An Object-Oriented Simulation Program for CMS

India-CMS (October, 2004)

Sunanda Banerjee (TIFR)

Authors:

S. Abdulline (FNAL), N. Amapane (U. Torino), V. Andreev (UCLA),
P. Arce (CIEMAT), S. Banerjee (TIFR), T. Boccali (SNS, Pisa),
M. Case (UC Davis), A. De Roeck (CERN), S. Dutta (U. Pisa),
G. Eulisse (NorthEastern U.), D. Elvira (FNAL), A. Fanfani (U. Bologna),
F. Ferro (INFN, Genova), M. Liendl (CERN), S. Muzaffar (NorthEastern U.),
A. Nikitenko (Imperial College), K. Lassila-Perini (HIP),
I. Osborne (NorthEastern U.), M. Stavrianakou (FNAL), T. Todorov (IReS),
L. Tuura (NorthEastern U.), H.P. Wellisch (CERN), J. Weng (Karlsruhe U.),
T. Wildish (Princeton U.), S. Wynhoff (Princeton U.), M. Zanetti (INFN),
A. Zhokin (ITEP), P. Zych (Warsaw U.)

Outline

- Overview
- Run and event management
- Geometry and Sensitive Detector
- Hits
- Generator interface and Physics
- CMS detector simulation and validation
  - Tracker
  - ECAL
  - HCAL
  - Muons
  - Forward detectors
- Magnetic Field
- Parameterized simulations
- Code Quality
- Performance
- Production
- Summary

OSCAR overview

<u>O</u>bject Oriented <u>S</u>imulation for <u>C</u>MS <u>A</u>nalysis and <u>R</u>econstruction

Full CMS simulation based on the Geant4 toolkit

- <u>Geant4</u>: physics processes describing in detail electro-magnetic and hadronic interactions; tools for the CMS detector geometry implementation; interfaces for tuning and monitoring particle tracking
- <u>CMS framework</u>: application control, persistency, common services and tools (magnetic field, generator interfaces and support for MC truth, infrastructure for hits and readout units,…), “action on demand” to selectively load desired modules, configure, tune application
- CMS changed from CMSIM/GEANT3 to OSCAR/GEANT4 end 2003;
- OSCAR used for substantial fraction of DC04 production; will be used for physics TDR production
- <u>CPU</u>: OSCAR ≤ 1.5 x CMSIM - with lower production cuts!
- <u>Memory</u>: ~110 MB/evt for pp in OSCAR ≈ 100 MB in CMSIM
- <u>Robustness</u>: from ~1/10000 crashes in pp events (mostly in hadronic physics) in DC04 production to 0 crashes in latest stress test (800K single particles, 300K full QCD events)

Run

Relies on COBRA for program's *main;* COBRA takes over and handles the application with a *SimApplication* and a *SimEvent* in the core

SimApplication instantiates and launches an event source factory the *SimEventSource*, which is an abstract reader of simulated events from the original source

SimEventSource instantiates the Mantis *RunManager*

RunManager instantiates a *G4RunManagerKernel* and controls standard components such as the selection and instantiation of generator, magnetic field and physics lists and interfaces to the run, event, stacking, tracking and stepping actions; it also handles

- Storage/retrieval of random number seeds for run and events
- Storage/retrieval of the cross-section tables built for a given detector configuration and physics list. Reading pre-built cross-section tables reduces initialization time by factor ~4

Event

SimEvent, inheriting from the COBRA *SimEvent*, manages the Monte Carlo truth – common for and sharable by all CMS applications (reconstruction, visualization etc); it consists of an interface to the transient event. (be it Geant3, Geant4, fast simulation) and an interface to a Geant4 event

Monte-Carlo truth, assembled at the *EventAction*, consists of

- the main event, its assigned weight and its type
- all particles with their tracks, vertices and decay trees from the original generator event
- all tracks produced during simulation and flagged for saving

Monte-Carlo truth organized so as to allow navigation from hits to their corresponding tracks and parent vertices

Geometry

Detector description in CMS is handled in the CMS Detector Description Database, DDD, a COBRA subsystem

Mantis provides mechanisms to convert DDD solids and materials to their Geant4 counterparts as well as the logical and physical volumes needed to build the Geant4 geometry for the chosen description

DDD SpecPars mechanism allows the definition of special parameter sets (extra attributes, field parameters, range cuts etc) to be associated with selected detectors

More than one million volumes are used to define CMS detector setup

Sensitive Detector

inherits from *G4VSensitiveDetector* and its concrete implementation implements the Geant4 *ProcessHits* method

is registered to the Geant4 sensitive detector manager but is instantiated and "attached" to the corresponding geometrical volumes at run time according to the set-up described in the configuration DDD/XML file

There is a possibility of "instrumenting" (making sensitive) any volume, for prototyping purposes or in order to facilitate studies of energy losses in dead materials or specific parts of the detector

Hits

Hit processing and hit collection are handled by the individual detectors, based on COBRA classes common for and sharable by all CMS applications; these common classes are managed by the COBRA *Profound* package

COBRA read-out factories handle the hit formatting as required for the digitization, which is handled outside the simulation, by the CMS reconstruction program *ORCA*

Generator Interface

Based on the COBRA GeneratorInterface packages and services. It provides a *trigger* method to produce a *RawHepEvent* or *HepMC::GenEvent*;

RunManager instantiates the chosen generator. All generators can be run-time configured in terms of

- the maximum number of events they can return
- the first event to be read
- An event vertex generator to be used (none, flat, Gaussian, test-beam specific)

Available generators:

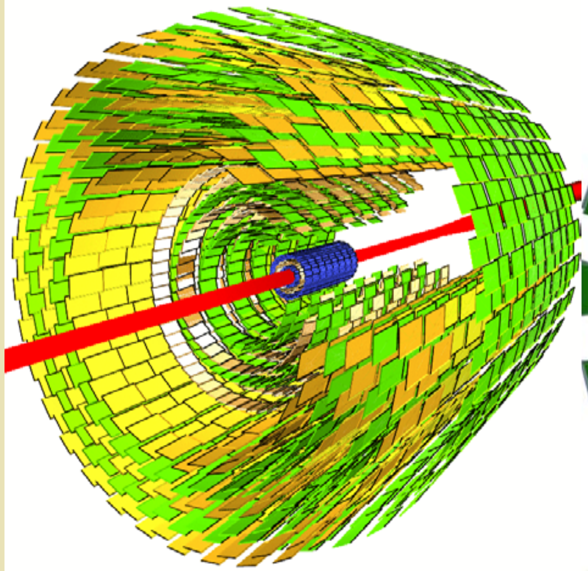
EventGunReader, EventNtplReader , *EventTxtReader*, *EventPythiaReader, EventStdHepReader, EventHepMCReader*

