Interaction with the Geant4 kernel

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Partially based on a presentation by G.A.P. Cirrone (INFN-LNS)

Part V: Write information on output files

Introduction: data analysis with Geant4

- For a long time, Geant4 did not attempt to provide/support **any data analysis** tools
  - The focus was given (and is given) to the central mission as a Monte Carlo simulation toolkit
  - As a general rule, the user is expected to provide her/his own code to output results to an appropriate analysis format
- Basic classes for data analysis have recently been implemented in Geant4 (g4analysis)
  - Support for histograms and ntuples
  - Output in **ROOT**, **XML**, **HBOOK** and **CSV** (ASCII)
  - Appropriate only for easy/quick analysis: for advanced tasks, the user must write his/her own code and to use an external analysis tool

Introduction: how to write simulation results

- Formatted (= human-readable) **ASCII files**
  - Simplest possible approach is comma-separated values (.csv) files
  - The resulting files can be opened and analyzed by tools such as: Gnuplot, Excel, OpenOffice, Matlab, Origin, ROOT, PAW, ...
- **Binary files** with complex analysis objects (Ntuples)
  - Allows to control what plot you want with modular choice of conditions and variables
    - Ex: energy of electrons knowing that (= cuts): (1) position/location, (2) angular window, (3) primary/secondary ...
  - Tools: Root , PAW, AIDA-compliant (PI, JAS3 and OpenScientist)

Output stream (G4cout)

- **G4cout** is a **iostream** object defined by Geant4.
  - The usage of this objects is exactly the same as the ordinary **std::cout** except that the output streams will be handled by **G4UImanager**
  - **G4endl** is the equivalent of **std::endl** to end a line
- Output strings may be displayed on another window or stored in a file
- One can also use the file streams (**std::ofstream**) provided by the C++ libraries

Output on screen – an example

```
void SteppingAction::UserSteppingAction(const G4Step* aStep)
{


  evtNb = eventAction -> Trasporto();

  G4String particleName = aStep -> GetTrack() -> GetDynamicParticle() -> GetDefinition() -> GetParticleName();
  G4String volumeName = aStep ->GetPreStepPoint() -> GetPhysicalVolume() -> GetName();
  G4double particleCharge = aStep -> GetTrack() -> GetDefinition() -> GetAtomicNumber();
  G4double PDG=aStep->GetTrack()->GetDefinition()->GetAtomicMass();


  G4Track* theTrack = aStep->GetTrack();
  G4double kineticEnergy = theTrack -> GetKineticEnergy();
  G4int trackID = aStep -> GetTrack() -> GetTrackID();
  G4double edep = aStep->GetTotalEnergyDeposit();
  G4String materialName = theTrack->GetMaterial()->GetName();
```

```
G4cout      << "Energy deposited--->" << " " << edep << " "
      << ”Charge--->" << " " << particleCharge << " "
      << ”Kinetic Energy --->" << "  " << kineticEnergy << " "
                  << G4endl;
```

Output on screen – an example

```
---> Begin of Event: 0
Energia depositata---> 9.85941e-22 Carica---> 6 Energia Cinetica---> 160
Energia depositata---> 8.36876 Carica---> 6 Energia Cinetica---> 151.631
Energia depositata---> 8.63368 Carica---> 6 Energia Cinetica---> 142.998
Energia depositata---> 5.98509 Carica---> 6 Energia Cinetica---> 137.012
Energia depositata---> 4.73055 Carica---> 6 Energia Cinetica---> 132.282
Energia depositata---> 0.0225575 Carica---> 6 Energia Cinetica---> 132.259
Energia depositata---> 1.47468 Carica---> 6 Energia Cinetica---> 130.785
Energia depositata---> 0.0218983 Carica---> 6 Energia Cinetica---> 130.763
Energia depositata---> 5.22223 Carica---> 6 Energia Cinetica---> 125.541
Energia depositata---> 7.10685 Carica---> 6 Energia Cinetica---> 118.434
Energia depositata---> 6.62999 Carica---> 6 Energia Cinetica---> 111.804
Energia depositata---> 6.50997 Carica---> 6 Energia Cinetica---> 105.294
Energia depositata---> 6.28403 Carica---> 6 Energia Cinetica---> 99.0097
Energia depositata---> 5.77231 Carica---> 6 Energia Cinetica---> 93.2374
Energia depositata---> 5.2333 Carica---> 6 Energia Cinetica---> 88.0041
Energia depositata---> 3.9153 Carica---> 6 Energia Cinetica---> 84.0888
Energia depositata---> 14.3767 Carica---> 6 Energia Cinetica---> 69.7121
Energia depositata---> 14.3352 Carica---> 6 Energia Cinetica---> 55.3769
```

