Benchmarking WLCG resources using HEP experiment workloads

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On behalf of the HEPiX CPU Benchmarking WG

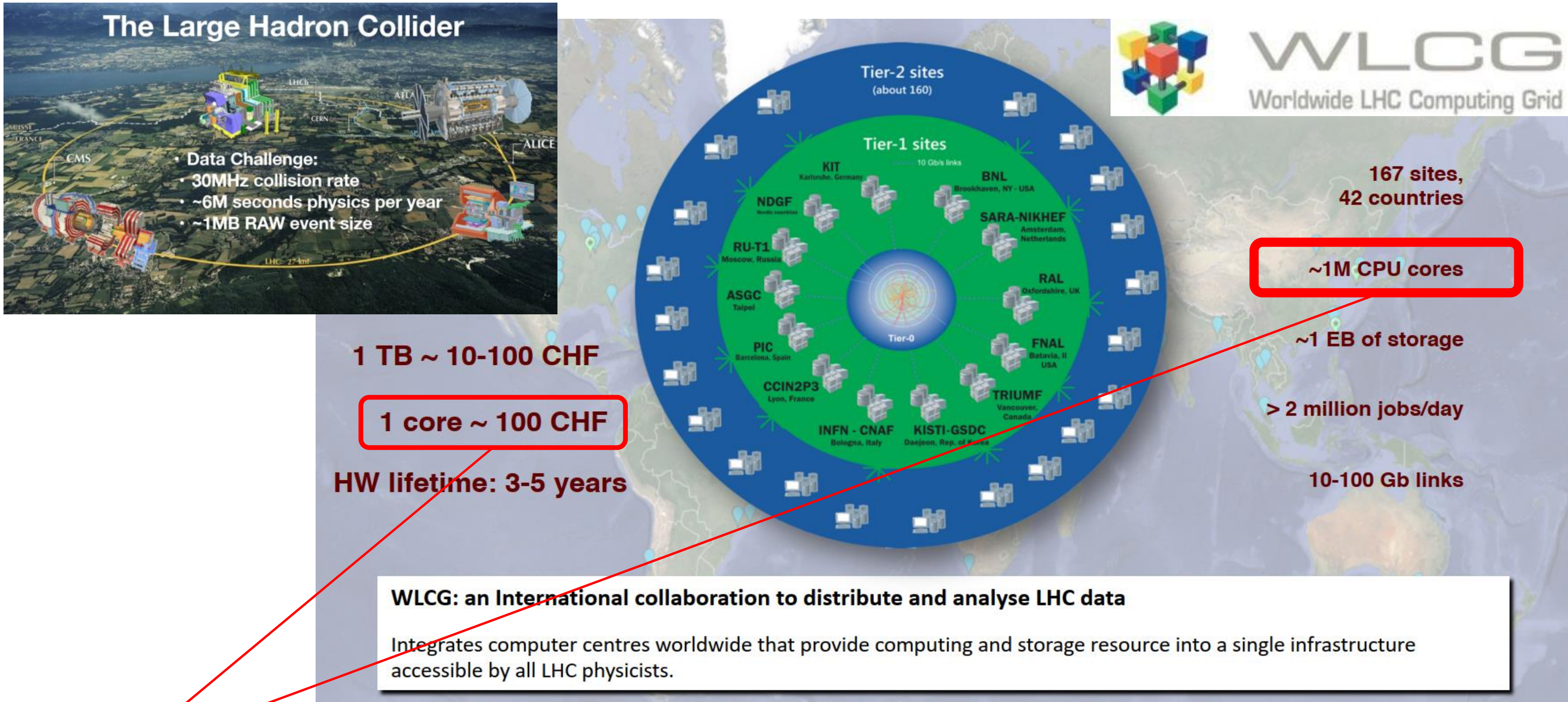
CHEP2019, 4 November 2019 – Adelaide, Australia

https://indico.cern.ch/event/773049/contributions/3473809

Outline

- Overview: CPU benchmarking in WLCG
  - –Why benchmarking?
  - –Current approach (HEP-SPEC06) and its limitations
- New approach: benchmarking using HEP experiment workloads
  - –Overview, implementation, status
  - –Applicability to HPCs and GPUs
- Conclusions

WLCG (Worldwide LHC Computing Grid): a varied computing landscape



S. Campana, ESPP, Grenada, May 2019

- *"CPU cores" are not all equivalent to one another* (sites are managed independently):
  - Some CPU cores are able to do more "work" than others per unit time (throughput)
  - Some CPU cores are more expensive than others

Why benchmarking CPU resources in WLCG?

