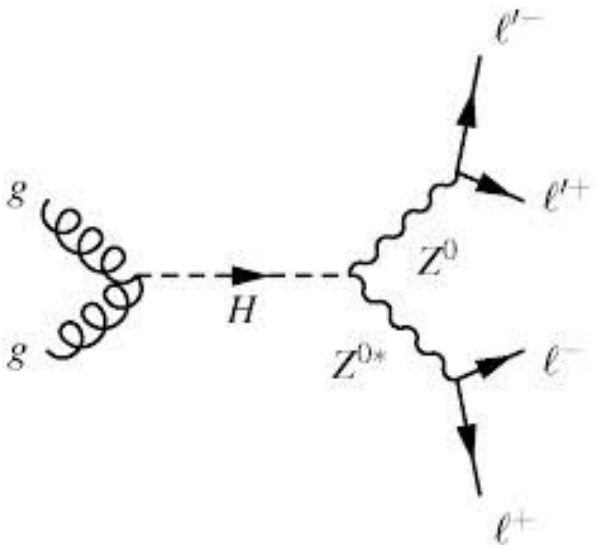
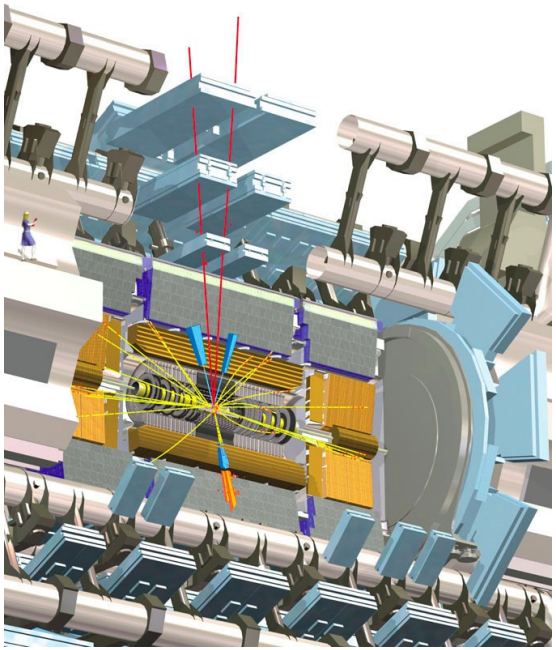
Event Simulation I: Introduction





Thorsten Kuhl

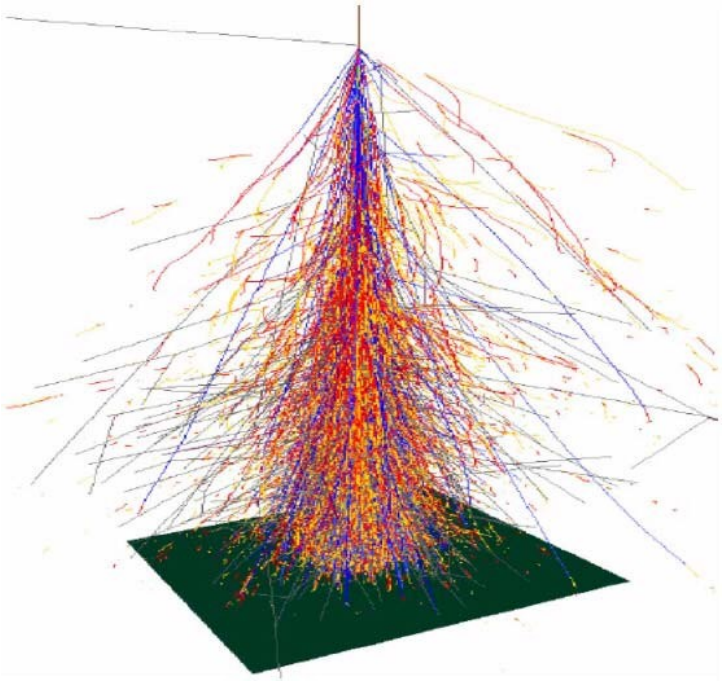
Graduate School, Mass-Spectrum-Symmetry
Autumn block course Berlin,
Sept. 29th-Oct. 2nd, 2014

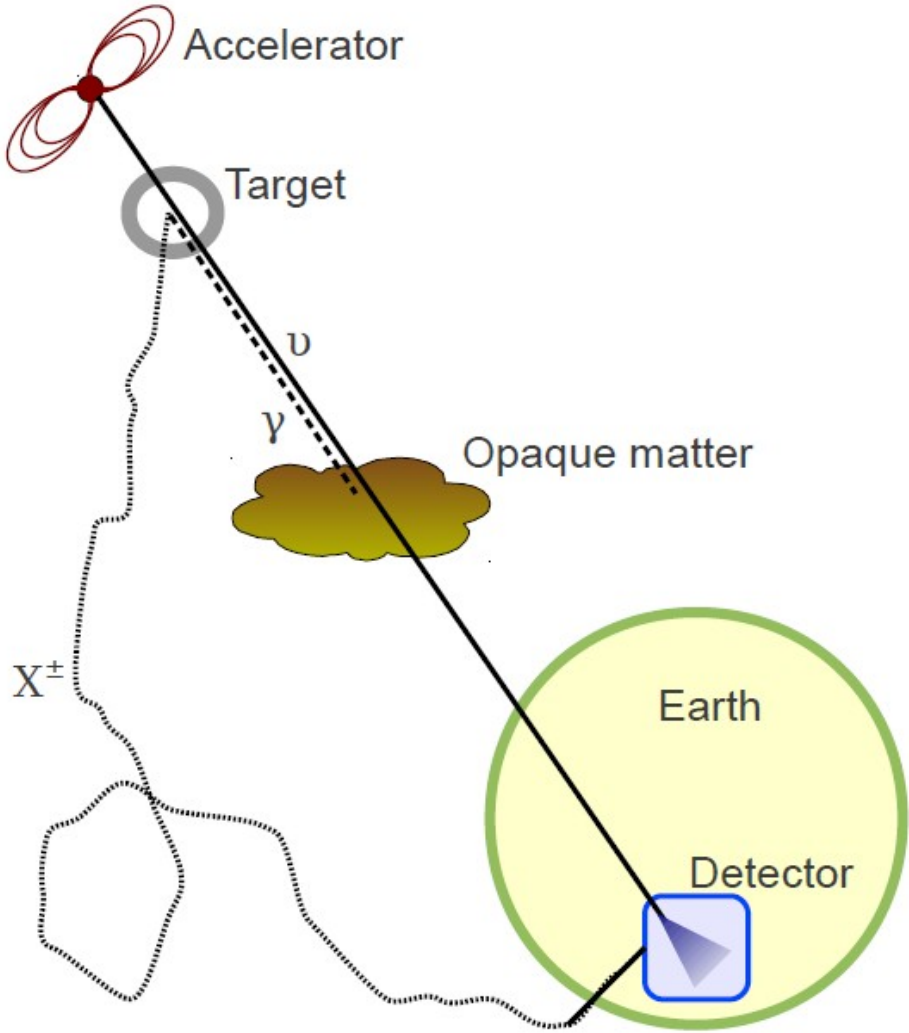
HELMHOLTZ | GEMEINSCHAFT

DESY

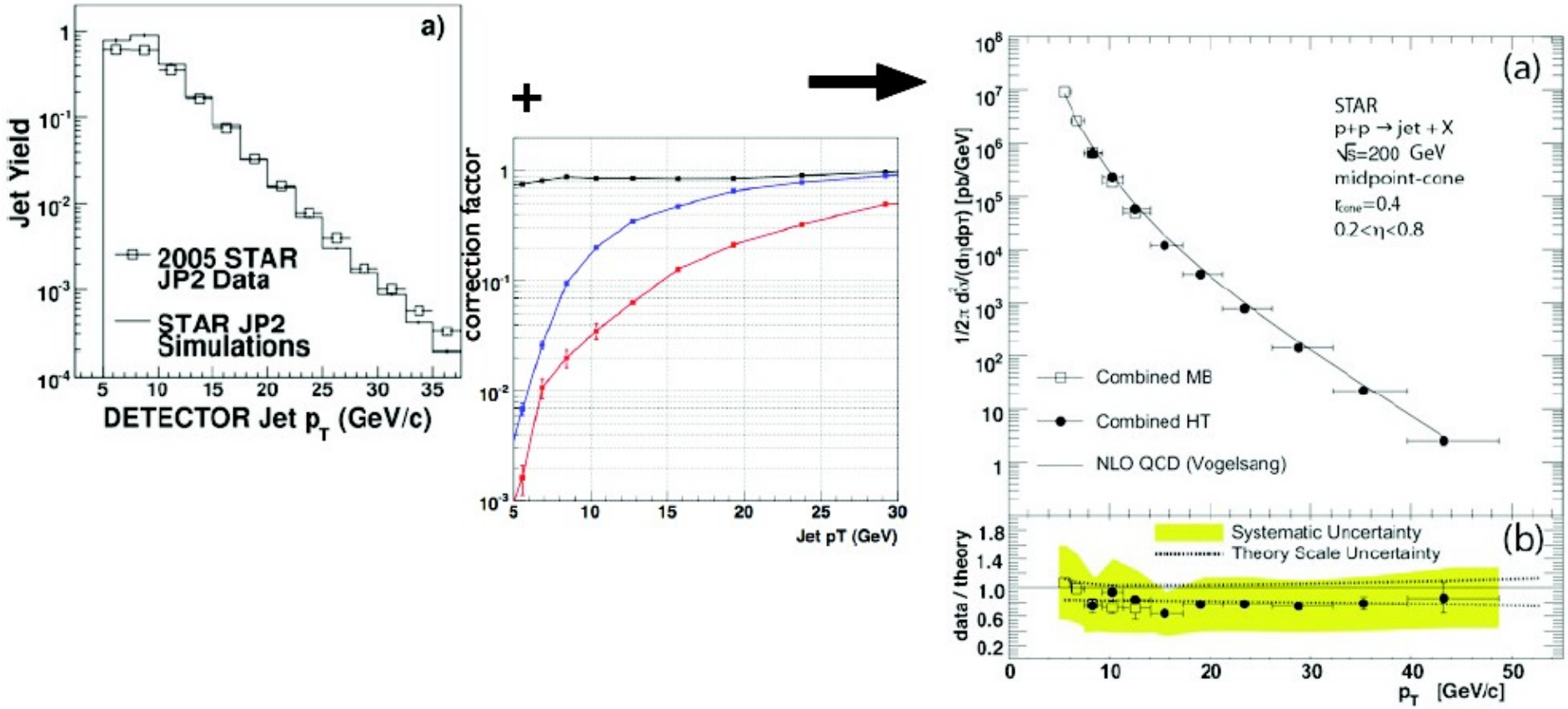
What is event simulation?

- Simulation of the nature as realistic as possible





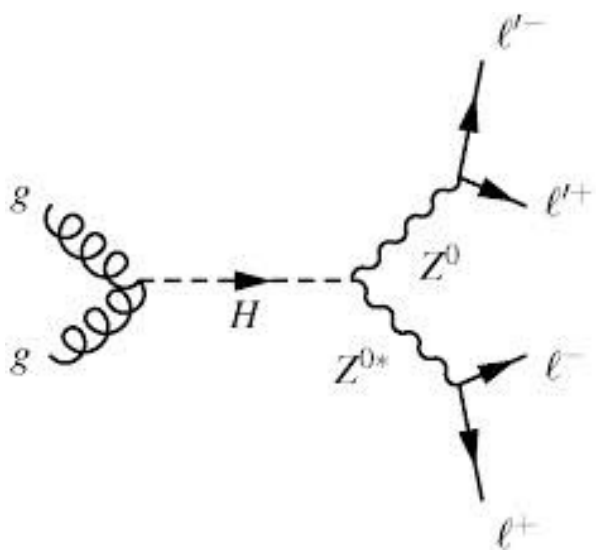
Why do we need simulation?

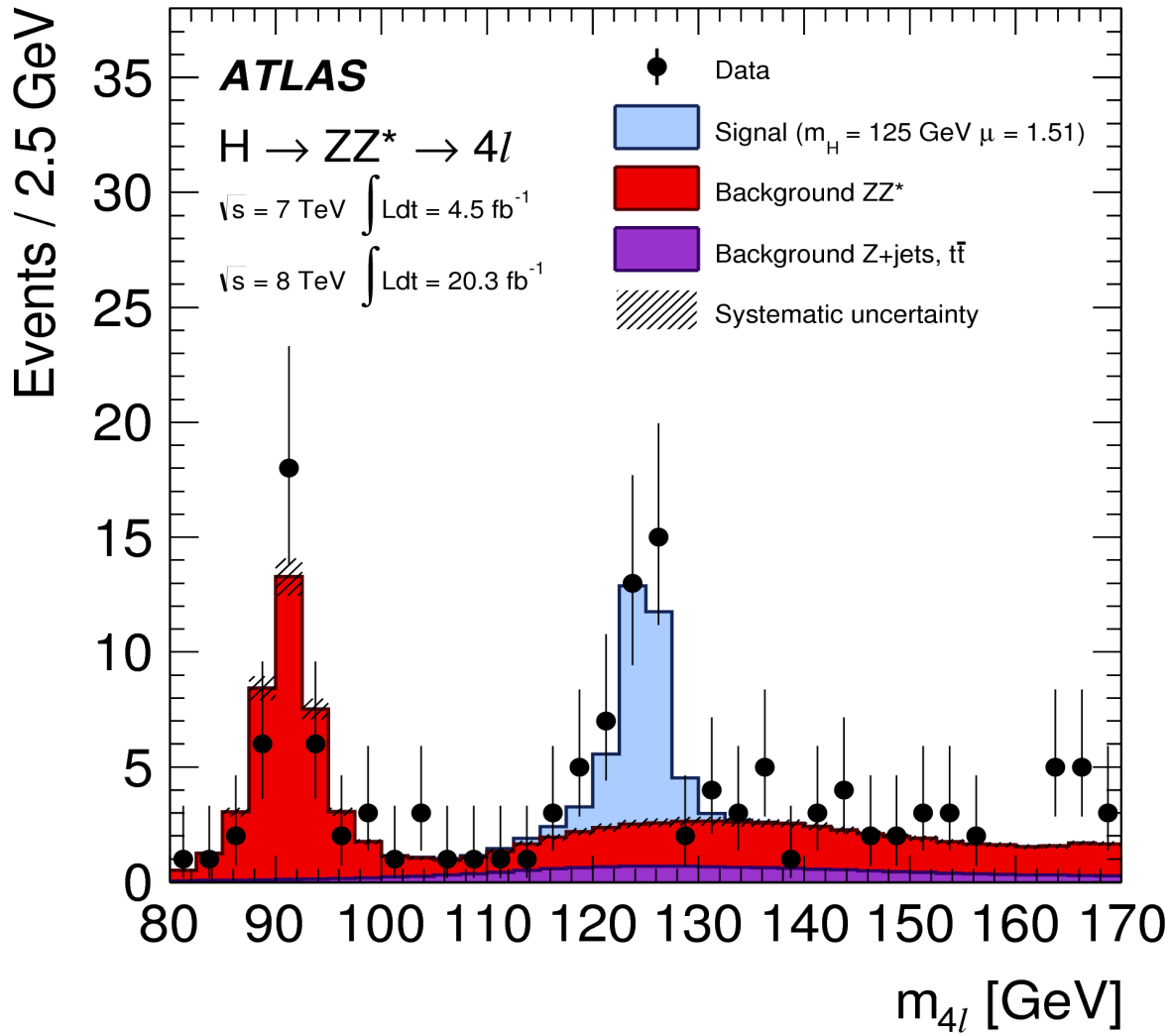


- Need of corrections of data:
  - experimental resolutions/smearing
  - selection efficiency

Why do we need event simulation?

