New directions in computing

Advanced Graduate Lectures on practical Tools, Applications and Techniques in HEP

Jun 16 – 20, 2025

RAL, Visitors Centre

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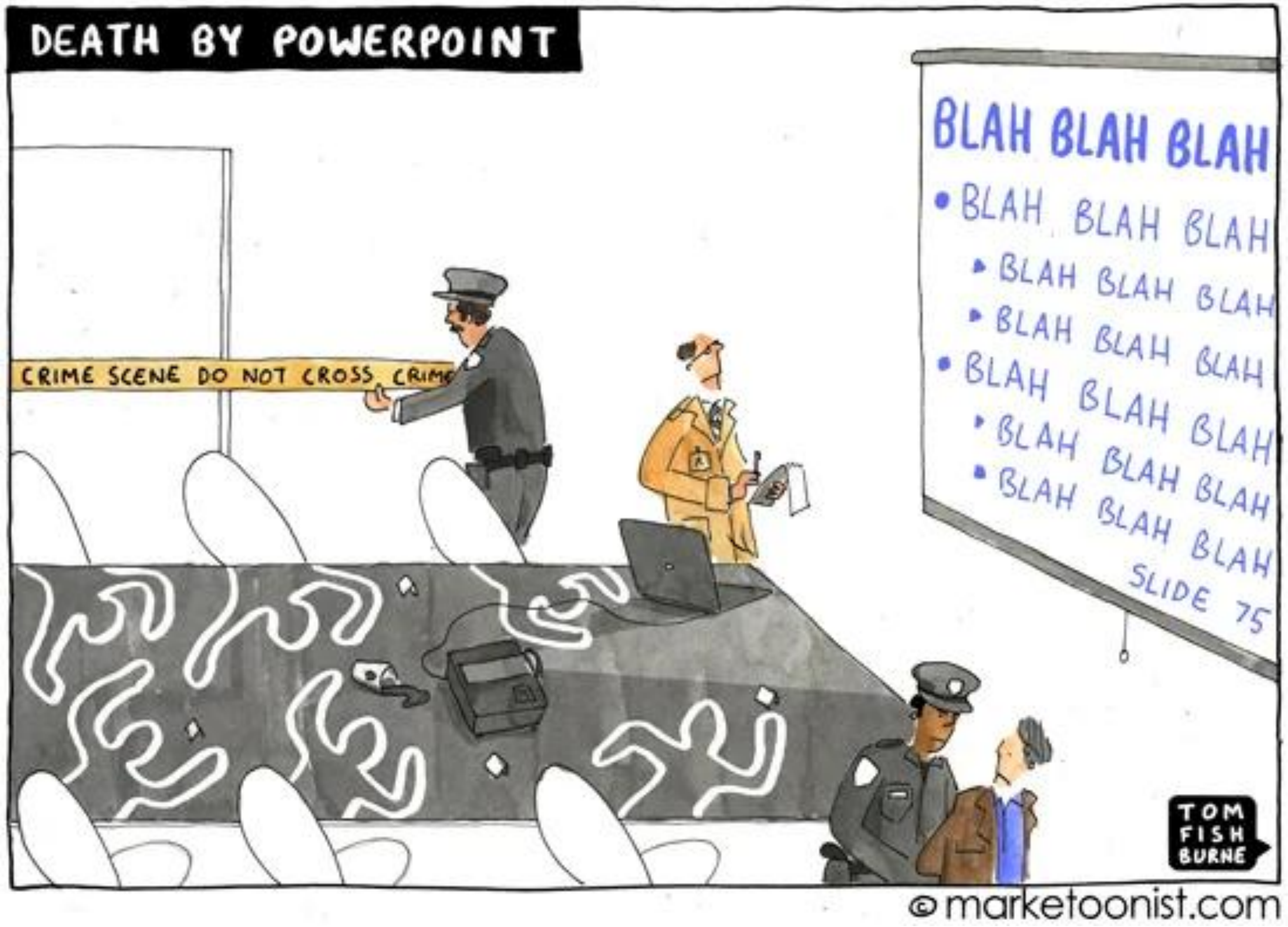
Rutherford Appleton Laboratory, Oxford

Overview:


DEATH BY POWERPOINT
CRIME SCENE DO NOT CROSS CRIME
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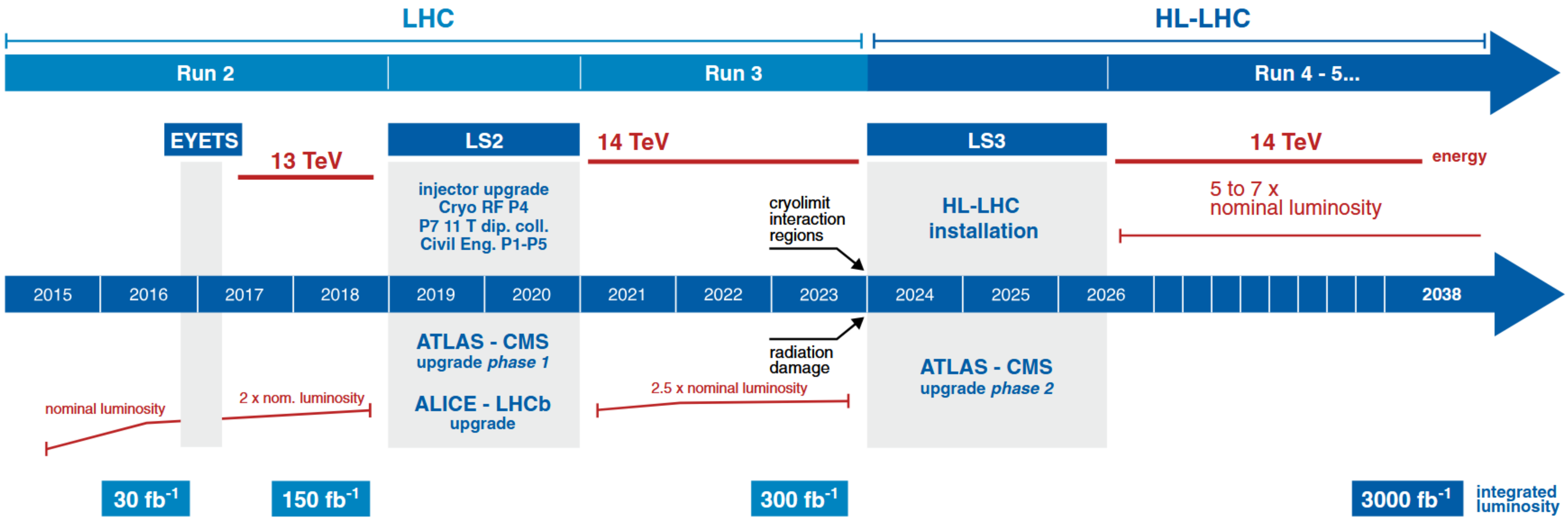
SLIDE 75
TOM FISH BURNE
© marketoonist.com

Overview:

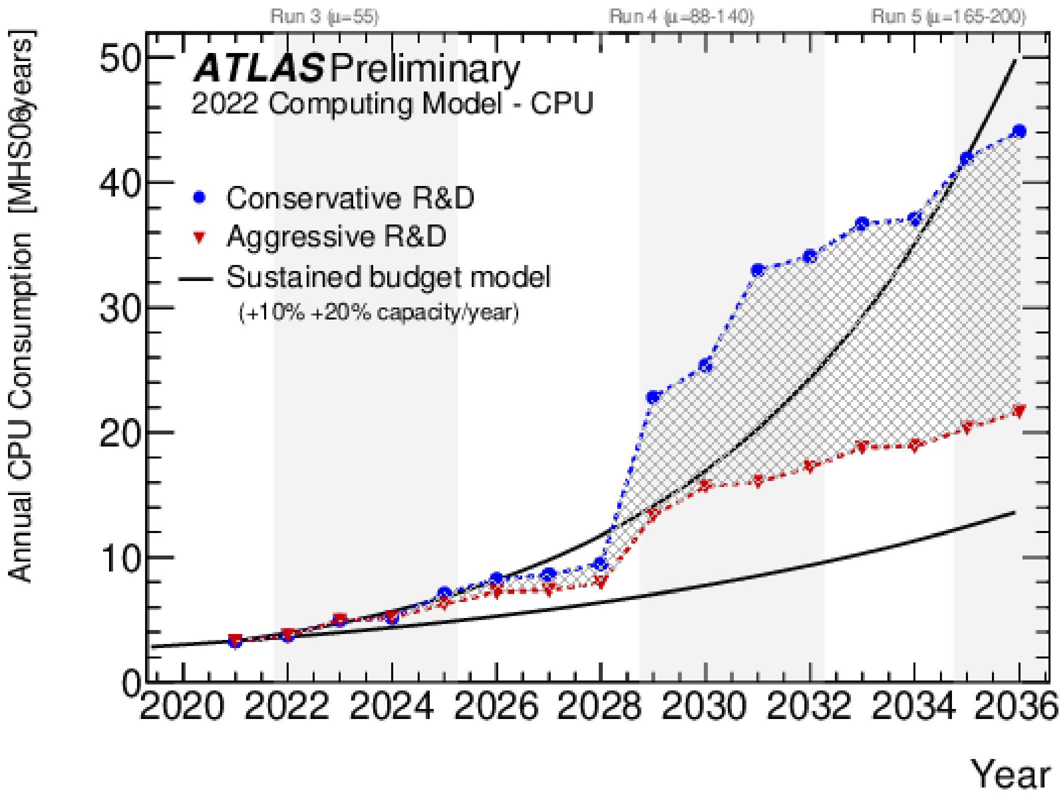
1. Landscape of research software projects .	~13m
2. Advancements in platforms and architectures.	~12m
3. HEP Computing Infrastructure: WLCG(Offline).	~10m
4. Languages and software engineering.	~10m
Break: Questions and discussion	~15m
5. Real-Time analysis (online)	~15m
6. GPU programming.	~20m
7. Future ?	~15m
End: Questions and discussion	~10m

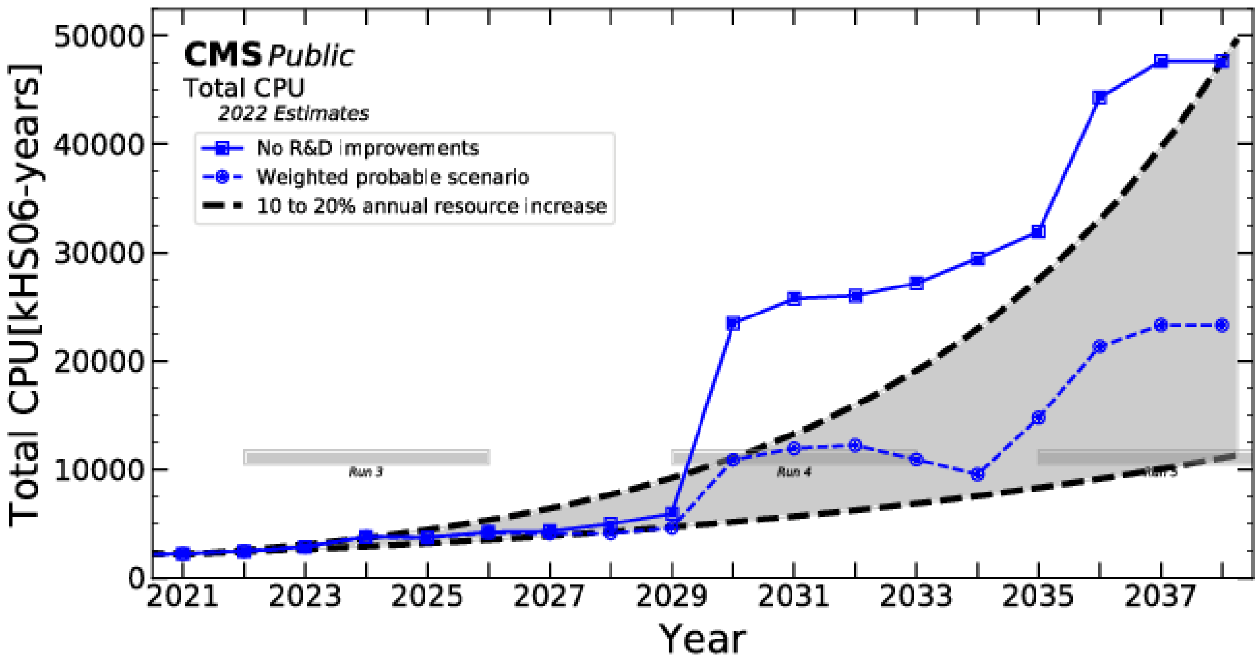
1. Landscape of research software projects

Landscape of research software projects



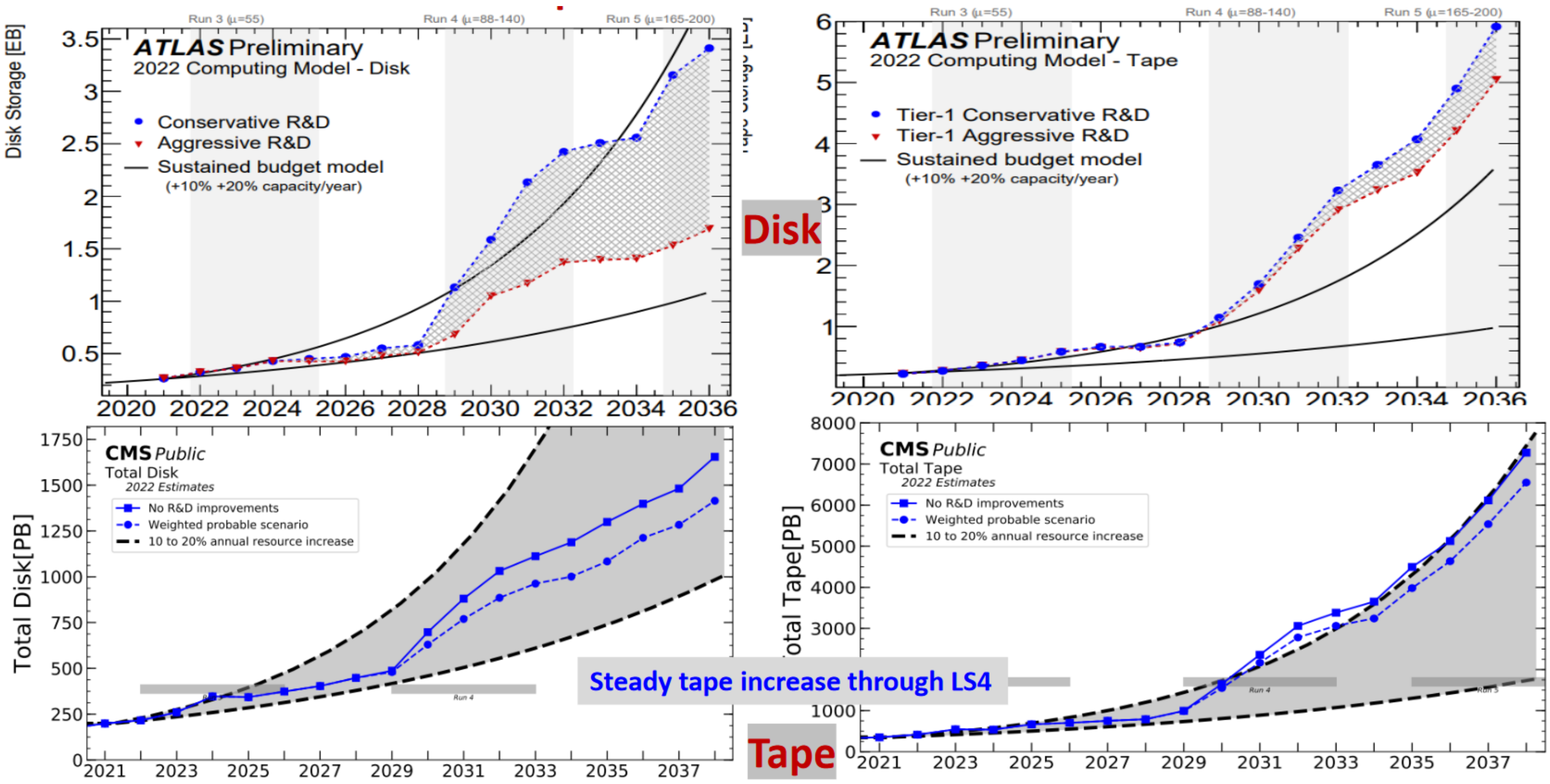
Landscape of research software projects



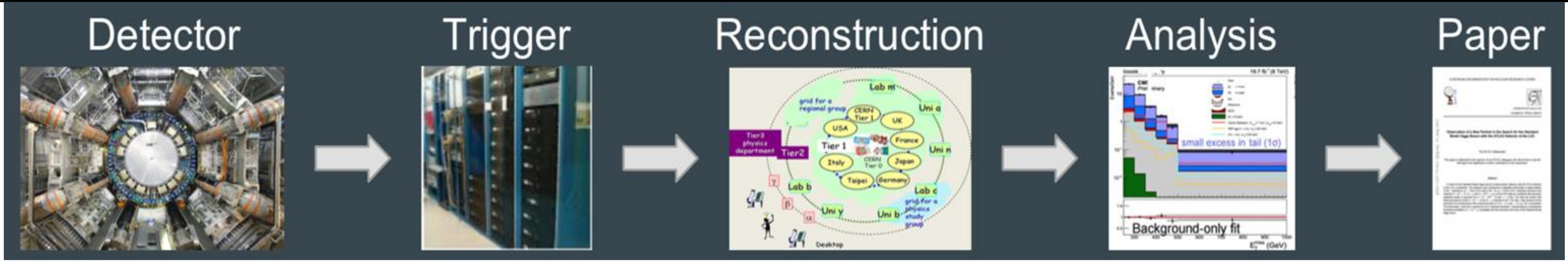


A naive extrapolation from today's computing model and techniques, even after assuming Moore's Law increases in capabilities, is insufficient to meet the expected resource needs for HL-LHC

Landscape of research software projects



Landscape of research software projects



WLCG Worldwide LHC Computing Grid & HSF HEP Software Foundation

Joint WLCG & HSF Workshop 2018

26–29 Mar 2018
Napoli, Italy
Europe/Zurich timezone

Landscape of research software projects

[10.1007/s41781-018-0018-8](https://doi.org/10.1007/s41781-018-0018-8)

HSF-CWP-2017-01
December 15, 2017

arXiv:1712.06982v5 [physics.comp-ph] 19 Dec 2018

A Roadmap for HEP Software and Computing R&D for the 2020s

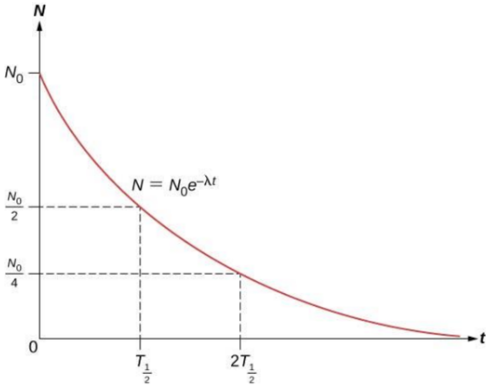
HEP Software Foundation[1]

Abstract: Particle physics has an ambitious and broad experimental programme for the coming decades. This programme requires large investments in detector hardware, either to build new facilities and experiments, or to upgrade existing ones. Similarly, it requires commensurate investment in the R&D of software to acquire, manage, process, and analyse the shear amounts of data to be recorded. In planning for the HL-LHC in particular, it is critical that all of the collaborating stakeholders agree on the software goals and priorities, and that the efforts complement each other. In this spirit, this white paper describes the R&D activities required to prepare for this software upgrade.

Contents

Monte Carlo generators

Aim to generate events as in Nature
→ get average and fluctuations right
→ make random choices, as in nature



Integrals as averages:

$$I = \int_{x_1}^{x_2} f(x)\, dx = (x_2 - x_1)\langle f(x) \rangle$$

$$I \approx I_N \equiv (x_2 - x_1)\frac{1}{N}\sum_{i=1}^{N} f(x_i)$$

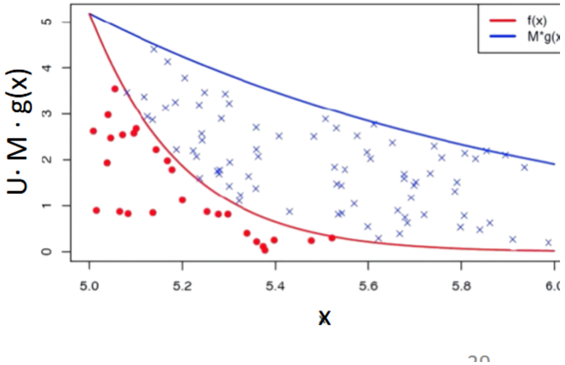
$$V = (x_2 - x_1)\int_{x_1}^{x_2}\left[f(x)\right]^2 dx - \left[\int_{x_1}^{x_2} f(x)\, dx\right]^2$$

$$I \approx I_N \pm \sqrt{V_N/N}$$

(central limit theorem)

Accept-reject method:

- Create an envelope around f(x) → M · g(x)
- Accept event x' with probability f(X')/[M · g(x')]

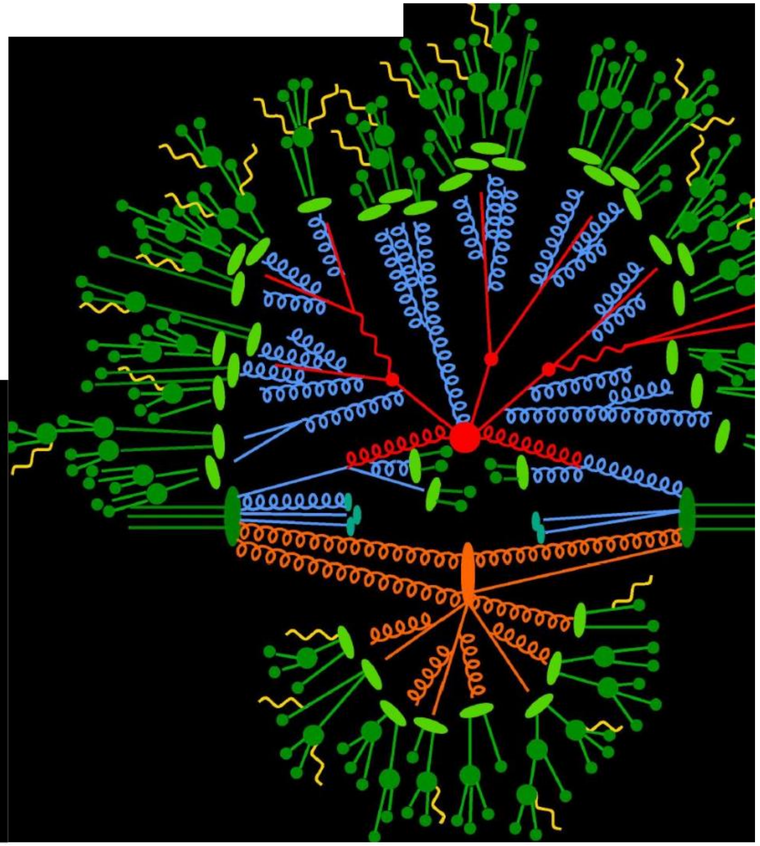


Monte Carlo generators

https://montecarlonet.org/

MCnet

Herwig
Pythia
MadGraph/aMC@NLO
Sherpa



hard scatter: matrix elements from first principles - incoming partons from parton-distribution functions(PDFs)
radiative corrections: resumming logarithms to all orders
multiple parton interactions: additional interactions between proton remnants
hadronisation: going colourless
hadron decays: from excited states to final-state particles
photon radiation: QED corrections

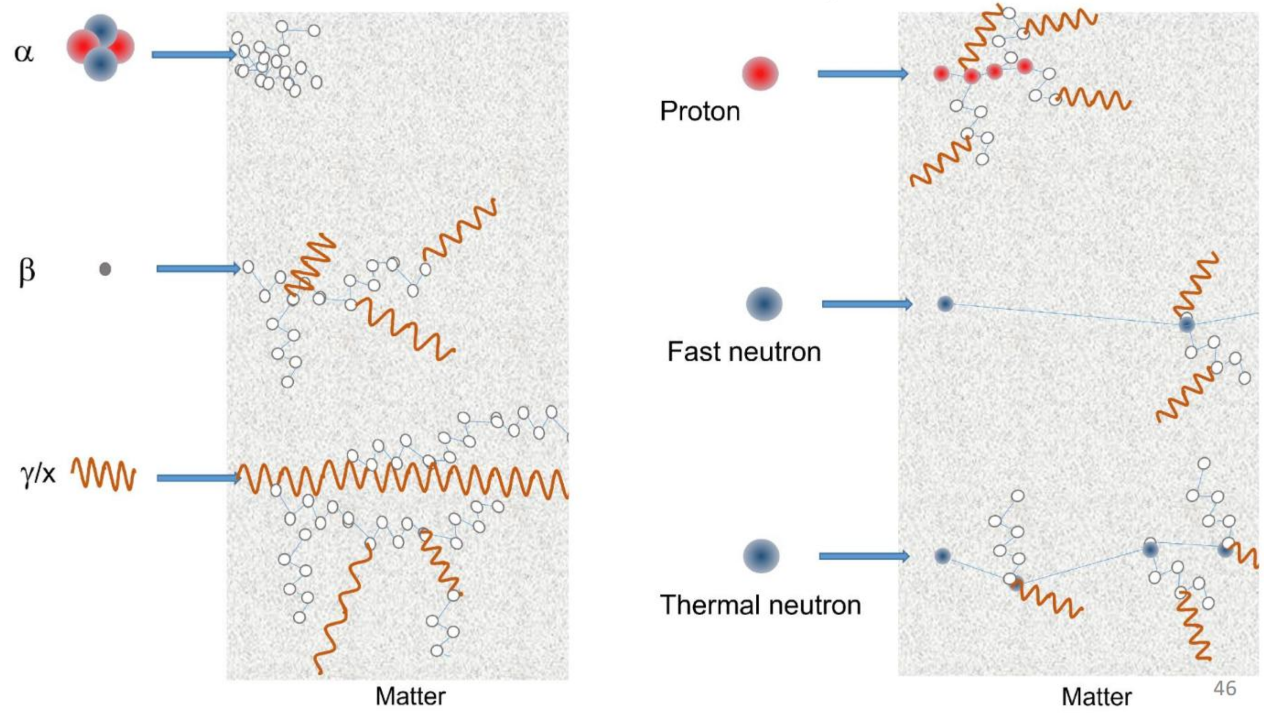
MadGraph: https://launchpad.net/mg5amcnlo
Pythia8: https://pythia.org/

Landscape of research software projects

MonteCarlo simulations

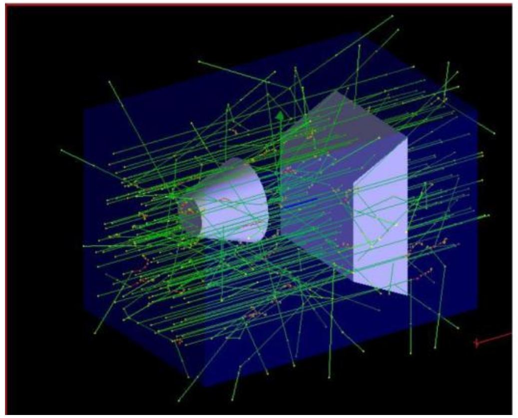
Interaction of charged particles with matter:

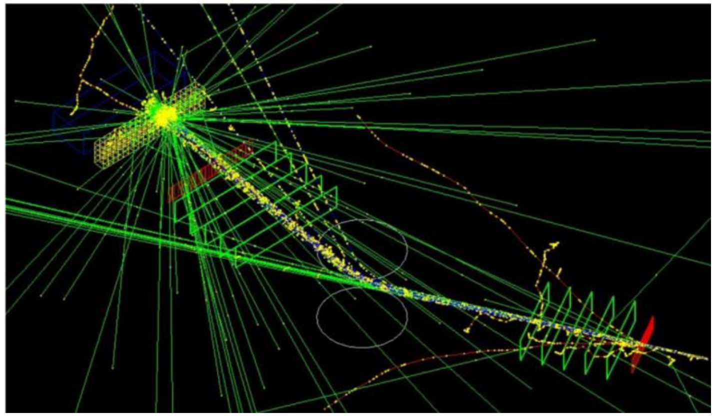
$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0} \right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)} \right) - \beta^2 \right] \quad \text{(Bethe-Bloch)}$$



GEANT4 A SIMULATION TOOLKIT https://geant4.web.cern.ch/

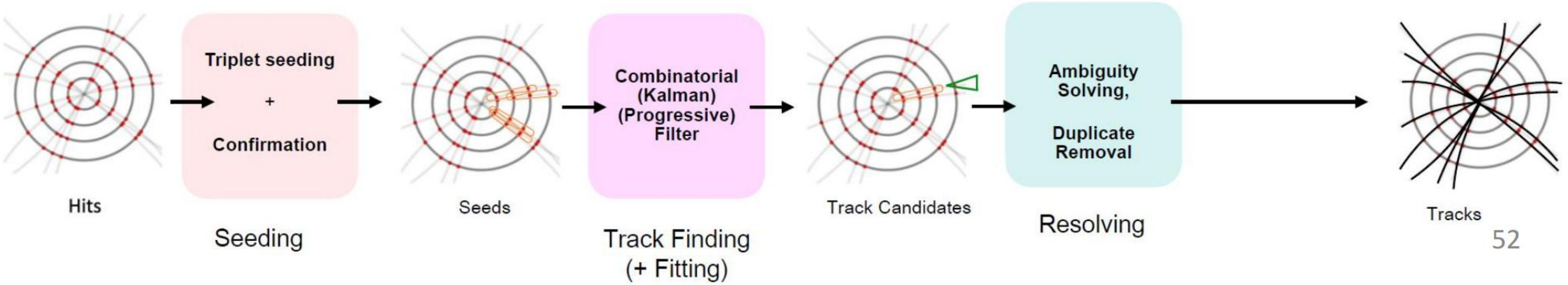
(GEometry ANd Tracking)
C++ simulation toolkit of the passage of particles through matter, using Monte Carlo methods





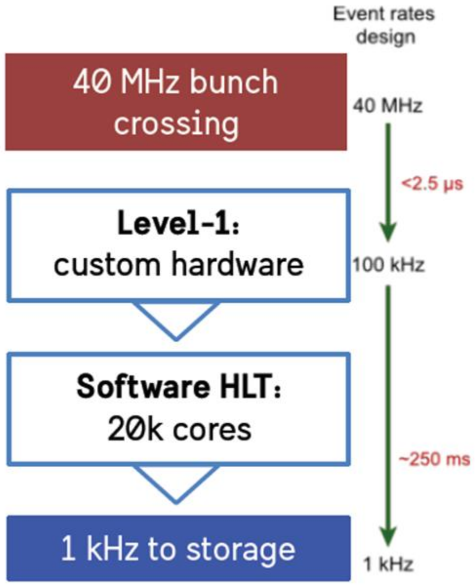
https://gitlab.cern.ch/geant4/geant4/-/tree/master/examples

Landscape of research software projects

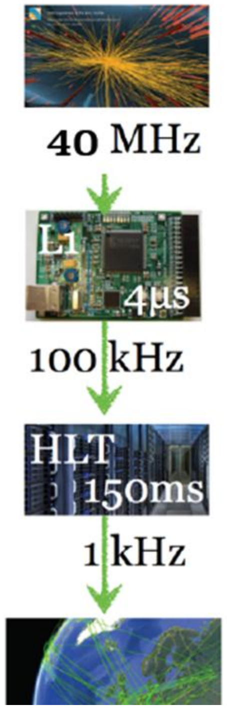


The trigger systems:

ATLAS

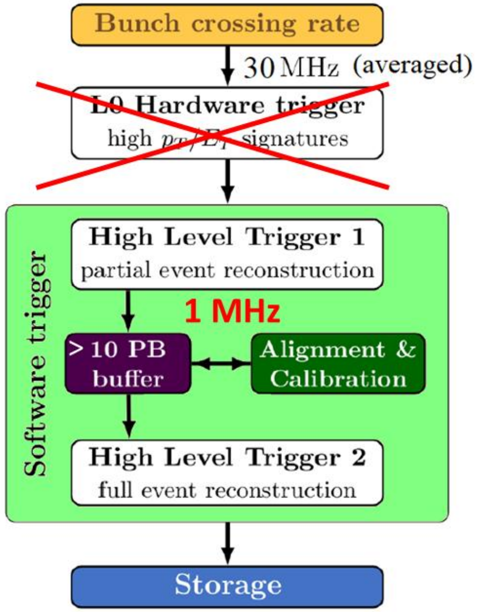


CMS



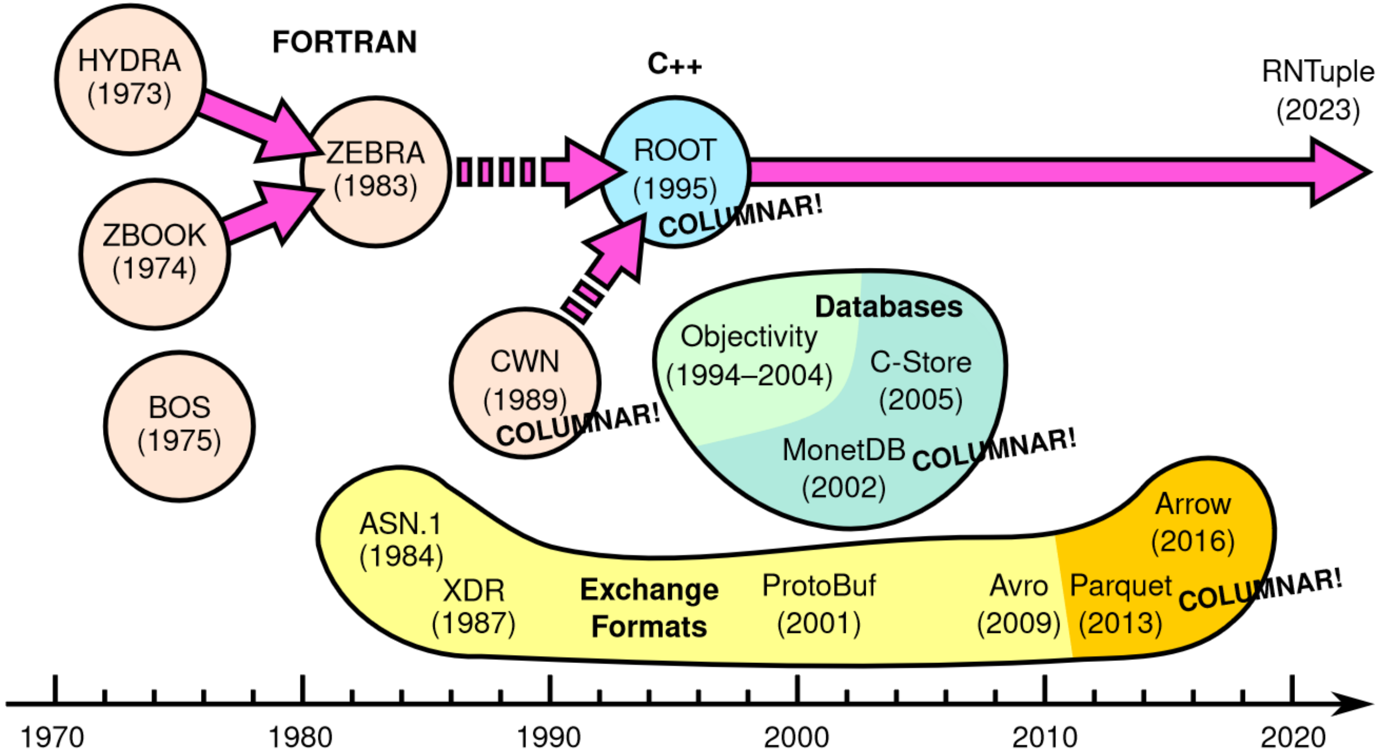
LHCb

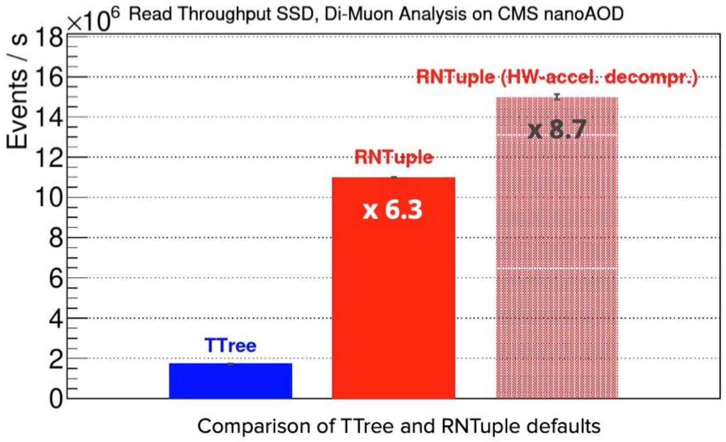
(Run3: 2022)



