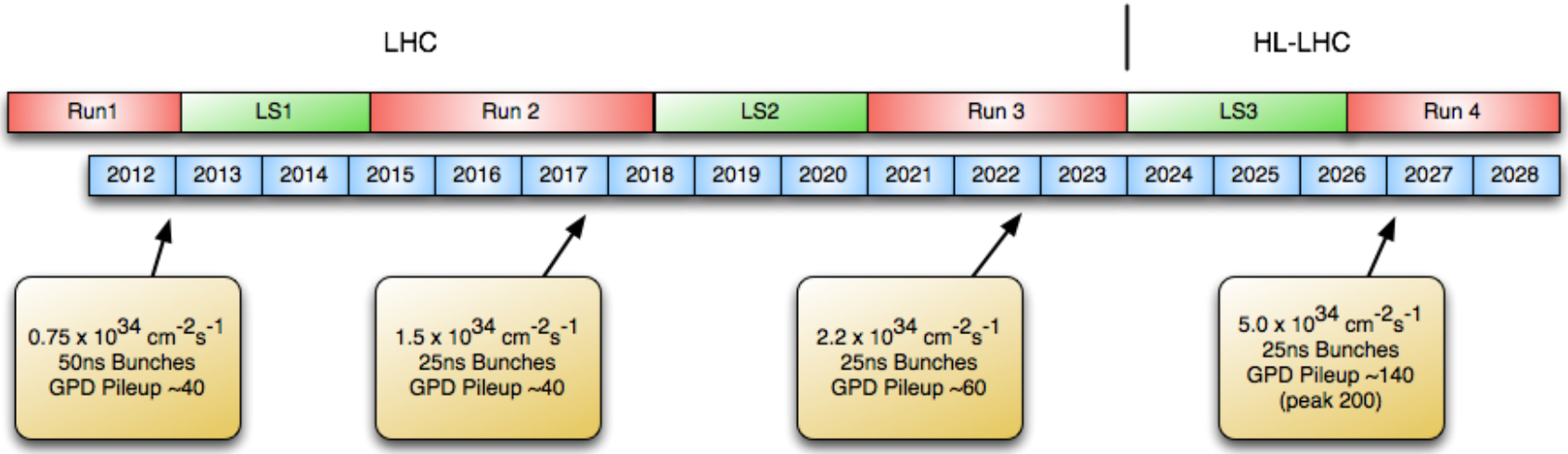
IT Challenges for the LHC Experiments

Dario Barberis

with the help of Roger Jones and
many colleagues in the LHC experiments

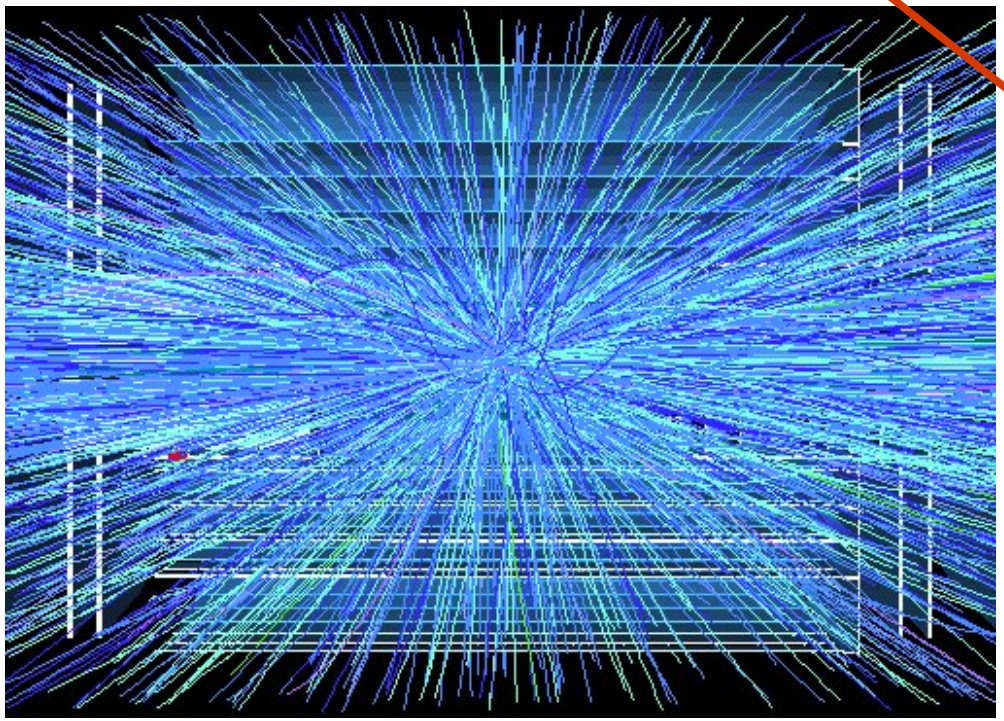
LHC to HL-LHC



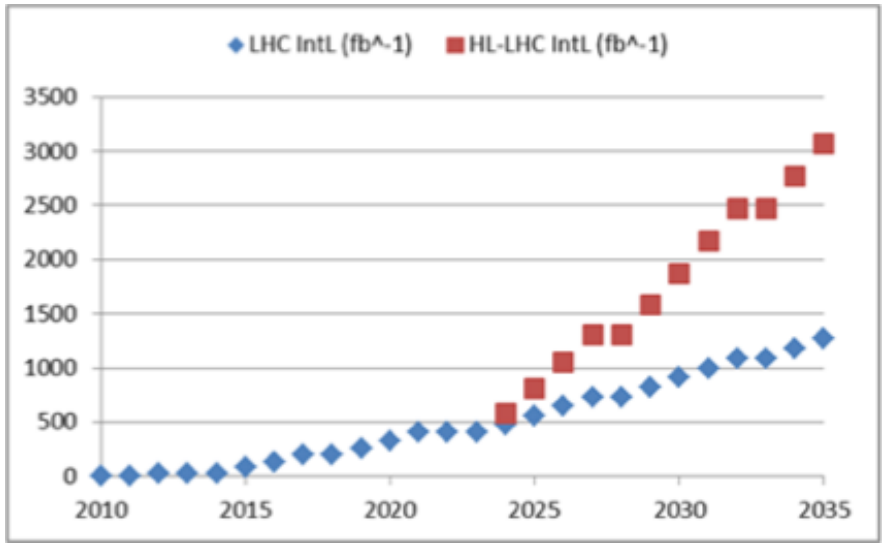
- Major upgrades for LHCb and ALICE come for Run 3 (2021)
  - LHCb: 40MHz readout with upgraded electronics and *full software trigger,* ***higher output rates***
  - ALICE: Upgrades to inner tracking and time projection chamber, 50kHz trigger less readout for Pb-Pb; ***new online/offline data reduction framework O2***
- Major upgrades for ATLAS and CMS come for Run 4 (2026)
  - New silicon inner tracker detectors with track triggers at L0/1 rates
  - **Must *adapt to very high pileup* (140-200) and *much higher trigger rates***
    - **Recall that *tracking is combinatoric*: factorial with pileup**

High Luminosity LHC

Event Complexity
x Rate



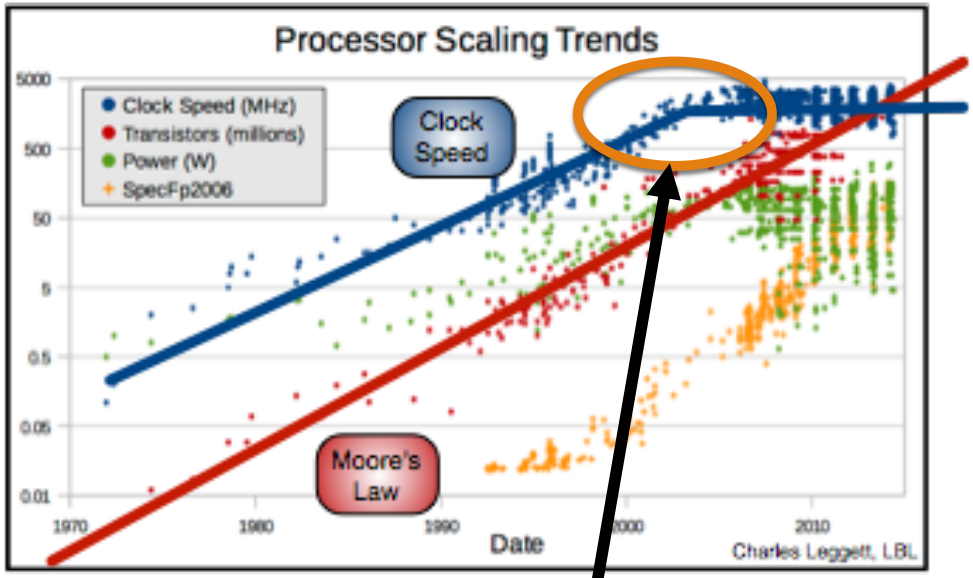
- Very high pile up
- Very high trigger acceptance rates
- Very challenging computing



Architecture

- The wider computing picture presents other challenges.
- The architectures become more diverse (accelerators, low power chips, GPUs, FPGAs….)
- The means by which compute is presented will also change
  - Clouds remain a buzz phrase - but this mainly means virtualising the private hardware
  - Commercial clouds currently can provide good burst capacity; leverage means University/institute provision will remain important

