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CSA06 Computing, Software and Analysis challenge at the Spanish Tier-1 and Tier-2 sites

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Abstract

This note describes the participation of the Spanish centres PIC, CIEMAT and IFCA as Tier-1 and Tier-2 sites in the CMS CSA06 Computing, Software and Analysis challenge. A number of the facilities, services and workflows have been demonstrated at the 2008 25% scale. Very valuable experience has been gained running the complex computing system under realistic conditions at a significant scale. The focus of this note is on presenting achieved results, operational experience and lessons learnt during the challenge.

1 Introduction

CMS undertakes periodic computing challenges of increasing scale and complexity to test its computing model and Grid computing systems. The computing challenges are aimed at establishing a working distributed computing system that implements the CMS computing model based on an underlying multi-flavour grid infrastructure. CMS dataflows and data processing workflows are exercised during a period of about a month targeting specific performance and scale goals. Performance values are measured, problems are identified and feedback into the design, integration and operation of the computing system is provided.

The CMS computing architecture[1] is based on a tier-organised structure of computing resources, based on a Tier-0 centre at CERN, 7 Tier-1 centres for organized mass data processing, and about 30 Tier-2 centres where user physics analysis and Monte Carlo production are performed. The Tier-0 is in charge of storing the data coming from the detector onto mass storage, performs a prompt reconstruction of the data and distributes the data among the Tier-1 centres. The Tier-1 sites archive on mass storage its share of data, run data reprocessing, organized group physics analysis for data selection and distribute down the selected data to Tier-2's for user analysis. Tier-1 centres also have the responsibility of storing Monte Carlo data produced at the Tier-2 sites.

The combined Computing, Software and Analysis challenge CSA06 [2] started on 2 October 2006, lasting approximately 6 weeks. It was designed to be a 25% capacity test of what is required for operations in 2008. The goals of the challenge were the following:

- Reconstruction at the Tier-0 at 40 Hz using the new CMSSW event processing framework.
- Distribution of raw and reconstructed data to the Tier-1 sites.
- Data skimming jobs at the Tier-1 sites and the resulted data propagated to the Tier-2 sites.
- Data analysis at the Tier-2 sites on the skimmed data.
- Demonstration of the re-reconstruction workflow at the Tier-1 sites.
- Demonstration of the calibration workflow, production of calibration/alignment datasets at the Tier-0, transfer to a Tier-1 and execution of calibration jobs at the Tier-1.

The Spanish Tier-1 and Tier-2 centres actively and successfully participated in CSA06. The Tier-1, PIC, is located in Barcelona. The Tier-2 distributed centre is a federation of two sites, CIEMAT in Madrid and IFCA in Santander.

2 Configuration

Production computing resources and services were used for CSA06 at the Spanish sites. No dedicated setup was deployed for the challenge. All CMS resources were dedicated to CSA06 since production activities were not run during the challenge with the exception of user analysis at the Tier-2 sites.

2.1 Hardware setup

Figure 1 shows the bandwidth and approximate latencies (half of the round trip time) of the different network sections between CERN and the Spanish sites. The traffic from CERN reaches Spain through the Geant-2 network infrastructure with a bandwidth of 10 Gbps. In Spain, Rediris, the Spanish academic network, transports the traffic with a bandwidth of 2.5 Gbps. In Catalonia, the Anella Cientifica network interconnects academic and research centres. The bandwidth available to PIC at the time of the challenge was limited to 1 Gbps with a guaranteed share of at least 800 Mbps. The total latency CERN-PIC is about 20 msec. PIC-CIEMAT and PIC-IFCA latencies are 9 msec and 15 msec respectively.

10 Gbps links have been deployed in 2007 in Spain as part of the Geant-2 infrastructure. PIC has recently joined the LHC Optical Private Network [3], a dedicated network infrastructure for the LHC Tier0 and Tier1 networking.

Figure 2 depicts the dataflows, workflows and computing resources involving the Spanish sites during CSA06. All resources are accessed via the LHC Computing Grid (LCG [4]) infrastructure and the dataflows and workflows are conducted using LCG middleware and tools as well as CMS-specific services built on top of them.

PIC received from CERN a continuous data stream of reconstructed data, at an average rate of 22 MB/s. As described in section 4, data skimming and re-reconstruction was conducted at PIC, while analysis on the skimmed

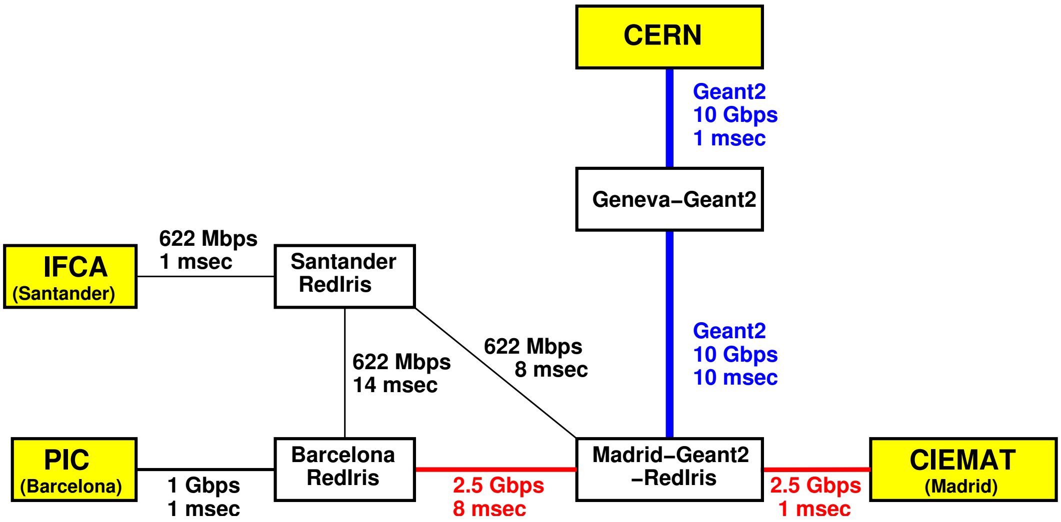


Figure 1: Network diagram showing the bandwidth and approximate latencies (half of the round trip time) of the different network sections between CERN and the Spanish sites.

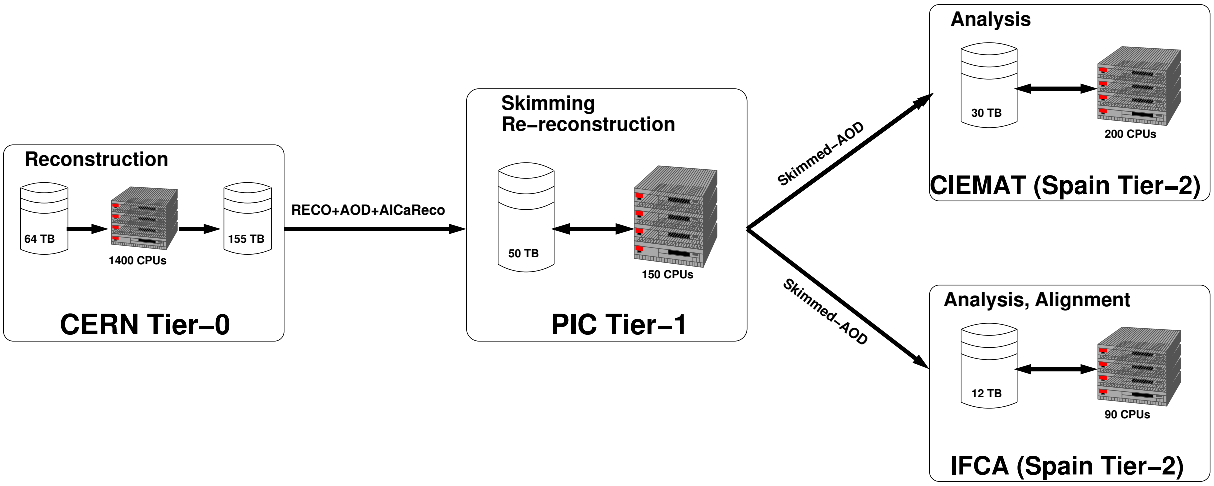


Figure 2: Dataflows and workflows in CSA06 at the Spanish sites. The disk and CPU capacities are also shown in the picture.

samples was run at CIEMAT and IFCA. In addition, data in a suitable format for calibration and alignment were forwarded to IFCA from CERN via PIC for alignment studies.

A minimum of 70 TB of storage capacity and 150 CPUs were required for a nominal-sized Tier-1 to participate in the challenge. PIC, with a size between 1/2 and 1/3 of a nominal Tier-1, contributed with 50 TB of dCache-managed [5] disk space and 150 CPUs. No data migration/recall to/from tape was exercised at PIC. The disk space capacity was distributed between 15 file servers each providing 3-4 TB. The large distribution of the storage capacity distributes the load of the simultaneous read/write operations (data transfers, processing jobs reads and writes) on the disk servers. A minimum of 5 TB and 20 CPUs were requested for a nominal Tier-2. CIEMAT contributed to the challenge with 30 TB of disk space under Castor [6] and 200 CPUs. IFCA deployed 12 TB of disk space under DPM [7] and 90 CPUs.

2.2 Computing services and workflows

Each site runs a set of PhEDEx [8] agents that manage data transfers. Relatively large files, of about 2.5 GB, were transferred to the sites to minimize the number of files and improve performance of network and storage systems. This lesson was learnt in the past DC04 data challenge [9] where the large number of small files caused a serious overhead in data operations. Data files are organized in data blocks, an arbitrary set of files, that are replicated and tracked together by the CMS data management system. One or more data blocks constitute a dataset defined in terms of physics content. The description of the data is kept in the global Dataset Bookkeeping Service [10], with an oracle database back-end at CERN. Completely replicated blocks and datasets are published by PhEDEx in the global Dataset Location Service [11], a LFC-based [12] catalogue that keeps track of the location of the data at sites at the level of file blocks. Local physical file names (PFN) and data access protocols at the sites are resolved at real-time by the jobs through a local Trivial File Catalogue (TFC [13]), a set of logical to physical file name conversion rules. In this approach, the structured namespace provided by the local storage system is used as a catalogue. The fileblock-based replication and the TFC-based resolution of PFNs largely minimizes the interaction with database catalogues and the Grid information system which might result in a higher reliability, performance and scalability.

The Tier-0 and each Tier-1 site runs a File Transfer Service (FTS[14]). All transfers from the Tier-0 are managed by the FTS server at the Tier-0 and all transfer between Tier-1 and Tier-2 sites are managed by the FTS server at the Tier-1 associated to the Tier-2 involved in the transfer. The FTS servers allow to implement bandwidth shares between different virtual organizations, allow to configure the transfer parallelism in each channel and are able to queue transfer requests. The FTS servers interact with the local storage at the sites via the SRM[15] interface which provides an uniform interface to the different implementations of pool managers (Castor, dCache, DPM). GridFTP [16] is used as data transfer protocol over the WAN.

Data skimming and re-reconstruction processing workflows at the Tier-1 sites are carried out using ProdAgent (PA) [17]. PA was originally developed for Monte Carlo production and was later easily extended to deal with the Tier-1 workflows. Those workflows are very similar to the case of multi-step MC processing where production jobs have to read input data to process (for example, reconstruction of previously produced simulated data). Furthermore, PA is currently being extended to execute the Tier-0 data processing workflows.

PA is built as a set of loosely coupled components that cooperate to carry out production workflows. Components are python daemons that communicate through a local mysql database. Work is split into these atomic components that encapsulate specific functionalities. PA includes components for job creation, submission and tracking, error handling and job cleanup, data merging and publication into global DBS/DLS/data transfer system. The interface to the different Grid flavours is done via plug-in's for the job creation, submission and tracking components. It is fairly simple to add new systems and customization.

Figure 3 shows the production workflow with PA. Processing jobs are sent to sites which store produced data at the local storage elements. File PFNs are resolved by means of the local TFC. Jobs report back to ProdAgent which triggers data merge jobs sent to the sites hosting the unmerged data. Job resubmission on error is automated. Data processing, bookkeeping, tracking and monitoring occurs in the local-scope databases of the ProdAgent instance. After successful processing, data bookkeeping and location information is promoted to the global scope databases and the data transfer system to make the produced data available for analysis and replication.

Processing jobs access conditions data (calibration and alignment constants) via a local squid-based web cache [18]. A distributed hierarchy of independent cache servers is introduced between the clients and a central database server. The FroNTier package[19] is used to encode the communication between database clients and server.

