Simulation Tool Overview

What is available, what requires updates and where are we going.

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*** List compiled as committer names over our simulation repositories.**

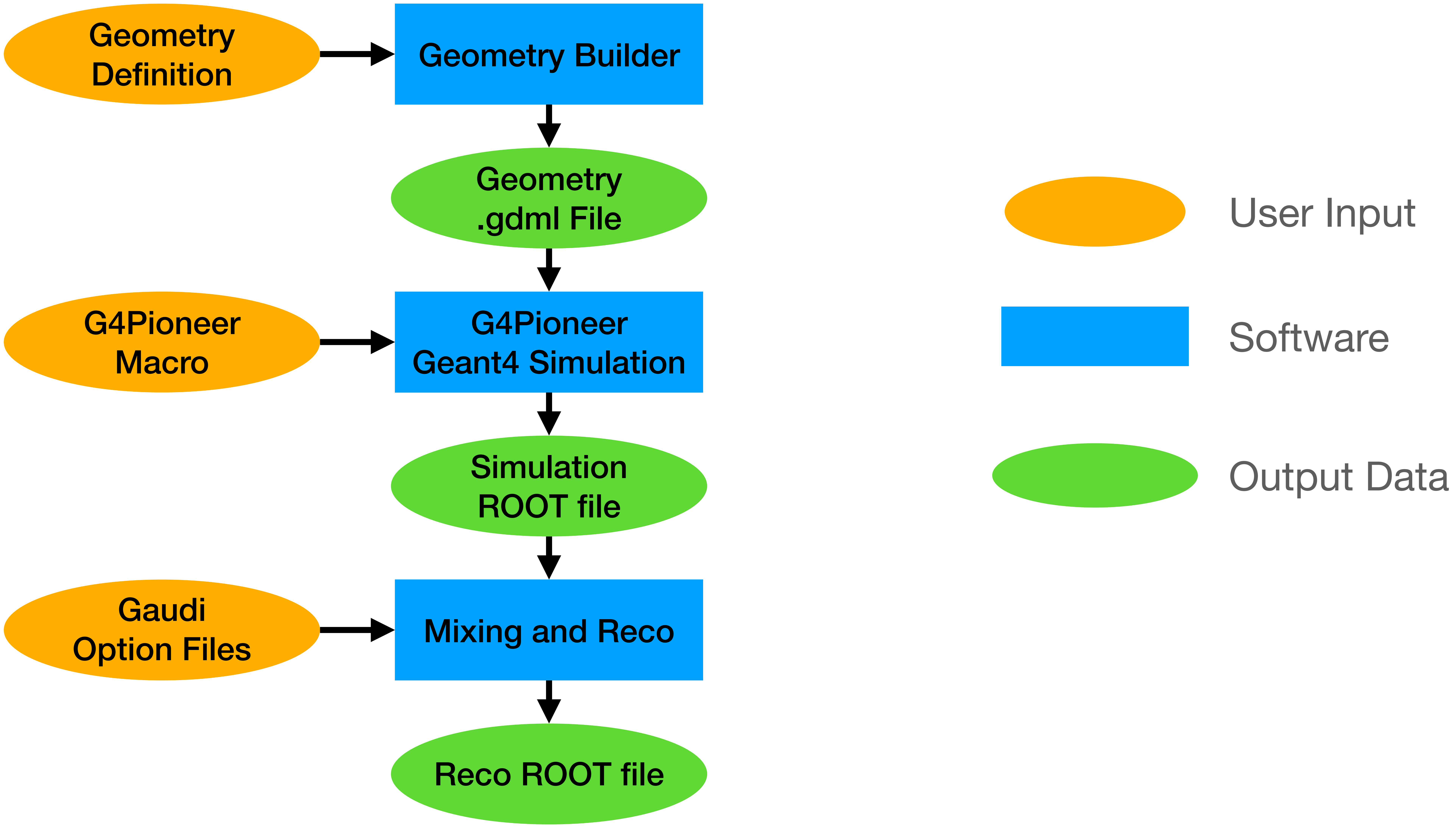
What is the Goal?

- **To Guide the Detector Design**
  Need to know which parts are crucial and where requirements are more relaxed. Where do we HAVE to spend the money and where can we save some?

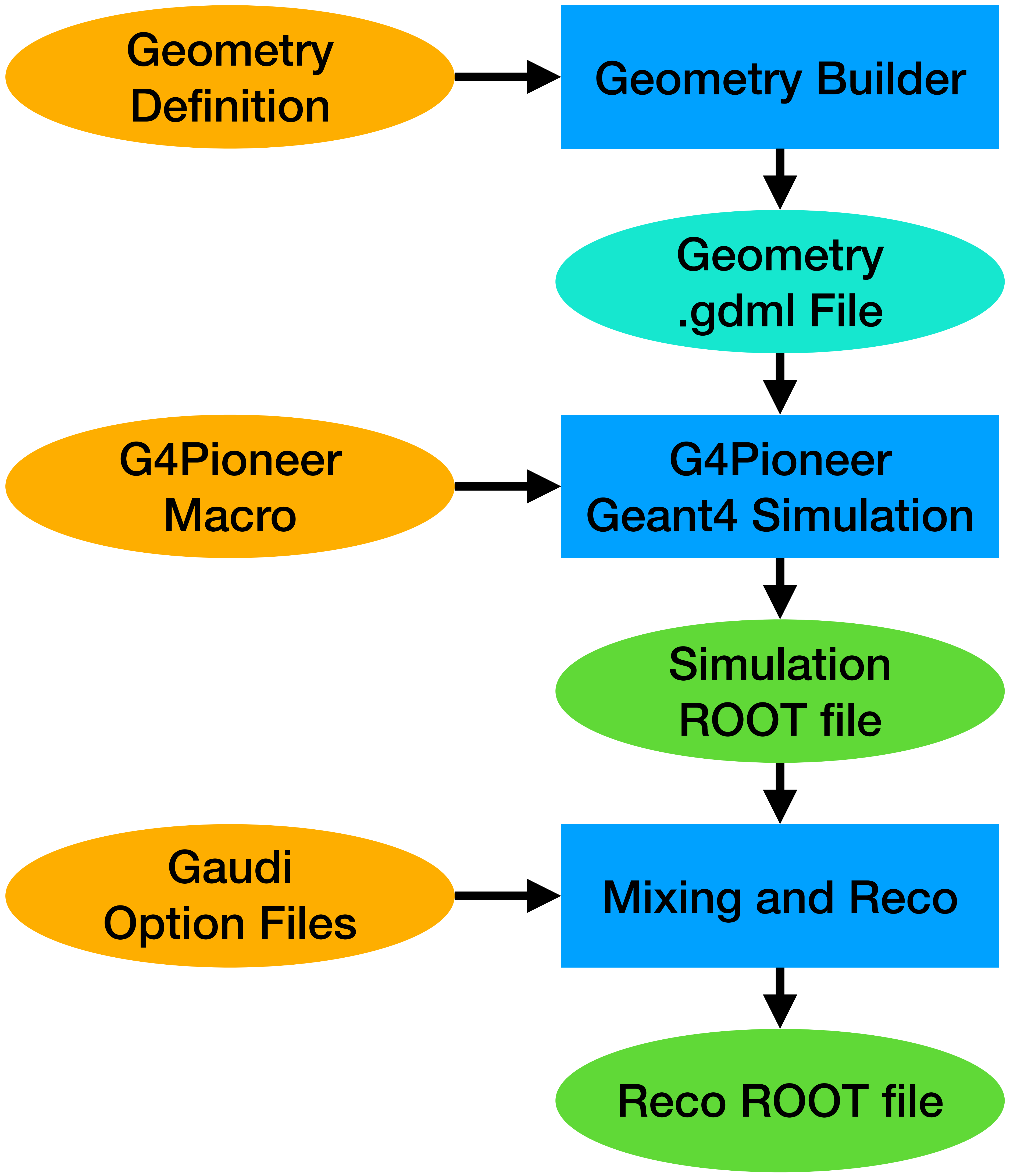
- **To Understand our Event Topologies**
  We know that there will be a $\pi \rightarrow e\nu$ tail underneath the michel spectrum - but how do they get there? What other events may fake a $\pi \rightarrow e\nu$ event?

- **To Develop our Reconstruction and Analysis**
  How do we process the data such that we can get a hold of all the numbers we need. What algorithms are promising and which ones only sound promising?

The Most Generic Workflow



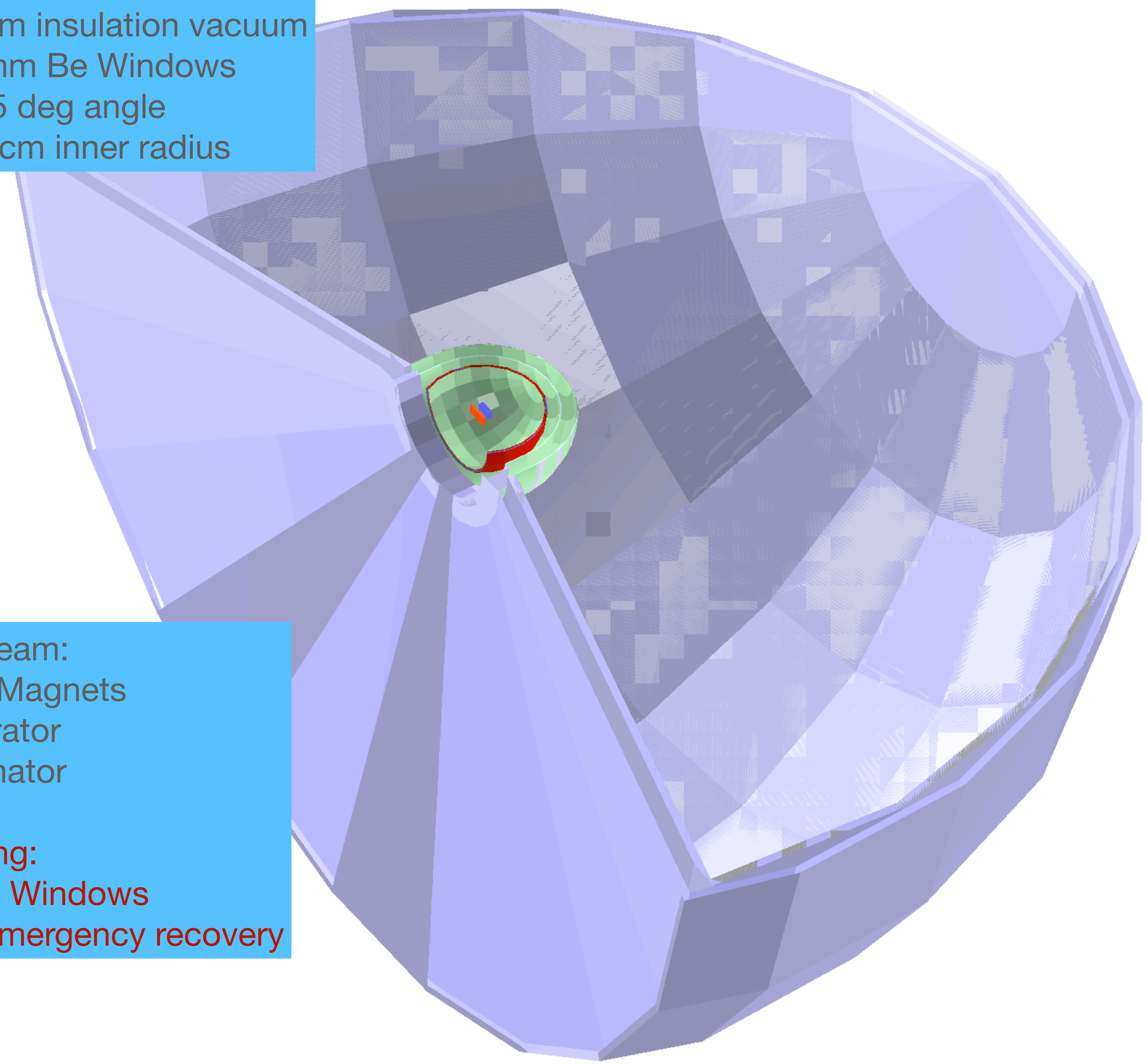
If you are looking at it offline



- Geometry Builder takes geometry definition file (e.g. default.json) and encodes it in a Geant4-readable way.
- The G4Pioneer macro file specifies all configurations for the Geant4 simulation such as Geometry file to read, physics list or beam configuration.
- The Geant4 Simulation (G4Pioneer) generates particles and tracks them through the defined geometry. It records steps (hits) in all declared sensitive detectors and writes them to a ROOT TTree in the simulation root file.
- Mixing and Reconstruction is based on Gaudi. It is configurable through user provided Gaudi option files. It converts the Geant4 events to something more realistic and tries to reconstruct and classify the events. The output is written to a dedicated reco TTree.