Processor Evolution



Our software developed here

- Moore's Law continues
  - Doubling transistor density every ~24 months
  - Exact doubling time has a significant effect when integrated out to LHC Run 4
    - CPUs could be between x10 and x30 denser
- Clock speed stalled ~2005
  - Single core performance is essentially also stalled
- Driven now by energy performance
  - Figure of merit is nJ per instruction
  - Mobile devices and data centres are the key volume markets
- **Memory consumption is a huge driver now**

Silicon Diversity

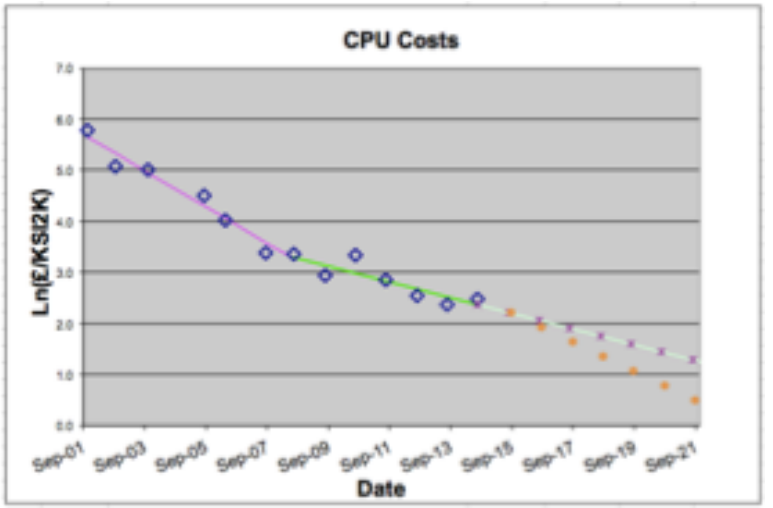
- Doubling transistor density does not double our computing throughput
  - On the die we have more and more cores
  - Lower memory per core
  - Larger caches, but with decreasing payoffs
  - Wide vector registers, ever harder to fully utilise
  - Built in ‘specialist’ features, e.g., integrated GPUs in Intel Skylake
  - Integrated network controllers — more ***System on a Chip*** (SoC)

- GPU type architectures throw away a lot of the assumptions of CPUs
  - Banks of cores executing the same computational kernels
  - Very fast, but very local memory (forget cache coherence)

- None of these features and architectures are trivial to take advantage of in our code
  - **Our frameworks and algorithms written for an earlier era and are hard to adapt**

Modern Computing Hardware

- Away from the detector itself we are firmly *Commodity Off The Shelf* (COTS)
- Increased transistor density does not reduce all the other costs involved in actually building a real server
- Or allow us to simply build computing systems with higher throughput per $/£/€/CHF/Kn
  - Disk: capacity still going up, but **i/o rates are basically the same as ever**
    - At the moment SSDs are not an affordable replacement for 500PB of spinning disks
  - Tape: Healthy progress (fewer technical challenges than on disks), as ever slow to read back
  - Network: Capacity keeps rising, allowing cross site boundaries to become less important, but data needs to be read from a physical device ***somewhere*** - and so far the network has been ~free

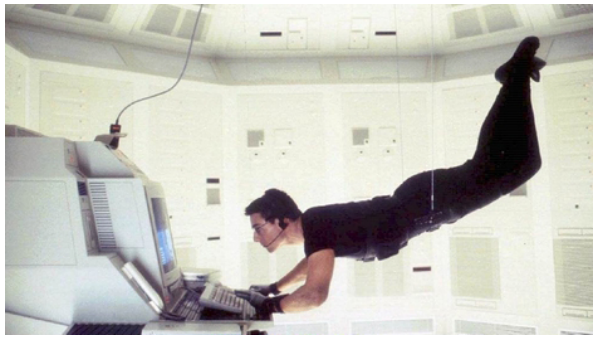


RAL Tier1 CPU Costs with projection

David Britton, Andrew Sansum, GridPP

Software Challenge

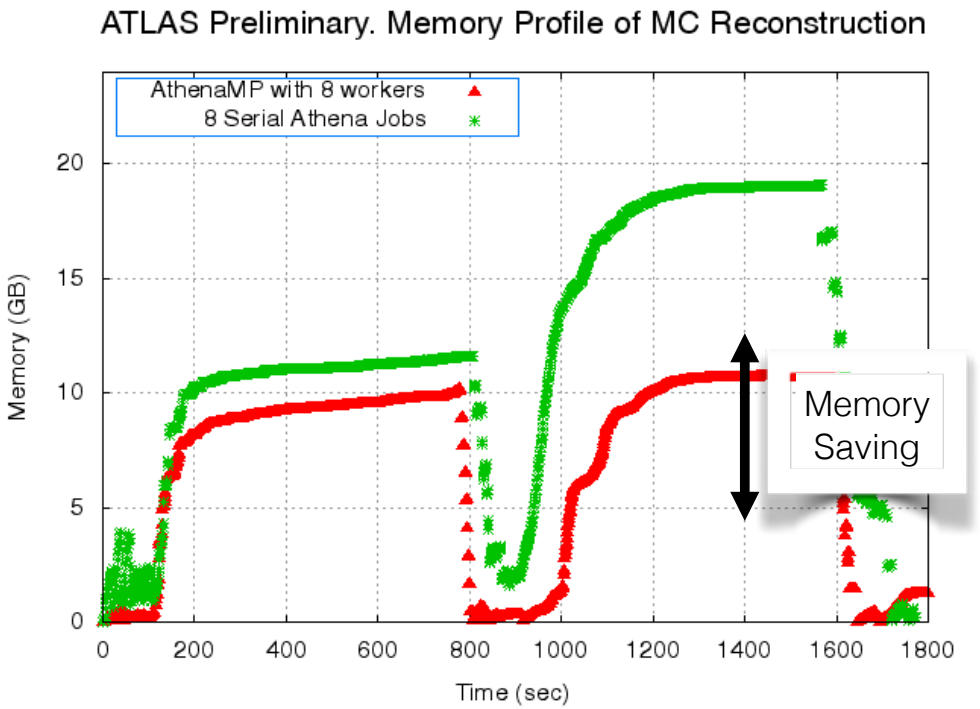
- Current computing hardware evolution is not providing any more free lunches
- Demands on software to support our physics goals are increasing
  - Higher trigger rates
  - Higher pileup
  - Need ***faster*** and ***better*** software
- Our software was written for a different era
  - By people who have often now moved on to new areas



- We need to train a new generation of physicists in modern programming methods
  - C++98 → C++11 → C++14
  - Modern tools and development methods
- This is to say nothing of evolving our computing infrastructure on top of whatever software we have to meet these challenges (virtualisation, clouds etc etc)

