CMS Detector Simulation

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JTerm III, Fermilab
January 13, 2009

Introduction

Monte Carlo samples in CMS are (will be) used to

- ❑ Develop reconstruction algorithms and trigger logics
- ❑ Generate large amounts of signal and background events for use in physics analysis.
- ❑ Understand/Demonstrate analysis procedures and methods based on data to derive calibrations, efficiencies, resolutions for high level physics objects.
- ❑ Directly derive calibrations, efficiencies, resolutions for high level objects in cases where data are biased or not available.

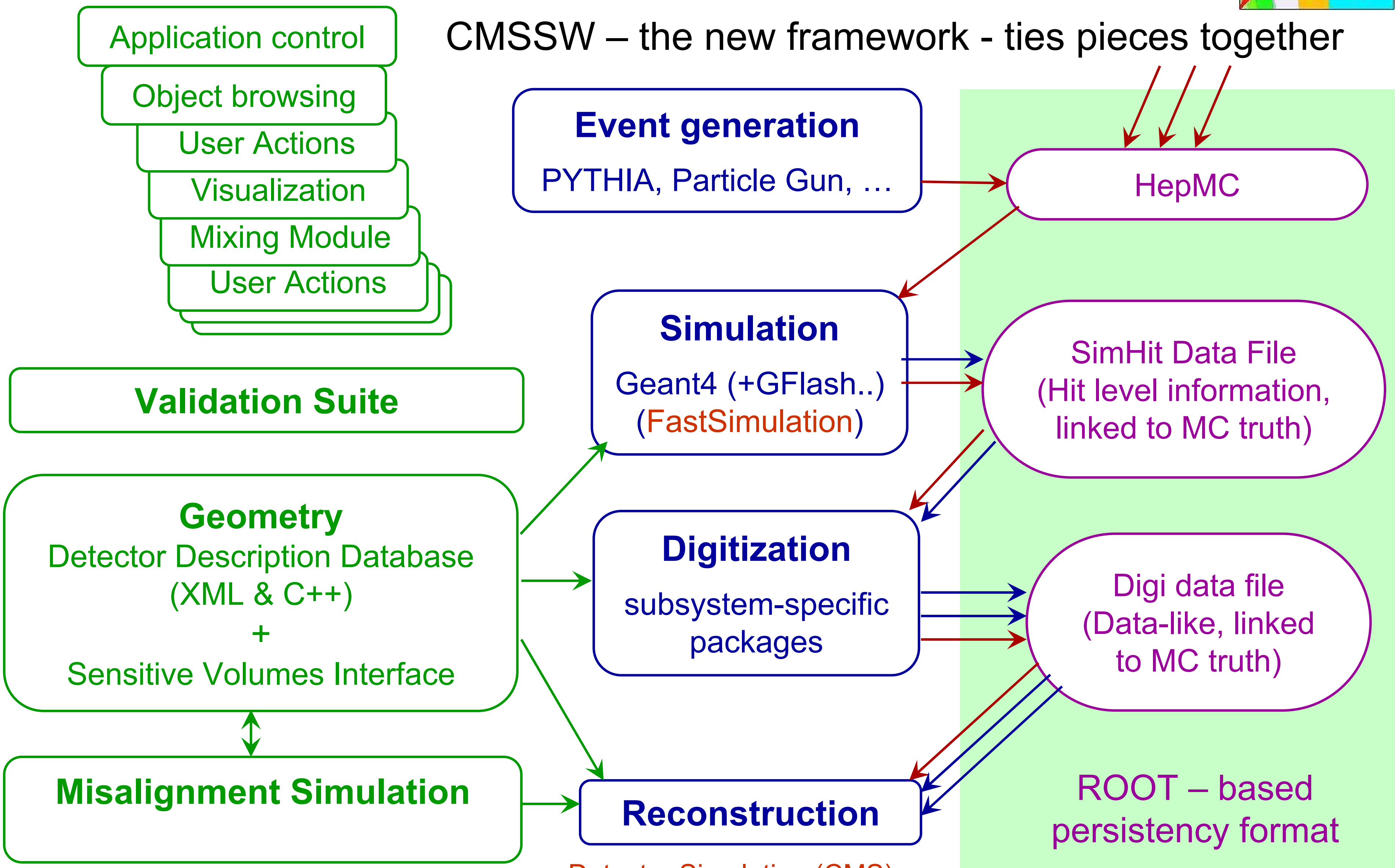
A data driven, realistic/accurate Monte Carlo, is an essential tool.

- ❖ Simulation effort started in CMS using GEANT3 more than a decade ago
- ❖ Evolved to the current design through several generations
- ❖ Two complementary approaches are available
  - ❖ Start from first principles (Full Simulation)
  - ❖ Use a fast parameterization (Fast Simulation)

Full Simulation

- Though in operation for a number of years, it's a live system – goals, requirements, tools evolve throughout the lifetime of the experiment
- Based on Geant4 (9.1.p02; in transition to 9.2):
  - Physics processes: electro-magnetic and hadronic interactions
  - tools for detector geometry and sensitive element response
  - interfaces for tuning and monitoring particle tracking
- + CMS offline framework and Event Data Model:
  - Manages application control at run time
  - Relies on the concept of event processing module (EDProducer)
  - Interface to common tools (generators, magnetic field, MC truth handling, infrastructure for hits, event mixing, digitization, …)
  - Ensures provenance tracking and event immutability