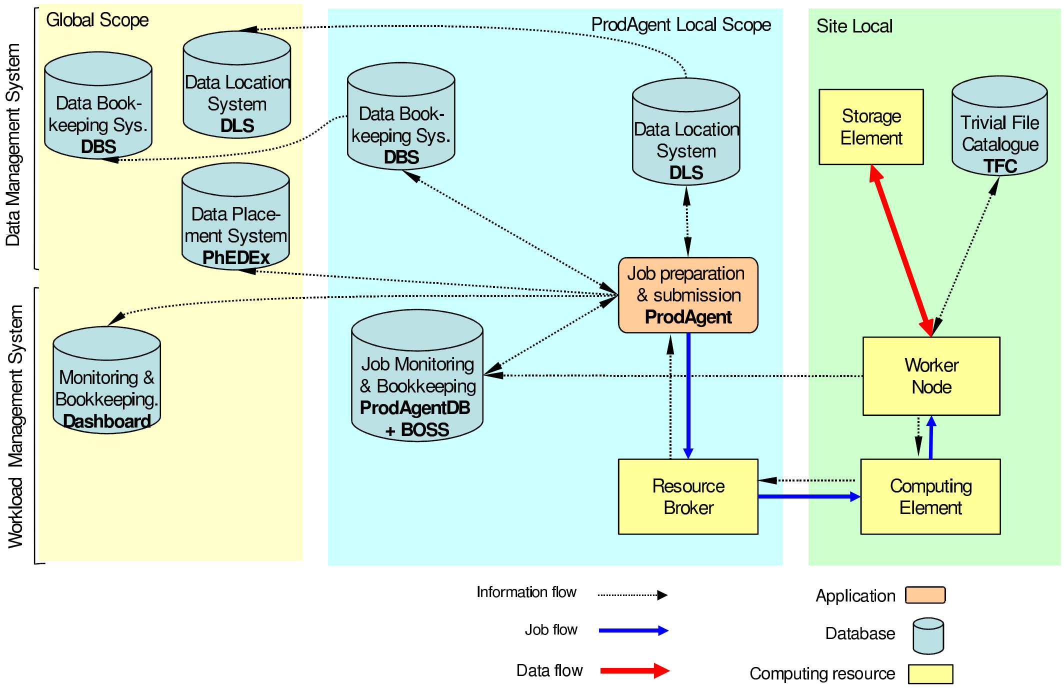


Figure 3: Production workflow with ProdAgent in LCG

Analysis of skimmed data samples is done at the Tier-2 sites using CRAB [20]. CRAB is a tool that allows users to run the CMSSW[21] processing and analysis framework on the Grid. It takes care of data discovery in the DBS/DLS catalogues, job preparation, submission, monitoring and output retrieval. In Figure 4 the analysis workflow with CRAB is sketched.

In addition to user analysis, a central job load generator (JobRobot) was run to continuously submit (fake) analysis jobs to the sites in order to reach certain level of job load.

Job monitoring and bookkeeping information is sent to a central database, the CMS Dashboard [22]. All CMS workload tools (ProdAgent, CRAB, JobRobot) send real-time information to the Dashboard (site name, exit code, etc). The Dashboard also gets job state information from the Grid workload management system.

Both for production and analysis purposes, CMSSW software versions are pre-installed at the sites in a shared filesystem accessible from the farm worker nodes. The installation is centrally managed by the CMS software manager that submits Grid installation jobs to the sites.

Sites establish locally shares and priorities for different job types (production, analysis, software installation). Different job types are mapped to different local unix users using VOMS [23]. VOMS is a system to classify users that are part of a Virtual Organization on the base of a set of attributes that will be granted to them upon request and to include that information inside Globus-compatible proxy certificates.

3 Pre-challenge Monte Carlo Production

During summer 2006 the production of the required Monte Carlo samples for the CSA06 challenge was conducted. It was the first large scale production with ProdAgent. Four teams were in charge of running production, one of them at CIEMAT.

One can see in Figure 5 the production scale reached by one ProdAgent instance ran at CIEMAT. One ProdAgent instance can submit up to 3000 jobs per day, limited by the serial submission of jobs in the LCG workload management system. It takes 20-30 seconds to submit a job to a LCG Resource Broker (RB). This includes authentication, upload of the input sandbox, interaction with RB network server, etc. Given a typical job duration of 12-24 hours corresponding to a 500-events job with a typical event processing time of 2-3 minutes, a ProdAgent instance can process up to 1.5 million events per day. The desired production scale is attained by running any number of parallel ProdAgent instances. Currently ProdAgent is in the process of implementing the bulk submission feature of the

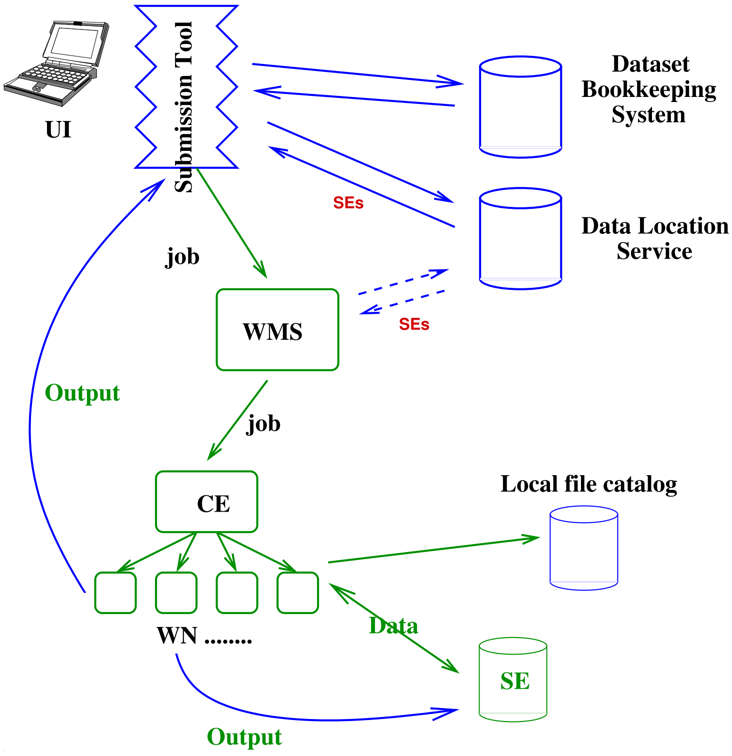


Figure 4: Analysis workflow with CRAB. CRAB interrogates the DBS and DLS to determine which data exists for a particular dataset and in which locations. It then submits the jobs to the Grid.

gLite [24] Workload Management System (the successor of LCG RB) to boost the number of jobs a ProdAgent instance can handle.

Production resources were distributed among production teams so that each team ran jobs at specific sites. This way each team was in charge of contacting specific site administrators to follow up potential problems with production at the sites. Only sites with a proved record of reliability and sufficient resources were included in the production team's white list.

Workload injection into ProdAgent was a manual operation. For a given workflow (input and output datasets, number of events, software version, configuration, production steps, etc) the production operator injects into ProdAgent certain number of jobs appropriate for the number of CPUs available to the ProdAgent instance. The lack of automatic injection of jobs into the system translates in periods of time where available resources are not fully exploited, as can be seen in Figure 5. Hence, job submission and number of running jobs were not uniform during the summer production. Currently ProdAgent is in the process of implementing a new component to queue jobs at ProdAgent level, monitor the available amount of resources and release jobs accordingly. This should lead to a much efficient use of the resources.

50 million events were requested for CSA06 and 67 million events were finally produced between all four production teams. Figure 6 shows the accumulated number of events with time for processing and merge jobs for the two ProdAgent instances run by the CIEMAT production team. Part of the unmerged sample could not be merged due to a disk loss in one of the sites. Figure 7 shows the distribution of produced events among the associated sites to the CIEMAT production team. Above two thirds of the production was done at CERN and one quarter at the Spanish sites.

In Figure 8 the event processing time for various datasets for processing (left) and merge jobs (right) is plotted. The processing of minimum bias event is typically 4 times faster than the processing of signal events. The same applies for merge jobs since the minimum bias event size is 4 times smaller and the duration of merge jobs (I/O dominated) is proportional to the amount of data to read. The two distinct peaks in the minimum bias sample for merge jobs correspond to the different performance of the storage system at two different sites.

Table 1 shows job failure percentages (relative to all submitted jobs) for processing and merge jobs for different failure reasons. The largest number of failures correspond to application failures and Grid inefficiencies. Appli-

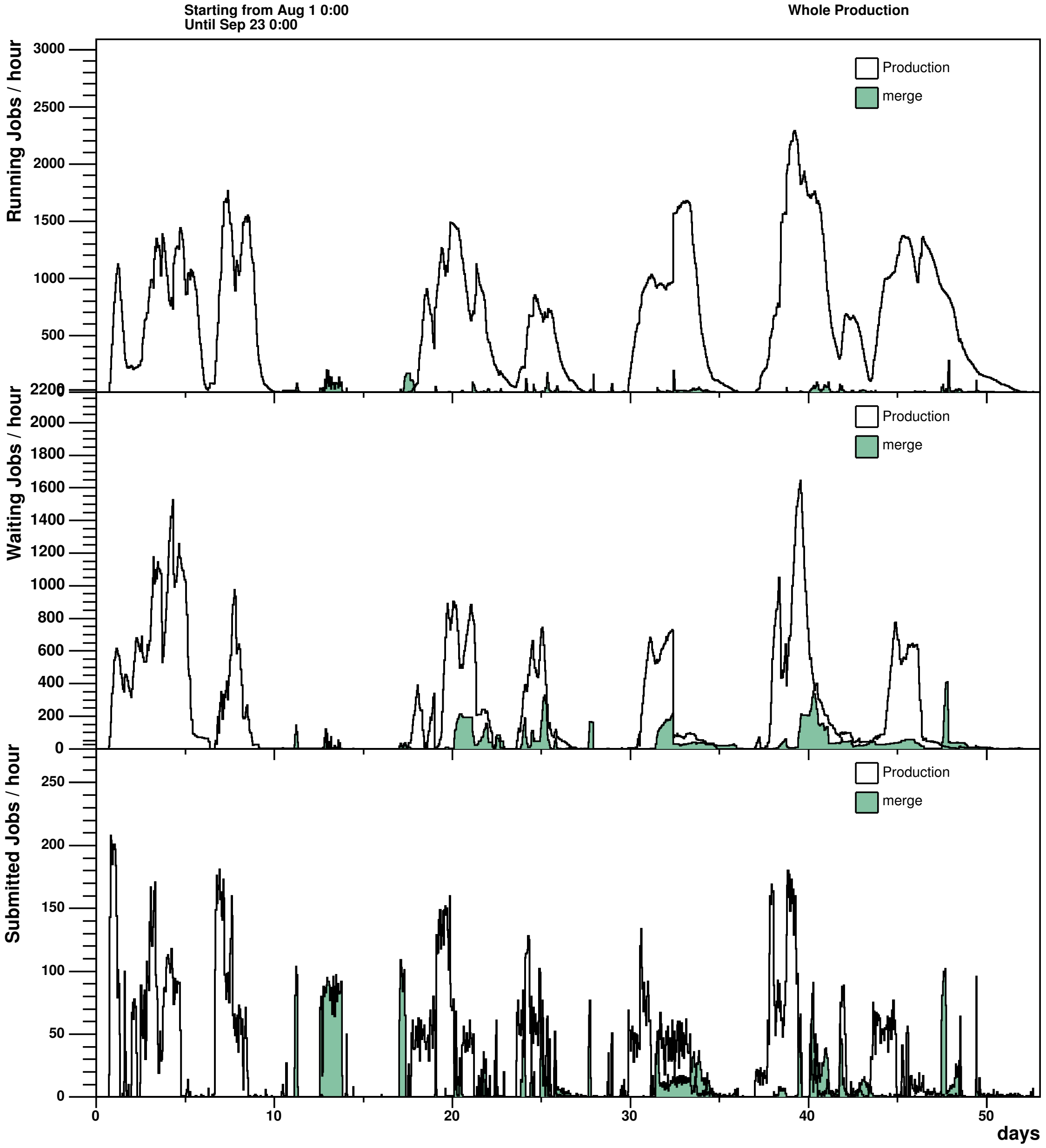


Figure 5: Number of jobs running (upper), queued at sites (middle) and submitted (lower) by a ProdAgent instance as a function of time for the summer 2006 MC production. For waiting and running jobs, the same job can enter more than one adjacent bin if its waiting or running period spans beyond one time bin (one hour)

cation failures include failures reading the input data. In fact, there is an increased number of application failures for merge jobs (10.6% vs 5.5%), which access a much larger number of input files than the processing jobs. Grid related failures include failures in global Grid services (RB, information system) and failures of Grid services at the sites (CE, WNs). Grid job failures typically occur when the exit code of the job cannot be communicated back to the RB (e.g. jobs that get killed due to hardware failures at the WNs or killed by the batch system after expiring the allocated time slot) or at job submission time when the destination site temporarily disappears from the Grid information system. This last reason explains the increased Grid failure rate for merge jobs. These jobs are submitted to a specific site (the site hosting the unmerged input data) while processing jobs can be run at any of the sites in the white list. If a particular site temporarily disappears from the the information system, merged jobs submitted to that site will abort while processing jobs will run in any of the remaining sites. Failures in storing the output file into the local storage account for about 4% of the errors. Around 2% of the jobs fail when accessing the experimental software from a shared repository (typically via NFS).

