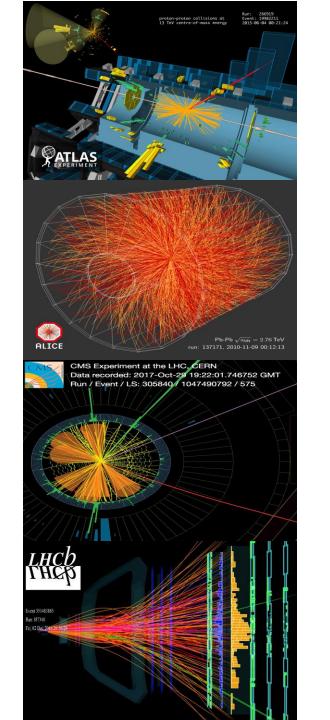
∂TRIUMF

The Worldwide LHC Computing Grid

Reda Tafirout

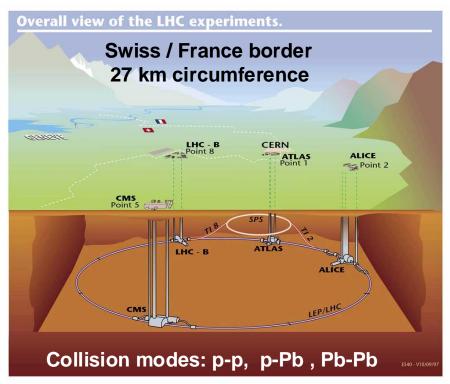
TRIUMF Science Week 2024



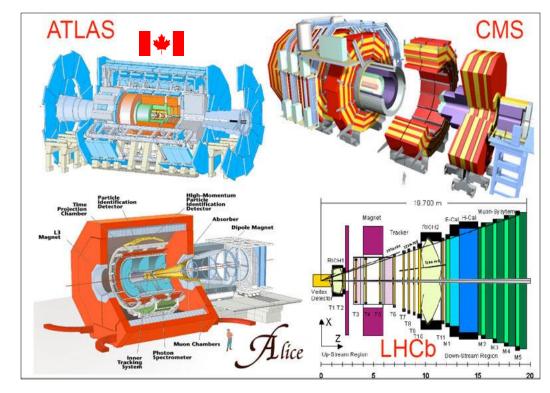
Discovery, accelerated

LHC Scientific Program Tools

Powerful Particle Accelerator



Sophisticated Detectors





Large-scale Distributed Computing





WLCG: global collaboration & effort

- Coordinated resource sharing across multiple organizations
- 164 sites in 42 countries (tiered structure)
- MoU's between parties participating in the project
 - CERN (Tier-0), Tier-1 centres, Tier-2 centres
 - Baseline services & roles
 - Service levels & up-times
 - Management structure & Grid operations
- Pledged resources updated yearly based on experiments requirements.



Tier-1: TRIUMF / SFU

Tier-2: Alliance sites (Victoria, SFU, Waterloo)





2024 pledge: ~2 EB tape, 1 EB disk, 550 kcores







65 MoU's 164 sites

42 countries

Digital Research Alliance of Canada

WLCG: many key components

- Middleware services
- Information system (sites configuration) ٠
- Security & authentication: IGTF (CA's)
- VO management service
- File transfer service & network provisioning
- Workload management
- Data management
- Accounting & monitoring
- Constant evolution while ensuring continuity •







