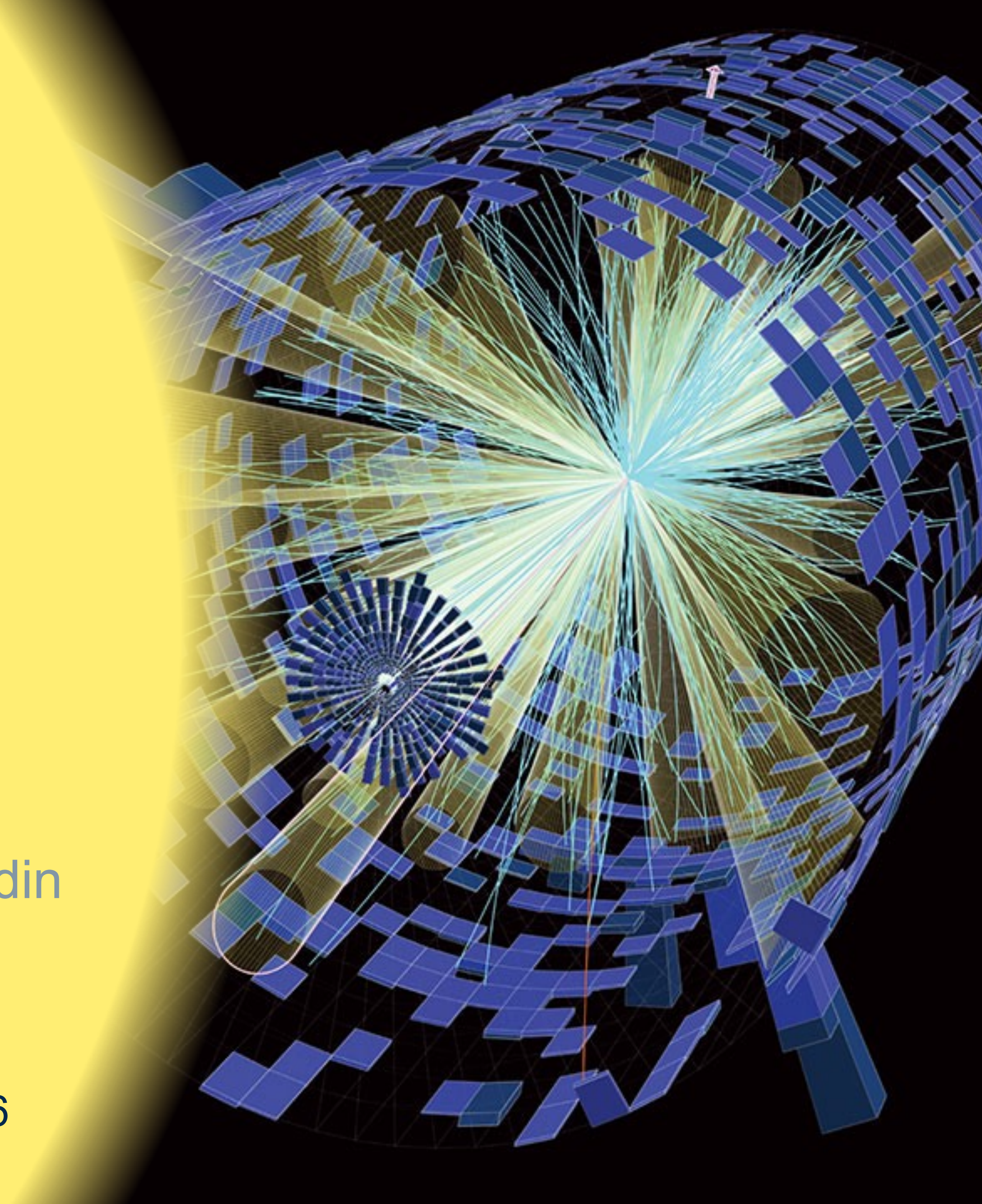
Tackling next HEP computing challenges

Sabine Crépé-Renaudin



IRN Terascale
Orsay

21 mars 2026

A journey in HEP computing recent developments

Travel

- Where we are ?
- What’s next ?
- A changing environment: challenges and opportunities
- What we would like to do better ?
- Ongoing efforts

Quite a wide subject, impossible to give justice to the huge amount of work done

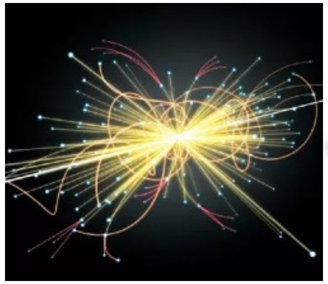
➜ An invitation to dig more and to participate to the adventure !

Where we are

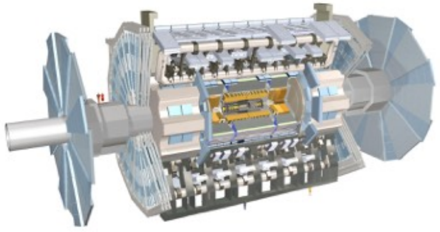
Data processing and analyses at the LHC

Experimental Data

40.10^6 collisions/s



150.10^6 channels
1,6 MB/collision

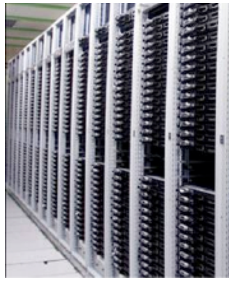


40 MHz

Level 1, hardware
~ 2.5 µs

100 kHz
50 GB/s

Level 2, software
(60k coeurs CPU)
~ 500 ms

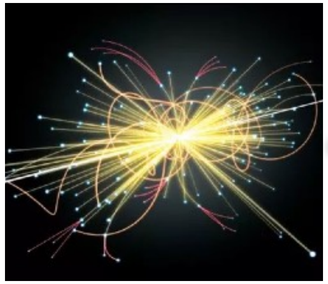


Triggers

Data processing and analyses at the LHC

Experimental Data

40.10^6 collisions/s



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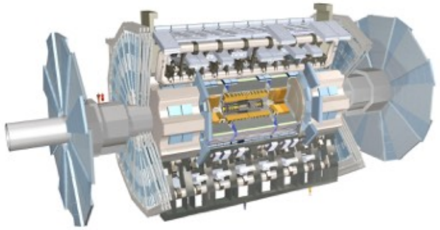

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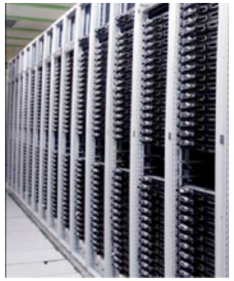
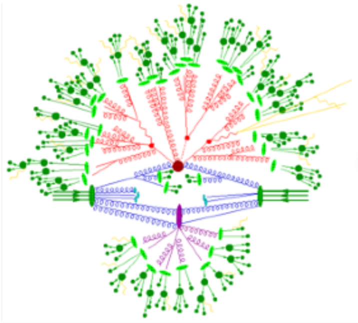
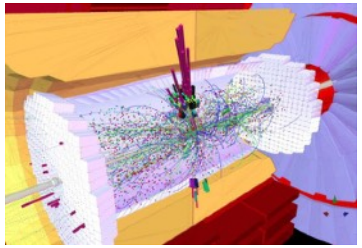


Triggers

Simulated Data



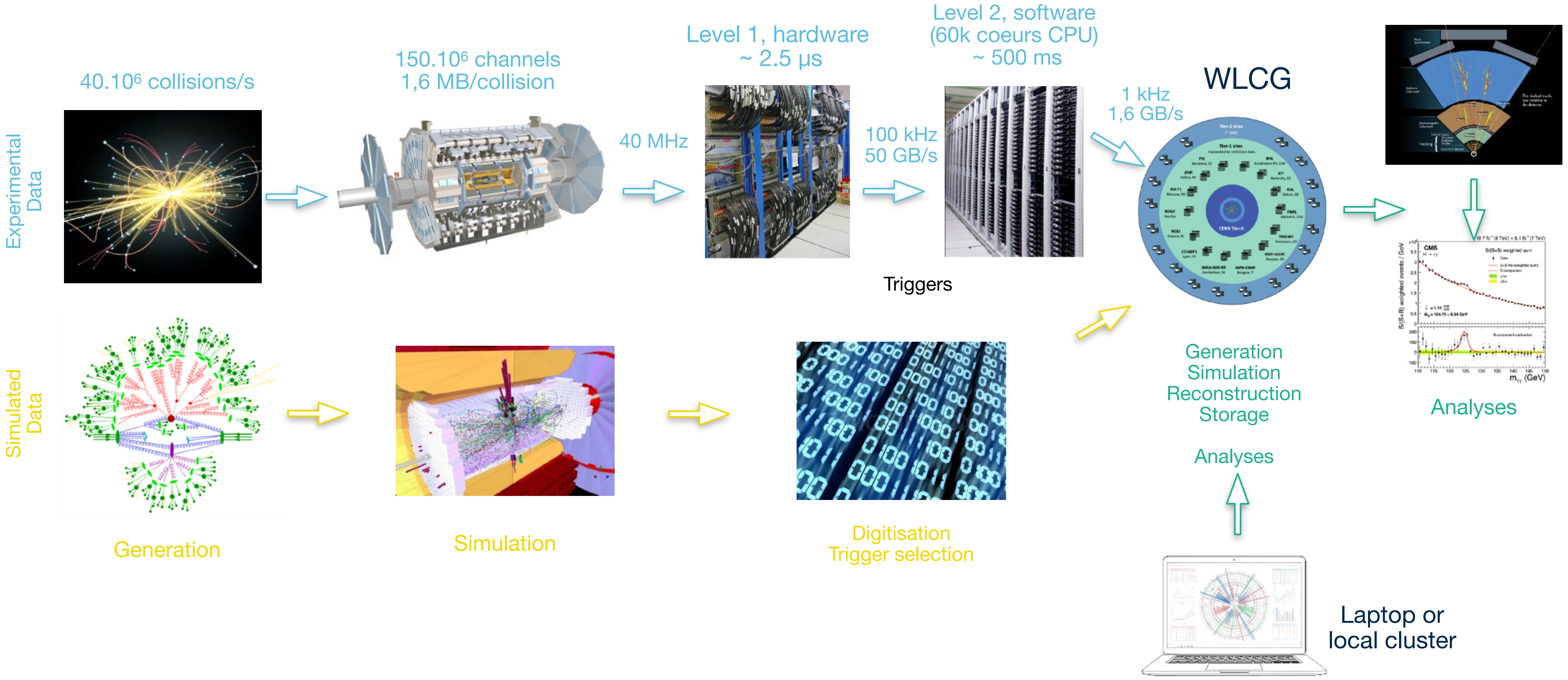
Generation



Simulation

Digitisation
Trigger selection

Data processing and analyses at the LHC



Complex set of components

Infrastructure and Hardware

- Triggers
- WLCG grid
  - grid sites : CPU, storage disks and tapes
  - network
- local analysis platforms/laptops

Middleware/interware and databases

- Data management and distribution: FTS, xrootd, webdav, DDM, Rucio, DIRAC, …
- Computing task management : Panda, DIRAC, …
- Software distribution: CVMFS
- Databases: conditions database, detectors, softwares, datasets, sites etc
- Monitoring : sites, computing tasks, storages, transfers, networks
- Communication, tickets systems: GGUS, JIRA

Softwares

- Trigger
- MC generation
- Simulation
- Reconstruction
- Analyse
- Monitoring

➜ 10s millions of code lines

Skilled people

- for all the components
- technicians, engineers and physicists

dCache
ROOT Data Analysis Framework
XRootD
CTA (Tape Archive)
EOS (File System)
CVMFS (Software Distribution)
CRIC (Information System)
FTS (File Transfer System)
RUCIO (Data Management)
DIRAC (Workload Management)
IAM
…

Data processing and analyses at the LHC

Experimental Data

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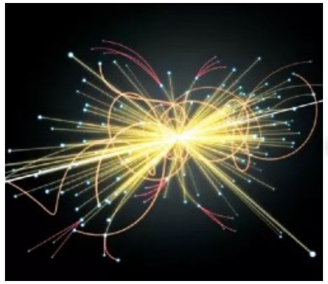

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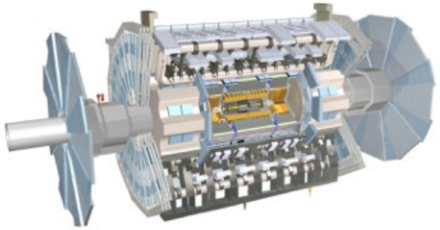

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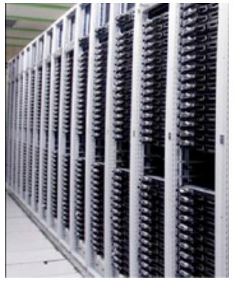
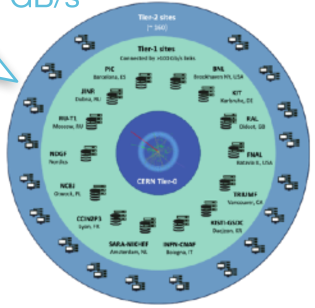


Triggers

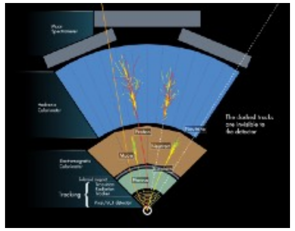
1 kHz
1,6 GB/s

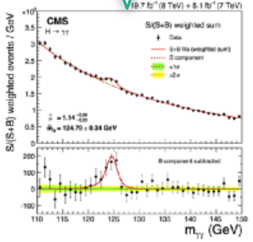
WLCG



Generation
Simulation
Reconstruction
Storage

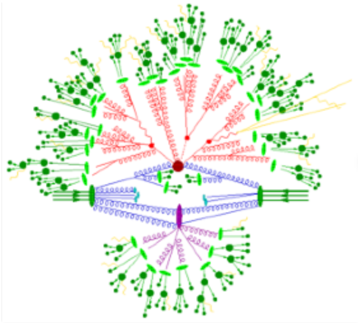
Analyses



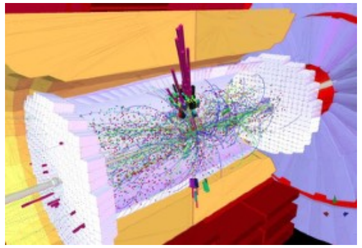


Analyses

Simulated Data



Generation



Simulation

Digitisation
Trigger selection

Laptop or
local cluster

Continuous improvements

Full Software trigger ex LHCb FPGA GPU CPU

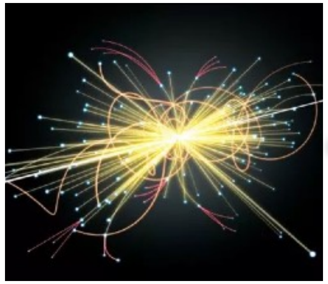
Grid is no more hierarchical
+ a lot of changes inside

+ storage management improvement, tape usage

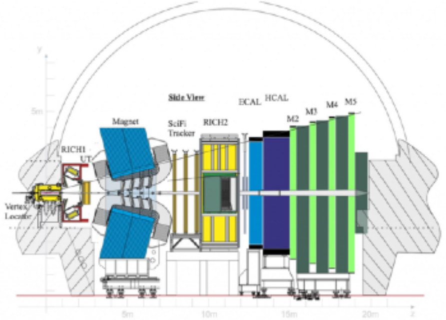
+ HPC
+ Clouds

Experimental Data

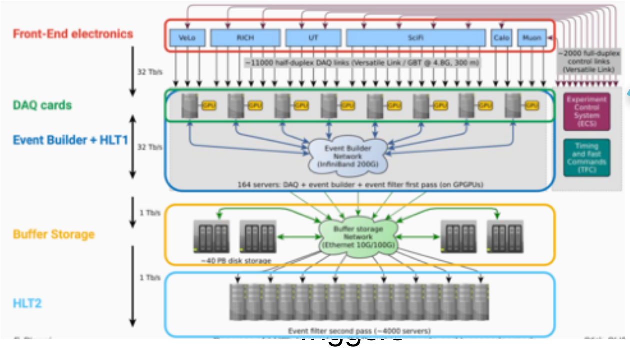
40.10⁶ collisions/s



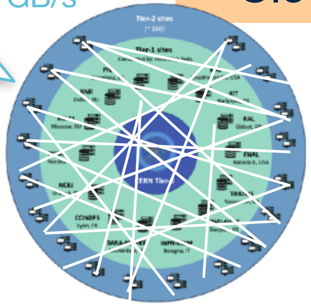
LHCb

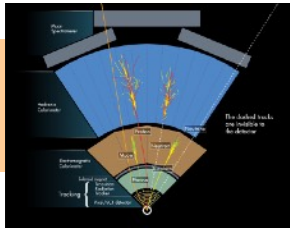


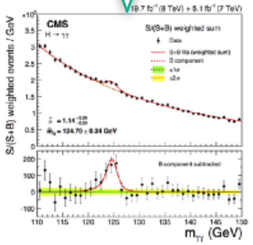
40 MHz



1 kHz
1,6 GB/s

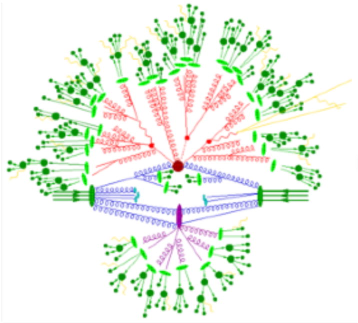






Analyses

Simulated Data



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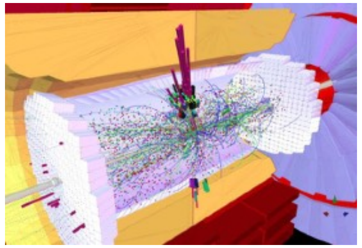


Simulation

Digitisation
Trigger selection

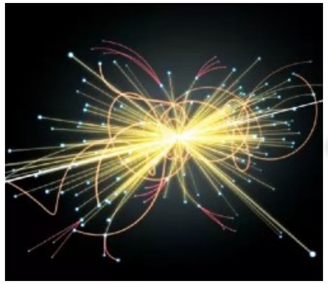
Generation
Simulation
Reconstruction
Storage

Analyses

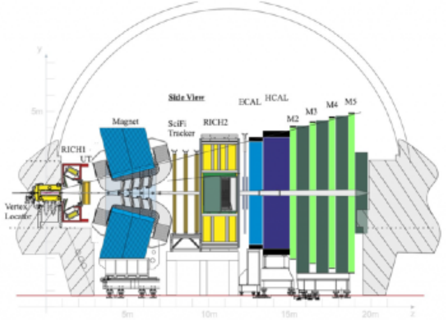
Continuous improvements

Experimental Data

40.10⁶ collisions/s

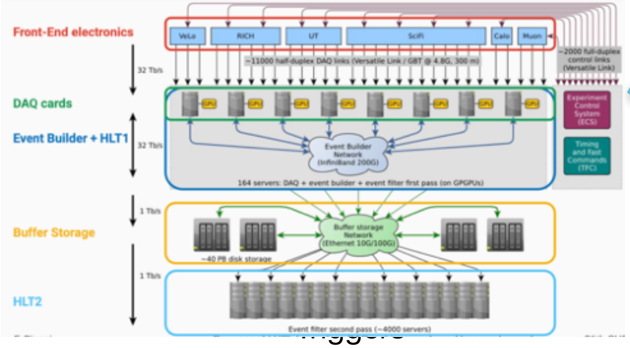


LHCb



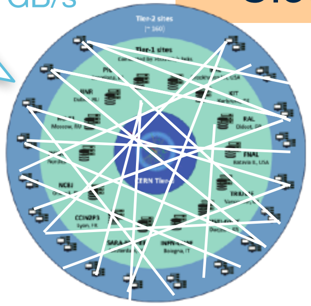
40 MHz

Full Software trigger ex LHCb FPGA GPU CPU



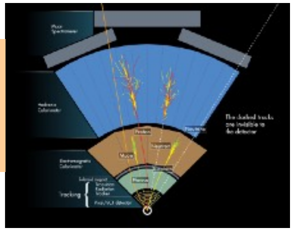
Grid is no more hierarchical
+ a lot of changes inside

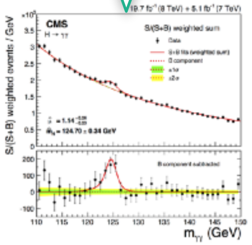
1 kHz
1,6 GB/s



+ storage management improvement, tape usage

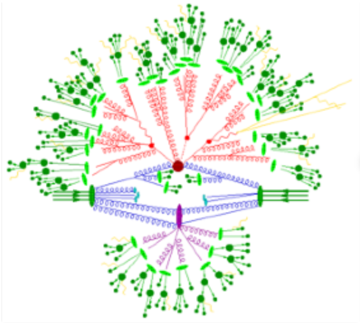
+ HPC
+ Clouds



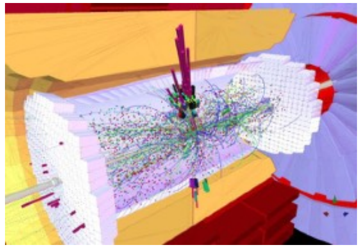


Analyses

Simulated Data



Generation



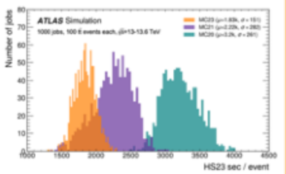
Simulation

Digitisation
Trigger selection

Generation
Simulation
Reconstruction
Storage

Analyses

Also a lot of evolutions in all the softwares
=> continuous effort to adapt to hardware (multiprocessor, multithreaded)
=> continuous improvement on performance



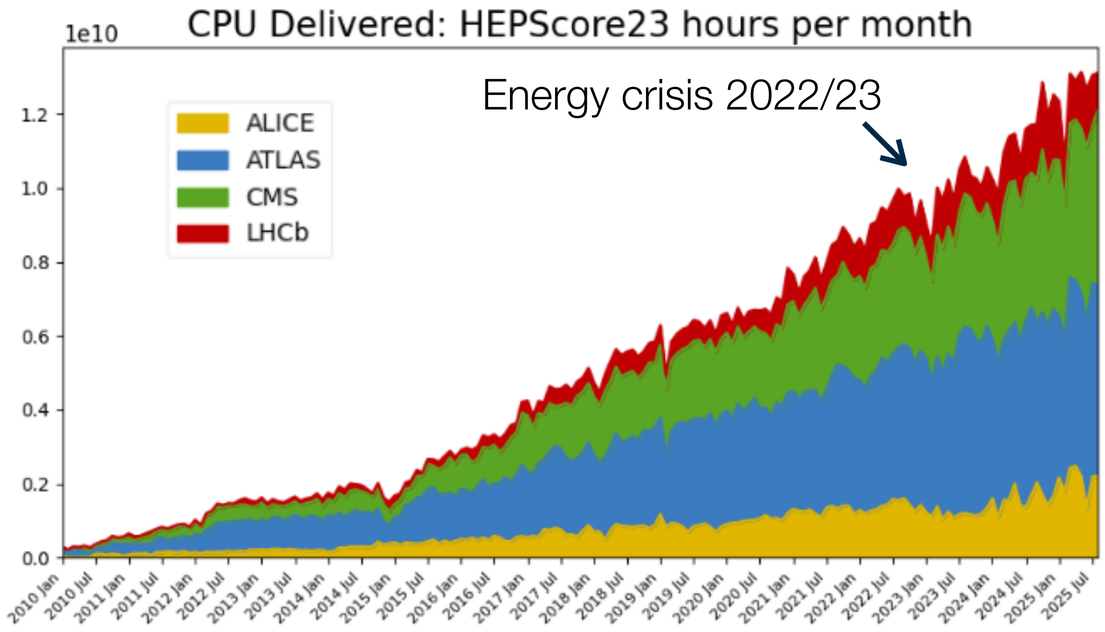
Scaling with time: computing

Evolution of computing requirements

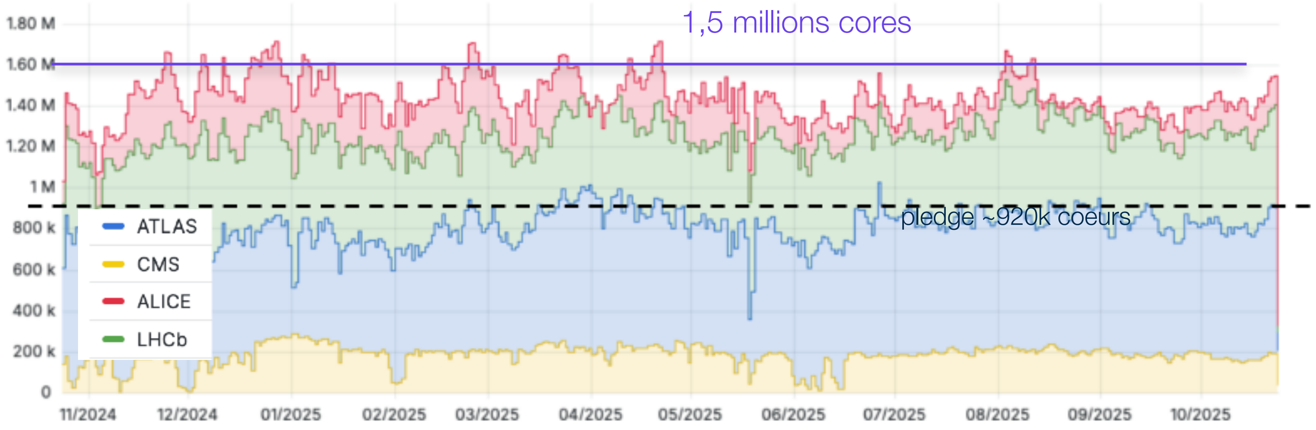
- HS23 unit = HEPScore23
  - ➜ 1 recent core ~10HS23 => **1.5 million cores**
- New benchmark deployed to better account for heterogeneous resources

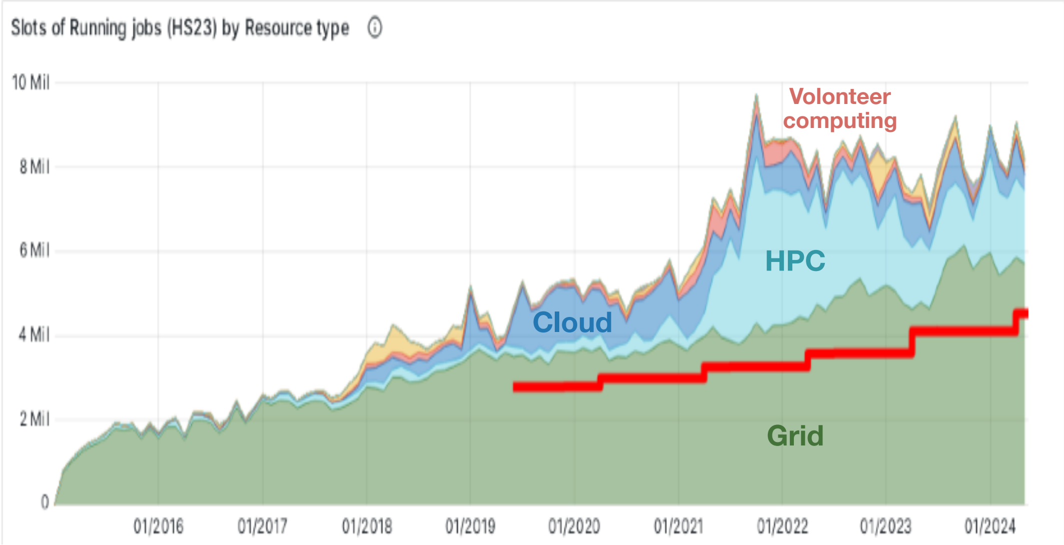
Resources used

- WLCG T0+T1+T2 and 3 pledged or opportunistic (Cloud/HPC/HLT/Volunteer Computing not taken into account unless part of a WLCG site)



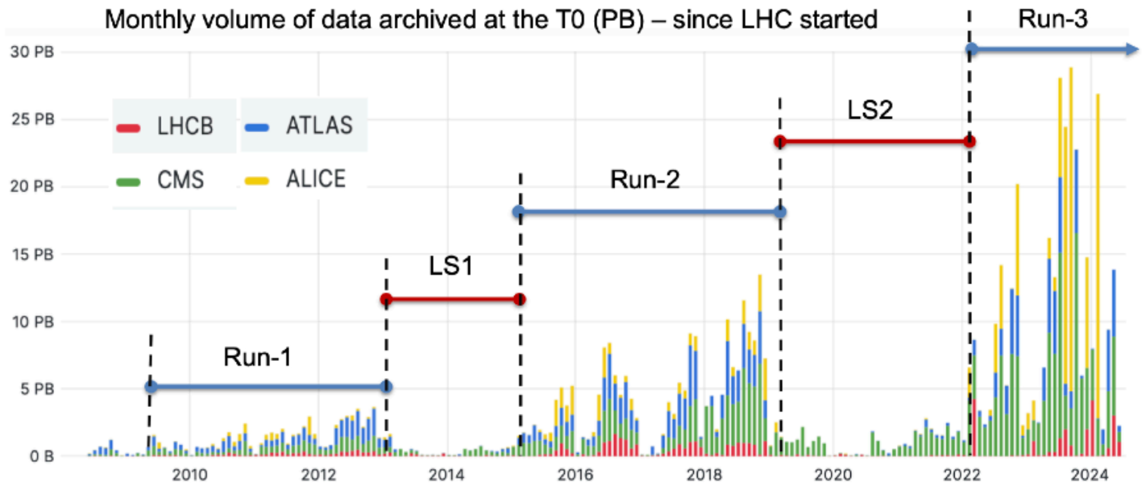
#cores in use (last 2 years) – ALL facilities (Grid, HLTs, HPCs)