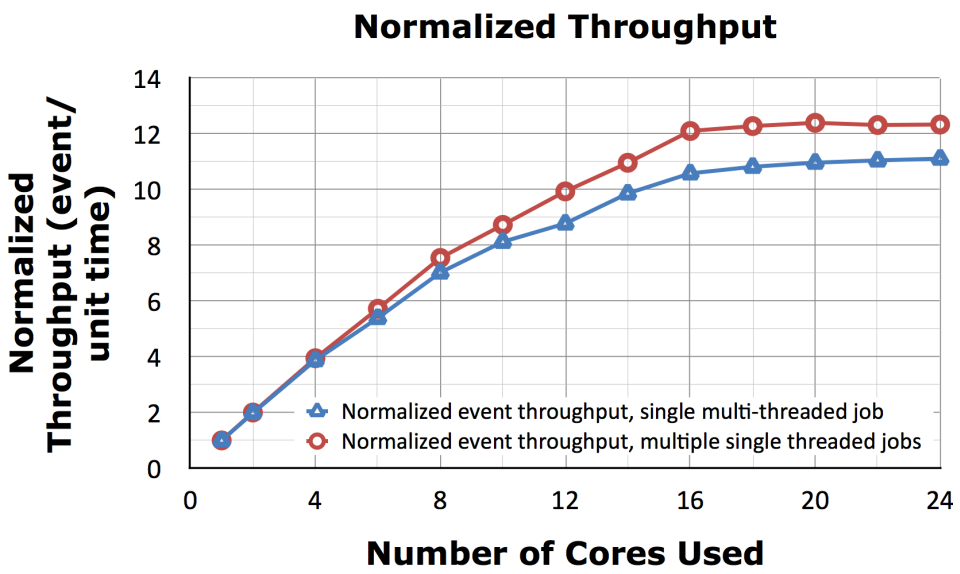
Framework Upgrades

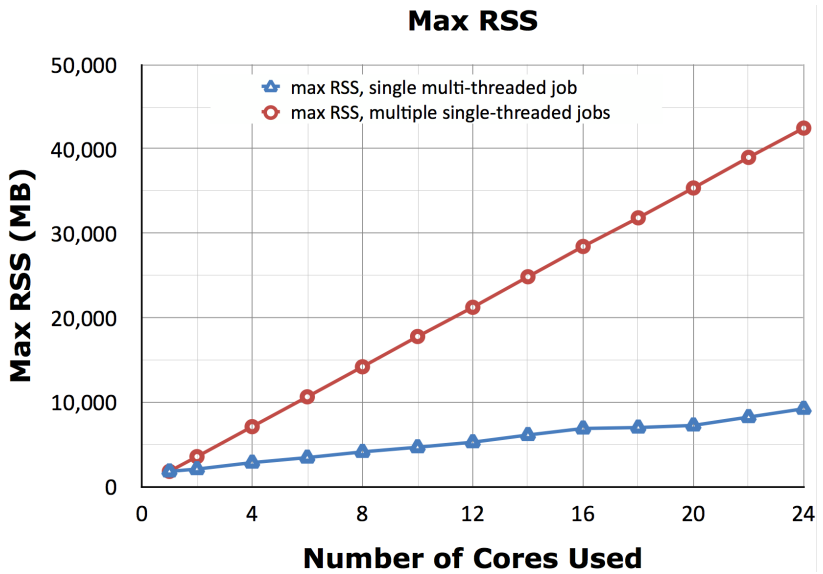
- LHC experiment software frameworks were developed in the serial processing era
- As multi-core CPUs became more common trivial multi-processing was used
  - On N core launch N jobs, **coarse grained parallelism**
- First attempt to make this better was ATLAS's **AthenaMP**
  - Start Athena in serial mode, then fork worker processes after initialisation
  - Large memory structures (geometry, magnetic field) are shared by Linux kernel
- However
  - Unlikely to scale, even to Run3 parameters
  - Use of opportunistic resources and Xeon Phi demands even better memory/core performance than today
- **Multi-threading** is the future
  - True heap level memory sharing between all threads
  - (Far greater opportunities for making mistakes)



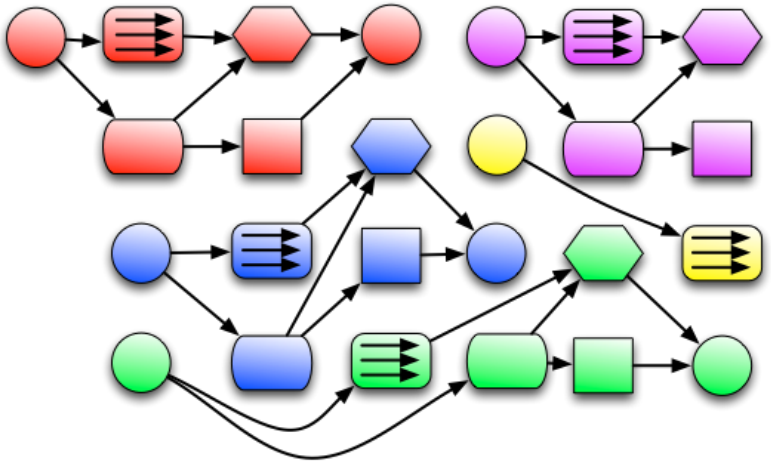
CMSSW Multi-threaded

- Split the concept of event processing into **global** and **stream**
  - Global sees the whole event and all transitions
  - Stream sees some events, in a defined sequence
    - c.f. an AthenaMP worker, on a thread
- **Thread-safety** is vital at the global level, less important at the stream level
  - Allows for a factorisation of the problem for framework transition
  - Good use made of static code checkers





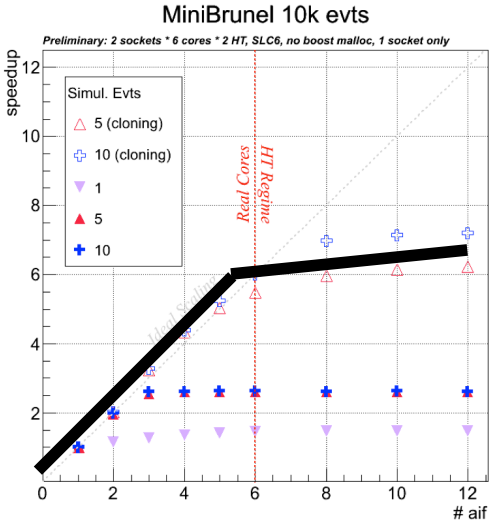
Gaudi



Multi-threaded processing cartoon: each colour is a different event, each shape a different algorithm

- Gaudi framework was initially developed by LHCb and later adopted by ATLAS
- Now being adapted to multi-threading
  - Designed to exploit concurrency at many levels
    - Event level concurrency — multiple events in flight
    - Algorithm concurrency — independent algorithms can run in parallel
    - In-algorithm parallelism — heavy cpu consumers can exploit parallelism themselves (e.g., clustering, jet algorithms)

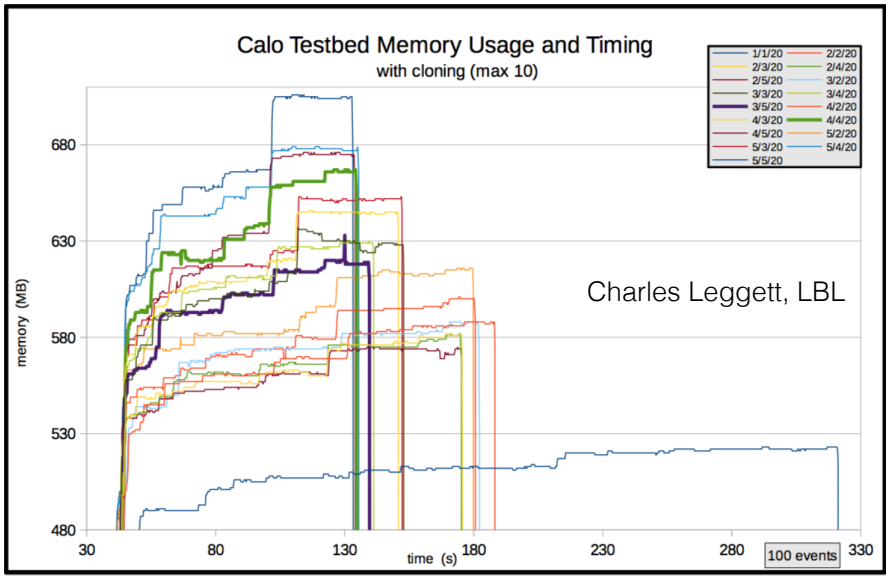
Mini-Brunel and AtlasHive



Benedikt Hegner, Danilo Piparo, CERN

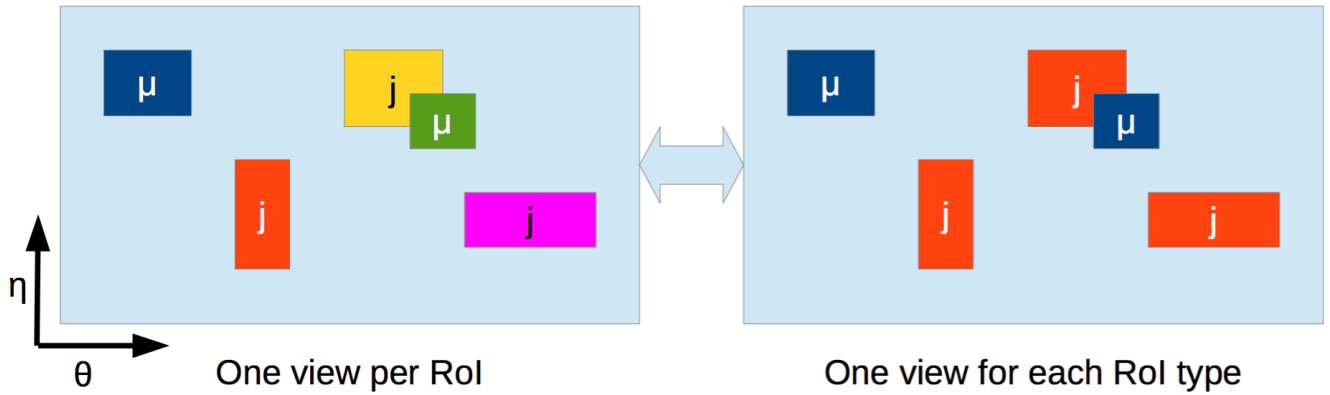
- Scaling of GaudiHive running LHCb mini-Brunel reconstruction
- Linear scaling up to CPU core count
- Expected boost from hyperthreading with only 10 events in flight
- Memory consumption only rises by 7% (limited reconstruction however)

- ATLAS Calorimeter testbed
- Best scaling x3.3 for 28% memory increase
  - Concurrency was limited here due to some serial components — expected improvements seen
- Multi-threaded simulation close to working