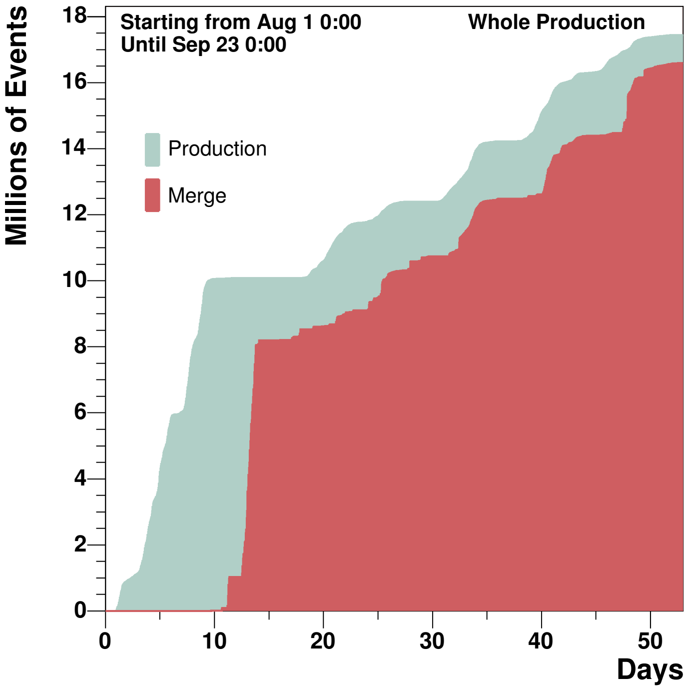


Figure 6: Accumulated number of produced events for processing and merge jobs.

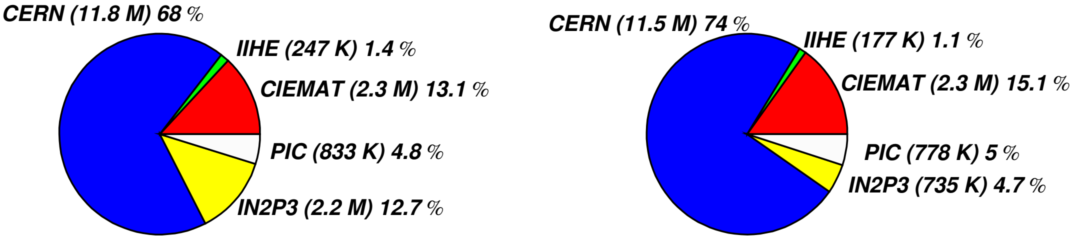


Figure 7: Distribution of produced events between the processing sites for unmerged (left) and merged data (right).

In Figure 9 the number of trials for a job to succeed is plotted for production and merge jobs. The efficiency for production jobs is 83% and 74% for merge jobs, yielding an overall efficiency of about 80%.

Efficient site support is critical for production efficiency. Most job failures are related to site problems (temporary glitches in site Grid services, problems reading and storing data in the local storage system, local batch system and WN misbehaviour, access to experimental software). A fast reaction of site admins is required to minimize production inefficiencies.

4 Tier-1 and Tier-2 Operations

The challenge had a staged start-up, beginning with reconstruction at the Tier-0 followed by data distribution to the Tier-1/Tier-2 sites and finally adding the event data processing workflows. We discuss in the following sections

Failure reason	Processing jobs	Merge jobs	All jobs
Application failure (including data access)	5.5%	10.6%	6.6%
Output data stage-out	4.0%	3.2%	3.8%
Experiment software configuration/access	2.6%	1.3%	2.3%
Grid related failures	5.2%	11.0%	6.7%
Total	17.3%	26.1%	19.4%

Table 1: Job failure rate for processing and merge jobs.

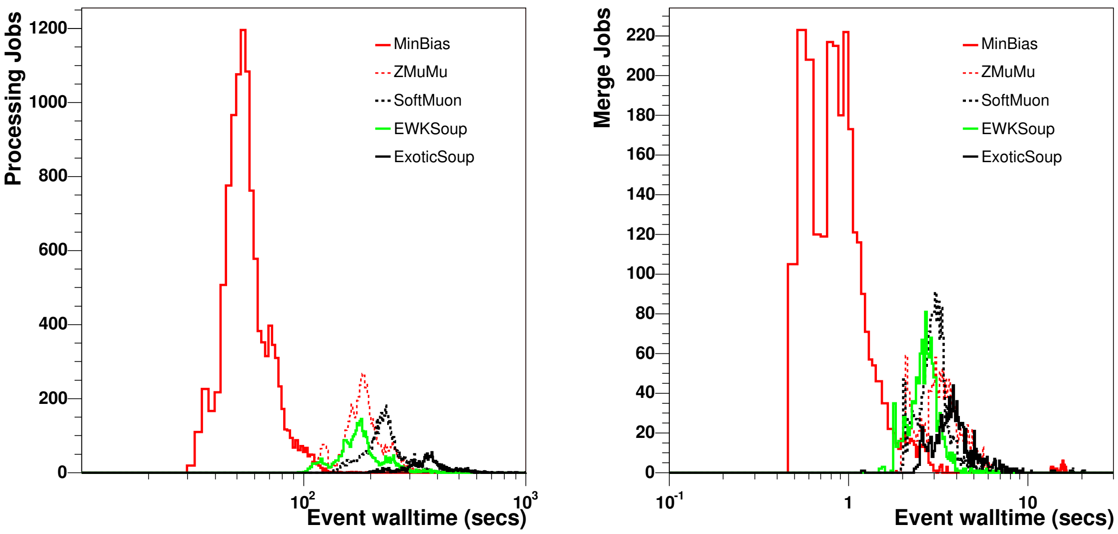
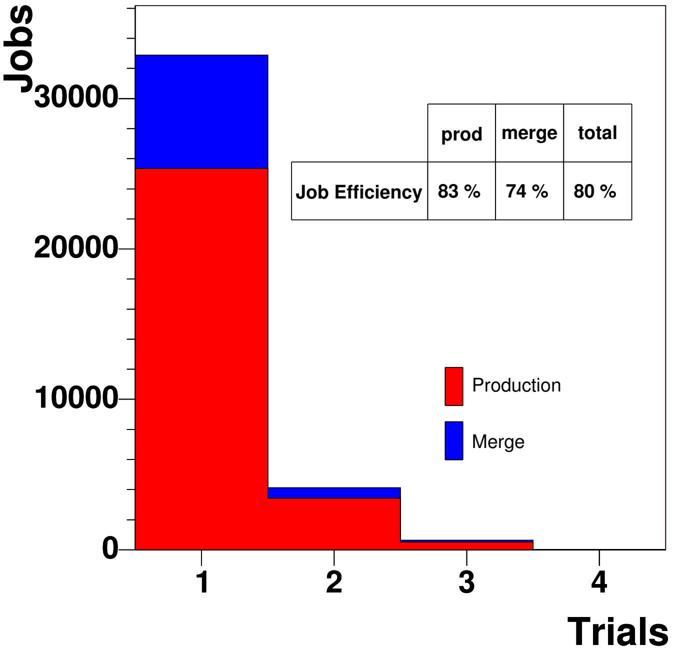


Figure 8: Wallclock event processing time for various datasets for processing jobs (left) and merge jobs (right).



	prod	merge	total
Job Efficiency	83 %	74 %	80 %

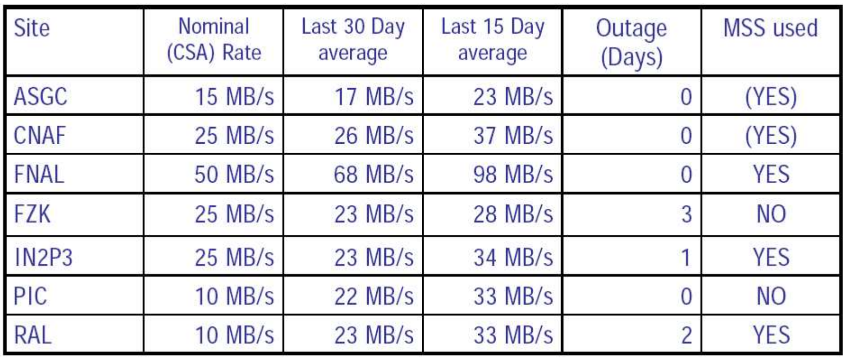
Figure 9: Distribution of trials required for a job to succeed, red for production jobs and blue for merge jobs.

data transfers, data skimming and re-reconstruction at PIC and user analysis demonstrations at CIEMAT and IFCA.

4.1 Data transfers

The tier-1 centers were expected to receive data from CERN at a rate of 25% the rate expected for 2008 and serve data to Tier-2 sites. Table 2 summarizes for every Tier-1 the expected and achieved rates. PIC was expected to get data at an average rate of 10 MB/s during the whole duration of the challenge. It achieved an average rate of 22 MB/s with a transfer success rate above 97%.

Figure 10 top-left shows the daily rate from CERN to PIC and from PIC to the Spanish Tier-2 sites, CIEMAT and IFCA. During the first week of the challenge rates were limited by data availability for transfer at CERN, as can be seen in Figure 10 top-right where the amount of data in queue waiting to be transferred is plotted. Transfers were running most of the time backlog free, except for concrete periods where a large amount of data



Site	Nominal (CSA) Rate	Last 30 Day average	Last 15 Day average	Outage (Days)	MSS used
ASGC	15 MB/s	17 MB/s	23 MB/s	0	(YES)
CNAF	25 MB/s	26 MB/s	37 MB/s	0	(YES)
FNAL	50 MB/s	68 MB/s	98 MB/s	0	YES
FZK	25 MB/s	23 MB/s	28 MB/s	3	NO
IN2P3	25 MB/s	23 MB/s	34 MB/s	1	YES
PIC	10 MB/s	22 MB/s	33 MB/s	0	NO
RAL	10 MB/s	23 MB/s	33 MB/s	2	YES

Table 2: Nominal and achieved transfer rates for the Tier-1 centers during CSA06.

were intentionally injected for transfer to test bursty transfers. Figure 10 bottom-left shows the accumulated amount of data transferred to each of the Spanish sites. About 60 TB of data were transferred from CERN to PIC while 30 TB and 15 TB were transferred from PIC to CIEMAT and IFCA respectively. Figure 10 bottom-right shows the transfer quality. IFCA had problems with the storage system in the first week of the challenge that prevented them to transfer any data. The quality of transfers to CIEMAT worsened somewhat in the last week of the challenge when non-regional Tier1-Tier2 transfer were exercised. The quality getting data from PIC for both CIEMAT and IFCA was excellent during the whole challenge.