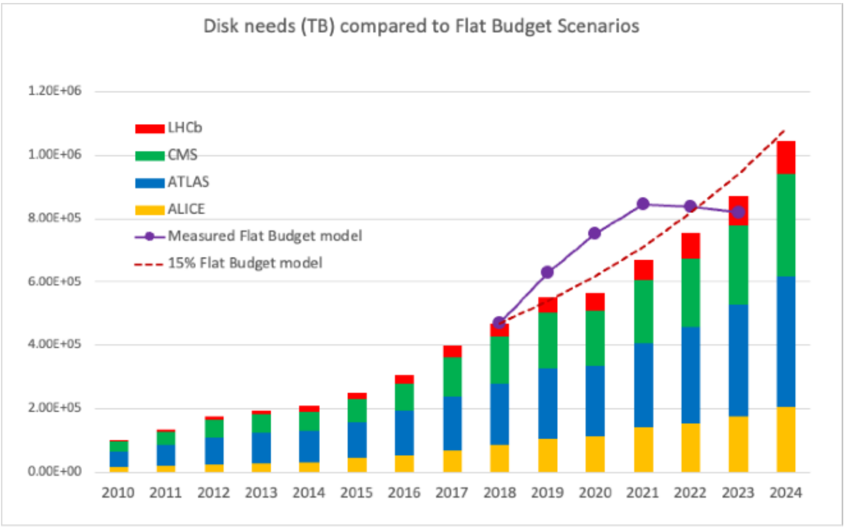


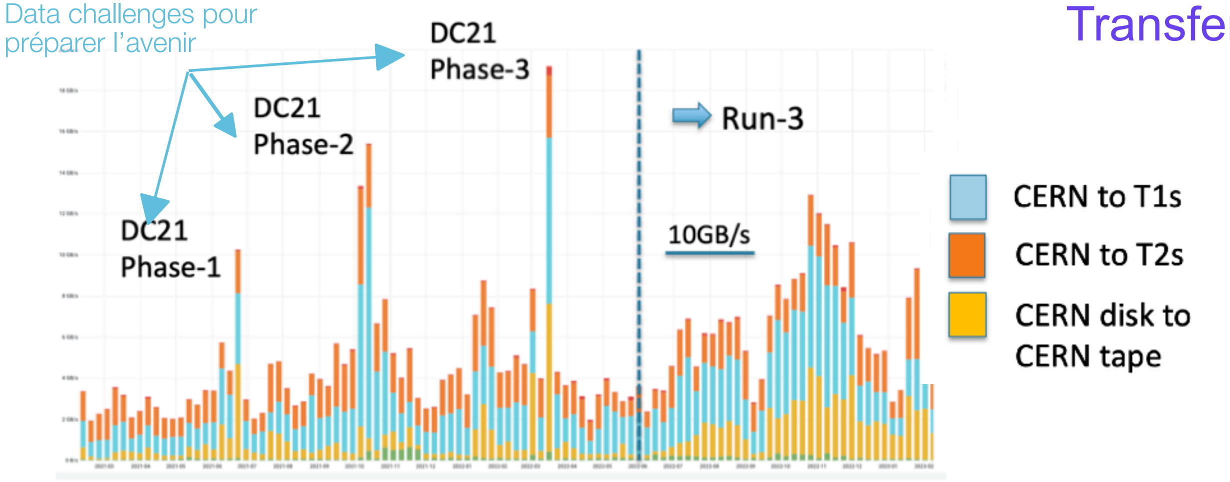


Scaling with time: storage

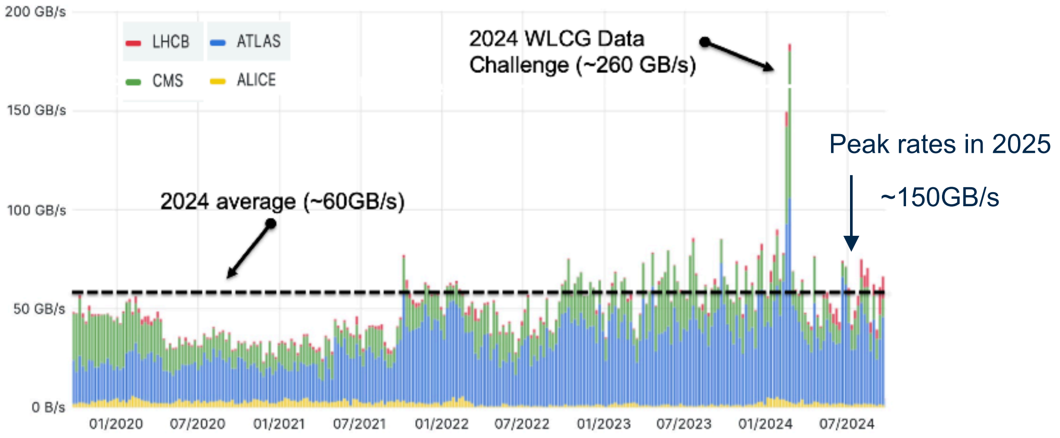
Total: ~ 3 Exaoctets data stored : disk + tapes



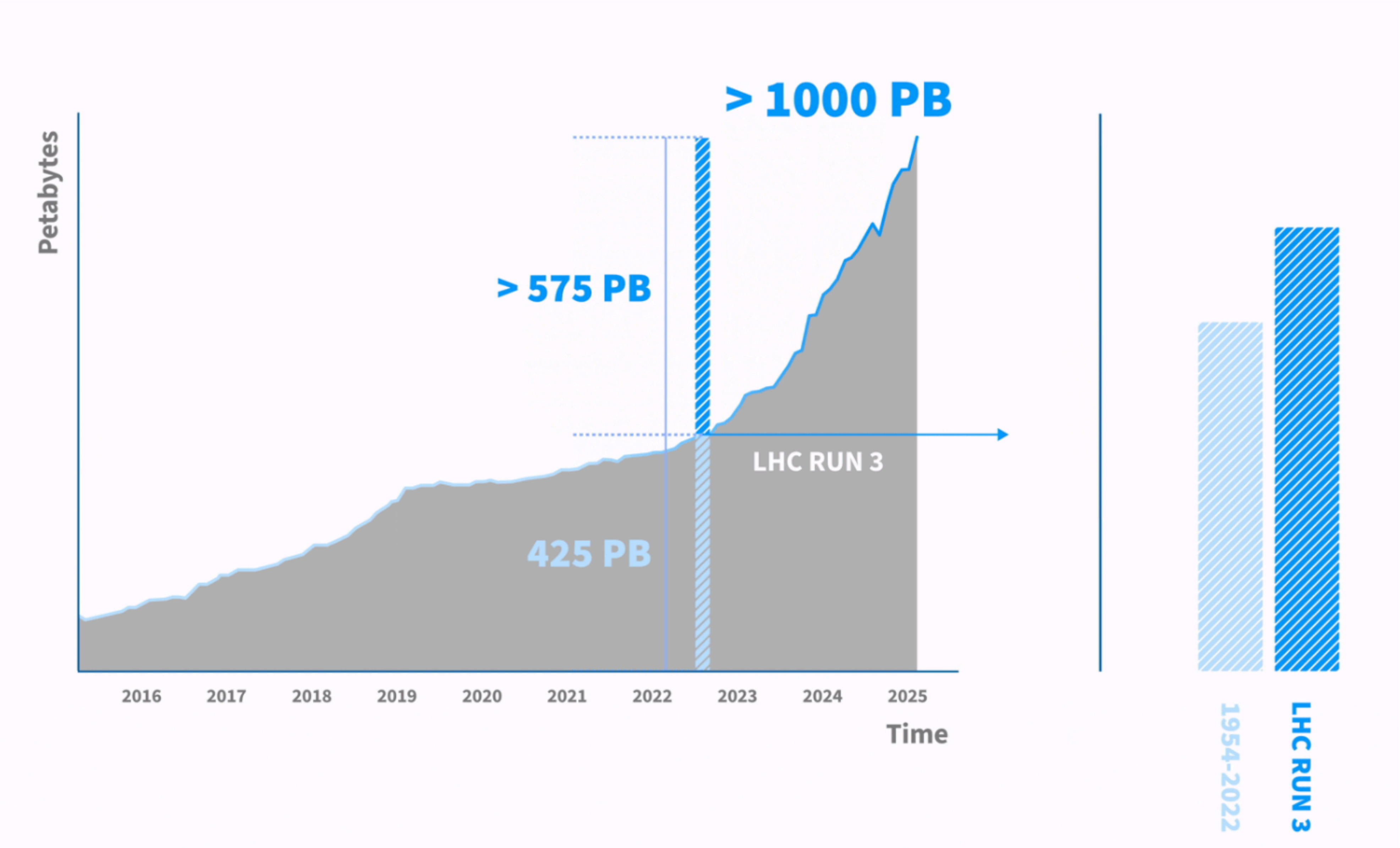




Transferts



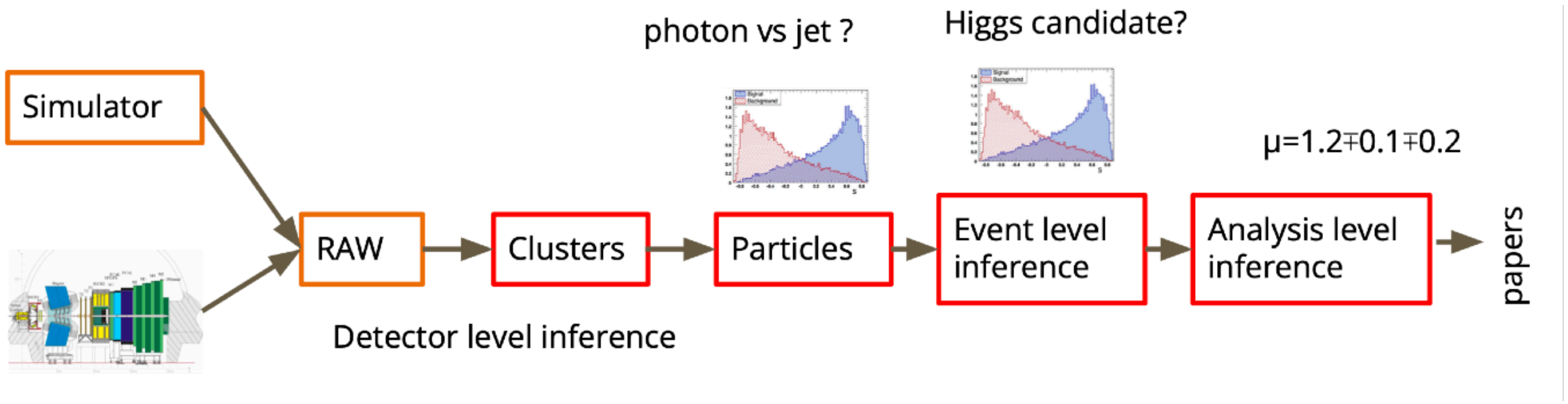
Faster and faster: data stored at CERN



Constantly evolving analysis techniques

Use of AI increasing

- Signal/background noise separation, particle identification: BDT widely used since the 1990s
- take a increasingly important place at all levels

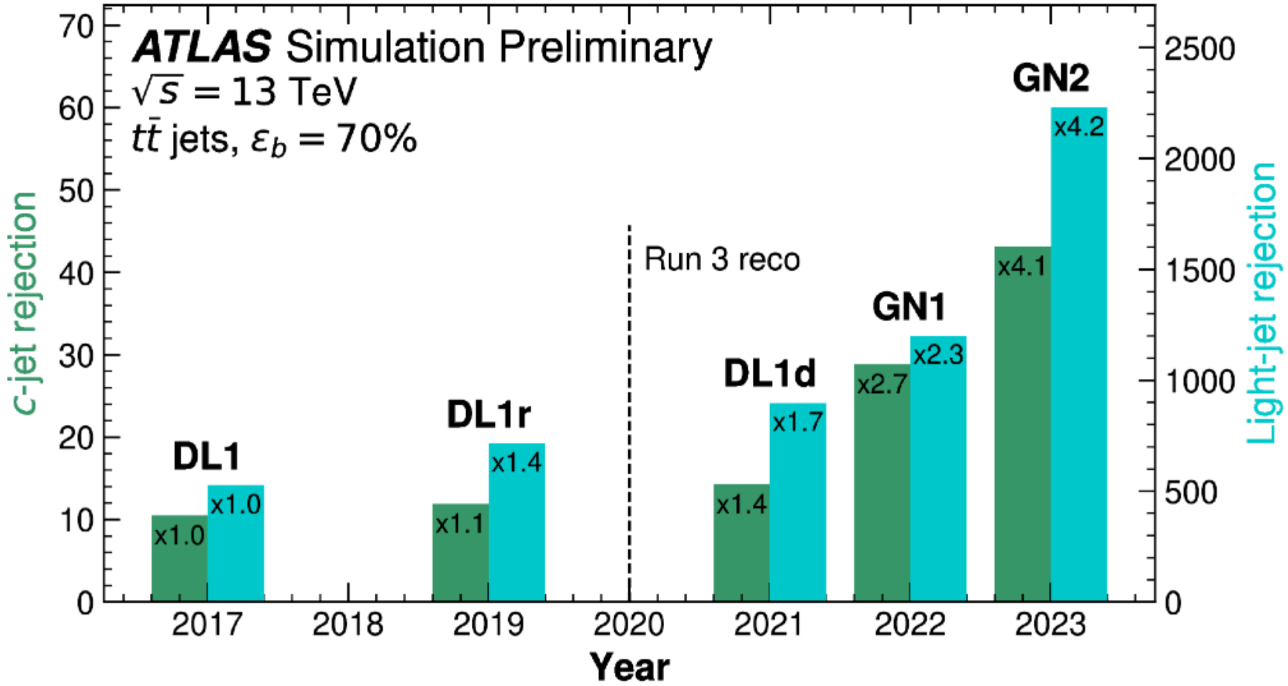


- Development of AI to accelerate simulation (digital twins, surrogate models), for selection, reconstruction, accelerator control, triggering and online analysis
- Use of various AI techniques: (BDT), conventional NN, variational autoencoder, Graph NN, DNN, generative adversarial NN
- developments to adapt them to our specific requirements: large data sets, highly accurate simulations
  - collaborations with AI researchers
- implementation on CPU, GPU or FPGA

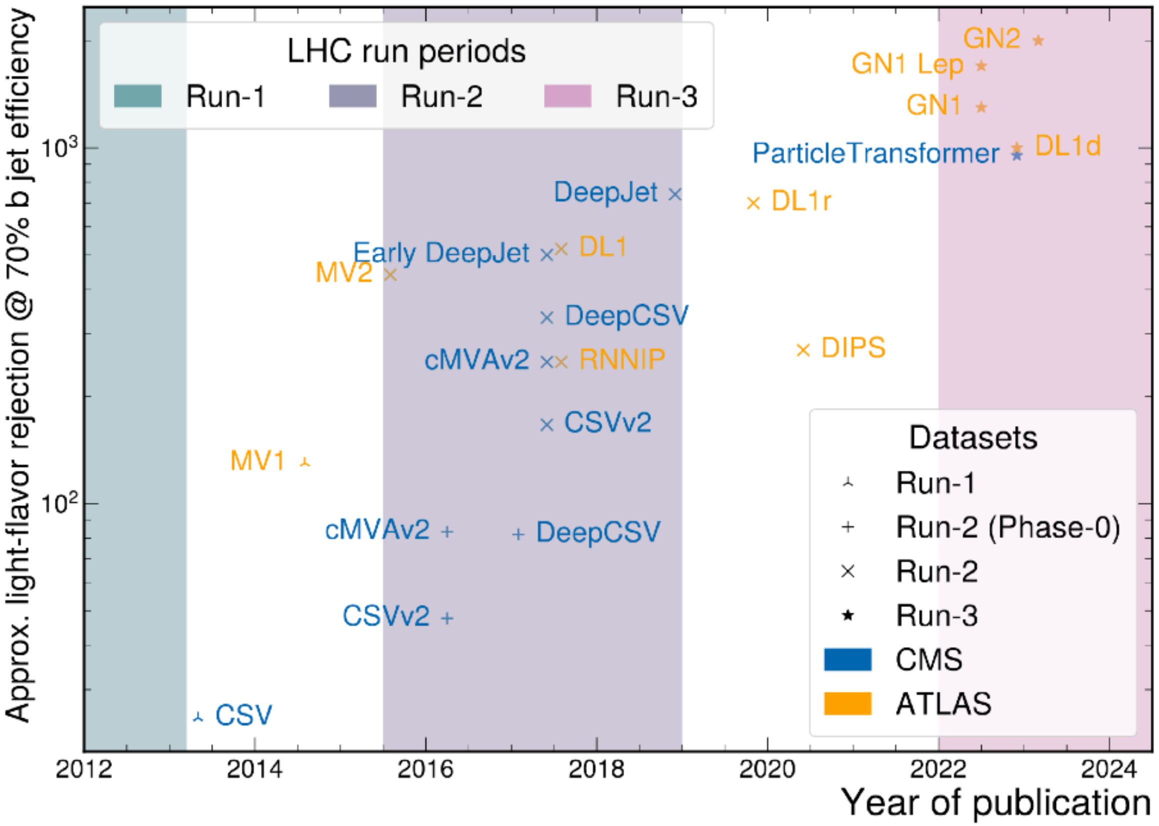
with some important gains

Examples : flavour tagging

- GN2 state-of-the-art jet flavour tagging algorithm,
- Transformer-based (https://arxiv.org/abs/1706.03762)



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/FTAG-2023-01/



https://arxiv.org/pdf/2404.01071

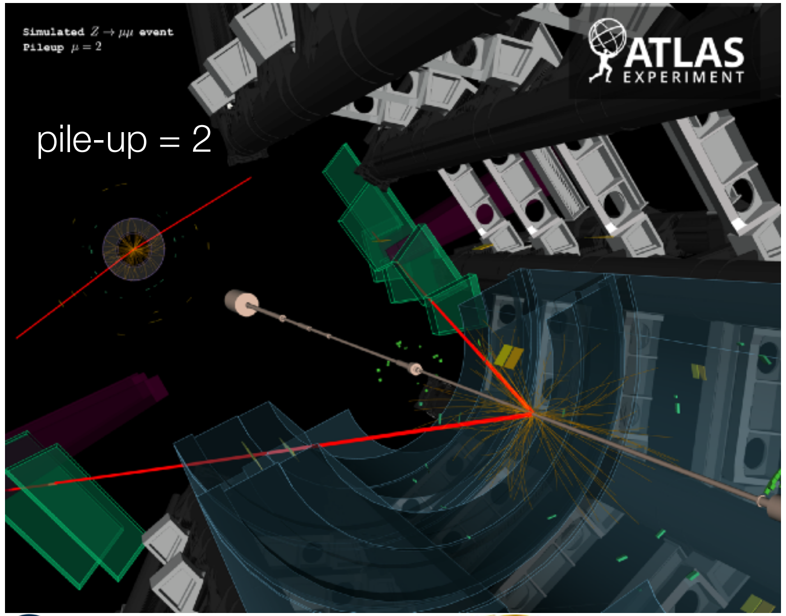
What’s next ?

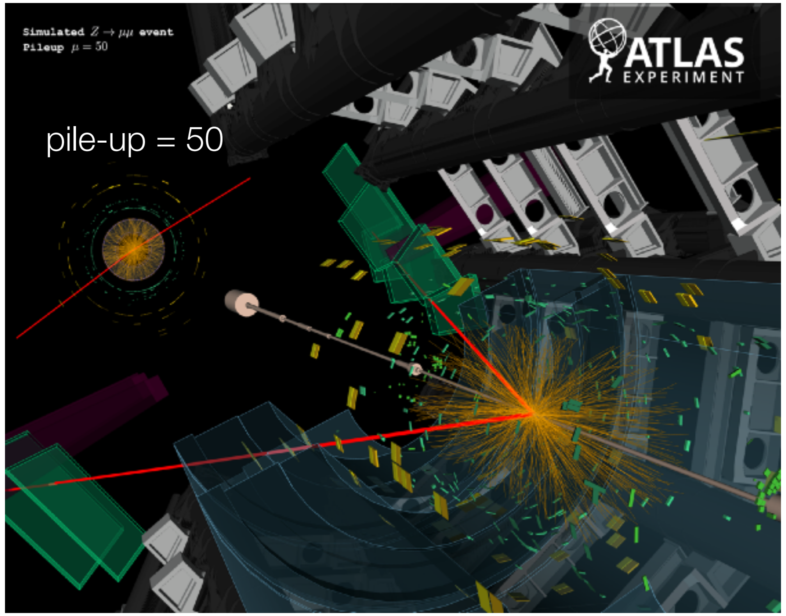
Future challenges: the HL-LHC

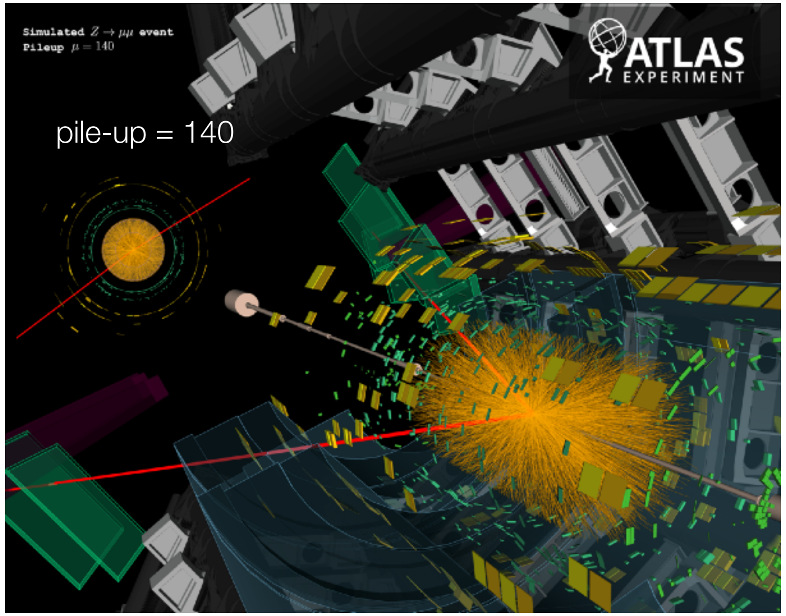
HL-LHC: a new phase of data

- accelerators and detectors upgrades
- a tenfold increase in the number of collisions
- much larger collision pile-ups

➜ more and more complex data







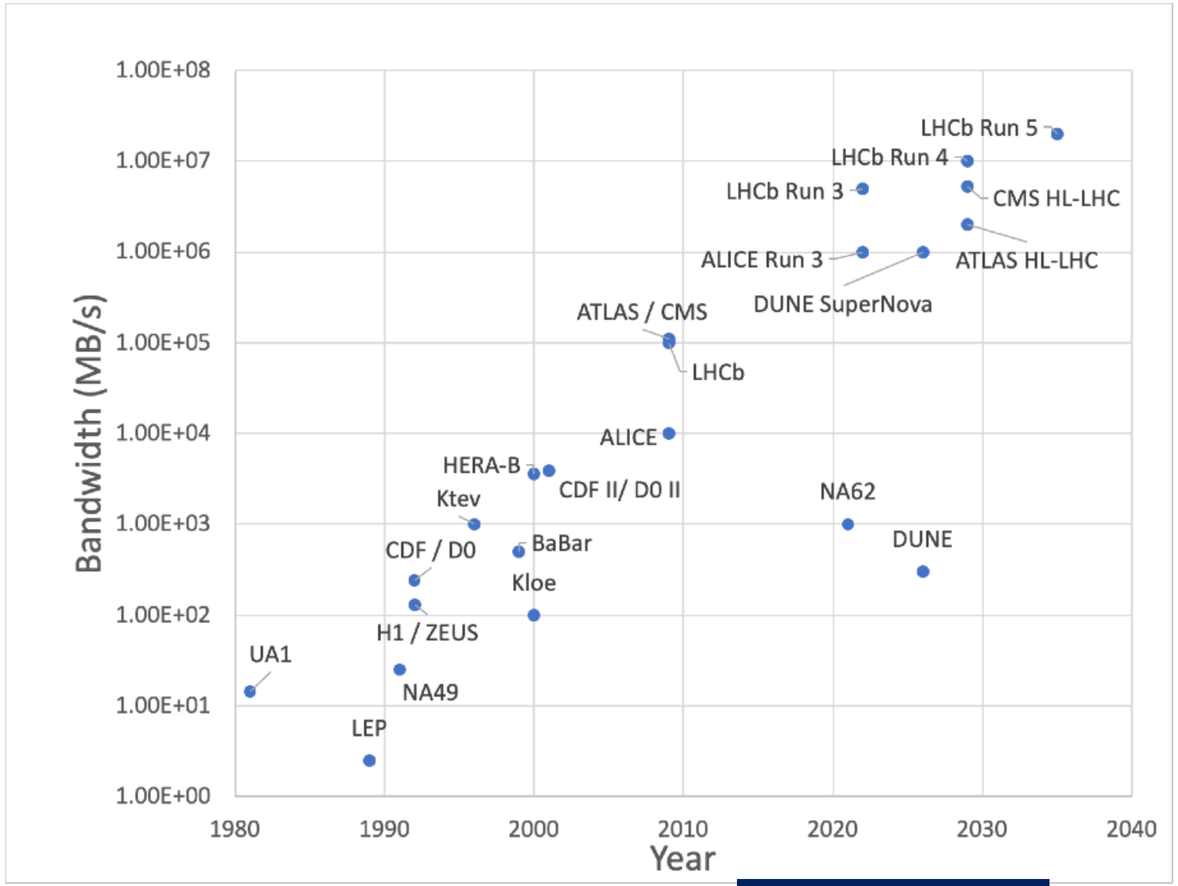
HL-LHC computing challenge

Data throughput at HL-LHC

- from detectors
    - LHC: 100 GB/s => HL-LHC 1-15 TB/s
- Running time : 5Ms/year
    - Data volume: 5-50 EB/year
    - Drastic reduction required at trigger level
    - Expected throughput from CERN to Tiers1 = 4.8Tb/s !

➜Also an analysis challenge

	LHC run1-2	HL-LHC run
analysis dataset	10 TB	1000 TB
used ressources	laptop	analysis facility



Credits: Alex Cerri, Sussex U.

HL-LHC computing needs

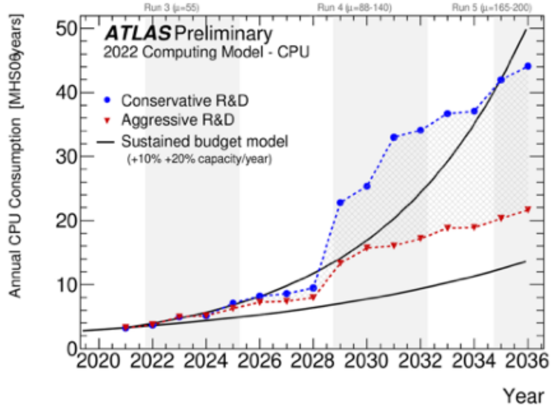
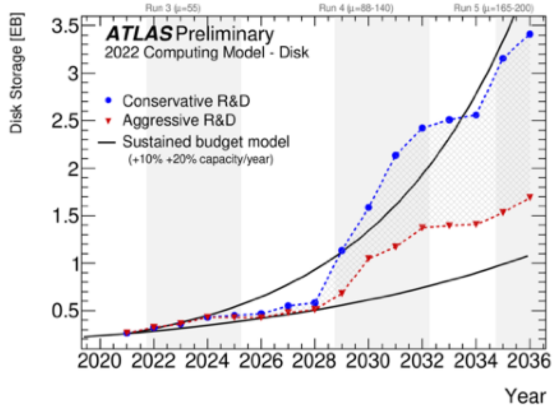
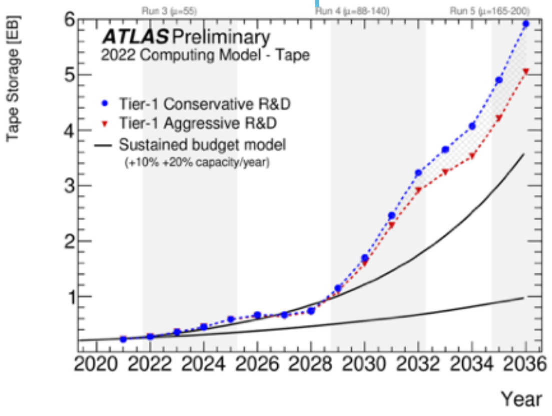
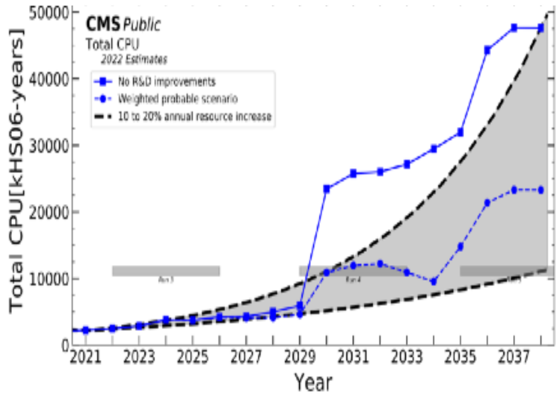
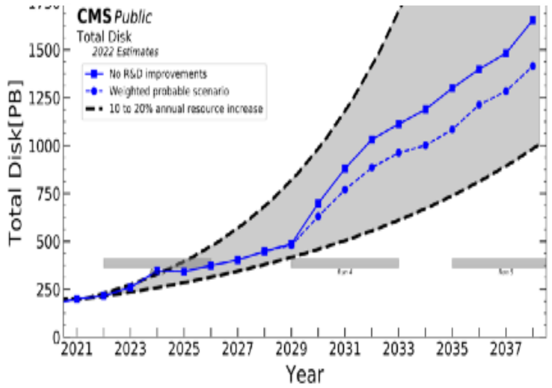
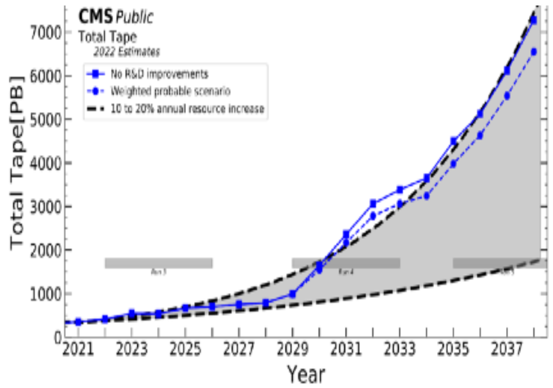
Needs multiplied by 10

- Experiments will collect exabytes of data each year

➜ Significant investment in R&Dneeded to meet the challenges while staying within budget and energy constraints