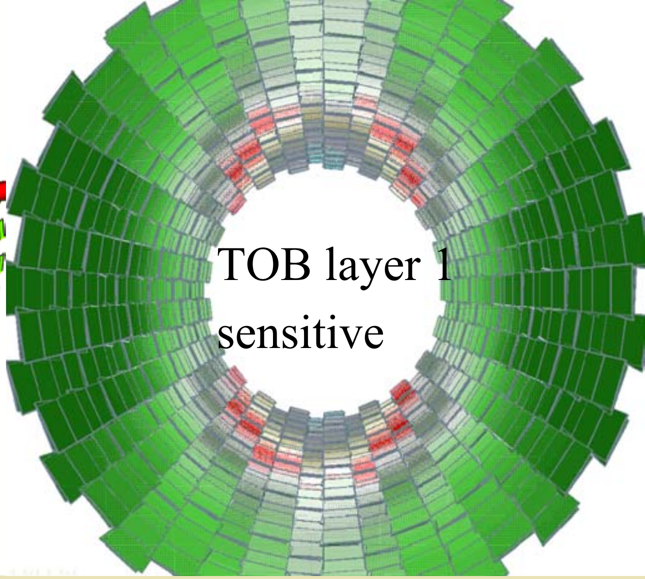
Physics

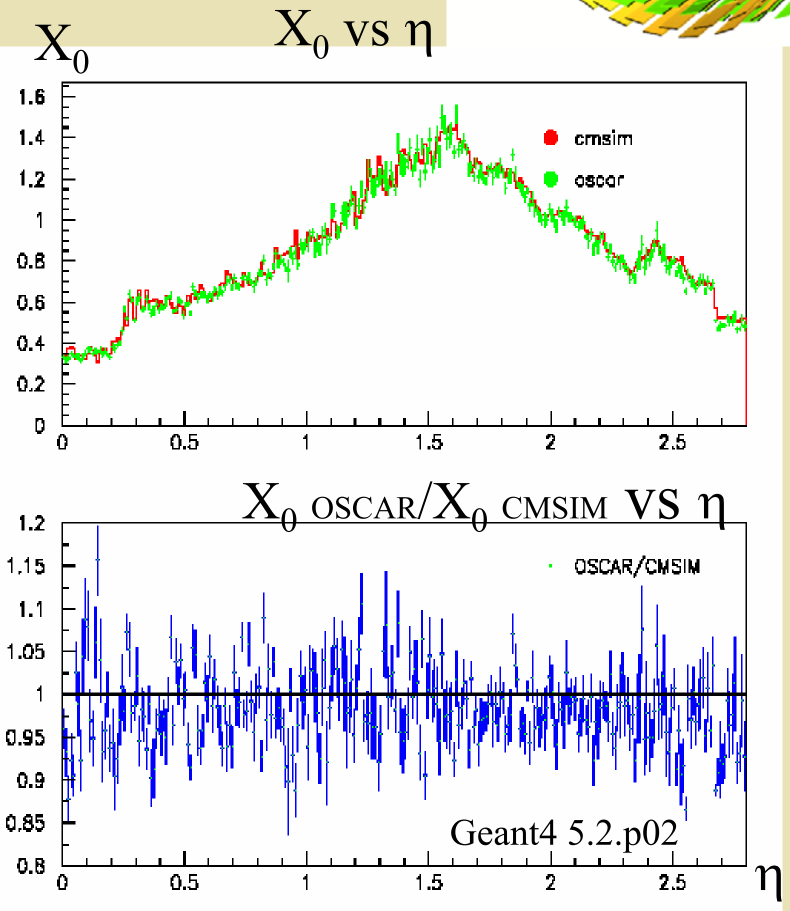
- an abstract physics list factory allows run-time selection and configuration of specific physics list
- physics cuts (i.e. range cuts) are implemented as cuts per region (set of volumes)
- the regions with the set of volumes (typical scheme distinguishes between “sensitive” and “dead” regions) and the cut values for electrons, positrons and photons are read at run-time from a DDD/XML file

Tracker

Detailed description of all active and passive components; material budget







Critical requirements for physics studies with tracker

Correct, navigable Monte Carlo truth (particle, track, vertex, history) with trace-ability of initial primary particle

Special treatment of hard brem with the assignment of new track for electron above threshold (500 MeV)