Simulation Software – CMS Solution

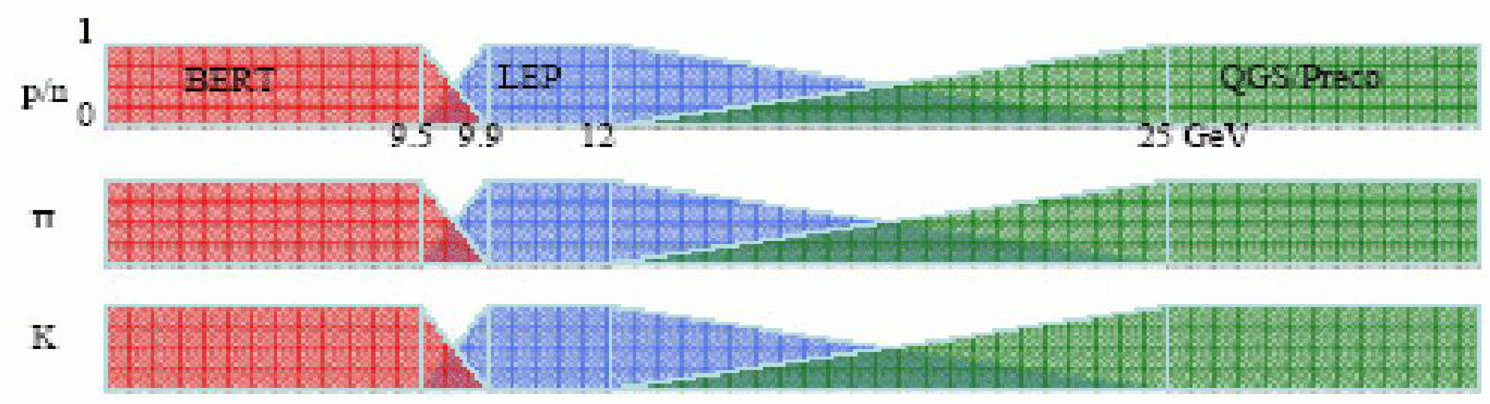


Interface to Geant4 (I)

- Core application = framework-based Event Data Producer with a customized interface between Geant4 and CMS Event Data Model
- Geometry is available to either simulation or reconstruction via the framework EventSetup;
  - uses XML-based Detector Description machinery, configurable at run time via a hierarchy of XML files; converts DD solids and materials to Geant4 counterparts
- Sensitive detectors associated with geometrical volumes through XML configuration files at run time
- Magnetic field based on dedicated geometry of magnetic volumes; provided by independent subsystem via EventSetup; field selection, propagation tuning configurable at run time

Interface to Geant4 (II)

- Variety of lists (LHEP, QGSP_BERT/QGSP_BERT_EMV, QGSP/QGSP_EMV, QGSC, FTFP,…) for modeling physics processes; run-time selection of physics list and production cuts, activation/tailoring of individual processes;
- Variety of Physics event generators (particle guns, Pythia, Herwig,…); generator information stored in HepMC format and interfaced to G4Event
- User actions allow access to Geant4 objects at any stage (run, event, track, step); used for tuning, diagnostics, custom bookkeeping
- Monte Carlo truth record with decay/interaction history of the generator's particles and selected tracks from Geant4 simulation



Event Mixing and Digitization

- In-time pileup :

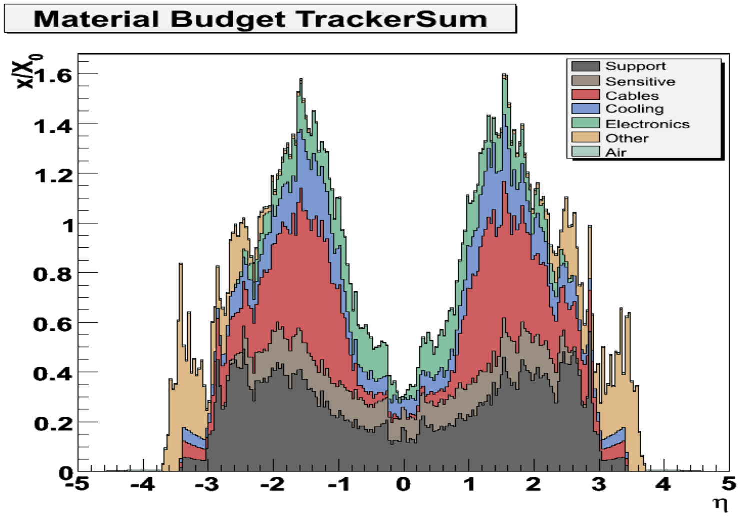
  LHC will produce ~3 (“low lum.”) or ~25 (“high lum.”) minimum bias interactions/crossing, on top of the trigger event
- Out-of-time pileup:

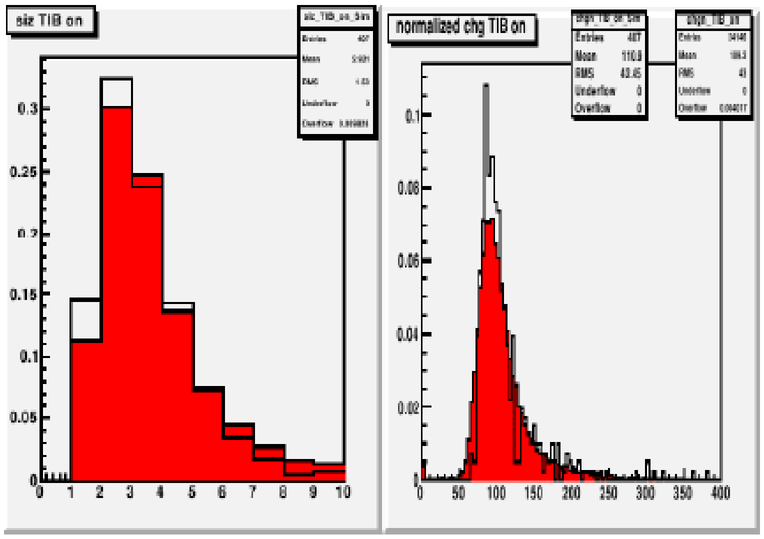
  Coming from bunch crossings before/after the trigger event
- Pileup events simulated separately from the physics events; merge of simulation outputs at hit level (reuse)
- Performed by a dedicated module, in a separate step
- Followed by simulation of the electronic readouts (Digi’s)
- Dedicated Digi module for each subsystem (separate steps)

Provide real data overlap tool for realistic pileup

Tracker

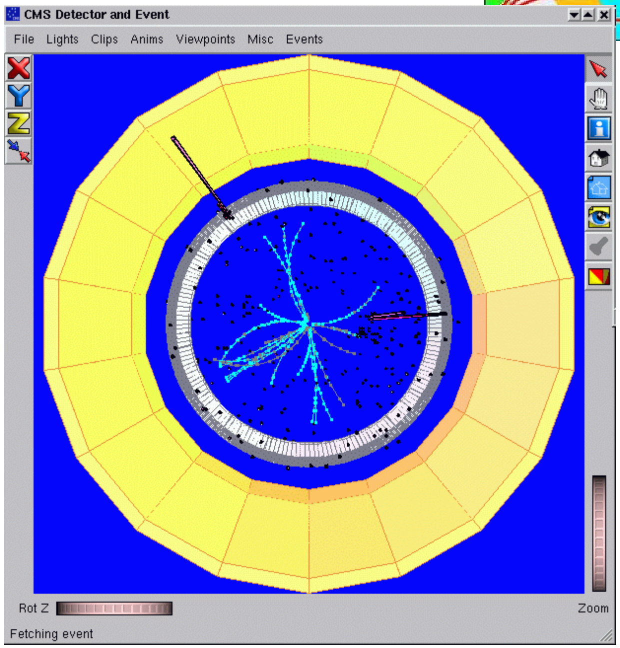
- Demands a high degree of accuracy:
  - Description of active and passive components
    - Review each component with full information from integration centres
    - Verify by weighing individual components
  - Correct, navigable Monte Carlo truth
  - Proper treatment of hard electron bremsstrahlung
- Extensively validated in terms of signal simulation, tracking, dE/dx, …

