenkov photons
- Geant4 is implemented as a set of C++ classes, a project is built with CMake
- Three main steps of user interaction
  1. Generation of primary events
  2. Definition of detector volumes and construction materials
  3. Evaluating energy losses, optical photons and writing the output
- Geant4 runs in steps inside each volume along each particle trajectory
- At every step it calculates energy deposition and possible creation of secondary particles
- Geant4 can execute a user-defined function along every step
- Such a function is handed all information about the step, the volume, and particles involved in the step
Resources for Geant4

Here is the list biased by my experience:

1. Book For Application Developers, `BookForApplicationDevelopers.pdf`
   - Comprehensive review of principles and functionalities
   - No need to read everything before doing something; first few pages of each chapter give enough information to begin with

   - Good to see class methods all in one place

3. Example codes in Geant4 source directory


Generating events, single particle

- The generator class is derived from `G4VUserPrimaryGeneratorAction`
- It creates its `G4ParticleGun`
- Functions of the particle gun allow to set vertex position, direction and energy
- Units of \( cm \) and \( GeV \) are provided by Geant4
- Function `GeneratePrimaries` is called automatically by Geant4 at the beginning of each event

```cpp
// Geant headers
#include "G4ParticleGun.hh"
#include "G4ParticleTable.hh"
#include "G4ParticleDefinition.hh"
#include "G4SystemOfUnits.hh"

// local headers
#include "GeneratorAction.h"

GeneratorAction::GeneratorAction() : G4VUserPrimaryGeneratorAction(), fGun(0) {
  fGun = new G4ParticleGun(1); // number of particles
  G4String nam = "gamma";
  G4ParticleDefinition* particle = G4ParticleTable::GetParticleTable()->FindParticle(nam);
  fGun->SetParticleDefinition(particle);
  fGun->SetParticleMomentumDirection(G4ThreeVector(0, 0, -1));
  fGun->SetParticlePosition(G4ThreeVector(0, 0.2*cm, 0));
  fGun->SetParticleEnergy(4.5*GeV);
}

void GeneratorAction::GeneratePrimaries(G4Event *evt) {
  fGun->GeneratePrimaryVertex(evt);
}
```

Generating events, uniform distribution

- Works like single particle generator from previous page
- Defines energy range over which the particles will be generated
- Energy for each event is obtained using `CLHEP::HepRandom`
- The `HepRandom::flat()` function provides values of uniform distribution

```cpp
// minimal and maximal energy, in GeV
fEmin = 0.5;
fEmax = 20.;
fGun = new G4ParticleGun(1); // number of particles
G4String nam = "gamma";
G4ParticleDefinition *particle = G4ParticleTable::GetParticleTable()->FindParticle(nam);
fGun->SetParticleDefinition(particle);
fGun->SetParticleMomentumDirection(G4ThreeVector(0, 0, -1));

// uniform random generator for energy values
fRand = new CLHEP::HepRandom();

void UniformGen::GeneratePrimaries(G4Event* evt) {
  G4double en = 0;
  while(en < fEmin) {
    en = fEmax * fRand->flat();
  }
  fGun->SetParticleEnergy(en*GeV);
  fGun->GeneratePrimaryVertex(evt);
}
```

Generating physics events by reading a generator output

```cpp
// particle loop
for (int itrk=0; itrk<ntrk; itrk++) {
    getline(fIn, line);
    // split the particle line
    tokenizer< char_separator< char > > trkline(line, sep);
    tokenizer< char_separator< char > >::iterator trk_it = trkline.begin();

    // get the momentum
    for (int i=0; i<2; i++) ++trk_it;
    ss.str("" ) ;
    ss.clear();
    ss << *(trk_it++) << " " << *(trk_it++) << " " << *(trk_it++);
    ss >> px >> py >> pz;

    // get pdg
    for (int i=0; i<3; i++) ++trk_it;
    ss.str("" ) ;
    ss.clear();
    ss << *(trk_it++);
    int pdg;
    ss >> pdg ;

    // select the photon
    if (pdg == 22) break;

} // particle loop

// generate the photon
G4ParticleGun gun(fGammaDef);

gun.SetParticleMomentum(G4ParticleMomentum(px*GeV, py*GeV, pz*GeV));
gun.SetParticlePosition(G4ThreeVector(vx*cm, vy*cm, vz*cm));
gun.GeneratePrimaryVertex(evt);
```