⇒ Extensive validation in terms of tracking and hit distributions

Tracker *cont'd*

Hits from minimum bias in Tracker

Pixel cut in G3 too high

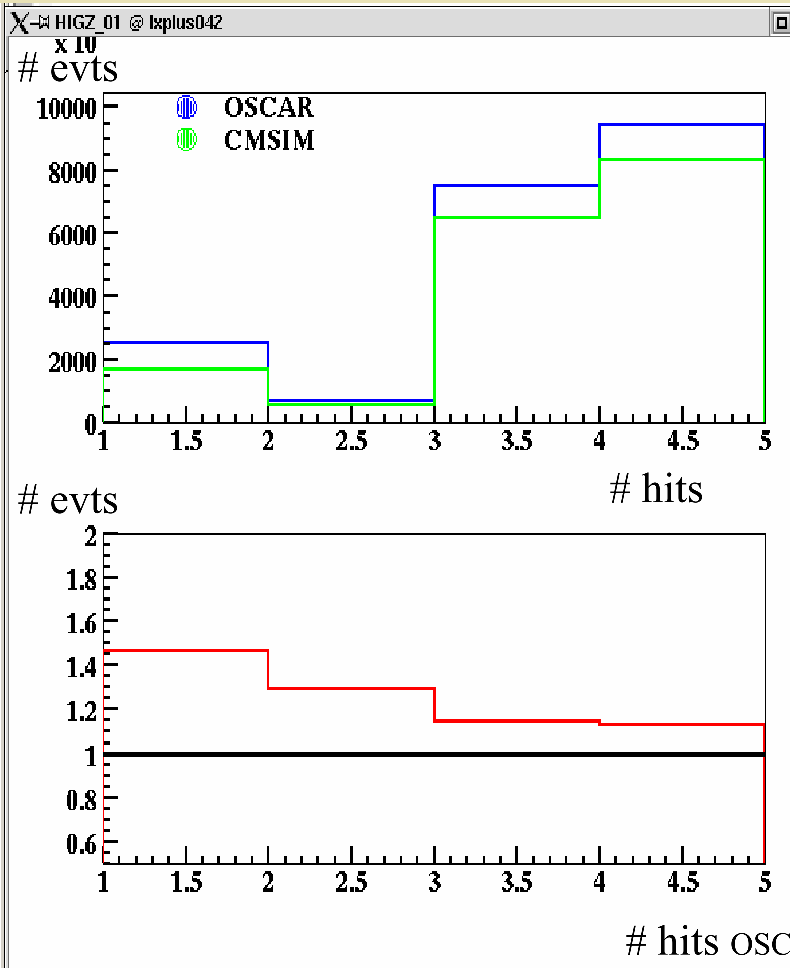
⇒10% increase expected

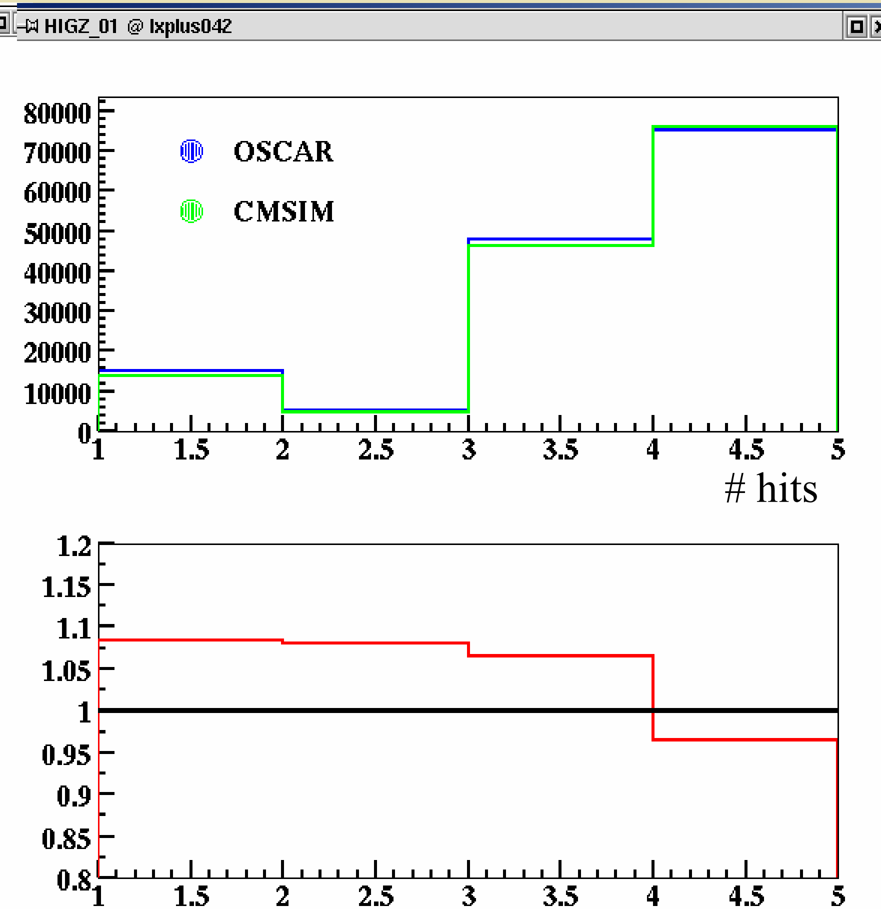
±5% differences in Si not significant

PixelBarrel PixelEndcap SiBarrel SiEndcap

Raw simulated hits

Reconstructed hits





hits OSCAR / # hits CMSIM

Geant4 5.2.p02

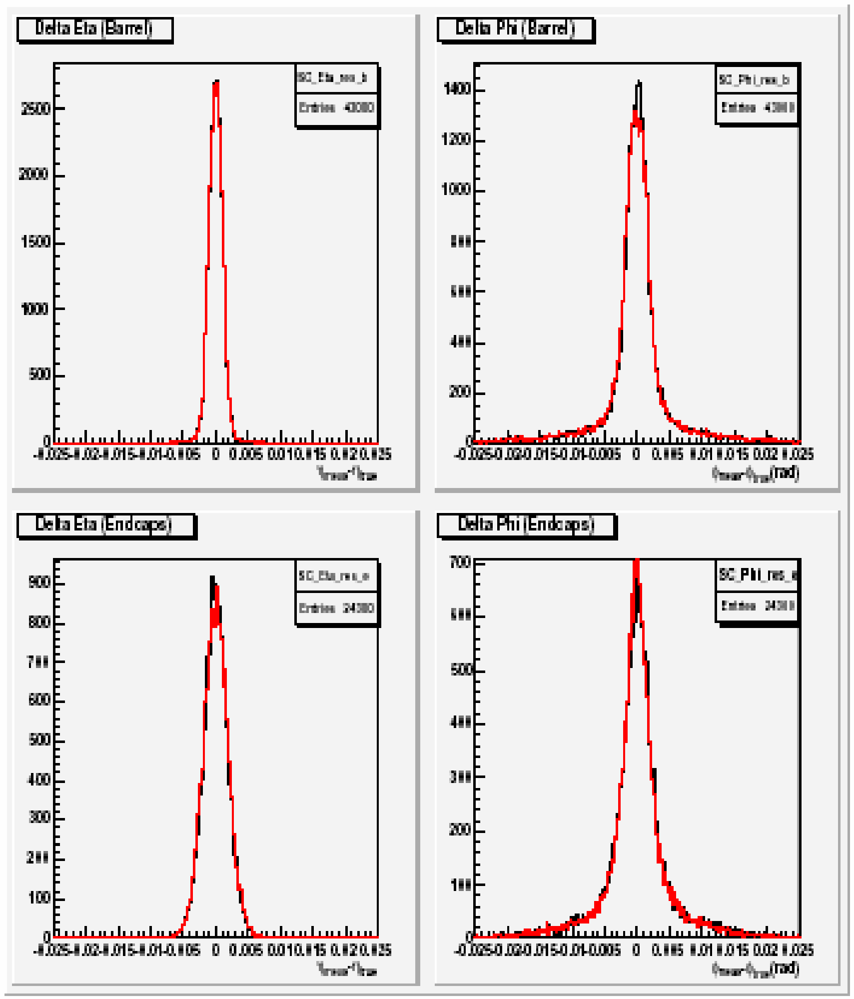
Electromagnetic Calorimeter (ECAL)

Comparisons with CMSIM/G3 and test beam data

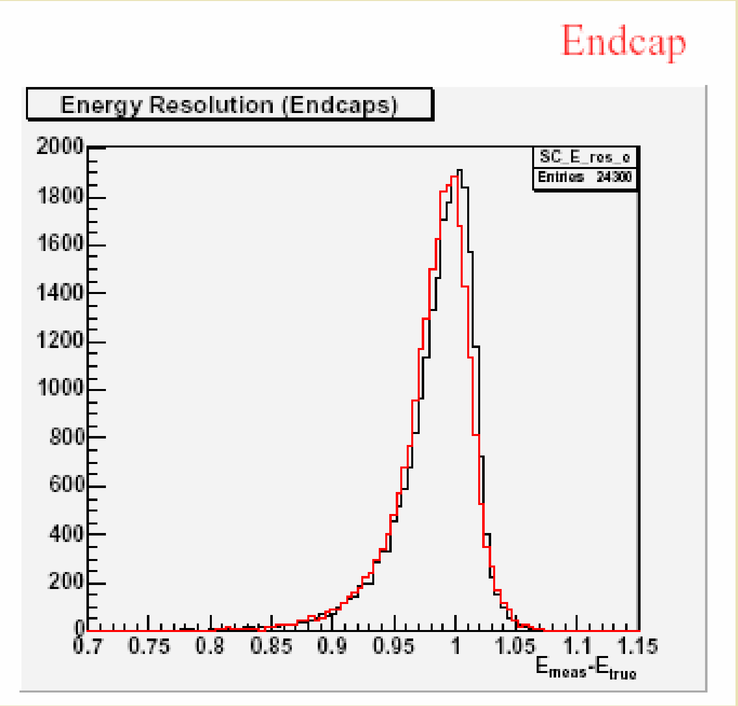
- Energy and position resolution
- Shower shape
- Hadronic showers
- Level-1 e/m trigger response
- Preshower response
- Performance studies

Position resolution

Red – OSCAR_2_3_0_pre5, black – CMS132



ECAL *cont'd*

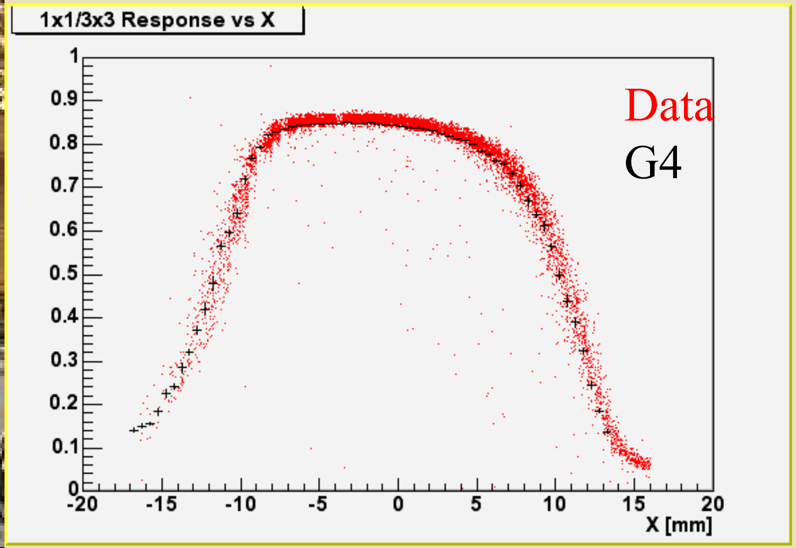


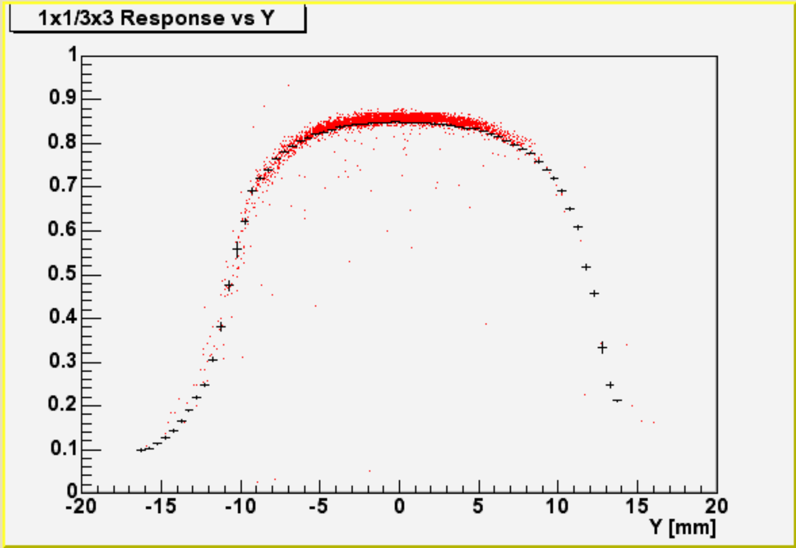
Energy resolution

ECAL standalone resolution for electrons, with bremsstrahlung recovery

Geant4 5.2.p02

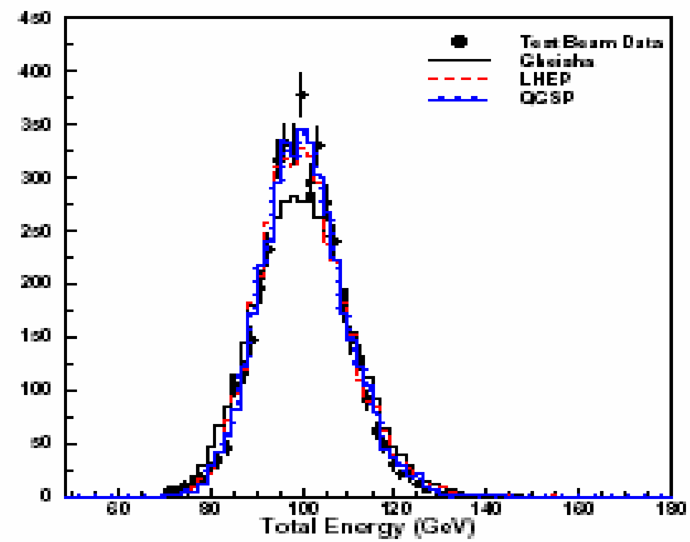
Single crystal containment: E_{1x1}/E_{3x3} versus position

