CMS: Full Detector Simulation

Outline

- ❑ Interface to Geant4
- ❑ Detector specific requirements
- ❑ Optimization issues
- ❑ Performance
- ❑ Anomalous Hits
- ❑ GFlash
- ❑ Summary

LHC Detector Simulations
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(On behalf of CMS collaboration)

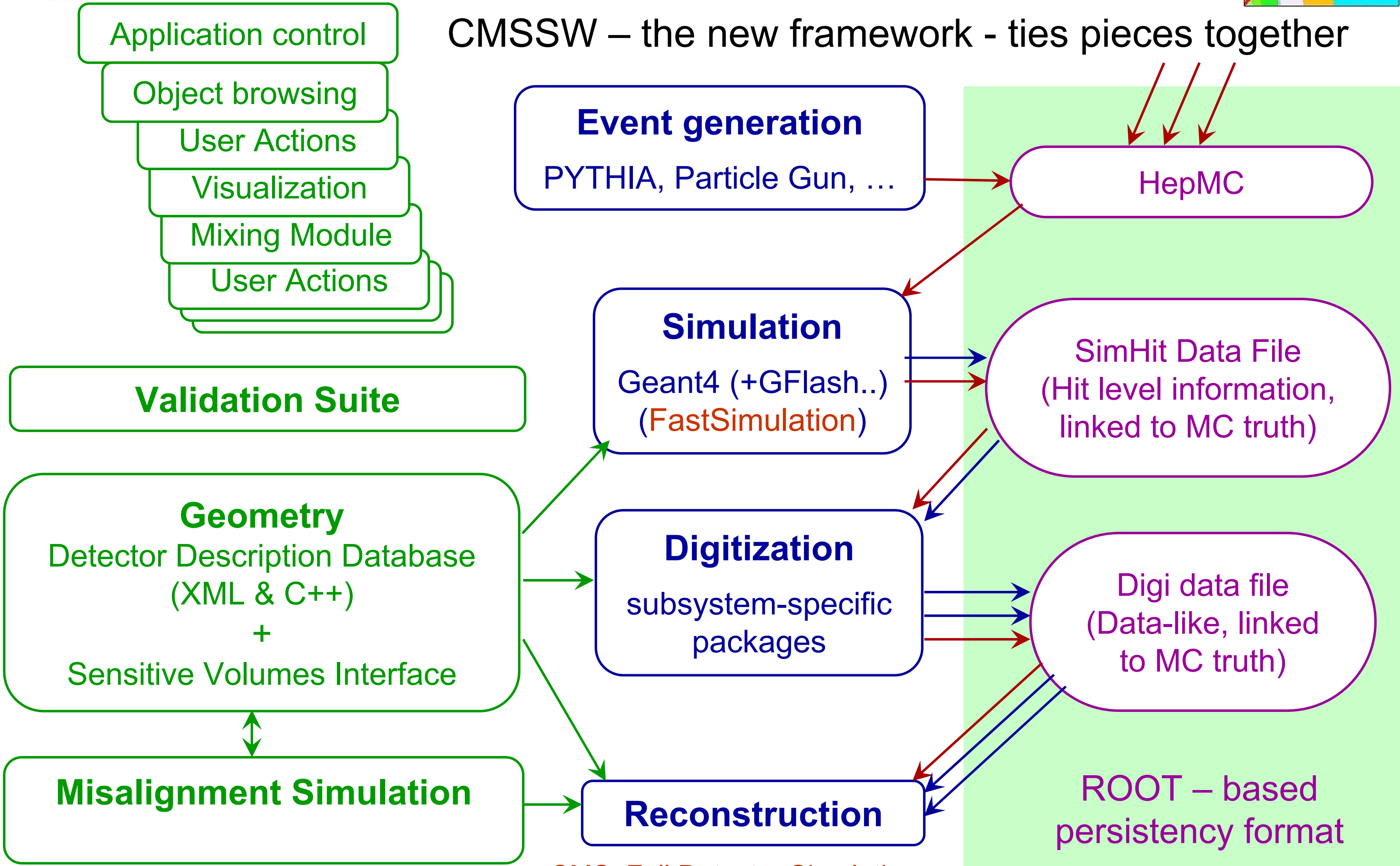
Framework Architecture

- CMS chooses to use a data driven, realistic/accurate Monte Carlo
- The simulation code is built like any CMSSW application in the form of special shared object libraries called plugins. In practice this means that there is only one command one needs to know to run these applications: cmsRun <some-configuration-file>
- Configurations are written in python.
- There are two types of plugins:
  - Module Plugins – EDProducers, EDFilters, EDAnalyzers, (EDLoopers, etc.). These are the worker components of the FW.
  - Data Object Plugins – also known as "root dictionaries" because they can also be loaded directly into the root application. These are most of the products of the above work, and form the elements of the EDM.

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 (9.4-cms2; in transition to 9.4.p02):
  - 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

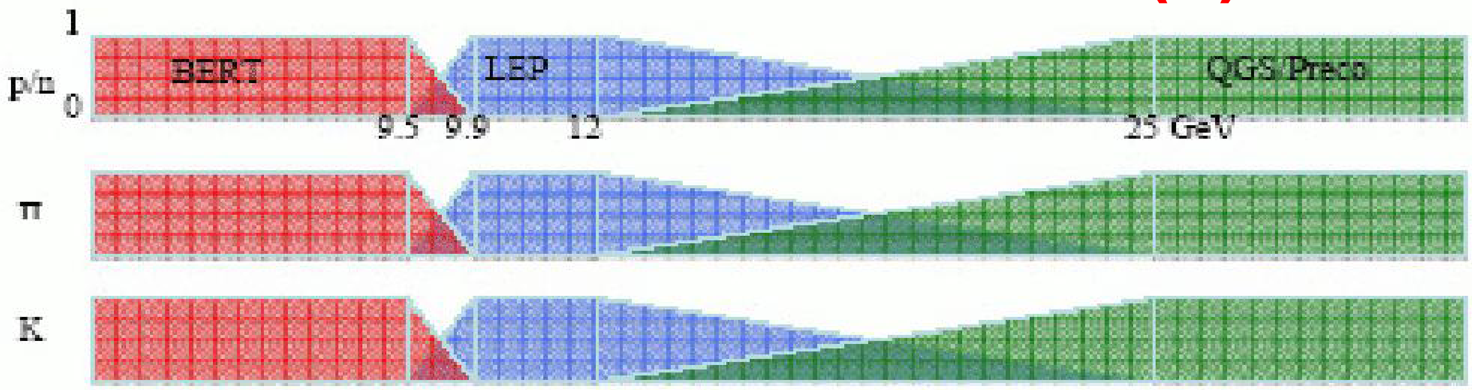
Simulation Software – CMS Solution



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 (QGSP_BERT/QGSP_BERT_EMV/QGSP_BERT_EML, QGSP/QGSP_EMV, QGSP_FTFP_BERT,FTFP_BERT…) for modeling physics processes; run-time selection of physics list and production cuts, activation/tailoring of individual processes;
- A number 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

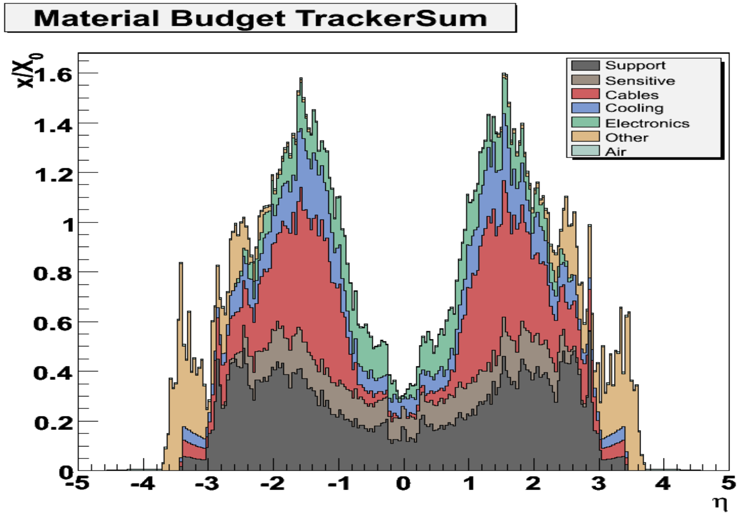
- In-time pileup :
  LHC will produce several minimum bias interactions/crossing on top of the trigger event
- Out-of-time pileup:
  Coming from bunch crossings before/after the trigger event
- Pileup events are simulated separately from the physics events; simulation outputs are merged at hit level (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)

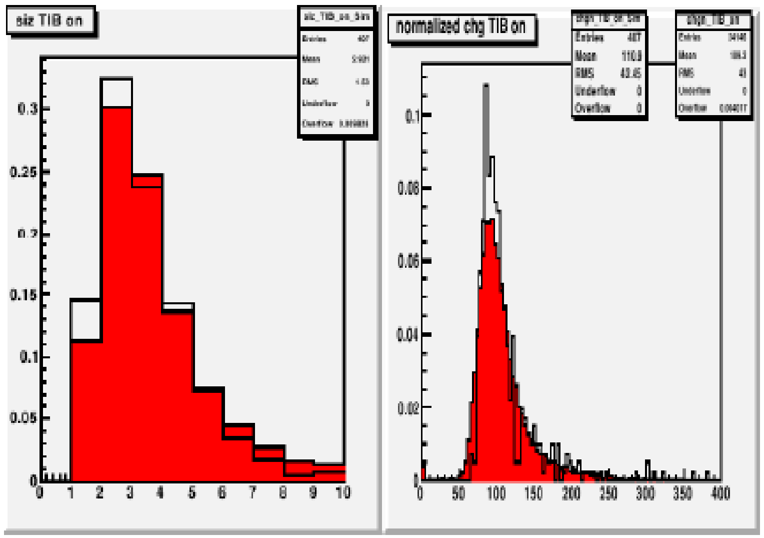
Workflow:

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

Tracker

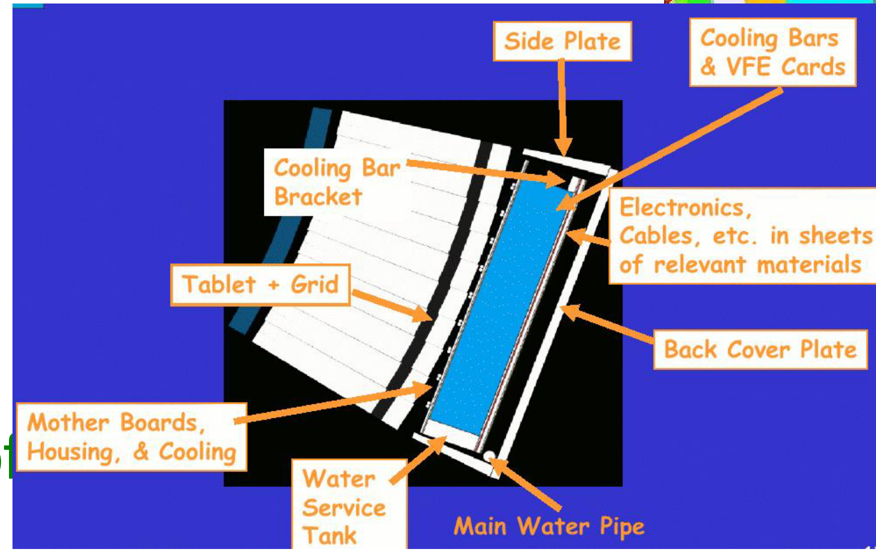
- ❑ Demands a high degree of accuracy:
  - – Description of active and passive components
    - ➢ Review each component with full information from integration centres
    - ➢ Verify by weighing individual components
  - – Correct, navigable Monte Carlo truth
  - – Proper treatment of hard electron bremsstrahlung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

