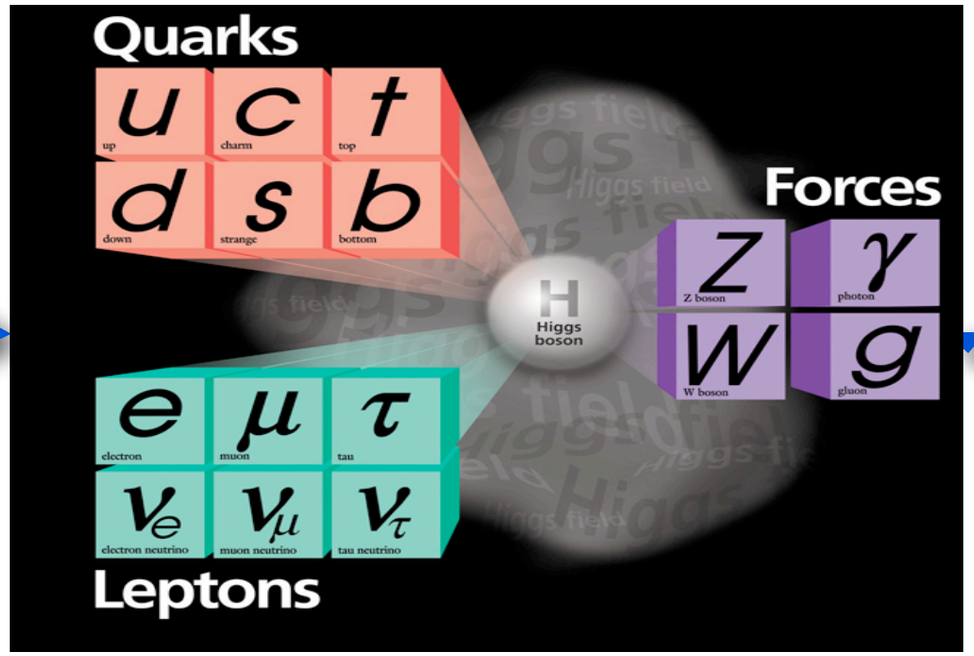
From Raw data to Physics Results (1/3)

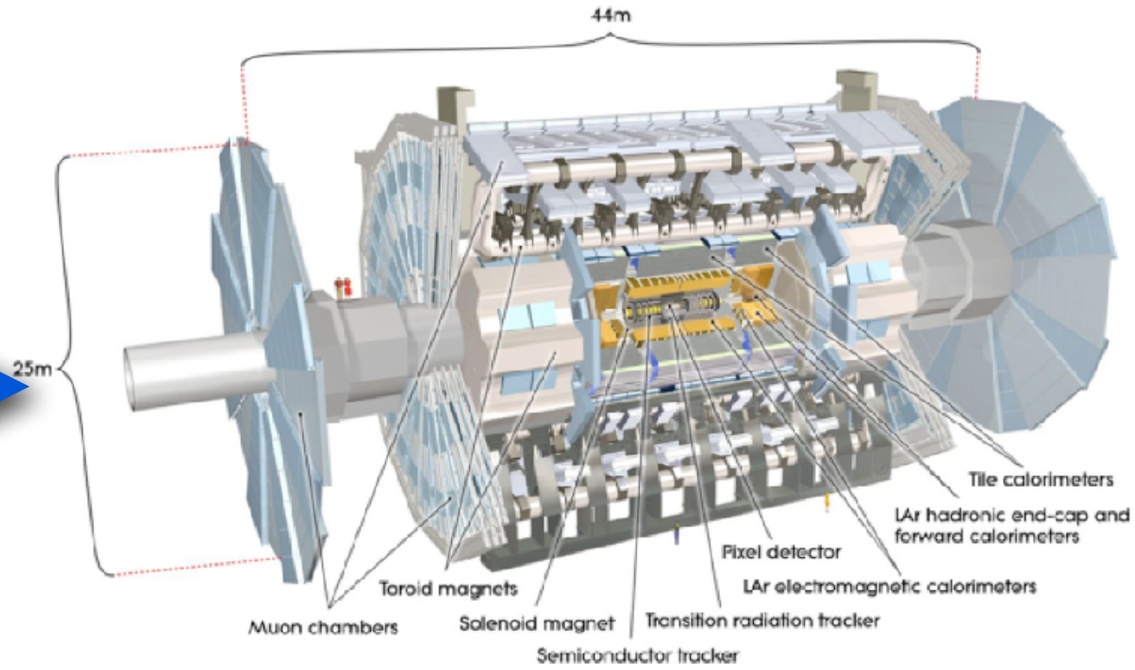
Dr Paul Laycock

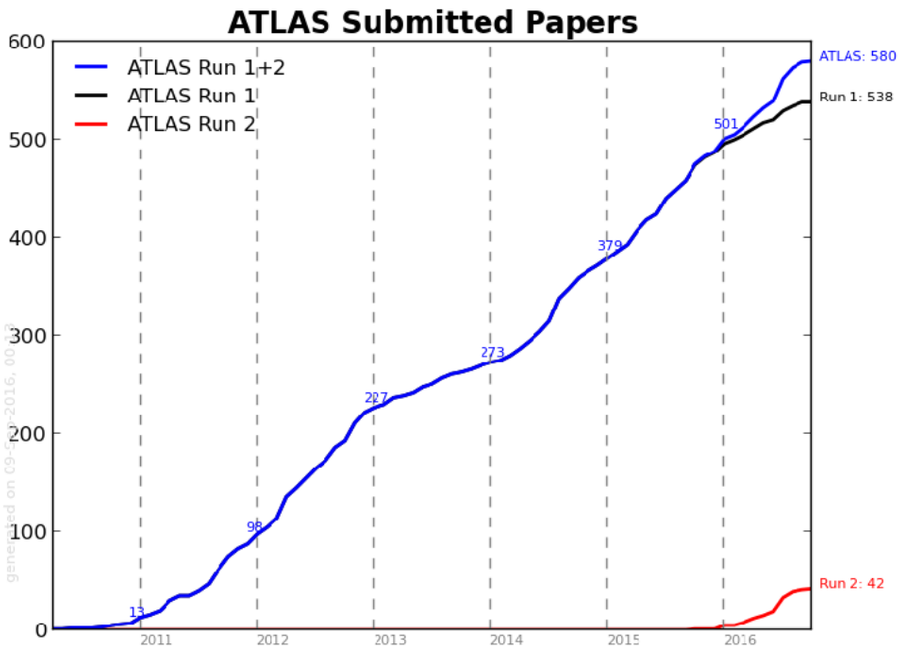
GWSC GRAVITATIONAL WAVE SCIENCE CENTER

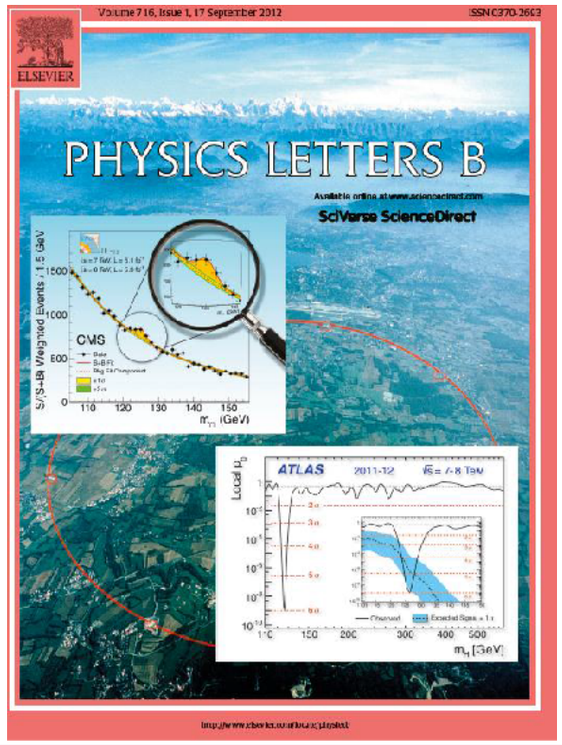
UNIVERSITÉ DE GENÈVE | Faculté des Sciences
Département d'astronomie

The particle physics cycle





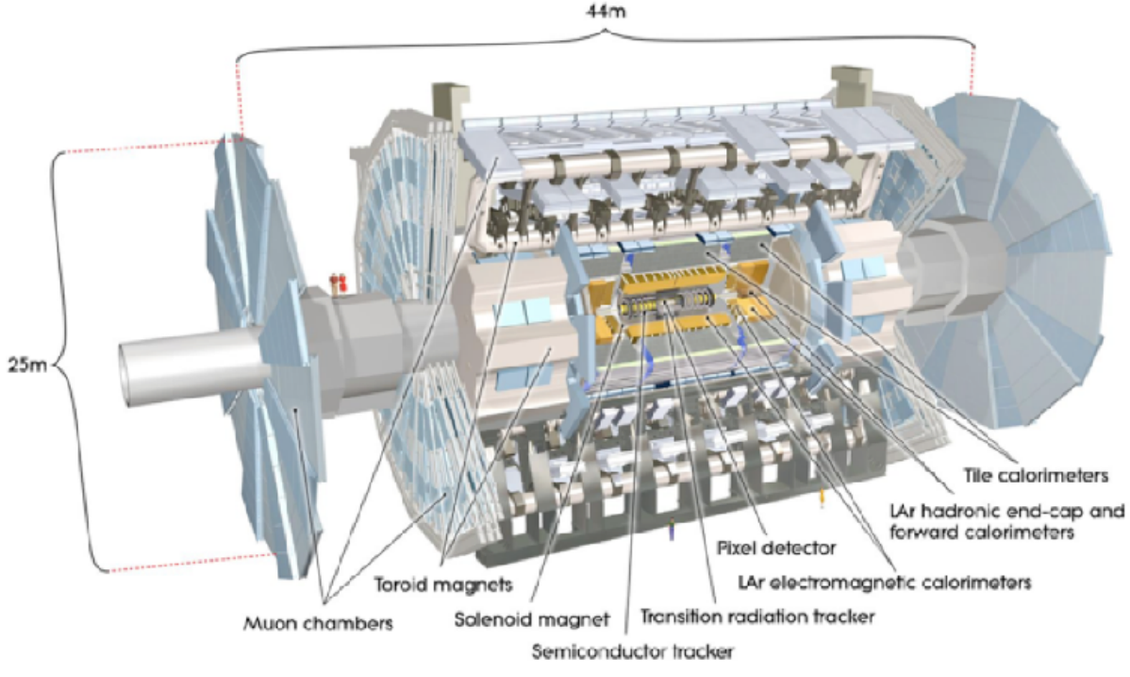




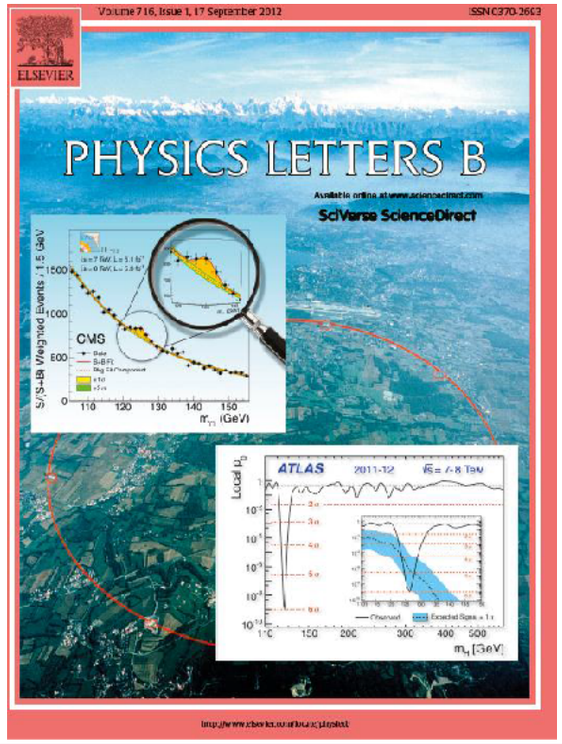
Experimental physics

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

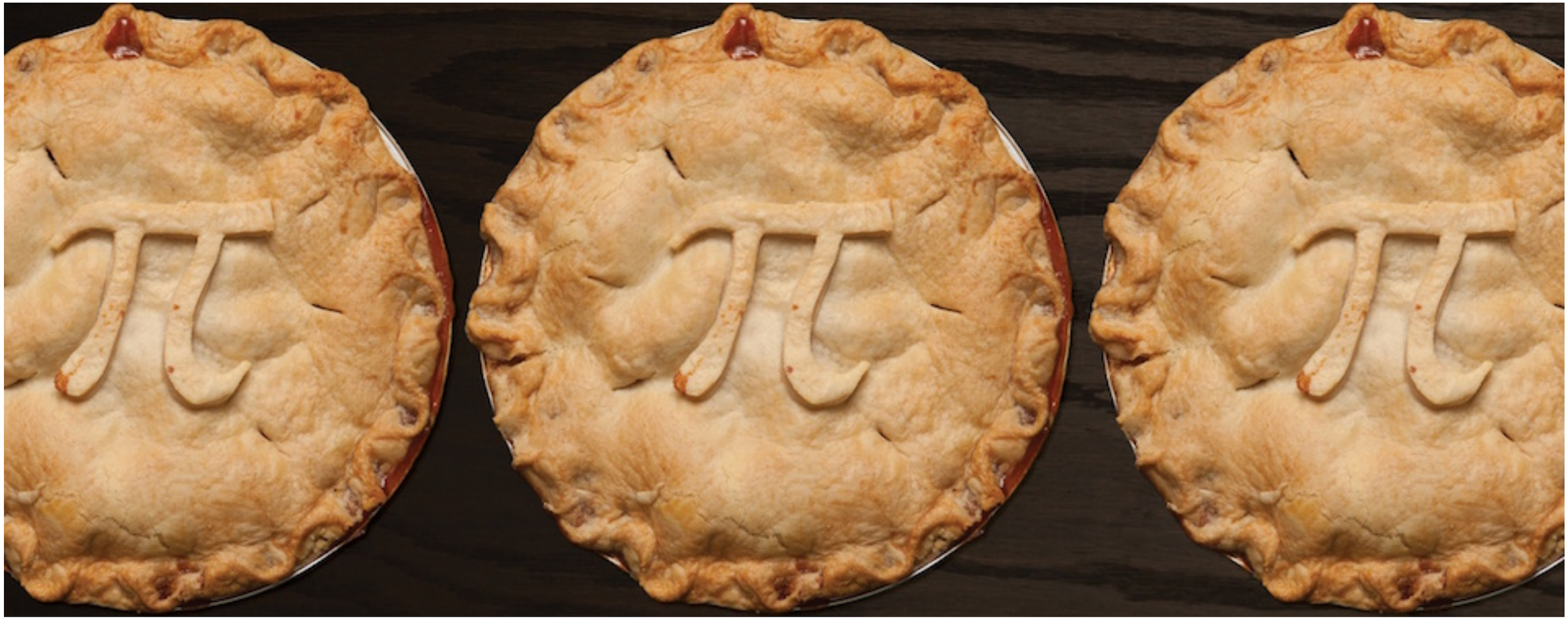
- ***Note*** *- Experimental physicists also need to propose, design and build new experiments (see previous slide)*



