

Dynamic Virtualized Deployment of Particle Physics Environments on a High Performance Computing Cluster

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Abstract The NEMO High Performance Computing Cluster at the University of Freiburg has been made available to researchers of the ATLAS and CMS experiments. Users access the cluster from external machines connected to the World-wide LHC Computing Grid (WLCG). This paper describes how the full software environment of the WLCG is provided in a virtual machine image. The interplay between the schedulers for NEMO and for the external clusters is coordinated through the **Roced** service. A cloud computing infrastructure is deployed at NEMO to orchestrate the simultaneous usage by bare metal and virtualized jobs. Through the setup, resources are provided to users in a transparent, automatized, and on-demand way. The performance of the virtualized environment has been evaluated for particle physics applications.

Keywords Virtualization · Particle Physics · Grid Computing · Benchmarks · Opportunistic Usage

1 Introduction

Particle physics experiments at the Large Hadron Collider (LHC) need a great quantity of computing resources. Herder-Str. 3, 79104 Freiburg, Germany

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sources for data processing, simulation, and analysis. This demand will be growing with the upcoming High-Luminosity upgrade of the LHC [1]. To help fulfill this requirement, High Performance Computing (HPC) resources provided by research institutions can be useful supplements to the existing World-wide LHC Computing Grid (WLCG) [2] resources allocated by the collaborations.

This paper presents the concepts and implementation of providing a HPC resource, the shared research cluster NEMO [3] at the University of Freiburg, to ATLAS and CMS users accessing external clusters connected to the WLCG with the purpose of accommodating data production as well as data analysis on the HPC host system. The HPC cluster NEMO at the University of Freiburg is deploying an **OpenStack** [4] instance to handle the virtual machines. The challenge is in provisioning, setup, scheduling, and decommissioning the virtual research environments (VRE) dynamically and according to demand. For this purpose, the schedulers on NEMO and on the external resources are connected through the **Roced** service [5].

A VRE in the context of this paper is a complete software stack as it would be installed on a compute cluster fitted to the demands of ATLAS or CMS workloads.

2 Virtualization infrastructure

Hardware virtualization has become mainstream technology over the last decade as it allows both to host more than one operating system on a single server and to strictly separate users of software environments. Hardware and software stacks are decoupled and therefore complete software environment can be migrated across hardware boundaries. While widespread in computer center operation this technique is rarely applied in HPC.

2.1 Computing at the University of Freiburg

The computer center at the University of Freiburg provides medium scaled research infrastructures like cloud storage, and especially HPC services adapted to the needs of various scientific communities. Significant standardization in hardware and software is necessary for the operation of compute systems comprised of more than 1000 individual nodes combined with a small group of administrators.

The level of granularity of the software stack provided is not fine enough to directly support the requirements of world-wide efforts like the ATLAS or CMS experiments. Therefore, novel approaches are necessary to

ensure optimal use of the system and to open the cluster to as many different use-cases as possible without increasing the operational effort. Transferring expertise from the operation of the established local private cloud, the use of **OpenStack** as a cloud platform has been identified as a suitable solution for NEMO. This approach provides a user defined software deployment in addition to the existing software module system. The resulting challenges range from the automated creation of suitable virtual machines to their on-demand deployment and scheduling.

2.2 Research Cluster NEMO

The research cluster NEMO is a cluster for state-wide research in the scientific fields Elementary Particle Physics, Neuroscience and Microsystems Engineering. It started its operation on the 1st of August 2016 and consists currently of 900 nodes with 20 physical cores and 128 GiB of RAM each. **Omni-Path** [6] spans a high speed low latency network of 100 Gbit/s between nodes. The parallel storage is based on **BEEGFS** [7] with 768 TB capacity.

2.3 Separation of software environments

The file system of a virtual machine or VRE is a disk image presented as a single file. From the computer center's perspective this image is a "black box" requiring no involvement or efforts like updates of the operating system or the provisioning of software packages of a certain version. From the researcher's perspective the VRE is an individual virtual node whose operating system, applications and configurations as well as certain hardware-level parameters, e.g. CPU and RAM, can be configured fully autonomously by the researcher within agreed upon limits.