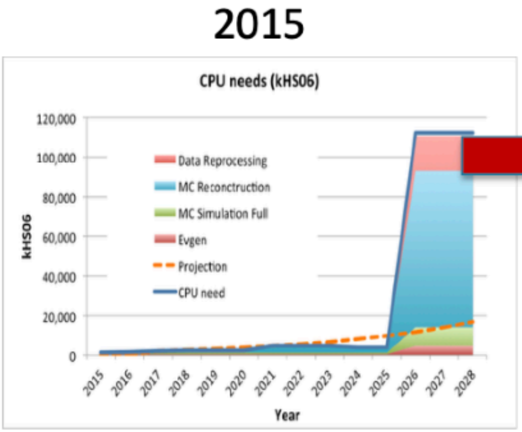
➜ Actually, R&D continuously progressing: the graphs below have already benefited from R&D efforts in previous years

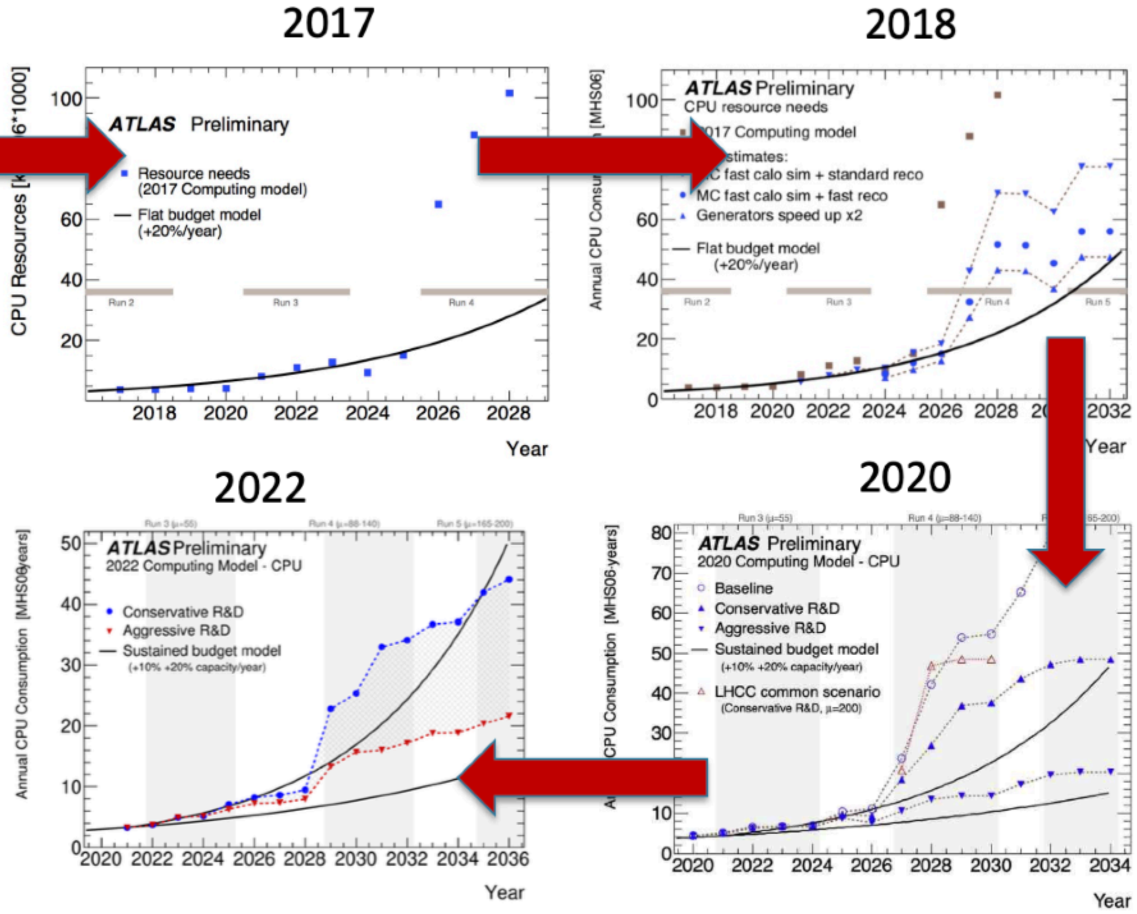
2022 estimates

	CPU	Disk	Tape
ATLAS			
CMS			

The result of continuous efforts

HL-LHC computing resource needs evolution





2015 projections: resource needs = 10x more than budget allows

2022 projections: resource needs compatible with budget (optimistic scenario)

[Simone Campana CHEP 2023]

HL-LHC computing needs

Needs multiplied by 10

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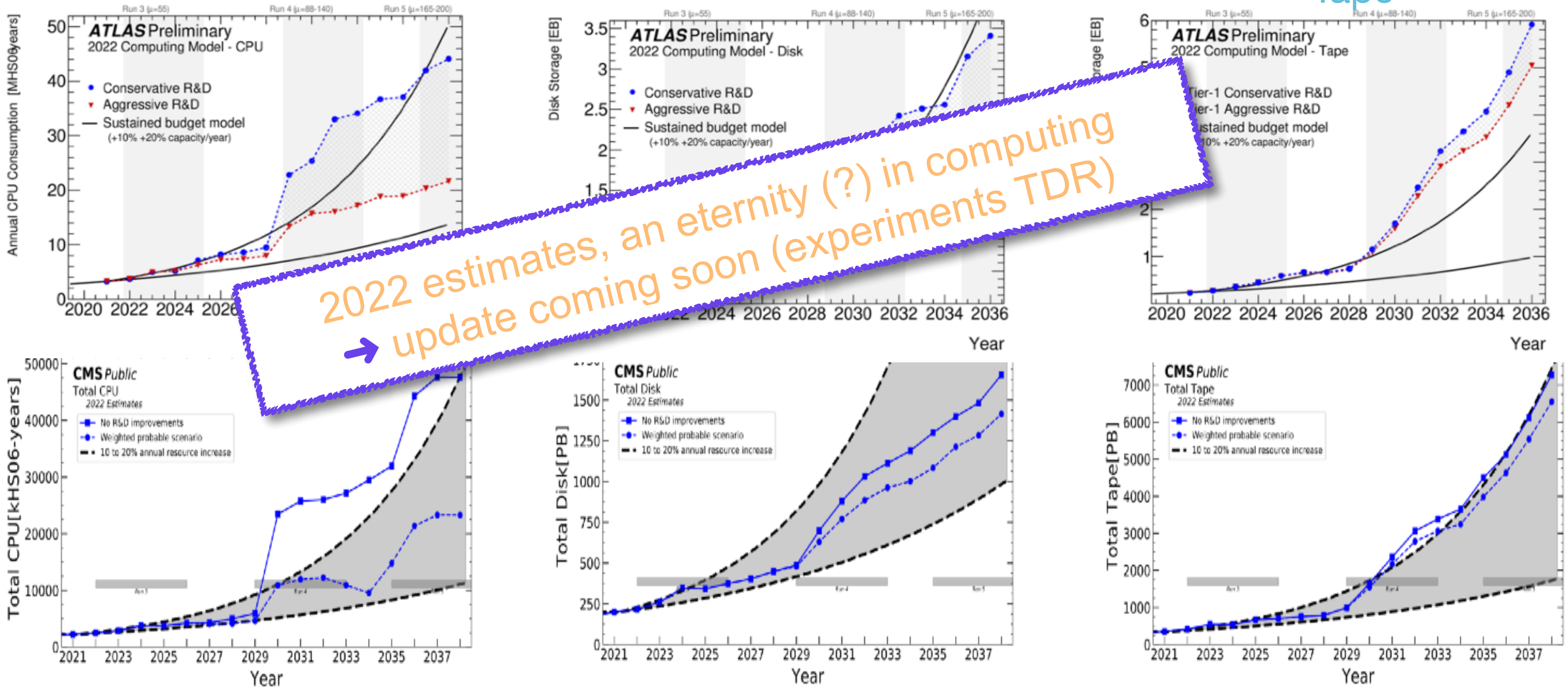
2022 estimates

CPU | Disk | Tape

ATLAS / CMS



2022 estimates, an eternity (?) in computing
➜ update coming soon (experiments TDR)

A large set of challenges to tackle !

Resources and organisation

- Grid: most of possibilities already studied and a lot already in use
  - datalake: big sites with storage and possibly of lighter site with only cache + play with quality of storage to avoid duplications
  - data carousel = organize data on tape to use it for reprocessing to save disk (tape ~cheaper)
- site will have to adapt to new technologies when needed
  - prices servers + fluids ?
  - cooling GPU is not cooling CPU…
  - minimize PUE
- access to HPC ressources: already used, good idea to increase the use ?

Analysis facility

- how to do analysis on 1PB of data ? (run 1-2 typical dataset was size 10 TB)
- Current workflows do not scale:
  - disk/tape are limited/expensive and analysis data are projected to occupy ~30% (ATLAS model)

Interware and databases

- what will be the interplay with others experiments/fields
- extending to different type of ressources (HPC cloud) and other science

Softwares: the greatest potential for improvement

- a lot's of past and ongoing work
- at all steps from generation to reconstruction, performance and analysis
- possible gains with new hardware (FPGA, GPU) ?
  - what stability with time ? what efficiency ?
- use of IA

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$
Geant4	1.2M	330	45 M$

Human resources

- adaptation, training, recognition
- competition wrt private sectors

A changing environment: challenges and opportunities

Growing computing needs

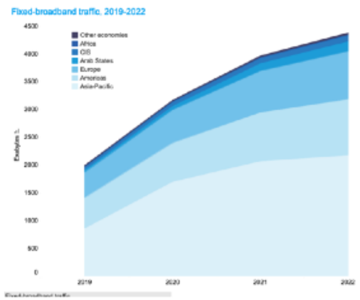
In our research fields

- Several experiments have or will have non negligible computing needs in the near future : DUNE, Belle II, JUNO ~ 10% LHC
- Also in astro-particle and cosmology: Vera Rubin/LSST, CTA, KM3NET, Euclid, ET and SKA and multi-messanger approach
- Nuclear physics: dynamic structuration ongoing, EuroLabs, FAIR, EIC, Lattice QCD…

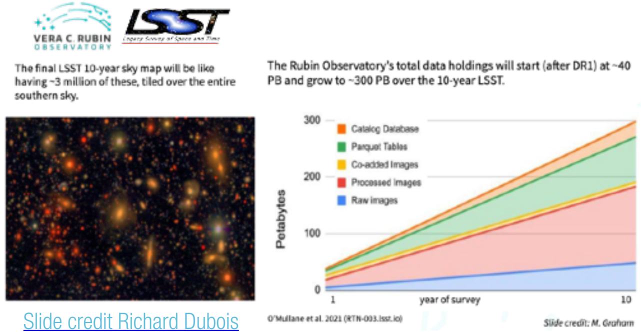
In other research fields and in society

- Importance of data growing everywhere: improved technologies easier to use and computing ressources more easily available, developments of AI etc

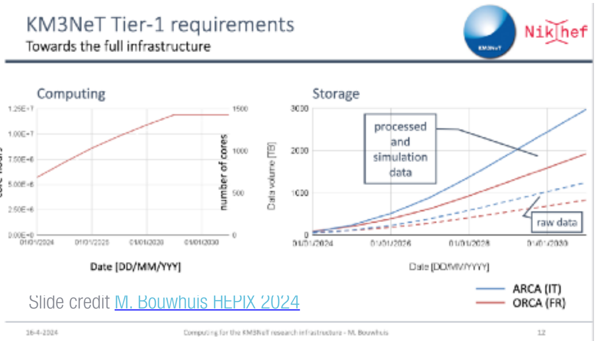
Internet Traffic



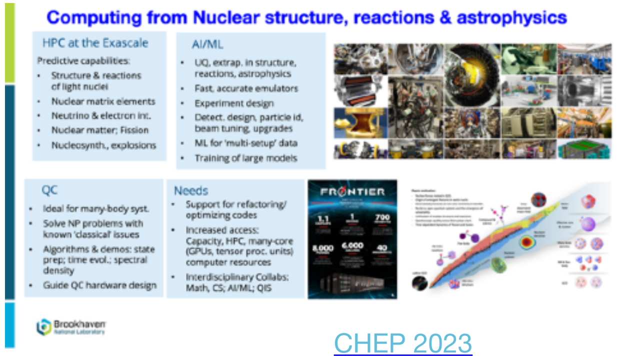
https://www.itu.int/itu-d/reports/statistics/2023/10/10/ff23-internet-traffic/



Slide credit Richard Dubois

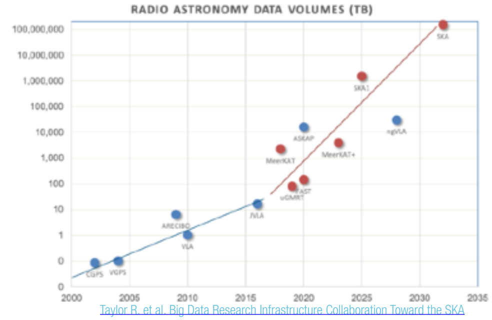


Slide credit M. Bouwhuis HEPIX 2024

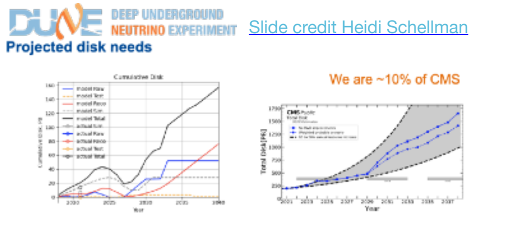


CHEP 2023

Rosie Bolton @ CHEP 2023



Taylor R. et al. Big Data Research Infrastructure Collaboration Toward the SKA (BRICSKA). doi: 10.1590/0001-3765202120201027. PMID: 34076205.



Slide credit Heidi Schellman

Figure 6.4: Estimated size of various disk samples in PB for DUNE and CMS at the HL-LHC for comparison. This estimate includes retention policies and multiple copies. The points show actual use in 2021 which was lower than planned due to delays in distributing second copies of samples to remote sites.

Artificial Intelligence

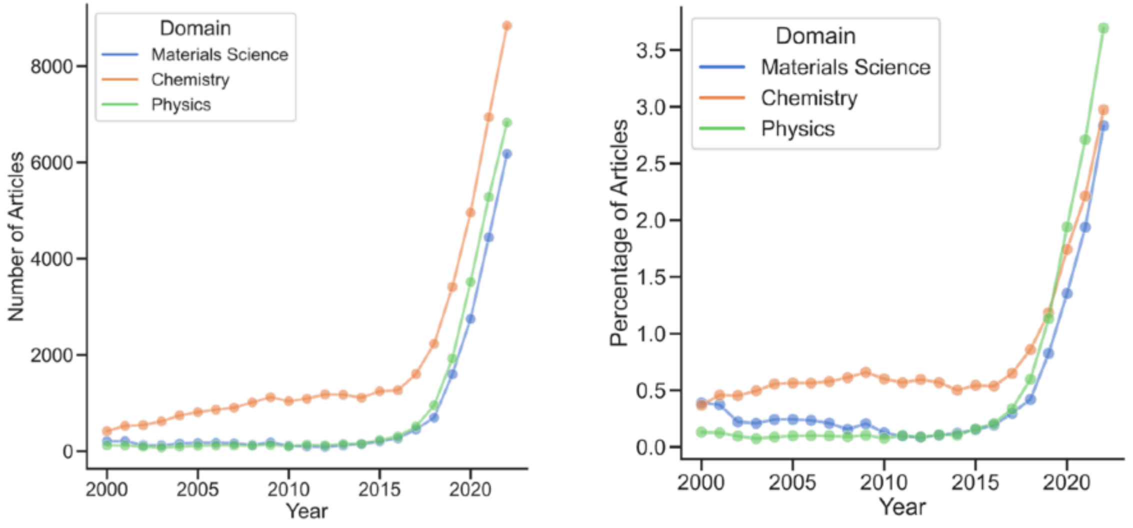
Use of AI since decades in HEP

- signal/background separation, particle identification, multivariate analysis… ex BDT widely used since 90'

Modern AI and computing ressources allow new usage

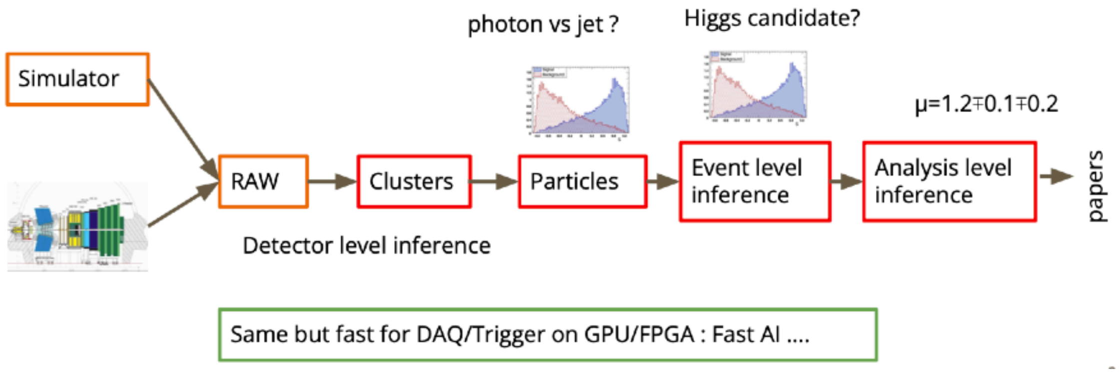
- generative models, unsupervised classification, low latency inference, transformers
- CPU, GPU, FPGA implementation
- AI assisted code generation
  - ➜ AI usage and developments at all stages of computing in our fields

ML Publications in Science



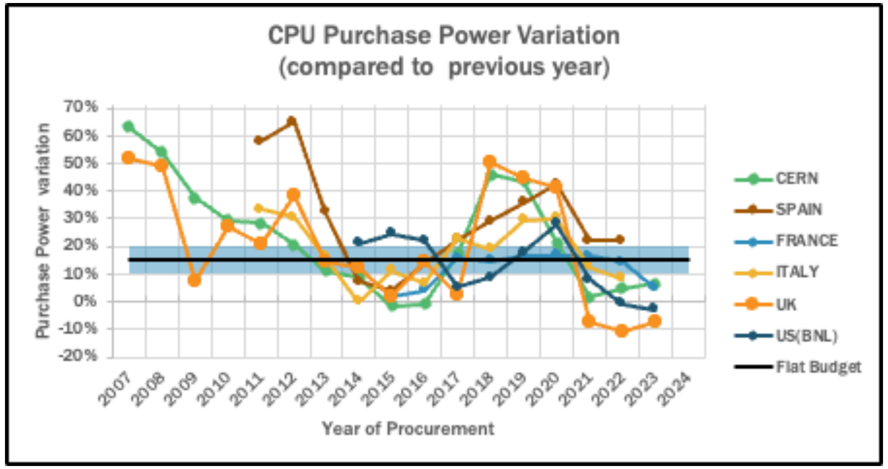
Ben Blaiszik, "2021 AI/ML Publication Statistics and Charts". Zenodo, Sep. 07, 2022. doi: 10.5281/zenodo.7057437.

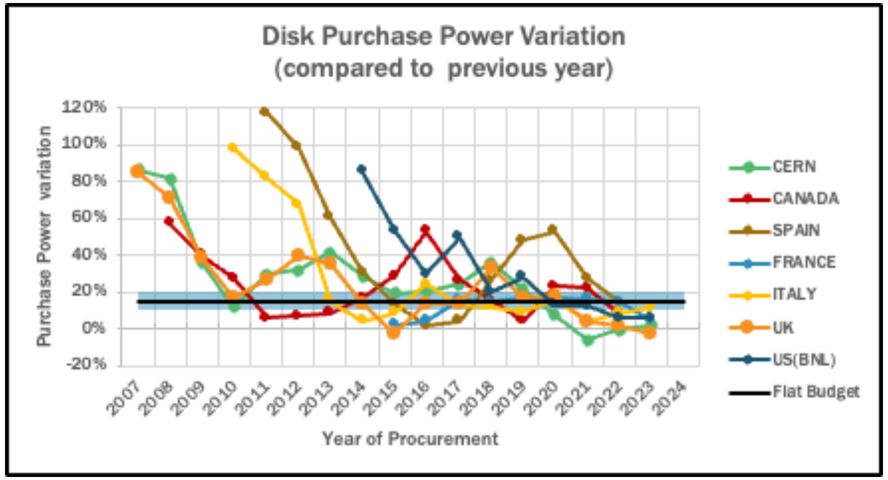
CHEP 2023



© David Rousseau

Hardware costs





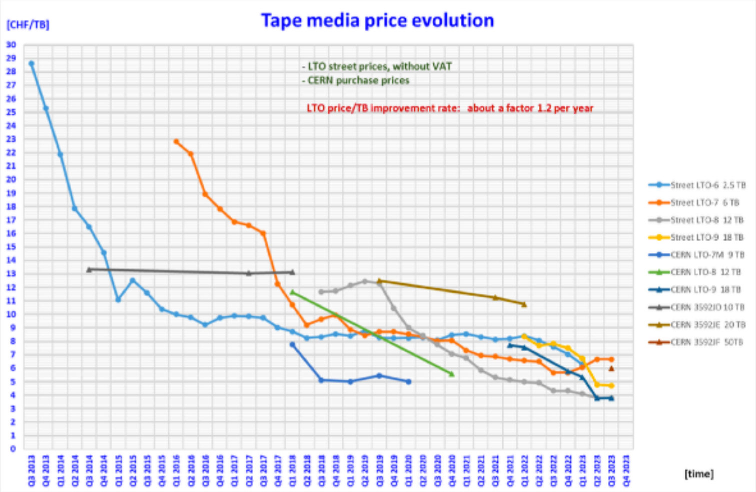
Increase of WLCG ressources within flat budget

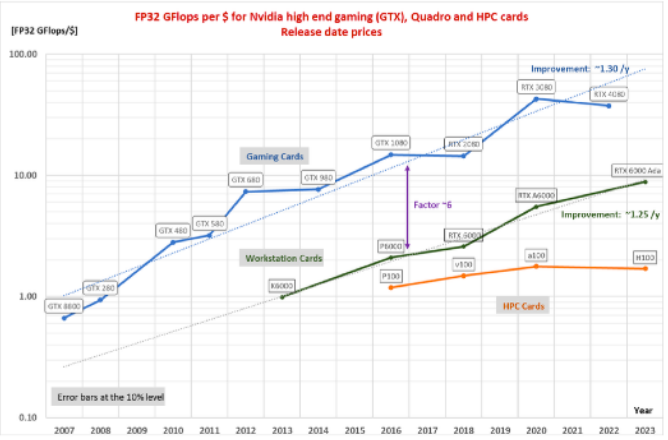
- WLCG model relies on decrease of CPU, disk and tape cost => need **~15%** increase of ressource every year for same budget to fulfil experiments needs
- Works well since beginning of LHC (one exception in 2017 with the outstanding performance of LHC)
- Observed average ressource increase in last 5 years (several countries report the evaluation) ➜ CPU: +14%/year, disk: +15%/year, tape media: +20%/year but no more true in the last years

➜ **Decision in 2025 to change the base of our computing model and go from 15 % to 10% for CPU and tape and 5% for disk**

Start to follow up GPU

- Trend in GigaFLOPS/USD is favourable for video games but flattened for HPC cards price
- Very volatile markets, long procurement times (52+ weeks of delivery time). High demand worldwide (AI/ML/ChatGPT)

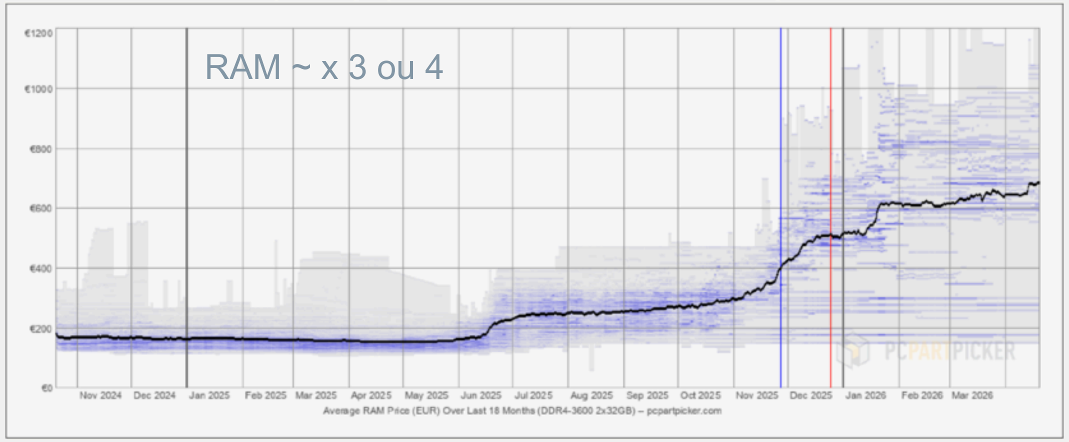




And this was before end of 2025…

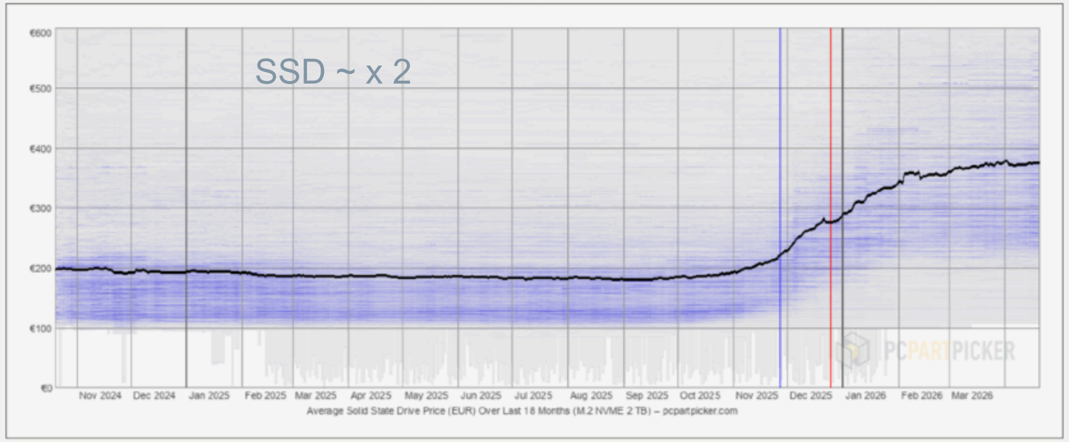
Price evolution since end of 2025

DDR4-3600 2x32GB (Average price in EUR over last 18 months)



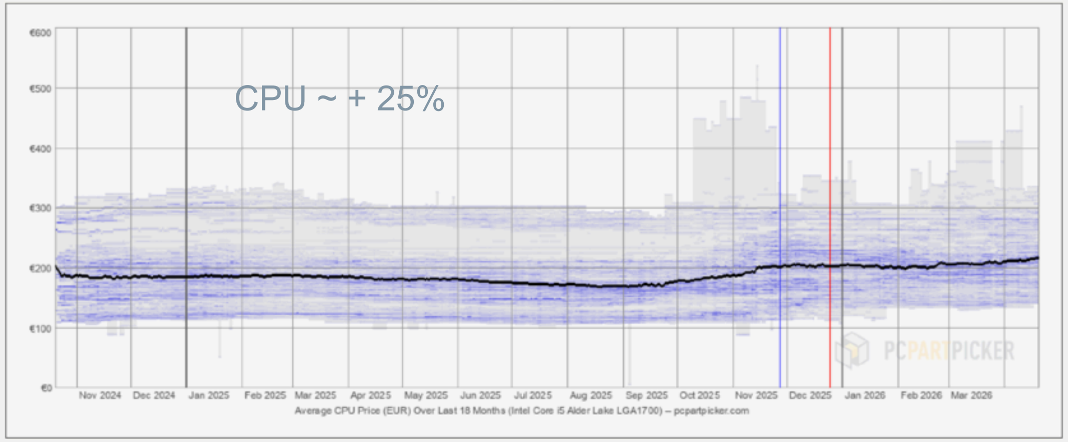
* Amazon pricing is not included in price trends graphs.

Solid State Drive - M.2 NVME 2 TB (Average price in EUR over last 18 months)



* Amazon pricing is not included in price trends graphs.

Intel Core i5 Alder Lake (LGA1700) (Average price in EUR over last 18 months)



* Amazon pricing is not included in price trends graphs.