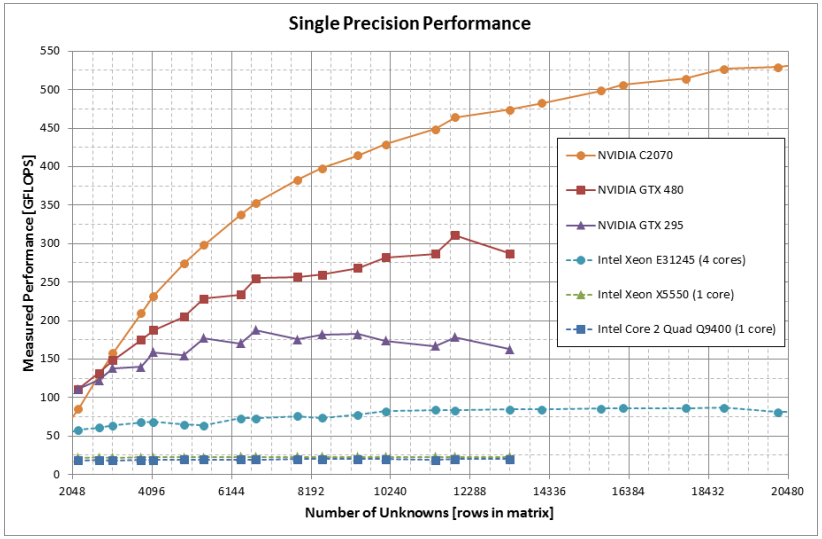
Gaudi and ATLAS HLT

- The efficiency of the ATLAS HLT requires partial event processing in a **region of interest** (RoI)
  - ATLAS want to manage this with unmodified offline code (currently not possible)
- This was not a concept in Gaudi originally
  - The extension to manage this is called an ***Event View***
- Currently assessing the impact of a design with one view per RoI…
  - Closer to the current HLT design, easier migration; harder scheduling problem
- …or one view per RoI type
  - Larger issue to migrate current code; easier for the scheduler



Ben Wynne

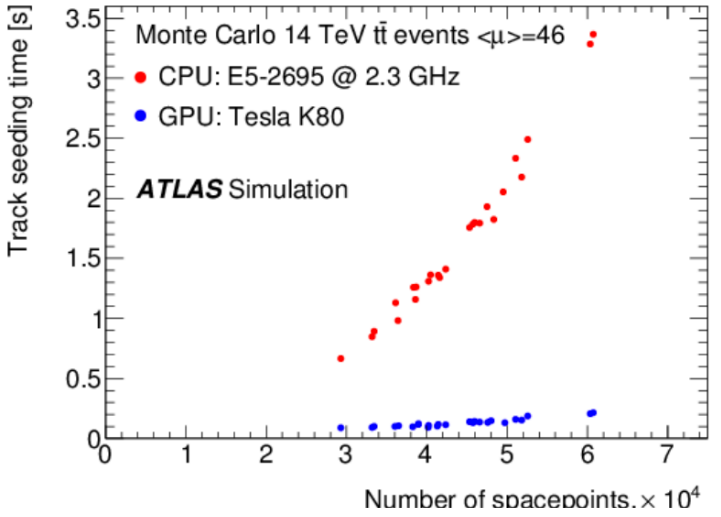
HLTs & GPUs

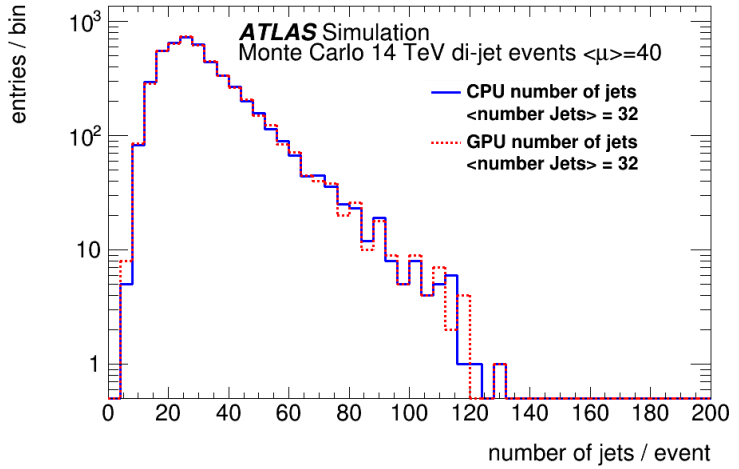


- Generally GPUs are much harder to use than OpenPower, ARM64 etc
  - Limited C++ support
    - Compilers still developing quite fast here — beware of vendor lock-in
  - Very different memory model
- However, online processing is a far more controlled environment than any generic grid site and has a more restricted workflow
  - Opportunities for GPUs are greater
    - e.g., ALICE have already deployed 50/50 split between GPU and CPU for their Run 2 trigger farm
- Raw FLOP power of GPUs does make them an option which we must take seriously

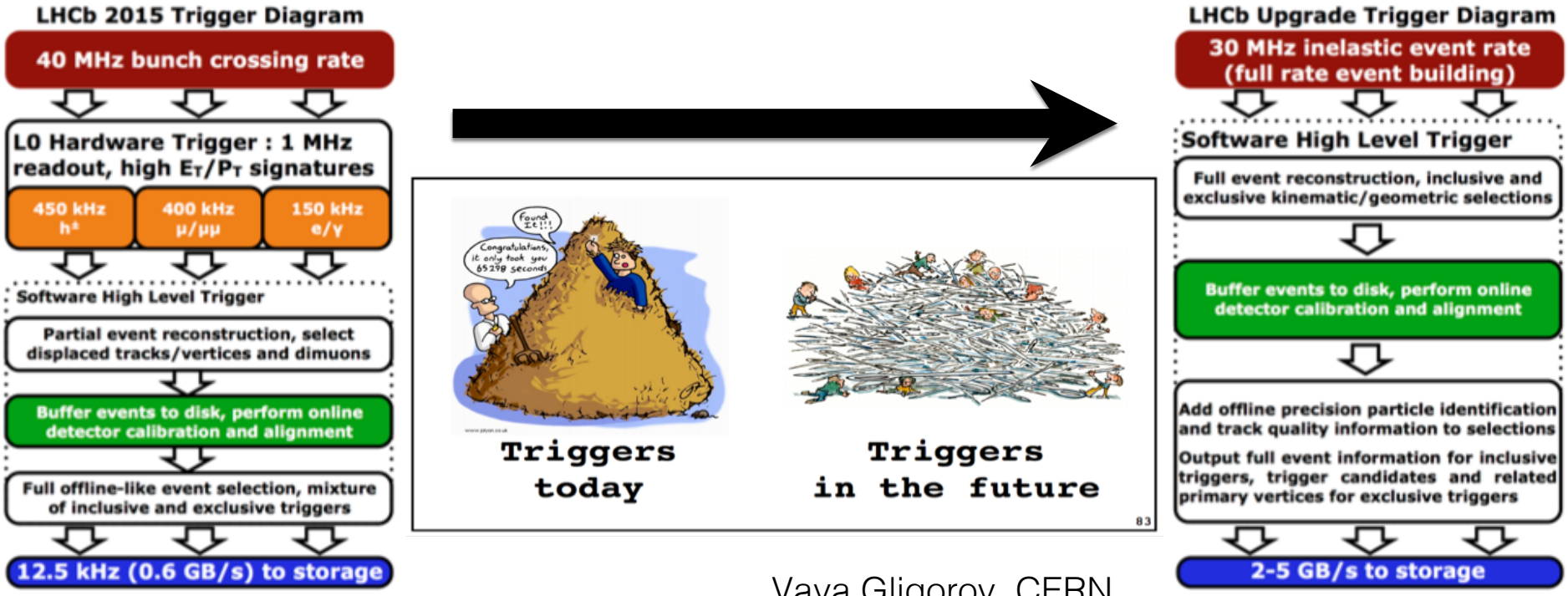
ATLAS HLT GPU demonstrator project

- HLT track finding in Inner Detector porting efforts
  - **Track seeding is 50% of CPU** spent on full scanned events
  - Careful validation of results — generally not bit for bit identical, so need to check physics level validity
  - Early results show a **x1.8 *overall* speed-up** when running with a Tesla K80 GPU
- Also work to port of topo clustering, muon segment finding and jet reconstruction
- However, further speed up requires **porting the 'long tail' of algorithms to GPU**
  - Diminishing returns in lines of code to port vs. eventual speed up
  - Need to also factor in costs of code maintenance and costs of physical infrastructure
- Still under investigation — no decision for Run 3 yet, with LHCb doing similar work, similarly with no firm conclusion yet





LHCb Run3 — Software Trigger

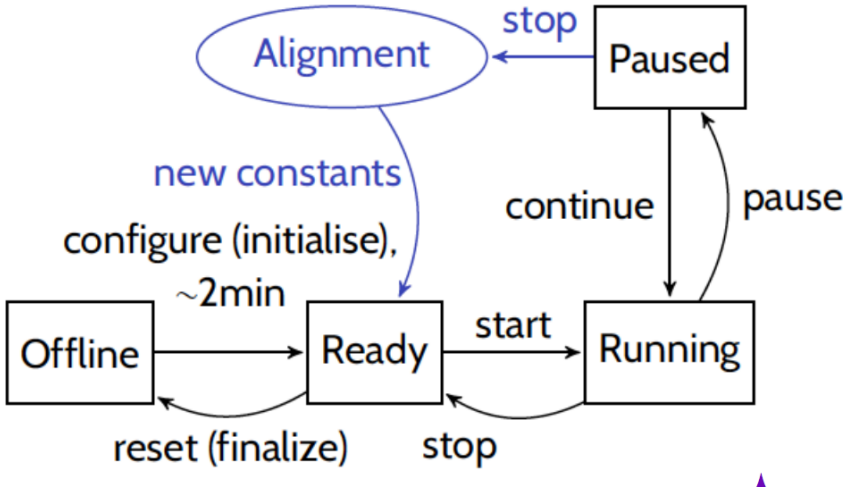


Vava Gligorov, CERN

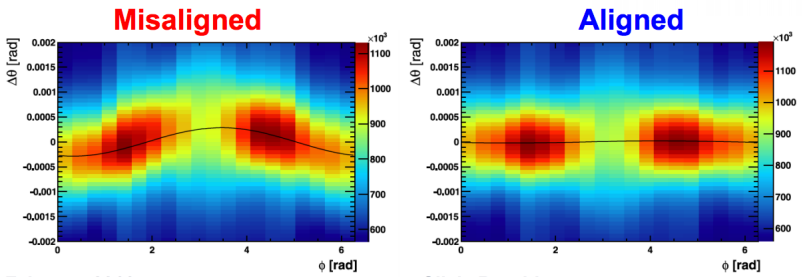
- 30MHz events to be triggered in software
  - 100kB event size → software trigger processes 3TB/s
- Significant strain on CPU efficiency of the trigger software
  - *Need considerable software improvements*