Landscape of research software projects

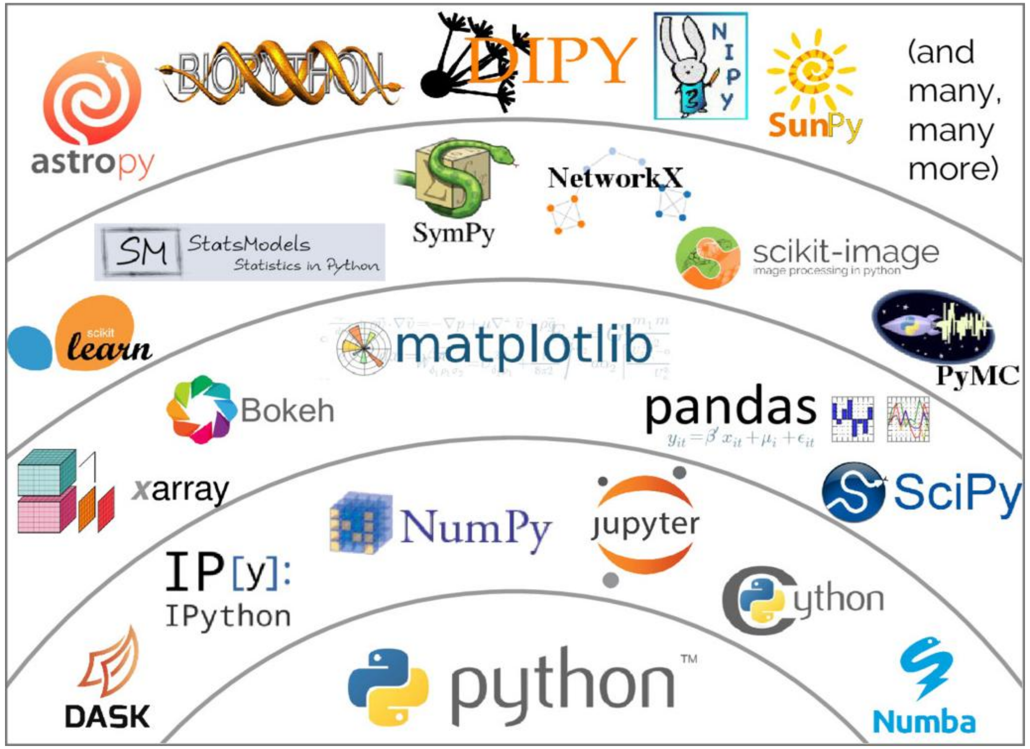
Internal ROOT data format: from TTree to RNtuple





- RNTuple is 10-20% smaller than TTree, resulting in storage saving
- Read throughput improves by x3-x5 with RNtuple

PyHEP ecosystem

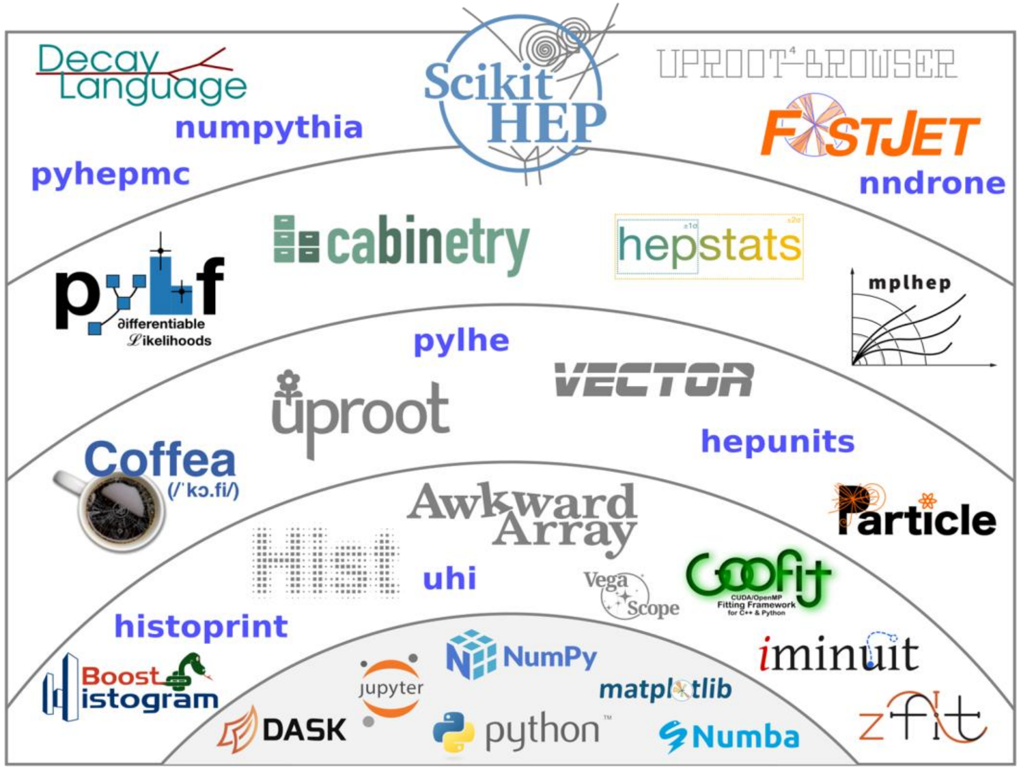


Application Specific

Domain Specific

Technique specific

Foundational



The full HEP ecosystem is of course wider, ROOT being prominent,

Landscape of research software projects

Full list at https://scikit-hep.org/packages

Basics
Awkward(array)
Vector
hepunits

Data manipulation & interoperability
uproot
Coffea
uproot-browser
hepconvert
formulate

Histogramming
boost-histogram
Hist
histoprint
UHI

HEP specific libraries and interfaces to HEP libraries
Particle
DecayLanguage
fastjet
pylhe
pyhepmc

Fitting and Statistics
iminuit
pyhf
cabinetry
resample
hepstats

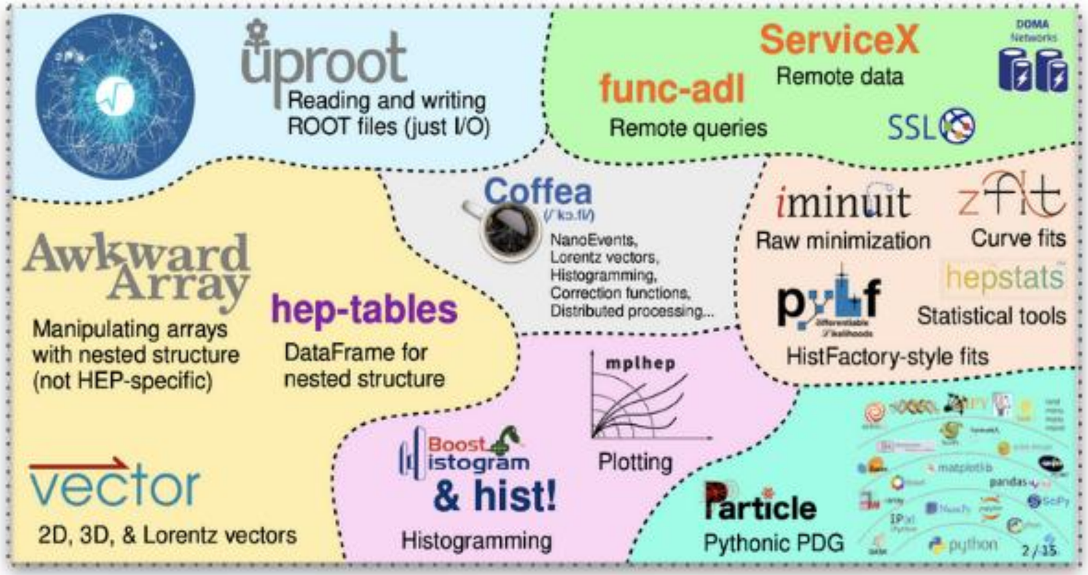
Visualisation
mplhep

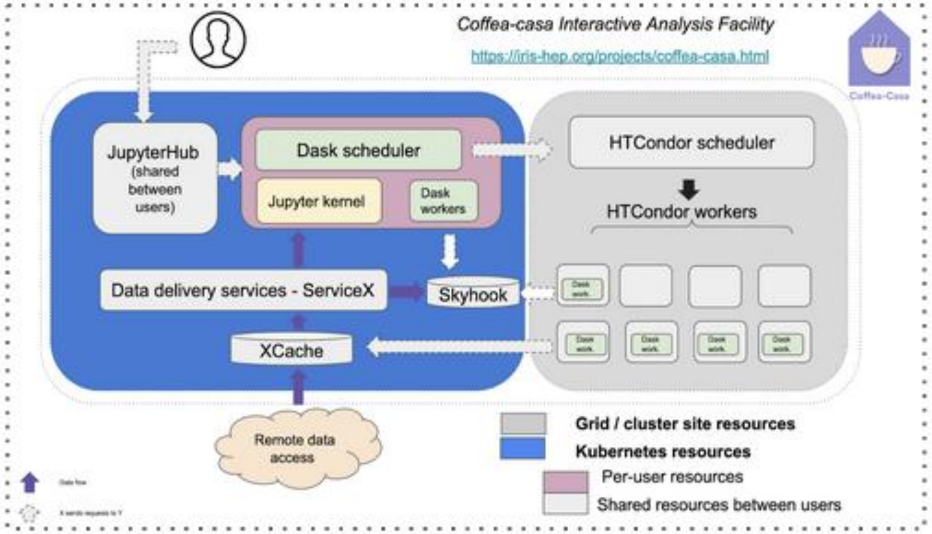
Landscape of research software projects

https://iris-hep.org/projects/agc.html

Analysis Tools

Analysis Facilities
(coffea-casa AF or any other facility matching tech.requirements)

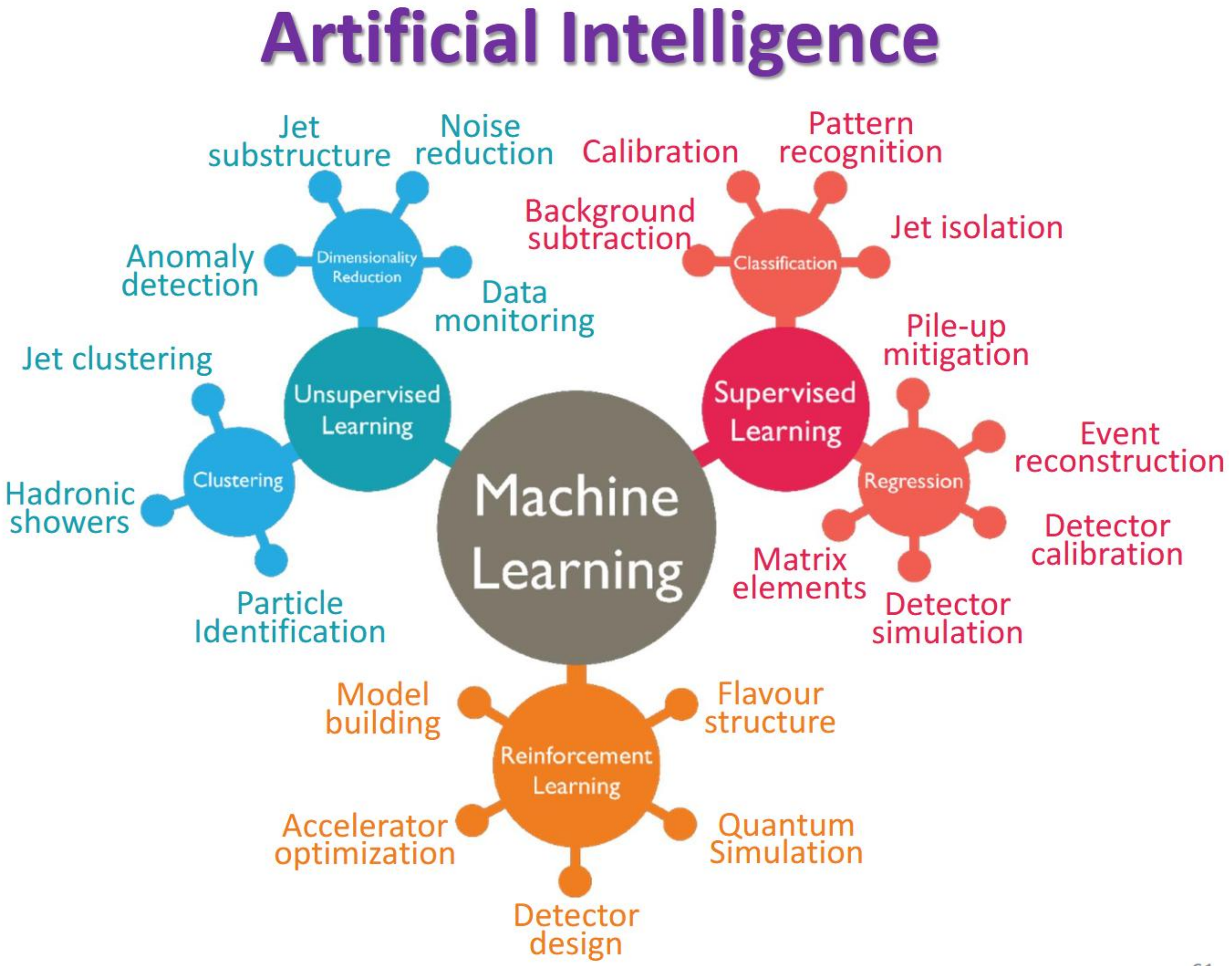


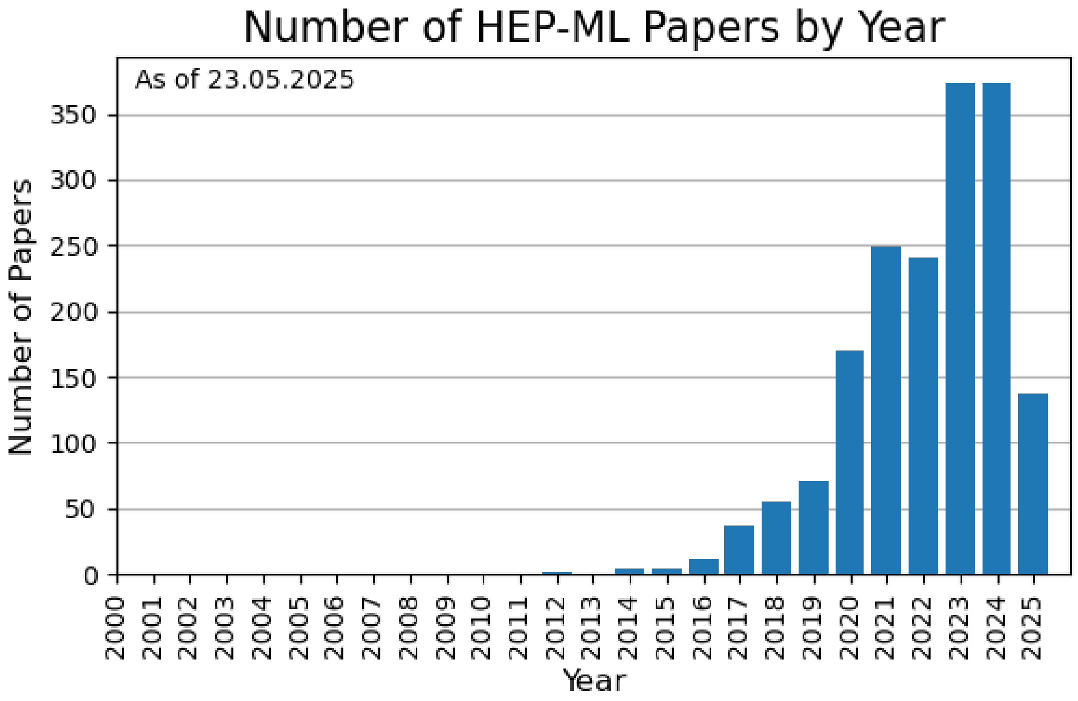


Execution of AGC analysis benchmark

Landscape of research software projects

https://iml-wg.github.io/HEPML-LivingReview/





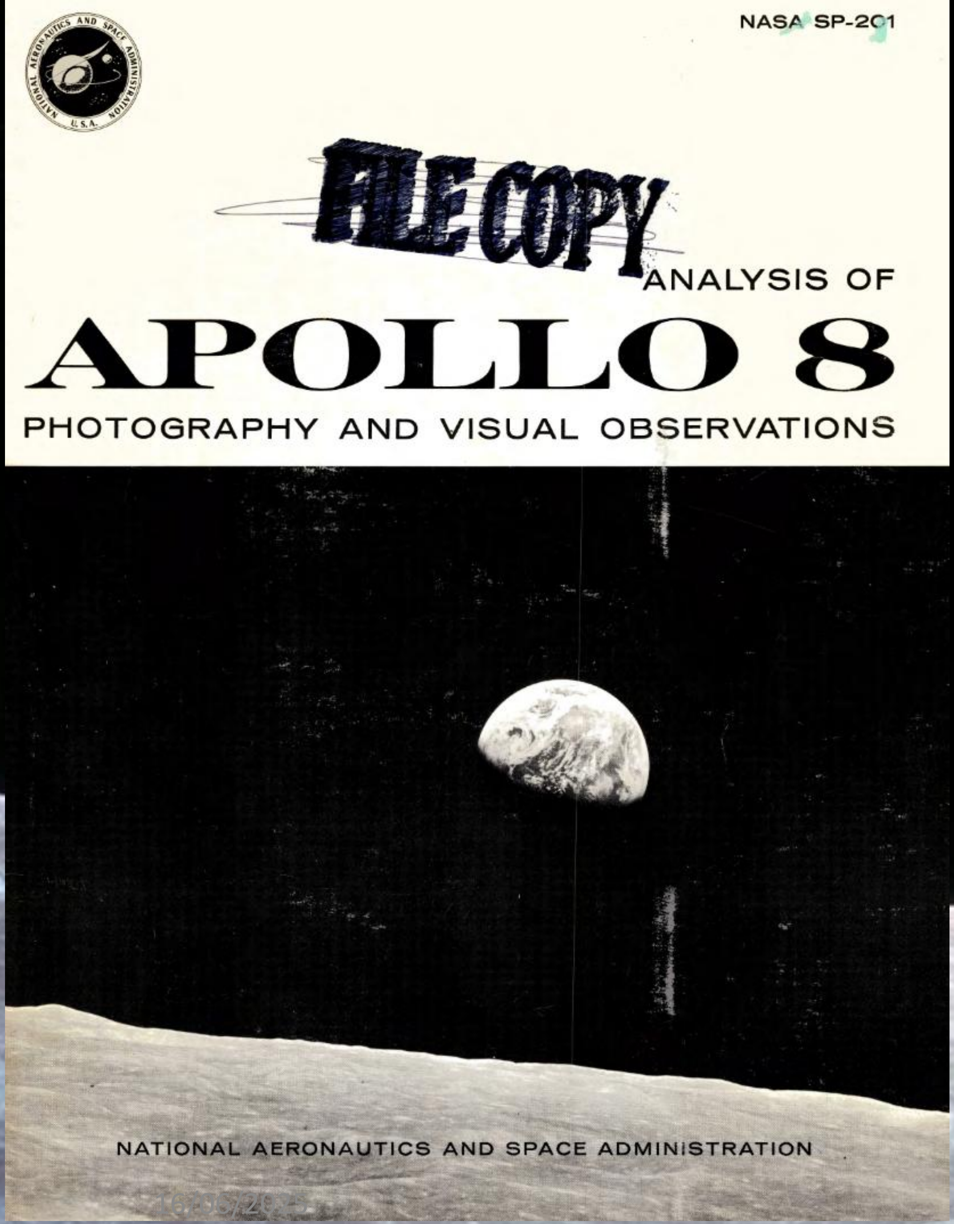
2. Advancements in platforms and architectures.

Advancements in platforms and architectures.

"New directions in science are launched by new tools much more often than by new concepts.
The effect of a concept-driven revolution is to explain old things in new ways.
The effect of a tool-driven revolution is to discover new things that have to be explained."

"Imagined Worlds" (1997) by Freeman Dyson

Advancements in platforms and architectures.

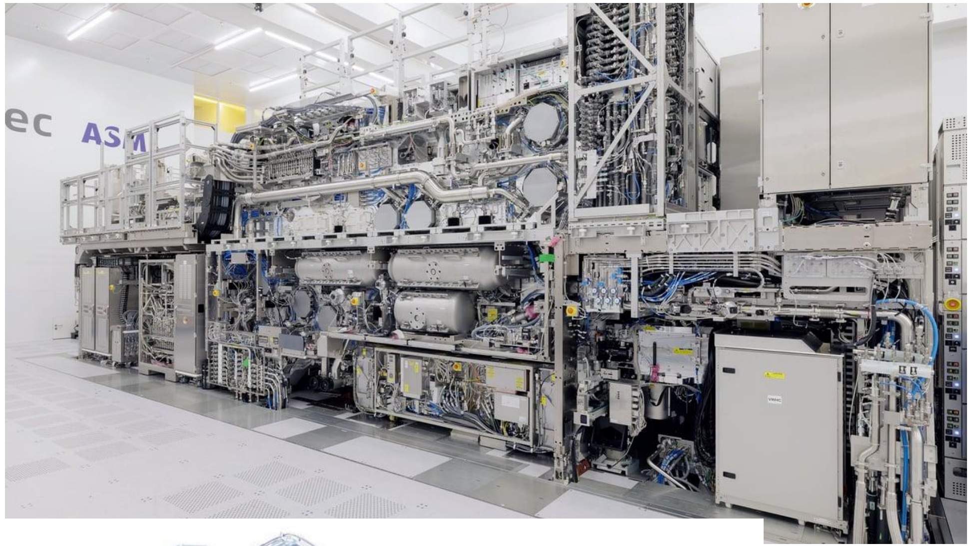


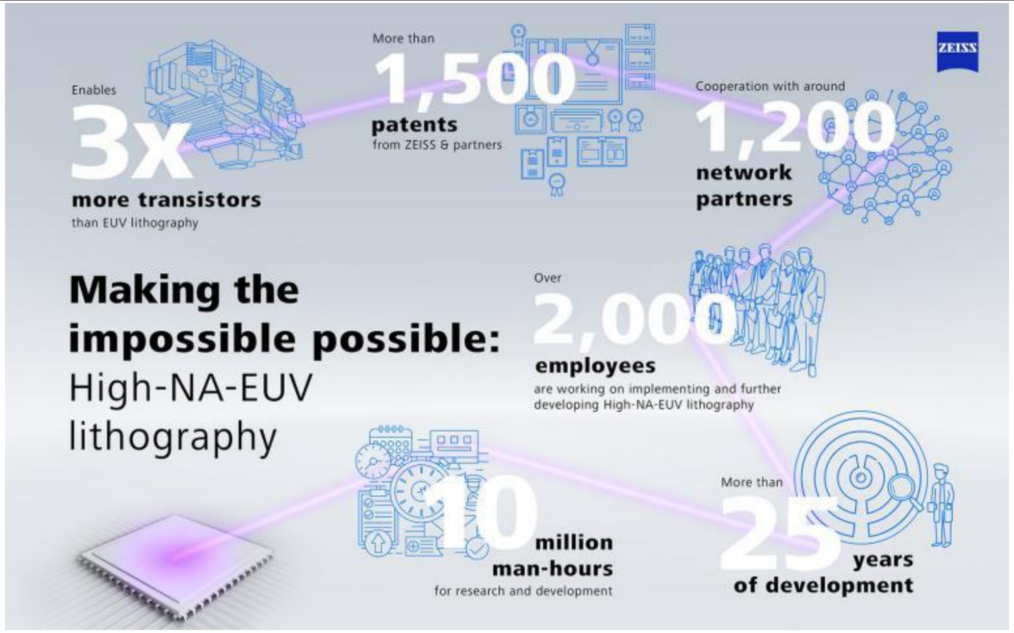
HASSELBLAD ON THE MOON

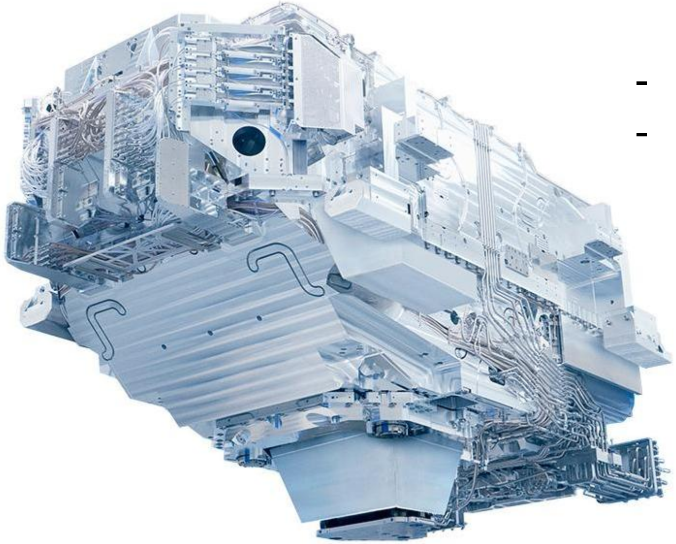
What could be deemed as one of the most iconic moments of Hasselblad in space was when the Apollo 11 mission successfully landed the Eagle on the Moon on 20 July 1969, signifying humanity's first steps off our own planet. A silver Hasselblad Data Camera (HDC) with Réseau plate, fitted with a Zeiss Biogon 60mm ƒ/5.6 lens, was chosen to document the lunar surface and attached to astronaut Armstrong's chest. A second black Hasselblad Electric Camera (HEC) with a Zeiss Planar 80mm ƒ/2,8 lens was used to shoot from inside the Eagle lunar module. The HDC had never been tested in space before, adding to the pressure of this once in a lifetime moment. Would the one Hasselblad camera used to shoot on the lunar surface capture the results everyone was hoping for? Working perfectly under the extreme conditions of the lunar surface, the HDC produced some of history's most iconic photographs. After the successful shooting on 21 July 1969, the Hasselblad was hoisted up to the lunar lander with a line. Securely removing the film magazines, both cameras with lenses were left behind on the Moon in order to meet narrow weight margins for successful return. The journeys home from the Moon made very special demands on what could return regarding weight; from Apollo 11 to the final Apollo 17 mission, a total of twelve camera bodies were left behind on the lunar surface. Only the film magazines containing the momentous images were brought back. The resulting photographs captured the history of humanity in the making.

Advancements in platforms and architectures.

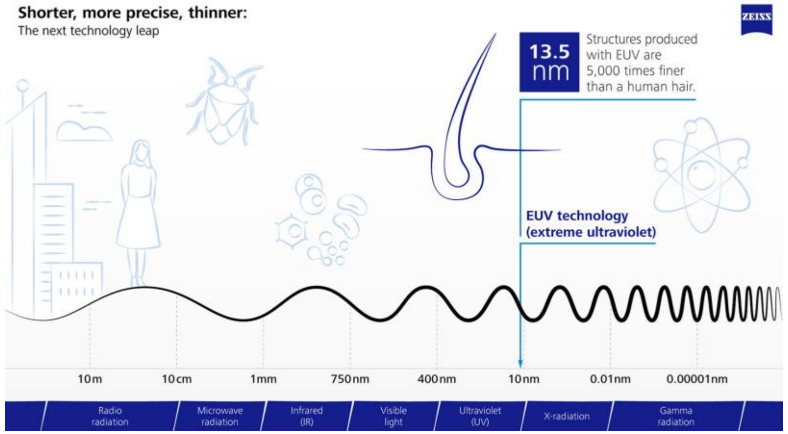
High-NA-EUV lithography at a glance



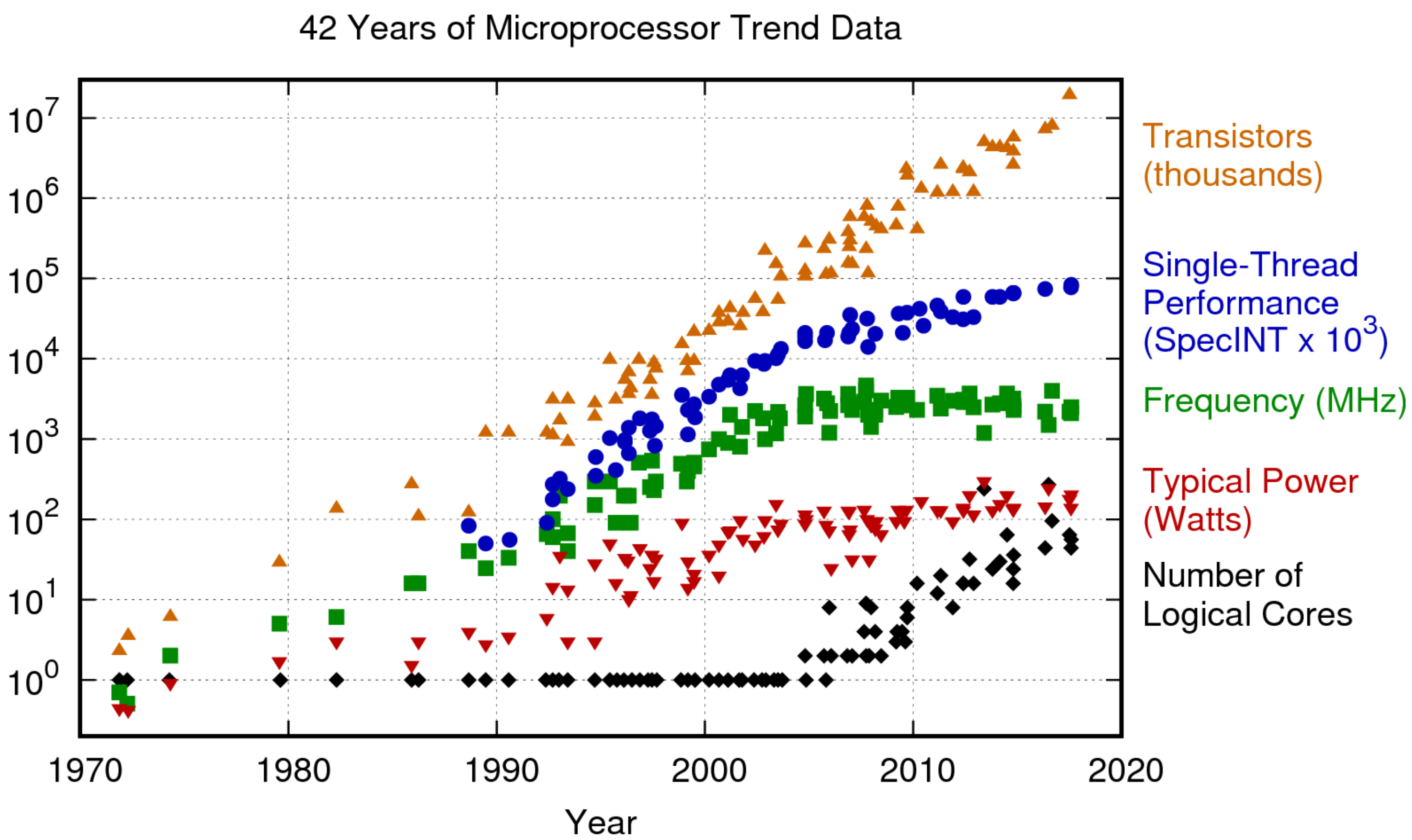




- ASML and Zeiss
- The world's most powerful pulsed industrial laser
  Will enable next generation of chips.
  - Intel 18A and 14A
  - 2.9x more density
  - Simiar plans by TSMC and

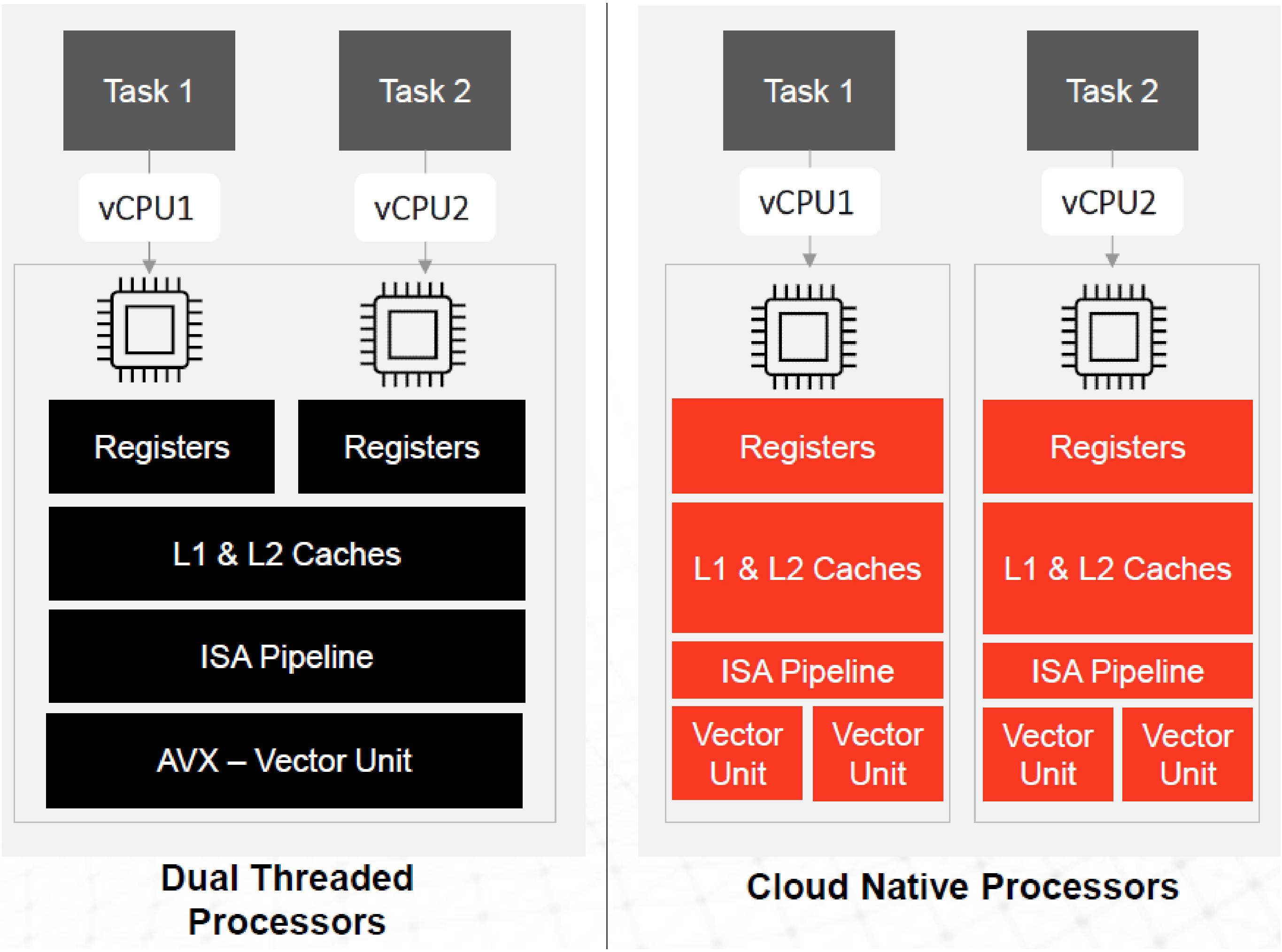


Advancements in platforms and architectures.



Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2017 by K. Rupp

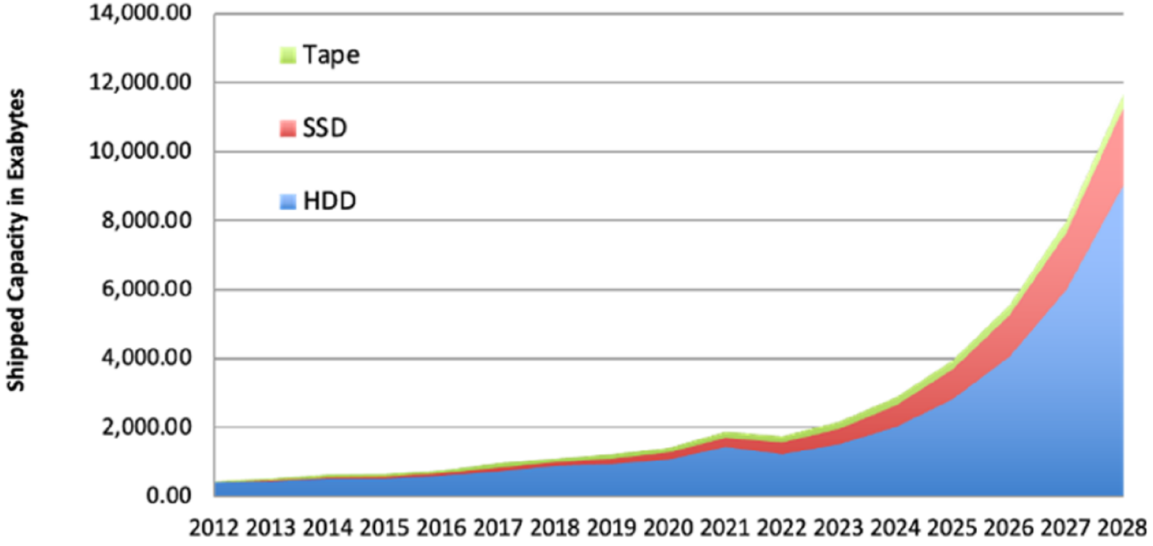
Advancements in platforms and architectures.



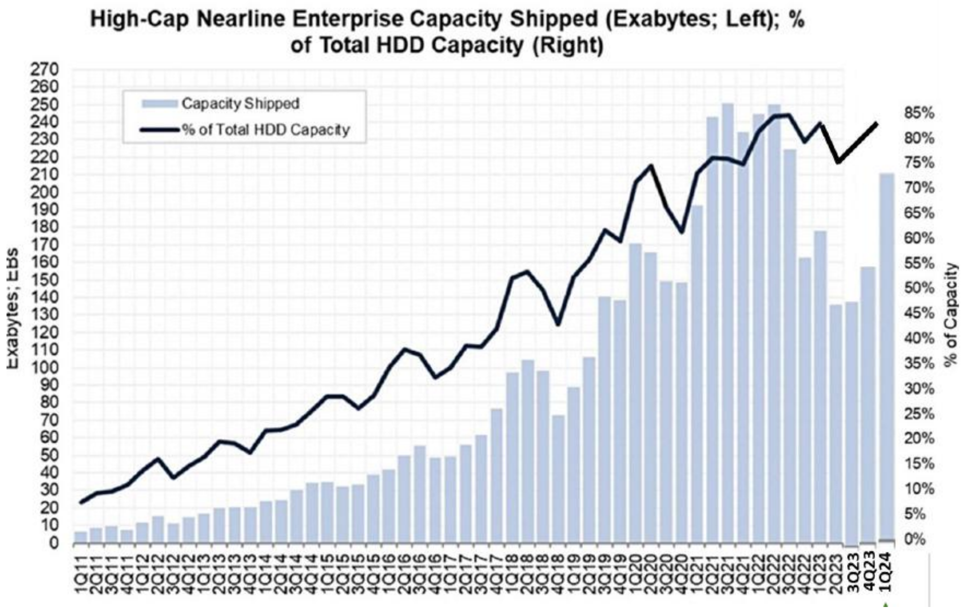
<u>For all workloads</u>

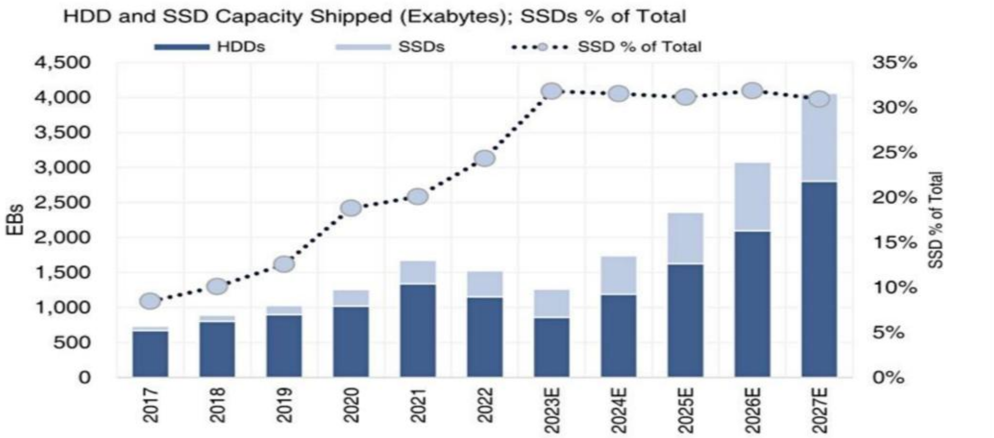
- Private resources in each core
- Resists noisy neighbour influence
- Predictable latency
- Linear Scaling
- Up to 384 Vector Engines
- Scale out requires SW optimisation
- Containerization of services and

Advancements in platforms and architectures.