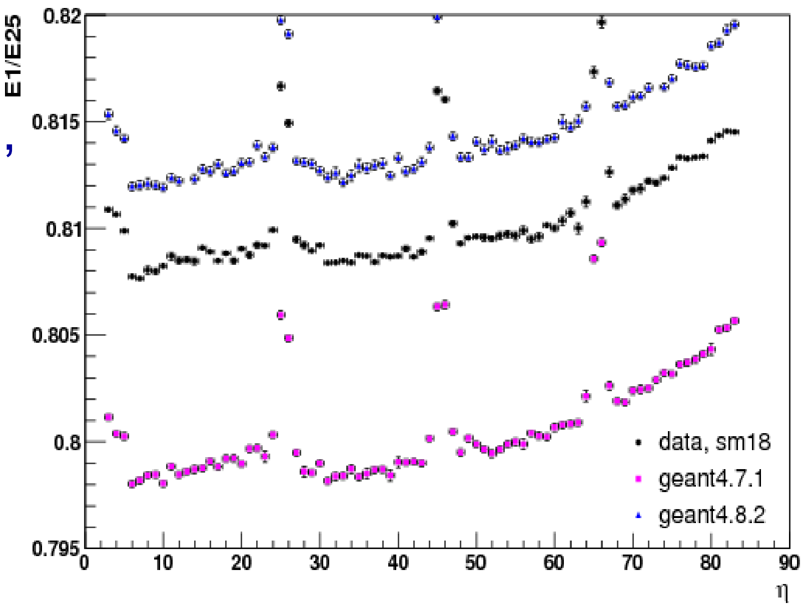




Electromagnetic Calorimeter

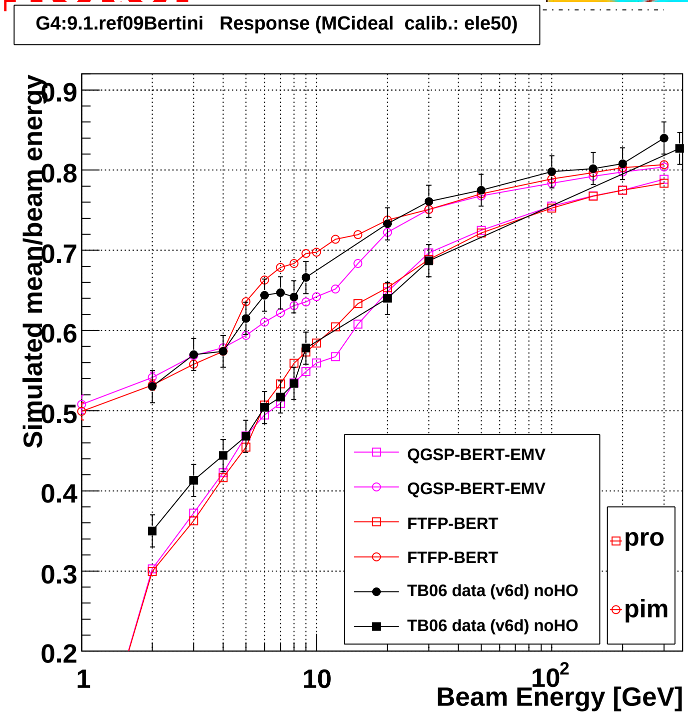
- ❑ Accurate description of geometry and material budget
  - – Independent alignment of modules, super-crystals, wafers, …
  - – Updated distribution of support, cooling, readout
- ❑ Good/complete implementation of physics process
  - – Transverse shower profile (containment, calibrations)
  - – Longitudinal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

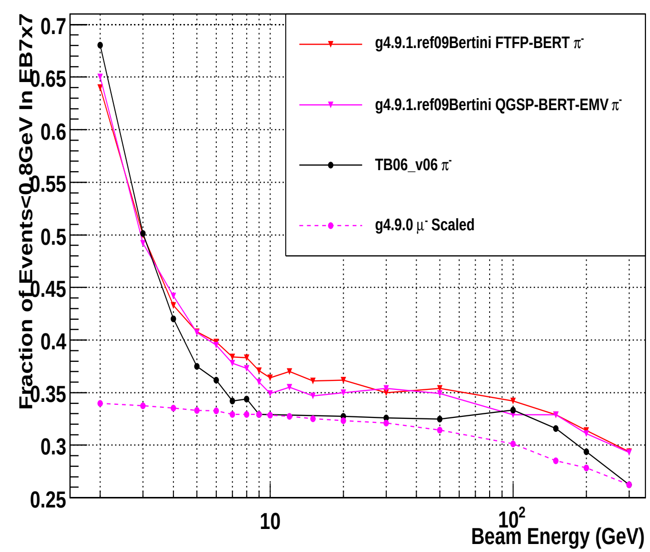




Hadron Calorimeter

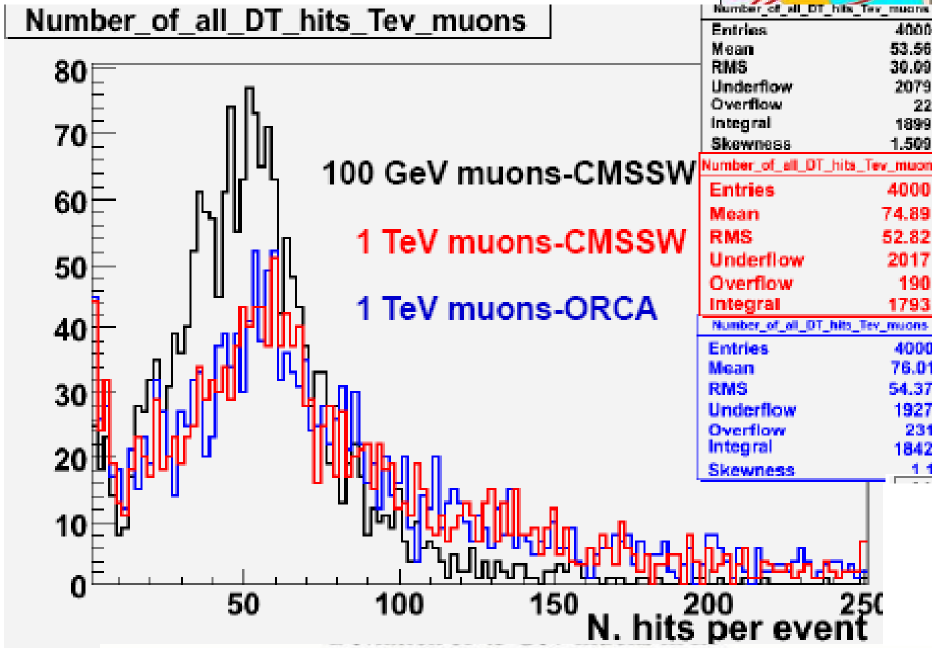
- Comparisons between single particle measurements in test beam: 2002-2007, with different HCAL modules, preceded by real ECAL super-module or prototype, to beams of π, e and μ over large energy range
- HCAL studies on energy resolution and linearity, e/π ratio, and shower profile instrumental in validating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

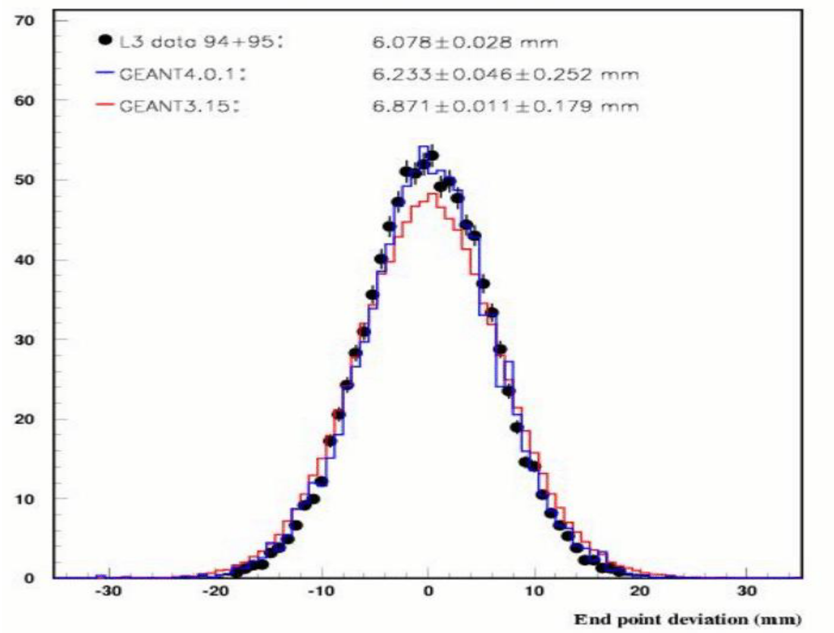




Muon System

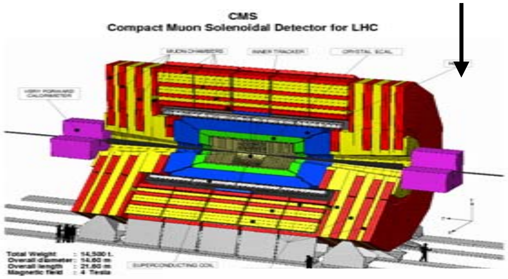
- Geometry description verified using the Cosmic data collected during MTCC, CRAFT, …
- Muon physics in G4 is extensively tested and validated in the energy range 10 GeV – 10 TeV
  - Improved description of μ bremsstrahlung, μ-nuclear effects, ..
  - Better description of multiple scattering (in agreement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



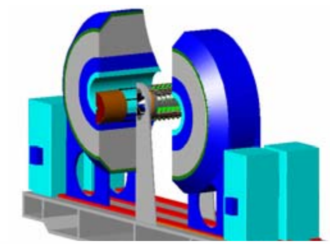


Forward Detectors

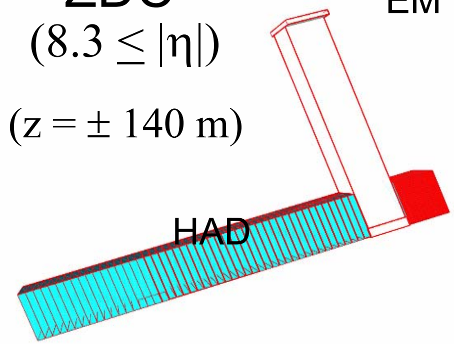
HF
$(3 \leq |\eta| \leq 5.2)$

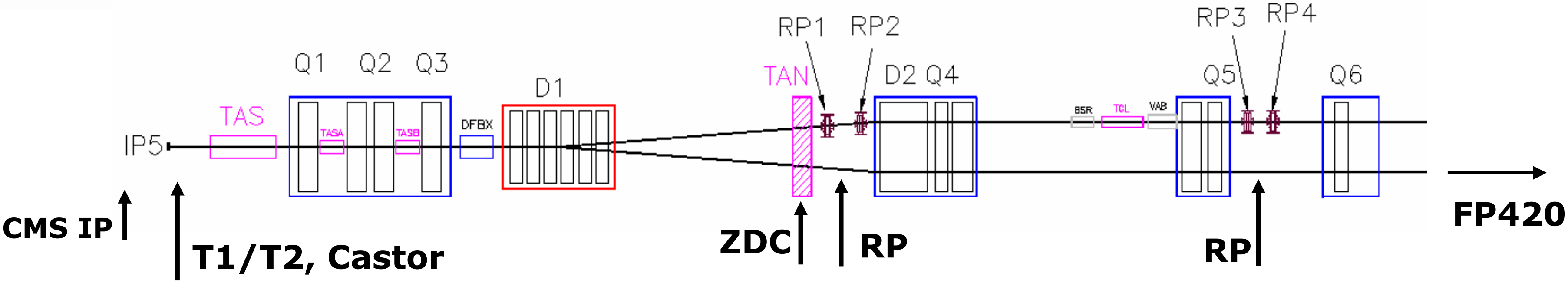


T1,T2
$(5.2 \leq \eta \leq 6.7)$
$(z = \pm\, 7.5, \pm\, 14.5$ m$)$

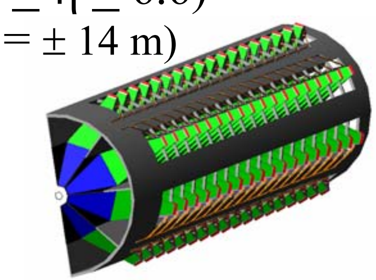


ZDC
$(8.3 \leq |\eta|)$
$(z = \pm\, 140$ m$)$

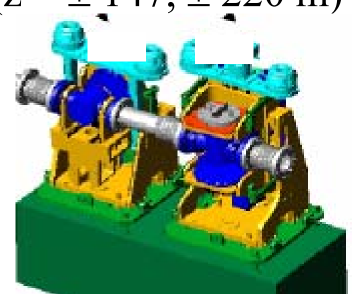




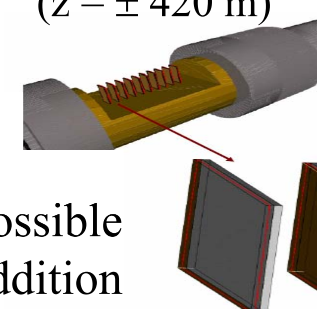
CASTOR
$(5.2 \leq \eta \leq 6.6)$
$(z = \pm\, 14$ m$)$



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



FP420
$(z = \pm\, 420$ m$)$



possible addition

CMS: Full Detector Simulation

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

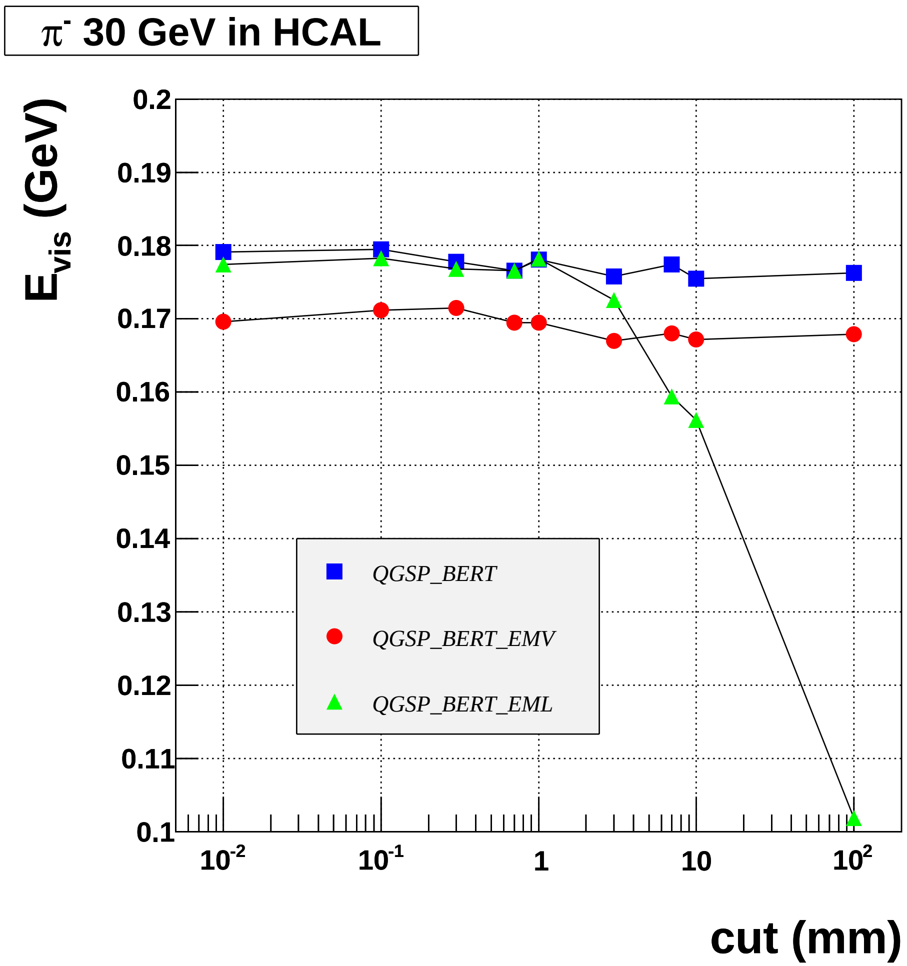
Performance Issues

	Minimum Bias	t-tbar	$Z \rightarrow e^+e^-$
CPU Time (s)			
QGSP_EMV	1.00	1.00	1.00
QGSP	1.16	1.20	1.17
QGSP_BERT_EMV	1.41	1.46	1.36
QGSP_BERT	1.58	1.69	1.53
Event size (Mb)			
QGSP_EMV	1.00	1.00	1.00
QGSP	1.01	1.03	1.00
QGSP_BERT_EMV	1.52	1.77	1.60
QGSP_BERT	1.52	1.72	1.58

