CMS Detector Simulation

Outline

- ❑ Introduction
- ❑ Full Simulation
- ❑ Fast Simulation
- ❑ Summary

Sunanda Banerjee

JTerm IV, Fermilab
August 5, 2009

Introduction

CMS has gone for a data driven, realistic/accurate Monte Carlo.

- 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)

Please visit the following sites for more information:

- https://twiki.cern.ch/twiki/bin/view/CMS/SWGuideSimulation
- https;//twiki.cern.ch/twiki/bin/view/CMS/SWGuideFastSimulation

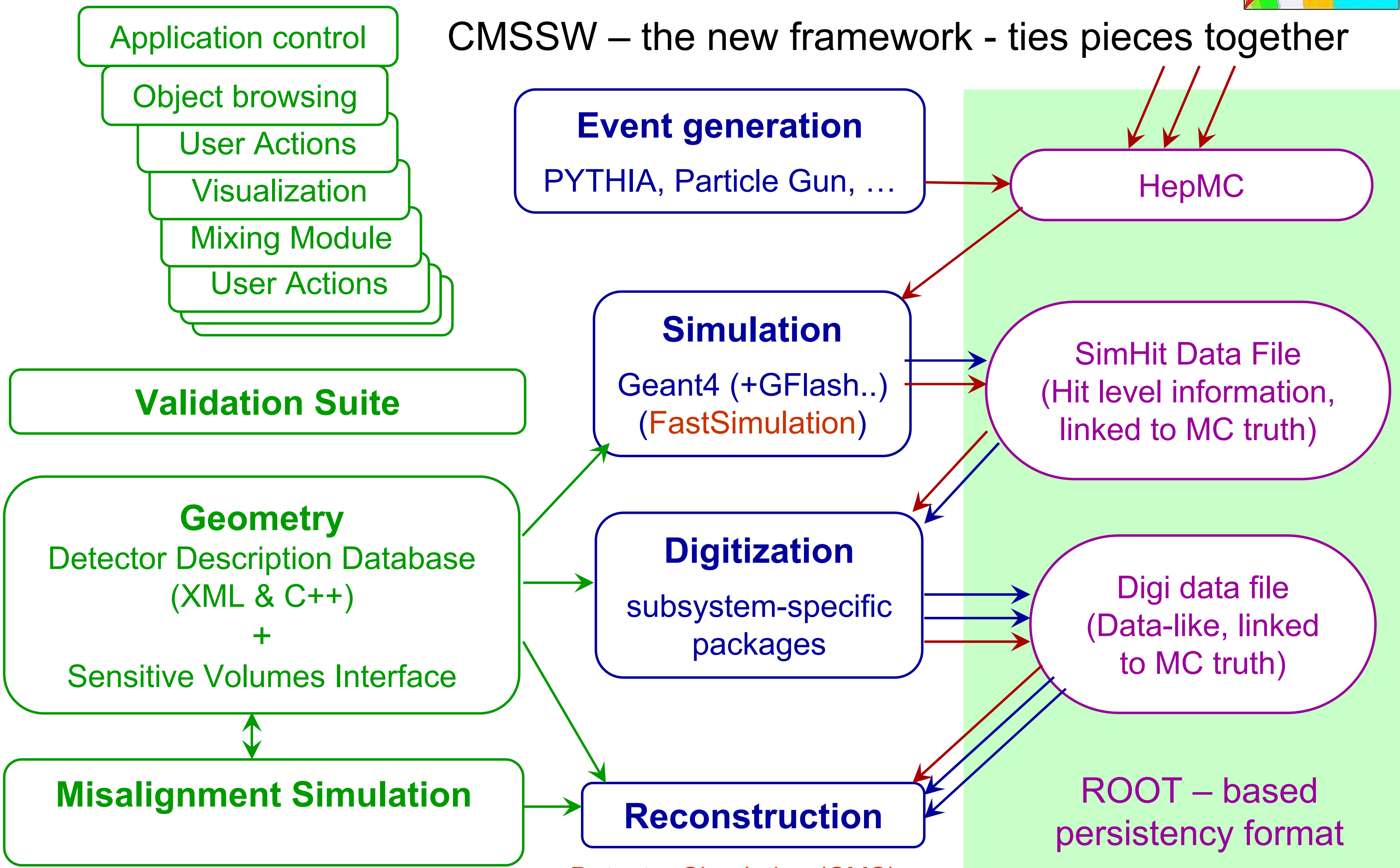
And also the work-book

- https;//twiki.cern.ch/twiki/bin/view/CMS/WorkBookGenIntro

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 (9.2.p01):
  - ❖ 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

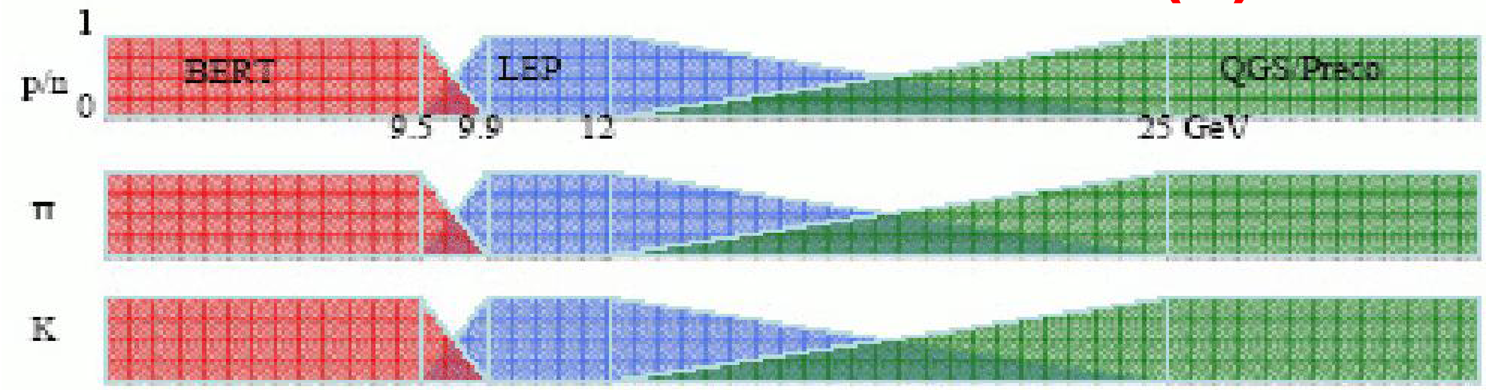
Simulation Software – CMS Solution



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:

