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Computing Models in High Energy Physics☆

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Abstract

High Energy Experiments (HEP experiments in the following) have been at least in the last 3 decades at the forefront of technology, in aspects like detector design and construction, number of collaborators, and complexity of data analyses. As uncommon in previous particle physics experiments, the computing and data handling aspects have not been marginal in their design and operations; the cost of the IT related components, from software development to storage systems and to distributed complex e-Infrastructures, has raised to a level which needs proper understanding and planning from the first moments in the lifetime of an experiment. In the following sections we will first try to explore the computing and software solutions developed and operated in the most relevant past and present experiments, with a focus on the technologies deployed; a technology tracking section is presented in order to pave the way to possible solutions for next decade experiments, and beyond. While the focus of this review is on offline computing model, the distinction is a shady one, and some experiments have already experienced contaminations between triggers selection and offline workflows; it is anticipated the trend will continue in the future.

1. Introduction

High Energy Experiments (HEP experiments in the following) have been the major players in scientific computing in the last decades, surpassing every other user as complexity of code, need for resources and number of researchers accessing those. While other sciences are progressing to reach the same level, in HEP no slowdown in the increase of complexity, needs and size of collaborations is expected; if anything, the future experiments will be relying even more on a large scale performant computing architecture. In the following sections we will first try to explore the computing and software solutions developed and operated in the most relevant past and present experiments, with a focus on the technologies deployed; a technology tracking section is then presented in order to pave the way to possible solution for next decade experiments, and beyond. While the focus of this review is on offline computing model, the distinction is a shady one, and some experiments have already experienced contaminations

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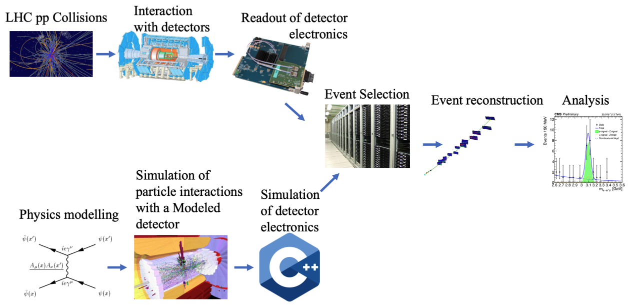

Figure 1: A typical processing workflow an an High Energy Physics Experiment, with Data and Simulation paths.

between triggers selection and offline workflows; it is anticipated more will follow the same model in the future.

2. A standard modelling of computing in High Energy Physics

In order to set the ground for the different experiment specific models, it is important to identify generic concepts when dealing with HEP computing. Due to the complicated modelling in the physics, in the simulation of collisions, in the description of the detector apparatus and in the performance of reconstruction algorithms, it is unfeasible to extract valuable information by comparing directly the collected data to theoretical hypotheses. What is instead typical is to try and attempt an uniform treatment of collision and simulated data, in order to infer the underlying physics from the comparison of high level physics quantities, like jets, identified leptons, reconstructed vertices and similar. In order to do so, parallel paths must be set for data and simulation processing, as much as possible using the same software. Figure 1 shows schematically a typical workflow, from data taking to the final analysis:

- Data events are collected by the experiment readout system, eventually filtered on hardware / software based facilities; reconstruction (software-based) interprets the event content in term of physics objects (tracks, vertices, jets,) which are used as input to further refinements in analysis;
- On a parallel path, simulated events are generated on computer farms, and the stable particles are used in input to programs simulating their interactions with a computer readable model of the detector. The frontend electronics is also simulated, producing signal in the same format as from the real detector components, which are then filtered, reconstructed and analysed by the same software used for data;
- The analysis results can be directly compared, thus inferring the properties of the physics processes under study.

Table 1: Main parameters of LEP collider and ALEPH experiment.

	LEP Parameters		ALEPH Computing Parameters	
LEP1 (1989-1994)			Recorded Data Volume	~ 2.5 TB
	Center of Mass Energy (GeV)	91	MC Data Volume	~ 5 TB
	Record instantaneous luminosity ($cm^{-2}s^{-}1$)	2.3 10^{31}	Total volume (multiple data formats, MC + data, ...)	~ 10 TB
	Z rate (Hz)	<1	Source lines of code	0.5 M
LEP2 (1995-2000)				
	Center-of-mass energy (GeV)	130-209		

3. Past Experiments

3.1. LEP

The Large Electron Positron Collider (LEP, CERN, Switzerland) has been operational form 1989 to 2000 with a first Run at the Z^0 peak, and a second Run initially meant to explore the WW boson pair production, and later pushing for the highest possible center of mass energy in order to attempt the discovery of a low mass Higgs boson. LEP supported 4 general purpose experiments [1][2][3][4], with similar physics goals and computing infrastructures. Table 1 shows computing parameters from LEP and ALEPH, quite typical among the 4 experiments.

The low interaction rate of LEP, combined with the small e^+e^- cross sections in both Runs, put very mild requirements on the computing infrastructure, which was for most part of the experiments lifetime completely CERN-centric. A single (or few) mainframe-class machine was enough to serve all offline oriented tasks, from re-processing, Monte Carlo simulation, and end user analysis. Examples of such machines are shown in Table 2. They moved, along the lifetime of the ALEPH experiments, from VAX stations to Unix systems from various vendors. In the very last years of ALEPH, CERN pushed for the switch of LEP experiments offline infrastructures to more economic Linux based computer farms, which have become the legacy environment for LEP. The same table shows the performance of the systems in CERN Units, and internal CERN classification in order to compare requests on different architectures. One CERN Unit was equivalent to ~3-4 Million Instruction per Second (MIPS[5]); in comparison, a single 2017 AMD Ryzen 7 1800X is quoted[6] over 300kMIPS (assuming the same benchmark still has a meaning with such different architectures). Storage wise, the same CERN centric approach was used, with raw and Monte Carlo samples on CERN tape systems and on the mainframe disks. Non CERN resources were installed mostly for analysis purposes, mimicking the systems in use at CERN. Only at the end of the LEP lifetime, profiting from the transition to off-the-shelf Linux based

Table 2: CERN Computing Infrastructure for the ALEPH Experiment.

ALEPH Equipment at CERN			
Year	Model	# of processors	"Power" in CERN Units
1984 -1990	ALWS VAX Station	110	60-336
1988-1990	CRAY	4	32
1989	FALCON DEC VMS	12	6-27
-1994	IBM + Siemens VM	2+2	12+13
1994	ALOHA Digital Unix	15	32
1994-1998	SHIFT9 SGI	8	136
1996	SHIFT50 DEC Alpha	4	320

systems, distributed operations became more typical, with especially Monte Carlo productions becoming possible at outside institutions.