- Possible increase by ~40% in CPU time, ~(50-80)% in Event size (depending on physics channel), ~(5-10)% increase in memory usage as a result of moving from QGSP_EMV to QGSP_BERT_EMV

More on EM Physics

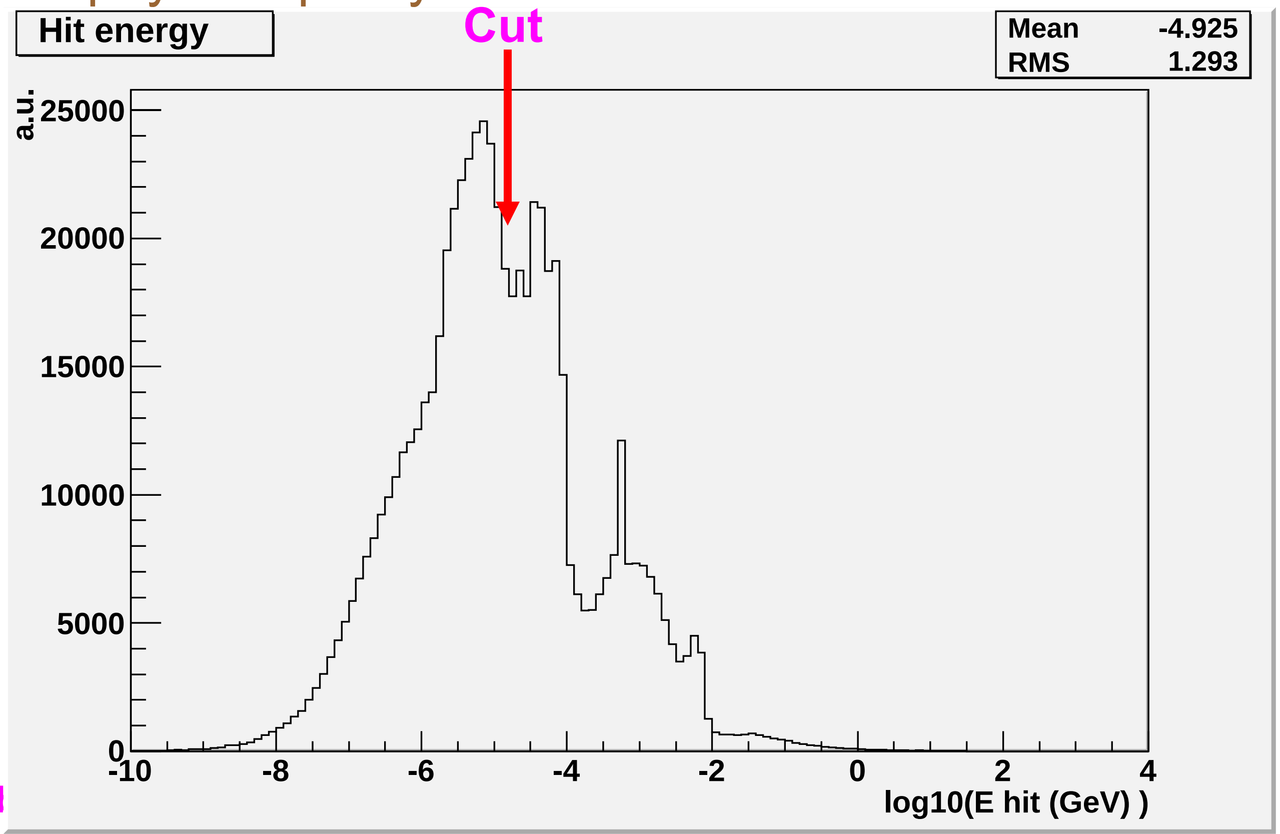
- By default production threshold in Geant4 are applied to ionization and bremsstrahlung. Extend this to other processes like Compton scattering, PE effect, … → Apply Cuts
- No change in physics if cuts are small enough. Gain in CPU time by ~25%



New CMS specific physics list QGSP_BERT_EML

Recover Space & Time

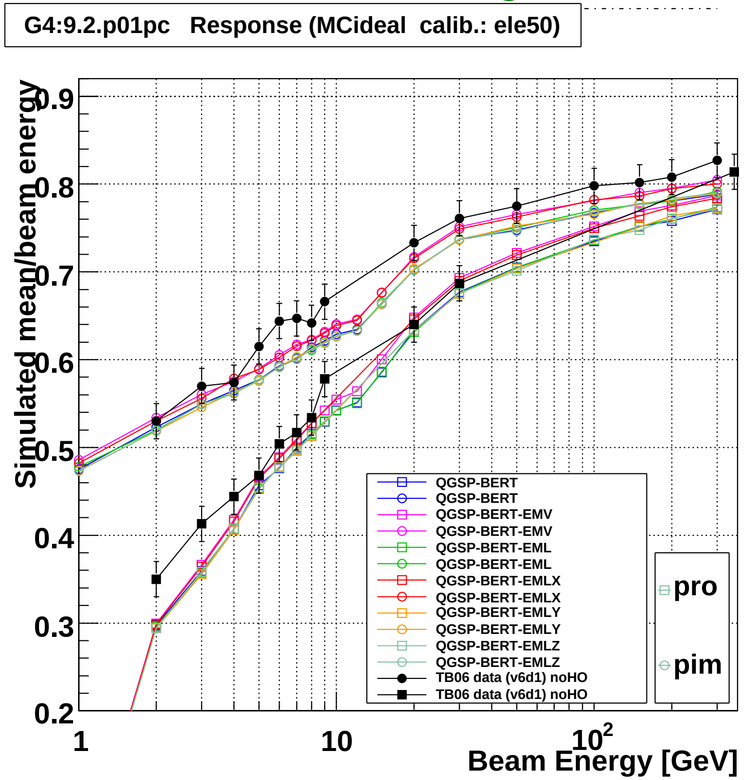
- All detector components have signal integration time significantly smaller than default time cut in Geant4. Make region specific cut on timing (SteppingAction and StackingAction)
- Many very low energy hits with Bertini cascade model. Study cut on energy deposit in a cell. Applicable to barrel and endcap calorimeter → calorimeter hit storage drops by a factor of 2. No impact on physics quality.



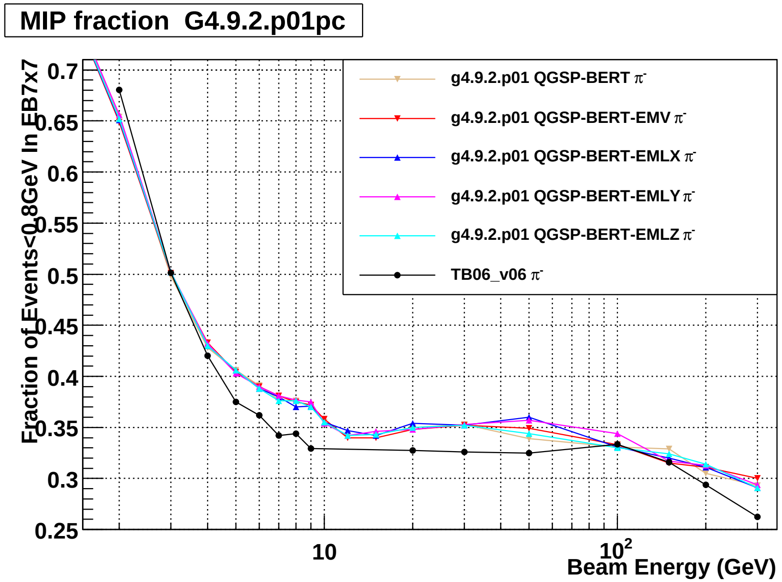
These measures + improvements in the Bertini cascade code recovered all the grounds lost in switching physics list.

Hadron Response Optimization

- Bertini cascade model had several improvements since 9.2
  - incorporation of Coulomb barrier
  - treatment of quasi-elastic scattering
- Bremsstrahlung of charged hadrons are allowed in EM physics list
- Possibility of having different multiple scattering models to electrons in different regions – included in CMS specific EM physics list (EML)



Try using UrbanMscModel2 for special regions (HCAL) which gives slightly smaller response (_EMLY or _EMLZ)

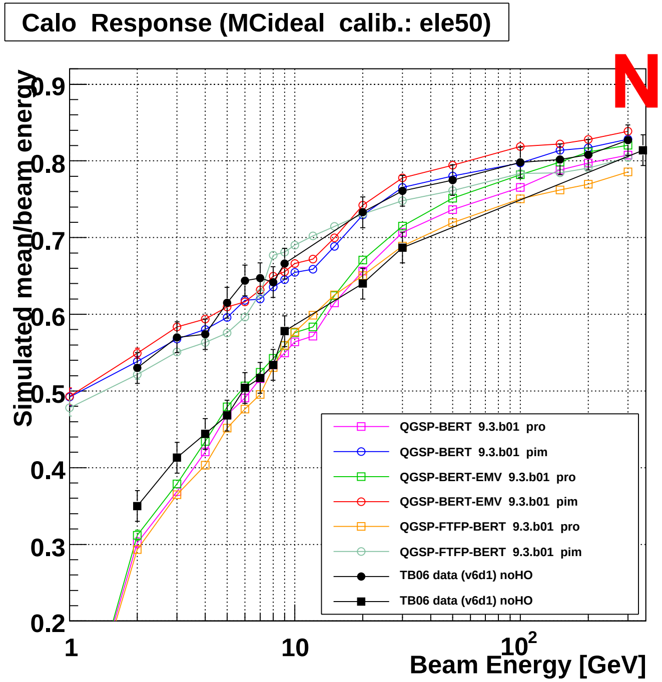


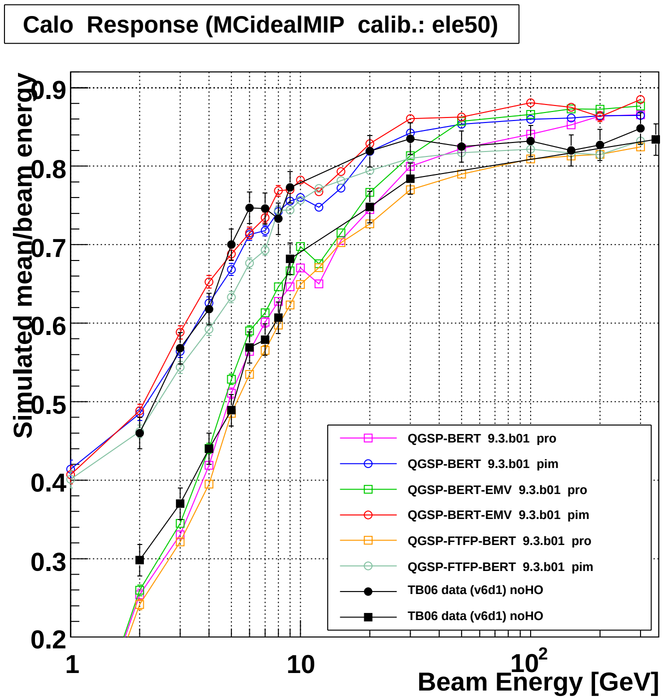
Standard EM Physics gives similar smaller response