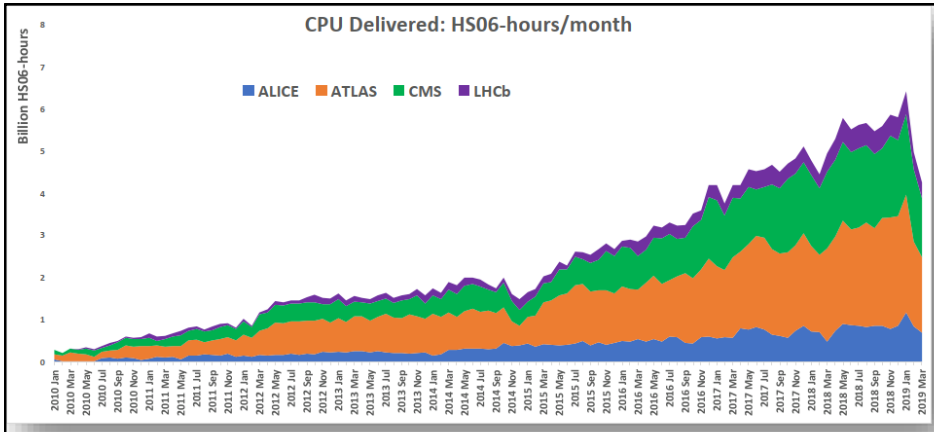
Two main use cases for WLCG:

- ***Accounting***
  - Experiments *request "X" CPU* resources to do their computing for one year
  - Funding agencies and sites *provision "X" CPU* resources to the experiments
  - Resource review boards *compare the "X" used to the "X" requested*
- ***Procurement***
  - Each site buys the CPU resources providing the *best "X" per CHF/EUR/…*

In addition:

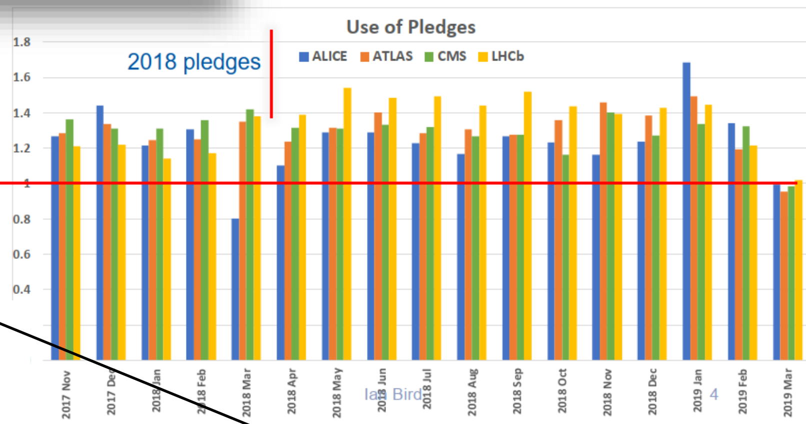
- **Scheduling**
- **Software optimizations**

WLCG accounting:
current benchmark is *HEP-SPEC06 (HS06)*



CPU Delivered

New peak: ~270 M HS06-days/month
~ 860 k cores continuous



Ian Bird, April 2019, Computing Resources Review Board

Very approximate rule of thumb: 10 HS06 per core (9M HS06 is ~0.9M cores)

HS06 is derived from SPEC CPU2006®

- Standard Performance Evaluation Corporation: industry standard since 1988
- *Real applications (from domains other than HEP), not a synthetic benchmark*
- After evaluating several subsets of SPEC CPU2006, chose the “all_cpp” subset
  – Seven C++ benchmarks (recompiled for HEP) – HS06 score is their geometric mean
  – Execution time: O(4h)

Bmk	Int vs Float	Description
444.namd	CF	92224 atom simulation of apolipoprotein A-I
447.dealII	CF	Numerical Solution of Partial Differential Equations using the Adaptive Finite Element Method
450.soplex	CF	Solves a linear program using the Simplex algorithm
453.povray	CF	A ray-tracer. Ray-tracing is a rendering technique that calculates an image of a scene by simulating the way rays of light travel in the real world
471.omnetpp	CINT	Discrete event simulation of a large Ethernet network.
473.astar	CINT	Derived from a portable 2D path-finding library that is used in game's AI
483.xalancbmk	CINT	XSLT processor for transforming XML documents into HTML, text, or other XML document types

$\left.\right\}$ 4 Floating Point benchmarks

$\left.\right\}$ 3 Integer benchmarks

HS06 was chosen because (in 2009) it seemed representative of HEP workloads

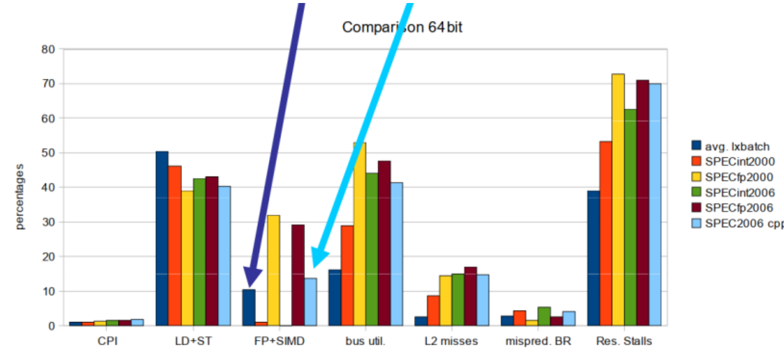
- *HS06 showed good correlation to the **throughputs** of HEP workloads*
  - Throughput (events per second) is the most relevant metric for HEP processing

Correlation	Generation	Simulation	Reconstruction	Total
Atlas	0.9969	0.9963	0.9960	0.9968
Alice pp MinBias	0.9994		0.9832	0.9988
Alice PbPb	0.9984		0.9880	0.9996
LhcB	0.9987			
CMS HiggsZZ	0.9982		0.9987	0.9983
CMS MinBias	0.9982		0.9974	0.9974
CMS QCD 80 120	0.9988		0.9987	0.9988
CMS Single Electron	0.9987		0.9942	0.9981
CMS Single MuMinus	0.9986		0.9926	0.9970
CMS Single PiMinus	0.9955		0.9693	0.9955
CMS TTbar	0.9985		0.9589	0.9987

