Version 11.1

Fast Simulation

Anna Zaborowska

October 19, 2023

Outline

1. What is fast simulation?
2. How to use it in Geant4
   - where
   - what
   - how

   } to parametrise
3. Short summary
4. Examples

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1. What is fast simulation?
2. How to use it in Geant4
   - where } to parametrise
   - what } to parametrise
   - how } to parametrise
3. Short summary
4. Examples

example
[link to code in G4 v11.1.p02]

```
...
```

What do we mean by fast simulation?

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Fast simulation hooks in Geant4 allow to overtake control over particles in certain regions – user decides what happens and when/if they return to the detailed simulation.

Why to use parameterisation / fast(er) simulation?

- Physics studies that assume certain detector performance
  - to speed-up simulation of already known detector (e.g. extracted efficiency/resolution from detailed simulation)

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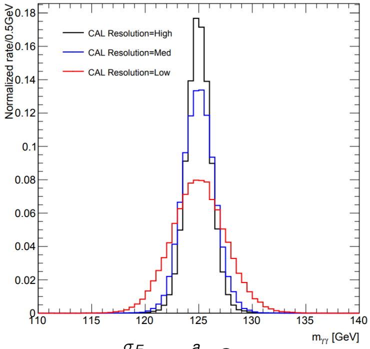
arXiv:1606.09408



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a=20%, c=2%

a=10%, c=1%

a=6%, c=0.7%

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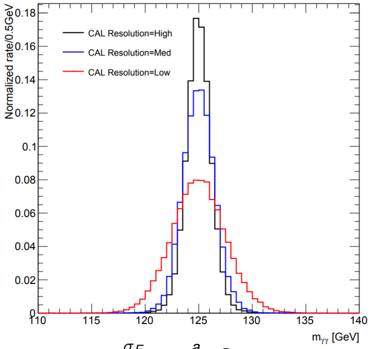

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  - to speed-up simulation of already known detector (e.g. extracted efficiency/resolution from detailed simulation)
  - to study impact of detector performance on physics observables (example in the plot: calorimeter resolution on Higgs mass)
  - to study in detail only one detector, with others parametrised (e.g. parametrised tracker in front of in-detail calorimeter)

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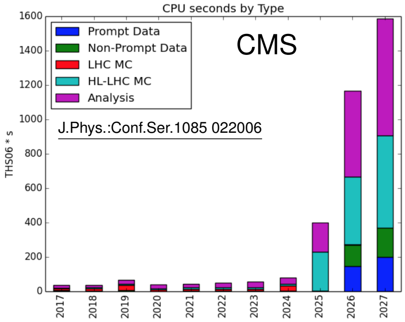
- To speed-up simulation in order to generate more data within same CPU time
  - to match available computing resources;
  - to provide sufficient amount of simulation data for comparison with the experimental data;



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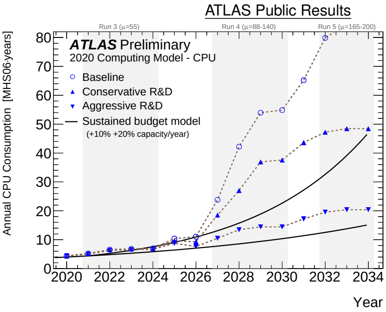

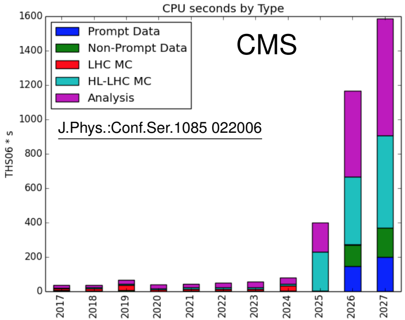

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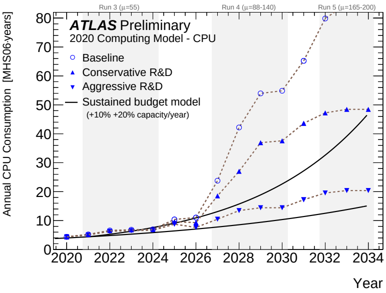
ATLAS Public Results



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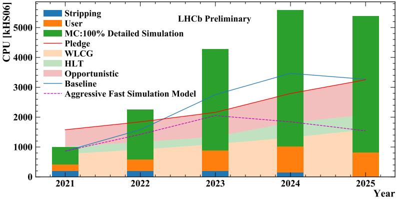
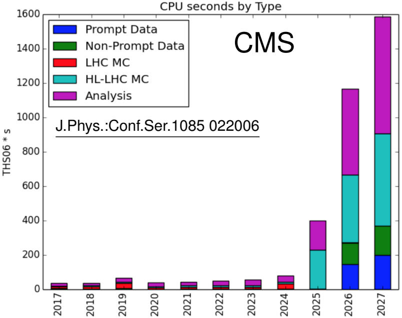
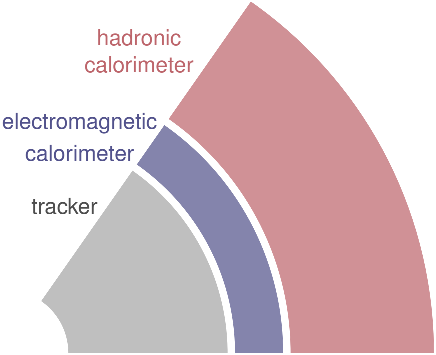




How we simulate particles?



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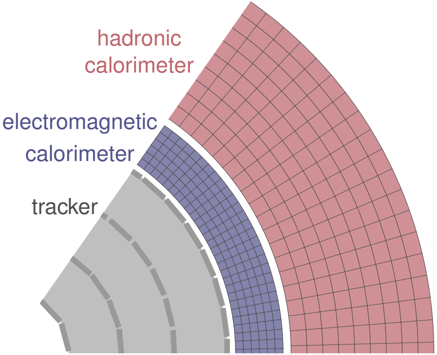

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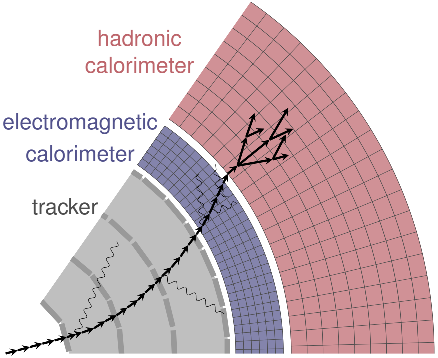

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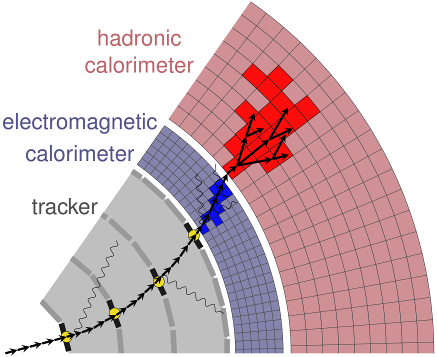

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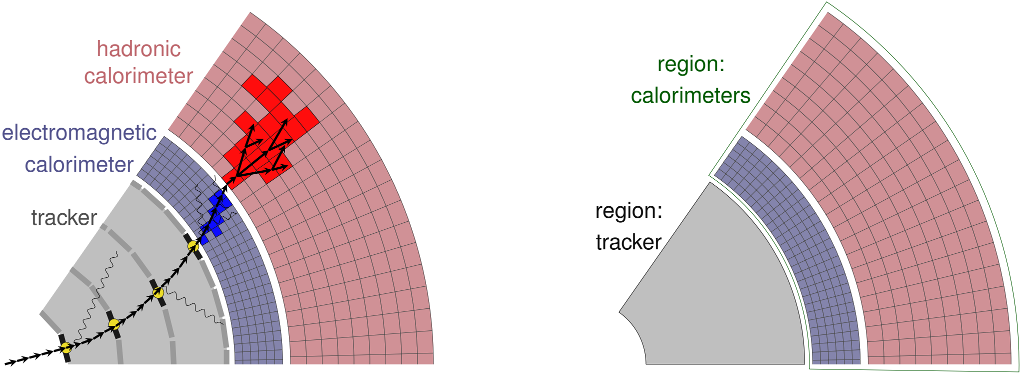

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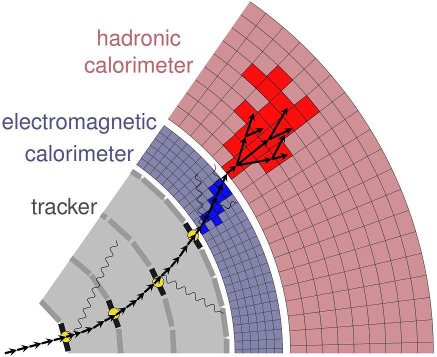

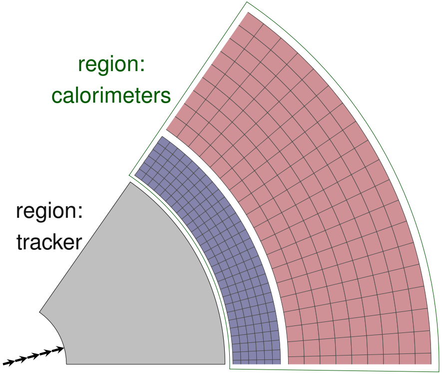

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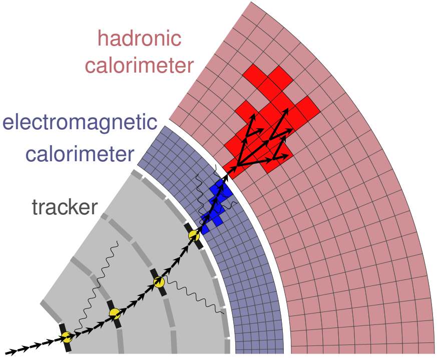

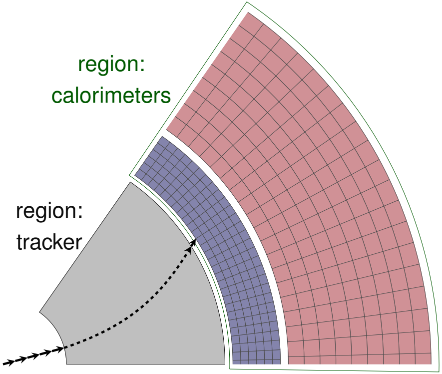

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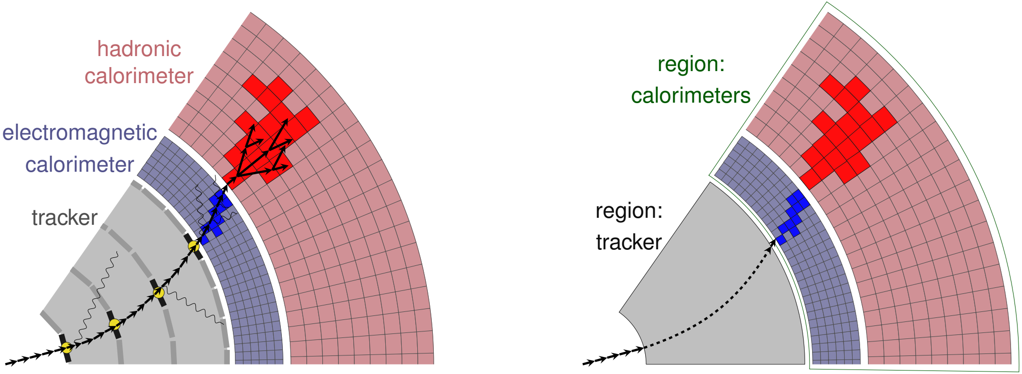
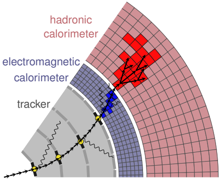


Fast simulation is a shortcut to the standard tracking and detailed simulation.