G1

AP EU TAG

FTS

International Grid Trust Federation

ΓF







HTCO

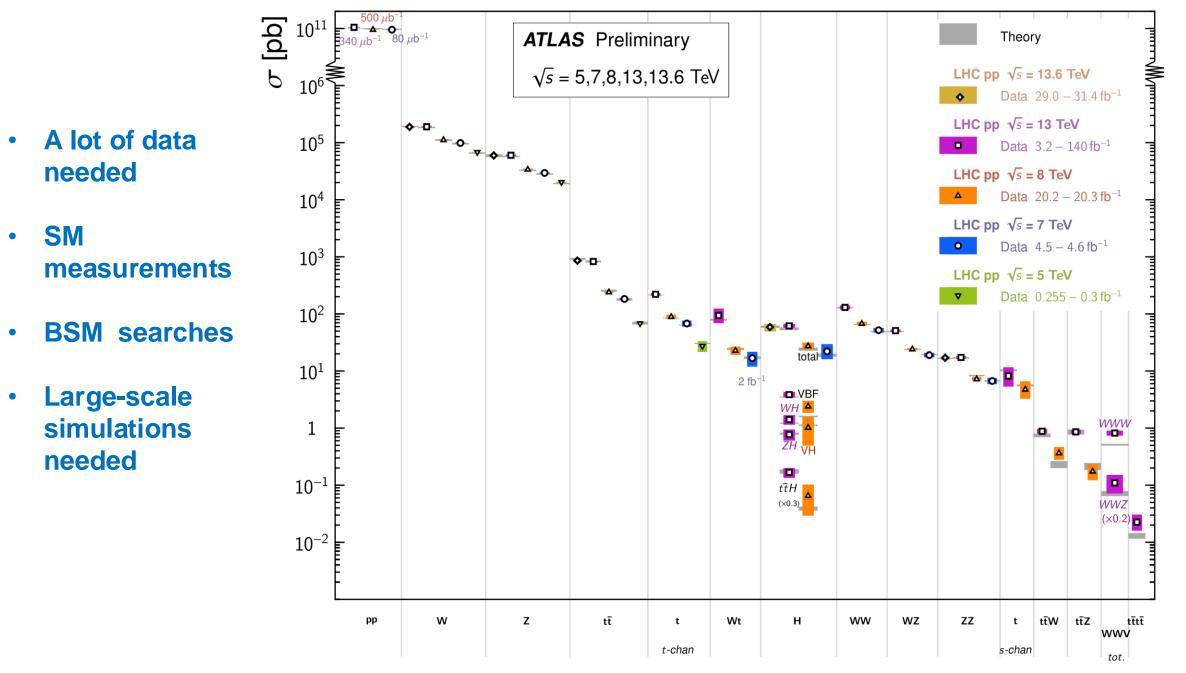




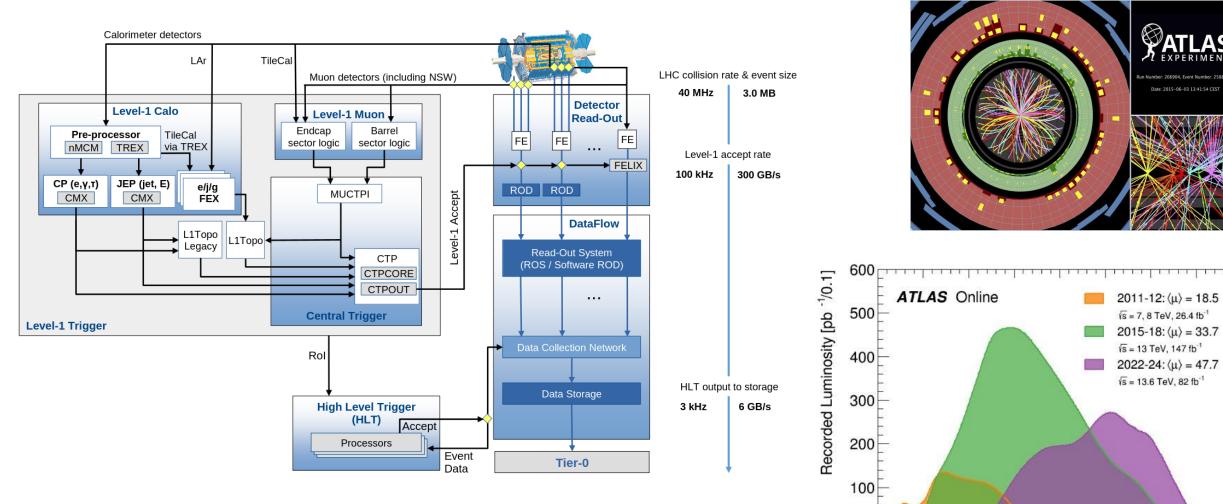
Standard Model Total Production Cross Section Measurements

