



**GEANT4**  
A SIMULATION TOOLKIT

Version 11.0

# Fast Simulation

Anna Zaborowska

October 12, 2022

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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2. How to use it in Geant4

- ▶ where
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- } to parametrise

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4. Examples

**example**

[link to code in G4 v11.0.p03](#)

...

# What do we mean by fast simulation?

Fast simulation **is not** Geant4 simulation that 'magically' produces results in less time.

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Fast simulation **is** a trade-off between simulation time and accuracy.

Time is gained by performing less operations in complicated region → no detailed physics of Geant4 → *parameterisation*.

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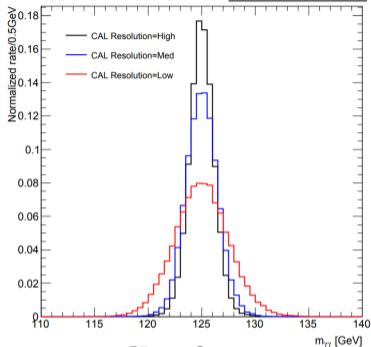
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Fast simulation hooks in Geant4 allow to overtake control over particles in certain regions – user decides what happens and when/if they return to the detailed simulation.

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

arXiv:1606.09408



$$\frac{\sigma E}{E} = \frac{a}{\sqrt{E}} \oplus c$$

$$a=20\%, c=2\%$$

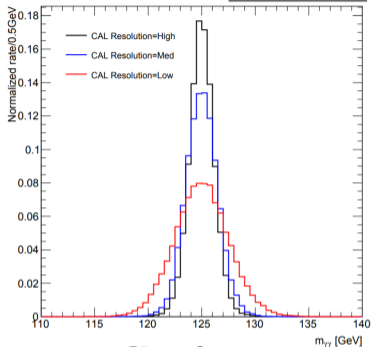
$$a=10\%, c=1\%$$

$$a=6\%, c=0.7\%$$

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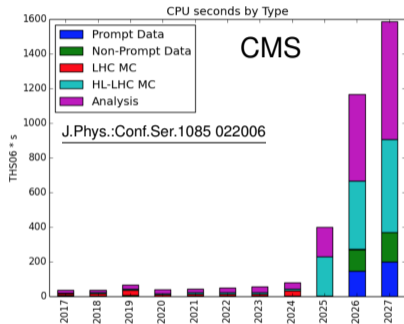
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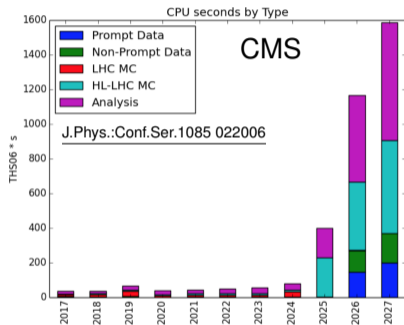
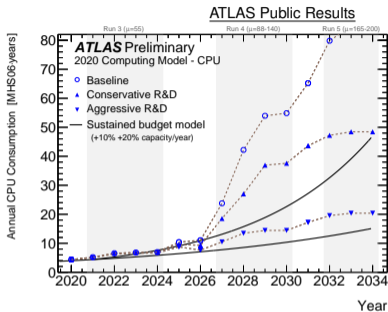
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  - ▶ to speed-up simulation of already known detector (e.g. extracted efficiency/resolution from detailed simulation)
  - ▶ to study impact of detector performance on physics observables (example in the plot: calorimeter resolution on Higgs mass)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

- ▶ 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;

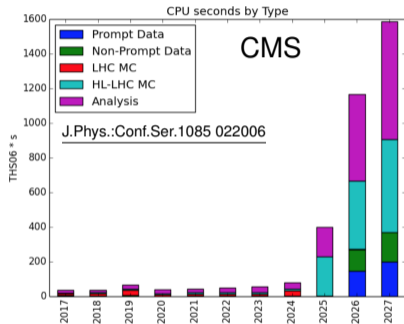
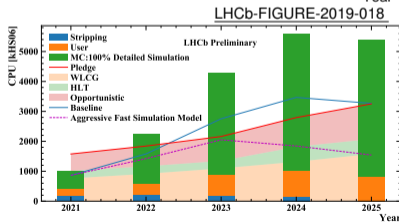
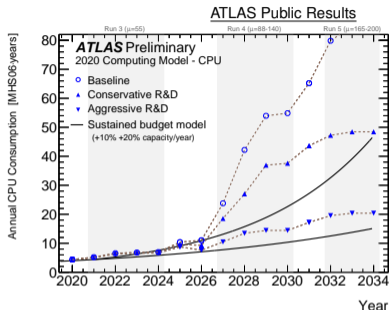


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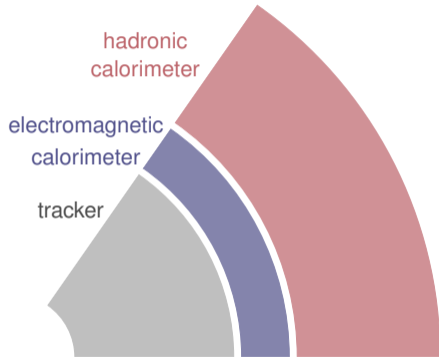


# Why to use parameterisation / fast(er) simulation?

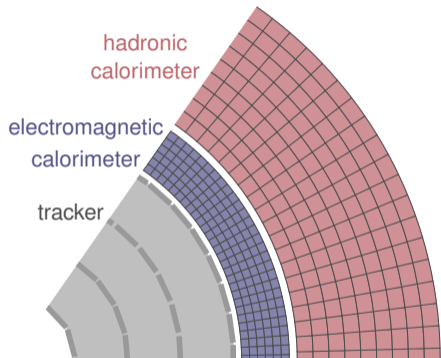
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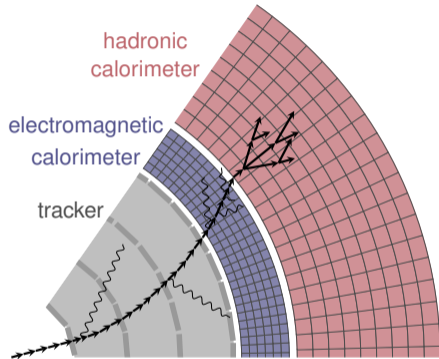
# How we simulate particles?