Simulation of particle passage



detailed / “full”
simulation

- detailed detector description
- definitions of particles and processes
- transport in e-m field

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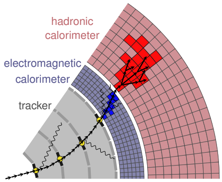
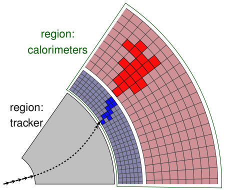


detailed / “full” simulation

parameterisation / “fast” simulation



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- where particles are parametrised
- which particles
- how/what happens

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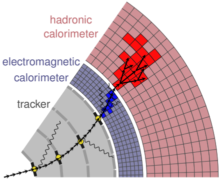

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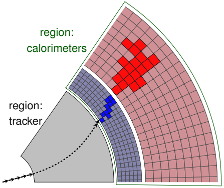

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- detector / use-case dependent

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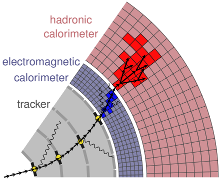

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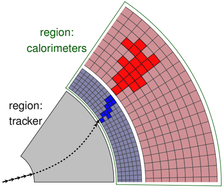

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Defining both 'full' and 'fast' simulation within one framework (Geant4) offers great flexibility to seamlessly mix both types.

Where?

Parameterisation may be realised within:

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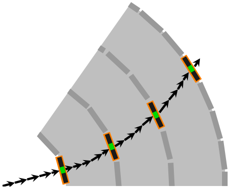
sub-volume

(many volumes)



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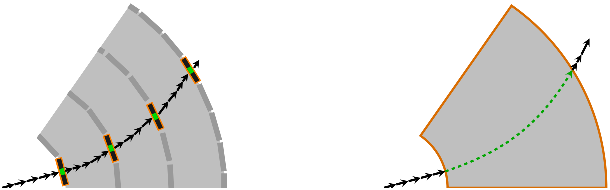

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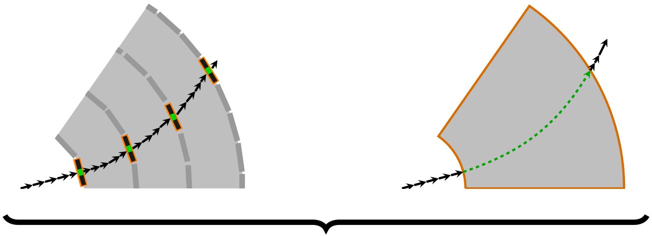

“mass” geometry

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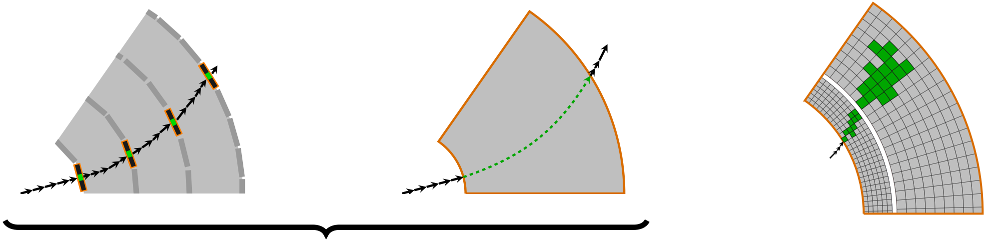

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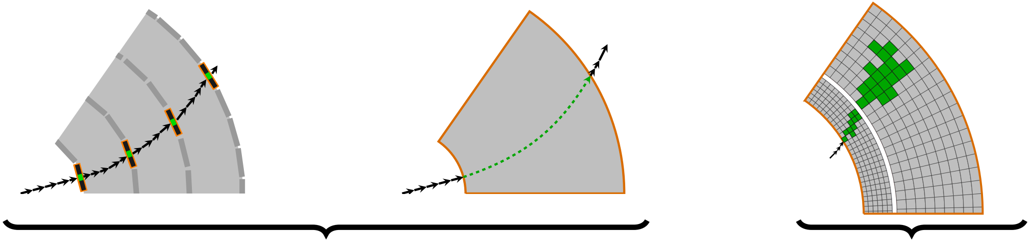

"mass" geometry | parallel geometry

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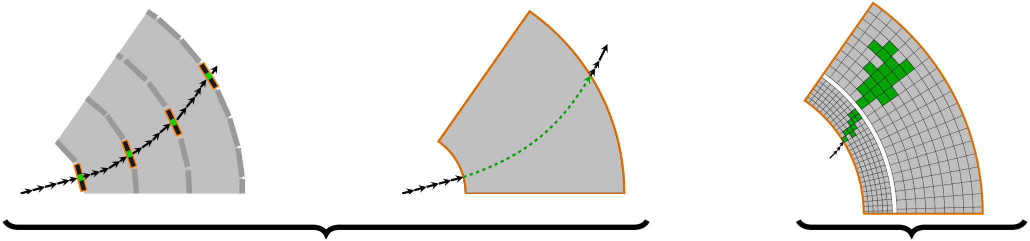

"mass" geometry — parallel geometry

Fast simulation in Geant4 is attached to **G4Region**
(associated to root G4LogicalVolume in either mass or parallel geometry).

G4Region (envelope)

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for mass geometry:

examples/extended/parameterisations/Par01/src/Par01DetectorConstruction.cc

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G4Region* caloRegion = new G4Region("EM_calo_region");
caloRegion->AddRootLogicalVolume(calorimeterLog); // calorimeterLog is a G4LogicalVolume
```

for parallel geometry:

examples/extended/parameterisations/Par01/src/Par01ParallelWorldForPion.cc

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  G4Region* ghostRegion = new G4Region("GhostCalorimeterRegion");
// ghostLogical is a G4LogicalVolume in parallel geometry, a box made of air encompassing
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G4FastSimulationPhysics helps to add parameterisation process on top of any other physics list (which is used where parameterisation is not invoked).

(since v10.3, for older versions consult user's guide or slide 29)

G4FastSimulationPhysics

for mass and parallel geometry:

examples/extended/parameterisations/Par01/examplePar01.cc

```
FTFP_BERT* physicsList = new FTFP_BERT; // G4VModularPhysicsList
G4FastSimulationPhysics* fastSimulationPhysics = new G4FastSimulationPhysics(); // helper
fastSimulationPhysics->BeVerbose();
// -- activation of fast simulation for particles having fast simulation models attached
   in the mass geometry:
fastSimulationPhysics->ActivateFastSimulation("e-");
fastSimulationPhysics->ActivateFastSimulation("e+");
fastSimulationPhysics->ActivateFastSimulation("gamma");
// -- activation of fast simulation for particles having fast simulation models attached
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fastSimulationPhysics->ActivateFastSimulation("pi+","pionGhostWorld");
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  - check particle type or intrinsic information (from G4ParticleDefinition)
  - check dynamic conditions (from G4FastTrack)
    - energy, momentum, direction, ... (from G4Track)

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  implementation of G4VFastSimulationModel class;

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Parameterisation trigger needs to be set in implementation of **G4VFastSimulationModel**,

Which particles?

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G4Region attached to G4LogicalVolume and linked to implementation of G4VFastSimulationModel;

☑ for selected particle types

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implementation of G4VFastSimulationModel class;

- check particle type or intrinsic information (from G4ParticleDefinition)
- check dynamic conditions (from G4FastTrack)
    - energy, momentum, direction, ... (from G4Track)
    - local coordinates (from G4LogicalVolume)

Parameterisation trigger needs to be set in implementation of **G4VFastSimulationModel**, which is added to **G4Region**.

G4VFastSimulationModel (1/4)

Core of the parameterisation:

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- **how**/what happens

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G4VFastSimulationModel (1/4)

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G4VFastSimulationModel(const G4String&, G4Region*)
```

examples/extended/parameterisations/Par01/src/Par01DetectorConstruction.cc

```
G4RegionStore* regionStore = G4RegionStore::GetInstance();

G4Region* caloRegion = regionStore->GetRegion("EM_calo_region");
// builds a model and sets it to the envelope of the calorimeter:
new Par01EMShowerModel("emShowerModel",caloRegion);
```

G4VFastSimulationModel (1/4)

Core of the parameterisation:

- **which** particles
- **how**/what happens

```
// constructor adds this model to G4FastSimulationManager of given envelope
G4VFastSimulationModel(const G4String&, G4Region*)
```

examples/extended/parameterisations/Par01/src/Par01DetectorConstruction.cc

```
G4RegionStore* regionStore = G4RegionStore::GetInstance();

G4Region* caloRegion = regionStore->GetRegion("EM_calo_region");
// builds a model and sets it to the envelope of the calorimeter:
new Par01EMShowerModel("emShowerModel",caloRegion);
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G4RegionStore* regionStore = G4RegionStore::GetInstance();

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new Par01EMShowerModel("emShowerModel",caloRegion);
```

G4VFastSimulationModel (2/4) — which particles?

Check intrinsic particle information (mass, charge, spin, quark content, ...)

```
virtual G4bool G4VFastSimulationModel::IsApplicable  (const G4ParticleDefinition&) = 0
```

G4VFastSimulationModel (2/4) — which particles?

Check intrinsic particle information (mass, charge, spin, quark content, ...)

```
virtual G4bool G4VFastSimulationModel::IsApplicable  (const G4ParticleDefinition&) = 0
```

Par01EMShowerModel.cc

```
G4bool Par01EMShowerModel::IsApplicable(const
↪  G4ParticleDefinition& particleType)
{




}
```

Par01PionShowerModel.cc

```
G4bool Par01PiModel::IsApplicable(const
↪  G4ParticleDefinition& particleType)
{



}
```

Par02FastSimModelTracker.cc

```
G4bool Par02FastSimModelTracker::IsApplicable( const
↪  G4ParticleDefinition& aParticleType ) {

}
```

G4VFastSimulationModel (2/4) — which particles?

Check intrinsic particle information (mass, charge, spin, quark content, ...)

```
virtual G4bool G4VFastSimulationModel::IsApplicable  (const G4ParticleDefinition&) = 0
```

Par01EMShowerModel.cc

```
G4bool Par01EMShowerModel::IsApplicable(const G4ParticleDefinition& particleType)
{
  return
    &particleType == G4Electron::ElectronDefinition() ||
    &particleType == G4Positron::PositronDefinition() ||
    &particleType == G4Gamma::GammaDefinition();
}
```

Par01PionShowerModel.cc

```
G4bool Par01PiModel::IsApplicable(const G4ParticleDefinition& particleType)
{
  return
    &particleType == G4PionMinus::PionMinusDefinition() ||
    &particleType == G4PionPlus::PionPlusDefinition();
}
```

Par02FastSimModelTracker.cc

```
G4bool Par02FastSimModelTracker::IsApplicable( const G4ParticleDefinition& aParticleType ) {

}
```

G4VFastSimulationModel (2/4) — which particles?

Check intrinsic particle information (mass, charge, spin, quark content, ...)

```
virtual G4bool G4VFastSimulationModel::IsApplicable  (const G4ParticleDefinition&) = 0
```

Par01EMShowerModel.cc

```
G4bool Par01EMShowerModel::IsApplicable(const
↪   G4ParticleDefinition& particleType)
{
  return
    &particleType ==
    ↪   G4Electron::ElectronDefinition() ||
    &particleType ==
    ↪   G4Positron::PositronDefinition() ||
    &particleType == G4Gamma::GammaDefinition();
}
```

Par01PionShowerModel.cc

```
G4bool Par01PiModel::IsApplicable(const
↪   G4ParticleDefinition& particleType)
{
  return
    &particleType ==
    ↪   G4PionMinus::PionMinusDefinition() ||
    &particleType ==
    ↪   G4PionPlus::PionPlusDefinition();
}
```

Par02FastSimModelTracker.cc

```
G4bool Par02FastSimModelTracker::IsApplicable( const
↪   G4ParticleDefinition& aParticleType ) {
  return aParticleType.GetPDGCharge() != 0;  // Applicable
  ↪   for all charged particles
}
```

G4VFastSimulationModel (3/4) — which particles?

Check dynamic conditions (momentum, direction, position, distance to boundary, ...)