Status: June 2024

5



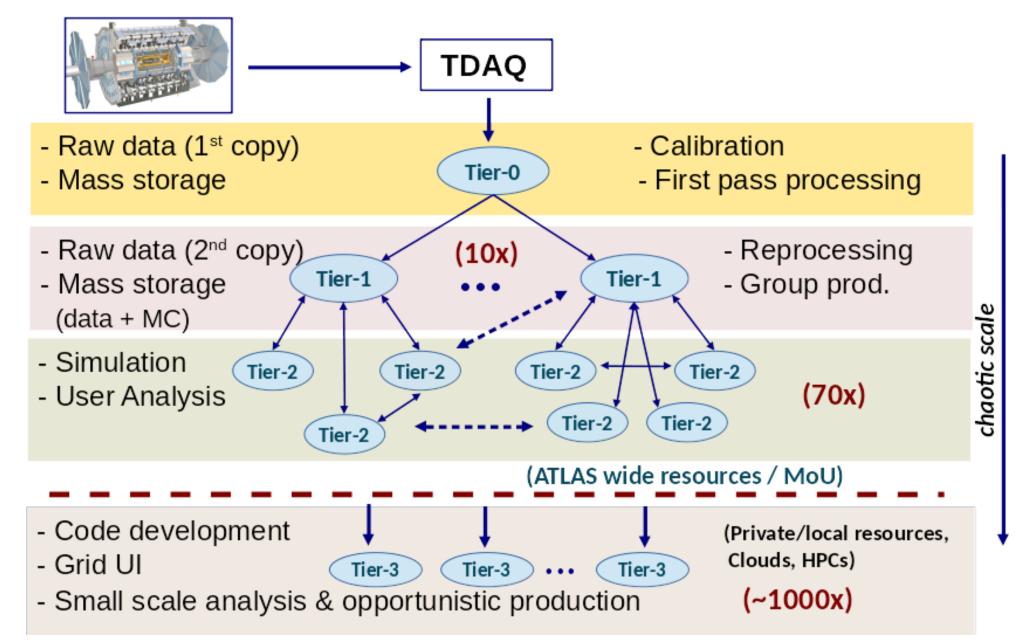
ATLAS TDAQ Chain



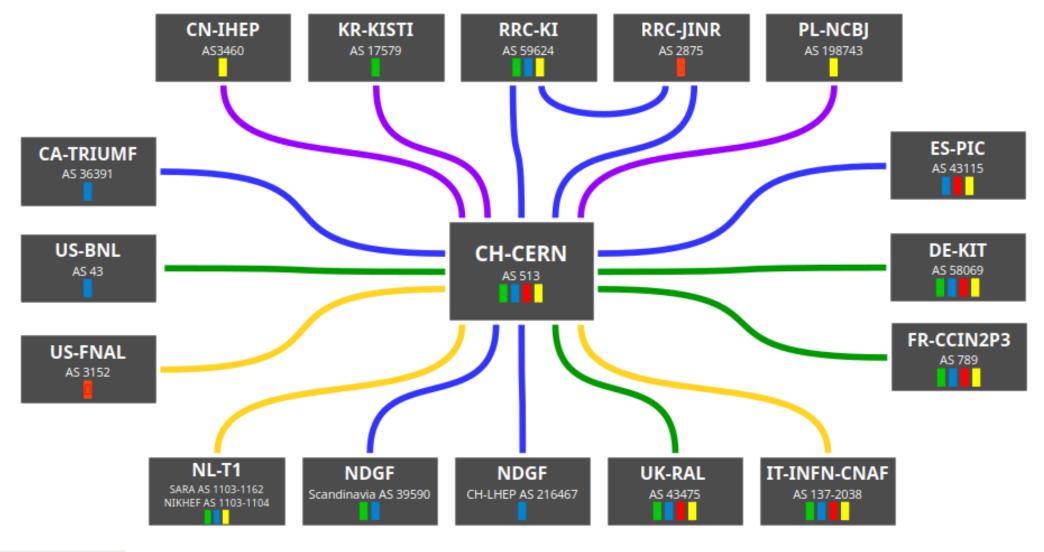
- From 40 MHz beam crossing to ~3 kHz (storage at T0)
- HLT farm scale: ~100,000 cores (dedicated)

Mean Number of Interactions per Crossing

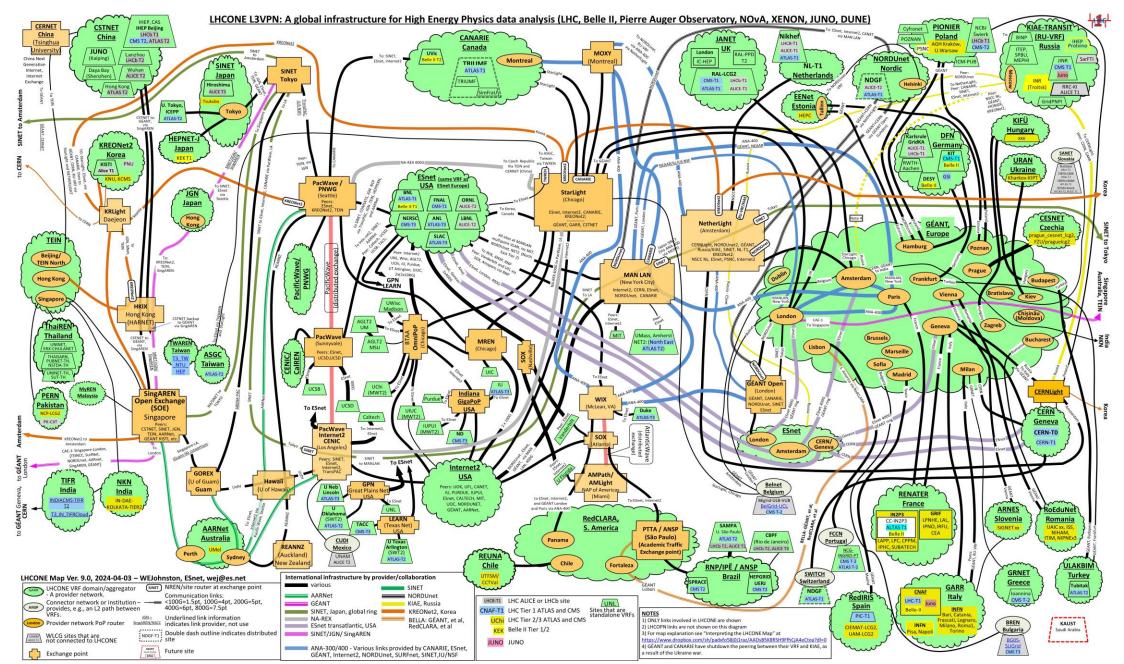
ATLAS Computing Model



LHC Optical Private Network (LHCOPN)

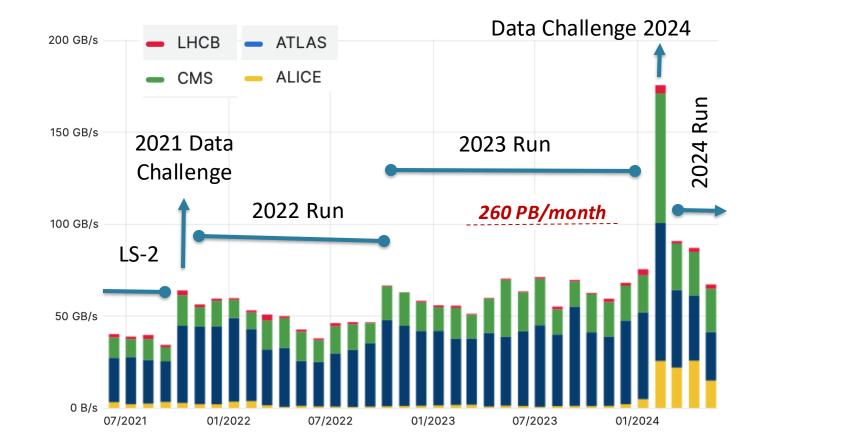


LHC Open Network Environment (LHCONE)