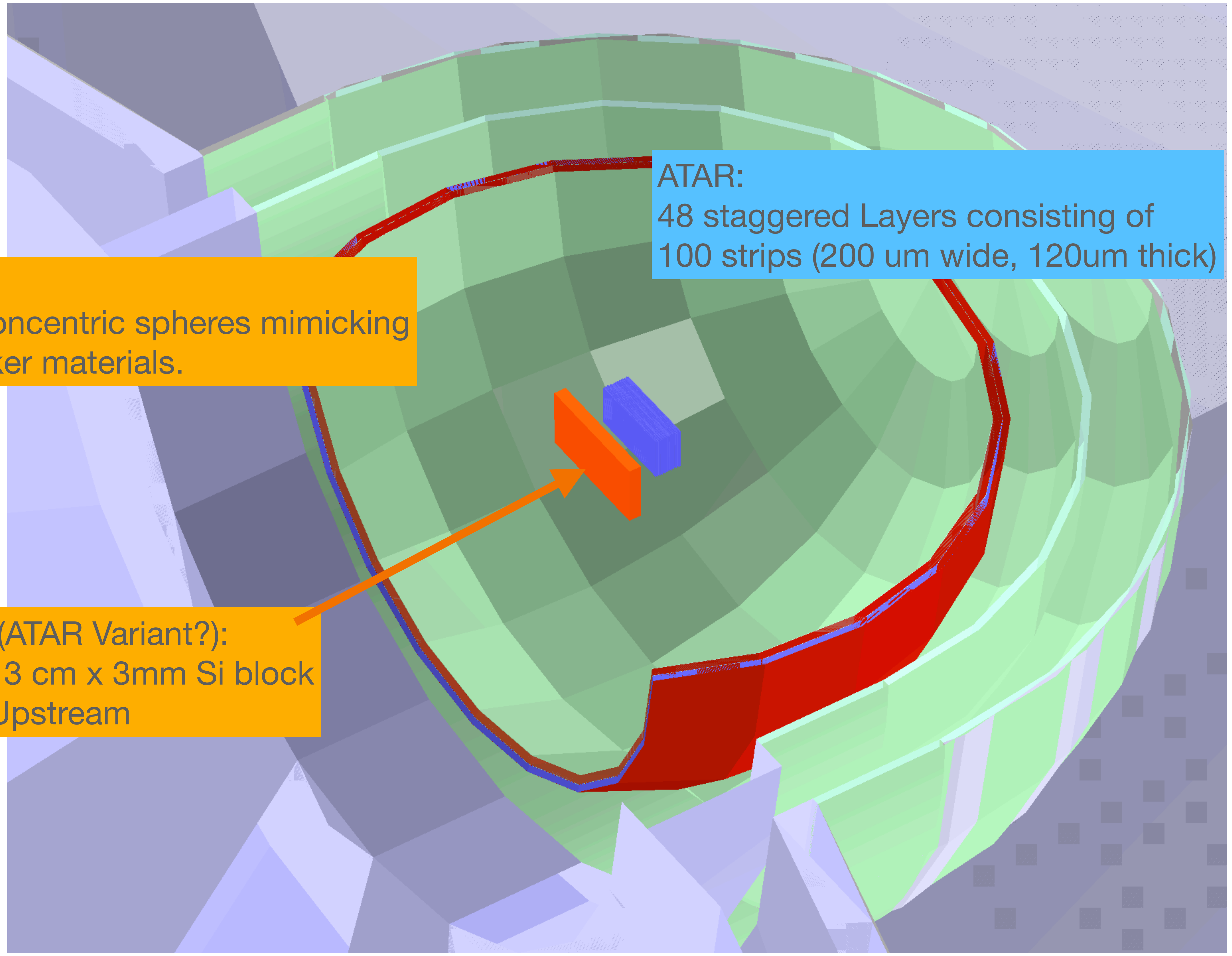
The Baseline Geometry Design

Calo:
25 X0 LXe
1 cm Al Walls
2 cm insulation vacuum
2 mm Be Windows
105 deg angle
10 cm inner radius



Upstream:
2 x 2 Magnets
Separator
Collimator

Missing:
Beam Windows
LXe emergency recovery



ATAR:
48 staggered Layers consisting of
100 strips (200 um wide, 120um thick)

Tracker:
Set of concentric spheres mimicking the tracker materials.

DTAR (ATAR Variant?):
3cm x 3 cm x 3mm Si block
1 cm Upstream

Where are the ATAR/DTAR Cables, Readouts, Support Structures ?!

Geometry Configuration - Global

Example available in `geometry/examples`

```
"debug":false,
"filename":"default",
"ScintScale":1,
"mother":{
    "material":"air",
    "xWidth":2000,
    "yWidth":2000,
    "zWidth":11000
},
```

Filename to be used

Global scale of the scintillation yield.
Set to .1 if you want to prescale PDE

“Air” actually implies Vacuum

The Experimental Hall volume.
All elements MUST stay within

Geometry Configuration - ATAR

Developer: **Adam,** (Josh, Siddhant)

```
"target":{
    "xPos": 0.0,
    "yPos": 0.0,
    "zPos": 0.0,
    "nLayers"    : 48,
    "layerStagger":0.03,
    "stripWidth": 0.02,
    "stripLength": 2.0,
    "stripThickness":0.012,
    "nStrips"    : 100,
    "stripMaterial": "Silicon",
    "electrodeWidth": 0.01,
    "electrodeMaterial":"Aluminum",
    "instrumentWithTILGAD":false,
    "TILGADTrenchWidth":0.0005,
    "backingAndElectrodeThickness":0.0002,
    "backingMaterial":"Aluminum",
    "hvThickness":0.001,
    "hvLengthPastSensor":0.04,
    "hvMaterial":"Kapton",
    "makeGuard":true,
    "guardWidth":0.04,
    "guardMaterial":"Silicon",
    "layerBuffer" : 0.0025,
    "debug":false
},
```

Target Position

Target Layout

Material Selection

Technology Selection

Geometry Configuration - Calorimeter

Developer: Patrick, ???

```
"calorimeter":{
    "debug":false,
    "geometry":"Pacman",
    "rIn": 10,
    "rActive": 70.24,
    "alpha": 75,
    "vacuumThickness": 2.0,
    "shellThickness": 1.0,
    "windowThickness": 0.2,
    "activeMaterial": "LXe",
    "vacuumMaterial": "Air",
    "shellMaterial": "Aluminum_black",
    "windowMaterial": "Beryllium",
    "Nsipms": 1000,
    "sipmSize": 4.0,
    "sipmThickness": 0.05,
    "sipmWindowThickness" : 0.05,
    "sipmMaterial" : "Silicon",
    "sipmWindowMaterial" : "LXe"
},
```

Calo Layout

70.24 cm LXe = 25 X0

2 cm insulation vacuum

1 cm Aluminium Walls

2 mm Beryllium Windows

Crude Photosensor implementation.
Note: SiPM right now stands for any photosensitive detector

Geometry Configuration - Tracker

Developers: Jaydeep, Patrick, Josh

```
"trackers":{
    "type":"urwell",
    "hackman":true,
    "trackers":[
        {
            "debug":false,
            "xPos": 0.0,
            "yPos": 0.0,
            "zPos": 0.0,
            "alpha":120,
            "rMin": 8.0,
            "layerMaterials":[
                "Glue","Copper","uRWELLGas","Copper",
                "Kapton", "Carbon", "Glue","Copper",
                "Glue","Copper","Kapton","Copper"
            ],
            "layerThickness":[
                0.01, 0.0005, 0.2, 0.0005,
                0.005, 0.00001, 0.0028, 0.0017,
                0.0028, 0.0017, 0.16, 0.0017
            ],
            "sensitive":[
                false, false, true, false,
                false, false, false, false,
                false, false, false, false
            ]
        }
    ]
},
```

Layout selection

Position and Size

Layer Composition

Geometry Configuration - DTAR*

Developers: Josh, Patrick

* Degrader TARget, one specific option of an upstream element.

```
"upstream":{
    "detectors":{
        "dtar":{
            "type":"degrader",
            "material":"Silicon",
            "xPos": 0.0,
            "yPos": 0.0,
            "zPos": -1,
            "xWidth":3,
            "yWidth":3,
            "zWidth":0.3,
            "isActive":true
        }
    }
},
```

- "detectors": Dictionary of all upstream elements
- "type": Use a degrader type element for DTAR
- "xPos", "yPos", "zPos": DTAR position
- "xWidth", "yWidth", "zWidth": DTAR dimensions, 3 cm x 3 cm x 3 mm
- "isActive": Make it active

Geometry Configuration - Magnets

Developers: Stefan

```
"no_magnet": {
    "magnets": [{
        "debug": false,
        "FieldGradient": -0.9899193091738064,
        "innerMaterial": "air",
        "outerMaterial": "Iron",
        "xPos": 0.0,
        "yPos": 0.0,
        "zPos": -235.0,
        "innerRadius": 12.5,
        "outerRadius": 35,
        "zLength": 40.0
    }, {
        "debug": false,
        "FieldGradient": 2.2189968979482377,
        "innerMaterial": "air",
        "outerMaterial": "Iron",
        "xPos": 0.0,
        "yPos": 0.0,
        "zPos": -185.0,
        "innerRadius": 12.5,
        "outerRadius": 35,
        "zLength": 40.0
    }, {
```

Magnet elements, disabled.
Change tag to “magnet” to enable.

Quadrupole field strength

Magnet material

Position

Dimensions

Second Quadrupole of the Doublet.