```
virtual G4bool G4VFastSimulationModel::ModelTrigger  (const G4FastTrack&) = 0
```

G4VFastSimulationModel (3/4) — which particles?

Check dynamic conditions (momentum, direction, position, distance to boundary, ...)

```
virtual G4bool G4VFastSimulationModel::ModelTrigger  (const G4FastTrack&) = 0
```

Par01EMShowerModel.cc

```
G4bool Par01EMShowerModel::ModelTrigger(const G4FastTrack& fastTrack)
{
  // Applies the parameterisation above 100 MeV:
  return fastTrack.GetPrimaryTrack()->GetKineticEnergy() > 100*MeV;
}
```

G4VFastSimulationModel (3/4) — which particles?

Check dynamic conditions (momentum, direction, position, distance to boundary, ...)

```
virtual G4bool G4VFastSimulationModel::ModelTrigger  (const G4FastTrack&) = 0
```

Par01EMShowerModel.cc

```
G4bool Par01EMShowerModel::ModelTrigger(const G4FastTrack& fastTrack)
{
  // Applies the parameterisation above 100 MeV:
  return fastTrack.GetPrimaryTrack()->GetKineticEnergy() > 100*MeV;
}
```

Par01PiModel.cc

```
G4bool Par01PiModel::ModelTrigger(const G4FastTrack& fastTrack) {
  // -- example -- position:
  fastTrack.GetPrimaryTrack()->GetPosition() // global coord.
  fastTrack.GetPrimaryTrackLocalPosition() // envelope coord.
  // -- example -- direction:
  fastTrack.GetPrimaryTrack()->GetMomentum().unit() // global
  fastTrack.GetPrimaryTrackLocalDirection() // envelope
  return true;
}
```

G4VFastSimulationModel (3/4) — which particles?

Check dynamic conditions (momentum, direction, position, distance to boundary, ...)

```
virtual G4bool G4VFastSimulationModel::ModelTrigger  (const G4FastTrack&) = 0
```

GFlashShowerModel.cc

```
G4bool GFlashShowerModel::ModelTrigger(const G4FastTrack & fastTrack )

{
  G4bool select = false;
  if(FlagParamType != 0)
  {
    G4double  ParticleEnergy = fastTrack.GetPrimaryTrack()->GetKineticEnergy();
    G4ParticleDefinition &ParticleType =
      *(fastTrack.GetPrimaryTrack()->GetDefinition());
    if(ParticleEnergy > PBound->GetMinEneToParametrise(ParticleType) &&
       ParticleEnergy < PBound->GetMaxEneToParametrise(ParticleType) )
    {
      // check conditions depending on particle flavour
      // performance to be optimized @@@@@@@
      Parameterisation->GenerateLongitudinalProfile(ParticleEnergy);
      select     = CheckParticleDefAndContainment(fastTrack);
      if (select) EnergyStop= PBound->GetEneToKill(ParticleType);
    }
  }
  return select;
}
```

G4VFastSimulationModel (4/4) – What happens?

Once particle is in a chosen volume, fulfils all conditions
– take over tracking within volume and decide what to do, e.g.:

- alter energy
- move to different position (e.g. exit from volume)
- create energy deposit(s)
- kill particle
- create secondaries

```
virtual G4bool G4VFastSimulationModel::DoIt(const G4FastTrack&, G4FastStep&) = 0
```

G4VFastSimulationModel (4/4) – What happens?

Once particle is in a chosen volume, fulfils all conditions
– take over tracking within volume and decide what to do, e.g.:

- alter energy
- move to different position (e.g. exit from volume)
- create energy deposit(s)
- kill particle
- create secondaries

```
virtual G4bool G4VFastSimulationModel::DoIt(const G4FastTrack&, G4FastStep&) = 0
```

input information: G4FastTrack → output information: G4FastStep

How to deposit energy with your model?

since Geant4 v10.7

- Helper classes (`G4FastHit`, `G4FastSimHitMaker`) to deposit energy at given positions (if within the sensitive detector).
- Geant4 will look for a sensitive detector at given position, and if found – deposit energy.

How to deposit energy with your model?

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- Helper classes (`G4FastHit`, `G4FastSimHitMaker`) to deposit energy at given positions (if within the sensitive detector).
- Geant4 will look for a sensitive detector at given position, and if found – deposit energy.

`G4FastSimHitMaker::make(const G4FastHit& aHit, const G4FastTrack& aTrack)` Par03EMShowerModel.cc

```
void Par03EMShowerModel::DoIt(const G4FastTrack& aFastTrack, G4FastStep& aFastStep)
{
  ...
  G4double energy = aFastTrack.GetPrimaryTrack()->GetKineticEnergy();
  ...
  G4ThreeVector position;
  ...
  G4int generatedHits = 0;
  while(generatedHits < fNbOfHits)
  {
    position = ...
    // Create energy deposit in the detector
    // This will call appropriate sensitive detector class
    fHitMaker->make(G4FastHit(position, energy / fNbOfHits), aFastTrack);
    generatedHits++;
  }
}
```

How to deposit energy with your model?

since Geant4 v10.7

- Helper classes (`G4FastHit`, `G4FastSimHitMaker`) to deposit energy at given positions (if within the sensitive detector).
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`G4FastSimHitMaker::make(const G4FastHit& aHit, const G4FastTrack& aTrack)` Par03EMShowerModel.cc

```
void Par03EMShowerModel::DoIt(const G4FastTrack& aFastTrack, G4FastStep& aFastStep)
{
  ...
  G4double energy = aFastTrack.GetPrimaryTrack()->GetKineticEnergy();
  ...
  G4ThreeVector position;
  ...
  G4int generatedHits = 0;
  while(generatedHits < fNbOfHits)
  {
    position = ...
    // Create energy deposit in the detector
    // This will call appropriate sensitive detector class
    fHitMaker->make(G4FastHit(position, energy / fNbOfHits), aFastTrack);
    generatedHits++;
  }
}
```

G4VFastSimSensitiveDetector

- `G4VFastSimSensitiveDetector` must me used as base class in addition to inheritance from the usual base class `G4VSensitiveDetector`.
- `ProcessHits(...)` method must be implemented and describe how hits should be saved in the hit collections.

G4VFastSimSensitiveDetector

since Geant4 v10.7

- `G4VFastSimSensitiveDetector` must me used as base class in addition to inheritance from the usual base class `G4VSensitiveDetector`.
- `ProcessHits(...)` method must be implemented and describe how hits should be saved in the hit collections.

G4VFastSimSensitiveDetector   examples/extended/parameterisations/Par03/include/zPar03SensitiveDetector.hh

```
class Par03SensitiveDetector
  : public G4VSensitiveDetector
  , public G4VFastSimSensitiveDetector
{
  ...
  /// Process energy deposit from the full simulation.
  virtual G4bool ProcessHits(G4Step* aStep, G4TouchableHistory* aROhist) final;
  /// Process energy deposit from the fast simulation.
  virtual G4bool ProcessHits(const G4FastHit* aHit, const G4FastTrack* aTrack,
                             G4TouchableHistory* aROhist) final;
  ...
}
```

Summary: fast simulation in Geant4

Step-by-step:

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1. Implement model that specifies **which** particles, under what conditions and **how** should be parameterised

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1. Implement model that specifies **which** particles, under what conditions and **how** should be parameterised
   user's implementation of **G4VFastSimulationModel**

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Step-by-step:

1. Implement model that specifies **which** particles, under what conditions and **how** should be parameterised
   user's implementation of **G4VFastSimulationModel**
2. Register the parameterisation(s) for the particles (**which**)

Summary: fast simulation in Geant4

Step-by-step:

1. Implement model that specifies **which** particles, under what conditions and **how** should be parameterised
   user's implementation of **G4VFastSimulationModel**
2. Register the parameterisation(s) for the particles (**which**)
   by adding to physics list **G4FastSimulationManagerProcess** and activating it for certain particles (recommended: via **G4FastSimulationPhysics**)

Summary: fast simulation in Geant4

Step-by-step:

1. Implement model that specifies **which** particles, under what conditions and **how** should be parameterised
   user's implementation of **G4VFastSimulationModel**
2. Register the parameterisation(s) for the particles (**which**)
   by adding to physics list **G4FastSimulationManagerProcess** and activating it for certain particles (recommended: via **G4FastSimulationPhysics**)
3. Specify **where** parameterisation takes place

Summary: fast simulation in Geant4

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1. Implement model that specifies **which** particles, under what conditions and **how** should be parameterised
   user's implementation of **G4VFastSimulationModel**
2. Register the parameterisation(s) for the particles (**which**)
   by adding to physics list **G4FastSimulationManagerProcess** and activating it for certain particles (recommended: via **G4FastSimulationPhysics**)
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   by creating **G4Region**, attaching a root G4LogicalVolume, and passing it to a constructor of implementation of G4VFastSimulationModel

Summary: fast simulation in Geant4

Step-by-step:

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   user's implementation of **G4VFastSimulationModel**
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   by creating **G4Region**, attaching a root G4LogicalVolume, and passing it to a constructor of implementation of G4VFastSimulationModel

Existing examples: `examples/extended/parameterisations/`

UI commands

Fast simulation messenger

```
/param/ // Fast Simulation print/control commands.
/param/showSetup // Show fast simulation setup (for each world: fast simulation manager
↪  process - which particles, region hierarchy - which models)
/param/listEnvelopes <ParticleName (default:all)> // List all the envelope names for a
↪  given particle (or for all particles if without parameters).
/param/listModels <EnvelopeName (default:all)> // List all the Model names for a given
↪  envelope (or for all envelopes if without parameters).
/param/listIsApplicable <ModelName (default:all)> // List all the Particle names a
↪  given model is applicable (or for all models if without parameters).
/param/ActivateModel <ModelName> // Activate a given Model.
/param/InActivateModel <ModelName> // InActivate a given Model.
```

Examples

Examples

Existing examples: `examples/extended/parameterisations/`

- `examples/extended/parameterisations/Par01/src/`
  - `Par01EMShowerModel.cc`
  - `Par01PionShowerModel.cc`
  - `Par01PiModel.cc`
- `examples/extended/parameterisations/Par02/src/`
  - `Par02FastSimModelEMCal.cc`
  - `Par02FastSimModelHCal.cc`
  - `Par02FastSimModelTracker.cc`
- `examples/extended/parameterisations/Par03/src/`
  - `Par03EMShowerModel.cc`
- `examples/extended/parameterisations/Par04/src/`
  - `Par04MLFastSimModel.cc`
- `GFlashShowerModel`

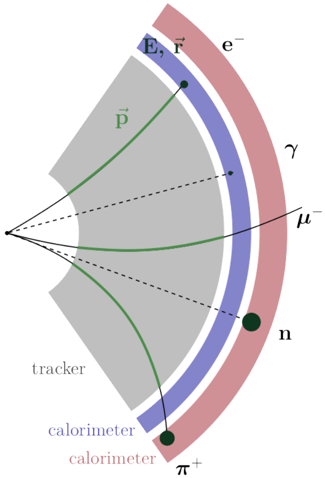
Example 1:

examples/extended/parameterisations/Par02

Example 1

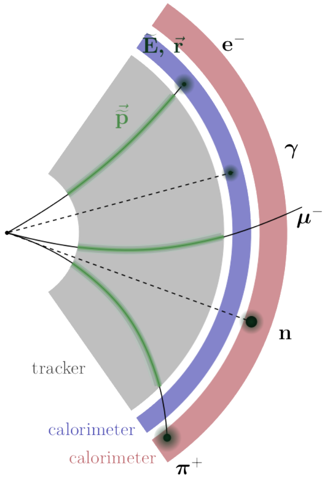
- Simple parameterisation

Example 1



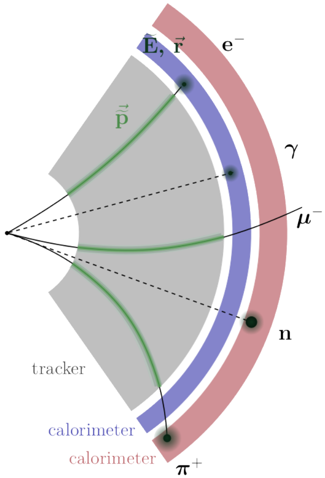
- Simple parameterisation

Example 1



- Simple parameterisation
- Smearing of the momentum in the tracker and energy in the calorimeter

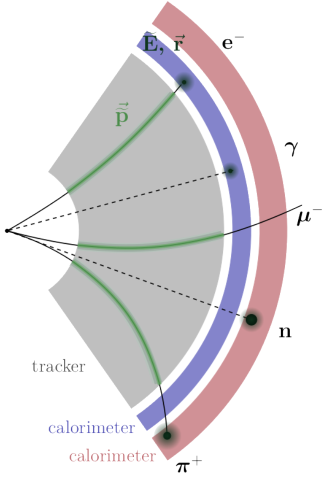
Example 1



- Simple parameterisation
- Smearing of the momentum in the tracker and energy in the calorimeter
- User input: detector resolution;

$$\sigma_{p_T} = 1.3\% \qquad \sigma_E = \frac{110\%}{\sqrt{E}} \oplus 9\%$$

Example 1



- Simple parameterisation
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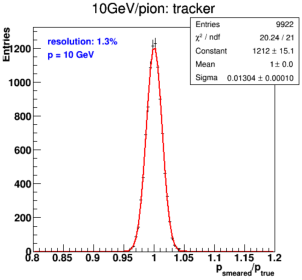

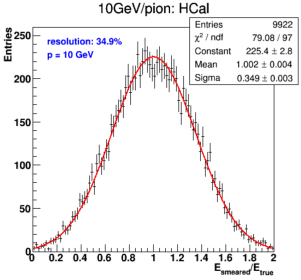

Example 1: detector construction

- from GDML;
- explore auxiliary information field to create regions

Example 1: detector construction

examples/extended/parameterisations/Par02

- from GDML;
- explore auxiliary information field to create regions

Par02FullDetector.gdml