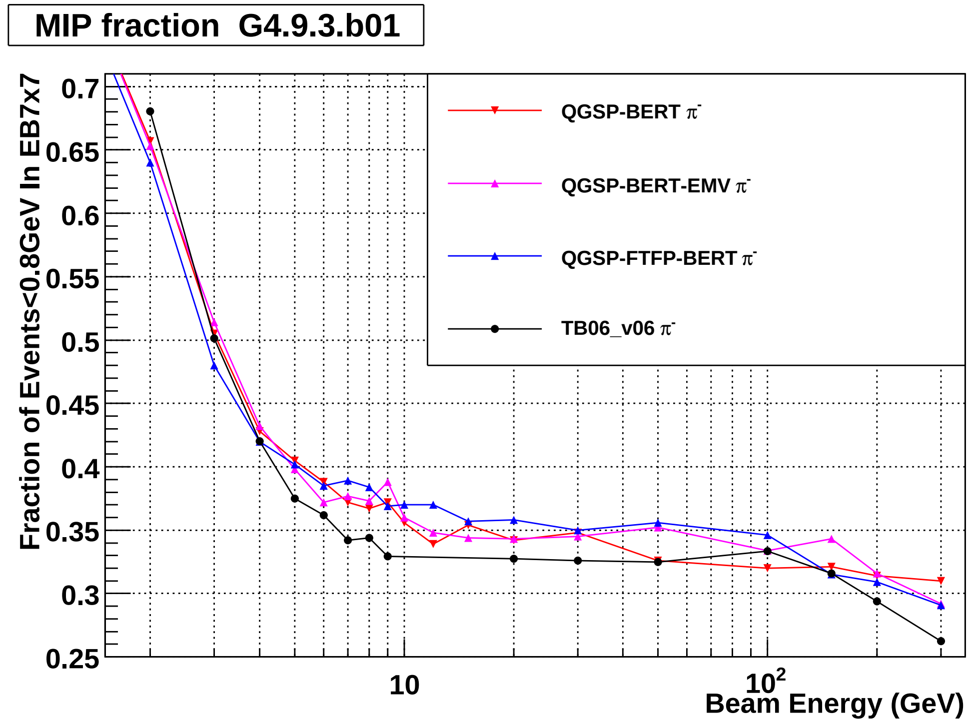
Charged hadron brems. explains the drop above 100 GeV

New Physics List since 9.3.b01

- Since Geant4 version 9.3.b01 we have several new physics lists out of which QGSP_FTFP_BERT looks rather promising
  - Transition around 5-10 GeV is quite smooth now
  - MIP fraction for FTF is slightly higher than LEP

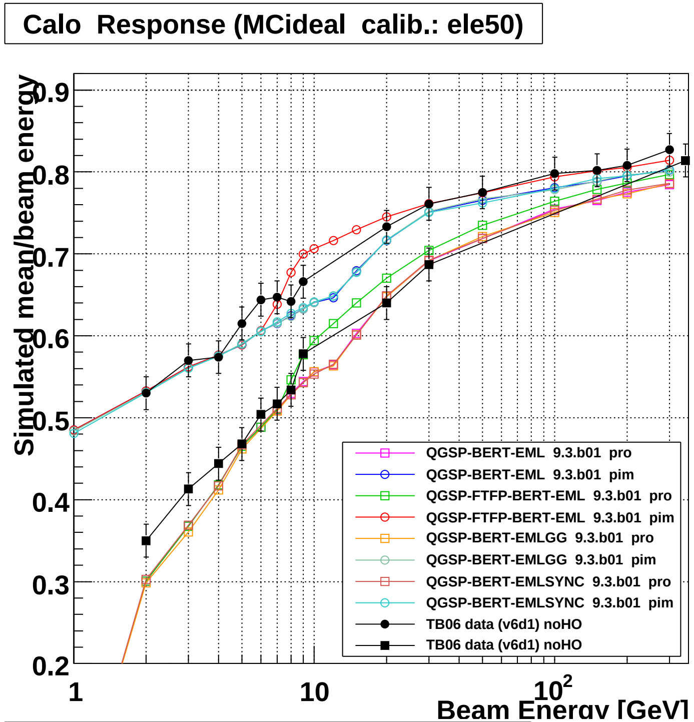


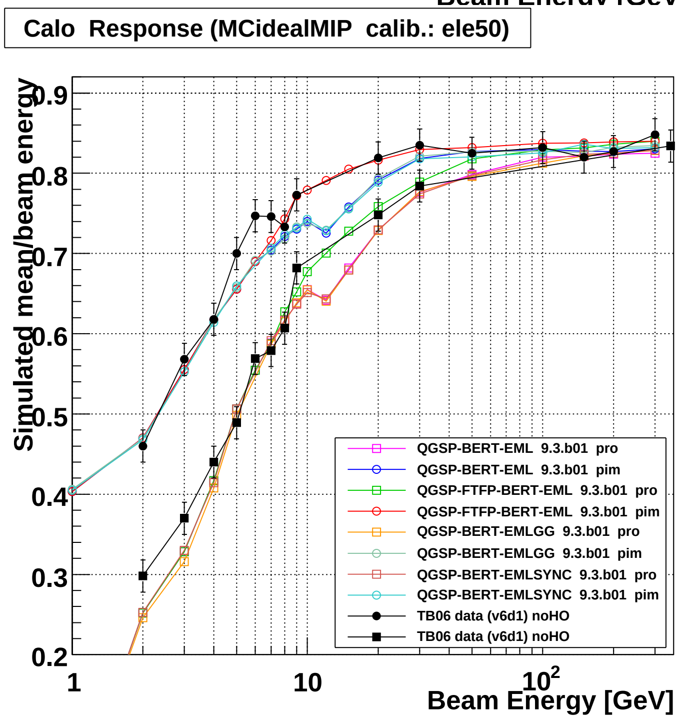


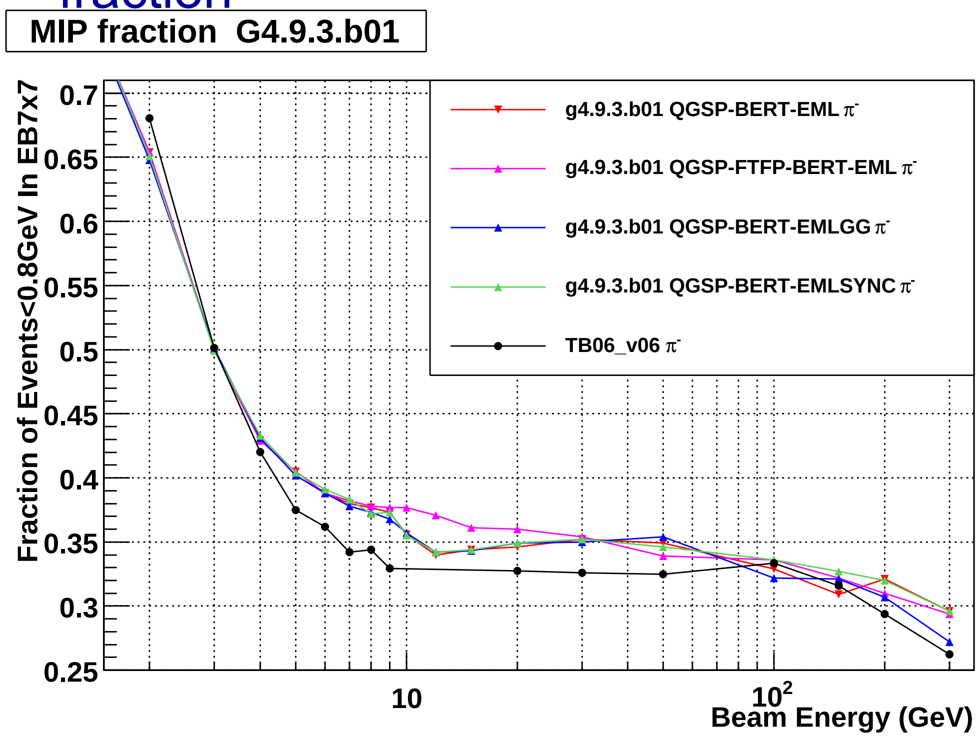


Other Attempt(s)

- Use Glauber-Gribov cross section parametrization
  - No impact on hadron response
  - MIP fraction agrees better at high E
- Use Synchrotron radiation – see impact on electron ID
  - No impact on hadron response or MIP fraction







Performance of Geant4 for CMS

- Use a current CMSSW version (4_4_0_pre7) and build it with 3 versions of Geant4
  - Geant4.9.4 with CMS specific patches to stop a few crashes (which were later included in patch01)
  - Geant4.9.4.p02
  - Geant4.9.5.b01
- Use (slc5_amd64_gcc434) on a 8-core Intel® Xeon® E5410 2.33GHz CPU
- Four sets of events are tried
  - 200 events from the minimum bias sample
  - 50 events from the ttbar sample
  - 50 events from $Z \rightarrow e^+e^-$ sample
  - 20 events from high p_T(3000-3500 GeV) QCD sample

Default Physics List

Default list for CMS: QGSP_FTFP_BERT_EML

Channel		9.4.cms	9.4.p02	9.5.b01
t-tbar	CPU (s)	92.4	91.8	93.2
	Size (GB)	1.01	1.02	1.02
	Memory (MB)	711	680	682
MinBias	CPU (s)	15.2	15.3	15.4
	Size (GB)	0.15	0.15	0.15
	Memory (MB)	679	649	647
$Z \rightarrow e^+e^-$	CPU (s)	54.6	54.9	55.6
	Size (GB)	0.53	0.53	0.53
	Memory (MB)	690	656	658
QCD (p_T =	CPU (s)	301.7	309.3	309.8
3.0-3.5TeV)	Size (GB)	1.68	1.71	1.70
	Memory (MB)	744	702	710

Old Default Physics List

Old default physics list for CMS: QGSP_BERT_EML

Channel		9.4.cms	9.4.p02	9.5.b01
t-tbar	CPU (s)	91.4	91.2	93.0
	Size (GB)	1.02	1.02	1.02
	Memory (MB)	691	657	660
MinBias	CPU (s)	14.7	14.6	14.8
	Size (GB)	0.15	0.15	0.15
	Memory (MB)	671	641	634
$Z \rightarrow e^+e^-$	CPU (s)	54.0	54.1	55.1
	Size (GB)	0.53	0.54	0.54
	Memory (MB)	673	649	645
QCD (p_T =	CPU (s)	298.4	295.8	306.5
3.0-3.5TeV)	Size (GB)	1.70	1.73	1.86
	Memory (MB)	716	683	708

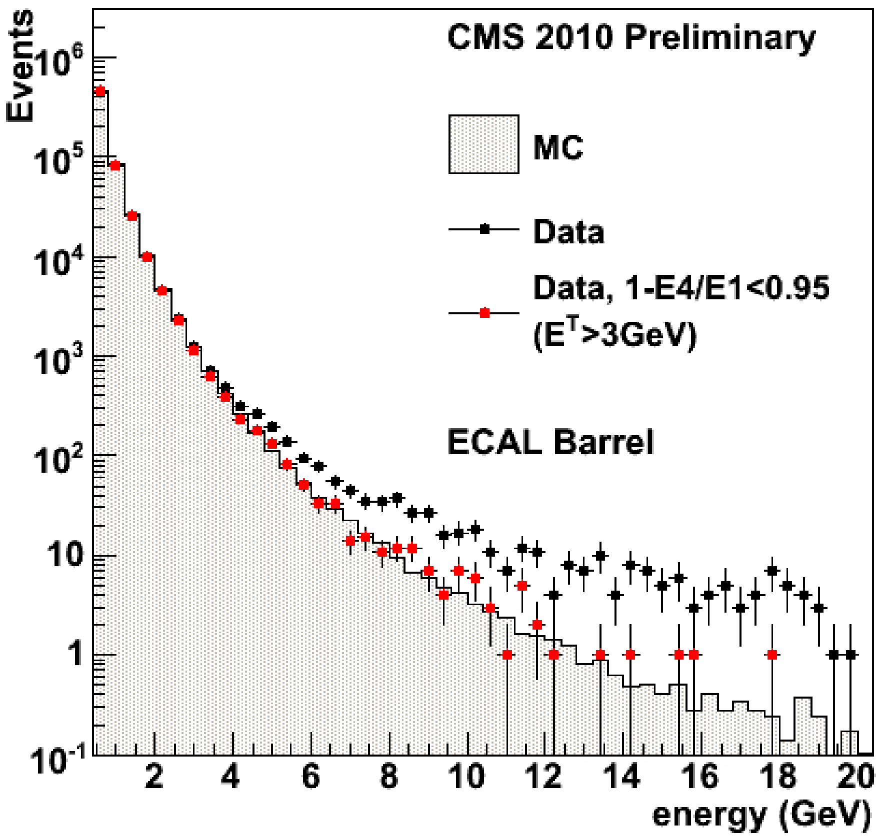
G4 Recommended Physics List

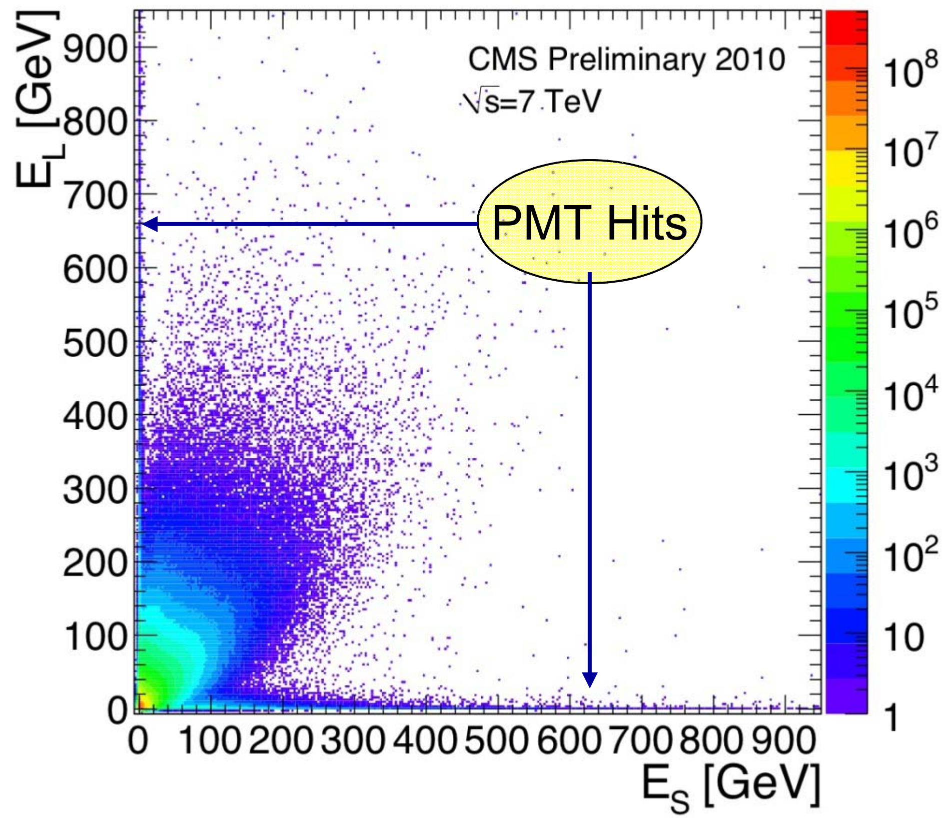
Recommended physics list from Geant4 Team: FTFP_BERT_EML