3.2. CDF

The CDF[7] experiment was operational from 1985 to 2011, at the $p\bar{p}$ Tevatron accelerator complex (FNAL, Batavia, US), in two distinct running periods; in the following, the second period at a center of mass energy of 1.96 TeV (more demanding from the computing point of view) is considered; data was collected at $\sim$ 60 MB/s. Run II collected data and simulation in various formats, for datasets to be made available long term totalling around 10 PB.

The CDF computing model[8, 9] had a large component local at Fermilab, where events selected by the trigger were stored to tape for further calibration, reconstruction and analysis. CDF users typically analysed the data at FNAL and used remote computer facilities for Monte Carlo production with the results sent back to FNAL for archival storage. The CDF analysis farm (CAF) was designed as an infrastructure developed to allow commodity hardware for data reconstruction, data analysis, simulated data production. CDF transitioned to a distributed paradigm in its last years, in order to avoid the need for dedicated farms: users could decentralize their analyses, by submitting and executing workflows in all the centers. At the hearth of the distributed computing infrastructure, the CAF ("Central Analysis Facility") at FNAL and distributed CAFs (dCAFs) where geographical jobs were turned into local batch systems, using HTCondor[12] at the end of the run.

The initial CAF was local to FNAL, and it was evolved to a model including dCAFs. Later in the CDF lifetime, the collaboration decided to adopt a GRID paradigm, in which the CAF was interfaced via Globus tools before, and LCG [13] later, and was finally able to reach tens of thousand of running jobs using the same infrastructure built for the LHC experiments, which were at that time in commissioning phase for computing.

3.3. BaBar

The BaBar[14] experiment took collision data the e^+e^- asymmetric PEP-II storage ring, at the $\Upsilon(4S)$ center of mass energy, from 1999 to 2008 for a total integrated luminosity of more than 500 fb^{-1}. Signal events ($\sim$30 Hz at production level) were

Figure 2: Long term plans for LHC. Courtesy of ATLAS.

mostly pairs of B mesons, with a decay multiplicity of slightly more than 5 per meson; considering a total readout rate close to 2 kHz, and a selection ~1/7 at trigger level, few MB/s were reaching the offline systems. The software model relied from the start on C++ code, with a novel attempt to use a commercial Data Base system for the storing of events and their metadata (Objectivity/DB[15]). The processing of RAW data was via a prompt reconstruction, followed by skims and reduced content samples, down to ~2 kB/event. Prompt computing was mostly at SLAC, with additional Tier-A centers participating to the distributing creation of Monte Carlo samples. The BaBar experiment pioneered many technologies seen in later experiments, like:

- The utilisation of commercial Data Base systems for event storage, later attempted also by LHC experiments. In a second phase, the Data Base was replaced by a more standard solution based on ROOT[16] IO streaming;
- The capability to access data without an explicit catalogue, and to stream data from remote sites, via the XrootD [17].

4. Current Experiments

4.1. LHC

The Large Hadron Collider (LHC[18], CERN, Switzerland) is the current hadronic collider at the energy frontier; it supports 4 major Experiments [19][20][21][22] which are the top computing resource utilisers in the science panorama, due to the combination of the accelerator parameters and the detectors design. Beam Operations started in 2009 (after a short run in 2008), and data taking periods (runs) are planned at least up to 2030 (see Figure 2).

Focusing on LHC Run II (2015-2018), Table 3 shows typical operating conditions. A brief description of the current LHC running can be found in reference[23].

The two general purpose and biggest experiments, ATLAS and CMS, delivered to offline collisions at above 1 kHz, with multi-PB sized raw data collected per year; ALICE and LHCb collect data at half the total annual size or less, due to the specificities of the heavy ion running and the event sizes. Most of the events are analysed via workflows not different from previous experiments, with an early prompt reconstruction pass following data taking by a few hours, which allows for data analysis within days. All the experiments consider legacy reprocessing of the same data months after the data acquisition, in order to profit from more refined calibrations and algorithms.

Table 3: LHC Run II typical conditions (2018).

LHC RunII parameters		**ATLAS & CMS conditions**		**ALICE conditions (HI run)**		**LHCb conditions**	
Center-of-mass energy [TeV]	13	Average prompt selection rate	~ 1 kHz (+ up to 6 kHz of parked data)	Average selection rate	~ 500 Hz	Average selection rate	7.5 kHz full readout + 4 kHz partial readout
Total Delivered Luminosity (pp)	160 fb^{-1}	Average number of pp inelastic superimposed collisions				Average number of pp inelastic superimposed collisions	~1.6
Top instantaneous luminosity (10^{34} cm^{-2} s^{-1})	1.9	Total data written to CERN tapes in 2018 [PB]	25+45	Total data written to CERN tapes in 2018 [PB]	12	Total data written to CERN tapes in 2018 [PB]	7

Table 4: WLCG Rebus resource deployments for 2019.

Resource Type	**Unit of Measurement**	**Year**	**Pledged Amount**	**Approx market value (Eur)**
CPU	HS06	2019	6.4M (~ corresponding to 640k computing cores)	64 MEur
Disk	TB	2019	500k	50 MEur
Tape	TB	2019	770k	15 MEur

The production of Monte Carlo Simulated events is by far the largest user of computing needs, via the generation of events, the simulation of their interactions with a modelled detector (Geant3[24] or Geant4 toolkits[25]), and a reconstruction mimicking the data workflow. The amount of needed resources drove in the late 90s to the realisation of GRID distribute infrastructures, now merged in the Worldwide LHC Computing GRID (WLCG[26]), with about 200 sites participating into LHC computing. The total amount of resources handled via WLCG, in 2019, is reported in Table 4[1].

The distributed computing infrastructure has been modelled before the start of LHC Runs essentially following MONARC[27] recommendations, as a hierarchy of computing centers with specific roles and functions:

- The Tier-0 is the center close to the experiment (hence, at CERN). Tier-0 has the task to perform fast turnaround calibrations, execute the prompt reconstruction step, and maintain a custodial copy of all the irreproducible RAW data on tape;
- The Tier-1s are regional centers (~10 per experiment) which maintain a second distributed custodial copy of the RAW data on tape, and provide CPU for more

[1] The unit of measurement are explained in the technology tracking section. The cost evaluation is based on back of the envelope estimates: 10 Eur/HS06, 100 Eur/TB disk, 20 Eur/TB tape

precise reconstruction passes; they contribute to the simulation processing;

- The Tier-2s are local centers, sized to provide support for the analysis activities of some 100 physicists; they also participate to the simulation processing.