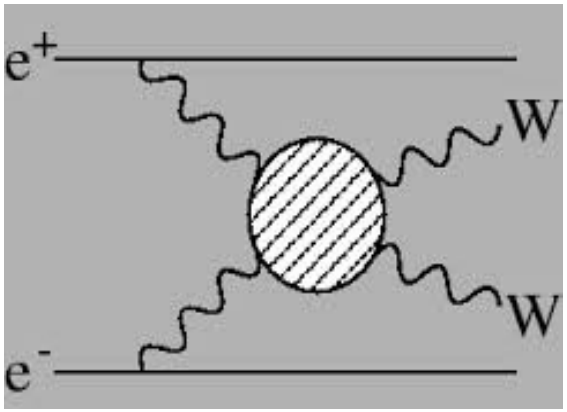
- Simulation of the known physics to discover new physics
  - Higgs → 4 leptons

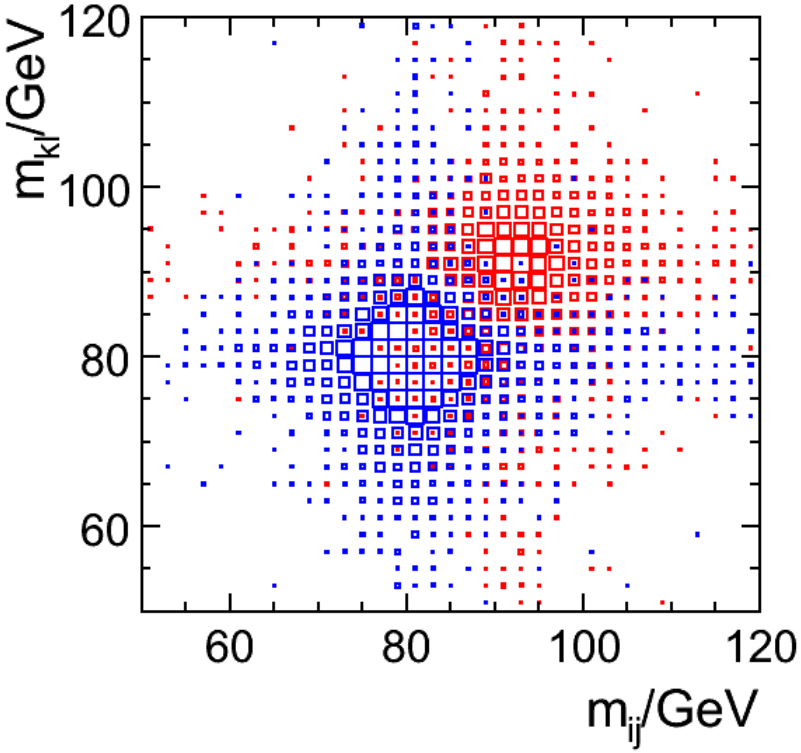




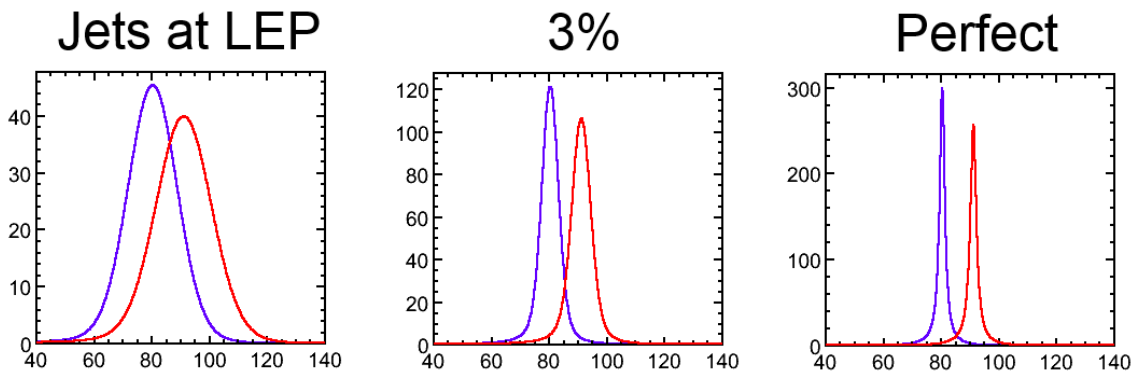
Designing new detectors/optimization

- Linear collider: optimization:
  - Bench mark: separation of Z and W Mass peak
  - Need optimization of detector and reconstruction



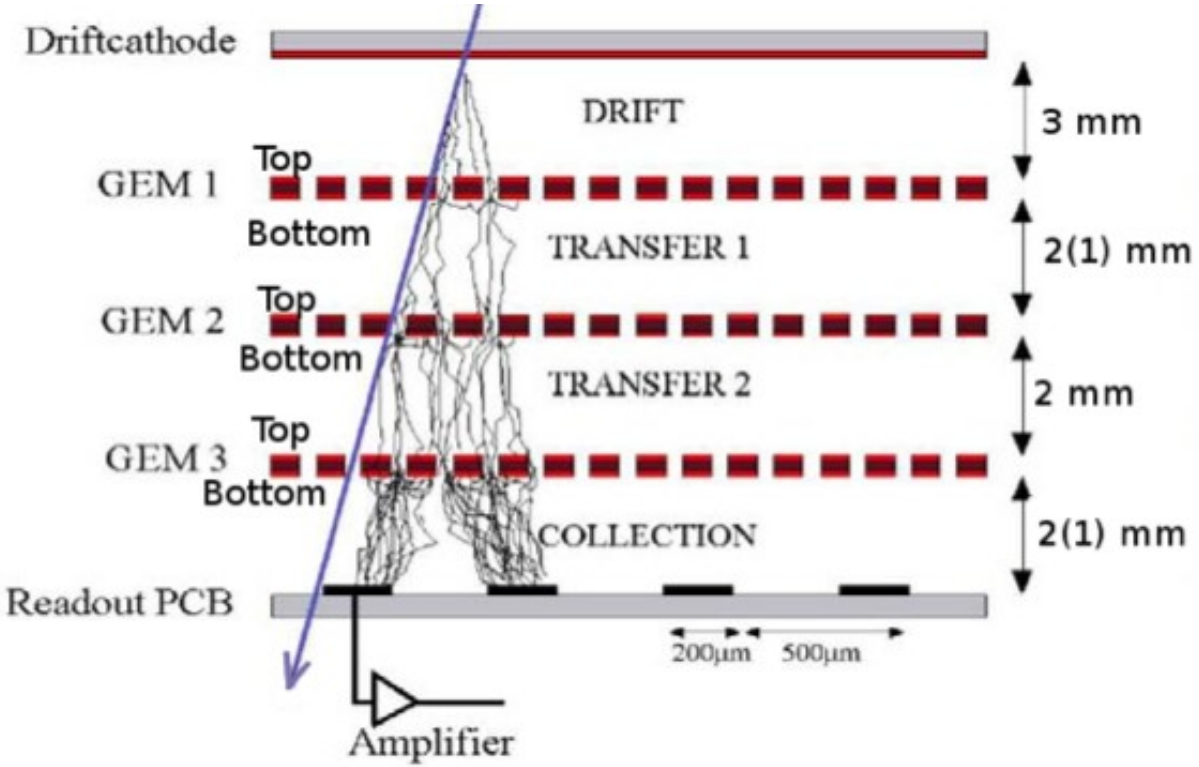


Particle flow: jet resolution heavily depends on tracks, electromagnetic and hadronic calorimeter

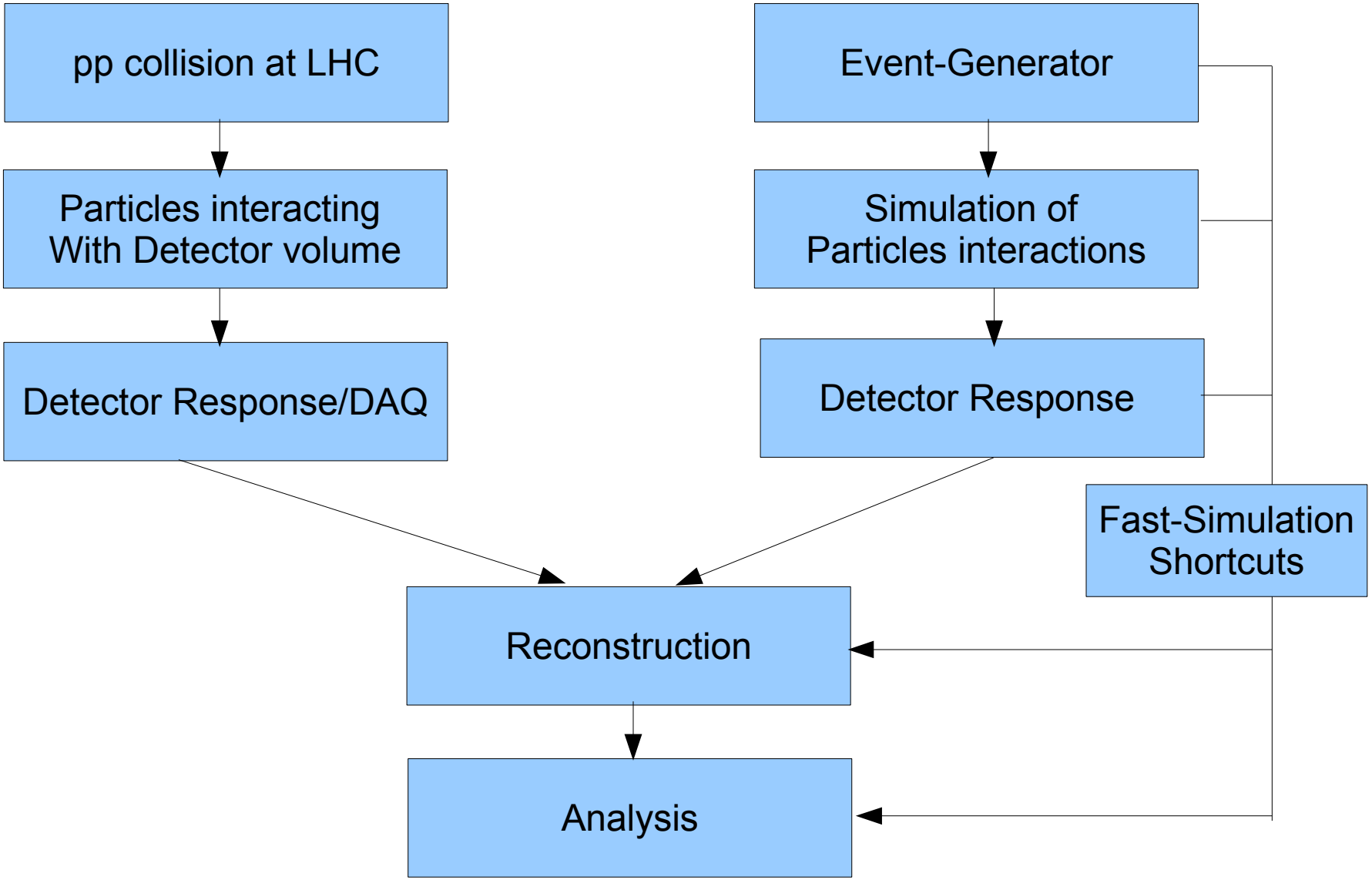


R&D of detectors

- Simulation of a triple GEM structure for the CMS muon chambers
  - Primary muon produce electron-hole pairs
  - Accelerated electrons in electromagnetic field produce secondary avalanche
  - Charge collection/readout



Principle: Nature → Simulation



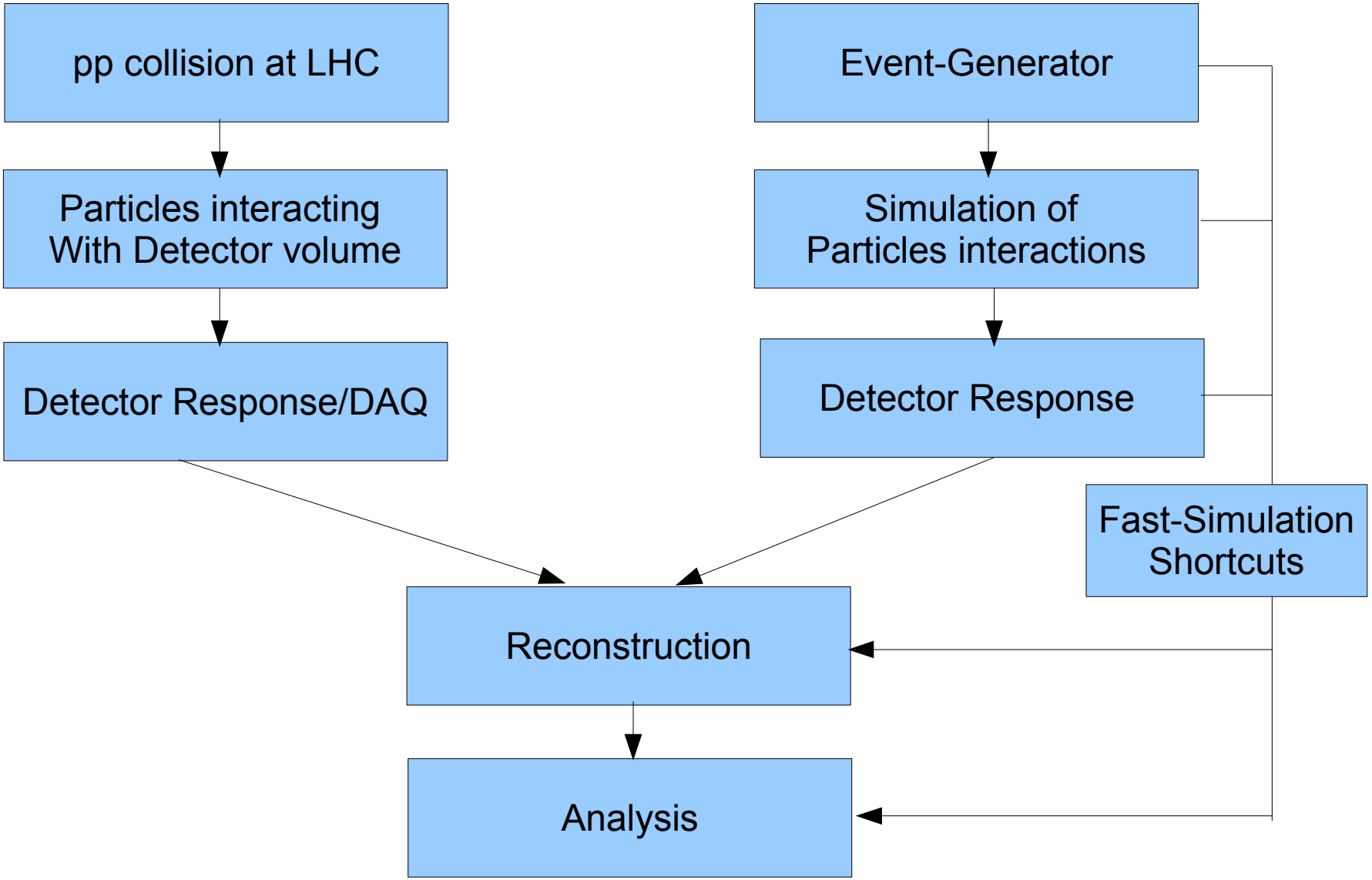
Content

- I: Overview
  - Basics of everything
- II: Event Generation:
  - Simulation of incoming particles till they hit the detector
- III: Detector Simulation
  - Interaction with material
  - “Digitization”: Detector and Electronic response
- IV: Fast simulation and Computing
  - Time issue: how to speed up
  - Corrections of residual differences (data vs simulation)
  - Computing Framework