Channel		9.4.cms	9.4.p02	9.5.b01
t-tbar	CPU (s)	94.7	94.1	
	Size (GB)	1.02	1.02	
	Memory (MB)	753	691	
MinBias	CPU (s)	15.2	15.2	15.5
	Size (GB)	0.15	0.15	0.15
	Memory (MB)	691	651	662
$Z \rightarrow e^+e^-$	CPU (s)	56.0	55.4	56.9
	Size (GB)	0.53	0.53	0.54
	Memory (MB)	696	660	664
QCD (p_T =	CPU (s)	311.8	312.8	311.5
3.0-3.5TeV)	Size (GB)	1.68	1.85	1.74
	Memory (MB)	753	741	717

Anomalous Hits in Calorimeter

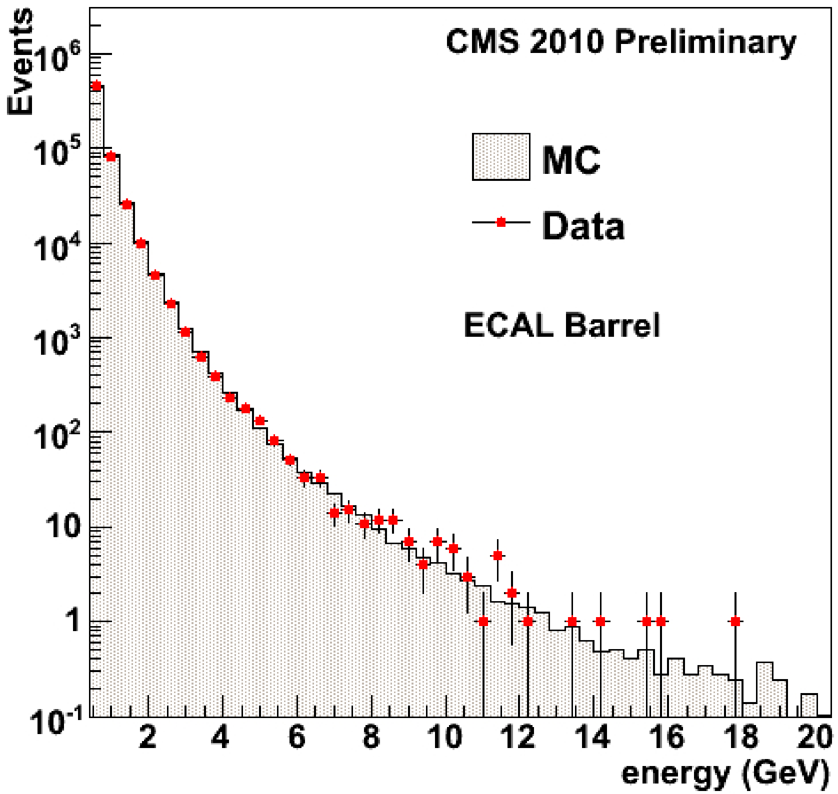
- Rare but anomalous high energy deposits are observed in the calorimeters
- Isolated single crystal hits seen in the barrel ECAL and long tails in energy deposit seen in HF which are either in short or long fibres

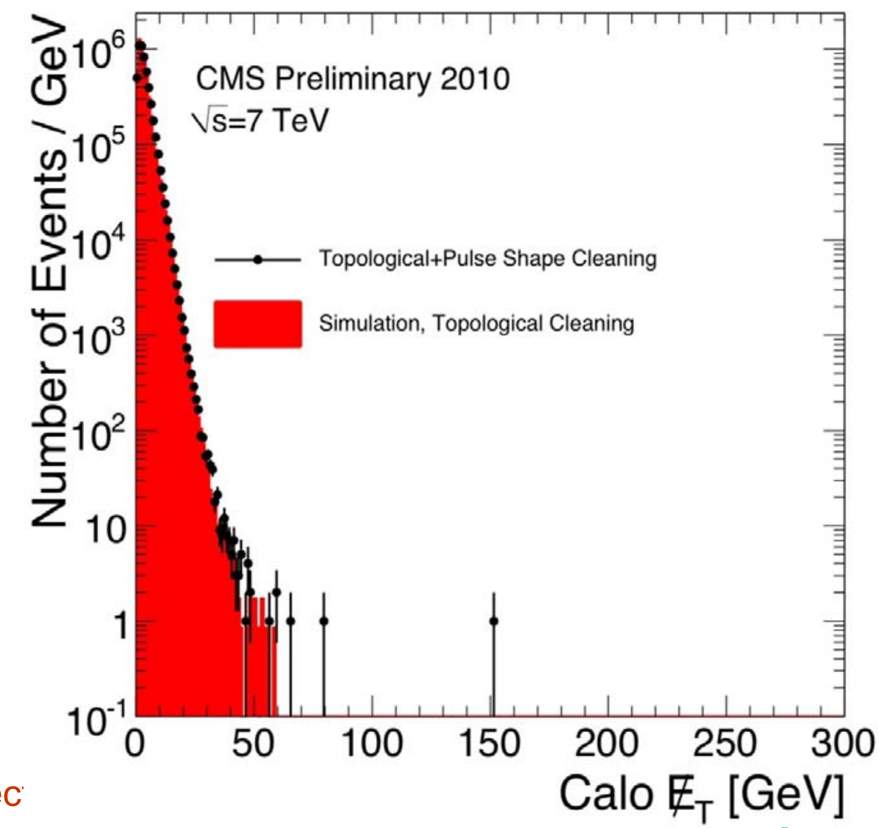




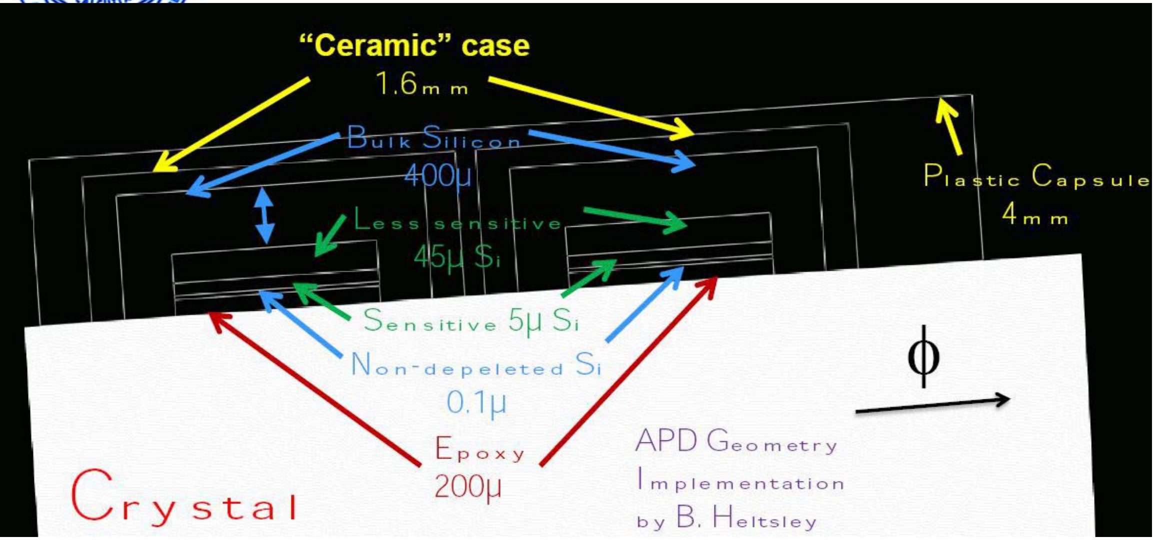
Hit Filters

- These anomalous hits are not show-stoppers. Filters based on topological properties and timings clean them up
- However one needs to understand the source of the hits and the effect of these in crowded environments

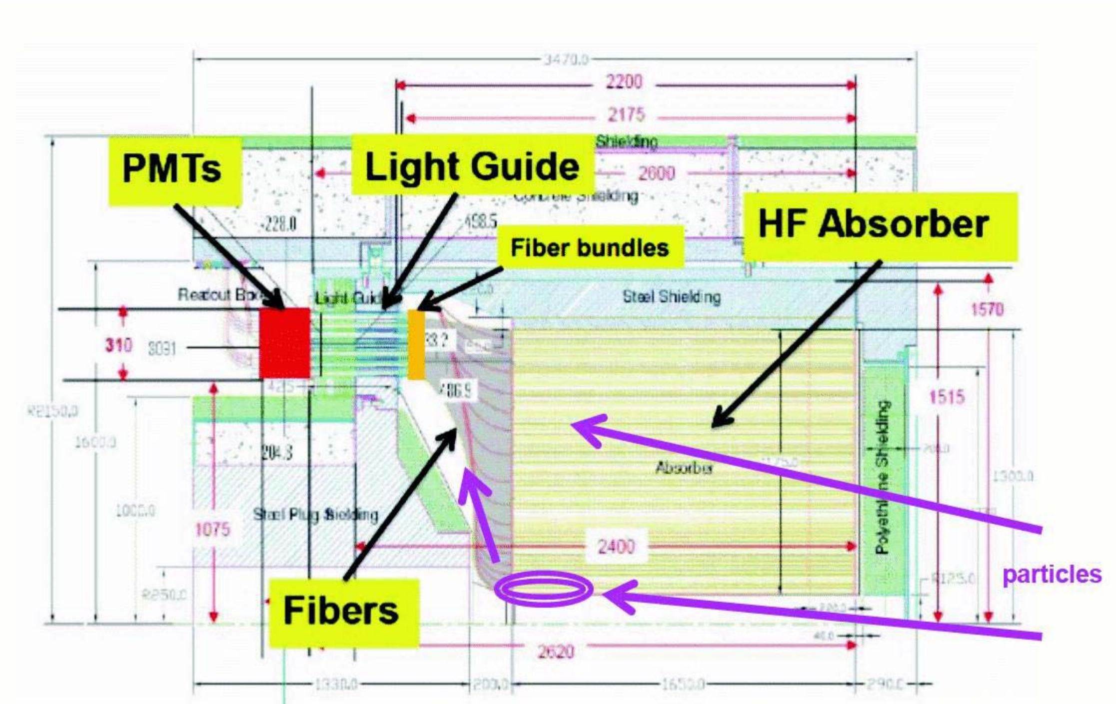




Anomalous Hits



- Anomalous crystal hits are identified to be due to energy deposits in thin layers of silicon in the APD's (induced by heavily ionizing particles produced in epoxy layers of neutrons)