- Standard C++ functions are used to read a particular output of event generator, in TX format in this case.
- Values of $v_x$, $v_y$ and $v_z$ and $p_x$, $p_y$ and $p_z$ are interpreted as $cm$ and $GeV$.
- They give vertex position and momentum of bremsstrahlung photon.
- The event itself is again generated with `G4ParticleGun`.

https://github.com/adamjaro/lmon/blob/master/src/TxReader.cxx
Creating a volume

- The first step is a shape, *G4Tubs* in this case
- Shape with material makes *logical* volume
- Logical volume placed with *G4PVPlacement* makes *physical* volume
- The world of a given project is a composition of physical volumes

```cpp
// ExitWindowV2::ExitWindowV2(const G4String& nam, G4double zpos, G4LogicalVolume* top):
  Detector(), G4VSensitiveDetector(nam), fName(nam) {
    G4cout << "ExitWindowV2: " << fName << G4endl;
  G4double dz = 2.5*mm; // length along z
  G4double radius = 10*cm; // inner radius
  G4double thickness = 1*mm; // exit window thickness
  //cylindrical U-shape
  G4Tubs *shape = new G4Tubs(fName, radius, radius+thickness, dz/2, 90*deg, 180*deg);
  //exit window material
  G4Material *mat = G4MaterialManager::Instance()->FindObjectBuildMaterial("G4_RL");
  //logical volume
  G4LogicalVolume *vol = new G4LogicalVolume(shape, mat, fName);
  //visualization
  G4VisAttributes *vis = new G4VisAttributes();
  vis->SetColor(0, 1, 0, 0.5);
  vis->SetForceSolid(true);
  vol->SetVisAttributes(vis);
  //100 rad in x-z plane by rotation along y
  G4RotationMatrix rot = G4ThreeVector(0, 1, 0), -8.1*rad); //typedef to CLHEP::HepRotation
  //placement with rotation at a given position along z
  G4ThreeVector pos(0, 0, zpos);
  G4Transform3D transform(rot, pos); // is HepGeom::Transform3D
  new G4PVPlacement(transform, vol, fName, top, false, 0);
  //ExitWindowV2
```

Figure: Outcome of the code on the left, half-pipe tilted along vertical axis *y*

https://github.com/adamjaro/lmon/blob/master/src/ExitWindowV2.cxx
Making a sensitive detector

- The particular detector has to be derived from `G4VSensitiveDetector`

- Geant4 then runs its `ProcessHits` function when making steps inside its sensitive volume

- All information about the step and associated particles comes from `G4Step`

- Information about the volume is provided by `G4TouchableHistory`

```cpp
#include "G4VSensitiveDetector.hh"

class ExitWindowV2 : public Detector, public G4VSensitiveDetector {

public:

  ExitWindowV2(const G4String& name, G4double zpos, G4LogicalVolume* top);

protected:

  virtual const G4String& GetName() const { return fName; }
  virtual void CreateOutput(TTree* tree);
  virtual void ClearEvent();
  virtual void FinishEvent();

public:

  virtual G4bool ProcessHits(G4Step* step, G4TouchableHistory*);

private:

};
```

https://github.com/adamjaro/lmon/blob/master/include/ExitWindowV2.h
Putting pieces together in project executable and by Geant4 Actions

The simulation is started by running the executable of the project

The executable runs construction of all volumes

Then loads the list of physics processes, including optional optical physics

And finally sets the user-defined actions

```cpp
// default run manager
G4RunManager *runManager = new G4RunManager;

// detector construction
runManager->SetUserInitialization(new DetectorConstruction);

// physics
FTFP_BERT *physicsList = new FTFP_BERT;
G4OpticalPhysics *opt = new G4OpticalPhysics();
physicsList->RegisterPhysics(opt);
runManager->SetUserInitialization(physicsList);

// action
runManager->SetUserInitialization(new ActionInitialization);

// visualization
G4VisExecutive *visManager = new G4VisExecutive;
visManager->Initialize();

// user interface manager
G4UImanager *UImanager = G4UImanager::GetUImanager();
```

**Figure:** Project executable run.cxx setting
DetectorConstruction, physics and ActionInitialization

**Figure:** Action initialization to set the event generator and functions to be run at the beginning of each event and at the beginning of the run

https://github.com/adamjaro/lmon/blob/master/run.cxx
https://github.com/adamjaro/lmon/blob/master/src/ActionInitialization.cxx
Constructing a simple framework

