Scientific and Quantum Computing

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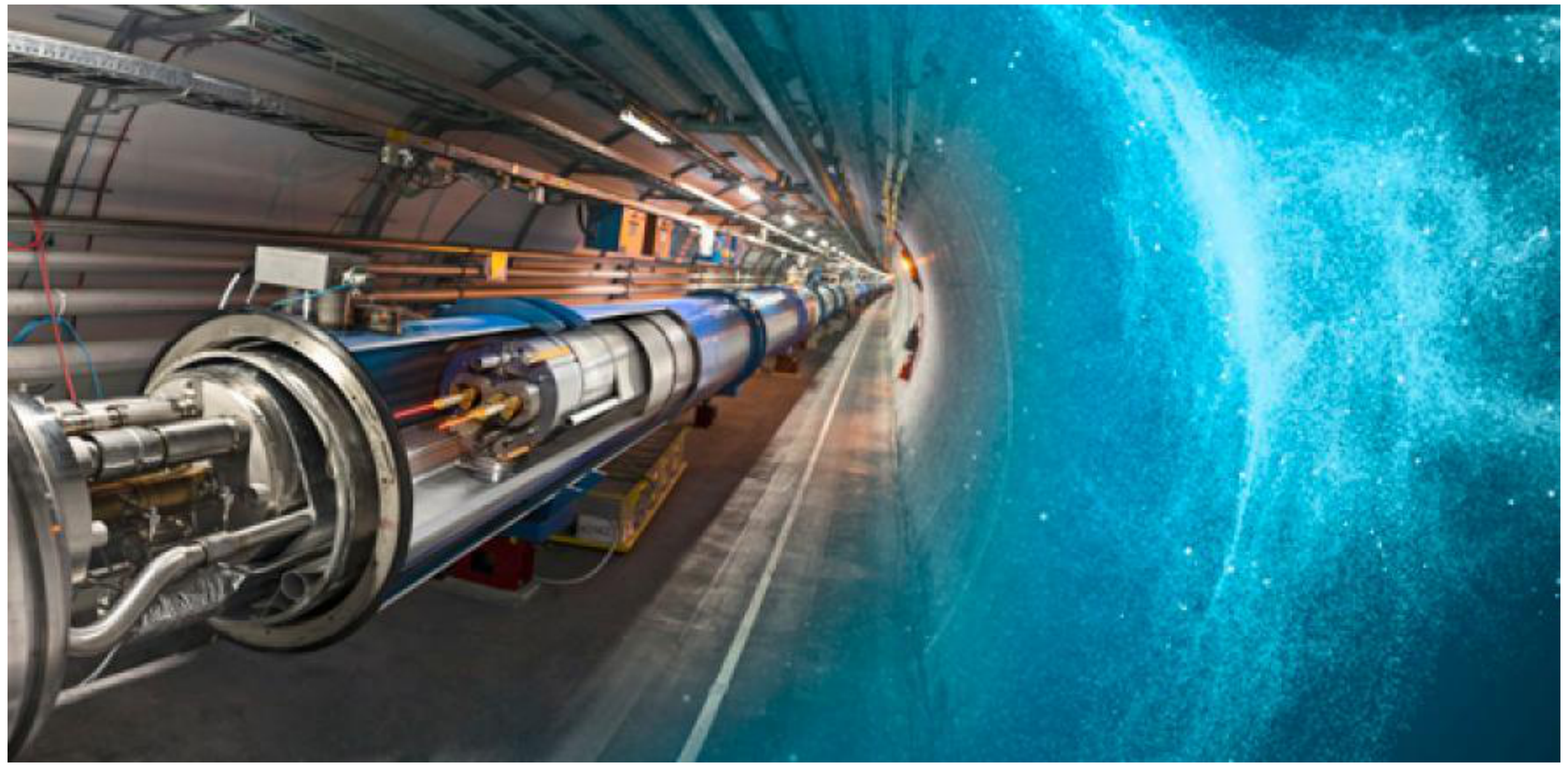
now



TRIUMF Science Week, Aug 16-20, 2021

European Strategy for Particle Physics Update 2020…

- The successful completion of the high-luminosity upgrade of the (LHC) machine and detectors should remain the focal point of European particle physics, together with continued innovation in experimental techniques.
  - *New experimental ideas are welcome and key to progress*
- The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited.
  - *ATLAS, CMS, LHCb and ALICE will continue to be upgraded and run till the end of the 2030s or early 2040s and beyond*

and High-Priority future initiatives…

An electron-positron **Higgs factory is the highest-priority** next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

- the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors

- Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron **Higgs and electroweak factory** as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.

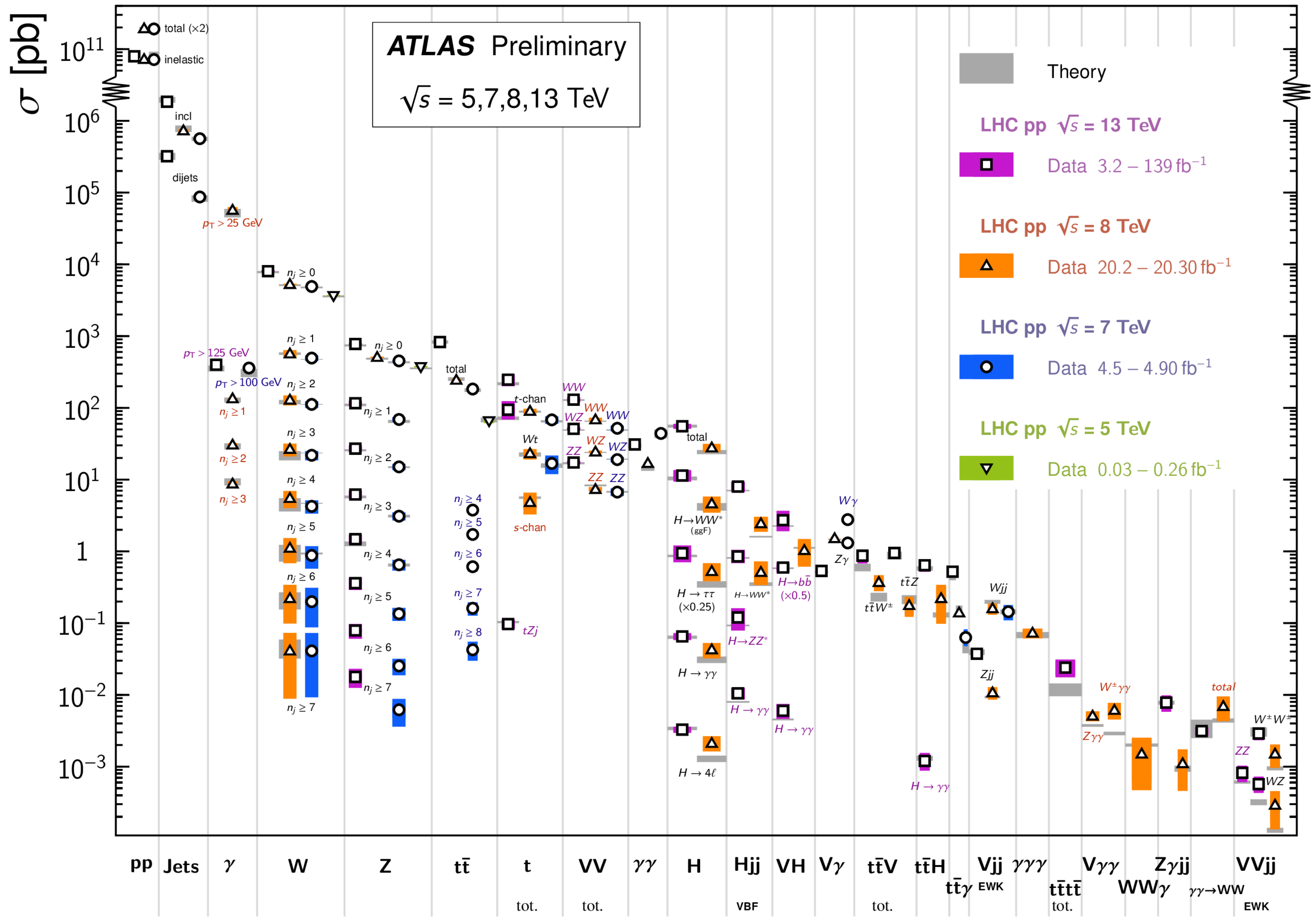
The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