Correlation of HEP-SPEC06 with several kinds of applications and different experiments

M. Michelotto et al. (2010)
J. Phys. Conf. Ser. 219 052009

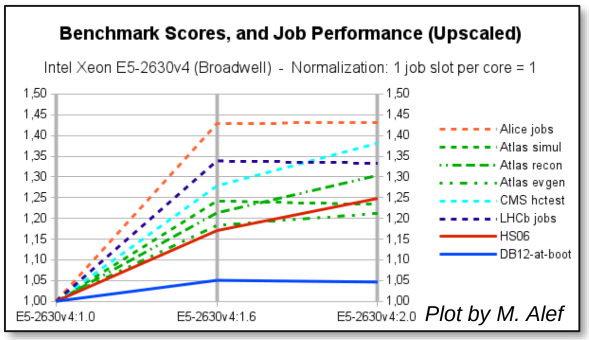
Similar FLOATING POINT fraction (~10%) for
HEP workloads on lxbatch** and **SPEC2006 "all_cpp"
(lower for SPEC INT, higher for SPEC FP)



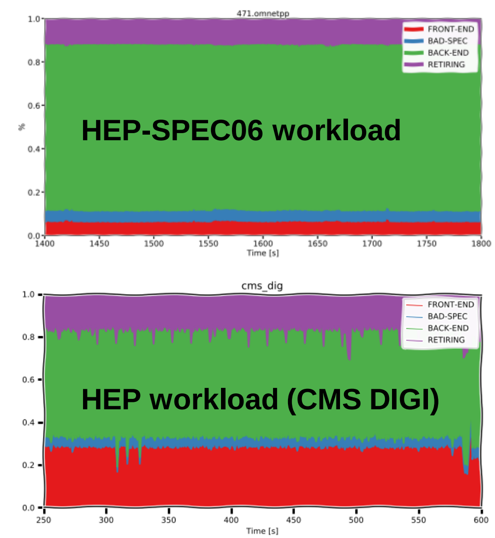
- *HS06 showed similar **CPU usage patterns** to those of HEP workloads*
  - Hardware performance counters (FP+SIMD, Load+Store, Mispredicted Branch)
    - Analysis using perfmon on lxbatch (compute nodes of LHC experiments at CERN)

After 10 years, HS06 does not describe HEP workloads well enough any longer

- *HS06 score shows poor correlation to the **throughputs** of HEP workloads*
  - Issue reported by ALICE, LHCb – somewhat better agreement for ATLAS, CMS
    - Use of 32-bit benchmark for 64-bit applications explains part of the discrepancy



D. Giordano, CHEP2018, Sofia, July 2018



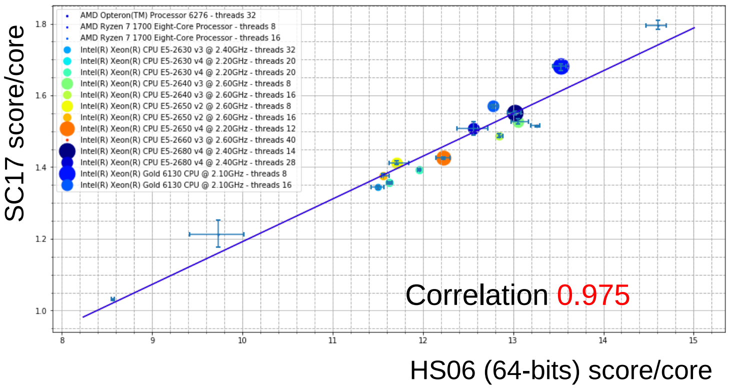
D. Giordano, WLCG GDB, May 2019

- *HS06 shows different **CPU usage patterns** from those of HEP workloads*
  - Hardware performance counters (front-end, back-end, retiring, bad speculation)
    - Analysis using the Trident toolkit, similar to that done with perfmon in the past

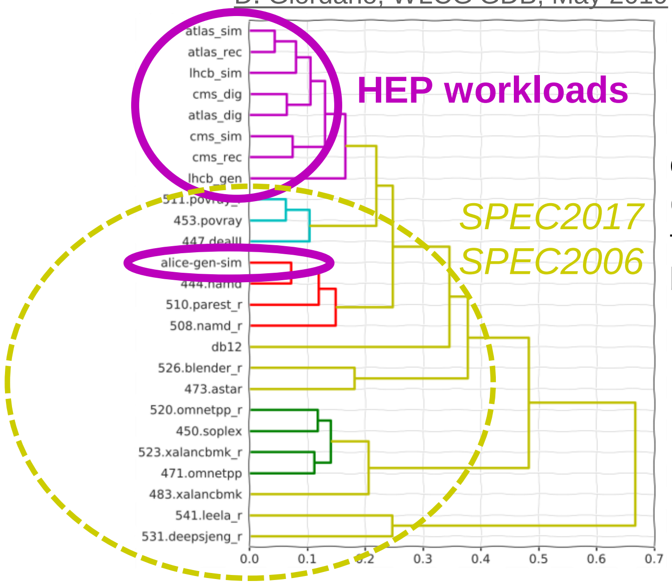
SPEC CPU 2017 has been evaluated, but it has the same issues as HS06