WLCG: global data transfers

Monthly data transfer throughput between WLCG sites (GB/s) – 3 years



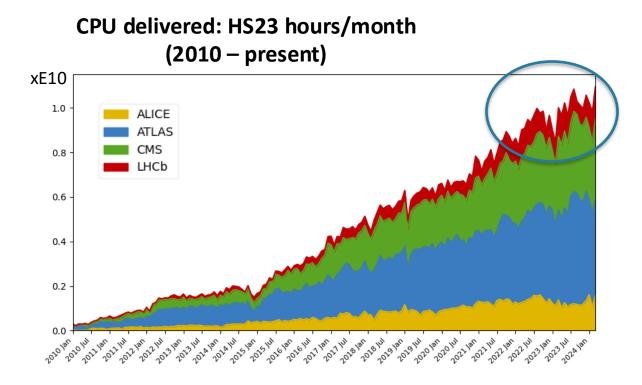
WLCG supports +40% more transfers since LS-2

Further scalability (x5) demonstrated in the Data Challenge

No strain to the services

WLCG: cpu delivered globally

• Growing number of computing resources provided to the LHC experiments (+20% since LS2)



- Drop in winter 2022/23: energy crisis in Europe with high natural gas costs (supply issue from Russia)
- Back to "normal" now

 HEPScore 2023 (HS23) is a common cpu benchmark unit (used in WLCG pledges & accounting)

ATLAS Distributed Computing Needs & HL-LHC Challenges

- ~10x data rate increase in Run-4
- Flat budget model "problematic"
- Significant development effort is required:

Run 4 (u=88-140

2020 2022 2024 2026 2028 2030 2032 2034 2036

- Improve software performance
- Leverage modern architectures
- Data challenges planned

Run 3 (u=55

ATLAS Preliminary

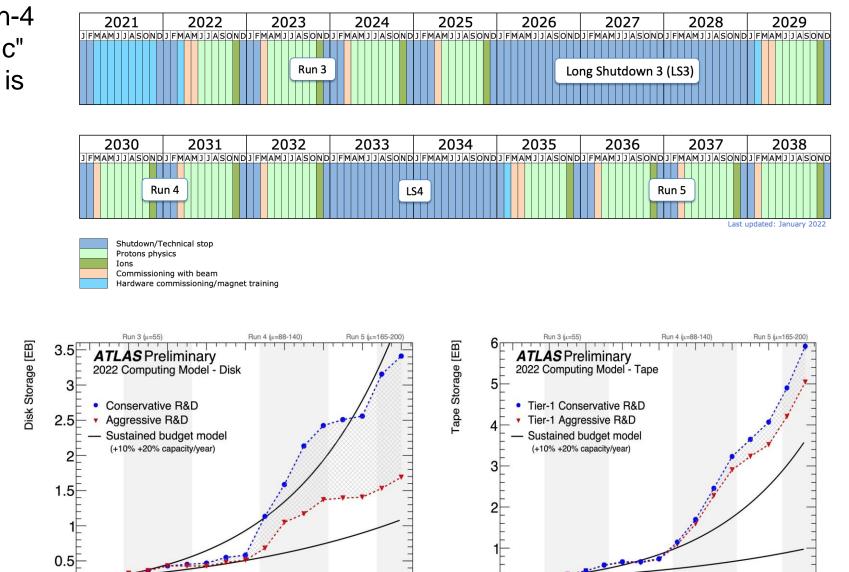
Conservative R&D

Sustained budget model

(+10% +20% capacity/year)

Aggressive R&D

2022 Computing Model - CPU



Year

2020 2022 2024 2026 2028 2030 2032 2034 2036

Year

2020 2022 2024 2026 2028 2030 2032 2034 2036

40

20

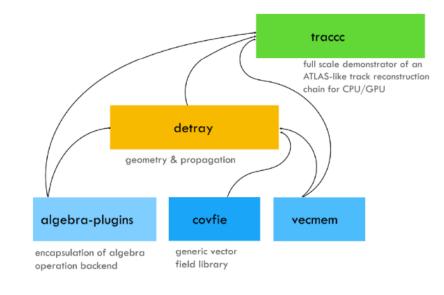
10

Run 5 (u=165-200

ATLAS Software & Computing Roadmap for the HL-LHC

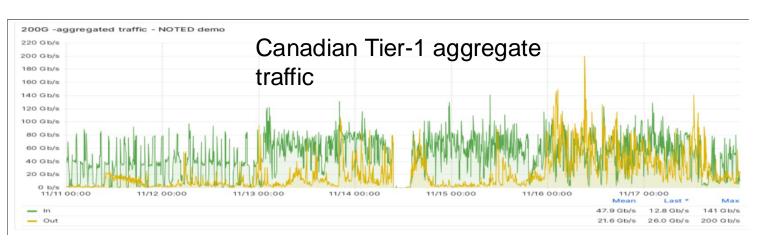
- Roadmap has several components dealing with various topics:
 - Network infrastructure ready for Run 4
 - Detector Description, Simulation and Digitization projects
 - HL-LHC datasets replicas and versions management
 - Core Software and Heterogeneous Computing / Accelerators
 - etc.
- ATLAS Heterogeneous Computing & Accelerators Forum established recently
- To tackle the combinatorics in a high luminosity environment, investigate tracking on GPU. For this to succeed:
 - define a suitable Event Data Model,
 - develop a toolchain that supports e.g. CUDA kernels
 - provide GPU friendly implementations of the geometry and magnetic field.