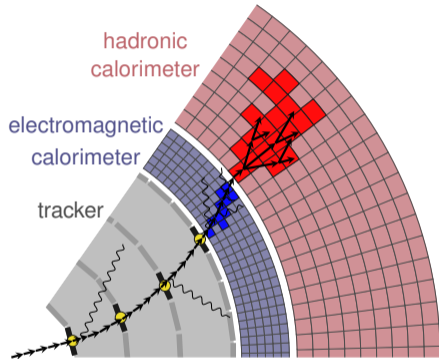
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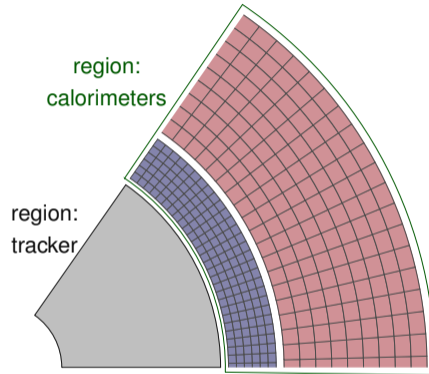
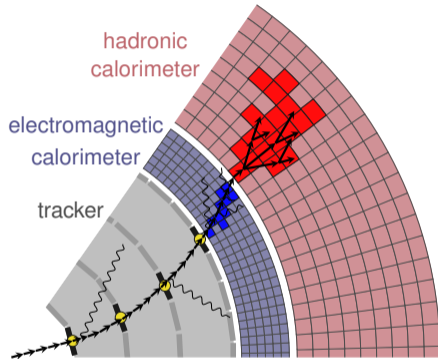


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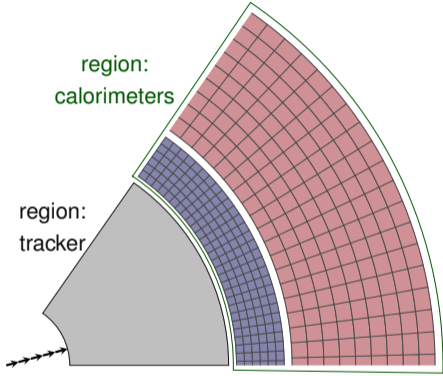
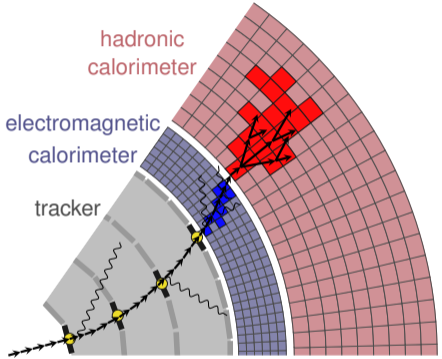




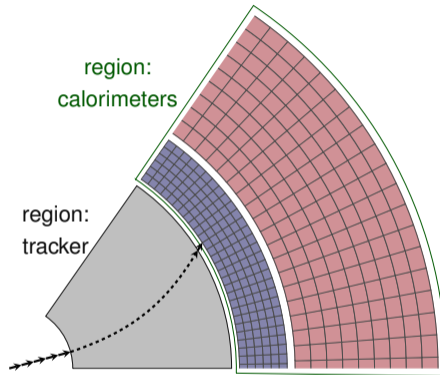
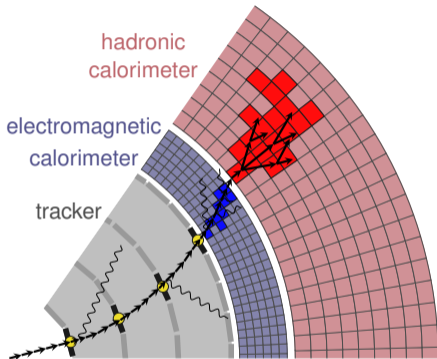
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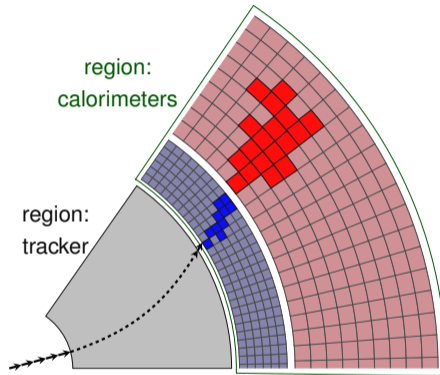
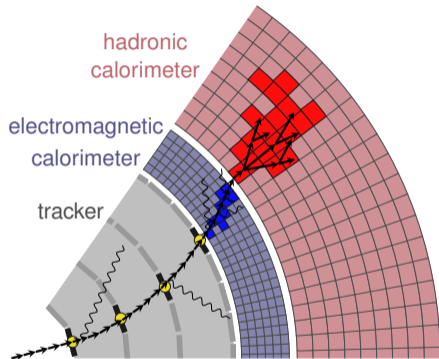


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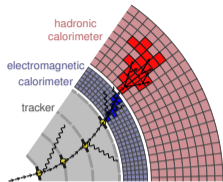


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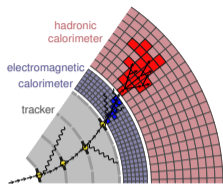


Fast simulation is a shortcut to the standard tracking and detailed simulation.



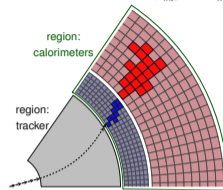
detailed / “full”  
simulation

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



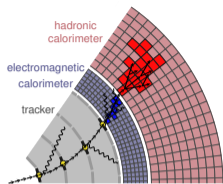
detailed / “full”  
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parameterisation  
/ “fast” simulation



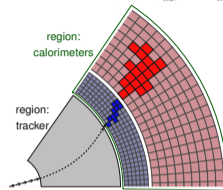
- ▶ detailed detector description
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- ▶ **where** particles are parametrised
- ▶ **which** particles
- ▶ **how/what** happens



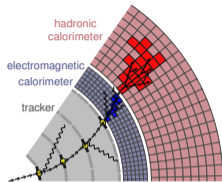
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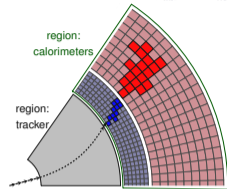
- ▶ detailed detector description
- ▶ definitions of particles and processes
- ▶ transport in e-m field
- ▶ Geant4 a standard toolkit

- ▶ **where** particles are parametrised
- ▶ **which** particles
- ▶ **how/what** happens
- ▶ detector / use-case dependent



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

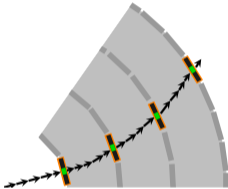


# Where?

Parameterisation may be realised within:

# Where?

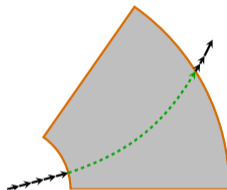
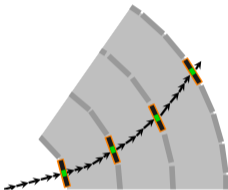
Parameterisation may be realised within:  
sub-volume  
(many volumes)



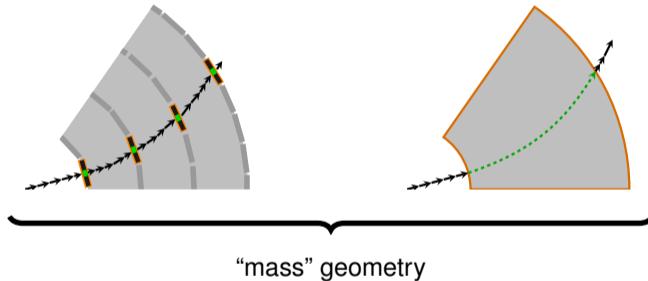
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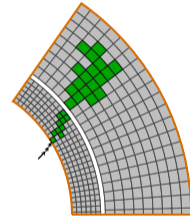
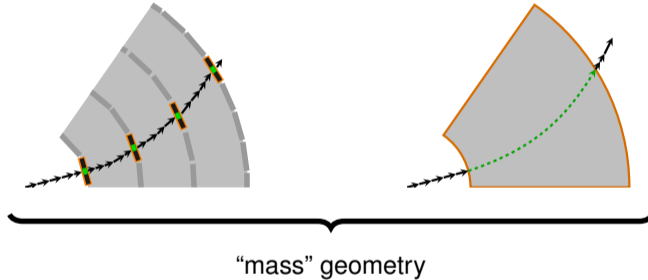