```
<volume name="TrackerBarrelLog">
  <materialref ref="Beryllium0x7ff5f9e3baf0"/>
  <solidref ref="TrackerBarrel"/>
  <auxiliary auxtype="FastSimModel" auxvalue="TrackerBarrel"/>
</volume>
```

Example 1: detector construction

- from GDML;
- explore auxiliary information field to create regions

Par02FullDetector.gdml

```
<volume name="TrackerBarrelLog">
  <materialref ref="Beryllium0x7ff5f9e3baf0"/>
  <solidref ref="TrackerBarrel"/>
  <auxiliary auxtype="FastSimModel"
  ↪   auxvalue="TrackerBarrel"/>
</volume>
```

Par02DetectorConstruction.cc

```
G4VPhysicalVolume* Par02DetectorConstruction::Construct() {
  G4GDMLParser parser;
  parser.Read( "Par02FullDetector.gdml" );
  const G4GDMLAuxMapType* aAuxMap = parser.GetAuxMap();
  for ( G4GDMLAuxMapType::const_iterator iter = aAuxMap->begin(); iter != aAuxMap->end(); ++iter ) {
    for ( G4GDMLAuxListType::const_iterator vit = (*iter).second.begin(); vit !=
    ↪  (*iter).second.end(); ++vit ) {
      if ( (*vit).type == "FastSimModel" ) {
        G4LogicalVolume* myvol = (*iter).first;
        if ( ( myvol->GetName() ).find( "Tracker" ) != std::string::npos ) {
          fTrackerList.push_back( new G4Region( myvol->GetName() ) );
          fTrackerList.back()->AddRootLogicalVolume( myvol );
        } else [...]
      }
    }
  } ...
}
```

Example 1: detector construction

- from GDML;
- explore auxiliary information field to create regions

Par02FullDetector.gdml

```
<volume name="TrackerBarrelLog">
  <materialref ref="Beryllium0x7ff5f9e3baf0"/>
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  <auxiliary auxtype="FastSimModel"
    auxvalue="TrackerBarrel"/>
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```
G4VPhysicalVolume* Par02DetectorConstruction::Construct() {
  G4GDMLParser parser;
  parser.Read( "Par02FullDetector.gdml" );
  const G4GDMLAuxMapType* aAuxMap = parser.GetAuxMap();
  for ( G4GDMLAuxMapType::const_iterator iter = aAuxMap->begin(); iter != aAuxMap->end(); ++iter ) {
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      (*iter).second.end(); ++vit ) {
      if ( (*vit).type == "FastSimModel" ) {
        G4LogicalVolume* myvol = (*iter).first;
        if ( ( myvol->GetName() ).find( "Tracker" ) != std::string::npos ) {
          fTrackerList.push_back( new G4Region( myvol->GetName() ) );
          fTrackerList.back()->AddRootLogicalVolume( myvol );
        } else [...]
      }
    }
  } ...
}
```

Example 1: detector construction

- from GDML;
- explore auxiliary information field to create regions

Par02FullDetector.gdml

```
<volume name="TrackerBarrelLog">
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</volume>
```

Par02DetectorConstruction.cc

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G4VPhysicalVolume* Par02DetectorConstruction::Construct() {
  G4GDMLParser parser;
  parser.Read( "Par02FullDetector.gdml" );
  const G4GDMLAuxMapType* aAuxMap = parser.GetAuxMap();
  for ( G4GDMLAuxMapType::const_iterator iter = aAuxMap->begin(); iter != aAuxMap->end(); ++iter ) {
    for ( G4GDMLAuxListType::const_iterator vit = (*iter).second.begin(); vit !=
    ↪  (*iter).second.end(); ++vit ) {
      if ( (*vit).type == "FastSimModel" ) {
        G4LogicalVolume* myvol = (*iter).first;
        if ( ( myvol->GetName() ).find( "Tracker" ) != std::string::npos ) {
          fTrackerList.push_back( new G4Region( myvol->GetName() ) );
          fTrackerList.back()->AddRootLogicalVolume( myvol );
        } else [...]
      }
    }
  } ...
}
```

Example 1: detector construction

- from GDML;
- explore auxiliary information field to create regions

Par02FullDetector.gdml

```
<volume name="TrackerBarrelLog">
  <materialref ref="Beryllium0x7ff5f9e3baf0"/>
  <solidref ref="TrackerBarrel"/>
  <auxiliary auxtype="FastSimModel"
  ↪   auxvalue="TrackerBarrel"/>
</volume>
```

Par02DetectorConstruction.cc

```
G4VPhysicalVolume* Par02DetectorConstruction::Construct() {
  G4GDMLParser parser;
  parser.Read( "Par02FullDetector.gdml" );
  const G4GDMLAuxMapType* aAuxMap = parser.GetAuxMap();
  for ( G4GDMLAuxMapType::const_iterator iter = aAuxMap->begin(); iter != aAuxMap->end(); ++iter ) {
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    ↪  (*iter).second.end(); ++vit ) {
      if ( (*vit).type == "FastSimModel" ) {
        G4LogicalVolume* myvol = (*iter).first;
        if ( ( myvol->GetName() ).find( "Tracker" ) != std::string::npos ) {
          fTrackerList.push_back( new G4Region( myvol->GetName() ) );
          fTrackerList.back()->AddRootLogicalVolume( myvol );
        } else [...]
      }
    }
  } ...
}
```

Example 1: detector construction

- from GDML;
- explore auxiliary information field to create regions and fast simulation models

Par02FullDetector.gdml

```
<volume name="TrackerBarrelLog">
  <materialref ref="Beryllium0x7ff5f9e3baf0"/>
  <solidref ref="TrackerBarrel"/>
  <auxiliary auxtype="FastSimModel"
  ↪   auxvalue="TrackerBarrel"/>
</volume>
```

Par02DetectorConstruction.cc

```
void Par02DetectorConstruction::ConstructSDandField() {
  for ( G4int iterTracker = 0; iterTracker < G4int(
  ↪   fTrackerList.size() ); iterTracker++ ) {
    // Bound the fast simulation model for the tracker subdetector
    // to all the corresponding Geant4 regions
    Par02FastSimModelTracker* fastSimModelTracker
    = new Par02FastSimModelTracker( "fastSimModelTracker",
    ↪   fTrackerList[ iterTracker ],
    ↪   Par02DetectorParametrisation::eCMS );
    // Register the fast simulation model for deleting
    G4AutoDelete::Register(fastSimModelTracker);
  }...
}
```

Example 1: detector construction

- from GDML;
- explore auxiliary information field to create regions and fast simulation models

Par02FullDetector.gdml

```
<volume name="TrackerBarrelLog">
  <materialref ref="Beryllium0x7ff5f9e3baf0"/>
  <solidref ref="TrackerBarrel"/>
  <auxiliary auxtype="FastSimModel"
  ↪   auxvalue="TrackerBarrel"/>
</volume>
```

Par02DetectorConstruction.cc

```
void Par02DetectorConstruction::ConstructSDandField() {
  for ( G4int iterTracker = 0; iterTracker < G4int(
  ↪   fTrackerList.size() ); iterTracker++ ) {
    // Bound the fast simulation model for the tracker subdetector
    // to all the corresponding Geant4 regions
    Par02FastSimModelTracker* fastSimModelTracker
    = new Par02FastSimModelTracker( "fastSimModelTracker",
    ↪   fTrackerList[ iterTracker ],
    ↪   Par02DetectorParametrisation::eCMS );
    // Register the fast simulation model for deleting
    G4AutoDelete::Register(fastSimModelTracker);
  }...
}
```

Example 1: physics list

- register by-hand G4FastSimulationManagerProcess
- process registered for all constructed particles

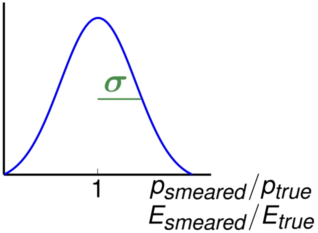
(Not recommended!
But also works for versions < 10.3)

Par02PhysicsList.cc

```
void Par02PhysicsList::AddParameterisation() {
  G4FastSimulationManagerProcess* fastSimProcess =
    new G4FastSimulationManagerProcess( "G4FSMP" );
  // Registers the fastSimProcess with all the particles as a discrete
  ↪  and
  // continuous process (this works in all cases; in the case that
  ↪  parallel
  // geometries are not used, as in this example, it would be enough to
  // add it as a discrete process).
  auto particleIterator=GetParticleIterator();
  particleIterator->reset();
  while ( (*particleIterator)() ) {
    G4ParticleDefinition* particle = particleIterator->value();
    G4ProcessManager* pmanager = particle->GetProcessManager();
    //pmanager->AddDiscreteProcess( fastSimProcess );    // No parallel
    ↪  geometry
    pmanager->AddProcess( fastSimProcess, -1, 0, 0 );  // General
  }
}
```

Example 1: models

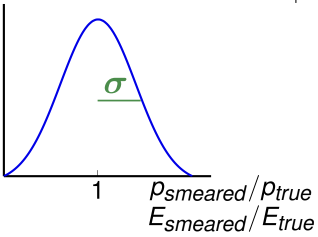
- smearing of momentum (tracker) / energy (calorimeters) with Gaussian;



Example 1: models

- smearing of momentum (tracker) / energy (calorimeters) with Gaussian;
- resolution defined arbitrarily in Par02DetectorParametrisation ([E] = GeV)