Another Doublet follows

Geometry Configuration - Collimator

Developers: **Stefan**

```
"no_collimator": {
    "debug": false,
    "collimatorMaterial": "Iron",
    "holeMaterial": "air",
    "xPos": 0.0,
    "yPos": 0.0,
    "zPos": -140.0,
    "xLength": 100.0,
    "yLength": 100.0,
    "zLength": 5.0,
    "xHolePos": 0,
    "yHolePos": 0,
    "xHoleLength": 1.0,
    "yHoleLength": 1.0
}
```

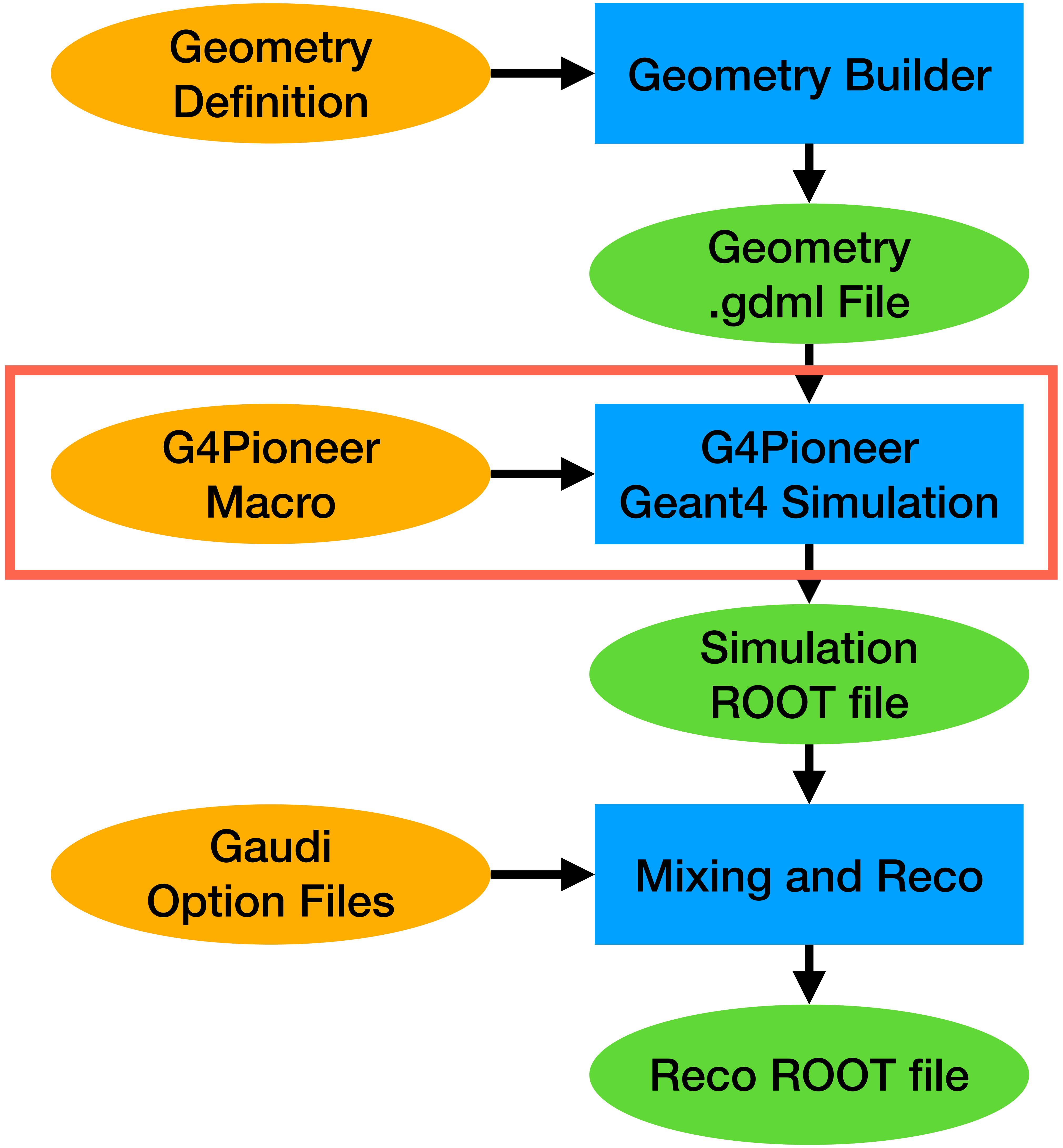
Collimator element, disabled.
Change tag to "collimator" to enable.