LHC/HL-LHC will be the primary tool of research at the energy frontier

The advantage and dilemma of the LHC

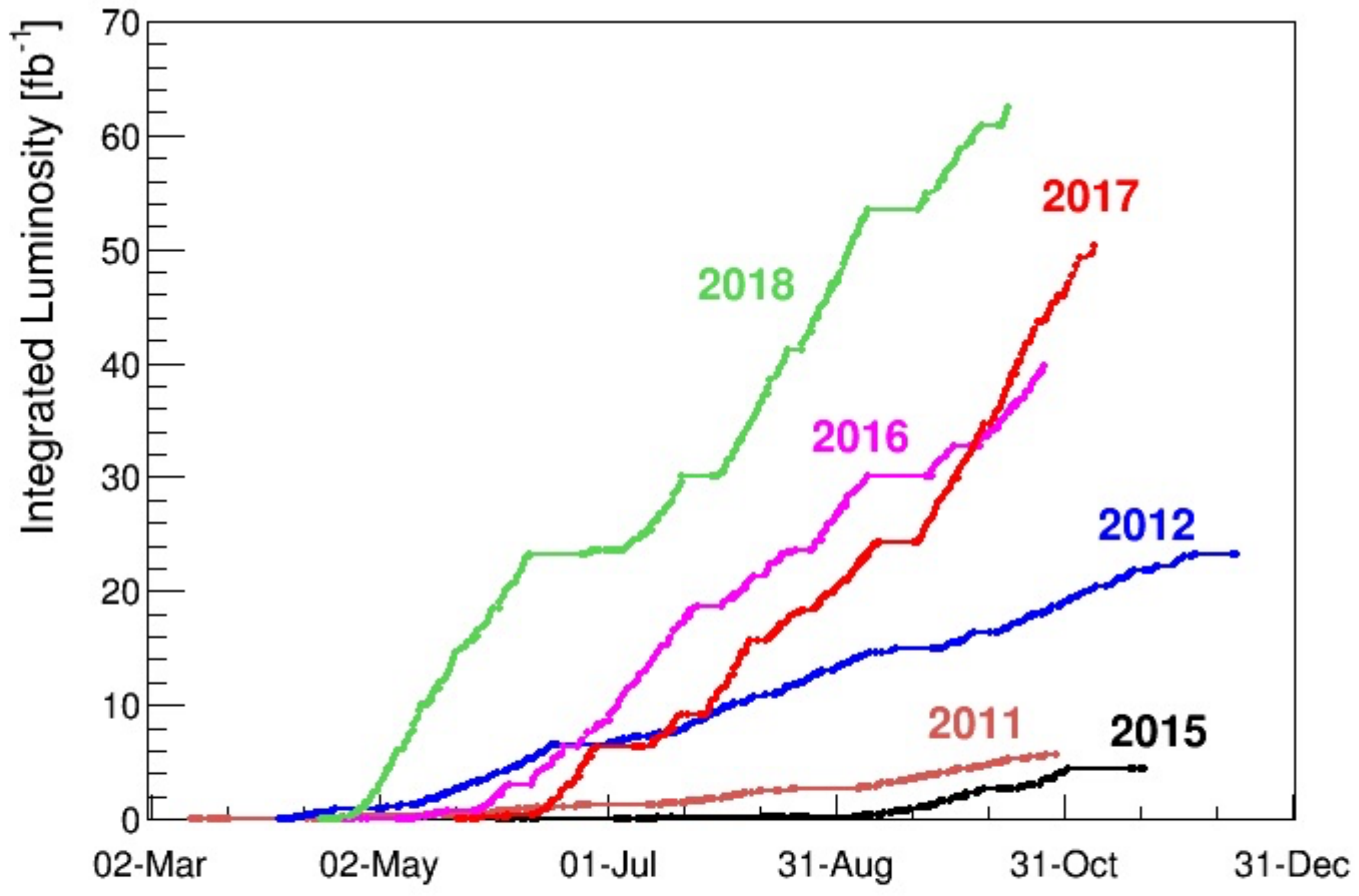
- pp-collisions offer tremendous interaction rates
    - We have learnt from Run 1 and 2 that New Physics is not strongly coupled to quarks and gluons in the energy regime we can explore up to a few TeV
    - Hence we have to resort to electroweak processes to search for New Physics or allow for very weakly interacting particles.
        - the strong interaction is largely a background
        - LHC will serve predominantly as a factory of weakly interacting particles - very much like an e^+e^-- or $\mu^+\mu^-$-collider

Standard Model Production Cross Section Measurements



Luminosities

- Effective cross sections range from ~nb to ~fb and smaller
- Searches thus require the highest sustainable luminosities at the LHC and the experiments to deal with the huge backgrounds
- The rates of "interesting events" are dominated by the smallest cross section. The current sensitivity is at the level of ~fb.
- HL-LHC will attain 3-4 ab^{-1} at ≥13.6 TeV; a factor ~20 of what is available today



LHC past and present and HL-LHC Plan

Resolution

- We have learnt from LEP and SLD, from BaBar and Belle/Belle II that full reconstruction of the complex final states is only possible with ultimate resolution
  - momentum and energy reconstruction
  - flavour tagging
  - particle identification

Experiments at the LHC / HL-LHC in perspective

- Experiments must - at least - provide the resolution of the best proposed detectors at e^+e^- factories and still reject the pile-up of other events
  - e.g. **Timing** has be added as an important tool to reject (slightly) out-of-time interactions (pile-up). This is a tremendous challenge and added complexity but a necessary tool to provide sensitivity to new physics.
    - ps-timing will also be key to make LHCb during Run 5 feasible

Flavour physics

- LHCb profits from the large cross section for b-quark production in pp-collisions but has to throttle the rate due to detector limitations (LHC is separating the beams laterally at the IP).

  - LHCb has published a wealth of results on b-physics and observed CP-violation in the charm system

  - For rare decays the detector rate capability needs to be improved; hence the LS2 upgrade, a rebuild of the detector, and plans for a further upgrade in LS4

