# Distributed Computing Grid Experiences in CMS

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*Abstract*-- **The CMS experiment is defining the computing system capable of serving, processing and archiving the large number of events that will be available when the detector will start collecting data. During the year 2004 CMS undertook a large scale data challenge to demonstrate the ability of the CMS computing system to cope with a sustained data-taking rate equivalent to 25% of the LHC startup rate. Its goals were to run CMS reconstruction at CERN for sustained period at 25Hz input rate, distribute the data to several Computing Centers and grant data accessibility at remote centers for analysis. Grid environments were utilized to complete the aspects of the challenge. In order to provide access to the data to all the world-wide dispersed physicists, CMS is developing a layer of software that uses the Grid tools to gain access to data and resources and that aims to provide physicists with a user friendly interface for submitting the analysis jobs. This work describes the data challenge experience with grid infrastructure and the current development of the CMS analysis system.**

## I. Introduction

THE Compact Muon Solenoid (CMS) is one of the four particle physics experiments associated with the Large Hadron Collider (LHC) currently being built at CERN. Even though the detector will not take data until 2007 there is a large-scale data simulation and analysis effort underway for CMS: the hundreds of physicist that contribute to the CMS collaboration, are currently taking part in computing intensive Monte Carlo simulation studies of the detector and its potential for discovering new physics. The CMS collaboration has a long-term need to perform large-scale simulations in which physics events are generated and their manifestations in the CMS detector are simulated. These simulation efforts support detector design and the design of real-time event filtering algorithms that will be used when CMS is running. Furthermore, running large-scale simulations develops the collaboration's working environment. Experience gained in developing this environment helps refine the design of reconstruction and analysis frameworks needed to process the large number of events that will be generated when the detector starts collecting data.

The challenge for CMS computing is therefore to cope with the very large-scale computational and data access requirements. The size of the required resources in terms of processing power and storage capacity, the complexity of the software and the geographical distribution of the CMS collaboration naturally imply a distributed computing and data access infrastructure. Grid technology is one of the most promising of such infrastructures to be investigated. CMS is collaborating with many Grid projects around the world in order to explore the maturity and availability of middleware implementations and architectures. CMS decided to actively participate in the Grid projects at their outset, with the aim of understanding how Grids might be useful for CMS and how CMS software needs to be adapted to maximize the benefit of using Grid functionalities and tools.

CMS requires that the design and construction of a computing system capable of managing CMS' data pass through a series of planned steps of increasing complexity, named *data* and *physics challenges*. The Data Challenge for CMS during the year 2004 (CMS DC04) was planned to reach a complexity scale equivalent to about 25% of that foreseen for LHC initial running. Its goal was to run CMS reconstruction at CERN for a sustained period of time at 25Hz input rate, distribute the data to the CMS regional centres and analyse them at remote sites.

To meet this challenge a large simulated event production, named the Pre-Challenge Production (PCP), of about 50 million events was undertaken during the preceding months. During the PCP, prototype CMS production infrastructures based on Grid middleware were deployed. The prototypes were based on early LHC Computing Grid [1](LCG-0 and

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LCG-1) systems, where most of the features used were provided by EU implemented middleware, and on grid environments like Grid3 [2], as used by the USMOP system [3] in the USA. Large scale productions were performed using these prototypes, demonstrating that it is possible to use them for real data production tasks [4].

During the CMS DC04, data distribution and data analysis at distributed sites ran in a prototype Grid environment using several LCG-2 tools. Automatic procedures were implemented to submit analysis jobs as new data came along. They were integrated with the Grid services, exhibiting good performances, enabling CMS to undertake Grid-enabled data analysis and to identify potential bottlenecks.

The next challenge, due by the end of 2005, will be the preparation of the CMS Physics Technical Design Report that will require analysis of hundreds of TB of data. CMS is developing a layer of software that uses the Grid tools to provide access to the whole data sample and analysis services to CMS physicists worldwide, via a user friendly interface for submitting analysis jobs. A combination of generic Grid tools and specialized CMS tools will be required to manage the data and optimise the use of computing resources.

The paper is organized as follow. Section II describes the CMS computing environment and the programs used for simulating and processing CMS event data. The experience on data distribution and analysis during the CMS Data Challenge 2004 is reported in Section III. Current activities to provide an user analysis system born of CMS' experience during DC04 , are described in Section IV. Section V summarizes the results and gives a short outlook.