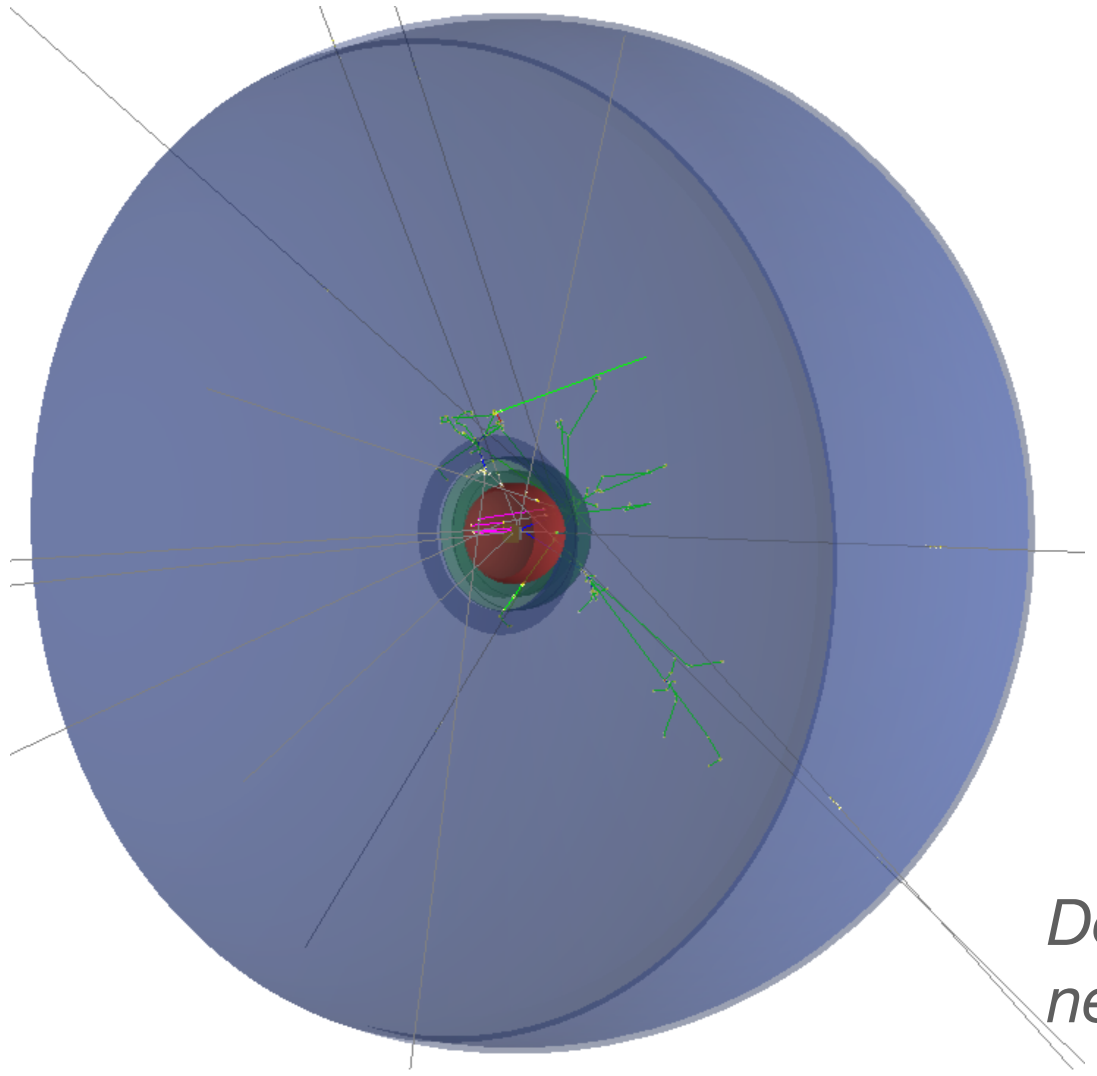
Position

Dimension

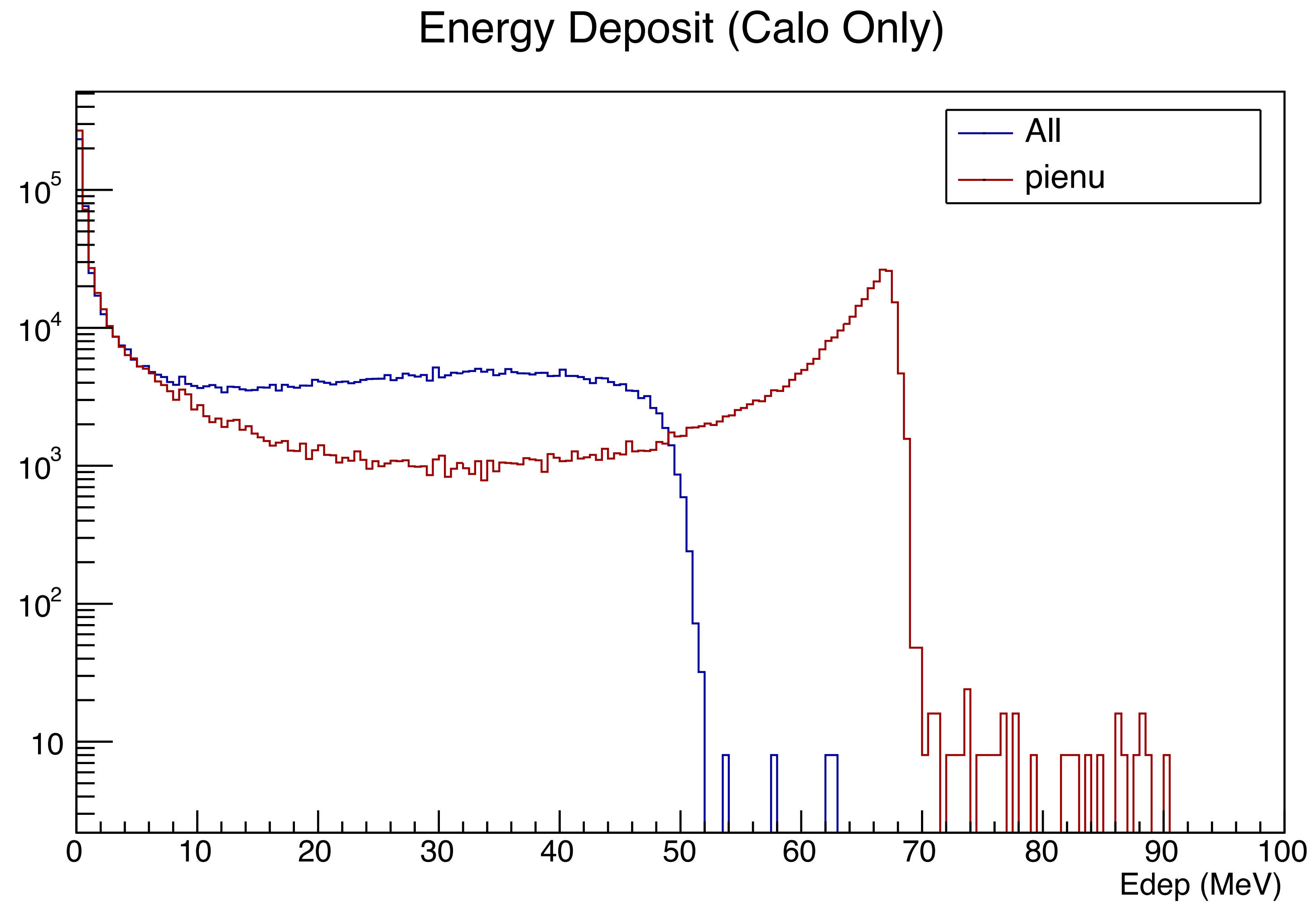
Hole Position / Dimension

The Geant4 based Simulation `G4Pioneer`



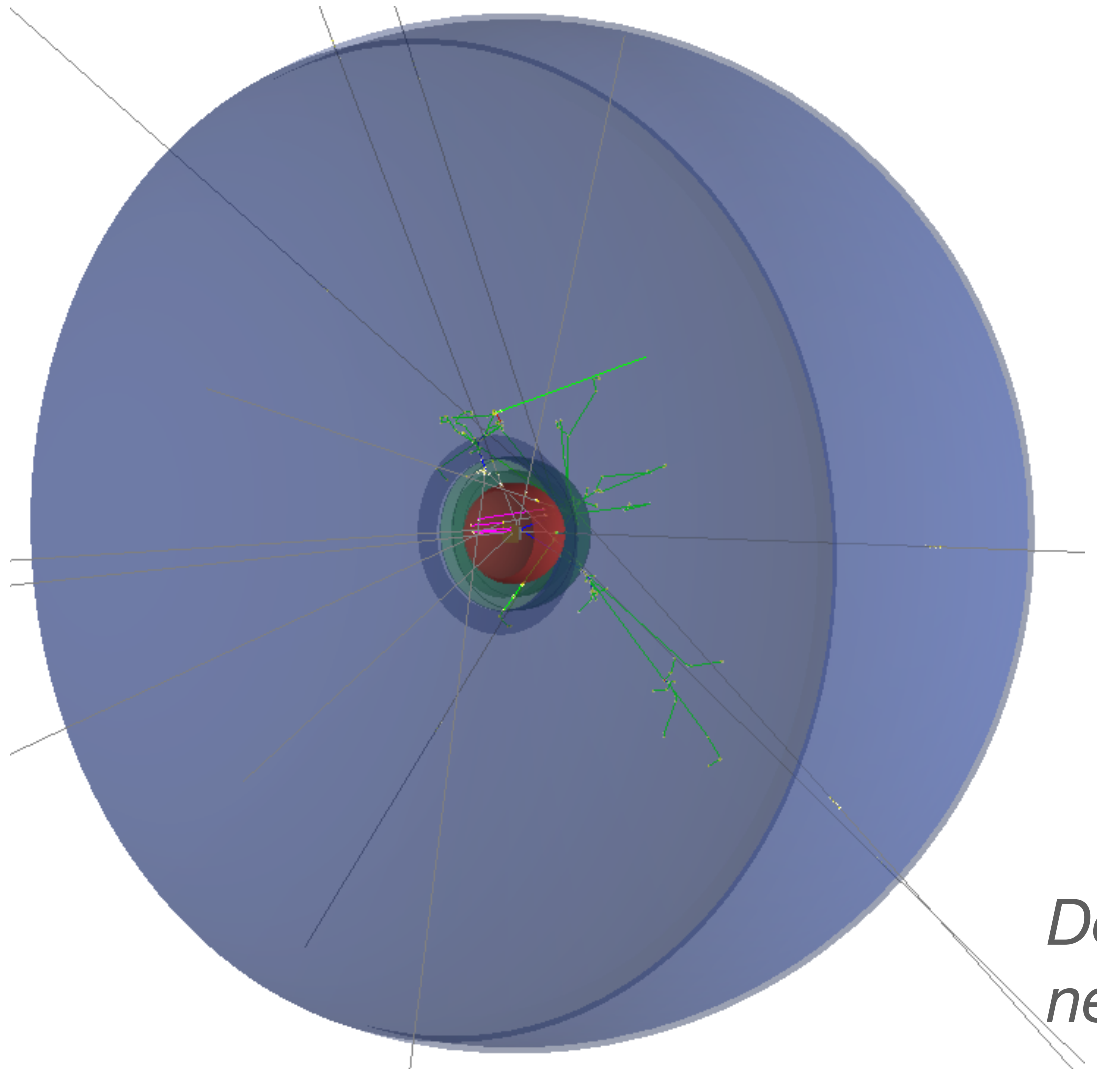


Don't mind the neutrinos (grey)

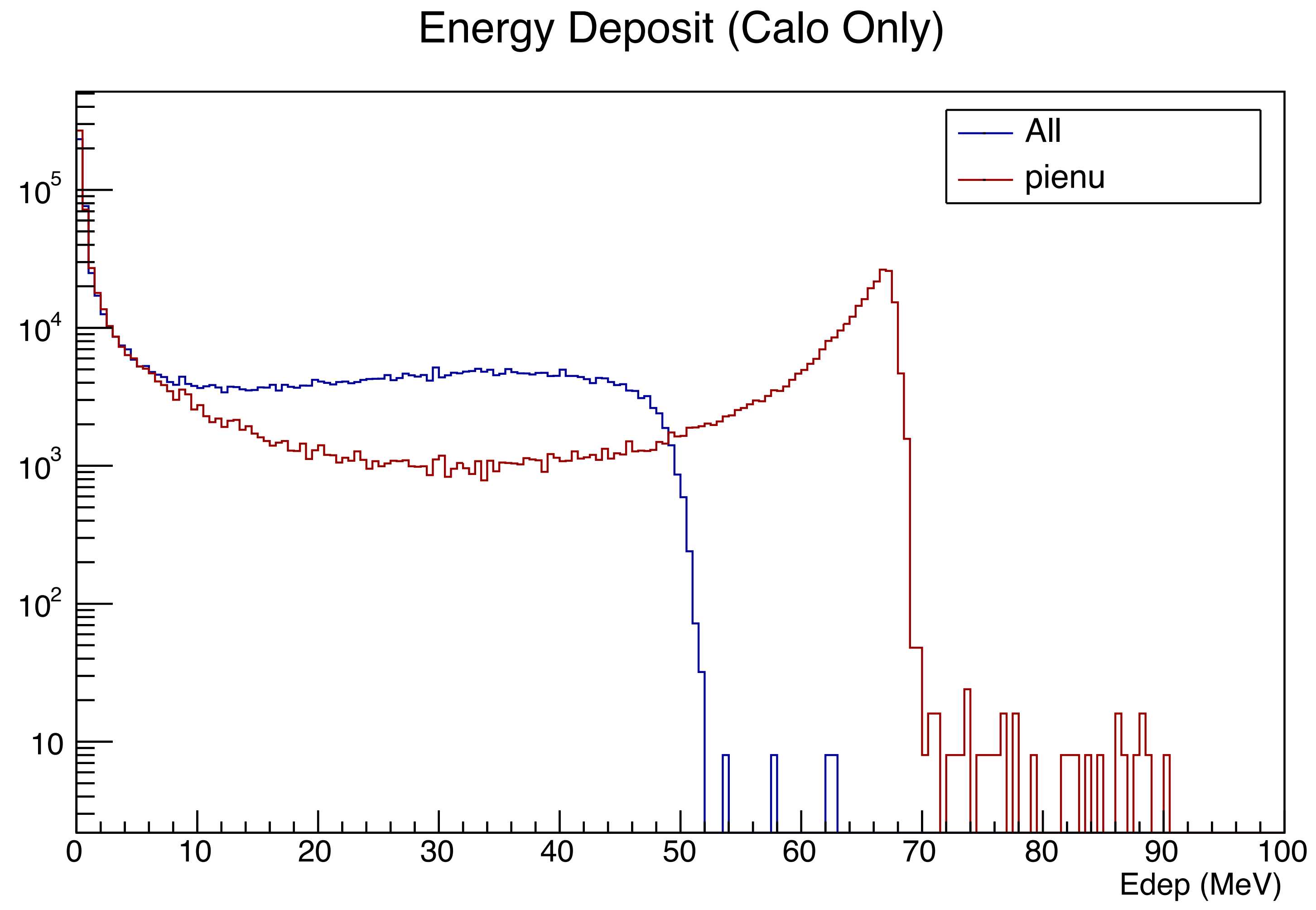


The Geant4 based Simulation `G4Pioneer`

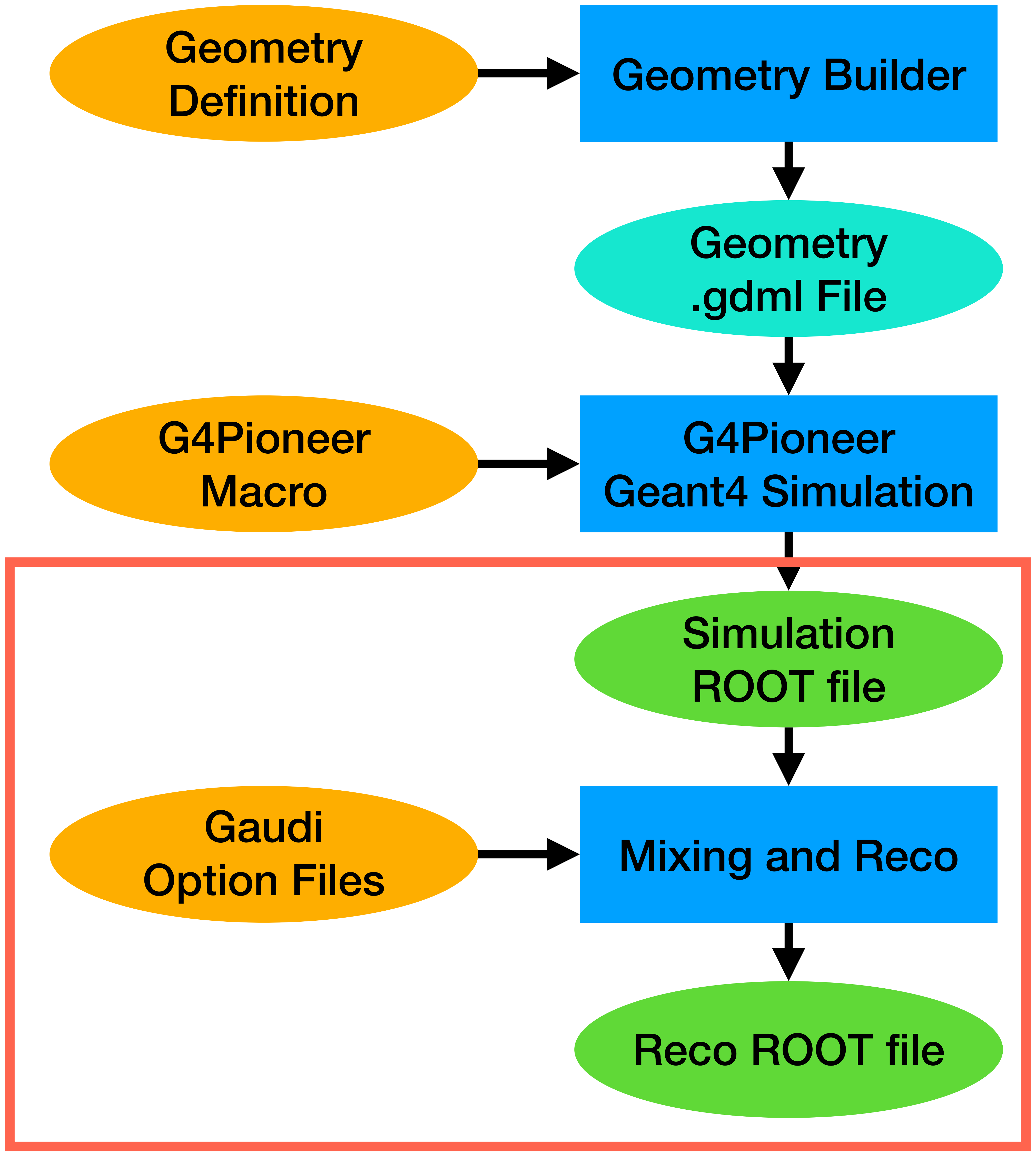
- User selects:
    - Geometry File
    - Physics to be used
    - Initial Condition
- G4Pioneer will create the particle according to the selected initial condition and propagate the particles through the geometry.