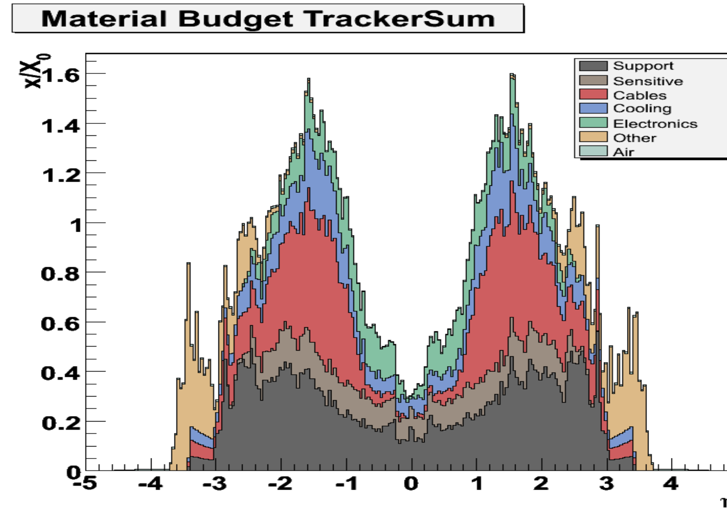
  Coming from bunch crossings before/after the trigger event
- Pileup events simulated separately from the physics events; merge of simulation outputs at hit level (reuse)
- Performed by a dedicated module, in a separate step
- Followed by simulation of the electronic readouts (Digi’s)
- Dedicated Digi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

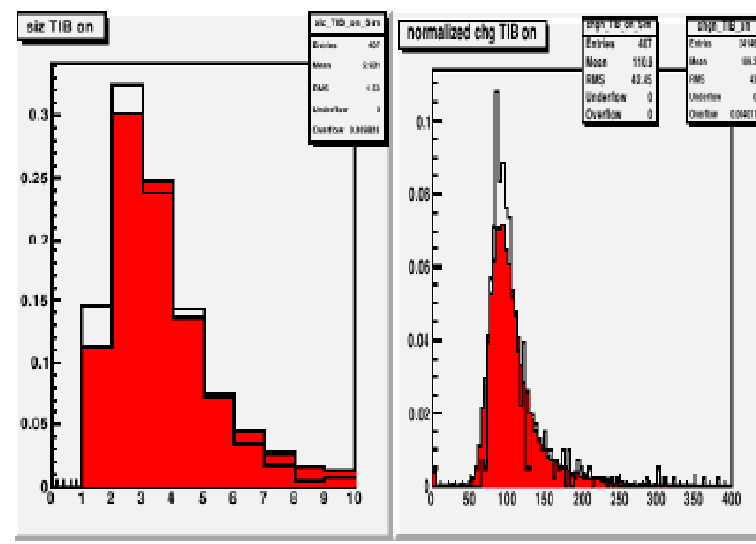
Workflow:

Generator → VertexSmear → Simulation → MixingModule → Digitization → L1Emulation → DigiToRaw

Tracker

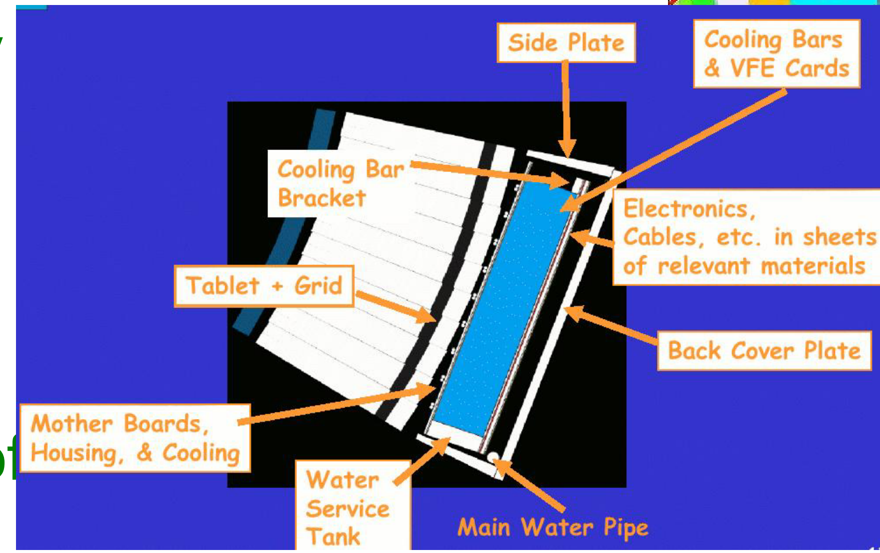
- ❑ Demands a high degree of accuracy:
  - – Description of active and passive components
    - ➢ Review each component with full information from integration centres
    - ➢ Verify by weighing individual components
  - – Correct, navigable Monte Carlo truth
  - – Proper treatment of hard electron bremsstrahlung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