  - so far the physics is limited by the performance (granularity) of the detector

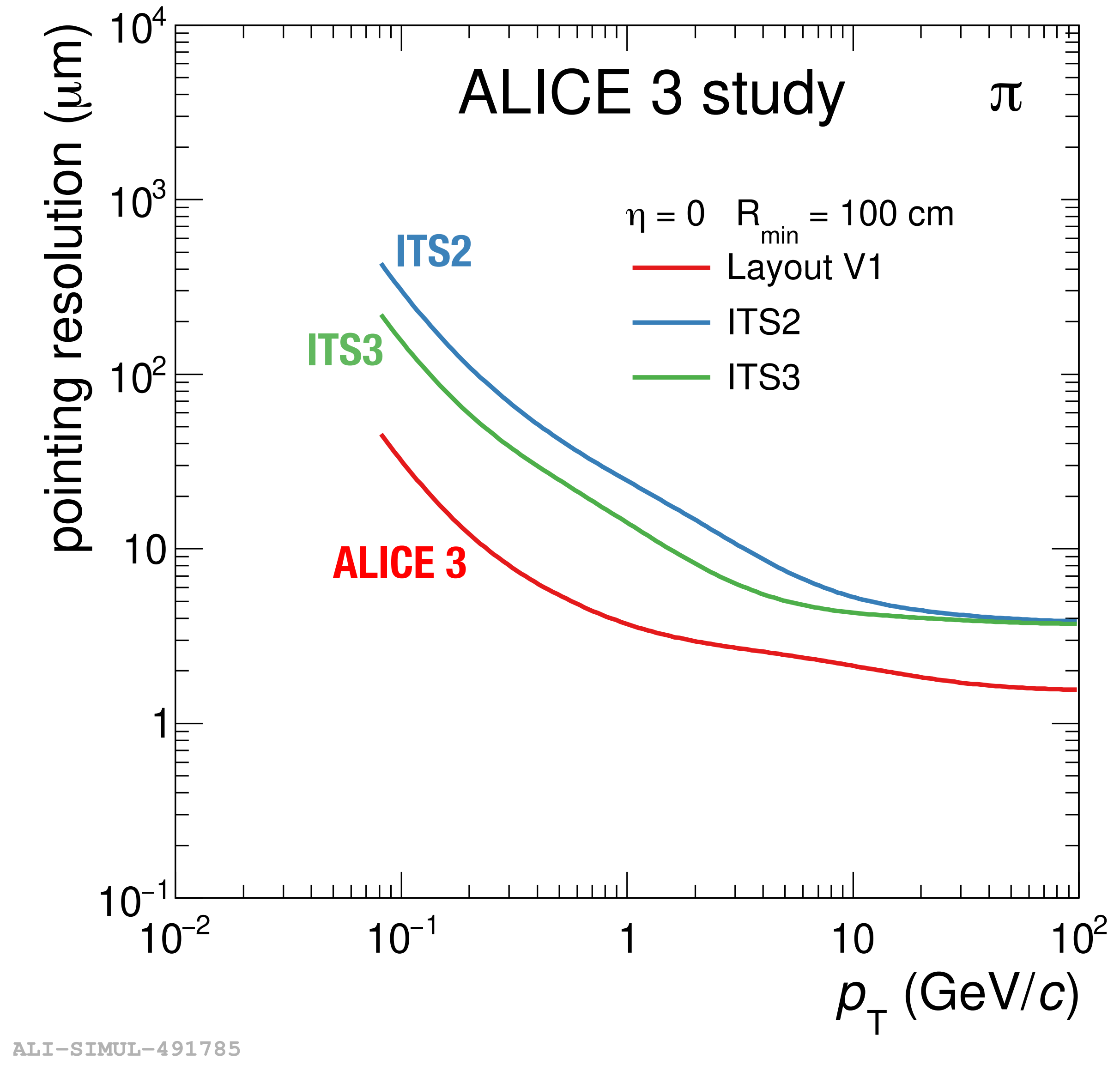
Heavy Ion Physics

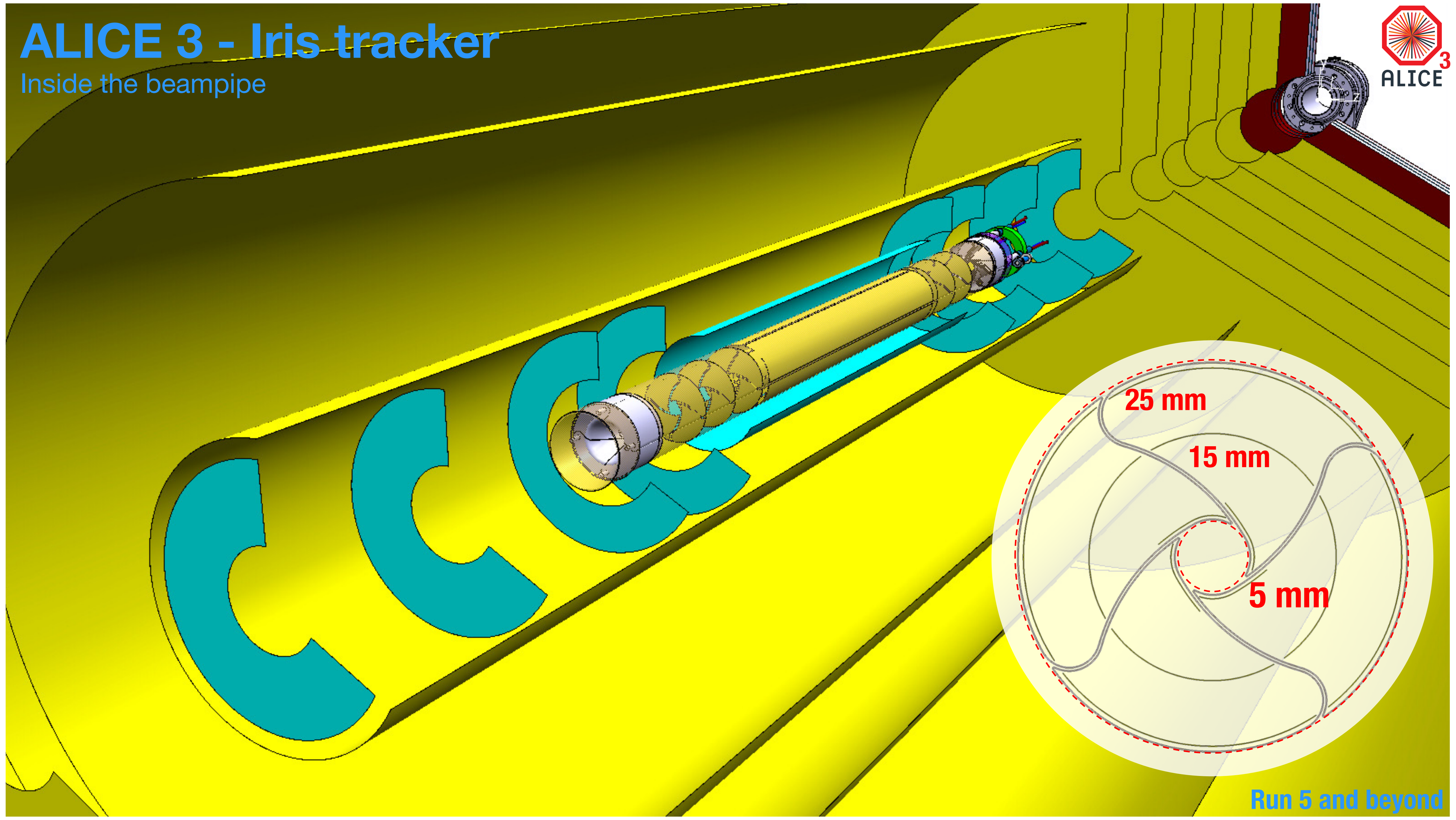
- The purpose of ALICE is primarily to study the strong interaction
    - comparison of PbPb to pp and pPb collisions and other ions
    - large cross sections and hence use only a small fraction of possible pp-luminosity
- Lessons, in particular from Run 1 and 2:
    - strangeness, charm and beauty production originate from different phases of the quark gluon plasma and hence prove particularly interesting
    - Need for higher rate capability

Experimental tools

Low mass detectors near beam - Example: Plans of ALICE 3

- 3 Inner layers closer to IP, (e.g. Iris tracker)
  - retractable innermost layer ~ 5 mm
  - X/X_0 ~0.1 % / layer