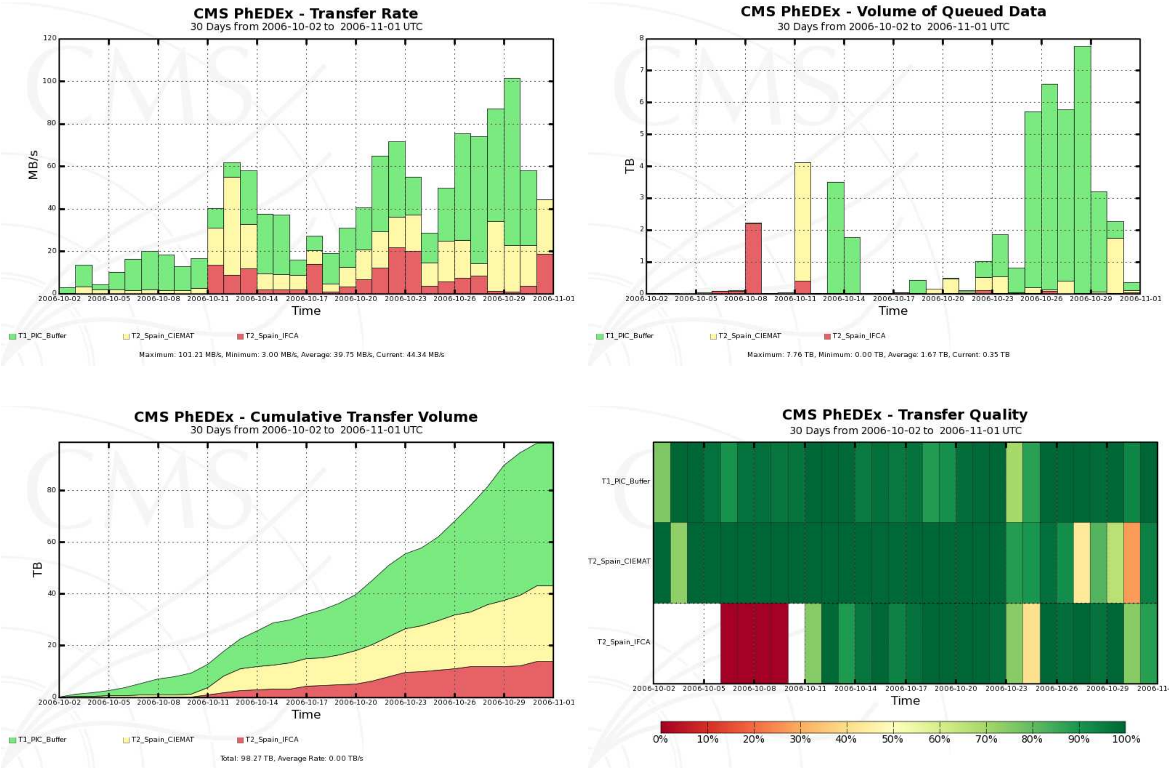


Figure 10: Transfer rates into the Spanish sites (top-left), data backlog (top-right), accumulated data volume transferred (bottom-left) and transfer quality (bottom-right).

Bursty data transfers from CERN to the Tier-1 sites were exercised during the challenge to test the ability to recover from large backlogs caused by potential transfer problems. Figure 11 top-left shows the hourly average rate achieved during one of the bursty transfers between CERN and PIC. An average rate of 80 MB/s was sustained during 10 hours with no single transfer error, saturating the available network bandwidth between CERN and PIC. Figure 11 top-right shows how the initial backlog of 3 TB steadily decreased and Figure 11 bottom shows the perfect transfer quality during this exercise.

In the CMS computing model each Tier-1 center hosts a copy of the whole sample of reconstructed data in AOD

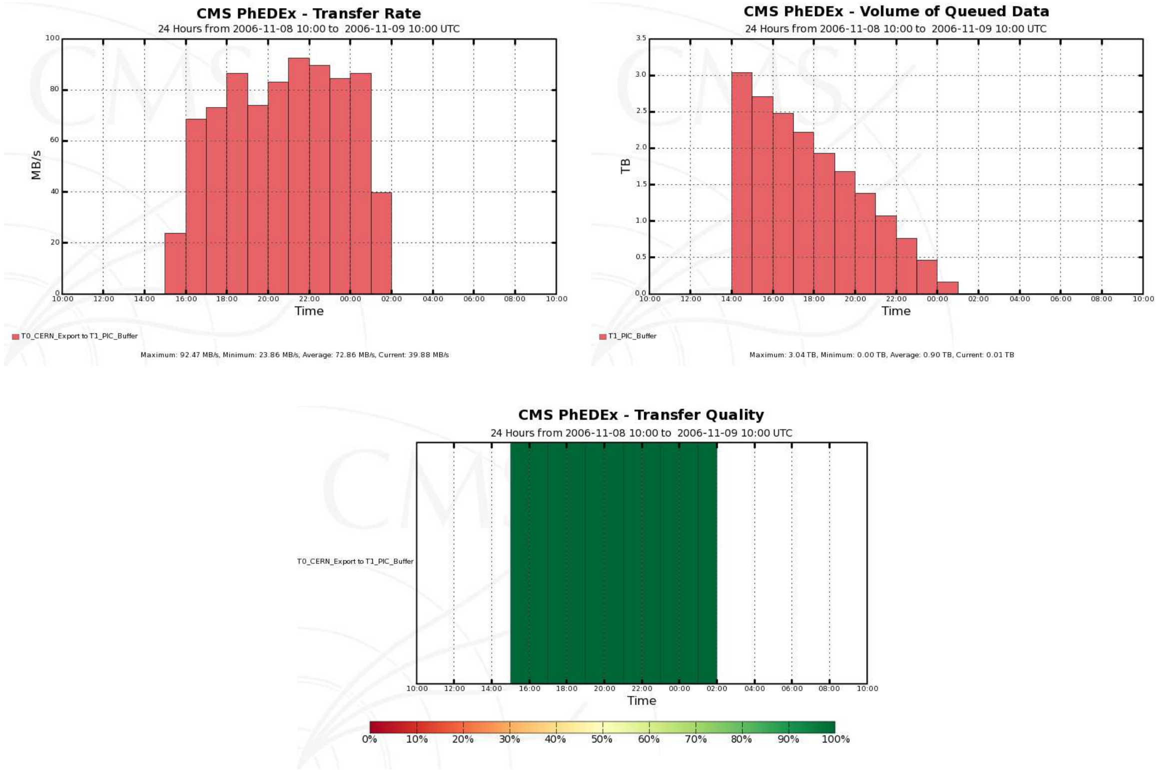


Figure 11: Bursty transfer from CERN to PIC to simulate the recovery from a period without transfers. Transfer rate (top-left), volume of data backlog (top-right) and transfer quality (bottom).

format, which contains a subset of the reconstruction information. However, it is anticipated that during the first years of the experiment data analysis will need access to the complete reconstruction information. Since the reconstructed data is split between the Tier-1 centers, efficient transfers of skimmed samples will have to be possible from any Tier-1 to any Tier-2 site. The simultaneous transfer of a dataset from PIC to many Tier-2 sites was exercised in CSA06. Figure 12 shows the quality of the transfer to each of the 25 Tier-2s participating in the exercise. The dataset was successfully transferred to most of the sites except for three of them which had persistent problems at the destination end.

Transfers from the Tier-1 centers to the Tier-2 sites are bursty in nature in the CMS computing model. Skimmed data at the Tier-1 sites have to be transferred to the interested Tier-2 sites as fast as possible as they become available. Figure 13 shows the bursty transfer from PIC to CIEMAT of 5 TB of data during 24 hours at an average rate of 60 MB/s with perfect transfer quality. The artificial backlog introduced at PIC for this exercise can be seen in Figure 10 for the date 2006-10-11.

Non-regional transfers from a Tier-1 other than PIC to CIEMAT and IFCA were also successfully exercised. Figure 14 shows that data were transferred from FNAL Tier-1 to both CIEMAT and IFCA at a rate about 20 MB/s with a good transfer quality.

4.2 Data skimming

Data skimming was conducted at the Tier-1 sites. Skimming jobs could run any number of filters producing the corresponding output files with the selected events. ProdAgent was used to carry out the skimming workflow. It automatically prepared the skimming jobs for the sample to be filtered, submitted and tracked them and finally automatically launched the corresponding merge jobs.

Several skimmings were run at PIC. We show in this section results for the skimming of one of the samples, the $Z^0 \rightarrow \mu\mu$ sample with about 2 million events. A bit less than 50% of the events were selected by the skimming filter. Figure 15 shows the number of skimming jobs submitted, queued, running and finished as a function of time and Figure 16 the accumulated number of skimmed and merged events. It took about 2 days to skim the sample and one additional day to perform the merging of the selected files.

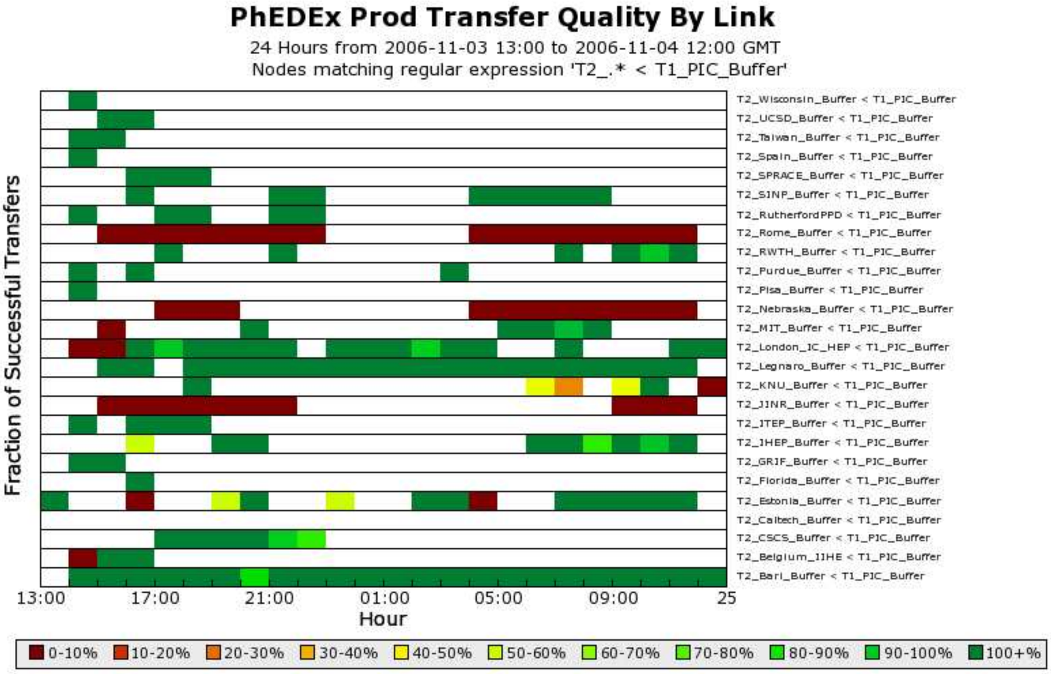


Figure 12: Quality of the simultaneous transfer of a dataset from PIC to 25 Tier-2 sites.

The event processing time for the skimming jobs is plotted in Figure 17. Few seconds were required to process each event. The two peaks in the picture correspond to two groups of machines with different CPU power at PIC.

Figure 18 shows for the skimming and merge jobs the Grid efficiency (fraction of submitted jobs that are not aborted due to Grid middleware problems), the Application efficiency (the fraction of jobs for which the skimming application finished successfully), the Stage out efficiency (the fraction of jobs for which the stage out of the output file onto the local mass storage succeeded) and the Job efficiency (out of the jobs that started to run at the worker node, the fraction of them that finished successfully, including inefficiencies accessing the experiment software and stage out inefficiencies). Application, job and stage out efficiencies were close to 100%. There was a 15% Grid inneficiency for skimming jobs due to temporary Grid problems. Failed jobs are automatically resubmitted by ProdAgent.

Figure 19 shows the input/output throughput (top) and the memory consumption (bottom) in one of the worker nodes during one day where several merge jobs were executed. One can see that skimming jobs during about one hour process the input data at a rate of about 1MB/s and, at the end, stage out the output file to the local storage at high speed (the bin size in the plots is 5 minutes). The RAM consumed by jobs slightly increases with the number of processed jobs up to about 600 MB.

4.3 Data re-reconstruction

The re-reconstruction workflow was demonstrated at the Tier-1 sites at the end of CSA06. The goal was to reprocess at least 100k events at every Tier-1. PIC reprocessed about 900k events as can be seen in Figure 20.

Figure 21 shows the number of jobs submitted, in queue, running and finished as a function of time. It took essentially two days to reprocess most of the data and one more day to merge the reprocessed data. The submission of merge jobs was delayed with respect to the appearence of reprocessed data due to temporary problems in the merge sensor component of the ProdAgent instance used for data reprocessing at PIC. In the normal operation, ProdAgent creates and submits merge jobs as soon as data to be merged become available.

The event reprocessing time is shown in Figure 22. In average 10 seconds were needed to re-reconstruct one event of the Z→ $\mu\mu$ sample used in the reprocessing exercise.

Events were reprocessed with high efficiency at PIC (see figure 23). There was only about 1% inneficiency in the Grid submission of jobs. Grid and site conditions can change rapidly so that job efficiencies may largely vary with time. Efficiencies achieved in particular exercises should not be taken as average efficiencies.