Real Time Calibration

- Don't want to discard information unless trigger produces "offline" quality reconstruction directly
  - Requires very fast and accurate calibration in "real time" == a few hours
- HLT1 runs — first pass reconstruction
- All events then buffered to disks on the HLT farm
- Real time calibration runs to assess calibration and alignment
- HLT2 runs with updated alignment to produce final outputs
- Most of farm occupied with HLT1 during data taking
  - Needs to be tuned to LHC data taking efficiency



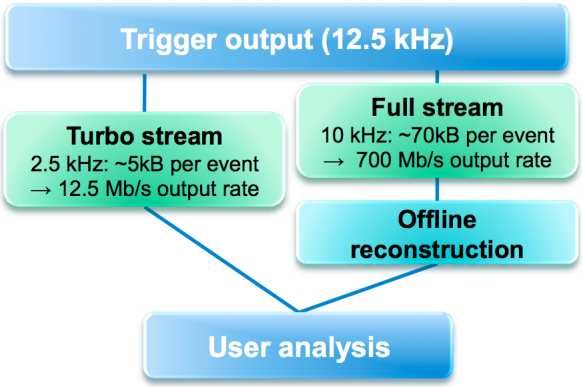
Alignment Workflow



RICH Alignment

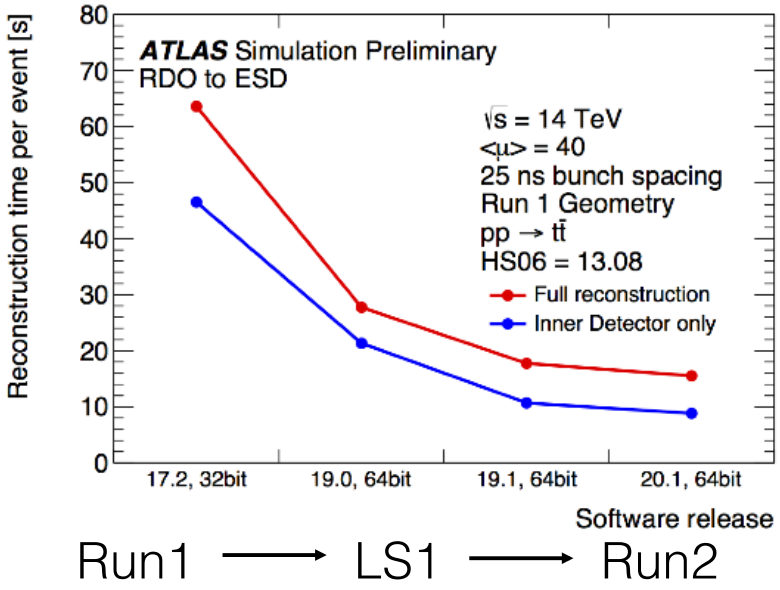
Silvia Borghi, Chris Parkes

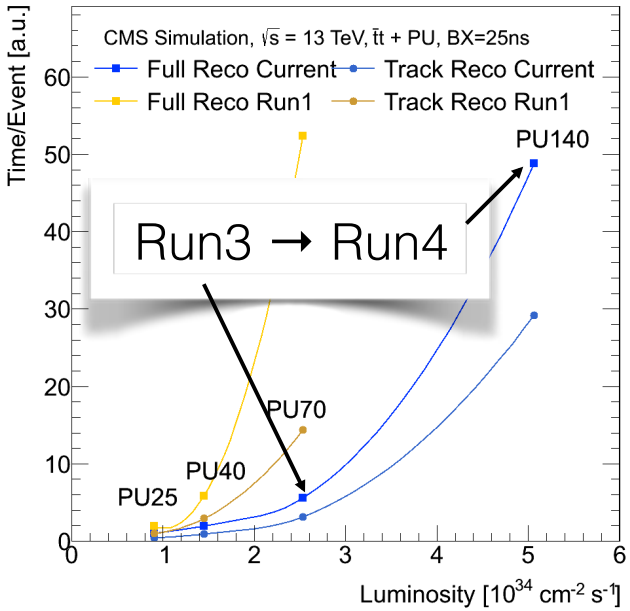
Turbo Stream



- Write ‘analysis-ready’ outputs DSTs directly online
  - Calculate luminosity information and resurrect trigger candidates
  - 70kB/event → 5kB/event
- Ideal for analyses with very high signal yields
- Already running and producing physics during Run 2
- Full deployment in Run 3
- Trigger stops being binary, but discriminates different signals and selects information to keep based on ultimate constraint of rate to offline
  - N_events x N_event_size = data rate
  - Can play with these parameters based on analysis needs
- Reduce offline resources, e.g., less need for reprocessing

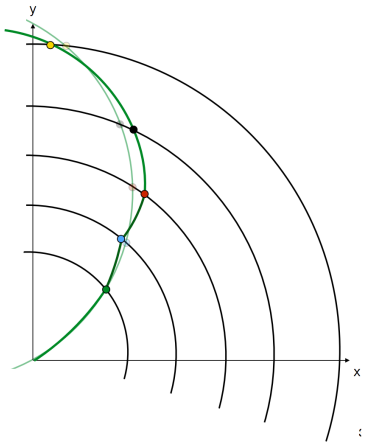
Tracking — On the road…





- HL LHC means high pileup ATLAS and CMS
  - Track reconstruction rates go from **1M tracks/s to 60M tracks/s**
  - **Combinatorics** of charged particle tracking become extremely challenging for GPDs
  - Even smart approaches have worse than linear scaling
- Impressive improvements for Run 2
  - Option to throw more and **more events in flight for Run 3**, but memory is not free
  - **Current strategies will actually just not work for Run 4**

Future Tracking

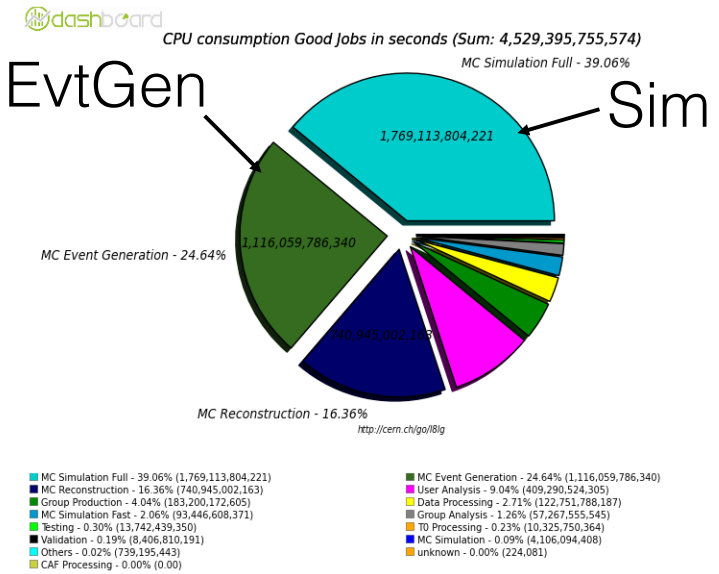


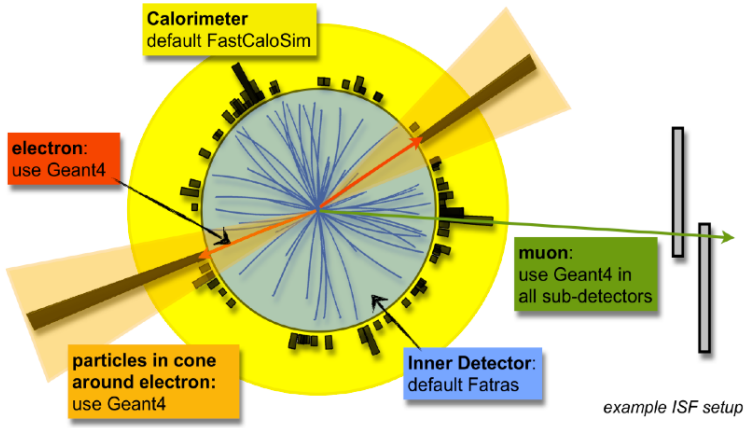
- Tricks for better scaling
  - **Truth tracking for MC**
  - Data: could **seed tracks from track triggers** (but track triggers are extremely difficult to simulate)
- Tracking from **cellular automata** parallelises much better
  - Local problem, instead of global
  - However, can the **physics performance** be maintained for ATLAS and CMS?
- **Conformal mapping techniques** (Hough transform) can parallelise much better
  - But they don't cope so well with material scattering
    - Need recovery strategies for kinked tracks
    - Maybe that will be **machine learning**
- Also want to **vectorise**
  - **Could give x8 speed up on 512bit registers**
  - Difficult and technically tricky work
- ACTS project factorises ATLAS tracking for FCC and other studies

Common Efforts:
HEP Software Foundation
Reconstruction Algorithm
Forum

Event Generation, Simulation, etc.