WLCG: last RRB

2026 Ressources

- start to see tension
- was forecast beginning of autumn before price big increase

Balance [%] 2026 Computing resources: (Pledged - RRB_Aproved) / RRB_Approved

		ATLAS	CMS	ALICE	LHCb	Total
Tier0	CPU	0	0	0	0	0
	Disk	0	0	0	0	0
	Tape	0	0	0	0	0
Tier1	CPU	1	6	-13	-14	-3
	Disk	0	-6	-14	-2	-4
	Tape	0	-7	1	-8	-3
Tier2	CPU	8	-3	1	-3	2
	Disk	-1	-11	6	-16	-4

	ATLAS	CMS	ALICE	LHCb	Total
CPU	4%	0%	-4%	-8%	0%
Disk	-1%	-7%	-2%	-3%	-3%
Tape	0%	-3%	0%	-4%	-2%

Hardware evolution

Computing architecture evolution

- Moore’s Law: transistor density still doubles every two years
- Clock speed stalls since 2000 too much power used
- Dennard’s scaling: power used by silicon device is independent on the number of transistor but proportional to the transistor area

New processors

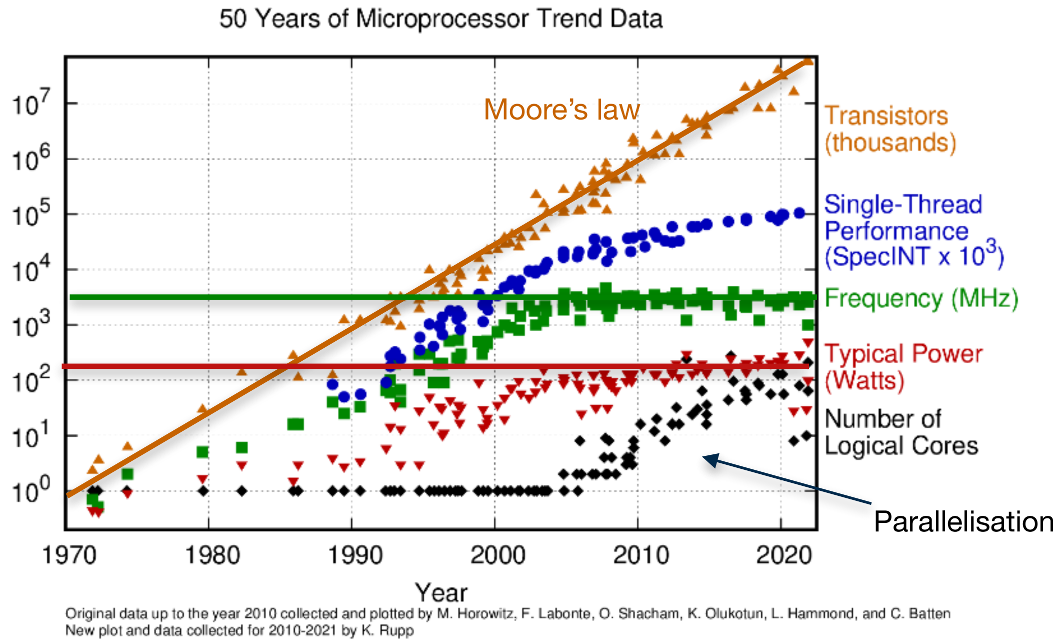
- GPU: multi-core servers with co-processors and complex memory configuration
  - in 2023 70% of Top500 machine power is from accelerators
  - power consumption controlled
  - multiple competing infrastructure and different programming langage
  - non-x86 CPU architectures share increasing (AMD, ARM)
- more energy efficient than x-86 CPU
- HPC FUGAKU is based on ARM

Consequences

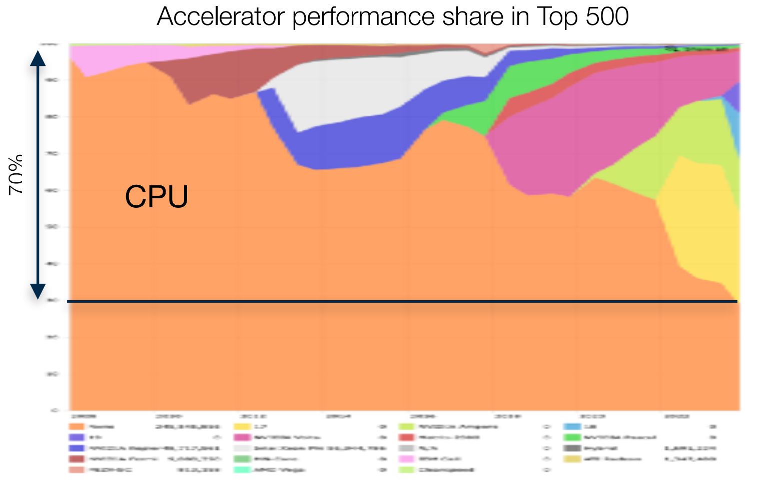
➜ **evolution towards more parallelism**

➜ **evolution towards heterogeneous system**

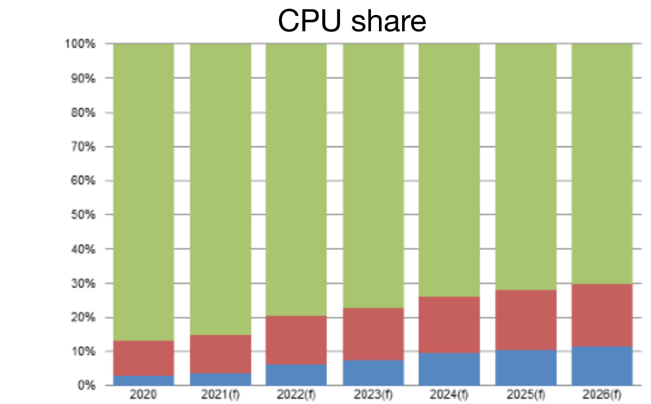
Next revolution: Quantum Computing



https://github.com/karlrupp/microprocessor-trend-data?tab=readme-ov-file



https://www.top500.org/statistics/overtime/



	2020	2021(f)	2022(f)	2023(f)	2024(f)	2025(f)	2026(f)
Intel	86.9%	85.3%	79.5%	77.4%	74.1%	72.0%	70.3%
AMD	10.1%	11.2%	14.3%	15.2%	16.3%	17.4%	18.2%
Arm and others	3.0%	3.5%	6.2%	7.4%	9.6%	10.6%	11.5%

https://www.digitimes.com/news/a20211007GS400.html&chid=2

Heterogenous resources

HPC

- Huge investments of countries in HPC machines, entering exascale area
- Challenges
  - very heterogeneous in hardware and policies
  - mostly GPU now
  - not generally suited for data-intensive processing
    - also a network issue !
  - security policies

Commercial clouds

- Clouds flexible, large ressources available
- Challenges:
  - interfaces
  - networking
  - procurement, economic model and vendor locking
- Cost effectiveness ? potentially interesting for special tasks or peak needs

Different hardware

- CPU, GPU, FPGA, ASIC
- Vendors: Intel, AMD, ARM, Power, NVIDIA
- and different programming libraries !

➜ **Need portable code**

- Portability libraries with abstraction layer to hide the backend implementation and use their parallelism efficiently

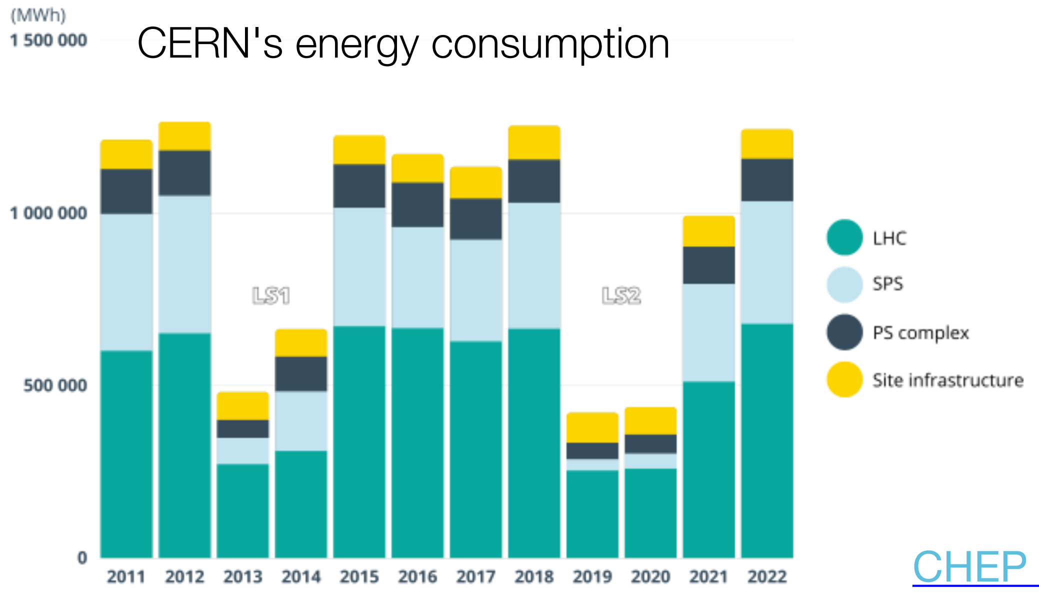
kokkos SYCL alpaka

What we would like to do better ?

Sustainability

Paris agreement goal

- Zero emission around 2100 => -50% by 2030
- To get the 50% in 2030 you have equivalently
  - to expand CO_2 free energies by a factor 12
  - to increase energy efficiency by a factor 2
  - to save energy by a factor 2



CHEP 2023

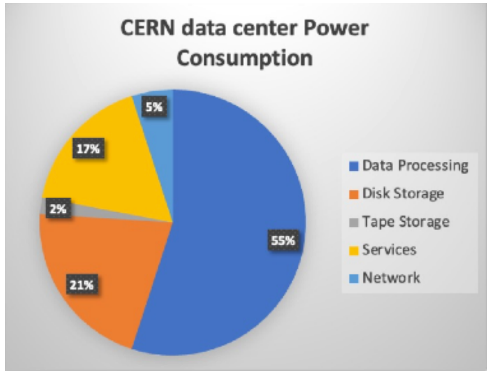
We are big consumers

- The CERN energy consumption is ~1.25TWh/year during LHC runs
- The CERN IT infrastructure contributes <5% in average
- CERN provides ~20% of the WLCG resources

Estimating the WLCG energy footprint for HL-LHC

Simone Campana CHEP 2023

Distribution of power consumption



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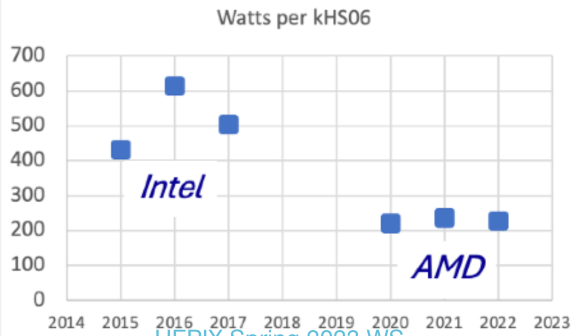
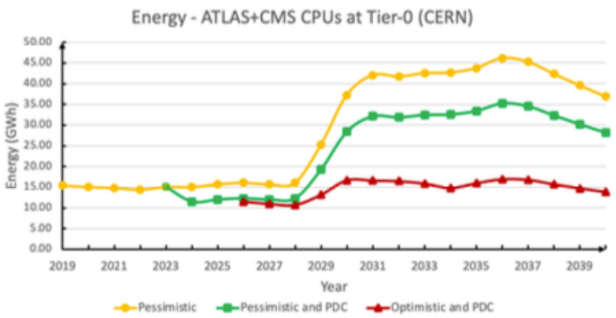
Watt/HS06



HEPIX Spring 2023 WS

\+

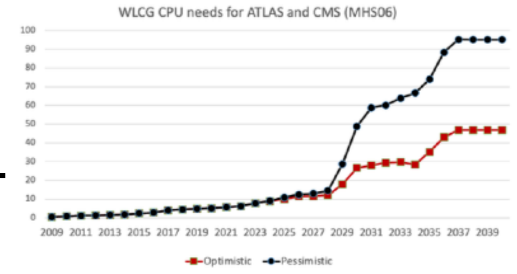
Power Usage Effectiveness (PUE) of computing centers



➜ Effect of new computing center @Prevessin

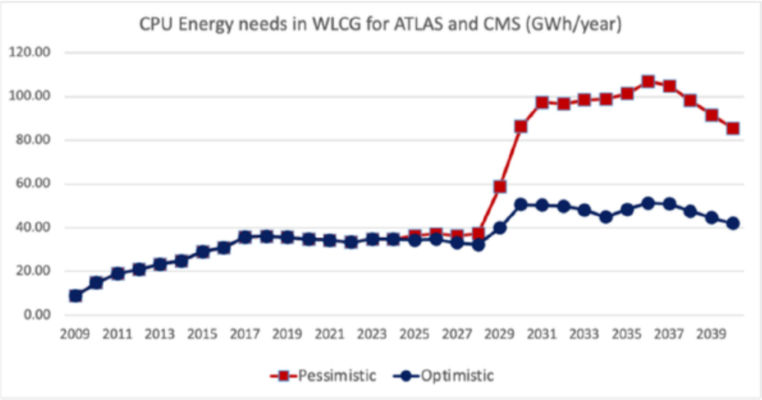
\+

CPU needs

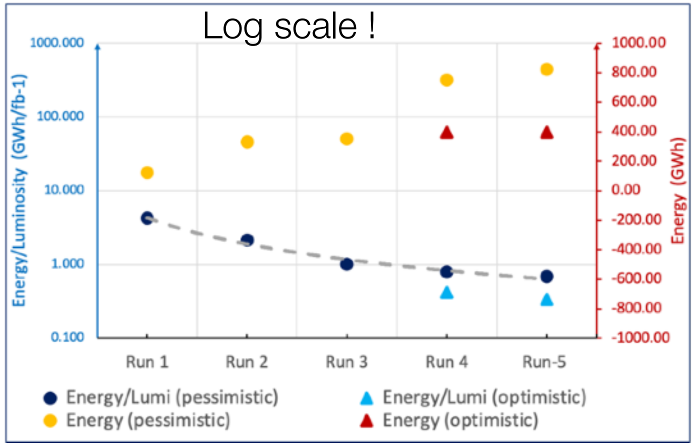


➜ Otimistic/pessimistic R&D scenarii

CPU energy needs per year



GWh and GWh/fb-1 estimation for WLCG



➜ Energy needs in Run-4 and Run-5:

- +100% compared to Run-2 in the pessimistic scenario
- +10% in the optimistic scenario

Initiatives to decrease our computing footprint

First measures

- Understand our current and future footprint and reduce everywhere as soon as we know how to do it
  - reduce use of older nodes
  - first study to reduce footprint: compare processors, decrease CPU clock speed when bad electricity footprint in country where it matters
  - when to renew servers: depends on the energy mix of you country

WLCG environmental Sustainability workshop (Cf Indico)

➜ First conclusions

- **Benchmarking:** include storage and potentially networking, which are significant contributors to energy consumption.
- **Physics per Unit of Energy Metric:** define a metric for "physics per consumed unit of energy" and its implications for the evolution of computing models
- **Facilitating the Adoption of Heterogeneous Architectures:** identify ways to support experiments in adopting new technologies, including GPUs and other heterogeneous architectures. This includes access to resources for development, profiling, and validation

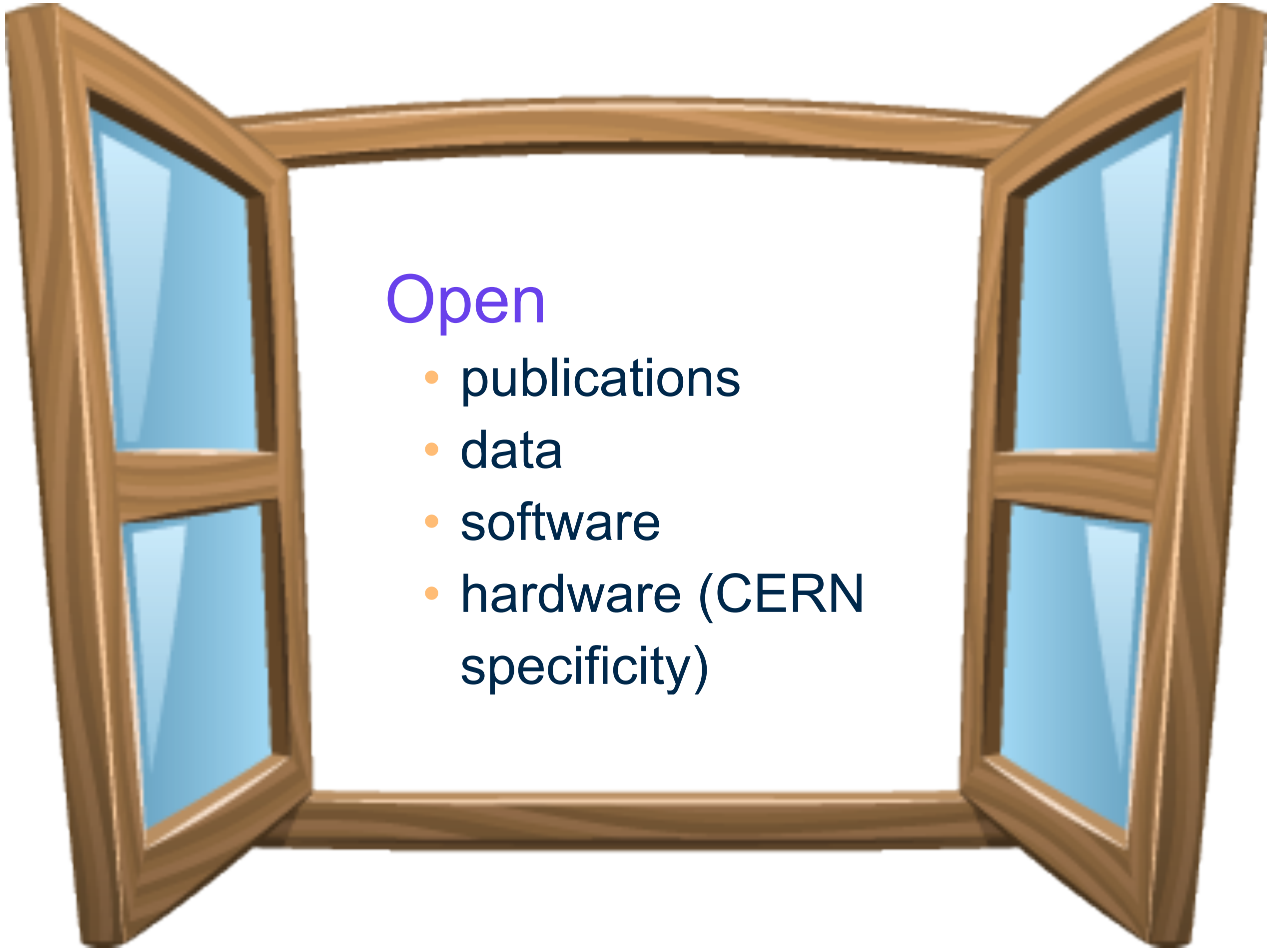
Next: sustainability conference for responsible research computing in May

- https://indico.cern.ch/event/1526482/

Open science

Objectives

- Public research => knowledge has to be shared back
- Data and analysis preservation
- Quality and reproducibility
- Allow reuse or new usage => new science
- valorisation



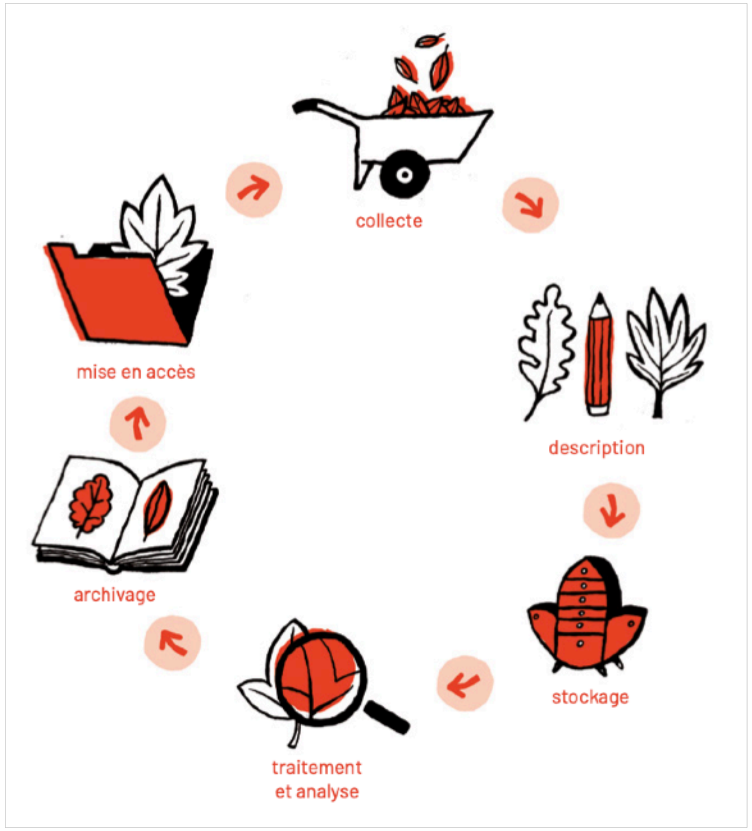
Open

- publications
- data
- software
- hardware (CERN specificity)

FAIR Data is also good practice

Open and FAIR data

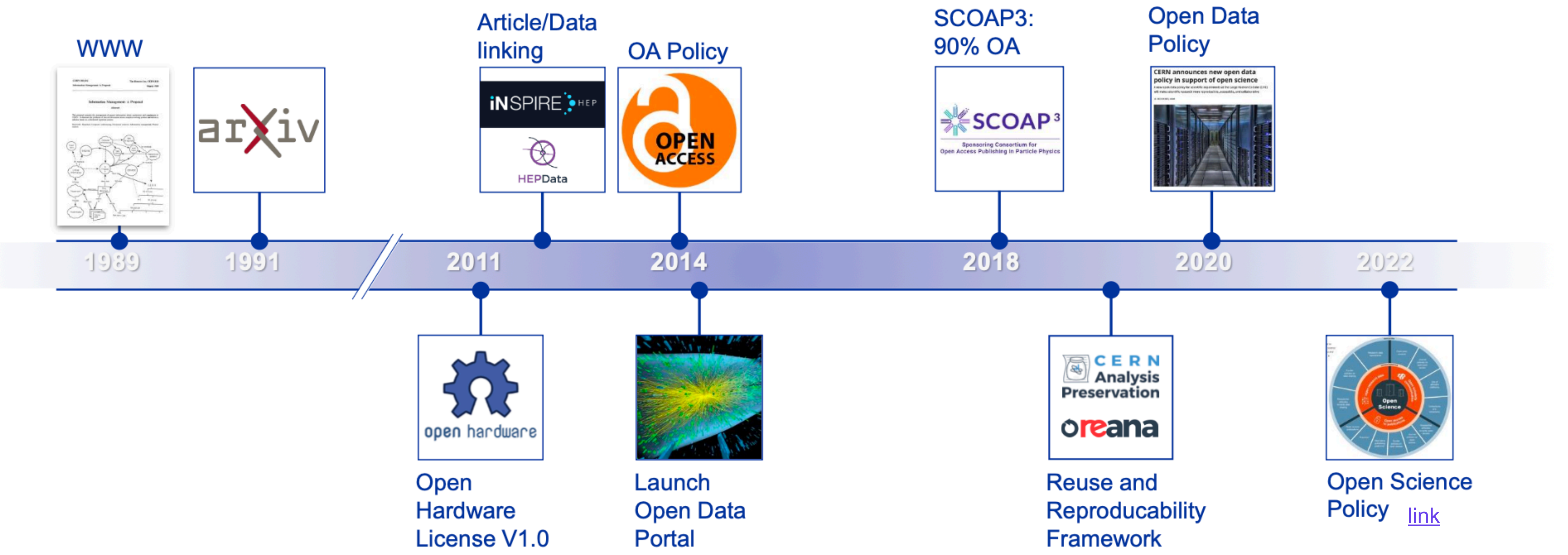
- FAIR = findable, accessible, interoperable, reusable
- does not just mean opening up data to the outside world
- but also good practices for data management throughout the entire cycle:
  - ➜ collecting high-quality data ➜ describing it with rich metadata
  - ➜ identifying it (not just with a DOI) and referencing it ➜ storing it in reliable storage facilities
  - ➜ process and analyse it ➜ delete, clean or archive it ➜ open it... or not
- software is part of the process and is also a type of data that follows the same rules: it must be referenced, versioned, stored and opened (if the conditions are met) + licence
  - the data and the corresponding software must be associated



Consequences

➜ Well-referenced data and software with well-defined metadata facilitate high-quality processing and analysis and enable checks, reproducibility, sharing and reuse to avoid duplication.

Open Science in HEP: a long story



S. Dallmeier-Tiessen | CERN OS Policy

Publications

SCOAP³ agreement

- https://scoap3.org/
- Partnership between 3,000 libraries, research organisations in 44 countries and 3 intergovernmental organisations (CERN, IAEA, JINR)
- Agreement with leading particle physics publishers for open publication at no cost to authors
- 7 editors, 11 journals
- Copyright belongs to authors and CC-BY licence
- Covers approximately 87% of scientific output

➜ 6,500 articles/year
➜ New => books: https://scoap3.org/scoap3-books/

INSPIRE-HEP

- INSPIRE (http://inspirehep.net/) : trusted community hub that helps researchers to share and find accurate scholarly information in high energy physics.
- Information platform for HEP community, comprising 8 interlinked databases on literature, conferences, institutions, journals, researchers, experiments, jobs and data.
- CERN, Fermilab, IHEP, IN2P3, TIB collaboration
- SLAC and DESY were pioneers and had important contributions but quit !
  - DESY partially replaced by TIB
  - Looking for new partners: INFN, UK…
- Serves the scientific community for almost 50 years
  - previously known as SPIRES
  - first website outside Europe and the first database on the web.
- Close interaction with the user community and with arXiv, ADS, HEPData, ORCID, PDG and publishers is the backbone of INSPIRE's evolution.

Publications

SCOAP3

iNSPIRE HEP

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➜ what publication model would you like ?

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- INSPIRE (http://inspirehep... ...ers to share and find...

New !
- beta release of the INSPIRE data collection
- extend content to quantum physics

...interlinked databases on ..., researchers, experiments, jobs and

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- beta release of the INSPIRE data collection
- extend content to quantum physics

…interlinked database… …researchers, exp…

- C…, Fermilab, IHEP, I…
- SLAC and D…

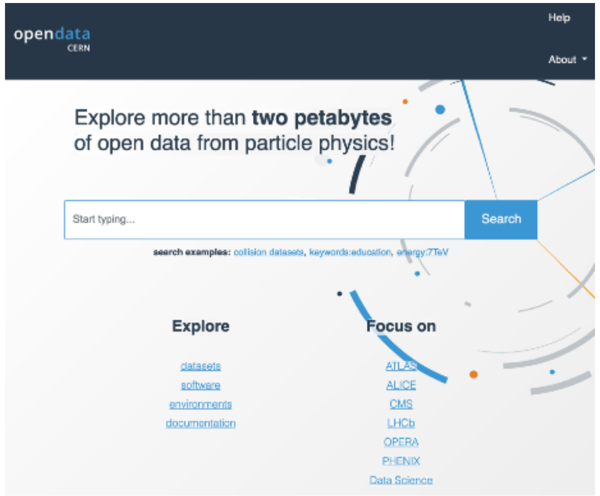
Raised concern after SLAC and DESY withdrawal
➜ ESPPU recommendation:
"A cornerstone of the particle-physics information infrastructure is the INSPIRE database, which provides comprehensive, HEP-focused information for each publication and integrates platforms such as PDG, arXiv, HEPData, and ORCID. As several regular funding sources have been reduced or discontinued, ensuring INSPIRE's long-term sustainability requires renewed international commitment and adequate funding from the European particle-physics community and beyond."

- Ser…
  - pre…
  - first…
- Close i… …unity and with arXiv, ADS, HEPData, ORCID, PDG an… …backbone of INSPIRE's evolution.