- Every detector, or part of the detector, in the luminosity framework inherits from `Detector` and from `G4VSensitiveDetector`
- Both base classes automatically run functions to manage output creation and Geant4 stepping
- It is easy to replace a simple model with more sophisticated detector

```cpp
//abstract base class for detectors

class Detector {
public:
    virtual ~Detector() {} //add Detector to all Detectors during detector construction
    virtual void Add(std::vector<Detector*> *vec) { vec->push_back(this); } //name of logical sensitive volume for Detector with sensitive volume
    virtual const G4String& GetName() const = 0; //output of the detector
    virtual void CreateOutput(TTree* T) {} //beginning of event
    virtual void FinishEvent() {} //end of event
};
```

**Figure**: Base class for the detector

```cpp
//detector loop
std::vector<Detector*>::iterator i;
for(i = fDet->begin(); i != fDet->end(); ++i) {
    Detector *det = *i;
    G4VSensitiveDetector *sd = dynamic_cast<G4VSensitiveDetector*>(det);
    if(!sd) continue;
    //detector inherits also from G4VSensitiveDetector, add it to Geant
    G4SDManager::GetSDmanager()->AddNewDetector(sd);
    SetSensitiveDetector(det->GetName(), sd);
    G4cout << "" << det->GetName() << G4endl;
} //detector loop
```

**Figure**: Registering every sensitive detector with Geant4 to make the mechanism with `ProcessHits` function working

https://github.com/adamjaro/lmon/blob/master/include/Detector.h
https://github.com/adamjaro/lmon/blob/master/src/DetectorConstruction.cxx
Writing output to ROOT tree

- Every detector is handed a pointer to the output ROOT TTree
- The detector can define its branches pointing to single numerical variables (example on the left)
- Or the branch could be and ROOT class, like histogram or TClonesArray
- Or the detector can add itself as a branch (example on the right)

```cpp
Double_t fEdep; // total energy deposited in optical photon detector
ULong64_t fnphot; // number of photons in event
ULong64_t fnscin; // scintillation photons
ULong64_t fnCerenkov; // Cerenkov photons

Double_t fTmin; // time of first detected photon
Double_t fTmax; // time of last detected photon
Double_t fTavg; // average time of all detected photons
```

Figure: ROOT variables in optical photon detector

**OpDet** to be written as a single branches in ROOT TTree

Figure: A detector which adds itself as a branch to the ROOT TTree; the `fAddr` is pointer to the detector object itself

https://github.com/adamjaro/lmon/blob/master/include/OpDet.h
https://github.com/adamjaro/lmon/blob/master/src/ExitWinZEUS.cxx
Running the simulation with a steering macro

- The project executable takes a steering macro as a command line parameter
- With the help of `G4GenericMessenger`, it is possible to configure the individual components
- Input from physics generator and output ROOT file also come from the messenger
- The messenger provides methods to create new commands

```
#run macro for EIC nodes
#detectors and components, 1 = include, 0 = do not include
/lmon/construct/collim 1  # collimator
/lmon/construct/magnet 1  # spectrometer magnet
/lmon/construct/euv2 1  # photon exit window
/lmon/construct/phot 1  # direct photon detector
/lmon/construct/up 1  # upper spectrometer calorimeter
/lmon/construct/down 1  # down spectrometer calorimeter

#init and run
/run/initialize

#input
/lmon/input/name /direct/eic/u/jadam/sim/lgen/data/lgen_18x275_10p1Mevt.txt

#output
/lmon/output/name ../data/lmon_18x275_all_0p25T_100kevt.root

#number of events
/run/beamOn 100000
```

https://github.com/adamjaro/lmon/blob/master/run_eic.mac
Use case of luminosity monitor

- Full Geant4 model of all essential part of luminosity monitor
- Preliminary design according to example from ZEUS
- Provides simulation chain from physics event generator to number of detected photoelectrons
Photon exit window

- Half-cylinder of 1 mm thick aluminum
- Conversion layer for the photons
- Also provides shielding against low energy background
- Although it will be a passive material, Geant4 can consider it as a detector to evaluate its performance as a conversion layer
- It was used as an example of sensitive detector in the previous section

https://github.com/adamjaro/lmon/blob/master/src/ExitWindowV2.cxx
https://github.com/adamjaro/lmon/blob/master/include/ExitWindowV2.h
Collimator