G4analysis tools

Native Geant4 analysis classes

- A basic analysis interface is available in Geant4 for histograms (1D and 2D) and ntuples
  - Make life easier because they are MT-compliant (no need to worry about the interference of threads)
- Unique interface to support different output formats
  - ROOT, AIDA XML, CSV and HBOOK
  - Code is the same, just change one line to switch from one to an other
- Everything done via the public analysis interface **`G4AnalysisManager`**
  - Singleton class: Instance()
  - **UI commands** available for creating histograms at run-time and setting their properties

g4analysis

- Selection of output format is hidden in a user-defined .hh file
- **All** the rest of the code **unchanged**
  - Unique interface

```
#ifndef MyAnalysis_h
#define MyAnalysis_h 1

#include "g4root.hh"
//#include "g4xml.hh"
//#include "g4csv.hh"  // can be used only with ntuples

#endif
```

Open file and book histograms

```
#include "MyAnalysis.hh"

void MyRunAction::BeginOfRunAction(const G4Run* run)
{
  // Get analysis manager
  G4AnalysisManager* man = G4AnalysisManager::Instance();
  man->SetVerboseLevel(1);
  man->SetFirstHistoId(1);

  // Creating histograms
  man->CreateH1("h","Title", 100, 0., 800*MeV);
  man->CreateH1("hh","Title",100,0.,10*MeV);

 // Open an output file
  man->OpenFile("myoutput");
}
```

Start numbering of histograms from ID=1

ID=1

ID=2

Open output file

Fill histograms and close

```
#include "MyAnalysis.hh"
void MyEventAction::EndOfEventAction(const G4Run* aRun)
{
  G4AnalysisManager* man = G4AnalysisManager::Instance();
  man->FillH1(1, fEnergyAbs);    ID=1
  man->FillH1(2, fEnergyGap);    ID=2
}
void MyRunAction::EndOfRunAction(const G4Run* aRun)
{
  G4AnalysisManager* man = G4AnalysisManager::Instance();
  man->Write();
  man->CloseFile();
}
MyRunAction::~MyRunAction()
{
  delete G4AnalysisManager::Instance();
}
```

Histograms - 1

- Support linear and log scales and un-even bins
- **`CreateH2()`** for 2D histograms

```
G4int CreateH1(const G4String& name, const G4String& title,
                  G4int nbins, G4double xmin, G4double xmax,
                  const G4String& unitName = "none",
                  const G4String& fcnName = "none",
                  const G4String& binSchemeName = "linear");

G4int CreateH1(const G4String& name, const G4String& title,
                  const std::vector<G4double>& edges,
                  const G4String& unitName = "none",
                  const G4String& fcnName = "none");
```

Histograms - 2

- Can change parameters of an existing histogram
- Can fill with a weight
- Methods to scale, retrieve, get rms and mean

```
G4bool SetH1Title(G4int id, const G4String& title);
G4bool SetH1XAxisTitle(G4int id, const G4String& title);
G4bool SetH1YAxisTitle(G4int id, const G4String& title);

G4bool FillH1(G4int id, G4double value, G4double weight =
1.0);

G4bool ScaleH1(G4int id, G4double factor);

G4int GetH1Id(const G4String& name, G4bool warn = true) const;
```

Histograms - 3

- UI support available, to change parameters (e.g. file name) at run-time

```
/analysis/setFileName name            # Set name for the
      histograms and ntuple file
/analysis/setHistoDirName name        # Set name for the
      histograms directory
/analysis/setNtupleDirName name       # Set name for the
      histograms directory
/analysis/setActivation true|false    # Set activation option
/analysis/verbose level               # Set verbose level

/analysis/h1/create
   name title [nbin min max] [unit] [fcn] [binScheme]     #
Create 1D histogram
```

