From Raw Data to Physics Results (1/3)

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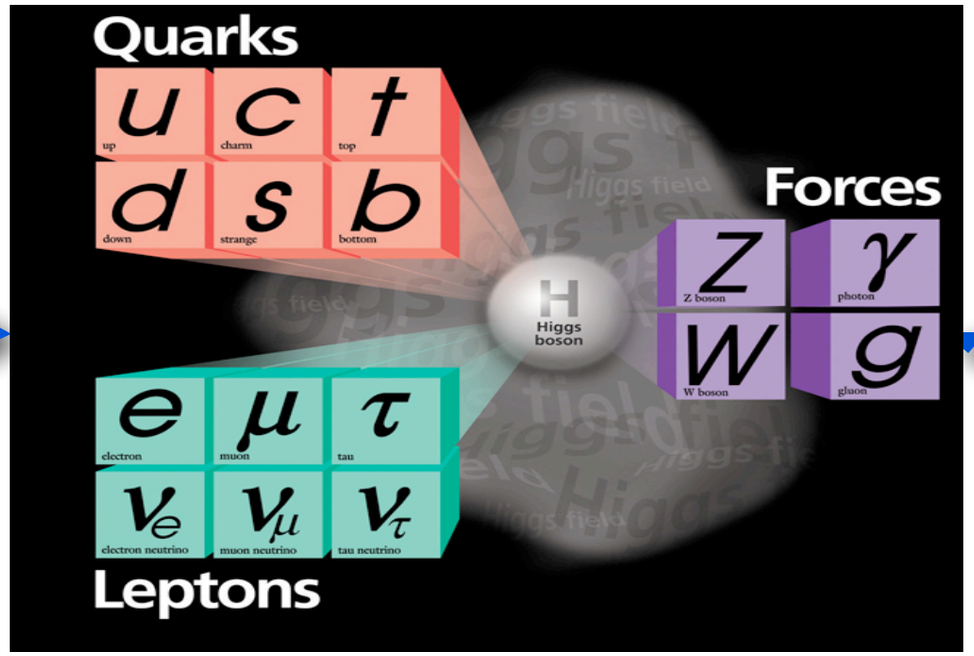
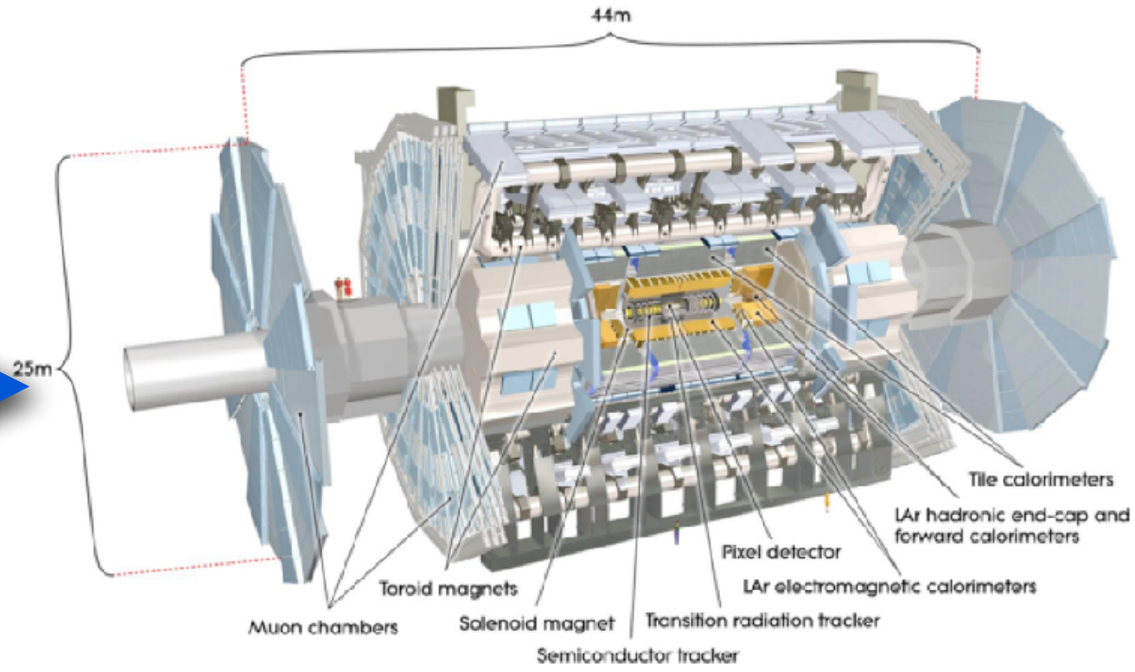
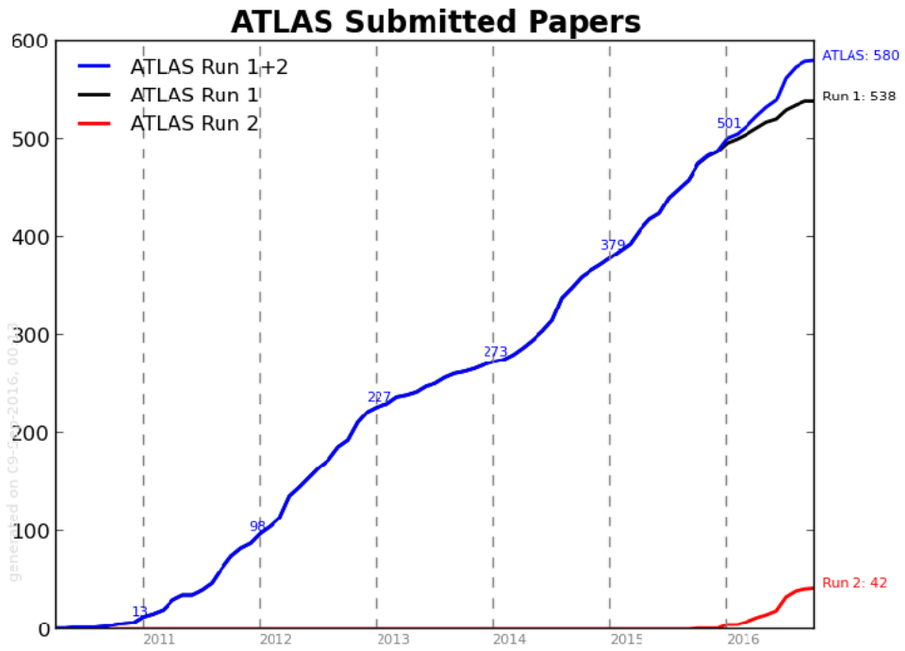
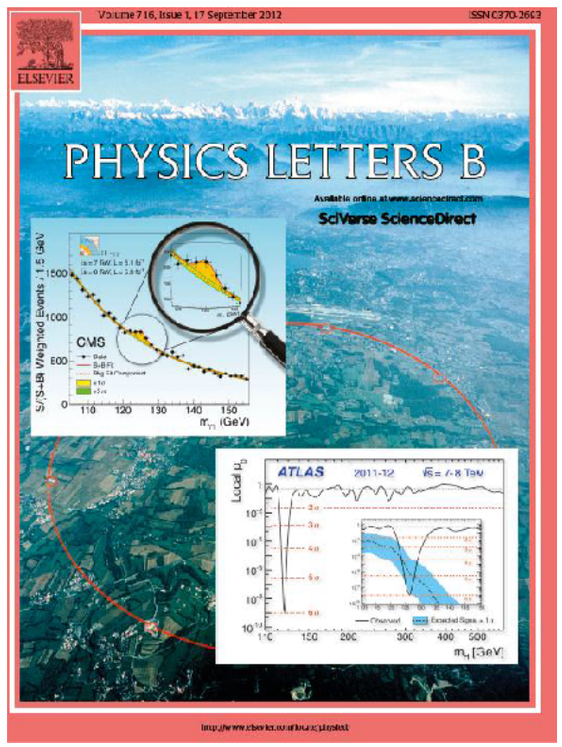
The particle physics cycle





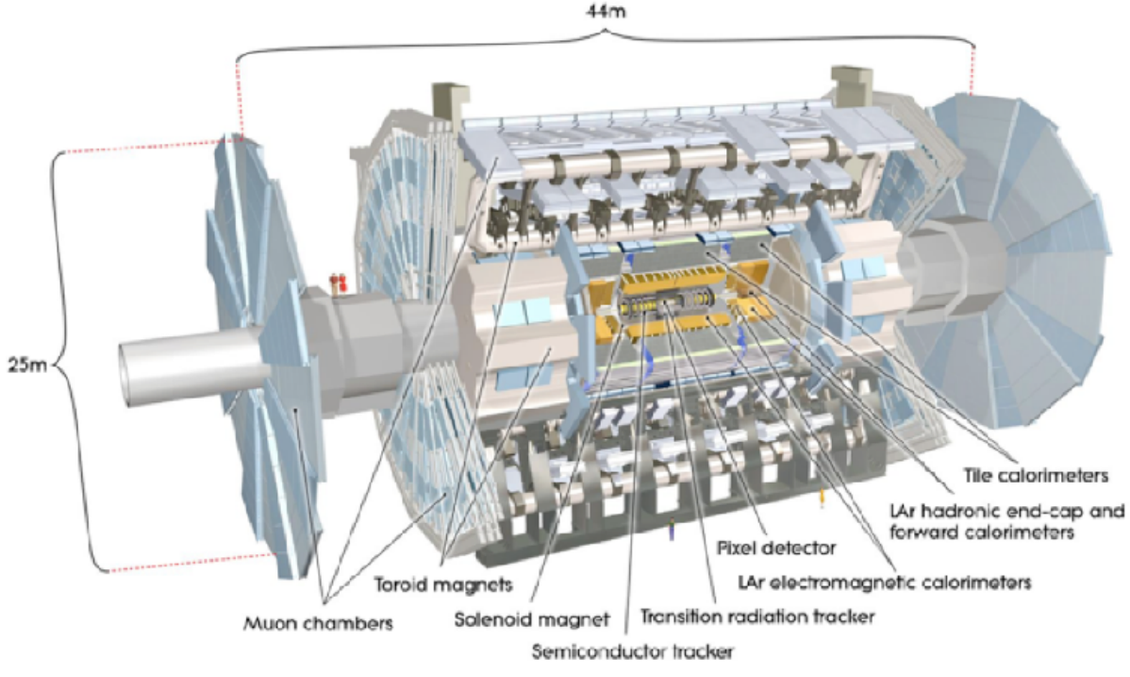




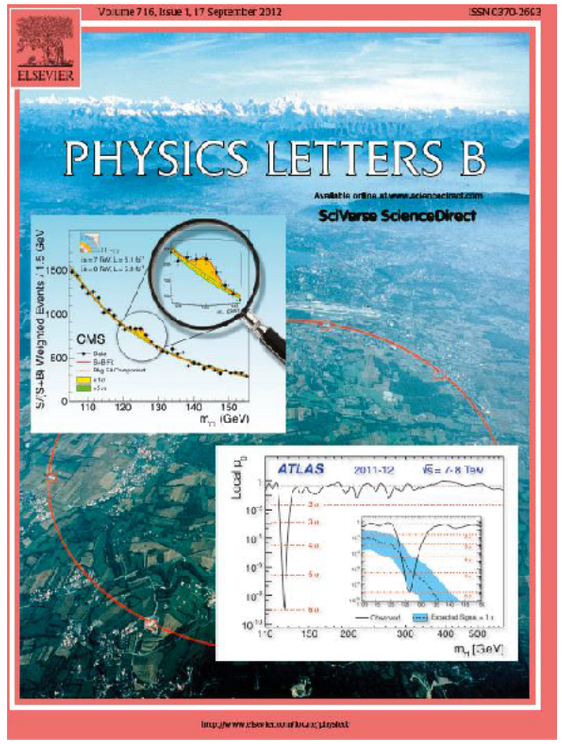
Experimental physics

- Much of the work of the experimental physicist is running experiments and extracting measurements from them

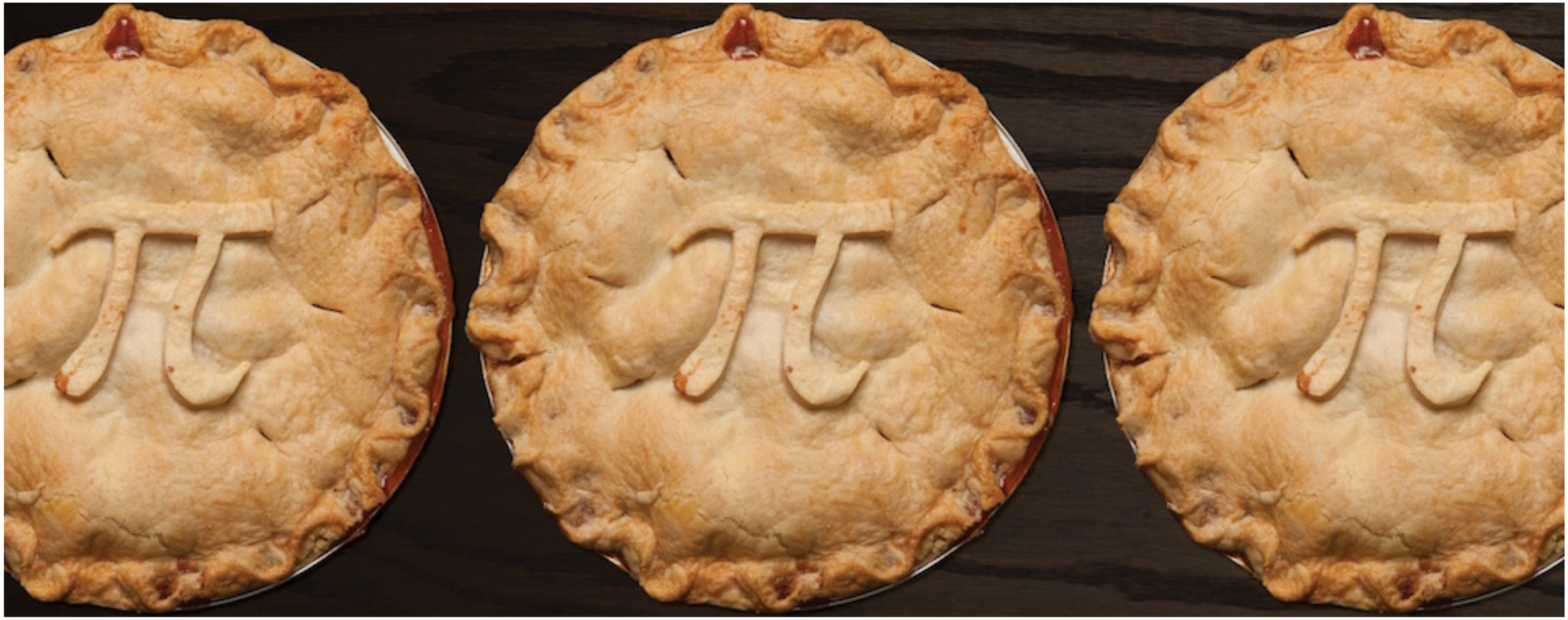
- ***Note*** *- Experimental physicists also need to propose, design and build new experiments (see previous slide)*



- These lectures are focused on understanding how we turn raw experimental detector data into physics results that we can publish
  - Results must be ***accurate***
  - with well understood ***precision***
  - It's important to understand the difference between these two words, we often confuse them



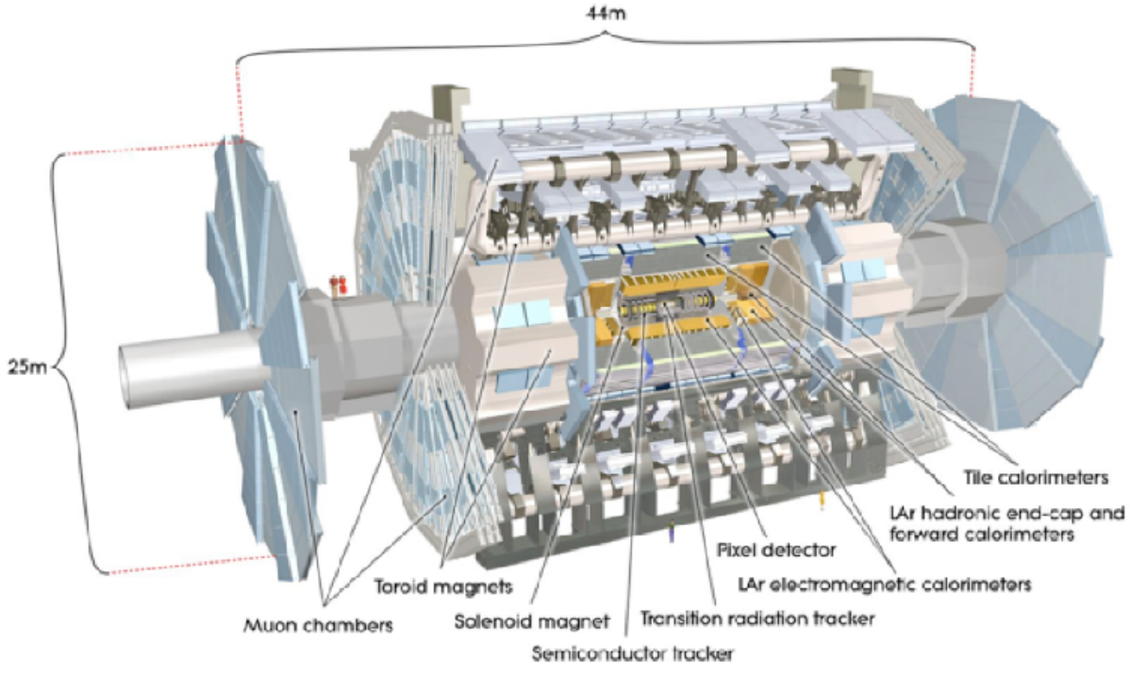
Accuracy and precision

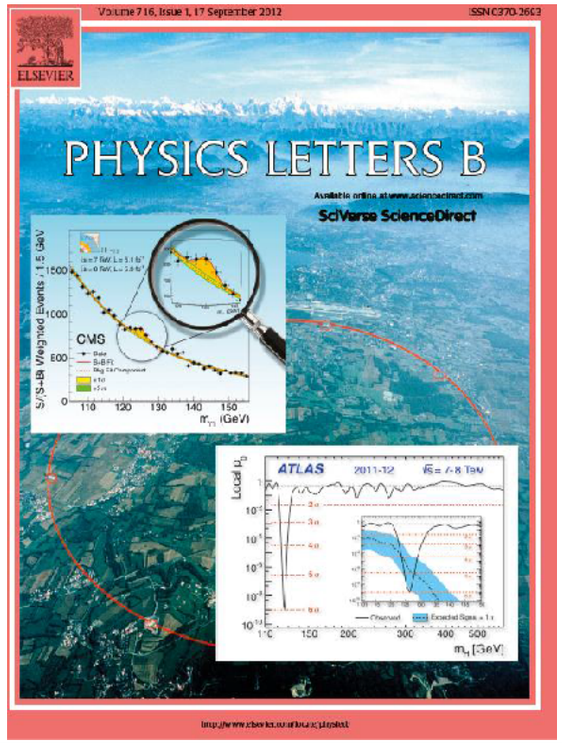


3.1416 ± 0.0001 $22/7 \pm 1$ 3.14159265 ± 0.1

Course outline

- **Lecture 1**
  - The journey of raw data from the detector to a publication
- **Lecture 2**
  - How we reconstruct fundamental physics processes from raw detector data
- **Lecture 3**
  - How we extract our signals from the mountain of data, finding needles in the haystack

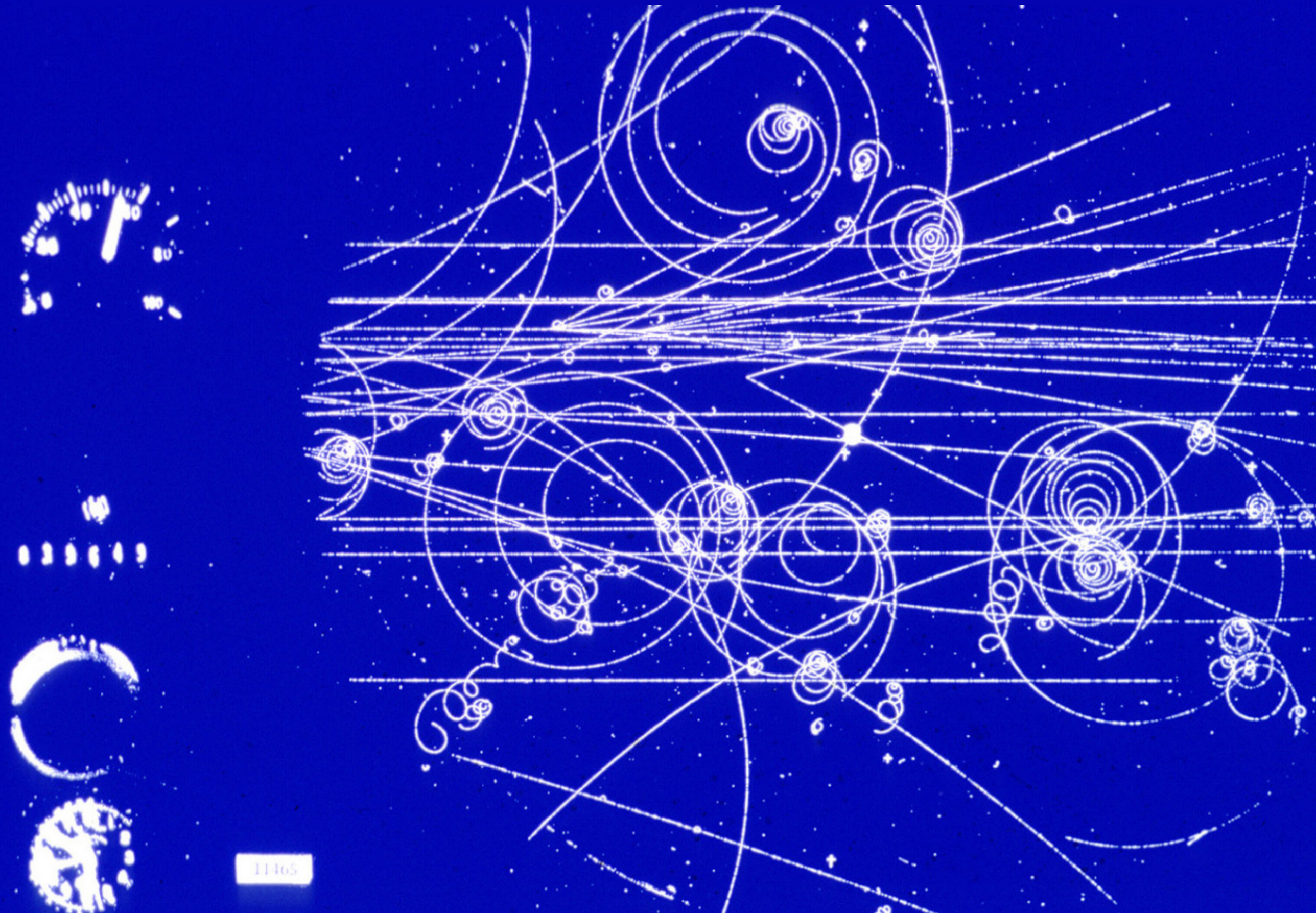




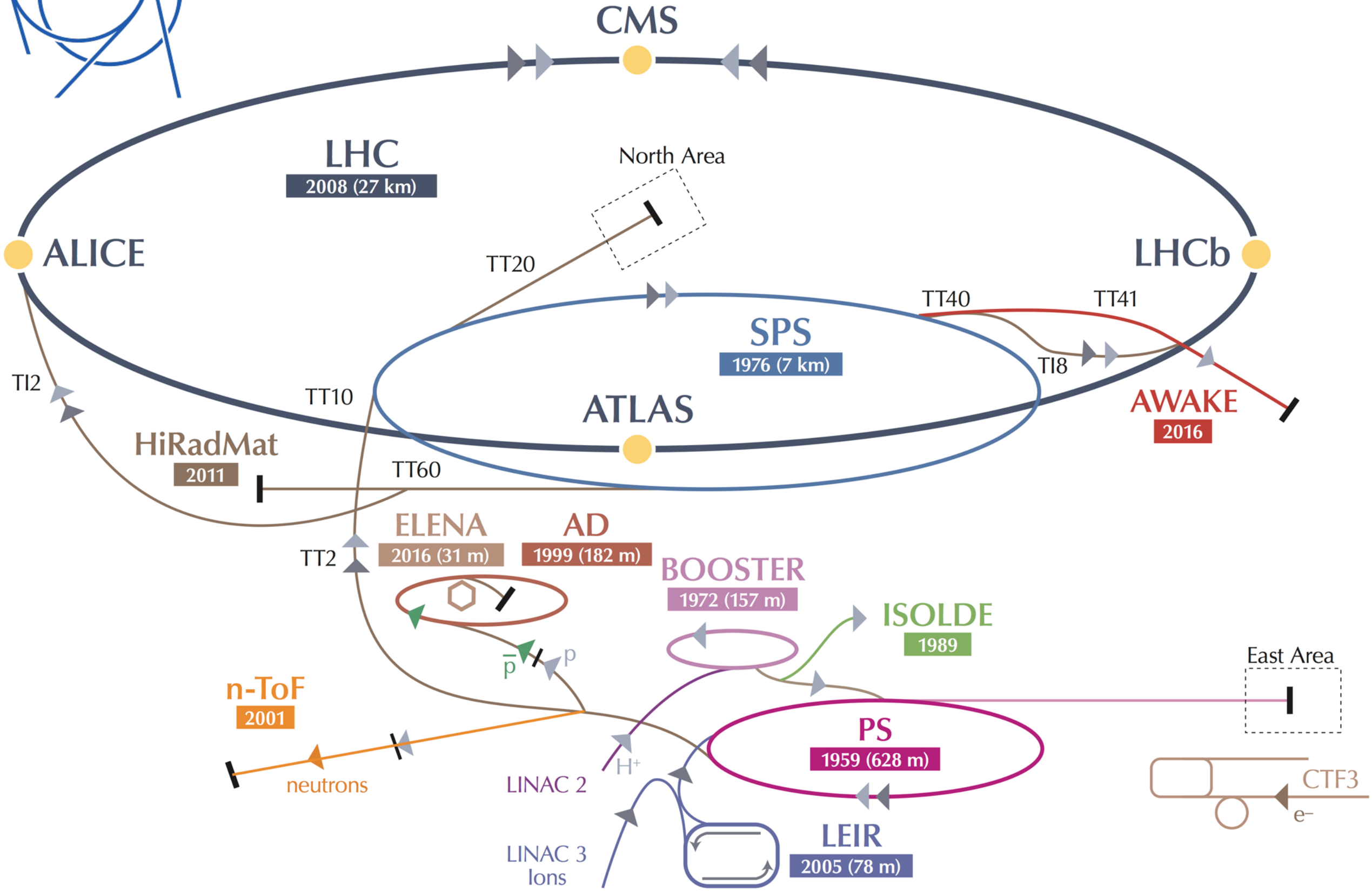
Experiments at CERN

- In the 1960s we used Bubble chambers, the one that you can see in the Microcosm was used…