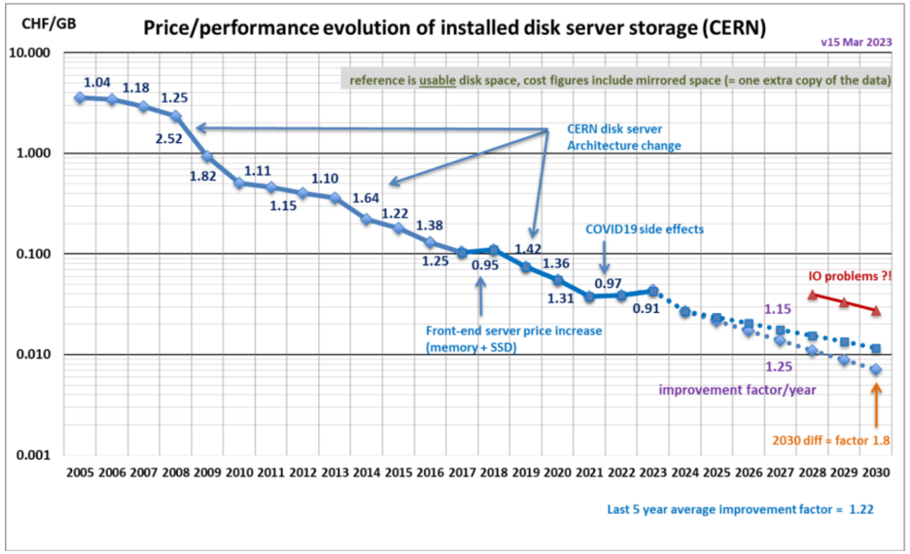


History and Projections for Digital Storage Capacity Shipments of HDDs, SSDs and Magnetic Tape
COUGHLIN ASSOCIATES CHART

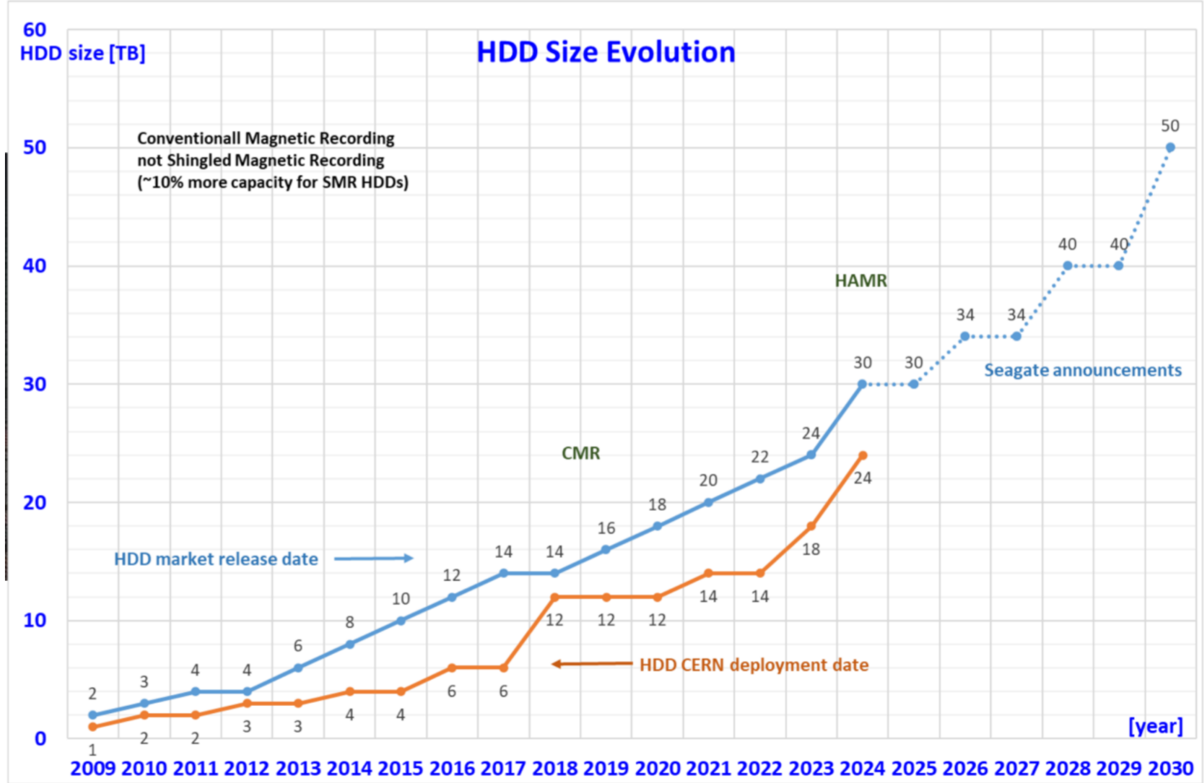


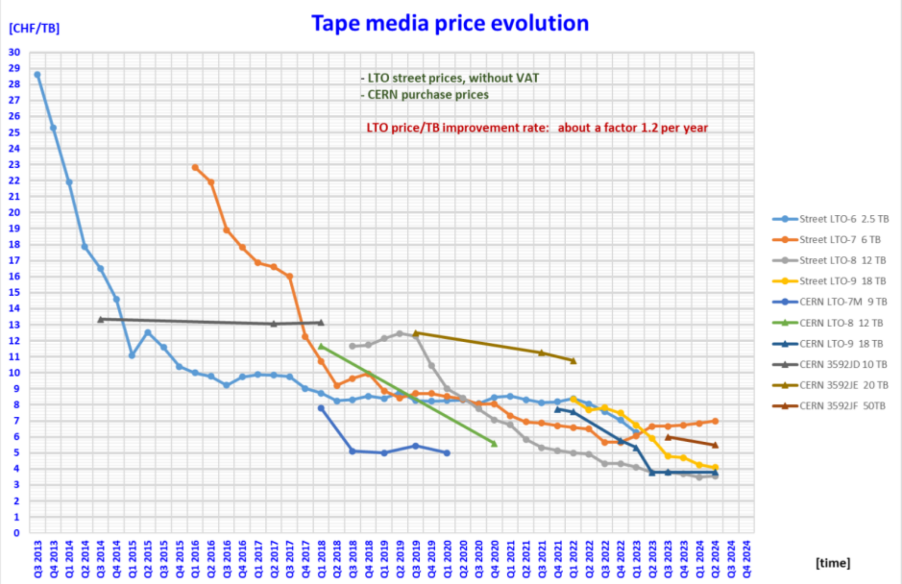


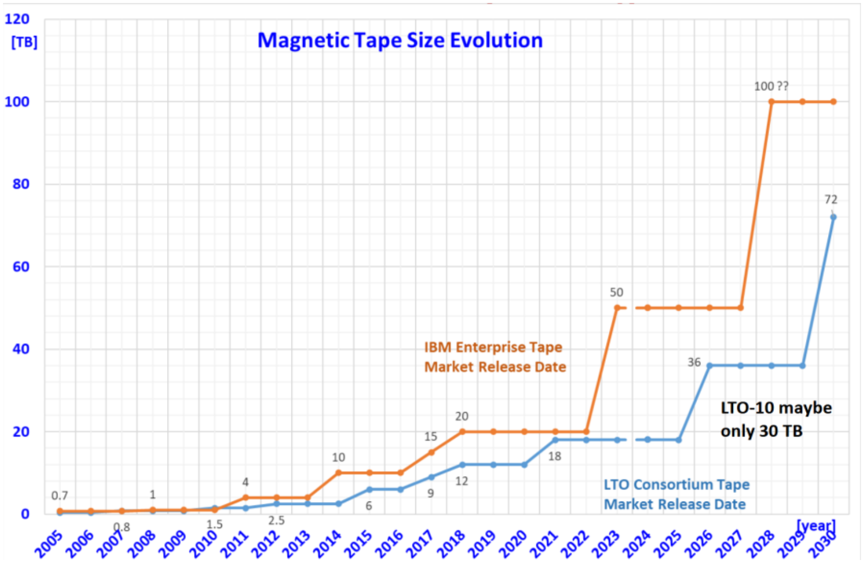
Source: Gartner; Wells Fargo Securities, LLC .



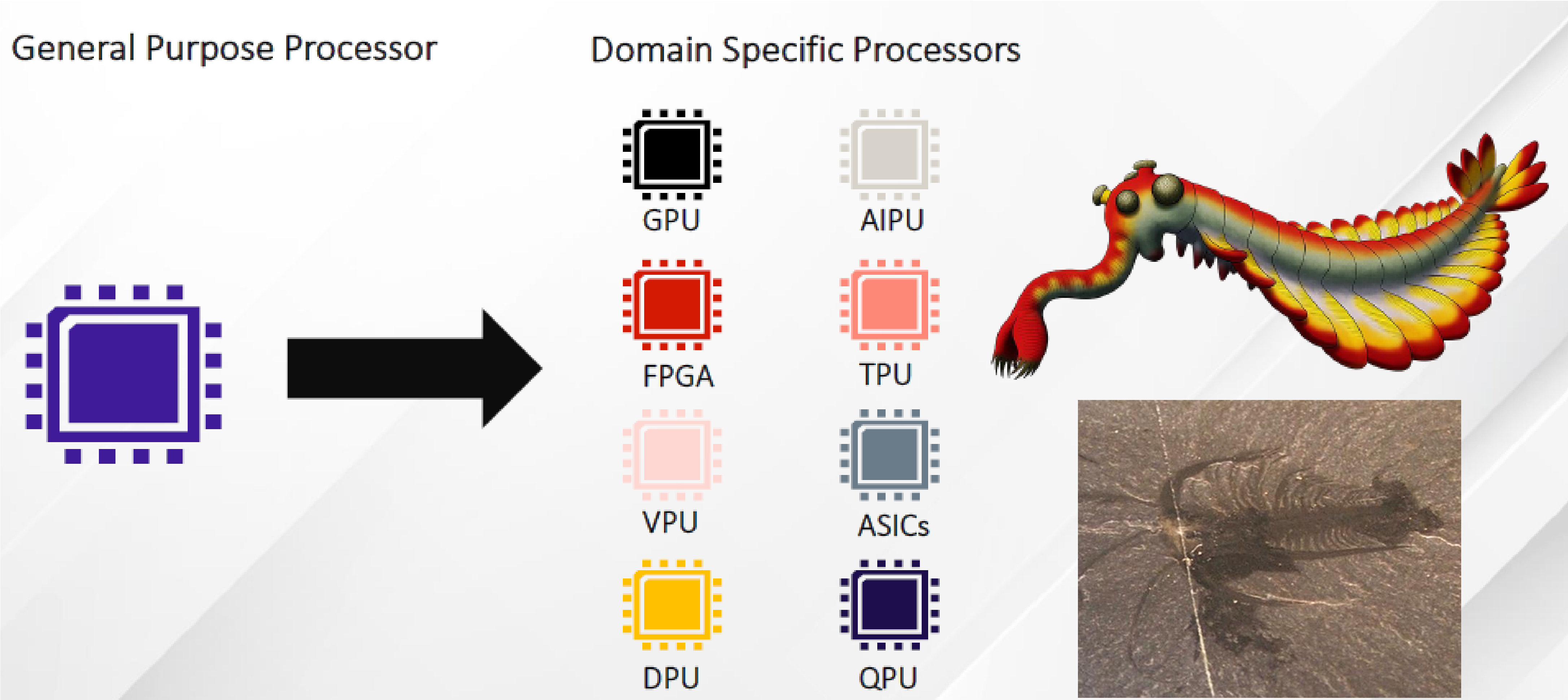
Advancements in platforms and architectures.





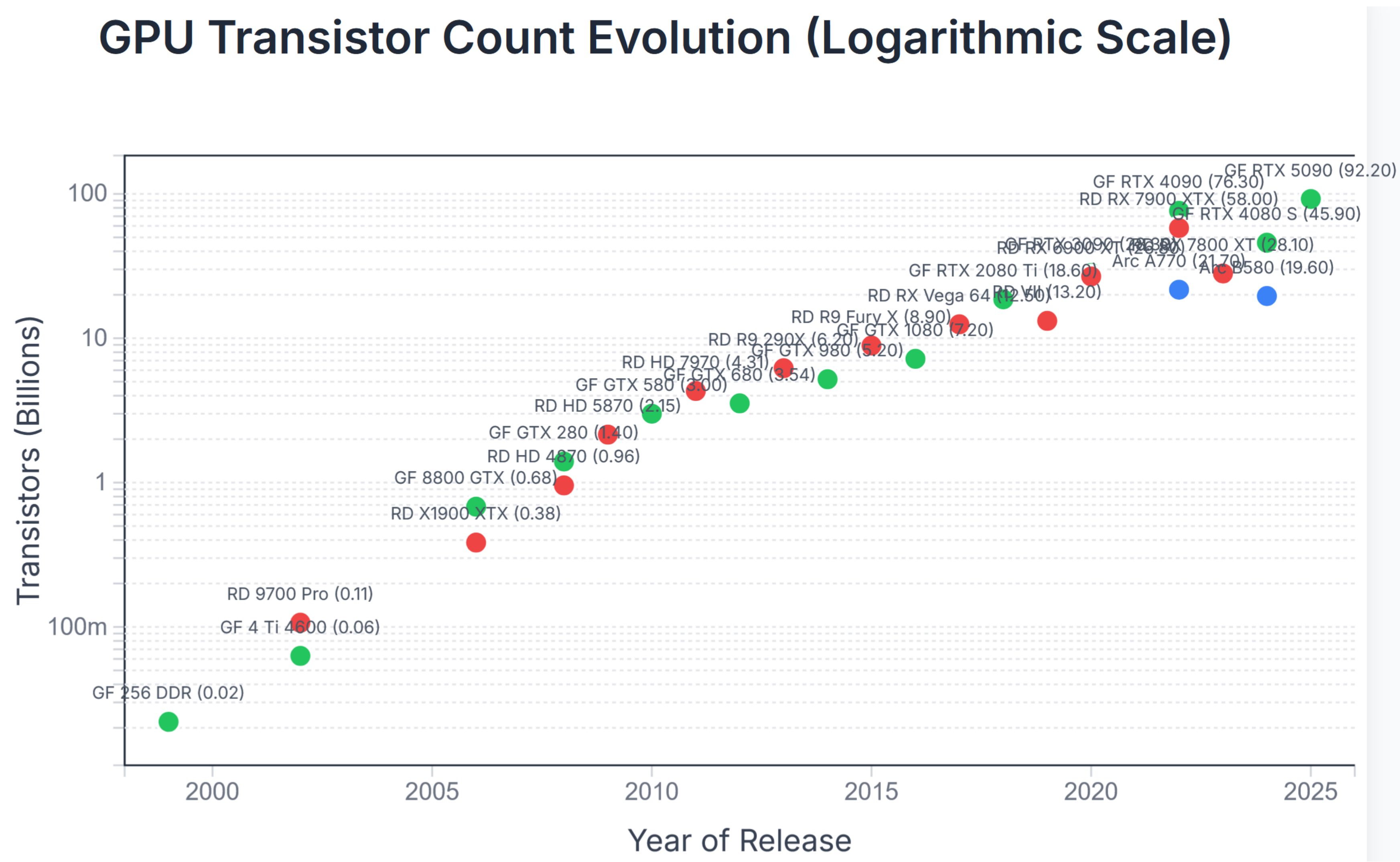


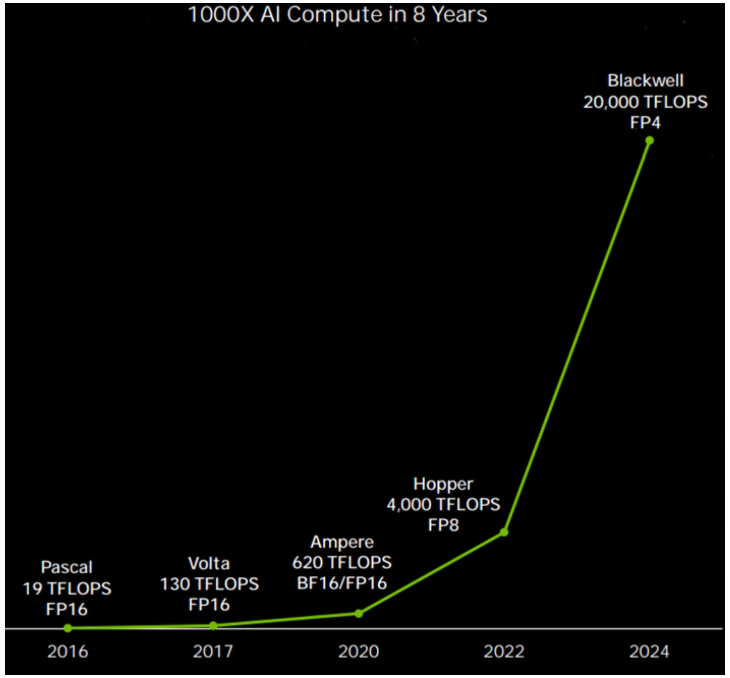
Advancements in platforms and architectures.



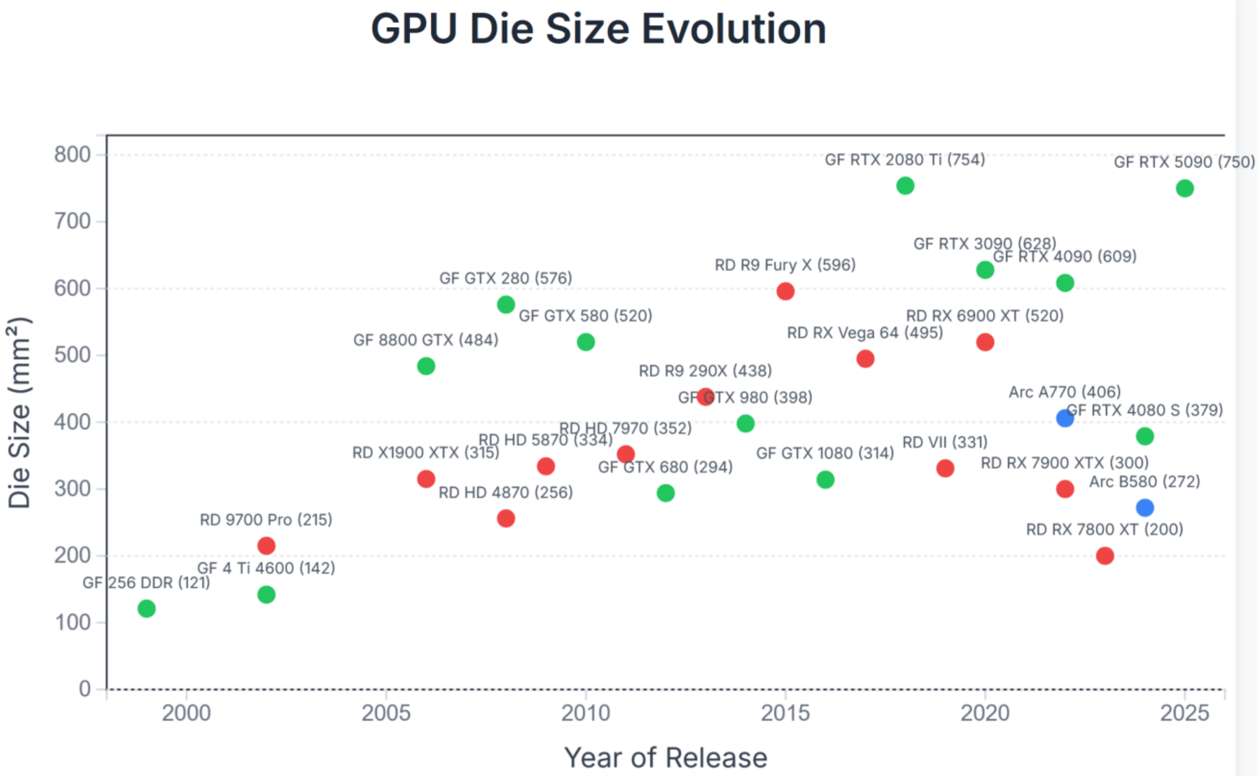
Architecture-aware optimizations in hot sections of our code can yield huge gains overall

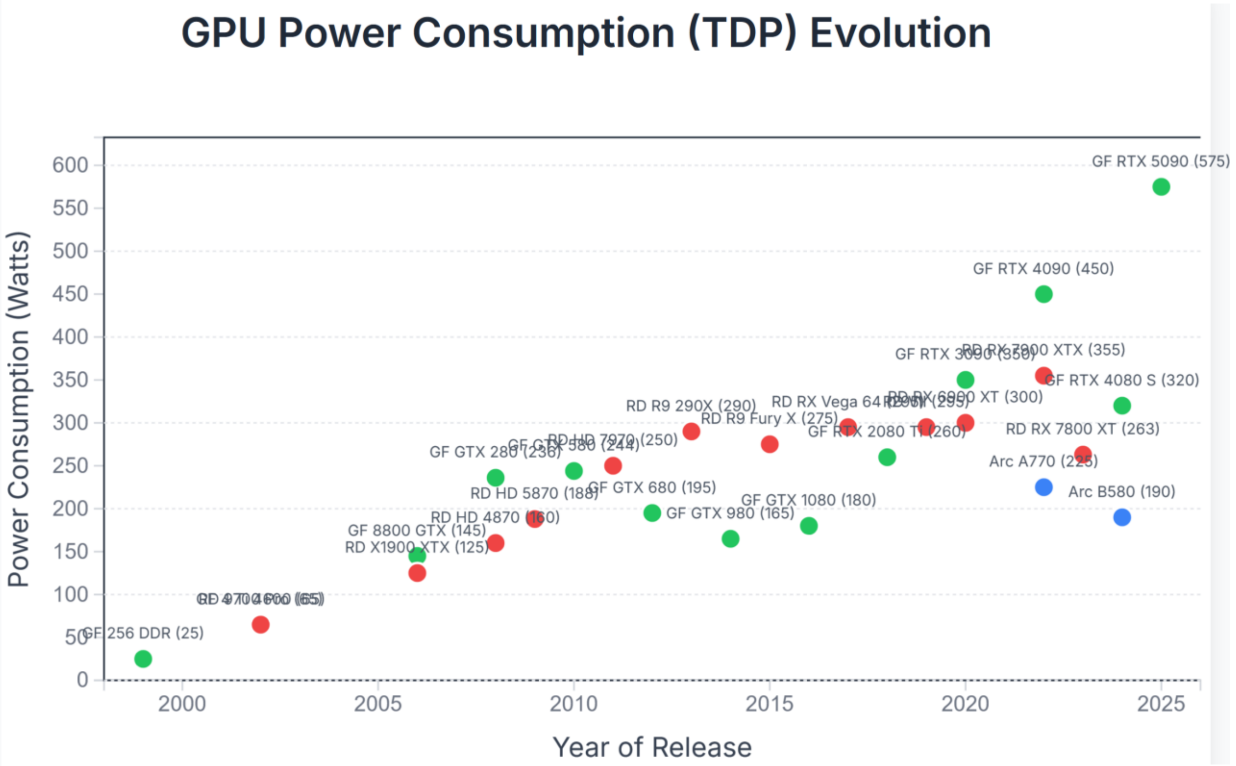
Advancements in platforms and architectures.





Advancements in platforms and architectures.





Advancements in platforms and architectures.

Dielectric-fibre surface waveguides for optical frequencies

[Kao&Hockham 1966](#)

K.C. Kao, B.Sc.(Eng.), Ph.D., A M I E E and G. A. Hockham, B.Sc.(Eng.), Graduate I.E.E.

Synopsis

A dielectric fibre with a refractive index higher than its surrounding region is a form of dielectric waveguide which represents a possible medium for the guided transmission of energy at optical frequencies. The particular type of dielectric-fibre waveguide discussed is one with a circular cross-section. The choice of the mode of propagation for a fibre waveguide used for communication purposes is governed by consideration of loss characteristics and information capacity. Dielectric loss, bending loss and radiation loss are discussed, and mode stability, dispersion and power handling are examined with respect to information capacity. Physical-realisation aspects are also discussed. Experimental investigations at both optical and microwave wavelengths are included.

List of principal symbols

J_n = nth-order Bessel function of the first kind

K_n = nth-order modified Bessel function of the second kind

$\beta = \frac{2\pi}{\lambda g}$, phase coefficient of the waveguide

J'_n = first derivative of J_n

K'_n =first derivative of J_n

h_I= radial wavenumber or decay coefficient

Ei relative permittivity

k_o free-space propagation coefficient

a = radius of the fibre

y = longitudinal propagation coefficient

k = Boltzman's constant(

T = absolute temperature, deg K

β_c = isothermal compressibility

λ = wavelength

n refractive index

$H_v^{(i)}$ = vth-order Hankel function of the ith type

H'_v = derivation of H_v

v = azimuthal propagation coefficient = $v_1 - jv_2$ —

L = modulation period

Subscript n is an integer and subscript m refers to the mth root of J_n=0

I Introduction

A dielectric fibre with a refractive index higher than its surrounding region is a form of dielectric waveguide which represents a possible medium for the guided transmission of energy at optical frequencies. This form of structure guides the electromagnetic waves along the definable boundary between the regions of different refractive indexes. The associated electromagnetic field is carried partially inside the fibre and partially outside it. The external field is evanescent in the direction normal to the direction of propagation, and it decays approximately exponentially to zero at infinity. Such structures are often referred to as open waveguides, and the propagation is known as the surface-wave mode. The particular type of dielectric-fibre waveguide to be discussed is one with a circular cross-section.

2 Dielectric-fibre waveguide

The dielectric fibre with a circular cross-section can support a family of H_{om} and E_{om} modes and a family of hybrid HE_{nm} modes. Solving the Maxwell equations under the boundary conditions imposed by the physical structure, the characteristic equations are as follows:

for HE_{nm} *modes*

$$\frac{n^2\beta^2}{k_o}\left(\frac{1}{u_1^2}+\frac{1}{u_2^2}\right)^2 = \left[\frac{E_1}{u_1}\frac{J'_n(u_1)}{J_n(u_1)}+\frac{E_2}{u_2}\frac{K'_n(u_2)}{K_n(u_2)}\right] \times \left[\frac{1}{u_1}\frac{J'_n(u_1)}{J_n(u_1)}+\frac{1}{u_2}\frac{K'_n(u_2)}{K_n(u_2)}\right] \quad (1)$$

for E_{om} modes

$$\frac{E_1}{u_1}\frac{J'_o(u_1)}{J_o(u_1)} = -\frac{E_2}{u_2}\frac{K'_o(u_2)}{K_o(u_2)} \quad (2)$$

for H_{om} modes

$$\frac{1}{u_1}\frac{J'_o(u_1)}{J_o(u_1)} = -\frac{1}{u_2}\frac{K'_o(u_2)}{K_o(u_2)} \quad (3)$$

The auxiliary equations defining the relationship between u_1 and u_2 are

$$u_1^2 + u_2^2 = (k_o a)^2 (E_1 - E_2)$$

$$h_1^2 = y^2 + k_o^2 E_1$$

$$-h_2^2 = y^2 + k_o^2 E_2$$

$u_i = h_i a$, i = 1 and 2

where subscripts 1 and 2 refer to the fibre and the outer region, respectively.

All the modes exhibit cutoffs except the HE_{11} mode, which is the lowest-order hybrid mode. It can assume two orthogonal polarisations, and it propagates with an increasing percentage of energy outside the fibre as the dimensions of the structure decrease. Thus, when operating the waveguide in the HE_{11} mode, it is possible to achieve a single-mode operation by reducing the diameter of the fibre sufficiently. Under this condition, a significant proportion of the energy is carried outside the fibre. If the outside medium is of a lower loss than the inside dielectric medium, the attenuation of the waveguide is reduced. With these properties, HE_{11} mode operation is of particular interest.

The physical and electromagnetic aspects of the dielectric-fibre waveguide carrying the HE_{11} mode for use at optical frequencies will now be studied in detail. Conclusions are drawn as to the feasibility and the expected performance of such a waveguide for long-distance-communication application.

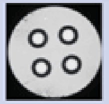
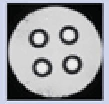
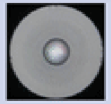
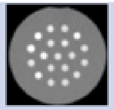
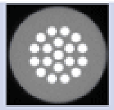
1151

Paper 5033 E, first received 24th November 1965 and in revised form 15th February 1966.
Dr Kao and Mr. Hockham are with Standard Telecommunication Laboratories Ltd., Harlow, Essex, England
PROC. IEE, Vol. 113, No. 7, JULY 1966

Nobel Prize in Physics in 2009

World Record Achieved in Transmission Capacity and Distance: With 19-core Optical Fiber with Standard Cladding Diameter 1,808 km Transmission of 1.02 Petabits per Second

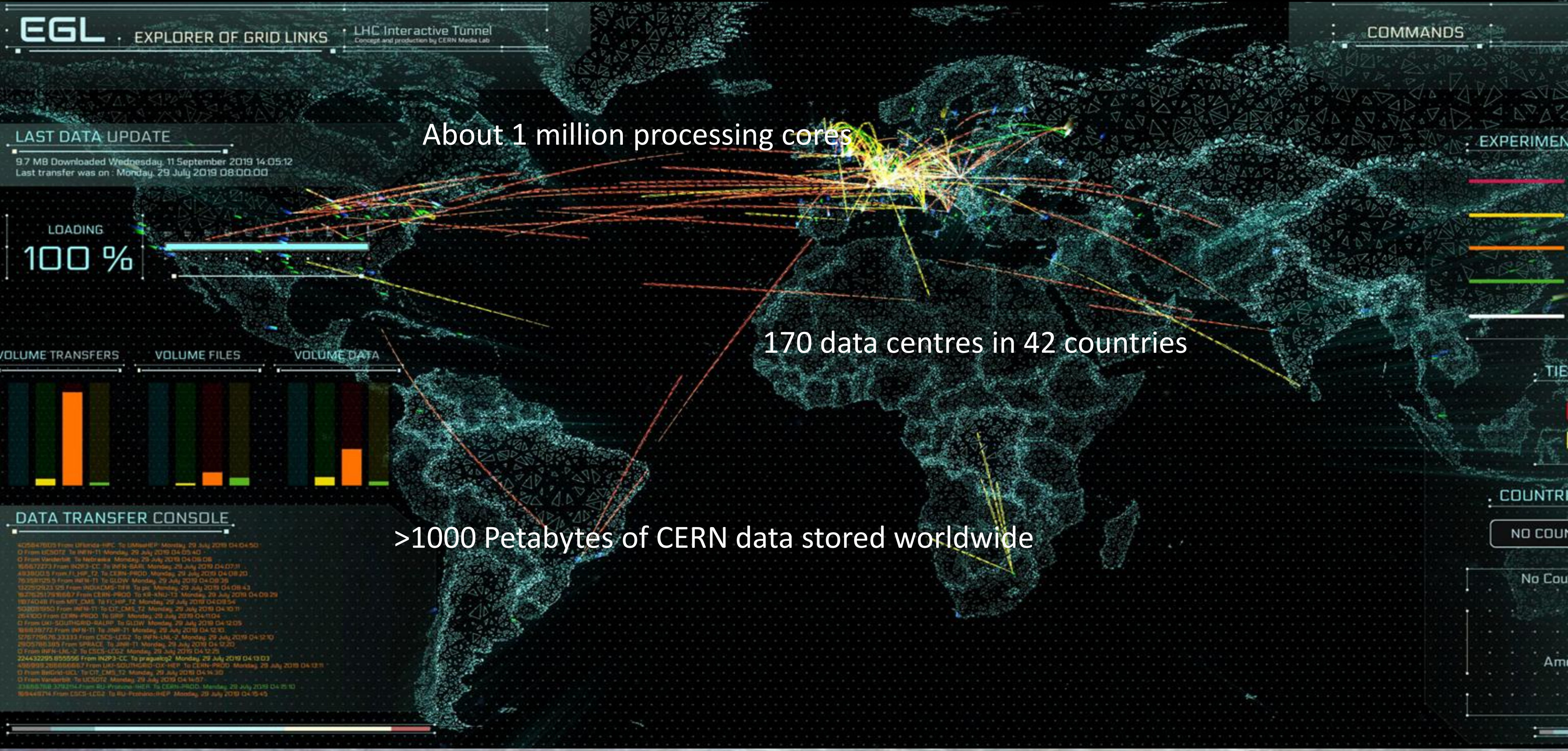
- Expectation for Future Long-Distance High-Capacity Optical Communication Infrastructure -