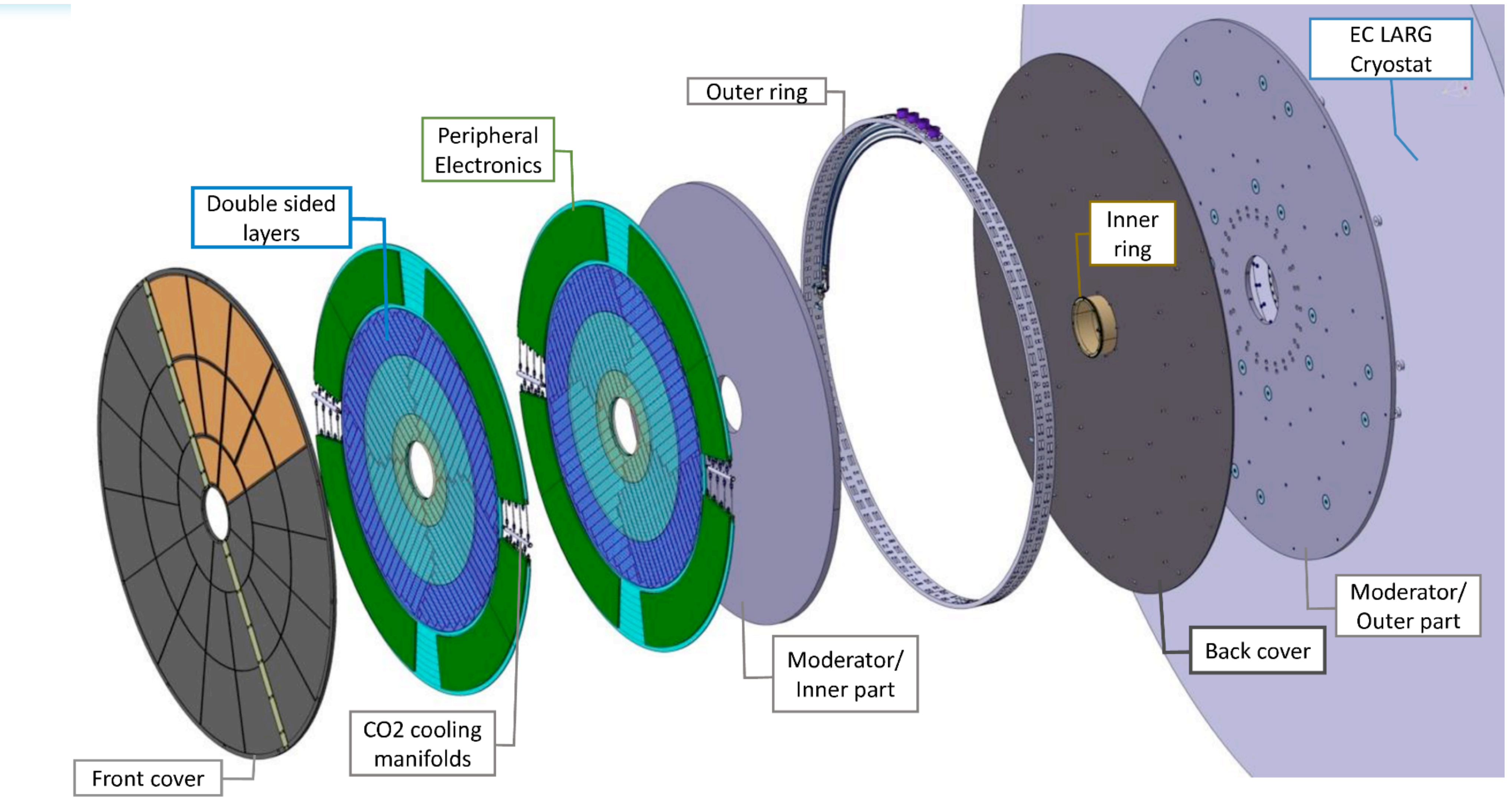


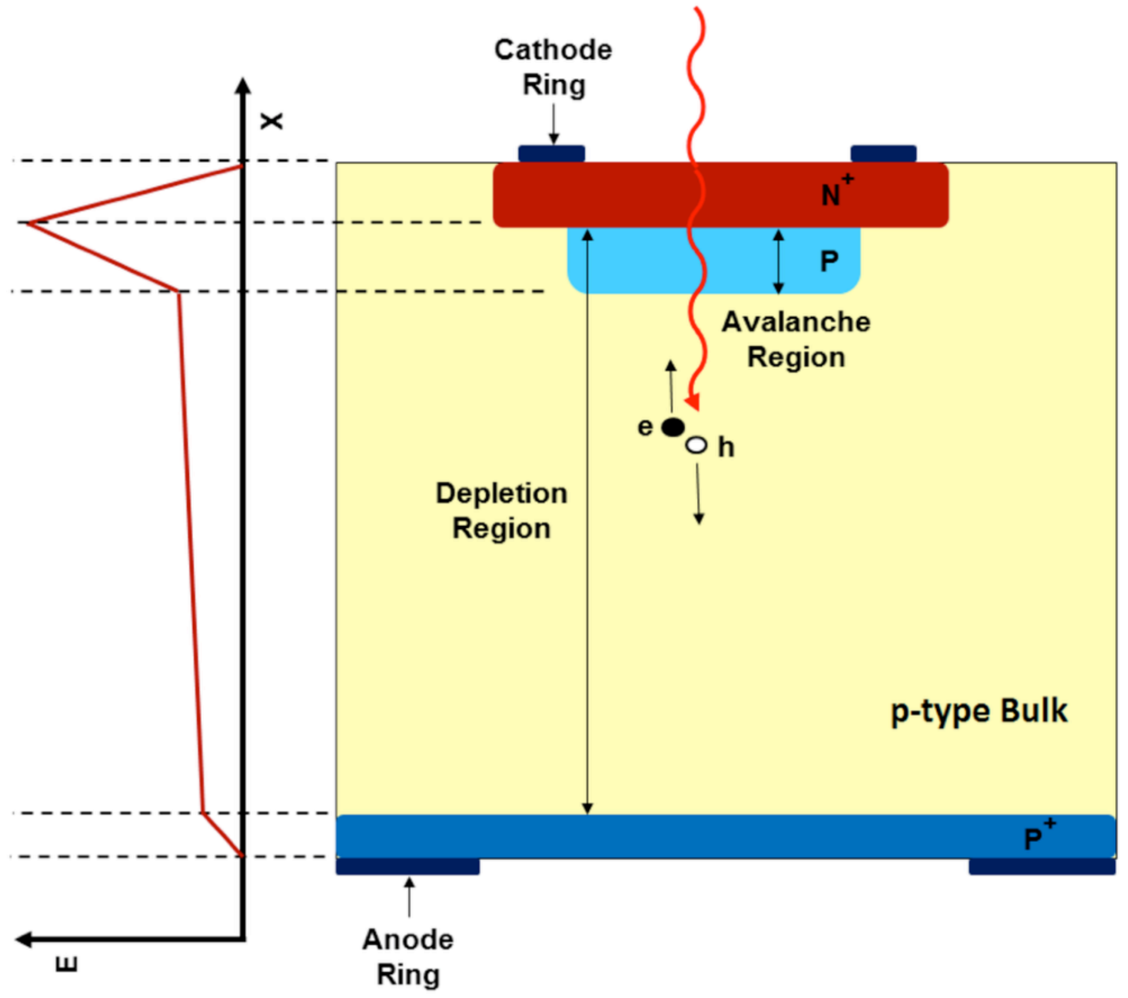


Will be used for flavour tagging

Timing - Example ATLAS HGTD

- 2 disks either side in gap between ATLAS barrel and end cap.
- Each instrumented double-sided layer supported by cryostat/support structure, moderator pieces for protection against back splash.
  - Acceptance at 2.4 < |η| < 4
  - Low-Gain Avalanche Silicon Detectors (LGAD) sensors
  - Enable precision timing, retain signal efficiency after heavy irradiation