… data analysis used to involve a person looking at pictures



Today @ CERN we have huge rates of collisions so that we can produce very rare events

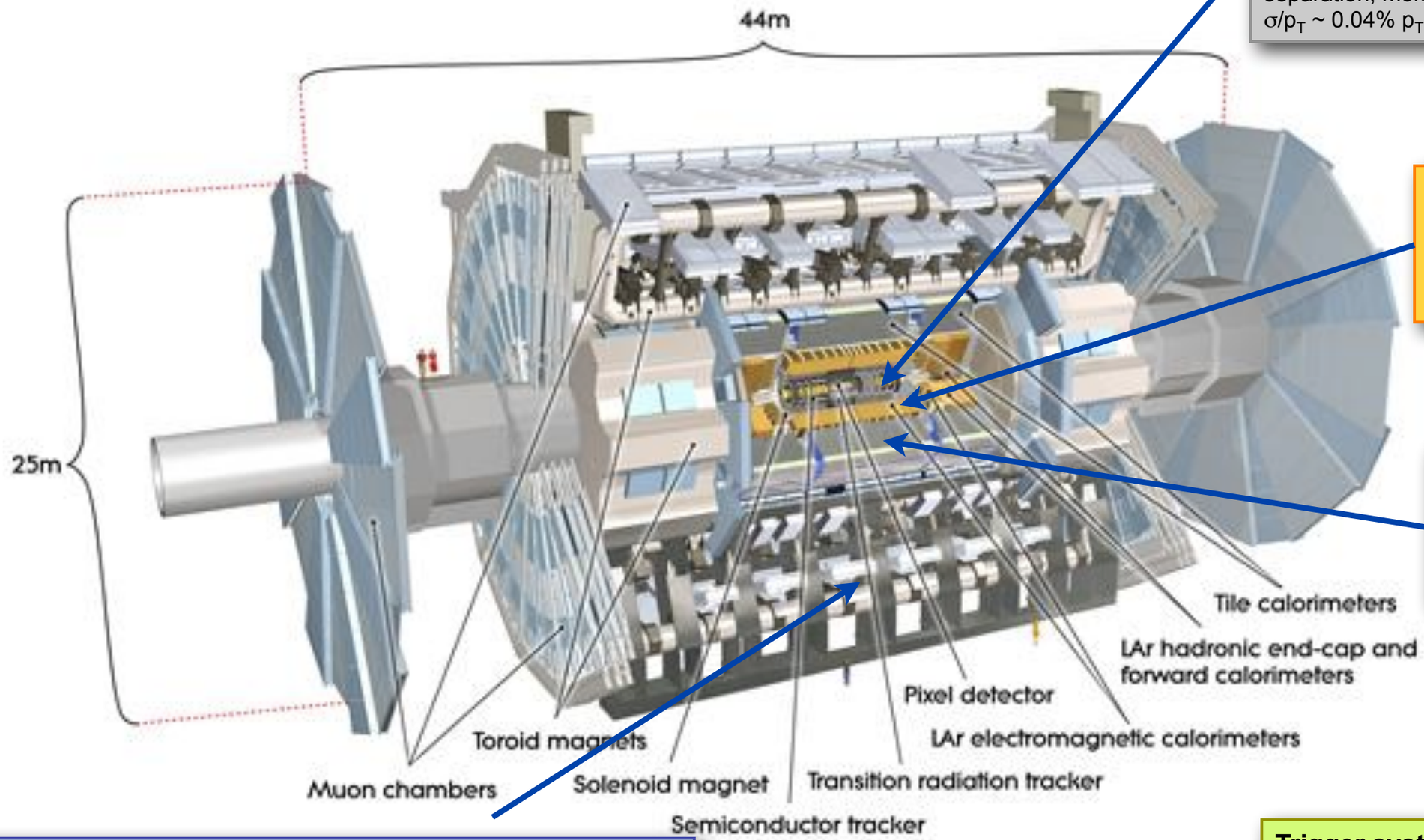


The ATLAS Detector @ LHC

L ~ 46 m, ∅ ~ 22 m, 7000 tons
~10^8 electronic channels

Inner Tracker (|η|<2.5, B=2T): Si Pixels, Si strips, Trans. Rad. Det. Precise tracking and vertexing, e/π separation, momentum resolution: $\sigma/p_T \sim 0.04\% \; p_T\,(\text{GeV}) \oplus 1.5\%$

EM calorimeter: Pb-LAr Accordion, e/γ trigger, id. and meas., energy res.: $\sigma/E \sim 10\%/\sqrt{E} \oplus 0.7\%$

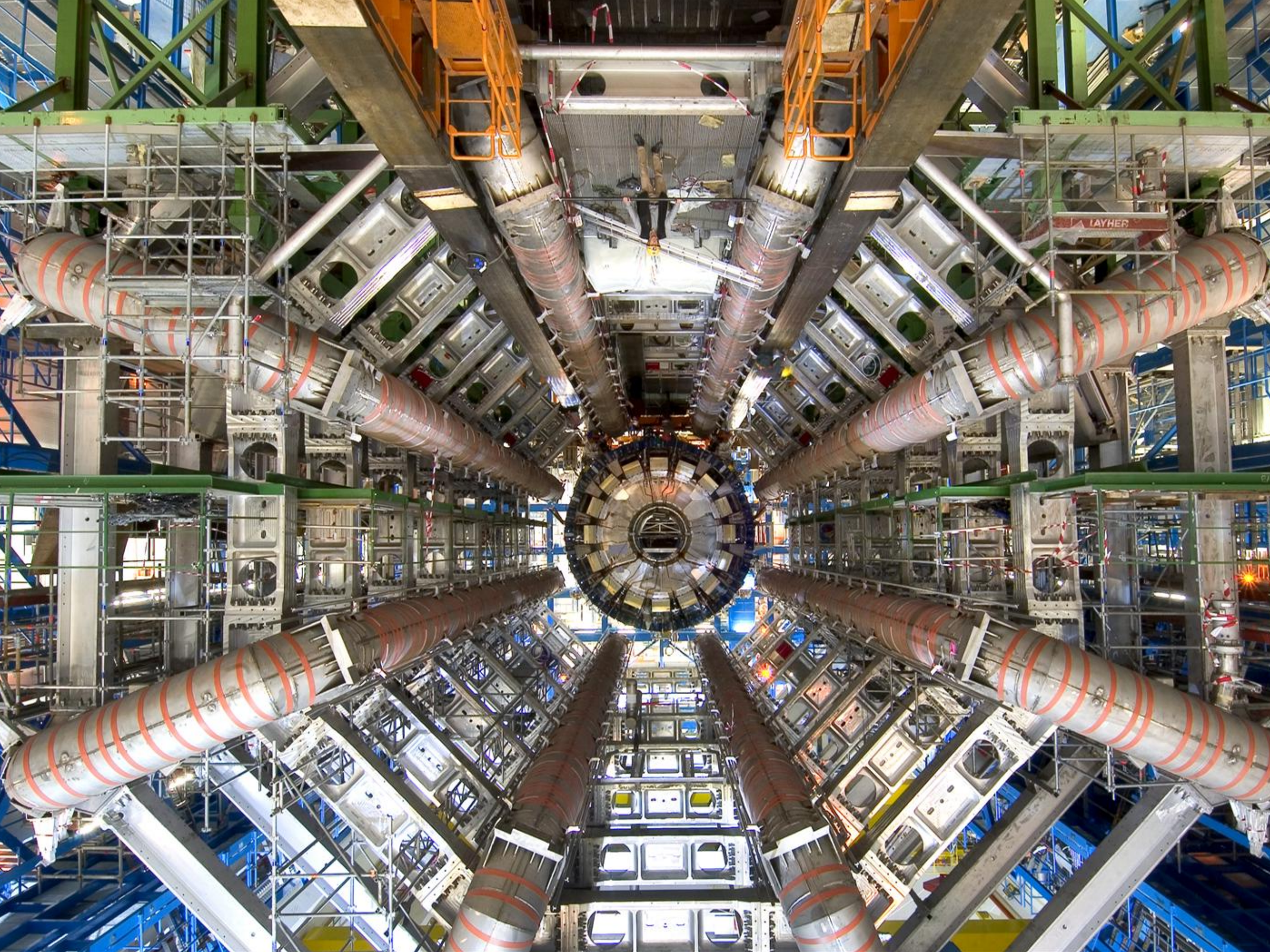


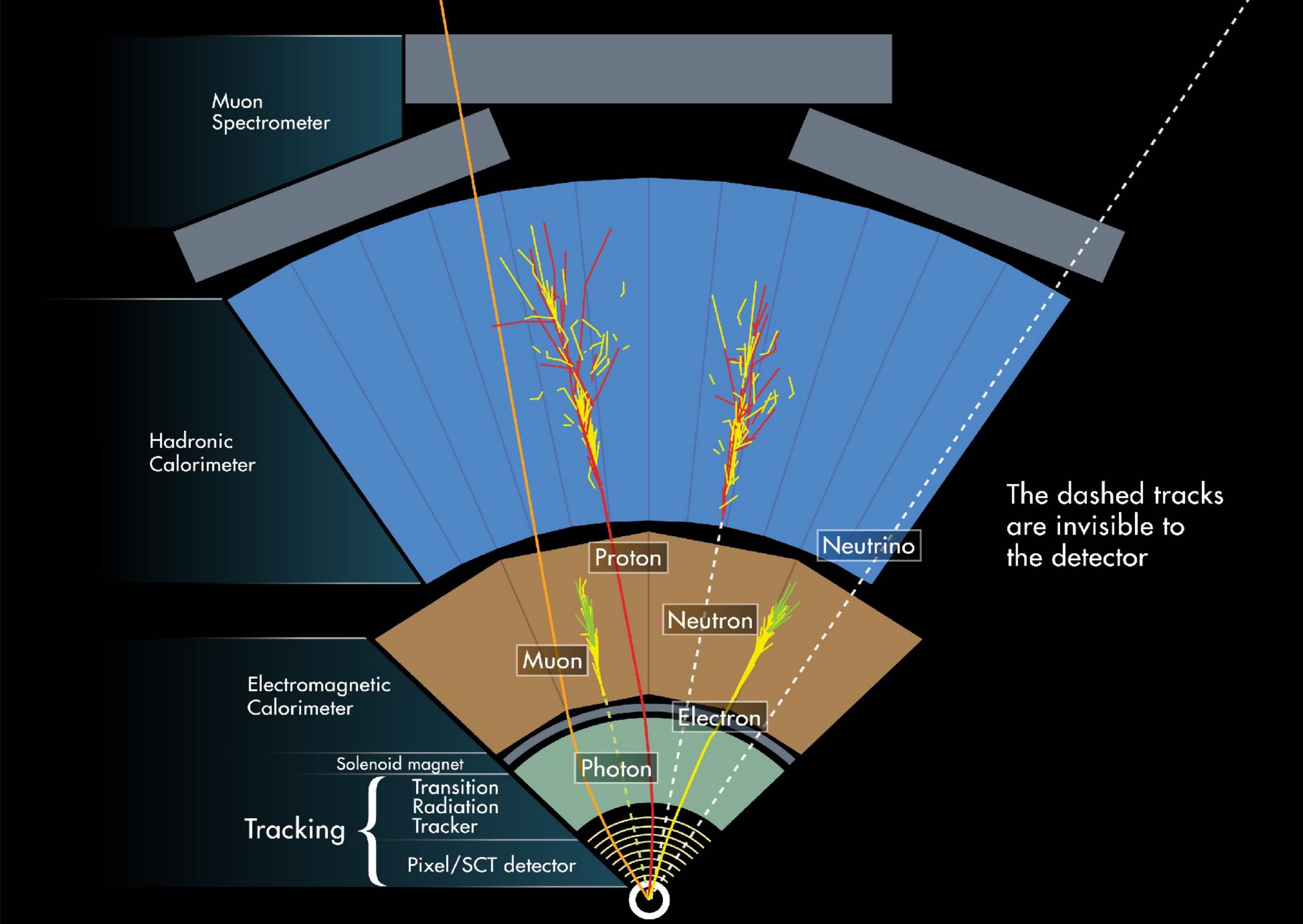
HAD calorimetry (|η|<5): Fe/scintillator Tiles (cen), Cu/W-LAr (fwd). trigger and meas. of jets and $E_{T,miss}$, energy res.: $\sigma/E \sim 50\%/\sqrt{E} \oplus 3\%$

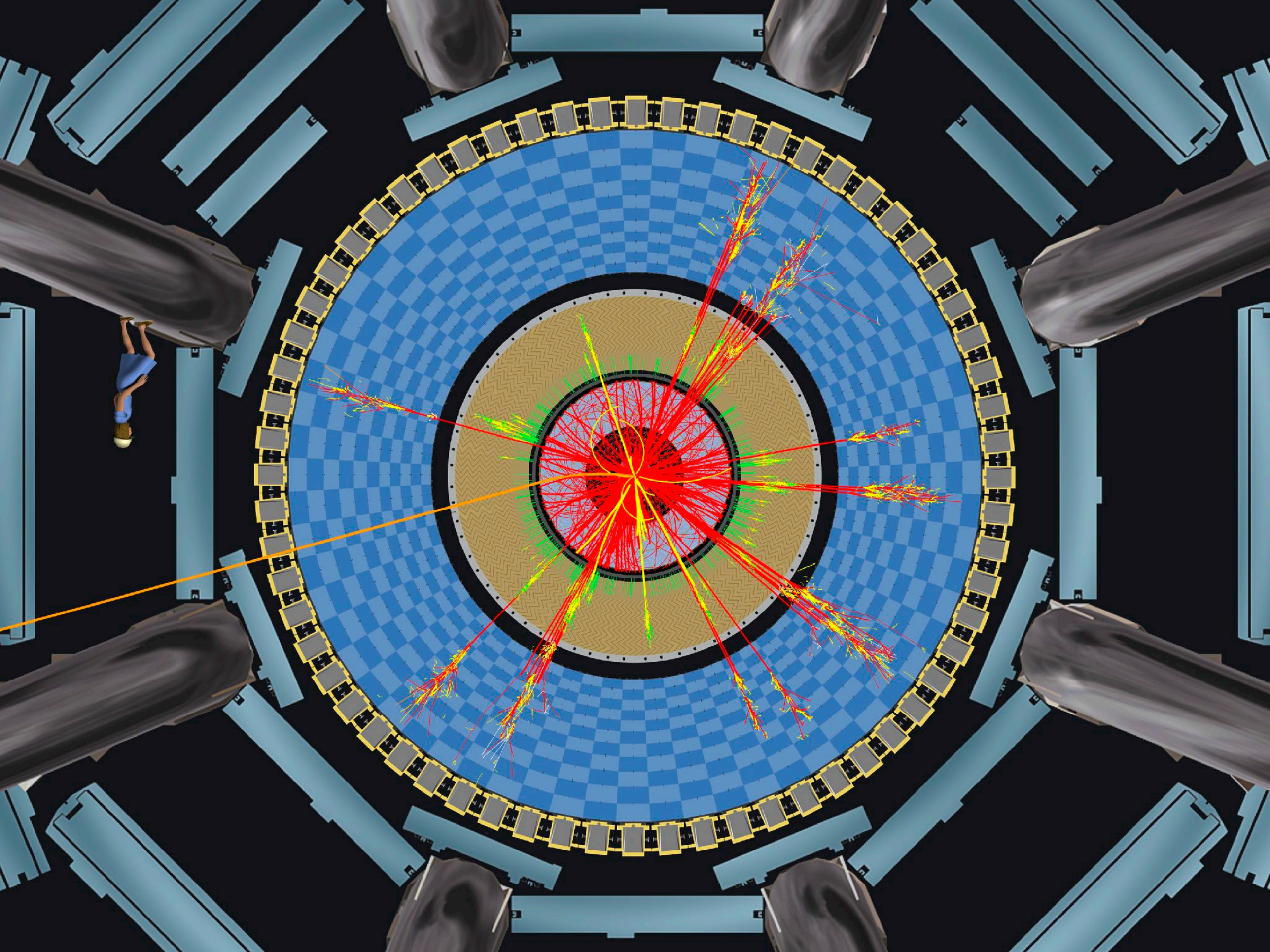
Muon Spectrometer: air-core toroids with gas-based muon chambers. trigger and meas. with momentum resolution < 10% up to $E_\mu \sim 1$ TeV

Trigger system: 3-levels reducing the IA rate from 40 MHz to ~200 Hz

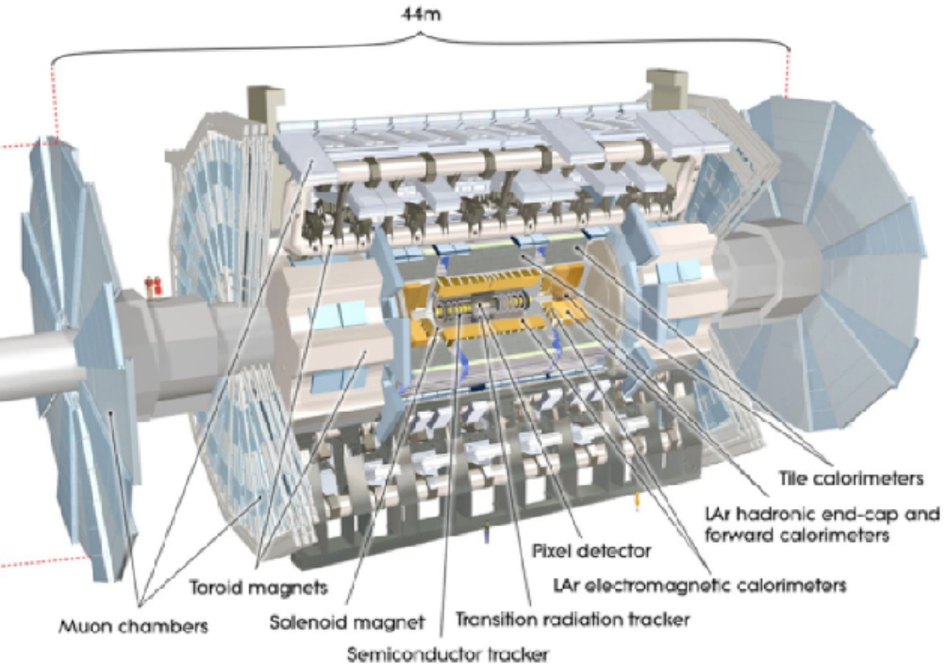
Millions of detector readout channels read out to reconstruct one "event"

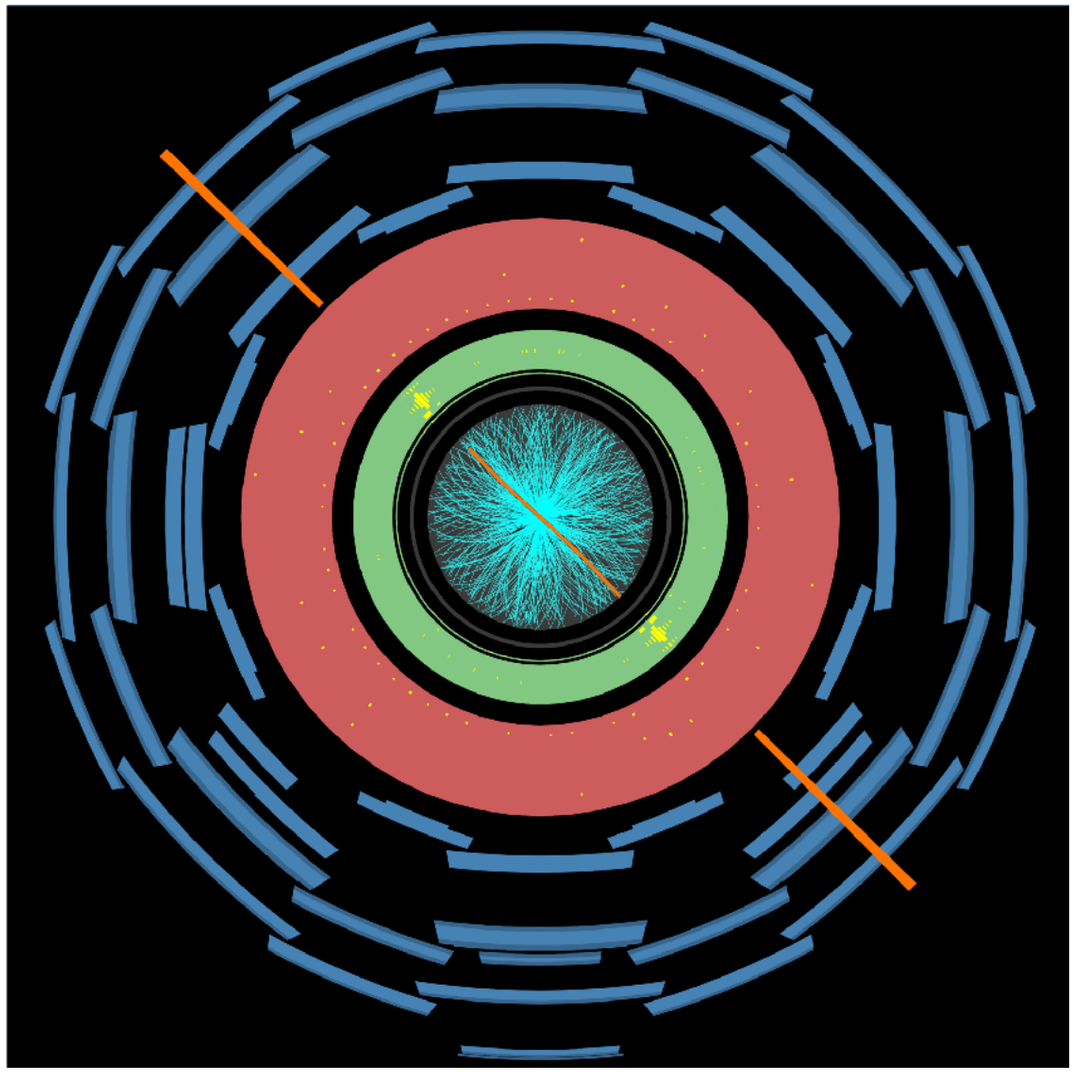

LAYHER


Muon
Spectrometer
Hadronic
Calorimeter
Electromagnetic
Calorimeter
Solenoid magnet
Tracking
Transition
Radiation
Tracker
Pixel/SCT detector
Proton
Neutrino
Neutron
Muon
Electron
Photon
The dashed tracks
are invisible to
the detector