- Block of stainless steel to shield the background
- The volume with opening inside is created with `G4SubtractionSolid`
- Outer shape and inner opening are created as `G4Box`

```cpp
//inner aperture in x and y
G4double dx = 9.6*cm;
G4double dy = 7*cm;
G4double len = 30*cm; //length
G4double siz = 50*cm; //outer size

//collimator shape
G4String nam = "Collimator";
G4Box *outer = new G4Box(nam, siz/2, siz/2, len/2);
G4Box *inner = new G4Box(nam, dx/2, dy/2, len/2);
G4SubtractionSolid *shape = new G4SubtractionSolid(nam, outer, inner);
```

Figure: Bremsstrahlung photon passing through the collimator

https://github.com/adamjaro/lmon/blob/master/src/Collimator.cxx
https://github.com/adamjaro/lmon/blob/master/include/Collimator.h
Spectrometer dipole magnet

- The magnet in Geant4 is a volume with magnetic field
- The shape for the magnet is **G4Box**
- The magnetic field is **G4UniformMagField**
- The field is associated with the volume by **G4LogicalVolume::SetFieldManager**

```cpp
// magnet shape
G4double dz = 60.*cm;
G4double xysiz = 10.*cm;
G4String nam = "Magnet";
G4Box *mshape = new G4Box(nam, xysiz, xysiz, dz/2.);
G4LogicalVolume *mvol = new G4LogicalVolume(mshape, mat, nam);

// magnetic field
G4UniformMagField *field = new G4UniformMagField(G4ThreeVector(0.25*tesla, 0, 0));
G4FieldManager *fman = new G4FieldManager();
fman->SetDetectorField(field);
fman->CreateChordFinder(field);
mvol->SetFieldManager(fman, true);
```

Figure: Electron and positron are deflected in the magnet
Photon detector

- Implemented as a composite calorimeter *CompCal*
- Consists of $7 \times 7$ PbWO$_4$ cells
- Each cell consists of $3 \times 3$ cm casing made of carbon fiber, 2 mm thick, holding the PbWO$_4$ crystal inside
- Length of each cell is 35 cm, same for casing and crystal
- Plot shows response to a 1 GeV photon
- The cell inherits from both *Detector* and *G4VSensitiveDetector*
- The calorimeter itself inherits only from *Detector*

https://github.com/adamjaro/lmon/blob/master/src/CompCal.cxx
https://github.com/adamjaro/lmon/blob/master/include/CompCal.h
Spectrometer detectors

- Pair of calorimeters for converted $e^+ e^-$ pairs
- Located in front of the photon detector
- Electrons and positrons are deflected by dipole magnet
- The plot shows event with $e^+$ and $e^-$ at 3 GeV

https://github.com/adamjaro/lmon/blob/master/src/CompCal.cxx
https://github.com/adamjaro/lmon/blob/master/include/CompCal.h
Simulating scintillation and Cerenkov optical photons

- Optical and scintillation properties for the Cell are defined in **OpTable**, Geant4 needs empiric parametrizations.
- Optical photons are detected in optical detector **OpDet**, placed at the end of the cell.
- The **ProcessHits** function of optical detector can get the origin of the photon.

**Figure**: One calorimeter cell with 2 MeV deposition on the far side (facing the IP) and optical photon detector (magenta) on the opposite side. Optical photons are shown as green lines.

```cpp
G4bool OpDet::ProcessHits(G4Step* step, G4TouchableHistory* ) {
  // Total energy deposition in optical detector
  fDep = step->GetTotalEnergyDeposit();
  //光学 photons only since now
  G4Track* track = step->GetTrack();
  if(track->GetDynamicParticle()->GetParticleDefinition() != G4OpticalPhoton::OpticalPhotonDefinition()) {
    return true;
  }
  // scintillation or Cerenkov photon
  G4int pttype = track->GetCreatorProcess()->GetProcessType();
  if(pttype == fScinType && pttype == fScinSubType) fScin++;
  // Cerenkov photons
  if(pttype == fCerenkoType && pttype == fCerenkoSubType) fCerenkov++;
}
```

https://github.com/adamjaro/lmon/blob/master/src/Cell.cxx
https://github.com/adamjaro/lmon/blob/master/src/OpTable.cxx

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Summary

- With Geant4 it is straightforward to begin with simple things up to integrating into big projects.