To increase the flexibility in hosted software environments, the standard bare metal operation of NEMO is extended with an installation of **OpenStack** components [8]. The NEMO cluster uses Adaptive's Workload Manager **Moab** [10] as a scheduler of compute jobs. **OpenStack** as well can schedule virtual machines on the same nodes and resources. To avoid conflicts, it is necessary to define the master scheduler which decides the job assignment to the worker nodes. Both **Moab** and **OpenStack** are unaware that another scheduler exists within the cluster and there is no API which enables them to communicate with each other. Since the majority of users still use the bare metal HPC cluster, **Moab** is deployed as the primary scheduler. It allows for detailed job description and offers sophisticated schedul-

ing features like fair-share, priority-based scheduling,¹⁶⁵ detailed time limits, etc. **OpenStack**'s task is to deploy¹⁶⁶ the virtual machines, but **Moab** will initially start the¹⁶⁷ VRE jobs and the VRE job will instruct **OpenStack**¹⁶⁸ to start the virtual machine on the reserved resources¹⁶⁹ with the required flavor, i.e. the resource definition in **OpenStack**.

When a VRE job is submitted to the NEMO clus-¹⁷⁰ter, **Moab** will first calculate the priority and the needed resources of the job and then inserts it into its queue.¹⁷¹ When the job is in line for execution and the requested¹⁷² resources are available, the job will start a script which¹⁷³ then starts the VRE on the selected node within the re-¹⁷⁴source boundaries. During the run-time of the VRE a¹⁷⁵ monitoring script regularly checks if the VRE is still¹⁷⁶ running and terminates the job when the VRE has¹⁷⁷ ended. When the job ends, **OpenStack** gets a signal to¹⁷⁸ terminate the virtual machine and the VRE job ends¹⁷⁹ as well. Neither **Moab** nor **OpenStack** have access inside¹⁸⁰ the VRE, so they cannot assess if the VRE is actually¹⁸¹ busy or idle. The software package **Roced** (described¹⁸² in further detail in Section 4) has been introduced to¹⁸³ solve this issue. It is used as a broker between different¹⁸⁴ HPC schedulers, translating resources and monitoring¹⁸⁵ usage inside the virtual machine, as well as starting and stopping VRE images on demand.

3 Generation of the VRE image

The VREs for ATLAS and CMS software environments¹⁸⁹ consist in **OpenStack** containers in the format of com-¹⁹⁰patible VM images. These images are provided in an¹⁹¹ automatized way allowing versioning and archiving of¹⁹² the environments captured in the images.¹⁹³

3.1 Packer combined with Puppet

A reasonable approach to generate the image is the¹⁹⁹ open-source tool **Packer** [11], interfaced to the system²⁰⁰ configuration framework **Puppet** [13]. **Packer** allows to²⁰¹ configure an image based on an ISO image file using a²⁰² **kickstart** [12] file and flexible script-based configura-²⁰³tion. It also provides an interface to **Puppet** making it²⁰⁴ particularly convenient if an existing **Puppet** role is to²⁰⁵ be used for the images. If the roles are defined accord-²⁰⁶ing to the hostname of the machine as is conventional in²⁰⁷ **Puppet** with **Hieradata**, the hostname needs to be set²⁰⁸ in the scripts supplied to **Packer**. Propagation of cer-²⁰⁹tificates requires an initial manual start of a machine²¹⁰ with the same hostname to allow handshake signing of²¹¹ the certificate from the **Puppet** server.

Packer's interface to **Puppet** allows a fully auto-²¹² mated image generation with up-to-date and version-²¹³ controlled configuration. At the end of the generation²¹⁴ run, the image is automatically transferred to the **Open-**²¹⁵**Stack** image server.

3.2 Image generation using the Oz toolkit

Another option to employ a fully-automated procedure²¹⁶ is to use the **Oz** toolkit [14]. All requirements and con-²¹⁷figuration options of an image can be specified through²¹⁸ a XML template file. The partitioning and installation²¹⁹ process of the operating system is fully automated, as²²⁰ **Oz** will use the remote-control capabilities of the local²²¹ hypervisor. After the installation of the operating sys-²²²tem, additional libraries and configuration files can be²²³ installed. Once the image has been created, it is auto-²²⁴ matically compressed and uploaded to a remote cloud²²⁵ site. This technique allows to build images in a repro-²²⁶ducible fashion, as all templated files are version con-²²⁷trolled using **git**. Furthermore, existing template files²²⁸ are easy to adapt to new sites and experiment configu-²²⁹rations.