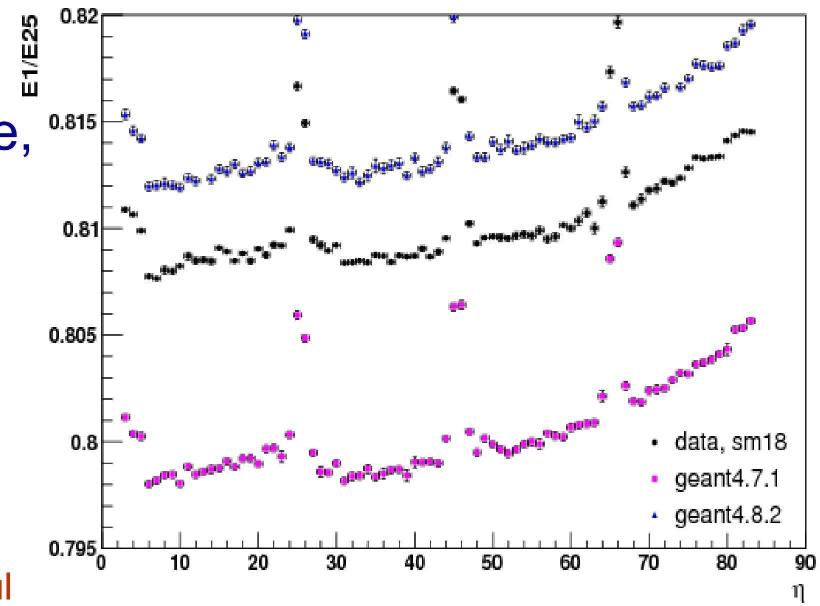




Electromagnetic Calorimeter

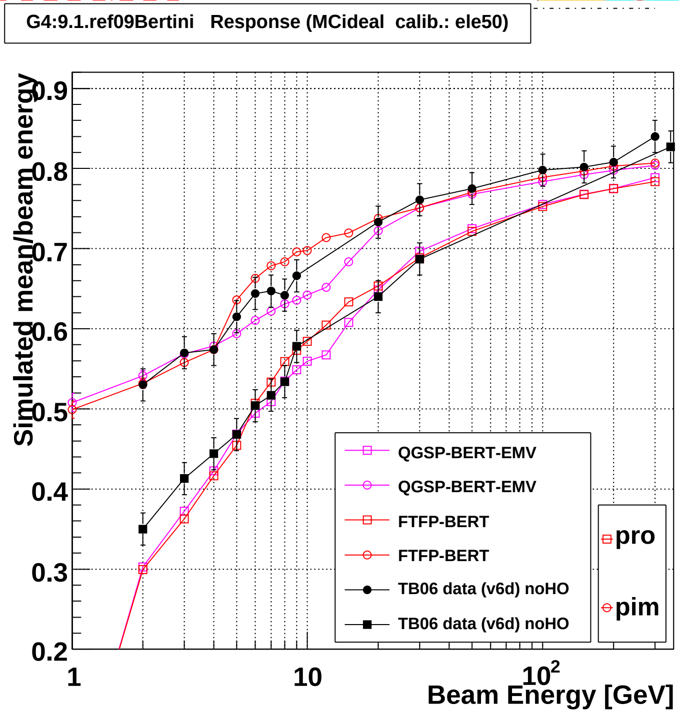
- Accurate description of geometry and material budget
  - Independent alignment of modules, super-crystals, wafers, …
  - Updated distribution of support, cooling, readout
- Good/complete implementation of physics process
  - Transverse shower profile (containment, calibrations)
  - Longitudinal shower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

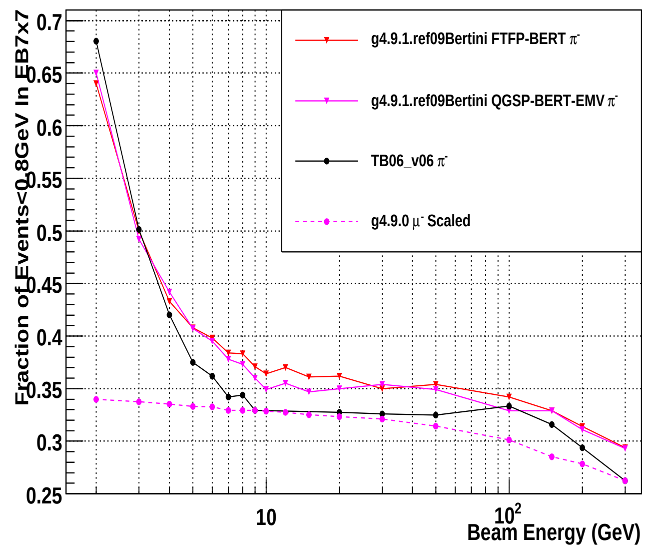




Hadron Calorimeter

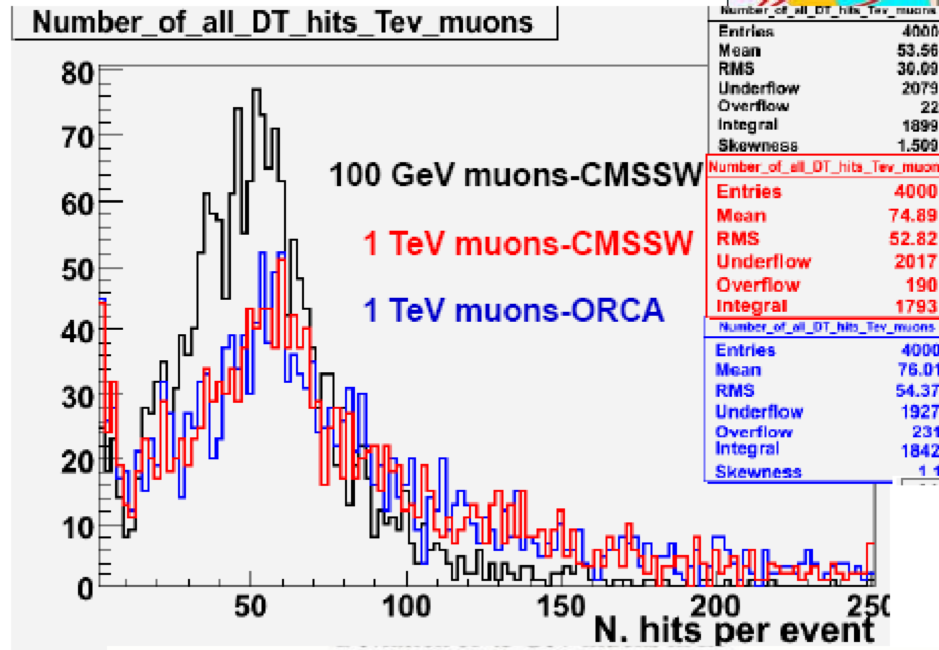
- Comparisons between single particle measurements in test beam: 2002-2007, with different HCAL modules, preceded by real ECAL super-module or prototype, to beams of π, e and μ over large energy range
- HCAL studies on energy resolution and linearity, e/π ratio, and shower profile instrumental in validating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