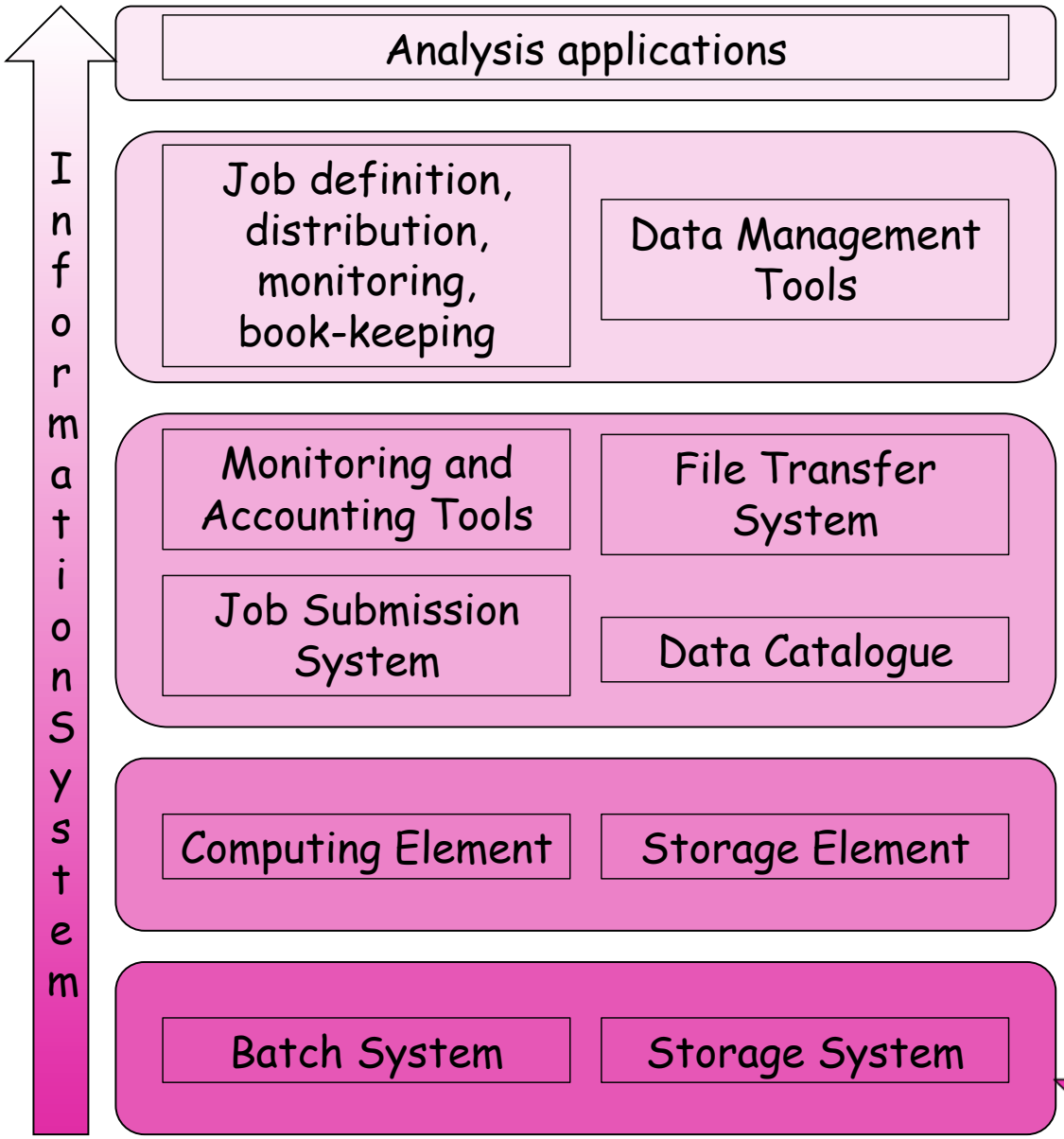
- Simulation eats up much of our distributed computing resources
  - **<u>Event generation becoming also important</u>** (NLO and beyond generators are expensive)
- Pileup scaling does not really apply to simulation
- Digitisation scaling is ~linear with pileup
  - But **mixing-in pileup events** is a nasty problem — either it's memory hungry or i/o intensive
- **Fast simulation** is increasingly important (ATLAS ISF pioneered mixing fast and full simulation)
  - Supported by fast tracking and reconstruction
- Some more radical approaches may bear fruit for HL-LHC
  - **GeantV** prototype attempts to bring **vectorisable code** to simulation
  - Transport many particles in each vector register
  - Bit it will require ***huge work*** to get the physics right in GeantV and for experiments to manage to adopt it





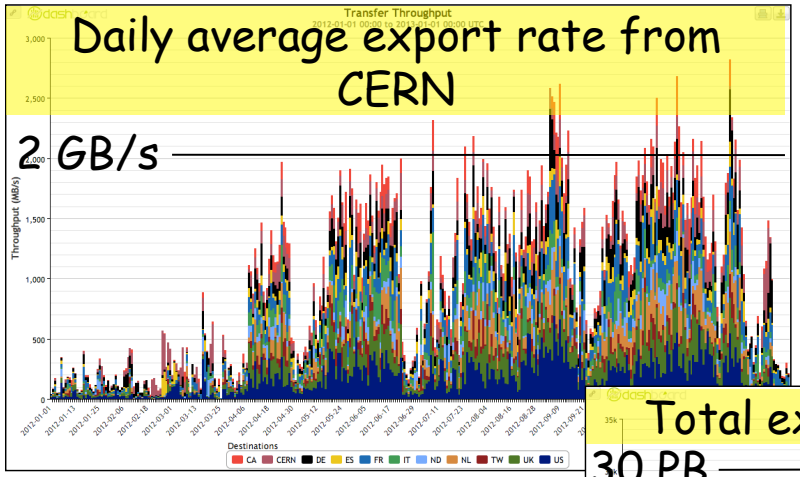
ATLAS ISF

Distributed Computing: Layered Service Structure

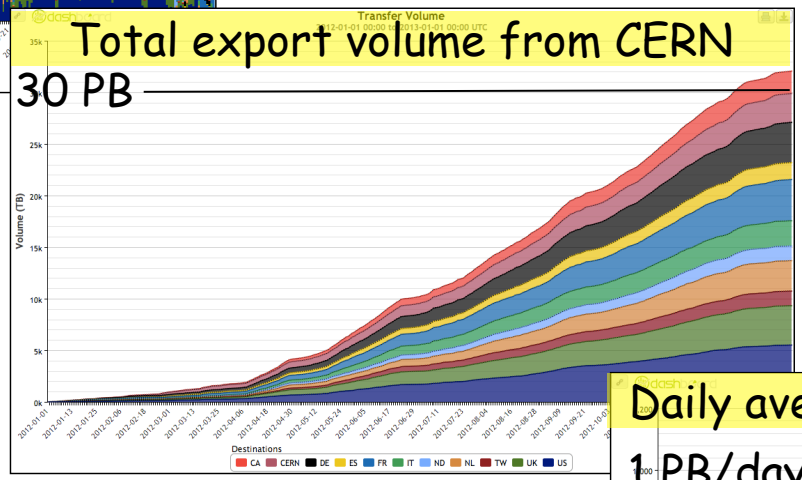


- Experiment applications (running jobs)
  - Written by physicists
- Experiment production and data management infrastructure
  - Written by computing experts in the experiments
- Common HEP application layer
  - Written by computing specialists at CERN and other laboratories
- Grid middleware
  - Funded by EU FP6/7+H2020, US DoE/NSF, national projects and academic institutions
- Local resources
  - Storage, batch, operating system

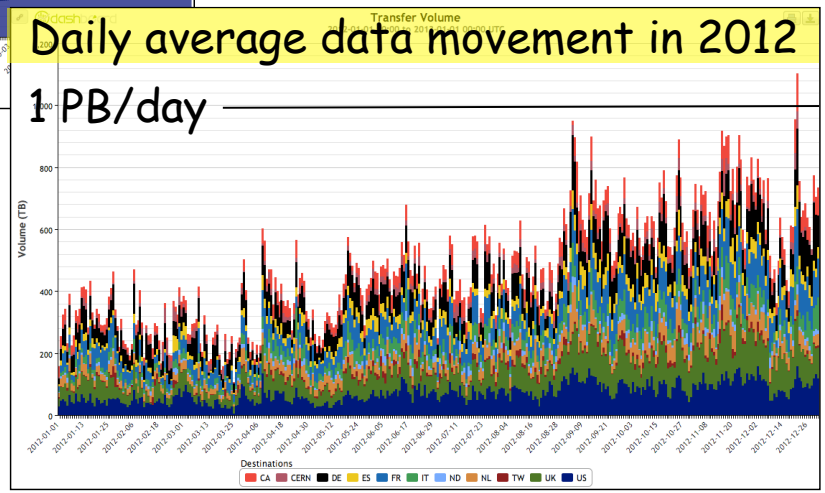
Does it all work? Yes!