The computing models actually used during LHC Run I and II (and III to a lesser extent) are evolutions of the MONARC model, and have somehow faded the different roles of the Tiers, in order to maintain a better operational efficiency, and a better utilisation of resources. While ATLAS, CMS and ALICE have similar computing models, in which RAW data is the main and more precious outcome of data taking, LHCb has transitioned to a more agile model, in which part of the data stream is analysed online and sent directly to analysers, to a great advantage for total computing needs. ATLAS and CMS are the general purpose experiments, collecting data in all LHC beam conditions, and in principle able to serve as both precision and discovery-driven experiments; ALICE is explicitly designed for the best performance when LHC collides ions, but takes data also in pp operations mostly for calibration purposes. LHCb is optimised for analysing events originating from b quark decays, and covers only one high angle regions.

The experiments deliver processed analysis samples to physicists, who use the same distributed computing system to perform final analysis steps involving simulation and data comparison, selections and fits; the level of central preprocessing of such samples slightly differs between experiments: from the fully centralised operations in ATLAS and ALICE, to user-submitted workflows in CMS and LHCb.

Upcoming LHC RunIII (2021-2024) operation models are diverging from the models described in [23]. ALICE and LHCb plan for 2021 a detector update and extended physics scopes, reached via an overhaul of the computing models. ALICE, in the effort of performing precise measurements of heavy flavour hadrons, low-momentum quarkonia and low mass di-leptons, needs to upgrade its selection rate to include the full 50 kHz interaction rate, which will be reconstructed in the online-offline O2 facility[28].

In order to sustain the rate ALICE plans to use computing accelerator technologies, as those described in a following section of this review, already in RunIII. LHCb is planning to substantially increase its data collection rate, up to the 30 MHz of the interaction rate, and up to 10 GB/s of event data. This is realised via a strong reliance in Turbo operation mode[29], which discards RAW events and just saves to offline high level reconstructed objects, analysis-ready.

ATLAS and CMS have scheduled major detector upgrades for LHC RunIV, also known as HL-LHC and described in a later section.

In general, LHC experiments computing has accomplished the mission to effectively serve the LHC data taking, even in presence of substantial deviations from the expected scenarios (like in 2016, when the accelerator delivered collisions at a larger rate than anticipated). The testament is in the total number of papers published by the four main collaborations, now close to 2500.

4.2. Belle II

The Belle II[30] experiment at the SuperKEKB accelerator complex at KEK (Tsukuba, Japan) started taking data in early 2018 for a commissioning run, while the first data

Table 5: Belle II Computing estimated needs for the year 2022.

Resource Type	Unit of Measurement	Year	Request
CPU	[HS06]	2024	~ 700k (corresponding to ~ 70k computing cores)
Disk	[PB]	2024	25k
Tape	[PB]	2024	35k

with the complete detector setup were collected in early 2019. The collision data come from e^+e^- collisions at the $\Upsilon(4S)$, with the main difference with respect to the previous generation of B-factories in the amount of B pairs to be collected, increased roughly by 50 times. The computing model is a derivation of the models used at LHC and deployed via WLCG, where resource needs are still higher due to the higher complexity of hadron-hadron interactions when compared to lepton-lepton. The computing model is deployed on a distributed tiered infrastructure, with KEK and PNNL[31] (and more recently BNL) as sites where raw data is stored and processed via prompt workflows, at least initially. The output of processing is directed to regional data centers, like KIT in Germany and CNAF in Italy. Additional computing sites serve a parallel purpose with Monte Carlo production. Following the parallel evolution in WLCG for LHC, technologies for distributing remote workflows are supporting GRIDs, Clouds, and standard owned computing clusters accessed via standard batch systems. The total computing resources needed, extrapolated to 2024, are a factor ~1/5x of what ATLAS or CMS have deployed for 2019, and thus do not constitute an insurmountable computing problem (see Table 5) even less considering the technology evolution in the years between 2019 and 2022.

5. Technology trends

An intense technology tracking activity is essential when planning and modelling operations at collider experiments. In all the experiments up and including LEP, the computing aspect was minor and usually neglected during the design process; computing and the related software was indeed a small fraction of the total cost, and the complexity could be handled when close to the final commissioning of the detector. The picture has started to change with the CDF experiment, and then the trend has become evident with BaBar and the LHC experiments. Nowadays, LHC experiments cost in term of resources a sizeable part of the operational yearly budget, and resource deployment worldwide can be evaluated to almost 200 MEur, as shown previously on table 4. The cost of the software development and maintenance is more difficult to estimate; an attempt can be done via using standard industry-grade tools like SLOCCount [32], which estimates the value of a code base by analysing the code. Table 6[2] shows the outcome for the CMS and ATLAS code bases, the largest in LHC.

Translation of resources into market value is a difficult task, country dependent and with large fluctuations tender by tender. Each funding agency maintains historical data

[2]CMS and ATLAS have opened the source code with a Apache 2.0 license, hence the code is downloadable from https://github.com/cms-sw/cmssw and https://gitlab.cern.ch/atlas.

Table 6: SLOCCount measured lines of source code for ATLAS and CMS.

Experiment Type	Source Lines of code (SLOC)	Development effort (person-years)	Total estimated cost to develop
ATLAS	5.5M	1630	220 M$
CMS	4.8M	1490	200 M$