## II. CMS COMPUTING ENVIRONMENT

LHC will produce 40 million bunch-crossings per second in the CMS detector, which corresponds to a data rate of about 1000 TB/s. The on-line system will reduce the rate to 100 events per second, equivalent to an estimated data rate of 100 MB/s, which is streamed to permanent store and used as input for off-line processing. The on-line system selects interesting events in two steps:

- the *Level-1 Trigger* which is implemented as custom designed hardware;
- the *High Level Trigger* which is implemented as software running on a computing (on-line) farm.

Detector data after the High Level Trigger selections are called *raw* data. The raw data event size will be approximately 1 MB and will be archived on persistent storage (~1 PB/year).

Raw data will be processed at CERN, creating new higher-level physics objects (Reconstructed objects). The raw and reconstructed data will be distributed to the computing centres of collaborating institutes, from where it will be made available to the collaboration for analysis.

Software has been produced both for simulating and processing CMS event data. Figure 1 describes the programs and data formats used.

- **Event Generation:** Pythia [5]and other generators that produce *N-tuple* files in the HEPEVT format [6];
- **Detector simulation**: OSCAR [7] is the package simulating the particle passage through the CMS detector, based on Geant-4 [8] toolkit and the CMS object-oriented framework COBRA [9]. The persistency layer used by the CMS framework is POOL [10]. Reading the generated N-tuples OSCAR produces simulated particle's positions in all sub-detectors, the so-called *Hits*.
- **Digitization**: This is the simulation of the Data Acquisition (DAQ) process and its output is the simulated detector response, called *Digis*. It is done by ORCA (Object-oriented Reconstruction for CMS Analysis) [9] that uses the CMS COBRA framework. It produces POOL files containing the so-called *Digis* starting from Hits POOL files.
- **Trigger simulation:** The simulation of the Level-1 trigger and of the High Level Trigger is done by ORCA, reading the Digis POOL files. Trigger simulation is normally run as part of the reconstruction phase.
- **Reconstruction:** Production of reconstructed data is done by ORCA starting from the Digis POOL files. Output files are also in the POOL format.
- **Analysis:** Both the Physics group and the end-user analysis is done using ORCA. It is possible to read any kind of POOL files produced in the previous steps. Visual analysis is done using IGUANACMS [11], a program that uses ORCA and OSCAR as back-end. It provides the functionalities needed for event displaying and statistical analysis.

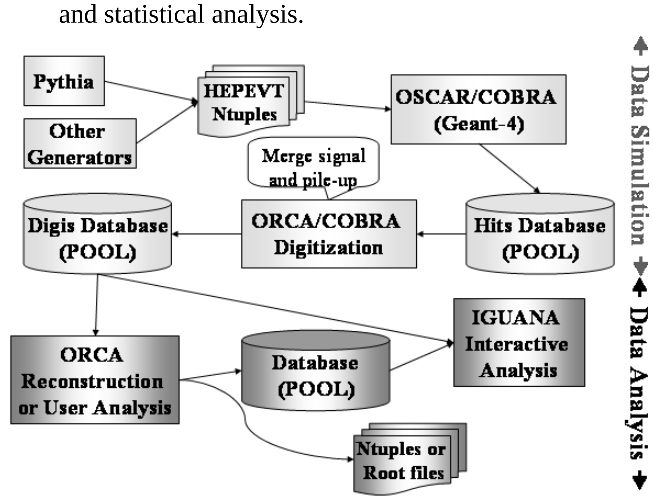


Fig. 1. CMS data formats and software used for data simulation and analysis.

A multi-Tier hierarchical distributed model is adopted in CMS to rationalize resource use. The detector is associated with a Tier 0 site. Tier 1 sites are typically large national computing centres with significant tape and disk capacity, and high bandwidth and availability network resources. Tier 2 sites are institutes with a good computing capacity that have the possibility to contribute to the institutional needs of the experiments as well as to the support of local users. Tier 3 centres are institutes with a more restricted availability of resources and/or services that basically provide support only to local users.