- 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



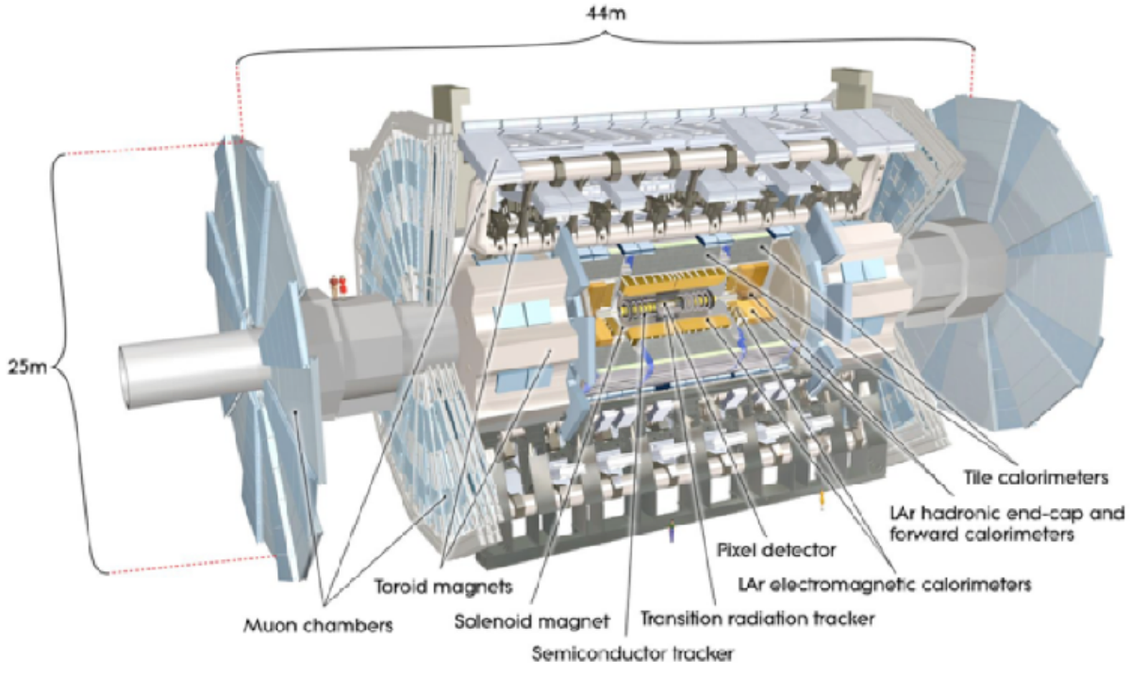
Accuracy and precision

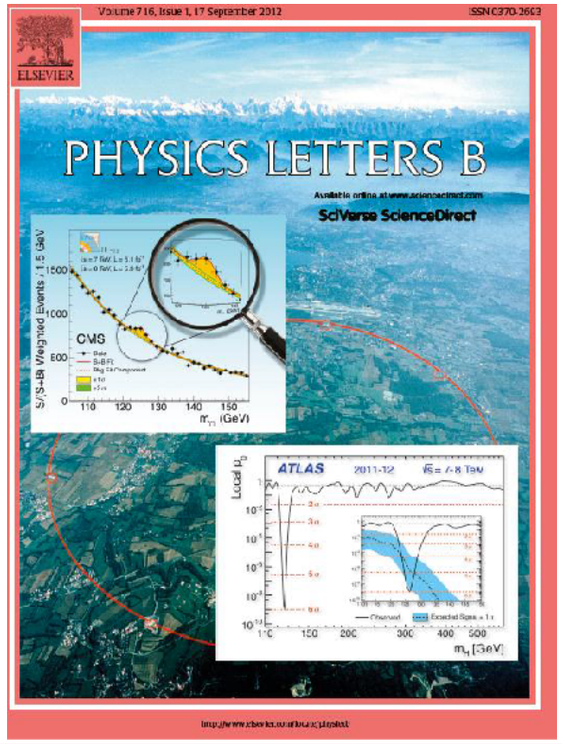


3.1416 ± 0.0001 $22/7 \pm 1$ 3.14159265 ± 0.1

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

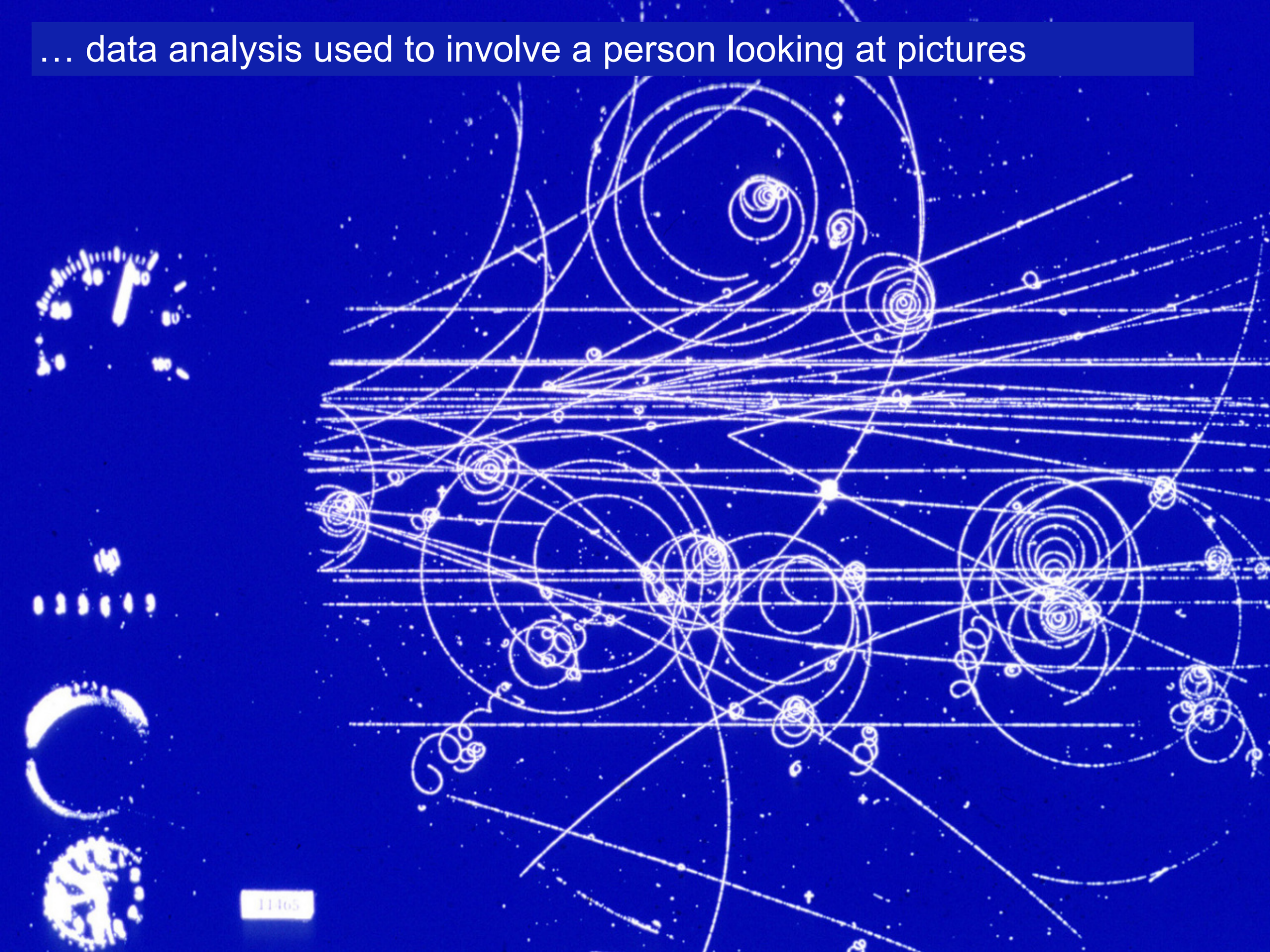




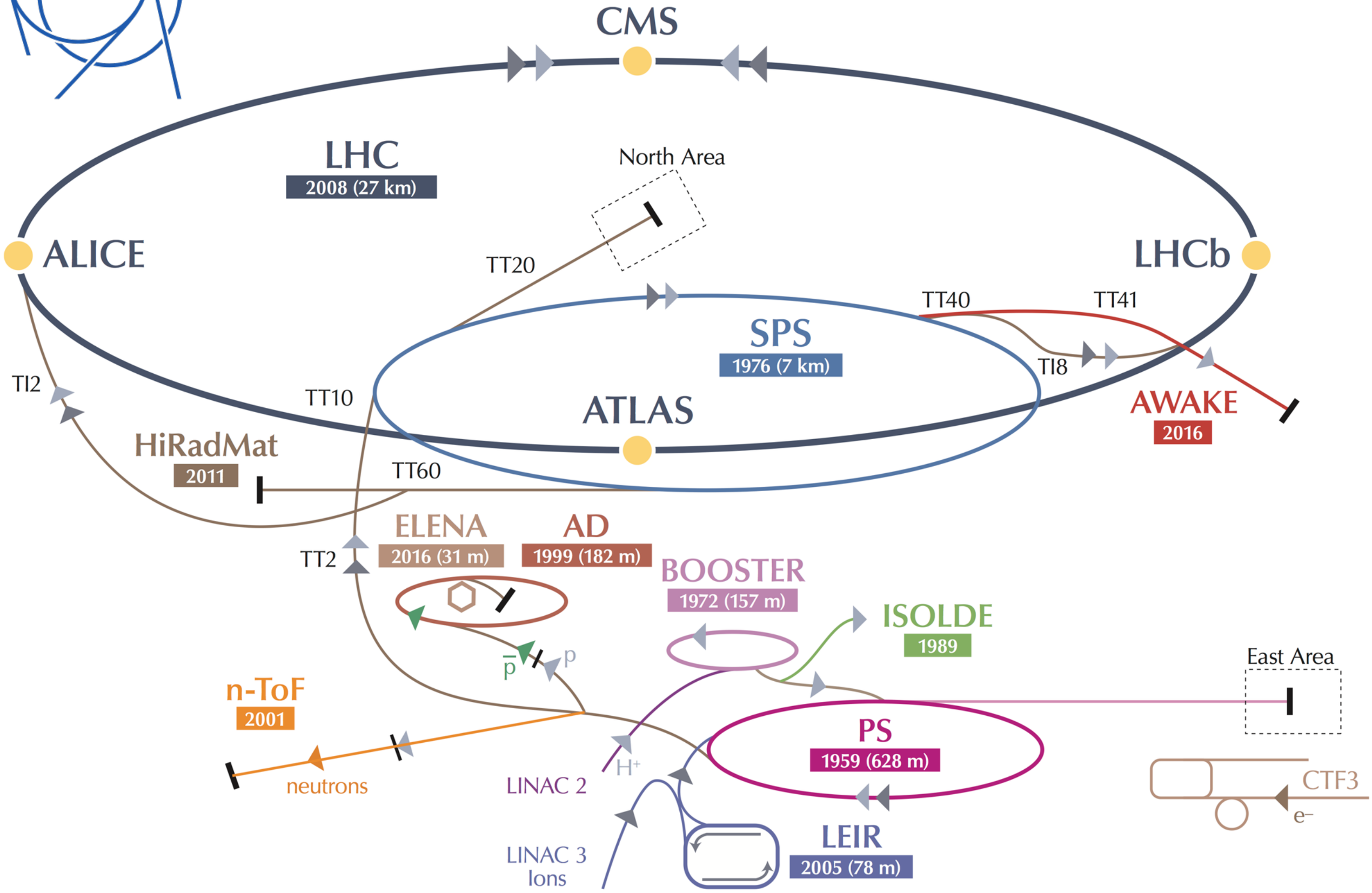
Experiments at CERN

- 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

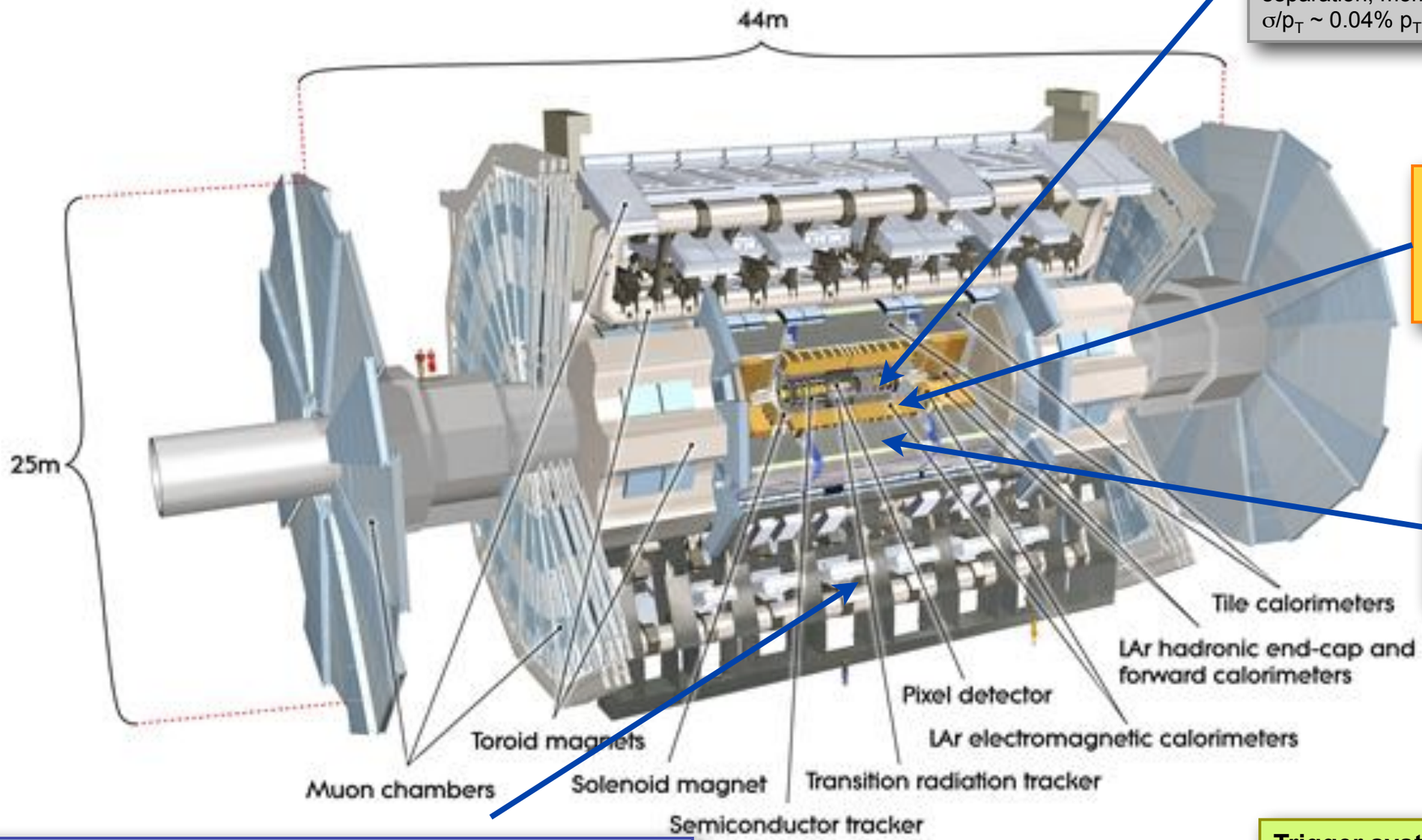


The ATLAS Detector @ LHC

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: σ/p_T ~ 0.04% p_T (GeV) ⊕ 1.5%

EM calorimeter: Pb-LAr Accordion, e/γ trigger, id. and meas., energy res.: σ/E ~ 10%/√E ⊕ 0.7%

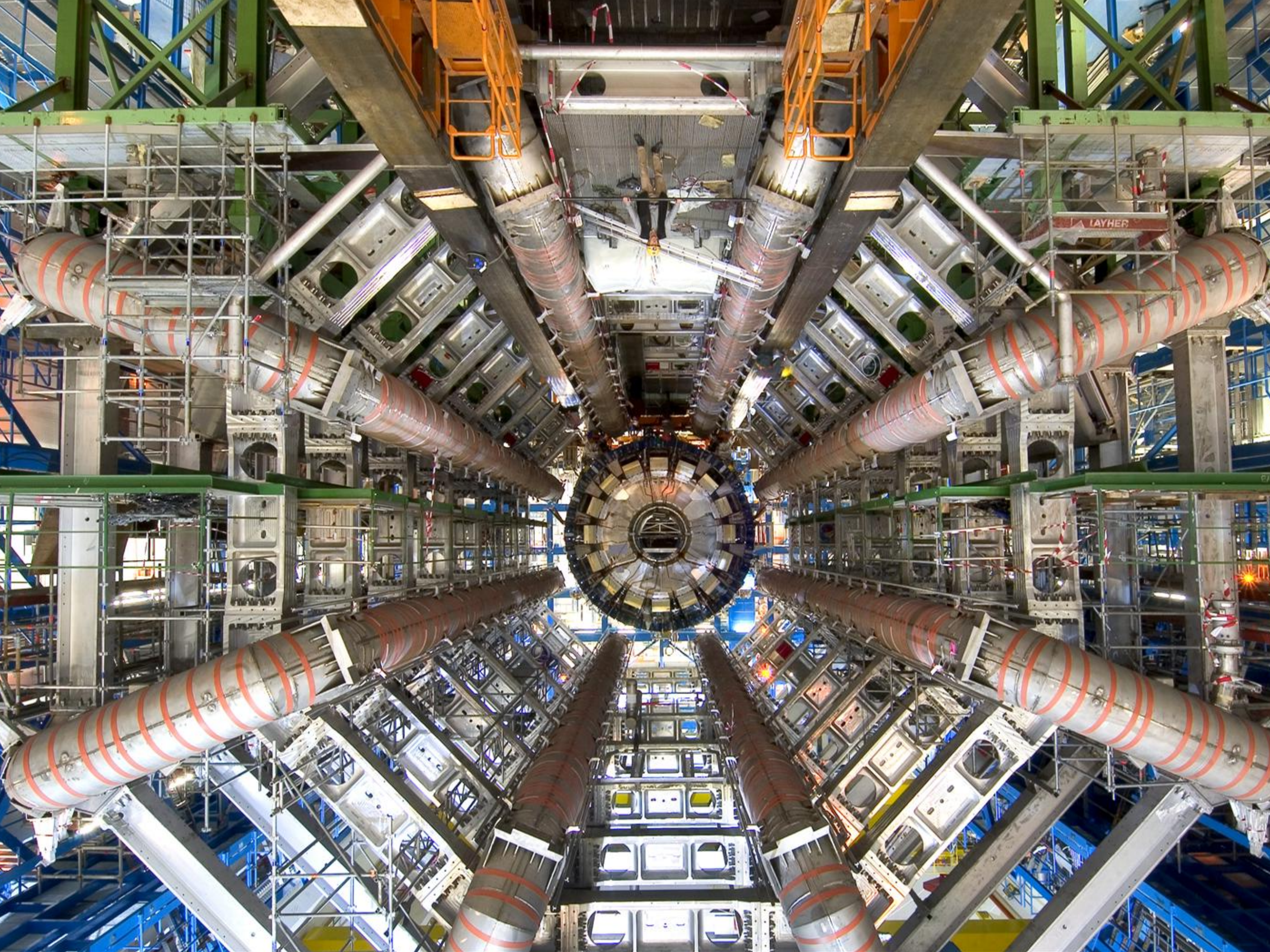


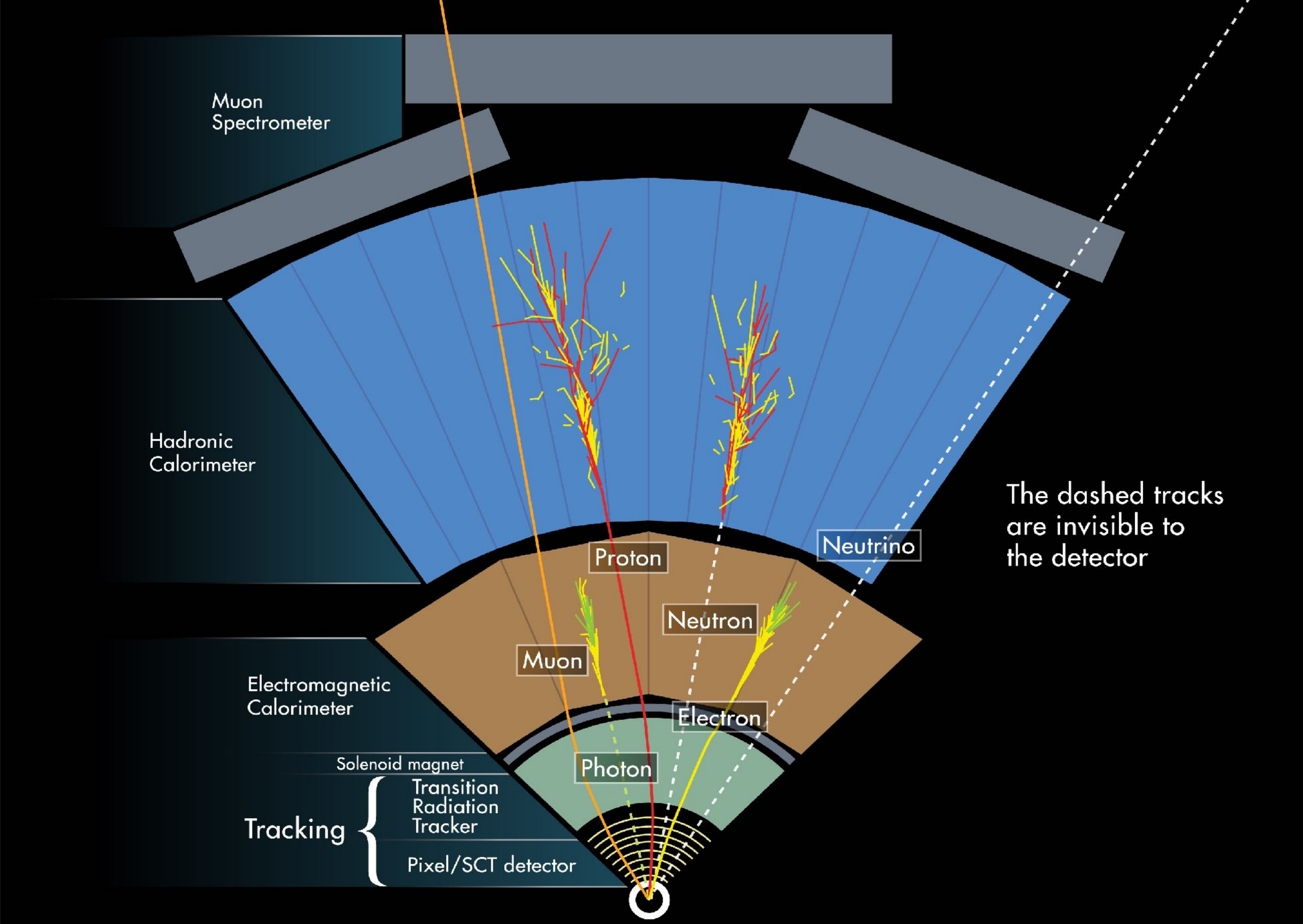
HAD calorimetry (|η|<5): Fe/scintillator Tiles (cen), Cu/W-LAr (fwd). trigger and meas. of jets and $E_{T,miss}$, energy res.: σ/E ~ 50%/√E ⊕ 3%

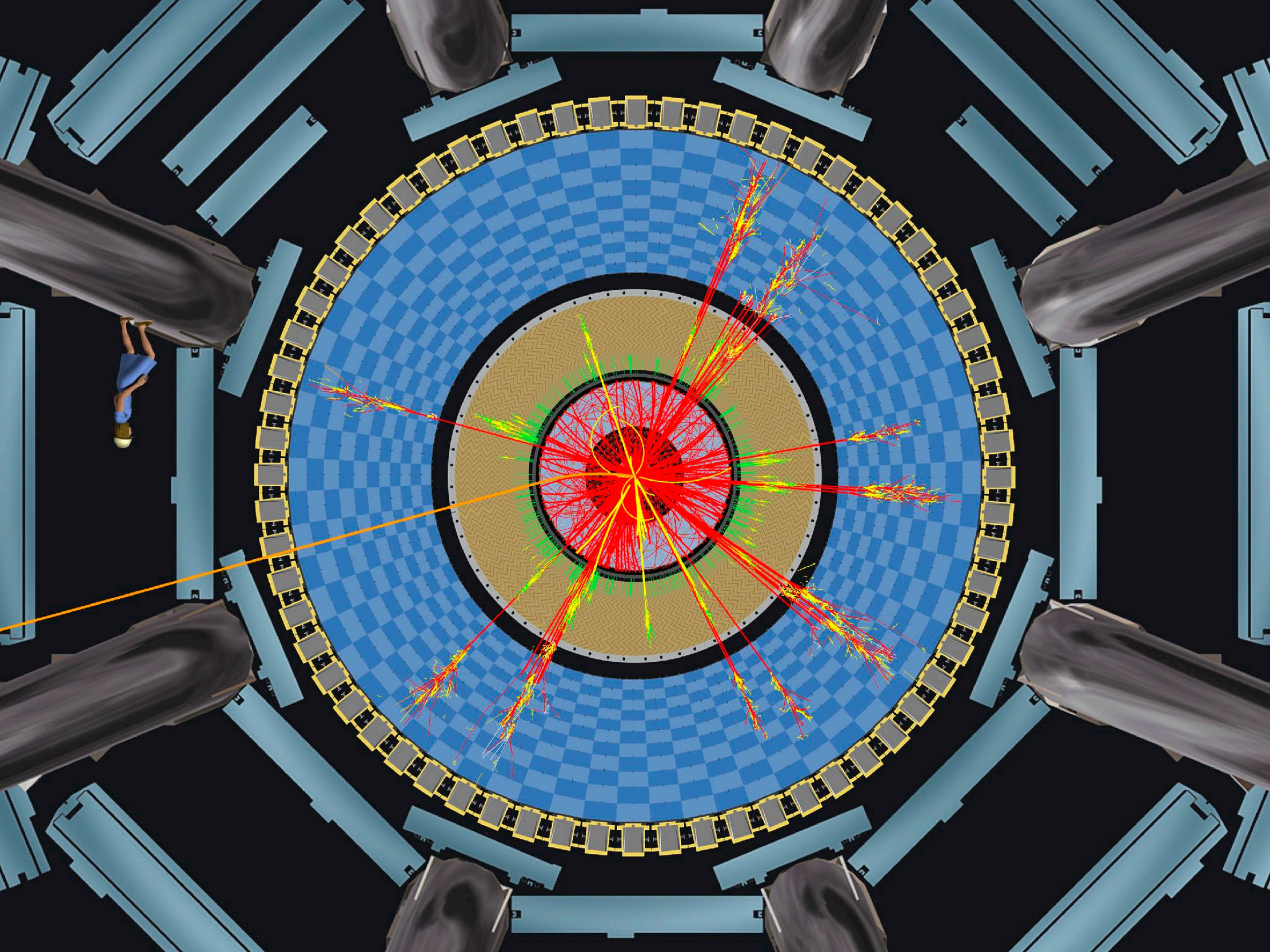
Muon Spectrometer: air-core toroids with gas-based muon chambers. trigger and meas. with momentum resolution < 10% up to E_μ ~ 1 TeV