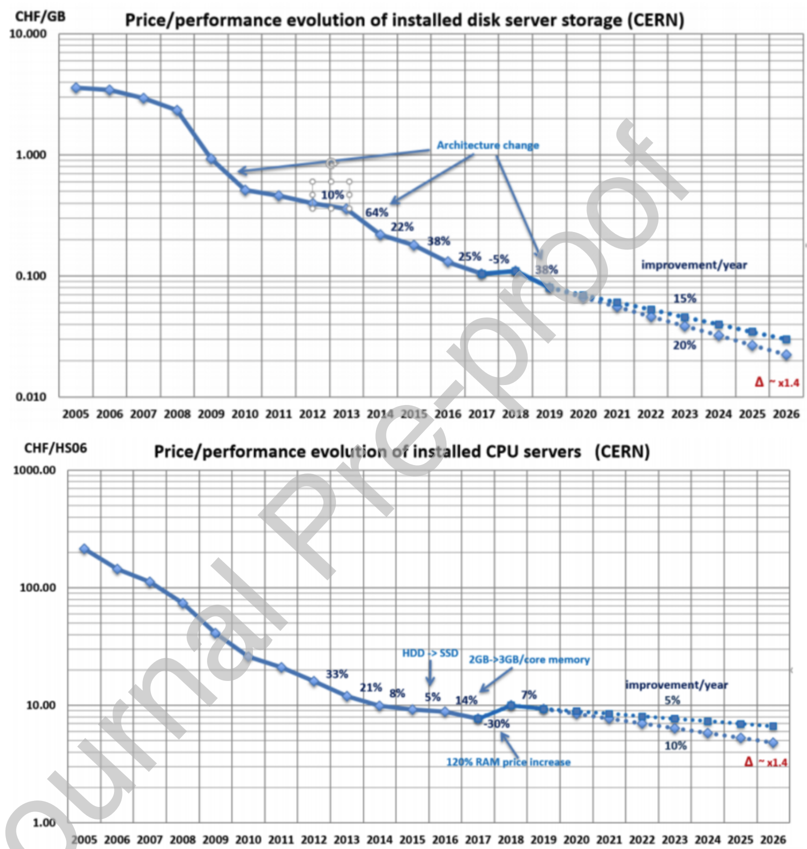

Figure 3: Historical and projected prices for computing resources [33].

on tenders and has a way to predict future costs by extrapolation. The most systematic and public between such archives is maintained by CERN[33]; yearly prices on decennial timescales for CPU and Disk are presented in Figure 3. Unit of measurements need an explanation:

- For Tape, the unit of measurement is the Petabyte, defined as 10^{15} bytes;
- For Disk, it is usable disk including costs for infrastructure: it is the available and served Tera/Petabytes after having considered RAID solutions, and includes

the cost for the I/O servers;

- For CPU, HepSpec06[34] is a benchmark specifically tailored on the needs of HEP, designed to scale linearly with the performance of the main applications. The year-over-year unit price per category, and its decline, are closely linked to the so-called Moores (and alike) laws[35], and reflect technology improvements in the fabrication, for example, of smaller and smaller transistors and of denser magnetic media.

The figures above show the trends for standard and consolidated technologies, limited to x86_64 compatible CPUs, and do not take into account completely new solutions like vector processors or similar. As detailed in the next section, the utilisation of more performant (per CHF/$/Eur) technologies could be a necessity for next generation of experiments, where the fractional cost of computing is expected to increase due to the needs to probe rare processes, and to increase the precision of key measurements.

It is very difficult to predict what a fast-changing sector like IT will be providing on the time scale of 10 years of more, but some trends seem established to a level which justifies work from the experiments.

5.1. CPU

It is difficult to predict large performance leaps in the now ubiquitous x86_64 architecture, at the basis of current experiments software. Different emerging architectures offer, at least on paper, better performance per CHF, already now. Figur 3 shows that it is difficult to predict a year-over-year improvement of prices in excess of 10%/y, while Moores law[35] was predicting originally that the number of component per integrated function is doubling about every 18 months (which would translate in a +60%/y). General Purpose Graphics Processing Units (GPGPUs) are a derivative of the graphic cards which have seen an explosion in recent years, mostly due to the video game market. They are vector processors, with thousands of available cores, and very limited capabilities for serial programming. Their utilisation is best suited in extremely parallel algorithms, where the same operation has to be performed on a series of input data (SIMD[36]); they also deploy an extremely rigid memory model, with access to external memory impacting on timing more than actual computing operations. While very difficult to objectively compare performance of CPUs and GPGPUs in general, given the different programming model, some selected applications have been ported and show large speedups; see [37, 38] for HEP specific examples of such comparisons. Field-Programmable Gate Arrays (FPGAs) offer a way to port algorithms in-silicon, either via low level languages like VHDL[39], or via synthetization from higher level languages[40]. The main interest in the technology comes from the acquisition of one of the main FPGA producers, ALTERA, by Intel[41]: this paves the way for a strict integration of current x86_64 and FPGA technologies, potentially on the same chip and with large communication bandwidths. FPGA based technologies have been common since many years in the online systems of experiments; an availability on offline systems paves the way to their utilisation as accelerators in standard workflows. Examples in such directions are [42, 43]. Tensor Processing Units (TPUs) are chips especially though for fast matrix manipulation. While not a completely new idea, they have gained renewed interest in the last years due to the emergent sector of Artificial Intelligence, where matrix algebra is a key tool in algorithms like gradient descent[45] for the training of Machine Learning systems. The current most powerful technical implementation is by Google[44], and powers the internal tools from the multinational, from search systems to decision systems; unfortunately, Googles TPUs are not available on the market, but just via direct partnership.

The cost of developing software for GPGPUs and FPGAs should not be underestimated. Current generation of experiment software has been developed in a collaborative way by hundreds of researchers, mostly physicists, lacking a professional training or formal CS preparation. The transition of such large and diverse developer base to parallel-aware programming is a big bet from the experiment communities. In general, a soft transition is attempted, where the old serial C++ code base is not obsoleted, but complemented with new parallel code using Heterogeneous Frameworks capabilities.

5.2. Storage

Existing and future (by current modelling) experiments are designed to use tiered storage systems, where cold storage (generally tape systems) is used to permanently store the irreproducible collision data, and to some extent to lower the total storage cost by offloading a fraction of the reproducible data, due to the relatively low price with respect to rotating disks (factors are 5-10x). Similarly to Moores law, Kryders law[35] states that Hard drive capacities (per unitary costs) are following a similarly exponential path, with a doubling every 18 months (amounting to +60%/y). Unfortunately, again as Moores law, recent results point towards a slower technology increase in recent years, closer to +10%/y. That said, the technology behind rotating magnetic disks is still improving, with a transition from Perpendicular recording (PMR) to Heat Assisted Recording (HAMR) and Microwave Assisted Recording (MAMR) to hit the market massively in the early 2020s[46], and paving the way to ~50 TB/disk systems available in the next 5 years. While this drives down the costs per TB, it has no direct implications on the number of Input Output Operations per Second (IOPS), which is already the limiting factor in IOPS intensive operations like random access analysis of compact data formats; technical solutions are merely more complicated disk mechanics, which come to a cost and to a more complex fabrication and possibly shorter lifetime. Solid State Disks are a reality in the consumer market since many years, but they are currently seldom used in HEP processing, mostly due to the larger costs with respect to rotating technologies. While the current trend in price difference between them[33] hints to a similar situation in the next years, solid state disks are becoming important as a tool to equalize and speed the access to large disk pools, via caches. Many efforts are currently ongoing in the community, as described in [48, 49, 50, 51]. Tape technologies are evolving with a pace compatible with +20%/y, but suffer from a decreasing market and a single large vendor (IBM), after ORACLE communicated the intention to leave the tape market[52][3]. Presently, tape cassettes still seem the most promising and cost effective solution for long term data preservation, with expected lifetimes 4-5x compared to magnetic disks [53].