Open data in HEP

CERN Opendata portal

- https://opendata.cern.ch/
- different goals: education, research

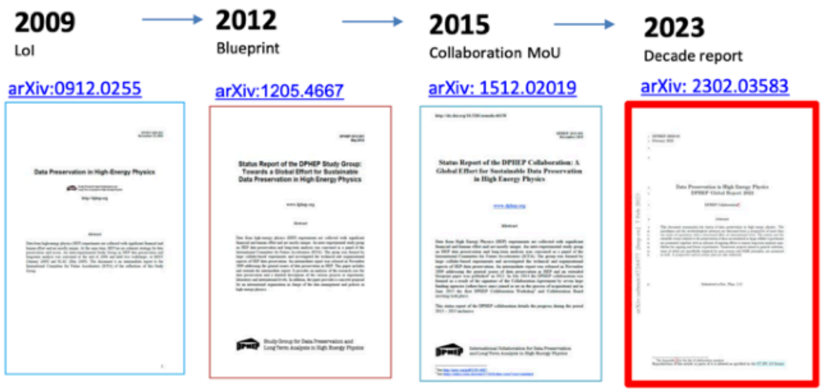


Analysis: HEPData and Rivet toolkit

- https://www.hepdata.net/
- Repository for publication-related High-Energy Physics data
- recommendations for analysis
- Rivet toolkit: https://rivet.hepforge.org/

DPHEP Collaboration

- data preservation => http://dphep.org
- last collaboration workshop in March 2026: [indico]()
  - LEP experiment and data (re)analyses
  - LHC Opendata
  - data preservation organisation
  - data preservation in experiments and technical solutions
  - new tools



Open data in HEP

➜ Main news

- Recommendations for Best Practices for Data Preservation and Open Science in HEP
  - https://arxiv.org/abs/2508.18892v1

- LHC Opendata
  - Run 1 released
  - ~ 25% run2 released
  - ATLAS released 2.7B events of event generation

- HepData
  - all ATLAS exotic analyses

Recommendations for Best Practices for Data Preservation and Open Science in HEP

Simone Campana[1], Irakli Chakaberia[2], Gang Chen[3]
Cristinel Diaconu[4,5], Caterina Doglioni[6], Dillon S. Fitzgerald[7]
Vincent Garonne[8], Anne Gentil-Beccot[1], Fleur Heiniger[1]
Michael D. Hildreth[9], Julie M. Hogan[10], Hao Hu[3]
Eric Lancon[8], Clemens Lange[11], Kati Lassila-Perini[12*]
Olivia Mandica-Hart[1], Zach Marshall[2], Thomas McCauley[9]
Harvey Newman[13], Mihoko Nojiri[14], Ianna Osborne[15]
Fazhi Qi[3], Salomé Rohr[1], Stefan Roiser[1]
Thomas Schörner[16], Ulrich Schwickerath[1], Elizabeth Sexton-Kennedy[17]
Seema Sharma[18], Tibor Šimko[1], Michael Sparks[6]
Graeme Andrew Stewart[16], Nicola Tarocco[1], Giacomo Tenaglia[1]
Gustavo Valdiviesso[19], Antonia Winkler[20,1], Christoph Wissing[16]

508.18892v1 [hep-ex] 26 Aug 2025

Scenario A - Minimum Requirements for Analysis Preservation
Scenario B - Approximate Re-interpretability
Scenario C - Maximum Re-interpretability

Minimum for a search to be re-useable

Not necessarily enough for strict combinations... but good enough for many analyses (especially searches)

Best case - aims to provide maximal information for reinterpretations. Should be gold standard for precision measurements

Software

Software needs also good practice

- quality
- documentation
- deployments
- forge
- licence
- archiving => Software heritage

Open Source/free software

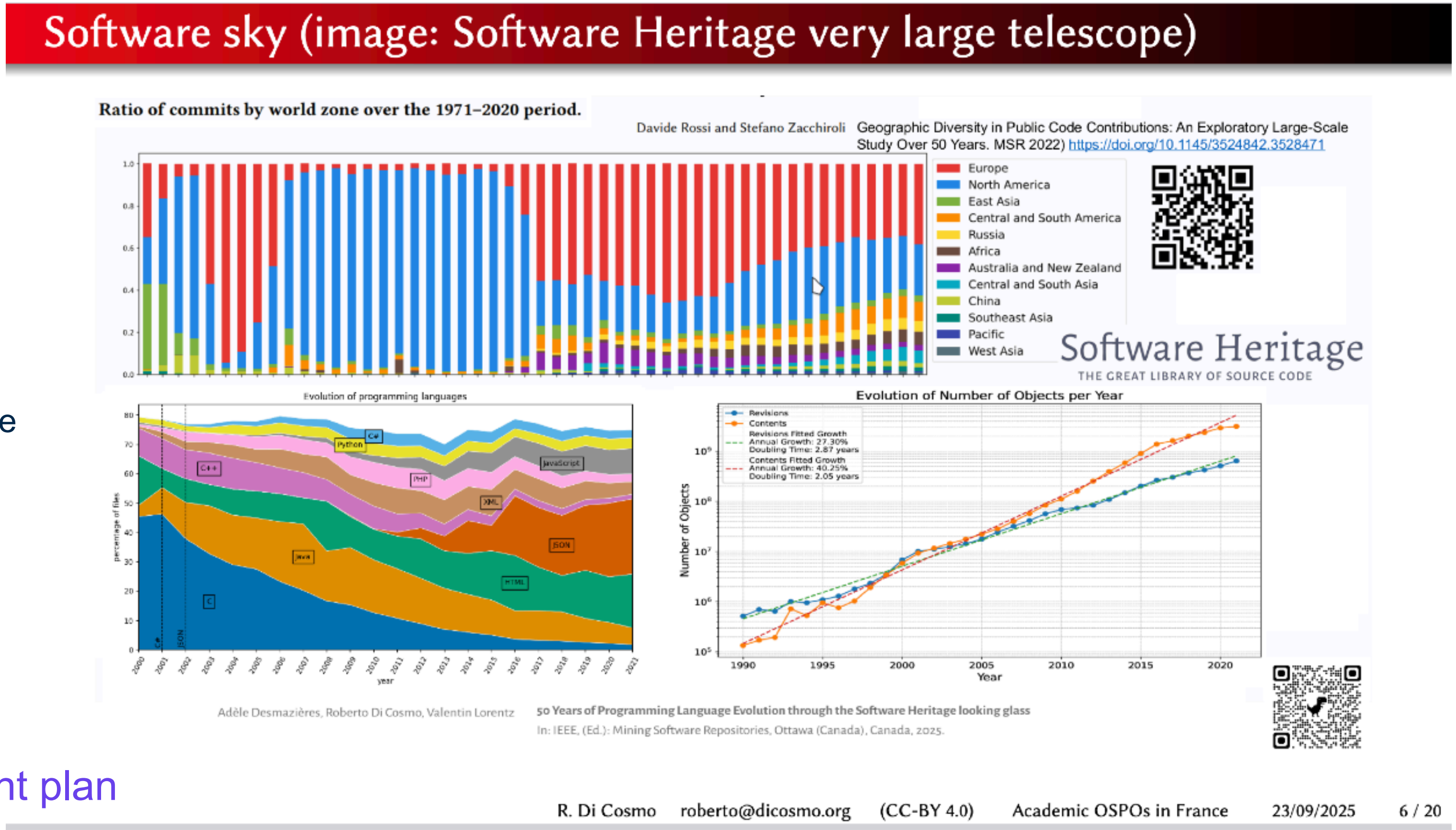
Software Heritage

- open software archives
- allows also to study software evolution: 75% of software without licence

Structure for help

- Open Source Program Offices (OSPOs)
  - CERN https://opensource.web.cern.ch/
  - start to be deployed ex GRICAD Grenoble https://ospo-uga.sciencesconf.org/

Work on developments of software management plan



Ongoing efforts

Preparation of HL-LHC

LHC experiments

- ALICE and LHCb have updated their computing model for run 3

➜ planning now for a Run5 upgrade, not yet approved

- ATLAS and CMS are preparing the computing infrastructure for HL-LHC
  - data challenges => DC24: target 25% of HL-LHC needs including the 4 LHC experiments + Belle2 + DUNE
    - New monitoring + Token AAI tested

➜ 2026 the year for writing

- CMS's Computing Conceptual Design Report (Computing CDR)
- ATLAS's Computing technical Design Report (Computing TDR)

➜ to be reviewed by LHCC

WLCG

- 2026 also the year of WLCG Technical Roadmap

➜ Technical Coordination Board

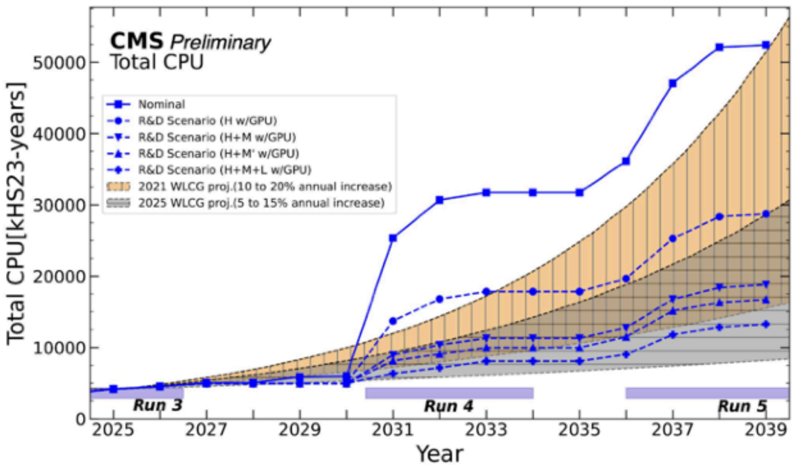
- to manage the Technical Roadmap process (group appointed by the WLCG MB, includes experiments, sites and tool stakeholders)

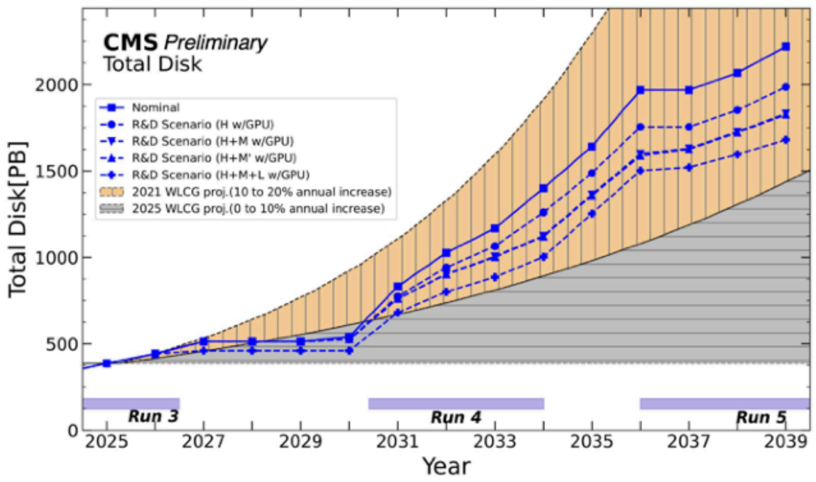
➜ Open Technical Forum

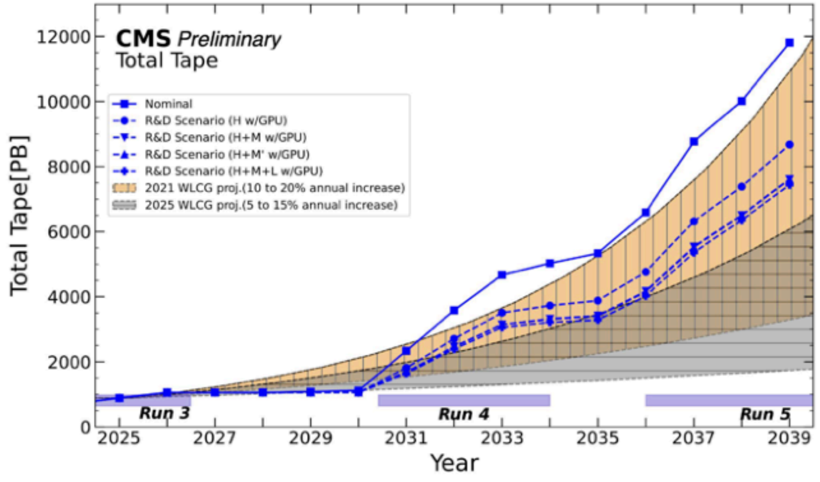
- open discussion forum to discuss technical aspects of the WLCG computing

CMS preview

CMS Resource Projection Study for HL-LHC: January 2026







https://cds.cern.ch/record/2953830/files/DP2026_004.pdf

➜ even in optimistic R&D scenarios, it does not fit for data

➜ include part of the workflow offloaded to GPU

- with H (high), M (medium), L (low) success probability
- Infrastructure readiness for GPU processing ?

HPC

HPC

- huge amount of computing resources
- in HEP use for LatticeQCD, AI…
- more opportunistic use for experiments

Difficult to use for experimental HEP

- Much stricter access policies
- nothing standard from one center to the other
- Limited connectivity no or feeble data management
- mostly GPUs

An opportunity ?

- depends on national policy
- A way to reduce (overall national) computing costs
- A way to give additional computing to HEP ?
- useful for AI
- threat our our CPU ressources ?

Strategy (see JENAA, ESPPU)

- Follow and influence if possible standardization efforts in HPCs (**EuroHPC EFP** and **DOE IRI**)
- HEP is not identified as a community by HPCs today
  - ➜ need to change this
- initiatives in this direction:
  - JENAA/HPC, white paper
  - SPECTRUM EU project with SKA
  - a proposal of Center Of Excellence coordinated by as answer to EuroHPC call

JENAA
Joint ECFA-NuPECC-APPEC Activities

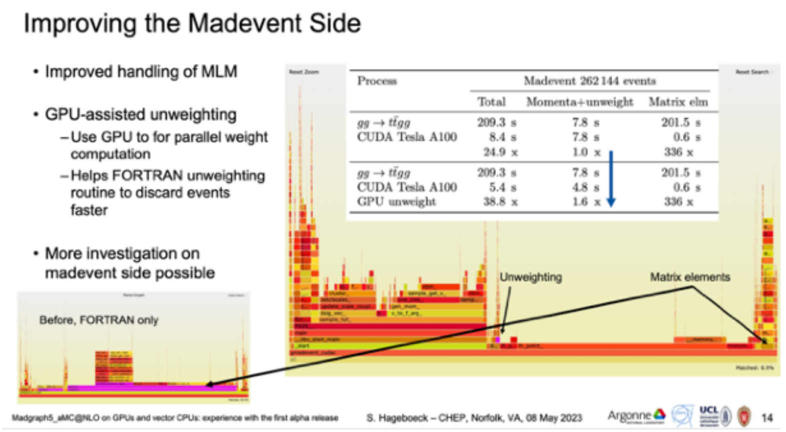
SPECTRUM

Software

Generation

➜ will represent 10-20% of HL-LHC Computing

- accounting and profiling to understand CPU costs, move to GPUs and vectorised code
- Sherpa, Madgraph5



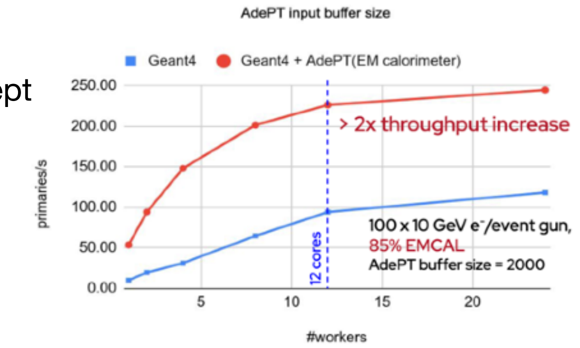
Process	Madevent 262 144 events		
	Total	Momenta+unweight	Matrix elm
$gg \to t\bar{t}gg$	209.3 s	7.8 s	201.5 s
CUDA Tesla A100	8.4 s	7.8 s	0.6 s
	24.9 x	1.0 x	336 x
$gg \to t\bar{t}gg$	209.3 s	7.8 s	201.5 s
CUDA Tesla A100	5.4 s	4.8 s	0.6 s
GPU unweight	38.8 x	1.6 x	336 x

[MadGraph CHEP 2023]

Simulation

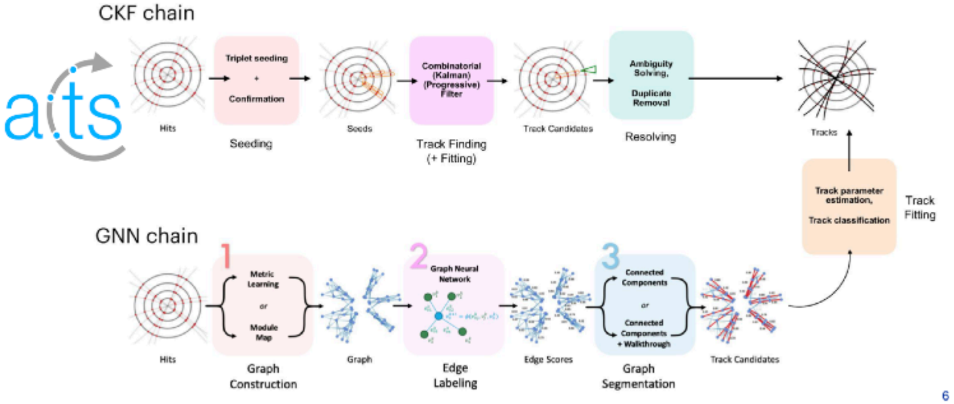
- use ML to accelerate fast simulation
- Full simulation: port EM shower simulation on GPU
  - [AdePT] (Accelerated demonstrator of electromagnetic Particle Transport), [Celeritas]

Adept



Reconstruction

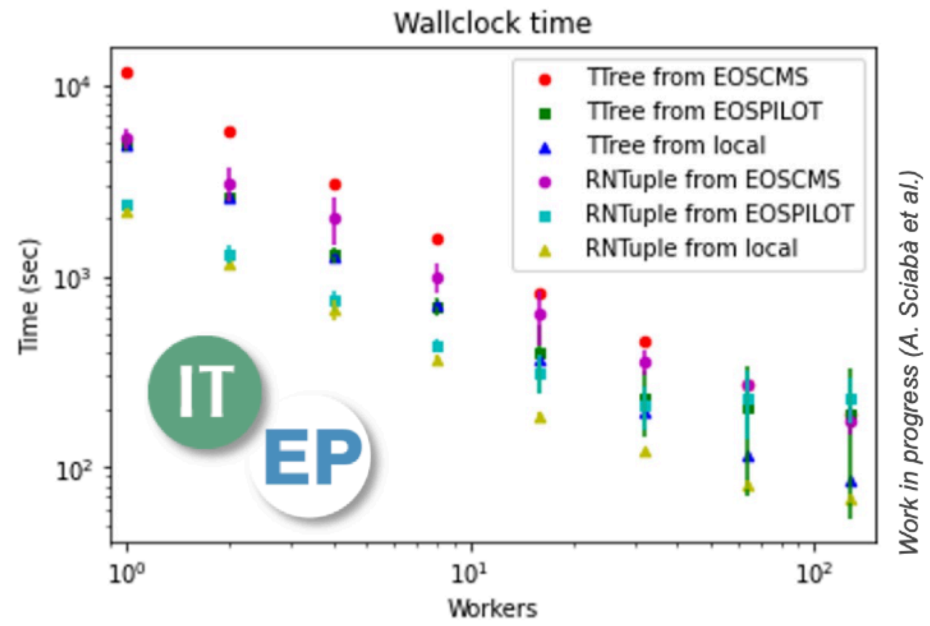
- R&D on track reconstruction with high pile-up
- ACTS project
  - R&D on method and algorithm, 2 main chains developed: Kalman Filter or Graph Neural Net (GNN)
  - R&D on parallelisation and performance portability



Analysis

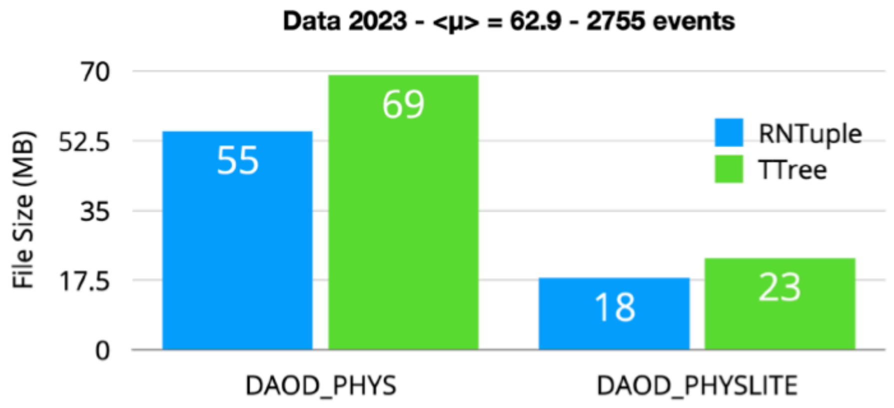
Tools

- new tools commonly used: Python, Jupyter notebooks/ browser frontends; data science tools
- Root update: new ROOT data format from TTree to RNTuple
  - 10-20% smaller files, x3 to x5 better single core performance
  - enables fast adaptation to modern technologies, like object stores



Data

- Developments of more compact formats and reducing data copies and intermediate formats
  ➜ NanoAOD and ATLAS PHYSLITE, target ~10kB/event for fast and lightweight analysis



Analysis facility

Analysis Facilities

- infrastructures tailored to provide an analysis ecosystem - tools and services
- Possibly also centers for large scale AI training
- Analysis Facilities White Paper: arXiv:2404.02100

Several initiatives

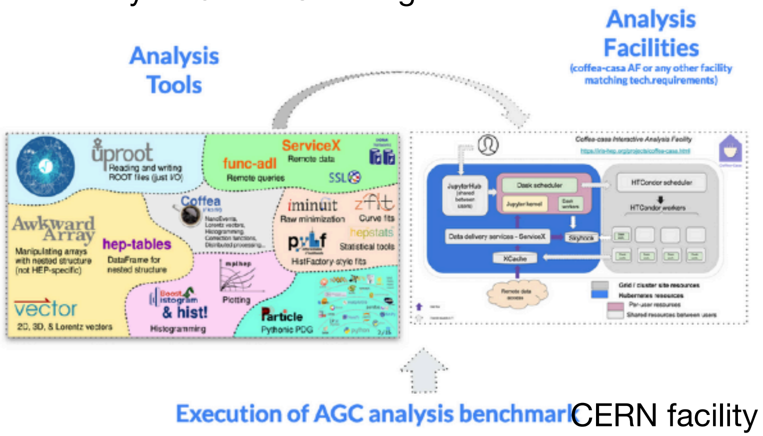
- IRIS-HEP Analysis Grand Challenge Link
- Analysis Facility prototype at CERN Link

Virtual Research Environment Link

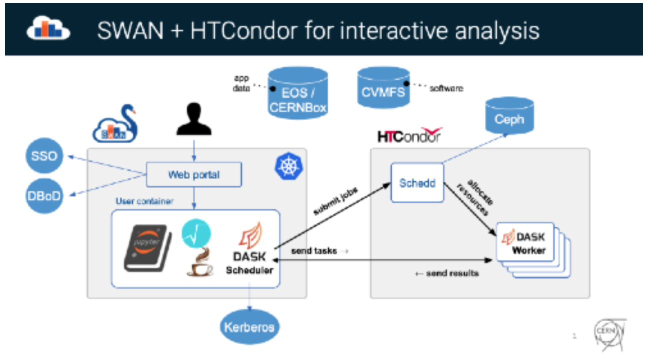
- development in EU-founded project in the line of EOSC building: ESCAPE
- open source platform with access to all the digital content needed to develop, share and reproduce an end-to-end scientific result in compliance with FAIR (findable, accessible, interoperable, reproducible) principles
- All the building blocks from storage to computing with AAI and notebook to analysis preservation

➜ Reana: reproductible research analysis platform Link
  - developed at CERN
  - allow to preserve, distribute and reproduce
  - flexible scalable and reusable => container

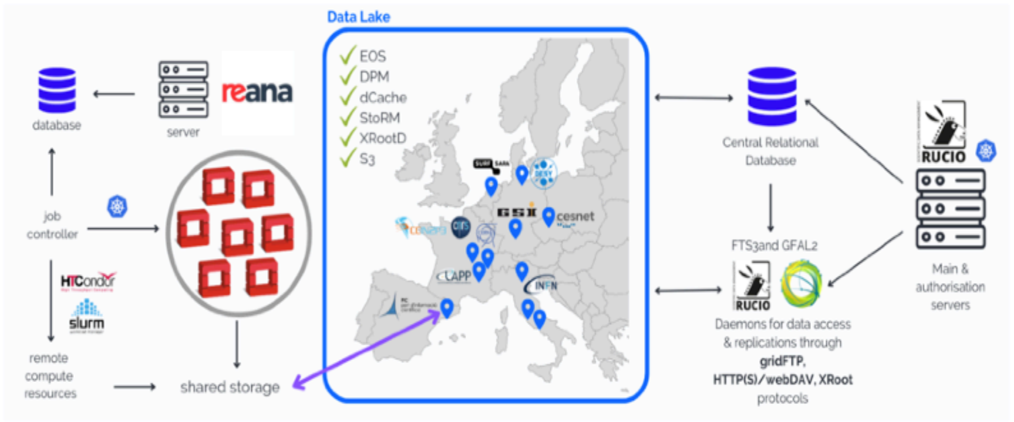
IRIS-HEP Analysis Grand Challenge



CERN facility software component



ESCAPE VRE



Artificial Intelligence

AI usage

- ESPPU: experiments explicitly mention AI as a cornerstone towards better and cheaper physics

AI needs

- Data
- Access to specific computing resources
- Access to experts, training
- Funding

Coordination

- in experiments
- R&D ?
- EUCAIF ?

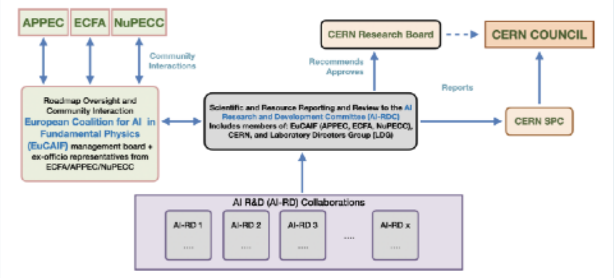
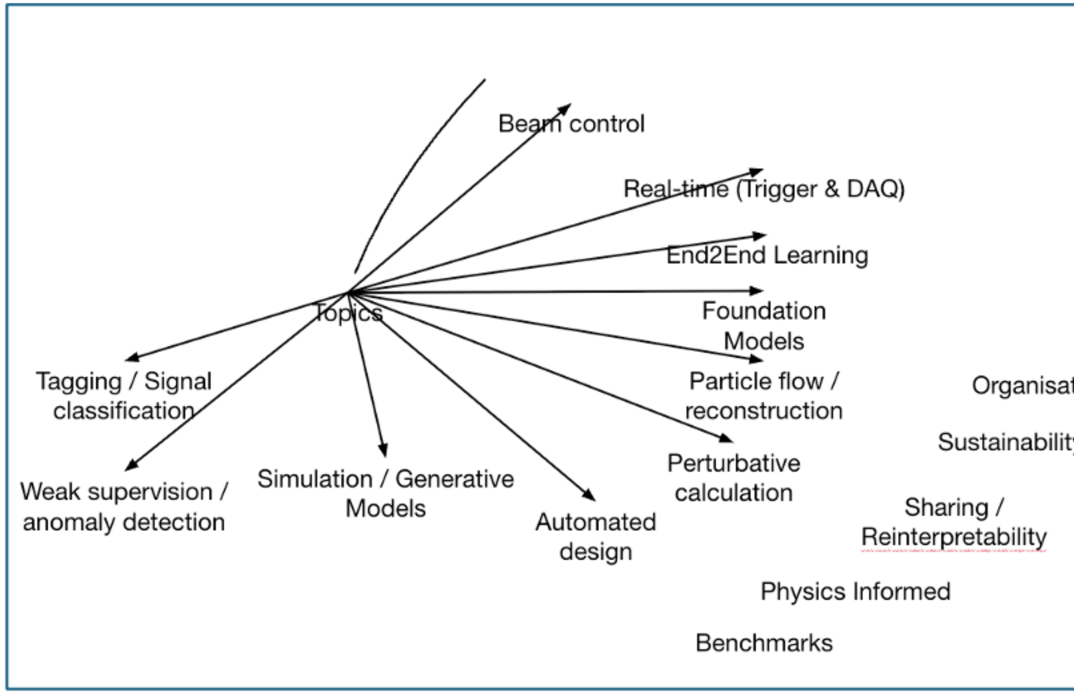


Figure 1. Structure of the proposed AI Research and Development collaborations (AI-RDs), the AI Research and Development Committee (AI-RDC), and integration with the European Coalition for AI in Fundamental Physics (EuCAIF), CERN, the European Committee for Future Accelerators (ECFA), the Nuclear Physics European Collaboration Committee (NuPECC), and the Astroparticle Physics European Consortium (APPEC).



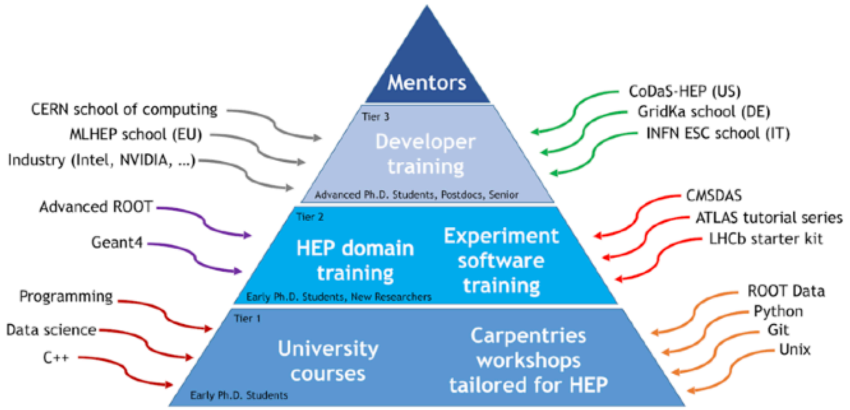
AI evolutions and tools

- very very fast developments
- needs huge investments
  - HR and time
  - infrastructure

Skilled and motivated people

Recognition

- Computing and software activities are fundamental in our research activities
  - they have huge impact on our physics results
  - their cost is similar than the one of the experiment
  - they are part of our experiments and are no more a « service »
- We need skilled and motivated people
  - Their work should be shared and publicised
  - Not only in dedicated meeting and conference !
  - Their expertise should be recognise also when physicists

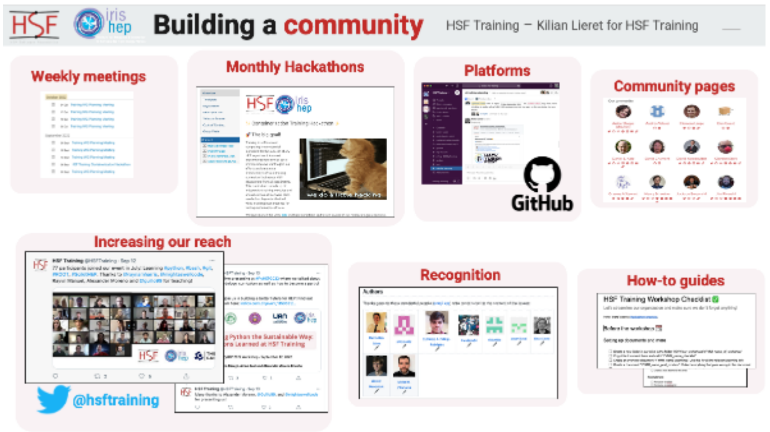


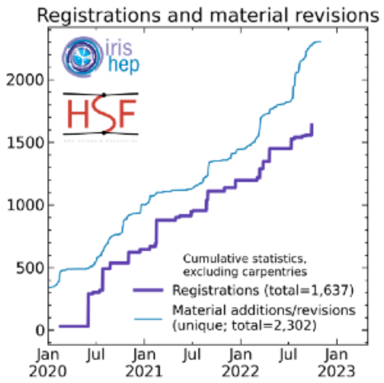
[M. Ballroom CHEP 2023]()

Training

- Students often lack of software and computing skills
- Computing and software are evolving quickly => continuous learning is needed

  ➜ tutorials, training are important and there are lot's of opportunities:
  - tutorials, school and training locally, by their institution, in collaborations, organised by the HEP Software Foundation (HSF)…
  - HSF as a forum to build the community and share knowledge
  - [Software Training in HEP]()





Conclusion

Conclusion

➜ Software and Computing are key elements of our experiments

Starting with a success

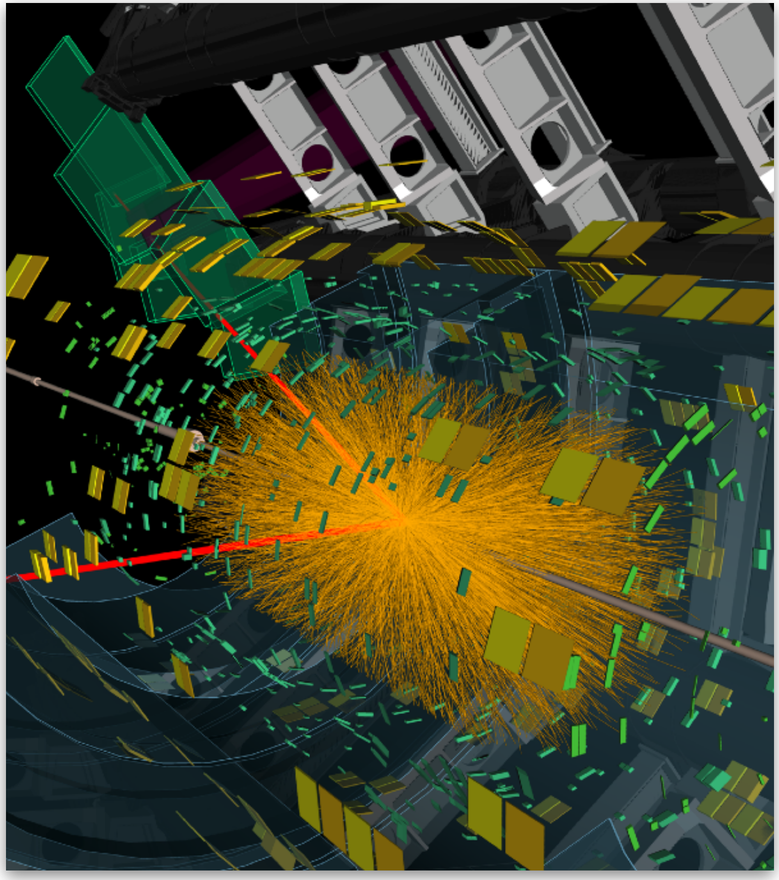
- Computing for LHC run1 and 2 with a complete and complex set of software, middleware and WLCG infrastructure at the Exa-scale successfully allows to store, process and analyse LHC data, leading to wonderful scientific results

Take up the HL-LHC software and computing challenge

- Infrastructure and software will have to cope for high luminosity (200 x run 2) + pile-up up to 200 + throughput ~10TB/s
- In a context that is rapidly evolving: hardware, technologies, cost ➜ constraints and opportunities
- Taking into account Open Science and effort to reduce our environmental footprint

Huge amount of work and R&D already done and still a lot ahead

- New developments integrated in production as soon as validated
- Software, hardware and computing models need to be adapted for heterogenous ressources, more parallelisation => flexibility needed to adapt to ressources not build for and by us
- Make best use of new technologies and technics: AI, progress done outside our field
- Be careful on consequences on the infrastructure, adapt it => cost ??
- Be prepared to the next (r)evolution like Quantum Computing
- Training is very important as proper recognition for the work done in the computing and software fields

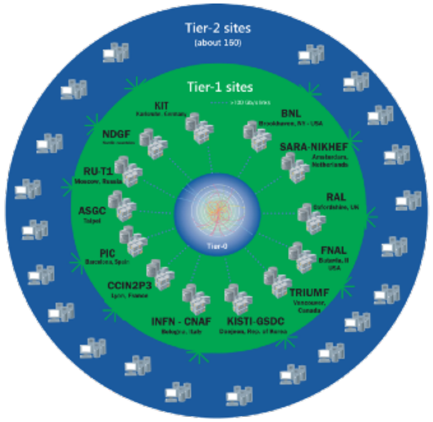


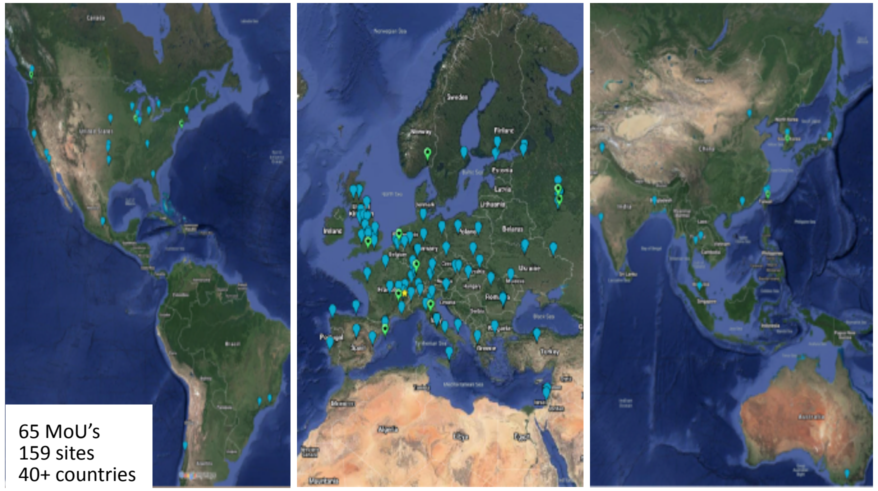
Thank you for your attention !