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

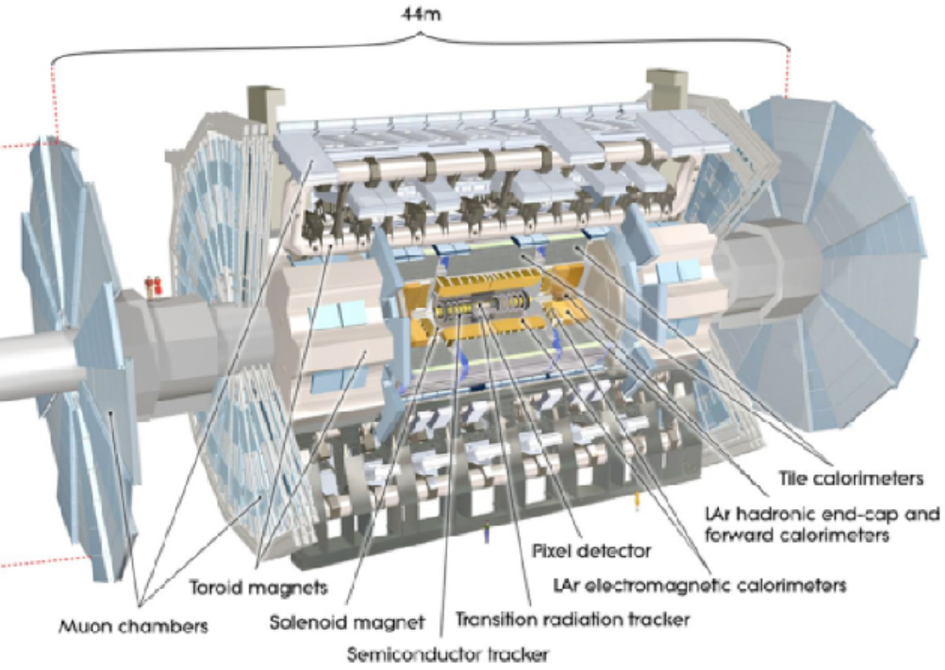
Millions of detector readout channels read out to reconstruct one "event"

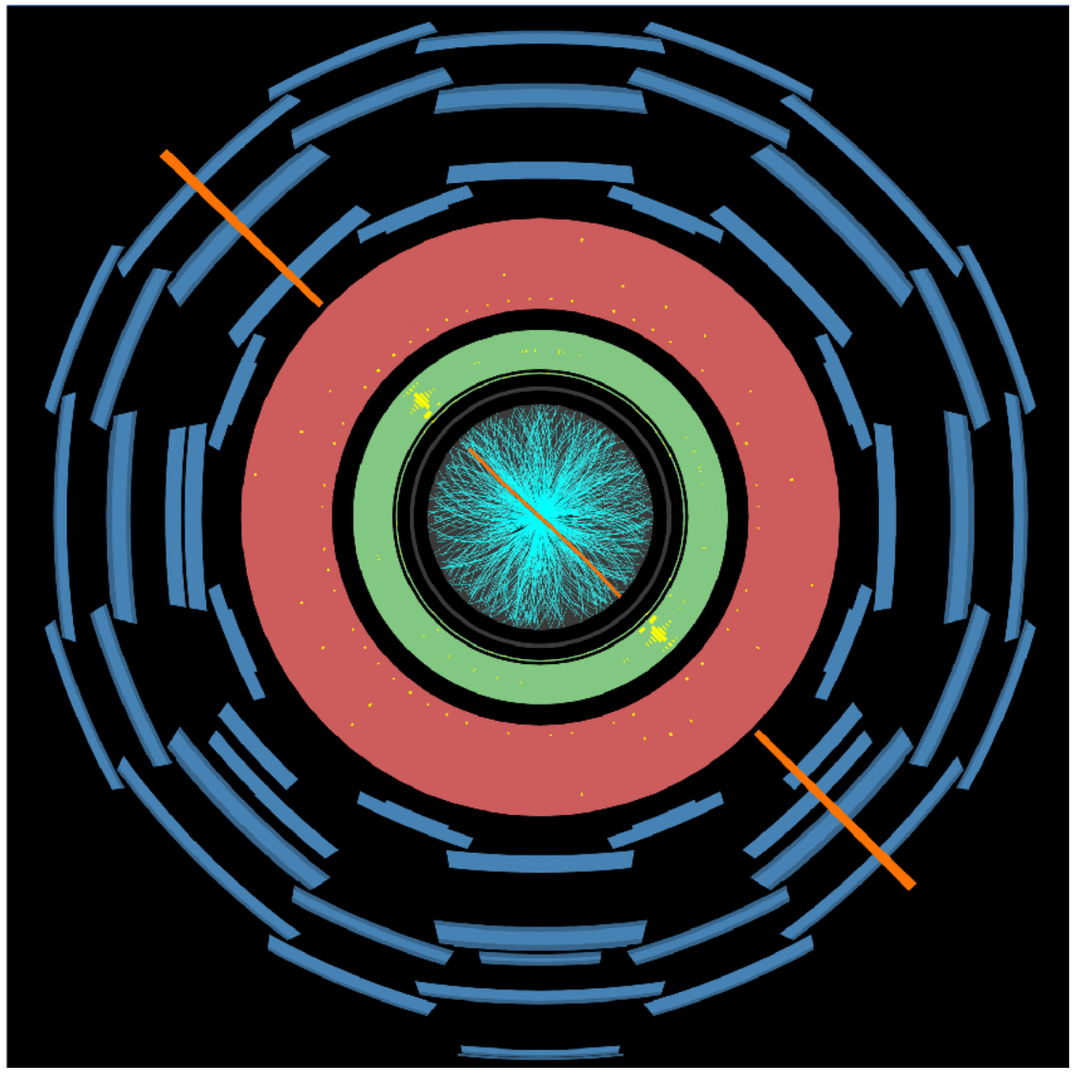

LAYHER


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



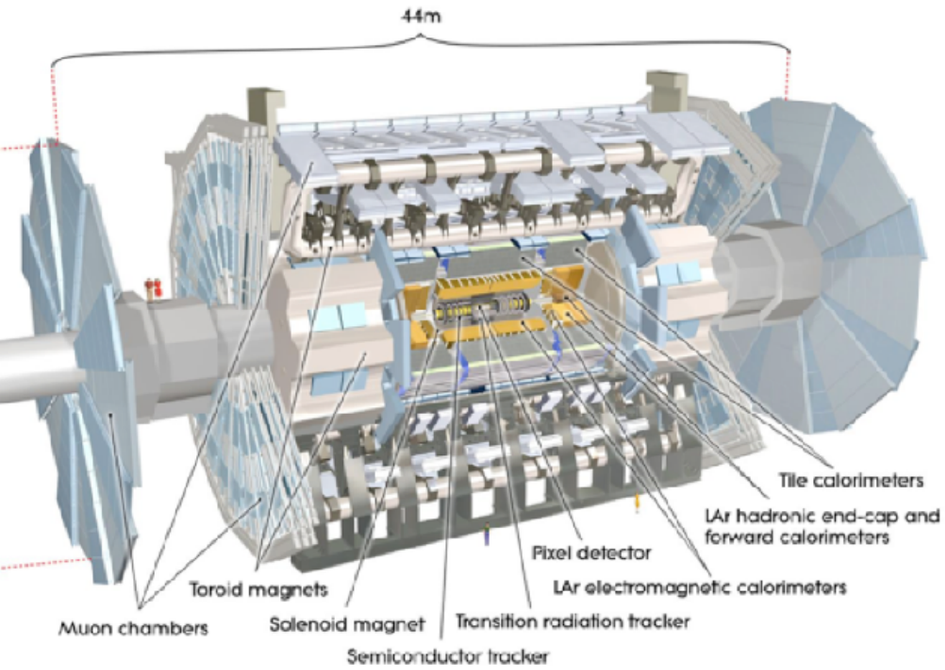
Event displays





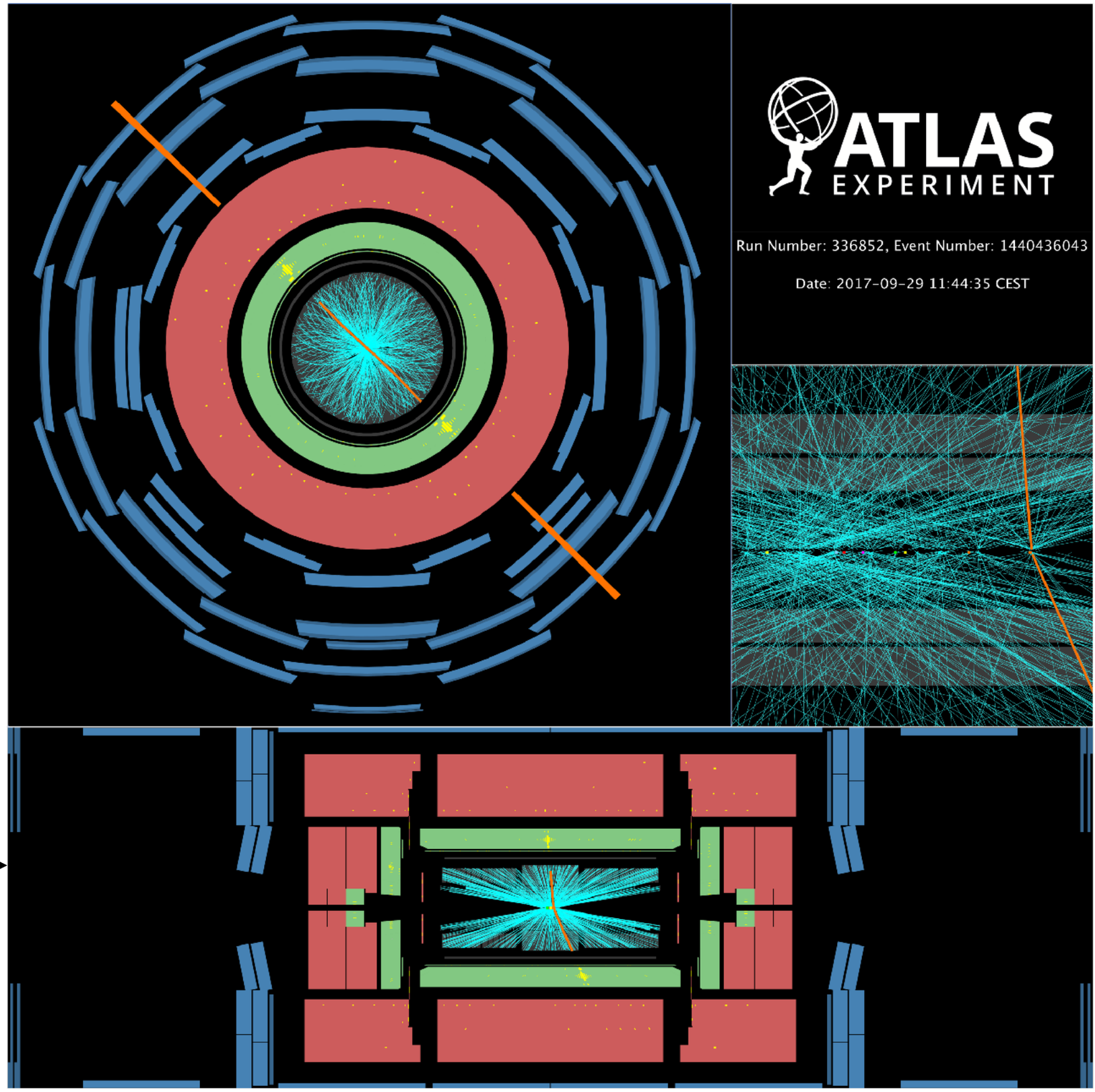
- Event displays are great ways for us to visualise what happened in a particle collision
- In this **ATLAS event display** (*right*) of a real proton collision, we are looking down the beam pipe, so the plane of the display is transverse to the proton beam direction
- ***Question**: Can you quantify 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

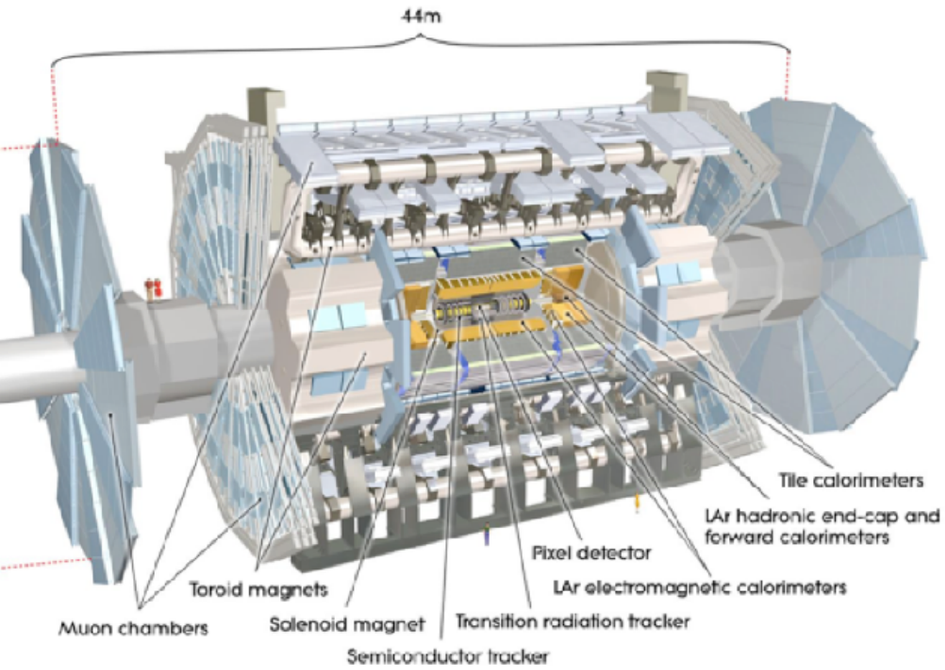


- This view shows the plane in the proton beam direction

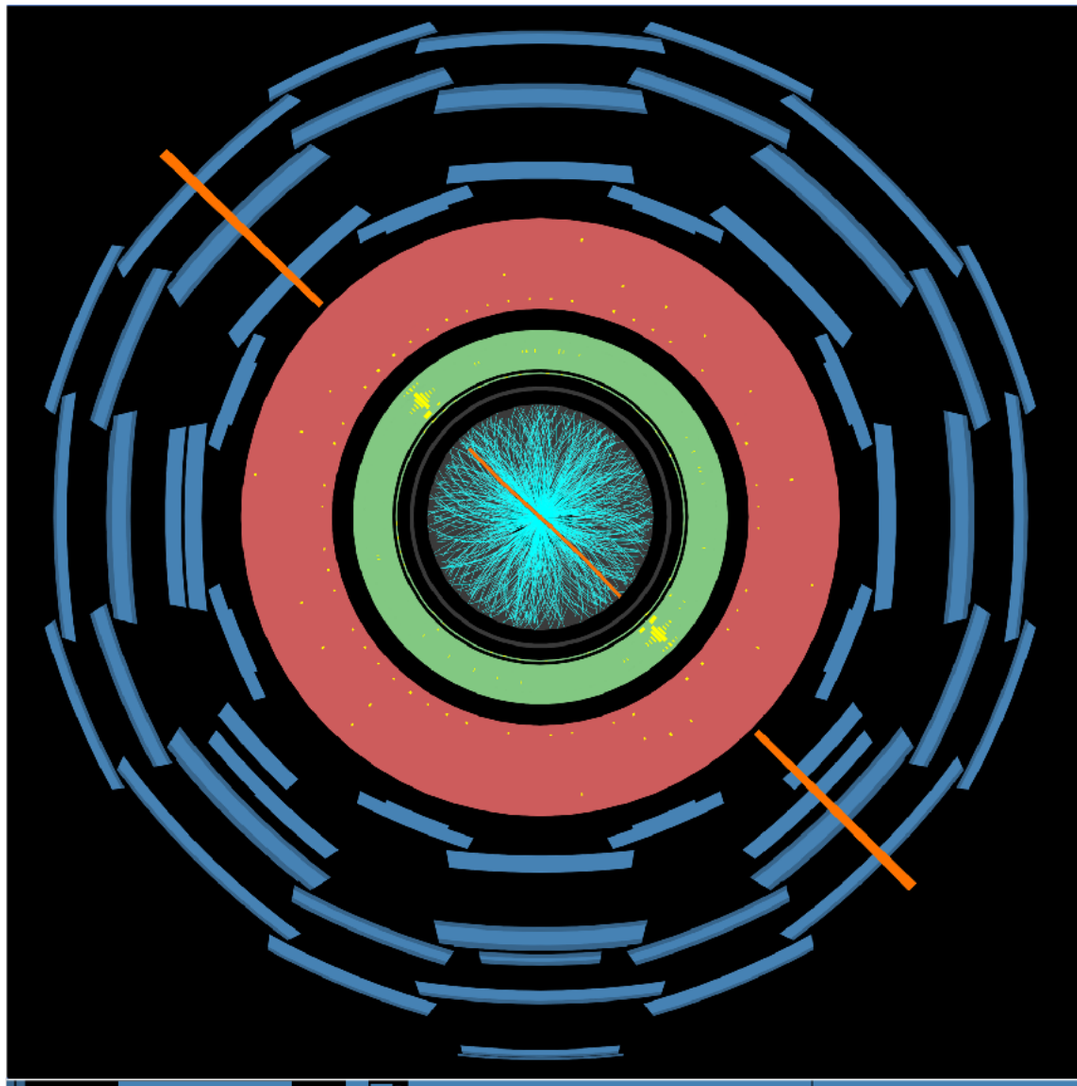
- Both **2D** views are often used to provide complementary information