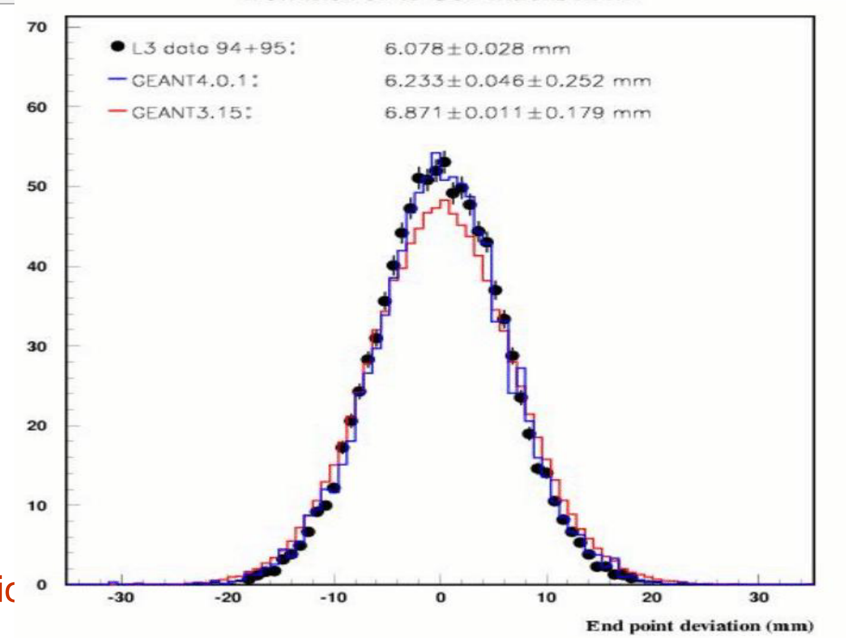




Muon System

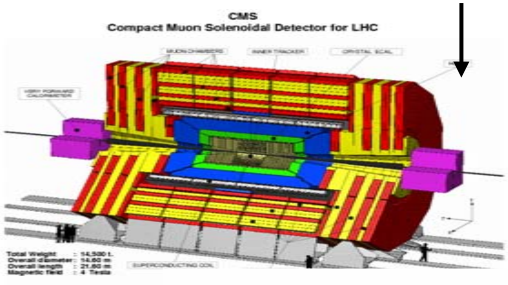
- Geometry description verified using the Cosmic data collected during MTCC, CRAFT, …
- Muon physics in G4 is extensively tested and validated in the energy range 10 GeV – 10 TeV
  - Improved description of μ bremsstrahlung, μ-nuclear effects, ..
  - Better description of multiple scattering (in agreement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



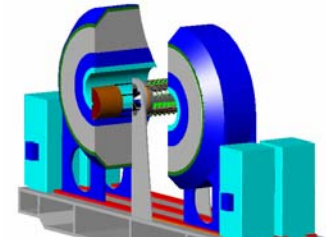


Forward Detectors

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

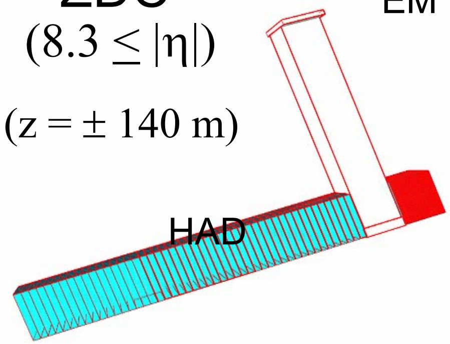


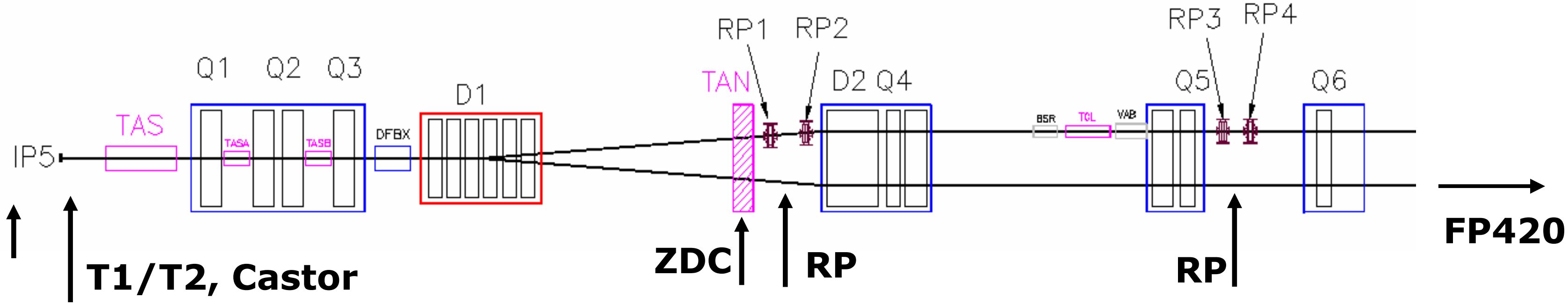
T1,T2
$(5.2 \leq \eta \leq 6.7)$
$(z = \pm 7.5, \pm 14.5 \text{ m})$