Part I: Overview

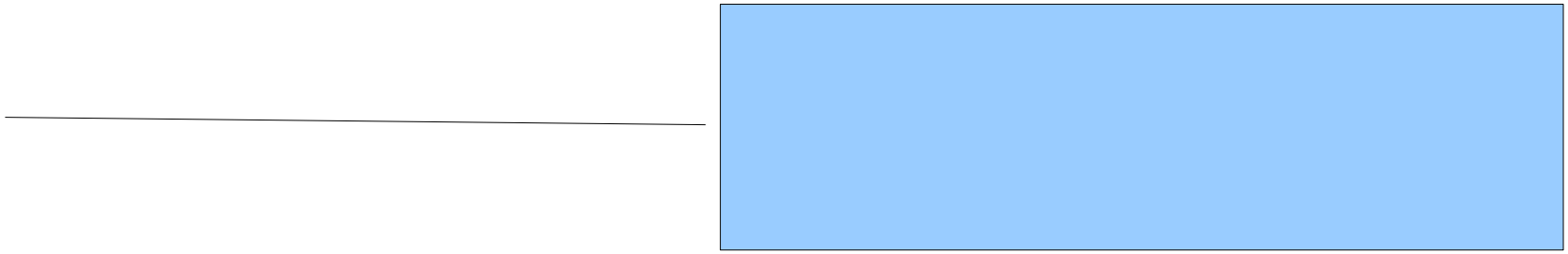
- Why event simulation?
- Event Generators (very brief)
- Building blocks:
  - Event generation
  - Detector Simulation
    - Particle passing Material
    - Electronic response
    - time dependence
  - Reconstruction and correction
- Technical implementation/Frameworks
  - Computing model
- Fast Simulation (very brief)

Principle: Nature → Simulation



First step: Event generation

- Generation of the particles which will hit the detector:
  - Particle gun: track hit detector with given angle and momentum (good enough for calorimeter with little space resolution):



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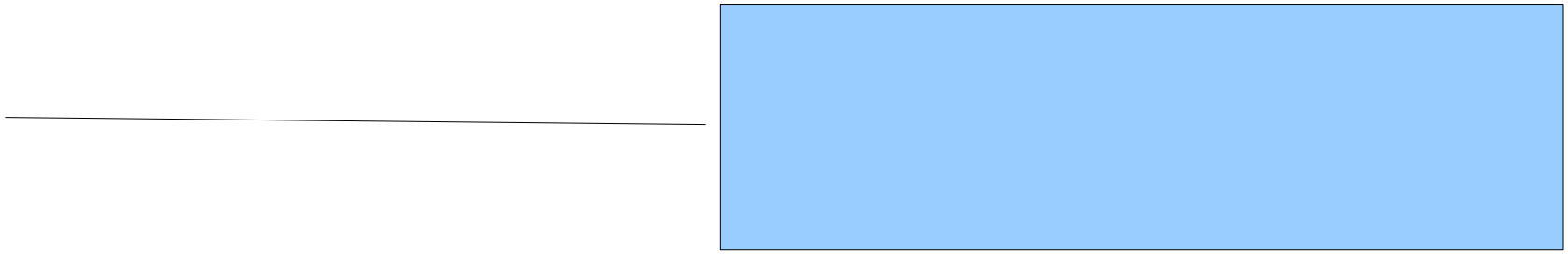
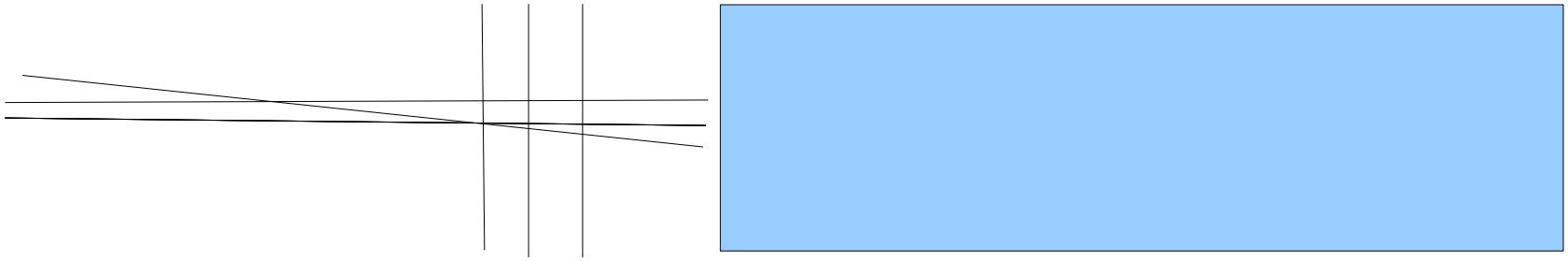


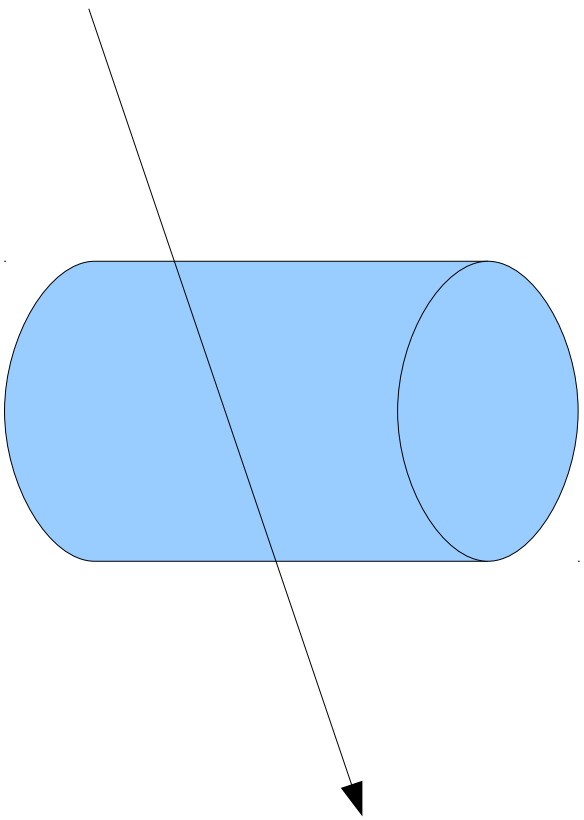
  - More sophisticated: Including beam spread (tracker in front of):

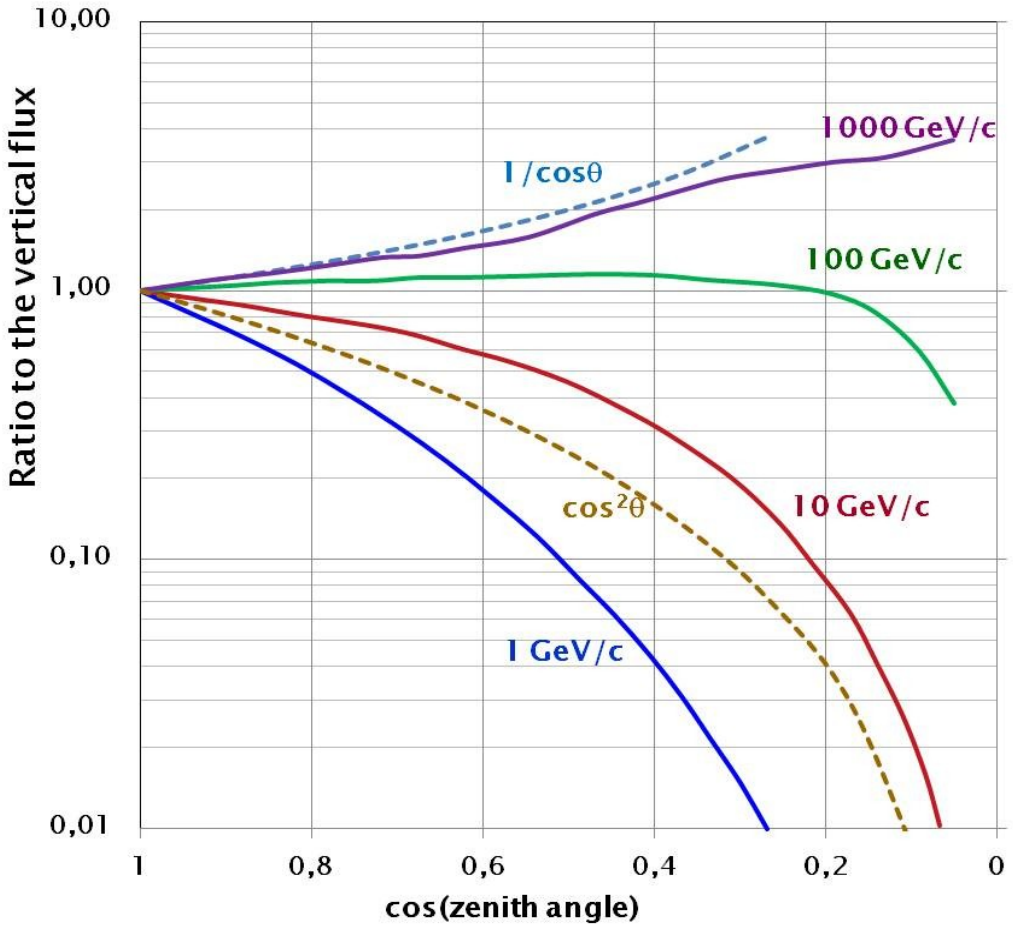


  - A more advances particle gun (initial gun with different angles, momentums)

First step: Event generation

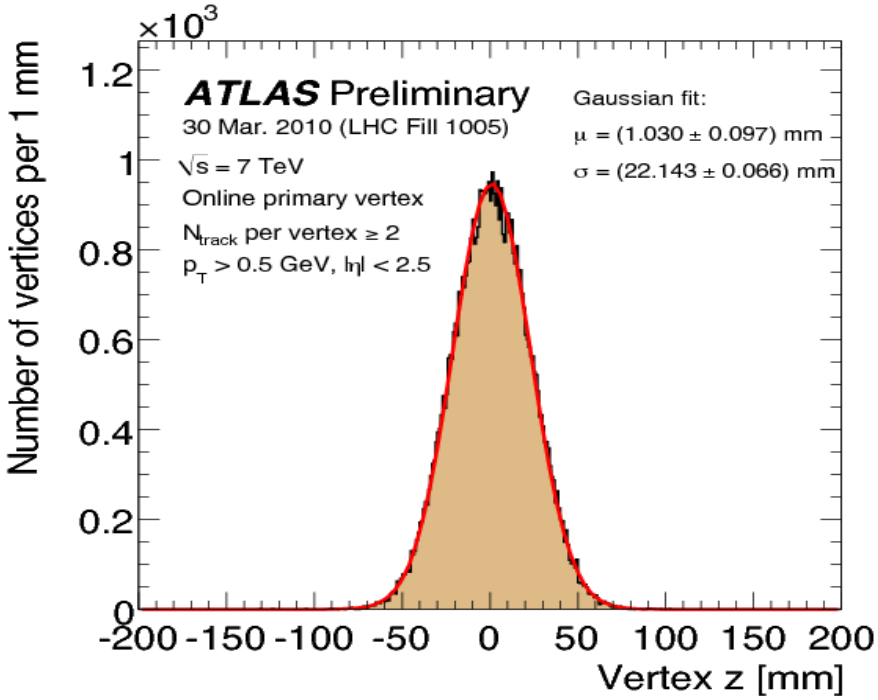
- Even more advanced: atmospheric muon spectrum: angular, momentum and intensity modulated particle gun (for example using formula from PDG)