Don't mind the neutrinos (grey)



MC Truth based Fast Reconstruction



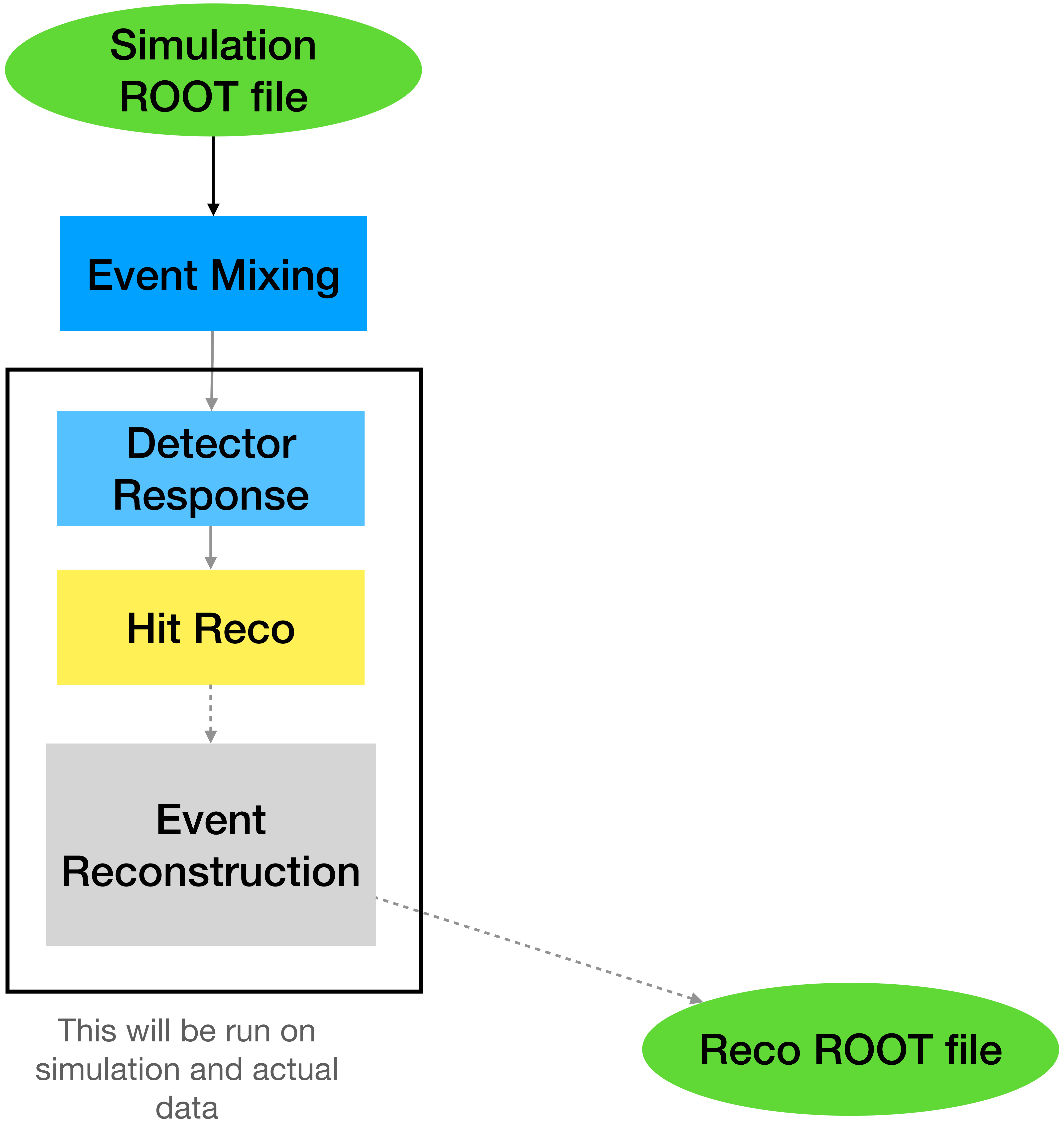
- The last step of the Simulation and Proto-Analysis framework under development.
- Produce samples with information easy to process by experts and younger colleagues alike
- Simulated samples can be analysed with standalone ROOT and the shared PIONEER library (no need to install Geant or Gaudi)
- Introduce important concepts that can become key metrics to benchmark our progress

MC Truth based Fast Reconstruction

Event Mixing

- Load events from the simulation file(s).
- Generate time separation between events.
- Align all event hits in time.
- Create a stream of Geant4 steps (hits).
- No hits get merged, the full data is still available.

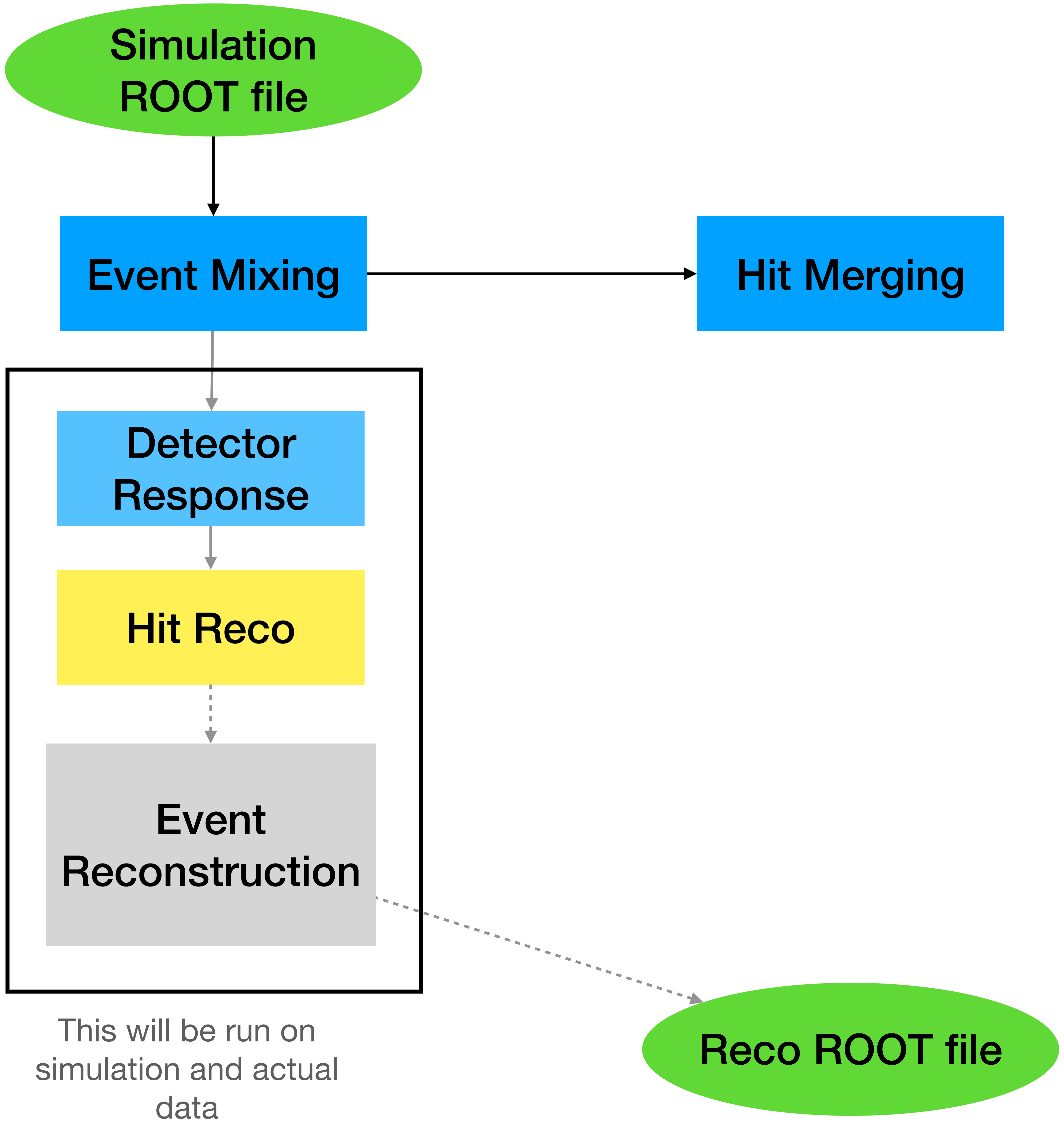
MC Truth based Fast Reconstruction



Full Detector Response and Reconstruction

- Turn the Geant4 hits into waveforms.
- Analyse waveforms to extract reconstructed hits.
- Reconstruct the full events based on the reco hits.
- Too complex for now - especially given that we don't know the details of each detector.

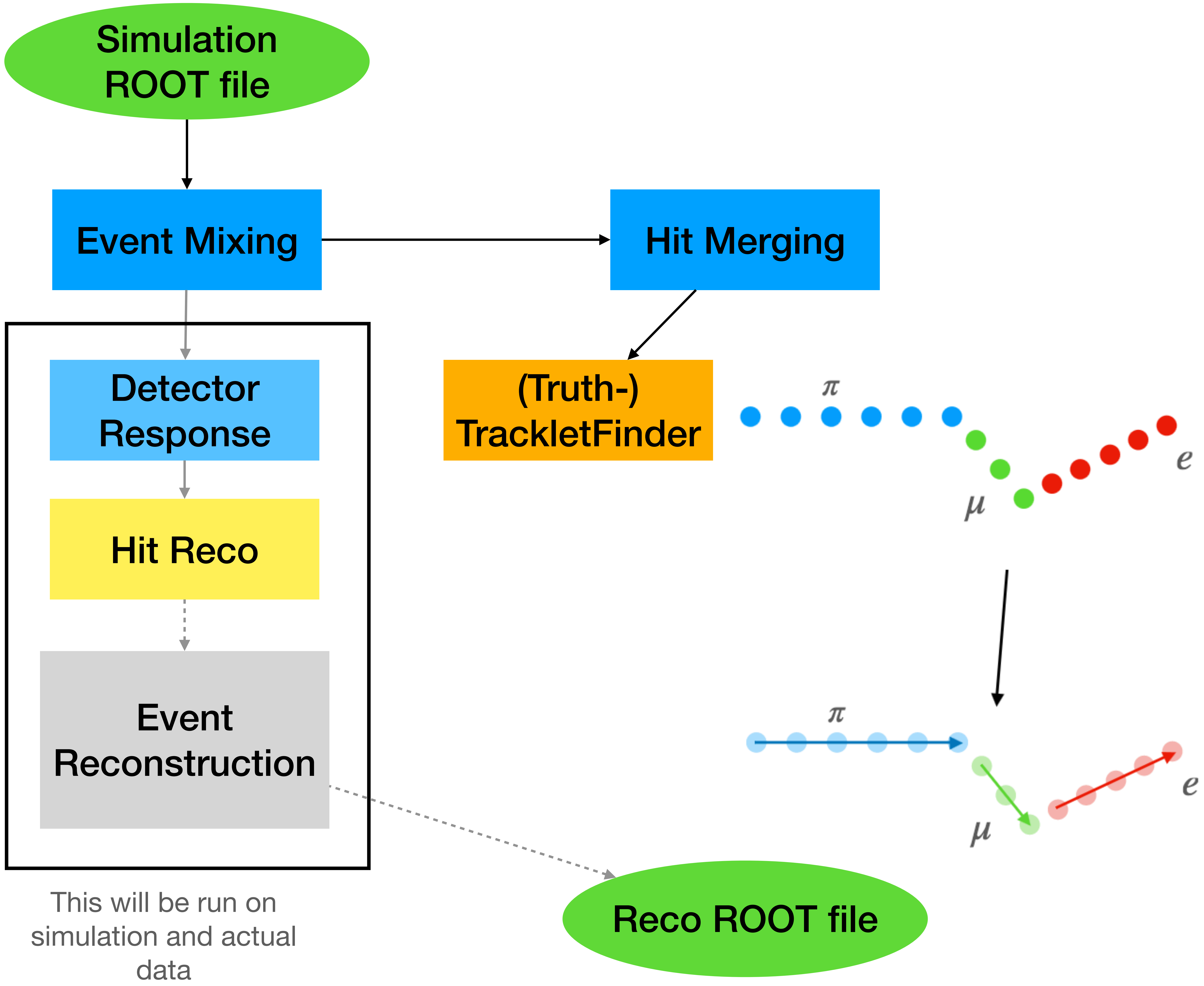
MC Truth based Fast Reconstruction



Hit Merging

- Merge hits based on some detector based criterion
- ATAR: Same strip (volume ID) within 1 ns.
- Tracker: within 0.5 mm and 5 ns
- Calo: Same volume ID and within 10 ns.