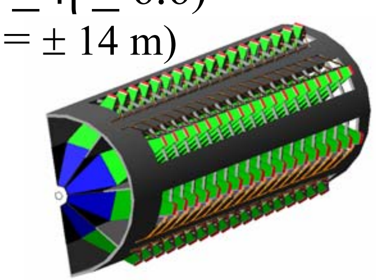
ZDC
$(8.3 \leq |\eta|)$

$(z = \pm 140 \text{ m})$

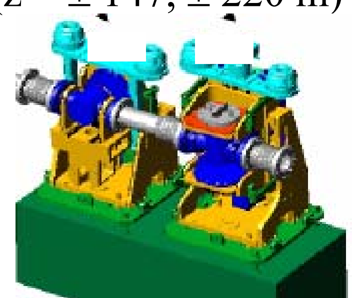




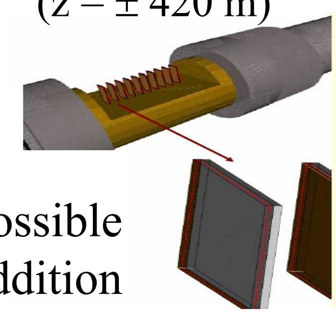
CASTOR
$(5.2 \leq \eta \leq 6.6)$
$(z = \pm 14 \text{ m})$



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



FP420
$(z = \pm 420 \text{ m})$



possible addition

Forward Detector Simulation

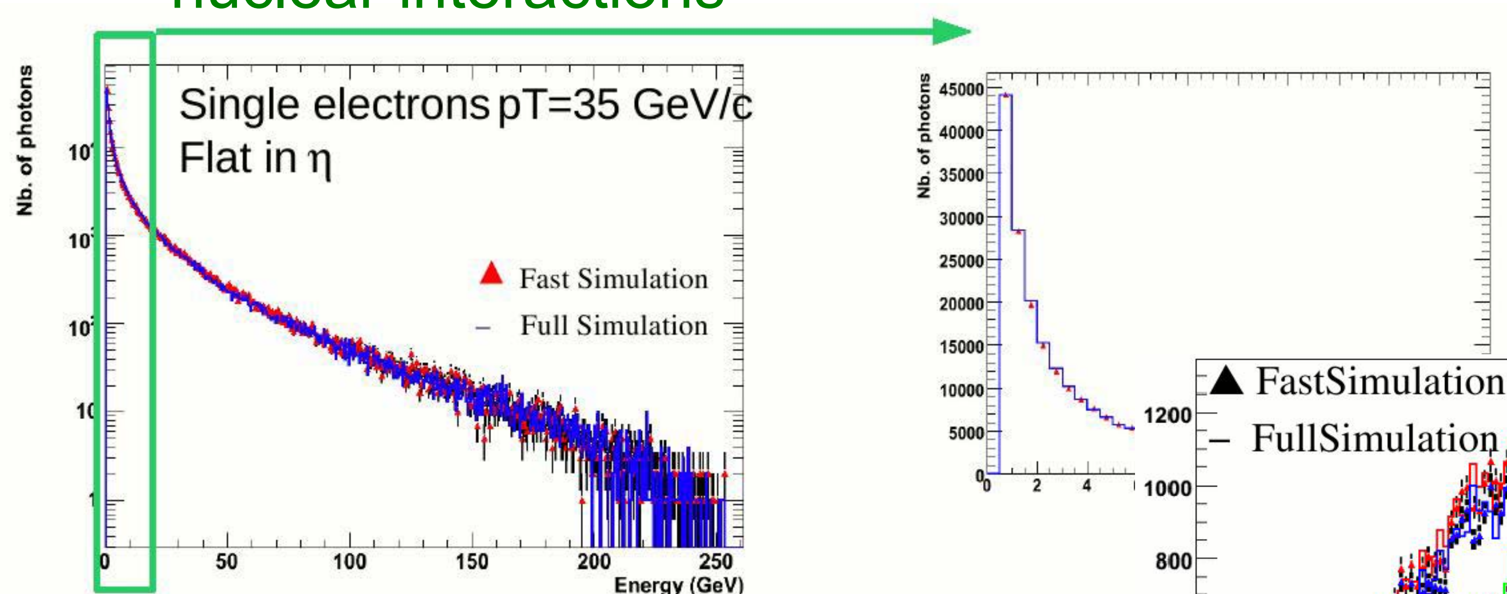
- Essential for diffractive and heavy ion programs
- Simulation of stand alone systems has been compared with test beam studies regarding energy resolution, leakage, …
- Simulation with central as well as forward detectors is foreseen:
  - Use filter to separate particles from event generators to be 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

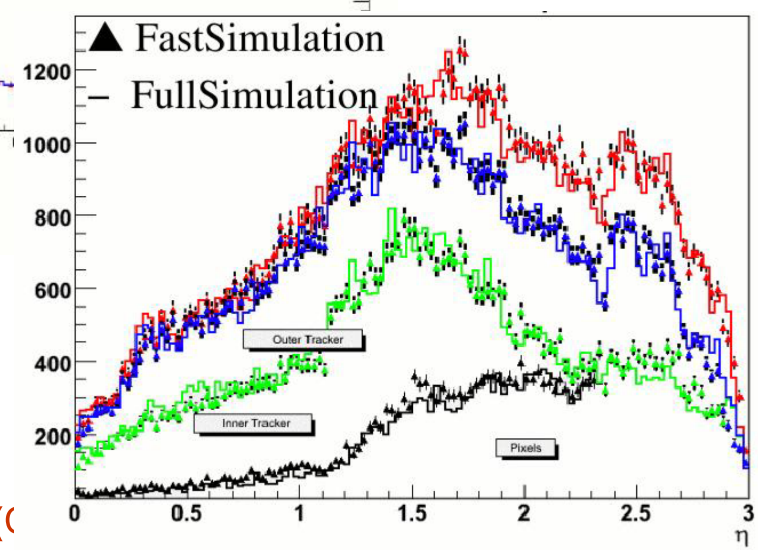
Fast Simulation

- 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)