[3] Luckily, more than one producer for the cassette media is still present.

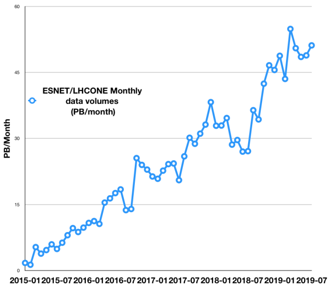

Figure 4: Year by year increase in ESNET (US research network) for the LHC traffic (data proints from [54]).

5.3. Networking

Geographical Networking is obviously essential when dealing with a distributed computing infrastructure. The initial MONARC model was strictly hierarchical, due to the need of dedicated and expensive network path between an handful of centers. The availability of more performant connections (mostly at the level of bandwidth) increases over time per unit cost, as happening for the other categories of technologies. Similarly to Moores law, Butters law[35] postulated that the amount of data coming out of an optical fiber is doubling every nine months, which would translate into an astonishing +150%/y; the real increase has been lower, but still at the level of +90%/y, as shown in Figure4.

In general, LHC experiments have rarely been network limited to date, with capacities indeed increasing faster than real utilisation; a few saturations have been reported only in transatlantic links. In the same time frame, non HEP experiments are also expected to raise the bar in network need, much beyond any reasonable HEP necessity: the Square Kilometer Array telescope (SKA, [55]) expects to need an aggregate bandwidth from telescopes to the core up to 15 Pbps [56], a number which will not be reached by HEP even with the experiments expected after 2040.

The lines of development in HEP are thus more towards smarter networking technologies, like

- Software Defined Networks (SDN, [57]), which are able to adapt and guarantee performance over temporary network paths, and can interact with the experiment software in order to optimize transfers;
- Content Delivery Networks (CDN, [50]), which focus on caching data in intermediate network locations, also based on predictions of user future needs;
- Named Data Networking (NDN, [58]), which make the networking aware of its content, and move the search for a given resource out from the user and to the infrastructure.
- Point-to-point DCI high capacity networks joining big data centers, as already used by the major commercial providers, to form a demilitarized zone (DMZ)

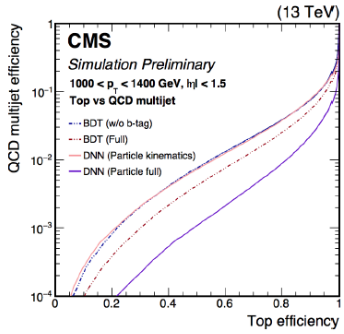

Figure 5: Performance boost between classic Boost Decision Trees (BTDs) and Deep Neural Networks (DNNs). The lower the curve, the better the performance in effectively selecting pure *b*-quark jets.

between owned centers which guarantee the data safety and in DataLake model (see section 6.3 and, for example, [59]).

None of this technologies is expected to be vital to the HEP field in the foreseeable future; still, they have added values which are worth pursuing, and in general are probably evolutions happening anyhow on the global internet infrastructure.

5.4. Machine Learning

Machine Learning (ML) technologies, and more in general Artificial Intelligence applied to HEP, is a rising field, with large expectations in the planning of future experiments. The top level expectation is the ability to replace human written algorithms, which have reached in many cases asymptotic performance (think of tracking Kalman Filter reconstruction [60], or selection based algorithms for tagging b quarks [61]) to new machine optimised tools, which use the intrinsic complexity of (i.e.) Deep Learning networks. At the moment this technology has been applied in production environments only as a (successful!) replacement of specific and well isolated algorithms, but has indeed shown the expected performance boost, as evident in Figure 5 [65].

Machine Learning tools are expected to play a much larger role in the next generation of experiments, potentially substituting the most complex algorithms like tracking [62][63] and calorimeter reconstruction [64]. They are not only expected to be more accurate and need less developer time, but in principle could be faster (depending on the internal network architecture) and be deployable on the online system. More forward-looking approaches are researching at Machine Learning as a tool which can substitute *in toto* the algorithmic reconstruction, using inputs as close as possible to raw detector data, and presenting in output reconstructed and physics grade objects or at least event classification; an example is in [66], but the field appear to be in its earliest phases of exploration. On a different level, Machine Learning seems to have very promising applications as a substitute / alternative to parametrised fast simulation. Recent computer science developments, like the realisation of Generative Adversarial Networks (GAN, [67]) have shown the capabilities to mimic the response of the precise and slow Full Simulation (with Geant4, usually) with much better timing performance, and are considered appropriate solutions for future fast simulation tools, with a low need for tedious and slow human tuning. Some examples can be found in [68], [69]. Finally, a more intrusive push for ML techniques in the next generation of experiments could come simply by technical arguments: ML tools, like Tensorflow[70], Keras[71], Theano[72] are written from the ground up to support accelerator technologies (GPGPUs and TPUs, but also FPGAs via high level synthesis), and as such a wide utilisation would shield HEP developers from the needs to explicitly support the architectures in the experiment codes. Training of large ML models is considered, today, the easiest way to effectively utilize High Performance Computing allocations, as detailed later in this paper; it is however unclear whether the same tools can be used effectively at inference level, thus really replacing standard production codes. A recent and comprehensive review of Machine Learning applications in HEP can be found in [65].

5.5. Big Data Tools

The current generation of running experiments, as already explained in previous sections, relies on a distributed computing infrastructure, on which processing workflows are sent as multiple independent jobs, each analysing / reconstructing / simulating a fraction of the input events. The strategy is optimal since introduces very mild correlations between jobs running at different facilities, which can be fast / slow and differently successful without much impact on the system (apart from a delayed closing of the final bits of the processing), it ensures an high throughput as overall events processed, but does not guarantee a fast turnaround for a single *mission critical* processing task. The use of more recent Big Data techniques allows for the best timing performance on a single large task, as can be important for analysis workflows close to deadlines. Approaches like MapReduce[73] using tools like Spark[74] or Pig[75] allow for optimal execution time of such tasks, using all the available resources in a system in a targeted way, but usually need ad-hoc optimised hardware. Experiments and Centers are prototyping systems alike as analysis facilities, with the solution scarcely popular for standard production oriented activities; examples can be found in [76][77][78].