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detector envelope  
(single volume)

assembly of volumes  
(non-physical volume)

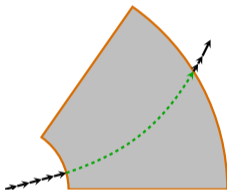
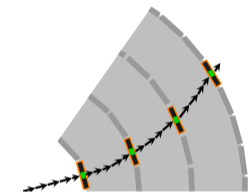


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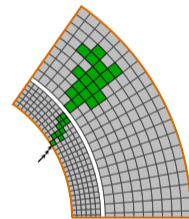
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"mass" geometry



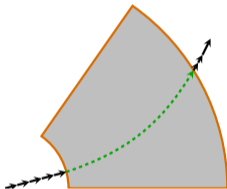
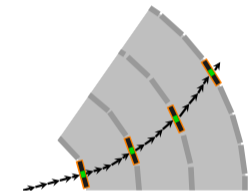
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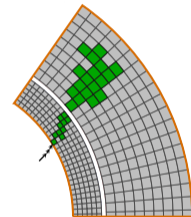
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"mass" geometry



parallel geometry

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

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## for mass geometry:

[examples/extended/parameterisations/Par01/src/Par01DetectorConstruction.cc](#)

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

## for parallel geometry:

[examples/extended/parameterisations/Par01/src/Par01ParallelWorldForPion.cc](#)

```
97 G4Region* ghostRegion = new G4Region("GhostCalorimeterRegion");
98 // ghostLogical is a G4LogicalVolume in parallel geometry, a box made of air encompassing
   ↳ both EM&H calorimeters
99 ghostRegion->AddRootLogicalVolume(ghostLogical);
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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](#))

## for mass and parallel geometry:

[examples/extended/parameterisations/Par01/examplePar01.cc](#)

```
112 FTFP_BERT* physicsList = new FTFP_BERT; // G4VModularPhysicsList
113 G4FastSimulationPhysics* fastSimulationPhysics = new G4FastSimulationPhysics(); // helper
114 fastSimulationPhysics->BeVerbose();
115 // - activation of fast simulation for particles having fast simulation models attached
    ↳ in the mass geometry:
116 fastSimulationPhysics->ActivateFastSimulation("e-");
117 fastSimulationPhysics->ActivateFastSimulation("e+");
118 fastSimulationPhysics->ActivateFastSimulation("gamma");
119 // - activation of fast simulation for particles having fast simulation models attached
    ↳ in the parallel geometry:
120 fastSimulationPhysics->ActivateFastSimulation("pi+", "pionGhostWorld");
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122 physicsList->RegisterPhysics( fastSimulationPhysics ); // attach to the physics list
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- within selected volumes

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- for selected particle types

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- ▶ check particle type or intrinsic information (from G4ParticleDefinition)

- within selected volumes

G4Region attached to G4LogicalVolume;

- for selected particle types

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- if trigger is issued

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

- within selected volumes

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

- within selected volumes

G4Region attached to G4LogicalVolume;

- for selected particle types

G4FastSimulationPhysics attached to physics list and activated for particles;

- if trigger is issued

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**,

- ✓ within selected volumes

G4Region attached to G4LogicalVolume and linked to implementation of G4VFastSimulationModel;

- ✓ for selected particle types

G4FastSimulationPhysics attached to physics list and activated for particles;

- ✓ if trigger is issued

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**.



Core of the parameterisation:

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

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---

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

---

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- ▶ **how**/what happens

---

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

---

[examples/extended/parameterisations/Par01/src/Par01DetectorConstruction.cc](#)

```
287 G4RegionStore* regionStore = G4RegionStore::GetInstance();
288
289 G4Region* caloRegion = regionStore->GetRegion("EM_calorimeter");
290 // builds a model and sets it to the envelope of the calorimeter:
291 new Par01EMShowerModel("emShowerModel", caloRegion);
```

---

Core of the parameterisation:

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

---

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// constructor adds this model to G4FastSimulationManager of given envelope  
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```

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[examples/extended/parameterisations/Par01/src/Par01DetectorConstruction.cc](#)

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288  
289 G4Region* caloRegion = regionStore->GetRegion("EM_calorimeter");  
290 // builds a model and sets it to the envelope of the calorimeter:  
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## G4VFastSimulationModel (2/4) — which particles?

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

---

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

---

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Par01EMShowerModel.cc

```
84 G4bool Par01EMShowerModel::IsApplicable(const
↳ G4ParticleDefinition& particleType)
85 {
86
87
88
89
90 }
```

Par01PionShowerModel.cc

```
82 G4bool Par01PiModel::IsApplicable(const
↳ G4ParticleDefinition& particleType)
83 {
84
85
86
87 }
```

Par02FastSimModelTracker.cc

```
78 G4bool Par02FastSimModelTracker::IsApplicable( const
↳ G4ParticleDefinition& aParticleType ) {
79
80 }
```

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```

Par01EMShowerModel.cc

```
84 G4bool Par01EMShowerModel::IsApplicable(const
↳ G4ParticleDefinition& particleType)
85 {
86     return
87     &particleType ==
↳ G4Electron::ElectronDefinition() ||
88     &particleType ==
↳ G4Positron::PositronDefinition() ||
89     &particleType == G4Gamma::GammaDefinition();
90 }
```

Par01PionShowerModel.cc

```
82 G4bool Par01PiModel::IsApplicable(const
↳ G4ParticleDefinition& particleType)
83 {
84     return
85     &particleType ==
↳ G4PionMinus::PionMinusDefinition() ||
86     &particleType ==
↳ G4PionPlus::PionPlusDefinition();
87 }
```

Par02FastSimModelTracker.cc

```
78 G4bool Par02FastSimModelTracker::IsApplicable( const
↳ G4ParticleDefinition& aParticleType ) {
79
80 }
```



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↳ G4ParticleDefinition& particleType)
85 {
86     return
87     &particleType ==
↳ G4Electron::ElectronDefinition() ||
88     &particleType ==
↳ G4Positron::PositronDefinition() ||
89     &particleType == G4Gamma::GammaDefinition();
90 }
```

Par01PionShowerModel.cc

```
82 G4bool Par01PiModel::IsApplicable(const
↳ G4ParticleDefinition& particleType)
83 {
84     return
85     &particleType ==
↳ G4PionMinus::PionMinusDefinition() ||
86     &particleType ==
↳ G4PionPlus::PionPlusDefinition();
87 }
```

Par02FastSimModelTracker.cc

```
78 G4bool Par02FastSimModelTracker::IsApplicable( const
↳ G4ParticleDefinition& aParticleType ) {
79     return aParticleType.GetPDGCharge() != 0; // Applicable
↳ for all charged particles
80 }
```

## 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](#)