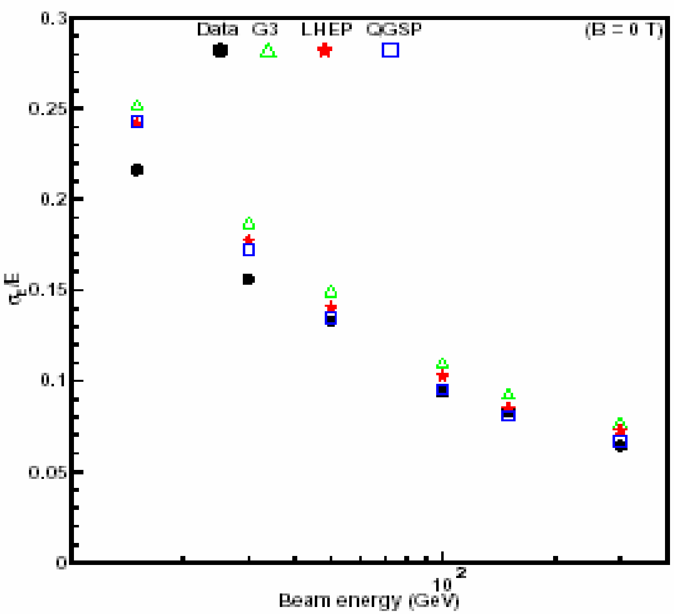




Hadron Calorimeter (HCAL)

Energy resolution

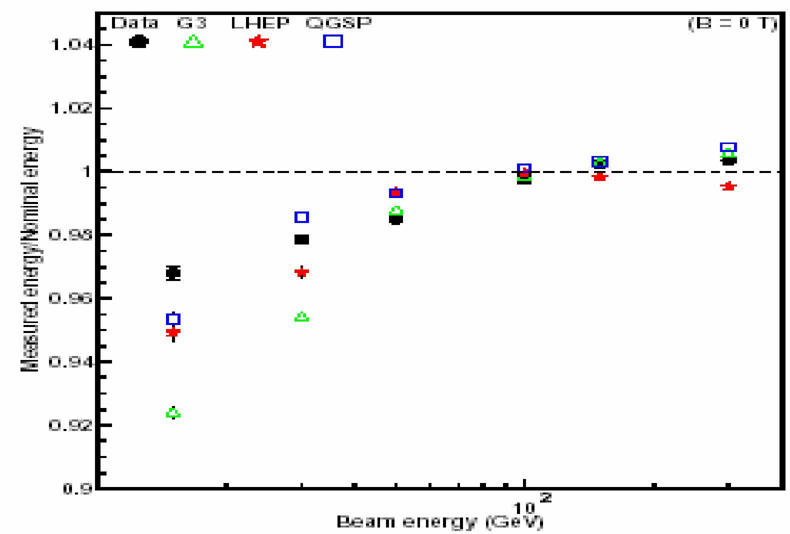




Extensive validation program with comparisons to G3 and several test beam data sets, incl. combined ECAL-HCAL runs; also in context of LCG simulation physics validation project