Ntuples

- g4tool supports ntuples
  - Any number of ntuples, each with any number of columns
  - The content can be **int/float/double**
- For more complex tasks (e.g. full functionality of ROOT TTrees) have to link ROOT directly
- Similar strategy as for histograms. Access happens through the common interface **`G4AnalysisManager`**
  - Saved on the same output file with histograms

Book ntuples

```
#include "MyAnalysis.hh"
void MyRunAction::BeginOfRunAction(const G4Run* run)
{
  // Get analysis manager
  G4AnalysisManager* man = G4AnalysisManager::Instance();
  man-> SetFirstNtupleId(1);

  // Creating ntuple
  man->CreateNtuple("name", "Title");
  man->CreateNtupleDColumn("Eabs");
  man->CreateNtupleDColumn("Egap");
  man->FinishNtuple();

  man->CreateNtuple("name2","title2");
  man->CreateNtupleIColumn("ID");
  man->FinishNtuple();
}
```

Start numbering of ntuples from ID=1 (for the `SetFirstNtupleId(1)` call)

ID=1 (for the first `CreateNtuple` / `CreateNtupleDColumn` lines)

ID=2 (for the second `CreateNtuple` line)

Fill ntuples

- File handling and general clean-up as shown for histograms

```
#include "MyAnalysis.hh"
void MyEventAction::EndOfEventAction(const G4Run* aRun)
{
  G4AnalysisManager* man = G4AnalysisManager::Instance();
  man->FillNtupleDColumn(1, 0, fEnergyAbs);
  man->FillNtupleDColumn(1, 1, fEnergyGap);
  man->AddNtupleRow(1);

  man->FillNtupleIColumn(2, 0, fID);
  man->AddNtupleRow(2);

}
```

ID=1, columns 0, 1

ID=2, column 0

Part VI: User-defined sensitive detectors: Hits and Hits Collection

The ingredients of user SD

- A powerful and flexible way of extracting information from the physics simulation is to **define your own SD**
- Derive **your own concrete classes** from the base classes and customize them according to your needs

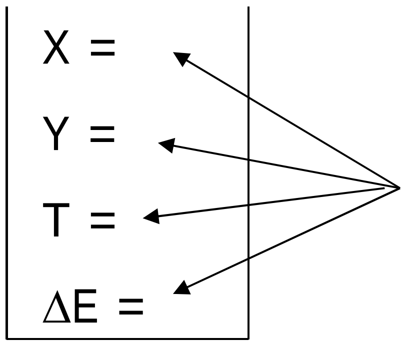
	Concrete class	Base class
Sensitive Detector	MySensitiveDetector	G4VSensitiveDetector
Hit	MyHit	G4VHit
		Template class
Hits collection		G4THitsCollection<MyHit*>

Hit class - 1

- Hit is a user-defined class which derives from the base class **`G4VHit`**. Two virtual methods
  - `Draw()`
  - `Print()`
- You can store various types of information by implementing your own concrete Hit class
- Typically, one may want to record information like
  - Position, time and ΔE of a step
  - Momentum, energy, position, volume, particle type of a given track
  - Etc.

Hit class - 2

A "Hit" is like a "container", a **empty box** which will store the information retrieved step by step



The Hit **concrete class** (derived by **`G4VHit`**) must be written by the user: the user must decide **which variables** and/or information the hit should store and **when** store them

The Hit objects are **created** and **filled** by the **`SensitiveDetector`** class (invoked at each step in detectors defined as sensitive). **Stored** in the "**HitCollection**", attached to the **`G4Event`**: can be retrieved at the EndOfEvent

Hit class - 3

Example

```
// header file: MyHit.hh

#include "G4VHit.hh"

class MyHit : public G4VHit {

 public:
   MyHit();
   virtual ~MyHit();
   ...

   inline void SetEnergyDeposit(G4double energy) { energyDeposit = energy; }

   inline G4double GetEnergyDeposit() { return energyDeposit;}

  ... // more get and set methods

private:
   G4double energyDeposit;
  ... // more data members
};
```

public methods to handle data member

data member (private)

Geant4 Hits

Since in the simulation one may have different sensitive detectors in the same setup (e.g. a calorimeter and a Si detector), it is possible to define **many Hit classes** (all derived by **`G4VHit`**) storing different information