A core set of Tier 1 sites will store raw and reconstructed data to safeguard against data loss at CERN, as well as providing facilities for analysis, some reconstruction and data distribution. Smaller sites, those associated with certain Physics analysis groups or Universities, will also contribute substantially to the analysis activities.

## III. CMS DATA CHALLENGE 2004 EXPERIENCE

CMS Data Challenge in 2004 (DC04) consisted in the following phases:

- Reconstruction of data in the CERN Tier-0 farm for a sustained period at 25Hz
- Data distribution to Tier-1 and Tier-2 sites
- Prompt data analysis at remote sites on arrival of data
- The monitoring and archiving of resource and process information

The aim of the challenge was to demonstrate the feasibility of this full chain of processes.

### A. Reconstruction

Digitized data were stored on Castor [12] Mass Storage System at CERN. A fake on-line process made these data available as input for the reconstruction with a rate of 40MB/s.

Reconstruction jobs were submitted to a computer farm of about 500 CPUs at CERN.Tier-0. The produced data (4MB/s) were stored on a Castor stage area, so files were automatically archived to tape. Some limitations concerning the use of Castor at CERN, due to the overload of the central tape stager, were found during DC04 operations.

### B. Data Distribution

For DC04 CMS developed a data distribution system over available Grid point-to-point file transfer tools, to form a directed and scheduled large-scale replica management system [13]. The distribution system was based on a structure of semi-autonomous software agents collaborating by sharing state information through a Transfer Management Data Base (TMDB). A distribution chain with a star shaped topology was used to propagate replicas from CERN to 6 Tier-1s and multiple associated Tier-2s in the USA, France, UK, Germany, Spain and Italy. Several data transfer tools were supported: the LCG Replica Manager tools [1], SRM (Storage Resource Manager) [14] specific transfer tools, and the SRB (Storage Resource Broker) [15]. A series of "export buffers" at CERN were used as staging posts to inject data into the domain of each transfer tool. Software agents at Tier-1 sites replicated files, migrated them to tape, and also made them available to associated Tier-2s. The final number of file-replicas at the end of the two months of DC04 was ~3.5 million. The data transfer (~6TB of data) to Tier-1s was able to keep up with the rate of data coming from the reconstruction at Tier-0. The total network throughput was limited by the small size of the files being pushed through the system [16].

A single Local Replica Catalog (LRC) instance of the LCG Replica Location Service (RLS) [17] was deployed at CERN to locate replicas CMS-wide. Transfer tools relied on the LRC component of the RLS as a global file catalogue to store physical file locations.

The Replica Metadata Catalog (RMC) component of the RLS was used as global metadata catalogue, registering the files attributes of the reconstructed data; typically the metadata stored in the RMC was the primary source of information used to identify logical file collections. Roughly 570k files were registered in the RLS during DC04, each with 5 to 10 replicas, and 9 metadata attributes per file (up to ~1 KB metadata per file). Some performance issues were found when inserting and querying information; the RMC was identified as the main source of these issues. The time to insert files with their attributes in the RLS- about 3s/file in optimal conditions- was at the limit of acceptability; however, service quality degraded significantly with extended periods of constant load at the required data rate. Metadata queries were generally too slow, sometimes requiring several hours to find all the files belonging to a given "dataset" collection. Several workarounds were provided to speed up the access to data in the RLS during DC04. However serious performance issues and missing functionality, like a robust transaction model, still need to be addressed.

### C. Data Analysis

Prompt analysis of reconstructed data on arrival was performed in real time at the Italian and Spanish Tier-1 and Tier-2 centres using the LCG infrastructure.

A set of software agents and automatic procedures were developed to allow analysis-job preparation and submission as data were replicated to Tier-1s [18]. The real-time analysis architecture is shown in Figure 2. The data arriving at the Tier-1 Castor data server (Storage Element) were replicated by a dedicated agent (Replica agent) to disk Storage Elements at Tier-1 and Tier-2 sites. Whenever new files were available on disk the Replica agent was also responsible for notifying an Analysis agent, which in turn triggered job preparation when all files of a given file set (run) were available. The jobs were submitted to an LCG-2 Resource Broker, which selected the appropriate site where to run the jobs.