```
94 G4bool Par01EMShowerModel::ModelTrigger(const G4FastTrack& fastTrack)
95 {
96     // Applies the parameterisation above 100 MeV:
97     return fastTrack.GetPrimaryTrack()->GetKineticEnergy() > 100*MeV;
98 }
```

## G4VFastSimulationModel (3/4) — which particles?

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

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

[Par01EMShowerModel.cc](#)

```
94 G4bool Par01EMShowerModel::ModelTrigger(const G4FastTrack& fastTrack)
95 {
96     // Applies the parameterisation above 100 MeV:
97     return fastTrack.GetPrimaryTrack()->GetKineticEnergy() > 100*MeV;
98 }
```

[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](#)

```
94 G4bool GFlashShowerModel::ModelTrigger(const G4FastTrack & fastTrack )
95
96 {
97     G4bool select = false;
98     if(FlagParamType != 0)
99     {
100         G4double ParticleEnergy = fastTrack.GetPrimaryTrack()->GetKineticEnergy();
101         G4ParticleDefinition &ParticleType =
102             *(fastTrack.GetPrimaryTrack()->GetDefinition());
103         if(ParticleEnergy > PBound->GetMinEneToParametrise(ParticleType) &&
104            ParticleEnergy < PBound->GetMaxEneToParametrise(ParticleType) )
105         {
106             // check conditions depending on particle flavour
107             // performance to be optimized @@@@
108             Parameterisation->GenerateLongitudinalProfile(ParticleEnergy);
109             select = CheckParticleDefAndContainment(fastTrack);
110             if (select) EnergyStop= PBound->GetEneToKill(ParticleType);
111         }
112     }
113     return select;
114 }
```

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
```

---

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

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- ▶ move to different position (e.g. exit from volume)
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- ▶ kill particle
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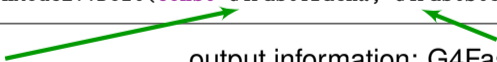
---

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

---

input information: G4FastTrack

output information: G4FastStep



- ▶ 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.



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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++;
    }
}
```

- ▶ 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++;
    }
}
```

- ▶ G4VFastSimSensitiveDetector must be 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.

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- ▶ 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;
...
}
```

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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2. Register the parameterisation(s) for the particles (**which**)



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user's implementation of **G4VFastSimulationModel**
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by adding to physics list **G4FastSimulationManagerProcess** and activating it for certain particles (recommended: via **G4FastSimulationPhysics**)

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3. Specify **where** parameterisation takes place

Step-by-step:

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

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Existing examples: `examples/extended/parameterisations/`

# UI commands

---

```
/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

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:

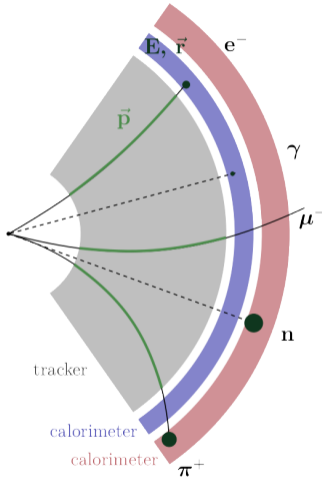
[examples/extended/parameterisations/Par02](#)

# Example 1

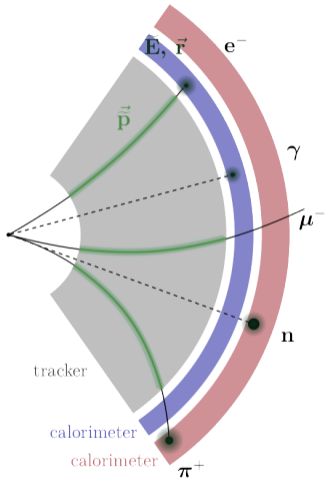
- ▶ Simple parameterisation

# Example 1

## ► Simple parameterisation

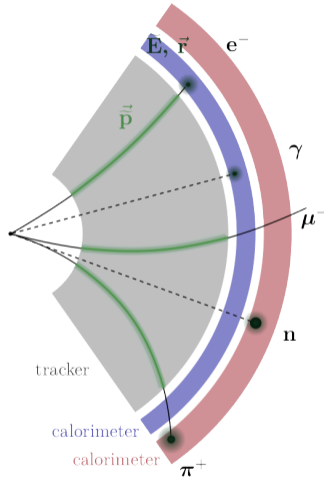


# Example 1



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

# Example 1

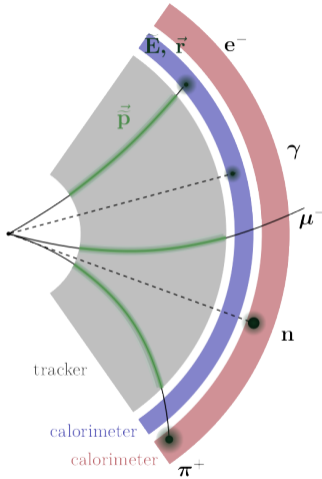


- ▶ Simple parameterisation
- ▶ Smearing of the momentum in the tracker and energy in the calorimeter
- ▶ User input: detector resolution;

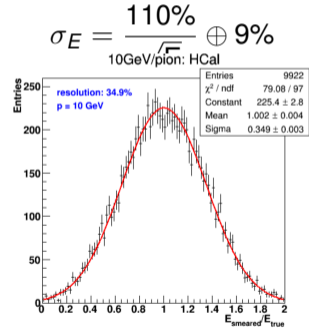
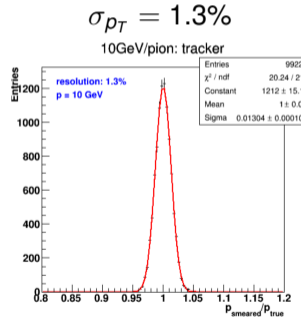
$$\sigma_{p_T} = 1.3\%$$

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

# Example 1



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



## Example 1: detector construction

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

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Par02FullDetector.gdml

```
111 <volume name="TrackerBarrelLog">
112   <materialref ref="Beryllium0x7ff5f9e3baf0"/>
113   <solidref ref="TrackerBarrel"/>
114   <auxiliary auxtype="FastSimModel"
↔   auxvalue="TrackerBarrel"/>
115 </volume>
```



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- ▶ from GDML;
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    ↪   auxvalue="TrackerBarrel"/>
115 </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 [...]
      }
    }
  }
}

```

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111 <volume name="TrackerBarrelLog">
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Par02DetectorConstruction.cc

```

G4VPhysicalVolume* Par02DetectorConstruction::Construct() {
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  parser.Read( "Par02FullDetector.gdml" );
  const G4GDMLAuxMapType* aAuxMap = parser.GetAuxMap();
  for ( G4GDMLAuxMapType::const_iterator iter = aAuxMap->begin(); iter != aAuxMap->end(); ++iter ) {
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        G4LogicalVolume* myvol = (*iter).first;
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        } else [...]
      }
    }
  }
  ...
}

```

# Example 1: detector construction

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

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111 <volume name="TrackerBarrelLog">
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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**

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```

111 <volume name="TrackerBarrelLog">
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    ↪ (*iter).second.end(); ++vit ) {
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        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