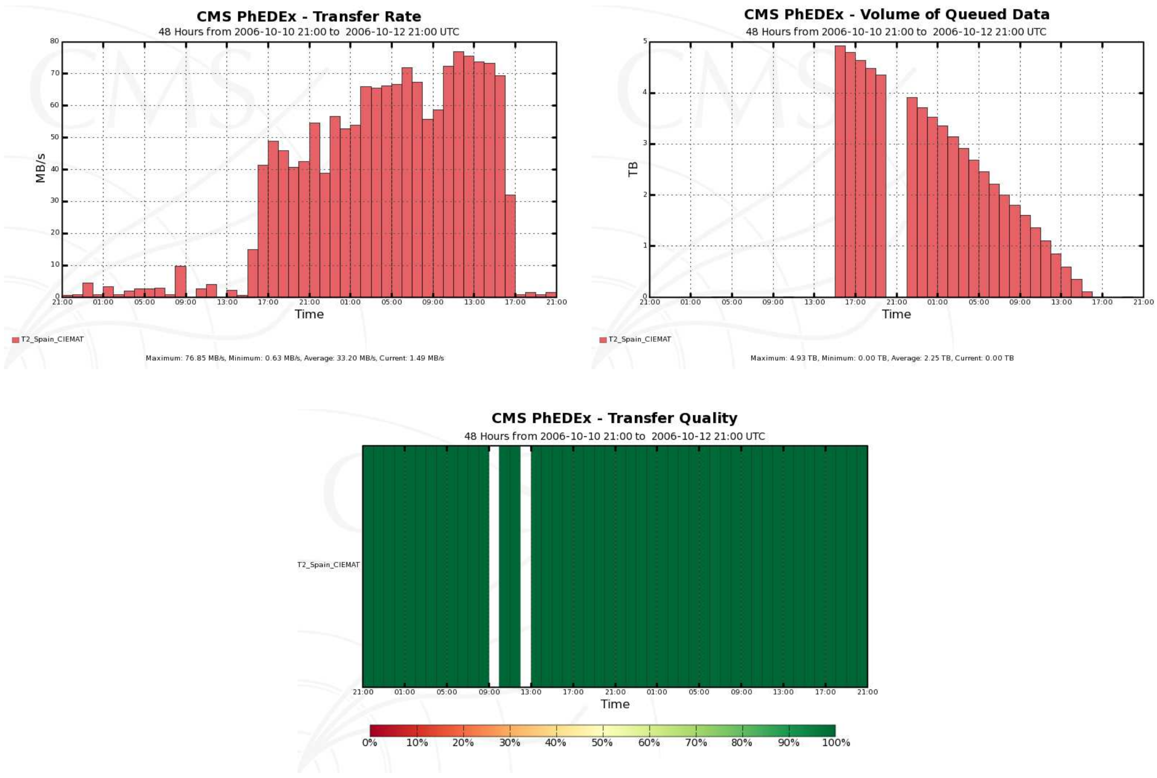


Figure 13: Bursty transfer of 5 TB of data from PIC to CIEMAT. Transfer rate (top-left), data backlog (top-right) and transfer quality (bottom).

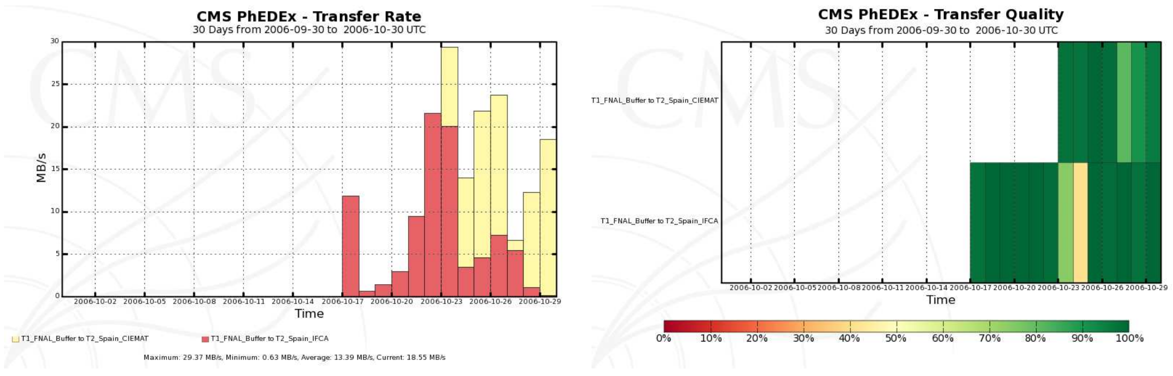


Figure 14: Non-regional transfers from FNAL Tier-1 to CIEMAT and IFCA. Transfer rate (left) and transfer quality (right).

Figure 24 shows the reconstructed invariant mass of the Z boson obtained from the data reconstructed at the Tier-0 ('ideal'), from events processed with misalignment as input for the alignment algorithm ('misaligned') and from events re-reconstructed at PIC using the alignment constants derived from the alignment algorithm ('realigned'). The degradation of the mass resolution and the recovery of the original value after the reprocessing with the proper alignment constants is clearly visible in the plot.

The improved calibration and alignment constants used in the data reprocessing were accessed via the local FroNTier cache. Figure 25 shows the data throughput in kB/s from the FroNTier cache to the reprocessing jobs. The small blue peaks correspond to fetches from the central database server at CERN to the local cache while the green histogram corresponds to direct fetches from the local FroNTier cache.

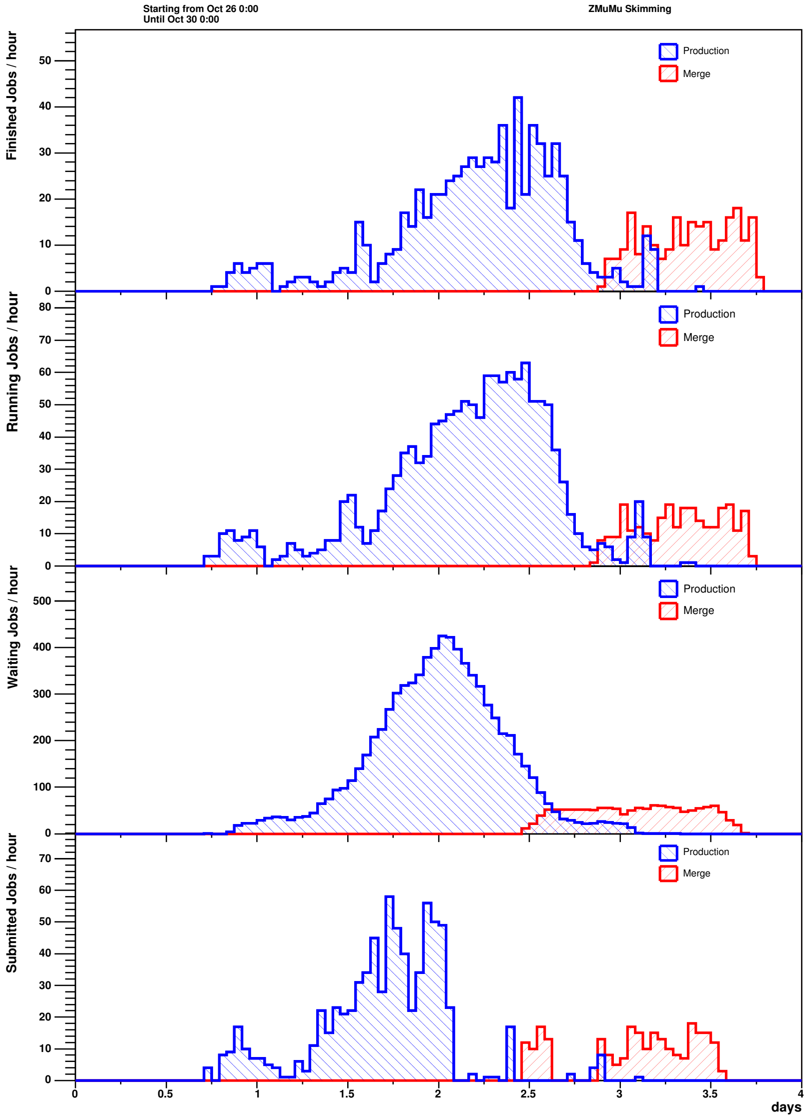


Figure 15: Number of submitted, queued, running and finished $Z^0 \rightarrow \mu\mu$ skimming processing and merge jobs as a function of time.

4.4 Data Analysis

A wide variety of physics analysis demonstrations were prepared by the physics groups for CSA06 in order to test the analysis workflow. We describe later in this section three analysis exercises carried out at the Spanish Tier-2 sites.

Figure 26-top shows the distribution between the sites of analysis jobs submitted by users during CSA06.A substantial number of analysis jobs was run at the Spanish sites. Few thousand analysis jobs were run at CIEMAT, IFCA and PIC with high efficiency. In order to stress the workload management system and to demonstrate a scale of job submission above 10000 jobs/day Grid-wide, fake analysis jobs were centrally submitted by means of a JobRobot which prepared and submitted fake analysis jobs according to the data published by the sites. These jobs complemented the smaller scale of user analysis jobs and stressed the storage system at the sites by reading data. Above 500k jobs were submitted by the JobRobot. CIEMAT received and executed with high efficiency a large number of JobRobot jobs as can be seen in Figure 26-bottom. PIC also run a large number of JobRobot jobs with a somewhat lower application efficiency while IFCA does not appear in the plot because it only includes the top-20 sites with more JobRobot jobs executed.

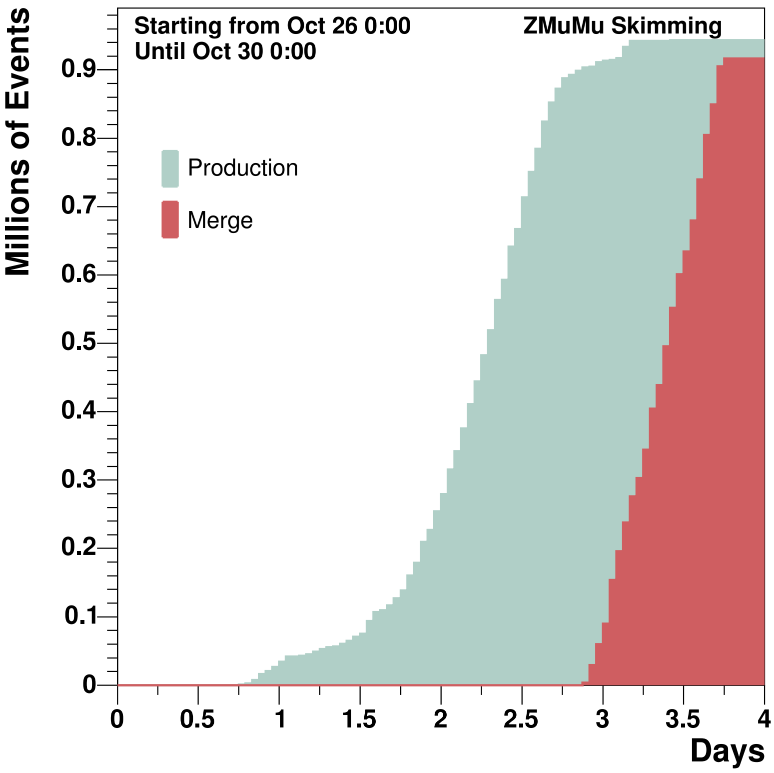


Figure 16: Accumulated number of events with time for processing and merge jobs for the $Z^0 \to \mu\mu$ skimming.

4.5 Dimuon studies

The samples skimmed at PIC (see section 4.2) were transferred to CIEMAT for analysis. The $Z^0 \to \mu\mu$ (2.04 million events) and the Soft Muon sample were filtered using an algorithm designed by CIEMAT physicists. Approximately half of the events in both samples passed the filter requirements (948 K events and 886 K events for $Z^0 \to \mu\mu$ and Soft Muon samples respectively).

Analysis jobs were submitted to CIEMAT using CRAB. The skimmed samples were processed using a simple CMSSW framework analyzer which saved the output histograms in root files (one per job) and archived into mass storage at runtime. An asynchronous script merged the output root files into a single one per dataset.

Figure 27 shows the average read performance (about 2 MB/s) of the analysis jobs reading the skimmed samples. That figure corresponds to an analysis event rate of a few Hz.