Optical Fiber	Uncoupled 4-Core Fiber	Uncoupled 4-Core Fiber	15-Mode Fiber	Coupled 19-Core Fiber	Achievement New Coupled 19-Core Fiber
Cross-sectional View					
Achieved Records	Jun. 2021	Oct. 2023	Mar. 2023	Mar. 2023	Apr. 2025
Data Rate (petabit/s)	0.319	0.138	0.273	1.7	1.02
Distance(km)	3,001	12,345	1,001	63.5	1,808
Capacity Distance Product (exabit / s・km)	0.95	1.71 Previous World Record	0.27	0.107	1.86 World Record
Wavelength Bands	S, C, L	S, C, L	C	C, L	C, L
MIMO Processing Load	None	None	Large	Moderate	Moderate

https://www.nict.go.jp/en/press/2025/05/29-1.html

3. HEP Computing Infrastructure: WLCG.

The Worldwide LHC Computing Grid (WLCG): Our cyberinfrastructure

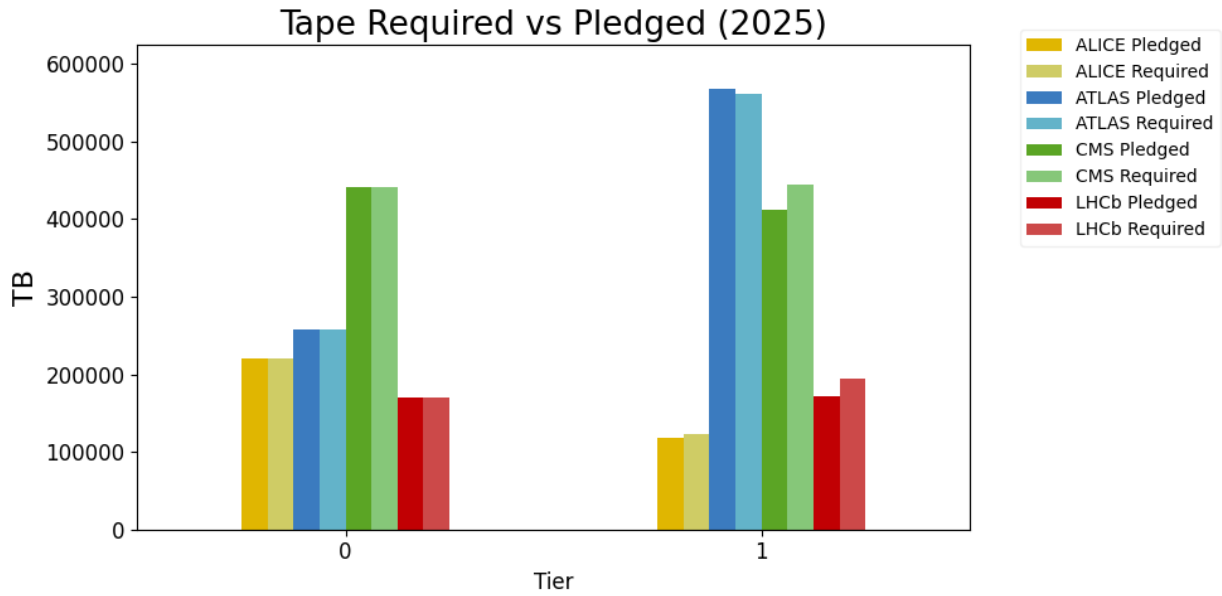


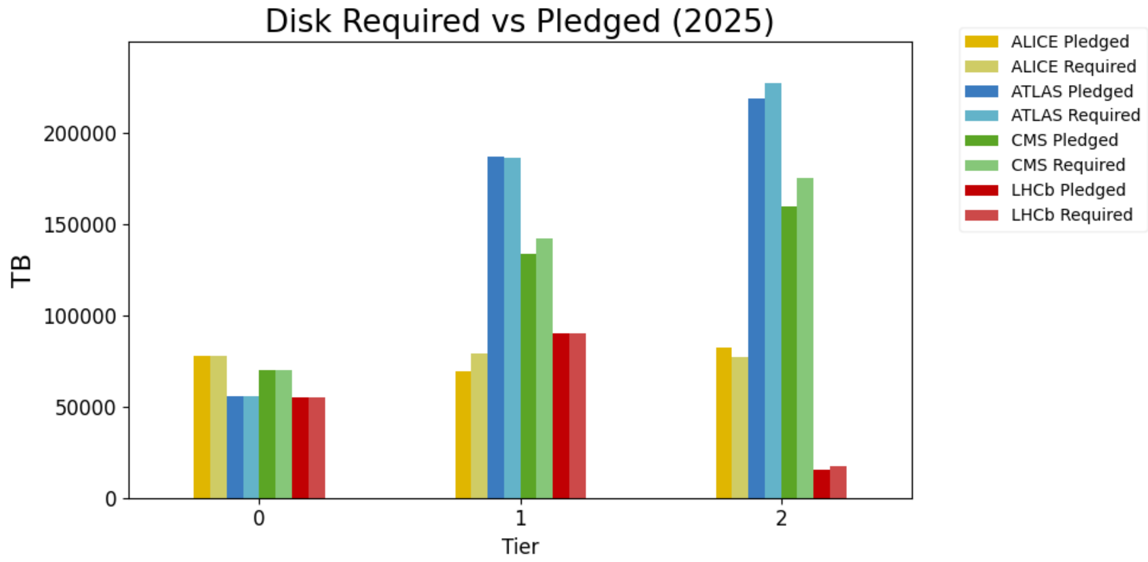
About 1 million processing cores

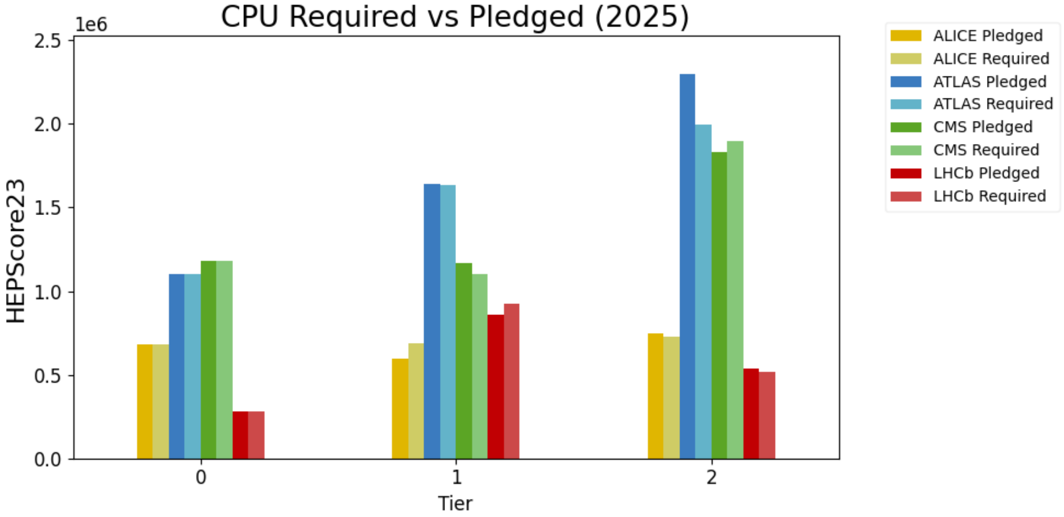
170 data centres in 42 countries

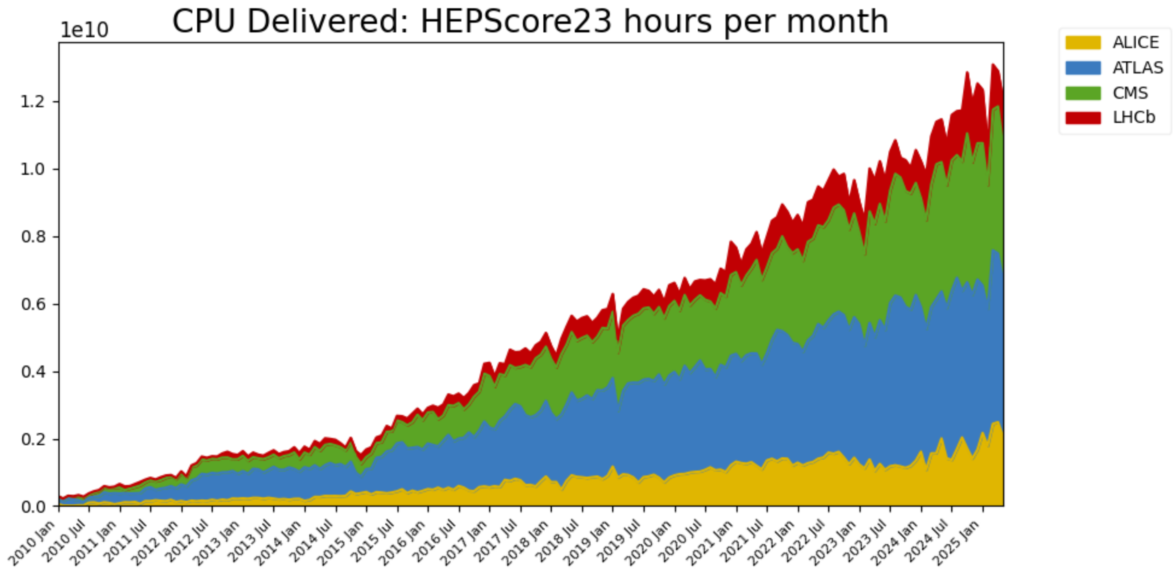
>1000 Petabytes of CERN data stored worldwide

HEP Computing Infrastructure: WLCG: Resource projection

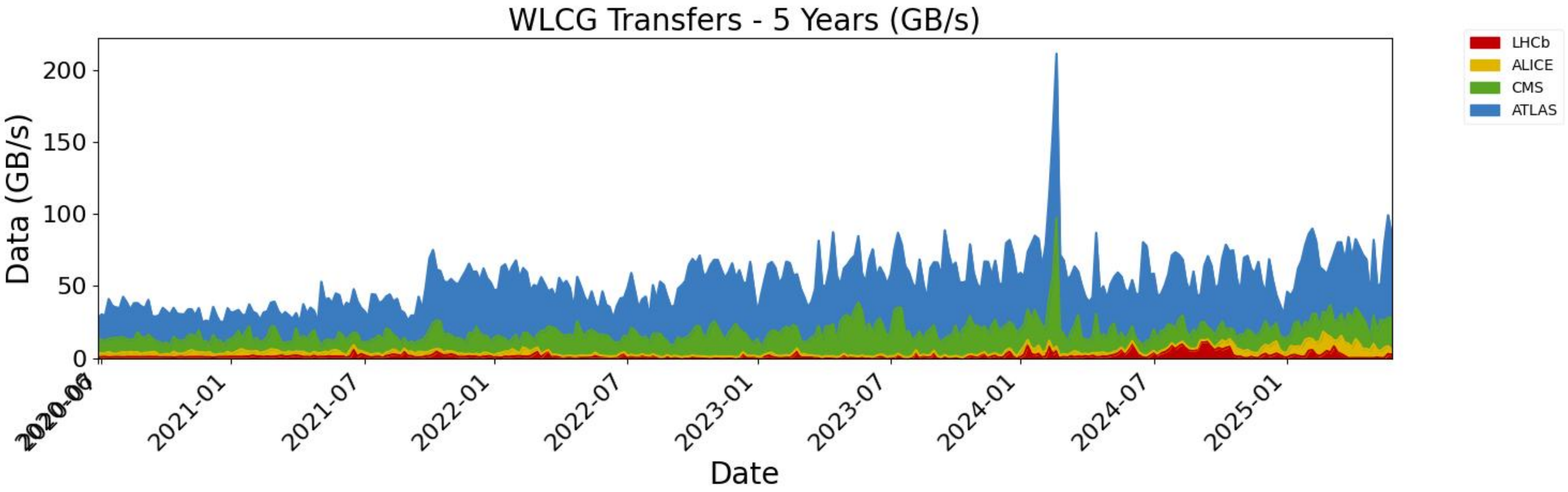


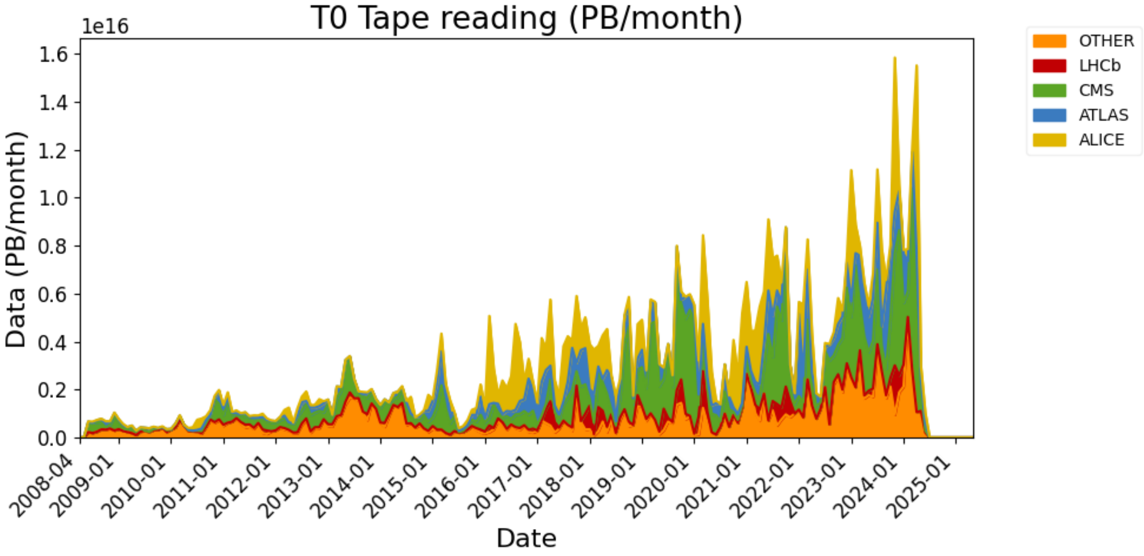


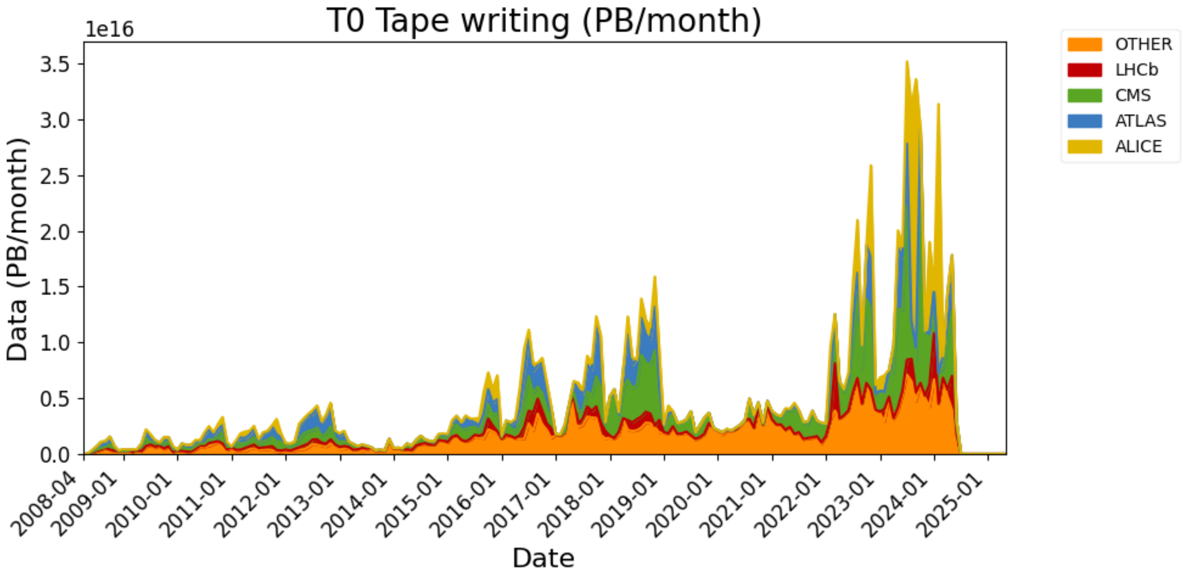




HEP Computing Infrastructure: WLCG: Resource projection

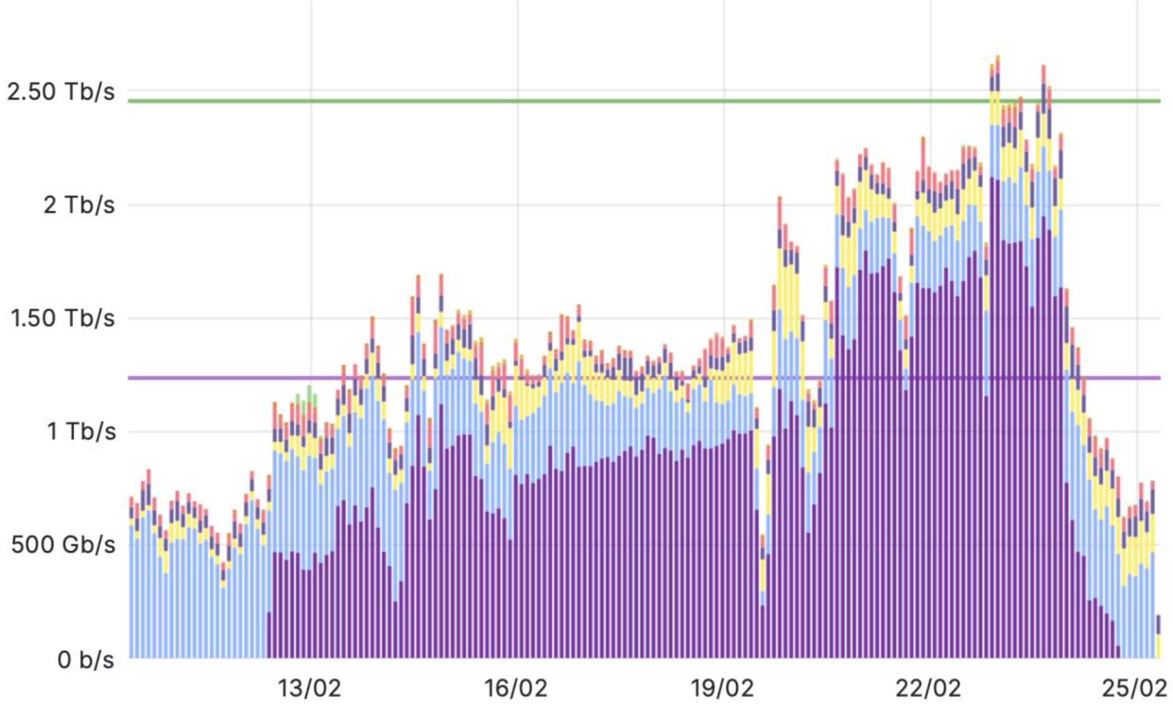




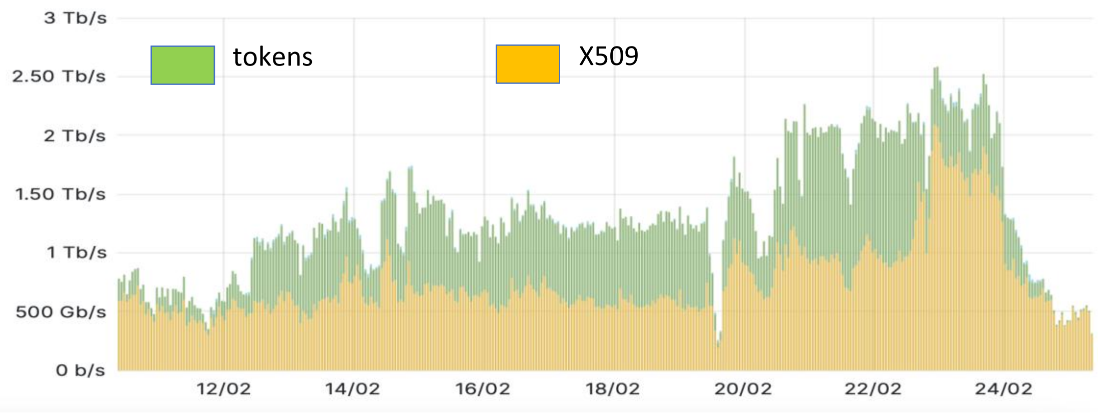


HEP Computing Infrastructure: WLCG: Data challenge

DC24 WLCG data transfers (Gbps) – 15 days: **all targets achieved**



New technologies (e.g. authentication tokens) introduced and validated



WLCG services successfully support DUNE and Belle-2 computing models

HEP Computing Infrastructure: AGC

200 Gbps →

180 TB dataset · *25% of file content* · *30 minutes*

CMS NanoAOD example

With **2 kB / event**, this means

- **90 B events,**
- **50 MHz event rate,**

or 1k cores with 50 kHz and 25 MB/s each.

ATLAS PHYSLITE example

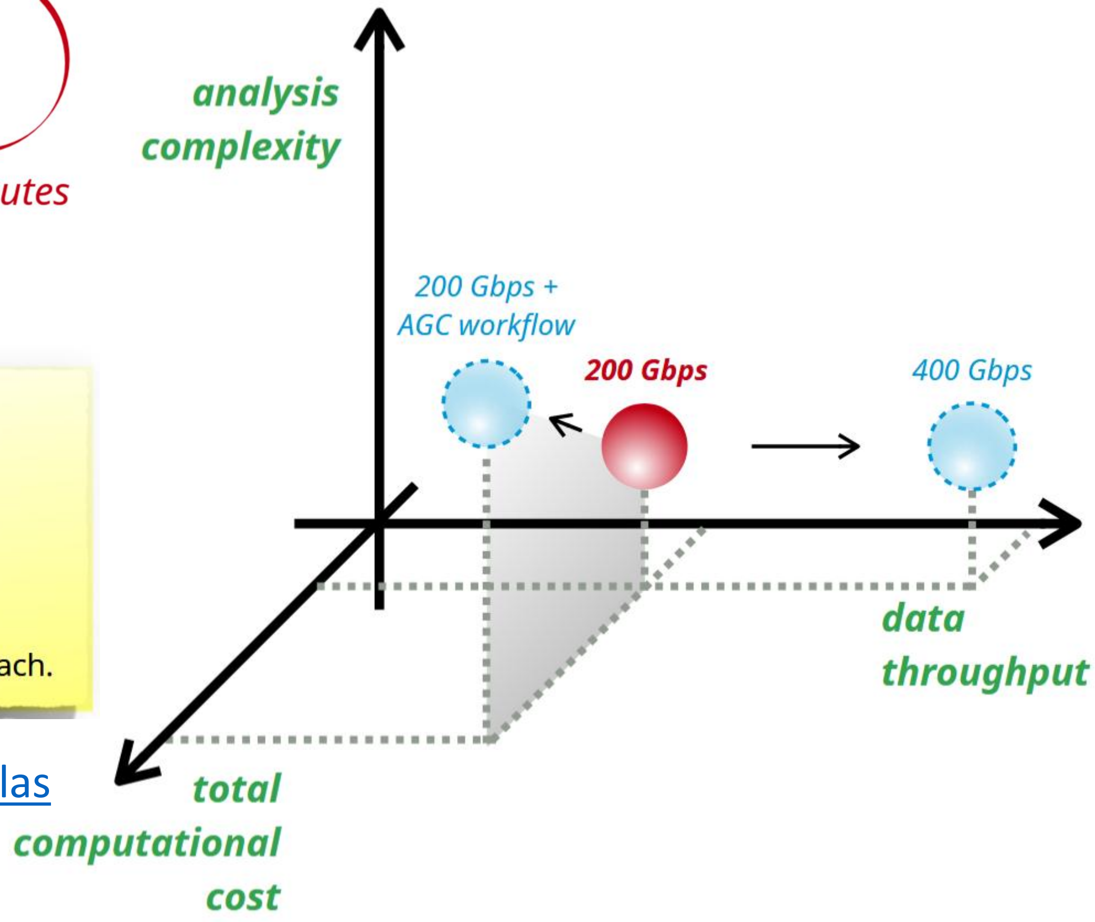
With **10 kB / event**, this means

- **18 B events,**
- **10 MHz event rate,**

or 2k cores with 5 kHz and 12.5 MB/s each.

iris-hep/idap-200gbps

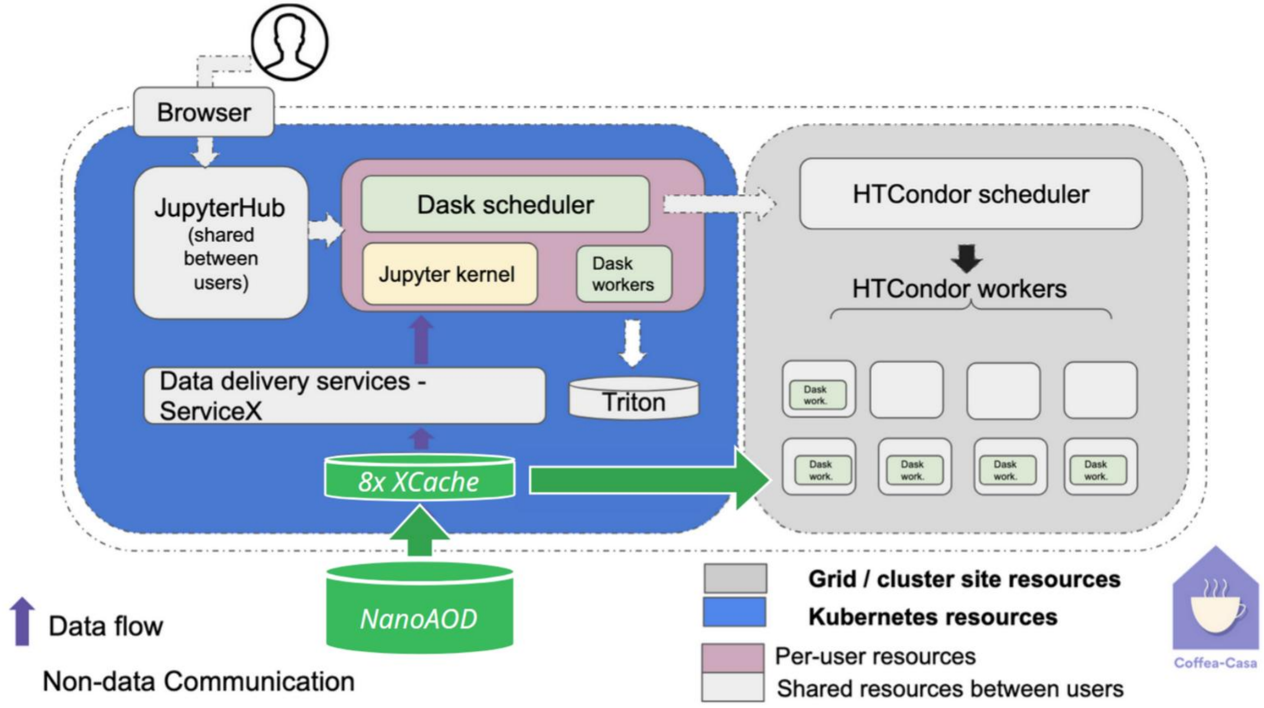
iris-hep/idap-200gbps-atlas



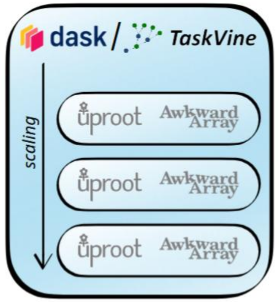
HEP Computing Infrastructure: AGC

CHEP24_AGC

HL-LHC physics analyses: 200 Gbps Challenge

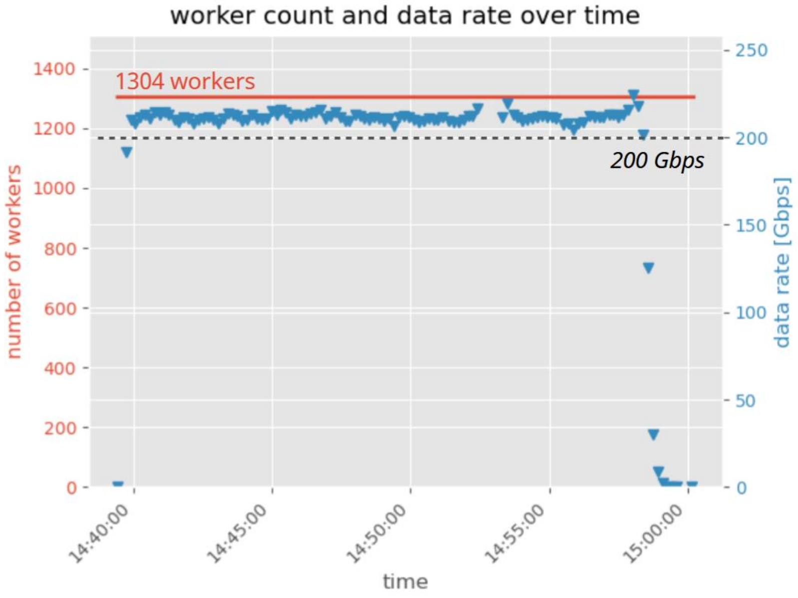


using 8 XCache instances behind 2x100 Gbps uplink each



Details for this example:

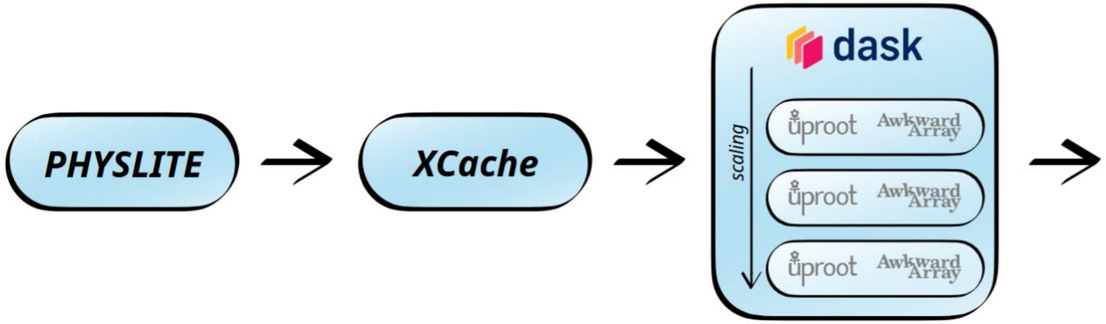
- 40 B events, 64k files
- 1304 workers
- 32 MHz event rate
- data processed (compressed): 30 TB
- data processed (uncompressed): 71 TB

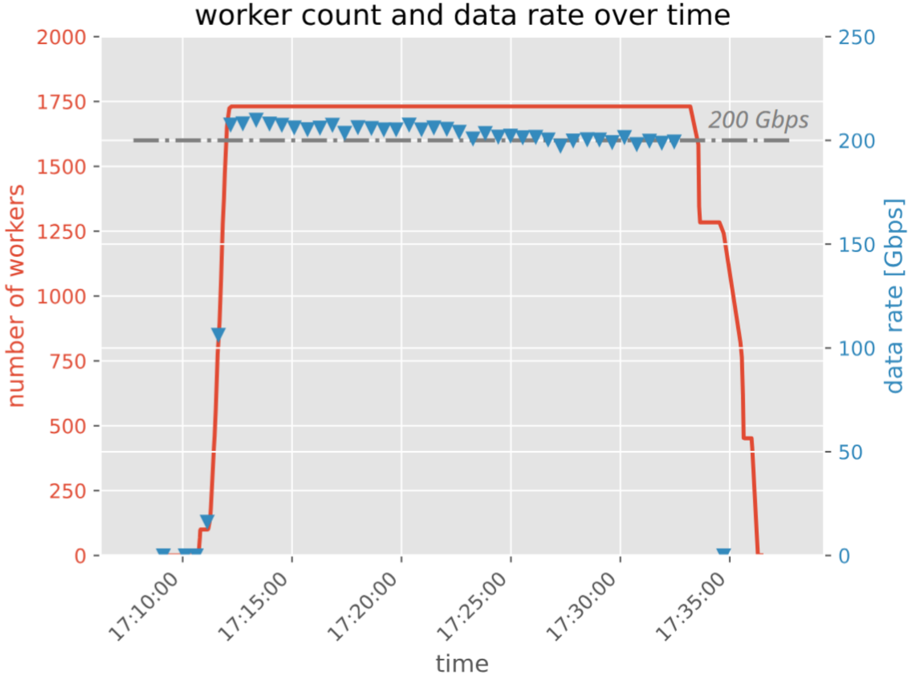


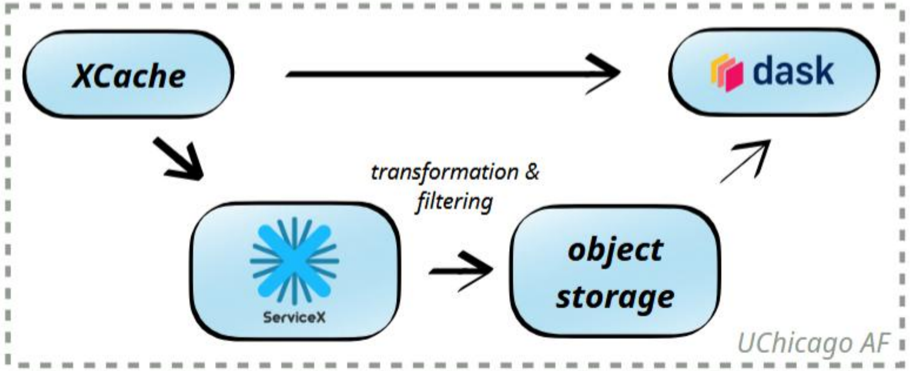
200+ Gbps with Dask + HTCondor

HEP Computing Infrastructure: AGC

- **200 Gbps sustained throughput of data for physics**







More details:

- 32 B events, 190 TB data, 218k files
- 1739 workers peak
- 15 MHz event rate, 5–20 kHz per core
- 200 Gbps throughput sustained
- data processed (compressed): 32 TB
- data processed (uncompressed): 80 TB

3. Languages and software engineering.

What if we could talk to a computer in a language closer to English

"The most dangerous phrase in the language is, ‘We’ve always done it this way.’”

Grace Hopper,
1952, Developer of world’s first Compiler (A-O)

Modern software project stack example

Executables (build)

GNU Make

CMake

Performance portability layer
(Backend header only files, BackendCommon.h, CPUID.h, CUDABackend.h, HIPBackend.h)

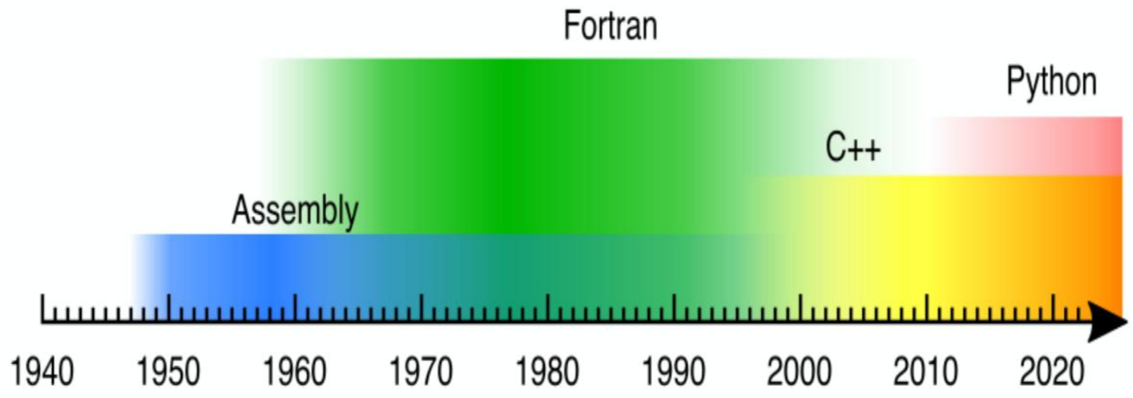
Compilers
(GCC, CLANG, CudaClang, HIPClang, NVCC, HIPCC)

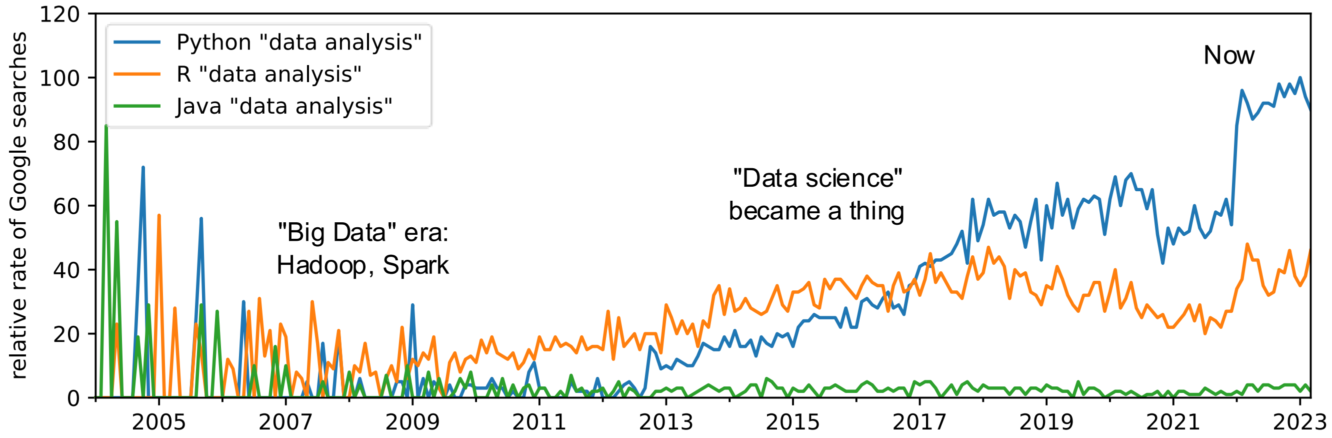
Python configuration (sequences, selection lines)

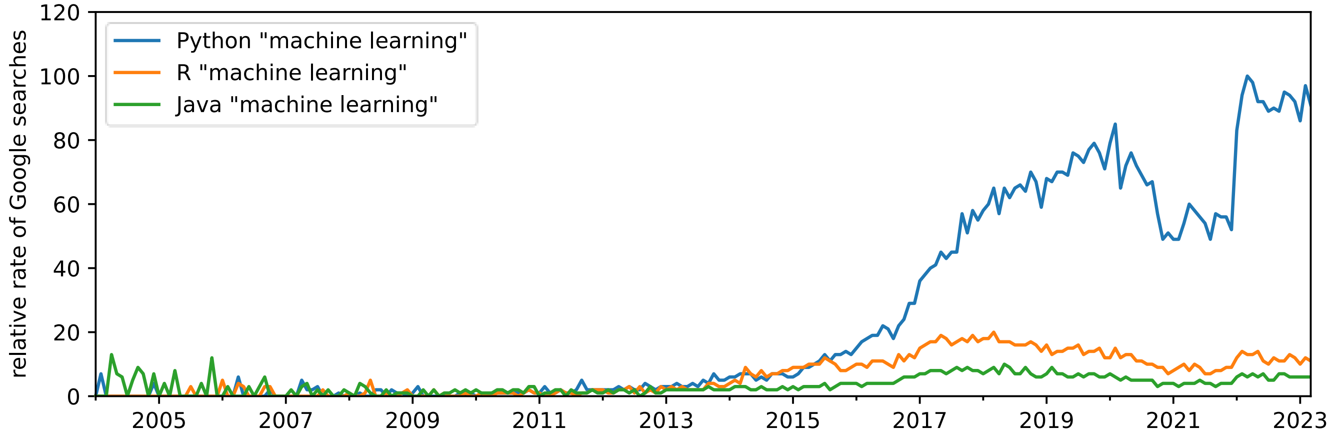
Base algorithms (C / C++, SYCL, CUDA, HIP)

External base libraries:
{ CUDA libraries, ROCm, HIP, boost-devel, zeromq-devel, zlib-devel, GSL or gls-lite, catch2 umesimd, ROOT, Python3 with (wrapt, cachetools, pydot, sympy)}

Languages and software engineering.

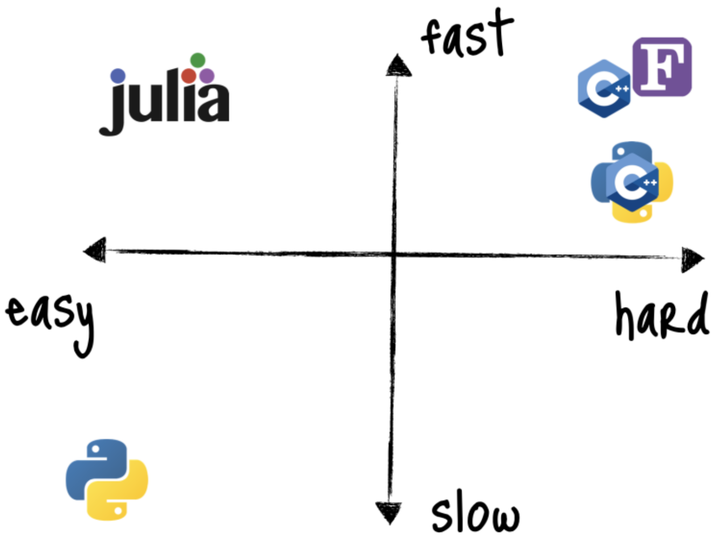






Languages and software engineering.

[CHEP24-JulieaHEP]



Metric	C++	Python	Julia
Performance	✅	❌	✅
Expressiveness	⚠️	✅	✅
Learning Curve	❌	✅	✅
Safety (memory)	⚠️	✅	✅
Composability	❌	⚠️	✅

- Julia isn't perfect or magic
  - Startup time
  - Only LLVM backend
  - Static binaries and performance analysis a bit cumbersome
  - Pure Julia ML libraries not beating PyTorch
- But it does have clear advantages in many areas
- So its tradeoffs compare favourably

Languages and software engineering.

Core Features in C++23

- **Modules**
  - Simplify code imports with import std;—reduces compile times and avoids header complexities.
  - Great for large projects: improved encapsulation and clarity.
- **String Enhancements**
  - New .contains() method for substring search: if (text.contains("word")).
- **std::print & std::println**
  - Clean, type-safe, and format-friendly output.
  - Example: std::println("Value is: {}", value);.
- **std::flat_map & std::flat_set**
  - Optimized for insertion-heavy workloads—use array-based storage for better cache performance.
- **Parallel Algorithms**
  - Built-in multi-core support via execution policies (std::execution::par): std::for_each(std::execution::par, data.begin(), data.end(), func);.
- **Debugging Tools**
  - std::stacktrace for error diagnosis and backtracing: efficient call stack inspection.