Dynamic network provisioning

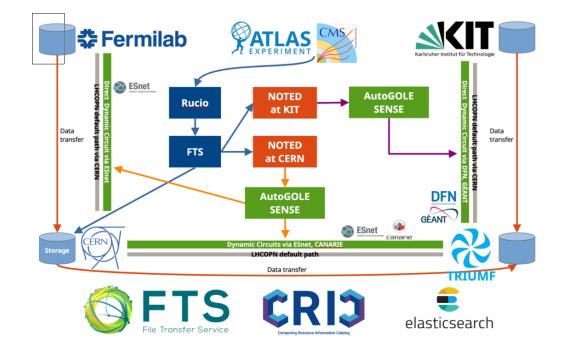
- Demonstration of software defined networks and dynamic circuit provisioning based on demand (Supercomputing 2023 conference)
- Collaboration between TRIUMF, CERN, FNAL, KIT and network providers
- Traffic from both ATLAS & CMS
- Also work on network packets marking (scientific tags) in collaboration with HEPNet Canada

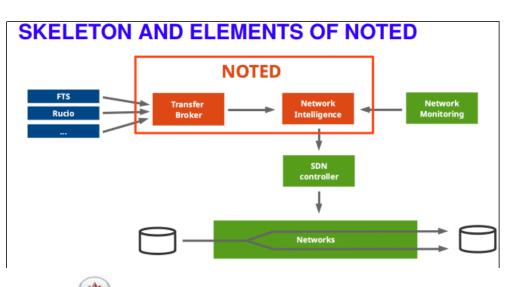


ESnet

ST 💥 R L I G H T

Fermilab canarie

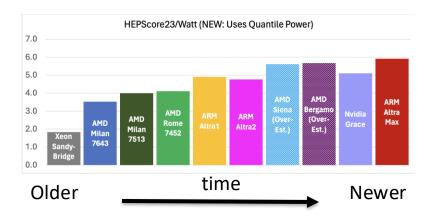




ARM CPUs & GPUs

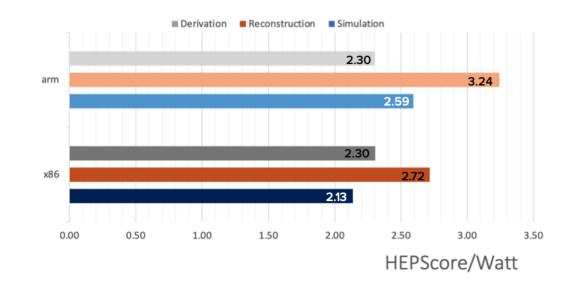
ARM CPUs process more events/Watt wrt x86

- Studies done with hardware Glasgow
- Differences between workflows
- Modern AMDs perform similarly to ARM

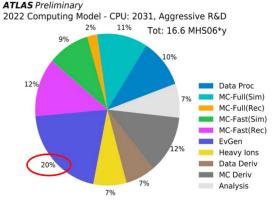


Experiment workflows ported to ARM

- ATLAS, ALICE: validation successful
- CMS, LHCb: in progress
- WLCG discussing about pledging ARM CPUs. Resources already available at various sites



GPUs (in HPCs): massive parallelization, Machine Learning toolkits



		madevent					
CUDA grid size		8192					
$gg \rightarrow t\bar{t}ggg$	MEs	$t_{\rm TOT} = t_{\rm Mad} + t_{\rm Mad}$	t _{MEs}	$N_{\rm events}/t_{\rm TOT}$	$N_{\rm events}/t_{\rm MEs}$		
	precision	[sec]		[events/sec]	[MEs/sec]		
Fortran	double	1228.2 = 5.0 + 1	223.2	7.34E1 (=1.0)	7.37E1 (=1.0)		
CUDA	double	19.6 = 7.4 +	12.1	4.61E3 (x63)	7.44E3 (x100)		
CUDA	float	11.7 = 6.2 +	5.4	7.73E3 (x105)	1.66E4 (x224)		
CUDA	mixed	16.5 = 7.0 +	9.6	5.45E3 (x74)	9.43E3 (x128)		

NVidia V100, Cuda 11.7, gcc 11.2

Conclusion & outlook

- WLCG: global infrastructure developed and operated over the last two decades
- Notable achievement: needs of LHC experiments successfully met
- Recent WLCG strategy document developed to tackle key areas:
 - Technical evolution
 - Financial sustainability
 - Heterogeneous grid infrastructure
 - Interaction with other communities with similar challenges
- The HL-LHC era will be a challenging computing environment
 - Need to ensure sustained innovation and development while ensuring continuing operations





Thank you Merci

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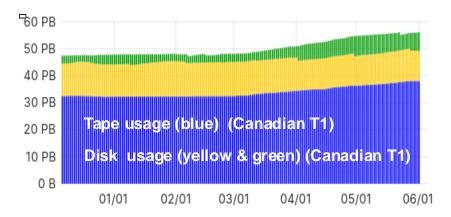