- *SC17 score shows poor correlation to the **throughputs** of HEP workloads*
  – Because it is highly correlated, i.e. essentially equivalent, to the HS06 score

D. Giordano, CHEP2018, Sofia, July 2018



D. Giordano, WLCG GDB, May 2019



Dendrogram of workload similarity (in 3-D space of front-end, back-end, bad-speculation %)

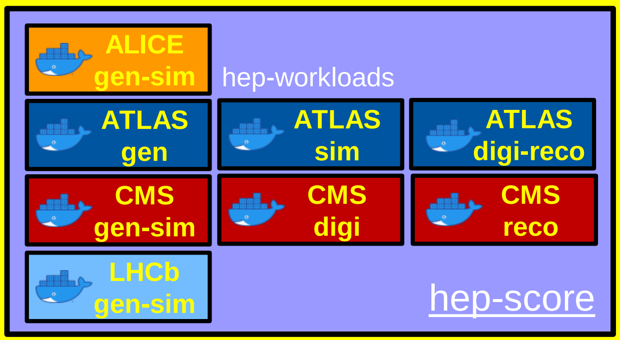
- *SC17 shows different **CPU usage patterns** from those of HEP workloads*
  – Whereas it has very similar CPU usage patterns to those of HS06

We are developing an alternative solution: benchmarking CPUs using HEP workloads

- Why did we choose HS06? Because it seemed representative of HEP WLs!
  - –Score correlated to HEP WL throughput, CPU usage similar to HEP WLs

- *By construction,* using HEP workloads directly is guaranteed to give
  - –*A score with <u>high correlation to the throughputs of HEP workloads</u>*
  - –*A <u>similar CPU usage pattern to that of HEP workloads</u>*

It seems obvious… why did we not do this before?

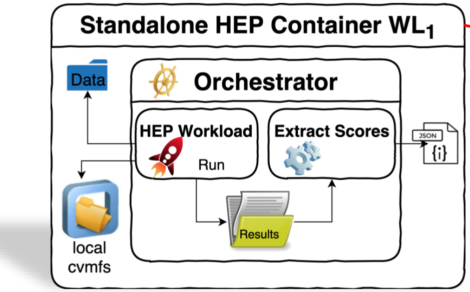


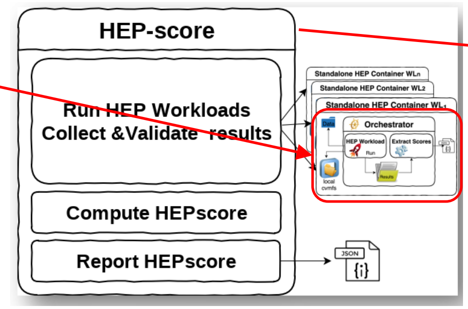
What allows us to do this now is the availability of *container technology!*

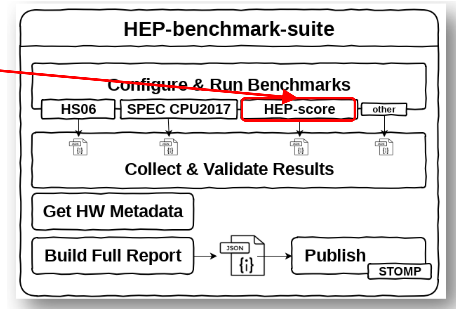
docker

“HEP benchmarks” project overview

- Three repositories under https://gitlab.cern.ch/hep-benchmarks:







hep-workloads
- *runs a single HEP workload*
- includes common and WL-specific infrastructure to build WL containers
- most active package so far

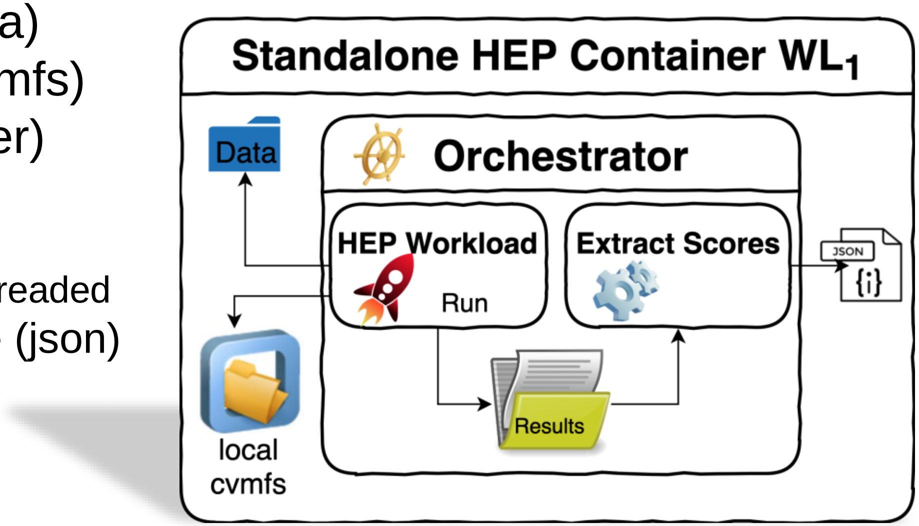
hep-score
- *runs several HEP workloads*
- average/combine individual scores to give *a single benchmark number*