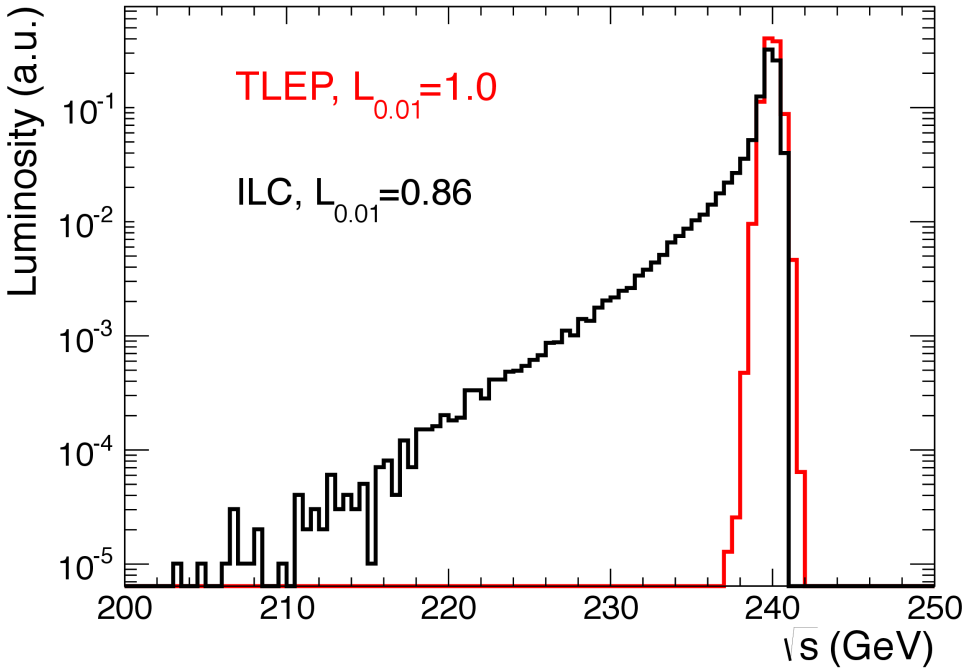




First step: Event generation

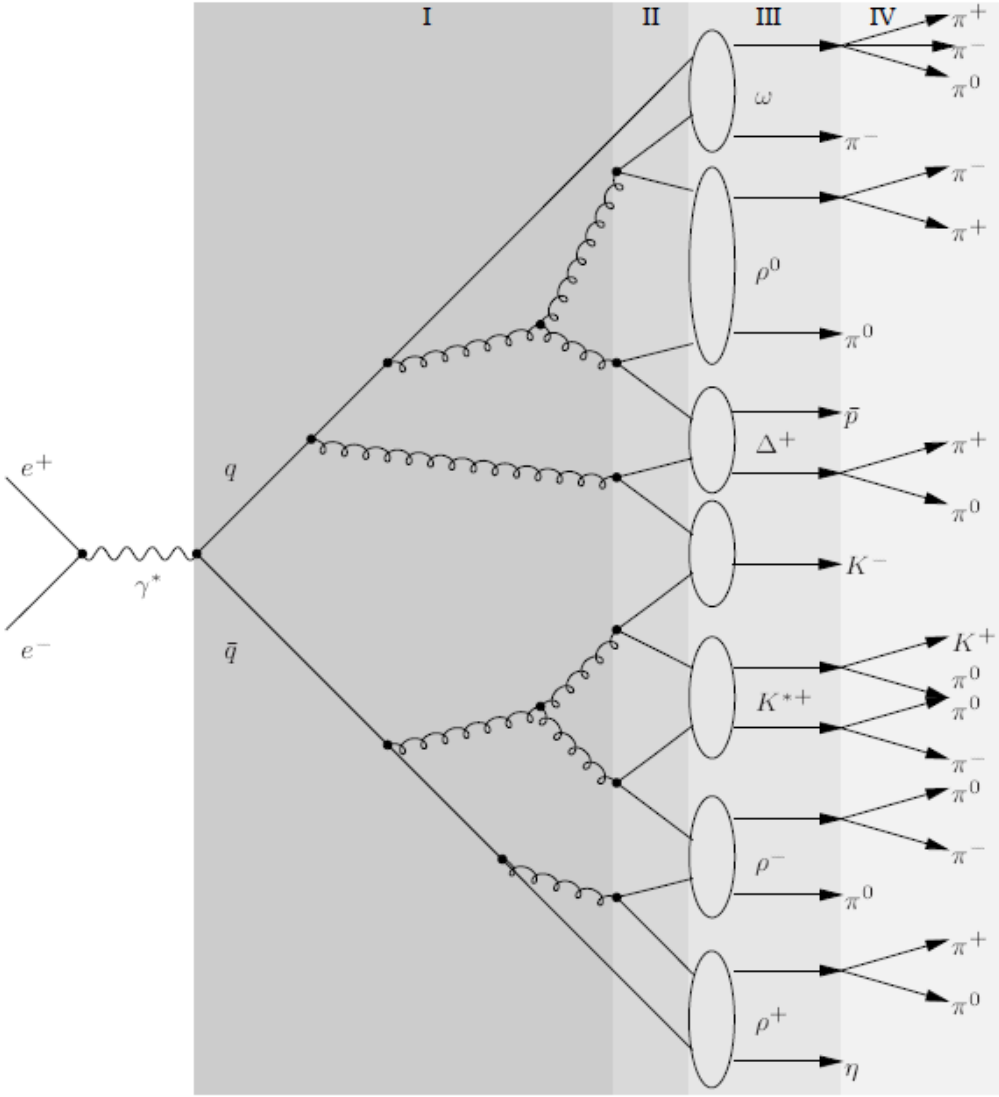
- Particle physics:
  - Proton beams are “simple”: no beam losses, small angular spread, simulation of the position in the interaction region
  - Electron/Positrons: Energy losses because of beam and beam-beam interactions





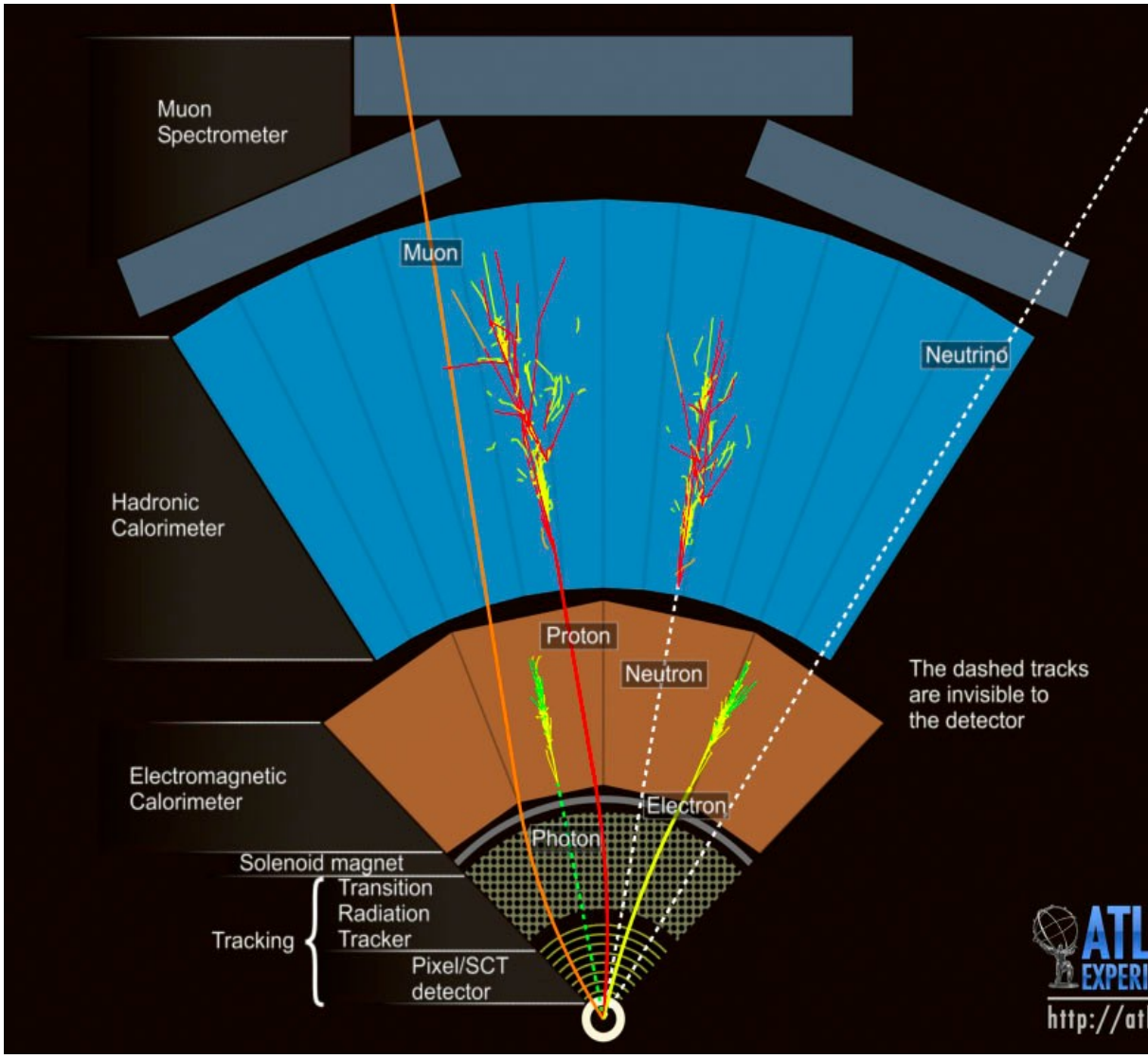
Event generation (todays late session)

- Complexed events in particle physics
- Modular simulation based on factorisation:
  - Incoming particles (external source)
  - (Hadron beam: PDF)
  - Matrix element
  - I: Parton shower
  - II: Fragmentation
  - III: Haronization
  - IV: Decays of short-life particles (that short that detector does not need to simulation interactions)
  - Stable particles (common format)



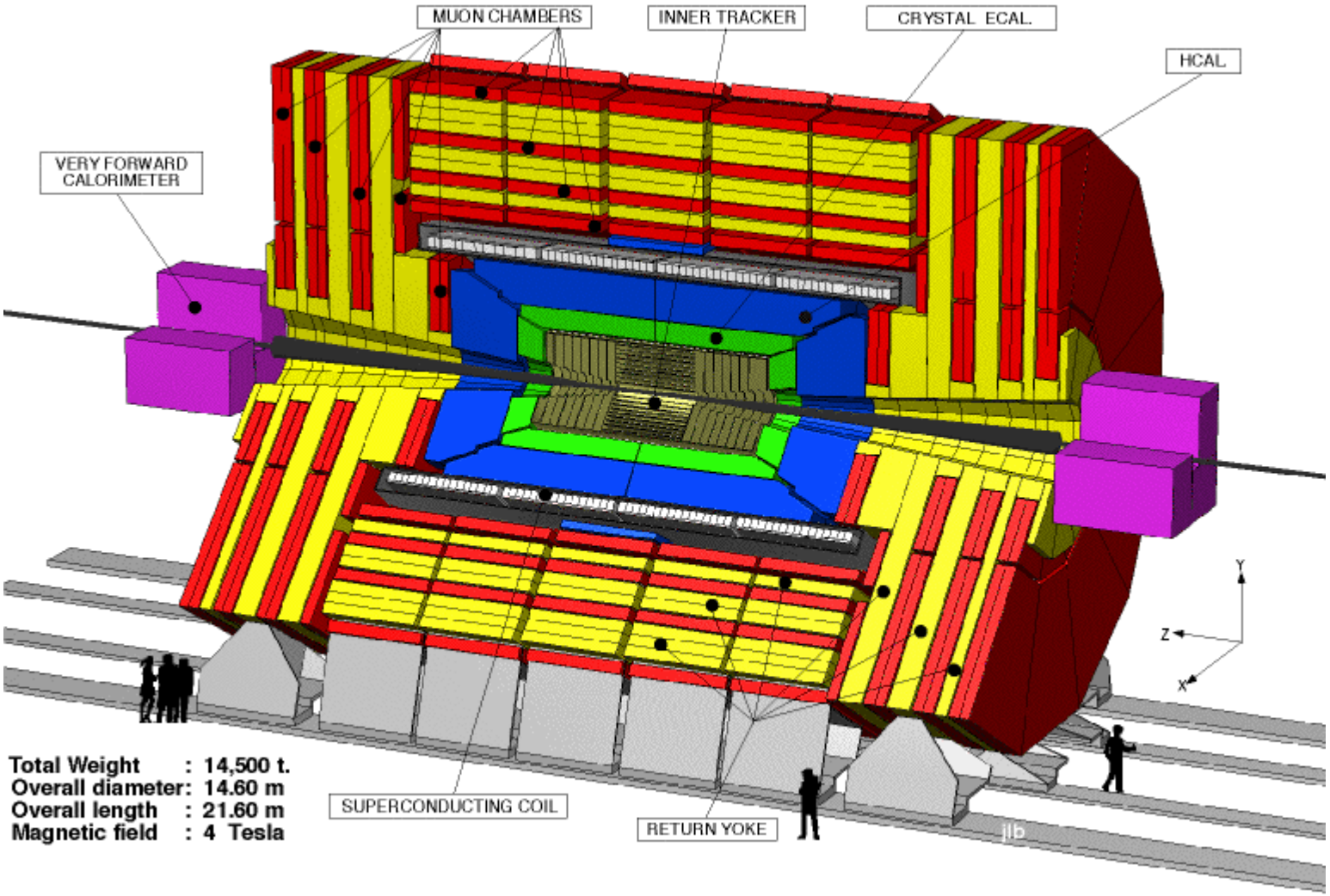
Particle detector in material

- Different kind of particles have different interaction lengths
  - Use different material to separate particle types



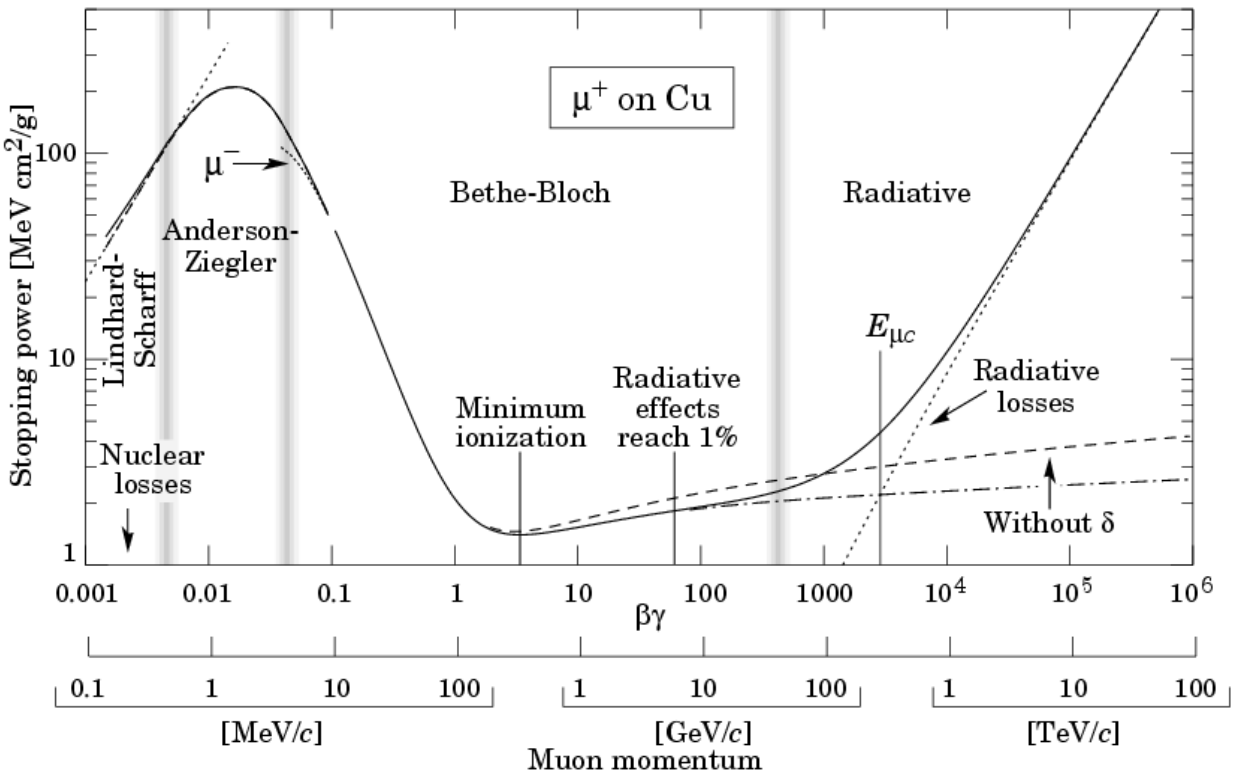
Particle passing detector material

> Complex systems/material distributions/ many subcomponents



What happen in the detector

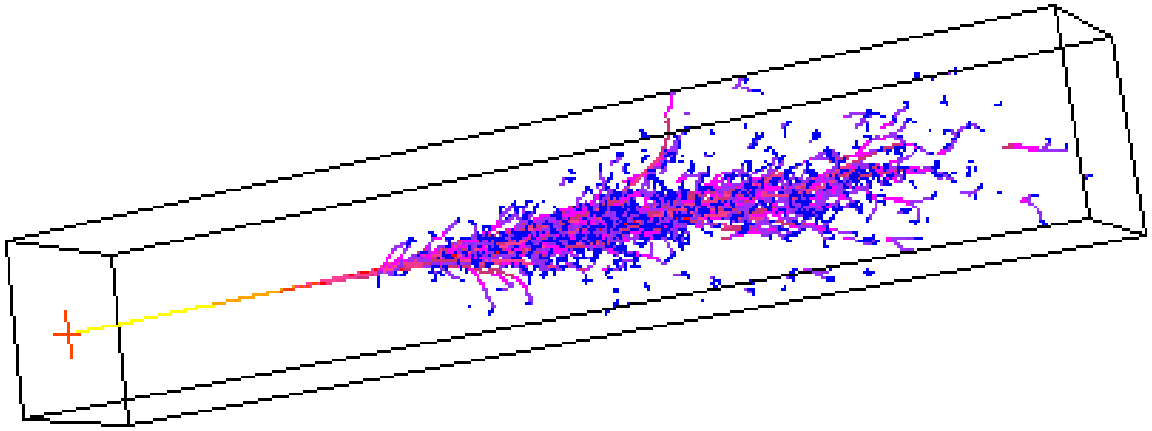
- Particle passing trough detector material (Geant 4 et all):
  - Energy loss (Bethe-Bloch)
  - Radiative losses/e^+e^--pair production
- Electromagnetic processes are well known/simply to simulate
- Important: low energetic cut off/ simulation step size