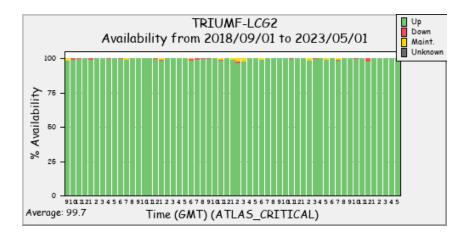
2024-07-23

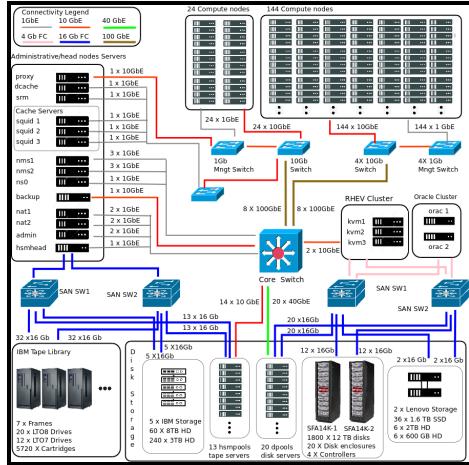
Additional Material

Canadian ATLAS Tier-1 Centre

- Dedicated facility operated 24/7 (per WLCG MoU)
- Key player and contributor within ATLAS Distributed Computing Operations:
 - Availability, Reliability, Scalability & Performance
 - Critical user support for the entire ATLAS collaboration
- Data storage, data processing, simulations and user analysis in a highly secure environment
- Initially located at TRIUMF since 2007
- Transitioned to SFU in 2018, co-located with Cedar/Alliance; continues to be under the perview of TRIUMF
- Operated as federation (new + old site) since 2017
- Current capacity: 9,300 cores ; 17 PB disk ; 46 PB tape







Energy efficiency

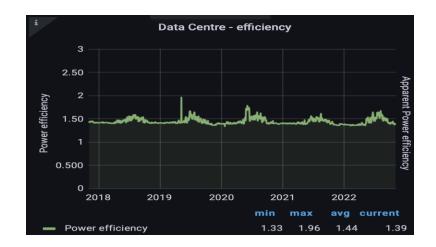
The electricity costs have been an unexpected development in the last couple of years. Environmental impact needs proper addressing!

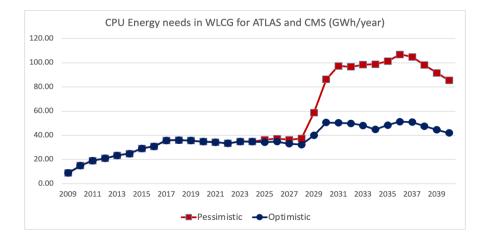
What to do:

- Improve software performance
- Leverage modern architectures
- Invest in the facilities

There is no magic wand, however.

The peak of energy need happens in 2036 (start of Run-5): 400% higher than 2022 in the pessimistic scenario and 50% higher in the optimistic scenario.





RNTuple

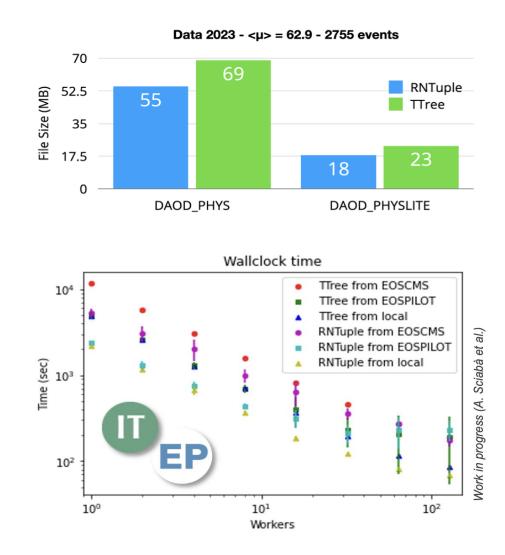
RNTuple is the successor of TTree, the ROOT columnar storage technology

Examples of recent commissioning progress:

ATLAS now capable to read/write all data formats in RNTuple, 20% saving in size for DAOD_PHYS. Substantial progress also for the other experiments

 Expected RNTuple speed-up improvements measured in a real environment at CERN using a community standard analysis benchmark

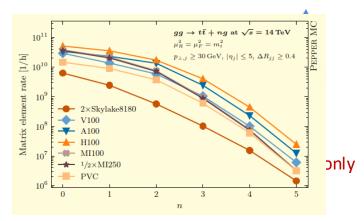
Take home message: **RNTuple progress well on schedule** thanks to a very good collaboration between experiments, CERN EP-SFT and IT



Event Generators

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

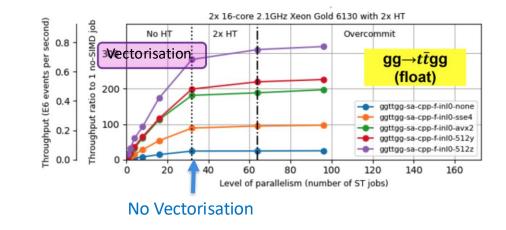
CPU + GPU



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

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: March 2023

 $\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$ $\sqrt{s} = 13 \text{ TeV}$