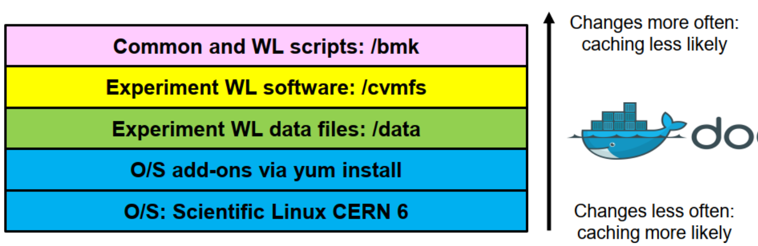
hep-benchmark-suite
- *runs several benchmarks* (hep-score, HS06 and others)
- collects results in a database

- Project organization
  - Team: core development and infrastructure, testing, experiment experts
    - Current contributors: M. Alef, J. M. Barbet, O. Datskova, D. Giordano, C. Grigoras, C. Hollowell, M. Javurkova-Pagacova, V. Khristenko, D. Lange, M. Michelotto, L. Rinaldi, E. Santorinaiou, A. Sciabà, A. Valassi
  - Track work progress via Jira Project and Twiki

From HEP reference workloads to containers: the hep-workloads project

- Main requirements:
  - Self-contained (no network), easy to use, fast/small, stable/reproducible…
- *One workload ↔ One standalone Docker container (with all dependencies)*
  - Operating system
  - Input data (event and conditions data)
  - Experiment-specific software (on cvmfs)
  - Orchestrator script (benchmark driver)
    - Sets environment
    - Runs application (many copies)
      - Each copy may be multi-process/threaded
    - Parses output to generate WL score (json)

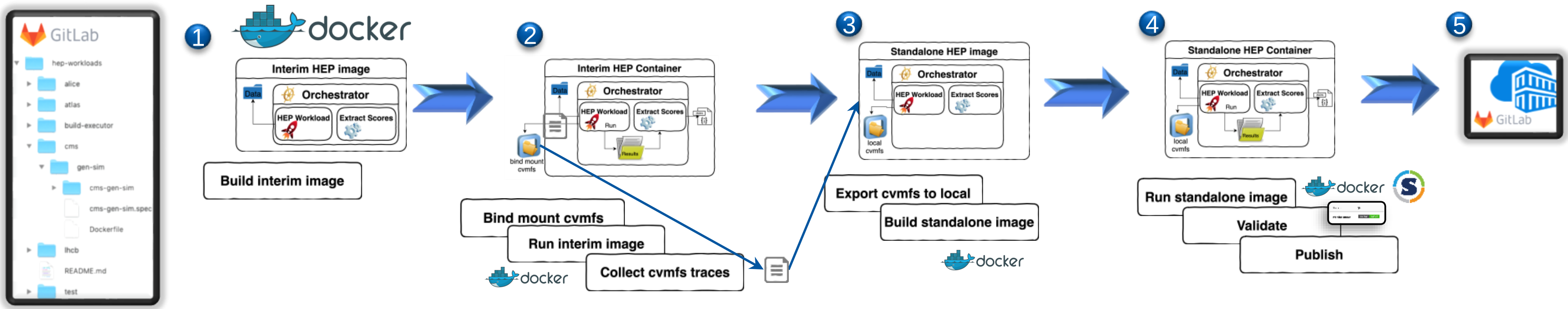




Docker WL images are made up of layers

Workload containers are built in the hep-workloads gitlab CI

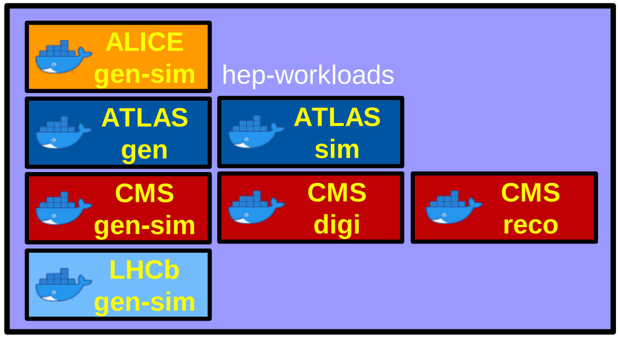
- *Main idea: experiment software is on /cvmfs, discover what is needed in a dry run*
- *Enabling technology: cvmfs tracing mechanism*



- Starting from gitlab repo containing only CI and WL orchestrator scripts:
  1. Build interim Docker image: /cvmfs is the standard network-connected service
  2. Run WL in interim Docker image: generate cvmfs traces listing which files were accessed
  3. Build standalone Docker image: /cvmfs is a local folder, copy all relevant files
  4. Test standalone Docker image (both in Docker and Singularity)
  5. Push standalone Docker to gitlab registry

The hep-workloads container registry: available images

- The following images can currently be downloaded and tested:
  - *GEN and SIM workloads are available for all four LHC experiments*
  - *DIGI and RECO workloads are available for CMS* (work in progress for ATLAS)
  - Available from https://gitlab.cern.ch/hep-benchmarks/hep-workloads/container_registry