Examples of dimuon invariant mass distributions for events from the two samples are displayed in Figure 28. Global muons correspond to tracks measured in the tracker as well as in the muon chambers. Standalone muons are track reconstructed using only the information in the muon chambers. The Standalone distributions correspond to the muon transverse momentum measurements at the muon chamber entrance position, which give a degraded dimuon mass distribution.

In the plots in Figure 29, the momentum of the StandAlone muons is taken at the vertex (solid blue histograms) and with a vertex constraint (open red histogram), which significantly improves the dimuon mass resolution.

4.6 Muon alignment

A muon alignment exercise was performed at IFCA. It is described in detail in [2] and a summary is given here. The goal of this analysis was to demonstrate the feasibility of performing the Muon System standalone alignment with tracks at a remote Tier-2. The exercise was foreseen to prove the data and workflow, but also the performance of the algorithms was tested. The exercise was split in several subtasks:

- Data import to T2 and prompt analysis
- Re-reconstruction: remote access to geometry DB

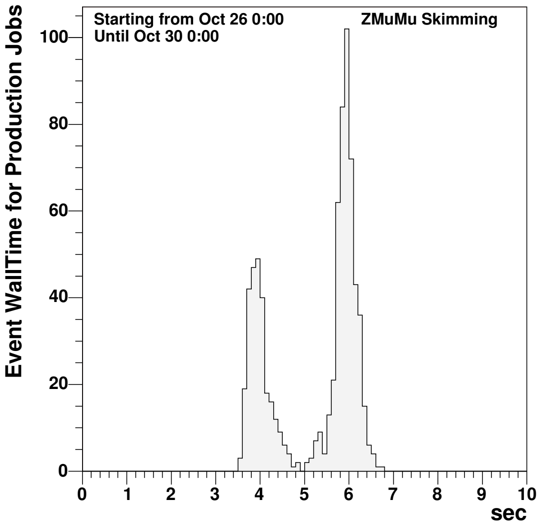


Figure 17: $Z^0 \rightarrow \mu\mu$ skimming event walltime.

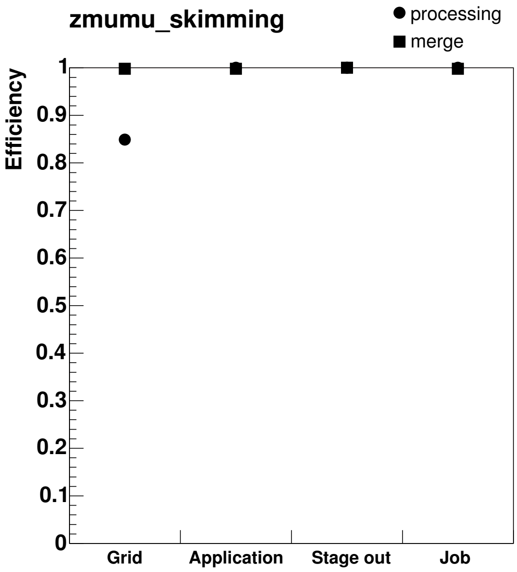


Figure 18: $Z^0 \rightarrow \mu\mu$ skimming job efficiencies.

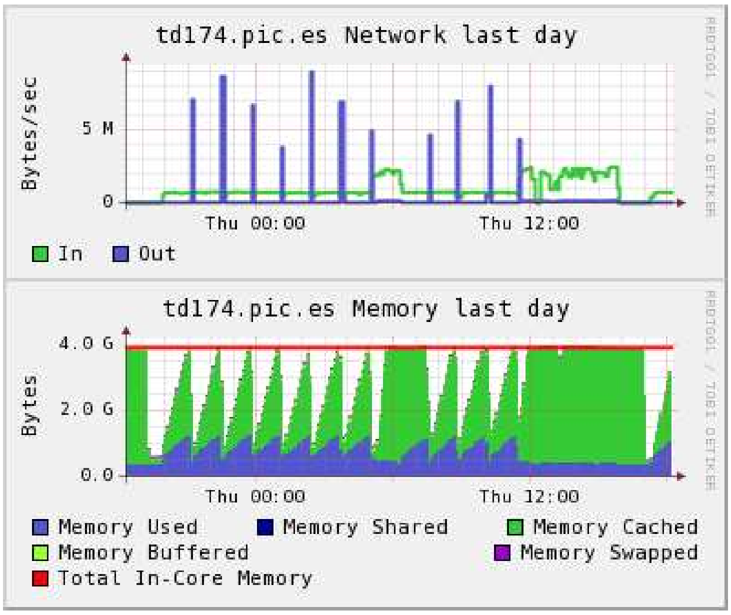


Figure 19: Input/output throughput (top) and memory usage (bottom) for merge jobs of the $Z^0 \rightarrow \mu\mu$ skimming.

- Extraction of alignment constants and production of re-aligned geometry file
- Re-Reconstruction with re-aligned geometry

The basic sample for this exercise was a 2 Million event sample of $Z^0 \rightarrow \mu\mu$ events. The full RECO sample was imported for the different versions as they were made available (4.4 TB for the last version) although many of the tasks could be performed onto the AlCaReco produced at CERN-T0 with a much smaller size of about 20 GB for the same 2 Million events. As soon as the sample was fully transferred, prompt analysis was performed using 90 CPU in which these jobs were prioritized. The jobs, submitted with the standard CRAB tools, consisted in running over the whole sample to check data quality producing basic distributions derived from standalone muon and global track quantities (transverse momentum and invariant mass, for dimuon case). The latency was dominated by the different steps in the data transfer. For the AlCaReco sample, results were available within the next day of the sample availability at Tier-0.

Re-reconstruction of the samples was performed locally at the Tier-2, starting from the digitized data contained in the RECO sample. Two different tests were done. On the first case, a distorted geometry Database is read

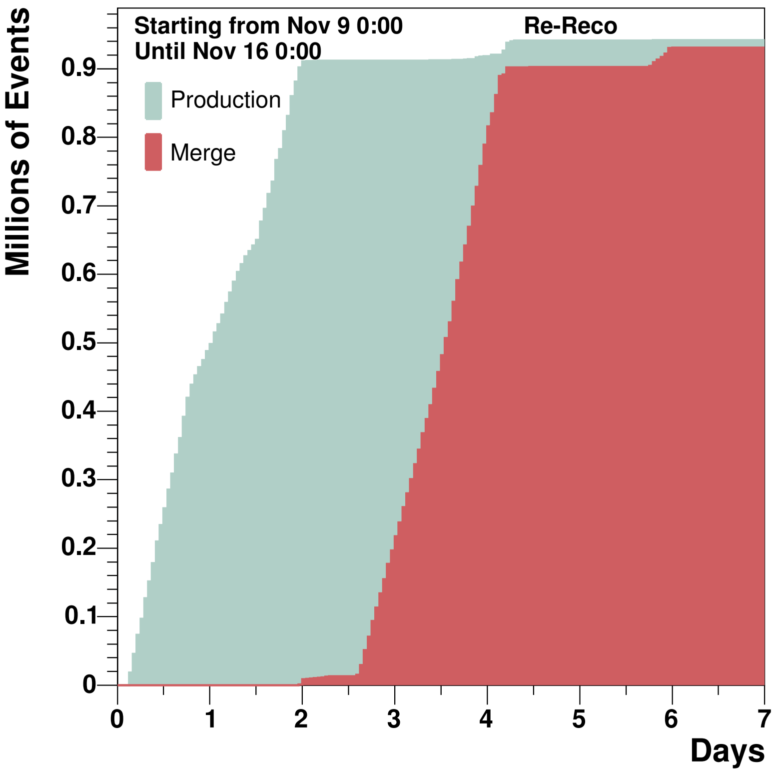


Figure 20: Number of accumulated events with time for the processing and merge jobs for the re-reconstruction demonstration run at PIC.

from the Tier-0. The one defined in the so-called ShortTerm Scenario, mimicking the misalignment conditions at the very beginning of data taking was used. The access was made with FroNTier through the local squid cache. Alternatively, the re-reconstruction was tested using a local DB, previously created off-line, which was supplied during the job submission, together with other input files. No significant delay was found due to the remote access to DB.

A simplified version of the Muon alignment with tracks algorithm was applied to the sample (AlCaReco) reconstructed with a distorted geometry in which Barrel chambers are displaced from their nominal position alternatively by 1 mm. The alignment constants obtained in this way are stored with MuonAlignment tools into a geometry DB, which constitutes an approximation of the nominal geometry. Muon reconstruction was again performed taking as input this geometry. Figure 30 shows the invariant mass for Standalone Reconstruction in the barrel, for each of the three geometries. It can be appreciated that the alignment recovers almost totally the precision given by the ideal geometry.

4.7 Selection of $t\bar{t}$ quark pairs in the di-lepton channel

Another analysis exercise was performed at IFCA, aiming at demonstrating the feasibility of performing a selection of pairs of top quarks in the di-lepton final state at a remote Tier-2. It is described in more detail in [2].

The di-lepton decay channel denotes the case where the two W bosons from the decaying $t\bar{t}$ pair both decay to final states containing an electron or a muon, accounting for about 5% of all $t\bar{t}$ standard model decays.

The original sample used consisted of about 5 million $t\bar{t}$ inclusive events. Skim jobs ran on that sample in order to select events having two high-P_T leptons in the final state. Skimmed data were transferred from FNAL Tier-1 to IFCA Tier-2 and then analyzed almost online, using CRAB and selection software. The whole $t\bar{t}$ in AODSIM format was also transferred to the Tier-2 in order to have an estimation of the main background to the di-lepton final state that comes from the semi-leptonic final state.

Figures 31 and 32 show the reconstructed muon spectra compared with the generated spectra, and the isolation variable for muons when they were matched and non-matched with respect to generated muons. The μ is considered matched if a generated μ is found within a cone of $\alpha = 0.15$ rad with respect to the reconstructed μ

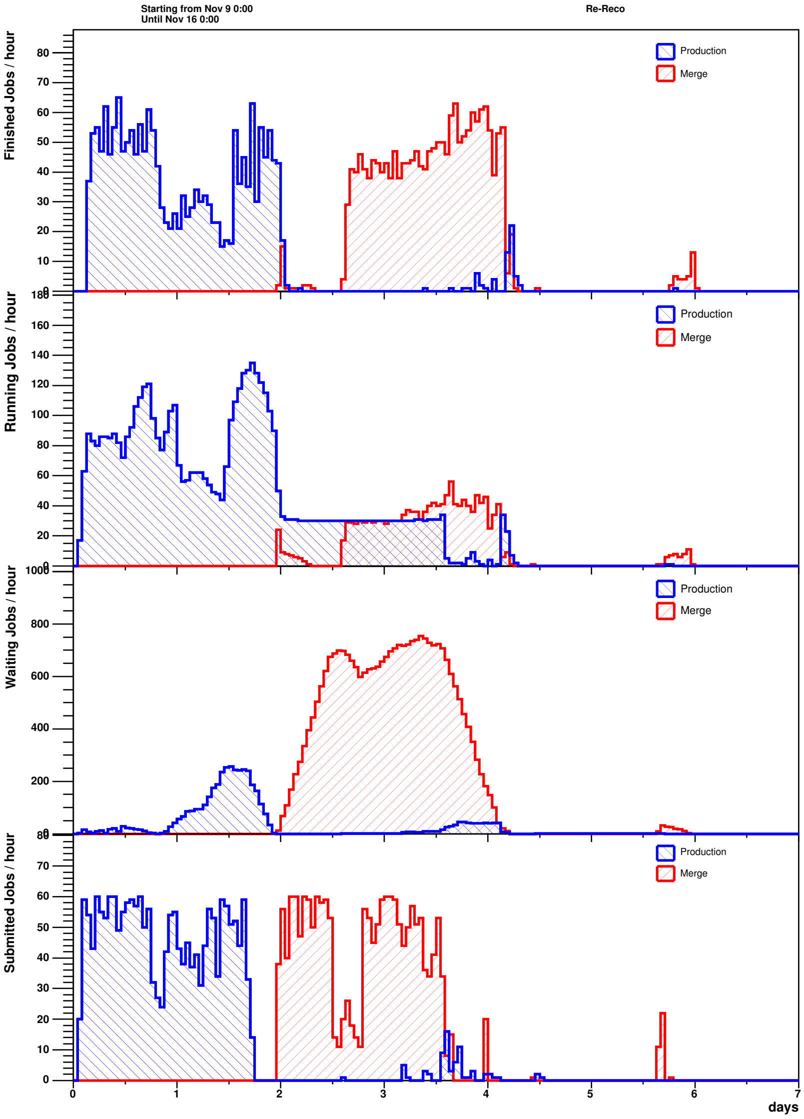


Figure 21: Number of submitted, queued, running and finished $Z^0 \to \mu\mu$ re-reconstruction processing and merge jobs as a function of time.

direction.