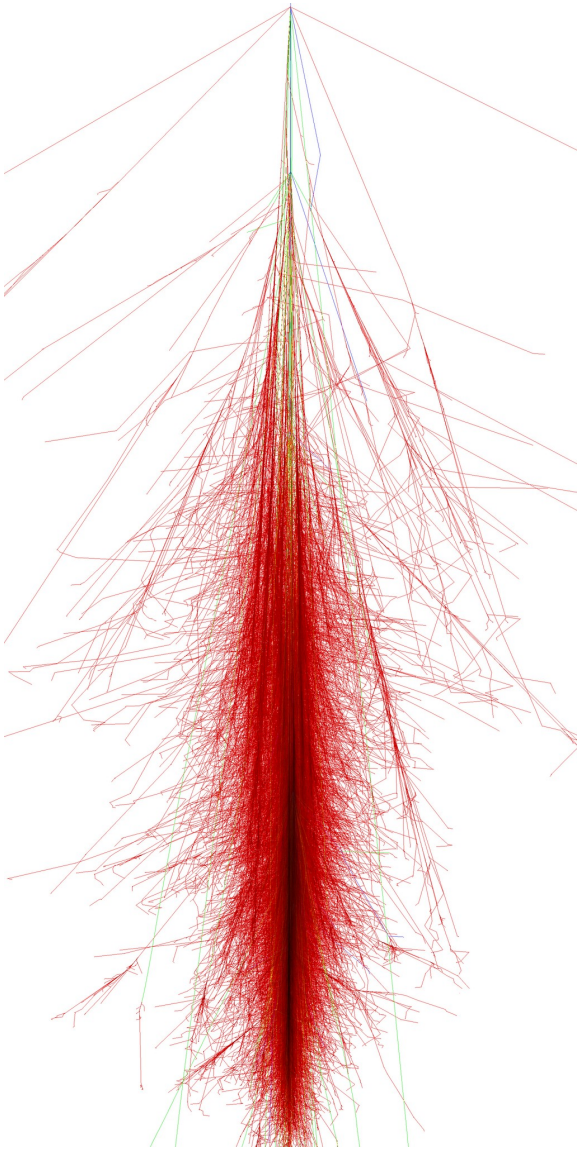


PDG

Particle passing detector material

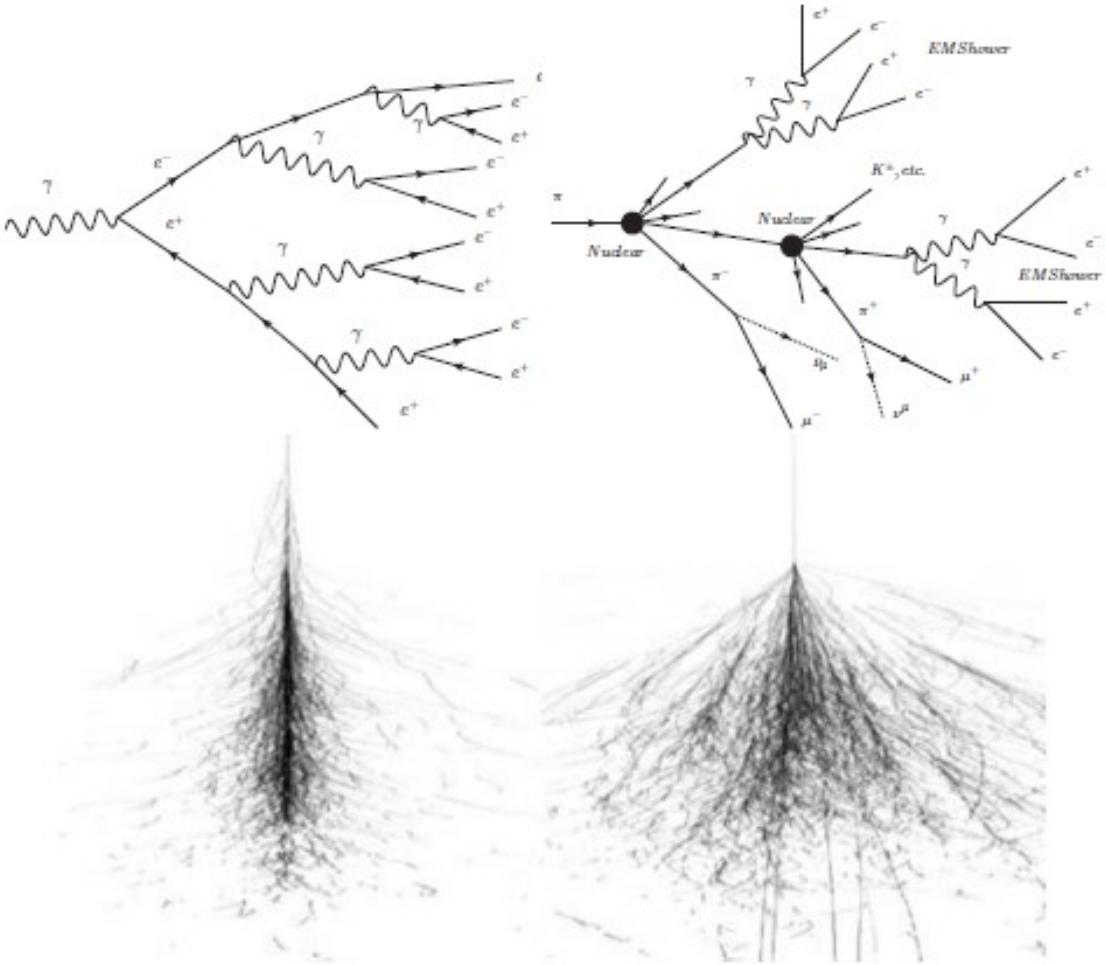
- Geant 3/4, Corsika
- Passive material: Air shower
- Active Material: lead glass detector
  - Tracking detectors (mostly dE/dX) easy to Simulate
  - Electromagnetic shower are well known
  - Challenging: hadronic shower, different physics lists





Comparison Electromagnetic/Hadronic shower

> Comparison: electromagnetic and hadronic shower

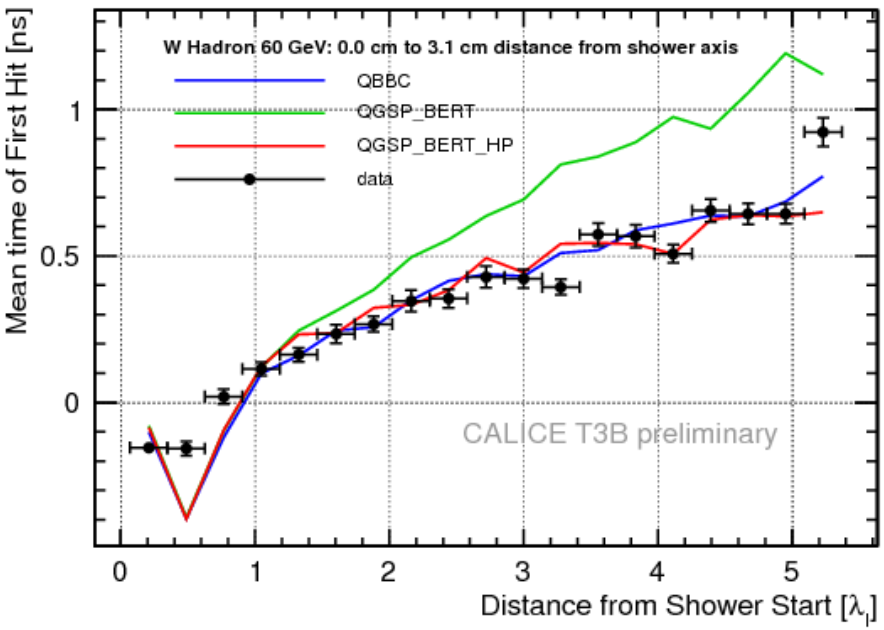


> Electromagnetic shower:
- Very limited number of well known processes
  - annihilation
  - radiation
  - some very low E
- homogeneous

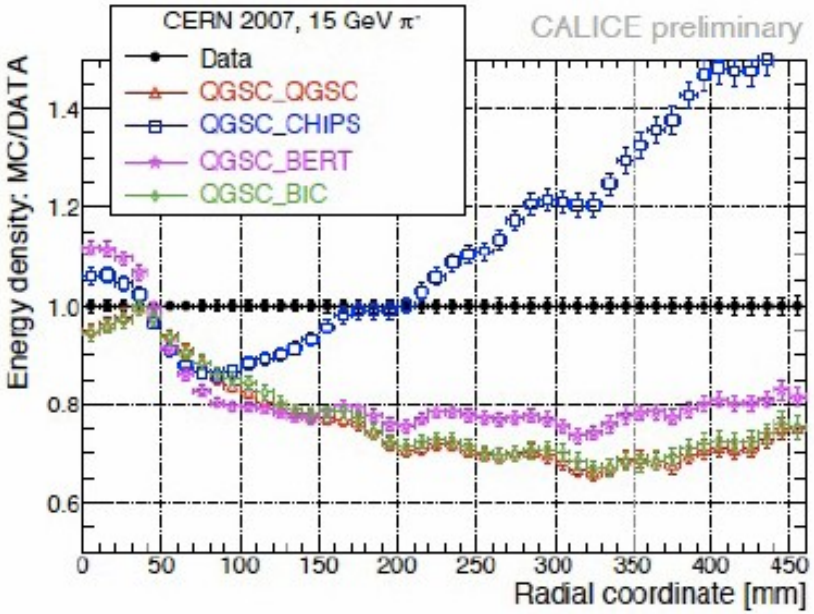
> Hadronic shower:
- Huge number of different interactions
- Neutral/charge particles
- Electromagnetic/strong interactions
- Very inhomogeneous

What happen in the detector

- Particle passing trough detector material (Geant 4 et all):
  - Hadronic interactions → the difficult part
  - Need improvements (Calice tracking calorimeter)
  - Even worse: low energetic neutrons

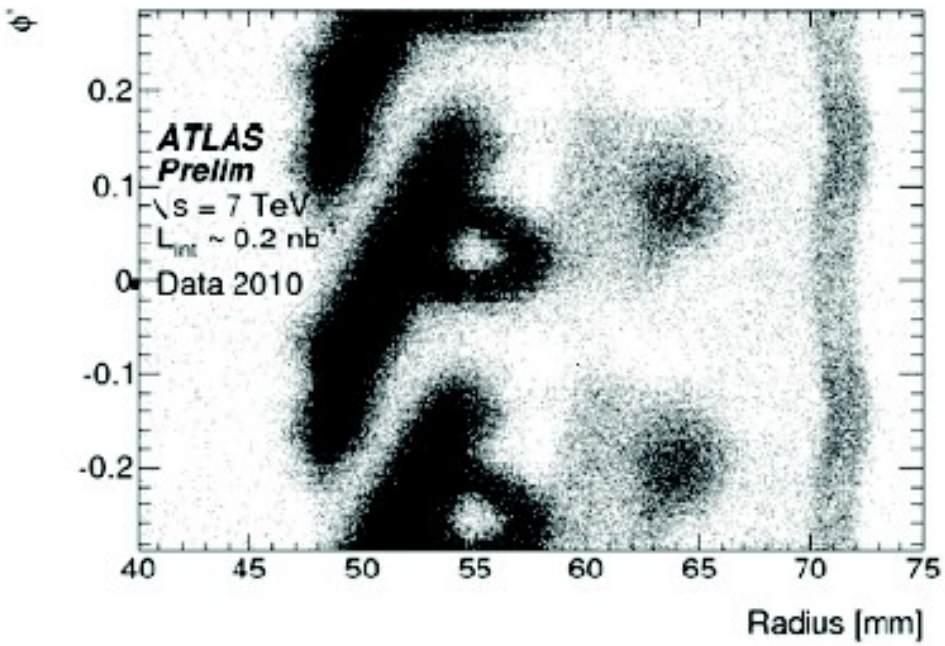


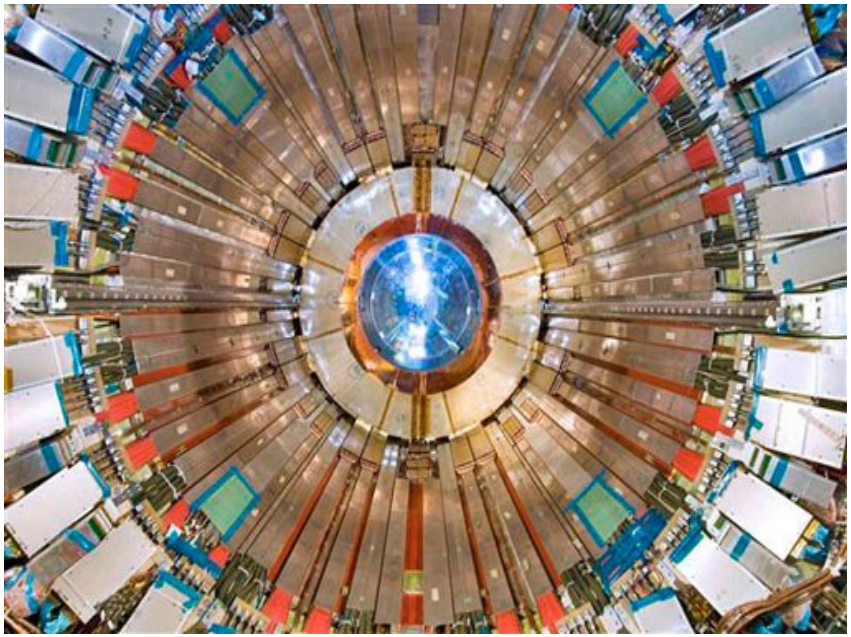
First interaction always with same list, further with different