Software approaches beyond evolutionary baseline: HLT

Complexity challenges ahead: Despite clever simplifications, the complexity bounds highlight significant challenges for future Runs.

	Theoretical problem	Simplification	
Data sorting	$O(n^2)$	-	**Quicksort or merge sort**
Track seeding	$O(2^n)$	$O(n \cdot log(n)^2)$	**Geometry or physical constrains,**
Track following	$O(2^n)$	$O(n \cdot log(n))$	**Kalman filter to most likelihood path**
Likelihood minimisation	$O(2^n)$	$O(n^6)$	**Gradient descent from exp to high-deg pol**
Clustering	$O(n^2)$	$O(\|V\| + \|E\|)$	**Graph based clustering**
Selections	$O(2^n)$	$O(n^2)$	**Exp to Quad**

Need for advancements in algorithms:

- Similar challenges for MC simulations and offline processing.
- Development of more advanced and efficient data traversal algorithms is essential to manage exponentially growing data throughput,

Languages and software engineering. Python for HEP: Tutorials

- Array oriented programming for particle physicists
  - https://hsf-training.github.io/array-oriented-programming/0-intro.html
  - https://github.com/hsf-training/array-oriented-programming

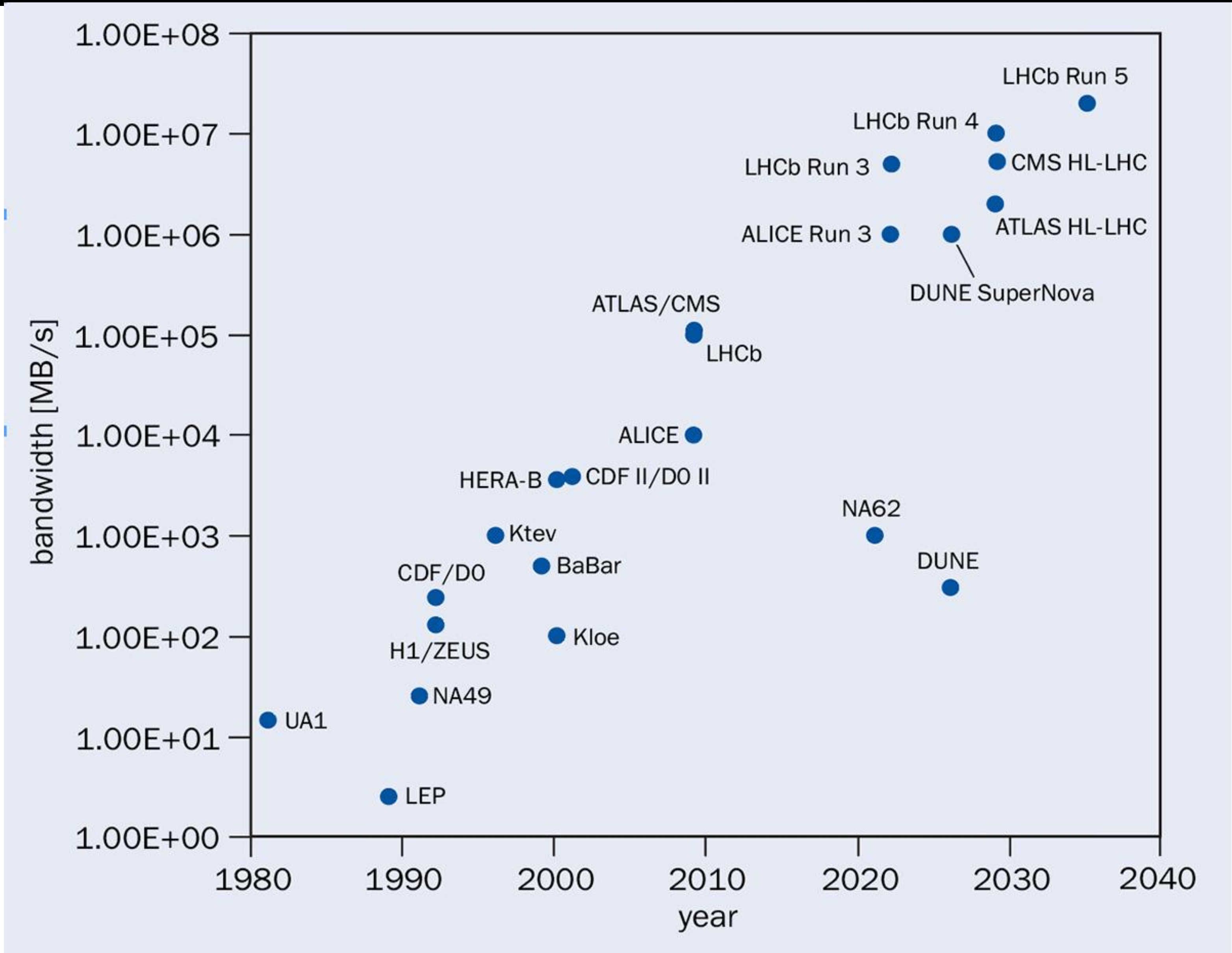
- Python with Exercises
  - https://research-software-collaborations.org/python-june2025/intro.html#
  - 15 Sorting Algorithms in 6 Minutes

Break: Questions and discussion

5. Real-Time (online) analysis

Real-Time Analysis (online)

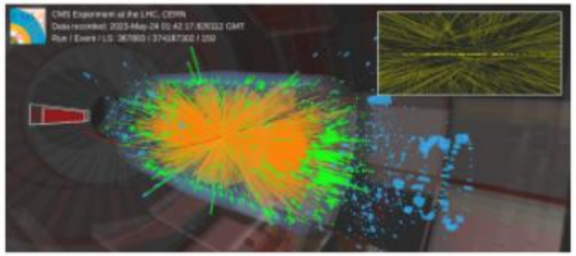
[Ref: CERN Courier Mar 2023]

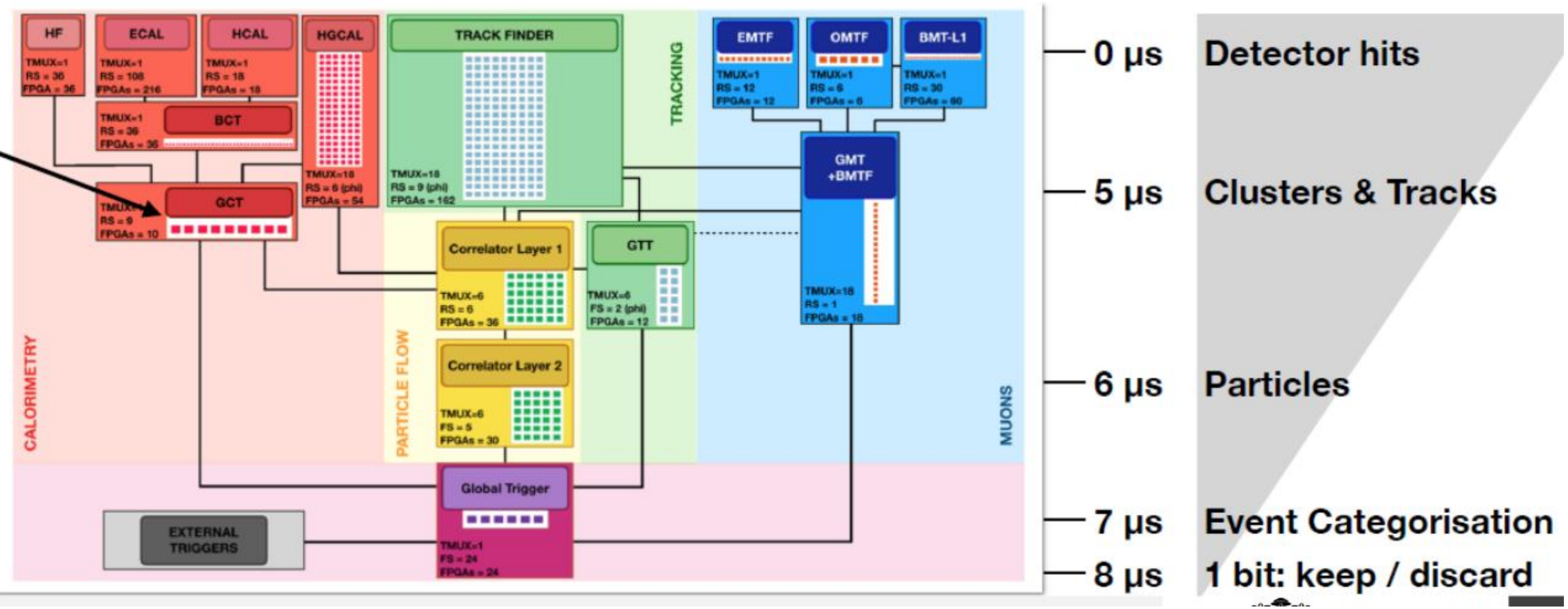


Real-Time Analysis (online): CMS Trigger Run3

t = 0

1 small box = 1 FPGA board with AMD VU13P FPGA



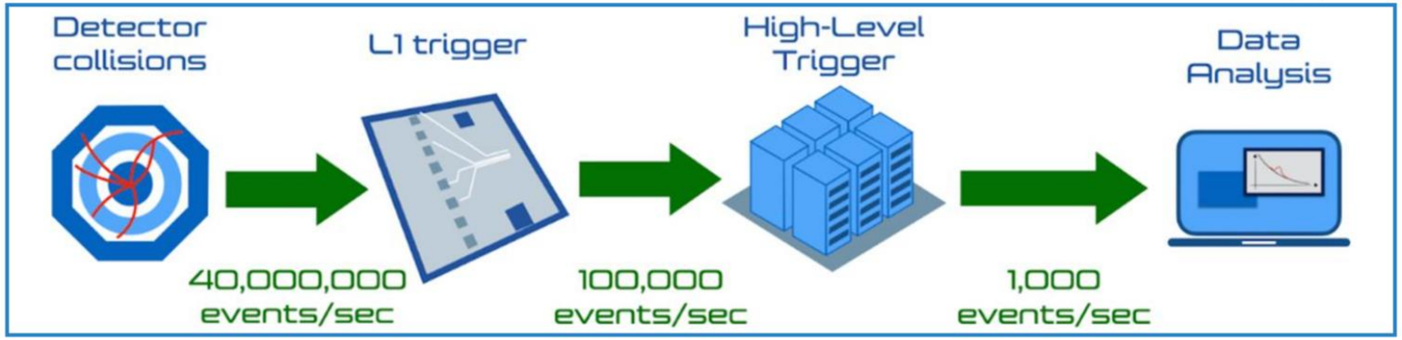


t < 12.5 µs

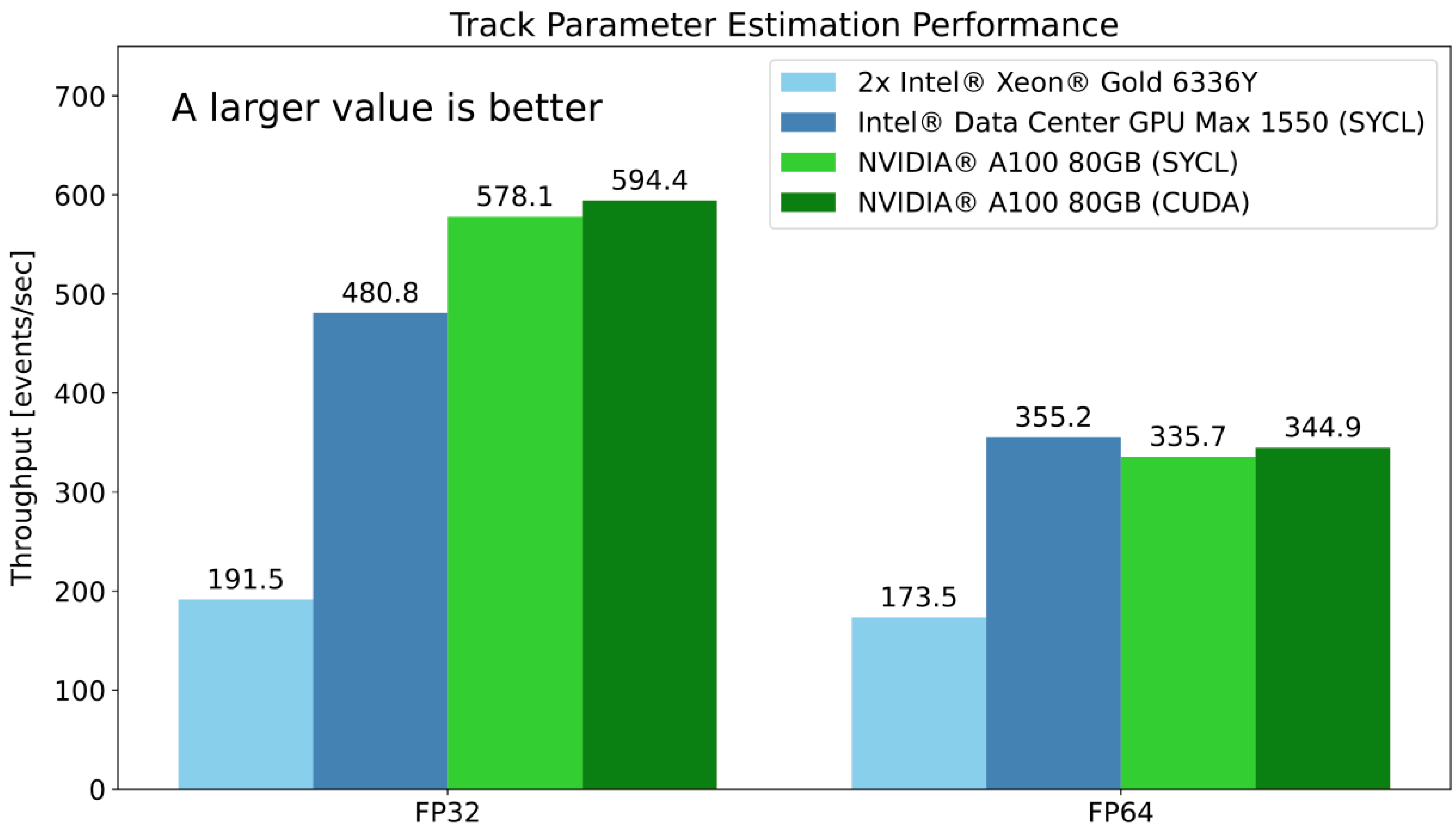
Each small box is one Xilinx Ultrascale+ FPGA

These have NNs and/or BDTs inside

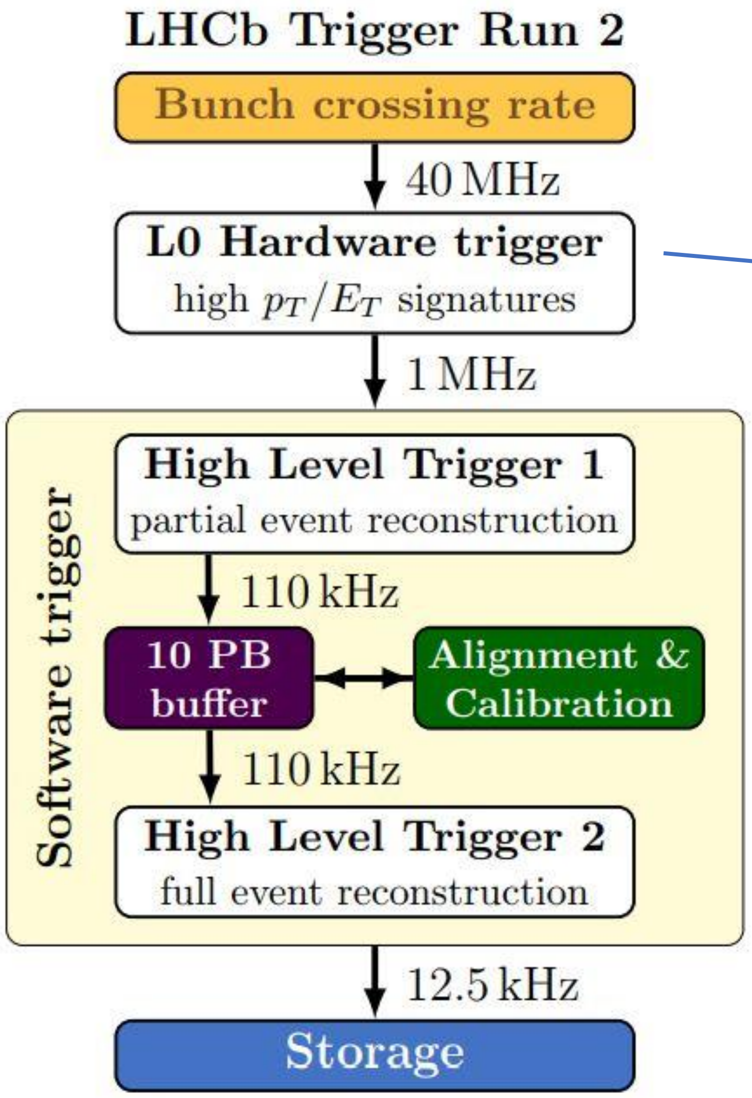
hls4ml Conifer

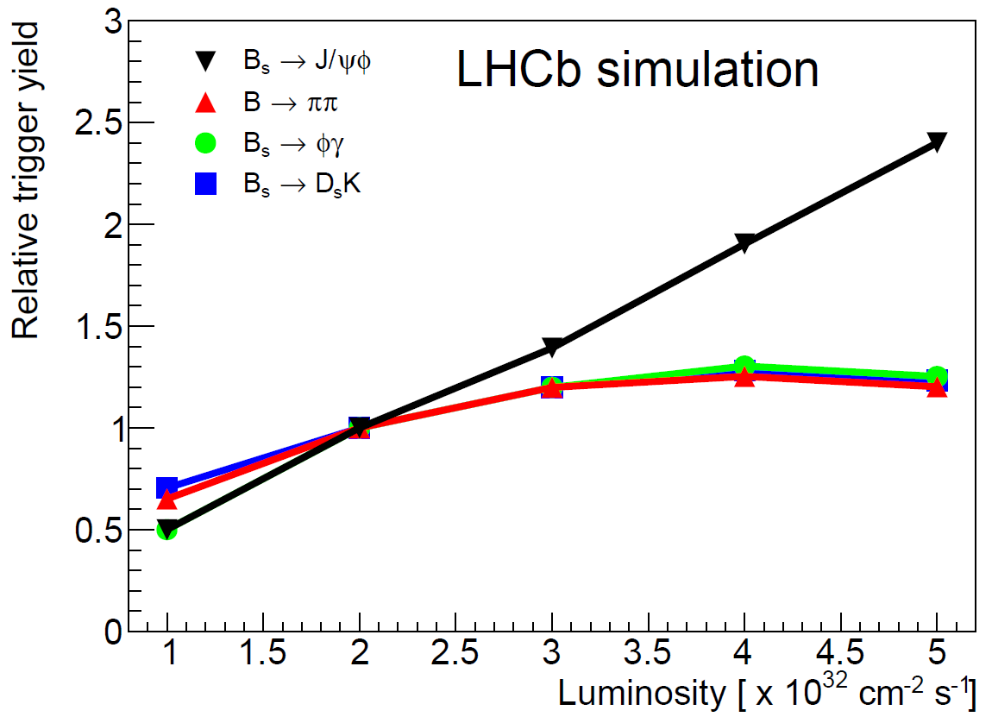


Real-Time Analysis (online): ATLAS ACTS



Real-Time Analysis (online): LHCb





- At high luminosities, hardware trigger cannot cope with the event rate and starts rejecting interesting events.
- Need to study properties of events in real time of collision.

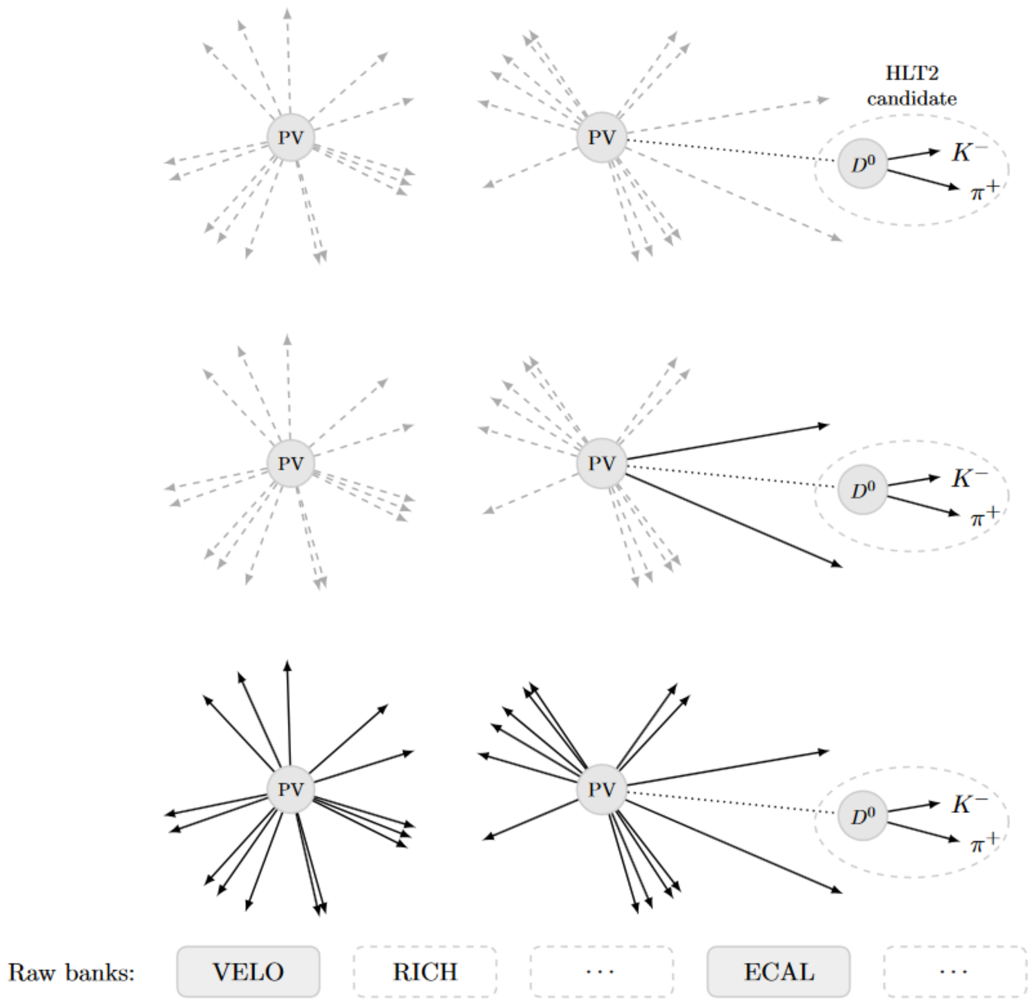
Real-Time Analysis (online): LHCb

What to keep and what to discard ?

we have to be also very careful with what we dismiss..

Real-Time Analysis (online): LHCb

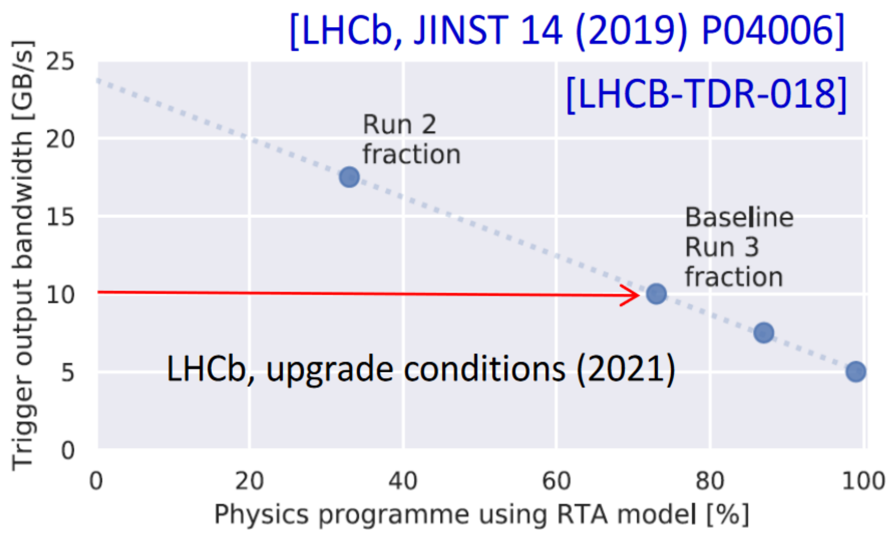
Bandwidth [GB/s] ~ Trigger output rate [kHz] x Average event size [MB]



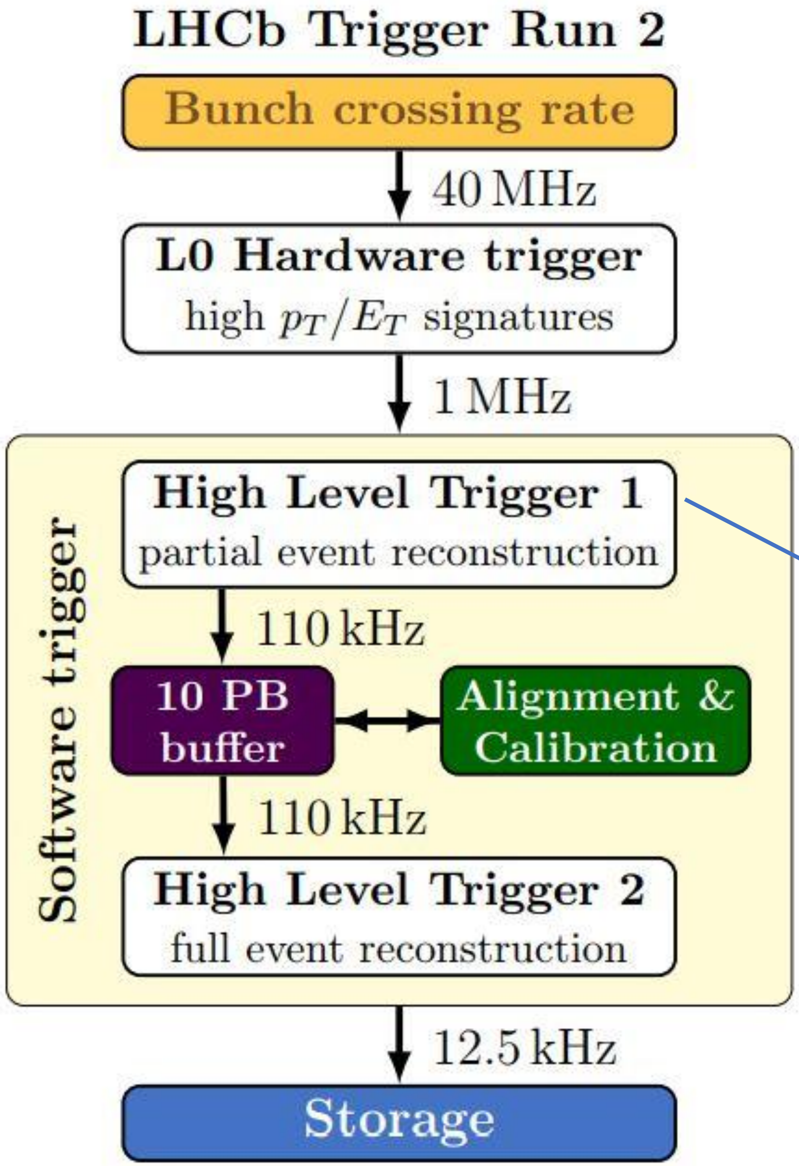
- Need to **reduce the event size**

Instead of raw data from the detector, store only the relevant information of interesting events.

- Need to reconstruct and **analyse** the events to select them in **real time.**



Real-Time Analysis (online): LHCb



LHCb Run2 HLT1 trigger configuration

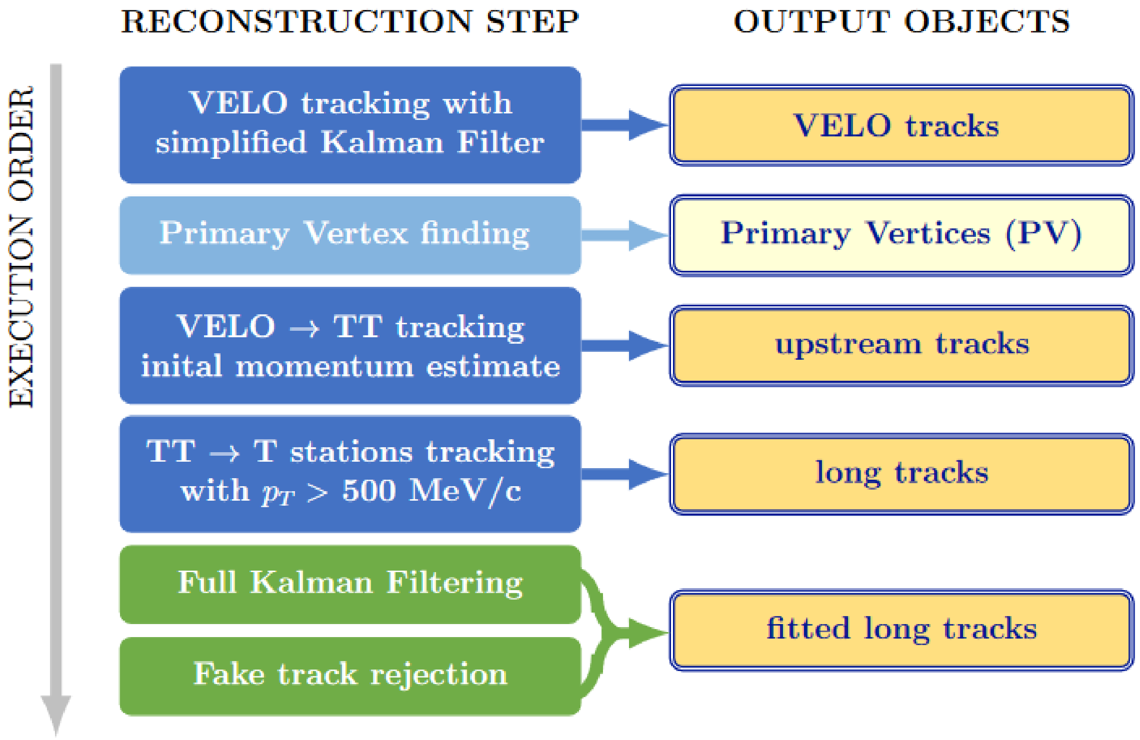
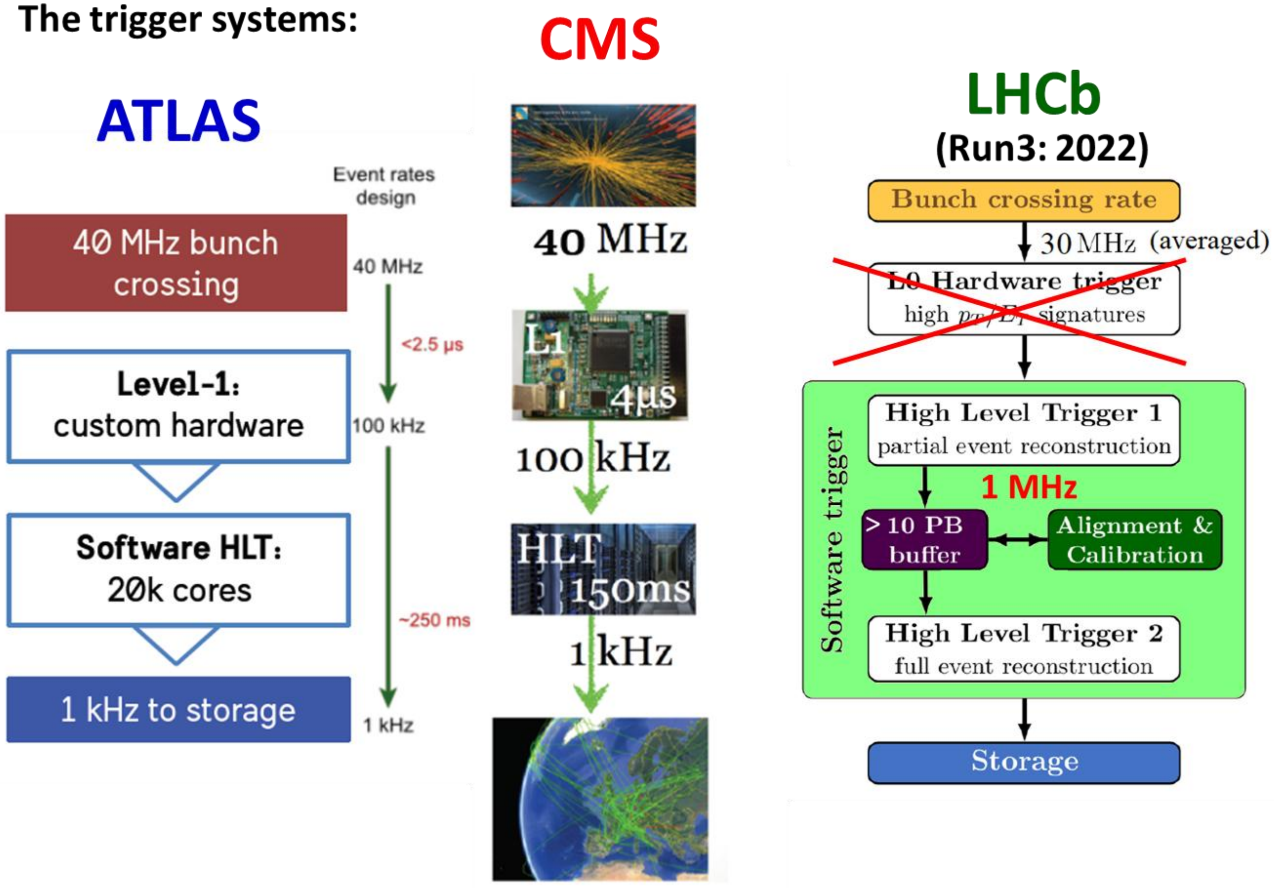


Figure 4: Sketch of the HLT1 track and vertex reconstruction.