5 Conclusions and Experience

CSA06 has been extremely useful and successful as a complete exercise of the CMS workload management and data management systems, execution of many of the CMS workflows and stress tests of site facilities. The intended functionality was demonstrated in the challenge. Several dataflows and workflows in the CMS computing model were missing however in CSA06. Data transfers between Tier-1 sites, non-regional transfers Tier1-Tier2 and Tier-2 to Tier-1 transfers were not exercised; reprocessing recalling from tape large amounts of data, to exercise the management of the disk cache in front of tape was not practiced; Monte Carlo production at the Tier-2 sites was not concurrently run with analysis activities; the Tier-0 did not include High Level Trigger processing and the storage manager. A new combined challenge, CSA07, is scheduled for September 2007 to simultaneously perform all CMS computing and offline activities at the 2008 50% scale. It will surely profit from the experience gained during the preparation and execution of CSA06.

CSA06 was very successful at the cost of a high operational load. There was a focused effort during the duration of the challenge where computing experts, managers, site administrators and CMS site contacts were supervising the operation of the system. As CMS transitions from development and integration to stable operations, it is expected

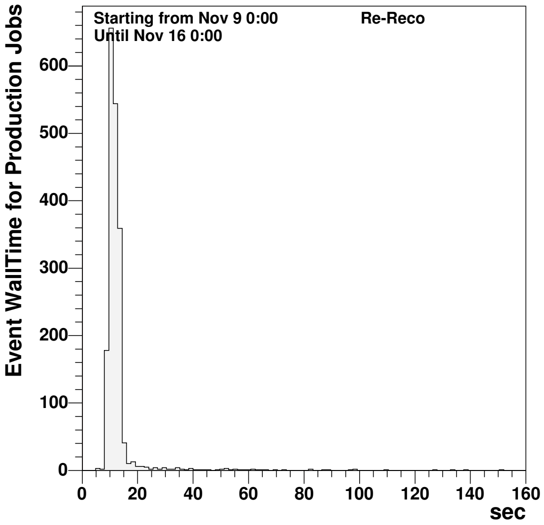


Figure 22: Reprocessing event walltime.

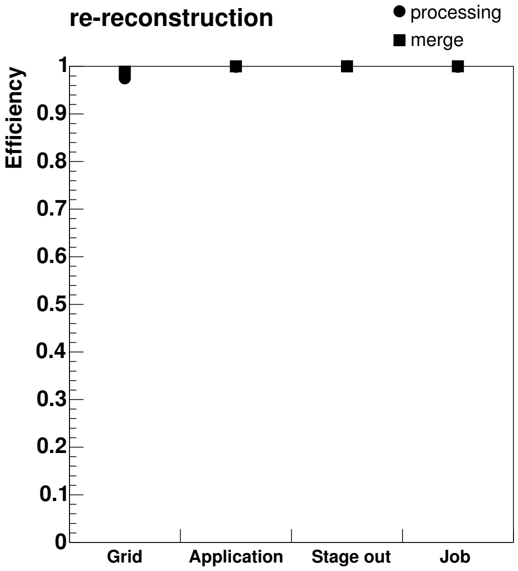


Figure 23: Reprocessing efficiencies.

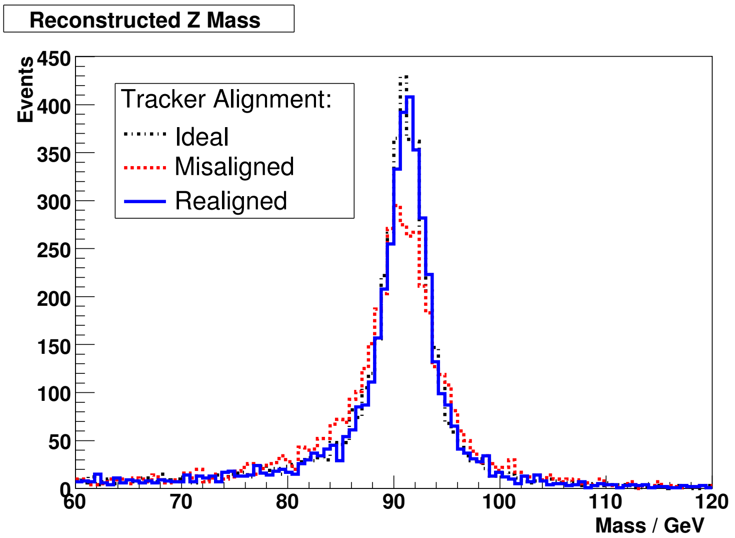


Figure 24: Reconstructed Z^0 invariant mass without misalignment ('ideal'), with misalignment ('misaligned') and after applying the alignment constants in the re-reconstruction ('realigned').

that the load to operate computing activities will be significantly reduced and a central operations team will take over the operation of data and workflows.

A tight contact and strong engagement of the computing sites is crucial for an efficient execution of the computing activities. The distributed nature of the CMS computing model and resources requires sites, with the help of the CMS computing groups, to be strongly involved in the integration of the computing systems, tuning of the performance of the facilities, and to react promptly in case of problems.

Scale testing continues to be an extremely important activity. Each step of doubling the capacity and activity level is far from trivial. Scaling problems are sometimes difficult to anticipate so that concerted exercises aimed at reaching certain scale goals are of crucial importance.

5.1 Data management

Data transfers from CERN to the Tier-1 centers worked remarkably well during CSA06, in fact much better than in previous transfer exercises. An appropriate support by the Castor team at CERN is crucial for the proper functioning of data export from CERN. Regional transfers from Tier-1 sites to associated Tier-2 sites worked well

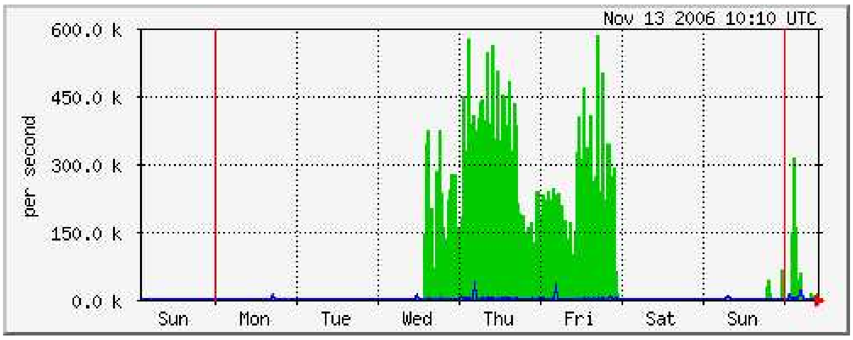


Figure 25: Data throughput in the local FroNTier cache used by the reprocessing jobs.

in general but non-regional transfer need to be much improved.

It takes quite some time to debug and tune a particular link. Many elements are involved in this process like available bandwidth, latencies, firewalls, configured transfer parallelism and time outs, FTS server configuration, SRM and gridFTP servers at both ends, PhEDEx configuration, tcp parameters, Linux I/O, file system specifics in disk servers, etc. Storage systems, SRM implementations and Grid middleware are at times quite unstable and unreliable. The different transfer layers gridFTP/SRM/FTS are not easy to configure properly and quite difficult to debug in case of problems.

The current FTS server architecture for data exports from Tier-1 sites can cause serious troubles to the exporting sites. In the current architecture, data exports from a Tier-1 to a Tier-2 are managed by the FTS server of the reference Tier-1 of the given Tier-2 involved in the transfer. This means that the source Tier-1 does not generally manage the transfers (only for regional Tier-2 sites) and that several FTS servers can be simultaneously involved in transfers from a Tier-1. This makes impossible for the source Tier-1 to control the maximum number of parallel transfers at the FTS level. A Tier-1 site can be flooded with transfer requests that can bring down its storage system. CMS has proposed to change the FTS server architecture so that the source Tier-1 controls all exports originated from it.

The ability of PhEDEx to perform multi-hop transfers implies that additional disk storage resources are required for buffering and managing the data in transfer at intermediate hops. The difficulty in managing the pass-through traffic (no archive to tape at Tier-1's, flushing the buffer once the data have reached the final destination) advised to switch off this feature during CSA06. If multi-hop transfers are enabled in the future, proper support in PhEDEx for managing pass-through traffic must be implemented.

In PhEDEx the source node of a data transfer is not specified, only the destination node. In case that several replicas of the same data exist, the PhEDEx routing system dynamically finds the best route taking into account the connection topology and the throughput record of the links. Dynamic routing will be particularly useful for Tier1-Tier1 transfers for AOD distribution after re-reconstruction but was not really needed in CSA06 where transfers were mostly pre-specified (Tier-0 → Tier-1's → regional-Tier-2's).

The management of data subscription, deletion and registration in DLS were manual operations in CSA06 which caused a significant load on the central PhEDEx team and site contacts. These operations have already been automated in PhEDEx. Now site administrators can request/modify/remove data subscriptions and request the removal of data blocks/datasets replicas via a local deletion PhEDEx agent. Prioritization of data transfers in PhEDEx was not supported during CSA06. It has been implemented now in PhEDEx and site administrators can change priorities of data transfers individually for every data subscription. Dynamic priorities will be important for Tier-1 to Tier-2 transfers were priorities mostly depend on the interest of the local physics community supported at a given Tier-2.

The synchronization of the different sources of data information (the transfer system, the Data Bookkeeping and Location Services and the local storage at sites) was also a manual operation leading often to inconsistencies. For example, after data loss at a site, the site administrator had to ask the central data management team to manually reflect the data loss in the data management system. It is planned that the Data Bookkeeping Service will be the unique authoritative source of information and the data transfer system will only transiently keep information of data in transfer. As a temporary solution, an automatic procedure to keep the data bookkeeping and transfer databases synchronized is under study. Tools to automatically and continuously synchronize the central data management databases with the data really existing on storage at the sites are also under development.

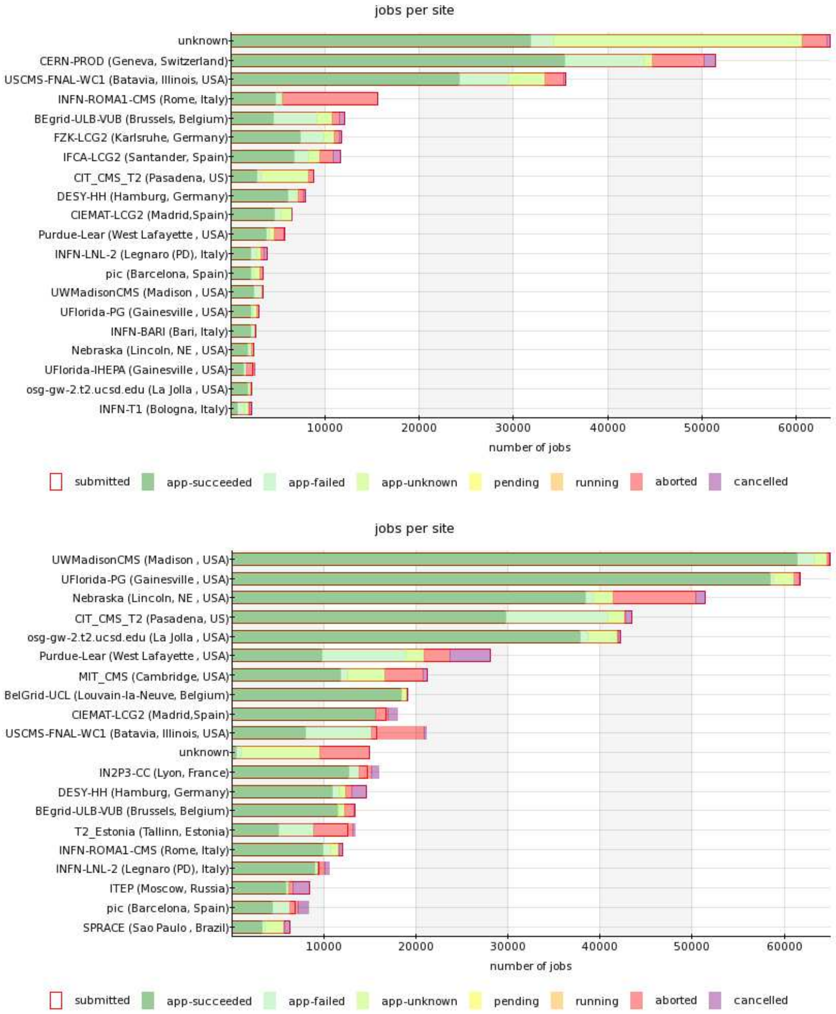


Figure 26: Distribution between the sites of CSA06 user analysis (top) and JobRobot fake analysis (bottom) jobs.