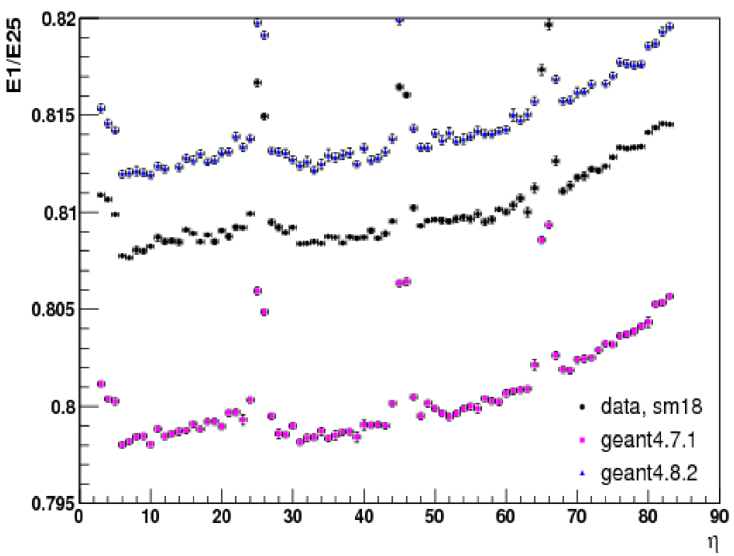




Electromagnetic Calorimeter

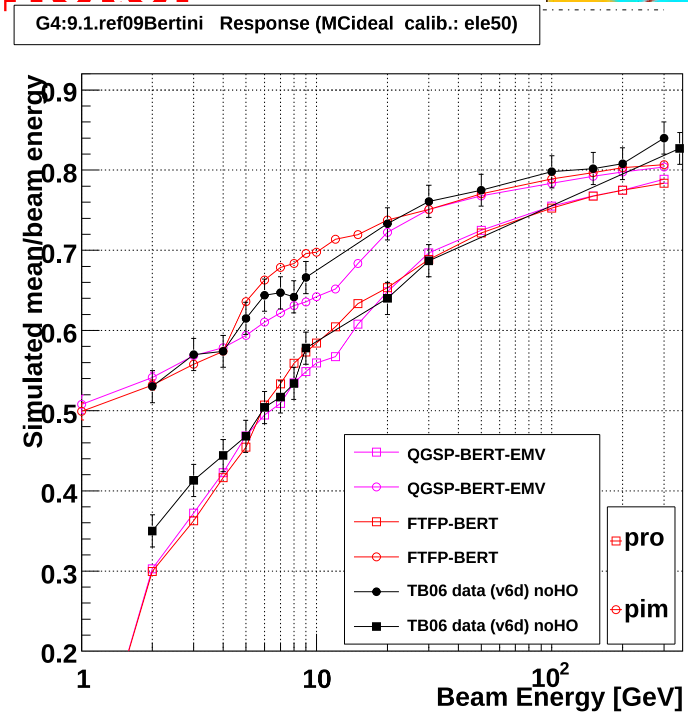
- Accurate description of geometry and material budget
  - Independent alignment of modules, super-crystals, wafers, …
  - Updated distribution of support, cooling, readout
- Good/complete implementation of physics process
  - Transverse shower profile (containment, calibrations)
  - Longitudinal shower profile (leakage, …)
- Validated extensively with test beam for energy measurement and transverse shower profiles