4 Interfacing batch systems and virtual resources using Roced

While HPC systems with support for virtualized re-²³⁰search environments and commercial cloud providers²³¹ offer the necessities to acquire computing and storage²³² capacity by dynamic resource booking, the comput-²³³ing needs of high energy physics research groups ad-²³⁴ditionally require workflow management systems capa-²³⁵ble of maintaining thousands of batch jobs. Some cloud²³⁶ providers, for example Amazon with AWS Batch [15],²³⁷ provide a service for workflow management, however²³⁸ these offerings are often limited to one specific cloud²³⁹ instance. To dynamically distribute batch jobs to multi-²⁴⁰ple sites and manage machine life-time on specific sites,²⁴¹ a combination of a highly-scalable batch system and a²⁴² virtual machine scheduler is desirable.

4.1 Roced

Many capable batch systems exist today and they can²⁴³ be interfaced to virtualization providers using the cloud²⁴⁴ meta-scheduler **Roced** (Responsive On-demand Cloud²⁴⁵ Enabled Deployment) which has been developed at the²⁴⁶ KIT since 2010 [5]. **Roced** is written in a modular fash-²⁴⁷ion in python and the interfaces to batch systems and²⁴⁸ cloud sites are implemented as so-called *Adapters*. This²⁴⁹

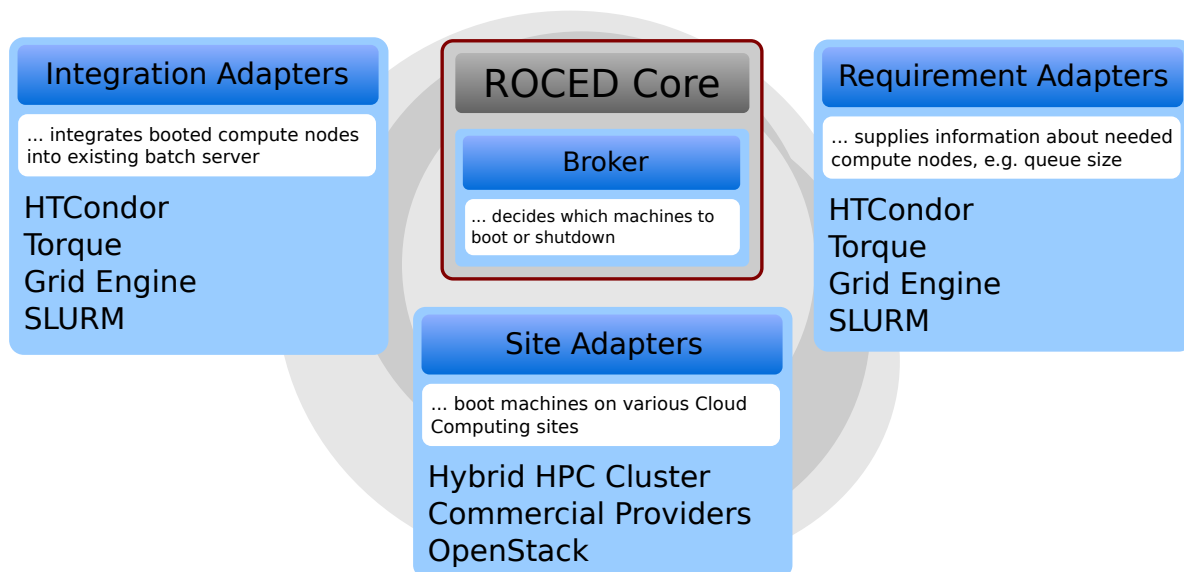


Fig. 1 Overview of the **Roced** modular design. The **Roced** Core contains the **Broker** which decides when and on which sites new virtual machines are booted. The **Requirement Adapters** report about the utilization and resource requirements of the attached batch systems. The **Site Adapter** is responsible to manage the lifetime of virtual machines on an cloud site and the **Integration Adapter** ensure that newly booted machines are integrated into the batch system.

makes **Roced** independent of specific user groups or workflows. It provides a scheduling core which collects the current requirement of computing resources and decides if virtual machines need to be started or can be stopped. One or more **Requirement Adapters** report the current queue status of batch systems to the central scheduling core. Currently, **Requirement Adapters** are implemented for the **Slurm**, **Torque/Moab**, **HTCondor** and **GridEngine** batch systems. The **Site Adapters** allow **Roced** to start, stop, and monitor virtual machines on multiple cloud sites. Implementations exist for **Amazon EC2**, **OpenStack**, **OpenNebula** and **Moab**-based virtualization at HPC centers. Special care has been put into the resilience of **Roced**: it can automatically terminate non-responsive machines and restart virtual machines in case some machines have dropped out. This allows VM setups orchestrated by **Roced** with thousands of virtual machines and many tens of thousands of jobs to run in production environments. The modular design of **Roced** is shown in Fig. 1.