	CMS-like	ALEPH-like	ATLAS-like
σ (Tracker)	1.3%	1%	1%
σ (EMCAL)	$\frac{3\%}{\sqrt{E}} \oplus \frac{12\%}{E} \oplus 0.3\%$	$\frac{18\%}{\sqrt{E}} \oplus 0.9\%$	$\frac{10\%}{\sqrt{E}} \oplus 0.17\%$
σ (HCAL)	$\frac{110\%}{\sqrt{E}} \oplus 9\%$	$\frac{85\%}{\sqrt{E}}$	$\frac{55\%}{\sqrt{E}} \oplus 6\%$



Example 1: models

`examples/extended/parameterisations/Par02`

- smearing of momentum (tracker) / energy (calorimeters) with Gaussian;
- resolution defined arbitrarily in Par02DetectorParametrisation ([E] = GeV)

	CMS-like	ALEPH-like	ATLAS-like
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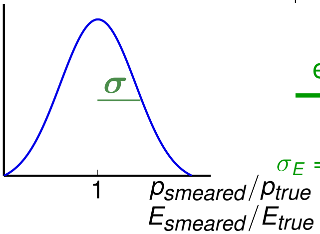

e.g. 10 GeV π^- →

$\sigma_p = 1.3\%$

$\sigma_E = \frac{110\%}{\sqrt{E}} \oplus 9\% \approx 35\%$

Example 1: models

- smearing of momentum (tracker) / energy (calorimeters) with Gaussian;
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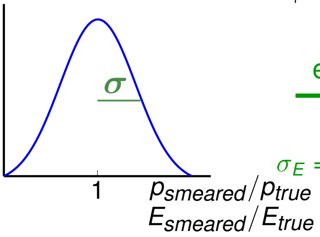

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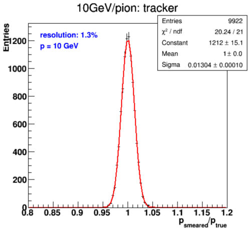

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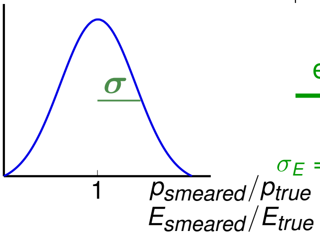

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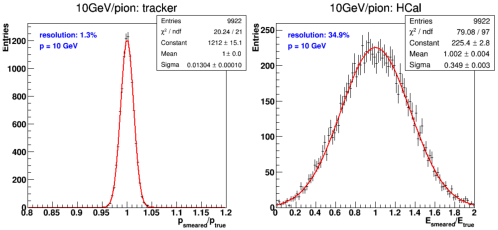

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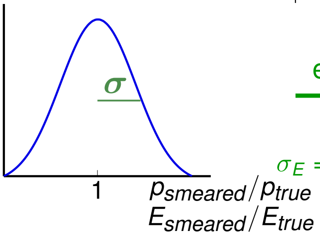

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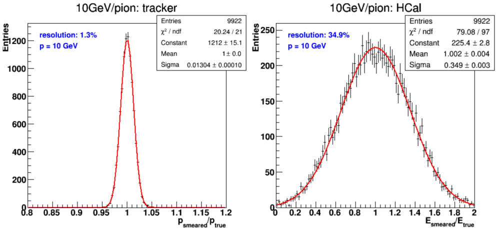

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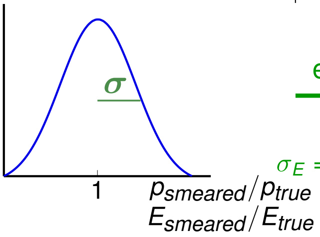

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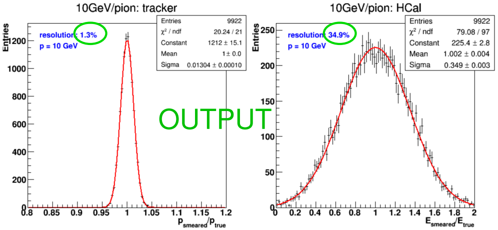

Example 1: models

- Tracker: transport it in EM field to the exit-from-envelope, smear momentum;

Par02FastSimModelTracker.cc

```
void Par02FastSimModelTracker::DoIt( const G4FastTrack& aFastTrack, G4FastStep& aFastStep ) {
  G4Track track = * aFastTrack.GetPrimaryTrack();
  ...
  G4PathFinder* fPathFinder = G4PathFinder::GetInstance();
  fPathFinder->ComputeStep( ... );
  aFastStep.ProposePrimaryTrackFinalPosition( endTrack.GetPosition() );
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```
void Par02FastSimModelEMCal::DoIt( const G4FastTrack& aFastTrack, G4FastStep& aFastStep ) {
  aFastStep.KillPrimaryTrack();
  aFastStep.ProposePrimaryTrackPathLength( 0.0 );
  G4double Edep = aFastTrack.GetPrimaryTrack()->GetKineticEnergy();
  G4double Esm; [...] // Esm = smeared Edep
  aFastStep.ProposeTotalEnergyDeposited( Esm );
}
```

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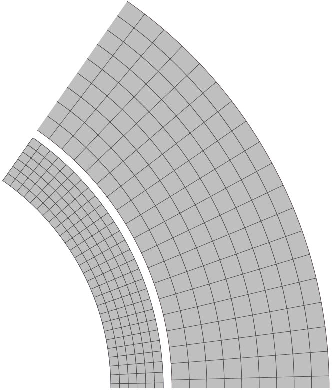
Example 2:

`examples/extended/parameterisations/Par01`

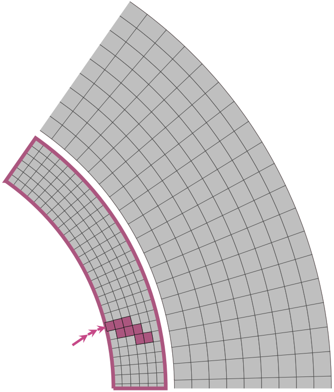
Example 2

Time consuming simulation of calorimeters replaced by creation of energy deposits.



Example 2

Time consuming simulation of calorimeters replaced by creation of energy deposits.



Par01EMShowerModel.cc

- electrons and photons
- electromagnetic calorimeter, envelope in mass geometry

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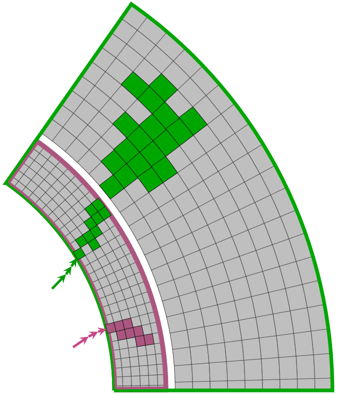

`Par01EMShowerModel.cc`

- electrons and photons
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`Par01PionShowerModel.cc`

- pions
- both calorimeters: envelope around EMCal and HCal $\Rightarrow$ parallel geometry

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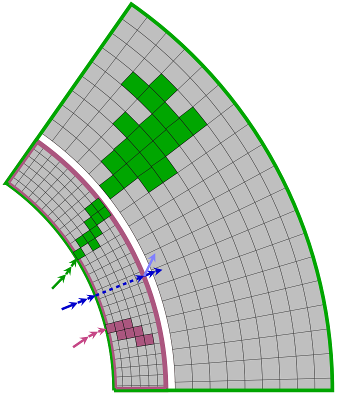


Par01EMShowerModel.cc

- electrons and photons
- electromagnetic calorimeter, envelope in mass geometry

Par01PionShowerModel.cc

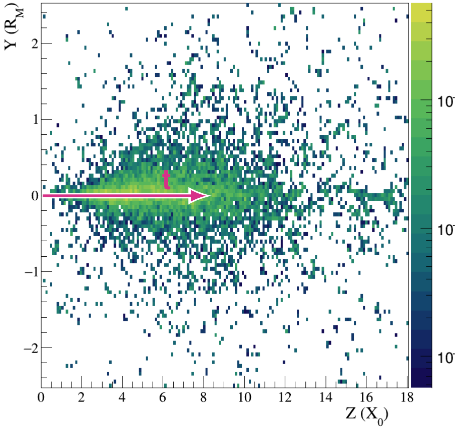
- pions
- both calorimeters: envelope around EMCal and HCal $\Rightarrow$ parallel geometry

Par01PiModel.cc

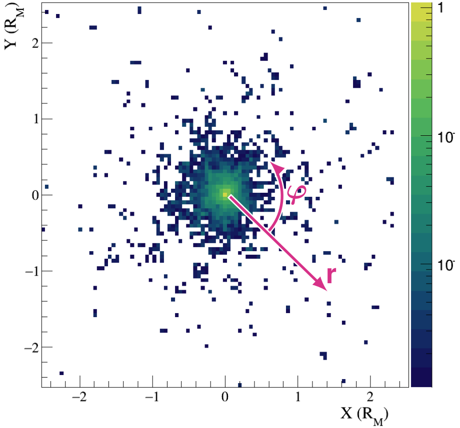
- create secondaries

Shower profiles

longitudinal profile



lateral profile



Example 2 – models

How to deposit energy E of electrons/photons? Par01EMShowerModel.cc

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How to deposit energy E of electrons/photons?

Par01EMShowerModel.cc

$$f(t, r, \varphi) = f(t)f(r)f(\varphi)$$

1. longitudinal shower profile $f(t)$
2. lateral profile $f(r)$
3. flat azimuthal angle distribution $f(\varphi)$

Example 2 – models

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$$f(\varphi) = \frac{1}{2\pi}$$

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1. longitudinal shower profile $f(t)$
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$$f(\varphi) = \frac{1}{2\pi}, \qquad f\,(t; k, \theta) = \frac{x^{k-1} e^{-\frac{x}{\theta}}}{\theta^k \Gamma(k)}$$

Example 2 – models

How to deposit energy E of electrons/photons? Par01EMShowerModel.cc

$$f(t, r, \varphi) = f(t)f(r)f(\varphi)$$

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3. flat azimuthal angle distribution $f(\varphi)$

$$f(\varphi) = \frac{1}{2\pi}, \quad f(t; k, \theta) = \frac{x^{k-1} e^{-\frac{x}{\theta}}}{\theta^k \Gamma(k)}, \quad f(r) = \begin{cases} \frac{0.9}{2 \cdot R_M} & \text{for} \quad |r| \leqslant R_M \\ \frac{0.1}{5 \cdot R_M} & \text{for} \quad R_M < |r| \leqslant 3.5 \cdot R_M \\ 0 & \text{for} \quad |r| \geqslant 3.5 \cdot R_M \end{cases}$$

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4. deposit energy $\Delta E = \frac{E}{N}$ in $N = 100$ points

Example 2 – models

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   - pick t, r and φ from $f(t)$, $f(r)$, and $f(\varphi)$

Example 2 – models

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4. deposit energy $\Delta E = \frac{E}{N}$ in $N = 100$ points
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   in (t,r,φ) inside electromagnetic calorimeter

Example 2 – models

Manual placement of hits. Not needed if `G4FastSimHitMaker` is used - see slide 18.