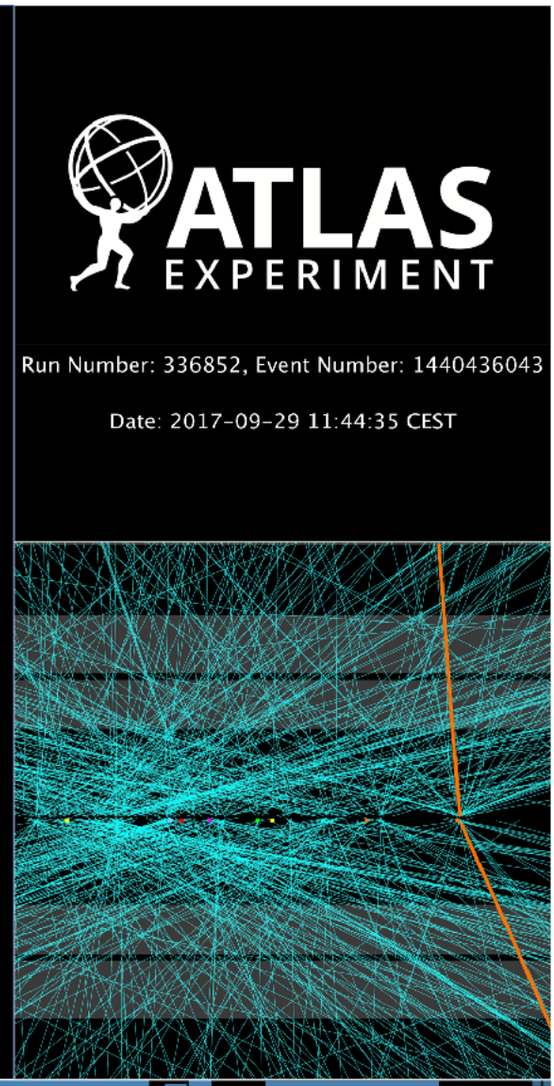


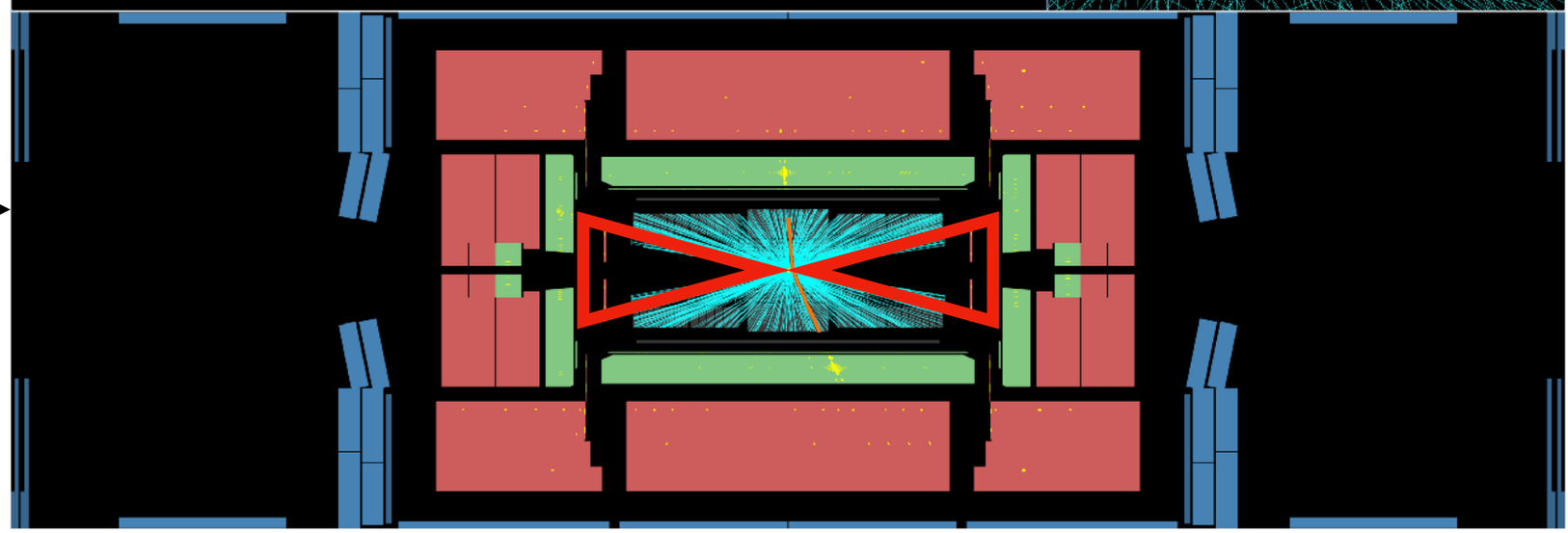
Event displays



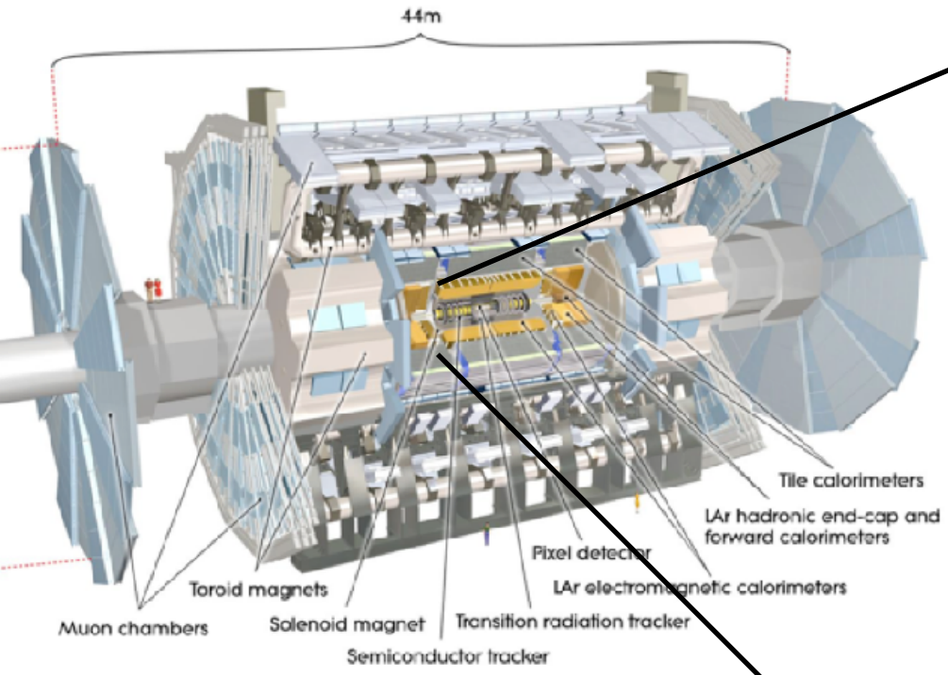
- Why are there gaps in the event display?

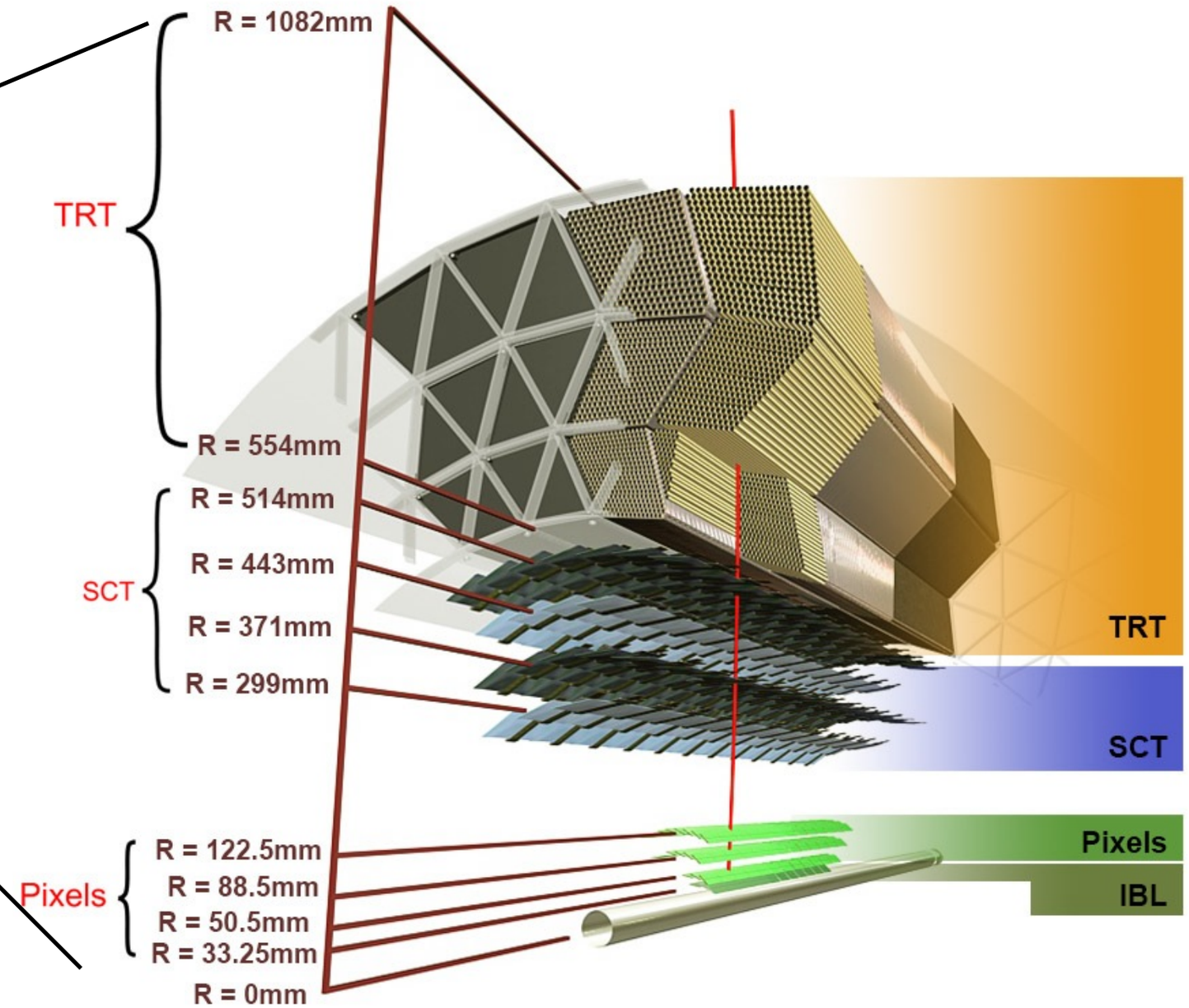






Detectors are real !

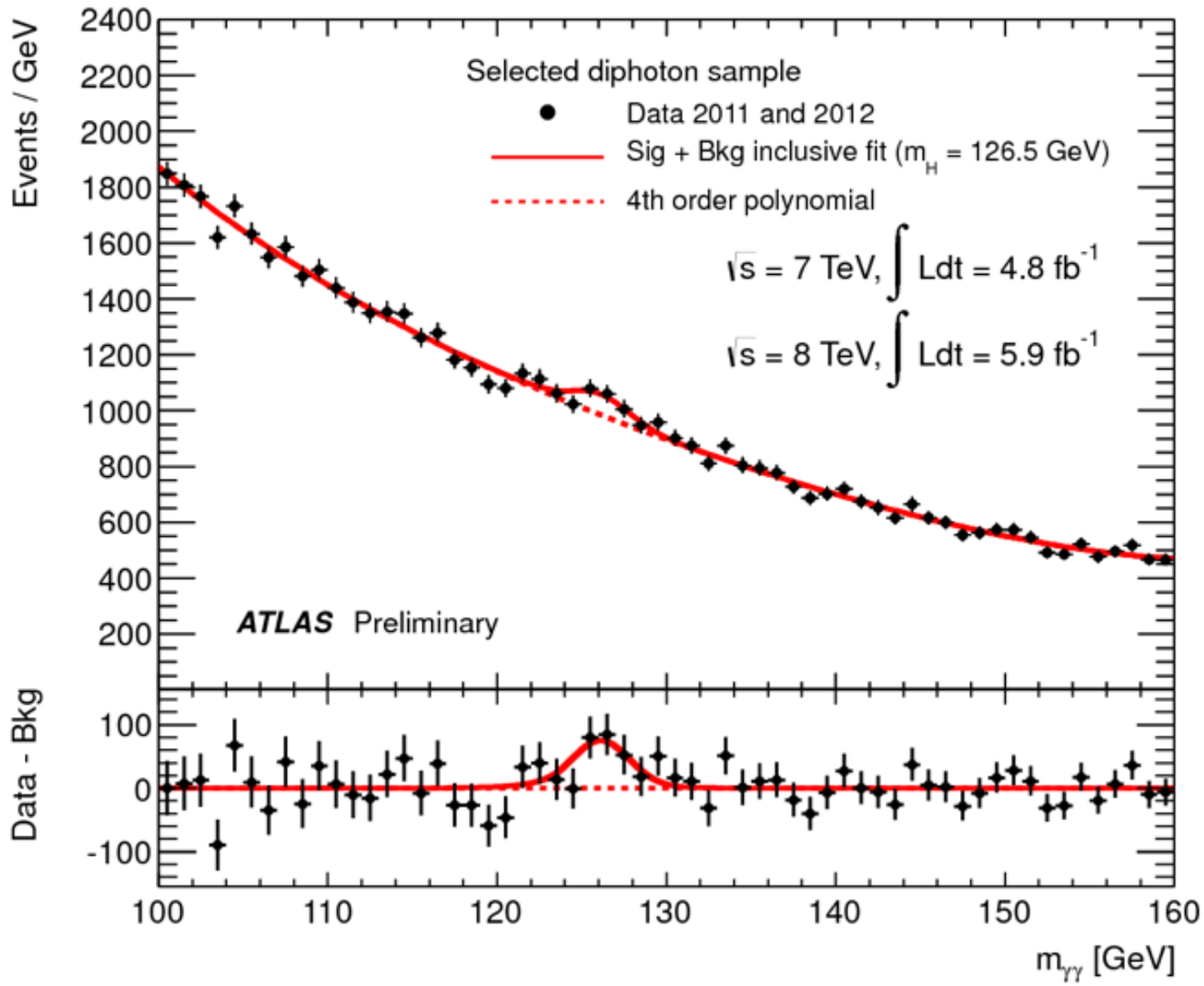




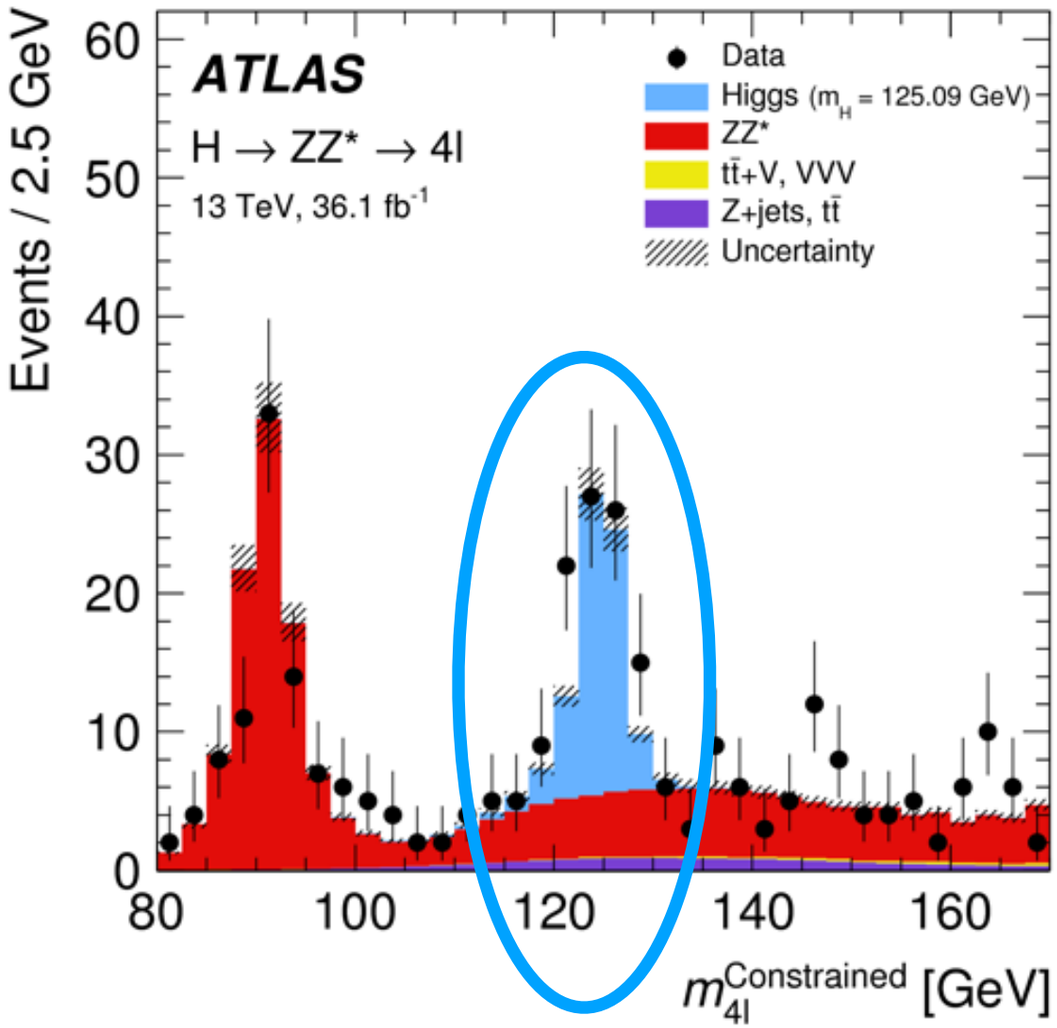
- There are gaps in the detector !

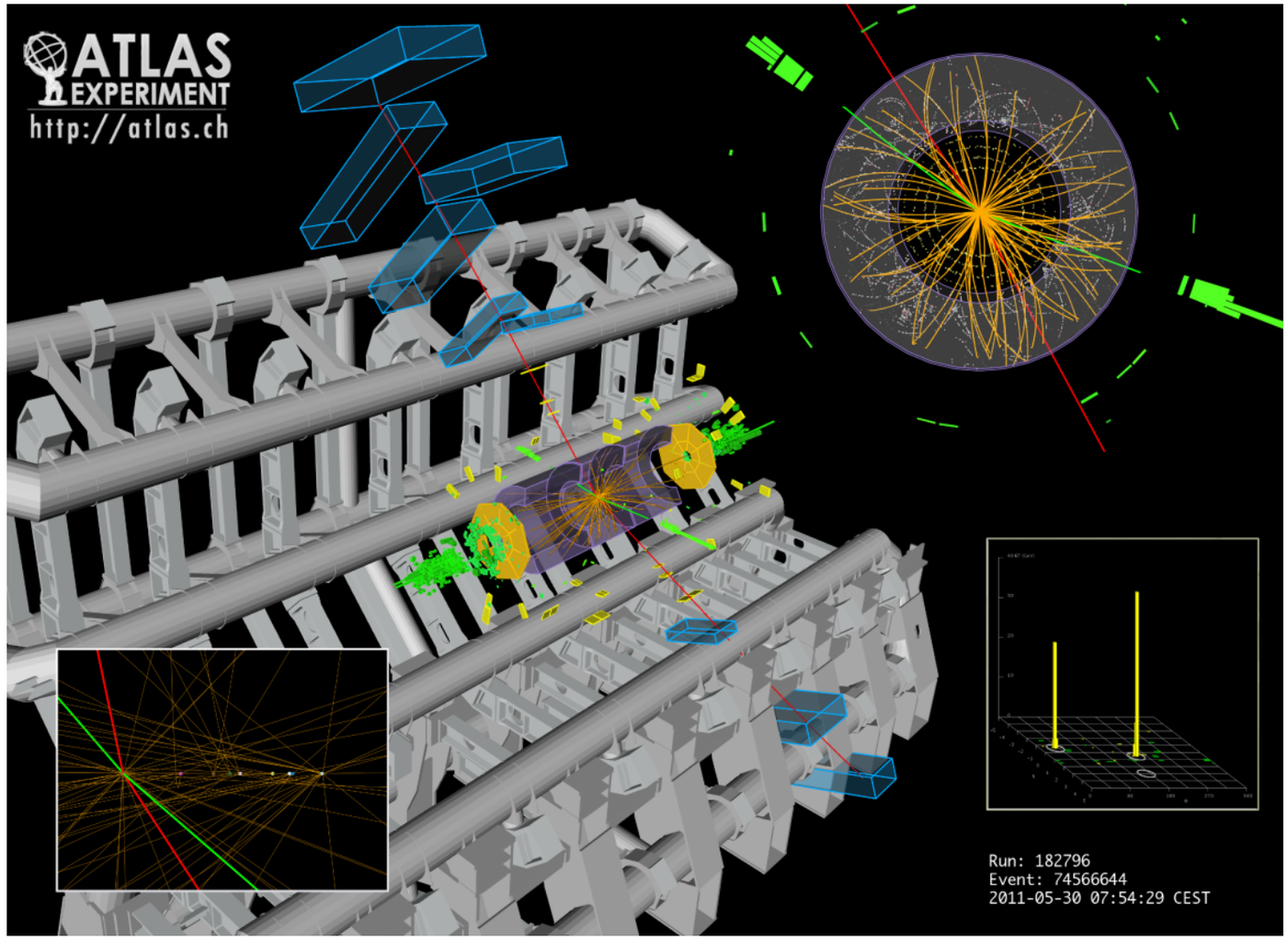
Discovering the Higgs boson: $H \rightarrow \gamma\gamma$

- 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***



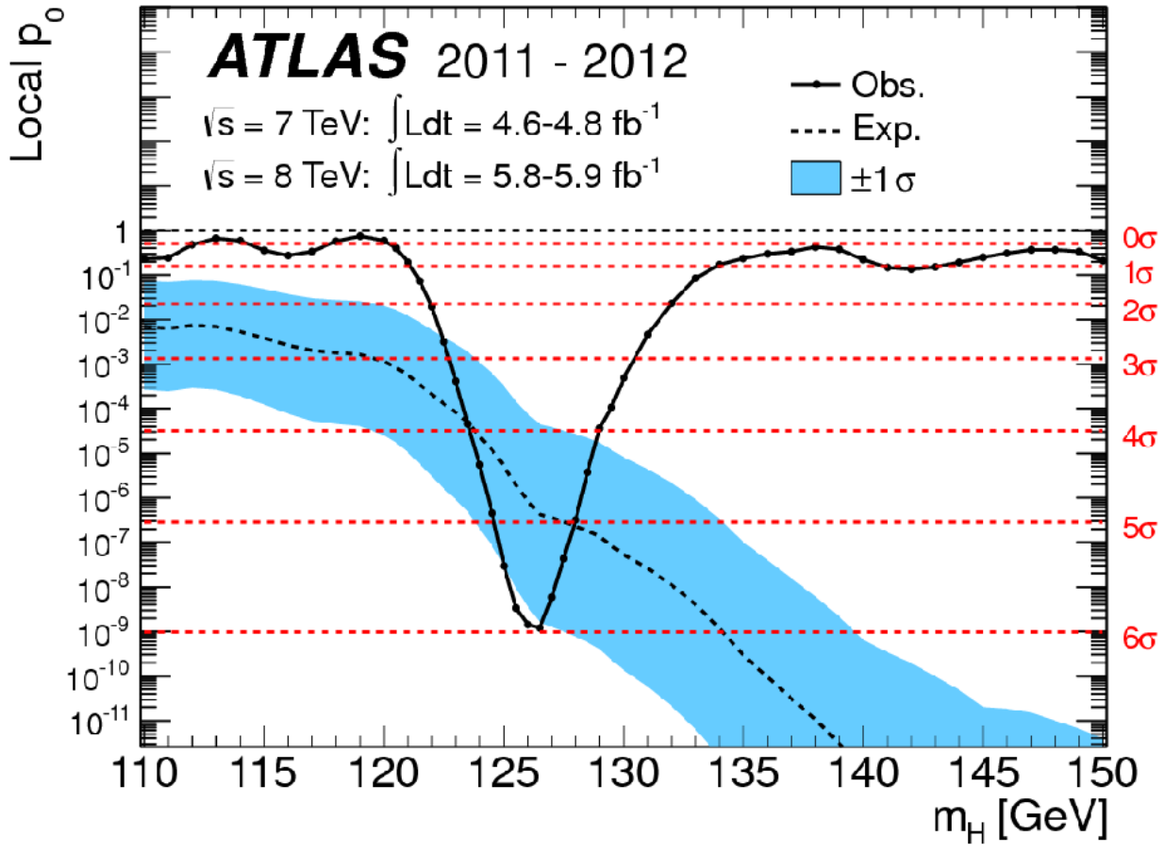
Discovering the Higgs Boson: $H \rightarrow ZZ \rightarrow 4l$