X =
Y =
T =
ΔE =

Class Hit1 :
public G4VHit

Z =
Pos =
Dir =

Class Hit2 :
public G4VHit

Hits Collection - 1

At each step in a detector defined as sensitive, the method **`ProcessHit()`** of the user SensitiveDetector class is inkoved: it must **create**, **fill** and **store** the Hit objects

Step 1	Step 2	Step 3	.....	Step N
X = 1	X = 2	X = 3		X = 3
Y = 2	Y = 0	Y = 2		Y = 2
T =3	T =3.1	T =4		T =6
ΔE = 1	ΔE = 2	ΔE = 3		ΔE = 1

Hits collection (= vector<Hit>)

Hits Collection - 2

- Once created in the sensitive detectors, objects of the concrete hit class **must be stored** in a **dedicated collection**
  - Template class **G4THitsCollection<MyHit>**, which is actually an array of **MyHit***
- The hits collections can be accesses in different phases of tracking
  - At the end of each event, through the **G4Event** (*a-posteriori event analysis*)
  - During event processing, through the Sensitive Detector Manager G4SDManager (*event filtering*)

The HCofThisEvent

Remember that you may have **many kinds of Hits**
(and Hits Collections)

X = 1
Y = 2
T =3
ΔE = 1

X = 2
Y = 0
T =3.1
ΔE = 2

X = 3
Y = 2
T =4
ΔE = 3

.....

X = 3
Y = 2
T =6
ΔE = 1

Z = 5
Pos = (0,1,1)
Dir =(0,1,0)

Z = 5.2
Pos = (0,0,1)
Dir =(1,1,0)

.....

Z = 5.4
Pos = (0,1,2)
Dir =(0,1,1)

HCofThisEvent

Attached to
`G4Event*`

Hits Collections of an event

- A **G4Event** object has a **G4HCofThisEvent** object at the end of the event processing (if it was successful)
  - The pointer to the G4HCofThisEvent object can be retrieved using the **G4Event::GetHCofThisEvent()** method
- The G4HCofThisEvent stores all hits collections creted within the event
  - Hits collections are accessible and can be processes e.g. in the EndOfEventAction() method of the User Event Action class

SD and Hits

- Using information from particle steps, a sensitive detector either
  - constructs, fills and stores one (or more) **hit object**
  - accumulates values to existing hits
- Hits objects can be filled with information in the **`ProcessHits()`** method of the SD concrete user class → next slides
  - This method has pointers to the current **`G4Step`** and to the **`G4TouchableHistory`** of the ReadOut geometry (if defined)

Sensitive Detector (SD)

- A specific feature to Geant4 is that a user can provide his/her own implementation of the detector and **its response** → customized

- To create a sensitive detector, **derive** your own concrete class from the **`G4VSensitiveDetector`** abstract base class
  - The principal purpose of the sensitive detector is to create hit objects
  - Overload the following methods (see also next slide):
    - **`Initialize()`**
    - **`ProcessHits()`** (Invoked for each step if step starts in logical volume having the SD attached)
    - **`EndOfEvent()`**

Sensitive Detector

```
class  G4VSensitiveDetector {
 public:
  ...
    virtual void Initialize(G4HCofThisEvent*);
    virtual void EndOfEvent(G4HCofThisEvent*);
 protected:
    virtual G4bool ProcessHits(G4Step* ,
                               G4TouchableHistory*) = 0;
 ...
};
```

abstract base class

pure virtual method

```
// header file: MySensitiveDetector.hh
#include "G4VSensitiveDetector.hh"
...
class MySensitiveDetector : public G4VSensitiveDetector {

  public:
    MySensitiveDetector(G4String name);
    virtual ~MySensitiveDetector();

    virtual void Initialize(G4HCofThisEvent*HCE);
    virtual G4bool ProcessHits(G4Step* step,
                               G4TouchableHistory* ROhist);
    virtual void EndOfEvent(G4HCofThisEvent*HCE);

  private:
    MyHitsCollection * hitsCollection;
    G4int collectionID;
};
```

User concrete SD class

SD implementation: constructor

- Specify a hits collection (by its unique name) for each type of hits considered in the sensitive detector:
  - Insert the name(s) in the collectionName vector

```
MySensitiveDetector::MySensitiveDetector(G4String detectorUniqueName)
                                : G4VSensitiveDetector(detectorUniquename),
                                  collectionID(-1) {

  collectionName.insert("collection_name");
}
```