Par01EMShowerModel.cc

```
void Par01EMShowerModel::DoIt(const G4FastTrack& fastTrack, G4FastStep& fastStep) {
  ...
  BuildDetectorResponse();
}
```

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```
void Par01EMShowerModel::BuildDetectorResponse() {
  for (size_t i = 0; i < feSpotList.size(); i++) {
    AssignSpotAndCallHit(feSpotList[i]);
  }
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  }
}
```

```
void Par01EMShowerModel::AssignSpotAndCallHit(const Par01EnergySpot &eSpot)
{
  FillFakeStep(eSpot);
  G4VPhysicalVolume* pCurrentVolume = fFakeStep->GetPreStepPoint()->GetPhysicalVolume();
  G4VSensitiveDetector* pSensitive;
  if( pCurrentVolume != 0 ) {
    pSensitive = pCurrentVolume->GetLogicalVolume()->GetSensitiveDetector();
    if( pSensitive != 0 ) {
      pSensitive->Hit(fFakeStep);
    }
  }
}
```

Example 2 – models

How to deposit energy E of pions?

Par01PionShowerModel.cc

Example 2 – models

How to deposit energy E of pions?

Par01PionShowerModel.cc

$$f(x,\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2 \Big/ 2\sigma^2}$$

1. longitudinal shower profile $f(t, 0, 20\text{cm})$
2. lateral profile $f(r, 0, 10\text{cm})$

Example 2 – models

How to deposit energy E of pions? Par01PionShowerModel.cc

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3. azimuthal angle

$$f(\varphi) = \frac{1}{2\pi}$$

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3. azimuthal angle

$$f(\varphi) = \frac{1}{2\pi}$$

4. deposit energy $\Delta E = \frac{E}{N}$ in $N = 50$ points

Example 2 – models

How to deposit energy E of pions?

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3. azimuthal angle

$$f(\varphi) = \frac{1}{2\pi}$$

4. deposit energy $\Delta E = \frac{E}{N}$ in $N = 50$ points
   - pick t, r and φ from $f(t)$, $f(r)$, and $f(\varphi)$

Example 2 – models

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2. lateral profile $f(r, 0, 10\text{cm})$
3. azimuthal angle

$$f(\varphi) = \frac{1}{2\pi}$$

4. deposit energy $\Delta E = \frac{E}{N}$ in $N = 50$ points
   - pick t, r and φ from $f(t)$, $f(r)$, and $f(\varphi)$

   in (t,r,φ) inside electromagnetic + hadronic calorimeter envelope

Example 2 – models

How to create secondaries?

Par01PiModel.cc

Par01PiModel.cc

```
// -- First, user has to say how many secondaries will be created:
fastStep.SetNumberOfSecondaryTracks(1);
G4ParticleMomentum direction(fastTrack.GetPrimaryTrackLocalDirection());
direction.setZ(direction.z()*0.5);
direction.setY(direction.y()+direction.z()*0.1);
direction = direction.unit(); // necessary ?
// -- dynamics (Note that many constructors exists for G4DynamicParticle
G4DynamicParticle dynamique(G4Gamma::GammaDefinition(),
                            direction,
                            fastTrack.GetPrimaryTrack()->
                            GetKineticEnergy()/2.);
G4double Dist;
Dist = fastTrack.GetEnvelopeSolid()->
DistanceToOut(fastTrack.GetPrimaryTrackLocalPosition(),
              direction);
G4ThreeVector posi;
posi = fastTrack.GetPrimaryTrackLocalPosition() + Dist*direction;
fastStep.CreateSecondaryTrack(dynamique, posi,
                              fastTrack.GetPrimaryTrack()->GetGlobalTime());
```

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              direction);
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fastStep.CreateSecondaryTrack(dynamique, posi,
                              fastTrack.GetPrimaryTrack()->GetGlobalTime());
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Example 2 – models

GEANT4 A SIMULATION TOOLKIT

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Example 2 – models

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posi = fastTrack.GetPrimaryTrackLocalPosition() + Dist*direction;
fastStep.CreateSecondaryTrack(dynamique, posi,
                              fastTrack.GetPrimaryTrack()->GetGlobalTime());
```

Example 2 – models

How to transport particles to the outer boundary? Par01PiModel.cc

Par01PiModel.cc

```
G4ThreeVector position;
G4double distance;
distance = fastTrack.GetEnvelopeSolid()->
  DistanceToOut(fastTrack.GetPrimaryTrackLocalPosition(),
                fastTrack.GetPrimaryTrackLocalDirection());
position = fastTrack.GetPrimaryTrackLocalPosition() +
  distance*fastTrack.GetPrimaryTrackLocalDirection();

// -- set final position:
fastStep.ProposePrimaryTrackFinalPosition(position);
```

Example 2 – models

examples/extended/parameterisations/Par01

How to transport particles to the outer boundary?

Par01PiModel.cc

Par01PiModel.cc

```
G4ThreeVector position;
G4double distance;
distance = fastTrack.GetEnvelopeSolid()->
  DistanceToOut(fastTrack.GetPrimaryTrackLocalPosition(),
                fastTrack.GetPrimaryTrackLocalDirection());
position = fastTrack.GetPrimaryTrackLocalPosition() +
  distance*fastTrack.GetPrimaryTrackLocalDirection();

// -- set final position:
fastStep.ProposePrimaryTrackFinalPosition(position);
```

Example 2 – models

How to transport particles to the outer boundary? Par01PiModel.cc

Par01PiModel.cc

```
G4ThreeVector position;
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distance = fastTrack.GetEnvelopeSolid()->
  DistanceToOut(fastTrack.GetPrimaryTrackLocalPosition(),
                fastTrack.GetPrimaryTrackLocalDirection());
position = fastTrack.GetPrimaryTrackLocalPosition() +
  distance*fastTrack.GetPrimaryTrackLocalDirection();

// -- set final position:
fastStep.ProposePrimaryTrackFinalPosition(position);
```

Example 3:

examples/extended/parameterisations/Par03

Example 3 – EM shower model

Based on PDG (chapter 33.5)

Par03EMShowerModel.cc

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Par03EMShowerModel.cc

1. longitudinal shower profile

$$\frac{\mathrm{d}E}{\mathrm{d}t} = E_0 b \frac{(bt)^{a-1} \mathrm{e}^{-bt}}{\Gamma(a)} \quad (33.35)$$

Example 3 – EM shower model

`examples/extended/parameterisations/Par03`

Based on PDG (chapter 33.5)

`Par03EMShowerModel.cc`

1. longitudinal shower profile

$$\frac{\mathrm{d}E}{\mathrm{d}t} = E_0 b \frac{(bt)^{a-1} \mathrm{e}^{-bt}}{\Gamma(a)} \tag{33.35}$$

$$b = 0.5 \ \ (Fig\ 33.21), \quad \frac{a-1}{b} = ln\frac{E}{E_c} + C_j, \ \ C_j = \begin{cases} +0.5 & \text{for}\gamma \\ -0.5 & \text{for} e^{\pm} \end{cases} \tag{33.36}$$

Example 3 – EM shower model

Based on PDG (chapter 33.5) Par03EMShowerModel.cc

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3. Deposit energy $\Delta E = \frac{E}{N}$ in N (100 by default) points sampling position from Gamma and Gaussian distributions

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2. Gaussian lateral profile with 90% energy deposited within a cylinder of radius equal to Moliere radius
3. Deposit energy $\Delta E = \frac{E}{N}$ in N (100 by default) points sampling position from Gamma and Gaussian distributions
4. Created hits are deposited in the detector using its readout geometry, using the helper class `G4FastSimHitMaker` that locates the volume, and calls appropriate sensitive detector class.

Example 4:

`examples/extended/parameterisations/gflash/gflash1`

Example 4 - previous Geant4 versions

Prior to v10.6, example `parameterisations/gflash/gflash1` was `parameterisations/gflash/`.

Set of examples is extended, to present different options:

Example	`gflash1`	`gflash2`	`gflash3`
Block of homogeneous material	mass geo	mass geo	mass geo
Crystals (readout geometry)	mass geo	mass geo	parallel geo
Sensitive detector	mass geo	mass geo	parallel geo
Envelope for parameterisation	mass geo	parallel geo	mass geo

Additionally, `examples/extended/parameterisations/gflash/gflasha` contains simple post-event analysis of shower shapes.

All examples feature parametrisation of the same homogeneous calorimeter, only technical details change.

Example 4

examples/extended/parameterisations/gflash/gflash1

- the only implementation of G4VFastSimulationModel in Geant4 (outside `examples/`)
- `arXiv:hep-ex/0001020`
- physics reference manual, chapter 18

Example 4

- the only implementation of G4VFastSimulationModel in Geant4 (outside `examples/`)
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$$dE(\bar{r}) = Ef(t)dtf(r)drf(\varphi)d\varphi$$

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- $f(t)$ and $f(r)$ parametrised as a function of particle's energy (E) and medium (Z)

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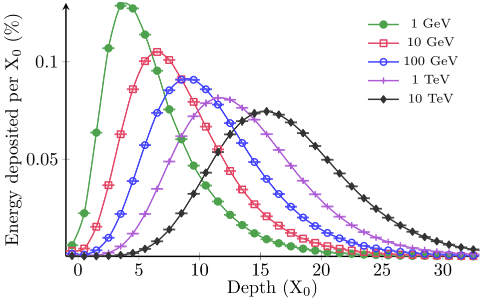
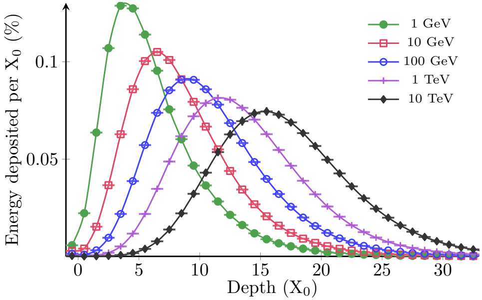
- flat distribution in azimuthal angle $f(\varphi) = \frac{1}{2\pi}$
- $f(t)$ and $f(r)$ parametrised as a function of particle's energy (E) and medium (Z)
- t and r are expressed in units of X_0 and R_M

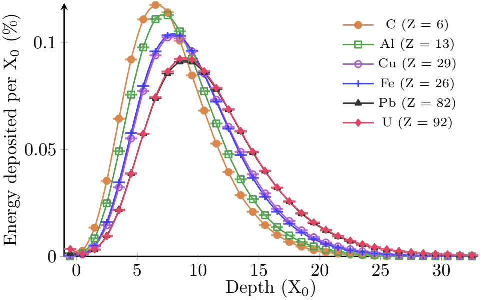
Example 4 - longitudinal profile



$$T \sim \ln E$$

Example 4 - longitudinal profile

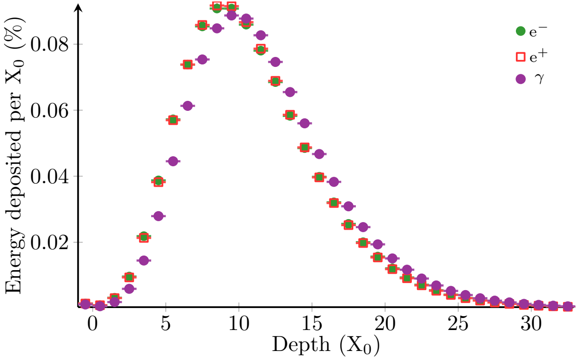




$$T \sim \ln E$$

Example 4 - longitudinal profile

examples/extended/parameterisations/gflash/gflash1



Example 4 - longitudinal profile

`examples/extended/parameterisations/gflash/gflash1`

$$f(t) = \left\langle \frac{1}{E} \frac{dE(t)}{dt} \right\rangle = \frac{(\beta t)^{\alpha-1} \beta e^{-\beta t}}{\Gamma(\alpha)}$$

Example 4 - longitudinal profile

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$$f(t) = \left\langle \frac{1}{E} \frac{dE(t)}{dt} \right\rangle = \frac{(\beta t)^{\alpha-1} \beta e^{-\beta t}}{\Gamma(\alpha)}$$