- 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**

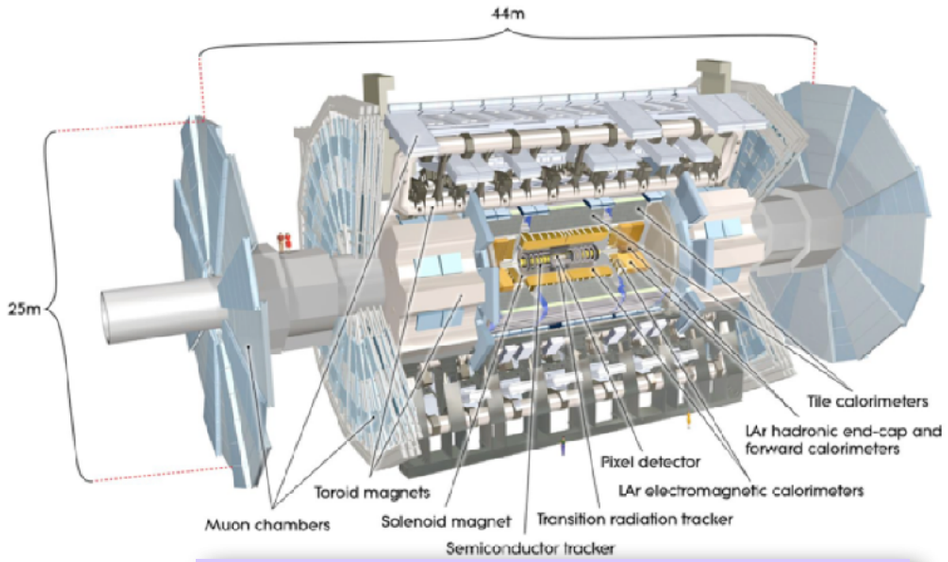
Higgs discovery on July 4th 2012



- 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**)

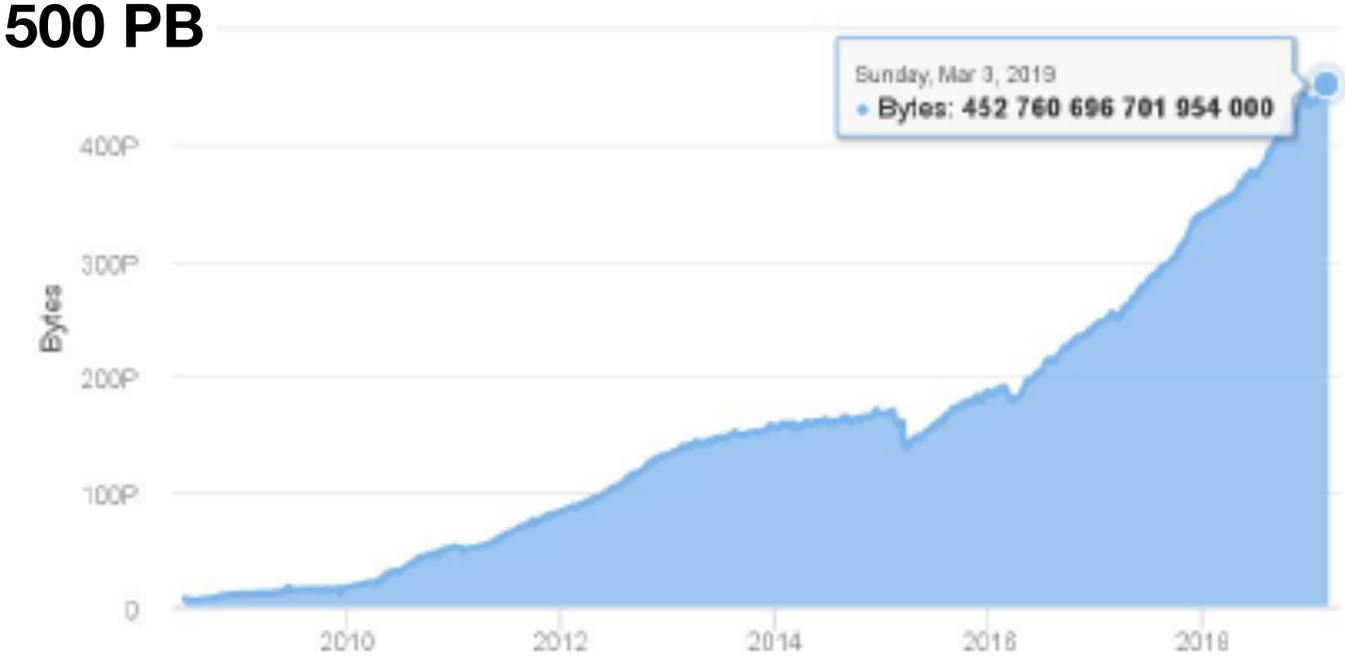
- ***Question*** *- Imagine we had several more Large Hadron Colliders, with a total of 9 independent measurements possible. Roughly how many measurements would you expect to lie* ***outside*** *the ±1σ blue band?*