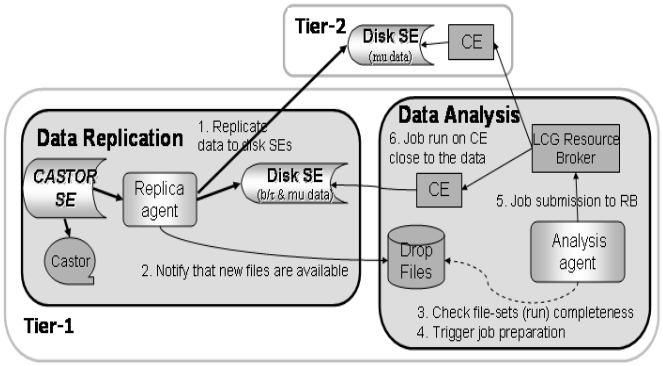


Fig. 2. Description of the real-time analysis architecture during CMD Data Challenge 2004.

The official release of the CMS software required for analysis (ORCA) was pre-installed on LCG-2 sites by the CMS software manager via grid jobs. The ORCA analysis executable and libraries for specific analyses were sent with the job.

The workflow of an analysis job in the LCG environment is shown in Figure 3. The job was submitted from the User Interface to the Resource Broker (RB) that interpreted the user requirements specified using the job description language (JDL). The Resource Broker queried the RLS to discover the location of the input files needed by the job and selected the Computing Element (CE) hosting those data. The LCG information system is used by the Resource Broker to find out the information about the available Grid resources (Computing Elements and Storage Elements). A Resource Broker and an Information System reserved for CMS were set-up at CERN. CMS could dynamically add or remove resources as needed.

The job ran on a Worker Node, performing the following operations: set the CMS environment to access the pre-installed ORCA software; read the input data from Storage Element with rfio protocol [12] whenever possible otherwise via LCG Replica Manager commands; execute the user provided executable; store the job output on a data server; and register it to the RLS to make it available to the whole collaboration.

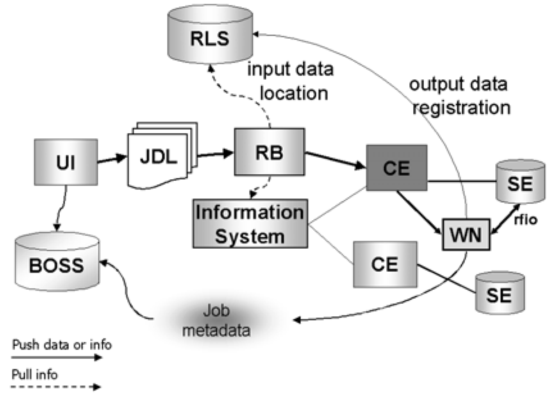


Fig. 3. Description of the analysis job operations in an LCG-2 environment during CMS Data Challenge 2004.

The analysis was run quasi continuously for two weeks submitting a total of more than 15000 jobs, with a job efficiency of 90-95%. The number of jobs ran per hour in a day is shown in Figure 4. Taking into account that the number of events per job varied from 250 to 1000 the maximum rate of jobs, ~260jobs/hour, translated into rate of analysed events of about 40 Hz .The LCG submission system could cope very well with the rate of data coming from CERN a maximum rate of analysed events of 40Hz. An average latency of 20 minutes between the appearance of the file at CERN and the start of the analysis job at the remote sites was measured during the last days of DC04 running, as reported in Figure 5.

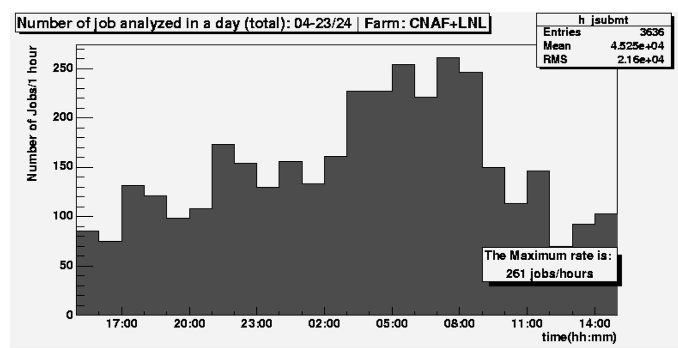


Fig. 4. Number of jobs per hour analysed in a day.