- Managed timely processing of all data without accumulating backlog
- Export of raw and processed data from CERN to Tier-1s and Tier-2s
- Production of Monte-Carlo simulated data samples at all sites and replication to other locations for analysis

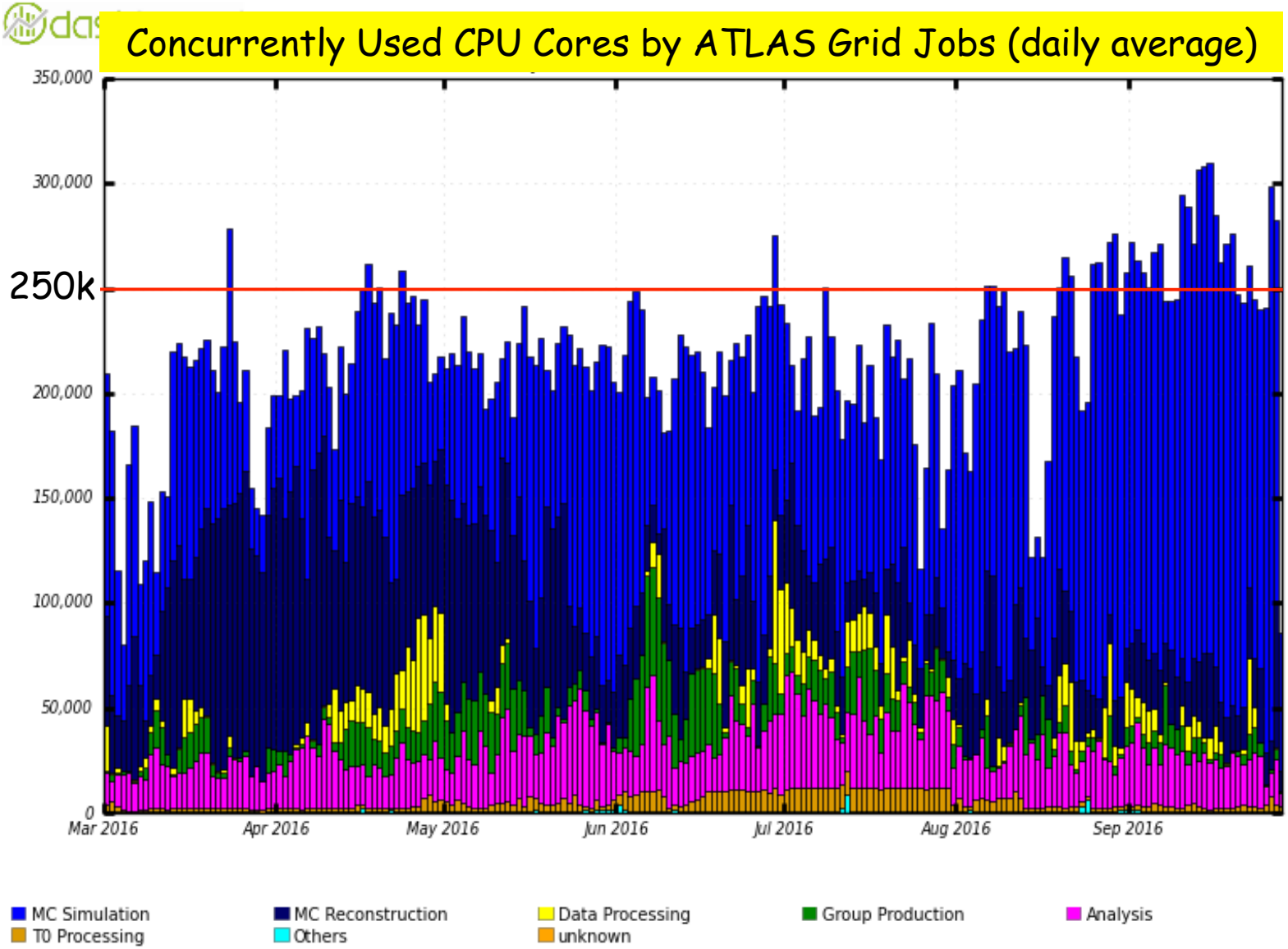


- Automatic increase and decrease of the number of replicas depending on data popularity for analysis (request rate for each dataset by analysis tasks)
- Periodic reprocessing of all data with better software, calibrations and alignments
- Distribution of reprocessed data

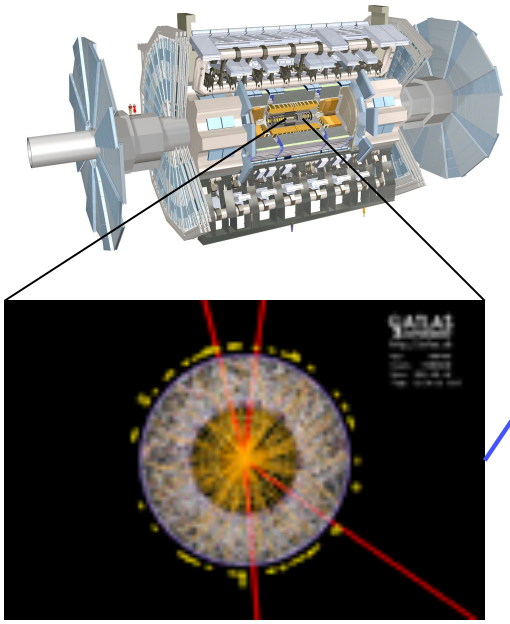


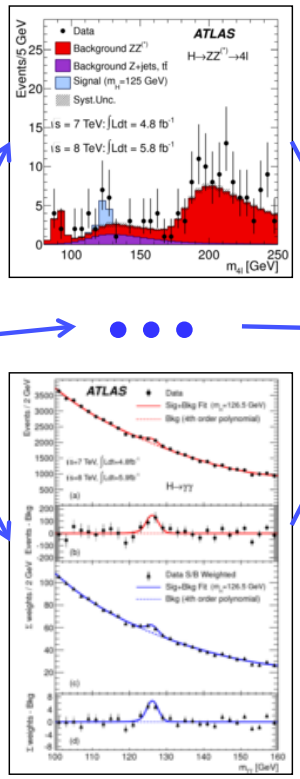
- Data replication between ATLAS sites peaked at 1 PB/day at the end of 2012 when all year's data were reprocessed and many people accessed them for analysis
- Excellent data transfer efficiency
  - Success rate ~100%

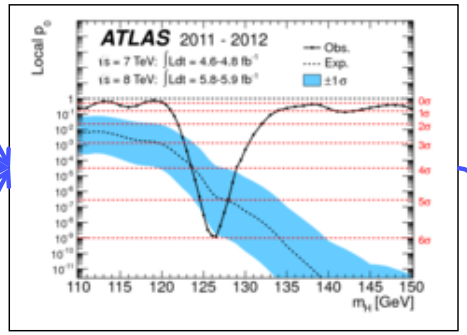
2016 Grid Production and Analysis



An analysis example: Higgs search







Great Discovery

Online selection

Offline selection and individual channel analysis

Statistical combination analysis

Rate: 1 PB/s

1 GB/s

Total: $3\ 10^{13}$ GB

$3\ 10^{7}$ GB

10^{5} GB

1 GB

People: many thousand

100-200

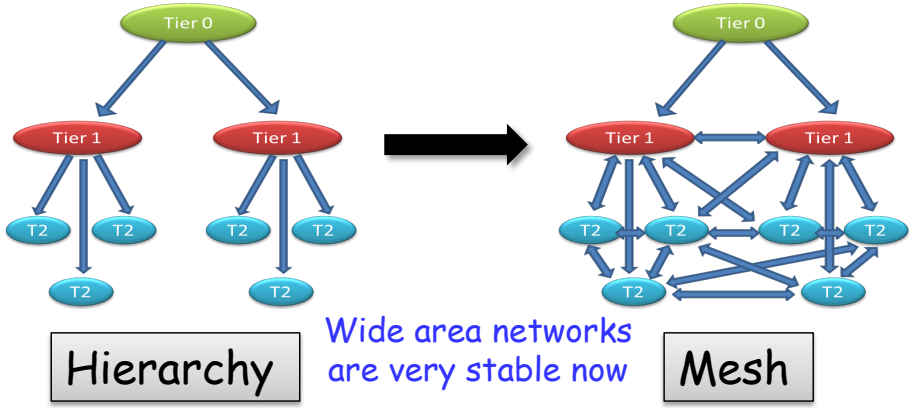
10-20

Computing Infrastructure Evolution

- Computing infrastructures are never static
- Since LHC experiments started developing their computing models 10 years ago, many conditions have changed:
  - Much increased network bandwidth in Europe and North America
    - Also increased digital divide with respect to the South of the world
  - The unit cost of CPUs decrease faster than storage and network costs
    - Good for High-Performance Computing applications but trouble for Data Intensive ones
  - Commercial providers started offering virtualised ("cloud") computing services
    - If the market is moving towards the cloud technology our community needs to adapt
  - Distributed file systems can be deployed across the WAN
    - If the bandwidth is sufficient of course