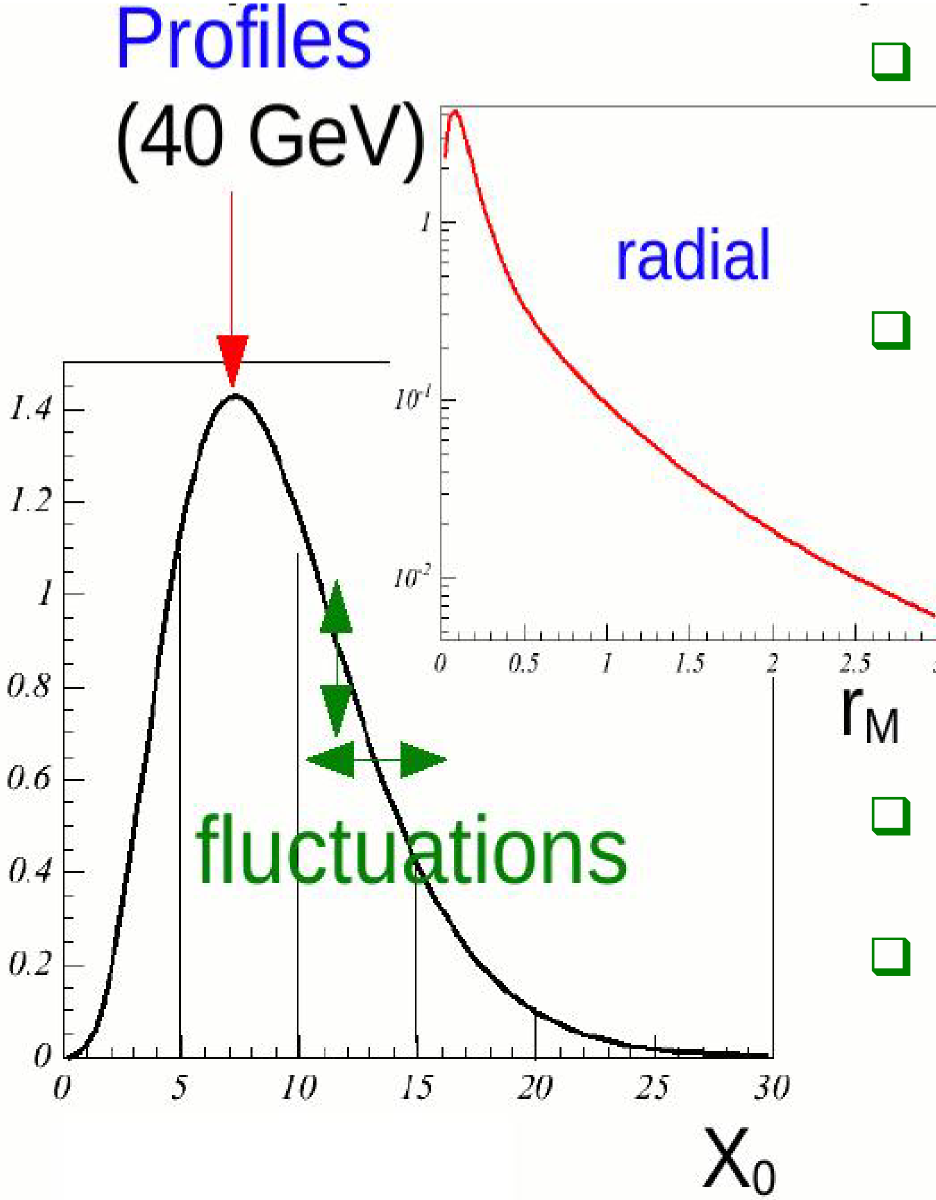
- Layer thicknesses of active/passive material are tuned to reproduce the number of photons in full and fast simulation
- Map thickness in term of x/X_0 to λ/λ_0 to parameterize nuclear interactions