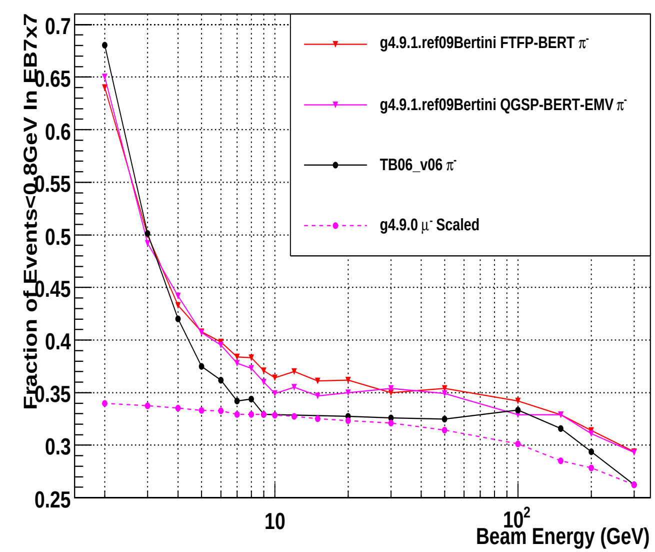




Hadron Calorimeter

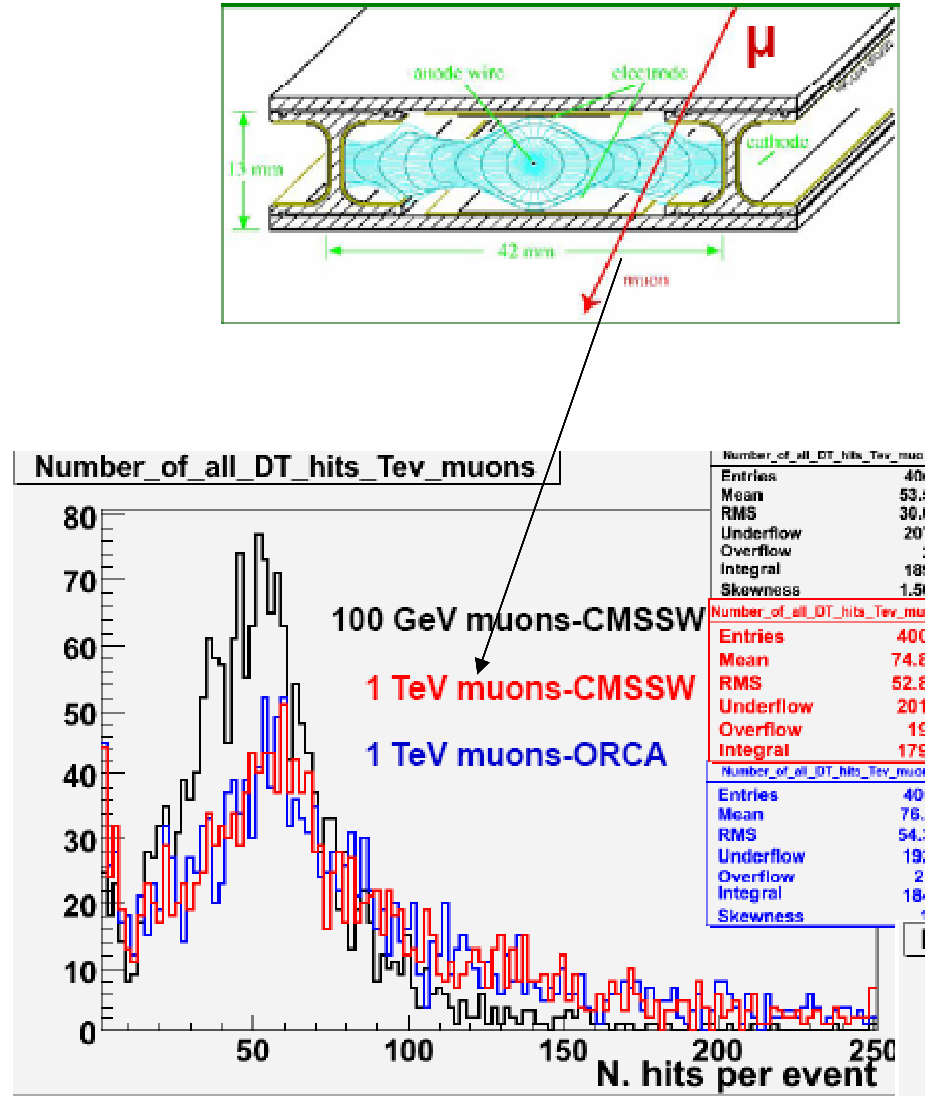
- Comparisons between single particle measurements in test beam: 2002-2007, with different HCAL modules, preceded by real ECAL super-module or prototype, to beams of π, e and μ over large energy range
- HCAL studies on energy resolution and linearity, e/π ratio, and shower profile instrumental in validating G4 hadronic physics models [parametric (LHEP) and microscopic (QGSP, QGSP_BERT,…)]
- Faithful description of timings, noise,
- Use of shower libraries, noise libraries, …





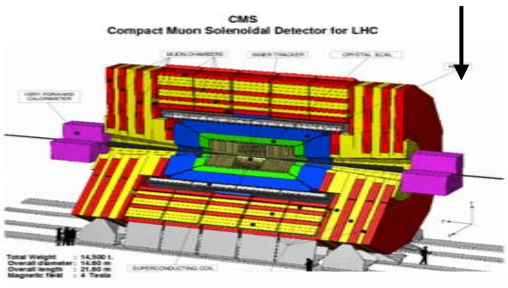
Muon System

- Geometry description verified using the Cosmic data collected during MTCC, CRAFT, …
- Muon physics in G4 is extensively tested and validated in the energy range 10 GeV – 10 TeV
  - Improved description of μ bremsstrahlung, μ-nuclear effects, ..
  - Better description of multiple scattering (in agreement of data)
- Validate new descriptions with earlier simulation and with test data



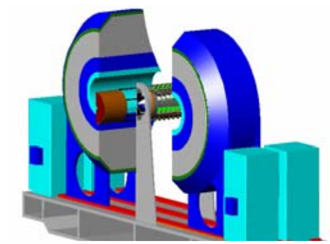
Forward Detectors

HF
$(3 \le |\eta| \le 5.2)$



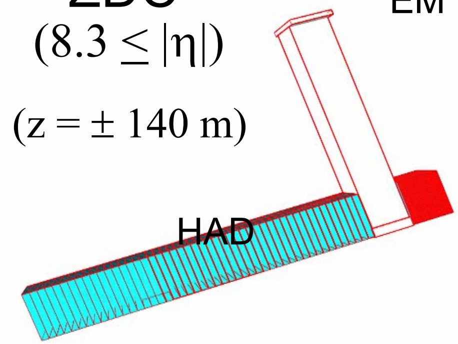
T1,T2
$(5.2 \le \eta \le 6.7)$

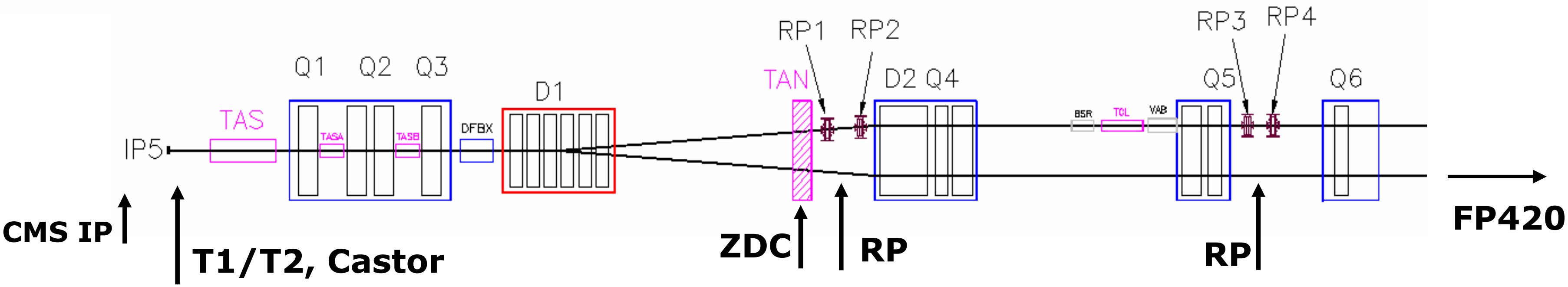
$(z = \pm 7.5, \pm 14.5$ m)



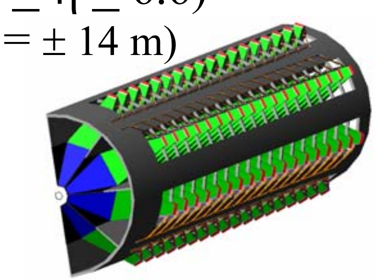
ZDC
$(8.3 \le |\eta|)$

$(z = \pm 140$ m)