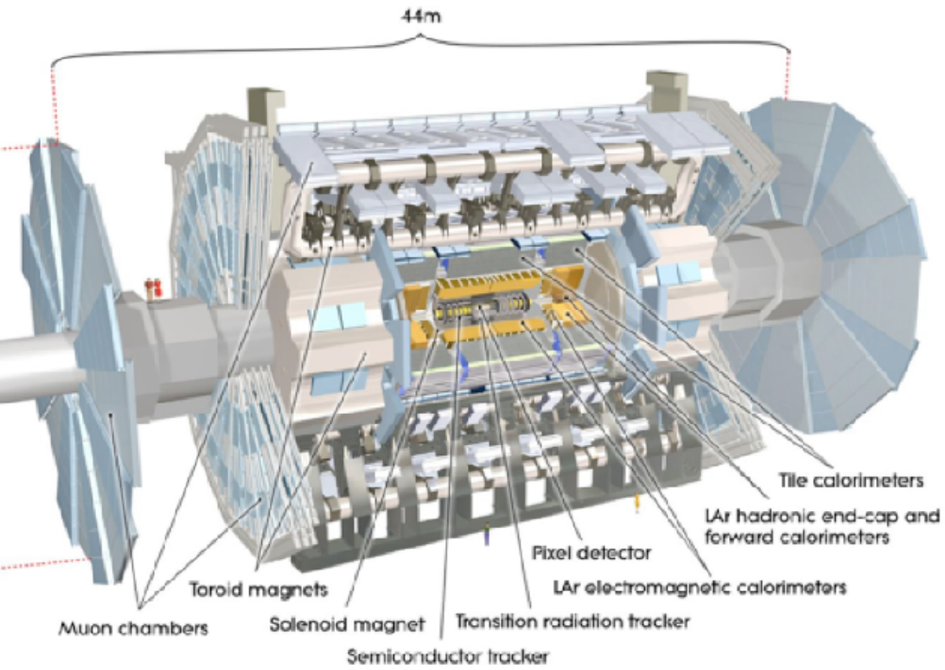
Event displays



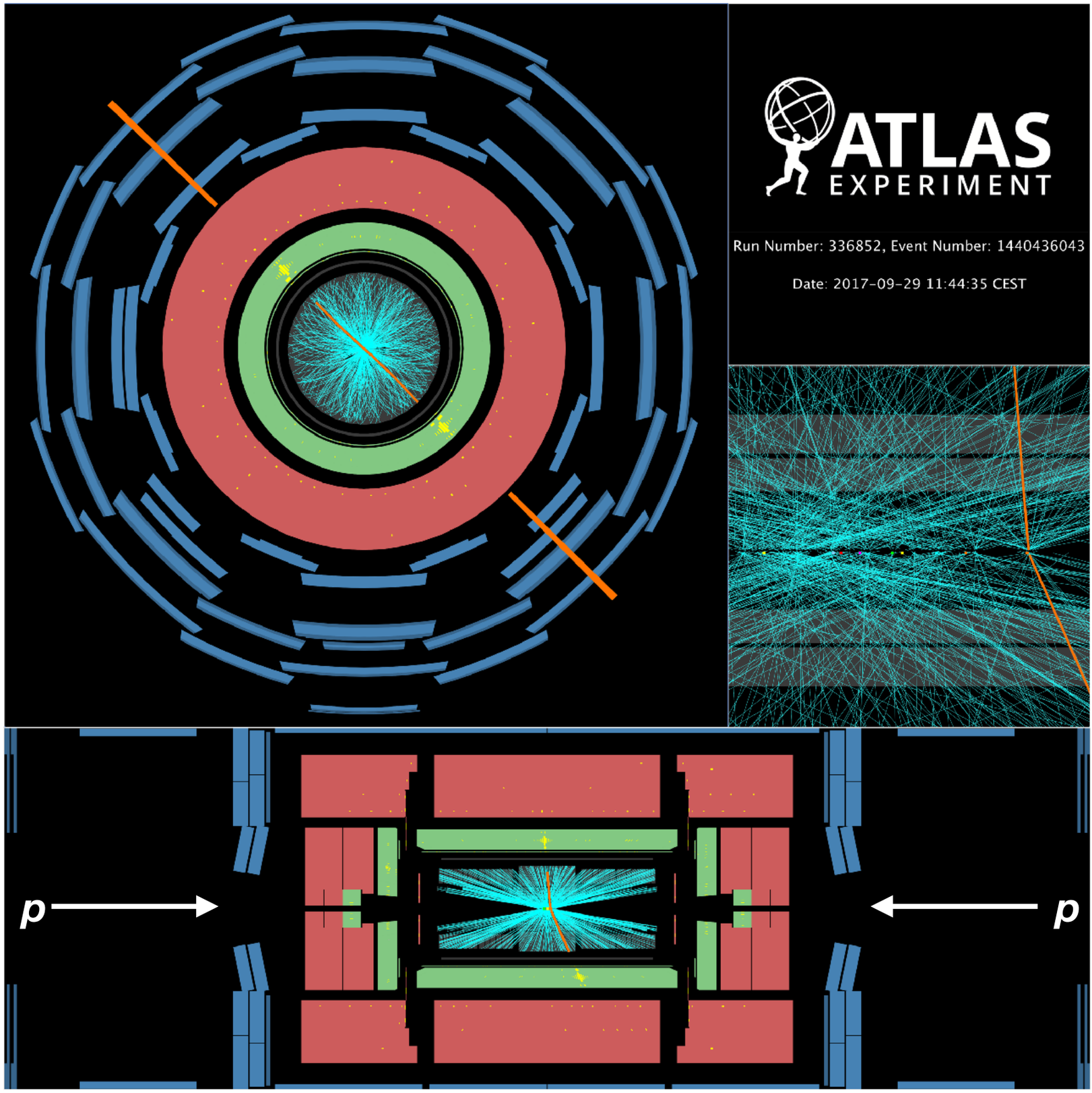


- Event displays are great ways for us to visualise what happened in a particle collision
- In this **ATLAS event display** (*right*) of a real proton collision, we are looking down the beam pipe, so the plane of the display is transverse to the proton beam direction
- ***Question**: Can you quantify the momentum in this plane **before** the proton collision*
  - *What does that tell you about the distribution of momentum **after** the collision?*
  - *Can you say which fundamental particle(s) is (are) observed in the event?*

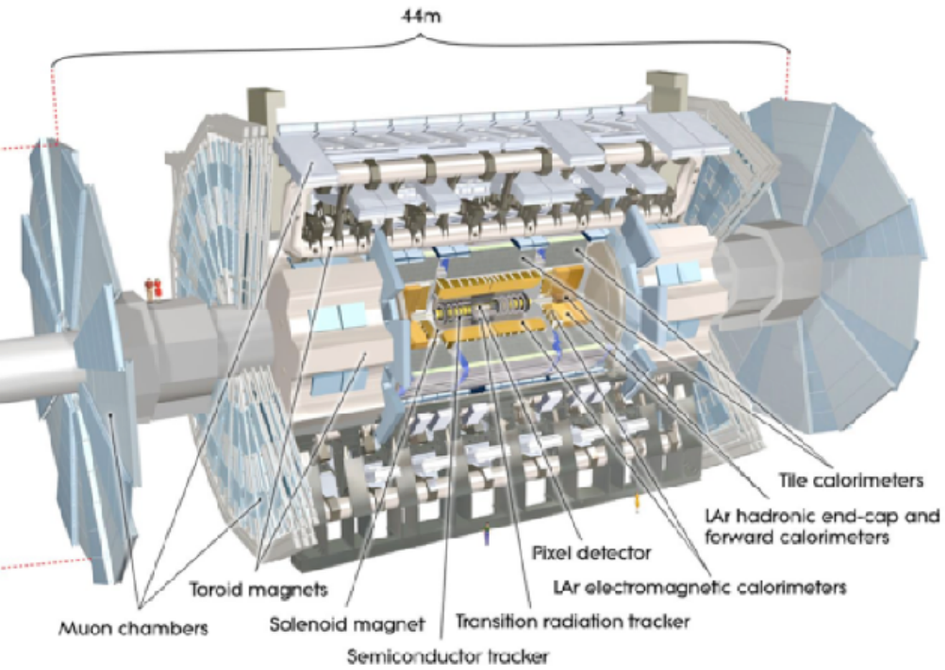
Event displays

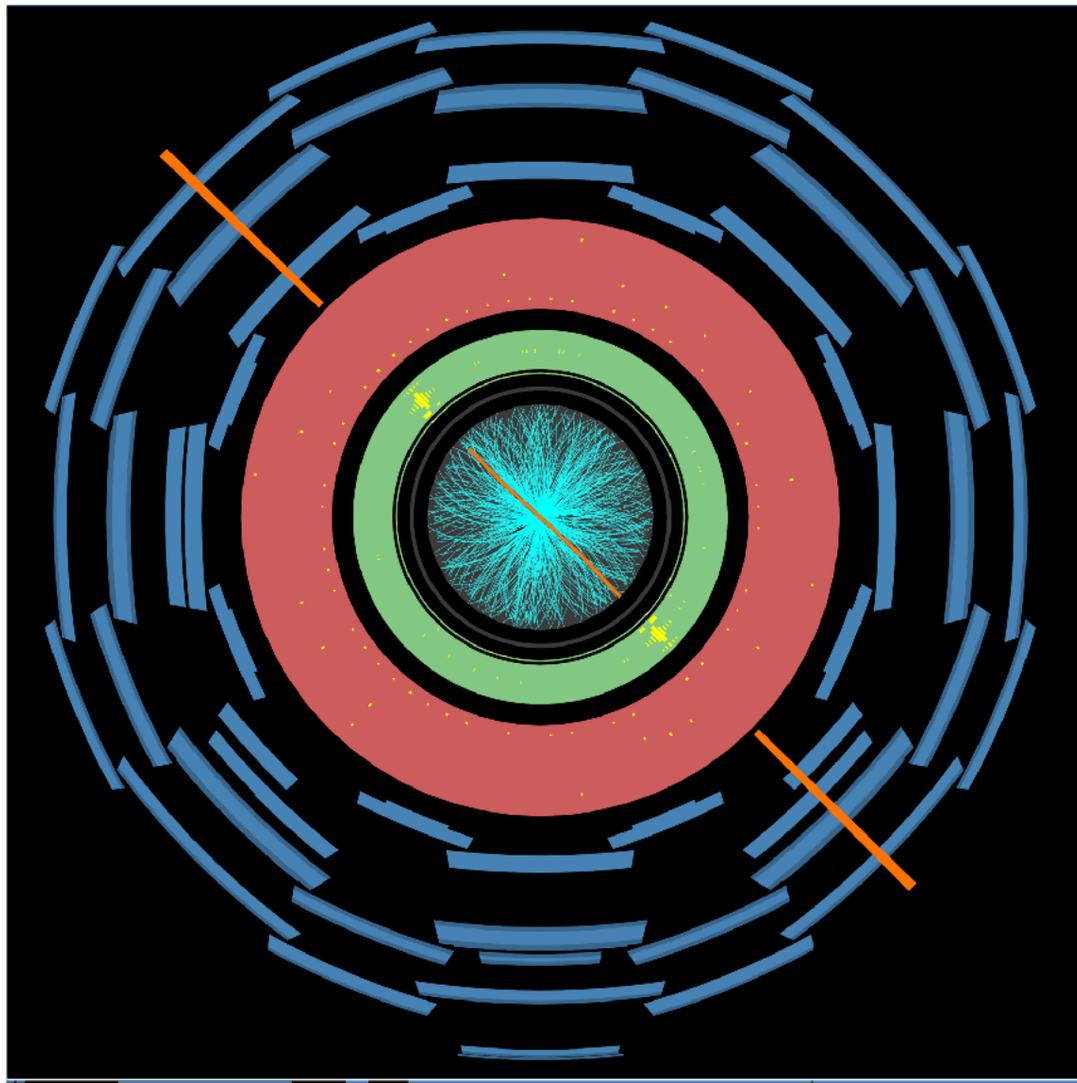


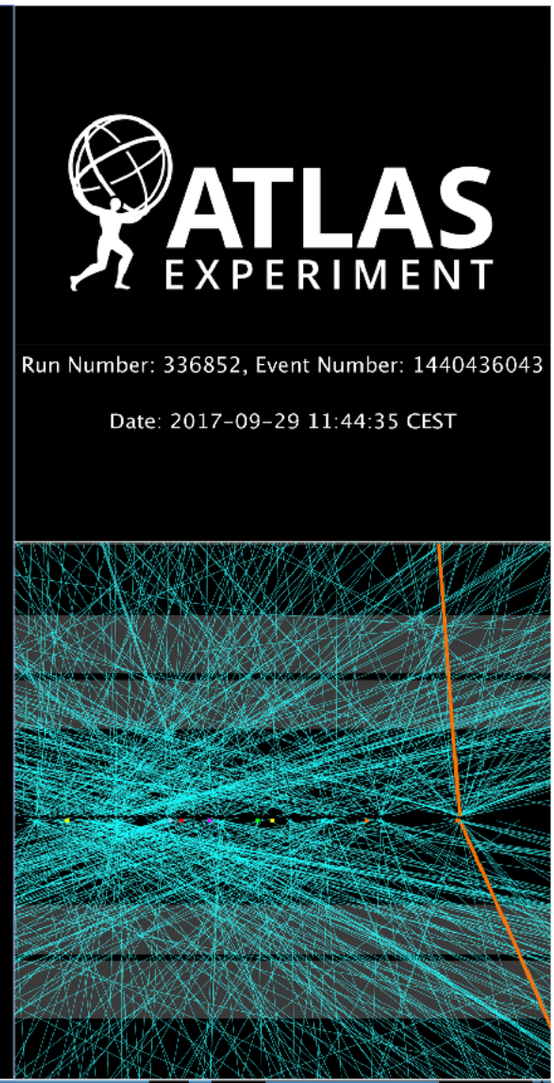
- This view shows the plane in the proton beam direction
- Both **2D** views are often used to provide complementary information

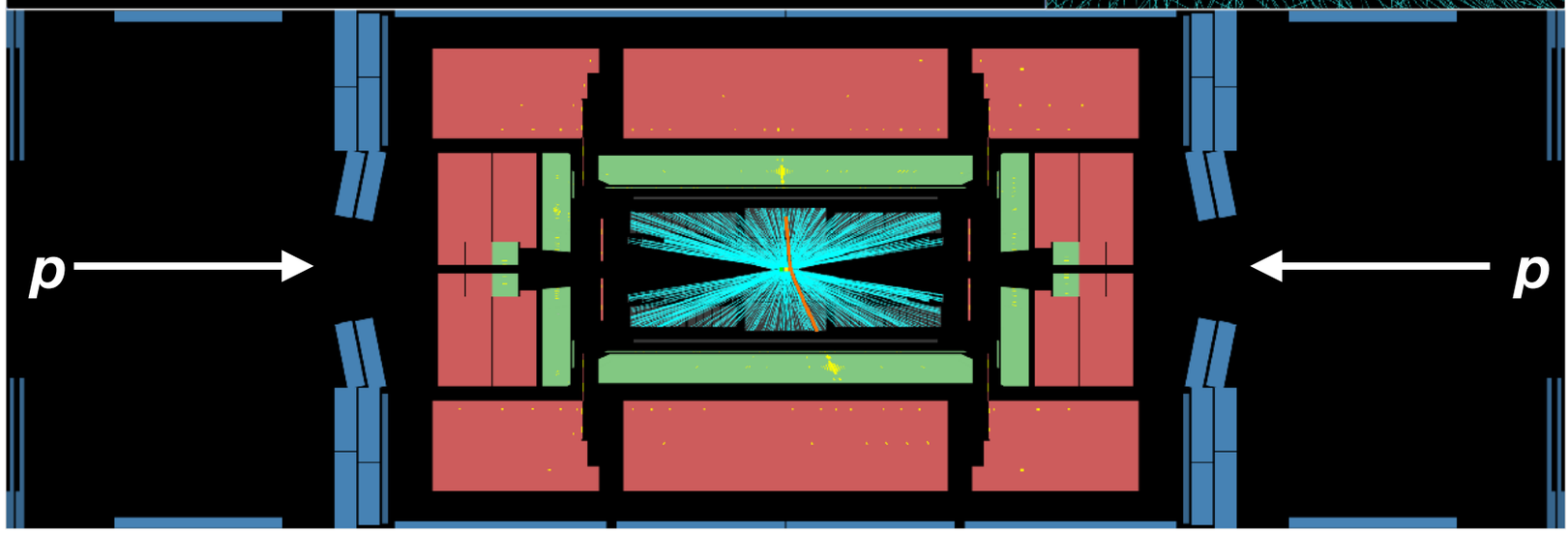


Event displays



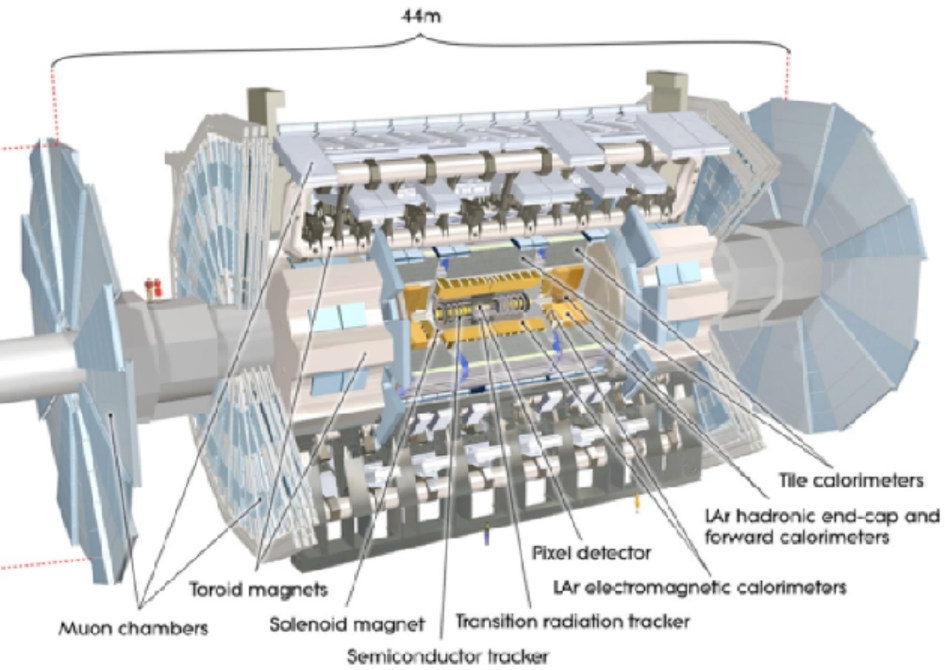




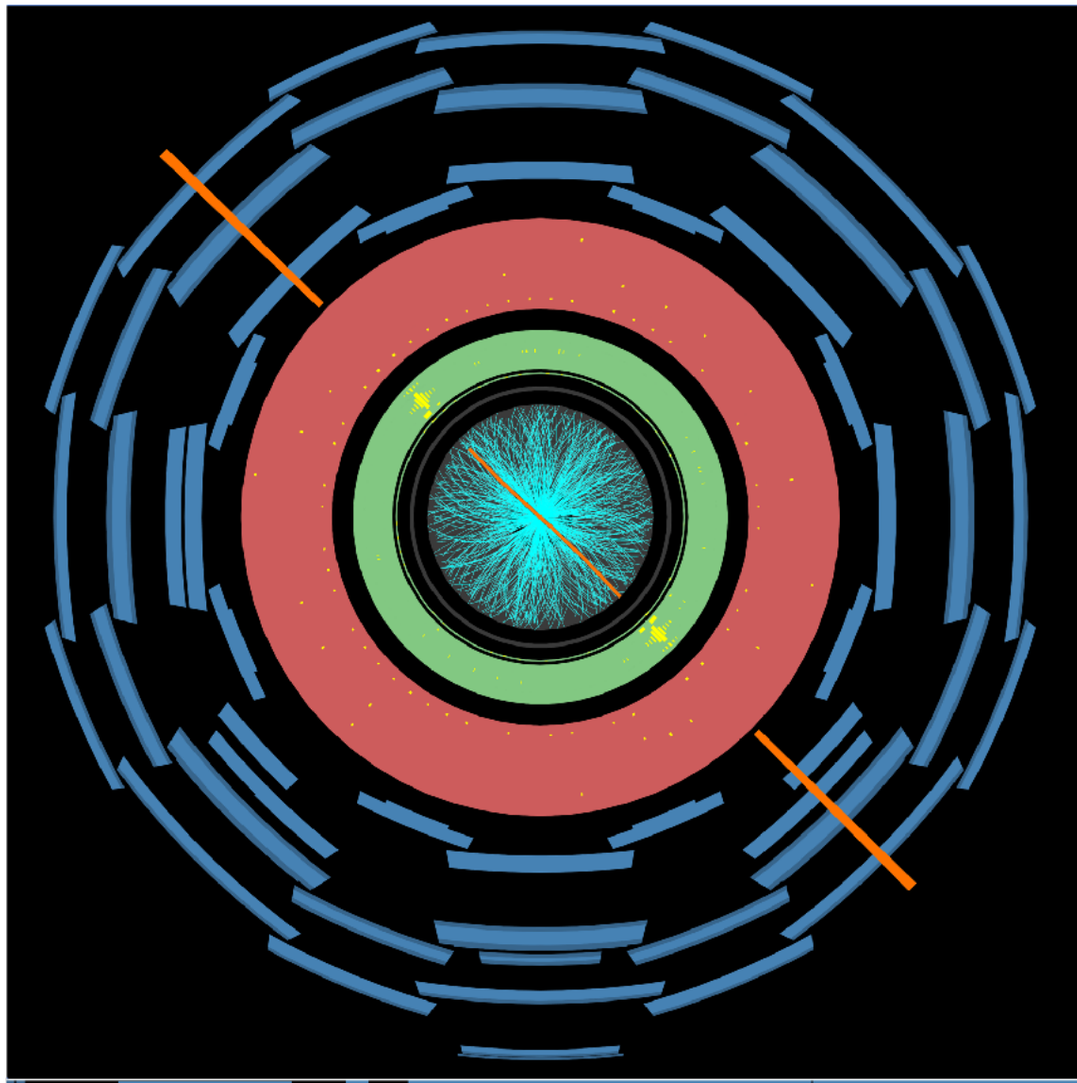


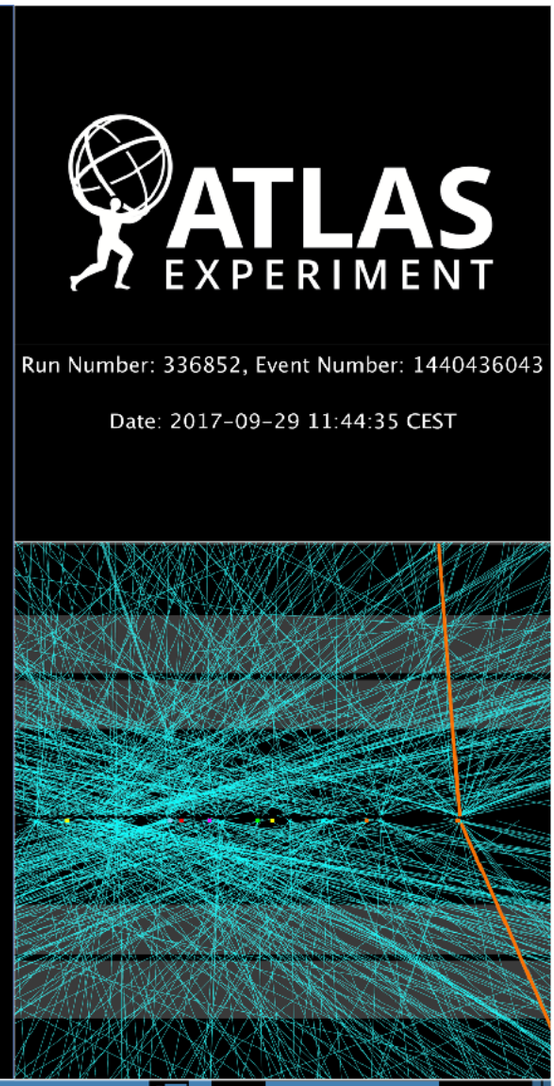
- This view shows the plane in the proton beam direction
- Both **2D** views are often used to provide complementary information
- **Q. See multiple track "vertices", points where tracks appear to originate, why?**