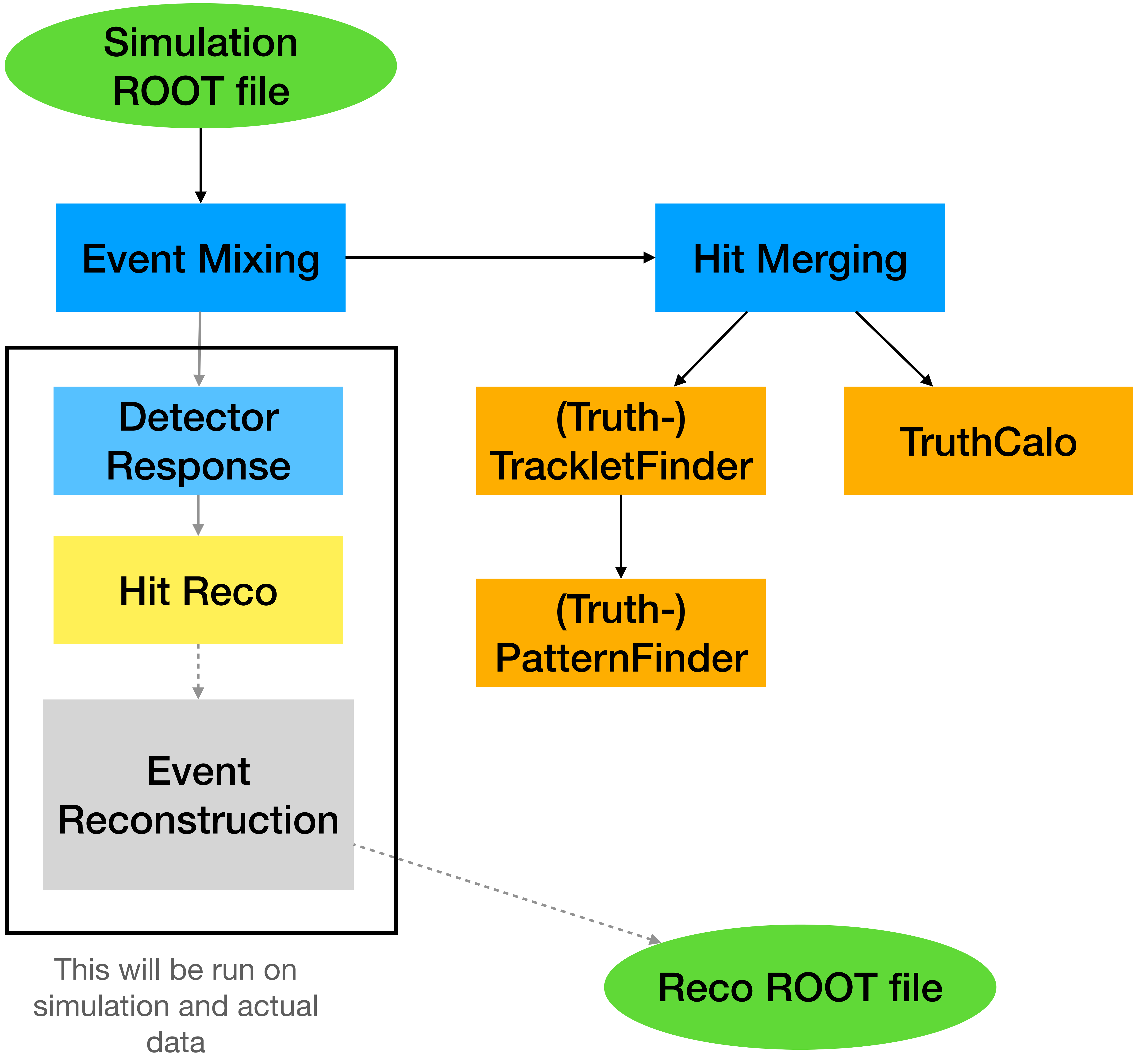
MC Truth based Fast Reconstruction



Truth-Tracklet-finder

- Collect hits based on truth values (G4 event/track ID) and store them in “tracklets”
- Only DTAR and ATAR can start tracklets, Tracker and Calo can be added as matching hits.
- Compute some track-specific quantities (e.g. StartPoint, StopPoint).

MC Truth based Fast Reconstruction



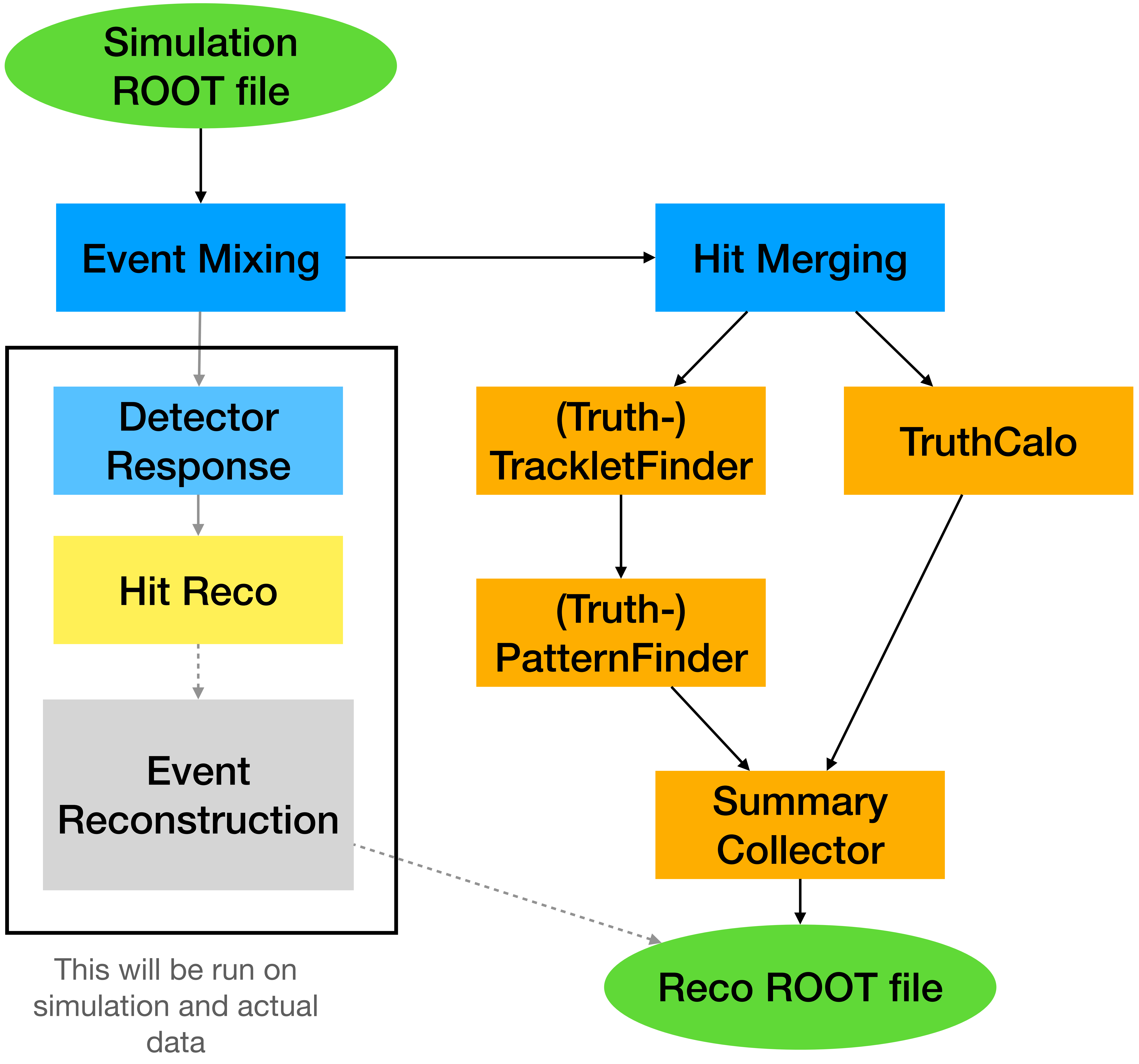
Truth-Pattern-finder

- Tracklets are gathered in patterns based on event ID.
- Output of those Truth-Algorithms are optimistic but can serve as benchmarks for future reco algorithms.

Truth-Calo

- Turns calo hits into calo reconstruction objects.
- Will be important for segmented calo designs.

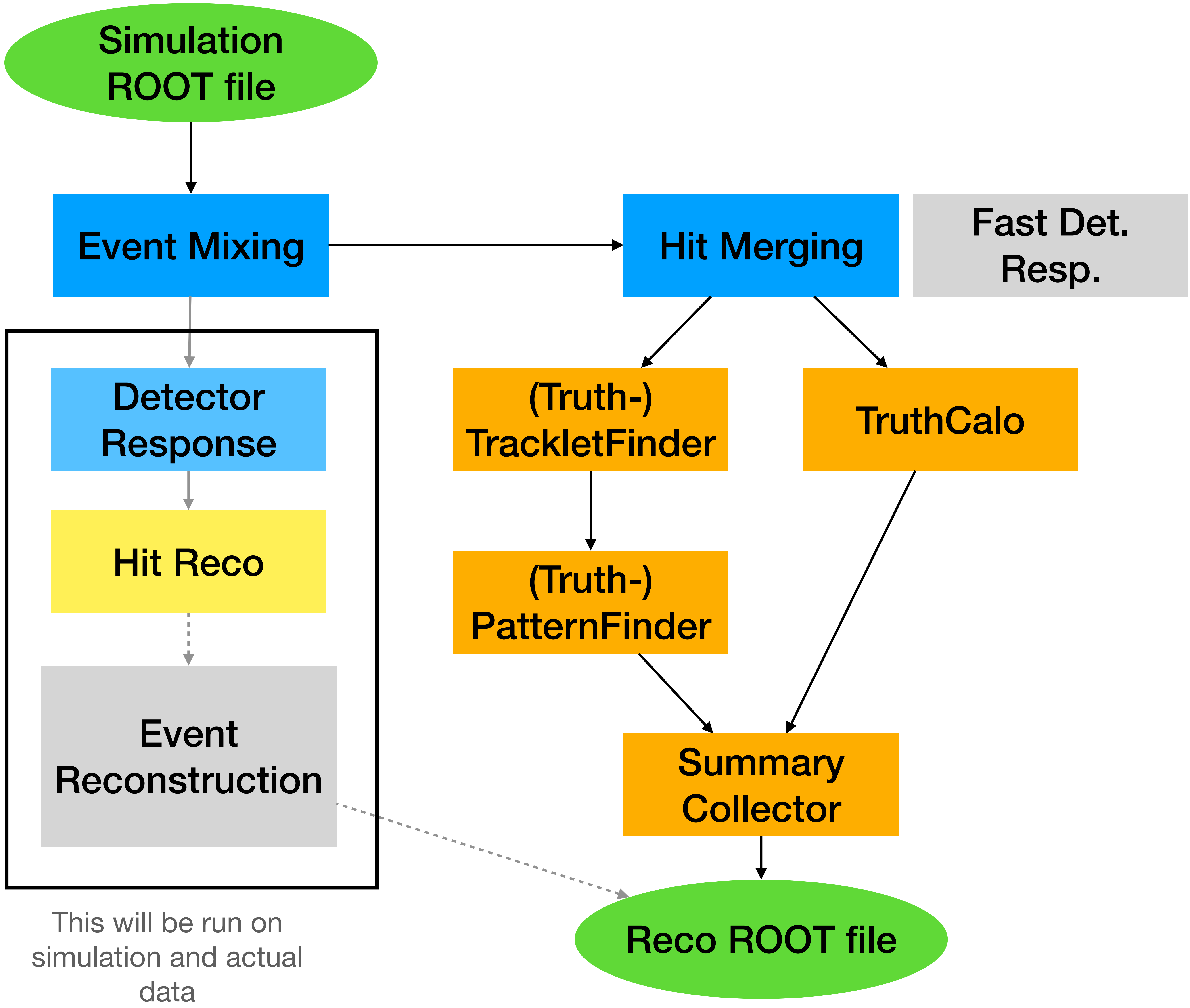
MC Truth based Fast Reconstruction



Summary Collector

- Match Calo deposits to patterns based on time information.
- Each calo deposit can match none, one or multiple patterns.
- Multiple summary objects are created in case of clearly distinct events.