5.6. Facilities

The current LHC distributed computing is implemented via facilities managed via the WLCG project[26]; the situation is similar for the other running experiments. The vast majority of these can be categorised as:

- Computing centers (medium to large) part of funding agencies general infrastructure, serving mostly LHC but also local experiments;
- Academic computing centers at Universities with local participation by scientists with a direct interest in LHC experiments.

These sites, built ~ 1 decade ago following the MONARC recommendations, are owned by the institutions, and support the experiment activities with local storage and processing power, typically via dedicated personnel with some level of experience on the experiment workflows. This is partially expected to change in the medium-long

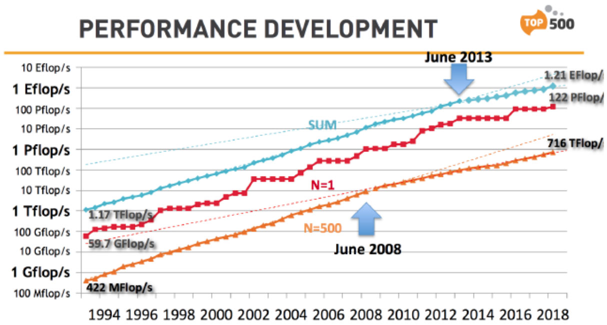

Figure 6: Evolution (from[79]), of the World-level HPC systems. Azure: sum of the top 500 most powerful systems; Orange: #500 on the list; Red: #1 on the list.

term future. The increase in processing needs, a described in the next sections, will inevitably force the experiments and their funding agencies to search for more economical solutions to HEP computing. Substantial savings could be realised by (for example):

- Utilising spare capacity (even temporary) at other owned centers, like those built for astronomy, astroparticle or genomics. While these center can be able to accommodate external workloads, it is very difficult they would also provide available storage or experienced personnel;
- Using commercial cloud grants / contracts to provide an equivalent processing power; the price can be extremely low, if there is no request for real time operations (the so-called spot market). For this to happen, the experiment software must be deployable via a cloud-aware solution, using virtual machines or containers. Also, it is very difficult to think about long term storage at the commercial provided, given its costs and the cost for data transfers;
- Using capacity at High Performance Computer centers (the supercomputers). These centers are built with use cases in mind including science, but are also important as industrial showcases at country level; the up-to-date worldwide list of systems [79] shows a consistent year-over-year performance improvement (Figure 6), and plans point to a first system able to achieve the Exascale (10^{18} floating point operations per second) by 2021[80]. Such performance are possible via a large scale utilisation of onboard accelerators, as previously explained, and as such the utilisation from the HEP experiment is complex at best. On the other side, countries with extensive HPC plans are reluctant to build an additional infrastructure for HEP, so funding for standard GRID/HEP sites is expected to diminish gradually, with our field basically obliged to find a way to use the HPC centers.

In all the above cases, the experiment software and the computing models need to be adapted if these new facilities have to be used. As already described in this review, this will imply a better utilisation of accelerators in HEP software stacks, and a decoupling of processing and storage resources at sites.

5.7. The long term future

Evolution of computing technologies has been reviewed in the previous section as adiabatic from current understanding: processing would be still silicon device based, storage either on magnetic or silicon-based media. The assumption is at the basis of Moores (and alike) laws, and allows for some long term extrapolation. The extrapolations do not hold in case of drastic technological transitions. The breakthrough we can realistically foresee in the next ~ 20 years (so a case of expected unexpected) is the commercial viability of Quantum Computing. As of today, generic or specialised Quantum Computers start to be available via Cloud interfaces ([81], [82], [83]), and software ecosystems are being built ([84], [85], [86]). While we are at the showcase stage, with few real applications at the moment, the trend is clearly pointing towards wide scale utilisation in the next decades [87], via the preparation of quantum states with more qbits, and with smaller errors. If usable Quantum Computers would appear in the time frame of next or next-to-next generation of collider, it could completely change the computing model and algorithms. Several applications are being studied on todays computers or emulators; the most promising ones for HEP utilisation are:

- The realisation of a controlled quantum state with the characteristics of another (ideal or real system) quantum state: for example, mimicking the Standard Model or some of its parts (starting from simple models, like in [88]) could result in predictions to be used as substitutes of current event generator; in principle the predictions would be exact given the imposed model, and not just approximations from power series expansions.
- The realisation of a general-purpose universal minimisation engine: the system, by using quantum annealing, would find minima faster, even if on a statistical basis requiring many runs [89]. While todays time consuming reconstruction and simulation algorithms are not based on finding minima, with the availability of such general purpose tool many could be rewritten to use a minimisation approach (think of tracking as a minimisation of hit residuals, of jet reconstruction in calorimeters as a minimisation of distance signal to jet axes [90]).
- The realisation of a general framework to reduce the impact of combinatorial explosion, typical in tools like track reconstruction on silicon devices[91]. A simultaneous traversing of all the possible hit combinations in track seeding would be able to reduce the explosion in algorithmic time, to a milder scaling.

There is no certainty adequate Quantum Computers will be available on the time scale considered in this review; still there are hints that a Quantum Revolution could indeed happen, which encourages the experiments to start at least initial level experimentations on the available emulators.

Table 7: Basic parameters for next generation of colliders, as known to-date.

Collider	Operations start date	Length [km]	Particles colliding	Type	Cms collision energy [GeV]	Instantaneous luminosity [10^{34} cm^{-2} s^{-1}]	Superimposed pp interactions
LHC (for reference)	2009	27	pp	Circular	7000, 8000, 13000, 14000	Up to 2	60 (peak), 35(average)
HL-LHC	2026	27	pp	Circular	14000	5, 7.5	200
ILC	>2030	~30	e^+e^-	Linear	250, 500	~1.5	
CLIC	>2035	11-50	e^+e^-	Linear	380, 1500, 3000	1.5 (@380 GeV), ~6 (@3000 GeV)	
CEPC	>2030	Up to 100	e^+e^-	Circular	91, 160, 240	30 (@91 GeV), 4 (@240 GeV)	
HE-LHC	>2040	27	pp	Circular	27000	16 500	
FCC-ee	>2040	100	e^+e^-	Circular	91, 160, 240, 365 200	(@91 GeV), ~1.5 (@365 GeV)	
FCC-hh	>2045	100	pp	Circular	100000	30	1000

6. Future Experiments

The HEP community is currently in the definition phase for the next generation of collider machines. A tentative summary table of what is under discussion can be found in table 7, including parameters of interest for computing estimates.