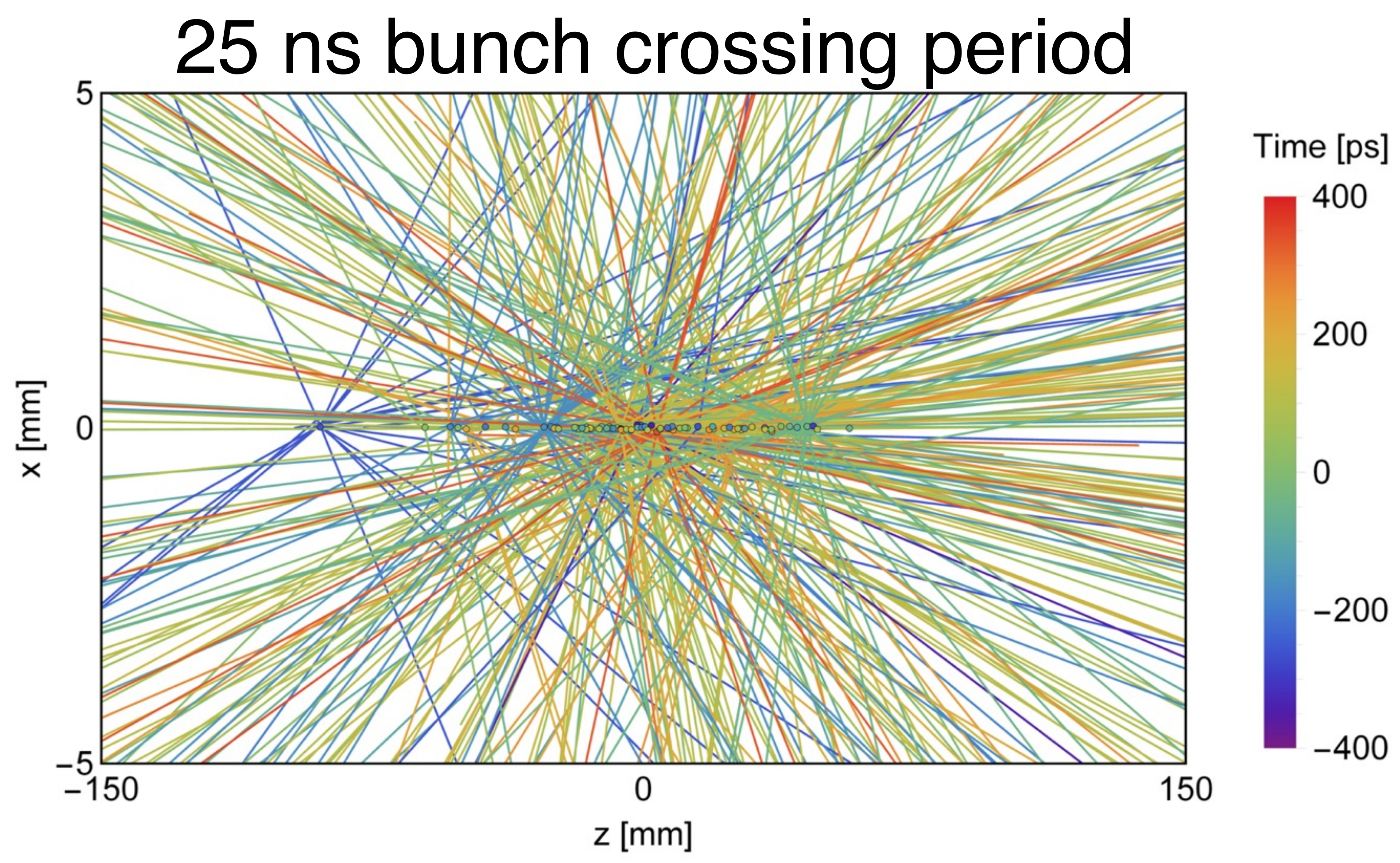


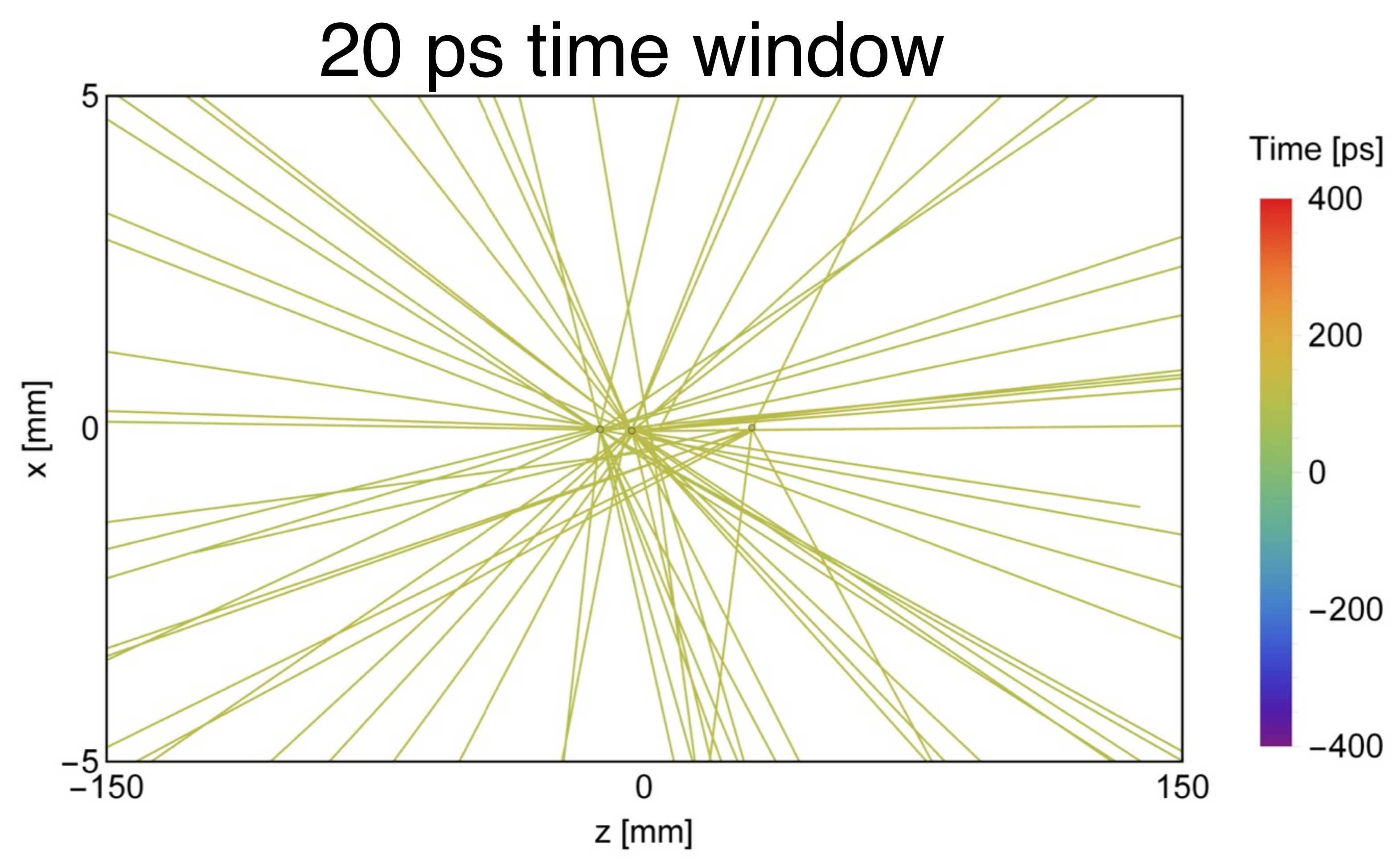
LGAD sensor: Silicon detector with internal low gain