Base class

```
class G4VSensitiveDetector {
 ...
 protected:
     G4CollectionNameVector collectionName;
     // This protected name vector must be filled in
     // the  constructor of the concrete class for
     // registering names of hits collections
 ...
};
```

SD implementation: Initialize()

- The `Initialize()` method is invoked at the beginning of each event
- Construct all hits collections and insert them in the `G4HCofThisEvent` object, which is passed as argument to Initialize()
  - The **`AddHitsCollection()`** method of G4HCofThisEvent requires the collection ID
- The unique collection ID can be obtained with `GetCollectionID()`:
  - GetCollectionID() cannot be invoked in the constructor of this SD class (It is required that the SD is instantiated and registered to the SD manager first).
  - Hence, we defined a private data member (collectionID), which is set at the first call of the Initialize() function

```
void MySensitiveDetector::Initialize(G4HCofThisEvent*HCE) {
  if(collectionID < 0)
        collectionID = GetCollectionID(0); // Argument : order of collect.
                                           // as stored in the collectionName
  hitsCollection = new MyHitsCollection
                   (SensitiveDetectorName, collectionName[0]);

  HCE -> AddHitsCollection(collectionID, hitsCollection);
}
```

SD implementation: ProcessHits()

- This **`ProcessHits()`** method is invoked for every step in the volume(s) which hold a pointer to this SD (= each volume defined as "**sensitive**")
- The main mandate of this method is to **generate hit(s)** or to accumulate data to existing hit objects, by using information from the current step
  - Note: Geometry information must be derived from the "PreStepPoint"

```
G4bool MySensitiveDetector::ProcessHits(G4Step* step,
                                         G4TouchableHistory*ROhist) {
  MyHit* hit = new MyHit();      // 1) create hit
...
  // some set methods, e.g. for a tracking detector:
  G4double energyDeposit = step -> GetTotalEnergyDeposit();   // 2) fill hit
  hit -> SetEnergyDeposit(energyDeposit); // See implement. of our Hit class
...
  hitsCollection -> insert(aHit);   // 3) insert in the collection
  return true;
}
```

SD implementation: EndOfEvent()

- This `EndOfEvent()` method is invoked at the end of each event.
  - Note is invoked before the EndOfEvent function of the G4UserEventAction class

```
void MySensitiveDetector::EndOfEvent(G4HCofThisEvent* HCE) {

}
```

Processing hit information - 1

- Retrieve the pointer of a hits collection with the **`GetHC()`** method of `G4HCofThisEvent` collection using the collection index (a G4int number)
- Index numbers of a hit collection are **unique** and don't change for a run. The number can be obtained by **`G4SDManager::GetCollectionID("name");`**
- Notes:
  - if the collection(s) are not created, the pointers of the collection(s) are NULL: **check** before trying to access it
  - Need an explicit cast from `G4VHitsCollection` (see code)

Processing hit information - 2

- Loop through the entries of a hits collection to **access individual hits**
  - Since the HitsCollection is a vector, you can use the **[] operator** to get the hit object corresponding to a given index
- **Retrieve** the information contained in this hit (e.g. using the Get/Set methods of the concrete user Hit class) and process it
- Store the output in analysis objects

Process hit: example

```
void MyEventAction::EndOfEventAction(const G4Event* event) {

 // index is a data member, representing the hits collection index of the
 // considered collection. It was initialized to -1 in the class constructor
 if(index < 0)   index =
   G4SDManager::GetSDMpointer() -> GetCollectionID("myDet/myColl");

 G4HCofThisEvent* HCE = event-> GetHCofThisEvent();

 MyHitsCollection* hitsColl = 0;
 if(HCE)  hitsColl = (MyHitsCollection*)(HCE->GetHC(index));

 if(hitsColl)  {
   int numberHits = hitsColl->entries();

   for(int i1= 0; i1 < numberHits ; i1++) {
     MyHit* hit = (*hitsColl)[i1];
     // Retrieve information from hit object, e.g.
     G4double energy = hit -> GetEnergyDeposit;
     ... // Further process and store information
   }
 }
}
```