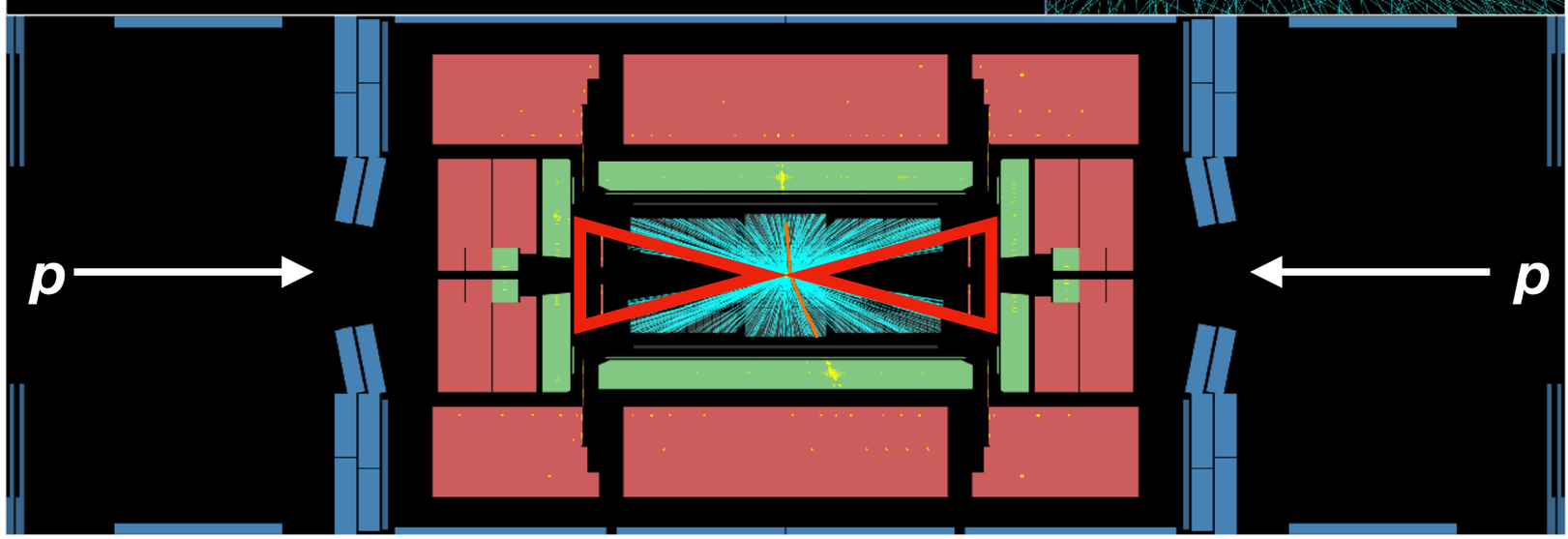
Event displays



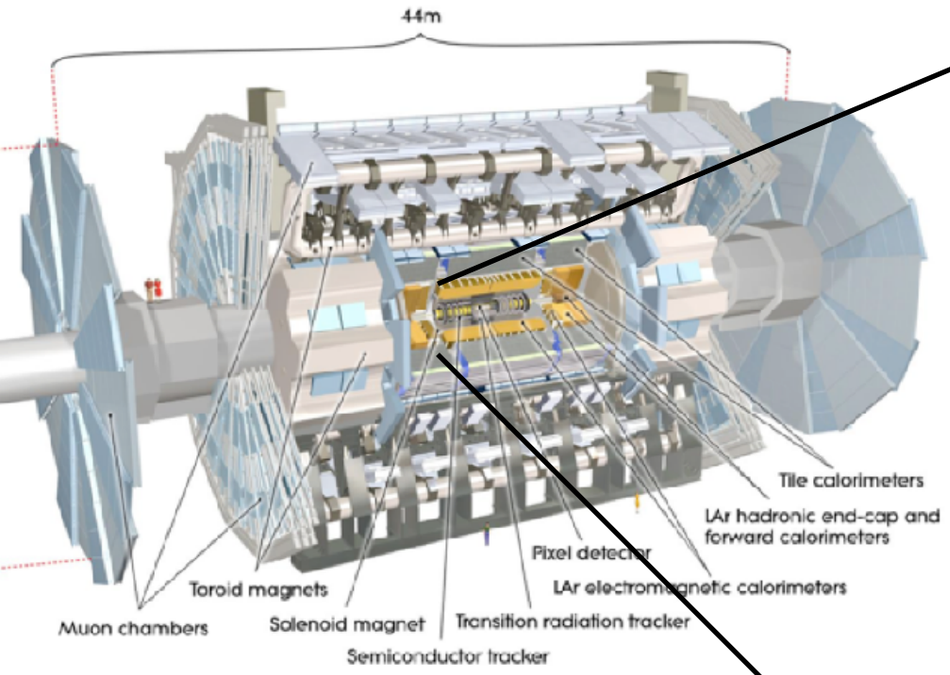
- Why are there gaps in the event display?

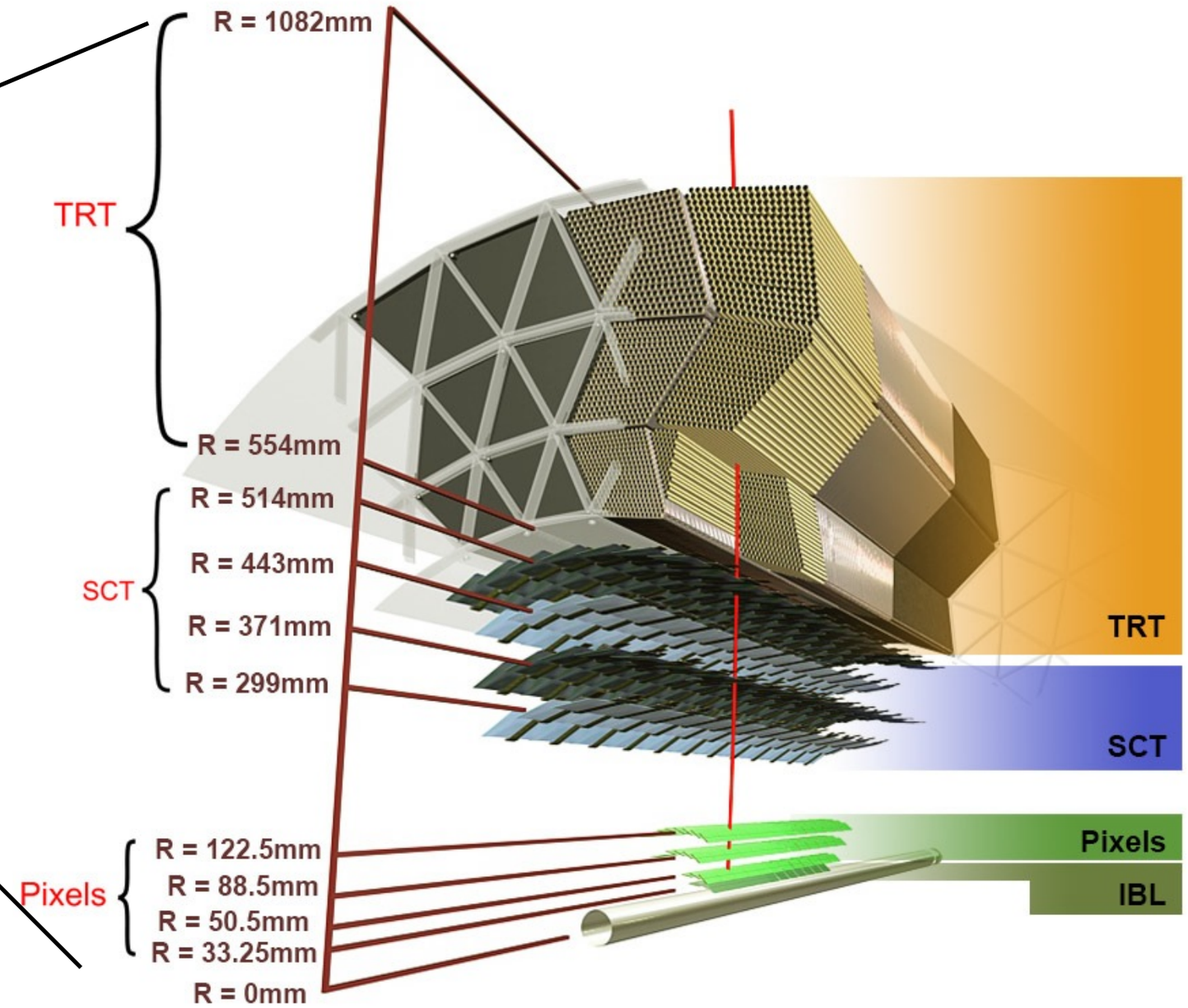






Detectors are real !

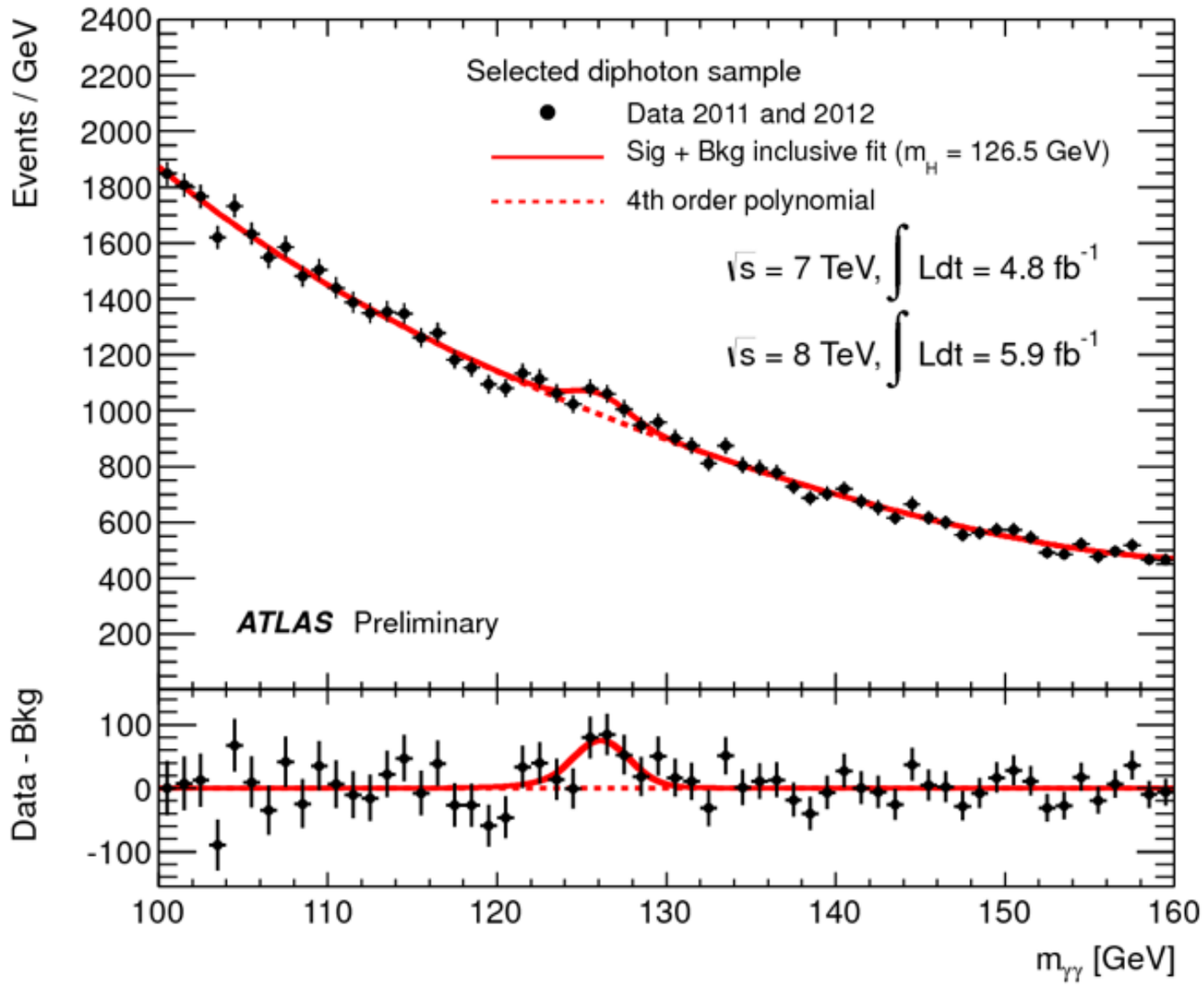




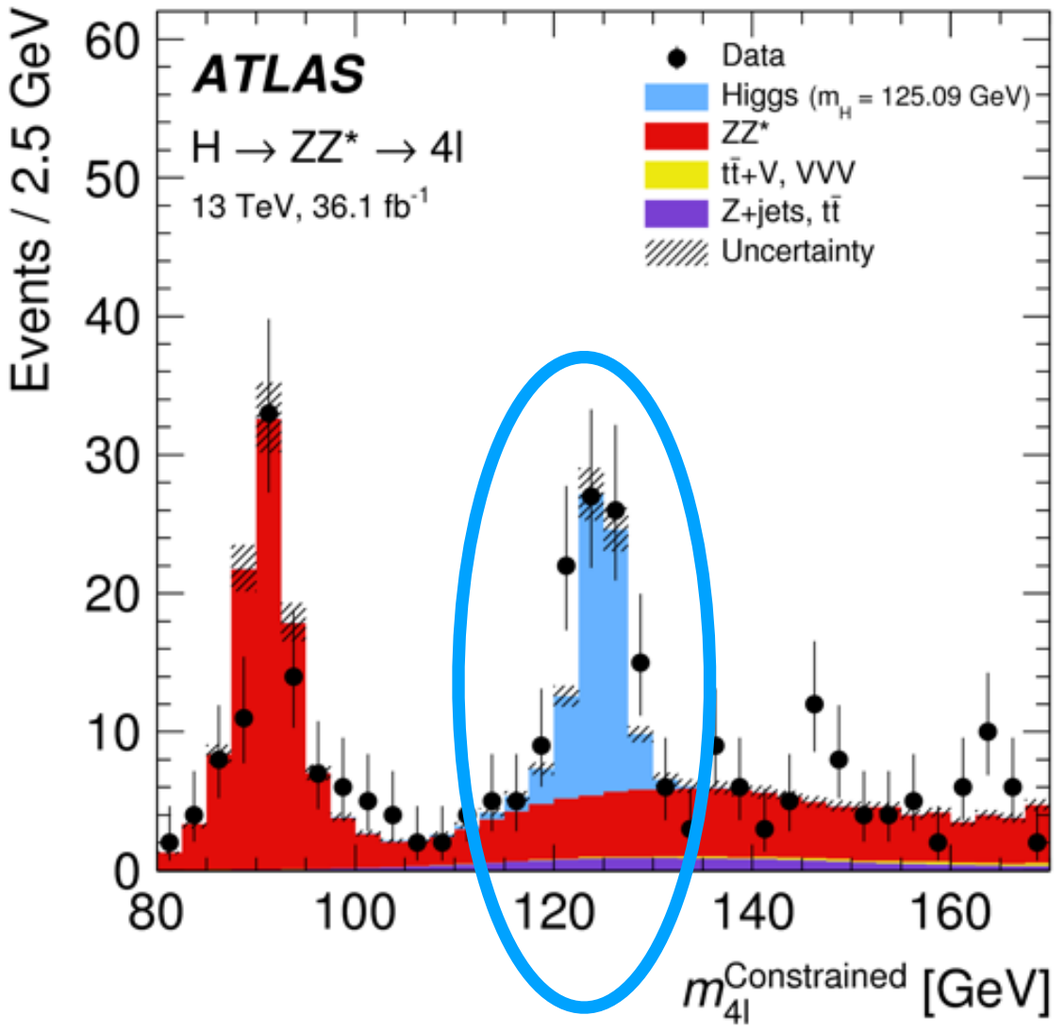
- There are gaps in the detector !

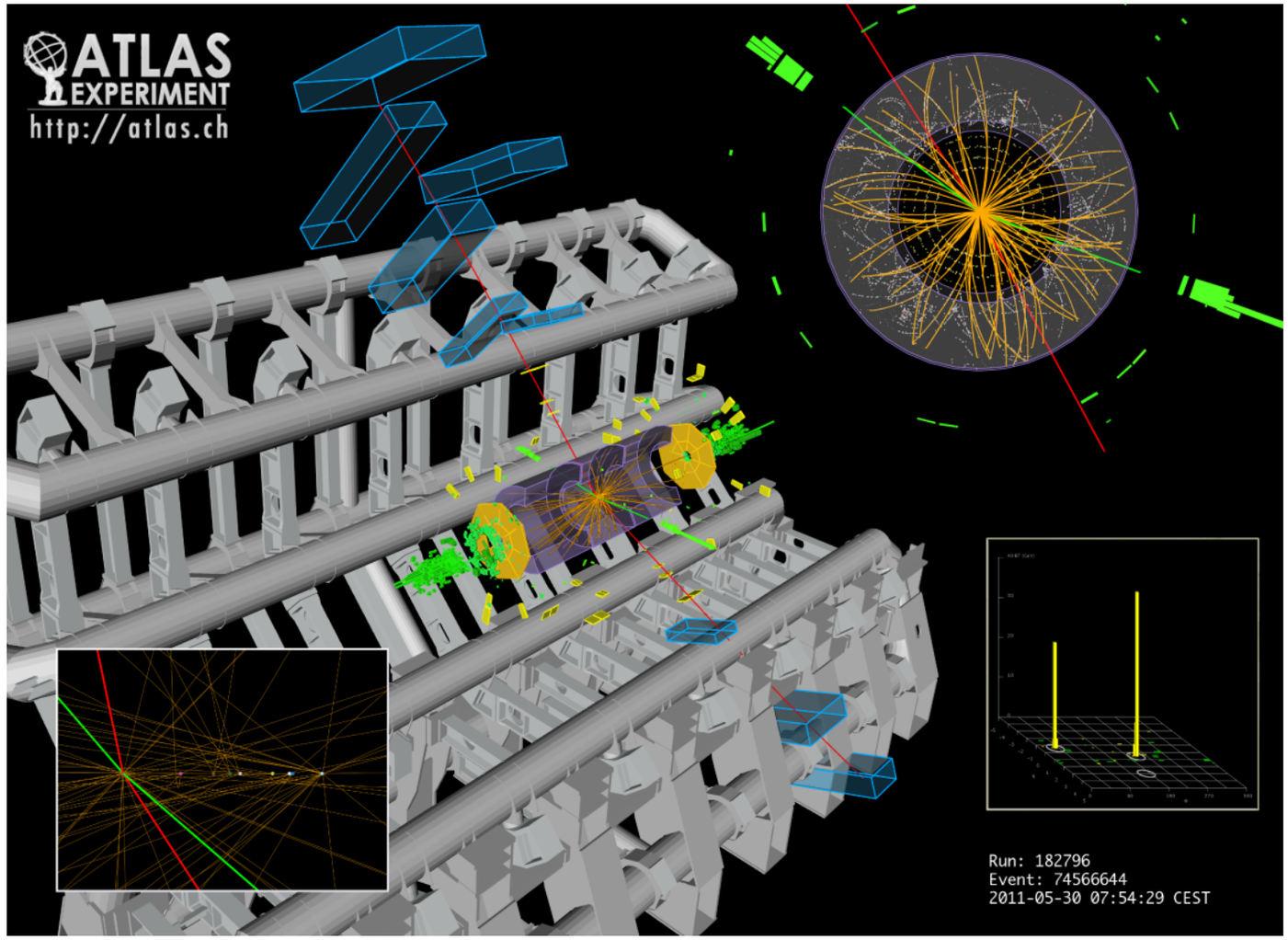
Discovering the Higgs boson: $H \rightarrow \gamma\gamma$

- There are billions of events and the ones we are really interested in are ***very rare***
- Often the interesting events are also ***very difficult to distinguish*** from background
  - Requires ***high precision detectors***, which means ***lots of data*** for each event
- The data are structured but each event is different - ***unique data science challenge***



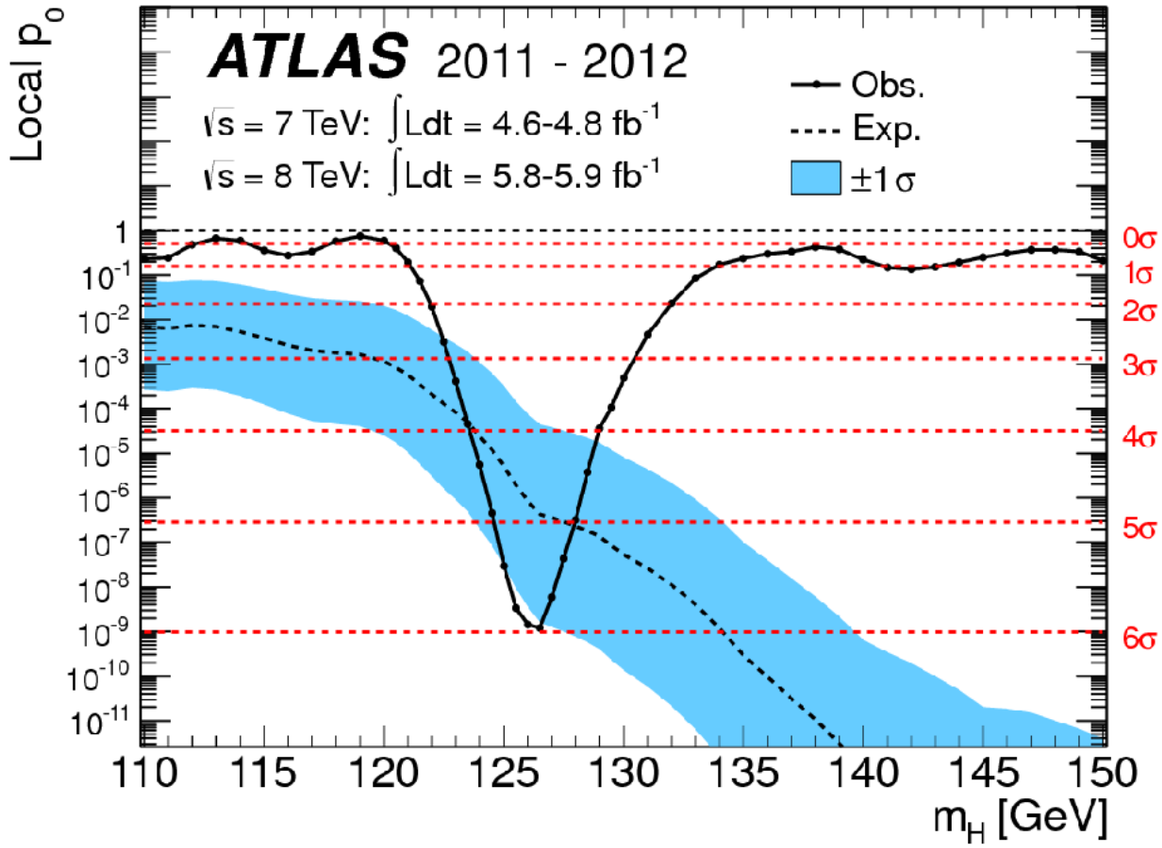
Discovering the Higgs Boson: $H \rightarrow ZZ \rightarrow 4l$





- Here we look for events with **two Z bosons** that have decayed to **four leptons**, and compare to ***simulations of different physics processes***
- If the **two Z bosons** were produced by the **decay of a Higgs boson**, when we reconstruct the invariant mass of the system we should see a **peak** at the **Higgs boson mass**

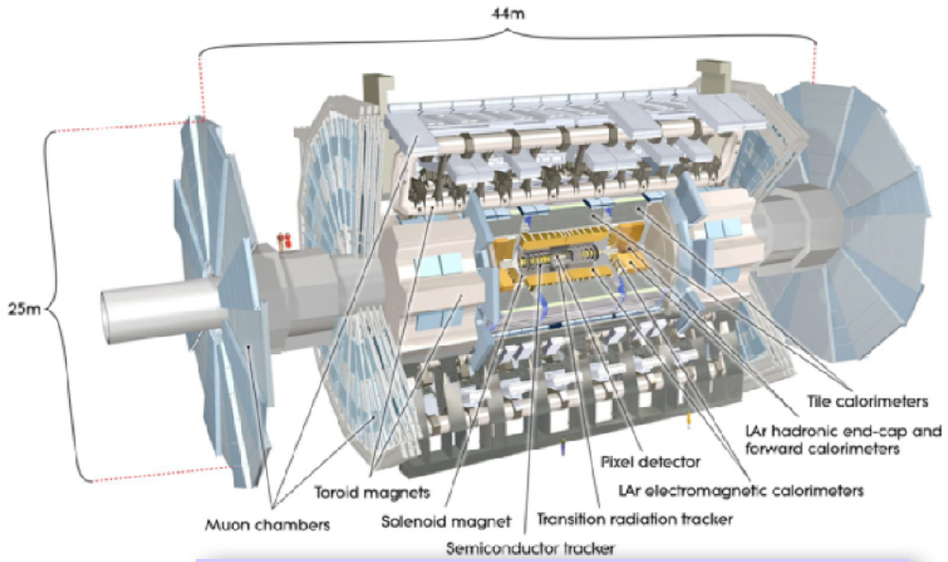
Higgs discovery on July 4th 2012



- In 2012 the number of observed events (**6σ**) was consistent with, and in excess of the number of events expected for a standard model Higgs (**5σ**)