The existence in PhEDEx of local agents interacting with the storage system at the sites, especially at the Tier-1 centers, has proven to be very useful. Configuration, tuning and debugging is easier for local CMS administrators. In addition, the SRM interface to the storage system still lacks some functionality (e.g. mass data pre-stage) that is implemented via the local agents.

It is very advisable to keep some level of data transfers between the sites outside the computing challenge periods. It helps very much to tune performance, check transfers after middleware or storage system changes, etc. Continuous dummy data transfers between sites are being kept now in PhEDEx with this purpose. About 60 TB per day are transferred between sites that way. Production data transfers (mainly Monte Carlo production data) are not enough yet to keep a reasonable level of data throughput in all links.

The new data organization and new data management services introduced in 2006 have helped to increase data handling efficiency. The introduction of the concept of data block, an arbitrary set of files that are tracked and replicated together, largely decreases the number of entries in the replica catalogue. The drawback of replicating data blocks is that transfer tails for few files in a block can significantly increase the latency in the availability of the replicas since a block is not published as available until it has been completely replicated. The classic file-based global replica catalogue used by the other LHC experiments has been replaced in CMS by the block-based Data Location Service plus a Local Trivial file Catalogue at each site, a simple flat file with mapping rules between logical file names and physical file names. This architecture avoids scaling problems as the number of entries in the global replica catalogue increases. It has the drawback that physical file names cannot be resolved remotely and therefore deletion of files has to happen via jobs or agents at the sites, stage in of remote data to process is not possible, etc.

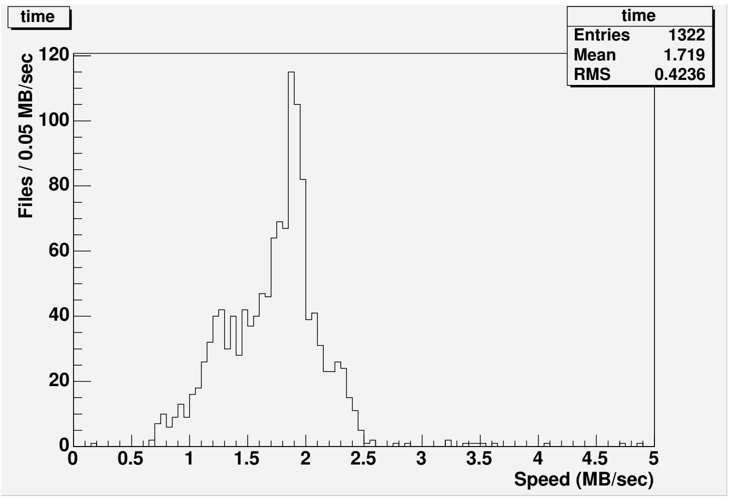


Figure 27: Input throughput for analysis jobs at CIEMAT.

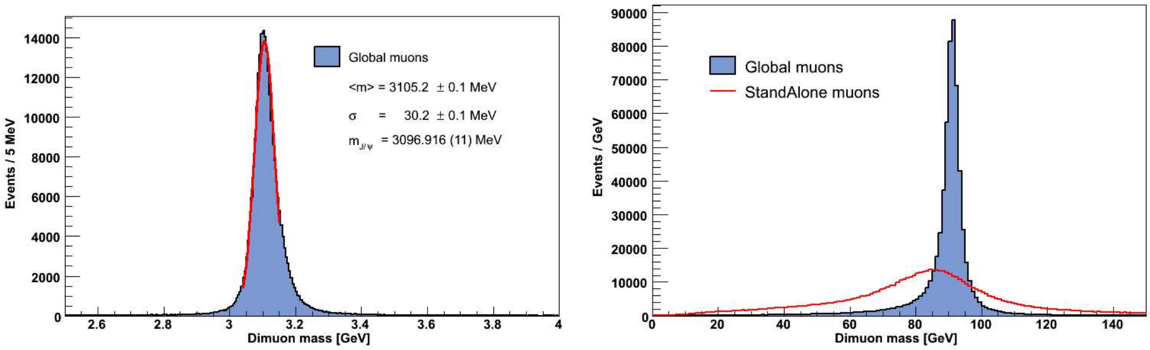


Figure 28: J/ψ (left) and Z^0 (right) dimuon invariant mass distributions from global and standalone muons.

A merging step has been introduced in the data processing workflows to increase the average size of files to few GBs. Larger files significantly reduce the overheads in data transfer, data mass storage and data bookkeeping, at the affordable price of complicating somewhat the processing workflows.

5.2 Workload management

ProdAgent, the tool for organized mass data processing (MC production, reprocessing, skimming and now being extended for Tier-0 processing), worked very well during CSA06. ProdAgent has provided automation, scalability, robustness and efficiency. Through a set of loosely coupled components production workflows are carried out in an automated fashion. ProdAgent is fully coupled to the various data management system components. Each ProdAgent instance runs its own local data and job tracking systems. Produced data are then promoted to the global data management databases, including the data transfer system. The new system brings scalability by the possibility of running any number of ProdAgent instances in parallel.

Skimming and data reprocessing were successfully demonstrated in CSA06. Multiple selection could be applied simultaneously. Merging and data registration components worked well. The design value for the input rate of skimming and analysis jobs of about 1 MB/s/slot was reached. However, retrieval from tape before data processing was not exercised. In CSA06 data were mostly available on disk. A coupling between ProdAgent and the data transfer system will be likely needed to automate mass data pre-stage at Tier-1 sites so that data processing is efficient and reliable.

Analysis workflows on skimmed data using CRAB were also successfully executed. The level of user analysis jobs was still low but it was complemented with a large number of fake analysis jobs submitted by the JobRobot with the aim of stressing the data serving capabilities of the sites.

The new CMS event data model and processing framework introduced in 2006 has greatly simplified workflows

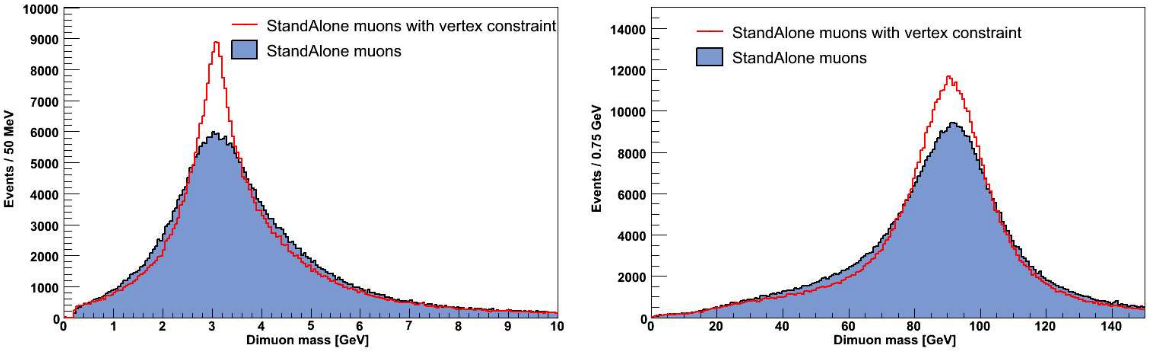


Figure 29: J/ψ (left) and Z^0 dimuon (right) invariant mass distributions from standalone muons with and without vertex constrain.

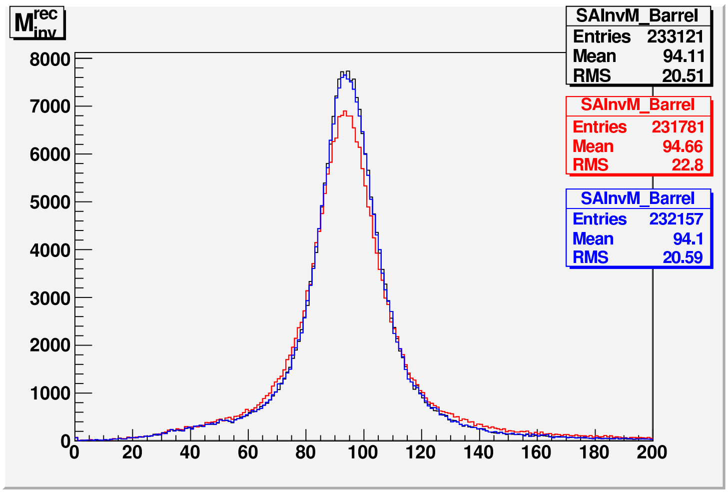


Figure 30: Reconstructed mass for $Z^0 \rightarrow \mu\mu$ sample with Global or Standalone Muons in the barrel for ideal (black), misaligned (red) and aligned (blue) geometry.

and publication for analysis. In particular, the ability to perform several processing steps in a job (generation, simulation, digitization and reconstruction) and the removal of the event metadata needed in the old event data model and processing framework have eased considerably production operations.

Robustness is still an important issue in the data processing system given the current unreliability and instability of global Grid services and sites (local storage and batch systems). Responsiveness of Grid and site administrators is still crucial for an efficient data processing.

Data processing on the Grid is still a manpower-consuming task. Further automation is needed and it is being implemented in ProdAgent. New components will take care of continuous job injection based on available computing resources or available data to be processed. Workflow management will be further automated coupling ProdAgent with a production manager component which in turn gets production work to be done from a production request system. Bulk operations will allow to increase the scale of jobs a single production instance can handle. Time-based jobs will allow to use more efficiently the computing resources. An extended global monitoring and accounting system will allow to analyze production performance and usage of resources for further optimization.

In CSA06 there was a lack of a proper validation step of configuration and software versions to identify problems well in advance prior to executing the processing workflows. Now that procedure has been implemented systematically producing a sizeable amount of events every time a new software version is released. Transparency for end users needs to be improved so that they can easily get a consistent picture of requests and status.

Acknowledgments

Many people at the sites and in the experiment have contributed to the organization, preparation and execution of

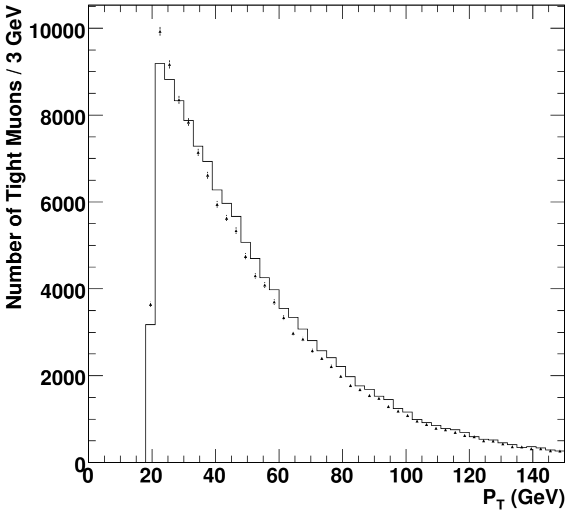


Figure 31: Distribution of reconstructed μ P_T (dots) compared with respect to the generated values (solid histogram) for μ selected after a P_T cut of 20 GeV.

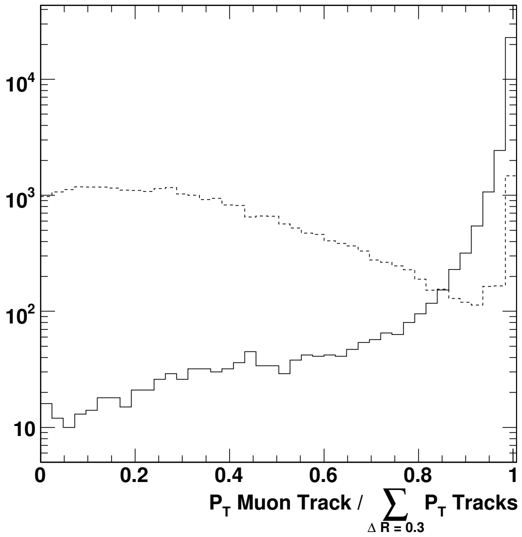


Figure 32: Distribution of variables used in μ isolation as described in the text. Solid line corresponds to matched μ, and dashed line to non-matched μ.

CSA06. Without their distributed and coordinated effort CSA06 would not have been a success. We are indebted to them.

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