retrieve index

retrieve all hits collections

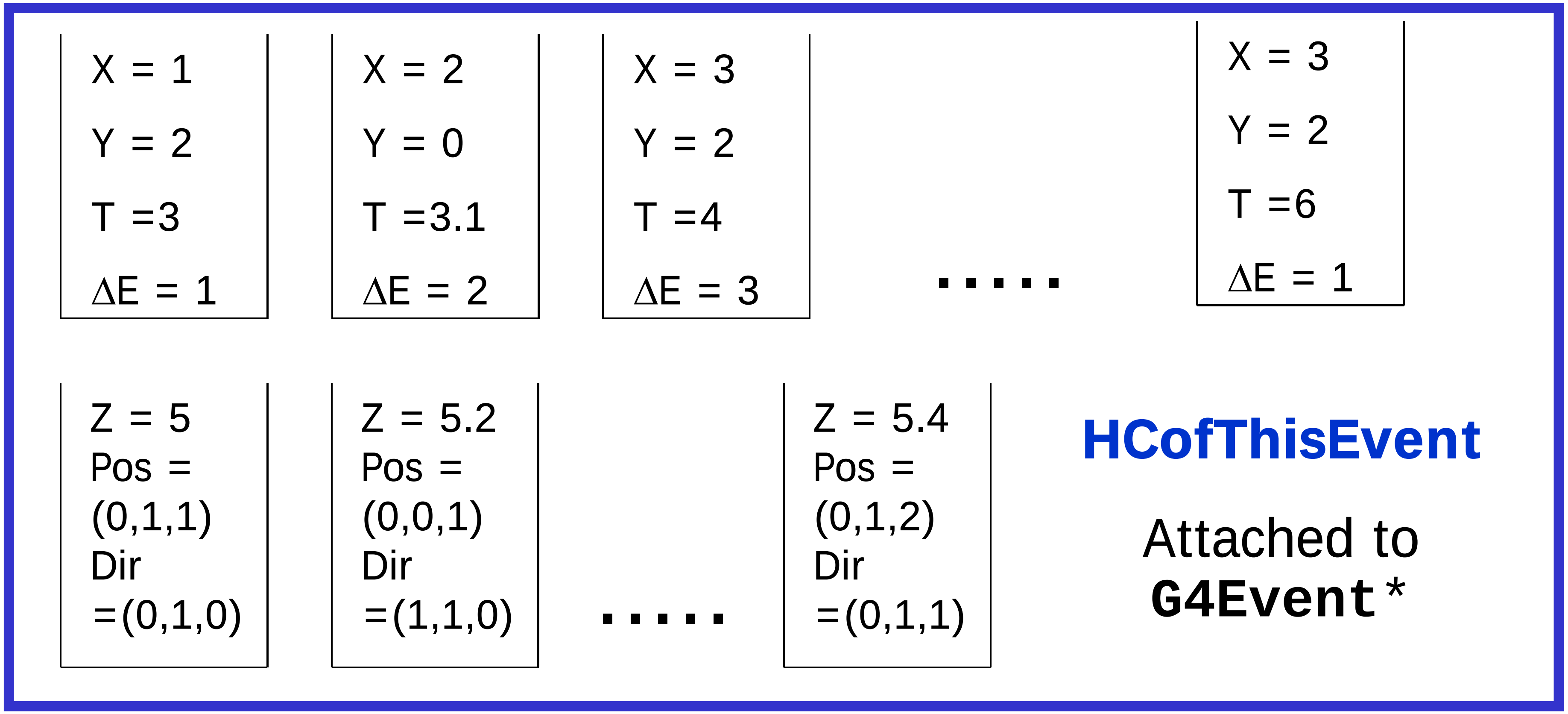
retrieve hits collection by index

cast

loop over individual hits, retrieve the data

The HCofThisEvent

Remember that you may have **many kinds of Hits**
(and Hits Collections)



Recipe and strategy - 1

- Create your detector geometry
  - Solids, logical volumes, physical volumes
- Implement a sensitive detector and assign an instance of it to the ***logical volume*** of your geometry set-up
  - Then this volume becomes “sensitive”
  - Sensitive detectors are active for each particle steps, if the step starts in this volume

Recipe and strategy - 2

- Create hits objects in your sensitive detector using information from the particle step
  - You need to create the hit class(es) according to **your requirements**
- **Store** hits in hits collections (automatically associated to the **`G4Event`** object)
- Finally, process the information contained in the hit in user action classes (e.g. **`G4UserEventAction`**) to obtain results to be stored in the analysis object