Questions ??

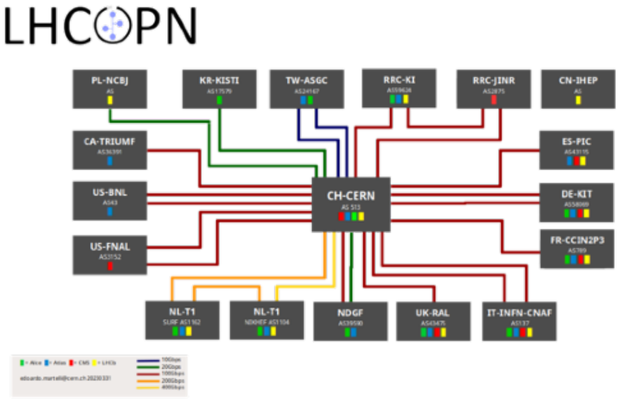
Bonus

WLCG





2 dedicated networks

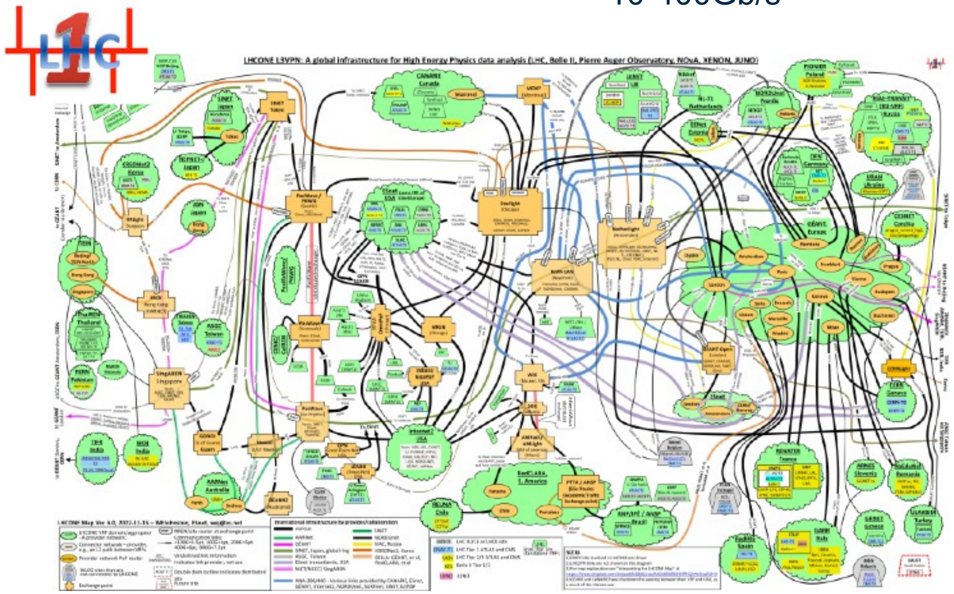


LHCOPN

- Tier 1 and Tier 0
- 13 countries, 3 continents
- 2.1 Tb/s to Tier 0

LHCONE

- 31 network providers
- 117 interconnected sites
- 5 continents
- 10-400Gb/s

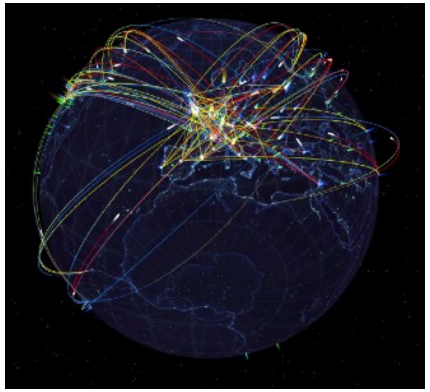


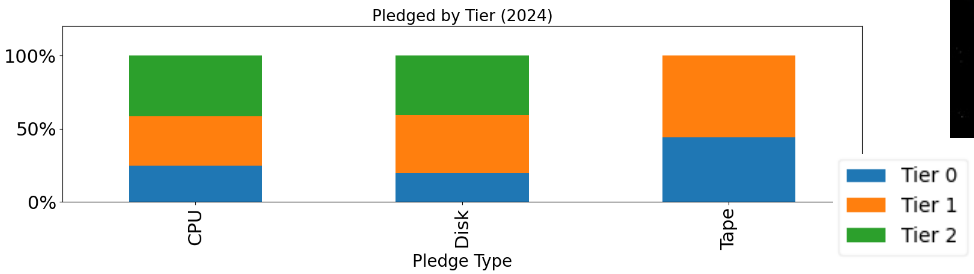
WLCG today

- 159 sites in 40 countries
  - Tier 0 at CERN, 14 Tier 1, Tier 2, Tier 3

➜ much less hierarchical than at the beginning,

➜ much more dynamic and automatised





CMS Resource Projection scenario

What are the GPU offloading scenarios for each task?

R&D scenario	H (only)	H+M	H+M'	H+M+L
Generation	Fraction of LO MadGraph	Fraction of LO and NLO MadGraph	Fraction of LO and NLO MadGraph	Approx. 90% of MadGraph
Simulation	None	Combination of GPU-enabled Full-Sim + ML-FullSim replacing Full-Sim for the HGCal	Approx. 50% ML-based FastSim replacing full sim for the HGCal	Combination of GPU-enabled Full-Sim + FlashSim
Reconstruction	Fraction of Tracking, vertexing & HGcal clustering	H + electron reco + ML based HGCal reco + ML PF	H + electron reco + ML based HGCal reco + ML PF	H + M + other ML-based developments + fraction of muon + MTD reco

High success probability : assigned to developments already integrated (at least partially) in CMSSW

Charis K. Koraka Heterogeneous architectures in WLCG - *Progress from Experiments:* Report from CMS - December 3rd 2025 14

https://indico.cern.ch/event/1526077/contributions/6773804/attachments/3185228/5667427/GPU@CMS_WLCG_ckk_Dec2025.pdf

FCC-ee computing needs

FCC estimation

➜ see ESPPU G Ganis talk

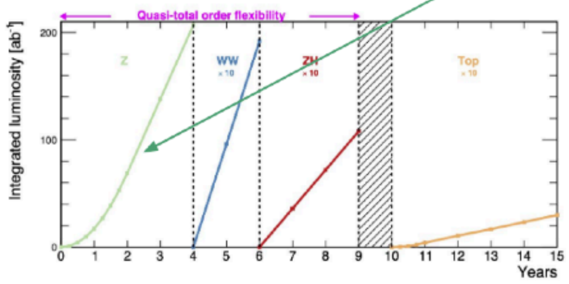
Hypothesis

- Sub-detector design : far from being frozen
  - ➜ use reference detector for scaling: CLD, FCC version of the CLIC detector
  - ➜ Event sizes (leptonic-hadronic): parametrized 1.2-18 kB, full sim 0.16-2.3 MB
- Algorithm design
- Workflows
- Computing technology
  - ➜ Processing time (leptonic-hadronic): parametrized 0.5-30 ms, full sim 1.6-23 s
- Statistics needs
  - ➜ Baseline assumption: MC ≈ expected data sample

FCC Z run estimation

Illustrative Storage Projection for Z Run

4 experiments, 4 equal years at Z

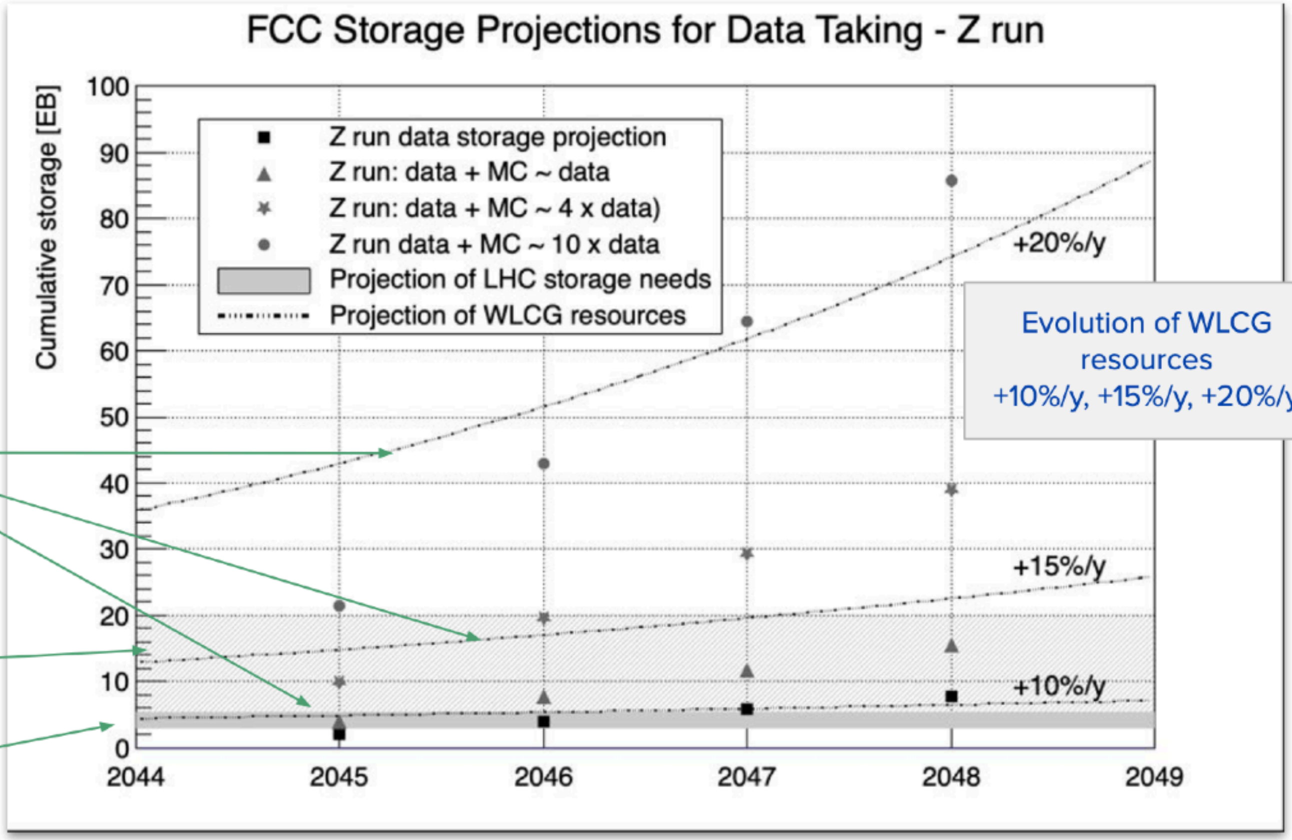


Evolution of WLCG disk resources
+10%/y, +15%/y, +20%/y

(starting point: 500 PB in 2020
≍ ATLAS+CMS + 10%)

LHC **tape** at the end of HL (≍ 5 EB)

LHC **disk** at the end of HL (≍ 5 EB)



Evolution of WLCG resources
+10%/y, +15%/y, +20%/y

ESPPU G Ganis talk

FCC Storage projection

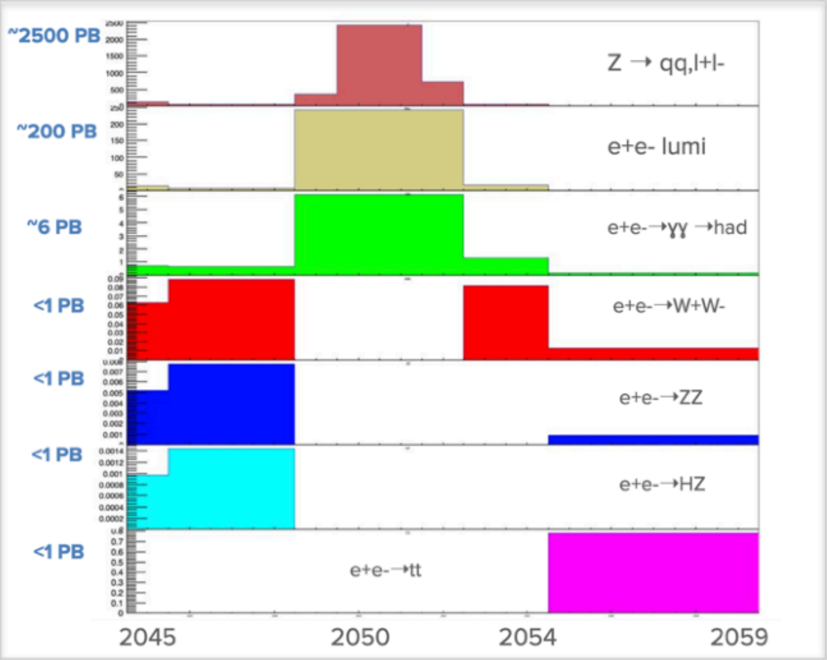
4 equally demanding experiments

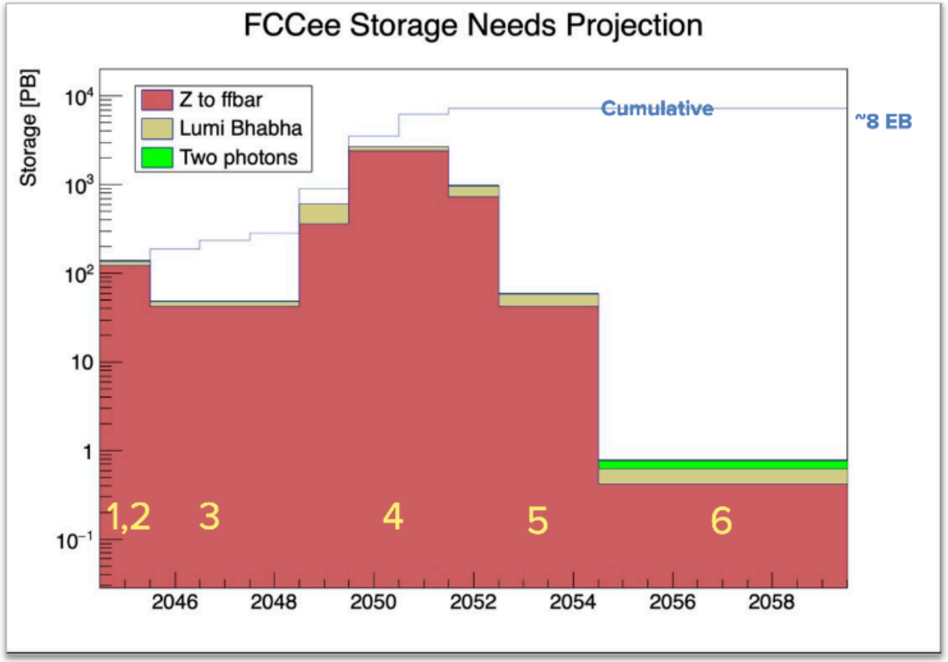
More realistic sequence (15 y operations)

1. 1-2 m 0.25 * nom_lumi run at Z
2. 1-2 m 0.25 * nom_lumi run at WW
3. 3.5 y HZ run
4. 4 y Z run (peak and off-peak)
5. 2 y WW run
6. 5 y ttbar run

1 day Z calibration runs every month during WW, HZ, ttbar runs

Based on P Janot et al (and P Janot private communication)





➜ Ultimate FCCee computational needs are o(HL-LHC)

ESPPU G Ganis talk

Initiatives and ongoing work

A collaborative effort beyond HL-LHC

Enlarge collaborations

- Common developments allow to share expertise, to share effort and find common solution when possible
  ➜ ease deployments and allow shared ressources and infrastructure

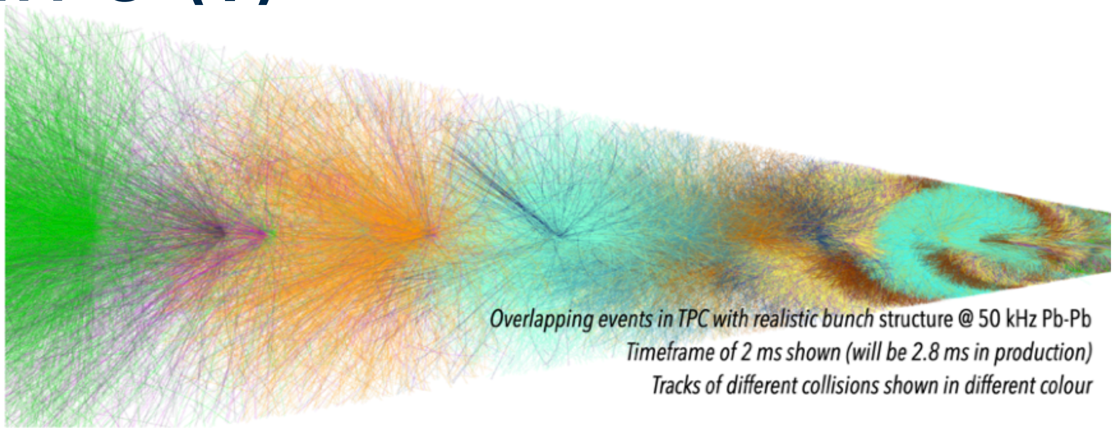
- Eased by international collaborations and programs
  - HEP Software Foundation (HSF), IRIS-HEP for software developments
  - WLCG/DOMA for WLCG infrastructure expands beyond LHC with DUNE, Belle-2, JUNO and VIRGO as WLCG observers
  - European programs for the development of the European Open Science Cloud (EOSC) => ESCAPE project for HEP, astronomy and nuclear physics, EVERSE project for software, Spectrum for HPC
  - JENA computing workshop to discuss synergies across the 3 communities

Heterogenous computing

GPU usage already in run 3 (I)

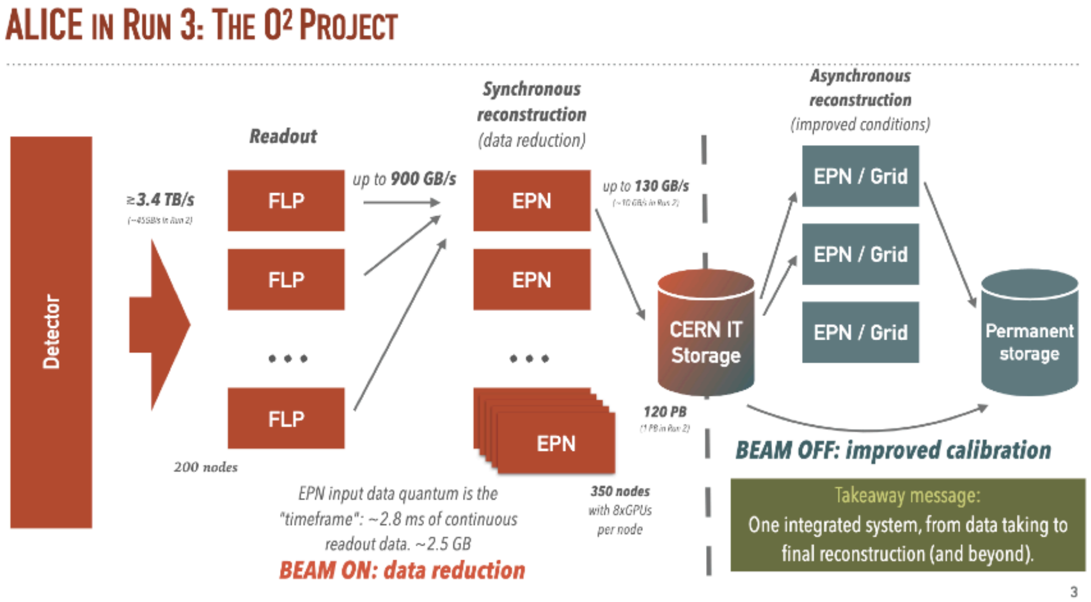
ALICE continuous readout

- Heavy ion data taking rate increased from 10 to 50 kHz at run 3
- With the high TPC latency, decision to operate in continuous readout mode **without trigger.**
  - ➜ Time-frame (TF) of 2.5-20ms instead of event acquisition



O2 facility

- First Level Processing (FLP): Readout + FPGA corrections to compress data and build the time-frames
- Event Processing Node (EPN): 8 GPUs AMD MI50 – 2 CPUs 32 core AMD Rome 7452
- online synchronous reconstruction and data reduction when beam on
- asynchronous reconstruction when beam off
- Offloading 60% of the processing to the GPU induces a speedup ~2.5x, expect 5x with 80%
- 2023 first use of EPN farm: 1/3 of data processed on EPN (CPU+GPU) and 2/3 on GRID (CPU)



Performance

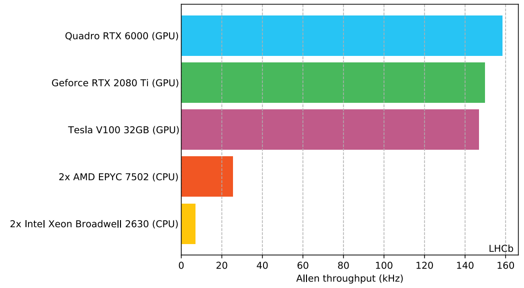
- 55 CPU 3.3GHz Cores equivalent to a single AMD-Mi50 GPU

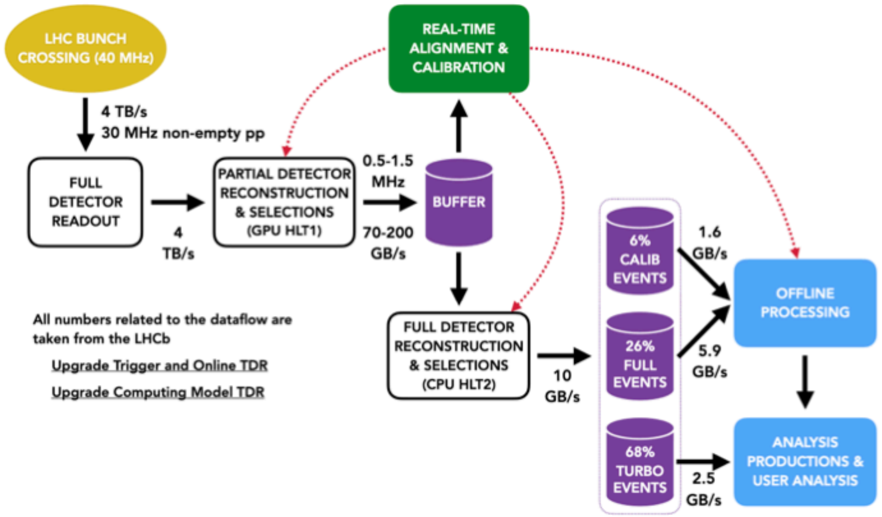
[WLCG-HSF 2023] [CHEP 2023]

GPU usage already in run 3 (II)

Full Software trigger at LHCb

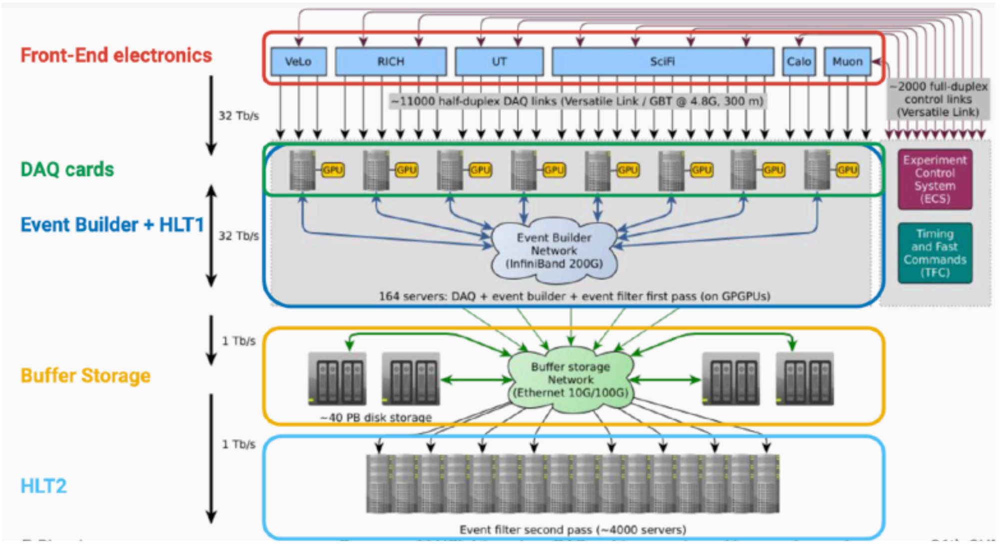
- For Run 3, LHCb is getting 5 × more collisions per second => trigger becomes the bottleneck
- Goal evolved from rejecting (trivial) background to categorise different ’signals’
- => Drop the L0 trigger, reconstruct 30 MHz of events before making trigger decision





RTA: Real-Time Analysis

- FPGAs-based clustering for Silicon Pixel detector
- HLT1: GPU based reconstruction
  - 163 RTX A5000s (one per Event Builder node)
  - software HLT1 sequence has been implemented in CUDA
- HLT2: CPU-based full reconstruction



Successfully commissioned

- In 2022: 40 Tbits/s network throughput achieved
  ➜ equivalent to 4% of the internet
- Achieving 30 MHz with less than 200 GPUs !