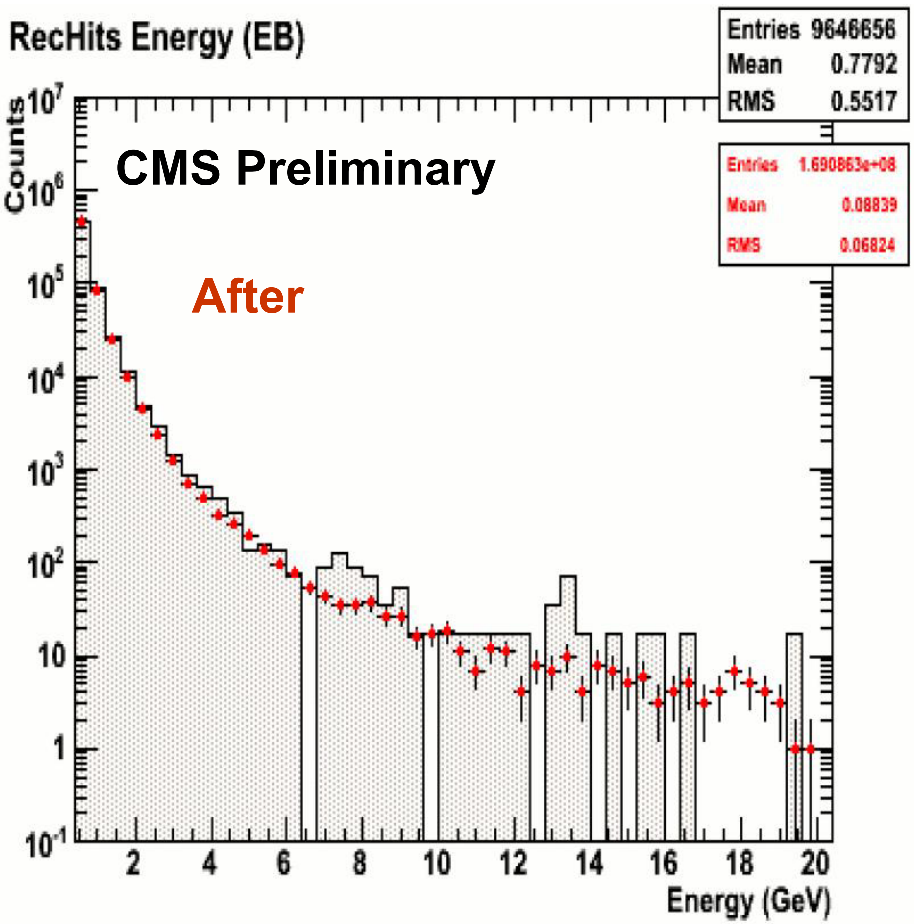


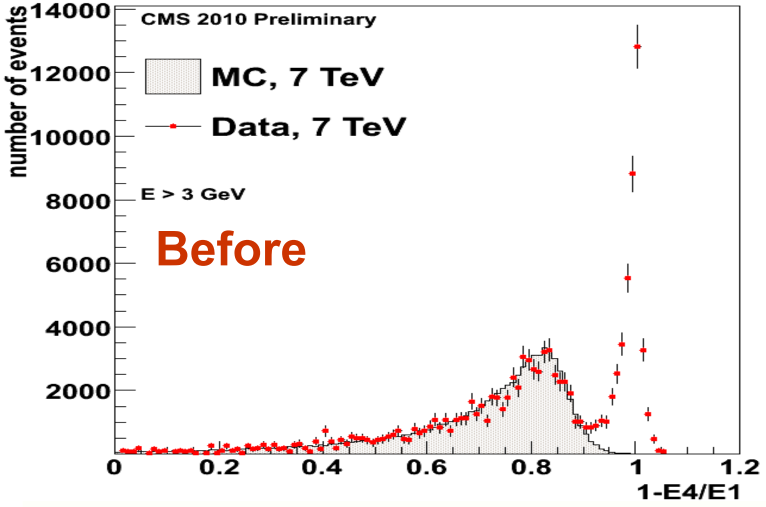
imulation

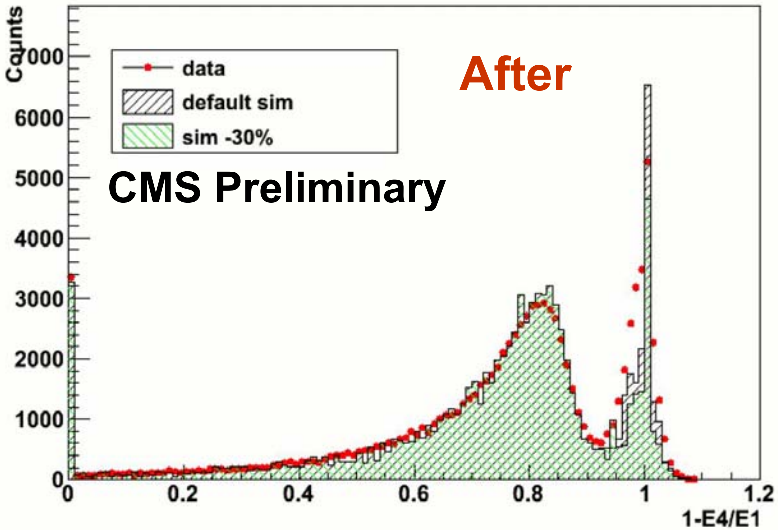
- Anomalous hits in HF are due to Cerenkov light produced by penetrating component of hadron showers in the fibres and the PMT photo-cathodes

Predictions from Simulation

- Introduce silicon layers in the APD and PMT cathode, fibres as sensitive detectors
- Try an improved neutron transport code from Geant4.

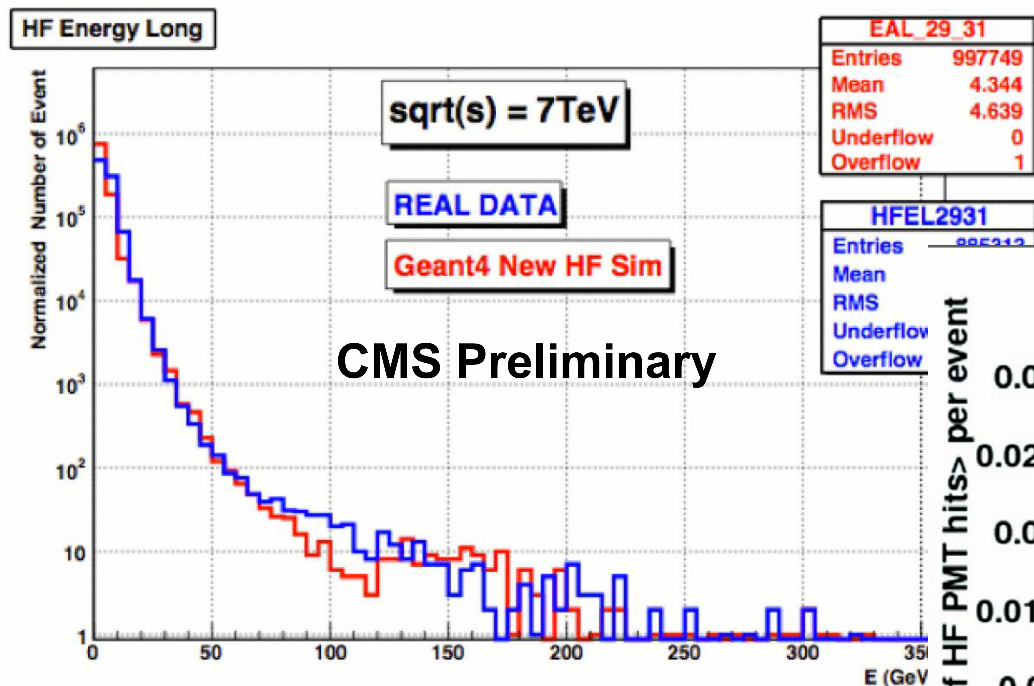


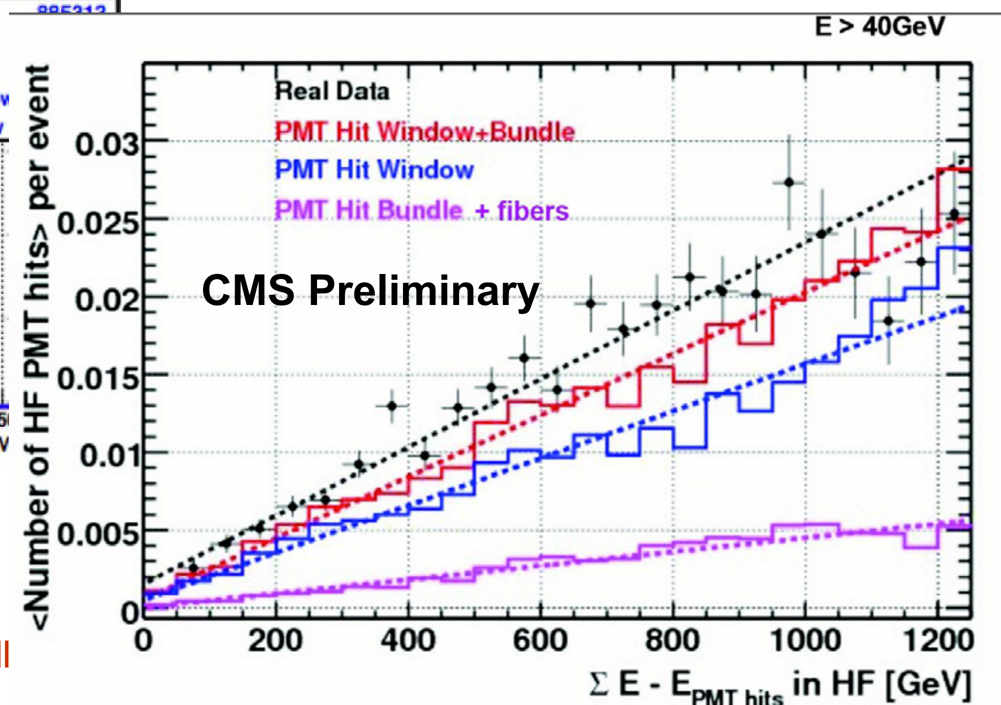




Hits in Forward Hadron Calorimeter

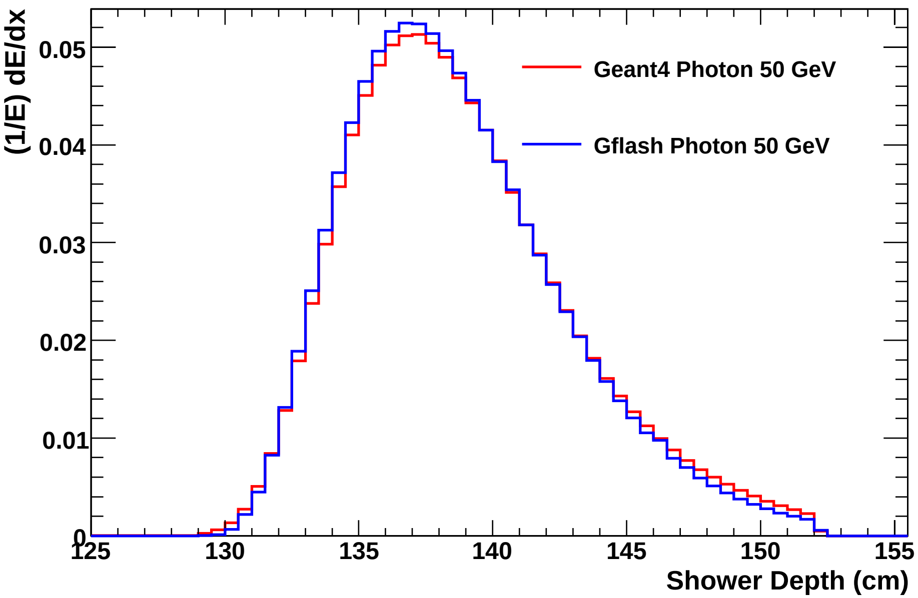
- Transport all hadrons entering HF using Geant4. The electromagnetic component of the shower in HF is replaced using parametrization.
- Energy spectrum as well as anomalous hit rate are well reproduced





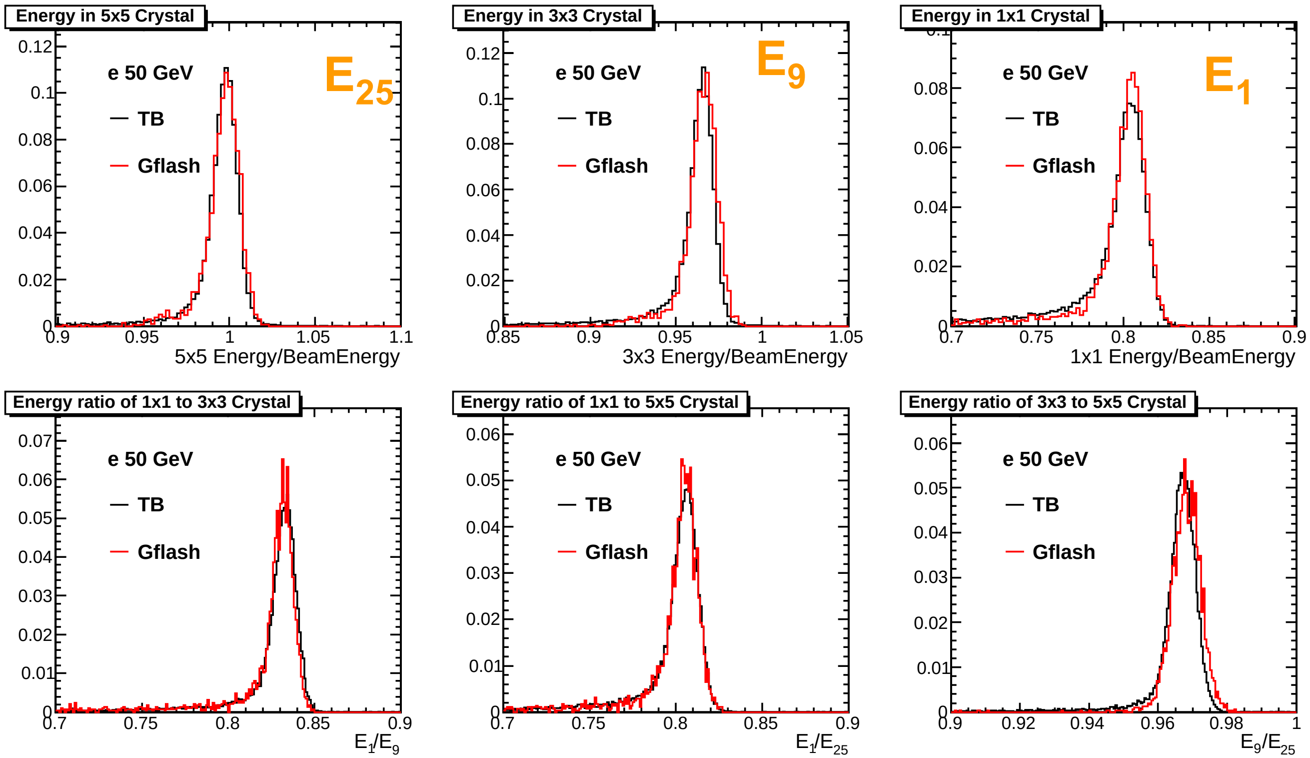
GFlash in Full Simulation

- GFlash provides an alternative approach to take care of shower simulation in calorimeter inside Full Simulation
  - Use parameterizations to describe longitudinal and lateral profiles in homogeneous and sampling calorimeters
  - Modify the standard parameterization developed originally for H1 to suite shower description in CMS composite calorimeter
  - Tune to test beam data for EM as well as hadron showers
  - It is flexible (easily tunable) and also fast