```

111 <volume name="TrackerBarrelLog">
112   <materialref ref="Beryllium0x7ff5f9e3baf0"/>
113   <solidref ref="TrackerBarrel"/>
114   <auxiliary auxtype="FastSimModel"
↪   auxvalue="TrackerBarrel"/>
115 </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);
  }..
}

```

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

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```

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```

Par02DetectorConstruction.cc

```

void Par02DetectorConstruction::ConstructSDandField() {
  for ( G4int iterTracker = 0; iterTracker < G4int(
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    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

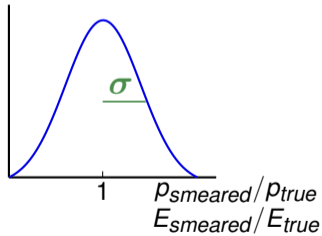
```

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;

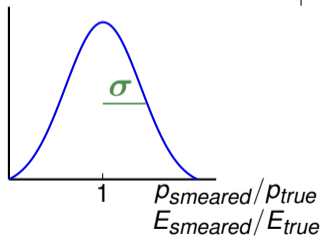




## Example 1: models

- ▶ smearing of momentum (tracker) / energy (calorimeters) with Gaussian;
- ▶ resolution defined arbitrarily in Par02DetectorParametrisation ( $[E] = \text{GeV}$ )

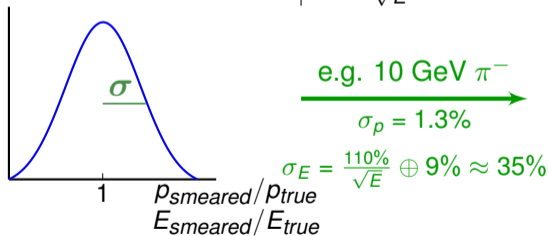
	CMS-like	ALEPH-like	ATLAS-like
$\sigma$ (Tracker)	1.3%	1%	1%
$\sigma$ (EMCAL)	$\frac{3\%}{\sqrt{E}} \oplus \frac{12\%}{E} \oplus 0.3\%$	$\frac{18\%}{\sqrt{E}} \oplus 0.9\%$	$\frac{10\%}{\sqrt{E}} \oplus 0.17\%$
$\sigma$ (HCAL)	$\frac{110\%}{\sqrt{E}} \oplus 9\%$	$\frac{85\%}{\sqrt{E}}$	$\frac{55\%}{\sqrt{E}}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



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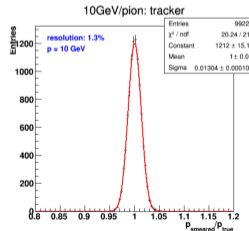
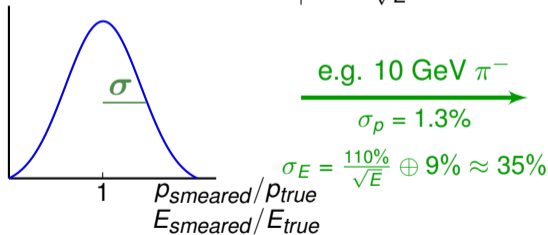
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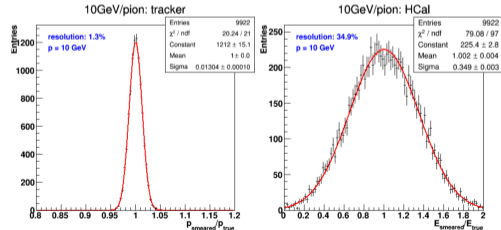
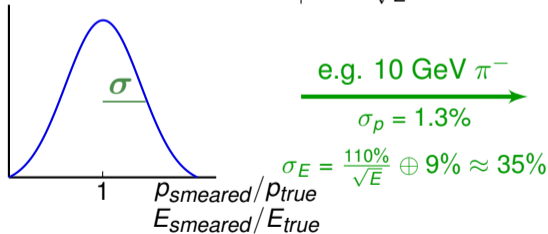
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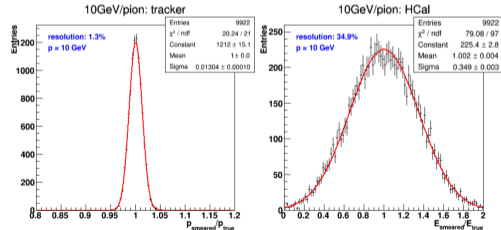
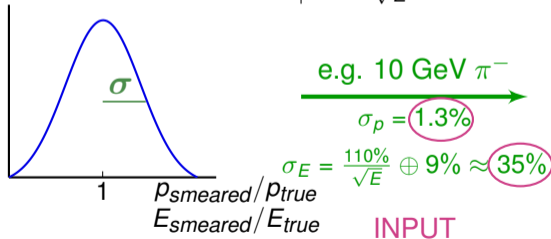
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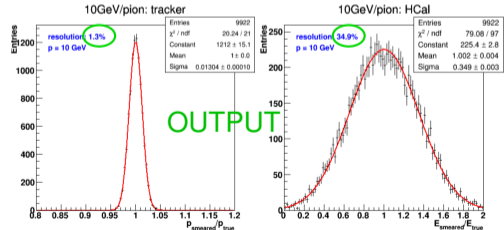
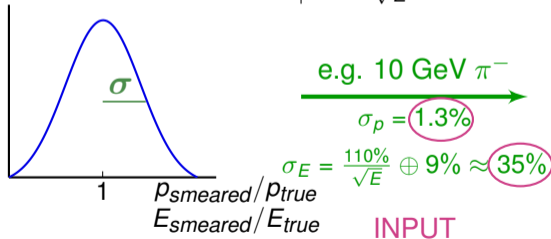
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## Example 1: models

- ▶ 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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[Par02FastSimModelTracker.cc](#)

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- ▶ Calorimeters: particles deposit all energy and are killed (e/ $\gamma$  in EMCal, hadrons in HCal);

Par02FastSimModelEMCal.cc