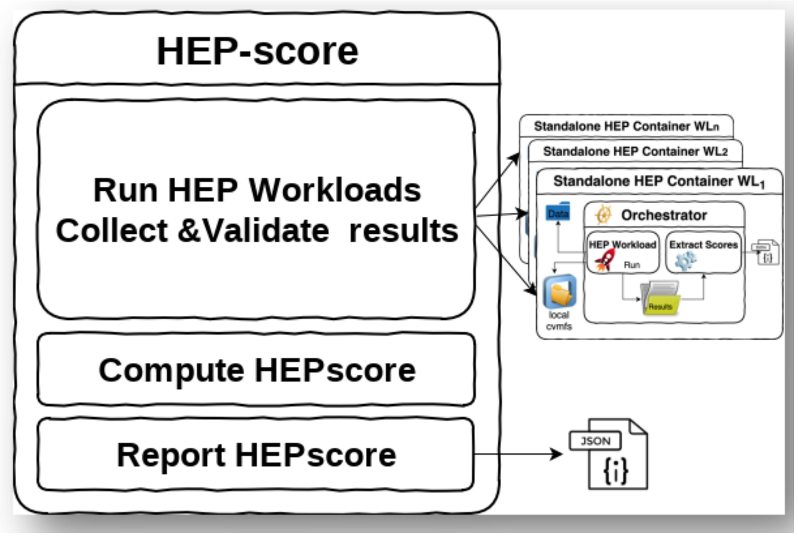
- *Executing one specific workload benchmark is a one-liner:*
  - Example for CMS DIGI, both via Docker and Singularity:

```
IMAGE=gitlab-registry.cern.ch/hep-benchmarks/hep-workloads/cms-digi-bmk:latest
docker run -v /tmp/results:/results $IMAGE
singularity run -B /tmp/results:/results docker://$IMAGE
```

  - A json summary and detailed logs are then found in /tmp/results on the host system

The hep-score benchmark: many degrees of freedom, one number

- Each HEP workload stresses different components of a computer system
  - Some are I/O intensive, others not; some are vectorized, others not…
- Using a single metric to characterize performance is difficult (and dangerous)
  - But this is what we often need for accounting and/or procurement
  - *Presently, HEP score is the geometric mean of a small subset of HEP workloads*
    - *But the json output also keeps a record of each individual WL score independently!*

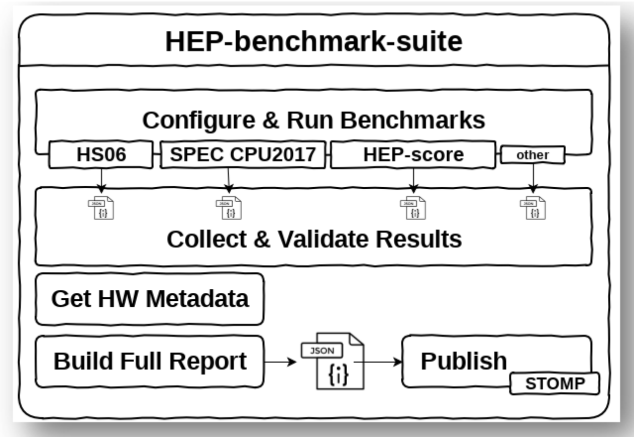


HEPscore19 prototype
(use the currently most stable and best understood workloads):

atlas-gen-bmk v1.1
atlas-sim-bmk v1.0
cms-gen-sim-bmk v1.0
cms-digi-bmk v1.0
cms-reco-bmk v1.0
lhcb-gen-sim-bmk v0.12

The hep-benchmark-suite toolkit

- A single toolkit to coordinate execution and result collection for several benchmarks
  - Example: execute HS06, SPEC2017 and HEP-SCORE on a set of reference machines
  - Collect results of all benchmarks in a global JSON document and upload it to a database



- Work in progress:
  - Identify a set of reference machines (like the "lxbench" cluster used for HS06 studies)
  - Systematically study the correlation of individual HEP WL's to one another and to HS06

Outlook: heterogeneous resources (HPCs, GPUs…)

- All of the work on hep-workloads described so far refers to x86 architectures
- WLCG computing is expected to go well beyond x86 in the medium term future
  - Non-x86 HPC supercomputers (ARM, Power9, GPUs…) will probably play a large role
- By and large, the software of the experiments is not yet production-ready for this
  - Porting and validating it (and having the people to do that) is one of the first priorities
  - But our new benchmarks must be ready in time to do the accounting for these resources!
- *Specifically: a HEP workload container involving GPUs is ready and is being tested*
  - CMS event reconstruction, with optional GPU offload of pixel tracking *(Patatrack)*
  - The container build approach described earlier applies also in this case

See CHEP 2019 contribution #62 "Bringing heterogeneity to the CMS software framework"

See CHEP 2019 contribution #130 "Heterogeneous reconstruction: combining an ARM processor with a GPU"

Conclusions

- After 10 years, HEP-SPEC06 no longer describes well enough HEP workloads
- Our solution: build a new benchmark directly from HEP workload throughputs
  - Enabling technologies: Docker containers and cvmfs tracing mechanism
- Status: individual containers exist for GEN-SIM workloads of all four experiments
  - And for the DIGI and RECO of CMS and ATLAS
- WIP: a first HEP-SCORE prototype built from a subset of those workloads exists
  - It presently defines the new overall benchmark as the geometric mean of individual scores
- WIP: the basic infrastructure to run the WLs on a set of reference machines exists
  - We will then systematically collect the data to compare WL's to one another and to HS06
- Outlook: can extend the idea and implementation to HPCs and non-x86 resources
  - A container for a workload with optional GPU offload (CMS Patatrack) is being tested