pile-up protection

Integrated Fast Timing - Example LHCb for Run 5

- Fast Timing for
  - VELO
  - RICH
  - ECAL
  - TORCH

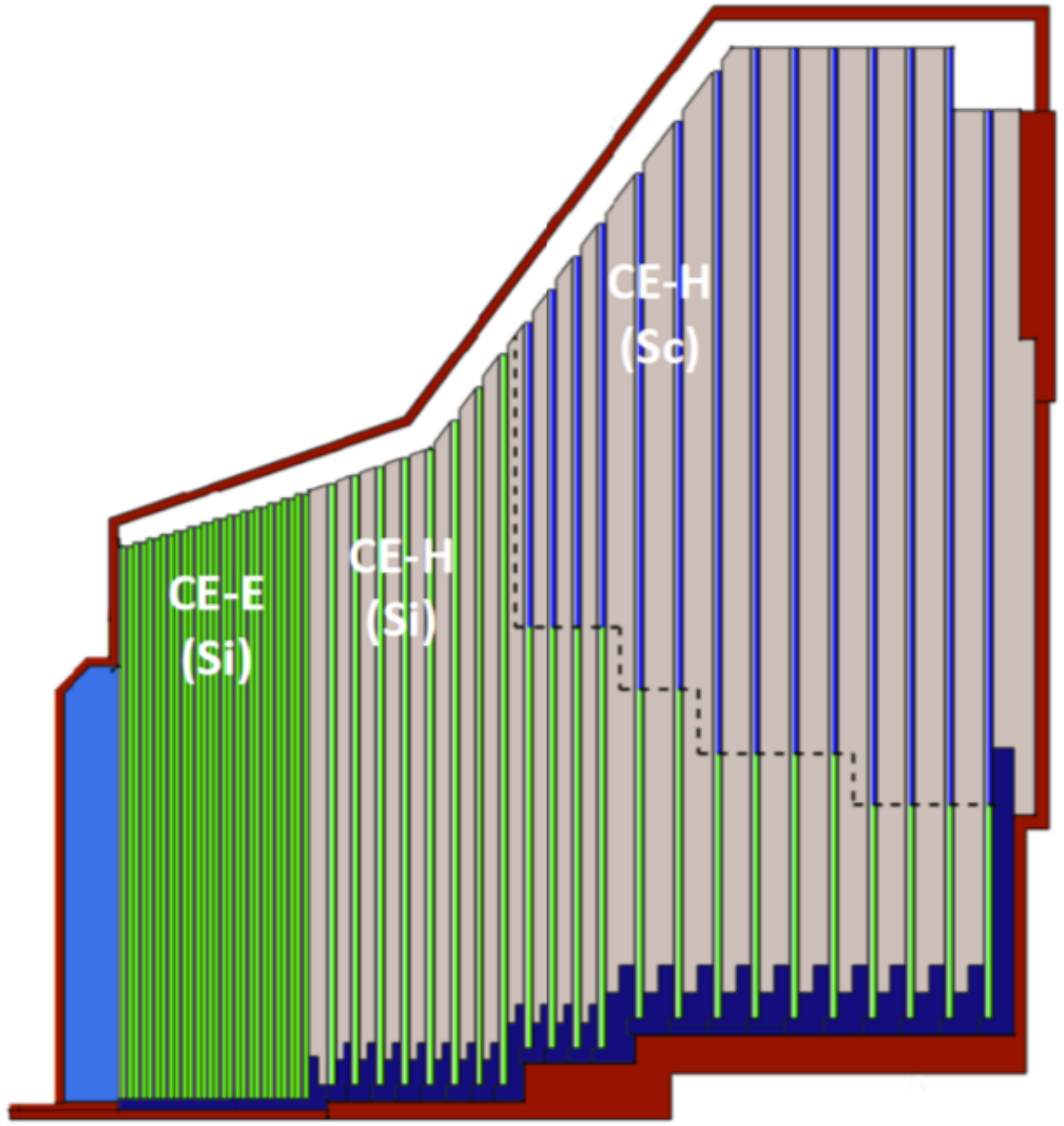




disentangling events

Precision Calorimetry - Example CMS

- Full replacement of existing CMS endcap ECAL and HCAL
- Integrated sampling calorimeter
- Absorber
  - EM section: Pb, CuW, Cu
  - Hadronic section: steel, Cu
- Active material
  - High radiation area: 8” hexagonal silicon sensors
  - Low radiation area: scintillator tiles with on-tile SiPM
- 5D imaging calorimeter
  - Extends tracking in forward regions
  - Highly granular spatial information
    - Si cell size: 0.5 cm^2 and 1.2 cm^2
    - Scintillator tile size: $(23\ mm)^2$ – $(55\ mm)^2$
  - Large dynamic range for energy measurements
  - Timing information to tens of picoseconds