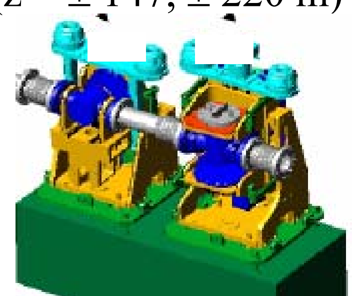




CASTOR
$(5.2 \le \eta \le 6.6)$
$(z = \pm 14$ m)

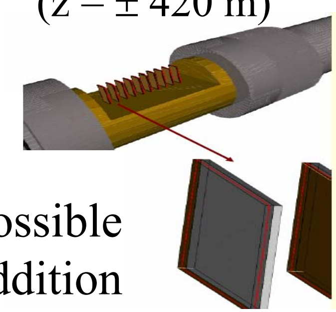


Roman Pots
$(z = \pm 147, \pm 220$ m)



Detector Simulation (CMS)

FP420
$(z = \pm 420$ m)



possible addition

Forward Detector Simulation

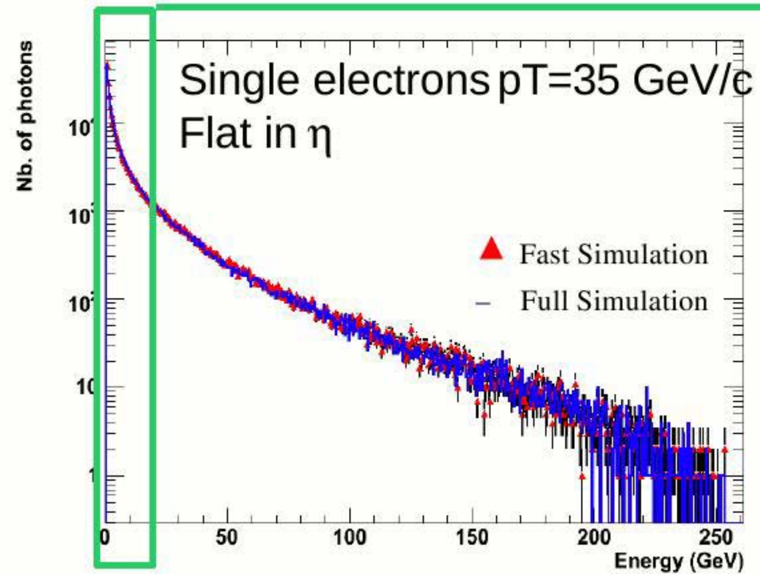
- Essential for diffractive and heavy ion programs
- Simulation of stand alone systems has been compared with test beam studies regarding energy resolution, leakage, …
- Simulation with central as well as forward detectors is foreseen:
  – Use filter to separate particles from event generators to be processed through central and forward detectors
  – Use a separate transport code Hector to transport particles within acceptance of forward detectors close to forward detectors
  – Also obtain beam interactions from a library obtained using MARS
  – Transport the particles in the central detector and also in the forward detector region using G4
  – Combine all the simulated hits to get the overall event

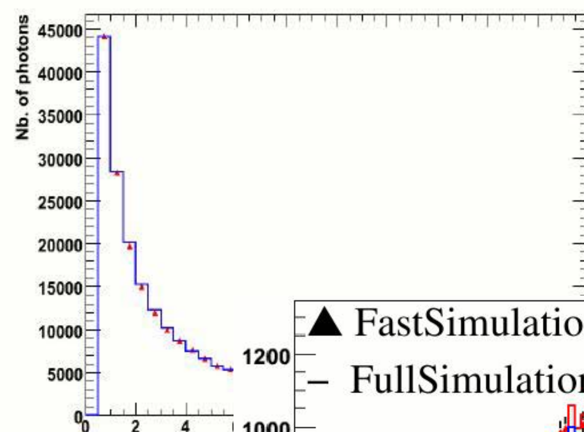
Fast Simulation

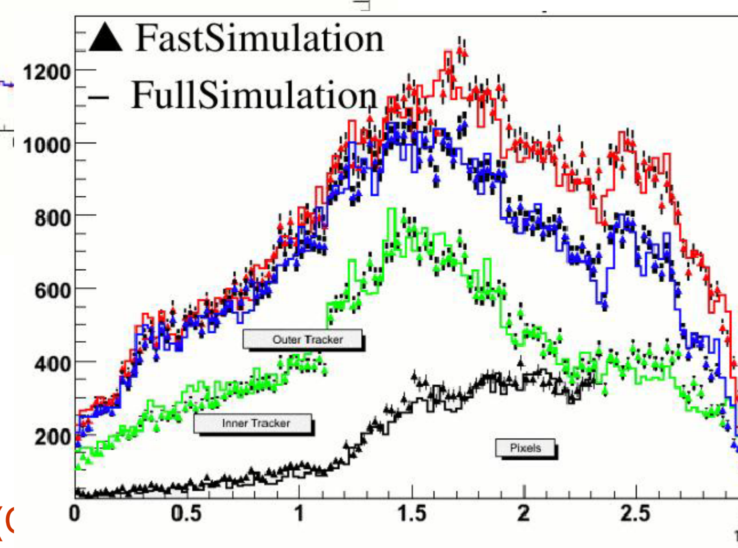
- Goal is to achieve the highest possible speed (possibly 1000 times faster than FullSim) without sacrificing much of the accuracy.
- Cannot use the same detailed description of the geomerty – use a simplified model. But keep some details to make a reasonable modeling of material effects
  - ~35% of electrons radiate more than 70% of their initial energy before reaching the ECAL
  - ~20% of pions undergo nuclear interaction in the tracker
- Use the same field map and magnetic field management as in the full simulation
- Incorporate the effect of bremsstrahlung, photon conversion, multiple scattering, nuclear interactions using analytical calculations or data files of nuclear interactions

Fast Simulation (Tracker)

- Layer thicknesses of active/passive material are tuned to reproduce the number of photons in full and fast simulation
- Map thickness in term of x/X_0 to λ/λ_0 to parameterize nuclear interactions