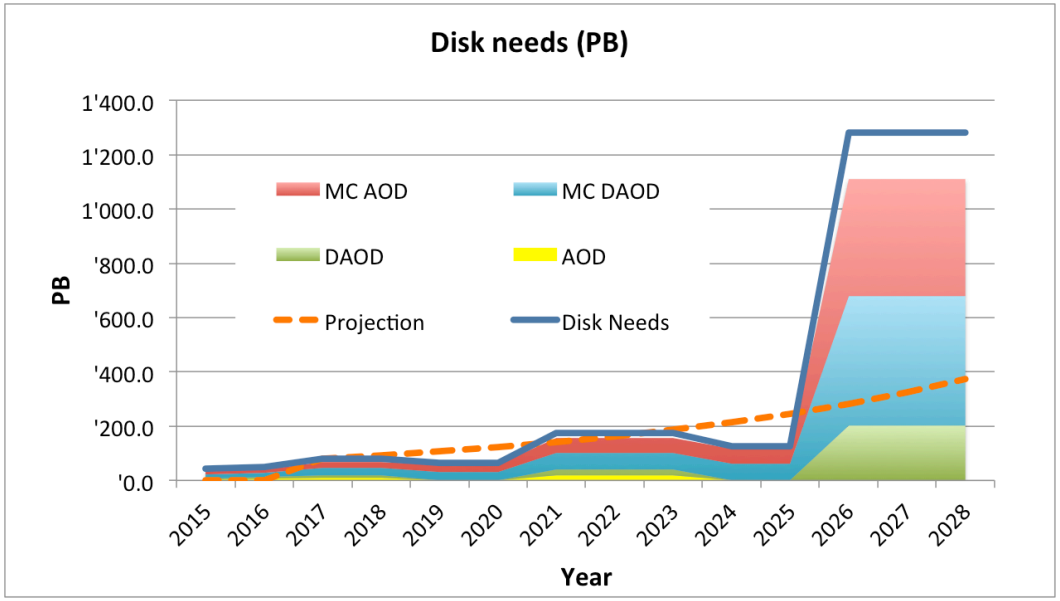
Evolution of the Computing Models

- Network bandwidth allows breaking the hierarchical site topology
- Distributed Storage Evolution:
  - Federated storage started in ATLAS and CMS, now nearing production use as a lightweight distributed file access and caching system
- Cloud Computing:
  - Potential to complement and augment the grid
  - Adoption of virtualization by computing facilities has begun
- Web services + local caches
  - Software distribution to sites
  - Access to Oracle resident data



What about Storage ?

Optimistic Scenario!



Even in the optimistic scenario, we are still far from solving the problem

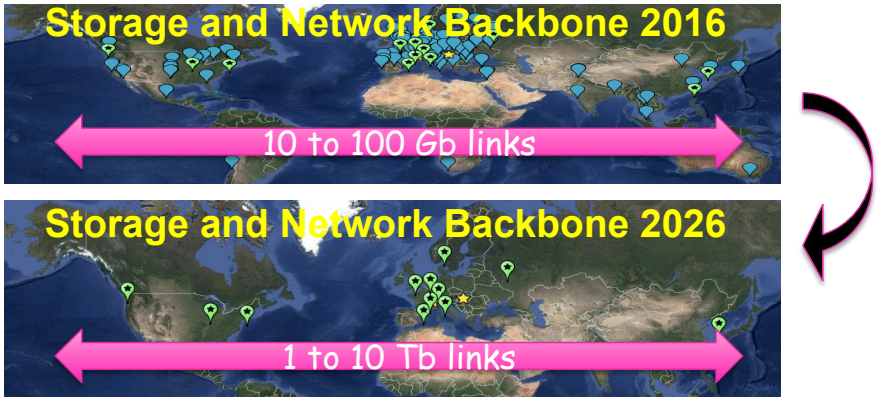
Analysis data formats are the main consumers.

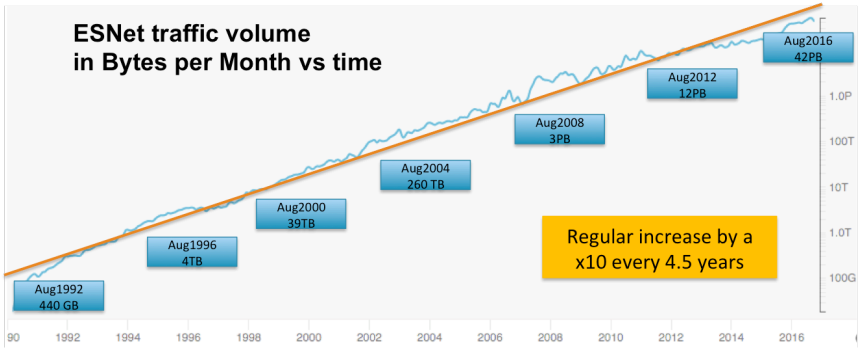
With no AOD on disk (run Train Analysis from AODs on TAPE) you get x4 above the resource projection

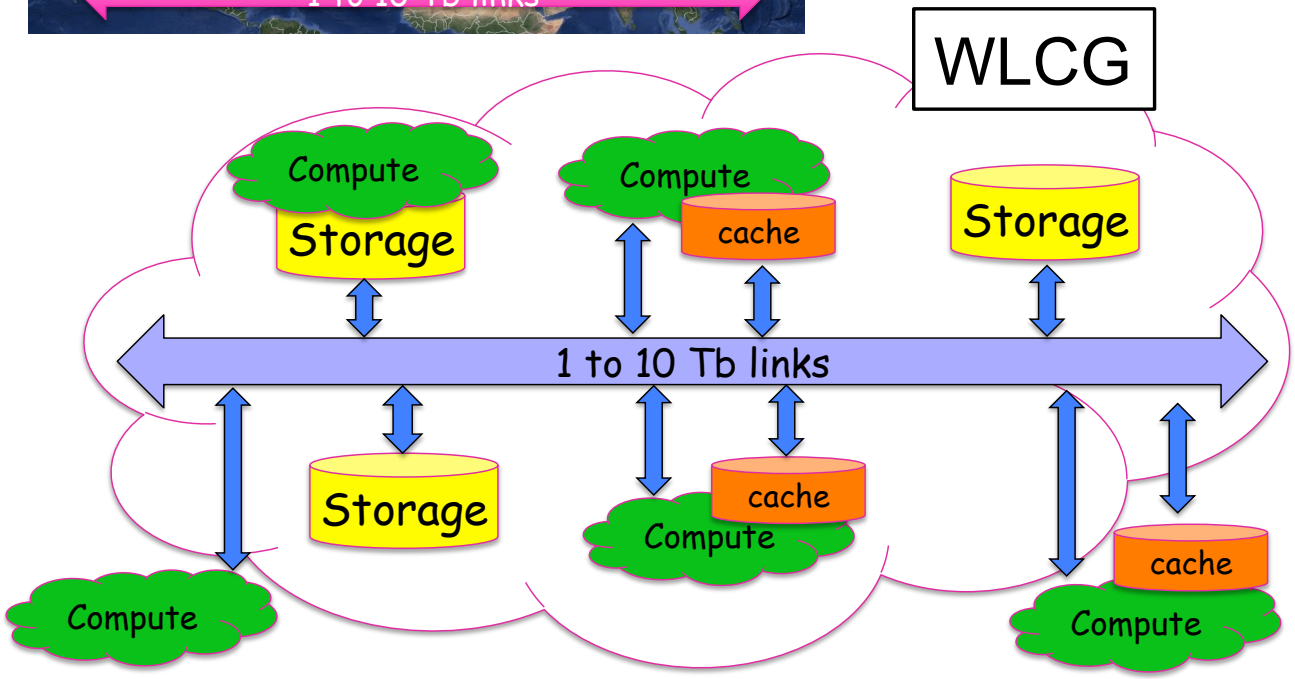
The remaining gain must come from re-thinking of distributed data management, distributed storage and data access.

A network driven data model allows to reduce the amount of storage, particularly for disk. Tape today costs at least 4 times less than disk.

Computing infrastructure in HL-LHC







- Network-centric infrastructure
- Storage and Compute loosely coupled
- Storage on fewer data centers in WLCG
- Heterogeneous computing facilities (Grid/ Cloud/HPC/ …) everywhere
- I/O optimisation and pervasive caching

Conclusions and Prospects

- Experiments are all progressing on significant upgrades for Run 3
  - Frameworks are evolving to multi-threading
    - Migration of millions of lines of existing C++ will not be easy at all
    - Need to train a new generation of coders in modern methods
- LHCb planning a software only trigger for Run 3
  - Real time alignment system and Turbo Stream
  - Still needs a large boost in software performance
- Study of GPGPUs might improve event selection at reduced costs
- Tracking for ATLAS and CMS must adapt to HL-LHC
  - Very likely to bring revolutionary changes in software
- Event generation, simulation and digitisation all need to be improved as well
- Effort in these areas is *critical to LHC experiments' success*
  - Great software will increase physics return; poor software will hamper it
- Funding & effort are not significant
  - Hope that HEP Software Foundation triggers efficiencies and new funding opportunities
  - White Paper due 2017, rather late for Run 3

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