Real-Time Analysis (online): LHCb

The trigger systems:

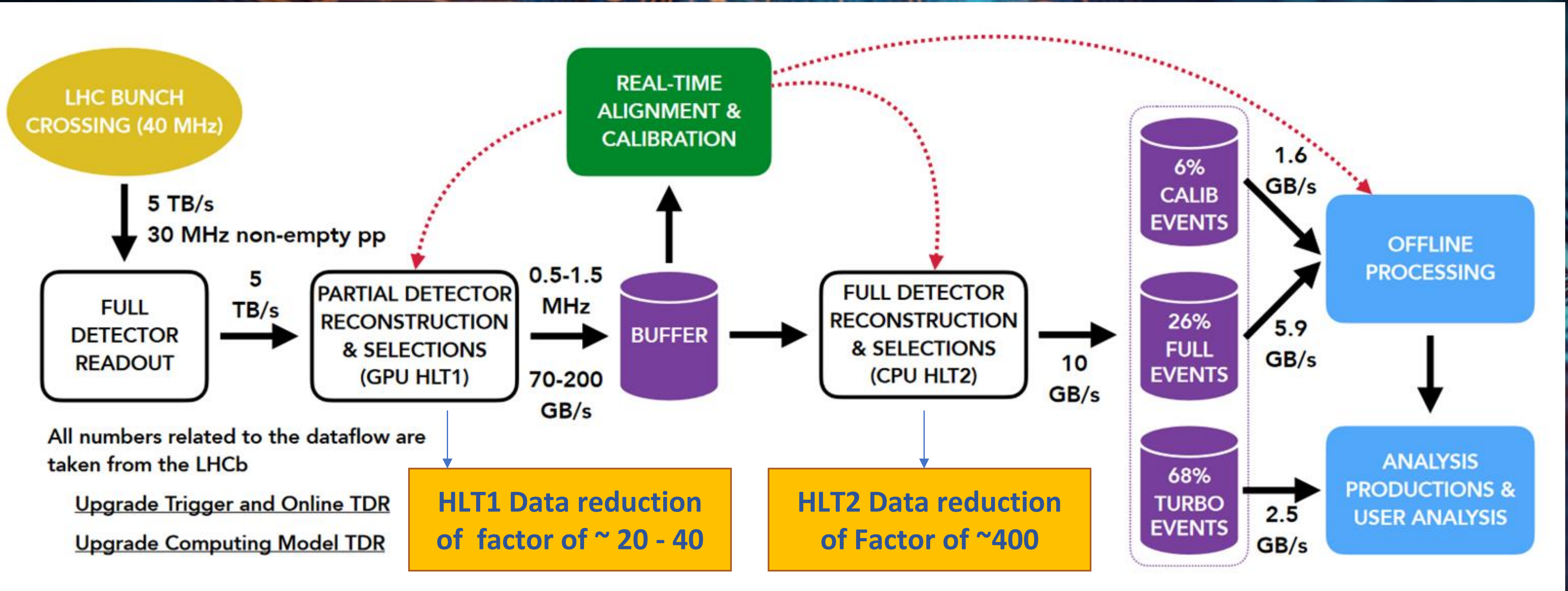


- At the end of Run2 (2018) HLT2 was processing ~68 events /s on a single node.
  - i.e in order to process 30 million events / s , we would have needed about 4,41,176 such nodes (CPU)
    ~ $ 80 M
  - Total budget of LHCb Upgrade-I for Run3 (including everything)
    ~ $ 58 M

Bandwidth [GB/s] ~ Trigger output rate [kHz] x Average event size [MB]

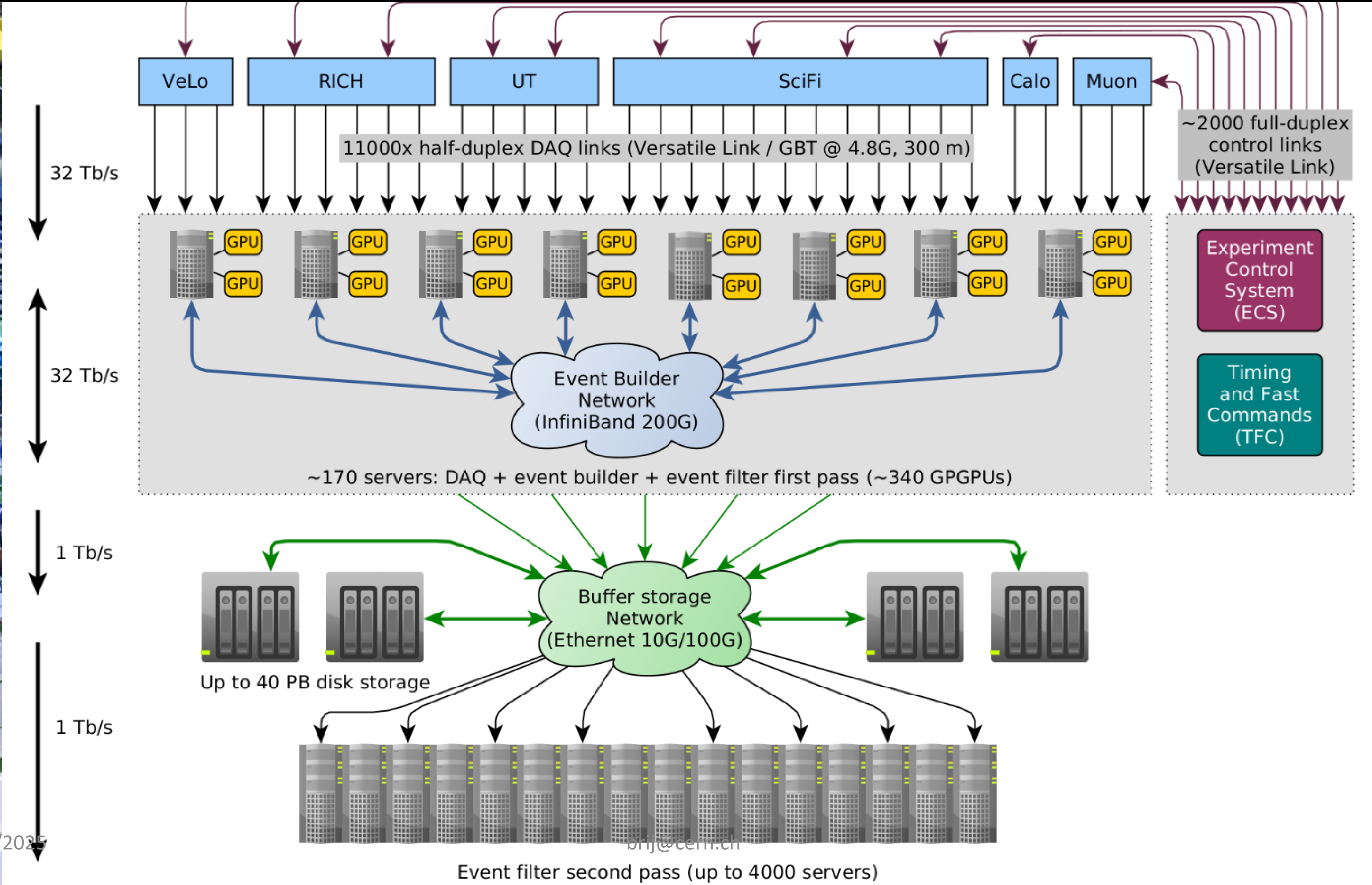
Bandwidth	Trigger output rate	Average event size
~ 1 GB/s	1 kHz (ATLAS & CMS) 12.5 kHz (LHCb)	Raw event data size ~1 MB (ATLAS and CMS) ~0.1 MB (LHCb)

Real-Time Analysis (online): LHCb



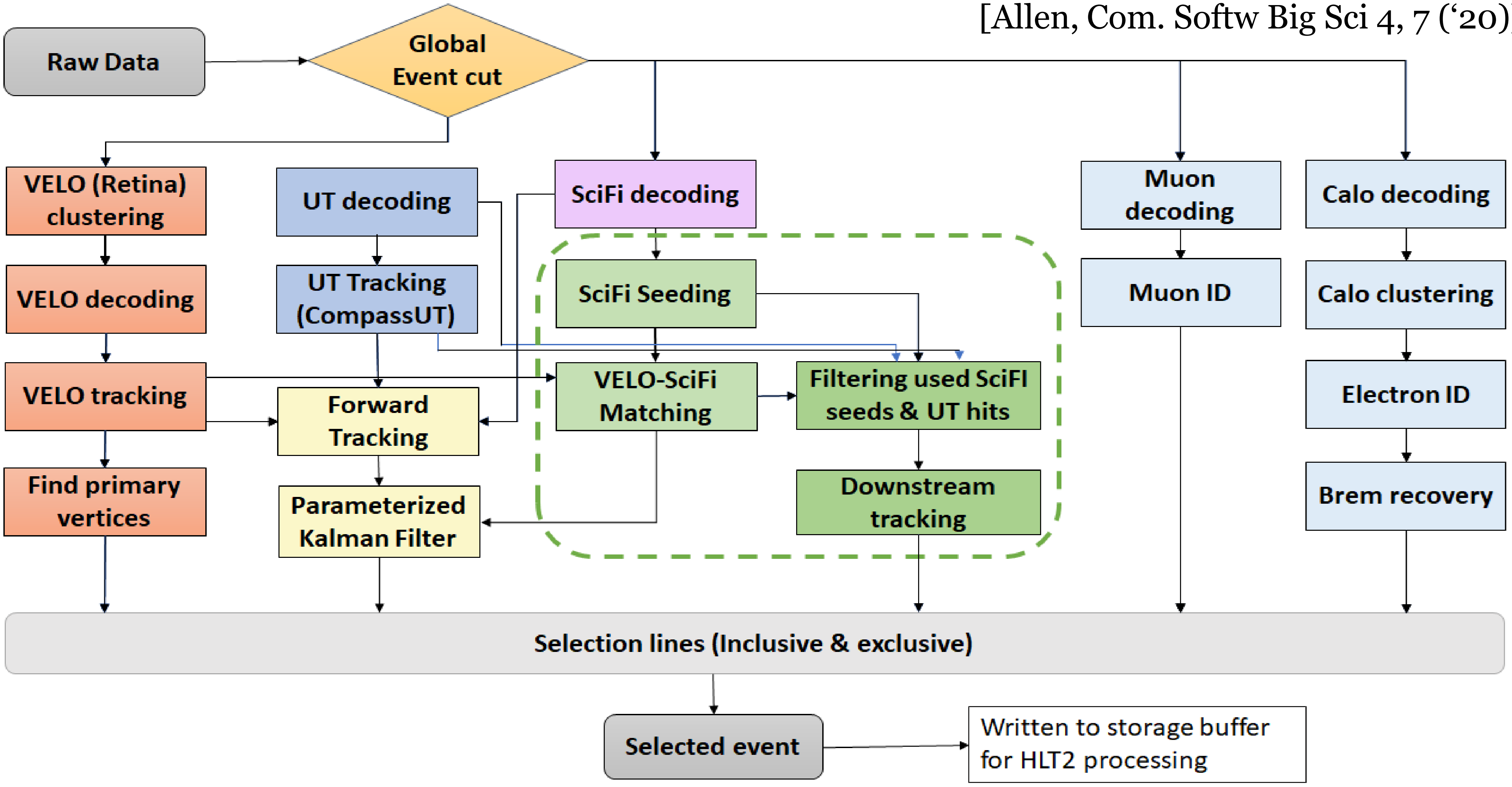
HLT1: Partial reconstruction of charged particle trajectories and few simple selection lines
HLT2: Full reconstruction and selection based on different decay chains and signatures
Must reduce without the loss in fidelity

Real-Time Analysis (online): LHCb

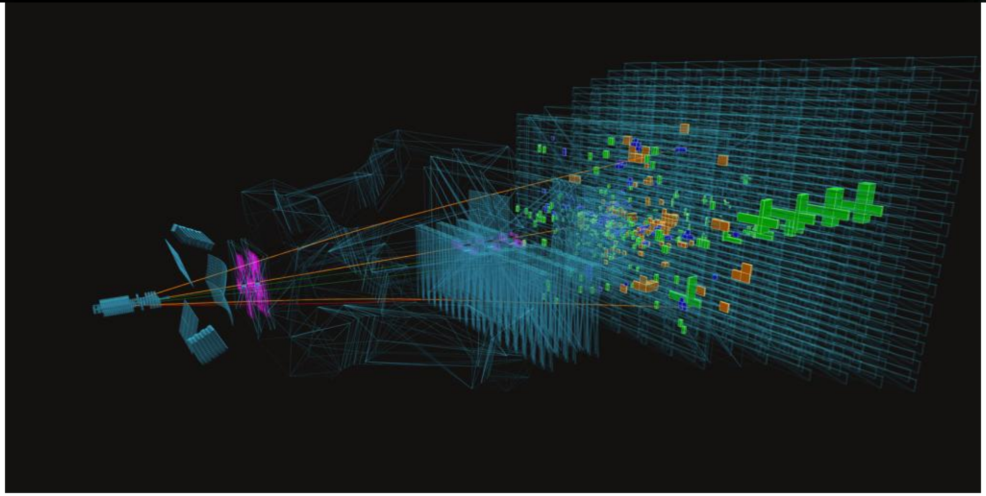


Real-Time Analysis (online): LHCb algorithms: HLT1 sequence (Run-3)

[Allen, Com. Softw Big Sci 4, 7 ('20)]



Real-Time Analysis (online): Tracking



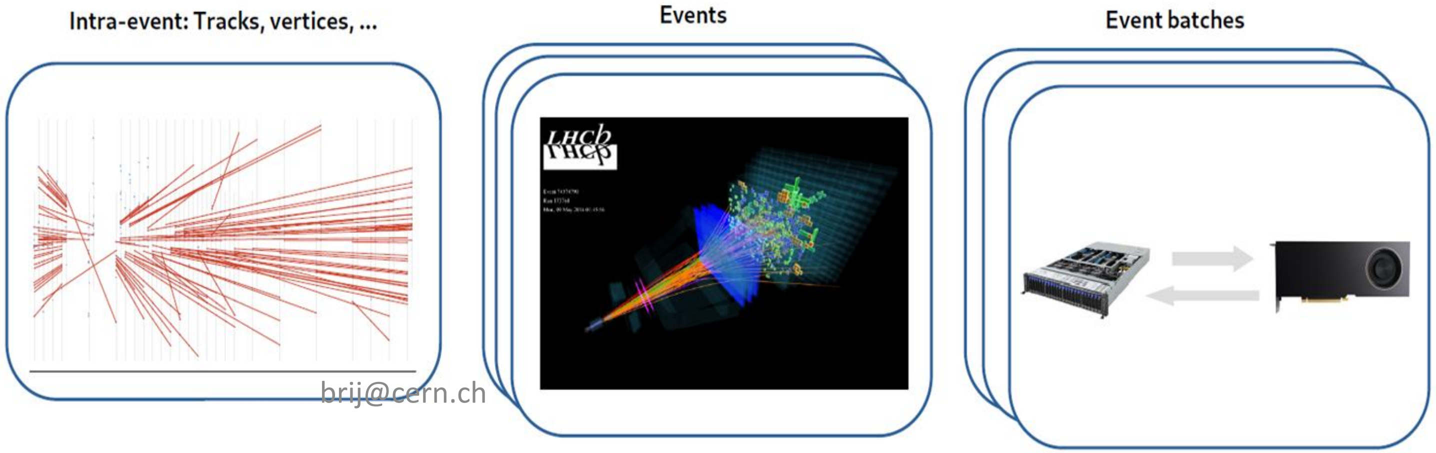
Track reconstruction (Tracking)

What

- ➢ Tracking deals with converting the signal from a subdetector (hits, clusters…) into a trajectory.
- ➢ Roughly speaking, two phases: pattern recognition and track fitting

Why

- ➢ We need to reconstruct trajectories of particles in our detector to:
  - ➢ Build vertices, measure decay topologies;
  - ➢ Measure momenta → measure invariant masses, angular variables (so… do physics).



Real-Time Analysis (online): Tracking

Computing and Software for Big Science (2020) 4:7
https://doi.org/10.1007/s41781-020-00039-7

ORIGINAL ARTICLE

Allen: A High-Level Trigger on GPUs

R. Aaij[1] · J. Albrecht[2] · M. Belous[3,4] · P. Billoir[5] · T. Boett
D. H. Cámpora Pérez[1,8] · A. Casais Vidal[7] · D. C. Craik[6]
B. Jashal[11] · N. Kazeev[3,4] · D. Martínez Santos[7] · F. Pisa
M. Rangel[16] · F. Reiss[5] · C. Sánchez Mayordomo[11] · R.
X. Vilasís Cardona[18] · M. Williams[6]

Received: 18 December 2019 / Accepted: 3 April 2020 / Published onl

Abstract
We describe a fully GPU-based implementation of the fir
taking in 2021. We demonstrate that our implementatio
LHCb detector and perform a wide variety of pattern r
particles, finding proton–proton collision points, identif
vertices of long-lived particles. We further demonstrate
GPU cards, that it is not I/O bound, and can be operated
high-throughput GPU trigger proposed for a HEP exper

Keywords GPU · Real-time data selection · Trigger · LF

arXiv:2503.13092v2 [hep-ex] 27 May 2025

A Downstream and vertexing algorithm for Long Lived Particles (LLP) selection at the first High level trigger (HLT1) of LHCb

V. Kholoimov[1], B. Kishor Jashal[1,2], A. Oyanguren[1], V. Svintozelskyi[1] and J. Zhuo[1]

[1]Instituto de Física Corpuscular (IFIC), University of Valencia- CSIC, Valencia, Spain.
[2]Rutherford Appleton Laboratory (RAL), Oxford, United Kingdom.

Abstract

A new algorithm has been developed at LHCb which is able to r
placed vertices in real time at the first level of the trigger (HLT1).
Tracker (UT) and the Scintillator Fiber detector (SciFi) of LHC
inside the Allen framework. In addition to an optimized strateg
(NN) implementation to increase the track efficiency and reduce t
throughput and limited time budget. Besides serving to reconstr
the Standard Model, the Downstream algorithm and the associa
largely increase the LHCb physics potential for detecting long-liv

Keywords: LHCb, HLT1, GPUs, downstream, LLPs

1 Introduction

The LHCb forward spectrometer is one of the main detectors at the Large Hadron Collider (LHC) accelerator at CERN, with the primary purpose of searching for new physics through studies of CP-violation and heavy-flavour hadron decays. It has been operating during its Run 1 (2011-2012) and Run 2 (2015-2018) periods with very high performance, recording an integrated luminosity of 9 fb^{-1} at center-of-mass energies of 7, 8, and 13 TeV and delivering a plethora of accurate physics results and new particles discoveries. One of the main issues concerning the present Run 3 was that, even if many physics results are statistically limited,

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VNIVERSITAT DE VALÈNCIA

Facultat de Física
Departament de Física Atòmica, Molecular i Nuclear
Institut de Física Corpuscular (UV-CSIC)

ng new discoveries:
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r detection of long-lived
ticles at LHCb

j Kishor Jashal

Directed by:
zazu de Oyanguren Campos

PhD thesis
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Effect of the high-level trigger for detecting long-lived particles at LHCb

Lukas Calefice[1,2], Arthur Hennequin[3], Louis Henry[4], Brij Jashal[4], Diego Mendoza[5], Arantza Oyanguren[5]*, Izaac Sanderswood[5], Carlos Vázquez Sierra[4], Jiahui Zhuo[5] and part of LHCb-RTA Collaboration

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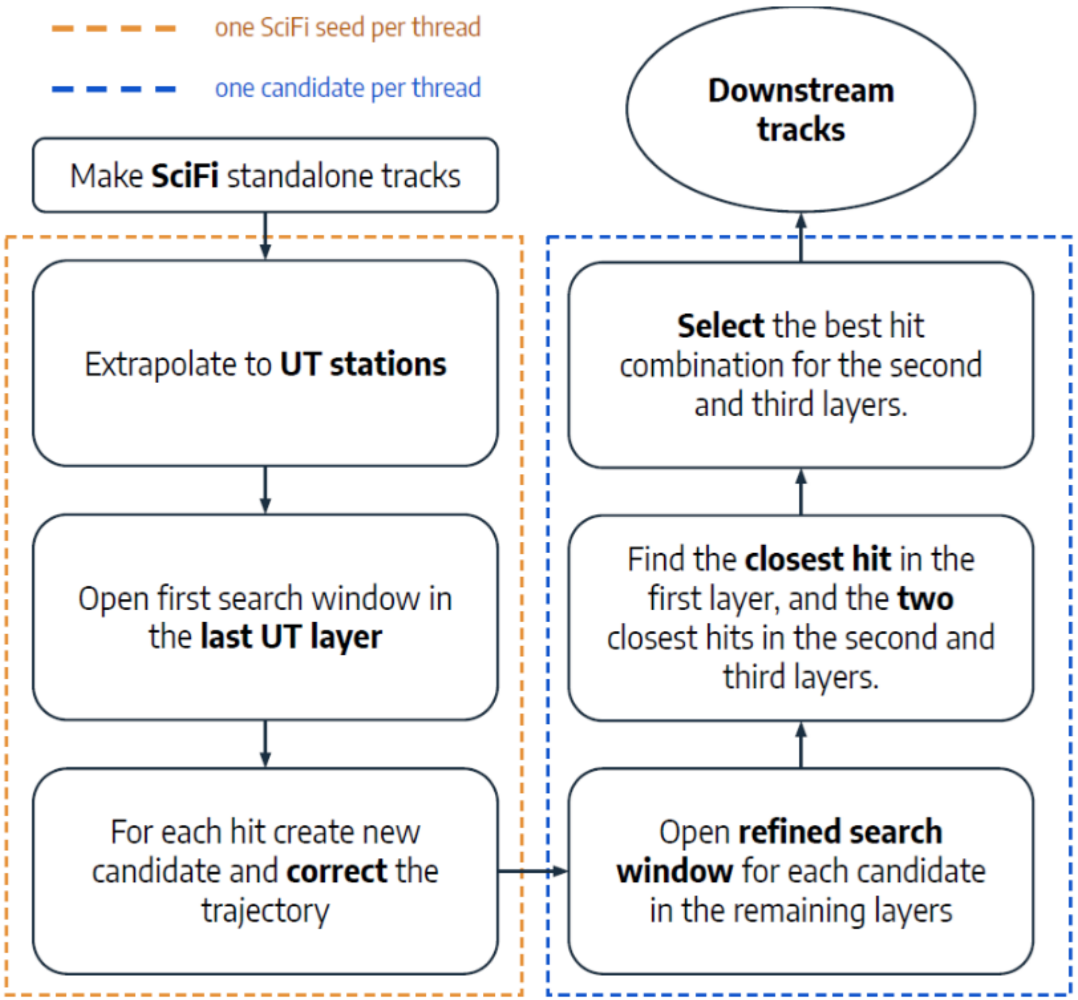
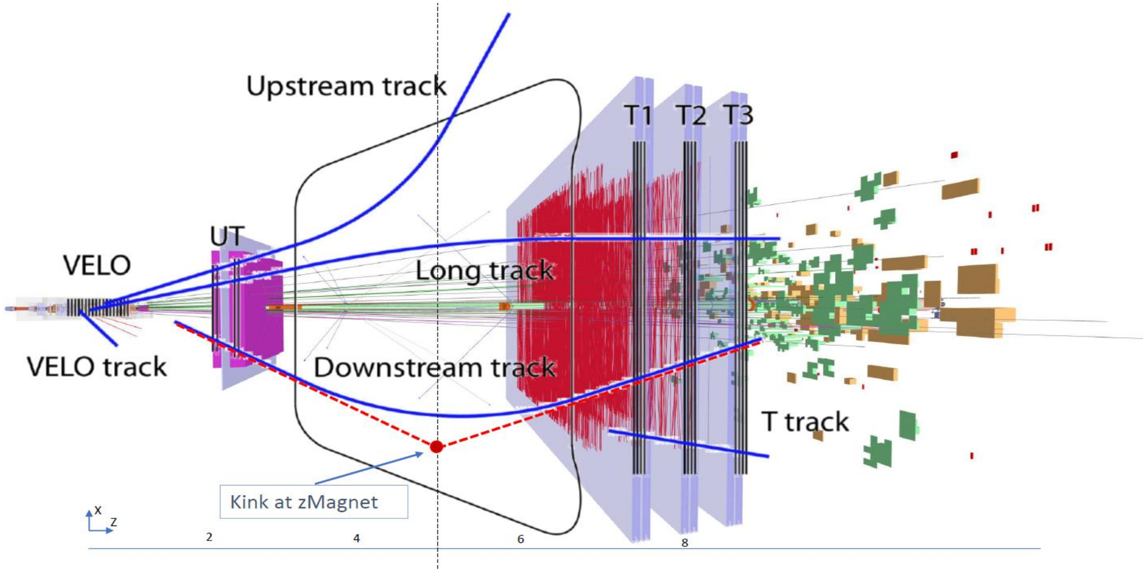
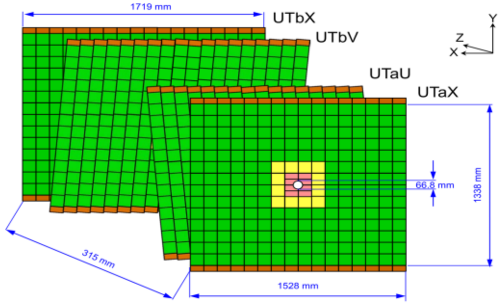
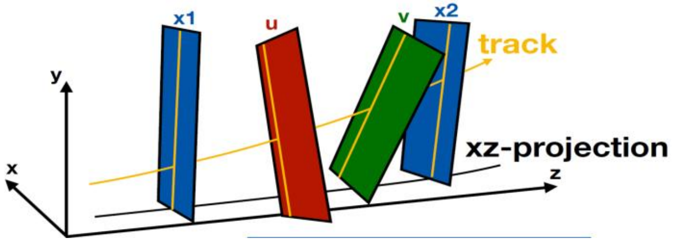
Long-lived particles (LLPs) show up in many extensions of the Standard Model, but they are challenging to search for with current detectors, due to their very displaced vertices. This study evaluated the ability of the trigger algorithms used in the Large Hadron Collider beauty (LHCb) experiment to detect long-lived particles and attempted to adapt them to enhance the sensitivity of this experiment to undiscovered long-lived particles. A model with a Higgs portal to a dark sector is tested, and the sensitivity reach is discussed. In the LHCb tracking system, the farthest tracking station from the collision point is the scintillating fiber tracker, the SciFi detector. One of the challenges in the track reconstruction is to deal with the large amount of and combinatorics of hits in the LHCb detector. A dedicated algorithm has been developed to cope with the large data output. When fully implemented, this algorithm would greatly increase the available statistics for any long-lived particle search in the forward region and would additionally improve the sensitivity of analyses dealing with Standard Model particles of large lifetime, such as K^0_S or Λ^0 hadrons.

Real-Time Analysis (online): Tracking









Real-Time Analysis (online): Tracking

Algorithm is divided into 3 main kernel functions:

Kernel function 1:
128 SciFi seeds per thread block

- Filtering used SciFi seeds
- For each input SciFi seed, extrapolate to last x layer (UTbX)
- Store up to 10 best candidates
- Update slope of each candidate using magnet point and hit position.

Kernel function 2:
256 candidates per thread block

- Add hits from rest of the UT layers
- Find best combination of U/V hits
- Compute the scores based on distance b/w extrapolation and real UT hit positions

Kernel function 3:
256 candidates per thread block

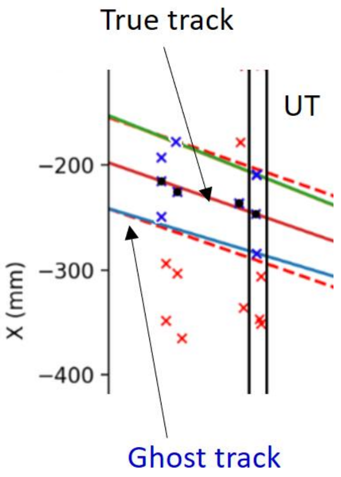
- Find best candidate based on the scores from previous function
- Check for hit duplication
- Perform ghost killing

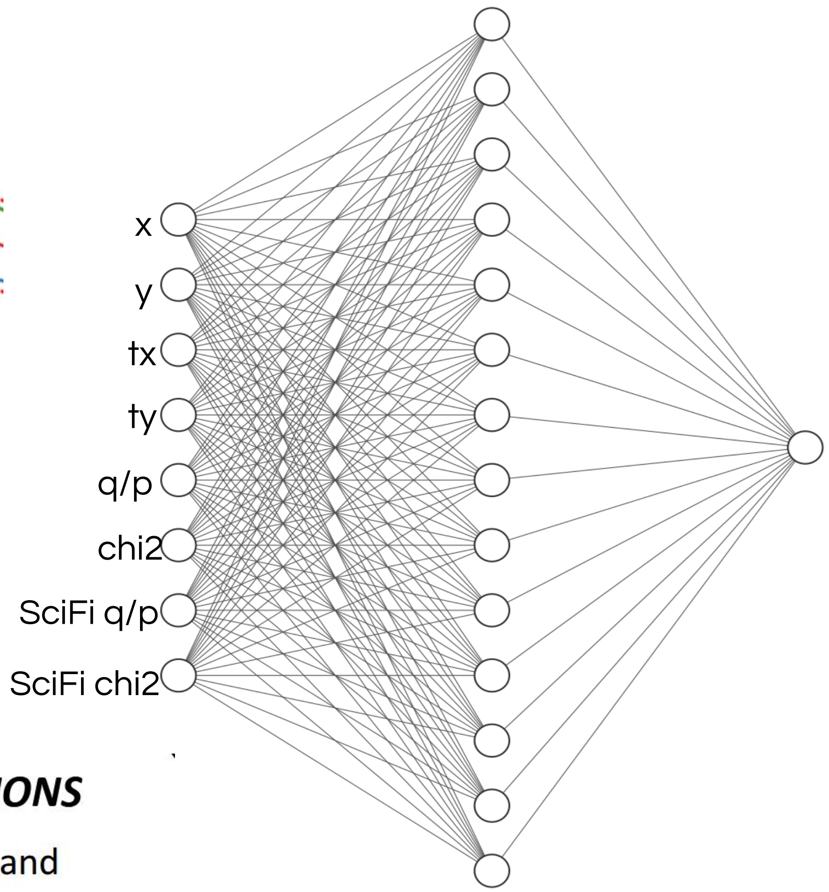
Prepare output:

- Copy hits and tracks to output (compact SOA container)
- Create standard multi-event viewer

Real-Time Analysis (online): Tracking

- A single hidden (14 nodes) layer fully connected NN
- It utilizes **8 variables** as input:
  - *Downstream* track state (**$x,y,t_x,t_y,q/p, \mathcal{X}^2$**)
  - SciFi track properties (**$q/p, \mathcal{X}_y^2$**)
- The model was trained using $B_s \to \phi\phi$ events.
- In order to boost speed, certain C++/CUDA tricks are applied, such as using **static structs**, employing **fast math functions**, and **unwinding for-loops**.





STATIC STRUCTURES

Fixing the number of input variables and the number of neurons (compile-time optimizations, registers vs global memory).

```
namespace DownstreamGhostKiller {

  namespace Model {
    constexpr unsigned num_node = 14;
    constexpr unsigned num_input = 8;
```

LOOP UNROLLING

Expanding for-loops using the NVCC-specific #pragma unroll directive (replicates the loop body multiple times).

```
// First layer
DownstreamHelpers::unwind<0, Model::num_node>([&](int i) {
  DownstreamHelpers::unwind<0, Model::num_input>([&](int j) {
    h1[i] += input[j] * Model::weights1[i][j];
  });
  h1[i] = ActivateFunction::relu(h1[i] + Model::bias1[i]);
});
```

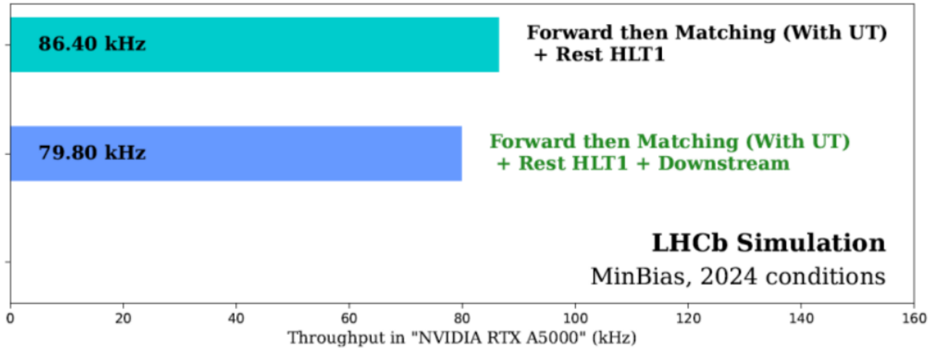
FAST MATH FUNCTIONS

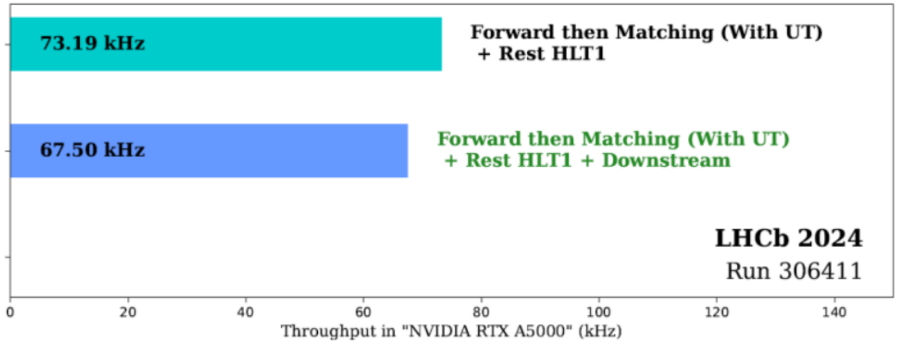
Such as `__fdividef` and `__expf`, to accelerate floating-point operations.

```
...
namespace ActivateFunction {
  // rectified linear unit
  __device__ inline float relu(const float x) {
    return x > 0 ? x : 0;
  }
  // sigmoid
  __device__ inline float sigmoid(const float x) {
    return __fdividef(1.0f, 1.0f + __expf(-x));
  }
} // namespace ActivateFunction
```

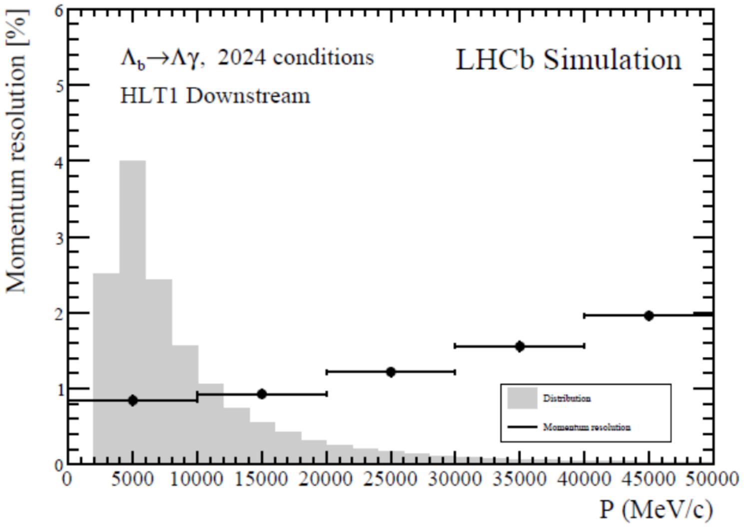
Real-Time Analysis (online): Tracking

- **Throughput:** -5 kHz, very fast algorithm! [RTX A5000 card]

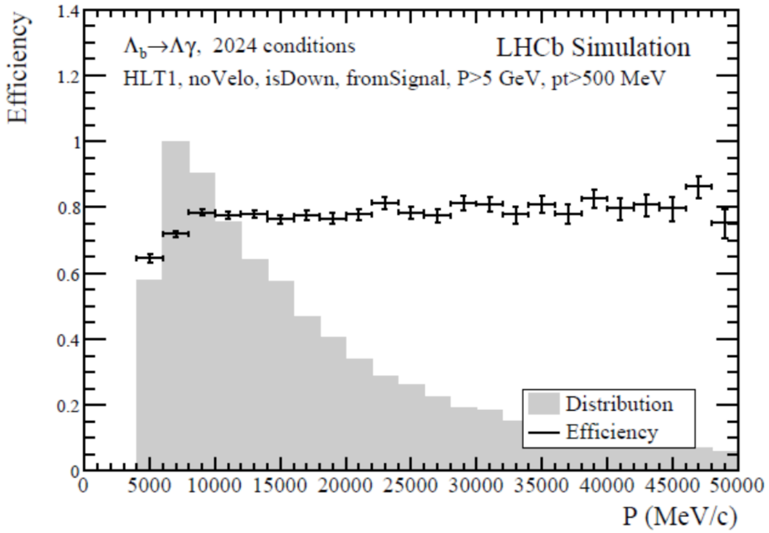




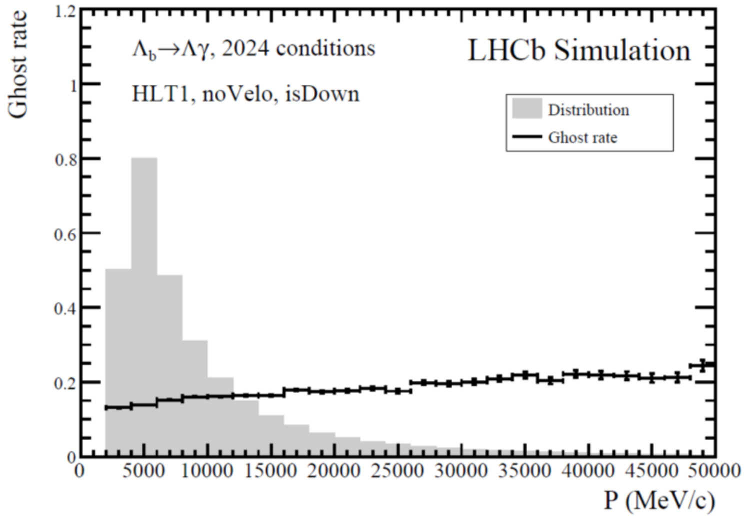
Track momentum resolution: 1-2 %



Efficiency: ~ 80 %



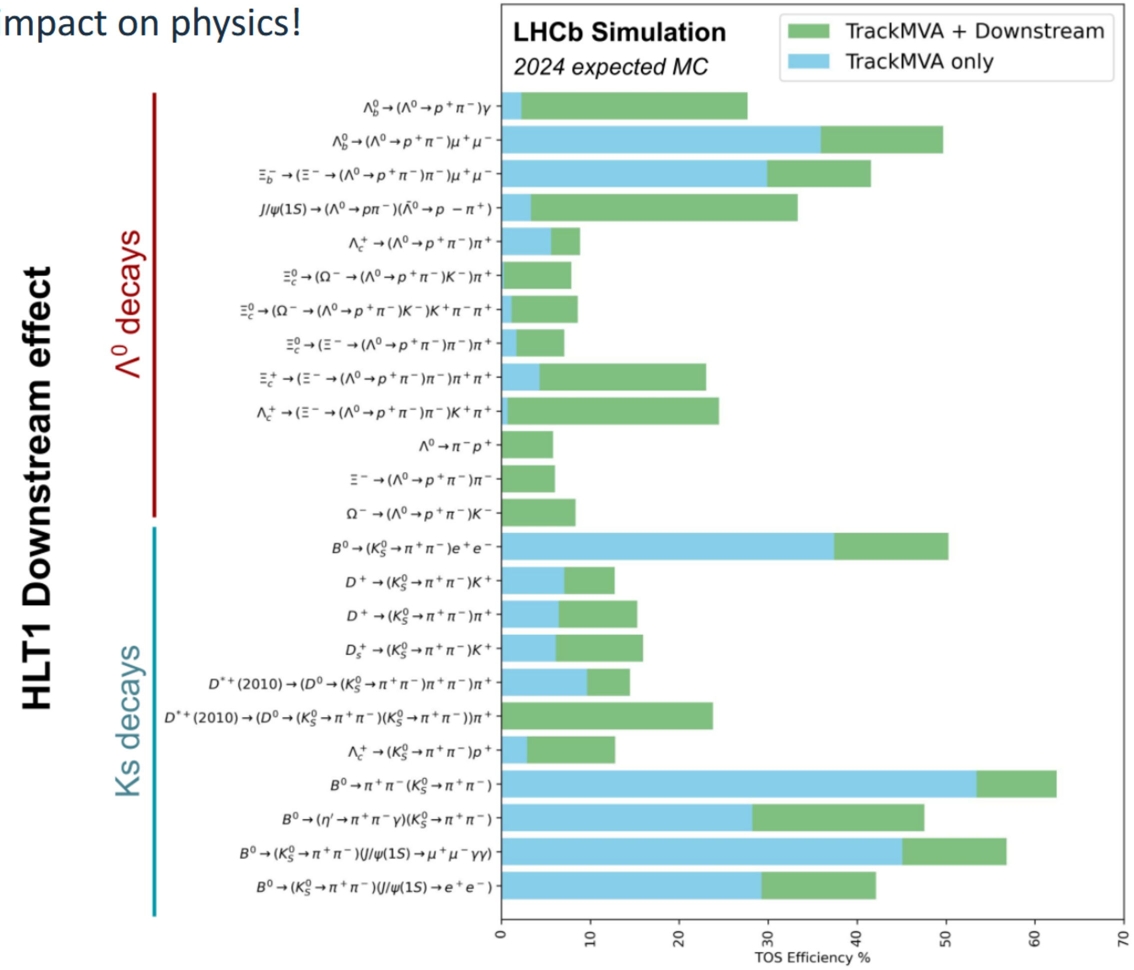
Ghosts < 20% !