Material distribution

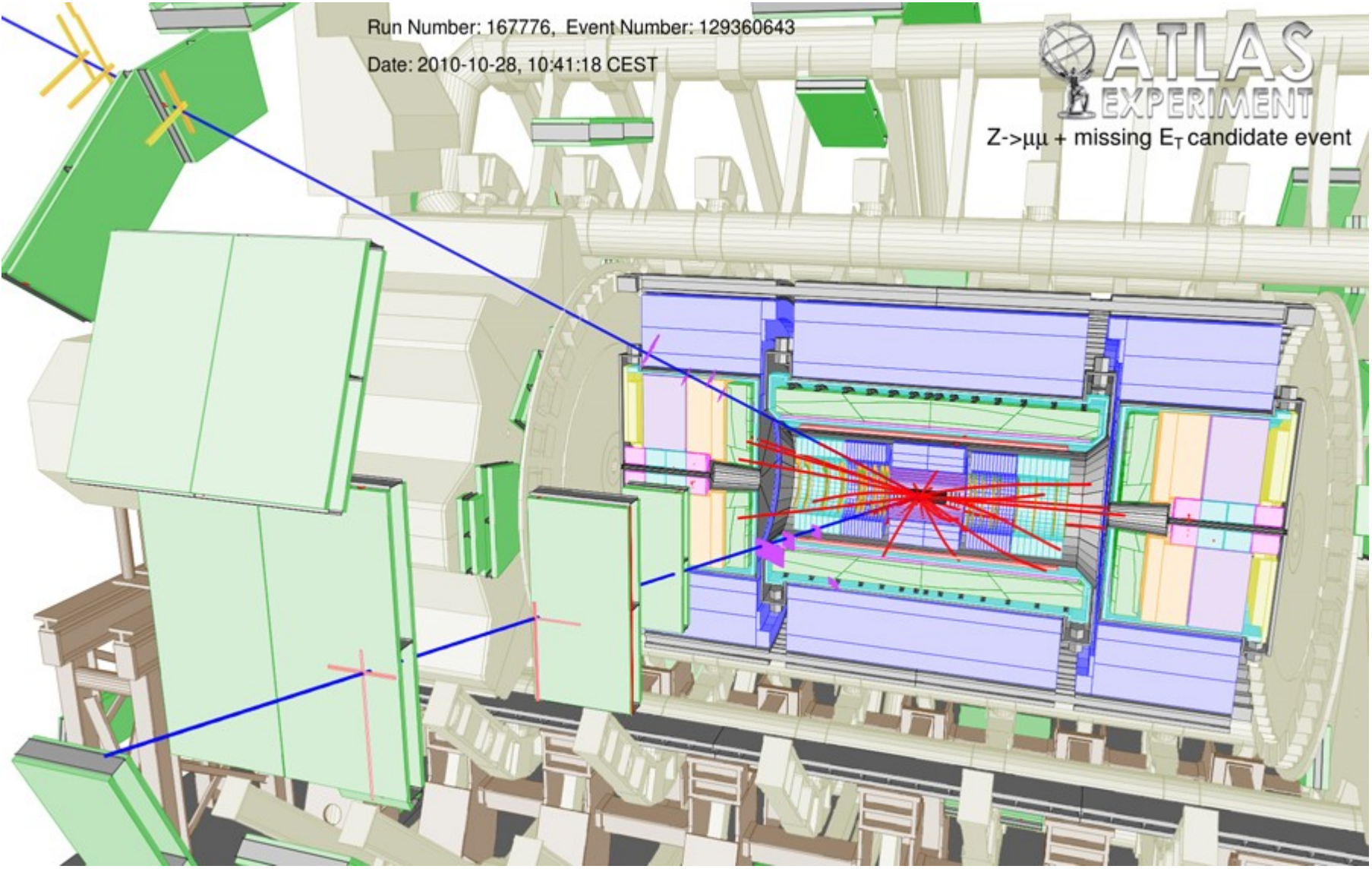
- Details of material distribution:
  - Tracker: very detailed picture of converted photons
    Alignment errors in simulation? (smeared by accuracy)





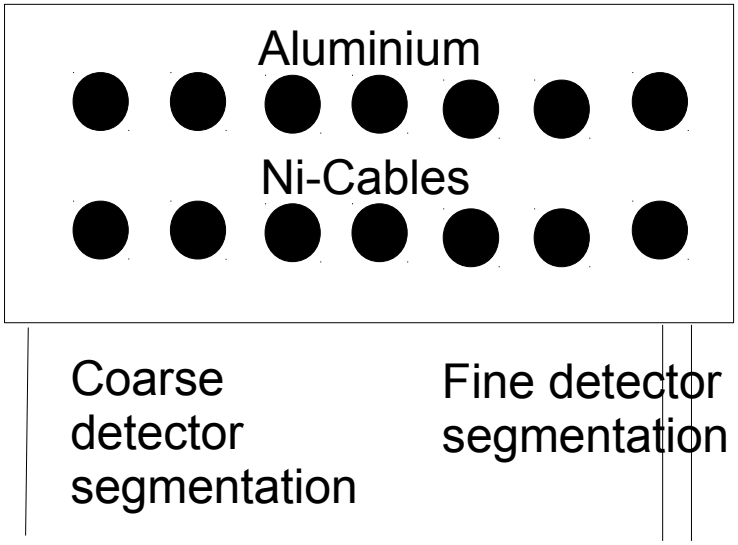
  - Cables in shower development: only averaging possible (picture)

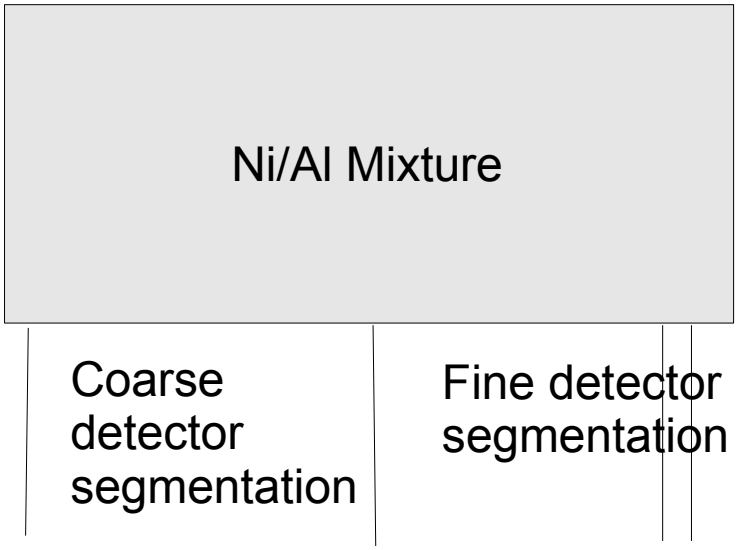
Atlas-Detector



Material distribution: details

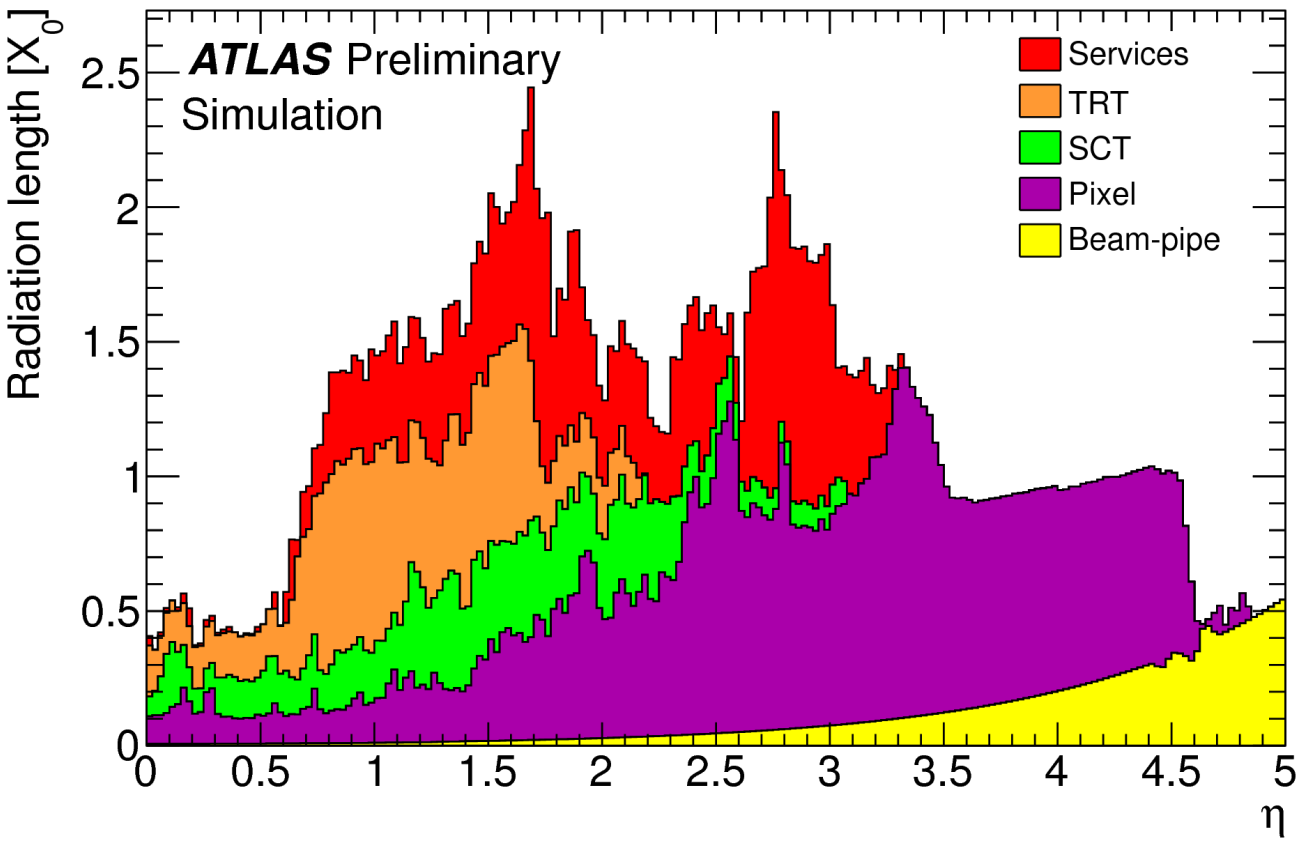
- Exact description: description of all individual components bigger then a a certain size
- Mixed material: Mixture of all material in a give volume: good average description of hadronic and electromagnetic interactions, but less inhomogeneous/tails (dense areas, scatter centers)
- Average material: One material with average A/Z, cannot describe interactions if materials are very different
- More complex: longitudinal segmentation
- Accuracy of material distribution ~ detector resolution





Material distribution

- Material in Front of the Atlas Electromagnetic Calorimeter
  - Including active and passive material
  - Importance of service material outside the given detector

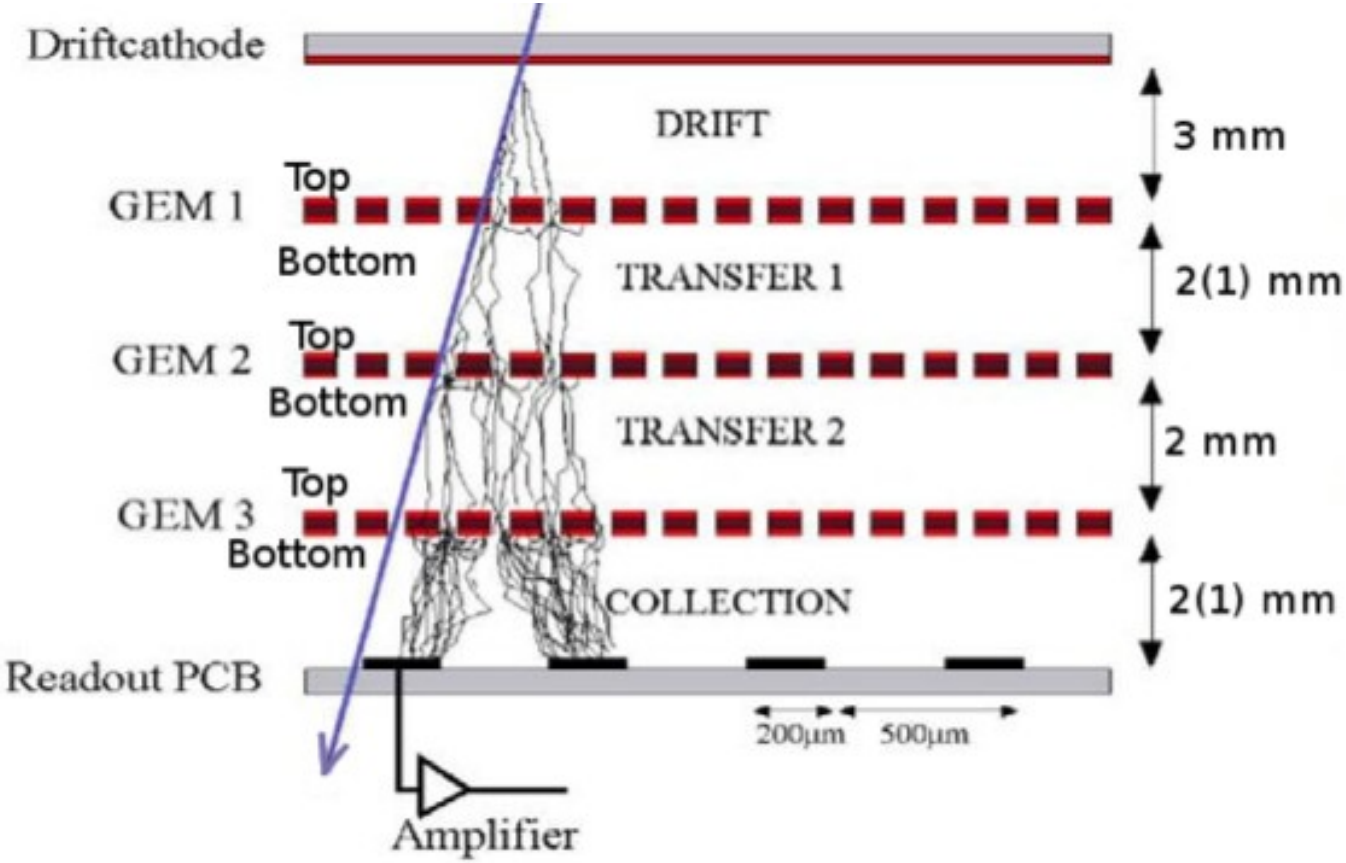


Detector/Electronic response: “Digitization”

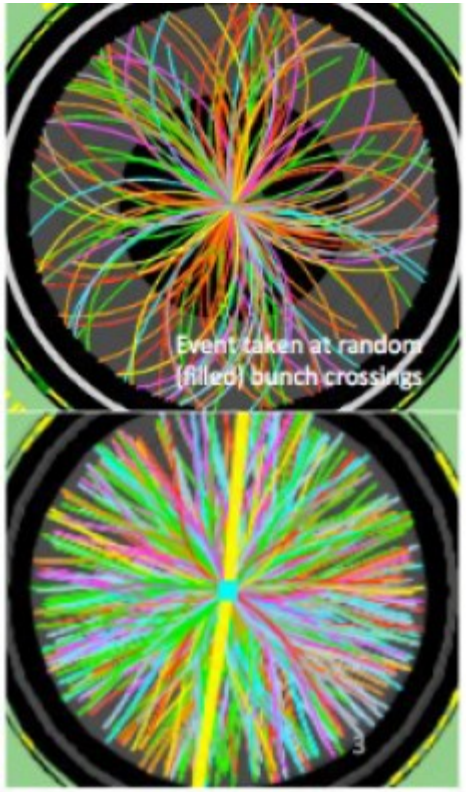
- “Digitization”: All processes after material interactions of the particles:
  - Drift of signal in the detector volume (TPC, RPC)
  - Collection of the signal
  - Active amplification of the detector (GEMs, Wires, photo multiplier ...)
  - Electronic response, amplification, noise, cross-talk, cable losses
  - Time dependence/overlay with previous and later interactions
- Accuracy very much dispense on the use-case:
  - Detailed description of drifts and amplification in R&D (needs much time
  - Application of simple analytic formulas on Geant 4 energy deposit for running detectors (fast and accuracy)
  - Using noise/amplification factors determined in real detector calibration.