Cut-away side view

Particle Flow Calorimetry

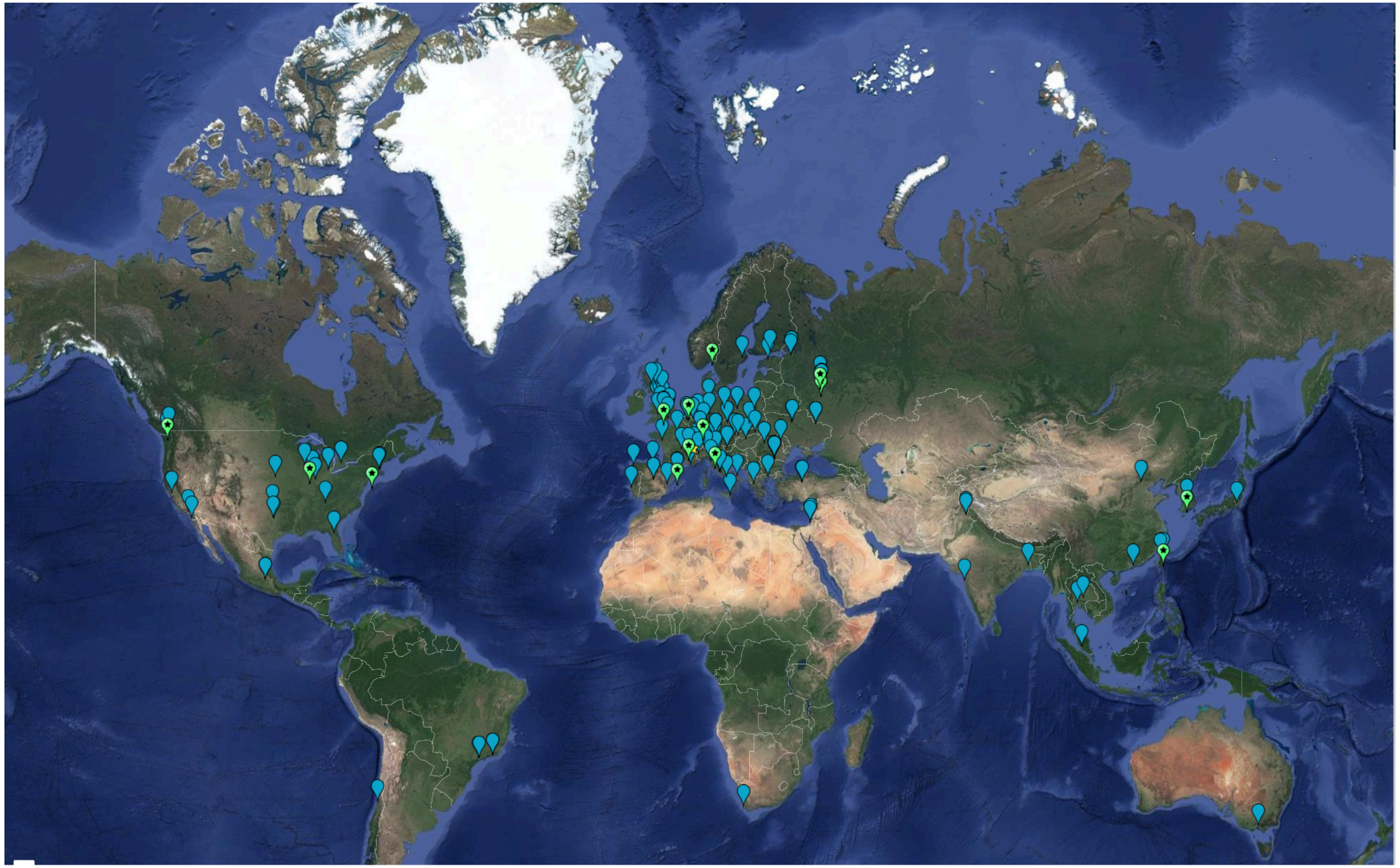
e.g. W-production in forward direction

Data rates will increase even faster…

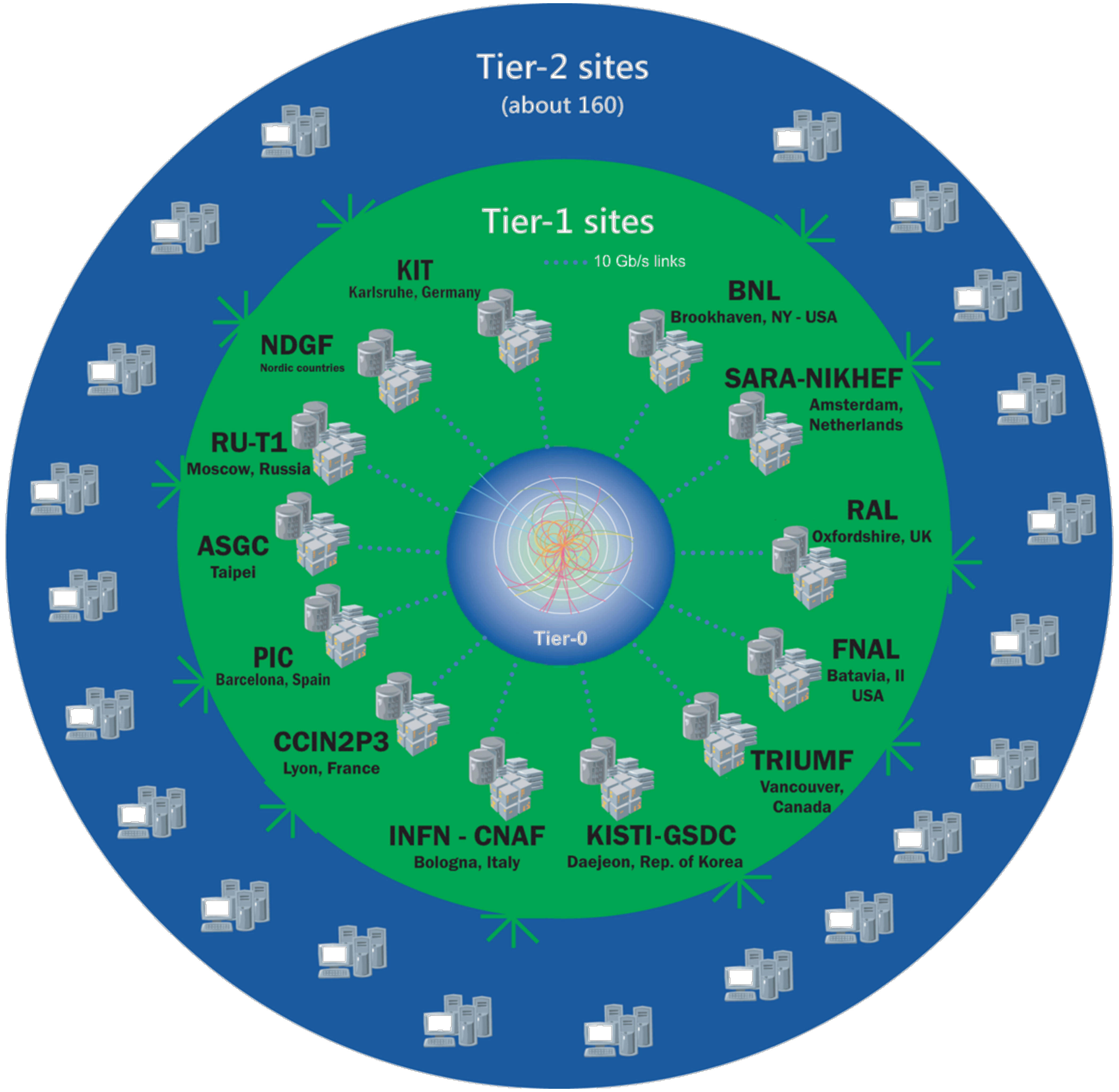
Worldwide LHC Computing Grid (WLCG)

- World-spanning computing network with single sign-on and optimum sharing

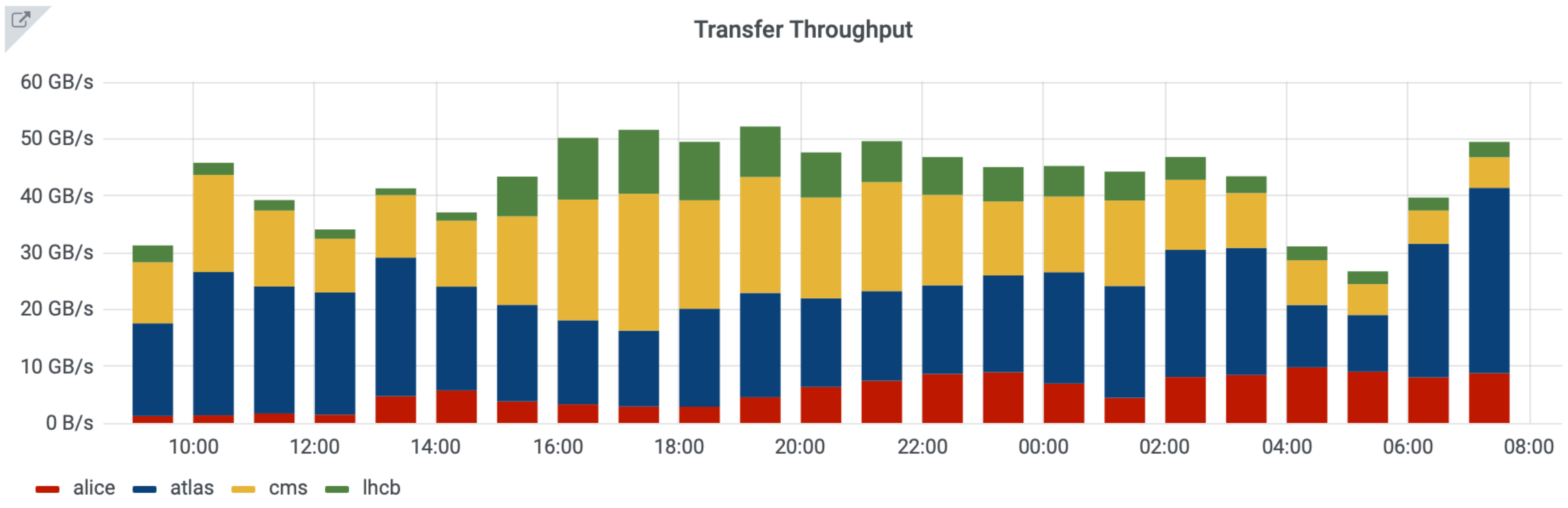
- Precursor to Cloud-based computing and a showcase for cost-efficient usage of local resources



WLCG network and data rates



Collaboration based on MoUs and institutional contributions (pledges), which are often supplemented by in-house efforts.