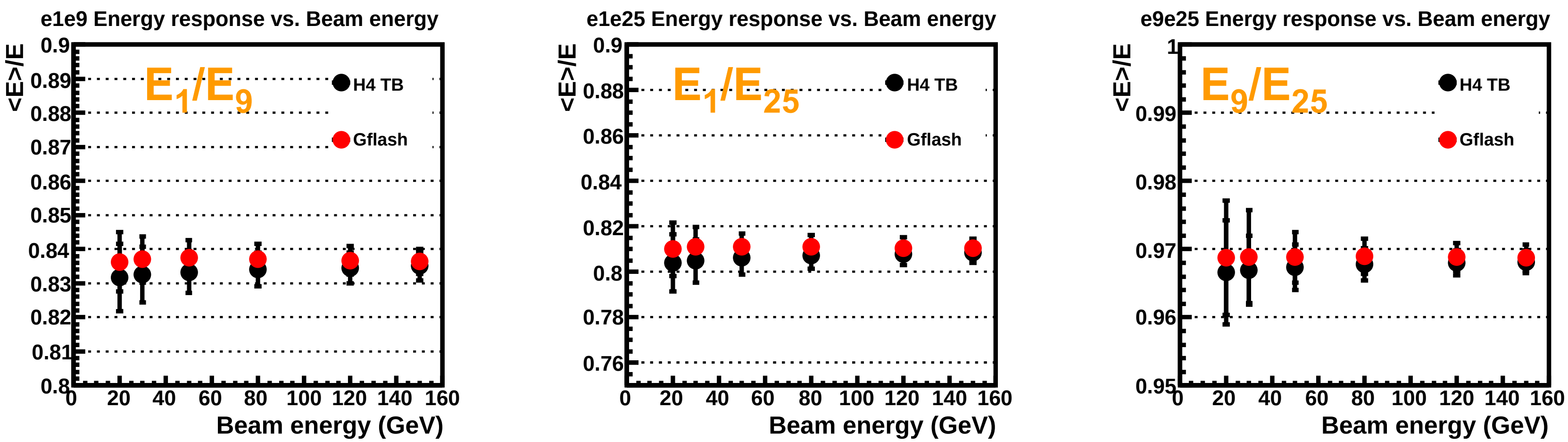


Photons are simulated through conversion of $\gamma \rightarrow e^+e^-$. The resulting longitudinal shower profile from the convolution of e^+/e^- showers match well with profile obtained from Geant4

EM Shower Parameterization



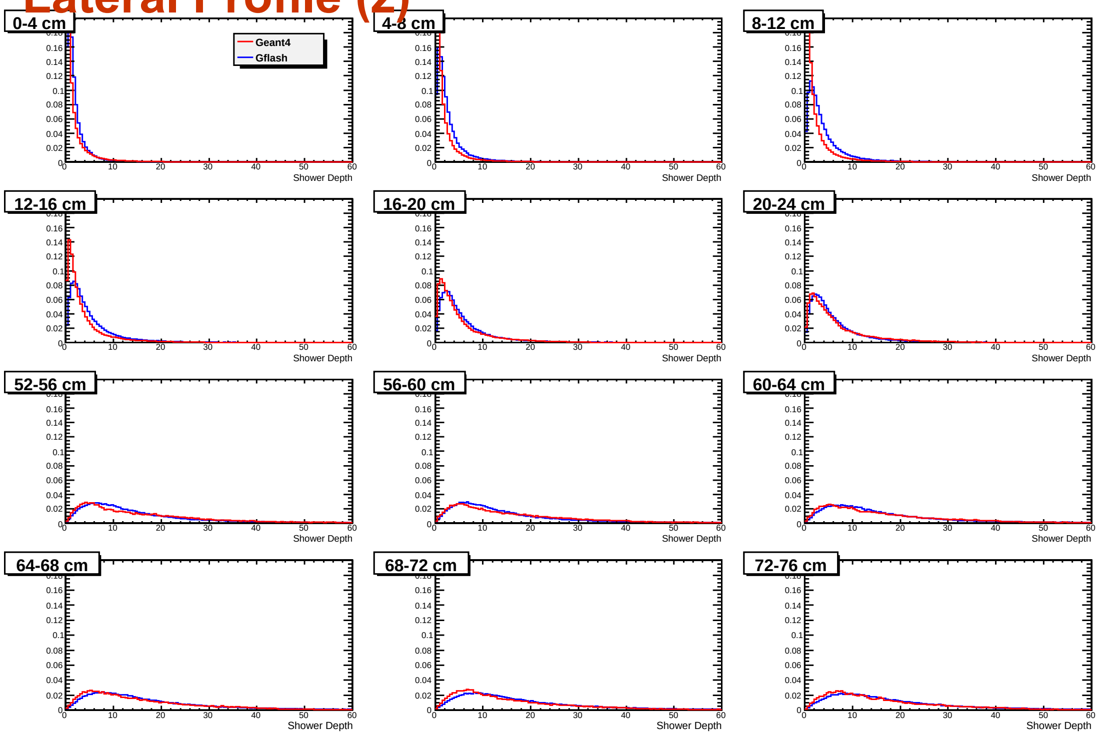
- Follow the same analysis path as done for the H4 TB setup
- Tune shower shapes, E_1/E_9, E_1/E_{25} & E_9/E_{25}, (not absolute scale) for all available energies



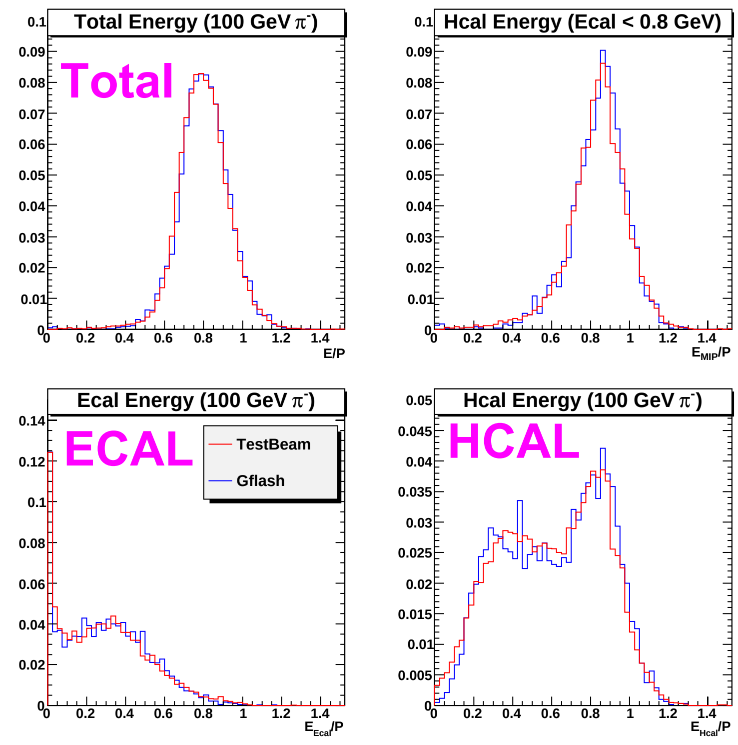
Hadron Showers in GFlash

- Follow hadrons with Geant4 till first interaction. Then substitute with GFlash.
- Parameterization depend on shower start point (ECAL, HCAL, in-between)
- Longitudinal shower profile is parameterized using log-normal distribution while lateral shower profile has a depth dependence parameterization.

Lateral Profile (z)