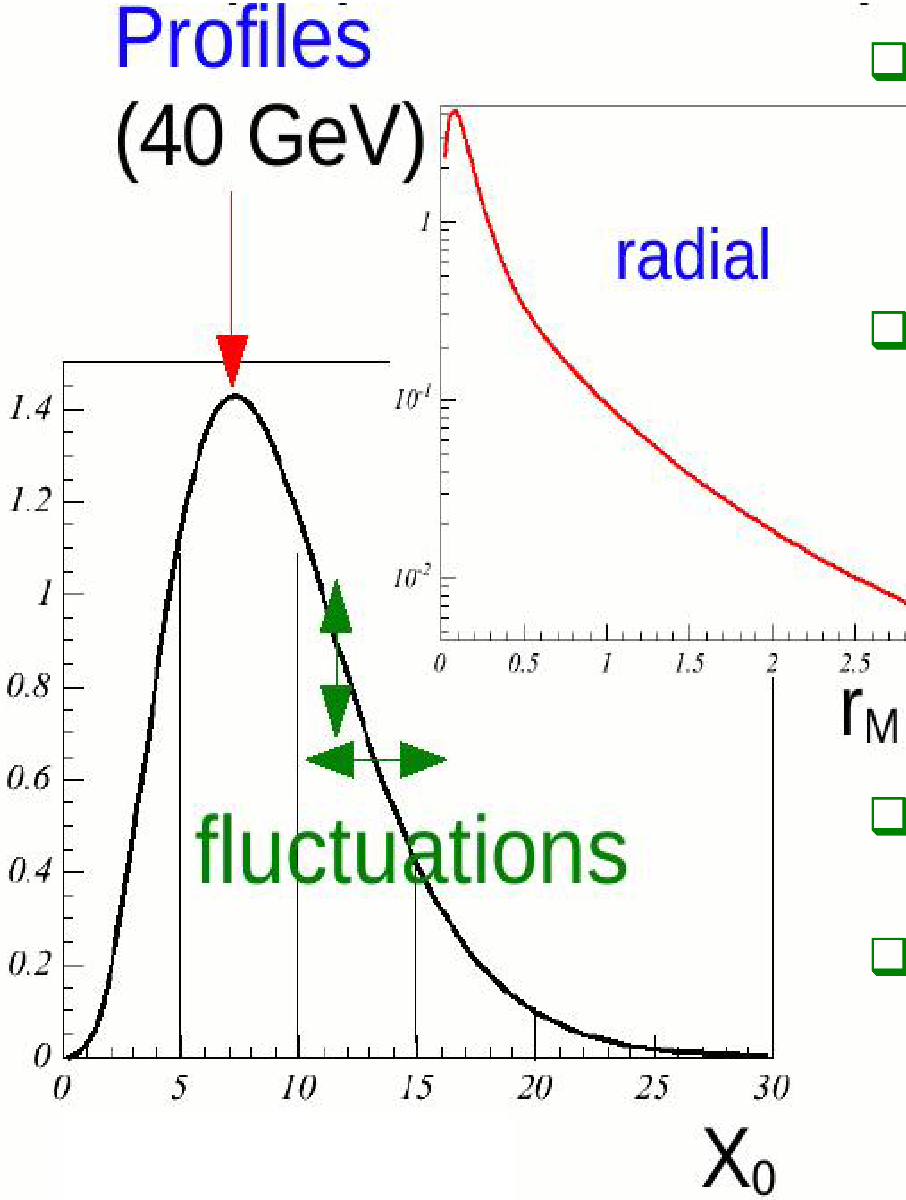






Number of interactions as well as secondary spectra are faithfully reproduced

Fast Simulation (Calorimeter)

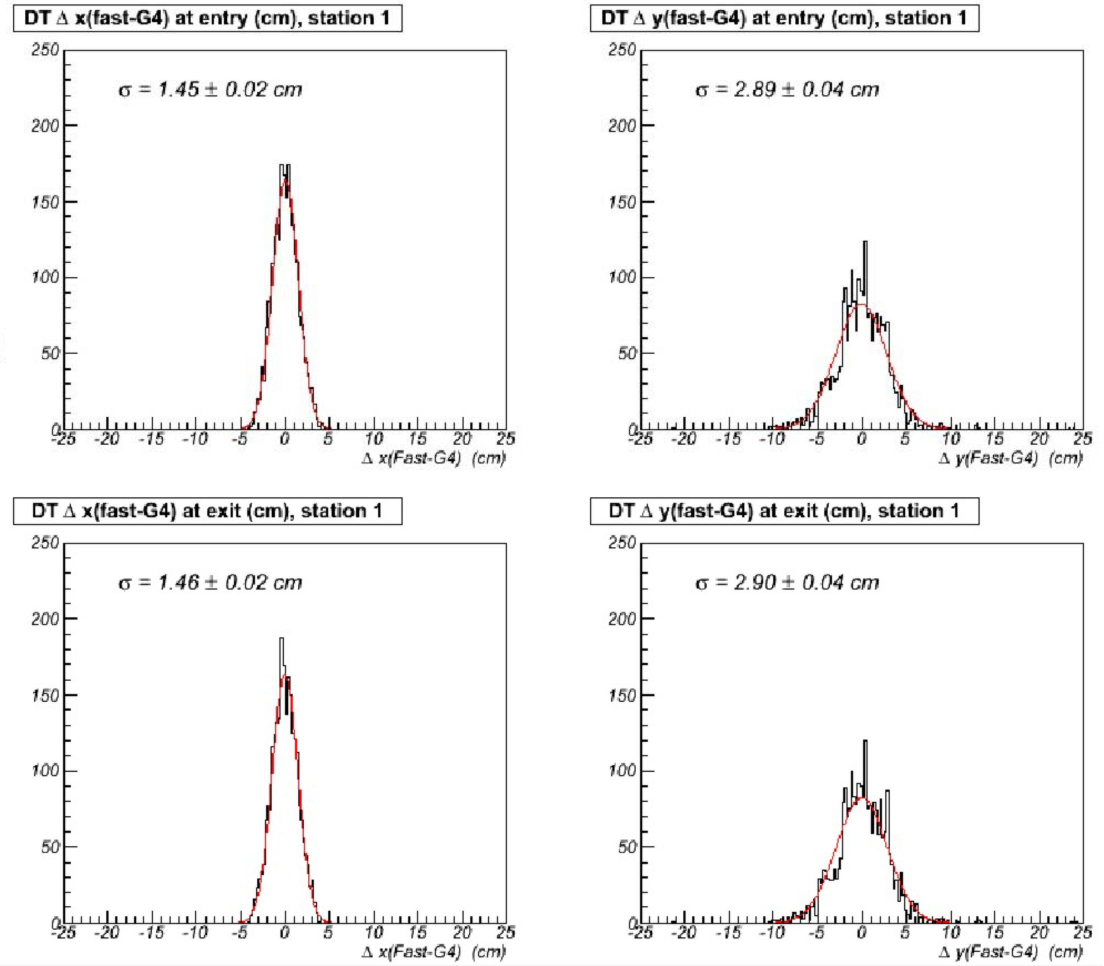


- Showers of all particles reaching the calorimeter are simulated individually using a shower parameterization following GFlash approach
- Each shower is made of a number (proportional to E) of spots distributed by shower profiles
  - Generate a longitudinal slice taking care of fluctuations
  - Distribute spots using lateral profile (uniform in φ)
- Exact parameterization depends on type of initial particle (EM/Hadron)
- Map the spots to the detailed geometry to take care of all geometric effects

ation (CMS)