CHEP2023 - 1 and CHEP 2023 - 2

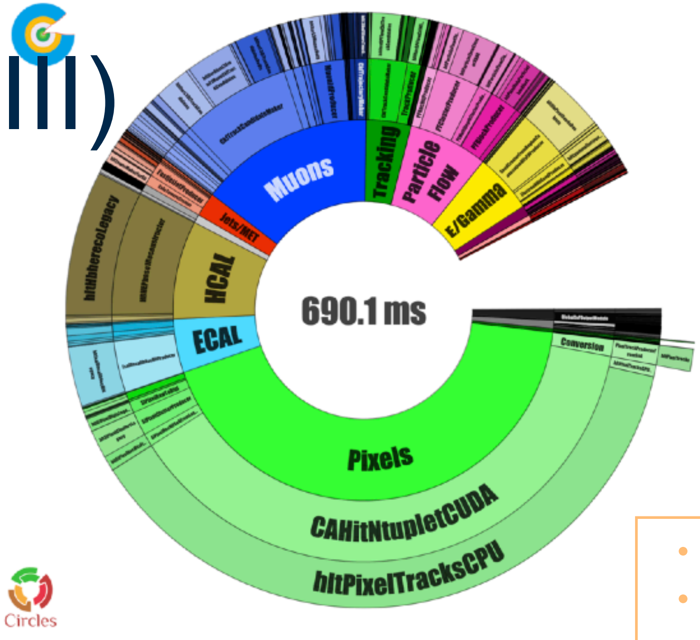
GPU usage already in run 3 (III)

CMS heterogenous HLT farm

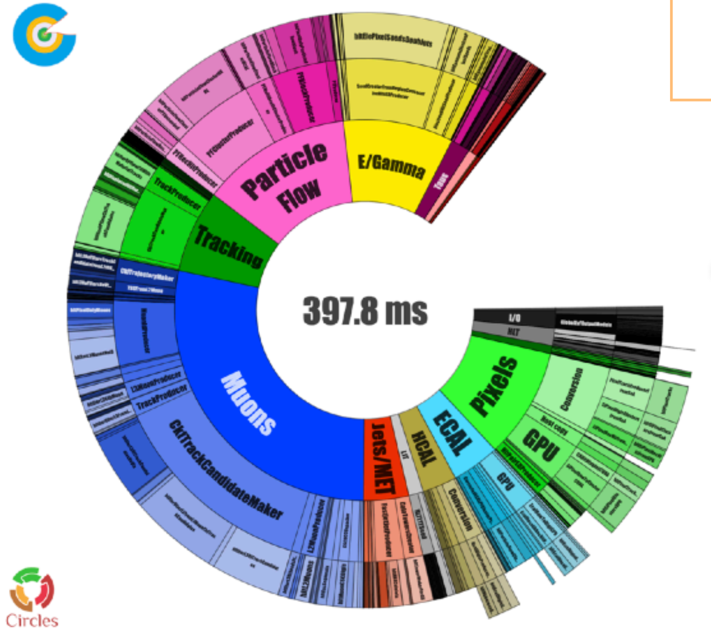
- HL-LHC will require ~one order of magnitude faster trigger
  - L1T 100kHz -> 750kHz (7.5x), pile-up 60 -> 200 (~3x) + more complex detectors
- => include GPUs at the HLT already for run 3
  - 200 nodes 2CPU+2GPU = ~26k CPU cores AMD Milan 7633 + 400 NVIDIA T4 GPUs
- HCAL, ECAL, pixel local reconstruction and pixel tracking on GPU => a lot of work needed to optimise software on these heterogenous architectures
- Allow scouting strategy = increasing event rate (lower thresholds) and decreasing event size to perform analysis directly with objects reconstructed at the HLT (no RAW data is stored

R&D in Performance Portability

- Porting Heterogenous Code to Alpaka (performance portability library) – to reduce dependency on hardware; kokkos and sycl also studied
- Aiming to offload 10% of (Run-3 and Phase-2) offline reconstruction by end of 2023



- Event throughput +80%
- Average time per event -40%
- Power consumption: -30%
- Experience gained for offline computing



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CMS CHEP 2023

Data Challenges

Objective

- progressively test the infrastructure by increasing data rate on top of production
- allows to test concurrently in real condition on a large set of sites end-to-end transfer capacities:
  - network, storage, middleware
- allows to test new technologies

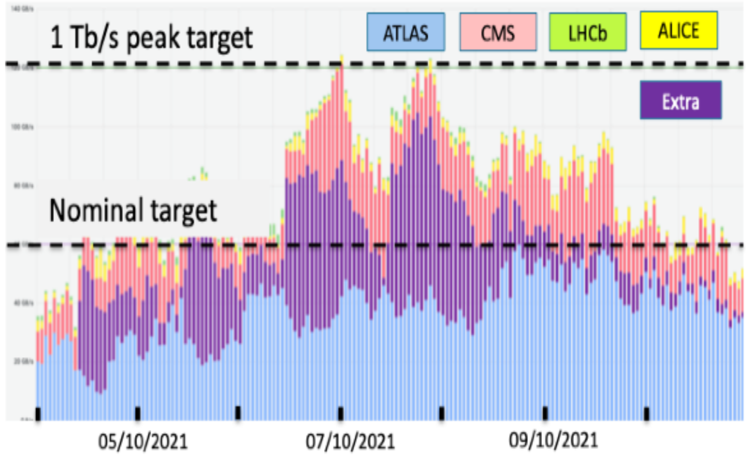
Campaigns

- DC21: target 10% of HL-LHC needs
  - 1Tb/s reached ! and lessons learned
  - 2021 Data Challenges Wrap Up

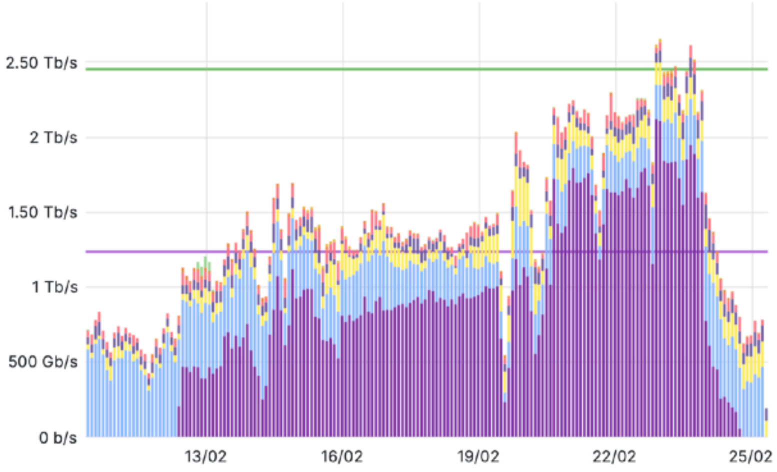
- DC24: target 25% of HL-LHC needs
  - 1,2 Tbps **minimal** scenario, 2,4 Tbps **flexible** scenario
  - including the 4 LHC experiments + Belle2 + DUNE
  - New monitoring following the DC21 post mortem, tokens usage tests
  - Token AAI tested

- DC27 50% of HL-LHC

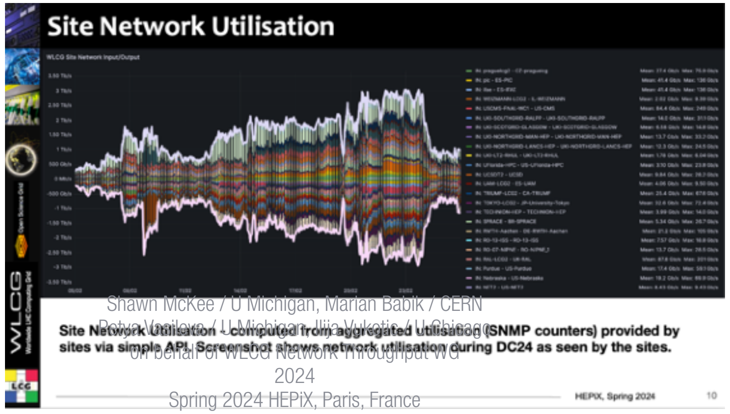
DC21 WLCG data transfers (Gbps) – 15 days



DC24 WLCG data transfers (Gbps) – 15 days



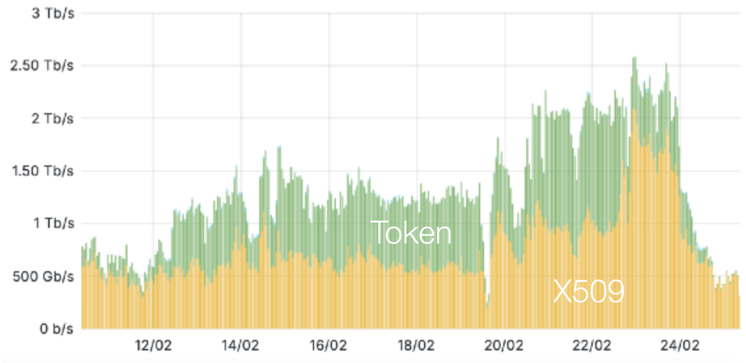
Site network monitoring



Site Network Utilisation - computed from aggregated utilisation (SNMP counters) provided by sites via simple API. Screenshot shows network utilisation during DC24 as seen by the sites.

Shawn McKee / U Michigan, Marian Babik / CERN
Petya Vasileva / U Michigan, Ilija Vukotic / U Chicago
on behalf of WLCG Network Throughput WG
2024
Spring 2024 HEPiX, Paris, France
https://indico.cern.ch/event/1377701/timetable/#20240417

Token utilisation in transfers



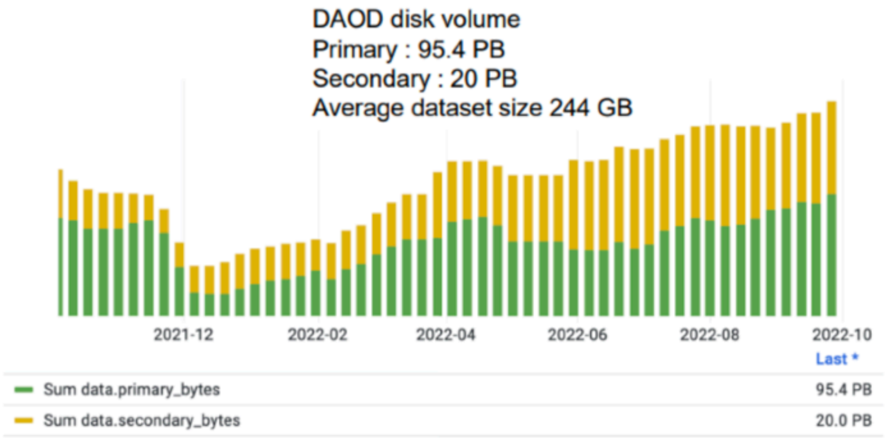
Introduction to token

IAM datachallenge WLCG-HSF 2024

Storage and data management

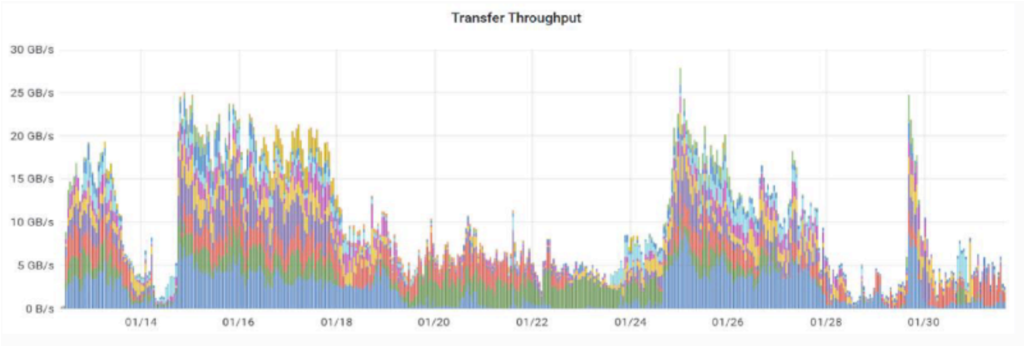
Difficult challenge

- No opportunistic storage and storage hard to operate => storage needs are the hardest ressource to fulfil
- Constant work to optimise data distribution ATLAS CHEP 2023
  - lifetime model, regular/automatic cleaning of unused or superseded data
- Early R&D and test through DOMA collaboration and ESCAPE EU project and experiment



Better usage of tape: data carousel

- tape driven workflow to allow job to get data directly from tape
  => disk space saving
- close collaboration between sites, experiments workflow and data management system
- in production in ATLAS with peak rate 20-25 GB/s
- develop now derived reconstruction data on demand
- Tape smart writing: find intelligent algorithms for file placement on tape



Tape staging from T0/T1s in 2023-01 (ATLAS DDM dashboard)

CHEP 2023

Storage and data management

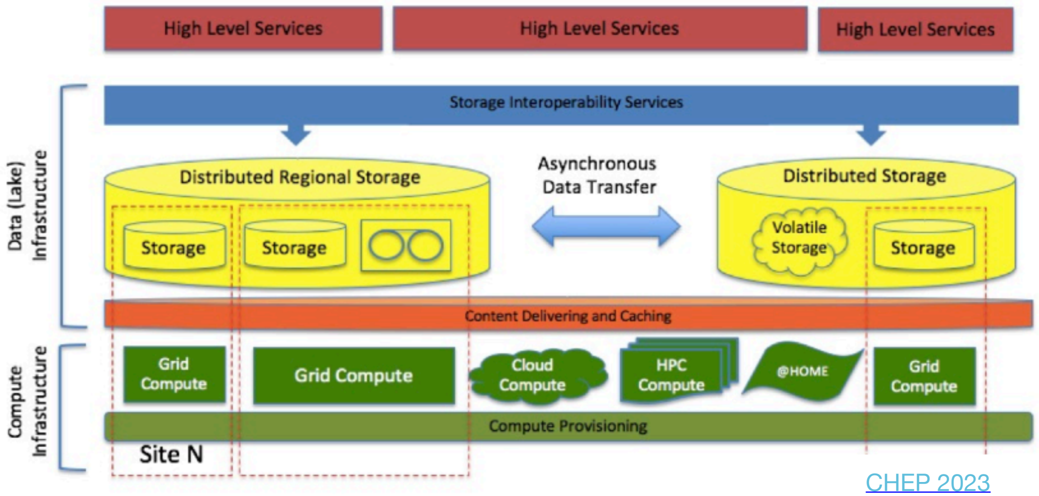
Data Lake

- Put data in a distributed federated storage that minimise replication, assure availability, with different storage quality level depending on the needs
- Serve data to remote (or local) compute ressources => grid, cloud, HPC, ..
- Simple caching is all that is needed at compute site (or none, if fast network)

ESCAPE Data Lake

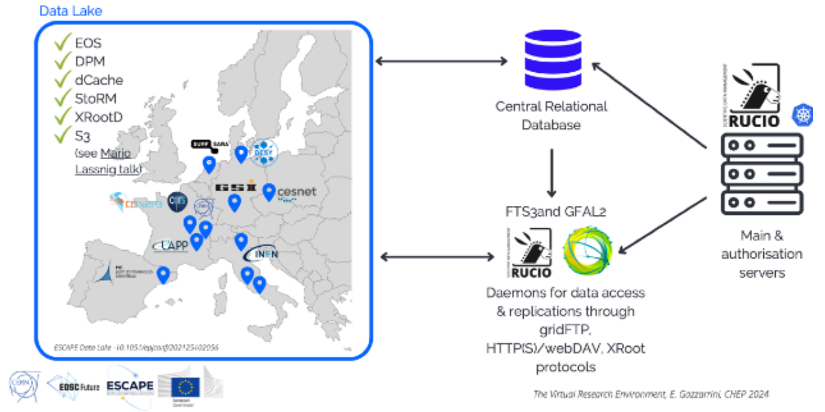
- Based on CERN File Transfer Service (FTS), Rucio data management and orchestration open-source tools
- Security assured through token based AAI
- HEP development benefited to astronomy and nuclear physics collaborations, now collaborative developments within ESCAPE new collaboration (CTA, SKA, LSST, KM3NET, LOFAR, FAIR, HL-LHC etc)
- Part of EOSC-Future Virtual Research Environment, successfully exploited with ESCAPE Dark Matter Science Project CHEP 2023 CHEP 2023

➜ See also Data lake implementation in the Nordic countries CHEP 2023



CHEP 2023

Rucio instance



CHEP 2023

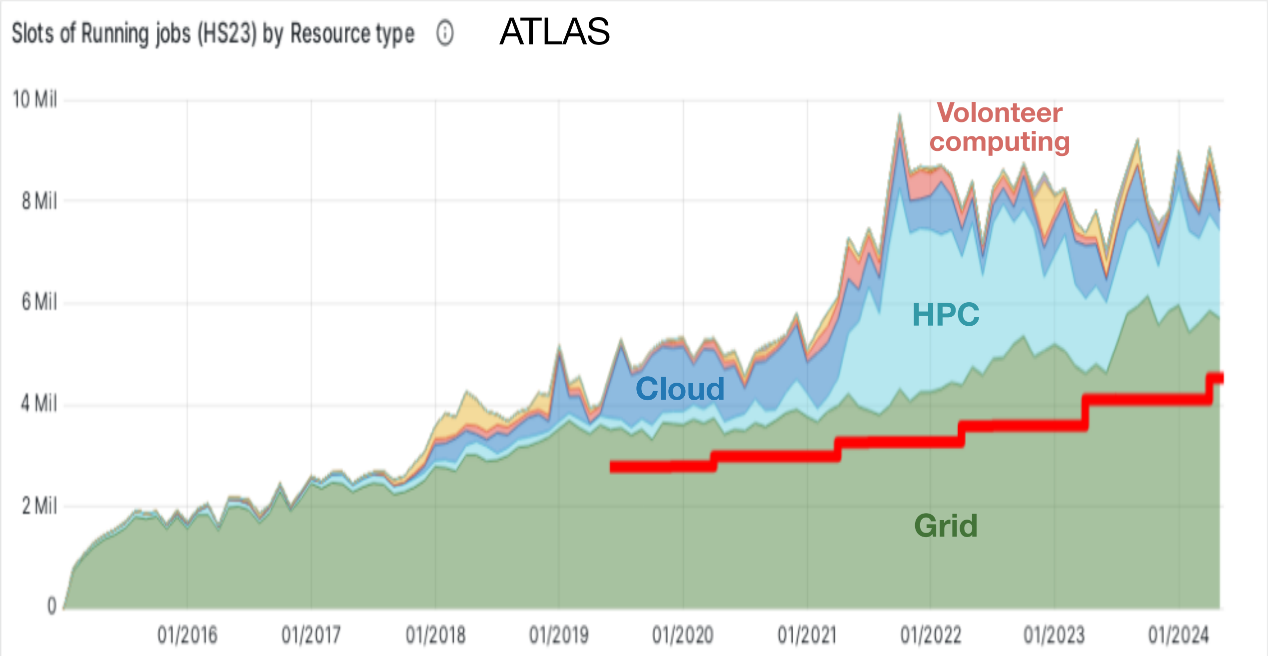
HPC usage

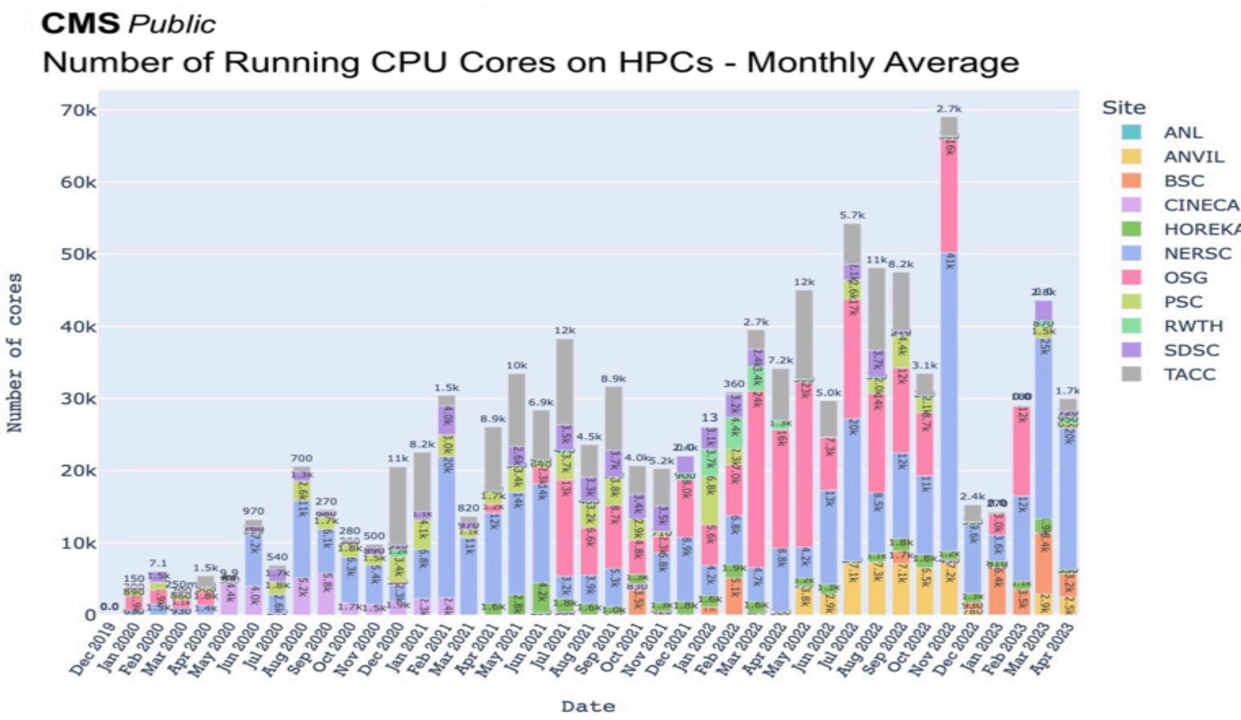
Increased use of HPC ressources

- Mostly for MC simulation, some MC reconstruction
- Exploiting HPCs could be
  - relatively easy for those which have policies similar to HEP sites ones
  - very complicated In other cases: workload management systems had to be creatively adapted in order to use these resources

Challenges

- low network connectivity on the worker nodes
- security rules prevent access to standard software repositories (CVMFS)
- Ingress/egress requirements
- ressources booking





Cloud ressources

➜ Clouds in WLCG sites have been used for a long time

Commercial Cloud usage

- Clouds have a lot of different ressources and allows for flexibility, on demand ressources
- Some challenges: interface, network, provider specificities, vendor locking
- Also procurement and economic model

➜ Cost effectiveness to be demonstrated

ATLAS Google project

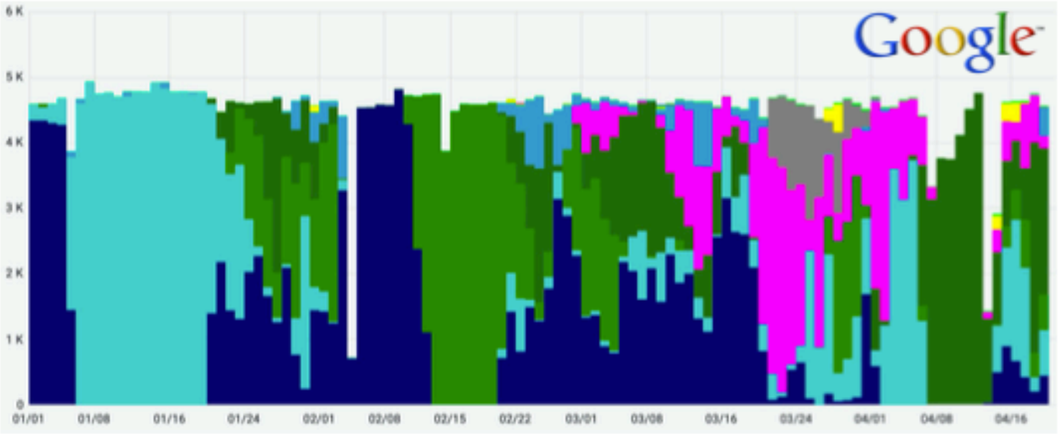
- Full integration of Google into ADC activities and infrastructure: important work to adapt data and job management tools (Panda, Rucio)
  - PanDA & Rucio developments are cloud-independent
  - Available for user analysis with Dask & Jupyter

➜ Work to understand cost of commercial cloud with respect to owning our ressources

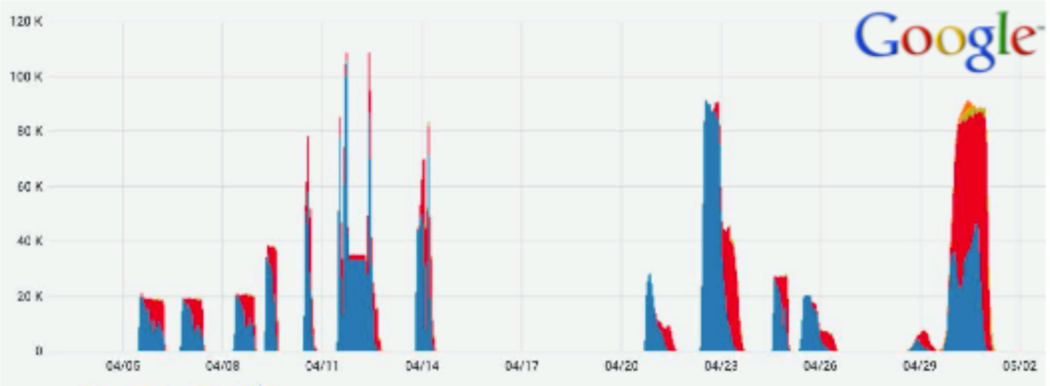
➜ Look for interesting use cases

- Cloud bursting: Dynamic/on-demand slot allocation
- Network offloading: Use Google network for transfers
- GPUs: On-demand GPU hardware
- Special analysis workflows: ML, fitting, special MCs

Running various w/flows on 5k job slots at the Google site



Bursting up to 100k slots for simulation and reconstruction jobs



ATLAS CHEP 2023

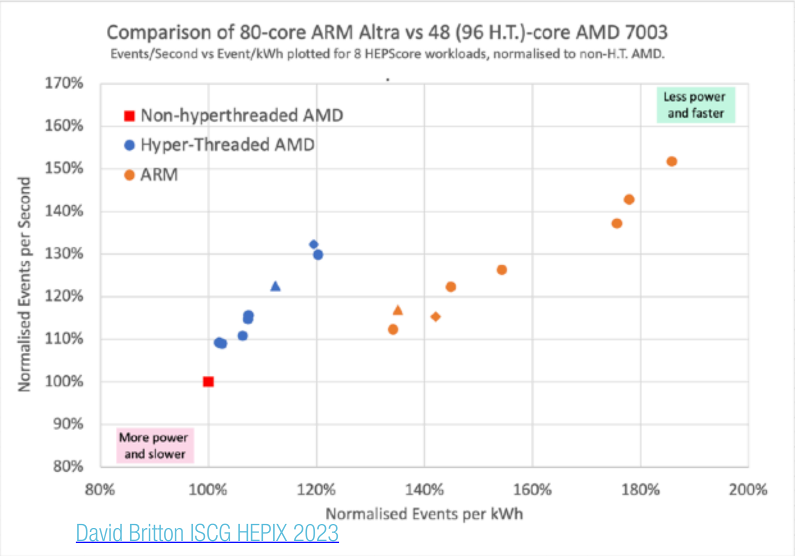
Heterogenous computing and Carbon footprint: ARM

ARM architecture

- Promising architecture with low power consumption
- some sites planning to provide resources
- => most of the LHC workloads ported to ARM. ATLAS software successfully validated and running. Ongoing validation for the 3 other LHC experiments

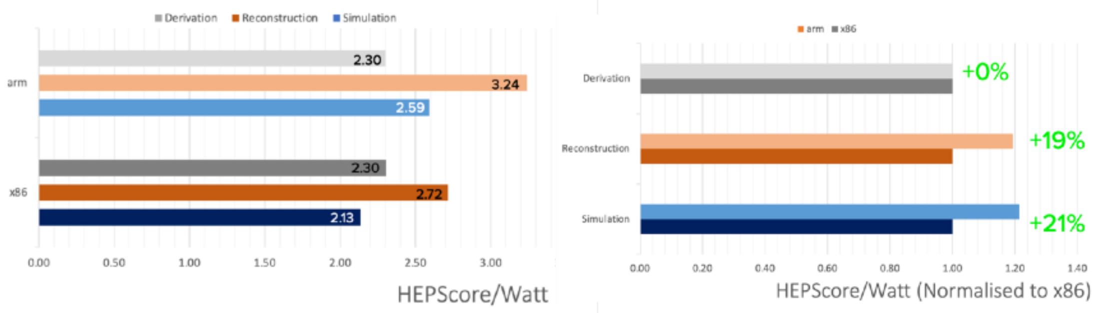
➜ In depth studies at Gridpp Glasgow site with very interesting results

ARM and AMD comparison

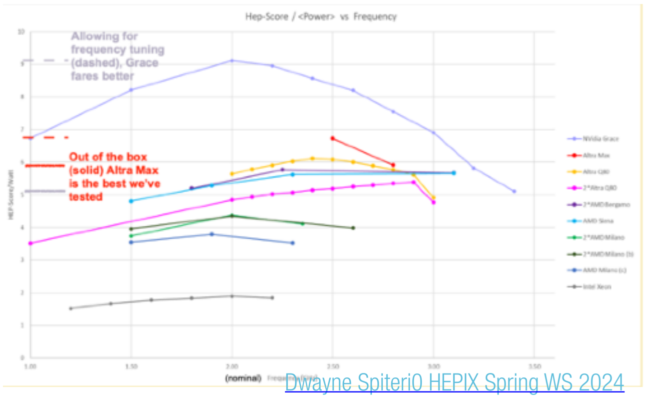


David Britton ISCG HEPIX 2023

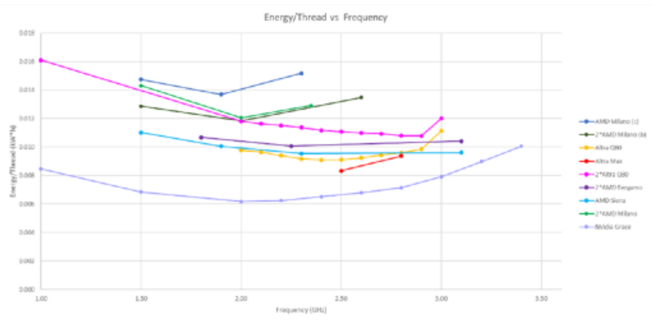
HEPScore/Watt workflow comparison



HEP-Score/Power vs frequency



Energy/thread vs frequency



Dwayne Spiteri0 HEPIX Spring WS 2024

Heterogenous computing and Carbon footprint: ARM

ARM architecture

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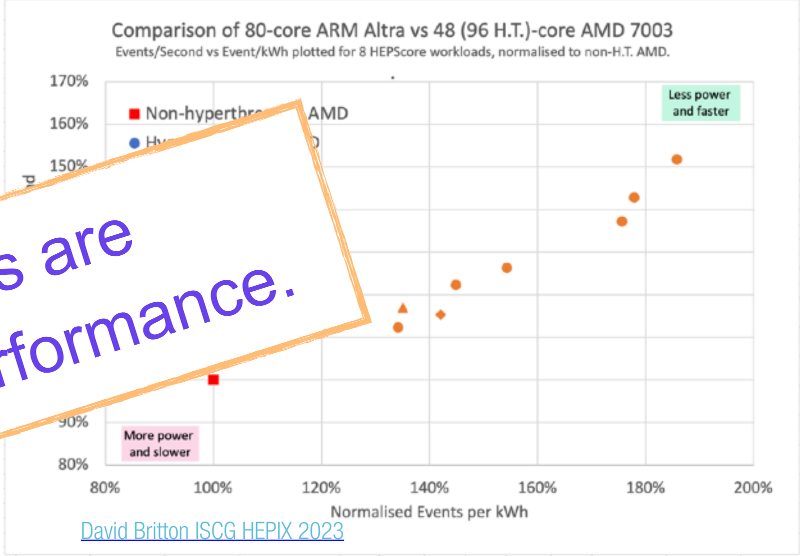
- some sites planning to provide resources
- => most of the LHC workloads ported to ARM. ATLAS software successfully validated and running. Ongoing validation for the 3 other [covered by overlay] experiments

➜ In depth studies at Gridp[covered by overlay] interesting results

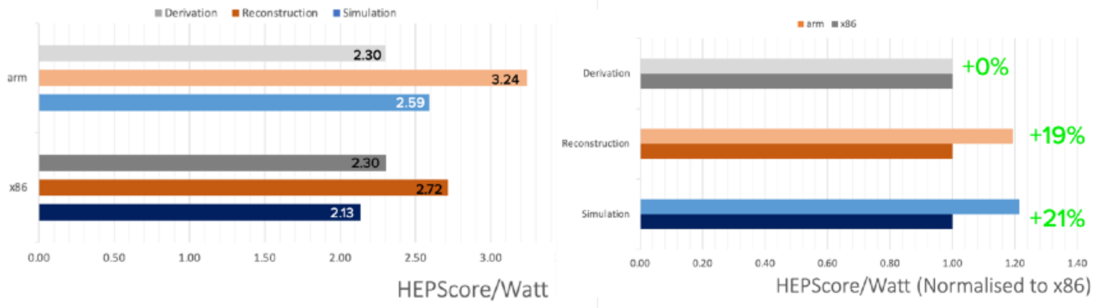
Other processor brands are joining this level of performance.