Exabyte-scale physics analysis



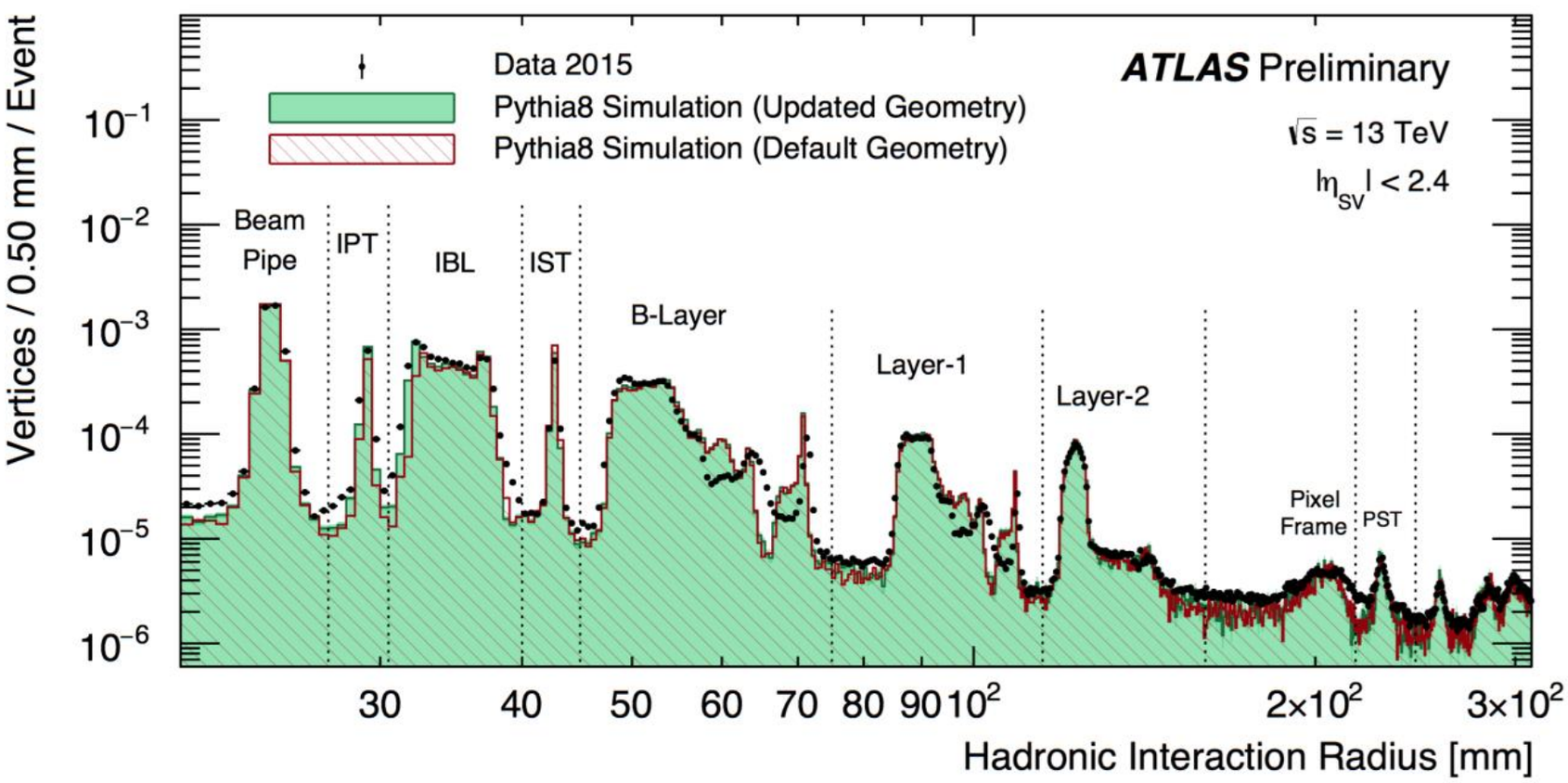
Exabytes of Data

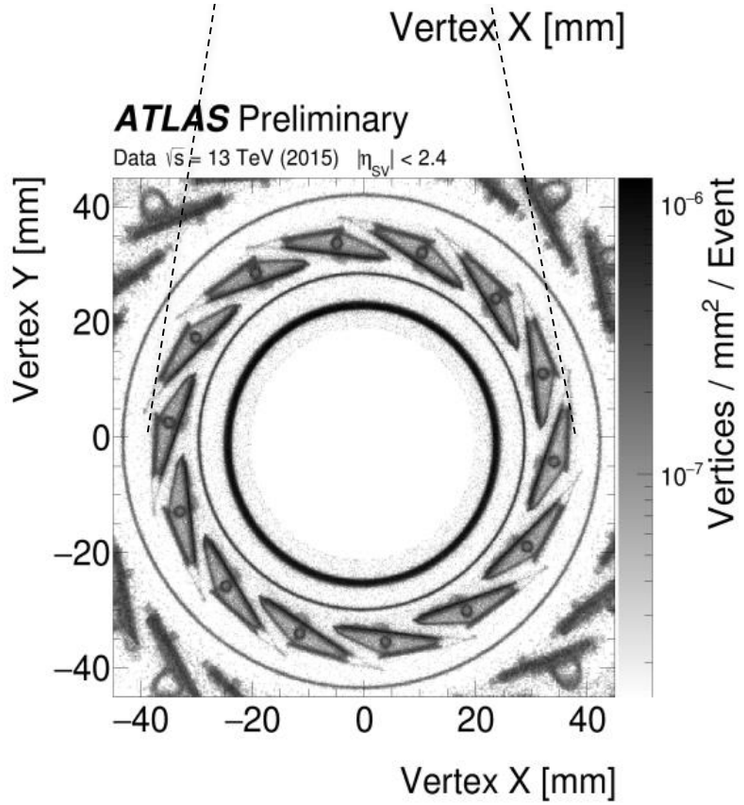
500 PB



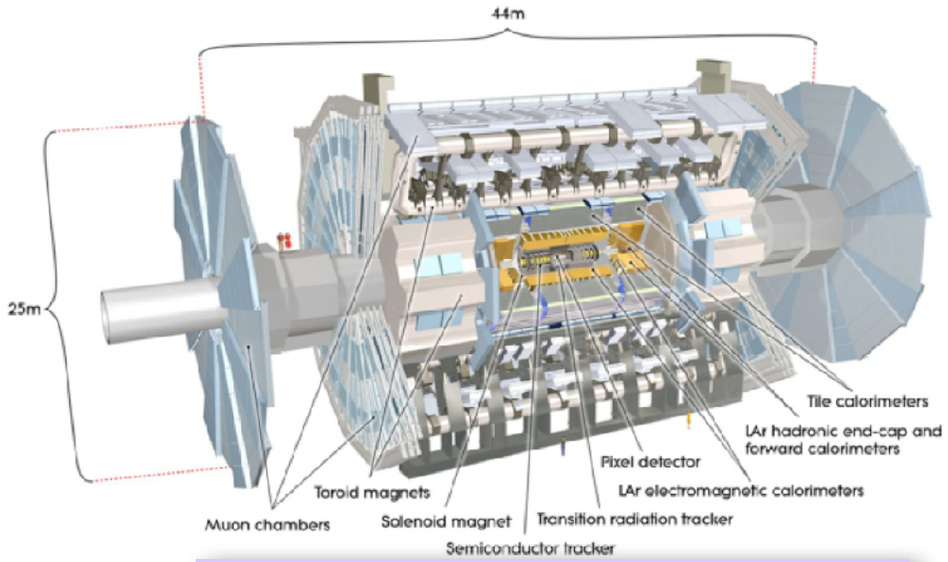
Simulation and understanding detectors

- 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***



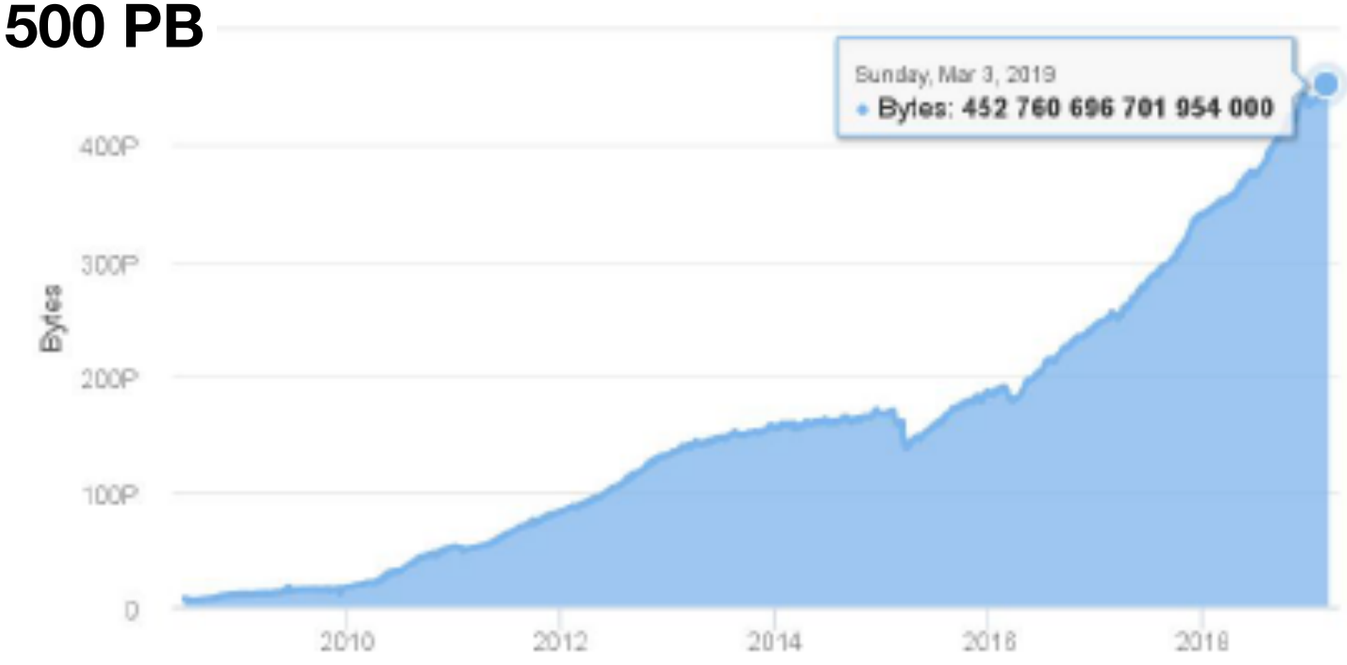


Exabyte-scale physics analysis

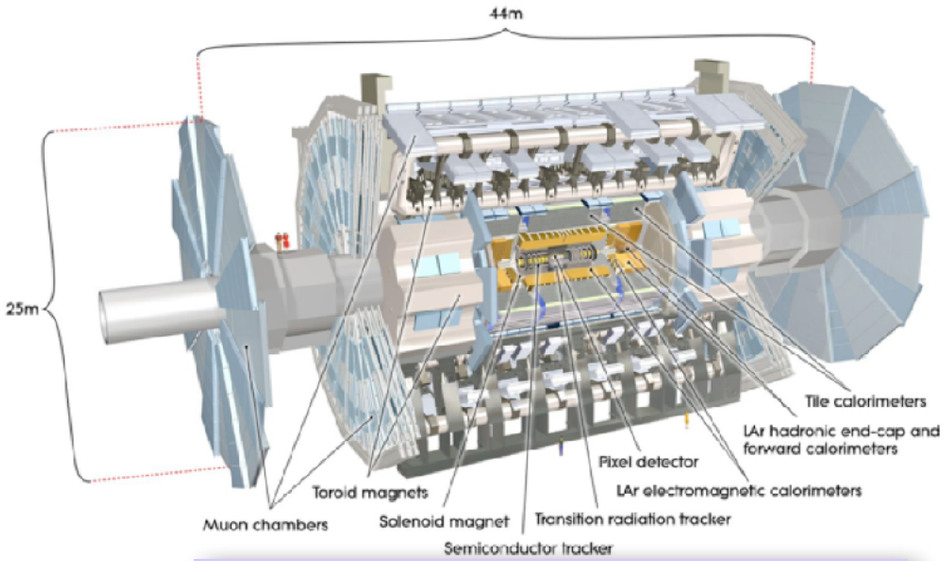


Exabytes of Data

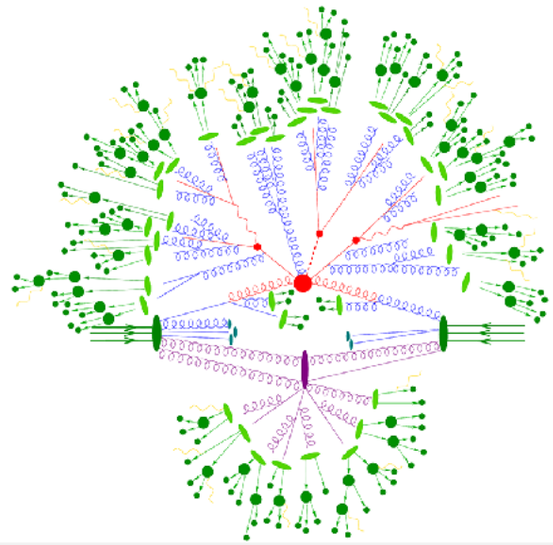
500 PB



Exabyte-scale physics analysis

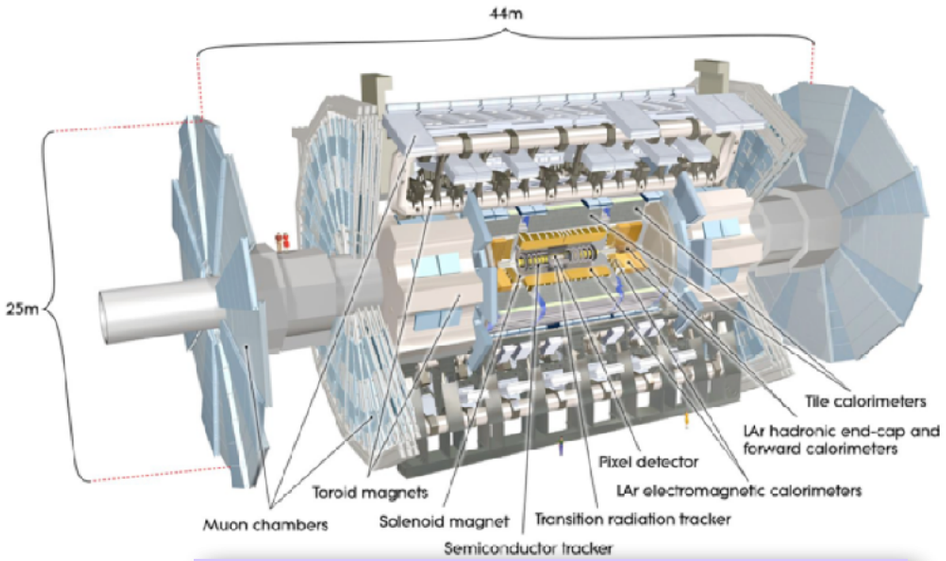


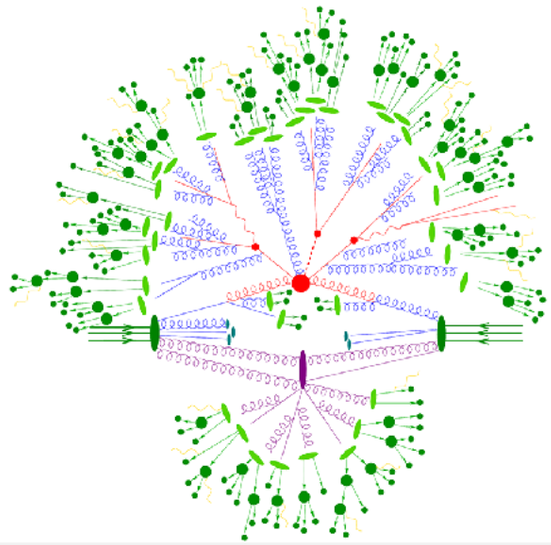
Exabytes of Data



Exabytes of Simulation

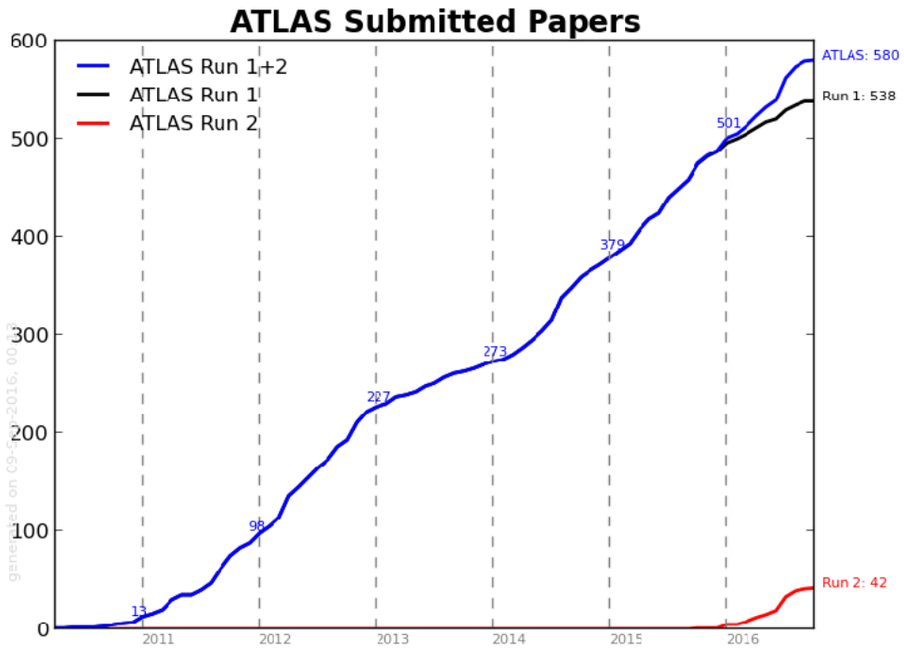
Exabyte-scale physics analysis





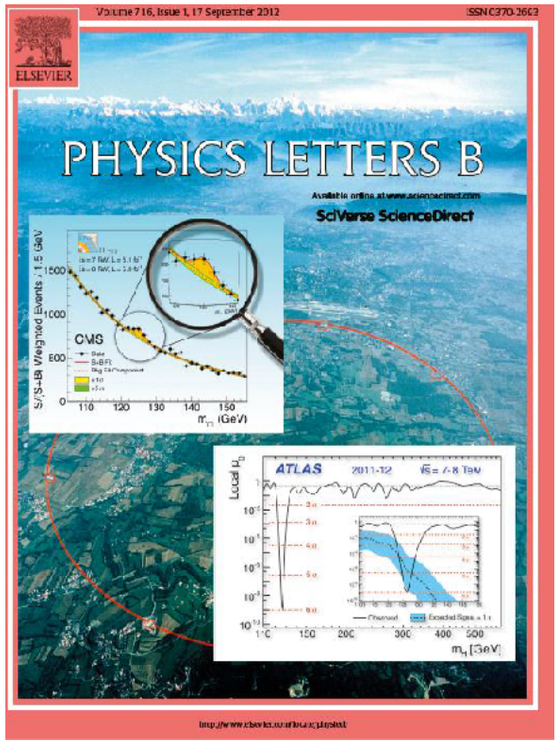
Exabytes of Data

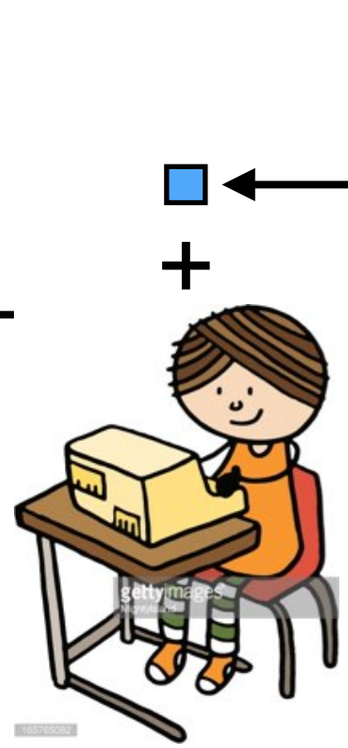
Exabytes of Simulation

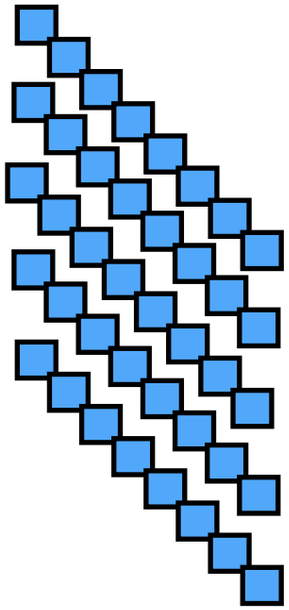


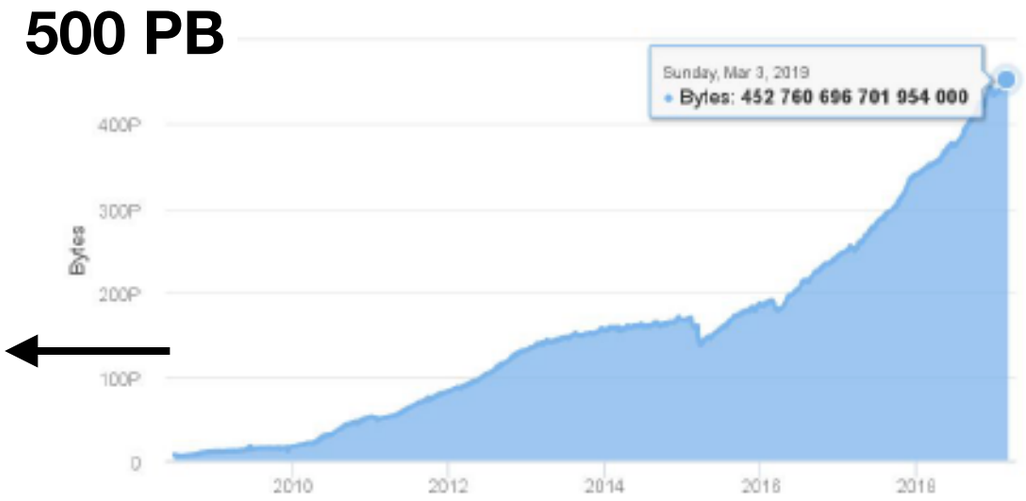
Publish!

Data analysis



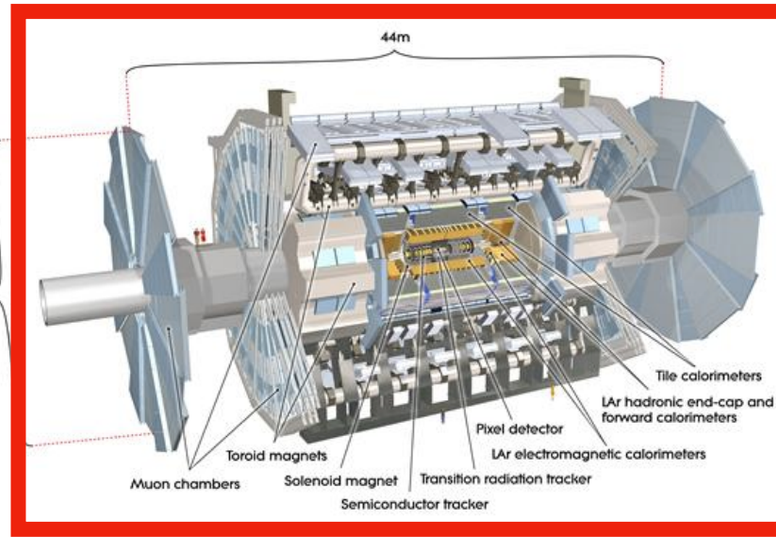






- *Analysis is performed on only a fraction of the data, for example only events with two photons*
- *How?*

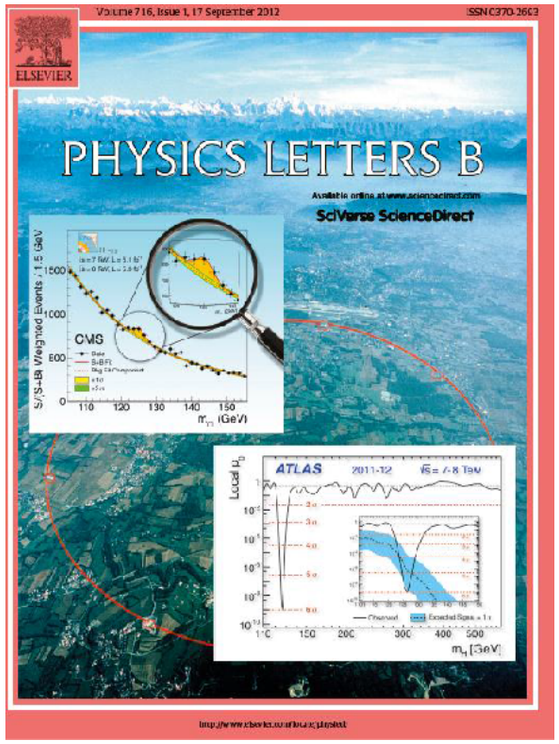
Data's journey



Trigger/DAQ

Data Preparation

Distributed computing



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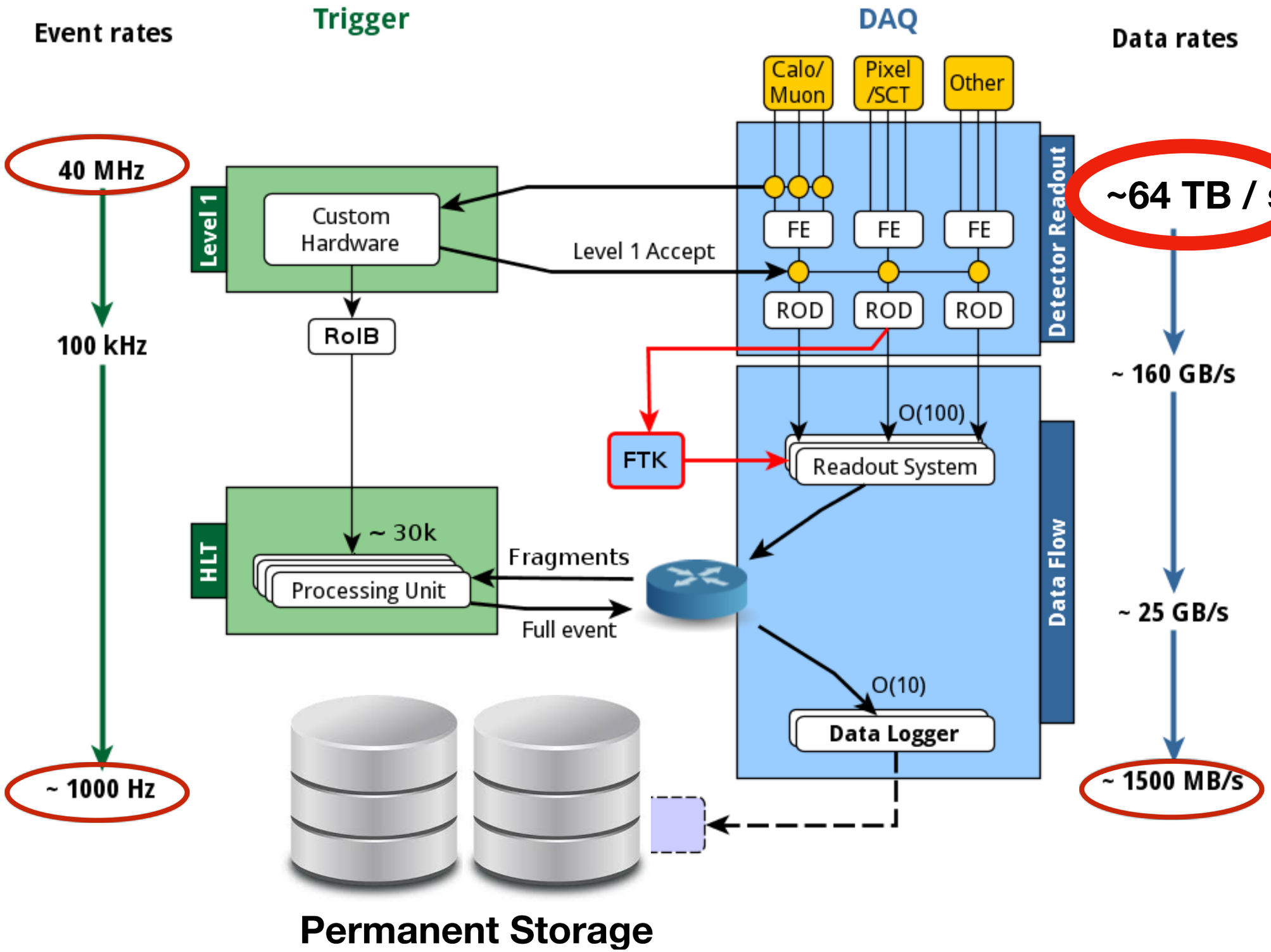
The Atlas Trigger and DAQ

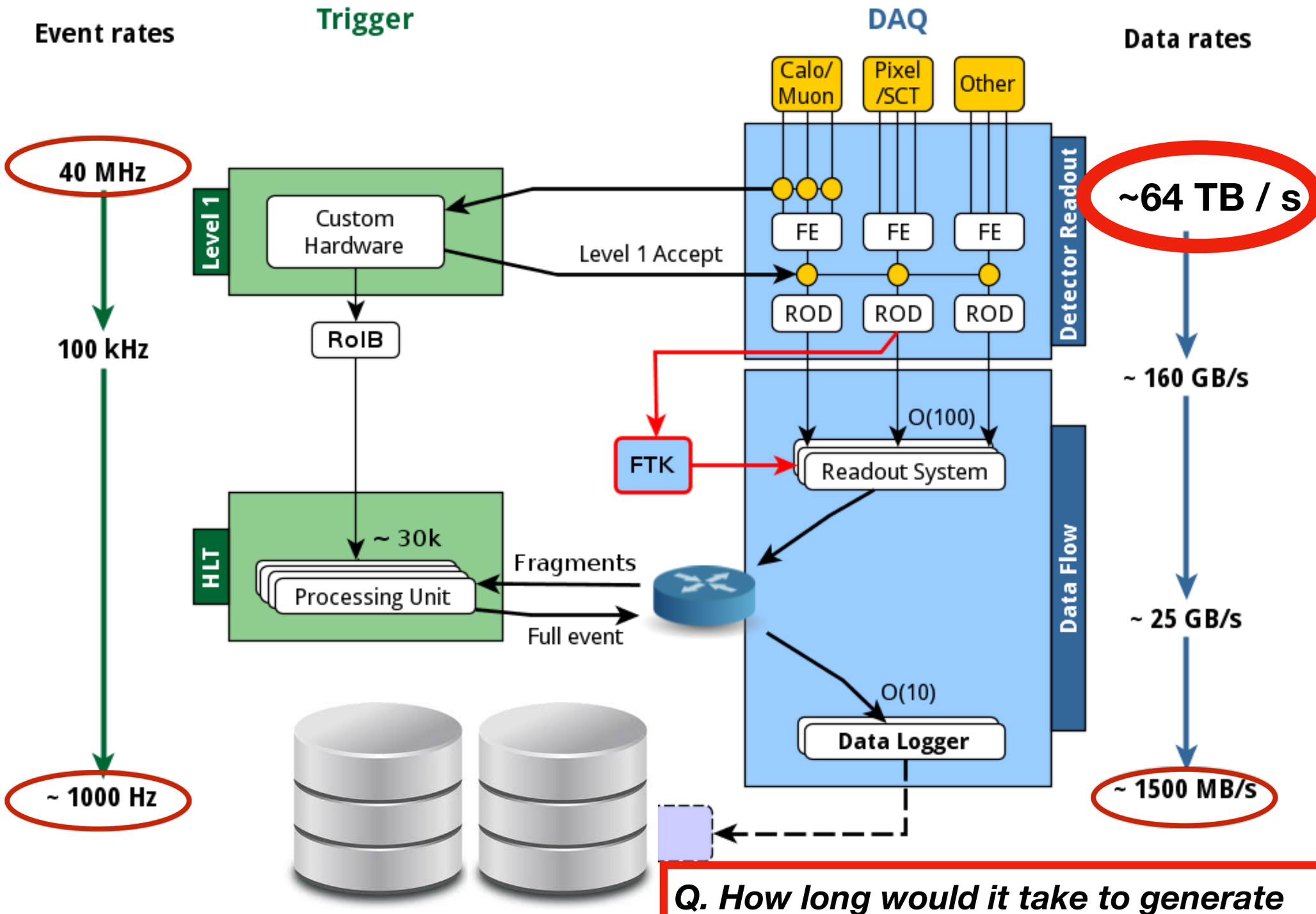
Rate of all proton-proton collisions produced by the LHC



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

The Atlas Trigger and DAQ

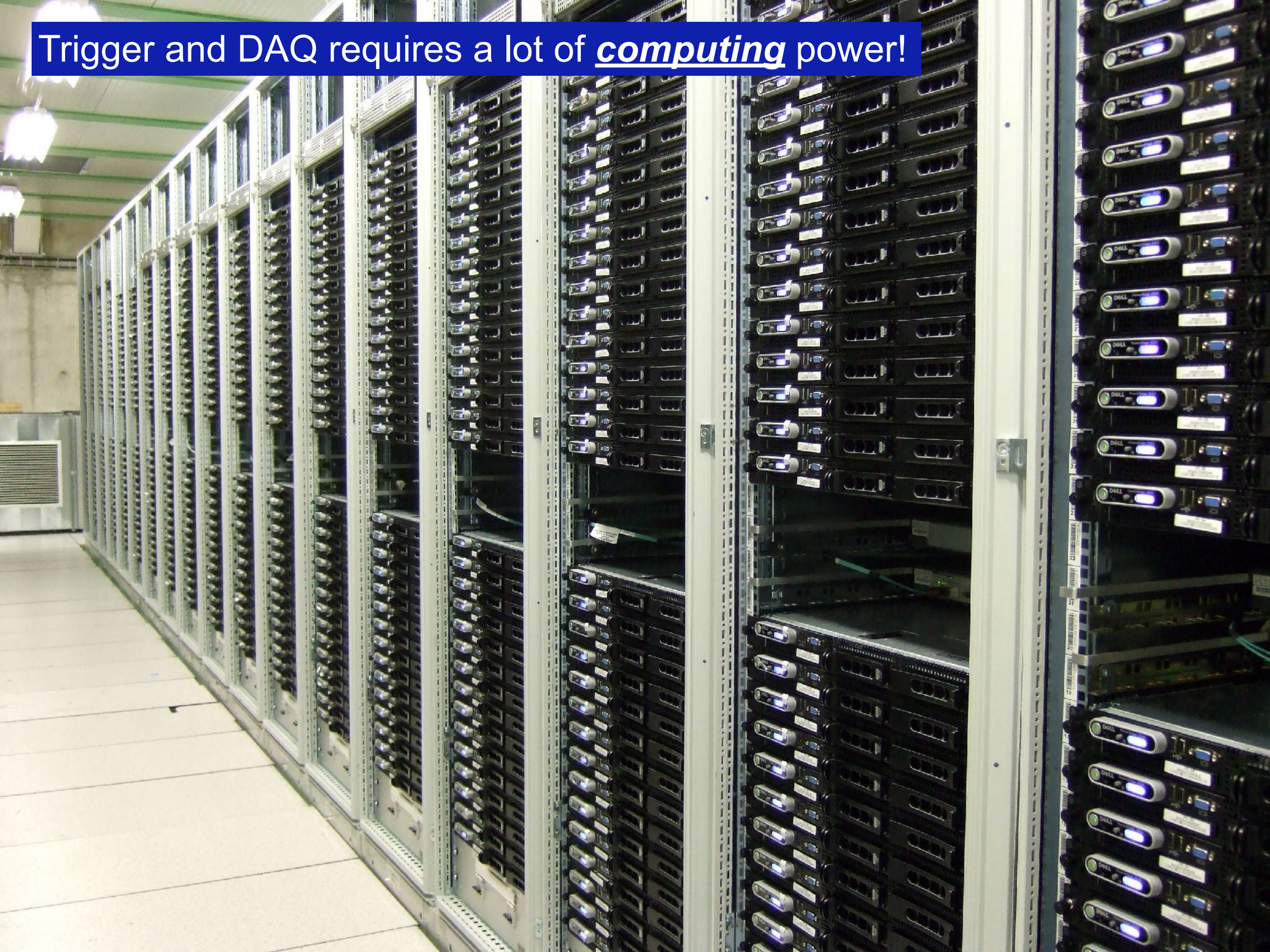
Rate of all proton-proton collisions produced by the LHC



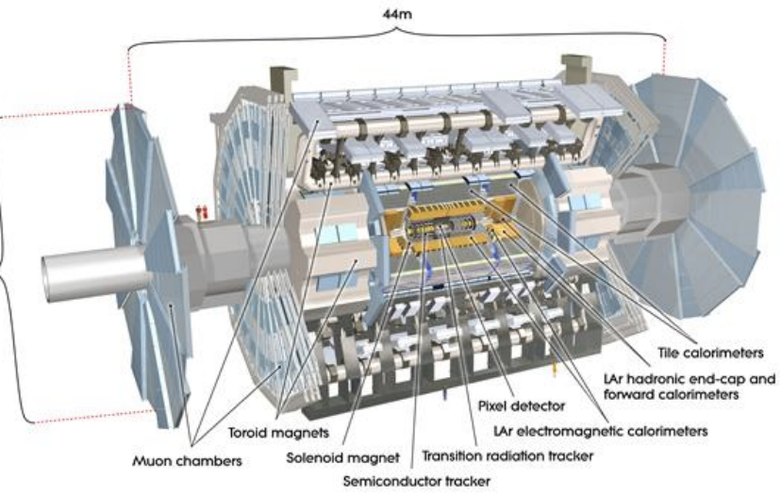
Rate of all *interesting* proton-proton collisions produced by the LHC

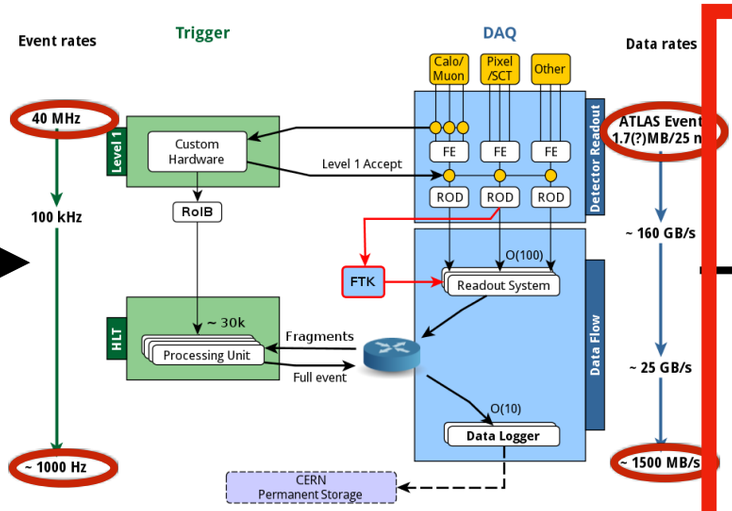
Q. How long would it take to generate 500PB of data if there were no Trigger?