Snapshot 17.8.2021

Computing needs for LHC Experiments

- CPU and Disk storage needs continue to rise - independent of data taking
  - Simulation taking larger share
- Tape is the most cost effective means of (intermediate) storage of data

CPU

Disk

Tape

Computing needs for simulation

- Traditionally a large share was taken by the very detailed Geant simulation of the detector (calorimeter shower).

- With the need for per cent and better precision higher-order Monte Carlo simulations (integration of matrix elements) take a large share

  - Simulation may account for 50% of the computing needs of an LHC experiment

Shift in Computing paradigm

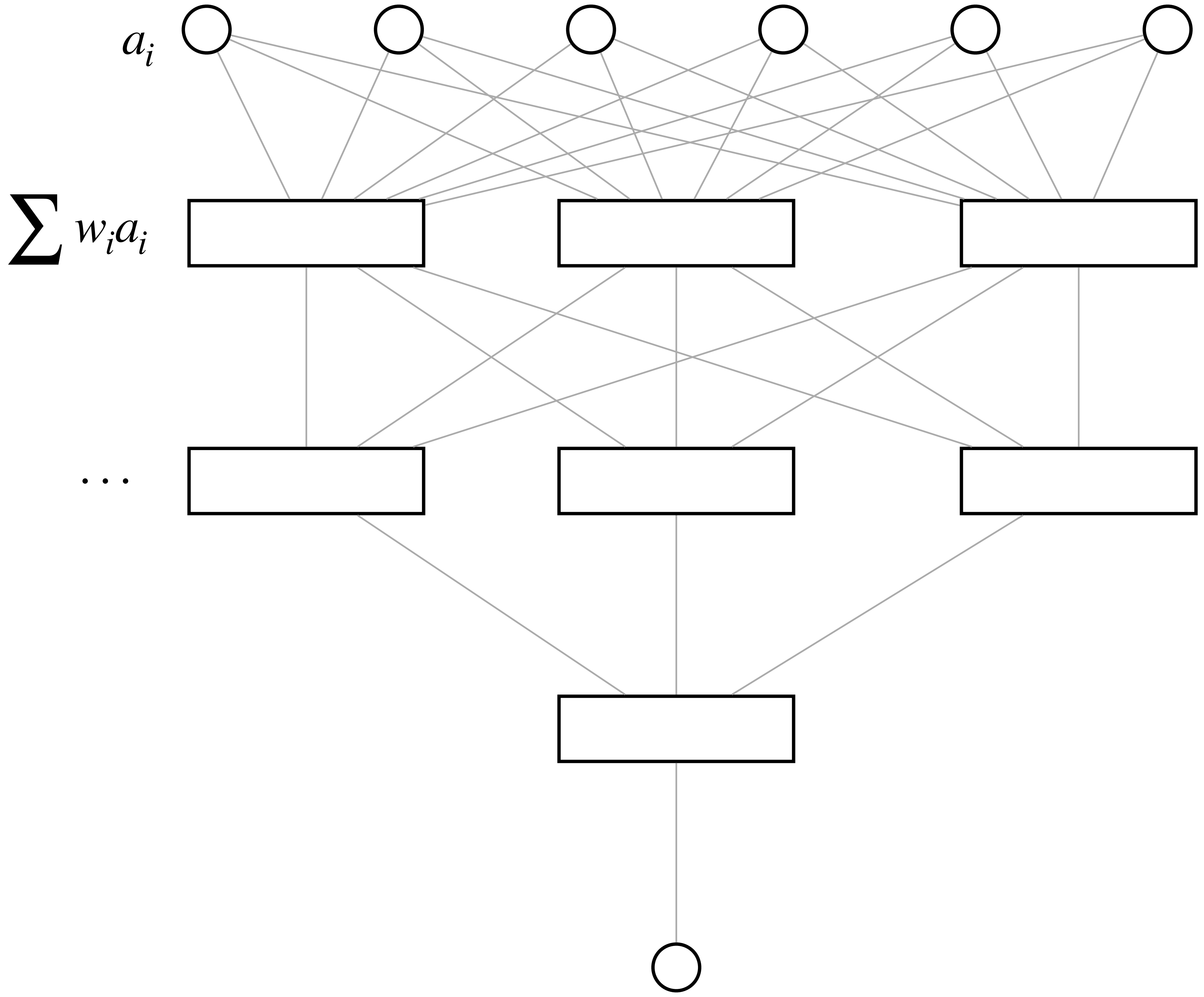
- GPUs have become considerably more cost-effective than traditional CPUs. Funding agencies request usage of cheaper hardware and have recognised to fund the necessary software development
- Supercomputers are often based entirely on GPUs
- Heterogenous computing environments have now become common place in Particle Physics
    - Massive adaptation of legacy code is necessary
    - There will be future need for adaptation (SoC- and FPGA-solutions)

Reformulation of the software problem as a linear system

- GPUs best work with problems of linear algebra
  - vectors, matrices
  - linear operations
- Restate the computing problem in a linear hyper-space

Machine Learning

- Large number of inputs
- Linear weights
- Multiple layers
  - deep learning



Application of linear systems

Some examples of applications of Machine Learning

- Shower simulations
  - learn from simulations and real data
- Signal discrimination
  - use all input variables (and forget about correlations)
  - much better separation and better signal / noise than in cut-based analyses
  - optimum exploitation of the available data sample

Quantum Computing

- Since we have begun to formulate the reconstruction / analyses challenges in a new (hyper-)space we may associate any state as a representation in this space.
- The physical solution is the (local) optimum in this hyper-space
- This is exactly the solution that we seek in quantum mechanics
  - A quantum computer is hence the ideal tool to solve for the optimum

Towards Quantum Computing

- Reformulate the physics problem in an adequate multi-dimensional representation
- Seek the optimum solution in this space
  - using GPUs
  - using Quantum Simulators (brute force classical minimisation)
- Apply to Quantum Computers once they become available and accessible
  - First steps are taken everywhere

Concerns: do we abandon understanding – abandon physics?

Some caveats about Machine Learning

- Data analysis and Inference
  - Enforcing symmetries that might be broken in observed data
  - Regularisation: Balance strict parametric form vs allowing for unphysical solutions
  - Causality: Role of learning simulators that allow to generalise and to extrapolate to different settings
  - Input from other fields of science
- Scaling of calculations (need a power plant to carry out a simulation satisfactorily)
  - higher order calculations?

Machine Learning as a special Tool of Variational Optimisation

- Often too many parameters suggest full description

- Big Data and Deep Learning
  - may be better to use hybrid approaches inspired by physical models

Machine Learning – classical or quantum

- If inversion of the problem is not possible - at least of the main drivers or features - we will not learn anything
  - Inductive bias
  - Compositionality
  - Symmetry
  - Causality
  - Separation
- in the end will not be able to generalise nor to predict outcome in a new setting

Summary

- Computing is undergoing a shift in paradigm – with the advent of heterogenous architectures we have to reformulate the computing problem, often from the start
- Machine learning is a gift to boosting resolution of detectors and calculation to unprecedented precision sometimes at the price of foregoing the physics understanding
- Quantum Computing will allow an even more elegant formulation and solution to variational optimisation