6.1. *Linear Collider Experiments*

The High Energy community is focusing R&D on Linear Colliders since decades, with the latest and today more understood proposed machines being the International Linear Collider (ILC[92]) and the Compact Linear Collider (CLIC[93]). They differ in technical solutions for the beam acceleration, with ILC optimised for 0.5 TeV center of mass energy, and CLIC for energies up to 3 TeV. Since these machines have been under study for years, their computing models are quite refined. Due to the lower cross section in leptonic collisions, and to the lower repetition rate than in circular machines, data rates are expected to be at most comparable with todays LHC experiments. Considering that even in most optimistic scenarios these experiments would be 15-20 years away from operations, in all the scenarios the computing needs would be satisfiable via todays technology, or any adiabatic evolution LHC can take [94].

6.2. *CEPC*

The Circular Electron Positron Collider (CEPC) is a proposed accelerator complex, colliding e^+e^- in a 100 km tunnel; its location is still undecided between a few Chinese provinces. It is expected to be able to provide collision events at various center of mass energies, notably including an Higgs factory via the ZH Higgs-strahlung [95] at an instantaneous luminosity around 5 10^{34} cm^{-2}s^{-1}. It is expected not to become operational before 2030. As at every leptonic machines, subject to cross sections lower than the hadronic counterparts, they do not present on paper enormous computing problems; time is also on their side, since a projected start of ~ 5 years after HL-LHC, buys an additional factor 2x from technology evolution.

6.3. HL-LHC

The process of approval for the High Luminosity LHC (HL-LHC) has completed, with an expected start of operations in 2026. The accelerator will deliver peak instantaneous luminosities approximatively 4-5x with respect to current LHC, and will be complemented with upgraded detectors, providing much higher readout granularity. The accelerator would be able to deliver much higher luminosities, hence it will be operated in levelling mode, delivering uniform collisions during the whole fill at average pileup up to 200 (from the ~35 we are used to in LHC RunII). The ATLAS and CMS experiments are expected to be operating at 5-7.5 10^{34} cm^{-2}s^{-1} constant luminosities, and in order to do so will need a large increase (up to a factor 7) of their selection rate to offline, in order not to cut important physics events. Currently, estimates point to the need of ~7.5 kHz of selection of events sized ~5 MB; the simple counting of RAW data (assuming a 6 Million seconds data taking period per year) drives towards half an Exabyte/year of storage when considering both experiments. The ATLAS and CMS experiments are actively working on a computing infrastructure from HL-LHC. A simple extrapolation of LHC computing models fails to meet sustainability, given the 7x from selection rate and the 5x from luminosity scaling, not even considering the super-linear timing behavior of task as reconstruction or the added complexity of detector apparatus. As hinted in the technology tracking section, no adiabatic technology improvement is expected to provide a factor >30x in the next 8 years. The approaches used to overcome the resource gaps are various, and include technology changes (computing architectures) and operational changes (reduced copies of data, reduced data formats, reduced reliance on Monte Carlo simulation, ..). The state of the art extrapolations for 2027, the first year after HL-LHC commissioning) are presented in Figures 7 and 8. Focussing again on CMS numbers, the expected numbers do not include yet any contribution from high performance accelerators, and are only 10-20x larger than the resources deployed in 2019, with the storage being noticeable on the low side.

Three R&D programmes are expected to drive down the storage needs, and are detailed in the following paragraphs. The DataLake [96] storage approach is a sharp deviation from the initial LHC computing model, in which storage and CPU resources had to be deployed in a symmetric and balanced among sites, in such a way that computing tasks would essentially read local site data. The initial approach was driven by the (lack of) trust in general purpose networking between distributed computing sites, which required input data to be present locally at the processing site; as a side effect, in order not to make match making inefficient, multiple input data copies needed to be available. The DataLake model comes from the realisation that, mostly thanks to services like Netflix and Youtube, the general connectivity between sites has much im-

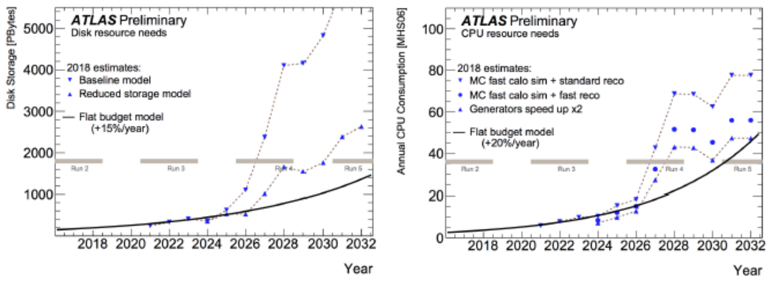

Figure 7: ATLAS Experiment projections for Computing resource needs in HL-LHC (from [98]).

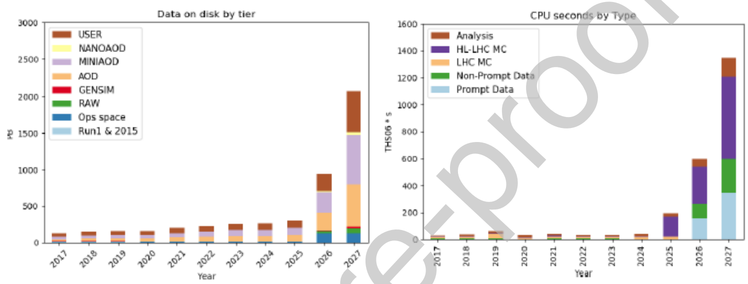

Figure 8: CMS Experiment projections for Computing resource needs in HL-LHC (from [99]).

proved, and is in many cases not different from costly dedicated lines[4]. This allows for a centralisation of storage into fewer and bigger sites, with the processing sites accessing remotely, via streaming or cache-mediated, the input data. The decoupling between storage and processing resources is welcome not only for the expected reduction of input copies (eventually down to a single copy, from the 1.5-10 typical today depending on the specific data type), natural in the model, but also in order to serve atypical processing resources, like disk-less temporary facilities, or grant-based HPC systems.