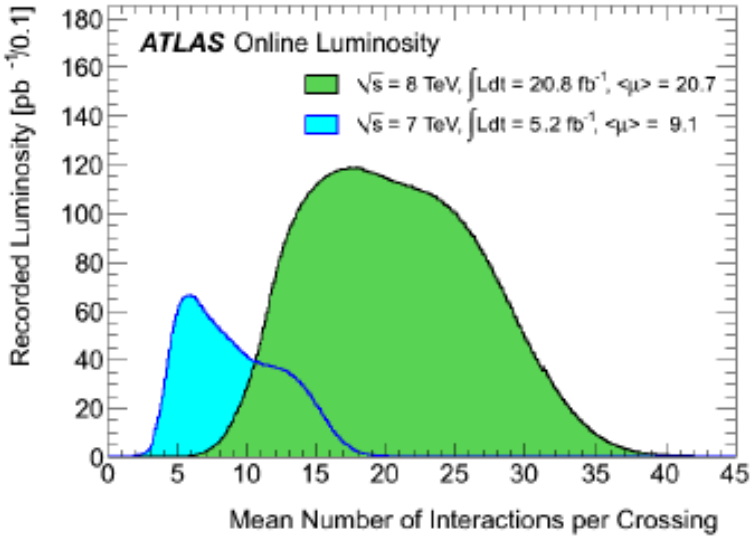
Detector/Eletronic response: “Digi

- Geant 4 simulation: distribution of charges on the blue line
- Simulation of the full secondary avalanche and th electronic response needs dedicated programs
- In complexed experiments not the full process is simulated, simplifications



Detector/Electronic response: Event overlay

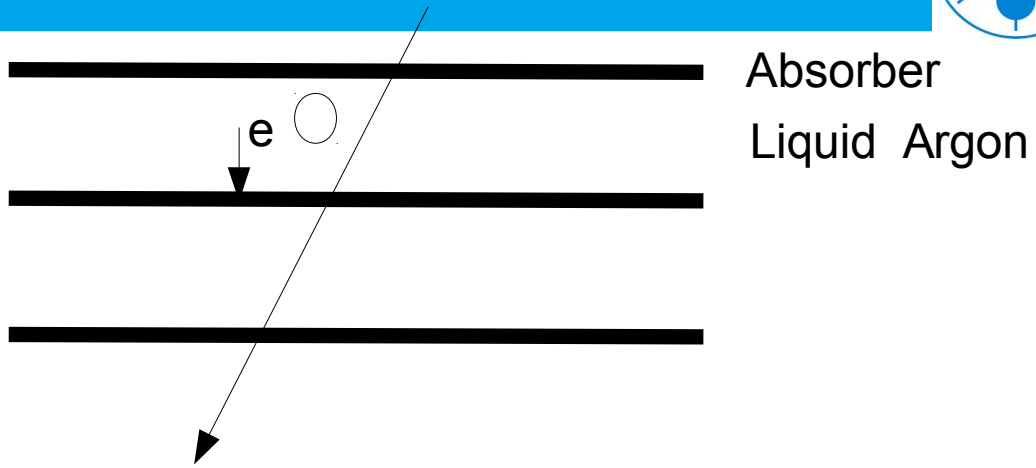


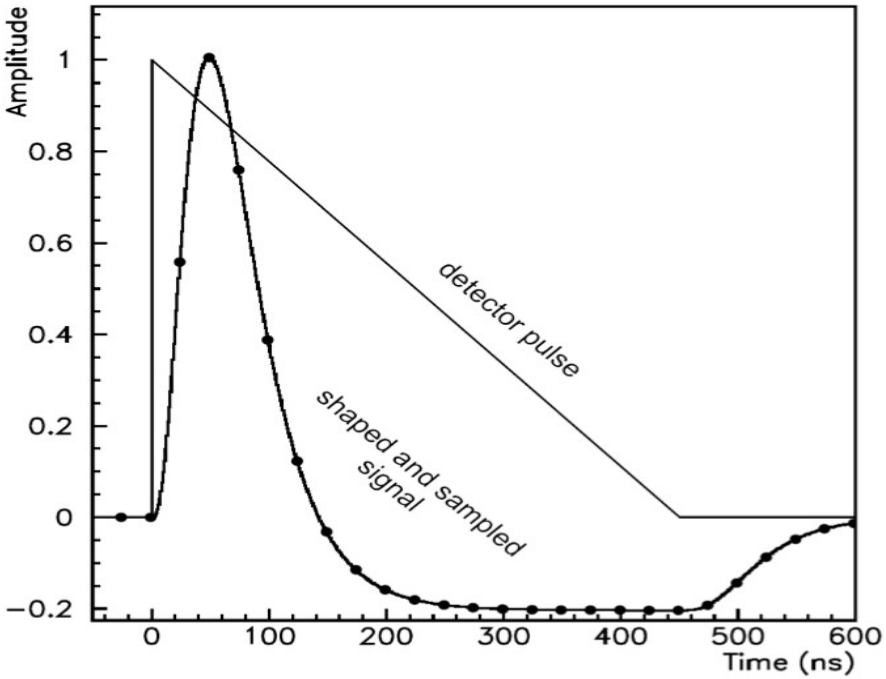


- LHC: more then 1 interaction per bunch crossing needed to find new physics
- Material interactions should be independent for every, response of electronics not
- Overlay of additional events in the same bunch crossing with correct beam profile and number of events at begin of digitization
- Cavern background

Detector/Electronic response: Time dependence

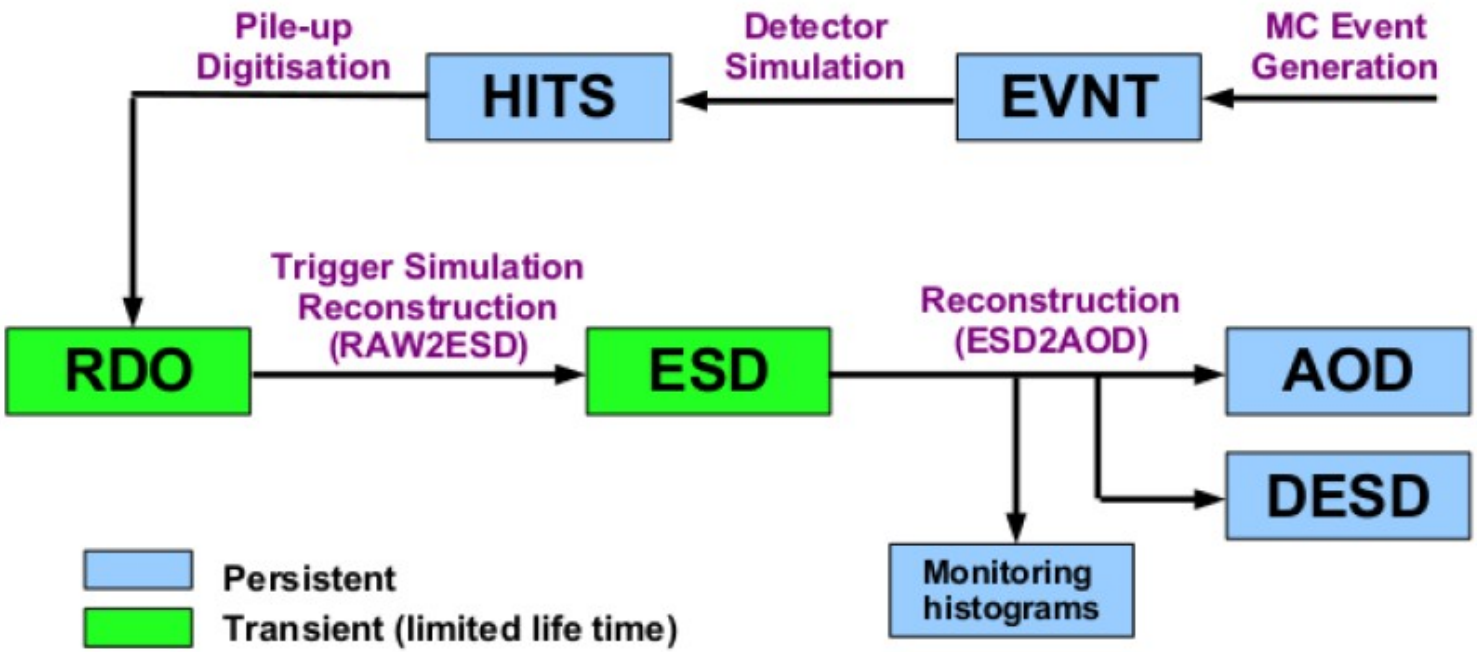
- LHC: Pile-up, overlay of ~20-40 events in time
- LHC bunch clock: 25ns
- Signal of the electromagnetic calorimeter is slow: Drift of electrons needs ~450ns
  - needs to superimpose ~20 interactions before and ~5 after the interesting physics event
- Needs to overlay ~20-40 interactions in ~20 bunch crossings at different time





Simulation framework

- Chain of jobs which do the different steps:
  - Generation
  - Simulation
  - Digitization
  - Reconstruction

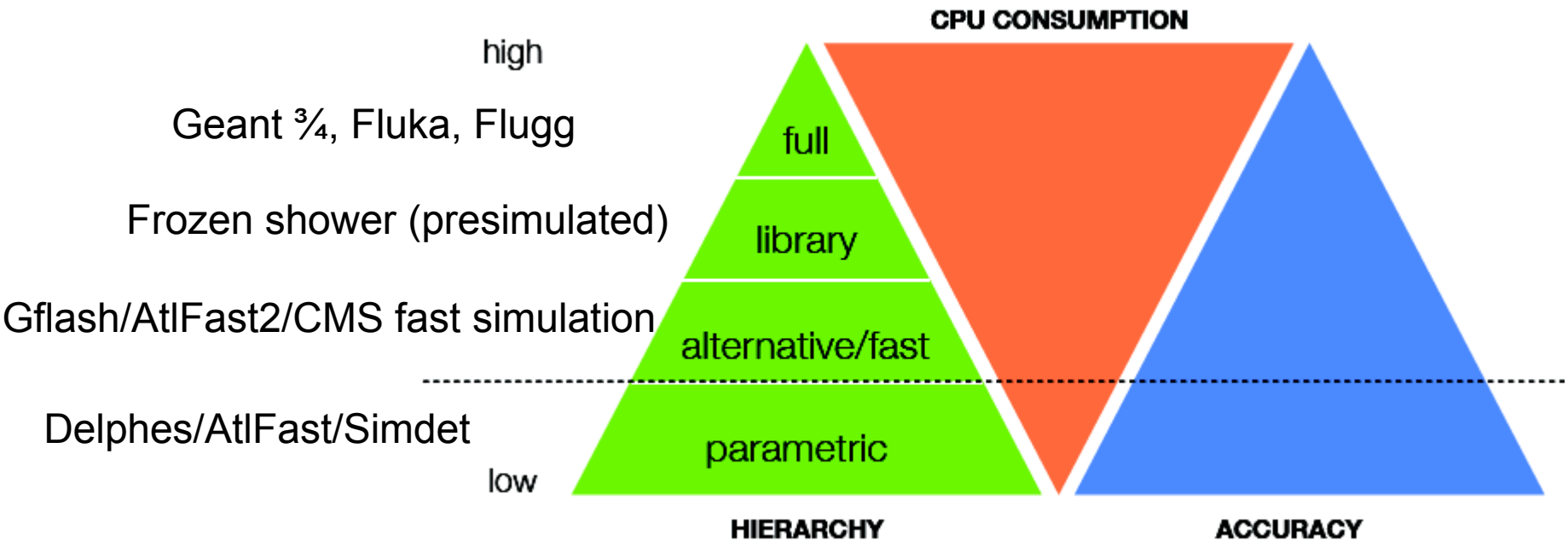


Simulation framework

- Time consumption of the steps are very different:
  - Generation: 1 second to days for O(1000) events
  - Simulation: Geant~10 Minutes/event (Atlas)
  - Digitization: O(seconds)/events
  - Reconstruction: O (few Minutes)/events (high pile up)
- Grid: Distributed Computing:
  - Needs to distribute jobs through the world
  - Collect jobs at the end for next step/combining a data set
  - Split and merge: Many jobs for slow steps, a few for fast steps
  - Tails in computing (crushes, side down time): first Simulation job could/should run before last generation job is finished, skipping of few crushing jobs
- Data bases for files, condition/calibration

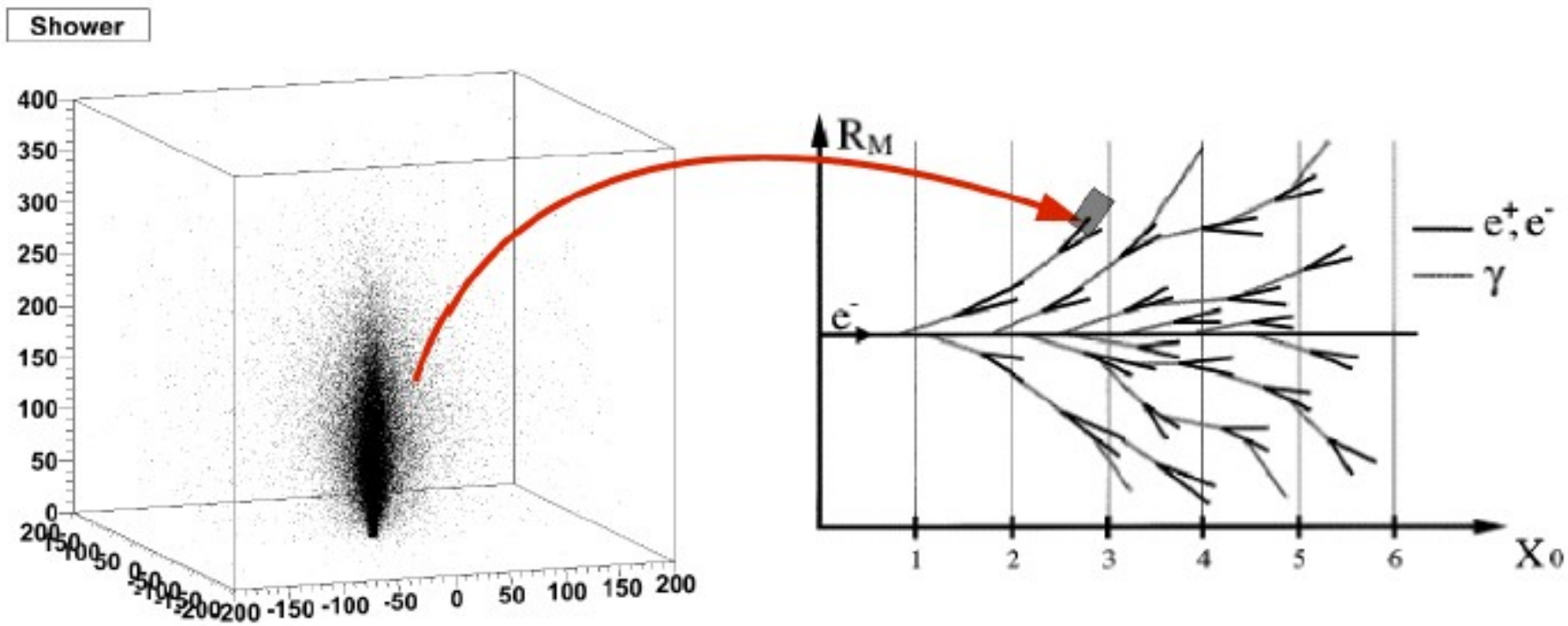
Fast Simulation: How to do?