Geant4 5.2.p02

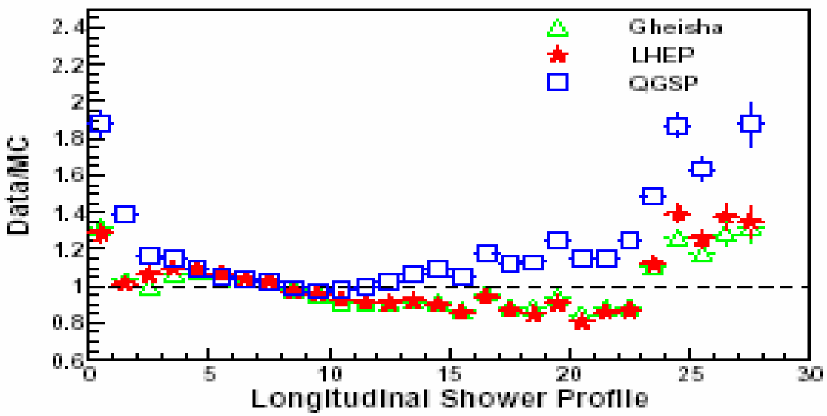
Non-linearity in energy response

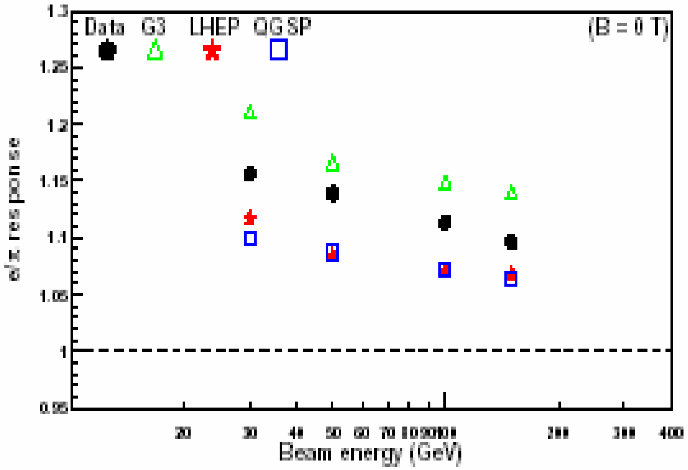


HCAL *cont'd*

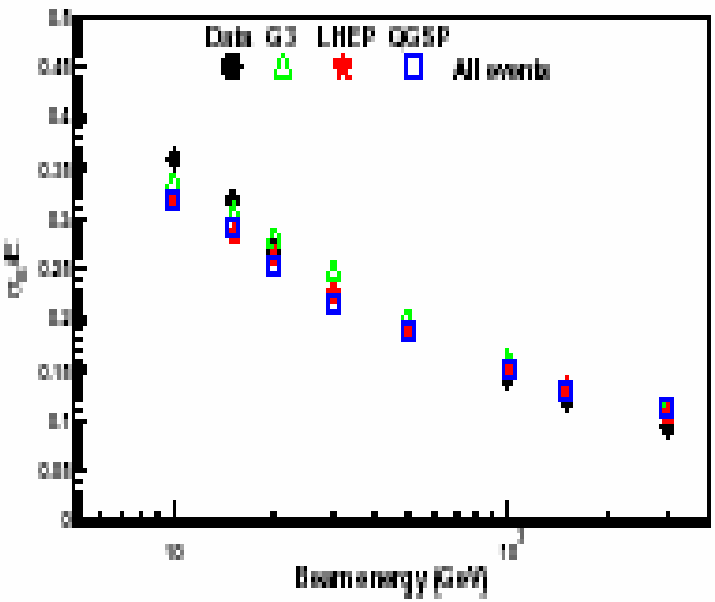
e/π: G3 ~3% higher, G4 ~4% lower

Longitudinal shower profile

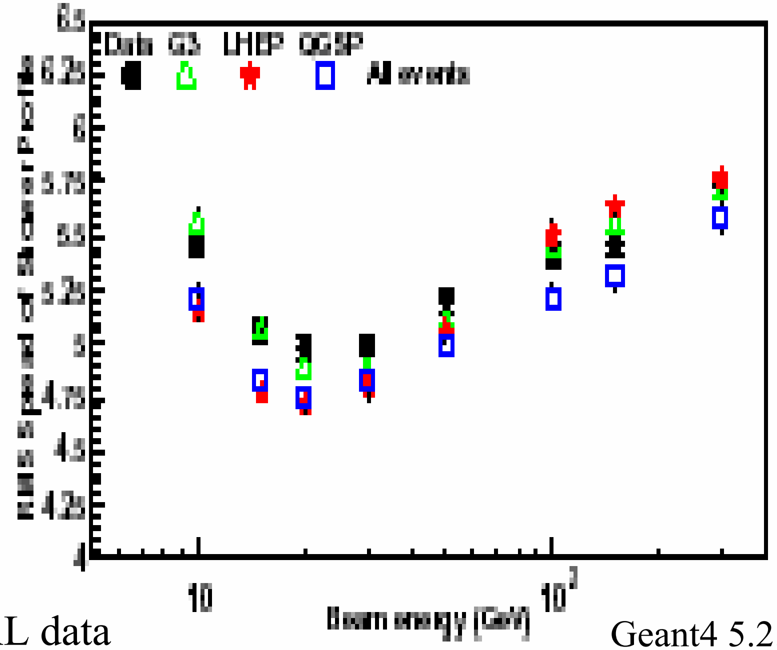




Energy resolution



Longitudinal shower profile



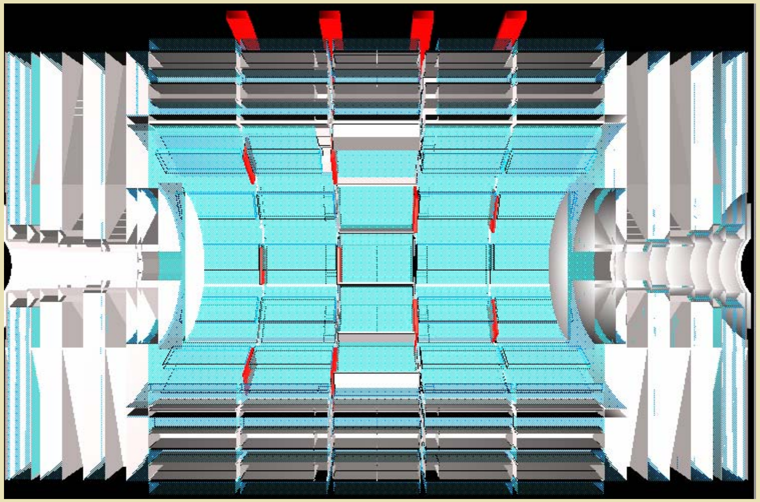
ECAL+HCAL data

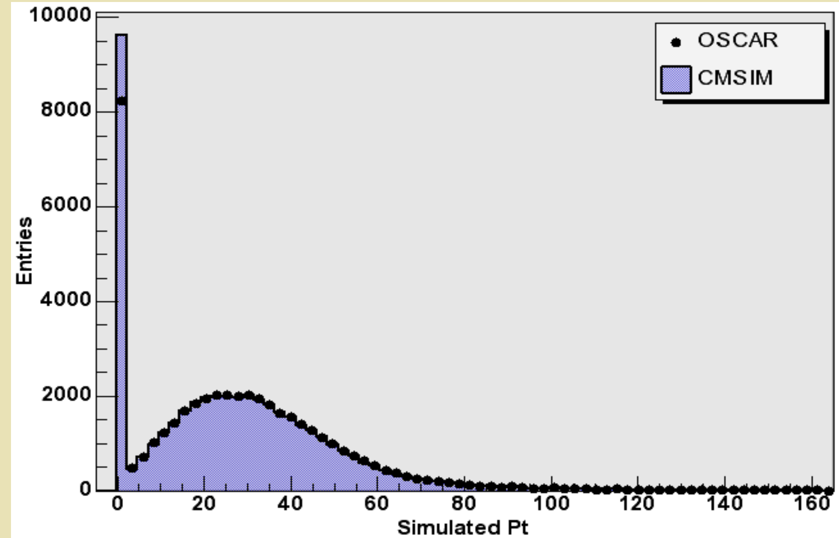
Geant4 5.2.p02

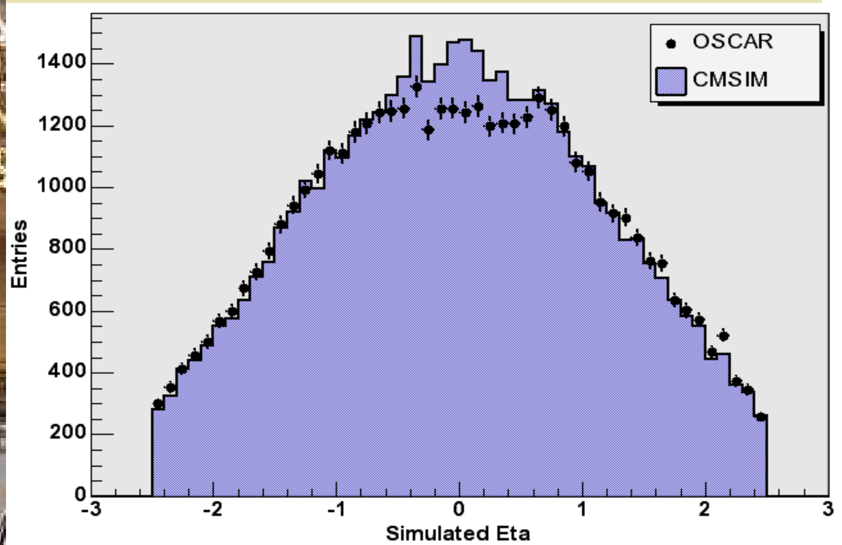
Muons

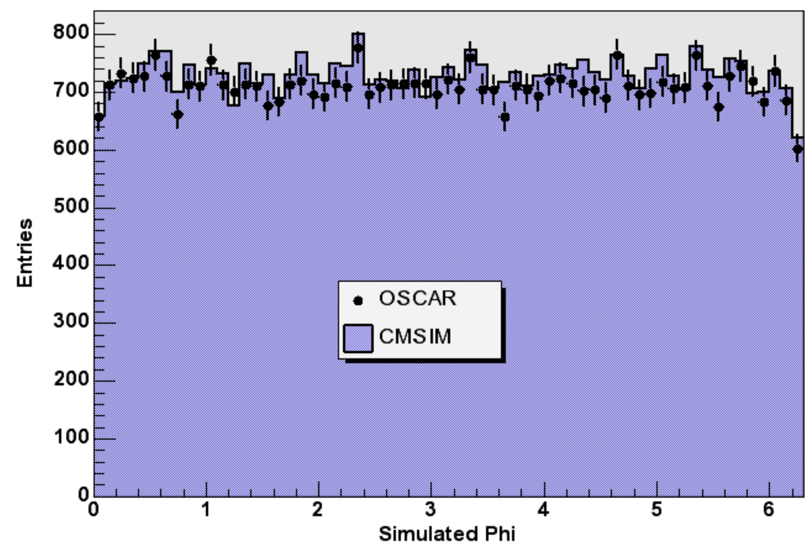
Detector and physics validation in terms of tracking and hit distributions with single μ's and Drell-Yan pairs (Mll=2TeV), and physics events (H→ZZ→4μ)