4.2 Using **HTCondor** as front-end scheduler

The open-source project **HTCondor** provides a workload management system which is highly configurable and modular [16]. Batch processing workflows can be submitted and are then forwarded by **HTCondor** to idle resources. **HTCondor** maintains a resource pool, which worker nodes in a local or remote cluster can join. Once **HTCondor** has verified the authenticity and features of

the newly joined machines, computing jobs are automatically transferred. Special features are available to connect from within isolated network zones, e.g. via a **Network Address Translation Portal**, to the central **HTCondor** pool. The **Connection Brokering (CCB)** service [17] is especially valuable to connect virtual machines to the central pool. These features and the well-known ability of **HTCondor** to scale to $O(100k)$ of parallel batch jobs makes **HTCondor** well suited as a workload management system for the use cases described in this paper.

The **VRE** for **CMS** contains the **HTCondor** client **startd**. This client is started after the machine has fully booted and connects to the central **HTCondor** pool at **KIT** via a shared secret. Due to **HTCondor**'s dynamic design, new machines in the pool will automatically receive jobs and the transfer of the job configuration and meta-data files is handled via **HTCondor**'s internal file transfer systems.

4.3 Using **Slurm** as front-end scheduler

Alternatively to the approach described above, the open-source workload managing system **Slurm** [18] has been interfaced into **Roced** by the **ATLAS** group at University of Freiburg. **Slurm** provides a built-in functionality for the dynamic startup of resources in the *Slurm Elastic Computing* module [19]. However, this module is based on the assumption of a fixed maximum startup time of the machines. In the considered case, due to the

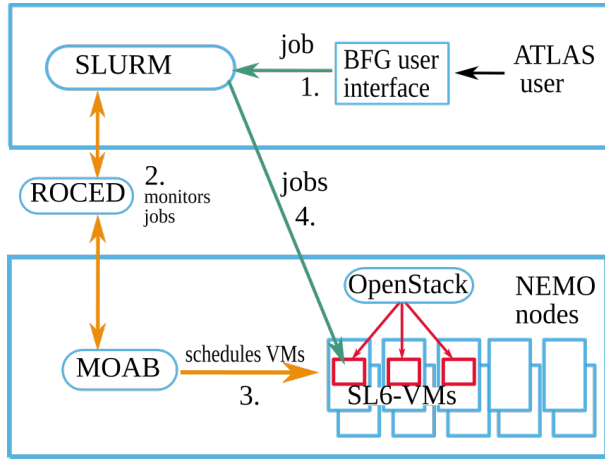


Fig. 2 Implementation of Roced with Slurm on the BFG cluster used by ATLAS researchers.

queue in the host system, the start of a resource can be delayed by a significant, varying time period. In addition the transfer of information, such as error states, from one scheduler to the other, and therefore to the user, is very limited. Therefore, Roced has been chosen as the interface between the Moab scheduler on the host system and the Slurm scheduler on the submission side. The scheduling system is illustrated in Fig. 2. For Slurm, it is necessary that each potential virtual machine is registered in the configuration at the time of start of the Slurm server as well as the client. Slurm configurations also need to be in agreement between server and client. Therefore, a range of hostnames is registered in the configuration in a way that is mapped to potential IP addresses of virtual machines. These virtual machines have a fixed number of CPUs and memory assigned and are registered under a certain Slurm partition. When a job is submitted to this partition and no other resource is available, information from the Slurm squeue and sinfo commands is requested and parsed for the required information.

Since the ATLAS Freiburg group comprises three sub-groups, each mapped to a different production account on NEMO, special care is taken to avoid interference of resources used by another account to ensure fairness on NEMO, while allowing jobs from one group to occupy otherwise idle resources of another group.