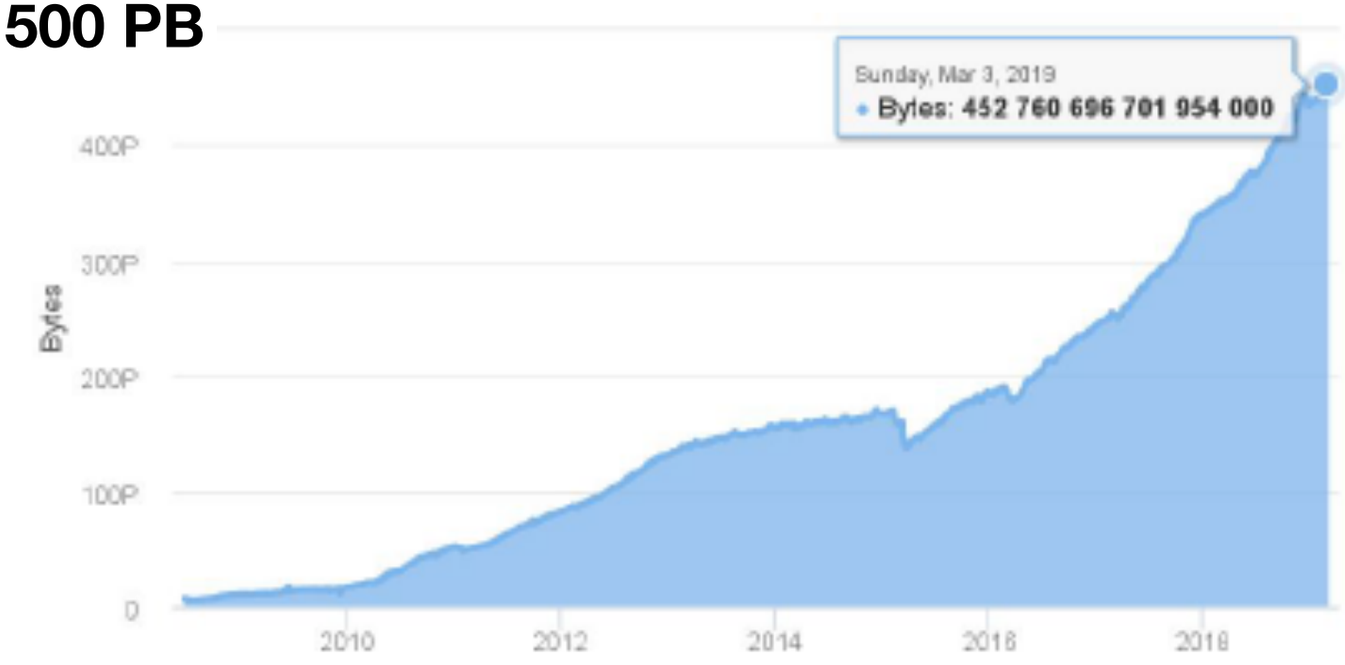
- ***Question*** *- Imagine we had several more Large Hadron Colliders, with a total of 9 independent measurements possible. Roughly how many measurements would you expect to lie* ***outside*** *the ±1σ blue band?*

Exabyte-scale physics analysis



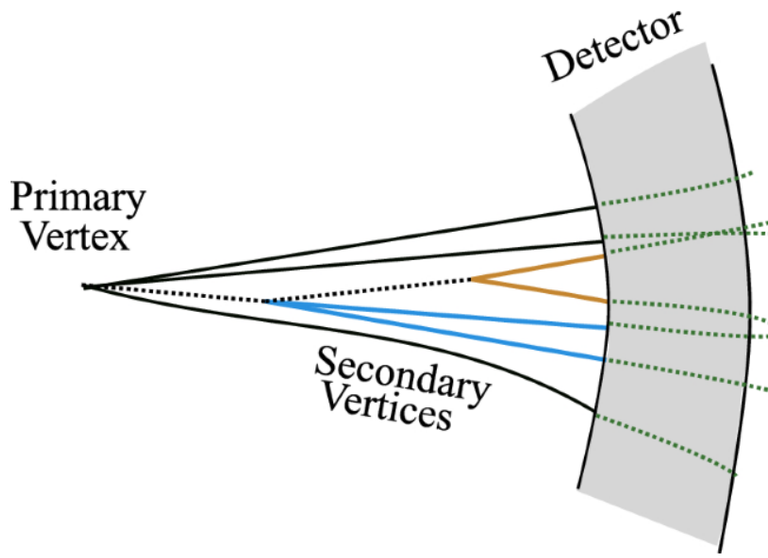
Exabytes of Data

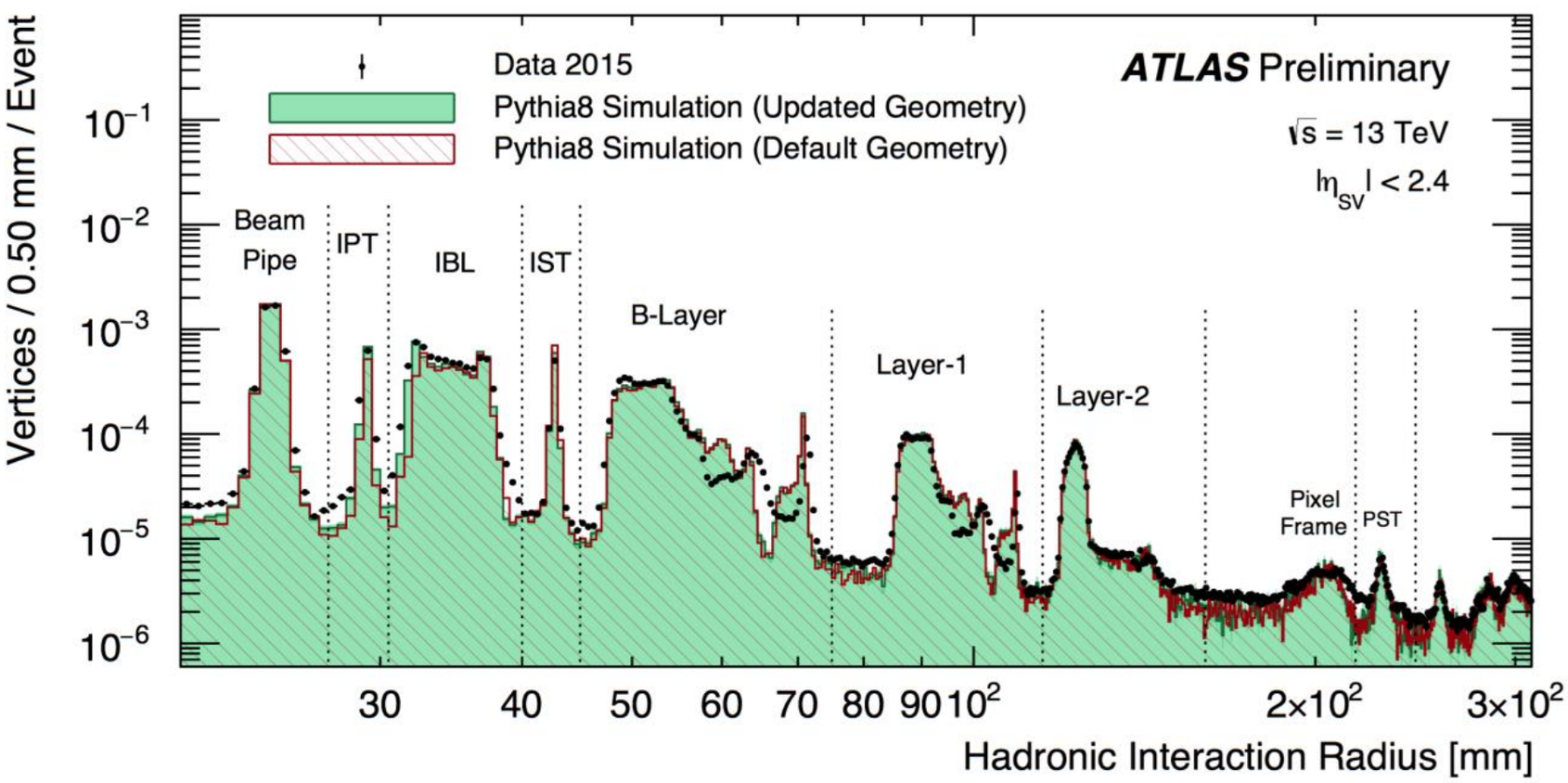
500 PB

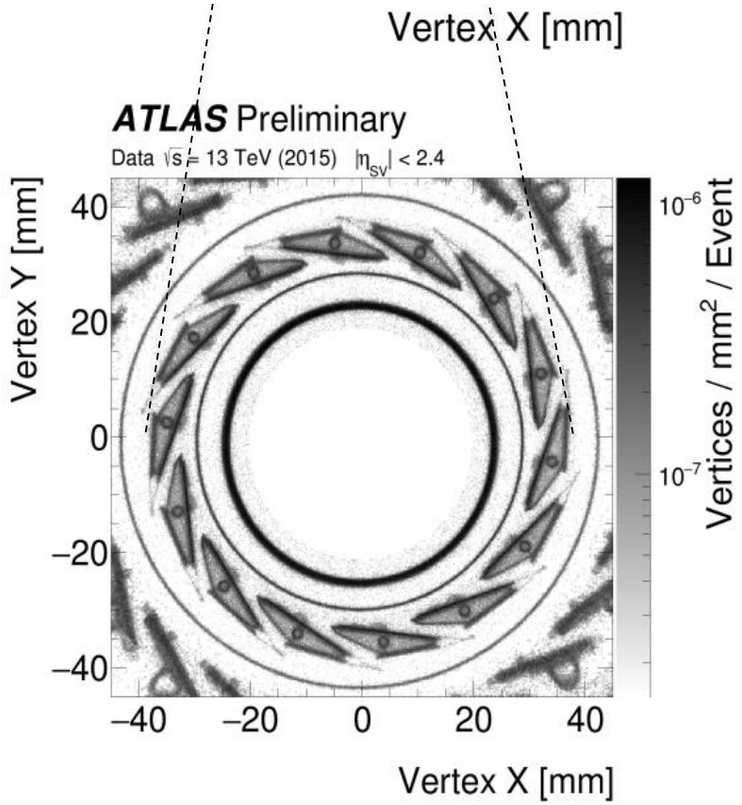


Simulation and understanding detectors

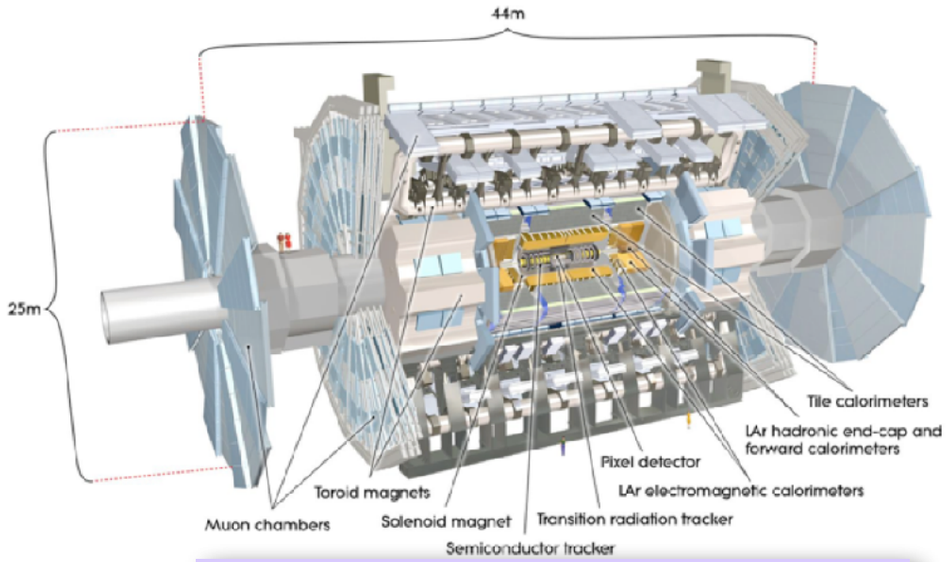
- We use **simulations** to model the detector as **accurately** and **precisely** as possible
- We ***test*** that our simulations are accurate ***using real data***
- We correct our simulations if necessary
- Once our simulation is an ***accurate model*** of our detector, we can use it to ***correct the data for detector response***





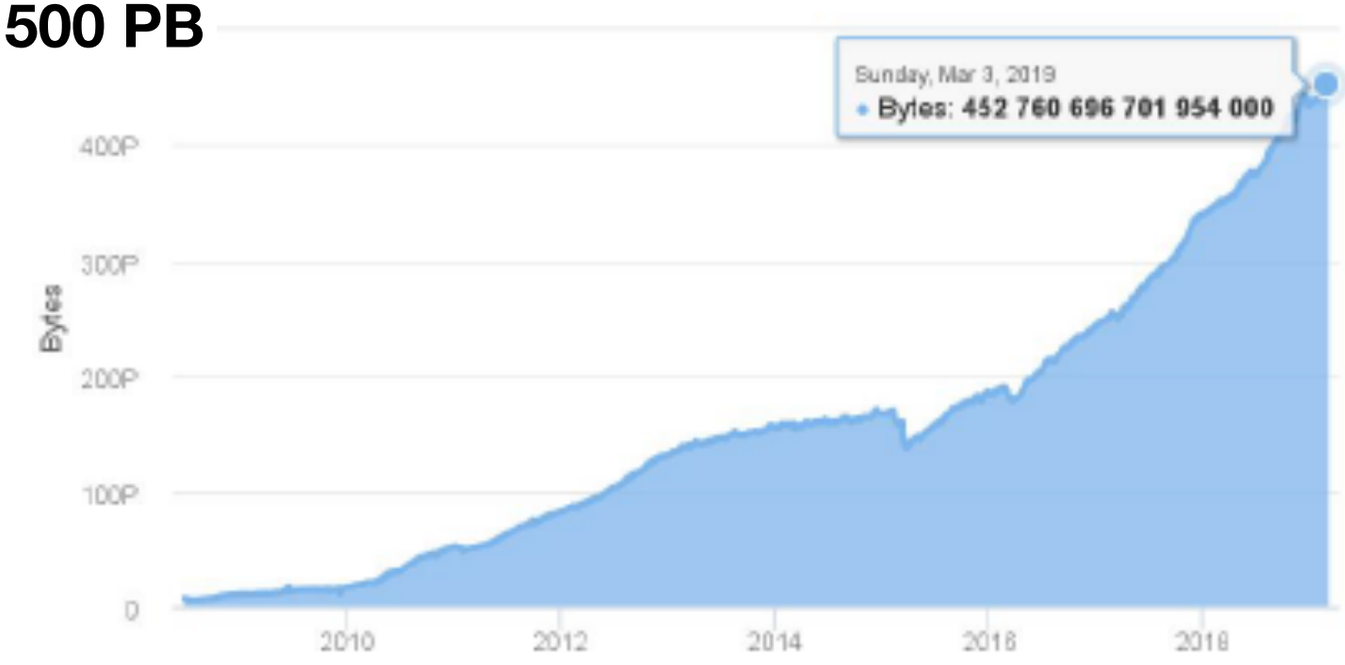


Exabyte-scale physics analysis

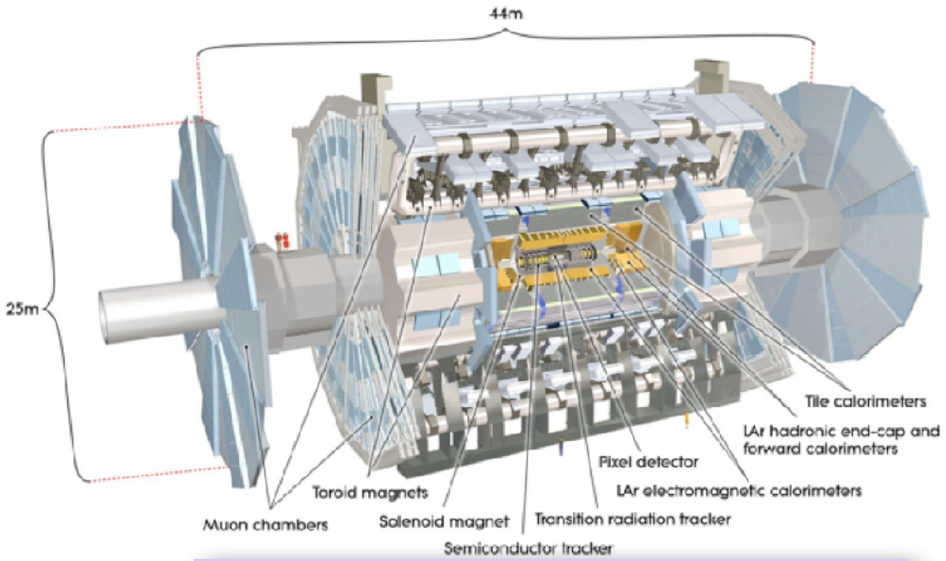


Exabytes of Data

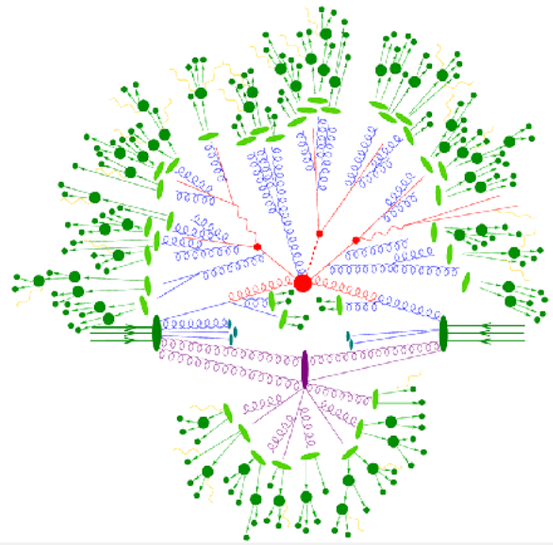
500 PB



Exabyte-scale physics analysis

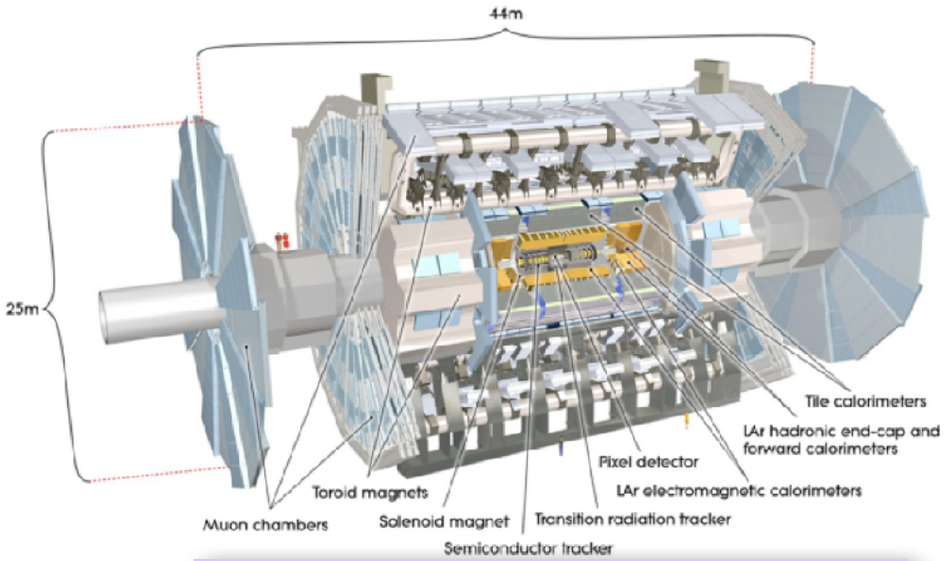


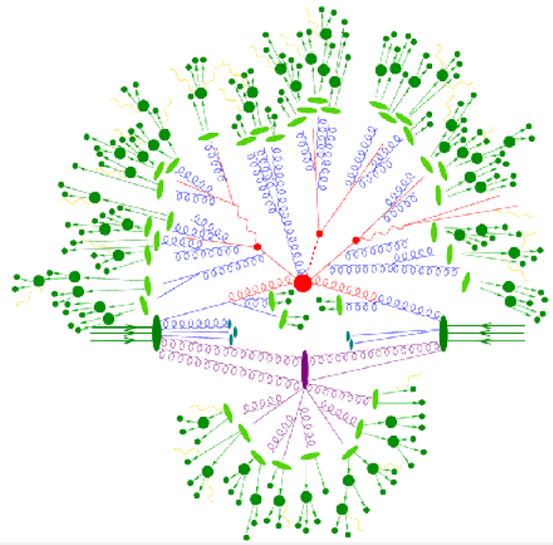
Exabytes of Data



Exabytes of Simulation

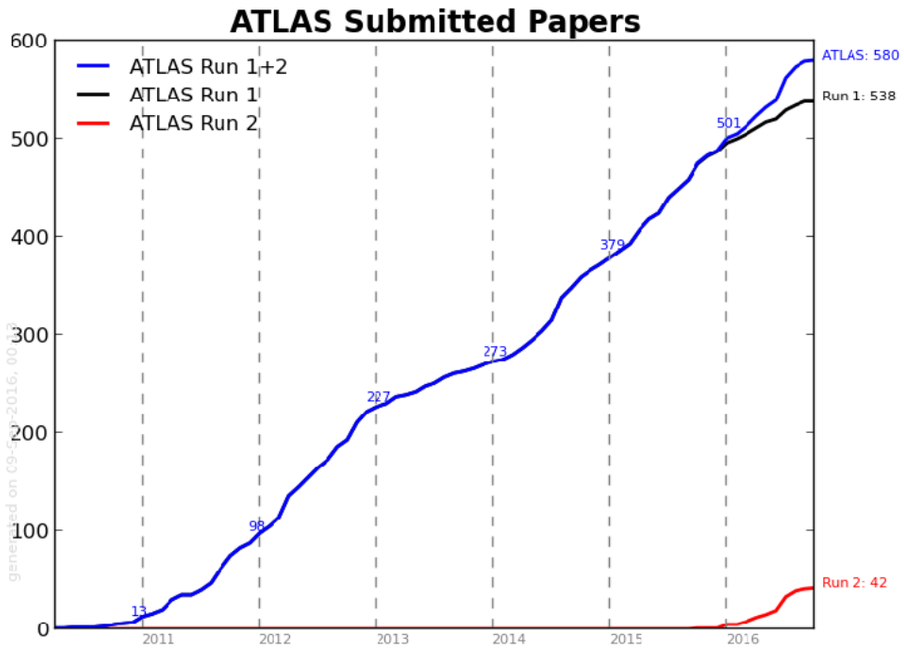
Exabyte-scale physics analysis





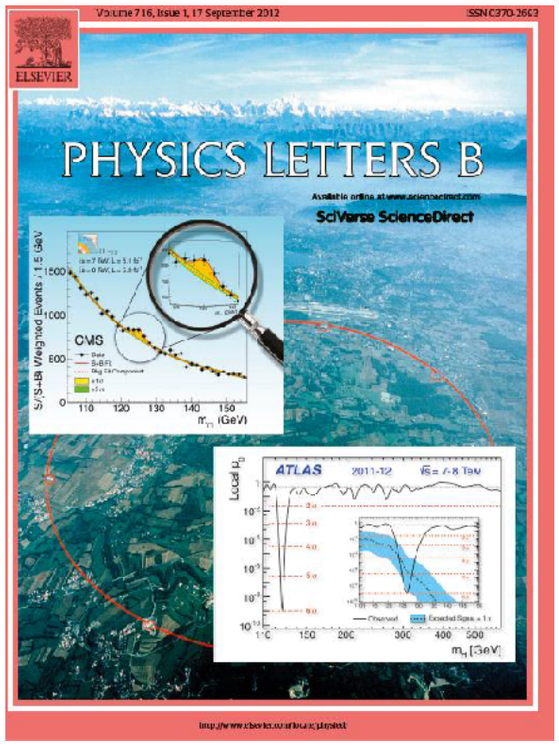
Exabytes of Data

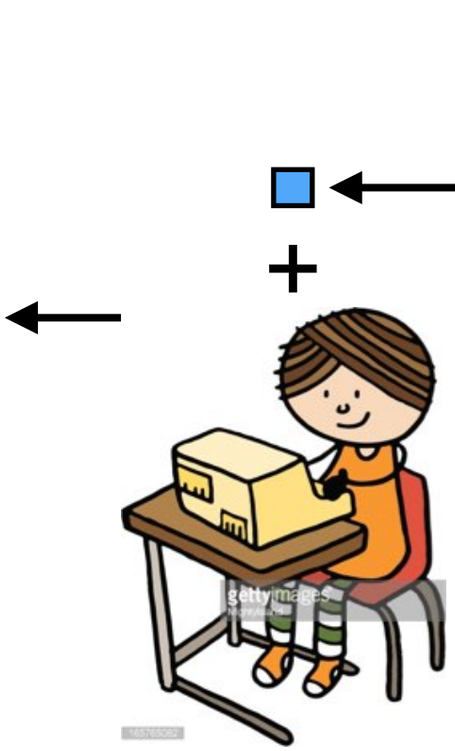
Exabytes of Simulation

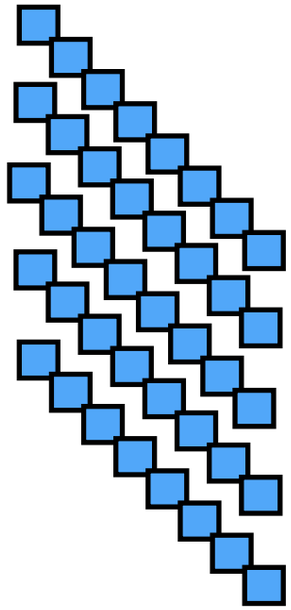


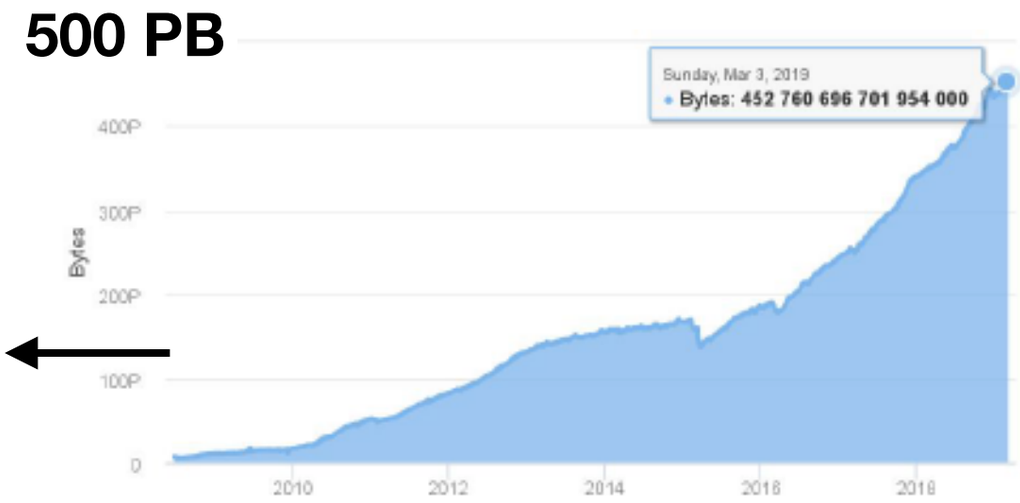
Publish!