Muon detector layout



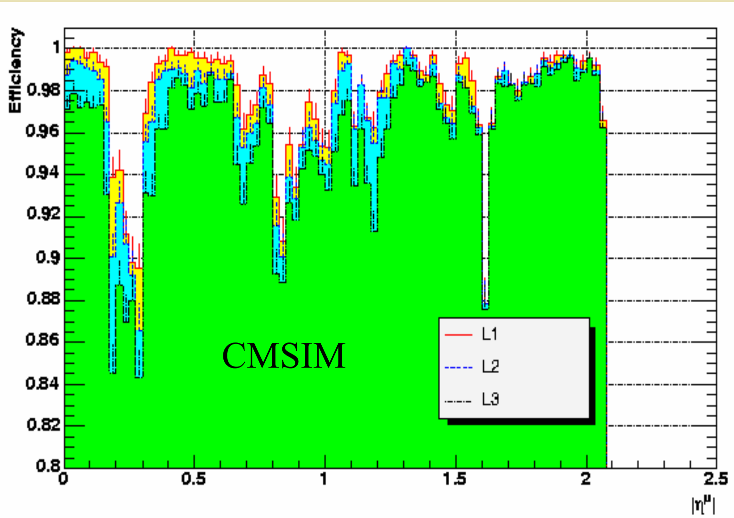




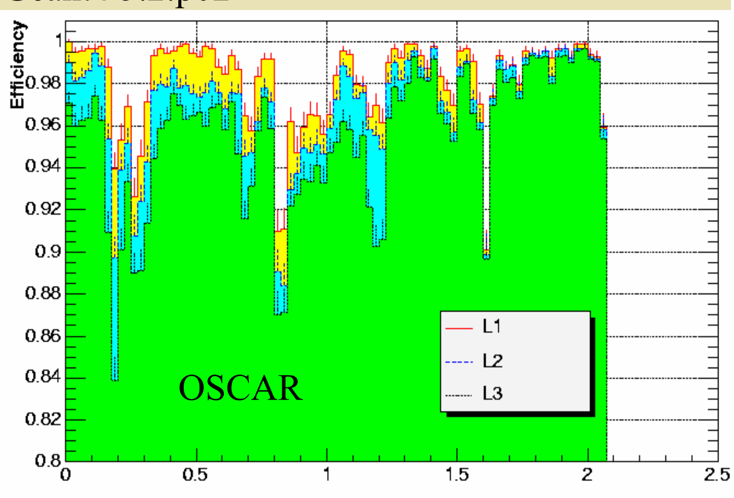


Muons *cont'd*

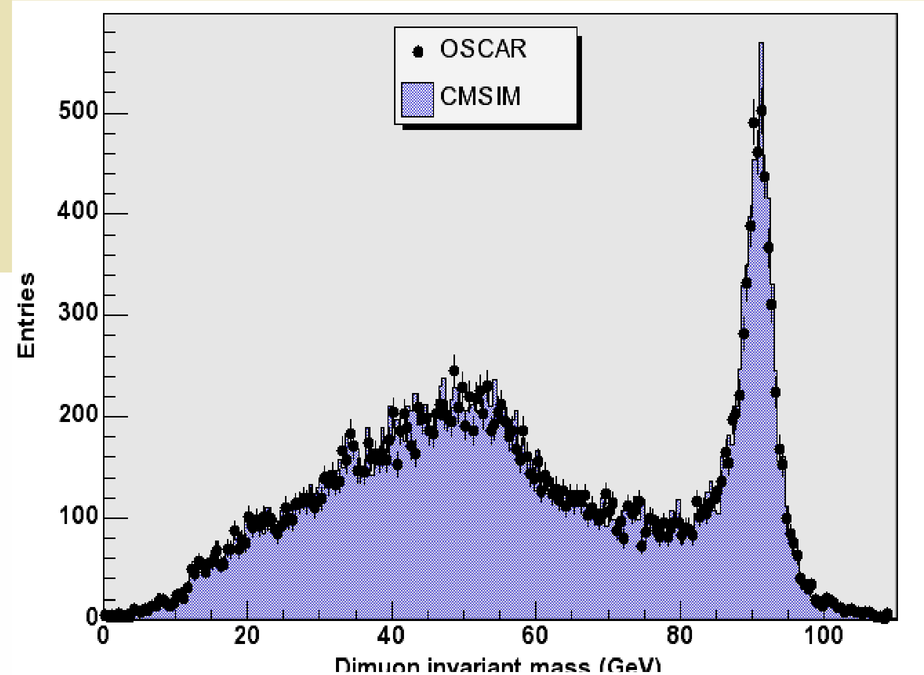
Trigger efficiency vs η

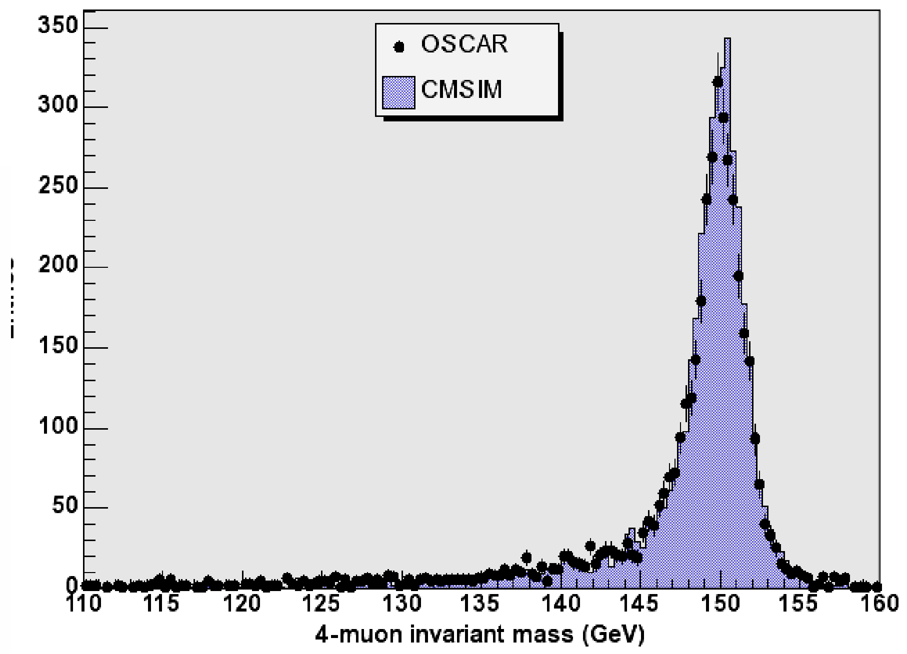


Geant4 5.2.p02



$H \to ZZ \to 4\mu$, $M_H = 150$ GeV



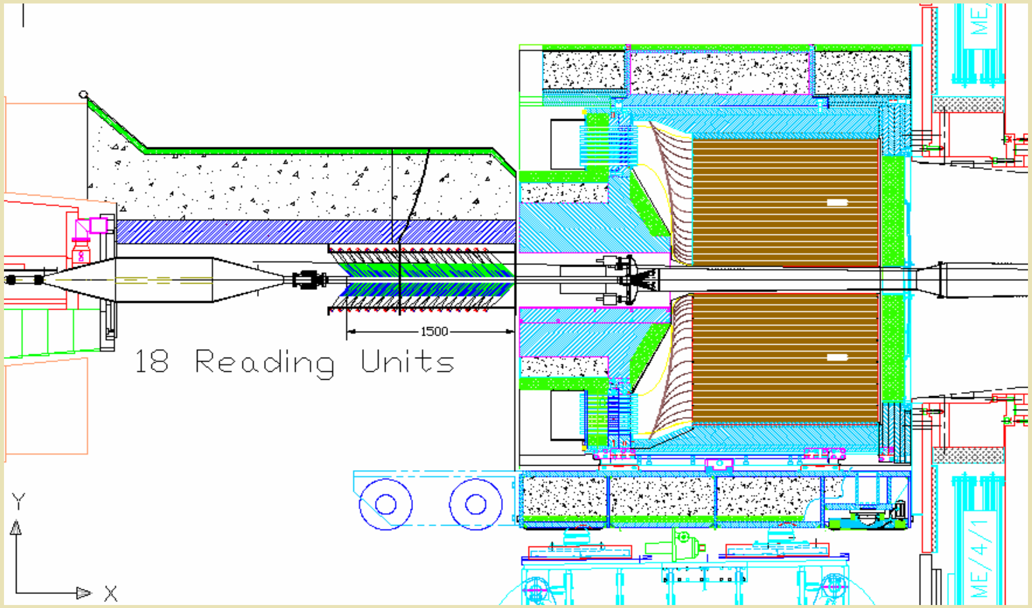


Forward Detectors

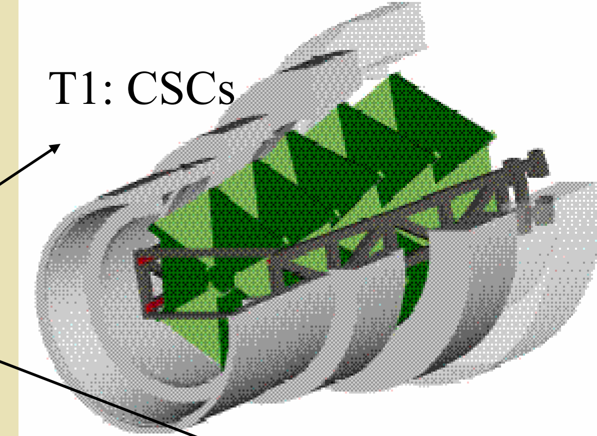
for diffractive and heavy ion physics

Castor Calorimeter
at 14.37 m (5.3 <η< 6.7)

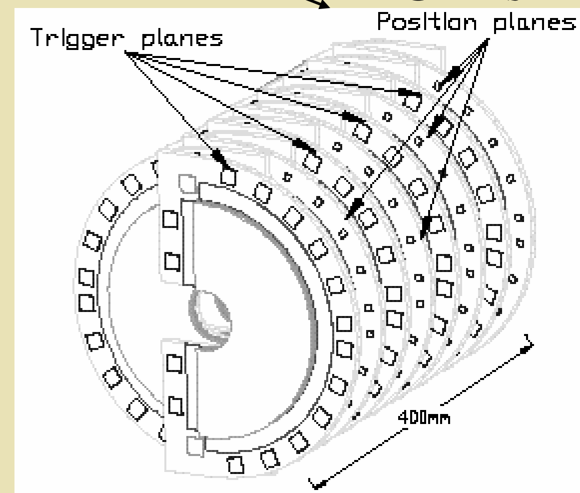
Totem Telescopes
at 7.5 m < z < 13.5

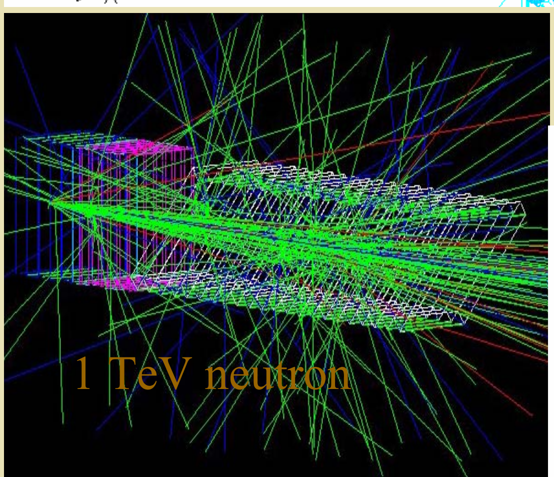


T1: CSCs

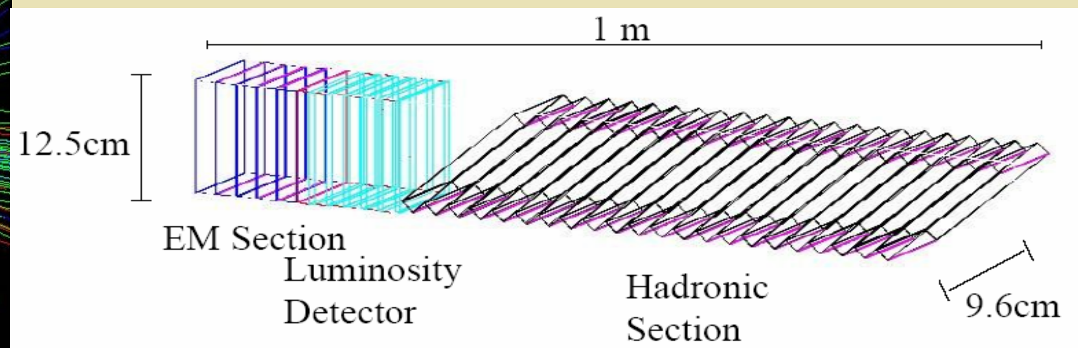


T2 GEMs





ZDC: Zero degree calorimeter
at 140 m



Magnetic Field

• inherits from *G4MagneticField* and implements the Geant4 method *GetFieldValue*, so that any standard CMS magnetic field can be loaded by the COBRA *CMSMagneticFieldLoader* and passed to Geant4