Bonus: HEP workload containers can be useful also beyond benchmarking!
Example: simulate a realistic load on the batch system of a WLCG site

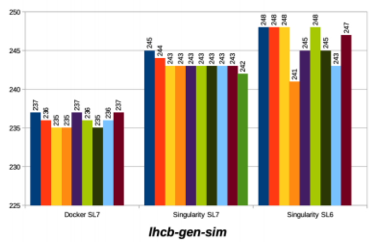
See CHEP 2019 contribution #52 "Managing the CERN batch system with kubernetes"

Backup slides

Validation studies for hep-workloads

- Careful analysis of robustness and accuracy of individual HEP benchmarks
  - Are the results of multiple measures reproducible?
  - How do results change as a function of input parameters (#events, #threads, #copies)
  - Are the results obtained with singularity and docker containers compatible?

Singularity SL6/SL7 Reproducibility – lhcb-gen-sim Results



Docker SL7 – avg 236; std dev 0.87; relative std dev 0.37%
Singularity SL7 – avg 243; std dev 0.68; relative std dev 0.28%
Singularity SL6 – avg 246; std dev 2.42; relative std dev 0.99%

Subatech

Work done

- Check TurboBoost setting
- Run SPECHEP06 benchmark on SL6(no-tboost), SL6, C7
- Run alice container with singularity on SL6(no-tboost), SL6, C7
- Run cms container with singularity on SL6,C7

HEPiX Benchmarking Group April 11th, 2019, Barbet-JM, Subatech

IMG: gitlab-registry.cern.ch/hep-benchmarks/hep-workloads/lhcb-gen-sim

LHCb	SCORE	MAX	MEDIAN	AVERAGE	MIN	DELTA
1	74.3413	2.6878	2.6497	2.655	2.6371	0.02
2	74.1764	2.6894	2.6471	2.6293	2.6293	0.02
3	74.1486	2.6753	2.6453	2.6482	2.6313	0.02
4	74.1965	2.6823	2.648	2.6499	2.636	0.02
5	74.0487	2.6965	2.6412	2.6446	2.6264	0.03
6	73.9005	2.682	2.6393	2.6393	2.6218	0.02
7	74.0591	2.6719	2.6433	2.645	2.6318	0.02
8	74.3032	2.6906	2.6474	2.6537	2.6366	0.02
9	74.2789	2.7107	2.6473	2.6528	2.6342	0.03
10	73.8947	2.6776	2.6351	2.6391	2.6237	0.02
	74.135		mean	2.646		
	0.157		stddev	0.008		
	0.002		ratio	0.003		

ATLAS gen-bkm workflow reproducibility: different host

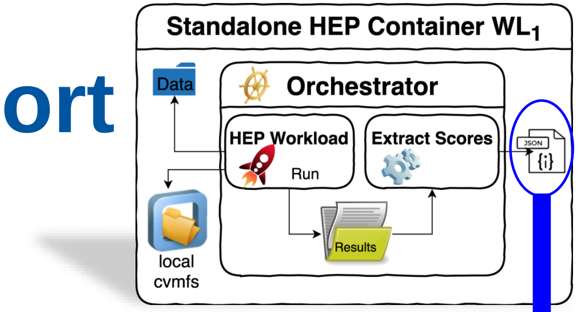
- host: **bmk14-cc7-uh3i4nnhjt** (Intel Xeon E5-2680 (2.4 GHz),14 logical processors)
- “saturation mode”: 14 copies and 25/100/500/2500 events
- “relaxed mode”: 7 copies and 25/100/500/2500 events
- number of events processed differ from the default setting with the '-e nevents' flag

-e nevents' flag	nb. of events processed
5	9
25	43
100	186
500	938
2500	4602

Martina Javurkova (UNI Freiburg) *Validation of ATLAS workloads* HEPiX WG 29/03/2019 10

- Use the most stable and best understood workloads for the first hep-score prototype!

The hep-workloads output report



JSON document with the essential information

- Configuration parameters
  - #copies, #threads, #events, status
- Benchmark score: **total node throughput**
  - **Events per wall second** (sum over all copies)
    - Or events per CPU second in some cases
  - Details for each application copy
    - Statistics: mean, median, max, min…
- Additional metrics for performance studies:
  - Memory and CPU utilization
- Workload metadata
  - Description, version, checksum


```
"report": {
  "wl-scores": {
    "gen-sim": 0.4438
  },
  "wl-stats": {
    "CPU_score": {
      "max": 0.0226,
      "score": 0.1123,
      "median": 0.0225,
      "avg": 0.0225,
      "min": 0.0222
    },
    "throughput_score": {
      "max": 0.0892,
      "score": 0.4438,
      "median": 0.089,
      "avg": 0.0888,
      "min": 0.088
    }
  },
  "log": "ok",
  "app": {
    "bmkdata_checksum": "e57b3ad19144b7e9574b97056fb35d11",
    "cvmfs_checksum": "b2ab0e3bd4ba1333ebfc7dc49a024536",
    "bmk_checksum": "fc73ae9f18c4ef90791f097cd31b45dc",
    "version": "v1.0",
    "description": "CMS GEN-SIM of ttbar events, based on CMSSW_10_2_9"
  },
  "threads_per_copy": 4,
  "copies": 5,
  "events_per_thread": 100
},
```

HEP software and computing evolves… so do HEP CPU benchmarks!