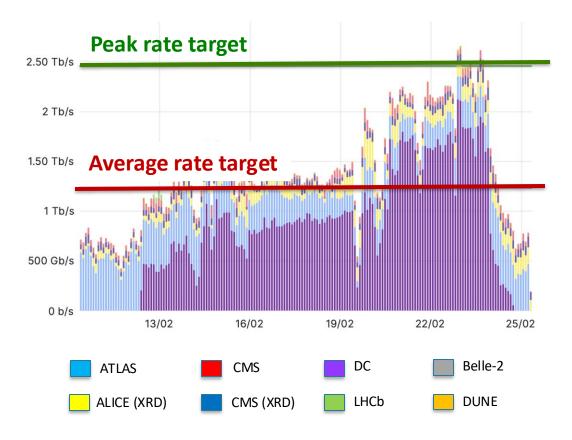
Model	<i>ℓ</i> ,γ	Jets† I	E ^{miss} T	∫£ dt[fb⁻	¹] Limit	- 	Reference
ADD $G_{KK} + g/q$ ADD non-resonant $\gamma\gamma$ ADD QBH ADD BH multijet RS1 $G_{KK} \rightarrow \gamma\gamma$ Bulk RS $G_{KK} \rightarrow WW/ZZ$ Bulk RS $g_{KK} \rightarrow tt$ 2UED / RPP	$\begin{array}{c} 0 \ e, \mu, \tau, \gamma \\ 2 \gamma \\ - \\ 2 \gamma \\ multi-channe \\ 1 \ e, \mu \end{array}$	$\begin{array}{c} 1-4 \ j \\ -2 \ j \\ \geq 3 \ j \\ -1 \\ \geq 1 \ b, \geq 1 \ J/2 \\ \geq 2 \ b, \geq 3 \ j \end{array}$	Yes - - - Yes Yes	139 36.7 139 3.6 139 36.1 36.1 36.1 36.1	М _р M _s M _{th} M _{th} M _{th} G _{KK} mass G _{KK} mass g _{KK} mass S KK mass 1.8 TeV	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	2102.10874 1707.04147 1910.08447 1512.02586 2102.13405 1808.02380 1804.10823 1803.09678
$\begin{array}{c} \mathrm{SSM}\ Z' \to \ell\ell\\ \mathrm{SSM}\ Z' \to \tau\tau\\ \mathrm{Leptophobic}\ Z' \to bb\\ \mathrm{Leptophobic}\ Z' \to tt\\ \mathrm{SSM}\ W' \to \ell\nu\\ \mathrm{SSM}\ W' \to \tau\nu\\ \mathrm{SSM}\ W' \to \psi\\ \mathrm{HVT}\ W' \to WZ \ \mathrm{model}\ \mathrm{B}\\ \mathrm{HVT}\ W' \to WZ \ \mathrm{model}\ \mathrm{B}\\ \mathrm{HVT}\ Z' \to WW \ \mathrm{model}\ \mathrm{B}\\ \mathrm{LRSM}\ W_R \to \mu N_R \end{array}$	$\begin{array}{c} 2 \ e, \mu \\ 2 \ \tau \\ 0 \ e, \mu \\ 1 \ e, \mu \\ 1 \ \tau \\ 0 \ -2 \ e, \mu \\ del \ C \ 3 \ e, \mu \\ 1 \ e, \mu \\ 2 \ \mu \end{array}$	$\begin{array}{c} - & - & - \\ 2 b \\ \geq 1 b, \geq 2 J \\ - & - \\ 2 j / 1 J \\ 2 j (VBF) \\ 2 j / 1 J \\ 1 J \end{array}$	- Yes Yes Yes Yes Yes Yes	139 36.1 139 139 139 139 139 139 139 139 139 80	Z' mass 2.42 Te Z' mass 2.42 Te Z' mass 2.1 TeV Z' mass 2.1 TeV W' mass 30 W' mass 340 GeV Z' mass 2' mass W' mass 340 GeV Z' mass 340 GeV		1903.06248 1709.07242 1805.09299 2005.05138 1906.05609 ATLAS-CONF-2021-02 ATLAS-CONF-2021-04 2004.14636 2207.03925 2004.14636 1904.12679
Cl qqqq Cl ℓℓqq Cl eebs Cl μμbs Cl tttt	_ 2 e, μ 2 e 2 μ ≥1 e,μ	2 j - 1 b 1 b ≥1 b, ≥1 j	- - - Yes	37.0 139 139 139 36.1	Λ Λ Λ 1.8 TeV Λ 2.0 TeV Λ 2.57 T	$\begin{array}{c c} \hline & 21.8 \ {\rm TeV} & \eta_{LL}^- \\ \hline & 35.8 \ {\rm TeV} & \eta_{LL}^- \\ g_* = 1 \\ g_* = 1 \\ C_{4t} = 4\pi \end{array}$	1703.09127 2006.12946 2105.13847 2105.13847 1811.02305
Axial-vector med. (Dirac DM) Pseudo-scalar med. (Dirac DN) Vector med. Z'-2HDM (Dirac I Pseudo-scalar med. 2HDM+a	DM) 0 e, μ	2 j 1 - 4 j 2 b	- Yes Yes	139 139 139 139 139	m _{med} 376 GeV m _{z'} 376 GeV m _a 800 GeV	$\begin{array}{llllllllllllllllllllllllllllllllllll$	ATL-PHYS-PUB-2022-0 2102.10874 2108.13391 ATLAS-CONF-2021-03
CJ Scalar LQ 1 st gen Scalar LQ 2 nd gen Scalar LQ 3 rd gen Scalar LQ 3 rd gen Scalar LQ 3 rd gen Scalar LQ 3 rd gen Vector LQ mix gen Vector LQ 3 rd gen	$\begin{array}{c} 2 \ e \\ 2 \ \mu \\ 1 \ \tau \\ 0 \ e, \mu \\ \geq 2 \ e, \mu, \geq 1 \ \tau \\ 0 \ e, \mu, \geq 1 \ \tau \\ \text{multi-channe} \\ 2 \ e, \mu, \tau \end{array}$	0 – 2 j, 2 b	Yes Yes Yes - Yes Yes Yes	139 139 139 139 139 139 139 139	LQ mass 1.8 TeV LQ mass 1.7 TeV LQ" mass 1.49 TeV LQ" mass 1.42 TeV LQ" mass 1.24 TeV LQ" mass 1.26 TeV LQ" mass 1.26 TeV LQ" mass 2.0 TeV LQ" mass 1.96 TeV	$\begin{array}{l} \beta=1\\ \beta=1\\ \mathcal{B}(\mathrm{LQ}_{3}^{\mathrm{u}}\rightarrow b\tau)=1\\ \mathcal{B}(\mathrm{LQ}_{3}^{\mathrm{u}}\rightarrow t\nu)=1\\ \mathcal{B}(\mathrm{LQ}_{3}^{\mathrm{u}}\rightarrow t\nu)=1\\ \mathcal{B}(\mathrm{LQ}_{3}^{\mathrm{u}}\rightarrow b\nu)=1\\ \mathcal{B}(\tilde{U}_{1}\rightarrow t\mu)=1, \mathrm{YM} \ \mathrm{coupl.}\\ \mathcal{B}(\mathrm{LQ}_{3}^{\mathrm{v}}\rightarrow b\tau)=1, \mathrm{YM} \ \mathrm{coupl.} \end{array}$	2006.05872 2006.05872 2303.01294 2004.14060 2101.11582 2101.12527 ATLAS-CONF-2022-05 2303.01294
$\begin{array}{c} \text{VLQ }TT \rightarrow Zt + X\\ \text{VLQ }BB \rightarrow Wt/Zb + X\\ \text{VLQ }T_{5/3}T_{5/3}T_{5/3} \rightarrow Wt + X\\ \text{VLQ }T \rightarrow Ht/Zt\\ \text{VLQ }T \rightarrow Ht/Zt\\ \text{VLQ }T \rightarrow Wb\\ \text{VLQ }T \rightarrow Hb\\ \text{VLL }\tau' \rightarrow Z\tau/H\tau \end{array}$	1 e, μ 1 e, μ	l		139 36.1 36.1 139 36.1 139 139	T mass 1.46 TeV B mass 1.34 TeV T _{5/3} mass 1.64 TeV T mass 1.64 TeV Y mass 1.8 TeV Y mass 1.85 TeV B mass 2.0 TeV τ' mass 898 GeV	SU(2) doublet SU(2) doublet $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3}Wt) = 1$ SU(2) singlet, $\kappa_T = 0.5$ $\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$ SU(2) doublet, $\kappa_B = 0.3$ SU(2) doublet	2210.15413 1808.02343 1807.11883 ATLAS-CONF-2021-04 1812.07343 ATLAS-CONF-2021-01 2303.05441
Excited quark $q^* \rightarrow qg$ Excited quark $q^* \rightarrow q\gamma$ Excited quark $q^* \rightarrow q\gamma$ Excited quark $b^* \rightarrow bg$ Excited lepton τ^*	- 1 γ - 2 τ	2j 1j 1b,1j ≥2j	- - -	139 36.7 139 139	q* mass q* mass b* mass τ* mass	6.7 TeV only u^* and d^* , $\Lambda = m(q^*)$ 5.3 TeV only u^* and d^* , $\Lambda = m(q^*)$ 3.2 TeV $\Lambda = 4.6 \text{ TeV}$	1910.08447 1709.10440 1910.08447 2303.09444
Type III Seesaw LRSM Majorana ν Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$ Multi-charged particles Magnetic monopoles	$2,3,4 e, \mu$ 2μ $2,3,4 e, \mu (SS)$ $2,3,4 e, \mu (SS)$ $-$ $-$ $-$ $-$ $-$ $-$ $-$ $-$ $-$ $-$		Yes - Yes - - - TeV	139 36.1 139 139 139 34.4	N ⁰ mass 910 GeV N _R mass 350 GeV H ^{±±} mass 350 GeV H ^{±±} mass 1.08 TeV multi-charged particle mass 1.59 TeV monopole mass 2.37 TeV	3.2 TeV $m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ DY production DY production DY production, $ q = 5e$ DY production, $ g = 1g_D$, spin 1/2	2202.02039 1809.11105 2101.11961 2211.07505 ATLAS-CONF-2022-034 1905.10130