```
void Par02FastSimModelEMCal::DoIt( const G4FastTrack& aFastTrack, G4FastStep& aFastStep ) {
    aFastStep.KillPrimaryTrack();
    aFastStep.ProposePrimaryTrackPathLength( 0.0 );
    G4double Edep = aFastTrack.GetPrimaryTrack()->GetKineticEnergy();
    G4double Esm; [...] // Esm = smeared Edep
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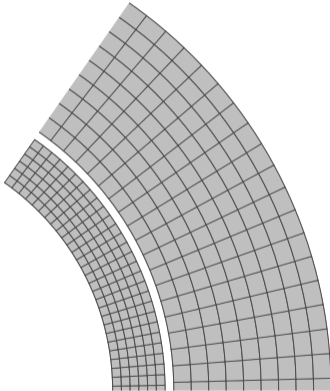
```
void Par02FastSimModelEMCal::DoIt( const G4FastTrack& aFastTrack, G4FastStep& aFastStep ) {
    aFastStep.KillPrimaryTrack();
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# Example 2:

[examples/extended/parameterisations/Par01](#)

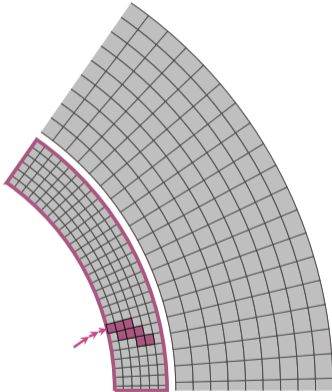
## Example 2

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



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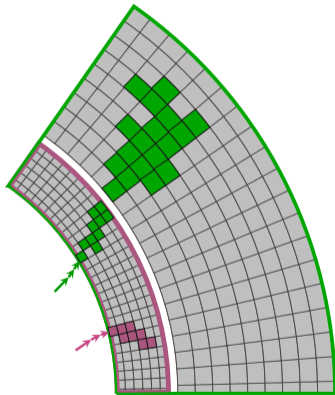


Par01EMShowerModel.cc

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

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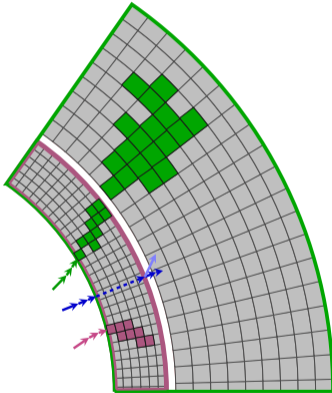
### Par01PionShowerModel.cc

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



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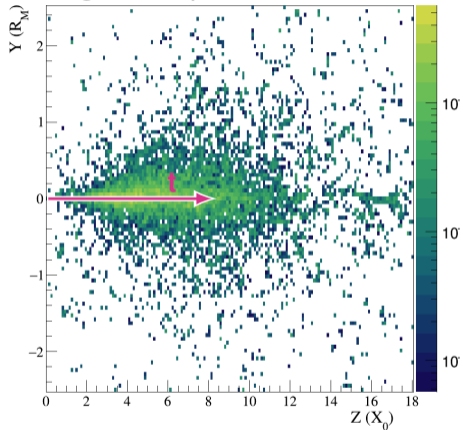
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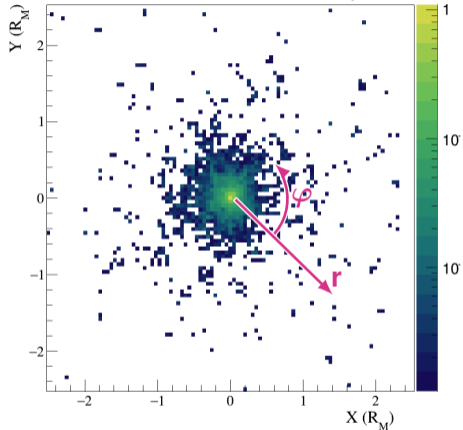
### Par01PiModel.cc

- ▶ create **secondaries**

## longitudinal profile



## lateral profile



## Example 2 – models

**How** to deposit energy  $E$  of electrons/photons?

Par01EMShowerModel.cc

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

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  - ▶ pick  $t$ ,  $r$  and  $\varphi$  from  $f(t)$ ,  $f(r)$ , and  $f(\varphi)$
 in  $(t, r, \varphi)$  inside electromagnetic calorimeter

## Example 2 – models

Par01EMShowerModel.cc

```
void Par01EMShowerModel::DoIt(const G4FastTrack& fastTrack, G4FastStep& fastStep) {  
    BuildDetectorResponse();  
}
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void Par01EMShowerModel::DoIt(const G4FastTrack& fastTrack, G4FastStep& fastStep) {  
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```
void Par01EMShowerModel::BuildDetectorResponse() {  
    for (size_t i = 0; i < feSpotList.size(); i++) {  
        AssignSpotAndCallHit(feSpotList[i]);  
    }  
}
```

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        AssignSpotAndCallHit(feSpotList[i]);
    }
}

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

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

1. longitudinal shower profile  $f(t, 0, 20\text{cm})$
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 in  $(t, r, \varphi)$  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()->
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Dist = fastTrack.GetEnvelopeSolid()->
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posi = fastTrack.GetPrimaryTrackLocalPosition() + Dist*direction;
fastStep.CreateSecondaryTrack(dynamique, posi,
                             fastTrack.GetPrimaryTrack()->GetGlobalTime());

```

## 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);
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## Example 2 – models

**How** to transport particles to the outer boundary?

Par01PiModel.cc

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114 G4ThreeVector position;  
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118                 fastTrack.GetPrimaryTrackLocalDirection());  
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## Example 2 – models

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# Example 3:

[examples/extended/parameterisations/Par03](#)

## Example 3 – EM shower model

examples/extended/parameterisations/Par03



Based on PDG (chapter 33.5)

Par03EMShowerModel.cc

## Example 3 – EM shower model

Based on PDG (chapter 33.5)

### 1. longitudinal shower profile

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$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)} \quad (33.35)$$

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Based on PDG (chapter 33.5)

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



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Based on PDG (chapter 33.5)

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### 2. Gaussian lateral profile with 90% energy deposited within a cylinder of radius equal to Moliere radius

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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	<u><a href="#">gflash1</a></u>	<u><a href="#">gflash2</a></u>	<u><a href="#">gflash3</a></u>
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

- ▶ the only implementation of G4VFastSimulationModel in Geant4 (outside examples/)
- ▶ [arXiv:hep-ex/0001020](https://arxiv.org/abs/hep-ex/0001020)
- ▶ [physics reference manual, chapter 18](#)

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$$dE(\vec{r}) = Ef(t)dtf(r)drf(\varphi)d\varphi$$

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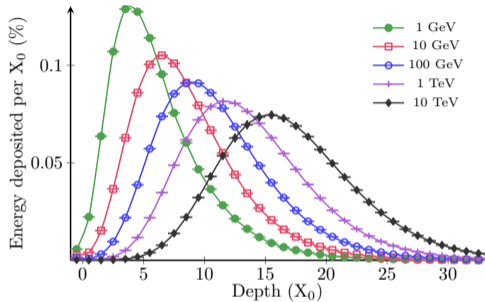
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- ▶  $f(t)$  and  $f(r)$  parametrised as a function of particle's energy ( $E$ ) and medium ( $Z$ )

## Example 4

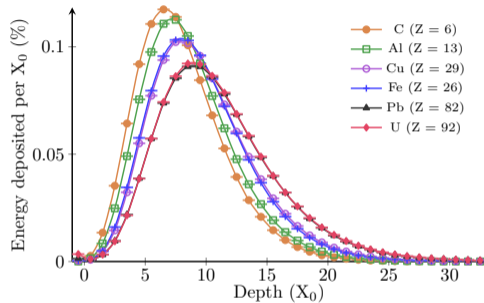
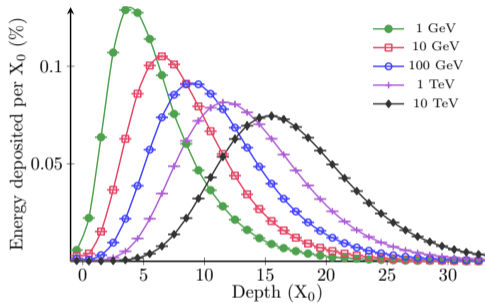
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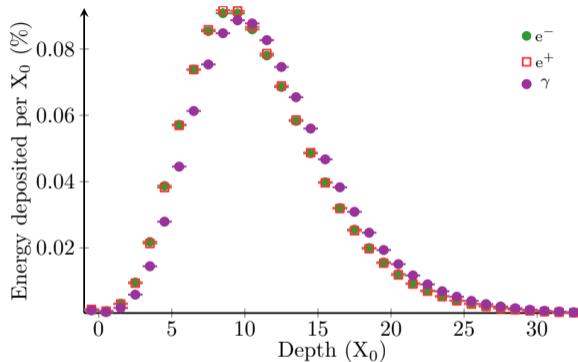
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- ▶  $t$  and  $r$  are expressed in units of  $X_0$  and  $R_M$



$$T \sim \ln E$$



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## Example 4 - longitudinal profile