MC Truth based Fast Reconstruction



Future Project: Fast. Det. Resp

- Currently, all detector response is applied after the reconstruction when filling histograms, e.g. 10% energy resolution for ATAR, 2 % for Calo.
- We know that certain responses won't be linear. (e.g. Gain Suppression in ATAR).
- Such effects can be dealt with in parallel to the hit merging and the impact on the result can be monitored immediately.

Dave Questions …

… and how to answer (some of) them

Calo physics questions

- Overall
  - Impact of Resolution and Depth on Ratio measurement (and tails)
  - Ideal inner radius for acceptance considerations
- LXe
  - Impact of **realistic window options** on resolution
  - Estimates of signals in the *n* hundred sensors vs entrance angles of electron (i.e, the dynamic range of pulse heights to l expected, which will guide electronics and calibrations)
  - **Pileup** from overlapping waveforms from Michel electrons
  - How important is photon tracking efforts within crystals or LXe volume?
  - Possibility of internal reflective baffles and a study of how many of these is "enough"
- LYSO crystals
  - Do our simulations match the test beam prediction? (to be determined soon)
  - What defines "Success" from upcoming PSI run? (Resolution; constant term)
  - If "yes" then, we must
    - Design tapered crystals, simulated response
    - Consider if the design can be evolved forward for the pibeta phase?
    - Can SICCAS make these crystals ? (assume 20 X0)
  - More so than for LXe, is resolution good enough? What does fine segmentation buy us?
- Overall: How do we come to a technical solution choice and then form just 1 Calo Team? (i.e, what 'big questions' should we articulate to help guide this decision and how can we work together?
- Recall, a Calo is much more than just the "material"
  - Sensors, Mechanics, Calibration System, LXe infrastructure *or* Crystal one by one testing and prep

Some of those are easy to solve with the current simulation.

Others need new features that require testing.

And then again some others require a deeper understanding and development of advanced reconstruction and analysis

And some are not in the scope of the simulation …

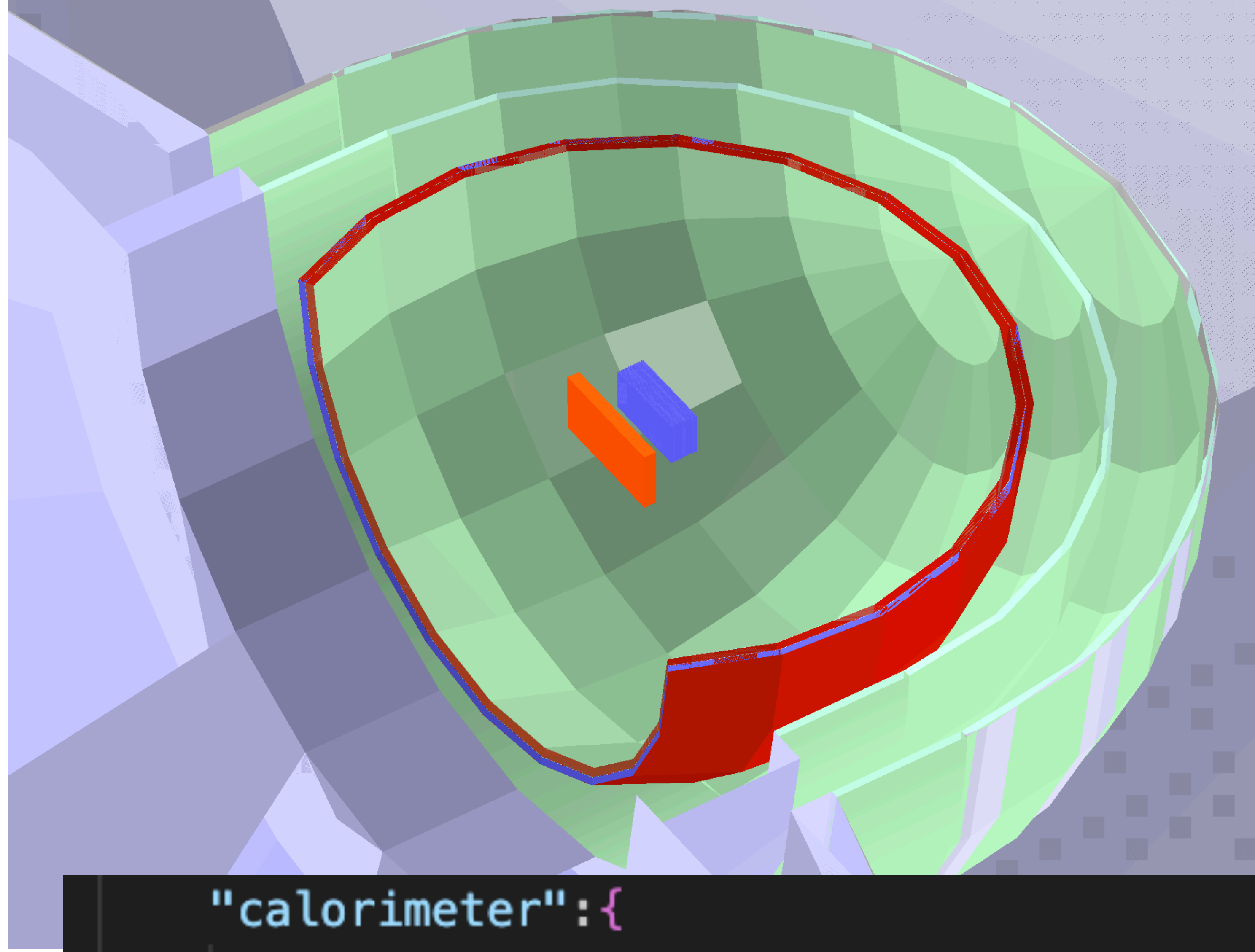
Dave's Questions

An Example: Impact of a realistic window

This requires only a few changes in the geometry.

1. Identify the actual options. Ask your local technician. Check out PSI regulations on Cryo Safety.
2. Change Material and thicknesses of the window.
3. Run `geometry-build` and get .gdml files for optimistic, realistic and pessimistic scenarios
4. Run `G4Pioneer`. Update `example.mac` to load your .gdml file and use the signal generator. (You care only about the positrons, no need to worry about pion stopping)
5. Plot `calo.Edep` for all samples, cut on `calo.time < 10` ns

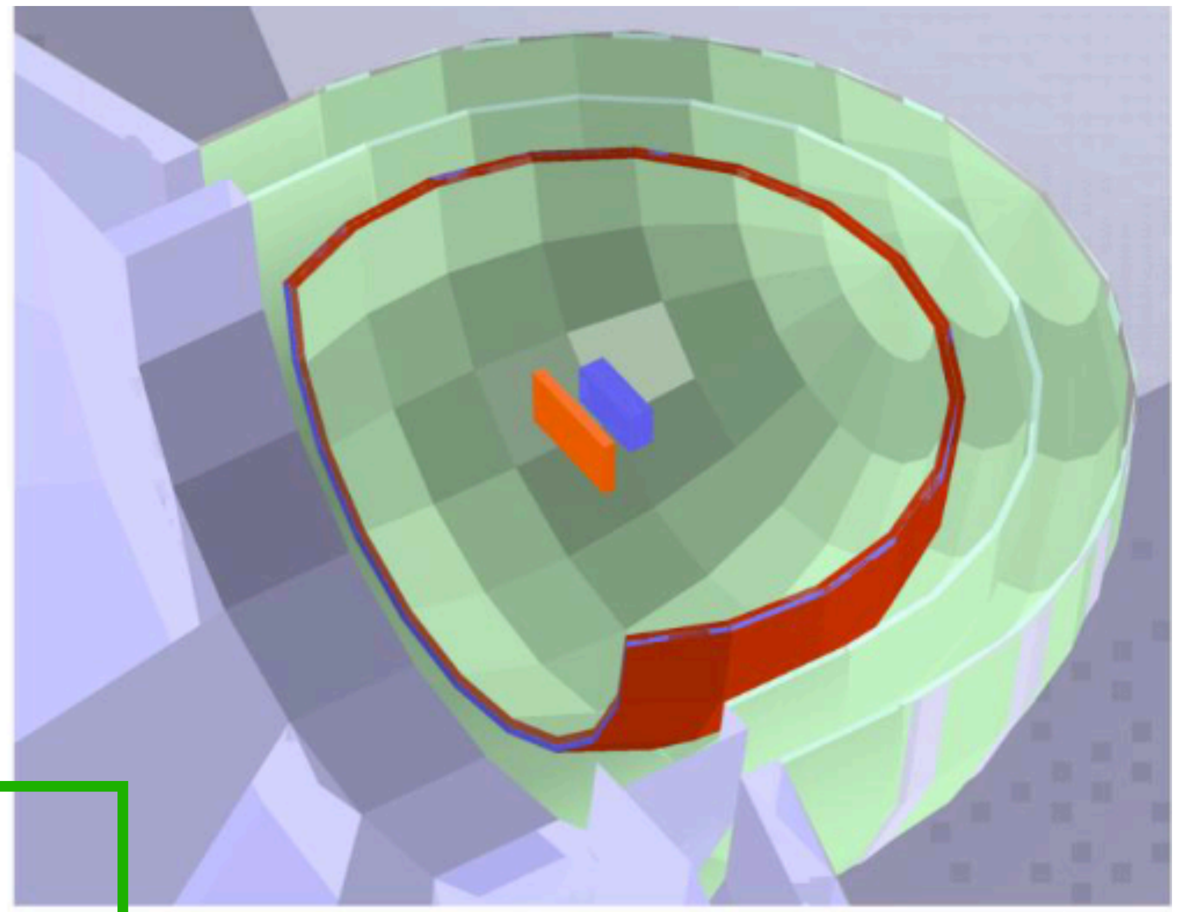
Bonus: Go into `calorimeter.py` and allow for asymmetric windows, such that one window is thinner than the other.



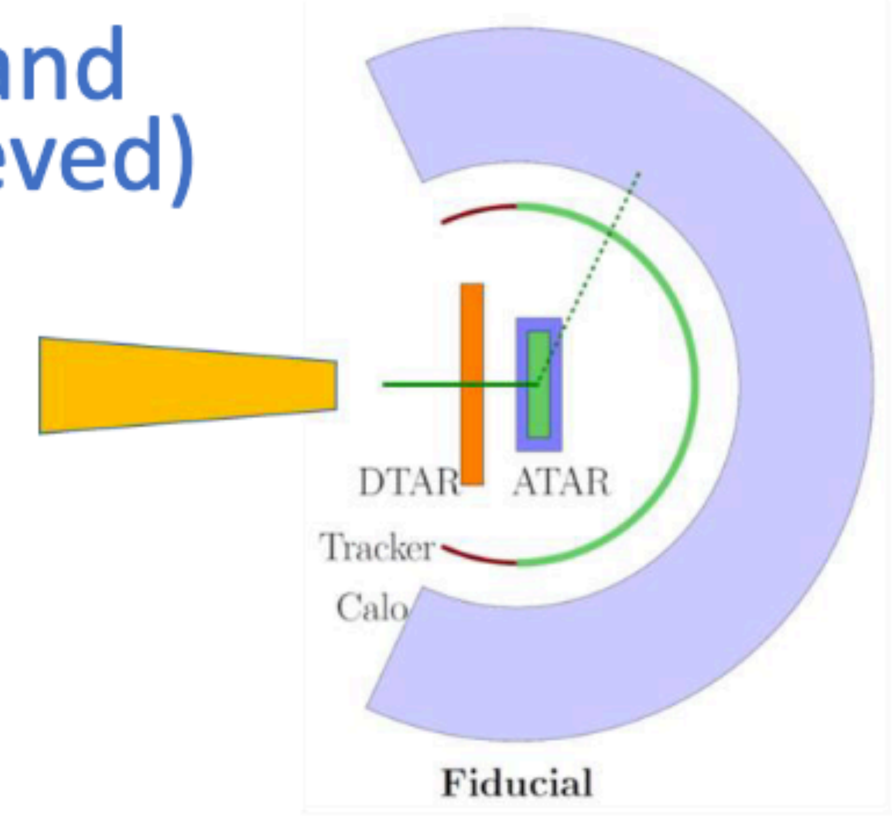
```
"calorimeter":{
    "debug":false,
    "geometry":"Pacman",
    "rIn": 10,
    "rActive": 70.24,
    "alpha": 75,
    "vacuumThickness": 2.0,
    "shellThickness": 1.0,
    "windowThickness": 0.2,
    "activeMaterial": "LXe",
    "vacuumMaterial": "Air",
    "shellMaterial": "Aluminum_black",
    "windowMaterial": "Beryllium",
    "Nsipms": 1000,
    "sipmSize": 4.0,
    "sipmThickness": 0.05,
    "sipmWindowThickness" : 0.05,
    "sipmMaterial" : "Silicon",
    "sipmWindowMaterial" : "LXe"
},
```