ATLAS BSM searches

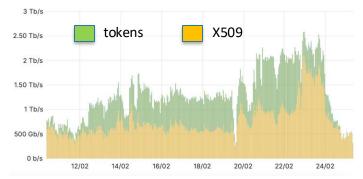
*Only a selection of the available mass limits on new states or phenomena is shown.

Data Challenge 2024 - Highlights

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



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



WLCG services successfully supports DUNE and Belle-2 computing models

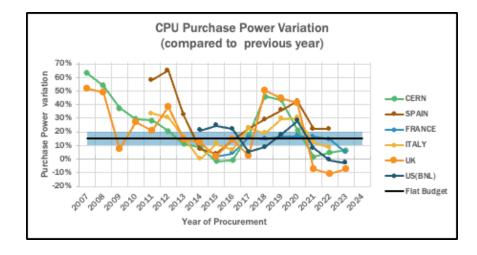
Hardware Cost Evolution

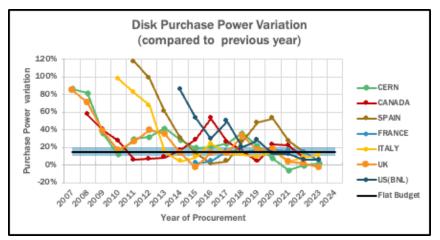
The WLCG "flat budget model" assumption: +15% CPU, disk and tape every year with the same level of funding

We now monitor the HW trends in many countires. Last 5 years average is compatible with the 15% assumption but look at the first derivative ...

CPU average variation (5 years): +14%







IRIS-HEP: analysis 200Gbps (Grand) Challenge

Launched by IRIS-HEP to commission analysis capabilities for HL-LHC

- Commission services at increasing scale + introduce innovative aspects
- \Rightarrow Show readiness at 25% of HL-LHC scale (same as for data challenge)

Analysis models evolving => metrics of success hard to quantify (25% of?)