ARM and AMD comparison

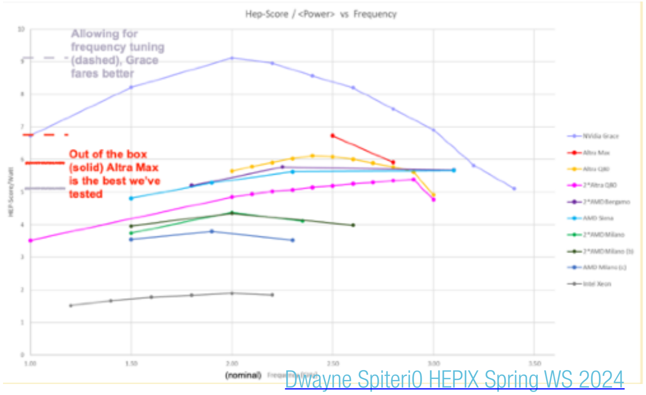


David Britton ISCG HEPIX 2023

HEPScore/Watt workflow comparis[covered by overlay]

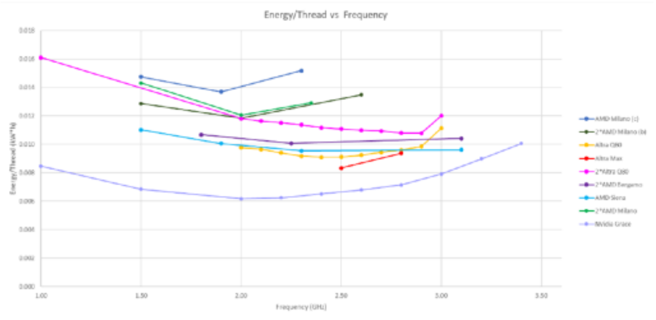


HEP-Score/Power vs frequency



Dwayne Spiteri0 HEPIX Spring WS 2024

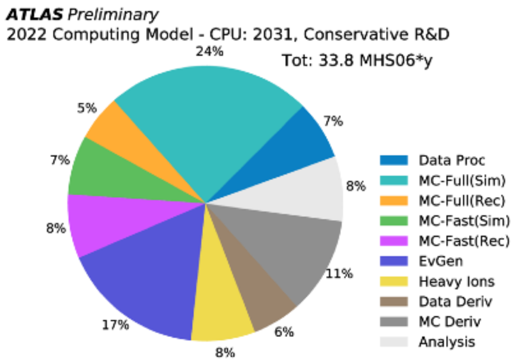
Energy/thread vs frequency

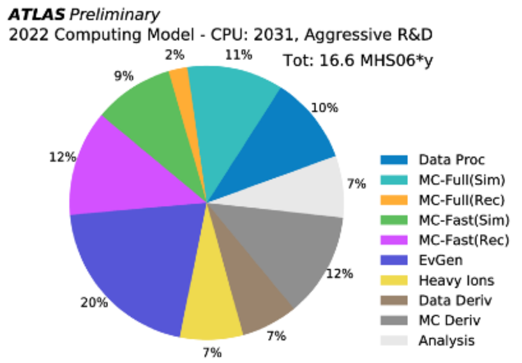


SOFTWARE

Event Generation

➜ will represent 10-20% of HL-LHC Computing





R&D in HSF Physics Event Generator WG

- Main Objectives [Ref]

- Accounting and profiling to understand CPU costs
- Move to GPUs and vectorised code
- Optimise phase space sampling and integration algorithms, including AI use

  ➜ see MadJax (differentiable per-event MEs)

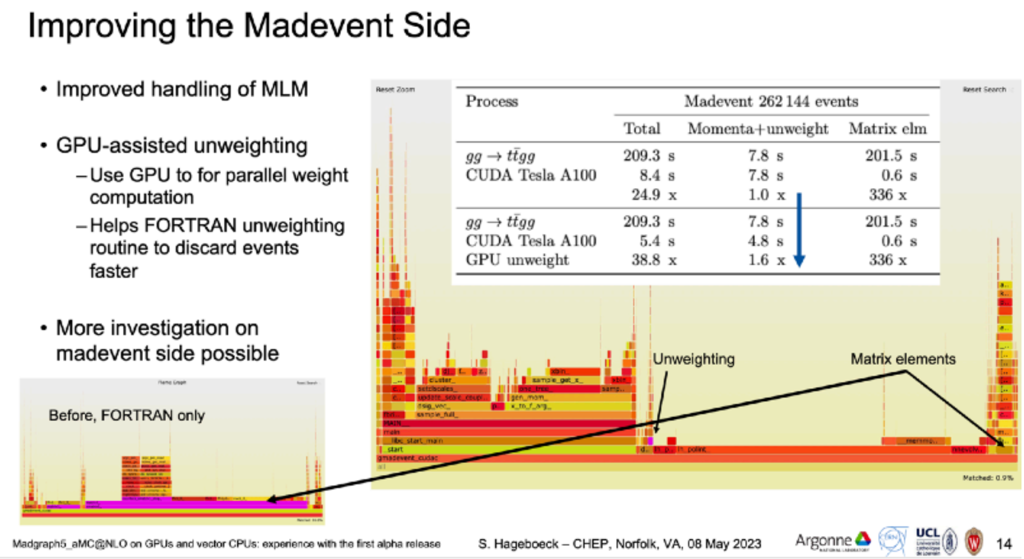
  - Research on reducing the cost associated with negative weight events

    ➜ see New Sherpa configuration by ATLAS that achieves 50% reduction of negative weights [Ref]
- Promote collaboration, training, funding and career opportunities

Example: MadGraph 5

- Matrix Element calculation in event generator can be efficiently parallelised using vector CPU or GPUs
  - Vector CPU: Speed ups of 6x for AVX512
  - GPU: 20x to 80x depending on the process using Tesla A100

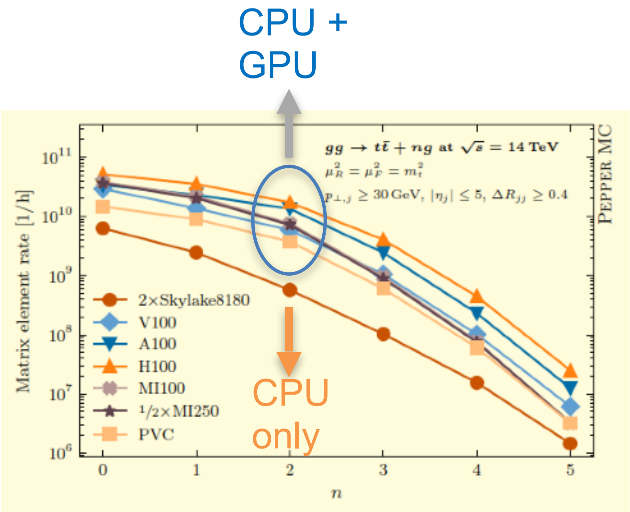
➜ reengineering of MG5aMC is a functional alpha release for LO QCD / EM processes, but weak interactions need more work



MadGraph CHEP 2023

Event Generators on GPUs

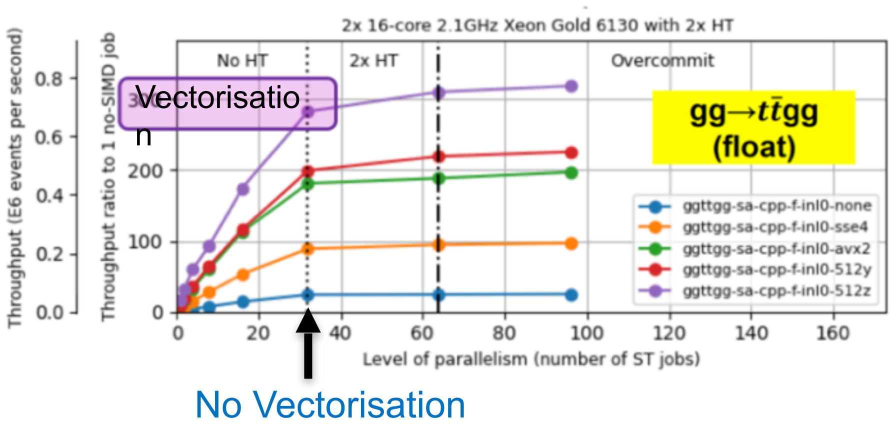
A very good candidate for GPU acceleration with benefits for many experiments



Sherpa gg->tt+ng

Matrix Element event throughput: up to x10 gain when using GPUs

Available for production



Madgraph gg->tt+ng (n=2)

GPU-enabled Leading Order: being released to production. By-product: enabling of CPU vectorisation: up to x8 gain in ME event throughput (x6 global). Note: all CPUs in WLCG provide vectorisation

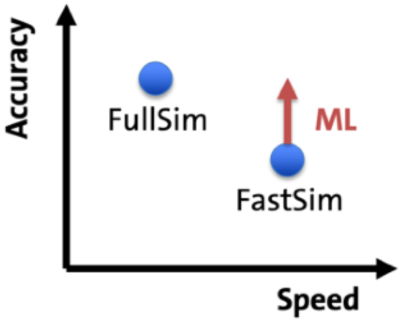
GPU-related work brings immediate benefits also on CPUs

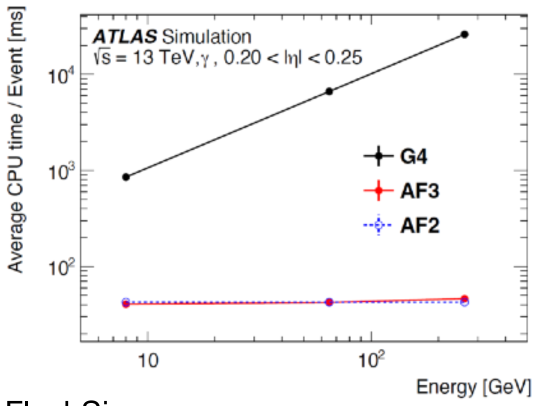
Simulation

Simulation impact

- Simulations are dominating Run 3 CPU usage: ALICE 50%, LHCb 90%, ATLAS 5
- Lot of R&D towards new technique and use of accelerators
- Need
  - to improve accurate full simulation for detector performance and training of last simulati
  - to make more use of fast simulation

Full vs fast Simulation

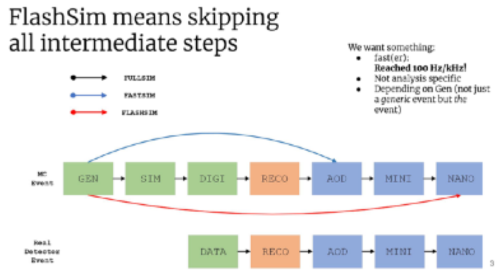




Fast simulation

- originally based on parameterisations of detector response, (generative) ML techniques now widely used
  - ➜ ATLAS AtlFast3, CMS FastSim and FlashSim
  - ➜ Porting fast simulations on heterogeneous resources, exploiting portability models Cf FastCaloSIm

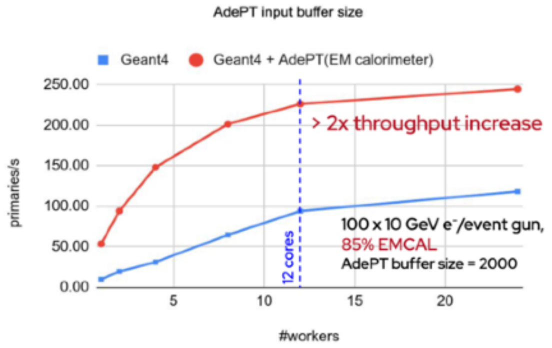
FlashSim



Full simulation

- Continuous progress to speed up Full Simulation:
  - ➜ same accuracy in the physics description, but faster
  - ➜ recent 20% improvement for ATLAS simulation (Woodcock Tracking of gamma – avoid to stop at volume boundaries)
- R&D with GPU prototypes: EM shower simulation on GPU
  - AdePT (Accelerated demonstrator of electromagnetic Particle Transport), Celeritas

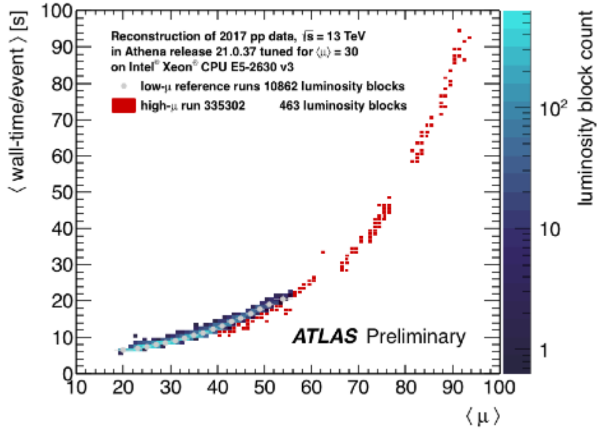
Adept

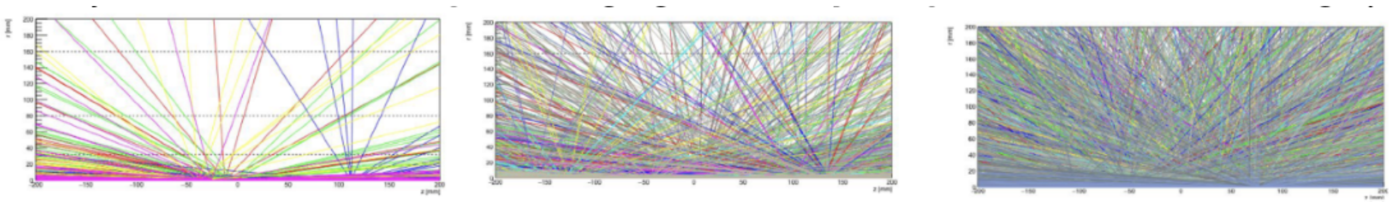


Reconstruction

R&D on track reconstruction with high pile-up

- non linear increase of needed computing ressource with event complexity for classical reconstruction algorithms

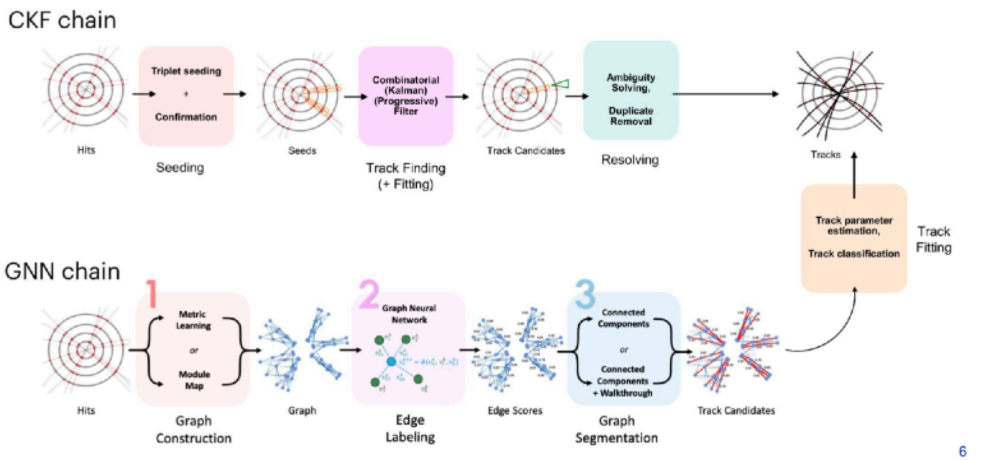




2010 <μ> ~ 5 — 2018 <μ> ~ 40 — 2029 <μ> ~ 200

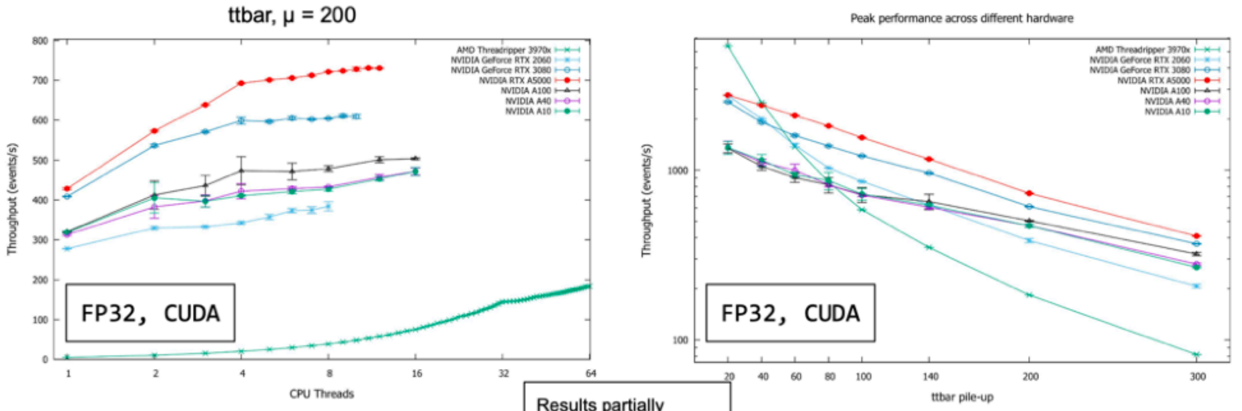
ACTS project

- ACTS open source project: toolbox for charged particle reconstruction for HEP/NP
- R&D on method and algorithm, 2 main chains developed: Kalman Filter or Graph Neural Net (GNN)
- R&D on parallelisation and performance portability
- On track to be used by ATLAS for track reconstruction by the LHC's Run-4



6

Event throughput for ttbar



Results partially generated on DAS-6.

GPUs become competitive at high pile-up. Highest performance observed on NVIDIA® workstation GPUs so far.

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Analysis

Analysis challenge

- Typical dataset size 10 TB (run 1-2) => 1000 TB (run 4)
- Current workflows do not scale:
  - disk/tape are limited/expensive and analysis data are projected to occupy ~30% (ATLAS model)
  - will need to go from Laptop to Analysis Facility

Analysis R&D

- Analysis workflow evolution: Columnar Analysis going from event loop to array programming and more use of Python ecosystem and industrial standards

  ➜ Coffea: python ecosystem -> ScikitHEP, Awkward array, DASK

  ➜ array programming solution for quick insights delivery
- Developments of more compact formats and reducing data copies and intermediate formats

  ➜ NanoAOD and ATLAS PHYSLITE

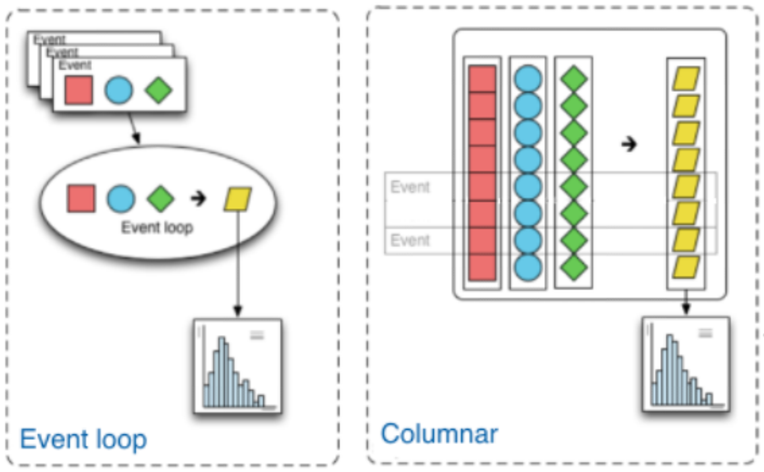
  ➜ target ~10kB/event for fast and lightweight analysis
- ROOT's Tree -> RNTuple, RDataFrame high level API for data analysis
  - encodings and I/O upgrade of the event data file format and access
  - Access to novel and future storage technologies: native support for HPC and cloud, object stores, direct disk-to-GPU data transfer
  - Collaboration with experiment for Event Data Model integration and optimisation

  ➜ 10-20% smaller files, x3 to x5 better single core performance

  ➜ enables fast adaptation to modern technologies, like object stores

  ➜ 2024 goal: release RNTuple 1.0 supporting the EDM of all experiments

Columnar Analysis

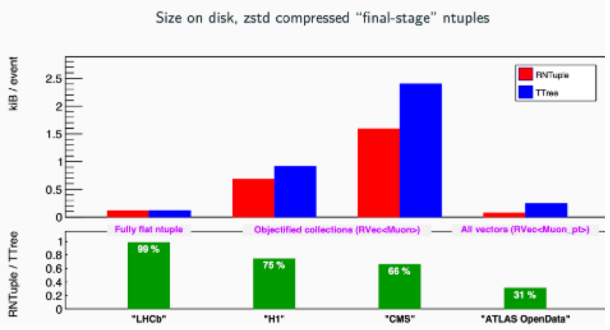


Python ecosystem

Coffea

ROOT Data Analysis Framework

File size



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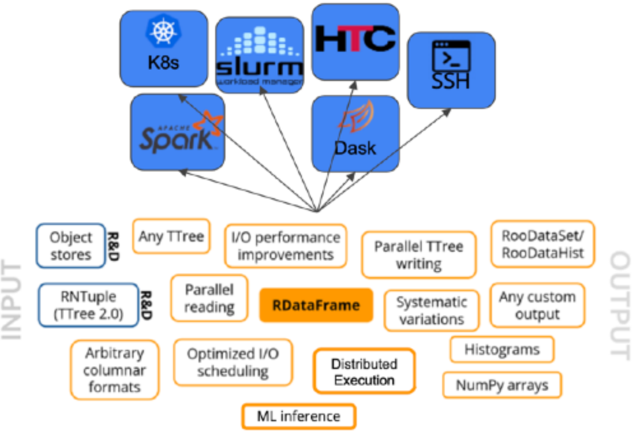
RDataFrame



WLCG-HSF2024

Analysis facility

➜ Several initiatives

IRIS-HEP Analysis Grand Challenge Link

- binned analysis, reinterpretation and end-to-end optimisation of physics analysis use cases
- includes the development of the required cyber infrastructure

Analysis Facility prototype at CERN Link

- both batch and interactive
- DASK, HT-Condor integration
- open for user tests (documentation)

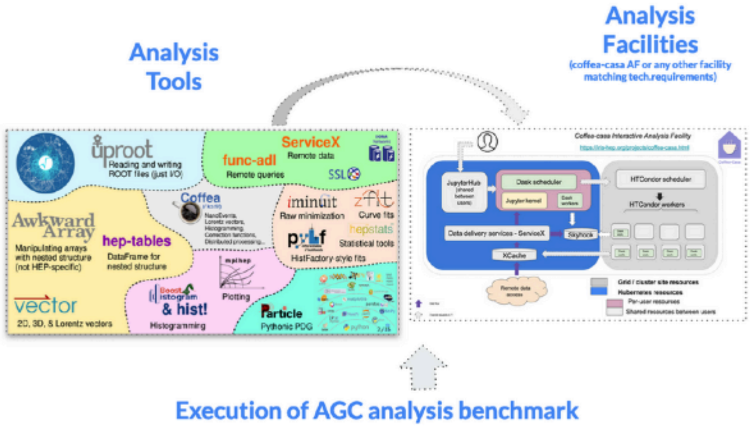
Virtual Research Environment Link

- development in EU-founded project in the line of EOSC building: ESCAPE
- open source platform with access to all the digital content needed to develop, share and reproduce an end-to-end scientific result in compliance with FAIR (findable, accessible, interoperable, reproducible) principles
- All the building blocks from storage to computing with AAI and notebook to analysis preservation

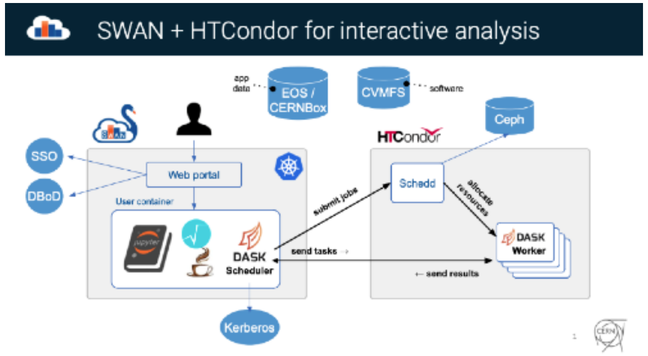
➜ Reana: reproductible research analysis platform Link
  - developed at CERN
  - allow to preserve, distribute and reproduce
  - flexible scalable and reusable => container

And more like INFN Napoli initiative Link

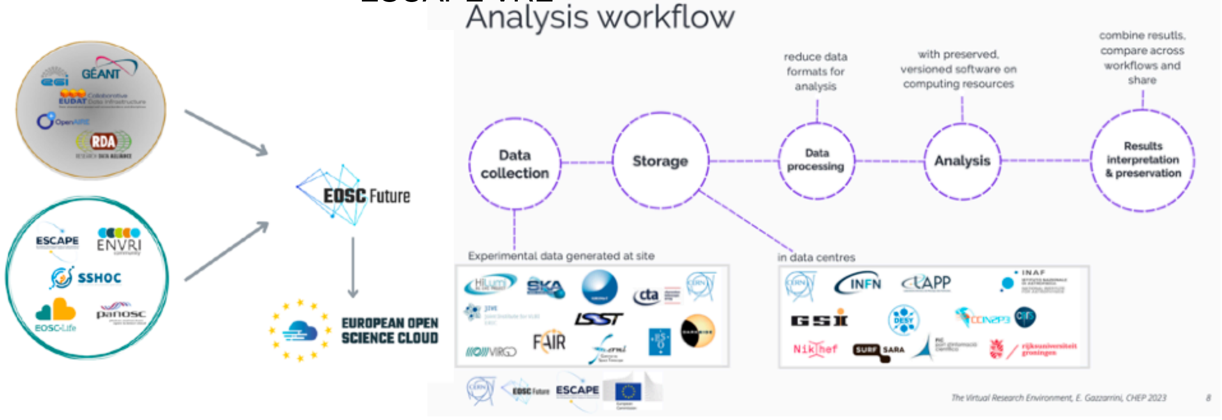
IRIS-HEP Analysis Grand Challenge



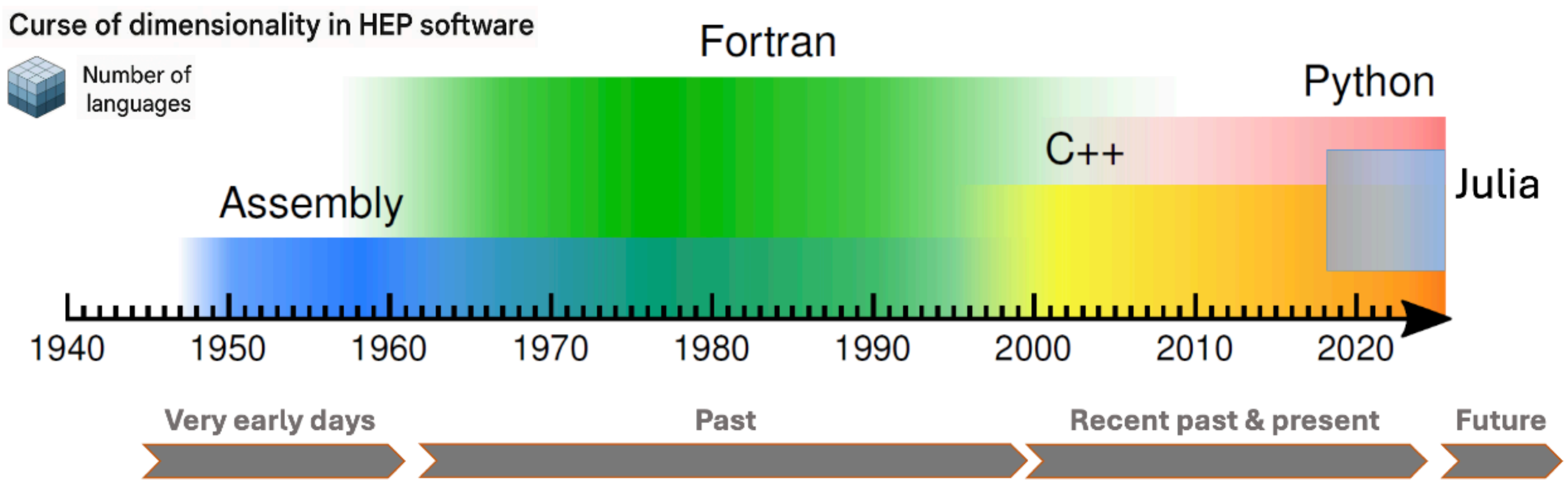
CERN facility software component



ESCAPE VRE



HEP software : language



Adapted from J. Pivarski

Metric	C++	Python	Julia
Performance	✅		✅
Ease-of-use		✅	✅
Learning Curve		✅	✅
Safety (memory)		✅	✅

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Evolution of usage

- Past essentially fortran, now C++ & Python (Python increasingly used in user analysis)
- Julia sneaking into the arena, especially in smaller experiments (high performance + productivity)
- Present & future: increasing mix of languages

Key4HEP

What HEP software for the future ?

- we don't know
- but we already need software to build the next machine
  - ➜ HEP community has agreed on one common software stack : ESPPU contribution #240 "members of the ILC, CLIC, FCC, CEPC and the Muon Collider communities ... decided to pool their resources to develop a common and shared software stack ... Key4hep project which has become the de facto standard for studying detector concepts in any currently foreseen future collider
  - ➜ https://key4hep.github.io/key4hep-doc/main/index.html
  - ➜ CHEP2020