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



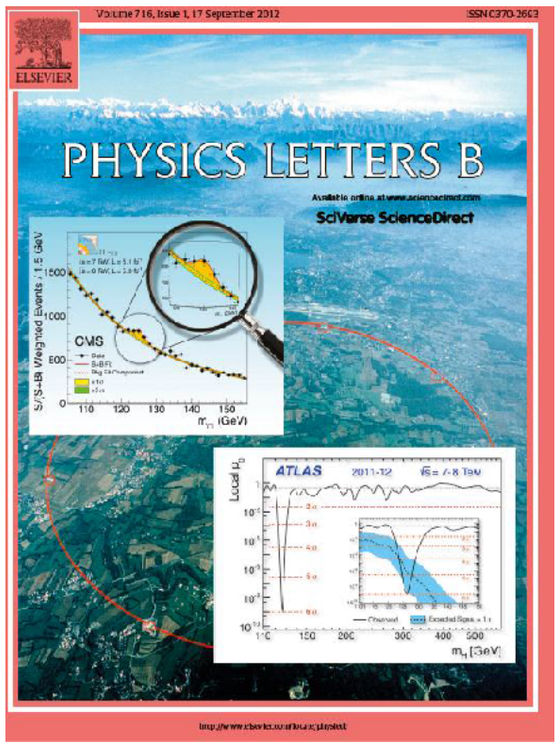
Data's journey





Data Preparation

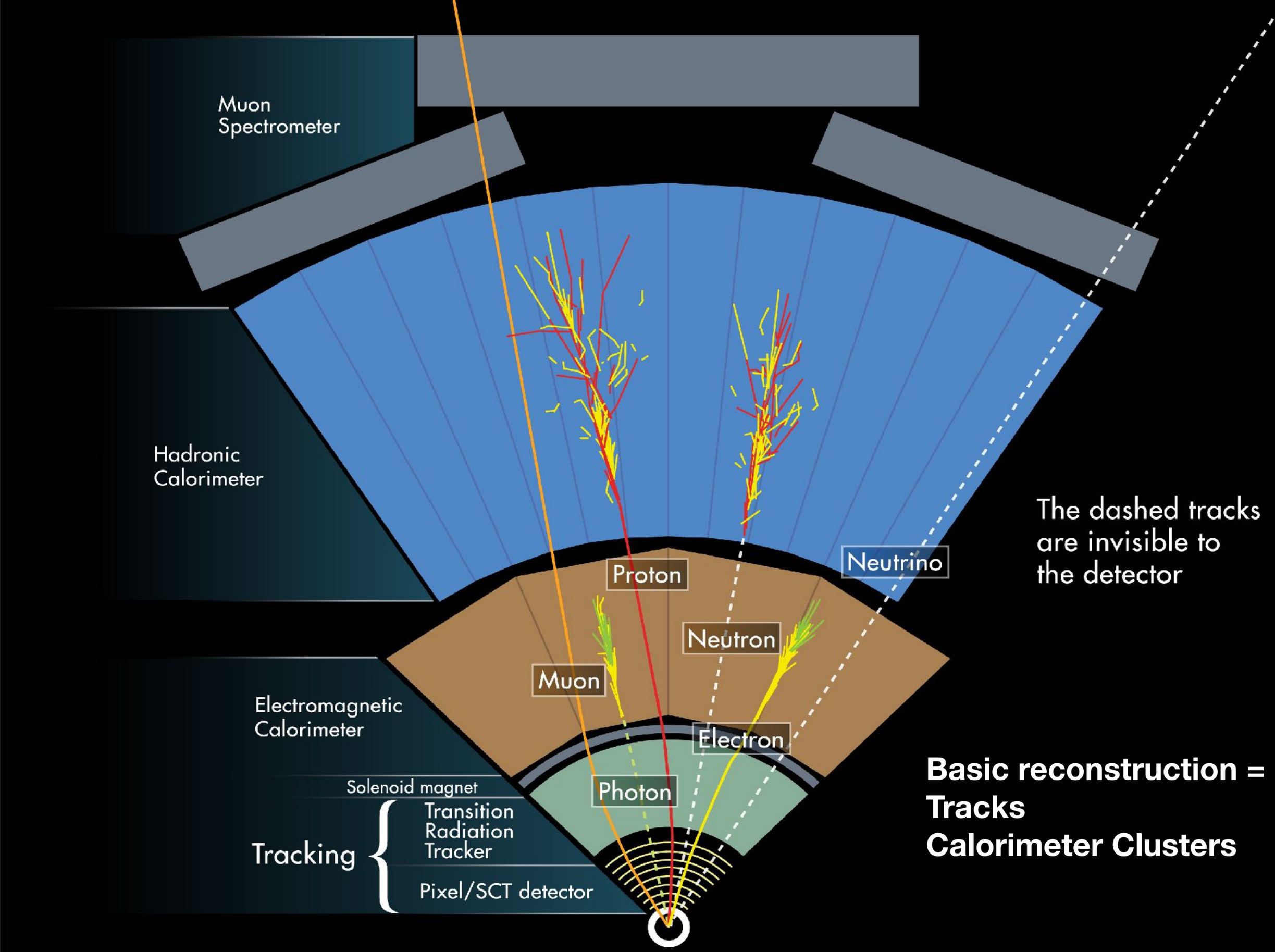
Distributed computing



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

ATLAS EXPERIMENT

Run Number: 265545, Event Number: 5720351

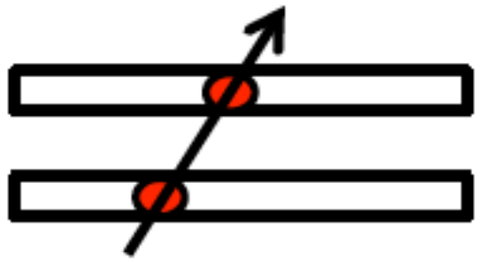
Date: 2015-05-21 10:39:54 CEST

Tracks are curved in the transverse plane

and straight in the longitudinal plane

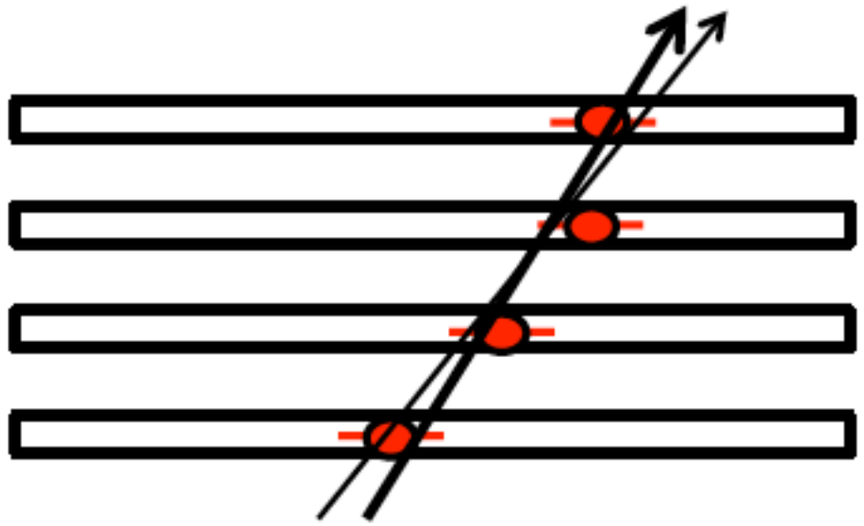
Track fitting

- 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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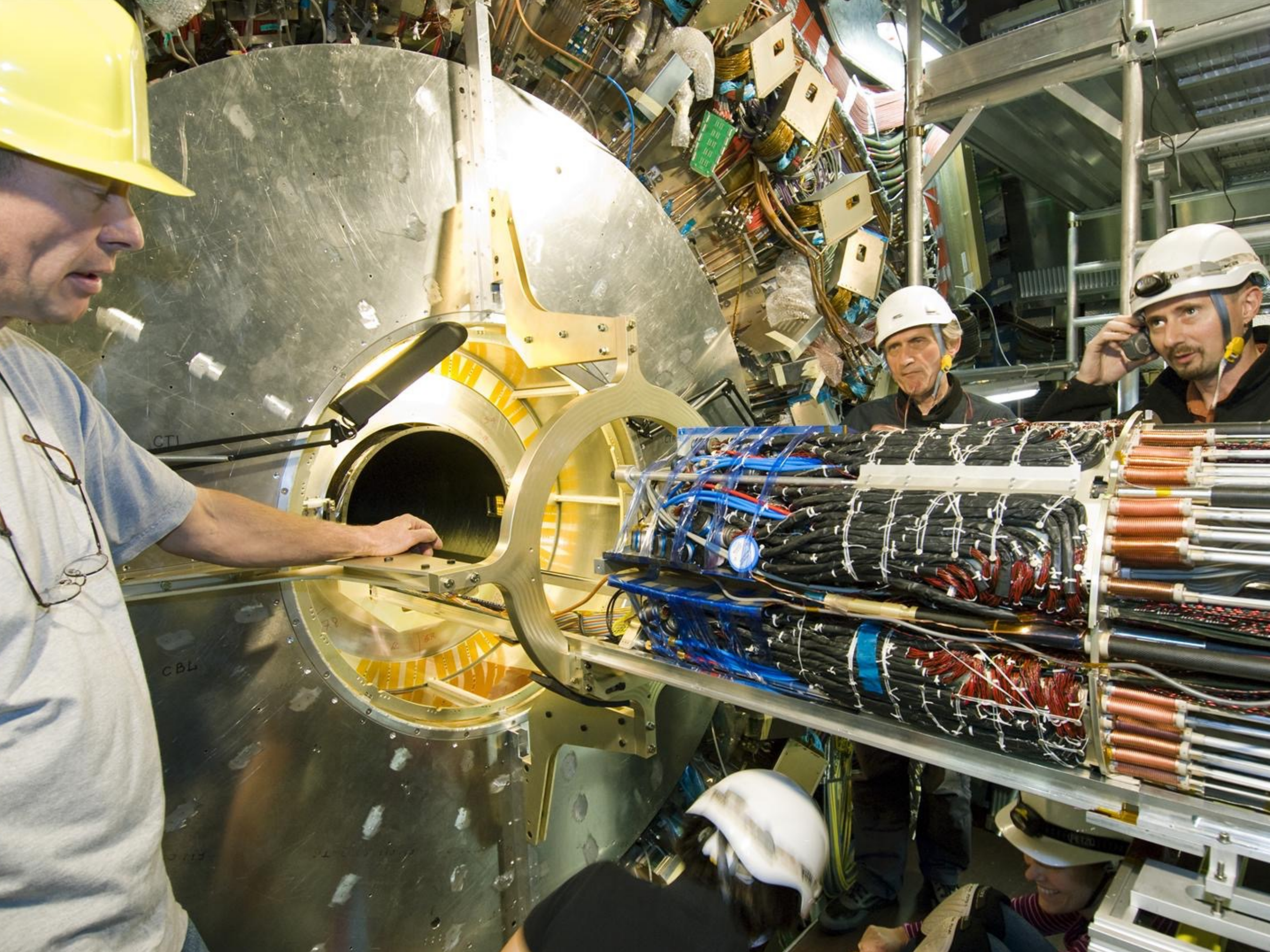
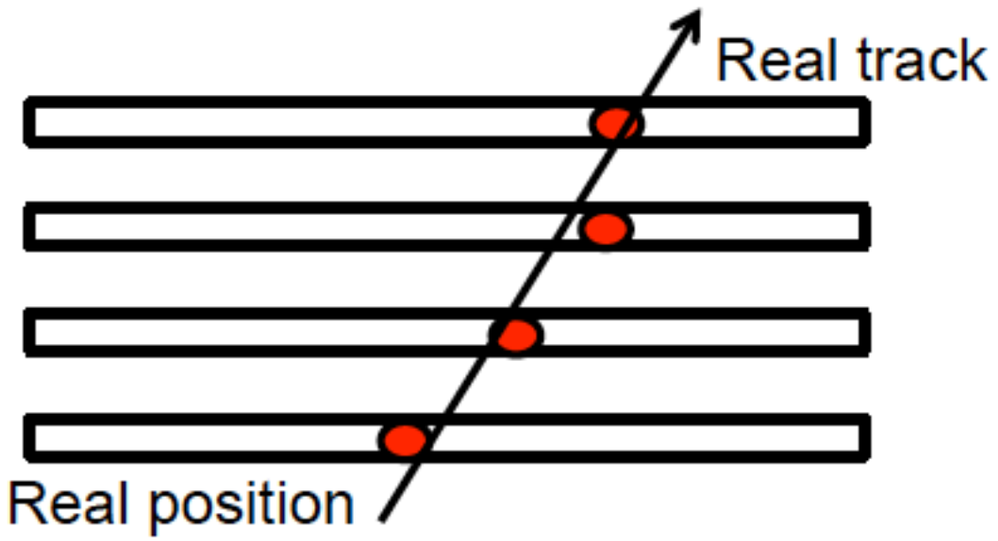


Real detector effects

- **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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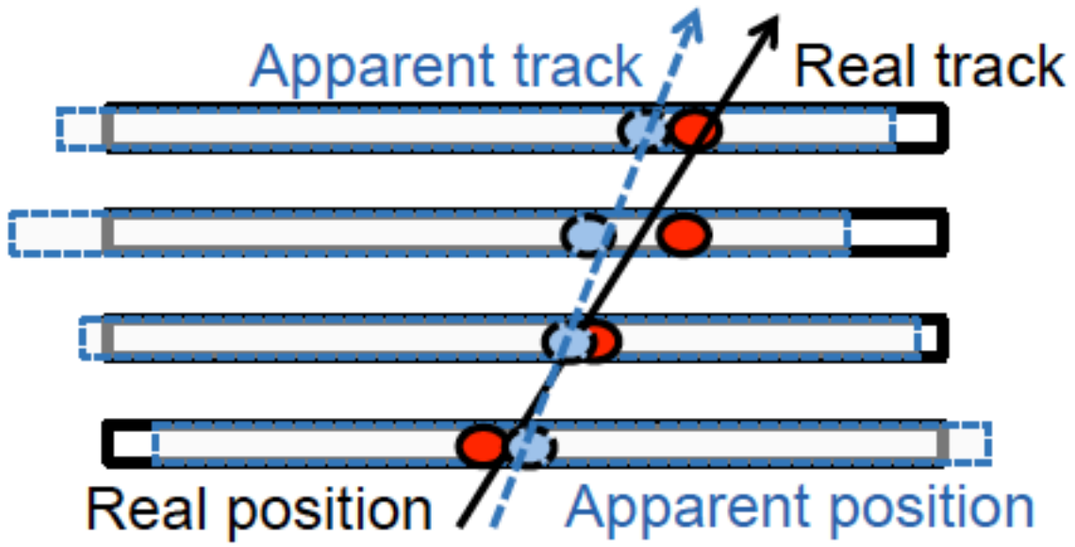

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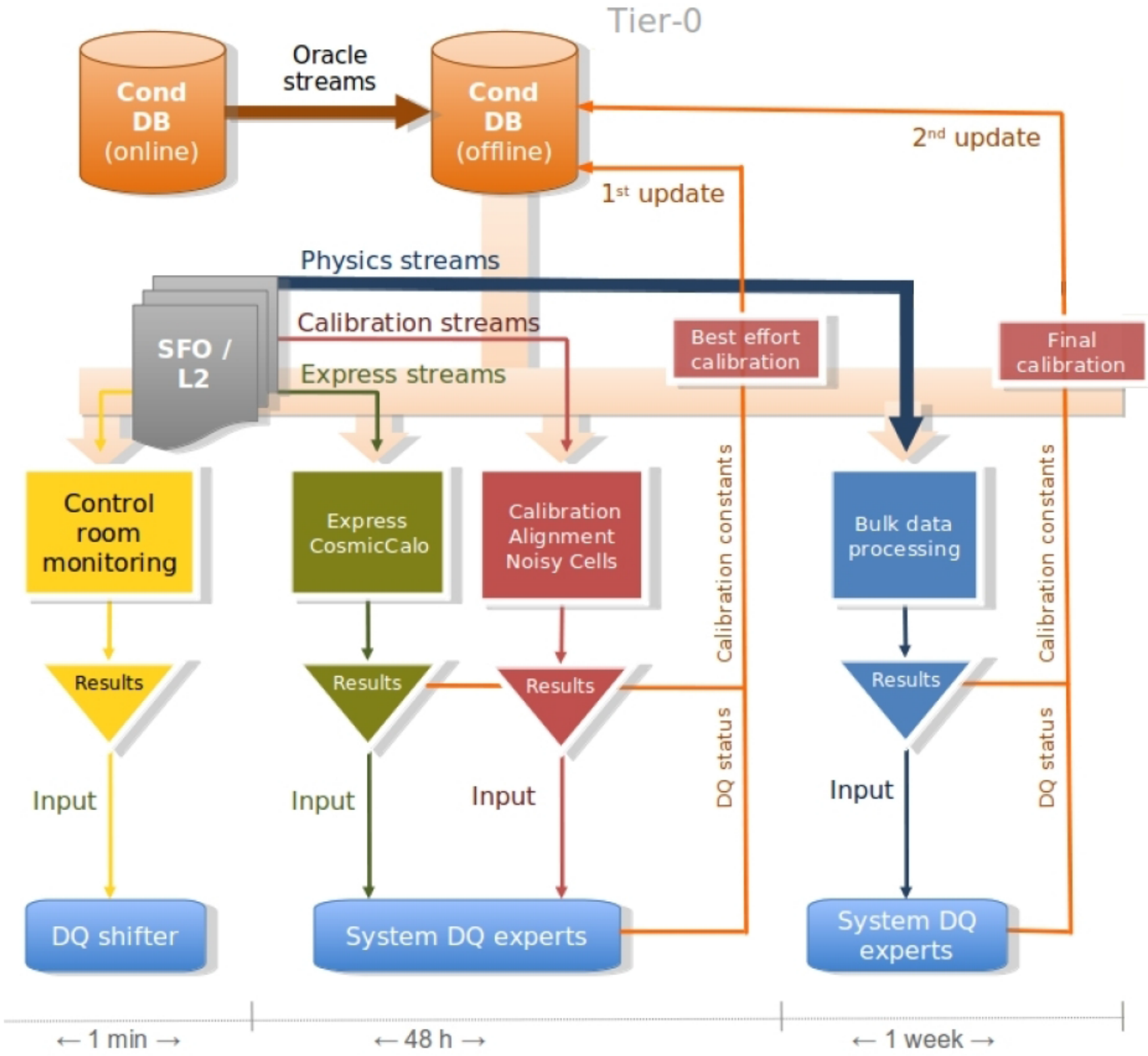
   - Maximise the amount of useful data

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 !!