Roced determines the amount of virtual machines to be started and sends the corresponding VRE job submission commands to Moab. After the virtual machine has booted, the hostname is set to the IP dependent name which is known to the Slurm configuration. A cron job executes several sanity checks on the system. Upon successful execution of these tests, the Slurm client running in the VM starts accepting the queued jobs. After completion of the jobs and a cer-

tain period of receiving no new jobs from the queue, the Slurm client in the machine drains itself and the machine shuts itself down. The IP address as well as the corresponding hostname in Slurm are released and can be reused by future VREs.

5 Analysis of performance and usage

The Roced-based solution described above has been implemented and put into production by the research groups at the University of Freiburg (Institute of Physics) and the Karlsruhe Institute of Technology (Institute of Experimental Particle Physics). To prove the usefulness of this approach statistical analyses of the performance of the virtualized setup both in terms of CPU benchmarks and usage statistics have been conducted.

5.1 Benchmarks

Benchmark tests are performed with the primary goal to measure the performance of the CPU for High Energy Physics applications. Alongside the legacy HEP-SPEC06 (HS06) benchmark [20], the performance of the compute resources is furthermore evaluated with the ATLAS Kit Validation KV [23], a fast benchmark developed to provide real-time information of the WLCG performance and available in the CERN benchmark suite [21]. The primary target is to measure the performance of the CPU for High Energy Physics applications. The KV benchmark is making use of the simulation toolkit GEANT4 [24] to simulate the interactions of single muon events in the detector of the ATLAS experiment and provides as output the number of events produced per second. It constitutes a realistic workload for High Energy Physics jobs.

To assess the impact of the virtualization, the performance of the identical hardware configuration (20 cores Intel Xeon E5-2630 CPUs) has been determined either deployed via the standard bare metal operation on the NEMO cluster (NEMO bare metal) and on the ATLAS Tier-3 center in Freiburg (ATLAS Tier-3 bare metal), or as virtual machines on the NEMO cluster (NEMO VM). On the ATLAS Tier-3 bare metal and on the virtual machines running on the NEMO cluster, hyper-threading (HT) technology is activated. Both are using Scientific Linux 6 [25] as the operating system. On the cluster NEMO bare metal jobs are restricted to 20 cores by cgroups, since the application mix is broader than on HEP clusters. The operating system is CentOS7 [26]. The scores of the HEP-SPEC06 and KV benchmarks have been determined for these three

configurations as a function of the number of cores actually used by the benchmarking processes. This number ranges from 2 to 40 for the ATLAS Tier-3 bare metal and for the NEMO VM, for which HT is enabled, and from 2 to 20 for the NEMO bare metal, for which HT is not implemented. The benchmarks have been run 20 times for each core multiplicity value, and the means and standard deviations of the corresponding distributions have been extracted.

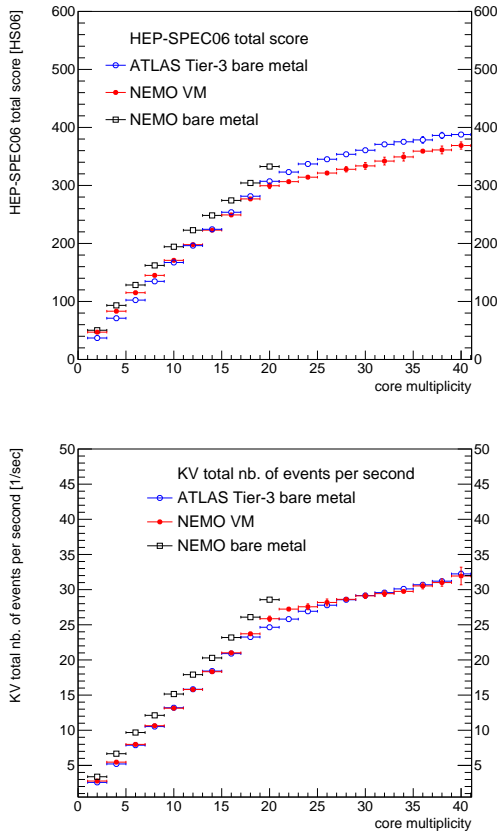


Fig. 3 Total score as a function of the core multiplicity for the HEP-SPEC06 (top) and KV (bottom) benchmarks for the ATLAS Tier-3 bare metal (blue open circles), the NEMO VMs (red full circles) and the NEMO bare metal (black open squares). The data points represent the average values of the benchmarks for each core multiplicity, and the vertical bars show the associated standard deviations.