As discussed previously, RAW data from detectors during pp collisions are 1-10 MB sized. The complete output of reconstruction, including all the charged tracks, the calorimetric deposits and the single detector responses can be up to a factor 10 bigger, and is rarely needed at the level of physics analyses. The experiments are dedicating a big effort in the definition of a physics object set still suitable for analyses activities. This would have two substantial effects:

- A reduction of the disk storage space needed, proportional to the decrease in size with respect to standard datasets.

[4]The total fraction of download traffic hold by Netflix is 15%, from a negligible level just a few years ago[97].

Table 8: CMS analysis data formats for analysis.

CMS Data Format Name	Main analysis data format for the period	Size (kB/event)
RECO	2010-2011	3000
AOD	2012-2015	400
MINIAOD	2016-2019	50
NANOAOD	2019-	1

- A reduction of the processing resources dedicated to analysis, since the reduced set would be preprocessed with close-to-final quantities for analysis, not requesting sizeable postprocessing.

The CMS experiment is currently leading the R&D effort. In Table 8 the evolution of the main input for analyses is shown, as a function of time; the increased understanding of the accelerator conditions, of the detector calibrations and of the analysis patterns has allowed for a reduction factor of 3000x from the early commissioning days, to the 2019 analysis scenarios. A similar pattern is expected to be valid for HL-LHC: after a commissioning period, CMS expects at least 50% of the analysis activities to be possible with the smallest NanoAOD data format[100].

In order to be able to utilize even small chunks of processing time, like on HPC systems when backfilling tasks during the preemption time of large parallel workflows, the granularity of tasks as events processed per job must be as elastic as possible. ATLAS is pioneering the utilisation of an Event Service[103], which can serve events in bunches as low as 1; such an approach, complicated from the point of view of book-keeping but very effective in the utilisation of spare CPU cycles, is being evaluated also by the other experiments. On the processing side, R&D is ongoing on the utilisation of high throughput accelerators as those detailed in a previous section. In general, an economically sustainable processing at HL-LHC will need to be able and utilize heterogeneous hardware, when made available for example at HPC sites or at online farms made available to offline uses when beam is off. The experiments are trying to modify their core frameworks in order to allow for asynchronous utilisation of external hardware, local or remote, even deferring the decision at process startup via auto identification of the available hardware [102]. The biggest worries along the capability to use different processing architectures come from the manpower needed to write a large part of the algorithms multiple times, and the physics level validation between those versions. While some initial solutions have been developed[104], currently the absence of an abstract framework/tool able to efficiently run on multiple architectures is felt as a limit; some initial investigations are happening via the HEP Software Foundation[105], targeting Kokkos[106] and Alpaka[107] as possible solutions.

6.4. HE-LHC

The High Energy LHC (HE-LHC[108]) is an evolution of HL-LHC, where the accelerator magnets are substituted in order to bring the center of mass energy from 14 to 27 TeV. At the same time, the accelerator luminosity is increased 3-5x with respect to HL-LHC, with the notable effect of increasing the pp interactions per bunch up to ~500 (and more in some extreme scenarios). If happening, HE-LHC will need upgraded detectors as well, whose characteristics are subject of current investigation, and is not scheduled to start before ~2040 [108], after HL-LHC will have collected 3 ab^{-1} of integrated luminosity. HE-LHC computing models are far from being complete, but on paper the complexity of events collected scales with the increased center of mass energy (via $dN/d\eta$, less than a factor 2x[109]) and more importantly with the number of superimposed pp interactions, increasing at most by a factor ~2.5. Naively assuming that efforts will be made to maintain the reconstruction time as linear as possible, a factor 2.5x in the years between 2026 and 2040 is doable via technology improvements, even more assuming that by the time HL-LHC will be commissioned, the utilisation of accelerators will be included in the experiment frameworks from ground-up. To be noticed, the linear assumption can hold only if, in presence of a larger instantaneous luminosity, the selection rate can stay constant; if it needs to be increased in order to maintain identical thresholds on physics objects, the effect can be much larger.

6.5. FCC-ee

The Future Circular Collider is an R&D project which aims at the understanding of the capabilities of a ~100 km accelerator complex, ideally at CERN, initially colliding e^+e^- at various center of mass energies (FCC-ee). The time line is after HL-LHC, possibly replacing HE-LHC and thus in operations ~2040. It is designed to run as an Higgs factory (via the ZH Higgs-strahlung[95]), and eventually at the ZZ, WW and tt center of masses. At the highest (and in some sense more interesting) center of mass energies, the bunch crossing rate is 1 MHz or less; this and the smaller interaction cross section in colliding leptons, drives the computing need to a comfortable level, attainable around ~2040 with a simple evolution of the HL-LHC model, of course assuming the latter has been successful in the meantime.

6.6. FCC-hh

FCC-hh is the evolution of FCC-ee, colliding protons instead of leptons; it is expected to follow FCC-ee, and explore the high energy frontier with a 100 TeV center of mass energy thus realistically not before 2045 at best. Its collision parameters, especially the instantaneous luminosity up to 30 10^{34} $cm^{-2}s^{-1}$, are expected to generate ~1000 inelastic pp collisions per event, a factor ~2x the nominal HE-LHC figures and less than 4x even considering the increased particle multiplicity in pp interactions. Extrapolating from that, and again naively assuming a linear scaling of computing needs with instantaneous luminosity, the factor 4x should be possible almost effort-less from the similar HE-LHC model. The limiting factor will come not from these extrapolations, which do not look terrible per se, but from the actual capability to record as much data as possible, compatibly with the available resources at that time. Event sizes are expected to be at least 10x with respect to HL-LHC (this in the range of 50-100 MB/event), and in the end the selection rate will be decided by the tension between the physics communities (which would like an as high as possible readout rate) and the financial impact of the computing infrastructure. In this logic, it is essential to plan upfront the utilisation of reduced data formats, and eventually explore solutions which exclude the persistent storage of the raw data.

7. Conclusions

In this review, we tried to cover the basic aspects of computing in High Energy Physics. Its weight, also when measured as cost, has increased in the last experiment generations, with the clear need of a computing model planning with the same level of detail than any other detector or accelerator component. In perspective, it has to be assumed that computing operation model and cost will be a key limitation at least in hadronic collider experiments, thus impacting directly on the physics exploitability of multi-billion accelerator infrastructure. The first in line is HL-LHC, which will have to prove in the next 10 years the capability to research, embrace and adopt in production new technogies, currently unknown to most of the physics userbase. We can consider that a good test of the capability of the HEP field to evolve and align, if nor drive, the scientific computing panorama.

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