Data analysis



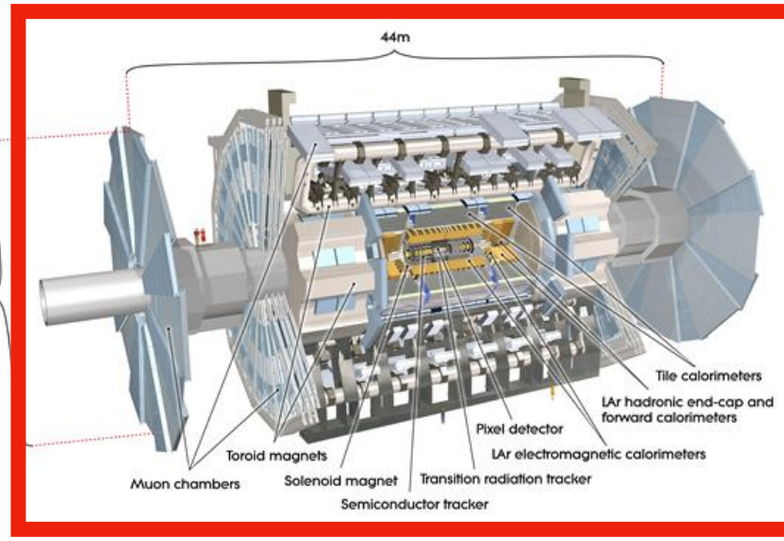






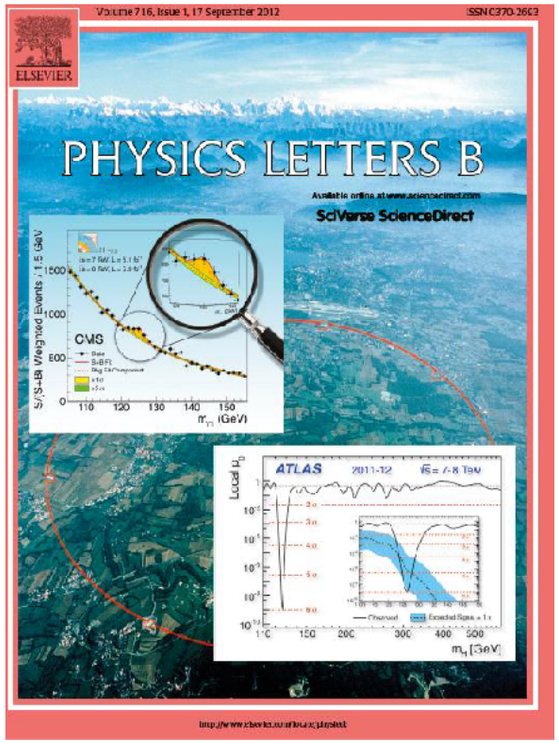
- ***Analysis is performed on only a fraction of the data, for example only events with two photons***
- ***How?***

Data's journey



Trigger/DAQ

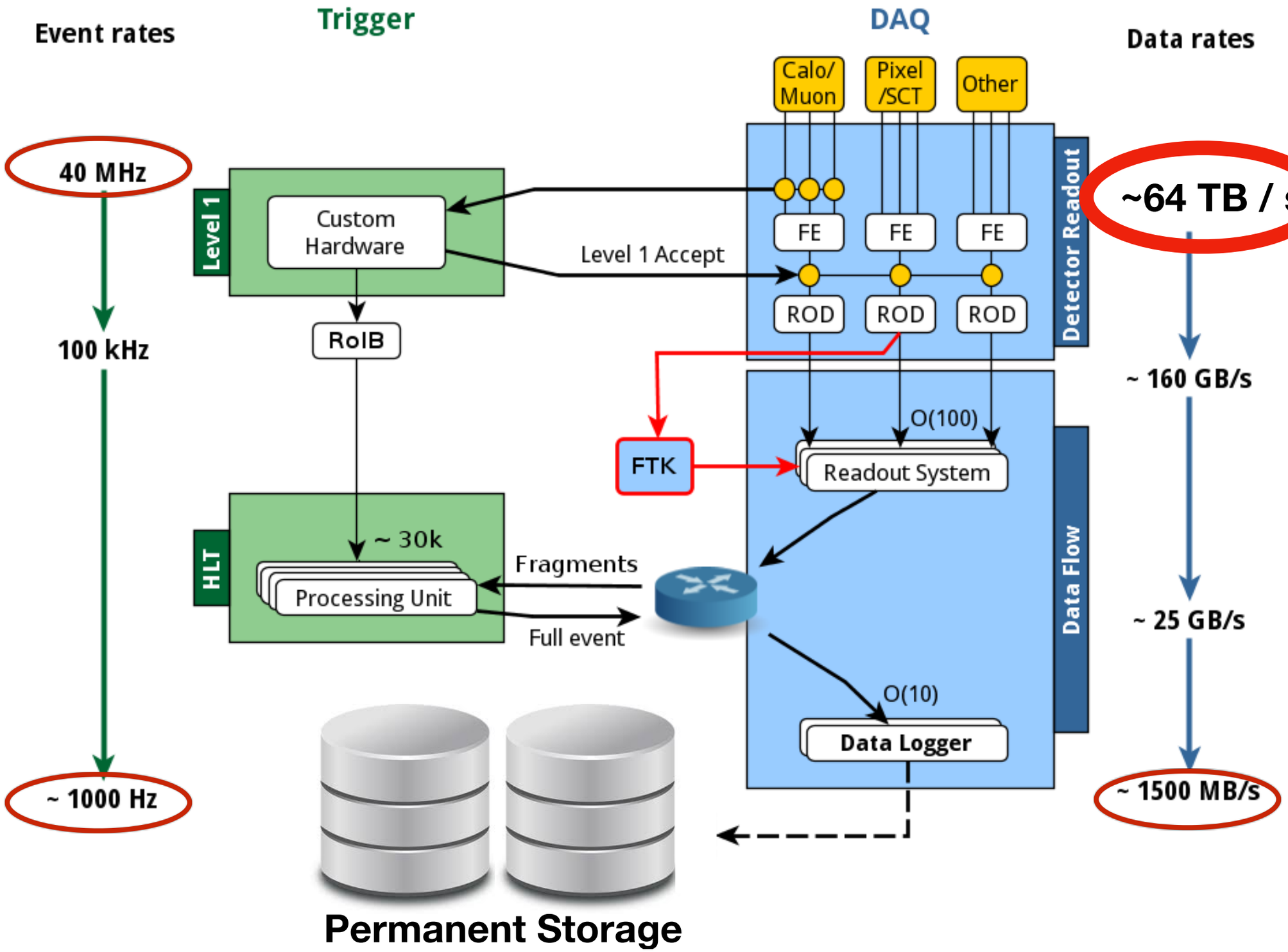
Data Preparation



Distributed computing

The Atlas Trigger and DAQ

Rate of all proton-proton collisions produced by the LHC

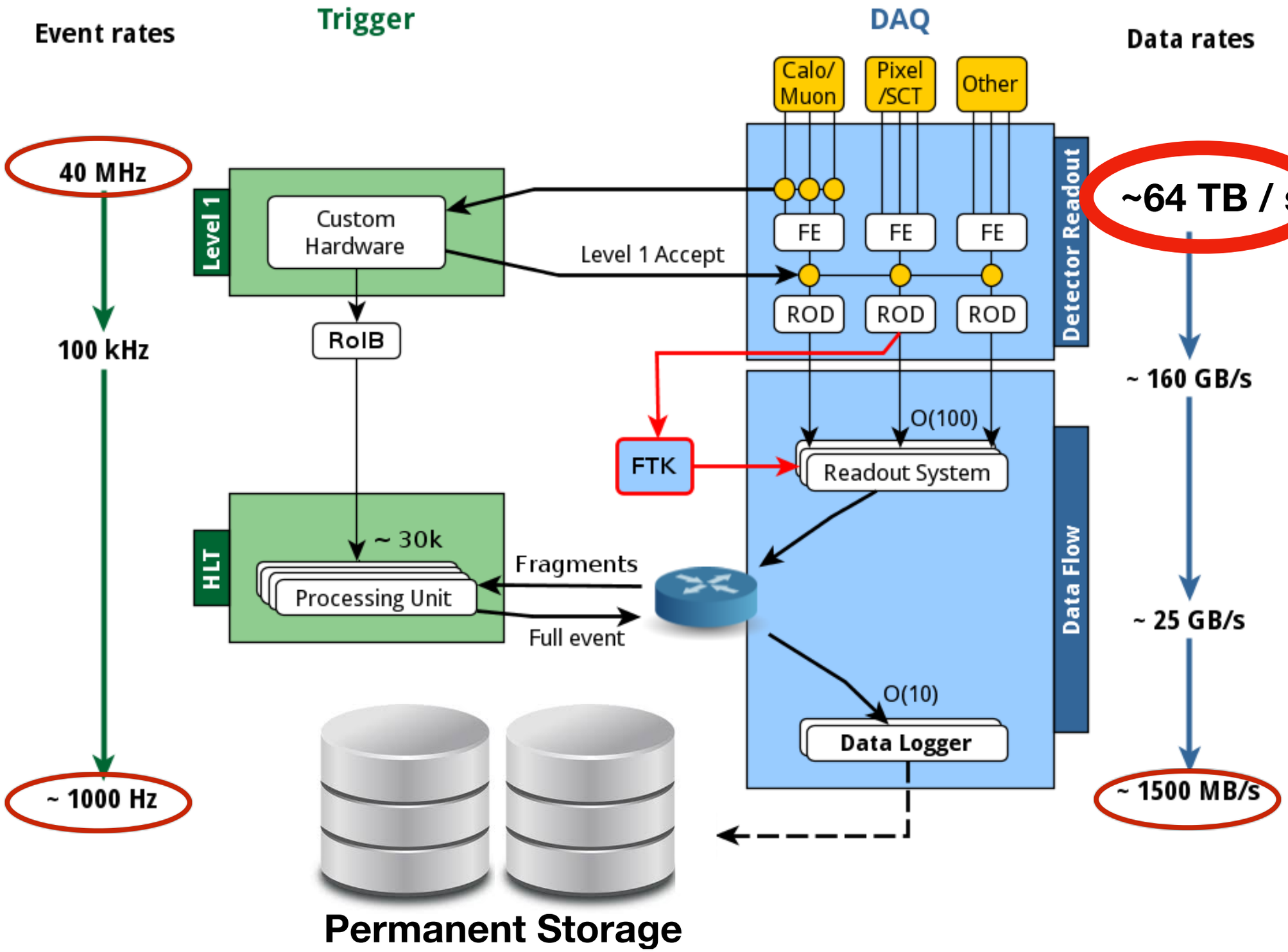


Rate of all *interesting* proton-proton collisions produced by the LHC

The Atlas Trigger and DAQ

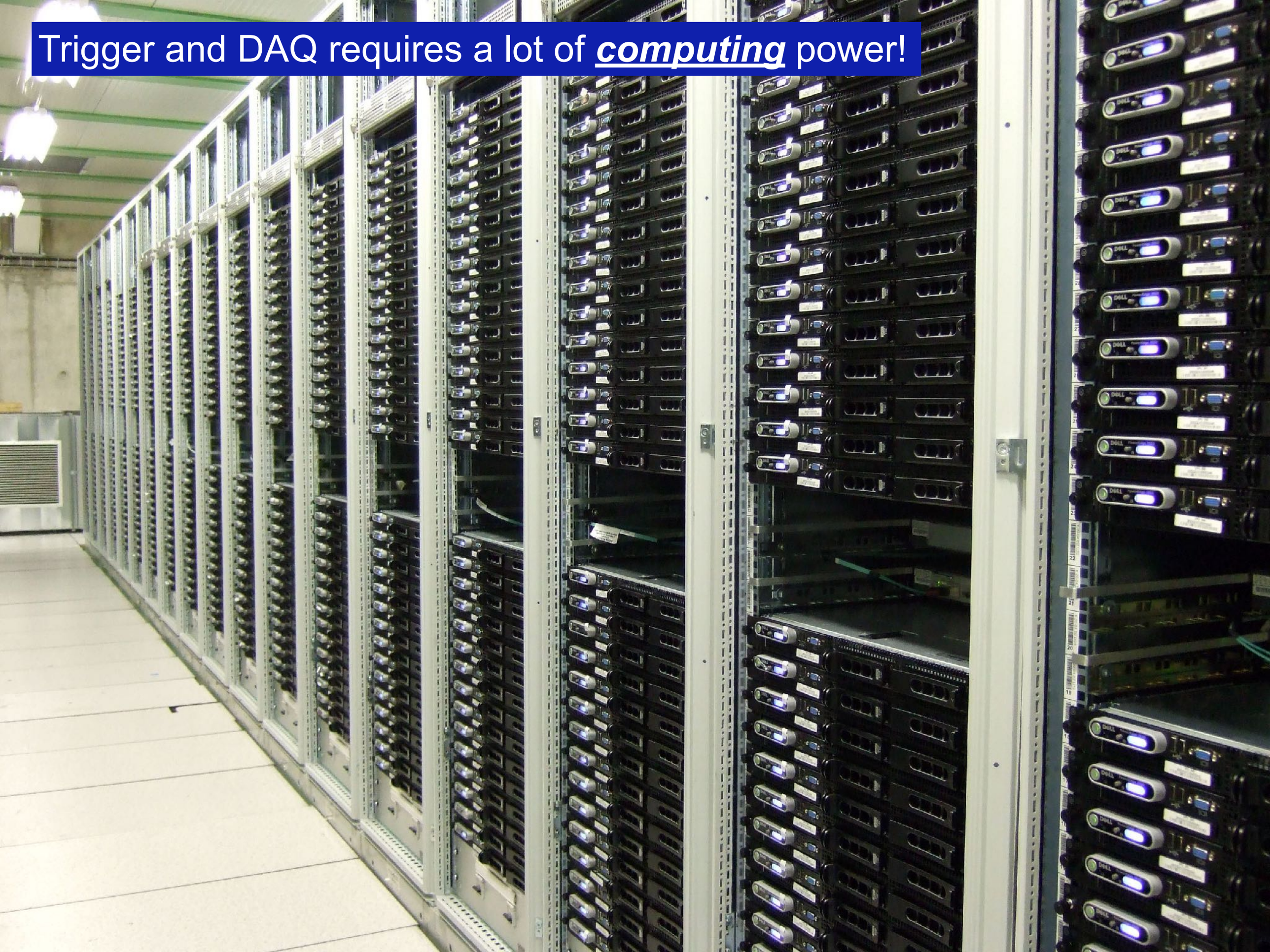
Q. How long would it take to generate 500PB of data if there were no Trigger?

Rate of all proton-proton collisions produced by the LHC

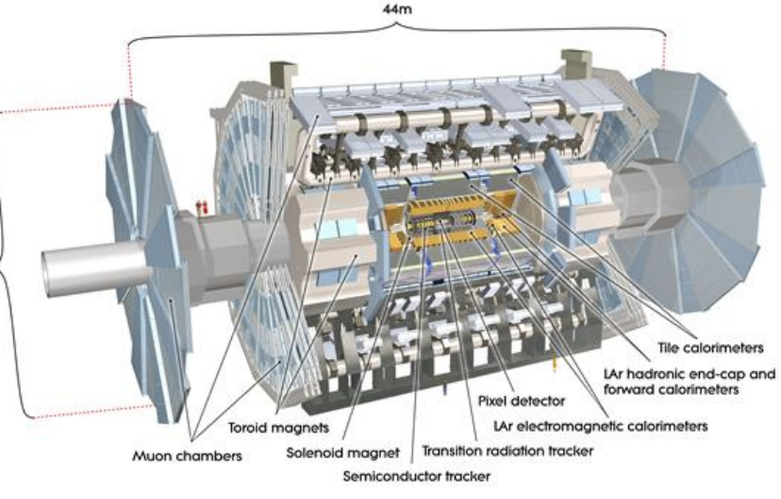


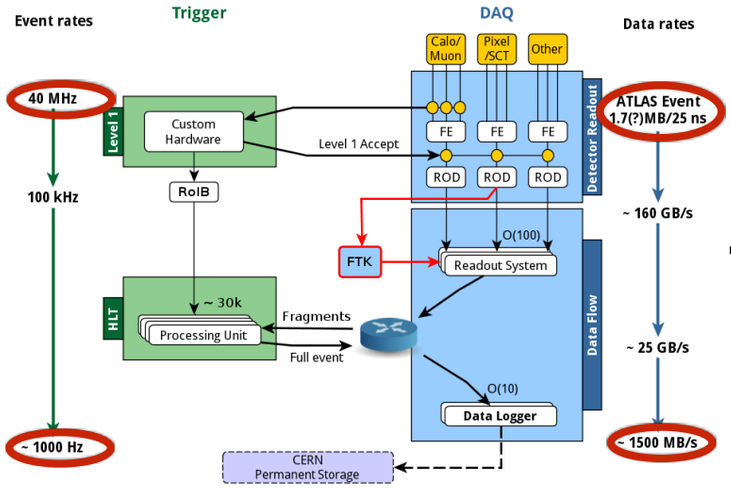
Rate of all *interesting* proton-proton collisions produced by the LHC

Trigger and DAQ requires a lot of ***computing*** power!