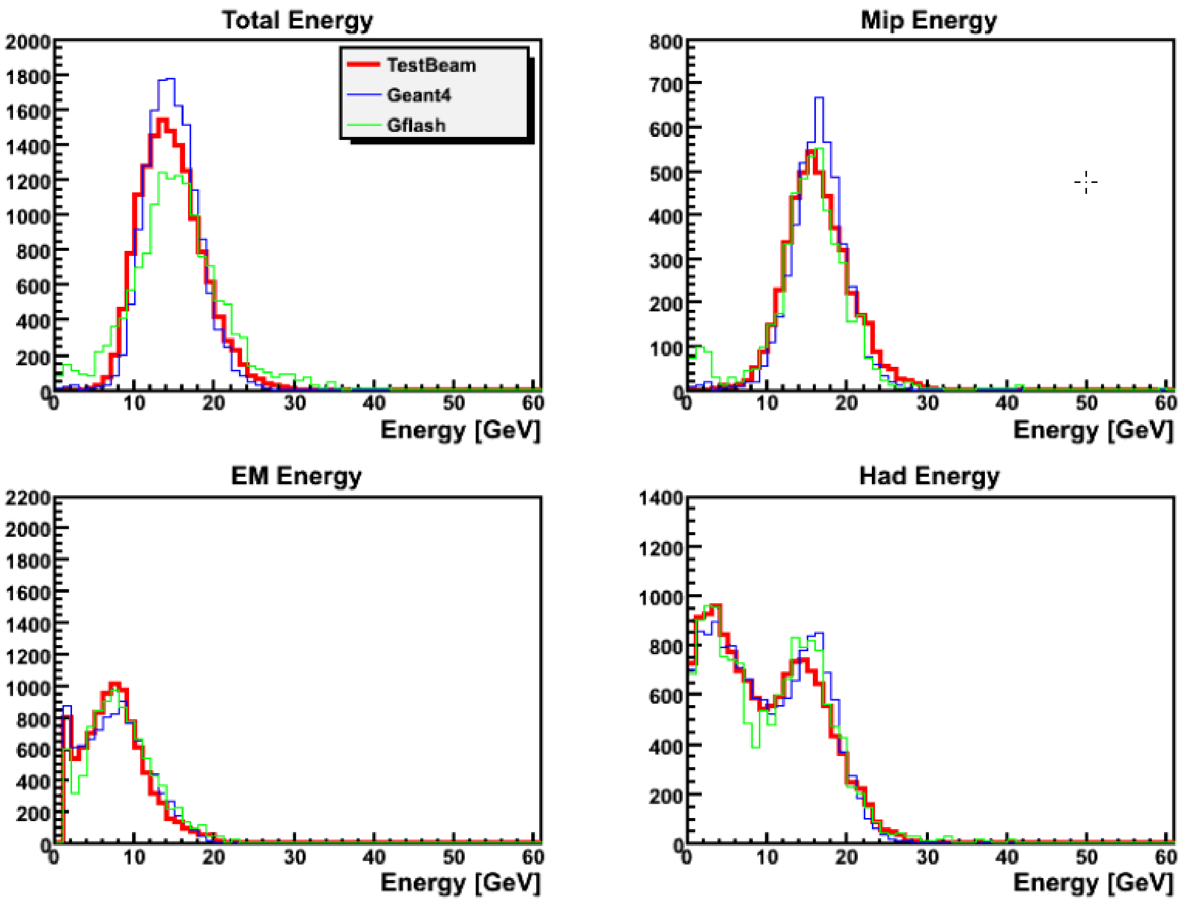
Fast Simulation (Muon)

- First approach was to smear generated particles according to tabulated efficiencies and resolutions
- Now simulation based on hits is available for muons with effects of multiple scattering in the iron yoke
- Many missing items
  - dE/dx smearing
  - Bremsstrahlung
  - Deposit in calorimeter
  - …..



GFlash in Full Simulation

- GFlash model is also used to parametrize EM and hadronic showers in the full simulation
- Use full particle tracking using Geant4 till the first interaction, then energy spots distribution according to a parameterized shower shape, taking into account also parameterized correlations/fluctuations