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

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

$$T = \ln y + l_1$$

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



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## Example 4 - longitudinal profile

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

### A.1 Homogeneous Media

#### A.1.1 Average longitudinal profiles

▶ shower maximum  $T = \frac{\alpha-1}{\beta}$

$$T_{hom} = \ln y - 0.858$$

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

▶ Description dependent on  $y = \frac{E}{E_c}$ :

#### A.1.2 Fluctuated longitudinal profiles

$$T = \ln y + l_1$$

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

$$\langle \ln T_{hom} \rangle = \ln(\ln y - 0.812)$$

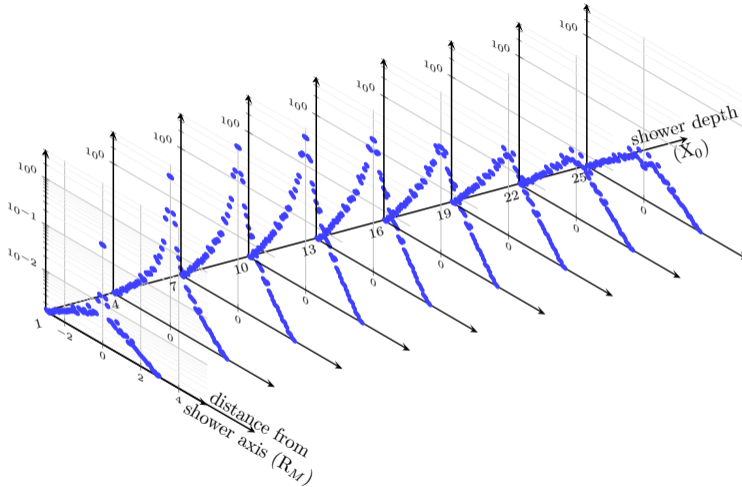
$$\sigma(\ln T_{hom}) = (-1.4 + 1.26 \ln y)^{-1}$$

$$\langle \ln \alpha_{hom} \rangle = \ln(0.81 + (0.458 + 2.26/Z) \ln y)$$

$$\sigma(\ln \alpha_{hom}) = (-0.58 + 0.86 \ln y)^{-1}$$

$$\rho(\ln T_{hom}, \ln \alpha_{hom}) = 0.705 - 0.023 \ln y$$

[arXiv:hep-ex/0001020](https://arxiv.org/abs/hep-ex/0001020)



## Example 4 – lateral profile

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

## Example 4 – lateral profile



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

## Example 4 – lateral profile

$$f(r) = \left\langle \frac{1}{dE(t)} \frac{dE(t, r)}{dr} \right\rangle = pf_{\text{core}}(r) + (1-p)f_{\text{tail}}(r) =$$
$$= p \frac{2rR_{\text{core}}^2}{(r^2 + R_{\text{core}}^2)^2} + (1-p) \frac{2rR_{\text{tail}}^2}{(r^2 + R_{\text{tail}}^2)^2}$$

## Example 4 – lateral profile

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

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

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

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

## Example 4 – lateral profile

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### A.1.3 Average radial profiles

$$R_{C, \text{hom}}(\tau) = z_1 + z_2\tau$$

$$R_{T, \text{hom}}(\tau) = k_1 \{ \exp(k_3(\tau - k_2)) + \exp(k_4(\tau - k_2)) \}$$

$$P_{\text{hom}}(\tau) = p_1 \exp \left\{ \frac{p_2 - \tau}{p_3} - \exp \left( \frac{p_2 - \tau}{p_3} \right) \right\}$$

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

$$\tau_i = \frac{t}{\langle t \rangle} \frac{\exp(\langle \ln \alpha \rangle)}{\exp(\langle \ln \alpha \rangle) - 1}$$

$$N_{\text{Spot}} = 93 \ln(Z) E^{0.876}$$

$$T_{\text{Spot}} = T_{\text{hom}}(0.698 + 0.00212Z)$$

$$\alpha_{\text{Spot}} = \alpha_{\text{hom}}(0.639 + 0.00334Z)$$

[arXiv:hep-ex/0001020](https://arxiv.org/abs/hep-ex/0001020)