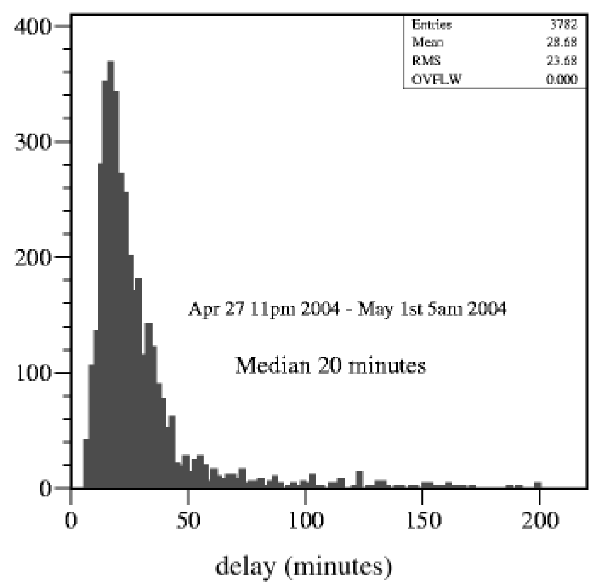


Fig. 5. Time elapsed from the file being available for distribution at CERN and its analysis at remote site.

### *D. Monitoring*

MonaLisa [19] and GridICE [20] were used to monitor the distributed analysis infrastructure, collecting detailed information about nodes and service machines (the Resource Broker, and Computing and Storage Elements), and were able to notify supervisors in the event of problems. CMS-specific job monitoring was done using BOSS [21]. BOSS extracts the specific job information to be monitored from the standard output and error of the job itself and stores it in a dedicated MySQL database. The job submission time, the time of start and end execution, the executing host are monitored by default. The user can also provide to BOSS the description of the parameters to be monitored and the way to access them by registering a job-type. An analysis specific job-type was defined to collect information like the number of analysed events, the datasets being analysed.

## IV. User Analysis

CMS distributed analysis activities are now in a research and design phase focused on providing an end-to-end analysis system. In general user analysis is a chaotic, non organized task, carried on concurrently by many independent users that do not have a deep knowledge of distributed computing environments. CMS is testing several prototypes of tools that act as an interface to such environments.

PhySh (Physics Shell) is an application that aims to reduce the number of different tools and environments that the CMS physicist must learn to interact with to use distributed data and computing services. In essence PhySh is an extensible "glue" interface among different services already present or to be coded, like locating physics data of interest, copying/moving event data to new locations, accessing software releases/repositories, and so on. The PhySh interface is modelled as a virtual file-system, since file-system interfaces are what most people are familiar with when dealing with their data. PhySh is based on the Clarens [22] Grid–enabled web service infrastructure. Clarens was developed as part of the Grid-Enabled Analysis environment (GAE)[23]. Clarens servers leverage the Apache web server to provide a scalable framework for clients to communicate with services using the SOAP and XML-RPC protocols. The architecture of Physh is shown in Figure 6.

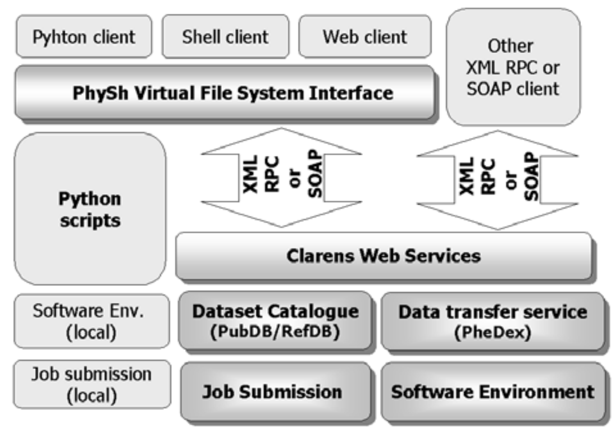


Fig. 6. Description of the PhySh architecture.

### *A. Data Access*

Analysts require a *Data Location* service, to discover what data exists and where, and a *Data Transfer* service to accommodate the needs of data distribution between multiple sites.