1980's
MIPS (M Instr Per Sec)
VUPS (VAX units)
CERN units

1990's – 2000's
SI2k (SPEC INT 2000)
INTEGER benchmarks
200 MB footprint

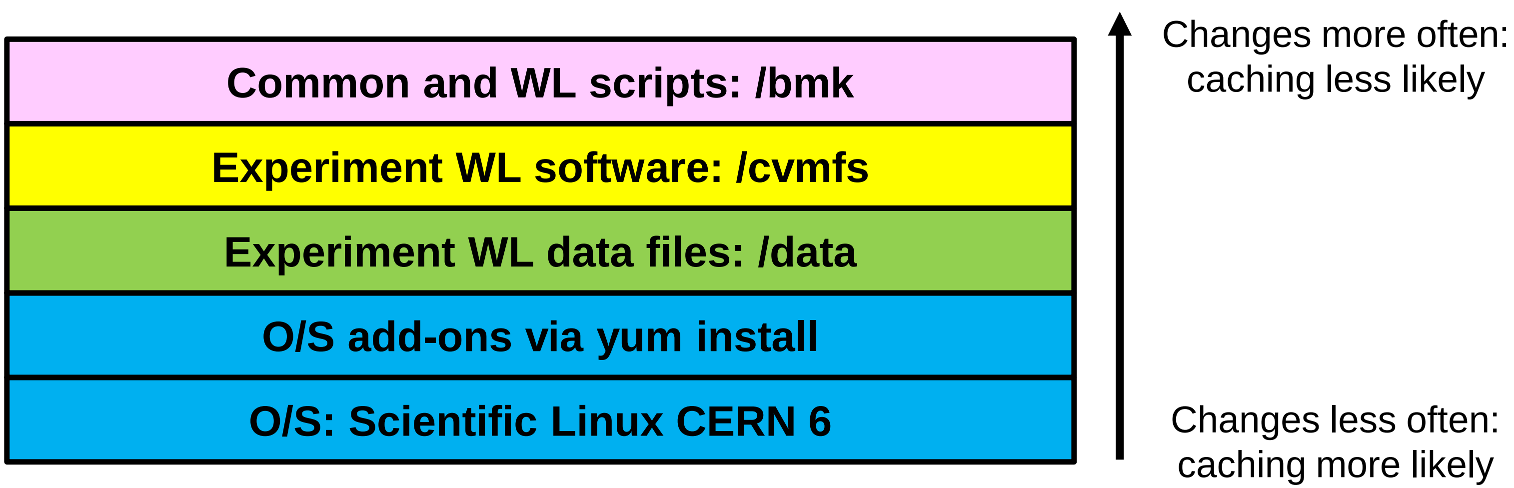
2009
HS06 (SPEC CPU 2006 all_cpp)
INTEGER + FP benchmarks
1 GB footprint
32-bit
x86 servers
single-threaded/process on multi-core

2019
2 GB footprint (or more)
64-bit
multi-threaded, multi-process
multi-core, many-core
vectorization (SSE, … AVX512)
x86 servers, HPCs
ARM, Power9, GPUs…?

- As time goes by, *WLCG computing is becoming more and more heterogeneous*
- One of the challenges is how to summarize performance using a single number
  - Unfortunately, this is needed at least for accounting purposes

Docker layers in hep-workloads images

- Docker container images are always made up of *layers*
  - Translating Docker images to Singularity also keeps this layer structure unchanged
  - From the bottom up, these layers can be *cached* until the first difference is found
- The hep-workloads CI builds these layers to make them as cacheable as possible
  - The bottom layers contain what is expected to change least often
  - The top layers may change more frequently (across different workloads or versions)
  - Advantage in the CI: faster builds/tests, save storage space (both Docker and Singularity)
    - Advantage for users: faster tests, save storage space (if Docker and Singularity caches are set up)



Redistribution: software and data licensing

- The software stacks of the four LHC experiments are all Open-Sourced
  – With slightly different licenses and copyright clauses

- Data-intensive experiment workload benchmarks (e.g. digi-reco) use Open Data
  – Approved by the relevant experiments

- We are in the process of clarifying the details of how to Open-Source our benchmark suite, while allowing its use by all interested parties

Fast benchmarks

- Two fast benchmarks have been found useful by the LHC experiments
  - ATLAS KV (KitValidation)
    - Essentially GEANT4 detector simulation (default: 100 single muon events)
    - Agreement with ATLAS and CMS simulation (M. Alef et al, Proc. CHEP2016)
  - DIRAC Benchmark 2012 (DB12)
    - Agreement with ALICE and LHCb (when DB12 runs at job time)

- Not robust enough to replace long-running benchmarks
  - DB12 dominated by the front-end call and branch prediction unit
  - SMT is not beneficial at all for DB12 when loading all CPU threads
  - KV shortness and event simplicity affected by systematics
    - Found in the performance studies of Meltdown/Spectre patches
    - Can be improved extending the test duration and event complexity

M. Guerri, CERN ITTF, April 2017

D. Giordano, CHEP2018, Sofia, July 2018