## Example 4 – model

ExGflashDetectorConstruction.cc

```

229 void ExGflashDetectorConstruction::ConstructSDandField()
230 {
231     // - sensitive detectors:
232     G4SDManager* SDman = G4SDManager::GetSDMpointer();
233     ExGflashSensitiveDetector* CaloSD
234     = new ExGflashSensitiveDetector("Calorimeter",this);
235     SDman->AddNewDetector(CaloSD);
236     fCrystal_log->SetSensitiveDetector(CaloSD);
237
238     // Get nist material manager
239     G4NistManager* nistManager = G4NistManager::Instance();
240     G4Material* pbW04 = nistManager->FindOrBuildMaterial("G4_PbW04");
241     // - fast simulation models:
242     // *****
243     // * Initializing shower modell
244     // *****
245     G4cout << "Creating shower parameterization models" << G4endl;
246     fFastShowerModel = new GFlashShowerModel("fFastShowerModel", fRegion);
247     fParameterisation = new GFlashHomoShowerParameterisation(pbW04);
248     fFastShowerModel->SetParameterisation(*fParameterisation);
249     // Energy Cuts to kill particles:
250     fParticleBounds = new GFlashParticleBounds();
251     fFastShowerModel->SetParticleBounds(*fParticleBounds);
252     // Makes the EnergieSpots
253     fHitMaker = new GFlashHitMaker();
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246     fFastShowerModel = new GFlashShowerModel("fFastShowerModel", fRegion);
247     fParameterisation = new GFlashHomoShowerParameterisation(pbW04);
248     fFastShowerModel->SetParameterisation(*fParameterisation);
249     // Energy Cuts to kill particles:
250     fParticleBounds = new GFlashParticleBounds();
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254     fFastShowerModel->SetHitMaker(*fHitMaker);
255     G4cout<<"end shower parameterization."<<G4endl;
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## Example 4 – model

ExGflashDetectorConstruction.cc

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229 void ExGflashDetectorConstruction::ConstructSDandField()
230 {
231     // - sensitive detectors:
232     G4SDManager* SDman = G4SDManager::GetSDMpointer();
233     ExGflashSensitiveDetector* CaloSD
234     = new ExGflashSensitiveDetector("Calorimeter",this);
235     SDman->AddNewDetector(CaloSD);
236     fCrystal_log->SetSensitiveDetector(CaloSD);
237
238     // Get nist material manager
239     G4NistManager* nistManager = G4NistManager::Instance();
240     G4Material* pbW04 = nistManager->FindOrBuildMaterial("G4_PbW04");
241     // - fast simulation models:
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## 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

[ExGflashSensitiveDetector.hh](#)

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GVFlashHomoShowerTuning can be used to change parameters ( $l_1, l_2, \dots, r_1, \dots$ )

## Example 4 – model

[ExGflashSensitiveDetector.hh](#)

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GFlashHomoShowerTuning can be used to change parameters ( $l_1, l_2, \dots, r_1, \dots$ )

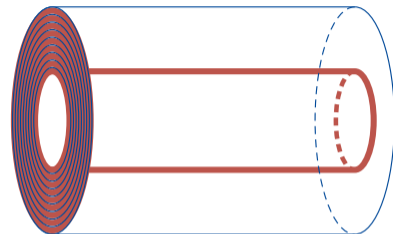
**Sampling calorimeter** For simulation in sampling detectors use GFlashSamplingShowerParameterisation and GFlashSamplingShowerTuning. Readout should collect signal from both active and passive material (e.g. by constructing SD in parallel world). Those calorimeters have not been tested in Geant4, so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

# Example 5:

[examples/extended/parameterisations/Par04](#)

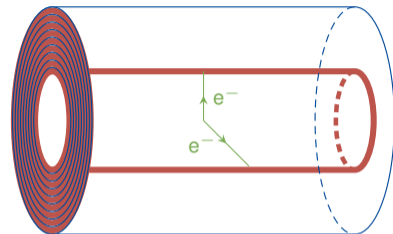
## Example 5

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



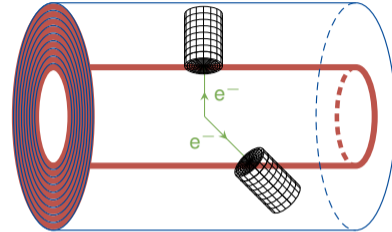
## Example 5

- ▶ examples/extended/parameterisations/Par04 new example since Geant4 11.0 release
- ▶ 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 fast sim model that is attached to calorimeter)



## Example 5

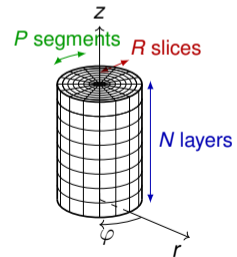
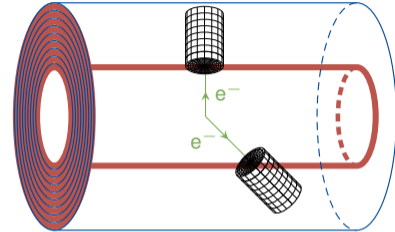
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- ▶ Particle direction and position is measured at the entrance to calorimeter (many possible ways to do it: we chose fast sim model that is attached to calorimeter)
- ▶ Scoring of energy deposits is done relative to the particle direction
- ▶ Similar granularity 'pictures' are obtained independently on angle



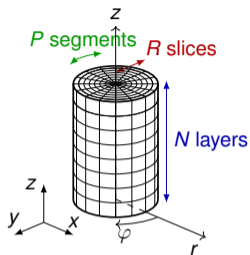


## Example 5

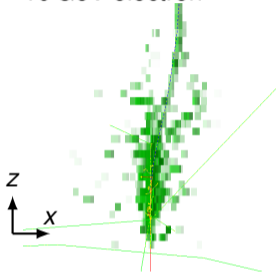
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- ▶ Scoring of energy deposits is done relative to the particle direction
- ▶ Similar granularity 'pictures' are obtained independently on angle
- ▶ Granularity of shower deposition is configurable



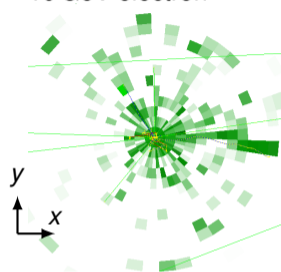
## Example 5 – EM showers



10 GeV electron

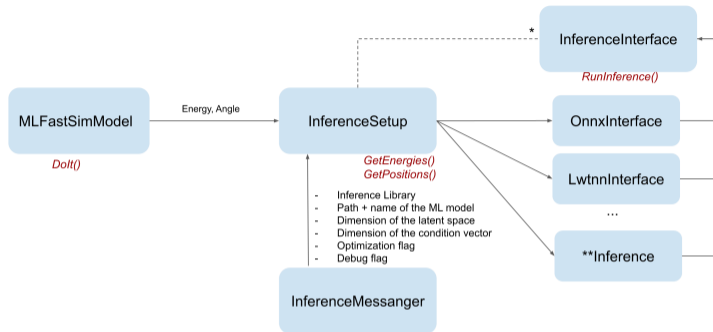


10 GeV electron



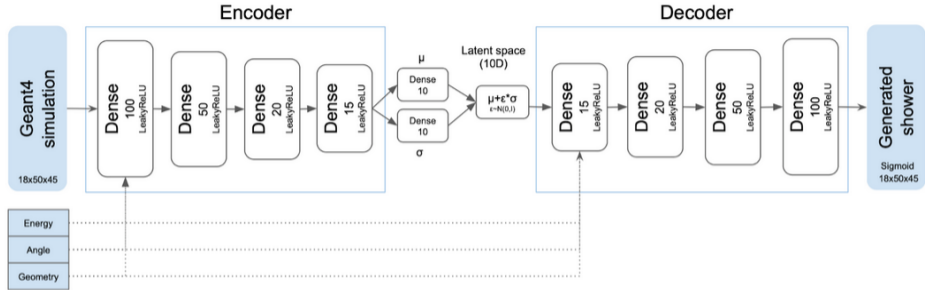
- ▶ Example uses 0.3 mm Si and 1.4 mm W layers
- ▶ Readout granularity is  $\Delta r \times \Delta\phi \times \Delta z = 2.3 \text{ mm} \times \frac{2\pi}{50} \times 3.4 \text{ mm}$  aiming for  $\Delta r \approx 0.25 R_M$  and  $\Delta z \approx 0.6 X_0$
- ▶ Number of readout cells is  $R \times P \times N = 18 \times 50 \times 45$  aiming for 95% containment of 1 TeV particles
- ▶ **Open access dataset for SiW (and scintillator-Pb) released [10.5281/zenodo.6082201](https://zenodo.org/record/6082201)**
- ▶ This dataset is a base of ML studies, including CaloChallenge.

## Example 5 – inference within C++ framework



- ▶ Fast simulation with ML within Geant4
- ▶ Demonstrates how to incorporate inference libraries (ONNX Runtime, LWTNN)
- ▶ Par04 can run full and fast simulation (if any of the inference libraries is available, e.g. via LCG)

# Example 5 – ML model



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**. More details on work on generalisation are discussed in our webpage: [g4fastsim.web.cern.ch](http://g4fastsim.web.cern.ch)

- ▶ Fast simulation can be used within Geant4;

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- ▶ Examples in [examples/extended/parameterisations/](#);

Questions/problems?

[anna.zaborowska@cern.ch](mailto:anna.zaborowska@cern.ch)