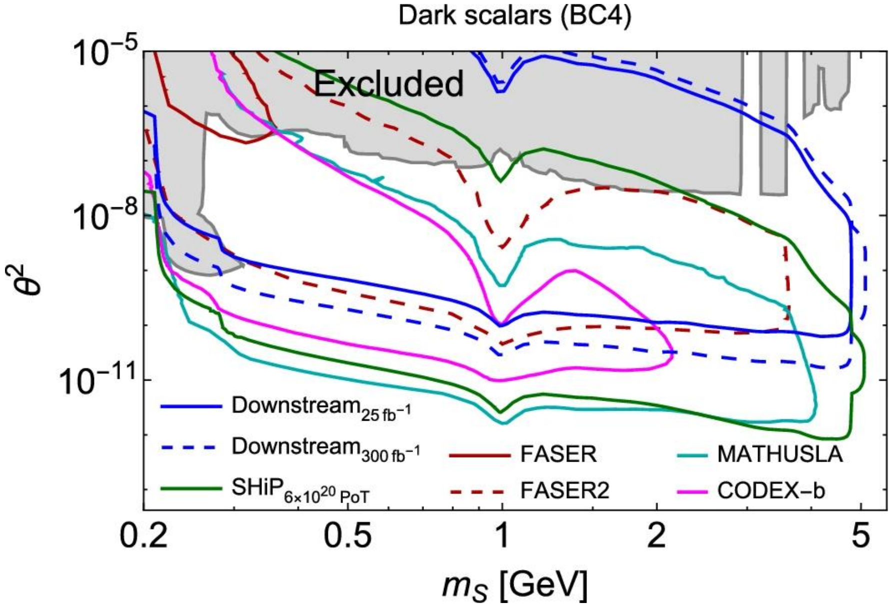


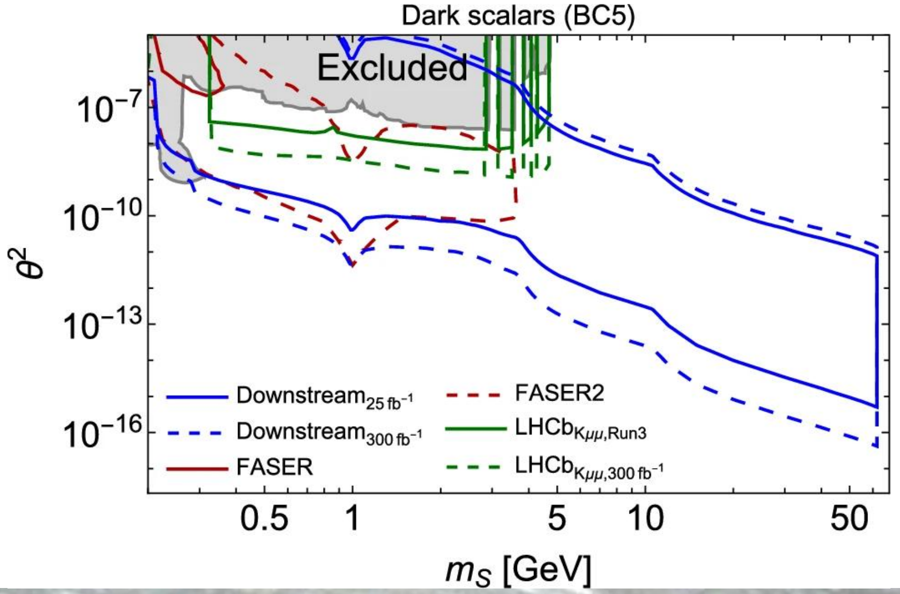
Real-Time Analysis (online): Tracking

10.1140/epjc/s10052-024-12906-3

Very high impact on physics!







6. GPU programming

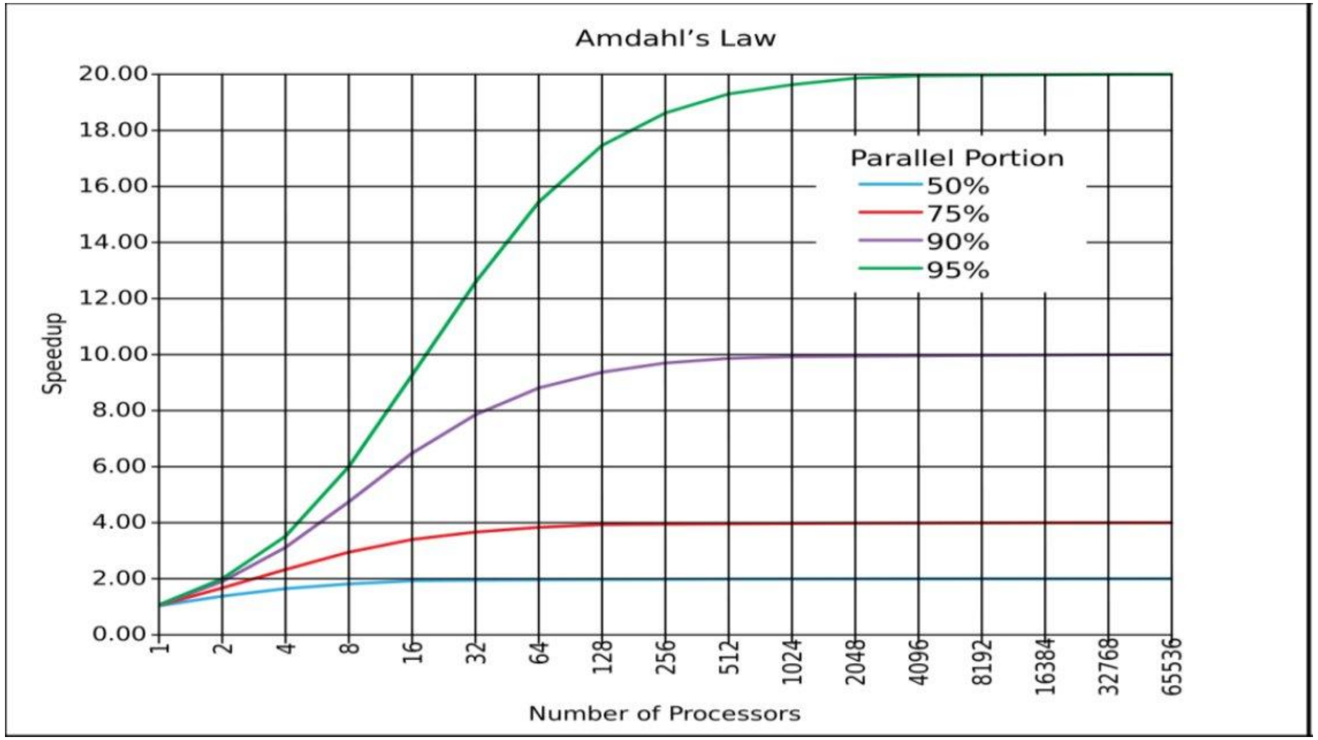
Instructions for hands-on sessions

Course repo – https://github.com/brij01/GPUCuda

GPU programming: a refresher

Ways to speed up an application:

– Reducing the **complexity** of the algorithm.
– Increasing the speed and capacity of the computing medium: clock **frequency**.
– Searching for tasks within the application that can be performed in **parallel**.

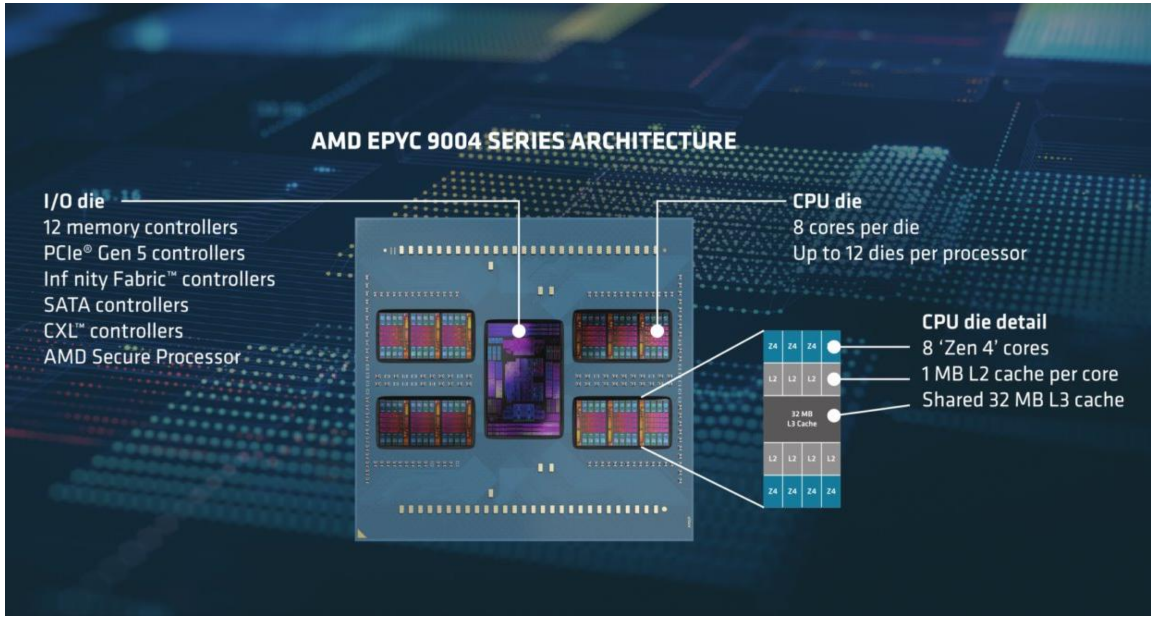


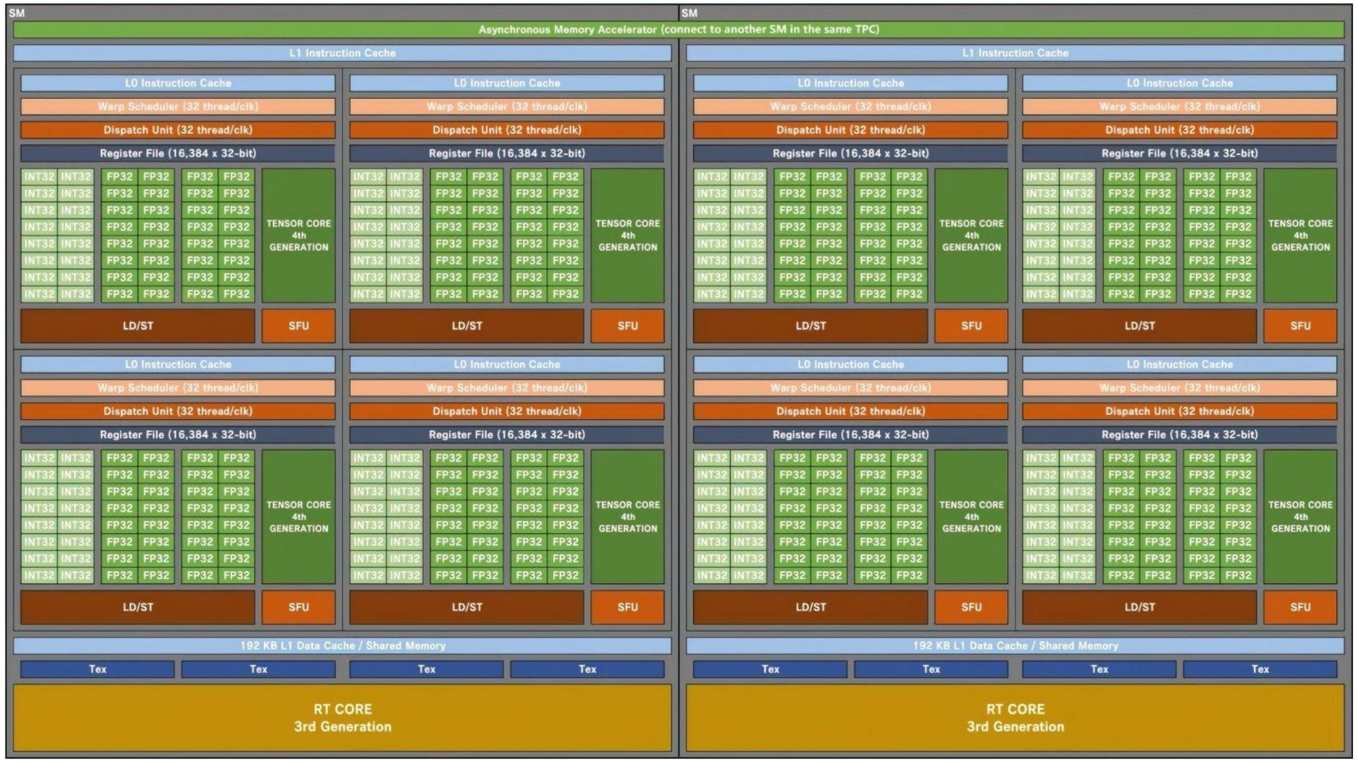
GPU programming: a refresher

GPGPU languages: Concepts are same, terminologies are different

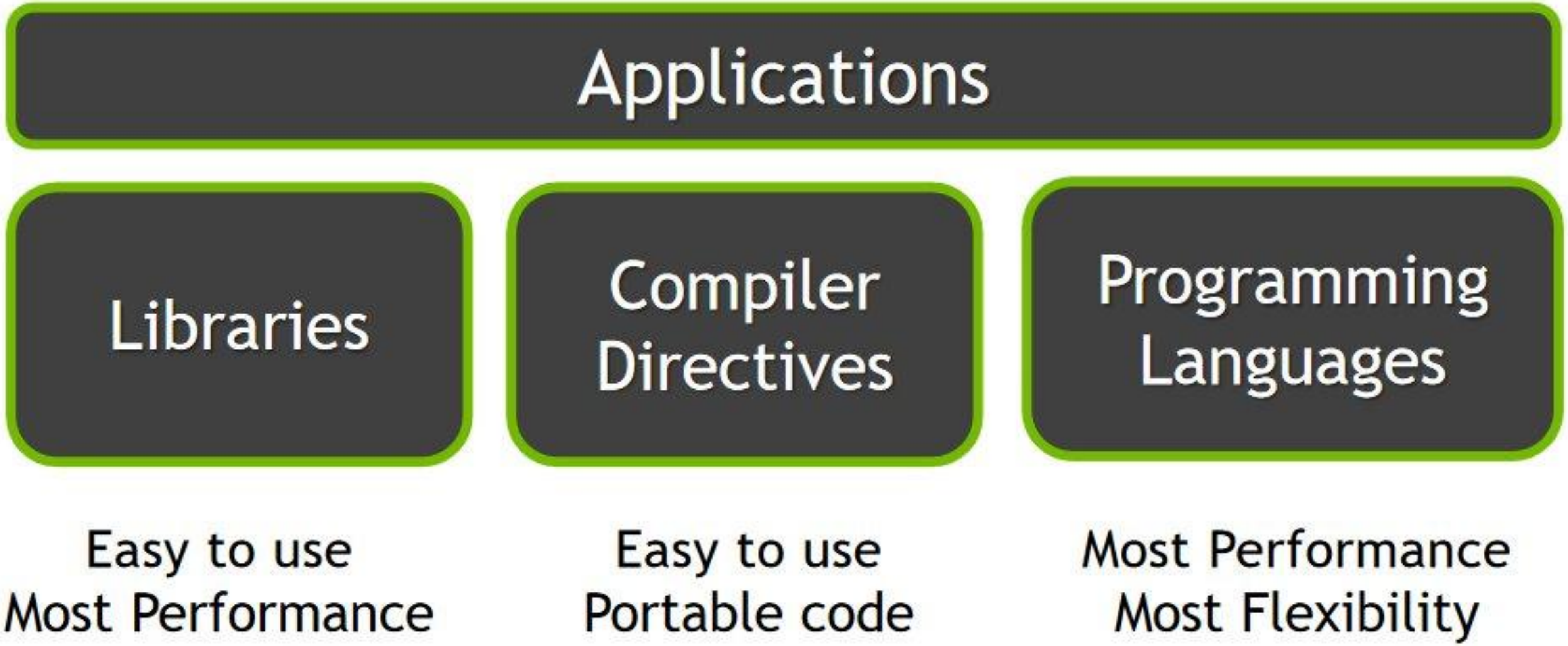
Language	Cuda	OpenAcc	HIP
Definition	kernel_name(...)`	kernel_name(...)`	kernel_name(...)`
Kernel Launch	`kernel_name<<<grid, block>>>(...)`	`clEnqueueNDRangeKernel(...)`	`hipLaunchKernelGGL(kernel_name, ...)`
Thread Indexing	`blockIdx.x`, `threadIdx.x`	`get_global_id(0)`, `get_local_id(0)`	`hipBlockIdx_x`, `hipThreadIdx_x`
Block Size	`blockDim.x`	`get_local_size(0)`	`hipBlockDim_x`
Grid Size	`gridDim.x`	`get_global_size(0) / get_local_size(0)`	`hipGridDim_x`
Shared Memory	`__shared__`	`__local`	`__shared__`
Memory Fence	`__syncthreads()`	`barrier(CLK_LOCAL_MEM_FENCE)`	`__syncthreads()`
Atomic Functions	`atomicAdd(...)`, `atomicSub(...)`, etc.	`atomic_add(...)`, `atomic_sub(...)`, etc.	`atomicAdd(...)`, `atomicSub(...)`, etc.

GPU programming: a refresher

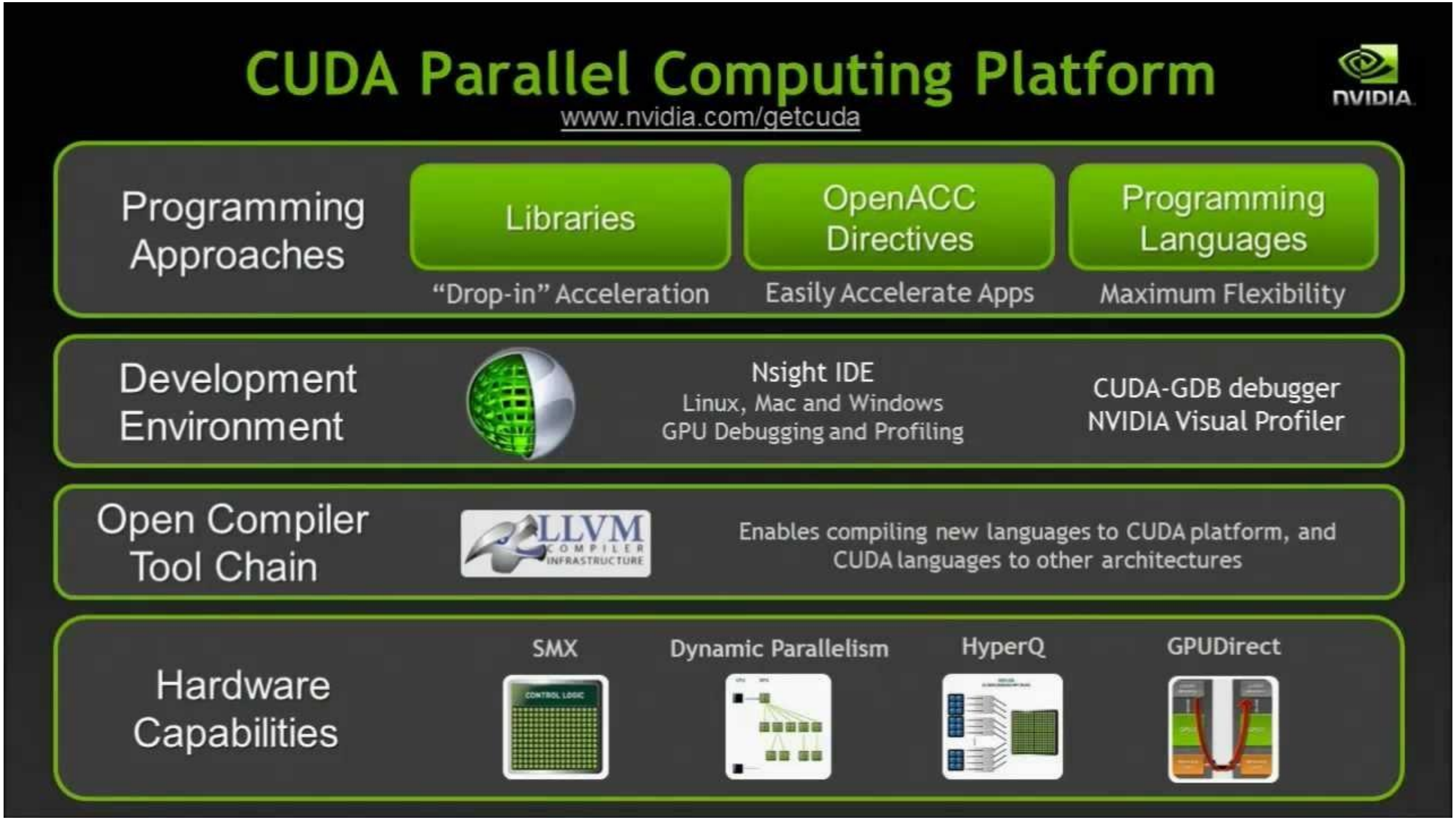




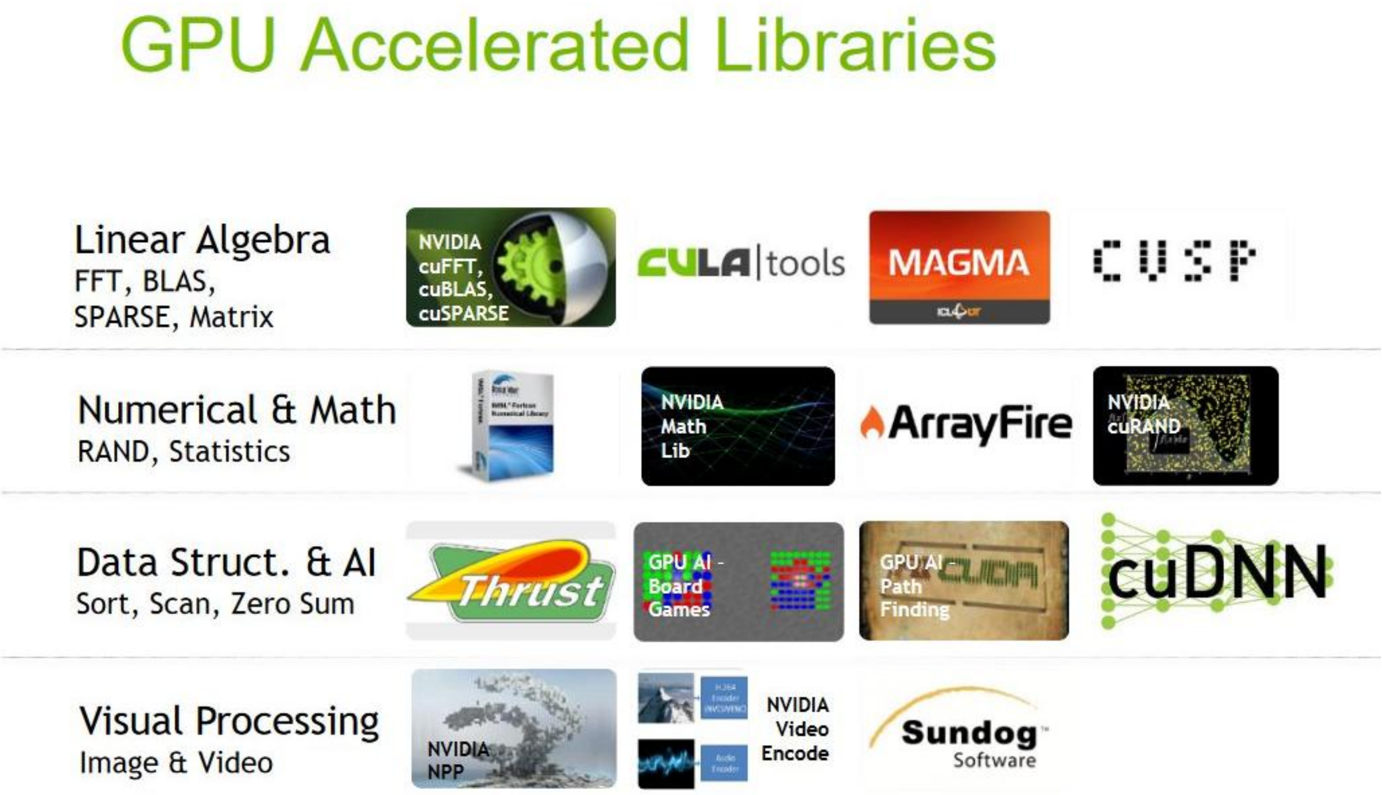
GPU programming: a refresher



GPU programming: a refresher



GPU programming: a refresher



Vector Addition in Thrust

```
thrust::device_vector<float> deviceInput1(inputLength);
thrust::device_vector<float> deviceInput2(inputLength);
thrust::device_vector<float> deviceOutput(inputLength);

thrust::copy(hostInput1, hostInput1 + inputLength,
    deviceInput1.begin());
thrust::copy(hostInput2, hostInput2 + inputLength,
    deviceInput2.begin());

thrust::transform(deviceInput1.begin(), deviceInput1.end(),
     deviceInput2.begin(), deviceOutput.begin(),
     thrust::plus<float>());
```

GPU programming: a refresher

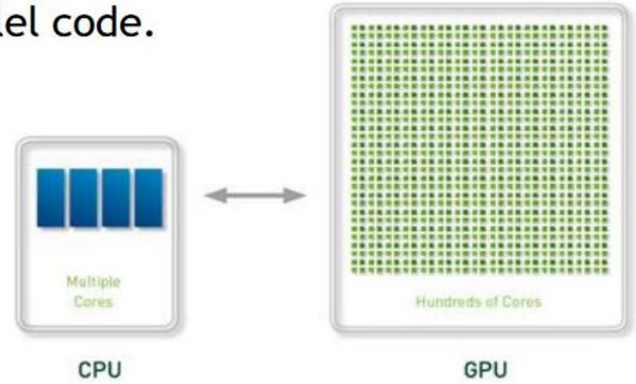
Compiler Directives: Easy, Portable Acceleration

- **Ease of use:** Compiler takes care of details of parallelism management and data movement
- **Portable:** The code is generic, not specific to any type of hardware and can be deployed into multiple languages
- **Uncertain:** Performance of code can vary across compiler versions

```c
#include <stdio.h>

int main() {
    int n = 100000;
    float a[n], b[n], c[n];

    // Initialize arrays
    #pragma acc parallel loop
    for (int i = 0; i < n; i++) {
        a[i] = i;
        b[i] = 2 * i;
    }

    // Perform vector addition
    #pragma acc parallel loop
    for (int i = 0; i < n; i++) {
        c[i] = a[i] + b[i];
    }

    // Print the result
    for (int i = 0; i < n; i++) {
        printf("%f + %f = %f\n", a[i], b[i], c[i]);
    }

    return 0;
}
```

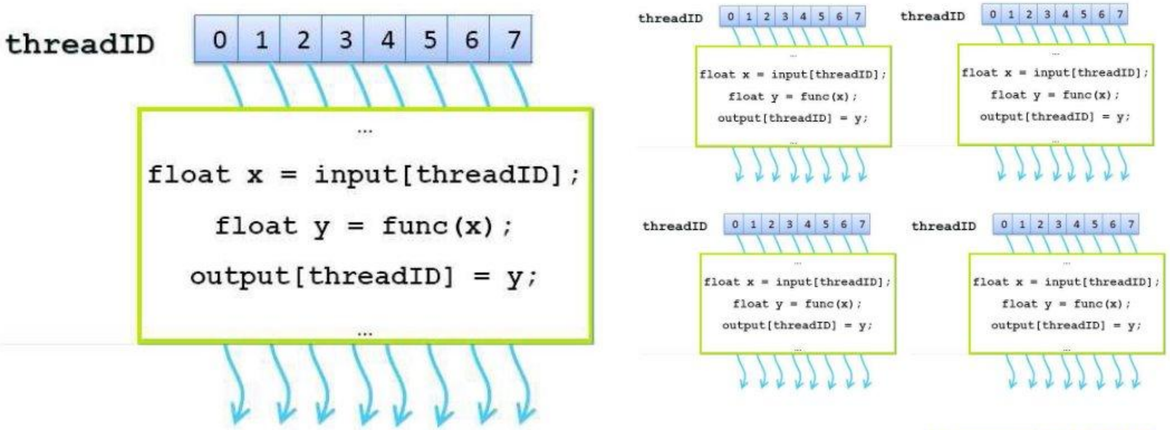
GPU programming: a refresher

- **CUDA** allows:
  - **To scale** the parallelism to thousands of **lightweigth** threads executed in hundreds of processors.
  - **To abstract** the GPU to programmers.
  - To compose an ***heterogenous system*** (CPU + GPU):
    - CPU for sequential code and control.
    - GPU for parallel code.



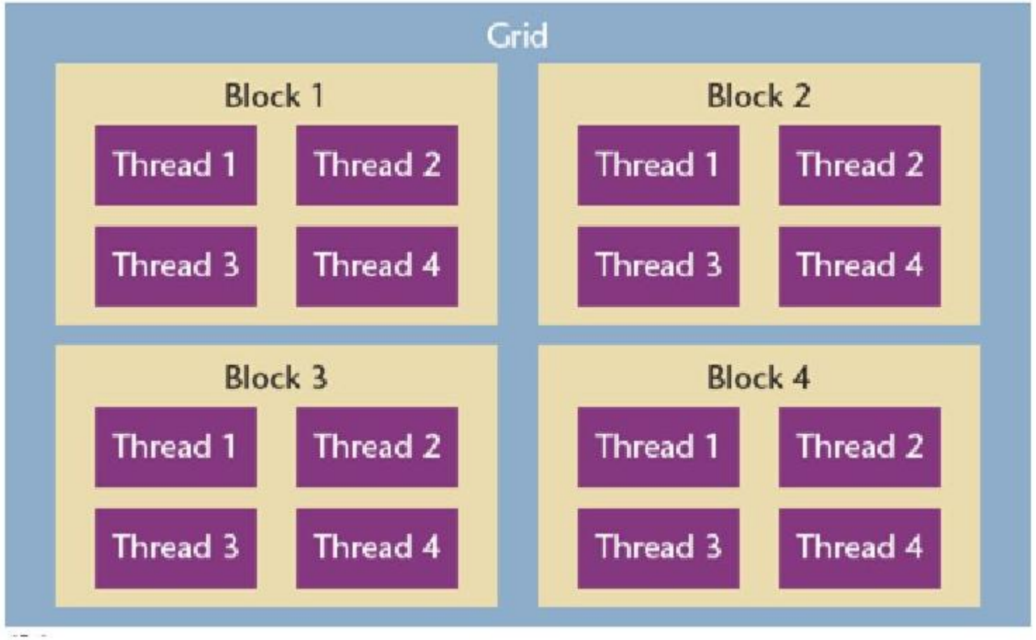
Introduction to CUDA

- The execution of threads is **SPMD** (**S**ingle **P**rogram **M**ultiple **D**ata): they run the same code (kernel) over different data (previously copied to the GPU).

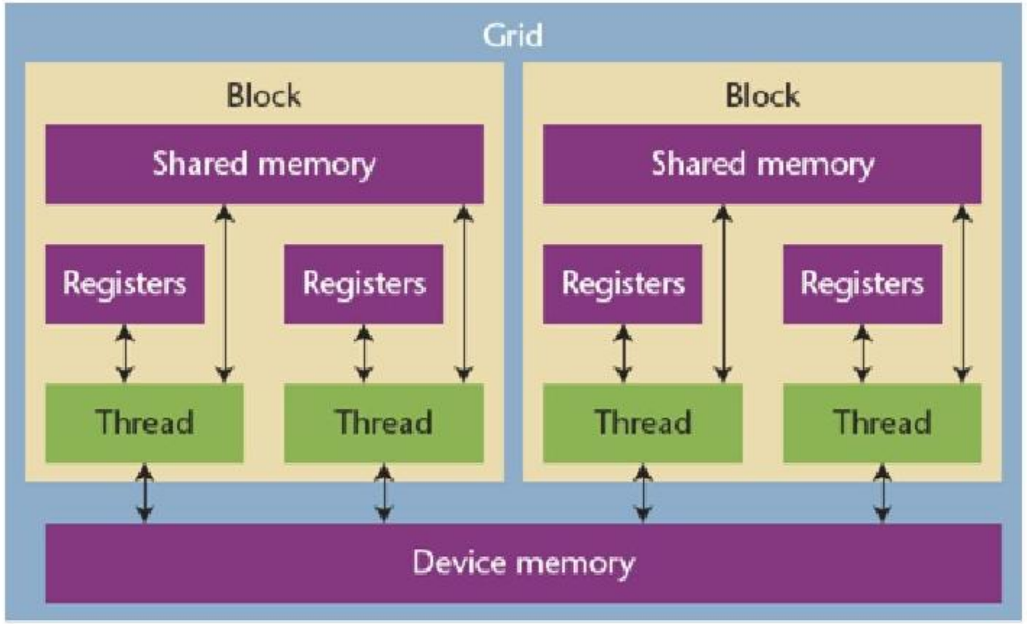


GPU programming: a refresher

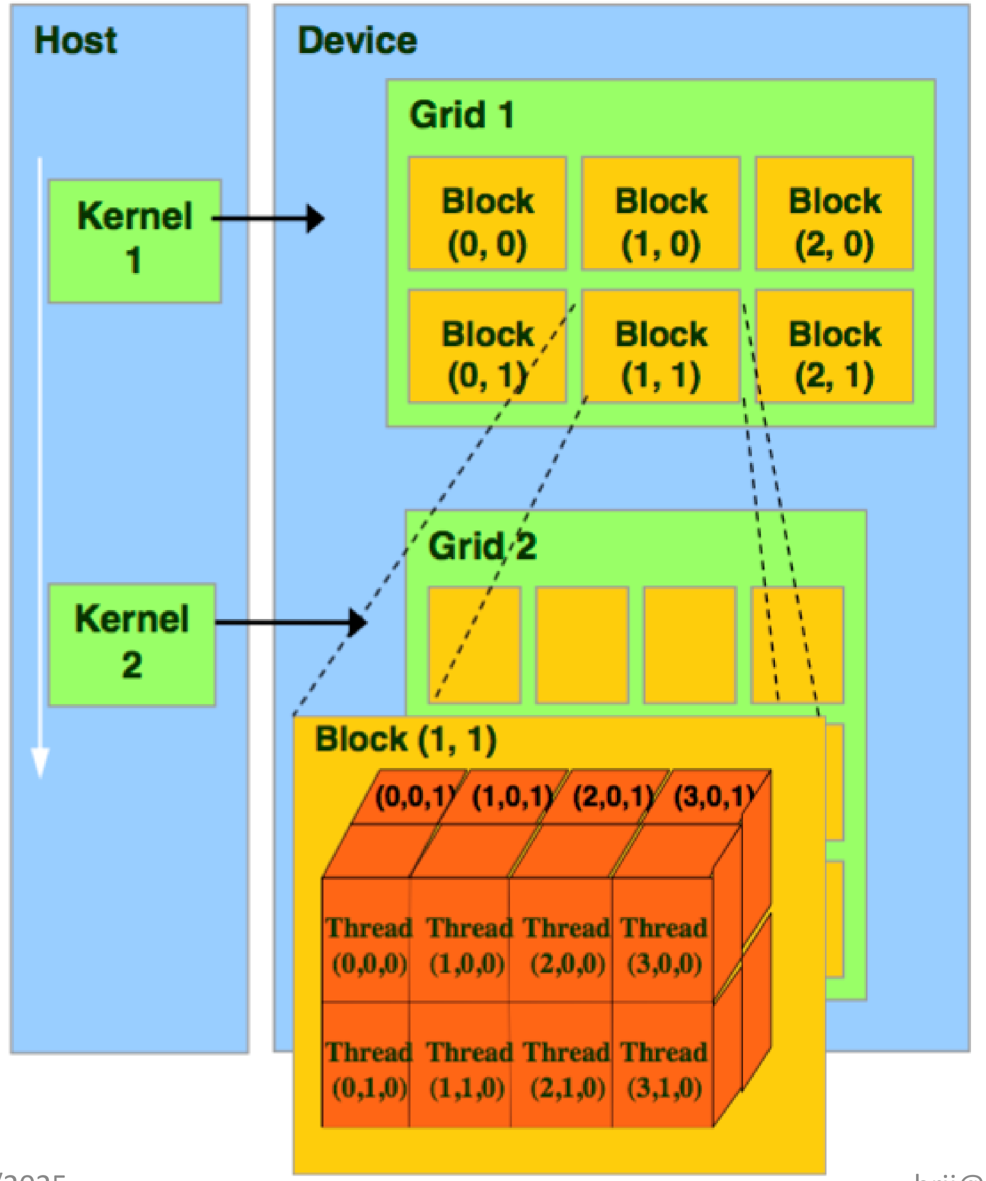
- **Hierarchy of threads in the model.**