Tune to data

CPU time saver

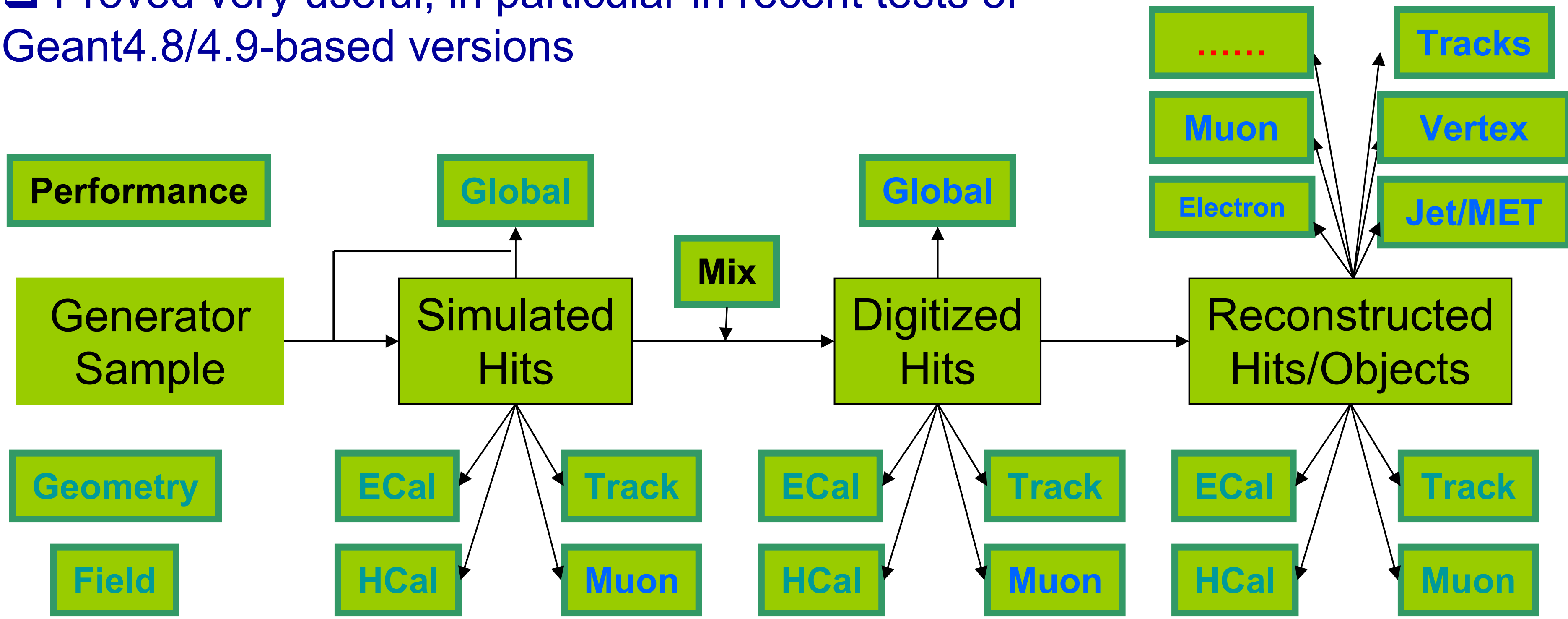
- ~ 10 at 10 GeV
- ~ 500 at 1 TeV

Software Validation

❑ Validation of physics processes modeling, via dedicated test beam setup simulation compared vs test beam data – feedback to Geant4

❑ Software Validation Suite, to ensure simulation (or other) software reliability, release-to-release, when changing Geant4 version, etc…

❑ Proved very useful, in particular in recent tests of Geant4.8/4.9-based versions

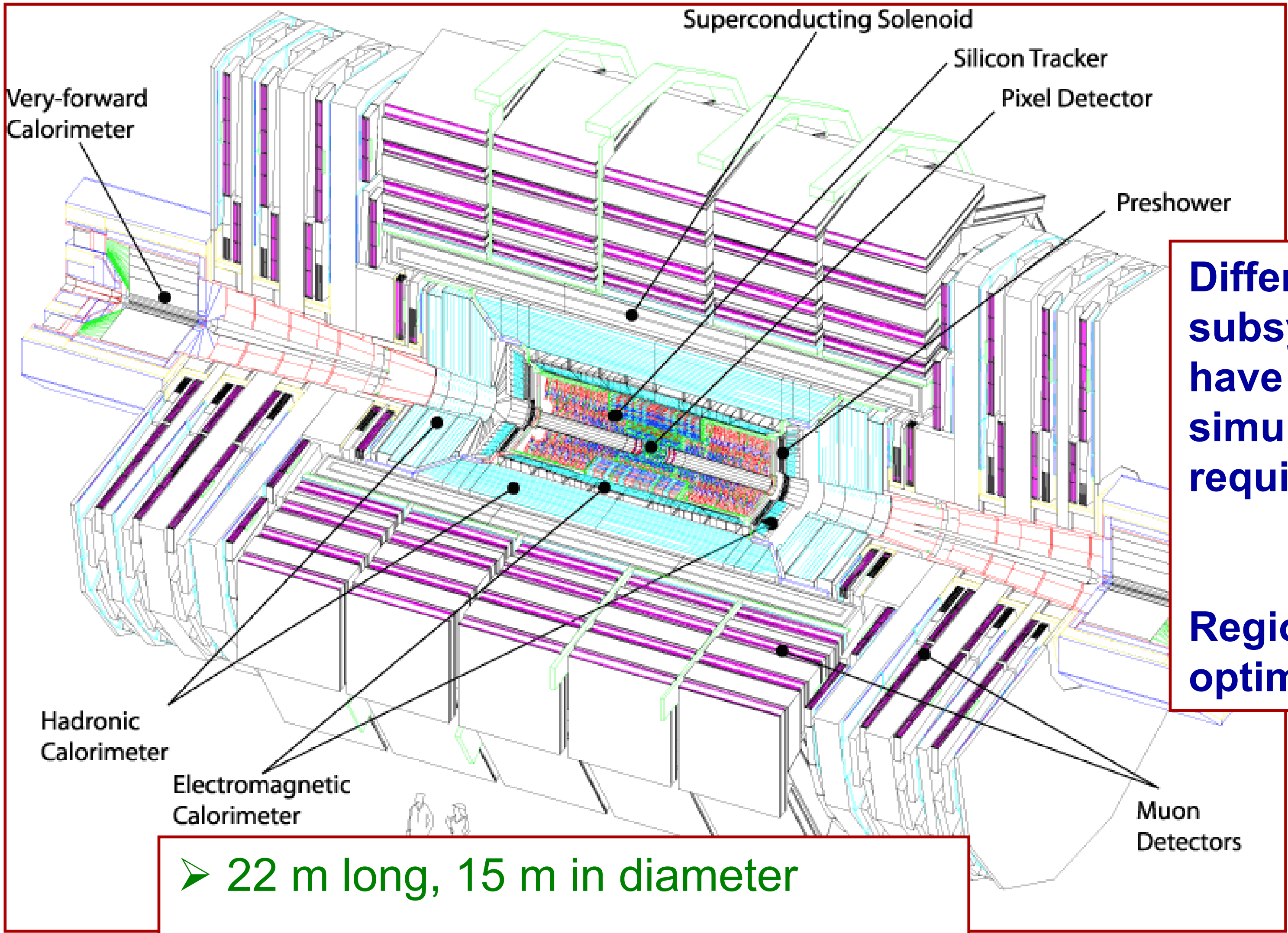


Summary

- CMS uses two different models for simulating detector response
- Simulation project is alive and is discussed in 4 forums: Full simulation, Fast simulation, CMS upgrade simulation, Calorimeter simulation task force
- Biggest challenge today is to tune simulation to data and make the necessary tools and also the strategy
- Data always tell us where we lack in understanding the detector (crucial for any discovery in LHC).
- There are many examples in the workbook to run simulation code.
- There are many missing holes and participation to fill these up is very much welcome. Many experts exist at LPC – please talk to them.

Backup Transparencies

The CMS Detector



Different subsystems have different simulation requirements

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Region based optimization

- 22 m long, 15 m in diameter
- Over a million geometrical volumes
- Many complex shapes