Analysts typically want to access large collections of data spanning many files; thus, file-based data access, as provided by many existing grid tools is not satisfactory. CMS-specific dataset catalogues that describe dataset characteristics and enable the location of replicas that comprise a dataset are under development. The Reference Database (RefDB)[24] is a Dataset Metadata Catalogue; it maintains audit trails of data production, information that associates files with datasets, and other bookkeeping metadata. The Publication Database (PubDB) manages information about "local" dataset catalogues, allowing the users to locate the data of a dataset and determine access methods. The information in PubDB can be used by users or by the Workload Management System [25] to decide where to submit a job analysing a given dataset. The natural design is to have distributed PubDBs, one per site that serves data, allowing the site data-manager to manage their local catalogues coherently and in a manner consistent with other CMS sites. The user can discover the available datasets querying the RefDB. A global map of all dataset catalogues is held in the RefDB through the links to the various PubDBs.

The CMS bulk data transfer management system is named PhEDEx (PHysics Experiment Data EXport) [13]. PhEDEx is a project born of CMS' experience during DC04. It retains the same architecture as that used during DC04, relying on a central "blackboard" to enable the exchange of information among a series of distributed agents. The principal current aim of PhEDEx is to incorporate the CMS distribution use cases of subscription pull of data where a site subscribes to all data in a given set and data are transferred as they are produced, and of random pull where a site or individual physicist just wishes to replicate an existent dataset in a one-off transfer.

The conceptual basis of data distribution for CMS is distribution through a hierarchy of sites, with smaller sites associating themselves to larger by subscribing to some subset of the data stored at the larger site. Subscription pull of data for CMS requires that many more sources of data must be accommodated within the system. To enable the addition of multiple data sources we borrow from established internet technology: where routes from single source to multiple destinations were hard coded into agents during DC04, in PhEDEx nodes in the distribution chain act as routers which share route information using an implementation of the RIP2 [26] algorithm. Any node in the network can act as a source of data, and a route from any node to any other node in the chain can be determined.

### B. Analysis Strategy

The current approach to analysis in CMS is to concentrate on simple analysis scenarios and learn from the implementation of simple use cases. The adopted analysis strategy using the Grid is to submit analysis jobs close to the data. The user typically wants to access a dataset in order to analyse it with his private code. The user provides, as specification of a Grid job, the dataset and the private code. On submission to the Grid a combination of specialized CMS tools and Grid components should take care of resource matching and submission to distributed sites.

The Workload Management System finds suitable computing resources (i.e. Computing Elements) to execute the job. Data discovery is one of the most important aspects in the match-making process, and a Data Location Interface is being developed to allow a uniform “query interface” for data location. This interface will provide the Workload Management System with the functionality to query several catalogues: the LCG Replica Location Service to perform file-based data location; the CMS specific dataset catalogues to perform dataset-based data location; or any upcoming data catalogue.

Several user-friendly tools dealing with job preparation, job splitting and job submission are under development. These tools are being integrated with middleware and tools already available and new ones being developed in several Grid projects: LCG, EGEE [27], Grid3, OSG[28].

## V. CONCLUSIONS

CMS is exploring the maturity and availability of middleware implementations and architectures of many Grid projects to provide access to the  data e and to the required services to a large number of globally dispersed CMS physicists.

In CMS Data Challenge 2004 the LCG environment provided the functionalities for distributed computing: global file and metadata catalogues, Grid point-to-point file transfer tools and infrastructure for data analysis.

The CERN Replica Location Service provided the replica catalogue functionality for all the data distribution chains. Major performance issues were found with data at the scale of the challenge.

A data distribution management layer was developed by CMS by loosely integrating available Grid components for wide area transfer. Over 6 TB of data were distributed to Tier-1 sites, reaching sustained transfer rates of 30 MB/s. The total network throughput was limited by the small size of the files being pushed through the system. Dealing with too many small files also increased the load in updating/querying the catalogue and also affected the scalability of Castor MSS.

The data analysis as soon as they arrived at the Tier-1 and Tier-2 sites was demonstrated using the LCG infrastructure. During the last days of the data challenge a median latency of ~20 minutes was measured between the appearance of the file at CERN and the start of the analysis job at the remote sites.

Current work is focused on developing a layer of software that uses the Grid tools to gain access to data and resources, and that aims to provide physicists with a user-friendly interface for submitting analysis jobs. This activity includes components from several Grid projects like LCG, EGEE, GRID-3, Clarens.

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