The HEP-SPEC06 and KV results are presented in Figure 3 for the three configurations considered. The total scores of the two benchmarks are increasing until the maximum number of physical cores has been reached, and are characterized by a flattening increase afterwards. The scores of the virtual machines running on the NEMO cluster are only slightly lower than those obtained for the NEMO bare metal, and the loss of

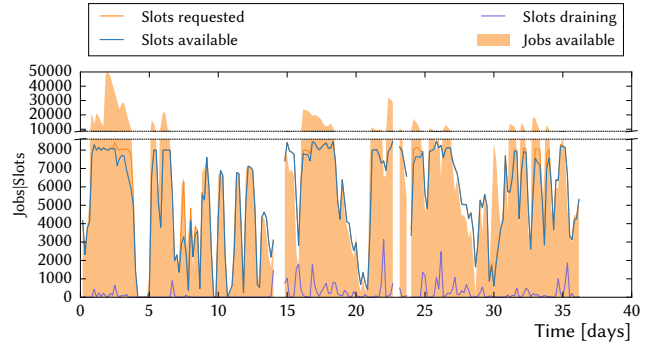


Fig. 4 Utilization of the shared HPC system by booted virtual machines. Up to 9000 virtual cores were in use at peak times. The fluctuations in the utilization reflects the patterns of the submission of jobs by the CMS users at the physics institute in Karlsruhe. The number of draining slots displays the amount of job slots still processing jobs while the rest of the node's slot are already empty.

performance due to the virtualization does not exceed 10%. For the VMs running on the NEMO cluster and the ATLAS Tier-3 bare metal, the interplay between the virtualization and the different operating systems leads to very similar scores for the two configurations, particularly for the KV benchmark, and the loss of performance is smaller than 10% as well.

5.2 Usage statistics

Fig. 4 shows the utilization of virtual machines which were orchestrated by Roved depending on the resource demands of the users of the KIT group. At peak times, up to 9000 virtual cores were filled with user jobs, consuming more than a half of the initial 16000 NEMO cores.

The usage of the hybrid cluster model is presented in Fig. 5. The diagram shows the shared usage of NEMO's cluster nodes running either bare-metal or virtualized jobs. The part of the cluster which runs virtualized jobs or VREs changes dynamically from job to job, since the VREs are started by a standard bare-metal job.

At the beginning the cluster was only containing the operating system and some basic development tools. Scientific software was added after the cluster was already in production mode. Since the VRE for the CMS project was already available when the NEMO cluster started, it could already use the whole cluster while other groups still had to migrate from other resources. This explains the high usage by VREs in the first months of operation. With more and more software being available for bare-metal usage the amount of VRE jobs decreased.



Fig. 5 Estimated usage of the NEMO cluster in the time from September 2016 to September 2018. The blue bars indicate the usage by jobs running directly in the hosts' operating system, while the orange bars are jobs running in virtual machines. The decrease of VRE jobs is partially explained by an increasing number of bare metal jobs submitted.

6 Conclusions and Outlook

A novel system for the dynamic, on-demand provisioning of virtual machines to run jobs in a high energy physics context on an external, not dedicated resource as realized at the HPC cluster NEMO at the University of Freiburg has been implemented. An interface between the schedulers of the host system and the external system from which requests are sent is needed to monitor and steer jobs in a scalable way. For this workflow the cloud meta-scheduler Ruced has been implemented and deployed for the described use-cases. The approach can be adapted to work with other platforms and could be extended to container technologies like Singularity [9].

The CPU performance and usage of the setup have been analyzed for the job execution environment. The expected performance loss due to the virtualization has been found to be sufficiently small to be compensated by the added flexibility and other benefits of this setup.

A possible extension of such a virtualized setup is the provisioning of functionalities for snapshots and migration of jobs. This would facilitate the efficient integration of long-running monolithic jobs into HPC clusters.

The provided solution extends the available compute resources for HEP calculations and could be one possibility to cope with new data from the upcoming High-Luminosity upgrade of the LHC. Since HEP VREs are perfect for backfilling this could be used on various cluster resources.

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