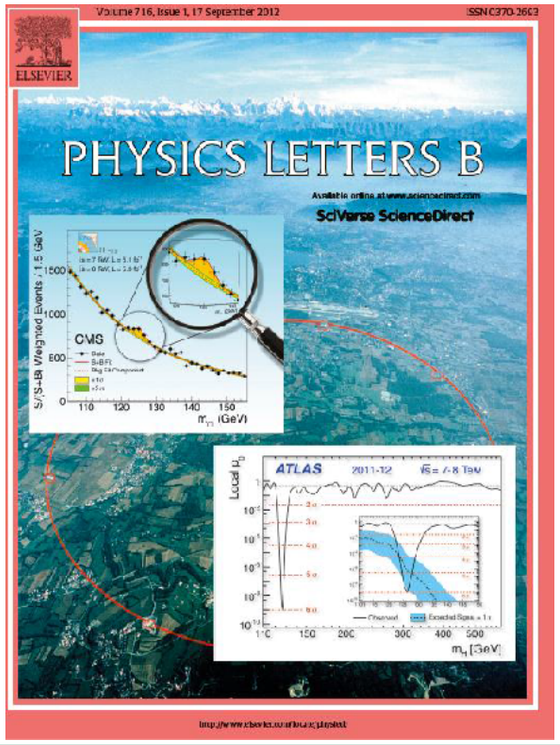


Data's journey

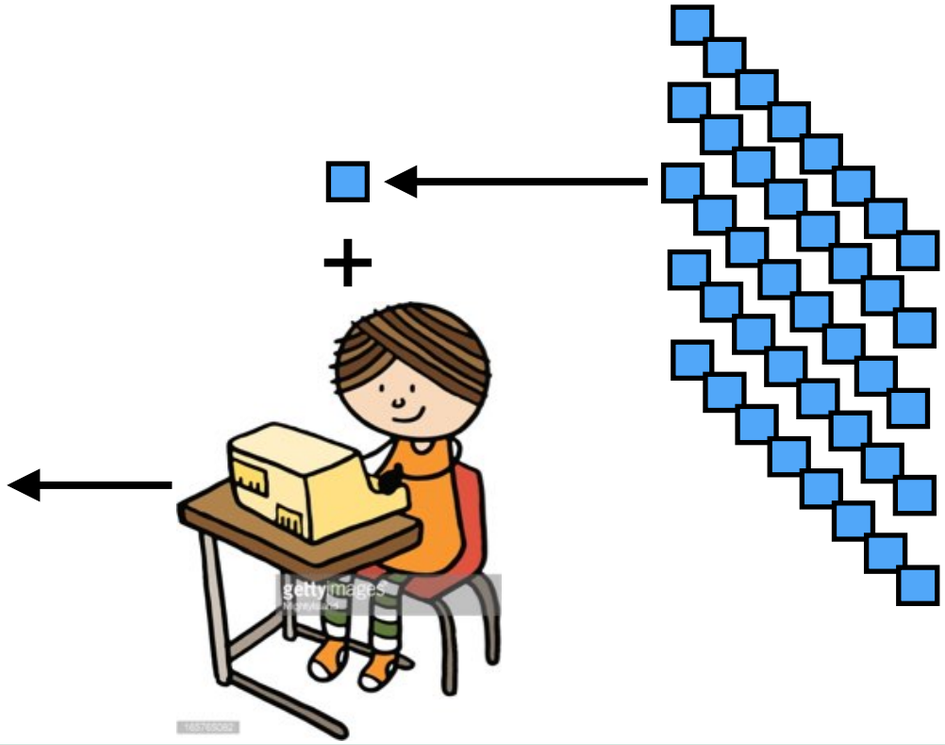




Data Preparation



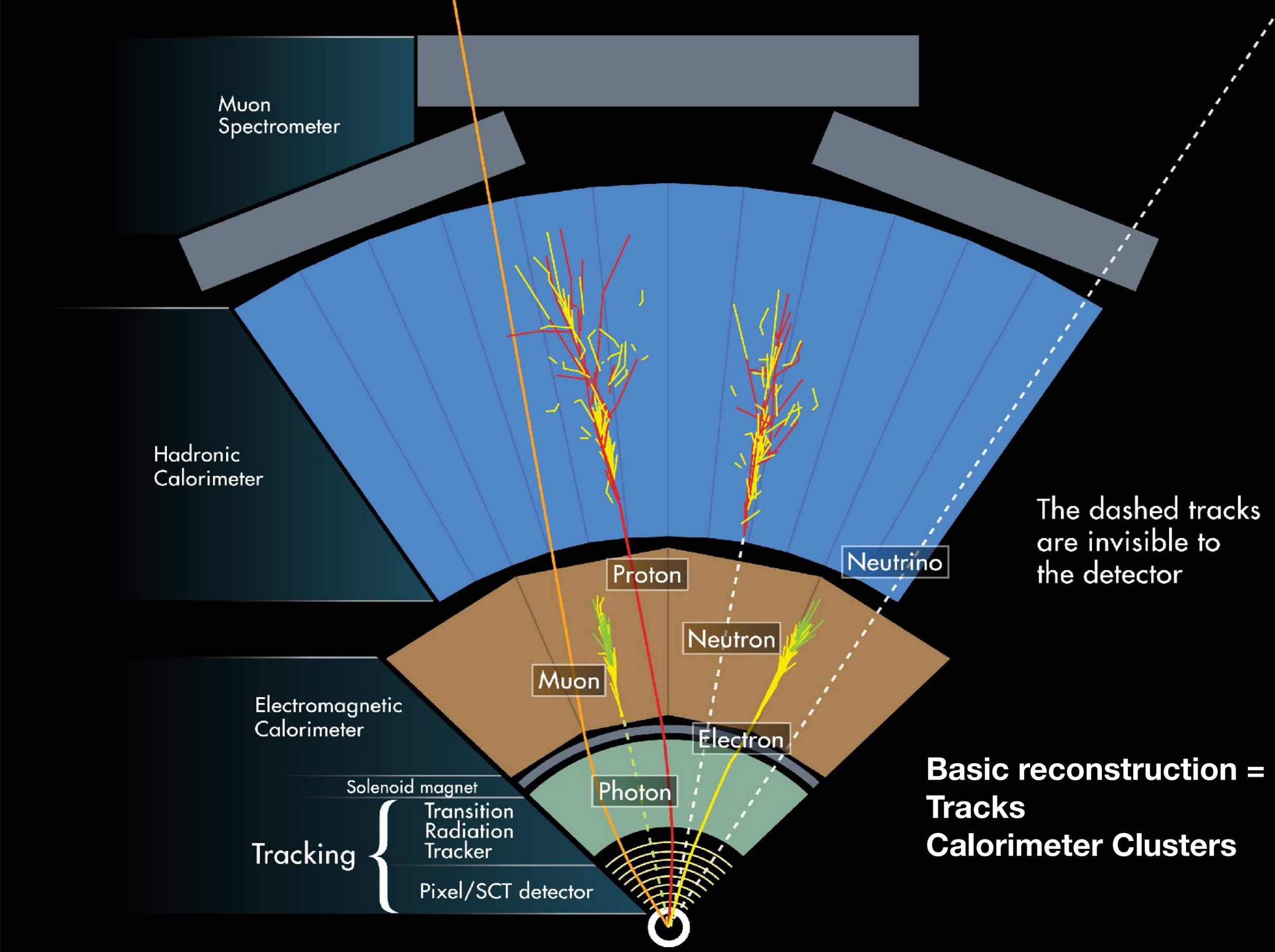
Distributed computing



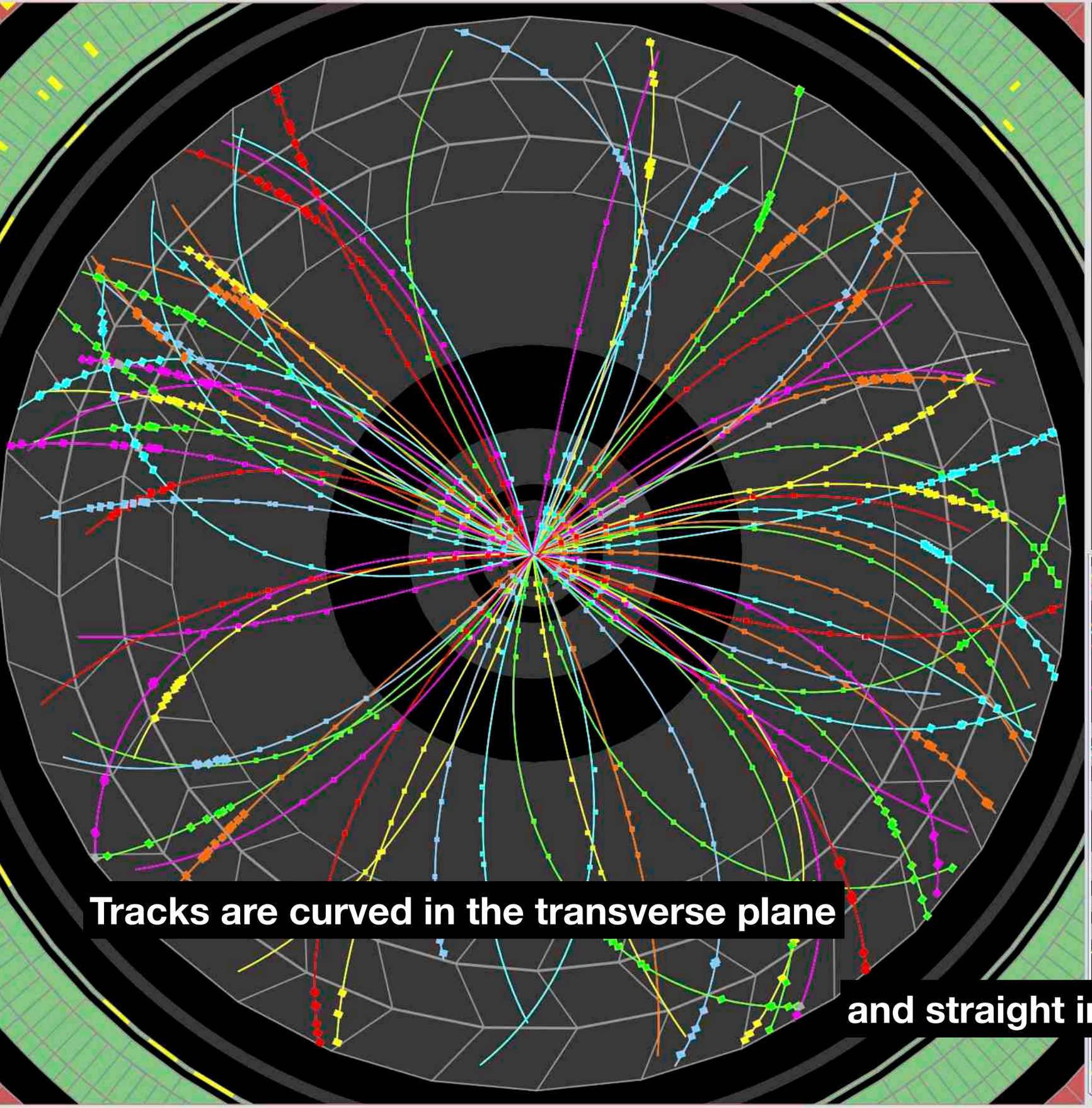
Data Preparation

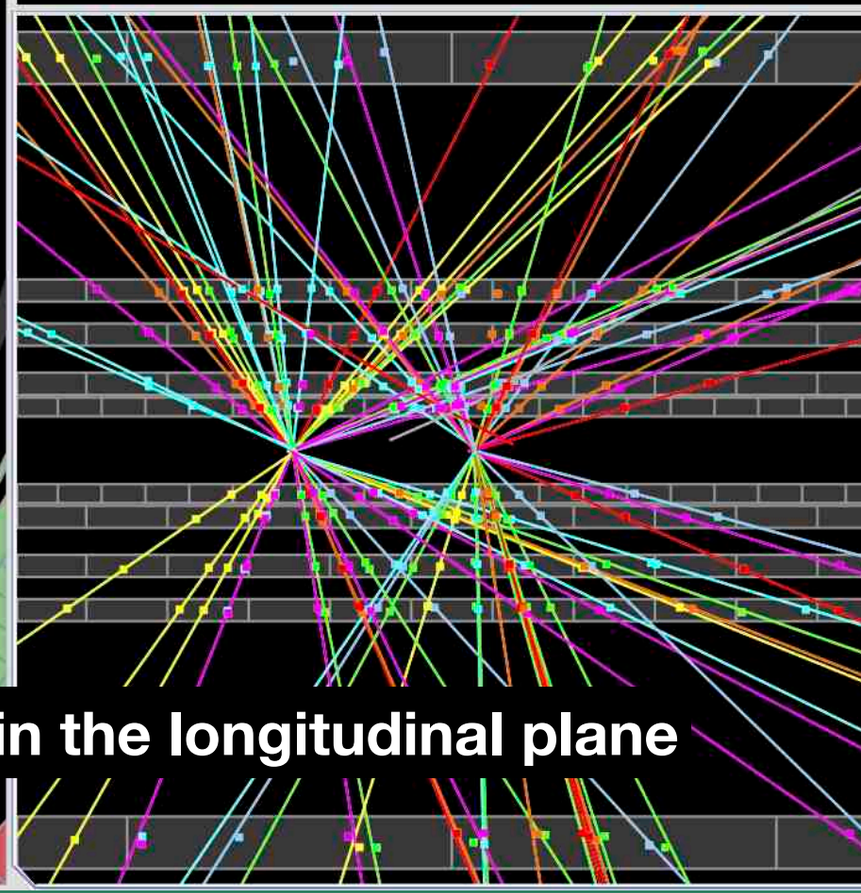
- Three major steps to **prepare data for physics analysis** and achieve
    - reliable, high quality data (yes, we ***reject*** low quality data)
    - the ***best performance*** from our detectors
    - readiness for ***physics analysis***

1. **Reconstruct physics signals** from the data
    - Produce information like how many muons does the event have?



Basic reconstruction =
Tracks
Calorimeter Clusters



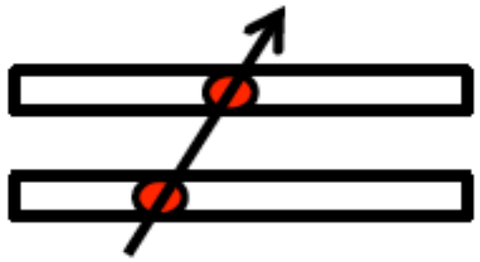


Tracks are curved in the transverse plane

and straight in the longitudinal plane

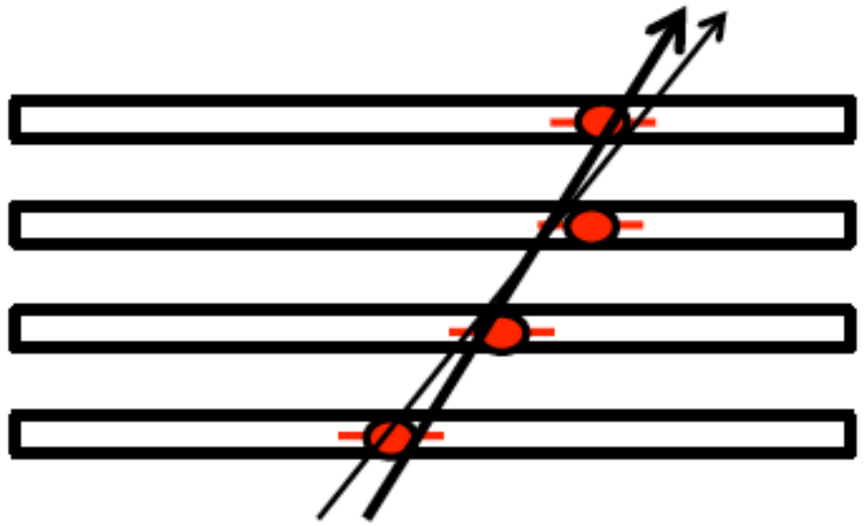
Track fitting

- Perfect measurement – ideal



- Imperfect measurement – reality

- Small errors and more points help to constrain the possibilities



- **Quantitatively:**
  - Parameterize the track;
  - Find parameters by Least-Squares-Minimization;
  - Obtain also uncertainties on the track parameters.

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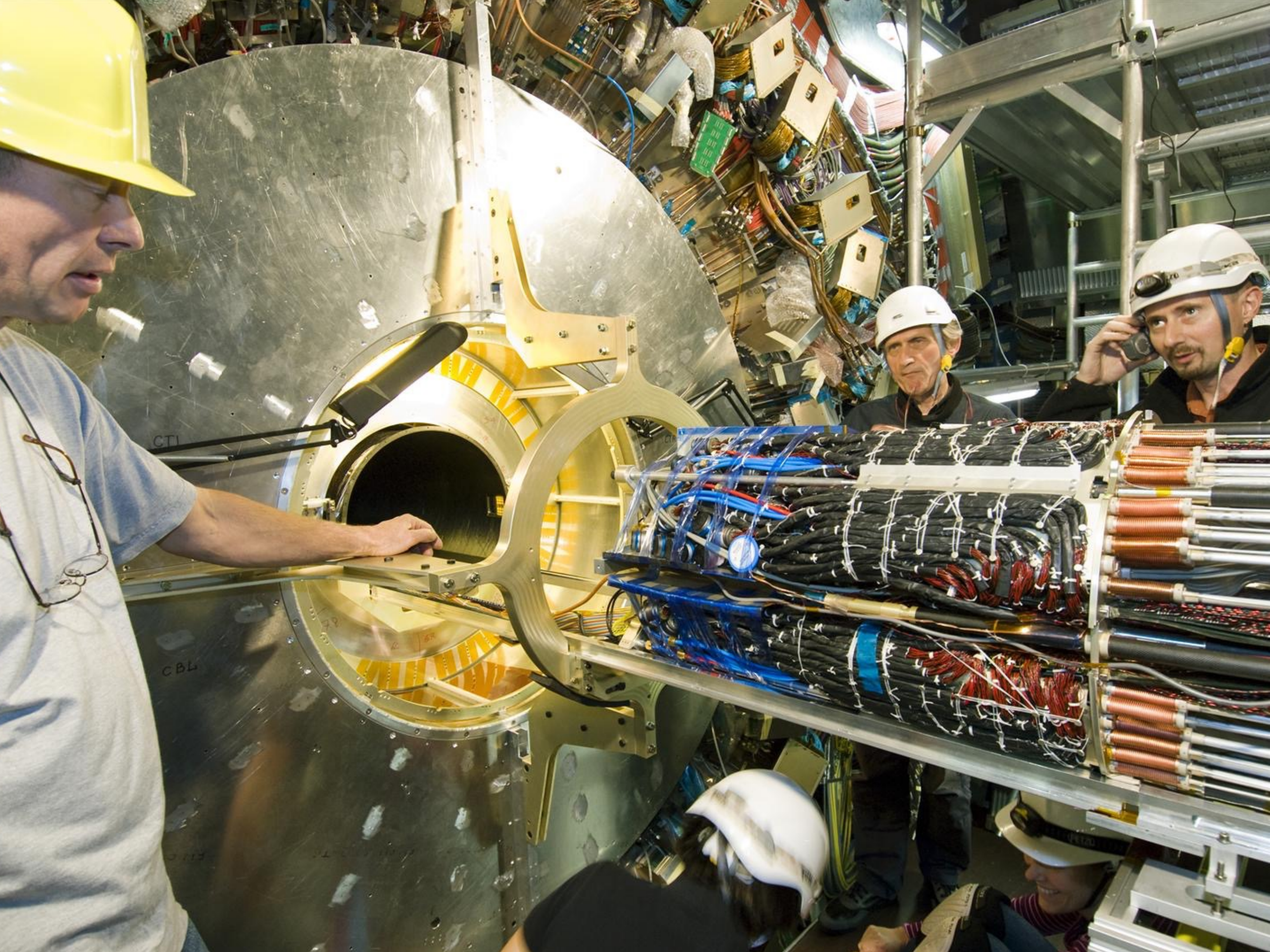
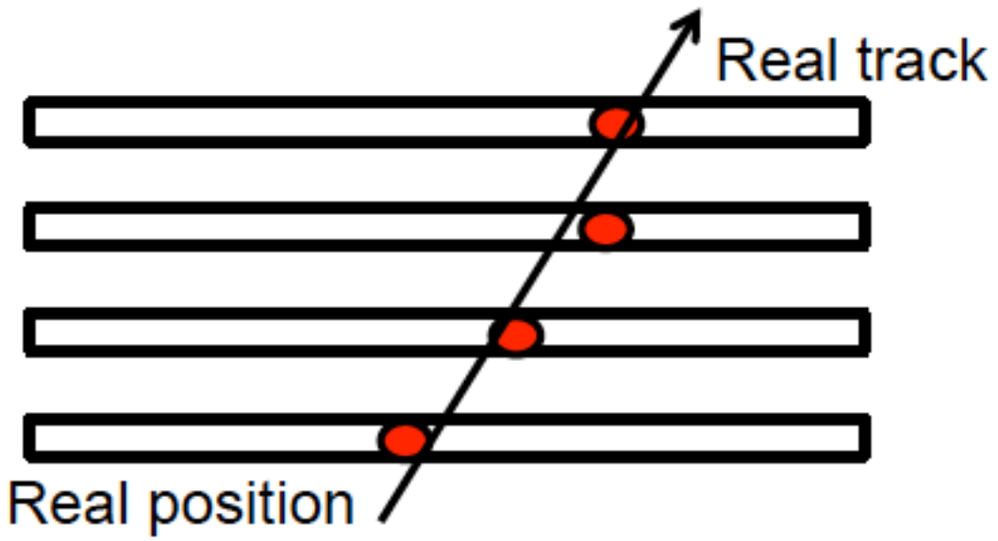
2. **Calibrate** the detectors
    - Correct imperfections, account for changes over time…



Real detector effects

- **Presence of Material**
  - Coulomb scattering off the core of atoms
  - Energy loss due to ionization
  - Bremsstrahlung
  - Hadronic interaction

- **Misalignment**
  - Detector elements not positioned in space with perfect accuracy.
  - Alignment corrections derived from data and applied in track reconstruction.



Correcting detector effects - calibration

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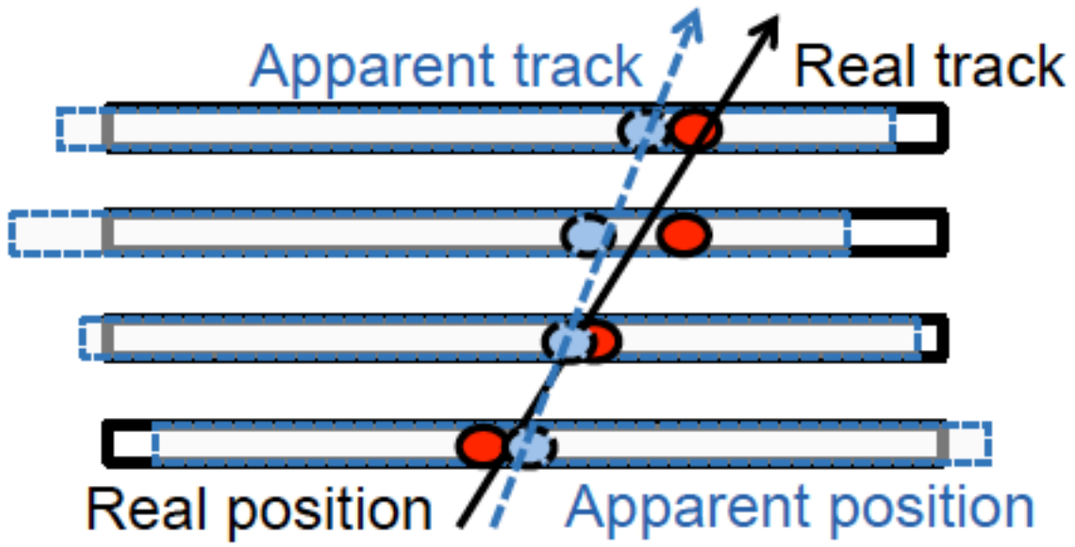

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2. **Calibrate** the detectors
   - Correct imperfections, account for changes over time… ✓
3. Make sure that the **data quality** is excellent, also in real time
   - Maximise the amount of useful data

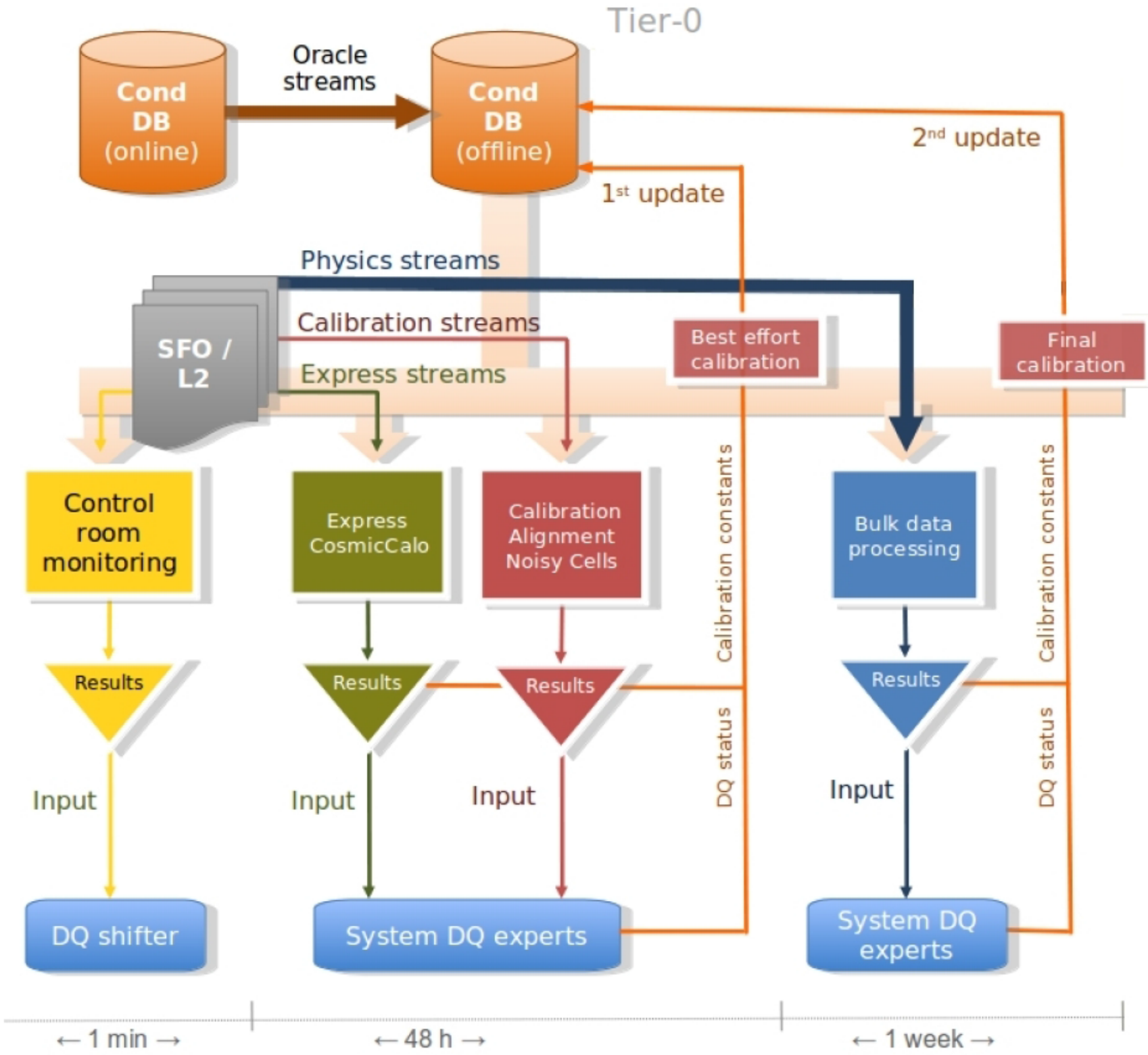
Data Quality

Check during data taking

Check a fraction of the data with a quick calibration

Check all of the data with the best calibration

- Publish this data !!