• is an observer of *world volume*, i.e. instantiates a field when notified that the detector has been built

• allows choice and configuration of *G4MagIntegratorStepper*, chord-finder and propagator, using the DDD SpecPars mechanism

• allows modeling, instantiation and configuration of local field managers for chosen detectors and particles, again using the DDD SpecPars mechanism

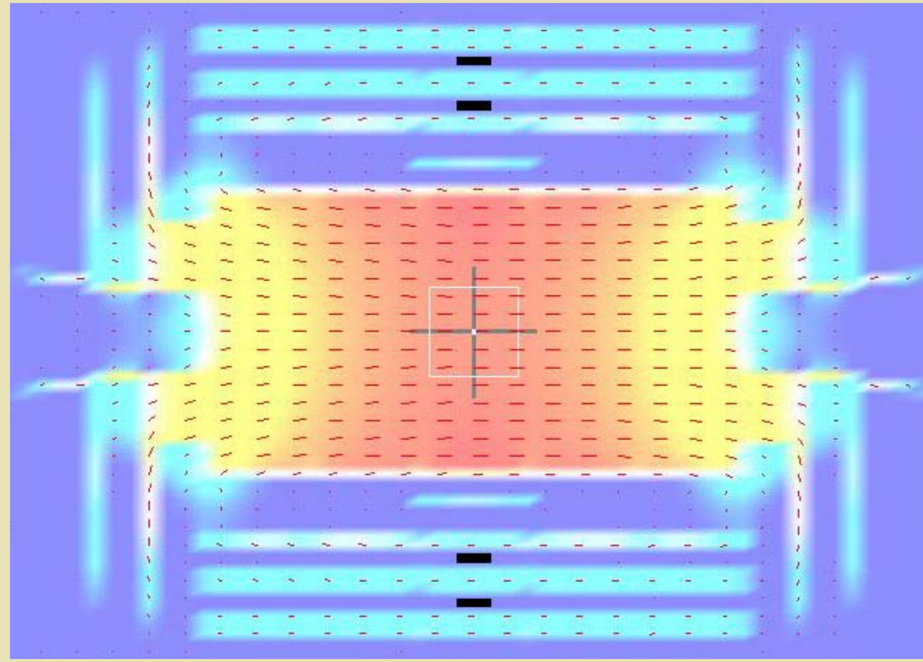
Local field managers, an important Geant4 feature, handle particles that are either of little interest or unlikely to escape a given detector or set of volumes and can therefore be propagated with relaxed criteria as to the accuracy of the stepping and chord finding

Designed to optimize simulation and reconstruction

Based on dedicated geometry of "magnetic volumes"

Decouple volume finding and interpolation within a volume

Field Map - TOSCA calculation



Time spent in magnetic field query (P4 2.8 GHz) for 10 minimum bias events (with delta=1mm) 13.0 s vs 23.6 s for G3/Fortran field

⇒ new field ~1.8-2 times faster than FORTRAN/G3

GEANT4 volumes can be connected to corresponding magnetic volumes

⇒ avoid volume finding ⇒ potential ~2x improvement

With G4, possible to use local detector field managers

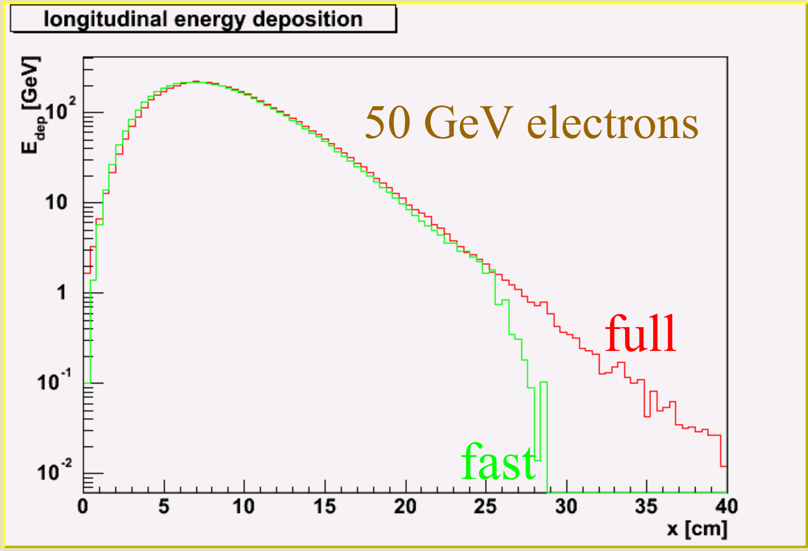
Parameterized Simulations

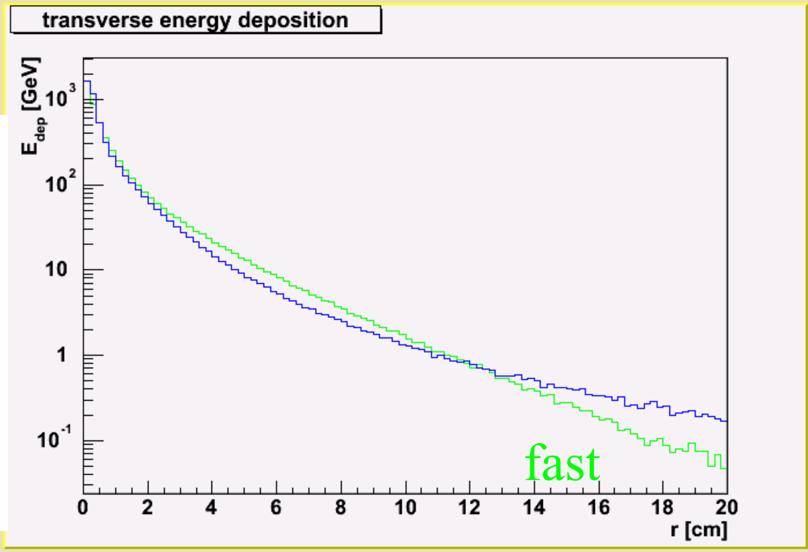
G4FLASH

Implementation of fast EM shower simulation in Geant4/OSCAR, using GFLASH parameterized showers

- tuning in progress

Geant4 6.2





Timing studies

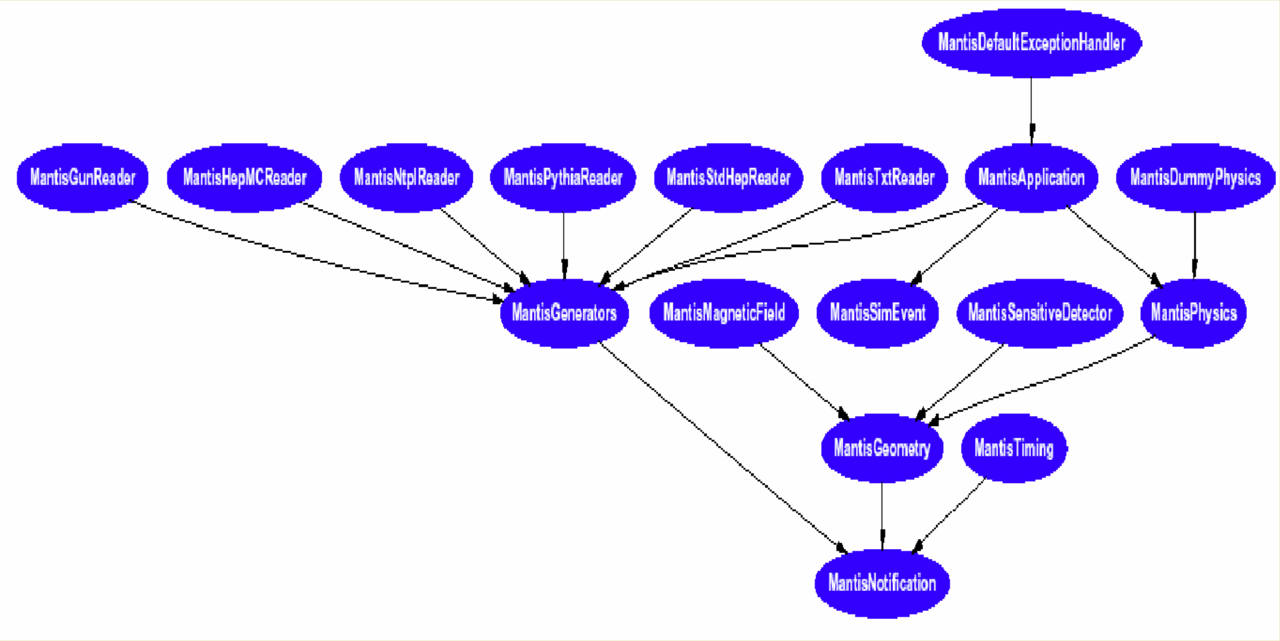
Electron energy	Time/event full simulation	Time/event fast simulation
1 GeV	0.8 s	0.5 s
10 GeV	1.9 s	0.6 s
100 GeV	16 s	0.7 s
300 GeV	57 s	1.0 s