- New physics processes are rare
  - Specially simulation of background needs huge number of events (few selected events out of millions)
  - Exchanging accuracy with CPU consumption:
    - full simulation: very accurate, several minutes per event
    - fast parametric truth smearing, 1/10 seconds per event



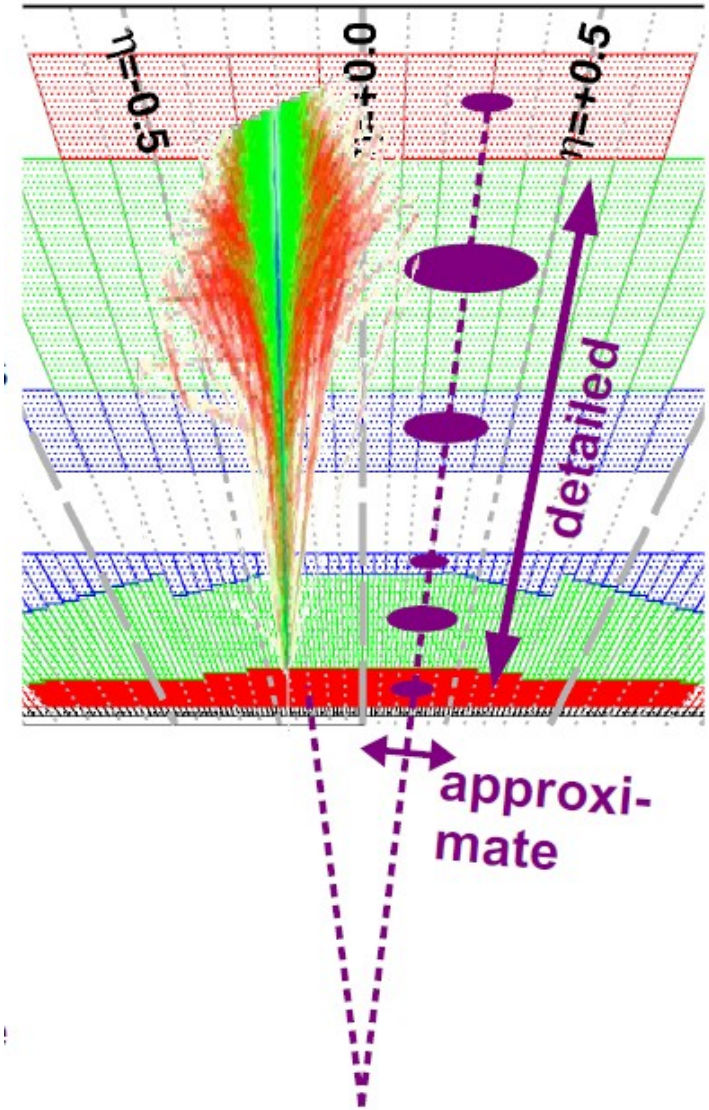
Fast Simulation: A few examples

- Frozen shower: Electromagnetic shower are homogeneous (vs hadronic shower)
  - Simulate only high energetic part with G4
  - use shower library (pre-simulated shower) below a cut off



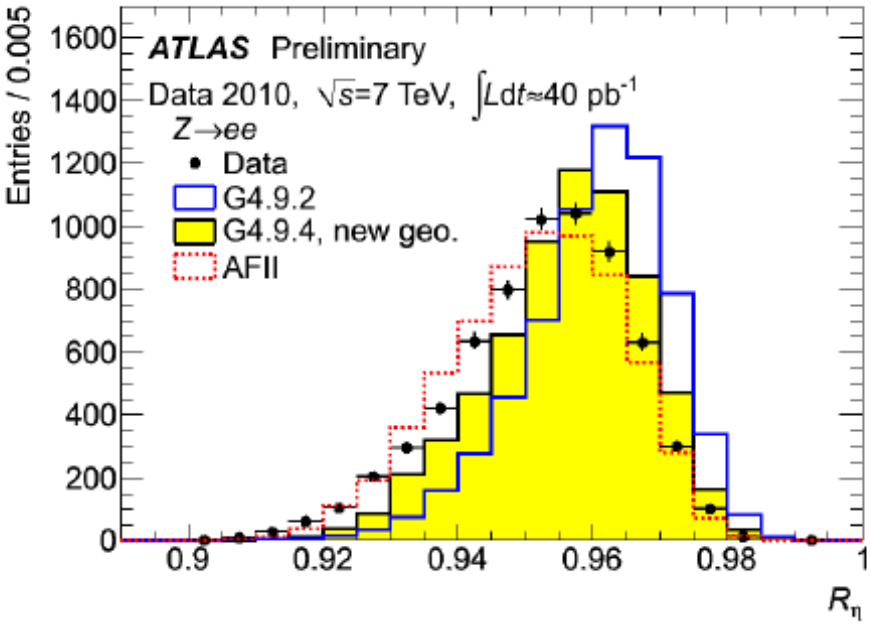
Fast Simulation: Parametric Simulation

- Atlas parametric simulation:
  - Deposit energy in different calorimeter layers using parametrisation for electrons and pions taken from MC or data



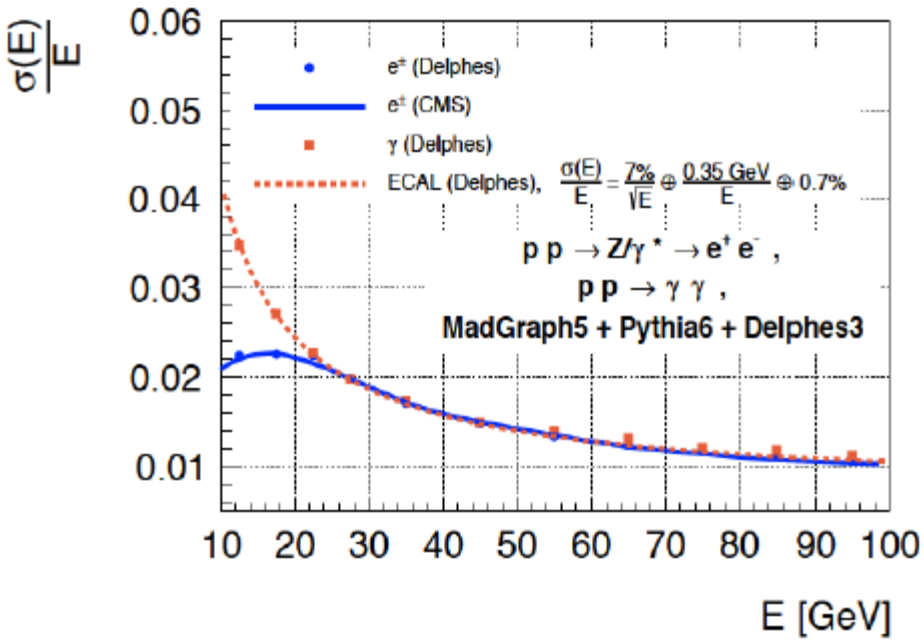
Fast Simulation: Always worse then full?

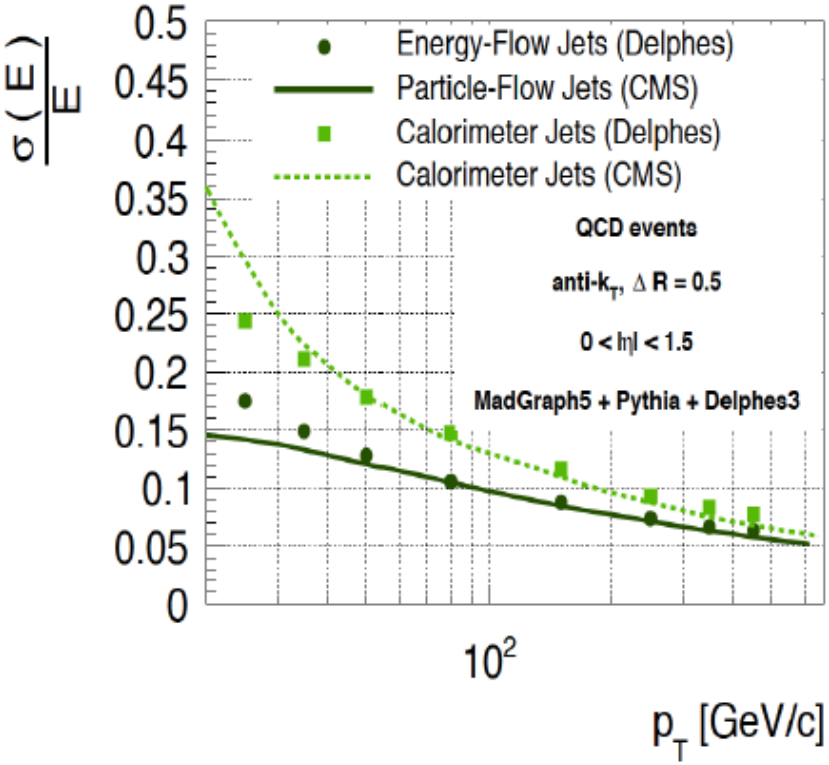
- A data driven parametrisation in complicated situation can be closer to data then full simulation:
  - Full simulation depends heavily on input:
    - good material description
    - physics lists (→ lesson 3)
  - Fast simulation can use data to optimize performance
    - isolated objects are described very well
    - limitation at overlapping structures (granularity, response)
    - limitation in tail description (hadronic showers)



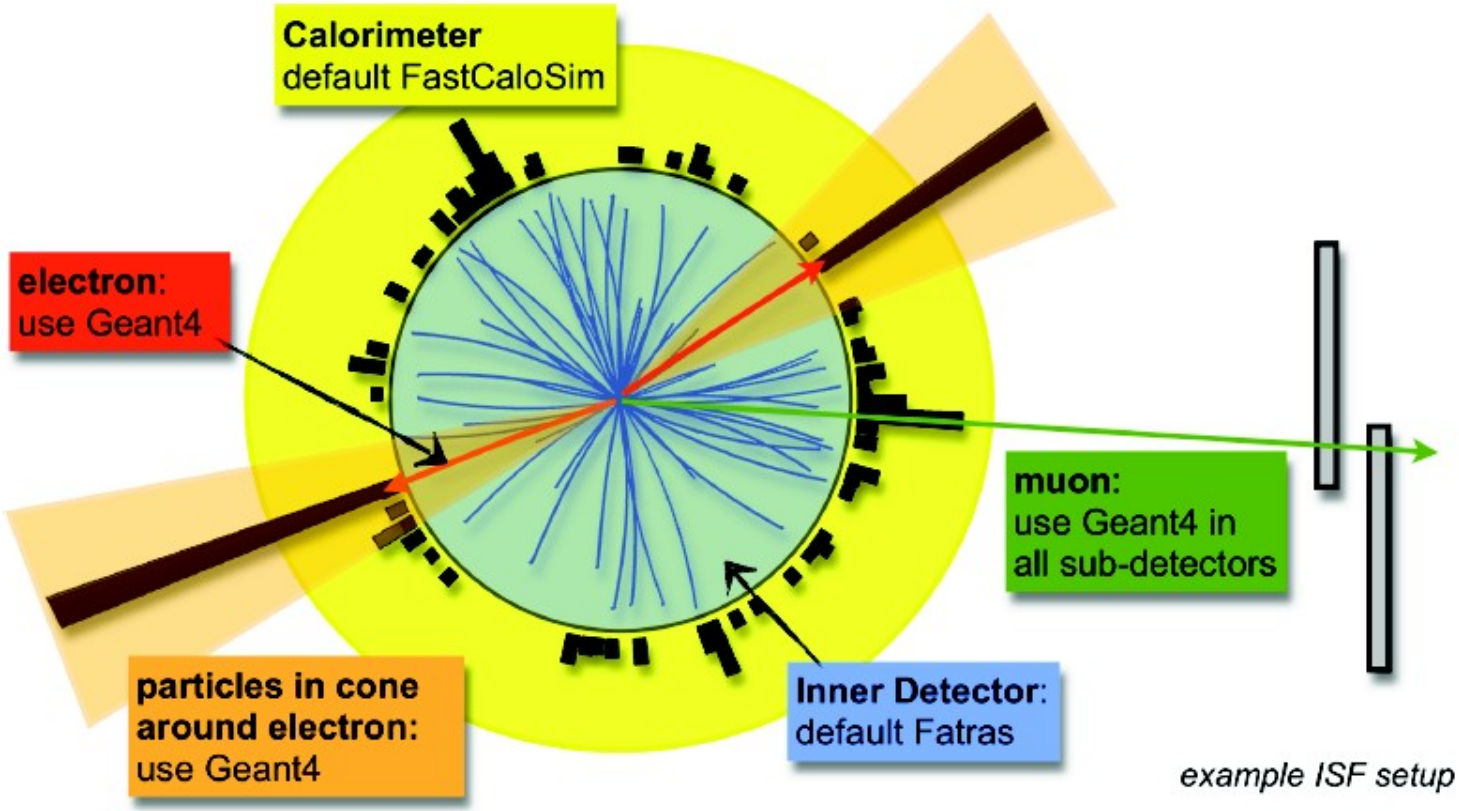
Fast Simulation: Truth track smearing/merging

- Delphes:
  - Smearing and merging from truth particles using a simplified but realistic detector geometry (incl. fake reconstruction)
  - Very good agreement for isolated particles, challenging are complex objects
  - Used for CMS upgrade simulatio





Mixed Simulation



- Simulate full were you need accuracy ($H \rightarrow \gamma\gamma$ the two photons or particles in a cone around the photons)
- Simulate fast the rest of the events

Summary

- Overview over Event Simulation:
  - Event Generation (Input)
  - Detector Simulation
    - Interacting of particles with material
    - Simulation of amplification/electronics
    - Importance of accurate material description
  - Computing:
    - Complex: job submission system
    - Many steps
- Search for new physics rare processes → fast simulation
  - Every simulation is a combination of full and fast components