Data Quality

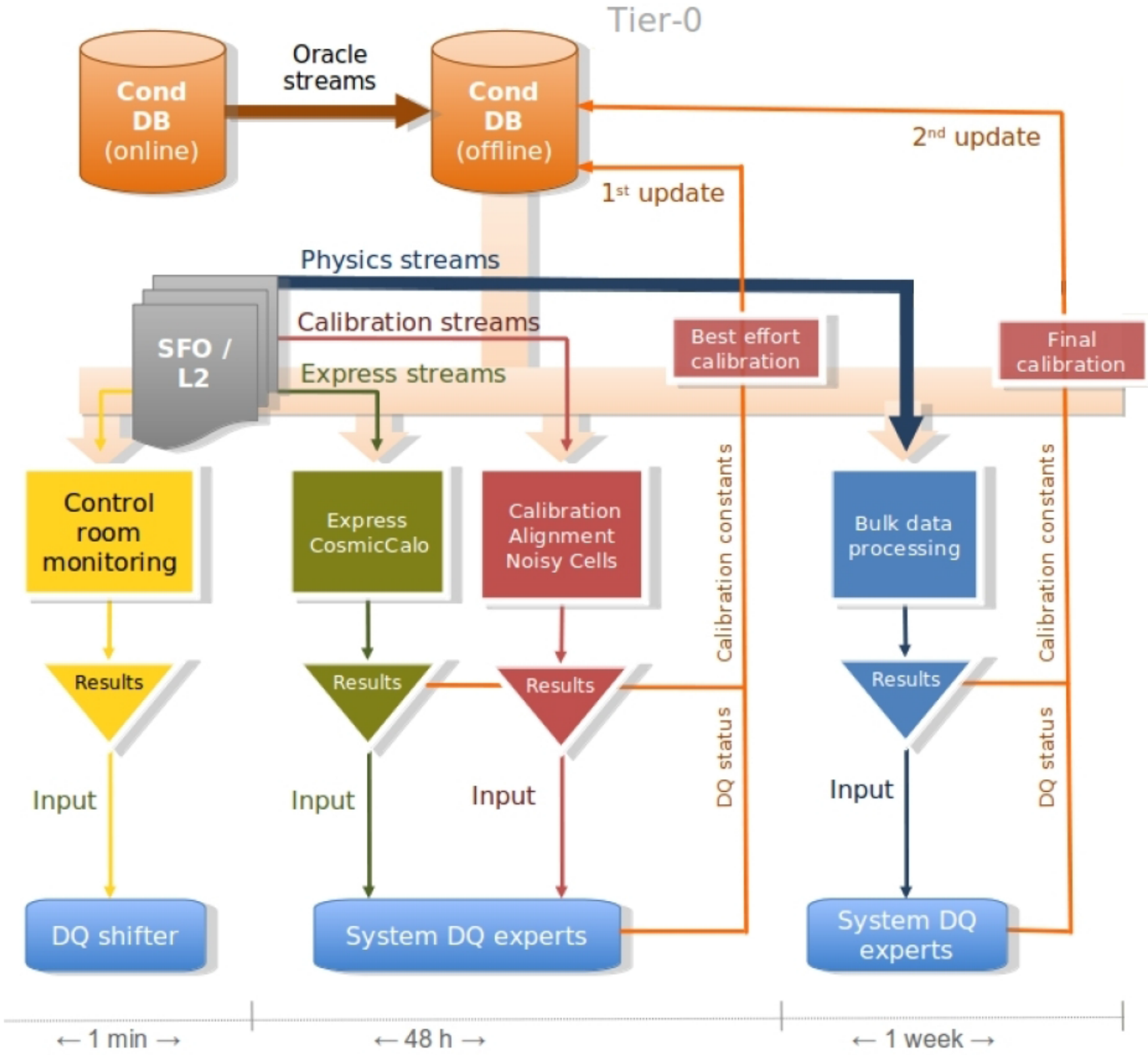
Check during data taking

Check a fraction of the data with a quick calibration

Check all of the data with the best calibration

- Publish this data !!

Q. If we can calibrate the data, why do we need to have Data Quality checks in the control room?



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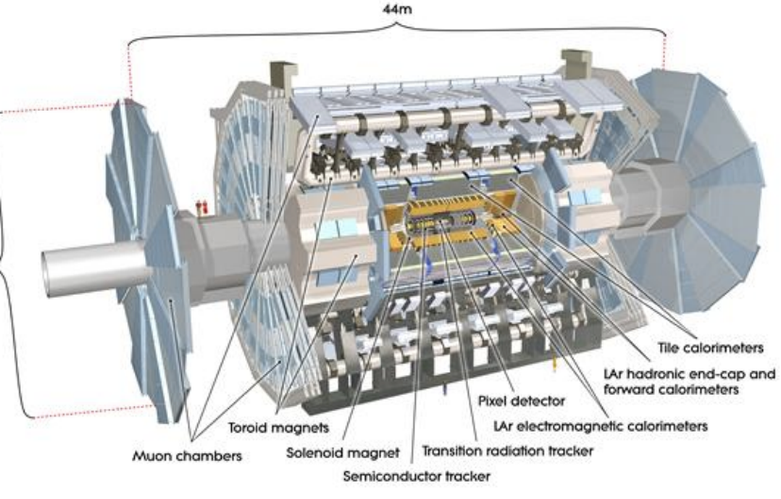
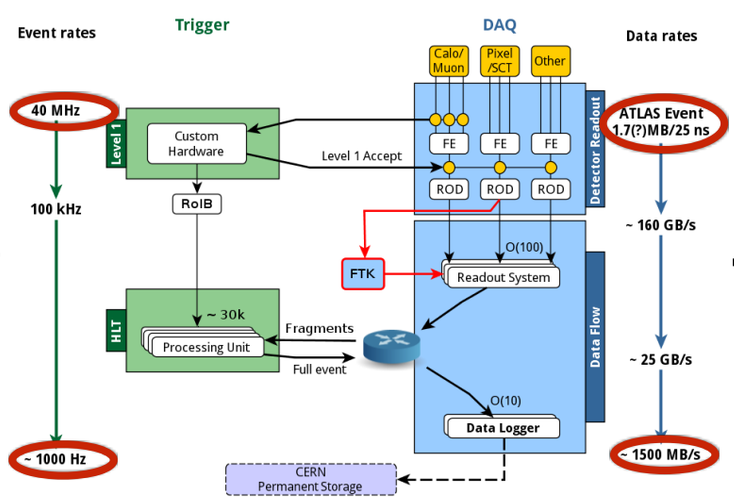
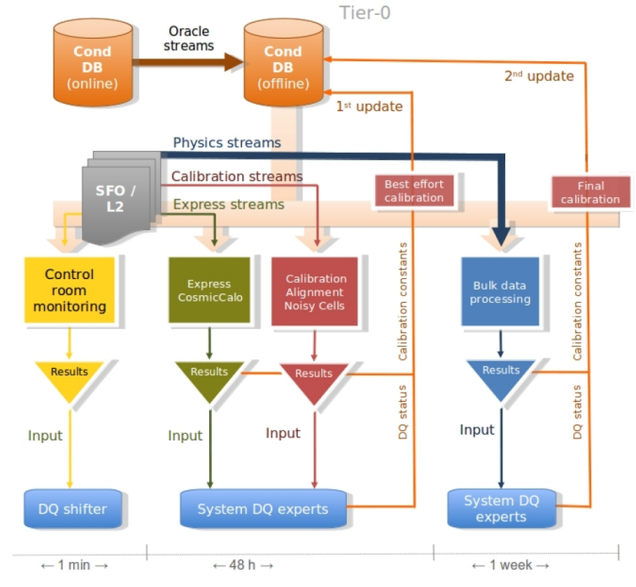
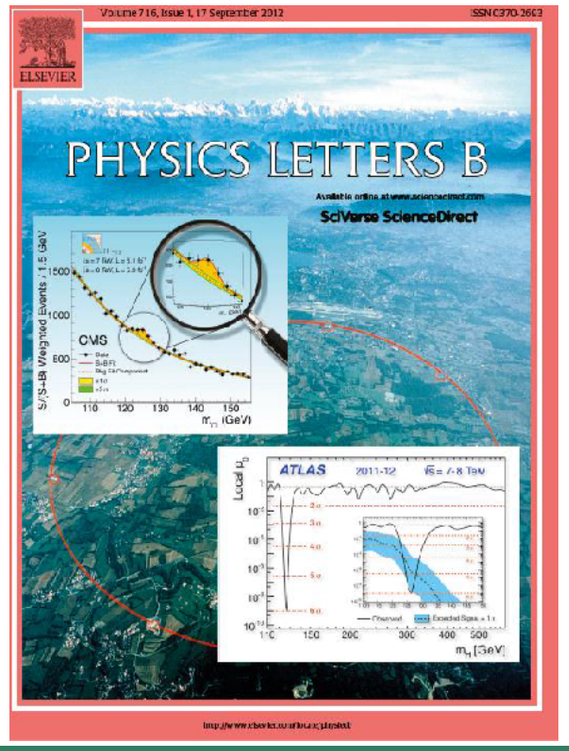
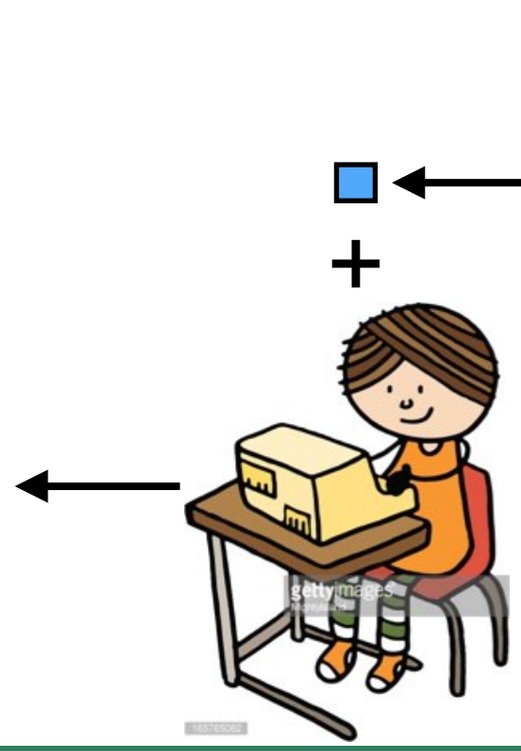
Data's journey









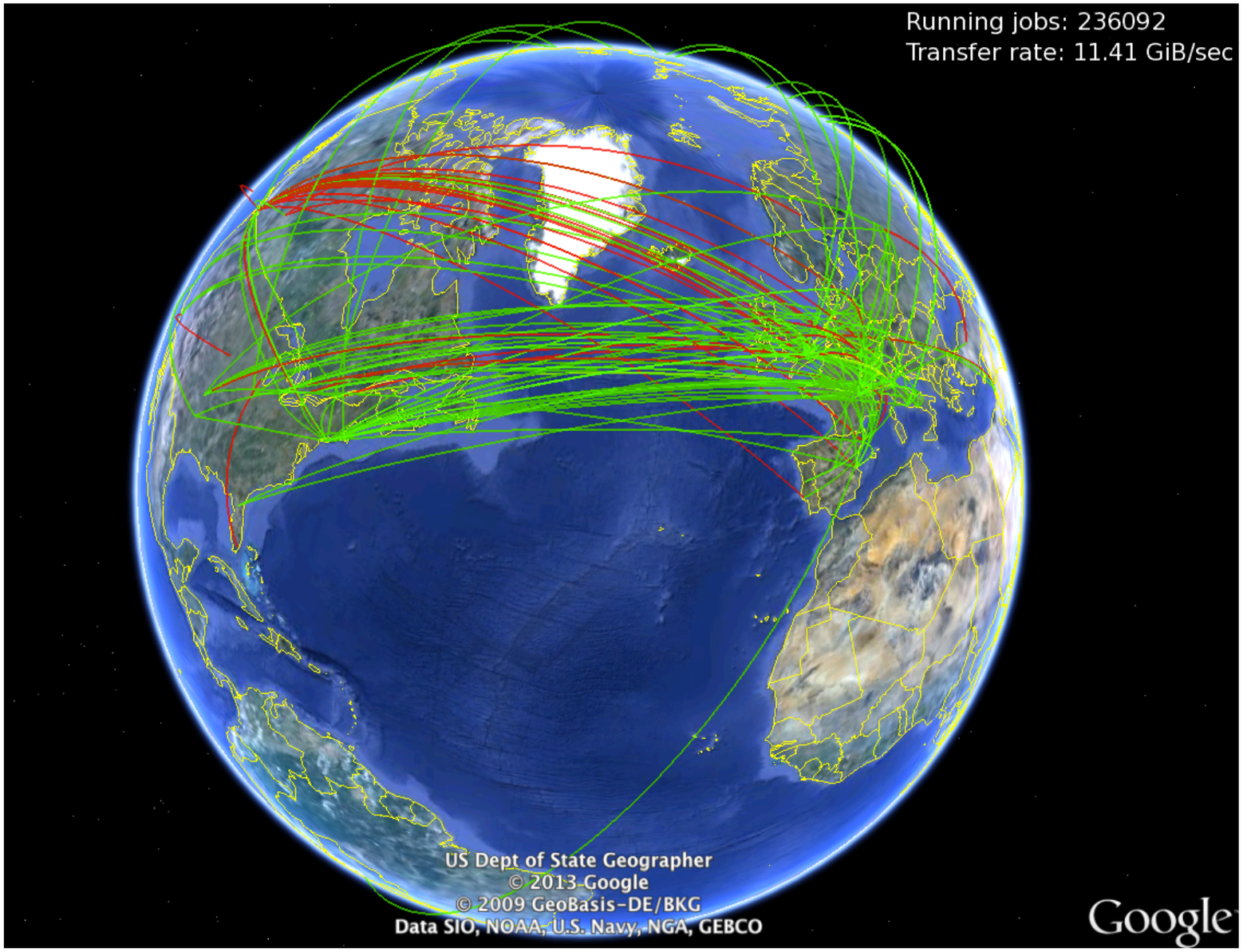


Distributed computing

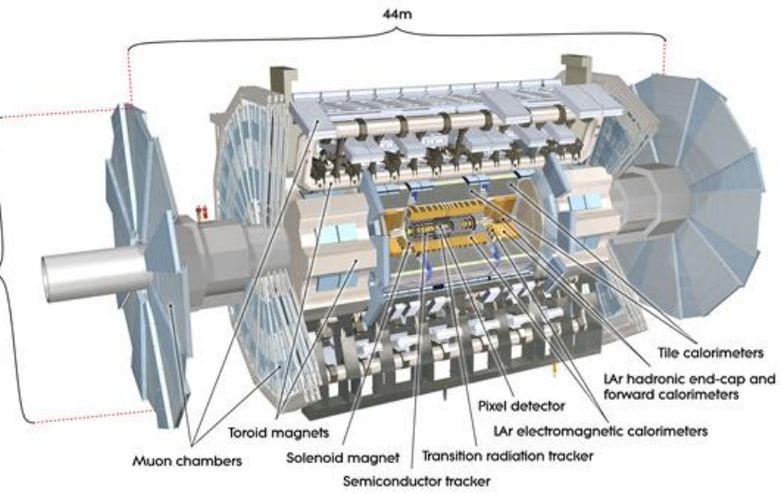
The Worldwide LHC Computing Grid

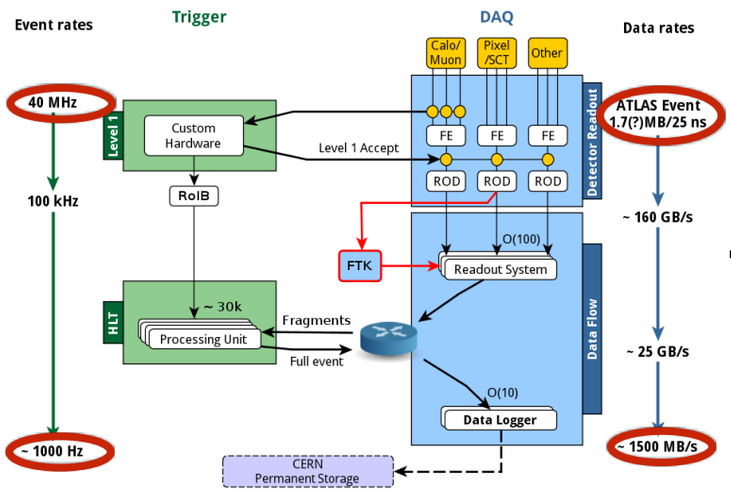
- Now the data has been ***prepared for physics analysis***, it's time to extract our favourite physics signal!

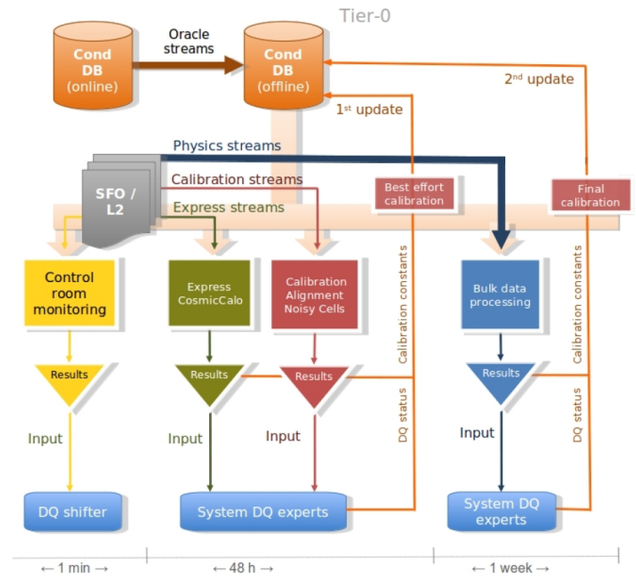
- Many experiments, particularly those at the **LHC**, use computing sites all over the world via **the grid** to
  - harness all of that ***computing power***
  - enable collaborators ***worldwide*** to access the data

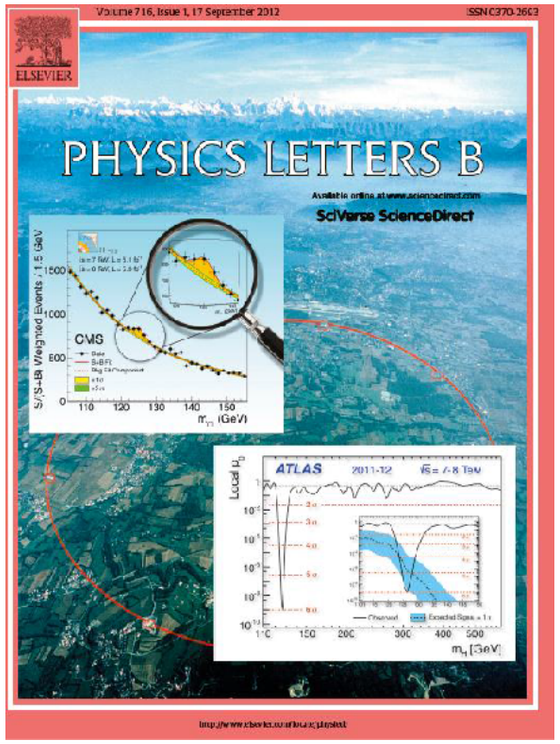


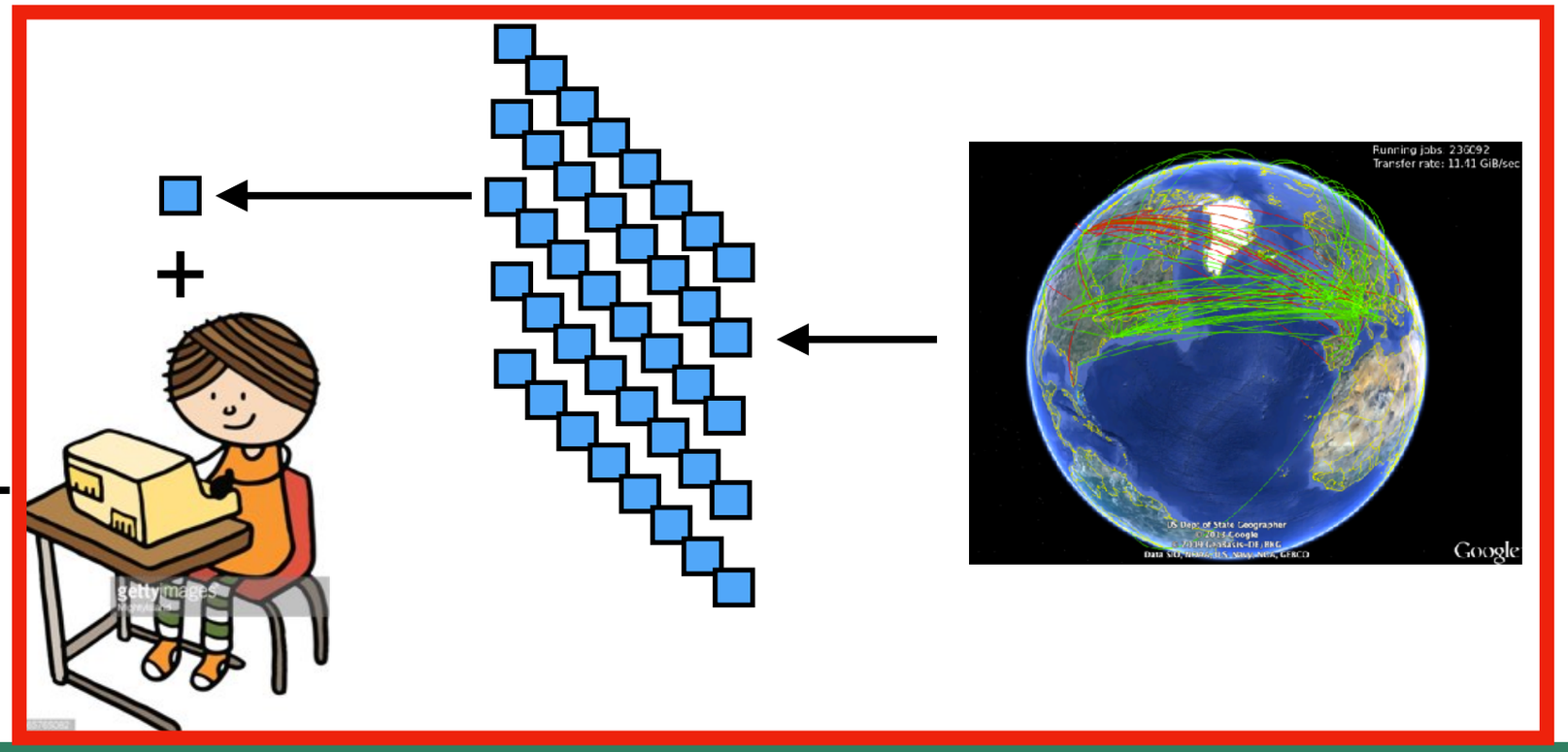
Data's journey







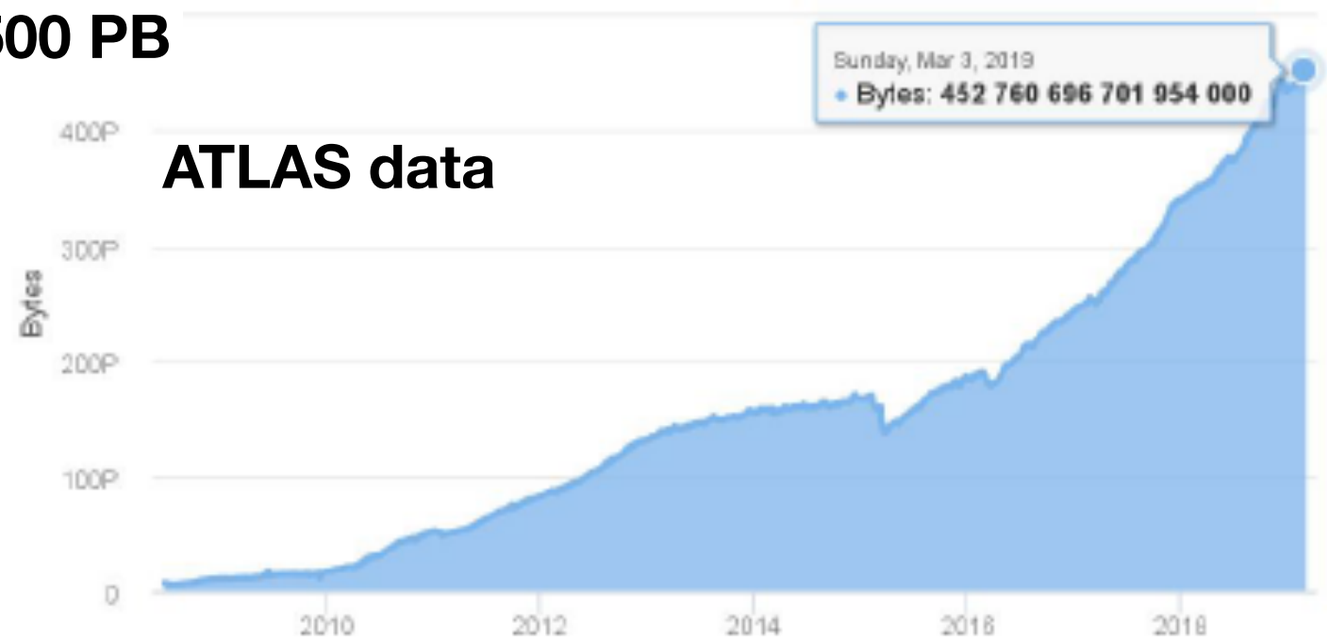




We did it !

- Our data is calibrated and with good data quality
- and we've reconstructed the physics objects in the data
  - ***The data is reliable, accurate, and ready for physics analysis***
- ***More detail on these topics in Lecture 2***
- ***Then we can extract our measurements in Lecture 3***

- ***Question**: How long would it take to read **500 PB** of ATLAS data? (Assume for simplicity you have off-the-shelf SSDs with read speed ~500MB/s)*



Contact details

- I am usually based at Geneva Observatory in Versoix, but will be here at CERN Wednesday 3rd through Friday 5th July

- email: paul.laycock@unige.ch