Code Quality

Code is distributed in three projects:

COBRA, OSCAR, Geometry

- The Framework *(Mantis)* has 17 packages in 5 levels
- CMS specific code are in *OSCAR* in 31 packages
- *Geometry* contains parametrisation and data to define detector geometry, sensitive detector, …



No cyclic dependency in the code

Performance

OSCAR performance optimized with a twist… (in heavy ion collisions)

55K generated particles, with 97K tracks from 80K vertices kept at the end of event

G3/CMSIM: chop event in slices of 100 tracks each and run them separately; *needed due to limitations from ZEBRA*

OSCAR/Geant4: run full HI events

Factor 5 performance improvement by improved calorimeter track selection and hit processing

Event cut in slices of 100 particles

CMSIM (G3)	230 min
OSCAR_2_4_5 (G4 5.2.p02)	320 min
OSCAR_3_4_0 (G4 6.2.p01)	180 min

Full event

CMSIM (G3)	Not possible
OSCAR_2_4_5 (G4 5.2.p02)	1010 min
OSCAR_3_4_0 (G4 6.2.p01)	210 min *(*)*

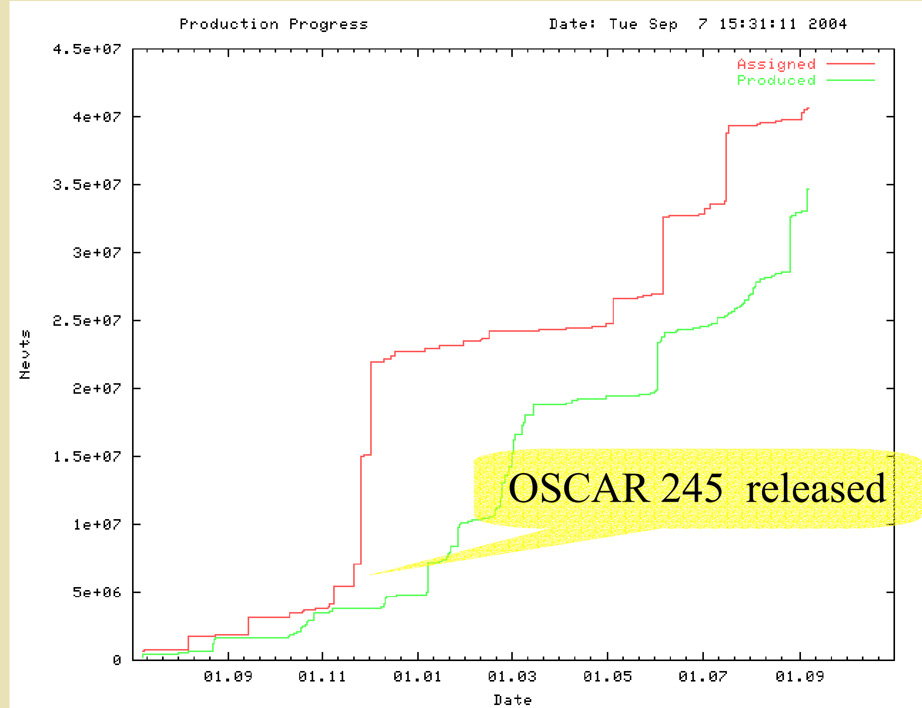
time/evt in given machine

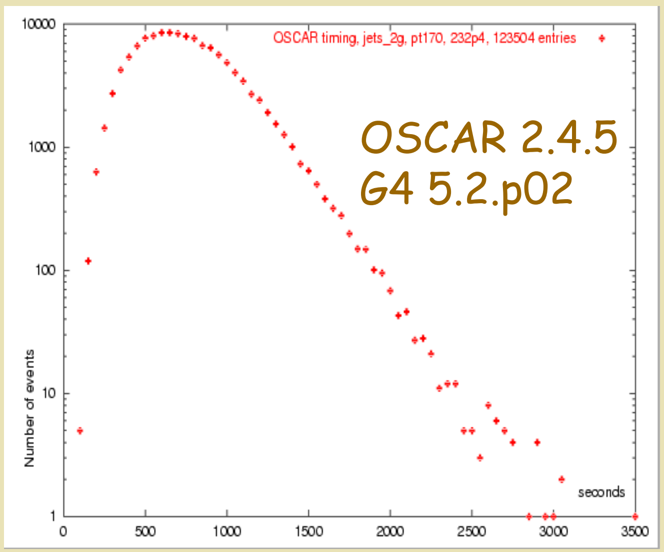
(*) 2.3 CPU hrs on P4 3.2 GHz

…effect entirely negligible in pp events!

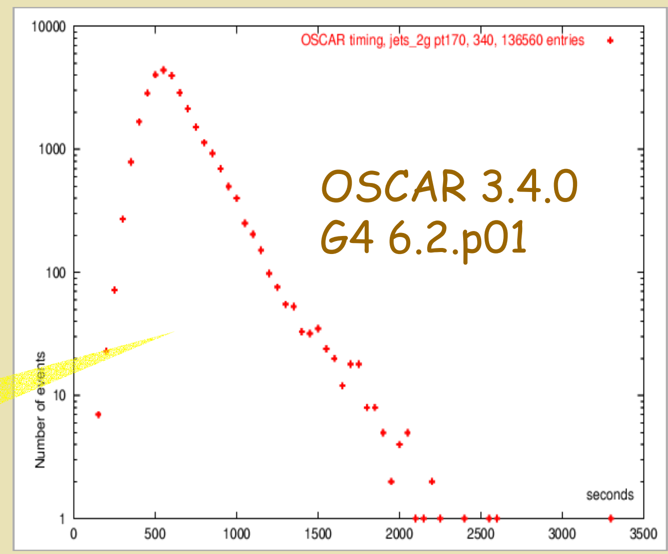
Production

OSCAR 2.4.5 in use for 10 months; longest-used version of any s/w in production; accounts for 35M of 85M events





wall-clock time normalized to 1 GHz CPU



Peak not moved, but tail significantly narrower. Nicer for production, easier to spot stuck jobs

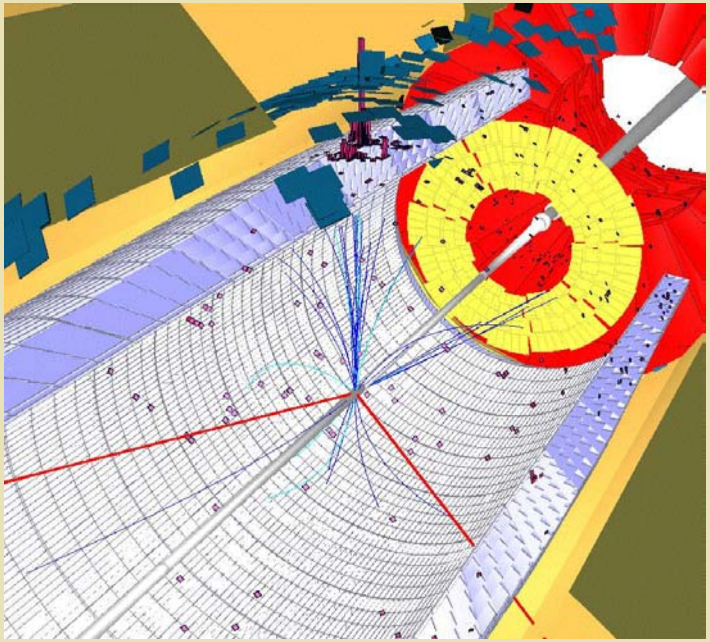
Summary and Outlook

In CMS, OSCAR, the OO simulation program based on the Geant4 toolkit, has successfully replaced its Fortran/Geant3 predecessor. It has been validated and adopted by all CMS detector and physics groups. It has proven robust and performant, easily extensible and configurable.

CMS has now entered sustained-mode production:

10M physics events/month through the full chain (simulation, digitization, …, DSTs)

SUSY event (leptons, missing E_T)



visualization with IGUANACMS