Number of interactions as well as secondary spectra are faithfully reproduced

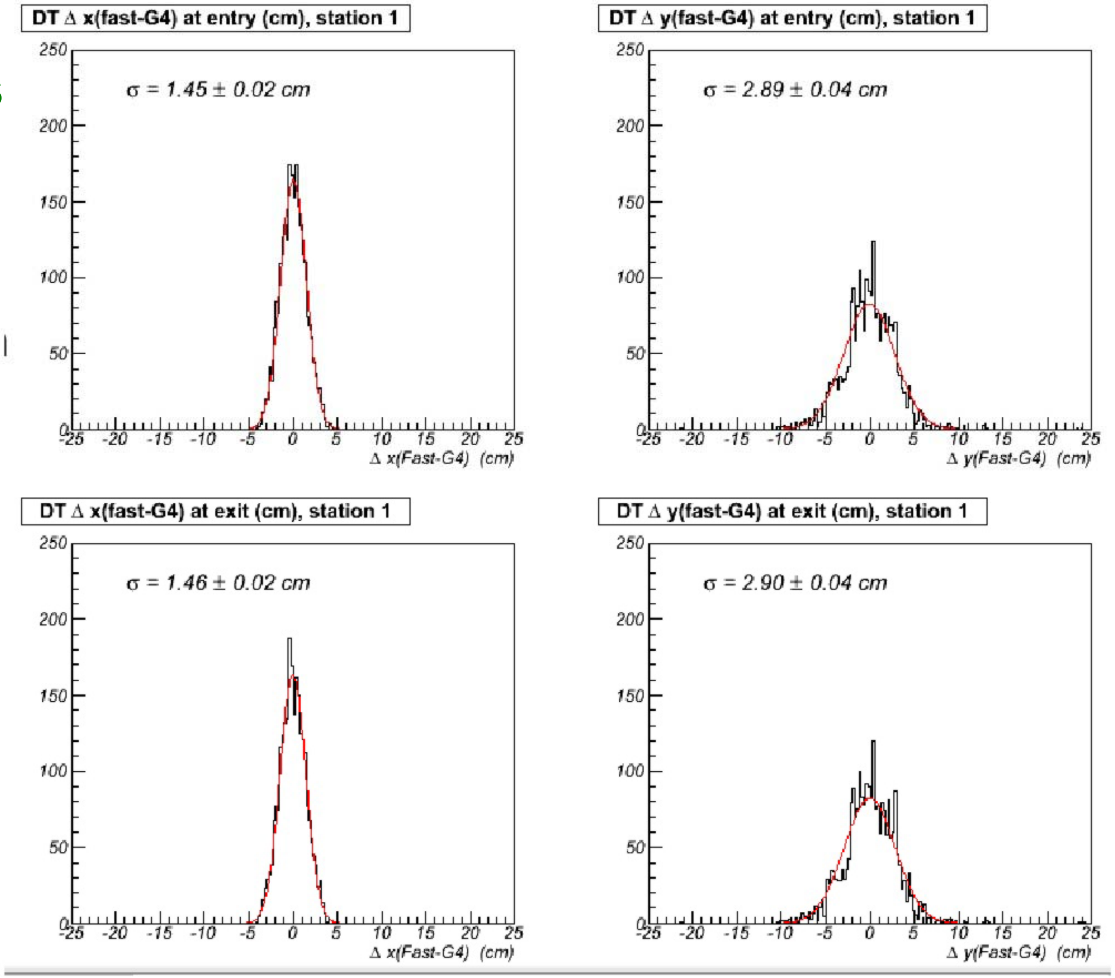
Fast Simulation (Calorimeter)



- 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

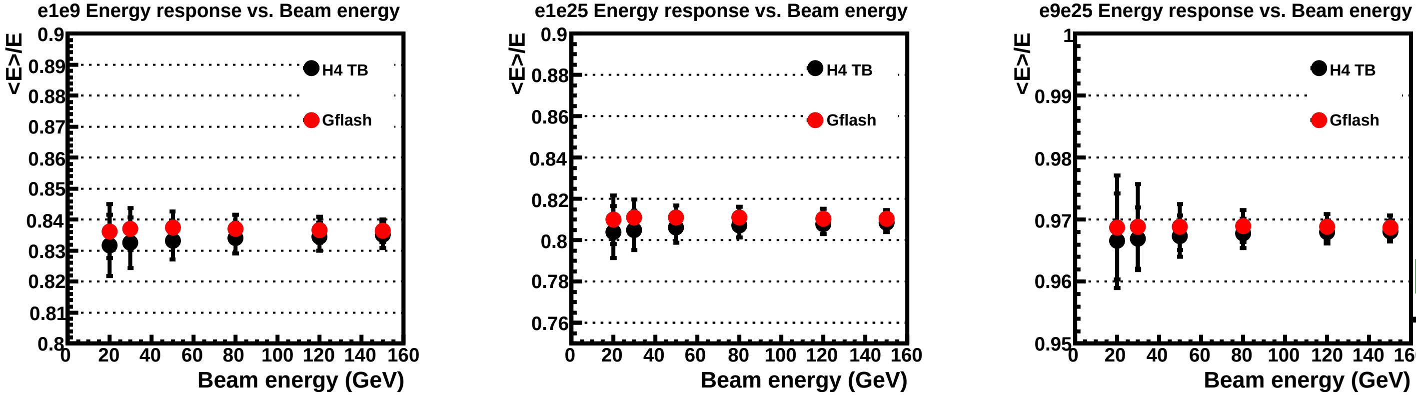
Fast Simulation (Muon)

- 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
  - …..



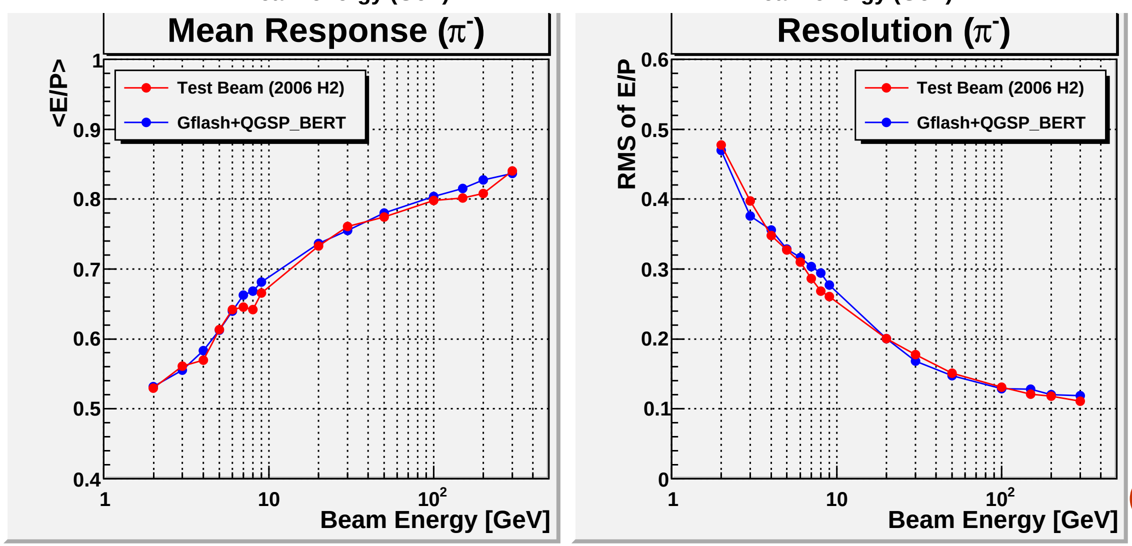
GFlash in Full Simulation

- 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 generate energy spot distribution according to a parameterized shower shape, taking into account also parameterized correlations/fluctuations