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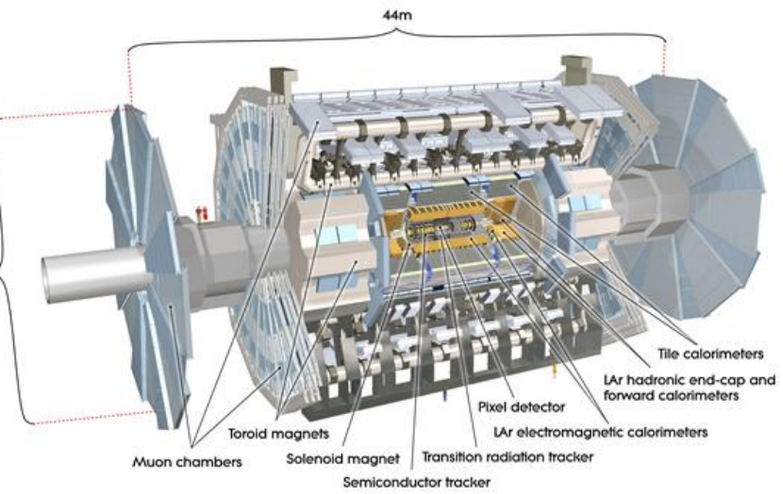
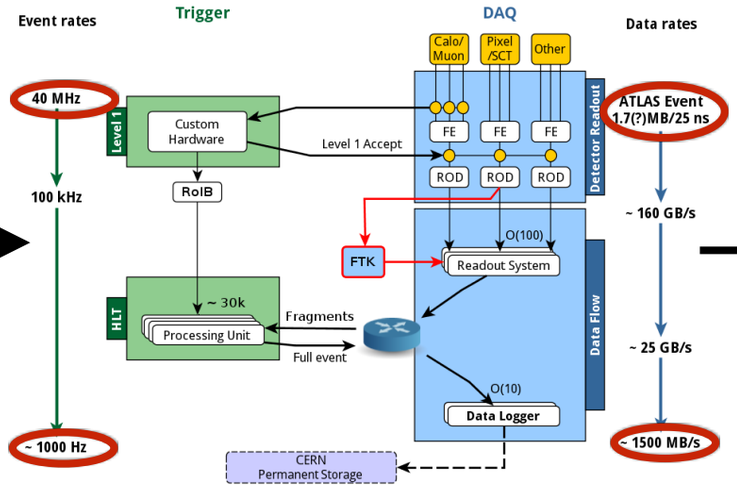
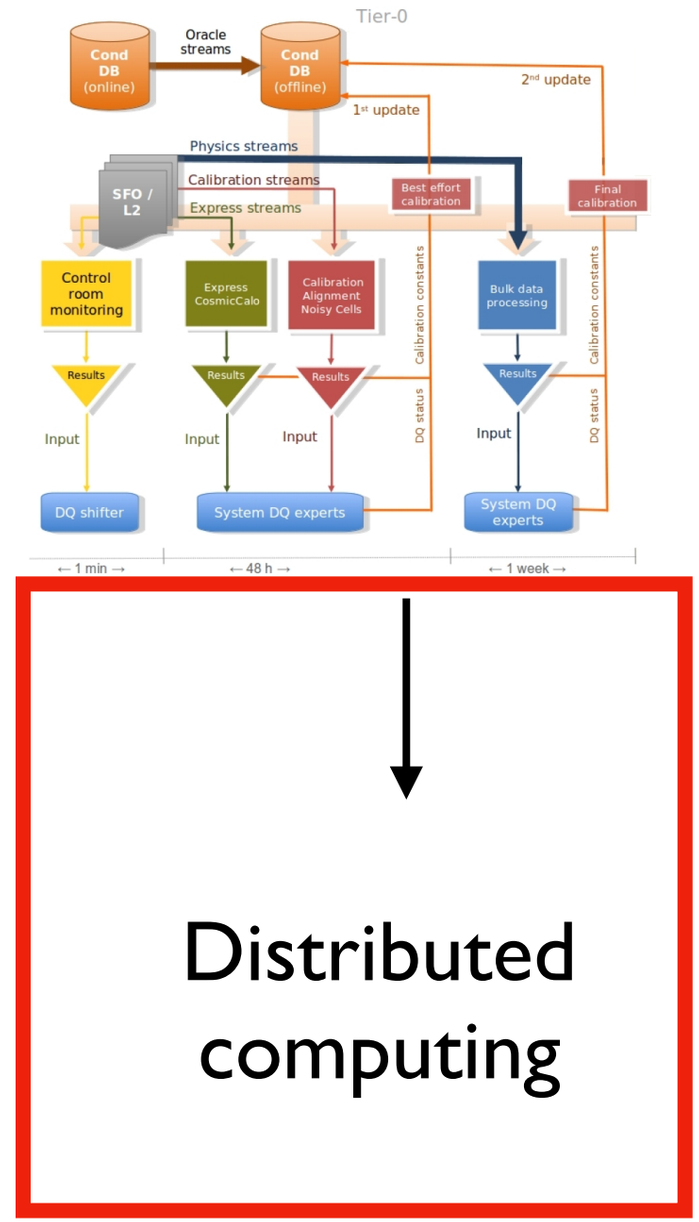
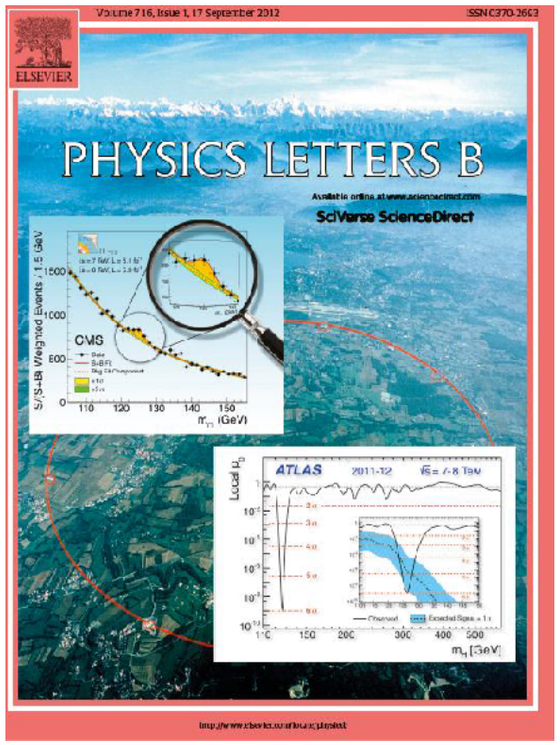
Data's journey







Distributed computing



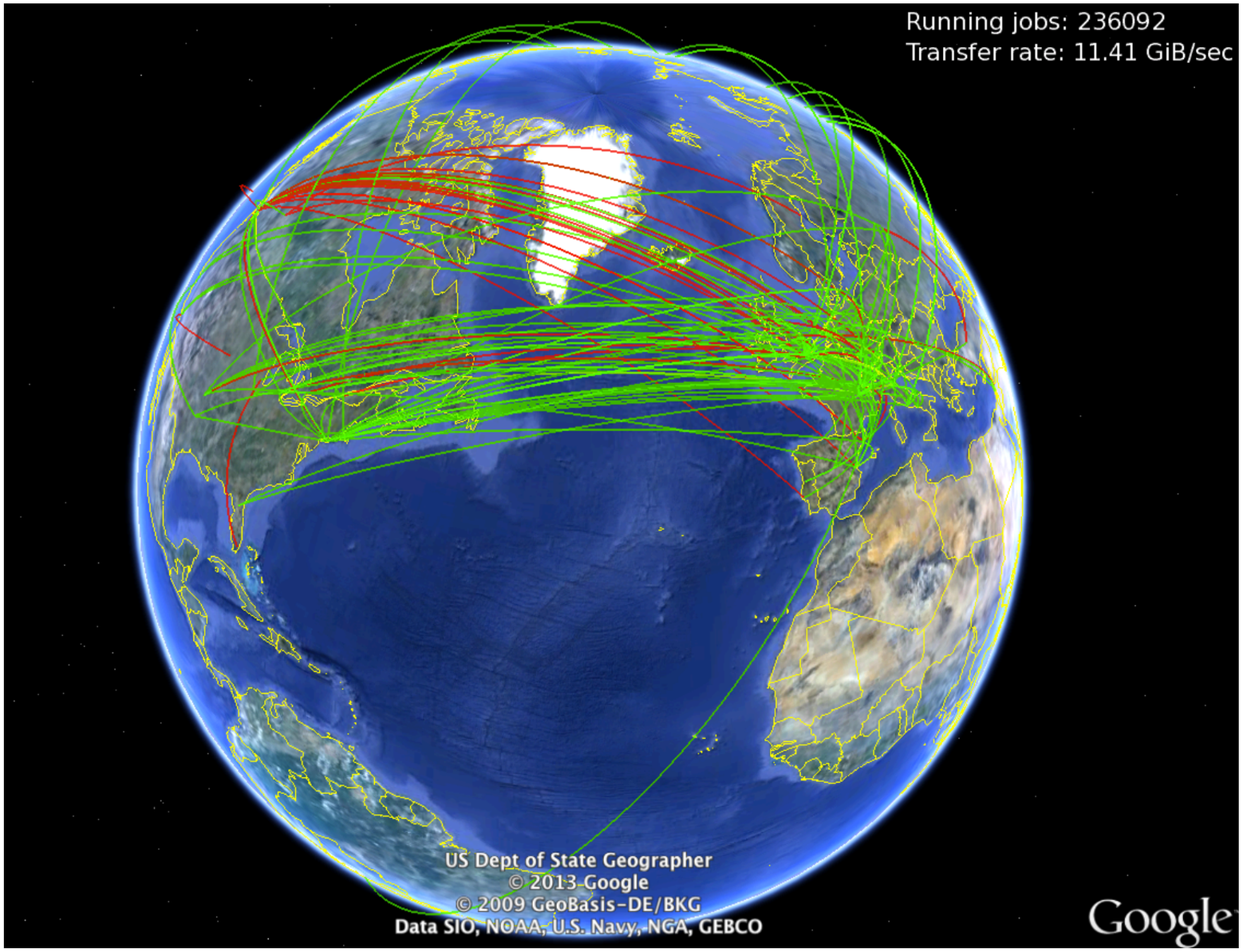
GWSC GRAVITATIONAL WAVE SCIENCE CENTER

UNIVERSITÉ DE GENÈVE Faculté des Sciences Département d'astronomie

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



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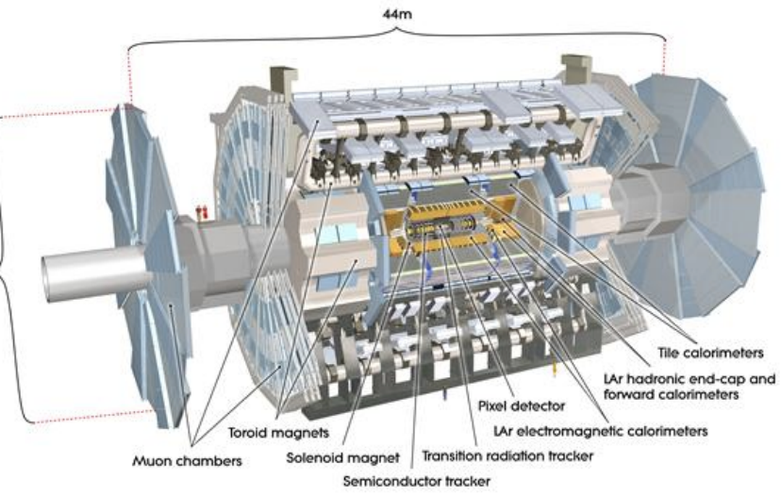
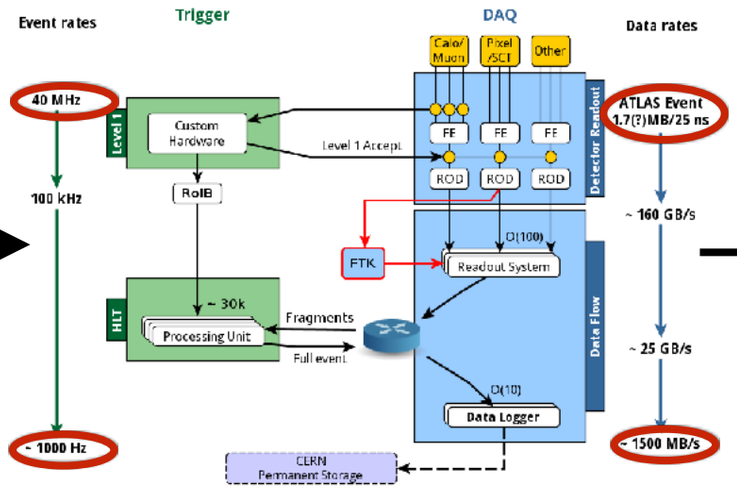
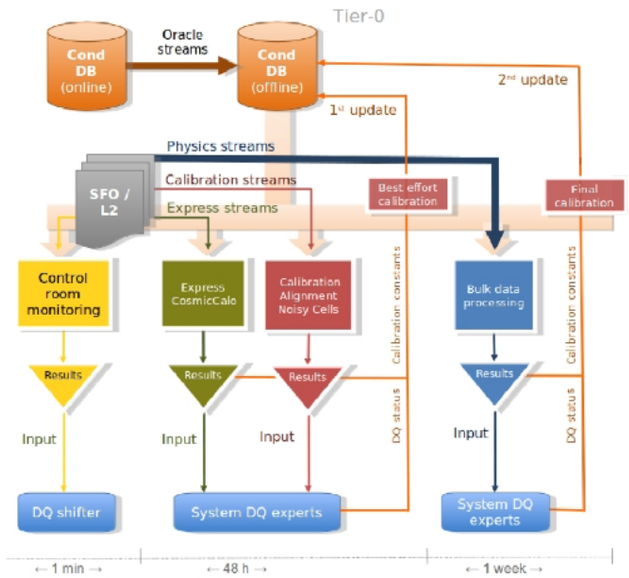
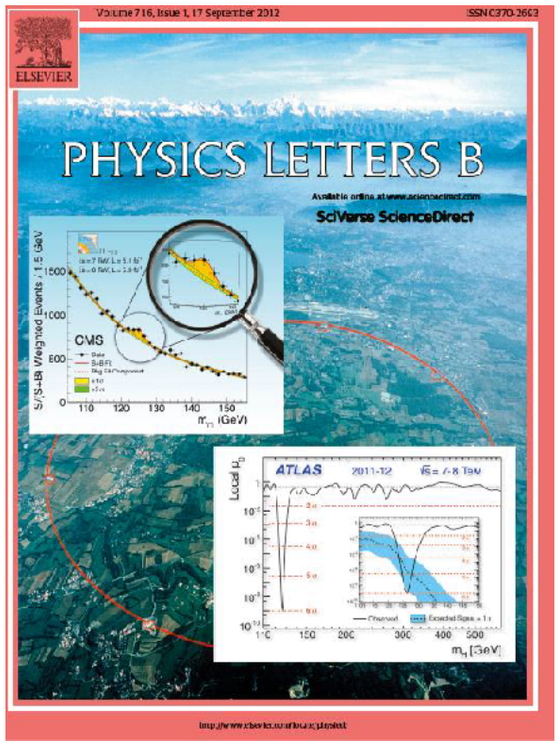
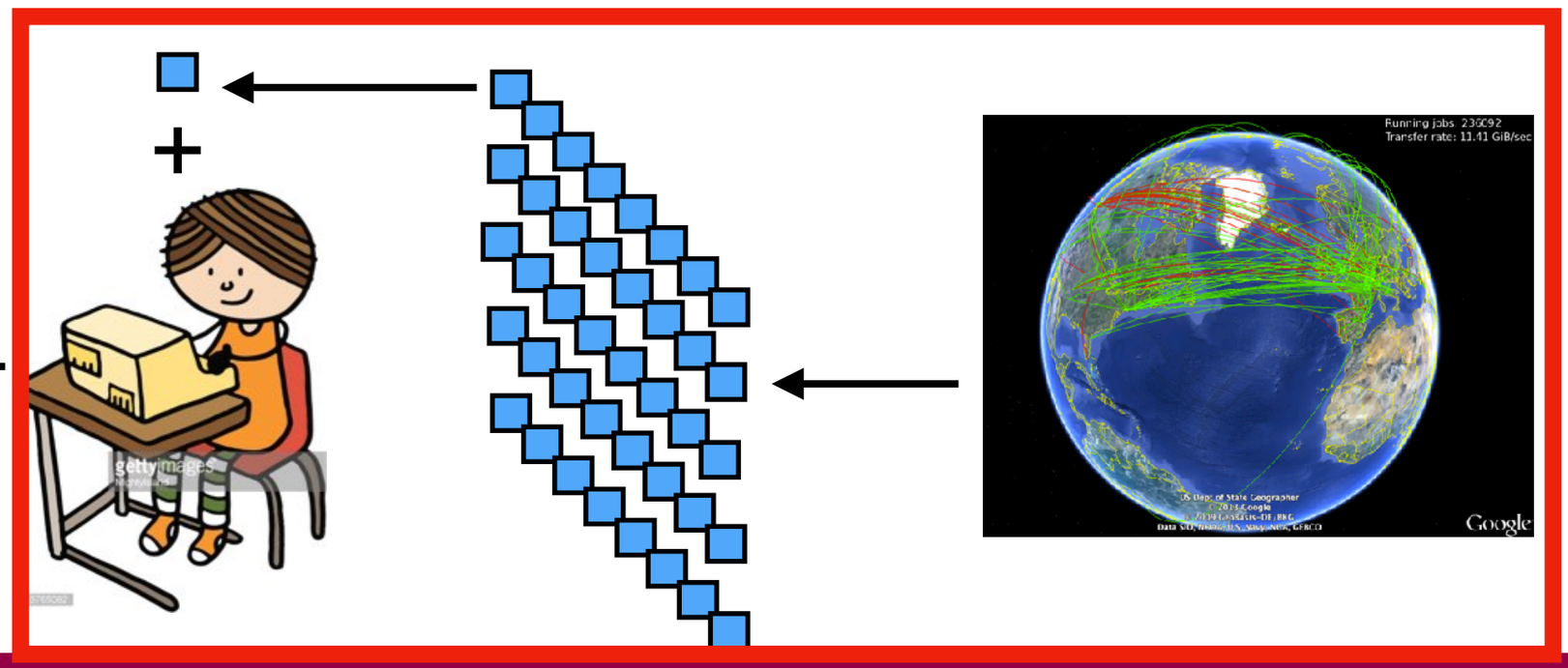








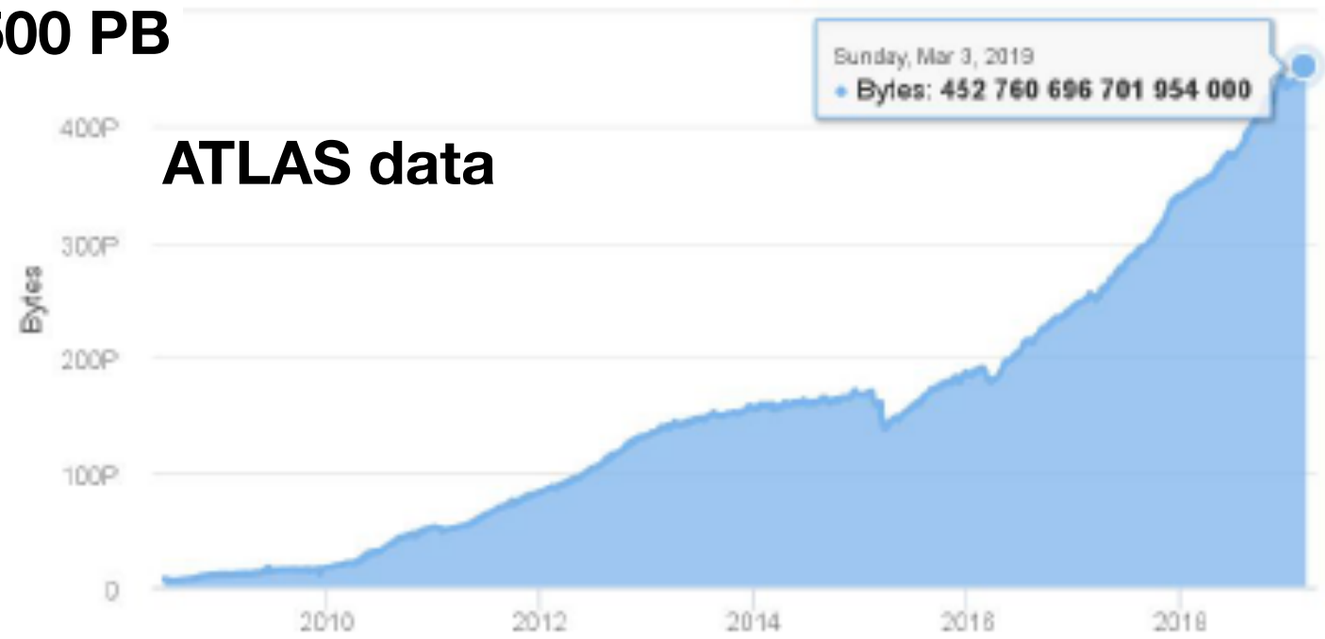


We did it !

- 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 28th through Friday 30th June.
    - I will be available for Q&A every afternoon from 3pm-4pm in restaurant 1, feel free to send questions to my email

- email: paul.laycock@unige.ch