Another two …

DTAR/ATAR/Tracker questions



- Overall
  - relative *Z* placement optimization
  - cabling material plans/corridors
  - physical support structures (if they are in the FV)
- DTAR
  - lateral dimensions & thickness are tied to beam momentum and spot size
  - segmentation and particle ID requirements (i.e, MIP vs Pi/Mu arrivals)
- ATAR
  - Incorporate realistic **resolution, saturation, dead material** in event Recon efforts.
  - A practical study: how large can ATAR be before diminishing returns on E loss and Bhabha enter? (important; tied to Beam we might "get" if desired is not achieved)
- Tracker
  - Optimize location wrt to ATAR and Calo for use in recon (and avoiding albedo)
  - Thickness we can tolerate
  - Spatial resolution we need; what about time resolution?
  - How many planes ?



DTAR Studies

A. DTAR Thickness:
   1. Get in contact with Stefan about his latest favourite beam configuration.
   2. Make a run with exaggerated DTAR thickness, Pions will stop in DTAR. Extract the amount of extra distance the Pions need to travel to land in the centre of ATAR.
   3. Subtract that distance to obtain the optimal DTAR Thickness.

B. DTAR Position:
   1. Create different geometries with different DTAR position, vary z-component only
   2. Check where pions stop. (e.g. check the decay branch and select MotherPDGID 211). How does the ratio between good stops (Centre ATAR) vs bad stops (elsewhere) change.
   3. Run the full reconstruction. Find topologies where positrons scatter in DTAR and thus make it past the event selection although it should be rejected. (Advanced)

DTAR Studies

C. DTAR Segmentation and Particle Identification:

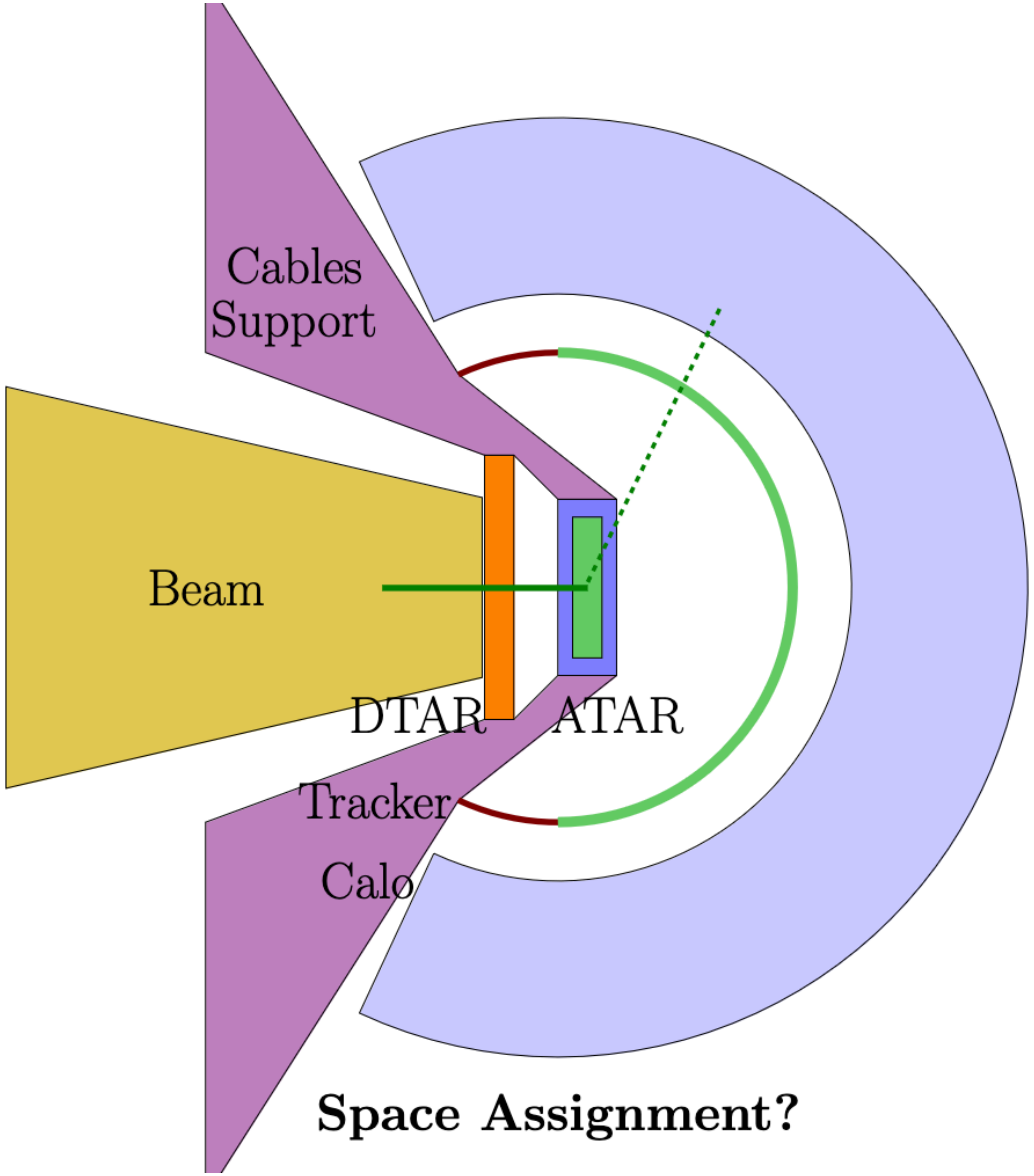
   1. Check the configuration for a strip type upstream detector. It might be similar to what you want to do.
   2. Run G4Pioneer and have a first look at energy deposit versus particle ID in the upstream branch.
   3. Run the reconstruction. Can you identify tracklets that pass through the DTAR based on energy deposits/other observables?

D. DTAR Lateral size (*also, mind ATAR cables/support)*

   1. Change the size of DTAR.
   2. Run G4Pioneer and reconstruction with Stefan's latest favourite beam.
   3. Can you use DTAR information (see C.3) to identify beam related pileup?
   4. Repeat B.3

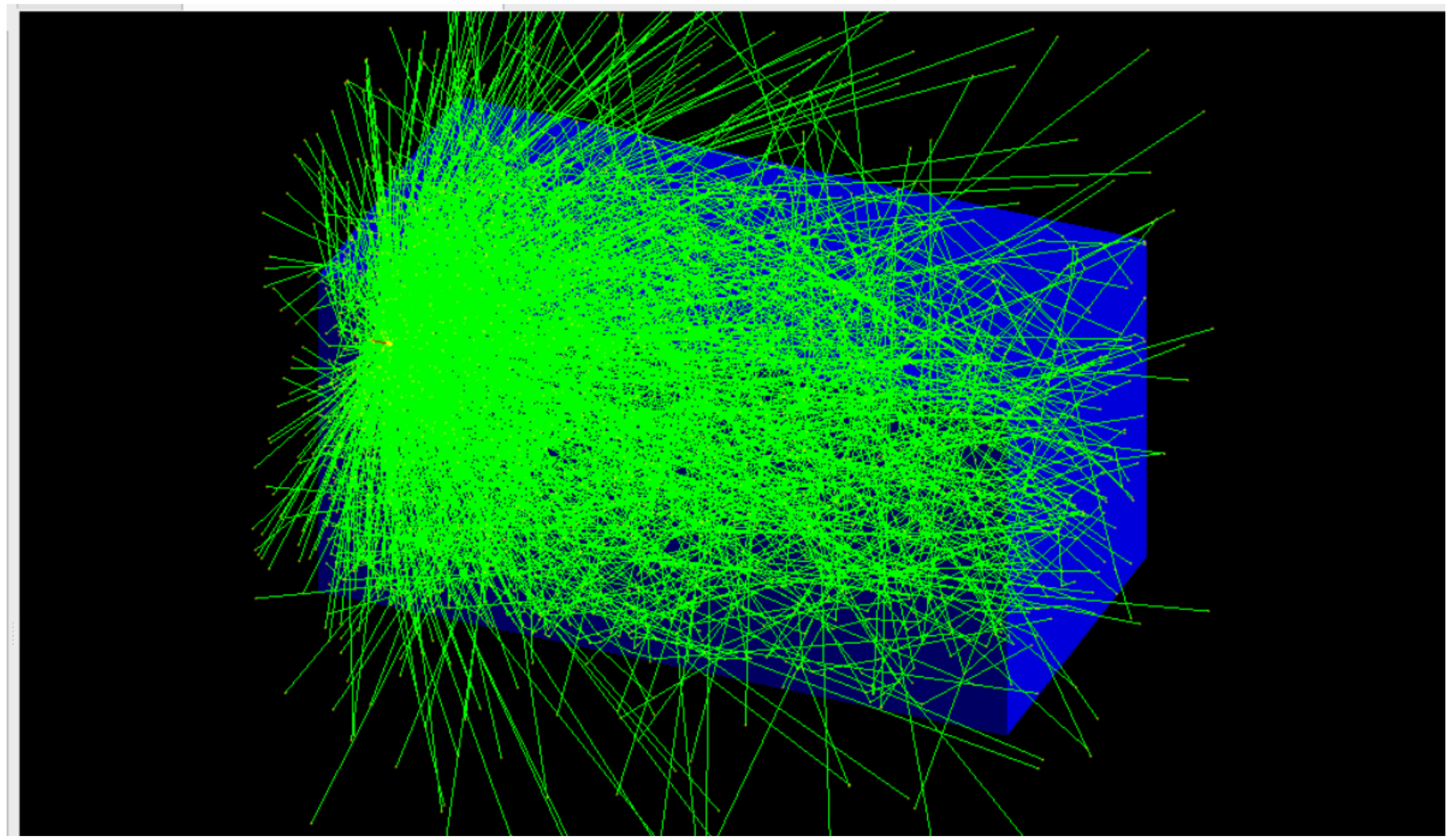
Next Steps - Geometry

- How much space is needed for:
  - Beam
  - Cables
  - Electronics
  - Support Structures
  - Xenon emergency recover
- How much space if left for Calo?
- How far can we extend the fiducial volume‘



Next Steps - Photon Tracking?

- We know that Geant4 Energy deposit is insufficient. We have to consider effects based on photon statistics.
- Do we have to chase all photons?
- Investigating the use of GPUs to track down individual photons (Yuchen, Colin, Aleksey)
- Can we use a probabilistic model and save a lot of computational power?



Picture of optical photons in a test project provided by Aleksey

Next Steps - Post Geant4 Processing

- Event Mixing is working, needs some more flexibility to forge specific pileup events.
- Require fast detector response to deal with effects such as gain saturation. This should go in parallel with hit merging.
- Unified Post-Processing, add hooks for existing work by ATAR simulation group.
- More realistic tracklet and pattern reconstruction, not relying on MC truth values.
- Unified Analysis for benchmark tests