Tune to data

Electron Response
TestBeam/GFlash



(CMS)

Pion Response/Resolution
TestBeam/GFlash

CPU time saver
- ~ 10 at 10 GeV
- ~ 500 at 1 TeV

Data Mixer

- ❑ Replace MC based "Mixer Module" with one from Data
  - Take detector noise, pile-up, etc. from data rather than trying to model it
  - Create the library from collision data using zero-bias trigger
  - Match the luminosity profile and overlay on signal MC event
- ❑ Mixing strategy is detector specific: can be done on Digis or Reconstructed Hits
  - Number of options for Tracking detectors
    - ➢ Combine Digis: calibrated, zero-suppressed, …
    - ➢ Combine at RecHit level, merge if in the same detector element
  - Combination scheme can be different for ECAL and HCAL
    - ➢ Re-digitization may be necessary

New WorkFlow:

Generator → VertexSmear → Simulation → MixingModule → Digitization → DataMixer → Partial Re-Digitization → L1Emulation → DigiToRaw

Also apply to FastSim

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 to make the necessary tools and strategy
- Data always tell us where we lack in understanding the detector (crucial for any discovery in LHC).
- There are many missing holes and participation to fill these up is very much welcome. Many experts exist at LPC – please talk to the experts and get involved.

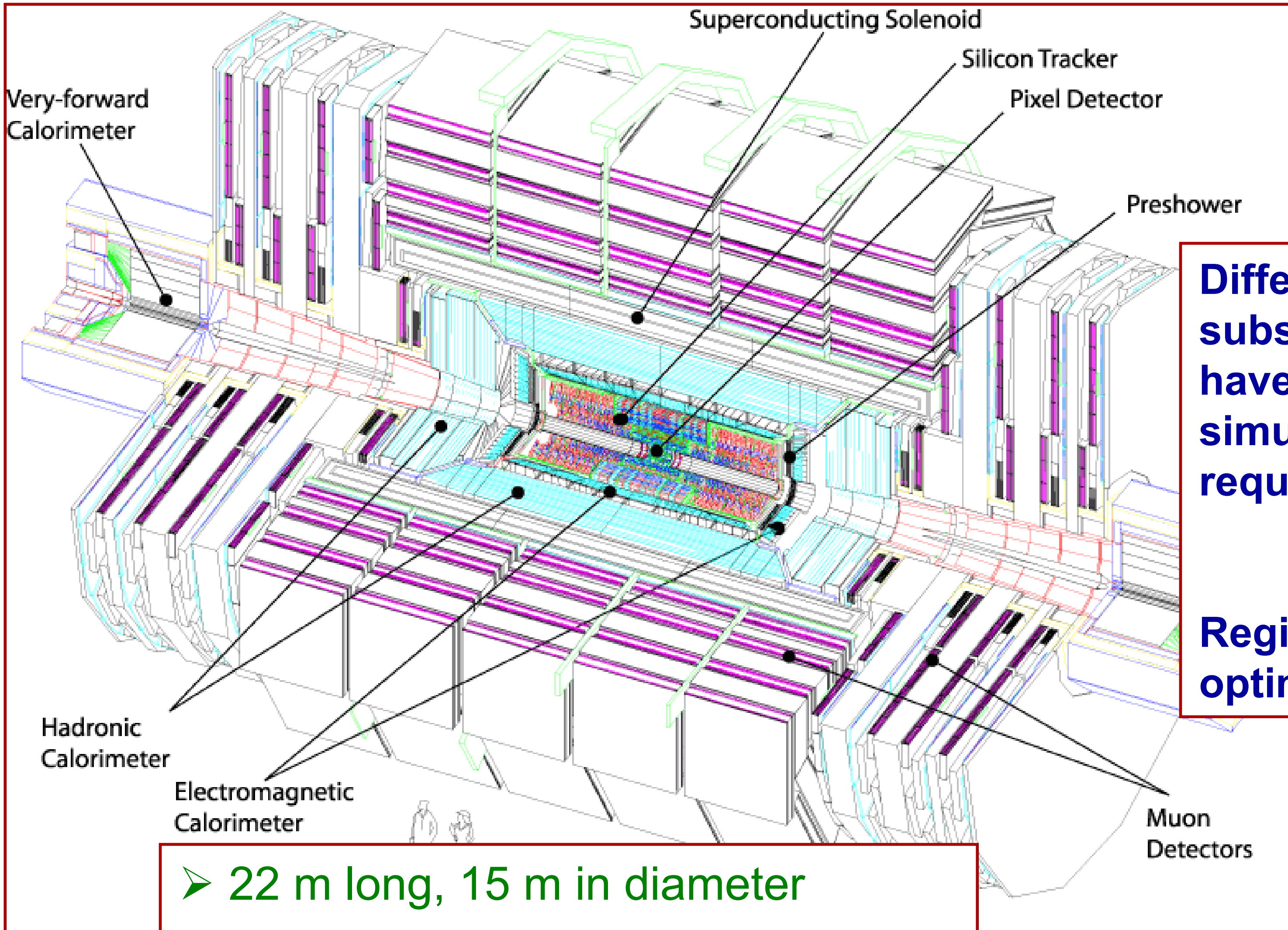
Backup Transparencies

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.

The CMS Detector



Different subsystems have different simulation requirements

⇓

Region based optimization

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

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