- shower maximum $T = \frac{\alpha-1}{\beta}$
- Description dependent on $y = \frac{E}{E_c}$:

$$T = \ln y + l_1$$
$$\alpha = l_2 + (l_3 + \frac{l_4}{Z}) \ln y$$

Example 4 - longitudinal profile

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A.1 Homogeneous Media

A.1.1 Average longitudinal profiles

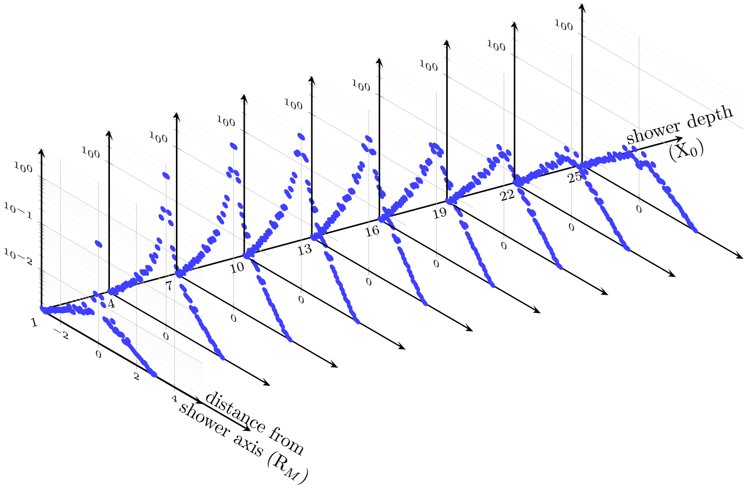
$$T_{hom} = \ln y - 0.858$$
$$\alpha_{hom} = 0.21 + (0.492 + 2.38/Z) \ln y$$

A.1.2 Fluctuated longitudinal profiles

$$\langle \ln T_{hom} \rangle = \ln(\ln y - 0.812)$$
$$\sigma(\ln T_{hom}) = (-1.4 + 1.26 \ln y)^{-1}$$
$$\langle \ln \alpha_{hom} \rangle = \ln\left(0.81 + (0.458 + 2.26/Z) \ln y\right)$$
$$\sigma(\ln \alpha_{hom}) = (-0.58 + 0.86 \ln y)^{-1}$$
$$\rho(\ln T_{hom}, \ln \alpha_{hom}) = 0.705 - 0.023 \ln y$$

arXiv:hep-ex/0001020

Example 4 – lateral profile



Example 4 – lateral profile

$$f(r) = \left\langle \frac{1}{dE(t)} \frac{dE(t,r)}{dr} \right\rangle$$

Example 4 – lateral profile

$$f(r) = \left\langle \frac{1}{dE(t)} \frac{dE(t,r)}{dr} \right\rangle = p f_{\mathrm{core}}(r) + (1-p) f_{\mathrm{tail}}(r) =$$

Example 4 – lateral profile

$$f(r) = \left\langle \frac{1}{dE(t)} \frac{dE(t,r)}{dr} \right\rangle = p f_{\mathrm{core}}(r) + (1-p) f_{\mathrm{tail}}(r) =$$

$$= p \frac{2rR_{\mathrm{core}}^2}{\left(r^2 + R_{\mathrm{core}}^2\right)^2} + (1-p) \frac{2rR_{\mathrm{tail}}^2}{\left(r^2 + R_{\mathrm{tail}}^2\right)^2}$$

Example 4 – lateral profile

examples/extended/parameterisations/gflash/gflash1

$$f(r) = \left\langle \frac{1}{dE(t)} \frac{dE(t,r)}{dr} \right\rangle = p f_{\text{core}}(r) + (1-p) f_{\text{tail}}(r) =$$

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Description dependent on $\tau = \frac{t}{T}$:

$$R_{\text{core}}(\tau) = r_1 + r_2 \tau$$

$$R_{\text{tail}}(\tau) = r_3 \left(\mathrm{e}^{r_4(\tau - r_5)} + \mathrm{e}^{r_6(\tau - r_7)} \right)$$

$$p(\tau) = r_8 \exp\left(\frac{r_9 - \tau}{r_{10}} - \exp\left(\frac{r_9 - \tau}{r_{10}} \right) \right)$$

Example 4 – lateral profile

$$f(r) = \left\langle \frac{1}{dE(t)} \frac{dE(t,r)}{dr} \right\rangle = pf_{\mathrm{core}}(r) + (1-p) f_{\mathrm{tail}}(r) =$$

$$= p \frac{2rR_{\mathrm{core}}^2}{\left(r^2 + R_{\mathrm{core}}^2\right)^2} + (1-p) \frac{2rR_{\mathrm{tail}}^2}{\left(r^2 + R_{\mathrm{tail}}^2\right)^2}$$

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Example 4 – lateral profile

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$$= p \frac{2rR^2_{\text{core}}}{(r^2 + R^2_{\text{core}})^2} + (1-p) \frac{2rR^2_{\text{tail}}}{(r^2 + R^2_{\text{tail}})^2}$$

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$$R_{\text{core}}(\tau) = \boldsymbol{r_1} + \boldsymbol{r_2}\tau$$

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A.1.3 Average radial profiles

$$R_{C,hom}(\tau) = z_1 + z_2\tau$$
$$R_{T,hom}(\tau) = k_1\{\exp(k_3(\tau - k_2)) + \exp(k_4(\tau - k_2))\}$$
$$p_{hom}(\tau) = p_1 \exp\left\{\frac{p_2 - \tau}{p_3} - \exp\left(\frac{p_2 - \tau}{p_3}\right)\right\}$$

with

$$z_1 = 0.0251 + 0.00319 \ln E$$
$$z_2 = 0.1162 + -0.000381Z$$
$$k_1 = 0.659 + -0.00309Z$$
$$k_2 = 0.645$$
$$k_3 = -2.59$$
$$k_4 = 0.3585 + 0.0421 \ln E$$
$$p_1 = 2.632 + -0.00094Z$$
$$p_2 = 0.401 + 0.00187Z$$
$$p_3 = 1.313 + -0.0686 \ln E$$

A.1.4 Fluctuated radial profiles

$$\tau_i = \frac{t}{\langle t \rangle_i} \frac{\exp(\langle \ln \alpha \rangle)}{\exp(\langle \ln \alpha \rangle) - 1}$$
$$N_{Spot} = 93 \ln(Z) E^{0.876}$$
$$T_{Spot} = T_{hom}(0.698 + 0.00212Z)$$
$$\alpha_{Spot} = \alpha_{hom}(0.639 + 0.00334Z)$$

arXiv:hep-ex/0001020

Example 4 – model

ExGflashDetectorConstruction.cc

```
void ExGflashDetectorConstruction::ConstructSDandField()
{
  // -- sensitive detectors:
  G4SDManager* SDman = G4SDManager::GetSDMpointer();
  ExGflashSensitiveDetector* CaloSD
  = new ExGflashSensitiveDetector("Calorimeter",this);
  SDman->AddNewDetector(CaloSD);
  fCrystal_log->SetSensitiveDetector(CaloSD);

  // Get nist material manager
  G4NistManager* nistManager = G4NistManager::Instance();
  G4Material*           pbWO4 = nistManager->FindOrBuildMaterial("G4_PbWO4");
  // -- fast simulation models:
  // **********************************************
  // * Initializing shower modell
  // ***********************************************
  G4cout « "Creating shower parameterization models" « G4endl;
  fFastShowerModel = new GFlashShowerModel("fFastShowerModel", fRegion);
  fParameterisation = new GFlashHomoShowerParameterisation(pbWO4);
  fFastShowerModel->SetParameterisation(*fParameterisation);
  // Energy Cuts to kill particles:
  fParticleBounds = new GFlashParticleBounds();
  fFastShowerModel->SetParticleBounds(*fParticleBounds);
  // Makes the EnergieSpots
  fHitMaker = new GFlashHitMaker();
  fFastShowerModel->SetHitMaker(*fHitMaker);
  G4cout«"end shower parameterization."«G4endl;
  // **********************************************
}
```

Example 4 – model

examples/extended/parameterisations/gflash/gflash1

ExGflashDetectorConstruction.cc

```
void ExGflashDetectorConstruction::ConstructSDandField()
{
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Example 4 – model

examples/extended/parameterisations/gflash/gflash1

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void ExGflashDetectorConstruction::ConstructSDandField()
{
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  G4SDManager* SDman = G4SDManager::GetSDMpointer();
  ExGflashSensitiveDetector* CaloSD
  = new ExGflashSensitiveDetector("Calorimeter",this);
  SDman->AddNewDetector(CaloSD);
  fCrystal_log->SetSensitiveDetector(CaloSD);

  // Get nist material manager
  G4NistManager* nistManager = G4NistManager::Instance();
  G4Material*          pbWO4 = nistManager->FindOrBuildMaterial("G4_PbWO4");
  // -- fast simulation models:
  // **********************************************
  // * Initializing shower modell
  // ***********************************************
  G4cout « "Creating shower parameterization models" « G4endl;
  fFastShowerModel = new GFlashShowerModel("fFastShowerModel", fRegion);
  fParameterisation = new GFlashHomoShowerParameterisation(pbWO4);
  fFastShowerModel->SetParameterisation(*fParameterisation);
  // Energy Cuts to kill particles:
  fParticleBounds = new GFlashParticleBounds();
  fFastShowerModel->SetParticleBounds(*fParticleBounds);
  // Makes the EnergieSpots
  fHitMaker = new GFlashHitMaker();
  fFastShowerModel->SetHitMaker(*fHitMaker);
  G4cout«"end shower parameterization."«G4endl;
  // **********************************************
}
```

Example 4 – model

examples/extended/parameterisations/gflash/gflash1

ExGflashDetectorConstruction.cc

```
void ExGflashDetectorConstruction::ConstructSDandField()
{
  // -- sensitive detectors:
  G4SDManager* SDman = G4SDManager::GetSDMpointer();
  ExGflashSensitiveDetector* CaloSD
  = new ExGflashSensitiveDetector("Calorimeter",this);
  SDman->AddNewDetector(CaloSD);
  fCrystal_log->SetSensitiveDetector(CaloSD);

  // Get nist material manager
  G4NistManager* nistManager = G4NistManager::Instance();
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  // -- fast simulation models:
  // **********************************************
  // * Initializing shower modell
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  G4cout « "Creating shower parameterization models" « G4endl;
  fFastShowerModel = new GFlashShowerModel("fFastShowerModel", fRegion);
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  fFastShowerModel->SetParameterisation(*fParameterisation);
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  fParticleBounds = new GFlashParticleBounds();
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  fHitMaker = new GFlashHitMaker();
  fFastShowerModel->SetHitMaker(*fHitMaker);
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```

Example 4 – model

ExGflashDetectorConstruction.cc

```
void ExGflashDetectorConstruction::ConstructSDandField()
{
  // -- sensitive detectors:
  G4SDManager* SDman = G4SDManager::GetSDMpointer();
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  = new ExGflashSensitiveDetector("Calorimeter",this);
  SDman->AddNewDetector(CaloSD);
  fCrystal_log->SetSensitiveDetector(CaloSD);

  // Get nist material manager
  G4NistManager* nistManager = G4NistManager::Instance();
  G4Material*           pbW04 = nistManager->FindOrBuildMaterial("G4_PbW04");
  // -- fast simulation models:
  // ***********************************************
  // * Initializing shower modell
  // ***********************************************
  G4cout « "Creating shower parameterization models" « G4endl;
  fFastShowerModel = new GFlashShowerModel("fFastShowerModel", fRegion);
  fParameterisation = new GFlashHomoShowerParameterisation(pbW04);
  fFastShowerModel->SetParameterisation(*fParameterisation);
  // Energy Cuts to kill particles:
  fParticleBounds = new GFlashParticleBounds();
  fFastShowerModel->SetParticleBounds(*fParticleBounds);
  // Makes the EnergieSpots
  fHitMaker = new GFlashHitMaker();
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Example 4 – model

examples/extended/parameterisations/gflash/gflash1

ExGflashDetectorConstruction.cc

```
void ExGflashDetectorConstruction::ConstructSDandField()
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  = new ExGflashSensitiveDetector("Calorimeter",this);
  SDman->AddNewDetector(CaloSD);
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  G4NistManager* nistManager = G4NistManager::Instance();
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  G4cout«"end shower parameterization."«G4endl;
  // **********************************************
}
```

Example 4 – model

ExGflashSensitiveDetector.hh

```
class ExGflashSensitiveDetector: public G4VSensitiveDetector,
                                 public G4VGFlashSensitiveDetector {
             ...
             virtual G4bool ProcessHits(G4Step*,G4TouchableHistory*);
             virtual G4bool ProcessHits(G4GFlashSpot*aSpot,G4TouchableHistory*);
             ...
};
```