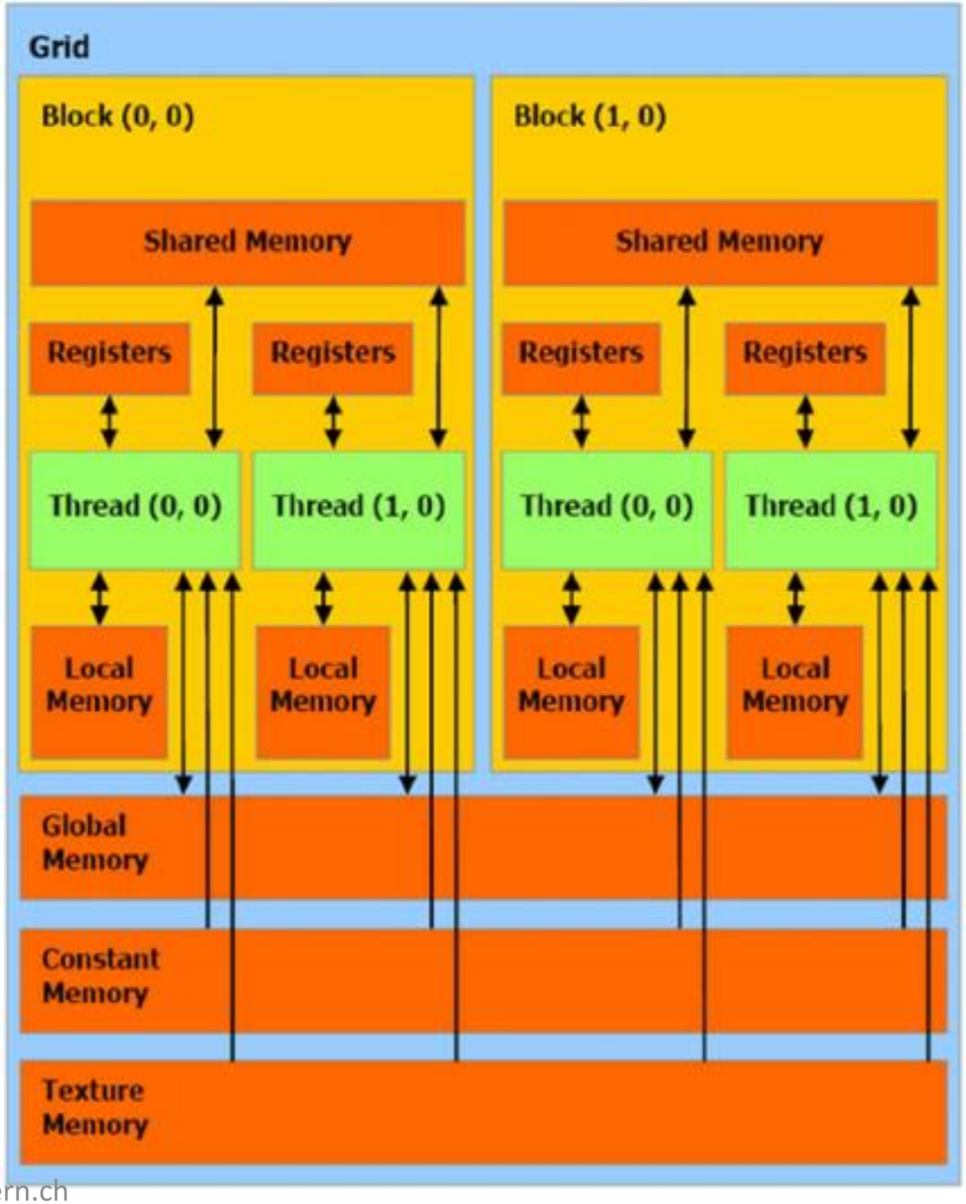


- **Hierarchy of memory in the model:**

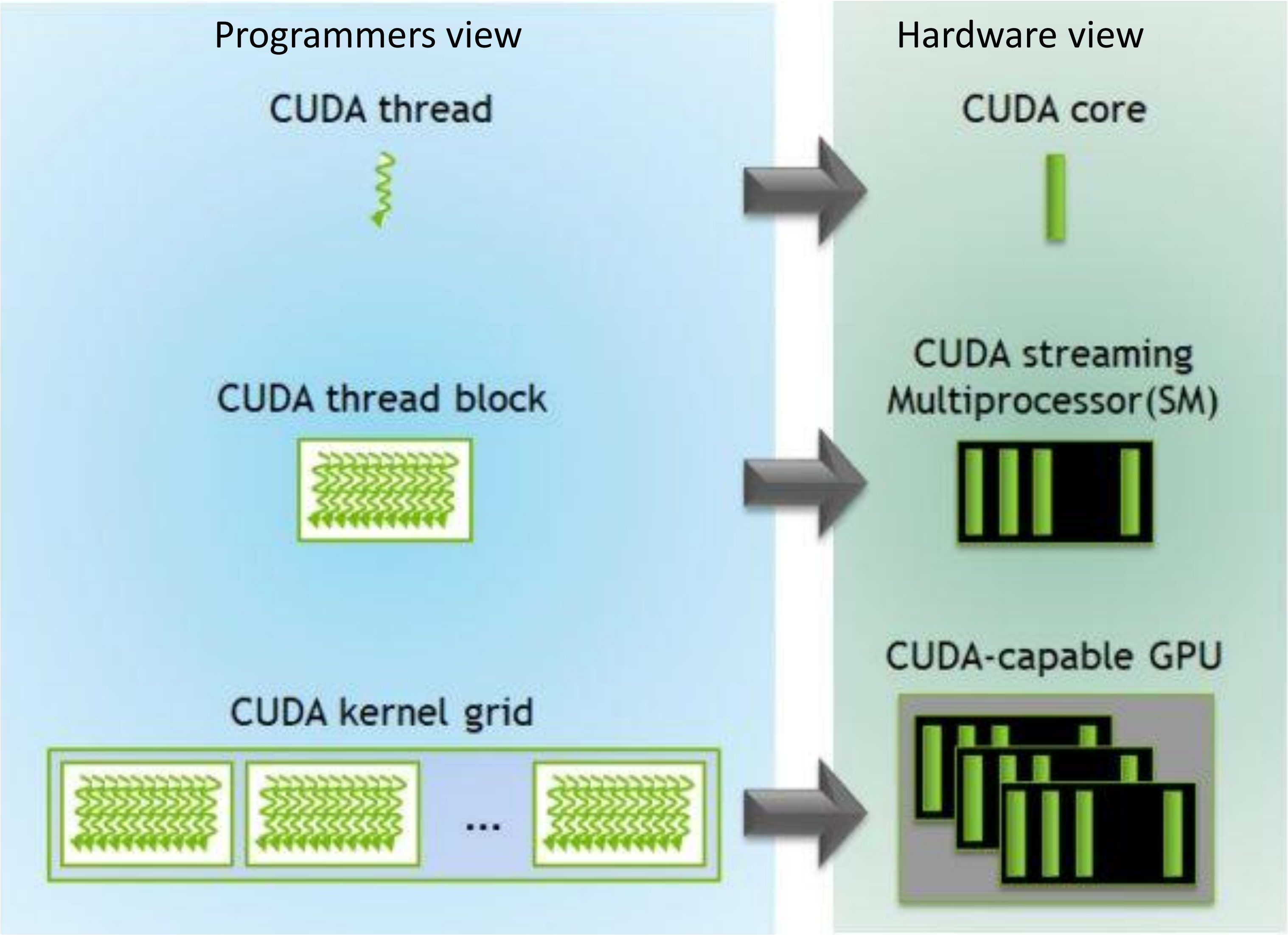


GPU programming: a refresher





GPU programming: a refresher



NVIDIA CUDA: Resources

Learn more

- Official web page and programming model guide:
  https://developer.nvidia.com/cuda-zone
- Training and courses: *https://developer.nvidia.com/cuda-training*
- NVIDIA Deep Learning Institute: https://courses.nvidia.com/courses

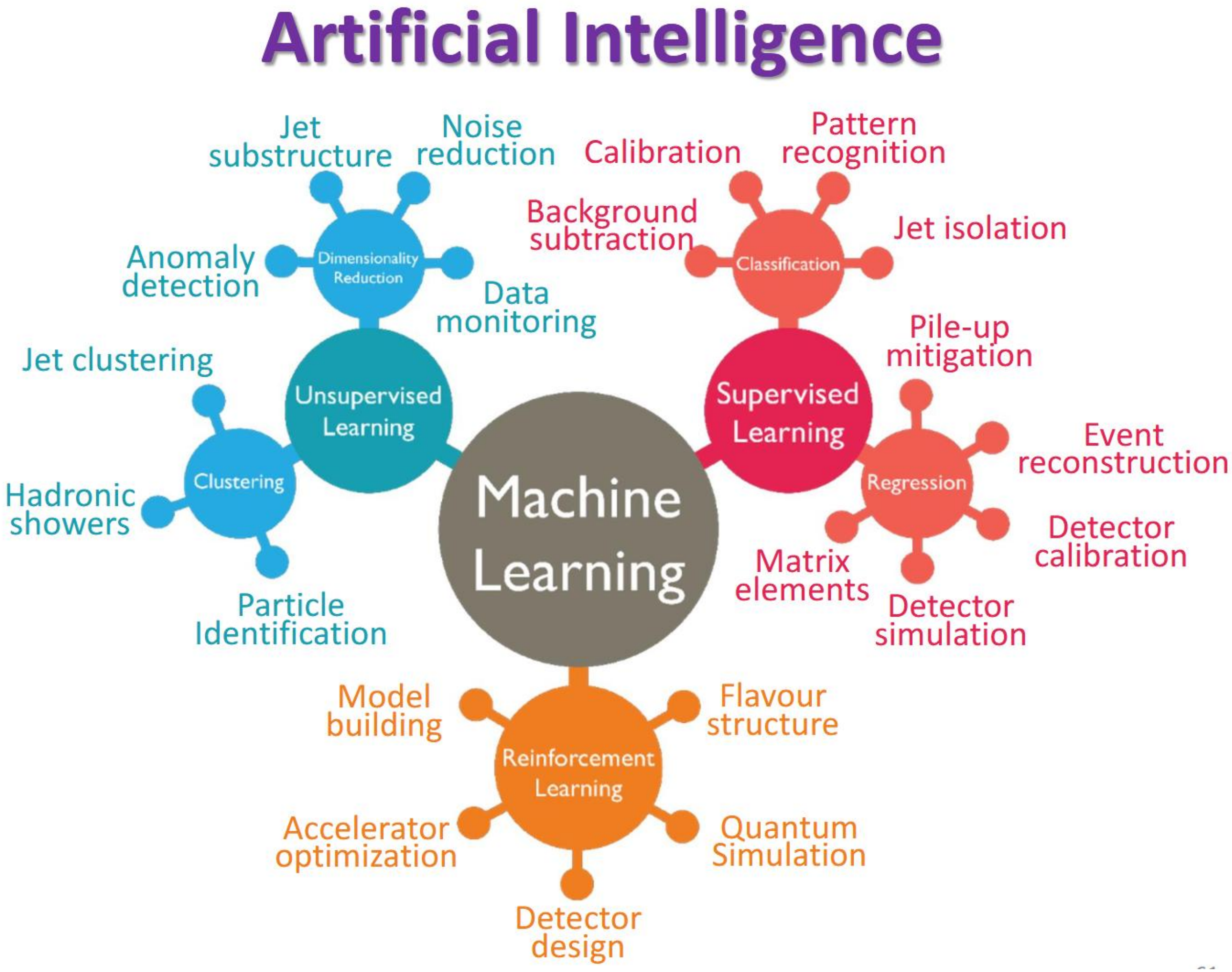
hgpu.org –Database with related Works on GPU

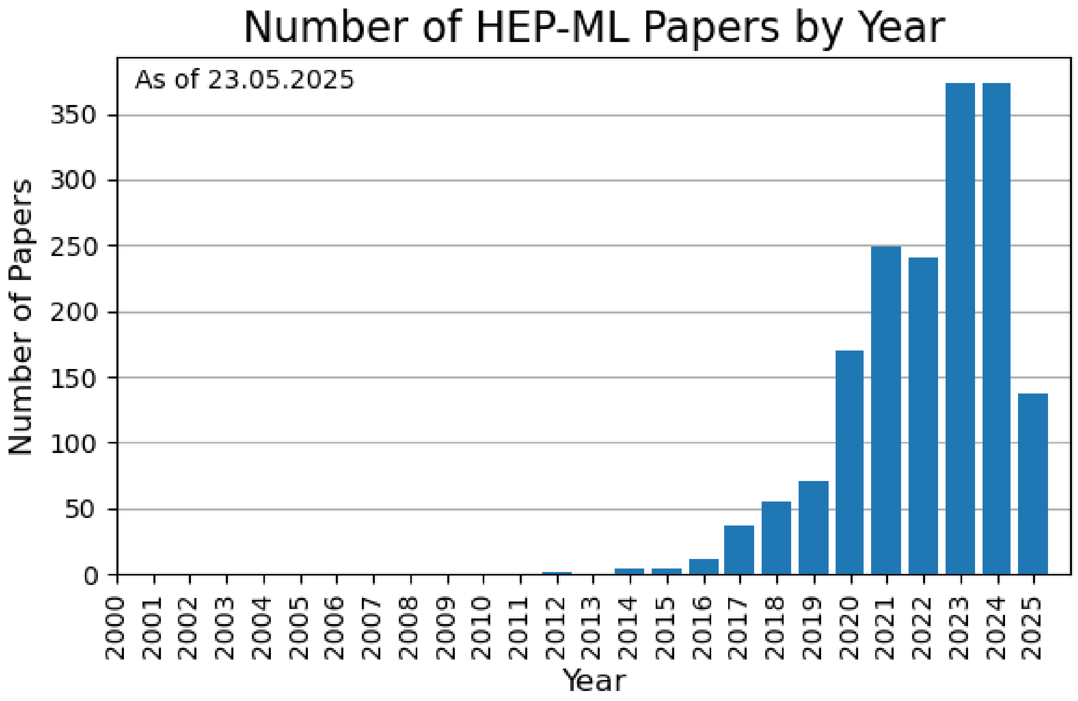
Google Colab: https://colab.research.google.com
Using GPUs on the cloud for free, based on Jupyter and Python.

7. Future ?

Generative AI

https://iml-wg.github.io/HEPML-LivingReview/





Generative AI

https://iml-wg.github.io/HEPML-LivingReview/

Formal Theory and ML

- Theory and physics for ML
- ML for theory

Classification

- Parameterized classifiers
- Representations
- Targets
- Learning strategies
- Fast inference / deployment

Experimental results.

This section is incomplete as there are many results that directly and indirec techniques. We will try to highlight experimental results that use deep learnir

- Performance studies
- Searches and measurements where ML reconstruction is a core component
- Final analysis discriminate for searches
- Measurements using deep learning directly (not through object reconstruction)

Generative models / density estimation

- GANs
- (Variational) Autoencoders
- (Continuous) Normalizing flows
- Diffusion Models
- Transformer Models
- Physics-inspired
- Mixture Models
- Phase space generation
- Gaussian processes
- Other/hybrid

Simulation-based (`likelihood-f

- Parameter estimation
- Unfolding
- Domain adaptation
- BSM
- Differentiable Simulation

Uncertainty Quantification

- Interpretability
- Estimation
- Mitigation
- Uncertainty- and inference-aware learning

Regression

- Pileup
- Calibration
- Recasting
- Matrix elements
- Parameter estimation
- Parton Distribution Functions (and related)
- Lattice Gauge Theory
- Function Approximation
- Symbolic Regression
- Monitoring

Generative AI

GitHub Copilot (… Gemini code assist, Q Developer, JetBrains AI, Cody)

- **Vibe coding** - you express the **what** and let AI handle most of the **how**.
- Reviews your code
- Produces documentation
- Creates issues
- Creates PRs for existing issues
- Assisted code review

AI Agents:

- Reinforcement Learning fine-tuned LLMs
- Can access web - no cutoff dates
- Create and execute code - it is actually nicer language for a lot of tasks

- OpenAI, DeepSearch, WebBrowse, Operator, Perplexity
- LangChain (+LangGraph), Microsoft AutoGen, CrewAI, Manus, Google ADK, WebArena, OSWorld, CodeAct
- AI using the whole computer; Manus and OpenManus

Generative AI: Model Context Protocol

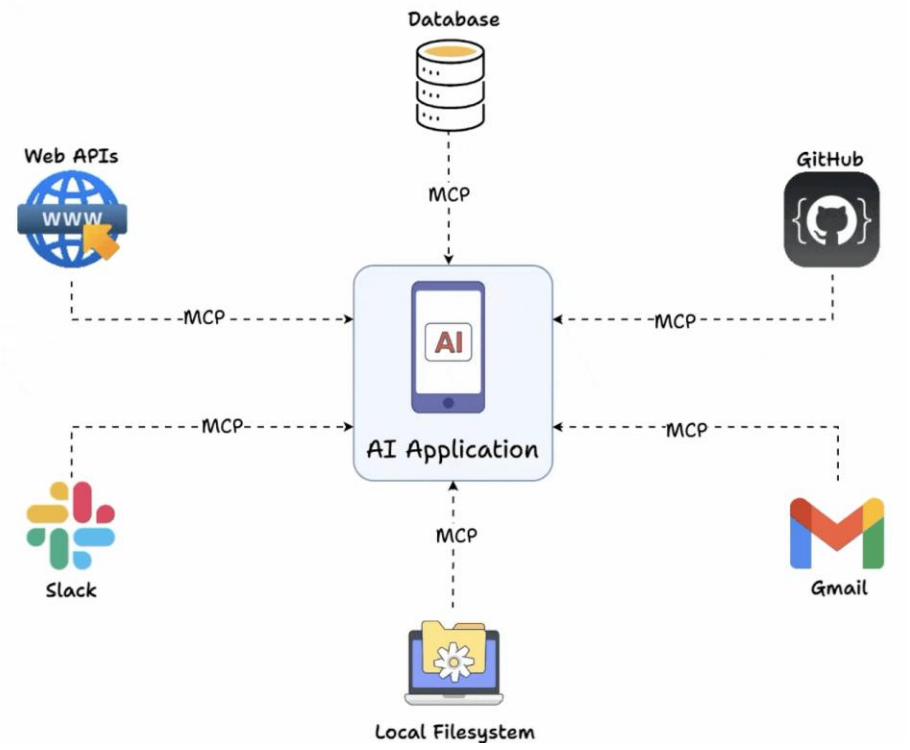
MCP is an open standard that connects Agents to data sources.

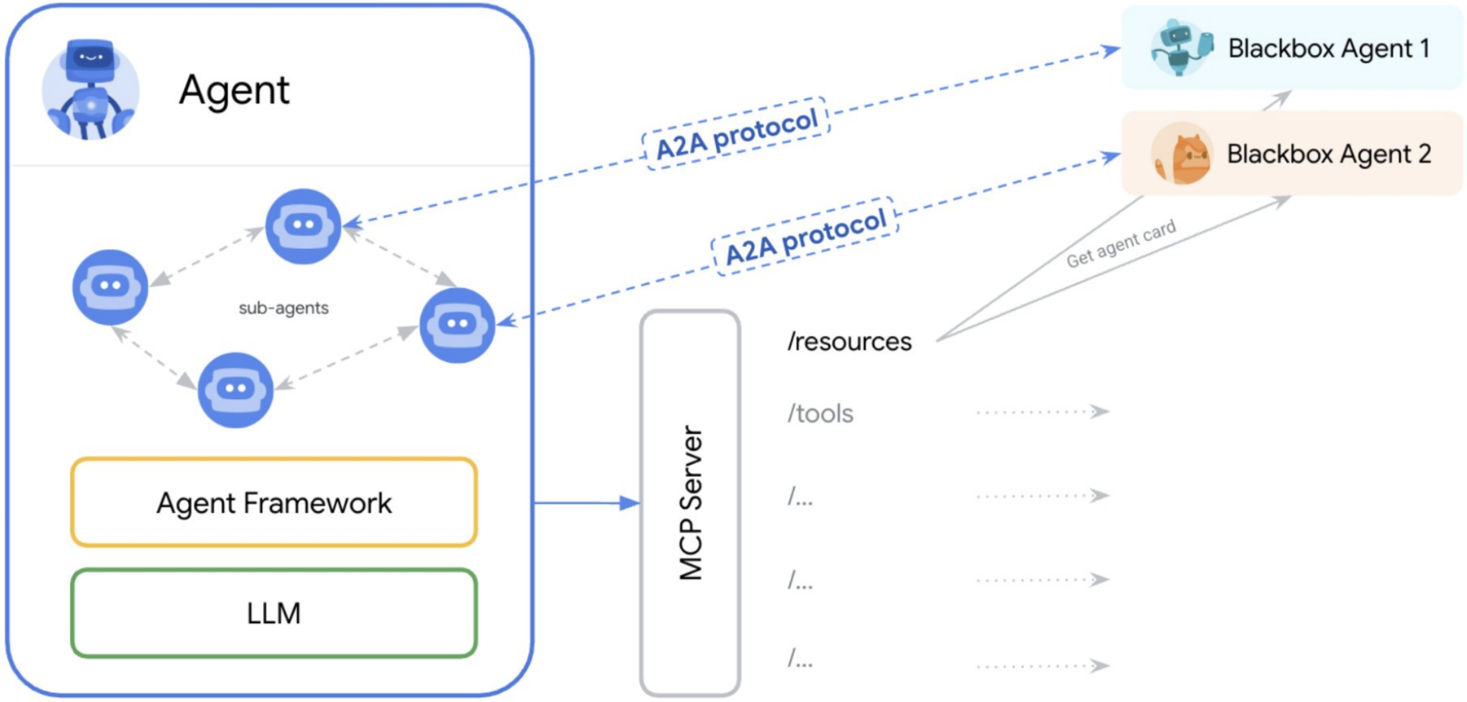
- Widely supported: MCP Servers catalogue
- TypeScript, Python, C#, and other MCP SDKs already exist.
- Stdio, SSE or streamable HTTP transport.

A2A

Agent-to-Agent communication protocol.

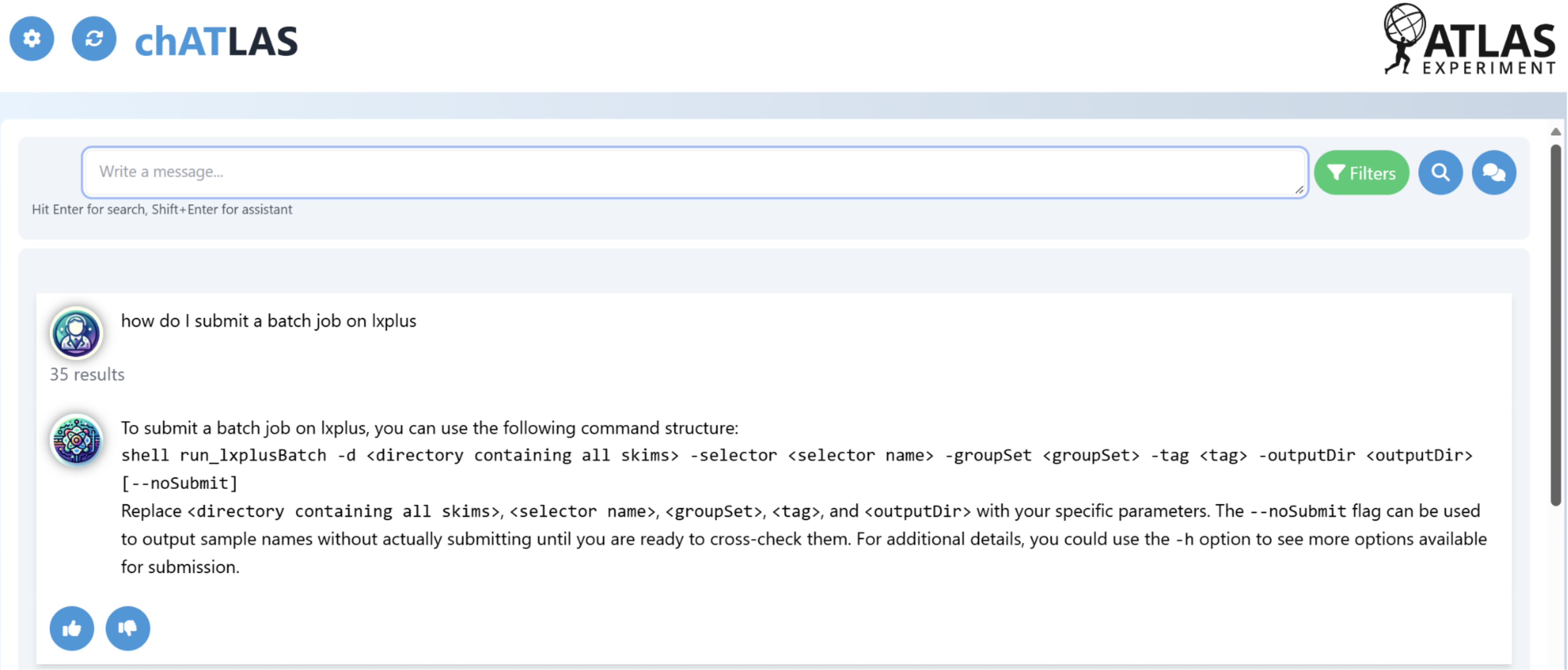
Google proposed, getting accepted.





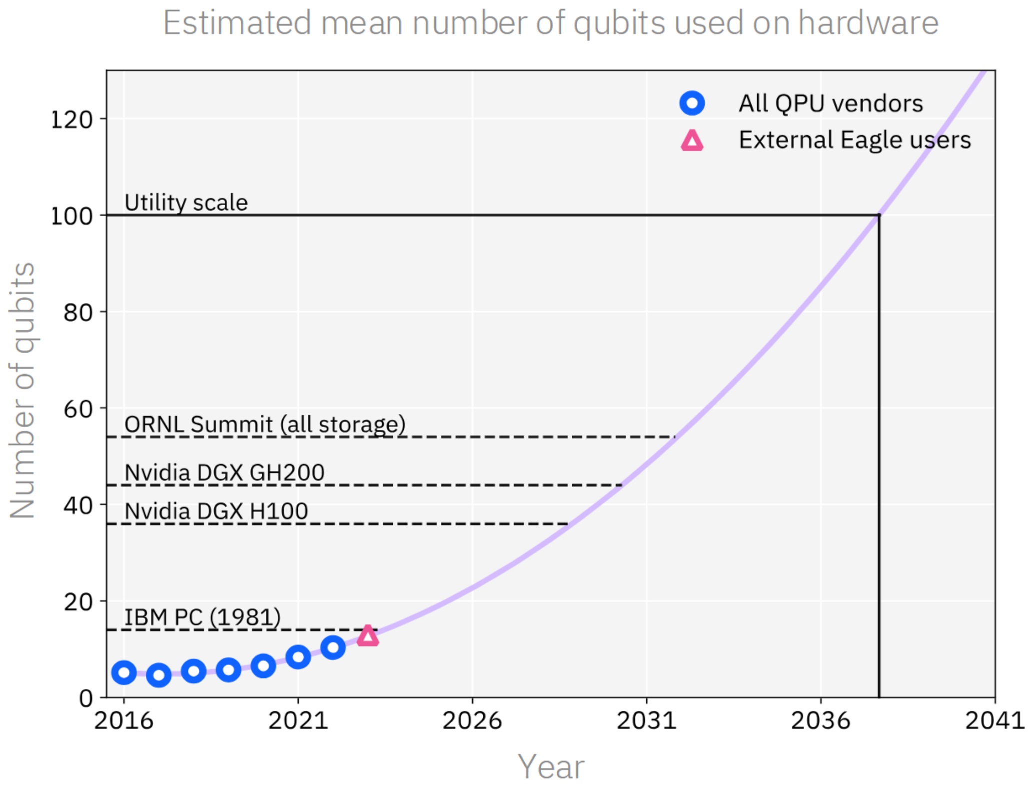
Generative AI:

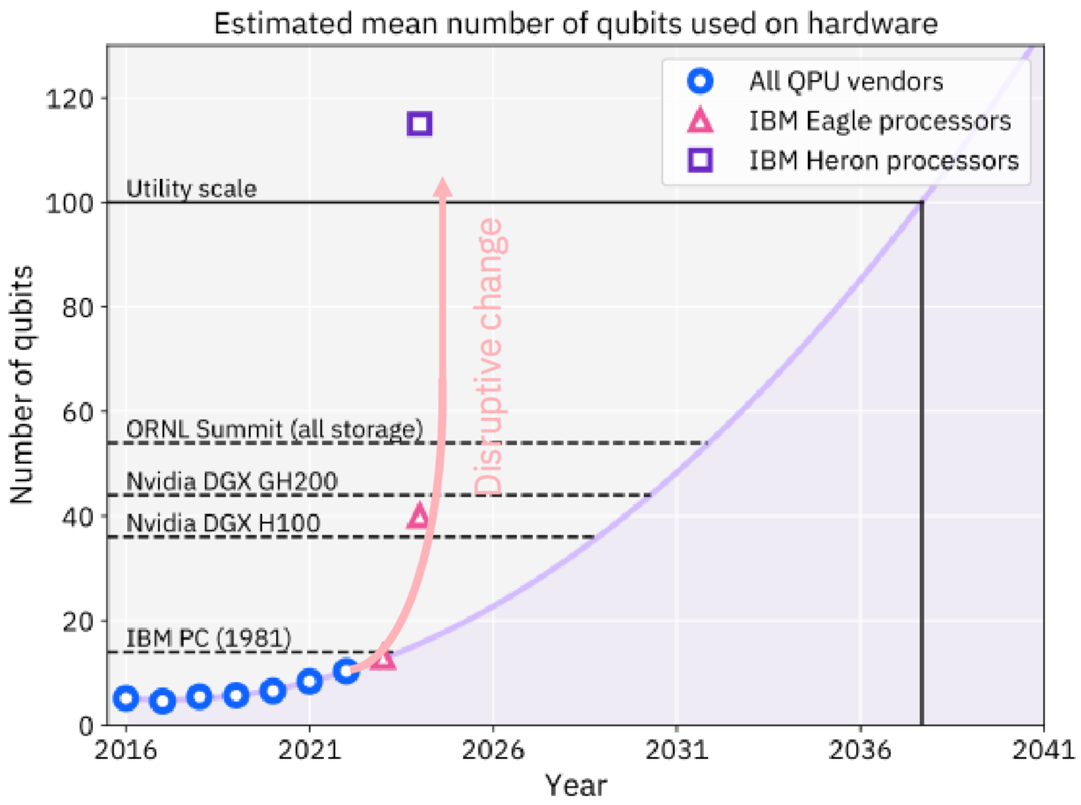
[chATLAS](#)
TWiki and CDS, eGroups, indico, scrapped, converted, chunked, embedded.
Deployed on CERN’s PaaS.



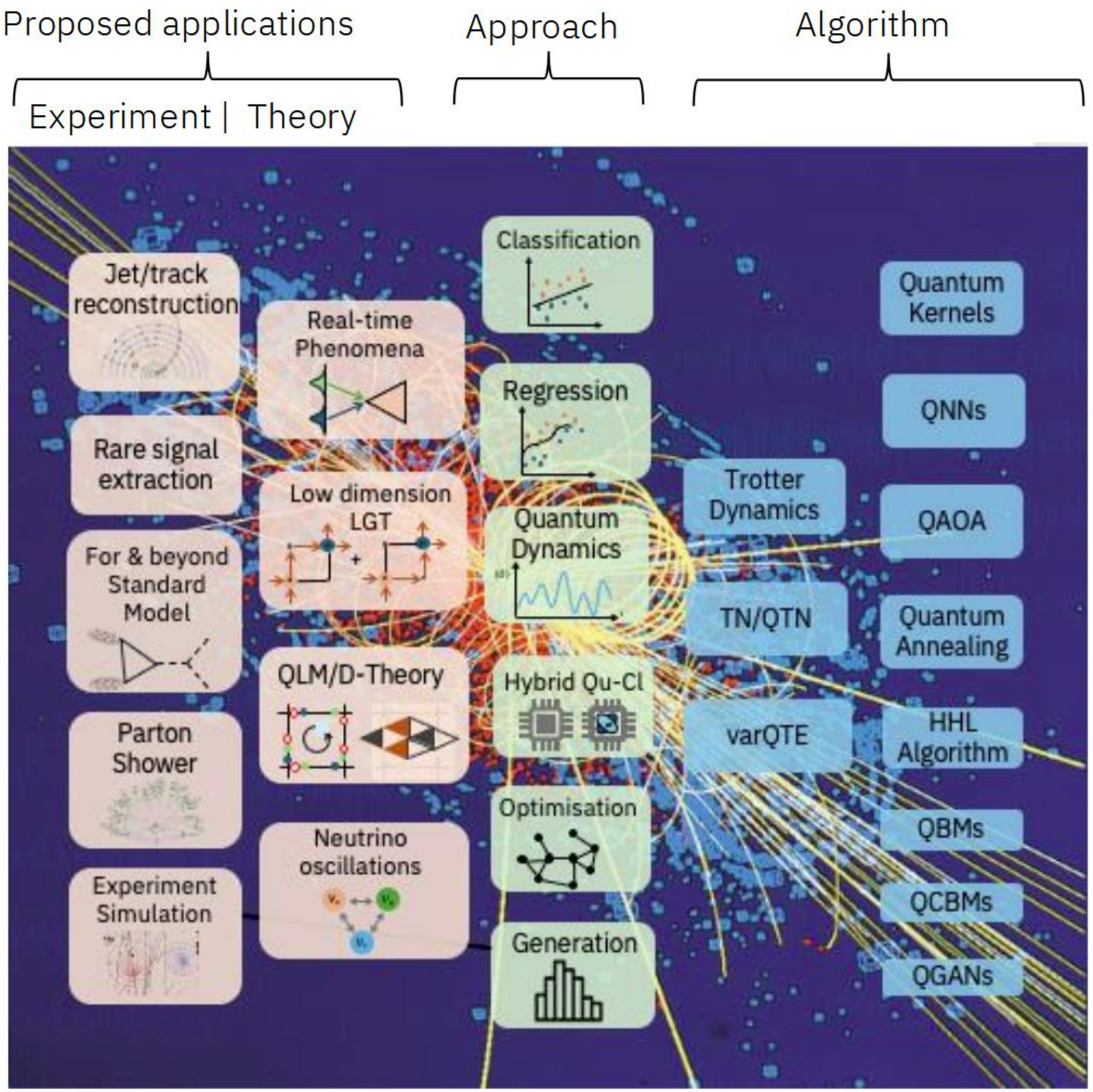
Quantum

IBM first to put the first quantum computer on the cloud in 2016, quantum computing has largely been in an exploratory phase. Experiments validate the tenets of quantum computation, but do not push the field beyond the reach of classical compute. To move beyond simple experiments to demonstrate the utility of quantum computing in multiple domains,





With quantum systems composed of 100+ qubits, researchers are beginning to explore algorithms and applications at scales beyond brute-force classical computation using IBM Quantum systems



The QC4HEP community paper

10.1103/PRXQuantum.5.037001

ROADMAP | OPEN ACCESS

PDF

Quantum Computing for High-Energy Physics: State of the Art and Challenges

Share

Alberto Di Meglio[1,*], Karl Jansen[2,3,†], Ivano Tavernelli[4,‡], Constantia Alexandrou[3,5], Srinivasan Arunachalam[6], Christian W. Bauer[7], Kerstin Borras[8,9], Stefano Carrazza[1,10], Arianna Crippa[2,11] *et al.*

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PRX Quantum **5**, 037001 – **Published 5 August, 2024**

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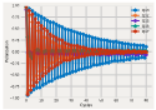
Abstract

Quantum computers offer an intriguing path for a paradigmatic change of computing in the natural sciences and beyond, with the potential for achieving a so-called quantum advantage—namely, a significant (in some cases exponential) speedup of numerical simulations. The rapid development of hardware devices with various realizations of qubits enables the execution of small-scale but representative applications on quantum computers. In particular, the high-energy physics community plays a pivotal role in accessing the power of quantum computing, since the field is a driving source for challenging computational problems. This concerns, on the theoretical side, the exploration of models that are very hard or even impossible to address with classical techniques and, on the experimental side, the enormous data challenge of newly emerging experiments, such as the upgrade of the Large Hadron Collider. In this Roadmap paper, led by CERN, DESY, and IBM, we provide the status of high-energy physics quantum computations and give examples of theoretical and experimental target benchmark applications, which can be addressed in the near future. Having in mind hardware with about 100 qubits capable of executing several thousand two-qubit gates, where possible, we also provide resource estimates for the examples given using error-mitigated quantum computing. The ultimate declared goal of this task force is therefore to trigger further research in the high-energy physics community to develop interesting use cases for demonstrations on near-term quantum computers.

Quantum

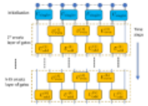


Characterizing quantum processors using discrete time crystals
arXiv:2301.07625
80 qubits / 7900 CX gates

materials

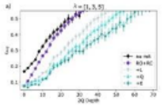
Evidence for the utility of quantum computing before fault tolerance
Nature, 618, 500 (2023)
127 qubits / 2880 CX gates

spin models



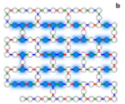
Simulating large-size quantum spin chains on cloud-based superconducting quantum computers
Phys. Rev. Research 5, 013183 (2023)
102 qubits / 3186 CX gates

spin models



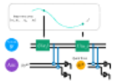
Best practices for quantum error mitigation with digital zero-noise extrapolation
arXiv:2307.05203
104 qubits / 3605 ECR gates

tools



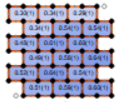
Uncovering Local Integrability in Quantum Many-Body Dynamics
arXiv:2307.07552
124 qubits / 2641 CX gates

materials



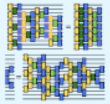
Quantum reservoir computing with repeated Measurements on superconducting devices
arXiv:2310.06706
120 qubits / 49470 gates + meas.

materials



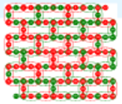
Realizing the Nishimori transition across the error threshold for constant-depth quantum circuits
arXiv:2309.02863
125 qubits / 429 gates + meas.

spin models



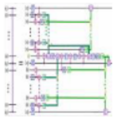
Scalable Circuits for Preparing Ground States on Digital Quantum Computers: The Schwinger Model Vacuum on 100 Qubits
PRX Quantum 5, 020315 (2024)
100 qubits / 788 CX gates

High energy physics



Scaling Whole-Chip QAOA for Higher-Order Ising Spin Glass Models on Heavy-Hex Graphs
arXiv:2312.00997
127 qubits / 420 CX gates

optimization

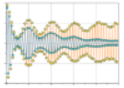


Efficient Long-Range Entanglement using Dynamic Circuits
arXiv:2308.13065
101 qubits / 504 gates + meas

tools

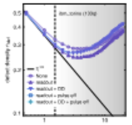
Quantum Simulations of Hadron Dynamics in the Schwinger Model using 112 Qubits
arXiv:2401.08044
112 qubits / 13,858 gates

High energy physics



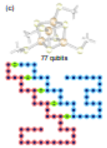
Unveiling clean two-dimensional discrete time quasicrystals on a digital quantum computer
arXiv:2403.16718
133 qubits / 15,000 CZ gates

materials



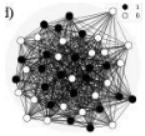
Benchmarking digital quantum simulations and optimization above hundreds of qubits using quantum critical dynamics
arXiv:2404.08053
133 qubits / 1440 CX gates

spin models



Chemistry Beyond Exact Solutions on a Quantum-Centric Supercomputer
arXiv:2405.05068
77 qubits / 3590 CZ gates

chemistry



Towards a universal QAOA protocol: Evidence of quantum advantage in solving combinatorial optimization problems
arXiv:2405.09169
109 qubits / 21,200 gates

optimization

Thank you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OR BECAUSE ITS FINISHED