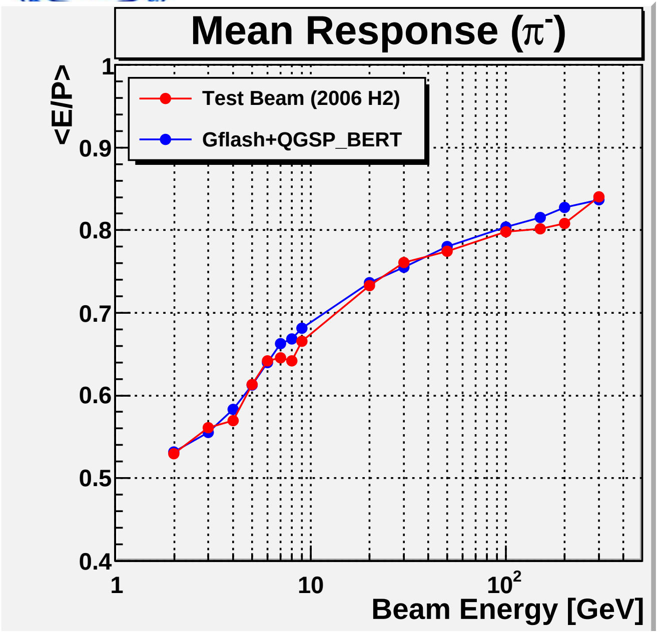


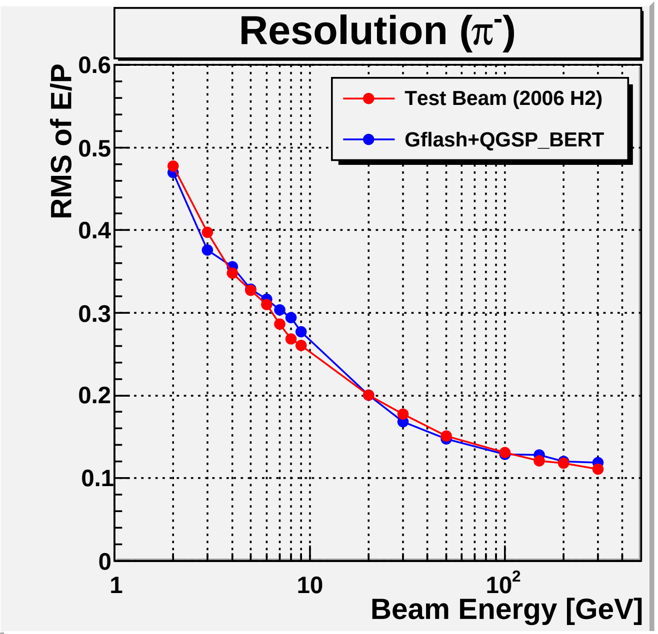
100 GeV π^-

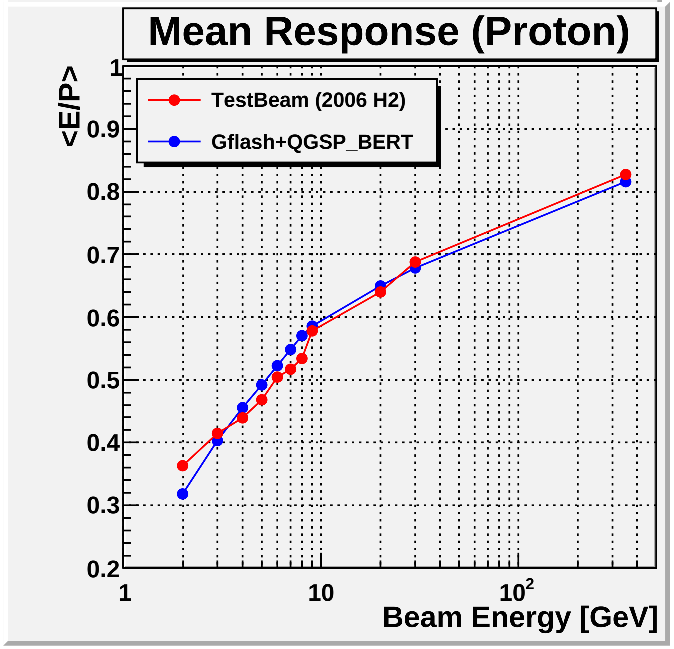


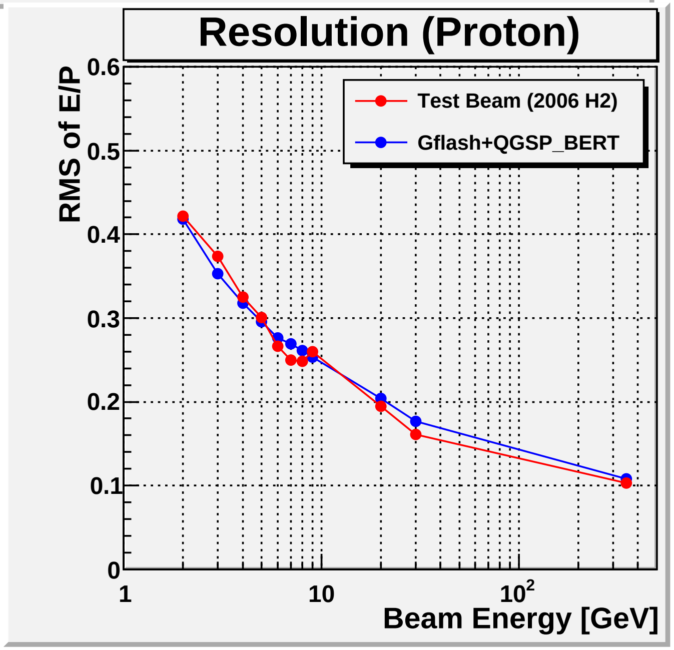
im

Tuning of Hadron Showers





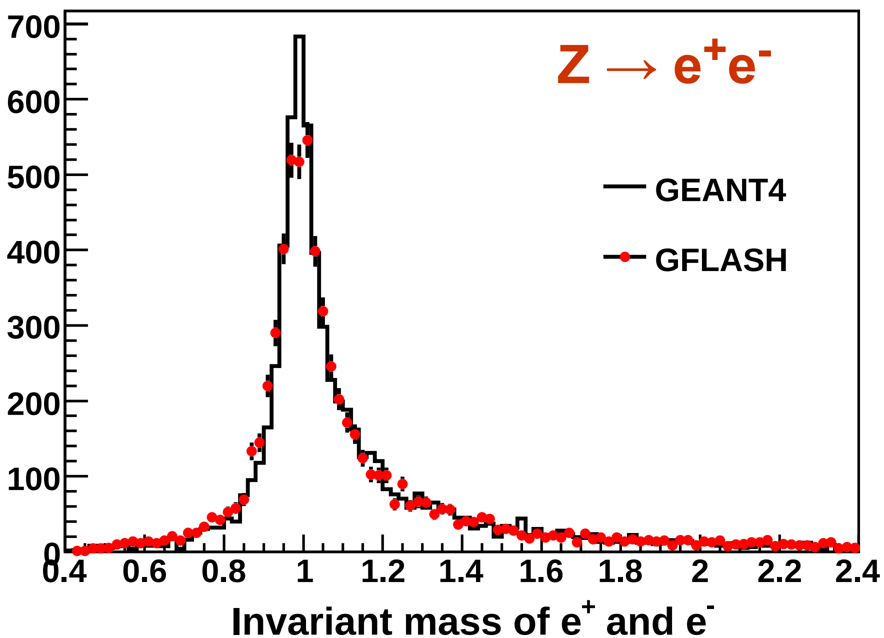


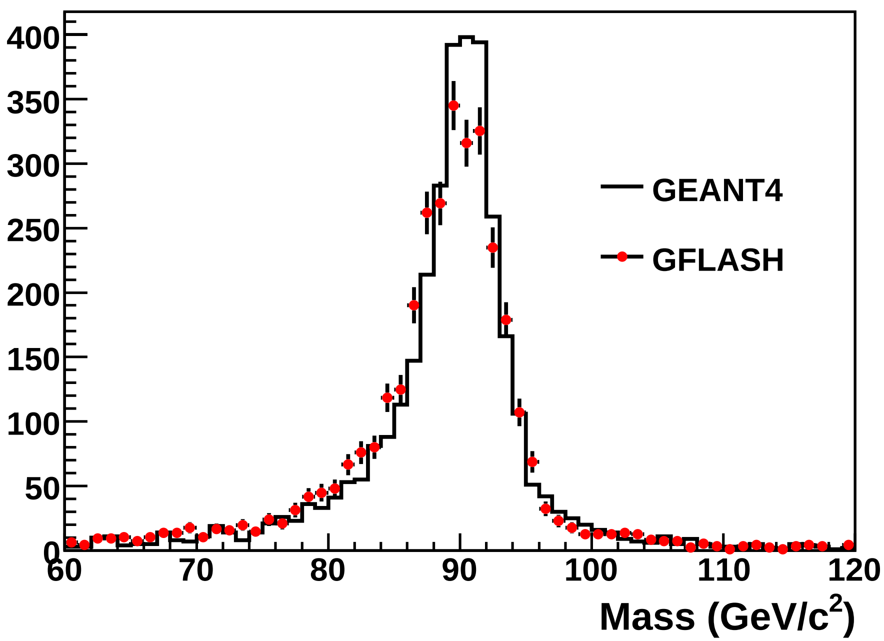


- Tune with test beam data for π's and p's.
- Extend tuning to anti-protons
- Have a special parameterization for HO
- Reduce threshold from current setting (1 GeV)
- Good agreement between Geant4 and GFlash for physics events

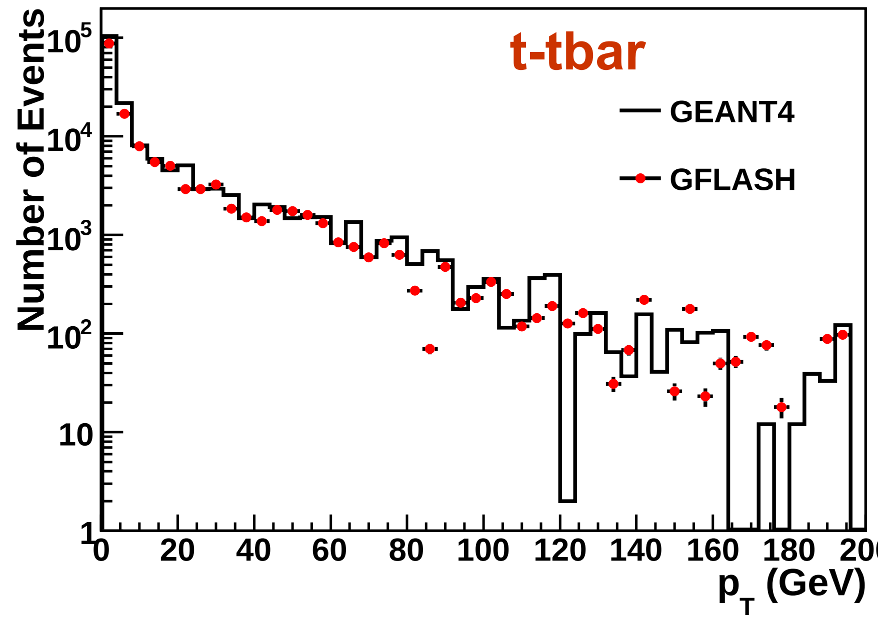
Application to Physics Events

SuperCluster Energy over track P of electron candidate

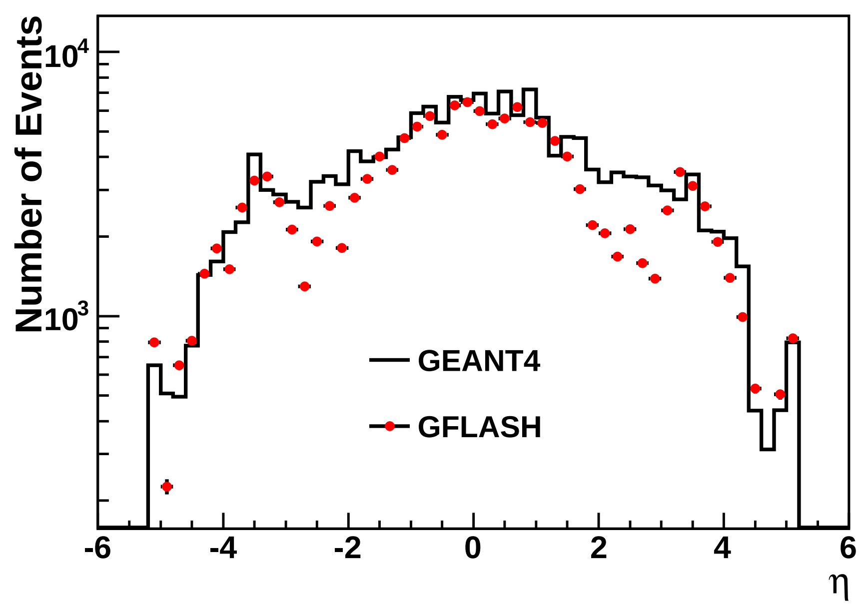




Transverse momentum of leading jet



Eta of leading jet



Summary

- CMS simulation, based on recent version of Geant4, is providing adequate service to understand the collision data
- Based on performance (both physics and computing), the chosen physics list is QGSP_FTFP_BERT_EML
- Full simulation helps in understanding some of the sources of anomalous hits in the detector
- There are a few issues still left which will be addressed in the validation talks
- We have a backup data driven solution using Gflash to address the calorimeter simulation

Backup Slides

Simulation in CMSSW

Root data file (HepMC) | Root data file (add SimHits) | Root data file (add Raw)

Generation → **Detector Simulation** → **Digitization** → **Reconstruction**

Generation: Particle gun, physics generator (vertices, particles)

Detector Simulation: Particle showers, EM Fields, based on Geant4 (SimHits)

Digitization: Modeling of electronic signal (Digis)

Overlay in-time min-bias events from same collision and out-of-time min-bias events from neighboring collisions

Min-Bias Generator

Signal Generator

CPU

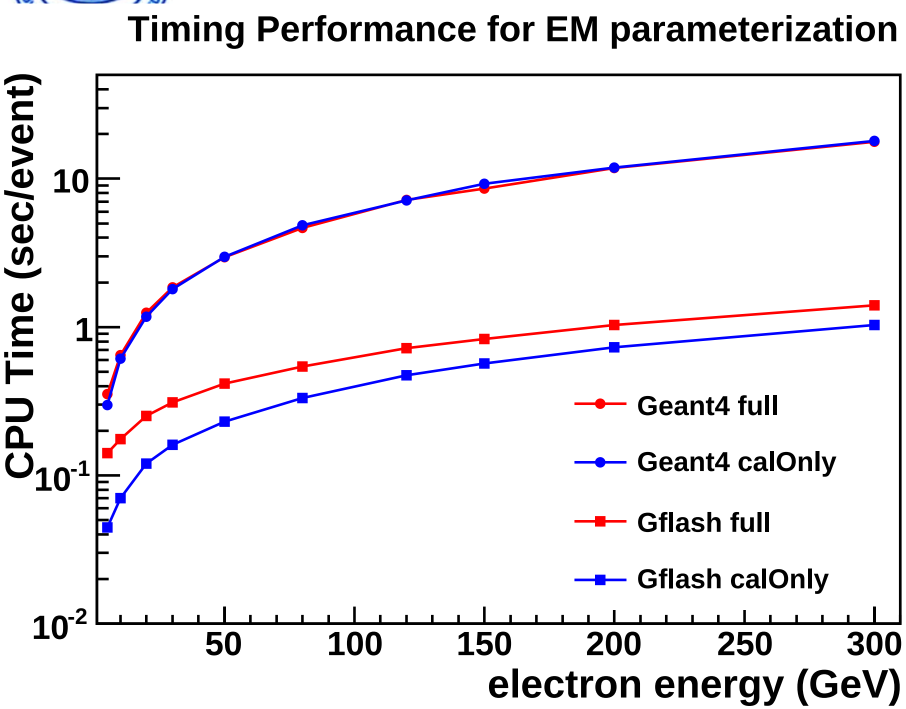
Min-Bias SimHits

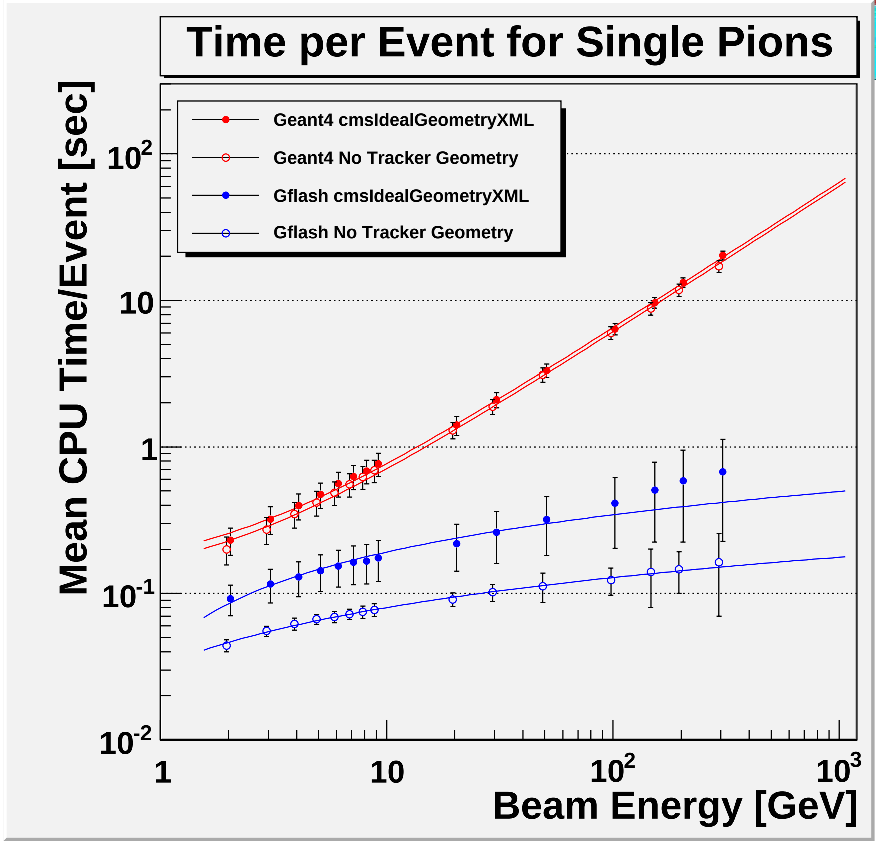
Signal SimHits

Event Digis

Event RawData

Performance Issues





Gain in CPU time by a factor between 3-1000 (3-100) depending on hadron (electron) energy

- Now a complete physics list exists in CMSSW_3_1_X where Geant4 tracking is replaced by GFlash in the barrel/endcap calorimeter
- Need to run it in production for several physics channels and validate that against full simulation