Example 4 – model

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class ExGflashSensitiveDetector: public G4VSensitiveDetector,
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          ...
};
```

GVFlashHomoShowerTuning can be used to change parameters (l_1, l_2, ... , r_1, ...)

Example 4 – model

examples/extended/parameterisations/gflash/gflash1

ExGflashSensitiveDetector.hh

```
class ExGflashSensitiveDetector: public G4VSensitiveDetector,
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            virtual G4bool ProcessHits(G4Step*,G4TouchableHistory*);
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            ...
};
```

GVFlashHomoShowerTuning can be used to change parameters (l_1, l_2, ... , r_1, ...)

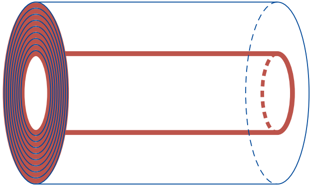
Sampling calorimeter For simulation in sampling detectors use GFlashSamplingShowerParameterisation and GFlashSamplingShowerTuning. Readout should collect signal from both active and pasive material (e.g. by constructing SD in parallel world). Those calorimeters have not been tested in Geant4, so implementation of GFlash in Geant4 may require further work (which is on-going).

Example 5:

examples/extended/parameterisations/Par04

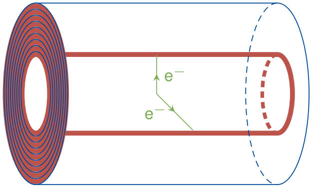
Example 5

- examples/extended/parameterisations/Par04 new example since Geant4 11.0 release
- WIP in public repo on gitlab
- Detector geometry is simplistic and easy to configure
- Collider-style concentric cylinders with up to two materials (active and optionally passive)



Example 5

- examples/extended/parameterisations/Par04 new example since Geant4 11.0 release
- WIP in public repo on gitlab
- Detector geometry is simplistic and easy to configure
- Collider-style concentric cylinders with up to two materials (active and optionally passive)
- Particle direction and position is measured at the entrance to calorimeter
  - many possible ways to do it
  - we chose to trigger on a fast sim model that is attached to calorimeter
  - LHCb's approach: introduce SD and store hits



Example 5

- examples/extended/parameterisations/Par04 new example since Geant4 11.0 release
- WIP in public repo on gitlab
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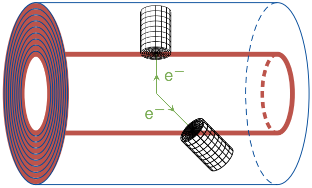
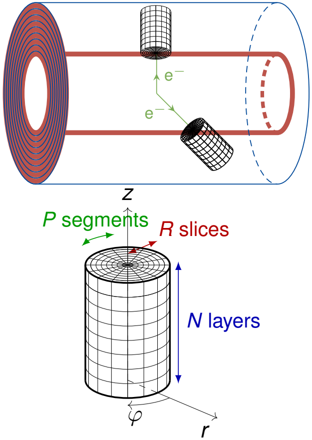
  - LHCb's approach: introduce SD and store hits
- Scoring of energy deposits relative to the particle direction
- Similar granularity 'pictures' obtained independently on angle

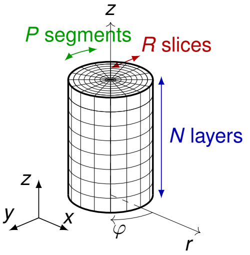


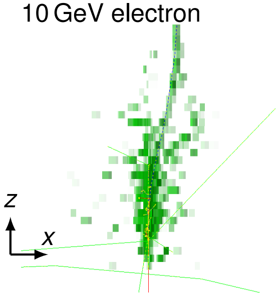
Example 5

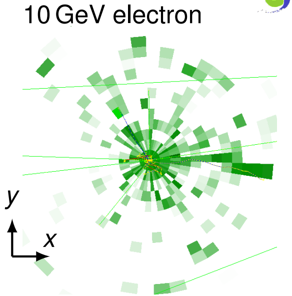
- examples/extended/parameterisations/Par04 new example since Geant4 11.0 release
- WIP in public repo on gitlab
- Detector geometry is simplistic and easy to configure
- Collider-style concentric cylinders with up to two materials (active and optionally passive)
- Particle direction and position is measured at the entrance to calorimeter
  - many possible ways to do it
  - we chose to trigger on a fast sim model that is attached to calorimeter
  - LHCb's approach: introduce SD and store hits
- Scoring of energy deposits relative to the particle direction
- Similar granularity 'pictures' obtained independently on angle
- Granularity of shower deposition is configurable



Example 5 – EM showers

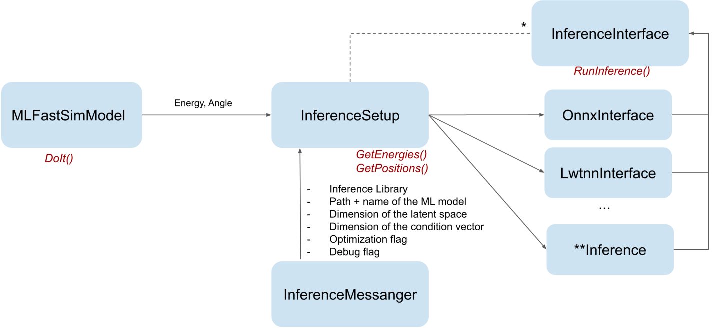




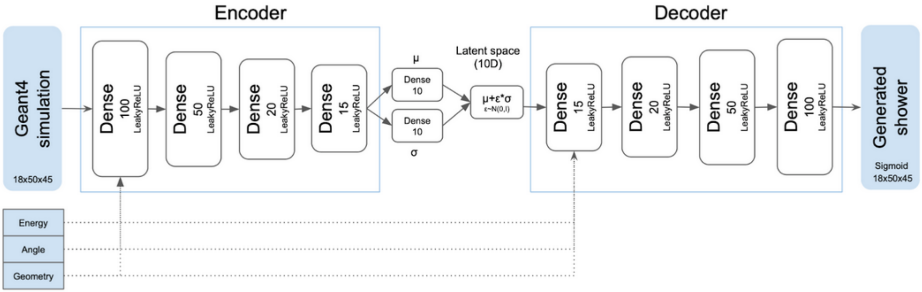


- Example uses 0.3 mm Si and 1.4 mm W layers
- Readout granularity is $\Delta r \times \Delta\varphi \times \Delta z = 2.3\,\text{mm} \times \frac{2\pi}{50} \times 3.4\,\text{mm}$ aiming for $\Delta r \approx 0.25\,R_M$ and $\Delta z \approx 0.6\,X_0$
- Number of readout cells is $R \times P \times N = 18x50x45$ aiming for 98% containment of 1 TeV particles
- **Open access dataset for SiW (and scintillator-Pb) released 10.5281/zenodo.6082201**
- This dataset is a base of ML studies, including CaloChallenge.

Example 5 – inference within C++ framework

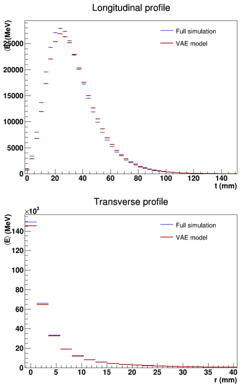


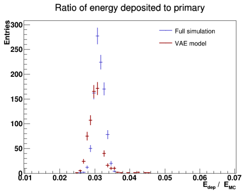
- Demonstrates how to incorporate inference libraries (ONNX Runtime, LWTNN, Torch since G4 11.1) that should be general enough for users to copy (one of) them, same with `MLFastSimModel`
- The user configuration (pre/post processing, IDs $\rightarrow$(xyz)) is done via `InferenceSetup`



Variational autoencoder that is a subject of study in our group. Provided model is trained on the specified geometry, it **requires changes with the changes to the geometry**.

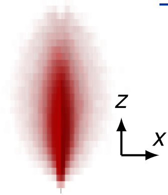
Example 5 – generated showers



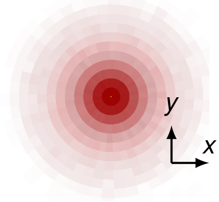


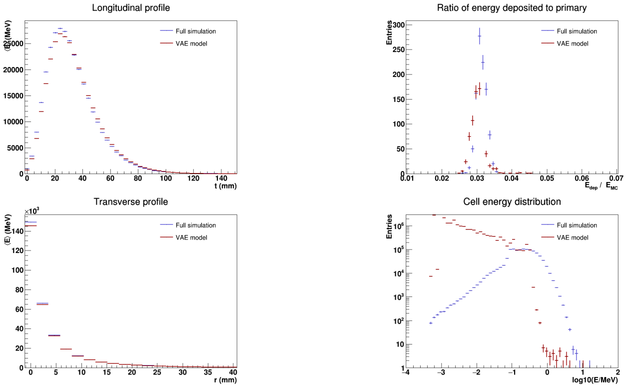
- Resonably good average distributions

Example 5 – generated showers



10 GeV electron





- Resonably good average distributions
- but VAE models can lead to smeared/blurry pictures
- Effect is negligible in low-granularity calorimeters, e.g. ATLAS: a similar VAE is presented in the CaloChallenge
- . . . but will be visible for high-granularity detectors

Example 5 - adaptation to other detectors

For those interested in trying out this approach, **instuctions** are provided at **g4fastsim.web.cern.ch**.

Meta-learning approach, MetaHEP (10.1016/j.physletb.2023.138079), uses a pretrained VAE. **Adaptation** does not require retraining from scratch, but **requires a dedicated full simulation** (scoring in a cylinder).

Open doors to other ML models: many models are developed within CaloChallenge. They all will require a dedicated simulation as described in those instructions.

MetaHEP

MetaHEP is an ML-aided fast shower simulation that is able to adapt quickly to a new geometry. More details can be found in the publication (10.1016/j.physletb.2023.138079). This instruction is a manual for users that want to use MetaHEP on their detectors.

Currently we provide a pre-trained VAE model with high granularity, pre-trained on two datasets DOI 10.5281/zenodo.6082201.

Work on a more accurate underlying model is on-going, but any new model or a change in granularity will not affect the overall procedure described in this manual.

The demonstrator is based on Par04 example of Geant4 and documents how to implement MetaHEP approach on the example of the key4HEP software. A similar approach may be implemented within any experiments framework.

Three consecutive steps are needed in order to integrate MetaHEP with experiment's software framework. Two first steps are necessary to access in a first validation if the underlying model offers satisfying results.

Step 1: Generate samples

Input (and output) of the ML fast shower model is a 3D regular grid (mesh) of energy deposits, centred around the incident particle momentum.

Preparation of input samples can be achieved in two ways:

1) Custom simulation that allows to score energy in the detector directly in the cylindrical mesh of desired dimensions. This allows to prepare a high granularity input and exploit to the great extend the ML model.

2) [experimental] Re-use of existing simulation datasets and mapping them into the cylindrical mesh. This method is not fully tested and can strongly depend on the difference between the granularity of the existing dataset and the granularity of the mesh. It may lead to lower accuracy as the output of the ML model will contain entries in the high granularity mesh. It allows however, to quickly progress to Step 2.

Step 2: Adapt a pre-trained model

While any model can be trained from scratch (including the VAE model released with Par04), there is a benefit of using a pretrained model, which is speed. It takes much less time to adapt the model.

If no changes were made to the size of the cylindrical mesh (number of voxels, because size of each dimension should change according to the radiation length and the Moliere radius), the meta learning approach may be applied. Adaptation of the pre-trained model is described in this section.

Step 3: Use ML fast shower simulation

Inference in the C++ framework can me applied using the classes prepared for Par04. Currently ONNX runtime, lwtn, and Torch are supported.

Summary

- Fast simulation can be used within Geant4;

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- Hooks to take over control in chosen volumes/for chosen particles;

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Questions/problems? anna.zaborowska@cern.ch